Thermal Hall effect in cuprates and spin liquids

CIFAR - Quantum Materials Program Meeting
Zoom, May 11-13, 2020

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
HARVARD

Enhanced thermal Hall effect in the square lattice Neel state,
Nature Physics **15**, 1290 (2019)

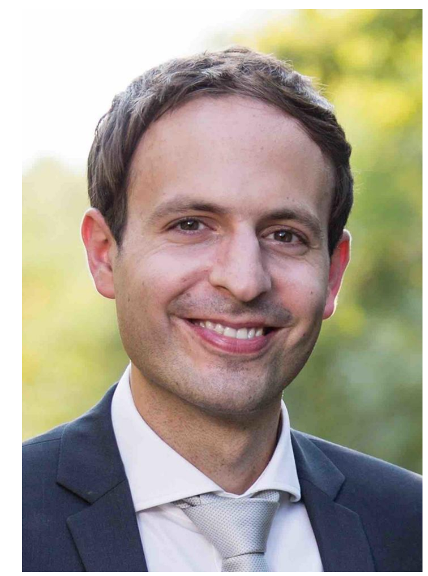
Gauge theories for the thermal Hall effect, arXiv:2002.01947

Unquantized thermal Hall effect in quantum spin liquids with spinon Fermi surfaces, arXiv:2005.02396

Shubhayu Chatterjee

Haoyu Guo

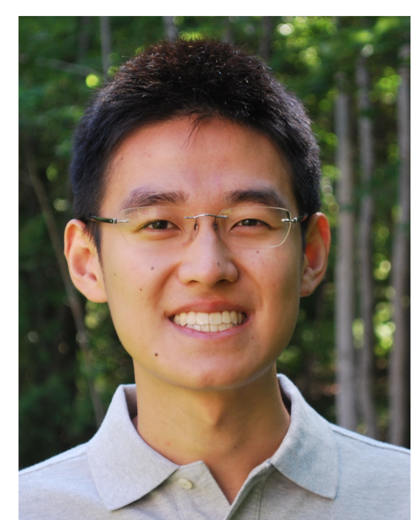
Rhine Samajdar



Mathias Scheurer

Yanting Teng

Cenke Xu



Yunchao Zhang

1. Thermal Hall in the cuprate pseudogap

2. Thermal Hall in the Neel state enhanced by a proximate abelian chiral spin liquid

3. Thermal Hall across a non-Abelian spin liquid to spinon Fermi surface transition

Giant thermal Hall conductivity in the pseudogap phase of cuprate superconductors

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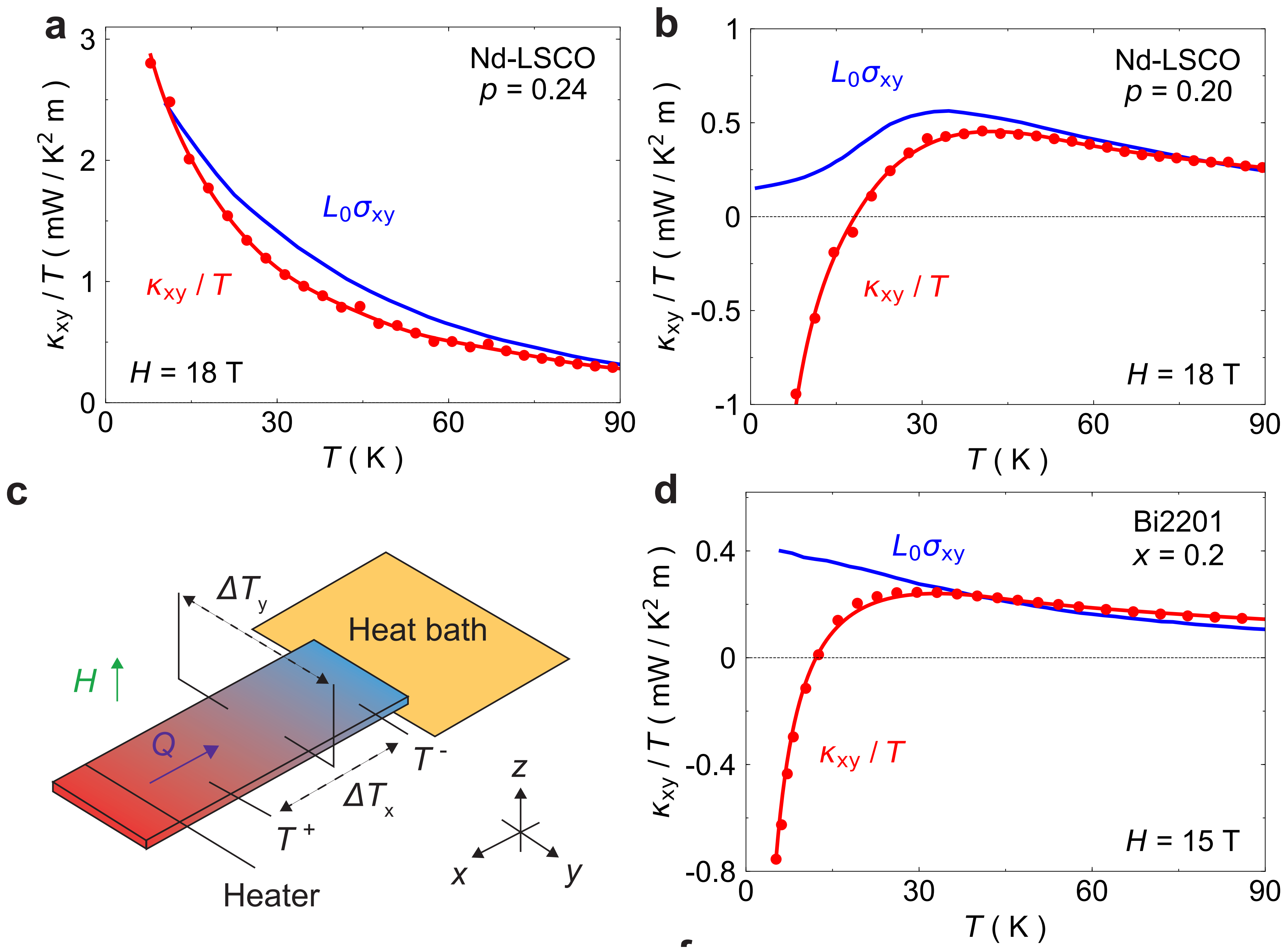
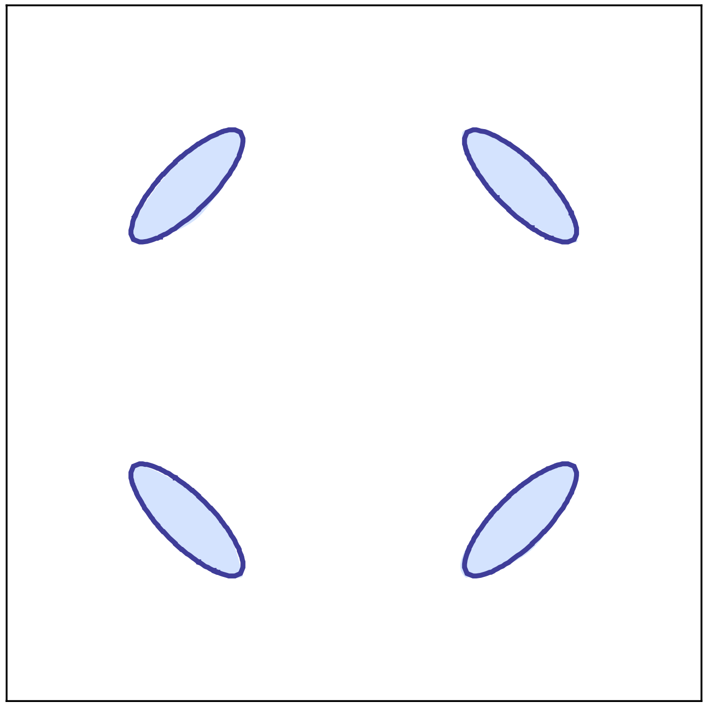
Nature **571**, 376 (2019)



Model for the pseudogap

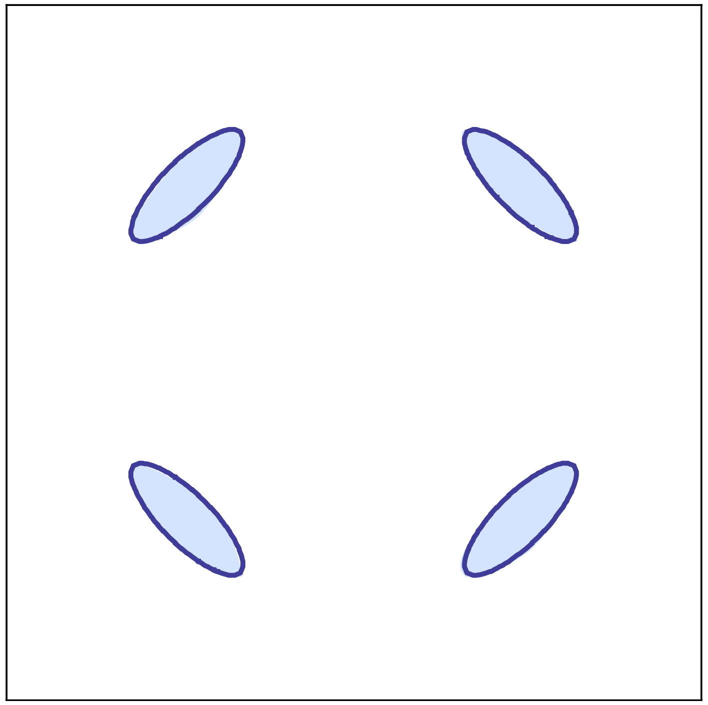
Fermionic 'chargons' of density δ in hole pockets.
The fermions carry electromagnetic gauge charge $+e$,
and charges $p = \pm 1$ under an emergent U(1) gauge field.
v is a valley index, $v_{\rm dis}$ is an impurity potential.

$$\mathcal{L}_f = \sum_{v=1,2} \sum_{p=\pm 1} f_{pv}^\dagger \left(\frac{\partial}{\partial \tau} - \mu - i p a_\tau - \frac{(\boldsymbol{\nabla} - i p \boldsymbol{a} - i e \boldsymbol{A}_{\rm em})^2}{2m^*} \right) f_{pv} + v_{\rm dis}(\boldsymbol{r}) f_{pv}^\dagger f_{pv}$$



Thermal Hall conductivity

$$\mathcal{L}_f = \sum_{v=1,2}\sum_{p=\pm 1} f_{pv}^\dagger \left(\frac{\partial}{\partial \tau} - \mu - ipa_\tau - \frac{(\boldsymbol{\nabla} - ip\boldsymbol{a} - ie\boldsymbol{A}_{\rm em})^2}{2m^*} \right) f_{pv}$$
$$+ v_{\rm dis}(\boldsymbol{r}) f_{pv}^\dagger f_{pv}$$



Leading order fermionic contribution is that implied by the Wiedemann-Franz law.

$$\sigma_{xy} = \left(\frac{\delta e^2 \tau}{m^*} \right) \omega_c \tau$$

$$\kappa_{xy}^0 = \frac{\pi^2 T}{3} \left(\frac{k_B}{e} \right)^2 \sigma_{xy}$$

Thermal Hall conductivity

$$\mathcal{L}_f = \sum_{v=1,2} \sum_{p=\pm 1} f^\dagger_{pv} \left(\frac{\partial}{\partial \tau} - \mu - i p a_\tau - \frac{(\boldsymbol{\nabla} - i p \boldsymbol{a} - i e \boldsymbol{A}_{\rm em})^2}{2m^*} \right) f_{pv}$$
$$+ v_{\rm dis}(\boldsymbol{r}) f^\dagger_{pv} f_{pv}$$

Integrating out the fermions leads to an effective action for the emergent U(1) gauge field

$$\mathcal{S}_a = \int d^2x d\tau \left[\frac{K_1(\boldsymbol{x})}{2} (\boldsymbol{\nabla} \times \boldsymbol{a})^2 + \frac{K_2(\boldsymbol{x})}{2} (\boldsymbol{\nabla} a_\tau - \partial_\tau \boldsymbol{a})^2 - \frac{i \sigma_{xy}(\boldsymbol{x})}{2e^2} \epsilon_{\mu\nu\lambda} a_\mu \partial_\nu a_\lambda \right] + \int \frac{d^2k d\omega}{8\pi^3} \gamma_k |\omega| \left[\boldsymbol{a}^T(k,\omega) \right]^2$$

Thermal Hall conductivity

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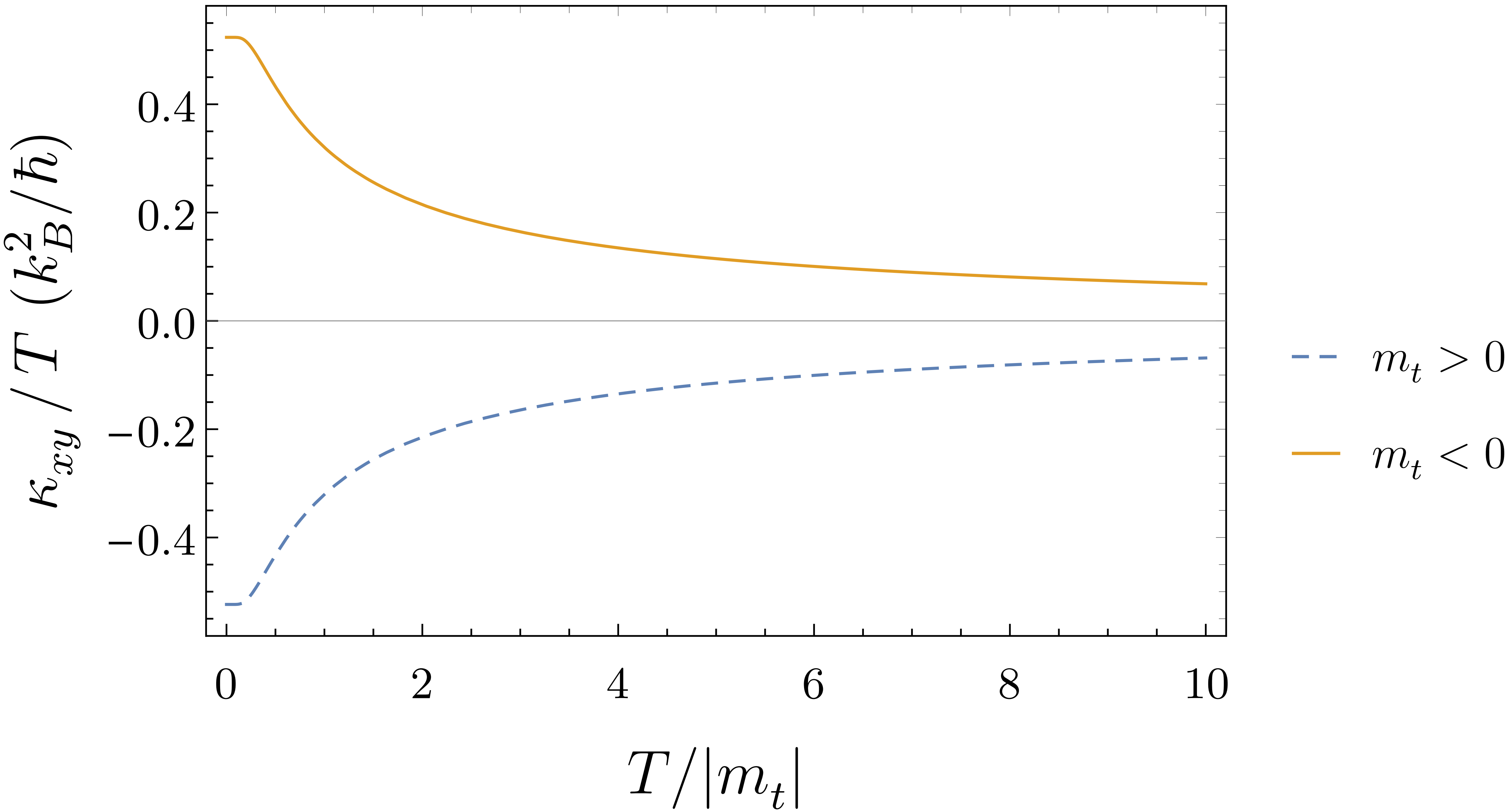
The gauge field contributes a thermal Hall conductivity, κ^1_{xy}, which has the *opposite sign* from the Wiedemann-Franz term determined from σ_{xy}.

