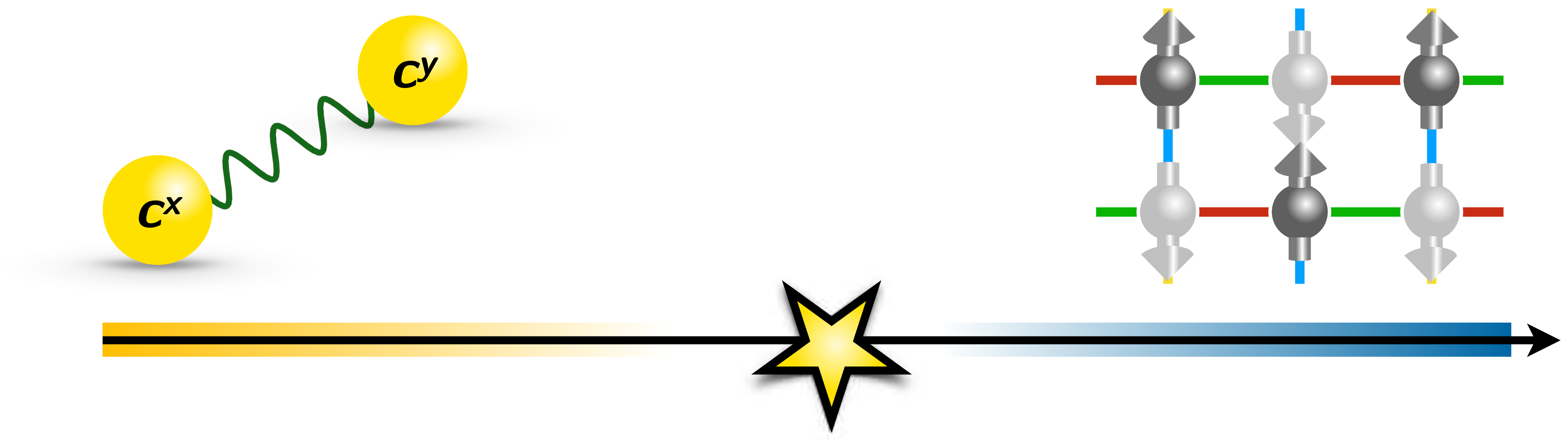
Quantum criticality between spin liquids and long-range order



Lukas Janssen
(TU Dresden)

Xiao-Yang Xu (San Diego)
Wei Wang (Beijing)
Zi Yang Meng (Hong Kong)
Michael Scherer (Cologne)

Urban Seifert (Santa Barbara)
Sreejith Chulliparambil (Dresden)
Hong-Hao Tu (Dresden)
Matthias Vojta (Dresden)
Xiao-Yu Dong (Gent)

Shouryya Ray (Dresden) → **Wed 17:00**
John Gracey (Liverpool)
Bernhard Ihrig (Cologne)
Daniel Kruti (Cologne)
Michael Scherer (Cologne)

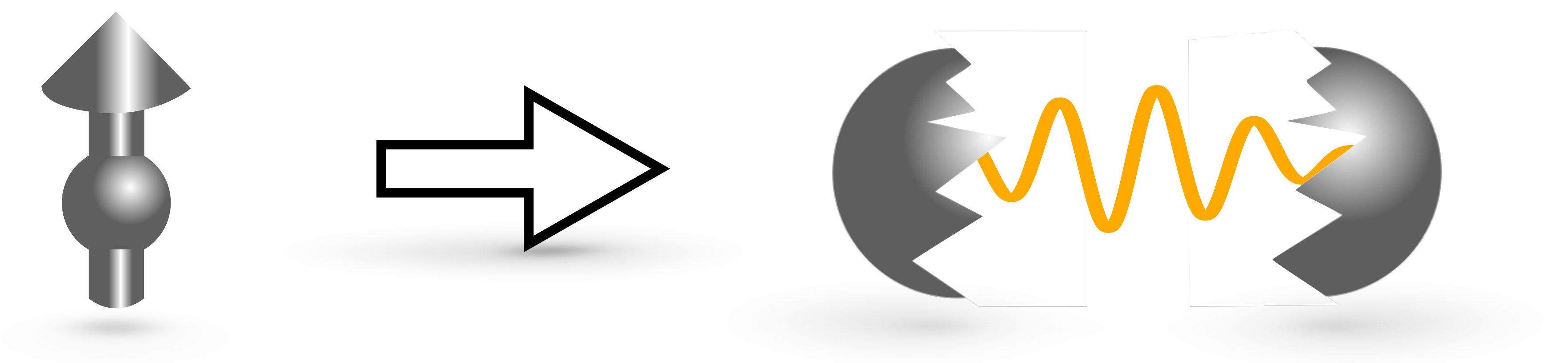
Emmy Noether-Programm
JA 2306/4-1
DFG Deutsche Forschungsgemeinschaft

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

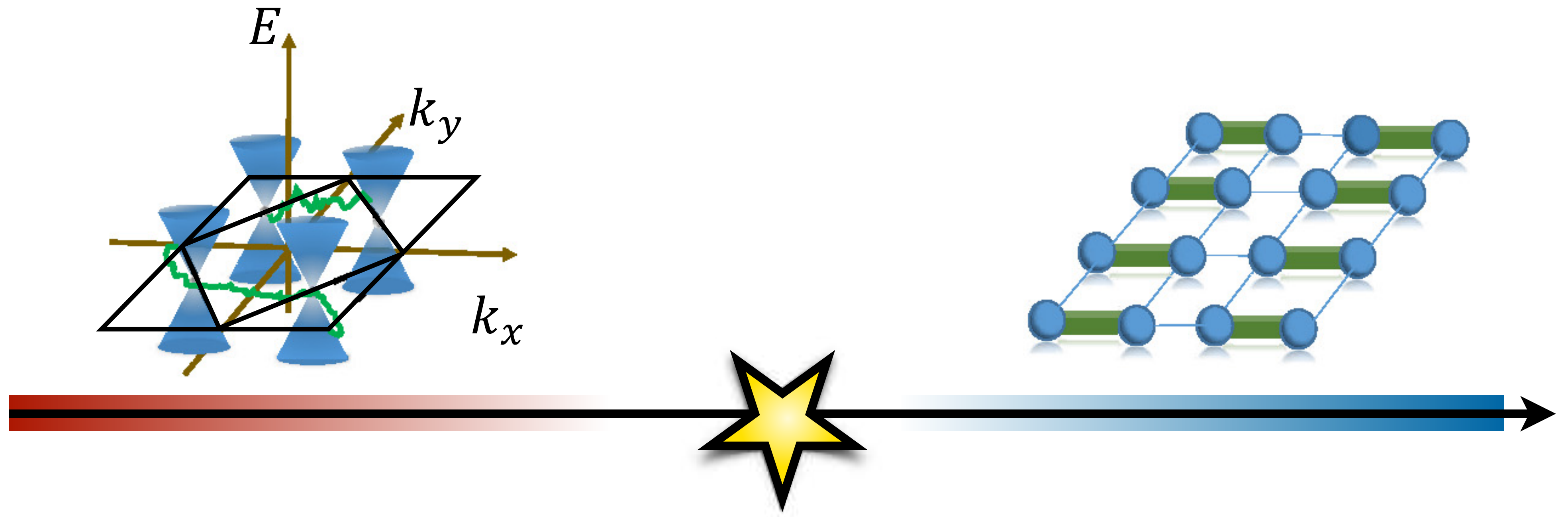
SFB 1143

Outline

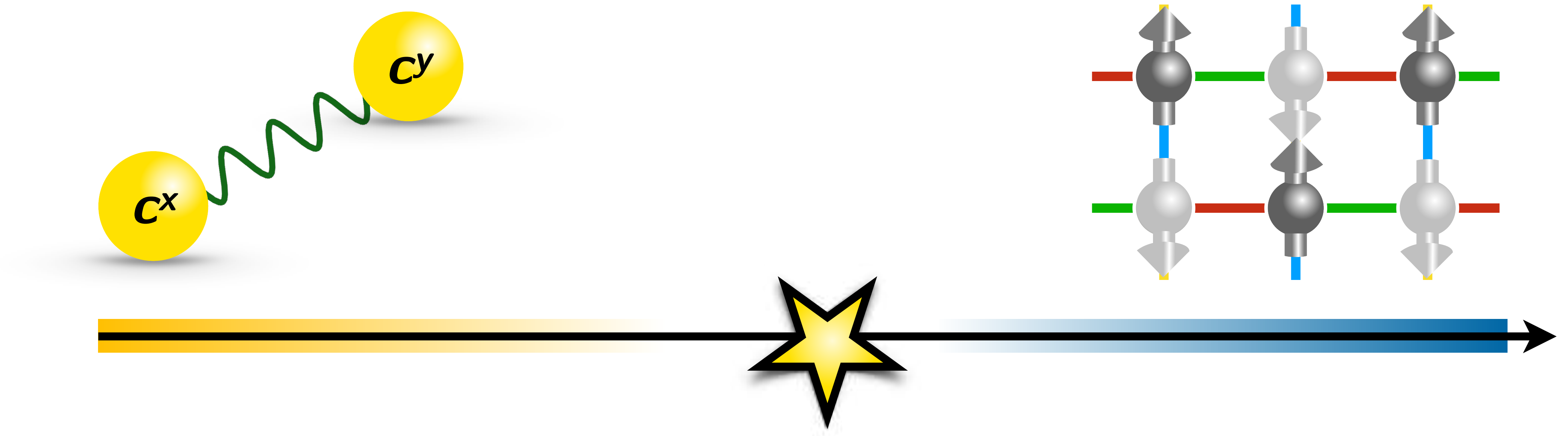
I. Introduction: Spin fractionalization



II. Example #1: Confinement transition in flatland U(1) gauge theory



III. Example #2: Spinon-metal—insulator transition in flatland $\mathbb{Z}_2$ gauge theory



IV. Conclusions: Spin-liquid criticality

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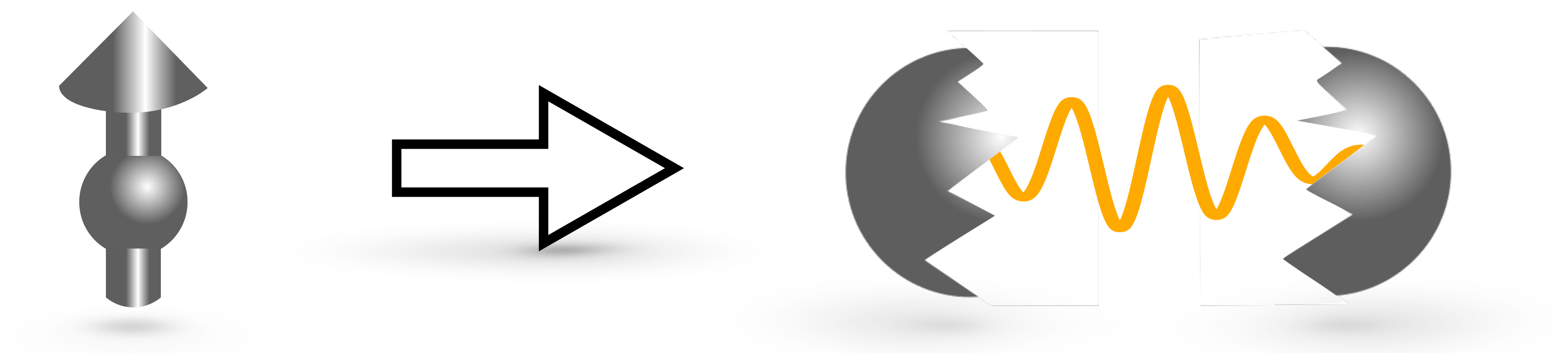

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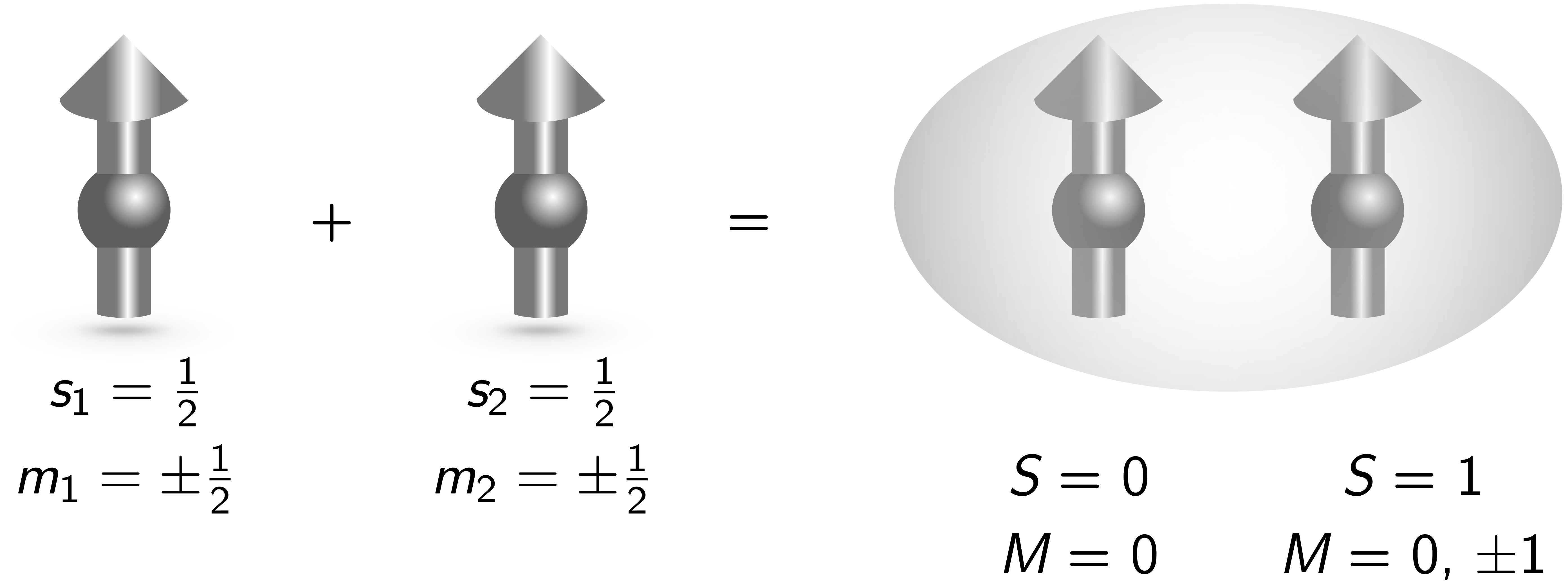
Introduction: Quantum numbers of composites

Free spins-1/2:



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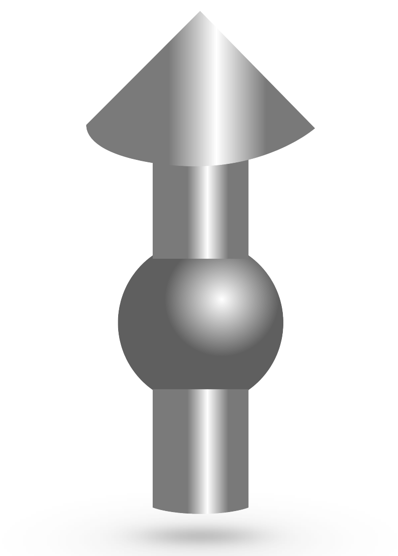
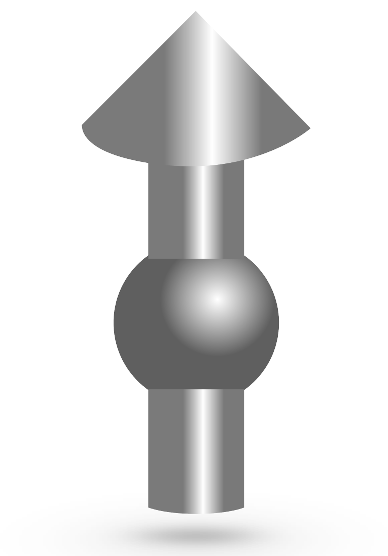


$s_1 = \frac{1}{2}$

$m_1 = \pm\frac{1}{2}$

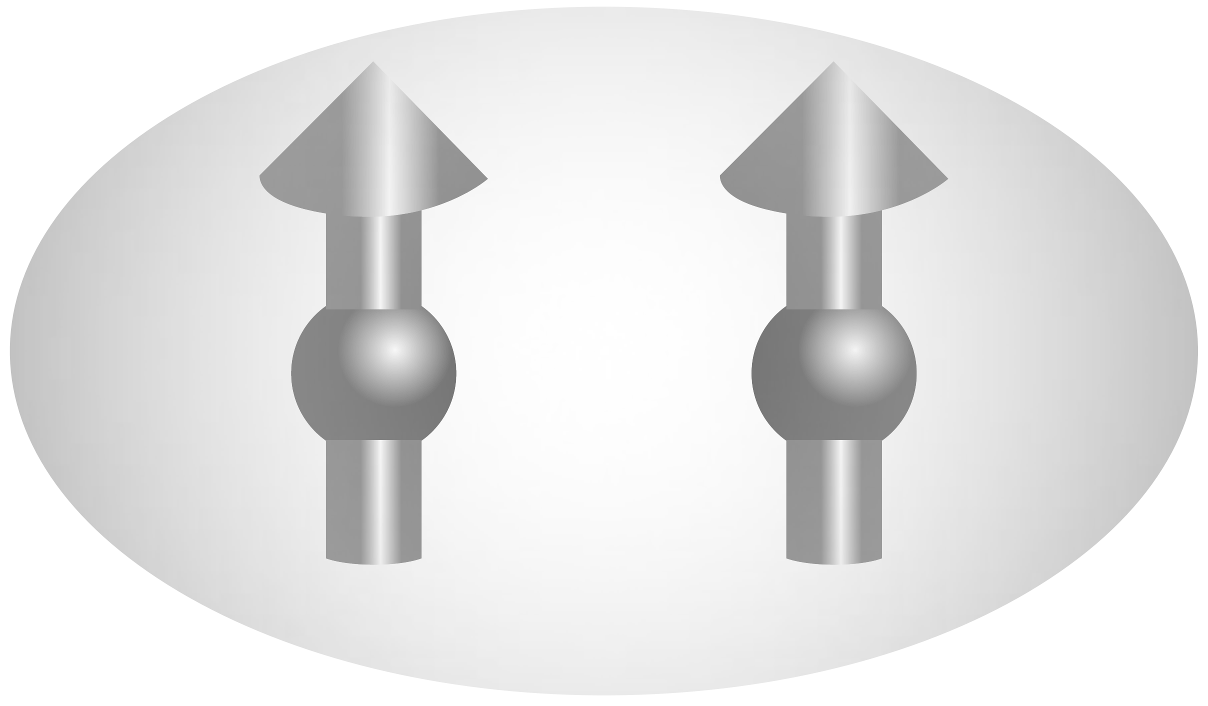
$+$



$s_2 = \frac{1}{2}$

$m_2 = \pm\frac{1}{2}$

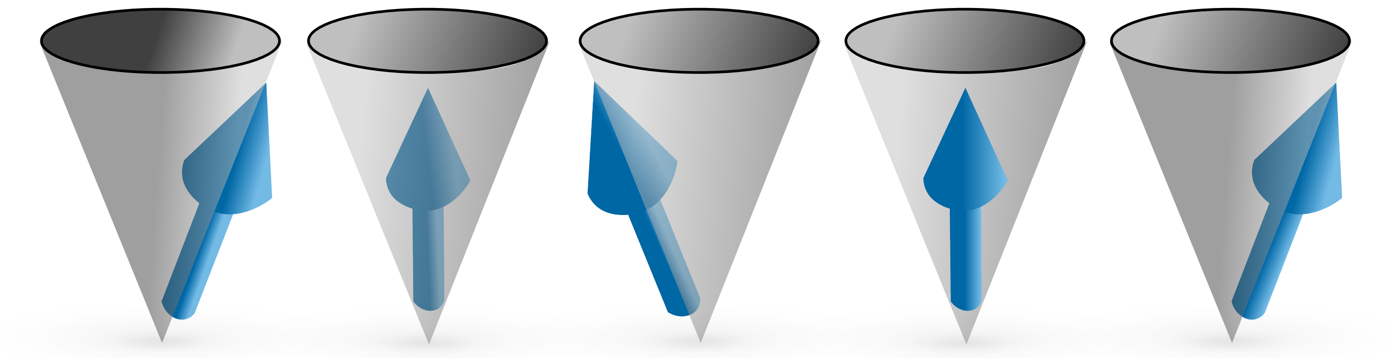
$=$



$S = 0$ $\quad$ $S = 1$

$M = 0$ $\quad$ $M = 0, \pm 1$

Interacting spins-1/2:



Magnons

$S = 1$

Introduction: Quantum numbers of composites

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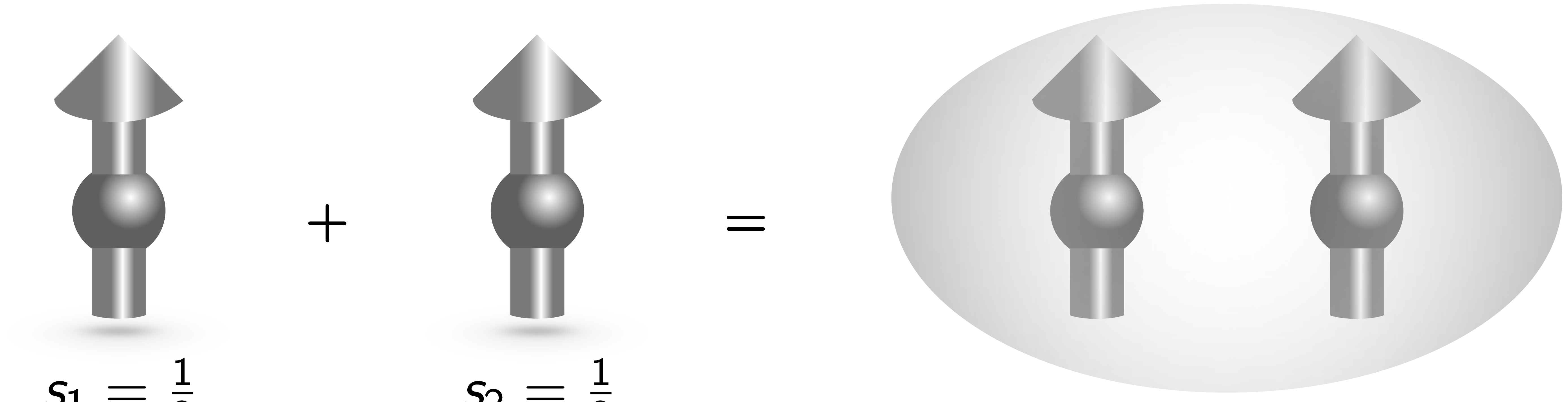

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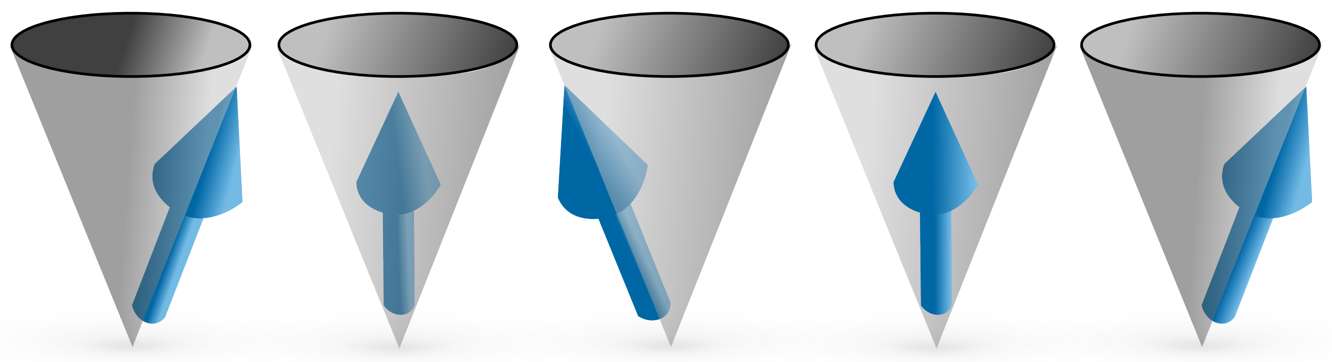

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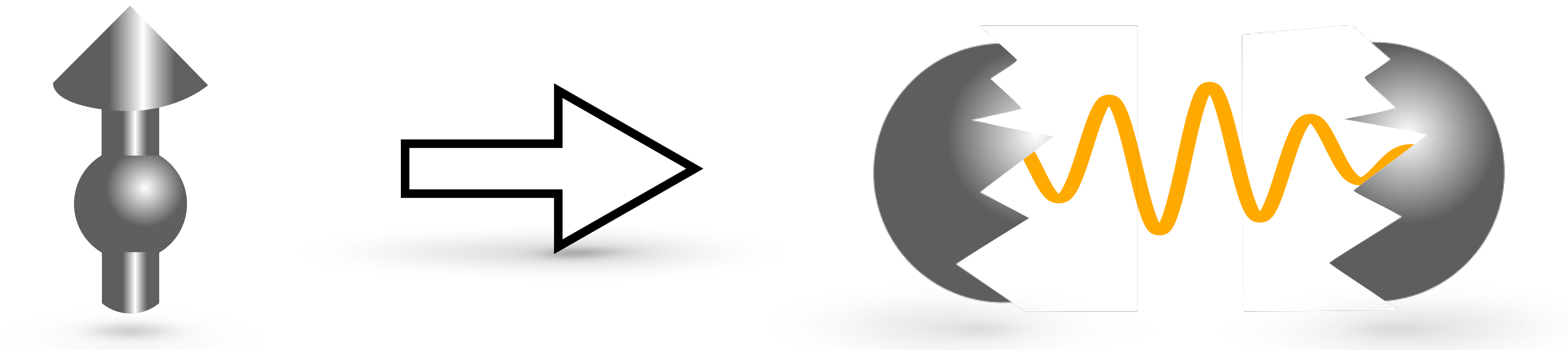
integer

$$\boxed{\text{Quantum numbers of composites} = n \cdot \text{quantum numbers of constituents}}$$

Introduction: Spin liquids



Fractionalization:

$\boxed{\text{Quantum numbers of collective excitations} \neq n \cdot \text{quantum numbers of constituents}}$

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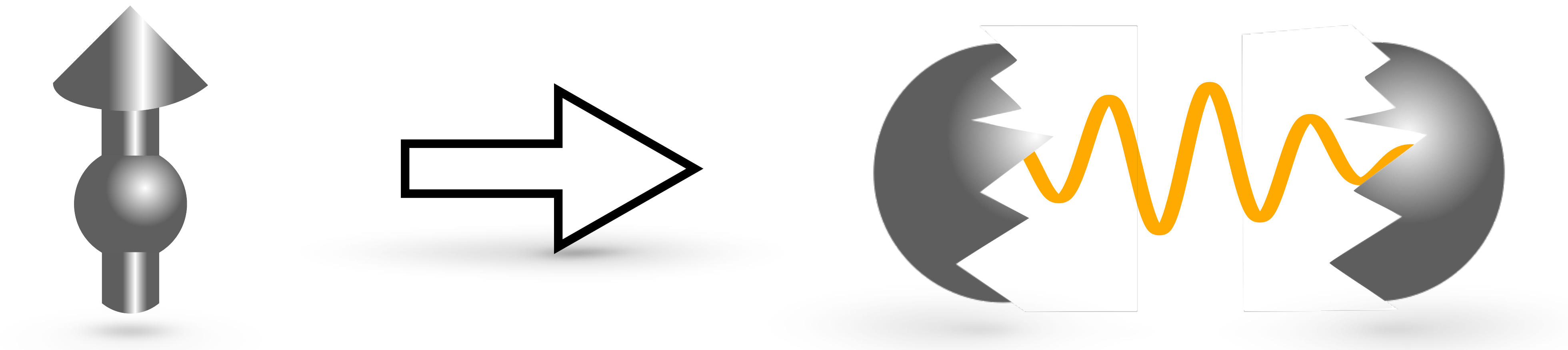

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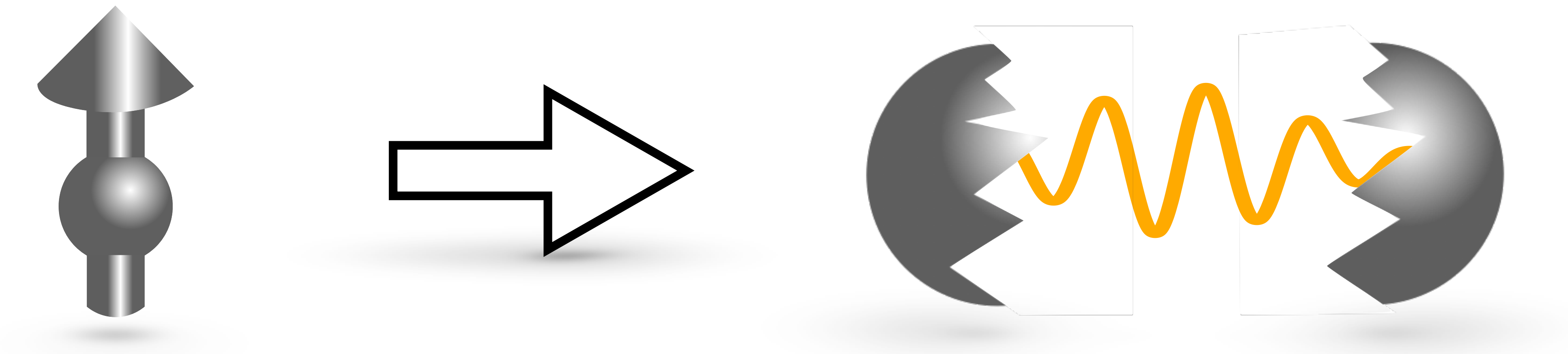
Parton decomposition:

$$\vec{S}_i = \frac{1}{2}\bar{\Psi}_i\vec{\sigma}\Psi_i$$

"Spinons"

