

Yang–Mills Mass Gap in 4D: Lattice $SU(N)$ and Every Compact Simple Group

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We prove that four-dimensional lattice Yang–Mills theory with any compact simple gauge group has a unique infinite-volume state, exponential clustering and an explicit mass gap at fixed lattice spacing, past the curvature limit of the ungauged theory, with the ranges $\beta_W \leq 0.345$ for $SU(2)$ and $\beta_W \leq 0.76$ for $SU(3)$. We also prove that one estimate of Dobrushin–Shlosman type in a cube of fixed physical size gives a mass gap in physical units for every continuum limit, and that this estimate, which holds at strong coupling and remains open along the continuum tuning, needs for $SU(N)$ a cube of side at least of order $(\beta_W / \log \beta_W)^{1/4}$.

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I. INTRODUCTION

Wilson’s lattice gauge theory [69] assigns an element Q_e of a compact group $G \subset U(N)$ to every link e of $\mathbb{Z}^4$ and weighs a configuration by $\exp(N\beta \sum_p \text{Re Tr } Q_p)$, where Q_p is the ordered product of the four link variables around the plaquette p .¹ At small $|\beta|$ the theory is under control: it has a unique infinite-volume state, correlations decay exponentially, and the transfer matrix has a gap [56, 60].² The question is how far into the

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¹ This is the normalisation of Shen, Zhu and Zhu [61] and of our earlier paper [13]. The conventional inverse coupling is $\beta_W = N^2\beta$, so the weight is $\exp(\frac{\beta_W}{N} \sum_p \text{Re Tr } Q_p)$; for $SU(2)$, identified with the unit quaternions, $\frac{1}{2} \text{Tr } Q_p = \text{Re } Q_p$ and $\beta_W = 4\beta$. Standard accounts of the lattice theory are the books of Montvay and Münster [53] and of Gattringer and Lang [31]; the Hamiltonian version is due to Kogut and Susskind [44].

² Strong-coupling results of this kind go back to Osterwalder and Seiler [56], who proved exponential clustering and a gap by a convergent expansion, and to Seiler’s monograph [60]; the general framework for lattice gauge fields and their continuum limits is that of Brydges, Fröhlich and Seiler [19]. More recent work treats the strong-coupling regime by probabilistic methods: the

coupling range such statements can be proved with explicit constants, since the problem of the continuum limit [40] begins where strong coupling ends and Bałaban's weak-coupling analysis [4–6] takes over.

Two methods give explicit ranges. The Bakry–Émery method [2, 3] of Shen, Zhu and Zhu [61] bounds the Hessian of the action; in [13] we showed that the sharp bound is $4d = 16$ and that no curvature argument for the ungauged measure goes beyond $|\beta| < 1/32$. The Dobrushin method [26, 27]³ bounds the influence of each link on the conditional law of another; for $SU(2)$ the single-link conditional law is a von Mises–Fisher law on the three-sphere, the sharp Kantorovich modulus⁴ of that family is one quarter [13] (Theorem 91 in Appendix I), and every link has eighteen partners, which gives $\beta_W < 2/9$ and nothing beyond, because the coefficients are attained.

Both limits come from the same count. A link of $\mathbb{Z}^4$ lies in six plaquettes and shares each with three other links. Gauge invariance makes part of this redundant: in a box, the variables on a forest of links can be set to the identity without changing any gauge-invariant expectation [24].⁵ The forest we use is a field of straight lines with one line through every site, chosen so that every plaquette contains exactly one fixed link. Then every free link has exactly twelve free partners, two in each of its plaquettes (Lemma 9), and both methods improve.

Theorem 1 ($SU(2)$). *Let $G = SU(2)$ and $0 \leq \beta_W < \frac{1}{3}$. For every gauge-invariant local observable O the expectations $W_\Lambda(O)$ in boxes with free boundary converge, along every sequence of boxes that exhausts $\mathbb{Z}^4$, to a limit $\omega(O)$ that does not depend on the sequence. The state ω is invariant under translations and the hypercubic group and reflection positive;⁶ truncated correlations of Lipschitz observables decay at every*

rate below $-\log(3\beta_W)$; and the transfer matrix has spectral gap

$$m \geq -\log(3\beta_W) > 0.$$

For $-\frac{1}{3} < \beta_W < 0$ all statements except reflection positivity and the gap hold.

The step behind Theorem 1 is short once the line field is in place.⁷ The number $\frac{1}{3}$ is also the end of the road for this kind of argument.

Theorem 2 (Ceiling). *Let F' be any set of links of $\mathbb{Z}^4$ without cycles, and give two distinct links outside F' that share a plaquette the coefficient $|\beta|$, the largest single-link Kantorovich coefficient of $SU(2)$. Then the weighted Dobrushin condition with these coefficients fails for $\beta_W \geq \frac{1}{3}$. For the line field the coefficients are attained, so no single-link Kantorovich argument in that gauge reaches $\beta_W = \frac{1}{3}$.*

The ceiling concerns coefficients between single links. Take instead as a block the three free links of one plaquette. The free links of the line field split into such triples with period two (Lemma 12), the coupling inside the block plaquette is no longer paid for, and each link keeps ten outside partners. The price is the sensitivity of a law on three spheres instead of one, which we bound analytically by integrating out the middle link of the block.

Theorem 3 ($SU(2)$ with plaquette blocks). *Let $G = SU(2)$ and $0 \leq \beta_W \leq 0.345$. The number $\alpha(\beta_W)$ of (4) is increasing, $\alpha(\frac{1}{3}) \leq 0.9561$ and $\alpha(0.345) \leq 0.9973$. The conclusions of Theorem 1 hold with decay at every rate below $-\frac{1}{2} \log \alpha(\beta_W)$ and a transfer-matrix gap*

$$m \geq -\frac{1}{2} \log \alpha(\beta_W) > 0;$$

at $\beta_W = \frac{1}{3}$ this gives $m \geq 0.0224$. For $-0.345 \leq \beta_W < 0$ all statements except reflection positivity and the gap hold.

At small coupling the rate of Theorem 1 is the better one, so both bounds stand side by side; Theorem 3 matters past $\beta_W = \frac{1}{3}$, where the gap of Theorem 1 has closed.

survey of Chatterjee [22], his large- N solution of $SO(N)$ lattice gauge theory at strong coupling [23] and its planar extension by Basu and Ganguly [9], the Langevin dynamics of Shen, Zhu and Zhu [61], and the area law in an enlarged region by Cao, Nissim and Sheffield [21]. For finite gauge groups Adhikari and Cao proved correlation decay at weak coupling [1]. In two dimensions the continuum Yang–Mills measure has been constructed by Gross, King and Sengupta [34], Driver [29] and Lévy [45]; in four dimensions Bałaban's renormalisation group, as expounded by Dimock [25], gives ultraviolet stability in finite volume, and Magnen, Rivasseau and Sénéor constructed the theory with an infrared cutoff [49]. None of these results gives a mass gap in physical units.

³ Dobrushin's theorem: if the conditional law of each variable given all others moves, in Kantorovich distance, by at most C_{xy} times the distance by which the variable at y moves, and $\sup_x \sum_y C_{xy} < 1$, then the Gibbs measure is unique and correlations decay at the rate given by the Neumann series of the matrix C . Dobrushin and Shlosman [28] replaced single variables by finite boxes, which is the form used in Sec. X.

⁴ The Kantorovich distance between two probability measures on a metric space is the least expected distance over their couplings, equivalently the largest difference of their integrals over 1-Lipschitz functions [67]. The modulus of a family of laws indexed by a metric space is the best Lipschitz constant of the map from the index to the law in that distance.

⁵ Creutz used a maximal tree to remove the gauge freedom completely; the temporal gauge, with all links in one direction fixed, is the special case of a family of straight lines. In a maximal tree almost every link is fixed in some region and none in others, so the number of partners of a free link is not uniform, and the temporal gauge leaves fourteen partners per link. The point here is a pattern that fixes exactly one link in every plaquette.

⁶ That is, $\omega(\vartheta(F)F) \geq 0$ for every F depending on the links on one side of a

lattice hyperplane, ϑ being the reflection in it. It gives the Hilbert space and the transfer matrix of Osterwalder and Schrader [54, 55] and of Osterwalder and Seiler [56], reconstructed in Appendix F.

⁷ The combination of a forest gauge fixing with the sharp quarter of [13] was first assembled during a run of Anaxia, the reasoning engine of the BLLM system [11], release v3.0.5. In that run the engine combines proof steps along typed links (a step that produces a single-link Kantorovich bound may only feed a step that consumes one), and in every run with typed crossing it reached a composite accepting a lattice mass gap for four-dimensional $SU(2)$ at $\beta_W < \frac{1}{3}$, which no untyped or random run reached. The composite was first proposed by the language model inside the engine, and the engine's network reproduces it. The engine did not supply the line field, the free-boundary limit, the ceiling, the curvature bound or anything in the $SU(3)$ part; the authors wrote and checked every proof in this paper. Release v3.1.0 of the engine [12] records its Yang–Mills runs in the failure log: the narrowing of the target from the continuum gap to explicit couplings in this gauge, the change from analytic one-link bounds to bounds certified box by box, and the change to blocks of several links. These records follow the course of the work and supply no step of the proofs.

The curvature method gains as well, and for every N . Let $\text{Hess} S_0$ be the Hessian of $\sum_p \text{Re Tr } Q_p$ on G^E and F the set of fixed links.

Theorem 4 (Curvature in the gauge). *For every N , every field Q and every tangent vector $v = (X_e Q_e)$ with $X_e = 0$ for $e \in F$,*

$$|\text{Hess} S_0(v, v)| \leq \frac{29}{2} |v|^2,$$

against the sharp constant 16 without gauge fixing. Consequently, for $G = \text{SU}(N)$ and $|\beta| < \frac{1}{29}$, or $G = \text{SO}(N)$, $N \geq 3$, and $|\beta| < \frac{N-2}{58N}$, the conclusions of Theorem 1 hold with the rate and gap of Theorem 5. For $\text{SU}(3)$ this is $\beta_W < \frac{9}{29} = 0.310$.

The constant $\frac{29}{2}$ is a statement about $\text{U}(N)$, so it holds on every closed subgroup, and the curvature of the group does the rest. This gives the theorem for every compact simple gauge group, the exceptional groups included, with an explicit gap. Let $\rho : G \rightarrow \text{U}(N)$ be a faithful unitary representation of a compact connected Lie group G , weigh a configuration by $\exp(N\beta \sum_p \text{Re Tr } \rho(Q_p))$, and let κ_G be the least Ricci⁸ curvature of G for the bi-invariant metric $\langle X, Y \rangle = -\text{Tr}(\rho(X)\rho(Y))$; we identify G with $\rho(G) \subset \text{U}(N)$.

Theorem 5 (Every compact simple group). *Suppose that the Lie algebra of G is semisimple, so that $\kappa_G > 0$, and that*

$$N|\beta| < \frac{29}{2} \kappa_G.$$

Then the conclusions of Theorem 1 hold, for $\beta < 0$ all of them except reflection positivity and the gap, with decay at every rate below

$$m_G(\beta) = \text{arccosh}\left(1 + \frac{1}{12} \left(\frac{\kappa_G}{N|\beta|} - \frac{29}{2}\right)\right) > 0$$

and a transfer-matrix gap $m \geq m_G(\beta)$. For a simple G , $\kappa_G = h^\vee/(2\ell_\rho)$, where $h^\vee$ is the dual Coxeter number and ℓ_ρ the Dynkin index of ρ ; Table I lists the values.

For $\text{SU}(N)$, $\kappa_G = \frac{N}{2}$, and for $\text{SO}(N)$, $\kappa_G = \frac{N-2}{4}$, so Theorem 5 contains the ranges of Theorem 4 and supplies their rate.⁹ For small $|\beta|$ the existence of a gap is classical for every compact group, with no explicit range [56, Thm. 3.6]; what is new is an explicit range for every group, past the range $N|\beta| < \kappa_G/16$ that the Hessian bound 16 gives without gauge fixing, and an explicit gap. As $\beta \rightarrow 0$ the gap grows like $\log \frac{\kappa_G}{6N|\beta|}$.

⁸ For a bi-invariant metric on a compact Lie group the Ricci curvature is $-\frac{1}{4} \text{Tr}(\text{ad } X)^2$ in the direction of X . It is positive for every $X \neq 0$ exactly when the Lie algebra is semisimple, and κ_G is its minimum over unit vectors.

⁹ The dual Coxeter number is $h^\vee = N$ for $\text{SU}(N)$, $N-2$ for $\text{SO}(N)$, $n+1$ for $\text{Sp}(n)$, 4, 9, 12, 18, 30 for G_2, F_4, E_6, E_7, E_8 , and the Dynkin index of a representation is normalised to one on the defining representation of $\text{SU}(N)$ [42, Ch. 6]. The identity $\kappa_G = h^\vee/(2\ell_\rho)$ is the statement that the Ricci tensor of a compact simple group with a bi-invariant metric is one quarter of the negative Killing form, $\text{Ric}(X, X) = -\frac{1}{4}B(X, X)$ [52], together with $B(X, X) = 2h^\vee \text{Tr}(\rho(X)^2)/\ell_\rho$. Lower Ricci bounds of the same kind, for special holonomy and for Riemannian submersions, are studied in [17, 32].

TABLE I. Least Ricci curvature $\kappa_G = h^\vee/(2\ell_\rho)$ of the compact simple groups in a faithful representation ρ of least dimension N , and the range of Theorem 5 for the conventional inverse coupling $\beta_W = N^2\beta$.

Group	ρ	$h^\vee$	ℓ_ρ	κ_G	$\beta_W <$
$\text{SU}(N)$, $N \geq 2$	$\mathbb{C}^N$	N	1	$\frac{N}{2}$	$\frac{N^2}{29}$
$\text{SO}(N)$, $N \geq 5$	$\mathbb{R}^N$	$N-2$	2	$\frac{N-2}{4}$	$\frac{N(N-2)}{58}$
$\text{SO}(3)$	$\mathbb{R}^3$	2	4	$\frac{1}{4}$	$\frac{3}{58}$
$\text{Sp}(n)$, $n \geq 2$	$\mathbb{C}^{2n}$	$n+1$	1	$\frac{n+1}{2}$	$\frac{2n(n+1)}{29}$
G_2	7	4	2	1	$\frac{14}{29}$
F_4	26	9	6	$\frac{3}{4}$	$\frac{39}{29}$
E_6	27	12	6	1	$\frac{54}{29}$
E_7	56	18	12	$\frac{3}{4}$	$\frac{84}{29}$
E_8	248	30	60	$\frac{1}{4}$	$\frac{124}{29}$

No Bakry–Émery argument for the ungauged measure can pass $|\beta| = \frac{1}{32}$ [13, Thm. C]; the gauge fixing changes the measure, not the metric, which is why it can. For $\text{SU}(2)$ the curvature range $\beta_W < \frac{4}{29}$ lies inside that of Theorem 1, and no curvature argument for the gauge-fixed $\text{SU}(2)$ measure passes $\beta_W = \frac{1}{3}$: when one active link e is -1 and all others are 1, the six plaquettes through e have variable -1 , and along a geodesic through Q_e the Hessian of $-\frac{\beta_W}{2} \sum_p \text{Re Tr } Q_p$ is $-6\beta_W$ times the metric of the unit sphere S^3 , whose Ricci curvature is 2, so the Bakry–Émery tensor is negative there once $\beta_W > \frac{1}{3}$. For $\text{SU}(3)$ the Dobrushin route goes much further.

Theorem 6 ($\text{SU}(3)$). *Let $G = \text{SU}(3)$ and $0 \leq \beta_W \leq \frac{3}{4}$. Then the conclusions of Theorem 1 hold, with decay at every rate below $-\log(1.33319\beta_W)$ and a transfer-matrix gap*

$$m \geq -\log(1.33319\beta_W) > 0.$$

The proof of Theorem 6 bounds the Kantorovich modulus of the one-link measure $\nu_b(dU) \propto e^{\text{Re Tr}(U^b)} dU$ on $\text{SU}(3)$ uniformly over staple sums b . Its analytic part is a lower bound for the spectral gap of ν_b through Bochner’s formula with a cross term (Lemma 29), a corrector chosen box by box among polynomials of degree two in the matrix entries (Lemma 30), the reduction of b to diagonal matrices (Lemma 31), the character expansion of the moments of ν_b (Lemma 32) and an interpolation inequality on boxes of staple sums (Lemma 33). The remaining step evaluates the resulting bound on 2341 boxes with rigorous error bounds; the theorem rests on that computation, which is described in full in Sec. VII G and Appendix E.

The plaquette blocks of Theorem 3 work for $\text{SU}(3)$ as well. They use the same modulus of the one-link measure, but only through the three links of a block, so they need $\Lambda(2\beta_W)$ small and not $2r\Lambda(r) < 1$: near the end of Theorem 6 they give a much larger gap, and they go past it.

Theorem 7 ($\text{SU}(3)$ with plaquette blocks). *Let $G = \text{SU}(3)$ and $0 \leq \beta_W \leq \frac{19}{25} = 0.76$. Then $\alpha_3(\beta_W) < 1$ for the number of (15), with $\alpha_3(0.72) \leq 0.9182$, $\alpha_3(\frac{3}{4}) \leq 0.9653$ and $\alpha_3(0.76) \leq 0.99950$. The conclusions of Theorem 1 hold with decay at every rate below $-\frac{1}{2} \log \alpha_3(\beta_W)$ and a transfer-matrix*

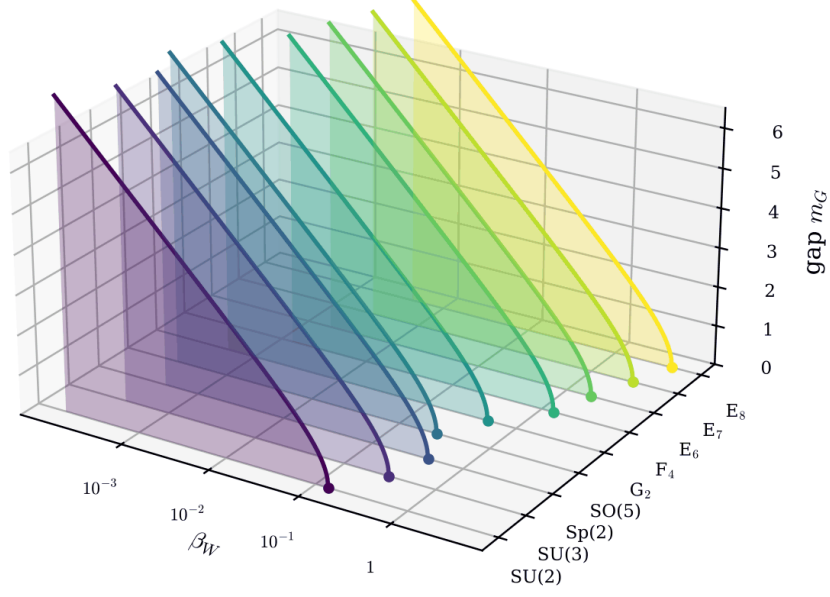


FIG. 1. The gap $m_G(\beta)$ of Theorem 5 as a function of $\beta_W = N^2\beta$ on a logarithmic scale, for nine groups in the representations of Table I. Each curve ends at the edge $\beta_W = 2N\kappa_G/29$ of the range, marked by a dot, where the gap tends to zero; as $\beta_W \rightarrow 0$ it grows like $\log(\kappa_G/(6N|\beta|))$. The curves differ only by the factor $N\kappa_G$, since m_G depends on $N|\beta|/\kappa_G$ alone.

TABLE II. Explicit ranges of uniqueness, decay and a transfer-matrix gap for four-dimensional lattice Yang–Mills theory. The first three rows hold for the ungauged measure; the last three are the results of this paper.

Method	SU(2), β_W	SU(3), β_W
Curvature, Shen–Zhu–Zhu [61]	$< \frac{1}{12}$	$< \frac{3}{16}$
Curvature, sharp [13]	$< \frac{1}{8}$	$< \frac{9}{32}$
Dobrushin, sharp quarter [13]	$< \frac{2}{9}$	
Curvature, forest gauge	$< \frac{4}{29}$	$< \frac{9}{29}$
Dobrushin, forest gauge	$< \frac{1}{3}$	$\leq \frac{3}{4}$
Plaquette blocks, forest gauge	≤ 0.345	≤ 0.76

gap

$$m \geq -\frac{1}{2} \log \alpha_3(\beta_W) > 0;$$

at $\beta_W = \frac{3}{4}$ this gives $m \geq 0.0177$, against $1.1 \cdot 10^{-4}$ from Theorem 6, and at $\beta_W = 0.76$, where Theorem 6 no longer applies, $m \geq 2.5 \cdot 10^{-4}$.

All seven theorems are statements at fixed lattice spacing. They do not touch the continuum limit, the crossover to Balaaban’s regime, or a gap in physical units, which together are the Clay problem; Sec. IX says where each method stops and what remains of the four open problems of [13]. The obstruction proved in [14], that a lattice gap uniform in lattice units forces trivial continuum two-point functions, applies to all of them.

The continuum step. Sec. X goes past that obstruction in one respect, through three implications, each proved.

- (I1) A Dobrushin–Shlosman condition on one cube of fixed physical size, uniform along the continuum tuning, gives a mass gap in physical units for every continuum limit (Theorems 43 and 45), also for observables smoothed by the spatial gradient flow (Proposition 46).
- (I2) The flowed observables, renormalised by one condition at a single physical separation, have reflection positive continuum limits along subsequences, and such a limit is nontrivial exactly when one ratio of lattice two-point functions stays away from zero (Theorem 47); that ratio is bounded above and below by ratios of correlations of one slice field at fixed physical separations (Proposition 50).
- (I3) Tree bounds on the truncated correlations give all the higher Schwinger functions as reflection positive distributions, imply the ratio bound, and carry the conditional mass gap to every polynomial in the smeared fields (Theorem 55); for a smooth packet they give the ratio with an explicit rate and a reference vector of finite energy (Proposition 59).

What is open. The inputs of (I1)–(I3), namely the cube condition along the tuning, the slice ratio in four dimensions and the tree bounds, are not proved, and so the nontrivial existence of the continuum limit and the gap in physical units remain open. Figure 3 shows how the proved statements, the implications and the open inputs fit together. The open inputs are measured as follows. The cube condition holds at strong coupling, fails

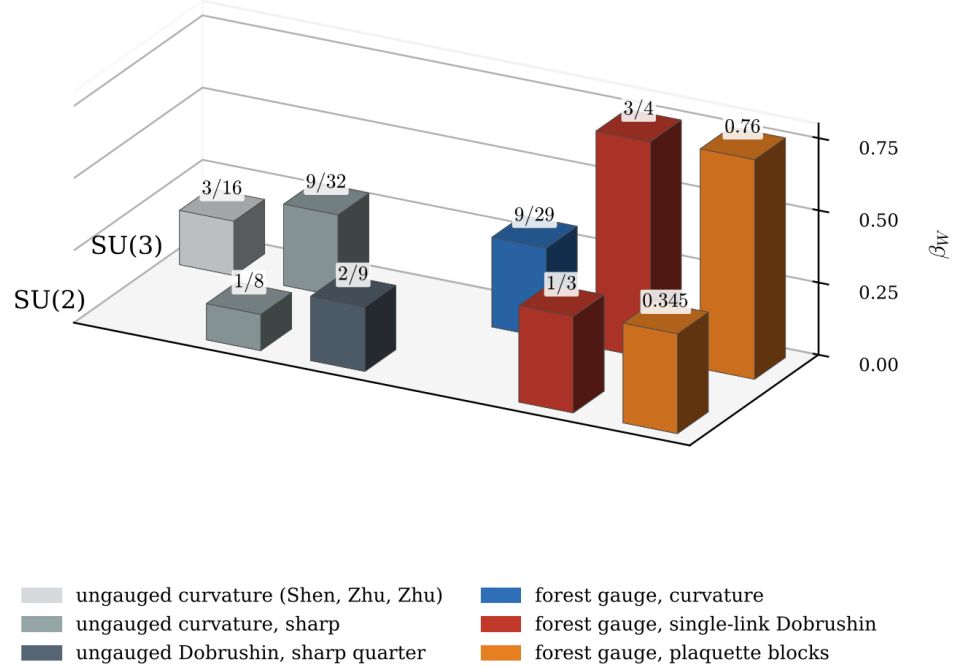


FIG. 2. Ranges of Table II. The height of each bar is the largest inverse coupling β_W covered by the method. Grey bars are methods for the ungauged measure; blue, red and orange bars use the forest gauge. For SU(2) the red bar ends at the ceiling of Theorem 2 and the orange bar, plaquette blocks, passes it (Theorem 3); for SU(3) the red bar is Theorem 6 and the orange bar, plaquette blocks, gives a larger gap there and passes it (Theorem 7).

at every fixed cube size at weak coupling, forces the gauge-fixed variables to be disordered on the scale of the cube, and cannot be reached from estimates on single lines of links; for SU(N) it needs cubes of side at least of order $(\beta_W / \log \beta_W)^{1/4}$ (Propositions 73 and 74). For a Gaussian field it holds at a fixed physical scale when the field has a mass and fails exactly, at every size, when it is massless (Proposition 64); it also fails for the quadratic approximation of the forest gauge itself (Proposition 65). The order-two cases of the tree bounds force the lattice gap below a fixed multiple of the lattice spacing, so no strong coupling expansion gives them (Proposition 58). The slice ratio holds in two dimensions, where it is the exact solution of lattice gauge theory (Remark 52), and fails for a field whose mass is fixed in lattice units; for the free field, conditioning an energy packet on averages over blocks leaves a fixed fraction of its ordinary variance at every lattice spacing, so a reduction to block averages has to be measured in the reflected norm (Proposition 53).

Plan. Sec. II constructs the line field. Sec. III shows that a Dobrushin bound for the gauge-fixed specification gives the full conclusion of Theorem 1. Secs. IV, V, VI, VII and VIII prove Theorems 1–7, and Sec. IX measures what is left; Sec. X proves (I1)–(I3) and measures the open inputs. The appendices contain the residue table of the line field, the comparison lemma and its version for blocks, the blocks of the local Hessian inequality, the details of the certified computation, the reconstruction of the transfer matrix with the equivalence of a gap and exponential clustering (Appendix F), the facts on

spectral measures and on the character expansion that the continuum step uses (Appendices G and H), and a complete proof of the sharp quarter for the single-link law of SU(2) (Appendices I–K), so that the paper does not depend on our earlier one for any step.

II. THE LINE FIELD

Write $e_0, \dots, e_3$ for the unit vectors of $\mathbb{Z}^4$ and (x, μ) for the link from x to $x + e_\mu$. A *direction field* is a map $\sigma : \mathbb{Z}^4 \rightarrow \{0, 1, 2, 3\}$; its links are $F = \{(x, \sigma(x)) : x \in \mathbb{Z}^4\}$. At each site put $\pi_x(\mu) = \sigma(x + e_\mu)$. The plaquette at x in the plane $\{\mu, \nu\}$ has the links (x, μ) , $(x + e_\mu, \nu)$, $(x + e_\nu, \mu)$, (x, ν) , so it contains

$$[\sigma(x) \in \{\mu, \nu\}] + [\pi_x(\mu) = \nu] + [\pi_x(\nu) = \mu] \quad (1)$$

links of F .

Lemma 8. *Every plaquette of $\mathbb{Z}^4$ contains exactly one link of F if and only if, at every site x , π_x fixes $\sigma(x)$ and permutes the other three directions cyclically.*

Proof. Fix x , let $s = \sigma(x)$ and let R be the set of the other three directions. For a plane $\{s, \nu\}$ the count (1) is $1 + [\pi_x(s) = \nu] + [\pi_x(\nu) = s]$; it equals one for all $\nu \in R$ exactly when $\pi_x(s) = s$ and $\pi_x(\nu) \neq s$ for $\nu \in R$, that is, when π_x fixes s and maps R into R . For a plane $\{\mu, \nu\} \subset R$ the count is $[\pi_x(\mu) =$

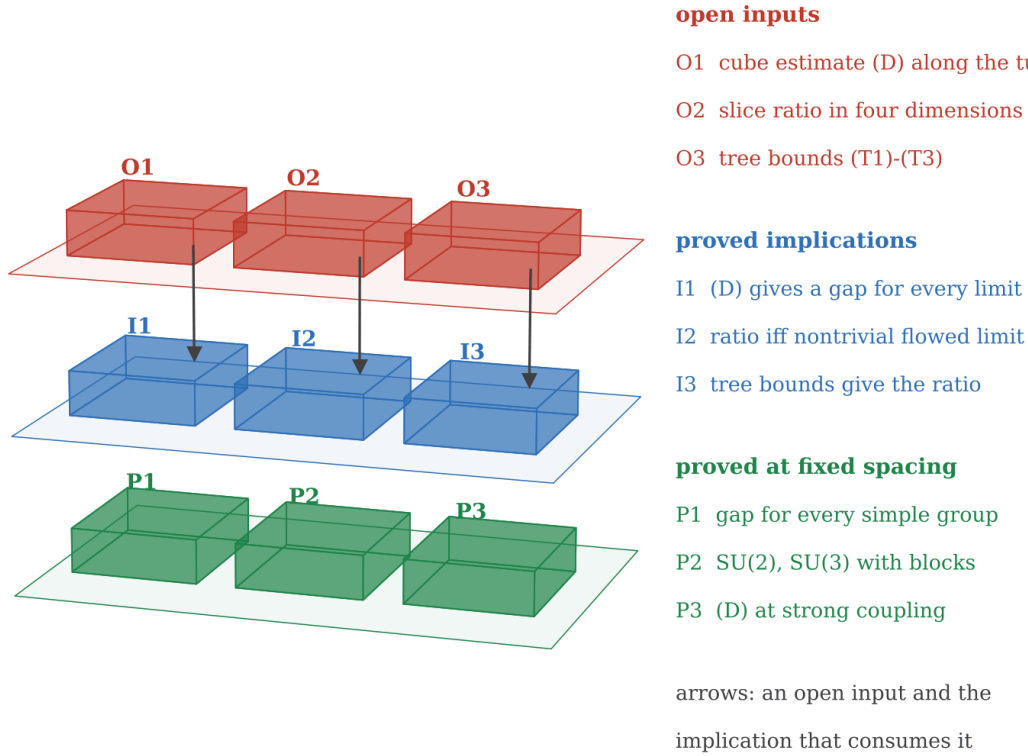


FIG. 3. The logical structure of the paper. Green: theorems at fixed lattice spacing (P1 the gap for every compact simple group, Theorem 5, P2 the plaquette blocks for SU(2) and SU(3), P3 the cube condition at strong coupling). Blue: the proved implications (I1)–(I3) of the continuum step. Red: their inputs, none of which is proved along the continuum tuning. Each arrow joins an open input to the implication that consumes it; no implication feeds its own input.

$v] + [\pi_x(v) = \mu]$. Draw an arrow $\mu \rightarrow \pi_x(\mu)$ for every $\mu \in R$ with $\pi_x(\mu) \in R \setminus \{\mu\}$. Each vertex of R has at most one outgoing arrow, and the condition says that each of the three pairs of R carries exactly one arrow. Three arrows on three vertices with out-degree at most one give out-degree exactly one everywhere, and a tournament on three vertices with all out-degrees one is a directed three-cycle. $\square$

From now on σ is the field of period two given in Table III of Appendix A, read from x modulo two. The table lists π_x at each of the sixteen residue classes; in each row π_x fixes $\sigma(x)$ and is a three-cycle on the rest, so every plaquette contains exactly one link of F by Lemma 8.¹⁰

Lemma 9. (i) F is a disjoint union of bi-infinite straight lines, one through every site: every site has exactly one outgoing and one incoming link of F , and both point in the direction $\sigma(x)$.

- (ii) For every box Λ (a product of four finite intervals, with the links and plaquettes it contains), $F \cap E(\Lambda)$ is a disjoint union of segments, hence a forest.
- (iii) A link $e = (x, \mu) \notin F$ lies in six plaquettes. Four of them contain a link of F that shares an end point with e , and these lie in the planes $\{\mu, \sigma(x)\}$ and $\{\mu, \pi_x(\mu)\}$. In the other two, which lie in the remaining plane $\{\mu, \rho\}$, the link of F is opposite to e .
- (iv) Every link outside F shares a plaquette with exactly twelve other links outside F , two in each of its plaquettes.

Proof. (i) Since π_x fixes $\sigma(x)$, $\sigma(x + e_{\sigma(x)}) = \sigma(x)$. Because σ has period two, $x - e_\mu \equiv x + e_\mu$, so also $\sigma(x - e_{\sigma(x)}) = \sigma(x)$, and the link $(x - e_{\sigma(x)}, \sigma(x))$ is in F . Conversely, if $(x - e_v, v) \in F$, then $\sigma(x - e_v) = v$, and straightness at $x - e_v$ gives $\sigma(x) = v$. So the incoming link is unique and continues the outgoing one.

(ii) A line meets a box in a segment, and distinct lines are disjoint.

(iii) The plaquettes of e are, for each $v \neq \mu$, the one at x and the one at $x - e_v$ in the plane $\{\mu, v\}$. A link of F sharing an end point with e is the outgoing or the incoming link of F at x or at $x + e_\mu$. At x both point in the direction $s = \sigma(x) \neq \mu$, and they lie in the plaquettes at x and at $x - e_s$ in the plane

¹⁰ There are exactly eight period-two direction fields with this property, all equivalent to σ under the symmetries of the lattice. A field with one fixed link at every site and one in every plaquette exists only in four dimensions: a link lies in $2(d-1)$ plaquettes and a site carries $d(d-1)/2$ of them, and $2(d-1) = d(d-1)/2$ forces $d = 4$. The statements of this section are also checked by decide in the Lean file GaugeFix.lean of the archive.

$\{\mu, s\}$. At $x + e_\mu$ both point in the direction $t = \pi_x(\mu)$, which lies in $R \setminus \{\mu\}$ because π_x is a three-cycle on R , and they lie in the plaquettes at x and at $x - e_t$ in the plane $\{\mu, t\}$. These four plaquettes are distinct because $s \neq t$. Each plaquette contains exactly one link of F , so in the two plaquettes of the third plane $\{\mu, \rho\}$ the link of F is a link of direction μ or ρ not touching e ; the links of direction ρ in such a plaquette touch e , so it is the opposite link.

(iv) Each of the six plaquettes contains e , one link of F and two other links, and two distinct links share at most one plaquette. $\square$

III. GAUGE FIXING AND THE FREE-BOUNDARY STATE

Let $G \subset U(N)$ be compact with Haar measure dU , and let Λ be a box. The Wilson measure with free boundary is

$$W_\Lambda(dQ) = \frac{1}{Z_\Lambda} \exp\left(N\beta \sum_{p \in P(\Lambda)} \text{Re Tr } Q_p\right) \prod_{e \in E(\Lambda)} dQ_e.$$

The measure is invariant under the gauge transformations $Q_{(x,y)} \mapsto g_x Q_{(x,y)} g_y^{-1}$ with $g \in G^\Lambda$. Call the links outside F *active* and write A for their set. For a function O of the links, O^F is O with every link of F set to the identity.

Lemma 10 (Gauge fixing). *Let μ_Λ^F be the probability measure on $G^{A \cap E(\Lambda)}$ whose density with respect to Haar measure is proportional to $\exp(N\beta \sum_{p \in P(\Lambda)} \text{Re Tr } Q_p^F)$. For every gauge-invariant O on $G^{E(\Lambda)}$,*

$$W_\Lambda(O) = \mu_\Lambda^F(O^F).$$

Proof. Each segment of $F \cap E(\Lambda)$ is a path $x_0, x_1, \dots, x_k$ along one direction. Given the variables on F , put $g_{x_0} = 1$ and $g_{x_{i+1}} = g_{x_i} Q_{(x_i, x_{i+1})}$ on every segment. The transformed field has $Q_e^g = 1$ on $F \cap E(\Lambda)$, and for fixed values on F the map $Q_\Lambda \mapsto Q_\Lambda^g$ is a product of left and right translations, which preserves Haar measure. Gauge invariance of the action and of O and the change of variables give the claim. $\square$

No leftover holonomy appears because $F \cap E(\Lambda)$ is a forest. The measures μ_Λ^F are finite-volume versions of the specification γ^F on G^A : for $e \in A$, γ_e^F resamples Q_e from the law with density proportional to $\exp(N\beta \sum_{p \ni e} \text{Re Tr } Q_p^F)$ given all other active links. No infinite-volume gauge transformation is performed; γ^F is a specification in its own right. Fix a metric δ on G of diameter D that is bi-invariant (for $SU(2)$ the chordal metric on S^3 , $D = 2$; for $SU(N)$ the Hilbert–Schmidt distance). The Kantorovich coefficient of e' on e is

$$C_{ee'} = \sup \frac{W_1(\gamma_e^F(\cdot | Q), \gamma_{e'}^F(\cdot | Q'))}{\delta(Q_e, Q_{e'})},$$

the supremum over pairs of configurations that differ only at e' . It vanishes unless e and e' share a plaquette.

Proposition 11. *Suppose that every row and every column of $(C_{ee'})$ sums to at most $\alpha < 1$. Then:*

- (i) γ^F has exactly one Gibbs measure μ_F ;
- (ii) for every gauge-invariant local O the limit $\omega(O) = \lim W_\Lambda(O)$ exists along every sequence of boxes exhausting $\mathbb{Z}^4$ and equals $\mu_F(O^F)$;
- (iii) ω is invariant under translations and the hypercubic group;
- (iv) if $\beta \geq 0$, ω is reflection positive for reflections in hyperplanes through sites and in hyperplanes bisecting links;
- (v) for gauge-invariant local O, O' with O Lipschitz in each link, $|\text{Cov}_\omega(O, O')| \leq C_{O, O'} e^{-\lambda \text{dist}(O, O')}$ for every $\lambda < -\log \alpha$;
- (vi) if $\beta \geq 0$, the transfer matrix of ω has spectral gap at least $-\log \alpha$.

Proof. (i) Gibbs measures exist by compactness, and the comparison lemma of Appendix B with $S = \emptyset$ shows that any two coincide.

(ii) Extend μ_Λ^F by Haar measure on the active links outside Λ , and let S be the set of active links with a plaquette outside $P(\Lambda)$; this includes every active link outside $E(\Lambda)$. For an active link $e \notin S$ all six plaquettes of e lie in $P(\Lambda)$, so the conditional law of Q_e under the extended measure is γ_e^F . Let T be the support of O^F and $\lambda < -\log \alpha$. The comparison lemma with weights $e^{-\lambda \text{dist}(\cdot, T)}$ gives

$$|\mu_\Lambda^F(O^F) - \mu_F(O^F)| \leq L \frac{\theta D}{1 - \theta} \sum_{z \in S} e^{-\lambda \text{dist}(z, T)},$$

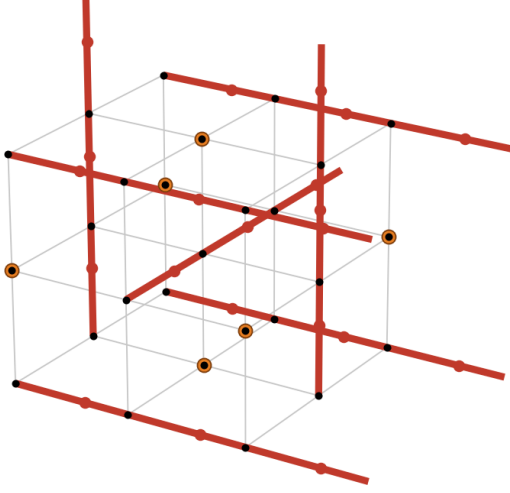
with $\theta = \alpha e^\lambda < 1$ and L a Lipschitz constant of O^F ; the sum is at most $C_T R^3 e^{-\lambda R}$ when R is the distance from T to the complement of Λ . For O continuous but not Lipschitz, approximate uniformly. Lemma 10 gives $W_\Lambda(O) = \mu_\Lambda^F(O^F)$.

(iii) $W_\Lambda(\tau_v O) = W_{\Lambda-v}(O)$, and the boxes $\Lambda - v$ also exhaust $\mathbb{Z}^4$; by (ii) the limit does not depend on the sequence. The line field is a device for computing W_Λ and is never shifted. The same argument applies to the hypercubic group.

(iv) For $\beta \geq 0$ the measure W_Λ is reflection positive for every box symmetric under the reflection [56], and reflection positivity passes to the limit along such boxes, which is ω by (ii).

(v) $\text{Cov}_\omega(O, O') = \text{Cov}_{\mu_F}(O^F, O'^F)$, and setting the links of F to the identity keeps the Lipschitz property. The bound is Corollary 79.

(vi) Let ϑ be a time reflection and τ_t a time translation. For gauge-invariant local O that are Lipschitz in each link, (v) gives $|\omega(\vartheta(\bar{O})\tau_t O) - \omega(O)|^2 \leq C_O e^{-\lambda t}$. On the support of O these functions are dense in the gauge-invariant part of $L^2(\omega)$: gauge-invariant functions are functions on the compact quotient of G^E by the gauge group, Lipschitz functions for the quotient metric are dense in L^2 of every finite measure on it, and they lift to gauge-invariant Lipschitz functions. By Proposition 82 the spectrum of the transfer matrix on the complement of the vacuum lies in $[0, e^{-\lambda}]$, for every $\lambda < -\log \alpha$. $\square$

(a) the line field in the slice $x_3 = 0$ 

(b) one plaquette in the gauge

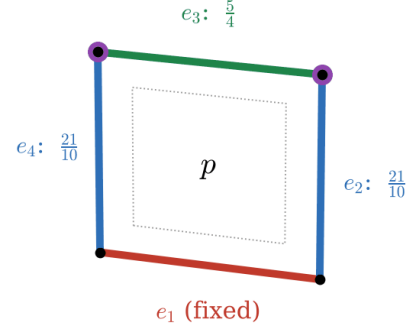


FIG. 4. (a) The line field in the slice $x_3 = 0$ of a box of side three. Thick red segments are the links of F in the directions 0, 1, 2, with a dot marking the direction of travel; an orange ring marks a site whose line leaves the slice in direction 3. Every line is straight (Lemma 9(i)), and the segments that leave the box are its boundary stubs. (b) One plaquette with its fixed link e_1 . The weights are those of the local inequality of Lemma 20 for the three free links: $\frac{21}{10}$ on the two links adjacent to e_1 and $\frac{5}{4}$ on the opposite one. The two purple corners are the ones that enter the corner form (7) once $Y_1 = 0$.

The proposition replaces the torus limits and the uniqueness of the ungauged Gibbs measure used in [13, Thm. F] by the free-boundary limit, which has all the properties the reconstruction of the transfer matrix needs.¹¹

IV. SU(2) UP TO ONE THIRD

Proof of Theorem 1. Identify SU(2) with the unit quaternions and use the chordal metric. For an active link e and a plaquette $p \ni e$, the staple s_p is the product of the other three link variables in the order that makes $\text{Re}(Q_e s_p) = \frac{1}{2} \text{Tr} Q_p$, with links of F equal to one. Since $N\beta \text{Re Tr} Q_p = 4\beta \langle Q_e, \bar{s}_p \rangle$ in $\mathbb{R}^4$, the conditional law of Q_e is the von Mises–Fisher law $v_b(dx) \propto e^{(x,b)} dx$ on S^3 with $b = 4\beta \sum_{p \ni e} \bar{s}_p$. Changing a partner e' by δ in the chordal metric changes one staple by an isometric image of that displacement, so b moves by $4|\beta|\delta$, and the sharp quarter (Theorem 91), $W_1(v_b, v_{b'}) \leq \frac{1}{4}|b - b'|$, gives $C_{ee'} \leq |\beta|$. By Lemma 9(iv) every row and column has twelve nonzero entries, so $\alpha \leq 12|\beta| = 3|\beta_W|$. Proposition 11 applies for $|\beta_W| < \frac{1}{3}$. $\square$

Proof of Theorem 2. For the line field, every staple of an active link contains two active links, so the six staples can be chosen with sum zero while the staple through a given partner e' moves

freely. At $b = 0$ the derivative of v_b in the direction h has Kantorovich norm $\frac{1}{4}|h|$ by Lemma 90(i), so $C_{ee'} = |\beta|$ exactly, and every row sum is $12|\beta| = 3|\beta_W|$.

Now let F' be any forest and C' the matrix of the statement. Suppose a positive weight w satisfies $C'w \leq \alpha w$. For a box Λ_n of side n let C_n be the principal submatrix on the active links of $E(\Lambda_n)$; then $C_n w \leq \alpha w$ on these links, and the Collatz–Wielandt inequality for nonnegative matrices gives $\rho(C_n) \leq \alpha$. Since C_n is symmetric, $\rho(C_n)$ is at least the mean row sum. The box has $4n^4 - O(n^3)$ links and n^4 sites, and a forest has fewer links than sites, so the number a of active links is at least $3n^4 - O(n^3)$. Let a_p be the number of active links of the plaquette p ; the box has $P = 6n^4 - O(n^3)$ plaquettes and $\sum_p a_p = 6a - O(n^3)$. Two links share at most one plaquette, so the row sums add up to $|\beta| \sum_p a_p (a_p - 1)$, and by convexity

$$\frac{|\beta|}{a} \sum_p a_p (a_p - 1) \geq \frac{|\beta|P}{a} \bar{a}(\bar{a} - 1) = 6|\beta|(\bar{a} - 1) - o(1),$$

with $\bar{a} = \sum_p a_p / P = 6a/P - o(1) \geq 3 - o(1)$. Hence $\alpha \geq 12|\beta| - o(1)$ for every n , and $\alpha \geq 12|\beta| = 3|\beta_W|$. $\square$

Without gauge fixing the same count gives eighteen partners and the ceiling $\beta_W = \frac{2}{9}$ of [13, Prop. 13]; the temporal gauge, a family of lines in one direction, leaves fourteen. The line field is optimal among forests: twelve is the mean number of partners forced by the number of free links, and it is attained at every link.

¹¹ On a torus the line field closes up into cycles, and the holonomies along them cannot be removed by a gauge transformation; the argument never uses a torus. The state ω is defined only on gauge-invariant observables, which is all that the Osterwalder–Schrader reconstruction [54–56] uses.

V. SU(2) PAST ONE THIRD: PLAQUETTE BLOCKS

Throughout this section $G = \text{SU}(2)$ is the group of unit quaternions with the chordal metric $|x - y|$, $\bar{x}$ is the conjugate, $\langle x, y \rangle = \text{Re}(x\bar{y})$ is the inner product of $\mathbb{R}^4$, and dx is the normalised Haar measure on S^3 . Left and right multiplication by unit quaternions and conjugation are isometries, and $\text{Re}(xyz) = \text{Re}(y\bar{z}x) = \langle y, \bar{z}\bar{x} \rangle$. Put

$$Z_0(c) = \int_{S^3} e^{\langle c, x \rangle} dx = \sum_{j \geq 0} \frac{(|c|^2/4)^j}{j!(j+1)!}, \quad c \in \mathbb{R}^4,$$

let $v_c(dx) \propto e^{\langle c, x \rangle} dx$ be the von Mises–Fisher law, and write $g = \log Z_0$, so that $\nabla g(c)$ is the mean and $\text{Hess} g(c)$ the covariance of v_c .

A. The blocks

A *block plaquette* is a plaquette of the set $\mathcal{B}$ described in Table IV of Appendix C, and its *block* is the set of its three active links.

Lemma 12. *The set $\mathcal{B}$ is invariant under translations by $2\mathbb{Z}^4$ and:*

- (i) *the blocks partition the active links;*
- (ii) *every plaquette $p \notin \mathcal{B}$ meets three distinct blocks, one in each of its active links;*
- (iii) *every active link lies in exactly five plaquettes outside $\mathcal{B}$, so it shares a plaquette outside $\mathcal{B}$ with exactly ten active links, none of them in its own block;*
- (iv) *if an active link j and a link of a block B lie in a common plaquette outside $\mathcal{B}$, then every link of B has its midpoint within distance 2 of the midpoint of j .*

Proof. All four statements are invariant under $2\mathbb{Z}^4$ and involve plaquettes at distance at most two from one site, so they hold on $\mathbb{Z}^4$ as soon as they hold on the torus $(\mathbb{Z}/P\mathbb{Z})^4$ with $P \geq 6$, where no such configuration wraps around. They are checked on the tori of side four and six by the program described in Appendix C; the side four already suffices for (i)–(iii). For (iii), an active link lies in six plaquettes, one of which is its block plaquette, and each of the other five contains two further active links, which lie in other blocks by (ii). $\square$

Fix a block plaquette p with active links e_1, e_2, e_3 . Reading the plaquette product cyclically and deleting its fixed link, $\frac{1}{2} \text{Tr} Q_p = \text{Re}(y_1 y_2 y_3)$, where y_i is Q_{e_i} or $Q_{e_i}^{-1}$. Every other plaquette containing e_i meets the block only in e_i by Lemma 12(ii) and contributes $4\beta \langle y_i, \bar{s} \rangle$ to the exponent, where s is the staple of y_i in it. Hence the conditional law of the block given all other active links is

$$\mu_b(dy) \propto \exp\left(\sum_{i=1}^3 \langle y_i, b_i \rangle + 4\beta \text{Re}(y_1 y_2 y_3)\right) dy_1 dy_2 dy_3, \quad (2)$$

with b_i the sum of $4\beta \bar{s}$ over the five staples, so that $|b_i| \leq 20|\beta|$. Inversion is an isometry of S^3 and preserves Haar measure, so we may work with y instead of Q . On $(S^3)^3$ we use the metric $d(y, y') = \sum_i |y_i - y'_i|$.

