Sign Problem Free Qubit Regularized Hamiltonian Lattice Gauge Theory

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Supported by:
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Collaborators

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Qubit Regularization of Gauge Theories

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Classical and Quantum Dimer Models

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Conclusions

Qubit Regularization

Can we formulate quantum field theories so that we can study them using a quantum computer?

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Formulate a Hamiltonian lattice field theory
with a finite local Hilbert space
with an appropriate "continuum limit."

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Qubit Regularization of the QFT

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↑

Qubit Regularization of the QFT

Continuum limit = UV Quantum Critical Point

Particular Interest in Asymptotically Free Massive Theories

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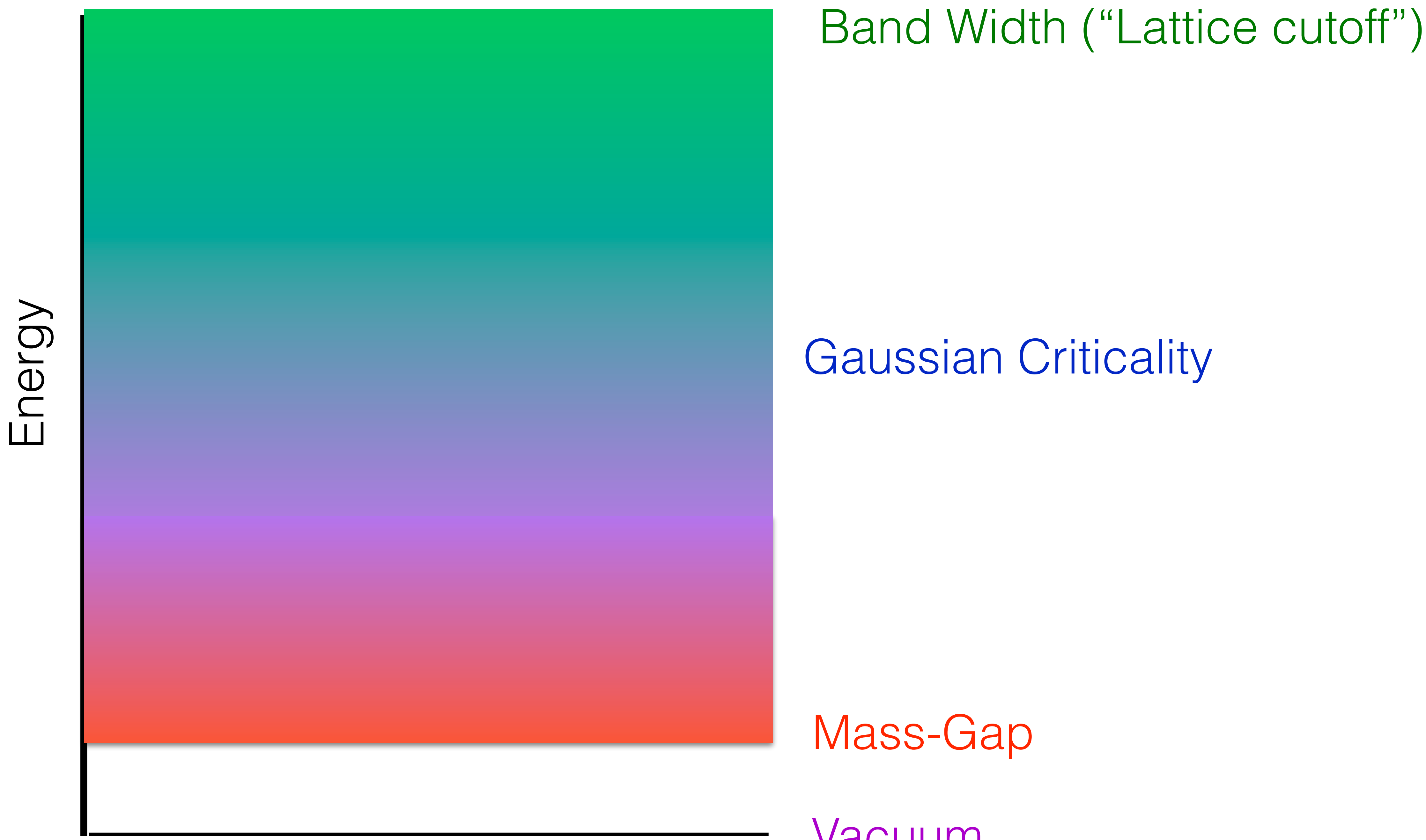

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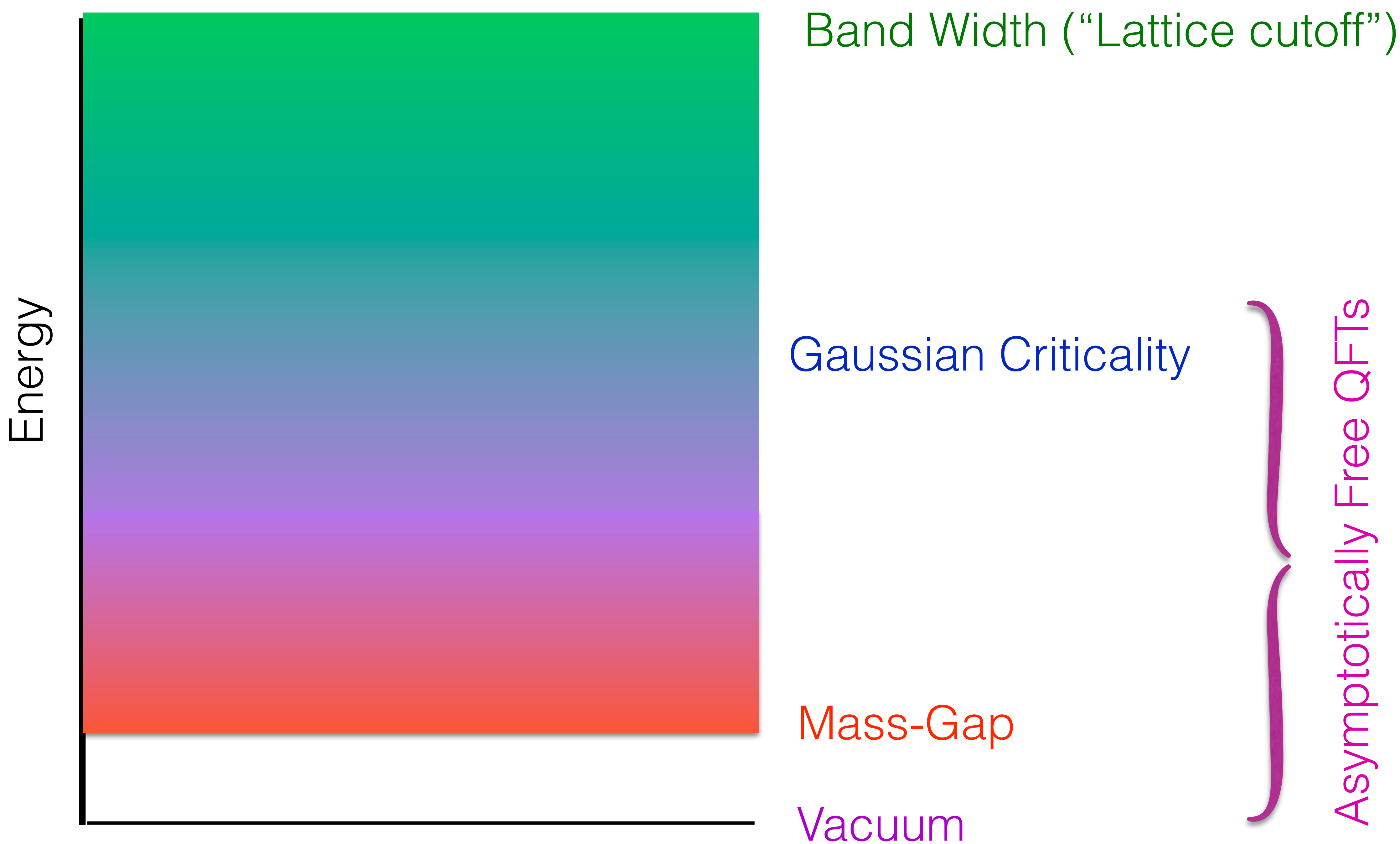

Example: O(3) Non-linear sigma model

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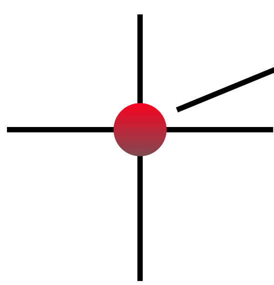
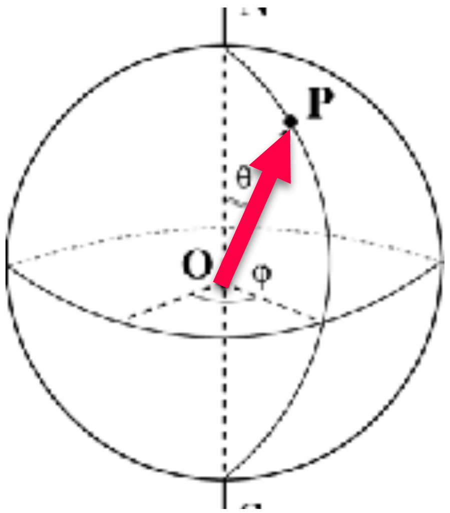
Traditional lattice Hilbert space

At each lattice site there is a quantum particle on a surface of a unit sphere





$$\vec{\phi}_x = (\phi_x^1, \phi_x^2, \phi_x^3)$$

$$\vec{\phi}_x \cdot \vec{\phi}_x = 1$$

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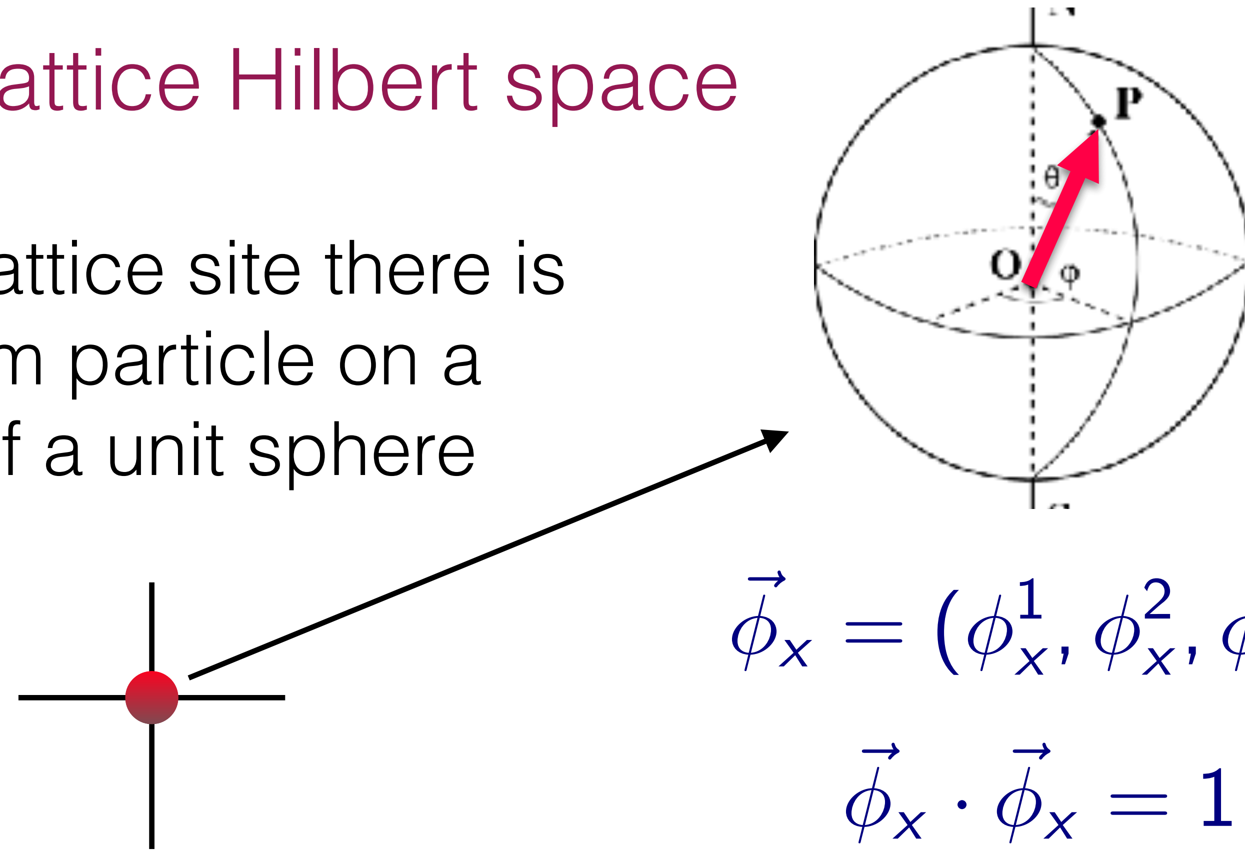

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Basis of the traditional Hilbert space $\mathcal{H}_{\text{Trad}}$:

$$\int d\Omega \; |\theta, \varphi\rangle\langle\theta, \varphi| \; = \; I \qquad\qquad \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \; | \; \ell, m \; \rangle\langle \; \ell, m \; | \; = \; I$$

"position basis"

"Representation basis"

