Title: Emergent O(4) Symmetry and Signatures of Deconfined Quantum Critical Point in Shastry-Sutherland Lattice Material SrCu2(BO3)2

Speakers:

Series: Condensed Matter

Date: April 16, 2019 - 3:30 PM

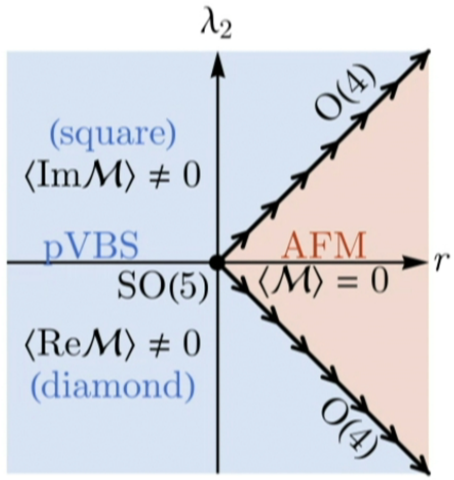
URL: http://pirsa.org/19040125

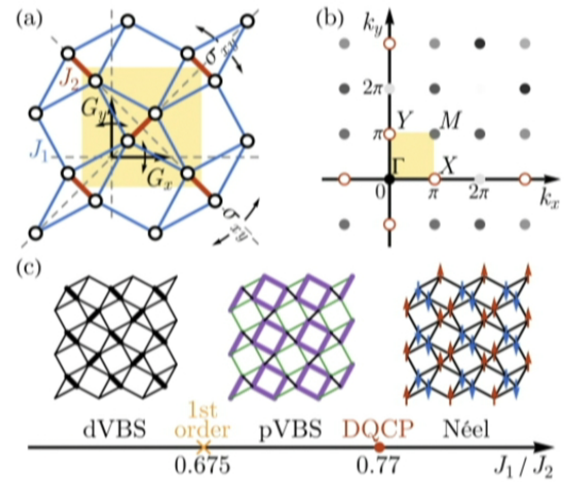
Abstract: We study the possibility of a deconfined quantum phase transition in a realistic model of a two dimensional Shastry-Sutherland quantum magnet, using both numerical and field theoretic techniques. We argue that the quantum phase transition between a two fold degenerate plaquette valence bond solid (pVBS) order and N\'eel ordered phase may be described by a deconfined quantum critical point (DQCP) with emergent O(4) symmetry. Further, using the infinite density matrix renormalization group (iDMRG) numerical technique, we verify the emergence of an intermediate pVBS order, between the dimer and Neel ordered phases. By analyzing the correlation length spectrum, we provide evidence for deconfinement and emergent O(4) symmetry at the phases transistion between the pVBS and N\'eel orders. Such a phase transition has been reported in the recent pressure tuned experiments in the Shastry-Sutherland lattice material SrCu2(BO3)2. The non-symmorphic lattice structure of the Shastry-Sutherland compound leads to extinction points in the scattering, where we predict sharp signatures of a DQCP in both the phonon and magnon spectra associated with the spinon continuua. Our results can guide future experimental studies of DQCP in quantum magnets.

Signatures of a Deconfined Phase Transition on the Shastry-Sutherland Lattice: Applications to Quantum Critical $SrCu_2(BO_3)_2$

Perimeter Institute

4.16.2019





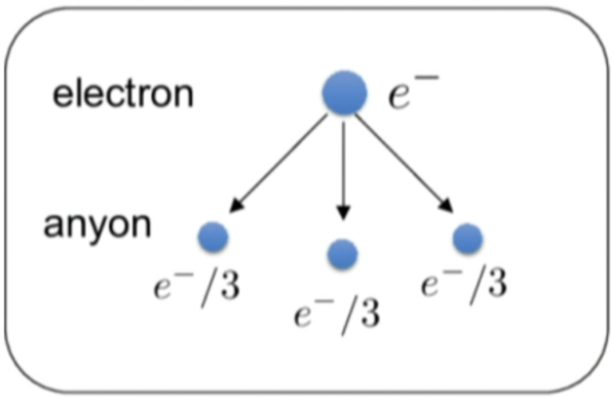
Jong Yeon Lee

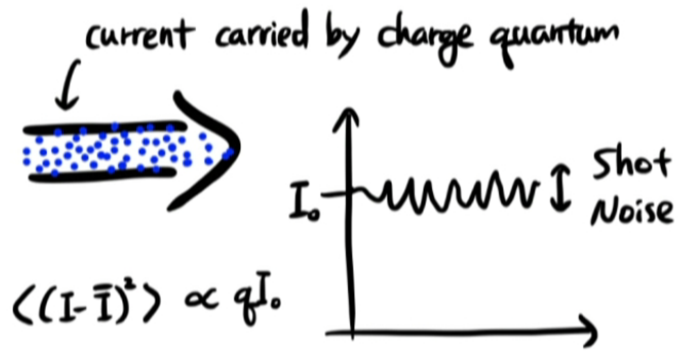
With Yi-Zhuang You, Subir Sachdev, and Ashvin Vishwanath

Review: Deconfined Quantum Criticality

Review: Deconfined Quantum Criticality

What is deconfinement?





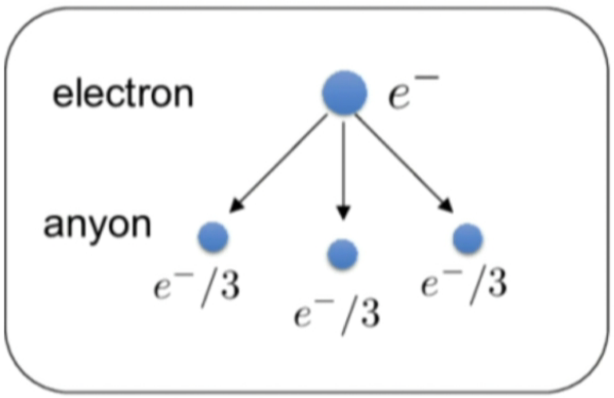
Fractional Quantum Hall at 1/3-filling

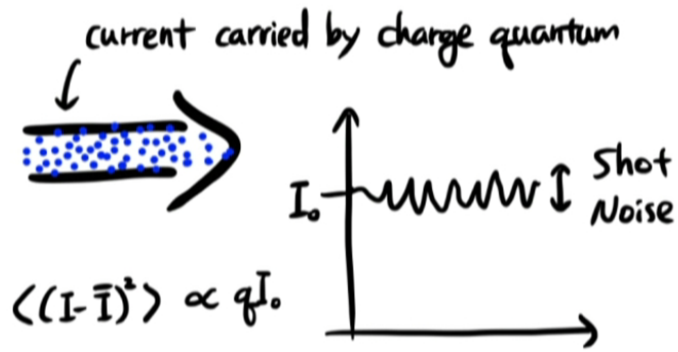
Fractionalized excitations are unbounded and move independently! — no longer confined

Figure from Xie Chen's Talk

Review: Deconfined Quantum Criticality

What is deconfinement?





Fractional Quantum Hall at 1/3-filling

Fractionalized excitations are unbounded and move independently! — no longer confined

Figure from Xie Chen's Talk

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

Landau-Ginzburg Theory

Two order parameters: Ψ **and** Φ

$$F \sim r_1 |\Psi_1|^2 + s_1 |\Psi_1|^4 + r_2 |\Phi_1|^2 + s_2 |\Phi_1|^4 + t |\Psi_1|^2 |\Phi_1|^2 + \cdots$$

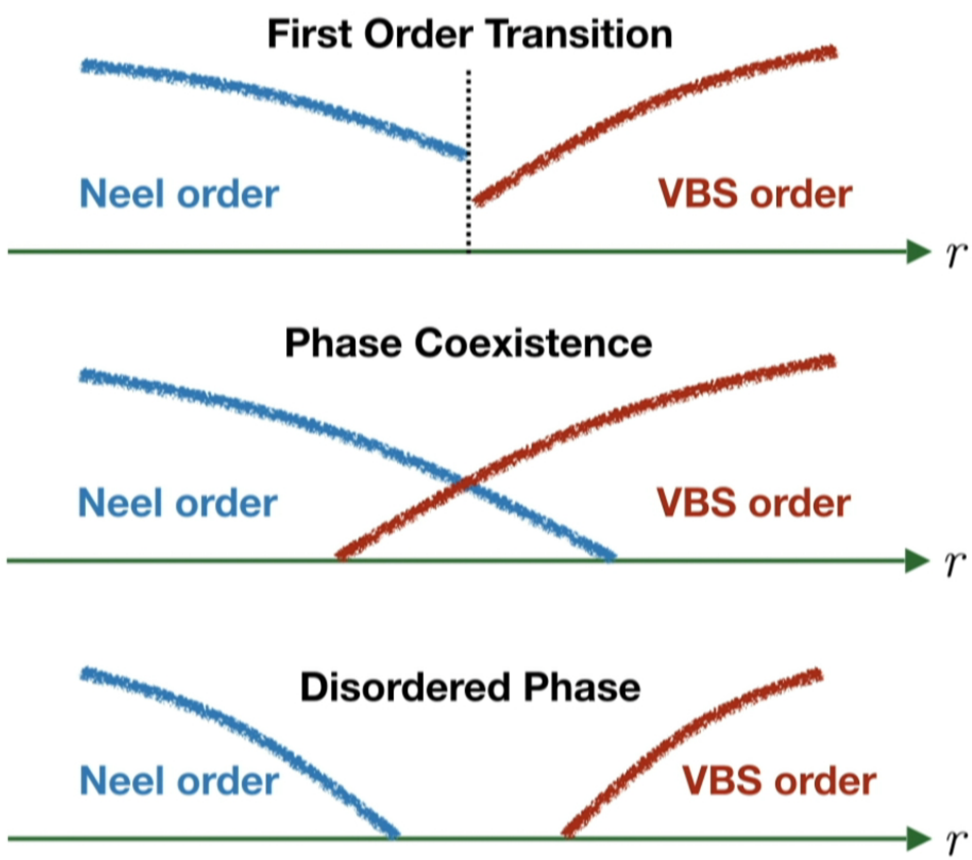
What is the most generic scenario for the phase transition between two different symmetry breaking phases?

$$G_{\text{tot}} = G_A \times G_B$$

G_A is broken ⟷ G_B is broken

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)



Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

Neel Order

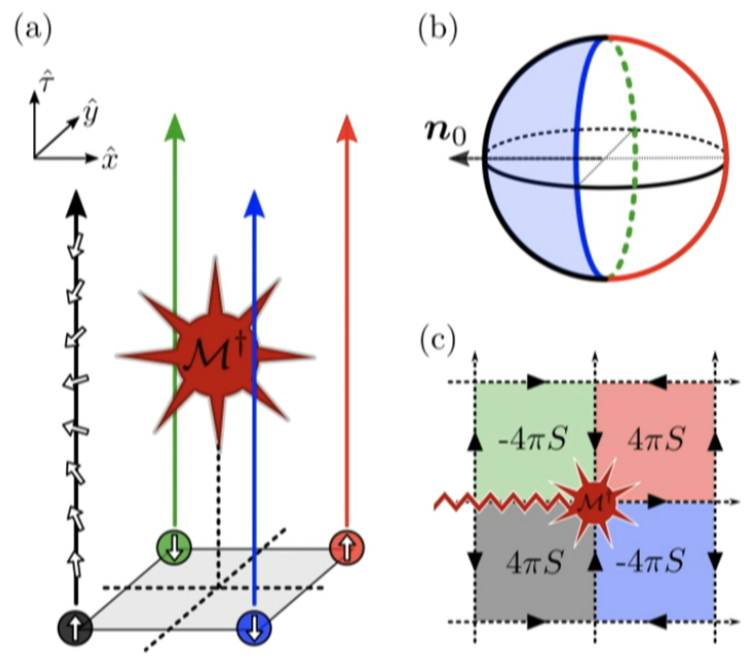
↓

Proliferation of Defects (Monopole in 2+1D)