B. The sensitivity of one block

Let λ_* and τ be a lower and an upper bound for the eigenvalues of $\text{Hess} g(c)$ on the ball $|c| \leq 24|\beta|$, and M an upper bound there for the norm of the third derivative $D^3 g(c)$ as a trilinear form. Put

$$w = 8\beta^2(\tau - \lambda_*), \quad s = \frac{1}{4} + (e^w - 1)e^w \sqrt{\tau},$$

$$C = 20|\beta|(4|\beta|\tau s + 16\beta^2 M), \quad K = \frac{(1 + |\beta|)s}{1 - C}, \quad (3)$$

assuming $C < 1$.

Lemma 13. *Let ν be a probability measure and $\lambda = e^R \nu / \nu(e^R)$ with $\text{osc} R \leq \omega$. For bounded f, h ,*

$$\text{Cov}_\lambda(f, h) \leq \text{Cov}_\nu(f, h) + (e^\omega - 1)e^\omega \text{sd}_\nu(f) \text{sd}_\nu(h).$$

Proof. We may assume $0 \leq R \leq \omega$. The density $\rho = e^R / \nu(e^R)$ lies in $[e^{-\omega}, e^\omega]$, so $\delta = \|\rho - 1\|_\infty \leq e^\omega - 1$. With $\tilde{f} = f - \nu f$ and $\tilde{h} = h - \nu h$,

$$\begin{aligned} \text{Cov}_\lambda(f, h) - \text{Cov}_\nu(f, h) &= \nu((\rho - 1)\tilde{f}\tilde{h}) \\ &\quad - \nu((\rho - 1)\tilde{f}) \nu((\rho - 1)\tilde{h}), \end{aligned}$$

and the right side is at most $(\delta + \delta^2) \text{sd}_\nu(f) \text{sd}_\nu(h)$ by the Cauchy–Schwarz inequality. $\square$

Lemma 14. *Let $\beta \geq 0$, $a, c_0 \in \mathbb{R}^4$ with $|a|, |c_0| \leq 20\beta$, and*

$$\kappa(dx) \propto \exp(\langle x, a \rangle + g(c_0 + 4\beta \bar{x})) dx \quad \text{on } S^3.$$

For every 1-Lipschitz f and every $h \in \mathbb{R}^4$:

- (i) $\text{Cov}_\kappa(f, \langle x, h \rangle) \leq s|h|$;
- (ii) *if c_0 moves in the direction k , then $|\frac{d}{dt} \text{Cov}_\kappa(f)| \leq (4\beta \tau s + 16\beta^2 M)|k|$.*

Proof. (i) Taylor’s formula at c_0 gives $g(c_0 + 4\beta u) = g(c_0) + 4\beta \langle \nabla g(c_0), u \rangle + R(u)$ with $R(u) = 8\beta^2 \text{Hess} g(\xi)(u, u)$ for some ξ on the segment, $|\xi| \leq 24\beta$. For $u = \bar{x}$ of norm one, $R(\bar{x}) \in [8\beta^2 \lambda_*, 8\beta^2 \tau]$, so $\text{osc} R \leq w$. Since $\langle \nabla g(c_0), \bar{x} \rangle = \langle x, \nabla g(c_0) \rangle$, κ is the tilt $e^R \nu / \nu(e^R)$ of $\nu = v_c$ with $c = a + 4\beta \nabla g(c_0)$. The sharp quarter, Theorem 91, gives $\text{Cov}_\nu(f, \langle x, h \rangle) = \frac{d}{dt} v_{c+th}(f) \leq \frac{1}{4}|h|$. A 1-Lipschitz function on a set of diameter two has $\text{sd} \leq 1$, and $\text{sd}_\nu \langle x, h \rangle \leq \sqrt{\tau}|h|$ because $|c| \leq |a| + 4\beta \leq 24\beta$. Lemma 13 gives (i).

(ii) The derivative is $\text{Cov}_\kappa(f, \langle \nabla g(c_0 + 4\beta \bar{x}), k \rangle)$. Write $\nabla g(c_0 + 4\beta u) = \nabla g(c_0) + 4\beta \text{Hess} g(c_0)u + N(u)$. The constant term does not contribute. The linear term is $\langle x, h \rangle$ with $h = 4\beta \text{Hess} g(c_0)k$, $|h| \leq 4\beta \tau |k|$, and contributes at most $4\beta \tau s |k|$ by (i). For $|u|, |u'| \leq 1$, $\|\text{Hess} g(c_0 + 4\beta v) - \text{Hess} g(c_0)\| \leq 4\beta M |v| \leq 4\beta M$ on the segment between them,

so $|N(u) - N(u')| \leq 16\beta^2 M|u - u'|$; the function $\langle N(\bar{x}), k \rangle$ is therefore $16\beta^2 M|k|$ -Lipschitz, its standard deviation is at most that constant, and its covariance with f is at most $16\beta^2 M|k|$. $\square$

Lemma 15. *Let $C < 1$. If b and b' satisfy $|b_i|, |b'_i| \leq 20|\beta|$ and differ only in one coordinate b_i , then*

$$W_1(\mu_b, \mu_{b'}) \leq K|b_i - b'_i|$$

in the metric d .

Proof. The map $y_1 \mapsto -y_1$ turns μ_b for β into the law for $-\beta$ with b_1 replaced by $-b_1$ and is an isometry, so we may take $\beta \geq 0$; the cyclic symmetry of $\text{Re}(y_1 y_2 y_3)$ lets us take $i = 1$. Let f be 1-Lipschitz for d and $\varepsilon = |b_1 - b'_1|$.

The middle link. Given y_1, y_3 , the law of y_2 is v_c with $c = b_2 + 4\beta \bar{y}_3 \bar{y}_1$, which does not involve b_1 . Changing y_1 by η moves c by $4\beta \eta$, and the sharp quarter moves v_c by at most $\beta \eta$ in W_1 . Hence $F(y_1, y_3) = \mathbb{E}[f | y_1, y_3]$ is $(1 + \beta)$ -Lipschitz in each variable, and $\mu_b(f) = \mu_b^{13}(F)$, where μ_b^{13} is the law of (y_1, y_3) :

$$\mu_b^{13} \propto e^{\langle y_1, b_1 \rangle + \langle y_3, b_3 \rangle} Z_0(b_2 + 4\beta \bar{y}_3 \bar{y}_1).$$

Since $|b_2 + 4\beta \bar{y}_3 \bar{y}_1| = |b_2 y_3 + 4\beta \bar{y}_1| = |y_1 b_2 + 4\beta \bar{y}_3|$, its conditional laws are

$$\begin{aligned} \kappa_1(dy_1 | y_3) &\propto e^{\langle y_1, b_1 \rangle + g(b_2 y_3 + 4\beta \bar{y}_1)} dy_1, \\ \kappa_3(dy_3 | y_1) &\propto e^{\langle y_3, b_3 \rangle + g(y_1 b_2 + 4\beta \bar{y}_3)} dy_3, \end{aligned}$$

both of the form of Lemma 14, with $|c_0| = |b_2|$.

Two sites. Integrating Lemma 14(i) along the segment from b_1 to b'_1 gives $W_1(\kappa_1, \kappa'_1) \leq s\varepsilon$ for the same y_3 . Moving y_3 to y'_3 moves $c_0 = b_2 y_3$ along a segment of length $|b_2||y_3 - y'_3| \leq 20\beta|y_3 - y'_3|$ inside the ball $|c_0| \leq 20\beta$, so Lemma 14(ii) gives $W_1(\kappa_1(\cdot | y_3), \kappa_1(\cdot | y'_3)) \leq C|y_3 - y'_3|$, and the same for κ_3 , which does not depend on b_1 . Let π be a coupling of μ_b^{13} and $\mu_{b'}^{13}$ minimising $d_1 + d_3$, $d_k = \mathbb{E}_\pi |y_k - y'_k|$. Replacing (y_1, y'_1) by an optimal coupling of $\kappa_1(\cdot | y_3)$ and $\kappa'_1(\cdot | y'_3)$ keeps a coupling, so minimality gives $d_1 \leq s\varepsilon + Cd_3$; in the same way $d_3 \leq Cd_1$. Hence $d_1 \leq s\varepsilon/(1 - C^2)$ and

$$|\mu_b(f) - \mu_{b'}(f)| \leq (1 + \beta)(d_1 + d_3) \leq \frac{(1 + \beta)s}{1 - C} \varepsilon = K\varepsilon. \quad \square$$

C. The constants

Lemma 16. *Write $g(c) = \varphi(|c|^2)$ and $r = |c|$. For $c \neq 0$ the eigenvalues of $\text{Hess} g(c)$ are $2\varphi'(r^2)$, three times, and $2\varphi'(r^2) + 4r^2\varphi''(r^2)$, and the norm of $D^3 g(c)$ is*

$$\max\left(|A + \Gamma|, \frac{2}{3}|A|\right), \quad A = 12r\varphi''(r^2), \quad \Gamma = 8r^3\varphi'''(r^2).$$

On the ball $r \leq 2.07$ every eigenvalue of $\text{Hess} g$ lies between 0.158491 and 0.25000001, and the norm of $D^3 g$ is at most 0.0615586.

Proof. Differentiating $\varphi(|c|^2)$ gives $D^2 g(v, v) = 2\varphi'|v|^2 + 4\varphi''\langle c, v \rangle^2$ and $D^3 g(v, v, v) = 12\varphi''\langle c, v \rangle|v|^2 + 8\varphi'''\langle c, v \rangle^3$. For $|v| = 1$ and $t = \langle c/r, v \rangle \in [-1, 1]$ the cubic form is $At + \Gamma t^3$, whose largest absolute value is attained at $t = \pm 1$ or at an interior critical point, where it equals $\frac{2}{3}|A||t| \leq \frac{2}{3}|A|$; by Banach's theorem [7] the supremum of a symmetric trilinear form on the diagonal of the unit sphere is its norm. The numerical bounds are obtained in ball arithmetic [41] from the series of Z_0 , truncated after forty terms with a proved bound on the tail, on $2 \cdot 10^4$ subintervals of $[0, 2.07]$; the program is described in Appendix C. $\square$

D. The proof of Theorem 3

Let γ^B be the block specification: for a block B , γ_B^B re-samples the three links of B from (2). It comes from the same interaction as γ^F , so the two specifications have the same Gibbs measures. Define the block coefficients

$$C_{Bj} = \sup \frac{W_1(\gamma_B^B(\cdot | Q), \gamma_B^B(\cdot | Q'))}{|Q_j - Q'_j|}$$

for an active link $j \notin B$, the supremum over pairs of configurations that differ only at j , with W_1 for the metric d .

Proposition 17. *Suppose that $\sum_B C_{Bj} \leq \alpha < 1$ for every active link j . Then the conclusions (i)–(vi) of Proposition 11 hold with $-\frac{1}{2} \log \alpha$ in place of $-\log \alpha$.*

Proof. The proof of Proposition 11 goes through with Lemma 80 of Appendix B in place of Lemma 78, and with the set S of part (ii), and the support of H in Corollary 79, enlarged to the union of the blocks that meet it. The enlargement multiplies the size of these sets by at most three and moves them by at most one, which changes only the constants. $\square$

Proof of Theorem 3. Let $|\beta| \leq 0.345/4$ and take the constants of Lemma 16, whose ball $r \leq 2.07$ contains $|c| \leq 24|\beta|$. With these fixed constants every quantity in (3) is increasing in $|\beta|$, and so is

$$\alpha(\beta_W) = 40|\beta|K. \quad (4)$$

Changing an active link j by η changes one staple of each of its ten partners outside its block by an isometric image of the displacement, so the field b_i of each such partner i moves by at most $4|\beta|\eta$, and Lemma 15, applied once for each of these ten fields, gives $\sum_B C_{Bj} \leq 40|\beta|K$. Evaluating (3) in ball arithmetic at $\beta_W = 0.345$ gives $w \leq 0.0054459$, $s \leq 0.252746$, $C \leq 0.050243$, $K \leq 0.289069$ and $\alpha \leq 0.99729$; at $\beta_W = \frac{1}{3}$ it gives $\alpha \leq 0.95602$. Proposition 17 applies. $\square$

Remark 18. Most of the range is kept. A second bound for the same sensitivity, which keeps the law of the middle link instead of linearising it, evaluated in floating point on a quadrature grid and maximised over the fields b by a random search followed by the Nelder–Mead method, gives 0.2783 at $\beta_W = 0.34$, against 0.2881 from Lemma 15, and $40|\beta|$ times it crosses one near $\beta_W = 0.357$. That computation is not certified and is not

used in the proof. Past this point the gain from integrating out one link is spent, and larger blocks are needed, such as the free links of a cube of the line field, whose sensitivity no longer reduces to two sites.

VI. CURVATURE IN THE GAUGE

In this section $G \subset U(N)$ is a closed connected subgroup with Lie algebra $\mathfrak{g}$ and the inner product $\langle X, Y \rangle = -\text{Tr}(XY)$; the bound of Theorem 4 is proved first for $U(N)$. A tangent vector at a field Q is $v = (X_e Q_e)$, $|v|^2 = \sum_e |X_e|^2$. For the plaquette at x in the plane $\mu < v$ number its links $e_1 = (x, \mu)$, $e_2 = (x + e_\mu, v)$, $e_3 = (x + e_v, \mu)$, $e_4 = (x, v)$, transport their vectors to x ,

$$Y_1 = X_{e_1}, \quad Y_2 = Q_{e_1} X_{e_2} Q_{e_1}^*, \quad Y_3 = Q_{e_4} X_{e_3} Q_{e_4}^*, \quad Y_4 = X_{e_4}, \quad (5)$$

and write $W = Q_p$. The second derivative of $\text{Re Tr } Q_p$ along the geodesic $Q_e(t) = e^{tX_e} Q_e$ is

$$\begin{aligned} f_p = & \sum_{i=1}^4 \text{Re Tr}(Y_i^2 W) + 2 \text{Re Tr}(Y_1 Y_2 W) + 2 \text{Re Tr}(Y_3 Y_4 W) \\ & - 2 \sum_{i \in \{1,2\}, j \in \{3,4\}} \text{Re Tr}(Y_i W Y_j), \end{aligned} \quad (6)$$

so that $\text{Hess } S_0(v, v) = \sum_p f_p$. To see this, write $Q_p = Q_{e_1} Q_{e_2} Q_{e_3}^* Q_{e_4}^*$. Since $Q_{e_1} e^{tX_{e_2}} = e^{tY_2} Q_{e_1}$ and $e^{-tX_{e_3}} Q_{e_4}^* = Q_{e_4}^* e^{-tY_3}$, the plaquette variable along the geodesic is $Q_p(t) = e^{tY_1} e^{tY_2} W e^{-tY_3} e^{-tY_4}$. Differentiating twice at $t = 0$ gives the four squares, the two products of neighbouring factors and the four products across W , and the squares and the product $W Y_3 Y_4$ are moved cyclically under the trace. The corner form of p is

$$c_p = 2\langle Y_1, Y_4 \rangle - 2\langle Y_1, Y_2 \rangle + 2\langle Y_2, W Y_3 W^* \rangle - 2\langle Y_3, Y_4 \rangle. \quad (7)$$

It collects the inner products of the transported vectors of two links that meet at a right angle at a corner of p .

Lemma 19. *On $\mathbb{Z}^4$, or on a box with free boundary, for every field Q and every square-summable X ,*

$$\begin{aligned} & \sum_y \left[|D_y X|^2 + \sum_\mu |X_{y,\mu} + Q_{y-e_\mu,\mu}^* X_{y-e_\mu,\mu} Q_{y-e_\mu,\mu}|^2 \right] \\ & = 4|X|^2 + \sum_p c_p, \end{aligned}$$

where $D_y X = \sum_\mu [X_{y,\mu} - Q_{y-e_\mu,\mu}^* X_{y-e_\mu,\mu} Q_{y-e_\mu,\mu}]$ is the covariant divergence and terms with a link outside the box are omitted.

Proof. At a site y write o_μ for the vector of the outgoing link in direction μ and i_μ for the transported vector of the incoming one, so that $D_y X = \sum_\mu (o_\mu - i_\mu)$. Every link is outgoing at one end and incoming at the other, so the squares $|o_\mu|^2 + |i_\mu|^2$, which appear once in $|D_y X|^2$ and once in $|o_\mu + i_\mu|^2$, add up to $4|X|^2$. The collinear cross term $-2\langle o_\mu, i_\mu \rangle$ of $|D_y X|^2$ cancels

the term $+2\langle o_\mu, i_\mu \rangle$ of $|o_\mu + i_\mu|^2$. The remaining cross terms of $|D_y X|^2$ pair two perpendicular ends at y , and each such pair is a corner of exactly one plaquette, with the sign and the transport of (7) (this is the proof of [13, Lemma 1]). In a box two perpendicular ends at y span a plaquette of the box, because a box is a product of intervals. $\square$

Lemma 20. *Let $k \in \{1, 2, 3, 4\}$, let $k \pm 1 \pmod{4}$ be the positions adjacent to k and $k + 2$ the opposite one. For every N , every $W \in U(N)$ and all $Y_1, \dots, Y_4 \in u(N)$ with $Y_k = 0$,*

$$\pm f_p + \frac{9}{10} c_p \leq \frac{21}{10} (|Y_{k-1}|^2 + |Y_{k+1}|^2) + \frac{5}{4} |Y_{k+2}|^2.$$

Proof. Replacing W by $-W$ changes the sign of f_p and fixes c_p , so the sign $\pm$ suffices. Conjugation by a unitary matrix preserves both sides, so we may take $W = \text{diag}(w_a)$. The form $\mathcal{F} = \text{RHS} - f_p - \frac{9}{10} c_p$ then splits into a block for each diagonal position a , in the real variables $y_i = -i(Y_i)_{aa}$, and a block for each pair $a \neq b$, in the complex variables $z_i = (Y_i)_{ab}$, since $(Y_i)_{ba} = -\bar{z}_i$. Appendix D shows that every block is positive definite. $\square$

Proof of the bound in Theorem 4. Every plaquette has exactly one link of F , and X vanishes on it. By Lemma 9(iii) each active link is adjacent to the fixed link in four of its plaquettes and opposite to it in two. Summing Lemma 20 over the plaquettes,

$$\sum_p (\pm f_p + \frac{9}{10} c_p) \leq (4 \cdot \frac{21}{10} + 2 \cdot \frac{5}{4}) |X|^2 = \frac{109}{10} |X|^2.$$

By Lemma 19, $\frac{9}{10} \sum_p c_p = \frac{9}{10} \Sigma - \frac{36}{10} |X|^2$, where $\Sigma \geq 0$ is the left side of the lemma. Hence

$$\pm \text{Hess } S_0(v, v) + \frac{9}{10} \Sigma \leq (\frac{109}{10} + \frac{36}{10}) |X|^2 = \frac{29}{2} |X|^2.$$

In a box, links near the boundary lie in fewer plaquettes and receive less. $\square$

The factor $\frac{9}{10}$ is chosen so that the corners are paid by the divergence identity at the price $\frac{36}{10}$ while the local blocks stay positive; Lemma 19 is the divergence identity of [13, Lemma 1] with the collinear term written as a square, so nothing is lost by Cauchy–Schwarz.

The two lemmas concern vectors in $u(N)$ and fields in $U(N)$, so the bound holds without change on every closed subgroup $G \subset U(N)$, the vectors X_e ranging over its Lie algebra $\mathfrak{g}$. It is also the Hessian of S_0 on G^E : the metric is bi-invariant, the geodesics of G through Q_e are the curves $e^{tX} Q_e$ with $X \in \mathfrak{g}$, which are geodesics of $U(N)$, and the Hessian is read off from second derivatives along geodesics.

Lemma 21. *Let $G \subset U(N)$ be closed and connected with simple Lie algebra $\mathfrak{g}$, let $\mathfrak{t} \subset \mathfrak{g}$ be a maximal abelian subalgebra, and write the eigenvalues of $\text{ad } H$ on $\mathfrak{g} \otimes \mathbb{C}$ and of H on $\mathbb{C}^N$, for $H \in \mathfrak{t}$, as $i\alpha(H)$ and $i\mu(H)$, with α running over the roots and μ over the weights of $\mathbb{C}^N$ counted with multiplicity. Then $\text{Ric}_G = \kappa_G \langle \cdot, \cdot \rangle$ with*

$$\kappa_G = \frac{\sum_\alpha \alpha(H)^2}{4 \sum_\mu \mu(H)^2} \quad (0 \neq H \in \mathfrak{t}).$$

Proof. For a bi-invariant metric the curvature is $R(X, Y)Z = -\frac{1}{4}[X, Y, Z]$ on left-invariant fields [52, Sect. 7], so for an orthonormal basis (E_i) of $\mathfrak{g}$,

$$\begin{aligned}\text{Ric}(X, X) &= \sum_i \langle R(E_i, X)X, E_i \rangle \\ &= \frac{1}{4} \sum_i |[X, E_i]|^2 = -\frac{1}{4} \text{Tr}(\text{ad}X)^2,\end{aligned}$$

since $\text{ad}X$ is skew. The Killing form $B(X, Y) = \text{Tr}(\text{ad}X \text{ad}Y)$ and $\langle \cdot, \cdot \rangle$ are invariant under the adjoint action, and $\mathfrak{g}$ is simple, so $B = -4\kappa \langle \cdot, \cdot \rangle$ for a constant κ and $\text{Ric} = \kappa \langle \cdot, \cdot \rangle$. On $H \in \mathfrak{t}$ the two forms are $B(H, H) = -\sum_\alpha \alpha(H)^2$ and $\langle H, H \rangle = -\text{Tr}H^2 = \sum_\mu \mu(H)^2$. $\square$

Table I evaluates the ratio of Lemma 21 for every compact simple Lie algebra and a faithful representation of least dimension, on the root systems of [39, Sect. 12.1]; the weights of the representations of dimensions 27 and 56 of E_6 and E_7 are the roots of E_8 with prescribed inner products with a subsystem A_2 , respectively A_1 , projected to its orthogonal complement, by the decompositions $248 = (78, 1) + (27, 3) + (27, \bar{3}) + (1, 8)$ and $248 = (133, 1) + (56, 2) + (1, 3)$ [62]. Taking for H the coroot $\theta^\vee$ of the highest root gives $\sum_\alpha \alpha(\theta^\vee)^2 = 4h^\vee$ and $\sum_\mu \mu(\theta^\vee)^2 = 2\ell_\rho$, so $\kappa_G = h^\vee/(2\ell_\rho)$, with the Dynkin index normalised to one on the defining representation of $\text{SU}(N)$. The ratio depends on $\mathfrak{g}$ and ρ only, so it is the same for every compact group with Lie algebra $\mathfrak{g}$, simply connected or not.

Lemma 22. *Let $e \neq e'$ be two links of a plaquette p , and write*

$$\text{Hess Re Tr } Q_p(v, v) = \sum_{e, e' \in p} H_{ee'}^p(X_e, X_{e'})$$

with bilinear forms satisfying $H_{ee'}^p(a, b) = H_{e'e}^p(b, a)$. Then $|H_{ee'}^p(a, b)| \leq |a||b|$ for all $a, b \in \mathfrak{u}(N)$ and every field.

Proof. By (6) the terms of f_p that mix two positions $i \neq j$ are $2\text{Re Tr}(Y_1 Y_2 W)$, $2\text{Re Tr}(Y_3 Y_4 W)$ and $-2\text{Re Tr}(Y_i W Y_j)$, so $H_{ee'}^p$ is $\pm \text{Re Tr}(abW)$ or $\pm \text{Re Tr}(aWb)$ after an isometric transport of a and b , and $|\text{Tr}(abW)| \leq \|a\|_{\text{HS}} \|bW\|_{\text{HS}} = |a||b|$. $\square$

Corollary 23. *Let $G \subset \text{U}(N)$ be closed and connected with semisimple Lie algebra and $N|\beta| < \frac{2}{29}\kappa_G$. For every box the measure μ_Λ^F satisfies the Bakry–Émery condition with $K = \kappa_G - \frac{29}{2}N|\beta| > 0$, uniformly in the box, and hence a logarithmic Sobolev inequality with constant $2/K$ and a Poincaré inequality with constant $1/K$.*

Proof. The set $\{Q_F = 1\}$ is a product factor, so its Ricci curvature is at least κ_G on every link, and the Hessian of the restricted action is the restriction of $N\beta \text{Hess } S_0$ to $X_F = 0$. Apply the bound and [3, Cor. 5.7.2]. $\square$

A. Decay with an explicit rate

Let A' be a finite set of active links and P' a finite set of plaquettes whose active links lie in A' . An action $S = \sum_{p \in P'} c_p \text{Re Tr } Q_p^F$ with $0 \leq c_p \leq 1$ is *admissible* if

$|\text{Hess } S(v, v)| \leq \frac{29}{2}|v|^2$ for all v tangent to $G^{A'}$. Two links lie in at most one common plaquette, so by Lemma 22 and Lemma 9(iv) the mixed blocks of its Hessian satisfy $|\text{Hess } S_{ee'}(a, b)| \leq |a||b|$, and each link has at most twelve partners. The action $S_\Lambda = \sum_{p \in P(\Lambda)} \text{Re Tr } Q_p^F$ of a box is admissible by the bound proved above, and so is every convex combination of two admissible actions. Let μ be the probability measure on $G^{A'}$ with density proportional to $e^{N\beta S}$ with respect to Haar measure, let $L = \Delta + N\beta \langle \nabla S, \nabla \cdot \rangle$ be its Langevin generator, which is self-adjoint in $L^2(\mu)$, and $P_t = e^{tL}$. Write ∇_e for the gradient in the factor of the link e , and for weights $w : A' \rightarrow (0, \infty)$ put $\Gamma^w(f) = \sum_e w_e |\nabla_e f|^2$; Γ is the case $w \equiv 1$.

Lemma 24. *Let $\lambda \geq 0$ and $w_e = e^{\lambda d_e}$, where $|d_e - d_{e'}| \leq 1$ whenever e and e' share a plaquette, and put*

$$K_\lambda = \kappa_G - N|\beta| \left(\frac{29}{2} + 12(\cosh \frac{\lambda}{2} - 1) \right).$$

Then $\Gamma^w(P_t f) \leq e^{-2K_\lambda t} P_t \Gamma^w(f)$ for every smooth f and $t \geq 0$.

Proof. Put $V = -N\beta S$. On the product manifold $M = G^{A'}$ the projection to the tangent space of one factor is parallel, the rough Laplacian commutes with it, and the Ricci tensor is block diagonal. Hence the Bochner–Weitzenböck formula $\nabla \Delta g = \bar{\Delta} \nabla g + \text{Ric}(\nabla g)$, applied factor by factor, together with the derivative of the drift, gives for smooth g

$$\begin{aligned}\frac{1}{2} L \Gamma^w(g) - \Gamma^w(g, Lg) \\ &= \sum_e w_e (|\nabla \nabla_e g|^2 + \text{Ric}_G(\nabla_e g, \nabla_e g)) \\ &\quad + \sum_{e, e'} w_e \text{Hess } V_{ee'}(\nabla_e g, \nabla_{e'} g),\end{aligned}$$

where $\Gamma^w(g, h)$ is the polarised form.¹² Put $u_e = \nabla_e g$ and $v_e = \sqrt{w_e} u_e$. By the symmetry of $\text{Hess } V$,

$$\begin{aligned}\sum_{e, e'} w_e \text{Hess } V_{ee'}(u_e, u_{e'}) &= \text{Hess } V(v, v) \\ &\quad + \sum_{e \neq e'} \left(\cosh \frac{\lambda(d_e - d_{e'})}{2} - 1 \right) \text{Hess } V_{ee'}(v_e, v_{e'}),\end{aligned}$$

because $\frac{w_e + w_{e'}}{2\sqrt{w_e w_{e'}}} = \cosh \frac{\lambda(d_e - d_{e'})}{2}$. The first term is at least $-\frac{29}{2}N|\beta||v|^2$. In the second only partners contribute, each with a coefficient at most $\cosh \frac{\lambda}{2} - 1$ and a block of norm at most $N|\beta|$, and $2|v_e||v_{e'}| \leq |v_e|^2 + |v_{e'}|^2$ with twelve partners per link bounds it by $12(\cosh \frac{\lambda}{2} - 1)N|\beta||v|^2$. Since $\text{Ric}_G \geq \kappa_G$ and $|v|^2 = \Gamma^w(g)$,

$$\frac{1}{2} L \Gamma^w(g) - \Gamma^w(g, Lg) \geq K_\lambda \Gamma^w(g).$$

For fixed t let $\varphi(s) = P_s \Gamma^w(P_{t-s} f)$, $0 \leq s \leq t$. Then $\varphi'(s) = P_s (L \Gamma^w(g_s) - 2\Gamma^w(g_s, Lg_s)) \geq 2K_\lambda \varphi(s)$ with $g_s = P_{t-s} f$, and $\varphi(0) \leq e^{-2K_\lambda t} \varphi(t)$ is the claim. $\square$

¹² For $w \equiv 1$ this is Bochner's identity $\Gamma_2 = |\nabla^2 g|^2 + (\text{Ric} + \text{Hess } V)(\nabla g, \nabla g)$; the weights enter only through the factor index, which the connection, the Laplacian and the Ricci tensor preserve, so only the off-diagonal blocks of $\text{Hess } V$ see them.

Lemma 25. Suppose $K_\lambda > 0$. Let f and g be smooth functions on G^A that depend only on the links of A_f and of B_g , and let D be the least number of steps from A_f to B_g in the graph on A' whose edges join links that share a plaquette. Then

$$|\text{Cov}_\mu(f, g)| \leq \frac{e^{-\lambda D/2}}{K_\lambda} \|\nabla f\|_\infty \sum_{e \in B_g} \|\nabla_e g\|_\infty,$$

where $\|\nabla f\|_\infty^2 = \sup \sum_e |\nabla_e f|^2$.

Proof. Since $K_0 \geq K_\lambda > 0$, Lemma 24 with $\lambda = 0$ gives $\Gamma(P_t f) \leq e^{-2K_0 t} \|\nabla f\|_\infty^2$, so $P_t f$ converges uniformly to a constant, which is $\mu(f)$ by invariance, M being connected. Since $\frac{d}{dt} \mu(g P_t f) = \mu(g L P_t f) = -\mu(\Gamma(g, P_t f))$,

$$\text{Cov}_\mu(f, g) = \int_0^\infty \mu(\Gamma(P_t f, g)) dt.$$

Let d_e be the smaller of D and the graph distance from e to A_f , so that $|d_e - d_{e'}| \leq 1$ for partners, $w_e = 1$ on A_f , $w_e = e^{\lambda D}$ on B_g , and $\Gamma^w(f) \leq \|\nabla f\|_\infty^2$. For $e \in B_g$, Lemma 24 gives $|\nabla_e P_t f|^2 \leq w_e^{-1} \Gamma^w(P_t f) \leq e^{-\lambda D} e^{-2K_\lambda t} \|\nabla f\|_\infty^2$. Hence $|\Gamma(P_t f, g)| \leq e^{-\lambda D/2} e^{-K_\lambda t} \|\nabla f\|_\infty \sum_{e \in B_g} \|\nabla_e g\|_\infty$, and integration in t gives the bound. $\square$

Proof of Theorem 5. Let $\lambda^* > 0$ solve $K_{\lambda^*} = 0$, so that $\frac{\lambda^*}{2} = m_G(\beta)$, and let $0 < \lambda < \lambda^*$; then $K_\lambda > 0$.

Decay in boxes. Lemma 25 with $S = S_\Lambda$ gives

$$|\text{Cov}_{\mu_\Lambda^F}(f, g)| \leq C_{f,g} e^{-\lambda D/2},$$

uniformly in the box.

Limit. For boxes $\Lambda \subset \Lambda'$ let $S_s = (1-s)S_\Lambda + sS_{\Lambda'}$ on the active links of Λ' , $s \in [0, 1]$, and μ_s the corresponding measure; S_s is admissible, μ_0 is μ_Λ^F times Haar measure on the active links outside Λ , and $\mu_1 = \mu_{\Lambda'}^F$. For smooth f of the active links of Λ ,

$$\frac{d}{ds} \mu_s(f) = N\beta \sum_{p \in P(\Lambda') \setminus P(\Lambda)} \text{Cov}_{\mu_s}(f, \text{Re Tr } Q_p^F),$$

and $|\nabla_e \text{Re Tr } Q_p| \leq \|Q_p\|_{\text{HS}} = \sqrt{N}$. A step in the graph of Lemma 25 moves a link by at most one lattice unit, so a plaquette at graph distance k from the support T of f lies within distance $k+1$ of T , there are at most $C_T(k+1)^4$ of them, and every plaquette outside $P(\Lambda)$ is at graph distance at least $R-1$, R the distance from T to the complement of Λ . Lemma 25 gives

$$|\mu_{\Lambda'}^F(f) - \mu_\Lambda^F(f)| \leq C_f R^4 e^{-\lambda R/2}.$$

The limit therefore exists along every increasing sequence of boxes, and two sequences are compared through their intersections, which are boxes. Continuous gauge-invariant O are uniform limits of smooth gauge-invariant ones, for instance of $e^{\tau \Delta} O$, since the heat semigroup of G^E commutes with left and right translations; with Lemma 10 the limit $\omega(O)$ of $W_\Lambda(O)$ exists for all of them.

Properties. Invariance and, for $\beta \geq 0$, reflection positivity follow as in Proposition 11(iii)–(iv). For Lipschitz O the functions $e^{\tau \Delta} O$ are smooth with the same Lipschitz constant, since $\text{Ric}_G \geq 0$ [3, Sect. 3.3], so the bound of the first step passes to ω and to Lipschitz observables. Two links of one plaquette have time coordinates that differ by at most one, so observables at time separation t are at graph distance at least $t - c$, and truncated correlations decay at every rate below $m_G(\beta)$. The gap follows from Proposition 82 as in Proposition 11(vi). $\square$

Proof of the rest of Theorem 4. By Lemma 21 and Table I, $\kappa_{\text{SU}(N)} = \frac{N}{2}$ and $\kappa_{\text{SO}(N)} = \frac{N-2}{4}$; for $\text{SO}(4)$, whose Lie algebra is $\mathfrak{so}(3) \oplus \mathfrak{so}(3)$ acting on $\mathbb{R}^4 \otimes \mathbb{C} = \mathbb{C}^2 \otimes \mathbb{C}^2$, each ideal gives $\frac{1}{2}$ by the same computation. The conditions of Theorem 4 are those of Theorem 5. $\square$

Remark 26. Let h_F be the supremum of $\pm \text{Hess } S_0$ on the gauge-fixed directions, so that uniform curvature reaches $|\beta| < 1/(2h_F)$ and no further. At the identity field $-\text{Hess } S_0$ restricted to $X_F = 0$ has the eigenvalue $9 + \sqrt{17} = 13.123$ on the torus of side two, so $9 + \sqrt{17} \leq h_F \leq \frac{29}{2}$. A gradient search over $\text{SU}(2)$ fields of periods two, four and six gives $h_F = 13.97401$, attained by an abelian field; certificates made of plaquette forms and vertex forms on the period-two cell cannot go below 14.384. With this gauge the curvature method stops between $|\beta| = \frac{1}{29}$ and $\frac{1}{26.25}$.

VII. SU(3) UP TO 3/4

In this section $G = \text{SU}(3)$, $\beta \geq 0$ and $\beta_W = 9\beta$. The distance on $\text{SU}(3)$ is $d(U, V) = \|U - V\|_{\text{HS}}$, which is at most the geodesic distance for $\langle X, Y \rangle = -\text{Tr}(XY)$; $K = \text{conv } \text{SU}(3)$; $A(M) = \frac{1}{2}(M - M^*)$ and P removes the trace. With this inner product $\text{Ric} = \frac{3}{2}$, the Casimir of the fundamental representation is $\lambda_F = \frac{8}{3}$ and that of the adjoint representation is 6.

A. Reduction to one link

The conditional law of an active link is

$$\nu_b(dU) \propto e^{\text{Re Tr}(Ub)} dU, \quad b = N\beta \sum_{p \ni e} S_p,$$

where S_p is the staple of e in p , a product of $\text{SU}(3)$ matrices and identities, or its adjoint. Six staples give $b \in rK$ with $r = 6N\beta = 2\beta_W$. For a matrix h put $\varphi_h(U) = \text{Re Tr}(Uh)$ and

$$L_h(b) = \sup\{\text{Cov}_{\nu_b}(g, \varphi_h) : g \text{ 1-Lipschitz for } d\},$$

$$\Lambda(r) = \sup_{b \in rK} \sup_{\|h\|_{\text{HS}}=1} L_h(b).$$

Changing a partner e' changes one staple by a matrix of norm $d(Q_{e'}, Q'_{e'})$. Along the segment b_t from b to b' , which stays in rK , $\frac{d}{dt} \nu_{b_t}(g) = \text{Cov}_{\nu_{b_t}}(g, \text{Re Tr}(U(b' - b)))$, so $W_1(\nu_b, \nu_{b'}) \leq N\beta \Lambda(r) d(Q_{e'}, Q'_{e'})$. With twelve partners per link,

$$\alpha \leq 12N\beta \Lambda(r) = 2r\Lambda(r) = 4\beta_W \Lambda(2\beta_W). \quad (8)$$

Since K is convex and contains 0, the mean of $I, \omega I, \omega^2 I$ with $\omega^3 = 1, r'K \subset rK$ for $r' \leq r$ and Λ is nondecreasing.

B. Gradients and one-forms

Lemma 27. *In the left trivialisation, $\nabla \varphi_c(U) = -PA(cU)$; if $V = \varphi_b$ then $\text{Hess} V(X, X) = \text{Re Tr}(UX^2b)$; and $\Delta \varphi_c = -\lambda_F \varphi_c$.*

Proof. $\frac{d}{dt} \text{Re Tr}(Ue^{tX}c)|_{t=0} = \text{Re Tr}(cUX) = -\langle PA(cU), X \rangle$ for $X \in \mathfrak{su}(3)$. On a group with a bi-invariant metric $\nabla_X X = 0$ for left-invariant X , so the Hessian is the second derivative along e^{tX} . The function φ_c is a matrix coefficient of the fundamental representation, on which the Casimir acts by λ_F . $\square$

Lemma 28. *The bottom of the spectrum of the rough Laplacian $\nabla^* \nabla$ on L^2 one-forms of $\text{SU}(3)$ is $\mu_0 = \frac{7}{6}$.*

Proof. Trivialise one-forms on the left, so that a one-form is a function $f : \text{SU}(3) \rightarrow \mathfrak{su}(3)$. For an orthonormal basis X_a acting as left-invariant vector fields, $\nabla_{X_a} Y = \frac{1}{2} [X_a, Y]$ and $\nabla_{X_a} X_a = 0$, so $\nabla^* \nabla = -\sum_a (\rho(X_a) + \frac{1}{2} \text{ad } X_a)^2$. On the isotypic part $V_\pi \otimes V_\pi^* \otimes \mathfrak{su}(3)$ of $L^2 \otimes \mathfrak{su}(3)$ put $A_a = \rho_\pi(X_a)$, $B_a = \text{ad } X_a$ and $T_a = A_a + B_a$, the action on the tensor product. Since A_a and B_a commute, $A_a + \frac{1}{2} B_a = \frac{1}{2} (A_a + T_a)$ and $A_a T_a + T_a A_a = A_a^2 + T_a^2 - B_a^2$, so on a component $\sigma \subset \pi \otimes \text{ad}$

$$\nabla^* \nabla = \frac{1}{2} (C_\pi + C_\sigma) - \frac{1}{4} C_{\text{ad}} = \frac{1}{2} (C_\pi + C_\sigma) - \frac{3}{2},$$

with $C(p, q) = \frac{2}{3} (p^2 + q^2 + pq + 3p + 3q)$ for the representation of highest weight (p, q) [30]. The components of $(p, q) \otimes (1, 1)$ are $(p+1, q+1)$, $(p+2, q-1)$, $(p-1, q+2)$, $(p+1, q-2)$, $(p-2, q+1)$, $(p-1, q-1)$ and (p, q) , the last with multiplicity two, one or zero as both, one or none of p, q are positive, and only those with nonnegative labels occur. For $\pi = (0, 0)$ the only component is $(1, 1)$, with value $\frac{3}{2}$. For $\pi = (1, 0)$ the components are $(2, 1)$, $(0, 2)$, $(1, 0)$, with values $\frac{31}{6}$, $\frac{19}{6}$, $\frac{7}{6}$, and $(0, 1)$ is conjugate. For $p+q \geq 2$ the smallest values occur at $(p-1, q-1)$, (p, q) , $(p-2, q+1)$ or $(p+1, q-2)$, and each is at least $\frac{1}{3} (2(p^2 + q^2 + pq) + 3(p+q) - 3) - \frac{3}{2} \geq \frac{3}{2}$. $\square$

C. The gap of the one-link measure

Lemma 29. *For $b \in rK$ the spectral gap of $L = \Delta + \langle \nabla V, \nabla \cdot \rangle$, $V = \varphi_b$, on $L^2(\nu_b)$ is at least*

$$\gamma(r) = \frac{39}{64} \mu_0 + \frac{3}{2} - \frac{r}{2} = \frac{283}{128} - \frac{r}{2}.$$

Proof. Let $-Lf = \lambda f$ with $\lambda > 0$, $\omega = df$ and $\eta = e^{V/2} \omega$; norms are in $L^2(dU)$. Bochner's formula integrated against ν_b gives $\lambda \nu_b |\omega|^2 = \nu_b |\nabla \omega|^2 + \nu_b ((\text{Ric} - \text{Hess } V)(\omega, \omega))$, and since $e^{V/2} \nabla \omega = \nabla \eta - \frac{1}{2} dV \otimes \eta$,

$$\lambda \|\eta\|^2 = \|\nabla \eta - \frac{1}{2} dV \otimes \eta\|^2 + \int (\text{Ric} - \text{Hess } V)(\eta, \eta). \quad (9)$$

Put $\mathcal{A} = \nabla \eta$ and $\mathcal{B} = \frac{1}{2} dV \otimes \eta$. Then

$$\langle \mathcal{A}, \mathcal{B} \rangle = \frac{1}{4} \int \langle \nabla V, \nabla |\eta|^2 \rangle = \frac{\lambda_F}{4} \int V |\eta|^2,$$

because $-\Delta V = \lambda_F V$. Writing $\|\mathcal{A} - \mathcal{B}\|^2 = \|\frac{5}{8} \mathcal{A} - \mathcal{B}\|^2 + \frac{39}{64} \|\mathcal{A}\|^2 - \frac{3}{4} \langle \mathcal{A}, \mathcal{B} \rangle$ and dropping the first term,

$$\|\mathcal{A} - \mathcal{B}\|^2 \geq \frac{39}{64} \mu_0 \|\eta\|^2 - \frac{1}{2} \int V |\eta|^2$$

by Lemma 28. With $\text{Ric} = \frac{3}{2}$, (9) gives $\lambda \|\eta\|^2 \geq (\frac{39}{64} \mu_0 + \frac{3}{2}) \|\eta\|^2 - \int (\text{Hess } V(\eta, \eta) + \frac{1}{2} V |\eta|^2)$, and the claim follows from the pointwise bound

$$\text{Re Tr}(MX^2) + \frac{1}{2} \text{Re Tr } M \leq \frac{r}{2} |X|^2, \quad M = bU \in rK, \quad (10)$$

since $\text{Hess } V(X, X) = \text{Re Tr}(MX^2)$ and $V = \text{Re Tr } M$. The maximum over $|X| = 1$ of the left side is convex in M , so it suffices to take $M = rW$ with $W \in \text{SU}(3)$ and, after a conjugation, $W = \text{diag}(e^{i\theta_k})$ with $\sum_k \theta_k = 0$; put $c_k = \cos \theta_k$. Write $X = iH$ with H Hermitian, traceless, $\text{Tr } H^2 = 1$, with diagonal d_k and entries H_{jk} . Then

$$\text{Re Tr}(WX^2) = -\sum_k c_k d_k^2 - \sum_{j < k} (c_j + c_k) |H_{jk}|^2,$$

with $\sum_k d_k^2 + 2 \sum_{j < k} |H_{jk}|^2 = 1$, so the maximum is the larger of $q_{\text{off}} = \max_{j < k} -\frac{1}{2} (c_j + c_k)$ and $q_{\text{diag}} = \max \{-\sum_k c_k d_k^2 : \sum d_k = 0, \sum d_k^2 = 1\}$. If l is the third index, $q_{\text{off}} + \frac{1}{2} \sum_k c_k = \frac{1}{2} c_l \leq \frac{1}{2}$. The value q_{diag} is minus the smaller eigenvalue of $\text{diag}(c)$ compressed to the plane $\sum d_k = 0$; the eigenvalues of the compression solve $\sum_k (c_k - \mu)^{-1} = 0$, that is $3\mu^2 - 2e_1\mu + e_2 = 0$ with e_1, e_2 the elementary symmetric functions of the c_k , so $q_{\text{diag}} = \frac{1}{3} (\sqrt{e_1^2 - 3e_2} - e_1)$. The inequality $q_{\text{diag}} + \frac{1}{2} e_1 \leq \frac{1}{2}$ is $\sqrt{e_1^2 - 3e_2} \leq \frac{1}{2} (3 - e_1)$, that is $e_1^2 - 4e_2 + 2e_1 - 3 \leq 0$. When $\sum \theta_k = 0$, $\sum c_k^2 = 1 + 2c_1 c_2 c_3$, and with this identity the left side equals $-2(1 - c_1)(1 - c_2)(1 - c_3) \leq 0$. $\square$

The weight $\frac{5}{8}$ is the one that gives the coefficient $\frac{1}{2}$ of V , and (10) is an equality at $W = I$. At $r = \frac{3}{2}$, $\gamma = \frac{187}{128}$.¹³

D. A corrector of degree two

Lemma 30. *For $b \in rK$, $\|h\| = 1$ and every smooth real function u on $\text{SU}(3)$,*

$$L_h(b) \leq \sqrt{\nu_b |\nabla u|^2} + \sqrt{\text{Var}_{\nu_b}(\varphi_h + Lu) / \gamma(r)}.$$

¹³ The direct Bochner bound, with Minkowski's inequality in place of the cross term, gives $(\sqrt{\mu_0} - \frac{g}{2}r)^2 + \frac{3}{2} - r$ with $g^2 = \max_W \|PA(W)\|^2 = 2.0655$; it is exact at $b = 0$, where the gap is $\frac{8}{3}$, but falls below γ for $r > 0.24$ and vanishes before $r = 1$.

Proof. Let $-L\psi = \phi_h - v_b\phi_h$. For a 1-Lipschitz g , $|\nabla g| \leq 1$ almost everywhere, because d is at most the geodesic distance, so $\text{Cov}(g, \phi_h) = v_b \langle \nabla g, \nabla \psi \rangle \leq v_b |\nabla \psi|$. Write $\psi = u + \chi$. Since $v_b(Lu) = 0$, χ solves $-L\chi = X - v_bX$ with $X = \phi_h + Lu$, and

$$v_b |\nabla \chi|^2 = \text{Cov}(\chi, X) \leq \sqrt{\text{Var} \chi \text{Var} X} \leq \sqrt{v_b |\nabla \chi|^2 \text{Var} X / \gamma}$$

by Lemma 29. Hence $v_b |\nabla \chi|^2 \leq \text{Var} X / \gamma$, and $v_b |\nabla \psi| \leq \sqrt{v_b |\nabla u|^2} + \sqrt{v_b |\nabla \chi|^2}$. $\square$

The best u is ψ itself, and then the second term vanishes. With $u = s\phi_h$, Lemma 27 gives $\phi_h + Lu = (1 - s\lambda_F)\phi_h + s\Gamma$ with $\Gamma = \langle \nabla V, \nabla \phi_h \rangle$; the choice $s = 1/\lambda_F$ removes ϕ_h and leaves the drift. This blended corrector reaches $\beta_W = \frac{45}{64}$ and stops near 0.715 (Sec. IX). We take u in a space of polynomials of degree two.

Let $\mathcal{P}_2$ be the real vector space of real polynomials of degree one or two in the entries u_{ij} of U and $\bar{u}_{ij}$ of $\bar{U}$. It has dimension 189: a basis (B_k) consists of $\frac{1}{2}(m + \bar{m})$ and $\frac{1}{2i}(m - \bar{m})$ for each pair $\{m, \bar{m}\}$ of conjugate monomials with $m \neq \bar{m}$, and m itself when $m = \bar{m}$. Identify $h \in \mathbb{C}^{3 \times 3}$ with $\mathbb{R}^{18}$ through the real and imaginary parts of its entries. For a real 189×18 matrix C put

$$q_h = \sum_k \sum_{m=1}^{18} C_{km} h_m B_k \in \mathcal{P}_2,$$

linear in h . For diagonal $b = \text{diag}(a_1, a_2, x_3 + iy_3)$ we have $V = \sum_k b_k \phi_{F_k}$ with $(b_k) = (a_1, a_2, x_3, y_3)$ and $F = (e_{11}, e_{22}, e_{33}, ie_{33})$, so

$$X_h = \phi_h + Lq_h = \phi_h + \Delta q_h + \sum_k b_k \langle \nabla \phi_{F_k}, \nabla q_h \rangle \quad (11)$$

is a polynomial of degree at most three, affine in b , while ∇q_h does not depend on b . The squares of these functions have degree at most six, so the quadratic forms $h \mapsto v_b |\nabla q_h|^2$ and $h \mapsto v_b [(X_h - \kappa)^2]$ are combinations of moments of v_b of degree at most six.

