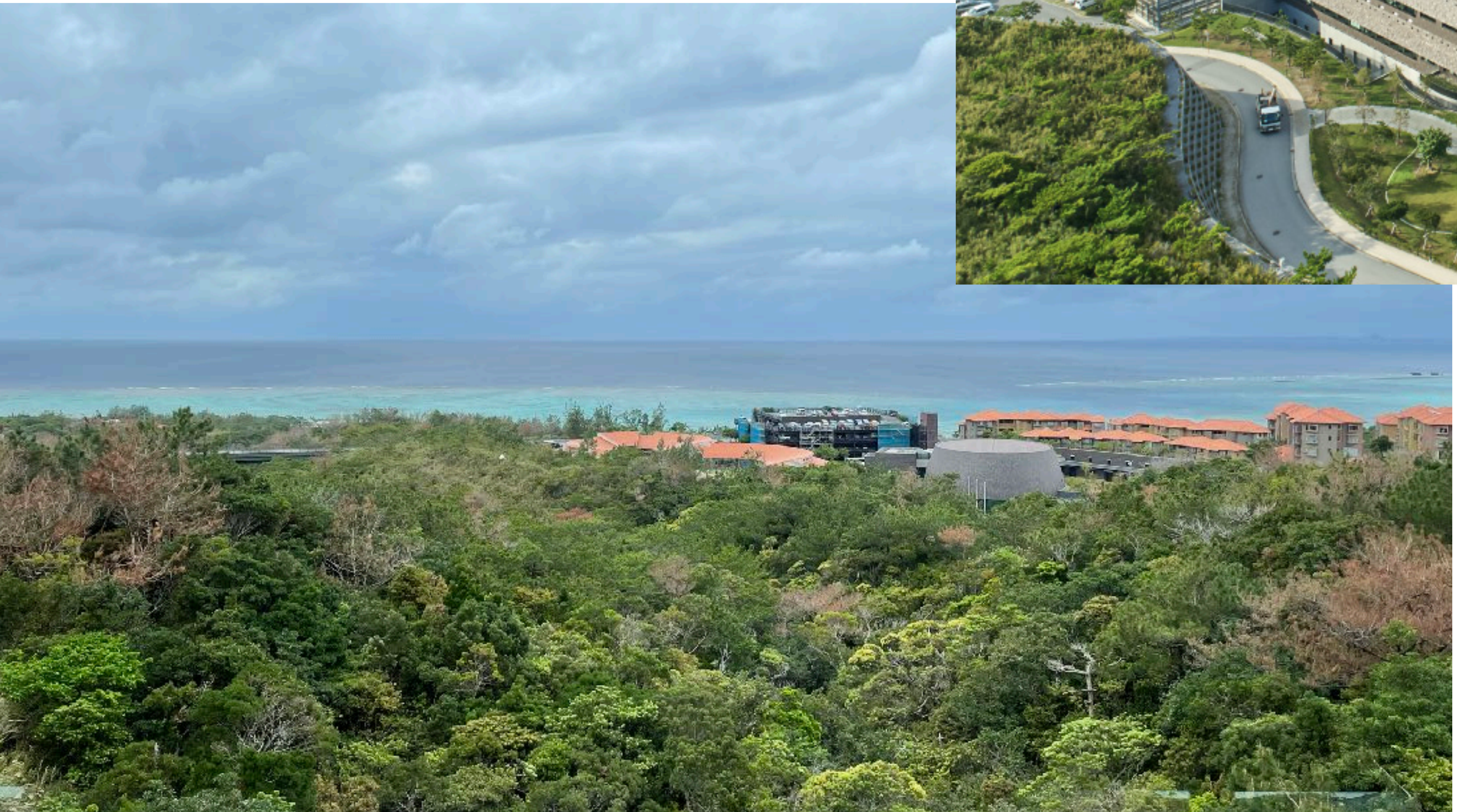
Topological transport of magnon polarons

Shu Zhang
Okinawa Institute of Science and Technology (OIST) Graduate School
Okinawa, Japan

@ SPICE-Workshop on
Quantum Geometry and Transport of Collective Excitations in (Non-)Magnetic Insulators
May. 6th 2025

OIST

OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY



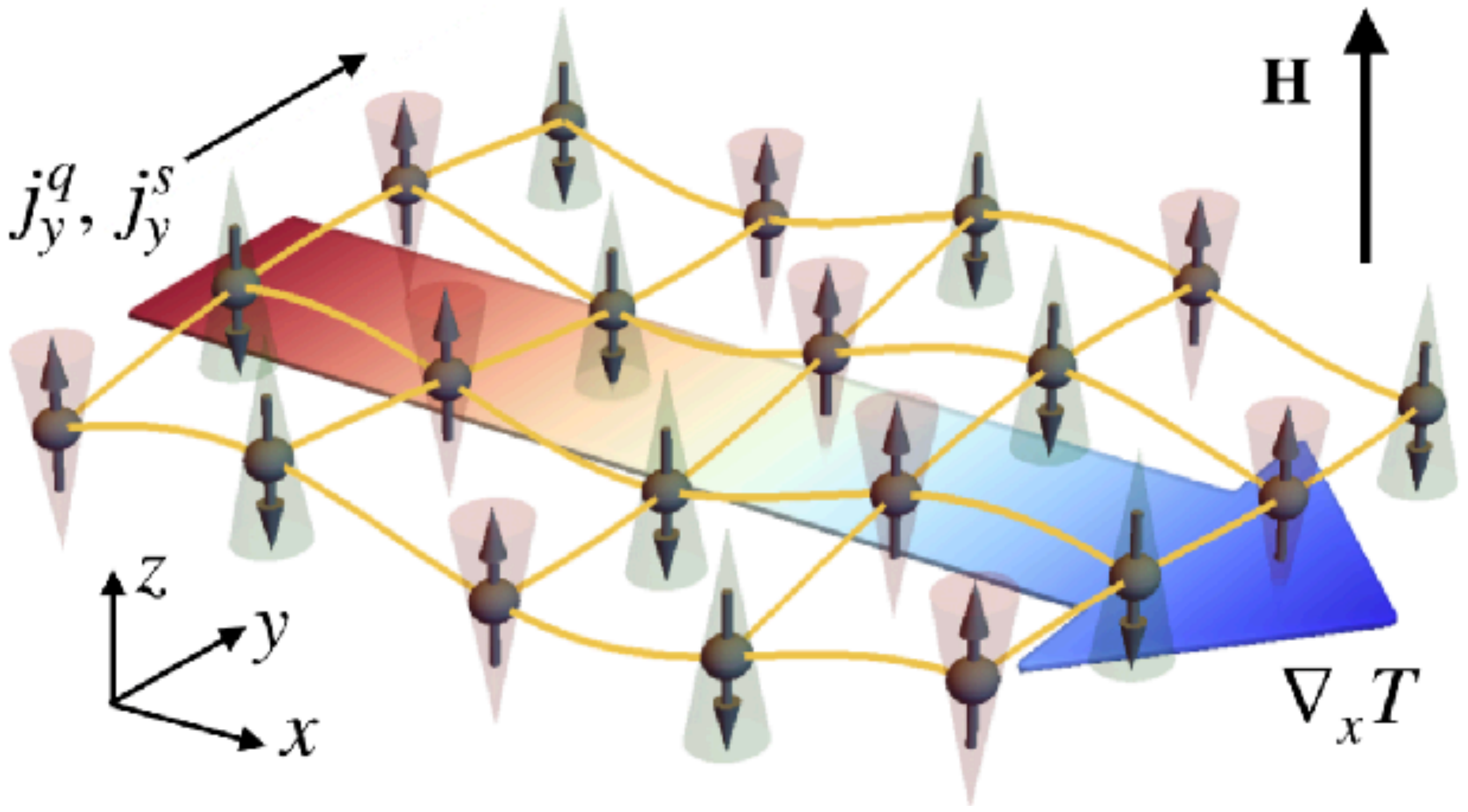
"Collective Dynamics and Quantum Transport" Unit

Contact: **shu.zhang@oist.jp**

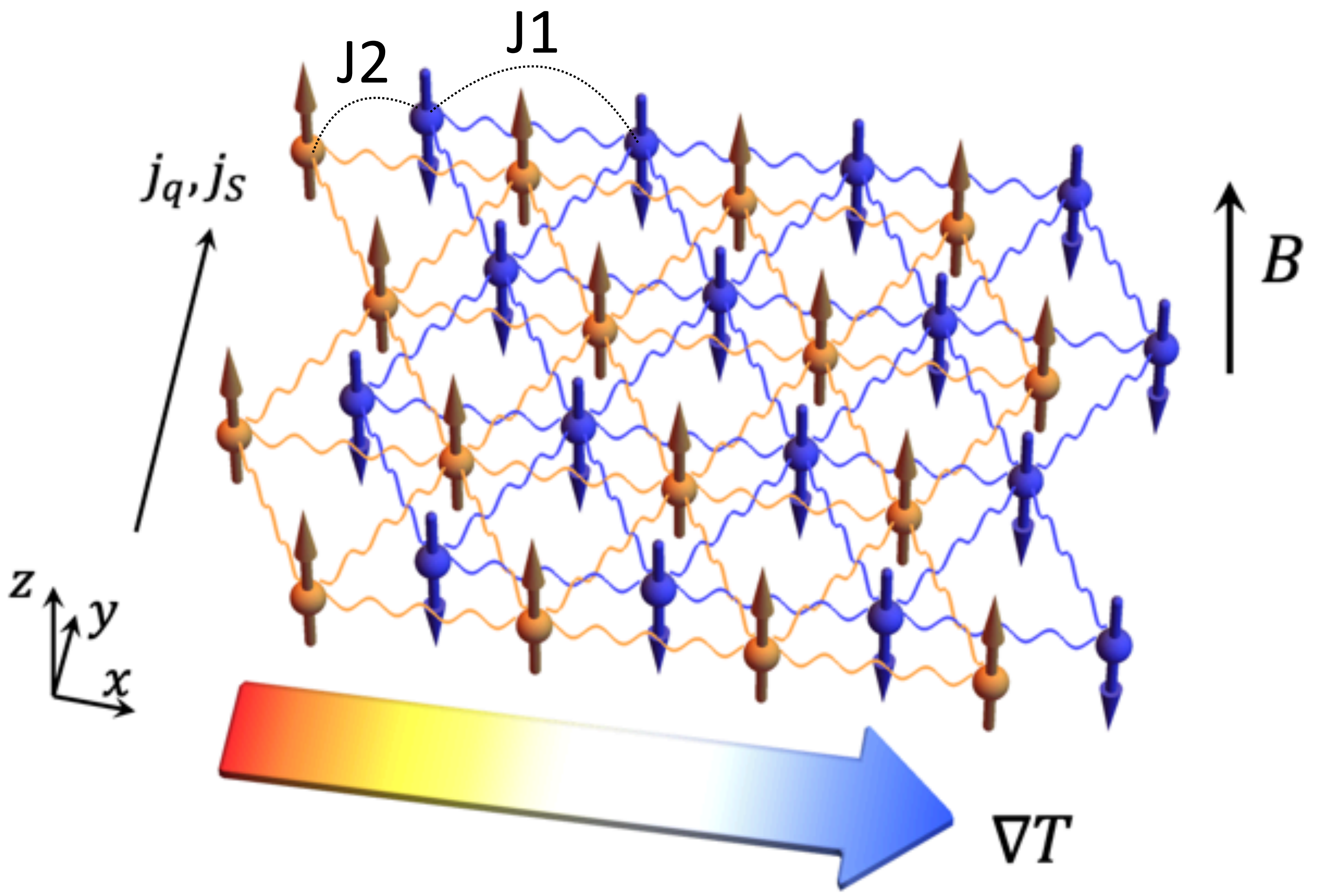
- Quantum matter and quantum transport
- Nonequilibrium dynamics and light-matter couplings
- Open quantum systems and quantum optics

Outline

- Topological magnon-phonon induced by magnetoelastic coupling
- Gernerically in collinear antiferromagnet: monolayer/bilayer
- Thermal Hall and Spin Nernst effects



SZ, Go, Lee, Kim, *Phys. Rev. Lett.* 124, 147204 (2020)



Lin and SZ, *Appl. Phys. Lett.* 124, 132402 (2024)

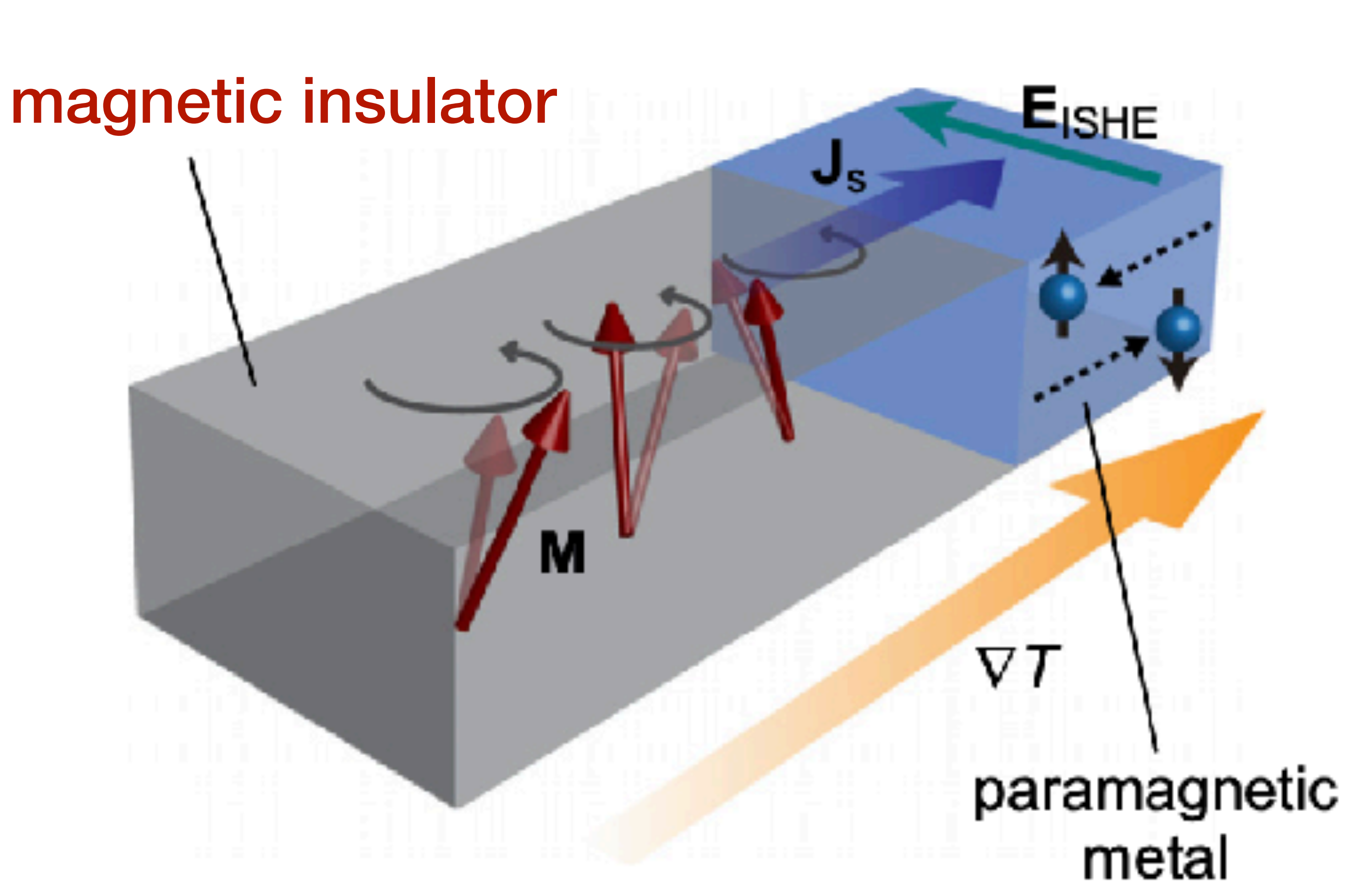
Spincaloritronics

Transport of spin and heat:

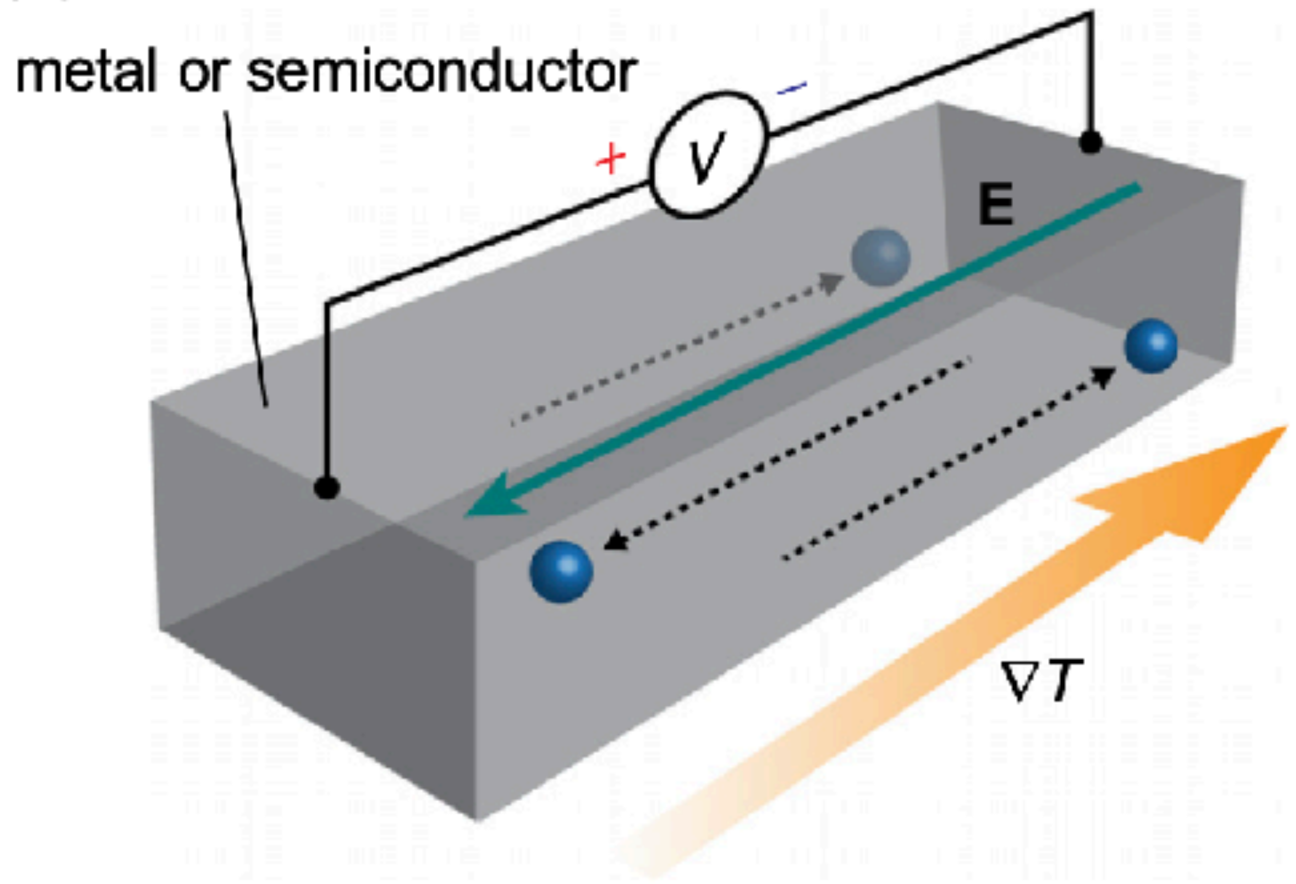
- Spintronic thermal devices
- Thermal management