Introduction: Spin liquids



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U(1) gauge redundancy:

$$\Psi_i \mapsto e^{i\lambda_i}\Psi_i$$

... full gauge redundancy: SU(2)
[Affleck *et al.*, PRB '88]

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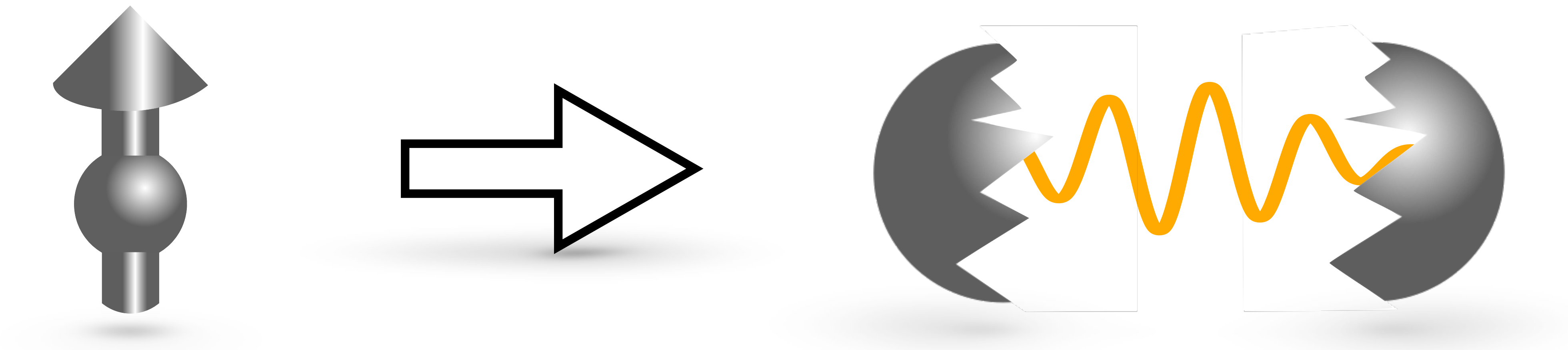

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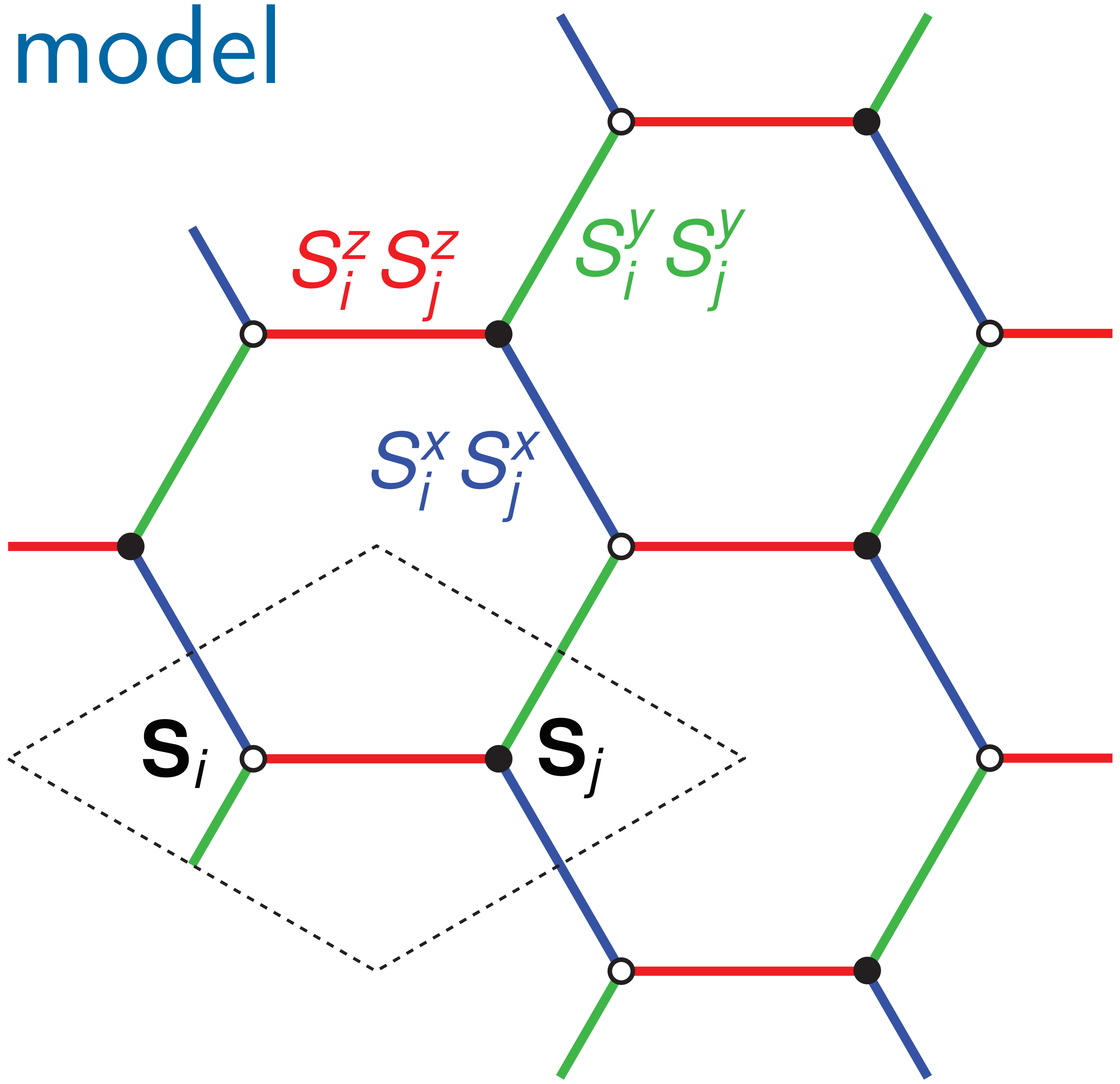
$\boxed{\text{Models featuring “deconfined” spinons?}}$

Introduction: Kitaev honeycomb model

Spins-1/2 on honeycomb lattice:



Alexei Kitaev

Hamiltonian:

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

[Kitaev, Ann. Phys. '06]

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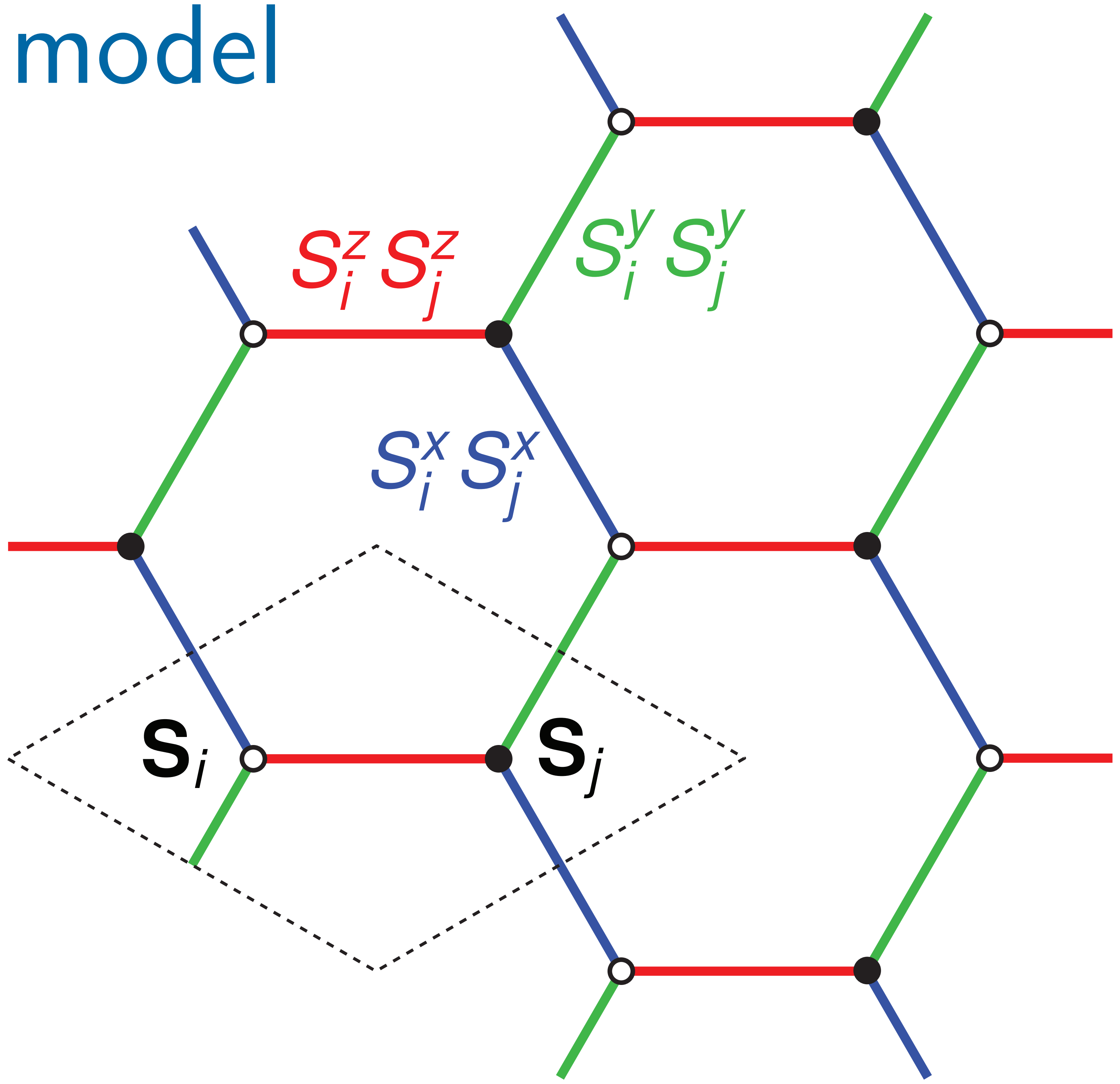

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Parton decomposition:

$$H \mapsto -iK \sum_{\langle ij \rangle} u_{ij} c_i c_j$$

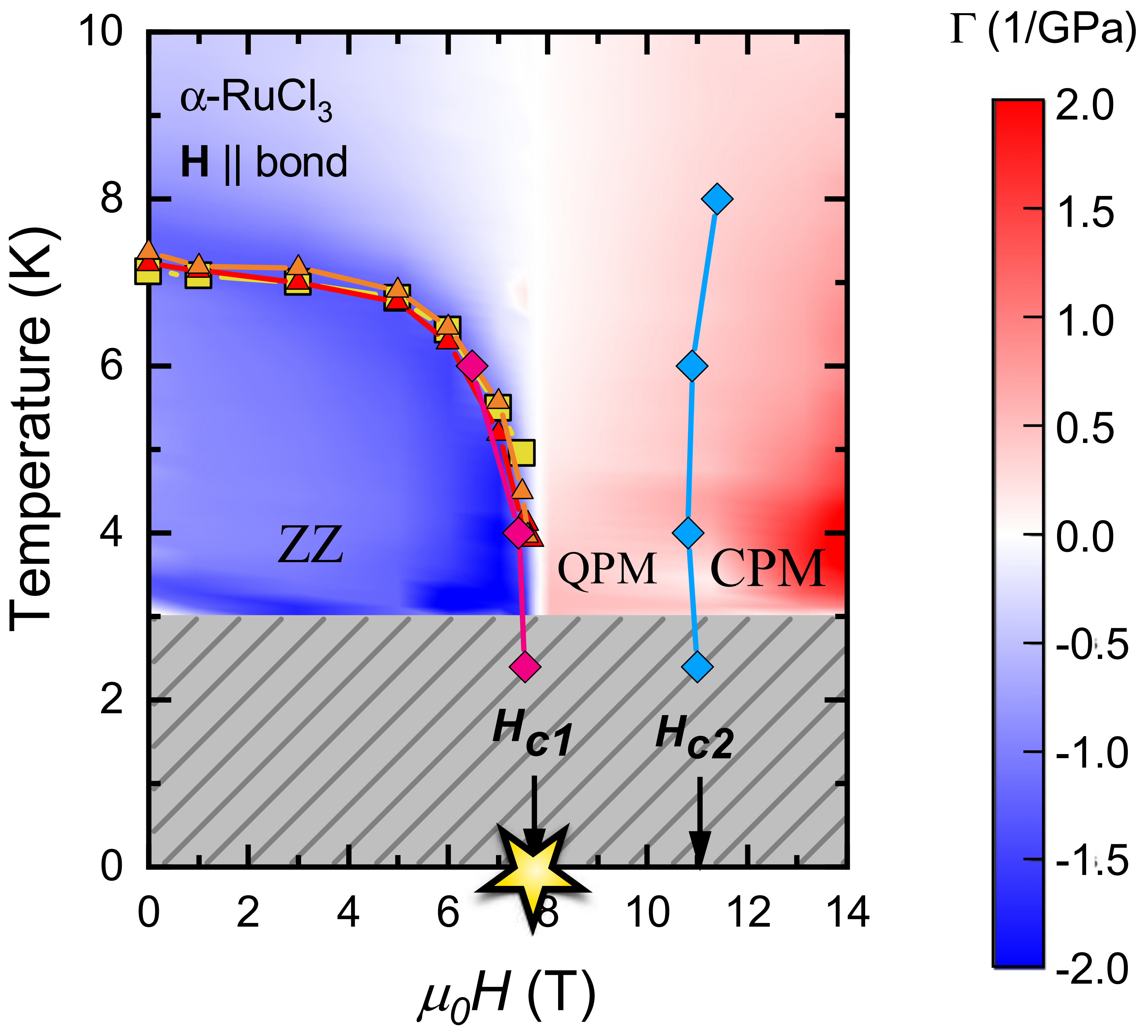
Majorana fermions $c^\dagger = c$

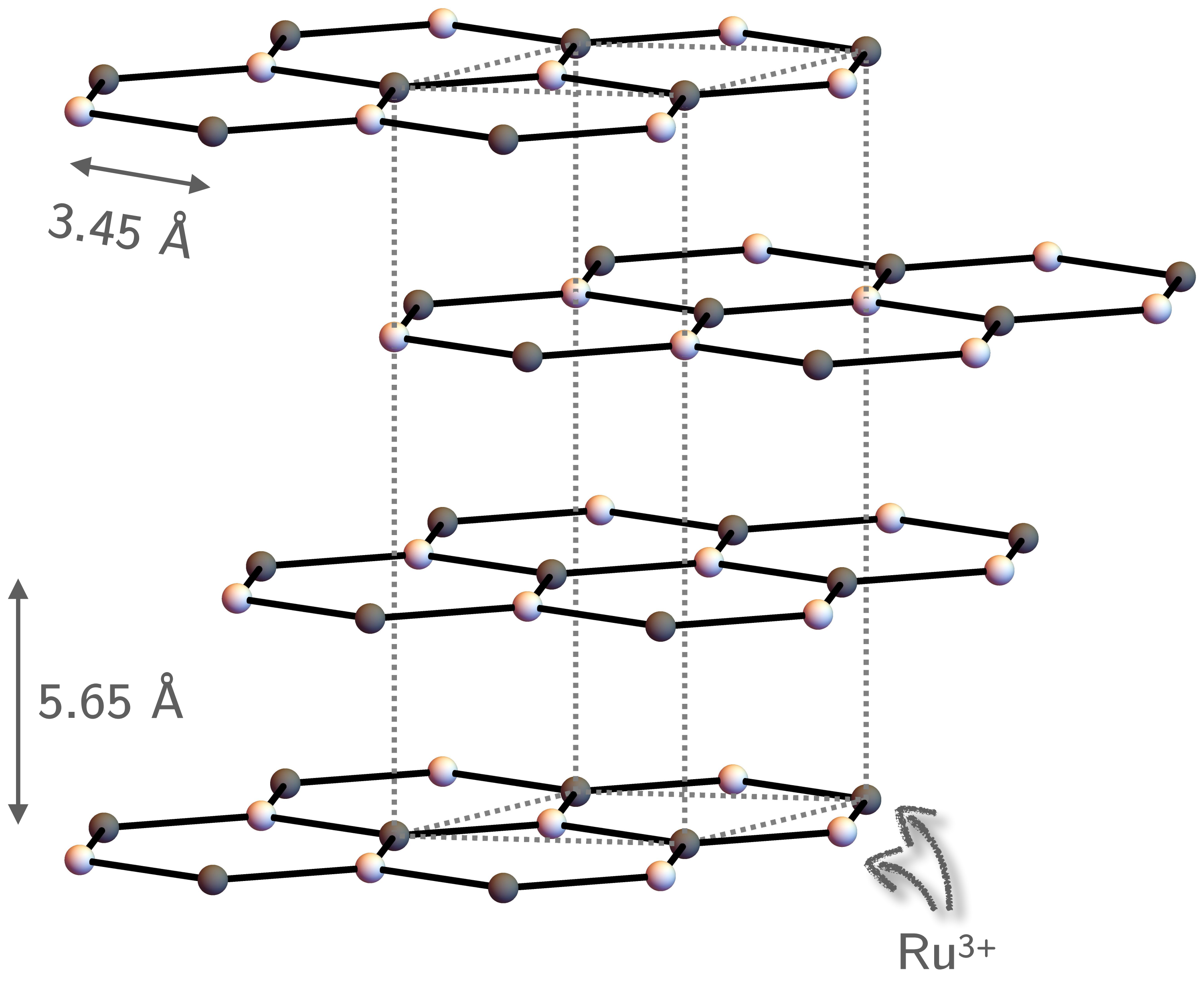
Static (!) $\mathbb{Z}_2$ gauge field

[Kitaev, Ann. Phys. '06]

Introduction: Spin-liquid criticality

α-RuCl₃:





[Wolter, Corredor, LJ, *et al.*, PRB '17]
[Gass, ..., LJ, *et al.*, PRB '21]

Introduction: Spin-liquid criticality

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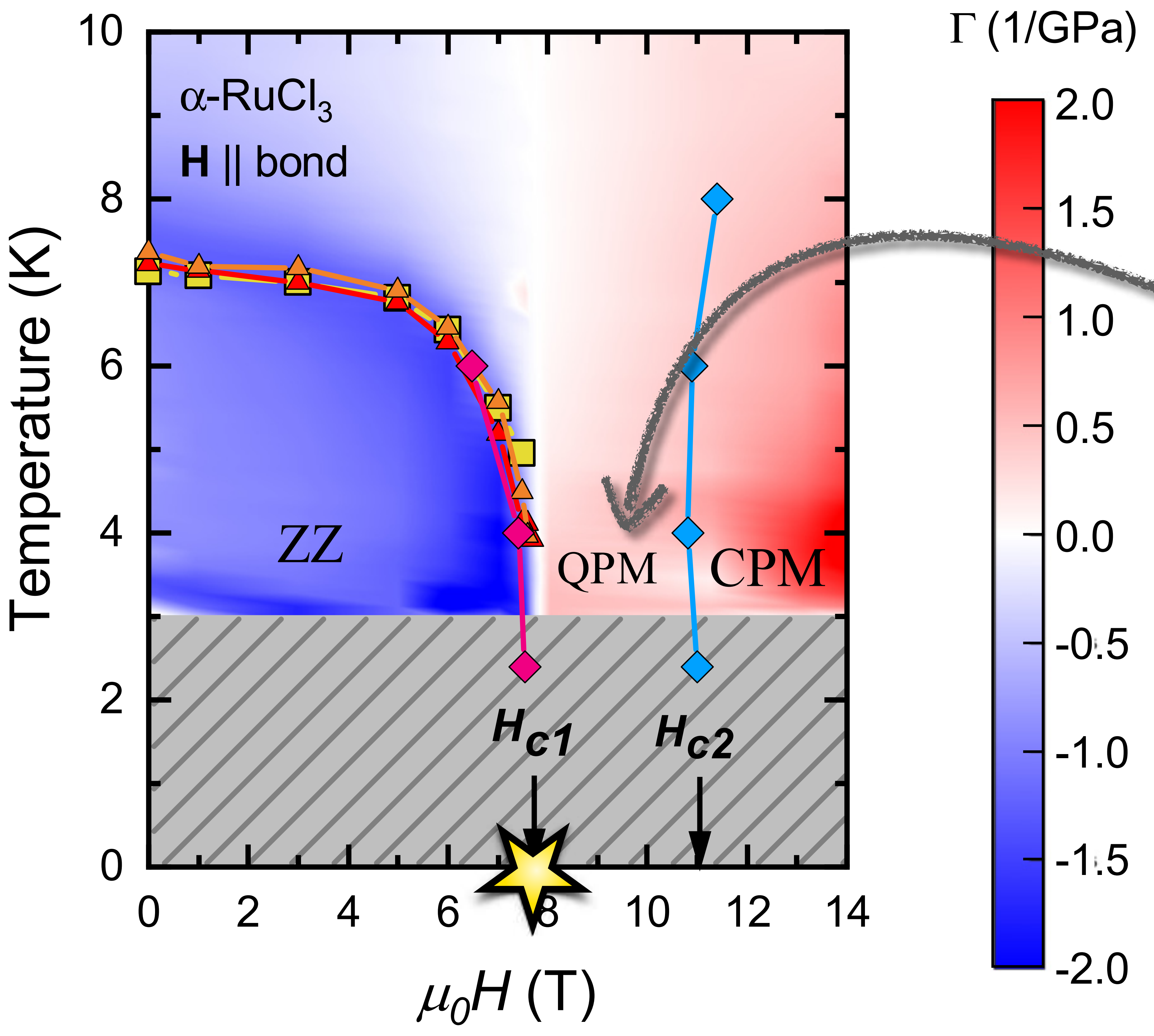

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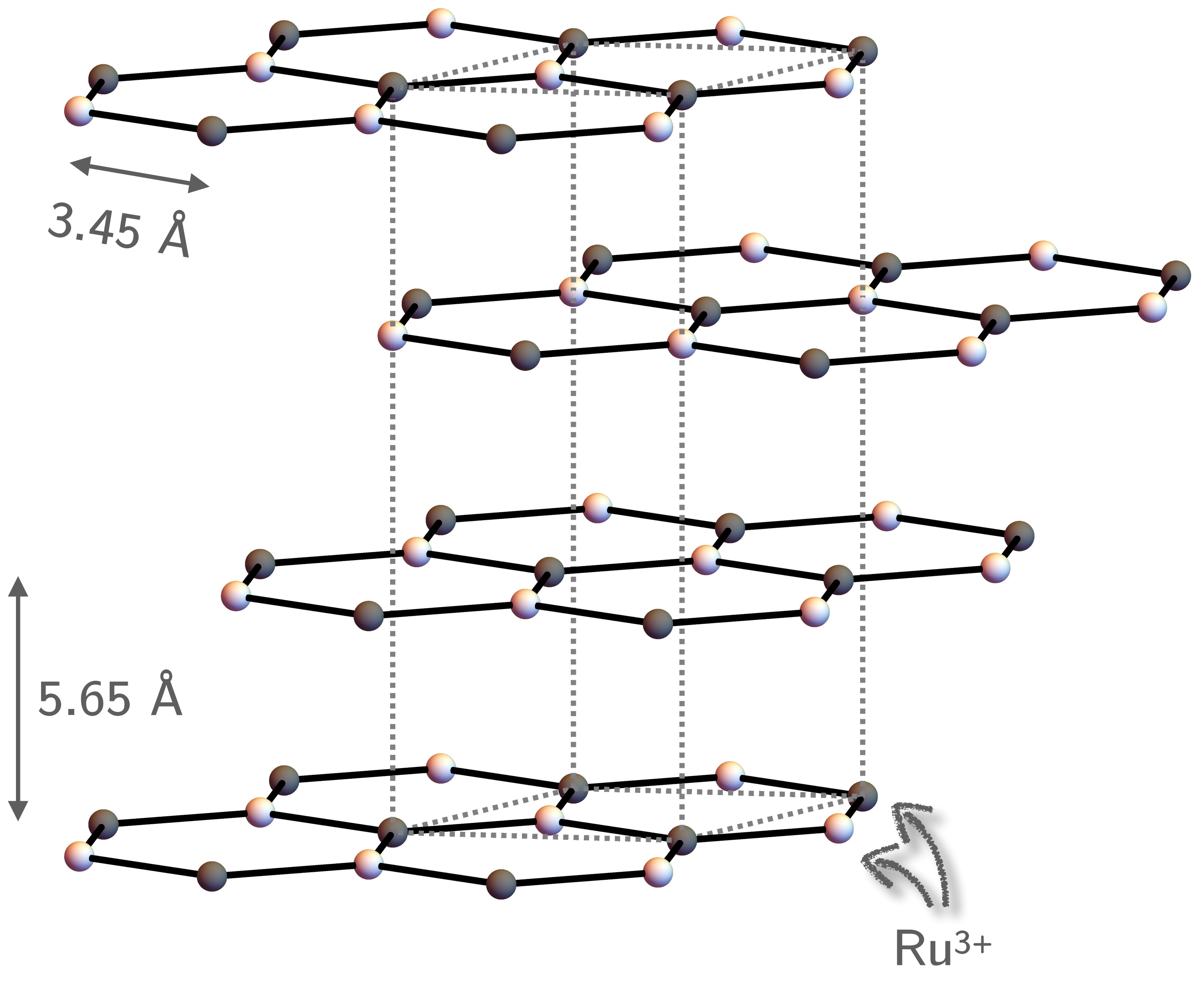

Nature of quantum paramagnet (QPM)?