Thermal Hall conductivity

$m_t \propto \sigma_{xy}$



The gauge field contribution $|\kappa^1_{xy}|$ is bounded by $(\pi/6)(k_B^2 T/\hbar)$.

Thermal Hall conductivity

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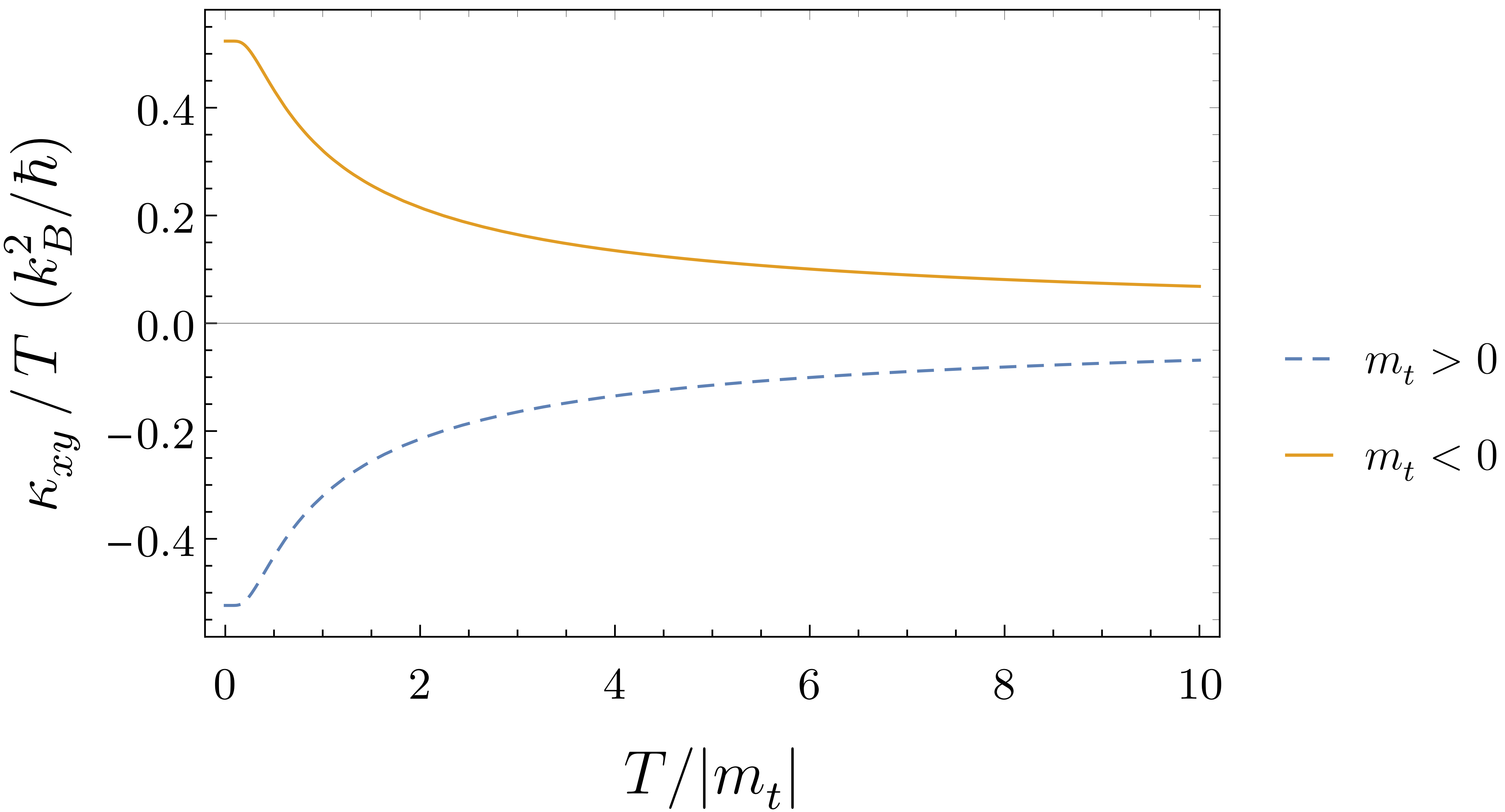

Needed: Phonon assisted emergent-photon transport ?

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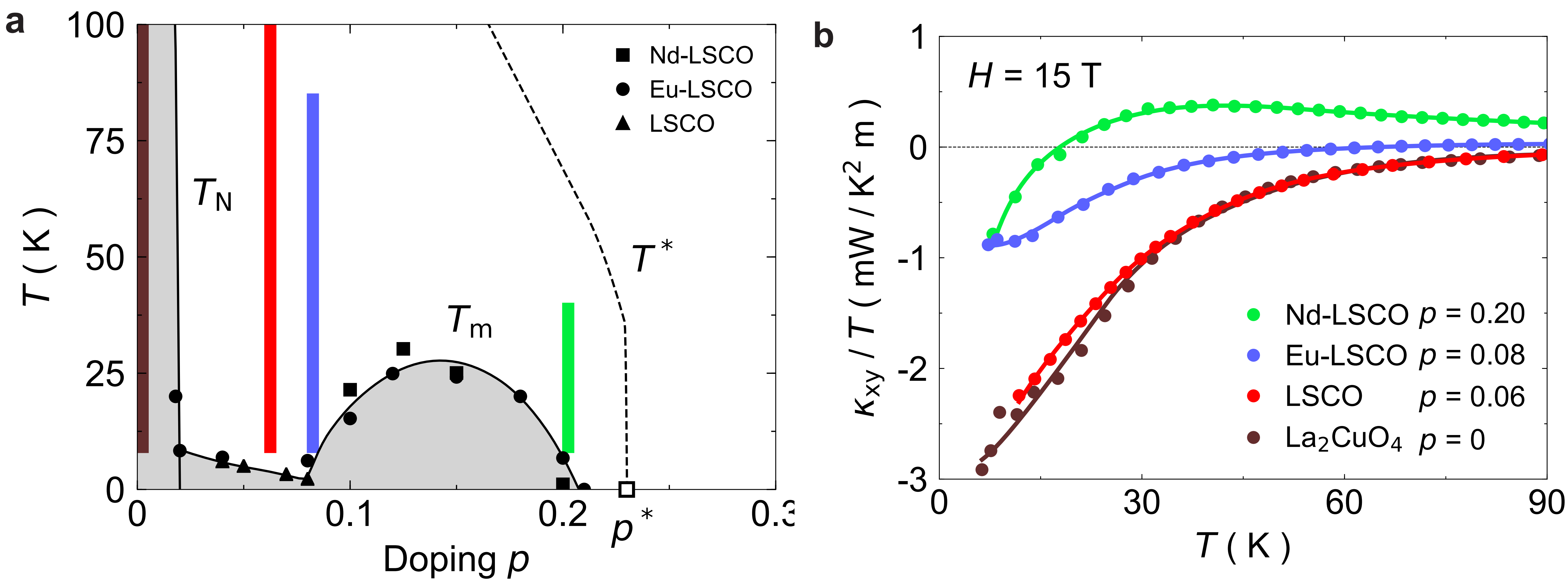
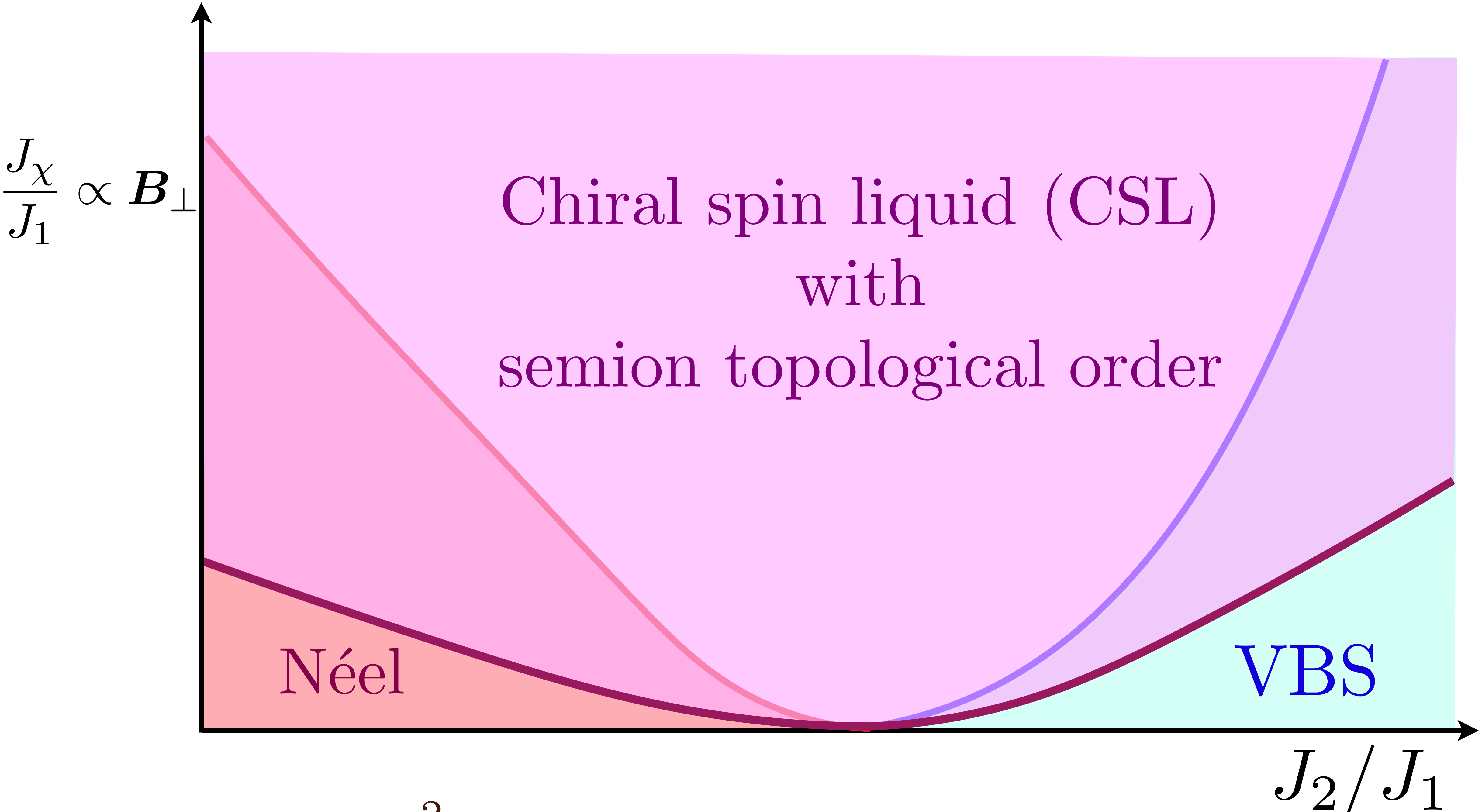


