Product Marginals and Density-Moment Thresholds for Ising Transfer Kernels

Lluis Eriksson
Independent researcher

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Abstract

Fix a positive Ising coupling. We construct strictly positive Boolean weights whose labelled marginals on every set of at most a fixed positive fraction of coordinates equal uniform product marginals, while exponentially many normalized transfer eigenvalues approach one exponentially fast. The Perron stationary law has the same marginals. Binary codes with positive primal and dual distances, a positive product admixture, and finite block estimates supply the construction. An exact parity spectrum distinguishes transfer relaxation from single-site heat-bath relaxation. Conversely, for Boolean noise parameter $0 < \rho < 1$, density moments of order $s > (1+\rho)/(1-\rho)$ imply a dimension-independent normalized transfer gap, even allowing zero weights. Below this exponent, every norm budget $B > 1$ admits positive densities with exponentially collapsing gaps. At the critical exponent $s = (1+\rho)/(1-\rho)$ the exact worst-case norm boundary is $B_* = 2^{1/s}$: smaller budgets give a positive gap, whereas at B_* and above collapse is possible with any prescribed density floor below one. We also identify the sharp worst-case boundary for the asymptotic escaped critical moment $\Theta = \lim_{K\to\infty} \sup_L \mathbb{E}[r_L^s \mathbf{1}_{r_L>K}]$. The condition $\Theta < 1$ gives an explicit uniform gap, while a collapsing family has $\Theta = 1$. More strongly, a single collapsing family has tail moment above one at most one and total moment at most two in every dimension; it meets the same tail cap simultaneously at every larger cutoff. For fixed $0 \le K < 1$, this tail cap instead guarantees a positive gap. Nevertheless stable one-vertex spikes realize every finite $\Theta > 0$, so critical-power uniform integrability is sufficient but not necessary. These conclusions use classical hypercontractivity, sign compression, balanced product tilts and rank-one perturbations. External priority is unestablished. Global many-body weights are allowed; no fixed-range Gibbs, local-dynamics or physical-gap conclusion follows.

The constructions serve different conclusions. The code family in Theorem 1 preserves labelled marginals and produces many slow transfer modes. The product tilts in Theorems 10 and 13 establish the moment-budget boundary, without the code family's marginal matching. The final section gives a sufficient tail condition, stable counterexamples to its necessity, and collapse at the finite-cutoff endpoint in Theorem 17. These are separate families; their properties are not asserted jointly.

1 The question and the transfer convention

Local marginal agreement and rapid relaxation are different kinds of information. The distinction is familiar in limited independence and Markov-chain theory, but a comparison must specify the dynamics: a slow single-site heat-bath chain does not automatically give a slow transfer operator. We make this distinction within a single fixed-coupling transfer family and require exact, rather than approximate, agreement of marginal input.

Let $\Omega_L = \mathbb{F}_2^L$, with Hamming distance $d(x,y)$. Fix $\beta > 0$ and put $q = e^{-2\beta}$. Our unweighted kernel is

$$M_\beta(x,y) = q^{d(x,y)} = e^{-\beta L} \exp\left(\beta \sum_{i=1}^{L} (-1)^{x_i + y_i}\right). \tag{1}$$

For a strictly positive probability law μ on Ω_L, define

$$A_\mu = \operatorname{diag}(\sqrt{\mu}) M_\beta \operatorname{diag}(\sqrt{\mu}). \tag{2}$$

The kernel M_β is a tensor power of $\left(\begin{smallmatrix} 1 & q \\ q & 1 \end{smallmatrix}\right)$ and is positive definite. The same is true of A_μ, which also has strictly positive entries. Write its eigenvalues in decreasing order as $\lambda_1 > \lambda_2 \geq \cdots > 0$, counting multiplicities, and set

$$\operatorname{gap}(A_\mu) = 1 - \lambda_2/\lambda_1.$$

Perron–Frobenius strictness gives a positive gap at each finite L; a bound uniform in L is a separate matter. Multiplying either kernel by a positive scalar does not change any eigenvalue ratio.

Let $u_L = \operatorname{Unif}(\Omega_L)$. Tensorization gives

$$\lambda_2(A_{u_L})/\lambda_1(A_{u_L}) = \frac{1-q}{1+q} = \tanh \beta. \tag{3}$$

For a law ν, the literal marginal input of order r is

$$\mathcal{M}_r(\nu) = (\nu_S : S \subseteq [L],\ |S| \leq r), \tag{4}$$

where coordinate labels are retained. Full conditional distributions, entrywise weight bounds, and the transfer matrix itself are not included in this tuple.

Theorem 1. *For each fixed $\beta > 0$ there are constants $\alpha, R, \gamma > 0$ such that, for all sufficiently large integers L, a strictly positive law μ_L on Ω_L has the following properties. Put $r_L = \lfloor \alpha L \rfloor$ and $m_L = 2^{\lceil RL \rceil}$.*

1. *$\mathcal{M}_{r_L}(\mu_L) = \mathcal{M}_{r_L}(u_L)$.*
2. *For every $2 \leq j \leq m_L$,*
$$0 < 1 - \lambda_j(A_{\mu_L})/\lambda_1(A_{\mu_L}) \leq 7e^{-\gamma L}. \tag{5}$$
3. *Let $v > 0$ be the unit Euclidean Perron vector of A_{μ_L}. The reversible Perron Doob chain*
$$P_L(x,y) = \frac{A_{\mu_L}(x,y) v_y}{\lambda_1 v_x}, \qquad \pi_L(x) = v_x^2, \tag{6}$$
has $\mathcal{M}_{r_L}(\pi_L) = \mathcal{M}_{r_L}(u_L)$ and the same normalized spectrum as A_{μ_L}.

One admissible choice is

$$R = \min\left\{\frac{1 - h(1/4)}{2}, \frac{\beta}{4 \log 2}\right\}, \quad h(\alpha) < R/2, \quad \gamma = \beta/2 - R \log 2 \geq \beta/4, \tag{7}$$

with $0 < \alpha < 1/2$ and binary entropy $h(p) = -p \log_2 p - (1-p) \log_2 (1-p)$.

There are at least $m_L - 1$ slow nonleading modes in this statement. We do not assert that their eigenvalues coincide. The positivity and strict gap at each finite size are compatible with their exponentially small separation from the Perron root. The theorem does not impose a uniform lower bound on the weights or a bounded interaction range.

2 Codes with two distance conditions

We include the coding argument to make all hypotheses of the spectral construction explicit. Simultaneously good primal and dual codes are classical; stronger algorithmic constructions are available [4]. The relation between code projections and limited independence is standard background for the marginal comparison [3].

Lemma 2. *Suppose $0 < \alpha, \delta < 1/2$ and $h(\alpha) < R < 1 - h(\delta)$. Put $k = \lceil RL \rceil$. If $k < L$ and*

$$2^{k-L(1-h(\delta))} + 2^{-k+Lh(\alpha)} < 1, \tag{8}$$

there is a binary linear code $C \subseteq \mathbb{F}_2^L$ of dimension k such that every nonzero codeword has weight at least δL and $C^\perp$ has no nonzero word of weight at most $\lfloor \alpha L \rfloor$. Every coordinate projection of C onto at most $\lfloor \alpha L \rfloor$ coordinates is surjective. The displayed conditions hold for all sufficiently large L.

Proof. Choose a uniformly random binary $k \times L$ matrix G. For each fixed nonzero row vector $z \in \mathbb{F}_2^k$, the word zG is uniform in $\mathbb{F}_2^L$. The probability that some such zG has weight less than δL is at most

$$2^k 2^{-L} \sum_{j \le \delta L} \binom{L}{j} \le 2^{k-L(1-h(\delta))}.$$

Failure of full row rank is included in this event, since it produces a zero word from a nonzero message. For a fixed nonzero column vector $w \in \mathbb{F}_2^L$, the vector Gw is uniform in $\mathbb{F}_2^k$. Thus the probability of a nonzero dual word with weight at most $\lfloor \alpha L \rfloor$ is at most

$$2^{-k} \sum_{1 \le j \le \alpha L} \binom{L}{j} \le 2^{-k+Lh(\alpha)}.$$

Their sum is less than one, so both failures can be avoided simultaneously.

For the entropy estimate, if $0 < p < 1/2$, set $z = p/(1-p) < 1$. Since $z^j \ge z^{pL}$ for $j \le pL$, the binomial theorem gives

$$\sum_{j \le pL} \binom{L}{j} \le z^{-pL}(1+z)^L = 2^{Lh(p)}.$$

This bound applies to the inclusive sums and hence to the strict-weight failure event as well. No integrality assumption on δL is needed.

If the columns indexed by S were dependent, their relation would give a nonzero word of $C^\perp$ supported in S. Consequently G_S has rank $|S|$ whenever $|S| \le \lfloor \alpha L \rfloor$. Uniform messages therefore give uniform projections onto $\mathbb{F}_2^S$. Finally, the exponents in (8) tend to minus infinity, since $k = RL + O(1)$ and both entropy inequalities are strict. □

3 A finite positive concentration estimate

The spectral step needs only the size and minimum distance of the code. The dual distance will enter through the marginal statement.

Proposition 3. *Let $C \subseteq \mathbb{F}_2^L$ be a binary linear code with size $m \ge 2$ and minimum nonzero weight d_C. Suppose its coordinate projections onto sets of size at most r are surjective. For $0 < \eta \le 1/2$, let*

$$\mu = (1-\eta)\,\mathrm{Unif}(C) + \eta u_L, \qquad s = (m-1)e^{-2\beta d_C}. \tag{9}$$

Then μ is strictly positive, $\mathcal{M}_r(\mu) = \mathcal{M}_r(u_L)$, and every $2 \le j \le m$ satisfies

$$0 < 1 - \lambda_j(A_\mu)/\lambda_1(A_\mu) \le 2s + 2m(\sqrt{\eta} + \eta). \tag{10}$$

Proof. Uniform codewords have uniform projections by surjectivity, and a mixture of two laws with the same marginals has those same marginals. The positive product part gives strict positivity at every configuration.

