Emergent chiral metal near a Kondo-breakdown quantum phase transition

Matthias Vojta
TU Dresden

Emergent chiral metal near a Kondo-breakdown quantum phase transition

Tom Drechsler (TU Dresden)
Urban Seifert (KITP Santa Barbara)

1. Kondo breakdown & fractionalized Fermi liquids
2. π-flux U(1) spin liquids
3. Mean-field theory: π-flux FL* - FL transition
4. Emergent chiral metal

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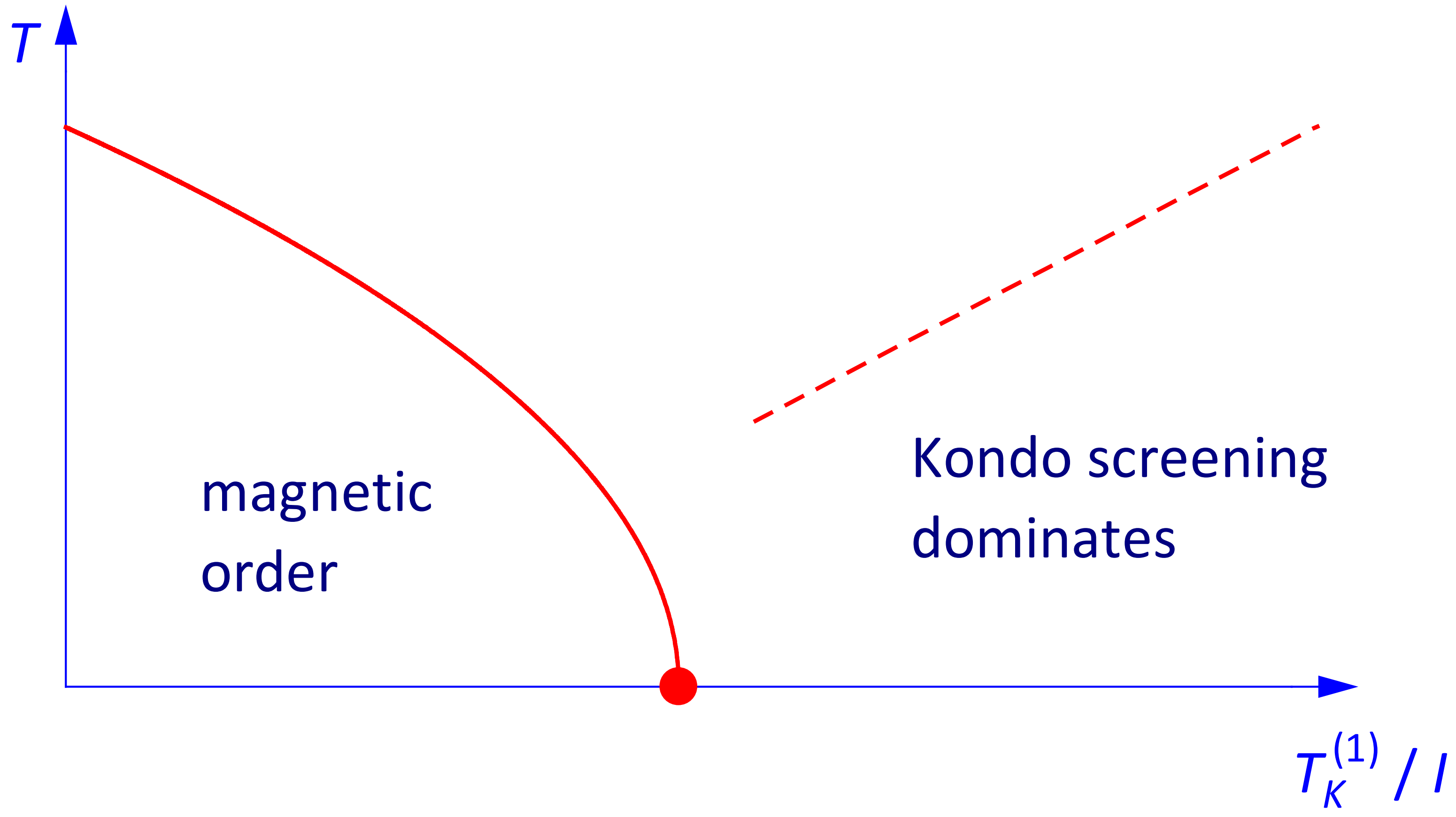
Deutsche Forschungsgemeinschaft DFG

Doniach‘s phase diagram

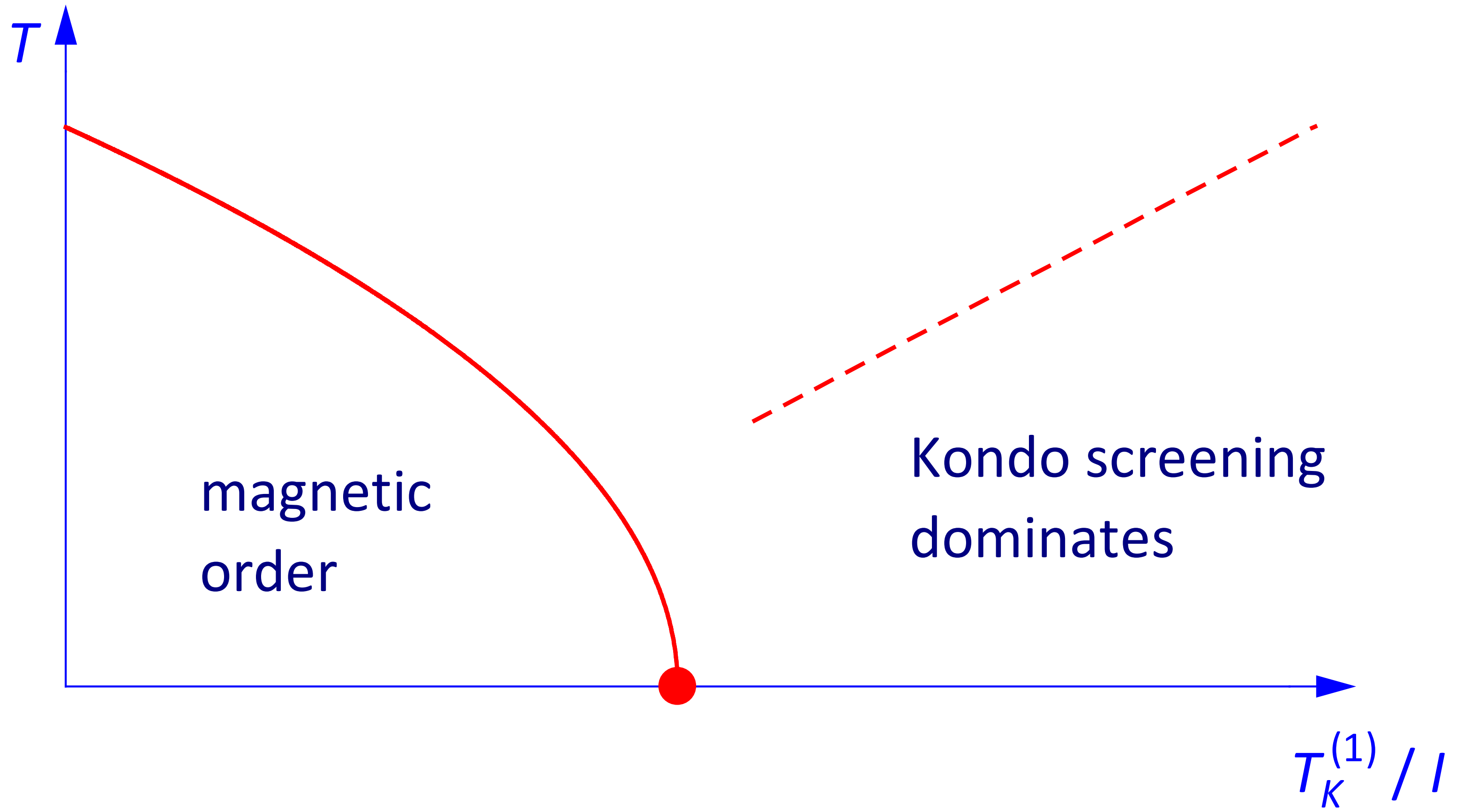
$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_\mathrm{K} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^\dagger_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + I \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$



Doniach, Physica B **91**, 231 (1977)

Doniach‘s phase diagram

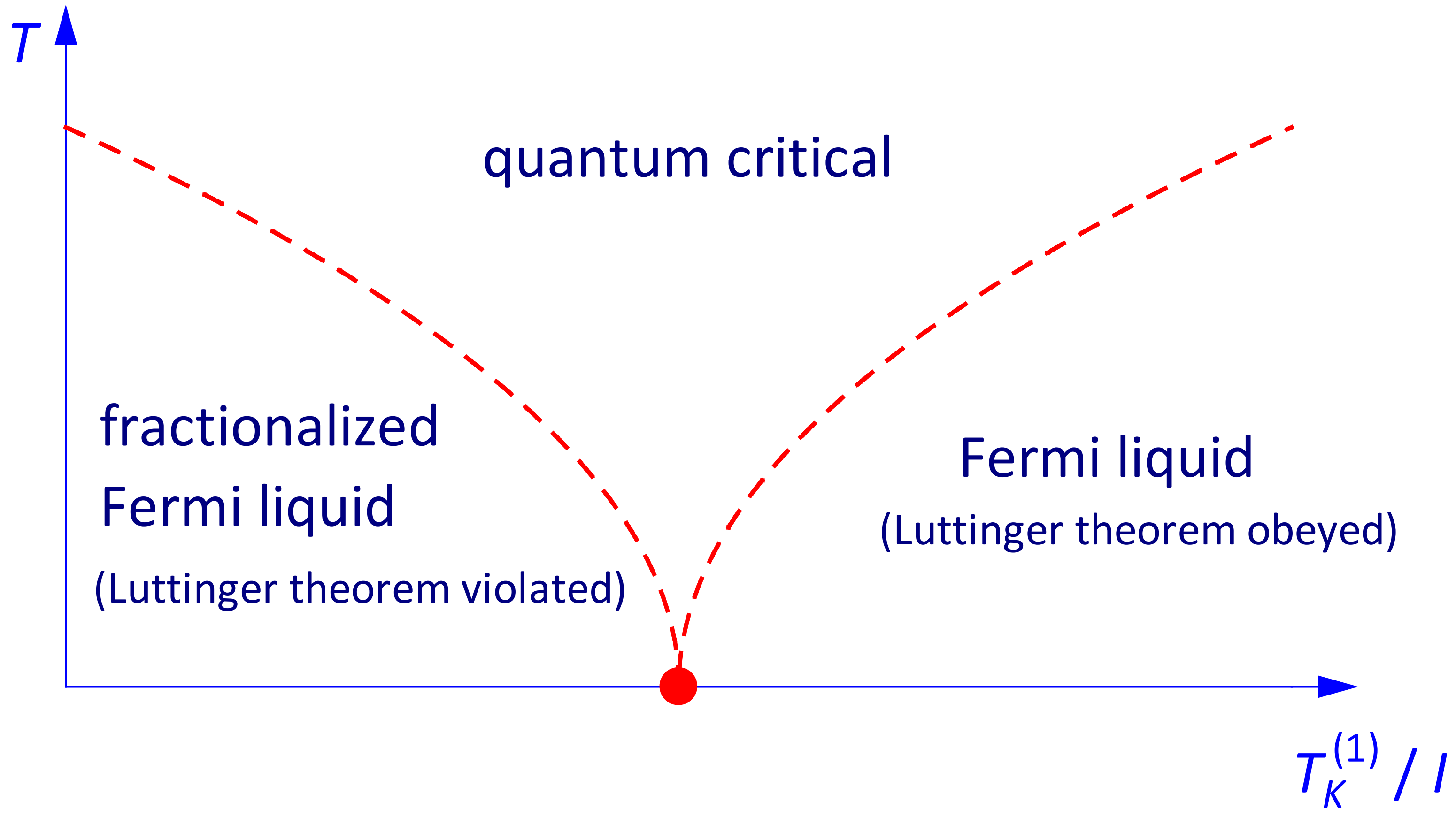
$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_\mathrm{K} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^\dagger_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + I \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$