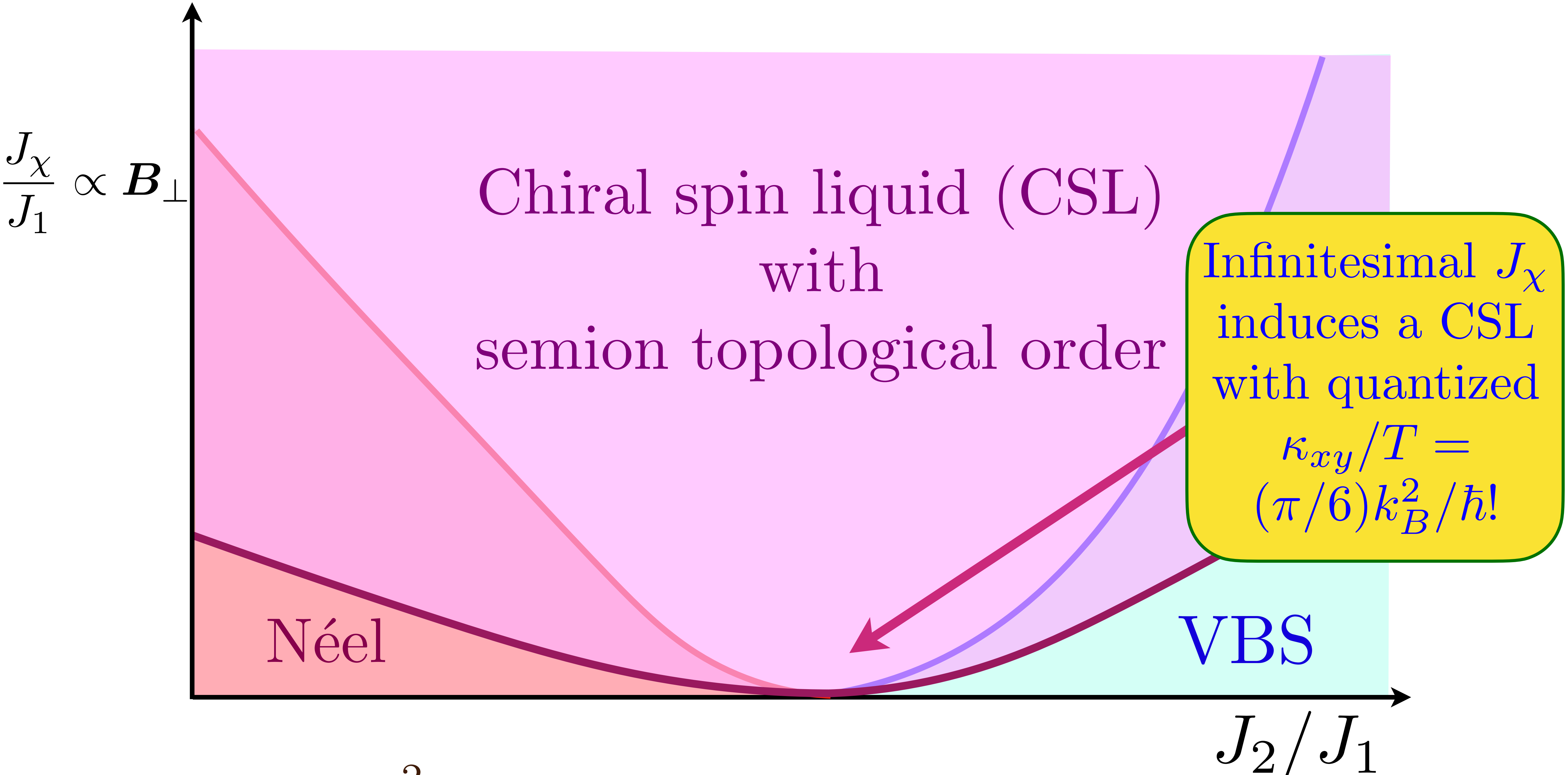
$$H = \sum_{\text{n.n.}} J_1 \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \sum_{\text{n.n.n.}} J_2 \boldsymbol{S}_i \cdot \boldsymbol{S}_j + J_\chi \sum_{\triangle} \boldsymbol{S}_i \cdot (\boldsymbol{S}_j \times \boldsymbol{S}_k)$$



$$\mathcal{S}_f = \int d^2 r d\tau \sum_{\alpha=1}^{2} \left[\overline{f}_\alpha \gamma^\mu (\partial_\mu - i A_\mu) f_\alpha + m_\chi \overline{f}_\alpha f_\alpha \right]$$

Quantum critical theory + J_χ

$$H = \sum_{\text{n.n.}} J_1 \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \sum_{\text{n.n.n.}} J_2 \boldsymbol{S}_i \cdot \boldsymbol{S}_j + J_\chi \sum_{\triangle} \boldsymbol{S}_i \cdot (\boldsymbol{S}_j \times \boldsymbol{S}_k)$$



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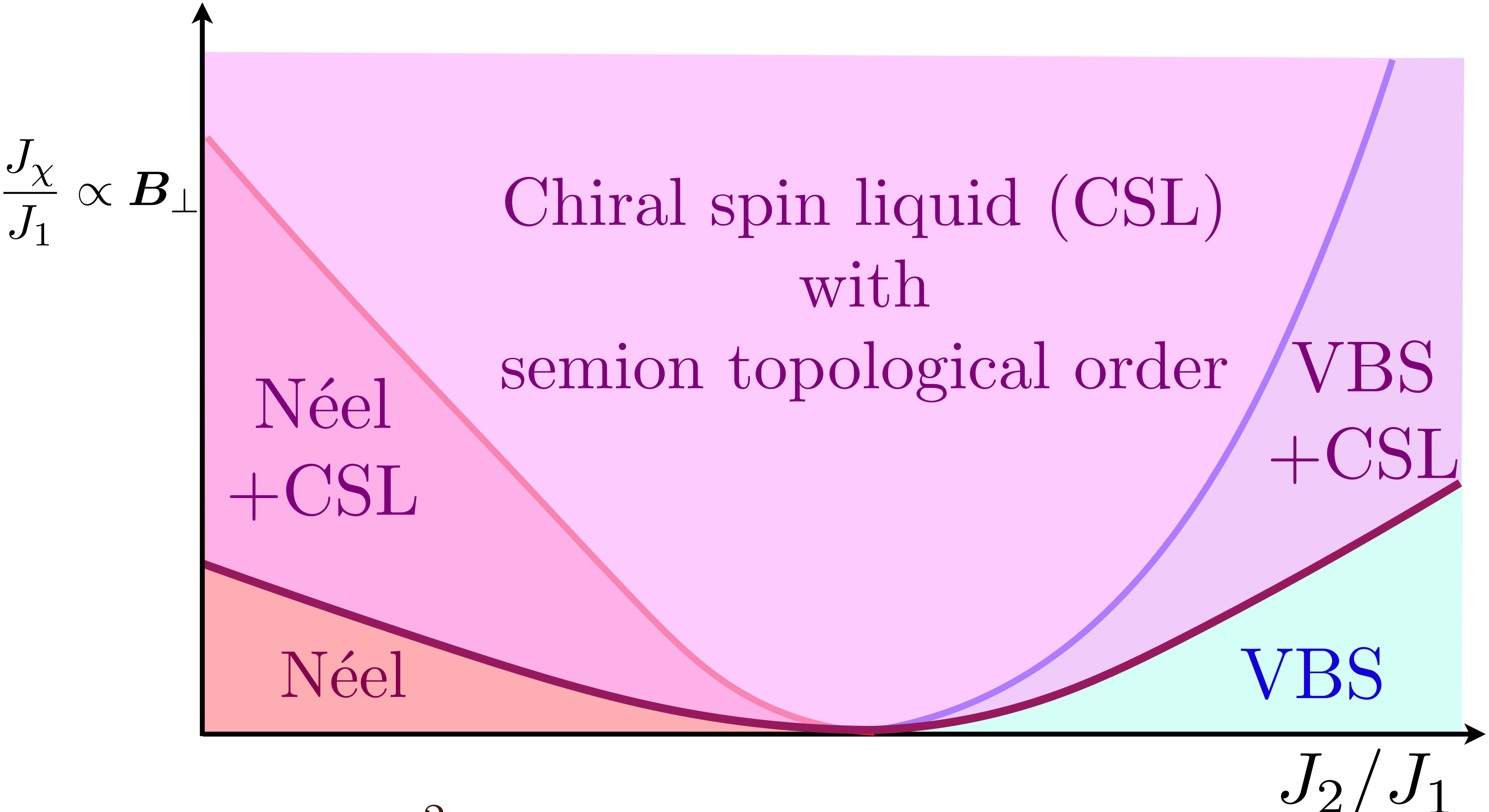

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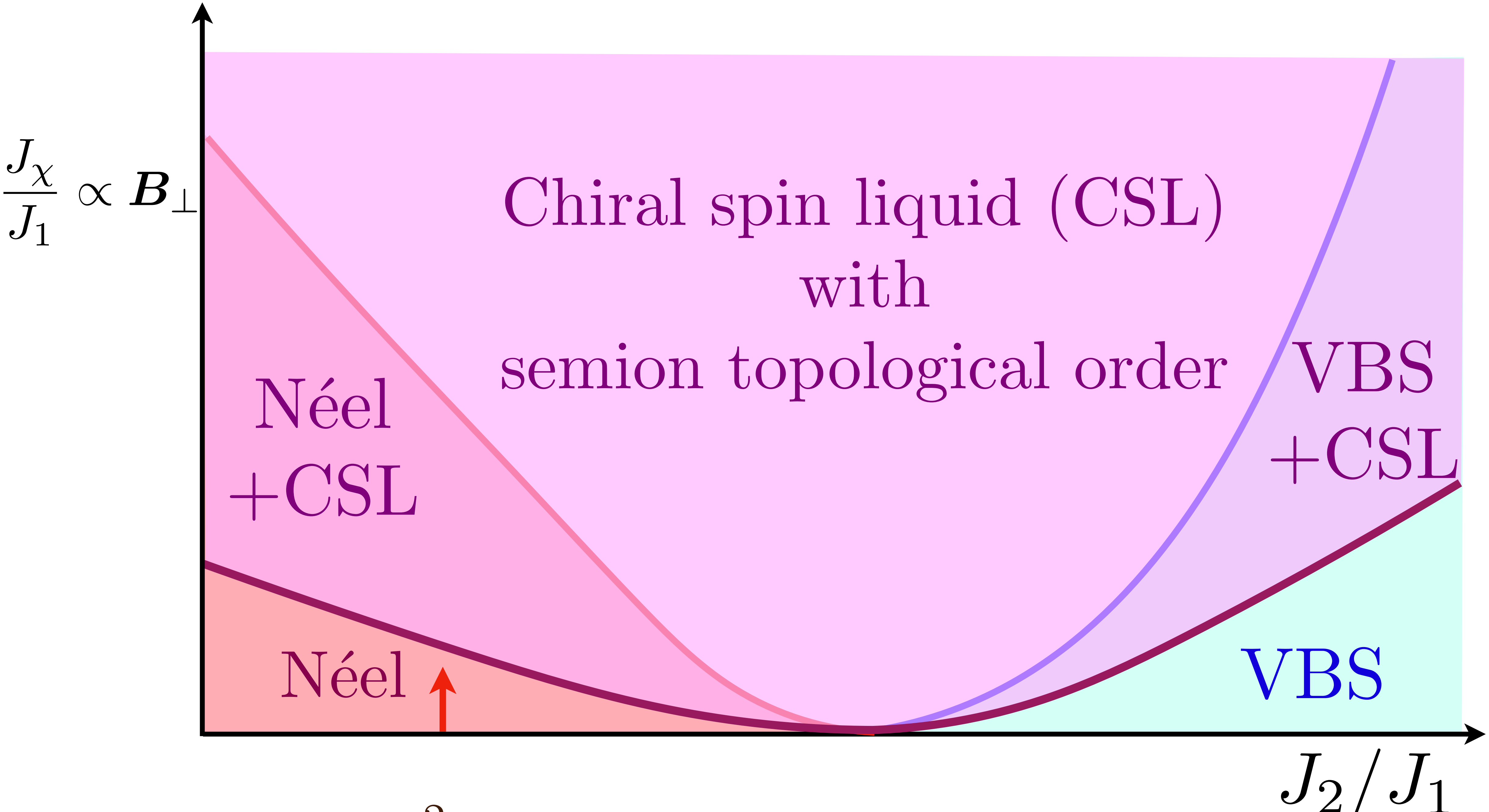
Quantum critical theory + J_χ + Néel order

$$H = \sum_{\text{n.n.}} J_1 \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \sum_{\text{n.n.n.}} J_2 \boldsymbol{S}_i \cdot \boldsymbol{S}_j + J_\chi \sum_{\triangle} \boldsymbol{S}_i \cdot (\boldsymbol{S}_j \times \boldsymbol{S}_k)$$



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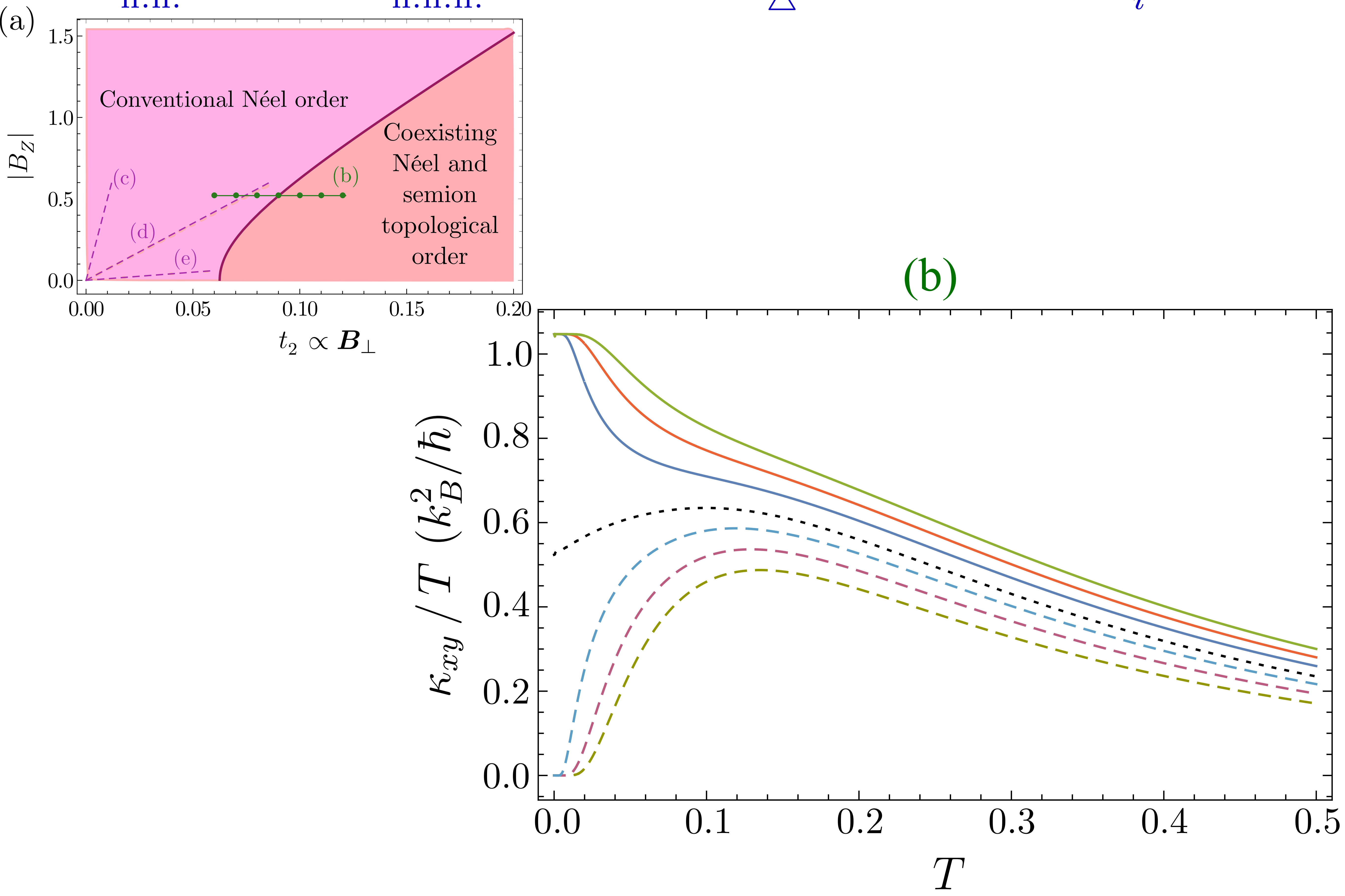

