Title: Fractionalized fermionic quantum criticality

Speakers: Lukas Janssen

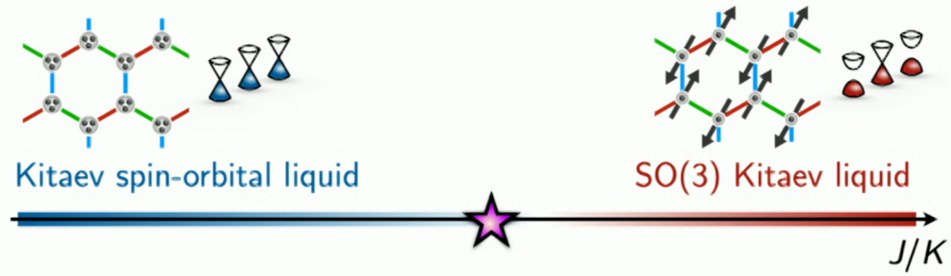
Collection: Quantum Criticality: Gauge Fields and Matter

Date: May 19, 2022 - 4:15 PM

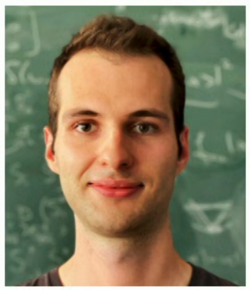
URL: https://pirsa.org/22050047

Abstract: In frustrated magnets, novel phases characterized by fractionalized excitations and emergent gauge fields can occur. A paradigmatic example is given by the Kitaev model of localized spins 1/2 on the honeycomb lattice, which realizes an exactly solvable quantum spin liquid ground state with Majorana fermions as low-energy excitations. I will demonstrate that the Kitaev solution can be generalized to systems with spin and orbital degrees of freedom. The phase diagrams of these Kitaev-Kugel-Khomskii spin-orbital magnets feature a variety of novel phases, including different types of quantum liquids, as well as conventional and unconventional long-range-ordered phases, and interesting phase transitions in between. In particular, I will discuss the example of a continuous quantum phase transition between a Kitaev spin-orbital liquid and a symmetry-broken phase. This transition can be understood as a realization of a fractionalized fermionic quantum critical point.

Fractionalized fermionic quantum criticality



Lukas Janssen
TU Dresden


Urban Seifert, Santa Barbara


Zihong Liu, Würzburg

Fakher Assaad, Würzburg
Sreejith Chulliparambil, Dresden
Xiao-Yu Dong, Ghent
Hong-Hao Tu, Dresden
Matthias Vojta, Dresden

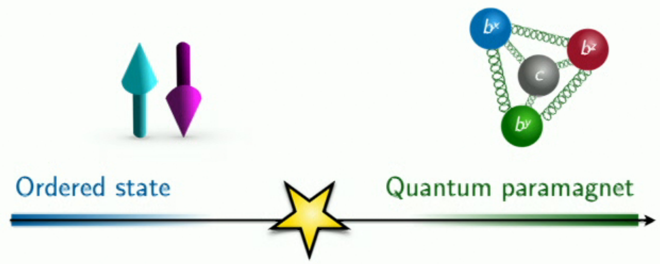
Emmy Noether-Programm DFG JA 2306/4-1

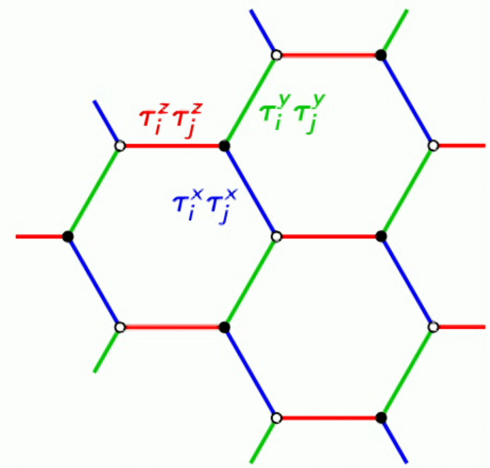
ct.qmat Complexity and Topology in Quantum Matter
Würzburg-Dresden Cluster of Excellence

SFB 1143

Outline

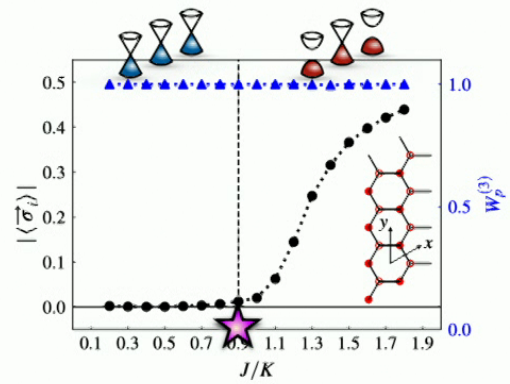
(1) Fractionalized quantum criticality





(2) Kitaev spin-orbital models

(3) Critical fractionalized fermions



(4) Conclusions

Slides available on https://tu-dresden.de/physik/qcm/vortraege

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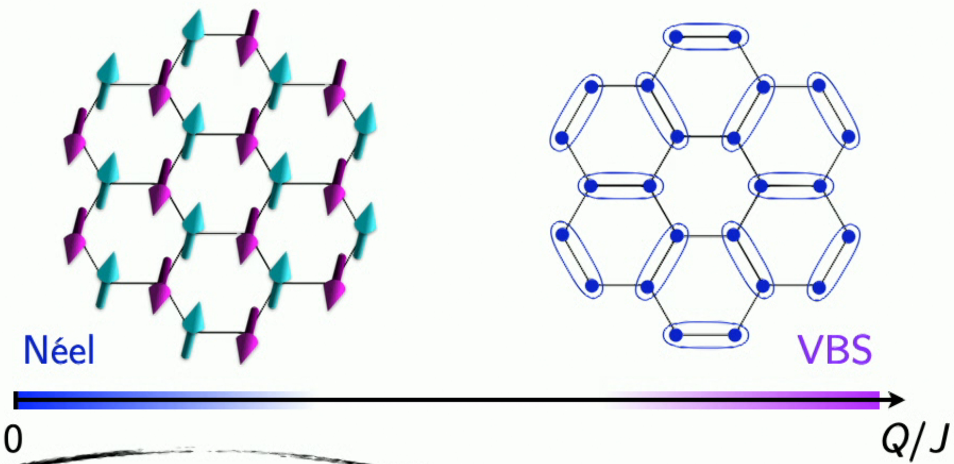
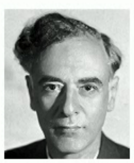
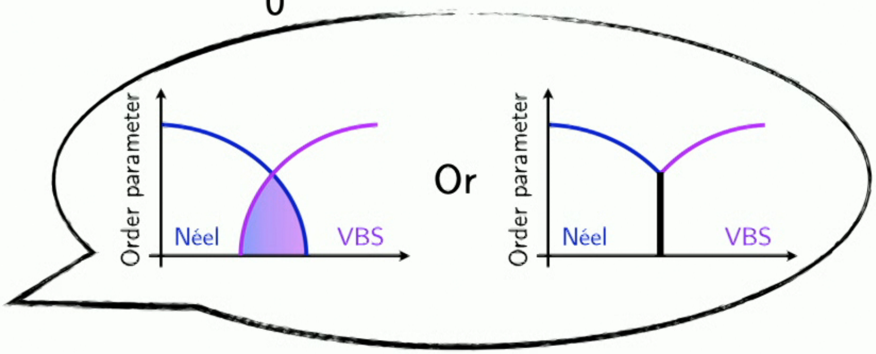
Deconfined quantum criticality