↓

Paramagnetic Phase

Defect (=Monopole) transforms non-trivially lattice-rotation symmetry. Condensation of Monopole leads to the VBS phase



"Haldane Phase"

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

Neel Order

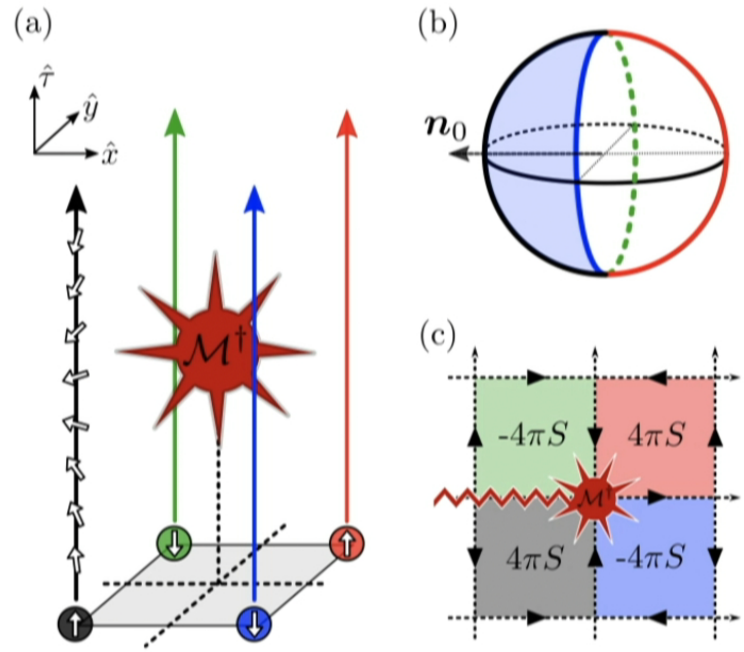
↓

Proliferation of Defects (Monopole in 2+1D)

↓

Paramagnetic Phase

Defect (=Monopole) transforms non-trivially lattice-rotation symmetry. Condensation of Monopole leads to the VBS phase



"Haldane Phase"

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

Neel Order

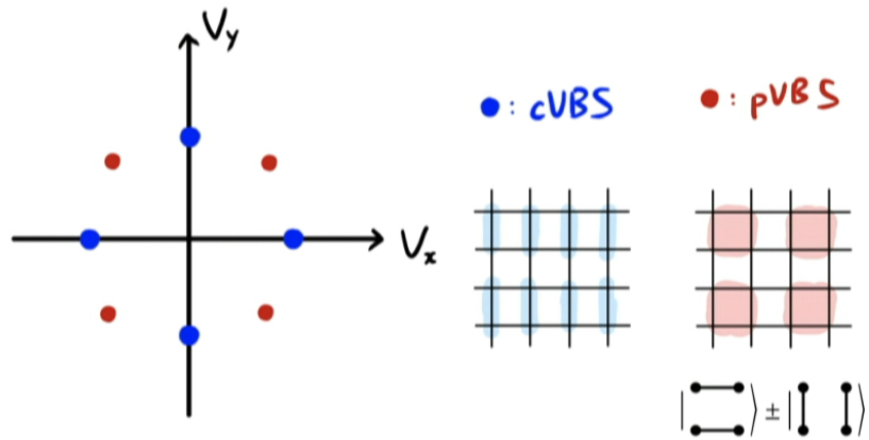
↓

Proliferation of Defects (Monopole in 2+1D)

↓

Paramagnetic Phase

$$\mathcal{M}^\dagger = \frac{1}{\sqrt{2}}\big((V_x + V_y) + \mathrm{i}(V_x - V_y)\big),$$



Condensation of Monopole leads to the VBS phase

<u>Which VBS phase?</u>
Depending on the phase of monopole condensate

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

VBS Order

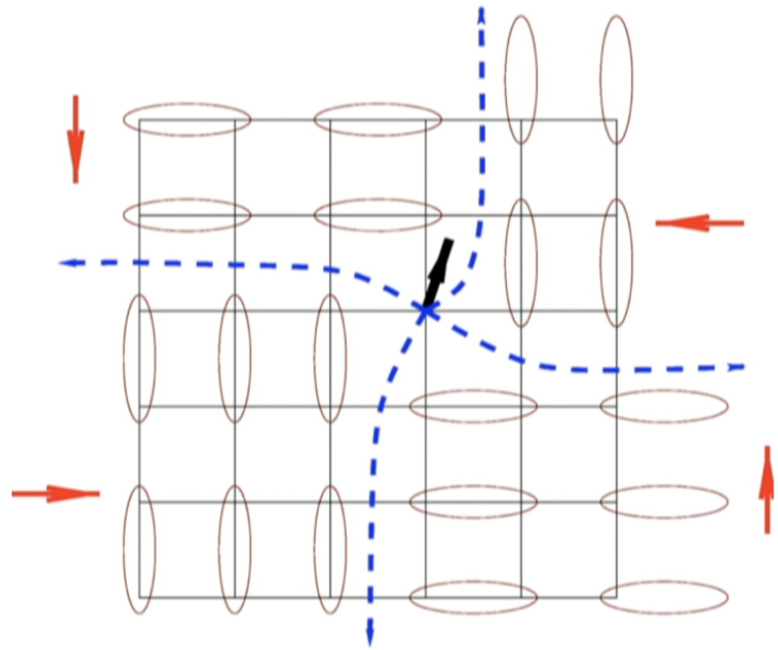
↓

Proliferation of Defects (Z_4 Vortex)

↓

Magnetic Phase

Defect (=Z_4 vortex) carries spin-1/2 representation. Condensation of it leads to the magnetic (Neel) phase



"Levin-Senthil Picture"

Figure from Levin and Senthil, PHYSICAL REVIEW B **70**, 220403(R) (2004)

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

Non-Linear Sigma Model for Neel order

$$\mathcal{S} = \int d\tau d^2 r \left[\left(\frac{\partial \mathbf{n}}{\partial \tau} \right)^2 + (\nabla \mathbf{n})^2 \right] + iS \sum_r (-1)^{r_x + r_y} \omega\left(\mathbf{n}(r)\right)$$

Introduce CP¹ theory with 'spinons'

Neel order parameter is expressed in terms of fractional degrees of freedom

$$\mathbf{n} = z^\dagger \vec{\sigma} z, \quad \text{where } (z_1, z_2)^T$$

$$\mathcal{L}_{\mathrm{CP}^1} = \sum_i |(\partial - ia) z_i|^2 + \kappa (\nabla \times a)^2 + \mu \sum_i |z_i|^2 + \lambda (\sum_i |z_i|^2)^2$$

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

VBS Order

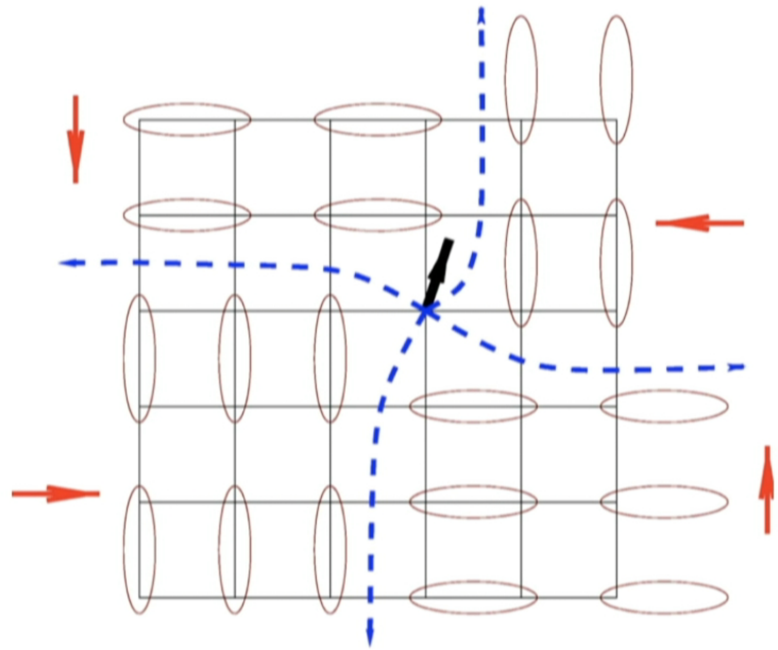
↓

Proliferation of Defects
(Z_4 Vortex)

↓

Magnetic Phase

Defect (=Z_4 vortex) carries spin-1/2 representation. Condensation of it leads to the magnetic (Neel) phase



"Levin-Senthil Picture"

Figure from Levin and Senthil, PHYSICAL REVIEW B **70**, 220403(R) (2004)

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

Non-Linear Sigma Model for Neel order

$$\mathcal{S} = \int d\tau d^2 r \left[\left(\frac{\partial \mathbf{n}}{\partial \tau} \right)^2 + (\nabla \mathbf{n})^2 \right] + iS \sum_r (-1)^{r_x + r_y} \omega\left(\mathbf{n}(r)\right)$$

Introduce CP^1 theory with 'spinons'

Neel order parameter is expressed in terms of fractional degrees of freedom

$$\mathbf{n} = z^\dagger \vec{\sigma} z, \quad \text{where } (z_1, z_2)^T$$

$$\mathcal{L}_{\mathrm{CP}^1} = \sum_i |(\partial - ia) z_i|^2 + \kappa (\nabla \times a)^2 + \mu \sum_i |z_i|^2 + \lambda (\sum_i |z_i|^2)^2$$

Review: Deconfined Quantum Criticality

T. Senthil, L. Balents, S. Sachdev, A. Vishwanath, and M. P. A. Fisher, Phys. Rev. B 70, 144407 (2004)

Neel order parameter is expressed in terms of fractional degrees of freedom $\mathbf{n} = z^\dagger \vec{\sigma} z, \quad \text{where } (z_1, z_2)^T$

$$\mathcal{L}_{\mathrm{CP}^1} = \sum_i |(\partial - ia) z_i|^2 + \kappa(\nabla \times a)^2 + \mu \sum_i |z_i|^2 + \lambda(\sum_i |z_i|^2)^2$$

	$V_x + iV_y$	$n_x + in_y$	n_z
in $\mathcal{L}$	$\mathcal{M}_a$	$2z_1^* z_2$	$\lvert z_1\rvert^2 - \lvert z_2\rvert^2$

Both Neel and VBS order parameters can be expressed in terms of spinons + gauge field