  - Waste heat recycle

Spin Seebeck effect

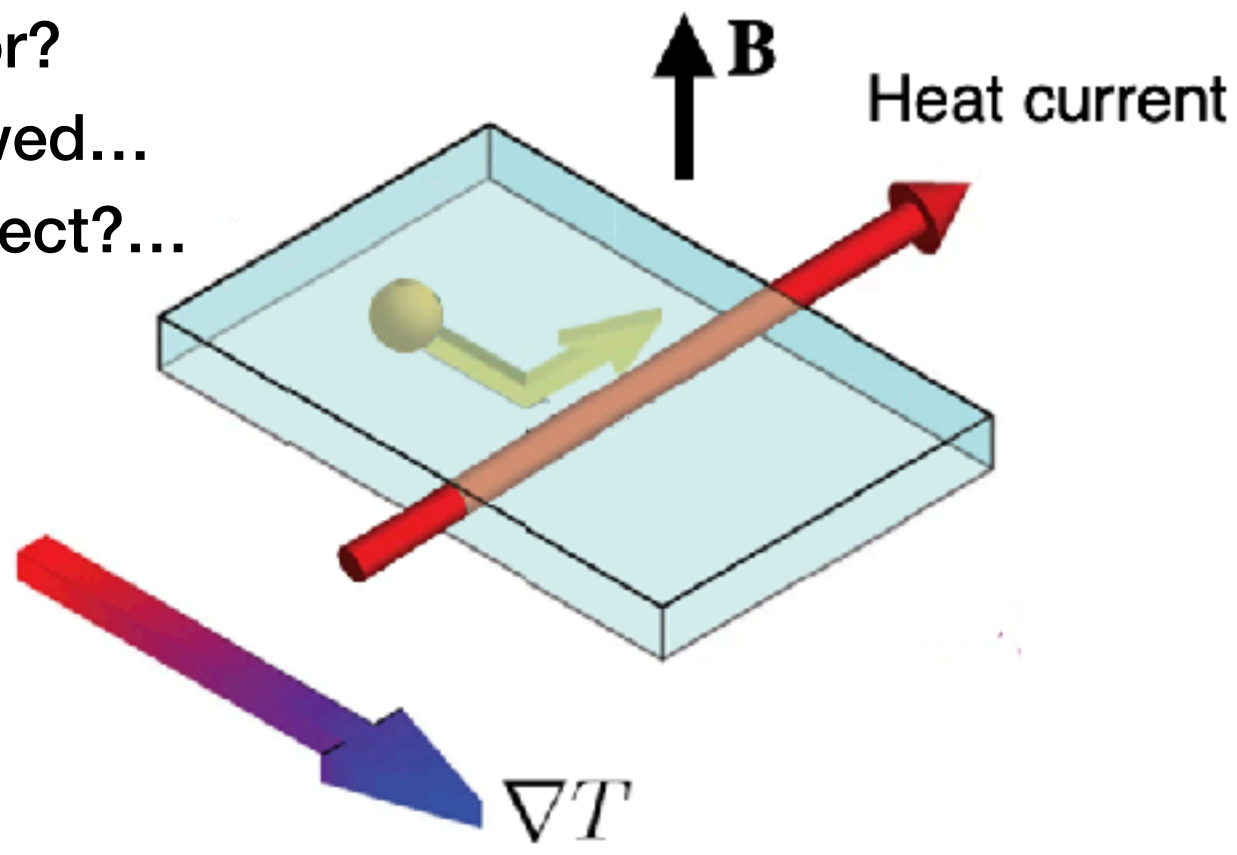


Seebeck effect

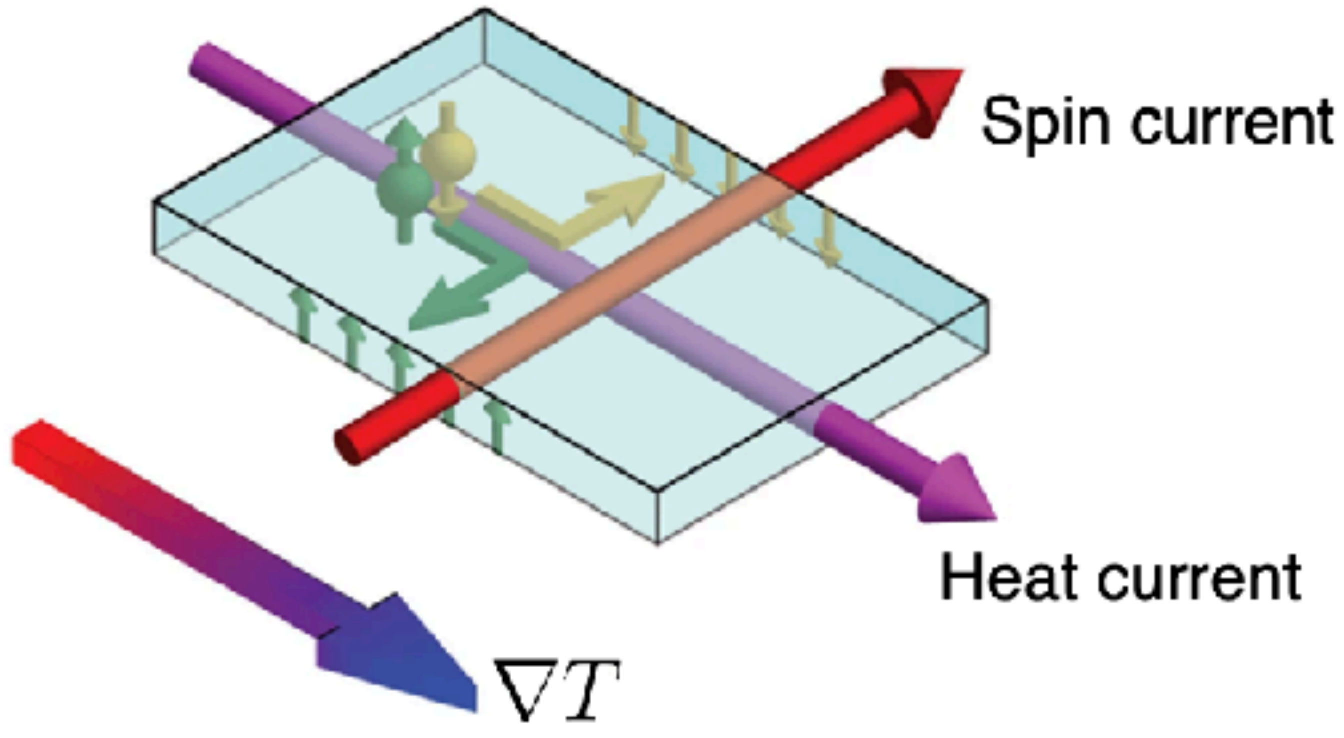


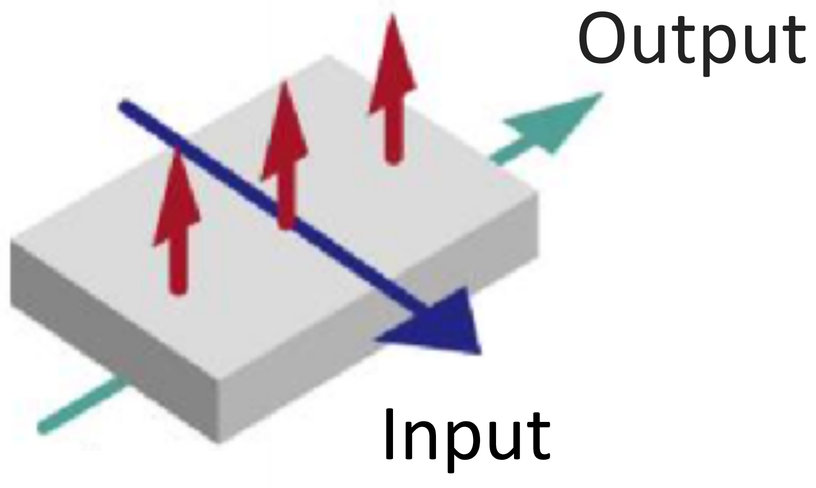
Transverse effects: Thermal Hall effect

In a magnetic insulator?
Yes! If symmetry allowed…
Model? Size of the effect?…



Spin Nernst effect

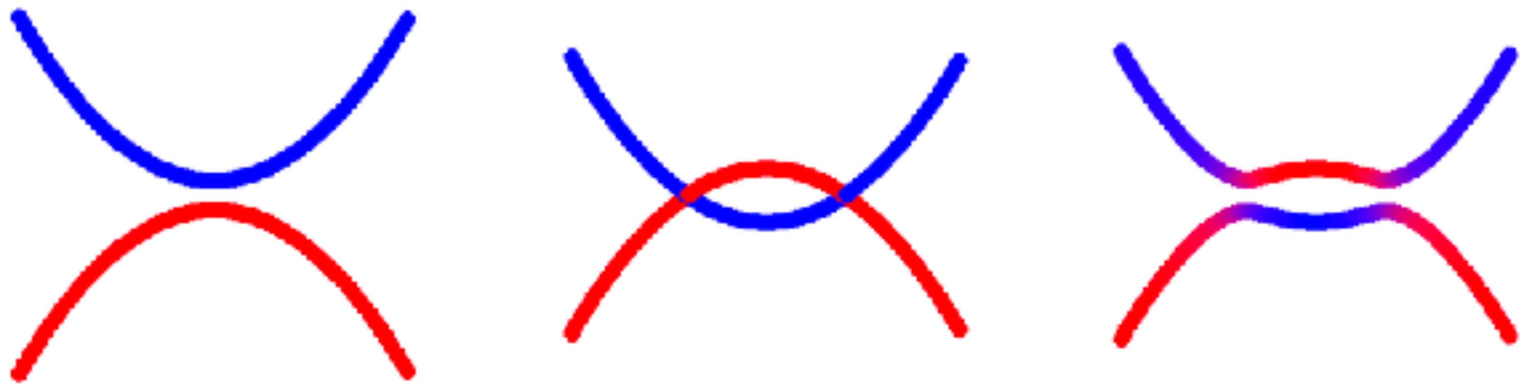




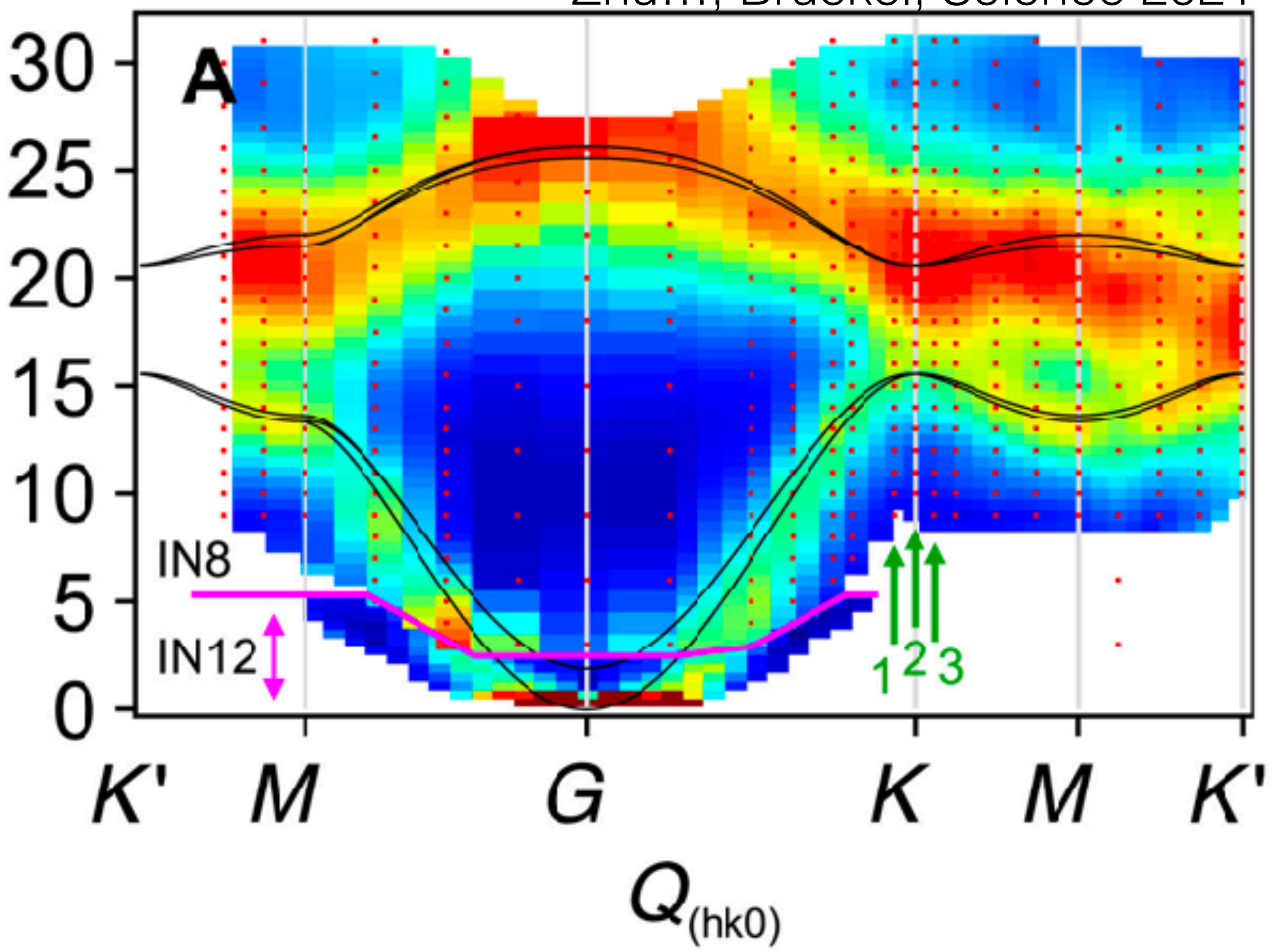
Meyer, … Goennenwei 2017
Uchida et. al. 2012, 2010, 2021