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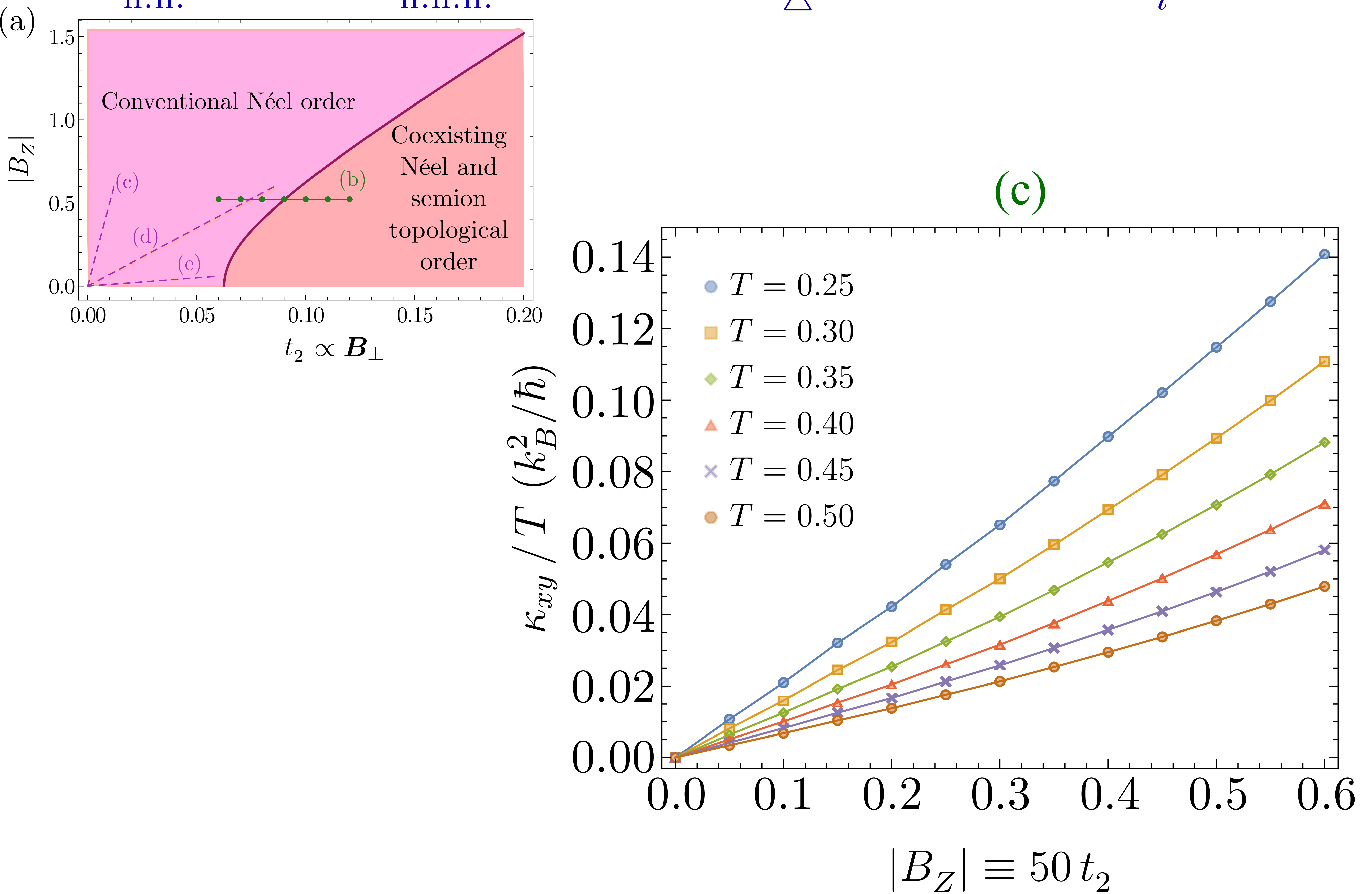

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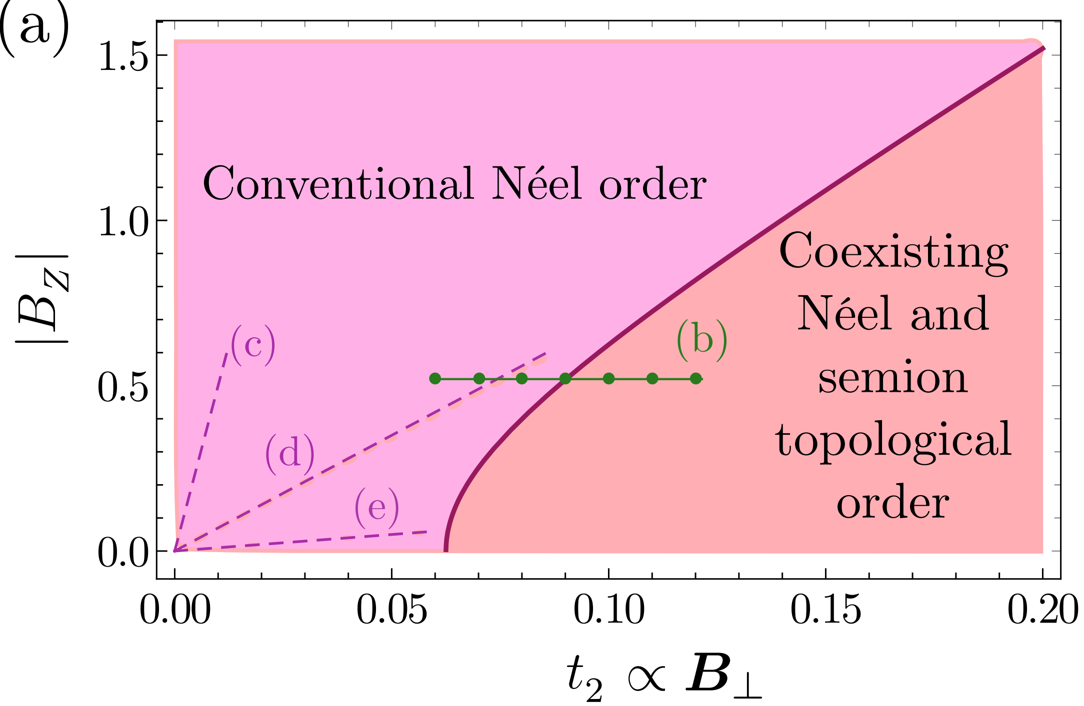

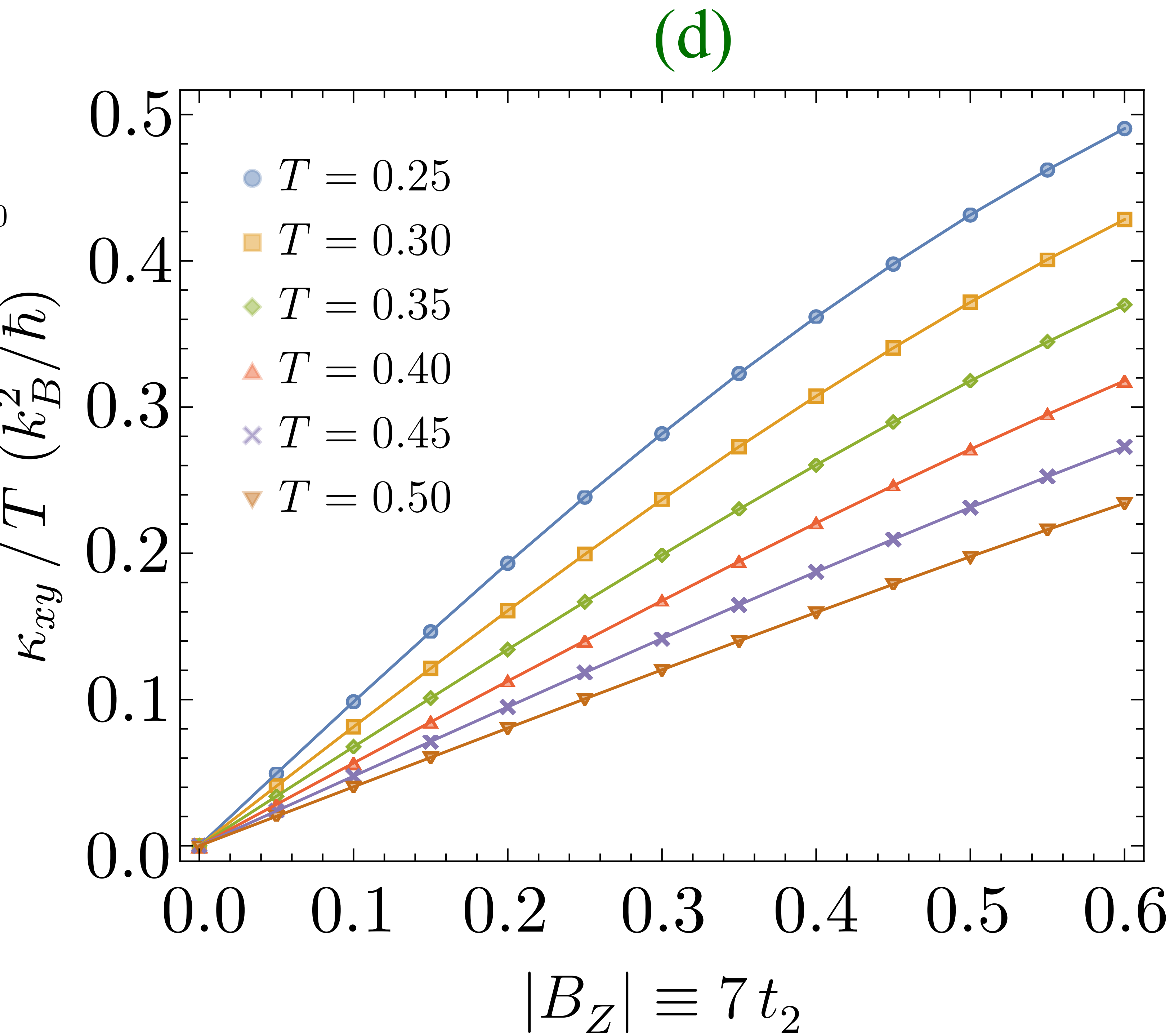

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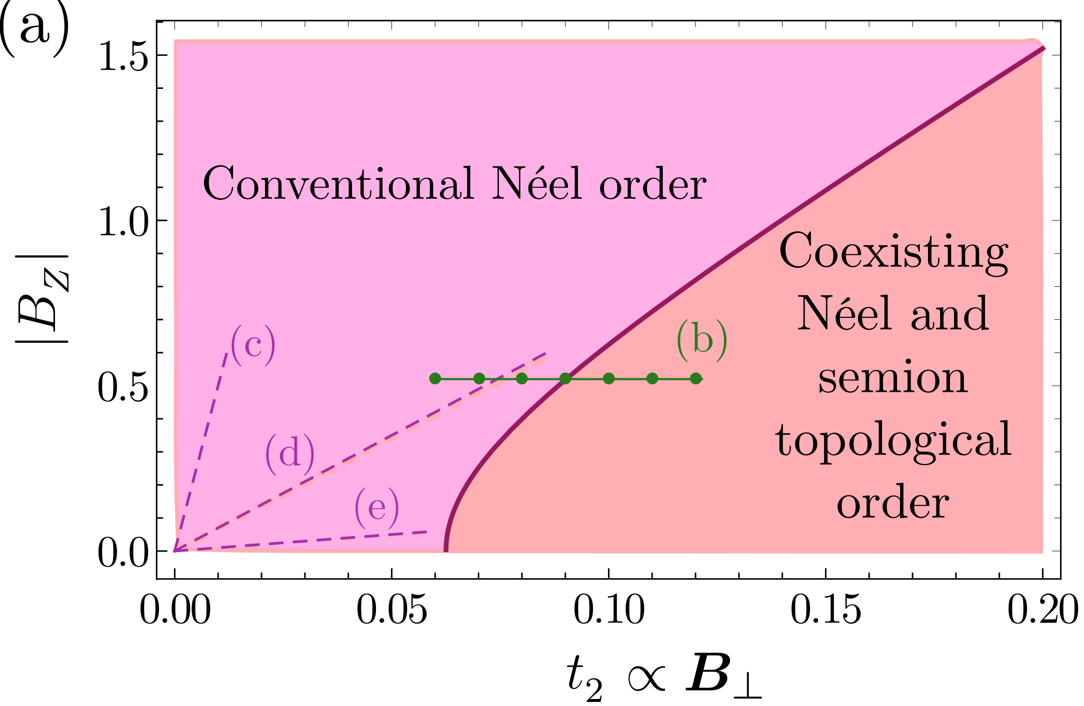