Competition between local-moment interactions and metallicity

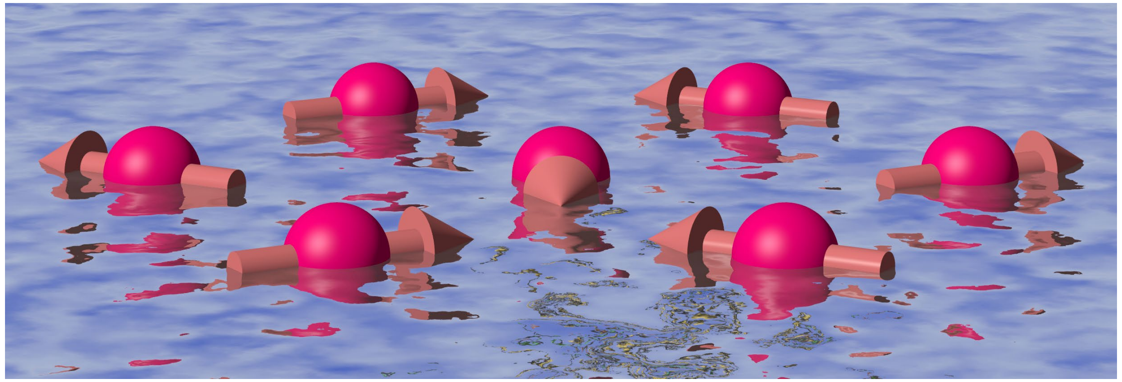
Kondo breakdown transitions

$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_{\rm K} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^\dagger_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + I \sum_{\langle ij\rangle} \vec{S}_i \cdot \vec{S}_j$$



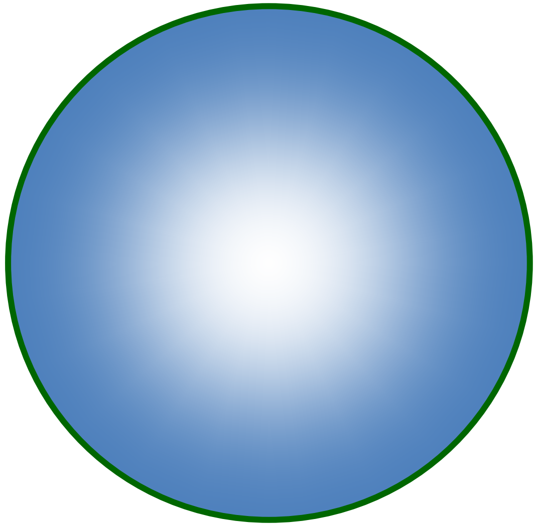
Senthil / Sachdev / Vojta, PRL **90**, 216403 (2003)
see also Si *et al.*, Coleman *et al.*

Fractionalized Fermi liquid



Local moments

+

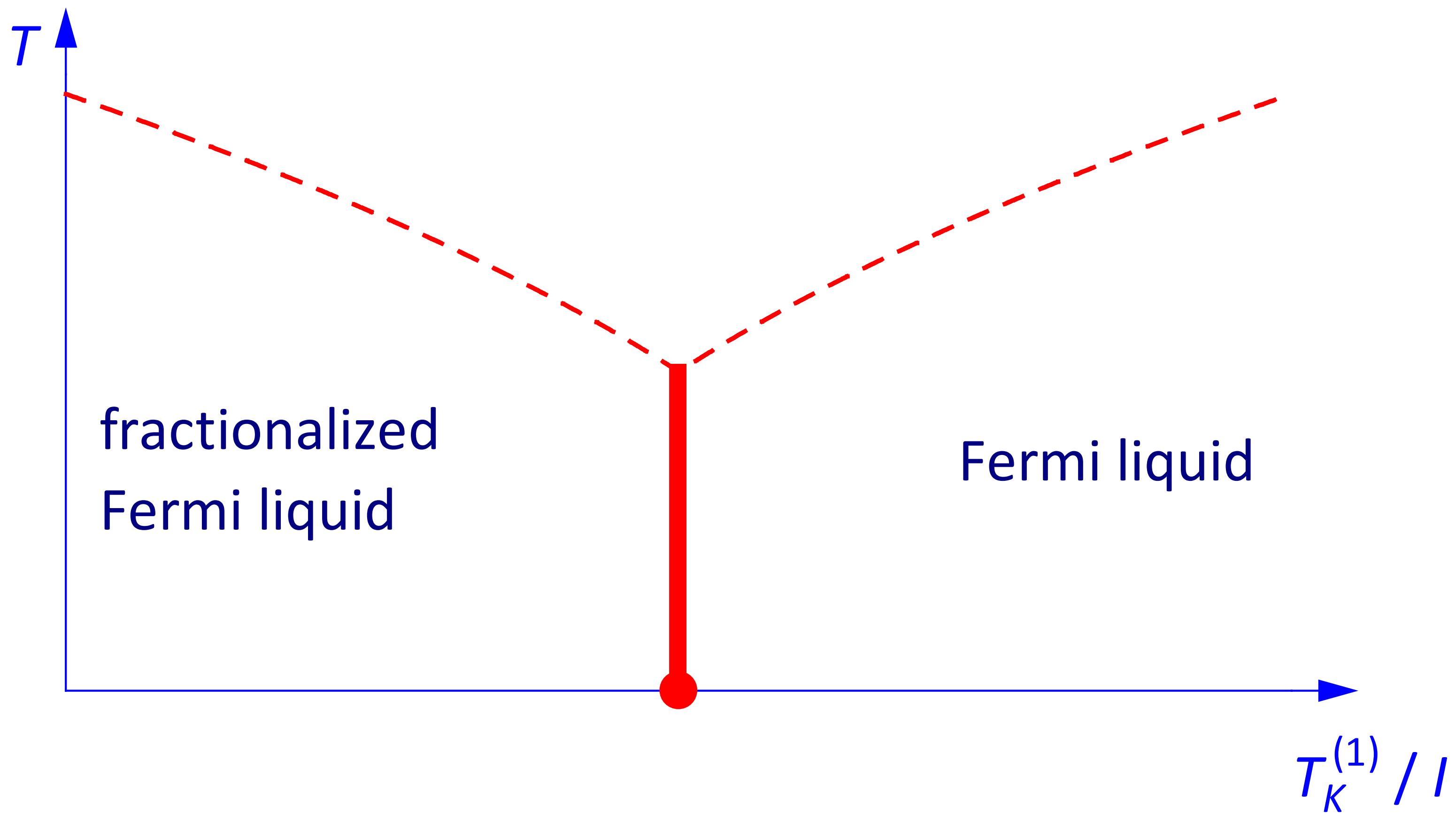


Conduction electrons

$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_{\mathrm{K}} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^\dagger_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + I \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

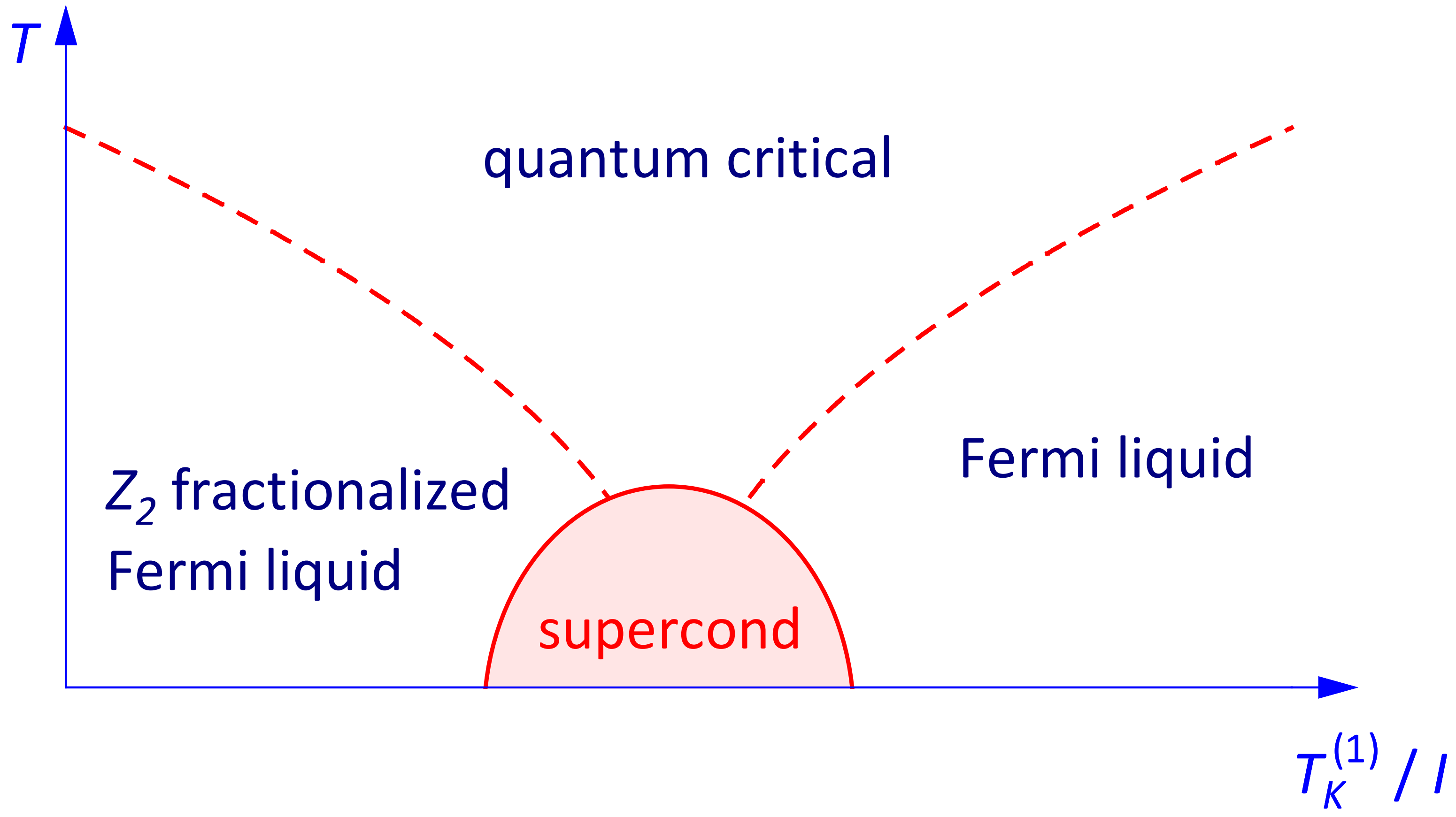
Kondo breakdown transitions: 1st order …

$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_{\mathrm{K}} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^\dagger_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + I \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$



Kondo breakdown transitions: Intermediate phases

$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_{\mathrm{K}} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^\dagger_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + I \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$



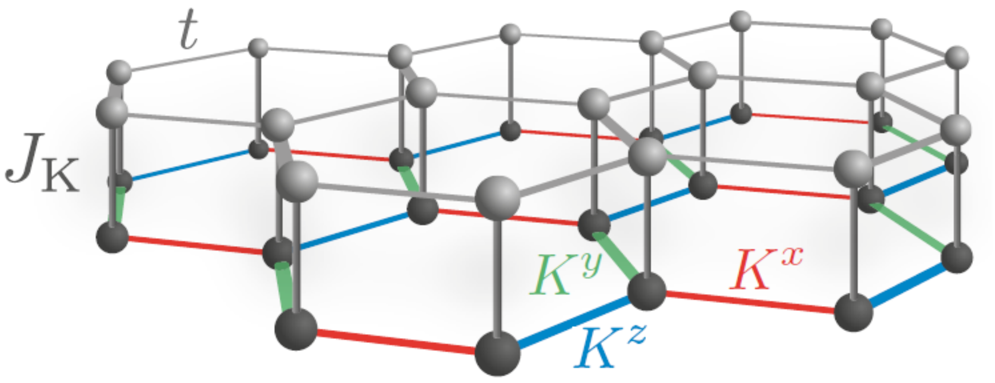
Kitaev Kondo lattice

$$\mathcal{H}_t = -t \sum_{\langle ij\rangle\sigma} (c_{i\sigma}^\dagger c_{j\sigma} + h.c.),$$

$$\mathcal{H}_K = -\sum_{\langle ij\rangle_\alpha} K^\alpha S_i^\alpha S_j^\alpha,$$

$$\mathcal{H}_J = \frac{1}{2} \sum_{i\sigma\sigma'\alpha} J_{\mathrm{K}}^\alpha c_{i\sigma}^\dagger \tau_{\sigma\sigma'}^\alpha c_{i\sigma'} S_i^\alpha$$