Topological magnons

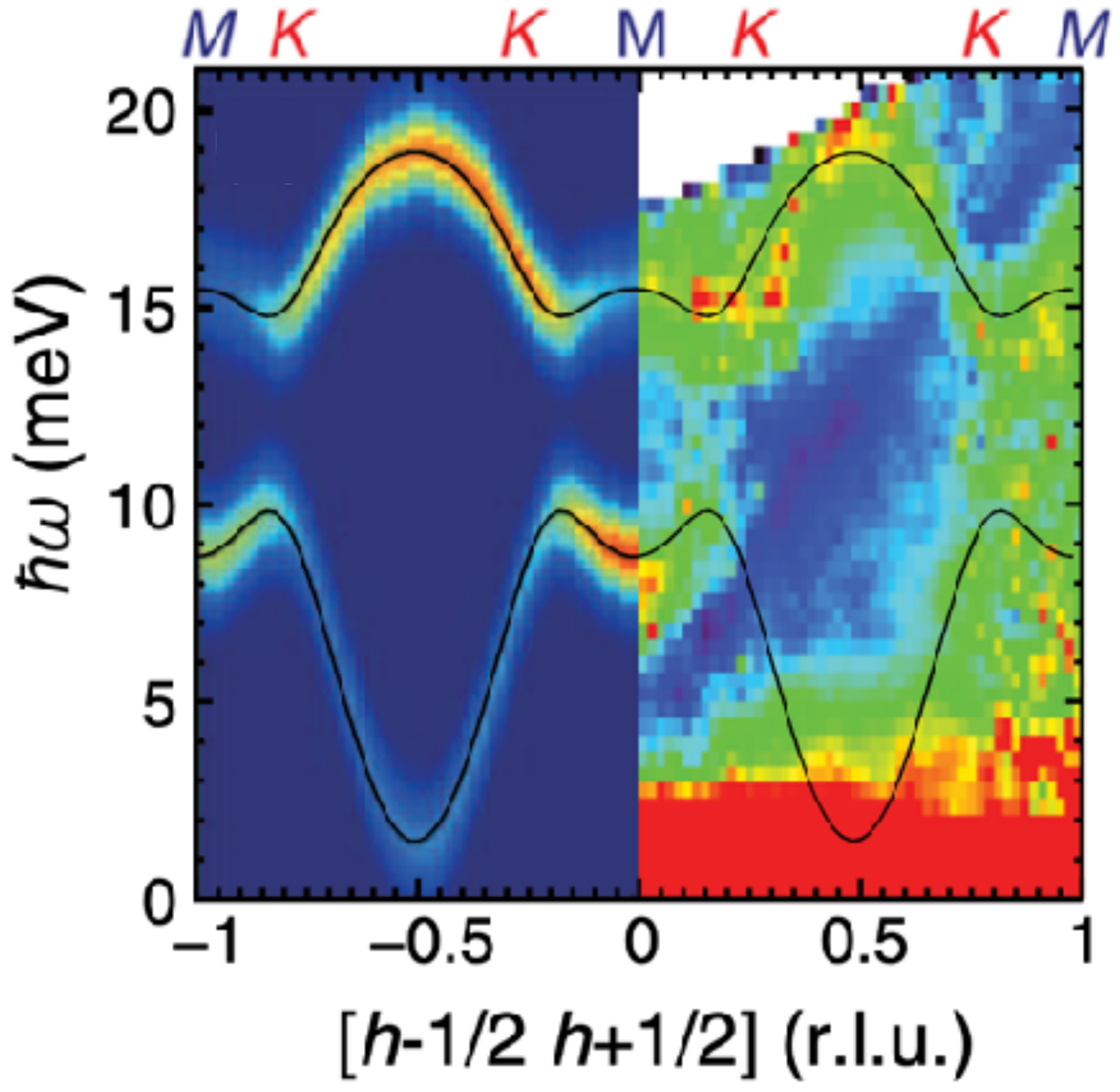
- Band inversion



CrGeTi3



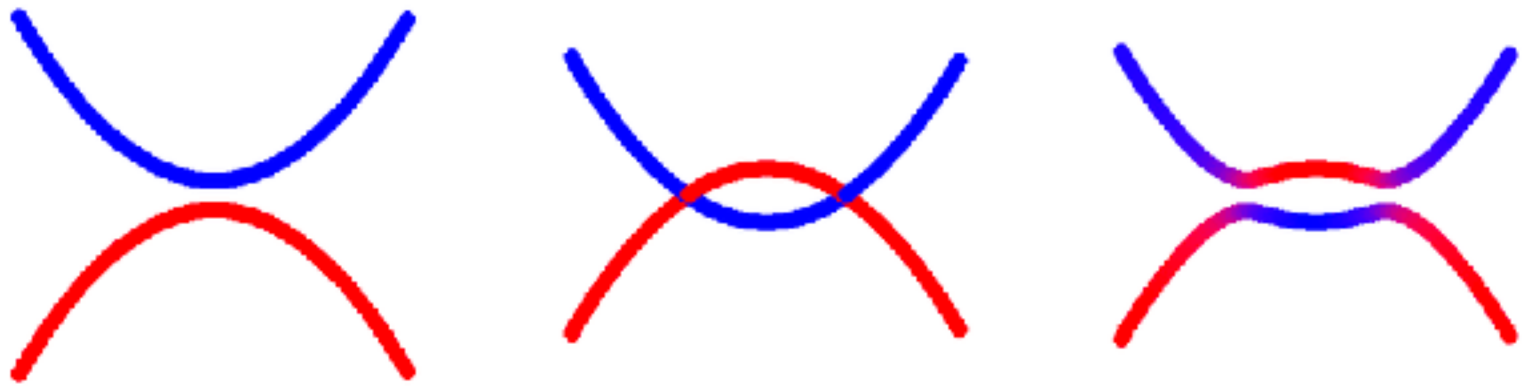
CrI3



Chen, …, Dai, PRX 2018

Topological magnons

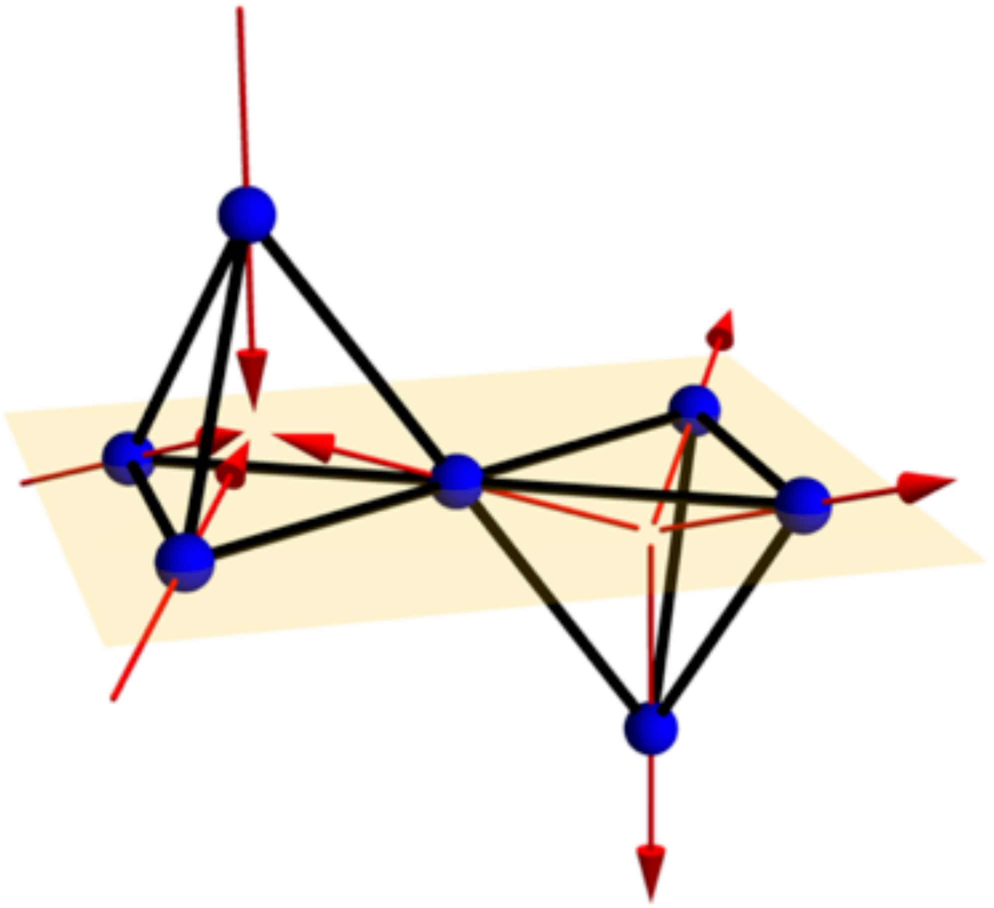
- Band inversion

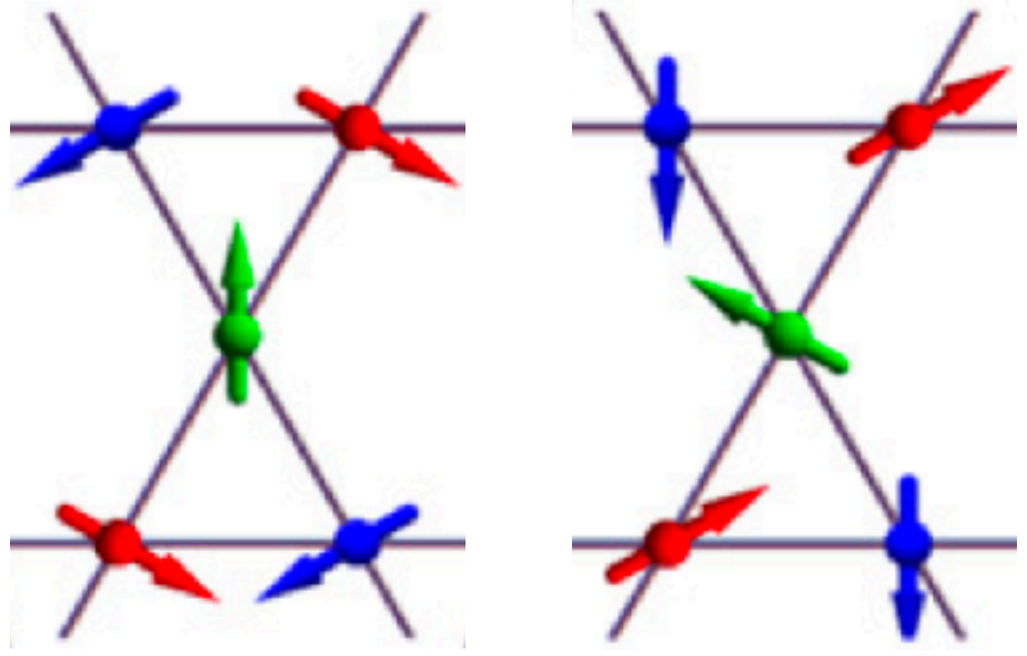


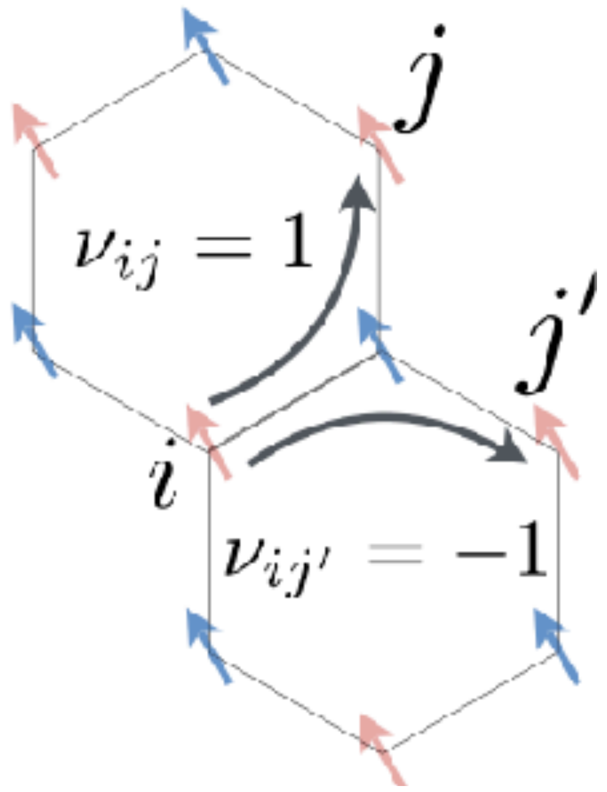
- Chirality

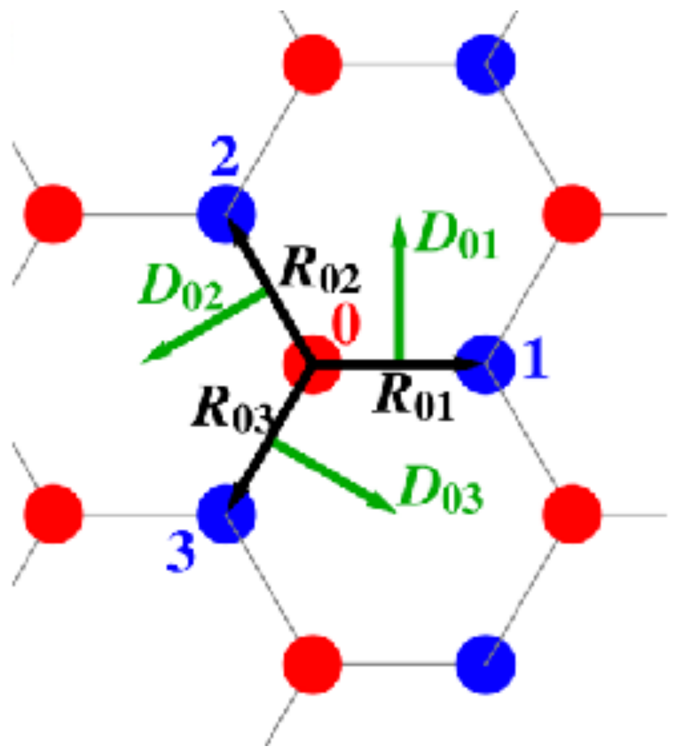
Noncoplanar/noncollinear ground states
Inversion-breaking Dzyaloshinskii-Moriya interactions,
Long-range dipolar interactions, …

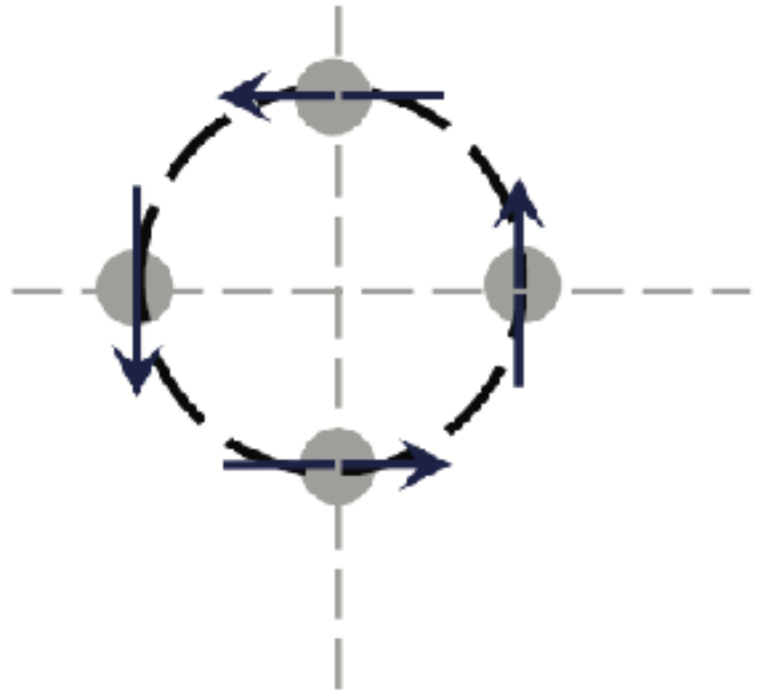
Sindou, et. al. 2013, 2014
Mook, Mertig, et. al. 2014, 2016, 2017, 2019
Kim, Ochoa, Zarzuela, Tserkovnyak 2016
Fiete, et. al. 2017, 2018, 2021
Zhang, …, Xiao 2019; Park, Nagoya, Yang 2020





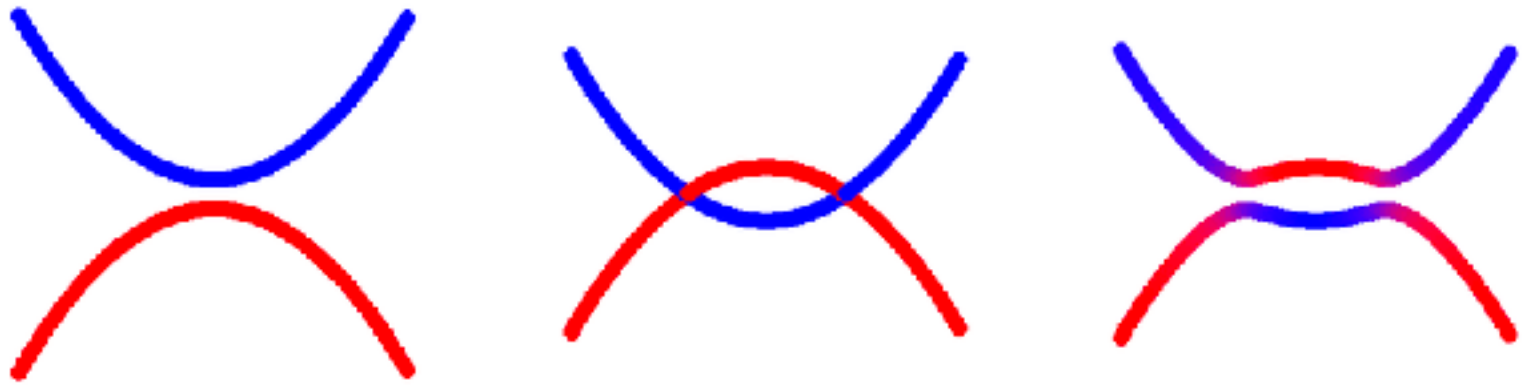






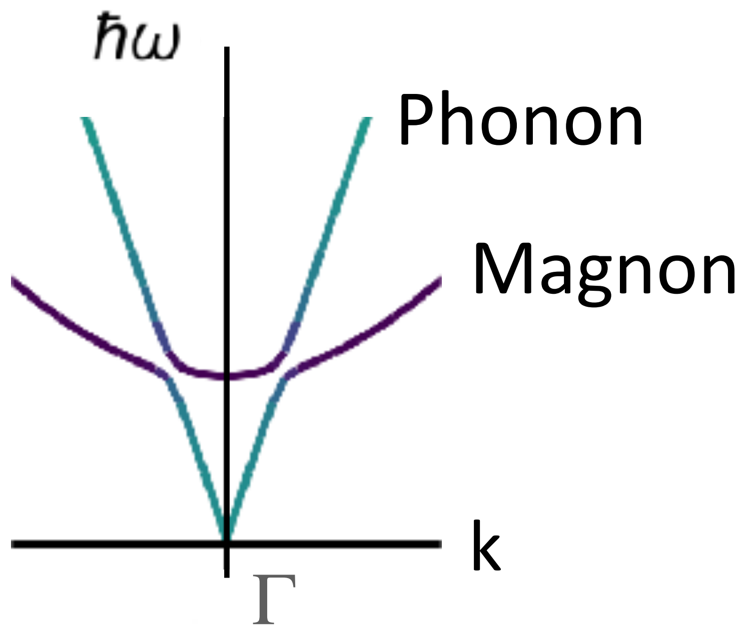
Topological magnons

- Band inversion

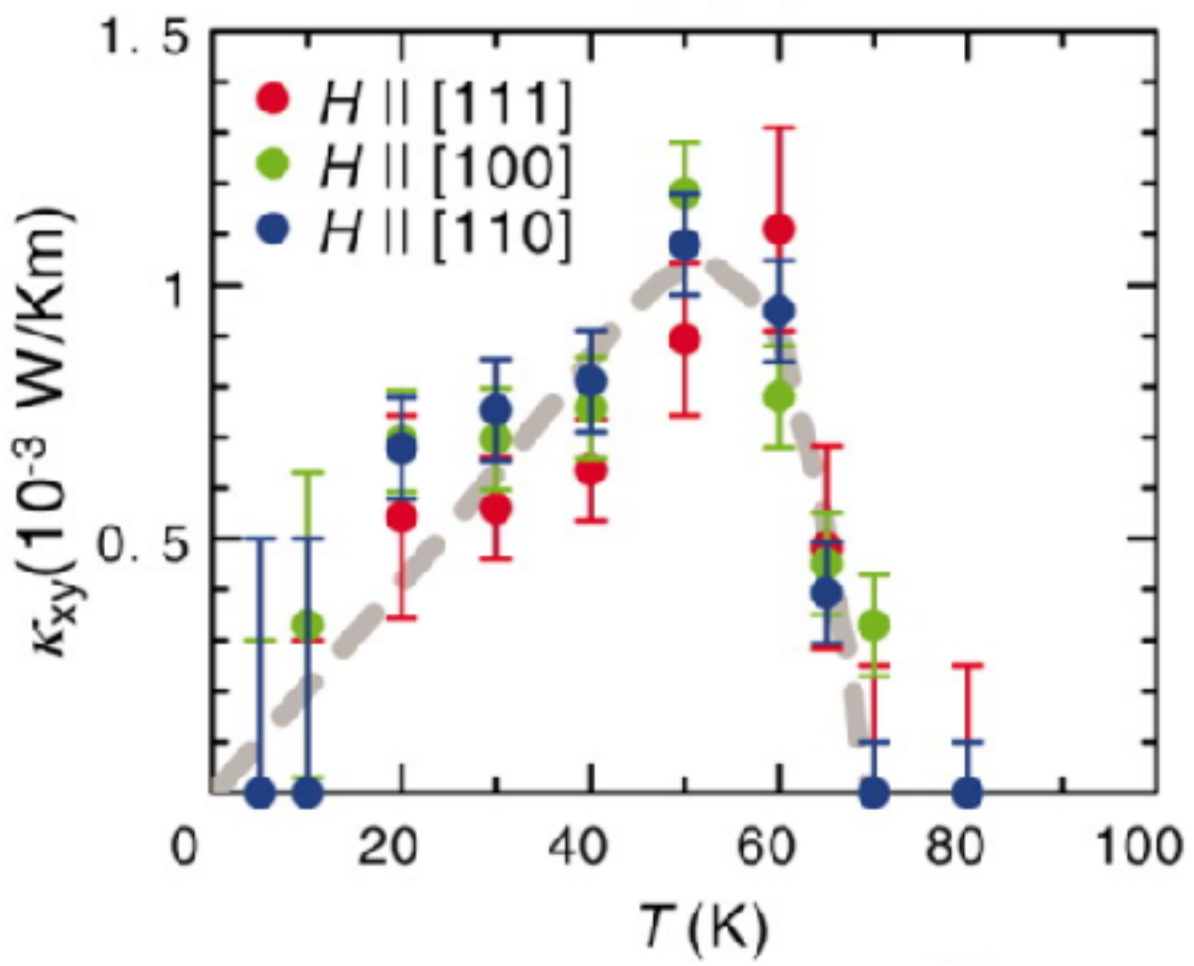


- Chirality
- Transport   Thermal Hall effect

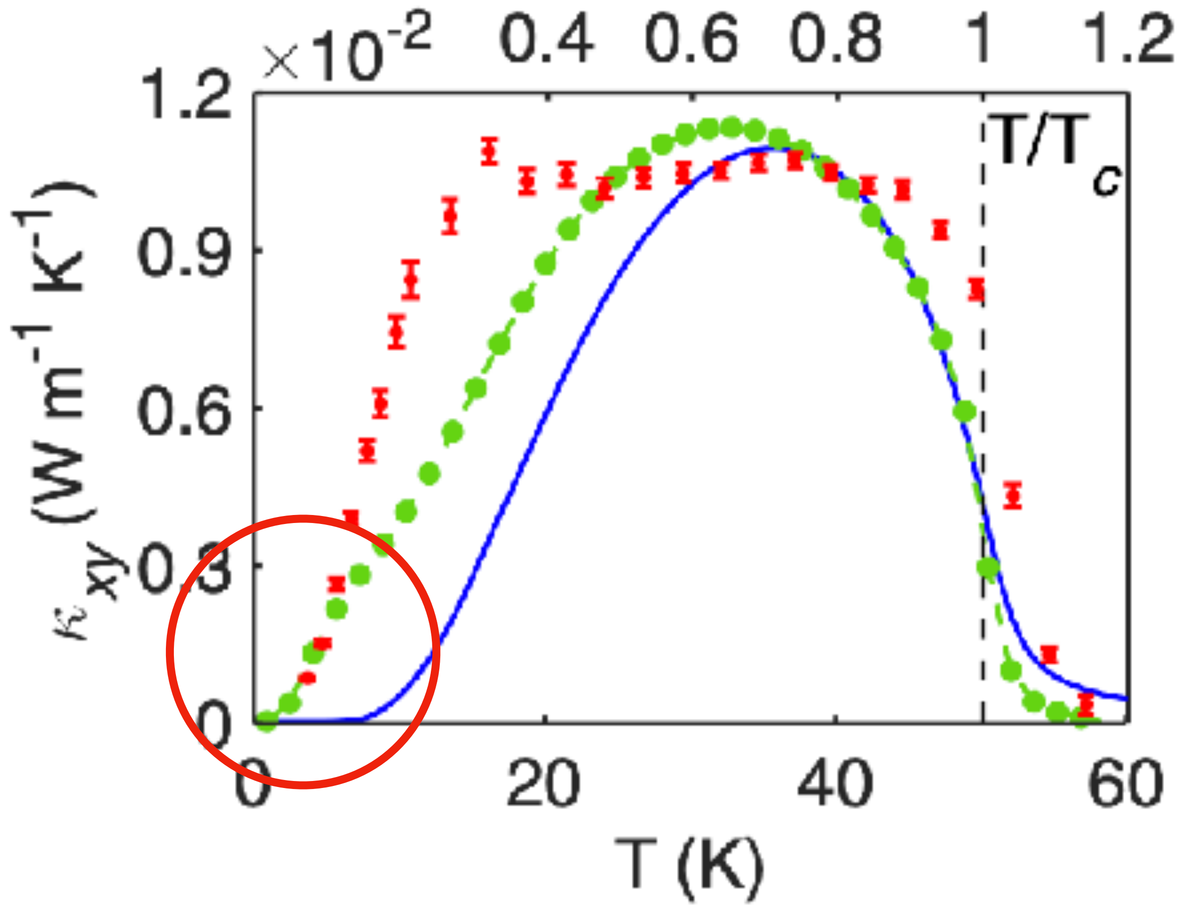
Magnetic ordering temperature ~50K
Debye temperature ~140K
Magnon-phonon coupling!