(singlet bond) $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

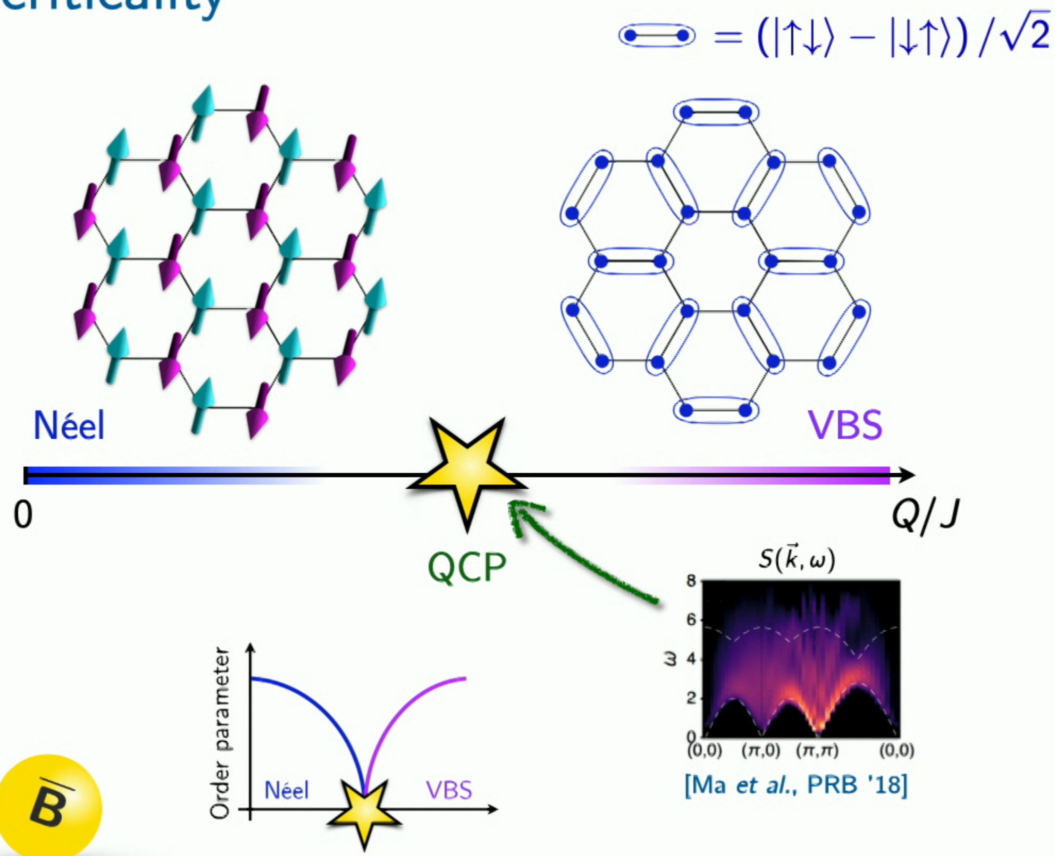


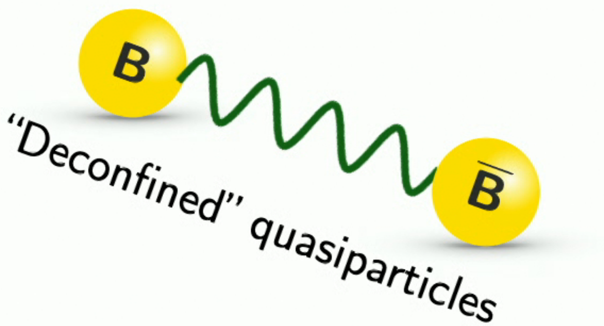


Landau



Deconfined quantum criticality





[Senthil *et al.*, Science '04]
[Pujari, Damle, Alet, PRL '13]
[Block, Melko, Kaul, PRL '13]
[Shao, Guo, Sandvik, Science '16]
...

→ talk by A. Sandvik

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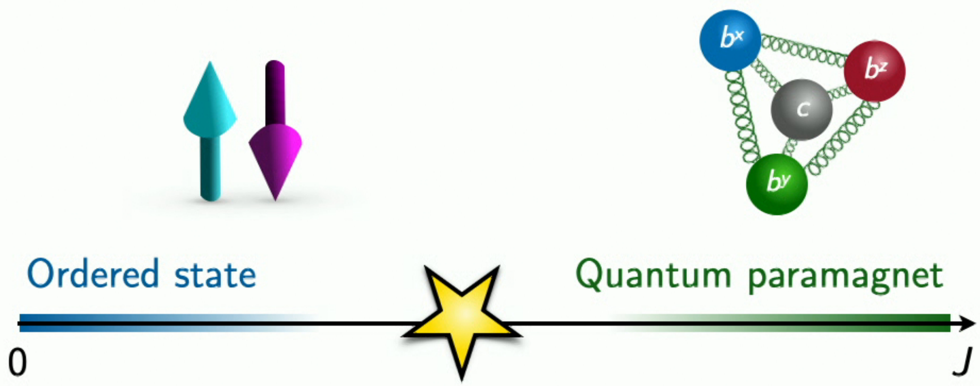
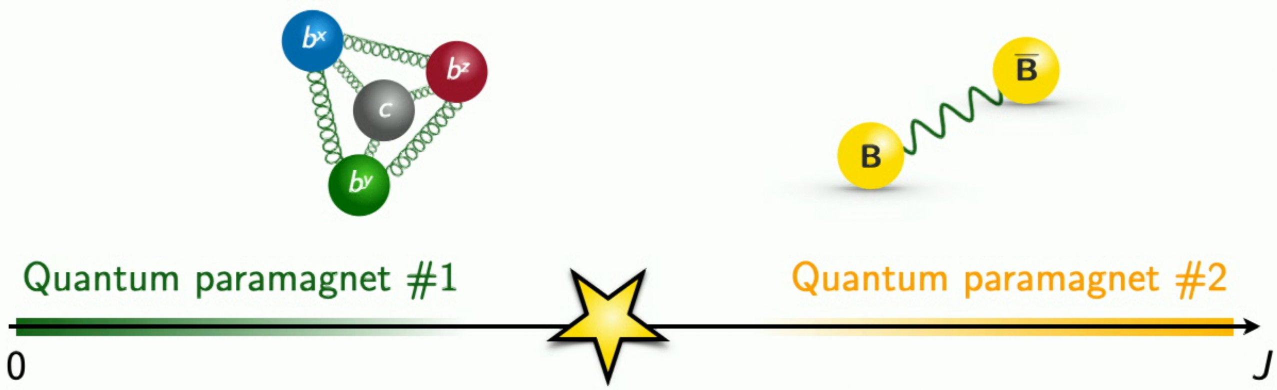
Spin-liquid transitions



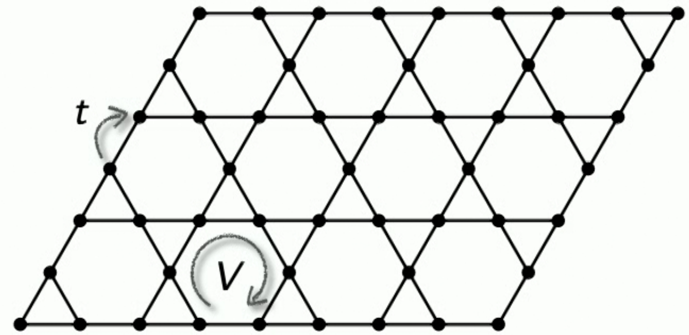
[Assaad & Grover, PRX '16]
[LJ, Wang, Scherer, Meng, Xu, PRB '20]
...