(a)



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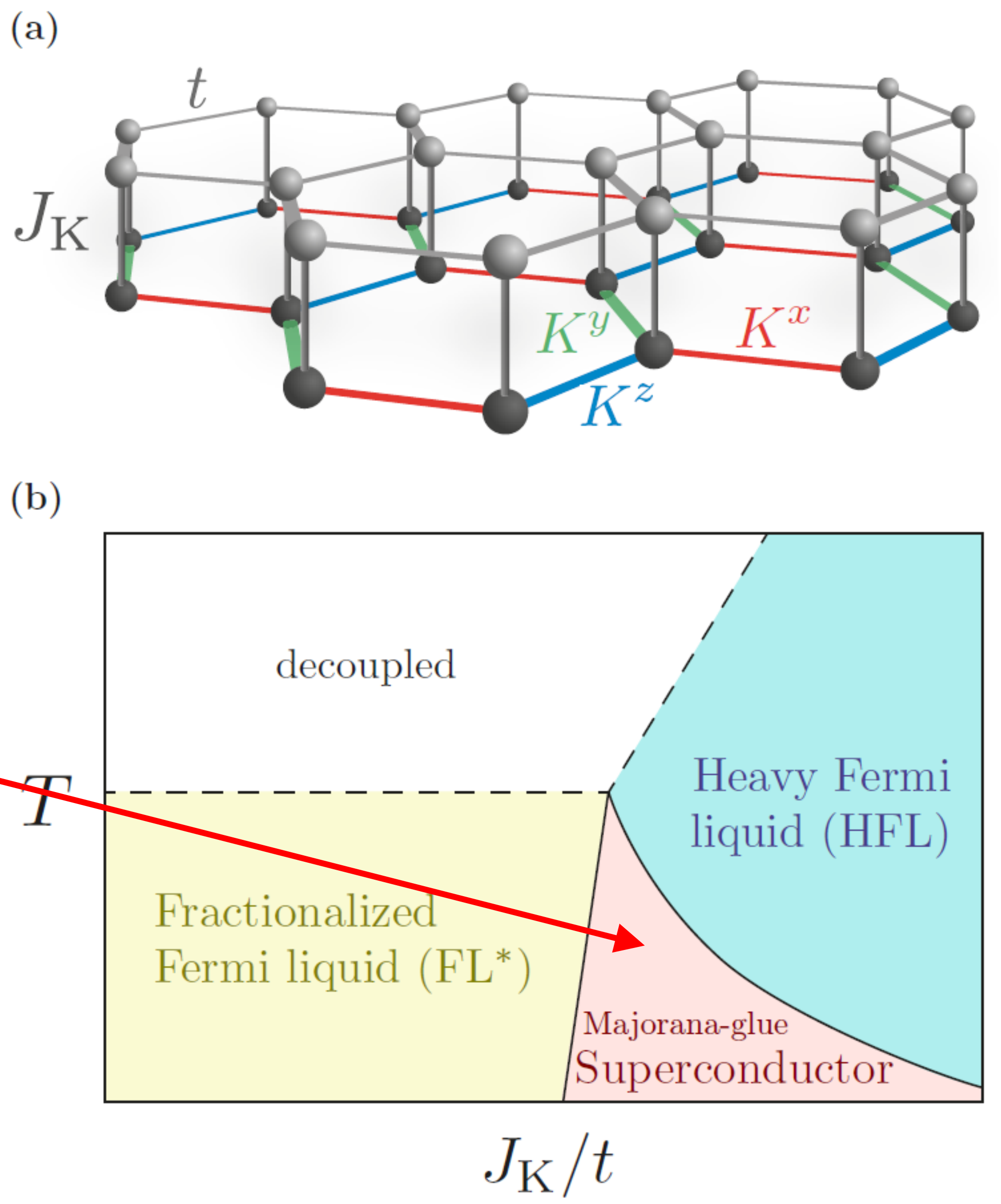

Spin-triplet, nematic s.c.

Seifert/Meng/Vojta, PRB **97**, 085118 (2018)

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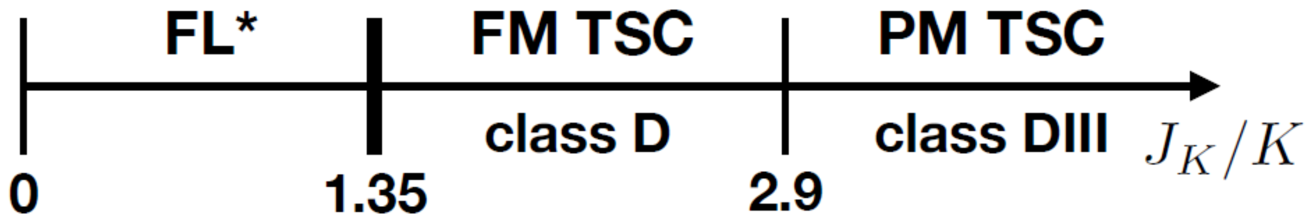
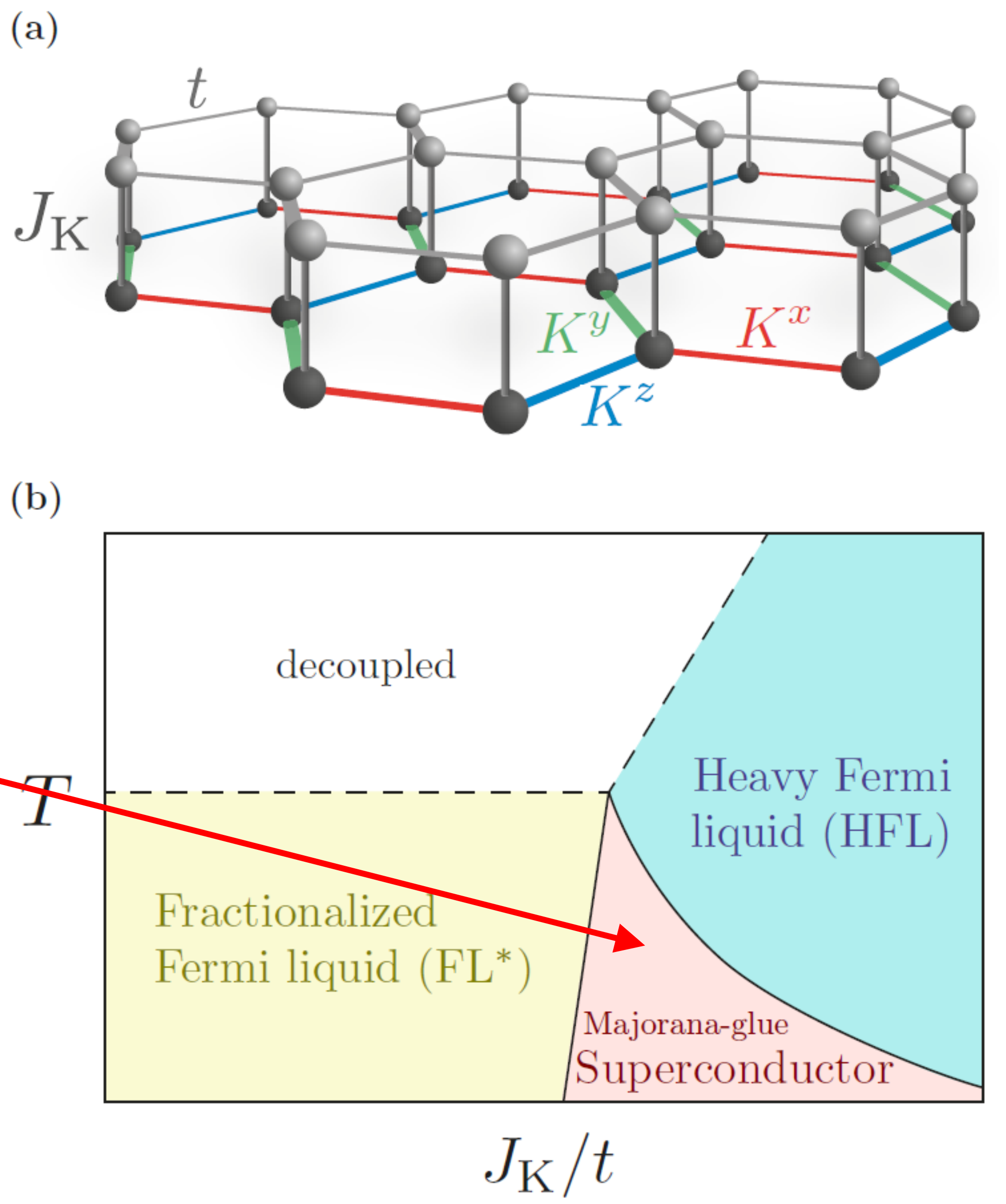
Spin-triplet, nematic s.c.



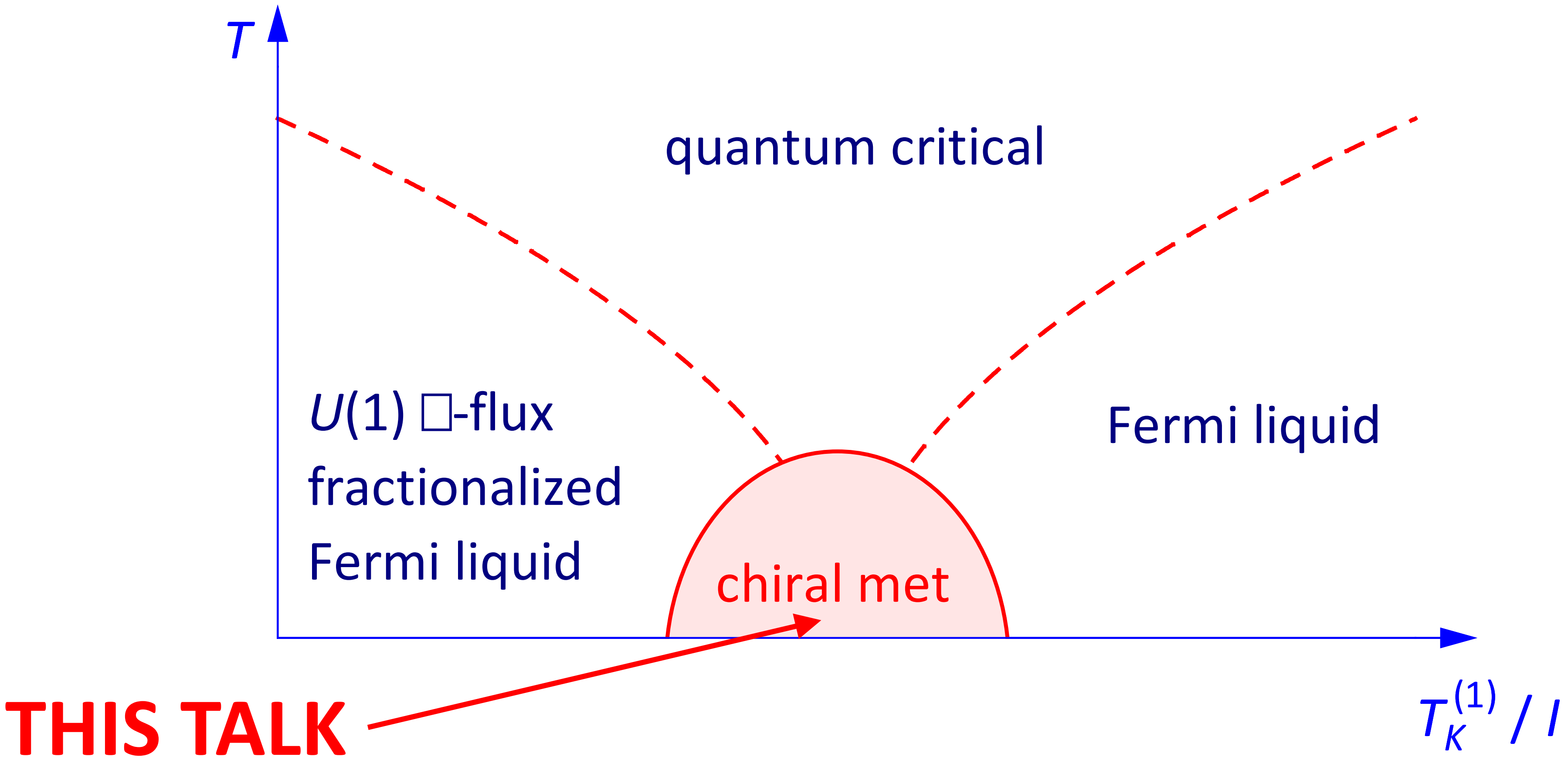


Choi/Kim *et al.*, PRB **98**, 155123 (2018)