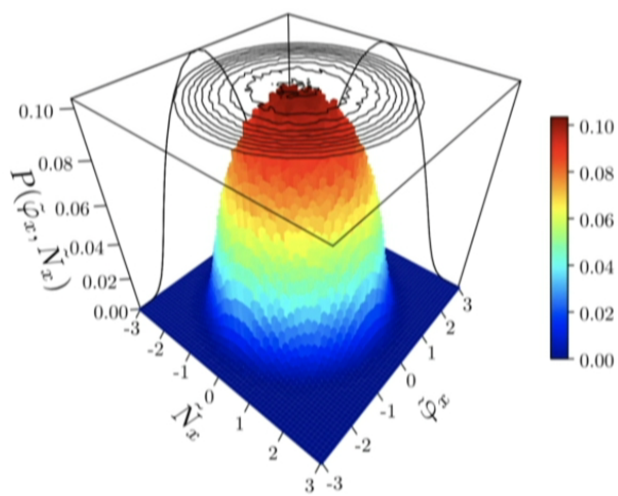
Review: Deconfined Quantum Criticality

Anders Sandvik, PRL **98,** 227202 (2007)
Nahum et al., PRL **115**, 267203 (2015)

Symmetry Enhancement: $\mathrm{SO}(3) \times Z_4 \longrightarrow \mathrm{SO}(3) \times \mathrm{U}(1) \longrightarrow \mathrm{SO}(5)$

Both VBS and Neel order parameter have similar anomalous dimension at the critical point $\eta \sim 0.26$

$$\langle N_i(r) \cdot N_i(0) \rangle \sim \langle V_i(r) \cdot V_i(0) \rangle \sim \frac{1}{r^{1+\eta}}$$



Evidence of Symmetry Enhancement

- Both operators have the same scaling dimension
- Fluctuations of both order parameters are scaling identically with system size
- Duality conjectures and fermionic PSG ansatz implies SO(5) emergent symmetry at the DQCP

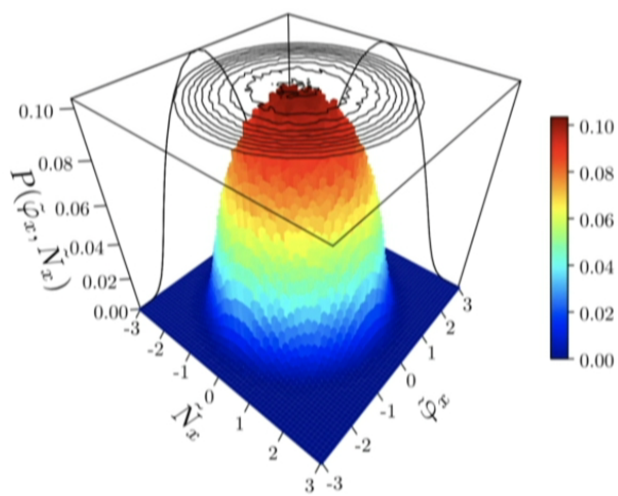
Review: Deconfined Quantum Criticality

Anders Sandvik, PRL **98,** 227202 (2007)
Nahum et al., PRL **115**, 267203 (2015)

Symmetry Enhancement: $\mathrm{SO}(3) \times Z_4 \longrightarrow \mathrm{SO}(3) \times \mathrm{U}(1) \longrightarrow \mathrm{SO}(5)$

Both VBS and Neel order parameter have similar anomalous dimension at the critical point $\eta \sim 0.26$

$$\langle N_i(r) \cdot N_i(0) \rangle \sim \langle V_i(r) \cdot V_i(0) \rangle \sim \frac{1}{r^{1+\eta}}$$



Evidence of Symmetry Enhancement

- Both operators have the same scaling dimension
- Fluctuations of both order parameters are scaling identically with system size
- Duality conjectures and fermionic PSG ansatz implies SO(5) emergent symmetry at the DQCP

Review: Deconfined Quantum Criticality

Anders Sandvik, PRL **98,** 227202 (2007)
Nahum et al., PRL **115**, 267203 (2015)

Symmetry Enhancement: $\mathrm{SO}(3) \times Z_4 \longrightarrow \mathrm{SO}(3) \times \mathrm{U}(1) \longrightarrow \mathrm{SO}(5)$

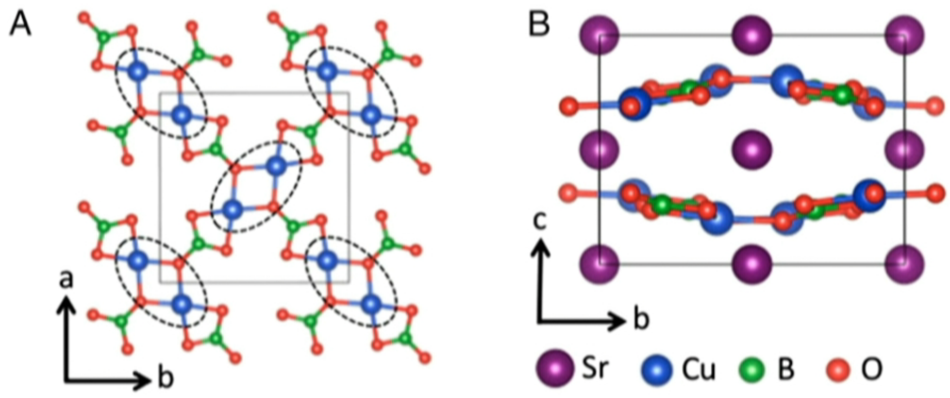
Both VBS and Neel order parameter have similar anomalous dimension at the critical point $\eta \sim 0.26$

$$\langle N_i(r) \cdot N_i(0) \rangle \sim \langle V_i(r) \cdot V_i(0) \rangle \sim \frac{1}{r^{1+\eta}}$$

$$\mathcal{L} \sim a + |\partial M|^2 + b|M|^2 + c|M|^4 +$$

N	0	1	2	3
γ	1.1596 ± 0.0020	1.2396 ± 0.0013	1.3169 ± 0.0020	1.3895 ± 0.0050
ν	0.5882 ± 0.0011	0.6304 ± 0.0013	0.6703 ± 0.0015	0.7073 ± 0.0035
η	0.0284 ± 0.0025	0.0335 ± 0.0025	0.0354 ± 0.0025	0.0355 ± 0.0025
β	0.3024 ± 0.0008	0.3258 ± 0.0014	0.3470 ± 0.0016	0.3662 ± 0.0025
ω	0.812 ± 0.016	0.799 ± 0.011	0.789 ± 0.011	0.782 ± 0.0013

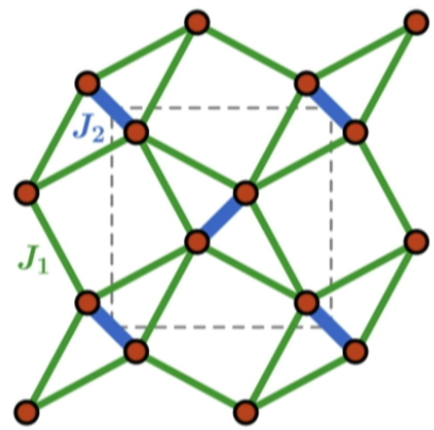
Shastry-Sutherland material: $SrCu_2(BO_3)_2$



Cu^{2+} ions
(d^9, $S=1/2$)

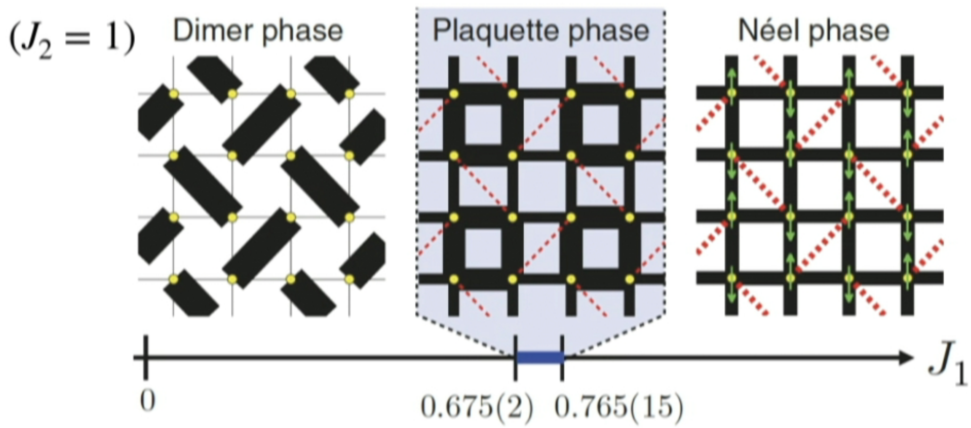
Kageyama, H. et al. Exact dimer ground state and quantized magnetization plateaus in the two-dimensional spin system $SrCu_2(BO_3)_2$. Phys. Rev. Lett. 82, 3168–3171 (1999).

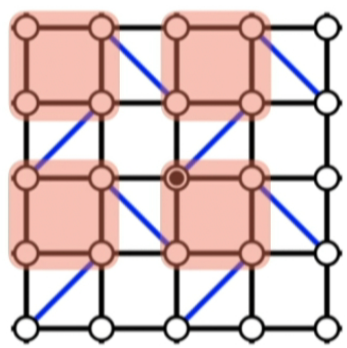
Miyahara, S. & Ueda, K. Theory of the orthogonal dimer Heisenberg spin model for $SrCu_2(BO_3)_2$. J. Phys. Condens. Matter 15, R327 (2003).



$$H = J_1 \sum_{ij \in \text{n.n.}} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + J_2 \sum_{ij \in \text{dimer}} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

2D Phase Diagram (IPEPS / Perturbation Theory)





Z₂ glide-reflection symmetry broken ground states

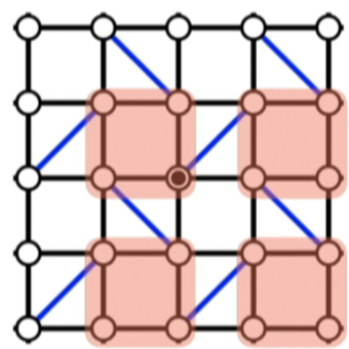
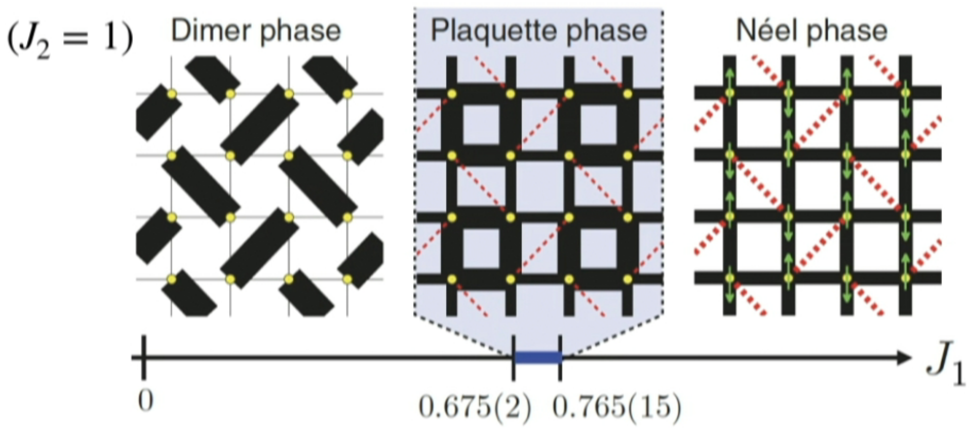
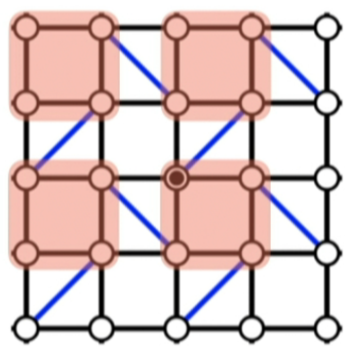