Every codeword has probability

$$a = (1-\eta)/m + \eta/2^L \ge 1/(2m).$$

The principal block of A_μ indexed by C is aM_{CC}. Its diagonal is a, and the off-diagonal row sums of M_{CC} are at most s: distinct codewords differ by a nonzero codeword of weight at least d_C. Thus all eigenvalues of M_{CC} lie in $[1-s, 1+s]$. For example, the norm of its symmetric off-diagonal part is bounded by the maximum absolute row sum. Principal interlacing gives

$$\lambda_j(A_\mu) \ge \lambda_m(A_\mu) \ge a(1-s) \quad (1 \le j \le m). \tag{11}$$

Independently, a coordinate Rayleigh vector gives $\lambda_1(A_\mu) \ge a$.

Write A_μ in C, C^c blocks. The outside principal block is positive semidefinite, and its trace is $\sum_{C^c} \mu = \eta(1 - m/2^L) \le \eta$, so its norm is at most η. For the rectangular cross block B, all entries of M_β are at most one, and therefore

$$\|B\|^2 \le \|B\|_{\mathrm{F}}^2 \le \left(\sum_C \mu\right)\left(\sum_{C^c} \mu\right) \le \eta.$$

The symmetric block matrix with off-diagonal blocks B, B^* and zero diagonal has norm $\|B\|$. Consequently

$$\|A_\mu - \mathrm{diag}(aM_{CC}, 0)\| \le \sqrt{\eta} + \eta, \qquad \lambda_1(A_\mu) \le a(1+s) + \sqrt{\eta} + \eta.$$

Subtract (11), divide by $\lambda_1 \ge a$, and use $a \ge 1/(2m)$ to obtain (10). Perron strictness proves the strict lower inequality. The upper bound is valid even when it is larger than one; no small-size success is claimed. □

Proof of Theorem 1, parts one and two. Use (7) and Lemma 2 with $\delta = 1/4$. The choice of R satisfies $0 < R < 1 - h(1/4)$ and $R \log 2 \le \beta/4$. Choose codes for sufficiently large L, and put

$$m = 2^{\lceil RL \rceil}, \qquad \eta = e^{-2\beta L}/m^2.$$

This number lies in $(0, 1/4]$. Since $d_C \ge L/4$ and $m \le 2e^{R(\log 2)L}$,

$$2(m-1)e^{-2\beta d_C} \le 4e^{-(\beta/2 - R\log 2)L} = 4e^{-\gamma L}.$$

Also, using $m \ge 2$ and $\gamma \le \beta$,

$$2m(\sqrt{\eta} + \eta) = 2e^{-\beta L} + 2e^{-2\beta L}/m \le 3e^{-\beta L} \le 3e^{-\gamma L}.$$

Proposition 3 now proves both claims. The condition $k < L$ ensures $m < 2^L$, so every asserted eigenvalue index exists. □

4 Stationary marginals survive the Perron transform

The weighting law in a transfer congruence need not equal the stationary law of its associated Markov chain. Matching the former alone would leave a significant interpretive gap. Code symmetry pays the latter exactly.

Lemma 4. *For the mixture (9), the Perron stationary law $\pi(x) = v_x^2$ satisfies $\mathcal{M}_r(\pi) = \mathcal{M}_r(u_L)$.*

Proof. For every $c \in C$, translation $x \mapsto x + c$ preserves μ, Hamming distance, and hence A_μ. The corresponding permutation commutes with A_μ and takes a positive unit Perron vector to another such vector. Uniqueness forces $v_{x+c} = v_x$, so π is invariant under translations by C. If $|S| \le r$, every translation on $\mathbb{F}_2^S$ lifts to some $c \in C$ by the assumed surjectivity. The S-marginal of π is therefore invariant under all translations and must be uniform. □

Completion of Theorem 1. The Perron eigenvector equation gives row sums one for (6). Symmetry gives detailed balance:

$$\pi(x)P_L(x,y) = v_x A_\mu(x,y) v_y/\lambda_1 = \pi(y)P_L(y,x).$$

Conjugation by $\mathrm{diag}(v)$ shows that P_L is similar to A_μ/λ_1. It has strictly positive entries and the claimed spectrum. Apply Lemma 4 to obtain its stationary marginal assertion. For the uniform weight, the Perron vector and stationary law are uniform, and (3) supplies the comparison chain. □

5 An exact parity control with different dynamics

The positive parity family

$$\mu_t(x) = 2^{-L}(1 + t\chi_{[L]}(x)), \qquad |t| < 1, \qquad \chi_S(x) = (-1)^{\sum_{i\in S} x_i}, \tag{12}$$

has all proper marginals equal to product marginals. Its single-site heat-bath gap tends to zero as $|t| \to 1$ at fixed size $L \ge 2$ and fixed finite positive site rates [6]. Nevertheless, its transfer ratio at fixed β is bounded uniformly away from one, as follows.

Proposition 5. *Let $L \ge 2$, $\rho = \tanh\beta$, and $|t| < 1$. Up to a common positive scalar, the spectrum of A_{μ_t} is the union over unordered complement pairs $\{S, S^c\}$ of the two roots*

$$\frac{z_s \pm \sqrt{z_s^2 - 4\Delta}}{2}, \quad z_s = \rho^s + \rho^{L-s}, \quad s = |S|, \quad \Delta = (1-t^2)\rho^L. \tag{13}$$

The Perron root is the upper root at $s = 0$, and the second eigenvalue is the upper root at $s = 1$. In particular,

$$\frac{\lambda_2(A_{\mu_t})}{\lambda_1(A_{\mu_t})} \le \frac{\rho + \rho^{L-1}}{1 + \rho^L} \le \tanh(2\beta) < 1. \tag{14}$$

The last bound is sharp as a supremum over $L \ge 2$ and $|t| < 1$.

Proof. The row-normalized product transfer $P_\beta = M_\beta/(1+q)^L$ acts on χ_S by $\rho^{|S|}$. Write $D_t = \mathrm{diag}\sqrt{1 + t\chi_{[L]}}$. The weighted congruence, apart from a common scalar, is $D_t P_\beta D_t$, which is similar to $P_\beta D_t^2$ since D_t is invertible. Multiplication by $\chi_{[L]}$ exchanges χ_S and χ_{S^c}. The coefficient block on that ordered pair is

$$\begin{pmatrix} \rho^s & t\rho^s \\ t\rho^{L-s} & \rho^{L-s} \end{pmatrix}.$$

Its trace is z_s and its determinant is Δ, yielding (13). The 2^{L-1} complement pairs exhaust the character basis, with repetitions counted as usual.

The largest z_s is $z_0 = 1 + \rho^L$, and the largest among proper pairs is $z_1 = \rho + \rho^{L-1}$. The upper root increases with z_s. The lower root in the empty/full pair is at most ρ^L, whereas the upper root for $s = 1$ is at least ρ. Every other lower root is no larger than its own upper root. This identifies the two largest eigenvalues.

For fixed $\Delta > 0$, the upper root divided by z is

$$\frac{1 + \sqrt{1 - 4\Delta/z^2}}{2},$$

which increases with $z \geq 2\sqrt{\Delta}$. Comparing $z_1 \leq z_0$ proves the first inequality in (14). For the second, write $b = \rho^{L-2} \leq 1$; the ratio is $\rho(1 + b)/(1 + \rho^2 b)$, increasing in b. Its maximum is $2\rho/(1 + \rho^2) = \tanh(2\beta)$. For $L = 2$ and $t \to 1$, $\Delta \to 0$, so equality is approached. □

This control rules out a tempting shortcut: the known parity heat-bath obstruction cannot be transferred by changing the name of the operator. The code construction uses a different geometric ingredient, a set of exponentially many mutually separated configurations while retaining surjective coordinate projections.

6 What marginal certificates cannot establish

Corollary 6. *Fix the constants of Theorem 1. Suppose F is a valid lower bound on the transfer gap for every strictly positive weight, and factors through the tuple*

$$(L, \beta, \mathcal{M}_{r_L}(\mu), \mathcal{M}_{r_L}(\pi)).$$

At the product input and for all sufficiently large L, its value is at most $7e^{-\gamma L}$. The same conclusion holds if only one of the two marginal tuples is supplied.

Proof. At the same L and β, the constructed weight and its stationary law supply exactly the same input as the uniform weight and uniform stationary law. A function of that input takes the same value on both. Validity on the constructed example and (5) for $j = 2$ force the asserted bound. □

The corollary does not assert that every such functional is zero or that the product chain is slow. Its actual gap is $1 - \tanh\beta$. Nor does it concern a certificate using full conditionals, uniform density bounds, the operator entries, or code membership: those are additional information. In particular, the weights here can have exponentially small probabilities and global many-body interactions. The theorem says nothing against a result restricted to uniformly controlled, fixed-range Gibbs weights. The Perron Doob chain updates a full configuration and is not a local single-site dynamics. We make no claim about continuum Yang–Mills, a physical mass gap, entropy tensorization, or a specified spatial mixing rate. The many-mode conclusion is spectral; no separate theorem about metastable sets is implicit.

7 Upper density control without a lower bound

The obstruction above allows the maximum density relative to product to increase with dimension. A uniform upper bound changes the conclusion; a positive lower bound is not required. Write

$\rho = \tanh\beta$ and let P_ρ be the Boolean noise operator in $L^2(u_L)$, whose Walsh multipliers are $\rho^{|S|}$. For a nonnegative density r with $\mathbb{E}_{u_L} r = 1$, put

$$T_r = \operatorname{diag}(\sqrt{r}) P_\rho \operatorname{diag}(\sqrt{r}).$$

Since $P_\rho = M_\beta/(1+e^{-2\beta})^L$, for $\mu = 2^{-L}r$ we have $A_\mu = 2^{-L}(1+e^{-2\beta})^L T_r$. Thus the eigenvalue ratios agree. Here zeros of r are allowed; we keep the zero eigenvalues outside its support in the full 2^L-dimensional list.

Theorem 7. *Let $L \geq 1$, $0 < \rho < 1$, $B \geq 1$, and $0 \leq r \leq B$ with $\mathbb{E}_{u_L} r = 1$. Set*

$$e_\rho = \frac{1+\rho^2}{(1-\rho)^2}, \qquad c(B,\rho) = B^{-1}(2B)^{-2e_\rho}.$$

The two largest eigenvalues of T_r satisfy $1 - \lambda_2/\lambda_1 \geq c(B,\rho) > 0$, independently of L. In particular, no positive lower bound on r is needed.