Seifert/Meng/Vojta, PRB **97**, 085118 (2018)

Kondo breakdown transitions

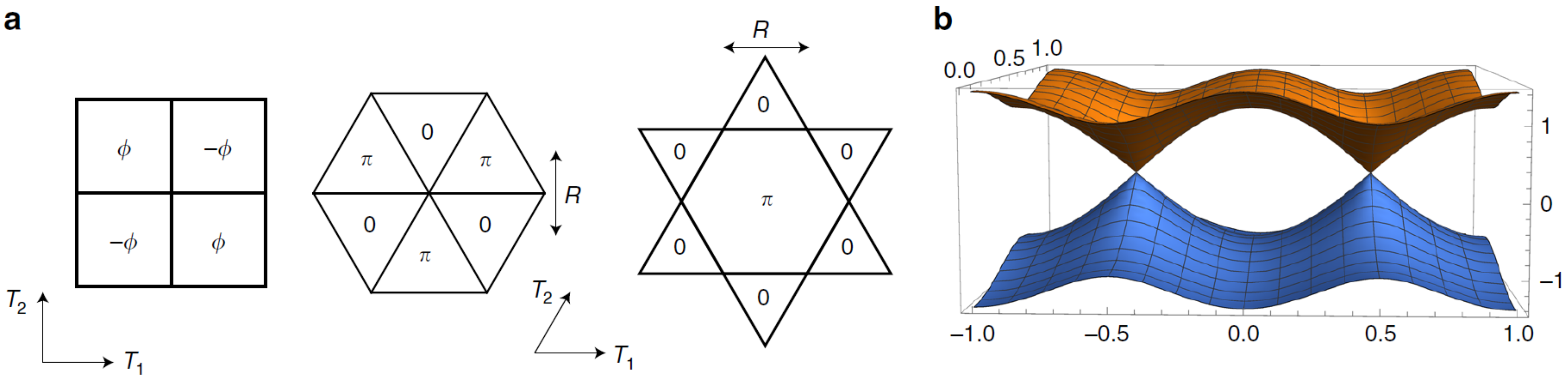
$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^{\dagger}_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_{\mathrm{K}} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^{\dagger}_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + I \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$



U(1) π-flux spin liquids

Fractionalized spinons hop in the presence of emergent gauge flux

$$\mathcal{H}_{\text{eff}} = J \sum_{\langle ij \rangle \sigma} \left(\chi_{j \leftarrow i} f^{\dagger}_{j\sigma} f_{i\sigma} + \text{h.c.} \right)$$

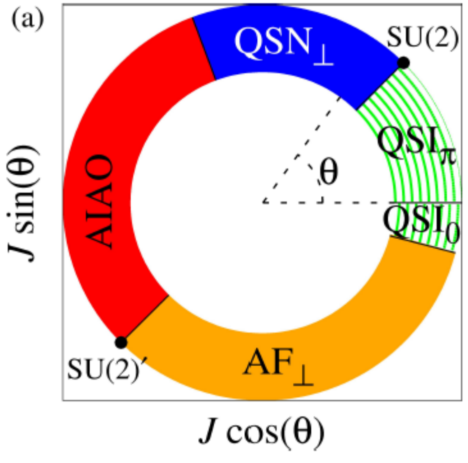


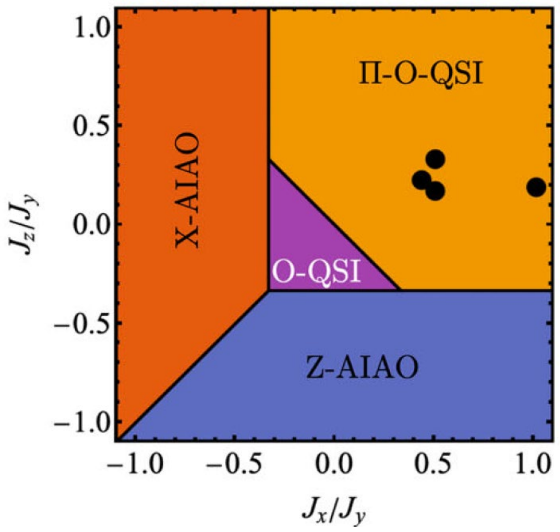
Song *et al.*, Nat. Commun. **10**, 4254 (2019)

Pyrochlore π-flux spin liquids

Dipolar-octupolar model for quantum spin ice hosts $U(1)_\pi$ spin-liquid phase

$$H_{\rm nn} = \sum_{\langle ij \rangle} J_y s_i^y s_j^y + [J_x s_i^x s_j^x + J_z s_i^z s_j^z + J_{xz}(s_i^x s_j^z + s_i^z s_j^x)]$$





Benton *et al.*, PRL **121**, 067201 (2018)
Desrochers *et al.*, PRB **105**, 035149 (2022)

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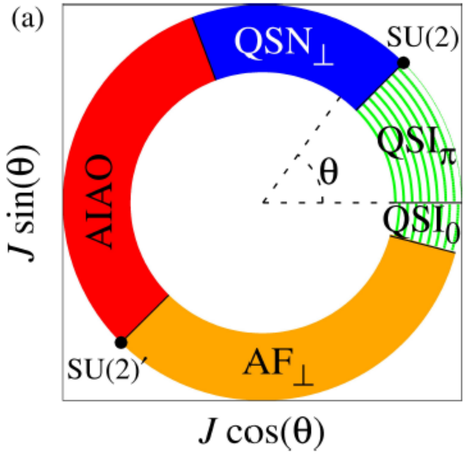
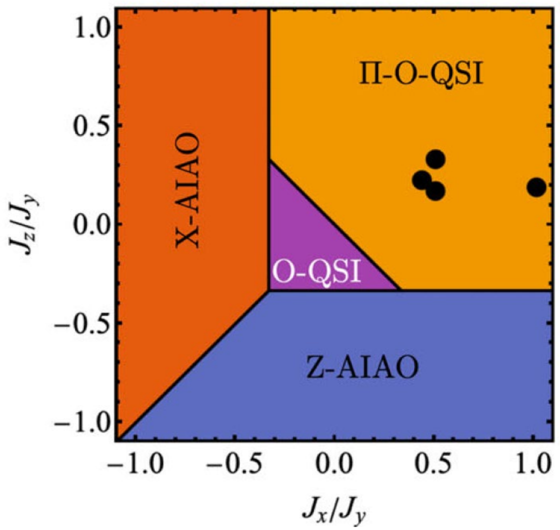
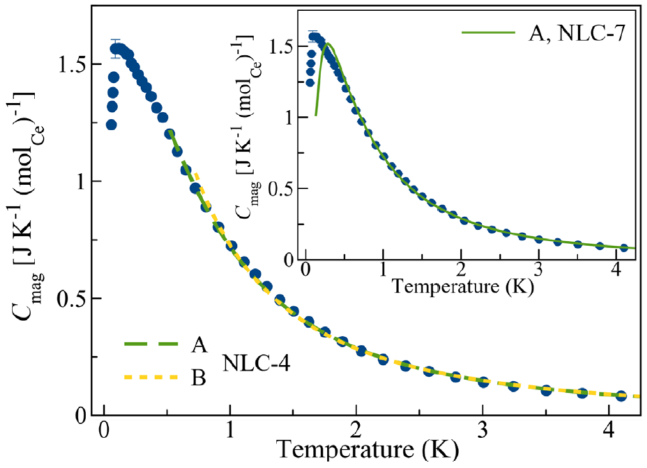
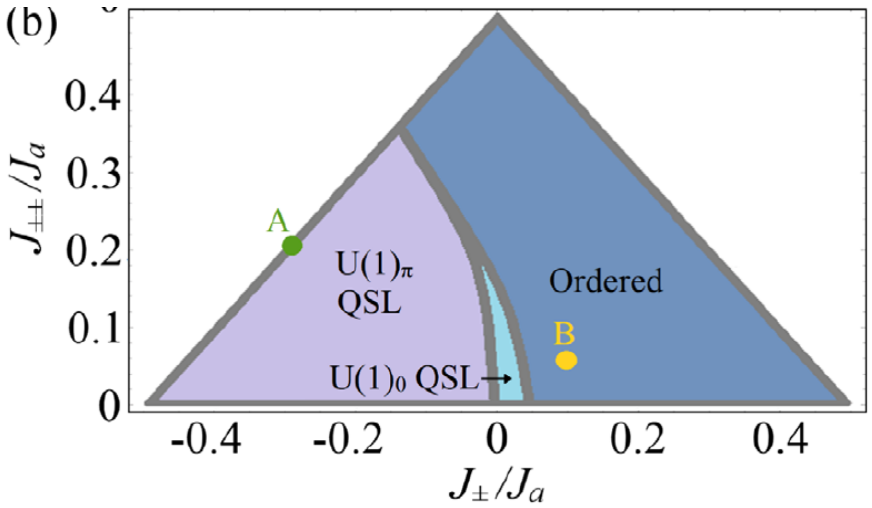




Benton *et al.*, PRL **121**, 067201 (2018)
Desrochers *et al.*, PRB **105**, 035149 (2022)

$Ce_2Zr_2O_7$: π-flux U(1) spin liquid !?

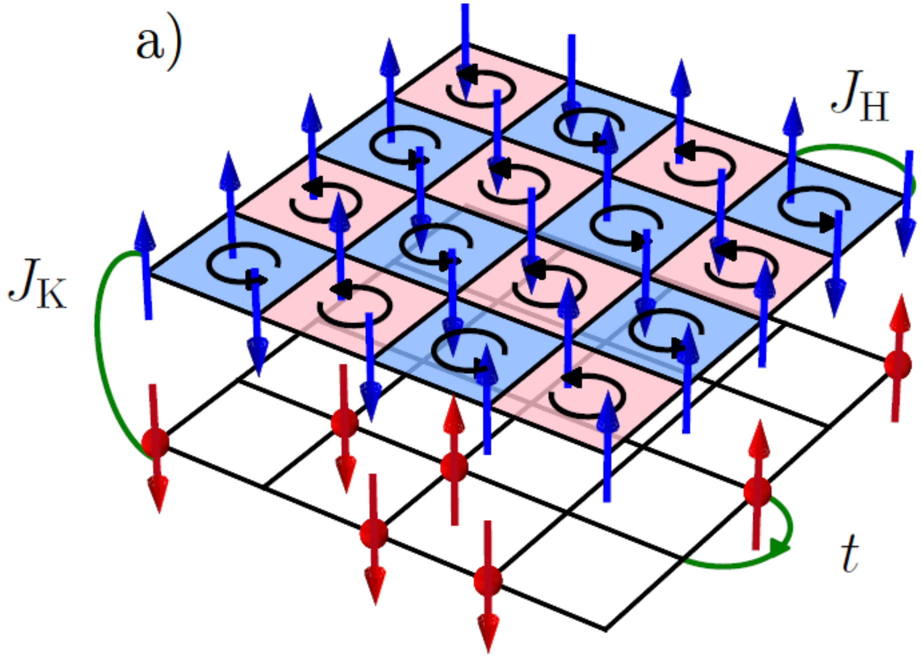




Smith *et al.*, PRX **12**, 021015 (2022)
Bhardwaj *et al.*, npj QM **7**, 51 (2022)

Kondo-Heisenberg lattice model & mean-field theory

$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_\mathrm{K} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^\dagger_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + J_\mathrm{H} \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j ,$$



Use square lattice for simplicity.
Use U(1) parton mean-field theory.

