Qubit Regularized Lattice Gauge Theories and their continuum limits

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(Duke University)

New Developments in Lattice Fermions
IQIS, Syracuse University, NY
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Relevant papers - arXiv: 2512.11068, 2603.01215

Supported by:
US Department of Energy

Collaborators

Siew

Liu

Bhattacharya

Outline

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Review: Hamiltonian Lattice Gauge Theories

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Monomer-Dimer-Tensor Network Basis

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What about Anomalies?

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Continuum limits

What about Anomalies?

Conclusions

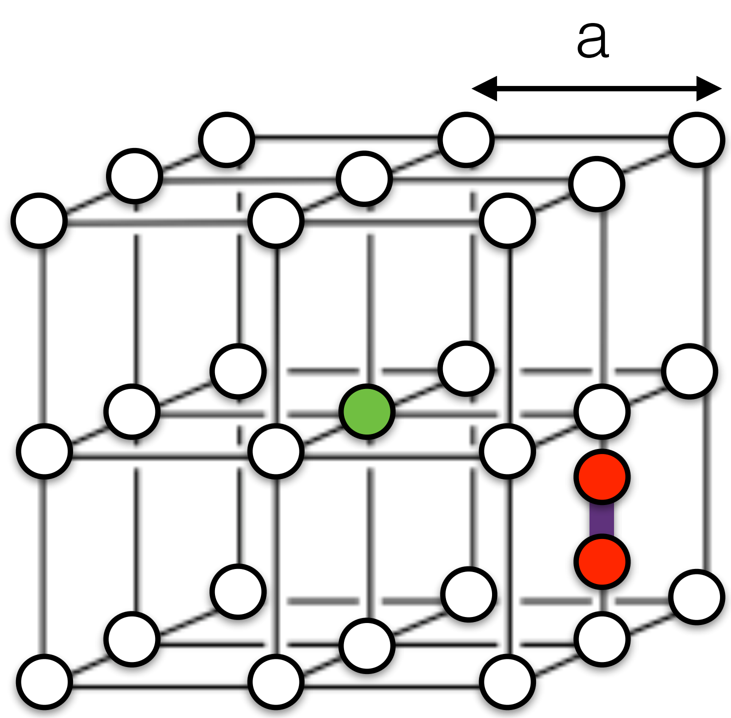
Hamiltonian Lattice Gauge Theory

Kogut and Susskind *Phys.Rev.D* 11 (1975) 395-408

Hilbert space of an SU(N) lattice gauge theory

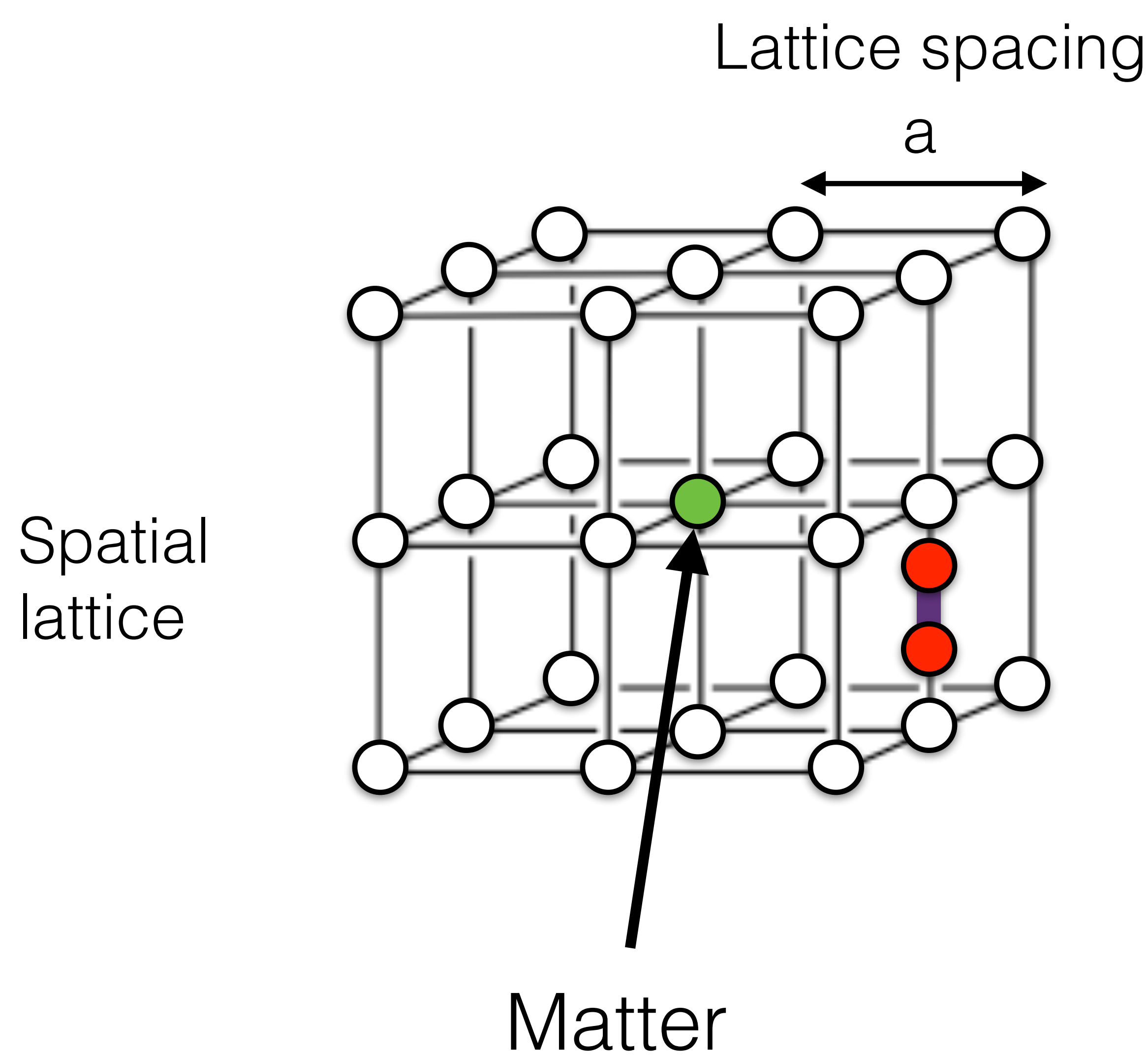
Hilbert space of an SU(N) lattice gauge theory

Lattice spacing



Spatial lattice

Hilbert space of an SU(N) lattice gauge theory



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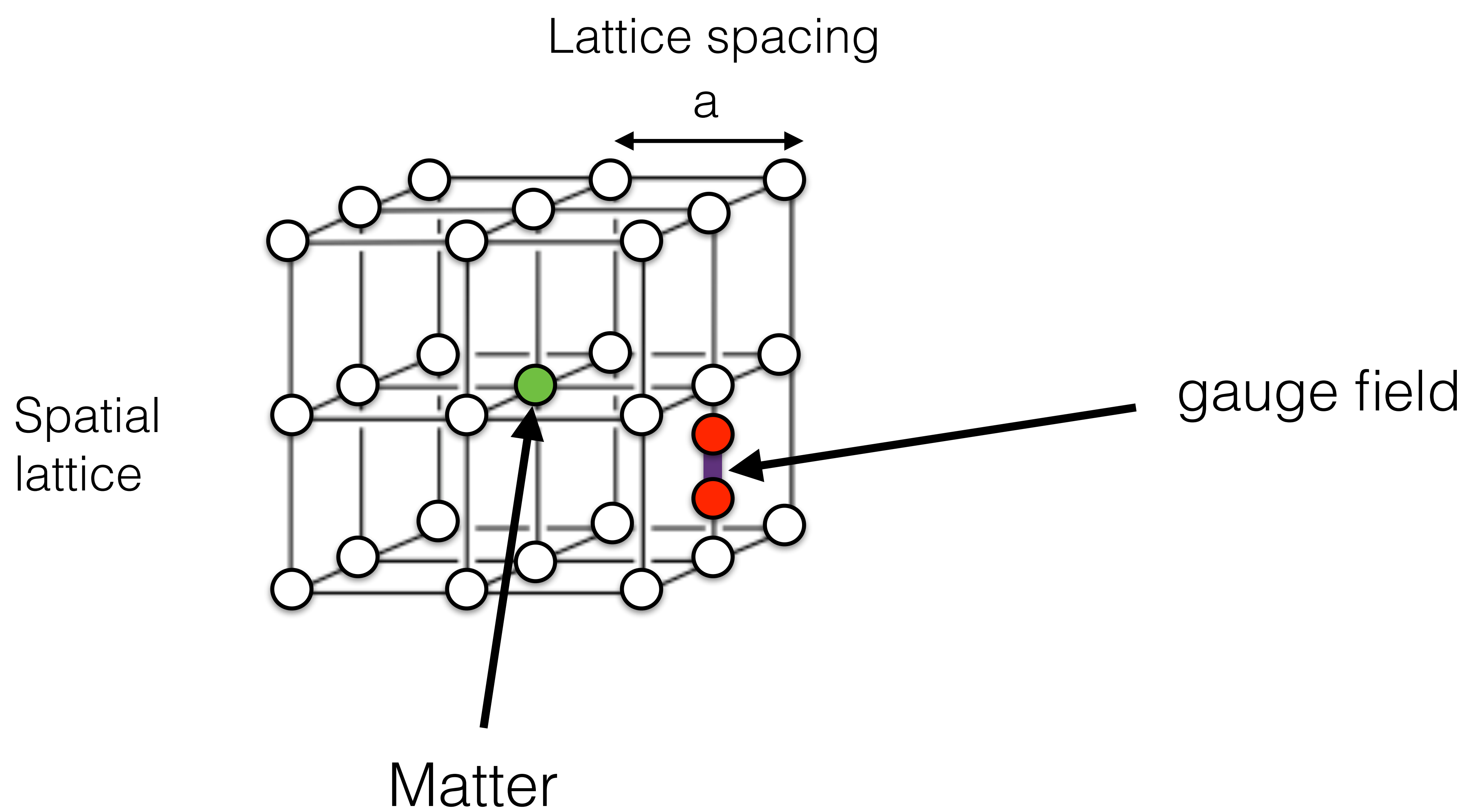

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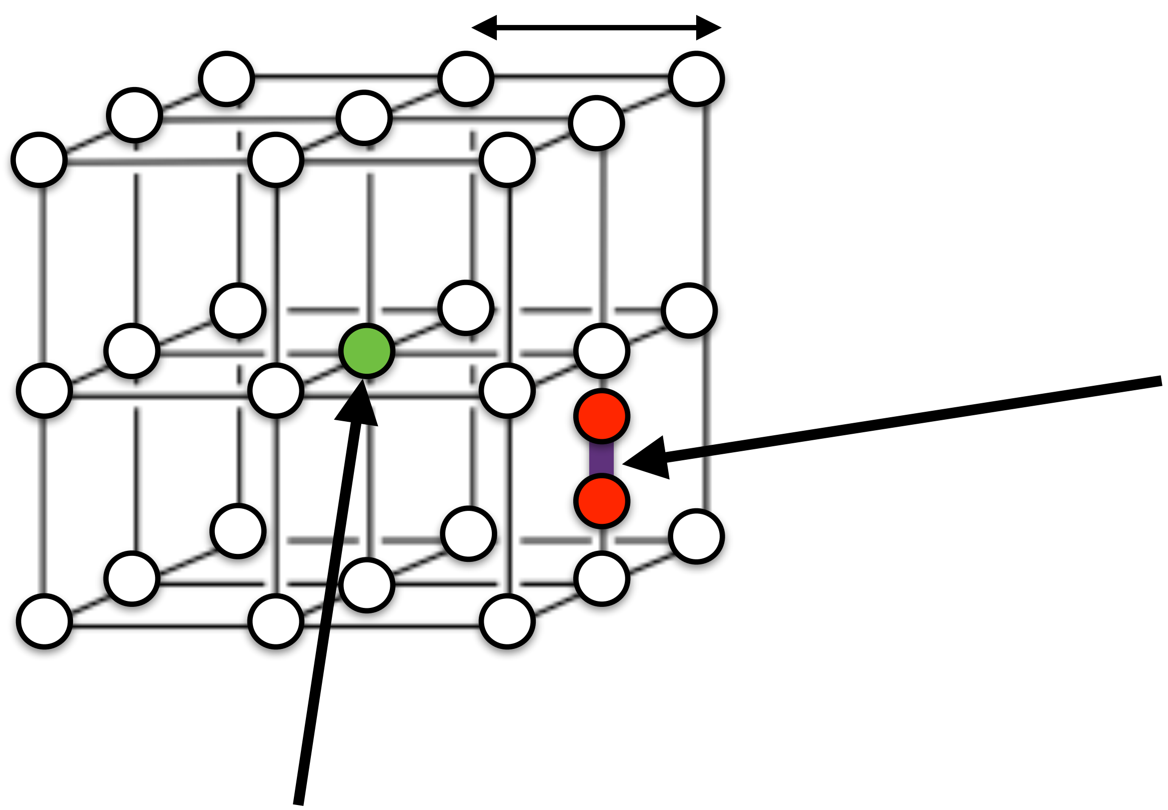

Fermions in some irreps of SU(N)

$$\dim(\mathcal{H}_s) = \text{finite}$$

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a

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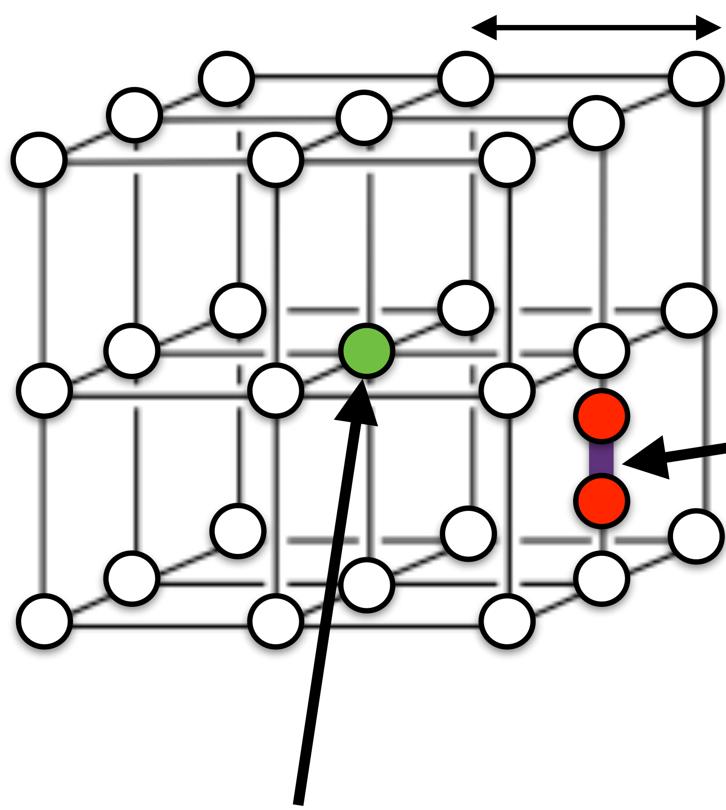

gauge field

Matter

Fermions in some irreps of SU(N)

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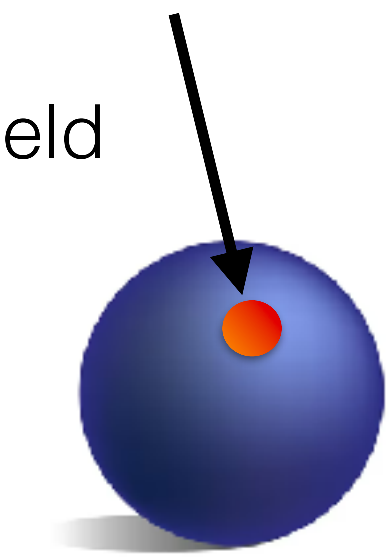
Particle on a SU(N) manifold!