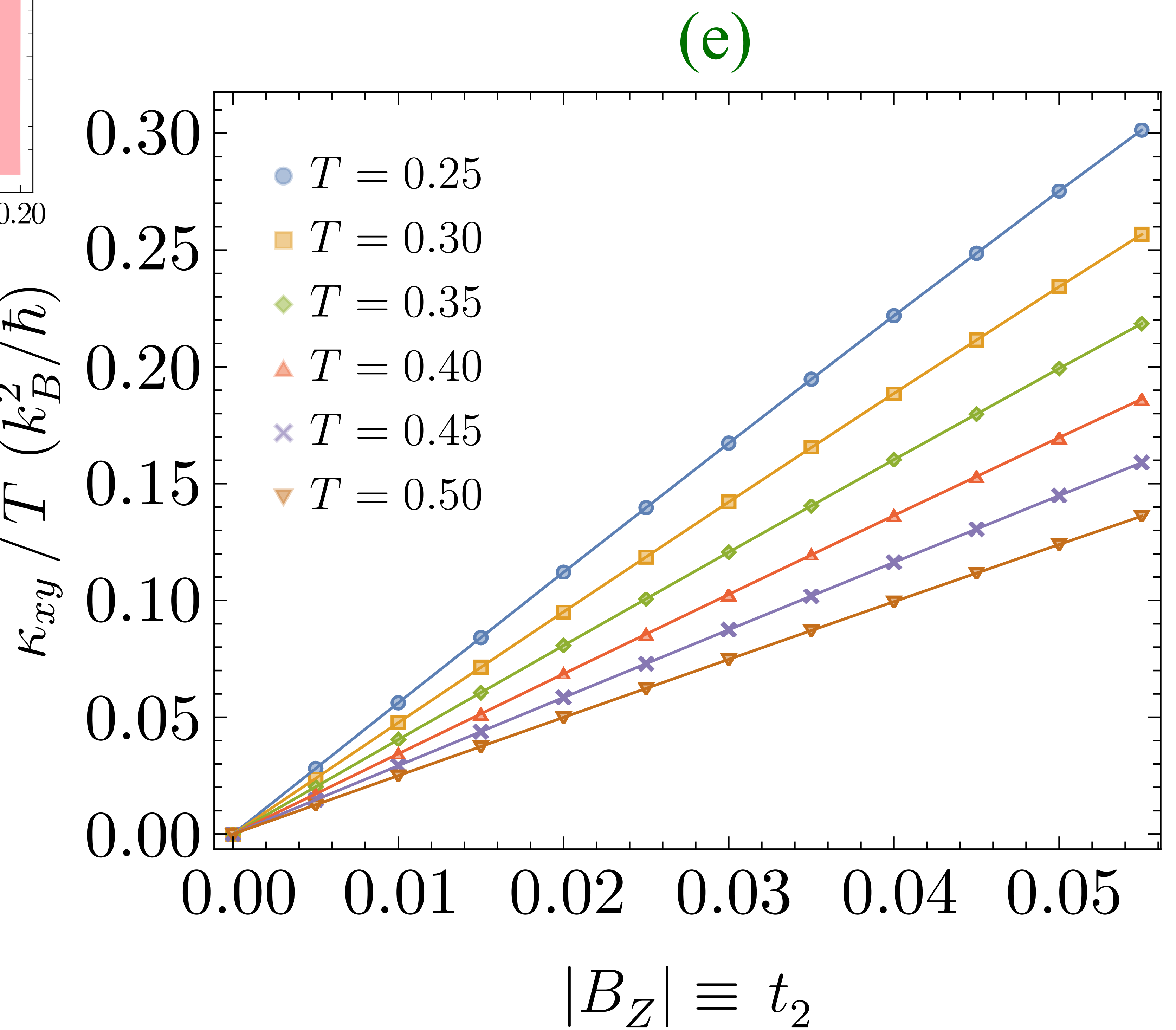

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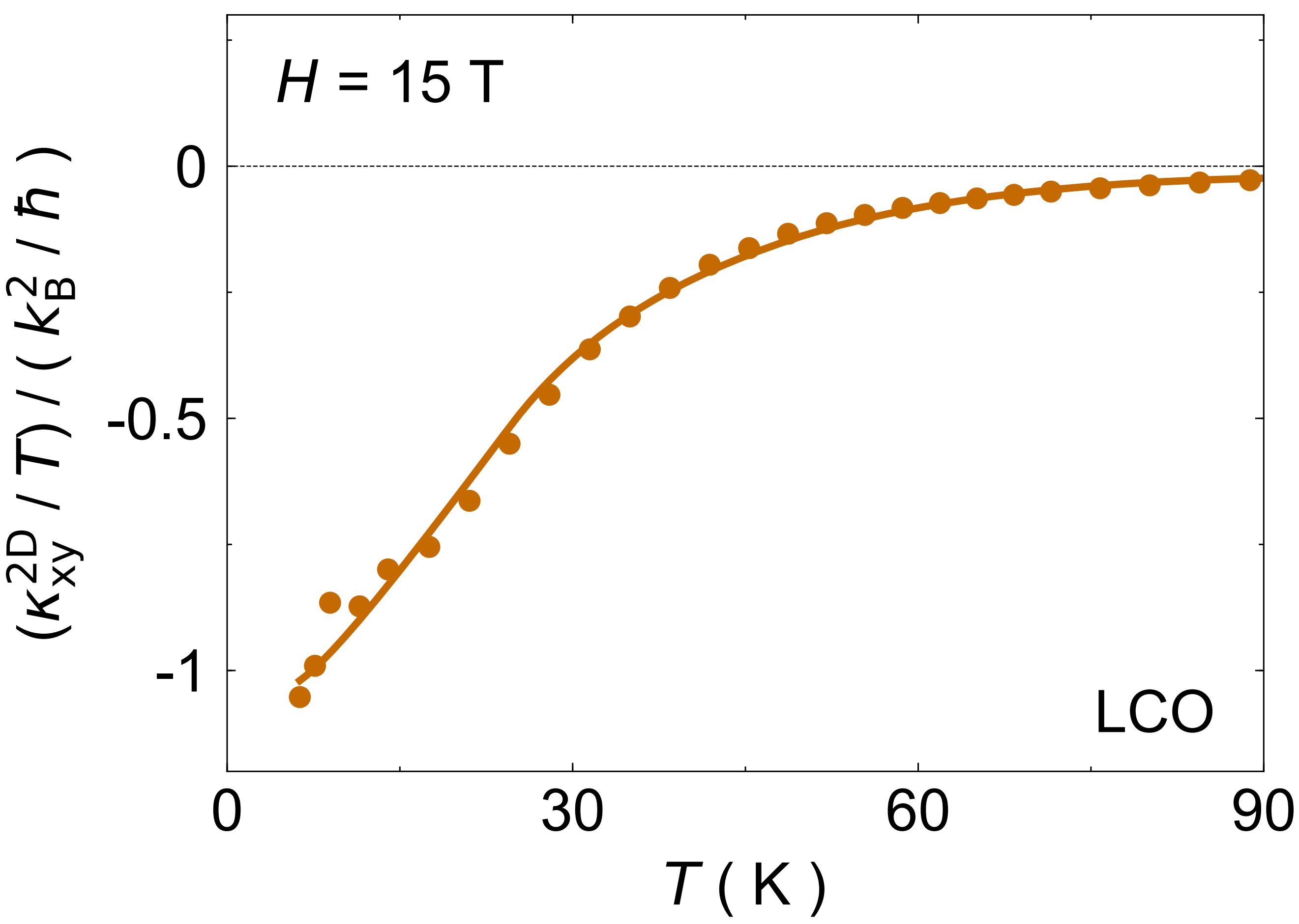

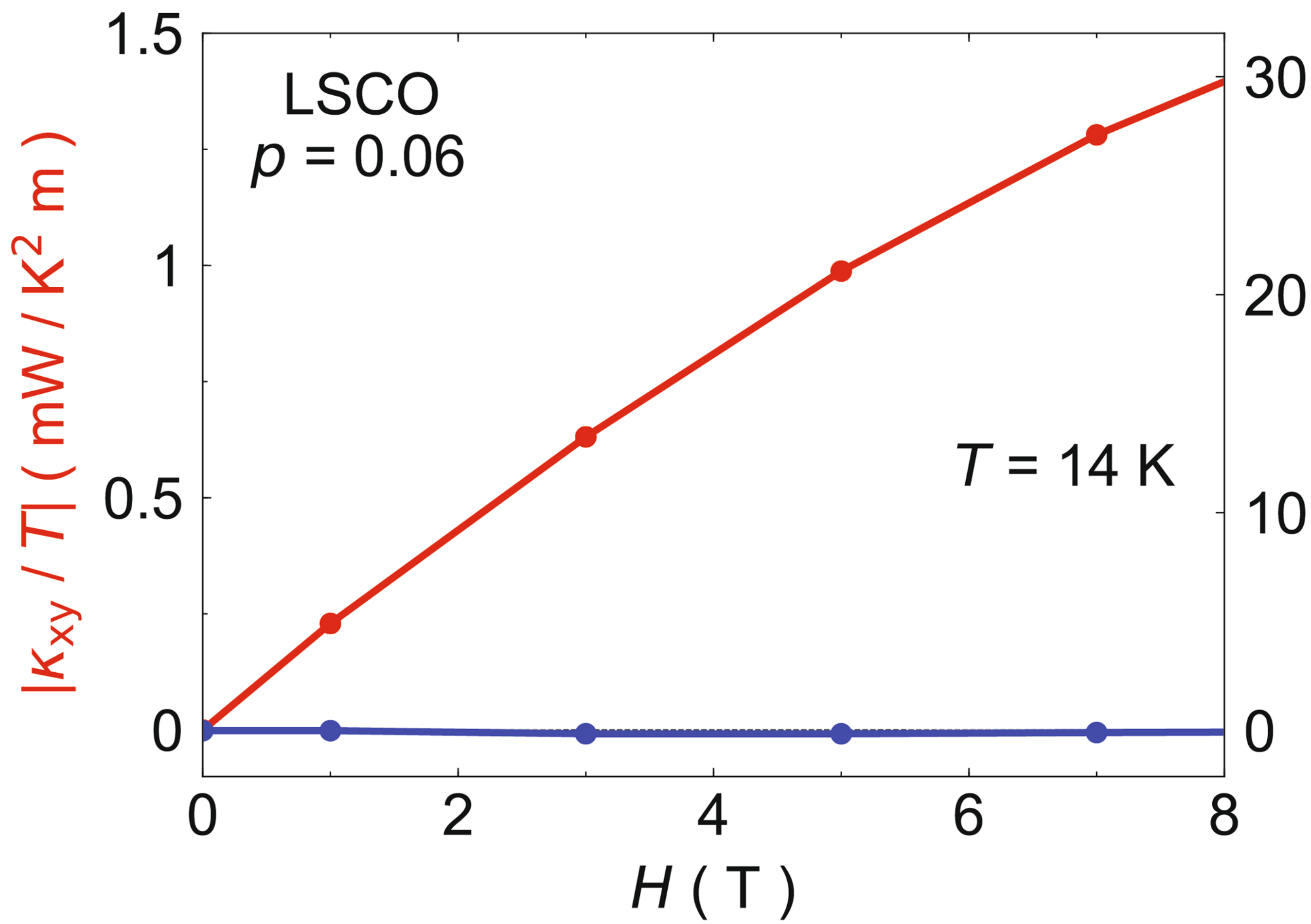

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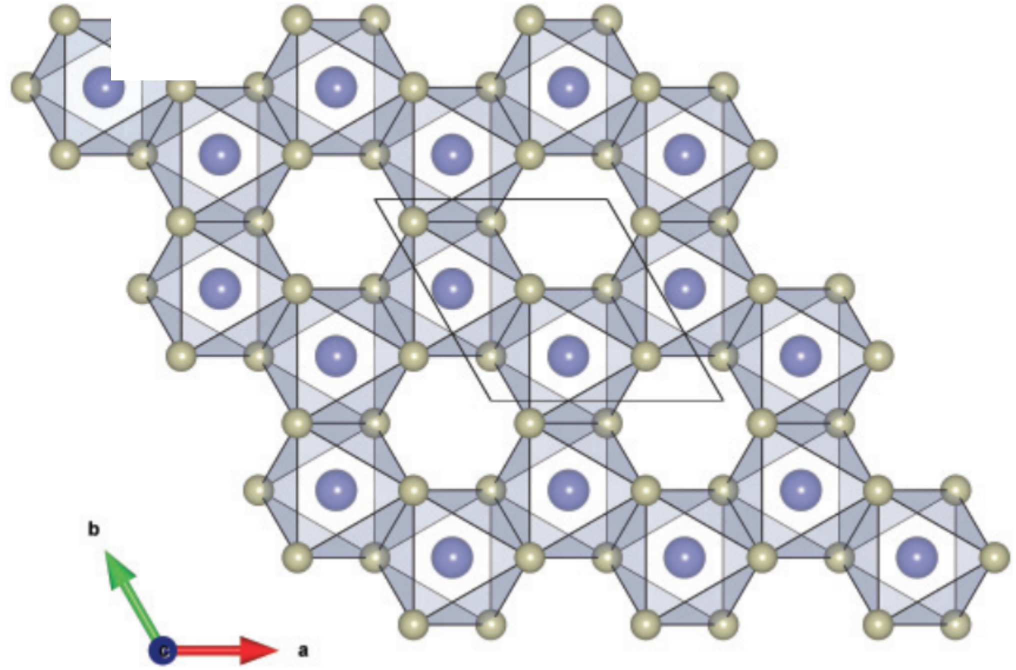
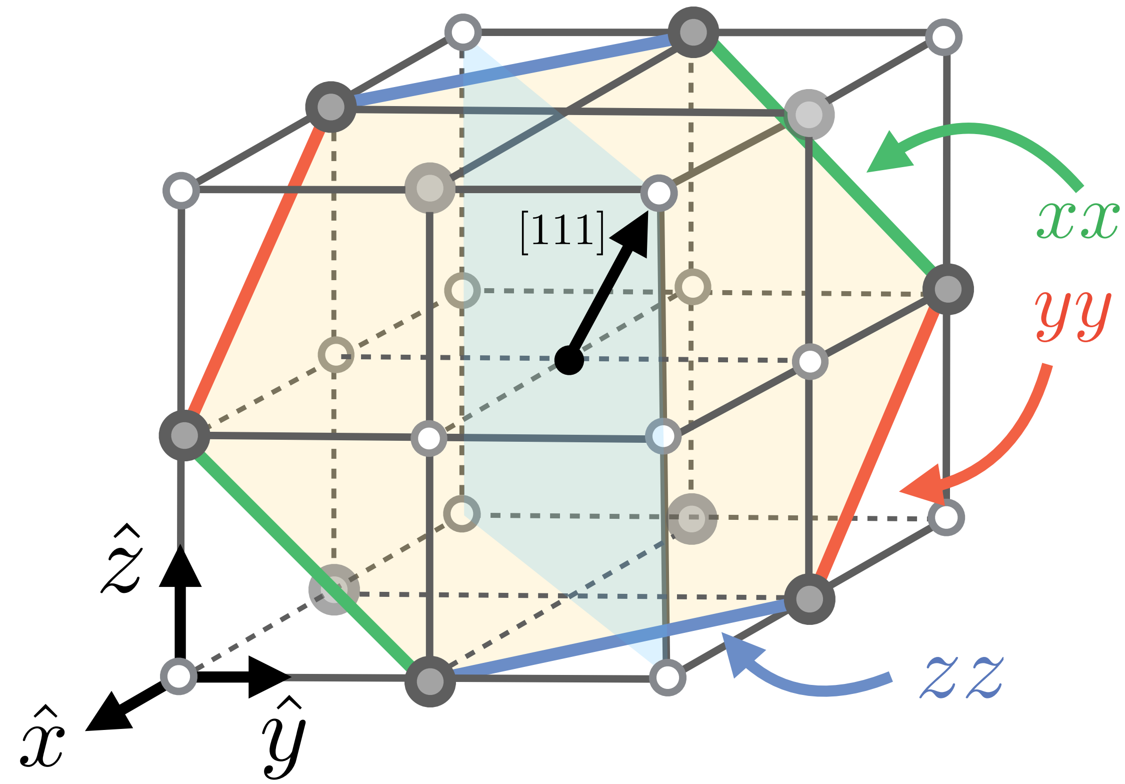
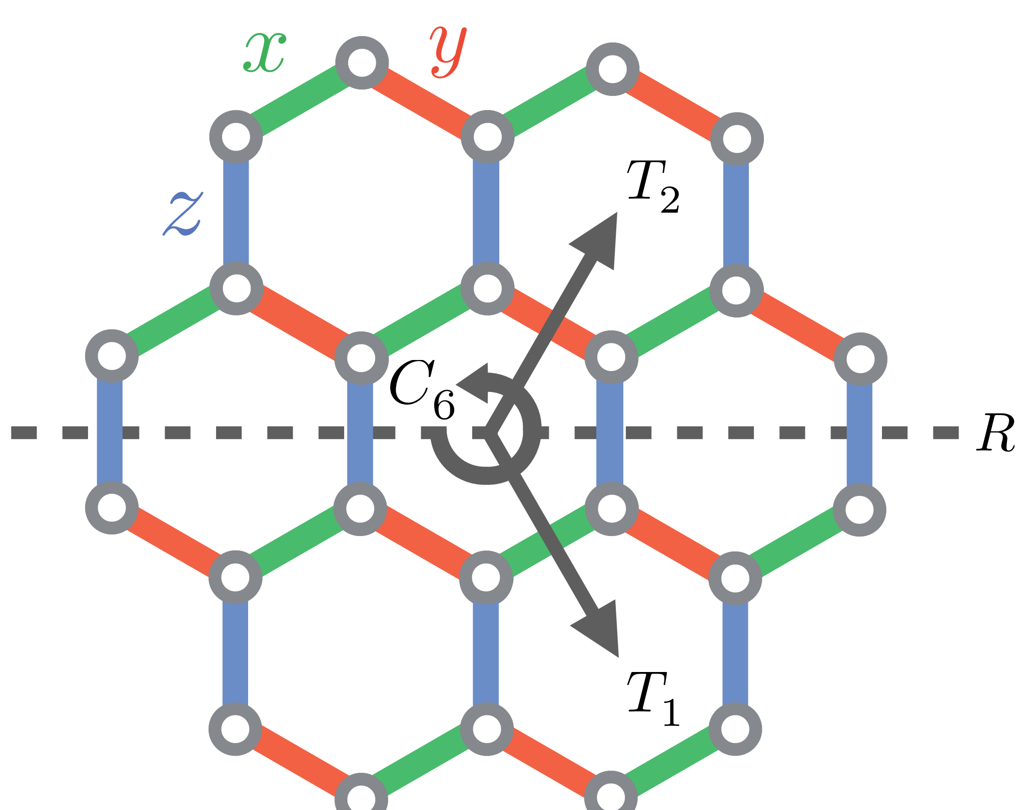
Yanting Teng