Homogeneous large-*N* saddle point
in local-moment sector is π-flux phase.

Footnote:
Need biquadratic exchange to suppress VBS.

Marston / Affleck, PRB **39**, 11538 (1989)

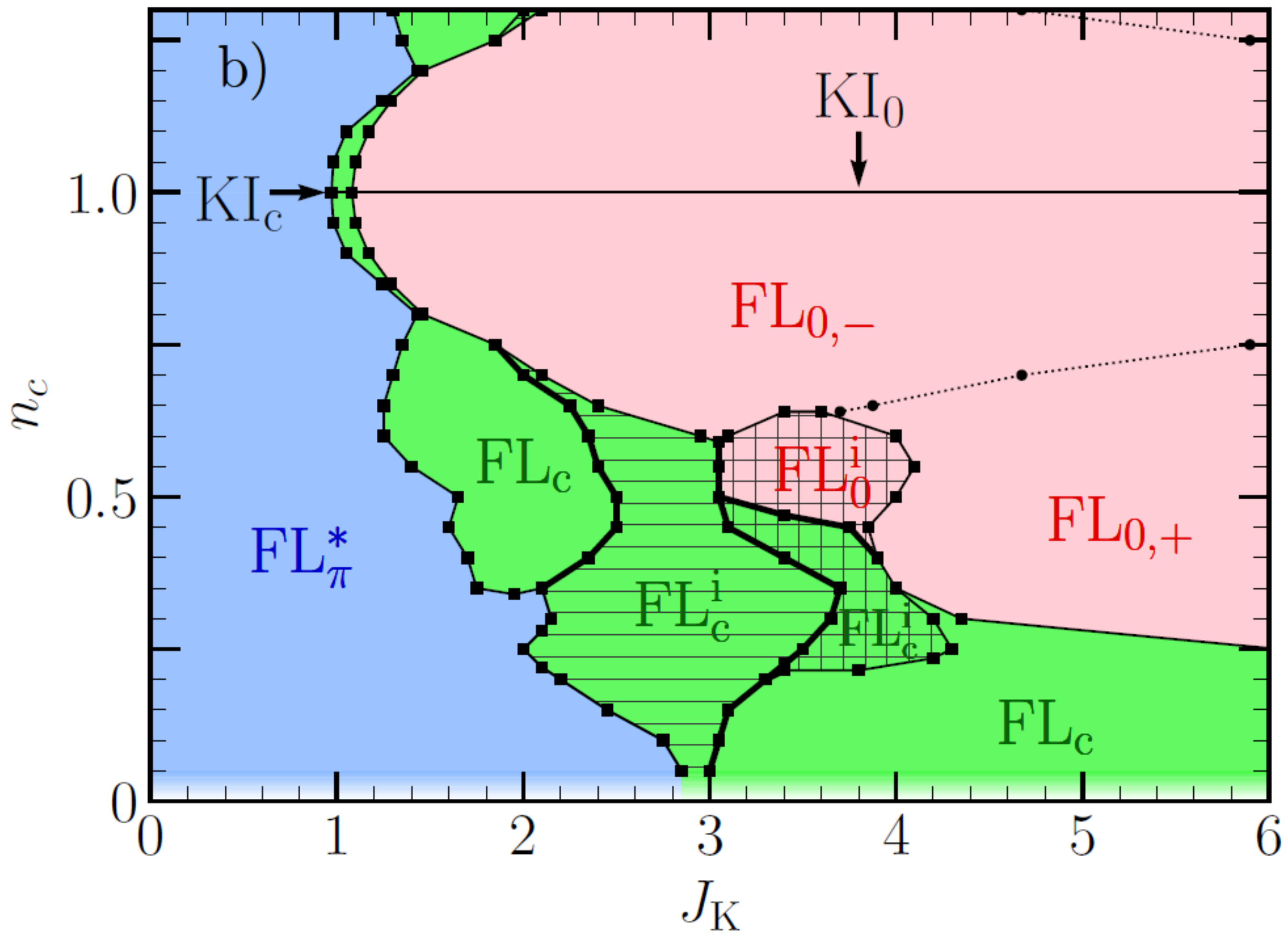
Kondo-Heisenberg lattice model & mean-field theory

$$\mathcal{H} = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + J_{\mathrm{K}} \sum_{i\sigma\sigma'} \vec{S}_i \cdot c^\dagger_{i\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} + J_{\mathrm{H}} \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j ,$$

$$\mathcal{H}_{\mathrm{biq}} = \frac{\kappa J_H}{2} \sum_{\langle ij \rangle} (\vec{S}_i \cdot \vec{S}_j)^2$$

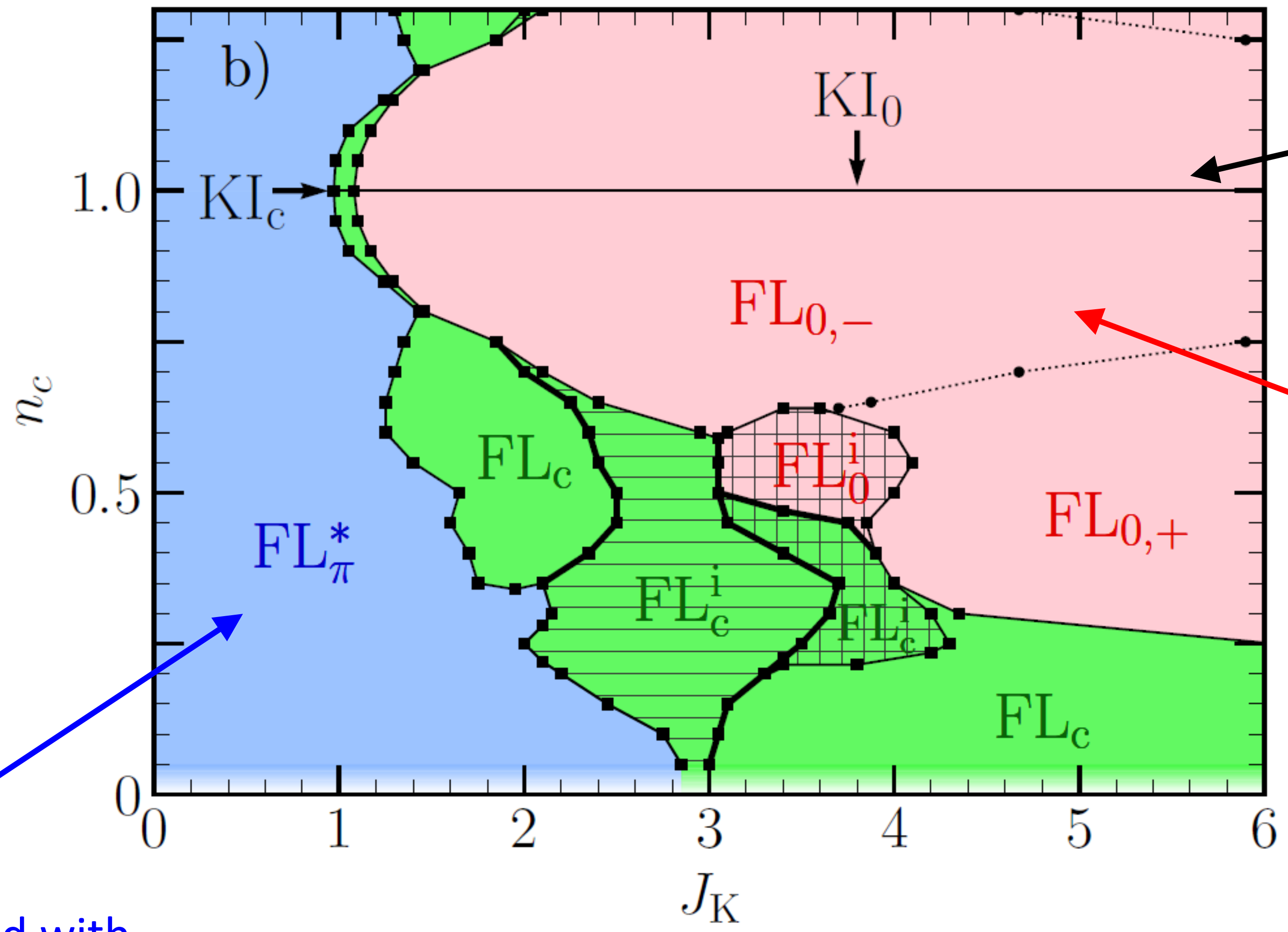
$$\mathcal{H}_{\mathrm{MF}} = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} - J_{\mathrm{K}} \sum_{i\sigma} (b_i c^\dagger_{i\sigma} f_{i\sigma} + \mathrm{h.c.}) - \tilde{J}_{\mathrm{H}} \sum_{\langle ij \rangle \sigma} \left[\chi_{j\leftarrow i} (1 - 2\tilde{\kappa} |\chi_{j\leftarrow i}|^2) f^\dagger_{j\sigma} f_{i\sigma} + \mathrm{h.c.} \right] - \sum_{i\sigma} \mu_i^f f^\dagger_{i\sigma} f_{i\sigma}$$

Mean-field phase diagram



Drechsler/Vojta, arXiv:2311.13641

Mean-field phase diagram



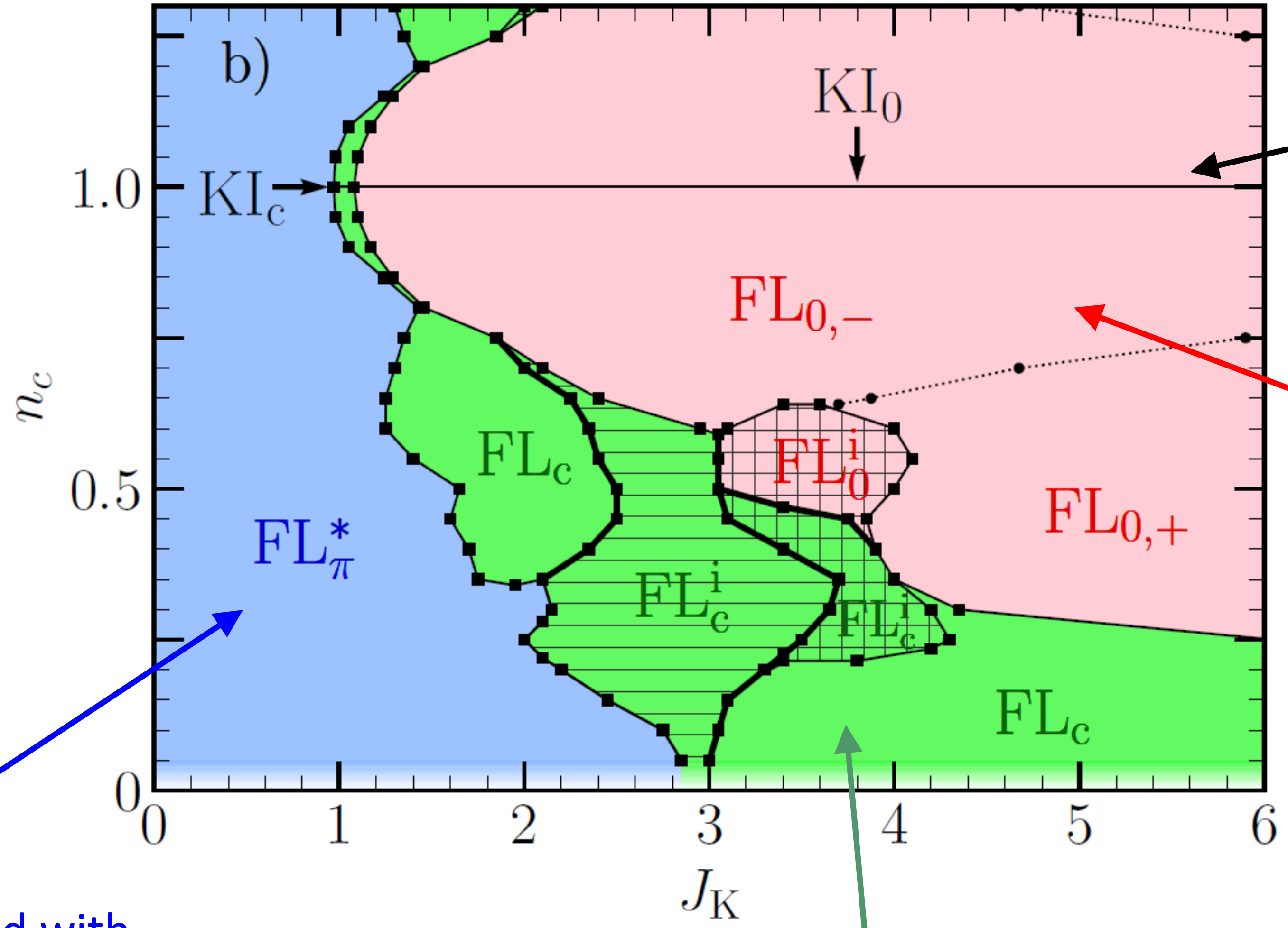
Kondo insulator for half-filled conduction band