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Link Hilbert space: Position Basis

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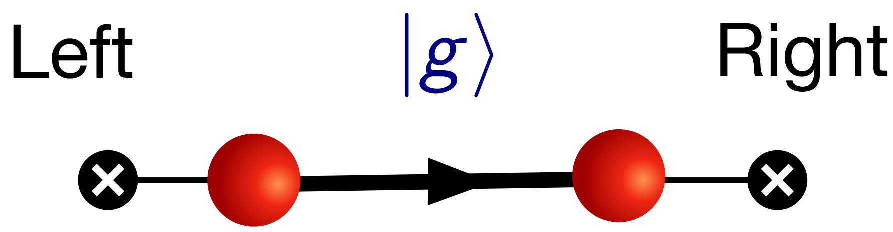
Position basis on links



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$$\langle g'|g\rangle \ = \ \delta(g - g')$$

$$|\psi\rangle \ = \ \int [dg]\ \psi(g)\ |g\rangle$$

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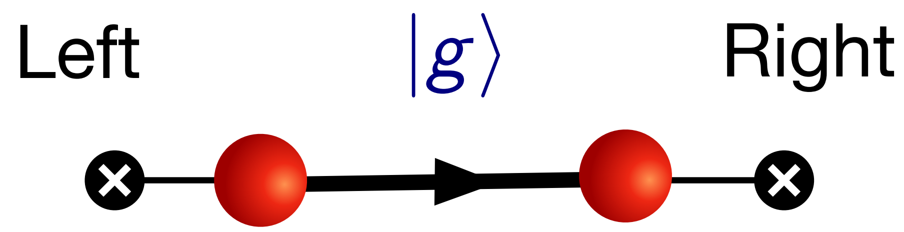

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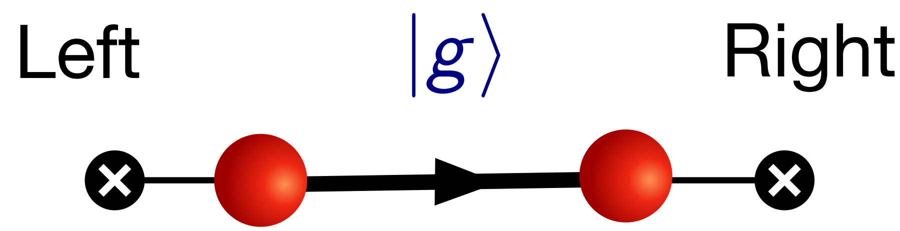

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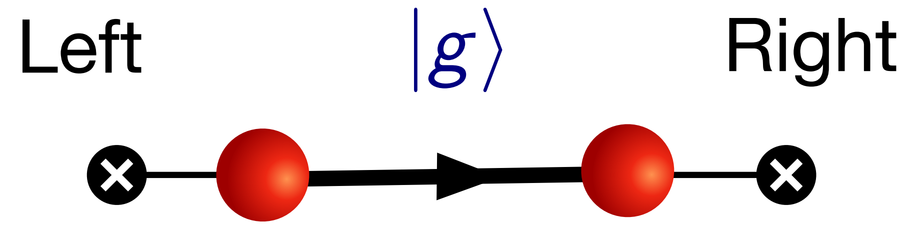
Physical Hilbert space:

Gauss Law Projector

$$\mathcal{H}_{\mathsf{Phys}} = \mathbb{P}_{\hat{G}=0}\Big(\mathcal{H}_{\mathsf{Full}}\Big)$$

Under a gauge transformation:

$$|g\rangle \;\rightarrow\; |h_L \; g \; h_R^{-1}\rangle$$



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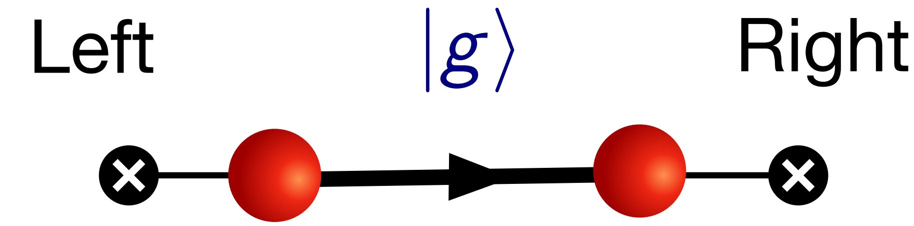

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Left transformations:

$$e^{-i\hat{L}^a h_L^a}\,|g\rangle \;=\; |h_L \; g\rangle$$

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$\hat{L}^a$ and $\hat{R}^a$ $a = 1, 2, \ldots N^2 - 1$ are the generators of left and right gauge transformations on the link.

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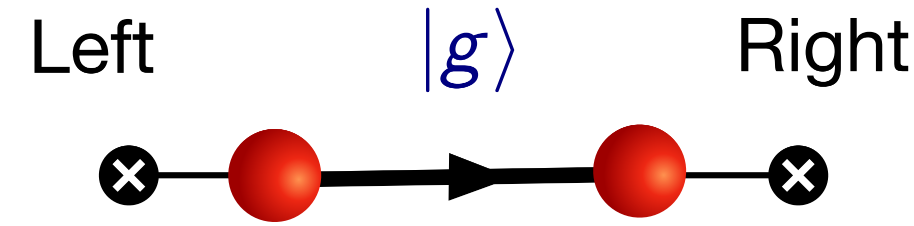

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$\hat{L}^a$ and $\hat{R}^a$ $a = 1, 2, \ldots N^2 - 1$ are the generators of left and right gauge transformations on the link.

$\hat{L}^a$ and $\hat{R}^a$ are like momentum operators! $[\hat{L}^a, \hat{R}^b] \;=\; 0$

Traditional Link Operators: $\hat{\mathcal{U}}^{\lambda}_{ij} \quad i, j = 1, 2, .., d_\lambda$

λ labels an irrep of SU(N)

d_λ dimension of the irrep

$$\hat{\mathcal{U}}^{\lambda}_{ij} \; |g\rangle \;=\; \underset{\text{irrep matrices}}{\underset{\uparrow}{D^{\lambda}_{ij}}}(g) \; |g\rangle$$

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Kogut Susskind Hamiltonian

$$H_{KS} \;=\; g^2 \sum_{\ell} (\hat{L}^a_\ell \; \hat{L}^a_\ell + \hat{R}^a_\ell \; \hat{R}^a_\ell) \;-\; \frac{1}{g^2} \sum_{\square} (\hat{\mathcal{U}}_\square + \hat{\mathcal{U}}^\dagger_\square)$$

Off-diagonal in
position basis

Diagonal in
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Off-diagonal in position basis

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Except in some simple cases,
computing the low lying energy levels of a lattice gauge theory
in the physical Hilbert space is very difficult!

Monomer-Dimer-Tensor Network Basis

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

Siew, SC, Bhattacharya, Phys.Rev.D 111 (2025), 114502

Link Hilbert space: Momentum Basis

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"momentum or (representation) basis"

$$|D^{\lambda}_{ij}\rangle = \int [dg] \sqrt{d_{\lambda}}\, D^{\lambda}_{ij}(g)\, |g\rangle$$

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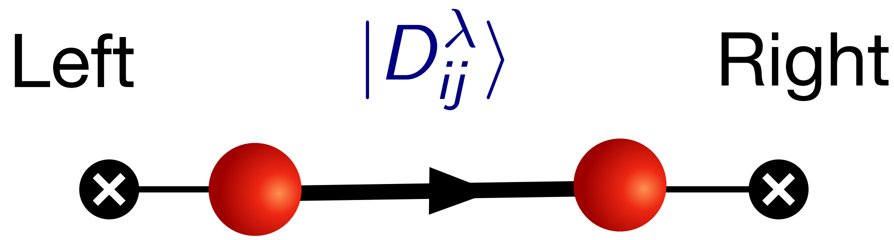

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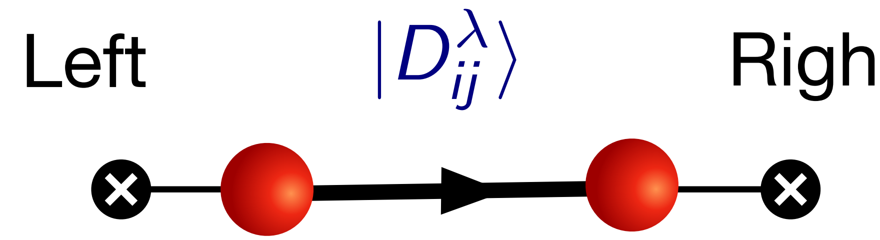

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sum over all
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Peter-Weyl Theorem

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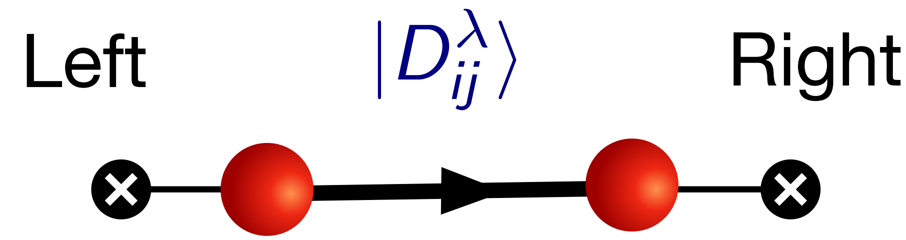

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Gauge transformations preserve irrep!

$$e^{-i\hat{L}^a h_L^a} \mid D_{ij}^{\lambda} \rangle = D_{ik}^{\lambda}(h_L^{-1}) \mid D_{kj}^{\lambda} \rangle$$

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Basis states for a irrep

$$\{|D^\lambda_{ij}\rangle\}, i, j = 1, 2, ..., d_\lambda$$

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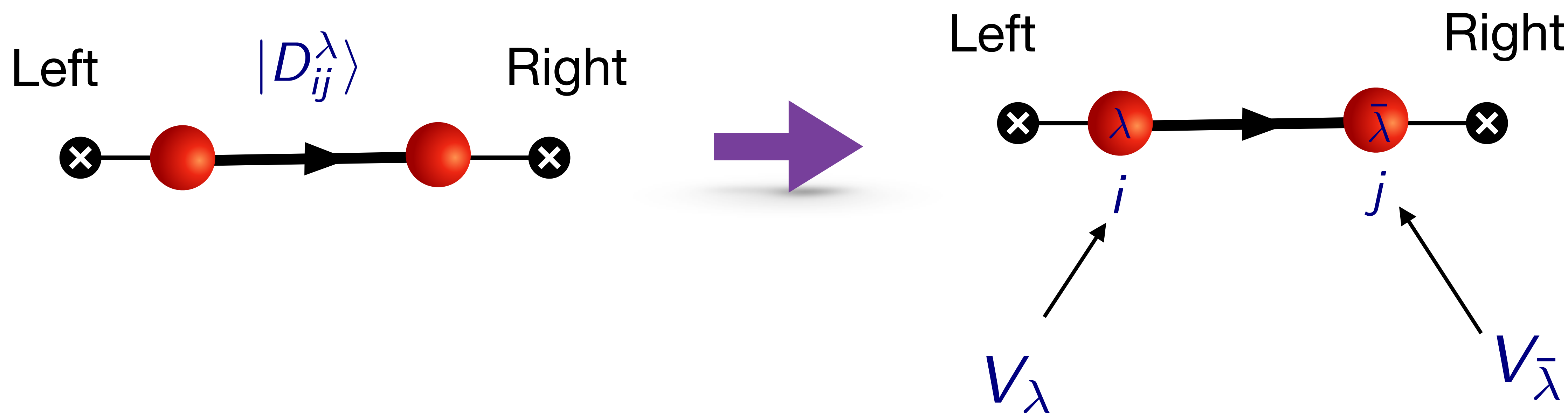

Projecting to the gauge invariant subspace becomes easy.