Continuum Physics: Universal step-scaling function

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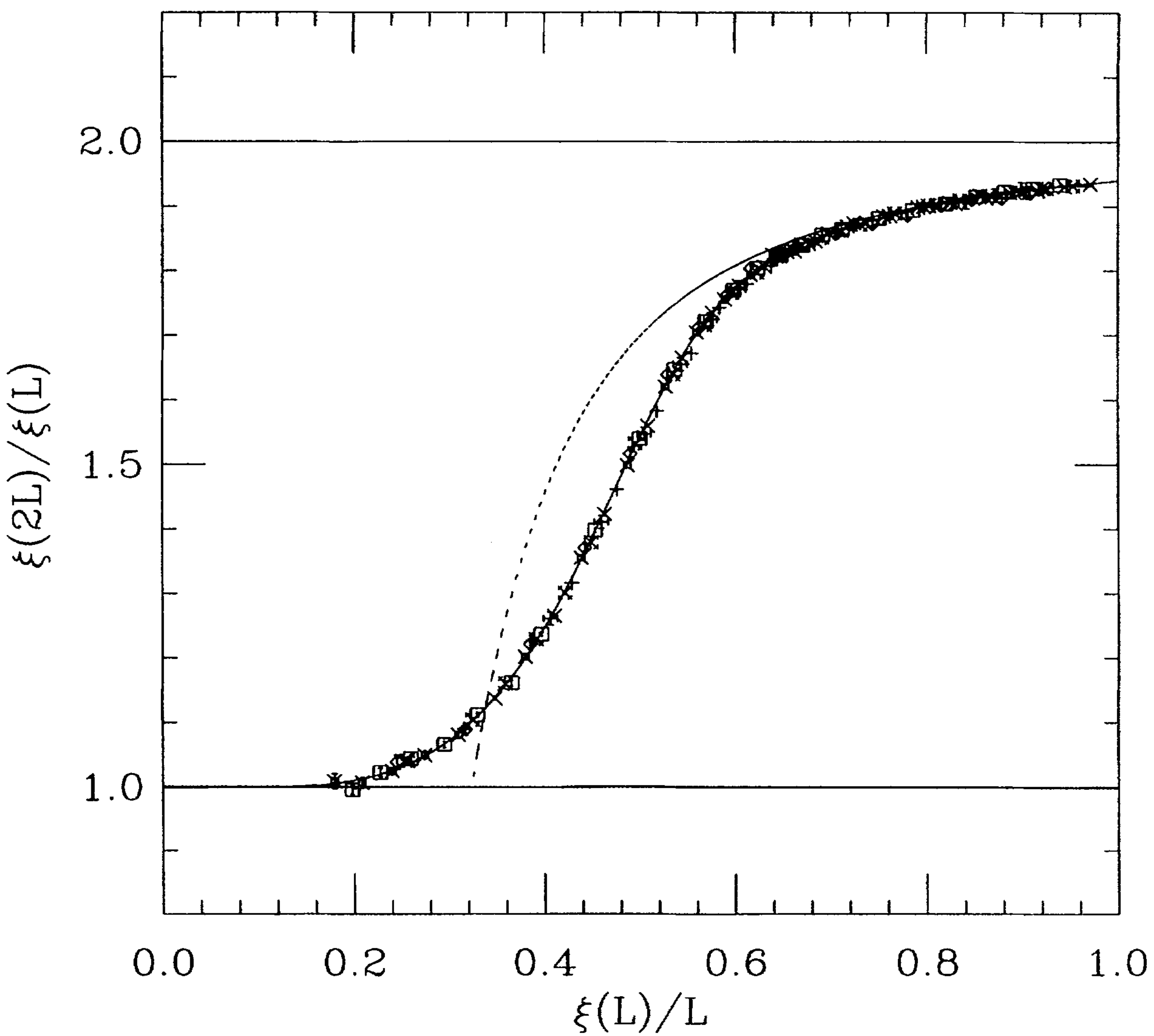

Caracciolo, et.al., PRL 75, 1891 (1995)

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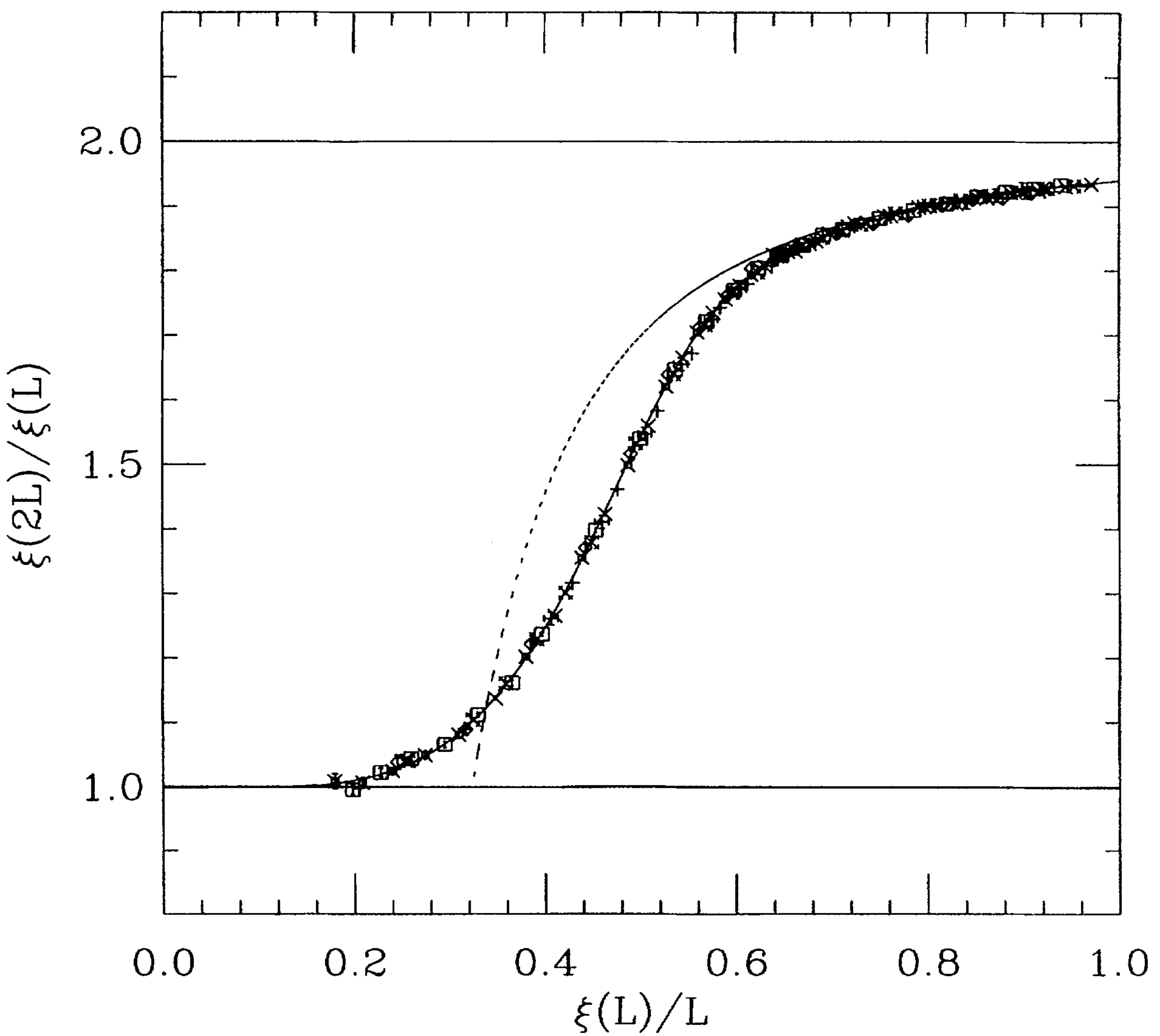

Qubit Regularization

Can we reproduce this continuum physics in a lattice model with a finite lattice Hilbert space?

Caracciolo, et.al., PRL 75, 1891 (1995)

Qubit regularized model

Bhattacharya, Buser, SC, Gupta, Singh PRL 126 (2021), 172001

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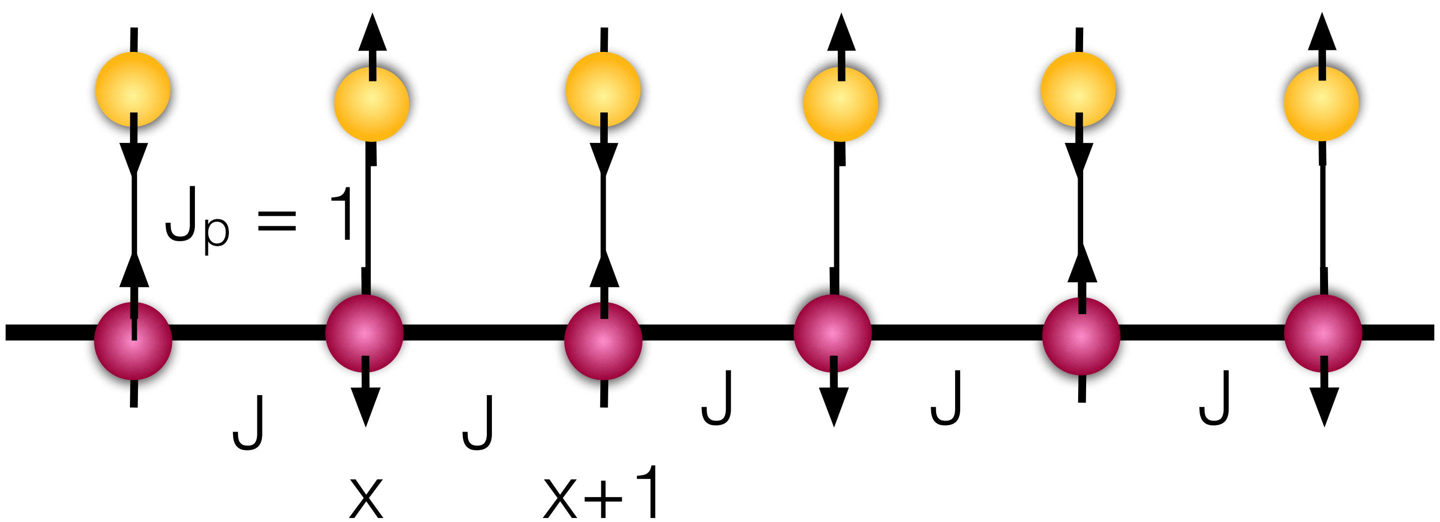
Heisenberg-Comb



$$H = \sum_x J\, \mathbf{S}_{x,1} \cdot \mathbf{S}_{x+1,1} + \mathbf{S}_{x,1} \cdot \mathbf{S}_{x,2}$$

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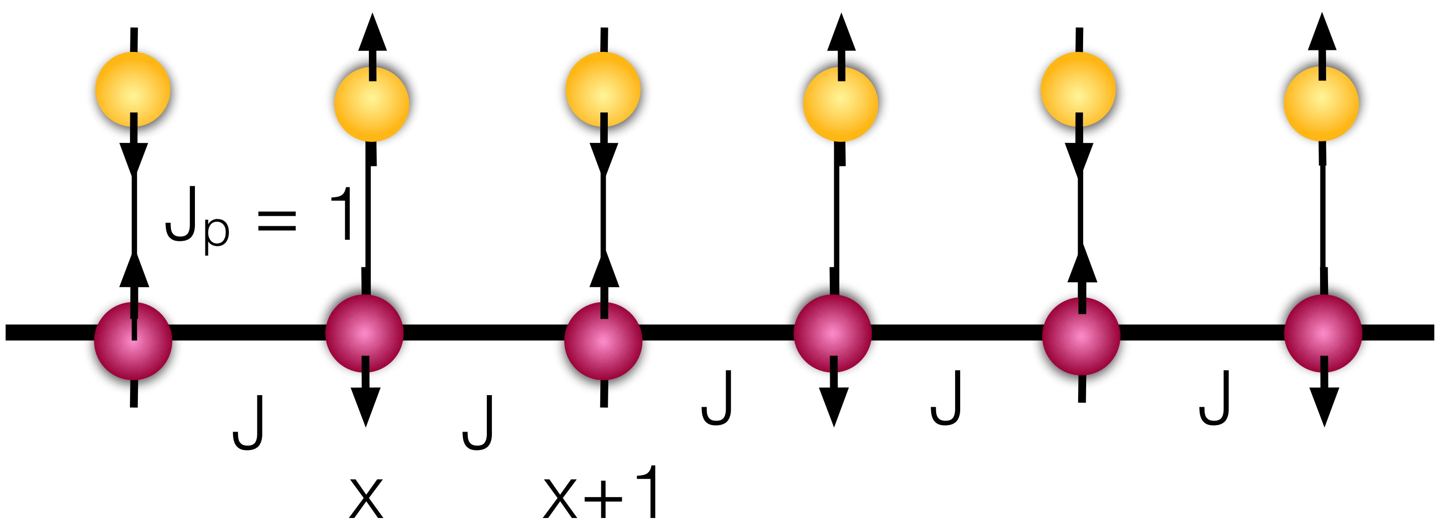

UV Quantum Critical Point:

$$J \to \infty$$

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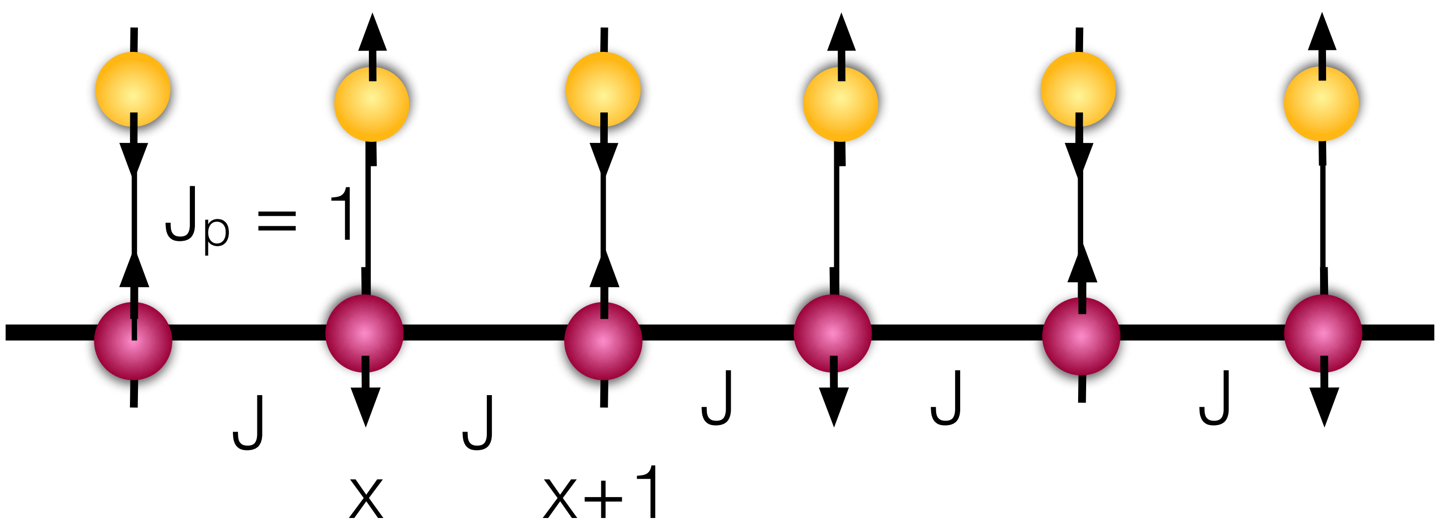

