Topological Magnons in CoTiO3

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Funding: NSF-MRSEC

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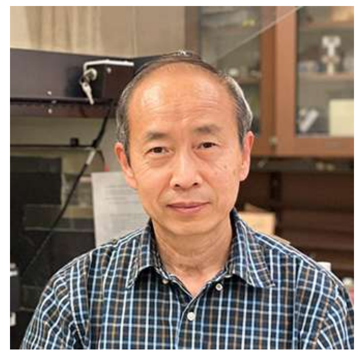

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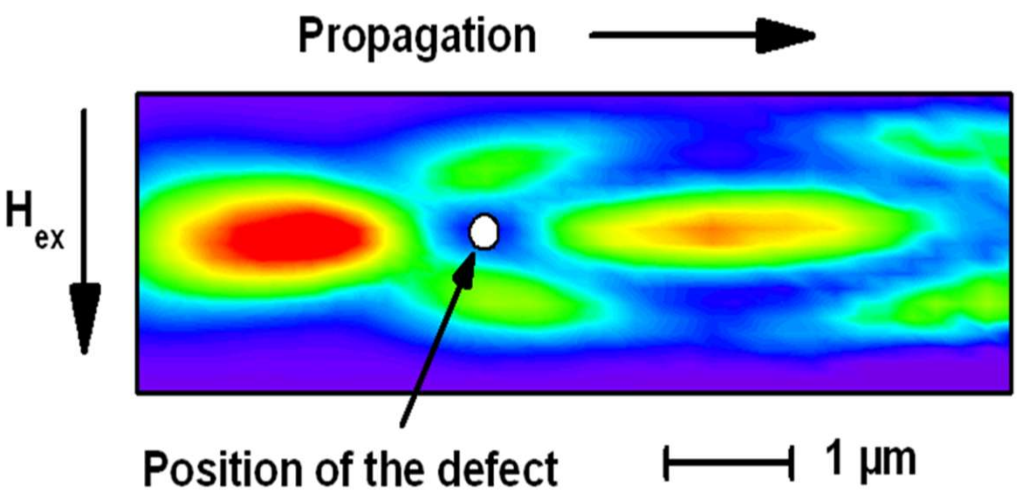
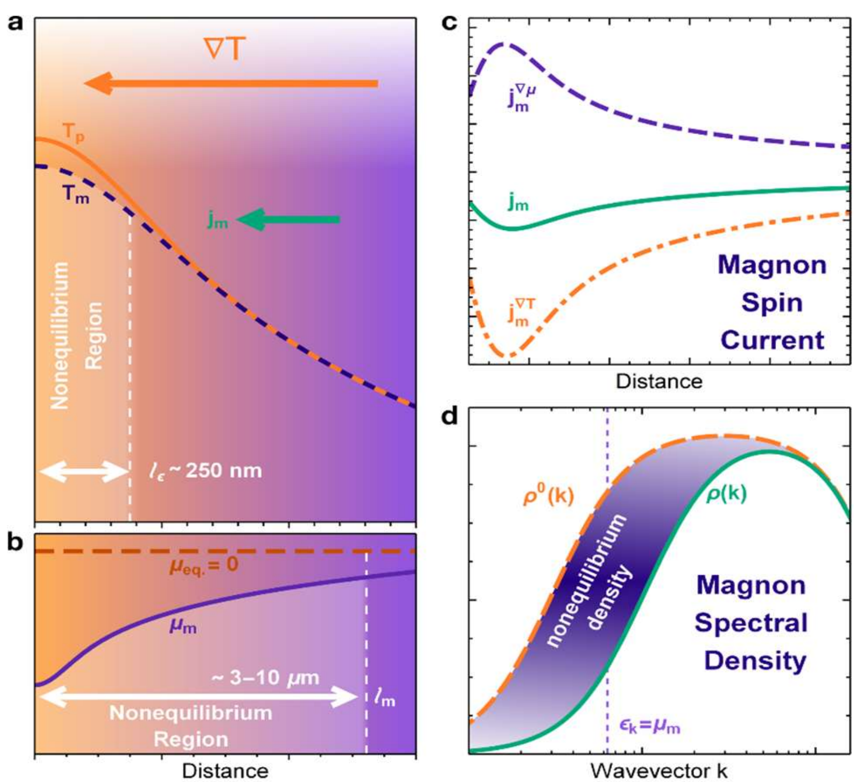
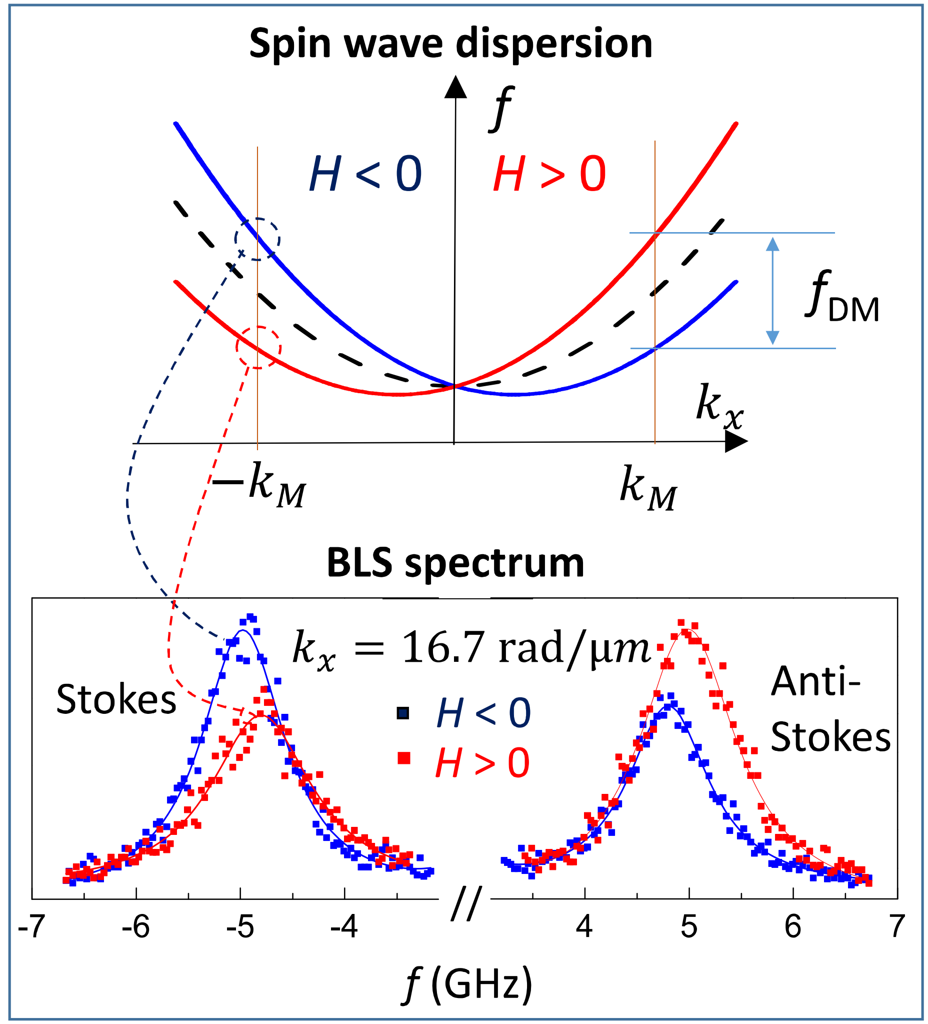
Magnons probed by inelastic light scattering

