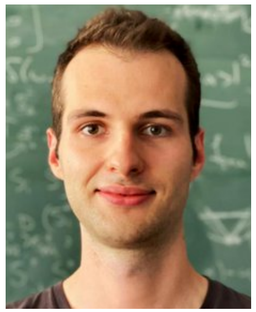
Fractionalized fermionic quantum criticality in spin-orbital Mott insulators

Lukas Janssen
(TU Dresden)

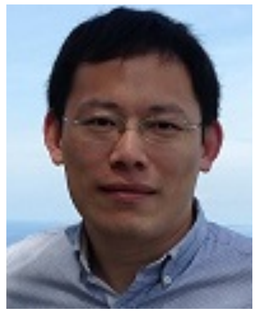


Urban Seifert

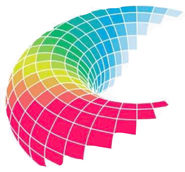
Xiao-Yu Dong

Sreejith Chulliparambil

Matthias Vojta



Hong-Hao Tu



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Complexity and Topology in Quantum Matter
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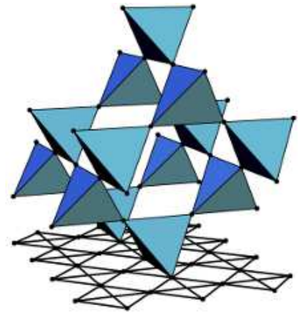


SFB 1143

Outline

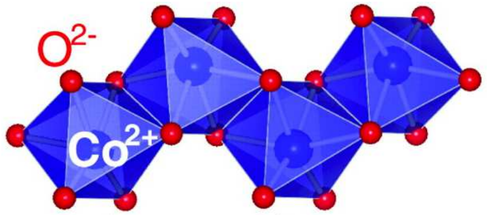
(1) Introduction: *"Beyond-Landau" quantum criticality*

(2) Spin-1/2: *Field-induced criticality in Kitaev materials*

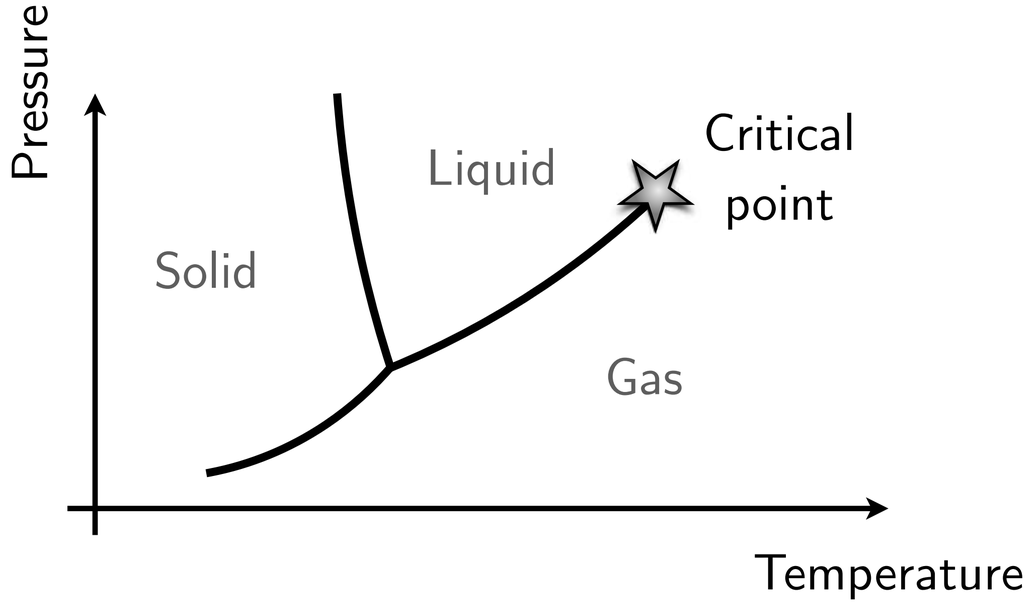
(3) Spin-3/2: *Fractionalized fermionic criticality in spin-orbital models*

(4) Conclusions

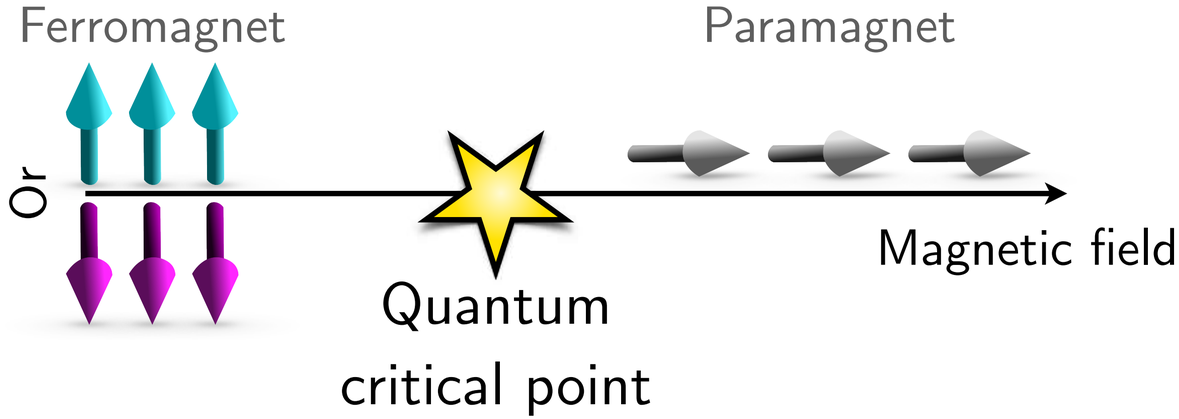
Classical vs quantum criticality



H_2O $\quad$ **$T > 0$**



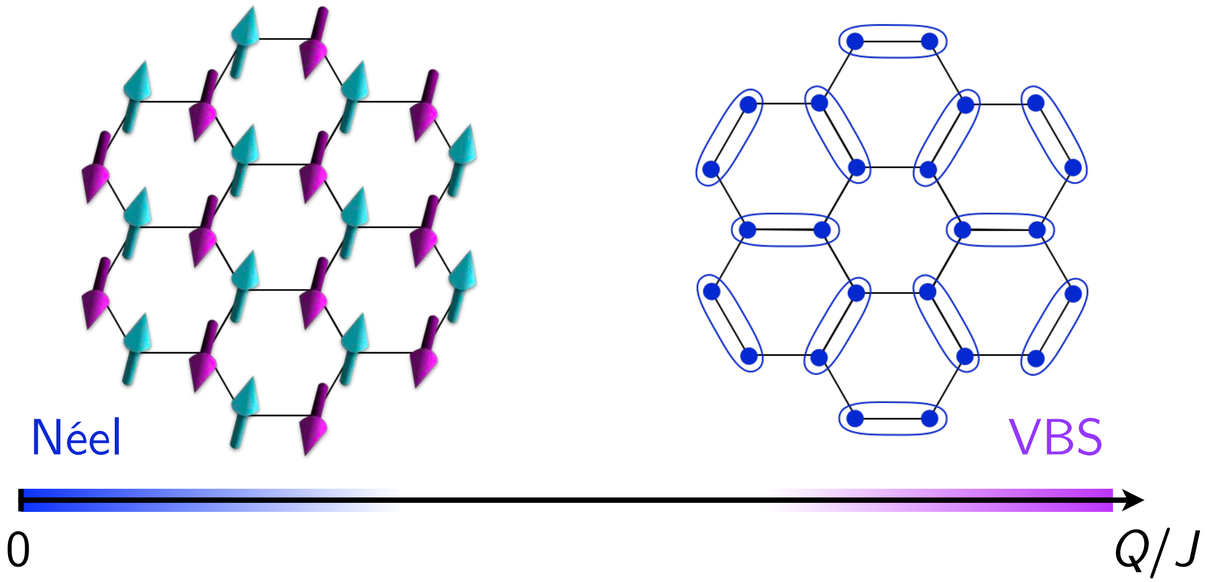
$CoNb_2O_6$ $\quad$ **$T \to 0$**



[Coldea *et al.*, Science '10]
[Kinross *et al.*, PRX '14]
...

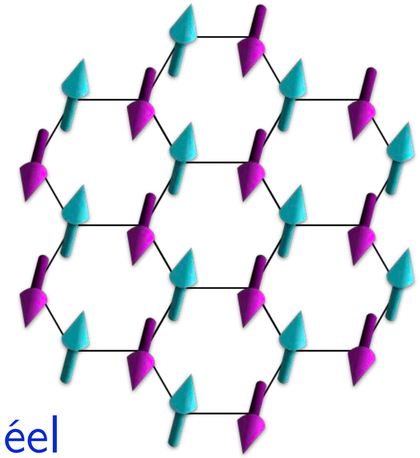
Deconfined quantum criticality

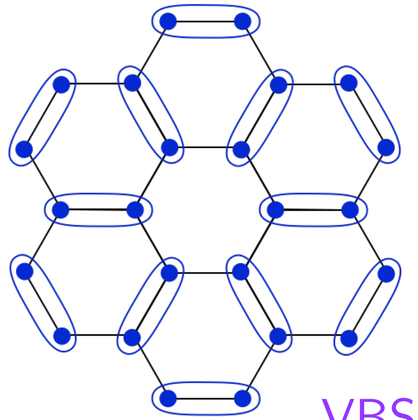
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$