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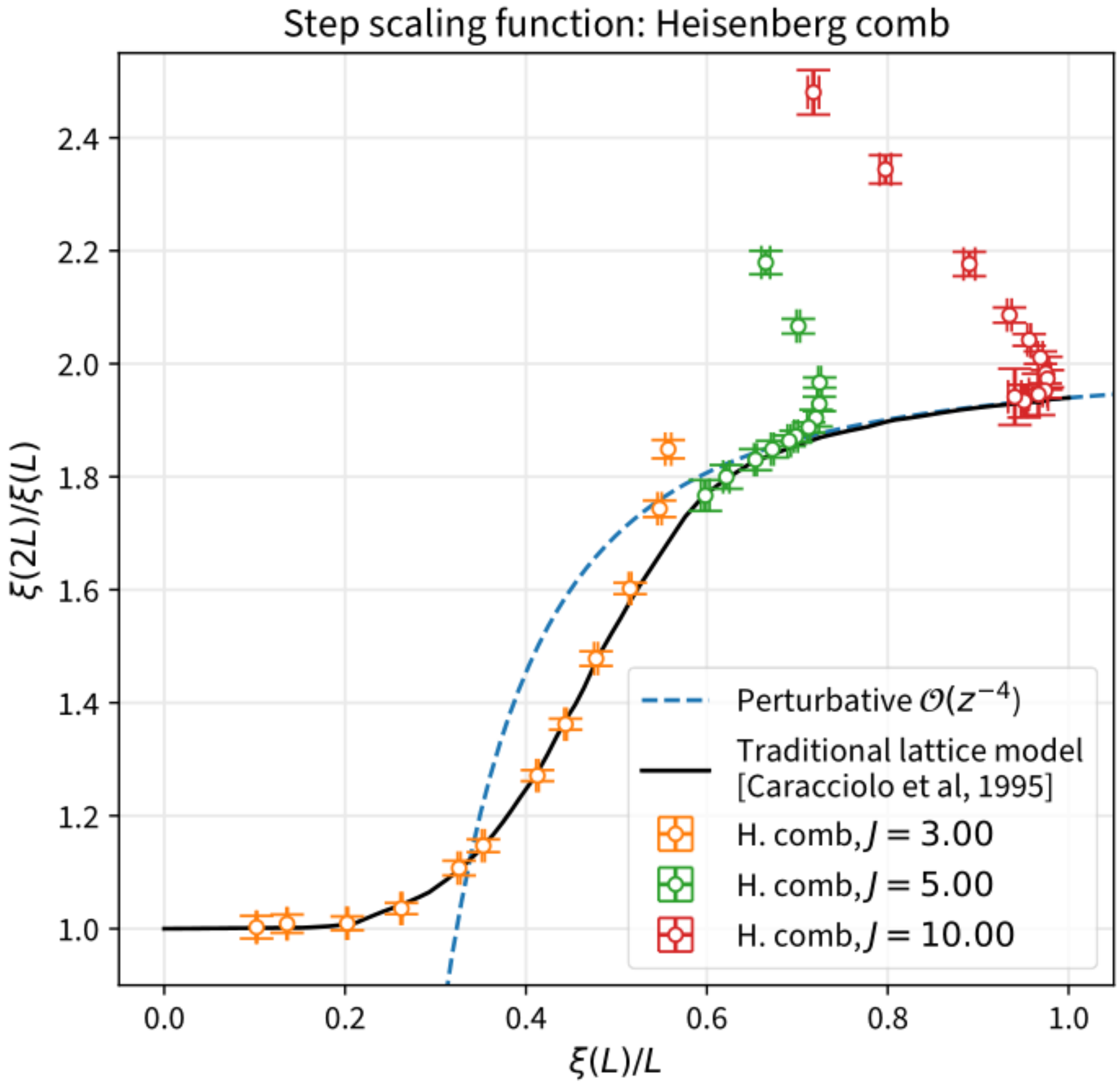
Note

$$J \rightarrow \infty \neq J = \infty$$

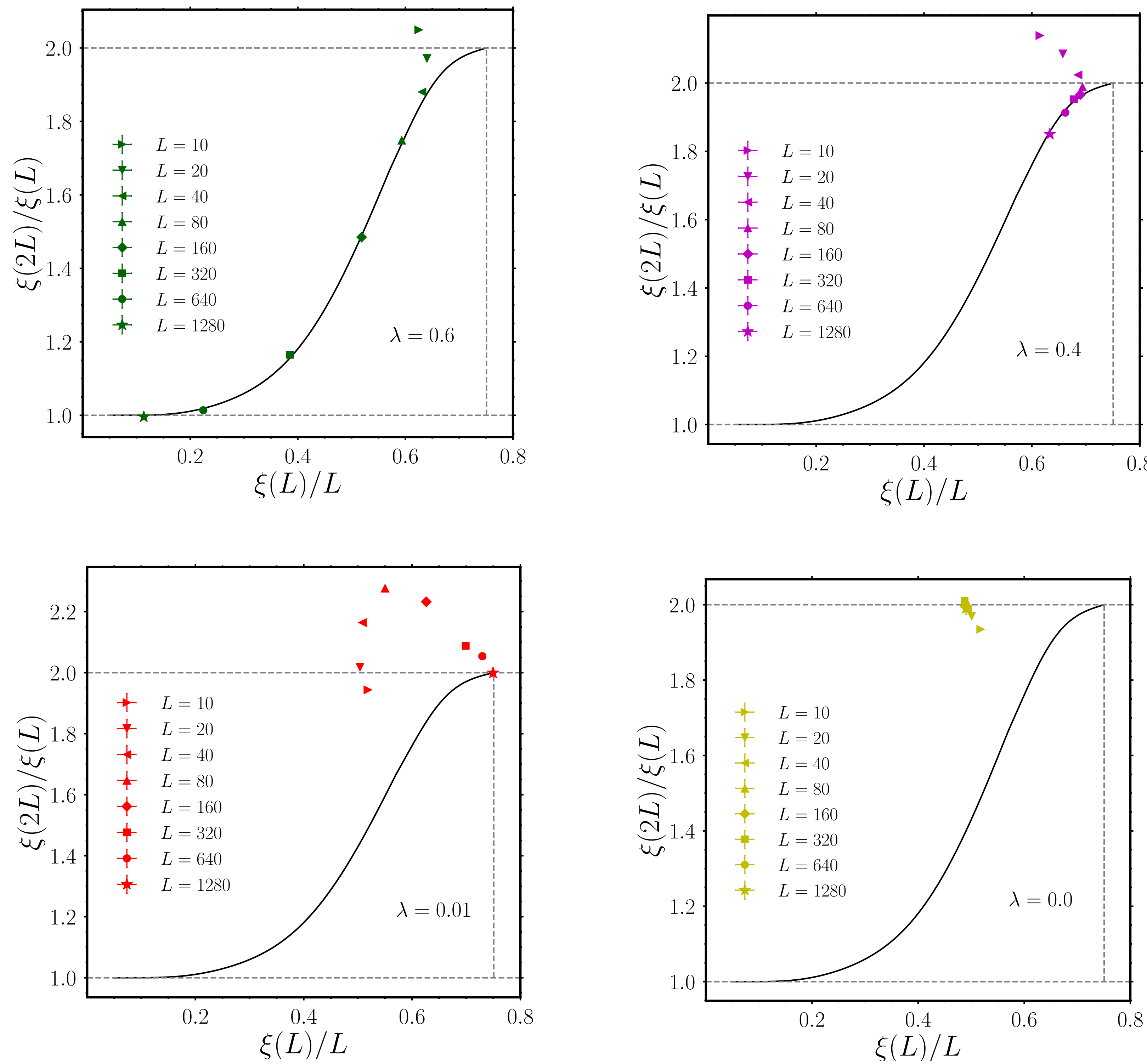
Universal Step Scaling Function

Bhattacharya, Buser, SC, Gupta, Singh PRL 126 (2021), 172001



Another Example:
Qubit Regularization of the BKT transition

Maiti, Banerjee, SC, Marinkovic, PRL 132 (2024), 041601



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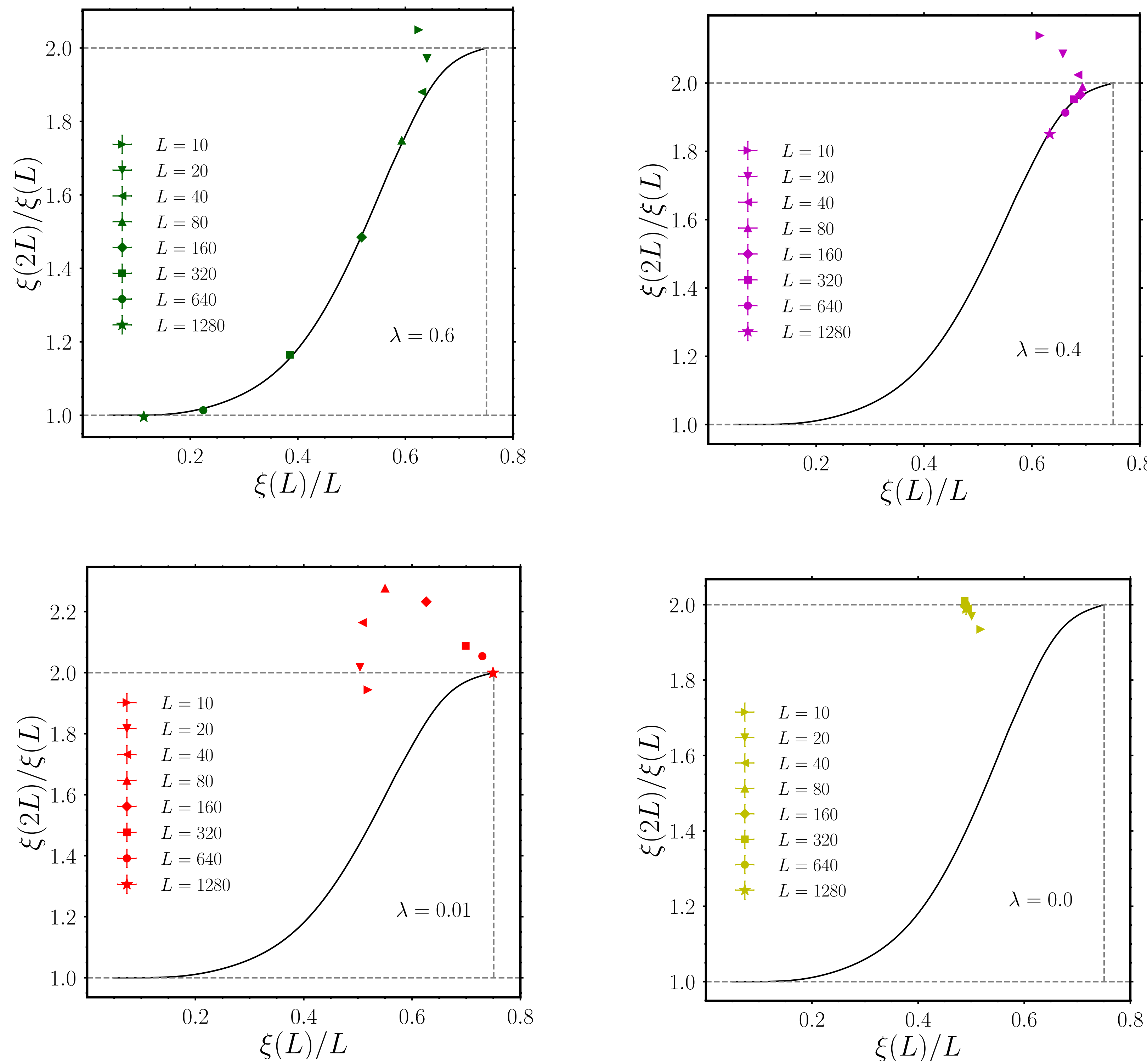

Again note:

$$\lambda \to 0 \quad \neq \lambda = 0$$

Qubit Regularization $\sim$ D-theory

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D-theory was an idea introduced by Uwe-Jens

Lattice 1998, Plenary talk by Wiese.

Brower, SC, Riederer, Wiese, NPB 693 (2004),149

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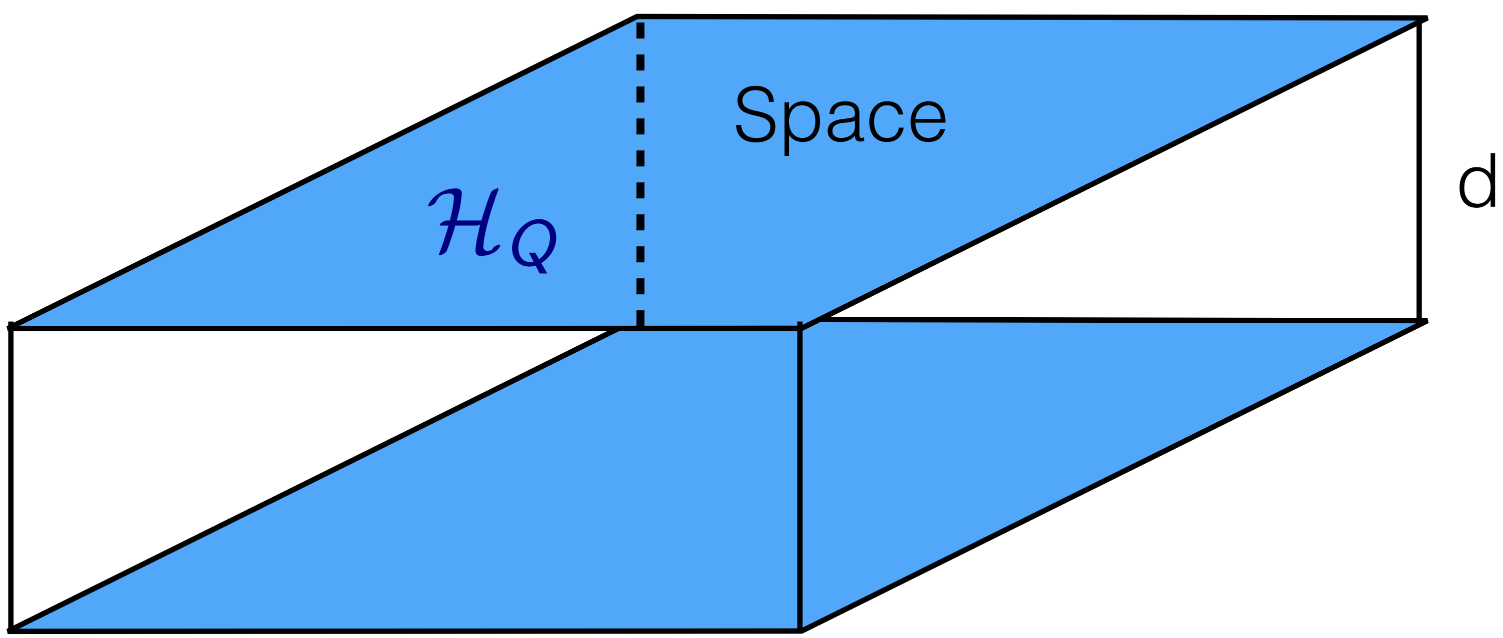

d is allowed to grow so the local Hilbert space can grow!