Proof. All norms and scalar products use u_L. The noise operator is positive semidefinite, fixes constants and is a contraction. Hence $\lambda_1 \leq B$. The unit vector $\sqrt{r}$ has Rayleigh quotient $\langle r, P_\rho r\rangle \geq (\mathbb{E} r)^2 = 1$, by Walsh expansion, so $1 \leq \lambda_1 \leq B$. On $S = \{r > 0\}$ the matrix is strictly positive; its Perron vector is positive on S and its leading eigenvalue is simple.

We use two classical Boolean hypercontractive inequalities. Put $q_* = 1 + \rho^{-2}$ and $p_* = 1 - \rho$. Then

$$\|P_\rho f\|_{q_*} \leq \|f\|_2, \qquad \langle f, P_\rho g\rangle \geq \|f\|_{p_*}\|g\|_{p_*} \quad (f, g \geq 0). \tag{15}$$

For clarity about conventions, equations (1.1)–(1.2) and tensorization in [7] use time $t = -\log\rho$ for the uniform Boolean semigroup. For the second inequality set $p_*' = p_*/(p_* - 1) = -(1-\rho)/\rho$. Then $\frac{1}{2}\log((1-p_*')/(1-p_*)) = -\log\rho$. The reverse inequality gives $\|P_\rho g\|_{p_*'} \geq \|g\|_{p_*}$; reverse Hölder gives the displayed bilinear bound. This is first applied to positive functions, then to $f+\varepsilon, g+\varepsilon$ and the limit $\varepsilon \downarrow 0$. Finite sums and $p_* > 0$ justify that limit; we do not take a negative moment of a function with zeros.

If $\lambda_2 < \lambda_1/2$, the gap exceeds $1/2$. Otherwise $\lambda_2 \geq 1/2$. Choose a real unit second eigenvector w orthogonal to the Perron vector. It vanishes off S and has both signs. Write $w = sh_+ - th_-$, where $s, t > 0$, $s^2 + t^2 = 1$, and h_+, h_- are nonnegative orthonormal functions with disjoint supports. Positivity and the eigenrelation give pointwise $\lambda_2 h_\pm \leq T_r h_\pm$: on the corresponding sign support this follows from the eigenrelation, and elsewhere from positivity. Integration against the unit $h_\pm$ gives $\lambda_2 \leq \langle \sqrt{r}h_\pm, P_\rho\sqrt{r}h_\pm\rangle$. For $f_\pm = \sqrt{r}\,h_\pm$ this yields

$$\lambda_2 f_\pm \leq r P_\rho f_\pm, \qquad \|f_\pm\|_{q_*} \leq \frac{B}{\lambda_2}\|f_\pm\|_2, \qquad \|f_\pm\|_2^2 \geq \langle f_\pm, P_\rho f_\pm\rangle \geq \lambda_2.$$

The middle inequality uses the first part of (15). No division by r occurs.

Let $\theta = p_*(q_*-2)/(2(q_*-p_*))$. Ordinary Hölder applied to powers of f gives $\|f\|_2 \leq \|f\|_{p_*}^{\theta}\|f\|_{q_*}^{1-\theta}$, since $1/2 = \theta/p_* + (1-\theta)/q_*$. This does not require a normed space at exponent $p_* < 1$: the Hölder weights $2\theta/p_*$ and $2(1-\theta)/q_*$ are positive and sum to one. Thus each sign part satisfies

$$\|f_\pm\|_{p_*} \geq \sqrt{\lambda_2}(B/\lambda_2)^{-e_\rho}, \qquad \frac{1-\theta}{\theta} = \frac{q_*(2-p_*)}{p_*(q_*-2)} = e_\rho.$$

By the second part of (15), the cross entry obeys

$$d = \langle h_+, T_r h_-\rangle = \langle f_+, P_\rho f_-\rangle \geq \lambda_2(B/\lambda_2)^{-2e_\rho}.$$

The compression of T_r to the basis (h_+, h_-) is $\left(\begin{smallmatrix} a & d \\ d & b \end{smallmatrix}\right)$. Its eigenvector $(s, -t)$ has eigenvalue λ_2, giving $a - \lambda_2 = dt/s$ and $b - \lambda_2 = ds/t$. Its other eigenvalue is $\lambda_2 + d/(st)$, because $s^2 + t^2 = 1$. The variational principle and $st \le 1/2$ now imply $\lambda_1 - \lambda_2 \ge d/(st) \ge 2d$. Consequently

$$1 - \frac{\lambda_2}{\lambda_1} \ge \frac{2\lambda_2}{\lambda_1}(B/\lambda_2)^{-2e_\rho} \ge B^{-1}(2B)^{-2e_\rho}.$$

This does not deteriorate when one sign part has small norm. In the previously omitted case, $c(B, \rho) \le 1/4 < 1/2$, since $e_\rho \ge 1$. If the support has one point, $\lambda_2 = 0$ and the gap is one, so that case is included as well. □

Corollary 8. *At fixed ρ, suppose a sequence has $\operatorname{gap}(T_{r_L}) \le Ke^{-\gamma L}$, with $K, \gamma > 0$. Then*

$$\max r_L \ge \left(\frac{2^{-2e_\rho}}{K}\right)^{1/(2e_\rho+1)} e^{\gamma L/(2e_\rho+1)}.$$

Proof. Apply Theorem 7 with $B = \max r_L \ge 1$ and rearrange. □

For Theorem 1, take $K = 7$ and its positive γ. The code mixture has maximum density $2^L(1-\eta)/|C| + \eta$, consistent with this necessary growth. Upper density growth alone is not asserted to be sufficient for collapse. Tiny minimum density alone cannot cause collapse under a uniform maximum-density bound. These are statements about this transfer family, not single-site heat-bath dynamics. The constants are not claimed optimal.

The moment analysis separates universal guarantees from adverse examples. The two strict exponent regimes are followed by auxiliary critical estimates and an explicit rate, then the exact critical-budget theorem. The final critical-tail section gives the sharp escaped-moment and fixed-cutoff boundaries, and a stable counterexample to necessity of uniform integrability. Earlier partial estimates are retained for their explicit rate and proof dependencies; they are not additional independent discoveries.

8 Density-moment threshold: the two strict regimes

A pointwise density cap is stronger than necessary. We next replace it by a dimension-independent finite moment. A second construction shows why one cannot simply assume that any finite moment suffices. All norms in this section use the uniform probability law u_L; the operator is the same T_r as in Section 7.

Theorem 9. *Fix $0 < \rho < 1$, $s > (1+\rho)/(1-\rho)$ and $B \ge 1$. For every $L \ge 1$ and density $r \ge 0$ with $\mathbb{E}r = 1$ and $\|r\|_s \le B$,*

$$\operatorname{gap}(T_r) \ge \min\{1/2, (2B)^{-2e}\} > 0, \qquad e = \frac{2\rho s}{(1-\rho)(s(1-\rho) - 1 - \rho)}.$$

Neither a pointwise upper bound nor a positive lower bound is assumed.

Proof. Set $A = 1 + \rho$, $p = 1 - \rho$, $t = 1 + 1/\rho$ and

$$Q = \frac{st}{s+t} = \frac{s(1+\rho)}{s\rho + 1 + \rho}.$$

The condition on s is exactly $Q > A$, so $Q > A > 1 > p > 0$. Ordinary Boolean hypercontractivity gives

$$\|P_{\sqrt{\rho}} f\|_2 \le \|f\|_A, \qquad \|P_\rho f\|_t \le \|f\|_A.$$

Indeed the noise thresholds are respectively $\sqrt{(A-1)/(2-1)} = \sqrt{\rho}$ and $\sqrt{(A-1)/(t-1)} = \rho$. The reverse bilinear inequality in (15) applies at exponent p.

As before, testing the unit vector $\sqrt{r}$ gives $\lambda_1 \geq 1$. For any real unit vector h, put $f = \sqrt{r}\, h$ and $A_0 = 2s/(s+1) > A$. Hölder and probability-space monotonicity give

$$\langle h, T_r h\rangle = \|P_{\sqrt{\rho}} f\|_2^2 \leq \|f\|_A^2 \leq \|f\|_{A_0}^2 \leq \|\sqrt{r}\|_{2s}^2 \|h\|_2^2 \leq B,$$

where $1/A_0 = 1/(2s) + 1/2$. Thus $1 \leq \lambda_1 \leq B$ without using a maximum-density estimate.

If $\lambda_2 < \lambda_1/2$, the gap is greater than $1/2$. Otherwise $\lambda_2 \geq 1/2$. On the nonempty support of r the matrix has strictly positive entries. A real unit second eigenvector vanishes off this support and has both signs, by orthogonality to the positive Perron vector. Write it as $w = ch_+ - dh_-$ with $c, d > 0$, $c^2 + d^2 = 1$ and nonnegative orthonormal disjoint sign parts. Positivity and the eigenrelation imply $\lambda_2 h_\pm \leq T_r h_\pm$ pointwise, including their zero sets. For either $f = \sqrt{r}\, h_\pm$, multiplication by $\sqrt{r}$ gives $\lambda_2 f \leq r P_\rho f$. Hölder with $1/Q = 1/s + 1/t$ yields

$$\|f\|_Q \leq (B/\lambda_2)\|f\|_A.$$

Integration against the unit sign part also gives $\lambda_2 \leq \langle f, P_\rho f\rangle \leq \|f\|_A^2$. Let $0 < \theta < 1$ solve $1/A = \theta/p + (1-\theta)/Q$. Hölder applied to powers, with positive weights $A\theta/p$ and $A(1-\theta)/Q$ summing to one, gives $\|f\|_A \leq \|f\|_p^\theta \|f\|_Q^{1-\theta}$. No triangle inequality at exponent $p < 1$ is used. Combining these bounds,

$$\|f\|_p \geq \sqrt{\lambda_2}(B/\lambda_2)^{-e}, \qquad e = \frac{1-\theta}{\theta} = \frac{Q(A-p)}{p(Q-A)} = \frac{2\rho s}{(1-\rho)(s(1-\rho)-1-\rho)}.$$