Deconfined quantum criticality

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



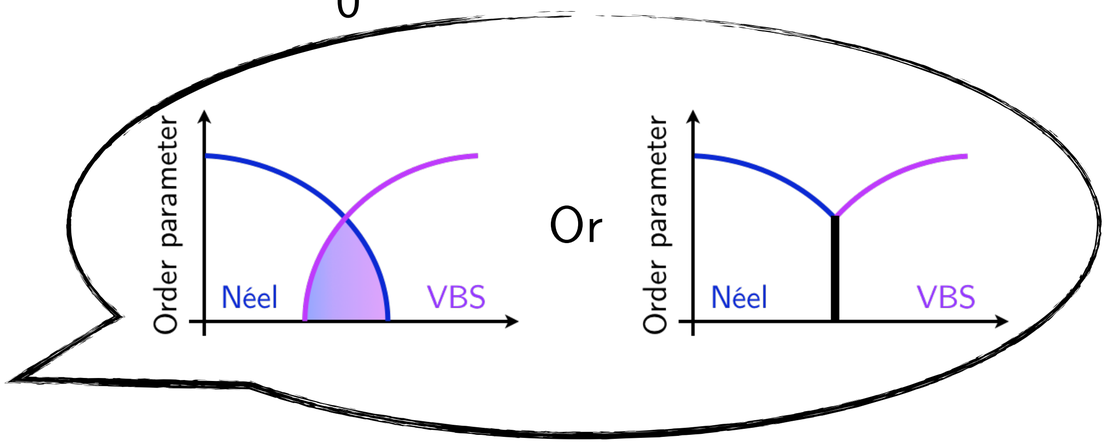


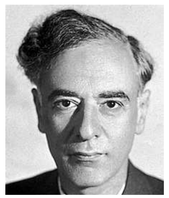
Néel

VBS

0

Q/J

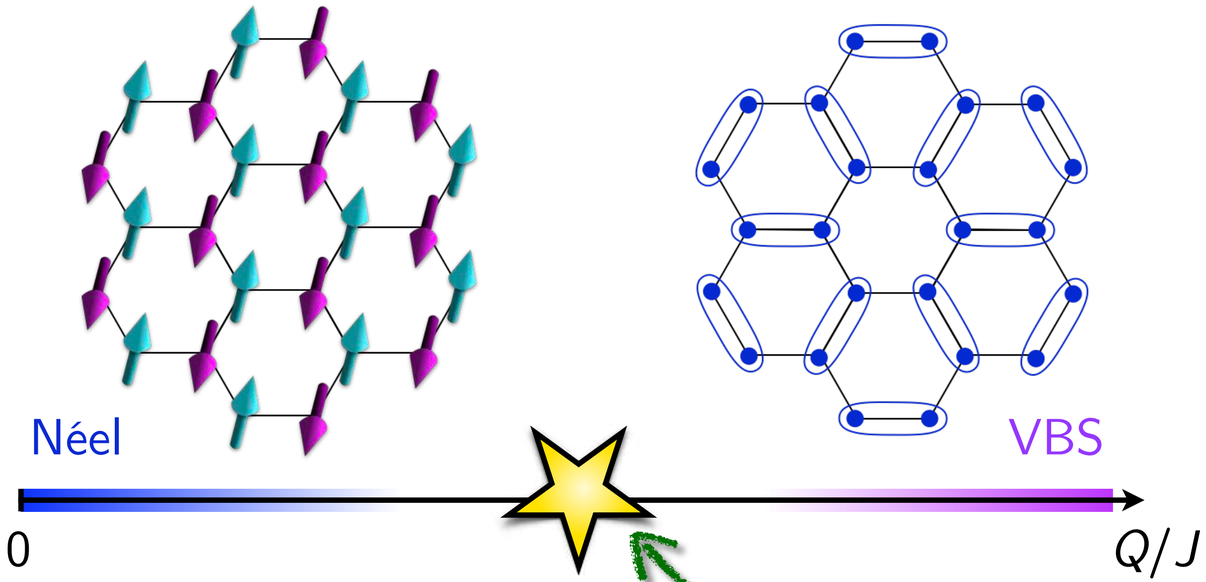


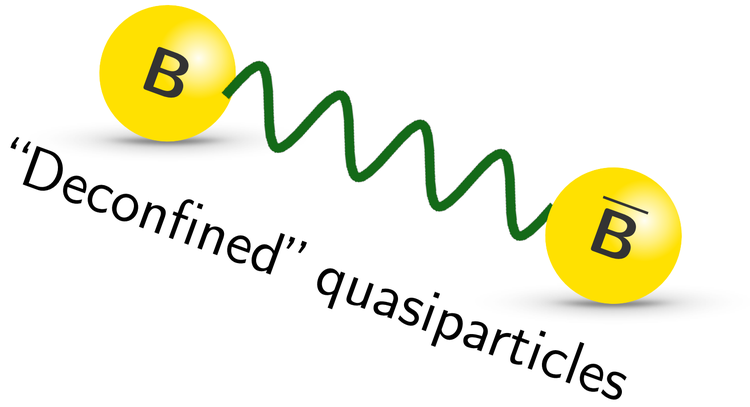


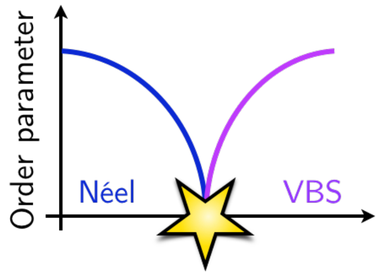
Landau

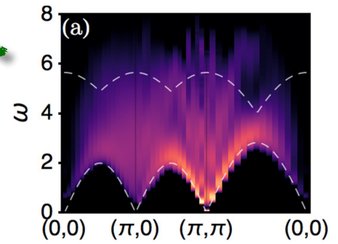
Deconfined quantum criticality

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





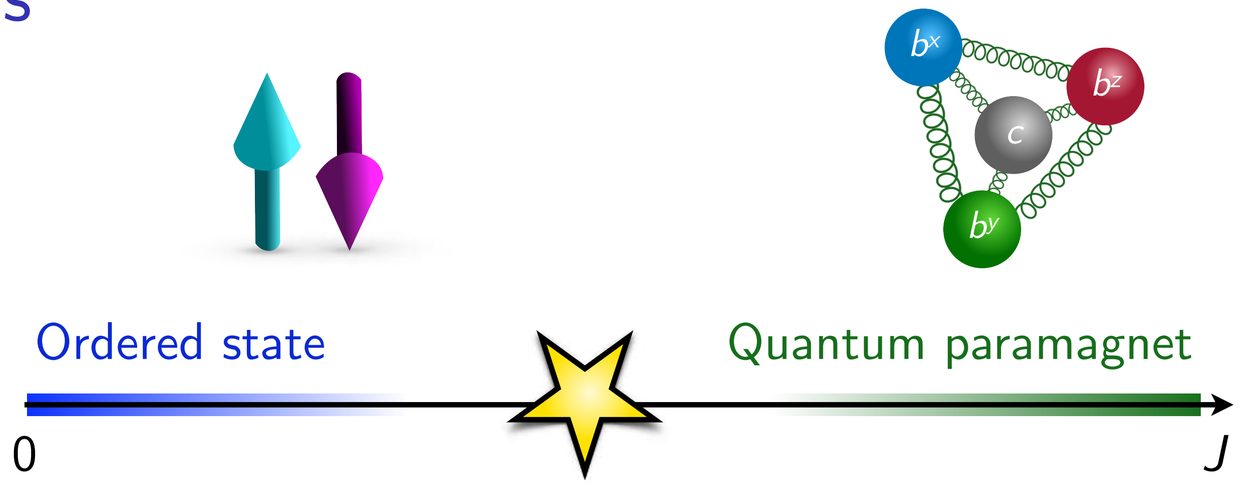




[Ma *et al.*, PRB '18]

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

Spin-liquid transitions



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

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

Outline

(1) Introduction: *"Beyond-Landau" quantum criticality*

(2) Spin-1/2: *Field-induced criticality in Kitaev materials*

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(4) Conclusions

Frustrated magnets

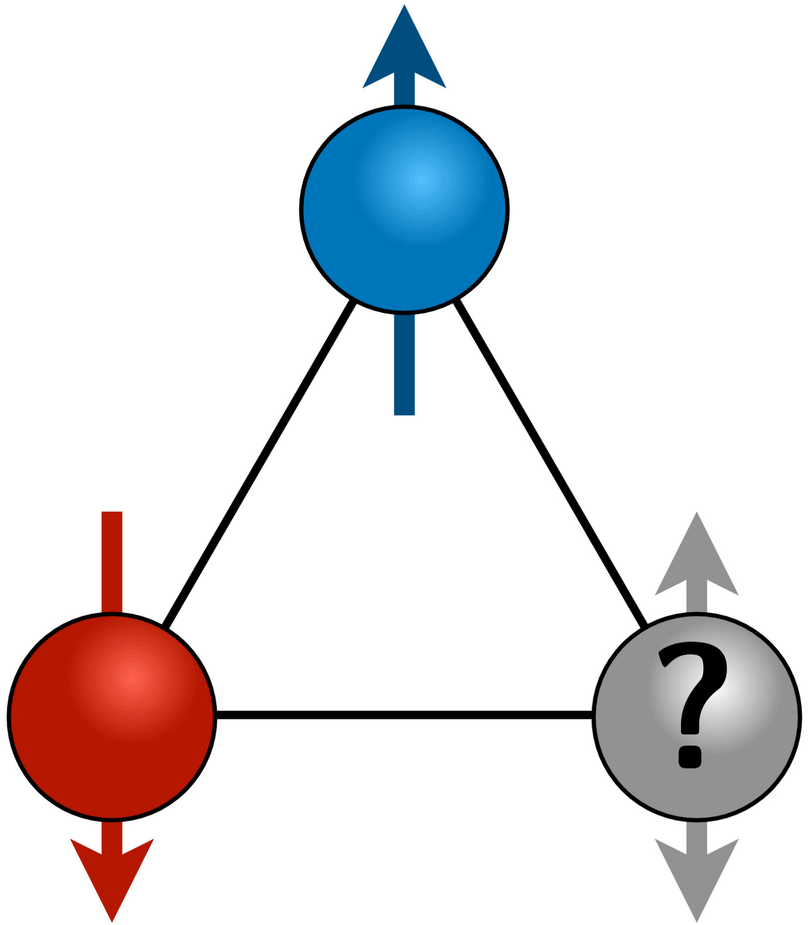
Frustration:

Not all local constraints can be simultaneously satisfied

Consequences:

Classical: Exponentially large ground-state manifold

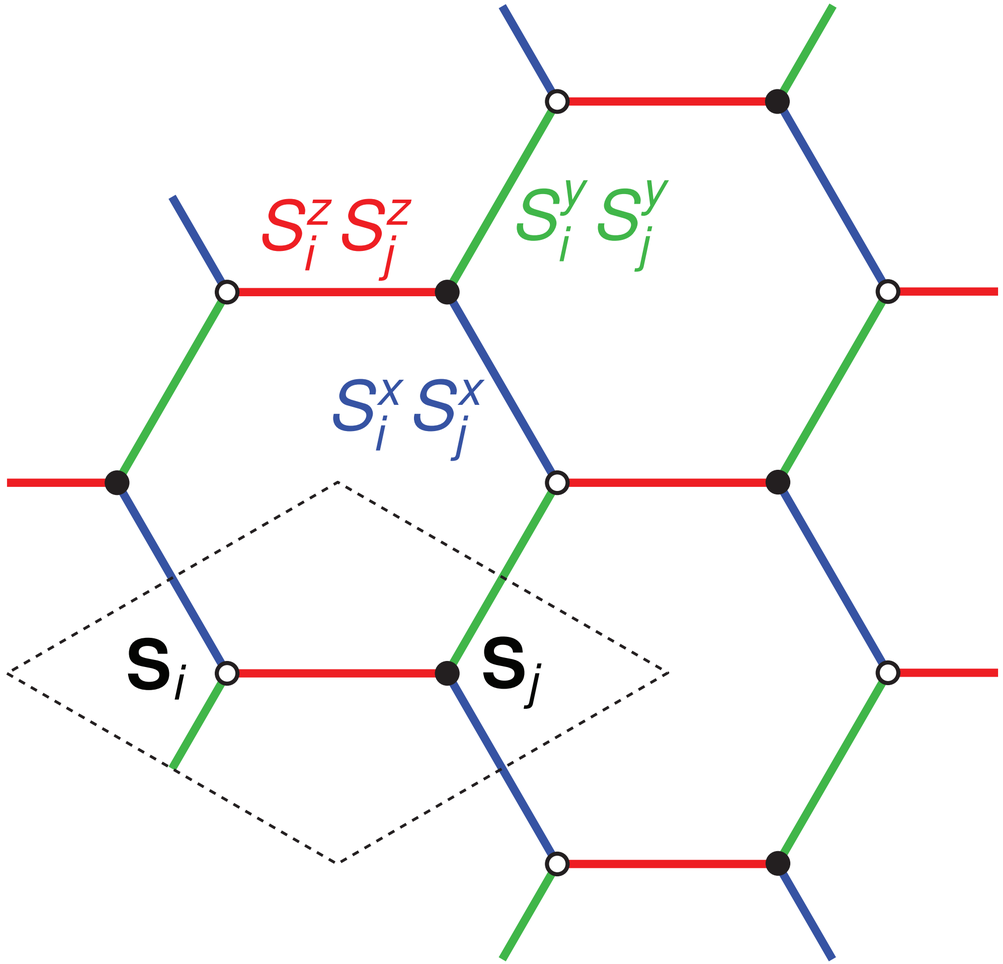
Quantum: New phases of matter?