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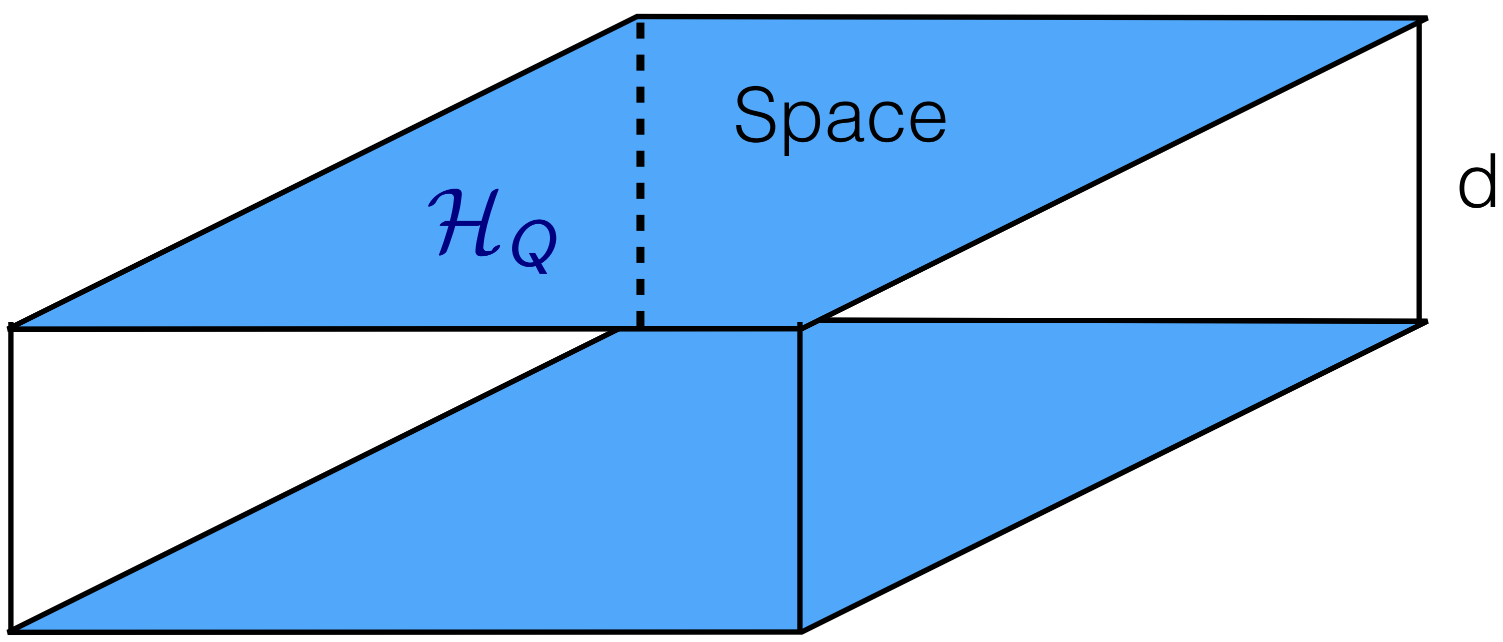

d is allowed to grow so the local Hilbert space can grow!

RG plays an important role!

Qubit Regularization of Gauge Theories

Traditional SU(N) lattice gauge theories

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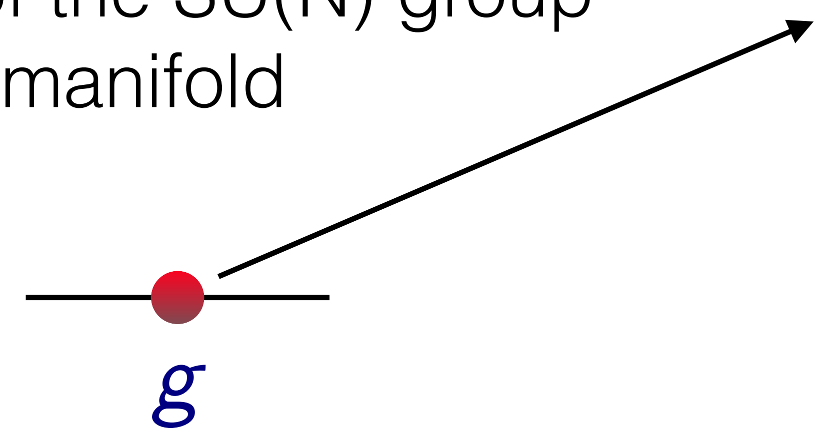
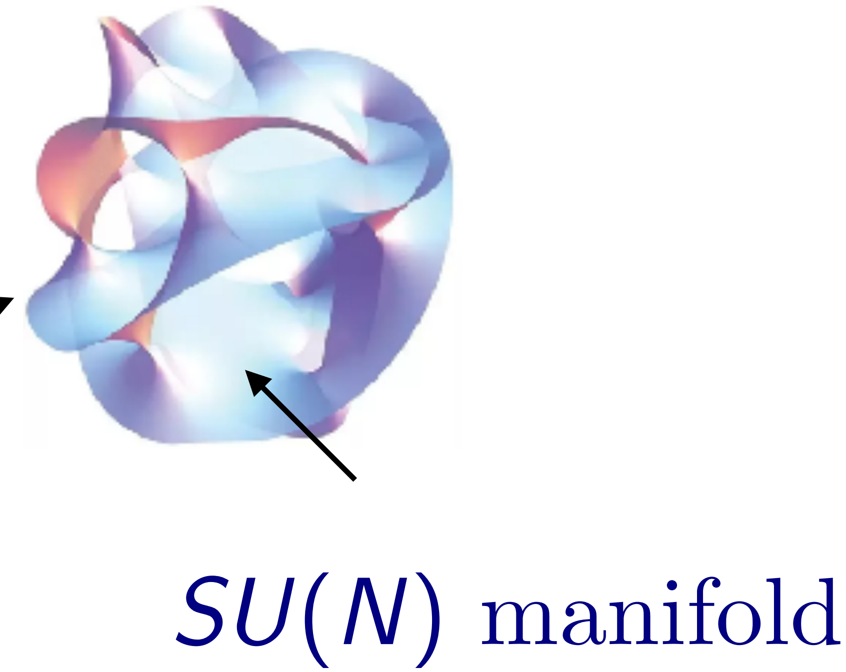
On each lattice link there is a quantum particle moving on the surface of the SU(N) group manifold





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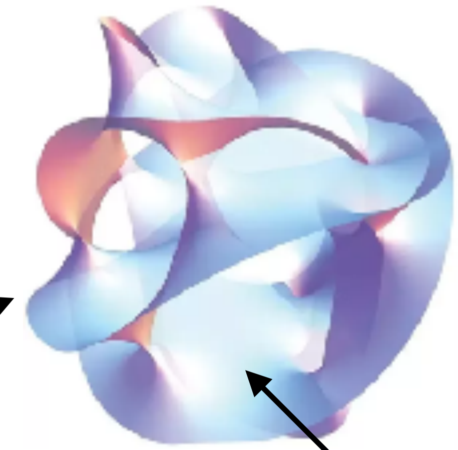

g

$SU(N)$ manifold

Basis of the full Hilbert space $\mathcal{H}_{\text{Trad}}$:

$$\int [dg] \; |g\rangle\langle g| = I$$

"position basis"

$$\sum_{\lambda} \sum_{i,j} |D^{\lambda}_{ij}\rangle\langle D^{\lambda}_{ij}| \; = \; \mathbb{I}$$

"Representation basis"

λ labels distinct irreps of SU(N)

This means the traditional link Hilbert space is given by

$$\mathcal{H}_{\text{Trad}} = \bigoplus_{\lambda} \mathcal{H}_{\lambda}$$ ⟵ Peter-Weyl Theorem

where $\mathcal{H}_{\lambda} = V_{\lambda} \otimes V_{\lambda}^{*}$ spanned by $\{|D_{ij}^{\lambda}\rangle\}, i, j = 1, 2, ..., d_{\lambda}$

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Qubit Regularized Hilbert Space $\mathcal{H}_{Q} = \bigoplus_{\lambda \in Q} V_{\lambda} \otimes V^{*}_{\lambda}$

$$dim(\mathcal{H}_{Q}) = \sum_{\lambda \in Q} (d_{\lambda})^{2}$$

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How does the "irrep space" formulation of a lattice gauge theory look like?

“Irrep space” formulation of traditional lattice gauge theories

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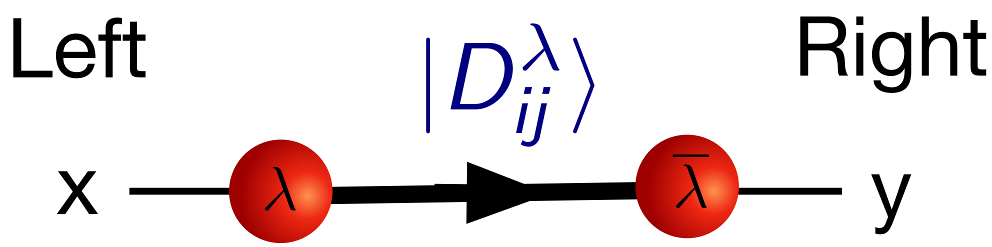
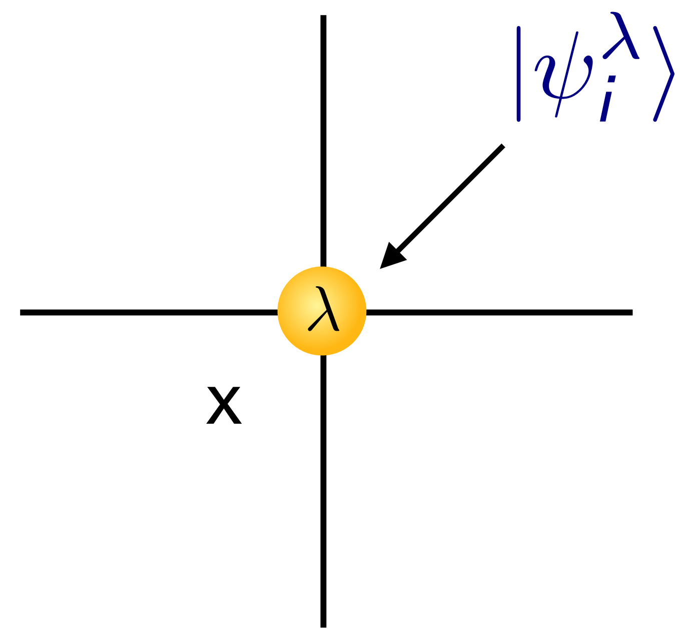


Lattice Link

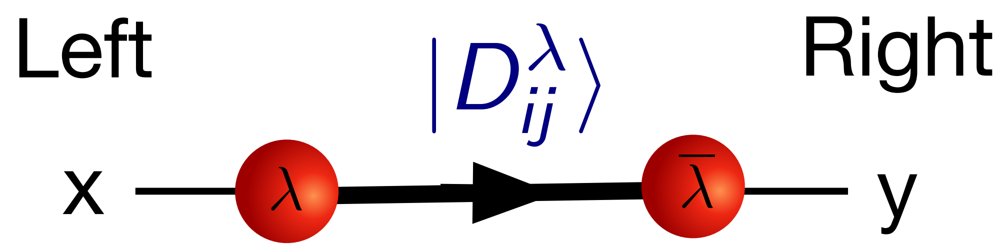
$$\dim(\mathcal{H}_\ell) = d_\lambda^2$$