Reverse hypercontractivity now bounds the cross entry by $D = \langle h_+, T_r h_-\rangle \geq \lambda_2 (B/\lambda_2)^{-2e}$. The two-dimensional compression, exactly as in the proof of Theorem 7, has eigenvalues λ_2 and $\lambda_2 + D/(cd)$. Since $cd \leq 1/2$, the variational principle gives

$$\operatorname{gap}(T_r) \geq \frac{2D}{\lambda_1} \geq \frac{2\lambda_2}{\lambda_1}(B/\lambda_2)^{-2e} \geq (2B)^{-2e}.$$

Here $2\lambda_2/\lambda_1 \geq 1$ and $\lambda_2 \geq 1/2$. Combining the two cases proves the claim. One-point support has $\lambda_2 = 0$ and is already covered. No step divides by r. □

Theorem 10. *Fix $0 < \rho < 1$, $1 < s < s_c := (1+\rho)/(1-\rho)$ and $B > 1$. There are strictly positive mean-one densities r_L, for every $L \geq 1$, with $\|r_L\|_s \leq B$ and $r_L \geq 1/B$, and constants $\kappa > 1$ and $0 < \omega < \kappa$, independent of L, such that*

$$0 < \operatorname{gap}(T_{r_L}) \leq 2(\omega/\kappa)^L + \varepsilon^{-1}\kappa^{-L}, \qquad \varepsilon = (B-1)/2.$$

Thus a uniform positive lower density does not prevent exponential gap collapse throughout the strict subcritical moment regime.

Proof. Relabel the cube as $\{-1,1\}^L$. For a fixed tilt $0 < \delta < 1$, put

$$n = \left(\frac{(1+\delta)^s + (1-\delta)^s}{2}\right)^{1/s}, \qquad w_\pm(x) = \frac{1 \pm \delta x}{n}, \qquad m = n^{-1}.$$

Strict convexity gives $n > 1$, while $\|w_\pm\|_s = 1$ and $\mathbb{E} w_\pm = m$. Define $R_{\pm,L}(x) = \prod_i w_\pm(x_i)$ and

$$Z_L = 1 + 2\varepsilon m^L, \qquad r_L = \frac{1 + \varepsilon(R_{+,L} + R_{-,L})}{Z_L}.$$

Product integration gives $\|R_{\pm,L}\|_s = 1$ and $\mathbb{E}R_{\pm,L} = m^L$. Hence $r_L > 0$, $\mathbb{E}r_L = 1$, $\|r_L\|_s \le (1+2\varepsilon)/Z_L \le B$, and $r_L \ge 1/Z_L \ge 1/B$.

Write $Q = P_{\sqrt{\rho}}$. Since $Q^2 = P_\rho$, the matrices $T_{r_L} = AA^*$ and $S_L = A^*A$, with $A = M_{\sqrt{r_L}}Q$, have identical spectra, including multiplicities. Here M_f denotes multiplication by f. Direct expansion gives

$$Z_L S_L = P_\rho + \varepsilon(X_L + Y_L), \qquad X_L = H_+^{\otimes L}, \quad Y_L = H_-^{\otimes L},$$

where the one-site matrices, in the orthonormal Walsh basis $(1, x)$, are

$$H_\pm = \frac{1}{n}\begin{pmatrix} 1 & \pm\delta\sqrt{\rho} \\ \pm\delta\sqrt{\rho} & \rho \end{pmatrix}.$$

They are positive definite and conjugate by $\mathrm{diag}(1,-1)$. Their common simple top eigenvalue is

$$\kappa(\delta) = \frac{1+\rho+\sqrt{(1-\rho)^2+4\rho\delta^2}}{2n(\delta)}.$$

At zero, $\kappa(0) = 1$, $(\log\kappa)'(0) = 0$, and differentiation yields

$$(\log\kappa)''(0) = \frac{2\rho}{1-\rho} - (s-1) > 0.$$

All functions are smooth near zero. Taylor's theorem therefore gives $\kappa > 1$ for every sufficiently small positive δ. Fix one such $\delta < 1$. This choice depends on ρ, s and is independent of L; no uniform exponential rate as $s \uparrow s_c$ is asserted.

Set $\omega = \|H_+^{1/2}H_-^{1/2}\|$. Positive definiteness and submultiplicativity give $0 < \omega \le \kappa$. If equality held, norm attainment at a unit vector v would force equality in both steps of

$$\|H_+^{1/2}H_-^{1/2}v\| \le \sqrt{\kappa}\,\|H_-^{1/2}v\| \le \kappa.$$

The second equality makes v a top eigenvector of H_-; the first then makes it a top eigenvector of H_+. But $H_+ - H_-$ has zero diagonal and nonzero equal off-diagonal entries, so is invertible. It cannot annihilate their common top eigenvector. Thus $\omega < \kappa$.

For $N = 2^L \ge 2$, use the N-by-$2N$ matrix $C = [\sqrt{X_L}, \sqrt{Y_L}]$. Its two Gram matrices satisfy

$$CC^* = X_L + Y_L, \qquad C^*C = \begin{pmatrix} X_L & \sqrt{X_L}\sqrt{Y_L} \\ \sqrt{Y_L}\sqrt{X_L} & Y_L \end{pmatrix}.$$

The block diagonal part has its two largest eigenvalues equal to κ^L. Tensorization of positive square roots and of operator norms gives $\|\sqrt{X_L}\sqrt{Y_L}\| = \omega^L$, which is also the norm of the self-adjoint off-diagonal perturbation. The variational eigenvalue bound consequently gives

$$\lambda_1(X_L + Y_L) \le \kappa^L + \omega^L, \qquad \lambda_2(X_L + Y_L) \ge \kappa^L - \omega^L > 0.$$

Indeed C^*C and CC^* have the same N positive eigenvalues, with N additional zeros only in C^*C, so both leading bounds transfer even when $L = 1$. Also $X_L + Y_L \ge X_L$ gives $\lambda_1(X_L + Y_L) \ge \kappa^L$.

Finally P_ρ is positive semidefinite of norm one. For $F_L = Z_L S_L$, the variational principle and norm bound imply

$$\lambda_1(F_L) \le \varepsilon(\kappa^L + \omega^L) + 1, \qquad \lambda_2(F_L) \ge \varepsilon(\kappa^L - \omega^L), \qquad \lambda_1(F_L) \ge \varepsilon\kappa^L.$$

Subtracting and dividing gives the claimed upper bound. The scalar Z_L cancels from the ratio, and S_L and the actual T_{r_L} have the same spectrum. Its entrywise positivity gives strict Perron separation at every finite L. Both terms in the upper bound decay exponentially, although the bound can exceed one at small L. □

Theorems 9 and 10 separate the two strict regimes at the same value s_c. The next two sections treat the critical exponent $s = s_c$: first quantitative bounds in two budget ranges, then the exact budget boundary including equality. At $B = 1$, Jensen forces $r = 1$ and the actual gap is $1 - \rho$; the sufficient lower bound is not claimed optimal. The tilted family does not claim product marginals for its weighting or stationary law. It isolates the moment obstruction for the same transfer operator, whereas Theorem 1 isolates the marginal-information obstruction. The earlier two-point-spike construction in the retained analytical sources covers the narrower interval $1 < s < \log 2/\log(2/(1+\rho))$; it remains valid but is superseded here by the product-tilt construction.

9 Auxiliary critical estimates and an explicit rate

At $s = s_c = (1+\rho)/(1-\rho)$ the size of the moment budget matters. We give a sufficient stability condition near $B = 1$ and a counterexample for every $B > 2$. These preliminary bounds are retained for their quantitative content. Section 10 then resolves the intervening budget range and the exact boundary. All norms in this section use the uniform probability measure u_L.

Theorem 11 (Small critical budgets)**.** *Fix $0 < \rho < 1$ and $s = s_c$. For any $L \geq 1$ and any density $r \geq 0$ with $\mathbb{E}r = 1$ and $\|r\|_s \leq B$, $B \geq 1$,*

$$\operatorname{gap}(T_r) \geq \max\{0, 1 - \rho - d_s(B)\}, \qquad d_s(B) = \begin{cases} (B^s - 1)^{1/s}, & s \geq 2, \\ \sqrt{\dfrac{2(B^s-1)}{s(s-1)}}\,(B+1)^{(2-s)/2}, & 1 < s < 2. \end{cases}$$

In particular, each fixed ρ admits a nontrivial interval of budgets $B > 1$ with a positive dimension-independent gap. No pointwise density bounds are required.

Proof. Put $Q = P_{\sqrt{\rho}}$ and $S_r = QM_rQ$, which has the spectrum of T_r. Ordinary Boolean hypercontractivity, recalled in [7, Eq. (1.1)], gives $\|Qf\|_q \leq \|f\|_2$ for $q = 2s/(s-1)$, since $\rho = (s-1)/(s+1) = 1/(q-1)$. Hölder's inequality with exponents s, q, q yields

$$|\langle f, QM_{r-1}Qg\rangle| \leq \|r-1\|_s \|Qf\|_q \|Qg\|_q \leq \|r-1\|_s \|f\|_2 \|g\|_2.$$

Thus $\|S_r - P_\rho\| \leq \|r-1\|_s$ and $\lambda_2(S_r) \leq \rho + \|r-1\|_s$. Also $\lambda_1(S_r) \geq \langle 1, S_r 1\rangle = 1$. It remains to show $\|r-1\|_s \leq d_s(B)$.