[Banerjee *et al.*, npj QM '18]
[Kasahara *et al.*, Nature '18]
[Czajka *et al.*, Nat. Phys. '21]

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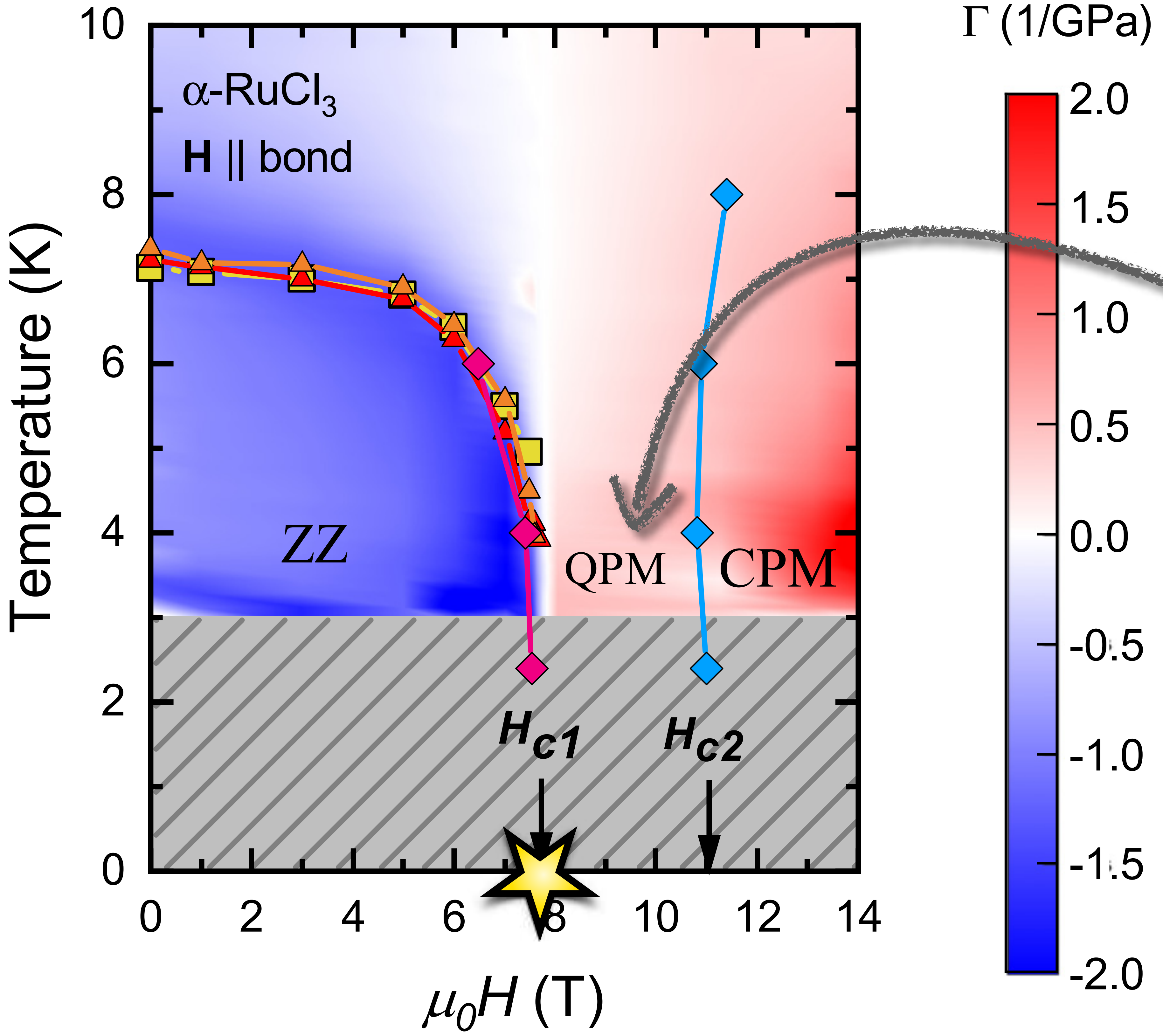

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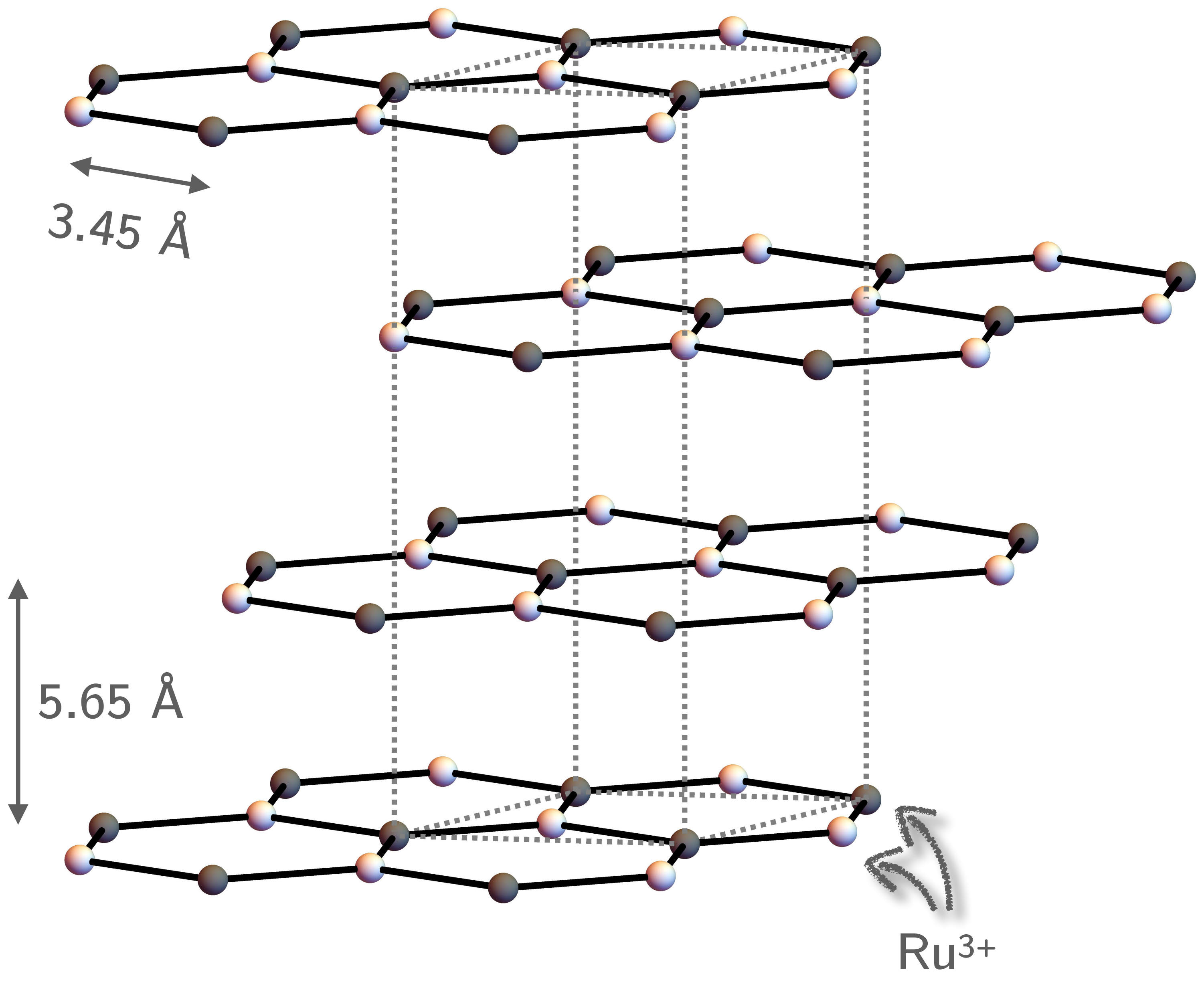

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This talk:

How do fractionalized excitations affect quantum criticality?

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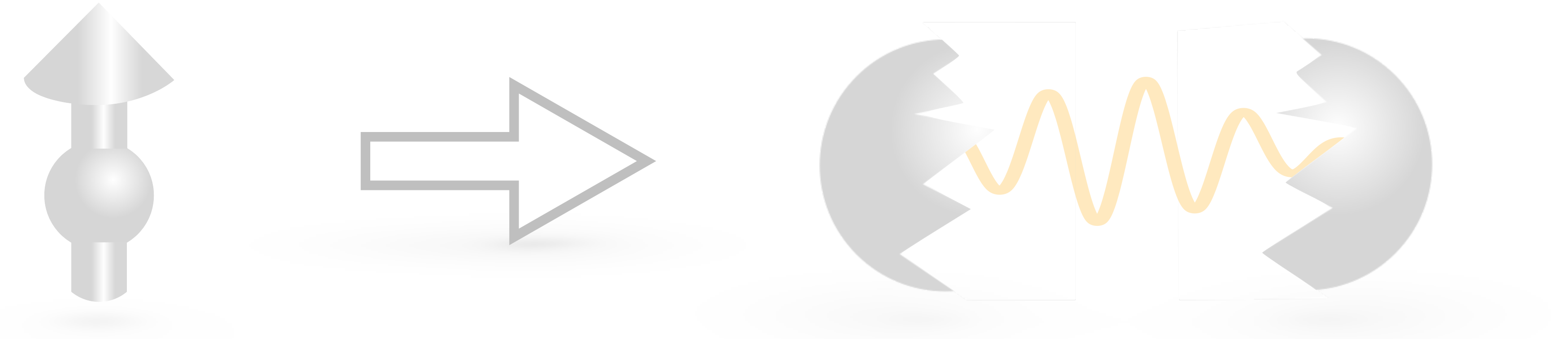

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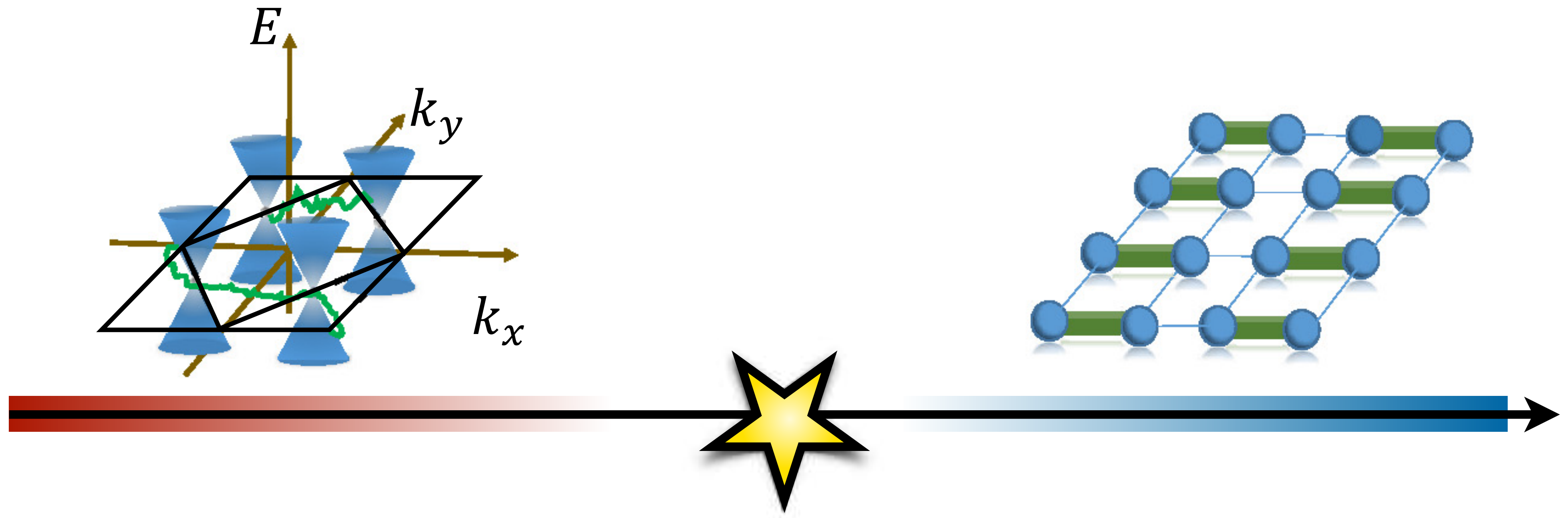

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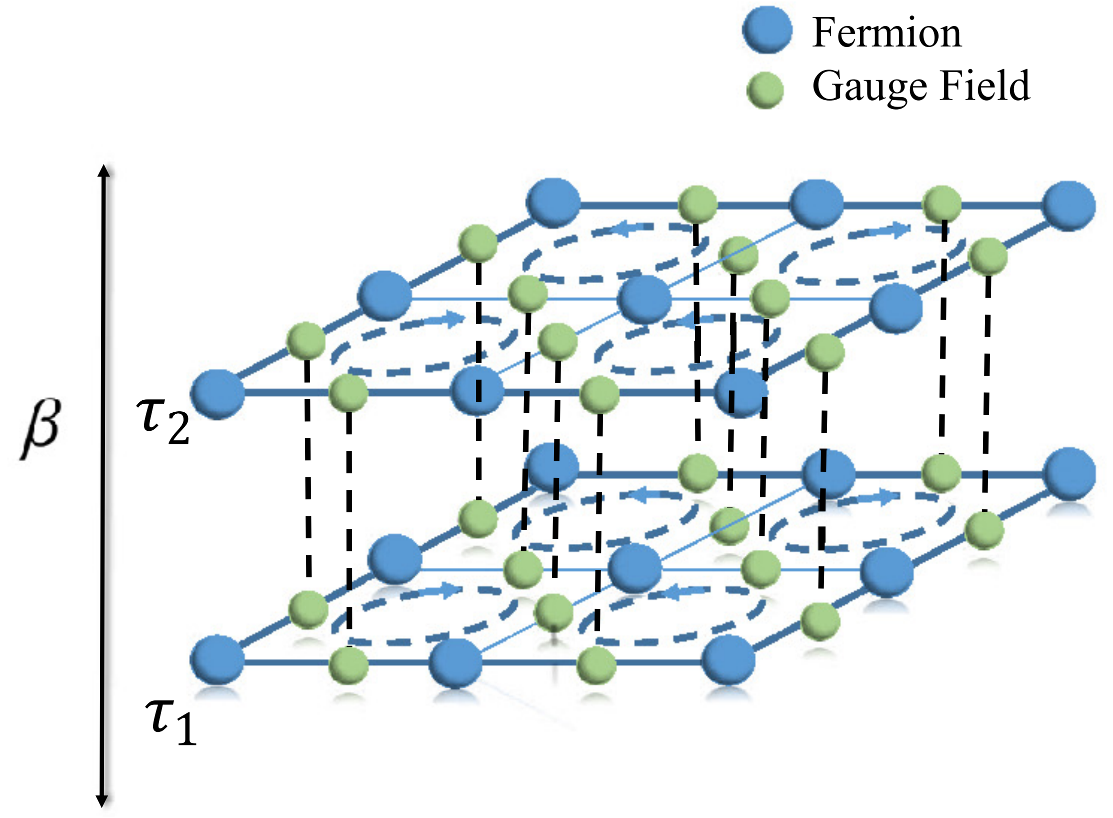
IV. Conclusions: Spin-liquid criticality

Flatland U(1) gauge theory: Lattice compact QED$_3$



Action (square lattice):

Compact U(1) gauge field

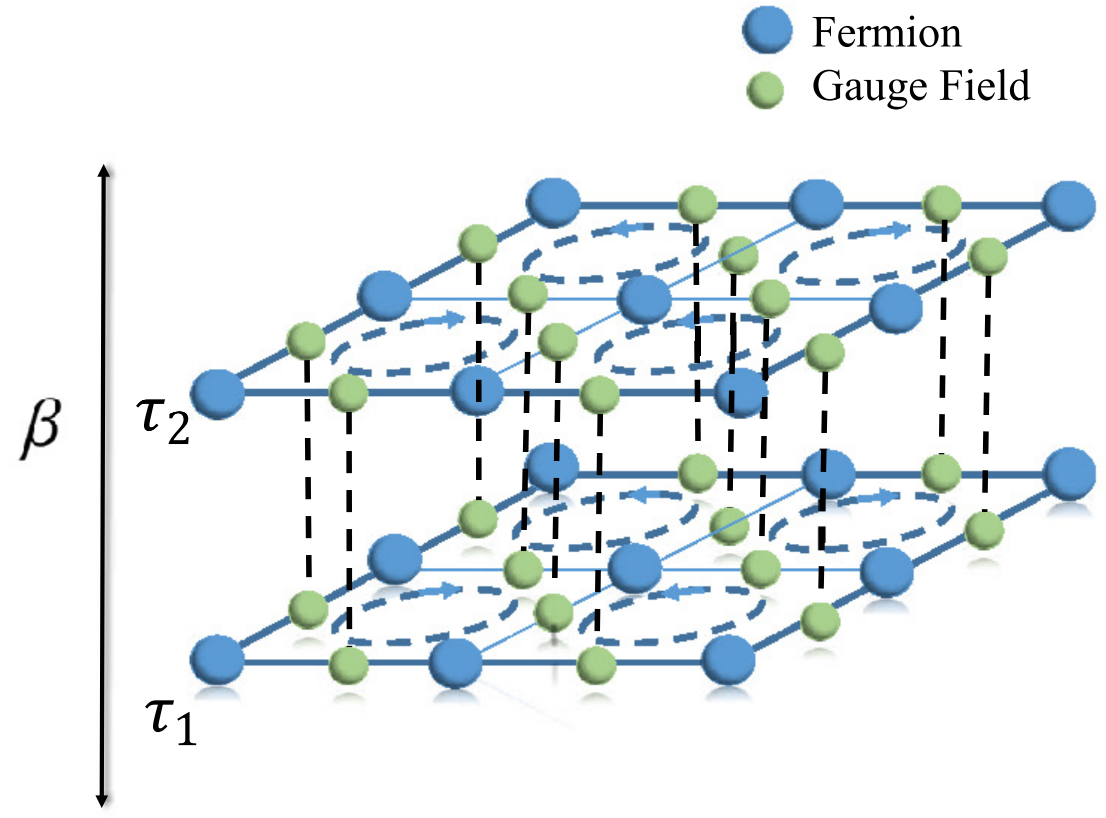
Fermions

$$S = \int_0^\beta d\tau \left[\sum_{\langle ij \rangle, \alpha} \psi^\dagger_{i\alpha} (\partial_\tau \delta_{ij} - t e^{i\varphi_{ij}}) \psi_{j\alpha} + \text{H.c.} \right.$$

$$\left. + \frac{4}{J N_\text{f}} \sum_{\langle ij \rangle} \frac{1 - \cos[\varphi_{ij}(\tau + 1) - \varphi_{ij}(\tau)]}{\Delta\tau^2} + \frac{K N_\text{f}}{2} \sum_{\square} \cos(\operatorname{curl} \varphi) \right]$$

... favors π flux for $K > 0$

Flatland U(1) gauge theory: Lattice compact QED$_3$



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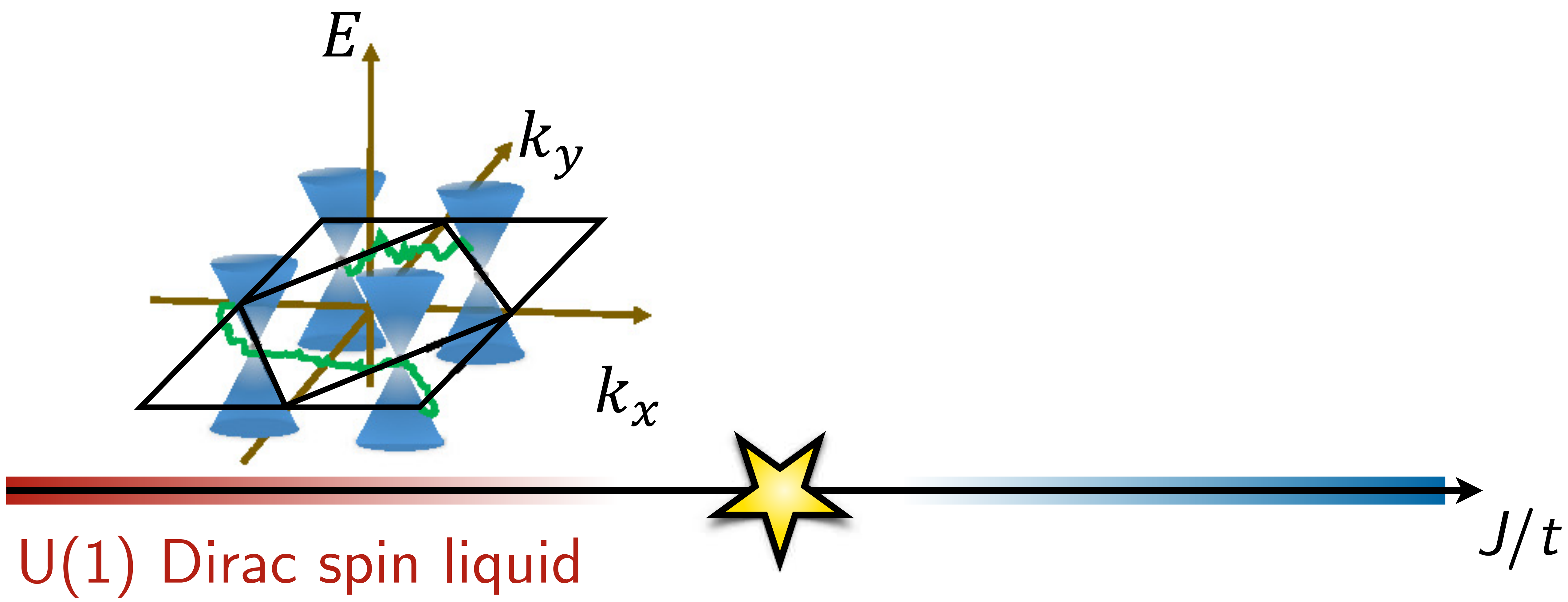

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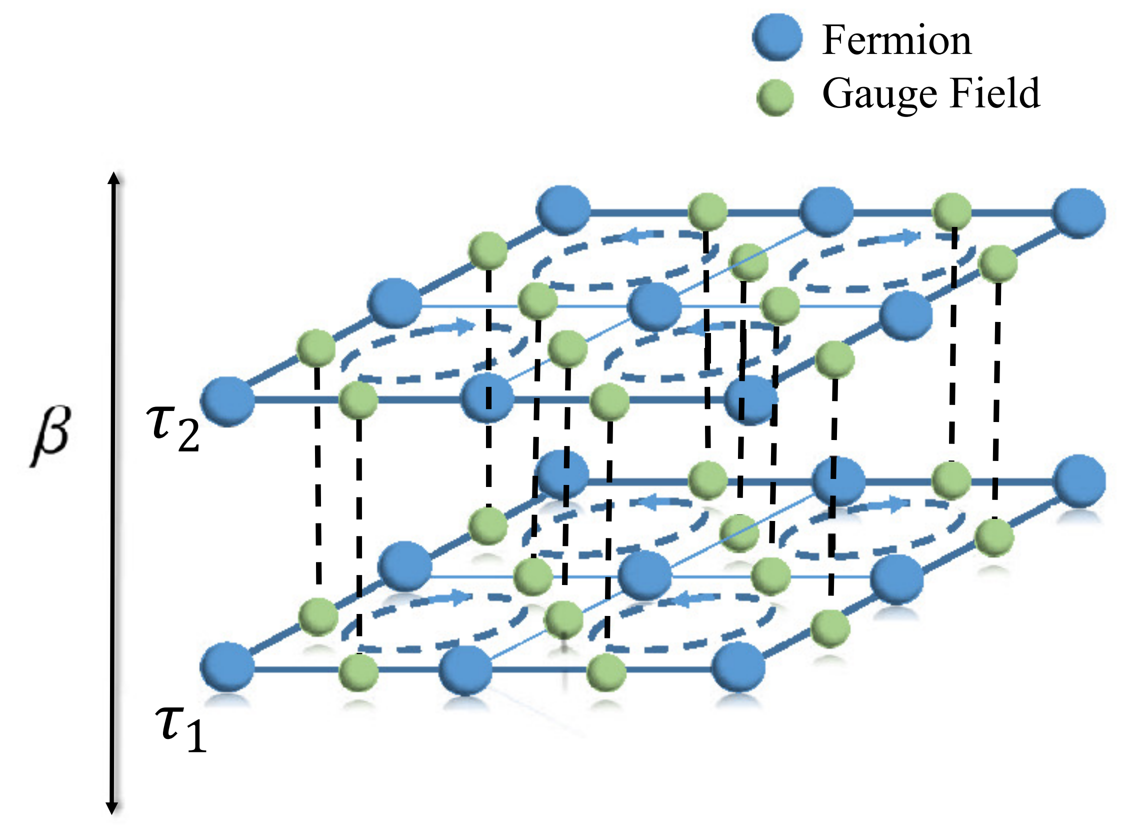

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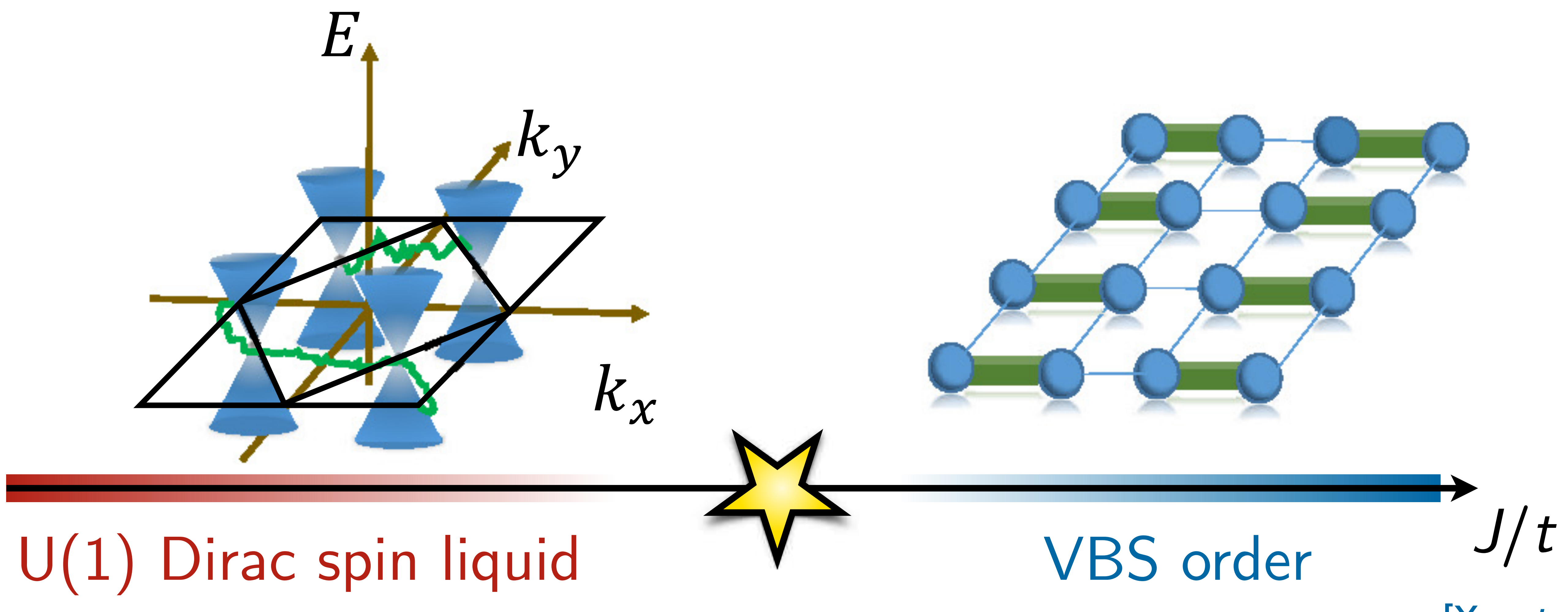

[Xu *et al.*, PRX '19]

Field theory: QED$_3$-Gross-Neveu-XY

Action (continuum):

Noncompact $U(1)$ gauge field

$$S = \int d\tau \int d^2\vec{x} \left[\bar{\psi}\gamma_\mu(\partial_\mu - iA_\mu)\psi + \phi^a\bar{\psi}\mu^a\psi + \frac{r}{2}\phi^a\phi^a + \frac{1}{2e^2}(\epsilon_{\mu\nu\rho}\partial_\nu A_\rho)^2 \right]$$

$a = x, y$

Dirac fermions

XY order parameter

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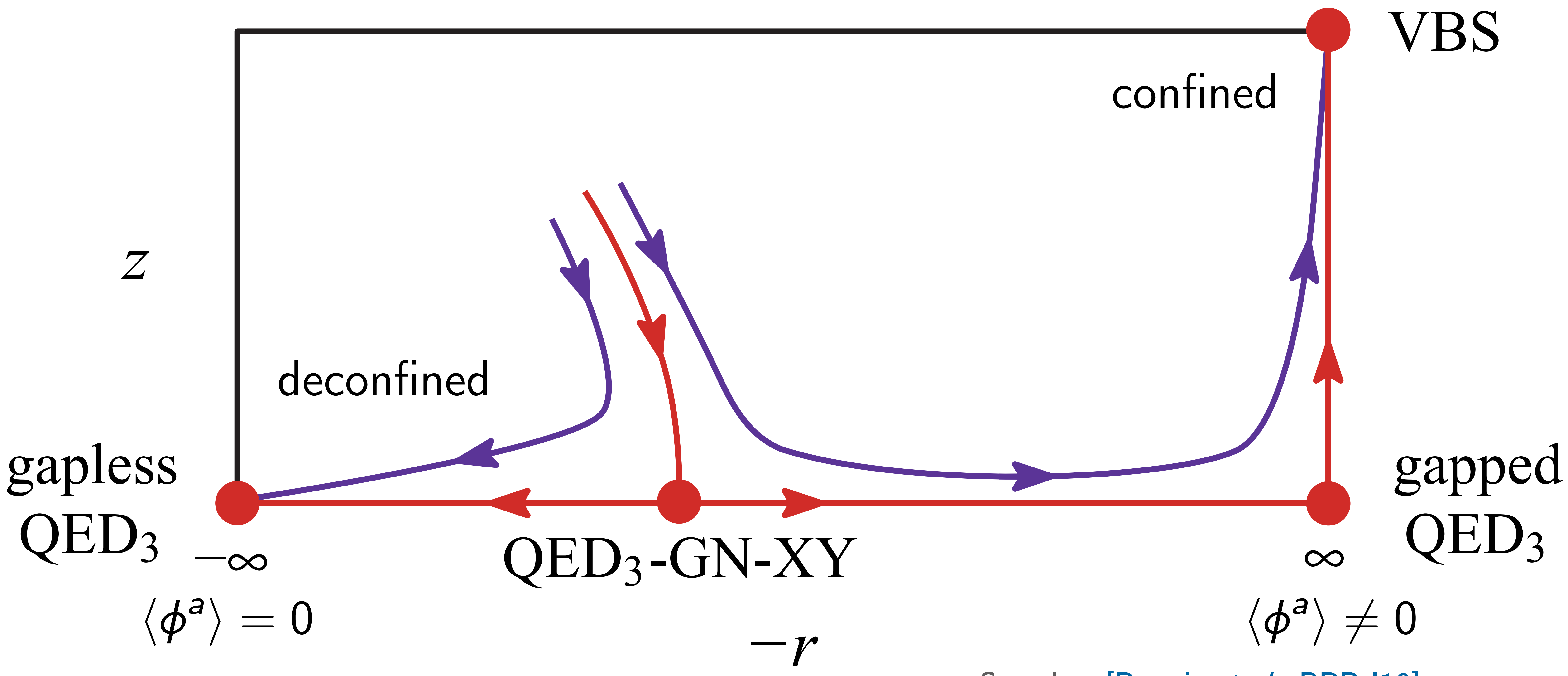
RG flow:



QED$_3$-GN-XY criticality:

$$\nu^{-1} = 1 - \frac{80}{3\pi^2 N_f} + \mathcal{O}(1/N_f^2)$$

$$\eta_\phi = 1 + \frac{56}{3\pi^2 N_f} + \mathcal{O}(1/N_f^2)$$

$$\Delta_{\text{VBS}} = 1 + \frac{28}{3\pi^2 N_f} + \mathcal{O}(1/N_f^2)$$

$$\Delta_{\text{AFM}} = 2 - \frac{40}{3\pi^2 N_f} + \mathcal{O}(1/N_f^2)$$

[LJ, Wang, Scherer, Meng, Xu, PRB '20]