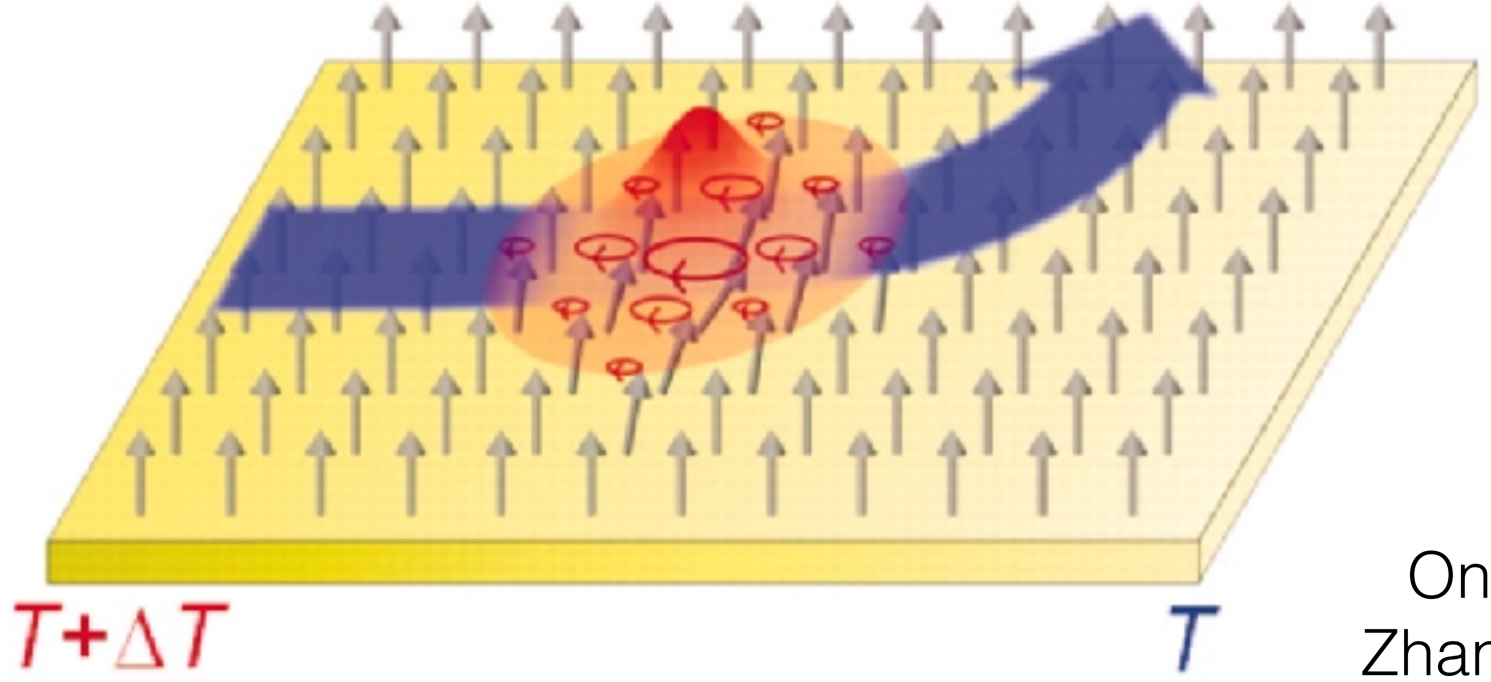


Lu2V2O7



VI3





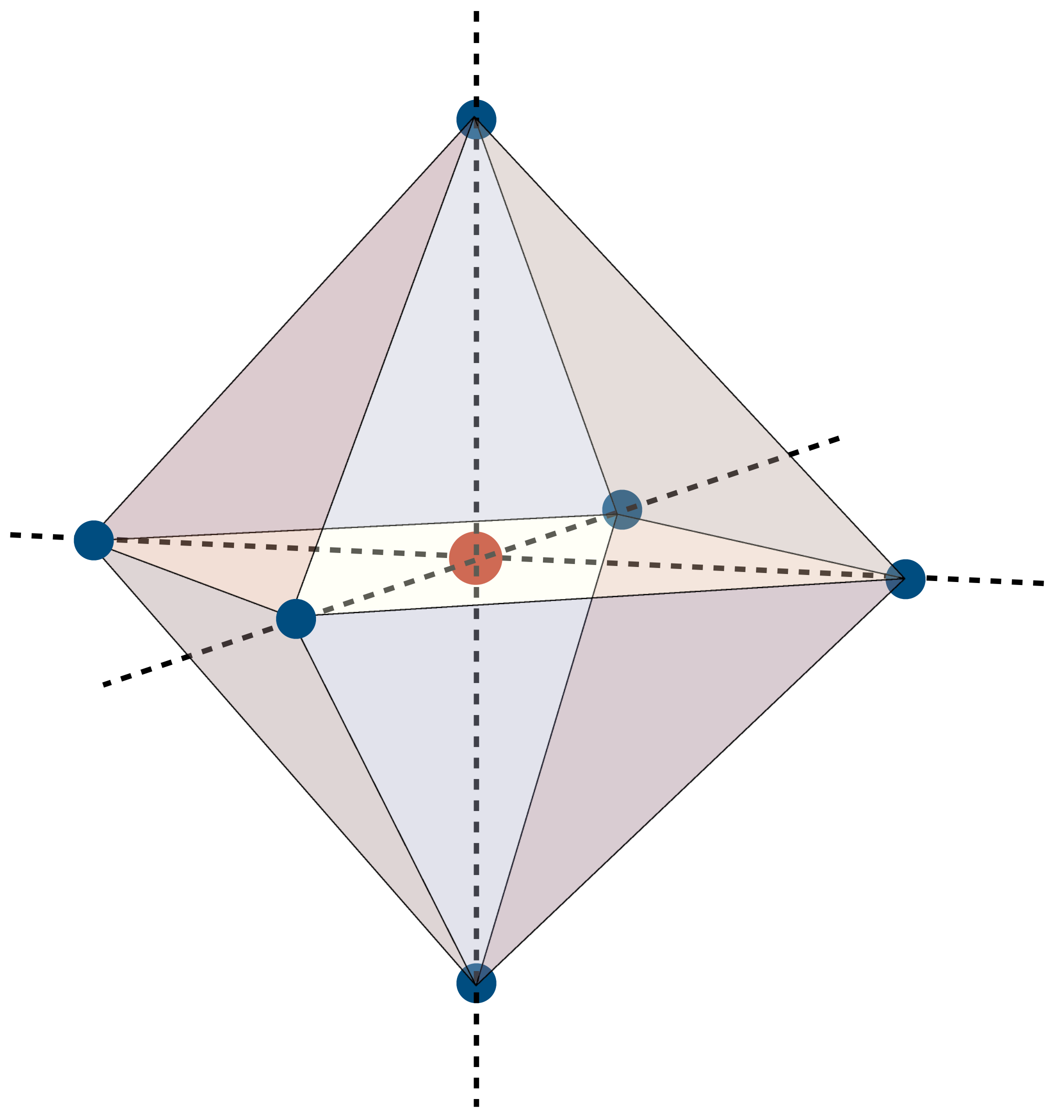
Onose, …, Tokura 2010
Zhang, …, Xiao, Ke 2021
Kong, … Cava 2019

Magnetoelastic coupling

$$\kappa \sum_{\ell,\delta} S^z_\ell (\mathbf{S}_\ell \cdot \hat{\mathbf{e}}_\delta)(u^z_\ell - u^z_{\ell+\delta})$$

Bond direction   Displacement

Magnetocrystalline anisotropy



- Symmetry! Kittel 1949, 1958

Magnon-Phonon Interaction

The interaction between magnetization direction and elastic strain (as observed as magnetostriction) is described by the magnetoelastic coupling.[5] To the first order in the strain components S_{ij} and to the second order in the direction cosines, the coupling in a *cubic* crystal is described by the magnetoelastic energy density

$$f_{\mathrm{me}} = b_1(\alpha_x^2 S_{xx} + \alpha_y^2 S_{yy} + \alpha_z^2 S_{zz}) + 2b_2(\alpha_x\alpha_y S_{xy} + \alpha_y\alpha_z S_{yz} + \alpha_z\alpha_x S_{zx}). \quad (20)$$

Spin   Strain

$$S_{yz} \equiv \tfrac{1}{2}\left(\frac{\partial R_y}{\partial z} + \frac{\partial R_z}{\partial y}\right); \quad S_{zx} \equiv \tfrac{1}{2}\left(\frac{\partial R_z}{\partial x} + \frac{\partial R_x}{\partial z}\right).$$

Magnetoelastic coupling

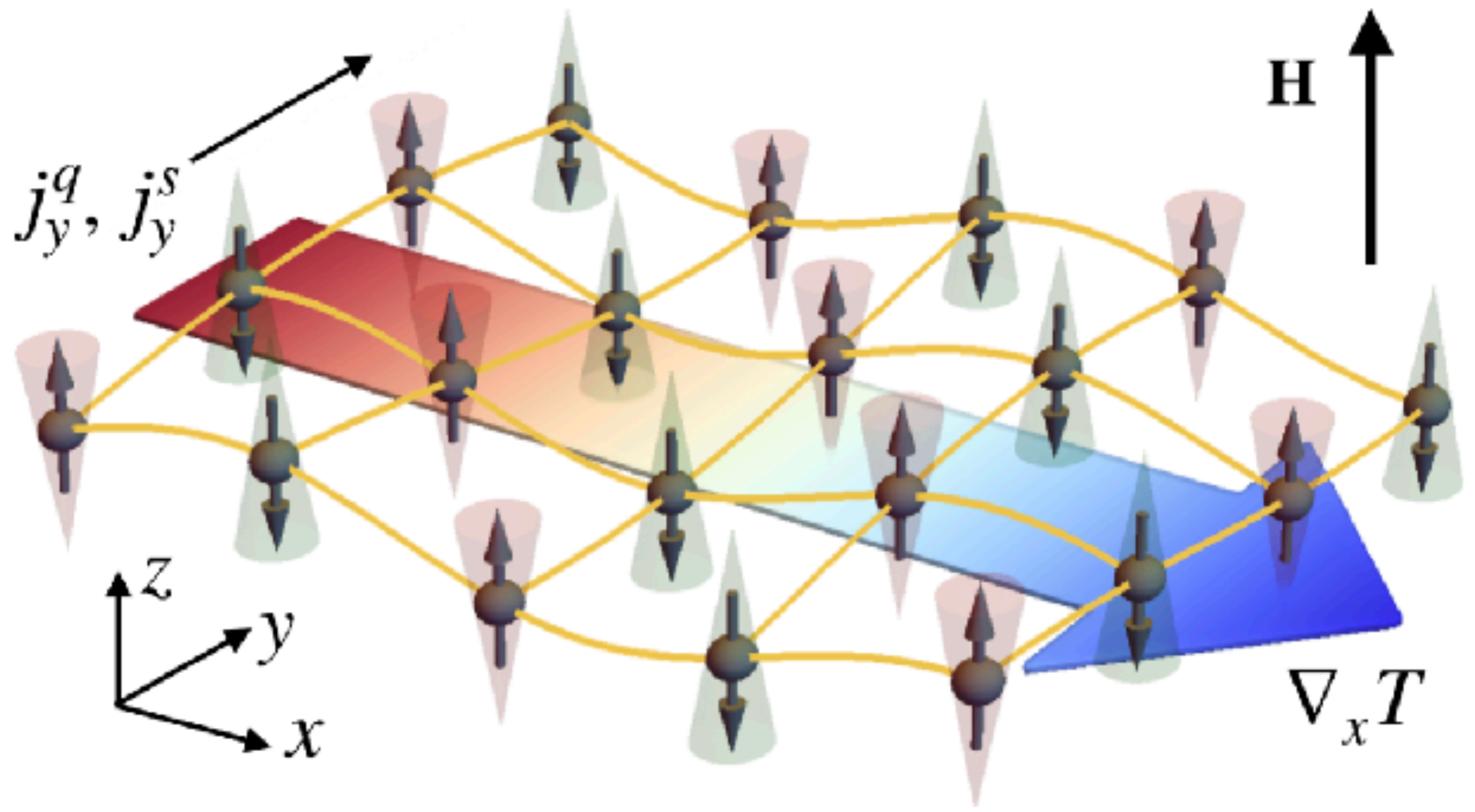
$$\kappa \sum_{\ell,\delta} S^z_\ell (\mathbf{S}_\ell \cdot \hat{\mathbf{e}}_\delta)(u^z_\ell - u^z_{\ell+\delta})$$

Bond direction   Displacement

Generally applicable

First order in both magnon and phonon fluctuations

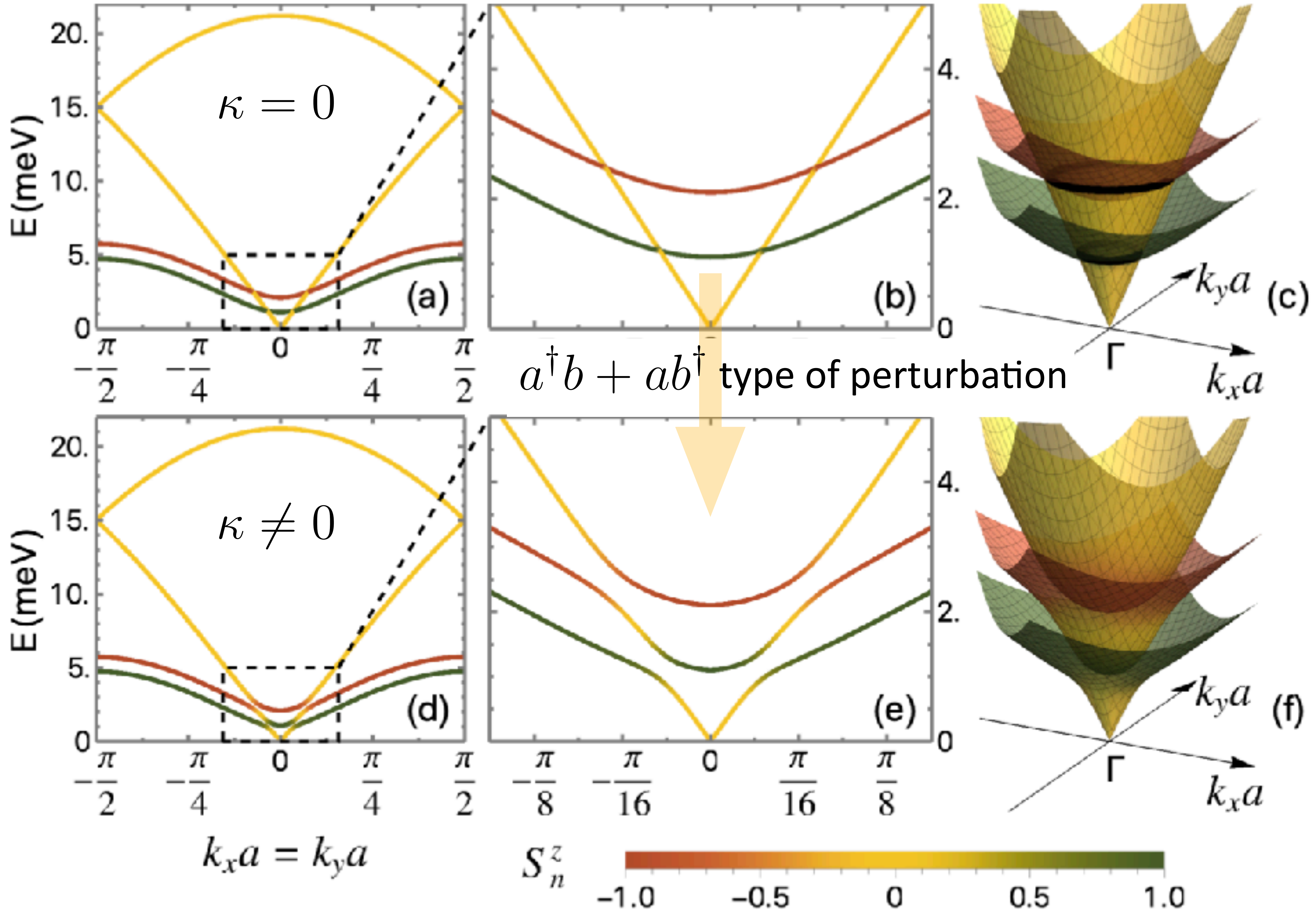
Kittel 1949, 1958
Thingstad, Kamra, Brataas, Sudbø PRL 2019
Go, Kim, Lee PRL 2019
SZ, Go, Lee, Kim PRL 2020: A 2D collinear antiferromagnet

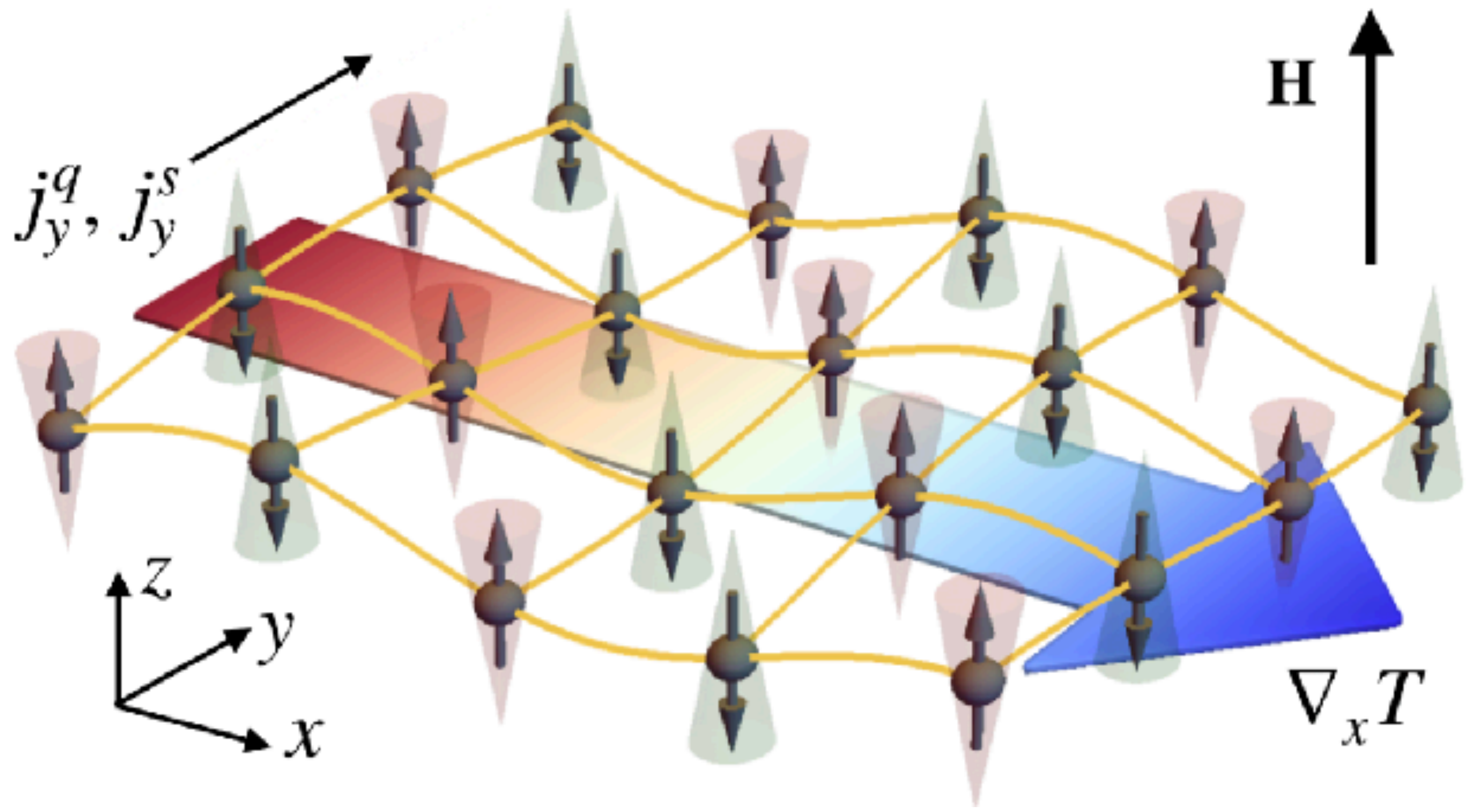


Topological magnon-phonon hybridization

A 2D collinear antiferromagnet (Heisenberg interaction + Easy-axis anisotropy)