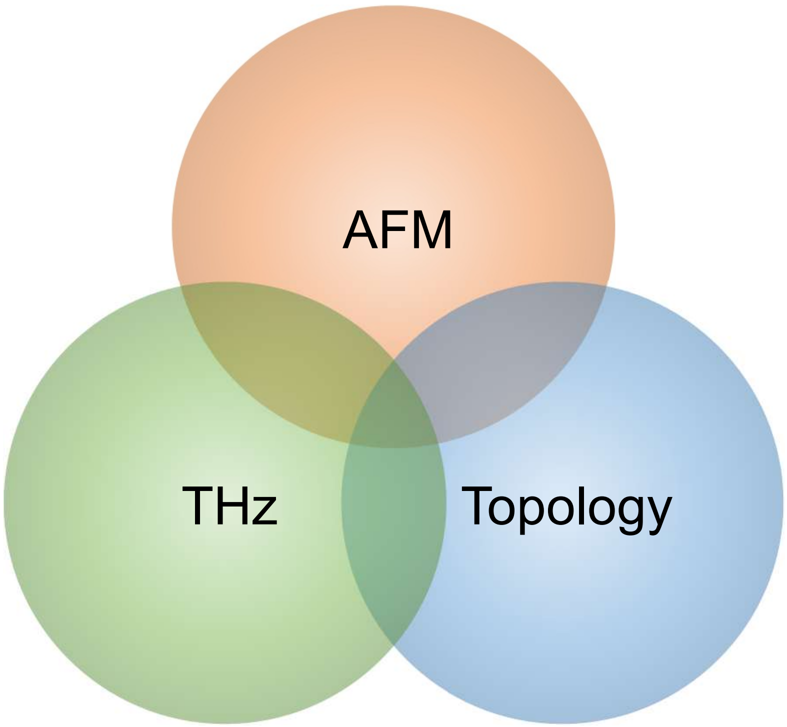






Appl. Phys. Lett. 95, 122510, 2009
Phys. Rev. Lett, 119, 027202, 2017
Phys. Rev. X, 10, 021029, 2020

Topological terahertz magnons in antiferromagnetic insulator



Magnonics (spintronics) application

Antiferromagnetic insulator
- Optimal for low-dissipation applications
- Robust in the presence of fluctuating field

THz frequency
- Fast dynamics

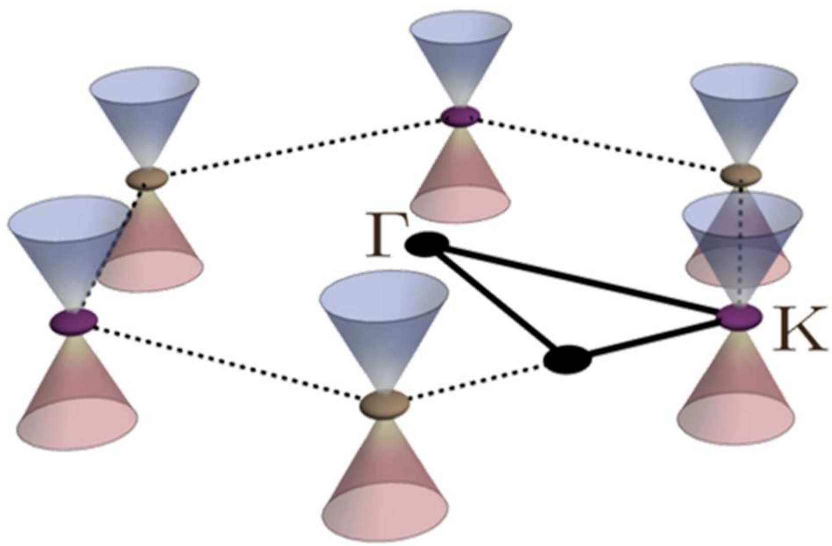
Topological magnons
- Protection from local defects in the materials