Lattice Site

$$\dim(\mathcal{H}_s) = d_\lambda$$

"Irrep space" formulation of traditional lattice gauge theories



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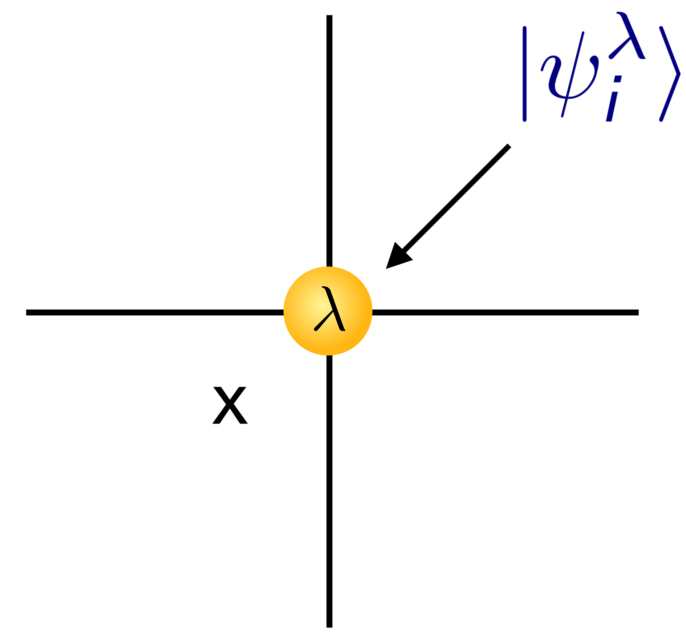
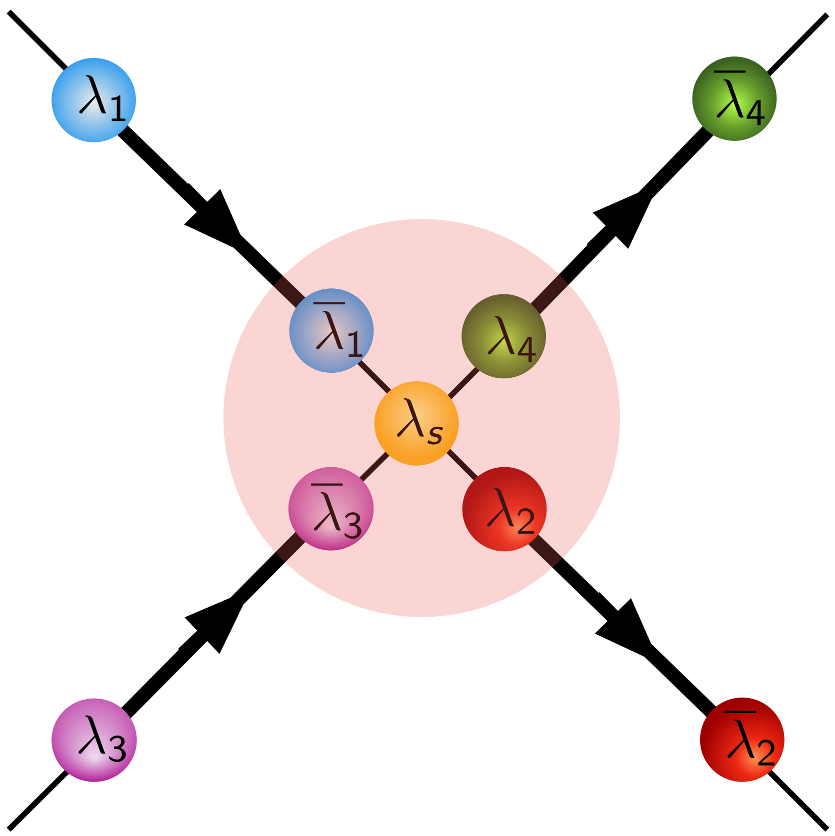


Lattice Site

$$\dim(\mathcal{H}_s) = d_\lambda$$

The physical Hilbert space is obtained by projecting to a gauge-invariant sector

Gauss Law

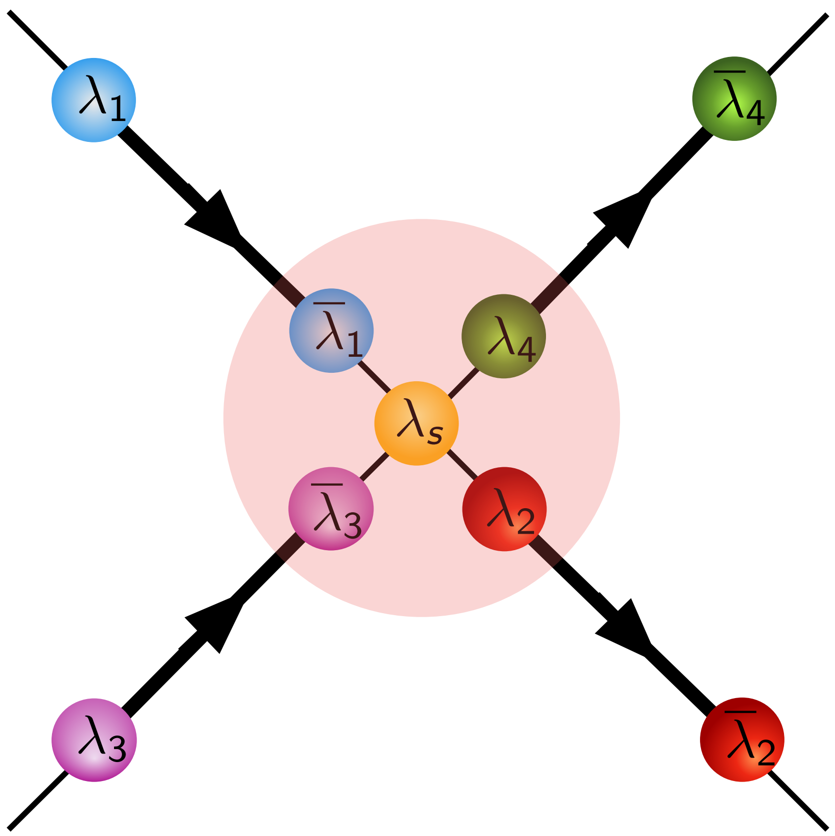


$$\mathcal{H}_s^g \;=\; \overline{\lambda}_1 \otimes \lambda_2 \otimes \overline{\lambda}_3 \otimes \lambda_4 \otimes \lambda_s.$$

α_s labels the basis states of the singlet space of $\mathcal{H}_s^g$

$$\alpha_s = 1, 2, ..., \mathcal{D}(\mathcal{H}_s^g)$$

Gauss Law



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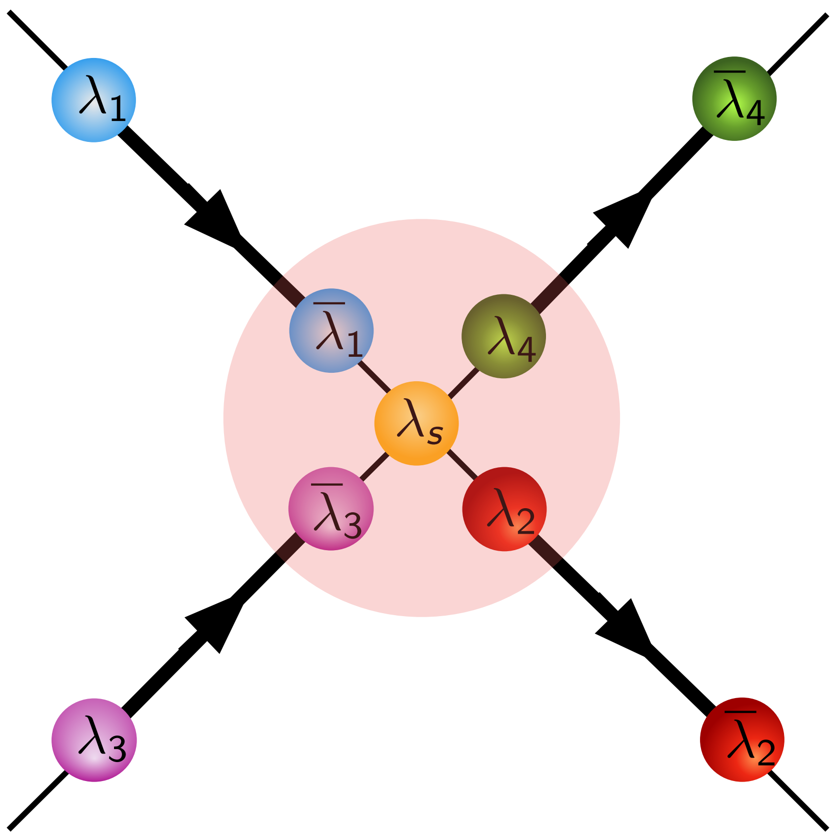
$$\alpha_s = 1, 2, \ldots, \mathcal{D}(\mathcal{H}_s^g)$$

A basis of the physical Hilbert space

$$|\{\lambda_s\}, \{\lambda_\ell\}, \{\alpha_s\}\rangle$$

Gauss Law



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$$\alpha_s = 1, 2, ..., \mathcal{D}(\mathcal{H}_s^g)$$

A basis of the physical Hilbert space

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All Clebsch-Gordan Coefficients have disappeared!

All irreps $\{\lambda_\ell\}$ are allowed in the traditional theory

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Qubit regularization works with a subset of these irreps

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Antisymmetric qubit regularization scheme

Hanqing Liu, SC Symmetry 14 (2022) 2 305,

$$Q = \{1, \underbrace{\square, \begin{smallmatrix}\square\\ \square\end{smallmatrix}, \dots}_{\text{All anti-symmetric irreps}}\}$$

Classical and Quantum Dimer Models

Every physical basis state of a lattice gauge theory in irrep formulation can be viewed as a configuration of monomers and dimers

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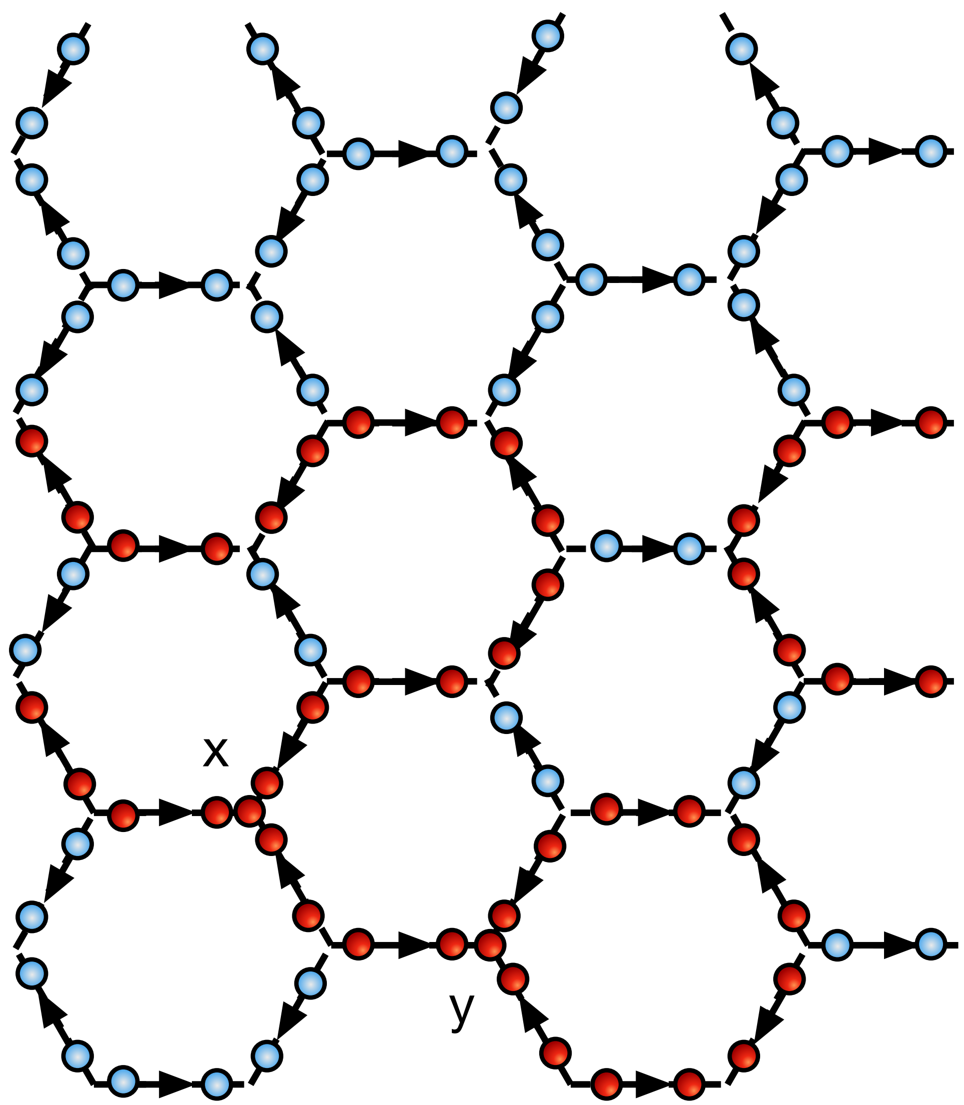
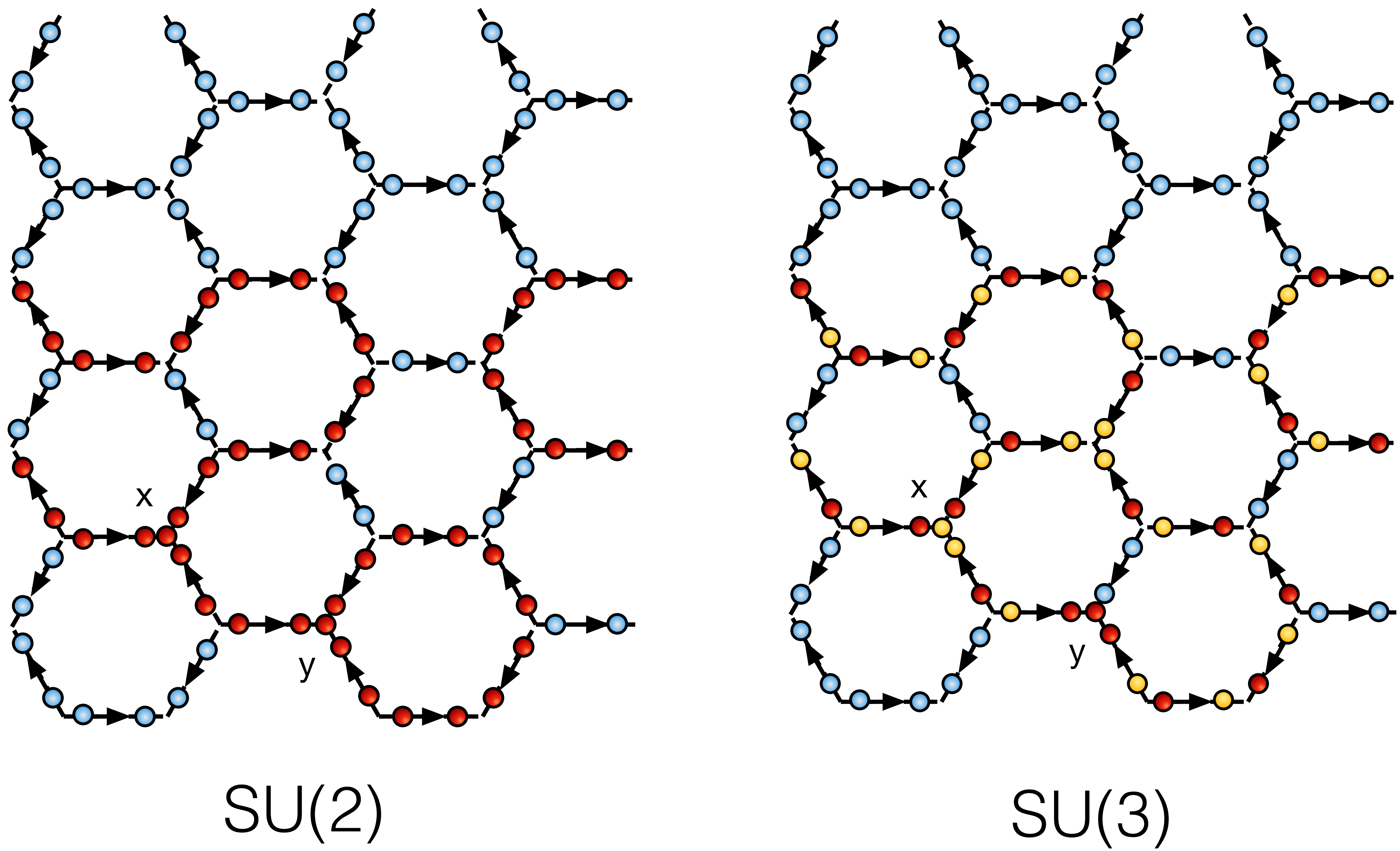