To compute Δ and $\langle \nabla f, \nabla g \rangle$ exactly we use the basis of $\mathfrak{su}(3)$

$$\begin{aligned} e_{jk} - e_{kj}, \quad i(e_{jk} + e_{kj}) \quad (j < k), \\ i(e_{11} - e_{22}), \quad i(e_{11} + e_{22} - 2e_{33}), \end{aligned}$$

acting as left-invariant fields $X_a f(U) = \frac{d}{dt} f(U e^{tX_a})|_{t=0}$, with weights $w_a = \frac{1}{2}$ for the first seven and $\frac{1}{6}$ for the last. Then $\sum_a w_a X_a \otimes X_a$ is the Casimir tensor of $\langle X, Y \rangle = -\text{Tr}(XY)$, so

$$\langle \nabla f, \nabla g \rangle = \sum_a w_a X_a f X_a g, \quad \Delta = \sum_a w_a X_a^2.$$

The fields map monomials to combinations of monomials of the same degree with coefficients in $\mathbb{Z}[i]$; for instance $\Delta \phi_h = -\frac{8}{3}\phi_h$, as in Lemma 27.

E. Orbits of staple sums

Lemma 31. *Let $V, W \in \text{SU}(3)$.*

(i) $L_h(VbW) = L_{V^{-1}hW^{-1}}(b)$ and $L_h(\bar{b}) = L_{\bar{h}}(b)$.

(ii) Every $b \in \mathbb{C}^{3 \times 3}$ is in the orbit of some $\text{diag}(a_1, a_2, z_3)$ with $a_1 \geq a_2 \geq |z_3|$ and $\text{Im} z_3 \geq 0$.

(iii) A diagonal matrix lies in K if and only if it lies in the convex hull of the diagonal torus T of $\text{SU}(3)$.

Proof. (i) If U has law v_{VbW} then WUV has law v_b ; the map preserves d and Haar measure, and $\phi_h(U) = \phi_{V^{-1}hW^{-1}}(WUV)$. For $\bar{b}$ use $U \mapsto \bar{U}$. (ii) Take a singular value decomposition $b = V_1 \Sigma W_1$ and move the determinants of V_1, W_1 into the last entry; a complex conjugation makes $\text{Im} z_3 \geq 0$. (iii) Let c be diagonal with nonzero entries of distinct moduli and let U maximise $\text{Re Tr}(cU)$ on $\text{SU}(3)$. The derivative along $\mathfrak{su}(3)$ vanishes, so the anti-Hermitian part of cU is a multiple $i\lambda I$ of the identity and $cU = H + i\lambda I$ with H Hermitian. Then $H^2 + \lambda^2 I = cc^*$ is diagonal with distinct entries, H commutes with it and is diagonal, and $U \in T$. Hence $\max_{\text{SU}(3)} \text{Re Tr}(cU) = \max_T \text{Re Tr}(cU)$ for such c , and by continuity for every diagonal c . A diagonal matrix outside $\text{conv} T$ is separated from it by such a functional, which then separates it from K . $\square$

Since every $b \in rK$ has operator norm at most r ,

$$\Lambda(r) = \sup \left\{ \sup_{\|h\|=1} L_h(b) : b \in \mathcal{R}_r \right\},$$

where $\mathcal{R}_r$ is the set of $\text{diag}(a_1, a_2, x_3 + iy_3) \in r \text{conv} T$ with $a_1 \geq a_2 \geq |x_3 + iy_3|$ and $y_3 \geq 0$, a subset of the box $[0, r]^2 \times [-r, r] \times [0, r]$ in the coordinates (a_1, a_2, x_3, y_3) .

F. Exact moments and interpolation

Lemma 32. *For $D, D' \in \mathbb{C}^{3 \times 3}$ let $\mathbb{E}_H$ be the Haar mean on $\text{SU}(3)$ and*

$$Z(D, D') = \mathbb{E}_H \exp\left(\frac{1}{2} \text{Tr}(UD) + \frac{1}{2} \text{Tr}(\bar{U}D')\right).$$

Then

$$Z(D, D') = \sum_{p \geq q \geq 0} \frac{s_{(p,q)}(DD'^T) G_{p,q}(\det D) G_{p,q}(\det D')}{d_{p,q}},$$

with $G_{p,q}(z) = \sum_{k \geq 0} c_{(p+k, q+k, k)} z^k$, $c_\lambda = 2^{-|\lambda|} / \prod \text{hooks}(\lambda)$, $d_{p,q} = \frac{1}{2}(p-q+1)(q+1)(p+2)$ and $s_{(p,q)}$ the Schur polynomial. The moments of degree j in U and k in $\bar{U}$ are $\mathbb{E}_H[u^\alpha \bar{u}^\beta e^{\text{Re Tr}(U^b)}] = 2^{|\alpha|+|\beta|} \partial_D^\alpha \partial_{\bar{D}}^\beta Z(b, \bar{b})$, the entry u_{ij} pairing with D_{ji} .

Proof. We use $(\text{Tr} X)^n = \sum_{\lambda \vdash n} f^\lambda s_\lambda(X)$, where f^λ is the number of standard tableaux of shape λ , given by the hook length formula [63, Cor. 7.21.6]. Expanding the exponential gives

$$e^{\frac{1}{2} \text{Tr} X} = \sum_{n \geq 0} \frac{(\text{Tr} X)^n}{2^n n!} = \sum_{\lambda} c_\lambda s_\lambda(X),$$

the sum over partitions with at most three parts. For $U \in \text{SU}(3)$ one has $s_{\lambda+(k,k,k)}(UD) = (\det D)^k s_\lambda(UD)$, so

$$e^{\frac{1}{2}\text{Tr}(UD)} = \sum_{p \geq q} G_{p,q}(\det D) \chi_{p,q}(UD),$$

where $\chi_{p,q}$ is the irreducible character of highest weight $(p,q,0)$ and $d_{p,q}$ its dimension. Since $\bar{U} = (U^{-1})^\top$, we have $\chi_{p,q}(\bar{U}D') = \chi_{p,q}(U^{-1}D'^\top)$, and Schur orthogonality [20, Ch. 2],

$$\mathbb{E}_H[\chi_p(UA)\chi_{p'}(U^{-1}B)] = \delta_{pp'} \frac{\chi_p(AB)}{d_p},$$

gives the expansion. The bound below gives absolute convergence. Finally $\text{Re Tr}(Ub) = \frac{1}{2} \text{Tr}(Ub) + \frac{1}{2} \text{Tr}(\bar{U}\bar{b})$. $\square$

The computation keeps $p \leq 34$ and $k \leq 11$. Every omitted partition has more than 34 boxes, and since $|s_\lambda(X)| \leq \dim(\lambda) \|X\|^{|\lambda|}$ and $\sum_{\lambda \vdash n} f^\lambda \dim \lambda = 3^n$ by Schur–Weyl duality, the omitted part of each factor is at most $\sum_{n > 34} (\frac{3}{2} \|D\|)^n / n!$; Cauchy’s estimate on a polydisc around b turns this into a bound for every derivative (Appendix E).

Lemma 33 (Interpolation on a box). *Let $Q = \prod_k [l_k, l_k + w_k]$ in the coordinates (a_1, a_2, x_3, y_3) , with corners b_i and multilinear weights $\omega_i(b) \geq 0$, $\sum_i \omega_i(b) = 1$, and let $\varsigma = w_1^2 + w_2^2 + \max(w_3^2, w_4^2)$. For $b \in Q$:*

- (i) $Z(b) \geq e^{-\varsigma/8} \sum_i \omega_i(b) Z(b_i)$;
- (ii) $v_b(f) \leq e^{\varsigma/8} \max_i v_{b_i}(f)$ for every $f \geq 0$ that does not depend on b ;
- (iii) if $Y_b = (\mathcal{A} + \sum_k (b_k - \beta_k) \mathcal{B}_k)^2$ with functions $\mathcal{A}, \mathcal{B}_k$ of U and a fixed point β , then

$$v_b(Y_b) \leq e^{\varsigma/8} \left(\max_i v_{b_i}(Y_{b_i}) + \sum_k \frac{w_k^2}{4} \frac{\max_i Z(b_i) v_{b_i}(\mathcal{B}_k^2)}{\min_i Z(b_i)} \right).$$

Proof. Write $E(b) = e^{\text{Re Tr}(Ub)} = \prod_k e^{c_k b_k}$, where

$$c = (\text{Re } u_{11}, \text{Re } u_{22}, \text{Re } u_{33}, -\text{Im } u_{33}),$$

so that $|c_k| \leq 1$ and $c_3^2 + c_4^2 \leq 1$. In each coordinate the chord of $e^{c_k x}$ over $[l_k, l_k + w_k]$ lies above the function and, by Hoeffding’s lemma [38] for a two-point variable, below $e^{c_k x} e^{c_k^2 w_k^2 / 8}$. Multiplying,

$$E(b) \leq \sum_i \omega_i(b) E(b_i) \leq E(b) e^{\sum_k c_k^2 w_k^2 / 8} \leq E(b) e^{\varsigma/8}. \quad (12)$$

Integrating the right inequality gives (i), and (ii) follows from the left one and (i). For (iii) let $\mathcal{F}(b) = Y_b E(b)$ and I_k the linear interpolation in the k -th coordinate, so that $\mathcal{F} - I_1 I_2 I_3 I_4 \mathcal{F} = \sum_k I_1 \cdots I_{k-1} (\mathcal{F} - I_k \mathcal{F})$. Along the k -th coordinate $\mathcal{F}$ is $\ell^2 e^{c_k x}$ times a positive factor, with ℓ affine of slope $\mathcal{B}_k$, and $\partial_k^2 \mathcal{F} = ((c_k \ell + 2\mathcal{B}_k)^2 - 2\mathcal{B}_k^2) E \geq -2\mathcal{B}_k^2 E$. With the Green kernel of the interval, whose integral is at most $w_k^2/8$,

$$\mathcal{F} - I_k \mathcal{F} \leq 2\mathcal{B}_k^2 \int G E \leq \frac{w_k^2}{4} \mathcal{B}_k^2 \sum_i \omega_i^{(k)} E(b_i)$$

by the left inequality of (12), with weights $\omega_i^{(k)} \geq 0$ of sum one that do not depend on U . The operators I_j have nonnegative weights of sum one; integrate over U and divide by $Z(b)$, bounded below by (i). $\square$

G. The cover and the theorem

Fix a box Q and a matrix C . For any constant κ , $\text{Var}(X_h) \leq v_b[(X_h - \kappa)^2]$; take $\kappa = \langle \kappa(b), h \rangle$ with $\kappa(b)$ affine in b , fitted to the means at the corners. By (11), $X_h - \kappa = \mathcal{A} + \sum_k (b_k - \beta_k) \mathcal{B}_k$ with β the centre of Q and $\mathcal{B}_k = \langle \nabla \varphi_{F_k}, \nabla q_h \rangle - \langle \partial_k \kappa, h \rangle$, and Lemmas 30 and 33 give, for all $b \in Q \cap \mathcal{R}_r$,

$$\sup_h L_h(b) \leq \sqrt{e^{\varsigma/8} \max_i \lambda_A(b_i)} + \sqrt{\frac{e^{\varsigma/8}}{\gamma(r)} \left(\max_i \lambda_V(b_i) + \frac{e_N}{\min_i Z(b_i)} \right)}, \quad (13)$$

where $e_N = \sum_k \frac{w_k^2}{4} \max_i Z(b_i) \lambda_k(b_i)$ and $\lambda_A, \lambda_V, \lambda_k$ are the largest eigenvalues of the quadratic forms $h \mapsto v_{b_i} |\nabla q_h|^2$, $h \mapsto v_{b_i} [(X_h - \kappa)^2]$ at $b = b_i$, and $h \mapsto v_{b_i} [\mathcal{B}_k^2]$ on $\mathbb{R}^{18}$. Their entries are moments of v_{b_i} of degree at most six, computed with rigorous error bounds (Appendix E); each largest eigenvalue is bounded above by an $LDL^\top$ factorisation of tI minus the computed form with certified positive pivots, plus the norm of its error matrix by Weyl’s inequality [36, 41].

The matrix C is chosen in each box in floating point. At the mean of the corner moments and at $b = \beta$, Lemma 30 for $u = q_h$ is a quadratic problem in C : for $\theta > 0$ we minimise the trace of $v |\nabla q|^2 + \theta \text{Var}(X)/\gamma$ over the 18 coordinate directions h , a least-squares problem of size 189, keep the θ on a geometric grid of 48 values from 0.05 to 80 that gives the smallest bound, and round C to multiples of 2^{-30} . Any choice gives a valid bound.

A box is discarded when it contains no point with $a_1 \geq a_2 \geq |z_3|$, or when a linear functional $\ell(b) = \text{Re Tr}(C^* b)$ satisfies $\min_Q \ell > r \max_T \ell$, which separates it from $r \text{conv } T$ and hence, by Lemma 31(iii), from $\mathcal{R}_r$.

Proposition 34. $2r\Lambda(r) \leq 0.999887$ at $r = \frac{3}{2}$.

Proof. The box $[0, r]^2 \times [-r, r] \times [0, r]$ is cut into 8192 boxes of side $r/8$. Of these, 841 survive the two tests, and 581 satisfy $2rB_Q < 1$ for the right side B_Q of (13), with $\gamma(r) = \frac{187}{128}$. Each of the other 260 is cut into sixteen boxes of side $r/16$; 1760 of these survive the tests, and all satisfy $2rB_Q < 1$. The 2341 certified boxes cover $\mathcal{R}_r$. The largest bound is 0.999887, on the box $[1.3125, 1.5] \times [0.9375, 1.125] \times [0.5625, 0.75] \times [0, 0.1875]$, and the median is 0.983. Figure 5 shows the cover, and Appendix E the error analysis. $\square$

The same cover at a larger r bounds $\Lambda(r)$ where $2r\Lambda(r)$ is no longer below one; the plaquette blocks of Section VIII use that bound.

Proposition 35. $2r\Lambda(r) \leq 1.029967$ at $r = \frac{38}{25}$.

Proof. As in the proof of Proposition 34, with $\gamma(r) = \frac{4643}{3200}$ and the threshold $2rB_Q < 1.03$: of the 8192 boxes of side $r/8$, 784 survive the two tests and 690 satisfy the threshold; each of the other 94 is cut into sixteen boxes of side $r/16$, of which 373 survive the tests, and all satisfy it. The 1063 certified boxes cover $\mathcal{B}_r$, and the largest bound is 1.029967. $\square$

Proof of Theorem 6. Proposition 34 gives

$$\Lambda\left(\frac{3}{2}\right) \leq \frac{0.999887}{3} < 0.333296.$$

For $\beta_W \leq \frac{3}{4}$ we have $2\beta_W \leq \frac{3}{2}$, and (8) with the monotonicity of Λ gives

$$\alpha \leq 4\beta_W \Lambda\left(\frac{3}{2}\right) < 1.333183\beta_W \leq \frac{3}{4} \cdot 1.333183 < 1.$$

Proposition 11 applies with the Hilbert–Schmidt metric. $\square$

VIII. SU(3) WITH PLAQUETTE BLOCKS

In this section $G = \text{SU}(3)$, $\beta \geq 0$, $\beta_W = 9\beta$, $N\beta = \beta_W/3$, and the notation is that of Sec. VII: d is the Hilbert–Schmidt distance, $K = \text{conv SU}(3)$, $v_c(dU) \propto e^{\text{Re Tr}(Uc)} dU$, $\phi_h(U) = \text{Re Tr}(Uh)$ and $\Lambda(r)$ is the modulus of (8). Put $Z(c) = \int e^{\text{Re Tr}(Uc)} dU$ and $g = \log Z$ on $\mathbb{C}^{3 \times 3}$, viewed as $\mathbb{R}^{18}$ with the inner product $\langle x, y \rangle = \text{Re Tr}(xy^*)$. The gradient of g at c is the conjugate mean $m(c)^*$, $m(c) = v_c(U) \in K$, and $\text{Hess } g(c)(h, h) = \text{Var}_{v_c}(\phi_h)$. Since $Z(VcW) = Z(c)$ for $V, W \in \text{SU}(3)$, the same holds for g .

The blocks are those of Lemma 12, which concerns the line field only and holds for every group. For a block plaquette with active links e_1, e_2, e_3 , $\text{Re Tr } Q_p = \text{Re Tr}(y_1 y_2 y_3)$ with $y_i = Q_{e_i}$ or $Q_{e_i}^{-1}$, and the conditional law of the block is

$$\mu_b(dy) \propto \exp\left(\sum_i \text{Re Tr}(y_i b_i) + N\beta \text{Re Tr}(y_1 y_2 y_3)\right) dy, \quad (14)$$

where b_i is $N\beta$ times the sum of the five staples of y_i outside the block plaquette, so $b_i \in 5N\beta K$ and $\|b_i\|_{\text{op}} \leq 5N\beta$. On $\text{SU}(3)^3$ we use $d(y, y') = \sum_i \|y_i - y'_i\|_{\text{HS}}$.

A. The sensitivity of one block

Let $r = 2\beta_W = 6N\beta$. Let λ_* and τ be a lower and an upper bound for the eigenvalues of $\text{Hess } g$ on rK , M an upper bound on rK for $|D^3 g(c)(u, v, v)|$ over unit vectors u, v , and $\gamma = \gamma(r)$ the gap of Lemma 29. Put

$$\begin{aligned} w &= \frac{3}{2}(N\beta)^2(\tau - \lambda_*), & s &= \Lambda(r) + (e^w - 1)e^w \sqrt{\tau/\gamma}, \\ C &= 5(N\beta)^2 \left(\tau s + \frac{\sqrt{3}N\beta M e^w}{\gamma} \right), \\ K_3 &= \frac{(1 + N\beta\Lambda(r))s}{1 - C}, & \alpha_3 &= 10N\beta K_3, \end{aligned} \quad (15)$$

assuming $C < 1$.

Lemma 36. Let $a, c_0 \in 5N\beta K$ and

$$\kappa(dx) \propto \exp(\text{Re Tr}(xa) + g(c_0 + N\beta x)) dx \quad \text{on } \text{SU}(3).$$

For every 1-Lipschitz f and every $h \in \mathbb{C}^{3 \times 3}$:

$$(i) \quad \text{Cov}_\kappa(f, \phi_h) \leq s \|h\|_{\text{HS}};$$

(ii) if c_0 moves in the direction k inside $5N\beta K$, then

$$\left| \frac{d}{dt} \kappa(f) \right| \leq N\beta (\tau s + \sqrt{3}N\beta M e^w / \gamma) \|k\|_{\text{HS}}.$$

Proof. (i) The segment from c_0 to $c_0 + N\beta x$ lies in $6N\beta K = rK$, and Taylor's formula gives

$$g(c_0 + N\beta x) = g(c_0) + N\beta \text{Re Tr}(xm(c_0)) + R(x)$$

with $R(x) = \frac{1}{2}(N\beta)^2 \text{Hess } g(\xi)(x, x)$. Since $\|x\|_{\text{HS}}^2 = 3$, $R \in [\frac{3}{2}(N\beta)^2 \lambda_*, \frac{3}{2}(N\beta)^2 \tau]$ and $\text{osc } R \leq w$. Hence κ is the tilt $e^R v / v(e^R)$ of $v = v_{c'}$ with $c' = a + N\beta m(c_0) \in rK$. By definition of Λ , $\text{Cov}_v(f, \phi_h) \leq \Lambda(r) \|h\|$. The function f is 1-Lipschitz for the geodesic distance, which dominates d , so $\text{sd}_v f \leq \gamma^{-1/2}$ by Lemma 29, and $\text{sd}_v \phi_h \leq \sqrt{\tau} \|h\|$. Lemma 13 gives (i).

(ii) The derivative is $\text{Cov}_\kappa(f, \langle \nabla g(c_0 + N\beta x), k \rangle)$. Write $\nabla g(c_0 + N\beta u) = \nabla g(c_0) + N\beta \text{Hess } g(c_0)u + N(u)$. The linear term is ϕ_h with $\|h\| \leq N\beta \tau \|k\|$ and contributes at most $N\beta \tau s \|k\|$ by (i). On the segment from c_0 the Hessian moves by at most $N\beta M \|u\| \leq \sqrt{3}N\beta M$, so $x \mapsto \langle N(x), k \rangle$ is $\sqrt{3}(N\beta)^2 M \|k\|$ -Lipschitz for d . The law κ is a tilt of v by a function of oscillation at most w , so its spectral gap is at least $e^{-w} \gamma$ by the Holley–Stroock lemma [37], and the covariance of two Lipschitz functions under κ is at most e^w / γ times the product of their constants. $\square$

Lemma 37. Let $C < 1$. If b, b' have all fields in $5N\beta K$ and differ only in b_i , then $W_1(\mu_b, \mu_{b'}) \leq K_3 \|b_i - b'_i\|_{\text{HS}}$ for the metric d .

Proof. By the cyclic symmetry of $\text{Re Tr}(y_1 y_2 y_3)$ we may take $i = 1$. Given y_1, y_3 , the law of y_2 is v_c with $c = b_2 + N\beta y_3 y_1 \in rK$. Changing y_1 by η in d moves c by $N\beta \eta$ and v_c by at most $N\beta \Lambda(r) \eta$ in W_1 , as in (8); so $F(y_1, y_3) = \mathbb{E}[f | y_1, y_3]$ is $(1 + N\beta \Lambda(r))$ -Lipschitz in each variable. The law of (y_1, y_3) is proportional to $e^{\text{Re Tr}(y_1 b_1) + \text{Re Tr}(y_3 b_3)} Z(b_2 + N\beta y_3 y_1)$, and $Z(b_2 + N\beta y_3 y_1) = Z(y_3^{-1} b_2 + N\beta y_1) = Z(b_2 y_1^{-1} + N\beta y_3)$, so its two conditional laws have the form of Lemma 36, with $c_0 = y_3^{-1} b_2$ and $c_0 = b_2 y_1^{-1}$. Moving y_3 to y'_3 moves $y_3^{-1} b_2$ along a segment in $5N\beta K$ of length at most $\|b_2\|_{\text{op}} \|y_3 - y'_3\| \leq 5N\beta \|y_3 - y'_3\|$. The coupling argument of Lemma 15 now gives $d_1 \leq s\epsilon + Cd_3$, $d_3 \leq Cd_1$ and $|\mu_b(f) - \mu_{b'}(f)| \leq (1 + N\beta \Lambda(r))(d_1 + d_3) \leq K_3 \epsilon$. $\square$

B. The constants and the proof of Theorem 7

Lemma 38. At $r = \frac{3}{2}$ every eigenvalue of $\text{Hess } g$ on rK lies in $[0.056015, 0.247316]$, and $|D^3 g(c)(u, v, v)| \leq 0.182126$ for $c \in rK$ and unit vectors u, v . At $r = \frac{38}{25}$ the same holds with $[0.054978, 0.248280]$ and 0.183546 .

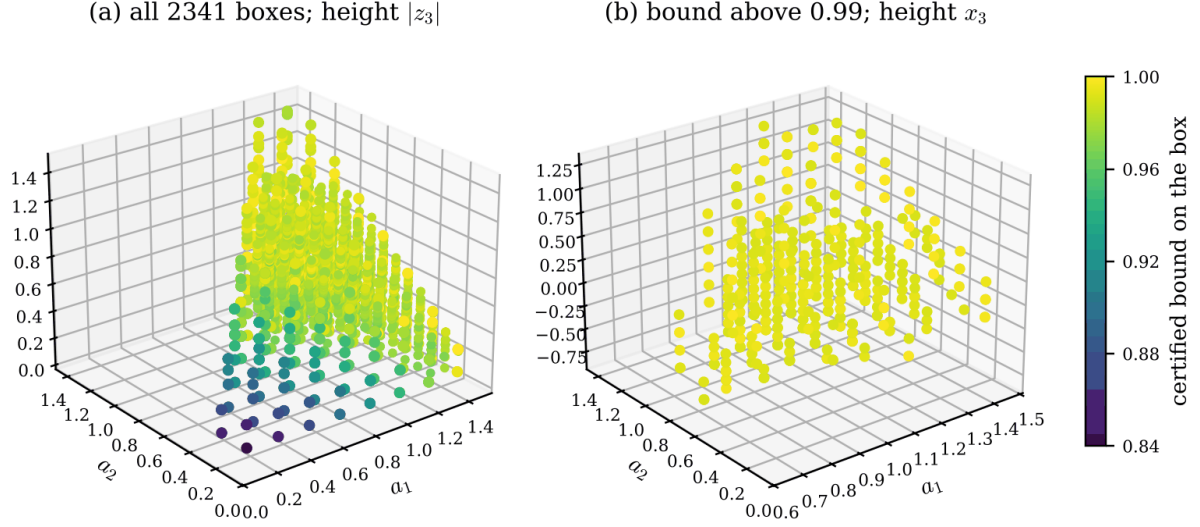


FIG. 5. The 2341 certified boxes at $r = \frac{3}{2}$, plotted at their centres in the coordinates (a_1, a_2) of the staple sum $\text{diag}(a_1, a_2, x_3 + iy_3)$, coloured by the certified bound on $2r \sup_h L_h$ over the box; the larger points are the boxes of side $r/8$. (a) All boxes, with height $|x_3 + iy_3|$. (b) The 419 boxes with bound above 0.99, with height x_3 ; the largest bounds sit in the interior of $\mathcal{R}_r$, not at its extreme points.

Proof. For $V, W \in \text{SU}(3)$, $g(VcW) = g(c)$ and $x \mapsto VxW$ is an isometry, so the eigenvalues of $\text{Hess } g$ and the norm of $D^3 g$ are constant on the orbits, and by Lemma 31 it suffices to bound them on $\mathcal{R}_r$. The derivatives of g are the cumulants of φ under v_c . Cut the box $[0, r]^2 \times [-r, r] \times [0, r]$ into boxes of side $r/8$ and keep the 841 (784 at $r = \frac{38}{25}$) that survive the two tests of Sec. VII G. On each box Q we compute, with rigorous error bounds, the moments of φ of degree at most three at the sixteen corners b_i and at the centre b_0 , and put $k = m(b_0)$, the mean of φ at the centre.

Upper bound. For $b \in Q$ and every h , $\text{Var}_{v_b}(\varphi_h) \leq v_b[(\varphi_h - \langle k, h \rangle)^2] \leq e^{\zeta/8} \max_i v_{b_i}[(\varphi_h - \langle k, h \rangle)^2]$ by Lemma 33(ii).

Lower bound. Integrating the right inequality of (12) against $f \geq 0$ and dividing by $Z(b) \leq \sum_i \omega_i Z(b_i)$, the left one, gives $v_b(f) \geq e^{-\zeta/8} \min_i v_{b_i}(f)$. With $f = (\varphi_h - v_b \varphi_h)^2$ this gives $\text{Var}_{v_b}(\varphi_h) \geq e^{-\zeta/8} \min_i \text{Var}_{v_{b_i}}(\varphi_h)$.

Third cumulant. Put $\delta = m(b) - k$. The mean value theorem and the upper bound give $\|\delta\| \leq \tau\rho + e$, with ρ the largest distance from b_0 in Q and e the error of the computed mean. Expanding the central moment about k ,

$$D^3 g(b)(u, v, v) = T_b(u, v, v) - \delta_u \text{Var}(\varphi_v) - 2\delta_v \text{Cov}(\varphi_u, \varphi_v) - \delta_u \delta_v^2,$$

with $T_b = v_b[(\varphi - k)^{\otimes 3}]$, $\delta_u = \langle \delta, u \rangle$ and the moments under v_b . For a function G of either sign, writing $G = G^+ - G^-$ and applying the two bounds above to $G^\pm$ gives $|v_b(G)| \leq (\max_i |v_{b_i}(G)| + \varepsilon \max_i v_{b_i}|G|)/(1 - \varepsilon)$ with $\varepsilon = 1 - e^{-\zeta/8}$. For $G = (\varphi_u - k_u)(\varphi_v - k_v)^2$ we use $|v_{b_i}(G)| \leq \|T_{b_i}\|$, the largest singular value of the 18×324 unfolding of T_{b_i} , and

$v_{b_i}|G| \leq 2\sqrt{3} v_{b_i}[(\varphi_v - k_v)^2]$, since $\|U - k\|_{\text{HS}} \leq 2\sqrt{3}$. The largest eigenvalues and singular values are bounded as in Sec. VII G, and the maxima over these boxes are the numbers stated (Appendix C). $\square$

Proof of Theorem 7. Let first $\beta_W \leq \frac{3}{4}$, so that $r = 2\beta_W \leq \frac{3}{2}$. Every field met in Lemmas 36 and 37 lies in $\frac{3}{2}K$, so the constants of Lemma 38 at $\frac{3}{2}$, $\Lambda(\frac{3}{2}) \leq \frac{0.999887}{3}$ from Proposition 34 and $\gamma = \gamma(\frac{3}{2}) = \frac{187}{128}$ apply; with these fixed constants every quantity in (15) is increasing in β_W . For $\frac{3}{4} < \beta_W \leq \frac{19}{25}$ the fields lie in $\frac{38}{25}K$, and the constants of Lemma 38 at $\frac{38}{25}$, $\Lambda(\frac{38}{25}) \leq \frac{1.029967}{3.04}$ from Proposition 35 and $\gamma(\frac{38}{25}) = \frac{4643}{3200}$ apply in the same way. Changing an active link j by η changes one staple of each of its ten partners outside its block by a matrix of norm η , so the field b_i of each such partner moves by $N\beta\eta$, and Lemma 37 gives $\sum_B C_{Bj} \leq 10N\beta K_3 = \alpha_3(\beta_W)$. In ball arithmetic, at $\beta_W = \frac{3}{4}$, $w \leq 0.017935$, $s \leq 0.34088$, $C \leq 0.043520$, $K_3 \leq 0.38609$ and $\alpha_3 \leq 0.96521$; at $\beta_W = 0.72$, $\alpha_3 \leq 0.91815$; at $\beta_W = 0.76$, with the second set of constants, $w \leq 0.018609$, $s \leq 0.34673$, $C \leq 0.045770$, $K_3 \leq 0.39454$ and $\alpha_3 \leq 0.99950$. Proposition 17, whose proof does not use the group, applies with the Hilbert–Schmidt metric. $\square$

Remark 39. Theorem 6 ends where $2r\Lambda(r)$ reaches one. The blocks remove the factor $\frac{12}{10}$ of the single-link sum and keep most of it after paying for the three links: at $\beta_W = \frac{3}{4}$ the gap bound rises from $1.1 \cdot 10^{-4}$ to 0.0177, and the block bound is the better one for $\beta_W \geq 0.715$. Before the corrections for the three links their sum is $\frac{10}{12}$ of the single-link sum $2r\Lambda(r)$, so it can stay below one while $2r\Lambda(r)$ is slightly above one;

Proposition 35 certifies $2r\Lambda(r) \leq 1.03$ at $r = 1.52$, which is enough at $\beta_W = 0.76$, with little room. Evaluated in floating point with the constants of a scan of $\mathcal{R}_r$, the block sum stays below one up to $\beta_W \approx 0.78$; that computation is not certified and is not used.

IX. WHERE THE METHODS STOP

SU(2). Theorem 2 closes the single-link route in every forest gauge at $\beta_W = \frac{1}{3}$. Blocks of several links, where the influence of a boundary link on a whole block is bounded at once, in the spirit of the Dobrushin–Shlosman criterion [28], pass it: plaquette blocks reach $\beta_W = 0.345$ (Theorem 3), and the sharper floating-point bound of Remark 18 stops near 0.357. Larger blocks are the next step.

Curvature. Remark 26 locates the end of the curvature method in this gauge between $|\beta| = \frac{1}{29}$ and $\frac{1}{26.25}$.

SU(3). The route of Sec. VII bounds the $H^{-1}(\nu_b)$ norm of $\phi_h - \nu_b \phi_h$, which is at least $L_h(b)$, and needs it uniformly on rK . Its Galerkin values (polynomials of degree two) at matrices of rK give $2r$ times the norm equal to 0.79 at $r = 1.25$, 0.89 at $r = 1.4$, 0.97 at $r = 1.5$ and 1.009 at $r = 1.55$, so the route stops at or below $\beta_W \approx 0.77$ even with exact constants. With $u = s\phi_h$, Lemma 30 stops earlier: in floating point its largest values on $\mathcal{R}_r$ lie on the face $\text{diag}(r, \rho, \rho)$ with ρ between $0.75r$ and $0.8r$, and $2r$ times the bound is 0.9458 at $r = 1.36$, 0.9767 at $r = 1.40$ and 1.0080 at $r = 1.44$, so this corrector ends near $\beta_W \approx 0.715$. With $u = q_h$ of degree two the largest values on the same face are 0.9305 at $r = 1.44$, 0.9729 at $r = 1.50$ and 1.0018 at $r = 1.54$ (Fig. 6), close to the Galerkin values. Lemma 29 therefore costs little at these couplings, and most of the distance between the floating-point value at $r = 1.5$ and the certified 0.999887 of Proposition 34 is the interpolation over boxes. Between $\beta_W = \frac{3}{4}$ and 0.77 there is room only for smaller boxes. The plaquette blocks of Theorem 7 use $\Lambda(2\beta_W)$ as well, with a little more room: they reach 0.76 with the certified cover of Proposition 35 and near 0.78 in floating point (Remark 39); past that one needs larger blocks, whose sensitivity does not go through the one-link modulus.

Other groups. For groups other than SU(2) and SU(3) only the curvature route is carried out here (Theorem 5), and it stops where the bound $\frac{29}{2}$ uses up the curvature of G , at $N|\beta| = \frac{29}{29}\kappa_G$. The Dobrushin route needs a bound for the Kantorovich modulus of the one-link measure of each group, which is not attempted here.

The four open problems. Our earlier paper [13] listed four problems between the strong-coupling results and the Clay problem [40]: (1) uniqueness and a gap at intermediate fixed coupling; (2) the crossover from strong coupling to Balaaban’s weak-coupling regime; (3) the continuum limit with the Osterwalder–Schrader axioms; and (4) a gap in physical units. The present paper moves the boundary of (1): for SU(2) from $\beta_W = \frac{2}{9}$ to 0.345, for SU(3) from $\frac{9}{32}$ to 0.76, with a gap at $\frac{3}{4}$ of 0.0177 in lattice units, and for every compact simple group, the exceptional groups included, past the curvature ceiling of the ungauged measure, with an explicit gap. It does not

close (1); the region between these values and the scaling region, near $\beta_W \approx 2.2$ for SU(2) and $\beta_W \approx 6$ for SU(3), is open, and with it problem (2). Problems (3) and (4) are not solved here. Every bound proved here is uniform in lattice units, so by [14] none of them can by itself produce a continuum mass gap; that requires control of the gap in physical units along the renormalisation group flow [4, 16].¹⁴

The continuum problem. Two general facts limit what can be imported into problems (3) and (4) above from constructions of continuum measures. Both concern a random distribution F on $\mathbb{R}^d$, a Borel probability measure on the tempered distributions with finite moments, and the growth condition

$$\mathbb{E}e^{F(\chi)} \leq e^{C(\|\chi\|_1 + \|\chi\|_2^2)} \quad \text{for all real } \chi \in \mathcal{S}(\mathbb{R}^d), \quad (16)$$

which is the growth condition of the regularity axiom of Glimm and Jaffe at $p = 2$ [33, Sect. 6.1, (6.1.5)]. It is the hypothesis under which reflection positivity across coordinate and diagonal hyperplanes is shown in [65] to give rotation invariance of the Schwinger functions, a step proposed there for the continuum limit of lattice gauge theories.

Proposition 40. *Let F satisfy (16), and suppose that its connected two-point function is, off the diagonal, a locally integrable function $S_2(x, y)$ with $S_2(x, y) \geq c|x - y|^{-2\Delta}(\log \frac{1}{|x - y|})^{-k}$ for $0 < |x - y| \leq r_0$, where $c > 0$, $k \geq 0$ and $2\Delta > d$. Then F does not exist: no random distribution has both properties.*

Proof. Applying (16) to χ and $-\chi$ and using $\cosh x \geq 1 + \frac{x^2}{2}$ gives $\mathbb{E}F(\chi)^2 \leq 2(e^{C(\|\chi\|_1 + \|\chi\|_2^2)} - 1)$. Fix nonnegative $\phi, \psi \in C_c^\infty(\mathbb{R}^d)$, not zero, with supports in a ball of radius $\frac{R}{2}$ and at distance $\delta > 0$ from each other, and put $\phi_\varepsilon(x) = \varepsilon^{-d/2}\phi(x/\varepsilon)$, and likewise ψ_ε . Then $\|\phi_\varepsilon\|_2 = \|\phi\|_2$ and $\|\phi_\varepsilon\|_1 = \varepsilon^{d/2}\|\phi\|_1 \leq \|\phi\|_1$ for $\varepsilon \leq 1$, so the covariance of $F(\phi_\varepsilon)$ and $F(\psi_\varepsilon)$ is bounded uniformly in ε by the Cauchy–Schwarz inequality. On the other hand the supports of ϕ_ε and ψ_ε are disjoint, and for u, v in the supports $\varepsilon\delta \leq |\varepsilon u - \varepsilon v| \leq \varepsilon R$. For $\varepsilon R \leq r_0$ and $\varepsilon R < 1$ the lower bound for S_2 therefore gives

$$\begin{aligned} \text{Cov}(F(\phi_\varepsilon), F(\psi_\varepsilon)) &= \varepsilon^d \iint \phi(u)\psi(v)S_2(\varepsilon u, \varepsilon v) du dv \\ &\geq cR^{-2\Delta}\varepsilon^{d-2\Delta}\left(\log \frac{1}{\varepsilon\delta}\right)^{-k} \|\phi\|_1 \|\psi\|_1, \end{aligned}$$

which tends to infinity as $\varepsilon \rightarrow 0$. $\square$

The action density $\text{Tr} F_{\mu\nu} F_{\mu\nu}$ has dimension $\Delta = 4$ in four dimensions. A two-sided short-distance law of the form $|x - y|^{-8}$ times the fourth power of the running coupling, which is

¹⁴ Every one of these approaches needs an input at physical length scales. Renormalisation group approaches to the ultraviolet behaviour of gauge and gravitational theories, of which [4, 25] are the rigorous ones for Yang–Mills theory, have also been proposed for the effective dimension of space-time [58] and for completions of quantum gravity [10, 15]; they do not bear on the infrared estimates needed here.

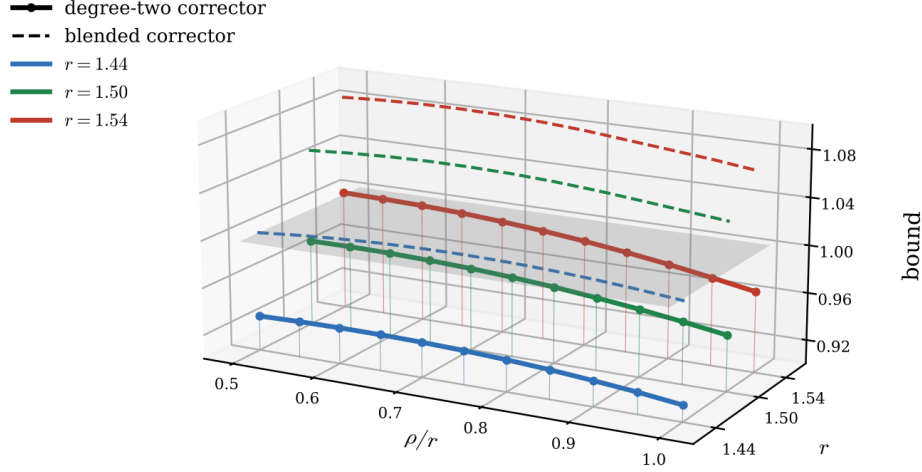


FIG. 6. The floating-point value of $2r \sup_h$ of the bound of Lemma 30 on the face $b = \text{diag}(r, \rho, \rho)$, as a function of ρ/r , for $r = 1.44, 1.50$ and 1.54 : dashed with the corrector $u = s\phi_h$ for the best s , solid with $u = q_h$ of degree two for the best C . The grey plane is the Dobrushin threshold one. The first corrector is above it already at $r = 1.44$; the second stays below it at $r = 1.50$, where Proposition 34 certifies the bound on all of $\mathcal{R}_r$, and crosses it by $r = 1.54$.

what asymptotic freedom¹⁵ predicts and what the conditional construction of [66] states for the smeared action density, has $2\Delta = 8 > 4$ and $k = 2$; so that field cannot satisfy (16), and rotation invariance for it has to come from another source, as in [66], where it is reduced to a separate infrared hypothesis. In three dimensions the free part of the action density already has $2\Delta = 6 > 3$. Condition (16) suits fields of dimension at most $\frac{d}{2}$, such as the field strength of the free Maxwell field, whose covariance is bounded in momentum space.

Positivity, symmetry and regularity do not produce a gap by themselves.

Proposition 41. *On $\mathbb{R}^4$ let F be the centred Gaussian random distribution with covariance*

$$\hat{C}(p) = \int_0^1 \frac{m^2}{|p|^2 + m^2} dm.$$

Then F is invariant under all Euclidean motions, reflection positive, satisfies (16) with $C = \frac{1}{2}$, and its Osterwalder–Schrader Hamiltonian has no gap above the vacuum.

Proof. Since $0 \leq \hat{C} \leq 1$, $\mathbb{E}e^{F(\chi)} = e^{\frac{1}{2}\langle \chi, C\chi \rangle} \leq e^{\frac{1}{2}\|\chi\|_2^2}$, with the unitary Fourier transform. Invariance is clear. The covariance is the integral over $m \in (0, 1)$, with the weight $m^2 dm$,

of the covariances of free fields of mass m , each of which is reflection positive [33, Sect. 6.2]; a positive combination of reflection positive covariances is reflection positive, and so is the Gaussian measure with such a covariance [33, Sect. 6.2]. For $\chi(t, \mathbf{x}) = h(t)g(\mathbf{x})$ with $h \geq 0$ supported in $t > 0$, not zero, and $\hat{g}(0) \neq 0$, the vector $v = F(\chi)$ is orthogonal to the vacuum, and after the Fourier transform in $\mathbf{x}$,

$$\begin{aligned} \langle v, e^{-sH} v \rangle &= \int_0^1 m^2 dm \int \frac{|\hat{g}(\mathbf{k})|^2}{2\omega} e^{-\omega s} \\ &\quad \times \left(\int_0^\infty h(t) e^{-\omega t} dt \right)^2 d\mathbf{k}, \end{aligned}$$

with $\omega = \sqrt{|\mathbf{k}|^2 + m^2}$ and constants absorbed in $\hat{g}$. If H had a gap $m_0 > 0$, the left side would be at most $e^{-m_0 s} \|v\|^2$. For $0 < \eta < m_0$ the part of the integral with $m, |\mathbf{k}| \leq \eta/2$ is at least $c_\eta e^{-\eta s}$ with $c_\eta > 0$, a contradiction as $s \rightarrow \infty$. $\square$

The Gaussian field of Proposition 41 is not a gauge theory; it shows only that an infrared estimate, such as a bound $\langle v_a, T_a^{[t/a]} v_a \rangle \leq C_\eta e^{-m_* t}$ uniform in the spacing a along the continuum tuning, has to be proved in addition to the axioms. The lattice bounds of this paper are of this form only with m_* proportional to $1/a$, and by [14] such bounds give trivial limits. The routes we know to a continuum gap therefore all stop at the same two estimates: the construction of the infinite-volume continuum measure past Balaaban’s small-field analysis [4, 6], which the conditional construction of [66] assumes clause by clause and which yields there a non-negative Hamiltonian without any statement on its spectrum, and a decay estimate in physical units at large scales. The finite-size criterion described in [66, Sect. 9.4] reduces a gap to a threshold condition on one box, uniformly in the cutoff; as stated there, the condi-

¹⁵ For $\text{SU}(N)$ the renormalisation group gives, with $b_0 = 11N/(48\pi^2)$ and the invariant scale Λ ,

$$g(a)^{-2} = 2b_0 \log \frac{1}{a\Lambda} + O(\log \log \frac{1}{a\Lambda}),$$

so the inverse coupling $\beta_W = 2N/g(a)^2$ grows like $\frac{11N^2}{12\pi^2} \log \frac{1}{a\Lambda}$ along the continuum tuning.

tion fails in every small box and would have to be checked at large scales, which the construction does not reach.

X. THE CONTINUUM STEP AT ONE PHYSICAL SCALE

The bounds of the preceding sections hold at fixed coupling and give a gap that is at least a fixed number in lattice units, and [14] shows that no such bound can produce a continuum gap. This section replaces the single-link condition of Proposition 11 by a condition on one cube of n^4 sites, averaged over its translates in the manner of Dobrushin and Shlosman [28], and proves that the condition gives a gap of order $1/n$ in lattice units. If it holds with n proportional to $1/a$, that is, in a cube of fixed physical size, the gap survives in physical units and passes to every continuum limit (Theorem 45). The two statements that remain unproved are named at the end: the cube estimate and the existence of the limit.

A. Averaged cubes

For a finite set $V \subset A$ let $\mathcal{W}(\cdot | Q)$ be the probability measure on G^V with density proportional to $\exp(N\beta \sum_{p \cap V \neq \emptyset} \text{Re Tr } Q_p^F)$ with respect to Haar measure, the links outside V being those of Q . Its conditional law of Q_e , $e \in V$, given the other links of V is γ_e^F . Write $d_V(Q_V, Q'_V) = \sum_{i \in V} \delta(Q_i, Q'_i)$ and, for $j \in A \setminus V$,

$$C_{V,j} = \sup \frac{W_1^{d_V}(\mathcal{W}(\cdot | Q), \mathcal{W}(\cdot | Q'))}{\delta(Q_j, Q'_j)},$$

the supremum over pairs that differ only at j ; $W_1^{d_V}$ is the Kantorovich distance for d_V . The coefficient vanishes unless j shares a plaquette with a link of V .

Let $n \geq 2$ be even and let V be the set of active links (x, μ) with $x \in [0, n)^4$. The direction field has period two, so the translations by $2\mathbb{Z}^4$ preserve F , A and γ^F , and the translates $V_x = V + x$, $x \in 2\mathbb{Z}^4$, satisfy $C_{V_x, j+x} = C_{V,j}$. Every active link lies in exactly $N_n = (n/2)^4$ of them. A *class* is an orbit of $2\mathbb{Z}^4$ on A , that is, a residue of the base point modulo two together with a direction; there are at most 64 classes. For a class c put

$$K_c = \sum_{j \in c \setminus V} C_{V,j}.$$

Definition 42. For $0 < \alpha < 1$, the condition $D(n, \alpha)$ at the coupling β is $K_c \leq \alpha N_n$ for every class c .

Since $\sum_{x \in 2\mathbb{Z}^4, j \notin V_x} C_{V_x, j} = \sum_x C_{V, j-x} [j-x \notin V] = K_{c(j)}$ for the class $c(j)$ of j , the condition says that the total influence of a link on the translates that do not contain it is at most the fraction α of the number of translates that do. Figure 7 shows the cubes.

For $n = 2$ it is a bound on blocks of 48 links. Distances between links are those of their midpoints; a link of V and a link sharing a plaquette with V are at distance at most $\rho_n = 2n$, and c_n denotes the number of active links within distance ρ_n of a given one.

Theorem 43. Let $\beta \geq 0$ and suppose that $D(n, \alpha)$ holds. Then statements (i)–(iv) of Proposition 11 hold, (v) holds for every $\lambda < \log(1/\alpha)/\rho_n$, and the transfer matrix of ω has spectral gap at least $\log(1/\alpha)/(2n)$.

Proof. The proof of Proposition 11 uses the coefficients $C_{ee'}$ only through Lemma 78 and Corollary 79. Lemma 81 of Appendix B gives the same conclusions under $D(n, \alpha)$, for every $\lambda > 0$ with $\alpha e^{\lambda \rho_n} < 1$, with the constant $\theta D/(1-\theta)$ replaced by $D(1 + c_n e^{\lambda \rho_n})/(1-\theta)$ and $\theta = \alpha e^{\lambda \rho_n}$. The measures used there are invariant under every γ_{V_x} with V_x disjoint from the exceptional set: a Gibbs measure of γ^F and its conditional measures given the links of a finite set by Lemma 81(a), and the extended finite-volume measure of part (ii) because every plaquette that meets such a V_x lies in $P(\Lambda)$. Part (vi) then follows from Proposition 82 as before, with every $\lambda < \log(1/\alpha)/(2n)$. $\square$

B. The continuum limit

Let $a_k = 2^{-k} a_0$ and let $\beta_k \geq 0$ be couplings, typically with $\beta_k \rightarrow \infty$. Suppose that the lattice states ω_k at β_k exist as in Proposition 11, with transfer matrices $\mathbb{T}_k$ on the reconstructed spaces $\mathcal{H}_k$ and vacua Ω_k (Appendix F). Let $\mathcal{T}$ be a complex vector space of test functions on $\mathbb{R}^4$ supported in $\{t > 0\}$ and, for each k , let $f \mapsto O_k(f)$ be a linear map from $\mathcal{T}$ to gauge-invariant local observables supported in positive lattice times; the example to keep in mind is $O_k(f) = Z_k \sum_x a_k^4 f(a_k x) \Phi(x)$ for a local gauge-invariant field Φ , a renormalisation constant Z_k and $\Phi(x)$ the translate of Φ to x . Write ϑ for the time reflection and τ_t for the time translation by t lattice steps.