Long-lived zone boundary magnons and chiral phonons in CoTiO3

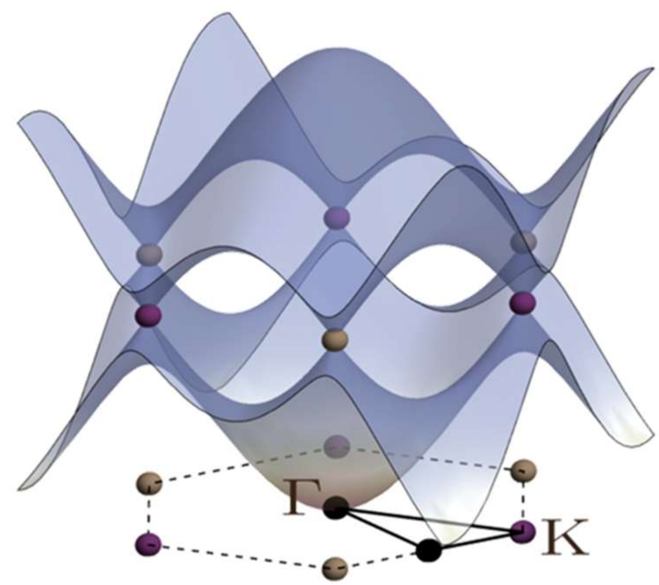
https://arxiv.org/abs/2504.14742; PNAS 2024, 121, e2304360121;
PRB, 110, 104419

Topological fermions and bosons

Fermionic system:
graphene, topological insulators



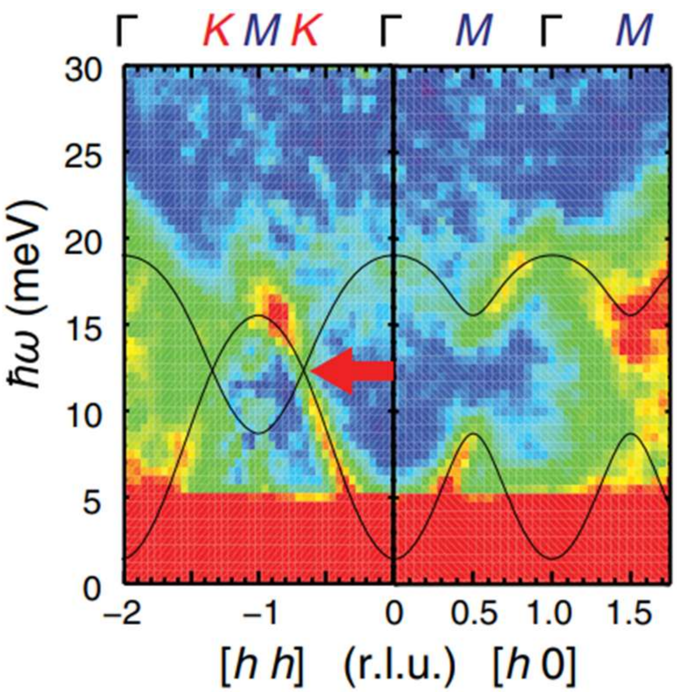
Bosonic system:
phonons, photonic crystals,
and magnons



How to probe bosonic magnon band structure?

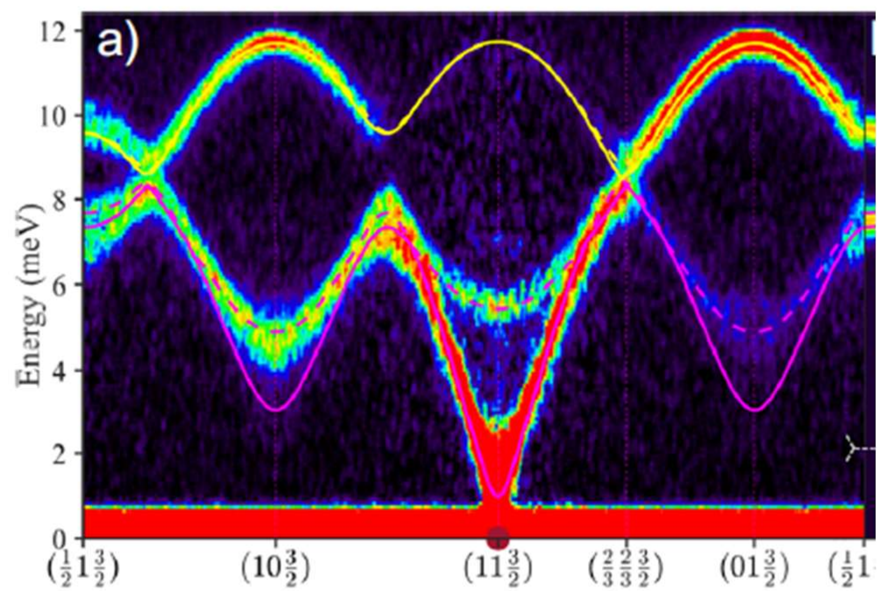
Topological magnons from inelastic neutron scattering