Heavy Fermi liquid with zero flux

Fractionalized Fermi liquid with π-flux local moment sector

Drechsler/Vojta, arXiv:2311.13641

Mean-field phase diagram



Kondo insulator for half-filled conduction band

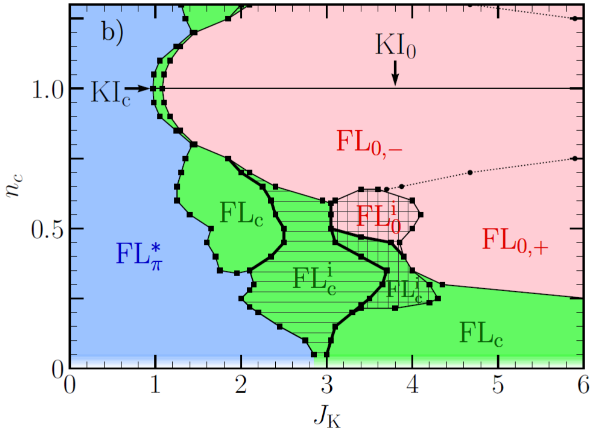
Heavy Fermi liquid with zero flux

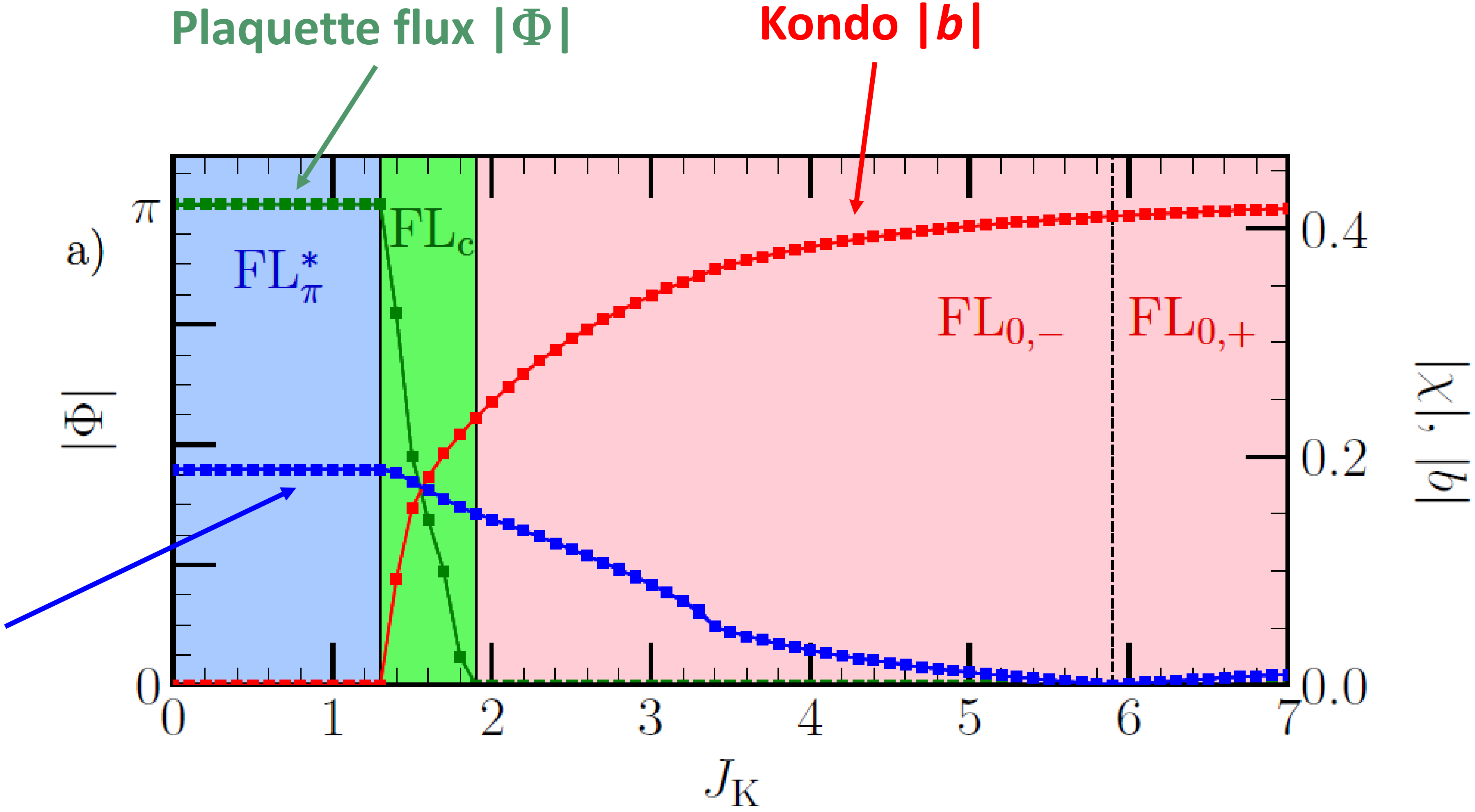
Fractionalized Fermi liquid with π-flux local moment sector