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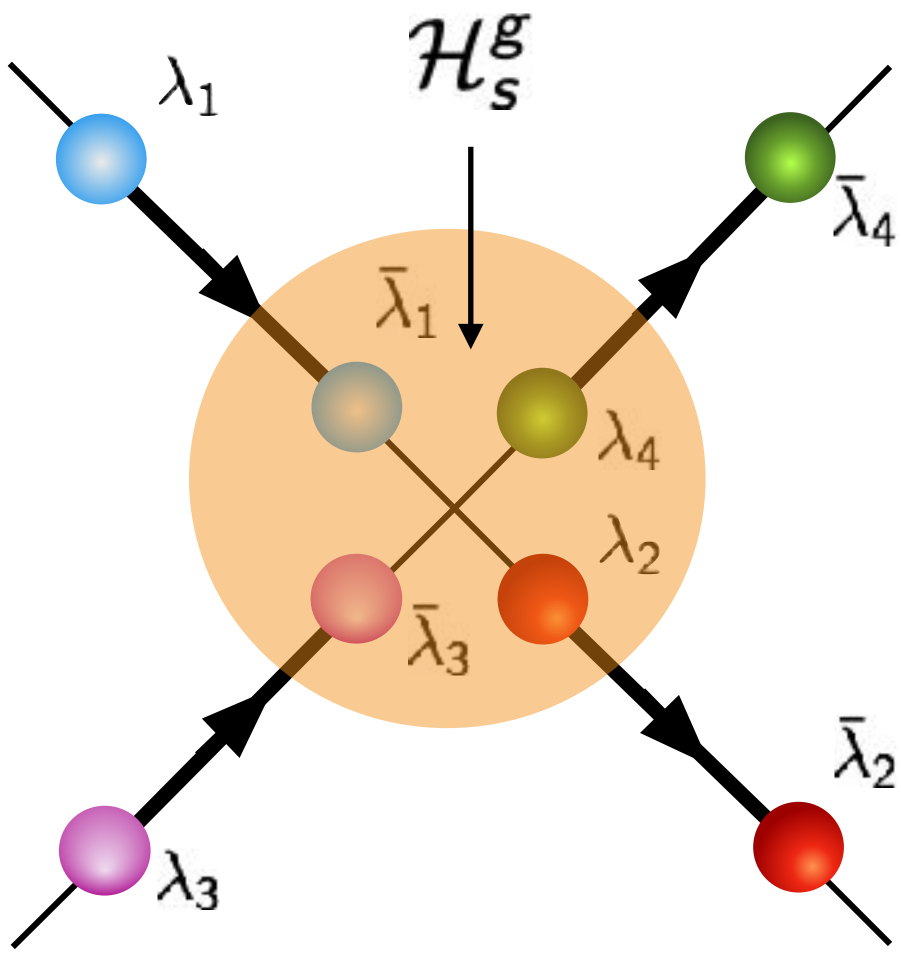
Local Hilbert space on which gauge transformations act



$$\mathcal{H}_s^g = V_{\bar{\lambda}_1} \otimes V_{\bar{\lambda}_3} \otimes V_{\lambda_2} \otimes V_{\lambda_4}$$

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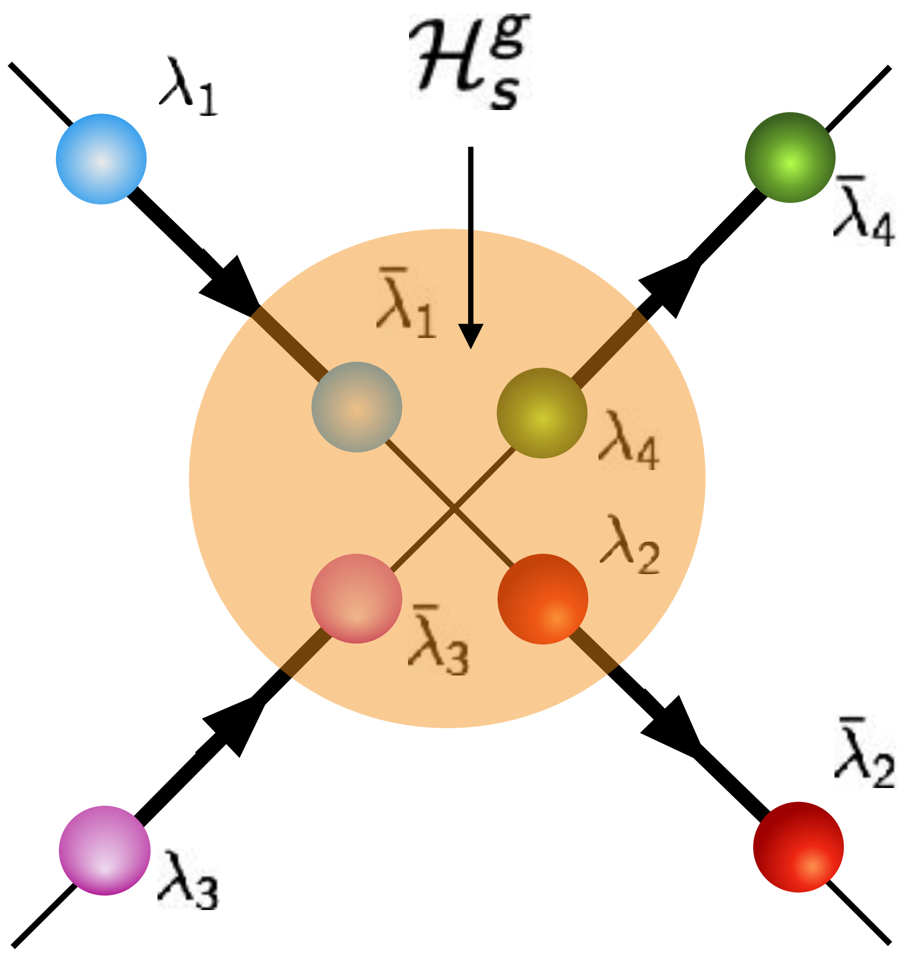

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Let $\alpha_s = 1, 2, \ldots, \mathcal{D}(\mathcal{H}_s^g)$ label the basis states of the singlet space

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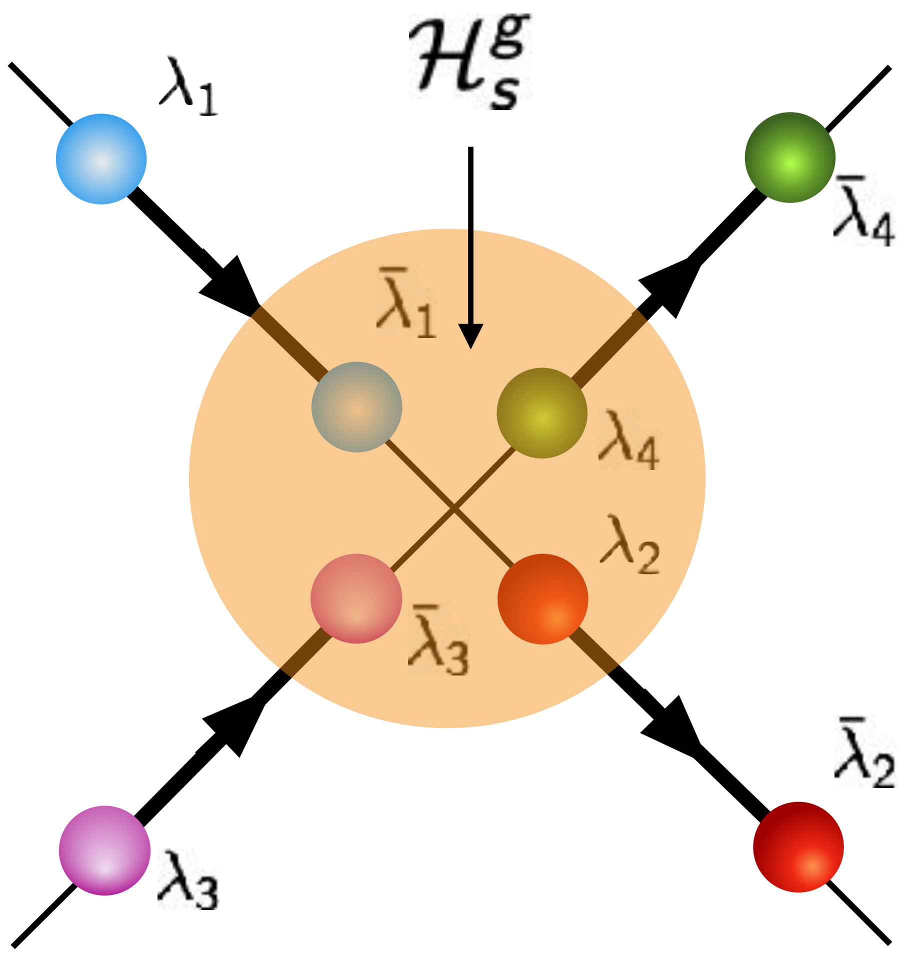

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The physical Hilbert space basis:

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

Dimer-Tensor-Network basis!

Introducing matter fields is easy!

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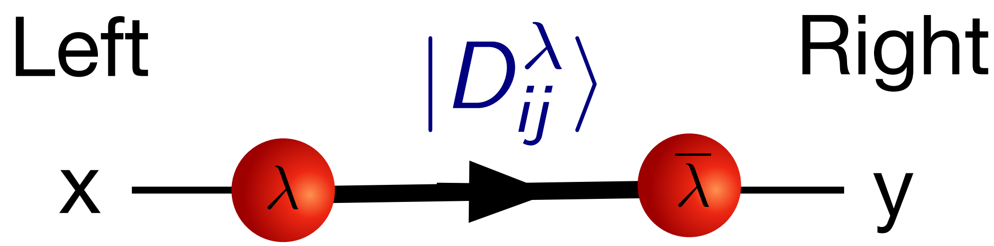
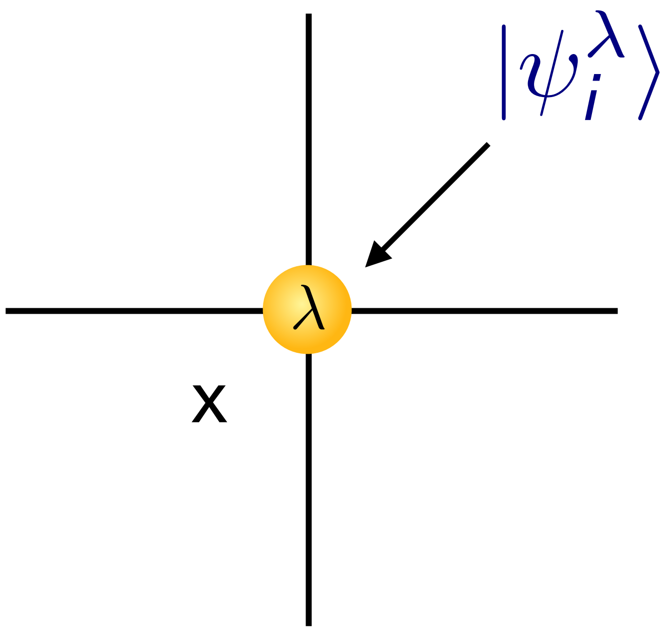


Dimer-Tensor

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



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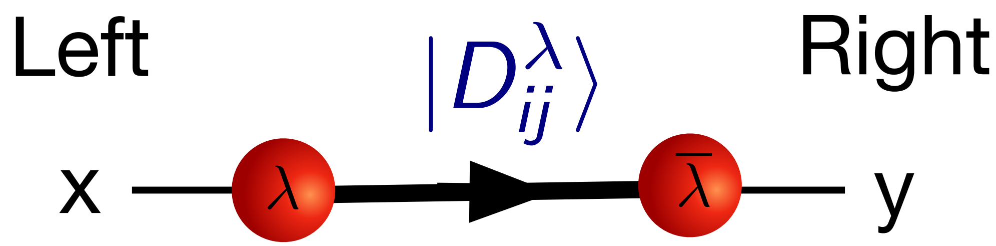

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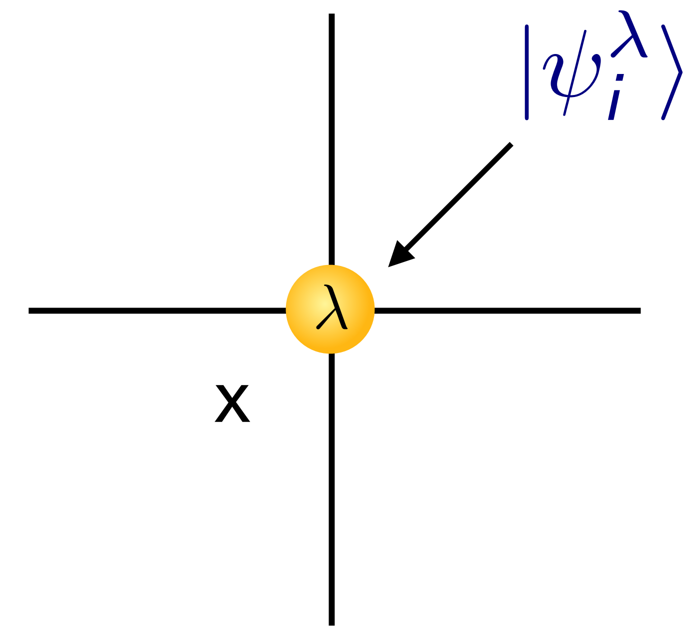
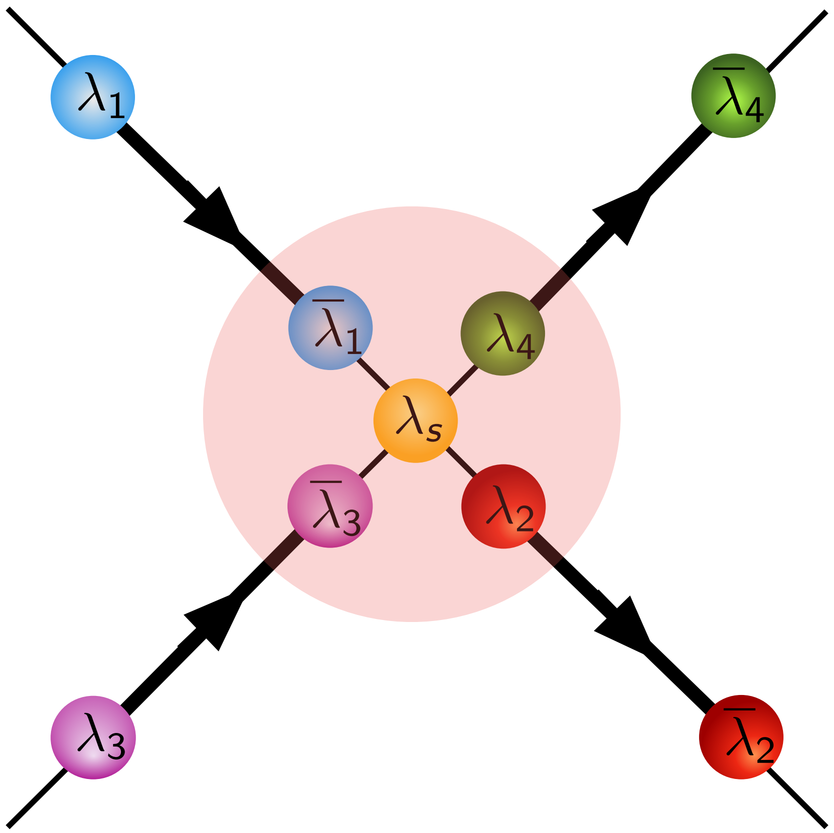