Antiferromagnetic coupling of 3 Ising spins

Kitaev honeycomb model

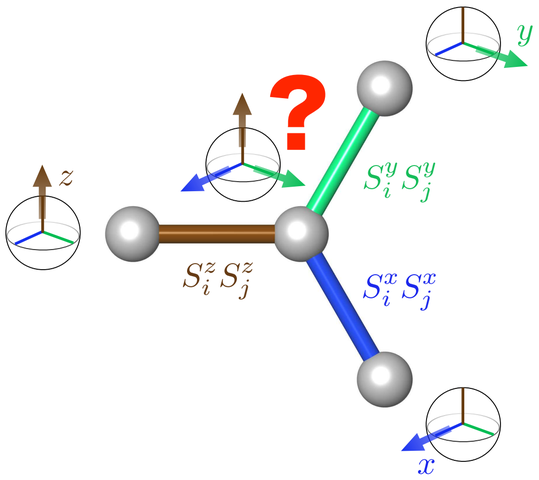
Spin-1/2 on honeycomb lattice:



Alexei Kitaev

Hamiltonian:

$$H = -K_x \sum_{\text{blue links}} \sigma_i^x \sigma_j^x - K_y \sum_{\text{green links}} \sigma_i^y \sigma_j^y - K_z \sum_{\text{red links}} \sigma_i^z \sigma_j^z$$



Exchange frustration

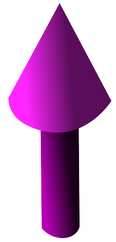
[Kitaev, Ann. Phys. '06]

Review: [Trebst, arXiv:1701.07056]

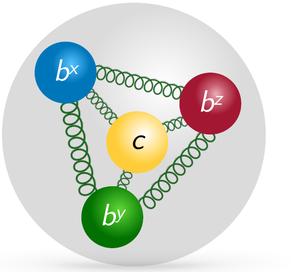
Parton construction

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

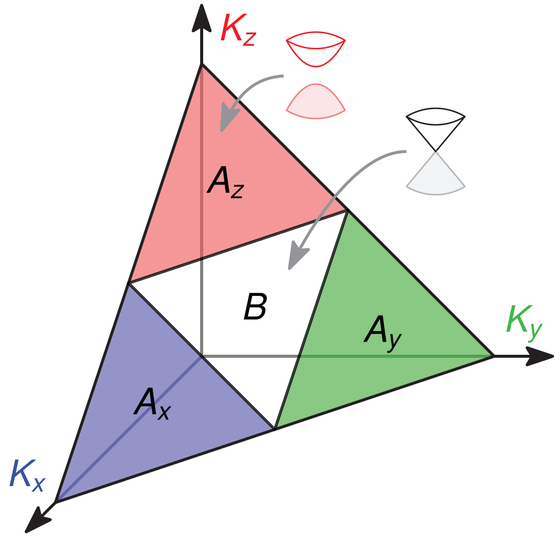
Fractionalization:

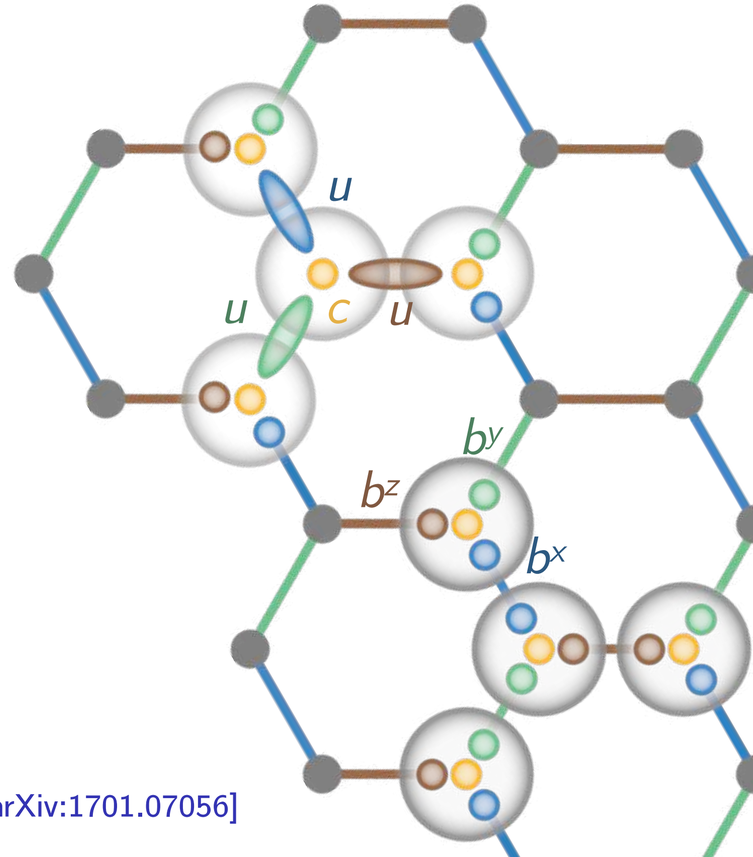
$$H \mapsto \tilde{H} = -i \sum_{\langle ij \rangle_\gamma} K_\gamma \underbrace{(i b_i^\gamma b_j^\gamma)}_{\equiv \hat{u}_{ij} = \hat{u}_{ij}^\dagger} c_i c_j$$

static!

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

Fermion spectrum:

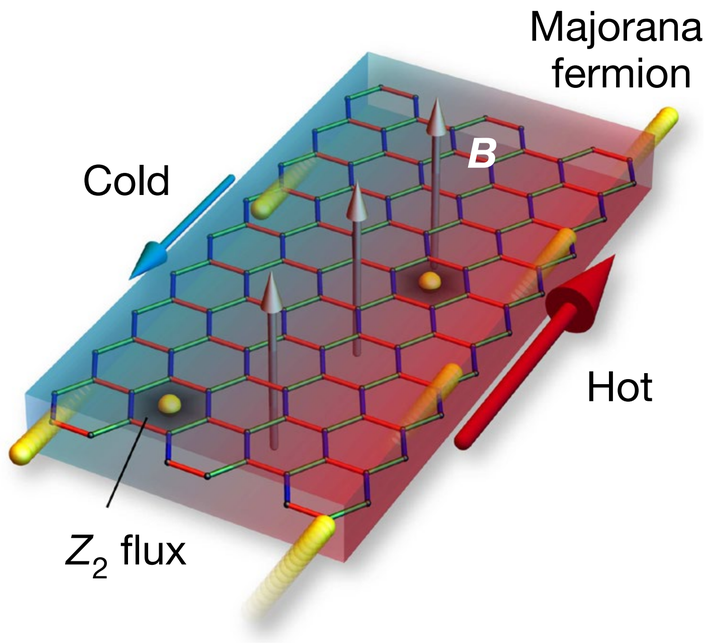


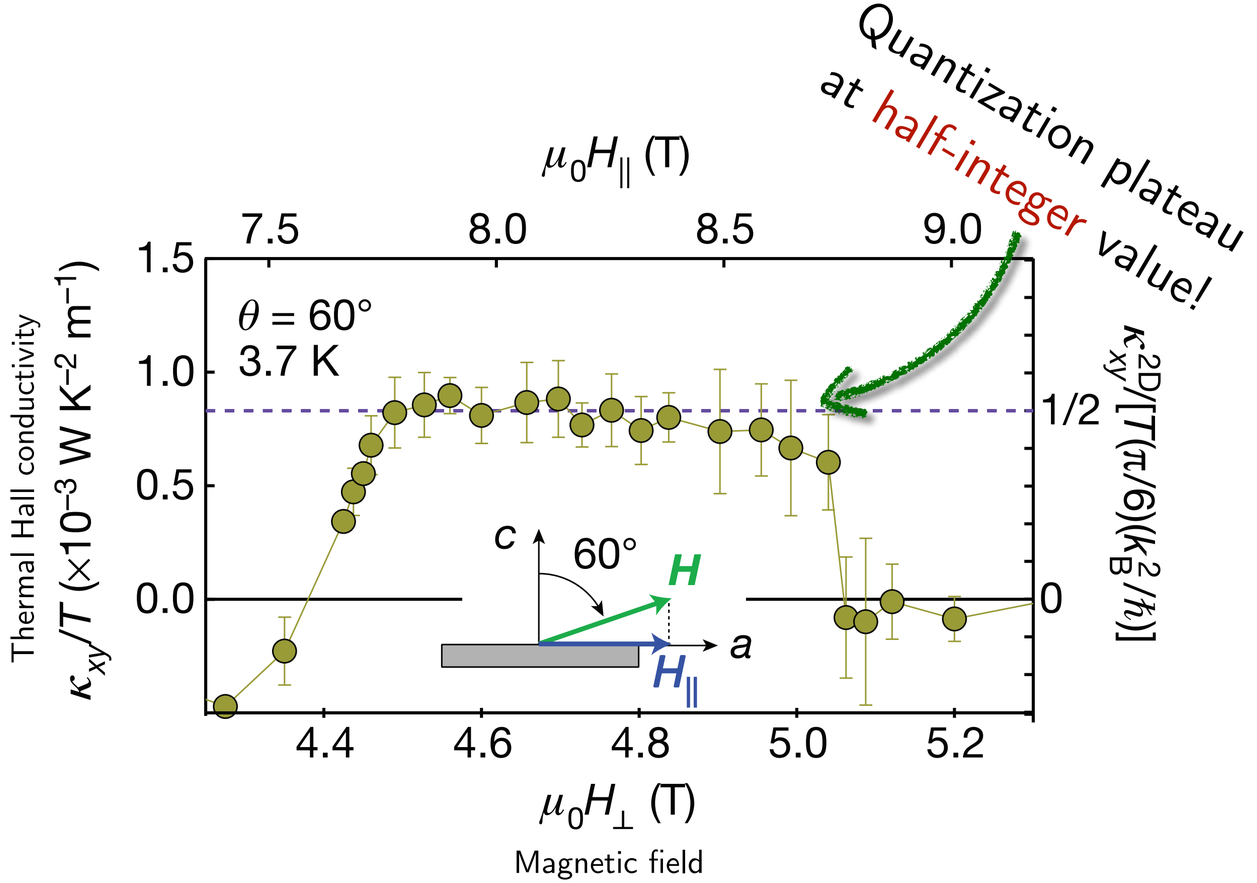


Review: [Trebst, arXiv:1701.07056]

Experimental search: α-$RuCl_3$ in field

Half-integer thermal Quantum Hall effect:





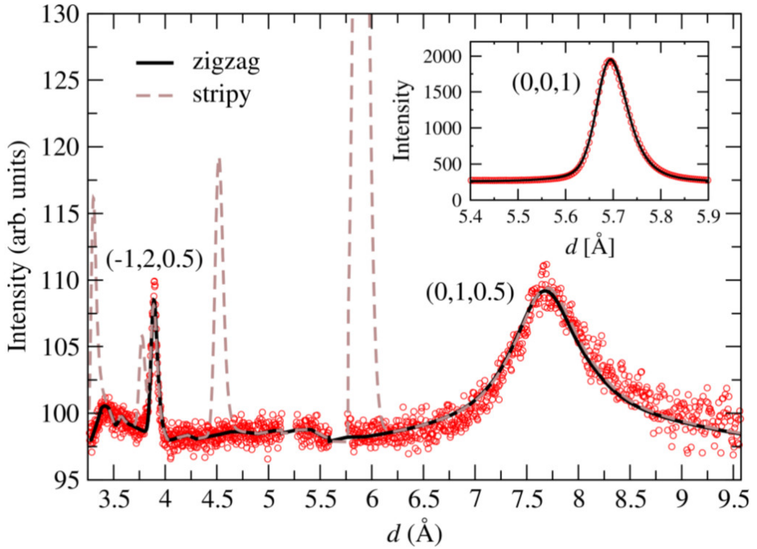
[Kasahara *et al.*, Nature '18]

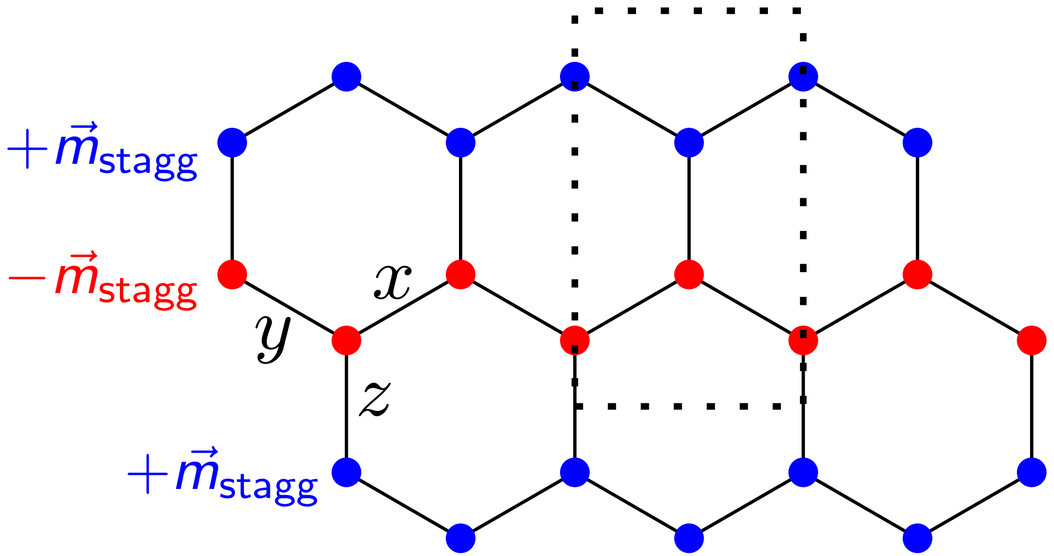
Topical Review: [LJ & Vojta, JPCM '19]

Smoking-gun signature of Majorana edge states?

α-$RuCl_3$ in zero field: Zigzag antiferromagnet

Neutron diffraction: [Johnson *et al.*, PRB '15]



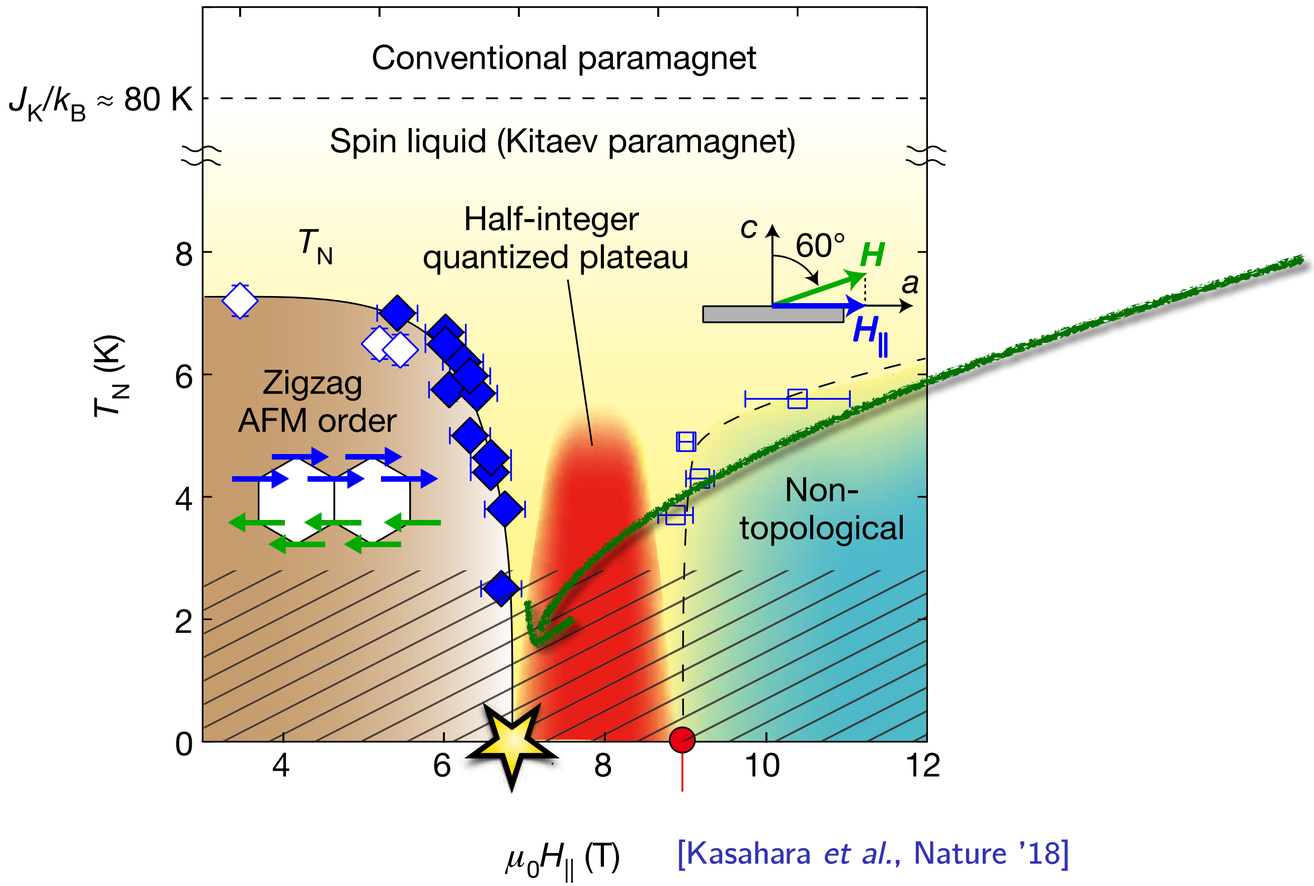


Extended Heisenberg-Kitaev models:

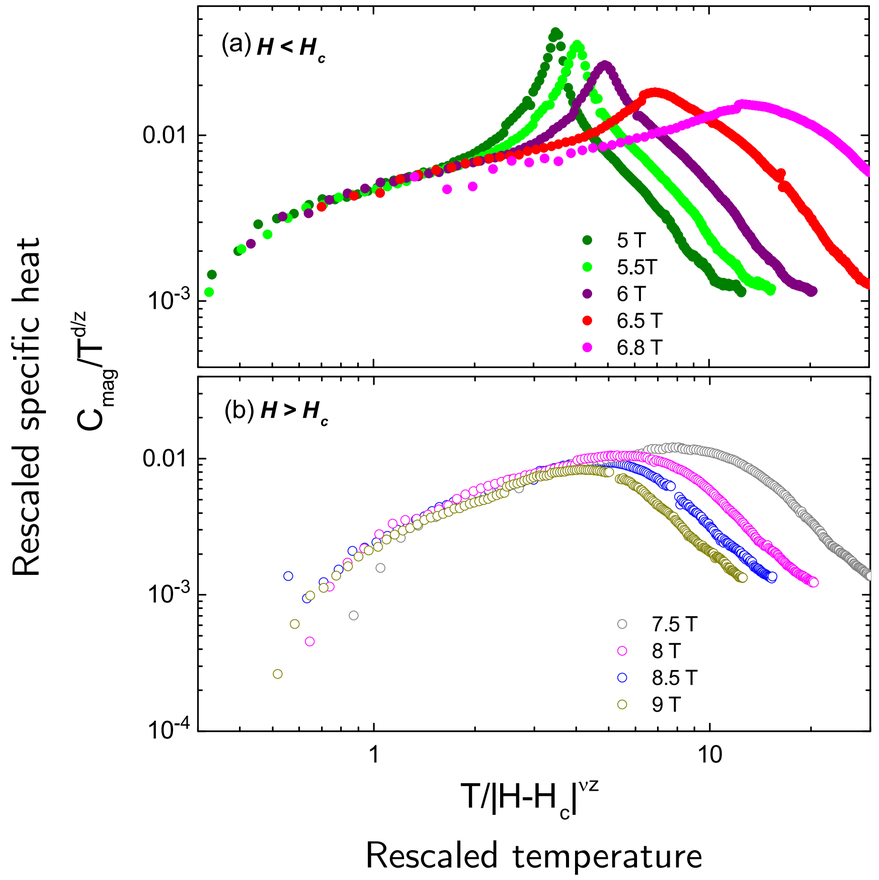
$$\mathcal{H} = \sum_{\langle ij \rangle} \left[J_1 \vec{S}_i \cdot \vec{S}_j + K_1 S_i^\gamma S_j^\gamma + \Gamma_1 (S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha) \right] + \sum_{\langle\langle\langle ij \rangle\rangle\rangle} J_3 \vec{S}_i \cdot \vec{S}_j + \dots$$

[Winter *et al.*, PRB '16]
[LJ, Andrade, Vojta, PRB '17]
[Kaib, Winter, Valentí, PRB '19]
[LJ, Koch, Vojta, PRB '20]
[Maksimov & Chernyshev, PRR '20]
...

α-$RuCl_3$: Field-induced quantum criticality



[Kasahara *et al.*, Nature '18]



... with $z \approx 1$ and $\nu \approx 0.7$

[Wolter, Corredor, LJ, *et al.*, PRB '17]

Fractionalized transition?