Definition 44. A *continuum limit* of (ω_k, O_k) is a Hilbert space $\mathcal{H}$ with a unit vector Ω , a self-adjoint operator $H \geq 0$ with $H\Omega = 0$, and a linear map $f \mapsto \psi(f)$ from $\mathcal{T}$ to $\mathcal{H}$ with dense range, such that for all $f, g \in \mathcal{T}$ and all dyadic $\tau \geq 0$,

$$\begin{aligned} \langle \psi(f), e^{-\tau H} \psi(g) \rangle &= \lim_{k \rightarrow \infty} \omega_k(\vartheta(\overline{O_k(f)}) \tau_{\tau/a_k} O_k(g)), \\ \langle \Omega, \psi(f) \rangle &= \lim_{k \rightarrow \infty} \omega_k(O_k(f)), \end{aligned}$$

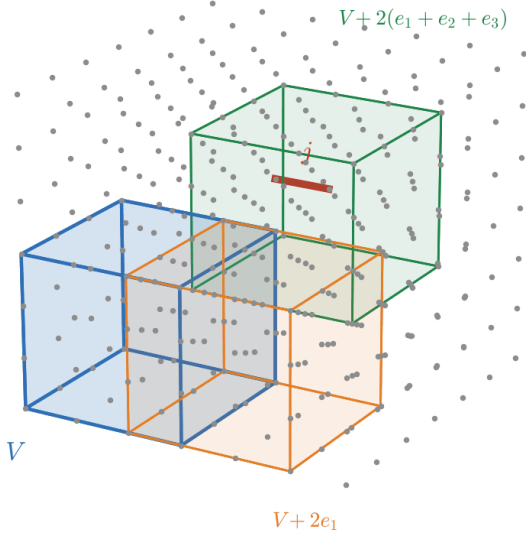
the limits taken over the k for which τ/a_k is an integer. It is *nontrivial* if $\mathcal{H} \neq \mathbb{C}\Omega$.

The Osterwalder–Schrader reconstruction [54, 55] produces such a limit from convergent renormalised Schwinger functions that satisfy the axioms; the definition records only what the next theorem uses.

Theorem 45. Suppose that there are $\alpha < 1$, $\ell > 0$ and even n_k with $n_k a_k \leq \ell$ such that $D(n_k, \alpha)$ holds at β_k for every k . Then every continuum limit of (ω_k, O_k) satisfies

$$\sigma(H) \subset \{0\} \cup [m_*, \infty), \quad m_* = \frac{\log(1/\alpha)}{2\ell},$$

and 0 is a simple eigenvalue. If the limit is nontrivial, $\sigma(H) \cap [m_*, \infty) \neq \emptyset$, so H has a mass gap of at least m_* .

(a) averaged cubes, $n = 4$ 

(b) one physical scale

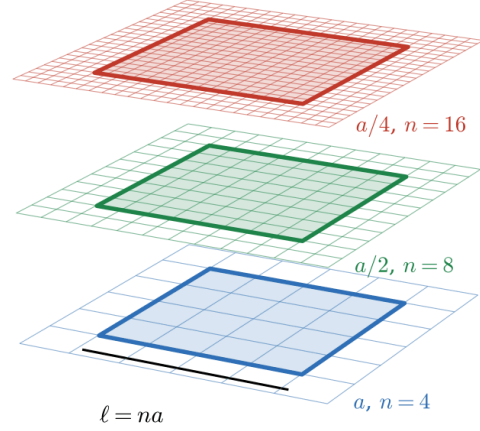


FIG. 7. (a) The cube V of side $n = 4$ and two of its translates by $2\mathbb{Z}^4$, drawn in three of the four dimensions. A link j outside V enters K_c through every translate whose boundary it touches, and $D(n, \alpha)$ compares that total with the $N_n = (n/2)^4$ translates that contain j . (b) The cube of Theorem 45: its physical side $\ell = na$ is held fixed while the spacing is halved, so n doubles at each step and the lattice gap $\log(1/\alpha)/(2n)$ is of order a/ℓ .

Proof. By Theorem 43 the state ω_k exists and $\mathbb{T}_k$ has gap at least $\log(1/\alpha)/(2n_k)$ on the complement of Ω_k . Let $f \in \mathcal{T}$, put $O = O_k(f)$ and $\varphi_k = \Psi_O - \omega_k(O)\Omega_k$. In the reconstruction of Appendix F, $\langle \Psi_F, \mathbb{T}_k^\dagger \Psi_H \rangle = \omega_k(\vartheta(\bar{F})\tau_t H)$, so $\langle \Omega_k, \Psi_O \rangle = \omega_k(O)$, and $\mathbb{T}_k \Omega_k = \Omega_k$; hence, for integers $t \geq 0$,

$$\begin{aligned} \langle \varphi_k, \mathbb{T}_k^t \varphi_k \rangle &= \omega_k(\vartheta(\bar{O})\tau_t O) - |\omega_k(O)|^2 \\ &\leq e^{-t \log(1/\alpha)/(2n_k)} \|\varphi_k\|^2. \end{aligned}$$

Take $\tau \geq 0$ dyadic and k large, so that $t = \tau/a_k$ is an integer; then $t/(2n_k) = \tau/(2n_k a_k) \geq \tau/(2\ell)$, and the right side is at most $e^{-m_* \tau} \|\varphi_k\|^2$. Both sides converge by Definition 44. With $\varphi = \psi(f) - \langle \Omega, \psi(f) \rangle \Omega$ and $e^{-\tau H} \Omega = \Omega$ the limit reads

$$\langle \varphi, e^{-\tau H} \varphi \rangle \leq e^{-m_* \tau} \|\varphi\|^2.$$

The maps $f \mapsto O_k(f)$ and $f \mapsto \psi(f)$ are linear, so the vectors φ form a linear subspace, and it is dense in $\Omega^\perp$ because the range of ψ is dense. The inequality extends to $\Omega^\perp$ by continuity, and from dyadic τ to all $\tau \geq 0$ by the strong continuity of $e^{-\tau H}$. For $\varphi \in \Omega^\perp$ with spectral measure μ_φ of H this says $\int e^{-\tau E} d\mu_\varphi(E) \leq e^{-m_* \tau} \mu_\varphi([0, \infty))$ for all $\tau \geq 0$; if $\mu_\varphi([0, m_* - \eta]) > 0$ for some $\eta > 0$, the left side is at least $\mu_\varphi([0, m_* - \eta])e^{-(m_* - \eta)\tau}$, which exceeds the right side for large τ . So μ_φ lives on $[m_*, \infty)$ for every $\varphi \in \Omega^\perp$, which gives both claims about 0, and the spectrum on $\Omega^\perp \neq \{0\}$ lies in $[m_*, \infty)$ and is not empty. $\square$

The theorem bypasses the obstruction of [14]: under the hypothesis the lattice gap is at least $\log(1/\alpha)/(2n_k)$, of order a_k/ℓ in lattice units, which tends to zero, and only its value in physical units is bounded below. In the language of [14]

the hypothesis implies the gap part (R2) of Hypothesis R, with $m = m_*$, and the conclusion holds for every continuum limit without a separate assumption on the gap.

C. Smoothed observables

The observables $O_k(f)$ of Definition 44 need not be local. The renormalised fields that one expects to converge are smoothed by the gradient flow of the Wilson action [47]¹⁶; at positive flow time their correlation functions are finite to all orders of perturbation theory once the coupling is renormalised [48]. Flow in all four directions mixes the two sides of the reflection plane, but the spatial flow of [59, Sec. II.B] does not: it flows the links of each time slice under the Wilson action of that slice and leaves the temporal links alone.

Fix a bi-invariant Riemannian metric on G . For a configuration U of all links of $\mathbb{Z}^4$ (for the states of this paper, the links of F equal to 1), let $\Phi_s(U)$, $s \in \mathbb{R}$, solve

$$\frac{d}{ds} U_e = -\nabla_e \sum_{p \supseteq e, p \text{ spatial}} (N - \text{Re Tr } U_p)$$

for every spatial link e , the sum running over the four plaquettes of the time slice of e that contain it, with the temporal links held fixed and ∇_e the gradient in the variable U_e .

¹⁶ The flow moves the gauge field along the negative gradient of the Wilson action. At positive flow time the flowed fields are smooth on the scale of the square root of the flow time, and in perturbation theory their gauge-invariant composite fields need no further renormalisation [47, 48].

Proposition 46. (i) Φ_s is defined on every configuration of the infinite lattice, $\Phi_s \circ \Phi_{s'} = \Phi_{s+s'}$, and Φ_s commutes with gauge transformations, with spatial and temporal translations and with the reflections in time. The link $\Phi_s(U)_e$ depends only on the spatial links of the time slice of e , and there are constants κ, c depending only on G such that, if Φ_s^R denotes the flow of the links of that slice within distance R of e with all other links held fixed,

$$\delta(\Phi_s(U)_e, \Phi_s^R(U)_e) \leq D e^{\kappa|s|} \frac{(c|s|)^{R+1}}{(R+1)!}$$

for every configuration U .

(ii) Let ω be a state as in Appendix F and O a bounded gauge-invariant function of finitely many links at times in $[t_0, t_1]$, continuous in them. Then $O \circ \Phi_s$ is a bounded gauge-invariant function of the links at times in $[t_0, t_1]$ and a uniform limit of gauge-invariant local functions at those times.

(iii) Theorem 45 holds with $O_k(f)$ replaced by $O_k(f) \circ \Phi_{s_k}$ for any $s_k \in \mathbb{R}$, in particular for $s_k = \tau/a_k^2$ at a fixed flow time τ in physical units.

(iv) The image measure $(\Phi_s)_* \omega$ is reflection positive, and its transfer matrix is unitarily equivalent to that of ω , the unitary fixing the vacuum.

Proof. (i) Embed G in a matrix algebra. The right side of the equation is a smooth function of the links of the four plaquettes containing e , tangent to G at U_e , so on the Banach space of bounded assignments of matrices to the spatial links it is a vector field that is bounded and Lipschitz on a neighbourhood of the configurations with values in G , with a Lipschitz constant that does not depend on the volume because every link meets finitely many others. The Picard–Lindelöf theorem gives a unique local solution; it stays on G because the field is tangent there, and since the field is bounded on G the solution exists for all s ; uniqueness gives the group law. The action of a time slice and the metric are invariant under gauge transformations, translations and the reflections, so the flow commutes with them by uniqueness. Since the equation of a spatial link involves only links of its own slice, so does the solution. For the comparison, let $d_{e'}(s)$ be the distance between the two flows at a link e' of the slice. Smoothness on the compact group gives constants κ_0, c_1 with $d_{e'}(s) \leq \int_0^{|s|} (\kappa_0 d_{e'} + c_1 \sum_{e'' \sim e'} d_{e''})$ for e' within distance R of e , where $e'' \sim e'$ means that the two links share a spatial plaquette (twelve neighbours), while $d_{e'} \leq D$ beyond. Iterating the integral form of this inequality, a term that reaches the links beyond distance R needs at least $R+1$ steps of $\sim$, and $\sum_{k>R} x^k/k! \leq e^x x^{R+1}/(R+1)!$; this gives the bound with $c = 12c_1$ and $\kappa = \kappa_0 + c$.

(ii) The truncated flow Φ_s^R commutes with gauge transformations for the same reason as Φ_s , so $O \circ \Phi_s^R$ is a gauge-invariant function of finitely many links at times in $[t_0, t_1]$. By (i) and the uniform continuity of O , it converges to $O \circ \Phi_s$ uniformly as $R \rightarrow \infty$.

(iii) The proof of Theorem 45 uses $O_k(f)$ only through the vectors $\Psi_{O_k(f)}$ and the identity $\langle \Psi_F, \mathbb{T}^t \Psi_H \rangle = \omega(\vartheta(\bar{F}) \tau_t H)$. By (ii) and the footnote in Appendix F, both extend to uniform limits of local functions at positive times, and $f \mapsto O_k(f) \circ \Phi_{s_k}$ is linear.

(iv) By (i), Φ_s and Φ_{-s} preserve the functions of the links at positive times and commute with ϑ and τ_t . Hence $(\Phi_s)_* \omega(\vartheta(\bar{F}) \tau_t H) = \omega(\vartheta(\bar{F} \circ \Phi_s) \tau_t (H \circ \Phi_s))$, which for $t = 0$ and $H = F$ is nonnegative, and $F \mapsto F \circ \Phi_s$ induces an isometry between the reconstructed spaces that intertwines the transfer matrices and fixes the vacuum; Φ_{-s} gives its inverse. $\square$

Part (iv) says that smoothing changes the variables and not the theory: it neither creates nor removes a gap. Its use is in the choice of the observables. With $O_k(f)$ the spatially flowed fields at a fixed physical flow time, for instance $Z_k \sum_x a_k^4 f(a_k x) (\mathcal{E}_\tau(x) - \omega_k(\mathcal{E}_\tau(x)))$ with $\mathcal{E}_\tau(x)$ the flowed action density of the slice, statement (E) asks for the convergence of correlation functions that are known to be finite in perturbation theory [48], and Theorem 45 applies to them. Theorem 47 below constructs their continuum limits along subsequences; their nontriviality is not proved here.

D. Renormalised flowed observables

The spatially flowed fields can be renormalised by one condition at a single physical separation, and their correlation functions then have continuum limits along subsequences without further assumptions. What remains open is whether such a limit is trivial, and that question reduces to one ratio of lattice two-point functions.

Fix a bounded gauge-invariant function Φ of finitely many spatial links of the slice $\{x_0 = 0\}$, continuous in them, a flow time $\tau > 0$ in physical units, and a nonzero test function $f_0 \in C_c(\mathbb{R}^4)$ supported in $\{t > 0\}$. Put $s_k = \tau/a_k^2$, write Φ_x for the translate of Φ to $x \in \mathbb{Z}^4$, and let

$$A_k = \sum_{x \in \mathbb{Z}^4} a_k^4 f_0(a_k x) (\Phi_x \circ \Phi_{s_k} - \omega_k(\Phi_x \circ \Phi_{s_k})),$$

$$C_k(\sigma) = \omega_k(\vartheta(\bar{A}_k) \tau_{\sigma/a_k} A_k)$$

for dyadic $\sigma \geq 0$ (the sum is finite, and σ/a_k is an integer for large k). By reflection positivity $C_k(0) \geq 0$; assume $C_k(0) > 0$ and set $Z_k = C_k(0)^{-1/2}$. Let $\mathcal{D}$ be the set of points $y = (t, y') \in \mathbb{R}^4$ with dyadic coordinates (in units of a_0) and $t > 0$, and for $y \in \mathcal{D}$ and k with $y/a_k \in \mathbb{Z}^4$ let A_k^y be the translate of A_k by y/a_k .

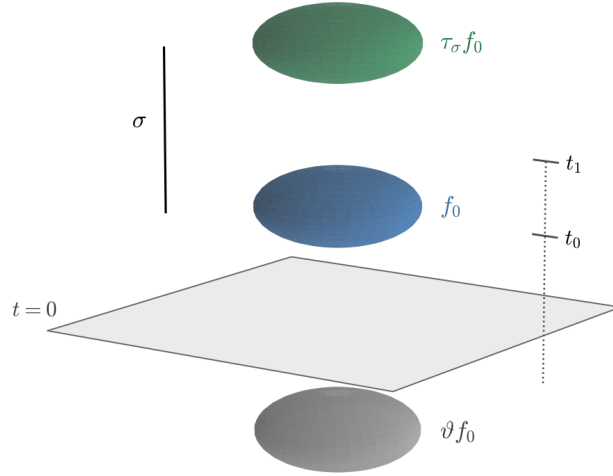
Theorem 47. (i) For $y, y' \in \mathcal{D}$ and every k with $y/a_k, y'/a_k \in \mathbb{Z}^4$,

$$Z_k^2 |\omega_k(\vartheta(\bar{A}_k^y) A_k^{y'})| \leq 1.$$

(ii) Every sequence of k has a subsequence along which $K(y, y') = \lim Z_k^2 \omega_k(\vartheta(\bar{A}_k^y) A_k^{y'})$ exists for all $y, y' \in \mathcal{D}$ and $\rho(\sigma) = \lim C_k(\sigma)/C_k(0)$ exists for all dyadic $\sigma > 0$. Along it there is a probability measure μ on $[0, \infty]$ with

$$\rho(\sigma) = \int_{[0, \infty]} e^{-\sigma E} d\mu(E) \quad (\sigma > 0),$$

the integrand being 0 at $E = \infty$.



$$C_k(\sigma) = \langle \Psi_{A_k}, \mathbb{T}_k^{\sigma/a_k} \Psi_{A_k} \rangle: \text{the reflected packet } \vartheta f_0 \text{ paired with the packet translated by } \sigma$$

FIG. 8. The packet f_0 of Theorem 47, supported in the time window $[t_0, t_1]$ above the reflection plane $t = 0$, its reflection ϑf_0 and its translate $\tau_\sigma f_0$ by σ in time. The correlation $C_k(\sigma)$ pairs the reflected packet with the translated one; $C_k(0)$ is the reflected norm that renormalises the packet.

(iii) Along such a subsequence, let $\mathcal{T}$ be spanned by the translates $f_0(\cdot - y)$, $y \in \mathcal{D}$, and one more function $f_* \in C_c(\mathbb{R}^4)$ supported in $\{t > 0\}$ outside their span, and let O_k be the linear map with $O_k(f_0(\cdot - y)) = Z_k A_k^y$ and $O_k(f_*) = 1$. Then (ω_k, O_k) has a continuum limit in the sense of Definition 44, on which the dyadic spatial translations act by unitary operators commuting with H .

(iv) This limit is nontrivial if and only if $\mu([0, \infty)) > 0$, if and only if $\rho(\sigma) > 0$ for one dyadic $\sigma > 0$, and then $\rho(\sigma) > 0$ for all of them. Consequently a nontrivial limit exists along some subsequence if and only if $\limsup_k C_k(\sigma)/C_k(0) > 0$ for some dyadic $\sigma > 0$.

(v) If the hypothesis of Theorem 45 holds, then μ is carried by $[m_*, \infty]$ and $\rho(\sigma) \leq e^{-m_* \sigma}$.

Proof. By Proposition 46(ii) each $\Phi_x \circ \Phi_{s_k}$, and hence each A_k^y , is a uniform limit of gauge-invariant local functions at times ≥ 1 , so the reconstruction of Appendix F applies to them (its footnote). Write $\Psi_k = Z_k \Psi_{A_k}$. Since $\langle \Omega_k, \Psi_{A_k} \rangle = \omega_k(A_k) = 0$ and $\|\Psi_k\|^2 = Z_k^2 C_k(0) = 1$, Ψ_k is a unit vector orthogonal to Ω_k . The relation $\langle \Psi_F, \mathbb{T}_k^y \Psi_H \rangle = \omega_k(\vartheta(\bar{F}) \tau_t H)$ for all F gives $\Psi_{\tau_t H} = \mathbb{T}_k^y \Psi_H$. Spatial translations commute with ϑ and with τ_t and leave ω_k invariant, so they act on the reconstructed space by unitaries $U_k(x)$ that commute with $\mathbb{T}_k$. Hence, for $y = (t, y')$,

$$Z_k \Psi_{A_k^y} = U_k(y'/a_k) \mathbb{T}_k^{t/a_k} \Psi_k.$$

(i) The left side of the inequality is $|\langle Z_k \Psi_{A_k^y}, Z_k \Psi_{A_k^{y'}} \rangle| \leq 1$, because $\|U_k\| = 1$ and $0 \leq \mathbb{T}_k \leq 1$.

(ii) The set $\mathcal{D} \times \mathcal{D}$ is countable and the numbers are bounded by (i), so a diagonal subsequence gives all the limits K ; the limits $\rho(\sigma)$ are among them, since $C_k(\sigma)/C_k(0) = \langle \Psi_k, \mathbb{T}_k^{\sigma/a_k} \Psi_k \rangle$ is the value of K at $y = y' = (\sigma/2, 0)$. Let ν_k be the spectral measure (Lemma 83) of $\mathbb{T}_k$ at Ψ_k , a probability measure on $[0, 1]$, and μ_k its image under $\lambda \mapsto -a_k^{-1} \log \lambda \in [0, \infty]$. Then $C_k(\sigma)/C_k(0) = \int e^{-\sigma E} d\mu_k(E)$. The space $[0, \infty]$ is compact, so a further subsequence has $\mu_k \rightarrow \mu$ weakly (Lemma 84), and $E \mapsto e^{-\sigma E}$ is continuous on $[0, \infty]$ for $\sigma > 0$.

(iii) A finite combination $\sum_j c_j f_0(\cdot - y_j)$ with distinct y_j that vanishes has Fourier transform $\hat{f}_0(p) \sum_j c_j e^{-ip \cdot y_j} = 0$; since $\hat{f}_0$ is analytic and not zero, the exponential sum vanishes on an open set and every c_j is zero. So the translates are linearly independent and O_k is well defined. On the space V of finite sums $v = \sum_y c_y \delta_y$ over $\mathcal{D}$ put $B(v, w) = \sum_y \bar{c}_y c'_y K(y, y')$. It is the limit of $\langle v_k, w_k \rangle$ with $v_k = \sum_y c_y Z_k \Psi_{A_k^y}$, hence positive semidefinite; let $\mathcal{H}_0$ be the completion of V modulo its null space. For dyadic $\sigma \geq 0$ and dyadic spatial x define $T(\sigma) \delta_y = \delta_{y+(\sigma, 0)}$ and $U(x) \delta_y = \delta_{y+(0, x)}$. At level k these are $\mathbb{T}_k^{\sigma/a_k}$ and $U_k(x/a_k)$, so in the limit $B(T(\sigma)v, w) = B(v, T(\sigma)w)$, $B(T(\sigma)v, T(\sigma)v) \leq B(v, v)$, $B(v, T(\sigma)v) \geq 0$, and $U(x)$ preserves B . Thus $T(\sigma)$ extends to commuting positive contractions on $\mathcal{H}_0$ with $T(\sigma)T(\sigma') = T(\sigma + \sigma')$, and $U(x)$ to unitaries commuting with them. For dyadic $\sigma > 0$ the kernel of $T(\sigma) = T(\sigma/2)^2$ equals that of $T(\sigma/2)$, so all these kernels coincide; and every δ_y with $y = (t, y')$ equals $T(t/2) \delta_{(t/2, y')}$, a vector in the range of a positive operator and so orthogonal to its kernel. Hence each $T(\sigma)$ is injective on $\mathcal{H}_0$, and

$H_0 = -\log T(1)$ is a self-adjoint operator with $H_0 \geq 0$ and $e^{-\sigma H_0} = T(\sigma)$ for dyadic σ , by the uniqueness of positive roots. Put $\mathcal{H} = \mathbb{C}\Omega \oplus \mathcal{H}_0$, $H = 0 \oplus H_0$, $\psi(f_0(\cdot - y)) = \delta_y$ and $\psi(f_*) = \Omega$. The range of ψ is dense, and the identities of Definition 44 hold: for two translates they are the limits defining K , with $\tau_{\sigma/a_k} A_k^{y'} = A_k^{y'+(\sigma,0)}$; and for f_* they read $\omega_k(1) = 1$ and $\omega_k(\vartheta(A_k^y)) = \omega_k(\tau_{\sigma/a_k} A_k^y) = 0$.

(iv) The limit is nontrivial exactly when $\mathcal{H}_0 \neq 0$, that is when $\|\delta_y\|^2 = K(y, y) = \rho(2t)$ is positive for some $y = (t, y')$. By (ii) and Lemma 85(b), $\rho(\sigma) > 0$ for one $\sigma > 0$ if and only if $\mu([0, \infty)) > 0$, and then $\rho(\sigma) > 0$ for every $\sigma > 0$. For the last statement choose a subsequence along which $C_k(\sigma)/C_k(0)$ tends to its limsup, and refine it by (ii).

(v) Under that hypothesis the proof of Theorem 45 gives $\nu_k([0, e^{-\log(1/\alpha)/(2n_k)}]) = 1$ because $\Psi_k \perp \Omega_k$, so μ_k is carried by $[\log(1/\alpha)/(2n_k a_k), \infty) \subset [m_*, \infty]$, and so is the weak limit μ . $\square$

The measure μ is the spectral measure of the renormalised flowed field in the limit: its part on $[0, \infty)$ is what survives as a state of the continuum theory, and its atom at ∞ is the weight that the field puts on energies that diverge in physical units. The theorem constructs the renormalised continuum observables and their reconstruction for every tuning, and it reduces their nontriviality to the lattice inequality

$$\limsup_{k \rightarrow \infty} \frac{C_k(\sigma)}{C_k(0)} > 0$$

for one physical separation σ : the flowed two-point function of the smeared packet at a fixed physical distance must not become negligible against its reflected norm $C_k(0)$. If the lattice gap stayed above some $m > 0$ in lattice units, the ratio would be at most $e^{-m\sigma/a_k}$ and the limit would be trivial, so the inequality is a condition on the tuning $\beta_k \rightarrow \infty$; it is not proved here. Nor are the independence of the limit from the subsequence, Euclidean invariance, or bounds on products of more than two renormalised fields, for which (i) gives nothing because Z_k may diverge (Theorem 55 reduces them to tree bounds); (E) requires all of these.

The denominator $C_k(0)$ is the reflected norm of the packet smeared by f_0 , not a coincidence limit of point fields, and the distinction matters. For the free massless scalar field in four dimensions with spatial momenta cut off at Λ , the covariance at spatial separation 0 is $(1 - (1 + \Lambda t)e^{-\Lambda t})/(4\pi^2 t^2)$ at time $t > 0$ and $\Lambda^2/(8\pi^2)$ at coincidence, so its ratio $2(1 - (1 + \Lambda t)e^{-\Lambda t})/(\Lambda t)^2$ tends to zero as $\Lambda \rightarrow \infty$, although the limiting field is the nontrivial Gaussian field; for packets smeared by f_0 the reflected norms of that field have finite positive limits and the ratio stays positive. The criterion of Theorem 47(iv) is about the smeared packets A_k only.

When the ratio is bounded below, renormalising at the separation σ instead of 0 removes the escape to infinite energy altogether, and one slab of the transfer matrix gives a sufficient condition for the bound. Write μ_k for the measures in the proof of Theorem 47.

Proposition 48. (i) Suppose $C_k(\sigma) \geq c C_k(0)$ for a dyadic $\sigma > 0$, a $c > 0$ and every k of a sequence. Let μ'_k be the spectral measure, in energies $E = -a_k^{-1} \log \lambda$, of the unit vector

$C_k(\sigma)^{-1/2} \Psi_{A'_k}$ with $A'_k = \tau_{\sigma/2a_k} A_k$. Then μ'_k is a probability measure on $[0, \infty)$,

$$\mu'_k([\Lambda, \infty)) \leq c^{-1} e^{-\sigma \Lambda}, \quad \int E^m d\mu'_k \leq c^{-1} \left(\frac{m}{e\sigma} \right)^m,$$

and $t \mapsto C_k(\sigma + t)/C_k(\sigma)$ is Lipschitz on $[0, \infty)$ with constant $(e\sigma c)^{-1}$. A subsequence of the μ'_k converges weakly to a probability measure on $[0, \infty)$ with the same bounds.

(ii) Suppose $\langle \Psi_k, (1 - \mathbb{T}_k) \Psi_k \rangle \leq C a_k$ for a constant C and every k of a sequence. Then $C_k(\sigma)/C_k(0) \geq e^{-2C\sigma}$ whenever $C a_k \leq \frac{1}{2}$ and σ/a_k is an integer, and $\mu_k([\Lambda, \infty)) \leq C(a_k + \Lambda^{-1})$ for every $\Lambda > 0$.

Proof. (i) We have $\Psi_{A'_k} = \mathbb{T}_k^{\sigma/2a_k} \Psi_{A_k}$, so the measure μ'_k is $e^{-\sigma E} d\mu_k(E)$ divided by its mass $C_k(\sigma)/C_k(0) \geq c$, and $e^{-\sigma E}$ vanishes at $E = \infty$. For $E \geq \Lambda$ we have $e^{-\sigma E} \leq e^{-\sigma \Lambda}$, and $E^m e^{-\sigma E} \leq (m/e\sigma)^m$ for all $E \geq 0$. The ratio in question is the integral of e^{-tE} against μ'_k , and the inequality $|e^{-tE} - e^{-sE}| \leq |t - s|E$ with the moment bound for $m = 1$ gives the Lipschitz bound. The tail bound makes the sequence tight on $[0, \infty)$, so Prokhorov's theorem gives the weak limit, and the bounds pass to it because $\{E > \Lambda\}$ is open and E^m is a monotone limit of bounded continuous functions.

(ii) Let ν_k be the spectral measure of $\mathbb{T}_k$ at Ψ_k on $[0, 1]$, a probability measure, and $n = \sigma/a_k$. By Jensen's inequality for the convex function λ^n ,

$$\frac{C_k(\sigma)}{C_k(0)} = \int \lambda^n d\nu_k \geq \left(\int \lambda d\nu_k \right)^n \geq (1 - C a_k)^n \geq e^{-2C a_k n},$$

since $\log(1 - x) \geq -2x$ on $[0, \frac{1}{2}]$. Moreover $C a_k \geq \int (1 - e^{-a_k E}) d\mu_k \geq (1 - e^{-a_k \Lambda}) \mu_k([\Lambda, \infty))$, and $1 - e^{-x} \geq x/(1 + x)$. $\square$

Part (ii) asks for an upper bound on a one-slab Dirichlet form, the opposite direction to a mass gap, which bounds such forms from below. In the box of Proposition 49, with g smooth, the time smearing supplies the factor a_k up to one ratio: in the notation of its proof, $\mathbb{T}_k = A$ and $\Psi_{A_k} = \sum_n w_n \mathbb{T}_k^n u$ with $w_n = a_k g(a_k n)$ and $u = a_k^{3/4} \psi_0$, and the identity $(1 - \mathbb{T}_k) \Psi_{A_k} = \sum_n (w_n - w_{n-1}) \mathbb{T}_k^n u$ gives $\langle \Psi_k, (1 - \mathbb{T}_k) \Psi_k \rangle \leq a_k \|g'\|_{L^1} \|u\| / \|\Psi_{A_k}\|$, so the hypothesis of (ii) holds when the vector u of a single slice stays comparable to the time-smeared packet. That comparison is not proved; Proposition 50 below bounds the ratio without it.

In a periodic spatial box the assumption $C_k(0) > 0$ is a theorem. Let $G = \text{SU}(N)$ with its defining representation, and replace $\mathbb{Z}^4$ by $\mathbb{Z} \times (\mathbb{Z}/L\mathbb{Z})^3$ with $L \geq 3$ and ω_k by the infinite-time Wilson state of the box. The proof of Theorem 47 uses only reflection positivity and the transfer matrix once the spatial translations are dropped, and parts (i)–(iv) hold in the box with $\mathcal{D}$ replaced by its points $(t, 0)$, the time translates of f_0 being independent by the same Fourier argument in t .

Proposition 49. In the box, let $f_0(t, x) = g(t)h(x)$ with $g, h \geq 0$, and let $\Phi = \sum_{i < j} (N - \text{Re Tr } Q_{ij})$ be the energy of the three spatial plaquettes at the origin. If $g(a_k n)h(a_k x) > 0$ for some $n \geq 1$ and some x , then $C_k(0) > 0$.

Proof. Lüscher proved that the transfer matrix is strictly positive [46]; we recall the argument because the proof uses it in this form.

The one-link kernel. Write χ for the character of the defining representation and $b = \beta_W > 0$. Then

$$e^{\frac{b}{N} \text{Re } \chi} = \sum_{m \geq 0} \frac{(b/2N)^m}{m!} (\chi + \bar{\chi})^m,$$

and $(\chi + \bar{\chi})^m$ is the character of $(\rho \oplus \bar{\rho})^{\otimes m}$. Every irreducible representation σ occurs in one of these tensor powers: their matrix coefficients span the algebra of polynomials in the entries of q and $\bar{q}$, which contains the constants and separates points, so it is dense in $C(G)$ by the Stone–Weierstrass theorem, while the matrix coefficients of a σ that never occurred would be orthogonal to it by Schur orthogonality. So the coefficient of every irreducible character in $e^{\frac{b}{N} \text{Re } \chi}$ is positive, and convolution with this function acts on each isotypic part of $L^2(G)$ by a positive scalar.

The transfer matrix. In the temporal gauge the transfer matrix of the box acts on the gauge-invariant part of $L^2(G^E)$, E the spatial links of one slice, as MKM , where K is the tensor product over E of the convolutions above and M is multiplication by the exponential of half the spatial plaquette weight [46, 56]. Both commute with gauge transformations, K is positive and injective by the first step, and M is positive and invertible, so $\langle v, MKMv \rangle = \langle Mv, KMv \rangle > 0$ for $v \neq 0$. Its kernel is a continuous positive function, and K is compact, so its largest eigenvalue λ_0 is simple with an eigenfunction $\psi_0 > 0$, and with $A = MKM/\lambda_0$, a function F of the slice at time $n \geq 0$ has $\Psi_F = A^n F \psi_0$ in the reconstruction, Ω being ψ_0 .

Conclusion. Let $F = \sum_x h(a_k x) \Phi_x \circ \Phi_{s_k}$ and $F^c = F - \omega_k(F)$. Then $\Psi_{A_k} = a_k^4 p(A) F^c \psi_0$ with $p(z) = \sum_{n \geq 1} g(a_k n) z^n$, a polynomial with nonnegative coefficients, not all zero, so $p > 0$ on $(0, 1]$ and $p(A)$ is injective. The function $\sum_x h(a_k x) \Phi_x$ vanishes at the configuration with every link 1 and is positive at one with a single nontrivial link at a site where $h(a_k x) > 0$; the flow Φ_{s_k} is a bijection, so F is not constant, and as F is continuous and $\psi_0 > 0$, $F^c \psi_0 \neq 0$. Hence $C_k(0) = \|\Psi_{A_k}\|^2 > 0$. $\square$

The proposition removes the one assumption of Theorem 47 in a box; it says nothing about the ratio of part (iv), on which nontriviality depends.

The ratio of Theorem 47(iv) can be compared with correlations of a single slice field. Suppose that $f_0(t, x) = g(t)h(x)$ with $g \geq 0$ supported in $[t_0, t_1]$, $t_0 < t_1$ positive and dyadic, let

$$U_k = \sum_{x \in \mathbb{Z}^3} a_k^3 h(a_k x) (\Phi_{(0,x)} \circ \Phi_{s_k} - \omega_k(\Phi_{(0,x)} \circ \Phi_{s_k}))$$

be the centred field of the slice at time 0, smeared in space only, and put $u_k = \Psi_{U_k}$ and

$$D_k(r) = \langle u_k, \mathbb{T}_k^{r/a_k} u_k \rangle = \omega_k(\vartheta(\bar{U}_k) \tau_{r/a_k} U_k)$$

for $r \in a_k \mathbb{Z}$, $r \geq 0$. Let $n_0 = \lceil t_0/a_k \rceil$ and $n_1 = \lfloor t_1/a_k \rfloor$.

Proposition 50. Assume $C_k(0) > 0$, and let $\sigma \geq 0$ with $\sigma/a_k \in \mathbb{Z}$.

(i) $D_k(r) > 0$ for every r , and

$$\frac{D_k(2a_k n_1 + \sigma)}{D_k(2a_k n_0)} \leq \frac{C_k(\sigma)}{C_k(0)} \leq \frac{D_k(2a_k n_0 + \sigma)}{D_k(2a_k n_1)}.$$

(ii) $\log D_k$ and $\log C_k$ are convex and nonincreasing on $a_k \mathbb{Z}_{\geq 0}$. If $D_k(r') \geq c D_k(r)$ with $r < r'$ and $c \leq 1$, then $D_k(\beta) \geq c^{\max(1, (\beta-\alpha)/(r'-r))} D_k(\alpha)$ whenever $r \leq \alpha < \beta$; if $C_k(\sigma) \geq c C_k(0)$ with $\sigma > 0$, then $C_k(\sigma') \geq c^{\sigma'/\sigma} C_k(0)$ for $\sigma' \geq \sigma$.

(iii) Let k run through a sequence. If $D_k(r') \geq c D_k(r)$ for dyadic $0 < r < r'$ with $r \leq 2t_0$, $a \in (0, 1]$ and every large k , then for every dyadic $\sigma \geq 0$ and every large k

$$C_k(\sigma) \geq c^{\max(1, (2t_1-2t_0+\sigma)/(r'-r))} C_k(0).$$

Conversely, if $C_k(\sigma) \geq c C_k(0)$ for a dyadic $\sigma > 0$ and every k , then $D_k(2t_0 + \sigma') \geq c^{\sigma'/\sigma} D_k(2t_1)$ for every dyadic $\sigma' \geq \sigma$ with $\sigma' > 2(t_1 - t_0)$ and every large k .

Proof. For a function F of the slice at time 0 and an integer $n \geq 0$ we have $\Psi_{\tau_n F} = \mathbb{T}_k^n \Psi_F$, since both have inner product $\omega_k(\vartheta(\bar{G}) \tau_n F)$ with every Ψ_G . By time translation invariance of ω_k , $A_k = \sum_n w_n \tau_n U_k$ with $w_n = a_k g(a_k n) \geq 0$, and $w_n = 0$ unless $n_0 \leq n \leq n_1$; so $\Psi_{A_k} = \sum_n w_n \mathbb{T}_k^n u_k$. Let ν be the spectral measure of $\mathbb{T}_k$ at u_k , on $[0, 1]$, and $W(\lambda) = \sum_n w_n \lambda^n$. Then

$$C_k(\sigma) = \int W(\lambda)^2 \lambda^{\sigma/a_k} d\nu(\lambda), \quad D_k(r) = \int \lambda^{r/a_k} d\nu(\lambda).$$

(i) Since $t_0 > 0$, $n_0 \geq 1$ and $W(0) = 0$; so $C_k(0) > 0$ forces $\nu((0, 1]) > 0$, and then $D_k(r) > 0$. For $0 \leq \lambda \leq 1$, $\|w\|_1 \lambda^{n_1} \leq W(\lambda) \leq \|w\|_1 \lambda^{n_0}$; inserting these bounds in $C_k(\sigma)$ and $C_k(0)$ gives the two inequalities.

(ii) Convexity of $j \mapsto \log \int \lambda^j d\rho$ for a positive measure ρ on $[0, 1]$ is Hölder's inequality, and the integrals decrease in j because $\lambda \leq 1$; take $\rho = \nu$ and $\rho = W^2 \nu$. If $\beta \leq r'$, monotonicity gives $D_k(\beta) \geq D_k(r') \geq c D_k(r) \geq c D_k(\alpha)$. If $\beta > r'$, the difference quotients of the convex function $\log D_k$ increase in both end points, so $(\log D_k(\beta) - \log D_k(\alpha))/(\beta - \alpha) \geq (\log D_k(r') - \log D_k(r))/(r' - r) \geq \log c/(r' - r)$. The statement on C_k is the same comparison of quotients on $[0, \sigma]$ and $[0, \sigma']$.

(iii) For large k the times $2t_0, 2t_1$ are multiples of a_k , and $2a_k n_0 \geq 2t_0, 2a_k n_1 \leq 2t_1$. Since D_k is nonincreasing, (i) gives

$$\frac{D_k(2t_1 + \sigma)}{D_k(2t_0)} \leq \frac{C_k(\sigma)}{C_k(0)} \leq \frac{D_k(2t_0 + \sigma)}{D_k(2t_1)}.$$

The first claim is the left inequality with (ii) for $\alpha = 2t_0 \geq r$ and $\beta = 2t_1 + \sigma$. For the second, (ii) gives $C_k(\sigma') \geq c^{\sigma'/\sigma} C_k(0)$, and the right inequality at σ' gives the claim, the two times being ordered because $\sigma' > 2(t_1 - t_0)$. $\square$

So for the packet $g \otimes h$ the open input of Theorem 47(iv) follows from an inequality between two correlations of one slice field,

$$\liminf_k D_k(r')/D_k(r) > 0 \quad \text{for one pair } 0 < r < r' \text{ with } r \leq 2t_0,$$

and by (iii) a uniform bound for one packet gives one for every packet $g' \otimes h$ with g' supported in $[t_1, \infty)$. The condition $r \leq 2t_0$ cannot be dropped: a bound at a later pair says nothing about an earlier packet, as $D_k(r) = (1 - 4^{-k})2^{-kr} + 4^{-k}2^{-r}$ shows, with $D_k(4)/D_k(3) \rightarrow \frac{1}{2}$ and $D_k(2)/D_k(1) \rightarrow 0$. A bound at a later pair does apply to the packet shifted forward in time, renormalised by its own reflected norm. The left inequality of (i) bounds the ratio without the comparison of u with the packet that was needed after Proposition 48(ii). Every bound on such ratios proved in this paper, at strong coupling or through Theorem 45, is an upper bound of the form $e^{-m(r'-r)/a_k}$; the inequality above is the opposite one and says that the slice field does not put its weight on energies that diverge in physical units. Reflection positivity and positivity of the transfer matrix do not give it, since a lattice theory with a fixed mass in lattice units has both and its ratio tends to zero. It holds for the free field.

Remark 51. Let D_k be defined as above for the massless free lattice field on $a_k\mathbb{Z}^4$ in place of Φ , with $h \in C_c^\infty(\mathbb{R}^3)$ and the lattice heat flow for a physical time $t_f > 0$ in place of the gradient flow. With $\hat{p}^2 = \sum_i (2a_k^{-1} \sin(a_k p_i/2))^2$, $\cosh(a_k \omega) = 1 + a_k^2 \hat{p}^2/2$ and $\hat{h}_k(p) = \sum_x a_k^3 h(a_k x) e^{-ia_k p \cdot x}$,

$$D_k(r) = \int_{[-\pi/a_k, \pi/a_k]^3} |\hat{h}_k(p)|^2 e^{-2t_f \hat{p}^2} \frac{e^{-r\omega}}{2a_k^{-1} \sinh(a_k \omega)} \frac{d^3 p}{(2\pi)^3}.$$

On the Brillouin zone $\hat{p} \geq 2|p|/\pi$ and $a_k^2 \hat{p}^2/2 \leq 6$; as $\operatorname{arccosh}(1+y)/\sqrt{2y}$ decreases on $(0, 6]$, $a_k \omega \geq \kappa a_k \hat{p}$ with $\kappa = \operatorname{arccosh} 7/\sqrt{12} > 0.76$, and $a_k^{-1} \sinh(a_k \omega) \geq \omega$. Since $|\hat{h}_k|$ is bounded uniformly in k , the integrands are dominated by a multiple of $e^{-8t_f|p|^2/\pi^2}/|p|$, which is integrable on $\mathbb{R}^3$, and they converge pointwise to $|\hat{h}(p)|^2 e^{-2t_f|p|^2} e^{-r|p|}/(2|p|)$. By dominated convergence $D_k(r')/D_k(r)$ tends to the corresponding positive ratio of continuum integrals; for $h = e^{-|x|^2}$, $t_f = 0.05$, $r = \frac{1}{2}$ and $r' = 1$ it is 0.6337.

Remark 52. The inequality also holds along the right tuning in two-dimensional $SU(N)$ lattice gauge theory, which is interacting and nonabelian but has no propagating gluons. Take the lattice $a_k\mathbb{Z} \times a_k\mathbb{Z}_{L_k}$ with $a_k L_k = \ell$ fixed, the weight $\prod_p \exp(\frac{\beta_k}{N} \operatorname{Re Tr} U_p)$ with $\beta_k = 2N/(g^2 a_k^2)$, and the temporal gauge. A gauge-invariant function of the links of one slice depends only on the conjugacy class of their holonomy V around the circle; this includes every spatially flowed and spatially smeared slice field, since the flow is gauge covariant. Let w_β be the probability density proportional to $e^{\frac{\beta}{N} \operatorname{Re Tr} U}$ with respect to Haar measure and, for an irreducible representation λ of dimension d_λ and character χ_λ , $\hat{c}_\lambda(\beta) = d_\lambda^{-1} \int \chi_\lambda w_\beta dU$. Between two slices put $W_x = V_x' V_x^{-1}$; the W_x are independent with density w_{β_k} , which is invariant under conjugation and inversion, and

$$\begin{aligned} V_1' \cdots V_L' &= W_1 (V_1 W_2 V_1^{-1}) \cdots \\ &\quad \cdots (V_1 \cdots V_{L-1} W_L (V_1 \cdots V_{L-1})^{-1}) V_1 \cdots V_L, \end{aligned}$$

so the new holonomy is QV with Q distributed as the L_k -fold convolution of w_{β_k} , independent of V . By Schur's lemma

(Lemma 86) the transfer matrix acts on class functions by $\chi_\lambda \mapsto \hat{c}_\lambda(\beta_k)^{L_k} \chi_\lambda$. The coefficients are real, since w_β is invariant under $U \mapsto \bar{U}$, nonnegative, since the exponential of $\frac{\beta}{2N}(\chi_F + \bar{\chi}_F)$ is a sum of characters with nonnegative coefficients, and below 1 for $\lambda \neq 0$. For a class function f with $\int f dU = 0$ and isotypic components of norms $|\hat{f}_\lambda|$, the slice correlation is therefore

$$D_k(r) = \sum_{\lambda \neq 0} |\hat{f}_\lambda|^2 e^{-r E_{\lambda,k}}, \quad E_{\lambda,k} = -\frac{\ell}{a_k^2} \log \hat{c}_\lambda(\beta_k).$$

Laplace's method¹⁷ at the unique maximum $U = 1$ of $\operatorname{Re Tr} U$, with $U = e^X$, $\operatorname{Re Tr} e^X = N + \frac{1}{2} \operatorname{Tr} X^2 + O(|X|^4)$, $\operatorname{Re Tr} X^3 = 0$, $\operatorname{Tr} \rho_\lambda(X) = 0$ and $\sum_a \rho_\lambda(T_a)^2 = -2C_2(\lambda)$ for an orthonormal basis of $\mathfrak{su}(N)$ in the norm $-\operatorname{Tr} X^2$, gives $\hat{c}_\lambda(\beta) = 1 - NC_2(\lambda)/\beta + O(\beta^{-2})$, with the Casimir normalised by $C_2 = (N^2 - 1)/(2N)$ on the fundamental representation (Lemma 87). Hence $E_{\lambda,k} \rightarrow g^2 \ell C_2(\lambda)/2$, and since $D_k(r) \leq \|f\|^2$,

$$\liminf_k \frac{D_k(r')}{D_k(r)} \geq \frac{|\hat{f}_\mu|^2}{\|f\|^2} e^{-r' g^2 \ell C_2(\mu)/2} > 0$$

for every $\mu \neq 0$ with $\hat{f}_\mu \neq 0$; for $f = \operatorname{Re Tr} V$ the ratio is exactly $e^{-(r'-r)E_{F,k}} \rightarrow e^{-(r'-r)g^2 \ell (N^2 - 1)/(4N)}$. This is the exact solution of two-dimensional lattice gauge theory, whose continuum limit is the measure of [29, 34, 45], written as the inequality. In two dimensions g^2 has the dimension of a mass squared and there is no ultraviolet problem, so the argument has no four-dimensional analogue. Nor does the spatial flow give the inequality by itself: it damps the spectral weight at large spatial momentum and leaves the weight at zero spatial momentum unchanged. For the free lattice field of Remark 51 with a mass M_k and the same flow, every energy is at least $m_k = a_k^{-1} \operatorname{arccosh}(1 + a_k^2 M_k^2/2)$, so $D_k(r') \leq e^{-m_k(r'-r)} D_k(r)$, which tends to zero relative to $D_k(r)$ when $a_k M_k$ is fixed.

A route to the slice ratio in four dimensions replaces the packet by its conditional expectations given averages of the field over blocks of increasing size and controls the error of each step. The free field shows in which norm such errors can be small. In the ordinary L^2 norm the first step already fails: conditioning on the averages over blocks of side two leaves a fixed fraction of the variance of an energy packet, at every lattice spacing.

Proposition 53. Let $d \geq 2$, let Λ be a periodic box in $\mathbb{Z}^d$ with even sides, let $\mu > 0$, and let ϕ be the Gaussian field on Λ with density proportional to $\exp(-\frac{1}{2} \sum_{x,v} (\nabla_v \phi(x))^2 - \frac{\mu^2}{2} \sum_x \phi(x)^2)$, where $\nabla_v \phi(x) = \phi(x + e_v) - \phi(x)$. Let $\mathcal{Z}$ be a set of blocks $B = 2z + \{0, 1\}^d$, let $\mathfrak{B}$ be the σ -algebra generated by the averages of ϕ over the blocks in $\mathcal{Z}$, let $f \geq 0$ on Λ , and let

$$F = \sum_{x \in \Lambda} f(x) \sum_{v=1}^d :(\nabla_v \phi(x))^2:,$$

¹⁷ For a smooth function with a unique nondegenerate maximum, $\int e^{\beta \phi} h$ has an expansion in powers of β^{-1} whose coefficients are Gaussian moments at the maximum; Lemma 87 carries it out here.