Monomer-Tensor

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

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

Local Hilbert space on which gauge transformations act



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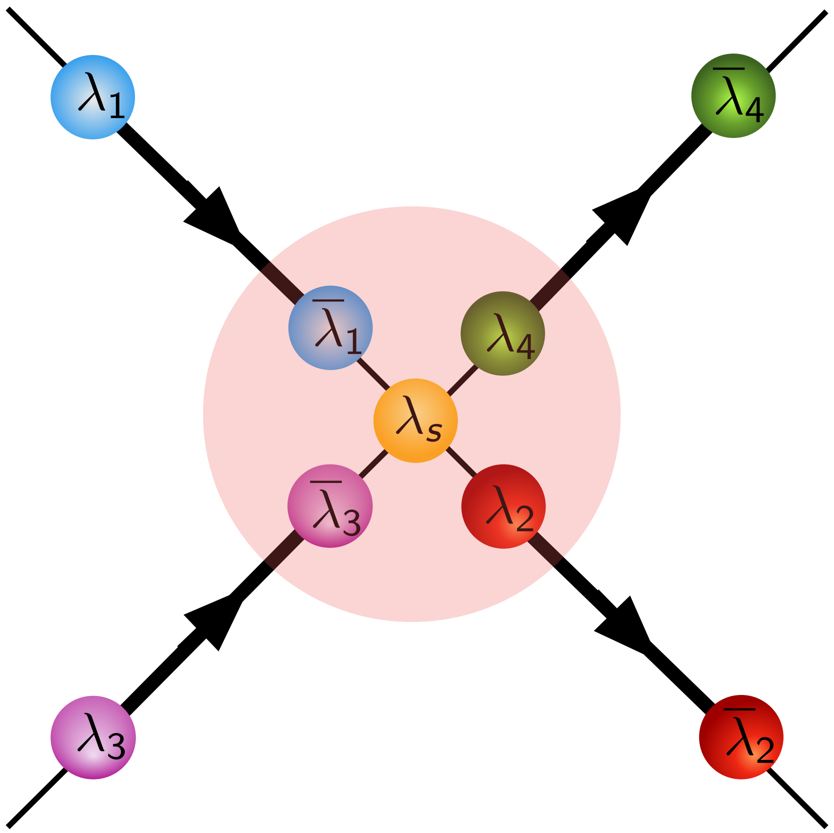

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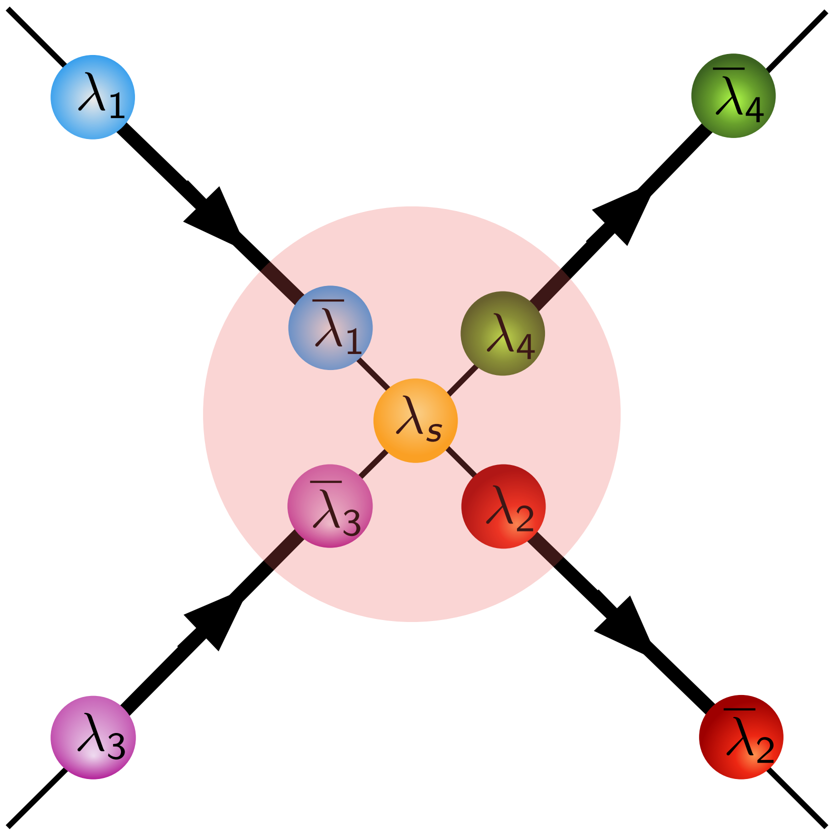

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With matter fields the physical Hilbert space of lattice gauge theories is given by

Monomer-Dimer-Tensor-Network basis!

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

Qubit Regularized Lattice Gauge Theories

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

Lattice gauge theories are not unique

Different Lattice Geometries

Different Lattice Actions

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There is a new parameter in the non-uniqueness space!

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$$\left.\begin{array}{c}\text{Choice of the set of link irreps} \\ |\{\lambda_s\}, \{\lambda_\ell\}, \{\alpha_s\}\rangle \\ \uparrow \\ Q = \{\lambda_\ell^1, \lambda_\ell^2, \cdots\}\end{array}\right\} \text{Qubit regularization}$$

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Qubit regularized lattice gauge theories:

- may lead to new continuum QFTs, or
- may lead to alternate ``regularization” of familiar QFTs

$$Q = \{1, \underbrace{\square\,, \begin{array}{|c|}\hline \\ \hline \\ \hline\end{array}\,, \ldots}_{\text{All anti-symmetric irreps}}\}$$

A simple qubit regularization scheme

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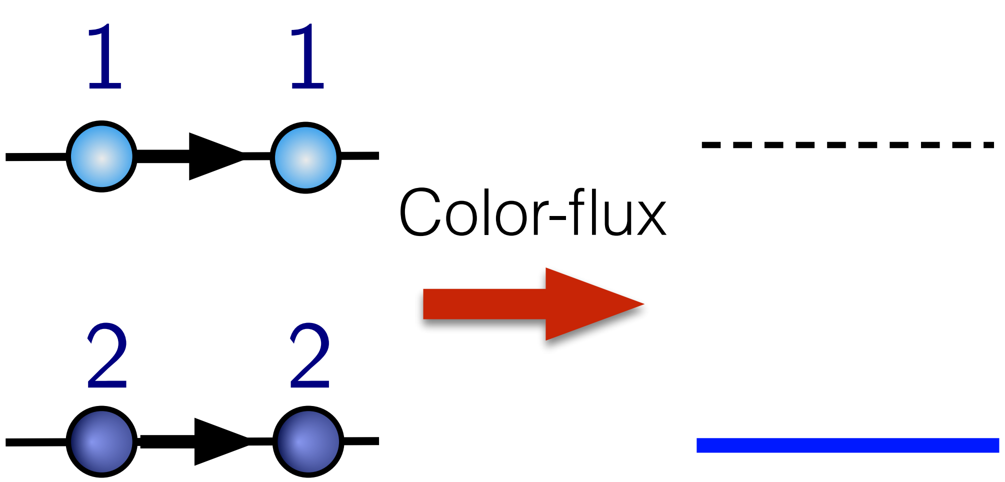
SU(2) Link Hilbert space



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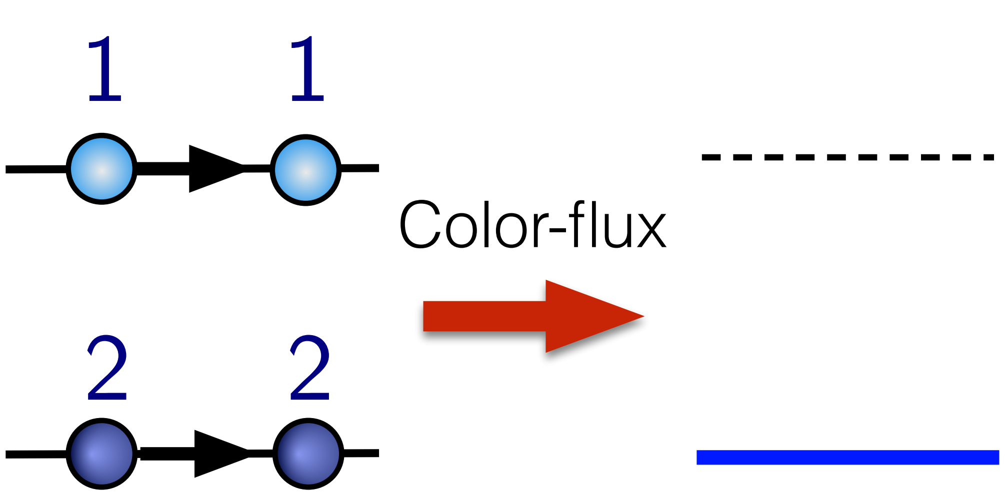
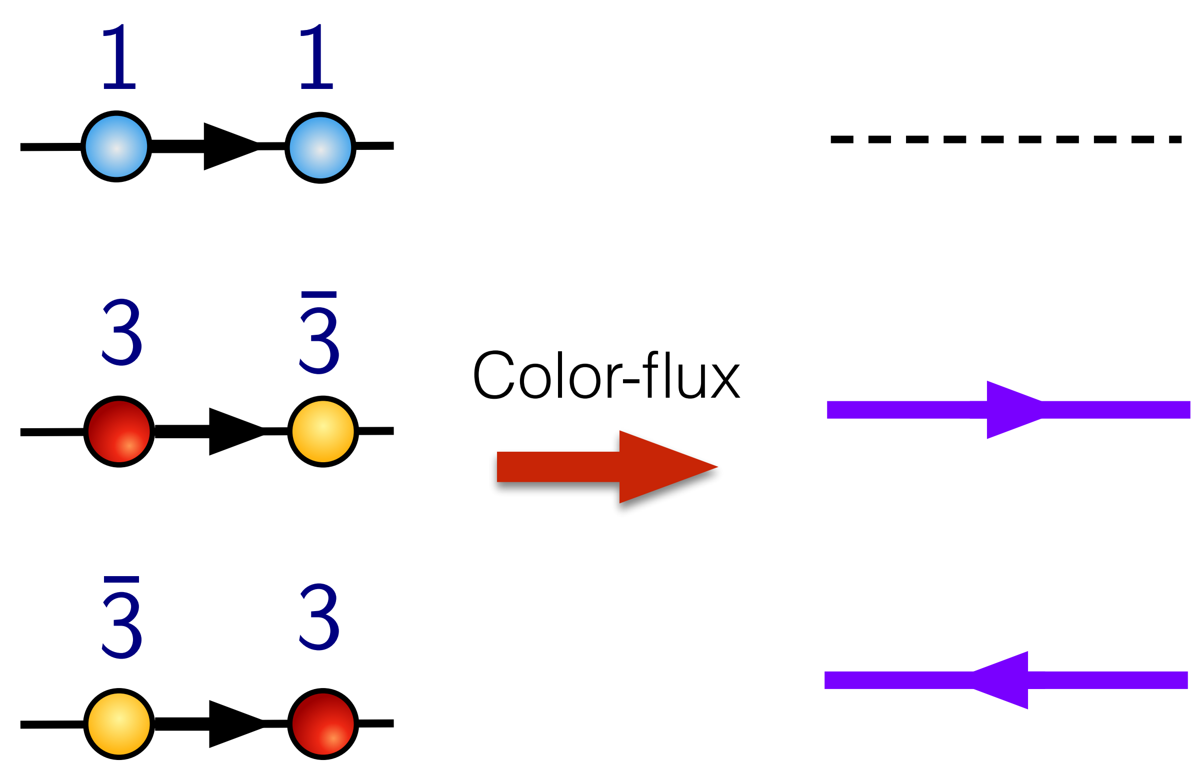
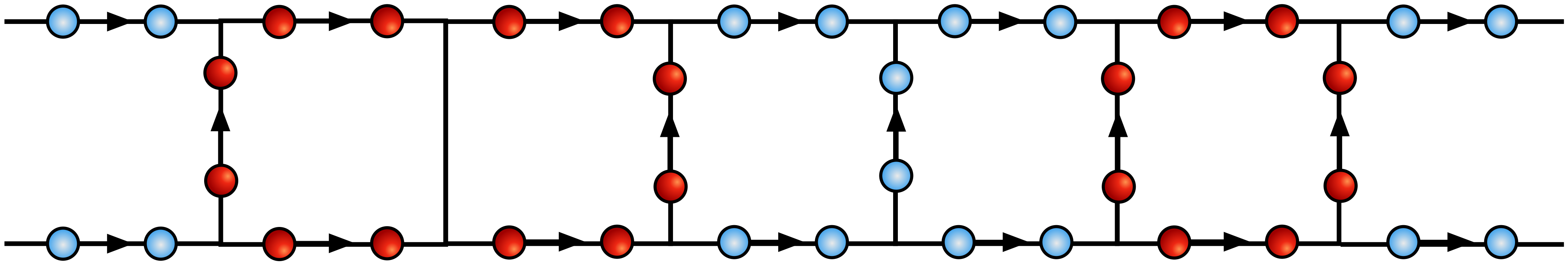