Extension to $\mathcal{O}(1/N_f^2)$: [Zerf *et al.*, PRD '20]

See also: [Dupuis *et al.*, PRB '19]

→ Talk Joseph Maciejko Tue 17:45

Evidence for QED$_3$-Gross-Neveu-XY criticality

Scenario 1: Conventional paramagnet

XY: $\nu \simeq 0.672$

$\eta_\phi \simeq 0.039$

Scenario 2: Dirac fermions

Gross-Neveu-XY: $\nu \simeq 1.07$

$\eta_\phi \simeq 0.97$

... for $N_f = 8$

→ Talk Sandro Sorella Mon 14:15

Scenario 3: Dirac fermions + U(1) gauge field

QED$_3$-Gross-Neveu-XY: $\nu \simeq 1.51$

$\eta_\phi \simeq 1.24$

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[LJ, Wang, Scherer, Meng, Xu, PRB '20]

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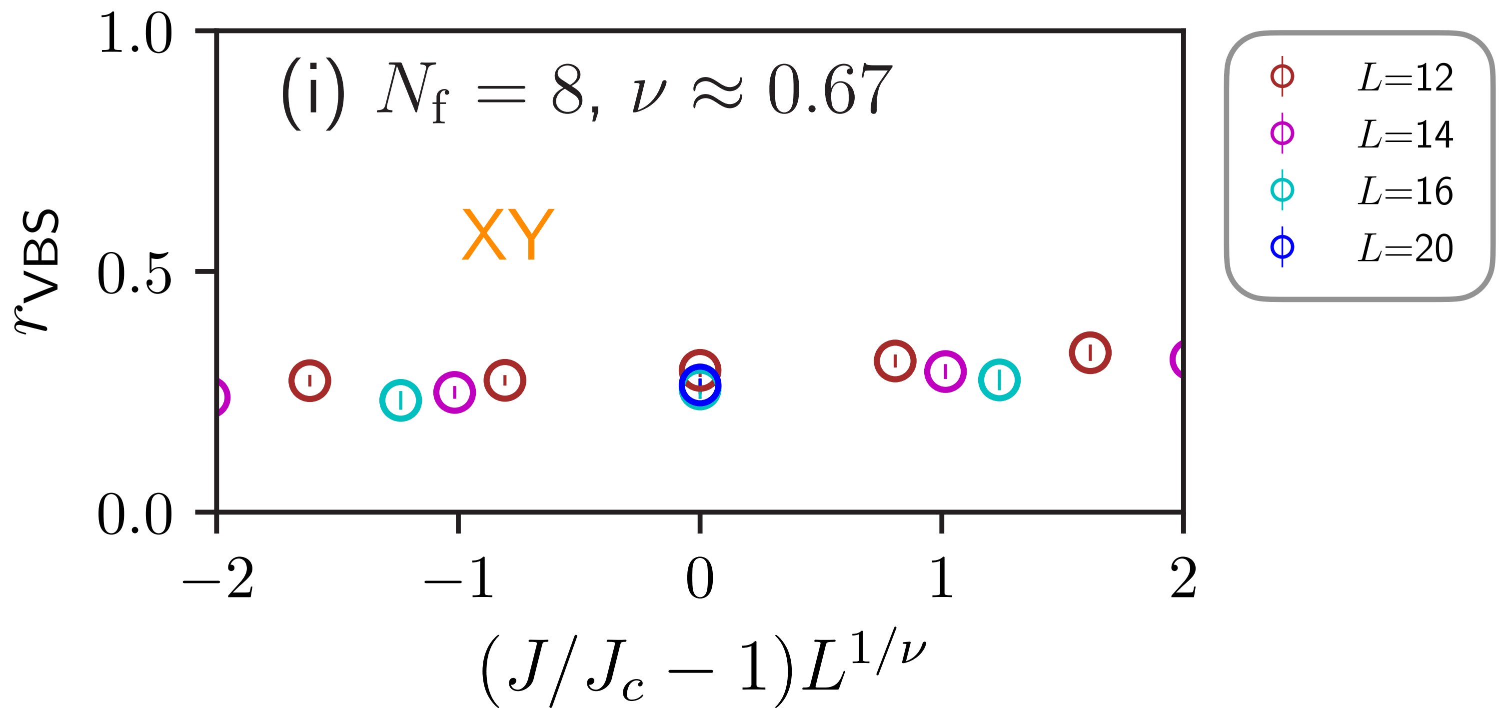

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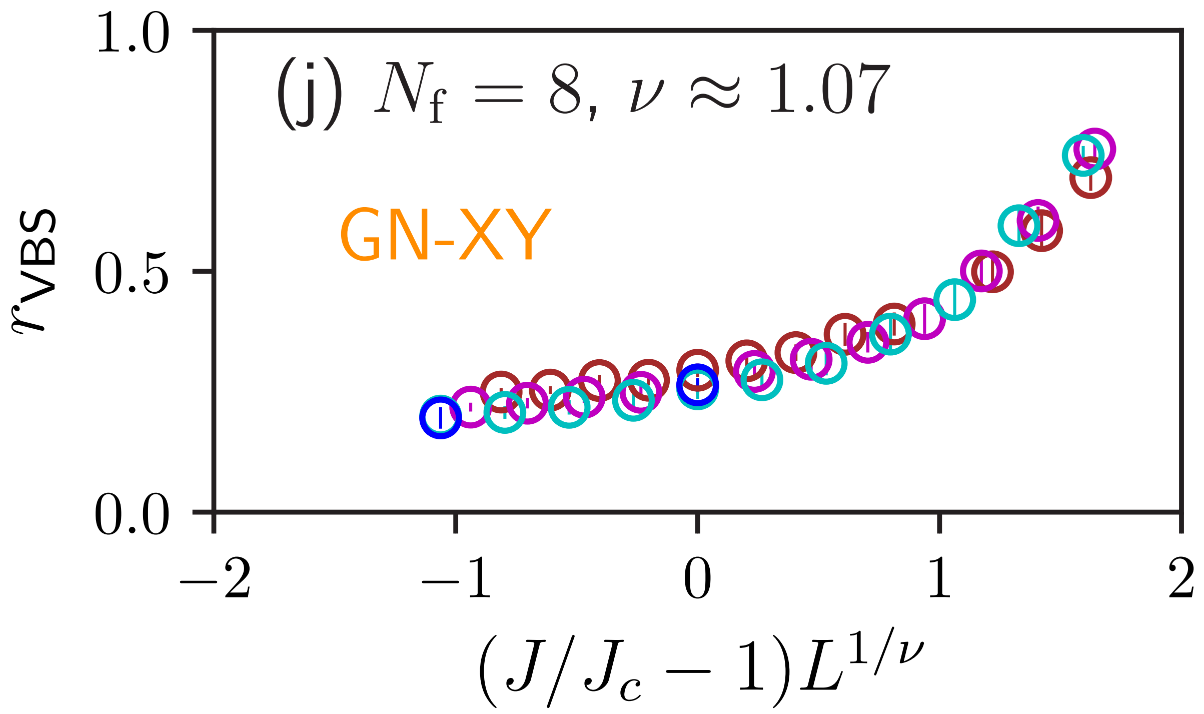

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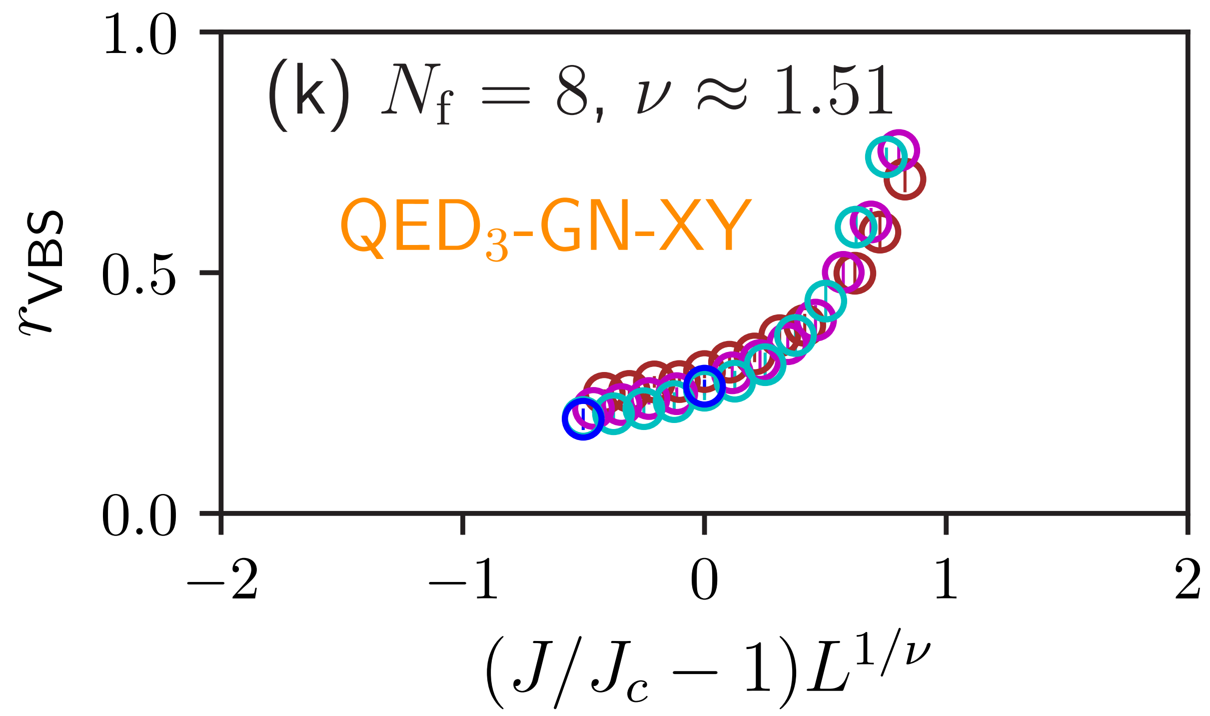

[LJ, Wang, Scherer, Meng, Xu, PRB '20]

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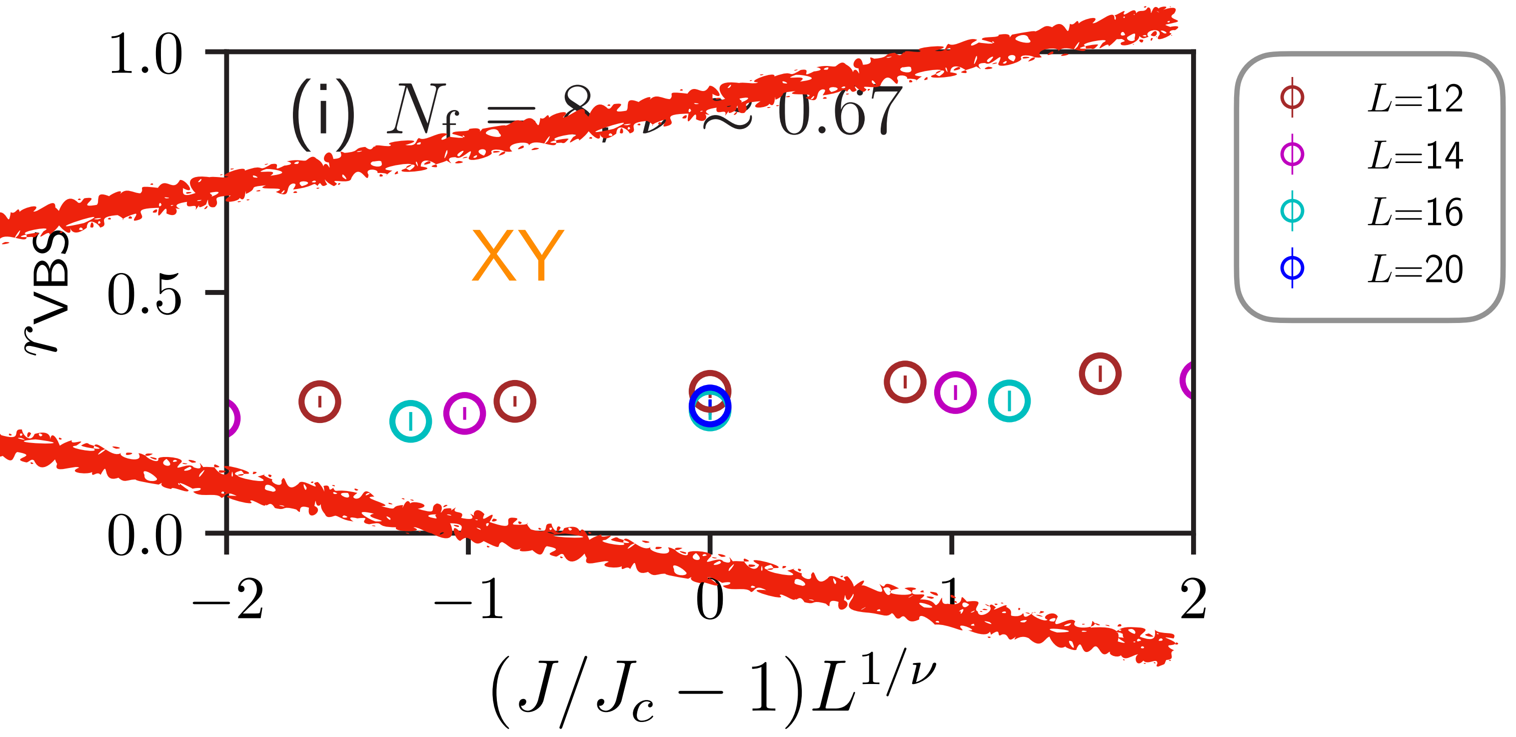

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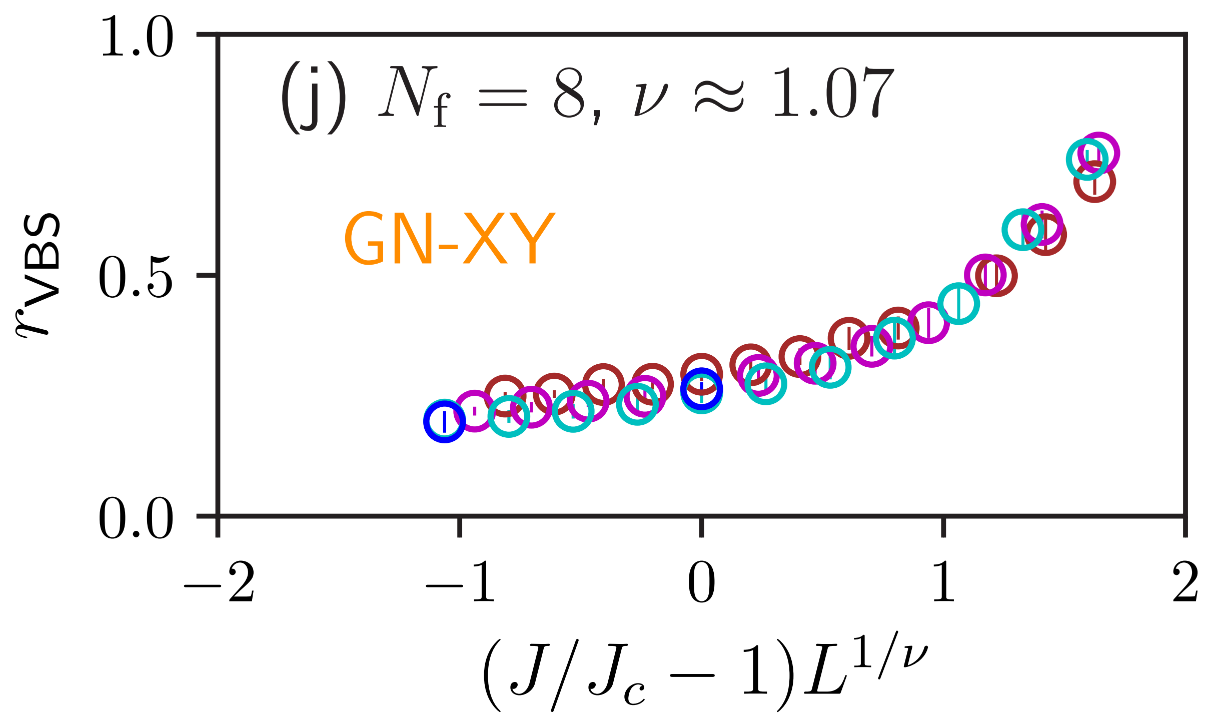

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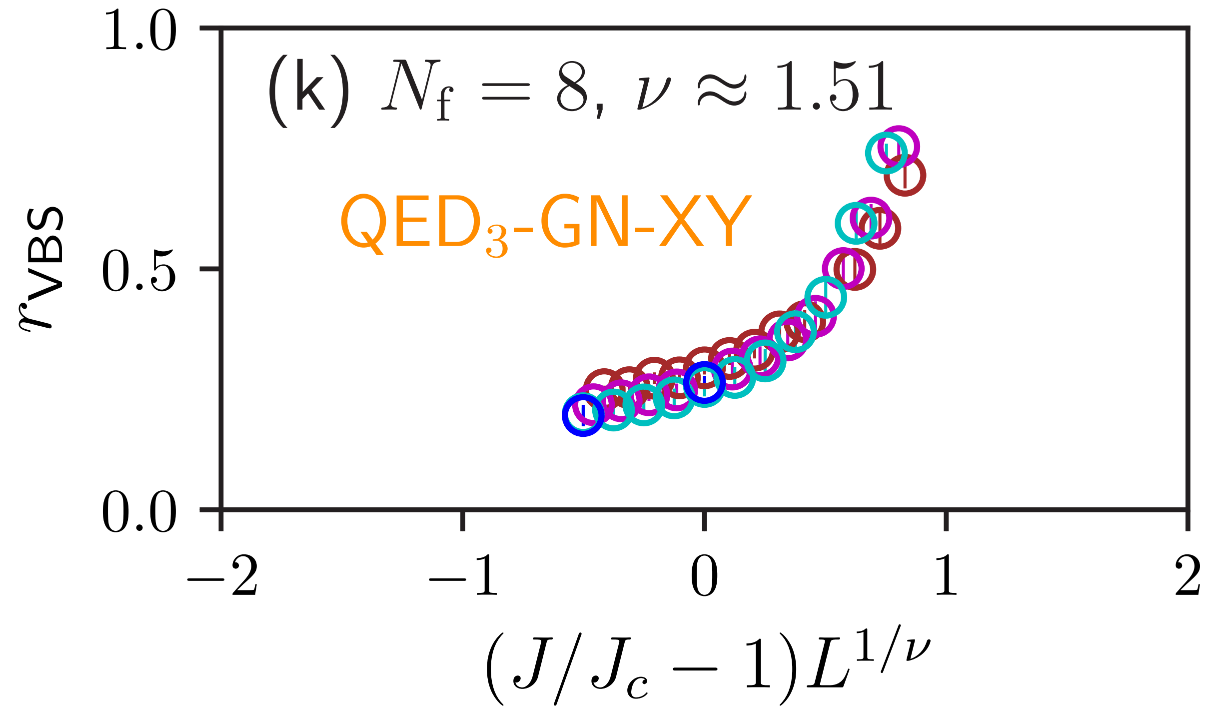

[LJ, Wang, Scherer, Meng, Xu, PRB '20]

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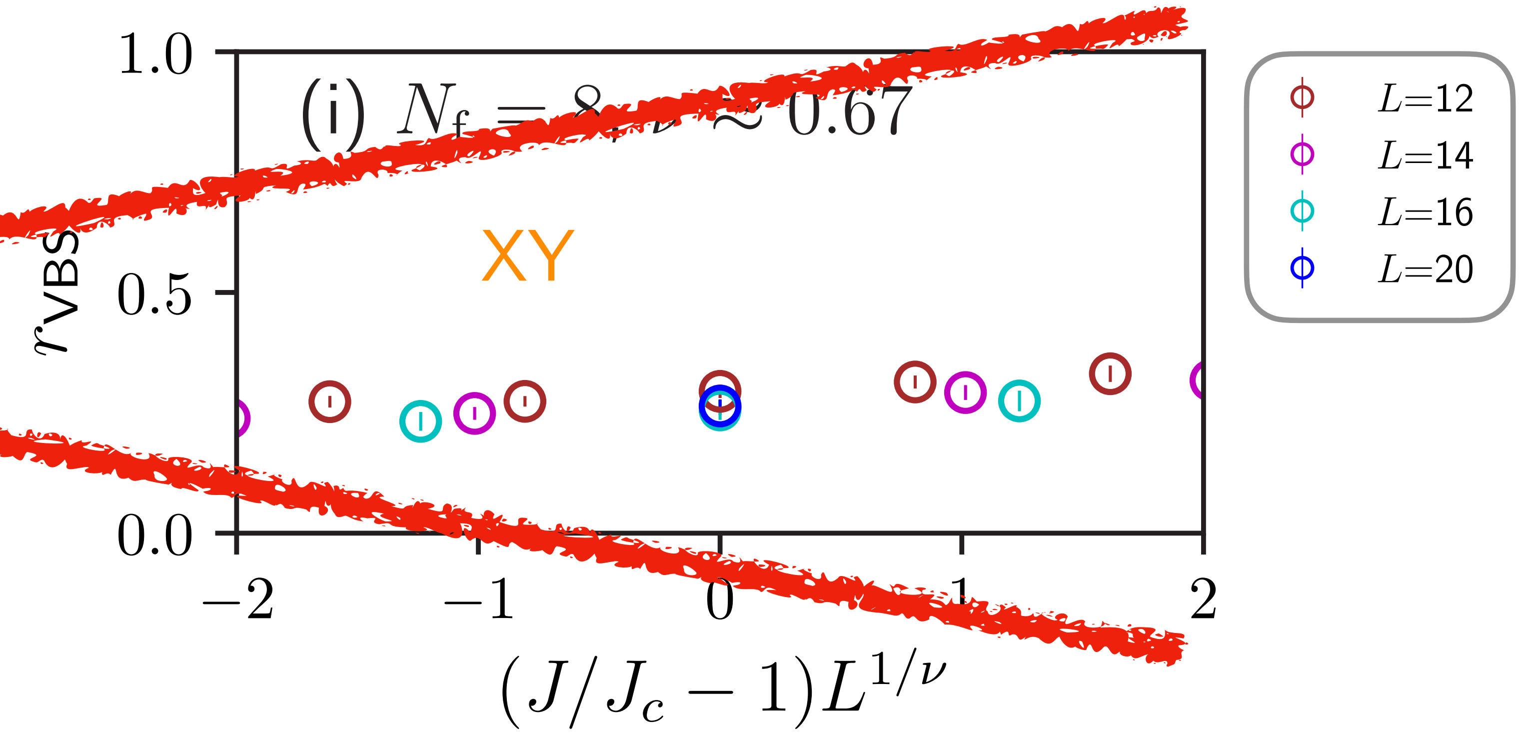

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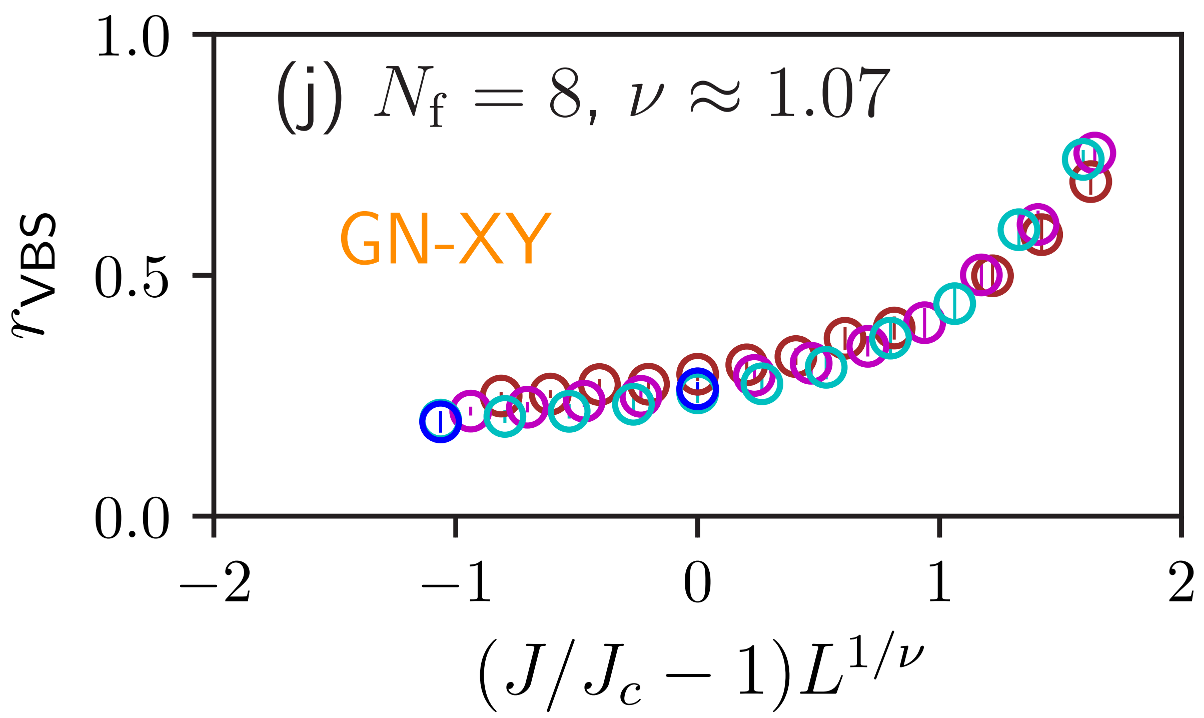