(a) holonomy on the circle

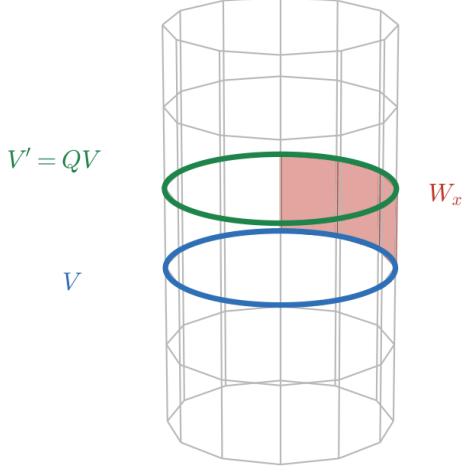
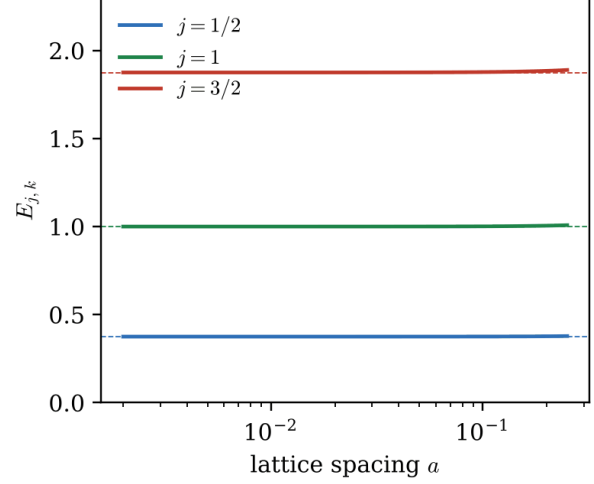
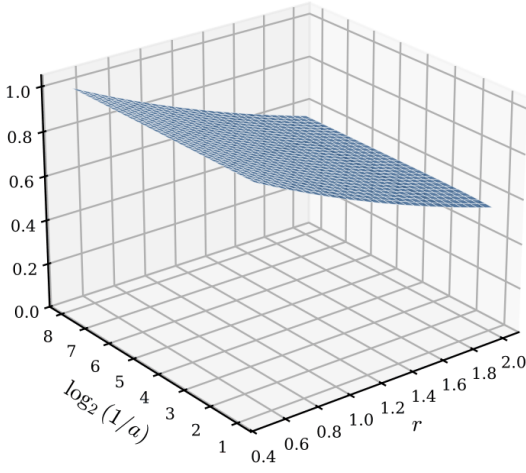
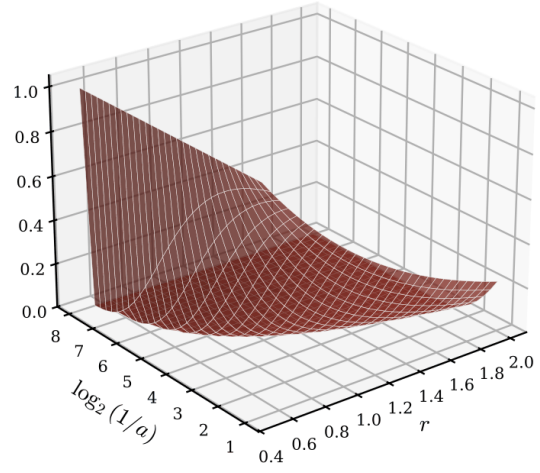
(b) $SU(2)$, $g^2 = \ell = 1$; limits $j(j+1)/2$ 

FIG. 9. Two-dimensional $SU(N)$ (Remark 52). (a) The lattice $a_k\mathbb{Z} \times a_k\mathbb{Z}_{L_k}$ drawn as a cylinder: the holonomy V of one slice, the holonomy $V' = QV$ of the next, and the plaquette variables W_x between them. (b) The energies $E_{j,k} = -(\ell/a_k^2) \log \hat{c}_j(\beta_k)$ of $SU(2)$ for $g^2 = \ell = 1$, with $\hat{c}_j(\beta) = I_{2j+1}(\beta)/I_1(\beta)$, against the lattice spacing; the dashed lines are the limits $j(j+1)/2$.

(a) $SU(2)$ in two dimensions

(b) mass 1/2 in lattice units



height: $D_k(r)/D_k(1/2)$ for $g^2 = \ell = 1$

FIG. 10. The ratio $D_k(r)/D_k(\frac{1}{2})$ over the separation r and the lattice spacing a_k . (a) Two-dimensional $SU(2)$ with $f = \text{Re Tr } V$ and $g^2 = \ell = 1$, where the ratio is $e^{-(r-1/2)E_{1/2,k}}$ and converges as $a_k \rightarrow 0$. (b) The term $e^{-(r-1/2)m_k}$ of the lowest energy m_k of a free field with mass $\frac{1}{2}$ in lattice units, which bounds the ratio from above and tends to zero at every $r > \frac{1}{2}$.

where $:X^2: = X^2 - \mathbb{E}X^2$. For $B = 2z + \{0, 1\}^d$ put $x_B = 2z$, $y_B = 2z + e_1 + e_2$ and

$$\alpha_B = \frac{1}{4} \sum_{w \in \{x_B, y_B\}} \left(d f(w) + \sum_{v=1}^d f(w - e_v) \right),$$

and $\sigma^2 = 2/(2d + \mu^2)$. (i) $\mathbb{E} \text{Var}(F | \mathfrak{B}) \geq 2\sigma^4 \sum_{B \in \mathcal{X}} \alpha_B^2$.
(ii) $\text{Var} F \leq 2d^2 \sum_x f(x)^2$.

(iii) Let $g \geq 0$ be a Lipschitz function on $\mathbb{R}^d$ with compact support and $\int g^2 > 0$. For $n \geq 1$ let Λ_n contain $n \text{supp } g$ in a fundamental domain, $f_n(x) = g(x/n)$, let $\mathcal{Z}_n$ contain every block that meets $n \text{supp } g$, and let $\mu = \mu_n \rightarrow 0$. Then for the packets F_n of f_n ,

$$\liminf_{n \rightarrow \infty} \frac{\mathbb{E} \text{Var}(F_n | \mathfrak{B}_n)}{n^d \int g^2} \geq 2^{1-d}, \quad \limsup_{n \rightarrow \infty} \frac{\text{Var} F_n}{n^d \int g^2} \leq 2d^2,$$

so $\mathbb{E} \text{Var}(F_n | \mathfrak{B}_n) \geq (2^{-d}d^{-2} - o(1)) \text{Var} F_n$.

Proof. (i) No two of the sites $x_B, y_B, B \in \mathcal{Z}$, are neighbours: their coordinate sums are even, and a neighbour of a site has a coordinate sum of the other parity. Let $\mathfrak{H} \supseteq \mathfrak{B}$ be generated by $\mathfrak{B}$ and by $\phi(w)$ for every w outside $\{x_B, y_B : B \in \mathcal{Z}\}$. By the law of total variance, $\text{Var}(F | \mathfrak{B}) = \mathbb{E}[\text{Var}(F | \mathfrak{H}) | \mathfrak{B}] + \text{Var}(\mathbb{E}[F | \mathfrak{H}] | \mathfrak{B})$, so $\mathbb{E} \text{Var}(F | \mathfrak{B}) \geq \mathbb{E} \text{Var}(F | \mathfrak{H})$. In the exponent of the density, a site w enters through $(d + \frac{\mu^2}{2})\phi(w)^2$ and through $-\phi(w)\phi(w')$ for each of its $2d$ neighbours w' . Given $\mathfrak{H}$, the block average fixes $s_B = \phi(x_B) + \phi(y_B)$, and with $u_B = \phi(x_B) - \phi(y_B)$ we have $\phi(x_B)^2 + \phi(y_B)^2 = \frac{1}{2}(s_B^2 + u_B^2)$. Since the free sites have only $\mathfrak{H}$ -measurable neighbours, the conditional density of $(u_B)_{B \in \mathcal{Z}}$ is proportional to $\prod_B \exp(-\frac{1}{4}(2d + \mu^2)u_B^2 + c_B u_B)$ with $\mathfrak{H}$ -measurable c_B : the u_B are conditionally independent Gaussians of variance σ^2 . A term $(\nabla_v \phi(w))^2$ contains at most one free site, and if it contains x_B , then $\phi(x_B) = \frac{1}{2}(s_B + u_B)$ shows that it is $\frac{1}{4}u_B^2$ plus a term linear in u_B plus an $\mathfrak{H}$ -measurable term; the same holds for y_B with $-u_B$. The terms containing x_B are those with $w = x_B$ and those with $w = x_B - e_v$, d of each kind, so

$$F = \sum_{B \in \mathcal{Z}} (\alpha_B u_B^2 + \beta_B u_B) + F_0$$

with $\mathfrak{H}$ -measurable β_B and F_0 . Writing $u_B = m_B + v_B$ with m_B the conditional mean, $\alpha_B u_B^2 + \beta_B u_B = \alpha_B v_B^2 + (2\alpha_B m_B + \beta_B)v_B + \text{const}$, and for a centred Gaussian v of variance σ^2 , $\text{Var}(\alpha v^2 + \gamma v) = 2\alpha^2 \sigma^4 + \gamma^2 \sigma^2$. By conditional independence, $\text{Var}(F | \mathfrak{H}) \geq 2\sigma^4 \sum_B \alpha_B^2$.

(ii) For centred jointly Gaussian X, Y , $\text{Cov}(:X^2:, :Y^2:) = 2\text{Cov}(X, Y)^2$. With $G_{v\rho}(x, y) = \mathbb{E}[\nabla_v \phi(x) \nabla_\rho \phi(y)]$,

$$\begin{aligned} \text{Var} F &= 2 \sum_{x, y} f(x) f(y) \sum_{v, \rho} G_{v\rho}(x, y)^2 \\ &\leq \sum_{x, y} (f(x)^2 + f(y)^2) \sum_{v, \rho} G_{v\rho}(x, y)^2. \end{aligned}$$

On the dual torus Λ^* , with $\hat{p}^2 = \sum_v |e^{ip_v} - 1|^2$,

$$G_{v\rho}(x, y) = \frac{1}{|\Lambda|} \sum_{p \in \Lambda^*} \frac{(e^{ip_v} - 1)(e^{-ip_\rho} - 1)}{\hat{p}^2 + \mu^2} e^{ip \cdot (x - y)},$$

and by Parseval $\sum_y G_{v\rho}(x, y)^2 = |\Lambda|^{-1} \sum_p |e^{ip_v} - 1|^2 |e^{-ip_\rho} - 1|^2 (\hat{p}^2 + \mu^2)^{-2} \leq 1$, since each factor $|e^{ip_v} - 1|^2$ is at most $\hat{p}^2$. The same holds for the sum over x , and (ii) follows.

(iii) If $\text{Lip } g = K$, every site entering α_B lies within distance 3 of $2z$, so $|\alpha_B - dg(2z/n)| \leq 3dK/n$. Hence $\sum_{B \in \mathcal{Z}_n} \alpha_B^2 \geq \sum_z (dg(2z/n) - 3dK/n)_+^2$, the sum running over z with $2z \in n \text{supp } g$, and this is $d^2(n/2)^d \int g^2(1 + o(1))$ as a Riemann sum on the grid $(2/n)\mathbb{Z}^d$. Since $\sigma^4 = 4/(2d + \mu_n^2)^2 \rightarrow d^{-2}$, (i) gives the first bound. By (ii) and $\sum_x g(x/n)^2 = n^d \int g^2(1 + o(1))$, the second follows. $\square$

For $d = 4$ and the energy density, $\text{Var} F_n$ grows like $(\ell/a)^4$ at a fixed physical size ℓ of the packet, and no step of conditioning on block averages removes more than a fraction $1 - 2^{-d}d^{-2} + o(1)$ of it. The reflected norm $C_k(0) = \omega_k(\vartheta(\bar{A}_k)A_k)$, which renormalises the packet in Theorem 47, involves the covariance

only between the support of ϑf_0 and that of f_0 , at a fixed physical distance. The errors of a blocking route have therefore to be measured in that norm; Figure 11 shows the blocks between the reflection plane and the packet.

E. Higher correlations

Theorem 47 controls two renormalised fields at a time, and part (i) of it gives nothing for more: Z_k may diverge while the fields $\Phi_x \circ \Phi_{s_k}$ stay bounded, so a bound on the norm of the renormalised packet as an operator is not available. A reflection positive process with a fixed gap and a two-point function independent of the cutoff can have divergent four-point functions at separated times (Remark 57), so no statement about the two-point function alone can replace the following hypothesis on the truncated correlations. In this subsection Φ is real-valued, as the energy of the plaquettes is; for a complex field the conjugate field has to be adjoined and (T1) imposed on all mixed cumulants. Write $\varphi_k(x) = \Phi_x \circ \Phi_{s_k}$, ω_k^T for the truncated correlations (joint cumulants) under ω_k , and for $f \in C_c(\mathbb{R}^4)$

$$A_k(f) = \sum_{x \in \mathbb{Z}^4} a_k^4 f(a_k x) (\varphi_k(x) - \omega_k(\varphi_k(x))),$$

so that $A_k = A_k(f_0)$ and $\bar{A}_k(f) = A_k(\bar{f})$. Let $w_k : \mathbb{Z}^4 \rightarrow [0, \infty)$ be even functions with $W_k = \sum_x w_k(x) < \infty$, let $r_k > 0$ be amplitude scales, and consider:

(T1) *Tree bounds.* For every $n \geq 2$ there is K_n , independent of k , with

$$|\omega_k^T(\varphi_k(x_1); \dots; \varphi_k(x_n))| \leq K_n r_k^n \sum_T \prod_{\{i, j\} \in T} w_k(x_i - x_j)$$

for all $x_1, \dots, x_n \in \mathbb{Z}^4$, the sum running over the trees T on $\{1, \dots, n\}$.

(T2) *Saturation.* $C_k(0) \geq c r_k^2 a_k^4 W_k$ for a $c > 0$ and every k .

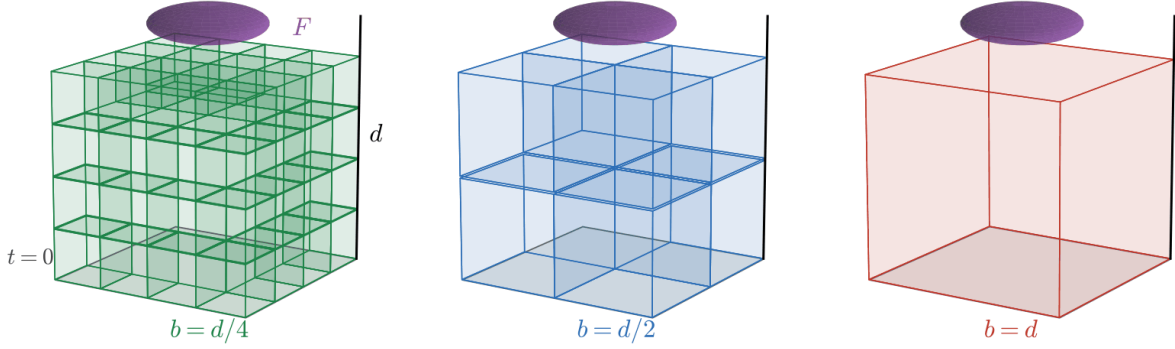
(T3) *Physical volume.* $B_* = \sup_k a_k^4 W_k < \infty$.

The amplitude r_k separates the size of the field from the volume over which it is correlated; Remark 56 shows why it is needed. For a compact $Q \subset \mathbb{R}^4$ let $|Q|_k = a_k^4 \#\{x \in \mathbb{Z}^4 : a_k x \in Q\}$; for a cube of side L it is at most $(L + a_0)^4$.

Lemma 54. Under (T1), for $n \geq 2$ and bounded $f_1, \dots, f_n$ with compact supports, f_1 supported in Q ,

$$\begin{aligned} &|\omega_k^T(A_k(f_1); \dots; A_k(f_n))| \\ &\leq K_n n^{n-2} r_k^n |Q|_k (a_k^4 W_k)^{n-1} \prod_{j=1}^n \|f_j\|_\infty. \end{aligned}$$

Proof. Joint cumulants of order $n \geq 2$ are multilinear and do not change when constants are added to the variables, so the left side is at most $a_k^{4n} \sum_{x_1, \dots, x_n} \prod_j |f_j(a_k x_j)|$ times the absolute value of the truncated correlation, the sums being finite. Insert (T1) and fix a tree T . With x_1 fixed, sum over the other points



block averages of side b between the plane $t = 0$ and the packet F at height d

FIG. 11. Block averages between the reflection plane $t = 0$ and a packet F at physical height d , for blocks of side $d/4$, $d/2$ and d . By Proposition 53 the first conditioning step already leaves a fixed fraction of the ordinary variance of the packet, so the errors of such steps have to be measured in the reflected norm.

one at a time, each time over a leaf of what remains of T other than 1; each such sum is at most W_k . The remaining sum over x_1 has at most $|Q|_k a_k^{-4}$ nonzero terms. There are n^{n-2} trees. $\square$

Theorem 55. Assume (T1)–(T3).

(i) For $n \geq 2$, f_j as in the lemma,

$$\begin{aligned} & |\omega_k^T(Z_k A_k(f_1); \dots; Z_k A_k(f_n))| \\ & \leq K_n n^{n-2} c^{-n/2} B_*^{n/2-1} |Q|_k \prod_{j=1}^n \|f_j\|_\infty, \end{aligned}$$

and the moments $\omega_k(\prod_j Z_k A_k(f_j))$ with all f_j supported in a cube Q are bounded by $M_n(Q) \prod_j \|f_j\|_\infty$, with $M_n(Q)$ independent of k .

(ii) Every sequence of k has a subsequence along which

$$S_n(f_1, \dots, f_n) = \lim_k \omega_k \left(\prod_{j=1}^n Z_k A_k(f_j) \right)$$

exists for all n and all $f_j \in C_c(\mathbb{R}^4)$. Each S_n is symmetric, multilinear, bounded by $M_n(Q) \prod_j \|f_j\|_\infty$ on functions supported in Q , hence a distribution on $(\mathbb{R}^4)^n$; it is invariant under all translations of $\mathbb{R}^4$ if the ω_k are translation invariant, and the kernel K of Theorem 47 along the subsequence is $K(y, y') = S_2(\bar{f}_0(\cdot - y) \circ \theta, f_0(\cdot - y'))$, with θ as in (iii).

(iii) Put $S_0 = 1$, $S_1 = 0$, and let θ be the reflection $t \mapsto -t$ of $\mathbb{R}^4$. For every finite family of $c_\alpha \in \mathbb{C}$ and $f_{\alpha,j} \in C_c(\mathbb{R}^4)$ supported in $\{t > 0\}$,

$$\sum_{\alpha, \beta} \bar{c}_\alpha c_\beta S \left(\prod_j \bar{f}_{\alpha,j} \circ \theta \cdot \prod_j f_{\beta,j} \right) \geq 0,$$

where S of a product of n test functions means S_n . Hence the Osterwalder–Schrader construction gives a Hilbert space

$\mathcal{H}$ with vacuum Ω and a dense set of vectors $\Psi(P)$ indexed by polynomials P in the smeared fields at positive times, with $\langle \Psi(P), \Psi(P') \rangle = S(\theta \bar{P} \cdot P')$; in particular the separated higher correlations of the renormalised fields are finite. The vector $\Psi(P_0)$ of the field smeared by f_0 is a unit vector orthogonal to Ω .

(iv) Suppose the ω_k are translation invariant. Then the time translations by $t \geq 0$ define on $\mathcal{H}$ a strongly continuous semigroup e^{-tH} with $H \geq 0$ self-adjoint, and the spatial translations a strongly continuous unitary group commuting with H . Moreover there is a dyadic $\sigma > 0$ with $C_k(\sigma) \geq \frac{1}{2} C_k(0)$ for all large k , so the limit of Theorem 47 is nontrivial.

(v) If $a_k^4 W_k \rightarrow 0$ along the subsequence, every S_n is given by Wick's rule from S_2 : the limit is the Gaussian field with covariance S_2 .

(vi) If the ω_k are translation invariant and the hypothesis of Theorem 45 holds, then 0 is a simple eigenvalue of H and $\sigma(H) \subset \{0\} \cup [m_*, \infty)$ with $m_* = \log(1/\alpha)/(2\ell)$, and $\Omega^\perp \neq 0$.

Proof. (i) By (T2), $Z_k^n = C_k(0)^{-n/2}$ is at most $(c r_k^2 a_k^4 W_k)^{-n/2}$; multiply the lemma by it, which cancels r_k^n , and use $(a_k^4 W_k)^{n/2-1} \leq B_*^{n/2-1}$ by (T3) for $n \geq 2$. A moment is the sum over partitions of $\{1, \dots, n\}$ of the products of the cumulants of the blocks; blocks of size one vanish because $A_k(f)$ is centred, and each block contributes the bound just proved with $|Q|_k \leq (L + a_0)^4$ for a cube of side L . This gives $M_n(Q)$.

(ii) For each cube $Q_L = [-L, L]^4$, $L \in \mathbb{N}$, the continuous functions supported in Q_L form a separable space under the supremum norm. Choose a countable dense set $\mathcal{F}$ of functions; by (i) the countably many sequences $\omega_k(\prod Z_k A_k(f_j))$, $f_j \in \mathcal{F}$, are bounded, and a diagonal subsequence makes all of them

converge. By multilinearity,

$$\begin{aligned} & \left| \omega_k \left(\prod_j Z_k A_k(f_j) \right) - \omega_k \left(\prod_j Z_k A_k(g_j) \right) \right| \\ & \leq M_n(Q) \sum_i \|f_i - g_i\|_\infty \prod_{j \neq i} \max(\|f_j\|_\infty, \|g_j\|_\infty) \end{aligned}$$

for functions supported in Q , so the limits exist for all $f_j \in C_c(\mathbb{R}^4)$ and obey the same bound. Symmetry and multilinearity pass to the limit. A multilinear form bounded in this way is separately continuous on $C_c^\infty(\mathbb{R}^4)$, so the Schwartz kernel theorem makes it a distribution. For dyadic y and large k , $y/a_k \in \mathbb{Z}^4$ and translation invariance of ω_k and of the flow (Proposition 46(i)) give $\omega_k(\prod_j Z_k A_k(f_j(\cdot - y))) = \omega_k(\prod_j Z_k A_k(f_j))$. For a real y take dyadic $y_m \rightarrow y$; the functions $f_j(\cdot - y_m)$ converge uniformly to $f_j(\cdot - y)$ with supports in one cube, so the bound above carries the invariance to y . The formula for K follows from $A_k^y = A_k(f_0(\cdot - y))$ and the argument of (iii) with $n = 2$.

(iii) Let ϑ be the lattice reflection of Appendix F and θ_k the corresponding reflection of $a_k \mathbb{Z}^4$; it differs from θ by a translation of length at most a_k . Since Φ is real and ϑ commutes with the flow, $\vartheta(\tilde{A}_k(f)) = A_k(\tilde{f} \circ \theta_k)$. Let $P_k = \sum_\beta c_\beta \prod_j Z_k A_k(f_{\beta,j})$ and $R_k = \sum_\alpha \tilde{c}_\alpha \prod_j Z_k A_k(f_{\alpha,j} \circ \theta)$, so that $\vartheta(\tilde{P}_k)$ is R_k with θ replaced by θ_k . Reflection positivity gives $\omega_k(\vartheta(\tilde{P}_k)P_k) \geq 0$. By (i), applied in a cube containing all the supports and their reflections, and by multilinearity, $|\omega_k(\vartheta(\tilde{P}_k)P_k) - \omega_k(R_k P_k)|$ is at most a constant independent of k times $\max_{\alpha,j} \|f_{\alpha,j} \circ \theta_k - f_{\alpha,j} \circ \theta\|_\infty$, which tends to zero by uniform continuity, while $\omega_k(R_k P_k)$ tends to the left side of (iii) by (ii). So the limit of the nonnegative numbers is the left side of (iii). The construction of $\mathcal{H}$ is the usual quotient of the polynomials at positive times by the null space of this form [54]. By the same approximation of θ by θ_k , $\|\Psi(P_0)\|^2 = \lim_k Z_k^2 C_k(0) = 1$, and $\langle \Omega, \Psi(P_0) \rangle = S_1(f_0) = 0$.

(iv) For a polynomial P at positive times let $\tau_t P$ be its time translate by $t \geq 0$, again at positive times. By translation invariance and $\theta \circ \tau_t = \tau_{-t} \circ \theta$, $\langle \Psi(\tau_t P), \Psi(P') \rangle = \langle \Psi(P), \Psi(\tau_t P') \rangle$, and $q_P(t) = \|\Psi(\tau_t P)\|^2 = \langle \Psi(P), \Psi(\tau_{2t} P) \rangle$. If P has degree at most d , every partition in (i) of the products in $q_P(t)$ has at most d blocks, each bounded by a multiple of $|Q|_k$ for a cube Q of side $O(1+t)$, so $q_P(t) \leq C_P(1+t)^{4d}$. The Cauchy–Schwarz inequality gives $q_P(t) \leq q_P(0)^{1/2} q_P(2t)^{1/2}$, hence by induction $q_P(t) \leq q_P(0)^{1-2^{-m}} q_P(2^m t)^{2^{-m}}$ for every m , and letting $m \rightarrow \infty$, $q_P(t) \leq q_P(0)$. So τ_t maps null vectors to null vectors and extends to a symmetric contraction $T(t)$ of $\mathcal{H}$; $T(s)T(t) = T(s+t)$, and $T(t) = T(t/2)^2 \geq 0$. By the bound of (ii) and uniform continuity of the translated test functions, $\|\Psi(\tau_t P) - \Psi(P)\| \rightarrow 0$ as $t \rightarrow 0$, so the semigroup is strongly continuous on a dense set, hence everywhere, and $T(t) = e^{-tH}$ with $H \geq 0$ self-adjoint [54]. Spatial translations preserve the form, have the opposite translations as inverses, commute with τ_t , and are strongly continuous by the same argument.

For the ratio let $f_{0,t} = f_0(\cdot - (t, 0))$. For dyadic $t > 0$ and large k , translation invariance gives $\tau_{t/a_k} A_k = A_k(f_{0,t})$, so by (iii)

$$C_k(t) - C_k(0) = \omega_k(A_k(\tilde{f}_0 \circ \theta_k) A_k(f_{0,t} - f_0)),$$

a covariance of two centred fields. The case $n = 2$ of (i) bounds Z_k^2 times it by $L_0 \|f_{0,t} - f_0\|_\infty$ with $L_0 = (K_2/c) \sup_k |Q|_k \|f_0\|_\infty$,

Q a cube containing the supports of $f_0 \circ \theta_k$ for all k . By uniform continuity of f_0 there is a dyadic $\sigma > 0$ with $L_0 \|f_{0,\sigma} - f_0\|_\infty \leq \frac{1}{2}$; then $C_k(\sigma)/C_k(0) \geq \frac{1}{2}$, and Theorem 47(iv) applies.

(v) For $n \geq 3$ the exponent $n/2 - 1$ in (i) is positive, so with $(a_k^4 W_k)^{n/2-1}$ in place of $B_*^{n/2-1}$ the cumulants of order $n \geq 3$ of the renormalised fields tend to zero. The moments are the sums over partitions of products of cumulants, so in the limit only the partitions into pairs remain, which is Wick's rule.

(vi) As in the proof of Theorem 45, $\mathbb{T}_k$ has gap at least $\log(1/\alpha)/(2n_k)$ on the complement of Ω_k . For a polynomial P at positive times let $v_k = \Psi_{P_k} - \omega_k(P_k)\Omega_k$ with P_k its lattice version. For dyadic t and large k ,

$$\omega_k(\vartheta(\tilde{P}_k)\tau_{t/a_k} P_k) - |\omega_k(P_k)|^2 = \langle v_k, \mathbb{T}_k^{t/a_k} v_k \rangle \leq e^{-m_* t} \|v_k\|^2,$$

and both sides are finite combinations of moments, which converge by (ii) and the approximation of θ in (iii). The limit is $\langle v, e^{-tH} v \rangle \leq e^{-m_* t} \|v\|^2$ for $v = \Psi(P) - \langle \Omega, \Psi(P) \rangle \Omega$. These v are dense in $\Omega^\perp$, so the inequality holds on $\Omega^\perp$ for all $t \geq 0$, and the spectral theorem gives the spectral statement as in Theorem 45. By (iii), $\Psi(P_0)$ is a unit vector in $\Omega^\perp$. $\square$

Part (iv) shows that the order-two cases of (T1) and (T2) already contain the lower bound on the ratio that Theorem 47(iv) needs; they are not harmless combinatorial assumptions, and proving them along the continuum tuning is at least as hard as that lower bound. Part (vi) passes the conditional mass gap of Theorem 45 to every polynomial in the smeared fields. Neither part proves Euclidean invariance, independence of the limit from the subsequence, or the reconstruction of the field operators, for which the growth of $M_n(Q)$ in n would also be needed.

Remark 56. The amplitude scale cannot be dropped for a bounded field. Suppose $\text{Var } \phi_k(0) \rightarrow 0$, as for the energy of the flowed plaquettes in lattice units when the flowed links approach the identity. Reflection invariance of ω_k , the Cauchy–Schwarz inequality and stationarity give

$$C_k(0) \leq \omega_k(|A_k|^2) \leq \left(a_k^4 \sum_x |f_0(a_k x)| \right)^2 \text{Var } \phi_k(0) \rightarrow 0.$$

With $r_k = 1$, (T2) then forces $a_k^4 W_k \rightarrow 0$, and by part (v) the limit is Gaussian. With r_k^2 of the order of $\text{Var } \phi_k(0)$ this is no longer forced. Choosing r_k does not prove (T1) or (T2).

Remark 57. Let $0 < \varepsilon < 1$, $m > 0$, let π be the probability measure on $\{-1, 0, 1\}$ with weights $\varepsilon/2$, $1 - \varepsilon$, $\varepsilon/2$, and let $P_t = e^{-mt} I + (1 - e^{-mt}) \Pi$ on $L^2(\pi)$, where $\Pi f = \pi(f)$ is the projection onto the constants. This is a symmetric Markov semigroup with $P_t \geq 0$ and gap m , so its stationary process is reflection positive. For $X(s) = s/\sqrt{\varepsilon}$ we have $\pi(X) = \pi(X^3) = 0$, $\pi(X^2) = 1$, $\pi(X^4) = 1/\varepsilon$ and $P_t X = e^{-mt} X$, so the two-point function is e^{-mt} for every ε , while for $t_1 \leq t_2 \leq t_3 \leq t_4$ and $q_i = e^{-m(t_{i+1} - t_i)}$ the four-point function is $q_3 \pi(X P_{t_2 - t_1} (X P_{t_3 - t_2} X^2)) = q_1 q_3 (q_2/\varepsilon + 1 - q_2)$, with truncated part $q_1 q_3 (q_2/\varepsilon - q_2 - 2q_2^2)$; both diverge as $\varepsilon \rightarrow 0$. By part (i), no choice of amplitude scales makes (T1)–(T3) hold for this family with constants independent of ε .

The hypotheses (T1)–(T3) are uniform cluster estimates for the continuum tuning $\beta_k \rightarrow \infty$, and the next proposition shows that they are estimates at a critical point: with the order-two cases alone the lattice gap is at most a fixed multiple of a_k , and the tree majorant carries a fixed fraction of its weight at a fixed physical distance. Let $m_k \in [0, \infty]$ be the gap of $\mathbb{T}_k$ on the complement of Ω_k , so that $\|\mathbb{T}_k v\| \leq e^{-m_k} \|v\|$ for $v \perp \Omega_k$, and let $t_0 > 0$ be the least time in the support of f_0 .

Proposition 58. (i) For every dyadic $\sigma > 0$ and every large k , $C_k(\sigma) \leq e^{-m_k \sigma / a_k} C_k(0)$. If $m_k / a_k \rightarrow \infty$, every limit of Theorem 47 is trivial; this is the case for $\beta_k = \beta$ fixed in the range of Theorem 5, where $m_k \geq m_G(\beta)$.

(ii) Suppose the ω_k are translation invariant and (T1) for $n = 2$ and (T2) hold. Then $m_k \leq a_k \log 2 / \sigma$ for every large k , where σ is the dyadic number of Theorem 55(iv), which depends only on K_2/c and f_0 . If also the hypothesis of Theorem 45 holds, then $m_* a_k \leq m_k \leq a_k \log 2 / \sigma$, and in particular $m_* \leq \log 2 / \sigma$.

(iii) Under (T1) for $n = 2$ and (T2), let Q be a cube containing the support of f_0 and $\gamma = c / (K_2 \|f_0\|_\infty^2 \sup_k |Q|_k)$. Then for every k

$$\sum_{z \in \mathbb{Z}^4, |z_0| \geq R_k} w_k(z) \geq \gamma W_k, \quad R_k = \frac{2t_0}{a_k} - 1.$$

If $w_k(z) = e^{-\mu_k |z_0|} u_k(\bar{z})$ with $\bar{z}$ the spatial part of z and $u_k \geq 0$ summable on $\mathbb{Z}^3$, then $\mu_k R_k \leq \log(2/\gamma)$, so the physical time decay rate of the majorant is at most $\log(2/\gamma) / (2t_0 - a_k)$.

Proof. (i) In the proof of Theorem 47, $C_k(\sigma)/C_k(0) = \langle \Psi_k, \mathbb{T}_k^{\sigma/a_k} \Psi_k \rangle$ with Ψ_k a unit vector orthogonal to Ω_k . The operator $\mathbb{T}_k$ is self-adjoint and fixes Ω_k , so it preserves the complement, and the inequality follows. If $m_k/a_k \rightarrow \infty$ then $\rho(\sigma) = 0$ for every dyadic $\sigma > 0$ along every subsequence, and the limit is trivial by Theorem 47(iv). At fixed β in the range of Theorem 5 the gap is at least $m_G(\beta) > 0$ in lattice units, and $a_k \rightarrow 0$; the spatial flow does not change the transfer matrix (Proposition 46(iv)).

(ii) Theorem 55(iv) uses (T1) and (T2) only for $n = 2$, since the exponent $n/2 - 1$ in part (i) vanishes there, and gives $C_k(\sigma) \geq \frac{1}{2} C_k(0)$ for large k . With (i), $e^{-m_k \sigma / a_k} \geq \frac{1}{2}$. Under the hypothesis of Theorem 45, the proof of that theorem gives $m_k \geq \log(1/\alpha) / (2n_k) \geq m_* a_k$.

(iii) $C_k(0) = \omega_k(A_k(\bar{f}_0 \circ \theta_k) A_k(f_0))$, a covariance of two centred fields, by the proof of Theorem 55(iv). A point x in the support of the first sum has $a_k x_0 \leq -t_0 + a_k$, and a point y in the support of the second has $a_k y_0 \geq t_0$, so $|x_0 - y_0| \geq R_k$. By (T1) for $n = 2$,

$$\begin{aligned} C_k(0) &\leq K_2 r_k^2 \|f_0\|_\infty^2 a_k^8 \sum_{a_k y \in Q} \sum_{|x_0 - y_0| \geq R_k} w_k(x - y) \\ &\leq K_2 r_k^2 \|f_0\|_\infty^2 |Q|_k a_k^4 \sum_{|z_0| \geq R_k} w_k(z), \end{aligned}$$

and (T2) bounds the left side below by $c r_k^2 a_k^4 W_k$. For the product form let $R' = \lceil R_k \rceil$; if $R' \leq 0$ there is nothing to prove, and otherwise

$$\frac{\sum_{|j| \geq R'} e^{-\mu_k |j|}}{\sum_{j \in \mathbb{Z}} e^{-\mu_k |j|}} = \frac{2e^{-\mu_k R'}}{1 + e^{-\mu_k}} \leq 2e^{-\mu_k R_k},$$

while the factor $\sum_{\bar{z}} u_k(\bar{z})$ cancels. So $2e^{-\mu_k R_k} \geq \gamma$. $\square$

So reflection positivity and decay do not supply (T2): at fixed β in the range of Theorem 5 the measures are reflection positive with exponential clustering, and $C_k(\sigma)/C_k(0) \rightarrow 0$, so no choice of w_k , r_k and constants satisfies the order-two cases of (T1) and (T2) together there. For the same reason no estimate whose constants give a lattice gap bounded below, as a convergent strong coupling expansion does [56], can give the tree bounds along the tuning: (T1) and (T2) hold, if at all, only along couplings where the lattice gap closes at least as fast as a_k . A mass gap in physical units, which bounds the decay of the two-point function, does not give the constants K_n either. By Theorem 55(v) the limit can be non-Gaussian only if $\liminf_k a_k^4 W_k > 0$; for the product majorants of part (iii) the time factor of W_k is $\coth(\mu_k/2) \geq 2/\mu_k$, which is of order $1/a_k$ at least, so the time direction alone is compatible with this. At a fixed physical flow time the flowed fields are smooth on the scale $\sqrt{\tau}$; majorants of product form for them are not proved here.

The order-two cases of (T1) and (T2) say more about the reference vector than part (iv) of Theorem 55 records: for a smooth f_0 they bound every time difference of the packet, which makes its energy distribution tight with finite moments and gives the ratio with an explicit rate. Recall the spectral measures μ_k on $[0, \infty]$ of the proof of Theorem 47, so that $C_k(\sigma)/C_k(0) = \int e^{-\sigma E} d\mu_k(E)$.

Proposition 59. Suppose the ω_k are translation invariant, (T1) holds for $n = 2$ and (T2) holds, and f_0 has $m \geq 1$ continuous time derivatives. Let Q be a cube containing the supports of $f_0(\cdot - (s, 0))$ for $0 \leq s \leq m a_0$, and $B_m = (K_2/c) \sup_k |Q|_k \|\partial_t^m f_0\|_\infty^2$.

(i) $\|(1 - \mathbb{T}_k)^m \Psi_k\|^2 \leq B_m a_k^{2m}$ for every k , where $\Psi_k = Z_k \Psi_{A_k}$.

(ii) $\int ((1 - e^{-a_k E})/a_k)^{2m} d\mu_k(E) \leq B_m$ and $\mu_k([\Lambda, \infty]) \leq B_m (a_k + \Lambda^{-1})^{2m}$ for $\Lambda > 0$. Every weak limit μ of the μ_k satisfies $\mu(\{\infty\}) = 0$ and $\int E^{2m} d\mu(E) \leq B_m$. If (T1)–(T3) hold, the unit vector $\Psi(P_0)$ of Theorem 55(iii)–(iv) lies in the domain of H^m , with $\|H^m \Psi(P_0)\|^2 \leq B_m$.

(iii) If $a_k \sqrt{B_1} \leq \frac{1}{2}$, then $C_k(\sigma) \geq e^{-2\sqrt{B_1} \sigma} C_k(0)$ for every $\sigma \in a_k \mathbb{Z}_{\geq 0}$, and the gap m_k of Proposition 58 satisfies $m_k \leq -\log(1 - a_k \sqrt{B_1}) \leq 2\sqrt{B_1} a_k$.

Proof. (i) Let $D_k f_0 = \sum_{j=0}^m (-1)^j \binom{m}{j} f_0(\cdot - (ja_k, 0))$. By translation invariance $\mathbb{T}_k^j \Psi_{A_k} = \Psi_{\tau_j A_k}$ and $\tau_j A_k = A_k(f_0(\cdot - (ja_k, 0)))$, so $(1 - \mathbb{T}_k)^m \Psi_{A_k} = \Psi_{A_k(D_k f_0)}$, and as in the proof of Theorem 55(iv) its squared norm is the covariance $\omega_k(A_k(D_k f_0 \circ \theta_k) A_k(D_k f_0))$. The function $D_k f_0$ is supported in Q and is an m -th difference with step a_k , so $\|D_k f_0\|_\infty \leq a_k^m \|\partial_t^m f_0\|_\infty$. Lemma 54 with $n = 2$ bounds the covariance by $K_2 r_k^2 |Q|_k a_k^4 W_k \|D_k f_0\|_\infty^2$, and (T2) bounds $C_k(0) = Z_k^{-2}$ below by $c r_k^2 a_k^4 W_k$.

(ii) By the spectral theorem the left side of (i) is $\int (1 - e^{-a_k E})^{2m} d\mu_k$, the integrand being 1 at $E = \infty$. For $E \geq \Lambda$, $(1 - e^{-a_k E})/a_k \geq (1 - e^{-a_k \Lambda})/a_k \geq \Lambda/(1 + a_k \Lambda)$, because $1 - e^{-x} \geq x/(1 + x)$; this gives the tail bound. The set $(\Lambda, \infty]$ is open in $[0, \infty]$, so $\mu((\Lambda, \infty]) \leq \liminf_k \mu_k((\Lambda, \infty]) \leq B_m \Lambda^{-2m}$,

and $\mu(\{\infty\}) = 0$. For a continuous χ with $0 \leq \chi \leq 1$ and support in $[0, L]$, the same inequality gives $E \leq (1 + a_k L)(1 - e^{-a_k E})/a_k$ on that support, so $\int \chi E^{2m} d\mu = \lim_k \int \chi E^{2m} d\mu_k \leq B_m$; letting χ increase to 1 gives the moment bound. The vector $\Psi(P_0)$ has $\langle \Psi(P_0), e^{-\sigma H} \Psi(P_0) \rangle = \lim_k C_k(\sigma)/C_k(0) = \int e^{-\sigma E} d\mu$ for dyadic $\sigma > 0$ along the subsequence, so its spectral measure for H is μ .

(iii) By (i) with $m = 1$ and the Cauchy–Schwarz inequality, $\langle \Psi_k, (1 - \mathbb{T}_k) \Psi_k \rangle \leq a_k \sqrt{B_1}$, which is the hypothesis of Proposition 48(ii) with $C = \sqrt{B_1}$. Since Ψ_k is a unit vector orthogonal to Ω_k , the same quantity is at least $1 - e^{-m_k}$. $\square$

Part (iii) makes Proposition 58(ii) explicit: the order-two tree and saturation bounds pin the lattice gap below $2\sqrt{B_1} a_k$, a physical mass of at most $2\sqrt{B_1}$, and give the ratio of Theorem 47(iv) at every separation. The open input of Theorem 47 is therefore implied by these two bounds for one smooth f_0 ; nothing here proves them for the Wilson action.

F. Estimates uniform in the coupling

Some local quantities of the Wilson measure can be controlled uniformly in β_W , the volume and the boundary condition, by integrating by parts in a single link. Such estimates hold along every tuning, but they concern local fields in lattice units, and the three results below show how far they are from the open inputs: the force has bounded moments but its centred form is a null vector of the reflected form, the plaquette has fluctuations of order β_W^{-2} but this is a single-site variance, and bare links over a fixed physical distance become independent Haar variables.

Let $G = \text{SU}(N)$, write $b = \beta_W$, so that the Wilson weight is e^{bS} with $S = \sum_p N^{-1} \text{Re Tr } Q_p$, and give $\mathfrak{g}$ the metric $\langle T, R \rangle = -\text{Tr}(TR)$. For a link e let S_e be the sum of the six plaquette terms containing e , X_T the derivative along $U_e \mapsto e^{uT} U_e$ at $u = 0$, ∇_e and Δ_e the gradient and Laplacian in U_e , $q = N^2 - 1$, $c_N = (N^2 - 1)/N$, and

$$E_e = b|\nabla_e S_e|^2, \quad W_e = E_e - c_N S_e = b|\nabla_e S_e|^2 + \Delta_e S_e.$$

Below, ω is a Wilson Gibbs state at $b > 0$: a finite-volume measure in which e is not fixed by the boundary condition, or an infinite-volume state whose conditional law of U_e given the other links is proportional to $e^{bS_e} dU_e$ with dU_e the Haar measure.

Proposition 60. (i) For every unit $T \in \mathfrak{g}$, $t \in \mathbb{R}$ and $0 \leq \eta < N/12$,

$$\begin{aligned} \mathbb{E}_\omega[e^{t\sqrt{b}X_T S_e} \mid U_e^c] &\leq e^{3t^2/N}, \\ \mathbb{E}_\omega[e^{\eta E_e} \mid U_e^c] &\leq (1 - 12\eta/N)^{-q/2}, \end{aligned}$$

so $\mathbb{E}_\omega E_e^m \leq m!(24/N)^m 2^{q/2}$ for $m \geq 1$, uniformly in b , the volume and the boundary condition. Moreover $\mathbb{E}_\omega E_e = c_N \mathbb{E}_\omega S_e$.

(ii) For a bounded function F of finitely many links, continuously differentiable in U_e , $\mathbb{E}_\omega[W_e F] = -\mathbb{E}_\omega[\langle \nabla_e S_e, \nabla_e F \rangle]$. In particular $\mathbb{E}_\omega[W_e F] = 0$ if F does not depend on U_e , and $\mathbb{E}_\omega[W_e W_f] = 0$ if no plaquette contains both e and f .

(iii) Let ω be reflection positive as in Appendix F, and let $A = \sum_e h_e W_e$ be a finite sum over links whose endpoints have times at least 2. Then $\omega(\vartheta(\bar{A})A) = 0$, so $\Psi_A = 0$: in the reconstructed Hilbert space the packets $\sum_e h_e E_e$ and $c_N \sum_e h_e S_e$ define the same vector.

Proof. (i) Along $u \mapsto e^{uT} U_e$ a plaquette term containing e is $N^{-1} \text{Re Tr}(e^{uT} V)$ or $N^{-1} \text{Re Tr}(V e^{-uT})$ with V unitary, whose second derivative is $N^{-1} \text{Re Tr}(T^2 e^{\pm uT} V)$. Since $-T^2 \geq 0$ and $\text{Tr}(-T^2) = 1$, $|\text{Tr}(T^2 M)| \leq 1$ for unitary M , so the second derivative of S_e along the curve is at most $6/N$ in absolute value. Taylor's formula with $u = t/\sqrt{b}$ gives $b(S_e(e^{tT/\sqrt{b}} U_e) - S_e(U_e)) \geq t\sqrt{b} X_T S_e(U_e) - 3t^2/N$. The conditional density is e^{bS_e}/Z with respect to Haar measure, and the left invariance of Haar measure gives $\mathbb{E}_\omega[e^{b(S_e(e^{tT/\sqrt{b}} U_e) - S_e(U_e))} \mid U_e^c] = 1$, which with the Taylor bound proves the first inequality. For the second let G_0 be a standard Gaussian vector in $\mathfrak{g}$, independent of ω ; then $e^{\eta|Y|^2} = \mathbb{E} e^{\sqrt{2\eta}\langle G_0, Y \rangle}$ for $Y = \sqrt{b}\nabla_e S_e$, and the first inequality in the direction of G_0 with $t = \sqrt{2\eta}|G_0|$ gives the bound $\mathbb{E} e^{6\eta|G_0|^2/N} = (1 - 12\eta/N)^{-q/2}$. With $\eta = N/24$ and $x^m \leq m! \eta^{-m} e^{\eta x}$ the moment bound follows. For the mean, $\sum_A T_A^2 = -c_N I$ in an orthonormal basis gives $\Delta_e S_e = -c_N S_e$, and the integral of the divergence of $e^{bS_e} \nabla_e S_e$ over G vanishes.

(ii) The integral over U_e of the divergence of $e^{bS_e} F \nabla_e S_e$ vanishes, and that divergence is $e^{bS_e} (W_e F + \langle \nabla_e S_e, \nabla_e F \rangle)$; integrate the conditional identity. The function W_f depends only on the links of the plaquettes containing f .

(iii) Each W_e in the sum depends on links with times at least 1, so $\vartheta(\bar{A})$ depends only on links with times at most 0, none of which is a link e of the sum. By (ii), $\omega(\vartheta(\bar{A})W_e) = 0$ for each e . $\square$

Proposition 61. Let $G = \text{SU}(2)$, $b \geq 0$, ω a Wilson Gibbs state at b and p a plaquette with a link that is not fixed by the boundary condition. Then

$$\text{Var}_\omega\left(\frac{1}{2} \text{Tr } Q_p\right) \geq \frac{1}{2^{19}(1+6b)^2}, \quad \mathbb{E}_\omega\left[1 - \frac{1}{2} \text{Tr } Q_p\right] \geq \frac{1}{4b+1}.$$

Proof. Let e be the link and identify $\text{SU}(2)$ with the unit quaternions. Given the other links, $U_e = x$ has density proportional to $e^{r \cdot x}$ with $|u| = 1$ and $0 \leq r \leq 6b$, since the six staples have norm one, and $\frac{1}{2} \text{Tr } Q_p = x \cdot v$ for a unit vector v fixed by the conditioning. Let $X = x \cdot u$ and $T = 1 - X$; the law of T has density proportional to $e^{-rt} \sqrt{t(2-t)}$ on $[0, 2]$. Put $n = 1 + r$. Since $e^{-rt} \leq e^2 e^{-nt}$, the normalisation is at most $e^2 \int_0^\infty \sqrt{2t} e^{-nt} dt = e^2 \sqrt{\pi/2} n^{-3/2} < 14n^{-3/2}$. On $I = [\frac{1}{4n}, \frac{1}{2n}]$ the density is at least $\frac{1}{2} n^{-1/2} e^{-1/2}$ and on $J = [\frac{1}{n}, \frac{3}{2n}]$ at least $\frac{1}{2} n^{-1/2} e^{-3/2}$, so $P(T \in I) \geq \frac{1}{224}$ and $P(T \in J) \geq \frac{1}{336}$. With an independent copy T' , $\text{Var } T = \frac{1}{2} \mathbb{E}(T - T')^2 \geq P(T \in I)P(T \in J)(2n)^{-2} > 2^{-19} n^{-2}$. By symmetry the conditional covariance of x is diagonal in u and $u^\perp$, with eigenvalues $\text{Var } X$ and $\mathbb{E}(1 - X^2)/3$; on I , $1 - X^2 = T(2 - T) \geq \frac{3}{8n}$, so $\mathbb{E}(1 - X^2)/3 \geq \frac{1}{1792n} \geq 2^{-19} n^{-2}$. Hence the conditional variance of $x \cdot v$ is at least $2^{-19}(1 + 6b)^{-2}$, and so is the variance, by the law of total variance. For the mean, integrating $\frac{d}{dX}(e^{rX}(1 - X^2)^{3/2})$ over $[-1, 1]$ gives $3\mathbb{E}X = r\mathbb{E}(1 - X^2) \leq r(1 - (\mathbb{E}X)^2)$, whence

$\mathbb{E}X \leq (\sqrt{9+4r^2} - 3)/(2r) \leq 2r/(2r+3)$ for $r > 0$, and $\mathbb{E}[1 - x \cdot v] \geq 1 - \mathbb{E}X \geq 3/(2r+3) \geq 1/(4b+1)$. $\square$

For the blocking statement let $G = \text{SU}(2)$, $B \geq 4$ an integer and, for a coarse edge (x, μ) , $V_{(x, \mu)} = \prod_{r=0}^{B-1} U_{(Bx+r\hat{\mu}, \mu)}$ the ordered product of the fine links along it.