SZ, Go, Lee, Kim Phys. Rev. Lett. 124, 147204 (2020)

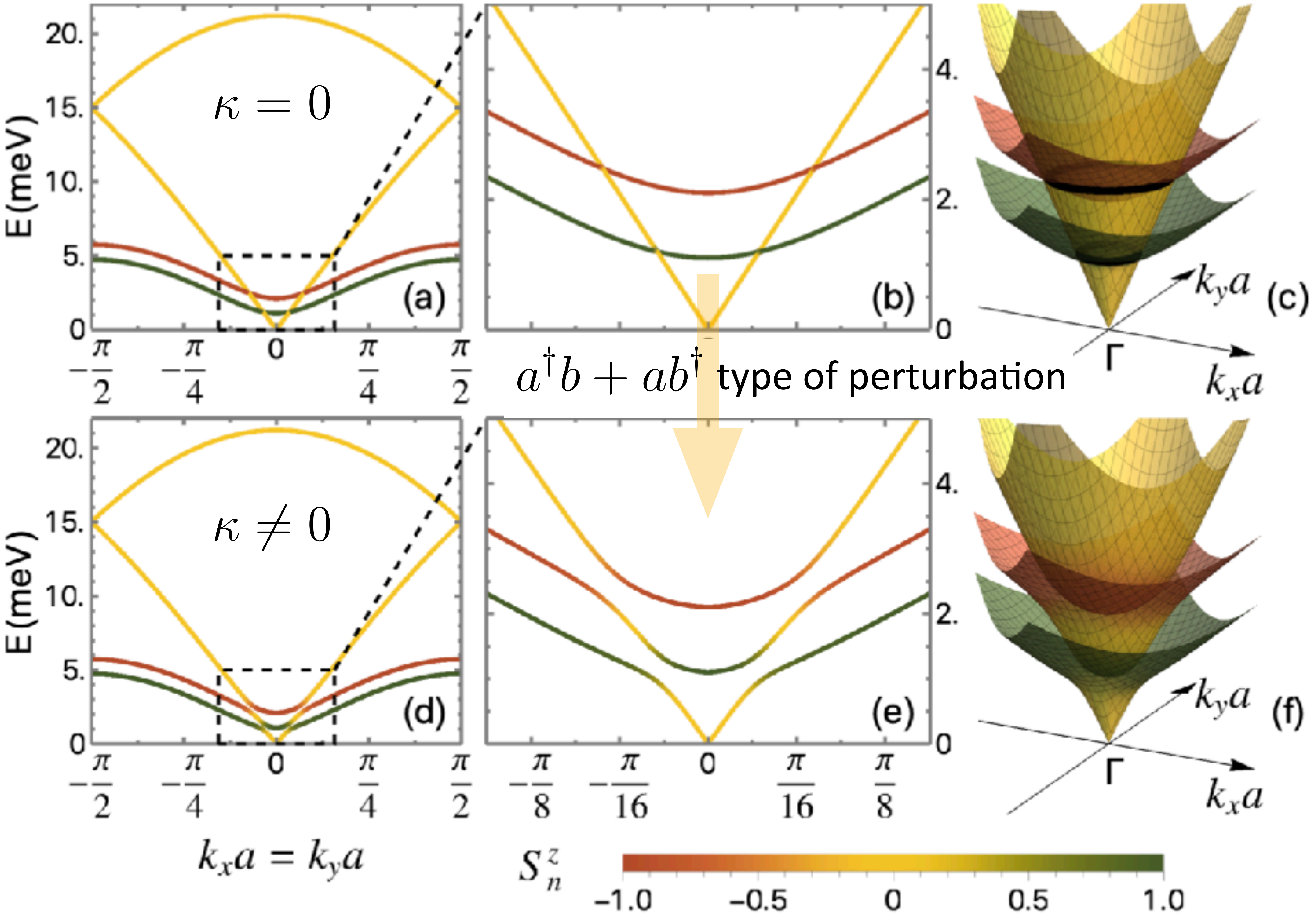


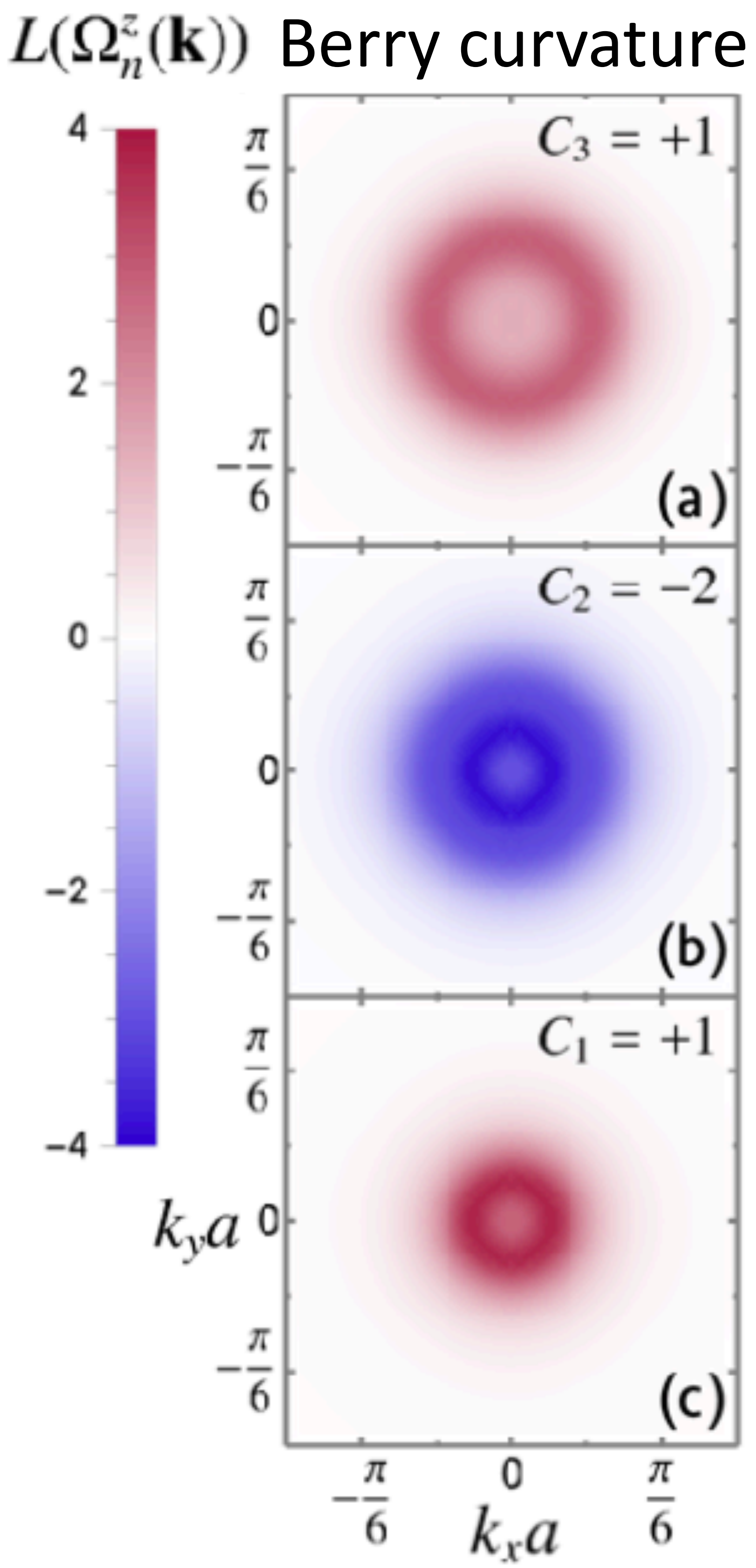


Topological magnon-phonon hybridization

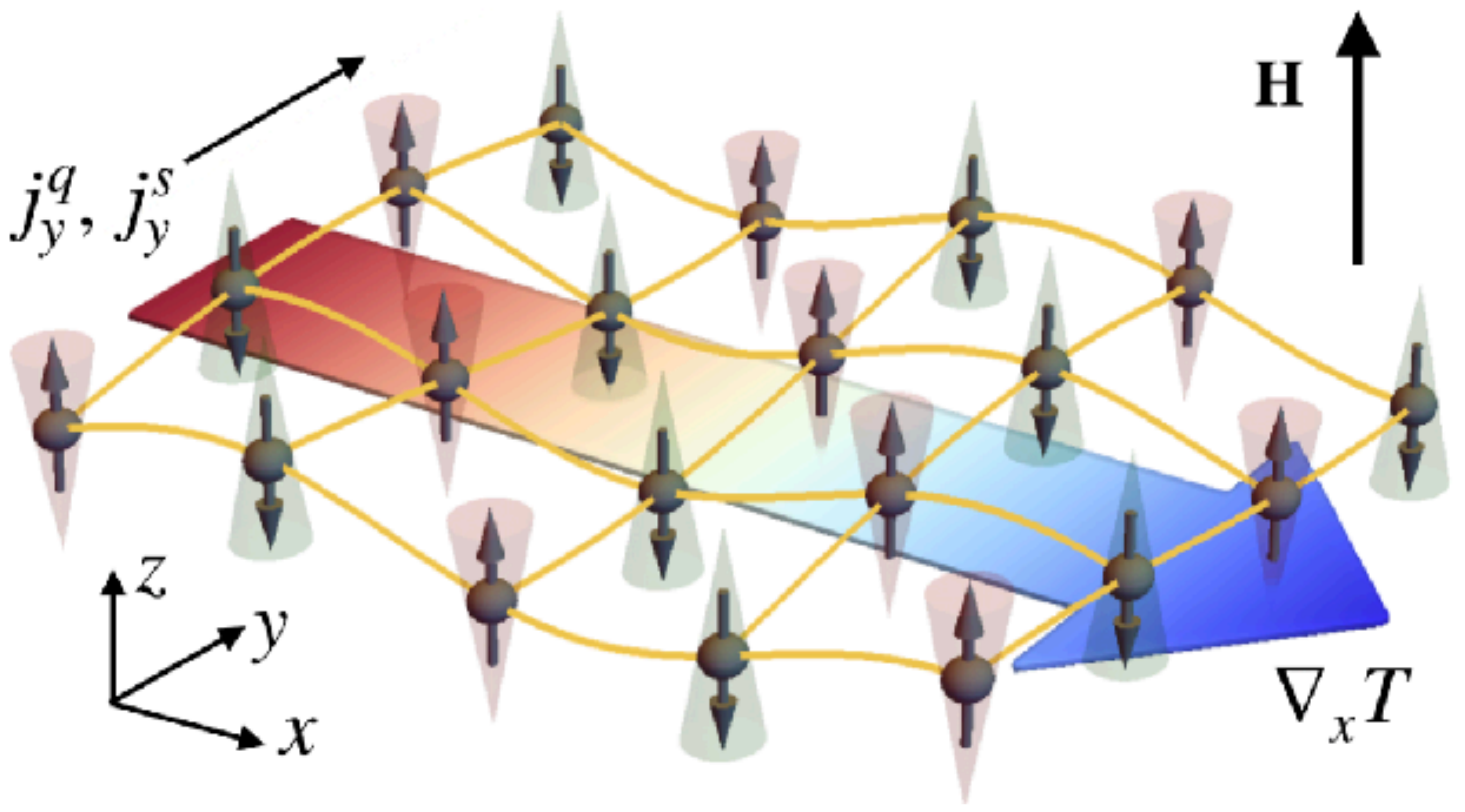
A 2D collinear antiferromagnet (Heisenberg interaction + Easy-axis anisotropy)

SZ, Go, Lee, Kim Phys. Rev. Lett. 124, 147204 (2020)





In the long-wavelength limit…

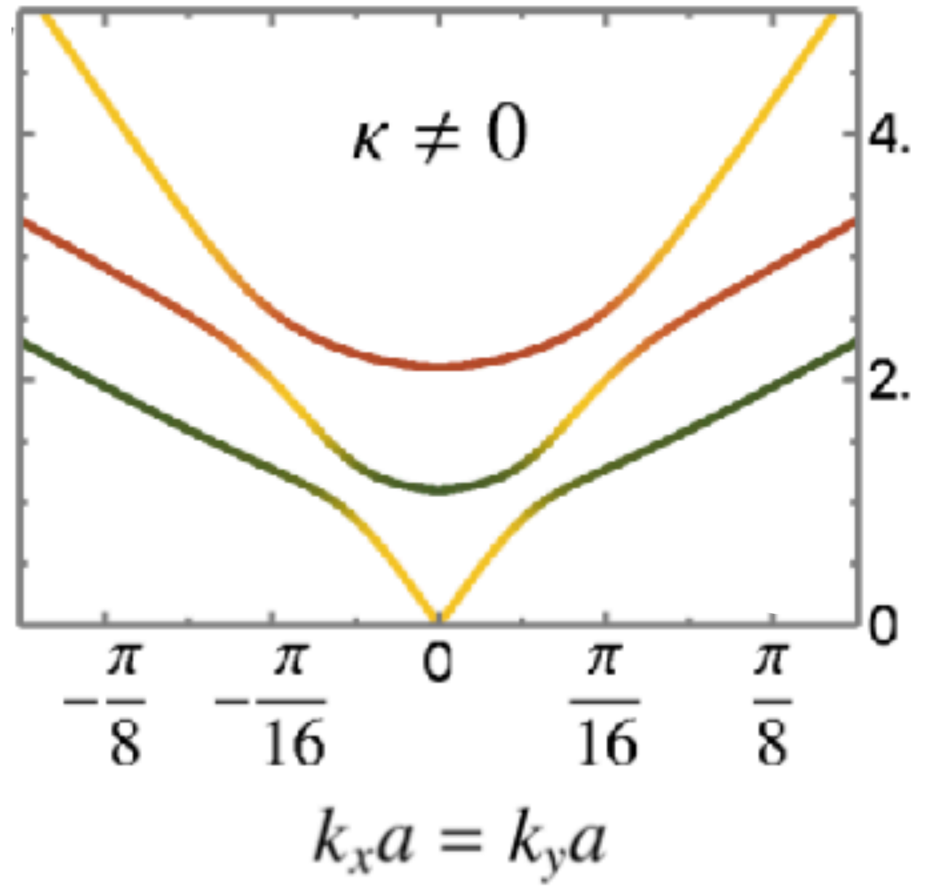


Magnetoelastic coupling $H_{\rm me} = \kappa \sum_{\ell,\delta} S_\ell^z (\mathbf{S}_\ell \cdot \hat{\mathbf{e}}_\delta)(u_\ell^z - u_{\ell+\delta}^z)$

Staggered magnetization

Form of a spin-orbit coupling → $-\frac{2\kappa S^2}{a}\mathbf{n} \cdot \nabla u^z$

Lattice constant



Continuum model Insensitive to lattice details

3-component field

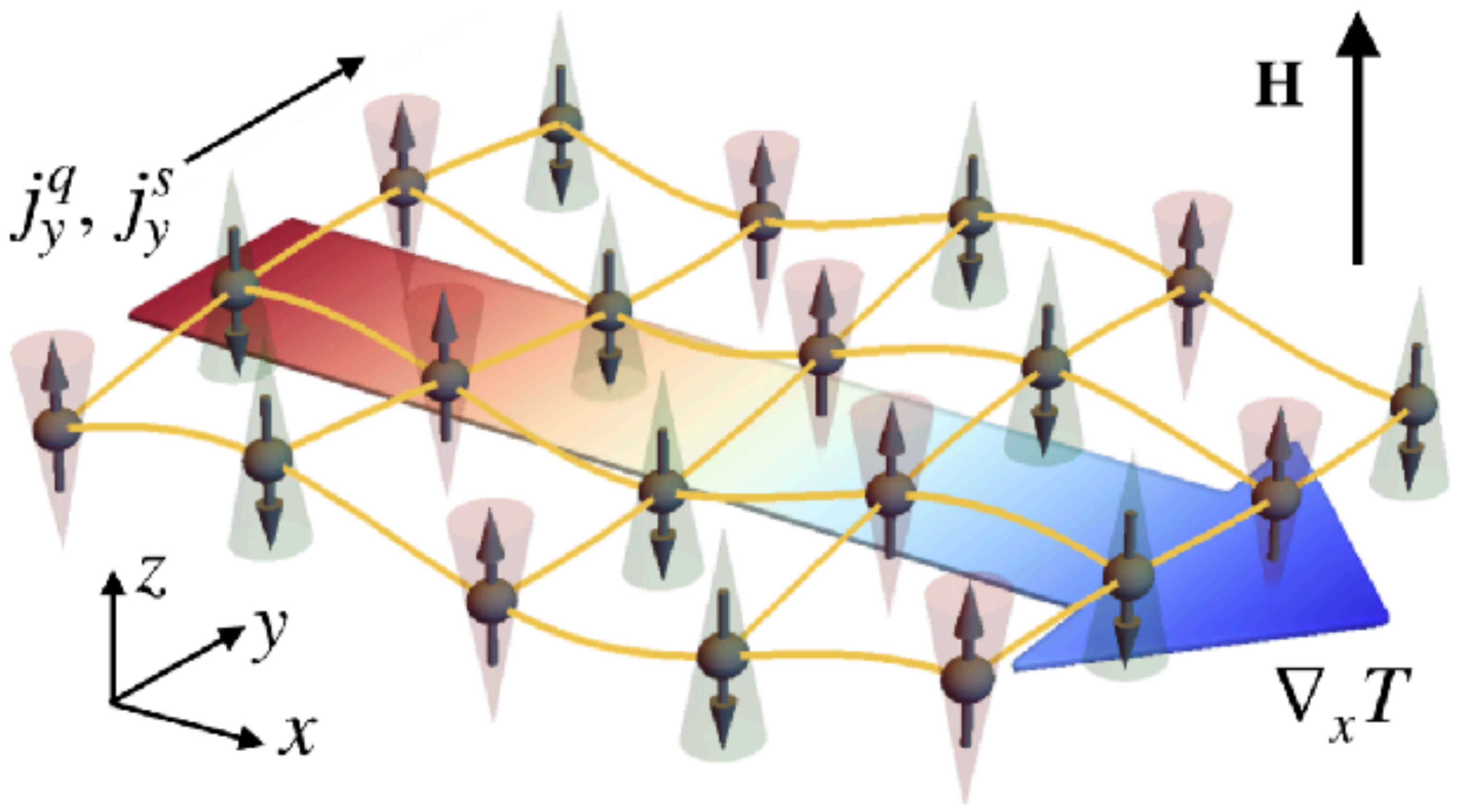
$$\mathcal{S}[\Psi] \approx \frac{1}{2}\int d^2\mathbf{k} \int d\omega\, \Psi^\dagger_{\mathbf{k},\omega} \left(\hbar\omega - \mathcal{G}_{\mathbf{k},\omega}\right) \Psi_{\mathbf{k},\omega}$$