Figure from Corboz and Mila, PHYSICAL REVIEW B **87**, 115144 (2013)

2D Phase Diagram (IPEPS / Perturbation Theory)





Z_2 glide-reflection symmetry broken ground states

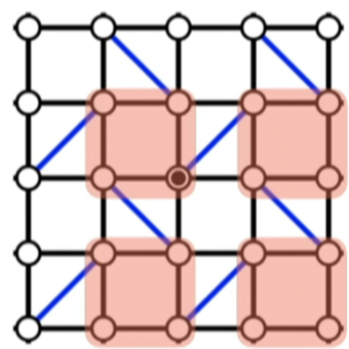
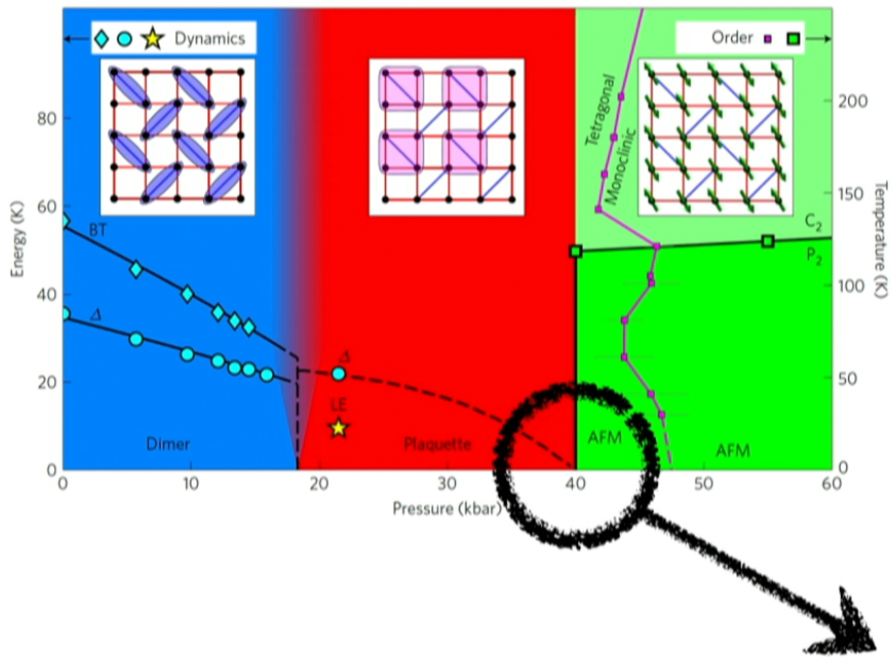


Figure from Corboz and Mila, PHYSICAL REVIEW B **87**, 115144 (2013)

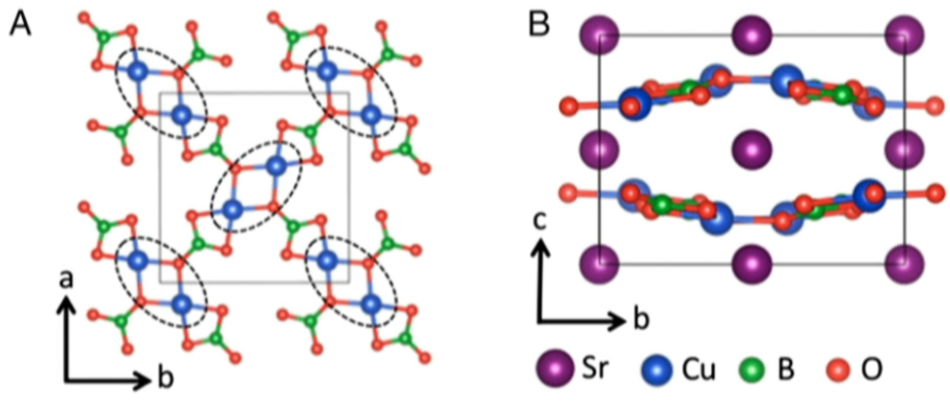
Recent Experiment with External Pressure



Candidate of Deconfined Quantum Critical Point!

Zayed et al. (2017), DOI: 10.1038/NPHYS4190

Shastry-Sutherland material: $SrCu_2(BO_3)_2$

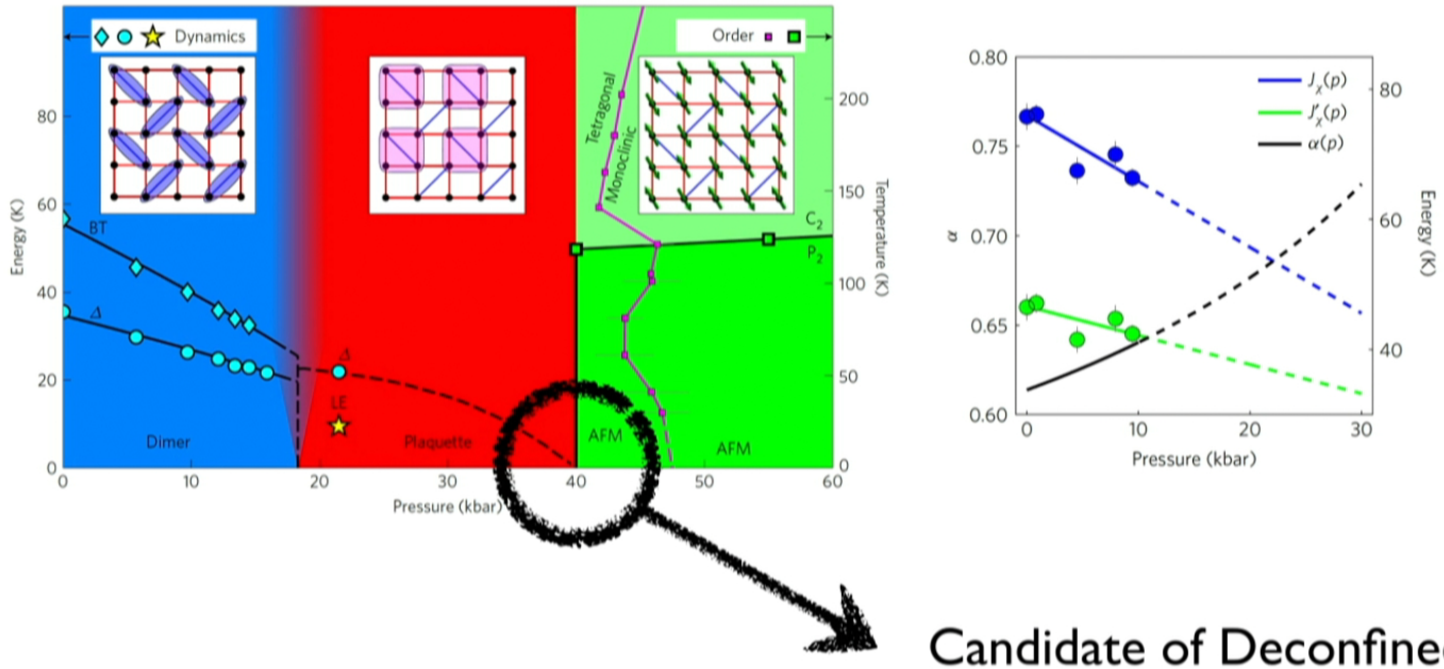


Cu^{2+} ions
(d^9, $S=1/2$)

Kageyama, H. et al. Exact dimer ground state and quantized magnetization plateaus in the two-dimensional spin system $SrCu_2(BO_3)_2$. Phys. Rev. Lett. 82, 3168–3171 (1999).

Miyahara, S. & Ueda, K. Theory of the orthogonal dimer Heisenberg spin model for $SrCu_2(BO_3)_2$. J. Phys. Condens. Matter 15, R327 (2003).

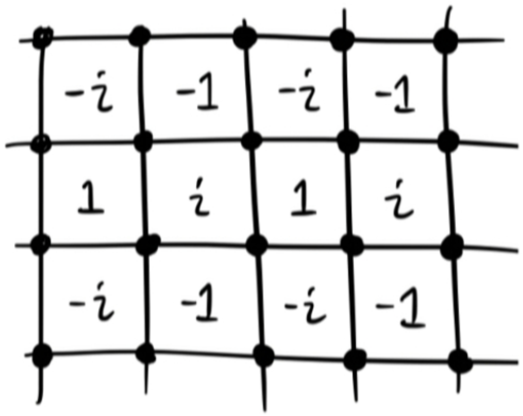
Recent Experiment with External Pressure



Candidate of Deconfined Quantum Critical Point!

Zayed et al. (2017), DOI: 10.1038/NPHYS4190

Symmetry Analysis — Monopole

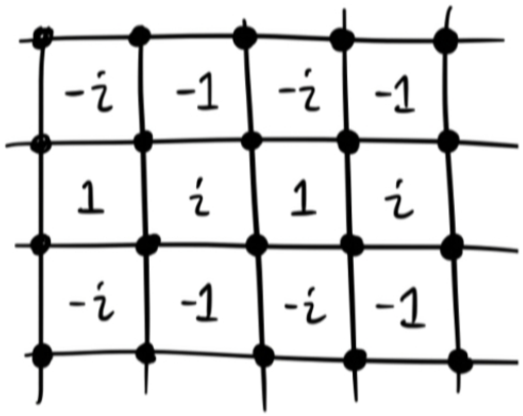


Monopole Berry phase
= Lattice Effect

Not considered in the CP^1 theory! — Its effect on the continuum field theory can be studied by symmetry analysis

Symmetries	Transformations
T_x	$\mathcal{M}^\dagger \mapsto -i\mathcal{M} \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$
T_y	$\mathcal{M}^\dagger \mapsto i\mathcal{M} \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$
$R_{\pi/4}$	$\mathcal{M}^\dagger \mapsto i\mathcal{M}^\dagger \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
σ_x	$\mathcal{M}^\dagger \mapsto i\mathcal{M} \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
σ_y	$\mathcal{M}^\dagger \mapsto -i\mathcal{M} \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
$\mathcal{T}$	$\mathcal{M}^\dagger \mapsto \mathcal{M} \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$