→ **talk by Z. Y. Meng**



[Metlitski, Mross, Sachdev, Senthil, PRB '15]
[LJ & He, PRB '17]
[Boyack, Lin, Zerf, Rayyan, Maciejko, PRB '18]
...

Example: Kagome-lattice Bose-Hubbard model

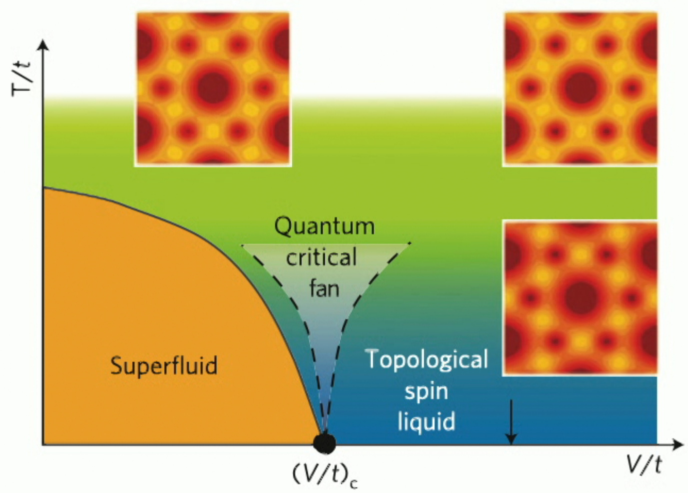


Hamiltonian:

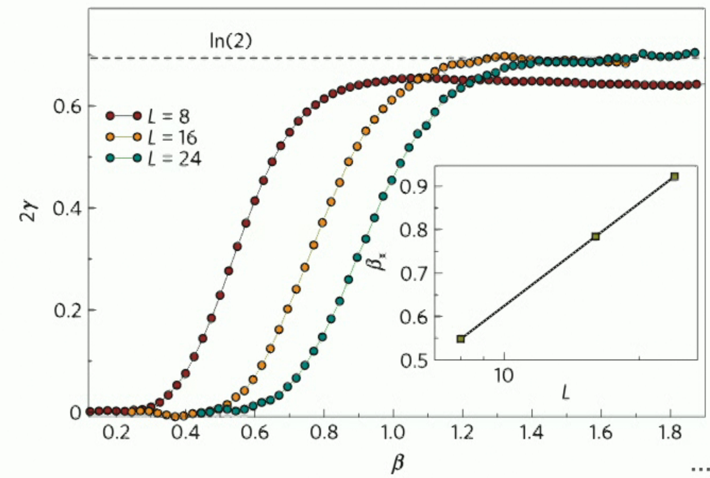
$$\mathcal{H} = -t \sum_{\langle ij \rangle} \left[b_i^\dagger b_j + b_i b_j^\dagger \right] + V \sum_{\hexagon} (n_{\hexagon})^2$$

... b_i hard-core bosons

Phase diagram:



Entanglement entropy: $S_n(A) = a\ell - \gamma + \dots$

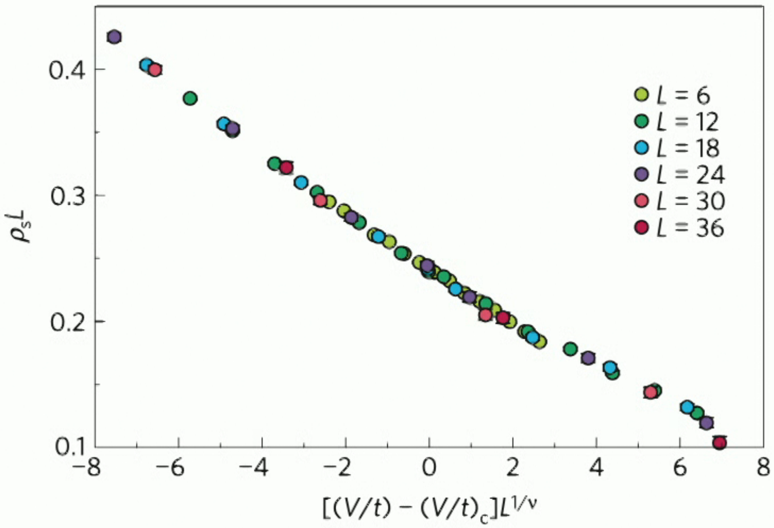


... in spin liquid phase

[Isakov, Hastings, Melko, Nat. Phys. '11]

Quantum critical scaling: XY*

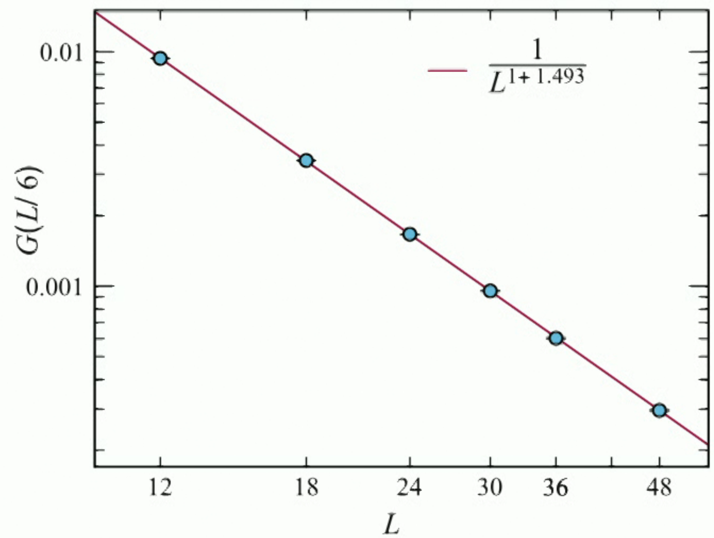
Superfluid density:



[Isakov, Hastings, Melko, Nat. Phys. '11]

$$\nu \approx 0.67 = \nu_{XY}$$

Two-point superfluid correlator:



[Isakov, Melko, Hastings, Science '12]

$$\eta \approx 1.49 \neq \eta_{XY} \approx 0.038$$

Order parameter *composite* of fractionalized particles!