Define $\phi_s(t) = t^s - 1 - s(t-1)$ for $t \geq 0$, so that $\mathbb{E}\phi_s(r) \leq B^s - 1$. For $s \geq 2$ and $u \geq 0$,

$$\phi_s(1+u) = s\int_0^u ((1+v)^{s-1} - 1)\,dv \geq u^s,$$

using $(1+v)^{s-1} \geq 1 + v^{s-1}$. For $0 \leq u \leq 1$, the derivative of $\phi_s(1-u) - u^s$ is $s[1 - (1-u)^{s-1} - u^{s-1}] \geq 0$ and its value at zero is zero. Hence $\phi_s(t) \geq |t-1|^s$, proving the first estimate by integration. For $1 < s < 2$, the integral Taylor remainder gives

$$\begin{aligned} \phi_s(t) &= s(s-1)(t-1)^2 \int_0^1 (1-v)[1 + v(t-1)]^{s-2}\,dv \\ &\geq \frac{s(s-1)}{2}\frac{(t-1)^2}{(t+1)^{2-s}}. \end{aligned}$$

At $t = 0$ the identity follows by continuity; the integral is finite for $s > 1$. For $W = (r-1)^2/(r+1)^{2-s}$, Hölder gives

$$\mathbb{E}|r-1|^s \leq (\mathbb{E}W)^{s/2}(\mathbb{E}(r+1)^s)^{(2-s)/2}.$$

Use $\mathbb{E}W \le 2(B^s-1)/(s(s-1))$ and $\|r+1\|_s \le B+1$. Both formulas for $d_s(B)$ tend to zero as $B \downarrow 1$. Positive semidefiniteness supplies the trivial zero lower bound. □

Theorem 12 (Balanced critical tilt)**.** *Fix $0<\rho<1$, $s=s_c$, and $B>2$. There are constants $c,d>0$, independent of L, and strictly positive densities r_L, for every $L\ge 1$, such that*

$$\mathbb{E}r_L = 1, \quad \|r_L\|_s \le B, \quad r_L \ge 1/B, \qquad 0 < \operatorname{gap}(T_{r_L}) \le 2\sqrt{B-1}\, e^{-cd^2L^{1/3}}.$$

Proof. For a uniform sign $x \in \{-1,1\}$ and $|\delta|<1$ define

$$n(\delta) = \left(\frac{(1+\delta)^s + (1-\delta)^s}{2}\right)^{1/s}, \quad w_\delta(x) = \frac{1+\delta x}{n(\delta)}, \quad m(\delta) = n(\delta)^{-1}.$$

The one-site matrix is

$$H(\delta) = \frac{1}{n(\delta)} \begin{pmatrix} 1 & \delta\sqrt{\rho} \\ \delta\sqrt{\rho} & \rho \end{pmatrix}, \qquad D = \operatorname{diag}(1,\rho).$$

It is positive definite with top eigenvalue

$$\kappa(\delta) = \frac{1+\rho+\sqrt{(1-\rho)^2+4\rho\delta^2}}{2n(\delta)}.$$

For $\tau(\delta) = \|D^{1/2}H(\delta)^{1/2}\|$, the square is the top eigenvalue of $D^{1/2}H(\delta)D^{1/2}$, so

$$\tau(\delta)^2 = \frac{1+\rho^2+\sqrt{(1-\rho^2)^2+4\rho^2\delta^2}}{2n(\delta)}.$$

These positive functions have even analytic logarithms near zero. Taylor expansion with bounded fourth derivative gives, at $s=s_c$,

$$\begin{aligned} \log n(\delta) &= \frac{\rho}{1-\rho}\delta^2 + O(\delta^4), \\ \log \kappa(\delta) &= O(\delta^4), \\ \log \tau(\delta) &= -\frac{\rho}{2(1-\rho^2)}\delta^2 + O(\delta^4). \end{aligned}$$

Indeed, the respective square-root numerators divided by two are $1+\rho\delta^2/(1-\rho)+O(\delta^4)$ and $1+\rho^2\delta^2/(1-\rho^2)+O(\delta^4)$. Consequently there are $0<\delta_*<1$, $C\ge 1$ and $c>0$ such that, for $|\delta|\le\delta_*$,

$$|\log\kappa(\delta)| \le C\delta^4, \qquad \log\tau(\delta) \le -c\delta^2.$$

For example, $c=\rho/[4(1-\rho^2)]$ works after reducing δ_*. Choose a fixed $0<d\le\delta_*$ with $Cd^4 \le \log(B-1)$, possible because $B>2$. Put

$$\delta_L = dL^{-1/3}, \quad a_L = \kappa(\delta_L)^{-L}, \quad R_L = \prod_{i=1}^{L} w_{\delta_L}(x_i), \quad Z_L = 1 + a_L m(\delta_L)^L, \quad r_L = \frac{1+a_L R_L}{Z_L}.$$

The coefficient balances the two top block eigenvalues exactly. Since $|\log a_L| \le Cd^4L^{-1/3} \le \log(B-1)$, we have $a_L \le B-1$ and $a_L \to 1$. Product measure gives $\|R_L\|_s = 1$ and $\mathbb{E}R_L = m(\delta_L)^L$, with $0<m(\delta_L)<1$. Therefore $\mathbb{E}r_L = 1$, $\|r_L\|_s \le (1+a_L)/Z_L \le B$, and $r_L \ge 1/Z_L \ge 1/B$ for every $L\ge 1$.

Let $X_L = H(\delta_L)^{\otimes L}$. Spectral equivalence gives $F_L = Z_L S_{r_L} = P_\rho + a_L X_L$. Both summands have top eigenvalue one. For the N by $2N$ matrix $\mathcal{C}_L = [P_\rho^{1/2}, \sqrt{a_L} X_L^{1/2}]$, $N = 2^L$, the Gram matrix $\mathcal{C}_L^* \mathcal{C}_L$ has those summands on its diagonal and off-diagonal block of norm

$$\eta_L = \sqrt{a_L}\, \tau(\delta_L)^L \le \sqrt{B-1}\, e^{-cd^2 L^{1/3}}.$$

Its block diagonal has two leading eigenvalues exactly one. The off-diagonal self-adjoint perturbation has norm η_L, whence $\lambda_1 \le 1 + \eta_L$ and $\lambda_2 \ge 1 - \eta_L$. The N positive eigenvalues of $\mathcal{C}_L \mathcal{C}_L^* = F_L$ are precisely the positive eigenvalues of $\mathcal{C}_L^* \mathcal{C}_L$; the latter has N additional zeros. Thus the bounds apply to the first two eigenvalues of F_L, including at $L = 1$. Since $F_L \ge P_\rho$, $\lambda_1(F_L) \ge 1$ and $\mathrm{gap}(F_L) \le 2\eta_L$. Scalar normalization and AA^*/A^*A preserve the ratio. Strict entrywise positivity of T_{r_L} gives its strictly positive finite-dimensional gap. □

The uniform component is a spectral channel here, rather than an additive error to discard. At the critical exponent the tilted top eigenvalue has zero quadratic variation, while its cross norm with the uniform channel has negative quadratic variation. The dimension-dependent tilt separates these orders, and balancing removes the residual diagonal mismatch. The small-budget estimate uses classical hypercontractivity and elementary perturbation theory; the large-budget family asserts neither matching marginals nor fixed-range interactions. The sufficient budget $B > 2$ is not optimal; the next section identifies the exact threshold without claiming a rate there.

10 The exact critical moment budget

The preceding balanced construction has a sharper limiting moment than the triangle inequality used to obtain its all-dimension rate bound. Combining that limit with a sign decomposition of a second eigenvector identifies the entire critical budget boundary. Throughout this section, all norms and expectations use uniform probability on $\{-1, 1\}^L$.

Theorem 13 (Exact critical budget)**.** *Fix $0 < \rho < 1$, $s = (1+\rho)/(1-\rho)$, and $B_* = 2^{1/s}$. For every $L \ge 1$ and $r \ge 0$ with $\mathbb{E} r = 1$,*

$$2\lambda_2(T_r)^s \le \mathbb{E} r^s. \tag{16}$$

Consequently $\|r\|_s \le B < B_*$ implies

$$\mathrm{gap}(T_r) \ge 1 - B/B_* > 0.$$

For each fixed $b \in (0,1)$ there are strictly positive densities $\widetilde{r}_L$, for every $L \ge 1$, such that

$$\mathbb{E}\widetilde{r}_L = 1, \qquad \|\widetilde{r}_L\|_s \le B_*, \qquad \widetilde{r}_L \ge b, \qquad \mathrm{gap}(T_{\widetilde{r}_L}) \longrightarrow 0.$$

Thus the infimum of the gap over all dimensions and densities with $\|r\|_s \le B$ is positive exactly for $1 \le B < B_*$. The same classification holds with any prescribed fixed floor $r \ge b$, $0 < b < 1$. The positive lower bound displayed above is not asserted optimal; no convergence rate at $B = B_*$ is asserted.

Proof. Two sign regions. Put $Q = P_{\sqrt{\rho}}$ and $p = 1 + \rho = 2s/(s+1)$. Endpoint Boolean hypercontractivity gives $\|Qg\|_2 \le \|g\|_p$. For h supported on C, Hölder's inequality gives

$$\begin{aligned} \langle h, T_r h \rangle &= \|Q(\sqrt{r}\, h)\|_2^2 \\ &\le \|\sqrt{r}\, h\|_p^2 \le \left(\mathbb{E}[r^s \mathbf{1}_C]\right)^{1/s} \|h\|_2^2. \end{aligned} \tag{17}$$

Indeed, before raising to $2/p$, the conjugate exponents are $2/(2-p)$ and $2/p$, and $p/(2-p) = s$.

On its nonempty active support $A = \{r > 0\}$, the matrix T_r is strictly entrywise positive. It has a simple positive Perron root and a Perron vector strictly positive on A. Its other coordinates form a zero block. If $\lambda_2 = 0$, (16) is immediate. Otherwise a real second eigenvector f vanishes off A and is orthogonal to the Perron vector. Both its positive and negative parts f_+, f_- are therefore nonzero, including when λ_2 has multiplicity greater than one. Entrywise positivity gives

$$\lambda_2 \|f_+\|_2^2 = \langle f_+, T_r f_+ \rangle - \langle f_+, T_r f_- \rangle \le \langle f_+, T_r f_+ \rangle.$$

Applying (17) on $\{f > 0\}$ yields $\lambda_2^s \le \mathbb{E}[r^s \mathbf{1}_{\{f>0\}}]$. The negative part gives the analogous bound on $\{f < 0\}$. Adding over these disjoint regions proves (16). No mean-zero condition under uniform measure is imposed on f. Finally $\sqrt{r}$ is a unit vector and

$$\lambda_1(T_r) \ge \langle r, P_\rho r \rangle \ge (\mathbb{E} r)^2 = 1$$

by the nonnegative Walsh eigenvalues. This proves the positive gap bound below B_*. At $B = 1$, strict Jensen forces $r = 1$ and the actual gap is $1 - \rho$.