Symmetry Analysis — Monopole

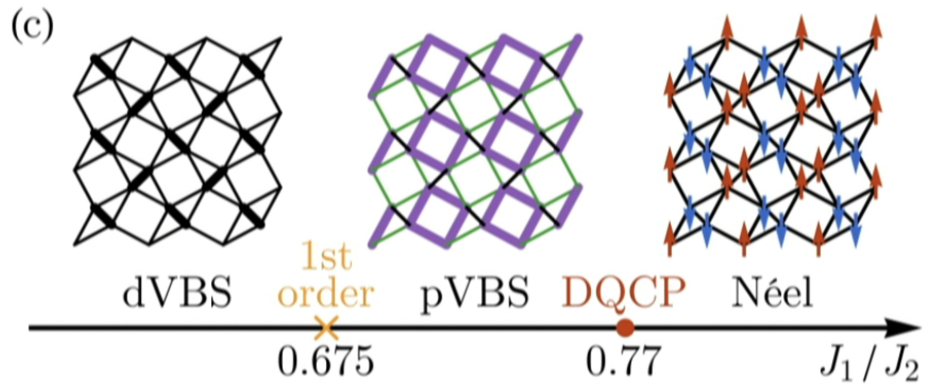


Monopole Berry phase
= Lattice Effect

Not considered in the CP[1] theory! — Its effect on the continuum field theory can be studied by symmetry analysis

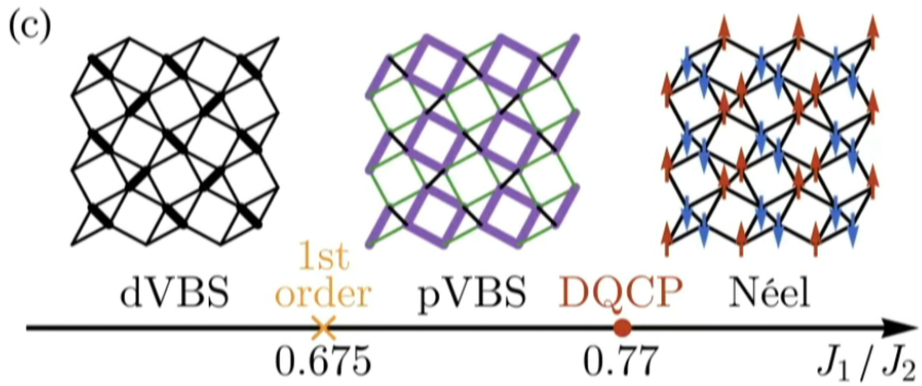
Symmetries	Transformations
T_x	$\mathcal{M}^\dagger \mapsto -i\mathcal{M} \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$
T_y	$\mathcal{M}^\dagger \mapsto i\mathcal{M} \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$
$R_{\pi/4}$	$\mathcal{M}^\dagger \mapsto i\mathcal{M}^\dagger \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
σ_x	$\mathcal{M}^\dagger \mapsto i\mathcal{M} \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
σ_y	$\mathcal{M}^\dagger \mapsto -i\mathcal{M} \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
$\mathcal{T}$	$\mathcal{M}^\dagger \mapsto \mathcal{M} \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$

Symmetry Analysis — Monopole



$$\mathcal{L}_{\mathcal{M}} \sim \mathcal{M}^\dagger + \mathcal{M} \quad \text{or} \quad i\left(\mathcal{M}^\dagger - \mathcal{M}\right)$$

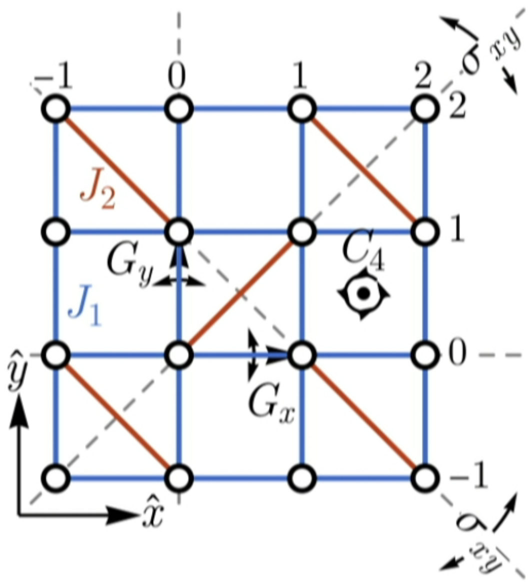
Symmetry Analysis — Monopole



$$\mathcal{L}_{\mathcal{M}} \sim \mathcal{M}^\dagger + \mathcal{M} \quad i\left(\mathcal{M}^\dagger - \mathcal{M}\right)$$

Symmetry Analysis — Monopole

Strategy: starting from Neel order in the square lattice (p4m), one can deduce how monopoles transform under the lattice symmetries of Shastry-Sutherland lattice (p4g)



G_{p4g}	G_{p4m}	Action
$\boldsymbol{T}_x$	T_x^2	$\mathcal{M}^\dagger \mapsto \mathcal{M}^\dagger \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
$\boldsymbol{T}_y$	T_y^2	$\mathcal{M}^\dagger \mapsto \mathcal{M}^\dagger \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
$\boldsymbol{\sigma}_{xy}$	$R_{\pi/2}\sigma_x$	$\mathcal{M}^\dagger \mapsto \mathcal{M} \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
$\boldsymbol{\sigma}_{x\bar{y}}$	$T_x T_y R_{\pi/2}\sigma_y$	$\mathcal{M}^\dagger \mapsto \mathcal{M} \quad \boldsymbol{n} \mapsto \boldsymbol{n}$
$\boldsymbol{g}_x$	$T_x\sigma_x$	$\mathcal{M}^\dagger \mapsto -\mathcal{M}^\dagger \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$
$\boldsymbol{g}_y$	$T_y\sigma_y$	$\mathcal{M}^\dagger \mapsto -\mathcal{M}^\dagger \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$
$\boldsymbol{R}_{\pi/4}$	$R_{\pi/4}^{\text{plaq}}$	$\mathcal{M}^\dagger \mapsto -\mathcal{M} \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$
$\mathcal{T}$	$\mathcal{T}$	$\mathcal{M}^\dagger \mapsto \mathcal{M} \quad \boldsymbol{n} \mapsto -\boldsymbol{n}$

Symmetry Analysis — Continuum Action

Square Lattice

$$\mathcal{L}_{\mathrm{CP}^1} = \sum_i |(\partial - ia) z_i|^2 + \cdots \quad + \quad \mathcal{L}_{\mathcal{M}} = r\mathcal{M}^\dagger \mathcal{M} + \lambda_4 \,\mathrm{Re}\, \mathcal{M}^4$$

IRRELEVANT at DQCP

All other lower-order monopole terms are suppressed by C_4 rotation symmetry

Shastry-Sutherland Lattice

$$\mathcal{L}_{\mathrm{CP}^1} = \sum_i |(\partial - ia) z_i|^2 + \cdots \quad + \quad \mathcal{L}_{\mathcal{M}} = r\mathcal{M}^\dagger \mathcal{M} + \lambda_2 \,\mathrm{Re}\, \mathcal{M}^2$$

RELEVANT at DQCP

All other monopole terms are suppressed by time-reversal-glide-reflection symmetry

Symmetry Analysis — Continuum Action

Square Lattice

$$\mathcal{L}_{\mathrm{CP}^1} = \sum_i |(\partial - ia)z_i|^2 + \cdots \;\; + \;\; \mathcal{L}_{\mathcal{M}} = r\mathcal{M}^\dagger\mathcal{M} + \lambda_4 \,\mathrm{Re}\,\mathcal{M}^4$$

IRRELEVANT at DQCP

All other lower-order monopole terms are suppressed by C_4 rotation symmetry

---

Shastry-Sutherland Lattice

$$\mathcal{L}_{\mathrm{CP}^1} = \sum_i |(\partial - ia)z_i|^2 + \cdots \;\; + \;\; \mathcal{L}_{\mathcal{M}} = r\mathcal{M}^\dagger\mathcal{M} + \lambda_2 \,\mathrm{Re}\,\mathcal{M}^2$$

RELEVANT at DQCP

All other monopole terms are suppressed by time-reversal-glide-reflection symmetry

Symmetry Analysis — Continuum Action

Relevant Perturbation! Would it lead to a first order transition?

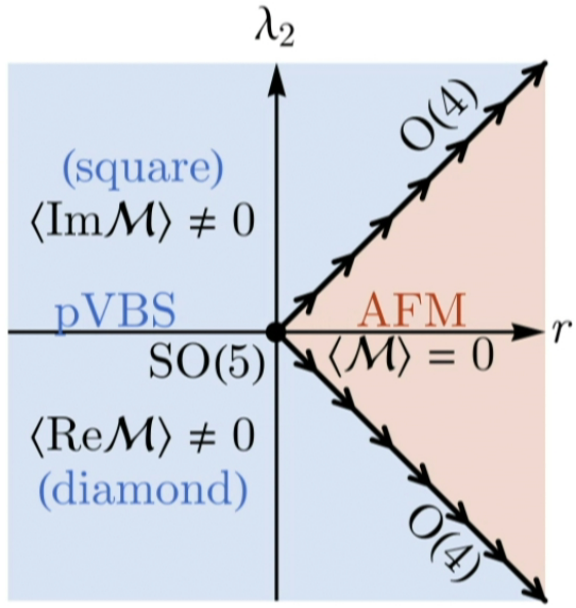
$$\mathcal{L}_{\mathcal{M}} = r\mathcal{M}^\dagger\mathcal{M} + \lambda_2\,\mathrm{Re}\,\mathcal{M}^2 + \cdots$$

$$\downarrow$$

$$\mathcal{L}_{\mathcal{M}} = \tilde{r}(\mathrm{Im}\,\mathcal{M})^2 + \tilde{\lambda}_2(\mathrm{Re}\,\mathcal{M})^2$$

$$\tilde{r} = r - \lambda_2 \text{ and } \tilde{\lambda}_2 = r + \lambda_2$$

Perturbation gaps out imaginary or real part of monopole fluctuations



Symmetry Analysis — Continuum Action

$$\mathcal{L}_{\mathcal{M}} = \tilde{r}(\mathrm{Im}\,\mathcal{M})^2 + \tilde{\lambda}_2(\mathrm{Re}\,\mathcal{M})^2$$

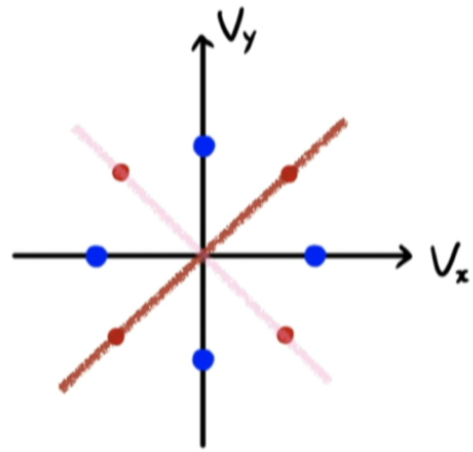
Perturbation gaps out imaginary or real part of monopole fluctuations

$$n = (N_x, N_y, N_z, V_x, V_y)$$

$$\big\downarrow \lambda_2 > 0$$

$$\tilde{n} = (N_x, N_y, N_z, \mathrm{Im}\,\mathcal{M})$$

$$\left(\ \mathrm{Im}\,\mathcal{M} \sim V_x - V_y\ \right)$$



Symmetry Analysis — Continuum Action

Relevant Perturbation! Would it lead to a first order transition?