... cf. $\eta_T \approx 1.54$ from field theory
[Chubukov, Sachdev, Senthil, NPB '94]

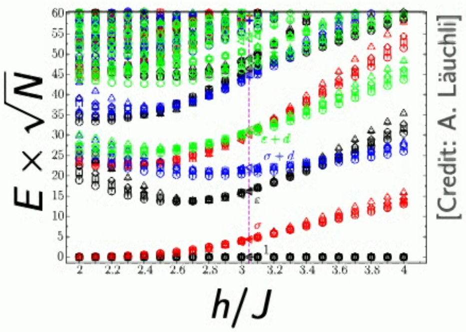
Finite-size spectroscopy: Ising vs Ising*

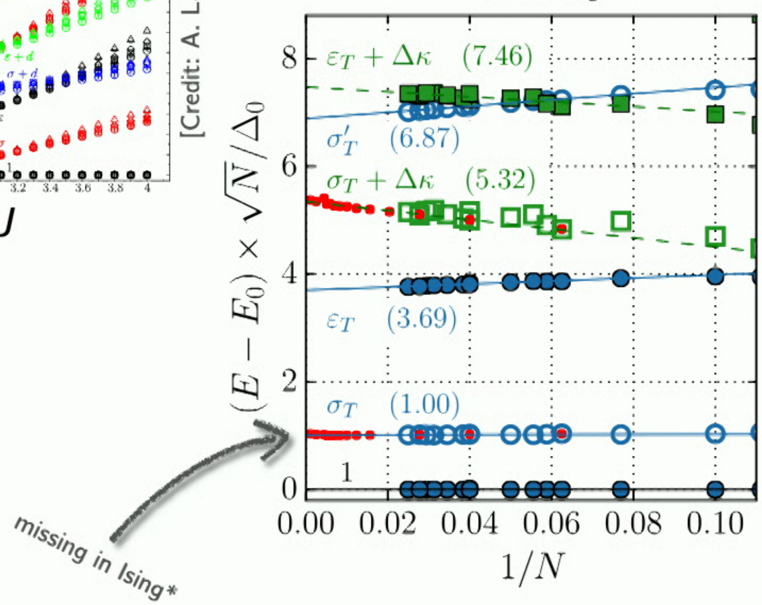
Transverse-field Ising:

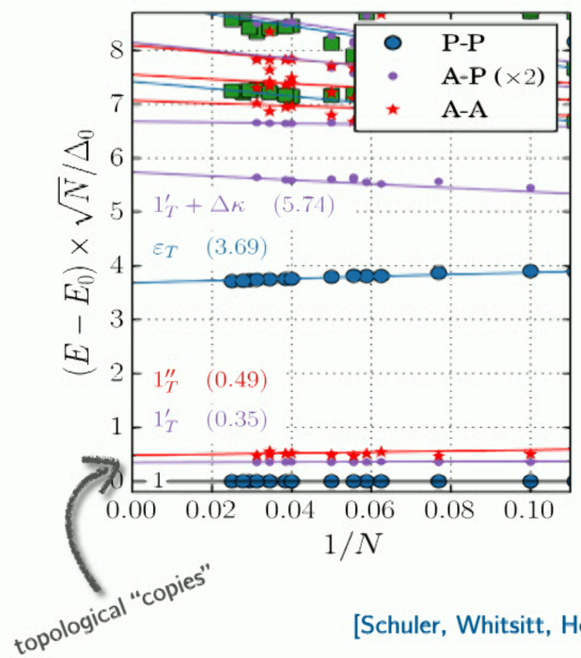
$$\mathcal{H} = -J\sum_{\langle ij\rangle} \sigma_i^z \sigma_j^z - h\sum_i \sigma_i^x$$

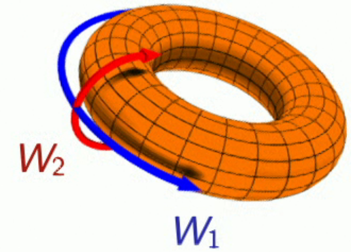
Transverse-field toric code:

$$\mathcal{H} = -J\sum_s \prod_{i\in s} \sigma_i^x - J\sum_p \prod_{i\in p} \sigma_i^z - h\sum_i \sigma_i^x$$



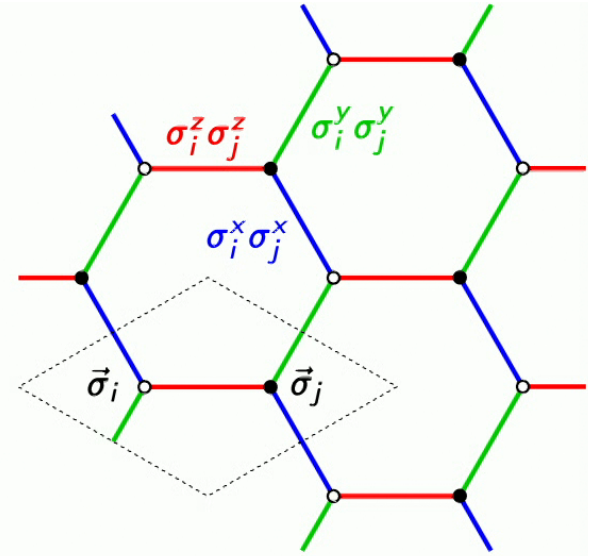






[Schuler, Whitsitt, Henry, Sachdev, Läuchli, PRL '16]

Kitaev spin-1/2 model

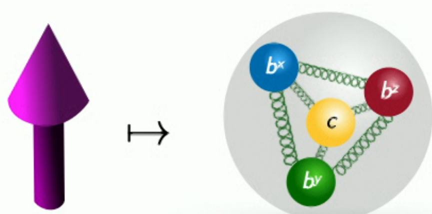


Hamiltonian:

$$\mathcal{H} = K \sum_{\text{blue links}} \sigma_i^x \sigma_j^x + K \sum_{\text{green links}} \sigma_i^y \sigma_j^y + K \sum_{\text{red links}} \sigma_i^z \sigma_j^z$$

Majorana representation:

$$\sigma^x \mapsto \tilde{\sigma}^x = i b^x c$$
$$\sigma^y \mapsto \tilde{\sigma}^y = i b^y c$$
$$\sigma^z \mapsto \tilde{\sigma}^z = i b^z c$$

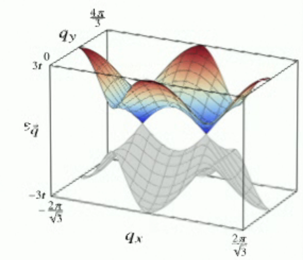


1 spin

4 Majoranas
with gauge constraint

Fractionalization:

$$\mathcal{H} \mapsto \tilde{\mathcal{H}} = iK \sum_{\langle ij \rangle_\gamma} \underbrace{(i b_i^\gamma b_j^\gamma)}_{\equiv \hat{u}_{ij} = \hat{u}_{ij}^\dagger} c_i c_j$$



with $\left[\hat{u}_{ij}, \tilde{\mathcal{H}}\right] = 0 \quad \Rightarrow \quad$ static $\mathbb{Z}_2$ gauge field!