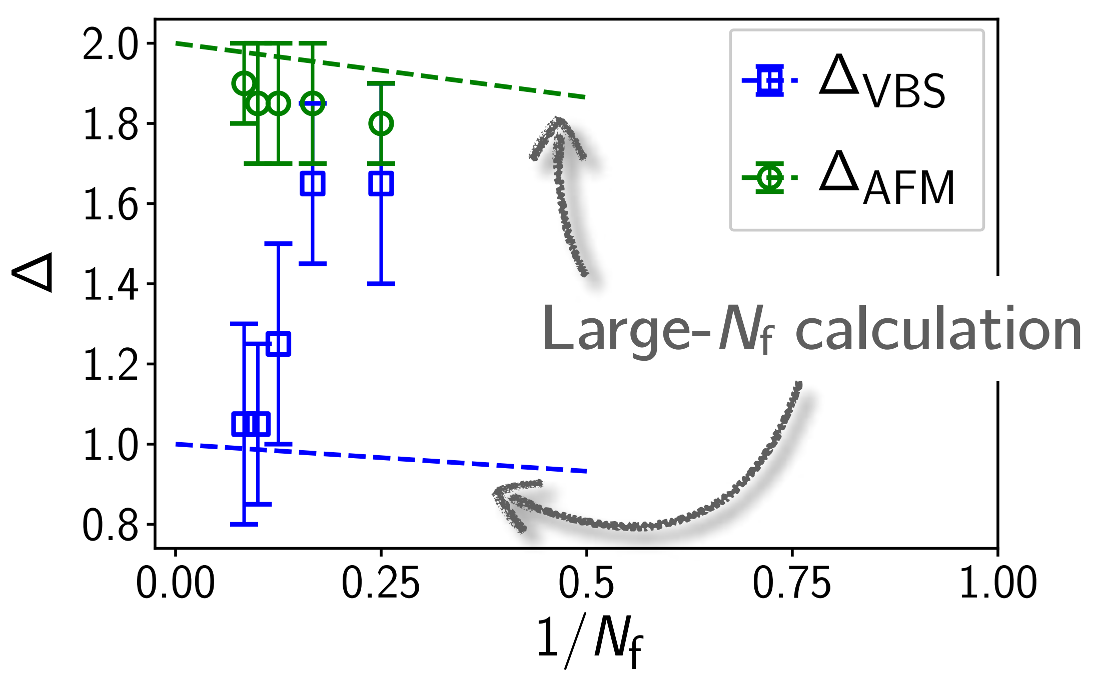

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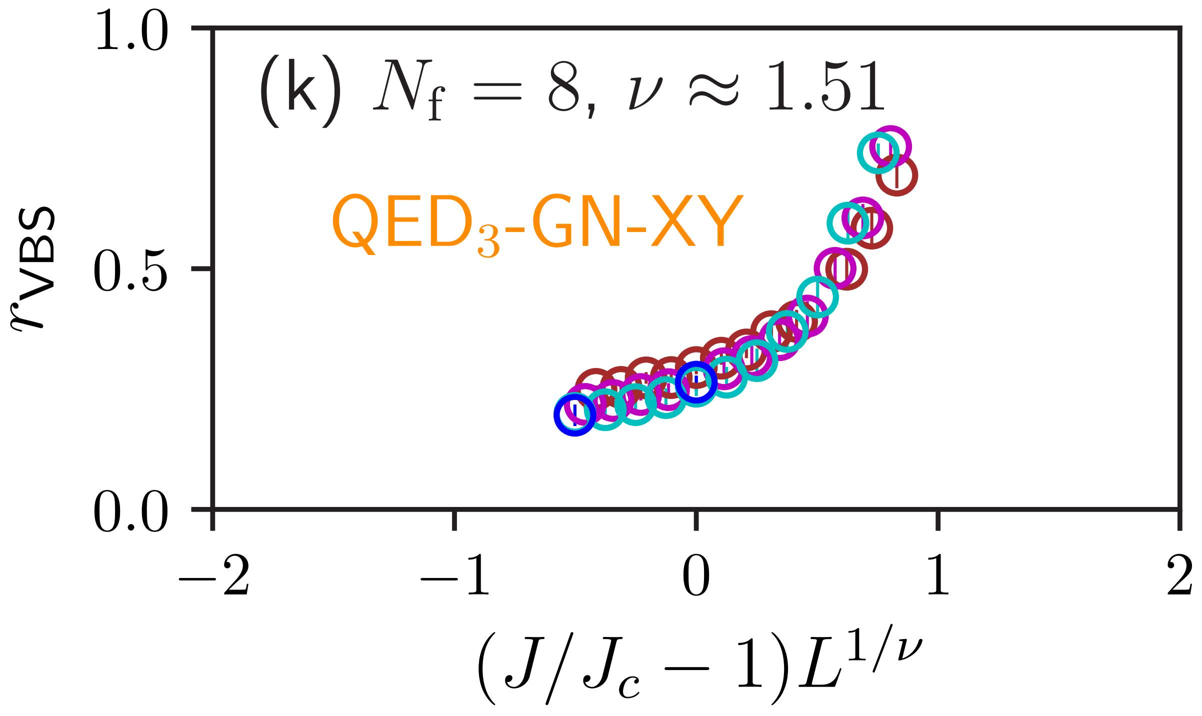
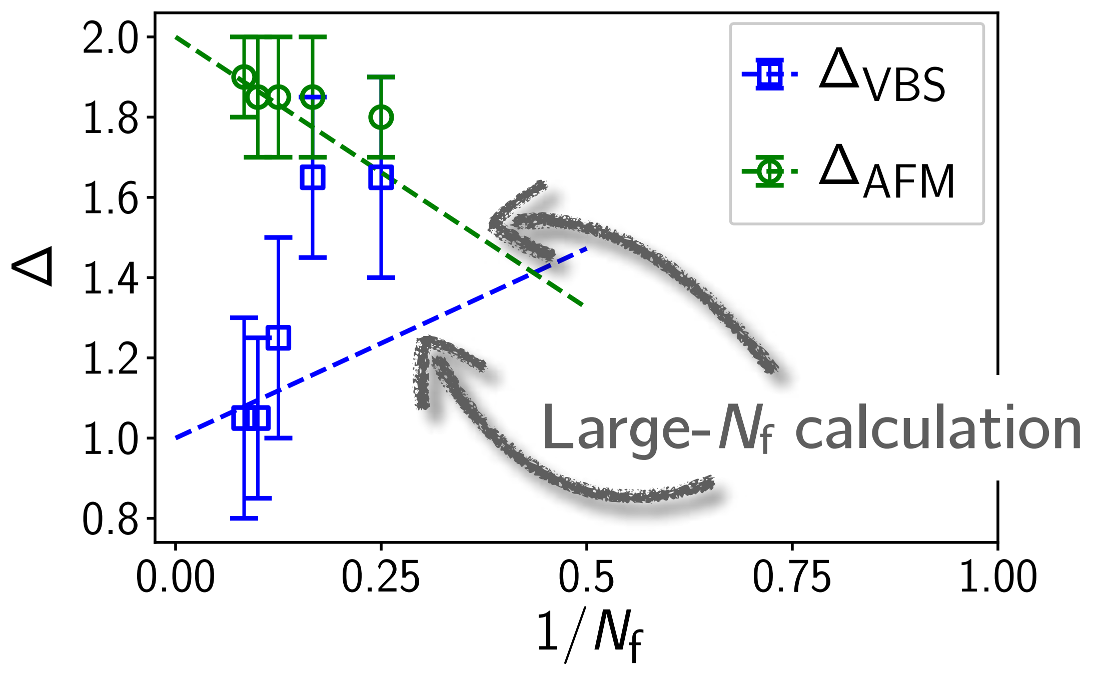
... for $N_f = 8$



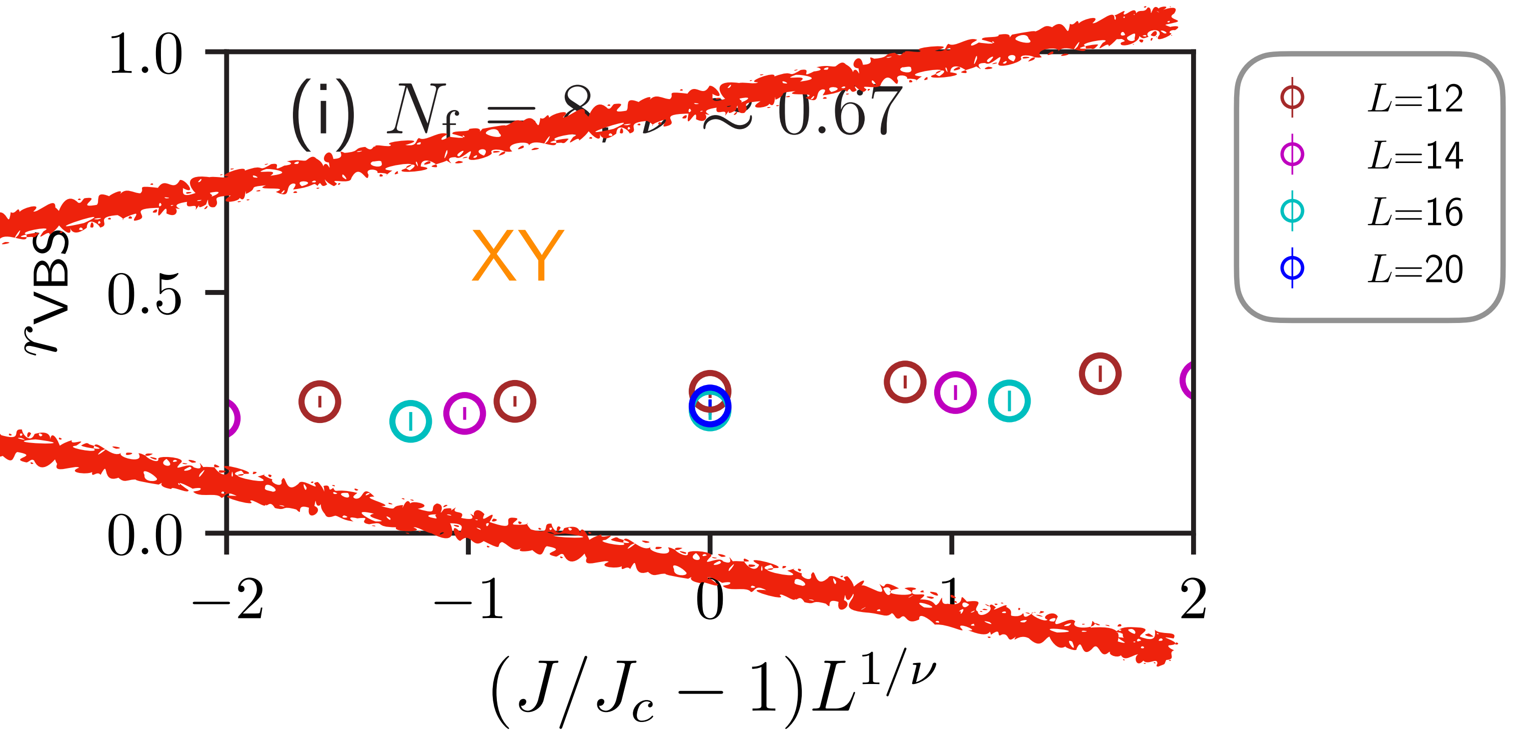


[LJ, Wang, Scherer, Meng, Xu, PRB '20]

Evidence for QED3-Gross-Neveu-XY criticality

~~Scenario 1: Conventional paramagnet~~

~~XY: $\nu \simeq 0.672$, $\eta_\phi \simeq 0.039$~~

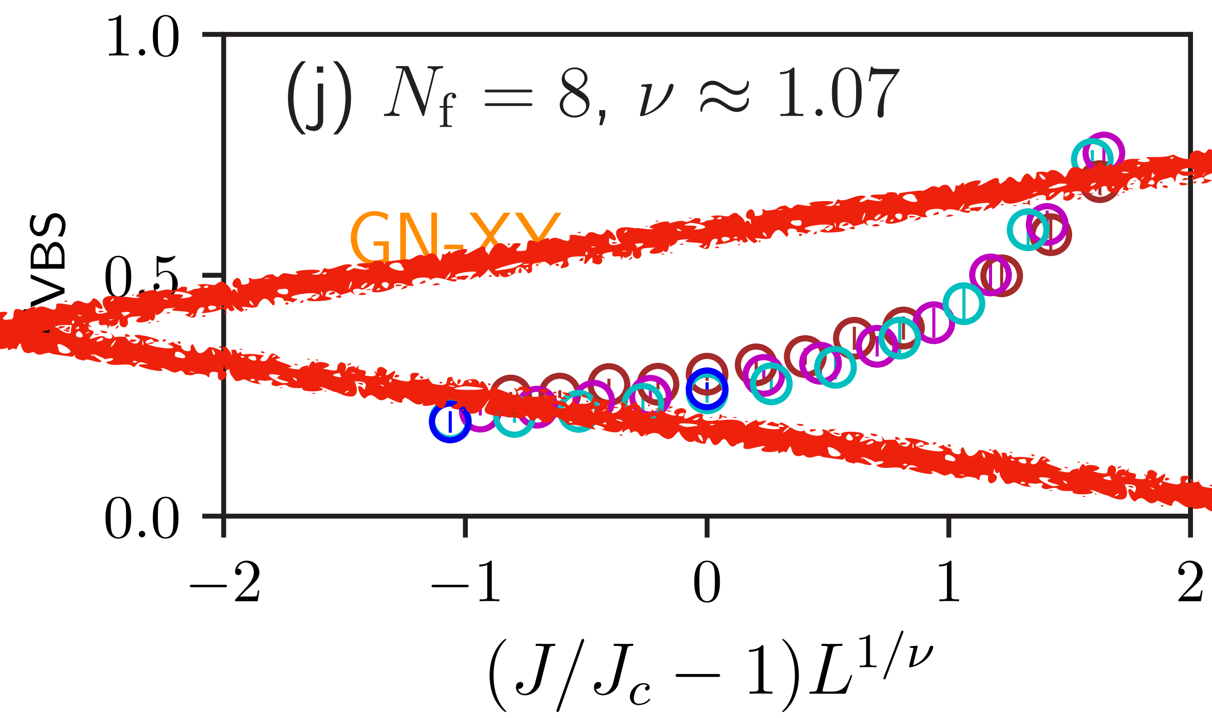


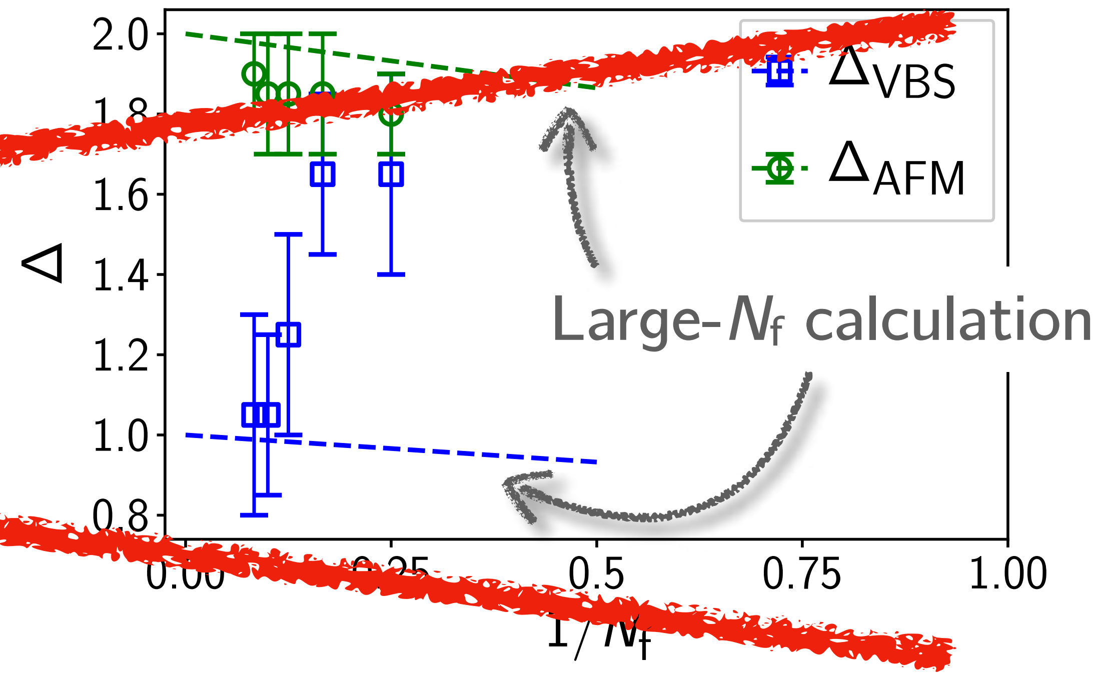
~~Scenario 2: Dirac fermions~~

~~Gross-Neveu-XY: $\nu \simeq 1.07$, $\eta_\phi \simeq 0.97$~~

... for $N_\mathrm{f} = 8$

→ **Talk Sandro Sorella Mon 14:15**

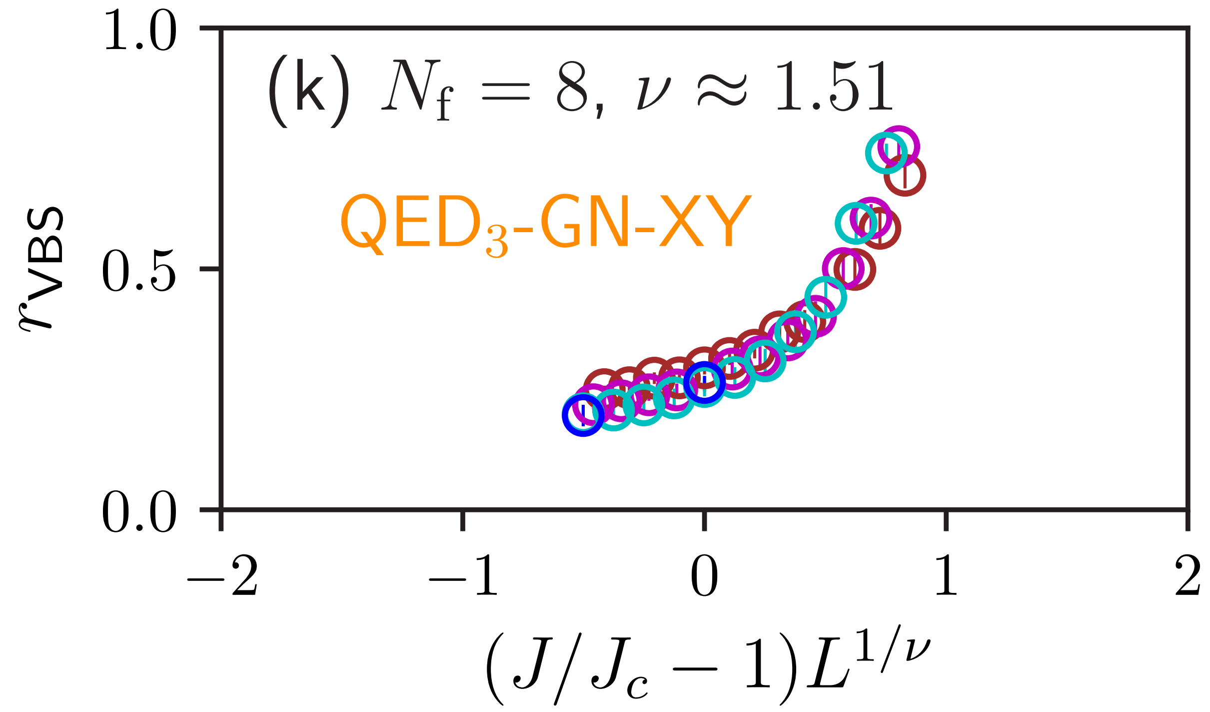


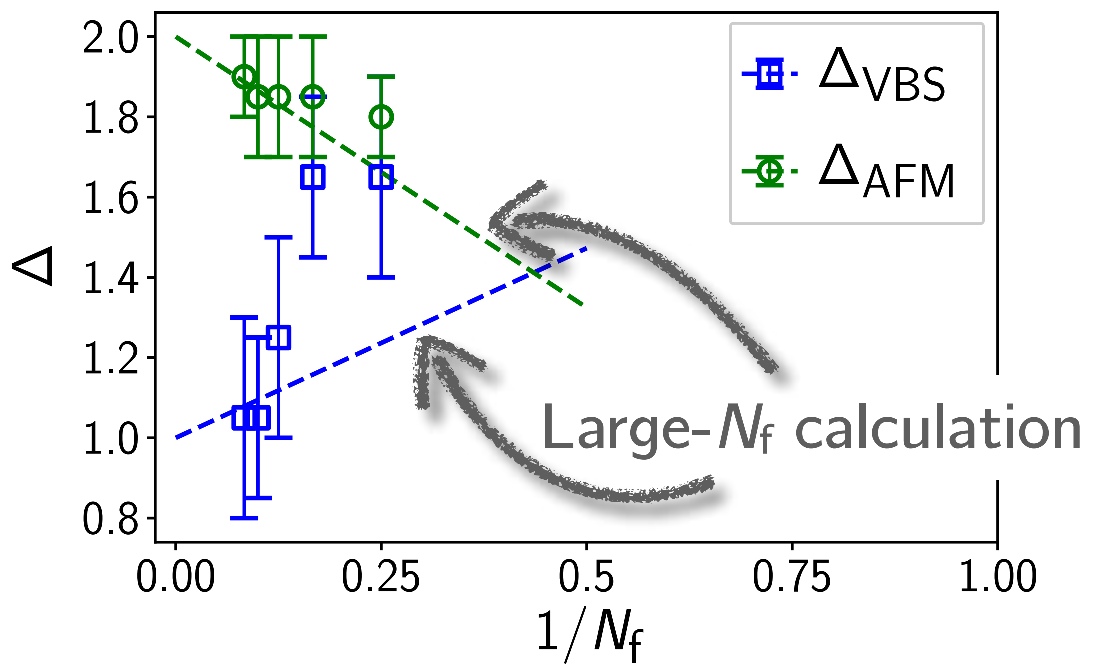


Scenario 3: Dirac fermions + U(1) gauge field

QED3-Gross-Neveu-XY: $\nu \simeq 1.51$, $\eta_\phi \simeq 1.24$

... for $N_\mathrm{f} = 8$

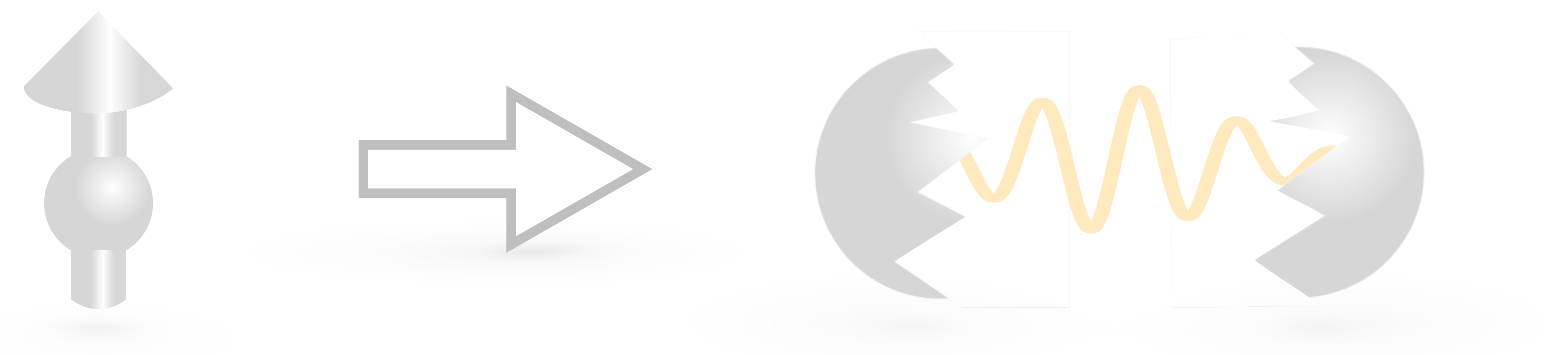




[LJ, Wang, Scherer, Meng, Xu, PRB '20]

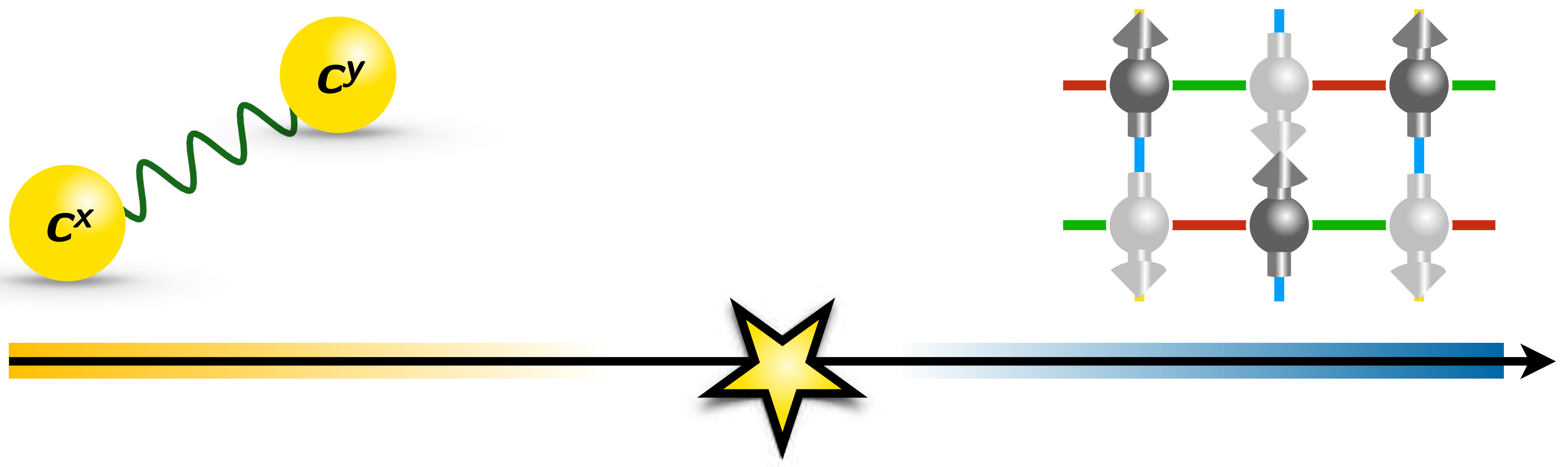
Outline

I. Introduction: Spin fractionalization



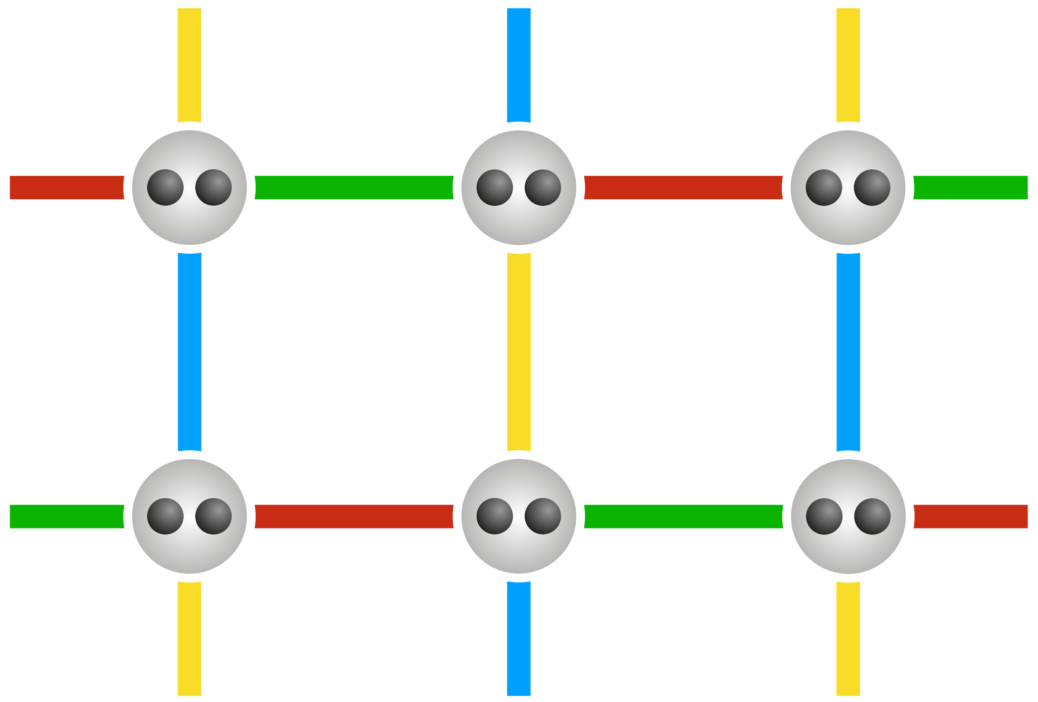
II. Example #1: Confinement transition in flatland U(1) gauge theory

III. Example #2: Spinon-metal—insulator transition in flatland $\mathbb{Z}_2$ gauge theory



IV. Conclusions: Spin-liquid criticality

Flatland $\mathbb{Z}_2$ gauge theory: Spin-orbital liquid



Spin-orbital generalization of Kitaev model:

$$H = -K \sum_{\langle ij \rangle_\gamma} \underbrace{(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y)}_{\text{XY spin}} \otimes \underbrace{\tau_i^\gamma \tau_j^\gamma}_{\text{Kitaev orbital}} + J^z \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z \otimes \mathbb{1}_i \mathbb{1}_j$$

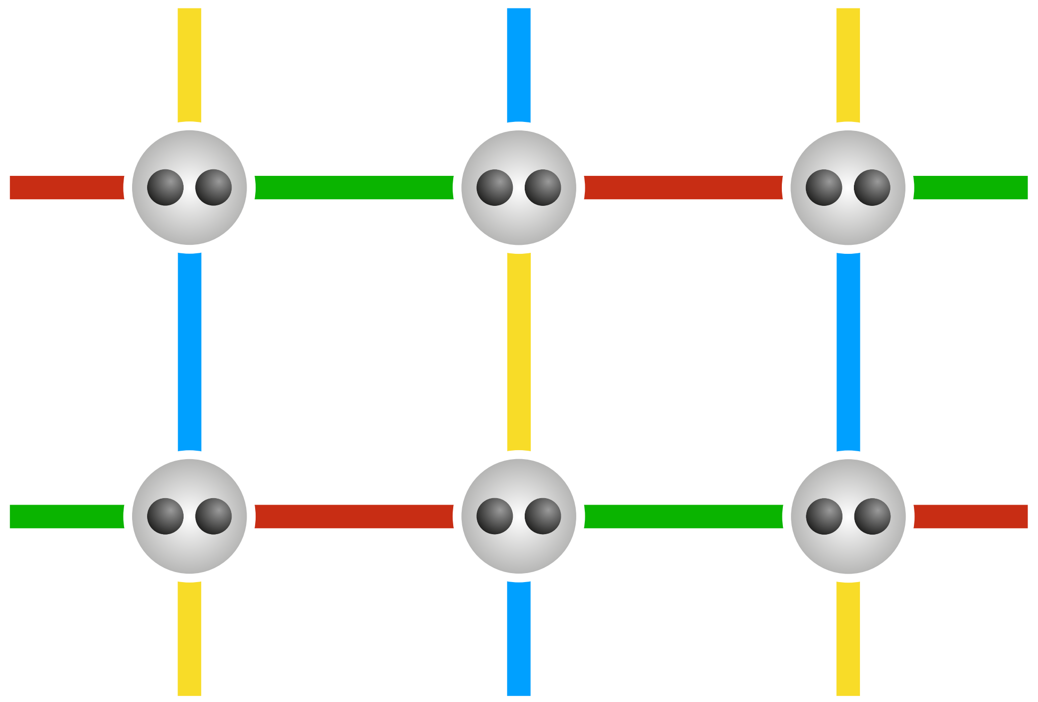
[Seifert, Dong, Chulliparambil, Vojta, Tu, LJ, PRL '20]

$J^z = 0$: ... recover known $j = 3/2$ model

[Yao, Zhang, Kivelson, PRL '09]

[Nakai, Ryu, Furusaki, PRB '12]