SU(2)

Every physical basis state of a lattice gauge theory in irrep formulation can be viewed as a configuration of monomers and dimers



Local Hamiltonians implement local changes to the monomer-dimer configurations

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Classical Hamiltonian

$$H_Q = \sum_{\ell} \hat{\mathcal{E}}_{\ell} \qquad \hat{\mathcal{E}}_{\ell} |D_{ij}^{\lambda}\rangle = (1 - \delta_{\lambda,1}) |D_{ij}^{\lambda}\rangle$$

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Quantum Hamiltonian

$$H_Q = \sum_{\ell} \hat{\mathcal{E}}_\ell - \delta \sum_{P} (\hat{\mathcal{U}}_P + \hat{\mathcal{U}}_P^{\dagger})$$

Non-traditional plaquette operators

$$\hat{\mathcal{U}}_P = \sum_{\lambda,\alpha,\lambda',\alpha'} c(\lambda,\alpha,\lambda',\alpha')\ |\lambda',\alpha'\rangle\langle\lambda,\alpha|$$

$$\hat{\mathcal{U}}_P^\dagger = \sum_{\lambda,\alpha,\lambda',\alpha'} c^*(\lambda,\alpha,\lambda',\alpha')\ |\lambda,\alpha\rangle\langle\lambda',\alpha'|$$

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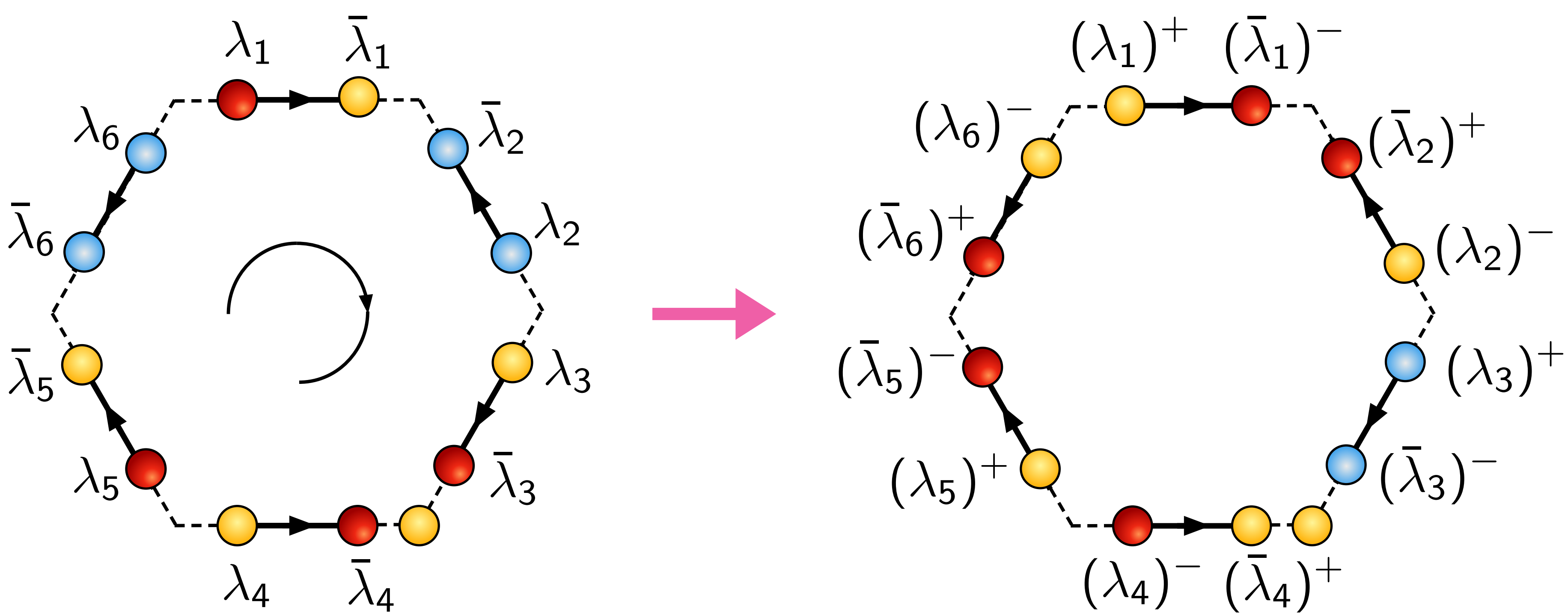
A simple example in the AS scheme:



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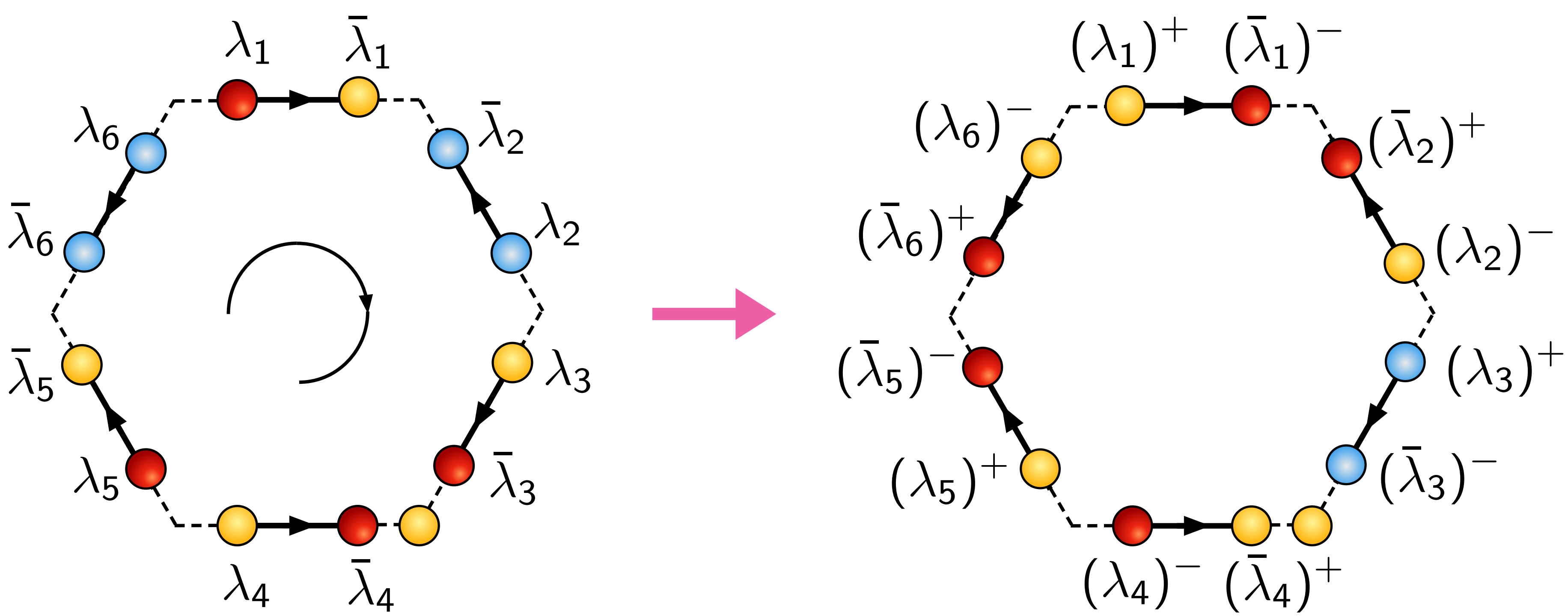

Models are sign problem free
if the coefficients are positive and real!

Classical Lattice Gauge Theories: Results

Asymptotic Freedom of Yang Mills theory

Deconfined phase at high temperatures

Confined massive phase at zero temperatures

Asymptotic Freedom of Yang Mills theory

Deconfined phase at high temperatures

Confined massive phase at zero temperatures

Classical lattice gauge theories may already show this finite temperature phase transitions

Asymptotic Freedom of Yang Mills theory

↓

Deconfined phase at high temperatures

Confined massive phase at zero temperatures

Classical lattice gauge theories may already show this finite temperature phase transitions

Think about the analogy with the Ising model!

Classical Hamiltonian

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$$H_Q = \sum_{\ell} \hat{\mathcal{E}}_\ell \qquad \hat{\mathcal{E}}_\ell |D^\lambda_{ij}\rangle = (1 - \delta_{\lambda,1}) |D^\lambda_{ij}\rangle$$

A "confinement" observable at finite temperatures

$$\chi = \frac{1}{V} \sum_{x,y} \frac{Z_{x,y}}{Z}$$

Confined phase: $\chi \sim \text{Const}$

Deconfined phase: $\chi \sim L^3$

Classical Hamiltonian

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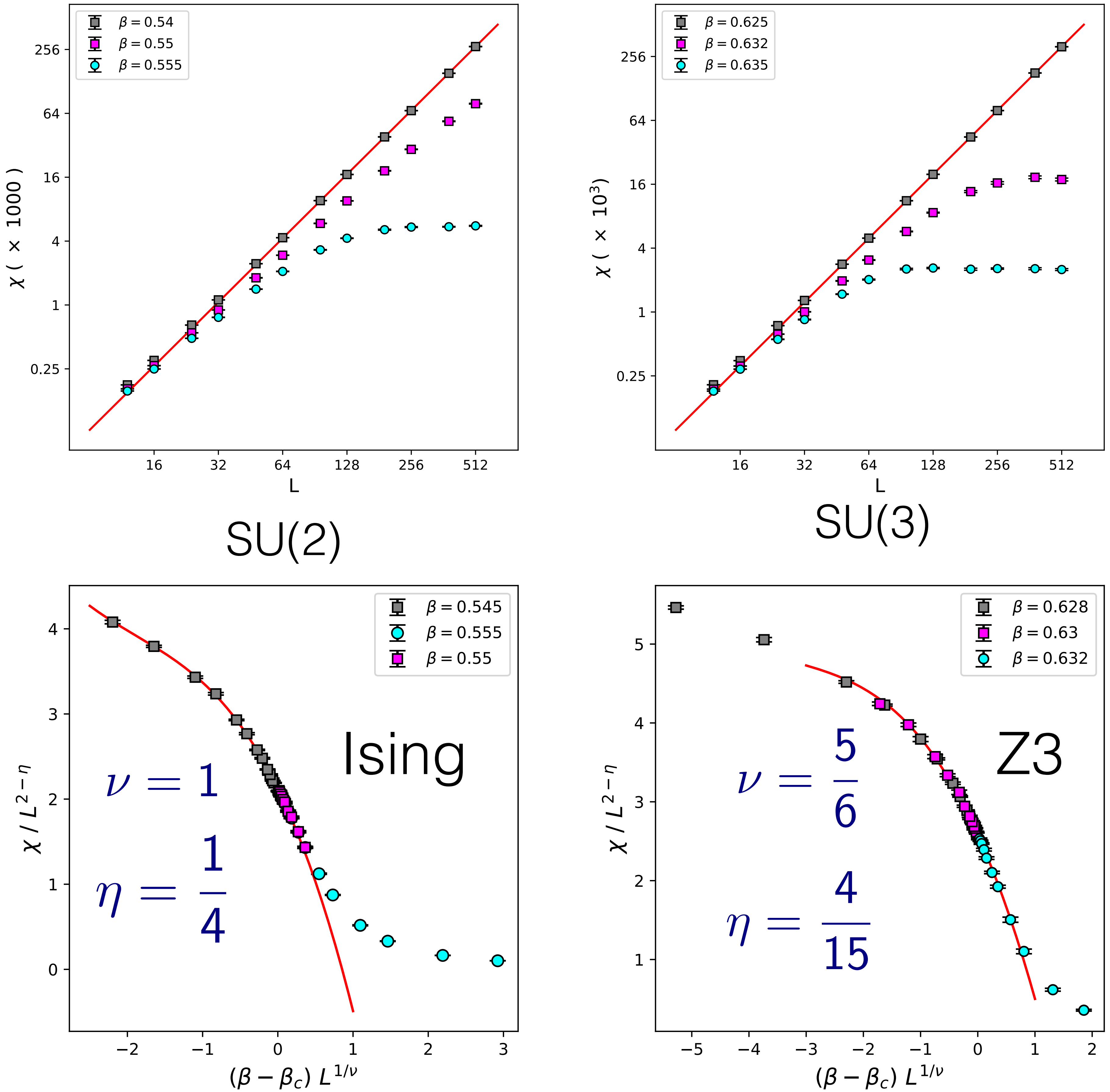
Expectation from traditional lattice gauge theory