CrI_3



L. Chen *et al*. Phys. Rev. X **8**, 041028 (2018)

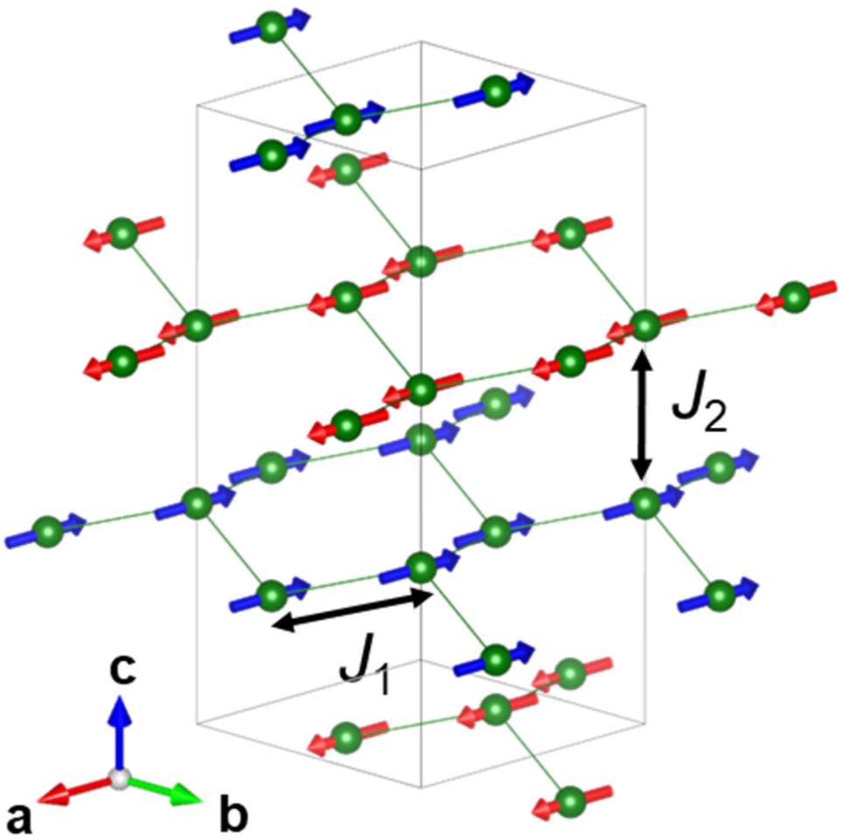
$CoTiO_3$



B. Yuan *et al*. Phys. Rev. X **10**, 011062 (2020)
M. Elliot *et al*. Nat Comm **12**, 3936 (2021)

- Limited energy resolution and sensitivity; no spatial resolution
- Thermal Hall effect observed in CTO

