Title: Models of deconfined criticality for square and triangular lattice antiferromagnets

Speakers: Henry Shackleton

Series: Quantum Matter

Date: December 04, 2023 - 11:00 AM

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Abstract: Frustrated quantum magnets provide a promising platform for realizing exotic phase transitions known as deconfined quantum critical points (DQCPs), where a conventional Landau-Ginzburg description fails and the resulting description involves emergent gauge fields. In the first part of my talk, I will propose a unified theory for describing a pair of continuous phase transitions numerically observed in the frustrated square lattice Heisenberg antiferromagnet, where a spin liquid phase appears to emerge in between Neel and valence bond solid (VBS) phases. The proposed DQCPs exhibit a plethora of unconventional phenomena, including anisotropic fixed points and dangerously irrelevant perturbations. In the second part of my talk, I will describe recent work analyzing an effective model of triangular lattice antiferromagnetism which supports coplanar magnetic order as well as VBS and spin liquid phases. We show that this effective model is sign-problem-free and amenable to large-scale Monte Carlo simulations, which reveal a direct transition between magnetic and VBS phases.

Zoom link https://pitp.zoom.us/j/98562300020?pwd=OXYrL0dJTGkzNk5memlVM0tqY3hNQT09

Models of deconfined criticality on square and triangular lattice antiferromagnets

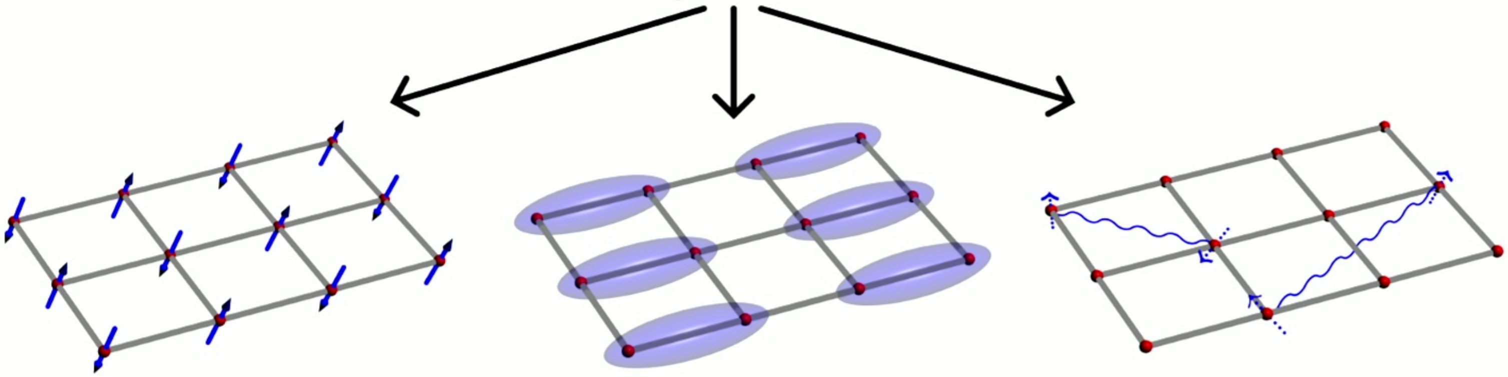
Henry Shackleton

December 4th, 2023

Harvard University

Quantum magnetism as a platform for exotic phases

$$H = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



Parton construction: versatile theoretical tool

$$\vec{S}_i \to b^\dagger_{i\alpha} \vec{\sigma}^{\alpha\beta} b_{i\beta} \, , \, f^\dagger_{i\alpha} \vec{\sigma}^{\alpha\beta} f_{i\beta}$$

Quantum magnetism as a platform for exotic phases

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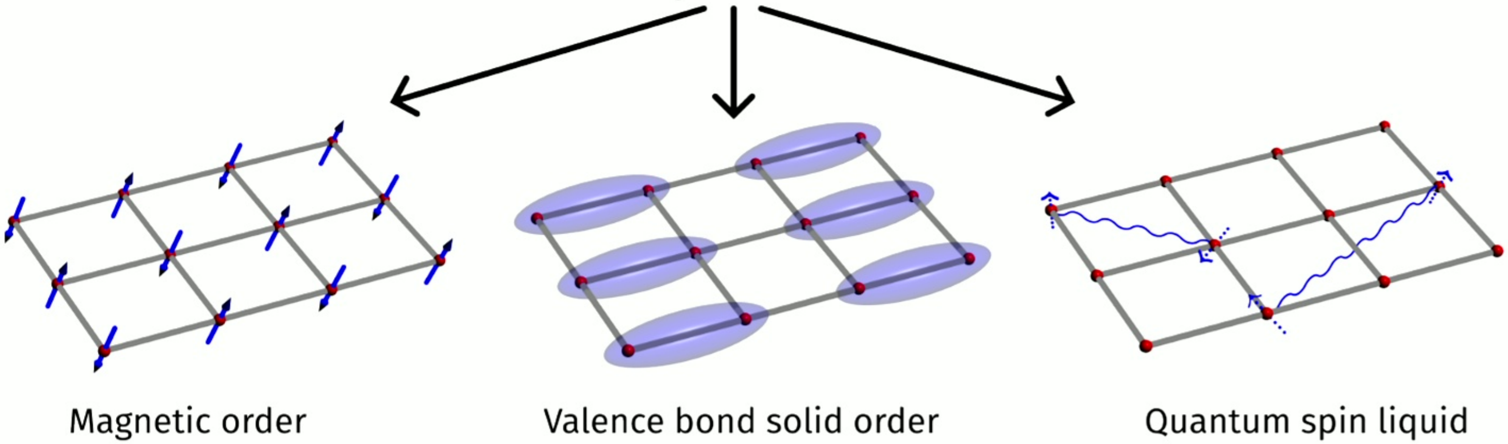


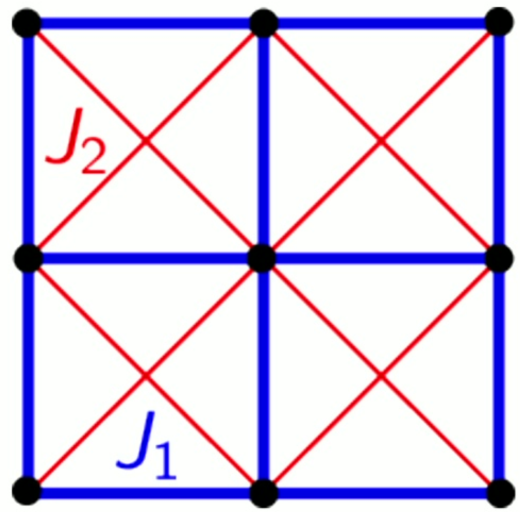
Square lattice: fermionic spinons for unifying numerically-observed Néel/spin liquid/VBS transitions

Triangular lattice: bosonic spinons for effective sign-problem-free model of triangular lattice DQCP

Deconfined criticality on the square lattice antiferromagnet

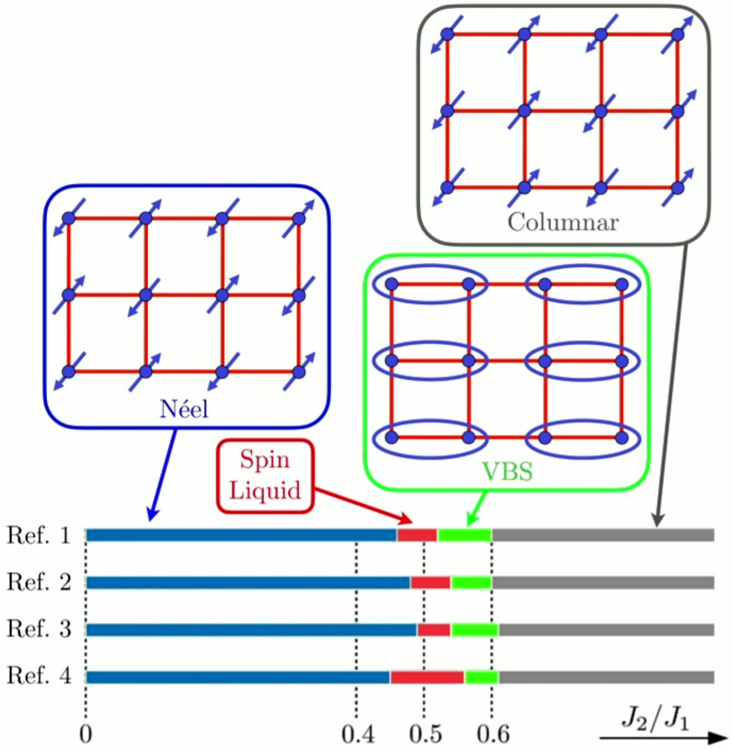
H. Shackleton and S. Sachdev, Journal of High Energy Physics 2022 (7), 1-35
H. Shackleton, A. Thomson, S. Sachdev, Physical Review B 104 (4), 045110