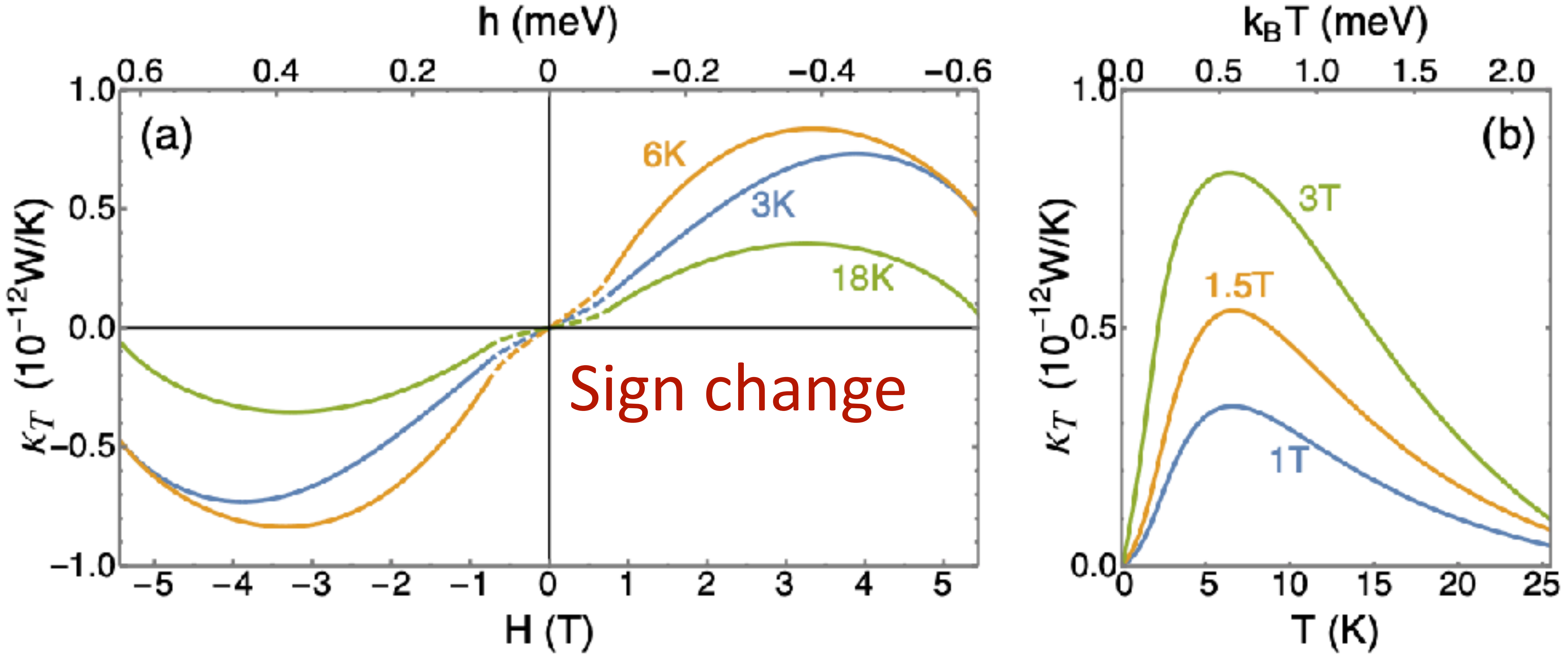
Inverse of Green's function
containing the topological structure

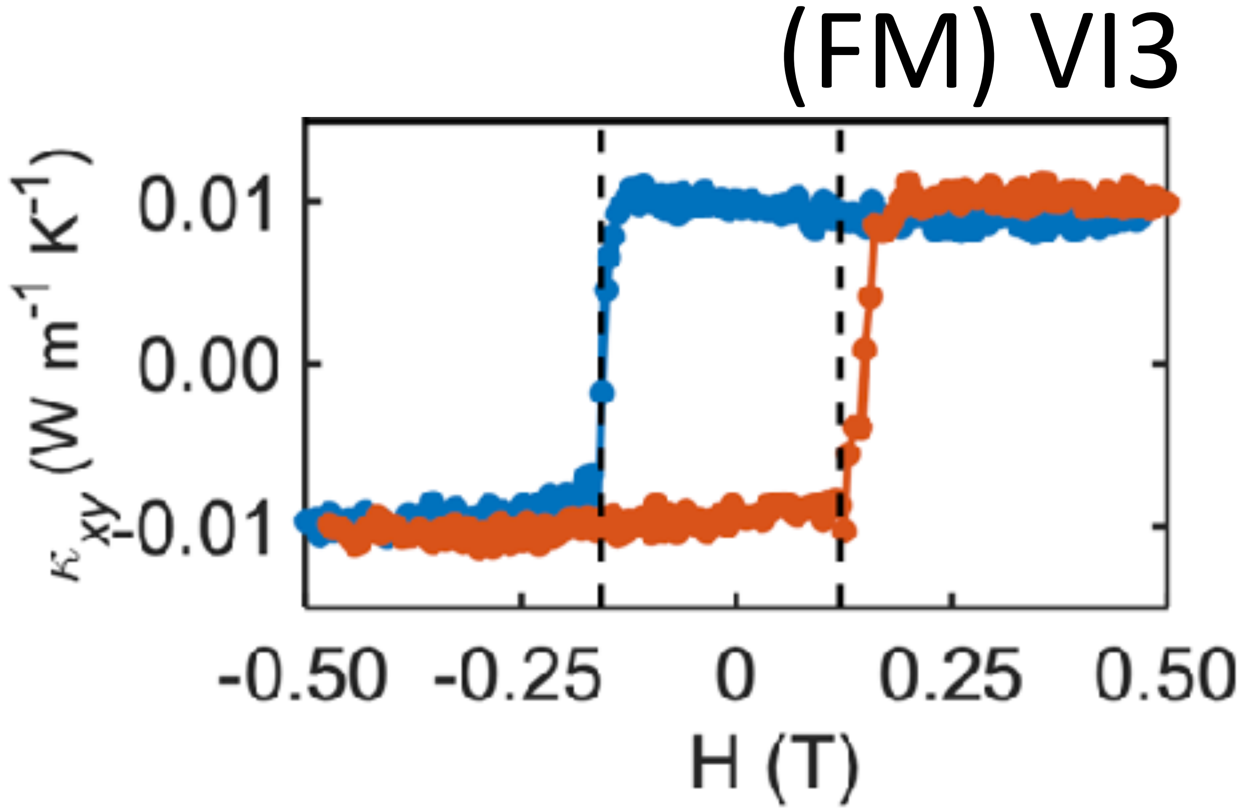
SZ, Go, Lee, Kim 2020

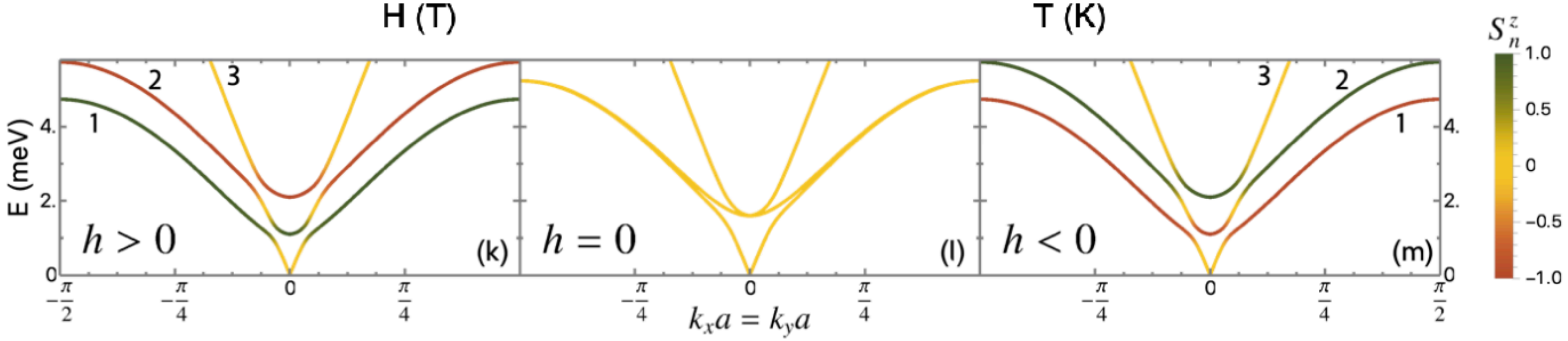
Thermal Hall effect

Predictions for MnPS3





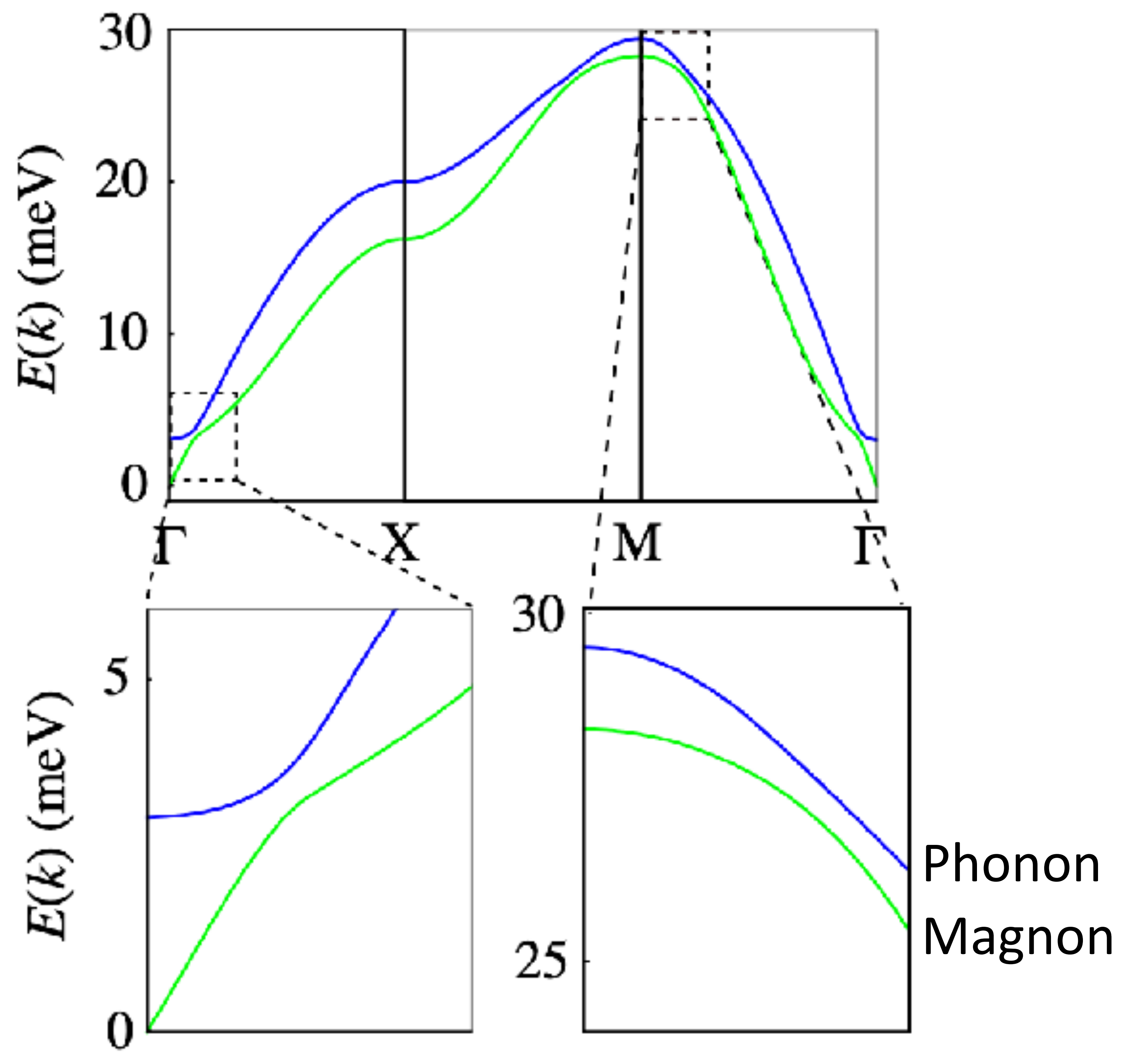


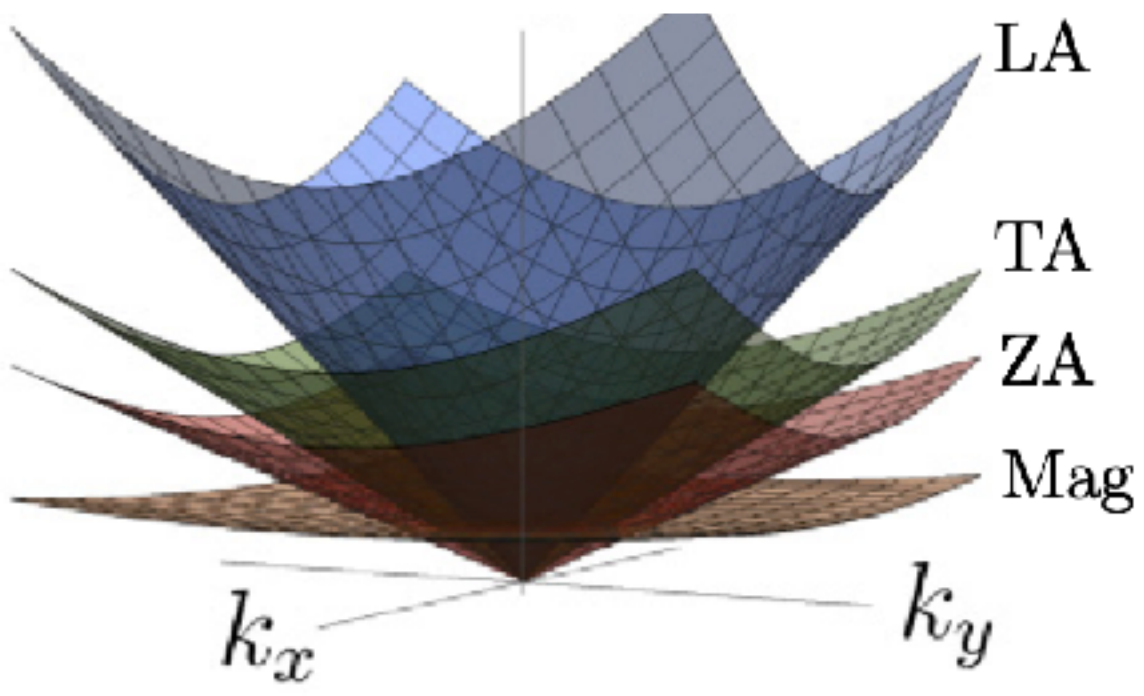


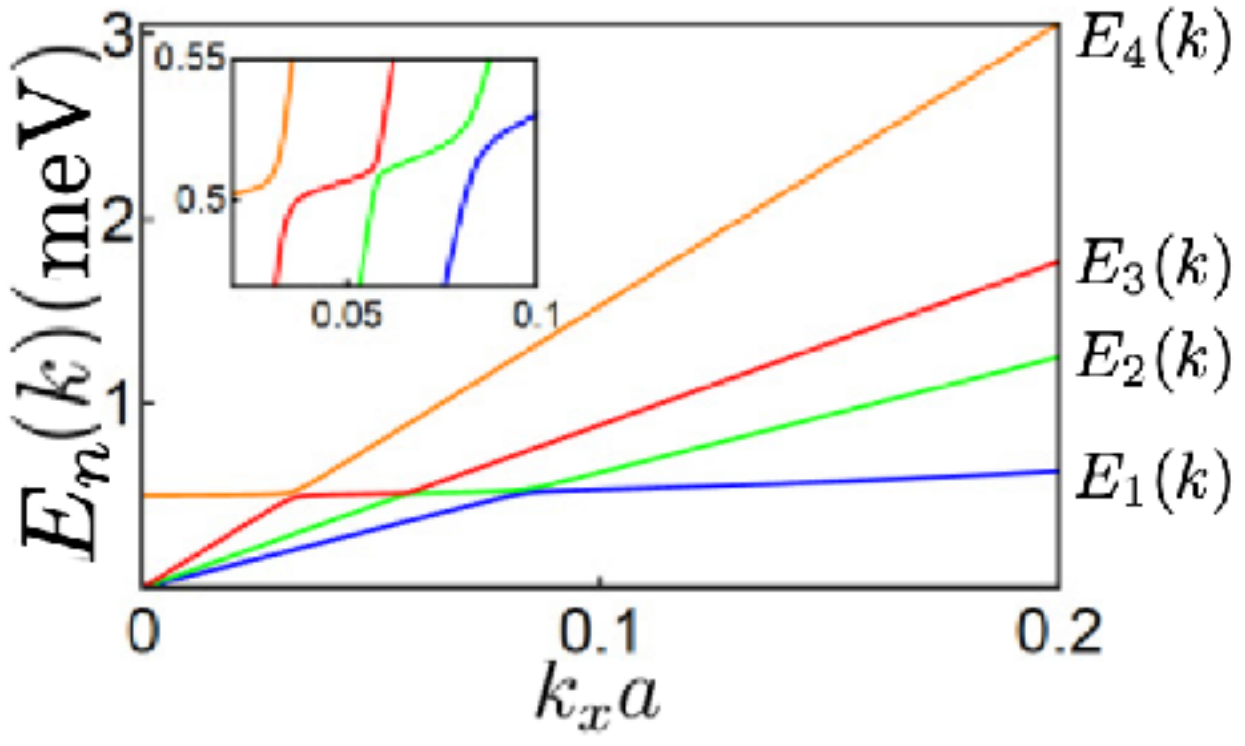
Zhang, ..., Xiao, Ke 2021
SZ, Go, Lee, Kim 2020