Honeycomb Magnetic Structure of $CoTiO_3$



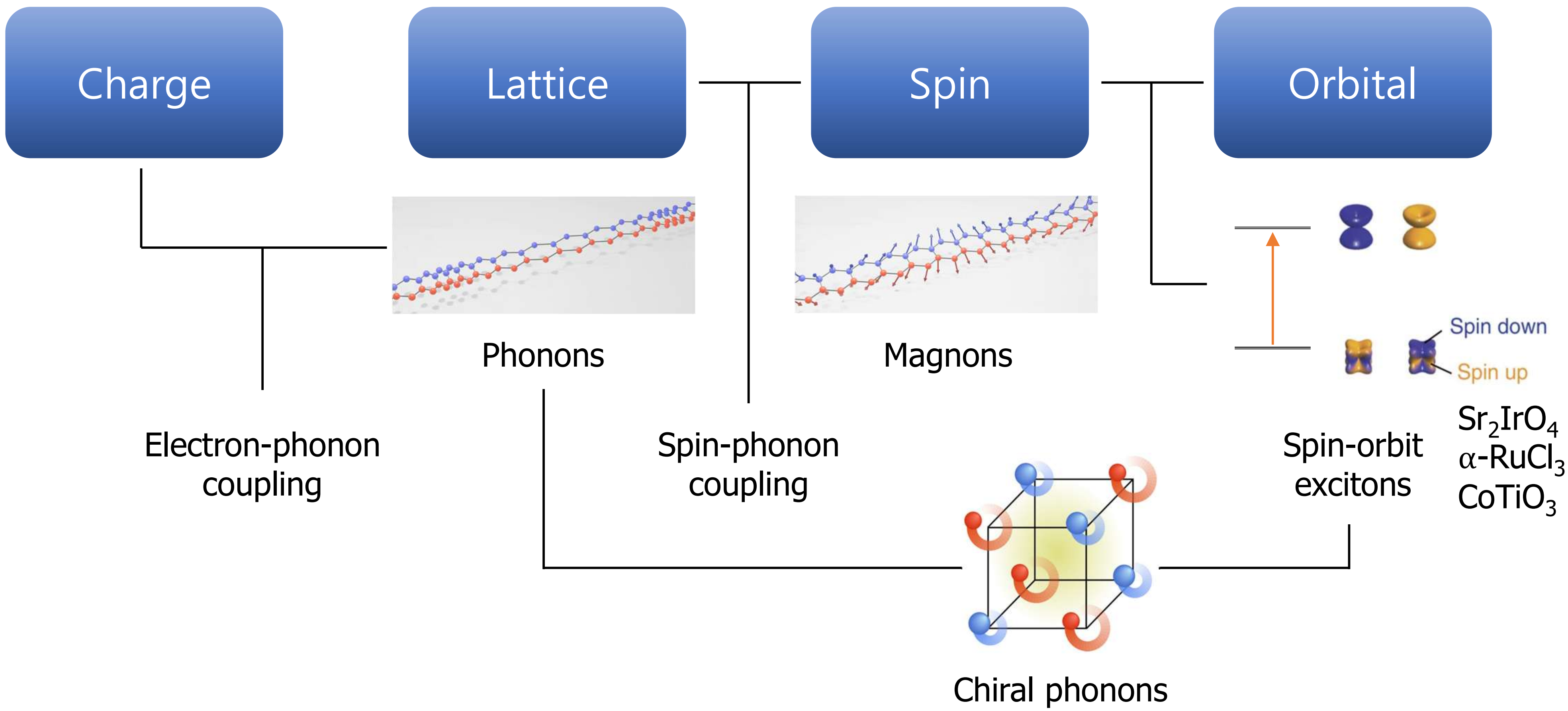
- 2D honeycomb lattice plane of Co^{2+} ions with buckling
- ABC stack
- FM order within each plane
- AFM order along the c axis
- Néel temperature (~38 K)

$$H = \sum_{i\delta} J_1 (S_i^x S_{i+\delta}^x + S_i^y S_{i+\delta}^y) + \sum_{i\gamma} J_2 (S_i \cdot S_{i+\gamma})$$