Flatland $\mathbb{Z}_2$ gauge theory: Spin-orbital liquid



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XY spin Kitaev orbital

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

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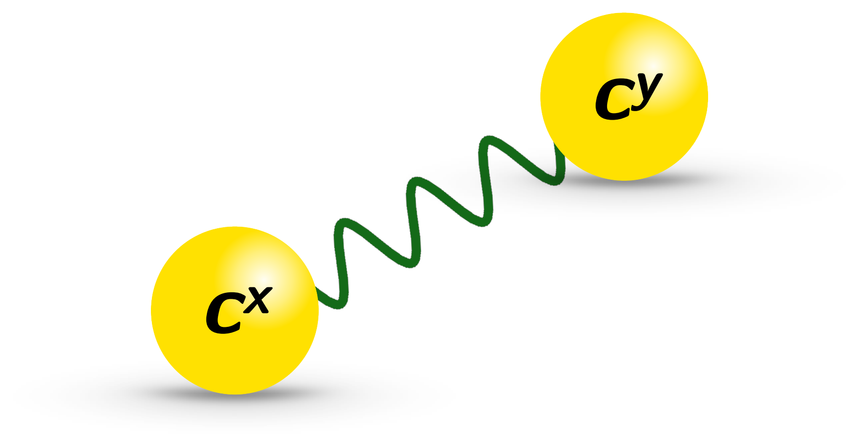
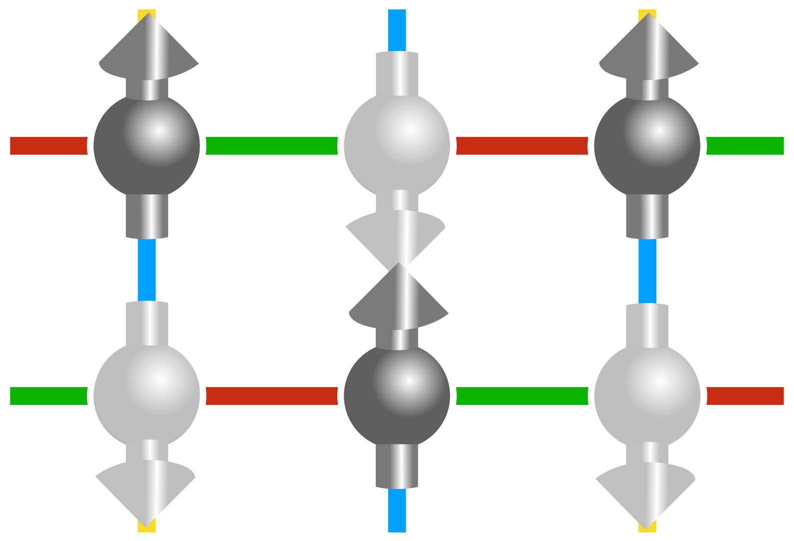
Phase diagram:



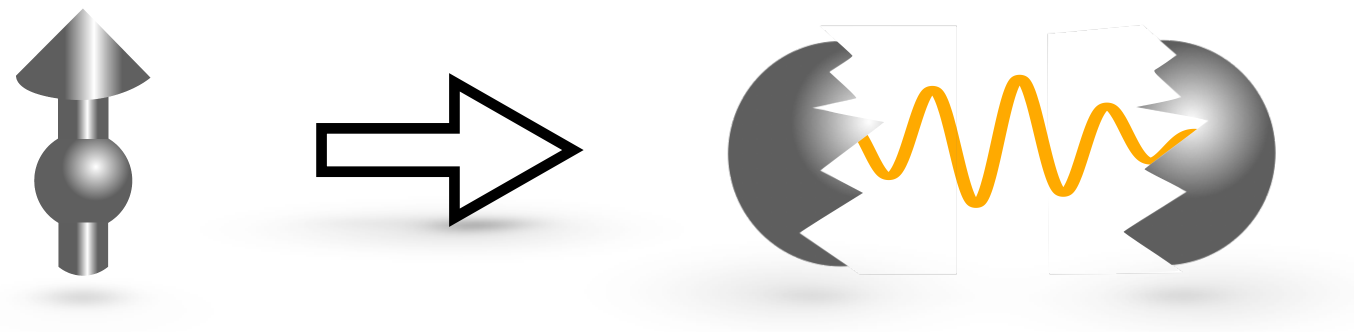


"Kitaev" spin-orbital liquid

Ising spin order

0 J^z/K

Flatland $\mathbb{Z}_2$ gauge theory: Mapping to π-flux model



Parton decomposition:

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

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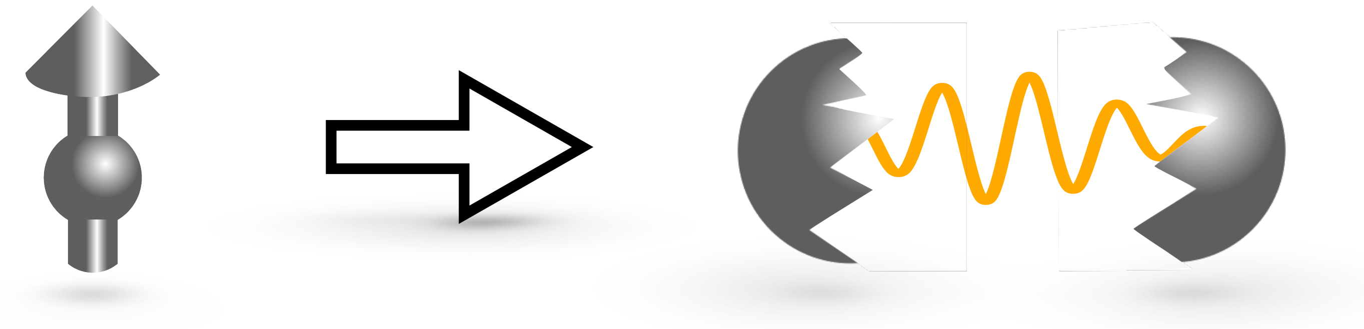

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hopping parameter $t = 2K$

$u_{ij} = i b^i b^j$

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

π-flux model:

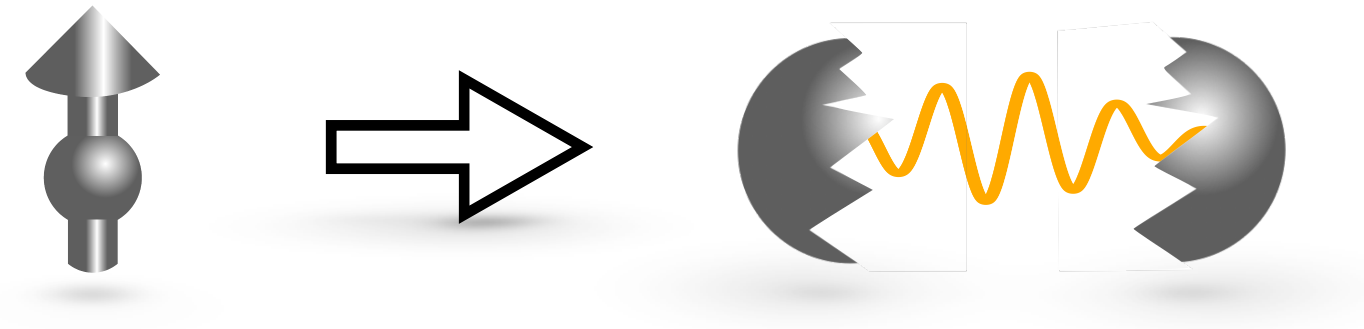
$$H \mapsto \sum_{\langle ij \rangle} \left[2K u_{ij} (f_i^\dagger f_j + f_j^\dagger f_i) + 4J^z (n_i - \tfrac{1}{2})(n_j - \tfrac{1}{2}) \right]$$

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

electron density $f^\dagger f$

Ground-state: π flux
[Lieb, PRL ’94]

Flatland $\mathbb{Z}_2$ gauge theory: Mapping to π-flux model



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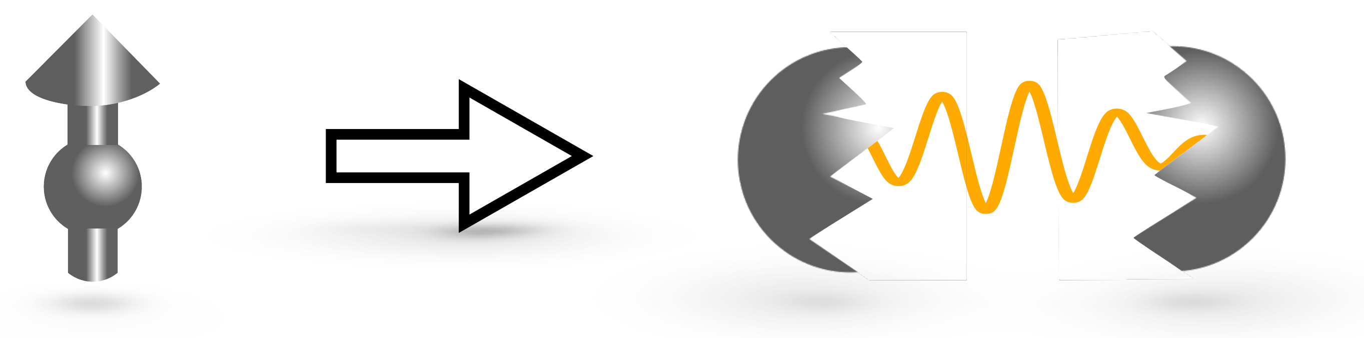
Static (!) $\mathbb{Z}_2$ gauge field

Flatland $\mathbb{Z}_2$ gauge theory: Mapping to π-flux model



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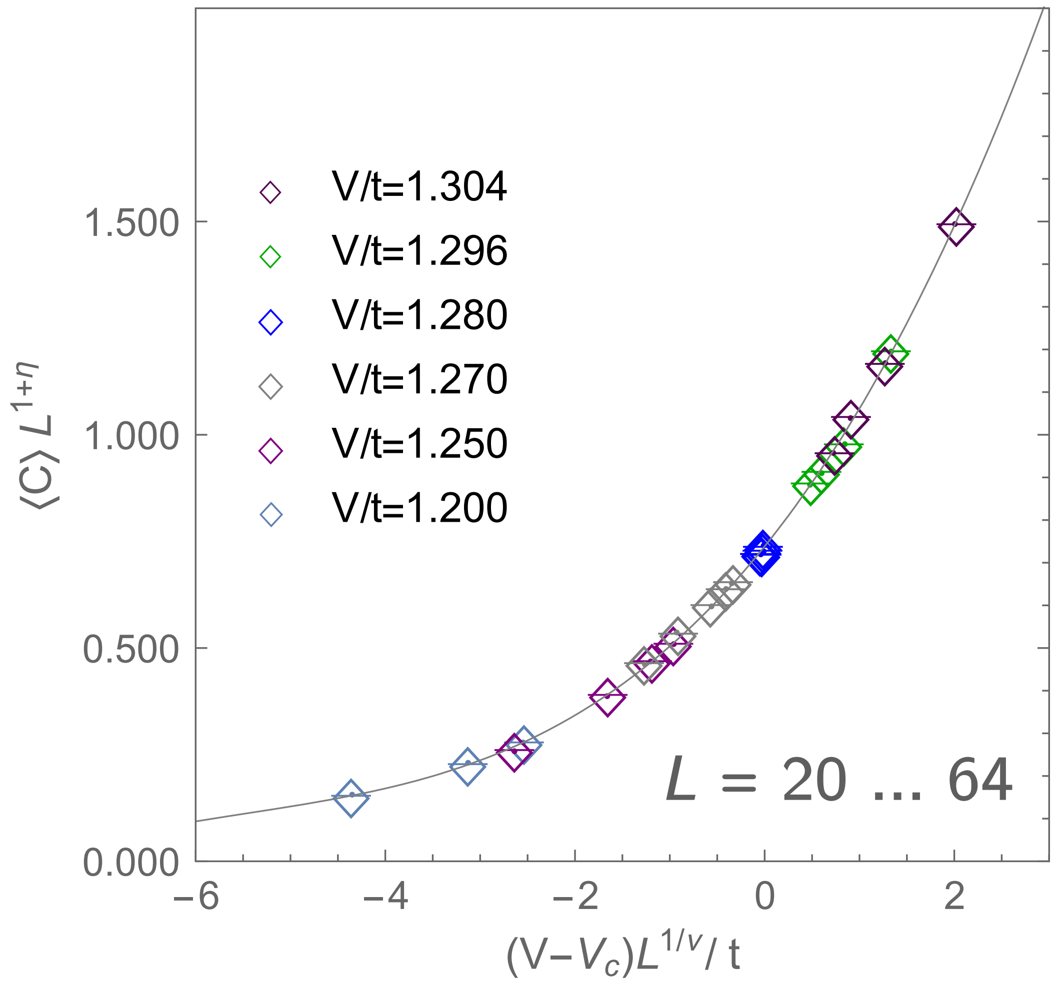
Kitaev spin-orbital model $\rightarrow$ Interacting fermions on π-flux lattice

Spinless fermions on π-flux lattice: QMC

$(V/t)_{\mathrm{c}} = 1.281(2)$



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

Spinless fermions on π-flux lattice: QMC

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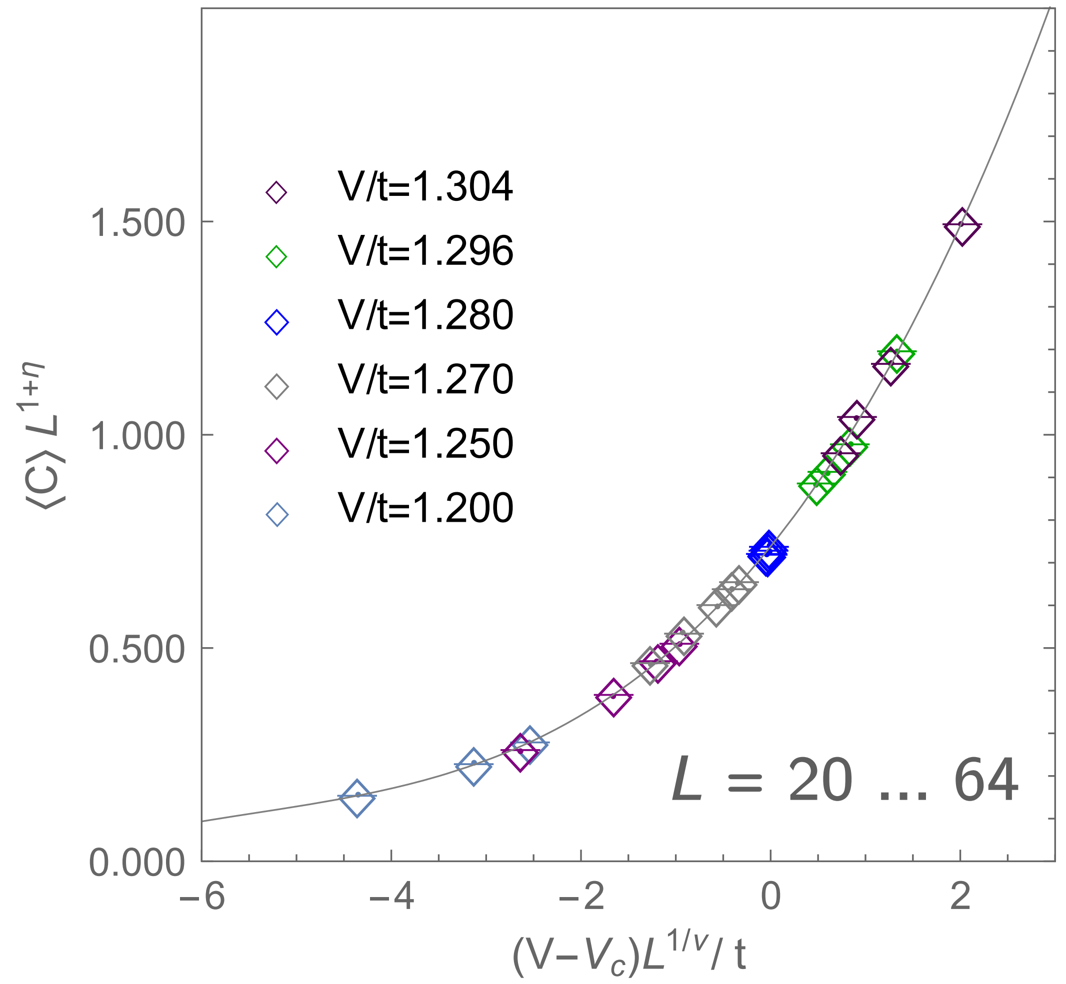

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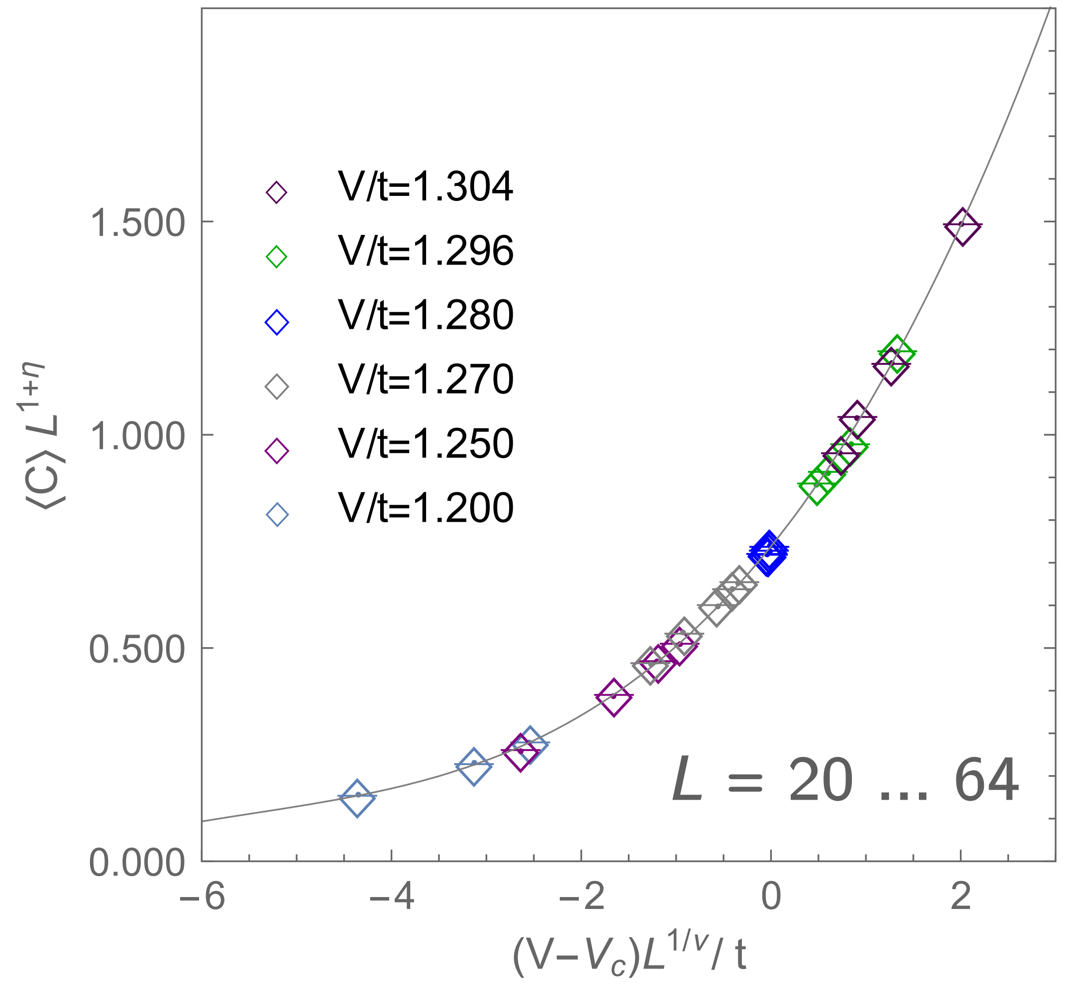
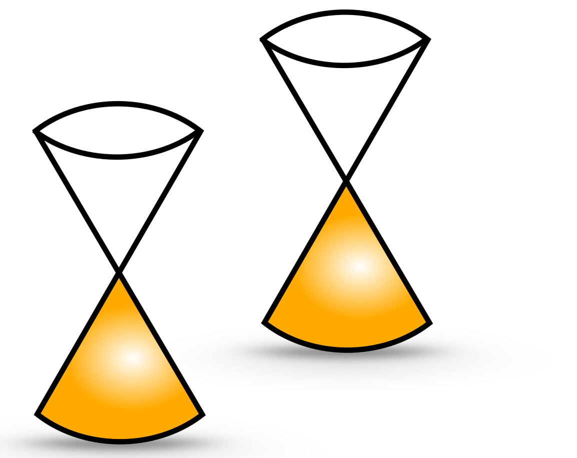
Gross-Neveu-$\mathbb{Z}_2$ universality: $1/\nu = 1.12(1)$, $\eta_\phi = 0.51(3)$, $\eta_\psi \approx 0.1$

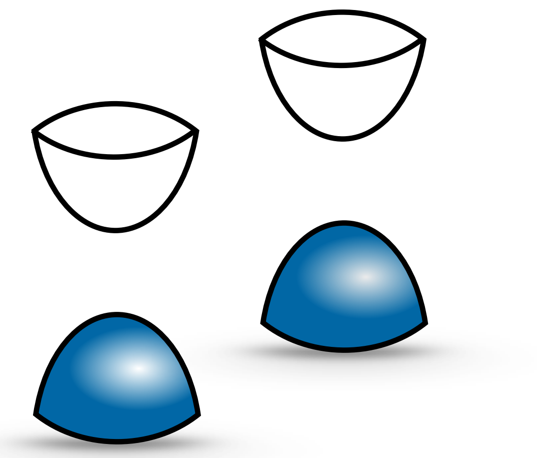
[Hands, Kocic, Kogut, Ann. Phys. '93]
[Gracey, IJMP '94]
[Braun, Gies, D Scherer, PRD '11]
[LJ & Herbut, PRB '14]
[Iliesiu *et al.*, JHEP '18]
[Ihrig, Mihaila, M Scherer, PRB '18]
...

$\rightarrow$ Talk David Poland Tue 17:00

Spinless fermions on π-flux lattice: QMC

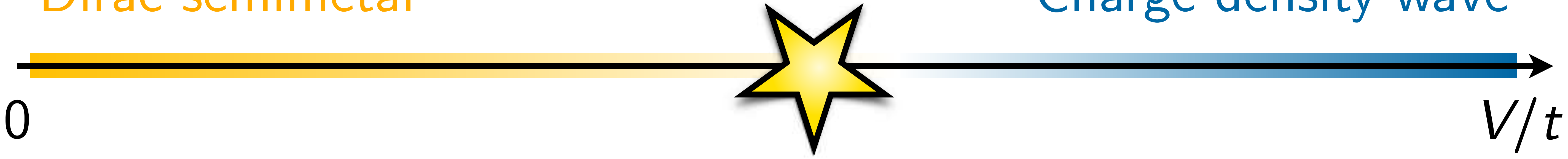






Dirac semimetal

Charge density wave



0

V/t

$(V/t)_c = 1.281(2)$

[Huffman & Chandrasekharan, PRD '17; PRD '20]
[Wang, Corboz, Troyer, NJP '14]
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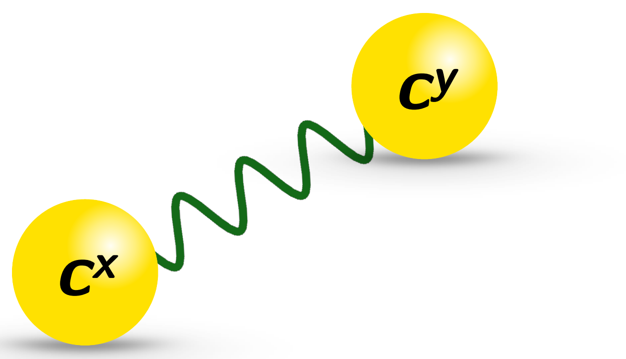
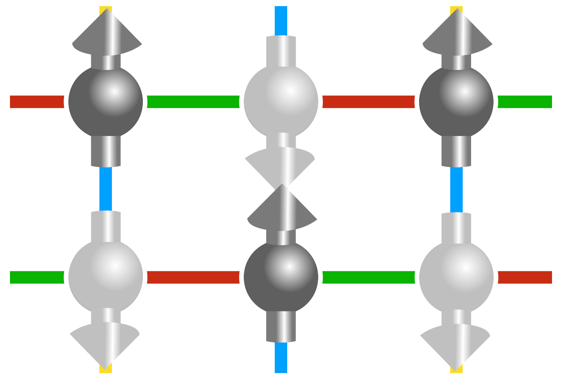
[Ihrig, Mihaila, M Scherer, PRB '18]
...

→ Talk David Poland Tue 17:00

Spin-orbital model:



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



"Kitaev" spin-orbital liquid

Ising spin order

0

J^z/K

$(J^z/K)_c = 0.642(2)$

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

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:

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

[Kitaev, Ann. Phys. '03]
[Trebst *et al.*, PRL '07]

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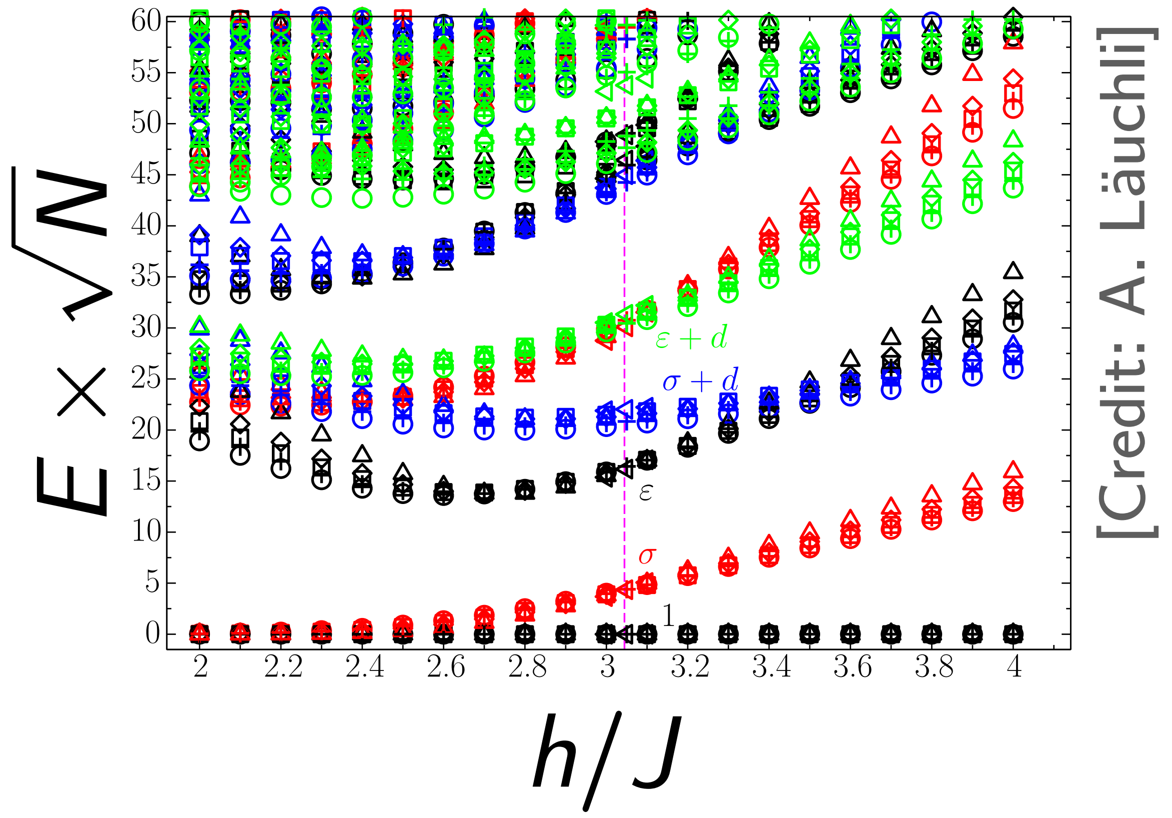
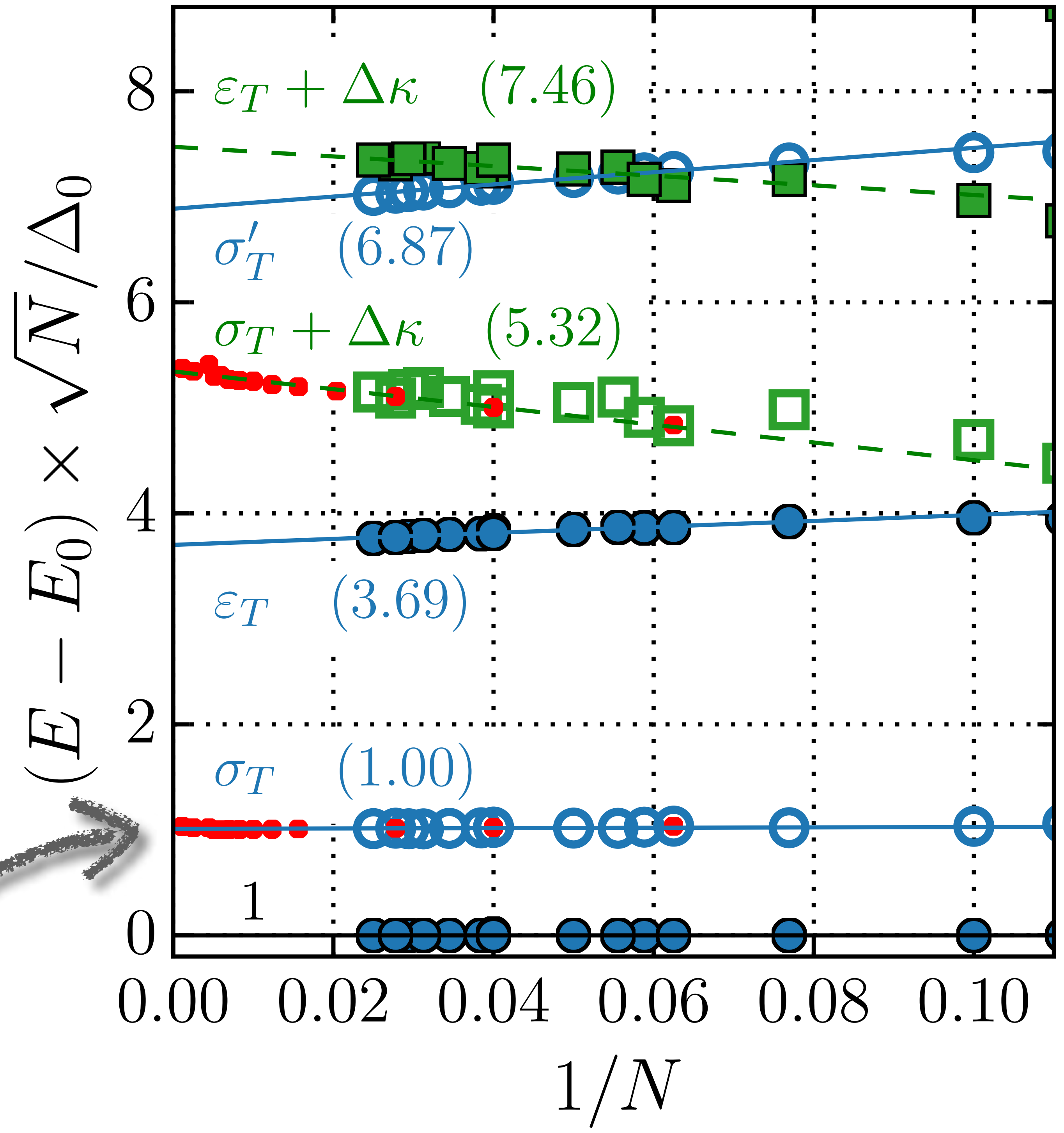
[Kitaev, Ann. Phys. '03]
[Trebst *et al.*, PRL '07]