Multimethod studies on $J_1 - J_2$ model indicate spin liquid phase



$$H = J_1 \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + J_2 \sum_{\langle\langle ij \rangle\rangle} \vec{S}_i \cdot \vec{S}_j$$

Multimethod studies on $J_1 - J_2$ model indicate spin liquid phase



[1]Wang and Sandvik, *Phys. Rev. Lett.*, 2018 [2]Ferrari and Becca, *Phys. Rev. B*,. 2020, [3]Nomura and Imada, *Phys. Rev. X*,. 2021 [4]Liu et al., *Phys. Rev. X*,. 2022

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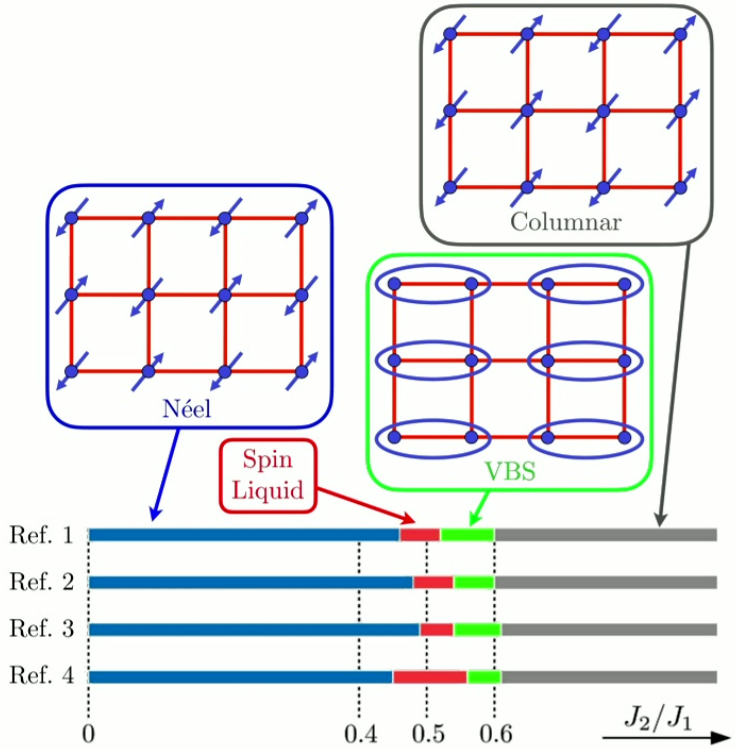
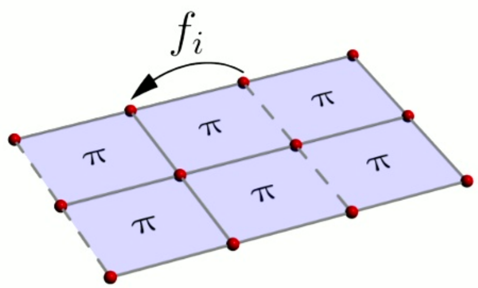
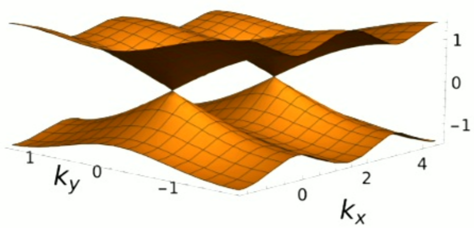


Assume VMC description of spin liquid, gapless fermionic spinons with d-wave pairing (Z2Azz13)

[1]Wang and Sandvik, *Phys. Rev. Lett.*, 2018 [2]Ferrari and Becca, *Phys. Rev. B*,. 2020, [3]Nomura and Imada, *Phys. Rev. X*,. 2021 [4]Liu et al., *Phys. Rev. X*,. 2022

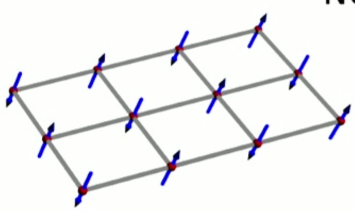
π-flux as a "parent" phase of a $\mathbb{Z}_2$ spin liquid

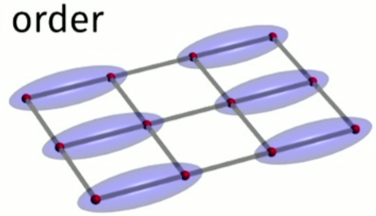




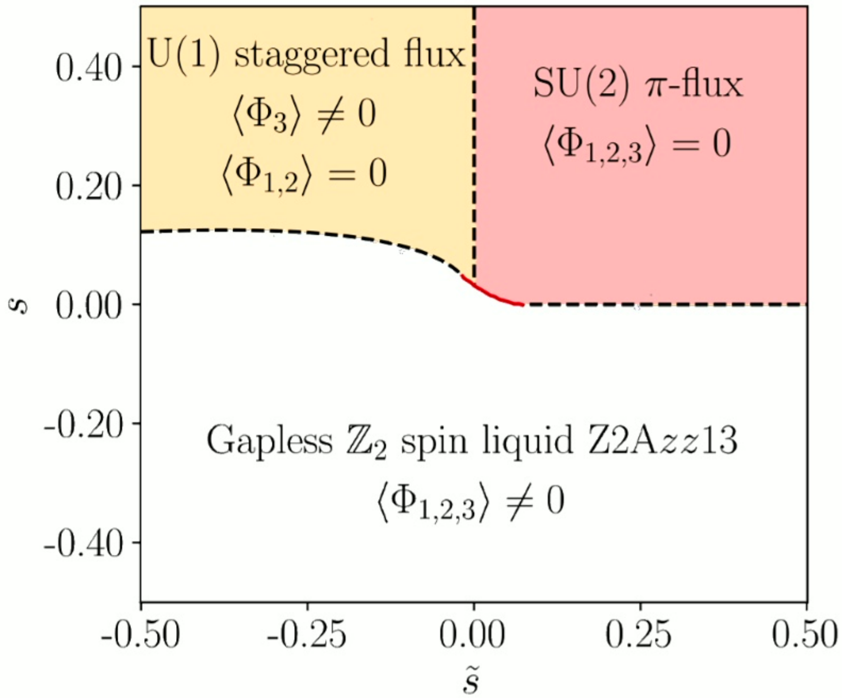
$N_f = 2$ QCD$_3$, emergent SO(5) symmetry → Higgs Φ_1^a, Φ_2^a; SU(2) → $\mathbb{Z}_2$ → Z2Azz13

Unstable to Néel/VBS order



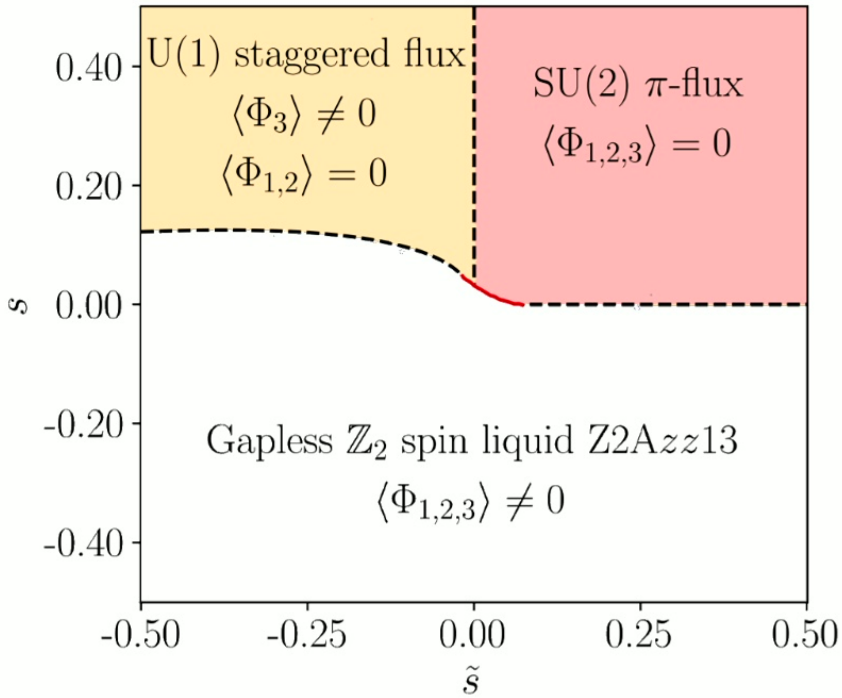


Multiple instabilities captured by proximity to Dirac spin liquid



Unique third Higgs field Φ_3^a, condense-able with mass $\tilde{s}$ along with Φ_1^a, Φ_2^a with mass s

Multiple instabilities captured by proximity to Dirac spin liquid



Unique third Higgs field Φ_3^a, condense-able with mass $\tilde{s}$ along with Φ_1^a, Φ_2^a with mass s

Which phase transitions correspond to which instability?