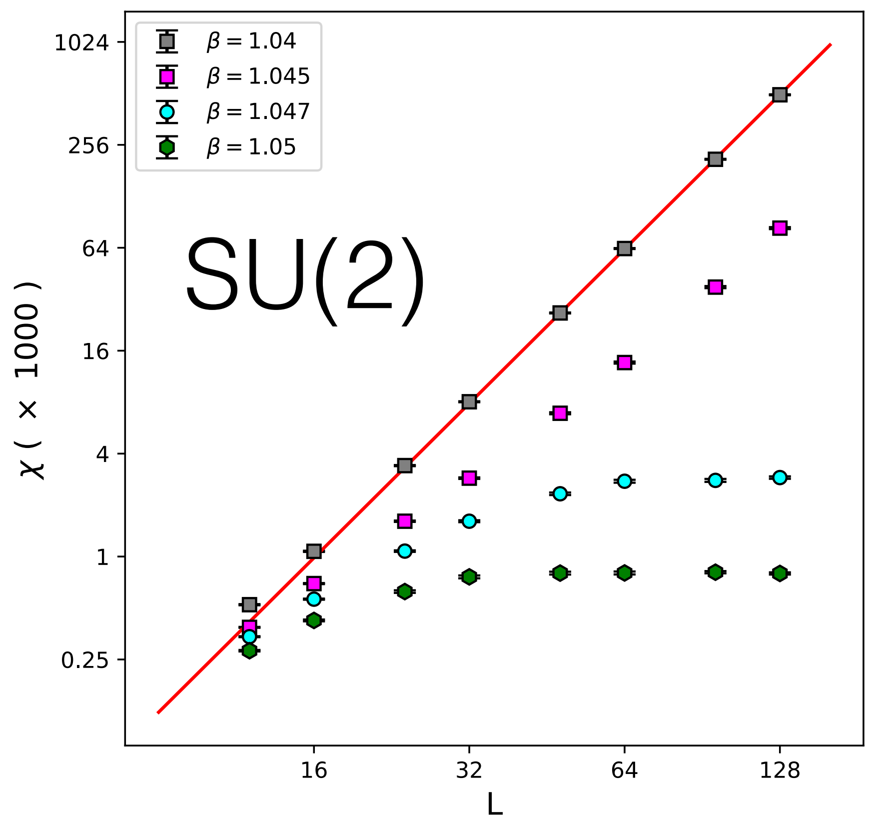
SU(2): Ising transition SU(3): Z3 transition

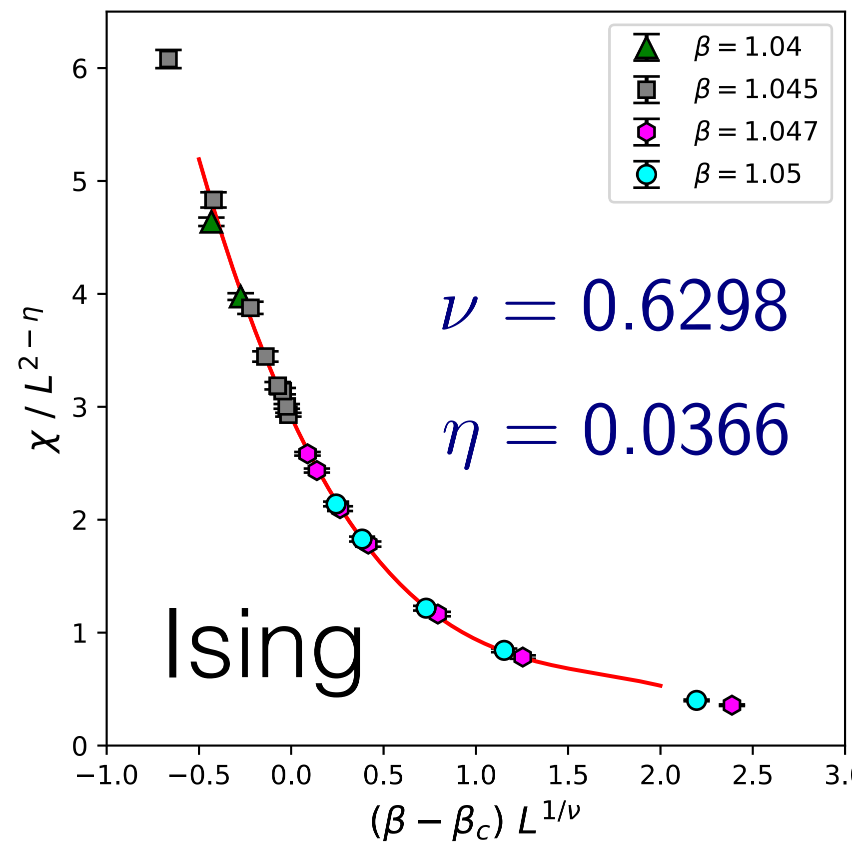
d=2

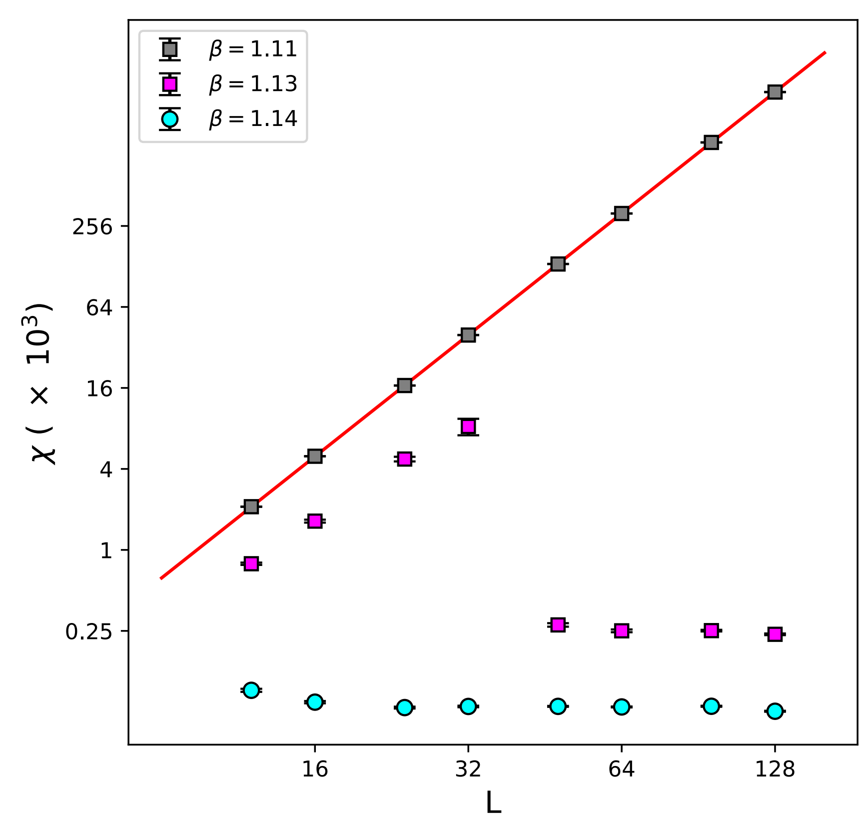


$\beta = 0.54$
$\beta = 0.55$
$\beta = 0.555$
χ (× 1000)
L
SU(2)
$\beta = 0.625$
$\beta = 0.632$
$\beta = 0.635$
χ (× 10^3)
L
SU(3)
$\beta = 0.545$
$\beta = 0.555$
$\beta = 0.55$
Ising
$\nu = 1$
$\eta = \frac{1}{4}$
$\chi / L^{2-\eta}$
$(\beta - \beta_c)\, L^{1/\nu}$
$\beta = 0.628$
$\beta = 0.63$
$\beta = 0.632$
Z3
$\nu = \frac{5}{6}$
$\eta = \frac{4}{15}$
$\chi / L^{2-\eta}$
$(\beta - \beta_c)\, L^{1/\nu}$

d=3







SU(3)
First order

Quantum Lattice Gauge Theories: Results

Quantum Hamiltonian

$$H_Q = \sum_{\ell} \hat{\mathcal{E}}_{\ell} - \delta \sum_{P} (\hat{\mathcal{U}}_P + \hat{\mathcal{U}}_P^{\dagger})$$

Non-traditional plaquette operators

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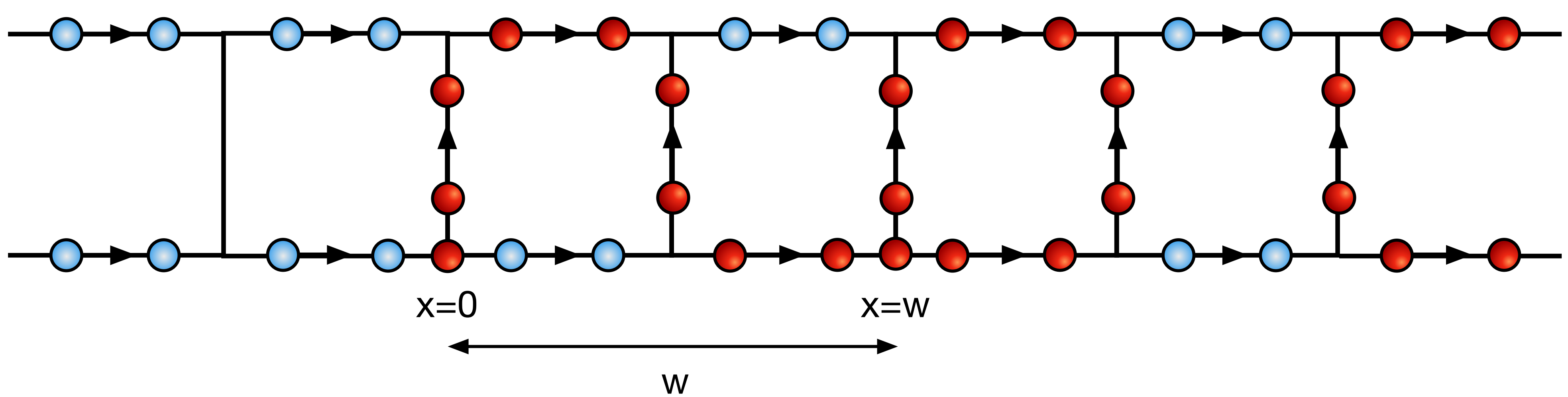
SU(2) gauge theory



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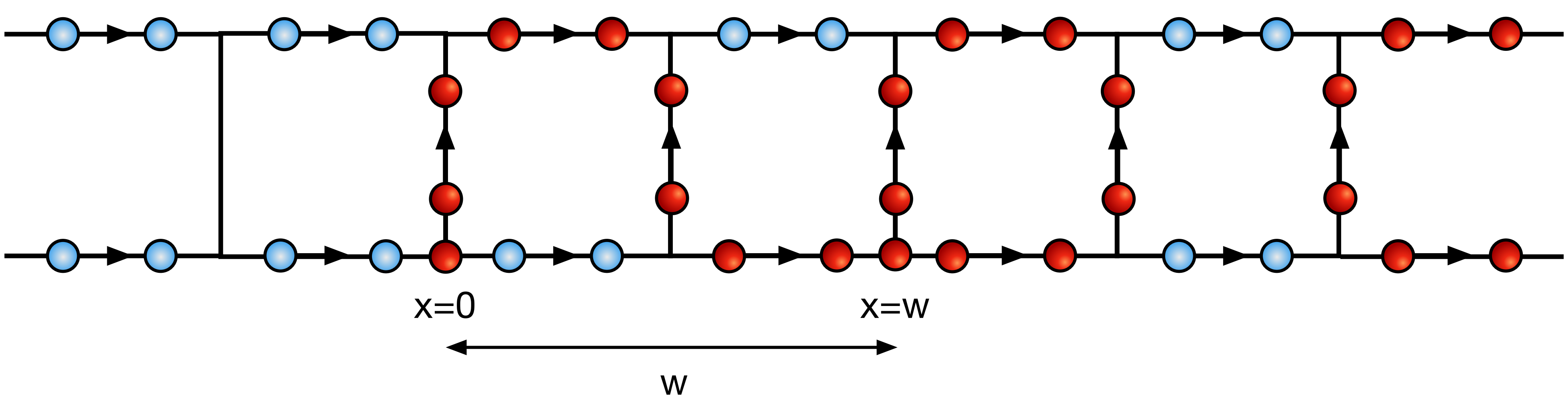

Confinement Observable: $E_\beta(w) = \mathrm{Tr}(H_Q e^{-\beta H_Q})/\mathrm{Tr}(e^{-\beta H_Q})$

For low temperatures: $E_\beta(\mathsf{w}) \;=\; E_0 + \sigma \mathsf{w}$

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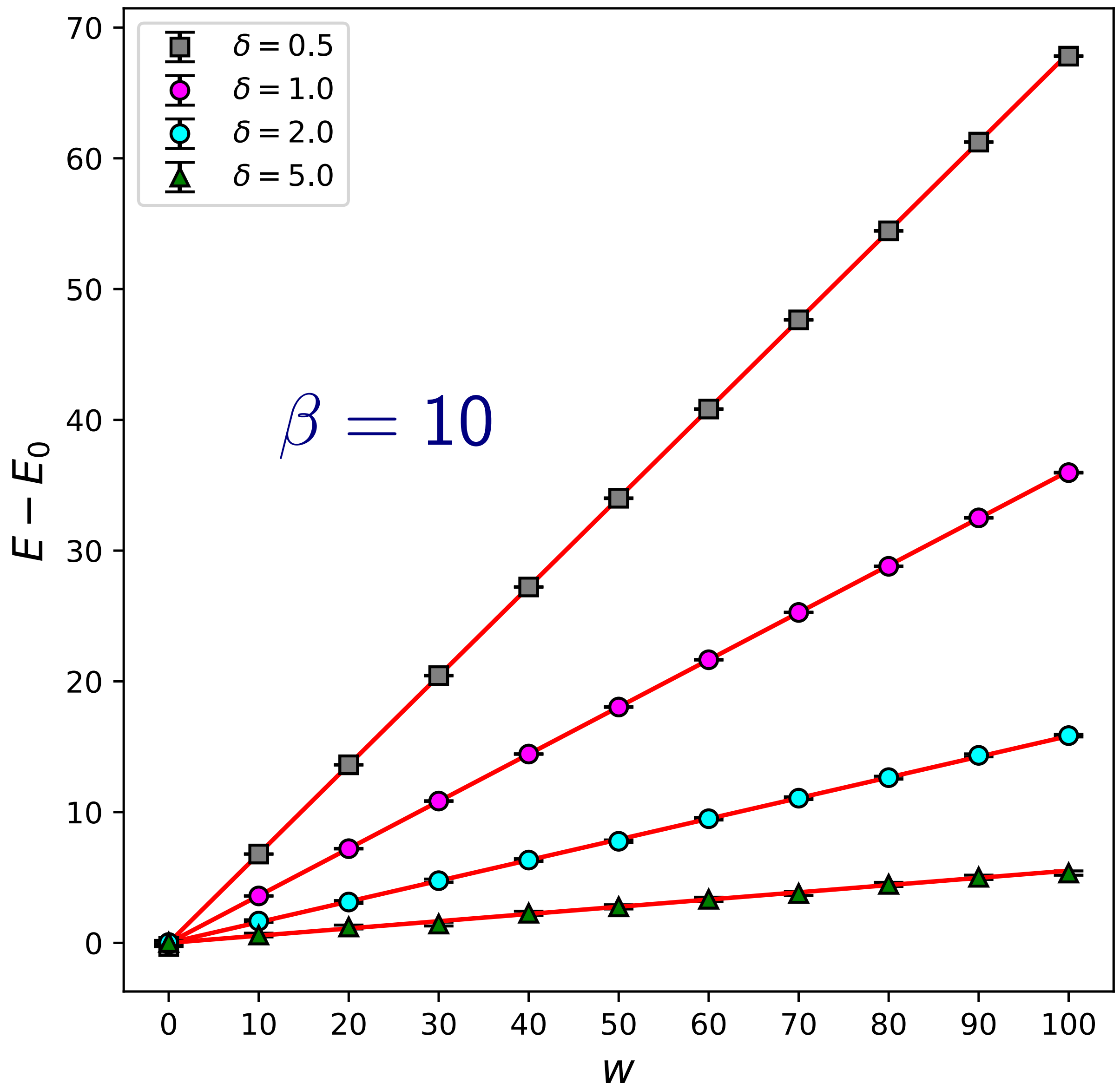