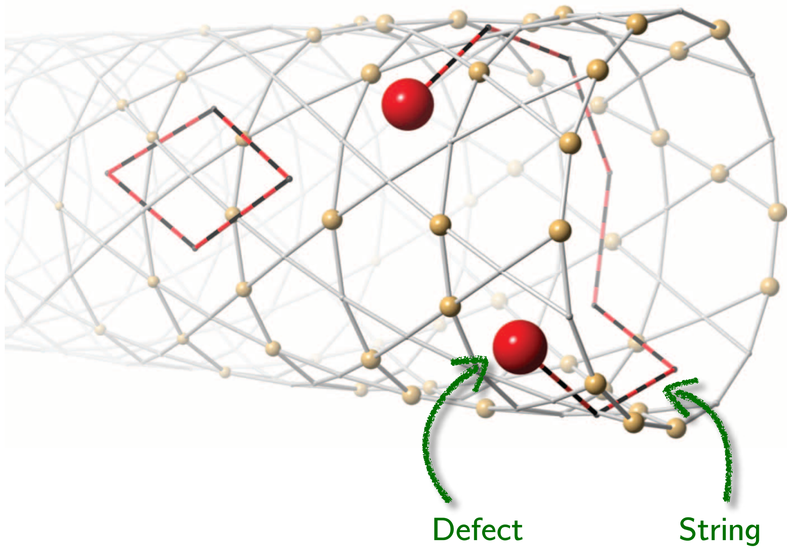
Fractionalized quantum criticality: XY*

Bose-Hubbard-like model (kagome lattice):

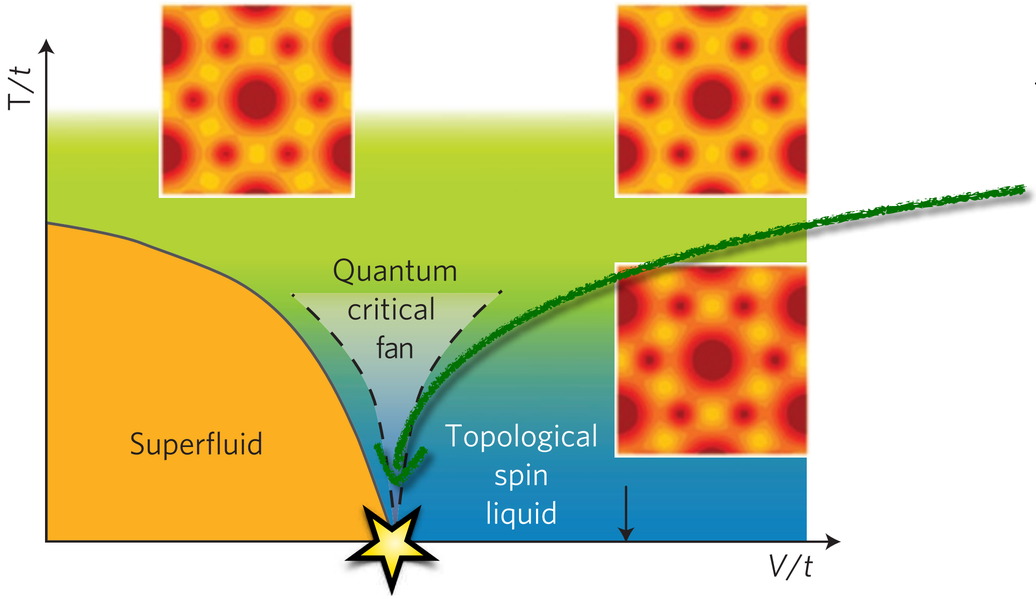
$$\mathcal{H} = -t \sum_{\langle ij \rangle} \left[b_i^\dagger b_j + b_i b_j^\dagger \right] + V \sum_{\hexagon} (n_{\hexagon})^2$$

Hopping bosons

Boson density in plaquette

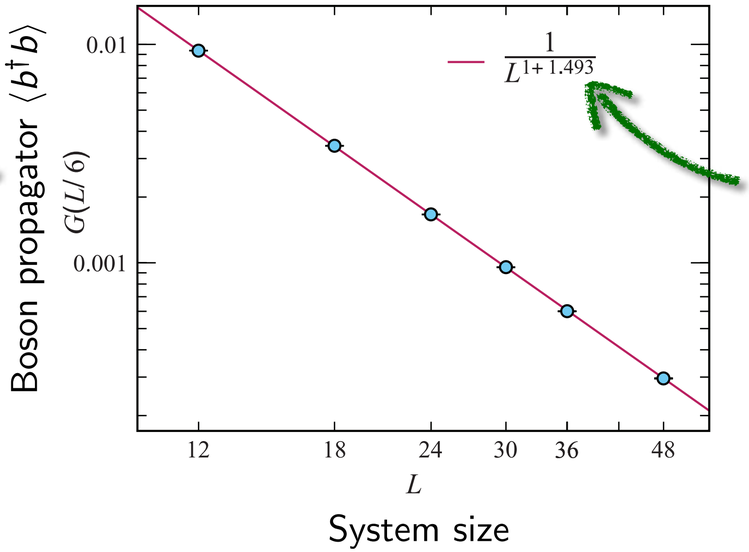


Phase diagram:



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

$V/t = (V/t)_c$



$\eta \approx 1.493$ (!)

... anomalous dimension of composite field

but $\nu \approx 0.67$

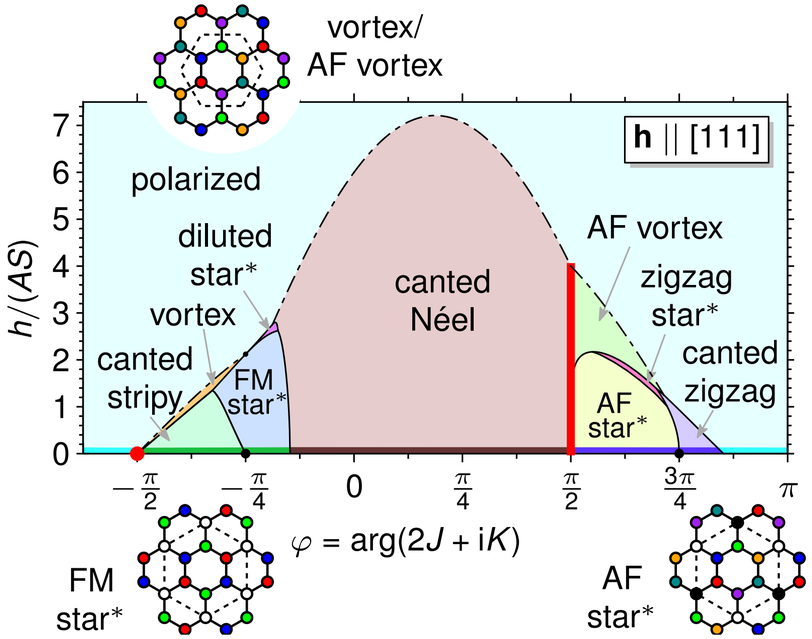
... as in conventional XY

[Isakov, Melko, Hastings, Science '12]

[Chubukov, Senthil, Sachdev, PRL '94]

Heisenberg-Kitaev models in field

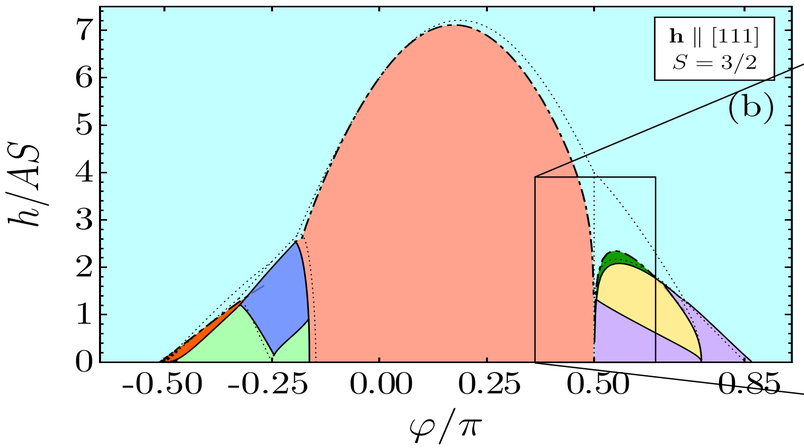
Classical ($S \to \infty$)



[LJ, Andrade, Vojta, PRL '16]

... linear spin-wave theory
& classical Monte Carlo

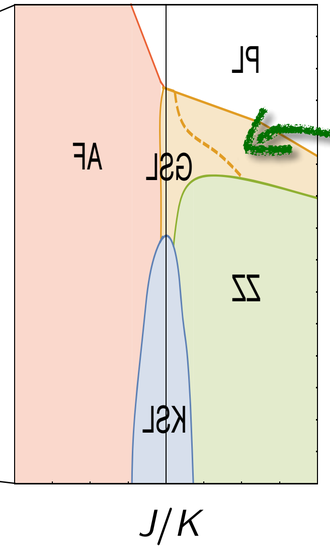
Semiclassical ($S = 3/2$)



[Consoli, LJ, Vojta, Andrade, PRB '20]

... nonlinear spin-wave theory

Quantum ($S = 1/2$)



Field-induced
spin liquid (!)

[Hickey & Trebst, Nat. Commun. '19]

... 24-site ED

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

... no sign-problem-free QMC available

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Generalizations of Kitaev model: Spin-orbital liquids

Spin + orbital + ... degrees of freedom:

$\sigma^\alpha \quad 2 \times 2$ $\qquad$ $\sigma^\alpha \otimes \tau^\beta = \gamma^i \quad 4 \times 4$ $\qquad$ ... $\qquad$ $\Gamma^\mu \quad 8 \times 8$

... can realize all 16 $\mathbb{Z}_2$ topological superconductors
[Chulliparambil, ..., LJ, Tu, arXiv:2005.13683]

Example #1 (square lattice):

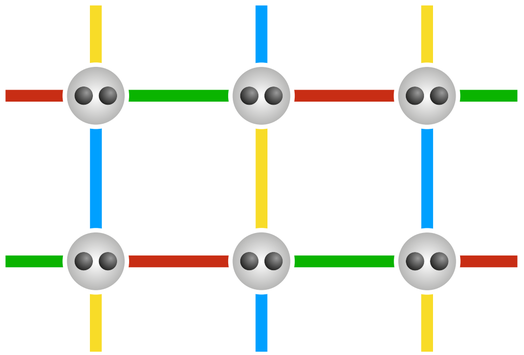
XY spin $\qquad$ Kitaev orbital

$$H_K = -K \sum_{\langle ij \rangle_\gamma} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) \otimes \tau_i^\gamma \tau_j^\gamma$$

Majorana representation:

$$\sigma^y \otimes \tau^x = i b^1 c^x$$
$$\sigma^y \otimes \tau^y = i b^2 c^x$$
$$\sigma^y \otimes \tau^z = i b^3 c^x$$
$$\sigma^x \otimes \mathbb{1} = i b^4 c^x$$
$$\sigma^z \otimes \mathbb{1} = i c^y c^x$$

... recover known model for $j = 3/2$ spin liquid:
[Yao, Zhang, Kivelson, PRL '09]
[Nakai, Ryu, Furusaki, PRB '12]

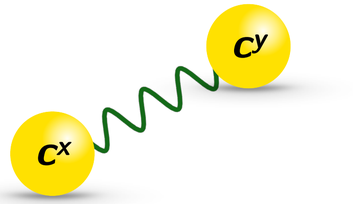


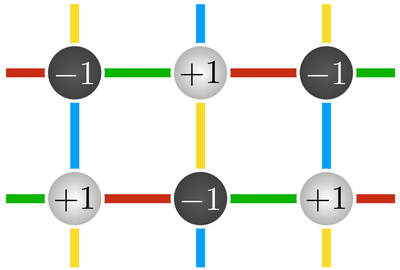
2 itinerant fermions

Static perturbations

"Heisenberg-Kitaev" spin-orbital model:

$$H = H_K + J^z \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z \otimes \mathbb{1}_i \mathbb{1}_j$$