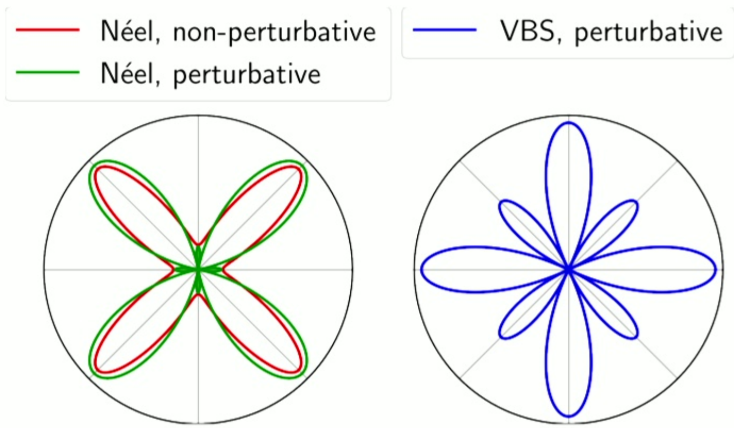
$U(1) \rightarrow \mathbb{Z}_2$ transition has fixed spinon anisotropy

Pure QED_3: fermion anisotropy irrelevant, emergent Lorentz symmetry [6]

QED_3 + critical Higgs: fixed point with non-zero anisotropy

$$\gamma^\mu k_\mu \pm \Phi(\gamma^y k_x + \gamma^x k_y)$$

$$\Phi_c \approx 0.458 + \mathcal{O}\left(N_f^{-1}\right)$$



[6] Hermele, Senthil, and Fisher, *Phys. Rev. B*,. 2005

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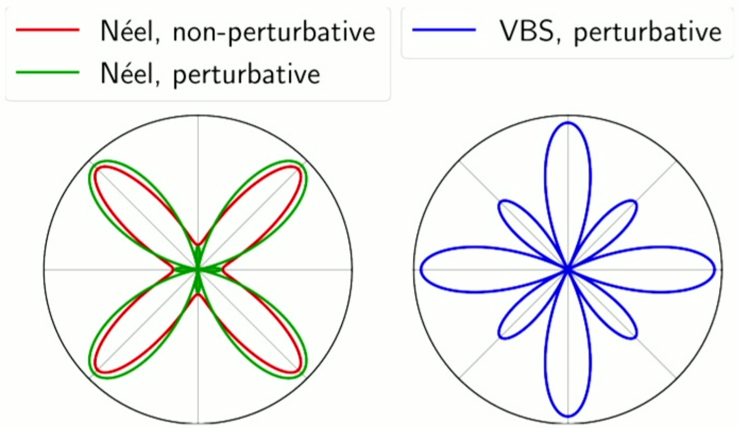
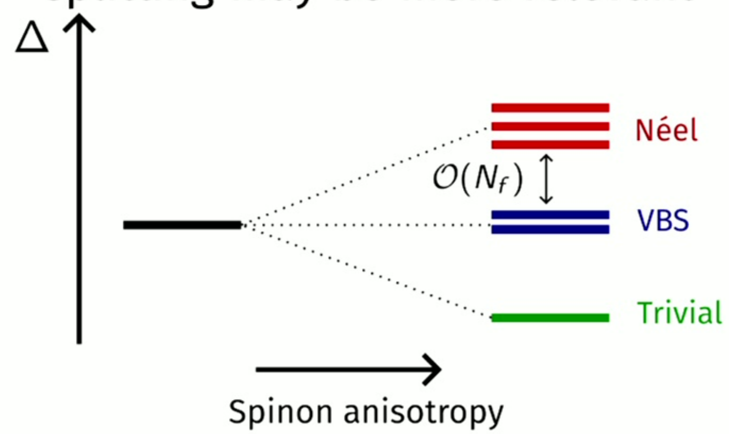


$\eta_{\text{Néel}} \sim \eta_{\text{VBS}}$, but monopole splitting may be more relevant



[6] Hermele, Senthil, and Fisher, *Phys. Rev. B*,. 2005

UV/IR mixing in $\mathrm{SU}(2) \to \mathbb{Z}_2$ transition

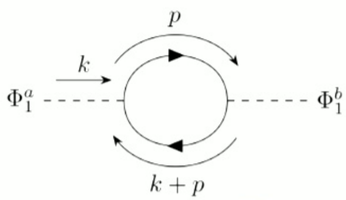
$$\mathcal{L} = \mathcal{L}_{N_f=2\ \mathrm{QCD}_3} + \lambda\left(\Phi_1^a \bar{\psi}\gamma^x \mu^z \sigma^a \psi + \Phi_2^a \bar{\psi}\gamma^y \mu^x \sigma^a \psi\right)$$

Valley (μ^z) — Gauge (σ^a)

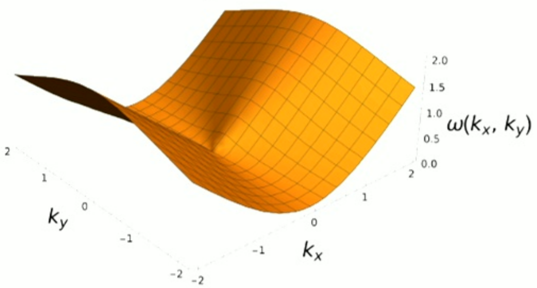
UV/IR mixing in SU(2) → $\mathbb{Z}_2$ transition

$$\mathcal{L} = \mathcal{L}_{N_f=2\ \mathrm{QCD}_3} + \lambda\left(\Phi_1^a \bar{\psi}\gamma^x\mu^z\sigma^a\psi + \Phi_2^a \bar{\psi}\gamma^y\mu^x\sigma^a\psi\right)$$

Conserved "currents"



$$\sim \frac{k_0^2+k_y^2}{\sqrt{k^2}}$$



Emergent "Higgs Bose liquid," extensive gapless modes regulated by (irrelevant) $\Phi\partial^2\Phi$ term

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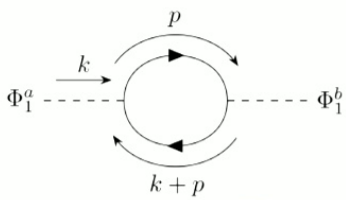

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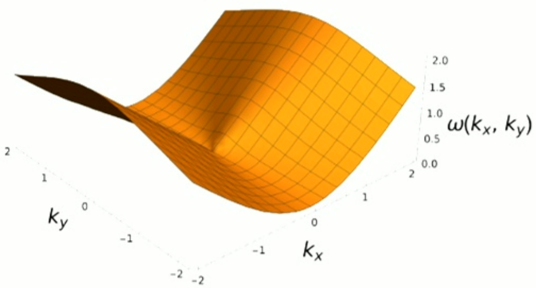


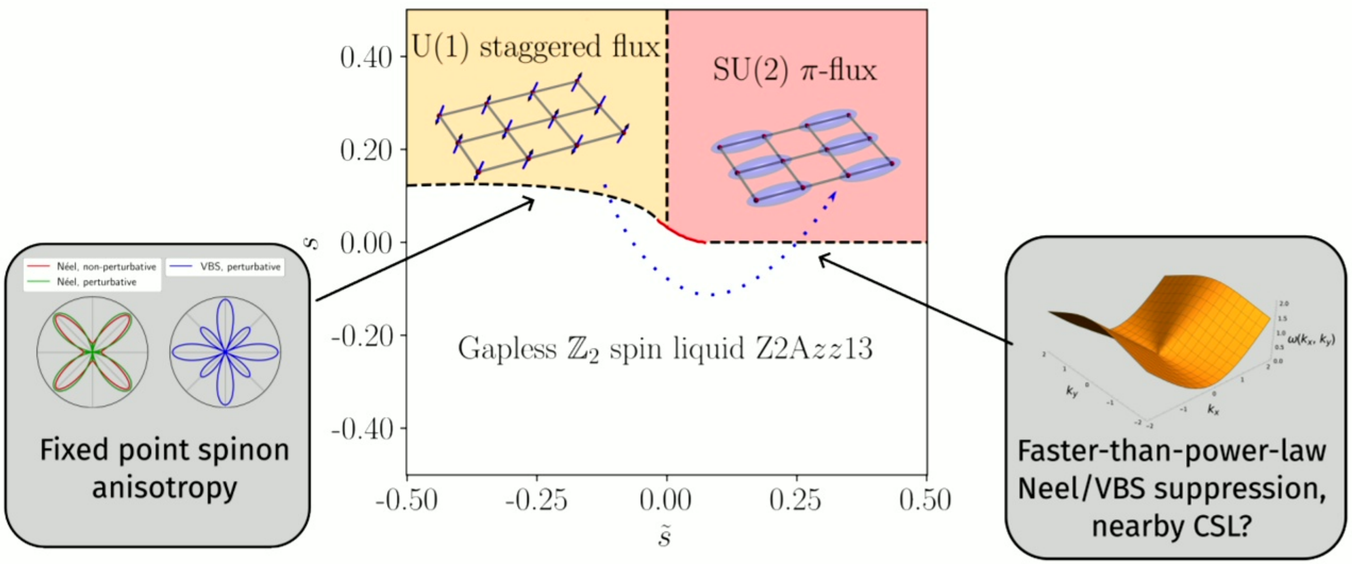
Emergent “Higgs Bose liquid,” extensive gapless modes regulated by (irrelevant) $\Phi\partial^2\Phi$ term