Ground-state flux pattern: $u = 1$
[Lieb, PRL '94]

→ talk by N. Trivedi

[Kitaev, Ann. Phys. '06]

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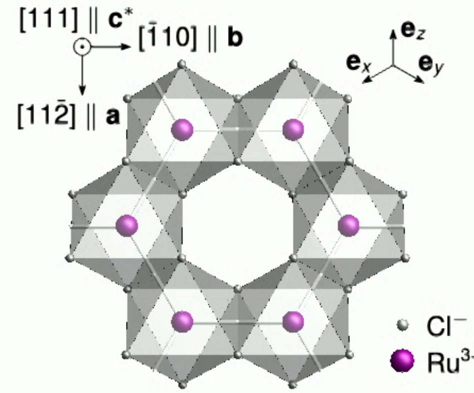
Kitaev-Heisenberg spin-1/2 model

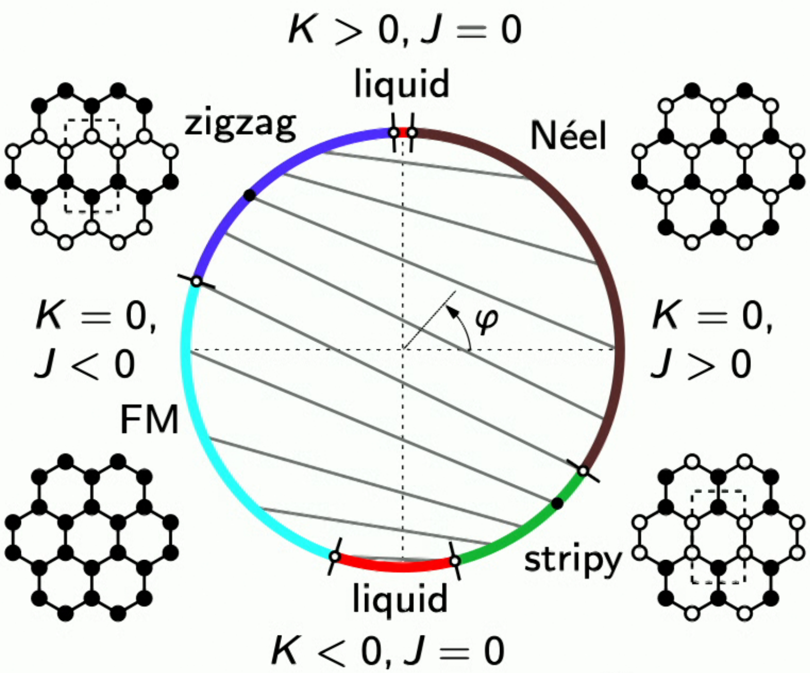
Hamiltonian:

$$\mathcal{H} = K \sum_{\langle ij \rangle_\gamma} \sigma_i^\gamma \sigma_j^\gamma + J \sum_{\langle ij \rangle} \vec{\sigma}_i \cdot \vec{\sigma}_j$$



... possible relevance to α-$RuCl_3$, Na_2IrO_3, $Na_2Co_2TeO_6$, ...

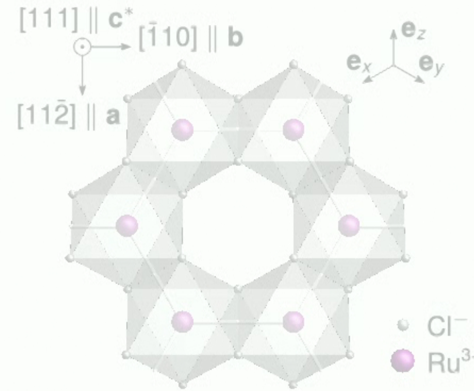
Phase diagram:



$$J = A \cos\varphi$$
$$K = 2A \sin\varphi$$

... from 24-site ED: [Chaloupka, Jackeli, Khaliullin, PRL '13]

Kitaev-Heisenberg spin-1/2 model

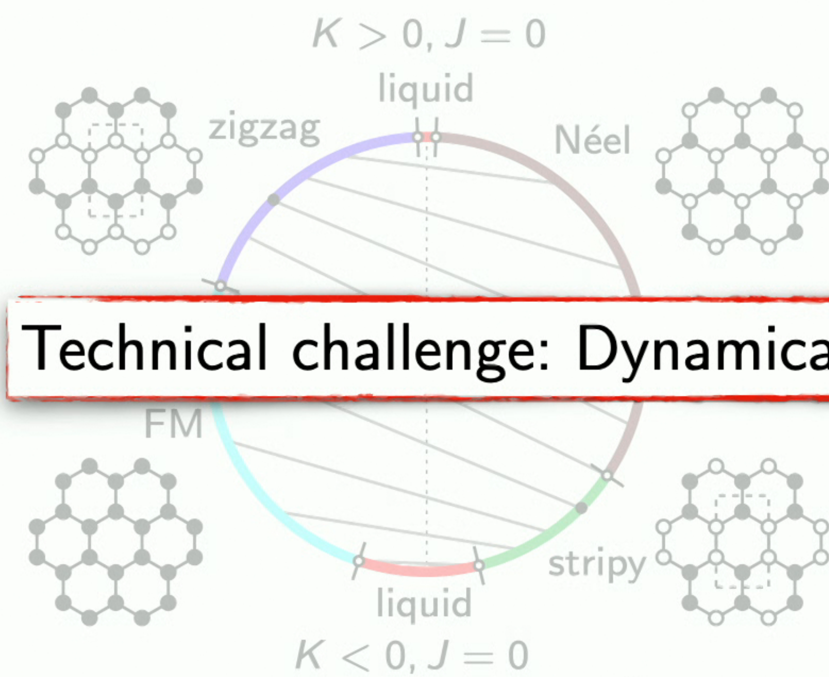


Hamiltonian:

$$\mathcal{H} = K \sum_{\langle ij \rangle_\gamma} \sigma_i^\gamma \sigma_j^\gamma + J \sum_{\langle ij \rangle} \vec{\sigma}_i \cdot \vec{\sigma}_j$$

... possible relevance to α-$RuCl_3$, Na_2IrO_3, $Na_2Co_2TeO_6$, ...

Phase diagram:



Technical challenge: Dynamical $\mathbb{Z}_2$ gauge field!

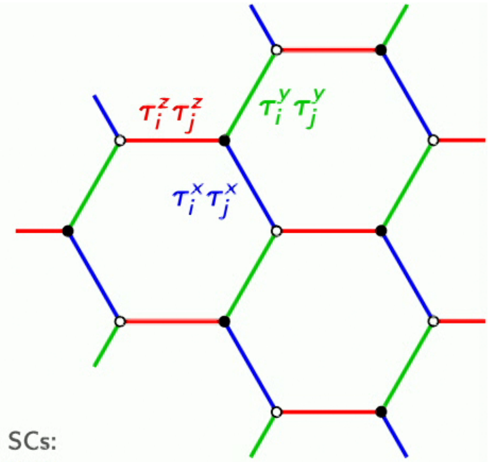
... no sign-problem-free QMC available: [Sato & Assaad, PRB '21]

... from 24-site ED: [Chaloupka, Jackeli, Khaliullin, PRL '13]

Kitaev spin-orbital models

Spin-orbital generalization:

$\sigma^\alpha \quad 2 \times 2$ $\qquad$ $\sigma^\alpha \otimes \tau^\beta = \gamma^i \quad 4 \times 4$



... can realize all 16 topological SCs:
[Chulliparambil, ..., LJ, Tu, PRB '20]

Hamiltonian:

$$\mathcal{H} = K \sum_{\langle ij \rangle_\gamma} \vec{\sigma}_i \cdot \vec{\sigma}_j \otimes \tau_i^\gamma \tau_j^\gamma$$

Heisenberg spin $\qquad$ Kitaev orbital

Majorana representation:

$$\sigma^y \otimes \tau^x = i b^1 c^x$$
$$\sigma^y \otimes \tau^y = i b^2 c^x$$
$$\sigma^y \otimes \tau^z = i b^3 c^x$$
$$\sigma^x \otimes \mathbb{1} = i c^y c^x$$
$$\sigma^z \otimes \mathbb{1} = i c^z c^x$$

Fractionalization:

$c \equiv \begin{pmatrix} c^x \\ c^y \\ c^z \end{pmatrix}$

$$\mathcal{H} \mapsto \tilde{\mathcal{H}} = iK \sum_{\langle ij \rangle_\gamma} \hat{u}_{ij} c_i^\top c_j$$

with $\left[\hat{u}_{ij}, \tilde{\mathcal{H}}\right] = 0$

... cf. also [Yao & Lee, PRL '11]

Kitaev-Heisenberg spin-orbital model

Hamiltonian:

$$\mathcal{H} = K \sum_{\langle ij \rangle_\gamma} \vec{\sigma}_i \cdot \vec{\sigma}_j \otimes \tau_i^\gamma \tau_j^\gamma + J \sum_{\langle ij \rangle} \underbrace{\vec{\sigma}_i \cdot \vec{\sigma}_j \otimes \mathbb{1}_i \mathbb{1}_j}$$

spin-1 matrices

$$\mapsto \frac{1}{4}(c_i^\top \vec{L} c_i) \cdot (c_j \vec{L} c_j)$$

with $[\hat{u}_{ij}, \mathcal{H}] = 0$ still static!