The balanced family's exact moment. Use the single-site quantities n, w, m, H, κ, τ from Theorem 12, with any sufficiently small fixed $d > 0$ and $\delta_L = dL^{-1/3}$. This step does not impose the earlier condition involving $B > 2$. Define

$$a_L = \kappa(\delta_L)^{-L}, \quad R_L = \prod_{i=1}^{L} w_{\delta_L}(x_i), \quad Z_L = 1 + a_L m(\delta_L)^L, \quad r_L = (1 + a_L R_L)/Z_L.$$

The critical expansions already proved give $a_L \to 1$ and $m(\delta_L)^L \to 0$, hence $Z_L \to 1$. For the latter limit, $\log m(\delta) = -(s-1)\delta^2/2 + O(\delta^4)$ and $L\delta_L^2 \to \infty$, whereas $L\delta_L^4 \to 0$. The overlap $\eta_L = \sqrt{a_L}\tau(\delta_L)^L$ tends to zero. More explicitly, the quadratic coefficient of $\log \tau$ is

$$\frac{1}{2}\left[\frac{\rho^2}{1-\rho^2} - \frac{s-1}{2}\right] = -\frac{\rho}{2(1-\rho^2)}.$$

The same Gram comparison, now without a prescribed all-L budget, gives $1 \le \lambda_1(S_L) \le 1 + \eta_L$ and $\lambda_2(S_L) \ge 1 - \eta_L$ for $S_L = P_\rho + a_L H(\delta_L)^{\otimes L}$. For large L, the second bound is positive, so it corresponds to a nonzero eigenvalue rather than an added Gram zero. Since $QM_{r_L}Q = S_L/Z_L$, both of its top eigenvalues tend to one. They are the actual eigenvalues of T_{r_L}: for $X = M_{\sqrt{r_L}}Q$, the square matrices X^*X and XX^* have identical spectra, including zeros and multiplicities.

For each fixed $0 < t < s$, direct single-site expansion yields

$$\log \mathbb{E} w_\delta^t = \frac{t(t-s)}{2}\delta^2 + O(\delta^4).$$

Thus $\mathbb{E} R_L^t \to 0$, while $\mathbb{E} R_L^s = 1$ exactly. The remainders may depend on fixed t; no uniformity near the endpoints is needed. Set $\theta = \min\{1, s/2\}$. Both θ and $s - \theta$ belong to $(0, s)$, and

$$0 \le (1+y)^s - 1 - y^s \le s2^{s-1}(y^\theta + y^{s-\theta}), \qquad y \ge 0. \tag{18}$$

For $0 \le y \le 1$, the mean-value theorem bounds the left side by $s2^{s-1}y \le s2^{s-1}y^\theta$. For $y \ge 1$, apply that bound to $1/y$ and multiply by y^s, obtaining $s2^{s-1}y^{s-1} \le s2^{s-1}y^{s-\theta}$. The lower bound follows from $s > 1$. Substitute $y = a_L R_L$ in (18) and take expectations. The two interior moments vanish and $a_L \to 1$, so

$$\mathbb{E}(1 + a_L R_L)^s = 1 + a_L^s + o(1) \longrightarrow 2.$$

Dividing by $Z_L^s \to 1$ proves $B_L := \|r_L\|_s \to 2^{1/s} = B_*$.

The exact boundary and a prescribed floor. Each r_L is nonconstant, so $B_L > 1$. Put

$$\varepsilon_L = \begin{cases} 0, & B_L \le B_*, \\ (B_L - B_*)/(B_L - 1), & B_L > B_*, \end{cases} \qquad \widetilde{r}_L = (1-\varepsilon_L) r_L + \varepsilon_L.$$

The only denominator used is positive. Since $B_L \to B_* > 1$, we have $0 \le \varepsilon_L < 1$ and $\varepsilon_L \to 0$. Normalization and positivity persist, and Minkowski gives

$$\|\widetilde{r}_L\|_s \le (1-\varepsilon_L) B_L + \varepsilon_L \le B_*.$$

Because $Z_L > 1$, both r_L and 1 are at least $1/Z_L$, so the mixture has that same floor.

For signed h, the dual endpoint estimate $\|Qf\|_q \le \|f\|_2$, $q = 2s/(s-1)$, and Hölder with $1/s + 2/q = 1$ give $\|QM_hQ\| \le \|h\|_s$. Hence

$$\|QM_{\widetilde{r}_L - r_L} Q\| \le \varepsilon_L \|1 - r_L\|_s \le \varepsilon_L (1 + B_L) \longrightarrow 0.$$

Weyl's bound and the exact X^*X/XX^* spectral identity imply that both top eigenvalues of $T_{\widetilde{r}_L}$ still tend to one. Its normalized gap therefore tends to zero. This argument requires neither pointwise upper control nor a square-root multiplier estimate.

Given fixed $0 < b < 1$, eventually $1/Z_L \ge b$. Replace the finite initial segment by the constant density 1. Every stated constraint then holds for every $L \ge 1$, with the same limiting gap. The same sequence is admissible for all $B \ge B_*$. Each finite transfer matrix remains strictly positive, so its individual gap is positive; only the dimension-free infimum vanishes. A floor $b = 1$ would force the uniform density and is explicitly excluded. □

The sign-region argument is classical. In the additive lattice setting, Biskup and König [2, Lemma 4.5 and Eq. (4.29)] bound the second eigenvalue using the two sign regions and split a potential budget between them. Here endpoint hypercontractivity gives the restricted s-moment estimate, while the balanced construction and vanishing dilution attain the boundary asymptotically. This comparison credits the mechanism; it does not establish historical priority of the exact multiplicative-cube classification. The new family makes no matching-marginal or fixed-range interaction claim.

11 The escaped critical-moment boundary

Fix $0 < \rho < 1$ and $s = (1+\rho)/(1-\rho)$ throughout this section. Expectations and norms refer to the uniform Boolean measure. Write $Q = P_{\sqrt{\rho}}$ and $T_r = M_{\sqrt{r}} P_\rho M_{\sqrt{r}}$, where $r \ge 0$ and $\mathbb{E}r = 1$. For a family indexed by $L \ge 1$, define

$$H(K) = \sup_L \mathbb{E}[r_L^s \mathbf{1}_{r_L > K}], \qquad \Theta = \lim_{K\to\infty} H(K) = \inf_{K \ge 1} H(K).$$

The nonnegative monotone limit is allowed to be infinite. Uniform integrability of the critical powers is the special case $\Theta = 0$.

Theorem 14 (Finite cutoff with tail budget below one)**.** *Suppose $K \ge 1$, $0 \le \tau < 1$, and $\mathbb{E}[r^s \mathbf{1}_{r>K}] \le \tau$. Put*

$$t = \tau^{1/(2s)}, \quad m = \frac{1+t}{2}, \quad d = \frac{1-t}{2}, \quad B_K = (K^{s-1} + \tau)^{1/s}.$$

Then

$$\operatorname{gap}(T_r) \geq \min\left\{1-m^2, \frac{2d^{2s^2}K^{1-s^2}}{B_K}\right\} > 0.$$

In particular, $\Theta < 1$ implies a dimension-independent positive gap. No optimality is claimed for the displayed positive constant.

Proof. For $w \geq 0$ and $\|h\|_2 = 1$, Hölder and forward hypercontractivity, with $p = 1+\rho$ and $p/(2-p) = s$, give

$$\|Q\sqrt{w}h\|_2^2 \leq \|\sqrt{w}h\|_p^2 \leq \|w\|_s.$$

Since $r^s\mathbf{1}_{r\leq K} \leq K^{s-1}r$, the total moment is at most $K^{s-1}+\tau$. Thus $\lambda_1(T_r) \leq B_K$. The unit vector $\sqrt{r}$ also gives $\lambda_1 \geq \langle r, P_\rho r\rangle \geq 1$ by the nonnegative Walsh spectrum. If the active support has one point, $\lambda_2 = 0$ and the gap is one. If $\lambda_2 < m^2$, the gap is greater than $1-m^2$.

Otherwise choose a real second eigenvector, orthogonal to the positive active Perron vector. Write it as $uh_+ - vh_-$, with $u, v > 0$, $u^2+v^2 = 1$, and disjointly supported nonnegative unit vectors h_+, h_-. Their uniform means need not be equal. Set $D = \langle h_+, T_r h_-\rangle > 0$. The eigenvector equations give

$$A_+ = \lambda_2 + (v/u)D, \qquad A_- = \lambda_2 + (u/v)D, \quad A_\pm = \langle h_\pm, T_r h_\pm\rangle.$$

For each sign split $f = \sqrt{r}h_\pm$ at $r = K$. Then $\|Qf\|_2 \geq m$ and $\|Qf_{\text{high}}\|_2 \leq t$, so

$$\|Qf_{\text{low}}\|_2 \geq d, \qquad \|f_{\text{low}}\|_p \geq d, \qquad \|f_{\text{low}}\|_2 \leq \sqrt{K}.$$

For $a = 1-\rho$ and $\theta = s^{-2}$ the identity $1/p = \theta/a + (1-\theta)/2$ and power-Hölder give $\|g\|_p \leq \|g\|_a^\theta \|g\|_2^{1-\theta}$. This applies ordinary Hölder to powers and requires no quasi-norm triangle inequality. The positive lower p-norm permits division; hence $\|f_{\text{low}}\|_a \geq d^{1/\theta}K^{-(1-\theta)/(2\theta)}$. Positivity and reverse hypercontractivity yield

$$D \geq \langle f_{+,\text{low}}, P_\rho f_{-,\text{low}}\rangle \geq d^{2s^2}K^{1-s^2}.$$

The sign compression has eigenvalues λ_2 and $\lambda_2 + D/(uv)$. Its largest eigenvalue is at most λ_1, so $\lambda_1 - \lambda_2 \geq 2D$. Dividing by $\lambda_1 \leq B_K$ proves the bound, including repeated second eigenvalues. Finally, if $\Theta < 1$, choose $\Theta < \tau < 1$ and a single finite K with $H(K) \leq \tau$. The same constants then apply to every L. □

Uniform integrability is sufficient but stronger than needed. For example, a bound

$$\sup_L \mathbb{E}[r_L^s \psi(r_L)] \leq C < \infty$$

with a nonnegative nondecreasing function ψ diverging at infinity implies $H(K) \leq C/\psi(K)$ when $\psi(K) > 0$. This is a weighted-moment condition; an arbitrary such ψ need not be a Young function or define a Luxemburg norm. A fixed $s+\varepsilon$ moment bound also implies $H(K) \leq K^{-\varepsilon}\sup_L \mathbb{E}r_L^{s+\varepsilon}$. Neither condition follows from a mere critical-moment bound.