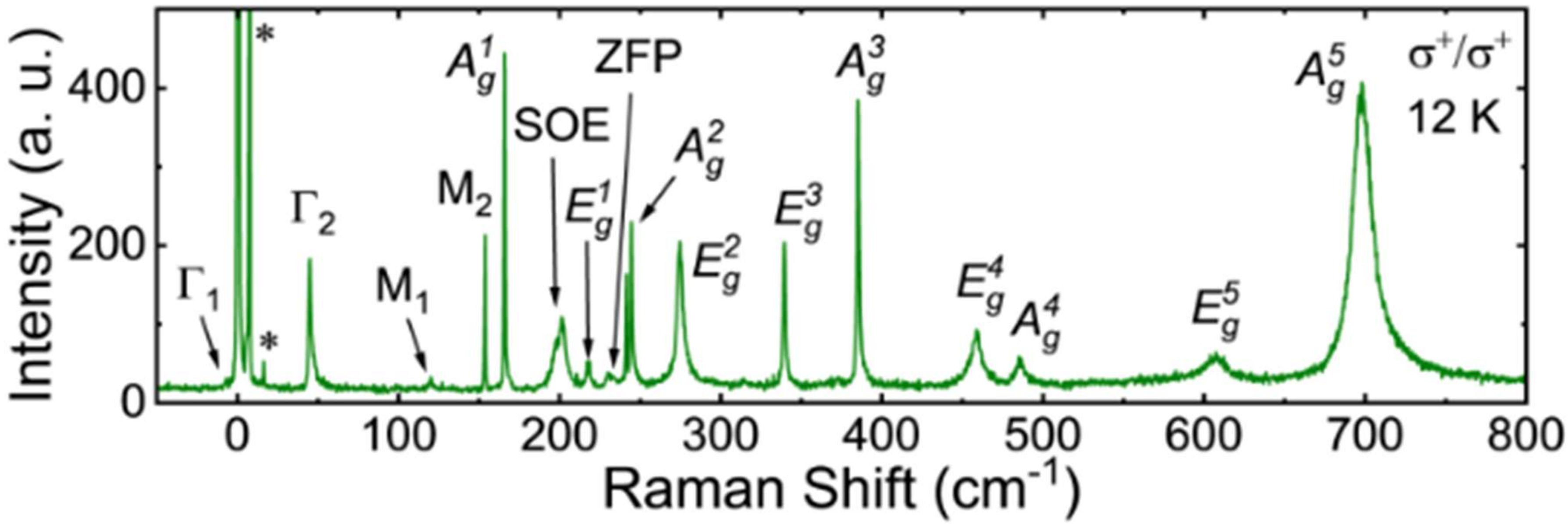
$$J_1 = -4.4\ meV$$
$$J_2 = 0.57\ meV$$

Easy-plane anisotropy

Collective excitations