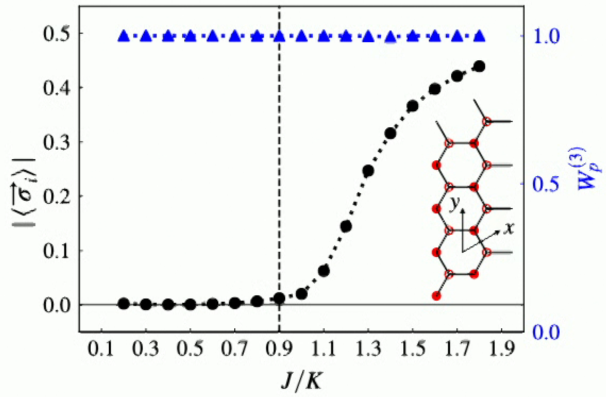
Phase diagram:

$\langle c_{iA}^\top \vec{L} c_{iA} \rangle \neq \langle c_{jB}^\top \vec{L} c_{jB} \rangle$

"spin density wave"

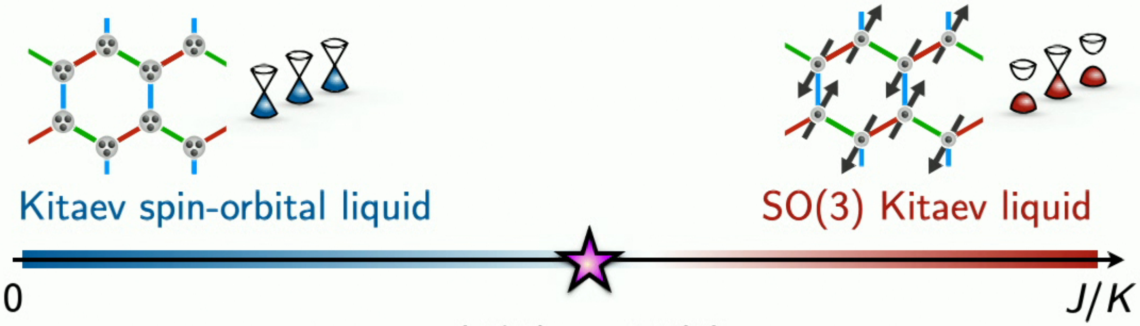
Gross-Neveu-SO(3)* transition

iDMRG:



... on cylinder with $L_y = 4$ unit cells

Phase diagram:



[Seifert, Dong, Chulliparambil, Vojta, Tu, LJ, PRL '20]

Effective field theory:

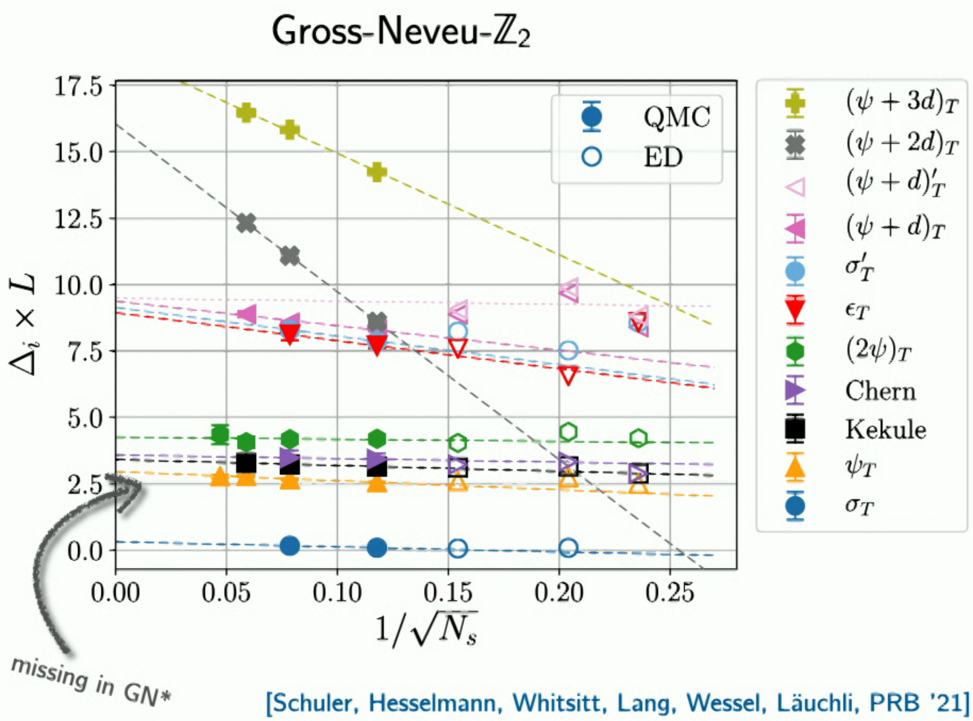
$$\mathcal{S} = \int d^2\vec{x}d\tau \left[\bar{\psi}\gamma^\mu\partial_\mu\psi + g\vec{\varphi}\cdot\bar{\psi}(\mathbb{1}_2\otimes\vec{L})\psi\right]$$

"Gross-Neveu-SO(3)"

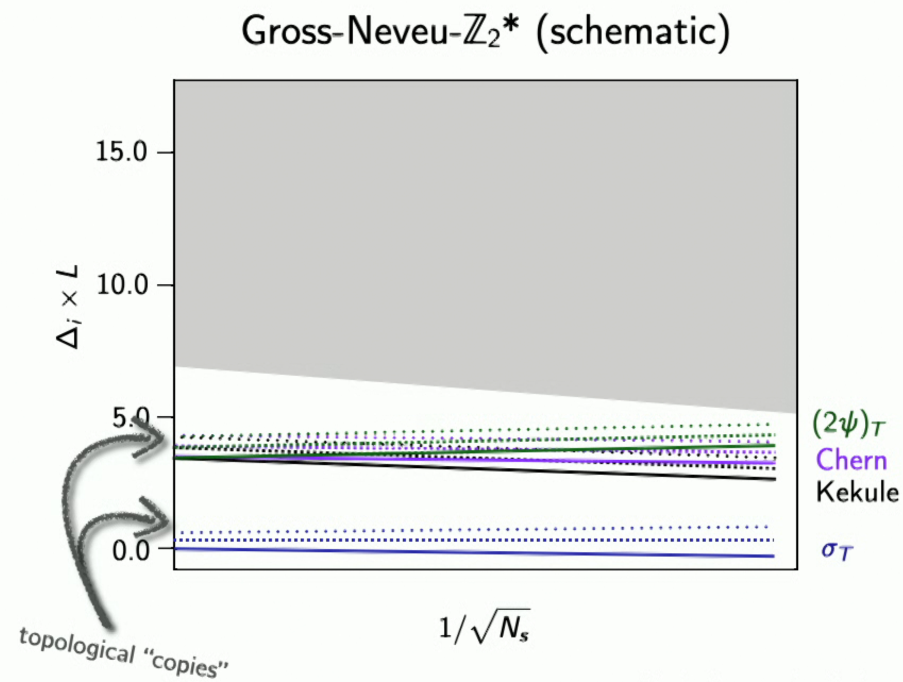
→ talk by M. Scherer

[Ray, Ihrig, Kruti, Gracey, Scherer, LJ, PRB '21]