$$G_{\text{Néel}}(r) \sim \exp\left[-\eta_{\text{Néel}} \ln^2(r/a)\right]$$

$$G_{\text{VBS}}(r) \sim \exp\left[-\eta_{\text{VBS}} \ln^2(r/a)\right]$$

$$\eta_{\text{Néel}} > \eta_{\text{VBS}}$$

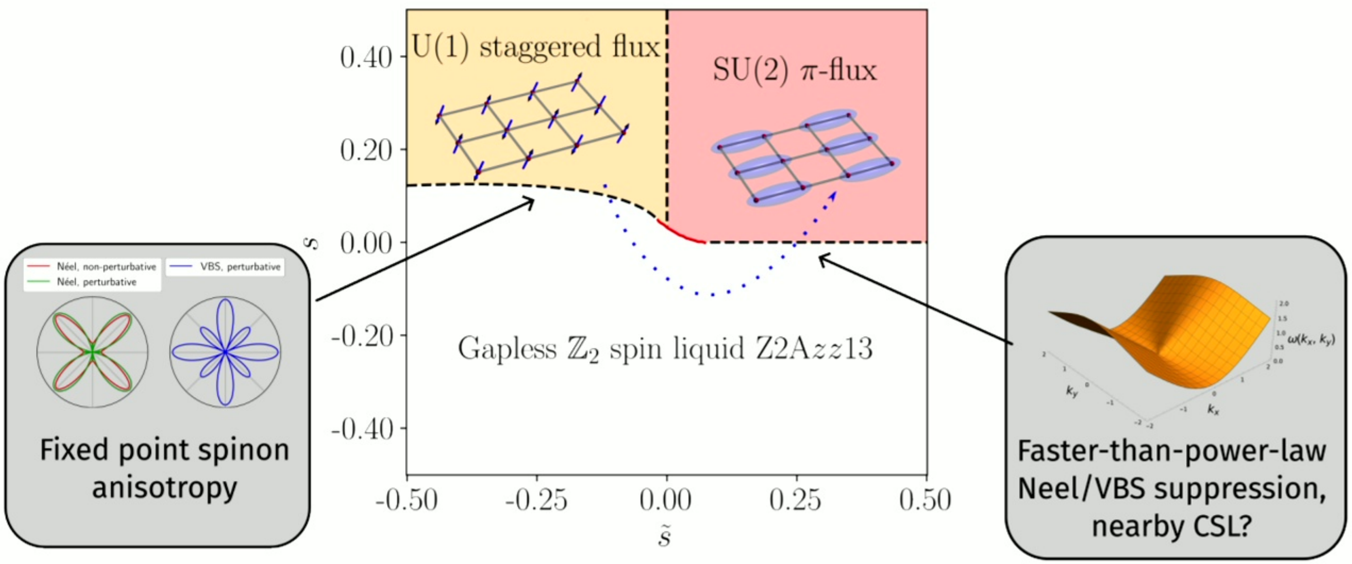
Summary and outlook



- Are $\log^2$ predictions accurate? Can we find a minimal model? With numerics?

[7] Lake and Senthil, *Phys. Rev. Lett.*, 2023.
[8] Gomes et al., *Phys. Rev. D*,. 1991.

Summary and outlook



- Are $\log^2$ predictions accurate? Can we find a minimal model? With numerics?
- Similar ideas in engineering NFLs[7], Thirring models[8]...

[7] Lake and Senthil, *Phys. Rev. Lett.*, 2023.
[8] Gomes et al., *Phys. Rev. D*,. 1991.

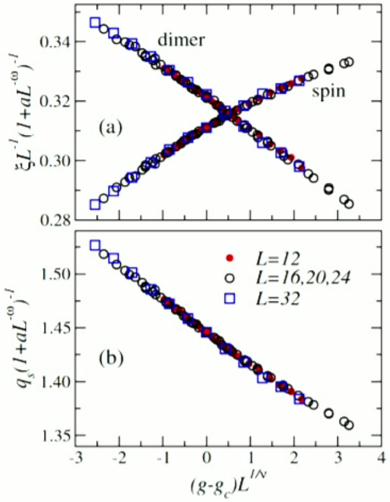
Effective models for triangular lattice quantum antiferromagnets

H. Shackleton and S. Sachdev, arXiv:2311.01572

Frustrated magnetism on non-bipartite lattices: a difficult problem

Bipartite lattices

Marshall sign rule allows for non-trivial "designer Hamiltonians" [9]



Non-bipartite lattice

Primarily restricted to variational ansatzes (DMRG, PEPS, NQS...) or ED

Candidate AF/VBS DQCP [10] remains unexplored numerically

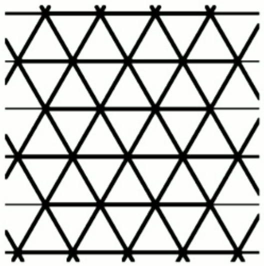
Goal: construct an effective model amenable to large-scale QMC simulations

[9] Sandvik, *Phys. Rev. Lett.*, 2007

[10] Jian et al., *Phys. Rev. B*,. 2018

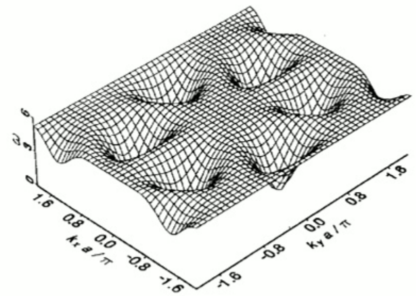
Effective models for triangular lattice quantum antiferromagnets

$$H = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



Effective model of bosonic spinons, U(1) gauge fluctuations Higgsed to $\mathbb{Z}_2$

$$\vec{S}_i \equiv b^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} b_{i\beta}$$

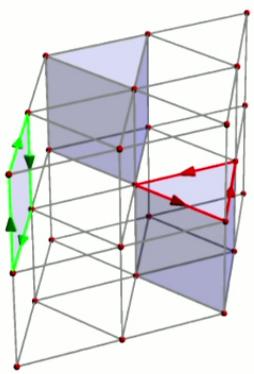


$$H = -J \sum_{j,\mu,\alpha} \left(z^*_{j,\alpha} z_{j+\hat{\mu},\alpha} + \text{c.c.} \right)$$

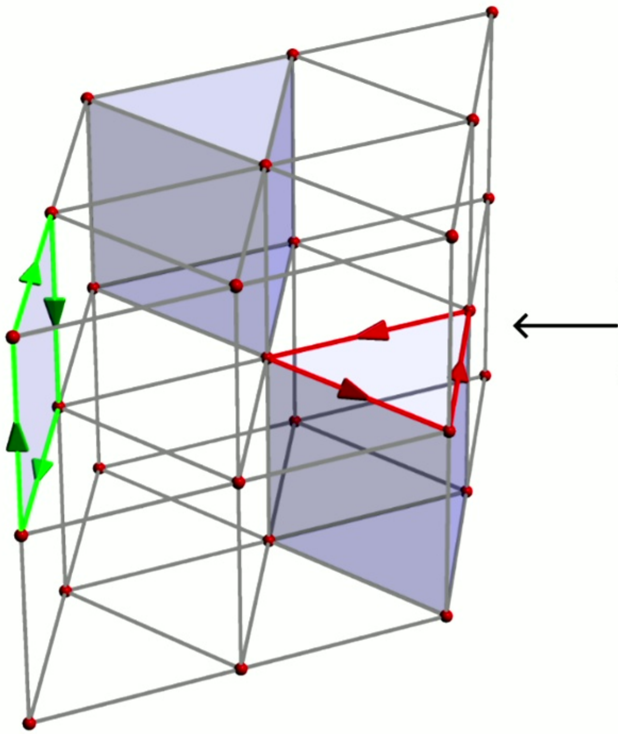
Couple to $\mathbb{Z}_2$ gauge field, mutual statistics captured by Berry phase

$$H = -J \sum_{j,\mu,\alpha} s_{j,j+\hat{\mu}} \left(z^*_{j,\alpha} z_{j+\hat{\mu},\alpha} + \text{c.c.} \right) - K \sum_{\triangle,\square} \prod_{\triangle,\square} s_{j,j+\hat{\mu}} + i\pi \sum_j s_{j,j+\hat{\tau}}$$