SU(3) Link Hilbert space



A qubit regularized SU(2) lattice gauge theory



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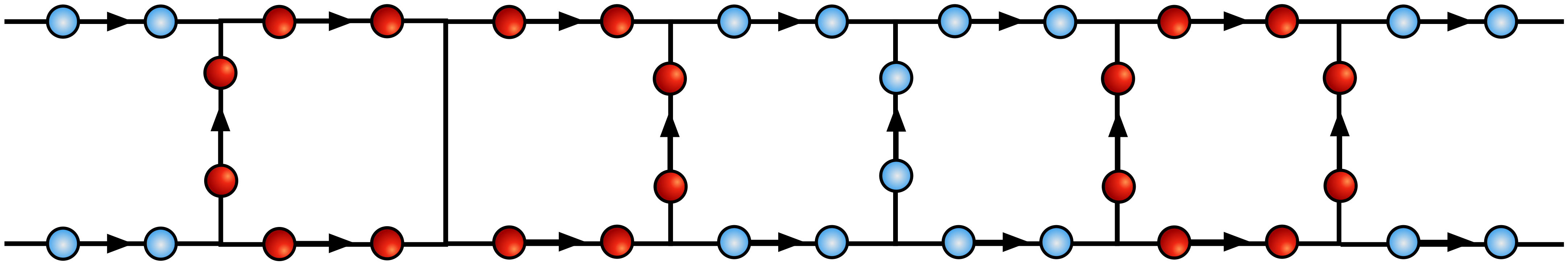
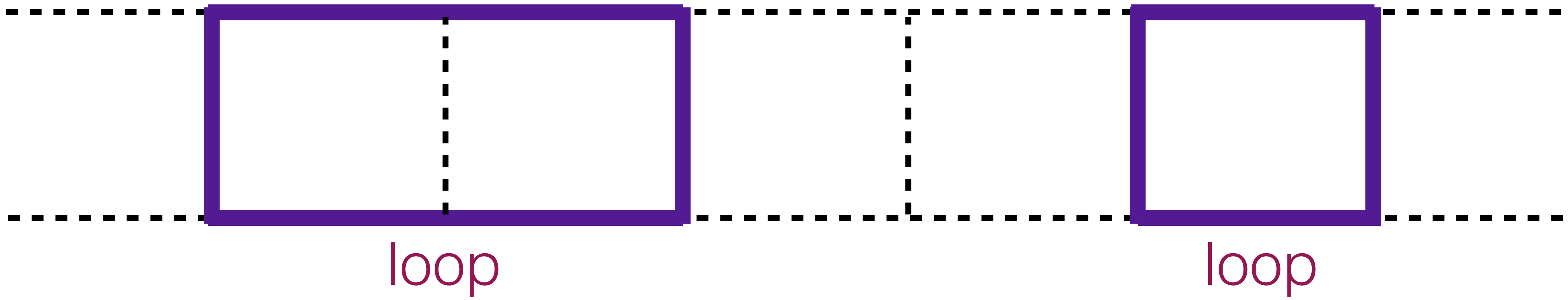


color-flux representation



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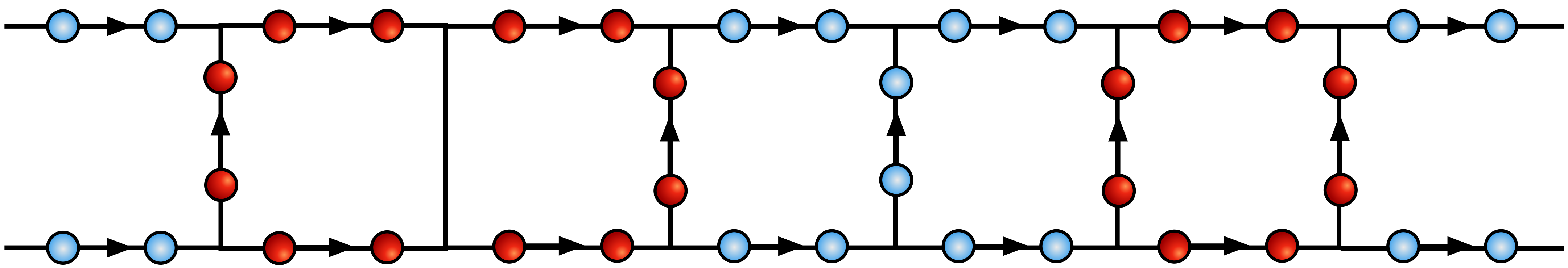

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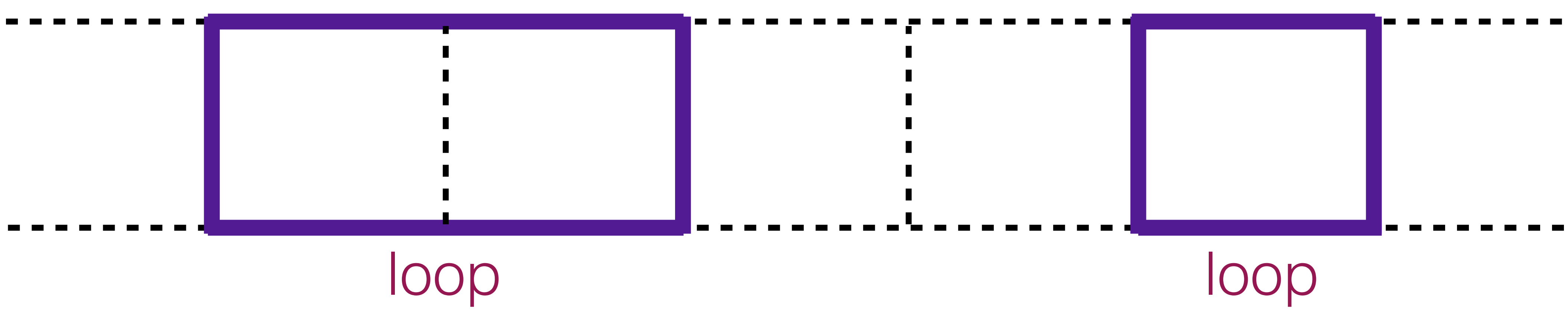
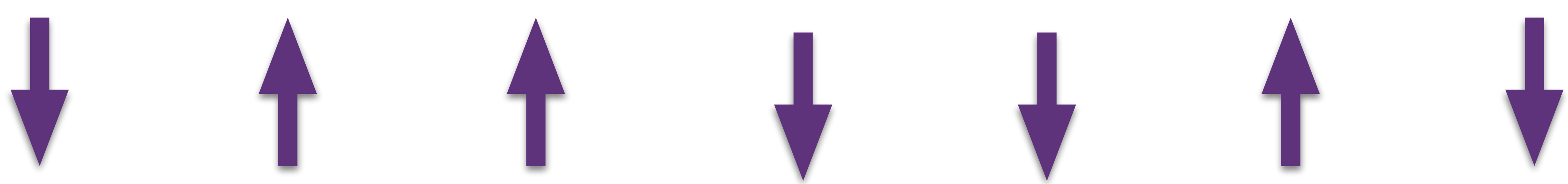
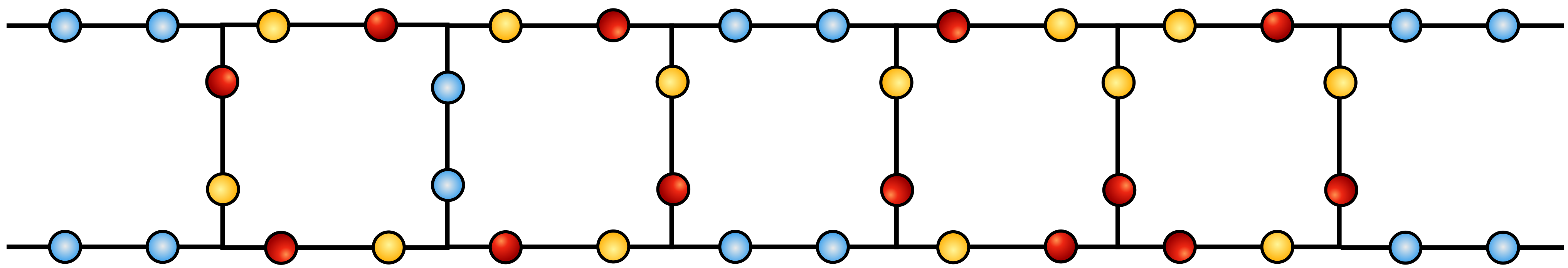


Quantum Ising Hilbert Space



A qubit regularized SU(3) lattice gauge theory



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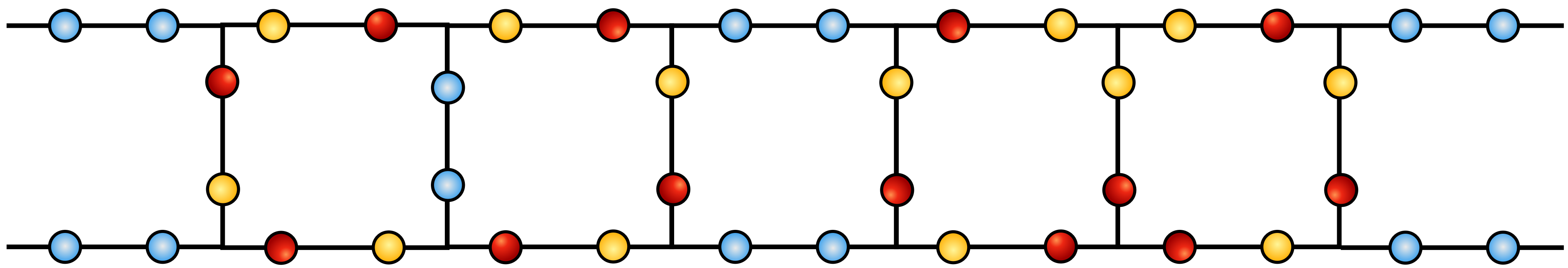
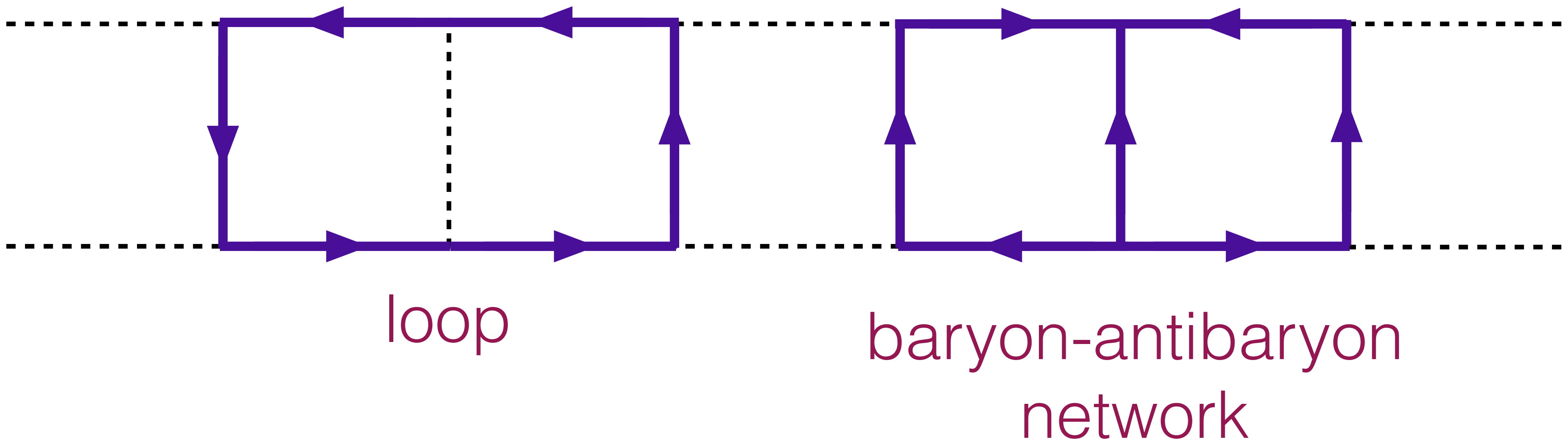


color-flux representation



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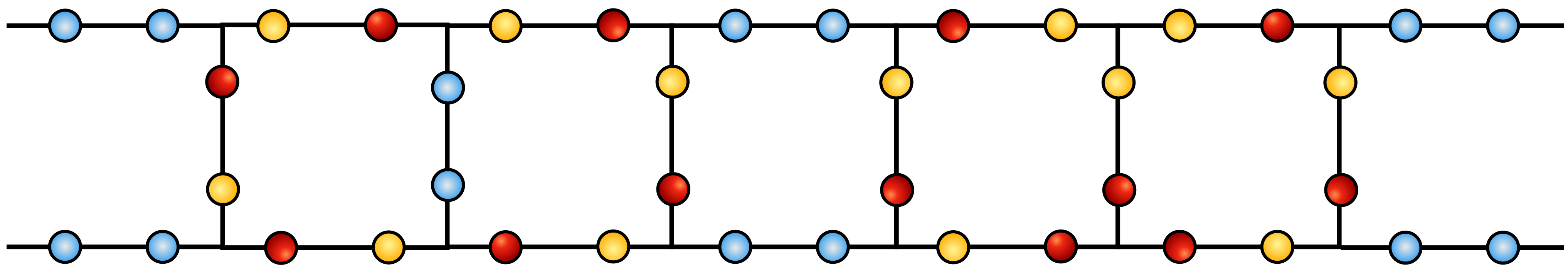

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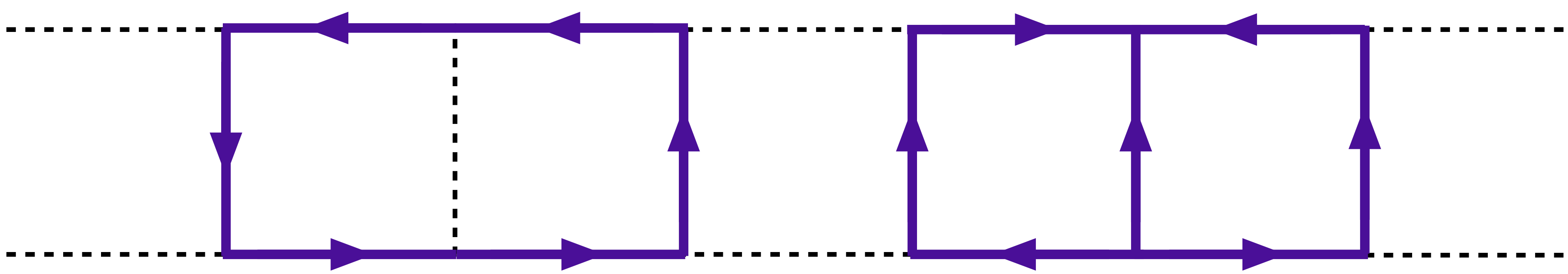
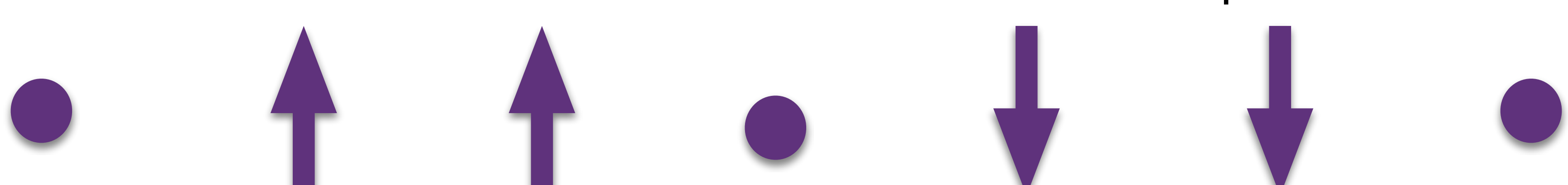