Proposition 62. *For every Wilson Gibbs state ω of $\text{SU}(2)$ at $b > 0$ and every set $\mathcal{E}$ of K coarse edges,*

$$\begin{aligned} \|\text{Law}_\omega((V_e)_{e \in \mathcal{E}}) - m^{\otimes K}\|_{\text{TV}} &\leq \frac{K}{2} e^{3b} \left(\frac{4b}{4b+1} \right)^{B-3} \\ &\leq \frac{K}{2} \exp\left(3b - \frac{B-3}{4b+1}\right), \end{aligned}$$

where m is the Haar measure. If F is a function of the V_e of a set of coarse edges at positive times, $|F| \leq 1$, and ε is this bound for those edges and their reflections, then $0 \leq \omega(\vartheta(\bar{F}^c)F^c) \leq 6\varepsilon$ with $F^c = F - \omega(F)$.

Proof. Select on each coarse edge the fine links with $1 \leq r \leq B-2$. No plaquette contains two selected links: collinear links do not share a plaquette, parallel coarse edges are B apart, and a plaquette containing a selected link of (x, μ) has its links in direction $v \neq \mu$ at μ -offsets $r, r+1 \in [1, B-1]$ from Bx , while coarse edges in direction v lie at offsets in $B\mathbb{Z}$. Given the other links, the selected ones are therefore independent, each with density $e^{r_i x \cdot u_i} / Z(r_i)$, $0 \leq r_i \leq 6b$. Convolution with such a density acts on the representation of spin $l \geq 1$ by $D^{(l)}(u_i)$ times $I_{l+1}(r_i)/I_l(r_i)$, whose absolute value is at most $I_2(r_i)/I_1(r_i)$ because $I_v(r)$ decreases in $v \geq 0$, and $I_2(r_i)/I_1(r_i) = \mathbb{E}X \leq 4b/(4b+1)$ by the proof of Proposition 61, so it contracts the mean-zero part of L^2 by that factor. The density is at most e^{6b} because $Z \geq 1$ by Jensen's inequality, so its distance to 1 in L^2 is at most e^{3b} . The conditional law of V_e is that of a product of $B-2$ such independent variables between two fixed ones, so its total variation distance to m is at most $\frac{1}{2} e^{3b} (4b/(4b+1))^{B-3}$, and the coarse edges are conditionally independent. Total variation distance from a product is at most the sum over the factors, and averaging over the conditioning does not increase it. For the last statement, under $m^{\otimes K}$ the covariance vanishes because F and its reflection depend on disjoint edges; replacing ω by $m^{\otimes K}$ changes $\omega(\vartheta(\bar{F})F)$ by at most 2ε and $|\omega(F)|^2$ by at most 4ε . $\square$

With $B = \ell/a_k$ for a fixed physical length ℓ and $b_k = O(\log(1/a_k))$ the bound tends to zero: the bare coarse links of a fixed coarse graph become independent Haar variables, their reflected form has rank one, and a renormalisation Z_k that keeps the reflected norm of $Z_k F^c$ at least $c > 0$ must grow at least like $(c/6\varepsilon)^{1/2}$. The renormalised flowed fields of Theorem 47 are not bounded functions of bare coarse links, and none of the three propositions bears on the slice ratio, the tree bounds or (D).

G. The two residues

Theorem 45 reduces a continuum mass gap to two statements, neither of which is proved here or, to our knowledge, anywhere else.

(D) *The cube estimate.* There are $\alpha < 1$ and $\ell > 0$ such that $D(n, \alpha)$ holds with $na \leq \ell$ along the continuum tuning $\beta = \beta(a) \rightarrow \infty$, uniformly in a .

(E) *The limit.* The renormalised Schwinger functions converge along $a_k = 2^{-k} a_0$ to Schwinger functions that satisfy the Osterwalder–Schrader axioms and are not those of the vacuum alone.

(D) and (E) together give the mass gap of the continuum theory; the remaining Clay requirements, Euclidean invariance and the local structure of the limit [40], belong to (E). (D) is a statement about a single cube of fixed physical size and a single coupling at each spacing; (E) is the construction problem, on which Bałaban's renormalisation group analysis [4–6] gives the ultraviolet part in finite volume.

Remark 63. The following count relates (D) to a correlation length. Suppose that the gauge-fixed field responds to a change of one link on the boundary of a cube through a Poisson kernel with decay length ξ in lattice units. Then the response summed over the cube is of order ξ , so K_c is of order $n^3 \xi$ and $D(n, \alpha)$ holds once $n \gtrsim \xi/\alpha$, that is, once $\ell \gtrsim \xi a/\alpha$, a fixed multiple of the physical correlation length. The hypothesis is that the gauge-fixed links decorrelate on the scale ξ , and it is a statement about the gauge, not about the gauge-invariant observables: the gauge here is built on straight lines, and in gauges of axial type the gauge-fixed variables can fluctuate on all scales while gauge-invariant observables cluster. Propositions 64 and 65 carry the count out exactly for Gaussian fields, and Proposition 65 shows that the quadratic approximation of the forest gauge fluctuates in this way. Where it does, (D) fails in this gauge and has to be posed for block-averaged variables, where it becomes part of the renormalisation group problem.

The count of Remark 63 can be carried out exactly for a Gaussian field, the quadratic approximation of the gauge-fixed theory at weak coupling, and shows what (D) asks of the gauge-fixed variables.

Proposition 64. *Let $d \geq 1$, $b > 0$, $t \geq 0$, let $n \geq 2$ be even and $V = [0, n]^d \cap \mathbb{Z}^d$. Given $\eta \in \mathbb{R}^{\mathbb{Z}^d \setminus V}$, let $\mathcal{W}(\cdot | \eta)$ be the Gaussian law on $\mathbb{R}^V$ with density proportional to*

$$\exp\left(-\frac{b}{2} \left[\sum_{\{x,y\} \cap V \neq \emptyset} (\phi_x - \phi_y)^2 + t \sum_{x \in V} \phi_x^2 \right] \right),$$

the first sum over nearest-neighbour pairs, with $\phi = \eta$ outside V . Define $C_{V,j}$, the classes c (residues modulo two) and K_c as above, with $d_V(\phi, \phi') = \sum_{x \in V} |\phi_x - \phi'_x|$ and $\delta(\eta_j, \eta'_j) = |\eta_j - \eta'_j|$, and put $N_n = (n/2)^d$. Then $K_c = \alpha_n(t) N_n$ for every class c , where

$$\alpha_n(t) = 1 - \frac{t}{n^d} \mathbf{1}^\top (t + L_n)^{-1} \mathbf{1}$$

and L_n is the Dirichlet Laplacian of V . In particular:

- (i) for $t = 0$, $K_c = N_n$ for every n and every b , so $D(n, \alpha)$ fails for every $\alpha < 1$;

(ii) for $t > 0$, $1 - \alpha_n(t) \geq (5/6)^d t n^2 / (t n^2 + 10d)$; for $d = 4$, $t = m^2 \alpha^2$ and $\ell/2 \leq n \alpha \leq \ell$ this gives $D(n, \alpha)$ with $\alpha = 1 - (5/6)^4 (m\ell)^2 / ((m\ell)^2 + 160)$, uniformly in a .

Proof. Let $A = t + L_n$ and $G = A^{-1}$, and let B be the matrix with $B_{xj} = 1$ when $x \in V$ and $j \notin V$ are neighbours. The law $\mathcal{W}(\cdot | \eta)$ has covariance $b^{-1}G$ and mean $GB\eta$. The matrix A has nonpositive off-diagonal entries and is positive definite, so $G \geq 0$ entrywise. Changing η_j by Δ translates the law by ΔGB_j , where B_j is the column of j . The coupling by translation gives $W_1^{dv} \leq |\Delta| \sum_x (GB_j)_x$, and the 1-Lipschitz function $\sum_x \phi_x$ gives the reverse inequality, so $C_{V,j} = \mathbf{1}^T GB_j$. Since $B\mathbf{1} = L_n \mathbf{1}$ (both count the exterior neighbours of each site),

$$\sum_{j \notin V} C_{V,j} = \mathbf{1}^T GL_n \mathbf{1} = \mathbf{1}^T \mathbf{1} - t \mathbf{1}^T G \mathbf{1} = n^d \alpha_n(t).$$

The reflection $x_i \mapsto n - 1 - x_i$ preserves V and the coefficients and, as n is even, exchanges the two residues of the coordinate x_i ; so the 2^d class sums are equal, and each is $n^d \alpha_n(t) / 2^d = \alpha_n(t) N_n$. This proves the formula and (i).

For (ii) let $v(i) = (i+1)(n-i)$ for $0 \leq i < n$ and $\psi(x) = \prod_i v(x_i)$. The one-dimensional Dirichlet Laplacian maps v to the constant 2, so with $s_1 = \sum_i v(i) = n(n+1)(n+2)/6$ and $s_2 = \sum_i v(i)^2 = n(n+1)(n+2)(n^2+2n+2)/30$,

$$\mathbf{1}^T \psi = s_1^d, \quad \psi^T A \psi = t s_2^d + 2d s_1 s_2^{d-1}.$$

By the Cauchy–Schwarz inequality for the form of A^{-1} , $\mathbf{1}^T G \mathbf{1} \geq (\mathbf{1}^T \psi)^2 / \psi^T A \psi$, hence

$$1 - \alpha_n(t) \geq \left(\frac{s_1^2}{n s_2} \right)^d \frac{t}{t + 2d s_1 / s_2} \geq \left(\frac{5}{6} \right)^d \frac{t n^2}{t n^2 + 10d},$$

since $s_1^2 / (n s_2) = \frac{5}{6} (n^2 + 3n + 2) / (n^2 + 2n + 2) \geq \frac{5}{6}$ and $2d s_1 / s_2 = 10d / (n^2 + 2n + 2) \leq 10d / n^2$. With $d = 4$ and $t n^2 = m^2 (n \alpha)^2 \geq (m\ell)^2 / 4$ the last fraction is at least $(m\ell)^2 / ((m\ell)^2 + 160)$. $\square$

The Gaussian field is not Yang–Mills theory, and the proposition is a benchmark for the condition, not a statement about the Wilson measure. It shows that the averaged cube condition is met at a fixed physical scale by a field with a mass and fails exactly, at every size and every stiffness, for a massless one. Small local fluctuations alone therefore give nothing: in the massless Gaussian field on $\mathbb{Z}^d$, $d \geq 3$, the variance of $\phi_x - \phi_{x+e_1}$ is $1/(db)$, which tends to zero as $b \rightarrow \infty$, and still $K_c = N_n$. A proof of (D) along the tuning has to produce in the gauge-fixed variables the loss that the parameter t supplies here, from the Wilson action alone.

The quadratic approximation of the forest gauge itself, with the plaquette action in place of the Laplacian, is no better than the massless field of Proposition 64(i).

Proposition 65. *Let $b > 0$, let n be even and V the cube of Definition 42. For real functions ϕ on the links of $\mathbb{Z}^4$ that vanish on F , let $(d\phi)_p$ be the sum of ϕ around the plaquette p with the signs of its orientation. Given $\eta \in \mathbb{R}^{A^V}$, let $\mathcal{W}(\cdot | \eta)$ be the law on $\mathbb{R}^V$ with density proportional to*

$$\exp\left(-\frac{b}{2} \sum_{p \cap V \neq \emptyset} (d\phi)_p^2\right),$$

with $\phi = \eta$ on $A \setminus V$ and $\phi = 0$ on F , and define $C_{V,j}$ and K_c as above with $d_V(\phi, \phi') = \sum_{i \in V} |\phi_i - \phi'_i|$ and $\delta(\eta_j, \eta'_j) = |\eta_j - \eta'_j|$. Then

$$\sum_c K_c \geq |V| = 48N_n,$$

so $K_c \geq N_n$ for some class c , and $D(n, \alpha)$ fails for every $\alpha < 1$, at every n and every b .

Proof. The laws. The quadratic form $\sum_{p \cap V \neq \emptyset} (d\phi)_p^2$ with $\phi = 0$ outside V vanishes only at $\phi = 0$: the argument of Corollary 70, written additionally, gives a function h on the sites with $\phi_{(x,\mu)} = h(x) - h(x + e_\mu)$, constant outside the box and along the lines of F , hence constant. So $\mathcal{W}(\cdot | \eta)$ is a Gaussian law whose covariance does not depend on η and whose mean is $\sum_j \eta_j u_j$ for some vectors $u_j \in \mathbb{R}^V$. Two exteriors that differ in finitely many links give translates of one law by $t = \sum_j (\eta'_j - \eta_j) u_j$; the coupling by translation and the 1-Lipschitz function $\sum_i \text{sign}(t_i) \phi_i$ show that their distance is $\|t\|_1$. In particular $C_{V,j} = \|u_j\|_1$, and

$$W_1^{dv}(\mathcal{W}(\cdot | \eta), \mathcal{W}(\cdot | \eta')) \leq \sum_j C_{V,j} |\eta'_j - \eta_j|.$$

Lines. By Lemma 9(i) the lines of F are straight, disjoint and cover the sites, and the two ends of an active link (x, μ) lie on different lines, since the line through x has direction $\sigma(x) \neq \mu$. For a line ℓ let h_ℓ be the indicator of its sites and $(dh_\ell)_{(x,\mu)} = h_\ell(x) - h_\ell(x + e_\mu)$. Then dh_ℓ vanishes on F and around every plaquette, so the density is invariant under $\phi \mapsto \phi + dh_\ell$, and $\mathcal{W}(\cdot | dh_\ell)$ is $\mathcal{W}(\cdot | 0)$ translated by the restriction of dh_ℓ to V . Hence

$$\sum_{i \in V} |(dh_\ell)_i| \leq \sum_{j \in A \setminus V} C_{V,j} |(dh_\ell)_j|.$$

Here $|(dh_\ell)_e| = 1$ when exactly one end of e lies on ℓ and 0 otherwise, so $\sum_e |(dh_\ell)_e| = 2$ for every active link e , the sum running over the finitely many lines that meet a link entering the inequality. Summing over these lines gives $2|V| \leq 2 \sum_j C_{V,j} = 2 \sum_c K_c$. $\square$

The proof uses only that gauge transformations constant on the lines of F move the whole cube while changing few boundary links, which is the behaviour of gauges of axial type anticipated in Remark 63. The class sums themselves, computed exactly in the archive for $n \leq 8$, lie between 1.5 and 11 times N_n and increase with n . Below the correlation length the theory is weakly coupled, and the quadratic approximation is its leading order there. A proof of (D) along the tuning therefore has to show that the nonperturbative regime reduces the cube coefficients of the forest gauge below N_n , or (D) has to be posed for other variables.

Remark 66. The other routes we tried stop at (D) or (E), or earlier.

(a) *Disjoint blocks.* The block criterion of Lemma 80 with a partition into cubes of side n requires, for a link on a face, that its influence on the neighbouring cube be less than

one. In the count of Remark 63 that influence is of order ξ , which grows like $1/a$. Averaging over the N_n translates divides it by the number of translates on whose boundary the link lies, a factor of order $1/n$, and this is why (D) is stated for averaged cubes.

- (b) *Rescaling a fixed lattice gap.* Any bound uniform in lattice units, such as those of Theorems 1–7, gives trivial continuum two-point functions [14]; rescaling it produces no gap.
- (c) *Assuming the gap.* Hypothesis R of [14] assumes the gap in physical units together with the limit. Theorem 45 replaces the gap part by the cube estimate (D), which concerns one box and one coupling at each spacing.
- (d) *Computation.* At a fixed coupling and a fixed small n , $D(n, \alpha)$ is a finite set of Kantorovich bounds and could in principle be certified as in Propositions 34 and 35; for $n = 2$ and $SU(2)$ the block already has 48 links and 144 real variables. (D) asks for it at infinitely many couplings with $n \rightarrow \infty$, which no finite computation covers.
- (e) *Axioms alone.* Proposition 41 shows that positivity, invariance and regularity do not force a gap, and Proposition 40 shows that the growth route to rotation invariance is closed for the action density. The infrared input therefore has to be an estimate such as (D).

H. What the cube estimate requires

This subsection proves four facts about $D(n, \alpha)$. It holds at small coupling for every even n above an explicit size (Proposition 68). It forces the gauge-fixed variables of a cube with trivial exterior to stay a fixed distance from the identity on average (Theorem 69, and Proposition 71 for $SU(2)$), so that for every fixed n it fails once β is large (Corollary 70). And it cannot be obtained from bounds on the conditional law of a single line of links that are uniform in the configuration around the line (Proposition 77). None of the four decides (D) along the continuum tuning, where n grows while β grows.¹⁸

For a finite $V \subset A$ and $j \in A \setminus V$ let $b(V, j)$ be the number of links of V that share a plaquette with j , and write $k \sim i$ when two active links share a plaquette.

Lemma 67. *Suppose that $C_{ee'} \leq c_0$ for all active e, e' , with $12c_0 < 1$. Then $C_{V,j} \leq c_0 b(V, j)/(1 - 12c_0)$ for every finite $V \subset A$ and every $j \in A \setminus V$.*

Proof. Fix Q, Q' that differ only at j , put $d = \delta(Q_j, Q'_j)$, $\mu = \mathcal{W}(\cdot | Q)$ and $\nu = \mathcal{W}(\cdot | Q')$. The couplings of μ and ν form a

weakly compact set on which $\pi \mapsto \int d_V d\pi$ is continuous, so one of them, π , minimises it; let $\rho_i = \int \delta(X_i, Y_i) d\pi$. Fix $i \in V$. Under μ the conditional law of X_i given the other links of V is $\gamma_i^F(\cdot | X)$, and likewise for ν . Replace (X_i, Y_i) by a pair drawn from an optimal coupling of $\gamma_i^F(\cdot | X)$ and $\gamma_i^F(\cdot | Y)$, chosen measurably [67, Cor. 5.22], and keep the other coordinates. The new coupling still has marginals μ and ν , and changing the links in which X and Y differ one at a time gives

$$W_1(\gamma_i^F(\cdot | X), \gamma_i^F(\cdot | Y)) \leq \sum_{k \in V, k \neq i} C_{ik} \delta(X_k, Y_k) + C_{ij} d.$$

Minimality of π therefore gives $\rho_i \leq c_0 \sum_{k \in V, k \sim i} \rho_k + c_0 [i \sim j] d$. Sum over $i \in V$: every ρ_k occurs at most twelve times by Lemma 9(iv), so $(1 - 12c_0) \sum_i \rho_i \leq c_0 b(V, j) d$. Since $W_1^{dv}(\mu, \nu) \leq \sum_i \rho_i$, dividing by d proves the lemma. $\square$

Proposition 68. *Let $n = 2m$ and let V be the cube of Definition 42. For every class c ,*

$$\sum_{j \in c \setminus V} b(V, j) \leq 10m^3 - 2m^2,$$

with equality for three classes. Consequently, if $C_{ee'} \leq c_0$ for all e, e' with $12c_0 < 1$, then $D(n, \alpha)$ holds for every $\alpha \in (0, 1)$ with

$$\alpha \geq \hat{\alpha}_n = \frac{c_0}{1 - 12c_0} \left(\frac{20}{n} - \frac{8}{n^2} \right).$$

For $SU(2)$ and $|\beta_W| < \frac{1}{3}$ this reads $\hat{\alpha}_n = \frac{|\beta_W|}{1 - 3|\beta_W|} \left(\frac{5}{n} - \frac{2}{n^2} \right)$, which is below one for every even $n > 5|\beta_W|/(1 - 3|\beta_W|)$.

Proof. Let $j = (y, \mu)$ lie in the class c , with $y \equiv r$ modulo two. A link of V that shares a plaquette with j has base point $y + d$ with $d \in \{-1, 0, 1\}^4$ and at most two nonzero coordinates, and the twelve offsets d depend only on c . For a fixed offset we count the $y \equiv r$ with $y + d \in [0, n]^4$ and $y \notin [0, n]^4$. In the coordinate l there are m values of $y_l \equiv r_l$ with $y_l + d_l \in [0, n]$, and one of them lies outside $[0, n]$ exactly when $d_l = 1$ and $r_l = 1$ (the value $y_l = -1$) or $d_l = -1$ and $r_l = 0$ (the value $y_l = n$). If q is the number of such coordinates, the count is $m^4 - m^{4-q}(m-1)^q$, that is $0, m^3$ or $2m^3 - m^2$ for $q = 0, 1, 2$. Summing over the twelve offsets, the class sum is $a_c m^3 - b_c m^2$, where b_c is the number of offsets with $q = 2$ and a_c is the number with $q = 1$ plus twice b_c . Reading the offsets from Table III, the pairs (a_c, b_c) over the 48 classes are $(2, 0)$, $(7, 0)$, $(7, 1)$, $(9, 1)$, $(9, 2)$ and $(10, 2)$ three times each and $(3, 0)$, $(4, 0)$, $(5, 0)$, $(6, 0)$ and $(8, 1)$ six times each. In every case $a_c \leq 10$ and $8 - a_c + b_c \geq 0$, so

$$(10m^3 - 2m^2) - (a_c m^3 - b_c m^2) = m^2((10 - a_c)m + b_c - 2) \geq m^2(8 - a_c + b_c) \geq 0,$$

with equality for the three classes with $(a_c, b_c) = (10, 2)$. By Lemma 67, $K_c \leq c_0(10m^3 - 2m^2)/(1 - 12c_0)$, and $N_n = m^4$ gives $K_c/N_n \leq \hat{\alpha}_n$. For $SU(2)$ the proof of Theorem 1 gives $c_0 = |\beta| = |\beta_W|/4$. $\square$

¹⁸ The four statements answer the question of which parts of (D) can be settled with the methods of this paper. The first places (D) in the range where the single-link method already works, the second and third show what any proof of (D) at weak coupling has to produce, and the fourth excludes the most direct one-dimensional route. The finite counts used below, from Table III, are rechecked by `cube_requirements.py` in the archive.

At $\beta_W = \frac{3}{10}$ and $n = 16$, for instance, $\hat{\alpha}_{16} = \frac{117}{128}$, and Theorem 43 gives the gap $\log \frac{128}{117}/32$, much weaker than Theorem 1. The proposition shows that the cube condition is not empty; it does not extend the range, because the absorption $12c_0 < 1$ is the single-link condition itself.

The next theorem uses the configuration in which every link outside V is the identity. Write $\mathcal{W}_V^1 = \mathcal{W}(\cdot | 1)$ and

$$\varepsilon_V(\beta) = \frac{1}{|V|} \sum_{i \in V} \int \delta(1, Q_i) d\mathcal{W}_V^1(Q)$$

for the mean distance of the gauge-fixed variables of the cube from the identity. Recall that δ is bi-invariant of diameter D .

Theorem 69. *Let n be even, V the cube of Definition 42, and suppose that $D(n, \alpha)$ holds at β . Then*

$$\varepsilon_V(\beta) \geq \frac{(1 - \alpha)D}{3}.$$

Proof. A flat configuration. By Lemma 9(i) and the period two of σ , the sixteen residues modulo two fall into eight pairs $\{r, r + e_{\sigma(r)}\}$, the residues met by one line of F . The eight residues 0010, 0011, 0100, 0110, 1001, 1011, 1100, 1101 form four of these pairs. Choose $z, w \in G$ with $\delta(z, w) = D$, put $g(x) = w$ if x is congruent to one of those eight residues and $g(x) = z$ otherwise, and let $Q_{(x, \mu)}^g = g(x)g(x + e_\mu)^{-1}$ for every link of $\mathbb{Z}^4$. Then g is constant on every line of F , so Q^g equals 1 on F , every plaquette variable of Q^g is 1, and Q^g has period two. By bi-invariance $\delta(1, Q_{(x, \mu)}^g) = \delta(g(x + e_\mu), g(x))$, which is D when x and $x + e_\mu$ receive different values and 0 otherwise; from Table III the first case occurs for exactly 32 of the 48 classes. Let δ_c be the common value of $\delta(1, Q_e^g)$ for e in the class c , so that $\sum_c \delta_c = 32D$.

Gauge covariance. Let $\Phi(Q)_{(x, \mu)} = g(x)Q_{(x, \mu)}g(x + e_\mu)^{-1}$ on G^V . The gauge transformation by g maps the configuration equal to Q_V on V and to 1 elsewhere to the one equal to $\Phi(Q_V)$ on V and to Q^g elsewhere; it leaves every plaquette trace unchanged and every link of F equal to 1, and Φ preserves Haar measure. Hence $\mathcal{W}(\cdot | Q^g) = \Phi_* \mathcal{W}_V^1$.

Upper bound. Only the finitely many links outside V that share a plaquette with V enter $\mathcal{W}_V$. Changing them one at a time from 1 to Q^g and applying the definition of $C_{V,j}$ at each step,

$$\begin{aligned} W_1^{d_V}(\mathcal{W}_V^1, \mathcal{W}(\cdot | Q^g)) &\leq \sum_{j \in A \setminus V} C_{V,j} \delta(1, Q_j^g) = \sum_c \delta_c K_c \\ &\leq \alpha N_n \sum_c \delta_c = 32 \alpha D N_n. \end{aligned}$$

Lower bound. The function $f(Q) = -\sum_{i \in V} \delta(Q_i, Q_i^g)$ is 1-Lipschitz for d_V . By gauge covariance and bi-invariance, $\int f d\mathcal{W}(\cdot | Q^g) = -\int \sum_i \delta(Q_i, 1) d\mathcal{W}_V^1 = -|V| \varepsilon_V$, and by the triangle inequality $\int f d\mathcal{W}_V^1 \leq -\sum_i \delta(1, Q_i^g) + |V| \varepsilon_V$. Every class has N_n links in V , so $\sum_i \delta(1, Q_i^g) = 32 D N_n$ and

$$W_1^{d_V}(\mathcal{W}_V^1, \mathcal{W}(\cdot | Q^g)) \geq 32 D N_n - 2|V| \varepsilon_V.$$

With $|V| = 48 N_n$ the two bounds give $96 N_n \varepsilon_V \geq 32(1 - \alpha) D N_n$. $\square$

Corollary 70. *For every even n and every $\alpha < 1$ there is $\beta_0(n, \alpha)$ such that $D(n, \alpha)$ fails at every $\beta \geq \beta_0(n, \alpha)$. In particular, if $D(n_k, \alpha)$ holds at couplings $\beta_k \rightarrow \infty$, then $n_k \rightarrow \infty$.*

Proof. For $\beta > 0$, $\mathcal{W}_V^1$ has density proportional to $e^{-N\beta S}$ with respect to Haar measure, where $S = \sum_{p \cap V \neq \emptyset} (N - \text{Re Tr } Q_p^F)$ is continuous and nonnegative on G^V and vanishes exactly when $Q_p^F = 1$ for every plaquette p that meets V . We show that this forces $Q_V = 1$. The other plaquettes have all their links equal to 1, so every plaquette variable is 1; since the plaquettes of $\mathbb{Z}^4$ fill every closed lattice path, there is a function h on the sites with $Q_{(x, \mu)} = h(x)h(x + e_\mu)^{-1}$ on every link, and h takes equal values at the two ends of every link on which $Q = 1$. Every link with base point outside $[0, n]^4$ is such a link. From a site with a coordinate at least n one can move in every positive direction along links of this kind, and from a site with a negative coordinate x_v one can move in the positive directions other than v until another coordinate reaches n ; so h is constant on the sites outside the box. Every line of F leaves the box, and h is constant along it, so h is constant and $Q_V = 1$.

Let U be a neighbourhood of 1 in G^V , $s = \min_{G^V \setminus U} S > 0$, and $U' \subset U$ a neighbourhood of 1 on which $S < s/2$. Then $\mathcal{W}_V^1(G^V \setminus U) \leq e^{-N\beta s} / (|U'| e^{-N\beta s/2})$, which tends to zero, so $\varepsilon_V(\beta) \rightarrow 0$ as $\beta \rightarrow \infty$, and Theorem 69 excludes $D(n, \alpha)$ once $\varepsilon_V(\beta) < (1 - \alpha)D/3$. $\square$

For $\text{SU}(2)$ the constant of Theorem 69 can be improved: a flat configuration with four values instead of two moves every class of active links, and the means of the gauge-fixed links are scalar.

Proposition 71. *Let $G = \text{SU}(2)$ with the chordal metric, let n be even, V the cube of Definition 42, and suppose that $D(n, \alpha)$ holds at β . Then*

$$\frac{1}{|V|} \sum_{i \in V} \left| \int \text{Re Tr } Q_i d\mathcal{W}_V^1 \right| \leq 2\alpha,$$

$$\frac{1}{|V|} \sum_{i \in V} \int \delta(1, Q_i)^2 d\mathcal{W}_V^1 \geq 2(1 - \alpha),$$

and $\varepsilon_V(\beta) \geq 1 - \alpha$.

Proof. Write $\langle \cdot, \cdot \rangle$ for the Euclidean product of quaternions; then $\text{Re Tr } q = 2\langle q, 1 \rangle$ and $\delta(p, q) = |p - q|$.

Four colours. Split the sixteen residues modulo two into the sets

$$\begin{aligned} X_1 &= \{0000, 1000, 0111, 1111\}, \\ X_2 &= \{0001, 0101, 1010, 1110\}, \\ X_3 &= \{0010, 0011, 1100, 1101\}, \\ X_4 &= \{0100, 0110, 1001, 1011\}. \end{aligned}$$

Each is the union of two of the eight pairs $\{r, r + e_{\sigma(r)}\}$, and Table III shows that r and $r + e_\mu$ lie in different sets for every residue r and every $\mu \neq \sigma(r)$. (The eight residues used in the proof of Theorem 69 form $X_3 \cup X_4$.) Let

$$\begin{aligned} z_1 &= (\mathbf{i} + \mathbf{j} + \mathbf{k})/\sqrt{3}, & z_2 &= (\mathbf{i} - \mathbf{j} - \mathbf{k})/\sqrt{3}, \\ z_3 &= (-\mathbf{i} + \mathbf{j} - \mathbf{k})/\sqrt{3}, & z_4 &= (-\mathbf{i} - \mathbf{j} + \mathbf{k})/\sqrt{3}, \end{aligned}$$

unit quaternions with $\langle z_k, z_l \rangle = -\frac{1}{3}$ for $k \neq l$, so that $\delta(z_k, z_l) = d_* = (8/3)^{1/2}$. Put $g(x) = z_k$ when the residue of x lies in X_k , and $Q_{(x,\mu)}^g = g(x)g(x+e_\mu)^{-1}$. As in the proof of Theorem 69, Q^g equals 1 on F , every plaquette variable of Q^g is 1, and $\mathcal{W}(\cdot | Q^g) = \Phi_* \mathcal{W}_V^1$ with $\Phi(Q)_{(x,\mu)} = g(x)Q_{(x,\mu)}g(x+e_\mu)^{-1}$; now $\delta(1, Q_e^g) = d_*$ for every active link e .

Upper bound. Changing the exterior links one at a time,

$$W_1^{dv}(\mathcal{W}_V^1, \mathcal{W}(\cdot | Q^g)) \leq d_* \sum_c K_c \leq 48 \alpha d_* N_n = \alpha d_* |V|.$$

Lower bound. Conjugating every link of V by one unit quaternion leaves the exterior 1, the links of F , Haar measure and every plaquette trace unchanged, so it preserves $\mathcal{W}_V^1$. The mean $m_i = \int Q_i d\mathcal{W}_V^1$, taken in the space of quaternions, therefore commutes with every unit quaternion, and $m_i = a_i 1$ with $a_i = \frac{1}{2} \int \text{Re Tr } Q_i d\mathcal{W}_V^1$ real. Since Φ acts on each link by a fixed left and right multiplication, the mean of Q_i under $\mathcal{W}(\cdot | Q^g)$ is $a_i Q_i^g$. Choose unit quaternions w_i with $\langle w_i, a_i Q_i^g - a_i 1 \rangle = |a_i| |Q_i^g - 1|$. The function $f(Q) = \sum_{i \in V} \langle w_i, Q_i \rangle$ is 1-Lipschitz for dv , and Kantorovich duality gives

$$W_1^{dv}(\mathcal{W}_V^1, \mathcal{W}(\cdot | Q^g)) \geq \sum_{i \in V} |a_i| \delta(1, Q_i^g) = d_* \sum_{i \in V} |a_i|.$$

Conclusion. Comparing the two bounds, $\sum_i |a_i| \leq \alpha |V|$, which is the first inequality. Since $\delta(1, q)^2 = 2 - 2\langle q, 1 \rangle$, $\int \delta(1, Q_i)^2 d\mathcal{W}_V^1 = 2(1 - a_i) \geq 2(1 - |a_i|)$, and averaging gives the second. As $\delta \leq 2$, $\delta \geq \delta^2/2$, and the bound on ε_V follows. $\square$

The four colours need nothing from $\text{SU}(2)$ except four elements whose pairwise quotients are conjugate, and every compact simple group contains such elements. For a metric that comes from a representation the bound then compares the cube with Haar measure.

Proposition 72. *Let G be a compact simple group, ρ a non-trivial irreducible unitary representation of G of dimension d , and $\delta(p, q) = \kappa^{-1/2} \|\rho(p) - \rho(q)\|_{\text{HS}}$ for some $\kappa > 0$. Let n be even, V the cube of Definition 42, and suppose that $D(n, \alpha)$ holds at β . Then*

$$\frac{1}{|V|} \sum_{i \in V} \left| \int \text{Tr } \rho(Q_i) d\mathcal{W}_V^1 \right| \leq \alpha d,$$

$$\frac{1}{|V|} \sum_{i \in V} \int \delta(1, Q_i)^2 d\mathcal{W}_V^1 \geq (1 - \alpha) \int_G \delta(1, q)^2 dq,$$

where dq is Haar measure, and $\varepsilon_V(\beta) \geq (1 - \alpha)D/2$.

Proof. Four elements. Let $\varphi: \text{SU}(2) \rightarrow G$ be the homomorphism of the $\text{SU}(2)$ subgroup of a root, and $z_1, \dots, z_4$ the tetrahedral quaternions of Proposition 71. For $k \neq l$ the quaternion $z_k z_l^{-1}$ has real part $\langle z_k, z_l \rangle = -\frac{1}{3}$; unit quaternions with equal real parts are conjugate in $\text{SU}(2)$, so the twelve elements $\varphi(z_k z_l^{-1})$ are conjugate in G , and by bi-invariance $\delta(\varphi(z_k), \varphi(z_l)) = d_*$ for all $k \neq l$, with one number d_* . If $d_* = 0$, then $\varphi(z_k z_l^{-1})$ lies in $\ker \rho$, a proper normal subgroup

of the simple group G and therefore central; it then commutes with $\varphi(\text{SU}(2))$, so it is central there, and $z_k z_l^{-1}$ lies in $\{\pm 1\} \ker \varphi \subset \{\pm 1\}$, which its real part $-\frac{1}{3}$ excludes. So $d_* > 0$.

The two bounds. Put $g(x) = \varphi(z_k)$ when the residue of x lies in X_k . The proof of Proposition 71 applies word for word: Q^g equals 1 on F and on every plaquette, $\delta(1, Q_e^g) = d_*$ on every active link, and $W_1^{dv}(\mathcal{W}_V^1, \mathcal{W}(\cdot | Q^g)) \leq \alpha d_* |V|$. Simultaneous conjugation of the links of V preserves $\mathcal{W}_V^1$, so the mean $\int \rho(Q_i) d\mathcal{W}_V^1$ commutes with $\rho(G)$, and by Schur's lemma it is $c_i I$ with $c_i = d^{-1} \int \text{Tr } \rho(Q_i) d\mathcal{W}_V^1$. Its mean under $\mathcal{W}(\cdot | Q^g)$ is $c_i \rho(Q_i^g)$. With matrices W_i of Hilbert–Schmidt norm $\kappa^{-1/2}$ chosen so that $\text{Re Tr}(W_i^* c_i (\rho(Q_i^g) - I)) = |c_i| \delta(1, Q_i^g)$, the function $f(Q) = \sum_i \text{Re Tr}(W_i^* \rho(Q_i))$ is 1-Lipschitz for dv , and Kantorovich duality gives $W_1^{dv} \geq d_* \sum_i |c_i|$. Hence $\sum_i |c_i| \leq \alpha |V|$, the first inequality.

Comparison with Haar measure. Since $\kappa \delta(1, q)^2 = 2d - 2\text{Re Tr } \rho(q)$ and $\int_G \text{Tr } \rho(q) dq = 0$ for a nontrivial irreducible ρ , $\int_G \delta(1, q)^2 dq = 2d/\kappa$, while $\int \delta(1, Q_i)^2 d\mathcal{W}_V^1 = 2d(1 - \text{Re } c_i)/\kappa \geq 2d(1 - |c_i|)/\kappa$. Averaging gives the second inequality. Finally $\kappa D^2 \leq 4d$, because $\|\rho(p) - \rho(q)\|_{\text{HS}} \leq 2\sqrt{d}$, so $\delta \geq \delta^2/D$ gives $\varepsilon_V \geq 2d(1 - \alpha)/(\kappa D) \geq (1 - \alpha)D/2$. $\square$

For $\text{SU}(N)$ with the Hilbert–Schmidt distance this improves the constant $\frac{1}{3}$ of Theorem 69 to $\frac{1}{2}$, and for $\text{SU}(3)$, where $D^2 = 9$ and the Haar mean of δ^2 is 6, to $\frac{2}{3}$: in a cube with the identity outside, $D(n, \alpha)$ leaves the gauge-fixed links at least the fraction $1 - \alpha$ of the disorder of independent Haar-distributed links.

The size $\beta_0(n, \alpha)$ in Corollary 70 comes from a compactness argument. For $\text{SU}(2)$ it can be made explicit, and then reads as a lower bound on the side of any cube that satisfies the condition.

Proposition 73. *Let $G = \text{SU}(2)$ with the chordal metric, so that $D = 2$, let $b = \beta_W \geq \frac{1}{9}$, let $n \geq 2$ be even and put $L(b) = 1 + \log 24 + \frac{3}{2} \log(9b)$. Then*

$$\frac{1}{|V|} \sum_{e \in V} \int \delta(1, Q_e)^2 d\mathcal{W}_V^1 \leq \frac{n^2(n+2)(2n+1)L(b)}{b},$$

so $\varepsilon_V(\beta)^2$ is at most the same quantity. Consequently, if $D(n, \alpha)$ holds at b , then

$$n^4 \geq \frac{2(1 - \alpha)b}{5L(b)}.$$

Proof. Put $m = n/2$. Under $\mathcal{W}_V^1$ every link outside V equals 1: the links of F always, the others by the choice of exterior. A plaquette that does not meet V therefore has plaquette variable 1.

Links as loops. Let $e = (x, \mu) \in V$, $y = x + e_\mu$, $\sigma = \sigma(x)$ and $\tau = \sigma(y)$. The directions σ, τ, μ are distinct: $\sigma \neq \mu$ because e is active; $\tau \neq \mu$ because otherwise the line of F through y would contain x , and the lines of F are disjoint; and $\tau \neq \sigma$ by Table III, in which $\sigma(x + e_\mu) \neq \sigma(x)$ whenever $\mu \neq \sigma(x)$. Since $0 \leq x_\sigma < n$, one of $n - x_\sigma$ and $x_\sigma + 1$ is at most m ; call it s and let $\varepsilon = \pm 1$ be the sign for which $x' = x + s\varepsilon e_\sigma$ has

σ -coordinate outside $[0, n)$. Choose $t \leq m$ and ε' in the same way for y and τ (note $y_\tau = x_\tau$). Let R_1 be the s plaquettes of the rectangle with corners $x, x', x' + e_\mu, y$ in the plane $\{\sigma, \mu\}$, and R_2 the st plaquettes of the rectangle with corners $y, x' + e_\mu, x' + e_\mu + t\varepsilon'e_\tau, y + t\varepsilon'e_\tau$ in the plane $\{\sigma, \tau\}$. The union $R(e) = R_1 \cup R_2$ is a disc, and its boundary runs from x along the line of F through x to x' , then to $x' + e_\mu$, along e_τ to $x' + e_\mu + t\varepsilon'e_\tau$, along e_σ to $y + t\varepsilon'e_\tau$, back along the line of F through y to y , and over e to x . The links of the first and fifth pieces lie in F . The links of the second and third pieces have base points with σ -coordinate $x'_\sigma \notin [0, n)$, and those of the fourth have base points with τ -coordinate outside $[0, n)$; none of them lies in V . So the holonomy of the boundary of $R(e)$ is $Q_e^{\pm 1}$. Adding the plaquettes of a disc one at a time along its boundary shows that this holonomy is a product of conjugates of the plaquette variables $(Q_p^F)^{\pm 1}$, $p \in R(e)$, one for each plaquette. By bi-invariance and the triangle inequality,

$$\delta(1, Q_e) \leq \sum_{p \in R(e)} \delta(1, Q_p^F), \quad |R(e)| = s(t+1) \leq m(m+1).$$

Multiplicity. If a plaquette p lies in $R_2(e)$, its plane is $\{\sigma, \tau\}$, μ is one of the two other directions, and the base point of p is $y + ae_\sigma + ce_\tau$ with $-m \leq a, c \leq m-1$. Given p , there are two ways to name the directions of its plane, two choices of μ and $(2m)^2$ of (a, c) , and they determine y , hence e ; so p lies in at most $16m^2$ of the sets $R_2(e)$. Likewise $p \in R_1(e)$ forces its plane to be $\{\sigma, \mu\}$ and its base point to be $x + ae_\sigma$ with $-m \leq a \leq m-1$, which leaves at most $4m$ links e . Every plaquette therefore lies in at most $16m^2 + 4m = 4n^2 + 2n$ of the discs $R(e)$.

The energy. For the chordal metric $\delta(1, q)^2 = 2 - \text{Re Tr } q$. Let $S = \sum_{p \cap V \neq \emptyset} \delta(1, Q_p^F)^2$; then γ_V^1 has density $e^{-bS/2}/Z$ with $Z = \int e^{-bS/2}$, the integral over $\text{SU}(2)^V$ with Haar measure. The function $t \mapsto \log \int e^{-tS}$ is convex and vanishes at $t = 0$, so its derivative at $t = b/2$, which is $-\int S d\gamma_V^1$, is at least $2 \log Z/b$. A plaquette that meets V contains at most three links of V and the other links are 1, so $\delta(1, Q_p^F)^2 \leq 3 \sum_{e \in p \cap V} \delta(1, Q_e)^2$; every link lies in six plaquettes, so $S \leq 18 \sum_{e \in V} \delta(1, Q_e)^2$ and $Z \geq I^{|V|}$ with $I = \int e^{-9b \delta(1, q)^2/2} dq$. The chordal distance is at most the geodesic one, and the geodesic ball of radius $r = (9b)^{-1/2} \leq 1$ has measure greater than $r^3/24$ (proof of Proposition 77), so $I \geq e^{-1}(9b)^{-3/2}/24$ and

$$\int S d\gamma_V^1 \leq \frac{2|V|L(b)}{b}.$$

Conclusion. The Cauchy–Schwarz inequality inside each disc squares the loop bound:

$$\begin{aligned} \delta(1, Q_e)^2 &\leq |R(e)| \sum_{p \in R(e)} \delta(1, Q_p^F)^2 \\ &\leq m(m+1) \sum_{p \in R(e)} \delta(1, Q_p^F)^2. \end{aligned}$$

Summing over $e \in V$ and using the multiplicity,

$$\sum_{e \in V} \delta(1, Q_e)^2 \leq m(m+1)(4n^2 + 2n)S = \frac{n^2(n+2)(2n+1)}{2}S,$$

and integrating against γ_V^1 gives the first bound; the bound on ε_V follows by the Cauchy–Schwarz inequality. If $D(n, \alpha)$ holds, Proposition 71 gives $2(1 - \alpha) \leq n^2(n+2)(2n+1)L(b)/b$, and $(n+2)(2n+1) \leq 5n^2$ for $n \geq 2$. $\square$

The loops and their multiplicity use nothing of $\text{SU}(2)$ but the bi-invariance of δ , and the energy uses only the form of the action and the measure of small balls. The bound therefore holds for every $\text{SU}(N)$, with the same power of n .

Proposition 74. *Let $G = \text{SU}(N)$, $N \geq 2$, with the weight $\exp(\frac{b}{N} \sum_p \text{Re Tr } Q_p)$, $b = \beta_W \geq N/9$, and the Hilbert–Schmidt distance $\delta(p, q) = \|p - q\|_{\text{HS}}$. Let $n \geq 2$ be even and put*

$$L_N(b) = 1 + \frac{N^2 - 1}{2} \log(81\pi^2 b) + N(N-1) \log \frac{12}{11}.$$

Then

$$\frac{1}{|V|} \sum_{e \in V} \int \delta(1, Q_e)^2 d\gamma_V^1 \leq \frac{Nn^2(n+2)(2n+1)L_N(b)}{b}.$$

Consequently, if $D(n, \alpha)$ holds at b , then

$$n^4 \geq \frac{2(1 - \alpha)b}{5L_N(b)}.$$

Proof. Loops. The discs $R(e)$ of the proof of Proposition 73 and the bound $4n^2 + 2n$ on their multiplicity do not depend on the group, and the loop bound uses only bi-invariance and the triangle inequality. With $S = \sum_{p \cap V \neq \emptyset} \delta(1, Q_p^F)^2$ the same Cauchy–Schwarz step gives $\sum_{e \in V} \delta(1, Q_e)^2 \leq \frac{1}{2}n^2(n+2)(2n+1)S$.

The energy. Since $\delta(1, q)^2 = 2N - 2\text{Re Tr } q$, the measure γ_V^1 has density $e^{-bS/(2N)}/Z$ with respect to Haar measure. As in the proof of Proposition 73, the convexity of $t \mapsto \log \int e^{-tS}$ gives $\int S d\gamma_V^1 \leq 2N \log(1/Z)/b$, and $S \leq 18 \sum_{e \in V} \delta(1, Q_e)^2$ gives $Z \geq I^{|V|}$ with $I = \int e^{-9b \delta(1, q)^2/2N} dq$.

Small balls. Give $\mathfrak{su}(N)$ the inner product $\text{Tr}(X^*Y)$ and $\text{SU}(N)$ the corresponding bi-invariant metric, of volume v_N . In exponential coordinates the Riemannian measure is $j(X) dX$, where dX is Lebesgue measure and

$$j(X) = \left| \det \frac{1 - e^{-\text{ad } X}}{\text{ad } X} \right| = \prod_{k < l} \left(\frac{\sin(\varphi_{kl}/2)}{\varphi_{kl}/2} \right)^2$$

if X has eigenvalues $i\theta_1, \dots, i\theta_N$ and $\varphi_{kl} = \theta_k - \theta_l$ [35, Ch. II, Thm. 1.7]; in particular $j \leq 1$. Every $q \in \text{SU}(N)$ is conjugate to a diagonal matrix with entries $e^{i\psi_k}$, $-\pi \leq \psi_k < \pi$; then $\sum_k \psi_k = 2\pi k_0$ with $|k_0| \leq N/2$, and changing $|k_0|$ of the ψ_k by $\mp 2\pi$ gives angles θ_k with sum zero and $|\theta_k| \leq 3\pi$. So $q = e^X$ with $X \in \mathfrak{su}(N)$ and $\|X\|_{\text{HS}} \leq 3\pi\sqrt{N}$, and $v_N \leq \omega_{N^2-1}(3\pi\sqrt{N})^{N^2-1}$, where ω_k is the volume of the unit ball of $\mathbb{R}^k$. Now let $\|X\|_{\text{HS}} \leq r \leq 1$. The eigenvalues have $|\theta_k| \leq 1 < \pi$, so $\exp$ is injective on this ball; $\delta(1, e^X)^2 = \sum_k |e^{i\theta_k} - 1|^2 \leq \|X\|_{\text{HS}}^2$; and $|\varphi_{kl}|/2 \leq (\theta_k^2 + \theta_l^2)^{1/2}/\sqrt{2} \leq 2^{-1/2}$, so each factor of $j(X)$ is at least $(1 - \frac{1}{2})^2$ because $\sin x/x \geq 1 - x^2/6$.

Dividing by v_N , the Haar measure of $\{q : \delta(1, q) \leq r\}$ is at least

$$\left(\frac{11}{12}\right)^{N(N-1)} \frac{\omega_{N^2-1} r^{N^2-1}}{v_N} \geq \left(\frac{11}{12}\right)^{N(N-1)} \left(\frac{r}{3\pi\sqrt{N}}\right)^{N^2-1}.$$

With $r = (N/9b)^{1/2} \leq 1$ this gives $I \geq e^{-1}$ times the right-hand side, and since $3\pi\sqrt{N}/r = 9\pi\sqrt{b}$, $\log(1/I) \leq L_N(b)$. Hence $\int S d\gamma_V^1 \leq 2N|V|L_N(b)/b$, and the first bound follows from the loops.

Conclusion. Proposition 72 with the defining representation and $\kappa = 1$, for which the Haar mean of $\delta(1, q)^2$ is $2N$, gives $2N(1-\alpha) \leq Nn^2(n+2)(2n+1)L_N(b)/b$ when $D(n, \alpha)$ holds, and $(n+2)(2n+1) \leq 5n^2$. $\square$

For every N , a cube on which the condition holds therefore has side at least of order $(\beta_W / \log \beta_W)^{1/4}$, with a constant that depends on N only through L_N , which grows like $\frac{N^2}{2} \log \beta_W$.