Exact sign-problem-free mapping, preserves emergent O(4) symmetry

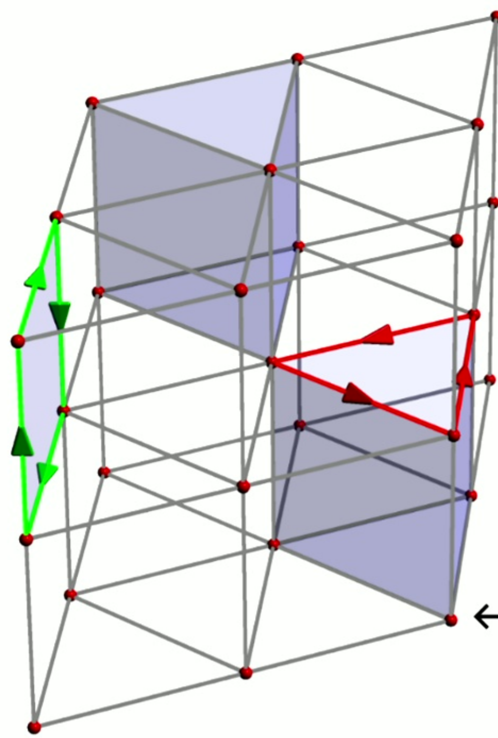


Duality transformation for bosons coupled to $\mathbb{Z}_2$ gauge fields



Bosonic "worldlines"
Two flavors for O(4)

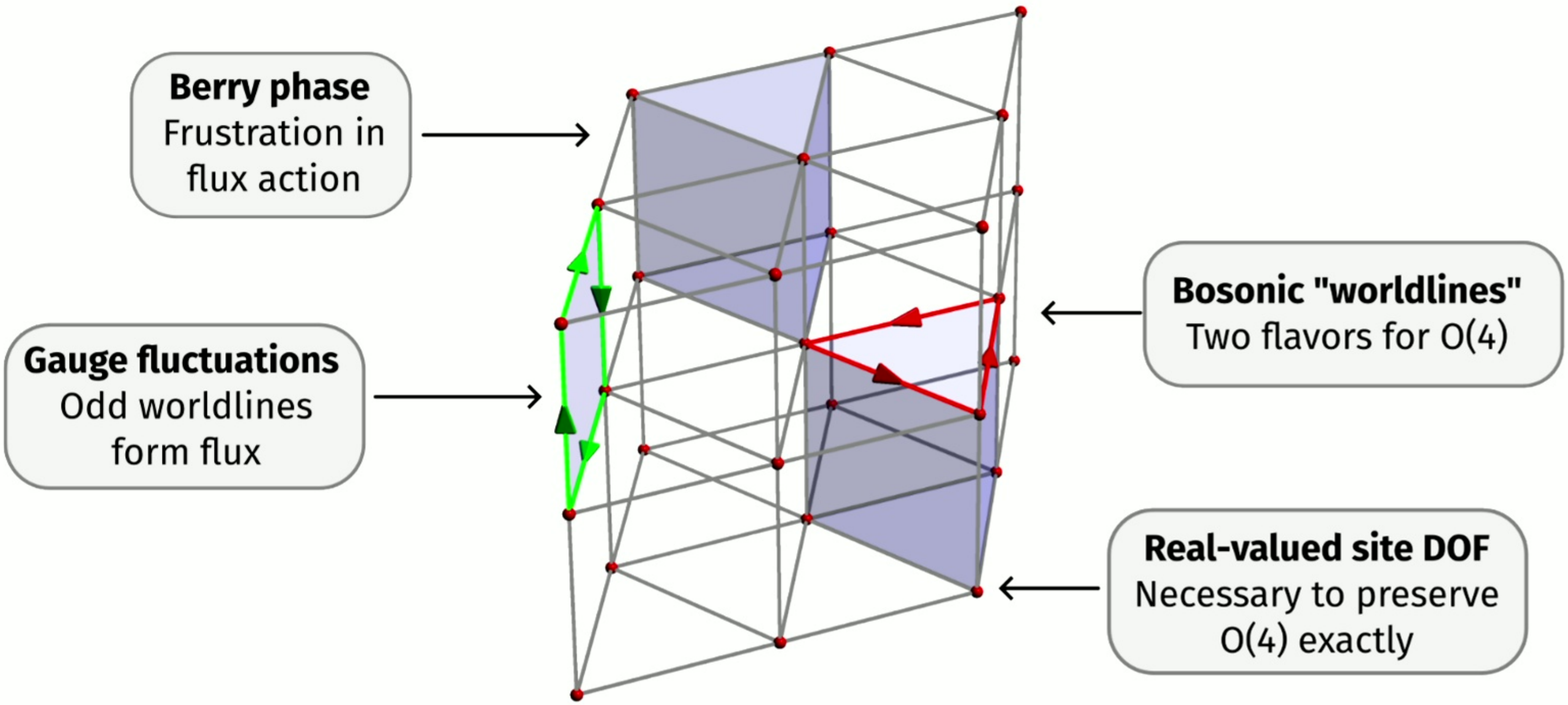
Duality transformation for bosons coupled to $\mathbb{Z}_2$ gauge fields



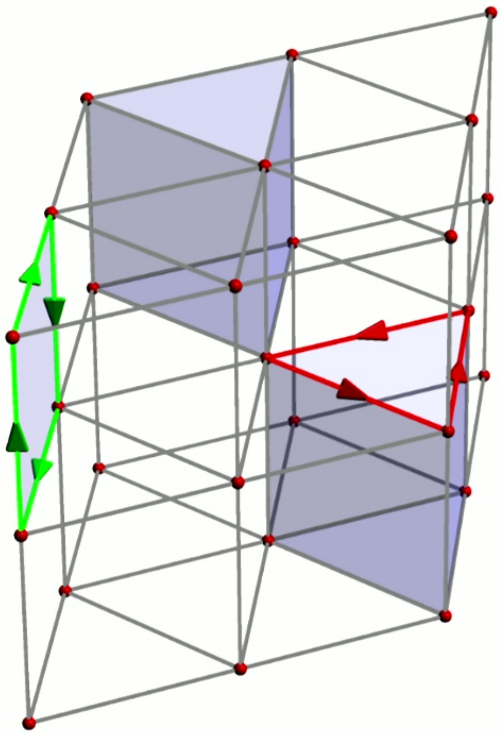
Bosonic "worldlines"
Two flavors for O(4)

Real-valued site DOF
Necessary to preserve O(4) exactly

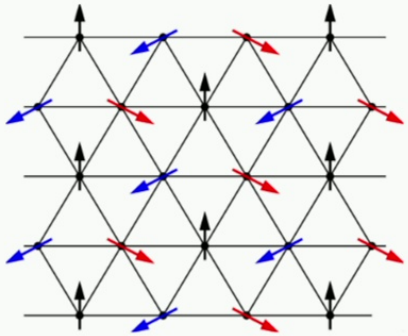
Duality transformation for bosons coupled to $\mathbb{Z}_2$ gauge fields



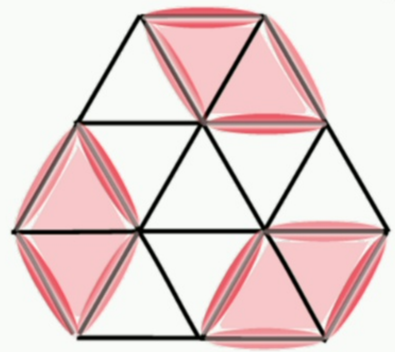
Phases identifiable in dual representation