3-State Quantum Clock Hilbert Space



Hamiltonian of a “Pure” qubit regularized gauge theory

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

Diagonal operators

Off-diagonal plaquette operators

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Similar to quantum dimer models in CMP

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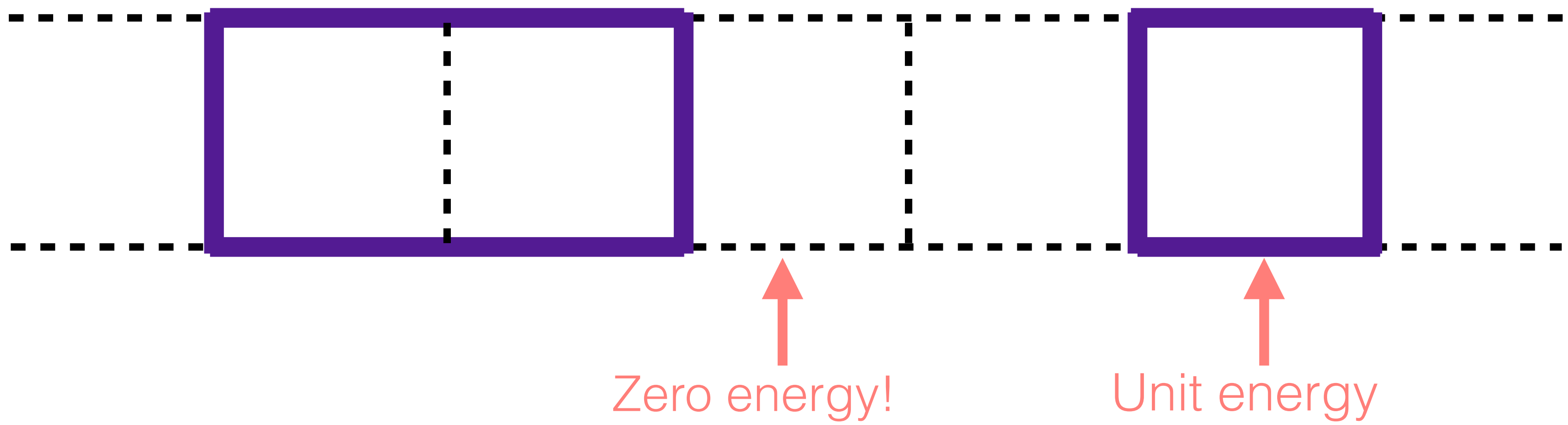

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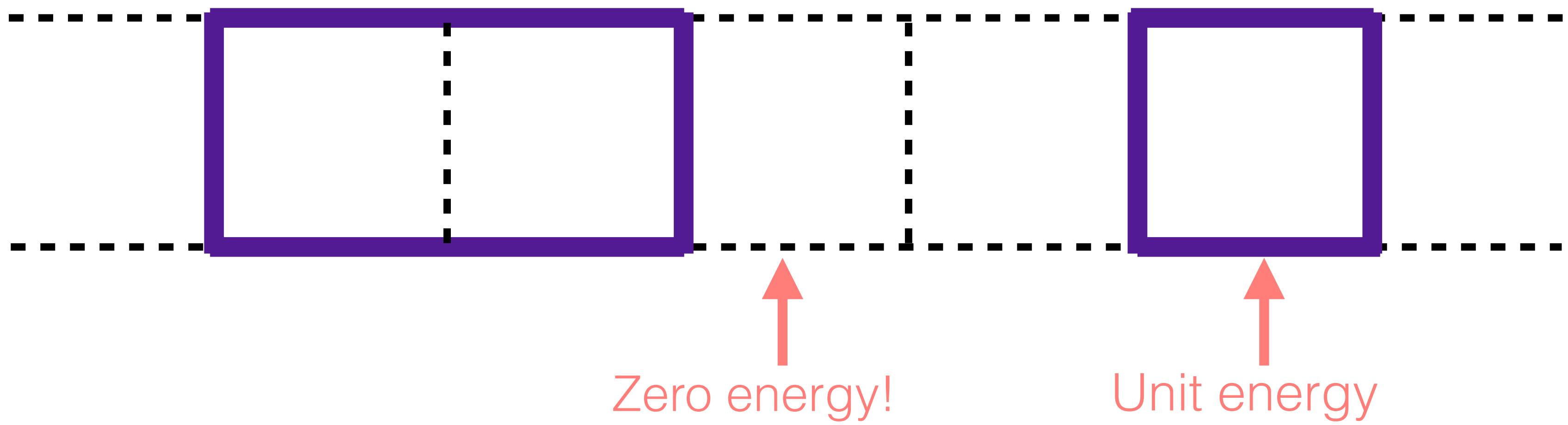

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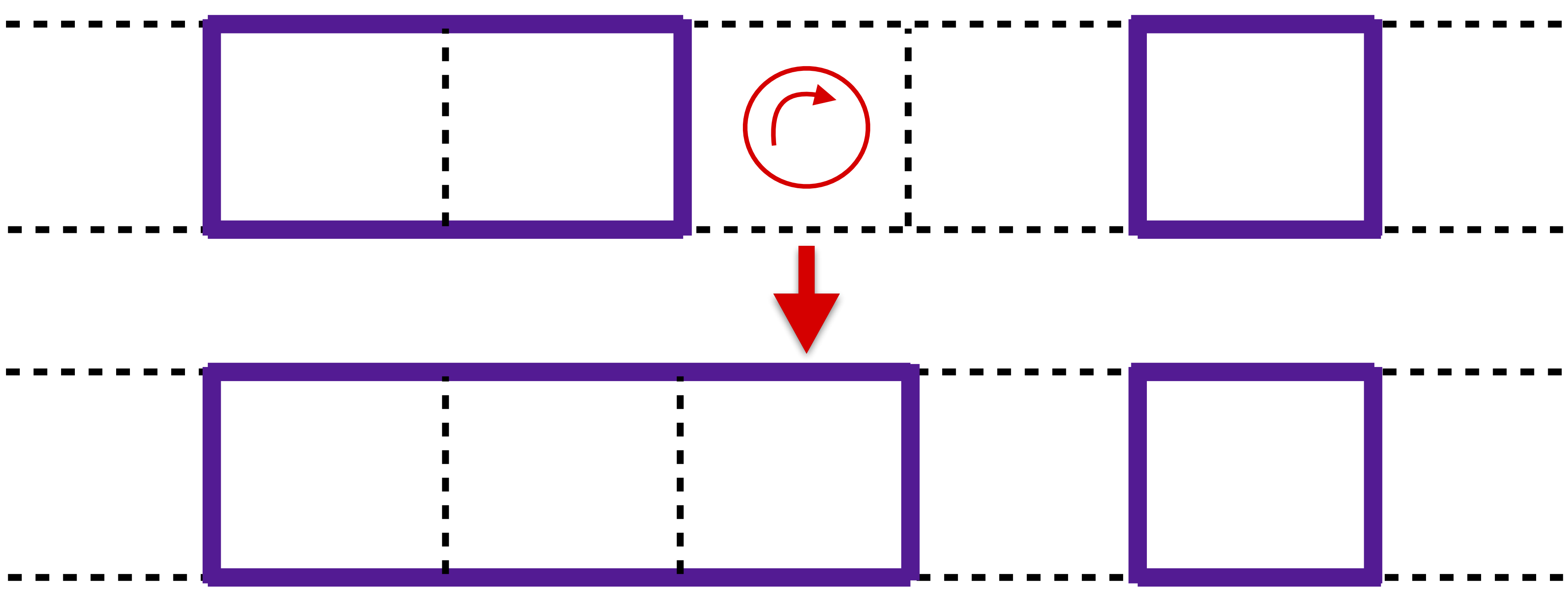

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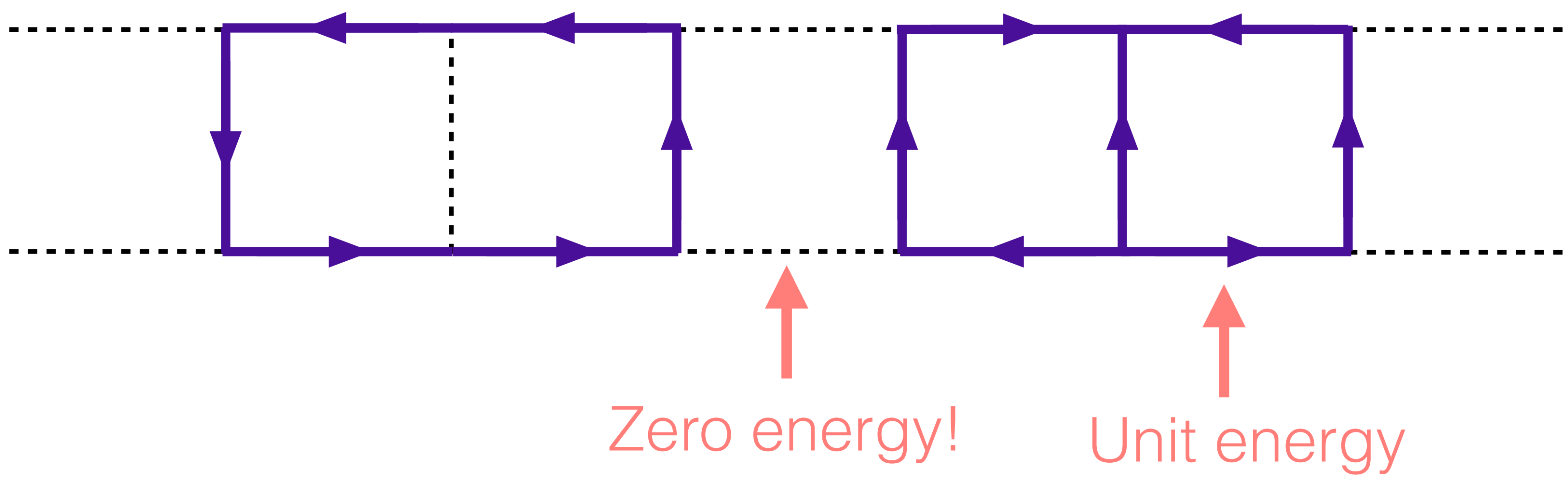

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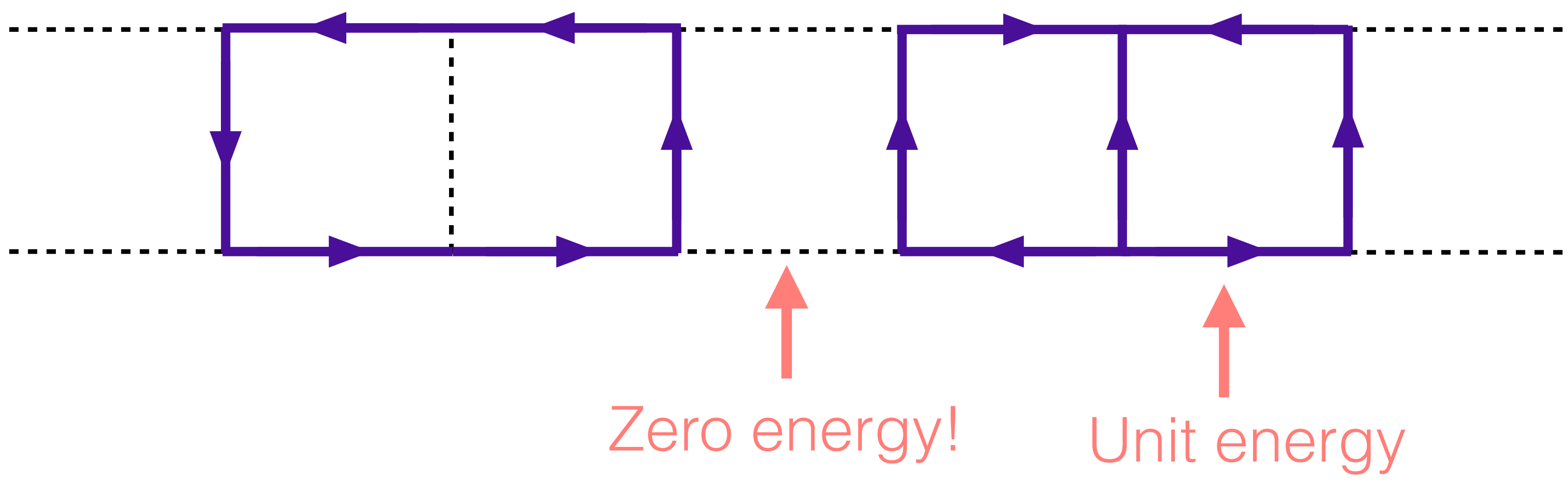