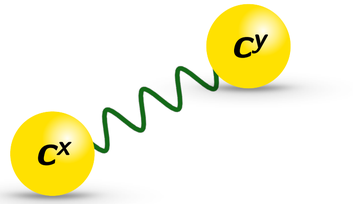
"Kitaev" spin-orbital liquid

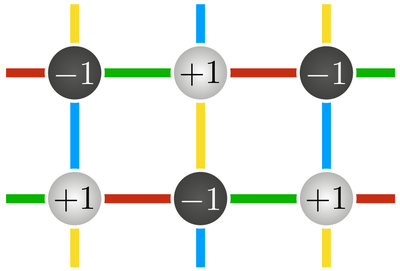
Ising spin order

Static perturbations

"Heisenberg-Kitaev" spin-orbital model:

$$H = H_K + J^z \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z \otimes \mathbb{1}_i \mathbb{1}_j$$





"Kitaev" spin-orbital liquid

Ising spin order

Parton representation:

hopping parameter $t = 2K$

π flux

nearest-neighbor repulsion $V = 4J^z$

$$H \mapsto \sum_{\langle ij \rangle} \left[2K u_{ij} (f_i^\dagger f_j + f_j^\dagger f_i) + 4J^z (n_i - \tfrac{1}{2})(n_j - \tfrac{1}{2}) \right]$$

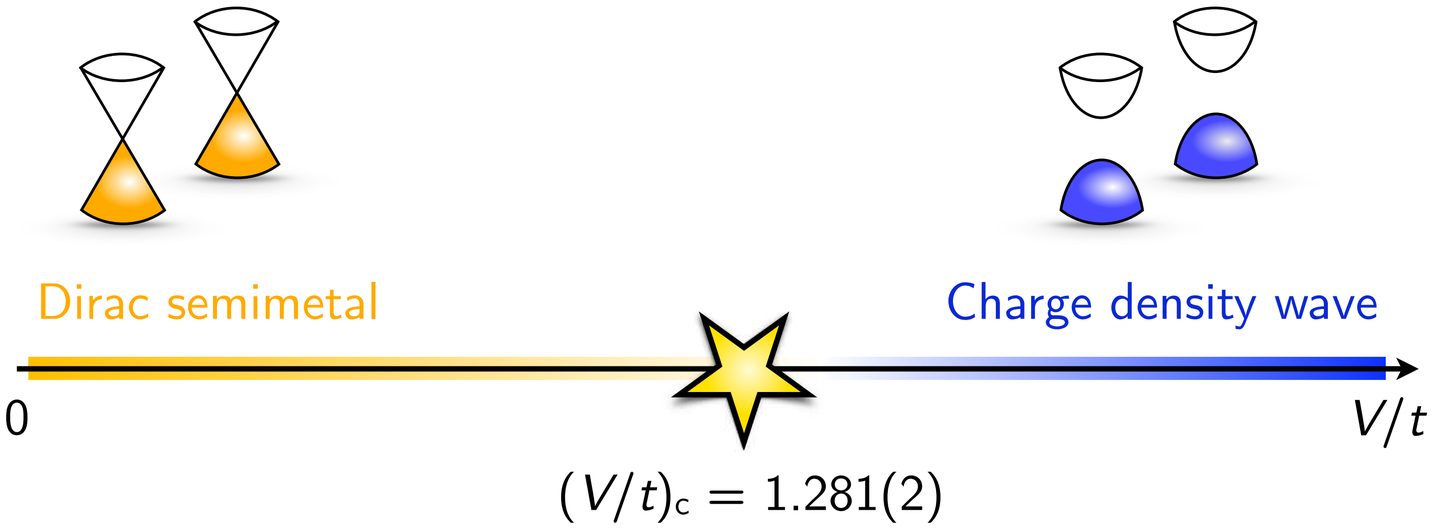
$f = \frac{1}{2}(c^x + ic^y)$

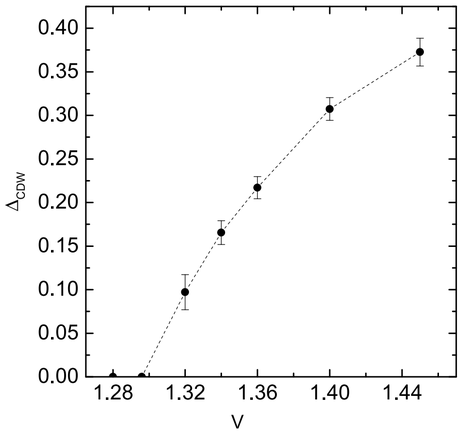
electron density $f^\dagger f$

Ground-state flux pattern:
[Lieb, PRL '94]

Spin-orbital model $\mapsto$ interacting fermions on π-flux lattice

Spinless fermions on π-flux lattice: QMC





[Wang, Corboz, Troyer, NJP '14]
[Li, Jiang, Yao, NJP '15]
[Huffman & Chandrasekharan, PRD '17; PRD '20]

Gross-Neveu-$\mathbb{Z}_2$ universality: $1/\nu = 1.12(1), \quad \eta_\phi = 0.51(3), \quad \eta_\psi \approx 0.1$

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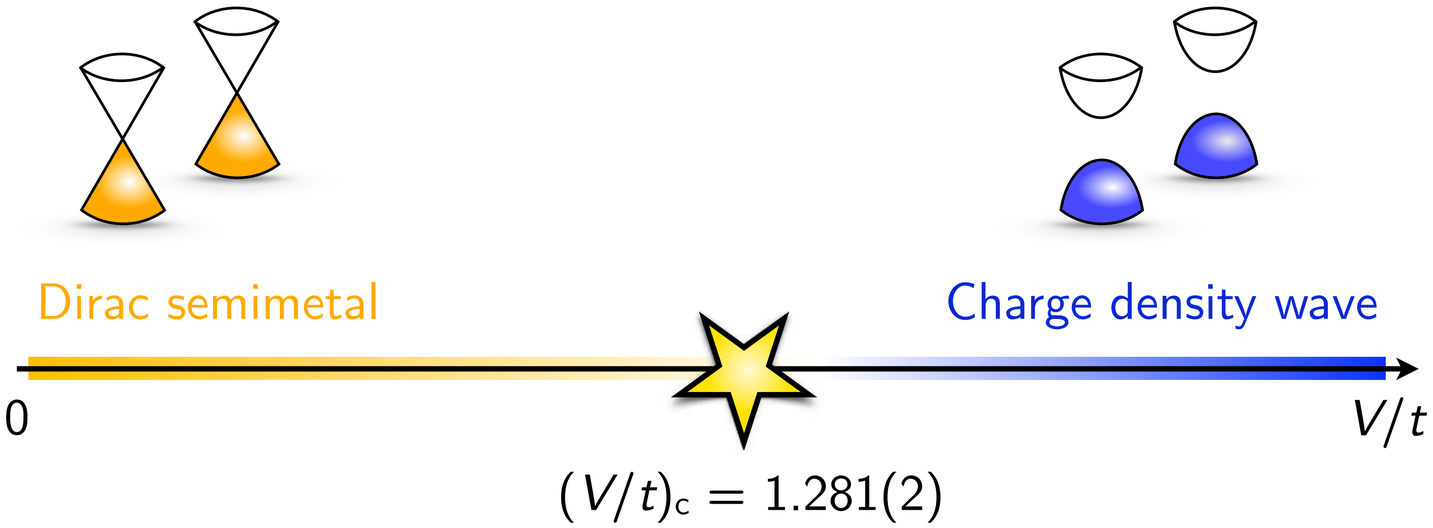

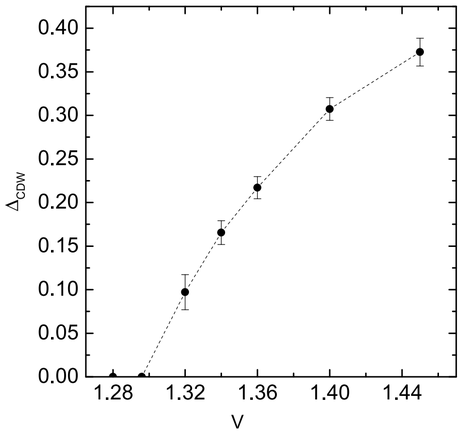

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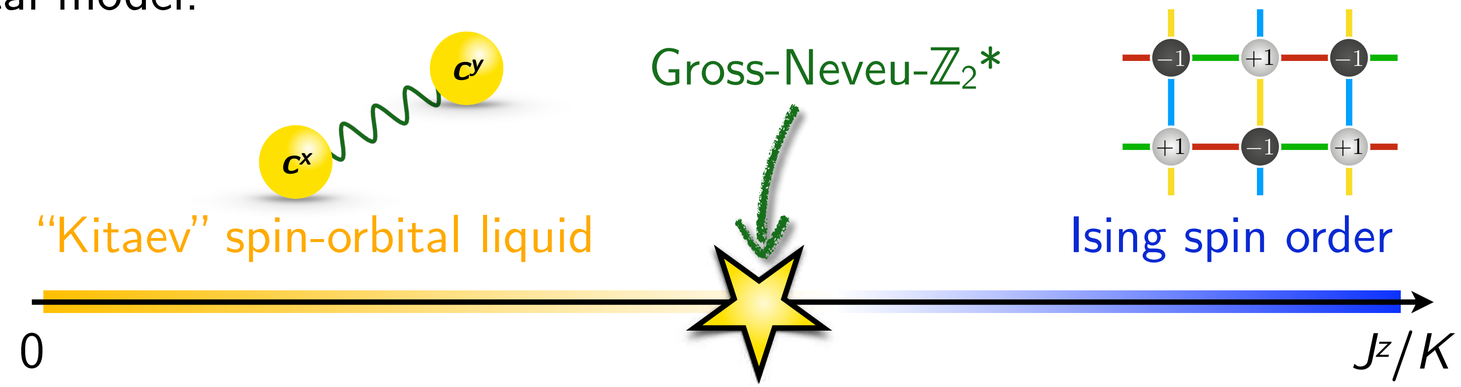
Spin-orbital model:

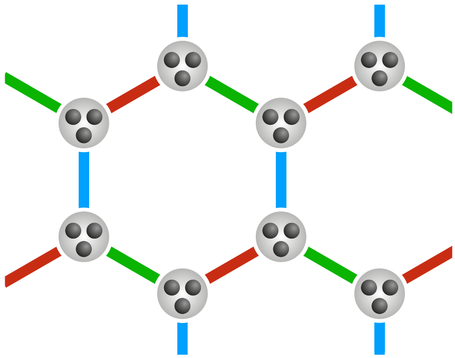


[Seifert, Dong, Chulliparambil, Vojta, Tu, LJ, arXiv:2009.05051]

Fractionalized fermionic universality classes

Example #2 (honeycomb lattice):

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



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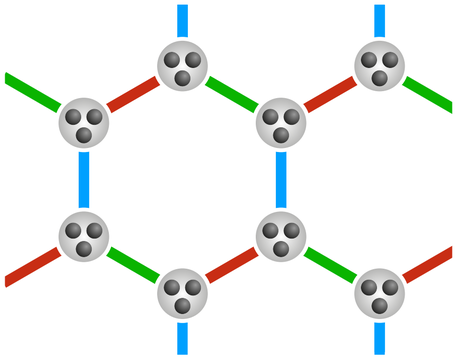

3 itinerant fermions

Majorana representation:

$c \equiv \begin{pmatrix} c^x \\ c^y \\ c^z \end{pmatrix}$ spin-1 matrices

$$H \mapsto \sum_{\langle ij \rangle} \left[K i u_{ij} c_i^\top c_j + \frac{J}{4} (c_i^\top \vec{L} c_i) \cdot (c_j^\top \vec{L} c_j) \right]$$

0 flux

Ordered state:

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

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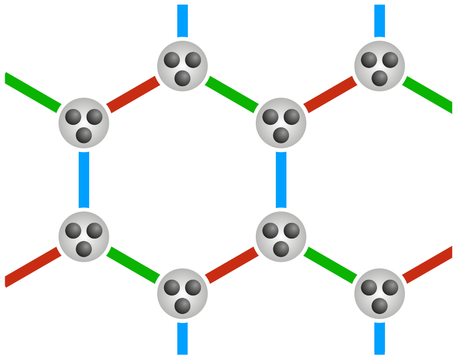

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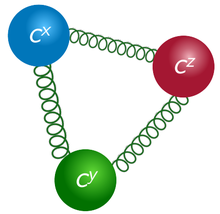
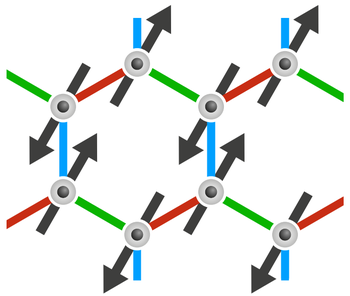


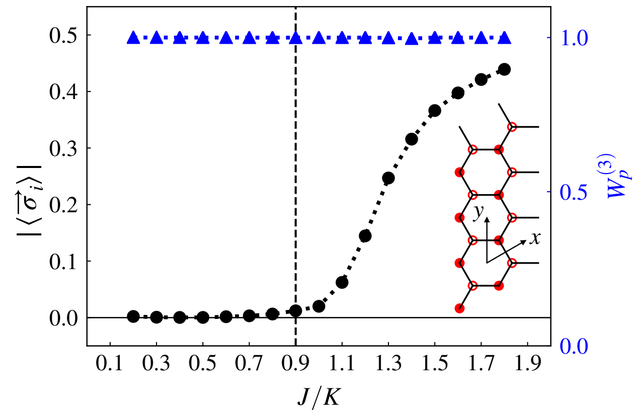


"Kitaev" spin-orbital liquid

Néel spin order

$(J/K)_c = 0.9(2)$

DMRG:



[Seifert, Dong, Chulliparambil, Vojta, Tu, LJ, arXiv:2009.05051]

Effective field theory: Gross-Neveu-SO(3)

Action:

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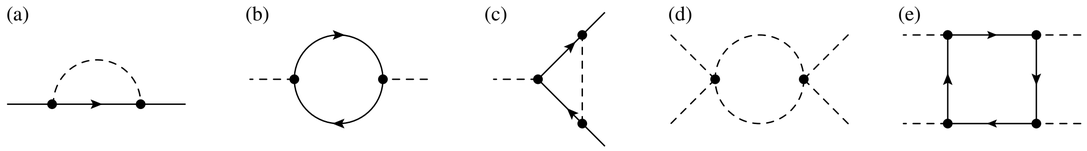
4 - ε expansion:



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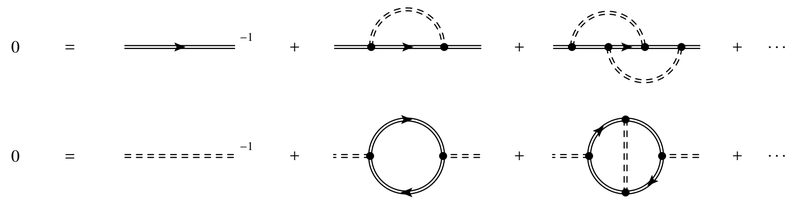
$1/N$ expansion:



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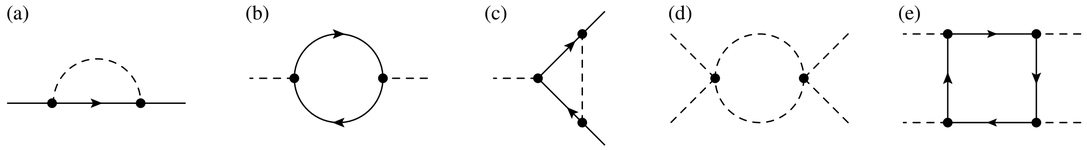

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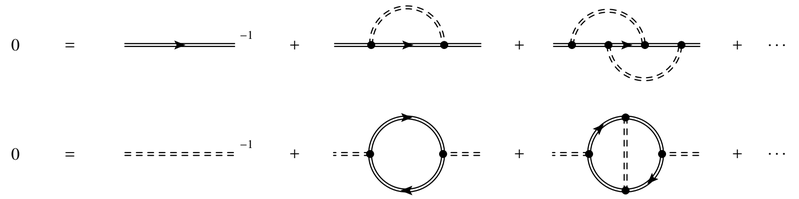

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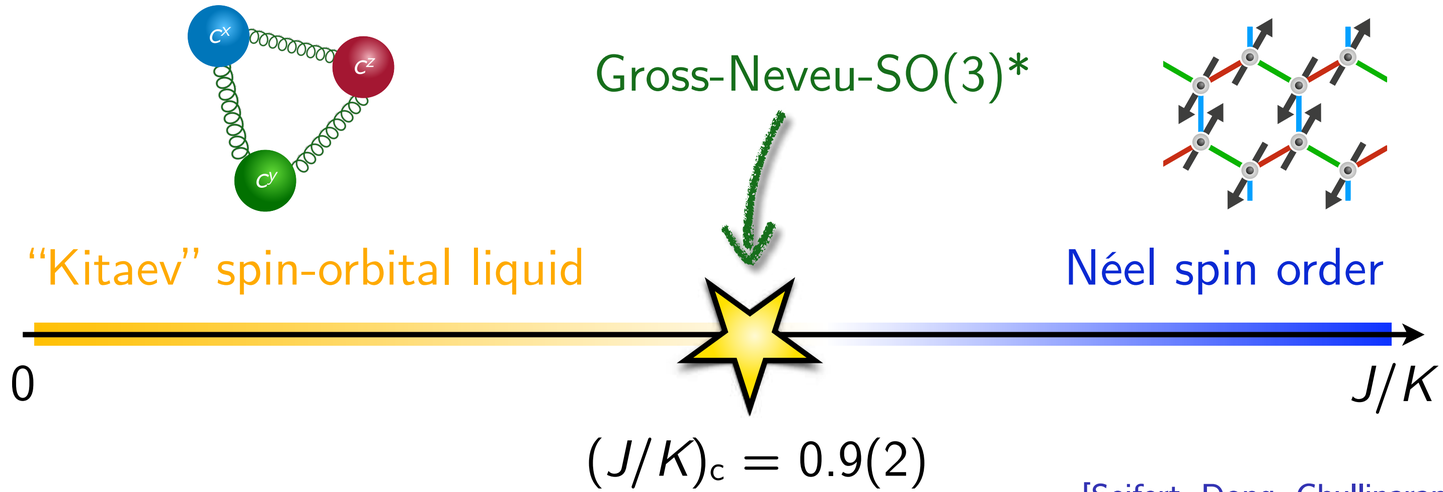

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Finite-size spectroscopy: Ising vs Ising*

Transverse-field Ising:

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

Transverse-field toric code:

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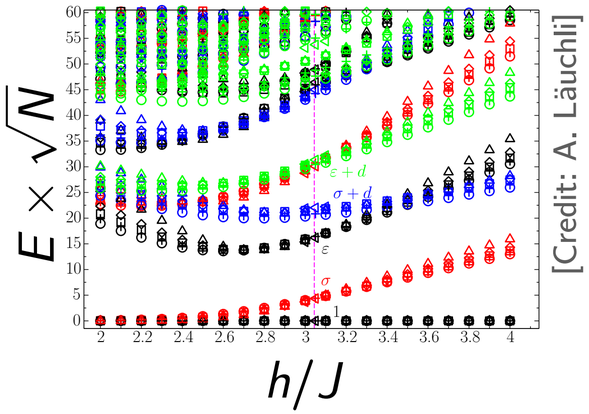
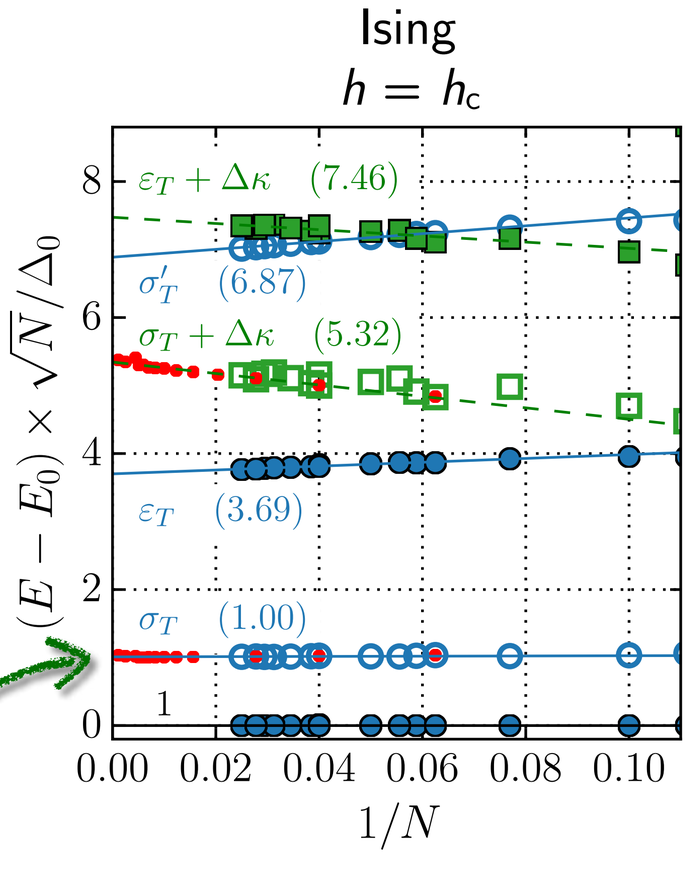


[Credit: A. Läuchli]



missing in Ising*

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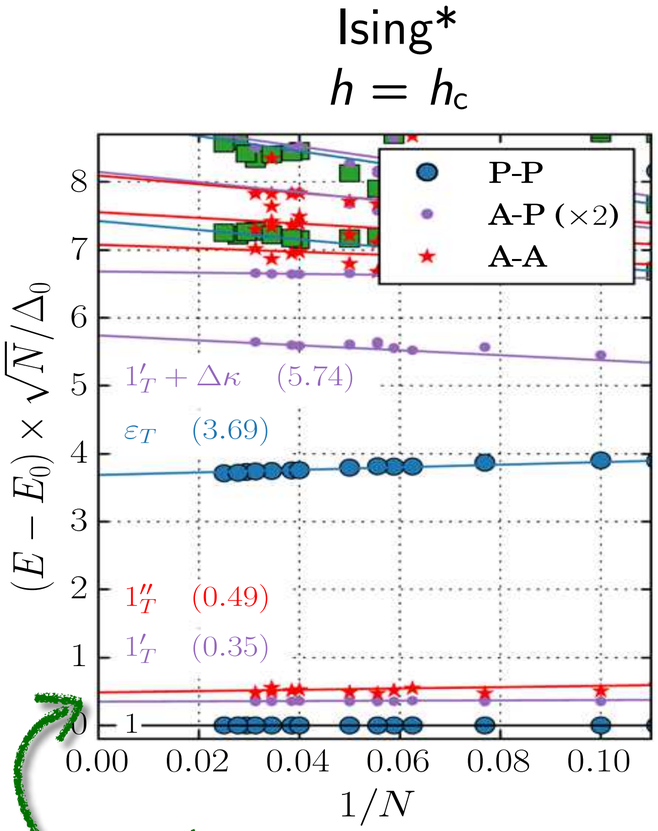
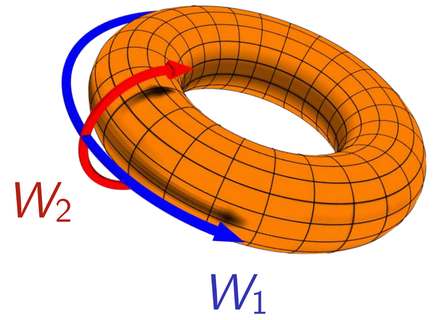