A total bound $\sup_L \|r_L\|_s \leq B$ does imply

$$\Theta \leq B^s - 1. \tag{19}$$

Indeed $\mathbb{E}[r_L\mathbf{1}_{r_L>K}] \leq B^sK^{1-s}$, while Jensen for $X_L = r_L\mathbf{1}_{r_L\leq K}$ gives $\mathbb{E}X_L^s \geq (1-B^sK^{1-s})_+^s$. Subtraction and the limit $K\to\infty$ prove (19). For $B < 2^{1/s}$ this recovers a positive gap. The direct exact-budget theorem already gives the stronger explicit lower bound $1 - B/2^{1/s}$.

Proposition 15 (Escaped moment with a stable gap)**.** *For any $M > 1$, $B > M^{1/s}$, and $0 < b < 1$, there are densities r_L with $\mathbb{E}r_L = 1$, $r_L \geq b$, $\|r_L\|_s \leq B$, and*

$$\mathbb{E}r_L^s \to M, \qquad \mathbb{E}[r_L^s \mathbf{1}_{r_L > K}] \to M - 1 \quad (K > 1 \text{ fixed}),$$

while $\mathrm{gap}(T_{r_L}) \to 1 - \rho$ *and* $\mathrm{gap}(T_{r_L}) \geq (1-\rho)/2$ *for every* $L \geq 1$.

Proof. Set $N = 2^L$, $c = (M-1)^{1/s}$, choose a vertex z_L, and first put

$$q_L = \frac{1 + cN^{1/s}\mathbf{1}_{z_L}}{Z_L}, \qquad Z_L = 1 + cN^{1/s-1}.$$

These densities have mean one, lower bound $1/Z_L \to 1$, and moments

$$\mathbb{E}q_L^s = \frac{1 - N^{-1} + (N^{-1/s} + c)^s}{Z_L^s} \longrightarrow 1 + c^s = M.$$

For each fixed $K > 1$ only the exceptional vertex eventually exceeds K, and its contribution tends to $c^s = M - 1$.

The operators T_{q_L} and $S_L = QM_{q_L}Q$ are isospectral, including multiplicities, since they are AA^* and A^*A for $A = M_{\sqrt{q_L}}Q$. In probability-normalized L^2, the vector $e_z = \sqrt{N}\mathbf{1}_{z_L}$ is a unit vector and $M_{\mathbf{1}_{z_L}} = |e_z\rangle\langle e_z|$. Therefore

$$S_L = \frac{P_\rho + cN^{1/s}Q|e_z\rangle\langle e_z|Q}{Z_L}, \qquad \|Q|e_z\rangle\langle e_z|Q\| = \langle e_z, P_\rho e_z\rangle = \left(\frac{1+\rho}{2}\right)^L.$$

It follows that $\|S_L - P_\rho\| \leq \delta_L$, where

$$\delta_L = \frac{cd_\rho^L + ca_\rho^L}{Z_L}, \quad d_\rho = 2^{-(1-1/s)}, \quad a_\rho = \frac{1+\rho}{2^{2\rho/(1+\rho)}}.$$

Both bases lie strictly between zero and one. For a_ρ, strict convexity of $t \log t$ on $[1,2]$ gives $(1+\rho)\log(1+\rho) < 2\rho \log 2$.

The largest two eigenvalues of P_ρ are 1 and ρ, counting multiplicity. The min-max principle bounds the changes in both by δ_L. Also $\langle 1, S_L 1\rangle = 1$, so $\lambda_1(S_L) \geq 1$. Consequently

$$\left|\frac{\lambda_2(S_L)}{\lambda_1(S_L)} - \rho\right| \leq (1+\rho)\delta_L.$$

Choose L_0 so that for every $L \geq L_0$ the floor and norm bounds hold and $c(d_\rho^L + a_\rho^L) \leq (1-\rho)/(2(1+\rho))$. Existence uses $B^s > M$ and the strict exponential contractions. Finally set $r_L = 1$ for $L < L_0$ and $r_L = q_L$ otherwise. The prefix has gap $1 - \rho$; the tail has the asserted common bound. All limits persist. □

Proposition 16 (Sharpness and nonnecessity of the tail criterion)**.** *The universal guarantee $\Theta < 1$ cannot be extended to $\Theta \leq 1$: the exact-budget family of Theorem 13 has $\Theta = 1$ and gaps tending to zero. For every finite $\Theta_0 > 0$, there are nevertheless families with $\Theta = \Theta_0$ and a uniform positive gap, even with an arbitrarily prescribed density floor below one. Thus $\Theta \geq 1$ is necessary for collapse, but not sufficient.*

Proof. First suppose $r_L \to 1$ in probability and $\mathbb{E}r_L^s \to M < \infty$. For each fixed $K > 1$, the function $F_K(x) = x^s \mathbf{1}_{x \le K}$ is bounded and continuous at one, so $\mathbb{E}F_K(r_L) \to 1$. This follows by splitting a neighborhood of one from its probability-small complement and works on the varying cubes. Therefore the tail moments tend to $M - 1$ for every such K, giving $\Theta \ge M - 1$. For the upper bound fix $\varepsilon > 0$ and $K_0 > 1$. For all sufficiently large L, the total moment is at most $M + \varepsilon$ and $\mathbb{E}F_{K_0}(r_L) \ge 1 - \varepsilon$. For every $K \ge K_0$ their tail moments are then at most $M - 1 + 2\varepsilon$. A larger cutoff kills the tails of the finitely many remaining finite functions. Taking the supremum over all L, then $K \to \infty$ and $\varepsilon \downarrow 0$, proves $\Theta = M - 1$. This finite-prefix step is required; the fixed-K limit alone would not justify exchanging the supremum and cutoff limit.

The diluted balanced family of Theorem 13 satisfies $r_L \to 1$ in probability: its tilt has every smaller positive moment tending to zero, while the balancing and dilution parameters tend to one and zero, respectively. Also $\lambda_2(T_{r_L}) \to 1$ and $2\lambda_2^s \le \mathbb{E}r_L^s \le 2$, so the critical moment tends to two. Hence $\Theta = 1$, while that family's gap tends to zero. Finally apply Proposition 15 with $M = 1 + \Theta_0$. Its densities converge to one in probability, have critical moment tending to M, and keep the positive gap there proved. Thus $\Theta = \Theta_0$. Its strict total-budget slack and finite-prefix replacement remain part of the construction. □

Theorem 17 (The fixed-cutoff endpoint)**.** *For every $0 < b < 1$, there is a single family of densities r_L with*

$$\mathbb{E}r_L = 1, \qquad r_L \ge b, \qquad \mathbb{E}r_L^s \le 2, \qquad \mathbb{E}[r_L^s \mathbf{1}_{r_L > 1}] \le 1$$

for every $L \ge 1$, but $\lambda_1(T_{r_L}), \lambda_2(T_{r_L}) \to 1$. Moreover $r_L \to 1$ in probability, $\mathbb{E}r_L^s \to 2$, and $\Theta = 1$. Thus the finite-cutoff guarantee in Theorem 14 cannot include $\tau = 1$ for $K \ge 1$, even under the exact total moment cap and a prescribed positive floor. The same family satisfies the tail cap at every $K \ge 1$ simultaneously; it depends on ρ and b, but not on K.

Proof. Use the undiluted product tilt R_L from the proof of Theorem 13. It satisfies

$$R_L > 0, \qquad \mathbb{E}R_L^s = 1, \qquad \mathbb{E}R_L^t \longrightarrow 0 \quad (0 < t < s).$$

Write $m_L = \mathbb{E}R_L \le 1$. The same proof supplies coefficients $\beta_L \to 1$ such that $w_L = (1 + \beta_L R_L)/Z_L$, with $Z_L = 1 + \beta_L m_L \to 1$, has both leading eigenvalues tending to one. Here β_L denotes the balancing coefficient previously called a_L; the new coefficient below is different. The product definition gives additional information at its own mean. For $\delta_L = dL^{-1/3}$ and the single-site normalizer $n(\delta_L)$, $m_L = n(\delta_L)^{-L} > 0$, so exactly

$$\frac{R_L}{m_L} = \prod_{i=1}^{L}(1 + \delta_L x_i), \qquad \mathbb{E}(R_L/m_L)^t = \left(\frac{(1+\delta_L)^t + (1-\delta_L)^t}{2}\right)^L.$$

Fix $0 < t < 1$. The logarithm of the bracket is an even smooth function on any fixed compact interval $|\delta| \le d < 1$. Taylor's theorem, with bounded fourth derivative there, yields

$$\log \frac{(1+\delta)^t + (1-\delta)^t}{2} = \frac{t(t-1)}{2}\delta^2 + O_{t,d}(\delta^4).$$

After multiplication by L, the leading term tends to minus infinity as $L^{1/3}$ and the remainder tends to zero. Markov's inequality gives $\mathbb{P}(R_L > m_L) \le \mathbb{E}(R_L/m_L)^t \to 0$. This relative-mean estimate does not follow from $R_L \to 0$ alone. Set

$$p_L = \mathbb{P}(R_L > m_L)^{1/s}, \quad a_L = 1 - p_L, \quad A_L = 1 - a_L m_L, \quad q_L = A_L + a_L R_L.$$

All three coefficients belong to $[0,1]$, $\mathbb{E}q_L = 1$, and $a_L, A_L \to 1$, whence $q_L \to 1$ in probability. The identity $q_L - 1 = a_L(R_L - m_L)$ shows that $E_L = \{q_L > 1\}$ equals $\{R_L > m_L\}$ when $a_L > 0$ and is empty when $a_L = 0$. In both cases the event inclusion holds. Minkowski gives

$$\|q_L \mathbf{1}_{E_L}\|_s \le A_L \mathbb{P}(E_L)^{1/s} + a_L \|R_L \mathbf{1}_{E_L}\|_s \le p_L + a_L = 1.$$

No division by a_L occurs; its zero endpoint gives $q_L = 1$.