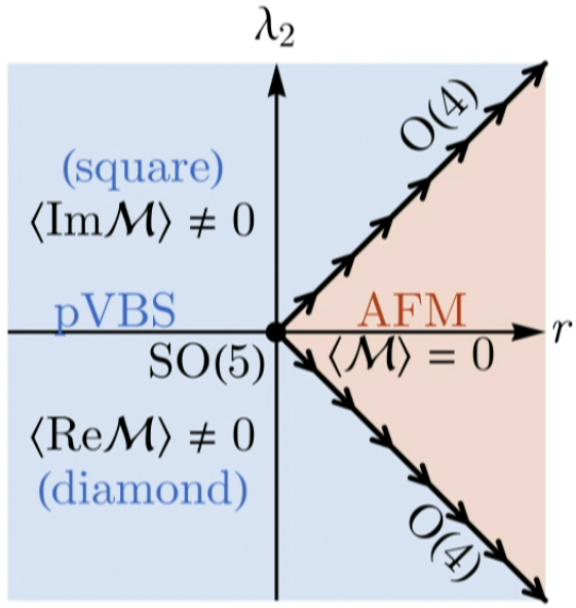
$$\mathcal{L}_{\mathcal{M}} = r\mathcal{M}^\dagger\mathcal{M} + \lambda_2 \,\mathrm{Re}\,\mathcal{M}^2 + \cdots$$

$$\downarrow$$

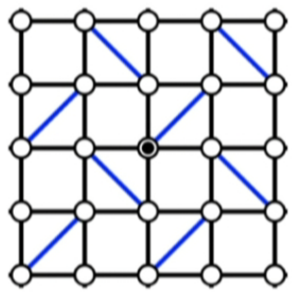
$$\mathcal{L}_{\mathcal{M}} = \tilde{r}(\mathrm{Im}\,\mathcal{M})^2 + \tilde{\lambda}_2(\mathrm{Re}\,\mathcal{M})^2$$

$$\tilde{r} = r - \lambda_2 \text{ and } \tilde{\lambda}_2 = r + \lambda_2$$

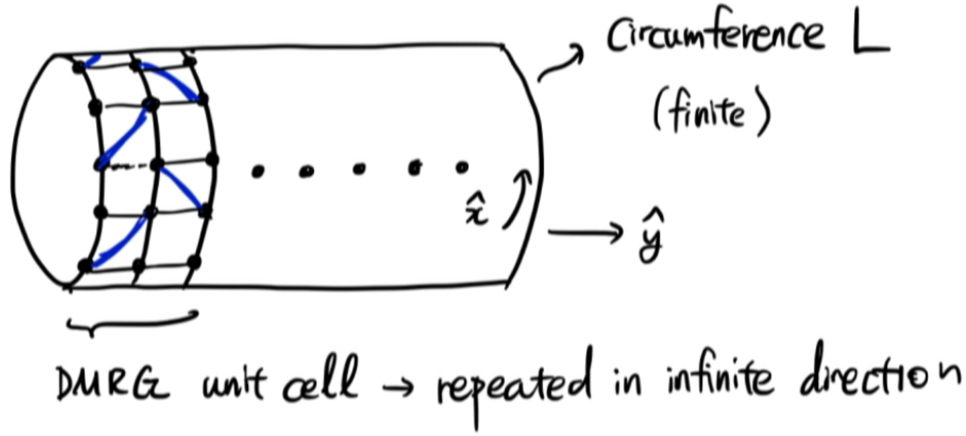
Perturbation gaps out imaginary or real part of monopole fluctuations

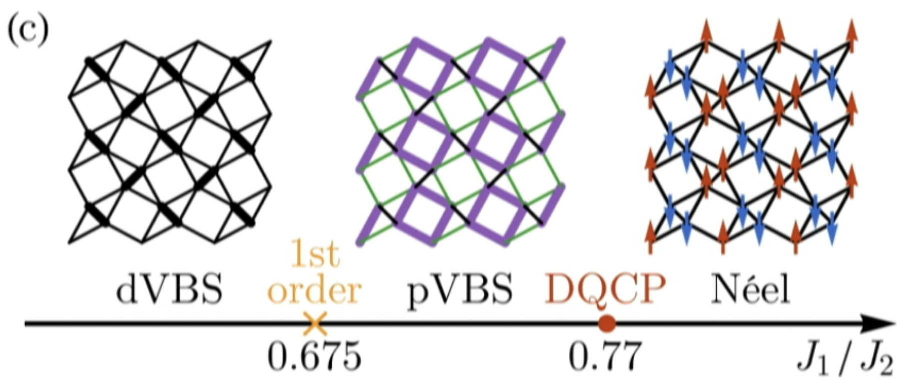


IDMRG study of phase transition



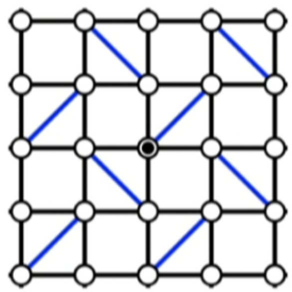
$$H = J_1 \sum_{ij \in \text{n.n.}} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + J_2 \sum_{ij \in \text{dimer}} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

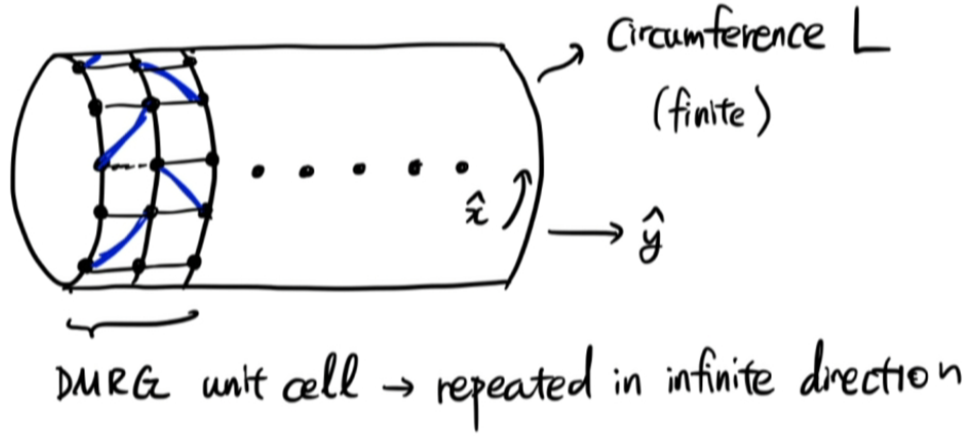




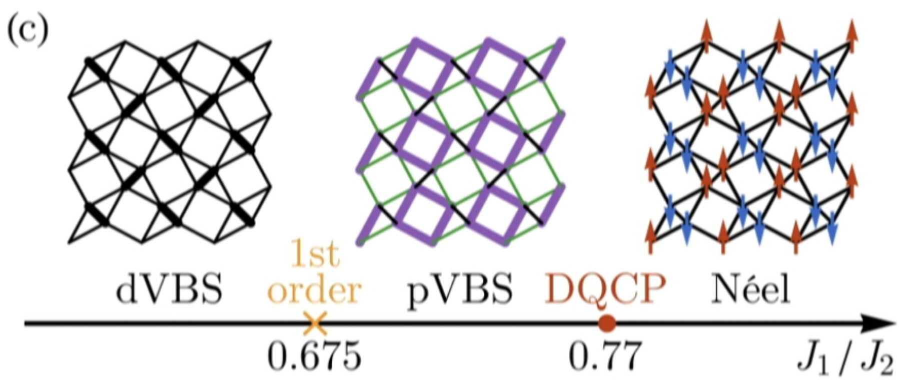
- L = 6, 8, 10 (double columns)
- Bond dimension up to 5000

IDMRG study of phase transition



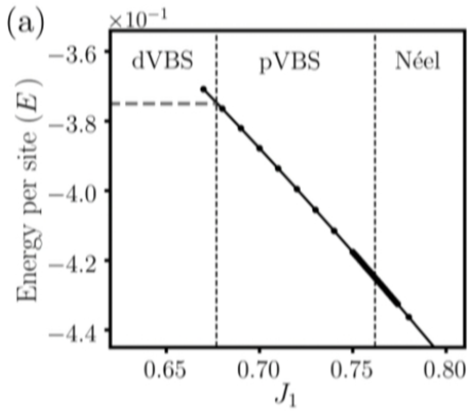


$$H = J_1 \sum_{ij \in \text{n.n.}} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + J_2 \sum_{ij \in \text{dimer}} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$



- L = 6, 8, 10 (double columns)
- Bond dimension up to 5000

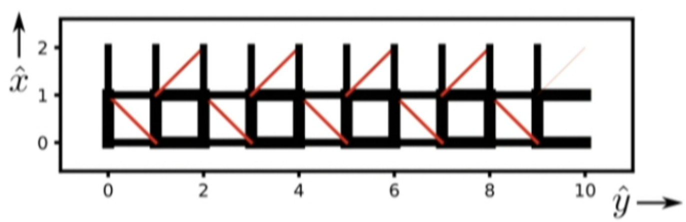
IDMRG study of phase transition

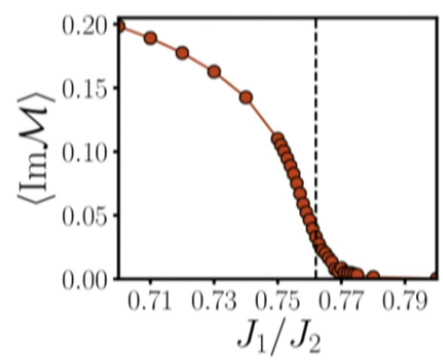


First order derivative of the energy seems continuous — weakly first order or second order transition

$$\mathcal{M}^\dagger = \frac{1}{\sqrt{2}}\big((V_x + V_y) + \mathrm{i}(V_x - V_y)\big),$$

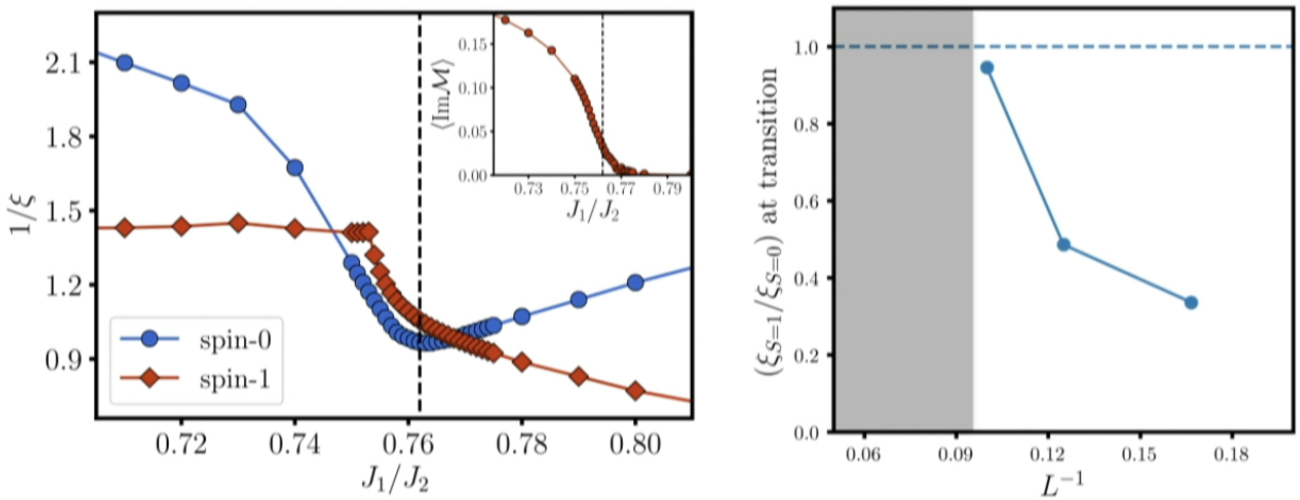
VBS has a singlet plaquette at the empty square