Magnetic order
(Asymmetric) prolifration
of current loops

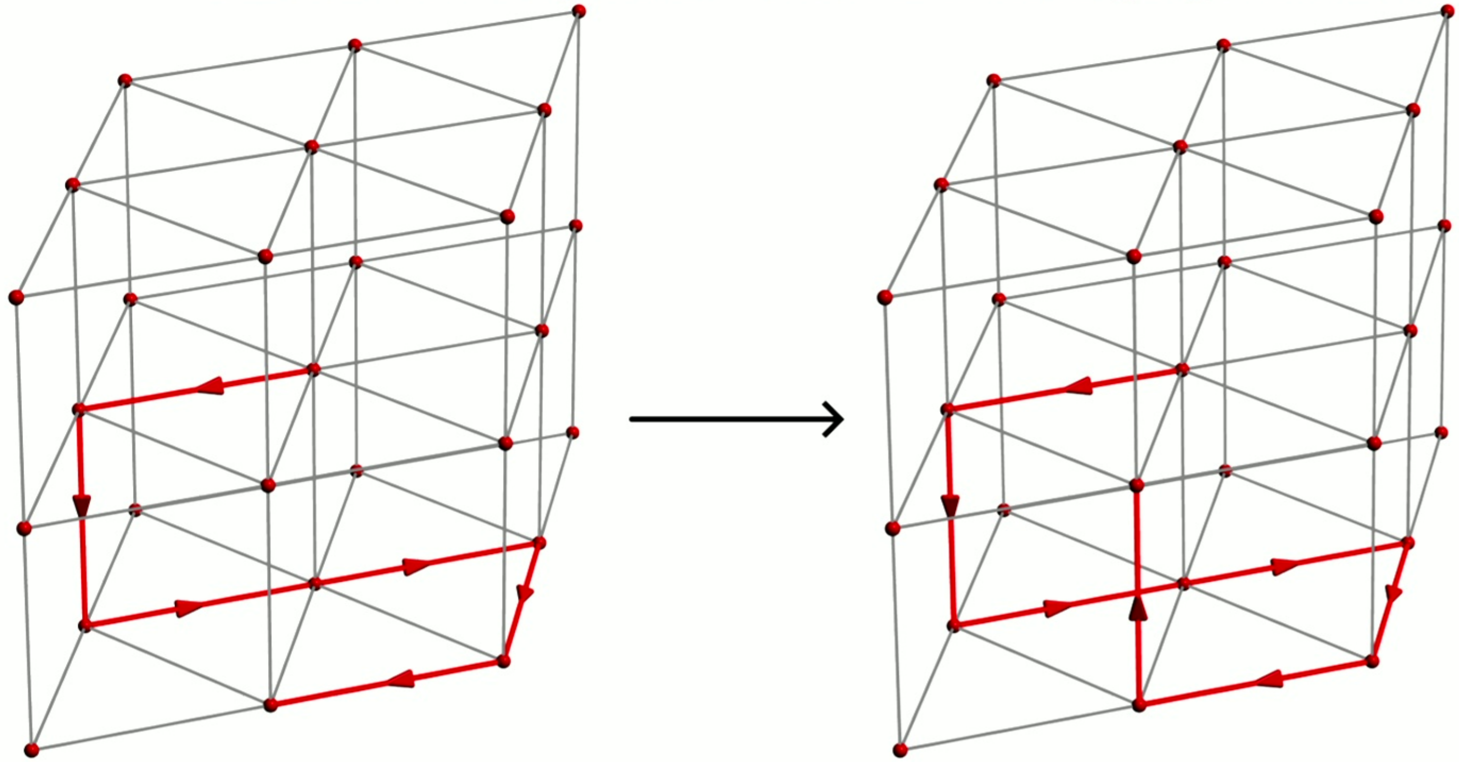


VBS order
Trans. symmetry breaking
of flux configurations



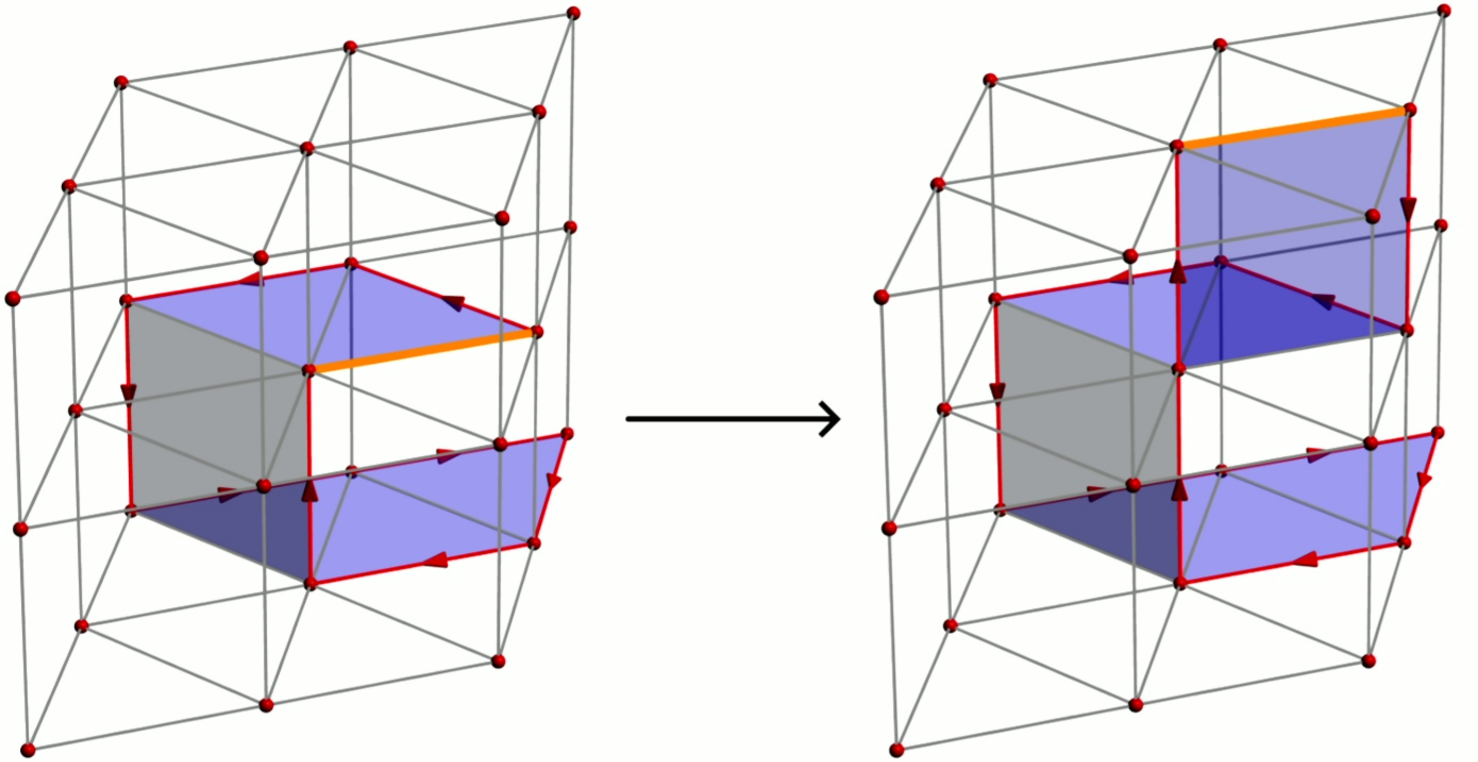
Worm algorithms difficult with gauge fluctuations

"Classical worm algorithm" effective without gauge fluctuations

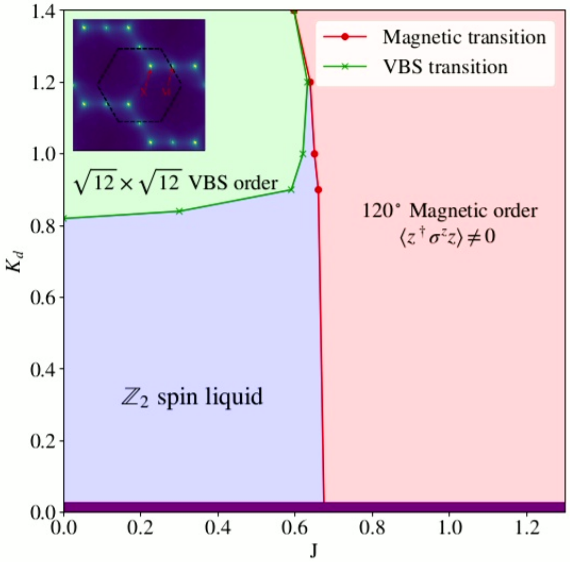


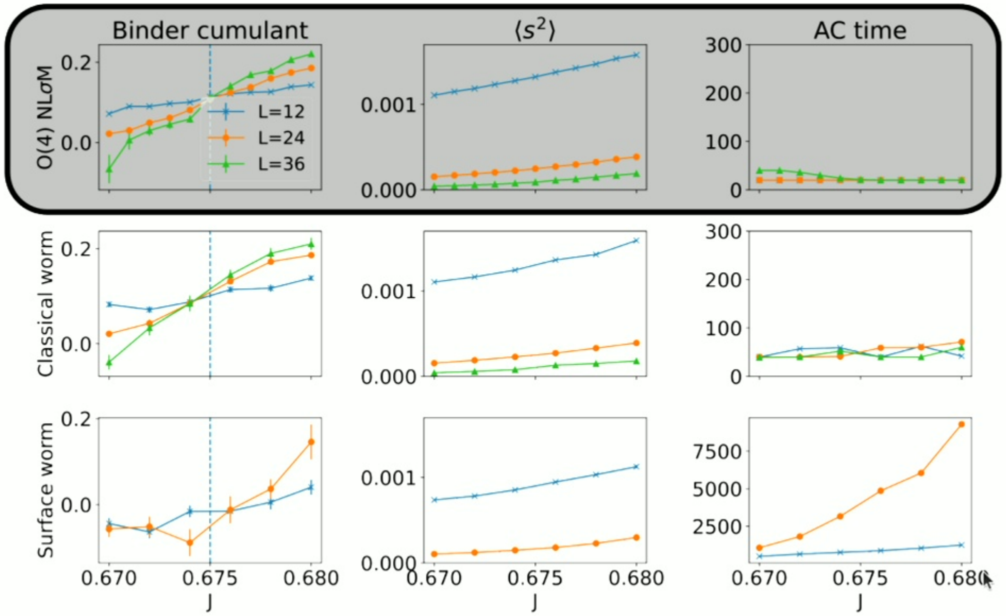
Worm algorithms difficult with gauge fluctuations