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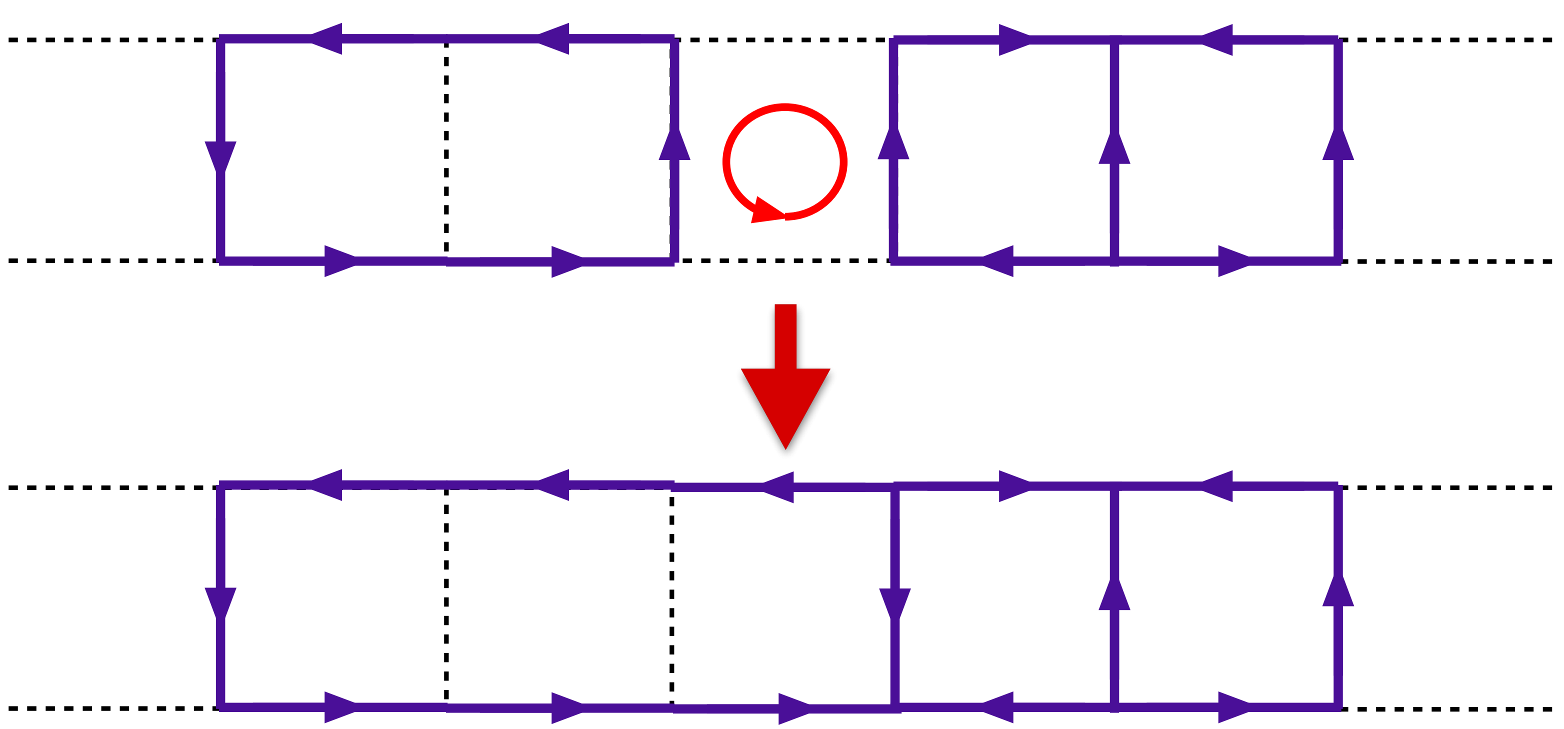

Continuum limits

Siew, SC, Bhattacharya arXiv: 2512.11068

Siew, SC, Bhattacharya arXiv: 2603.01215

Continuum Limits via the RG flow perspective

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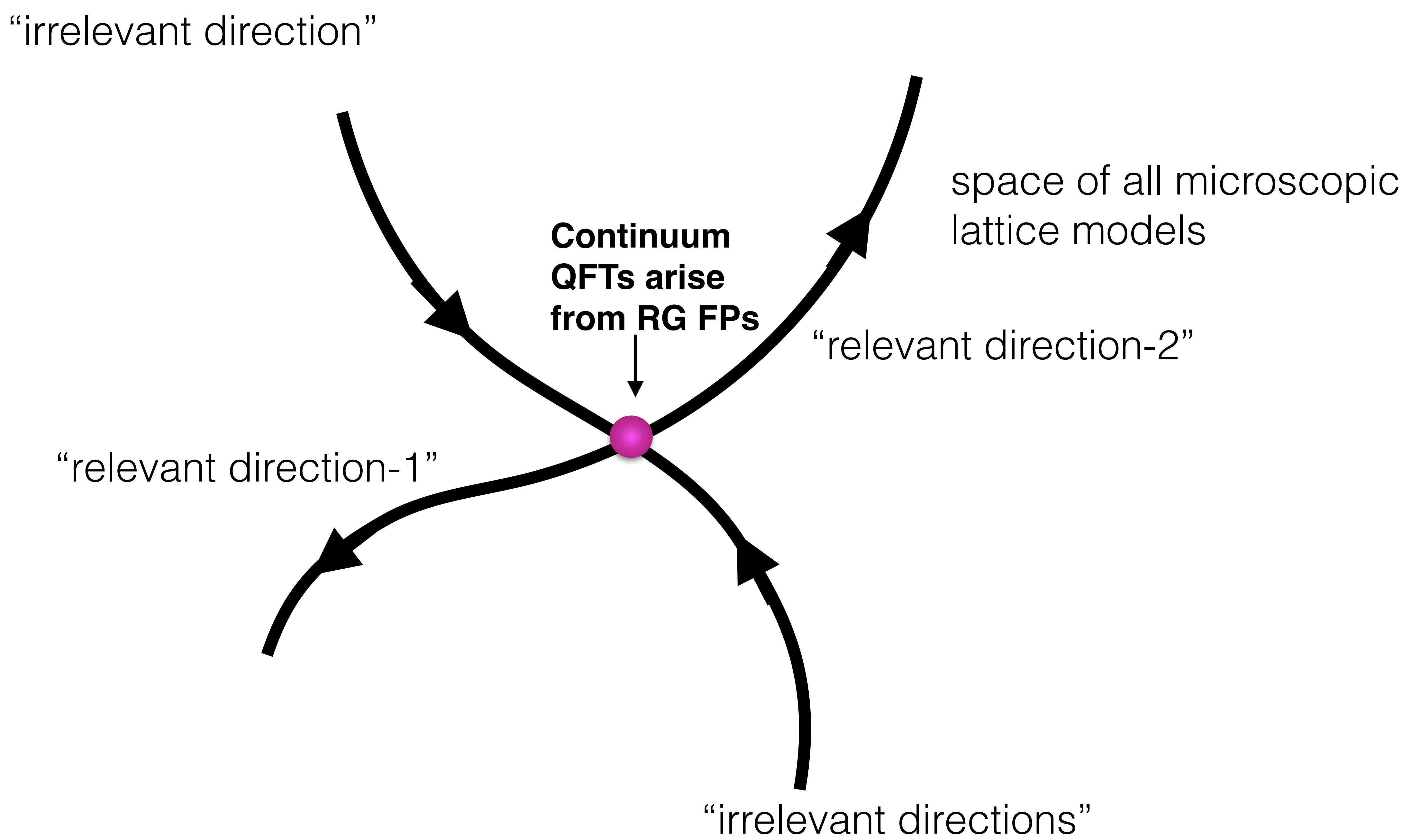

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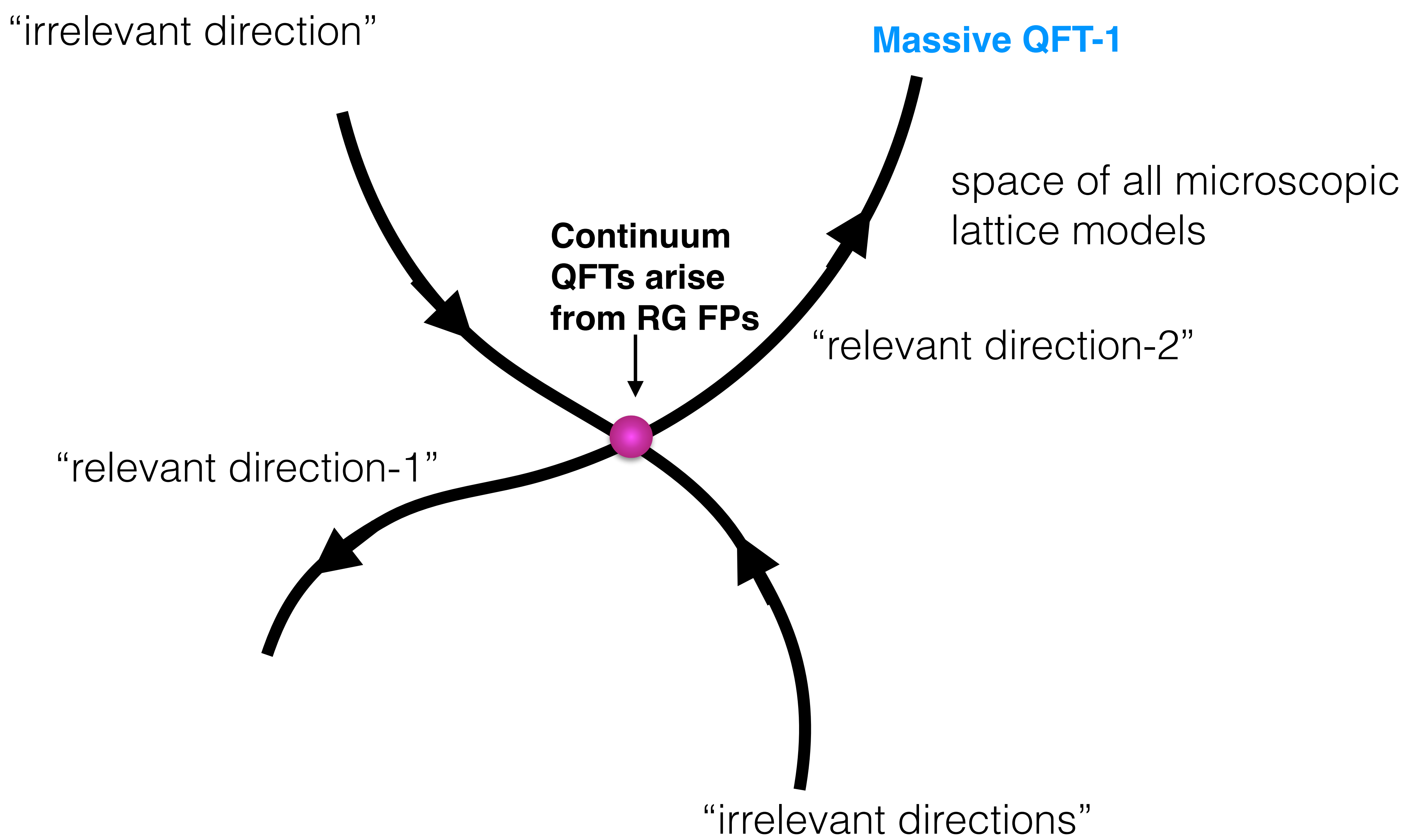

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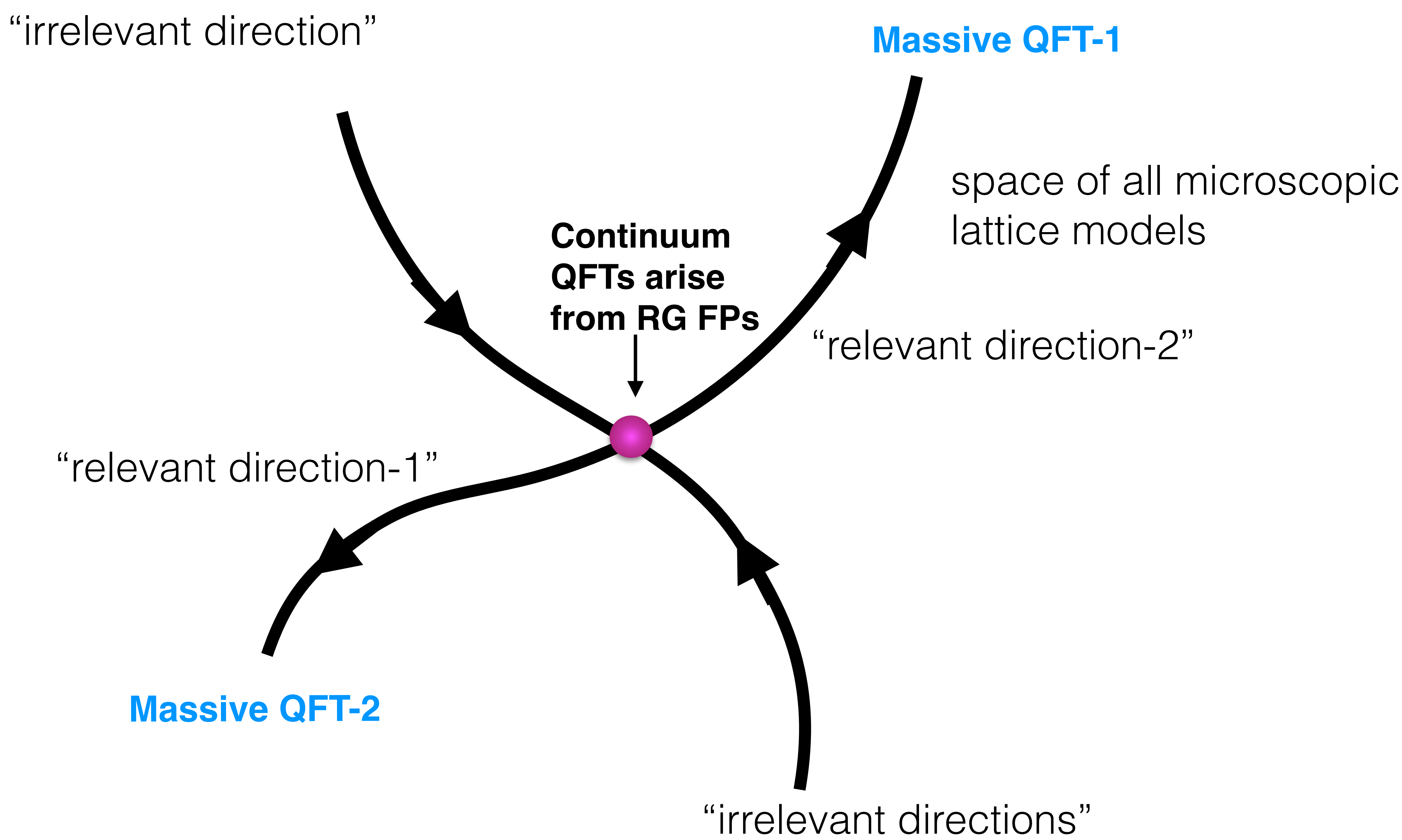