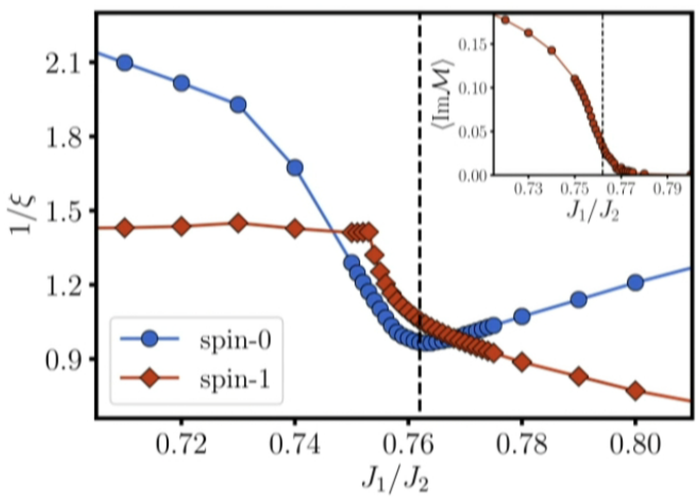
IDMRG study of phase transition

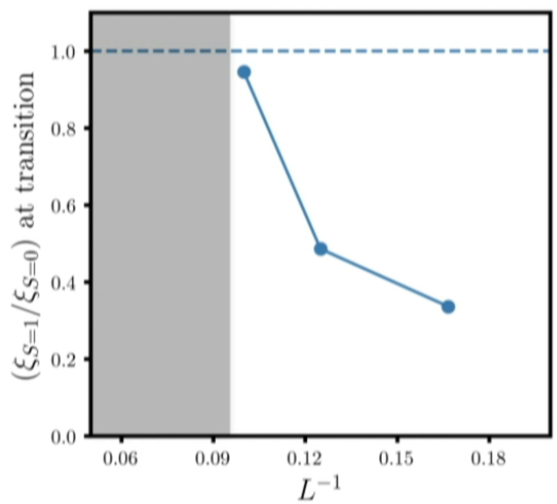
Correlation Length Spectra



IDMRG study of phase transition

Correlation Length Spectra

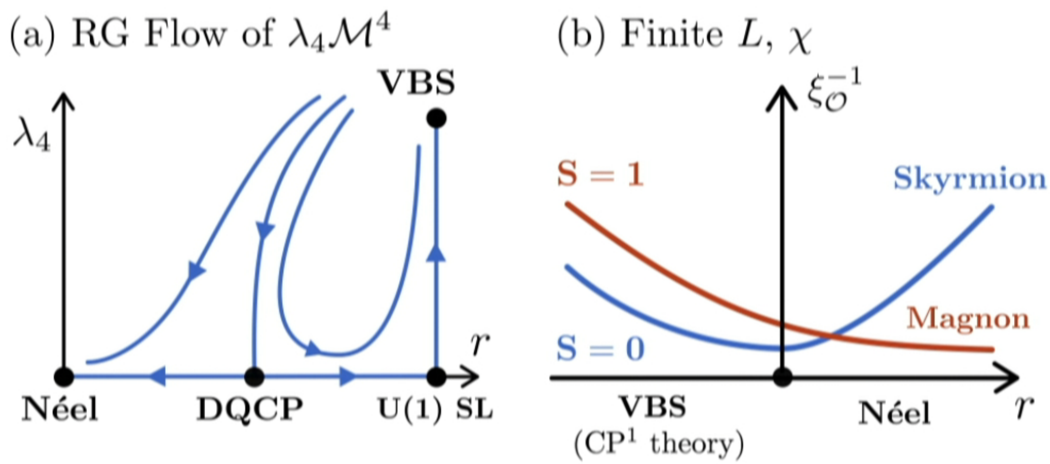




Absence of Dangerously Irrelevant Operator

Conventional SO(5) or easy-plane O(4) DQCP

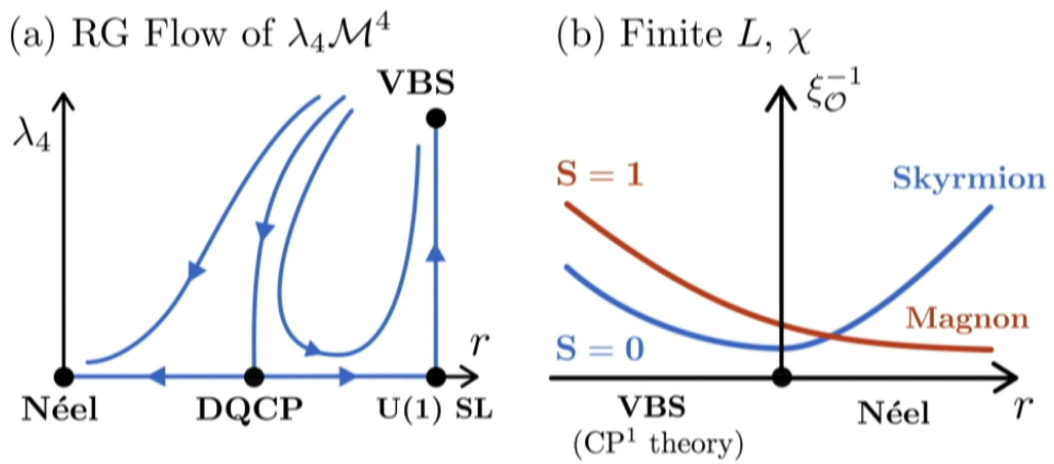
There is a separation of length scales between correlation length for spin and VBS fluctuations due to the emergent U(1) symmetry



Absence of Dangerously Irrelevant Operator

Conventional SO(5) or easy-plane O(4) DQCP

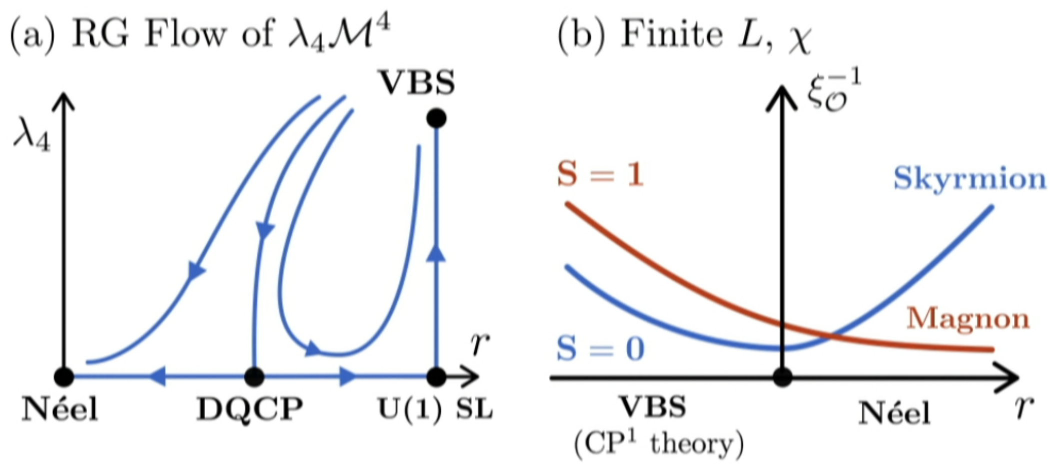
There is a separation of length scales between correlation length for spin and VBS fluctuations due to the emergent U(1) symmetry



Absence of Dangerously Irrelevant Operator

Conventional SO(5) or easy-plane O(4) DQCP

There is a separation of length scales between correlation length for spin and VBS fluctuations due to the emergent U(1) symmetry



Identify Noether Currents

- Emergent O(4) symmetry rotates the O(4) vector

$$\boldsymbol{n} = (n_1, n_2, n_3, n_4)$$

$$\mathcal{L}[\boldsymbol{n}] = \frac{1}{g}(\partial_\mu \boldsymbol{n})^2 + \frac{\mathrm{i}\Theta}{2\pi^2}\epsilon^{abcd} n_a \partial_\tau n_b \partial_x n_c \partial_y n_d$$

- Noether theorem
  - Each generator T_{ab}: $\boldsymbol{n} \to e^{\mathrm{i}\theta T_{ab}}\boldsymbol{n} \quad (a, b = 1, 2, 3, 4)$
  - Associate with a conserved current J^μ_{ab} with $\partial_\mu J^\mu_{ab} = 0$

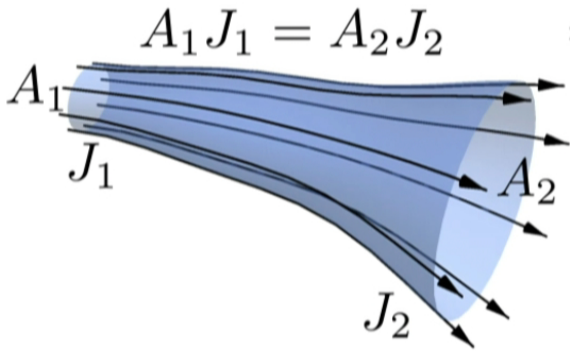
$$J^\mu_{ab} = \frac{\delta \mathcal{L}}{\delta(\partial_\mu \boldsymbol{n})} \cdot (\mathrm{i}T_{ab}\boldsymbol{n}) = n_a \partial_\mu n_b - n_b \partial_\mu n_a$$

  - SO(4) has 6 generators, each current has (2+1) space-time components → altogether 18 components
  - Not all of them appear in the spin excitation spectrum …

From Yi-Zhuang You's Talk

Conservation Law from Scaling Dimension

- In (2+1)D space-time, conserved current must scale as



$$\Rightarrow \quad J \sim 1/A \sim 1/r^2$$

Current-current correlation must decay with exact power

$$\langle J^{\mu}_{ab}(r) J^{\mu}_{ab}(0) \rangle \sim \frac{1}{r^4}$$

- Non-conserved current will not follow the precise scaling

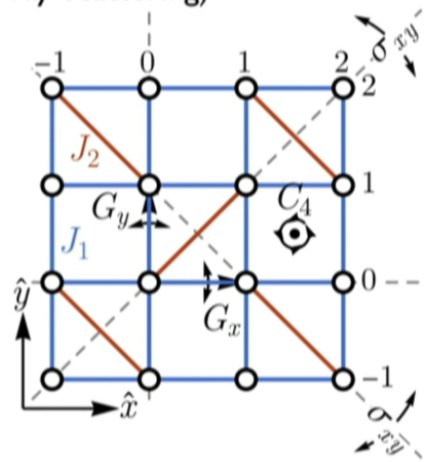
$$\langle J^{\mu}_{ab}(r) J^{\mu}_{ab}(0) \rangle \sim \frac{1}{r^{4+\eta}}$$ ← "anomalous" dimension