"Surface worm algorithm" works well but still has diverging AC



Monte Carlo simulations establish AF, VBS, and spin liquid phases





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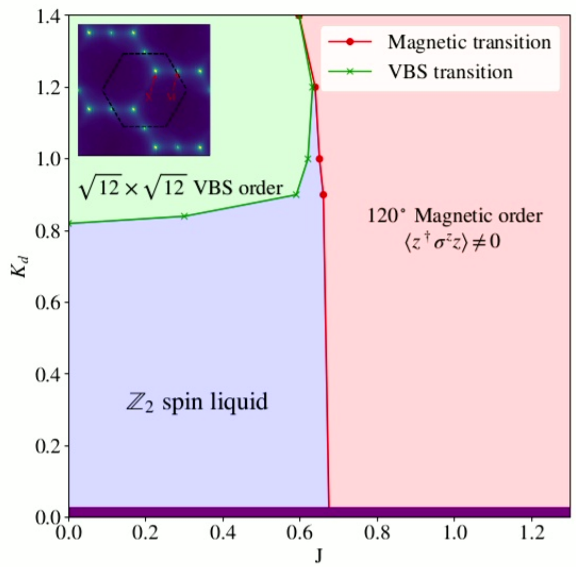
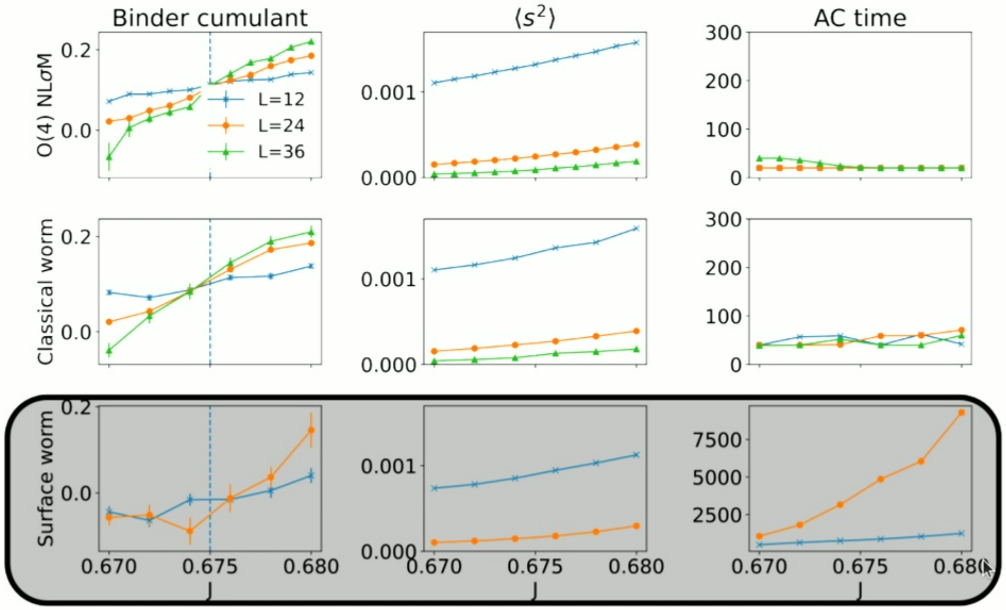
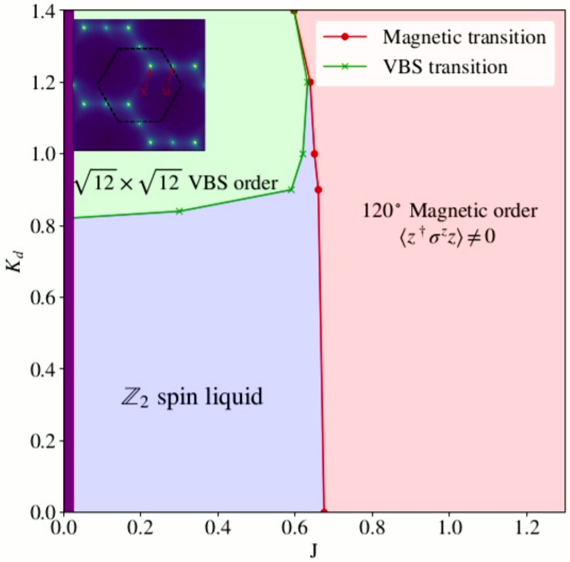
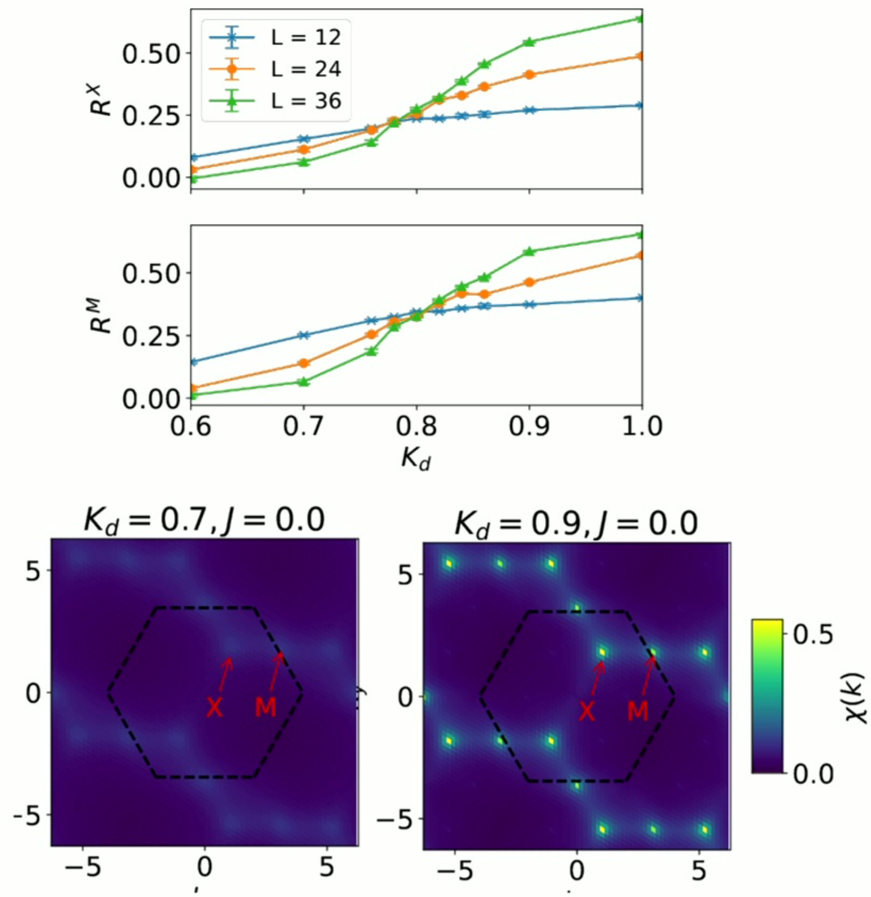




SWA still identifies transition, although restricted to small systems

Monte Carlo simulations establish AF, VBS, and spin liquid phases





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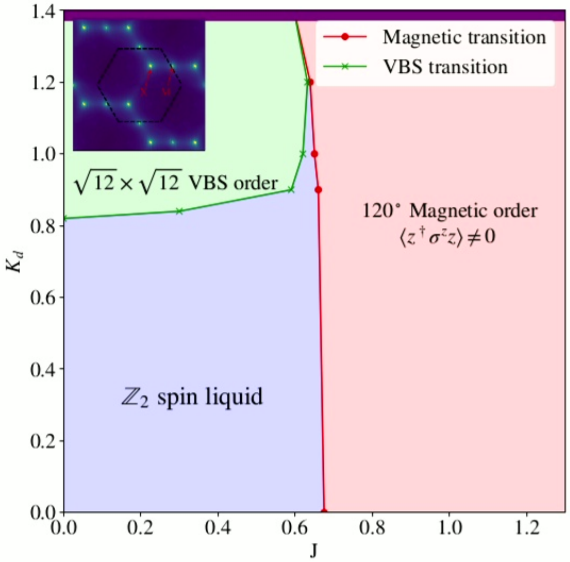
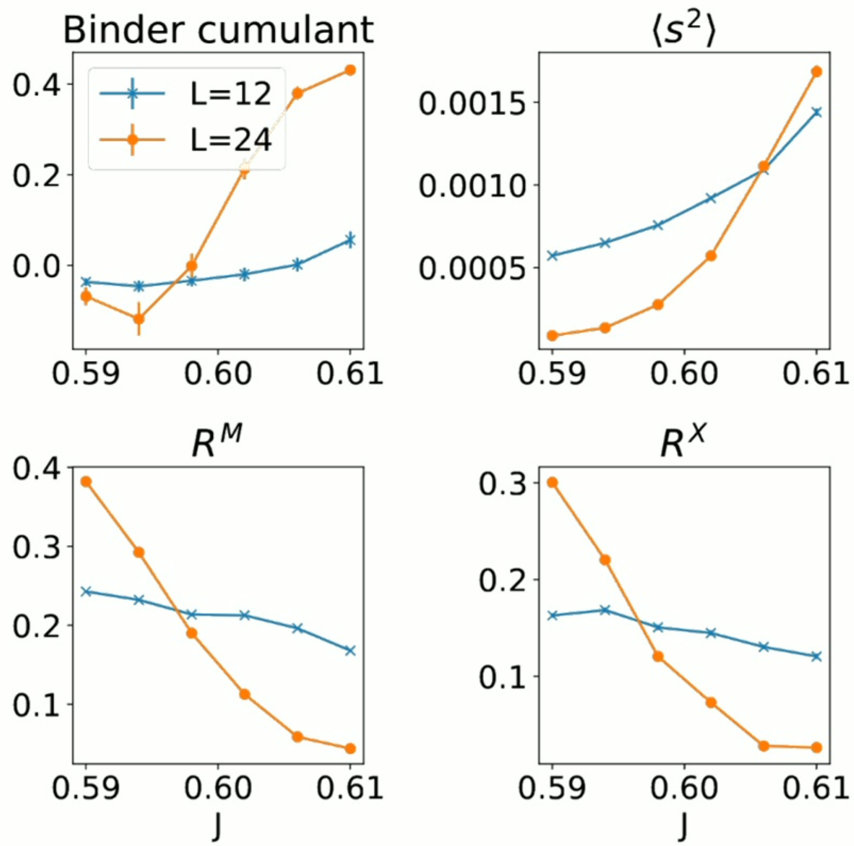
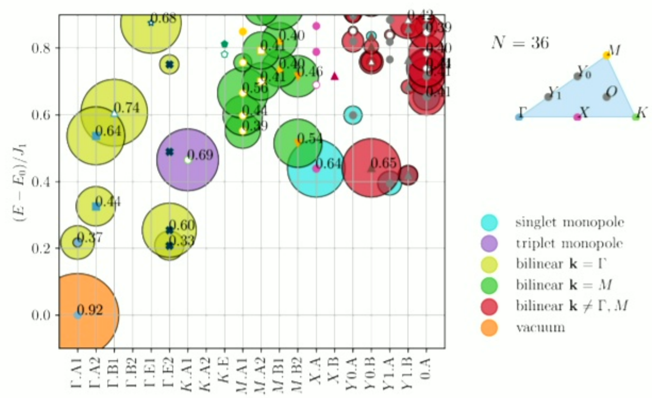
Monte Carlo simulations establish AF, VBS, and spin liquid phases