Tunability

Magnon band is generally tunable by magnetic field





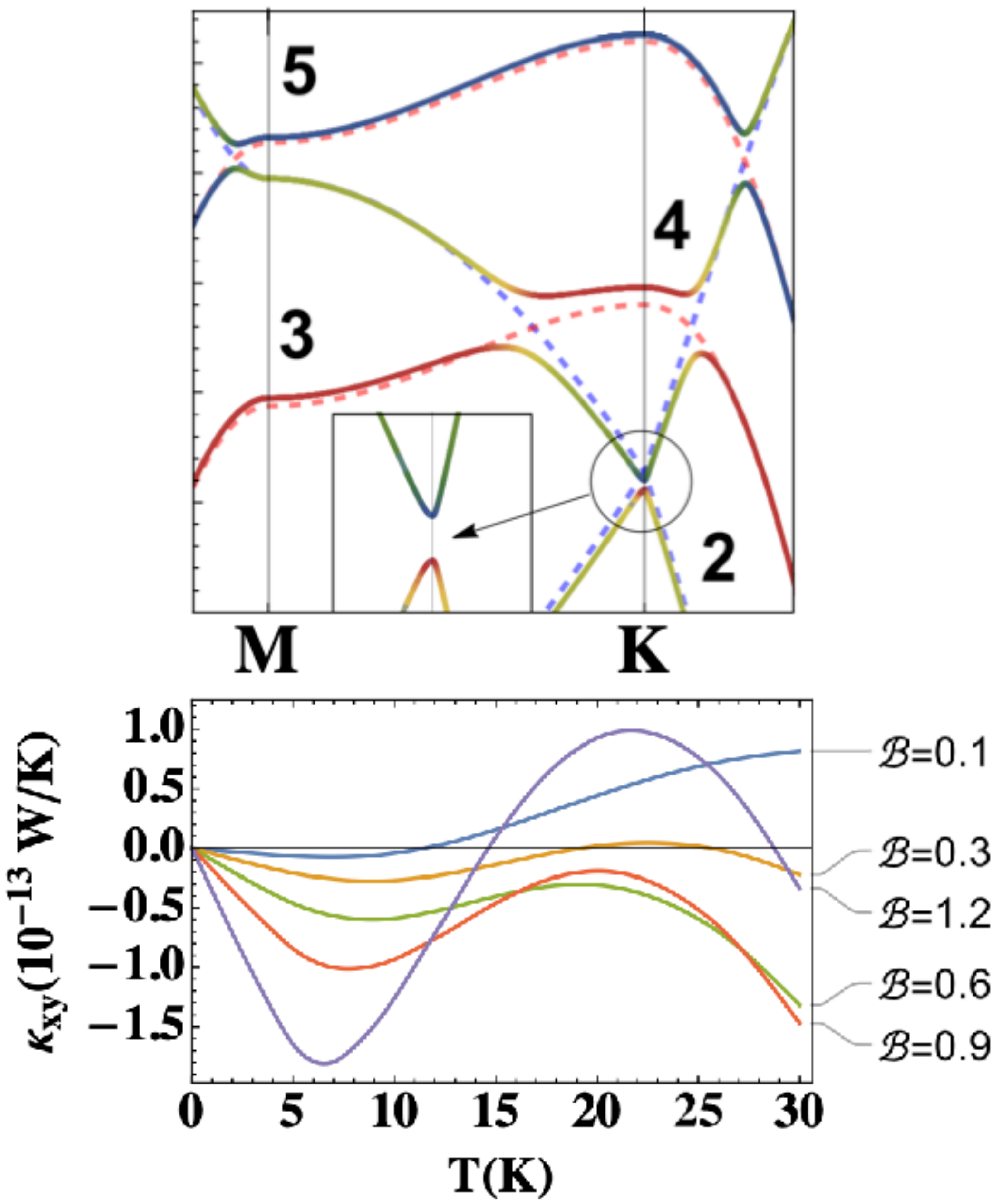


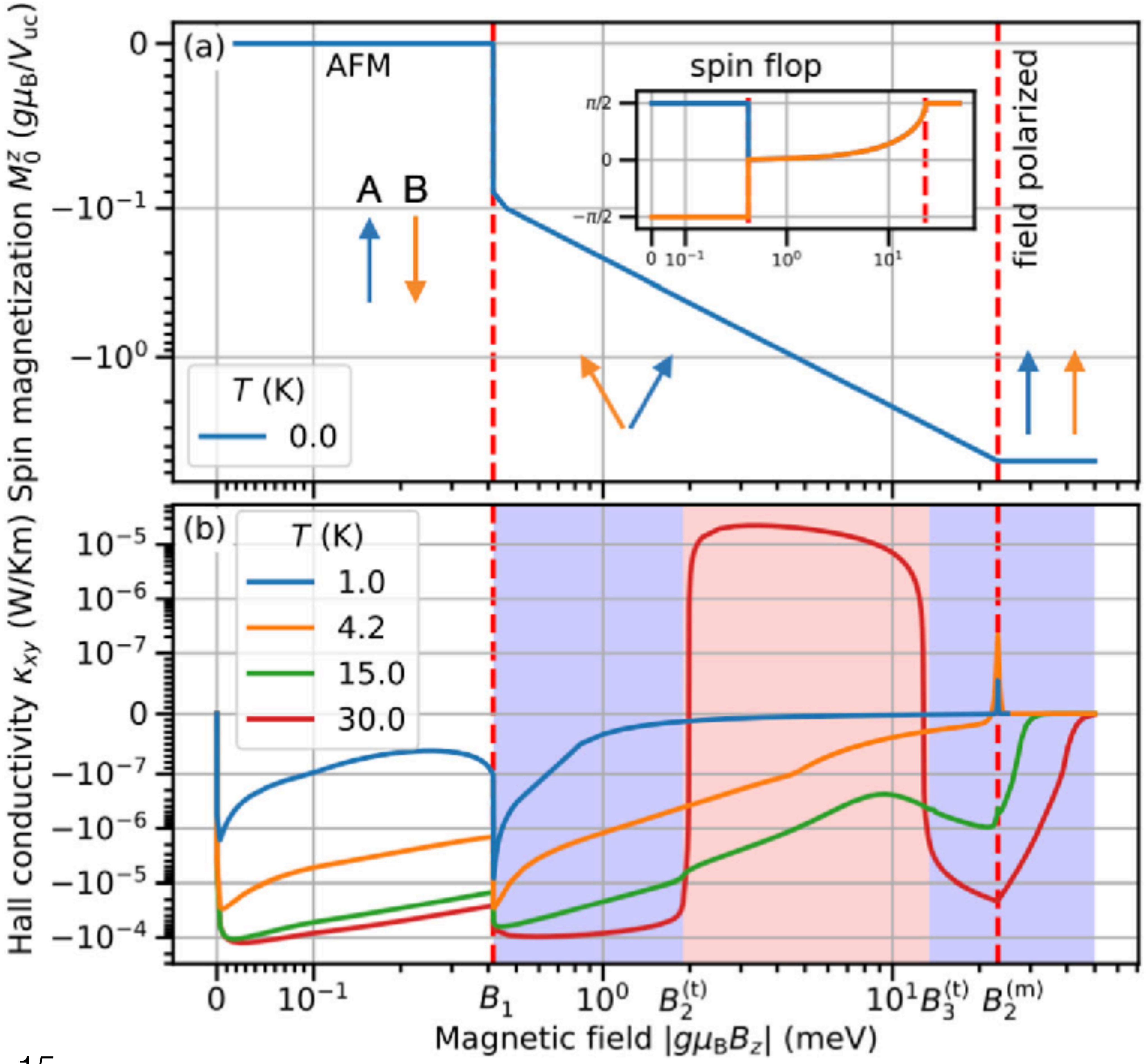
Go, Kim, Lee 2019
Shen, Kim 2020

Tunability

By temperature change & across magetic phase transition…

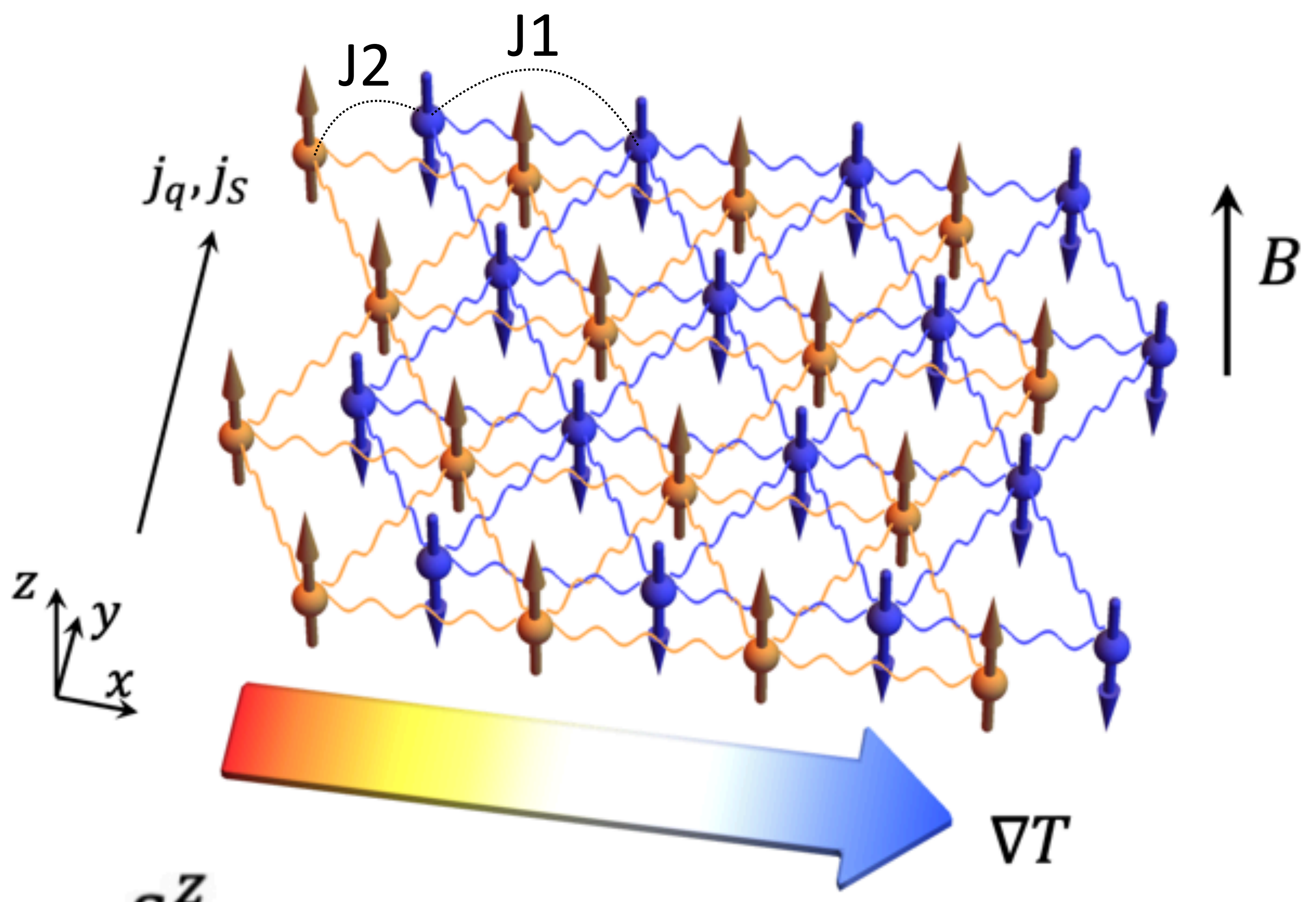
Ma, Fiete 2021
Neumann, Mook, Henk, Mertig 2022





Bilayer van der Waals magnet

Lin, **SZ**, Appl. Phys. Lett. 2024

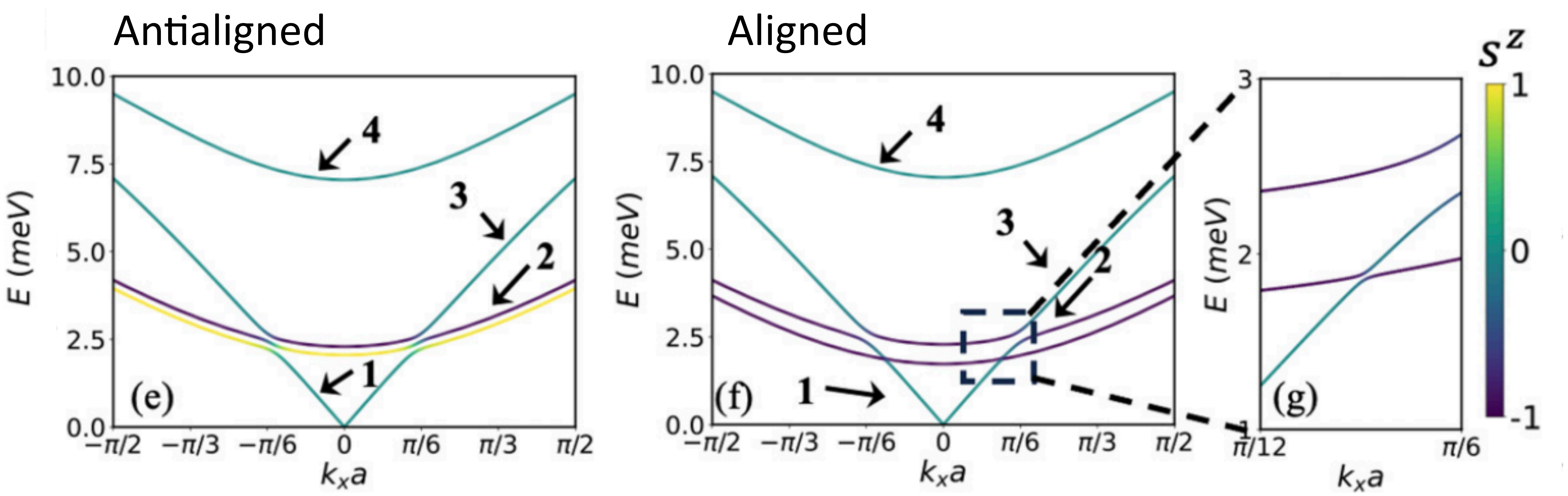


FM intralayer J1 $\gg$ AFM interlayer J2 $\sim$ Magnetoelastic coupling κ

Field induced metamagnetic transition

Candidate: FeCl2 with splitting at hybridization ~0.32meV

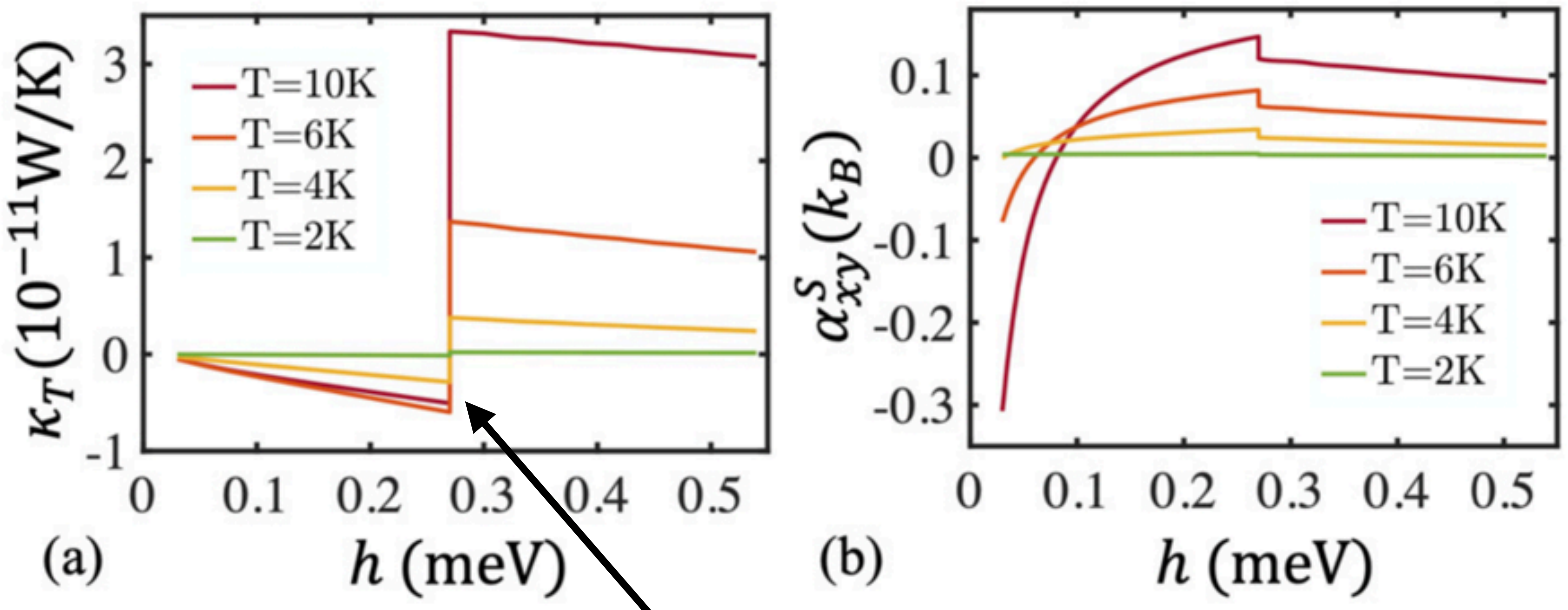
Siebeck and Houmann 1976



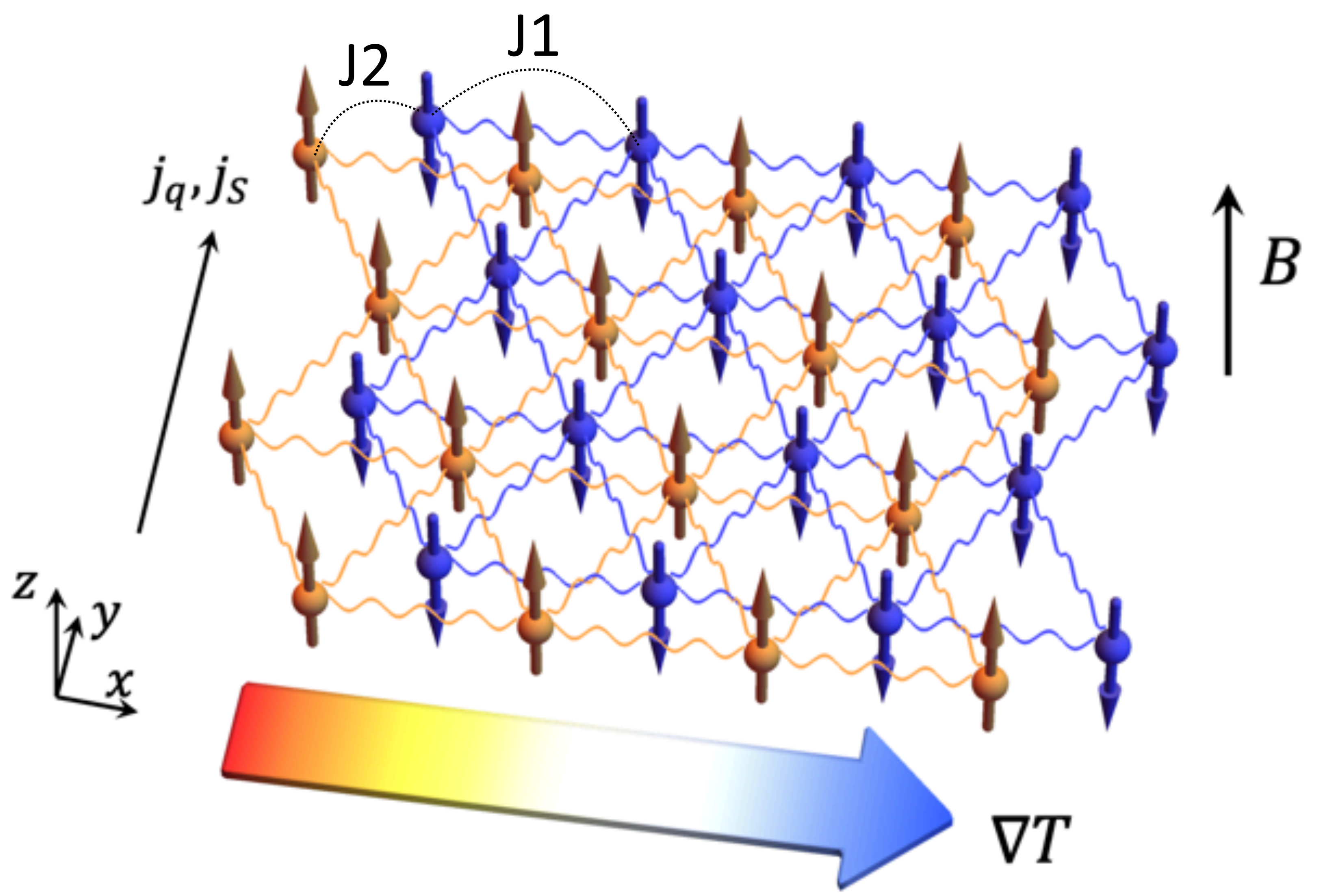
Transport across metamagnetic transition

Lin, **SZ**, Appl. Phys. Lett. 2024

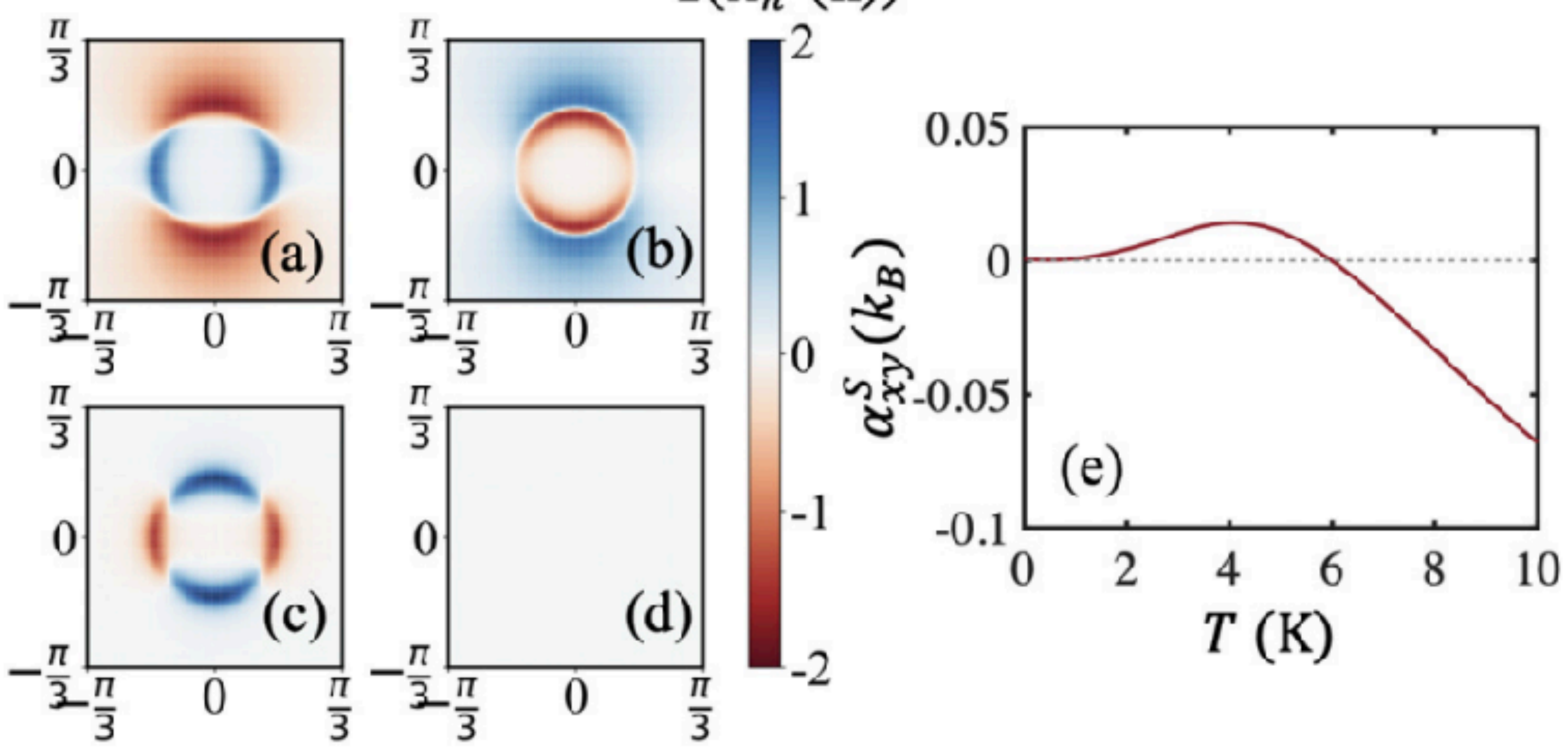
FeCl2: Thermal Hall Spin Nernst



Metamagnetic transition



Antialigned



$$\Omega_n^z(\mathbf{k}) = -\sum_{m\neq n} \frac{2\mathrm{Im}\langle n|v_x|m\rangle\langle m|v_y|n\rangle g_{nn}g_{mm}}{[g_{nn}E_n(\mathbf{k}) - g_{mm}E_m(\mathbf{k})]^2}$$