Gross-Neveu vs Gross-Neveu*



[Schuler, Hesselmann, Whitsitt, Lang, Wessel, Läuchli, PRB '21]



... testable in future simulations

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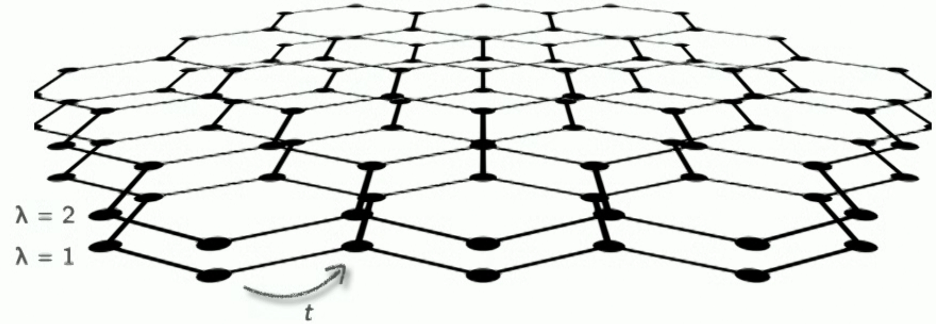
Sign-problem-free bilayer model

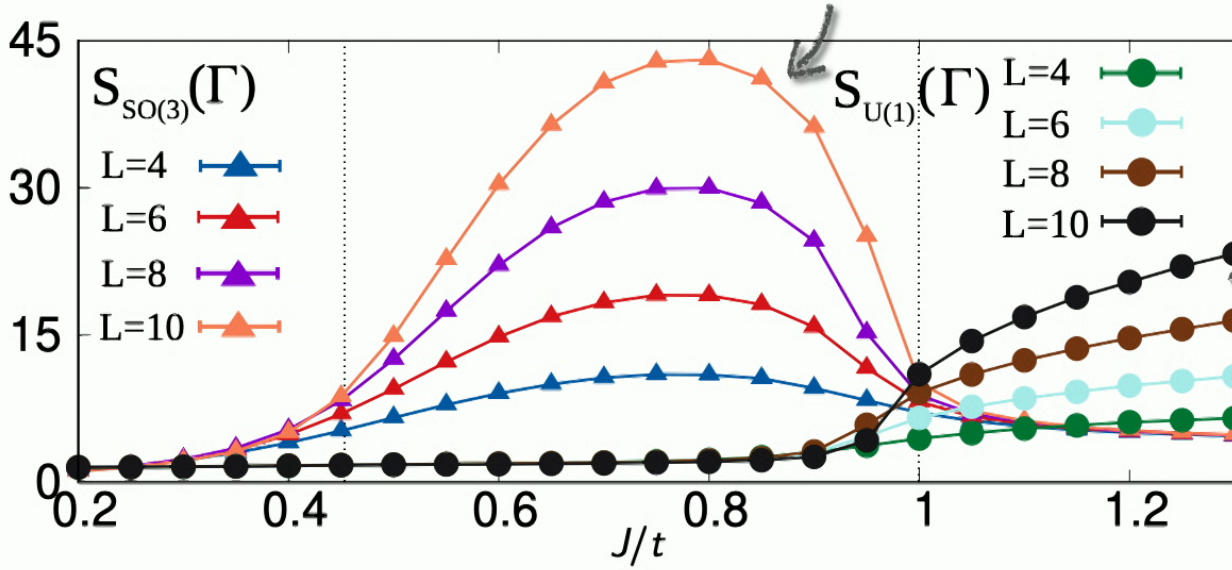
Hamiltonian:

$$\mathcal{H} = -t \sum_{\langle ij \rangle} c^\dagger_{i\lambda} c_{j\lambda} - J \sum_i \left(c^\dagger_{i\lambda} \vec{L} \tau^z_{\lambda\lambda'} c_{i\lambda'} \right)^2$$



... with SO(3) × $U_\lambda(1)$ × U_c × $\mathbb{Z}_2$ symmetry

QMC structure factors:



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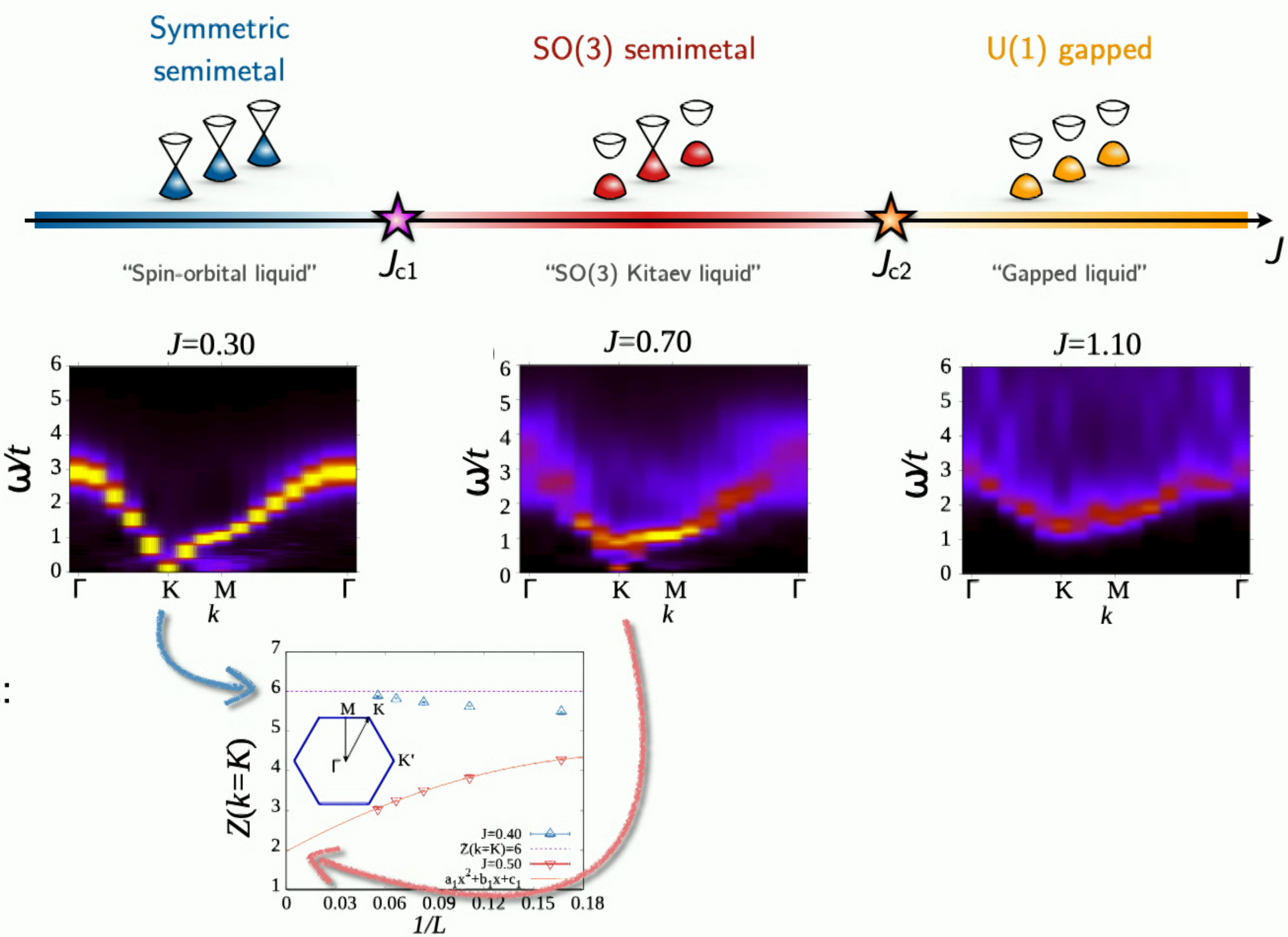
Sign-problem-free bilayer model