Heavy-fermion metal with T-breaking staggered flux

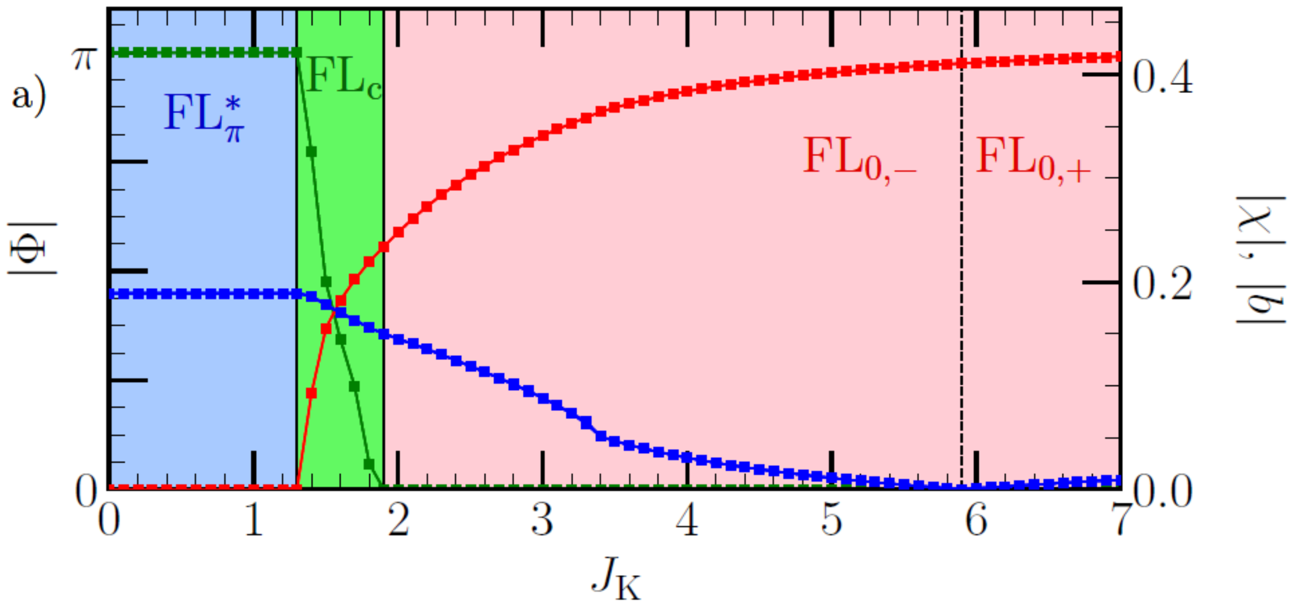
Drechsler/Vojta, arXiv:2311.13641

Mean-field parameters

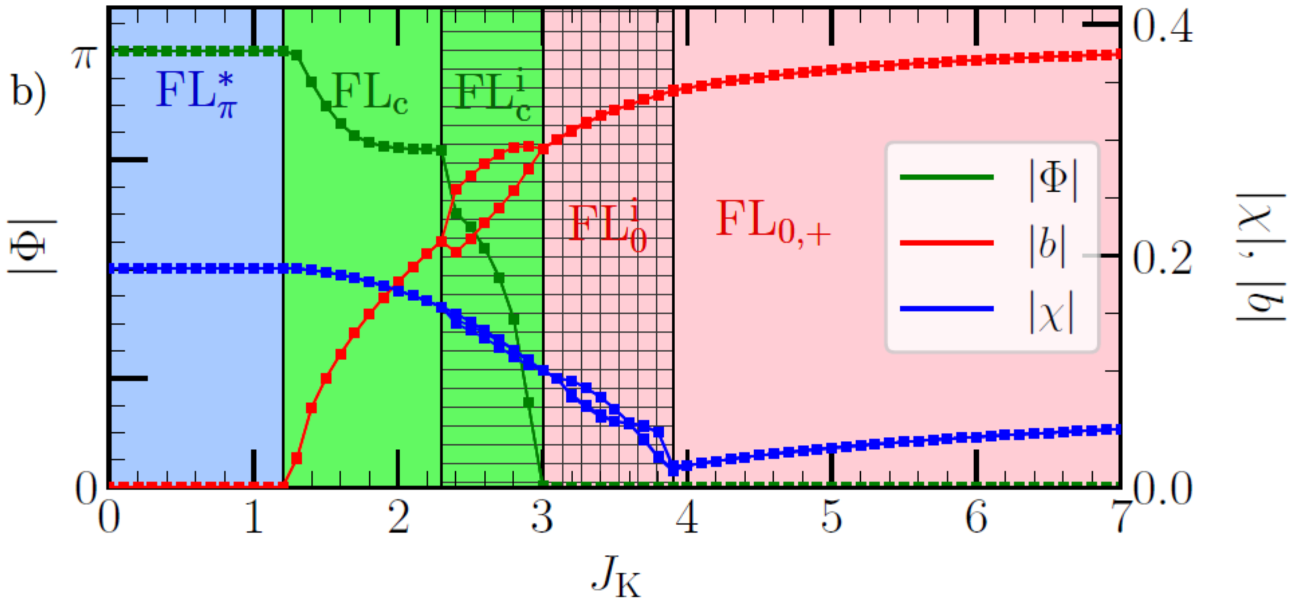




Mean-field parameters

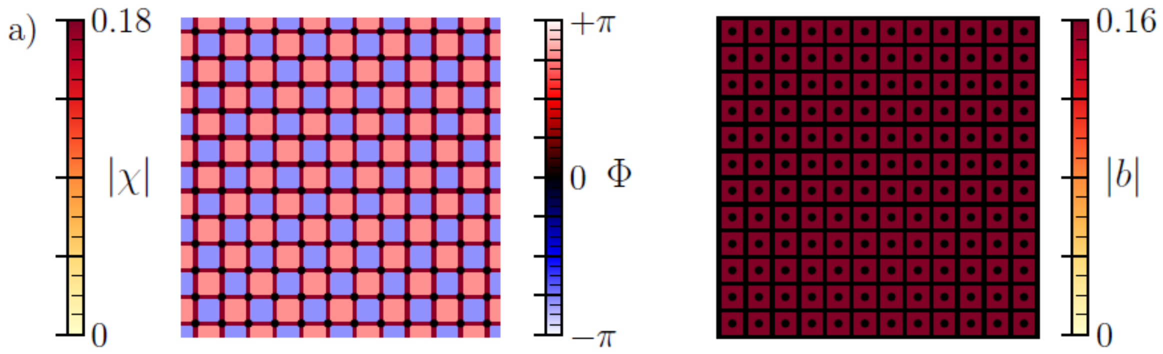


Simple FL_c intermediate phase



Multiple intermediate phases: FL_c, FL_c^i, FL_0^i

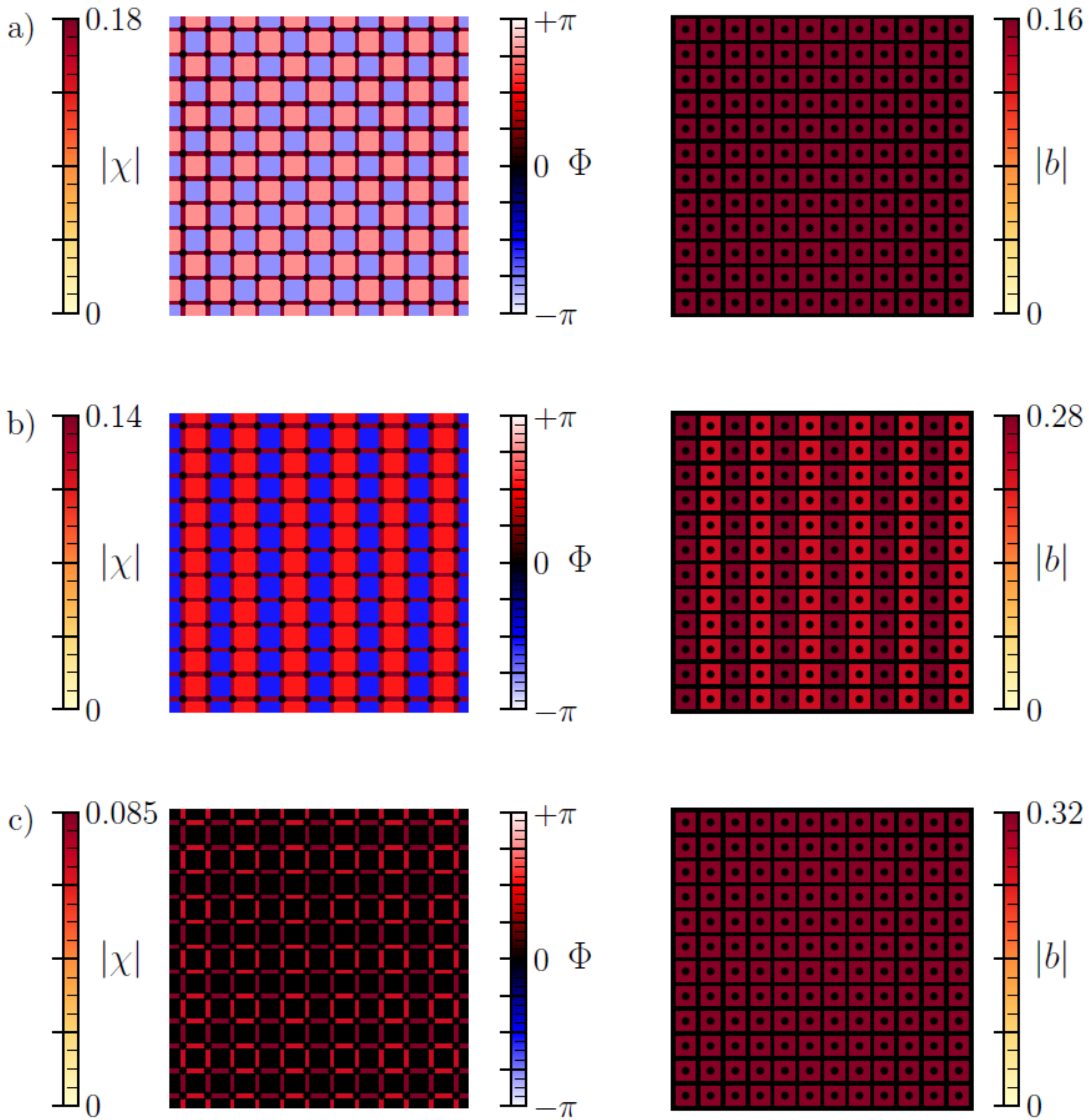
Mean-field parameters: Spatial structure



FL_c:
Staggered flux, homogeneous otherwise

Drechsler/Vojta, arXiv:2311.13641

Mean-field parameters: Spatial structure



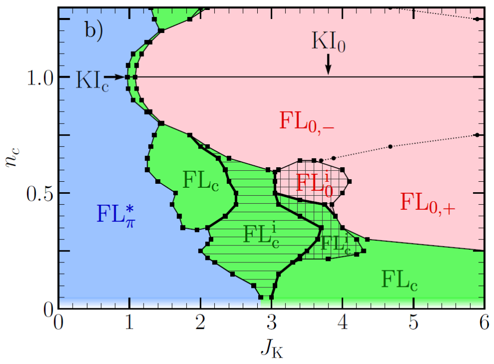
FL_c:
Staggered flux, homogeneous otherwise