Remark 75. The proof loses the area of a disc, of order n^2 , in passing from plaquettes to links, and on loops that loss is of the right order. On the periodic lattice $(\mathbb{Z}/L\mathbb{Z})^4$ with L even and coordinates $0 \leq x_j < L$, let $\phi = 4\pi/L^2$, $q(\theta) = \cos \theta + i \sin \theta$, and put $U_{(x,2)} = q(\phi x_1)$, $U_{(x,1)} = q(-\phi L x_2)$ when $x_1 = L-1$, and $U = 1$ on every other link. Every plaquette of the plane $\{1, 2\}$ equals $q(\phi)$, including those on the seam $x_1 = L-1$ and at the corner $x_1 = x_2 = L-1$, where the angle is $\phi - 4\pi$; all other plaquettes equal 1. So every plaquette variable lies within ϕ of the identity, while the boundary of the square $[0, L/2]^2$ of the plane $\{1, 2\}$ has holonomy $q(\phi L^2/4) = -1$, at the largest possible distance $D = 2$, against the bound $\phi L^2/4 = \pi$ given by the disc. Every staple sum of this configuration is parallel to its link, so it is a stationary point of the Wilson action, and gradient flow [47] does not change it. Plaquette variables within $O(n^{-2})$ of the identity therefore do not force loops of length n near the identity, and an argument of the kind above that places gauge-fixed links near the identity needs plaquette bounds of order $o(n^{-2})$.

Up to the factor $L(b)^{1/2}$ the rate $b^{-1/2}$ of Proposition 73 is the right one, and the lower bound below holds for every n and every exterior.

Proposition 76. *Let $G = \text{SU}(2)$ with the chordal metric and $b = \beta_W > 0$. For every Gibbs specification of the gauge-fixed theory, every active link e and every configuration of the other links, the conditional law of Q_e satisfies*

$$\int \delta(1, Q_e) d\mu_e \geq \frac{1}{9 \max(6b, 1)^{1/2}}.$$

In particular $\varepsilon_V(\beta) \geq \frac{1}{9} \max(6b, 1)^{-1/2}$ for every n ; at every fixed n , $\varepsilon_V(\beta)$ lies between constant multiples of $b^{-1/2}$ and $(L(b)/b)^{1/2}$.

Proof. Write $\langle \cdot, \cdot \rangle$ for the Euclidean product of quaternions, so that $\text{Re Tr } q = 2\langle q, 1 \rangle$. The six plaquettes that contain e contribute $\exp(b\langle Q_e, W_p \rangle)$ to the conditional density, with $|W_p| = 1$; so μ_e has density $e^{\langle u, v \rangle} / Z(|v|)$ with respect to normalised Haar measure, for some v with $a = |v| \leq 6b$. Put

$a' = \max(a, 1)$ and $\eta = a'^{-1/2} \leq 1$. On the geodesic ball of radius η about $v/|v|$ the exponent is at least $a(1 - \eta^2/2) \geq a - \frac{1}{2}$, and that ball has measure greater than $\eta^3/24$ (proof of Proposition 77); hence $Z(a) \geq e^{a-1/2} \eta^3/24$ and the density is at most $24e^{1/2} a^{3/2}$ (for $a < 1$ directly, since $Z \geq 1$ by Jensen's inequality). A chordal ball of radius r is a geodesic ball of radius θ with $2\sin(\theta/2) = r$, so $\theta \leq \pi r/2$, and its measure is $(\theta - \sin \theta \cos \theta)/\pi \leq 2\theta^3/(3\pi) \leq \pi^2 r^3/12$. With $r = \frac{2}{9} a'^{-1/2}$,

$$\mu_e(\delta(1, Q_e) < r) \leq 24e^{1/2} a^{3/2} \frac{\pi^2 r^3}{12} = 2e^{1/2} \pi^2 \left(\frac{2}{9}\right)^3 < \frac{1}{2},$$

so the mean of $\delta(1, Q_e)$ is at least $r/2 = \frac{1}{9} a'^{-1/2}$. Averaging over $e \in V$ and over the configuration gives the bound on ε_V . $\square$

Along the continuum tuning Theorem 69 says the following. If (D) holds, then in a cube of fixed physical size ℓ with the identity outside, the forest-gauge variables stay on average at distance at least $(1 - \alpha)D/3$ from the identity, and at least $1 - \alpha$ for $\text{SU}(2)$, at every spacing. This is not a contradiction: $n = \ell/a$ grows like $1/a$, while asymptotic freedom makes $\beta(a)$ grow only like $\log(1/a)$, and the corollary concerns fixed n . The size bound of Proposition 73 is likewise met along the tuning, since its right side grows only like $\log(1/a)$. It turns the hypothesis of Remark 63, that the gauge-fixed links decorrelate on the scale of the cube, into a necessary condition: (D) requires the forest-gauge variables to be disordered at a fixed physical scale. For gauge-invariant observables of a massive theory that disorder is clustering; for the gauge-fixed variables it is not proved.

The last statement concerns the following strategy: control the conditional law of one line of links, given everything else, uniformly in the configuration around it, and assemble the cube from lines. Fix a site x , let $s = \sigma(x)$ and $\mu \neq s$, and let $c_k = (x + ke_s, \mu)$, $k \in \mathbb{Z}$. All c_k are active, since σ is constant along the line through x .

Proposition 77. *Let $G = \text{SU}(2)$, identified with the unit quaternions, and $b = \beta_W \geq 1$. There is a configuration of the active links outside $\{c_k\}$, independent of b , for which the conditional law of $(Q_{c_k})_k$ has a ten-step transfer operator, similar to a positive self-adjoint operator K_b on $L^2(S^3)$ with simple top eigenvalue Λ_b , whose gap satisfies*

$$0 < 1 - \frac{\Lambda_{b,1}}{\Lambda_b} \leq e^{20} 24^{10} b^{15} e^{-b/1280},$$

where $\Lambda_{b,1}$ is the next point of the spectrum.

Proof. The interactions. By Lemma 9(iii), c_k lies in two plaquettes of the plane $\{\mu, s\}$, which contain c_{k-1} or c_{k+1} , the link $(x + ke_s, s)$ or $(x + (k-1)e_s, s)$ of F , and an active twist link of direction s ; and in four plaquettes of the planes $\{\mu, t\}$ and $\{\mu, \rho\}$, each containing c_k , one link of F and two active links not on the line. The four plaquettes at c_k lie in the hyperplane of s -coordinate $x_s + k$, so these plaquettes at different k share no link; two plaquettes through c_k share no other link; and their links have directions other than s , so they are not twists.

Set every twist to 1; then the plaquette at $x + ke_s$ in the plane $\{\mu, s\}$ contributes $b\langle q_k, q_{k+1} \rangle$ to the exponent, with $q_k = Q_{c_k}$. In each of the four other plaquettes at c_k set one of its two links to 1 and the other to X ; after a cyclic rotation and possibly an inversion the plaquette variable is $q_k X^{\pm 1}$ or $q_k^{-1} X^{\pm 1}$, and since $\text{Re}(q\bar{u}) = \text{Re}(\bar{q}u) = \langle q, u \rangle$ for unit quaternions, X can be chosen so that the plaquette contributes $b\langle q_k, u \rangle$ for any prescribed unit vector u . Every other active link is set to 1. Four unit vectors add up to any vector of length at most 4 (two copies each of $t \pm (1 - |t|^2)^{1/2}v$ with $t = v/4$ and $v \perp t$ a unit vector), so the conditional density of the line is proportional to $\exp(b \sum_k \langle q_k, q_{k+1} \rangle + \sum_k \langle h_k, q_k \rangle)$ for any fields h_k with $|h_k| \leq 4b$.

The fields. Let $a = \frac{1}{2}$, $c = \frac{\sqrt{3}}{2}$, let $e_1, \dots, e_4$ be the standard basis of $\mathbb{R}^4$, and let r_k have period ten with $(r_0, \dots, r_9) = a(e_1, -e_1, e_2, -e_2, e_3, -e_3, e_3, -e_2, e_2, -e_1)$. Put $h_k = b(2r_k - r_{k-1} - r_{k+1})$, so $|h_k| \leq 4ab = 2b$, and the configuration is independent of b because h_k/b is. With $v_k = q_k - r_k$ and $|q_k| = 1$, $|r_k| = a$, summation by parts gives, over $0 \leq k \leq 9$,

$$\begin{aligned} \frac{1}{2} \sum_k |v_{k+1} - v_k|^2 &= \sum_k (1 - \langle q_k, q_{k+1} \rangle) - \frac{1}{b} \sum_k \langle h_k, q_k \rangle \\ &\quad + \frac{1}{2} \sum_k |r_{k+1} - r_k|^2 + B(q_0) - B(q_{10}), \end{aligned}$$

with $B(q) = \langle q, r_0 - r_9 \rangle$. The boundary terms only conjugate the ten-step transfer kernel by a multiplication operator, so up to similarity it is

$$K_b(x, y) = \int_{(S^3)^9} \exp\left(-\frac{b}{2} \sum_{k=0}^9 |v_{k+1} - v_k|^2\right) dq_1 \cdots dq_9,$$

with $q_0 = x$, $q_{10} = y$ and normalised Haar measure. The sequence $r_0, \dots, r_{10}$ is a palindrome, so $K_b = B_b B_b^*$ for the five-step kernel B_b ; K_b is compact, positive and self-adjoint with a continuous positive kernel, its top eigenvalue Λ_b is simple, and its eigenfunction $\psi_b > 0$ is even under the reflection $x_4 \mapsto -x_4$, which commutes with K_b .

A barrier. Let $E = \frac{1}{2} \sum_{k=0}^9 |v_{k+1} - v_k|^2$ and suppose that $(q_0)_4 \geq 0 \geq (q_{10})_4$ and $E \leq \frac{1}{1280}$. Put $\Delta = (20E)^{1/2} \leq \frac{1}{8}$ and $w = v_0$; by Cauchy–Schwarz $|w - v_k| \leq \Delta$ for all k , and $0 \leq w_4 \leq \Delta$ because the r_k have no fourth coordinate. From $|v_k + r_k| = 1$, $||w + r_k|^2 - 1| \leq \Delta(2 + \Delta) =: \eta$ for $0 \leq k \leq 5$. The pairs $r_k = \pm ae_l$ give $|w_l| \leq \eta/(2a) = \eta$ for $l = 1, 2, 3$ and $|w|^2 \geq \frac{3}{4} - \eta$, so $\frac{3}{4} \leq 3\eta^2 + \Delta^2 + \eta \leq 3(\frac{17}{64})^2 + \frac{1}{64} + \frac{17}{64} = \frac{2019}{4096}$, a contradiction. Hence $K_b(x, y) \leq e^{-b/1280}$ whenever $x_4 \geq 0 \geq y_4$.

The top eigenvalue. Let $\varepsilon = b^{-1/2}$. The geodesic ball of radius $\varepsilon \leq 1$ in S^3 has normalised measure $\frac{2}{\pi} \int_0^\varepsilon \sin^2 \theta d\theta \geq \frac{8\varepsilon^3}{3\pi^3} > \frac{\varepsilon^3}{24}$. If each q_k lies in the ball of radius ε about $r_k + ce_4$, then $|v_k - ce_4| \leq \varepsilon$ and $E \leq 20\varepsilon^2$, so the integrand is at least e^{-20} . Testing K_b on the normalised indicator of the ball about $r_0 + ce_4$ gives $\Lambda_b \geq e^{-20}(\varepsilon^3/24)^{10} = e^{-20}24^{-10}b^{-15}$.

The gap. Let $\phi(x) = \text{sign}(x_4)\psi_b(x)$, a unit vector orthogonal

to ψ_b . Then

$$\begin{aligned} \Lambda_b - \langle \phi, K_b \phi \rangle &= 4 \int_{x_4 > 0 > y_4} \psi_b(x) K_b(x, y) \psi_b(y) dx dy \\ &\leq e^{-b/1280}, \end{aligned}$$

because $\int_{x_4 > 0} \psi_b \leq \frac{1}{2}$ by Cauchy–Schwarz. By the variational principle $\Lambda_{b,1} \geq \langle \phi, K_b \phi \rangle$, and dividing by the lower bound on Λ_b proves the estimate; the gap is positive because Λ_b is simple. $\square$

The exterior of Proposition 77 is legal at every coupling, so a bound on the conditional law of single lines that is uniform in the exterior cannot be better than $e^{-b/1280}$ up to powers of b , and an argument of this kind cannot give (D) along the tuning. A proof of (D) has to use what such a bound discards: the joint resampling of the transverse links inside the cube, which the averaged coefficients $C_{V,j}$ retain, or the smallness of the probability of such exteriors under the Wilson measure.

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DATA AND CODE AVAILABILITY

The analytic proofs are complete as written, except the evaluations in Propositions 34 and 35 and Lemma 38 and the numerical bounds of Lemma 16, which are computations with rigorous error bounds, and the finite check of Lemma 12. The repository `creelie/4Y-M` contains the $\text{\LaTeX}$ source of this paper; the programs of that computation, in Python with `python-flint` (FLINT and Arb) and a C kernel for products of Taylor polynomials, with their outputs and the list of certified boxes; the programs and outputs of the earlier certificate at $\beta_W = \frac{45}{64}$; independent checks in exact rational arithmetic of Lemmas 20 and 28 and of (10); numerical checks of Lemma 19 on tori; the searches of Remark 26 and Sec. IX; and a Lean 4 certificate of the line field (Lemmas 8 and 9 for the table of Appendix A, by `decide`); and the programs of Appendix C for the plaquette blocks, with the floating-point search of Remark 18; and

an exact computation of the curvatures of Table I from the root systems; and exact checks of the finite counts, of the discs and of the Gaussian benchmark of Sec. XH, with Monte Carlo estimates of the influence coefficients and of ε_V that the proofs do not use. This paper accompanies release v3.18.0 of the archive, <https://github.com/creelie/4y-m/releases/tag/v3.18.0>. The PDF of this paper is at <https://github.com/creelie/4Y-M/blob/main/preprintYangMillsForestGauge/YangMillsForestGauge.pdf>. The computations and the Lean, Python and shell checks were run with AI assistance (Claude Opus 5.5, Claude Fable 5.1 with Ultracode, GPT-6.1 Sol Ultra and GPT-6 Astra Ultra) under the direction of Deep Bhattacharjee. The first composite behind Theorem 1 was assembled by the Anaxia engine of the BLLM system [11], release v3.0.5, as described in the footnote to that theorem; release v3.1.0 [12] records the engine's Yang–Mills runs in its failure log, whose last Yang–Mills entry is the change from single links to blocks of several links; the plaquette blocks of Sec. V, the bound of Lemma 15, their SU(3) version in Sec. VIII and the certified constants were found and checked by the authors. All three authors approved the final text.

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Appendix A: The line field

Table III lists, for each residue class of x modulo two, the direction $\sigma(x)$ and the permutation $\pi_x(\mu) = \sigma(x + e_\mu)$. In every row π_x fixes $\sigma(x)$ and is a three-cycle on the other directions, which is the condition of Lemma 8.

Appendix B: The comparison lemma

Let (G, δ) be a compact group with a bi-invariant metric of diameter D , $\Omega = G^A$, and $C_{ee'}$ the coefficients of Sec. III, with row and column sums at most $\alpha < 1$ and $C_{ee'} = 0$ unless e, e' share a plaquette, so that $|e - e'| \leq 1$ for the distance of link midpoints. Fix $\lambda > 0$ with $\theta = \alpha e^\lambda < 1$.

Lemma 78. *Let $S \subset A$, possibly infinite, and let μ_1, μ_2 be probability measures on Ω invariant under γ_e^F for every $e \notin S$. Let $T \subset A \setminus S$ be finite, $w_b = e^{-\lambda \text{dist}(b, T)}$, and suppose $\sum_{z \in S} w_z < \infty$. There is a coupling of μ_1, μ_2 whose link distances $\rho(b) = \mathbb{E} \delta(\sigma_b, \sigma'_b)$ satisfy*

$$\sum_{b \notin S} w_b \rho(b) \leq \frac{\theta D}{1 - \theta} \sum_{z \in S} w_z.$$

If $S = \emptyset$ then $\mu_1 = \mu_2$.

TABLE III. The line field: x modulo two (digits $x_0 x_1 x_2 x_3$), the direction $\sigma(x)$ and the values $\sigma(x + e_\mu)$ for $\mu = 0, 1, 2, 3$.

x	$\sigma(x)$	$\mu = 0$	$\mu = 1$	$\mu = 2$	$\mu = 3$
0000	0	0	2	3	1
1000	0	0	3	1	2
0100	2	3	0	2	1
1100	3	2	0	1	3
0010	3	1	2	0	3
1010	1	3	1	0	2
0110	2	1	3	2	0
1110	1	2	1	3	0
0001	1	2	1	3	0
1001	2	1	3	2	0
0101	1	3	1	0	2
1101	3	1	2	0	3
0011	3	2	0	1	3
1011	2	3	0	2	1
0111	0	0	3	1	2
1111	0	0	2	3	1

Proof. The couplings form a weakly compact set and $\Psi(\pi) = \sum_b w_b \mathbb{E} \pi \delta(\sigma_b, \sigma'_b)$ is weakly continuous because $\sum_b w_b < \infty$; let π^* be a minimiser. For $e \notin S$ replace the pair (σ_e, σ'_e) by a sample of an optimal coupling of $\gamma_e^F(\cdot | \sigma)$ and $\gamma_e^F(\cdot | \sigma')$, chosen measurably [67, Cor. 5.22]. Both μ_i are invariant, so the result is again a coupling, and changing the finitely many links that enter γ_e^F one at a time gives $W_1 \leq \sum_{e'} C_{ee'} \delta(\sigma'_e, \sigma'_e)$. Minimality gives $\rho(e) \leq \sum_{e'} C_{ee'} \rho(e')$. Multiply by w_e and sum over $e \notin S$; where $C_{ee'} \neq 0$, $w_e \leq e^\lambda w_{e'}$, so

$$\sum_{e \notin S} w_e \rho(e) \leq \theta \left[\sum_{e' \notin S} w_{e'} \rho(e') + \sum_{z \in S} w_z \rho(z) \right],$$

all sums are finite, and $\rho \leq D$ on S . If $S = \emptyset$, $\rho \equiv 0$. $\square$

Corollary 79. *Let μ be the Gibbs measure of γ^F , F a local function with support S_F , L_F -Lipschitz in each link, and H bounded with finite support S_H disjoint from S_F . Then*

$$|\text{Cov}_\mu(F, H)| \leq \|H\|_\infty L_F \frac{\theta D}{1 - \theta} |S_H| e^{-\lambda \text{dist}(S_F, S_H)}.$$

Proof. Condition on the links of S_H [43, Ch. 3]; the conditional measures $\mu^\sigma = \mu(\cdot | \sigma_{S_H})$ are invariant under γ_e^F for $e \notin S_H$. Lemma 78 with $S = S_H$ and $T = S_F$, for which $w_b = 1$ on S_F and $w_z \leq e^{-\lambda \text{dist}(S_F, S_H)}$ on S_H , gives $|\mu^\sigma(F) - \mu^{\sigma'}(F)| \leq L_F \sum_{b \in S_F} \rho(b) \leq L_F \frac{\theta D}{1 - \theta} |S_H| e^{-\lambda \text{dist}(S_F, S_H)}$ for any two boundary values. Since H depends only on σ_{S_H} , $\text{Cov}_\mu(F, H) = \iint H(\sigma) (\mu^\sigma(F) - \mu^{\sigma'}(F)) d\mu(\sigma) d\mu(\sigma')$, and the bound follows. $\square$

Lemma 80. *Let the blocks partition A , let C_{Bj} be the block coefficients of Sec. V, with $\sum_B C_{Bj} \leq \alpha < 1$ for every j and $C_{Bj} = 0$ unless every link of B lies within distance 2 of j , and fix*

$\lambda > 0$ with $\theta = \alpha e^{2\lambda} < 1$. Let $S \subset A$ be a union of blocks and let μ_1, μ_2 be invariant under γ_B^β for every block $B \not\subset S$. With T, w_b as in Lemma 78 and $\sum_{z \in S} w_z < \infty$, there is a coupling with $\sum_{b \notin S} w_b \rho(b) \leq \frac{\theta D}{1-\theta} \sum_{z \in S} w_z$, and $\mu_1 = \mu_2$ if $S = \emptyset$.

Proof. Take a minimiser π^* of Ψ as before. For a block $B \not\subset S$ replace (σ_B, σ'_B) by an optimal coupling, for the metric d , of the two block laws; it is again a coupling, and changing the boundary links one at a time bounds the expected new d -distance by $\sum_j C_{Bj} \rho(j)$. Put $\bar{w}_B = \max_{i \in B} w_i$. Minimality gives

$$\sum_{i \in B} w_i \rho(i) \leq \bar{w}_B \sum_j C_{Bj} \rho(j),$$

and $\bar{w}_B \leq e^{2\lambda} w_j$ whenever $C_{Bj} \neq 0$. Summing over the blocks outside S and using the column sums,

$$\sum_{b \notin S} w_b \rho(b) \leq \theta \left[\sum_{j \notin S} w_j \rho(j) + \sum_{z \in S} w_z \rho(z) \right],$$

which gives the claim as in Lemma 78. $\square$

Lemma 81. Let $n \geq 2$ be even, let $V_x, x \in 2\mathbb{Z}^4$, be the translates of Sec. X, and suppose that $D(n, \alpha)$ holds.

- (a) If a probability measure μ on G^A is invariant under γ_e^F for every e in a finite set V , it is invariant under γ_V .
- (b) Fix $\lambda > 0$ with $\theta = \alpha e^{\lambda \rho_n} < 1$. Let $S \subset A$, and let μ_1, μ_2 be invariant under γ_x for every x with $V_x \cap S = \emptyset$. With T, w_b as in Lemma 78 and $\sum_{z \in S} w_z < \infty$, there is a coupling with

$$\sum_{b \notin S} w_b \rho(b) \leq \frac{D(1 + c_n e^{\lambda \rho_n})}{1 - \theta} \sum_{z \in S} w_z,$$

and $\mu_1 = \mu_2$ if $S = \emptyset$.

Proof. (a) Let ν_η be the conditional law of Q_V given the links η outside V . For bounded f on G^V and bounded g of η , $\gamma_e^F(fg) = g \gamma_e^F f$ for $e \in V$, so invariance gives $\int g(\eta) (\nu_\eta(\gamma_e^F f) - \nu_\eta(f)) d\mu = 0$ for all g ; taking f in a countable dense set of continuous functions, ν_η is invariant under every $\gamma_e^F(\cdot | \cdot, \eta)$, $e \in V$, for μ -almost every η . So is $\gamma_V(\cdot | \eta)$, whose conditional laws of single links are the γ_e^F . The composition P_η of the kernels γ_e^F , $e \in V$, in a fixed order has a density with respect to Haar measure on G^V bounded below by a positive constant, because each single-link density is at least $e^{-12N^2\beta}$ times its maximum over the group. A Markov kernel with such a lower bound has at most one invariant probability measure (Doebelin's condition), so $\nu_\eta = \gamma_V(\cdot | \eta)$.

(b) Let π^* minimise Ψ as in Lemma 78 and call x admissible if $V_x \cap S = \emptyset$. For admissible x replace $(\sigma_{V_x}, \sigma'_{V_x})$ by an optimal coupling, for d_{V_x} , of the two block laws; both μ_i are invariant, so the result is a coupling, and changing the boundary links one at a time bounds the new expected d_{V_x} -distance by $\sum_j C_{V_x, j} \rho(j)$. With $\bar{w}_x = \max_{i \in V_x} w_i$, minimality gives

$$\sum_{i \in V_x} w_i \rho(i) \leq \bar{w}_x \sum_{j \notin V_x} C_{V_x, j} \rho(j),$$

and $\bar{w}_x \leq e^{\lambda \rho_n} w_j$ whenever $C_{V_x, j} \neq 0$. Let S' be the set of links outside S that lie in a translate meeting S ; each is within distance ρ_n of a link of S , so $\sum_{i \in S'} w_i \leq c_n e^{\lambda \rho_n} \sum_{z \in S} w_z$. A link outside $S \cup S'$ lies in N_n translates, all admissible. Summing over admissible x and using $\sum_{x: j \notin V_x} C_{V_x, j} = K_c(j) \leq \alpha N_n$,

$$N_n \sum_{i \notin S \cup S'} w_i \rho(i) \leq \theta N_n \left[\sum_{i \notin S \cup S'} w_i \rho(i) + \sum_{i \in S \cup S'} w_i \rho(i) \right].$$

All sums are finite and $\rho \leq D$, so $\sum_{i \notin S \cup S'} w_i \rho(i) \leq \frac{\theta D}{1-\theta} (1 + c_n e^{\lambda \rho_n}) \sum_{z \in S} w_z$; adding $\sum_{i \in S'} w_i \rho(i) \leq D c_n e^{\lambda \rho_n} \sum_{z \in S} w_z$ gives the bound. If $S = \emptyset$ then $S' = \emptyset$ and $\rho \equiv 0$. $\square$

The covariance bound of Corollary 79 follows from part (b) in the same way, with $\theta D/(1-\theta)$ replaced by $D(1 + c_n e^{\lambda \rho_n})/(1-\theta)$, since the conditional measures μ^σ there are invariant under γ_x for $V_x \cap S_H = \emptyset$ by part (a).

Appendix C: The plaquette blocks

Table IV lists the block plaquettes of Sec. V modulo $2\mathbb{Z}^4$: the plaquette at x in the plane $\{\mu, \nu\}$ is a block plaquette exactly when x modulo two and $\{\mu, \nu\}$ appear in the table. Eight lie in the plane $\{0, 1\}$ and eight in $\{2, 3\}$; together they contain the 48 active links of a cell of side two, each once.

TABLE IV. The sixteen block plaquettes modulo two: the base point x (digits $x_0 x_1 x_2 x_3$ modulo two) and the plane.

x	plane	x	plane
0000	$\{0, 1\}$	0000	$\{2, 3\}$
0001	$\{0, 1\}$	0011	$\{2, 3\}$
0010	$\{0, 1\}$	0100	$\{2, 3\}$
0011	$\{0, 1\}$	0111	$\{2, 3\}$
1100	$\{0, 1\}$	1000	$\{2, 3\}$
1101	$\{0, 1\}$	1011	$\{2, 3\}$
1110	$\{0, 1\}$	1100	$\{2, 3\}$
1111	$\{0, 1\}$	1111	$\{2, 3\}$

The program `cover.py` in the folder `strong-coupling/g/gauge-fixed/blocks/` of the archive finds this set by an exact-cover search on the torus of side two and checks Lemma 12 on the tori of side four and six. The program `constants.py` evaluates the bounds of Lemma 16 in ball arithmetic with `python-flint` at 120 bits: the series of Z_0 and of its first three derivatives in $s = r^2$ is summed to forty terms, and the tail is bounded for $s \leq 5$ by twice the first omitted term $(5/4)^{40} 40^3 / (40! 41!)$, because consecutive terms decrease by a factor below one half. The program `alpha.py` evaluates the constants of (3) and α at a given β_W , read exactly.

For $SU(3)$ the folder `strong-coupling/gauge-fixed/blocks/su3/` contains `consts.py`, which evaluates the bounds of Lemma 38 on the 841 boxes of side $\frac{3}{16}$ at $r = \frac{3}{2}$ and the 784 boxes of side $\frac{19}{100}$ at $r = \frac{38}{25}$ with the moments of Appendix E, and `alpha3.py`, which reads these bounds and

the cover of Proposition 34 or Proposition 35 and evaluates the constants of (15) and α_3 in ball arithmetic at 120 bits; its outputs at $\beta_W = \frac{3}{4}$ and 0.76 are listed with the bounds of each box. The cover of Proposition 35 is computed by the program of Appendix E with `--r 38/25 --thr 1.03`.

Appendix D: The blocks of Lemma 20

Diagonal blocks. Let $w_a = e^{i\phi}$. On the diagonal part, $f_p = -\cos \phi (y_1 + y_2 - y_3 - y_4)^2$ and $c_p = 2(y_1 y_4 - y_1 y_2 + y_2 y_3 - y_3 y_4)$, so

$$\mathcal{F} = \sum_i \alpha_i y_i^2 + \cos \phi (y_1 + y_2 - y_3 - y_4)^2 - \frac{2}{3}(y_1 y_4 - y_1 y_2 + y_2 y_3 - y_3 y_4)$$

with $y_k = 0$ and weights $\alpha_{k+1} = \frac{21}{10}$, $\alpha_{k+2} = \frac{5}{4}$. It is affine in $\cos \phi$, so positivity at $\cos \phi = \pm 1$ suffices. For $k = 1$ and $\cos \phi = 1$ the matrix in (y_2, y_3, y_4) is

$$\begin{pmatrix} \frac{31}{10} & -\frac{19}{10} & -1 \\ -\frac{19}{10} & \frac{9}{4} & \frac{19}{10} \\ -1 & \frac{19}{10} & \frac{31}{10} \end{pmatrix},$$

and Table V lists the leading principal minors for every position; all are positive.

TABLE V. Leading principal minors of the diagonal blocks of Lemma 20.

Fixed link	$\cos \phi = 1$	$\cos \phi = -1$
e_1, e_4	$\frac{31}{10}, \frac{673}{200}, \frac{8421}{2000}$	$\frac{11}{10}, \frac{53}{200}, \frac{21}{2000}$
e_2	$\frac{31}{10}, \frac{861}{100}, \frac{8421}{2000}$	$\frac{11}{10}, \frac{21}{100}, \frac{21}{2000}$
e_3	$\frac{9}{4}, \frac{673}{200}, \frac{8421}{2000}$	$\frac{1}{4}, \frac{53}{200}, \frac{21}{2000}$

Pair blocks. Let $w_a = e^{i(\chi + \vartheta)}$ and $w_b = e^{i(\chi - \vartheta)}$. The terms of f_p carry $w_a + \bar{w}_b = 2\cos \chi e^{i\vartheta}$ or its conjugate, and c_p carries $w_a \bar{w}_b = e^{2i\vartheta}$, so the Hermitian matrix $M(m, \vartheta)$ of $\mathcal{F}$, $m = \cos \chi$, is affine in m with $M(-1, \vartheta) = M(1, \vartheta + \pi)$, and $m = 1$ suffices. For the fixed link e_2 , in the variables (z_1, z_3, z_4) and with $c = \cos \vartheta$,

$$M = \begin{pmatrix} \frac{21}{5} + 2c & -2e^{i\vartheta} & -\frac{9}{5} - 2e^{i\vartheta} \\ -2e^{-i\vartheta} & \frac{21}{5} + 2c & \frac{9}{5} + 2e^{-i\vartheta} \\ -\frac{9}{5} - 2e^{-i\vartheta} & \frac{9}{5} + 2e^{i\vartheta} & \frac{5}{2} + 2c \end{pmatrix}.$$

With $u = \cos^2(\vartheta/2) \in [0, 1]$ its leading principal minors are

$$\frac{20u+11}{5}, \quad \frac{(20u+1)(20u+21)}{25}, \quad \frac{400u(40u^2-23u+4)+21}{250},$$

and $40u^2 - 23u + 4$ has negative discriminant $529 - 640$. The other positions give the same determinant and the leading minors $\frac{20u+11}{5}$ or $\frac{8u+1}{2}$ and $\frac{800u^2-180u+53}{50}$, whose discriminant $32400 - 169600$ is negative. Every block is positive definite.

The inequality is not tight. In floating point the least eigenvalue of the whole form over $W \in U(N)$, $N \leq 4$, is 0.0149, which is also the least eigenvalue of the exact blocks; this slack is what the choice of the weights $\frac{21}{10}, \frac{5}{4}, \frac{9}{10}$ trades against the constant $\frac{29}{2}$.

Appendix E: The certified computation

Truncation. For a corner b of a box the moments of Lemma 32 are derivatives of Z at $(b, \bar{b})$. The truncated series is $\mathbb{E}_H[A_t(UD)B_t(\bar{U}D')]$ with A_t the part of $\sum_\lambda c_\lambda s_\lambda(UD)$ over partitions with $\lambda_1 - \lambda_3 \leq 34$ and $\lambda_3 \leq 11$, and B_t likewise. Every omitted partition has $|\lambda| > 34$, because $3 \cdot 12 > 34$, and the omitted part is at most $T(\|D\|) = \sum_{n>34} (\frac{3}{2}\|D\|)^n/n!$ in modulus. On the polydisc $|D_{ij} - b_{ij}| \leq \rho$, $\|D\| \leq \|b\| + 3\rho$, and Cauchy's estimate bounds the α -th derivative of the omitted part by $\alpha! \rho^{-|\alpha|} T(\|b\| + 3\rho)$. The derivatives of the full exponential are at most $2^{-|\alpha|} e^{v/2}$ with $v = \sum_k |b_k|$, since $|\text{Tr}(Ub)| \leq \sum_k |b_k|$ for diagonal b . With $\varepsilon_\alpha = 2^{|\alpha|} \alpha! \rho^{-|\alpha|} T(\|b\| + 3\rho)$ the truncated moment differs from the true one by at most $\varepsilon_\alpha e^{v/2} + (e^{v/2} + \varepsilon_\alpha) \varepsilon_\beta$, and ρ is chosen to minimise $\rho^{-6} T$. The largest error bound of an unnormalised moment at any corner is 1.7×10^{-11} .

Weight zero. Conjugation by the diagonal torus T preserves Haar measure and $\text{ReTr}(Ub)$ for diagonal b , and multiplies u_{ij} by $t_i t_j^{-1}$; a moment of a monomial on which T acts by a nontrivial character is therefore 0, and only 8278 of the 134596 monomials of degree at most six have the trivial character. The functions $\text{Tr}(X)$, $e_2(X)$, $\det X$ of $X = DD'^T$ and $\det D$, $\det D'$ are invariant under the same action on the variables, so after these are formed in the full ring of Taylor polynomials of degree six in the 18 variables, the series is computed in the subring of weight-zero monomials.

Rounding. The truncated series is a Taylor polynomial of total degree six in the 36 real directions of $(D - b, D' - \bar{b})$, computed in double precision. Every operation is repeated on absolute values and carries an operation count n , so that the computed coefficient differs from the exact one by at most $\gamma_n = nu/(1 - nu)$, $u = 2^{-53}$, times the absolute-value coefficient [36, Sec. 3.1]. With C in $2^{-30}\mathbb{Z}$, the polynomials $2^{31}q_h$, $X_a(2^{31}q_h)$, $12 \cdot 2^{31}(\varphi_h + \Delta q_h)$ and $12 \cdot 2^{31}\langle \nabla \varphi_{F_k}, \nabla q_h \rangle$ for the coordinate vectors h have coefficients in $\mathbb{Z}[i]$, and every partial sum in their computation is bounded, through the same operations on absolute values, by less than 2^{50} ; they are therefore computed exactly. Normalisation by Z , the products with the corner coordinates, the quadratic forms and their error matrices are formed with the same bookkeeping, and the largest eigenvalues are bounded in ball arithmetic [41].

Separation. The functional c of a discarded box is the dual solution of a linear program for the gauge of the centre of the box with respect to a 72×72 grid of T . Only the final inequality is used: $\max_T \ell$ is bounded by its maximum over a 512×512 grid plus $\frac{1}{2}H\delta^2/2$, with $\delta = 2\pi/512$ and $H = |c_1| + |c_2| + 2|c_3|$ a bound for its Hessian on the torus, and the inequality is checked with relative margin 10^{-12} .

Running time. The moments at one corner take about one and a half seconds and the bound on one box about two and

a half seconds on one core. The cover runs in about an hour on four cores and writes every certified box with its θ and its bound.

Appendix F: The transfer matrix

This appendix recalls the Osterwalder–Schrader reconstruction for the lattice [54–56] in the form used for the gaps, following our earlier paper [13].

Let ω be a state on the gauge-invariant local functions of $\mathbb{Z}^4$ that is invariant under translations and the hypercubic group and reflection positive for reflections in planes through sites and in planes bisecting links; by Proposition 11(iii)–(iv) and its analogues in the other theorems, the states of this paper are of this kind. The reconstruction gives a Hilbert space with a vector Ω , a map $F \mapsto \Psi_F$ with dense range, and a self-adjoint $\mathbb{T}$ with $0 \leq \mathbb{T} \leq 1$, $\mathbb{T}\Omega = \Omega$ and $\langle \Psi_F, \mathbb{T}'\Psi_H \rangle = \omega(\vartheta(\bar{F})\tau_t H)$, where ϑ is the time reflection and τ_t the time translation.¹⁹

Proposition 82. *For $m > 0$ the following are equivalent:*

- (a) *the spectrum of $\mathbb{T}$ on $\Omega^\perp$ lies in $[0, e^{-m}]$;*
- (b) *for every F in a class of gauge-invariant local functions supported at times in a bounded interval and dense in $L^2(\omega)$ on each such support, there is $C_F < \infty$ with $0 \leq \omega(\vartheta(\bar{F})\tau_t F) - |\omega(F)|^2 \leq C_F e^{-mt}$ for all $t \geq 0$.*

Under (a) one may take $C_F = \|\mathbb{T}\|_\infty^2$ for every bounded F .

Proof. If (a) holds, then

$$\omega(\vartheta(\bar{F})\tau_t F) - |\omega(F)|^2 = \langle \Psi'_F, \mathbb{T}'\Psi'_F \rangle$$

with $\Psi'_F = \Psi_F - \langle \Omega, \Psi_F \rangle \Omega \in \Omega^\perp$; this number lies in $[0, e^{-mt} \|\Psi_F\|^2]$, and $\|\Psi_F\|^2 \leq \|F\|_\infty^2$. Conversely, let σ be the spectral measure of $\mathbb{T}$ at Ψ'_F and let $\delta > 0$. Then

$$\sigma((e^{-m+\delta}, 1])e^{(-m+\delta)t} \leq C_F e^{-mt}$$

for all t , so $\sigma((e^{-m+\delta}, 1]) = 0$. The spectral projection of $(e^{-m}, 1]$ restricted to $\Omega^\perp$ therefore annihilates the vectors Ψ'_F of the class, which are dense by the footnote above, and it vanishes. $\square$

Appendix G: Spectral measures and Laplace transforms

This appendix collects the facts on spectral measures that the continuum step uses, with proofs.

¹⁹ Ψ_F is the class of F in the completion of the positive-time local functions for the form $\langle F, H \rangle = \omega(\vartheta(\bar{F})H)$, which is positive semidefinite by reflection positivity. Since $|\omega(\vartheta(\bar{F})F)| \leq \omega(|F|^2)$ by the Cauchy–Schwarz inequality and the invariance of ω under ϑ , functions that are close in $L^2(\omega)$ give close vectors.

Lemma 83. *Let T be a self-adjoint operator on a Hilbert space with $0 \leq T \leq 1$ and let ψ be a unit vector. There is a unique probability measure ν on $[0, 1]$ with $\langle \psi, h(T)\psi \rangle = \int h d\nu$ for every bounded Borel function h on $[0, 1]$. If $T\psi' = \psi'$ implies $\langle \psi', \psi \rangle = 0$, then $\nu(\{1\}) = 0$. If μ is the image of ν under $\lambda \mapsto -c^{-1} \log \lambda \in [0, \infty]$ for some $c > 0$, then $\langle \psi, T^{\sigma/c} \psi \rangle = \int_{[0, \infty]} e^{-\sigma E} d\mu(E)$ for $\sigma > 0$, with the integrand 0 at $E = \infty$.*

Proof. The spectral theorem [57, Sec. VII.2] gives the measure ν , carried by the spectrum of T , which lies in $[0, 1]$; uniqueness holds because the moments $\int \lambda^n d\nu = \langle \psi, T^n \psi \rangle$ determine a measure on a compact interval, polynomials being dense in $C[0, 1]$. The spectral projection $P = \mathbf{1}_{\{1\}}(T)$ projects onto the eigenvectors of T with eigenvalue 1, so $\nu(\{1\}) = \|P\psi\|^2 = \langle P\psi, \psi \rangle = 0$ under the hypothesis. The last identity is the change of variables $\lambda^{\sigma/c} = e^{-\sigma E}$ for $\lambda = e^{-cE}$, with $\lambda = 0$ corresponding to $E = \infty$. $\square$

Lemma 84. *Every sequence of probability measures on a compact metric space K has a subsequence that converges weakly, that is, against every continuous function, to a probability measure on K .*

Proof. $C(K)$ is separable; let (h_j) be dense. The numbers $\int h_j d\mu_k$ are bounded by $\|h_j\|_\infty$, so a diagonal subsequence makes all of them converge. By density the limit $\Lambda(h) = \lim \int h d\mu_k$ exists for every $h \in C(K)$; Λ is linear, positive and $\Lambda(1) = 1$, so by the Riesz representation theorem it is integration against a probability measure. $\square$

Lemma 85. *Let μ be a probability measure on $[0, \infty]$ and $\rho(\sigma) = \int e^{-\sigma E} d\mu(E)$ for $\sigma > 0$.*

- (a) *ρ is nonincreasing and log-convex: $\rho(\sigma)^2 \leq \rho(\sigma - s)\rho(\sigma + s)$ for $0 < s < \sigma$.*
- (b) *$\rho(\sigma) > 0$ for one $\sigma > 0$ if and only if $\mu([0, \infty)) > 0$, and then $\rho(\sigma) > 0$ for every $\sigma > 0$.*
- (c) *$\rho(\sigma) \rightarrow \mu([0, \infty))$ as $\sigma \downarrow 0$.*
- (d) *If μ is carried by $[m, \infty]$, then $\rho(\sigma) \leq e^{-m\sigma}$.*
- (e) *For $M > 0$, $\mu([0, M]) \geq \rho(\sigma) - e^{-\sigma M}$.*
- (f) *If $\mu_k \rightarrow \mu$ weakly on $[0, \infty]$, then $\int e^{-\sigma E} d\mu_k \rightarrow \rho(\sigma)$ for every $\sigma > 0$.*

Proof. (a) The integrand decreases in σ . By the Cauchy–Schwarz inequality,

$$\left(\int e^{-\sigma E} d\mu \right)^2 \leq \int e^{-(\sigma-s)E} d\mu \int e^{-(\sigma+s)E} d\mu.$$

(b) The integrand is positive exactly on $[0, \infty)$. (c) The integrand increases to $\mathbf{1}_{[0, \infty)}$ as $\sigma \downarrow 0$, and monotone convergence applies. (d) The integrand is at most $e^{-m\sigma}$ on $[m, \infty]$. (e) Split the integral at M : it is at most $\mu([0, M]) + e^{-\sigma M}$. (f) For $\sigma > 0$ the function $E \mapsto e^{-\sigma E}$, extended by 0 at ∞ , is continuous on $[0, \infty]$. $\square$

By (b) and (e), a lower bound $\rho(\sigma) \geq c > 0$ at one σ places mass at least $c/2$ on the bounded interval $[0, \sigma^{-1} \log(2/c)]$; for the measures μ_k of Theorem 47 a bound uniform in k therefore makes them tight on $[0, \infty)$ with a fixed fraction of their mass.

Appendix H: The character expansion

Let G be a compact connected Lie group with normalised Haar measure dU . For an irreducible unitary representation ρ_λ of dimension d_λ write $\chi_\lambda = \text{Tr} \rho_\lambda$. The characters form an orthonormal basis of the square-integrable class functions (Peter–Weyl and Schur orthogonality [20, Chs. 2–4]).

Lemma 86. *Let $w \in L^1(G)$ be a class function with $w(U^{-1}) = w(U)$, and put $\hat{c}_\lambda = d_\lambda^{-1} \int w \chi_\lambda dU$. Then $\int w(U) \rho_\lambda(U) dU = \hat{c}_\lambda I$, and $\int w(U) \chi_\lambda(U^{-1}V) dU = \hat{c}_\lambda \chi_\lambda(V)$.*

Proof. $M = \int w(U) \rho_\lambda(U) dU$ commutes with every $\rho_\lambda(V)$, since $w(VUV^{-1}) = w(U)$ and Haar measure is invariant; by Schur’s lemma $M = cI$, and taking traces gives $c = \hat{c}_\lambda$. Then $\int w(U) \chi_\lambda(U^{-1}V) dU = \text{Tr}(\int w(U) \rho_\lambda(U^{-1}) dU \rho_\lambda(V))$, and the substitution $U \mapsto U^{-1}$ with $w(U^{-1}) = w(U)$ turns the integral into M . $\square$

Lemma 87. *Let $G = \text{SU}(N)$ and $\beta > 0$, and let*

$$w_\beta(U) = e^{\frac{\beta}{N} \text{Re Tr } U} / \int e^{\frac{\beta}{N} \text{Re Tr } V} dV.$$

Then $\hat{c}_\lambda(\beta) = d_\lambda^{-1} \int w_\beta \chi_\lambda dU$ is real, $0 \leq \hat{c}_\lambda(\beta) \leq 1$, and $\hat{c}_\lambda(\beta) < 1$ for $\lambda \neq 0$. Moreover

$$\hat{c}_\lambda(\beta) = 1 - \frac{NC_2(\lambda)}{\beta} + O(\beta^{-2}) \quad (\beta \rightarrow \infty),$$

where $-\sum_a \rho_\lambda(T_a)^2 = 2C_2(\lambda)I$ for a basis (T_a) of $\mathfrak{su}(N)$ orthonormal for $|X|^2 = -\text{Tr} X^2$, so that $C_2 = (N^2 - 1)/(2N)$ on the fundamental representation.

Proof. Since $w_\beta(\bar{U}) = w_\beta(U)$ and $\chi_\lambda(\bar{U}) = \overline{\chi_\lambda(U)}$, and complex conjugation preserves Haar measure, $\int w_\beta \chi_\lambda = \int w_\beta \bar{\chi}_\lambda$, which is the complex conjugate of the left side; so $\hat{c}_\lambda$ is real. Next, w_β is a multiple of $\exp(\frac{\beta}{2N}(\chi_F + \bar{\chi}_F)) = \sum_m \frac{1}{m!} (\frac{\beta}{2N})^m (\chi_F + \bar{\chi}_F)^m$, and each power is the character of a representation, hence a sum of irreducible characters with non-negative integer coefficients. By orthonormality $\int w_\beta \bar{\chi}_\lambda \geq 0$, so $\hat{c}_\lambda \geq 0$. As $|\chi_\lambda(U)| \leq d_\lambda$, with $\text{Re} \chi_\lambda(U) = d_\lambda$ only where $\rho_\lambda(U) = I$, a proper closed subgroup when $\lambda \neq 0$ and so a Haar null set, and $w_\beta > 0$ everywhere, $\hat{c}_\lambda = d_\lambda^{-1} \int w_\beta \text{Re} \chi_\lambda < 1$ for $\lambda \neq 0$.

For the expansion, $\text{Re Tr } U \leq N$ with equality only at $U = I$, so outside a neighbourhood $\{U = e^X : |X| < \delta\}$ both integrals $\int e^{\frac{\beta}{N} \text{Re Tr } U} \chi_\lambda$ and $\int e^{\frac{\beta}{N} \text{Re Tr } U}$ are smaller than their values near I by a factor $e^{-c\beta}$. Near I write $U = e^X$; the Haar density in these coordinates is $j(X) = 1 + O(|X|^2)$, even in X . For antihermitian X , $\text{Tr} X^3$ is imaginary, so

$$\frac{1}{N} \text{Re Tr } e^X = 1 - \frac{1}{2N} |X|^2 + r(X), \quad 0 \leq r(X) \leq C|X|^4,$$

and $d_\lambda^{-1} \chi_\lambda(e^X) = 1 + d_\lambda^{-1} \text{Tr} \rho_\lambda(X) + \frac{1}{2d_\lambda} \text{Tr} \rho_\lambda(X)^2 + c_3(X) + O(|X|^4)$, with c_3 cubic and $\text{Tr} \rho_\lambda(X) = 0$, since $\mathfrak{su}(N)$ is perfect. Let $\langle \cdot \rangle$ denote the average against the Gaussian weight

$e^{-\beta|X|^2/(2N)}$, under which the coordinates x_a of $X = \sum x_a T_a$ are independent with variance N/β . With $h = j e^{\beta r}$,

$$\begin{aligned} \hat{c}_\lambda(\beta) &= \frac{\langle d_\lambda^{-1} \chi_\lambda(e^X) h \rangle}{\langle h \rangle} + O(e^{-c\beta}) \\ &= 1 + \frac{\langle \frac{1}{2d_\lambda} \text{Tr} \rho_\lambda(X)^2 h \rangle}{\langle h \rangle} + \frac{\langle (c_3(X) + O(|X|^4)) h \rangle}{\langle h \rangle}, \end{aligned}$$

the averages being taken over $|X| < \delta$. Under $\langle \cdot \rangle$, $|X|^{2m}$ has mean of order β^{-m} and $\beta|r(X)| \leq C\beta|X|^4$ has mean of order β^{-1} , so $h = 1 + O(\beta^{-1})$ in every moment. The weight h is even in X , since $\text{Tr} X^k$ is imaginary for odd k and j is even, so the odd term c_3 contributes nothing; the quartic remainder and the correlation of the quadratic term with $h - 1$ contribute $O(\beta^{-2})$. Finally $\langle \text{Tr} \rho_\lambda(X)^2 \rangle = \frac{N}{\beta} \sum_a \text{Tr} \rho_\lambda(T_a)^2 = -\frac{2NC_2(\lambda)d_\lambda}{\beta}$, which gives the expansion. For $\text{SU}(2)$ and the representation of spin j the integrals are explicit, $\hat{c}_j(\beta) = I_{2j+1}(\beta)/I_1(\beta)$ with the modified Bessel functions I_n , in agreement with $C_2 = j(j+1)$. $\square$

Appendix I: The single-link law of $\text{SU}(2)$

This appendix proves the sharp quarter, $W_1(v_b, v_{b'}) \leq \frac{1}{4}|b - b'|$ for the one-link law of $\text{SU}(2)$, which Theorems 1 and 3 use, and the exact value at $b = 0$, which Theorem 2 uses. The argument is that of our earlier paper [13]; it is given in full so that the present paper is self-contained.