  - A vanishing η indicates the current conservation
  - This exponent can be measured from spin-spin correlation, given their correspondence to the O(4) current

From Yi-Zhuang You's Talk

Spectral Signature of DQCP

(Inelastic Neutron Scattering or Resonant Inelastic X-ray Scattering)



Glide-reflection symmetry — Extinction of some Bragg peaks

$$S(Q_x, Q_y) = e^{\mathrm{i}Q_x/2} S(Q_x, -Q_y) = e^{\mathrm{i}Q_y/2} S(-Q_x, Q_y)$$

$$S = 0 \quad \text{if} \quad Q \in \pi(2\mathbb{Z}+1, 0) \text{ or } \pi(0, 2\mathbb{Z}+1)$$

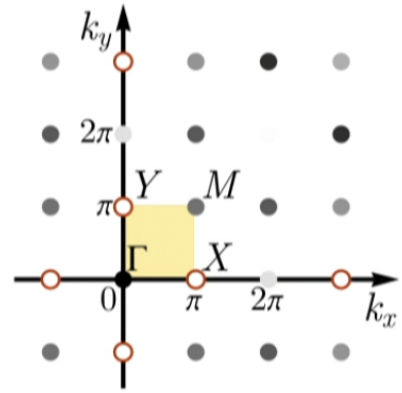
Spectral Signature of DQCP

(Inelastic Neutron Scattering or Resonant Inelastic X-ray Scattering)

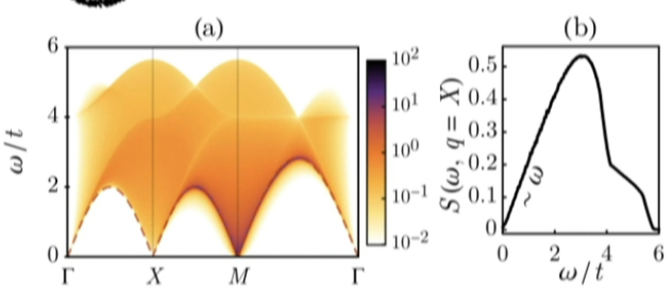
Glide-reflection symmetry — Extinction of some Bragg peaks

$$S(Q_x, Q_y) = e^{\mathrm{i}Q_x/2} S(Q_x, -Q_y) = e^{\mathrm{i}Q_y/2} S(-Q_x, Q_y)$$

$$S = 0 \quad \text{if} \quad Q \in \pi(2\mathbb{Z}+1, 0) \text{ or } \pi(0, 2\mathbb{Z}+1)$$



1 Magnon Spectrum (S=1)



conserved current of O(4) symmetry

$$\boldsymbol{J}_y = \boldsymbol{n}\partial_y \operatorname{Im}\mathcal{M} - \operatorname{Im}\mathcal{M}\partial_y \boldsymbol{n}$$

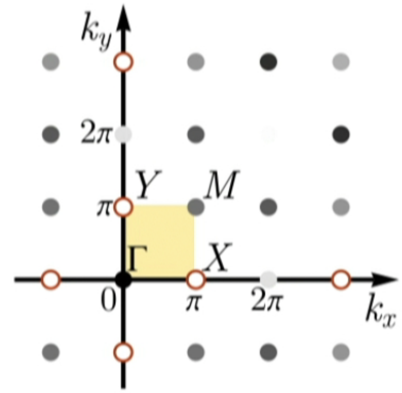
Spectral Signature of DQCP

(Inelastic Neutron Scattering or Resonant Inelastic X-ray Scattering)

Glide-reflection symmetry — Extinction of some Bragg peaks

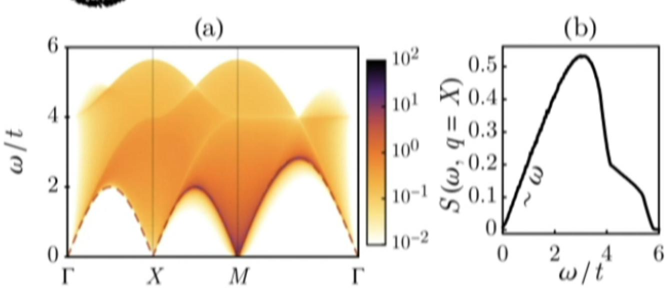
$$S(Q_x, Q_y) = e^{\mathrm{i}Q_x/2} S(Q_x, -Q_y) = e^{\mathrm{i}Q_y/2} S(-Q_x, Q_y)$$

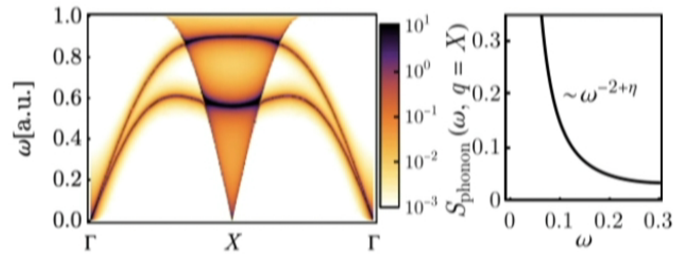
$$S = 0 \quad \text{if} \quad Q \in \pi(2\mathbb{Z}+1, 0) \text{ or } \pi(0, 2\mathbb{Z}+1)$$



① Magnon Spectrum ($\mathrm{S}=1$)

② Phonon Spectrum ($\mathrm{S}=0$)





conserved current of O(4) symmetry

$$\boldsymbol{J}_y = \boldsymbol{n}\partial_y \operatorname{Im}\mathcal{M} - \operatorname{Im}\mathcal{M}\partial_y \boldsymbol{n}$$

$$\mathcal{L}_{\text{VBS-phonon}} \sim u_x V_x + u_y V_y$$

$$S_{\text{phonon}}(\omega, \boldsymbol{q} = X) \propto \omega^{-2+\eta}$$

Interlayer Coupling

$$\mathcal{S}^{(l)}_{\mathrm{DQCP}} = \int d^3x \frac{1}{2g}(\partial_\mu \Phi^{(l)})^2 + 2\pi \mathrm{i}\Gamma_{\mathrm{WZW}}[\Phi^{(l)}]$$

$$\mathcal{S} = \sum_l \mathcal{S}^{(l)}_{\mathrm{DQCP}} - \sum_l \int d^3x\, g^{ab}\Phi^{(l)}_a \Phi^{(l+1)}_b$$

Depending on the locking parameterized by g^{ab}, WZW-terms in neighboring neighbors would get canceled or added up

Canceled — Becomes Theta-term!

Added — System behaves as a classical system!

Interlayer Coupling

$$\mathcal{S}^{(l)}_{\rm DQCP} = \int d^3x \frac{1}{2g}(\partial_\mu \Phi^{(l)})^2 + 2\pi \mathrm{i}\Gamma_{\rm WZW}[\Phi^{(l)}]$$

$$\mathcal{S} = \sum_l \mathcal{S}^{(l)}_{\rm DQCP} - \sum_l \int d^3x\, g^{ab}\Phi_a^{(l)}\Phi_b^{(l+1)}$$

Depending on the locking parameterized by g^{ab}, WZW-terms in neighboring neighbors would get canceled or added up

Canceled — Becomes Theta-term!

Added — System behaves as a classical system!

Interlayer Coupling

Canceled — Becomes Theta-term!

3+1D NLsM with O(5) vector and theta-term

↕

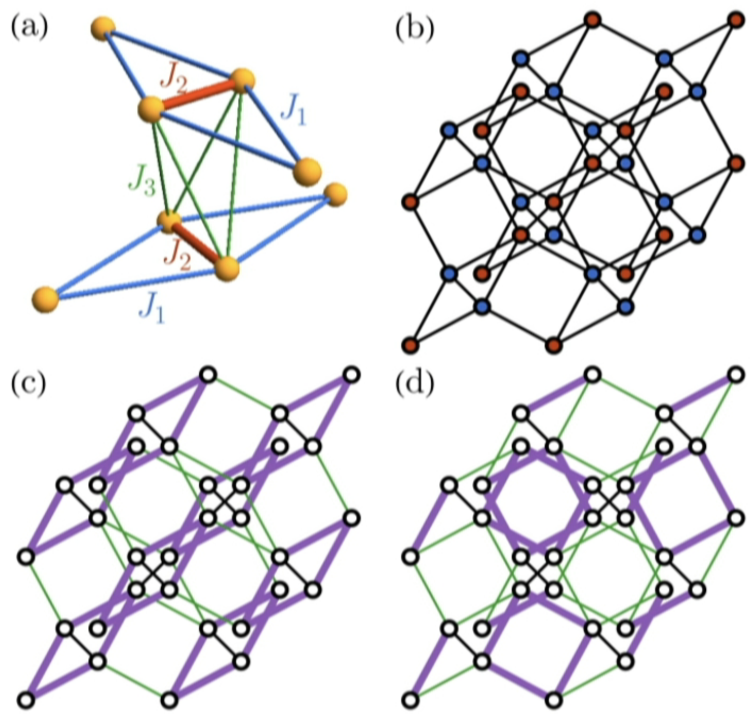
$$\mathcal{L} = \bar{\psi}(\gamma^\mu D_\mu + m + \mathrm{i}\gamma^5 \Phi_a \Gamma^a)\psi.$$

SU(2) QCD with m=0

The number of Dirac fermion flavors (N=2) is not enough to avoid a chiral symmetry breaking in 3+1D.

Flow to first-order transition

Interlayer Coupling



$$\boldsymbol{n}^{(l)} = \boldsymbol{n}^{(l+1)}$$
$$\mathrm{Im}\,\mathcal{M}^{(l)} = -\,\mathrm{Im}\,\mathcal{M}^{(l+1)}$$
$$\mathrm{Re}\,\mathcal{M}^{(l)} = \mathrm{Re}\,\mathcal{M}^{(l+1)}$$

$$g^{aa} = (+,+,+,+,-)$$

Flow to first-order transition

Interlayer Coupling

$$\mathcal{S}^{(l)}_{\mathrm{DQCP}} = \int d^3x \frac{1}{2g}(\partial_\mu \Phi^{(l)})^2 + 2\pi \mathrm{i}\Gamma_{\mathrm{WZW}}[\Phi^{(l)}]$$

$$\mathcal{S} = \sum_l \mathcal{S}^{(l)}_{\mathrm{DQCP}} - \sum_l \int d^3x\, g^{ab} \Phi^{(l)}_a \Phi^{(l+1)}_b$$

Depending on the locking parameterized by g^{ab}, WZW-terms in neighboring neighbors would get canceled or added up

Canceled — Becomes Theta-term!

Added — System behaves as a classical system!

Summary

- Monopole symmetry analysis — O(4) DQCP is possible
- Infinite DMRG study
  - Phase diagram confirmed
  - Absence of dangerously irrelevant scaling
  - Emergent O(4) symmetry
- Predicted spectral features of the emergent O(4) symmetry, which can be probed by INS, RIXS or NMR
- Coupling 2+1D DQCP into 3+1D — leads to the first order

Acknowledgements

Yizhuang You (Harvard-UCSD) | Subir Sachdev (Harvard) | Ashvin Vishwanath (Harvard)