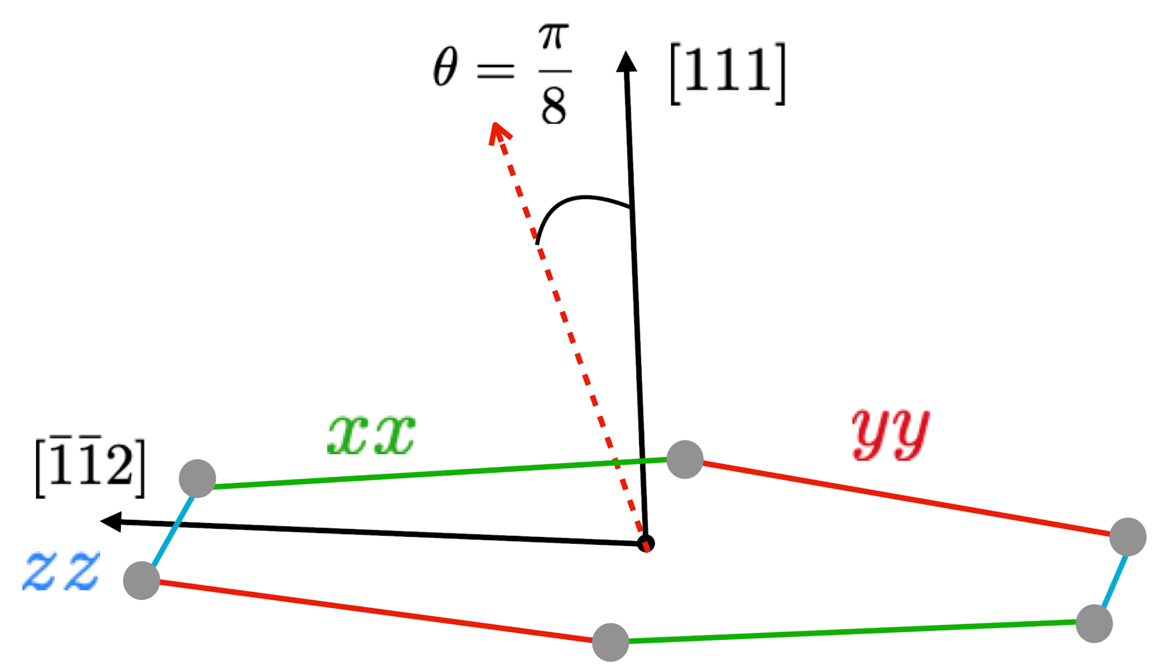
K. W. PLUMB et al, PRB **90**, 041112(R) (2014)