1. The von Mises–Fisher law

Identify $\text{SU}(2)$ with the unit quaternions, that is with the unit sphere $S^3 \subset \mathbb{R}^4$, so that $\text{Re Tr } U = 2x_0(U)$ and $\text{Re Tr}(UV) = 2\langle u, \bar{v} \rangle$ for the Euclidean inner product of $\mathbb{R}^4$ and quaternion conjugation $v \mapsto \bar{v}$. Fix a link e and the field off e . Every plaquette through e can be rotated cyclically so that its trace reads $\text{Re Tr}(Q_e A_p)$ with $A_p \in \text{SU}(2)$, the staple of e in p . The action therefore depends on Q_e only through

$$N\beta \sum_{p \ni e} \text{Re Tr}(Q_e A_p) = \langle x, b \rangle, \quad b = 4\beta \sum_{p \ni e} \bar{A}_p \in \mathbb{R}^4,$$

with $x = Q_e \in S^3$. Since there are six staples, each of norm one,

$$\kappa := |b| \leq y := 24|\beta|. \quad (\text{I1})$$

The conditional law of Q_e is the von Mises–Fisher law²⁰

$$v_b(dx) = Z(\kappa)^{-1} e^{\langle x, b \rangle} \sigma(dx) \quad (\text{I2})$$

²⁰ On the sphere $S^{p-1} \subset \mathbb{R}^p$ the von Mises–Fisher law with mean direction μ and concentration κ has density proportional to $e^{\kappa \langle x, \mu \rangle}$ with respect to the surface measure, and its normalising constant is $(2\pi)^{p/2} I_{p/2-1}(\kappa) / \kappa^{p/2-1}$; it is the maximum entropy law with prescribed mean resultant, and it plays on the sphere the role of the Gaussian in $\mathbb{R}^p$. For $p = 4$ the Bessel index is 1. The mean resultant length $\mathbb{E} \langle x, \mu \rangle = I_{p/2}(\kappa) / I_{p/2-1}(\kappa)$ is the function A of Lemma 89. See Mardia and Jupp [50], Ch. 9, for these facts and for the tangent-normal decomposition used in Appendix J.

on the unit sphere, with σ the normalised surface measure. We use coordinates in which $b = \kappa e_1$. The density of $t = x_1$ is proportional to $(1 - t^2)^{1/2} e^{\kappa t}$ on $[-1, 1]$, so $Z(\kappa) = 2I_1(\kappa)/\kappa$ with the modified Bessel function I_1 , normalised so that $Z(0) = 1$.

Lemma 88. *For every $\kappa \geq 0$ the law ν_b on the unit sphere S^3 satisfies the Poincaré inequality $\text{Var}_{\nu_b}(g) \leq \frac{1}{3} \int |\nabla g|^2 d\nu_b$, and the constant $\frac{1}{3}$ is attained at $\kappa = 0$.*

Proof. In the polar angle $\theta \in (0, \pi)$ from e_1 the generator of the reversible diffusion of ν_b is $L = \partial_\theta^2 + b(\theta)\partial_\theta + \sin^{-2}\theta \Delta_{S^2}$ with $b(\theta) = 2\cot\theta - \kappa \sin\theta$. On spherical harmonics of degree ℓ on S^2 it acts as a Sturm–Liouville operator L_ℓ with potential $\ell(\ell+1)\sin^{-2}\theta$. A ground state comparison of Barta’s type [8] with the trial function $\psi = \sin\theta e^{a\kappa \cos\theta}$ gives $-L_1\psi \geq 3\psi$ for $a = -\frac{1}{5}$, and the same trial function with $a = -\frac{2}{5}$ gives the bound 3 for the derivatives of zonal eigenfunctions; Appendix J carries out both computations. Hence every nonzero eigenvalue of $-L$ is at least 3. At $\kappa = 0$ the first eigenvalue of the Laplacian of the unit S^3 is 3. $\square$

2. Moments

Let $A(\kappa) = \mathbb{E}_{\nu_b} x_1 = Z'(\kappa)/Z(\kappa) = I_2(\kappa)/I_1(\kappa)$.

Lemma 89. *For every $\kappa > 0$, in coordinates with $b = \kappa e_1$,*

(i) $\mathbb{E}x_2^2 = \mathbb{E}x_3^2 = \mathbb{E}x_4^2 = A/\kappa$, $\mathbb{E}(1 - x_1^2) = 3A/\kappa$, the covariance matrix of x is $\text{diag}(A', A/\kappa, A/\kappa, A/\kappa)$, and $A' = 1 - A^2 - 3A/\kappa$;

(ii) $\frac{\kappa}{2 + \sqrt{\kappa^2 + 4}} \leq A(\kappa) \leq \frac{\kappa}{1 + \sqrt{\kappa^2 + 9}}$;

(iii) $A' \leq A/\kappa \leq (1 + \sqrt{\kappa^2 + 9})^{-1} \leq \frac{1}{4}$;

(iv) $A(\kappa) \geq \kappa / (\frac{3}{2} + \sqrt{\kappa^2 + 25/4})$.

Proof. (i) Integrating by parts against $\frac{d}{dt}(1 - t^2)^{3/2} = -3t(1 - t^2)^{1/2}$ gives $\kappa \mathbb{E}(1 - x_1^2) = 3\mathbb{E}x_1$, and the three coordinates x_2, x_3, x_4 are exchangeable under ν_b , with $\sum_i x_i^2 = 1$. The off-diagonal covariances vanish by the reflections $x_i \mapsto -x_i$, $i \geq 2$, and $A' = \text{Var}x_1$ because $A = (\log Z)'$. (ii) By (i), A solves the Riccati equation $A' = 1 - A^2 - 3A/\kappa$ with $A(\kappa) = \kappa/4 + O(\kappa^3)$. Appendix J shows that the left side of (ii) is a subsolution and the right side a supersolution of this equation, with the same behaviour at 0, and concludes by comparison. (iii) The middle inequality is (ii). For the first, put $s = \sqrt{\kappa^2 + 4}$. By (ii), $4A/\kappa \geq 4/(2 + s)$ and $1 - A^2 \leq 1 - \kappa^2/(2 + s)^2$, and

$$1 - \frac{\kappa^2}{(2 + s)^2} \leq \frac{4}{2 + s} \iff (2 + s)^2 - \kappa^2 \leq 4(2 + s) \\ \iff s^2 - \kappa^2 \leq 4,$$

which holds with equality. So $A' = 1 - A^2 - 3A/\kappa \leq A/\kappa$. (iv) is the comparison of (ii) with a third barrier, which improves the lower bound of (ii); it is carried out in the same appendix. $\square$

3. The Lipschitz rate of the family

Let δ be the chordal metric $\delta(x, x') = |x - x'|$ on S^3 and W_1 the Kantorovich distance for δ . For $c \in \mathbb{R}^4$ and a unit vector $h \in \mathbb{R}^4$ put

$$L(c, h) = \sup_g \text{Cov}_{\nu_c}(g, \langle h, x \rangle), \quad (13)$$

the supremum over 1-Lipschitz functions g for δ . Since $\frac{d}{dt} \nu_{c+th}(g) = \text{Cov}_{\nu_{c+th}}(g, \langle h, x \rangle)$, the Kantorovich–Rubinstein duality gives, for all b, b' ,

$$W_1(\nu_b, \nu_{b'}) \leq |b - b'| \sup_{c \in [b, b']} L\left(c, \frac{b' - b}{|b' - b|}\right). \quad (14)$$

By rotation invariance $L(c, h)$ depends only on $\kappa = |c|$ and on the angle φ between h and $c^\perp$, and we write $L(\kappa, \varphi)$.

Lemma 90. *For all c and h , $L(c, h) \leq 1/(2\sqrt{3})$. Moreover:*

(i) at $c = 0$, $L(0, h) = \frac{1}{4}$ for every h ;

(ii) if $h \perp c$, then $L(c, h) = \mathbb{E}_{\nu_c} x_2^2 = A(\kappa)/\kappa \leq \frac{1}{4}$;

(iii) if $\kappa \geq \sqrt{88}/3 \approx 3.127$, then $L(c, h) \leq \frac{1}{4}$ for every h .

Proof. A 1-Lipschitz function for δ is 1-Lipschitz for the geodesic distance, which is larger, so $|\nabla g| \leq 1$ almost everywhere, and Lemma 88 gives $\text{Var} g \leq \frac{1}{3}$. By Lemma 89(i), (iii) the largest eigenvalue of the covariance of x is $A/\kappa \leq \frac{1}{4}$, so $\text{Var}\langle h, x \rangle \leq A/\kappa$. The Cauchy–Schwarz inequality gives

$$L(c, h) \leq (\frac{1}{3}A/\kappa)^{1/2} \leq \left(3(1 + \sqrt{\kappa^2 + 9})\right)^{-1/2} \leq \frac{1}{2\sqrt{3}}. \quad (15)$$

(i) and (ii) are reflection arguments. Let R be the reflection in the hyperplane $h^\perp$, and suppose ν_c is R -invariant, which is the case when $c = 0$ or $h \perp c$. Then $\mathbb{E}\langle h, x \rangle = 0$ and

$$\text{Cov}(g, \langle h, x \rangle) = \mathbb{E}[(g(x) - g(Rx))\langle h, x \rangle; \langle h, x \rangle > 0] \\ \leq \mathbb{E}[2\langle h, x \rangle^2; \langle h, x \rangle > 0] = \mathbb{E}\langle h, x \rangle^2,$$

since $\delta(x, Rx) = 2|\langle h, x \rangle|$. Equality holds for $g = \langle h, x \rangle$, which is 1-Lipschitz. At $c = 0$, $\mathbb{E}\langle h, x \rangle^2 = \frac{1}{4}$; for $h \perp c$, $\mathbb{E}\langle h, x \rangle^2 = A/\kappa$. (iii) By (15), $L \leq \frac{1}{4}$ as soon as $1 + \sqrt{\kappa^2 + 9} \geq \frac{16}{3}$, that is $\kappa^2 \geq \frac{88}{9}$. $\square$

The reflection settles the directions $h \perp c$ and the point $c = 0$; for an oblique h the reflection no longer preserves ν_c , and the Cauchy–Schwarz bound (15) is too weak for $\kappa < \sqrt{88}/3$. The next theorem closes this case.

Theorem 91 (The sharp quarter). *For every $c \in \mathbb{R}^4$ and every unit vector $h \in \mathbb{R}^4$,*

$$L(c, h) \leq \frac{1}{4},$$

with equality at $c = 0$. Equivalently, $W_1(\nu_b, \nu_{b'}) \leq \frac{1}{4}|b - b'|$ for all $b, b' \in \mathbb{R}^4$, and the constant $\frac{1}{4}$ is the best possible.

The equivalence is (I4) in one direction and the derivative formula above it in the other; the sharpness is Lemma 90(i). The metric matters.²¹ The proof has four steps. A Lipschitz function on S^3 extends to the unit ball $B \subset \mathbb{R}^4$, and Green's formula in B bounds the covariance by a negative Sobolev norm of the density (Lemma 92). This norm splits into a zonal and a transverse part, both explicit series in modified Bessel functions (Lemma 93). The transverse part is at most $\frac{1}{4}$ because a certain power series has nonnegative coefficients (Proposition 95), and the zonal part is at most $\frac{1}{4}$ by a Riccati comparison (Proposition 96).

4. Harmonic extension

Let σ be the normalised surface measure of S^3 and H_k the space of spherical harmonics of degree k , the restrictions to S^3 of harmonic homogeneous polynomials of degree k on $\mathbb{R}^4$. The spaces H_k are orthogonal in $L^2(\sigma)$ and span it; we write u_k for the component of u in H_k , and for u with $\int u d\sigma = 0$ we put

$$\mathcal{Q}(u) = \sum_{k \geq 1} \frac{1}{k} \|u_k\|_{L^2(\sigma)}^2. \quad (\text{I6})$$

This is $\langle u, \Lambda^{-1}u \rangle$ for the Dirichlet-to-Neumann operator Λ of B , which acts on H_k as multiplication by k .

Lemma 92. *Let u be a real-analytic function on S^3 with $\int u d\sigma = 0$ and let g be 1-Lipschitz for the chordal metric. Then*

$$\int_{S^3} g u d\sigma \leq \frac{1}{2} \mathcal{Q}(u)^{1/2}.$$

Proof. The chordal metric is the Euclidean metric of $\mathbb{R}^4$ restricted to S^3 , so McShane's extension $G(y) = \inf_{x \in S^3} (g(x) + |x - y|)$ is 1-Lipschitz on $\mathbb{R}^4$ and equals g on S^3 [51]; by Rademacher's theorem $|\nabla G| \leq 1$ almost everywhere. Let $\psi = \sum_{k \geq 1} k^{-1} r^k u_k(\omega)$ in polar coordinates $y = r\omega$. Each term is a harmonic polynomial, the series converges with all derivatives on the closed ball because u is real-analytic,²² and $\partial_r \psi = u$ on S^3 . Green's formula for the Lipschitz function G and the smooth harmonic function ψ reads $\int_{S^3} G \partial_r \psi dS = \int_B \nabla G \cdot \nabla \psi dy$. With $|S^3| = 2\pi^2$ and $|B| = \pi^2/2$ the Cauchy–Schwarz inequality gives

$$\int g u d\sigma = \frac{1}{2\pi^2} \int_B \nabla G \cdot \nabla \psi dy \leq \frac{|B|^{1/2}}{2\pi^2} \left(\int_B |\nabla \psi|^2 dy \right)^{1/2}.$$

²¹ In the geodesic metric of S^3 the statement is false already at $c = 0$: the function $\arcsin x_2$ is geodesically 1-Lipschitz and its covariance with x_2 under the uniform law is $\frac{8}{9\pi} \approx 0.283 > \frac{1}{4}$. A proof therefore has to use that the chordal distance between two points is shorter than their geodesic distance, that is, it has to see the sphere from the ball it bounds. The proof below does exactly this: it extends a chordally Lipschitz function to the ball and integrates by parts there.

²² For real-analytic u the norms $\|u_k\|$ decay geometrically in k , and the supremum of a function in H_k is at most $(\dim H_k)^{1/2} = k+1$ times its $L^2(\sigma)$ norm, so the series for ψ and for each of its derivatives converge uniformly on $\bar{B}$.

Green's formula once more gives $\int_B |\nabla \psi|^2 = \int_{S^3} \psi \partial_r \psi dS = 2\pi^2 \sum_k k^{-1} \|u_k\|^2 = 2\pi^2 \mathcal{Q}(u)$, and the right side becomes $\frac{1}{2} \mathcal{Q}(u)^{1/2}$. $\square$

The lemma is a form of Thomson's principle. By Kantorovich–Rubinstein duality, $\sup_g \int g u d\sigma$ is the least cost of a flow in $\mathbb{R}^4$ that carries the positive part of $u d\sigma$ to its negative part, the cost being the total length travelled by the mass.²³ The harmonic field $\nabla \psi$ is one such flow, through the interior of the ball, and the lemma computes its cost. At $c = 0$ the flow is optimal: for $u = \langle h, x \rangle$ one has $\psi = \langle h, y \rangle$, the field $\nabla \psi = h$ is constant, the Cauchy–Schwarz inequality is an equality, and $\mathcal{Q}(u) = \|u\|^2 = \frac{1}{4}$.

5. Spectral decomposition

Fix $c = \kappa e_1$ with $\kappa > 0$ and write $h = \cos \phi e_1 + \sin \phi e_2$, which is no loss of generality by rotation invariance. Let $\rho = dv_c/d\sigma = e^{\kappa x_1}/Z(\kappa)$, $Z(\kappa) = \int e^{\kappa x_1} d\sigma = 2I_1(\kappa)/\kappa$, and

$$u = (\langle h, x \rangle - \mathbb{E}_{v_c} \langle h, x \rangle) \rho,$$

so that $\text{Cov}_{v_c}(g, \langle h, x \rangle) = \int g u d\sigma$ and $\int u d\sigma = 0$. Let U_n be the Chebyshev polynomials of the second kind and put

$$d_n(\kappa) = \frac{(n+1)I_{n+1}(\kappa)}{I_1(\kappa)}, \quad n \geq 0. \quad (\text{I7})$$

Lemma 93. *With this notation*

$$\mathcal{Q}(u) = \cos^2 \phi \mathcal{Q}_z(\kappa) + \sin^2 \phi \mathcal{Q}_x(\kappa),$$

where

$$\mathcal{Q}_z = \sum_{n \geq 1} \frac{d'_n(\kappa)^2}{n}, \quad \mathcal{Q}_x = \frac{1}{3\kappa^2} \sum_{n \geq 1} (n+2) d_n(\kappa)^2.$$

Proof. The functions $U_n(x_1)$, $n \geq 0$, are the zonal harmonics: $U_n(x_1) \in H_n$, and they are orthonormal in $L^2(\sigma)$ (Appendix K). The expansion $e^{\kappa t} = \frac{2}{\kappa} \sum_n (n+1) I_{n+1}(\kappa) U_n(t)$ of the same appendix gives $\rho = \sum_n d_n(\kappa) U_n(x_1)$, with $d_0 = 1$.

Write $u = \cos \phi u_z + \sin \phi u_x$ with $u_z = (x_1 - A)\rho$ and $u_x = x_2\rho$; here $\mathbb{E}_{v_c} x_1 = A$ and $\mathbb{E}_{v_c} x_2 = 0$. The reflection $x_2 \mapsto -x_2$ maps each H_k to itself, fixes u_z and reverses u_x , so the components of u_z and u_x in each H_k are orthogonal and the cross term in $\mathcal{Q}(u)$ vanishes.

Since $A = Z'/Z$, we have $u_z = \partial_\kappa \rho = \sum_n d'_n(\kappa) U_n(x_1)$, and the component of u_z in H_n is $d'_n U_n(x_1)$, of norm $|d'_n|$. This gives $\mathcal{Q}_z$.

²³ This is the Beckmann formulation of the transport problem with cost $|x - y|$: the optimal cost equals the least $\int |V|$ over vector measures V on $\mathbb{R}^4$ with divergence $u d\sigma$. Restricting the flow to the closed ball does not change the infimum, since projecting onto $\bar{B}$ shortens paths. The gradient $\nabla \psi$ on B is one admissible flow. It minimises the energy $\int |V|^2$ rather than the cost $\int |V|$, and the Cauchy–Schwarz inequality converts one into the other at the price of the factor $|B|^{1/2}$.

For u_x , let $y(t) = \cos t e_1 + \sin t e_2$. The law $\nu_{\kappa y(t)}$ has density $\rho_t = e^{\kappa \langle y(t), x \rangle} / Z(\kappa) = \sum_n d_n(\kappa) U_n(\langle y(t), x \rangle)$, and $\partial_t \rho_t|_{t=0} = \kappa x_2 \rho$. The function $U_n(\langle y(t), x \rangle)$ lies in H_n for every t , hence so does its derivative $x_2 U'_n(x_1)$ at $t = 0$, and the component of u_x in H_n is $\kappa^{-1} d_n x_2 U'_n(x_1)$. Its norm follows from the eigenvalue $n(n+2)$ of the Laplacian of S^3 on H_n . For $f = U_n(x_1)$,

$$\begin{aligned} n(n+2) &= n(n+2) \|f\|^2 = \int |\nabla_{S^3} f|^2 d\sigma \\ &= \int U'_n(x_1)^2 (1-x_1^2) d\sigma, \end{aligned}$$

since the tangential gradient of x_1 has squared length $1-x_1^2$. Given x_1 , the point (x_2, x_3, x_4) is uniform on the sphere of radius $(1-x_1^2)^{1/2}$, so $\mathbb{E}[x_2^2 | x_1] = \frac{1}{3}(1-x_1^2)$ and $\|x_2 U'_n(x_1)\|^2 = \frac{1}{3}n(n+2)$. Summing $n^{-1} \kappa^{-2} d_n^2 \cdot \frac{1}{3}n(n+2)$ over $n \geq 1$ gives $\mathcal{Q}_x$. $\square$

By Lemmas 92 and 93,

$$L(\kappa, \varphi) \leq \frac{1}{2} \max(\mathcal{Q}_z(\kappa), \mathcal{Q}_x(\kappa))^{1/2}, \quad (\text{I8})$$

and Theorem 91 follows once both parts are at most $\frac{1}{4}$. Both are $\frac{1}{4}$ at $\kappa = 0$, by continuity from the values $d_1 \sim \kappa/2$, $d'_1 \rightarrow \frac{1}{2}$ and $d_n = O(\kappa^n)$.

6. Three Bessel sums

The series of Lemma 93 reduce to closed forms. Write I_j for $I_j(\kappa)$.

Lemma 94. *For every $\kappa > 0$,*

$$\begin{aligned} \sum_{j \geq 1} j^2 I_j^2 &= \frac{\kappa}{4} I_1(2\kappa), & \sum_{j \geq 1} j^3 I_j^2 &= \frac{\kappa^2}{4} (I_0^2 + I_1^2), \\ I_1(2\kappa) &= 2 \sum_{j \geq 1} I_{j-1} I_j. \end{aligned}$$

The first and third identities follow from Parseval's formula for $e^{\kappa \cos \theta} = \sum_{j \in \mathbb{Z}} I_j e^{ij\theta}$, and the second from the recurrences of I_j by telescoping; Appendix K gives the proofs.

7. The transverse part

Proposition 95. $\mathcal{Q}_x(\kappa) \leq \frac{1}{4}$ for every $\kappa \geq 0$.

Proof. By (I7), $\mathcal{Q}_x = (3\kappa^2 I_1^2)^{-1} \sum_{j \geq 2} j^2 (j+1) I_j^2$, and the sum equals $\sum_{j \geq 1} (j^3 + j^2) I_j^2 - 2I_1^2$. By Lemma 94, $\mathcal{Q}_x \leq \frac{1}{4}$ is equivalent to

$$\mathcal{D}(\kappa) := (8 + 2\kappa^2) I_1^2 - \kappa^2 I_0^2 - \kappa I_1(2\kappa) \geq 0. \quad (\text{I9})$$

Each term is an entire function of κ that is even after the factor κ^2 is removed, so $\mathcal{D}(\kappa) = \sum_{n \geq 0} \mathcal{D}_n \kappa^{2n}$. Lemma 98 of Appendix K computes the coefficients: $\mathcal{D}_0 = \mathcal{D}_1 = 0$, and for $n = m+1 \geq 2$

$$\mathcal{D}_n = \frac{N_m}{4^m m! (m+1)! (m+1)(m+2)},$$

with

$$\begin{aligned} N_m &= \binom{2m}{m} (4(2m+1) + (m-1)(m+1)(m+2)) \\ &\quad - 4^m (m+1)(m+2). \end{aligned}$$

The numerator N_m vanishes for $m = 0, 1, 2$ and is positive for $m \geq 3$ (Lemma 98). So every coefficient of $\mathcal{D}$ is nonnegative and $\mathcal{D} \geq 0$. $\square$

The first nonzero coefficient is $\mathcal{D}_4 = \frac{1}{2304}$, so $\frac{1}{4} - \mathcal{Q}_x = \mathcal{D}/(12\kappa^2 I_1^2)$ is of order κ^4 at 0: the transverse part leaves the value $\frac{1}{4}$ very slowly, which is why no estimate that loses a constant can prove the proposition.

8. The zonal part

Let $A = I_2/I_1$ as before, so that $d_1 = 2A$ and, by Lemma 89(i), $A' = 1 - A^2 - 3A/\kappa$.

Proposition 96. *For $0 < \kappa \leq \sqrt{88}/3$,*

$$\mathcal{Q}_z(\kappa) \leq \frac{1}{4} + 4A'^2 + \frac{A^2}{4} - \frac{A}{2\kappa} - \frac{2A^2}{\kappa^2} < \frac{1}{4}.$$

Proof. The higher modes. With $r_v = I_{v+1}/I_v$ the recurrence $I'_v = I_{v+1} + \frac{v}{\kappa} I_v$ gives

$$\frac{d'_n}{d_n} = \frac{I'_{n+1}}{I_{n+1}} - \frac{I'_1}{I_1} = \frac{n}{\kappa} + r_{n+1} - r_1.$$

By Lemma 99 of Appendix K, $r_{n+1} \leq r_1$, and $r_1 = A \leq \kappa/4$ by Lemma 89(iii). Hence $-n/\kappa \leq n/\kappa - \kappa/4 \leq d'_n/d_n \leq n/\kappa$ for $n \geq 2$ and $\kappa^2 \leq 16$, so $d_n^2 \leq n^2 d_n'^2 / \kappa^2$. With $d'_1 = 2A'$,

$$\mathcal{Q}_z \leq 4A'^2 + \frac{1}{\kappa^2} \sum_{n \geq 2} n d_n'^2 = 4A'^2 + \frac{S_3 - S_2 - 4I_2^2}{\kappa^2 I_1^2},$$

where $S_2 = \sum_{j \geq 1} j^2 I_j^2$ and $S_3 = \sum_{j \geq 1} j^3 I_j^2$; the second form uses $n d_n'^2 = (j-1) j^2 I_j^2$ with $j = n+1$.

The closed form. The recurrences $I_0 - I_2 = \frac{2}{\kappa} I_1$ and $I_1 - I_3 = \frac{4}{\kappa} I_2$ give $I_0/I_1 = 2/\kappa + A$ and $I_2/I_1 = A - 4A^2/\kappa$. By Lemma 94, $S_3/(\kappa^2 I_1^2) = \frac{1}{4}(2/\kappa + A)^2 + \frac{1}{4}$, and, keeping three terms of the third identity,

$$\frac{S_2}{\kappa^2 I_1^2} \geq \frac{I_0 I_1 + I_1 I_2 + I_2 I_3}{2\kappa I_1^2} = \frac{1}{2\kappa} \left(\frac{2}{\kappa} + 3A - \frac{4A^2}{\kappa} \right).$$

Collecting terms, $\mathcal{Q}_z \leq \frac{1}{4} + 4A'^2 + T(A)$ with $T(a) = \frac{a^2}{4} - \frac{a}{2\kappa} - \frac{2a^2}{\kappa^2}$, which is the first inequality.

The barrier. Let $s = \sqrt{\kappa^2 + 25/4}$ and $A_b = \kappa/(\frac{3}{2} + s)$. By Lemma 89(iv), $A_b \leq A \leq \kappa/4$. The function $a \mapsto 1 - a^2 - 3a/\kappa$ decreases on $a \geq 0$, and $A' \geq 0$ because $A' = \text{Var } x_1$, so $0 \leq A' \leq \alpha := 1 - A_b^2 - 3A_b/\kappa$. For $\kappa^2 \leq 12$ the quadratic T decreases on $[0, \kappa/4]$, since

$$T(a) - T(a') = (a' - a) \frac{2\kappa - (a + a')(\kappa^2 - 8)}{4\kappa^2}$$

and $(a + a')(\kappa^2 - 8) \leq \frac{\kappa}{2}(\kappa^2 - 8) \leq 2\kappa$ there. So $\mathcal{Q}_z \leq \frac{1}{4} + 4\alpha^2 + T(A_b)$. With $\kappa^2 = s^2 - \frac{25}{4}$ and $A_b/\kappa = 2/(2s+3)$ both terms are rational in s : $\alpha = 16/(2s+3)^2$, and

$$4\alpha^2 + T(A_b) = \frac{(2s-5)p(s)}{4(2s+3)^4}, \quad (I10)$$

$$p(s) = 8s^3 + 28s^2 - 98s - 695.$$

For $0 < \kappa \leq \sqrt{88}/3$ we have $\frac{5}{2} < s \leq \sqrt{577}/6 < 4.004$. On $s \geq \frac{5}{2}$ the cubic p increases, since $p'(s) = 24s^2 + 56s - 98 > 0$, and $p(4.004) < -120$. So the right side of (I10) is negative. $\square$

9. Proof of Theorem 91

At $c = 0$ the theorem is Lemma 90(i), and for $|c| \geq \sqrt{88}/3$ it is Lemma 90(iii). For $0 < |c| < \sqrt{88}/3$, Propositions 95 and 96 give $\mathcal{Q}_x, \mathcal{Q}_z \leq \frac{1}{4}$, and (I8) gives $L \leq \frac{1}{4}$. $\square$

Appendix J: Computations for the single-link law

1. Barta's inequality

Let $\rho(\theta) = \sin^2 \theta e^{\kappa \cos \theta}$ on $(0, \pi)$, let V be a continuous potential, and let

$$T = -\rho^{-1} \partial_\theta \rho \partial_\theta + V.$$

If $\psi > 0$ is smooth on $(0, \pi)$ with $\rho \psi^2 = O(\sin^4 \theta)$ at the end points and $T\psi \geq \lambda_0 \psi$, then

$$\int (|h'|^2 + Vh^2) \rho d\theta \geq \lambda_0 \int h^2 \rho d\theta$$

for every smooth h vanishing to first order at 0 and π . Indeed, writing $h = \psi u$ and integrating by parts, the boundary terms $\rho \psi \psi' u^2$ vanish and

$$\int (|h'|^2 + Vh^2) \rho = \int \rho \psi^2 |u'|^2 + \int \frac{T\psi}{\psi} h^2 \rho \geq \lambda_0 \int h^2 \rho.$$

This is the inequality of Barta [8] in the form of a ground state transformation.

2. The computations of Lemma 88

The generator of the reversible diffusion of v_b on S^3 is $L = \Delta_{S^3} + \kappa \nabla_{x_1} \cdot \nabla$. In the polar angle θ from e_1 the round metric is $d\theta^2 + \sin^2 \theta g_{S^2}$, so $\Delta_{S^3} = \partial_\theta^2 + 2 \cot \theta \partial_\theta + \sin^{-2} \theta \Delta_{S^2}$, and $\nabla_{x_1} \cdot \nabla = -\sin \theta \partial_\theta$. On $h(\theta) Y_\ell$ with a spherical harmonic Y_ℓ of degree ℓ on S^2 the operator acts as $L_\ell = \partial_\theta^2 + b \partial_\theta - \ell(\ell+1) \sin^{-2} \theta$, $b = 2 \cot \theta - \kappa \sin \theta = \rho'/\rho$, so $-L_\ell = T$ with $V = \ell(\ell+1) \sin^{-2} \theta$.

Degree $\ell \geq 1$. Take $\psi = \sin \theta e^{a \kappa \cos \theta}$. Then $\psi'/\psi = \cot \theta - a \kappa \sin \theta$ and $\psi''/\psi = (\psi'/\psi)^2 + (\psi'/\psi)'$, and a short computation gives

$$\frac{-L_1 \psi}{\psi} = 3 + (1 + 5a) \kappa \cos \theta - a(1 + a) \kappa^2 \sin^2 \theta.$$

For $a = -\frac{1}{5}$ this is $3 + \frac{4}{25} \kappa^2 \sin^2 \theta \geq 3$. Since $V = \ell(\ell+1) \sin^{-2} \theta \geq 2 \sin^{-2} \theta$ for $\ell \geq 1$, Barta's inequality gives $-L_\ell \geq 3$ on every sector with $\ell \geq 1$.

Degree $\ell = 0$. Let $g(\theta)$ be a zonal eigenfunction, $-L_0 g = \lambda g$, g not constant, so that $g'(0) = g'(\pi) = 0$. Differentiating $g'' + b g' = -\lambda g$ gives, for $h = g'$,

$$-(h'' + b h') - b' h = \lambda h, \quad -b' = \frac{2}{\sin^2 \theta} + \kappa \cos \theta,$$

so h is an eigenfunction of T with $V = 2 \sin^{-2} \theta + \kappa \cos \theta$, with eigenvalue λ , and $h \neq 0$ vanishes at both ends. With the same ψ ,

$$\frac{T\psi}{\psi} = 3 + (2 + 5a) \kappa \cos \theta - a(1 + a) \kappa^2 \sin^2 \theta,$$

which for $a = -\frac{2}{5}$ is $3 + \frac{6}{25} \kappa^2 \sin^2 \theta \geq 3$. Barta's inequality applied to h gives $\lambda \geq 3$. Together with the case $\ell \geq 1$ every nonzero eigenvalue of $-L$ is at least 3, which is Lemma 88; the spectrum is discrete because S^3 is compact and the drift is smooth.

3. Moments

The density of $t = x_1$ under v_b is proportional to $(1 - t^2)^{1/2} e^{\kappa t}$. For every smooth ϕ on $[-1, 1]$,

$$\frac{d}{dt} \left[(1 - t^2)^{3/2} e^{\kappa t} \right] = (1 - t^2)^{1/2} e^{\kappa t} (\kappa(1 - t^2) - 3t),$$

and integration by parts gives $\mathbb{E}[\phi'(t)(1 - t^2)] = \mathbb{E}[\phi(t)(3t - \kappa(1 - t^2))]$. With $\phi = 1$ this is $\kappa \mathbb{E}(1 - x_1^2) = 3 \mathbb{E}x_1$, the identity of Lemma 89(i). With $\phi = t^k$ it gives the recursion

$$m_{k+2} = m_k - \frac{k+3}{\kappa} m_{k+1} + \frac{k}{\kappa} m_{k-1}, \quad m_k = \mathbb{E}x_1^k,$$

from $m_0 = 1$ and $m_1 = A$; all polynomial moments of v_b are rational in κ and $A(\kappa)$.²⁴

4. The Riccati barriers

By Lemma 89(i), A solves $A' = \mathcal{F}(\kappa, A) := 1 - A^2 - 3A/\kappa$ on $(0, \infty)$, and $A(\kappa) = \frac{\kappa}{4} - \frac{\kappa^3}{96} + O(\kappa^5)$ from the series of I_1 and I_2 . Let $s = \sqrt{\kappa^2 + 4}$, $u = \sqrt{\kappa^2 + 9}$, $\phi_- = \kappa/(2 + s)$ and $\phi_+ = \kappa/(1 + u)$. Direct differentiation gives

$$\phi'_- - \mathcal{F}(\kappa, \phi_-) = -\frac{\kappa^2}{s(s+2)^2} \leq 0,$$

$$\phi'_+ - \mathcal{F}(\kappa, \phi_+) = \frac{(u-3)^2}{u(1+u)^2} \geq 0,$$

²⁴ For instance $m_2 = 1 - 3A/\kappa$, $m_3 = A - 3/\kappa + 12A/\kappa^2$ and $m_4 = m_2 - 5m_3/\kappa + 2A/\kappa$. The joint moments with x_2, x_3, x_4 follow from exchangeability: $\mathbb{E}[\phi(x_1)x_2^2] = \frac{1}{3} \mathbb{E}[\phi(x_1)(1 - x_1^2)]$.

and $\phi_{\pm} = \frac{\kappa}{4} + O(\kappa^3)$.²⁵ The comparison is singular at 0 because of the term $3A/\kappa$, and we carry it out with an integrating factor. Let $D = A - \phi_-$. Then

$$\begin{aligned} D' &= \mathcal{F}(\kappa, A) - \mathcal{F}(\kappa, \phi_-) - (\phi'_- - \mathcal{F}(\kappa, \phi_-)) \\ &= -\left(A + \phi_- + \frac{3}{\kappa}\right)D + R, \end{aligned}$$

with $R = \kappa^2/(s(s+2)^2) \geq 0$. Put $\mu(\kappa) = \kappa^3 \exp \int_0^\kappa (A + \phi_-)$. Then $(\mu D)' = \mu R \geq 0$, and $\mu D = O(\kappa^6) \rightarrow 0$ as $\kappa \rightarrow 0$, so $\mu D \geq 0$ and $A \geq \phi_-$. The same argument with $D = \phi_+ - A$ and $R = (u-3)^2/(u(1+u)^2)$ gives $A \leq \phi_+$. This is Lemma 89(ii).

For (iv) let $s = \sqrt{\kappa^2 + 25/4}$ and $\phi_b = \kappa/(\frac{3}{2} + s)$. Since $s^2 - \frac{9}{4} = \kappa^2 + 4$, the same differentiation gives

$$\phi'_b - \mathcal{F}(\kappa, \phi_b) = -\frac{5(s - \frac{5}{2})}{2s(\frac{3}{2} + s)^2} \leq 0,$$

so ϕ_b is a subsolution, and $\phi_b = \frac{\kappa}{4} - \frac{\kappa^3}{80} + O(\kappa^5)$.²⁶ Hence $A - \phi_b = \frac{\kappa^3}{480} + O(\kappa^5)$, and the integrating-factor argument above, with $D = A - \phi_b$, $R = \frac{5(s-5/2)}{2s(3/2+s)^2} \geq 0$ and $\mu = \kappa^3 \exp \int_0^\kappa (A + \phi_b)$, gives $\mu D = O(\kappa^6)$ at 0, $(\mu D)' = \mu R \geq 0$, and so $A \geq \phi_b$. Since $\frac{3}{2} + \sqrt{\kappa^2 + 25/4} < 2 + \sqrt{\kappa^2 + 4}$ for $\kappa > 0$, this improves the lower bound of (ii).

Appendix K: Bessel functions

This appendix proves the auxiliary statements used in Appendix I for Theorem 91. Throughout, $I_j = I_j(\kappa)$ with $\kappa > 0$, and $I_{-j} = I_j$ for integers j . We use the series

$$I_\nu(\kappa) = \sum_{i \geq 0} \frac{(\kappa/2)^{2i+\nu}}{i!(i+\nu)!},$$

the integral $I_j(\kappa) = \pi^{-1} \int_0^\pi e^{\kappa \cos \theta} \cos j\theta d\theta$, the Fourier series $e^{\kappa \cos \theta} = \sum_{j \in \mathbb{Z}} I_j e^{ij\theta}$ and the recurrences

$$I_{j-1} - I_{j+1} = \frac{2j}{\kappa} I_j, \quad I'_j = I_{j+1} + \frac{j}{\kappa} I_j, \quad (\text{K1})$$

all of which are in Watson's treatise [68], §§3.7, 3.71, 2.22. All series below converge absolutely, because $0 < I_j \leq (\kappa/2)^j e^\kappa / j!$.

²⁵ For the first identity write $\phi_- = (s-2)/\kappa$, which follows from $s^2 - 4 = \kappa^2$; then $\phi'_- = (\kappa^2/s - s + 2)/\kappa^2$ and $1 - \phi_-^2 - 3\phi_-/\kappa = (\kappa^2 - (s-2)^2 - 3(s-2))/\kappa^2$, and the difference simplifies with $s^2 = \kappa^2 + 4$. The second is the same computation with $\phi_+ = \kappa(u-1)/(u^2-1) = \kappa(u-1)/(\kappa^2+8)$ in place of ϕ_- and $u^2 = \kappa^2 + 9$ in place of $s^2 = \kappa^2 + 4$. After clearing the denominator $\kappa^2(1+u)^2$ the numerator becomes $\kappa^2(u-3)^2/u$, which is the stated residual.

²⁶ With $\phi_b = \kappa(s - \frac{3}{2})/(\kappa^2 + 4)$ one has $\phi'_b = (\frac{3}{2}s + \frac{25}{4})/(s(\frac{3}{2} + s)^2)$, using $ds/d\kappa = \kappa/s$; and $\mathcal{F}(\kappa, \phi_b) = 1 - \phi_b^2 - 3/(\frac{3}{2} + s)$. Clearing the denominator $s(\frac{3}{2} + s)^2$ and replacing κ^2 by $s^2 - \frac{25}{4}$ leaves $-\frac{5}{2}s + \frac{25}{4}$ in the numerator, which is the stated residual. The expansion follows from $s = \frac{5}{2} + \frac{\kappa^2}{5} + O(\kappa^4)$.

1. Zonal harmonics

Under σ the coordinate x_1 has the density $\frac{2}{\pi}(1-t^2)^{1/2}$ on $[-1, 1]$, the area of the two-sphere $\{x_1 = t\}$ being proportional to $1-t^2$ and its normal speed to $(1-t^2)^{-1/2}$. The Chebyshev polynomials $U_n(\cos \theta) = \sin((n+1)\theta)/\sin \theta$ satisfy

$$\int U_n U_m d\sigma = \frac{2}{\pi} \int_0^\pi \sin((n+1)\theta) \sin((m+1)\theta) d\theta = \delta_{nm},$$

and $U_n = C_n^{(1)}$ is the Gegenbauer polynomial of index $\frac{4-2}{2} = 1$, so $U_n(\langle y, x \rangle)$ is the zonal harmonic of degree n on S^3 with pole y : $|x|^n U_n(\langle y, x \rangle / |x|)$ is a harmonic polynomial on $\mathbb{R}^4$ [64], Ch. IV, §2.

Lemma 97. $e^{\kappa t} = \frac{2}{\kappa} \sum_{n \geq 0} (n+1) I_{n+1}(\kappa) U_n(t)$ in $L^2(\frac{2}{\pi}(1-t^2)^{1/2} dt)$, and uniformly on $[-1, 1]$.

Proof. With $t = \cos \theta$ and $2 \sin \theta \sin((n+1)\theta) = \cos n\theta - \cos(n+2)\theta$, the n -th coefficient is

$$\begin{aligned} \frac{2}{\pi} \int_0^\pi e^{\kappa \cos \theta} \sin((n+1)\theta) \sin \theta d\theta &= I_n - I_{n+2} \\ &= \frac{2(n+1)}{\kappa} I_{n+1}, \end{aligned}$$

by (K1). Since $|U_n| \leq n+1$ and I_{n+1} decays factorially, the series converges uniformly. $\square$

2. Proof of Lemma 94

Let $F(\theta) = e^{\kappa \cos \theta} = \sum_j I_j e^{ij\theta}$. Then

$$F'(\theta) = -\kappa \sin \theta F(\theta) = \sum_j ij I_j e^{ij\theta},$$

and Parseval's formula gives

$$\begin{aligned} \sum_{j \in \mathbb{Z}} j^2 I_j^2 &= \frac{\kappa^2}{2\pi} \int_0^{2\pi} \sin^2 \theta e^{2\kappa \cos \theta} d\theta \\ &= \frac{\kappa^2}{2} (I_0(2\kappa) - I_2(2\kappa)) = \frac{\kappa}{2} I_1(2\kappa), \end{aligned}$$

the last step by (K1) at the argument 2κ . Halving gives the first identity. The coefficient of $e^{i\theta}$ in $F^2 = e^{2\kappa \cos \theta}$ is $I_1(2\kappa) = \sum_{j \in \mathbb{Z}} I_j I_{1-j}$, and the terms with $j \leq 0$ repeat those with $j \geq 1$; this is the third identity.

For the second, $j I_j = \frac{\kappa}{2} (I_{j-1} - I_{j+1})$ by (K1), so

$$\sum_{j \geq 1} j^3 I_j^2 = \frac{\kappa^2}{4} \sum_{j \geq 1} j (I_{j-1}^2 + I_{j+1}^2 - 2I_{j-1} I_{j+1}).$$

Shifting indices, $\sum_{j \geq 1} j (I_{j-1}^2 + I_{j+1}^2) = I_0^2 + \sum_{m \geq 1} 2m I_m^2$, and $\sum_{m \geq 1} 2m I_m^2 = \kappa \sum_{m \geq 1} (I_{m-1} I_m - I_m I_{m+1}) = \kappa I_0 I_1$ by telescoping. For the mixed term write $j = \frac{1}{2}((j-1) + (j+1))$ and

apply (K1) to $(j-1)I_{j-1}$ and to $(j+1)I_{j+1}$, using $I_{-1} = I_1$ at $j = 1$:

$$jI_{j-1}I_{j+1} = \frac{\kappa}{4} [(I_{j-1}I_j - I_jI_{j+1}) + (I_{j-2}I_{j+1} - I_{j-1}I_{j+2})].$$

Both brackets telescope, to I_0I_1 and to $I_{-1}I_2 = I_1I_2$, so $\sum_{j \geq 1} jI_{j-1}I_{j+1} = \frac{\kappa}{4}(I_0I_1 + I_1I_2)$. Altogether

$$\sum_{j \geq 1} j^3 I_j^2 = \frac{\kappa^2}{4} (I_0^2 + \frac{\kappa}{2} I_1(I_0 - I_2)) = \frac{\kappa^2}{4} (I_0^2 + I_1^2). \quad \square$$

3. The coefficients of $\mathcal{D}$

Lemma 98. Write $\mathcal{D}(\kappa) = \sum_{n \geq 0} \mathcal{D}_n \kappa^{2n}$ for the function of (19). Then $\mathcal{D}_0 = \mathcal{D}_1 = 0$, and for $m \geq 1$

$$\mathcal{D}_{m+1} = \frac{N_m}{4^m m! (m+1)! (m+1)(m+2)},$$

with $N_m = \binom{2m}{m} (4(2m+1) + (m-1)(m+1)(m+2)) - 4^m(m+1)(m+2)$. Moreover $N_m = 0$ for $m \leq 2$ and $N_m > 0$ for $m \geq 3$.

Proof. The coefficients. Multiplying the series of I_0 and I_1 and collecting powers,

$$I_0^2 = \sum_{m \geq 0} \alpha_m \kappa^{2m}, \quad I_1^2 = \sum_{m \geq 0} \beta_m \kappa^{2m+2},$$

$$\kappa I_1(2\kappa) = \sum_{m \geq 0} \frac{\kappa^{2m+2}}{m! (m+1)!},$$

where

$$\alpha_m = \frac{1}{4^m} \sum_{i=0}^m \frac{1}{i!^2 (m-i)!^2},$$

$$\beta_m = \frac{1}{4^{m+1}} \sum_{i=0}^m \frac{1}{i! (i+1)! (m-i)! (m-i+1)!}.$$

By Vandermonde's identity, $\sum_i \binom{m}{i}^2 = \binom{2m}{m}$ and $\sum_i \binom{m}{i} \binom{m+2}{i+1} = \binom{2m+2}{m+1}$, so

$$\alpha_m = \frac{\binom{2m}{m}}{4^m m!^2}, \quad \beta_m = \frac{\binom{2m+2}{m+1}}{4^{m+1} m! (m+2)!}.$$

The coefficient of κ^{2m+2} in $\mathcal{D}$ is $\mathcal{D}_{m+1} = 8\beta_m + 2\beta_{m-1} - \alpha_m - 1/(m!(m+1)!)$, with $\beta_{-1} = 0$; for $m = 0$ it is $\frac{8}{4} - 1 - 1 = 0$, and $\mathcal{D}_0 = 0$ because every term of $\mathcal{D}$ is $O(\kappa^2)$. For $m \geq 1$ put $\Delta = 4^m m! (m+1)! (m+1)(m+2)$ and $b = \binom{2m}{m}$. With $\binom{2m+2}{m+1} = \frac{2(2m+1)}{m+1} b$,

$$8\beta_m = \frac{4(2m+1)b}{\Delta}, \quad \alpha_m = \frac{(m+1)^2(m+2)b}{\Delta},$$

$$2\beta_{m-1} = \frac{2m(m+1)(m+2)b}{\Delta},$$

$$\frac{1}{m!(m+1)!} = \frac{4^m(m+1)(m+2)}{\Delta},$$

and $2m - (m+1) = m-1$ gives $\mathcal{D}_{m+1} = N_m/\Delta$.

The sign. Directly, $N_0 = N_1 = N_2 = 0$ ($2-2, 24-24, 192-192$), $N_3 = 80$, $N_4 = 1140$ and $N_5 = 10416$. For $m \geq 6$ we first show $16^m \leq 4m \binom{2m}{m}^2$ for $m \geq 1$ by induction: it is an equality at $m = 1$, and $(m+1) \binom{2m+2}{m+1} = 2(2m+1) \binom{2m}{m}$ gives

$$4(m+1) \binom{2m+2}{m+1}^2 = \frac{16(2m+1)^2}{m+1} \binom{2m}{m}^2$$

$$\geq \frac{16(2m+1)^2}{4m(m+1)} 16^m \geq 16^{m+1}.$$

Since $(m-1)^2 \geq 4m$ for $m \geq 6$, it follows that $\binom{2m}{m}^2 (m-1)^2 \geq 16^m$, that is $\binom{2m}{m} (m-1) \geq 4^m$, and

$$N_m = \left(\binom{2m}{m} (m-1) - 4^m \right) (m+1)(m+2)$$

$$+ 4(2m+1) \binom{2m}{m} > 0.$$

□

4. Monotonicity of Bessel ratios

Lemma 99. For $n \geq 1$ and $\kappa > 0$, $I_{n+2}(\kappa)/I_{n+1}(\kappa) \leq I_2(\kappa)/I_1(\kappa)$.

Proof. We use a lemma of Biernacki and Krzyż [18]: if $f = \sum a_j x^j$ and $g = \sum b_j x^j$ have positive coefficients and a_j/b_j is nonincreasing in j , then f/g is nonincreasing on $x > 0$. Indeed

$$f'g - fg' = \sum_{i,j} (i-j) a_i b_j x^{i+j-1}$$

$$= \frac{1}{2} \sum_{i,j} (i-j) b_i b_j \left(\frac{a_i}{b_i} - \frac{a_j}{b_j} \right) x^{i+j-1} \leq 0.$$

Take $x = \kappa^2$, $f = I_{n+1}(\kappa)/\kappa^{n+1}$ and $g = I_1(\kappa)/\kappa$. Then $a_j/b_j = 2^{-n}(j+1)!/(j+n+1)!$ decreases in j , so $I_{n+1}/(\kappa^n I_1)$ is nonincreasing in κ . Its logarithmic derivative is, by the second recurrence of (K1),

$$\frac{n+1}{\kappa} + \frac{I_{n+2}}{I_{n+1}} - \frac{n}{\kappa} - \frac{1}{\kappa} - \frac{I_2}{I_1}$$

$$= \frac{I_{n+2}}{I_{n+1}} - \frac{I_2}{I_1} \leq 0.$$

□

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