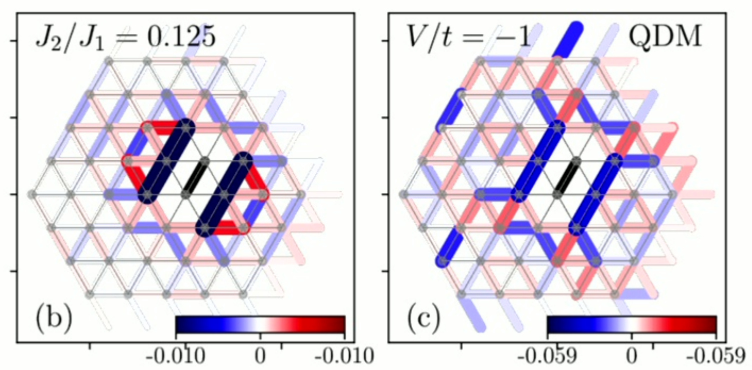




Applications to Heisenberg models

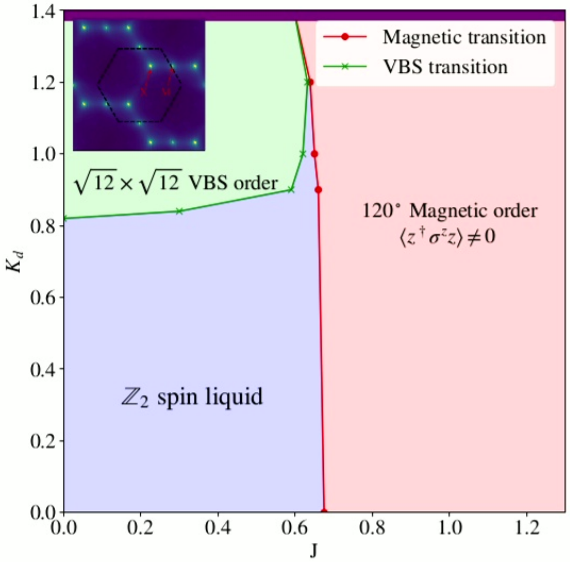
Low-energy spectrum of $J_1 - J_2$ model has high overlap with Dirac spin liquid and $\sqrt{12} \times \sqrt{12}$ VBS[11]

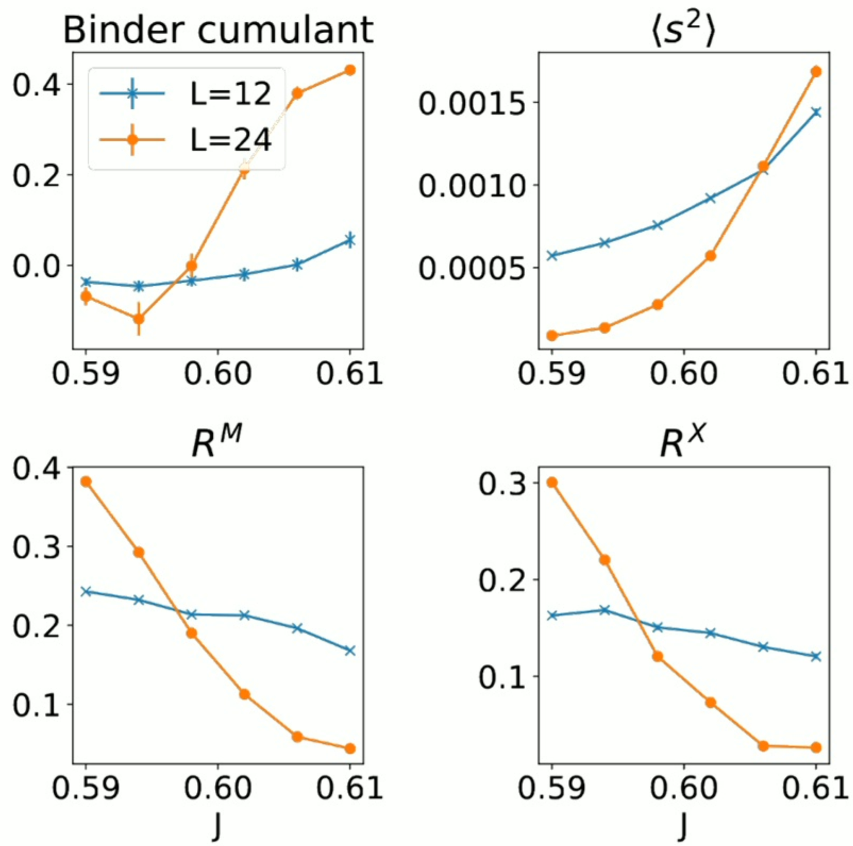




[11] Wietek, Capponi, and Läuchli, *arXiv e-prints*, 2023.

Monte Carlo simulations establish AF, VBS, and spin liquid phases





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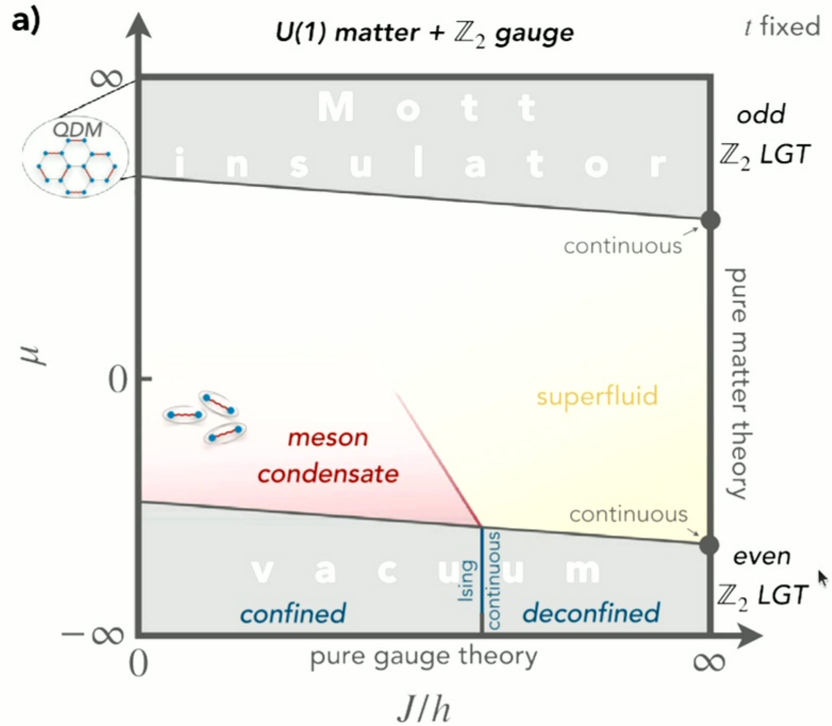
Outlook and future directions

- Bosons coupled to discrete gauge fields remains a relatively unexplored research direction, also relevant for quantum simulators [12]
- PIMC formulation is rather rudimentary, can this mapping be applied to continuous time? SSE?



[12] Homeier et al., *Commun. Phys.*, 2023