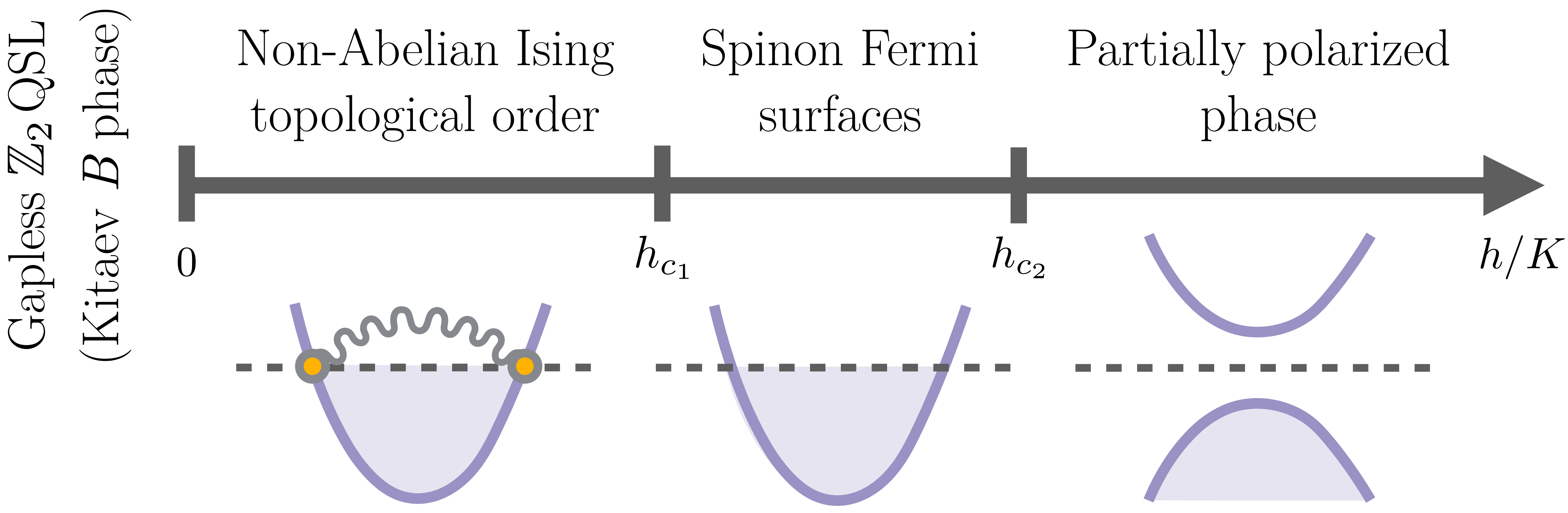


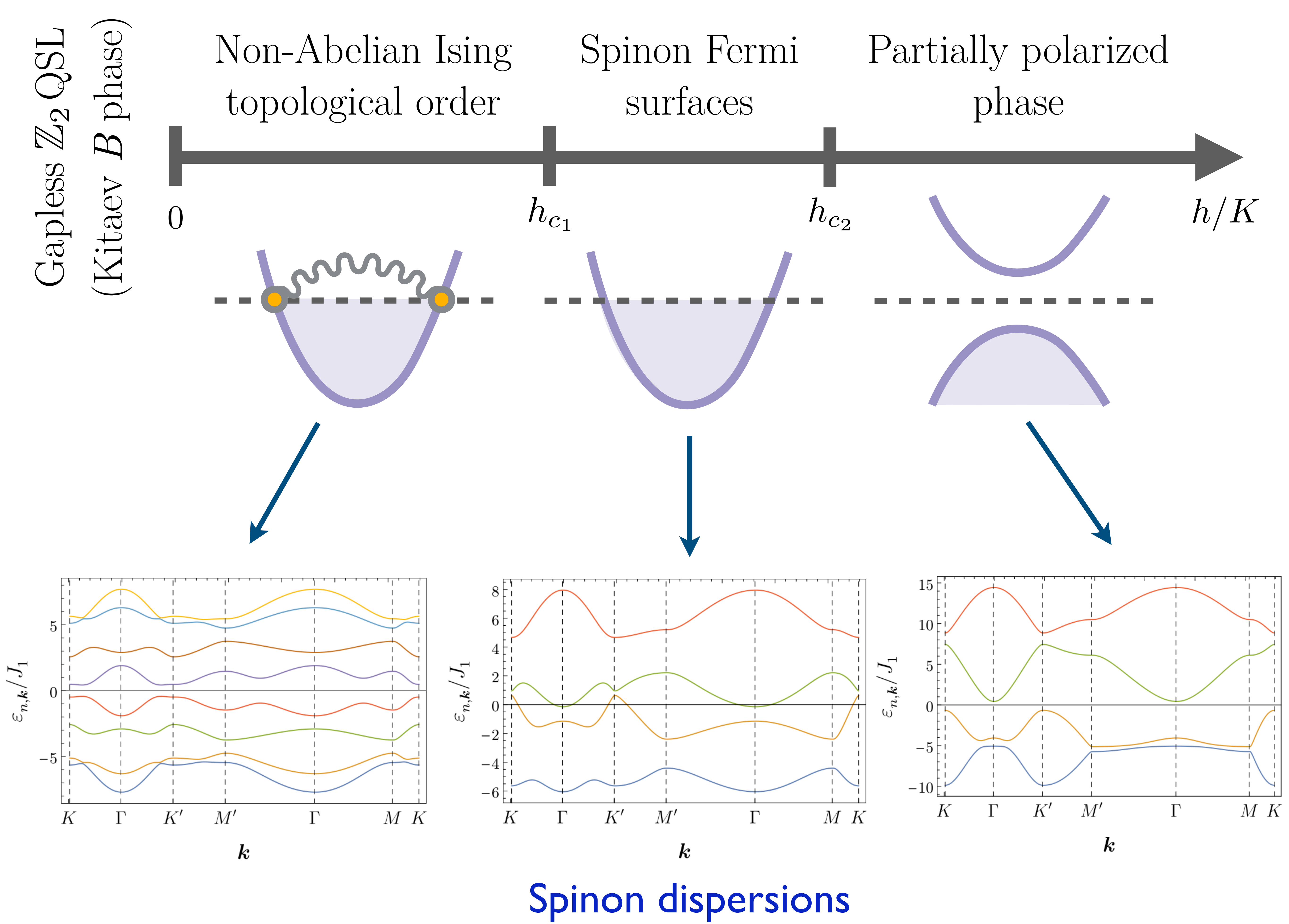
α-$RuCl_3$








Gapless $\mathbb{Z}_2$ QSL
(Kitaev B phase)
Non-Abelian Ising
topological order
Spinon Fermi
surfaces
Partially polarized
phase
0
h_{c_1}
h_{c_2}
h/K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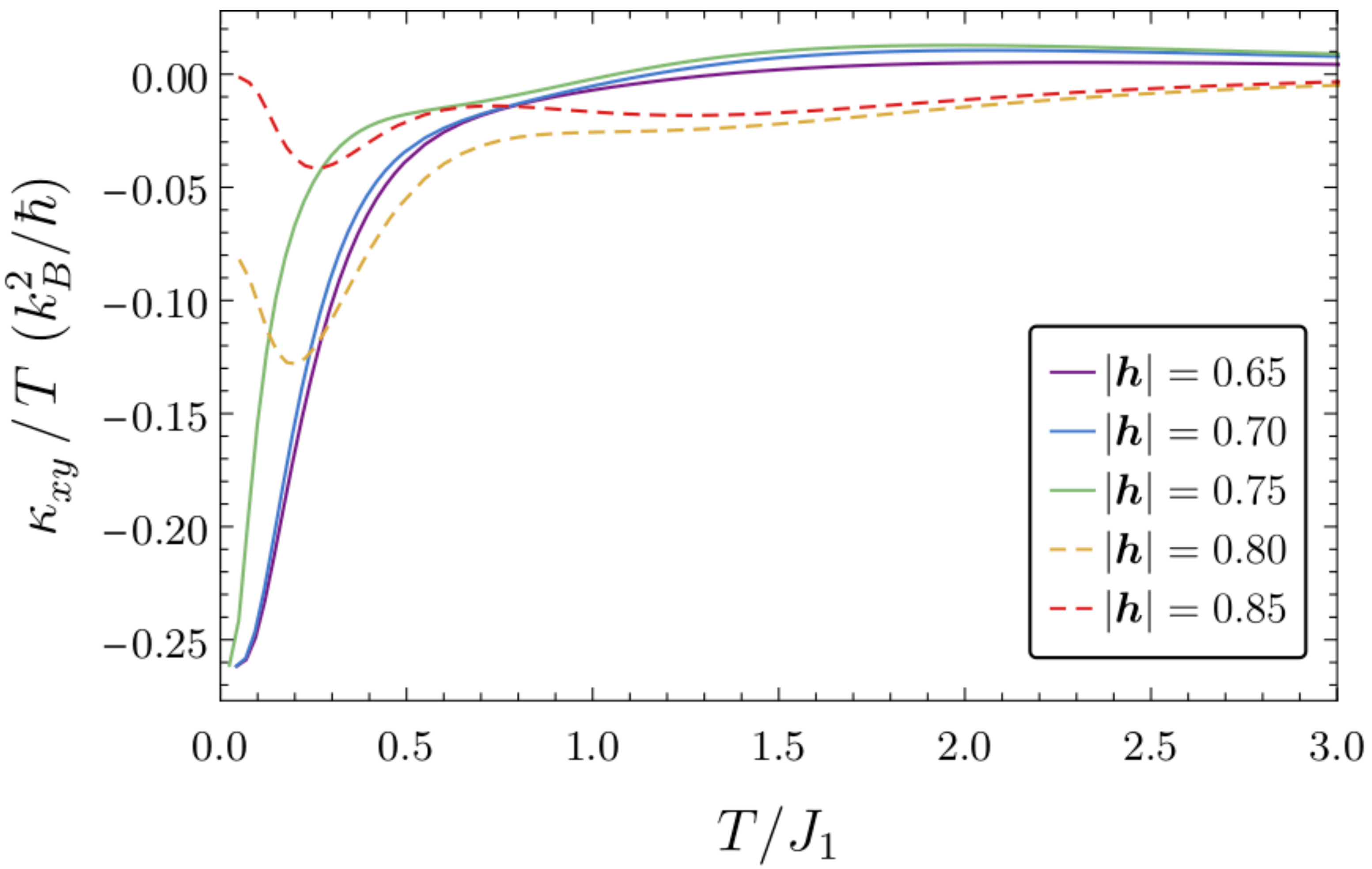
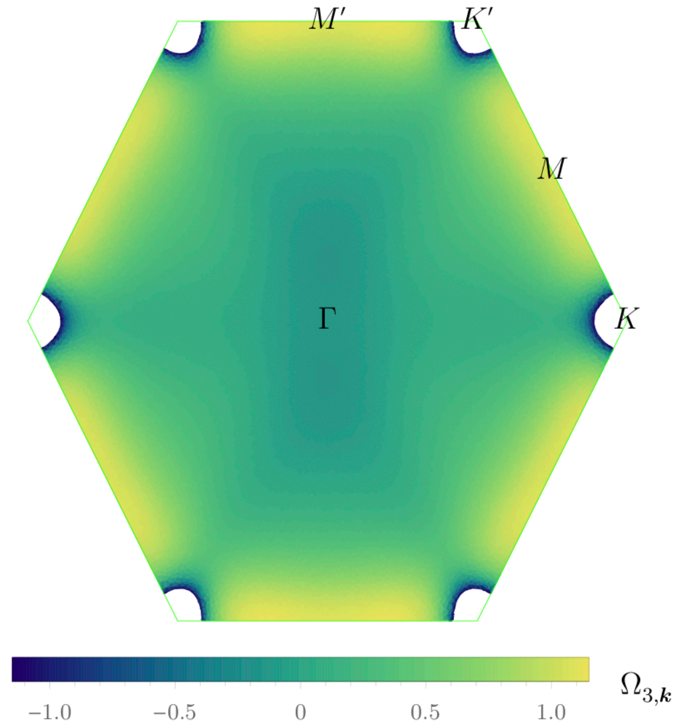
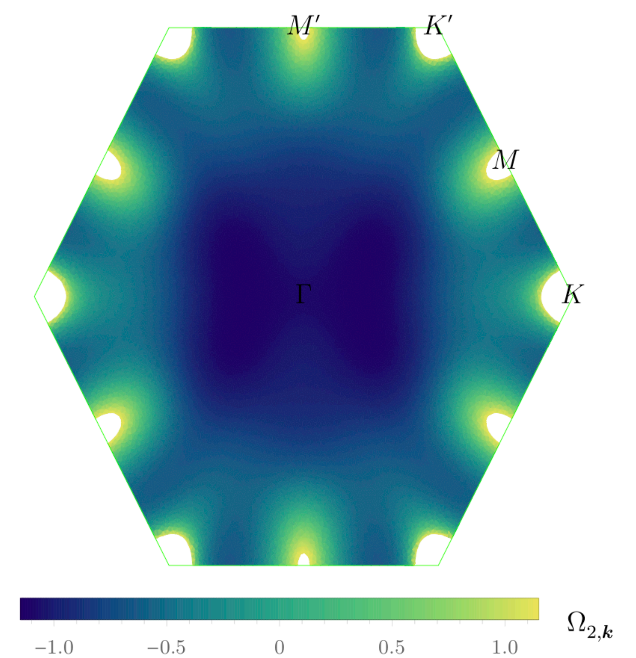
0
h_{c_1}
h_{c_2}
h/K
$\varepsilon_{n,\boldsymbol{k}}/J_1$
K Γ K' M' Γ M K
$\boldsymbol{k}$
Spinon dispersions

Temperature dependence for fixed field

Ising Topological Order (ITO, solid) to Spinon Fermi surface (SFS, dashed)



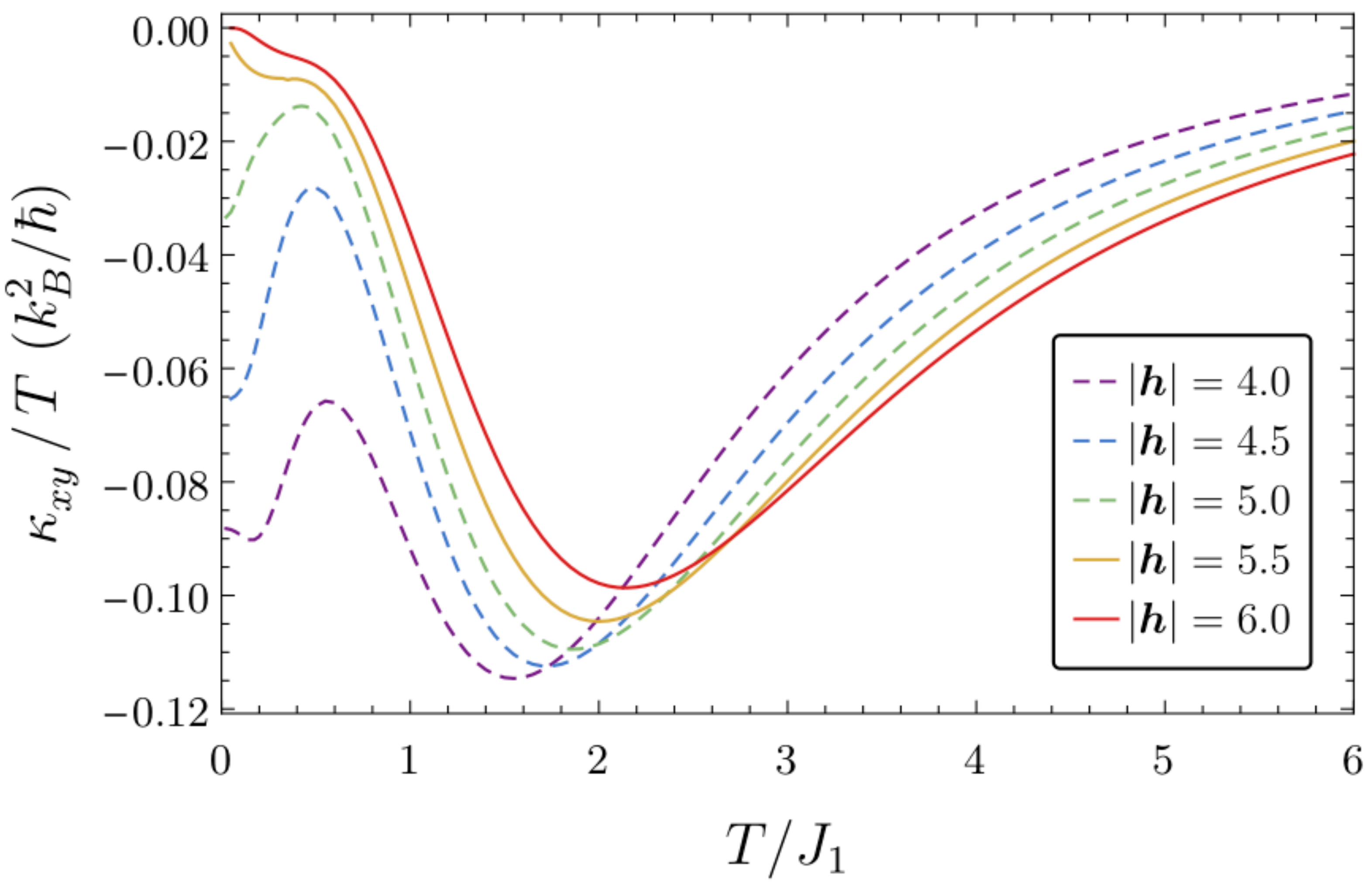


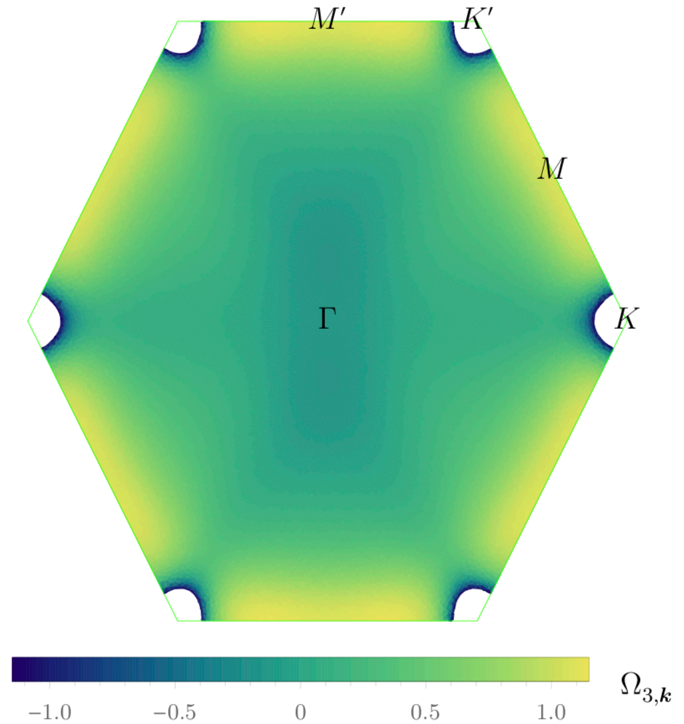


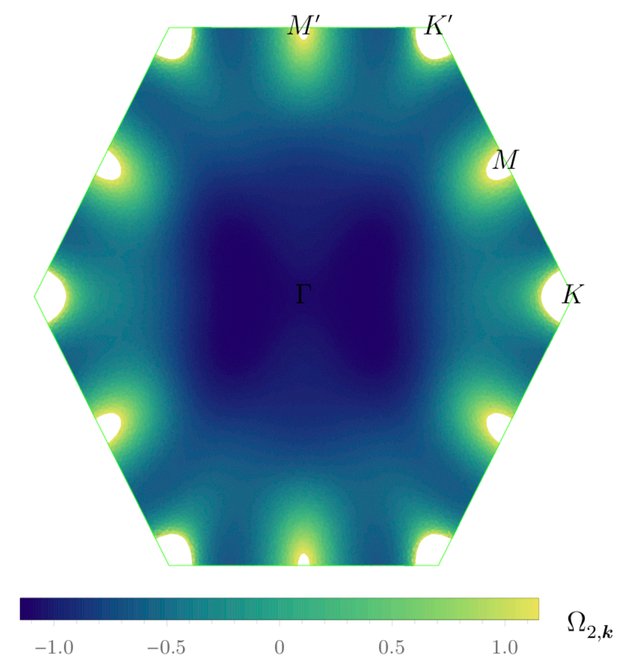
Spinon Berry curvatures

Temperature dependence for fixed field

Spinon Fermi surface (SFS, dashed)
to Partially polarized (solid)