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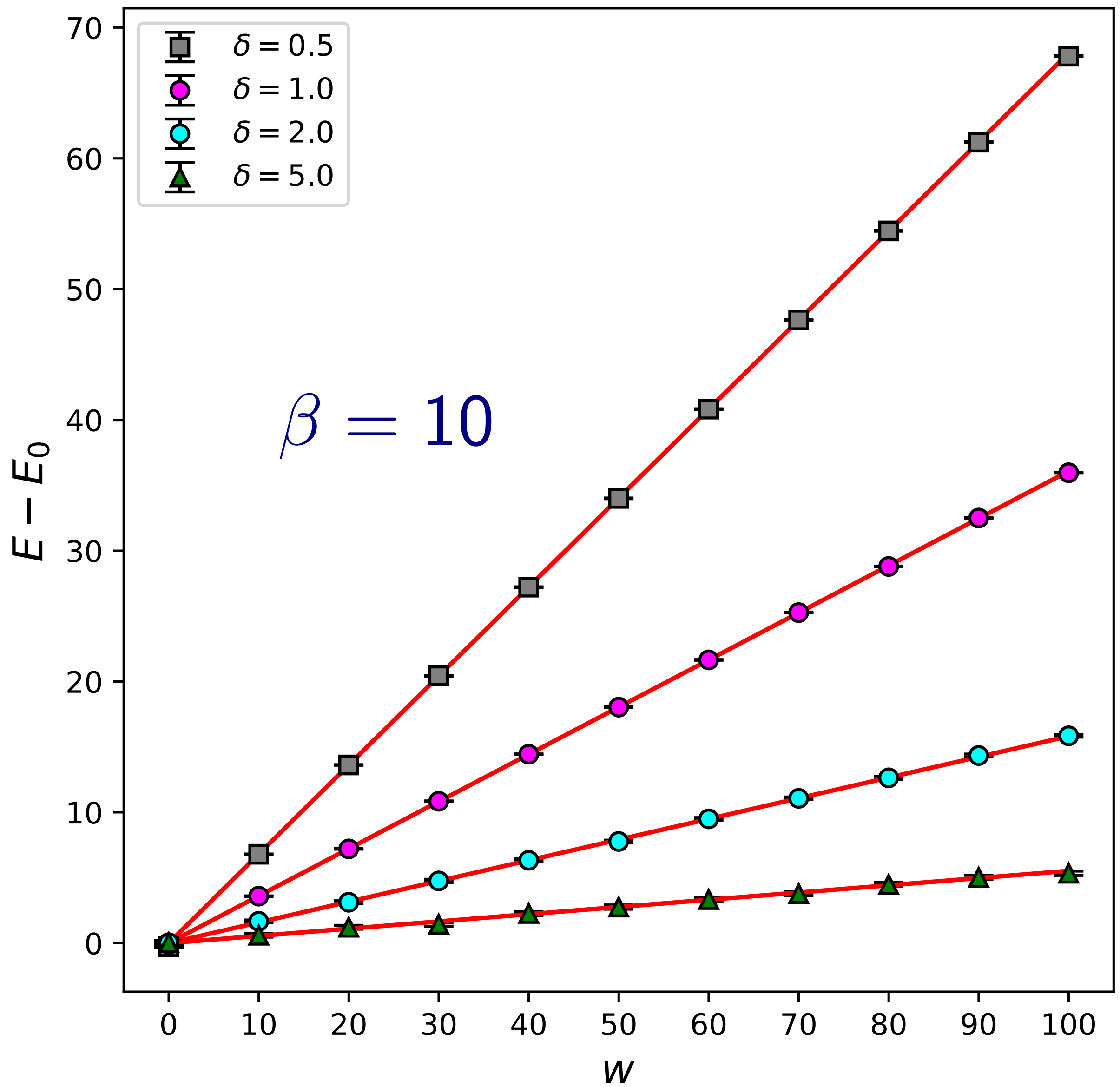

$$E_0 \approx -2L\delta + \frac{3L}{2} - \frac{9L}{32}\delta^{-1} - \frac{L-1}{8}\delta^{-2} \; ,$$

$$\sigma \approx \frac{1}{4}\delta^{-1} + \frac{1}{8}\delta^{-2} \; .$$

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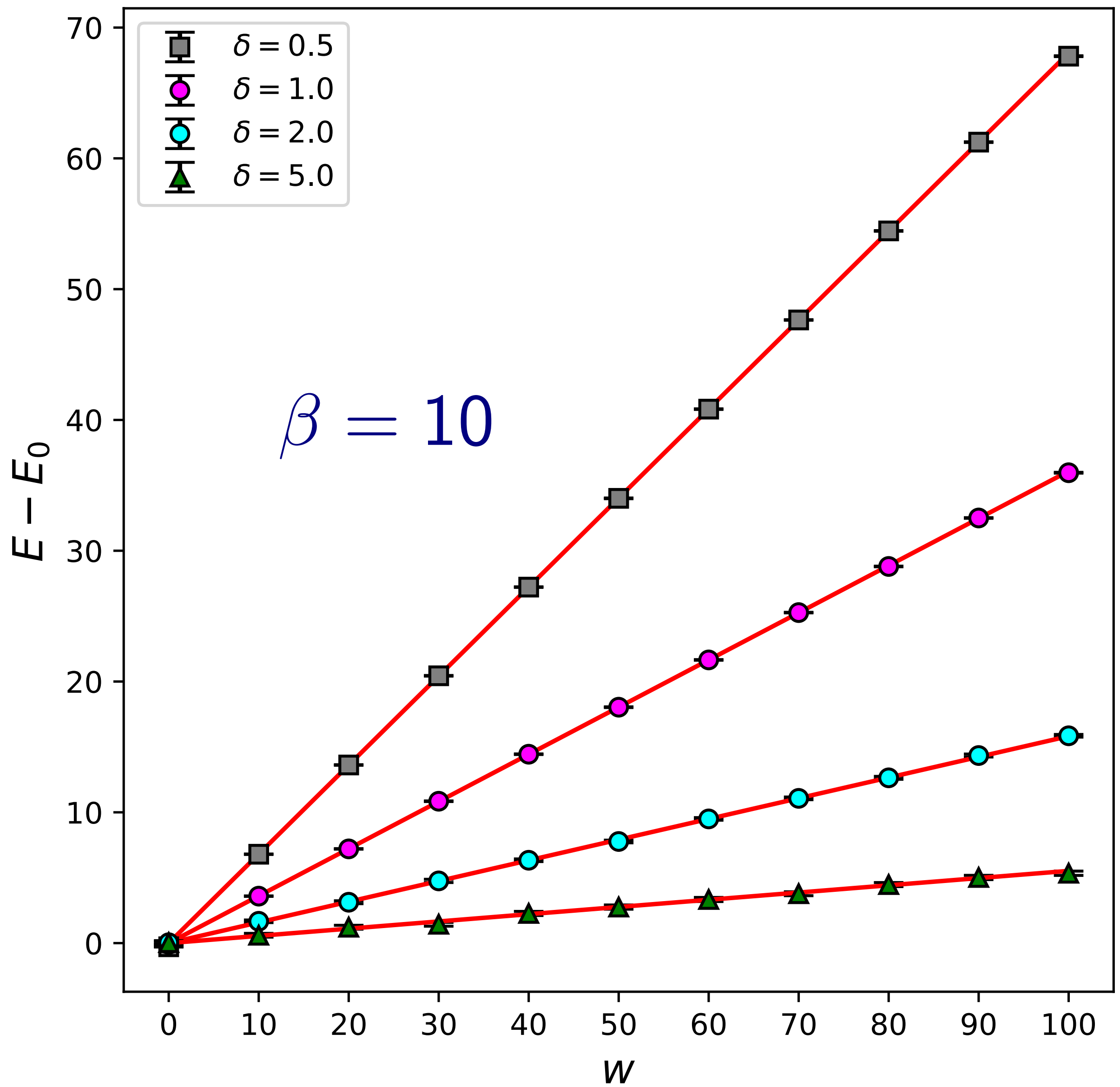

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δ	Monte Carlo			PT Eq. (43)	
	E_0	σ	χ^2/DOF	E_0	σ
0.5	-24.17(2)	0.6805(3)	0.34	-55.75	1.000
1.0	-89.04(4)	0.3608(6)	0.40	-90.50	-0.375
2.0	-267.36(8)	0.158(2)	0.40	-267.16	0.156
5.0	-856.1(2)	0.055(2)	0.51	-856.12	0.055

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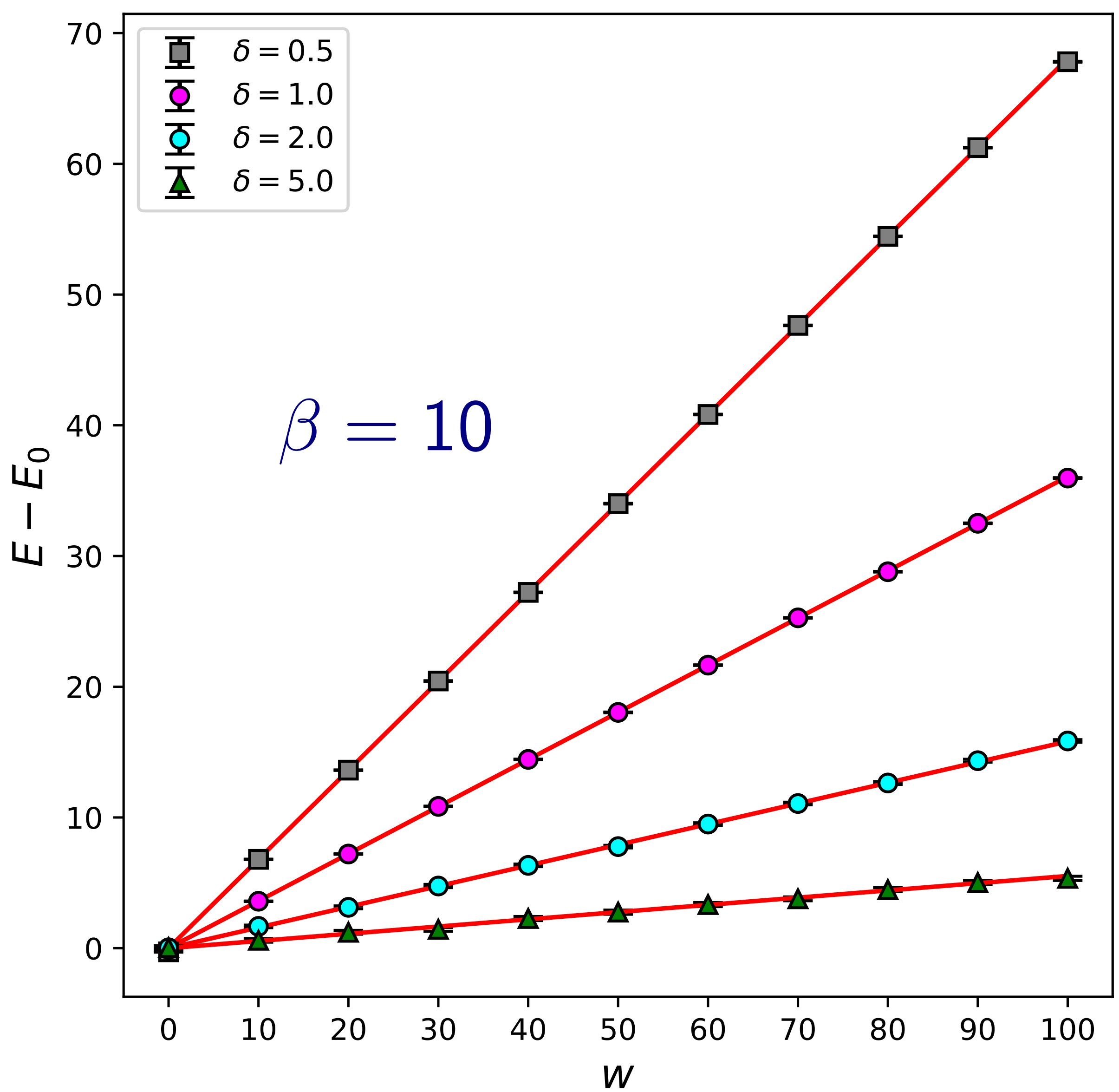

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Increasing δ reduces the string tension as expected

It is possible to extend these calculations to higher dimensions

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But at least there are no sign problems!

Conclusions

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Can Yang-Mills theory arise at a quantum critical point of some quantum dimer model?