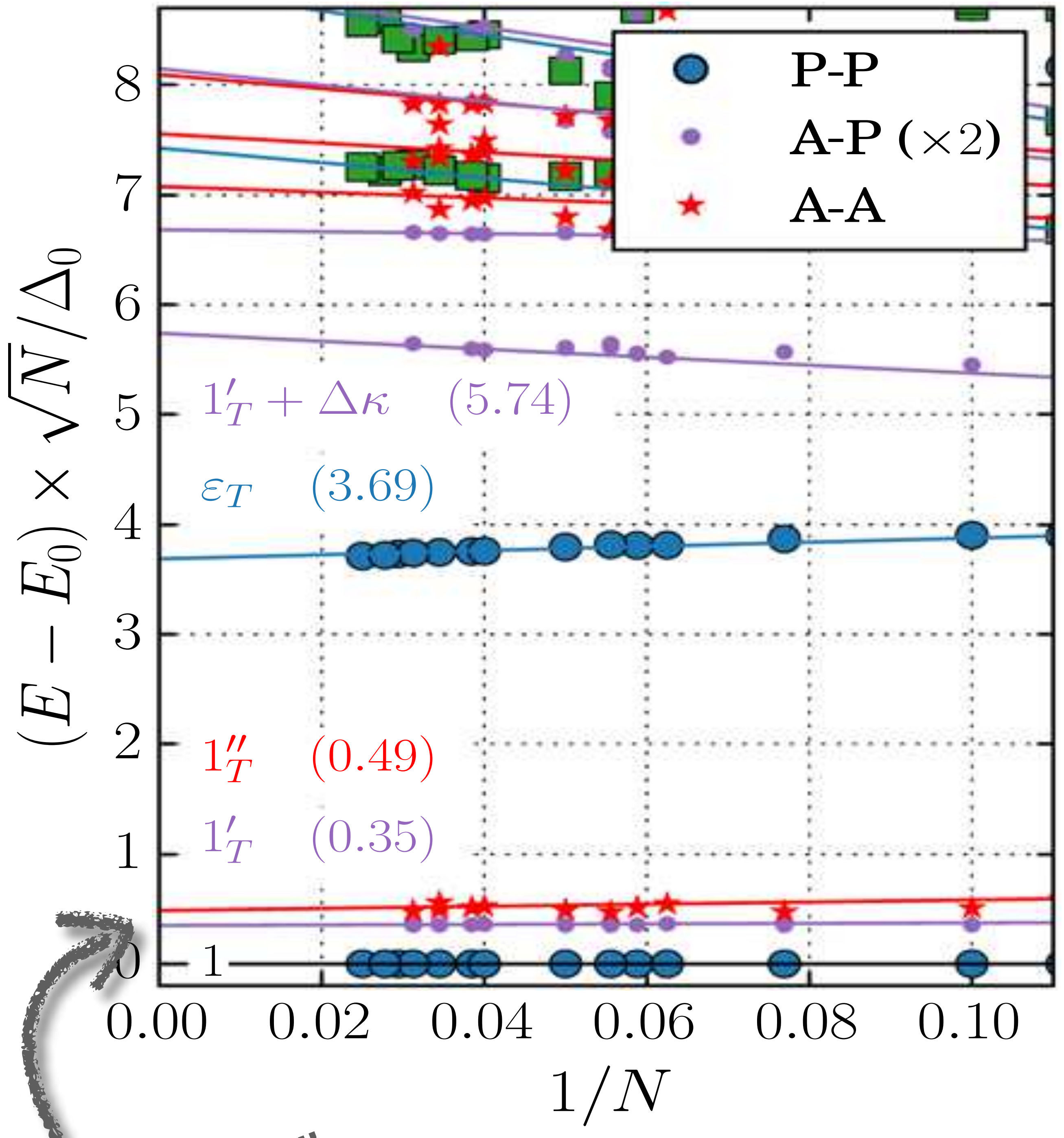


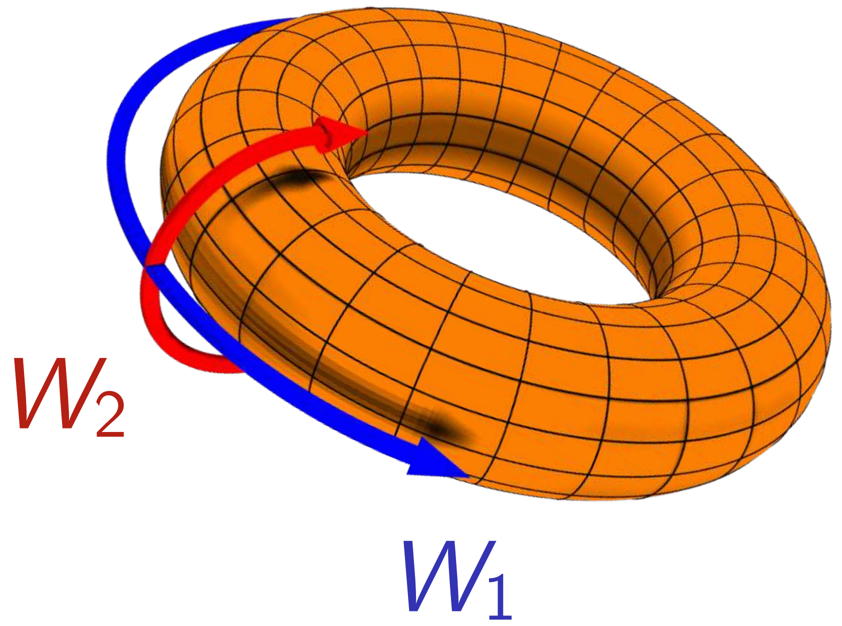
Ising
$h = h_c$



missing in Ising*

Ising*
$h = h_c$

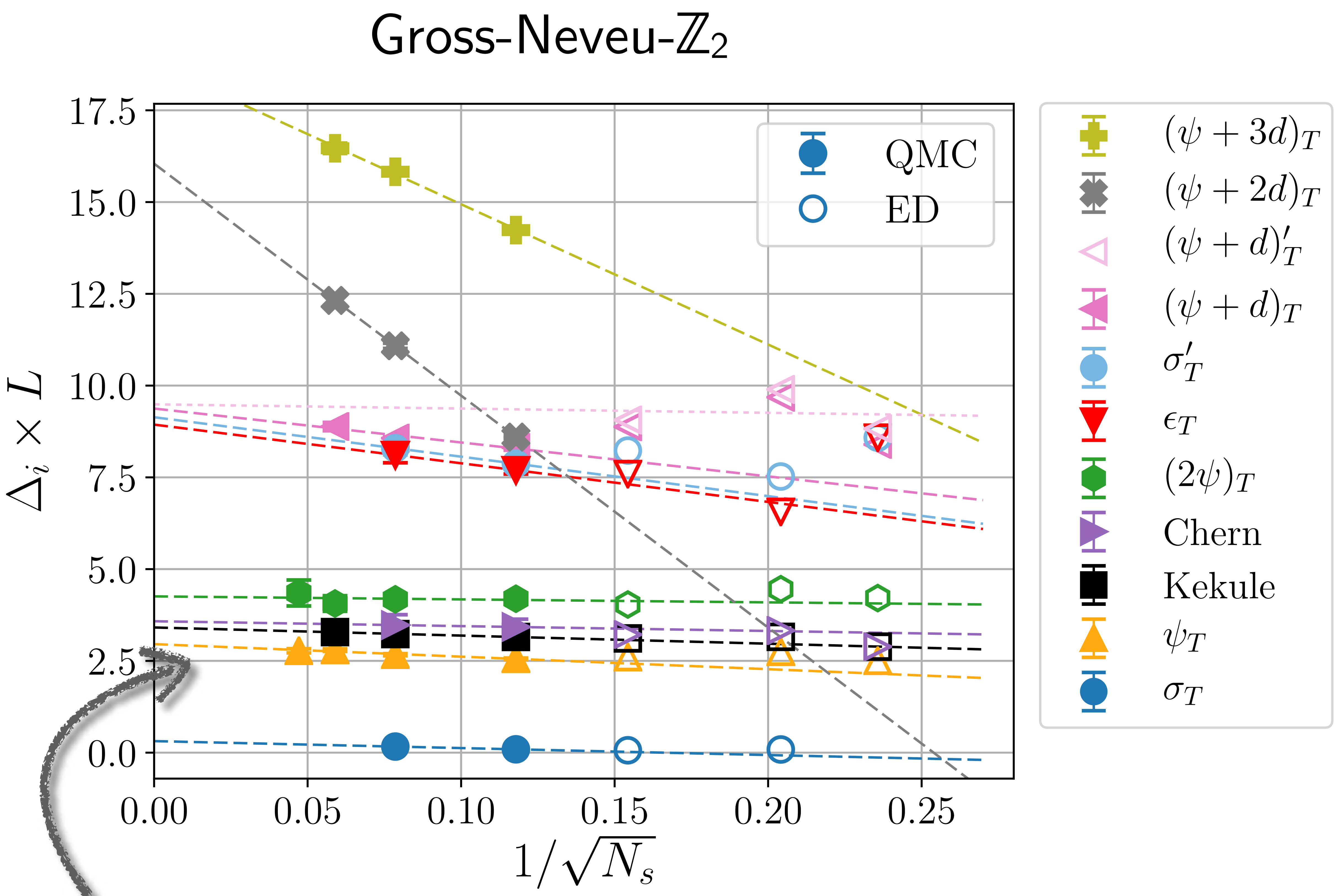




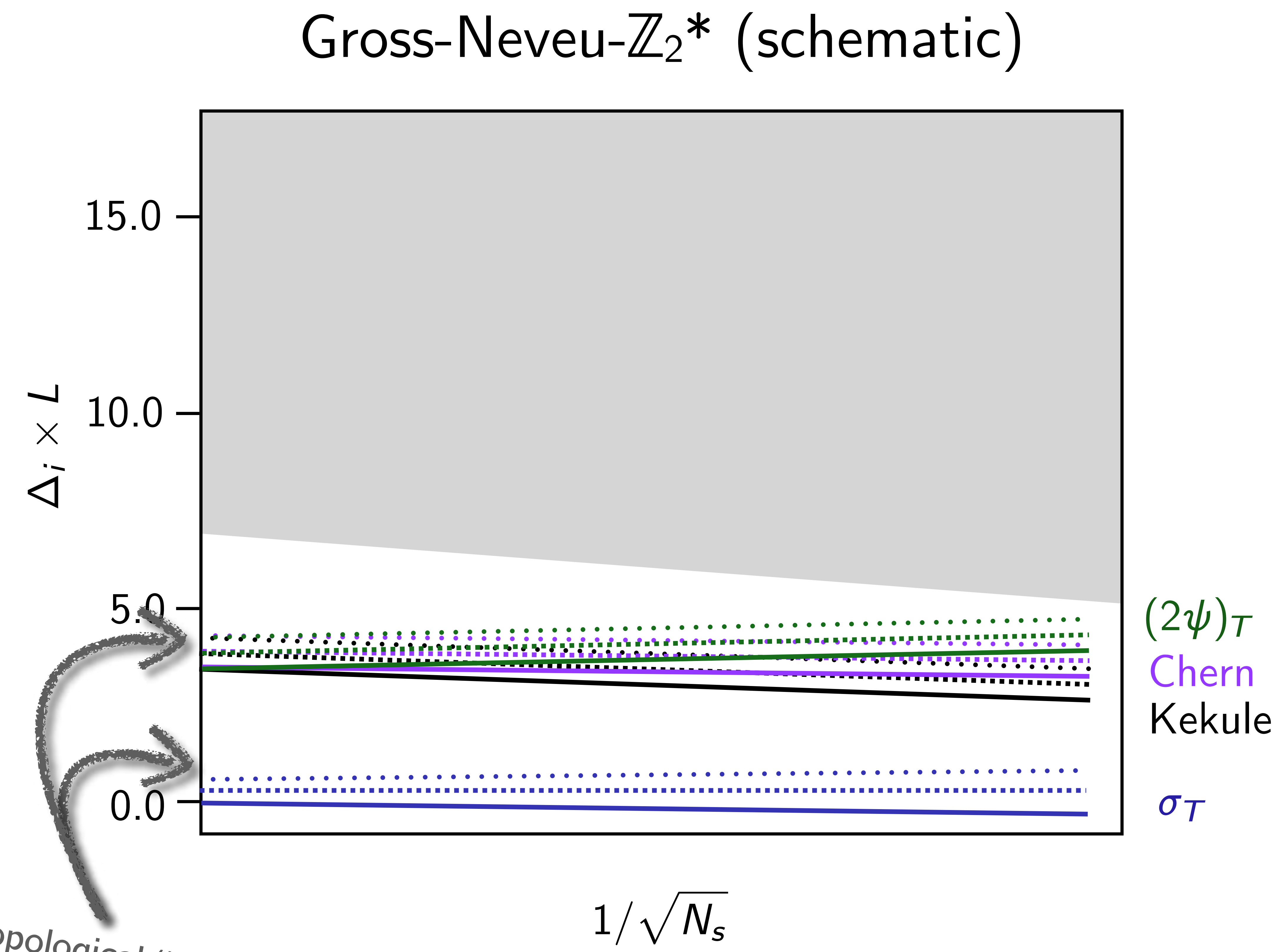
topological "copies"

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

Gross-Neveu vs Gross-Neveu*



missing in GN*



topological "copies"

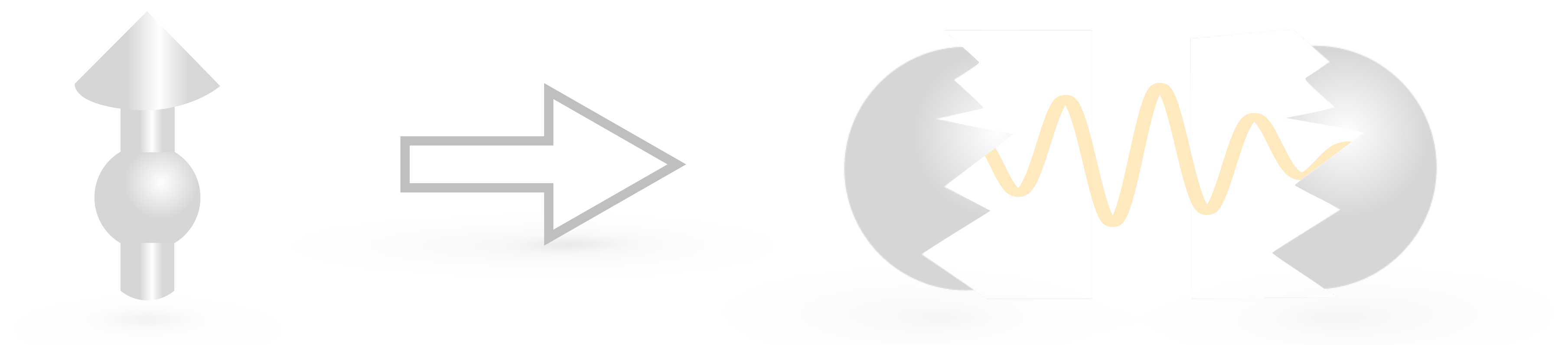
[Schuler, Hesselmann, Whitsitt, Lang, Wessel, Läuchli, PRB '21]

... testable in future simulations

→ Poster Thomas Lang

Outline

I. Introduction: Spin fractionalization



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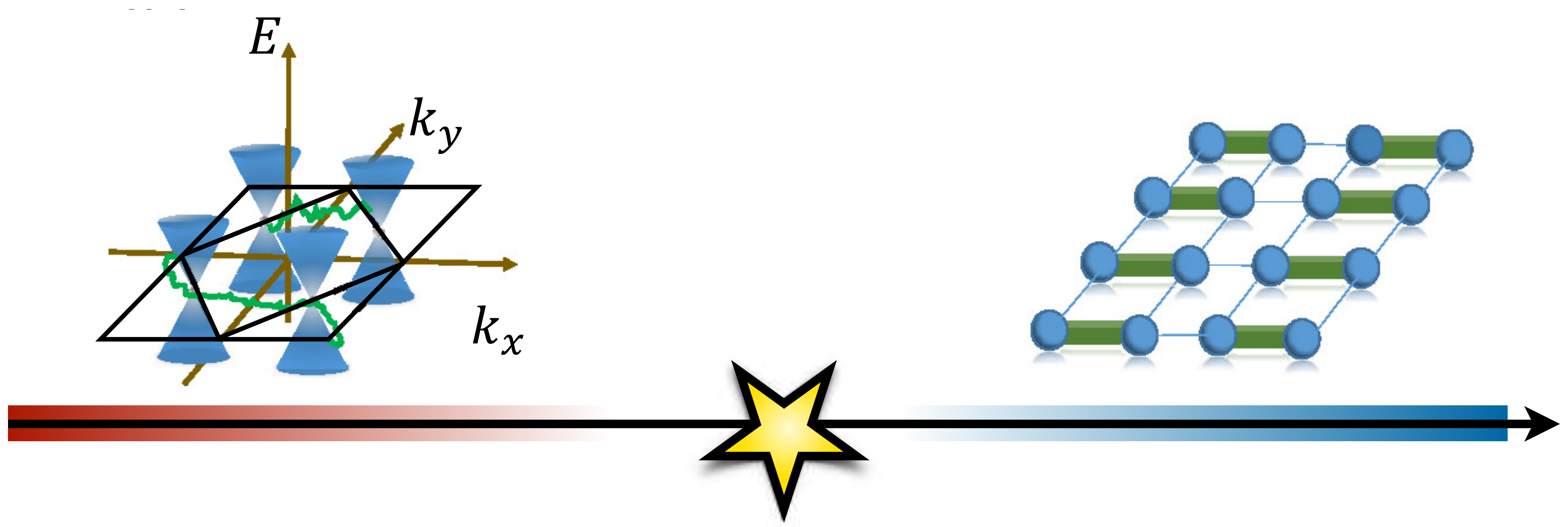
IV. Conclusions: Spin-liquid criticality

Conclusions: Spin-liquid criticality

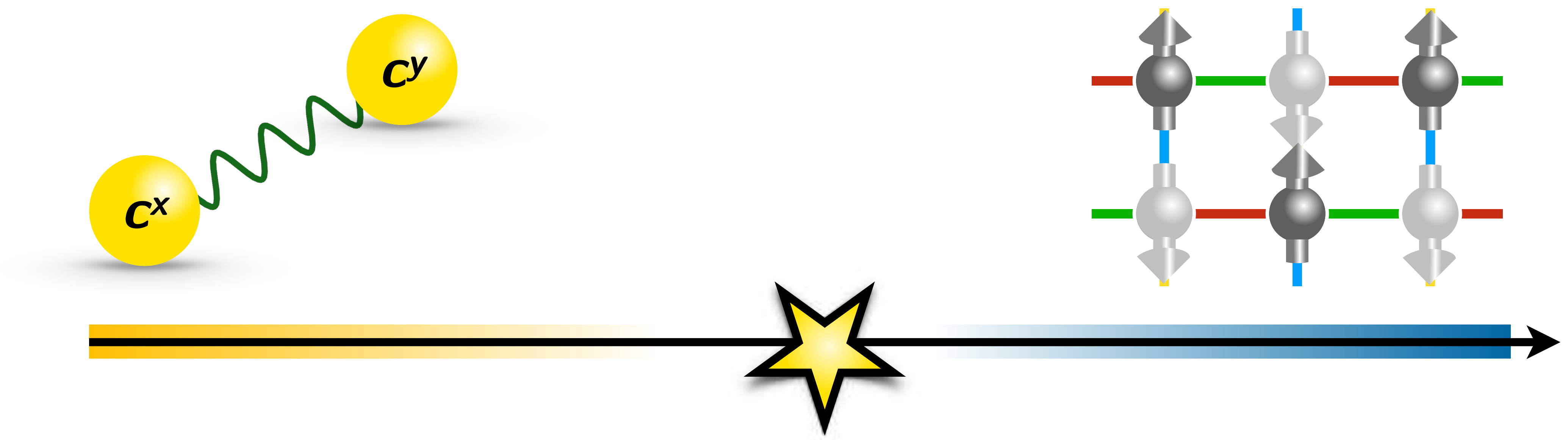
Confinement transition:



QED$_3$-Gross-Neveu-XY

[LJ, Wang, Scherer, Meng, Xu, PRB ’20]

Spinon-metal—insulator transition:

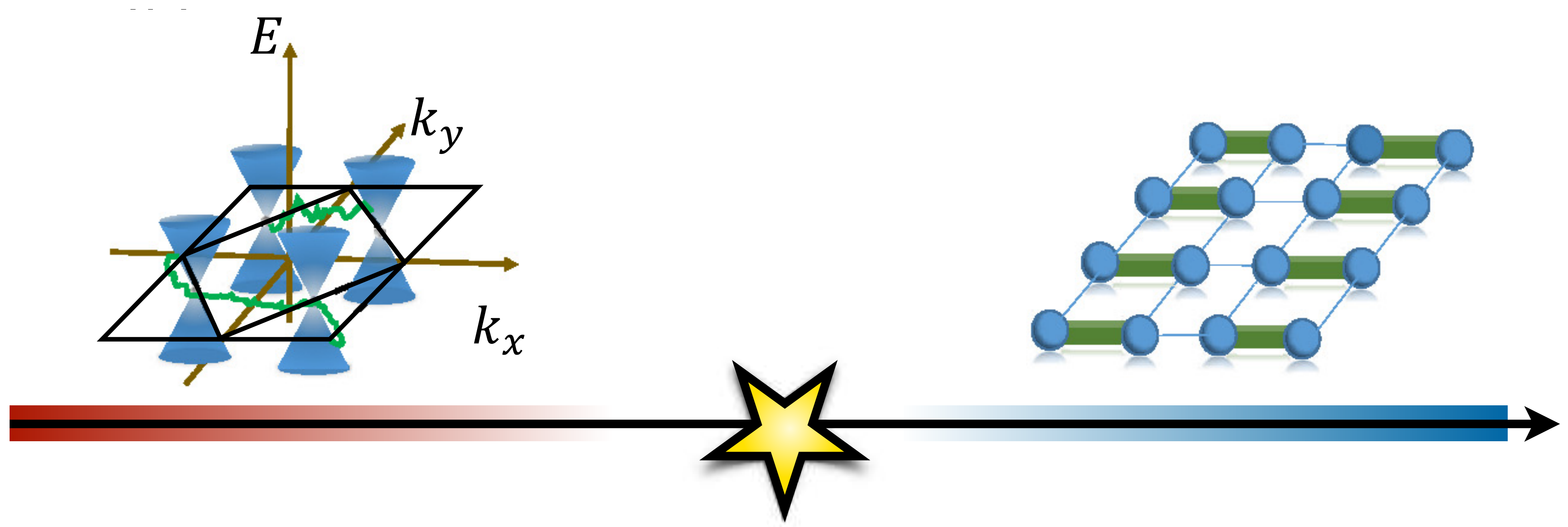


Gross-Neveu-$\mathbb{Z}_2$*

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

Conclusions: Spin-liquid criticality

Confinement transition:



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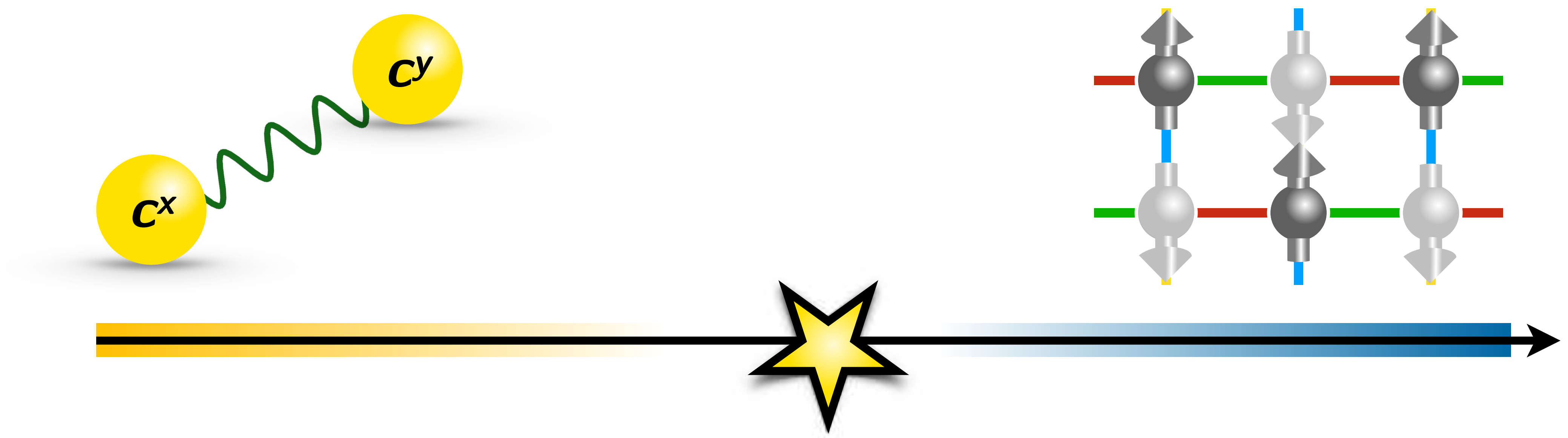