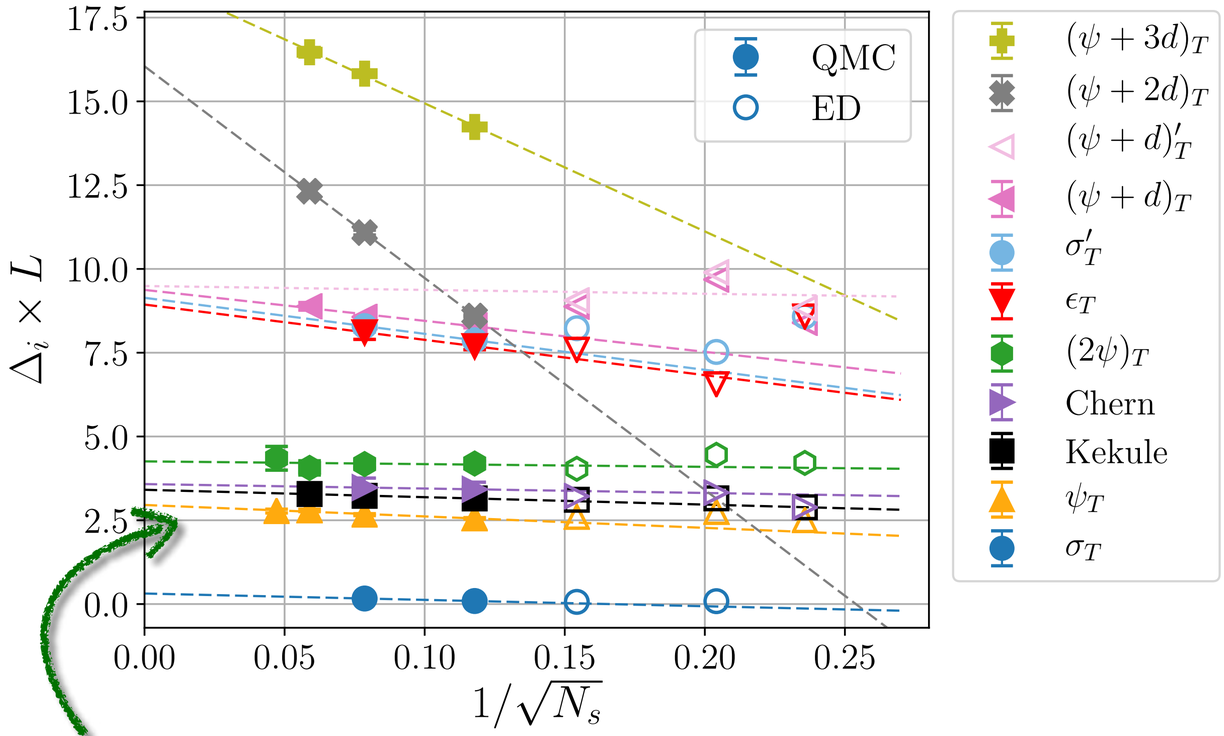


topological "copies"

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

Gross-Neveu vs Gross-Neveu*

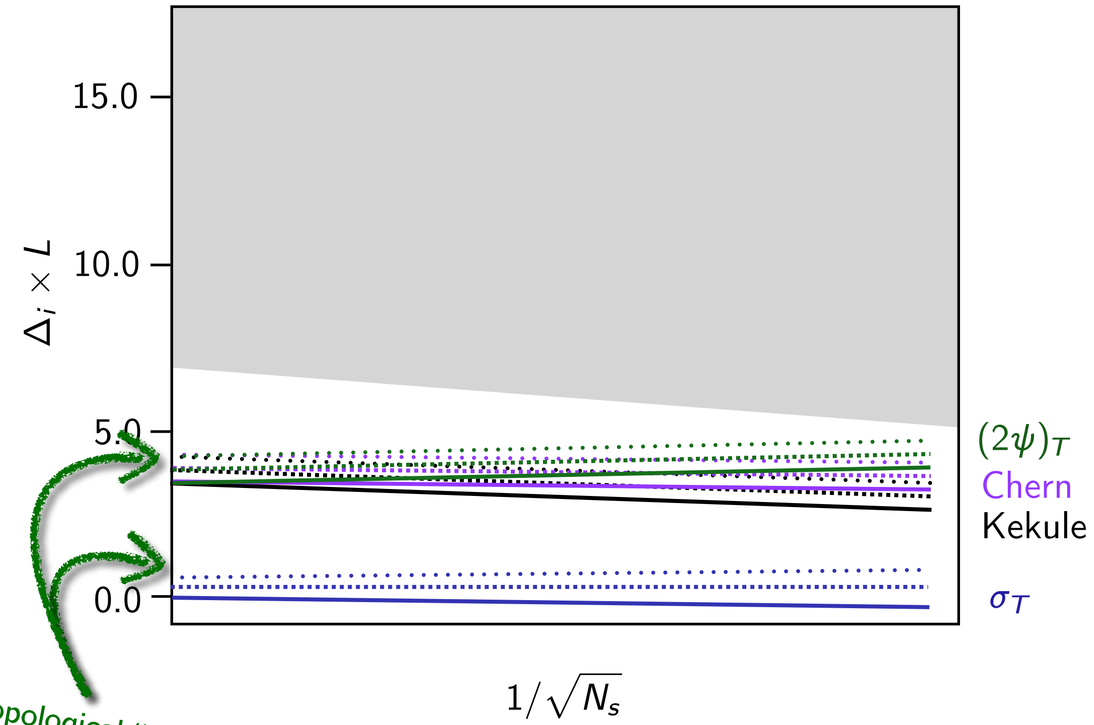
Gross-Neveu-$\mathbb{Z}_2$



missing in GN*

[Schuler *et al.*, arXiv:1907.05373]

Gross-Neveu-$\mathbb{Z}_2$* (schematic)



topological "copies"

... testable in future simulations

Outline

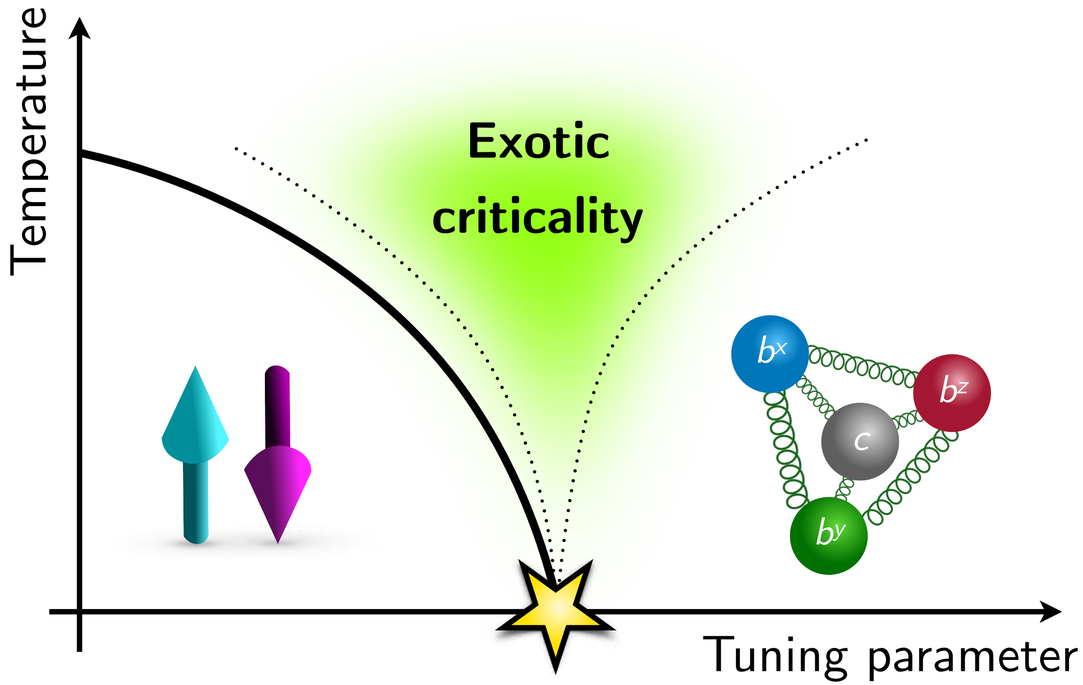
(1) Introduction: *"Beyond-Landau" quantum criticality*

(2) Spin-1/2: *Field-induced criticality in Kitaev materials*

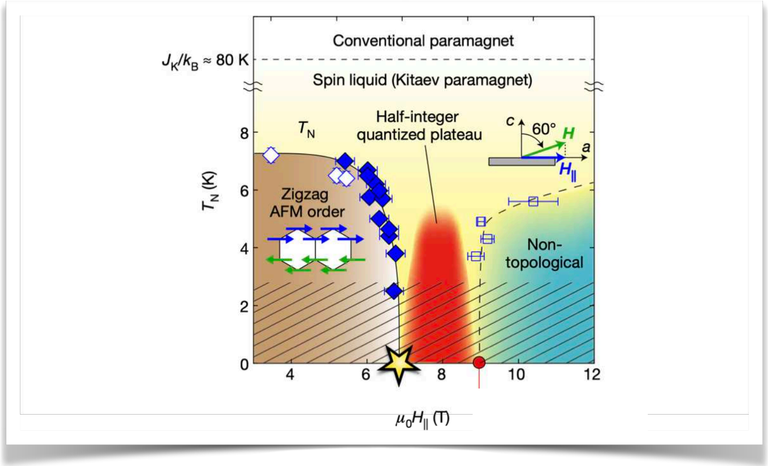
(3) Spin-3/2: *Fractionalized fermionic criticality in spin-orbital models*

(4) Conclusions

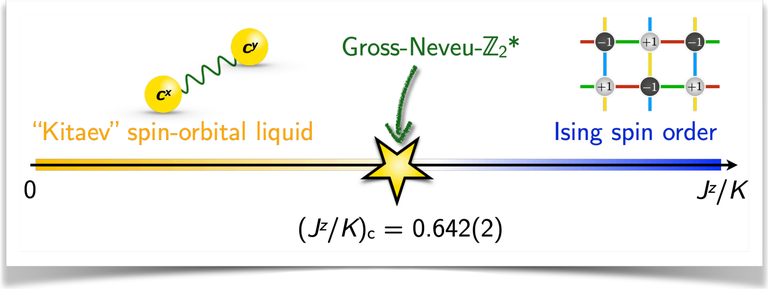
Conclusions



α-$RuCl_3$ in field



Square-lattice spin-orbital model



Honeycomb-lattice spin-orbital model