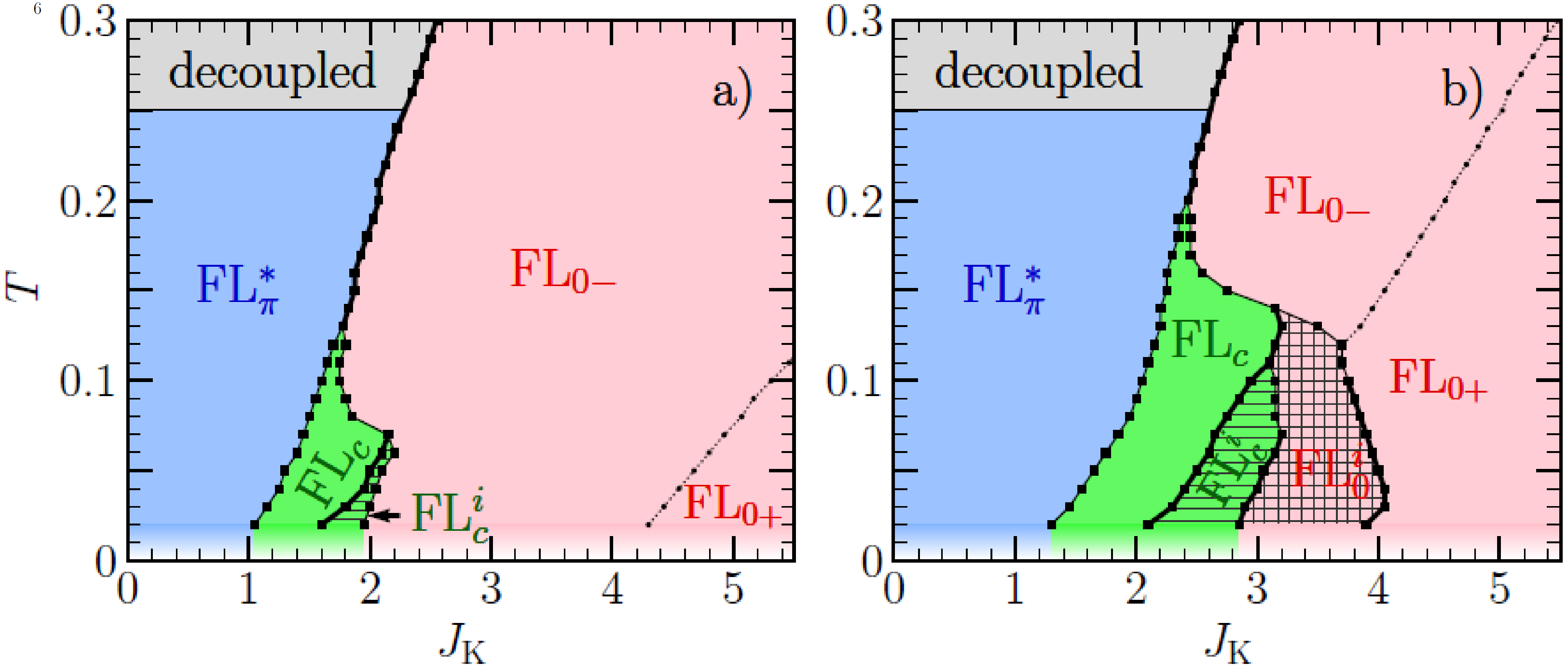
FL_c^i:
Modulated flux and Kondo

FL_0^i:
Box-like bond order, sites equivalent

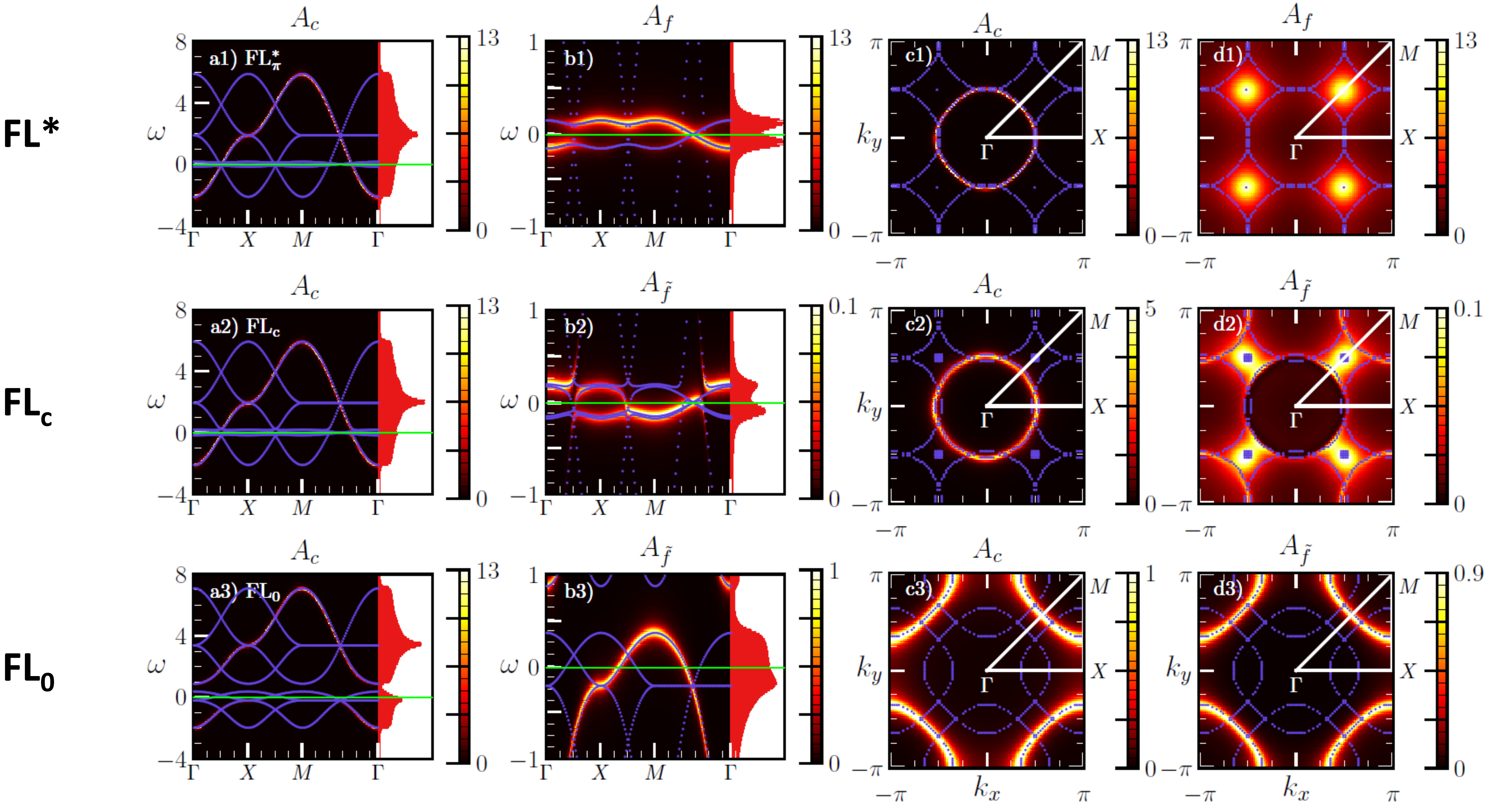
Drechsler/Vojta, arXiv:2311.13641

Mean-field phase diagrams at finite T

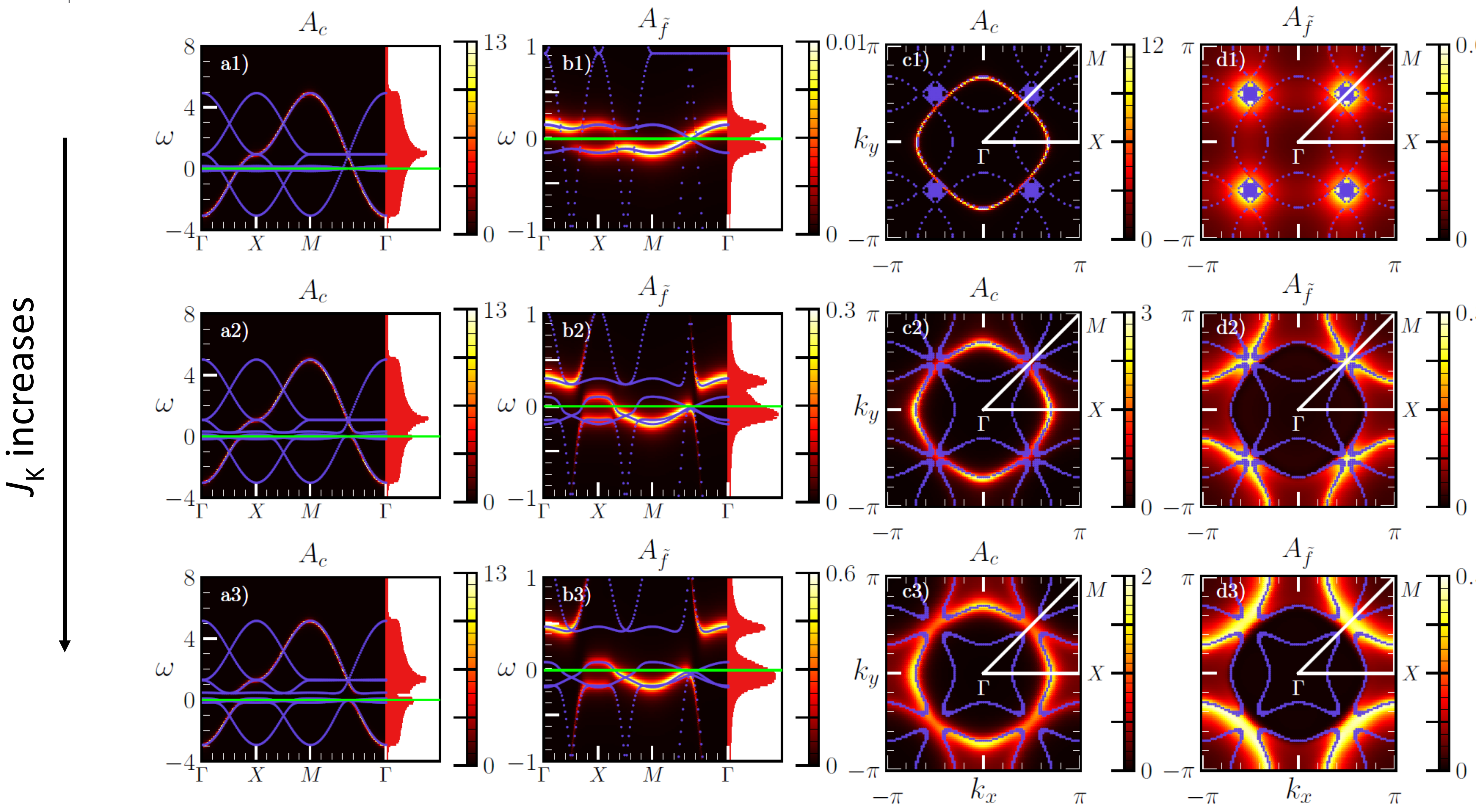




Electronic spectral function



Electronic spectral function in FL_c



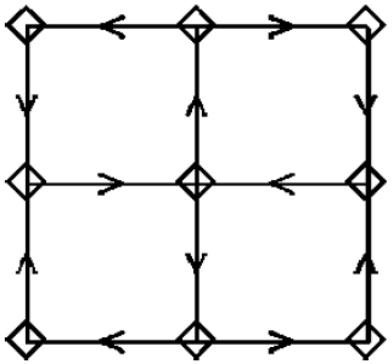
Staggered flux phases …

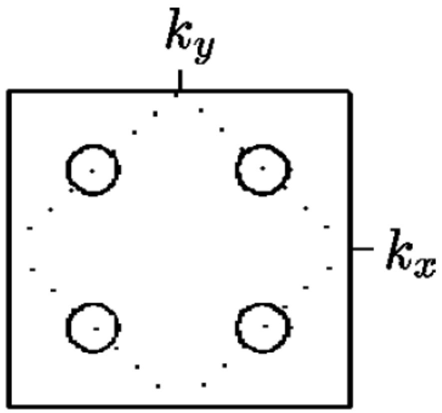
PHYSICAL REVIEW B, VOLUME 63, 094503

Hidden order in the cuprates

Sudip Chakravarty,[1] R. B. Laughlin,[2] Dirk K. Morr,[3] and Chetan Nayak[1]

FL$_c$ is heavy-electron version of *d*-density wave (or staggered flux) phase

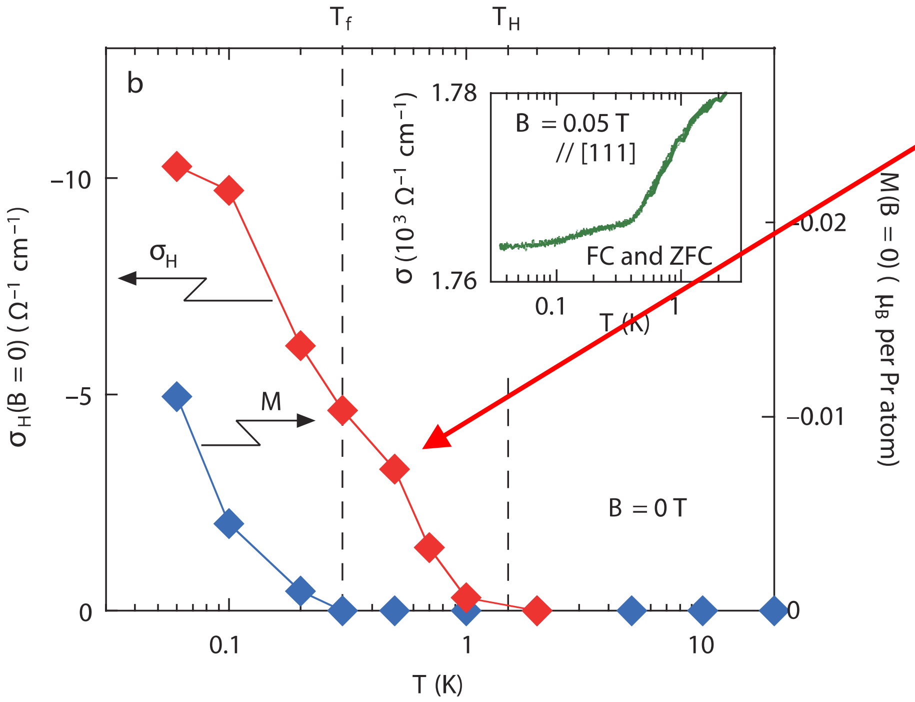




$$y = i \sum_{\mathbf{k},s} f(\mathbf{k}) \langle c^{\dagger}_{\mathbf{k}+\mathbf{Q},s} c_{\mathbf{k},s} \rangle$$

$Pr_2Ir_2O_7$ – a candidate material?

- Kondo coupling between Ir 5*d* conduction electrons and Pr 4*f* moments
- Small carrier concentration (proximity to quadratic band touching)
- Anomalous Hall effect for $T < 1.5$ K
  → time reversal broken without long-range spin order



Metallic chiral spin liquid (=FL*) at finite J_K?

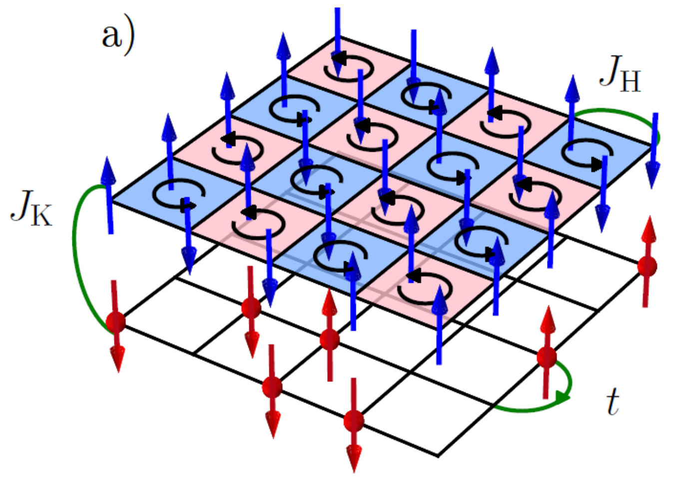
Machida *et al.*, Nature **463**, 210 (2010)

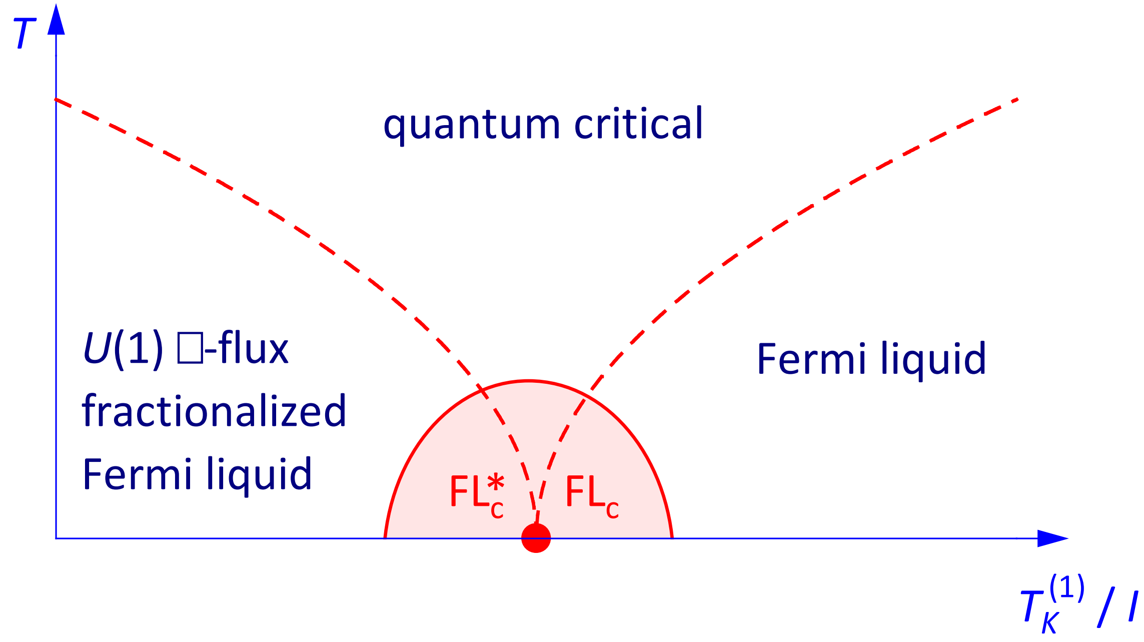
Summary

- Chiral metal (FL_c) naturally emerges near transition $U(1)_\pi$ FL* <-> FL

- Mean-field FL_c phase is confined.
  Beyond mean-field a deconfined version FL_c* is conceivable.

- Outlook:
  Other lattices
  Exact numerics





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