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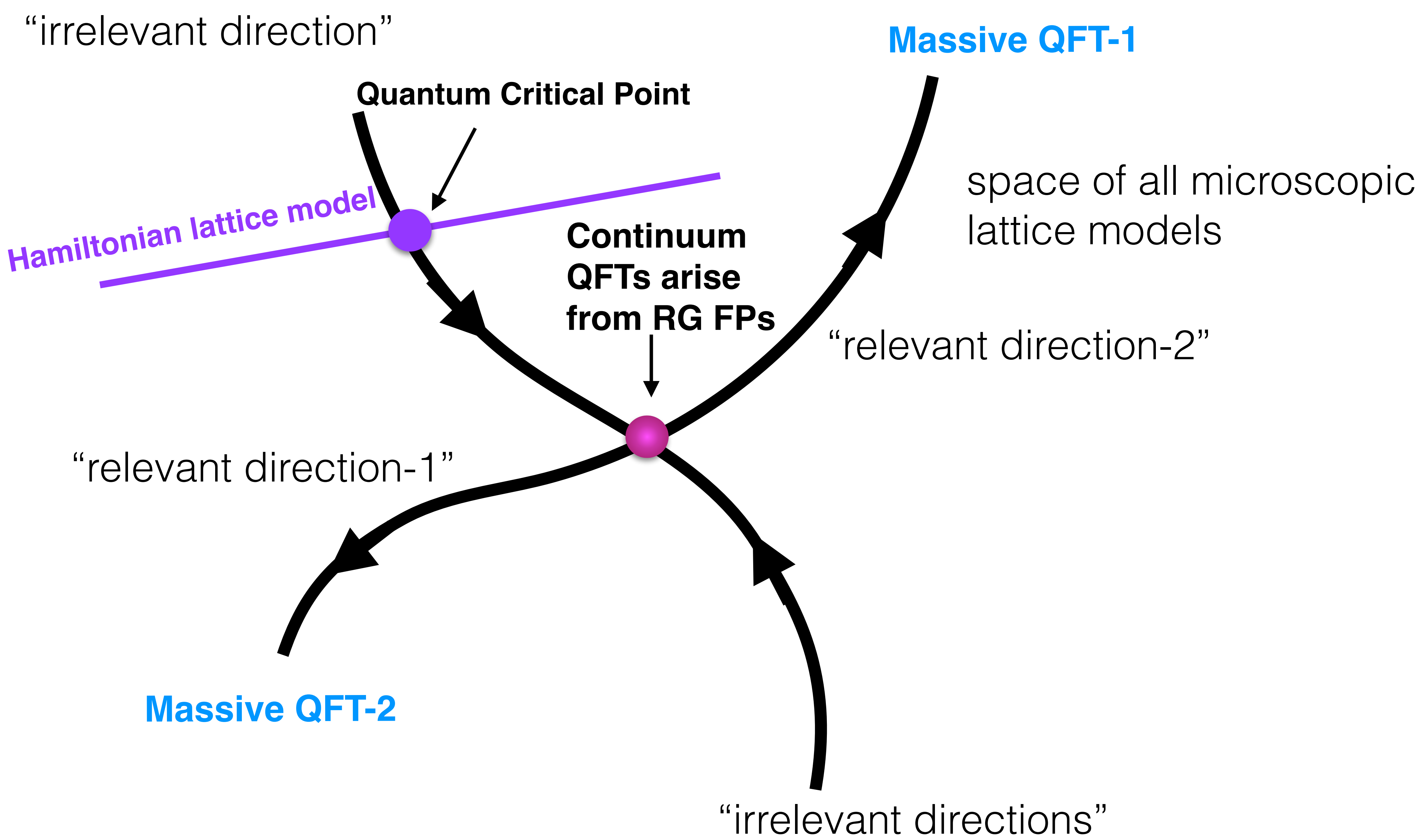

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5. Study physical quantities as a function of μ

   for large box sizes L and small values of h

$\mu \to 0$ (UV) $\qquad\qquad$ $\mu \to \infty$ (IR)

Continuum Limit of Plaquette Chains

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Hamiltonian: 3-couplings

$$H_{pc} = \kappa_c \sum_{\ell_c} \hat{\mathcal{E}}_{\ell_c} + \kappa_r \sum_{\ell_r} \hat{\mathcal{E}}_{\ell_r} - g \sum_{P} \left(\hat{\mathcal{U}}_P + \hat{\mathcal{U}}_P^\dagger \right)$$

chain rung plaquette

Color-flux energy

Changes color-flux

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What is the connection with gauge theory?

String-Tension

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Introduce heavy matter fields at fixed positions

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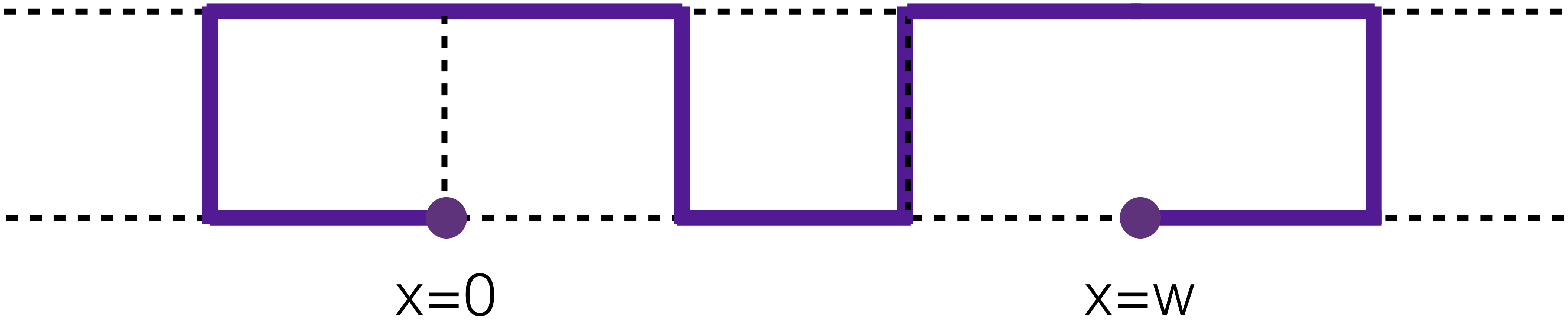
SU(2) configuration



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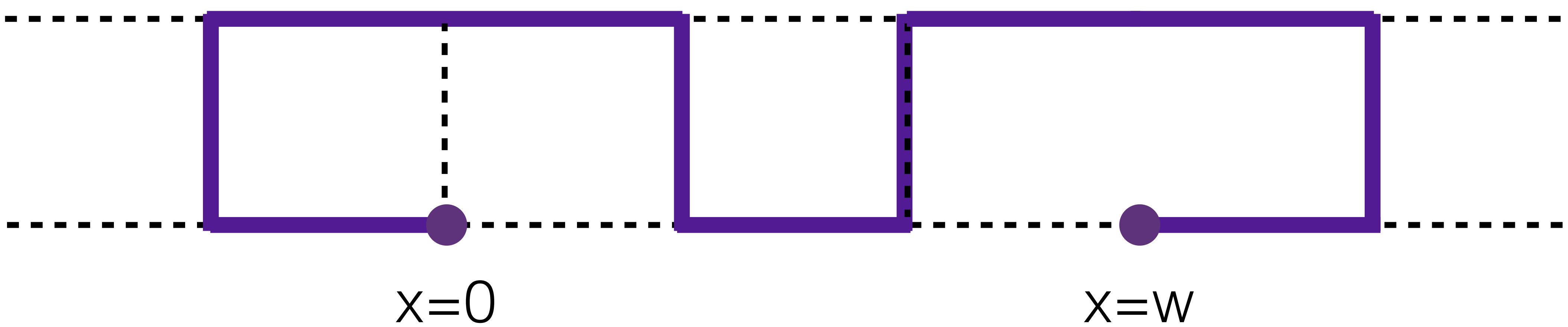

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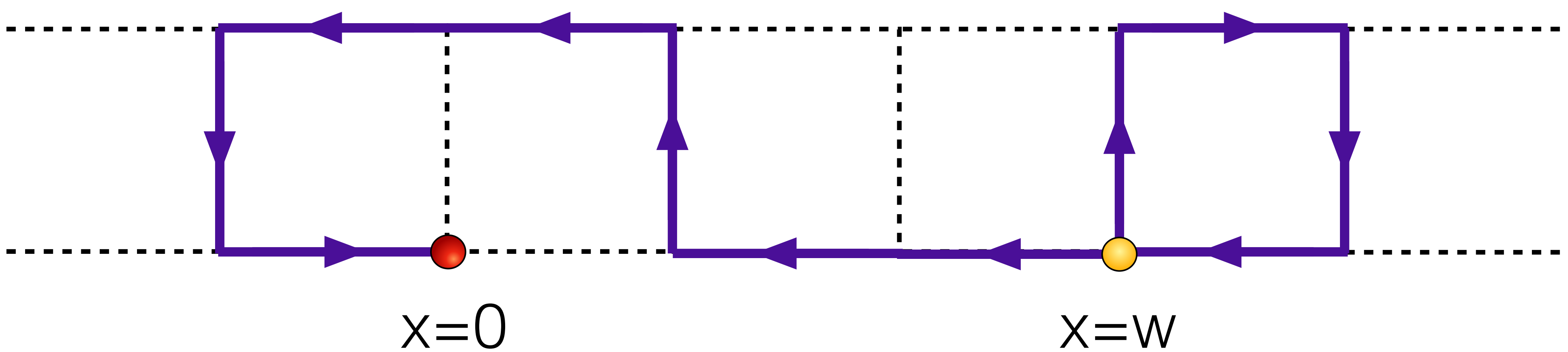

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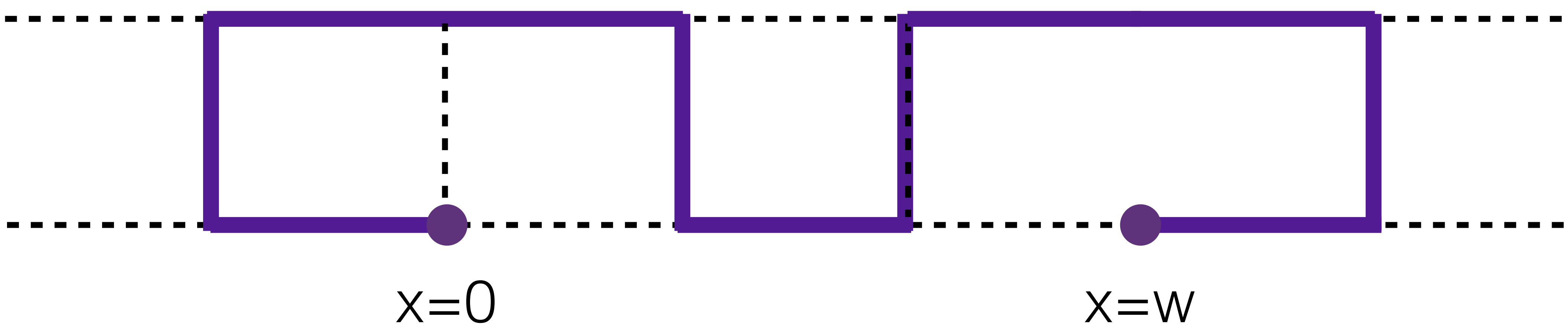

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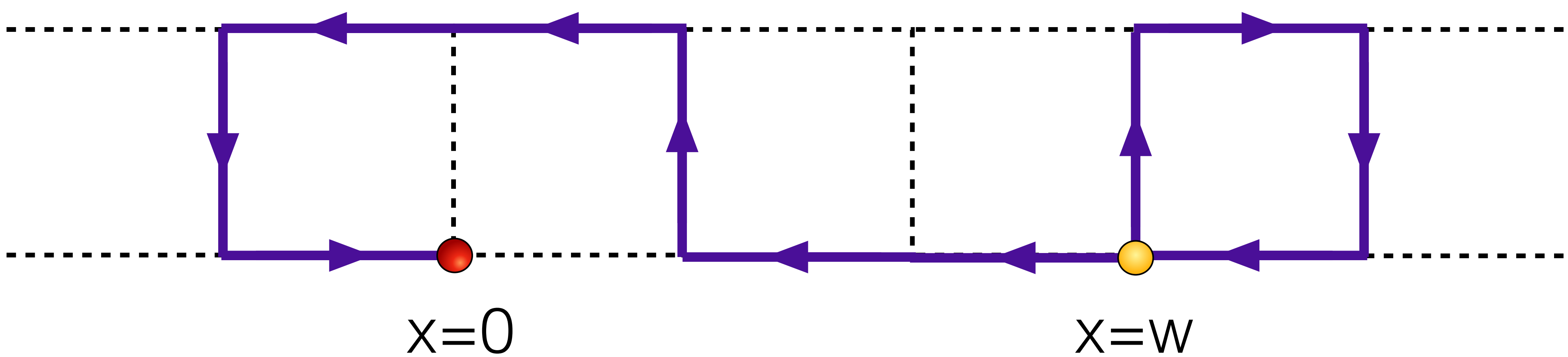

$$V(\mathrm{w}) = \mathrm{E}_0^+(\mathrm{w}) - \mathrm{E}_0^+ \,, \qquad V(\mathrm{w}) = \alpha + \bar{\sigma}\,\mathrm{w} \,,$$

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SU(3) case: 1.459(2)

2+1D SU(3):
Athenodorou & Teper JHEP 02 (2017) 015 ≈ 1.46

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Athenodorou & Teper JHEP 02 (2017) 015 ≈ 1.46

String-Tension vs Glueball Mass Ratios in the Continuum

SU(2) case: 0.249(1)

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Athenodorou & Teper JHEP 02 (2017) 015 ≈ 0.23

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Or will infinite local lattice Hilbert space be Important somehow to reproduce some continuum QFTs?

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Can we get similar continuum limits in higher dimensions and if yes what are they?