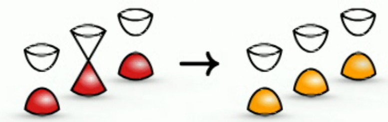
Phase diagram:

Fermion spectral function:

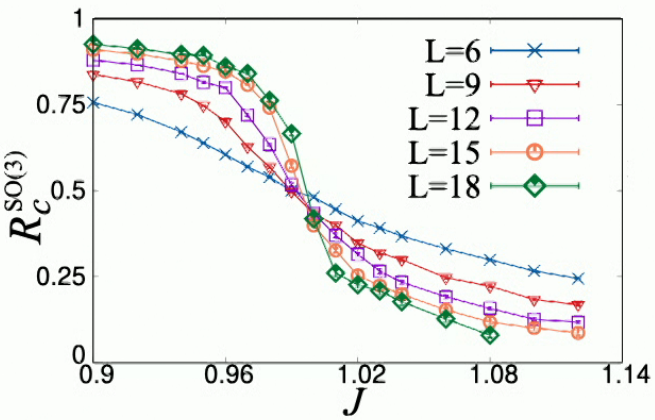
Quasiparticle weight:

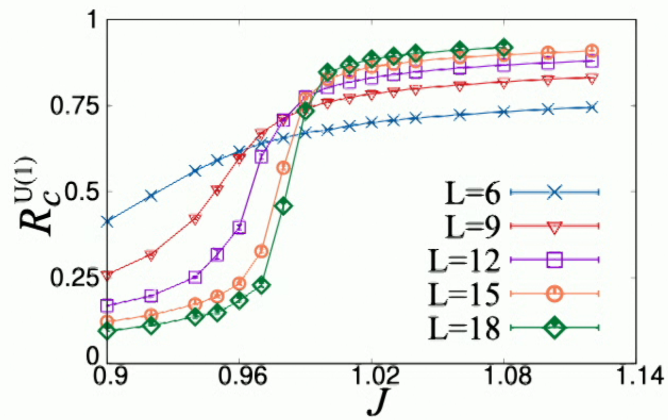


SO(3)-U(1) transition at J_{c2}

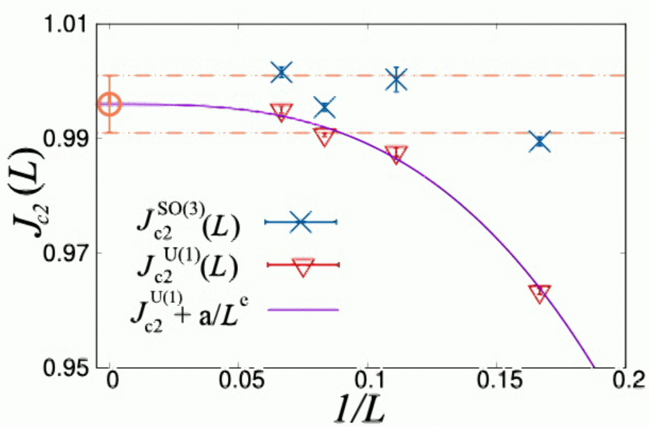


Correlation ratios:





Critical couplings:



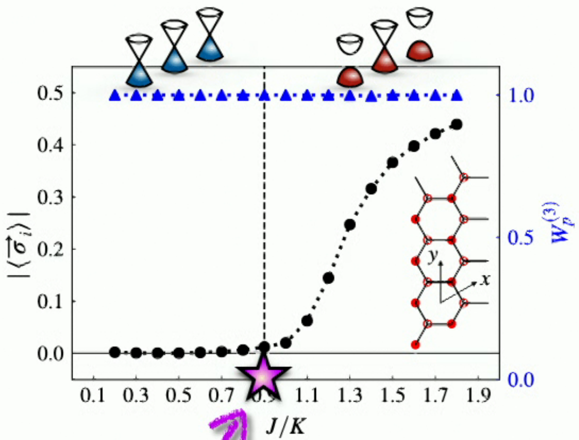
$\Rightarrow \quad J_{c2}^{SO(3)} = J_{c2}^{U(1)}$ unique!

Metallic deconfined QCP?

[Liu, Vojta, Assaad, LJ, PRL '22 (Editors' Suggestion)]

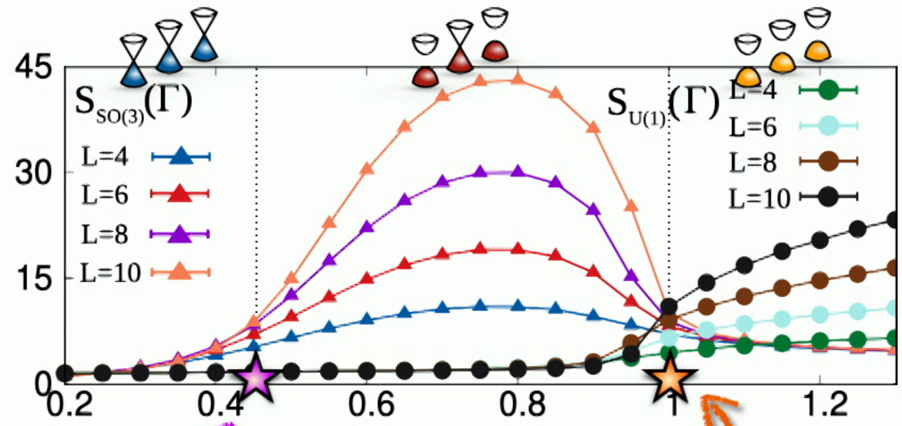
Conclusions

Kitaev-Heisenberg spin-orbital model:



Gross-Neveu-SO(3)*

Effective bilayer honeycomb model:



Gross-Neveu-SO(3)

Metallic deconfined QCP?

[Seifert, Dong, Chulliparambil, Vojta, Tu, LJ, PRL '20]

[Liu, Vojta, Assaad, LJ, PRL '22 (Editors' Suggestion)]