Spin current Magnon current

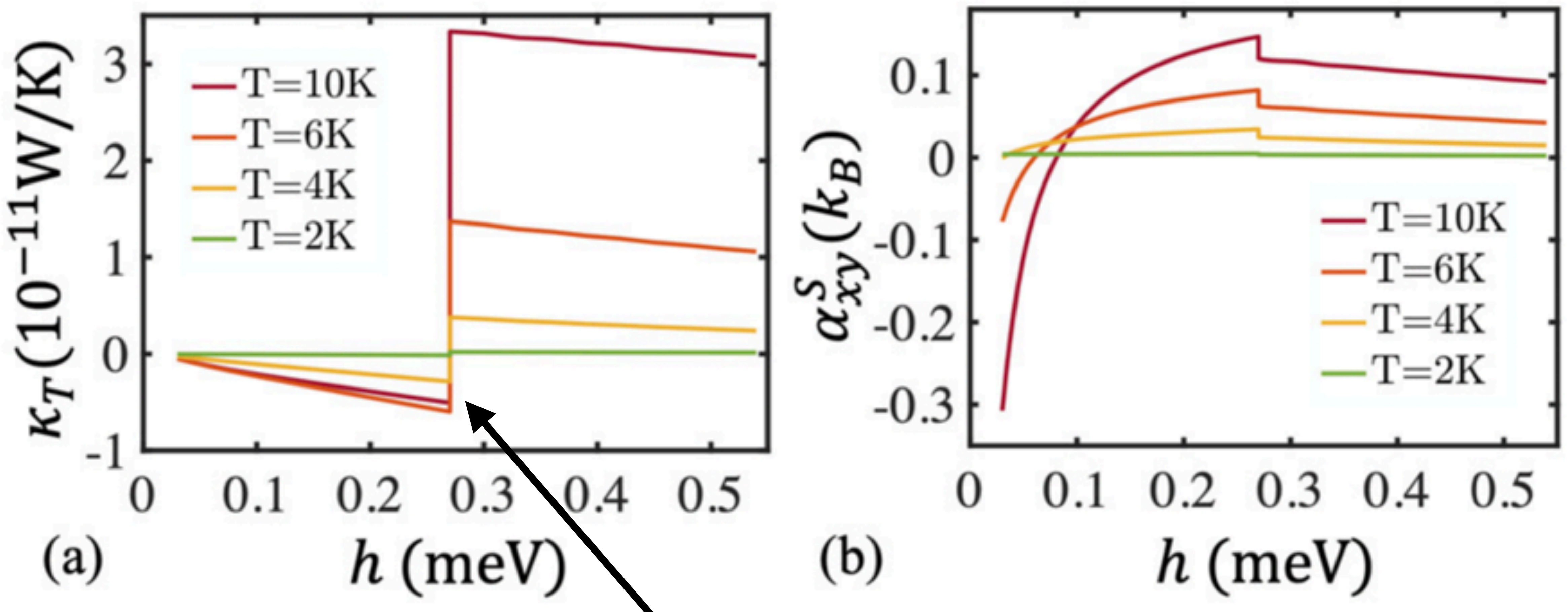
$$\Omega_n^{s,z}(\mathbf{k}) = -\sum_{m\neq n} \frac{2\mathrm{Im}\langle n|\theta_x|m\rangle\langle m|v_y|n\rangle g_{nn}g_{mm}}{[g_{nn}E_n(\mathbf{k}) - g_{mm}E_m(\mathbf{k})]^2}$$

BdG normalization

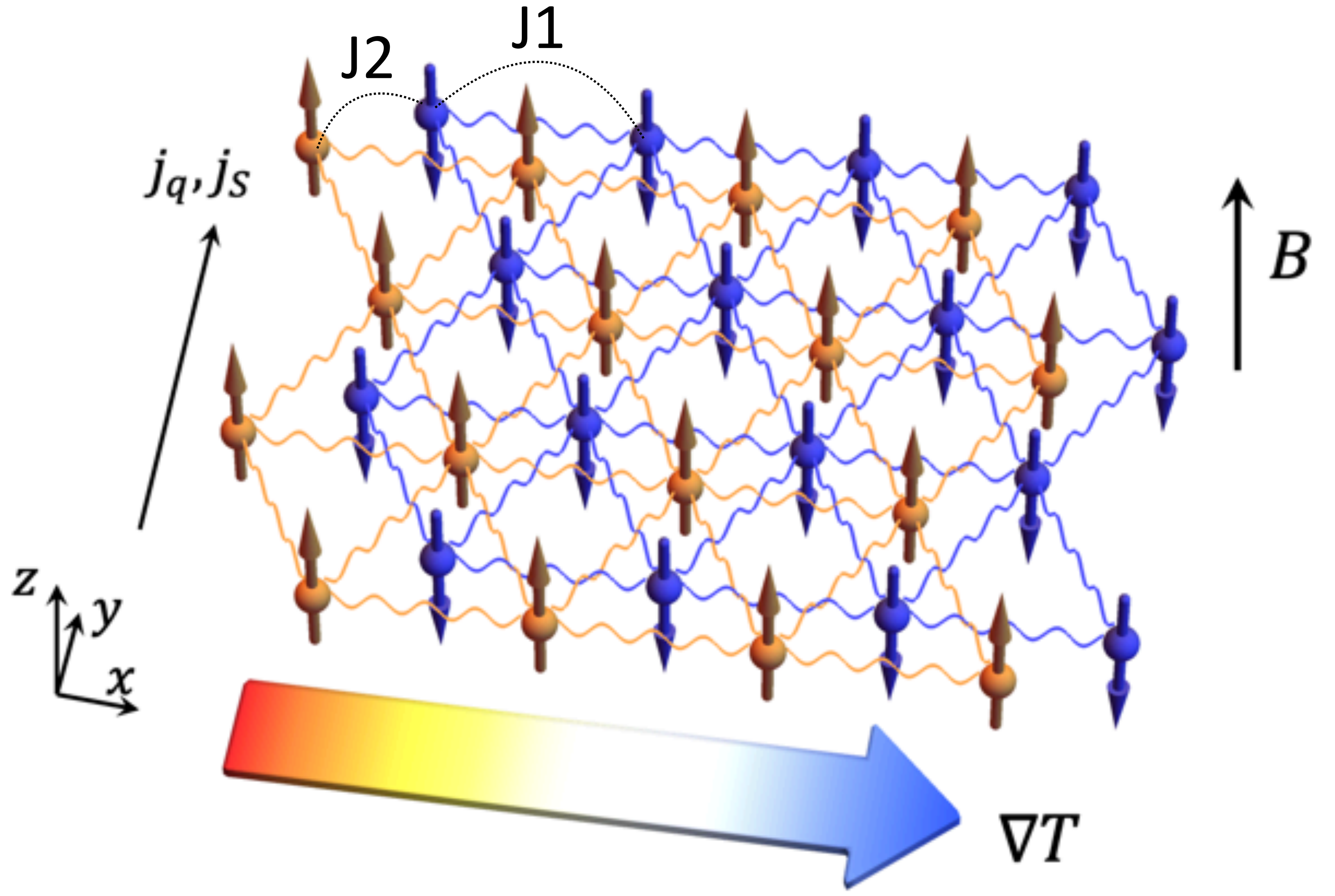
Experimental observation

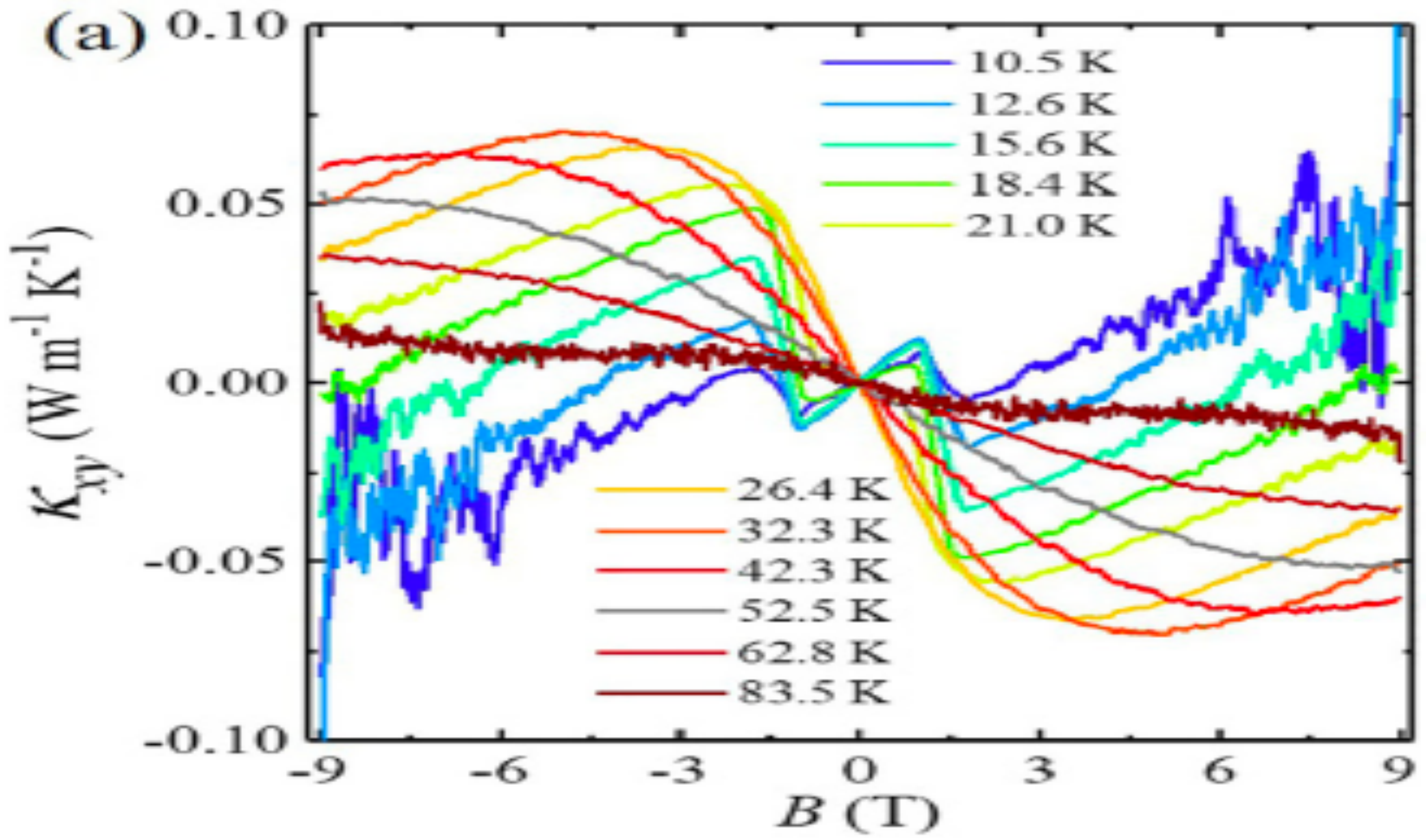
Lin, **SZ**, Appl. Phys. Lett. 2024

FeCl2: Thermal Hall Spin Nernst



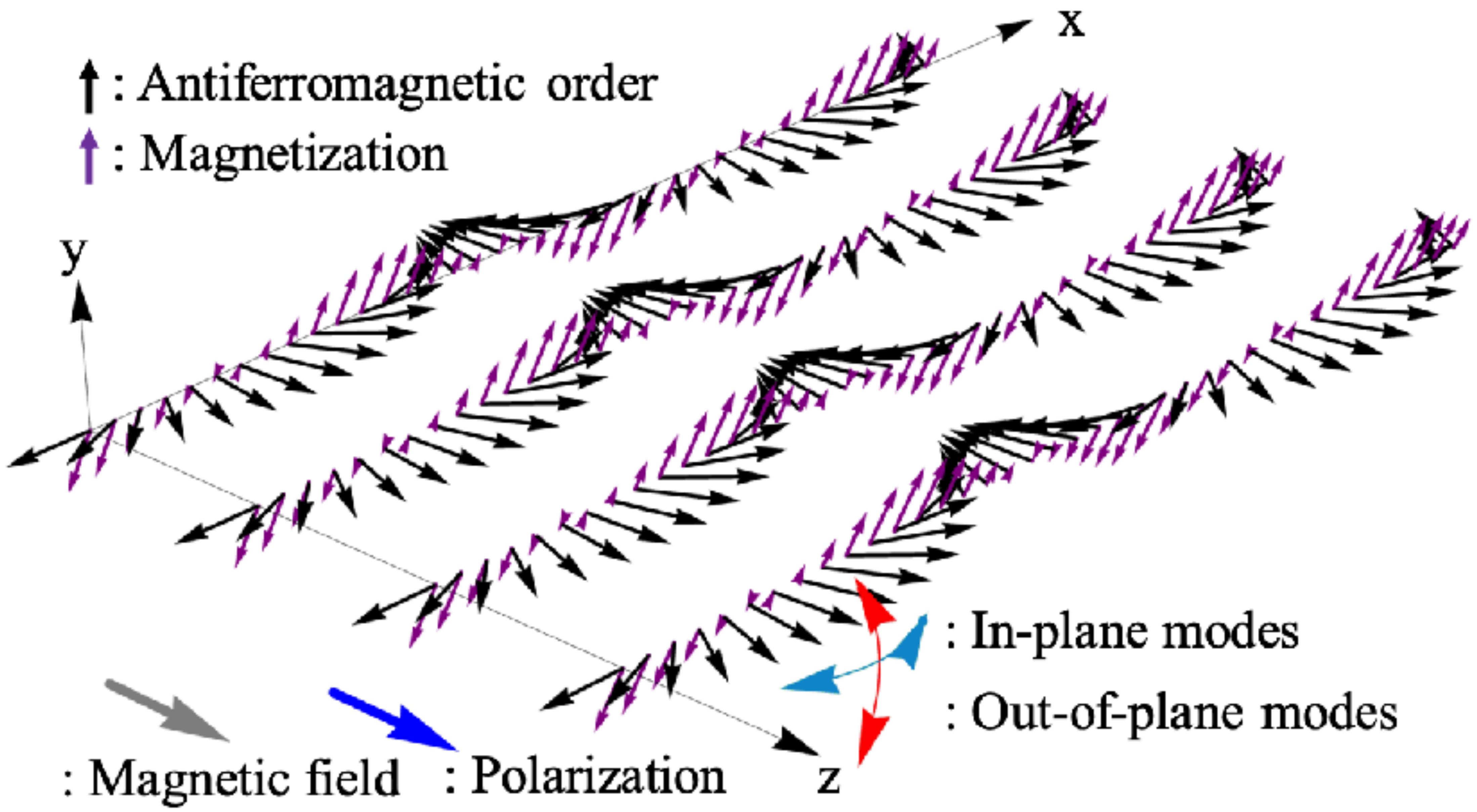
Metamagnetic transition

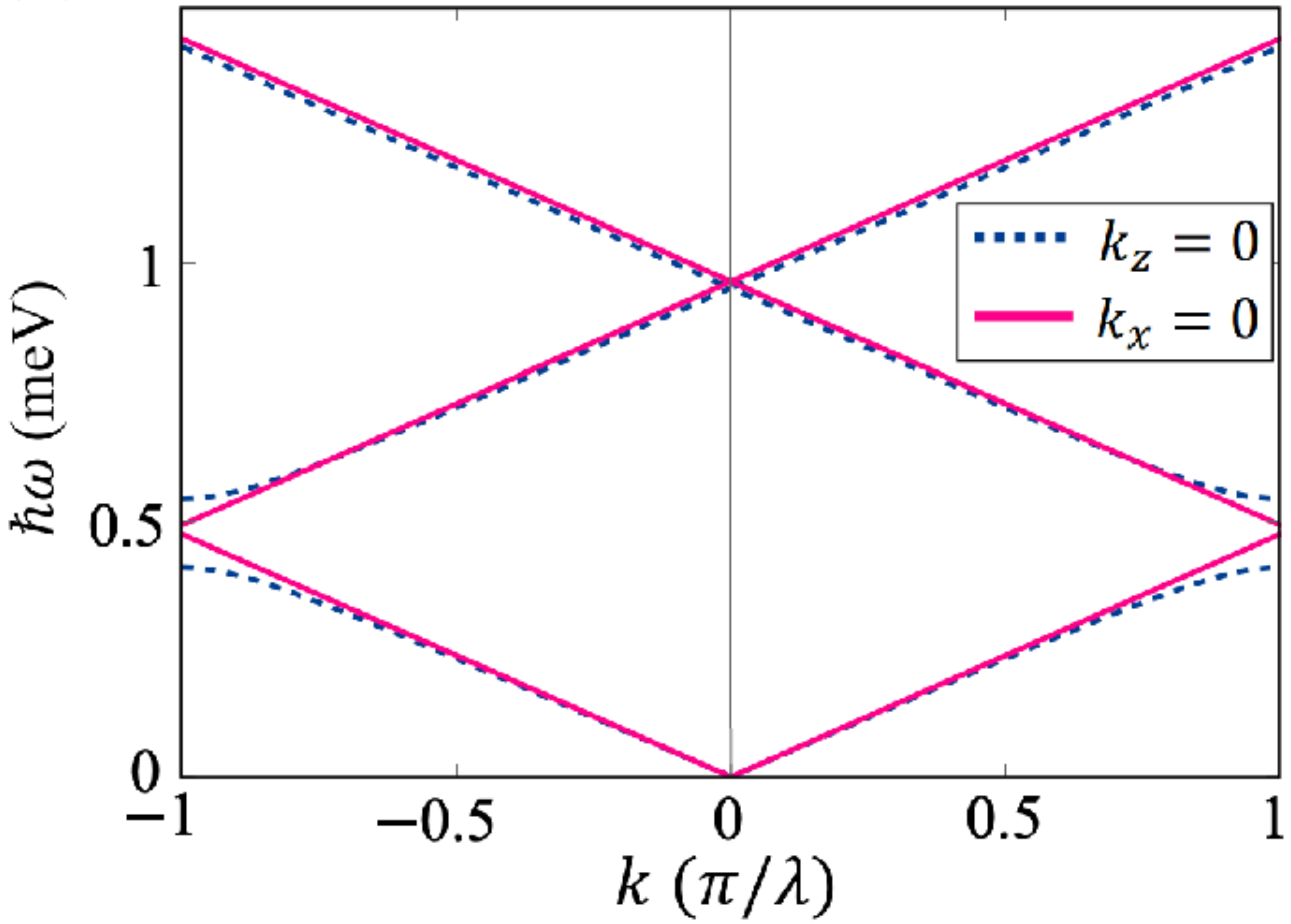




Xu, et. al. PRB Letter, 2023

Magnons in (multiferroic) spin cycloids





H. W. Park, SZ, … S. K. Kim, arXiv:2503.11135

Period of the cycloid superlattice

Summary

- Magnetoelastic coupling induced topological magnon-phonon hybridization
- Collinear antiferromagnet: monolayer/bilayer
- Thermal Hall and Spin Nernst effects

SZ, Go, Lee, Kim, *Phys. Rev. Lett.* 124, 147204 (2020)
Lin and SZ, *Appl. Phys. Lett.* 124, 132402 (2024)

Acknowledgement

Se Kwon Kim
@ KAIST

Zhi-Xing Lin
@ Princeton