Gross-Neveu-$\mathbb{Z}_2$*

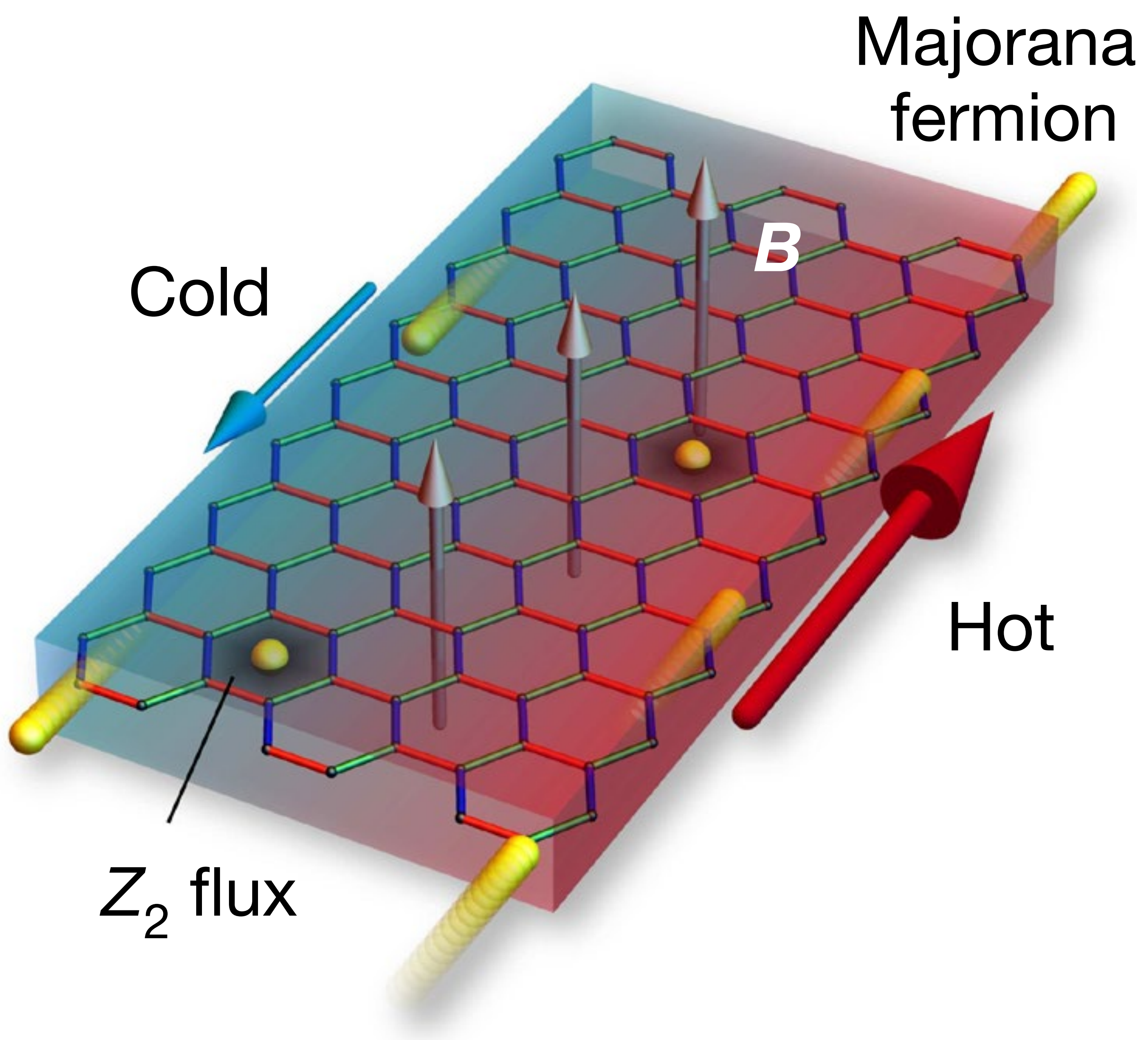
[Seifert, Dong, Chulliparambil, Vojta, Tu, LJ, PRL '20]

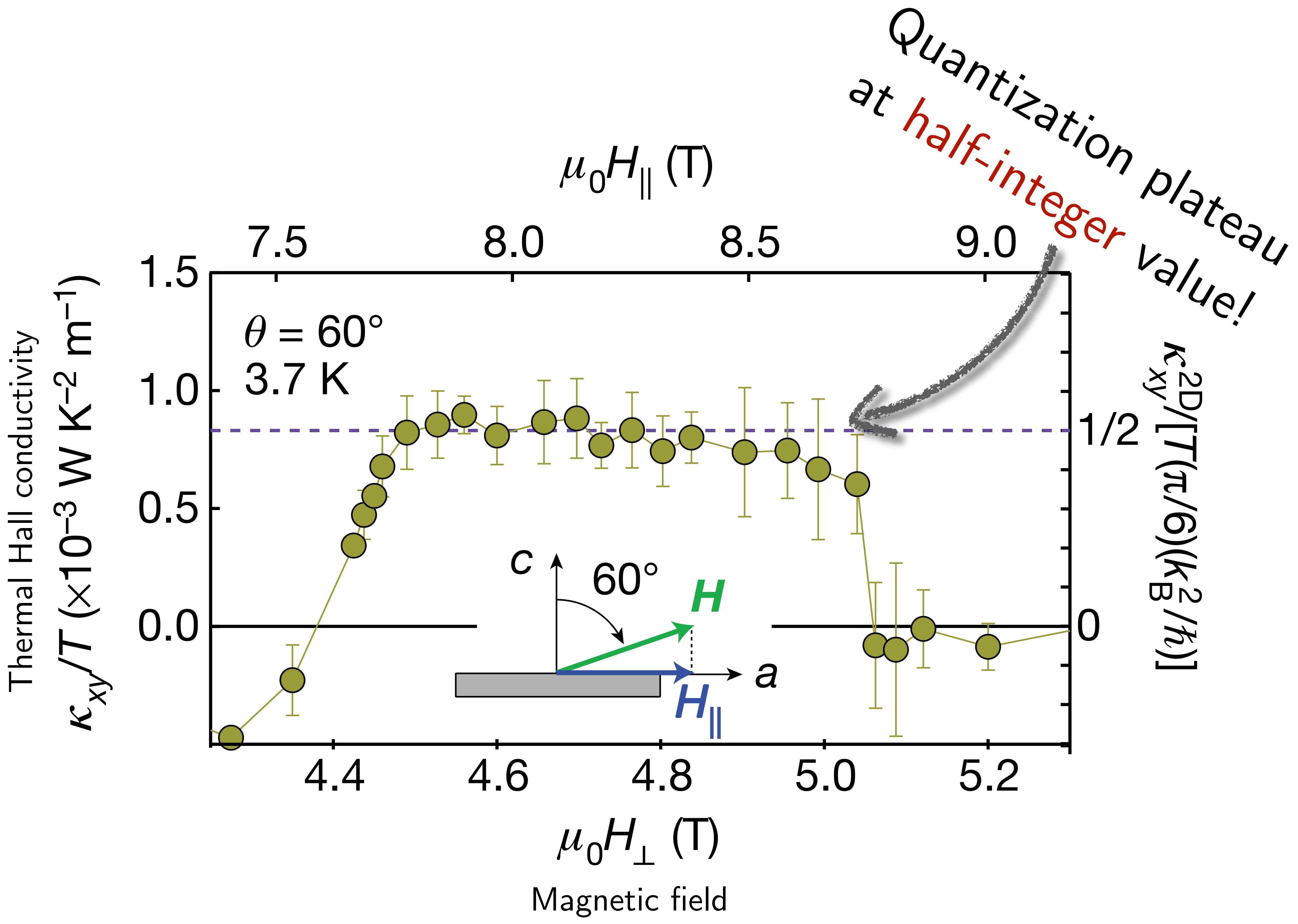
Many further possibilities: $\rightarrow$ **Talk Shouryya Ray @ Wed 17:00** [Ray, Ihrig, Kruti, Gracey, Scherer, LJ, PRB '21]

$\rightarrow$ **Poster Wilhelm Krüger** [Krüger, LJ, arXiv:2107.00661]

Thermal conductivity of α-RuCl3: Thermal Hall effect

Transversal heat conductivity:

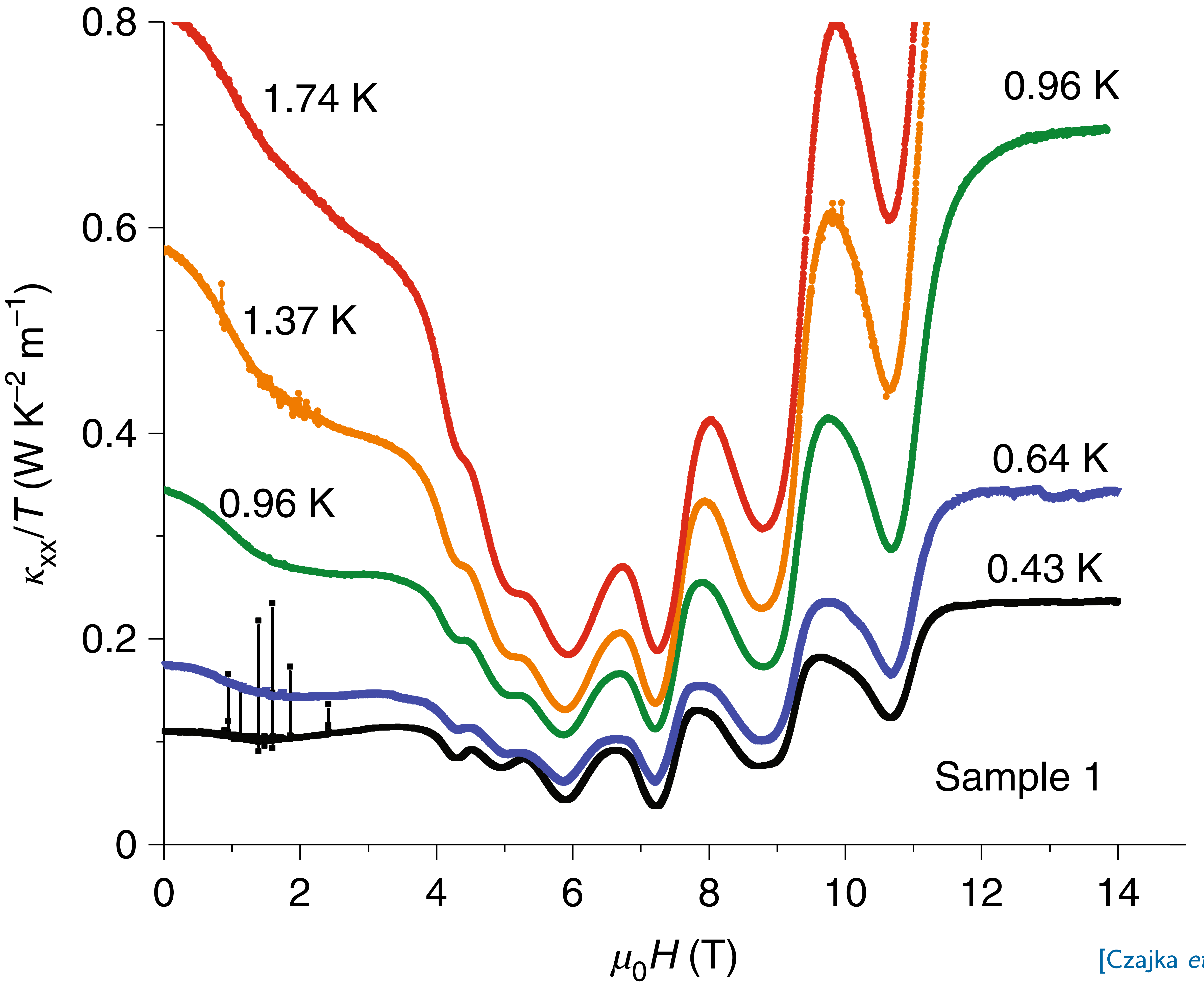


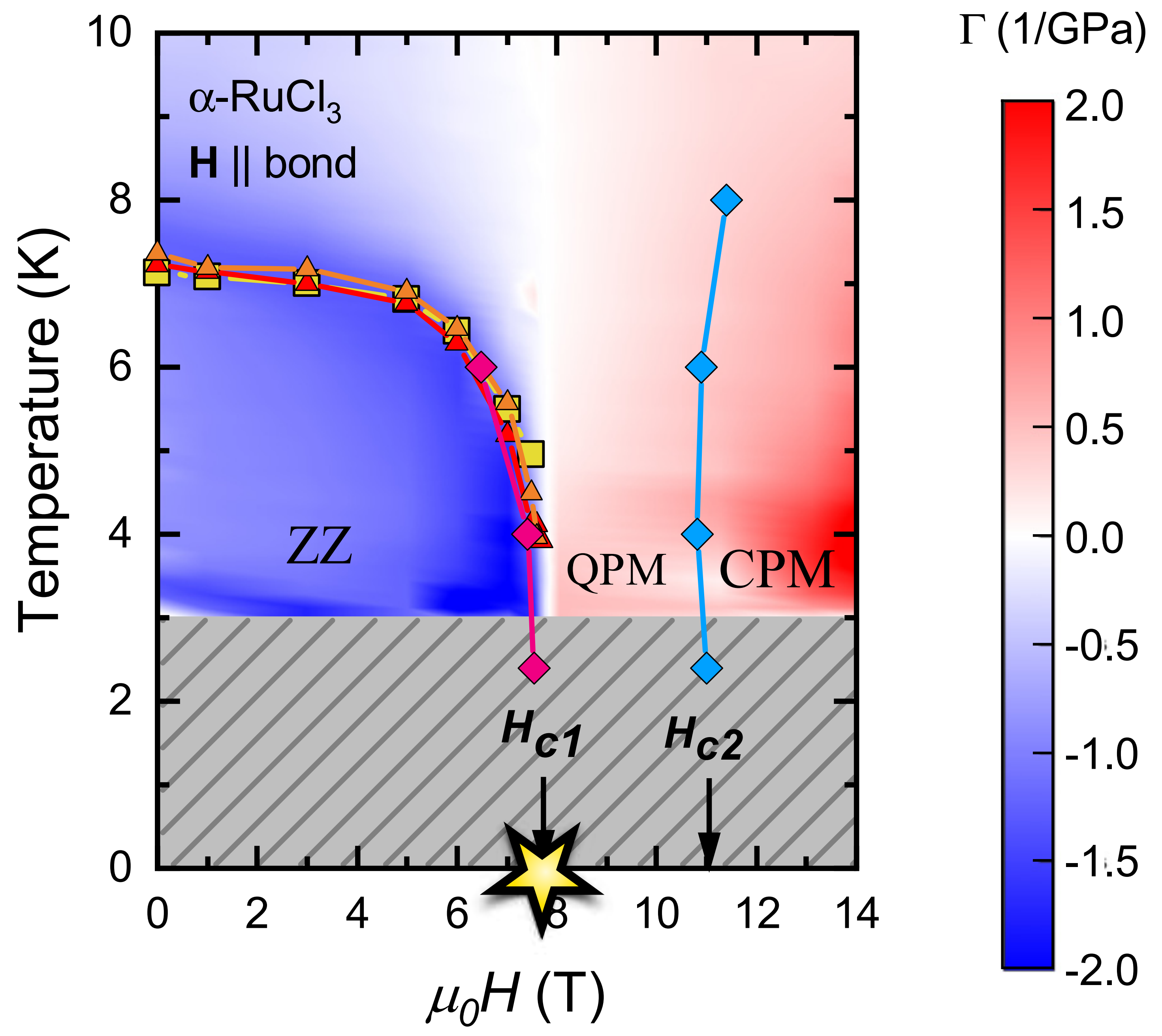


[Kasahara *et al.*, Nature '18]
Topical Review: [LJ & Vojta, JPCM '19]

Smoking-gun signature of Majorana edge states?

Thermal conductivity of α-RuCl3: Quantum oscillations

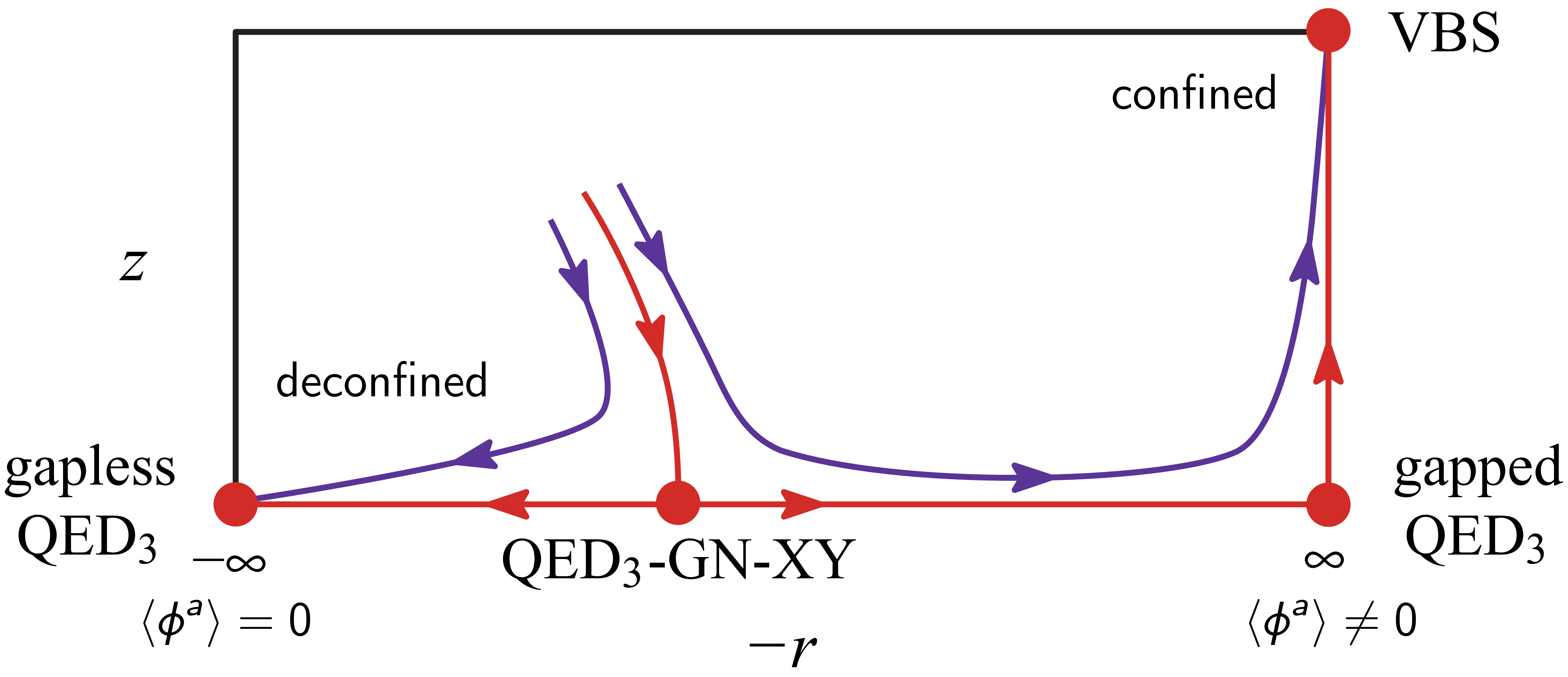




[Gass, ..., LJ, *et al.*, PRB '21]

[Czajka *et al.*, Nat. Phys. '21]

Monopole proliferation



Monopole scaling dimension:

$$\Delta_{q=\frac{1}{2}} = \begin{cases} 0.265 \cdot 2N_\mathrm{f} - 0.0383 + \mathcal{O}(1/N_\mathrm{f}), & \mathrm{QED}_3 \\ 0.195 \cdot 2N_\mathrm{f} + \mathcal{O}(1/N_\mathrm{f}^0), & \mathrm{QED}_3\text{-GN-XY} \end{cases}$$

[Pufu, PRD '14]

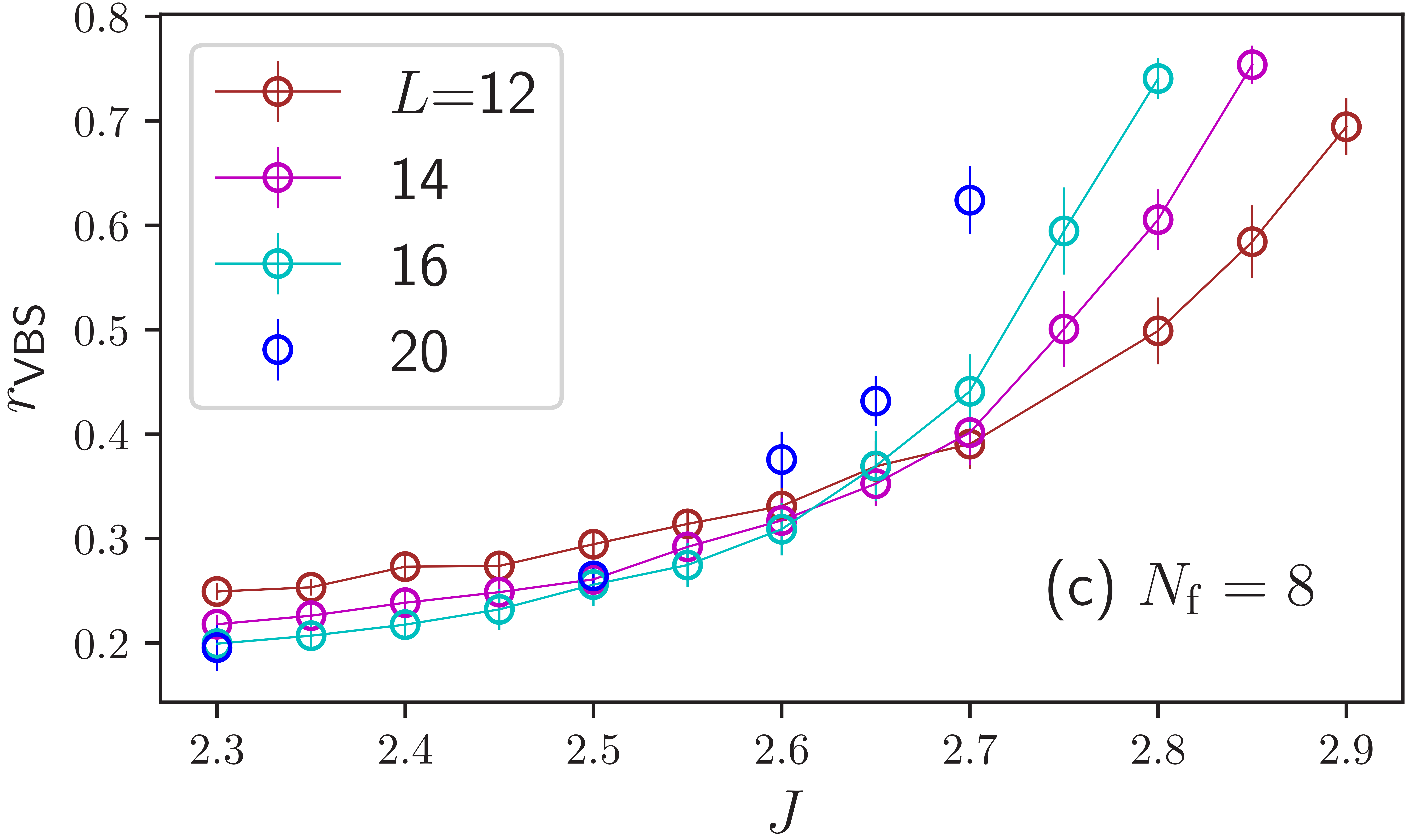
Calculation originally done for QED$_3$-GN-Heisenberg:

[Dupuis, Paranjape, Witczak-Krempa, PRB '19]

Critical flavor number:

$$N_{\mathrm{f,c}} \simeq \begin{cases} 5.7, & \mathrm{QED}_3 \\ 7.7, & \mathrm{QED}_3\text{-GN-XY} \end{cases}$$

VBS correlation ratio



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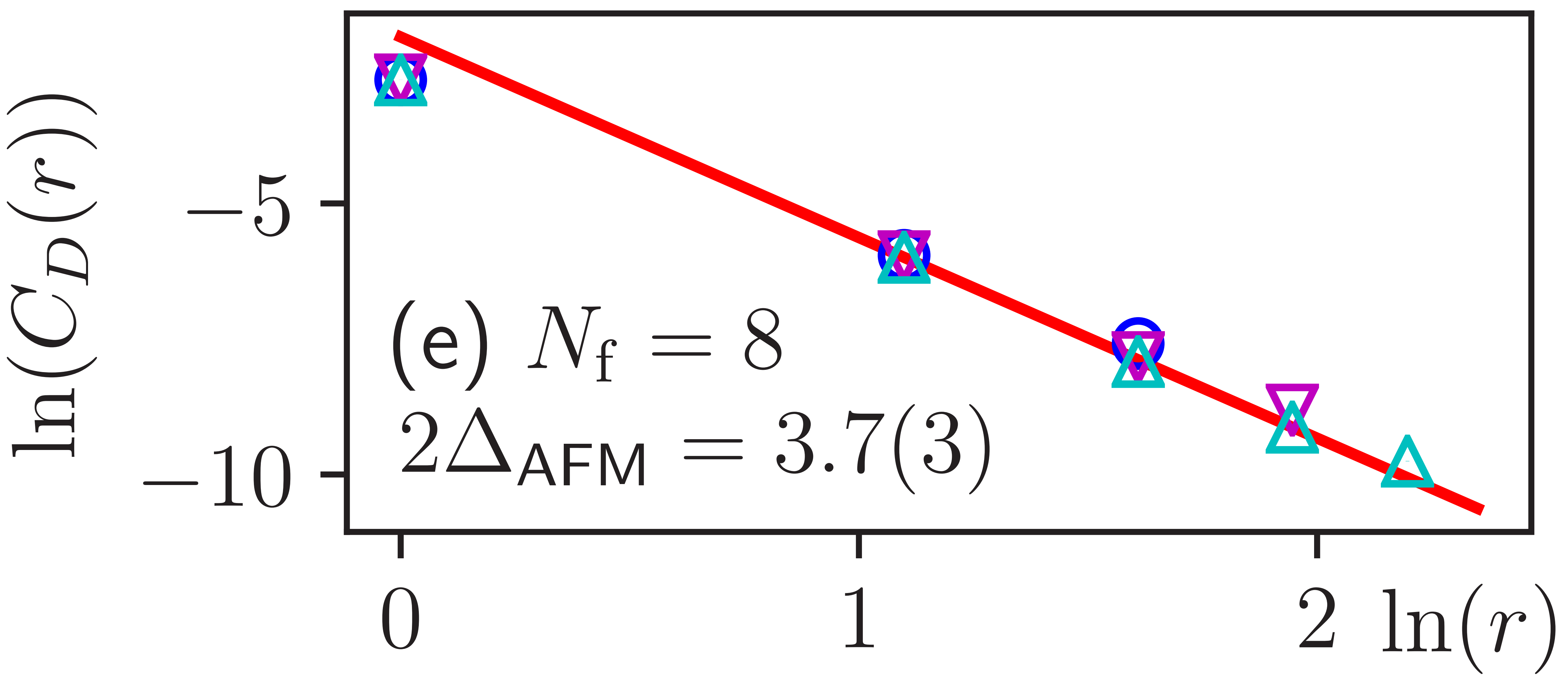
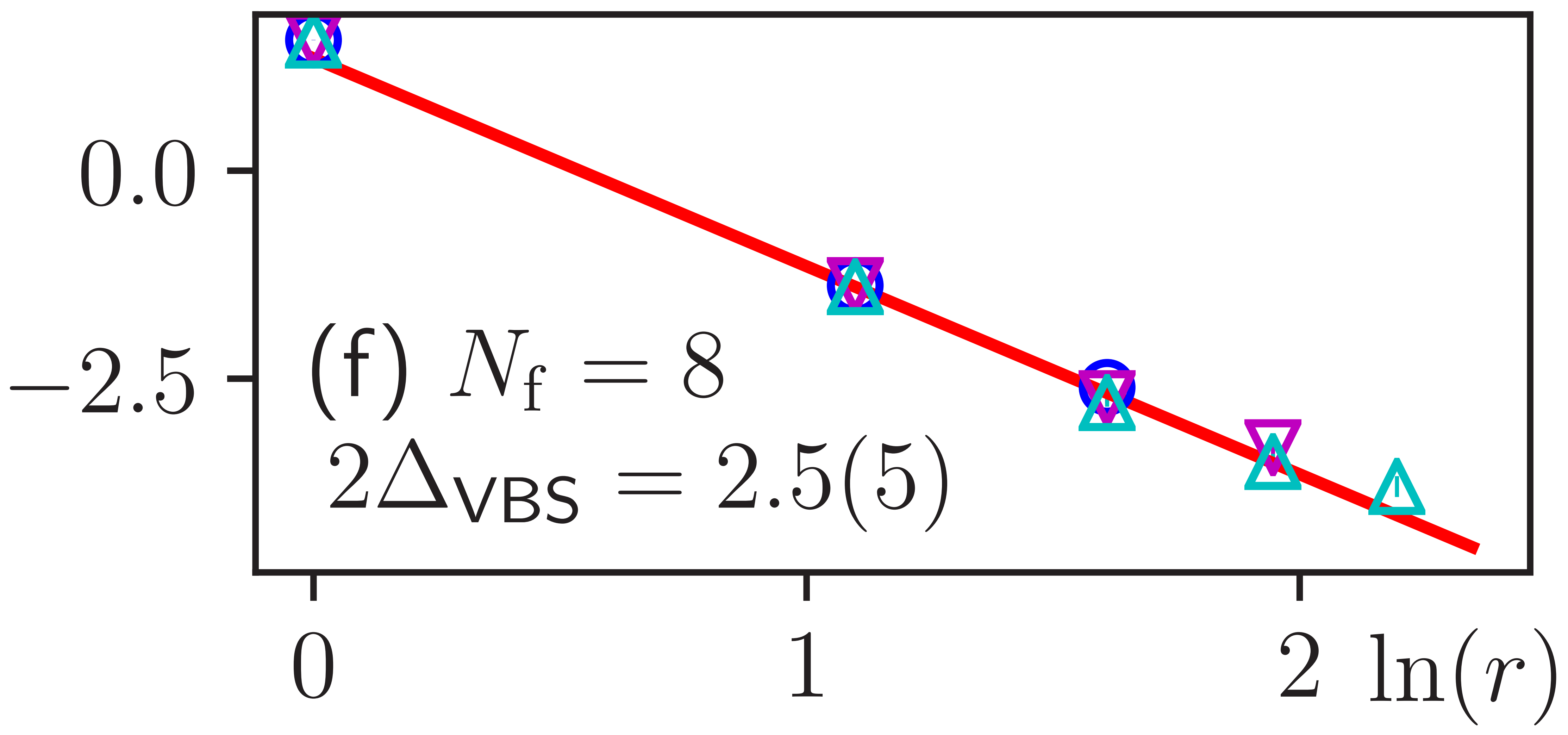
Decay of critical correlators

Dimer correlator



Spin correlator



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