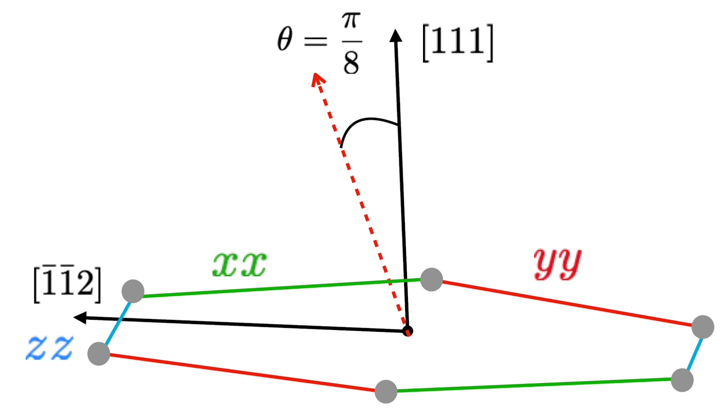




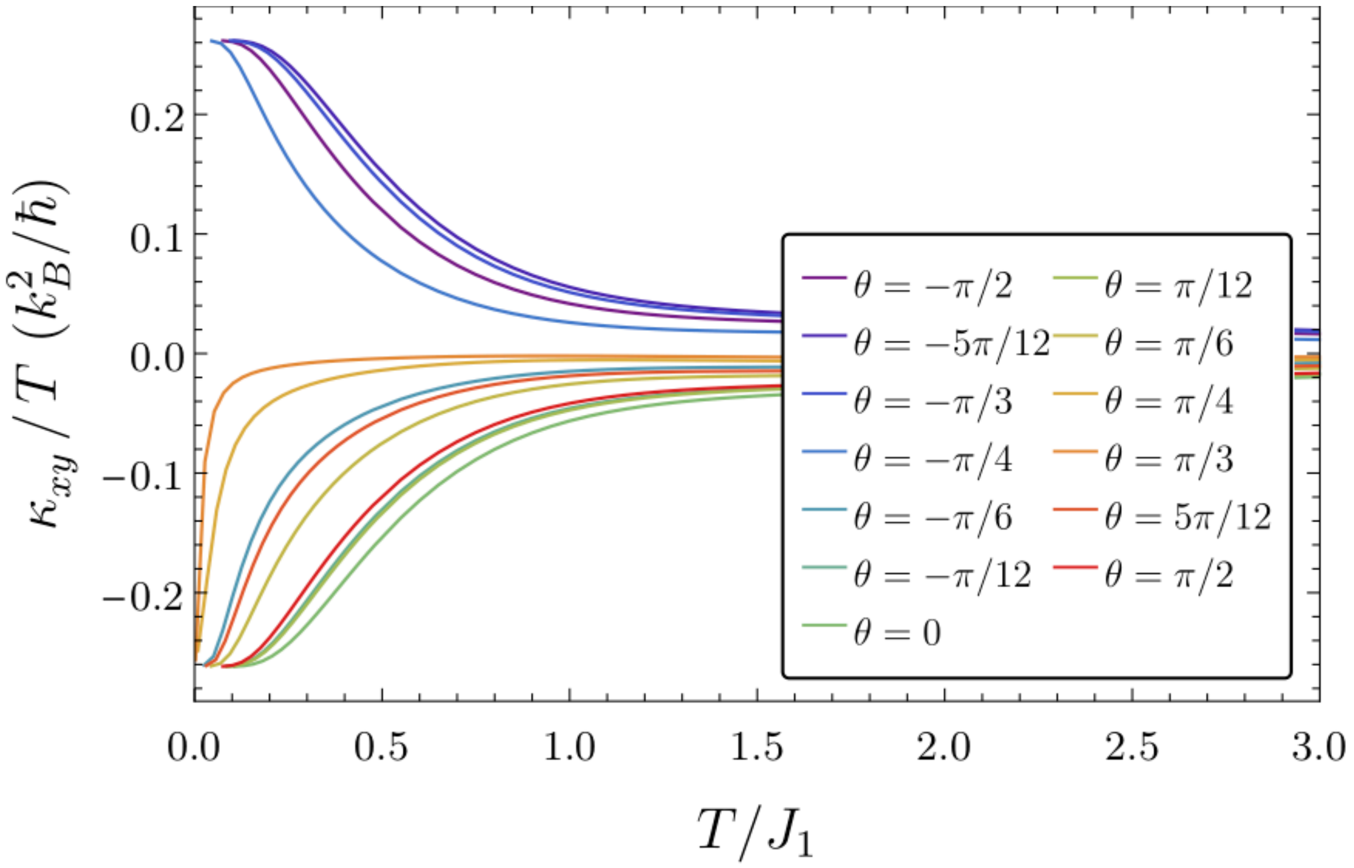


Spinon Berry
curvatures

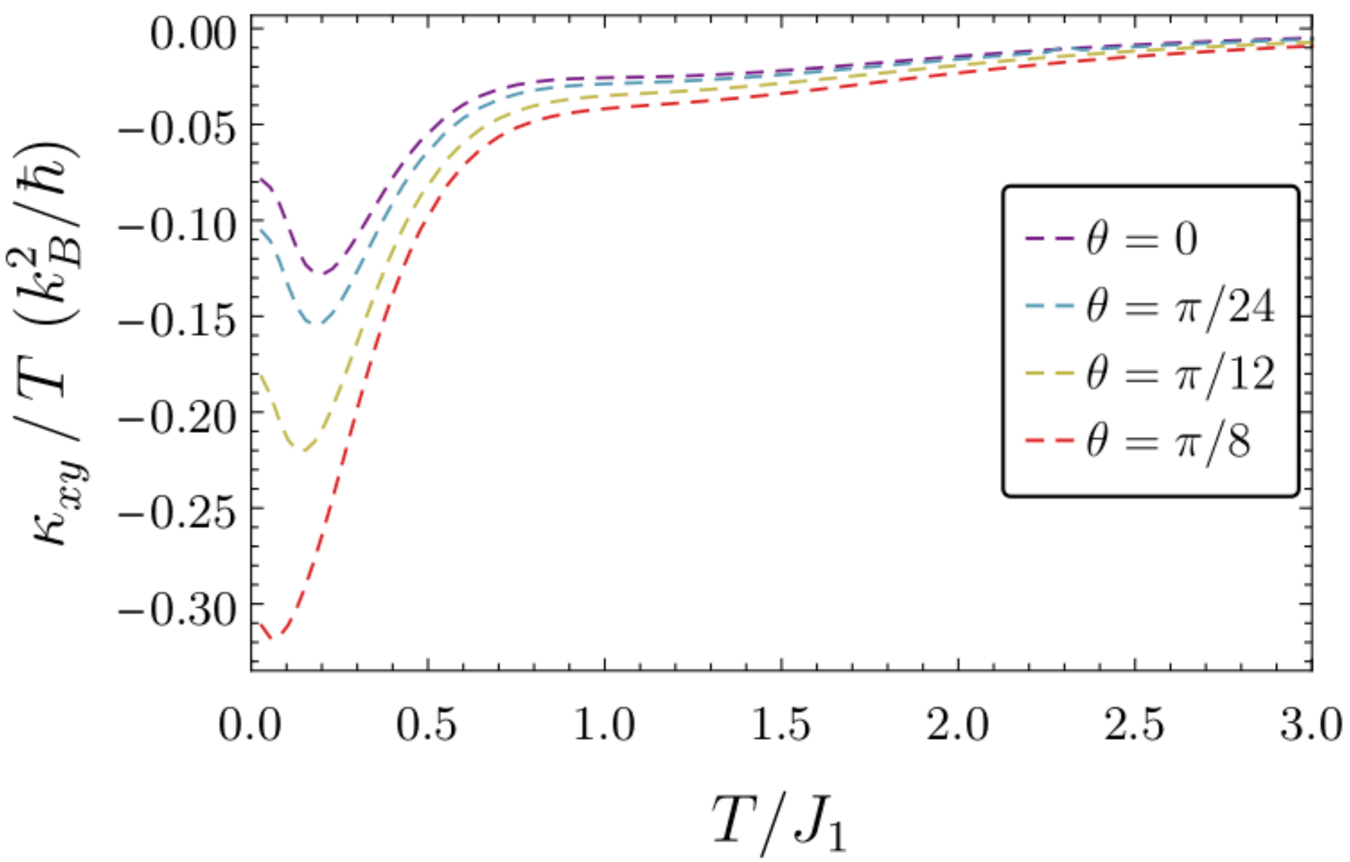
Rotating magnetic field



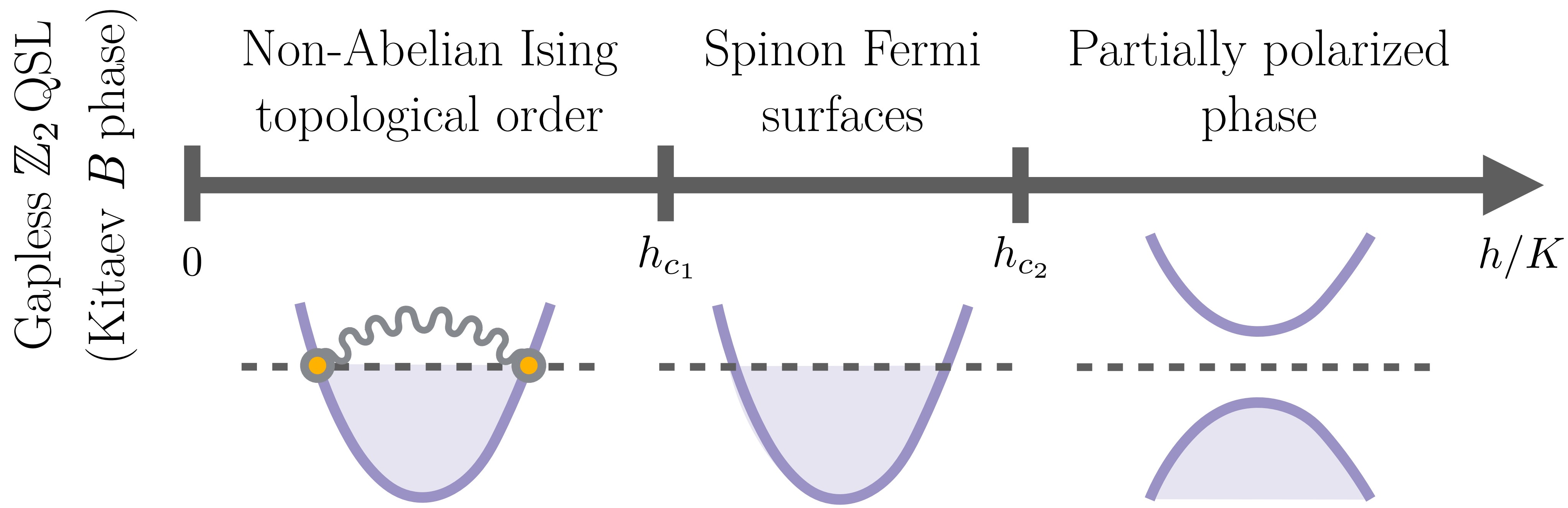
ITO



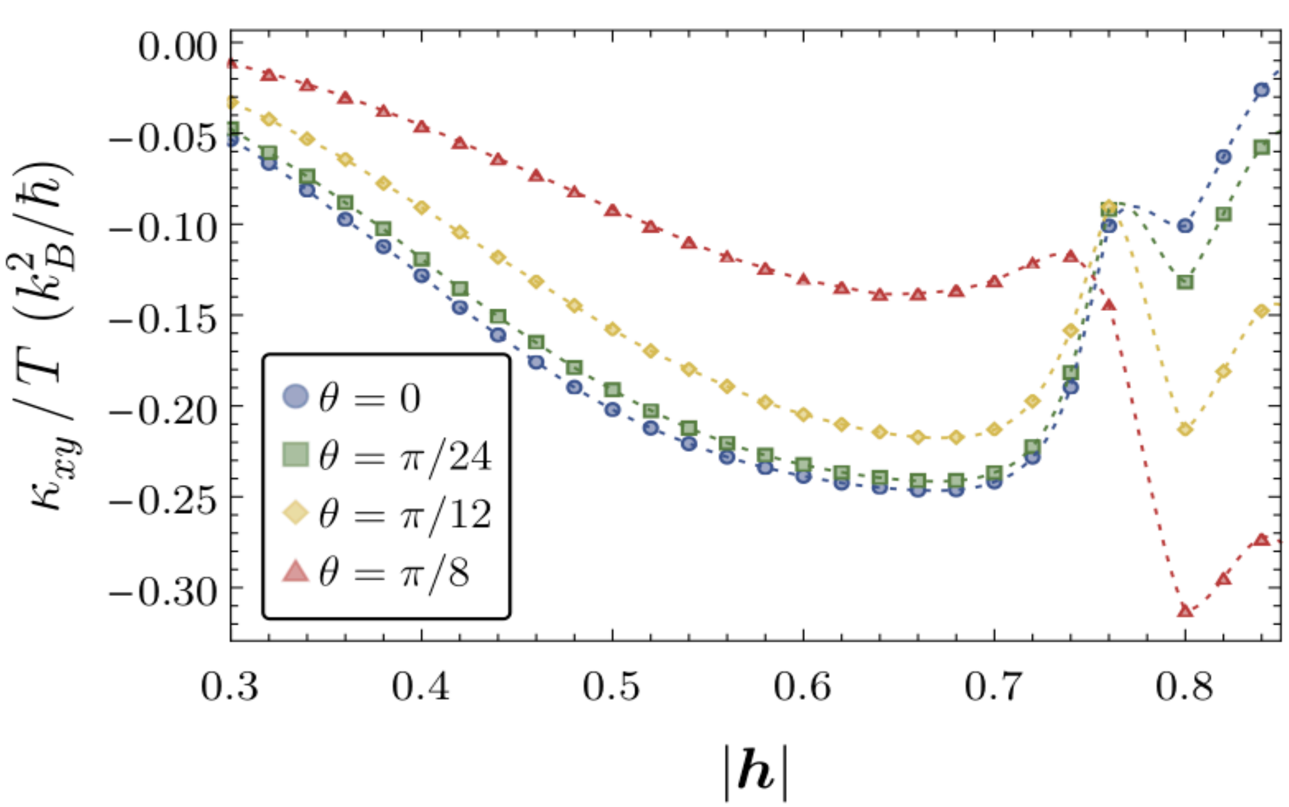
SFS



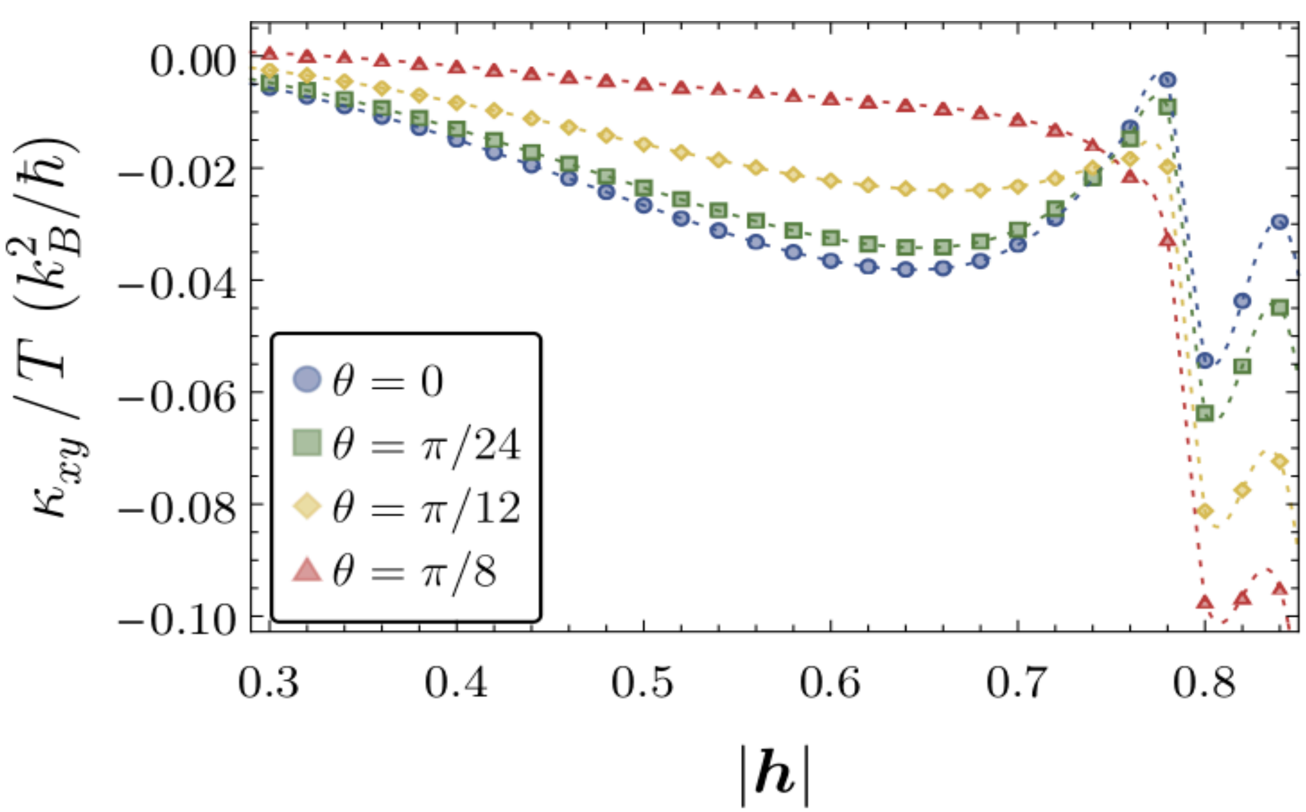
Field dependence for fixed temperatures



$h_{c1} = 0.46$



$T/J_1 = 0.1$



$T/J_1 = 0.5$