Put $S(v) = QM_vQ$. Endpoint forward hypercontractivity maps L^2 to $L^{2s/(s-1)}$ with norm at most one. Hölder therefore gives $\|QM_hQ\| \le \|h\|_s$ for every real h. In particular, $\|QM_{R_L}Q\| \le 1$, and

$$\|S(q_L) - S(w_L)\| \le |A_L - Z_L^{-1}| + |a_L - \beta_L/Z_L| \longrightarrow 0.$$

The square matrices $S(v)$ and T_v are X^*X and XX^* for $X = M_{\sqrt{v}}Q$, so are isospectral with multiplicities. The min-max perturbation bound thus transfers both actual leading eigenvalue limits to T_{q_L}.

We next prove $M_L := \mathbb{E}q_L^s \to 2$. The lower bound is $M_L \ge A_L^s + a_L^s \mathbb{E}R_L^s \to 2$. For a fixed $T > 0$, $q_L^s \mathbf{1}_{R_L \le T}$ converges in probability to one and is bounded by $(1+T)^s$, so its expectation tends to one. On $R_L > T$, $q_L^s \le (1 + 1/T)^s R_L^s$. Consequently $\limsup_L M_L \le 1 + (1+1/T)^s$. Letting $T \to \infty$ proves the claim. This auxiliary truncation is used only for the moment limit.

Set $\varepsilon_L = 0$ when $M_L \le 2$, and otherwise set $\varepsilon_L = (M_L - 2)/(M_L - 1)$. Then $0 \le \varepsilon_L < 1$ and $\varepsilon_L \to 0$. The mean-one density $v_L = (1 - \varepsilon_L)q_L + \varepsilon_L$ satisfies, by convexity,

$$\mathbb{E}v_L^s \le (1 - \varepsilon_L)M_L + \varepsilon_L \le 2.$$

Since $\varepsilon_L < 1$, the events $v_L > 1$ and $q_L > 1$ coincide. On this event $v_L \le q_L$, so pointwise $v_L^s \mathbf{1}_{v_L > 1} \le q_L^s \mathbf{1}_{q_L > 1}$. The strict tail cap at one is preserved. Also $S(v_L) - S(q_L) = \varepsilon_L(P_\rho - S(q_L)) \to 0$ in operator norm, since $\|S(q_L)\| \to 1$. Both eigenvalue limits persist, as does convergence in probability to one. The two-sign estimate (16) gives $2\lambda_2(T_{v_L})^s \le \mathbb{E}v_L^s \le 2$, and hence the critical moment tends to two.

Since $v_L \ge A_L \to 1$, replace a finite initial segment by $r_L = 1$ and use $r_L = v_L$ thereafter to impose $r_L \ge b$ in every dimension. The prefix has empty strict tail above one, and all limits are unchanged. For every $K \ge 1$, the tail integrand is pointwise at most the one at cutoff one. Thus this same family works simultaneously for all such K. For each fixed $J > 1$, the bounded truncation $r_L^s \mathbf{1}_{r_L \le J}$ has expectation tending to one. Thus the J-tail tends to one, giving $H(J) \ge 1$. The all-dimension tail bound at one also gives $H(J) \le 1$ for every $J > 1$. Therefore $H(J) = 1$ for every $J > 1$ and $\Theta = 1$. □

Each finite matrix in this construction has a positive Perron gap; the gaps tend to zero with dimension. The two moment caps are inequalities in each dimension, with total moment equality asserted only in the limit. The mean-relative probability coefficient resolves the cutoff-one case without a dimension-dependent cutoff.

Corollary 18 (Cutoffs below one)**.** *For $0 \le K < 1$, a nonnegative mean-one density satisfying $\mathbb{E}[r^s \mathbf{1}_{r > K}] \le 1$ has*

$$\operatorname{gap}(T_r) \ge 1 - \left(\frac{1 + K^{s-1}}{2}\right)^{1/s} > 0.$$

Proof. Pointwise $r^s \mathbf{1}_{r \le K} \le K^{s-1} r$, including $K = 0$. Thus $\mathbb{E}r^s \le 1 + K^{s-1} < 2$. The two-sign bound and $\lambda_1 \ge 1$ give $\lambda_2/\lambda_1 \le \lambda_2 \le (\mathbb{E}r^s/2)^{1/s}$. □

No optimality is claimed for this lower constant or for a general tail-budget threshold below cutoff one. The displayed bound is uniform in dimension for fixed $K < 1$, not uniform as K approaches one.

These are worst-case statements about a specialized fixed Boolean congruence. Scalar tails under the base measure are not the operator-tail functionals under a Perron invariant measure in [11]. The cutoff bound refines the same sign-truncation proof; it is not an independent method or a claim of historical priority. The qualitative boundary is sharp, while the positive constant is not optimized.

12 Comparison with hyperbounded and perturbation results

The value s_c is the classical Boolean hypercontractive boundary, not a new integrability scale. Indeed, for $a_s = 2s/(s+1)$, the norm-one estimate $\|P_{\sqrt{\rho}} f\|_2 \le \|f\|_{a_s}$ holds when $s \ge s_c$ by the standard inequality recalled in [7]. Its local sharpness is seen from $f = 1 + ux$ on one bit: $\|P_{\sqrt{\rho}} f\|_2^2 = 1 + \rho u^2$, whereas $\|f\|_{a_s}^2 = 1 + (a_s - 1)u^2 + o(u^2)$. Tensorization amplifies a violated one-bit norm bound. Such top-norm growth alone does not imply a closing normalized spectral gap; Theorem 10 adds two antipodal channels and their Gram comparison to obtain a near-degenerate second eigenvalue.

The inequalities and matrix arguments used above are classical. Related literature already supplies both qualitative gap criteria and, under different hypotheses, dimension-independent quantitative perturbation bounds. Miclo's Theorem 1 in [10] gives a gap for ergodic self-adjoint hyperbounded Markov operators. Section 6 and Proposition 11 also discuss a norm-budget transition at two for the fourth power of an L^2-to-L^4 Markov norm; this is an important precedent for budget thresholds, not the raw density norm used here. Hyperboundedness alone does not give a general quantitative gap. Wang's Theorem 1.1 in [11] gives a tail-norm criterion for the gap of an invariant Markov operator's symmetrization. These fixed-space conclusions must not be confused with a bound uniform over a family of increasing dimensions.

Here T_r is generally not Markov in u_L. Its Perron Doob transform is Markov in its own stationary law, which generally differs from ru_L. The ground-state multiplication is an L^2 isometry between these spaces, but does not automatically identify their higher norms uniformly in L. Thus an implication from a qualitative hyperboundedness theorem would still need a quantitative change-of-measure argument.

Gross's Theorem 2.2 in [8] does give dimension-independent gaps for additive Schrödinger perturbations on Riemannian probability manifolds with a base logarithmic Sobolev inequality and suitable moments of both e^V and e^{-V}. We have not identified that additive operator with the logarithm of this discrete transfer congruence. Our moment hypothesis in Theorem 9 supplies no inverse-density moment and permits zeros. In contrast, the counterexamples in Theorems 10 and 12 have $r \ge 1/B$ and therefore bounded inverse moments. For these families, missing inverse control is not a distinction from Gross; the operator/form and exponent correspondences are the unestablished steps. Glück [9] gives hyperboundedness criteria and uniform essential spectral-radius estimates; those estimates alone do not control the second eigenvalue of a finite matrix. These differences do not prove originality or exclude a stronger implication. Aida's directly accessible author preprint [1] uses an additive Schrödinger form with a derivation and chain-rule hypotheses, together with ground-state and weak-Poincaré inputs. Its setup and Theorem 10 were read in a targeted comparison; no identification of those hypotheses with this multiplicative Boolean transfer congruence has been established. No external priority, improvement over this literature, or exhaustive novelty clearance is asserted.

13 Relation to predecessors and reproducibility

The congruence analysis in [5] permits positive weights concentrating on an antipodal pair, with a transfer ratio tending to one as volume grows. Such a pair fails to preserve pair marginals. The parity analysis in [6] preserves every proper marginal but concerns a heat-bath generator; Proposition 5 shows precisely why it does not supply the transfer conclusion. The present synthesis obtains linear-order marginal matching for both the weight and the Perron stationary law, together with exponentially many slow transfer modes.

The code ingredients and the matrix methods are classical. In particular, Lemma 2 is an elementary existence argument, not a new code construction and not an efficient encoding claim. The citation to [3] supplies general limited-independence background, not a direct historical attribution for the dual-distance projection equivalence proved here. Work on simultaneously good primal and dual codes, including [4], is stronger in algorithmic aspects. Our targeted primary-source check did not identify the exact joint conclusion above; this is not proof of historical priority. External originality and the importance of this specialization remain unestablished.

All proofs are finite-dimensional and analytical. No numerical experiment or formal verification is needed or claimed. A source package retains the preregistered proof checks, complete analytical audit, source hashes and this manuscript. The permanent source tree is `papers/marginal-transfer` at the source commit below. The earlier spike proof is retained there in `evidence296/finite-moment296A.txt`; the balanced critical proof and its complete source audit are retained in `evidence298`. The exact-budget proof, registered checks and full analytical source audit are retained in `evidence299`. The full analytical reports, contexts, assignments and source bindings for the grouped tail results are in `evidence305` and `evidence307`. Their public-subset manifests explicitly identify private reference PDFs and an unrelated local directory index omitted from the original audit manifests; no redistribution of these files is implied. The exact v4 PDF assessment is preserved there solely as historical evidence, with all seven objections and a separate author response. Historical partial results and exact-PDF reviews keep their original artifact identities; this revision neither changes those reports nor inherits their grades. Document reproduction is a separate check of exact bytes and layout, not an independent proof of the theorems.

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