and their coupling

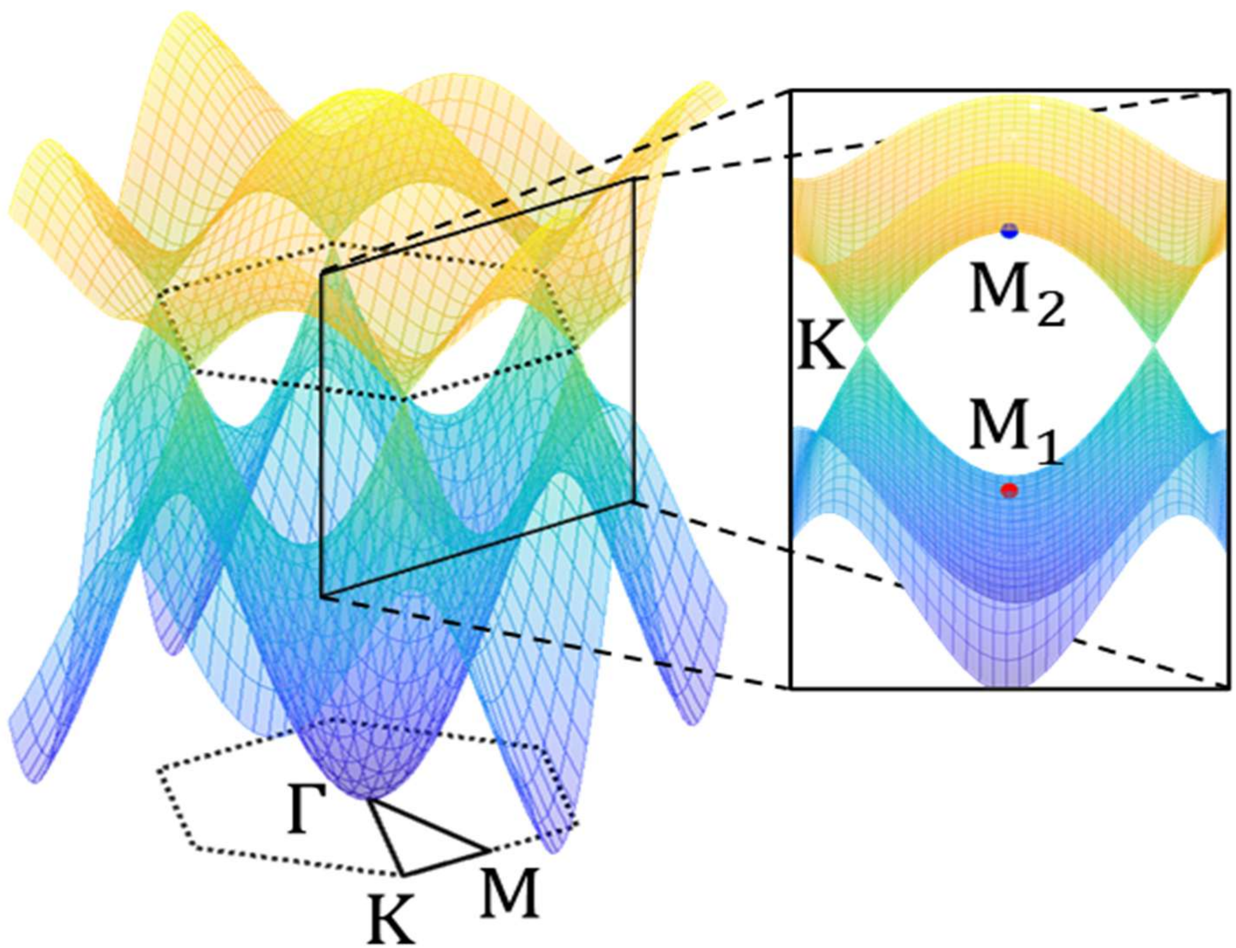


Raman spectrum

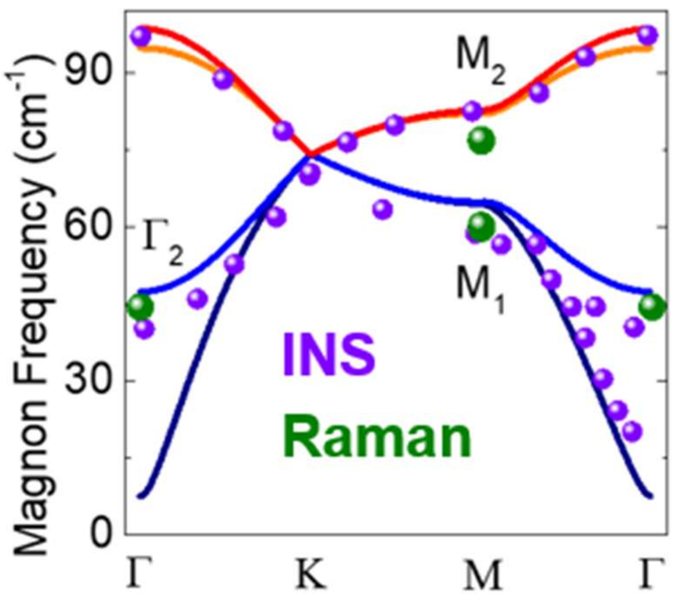


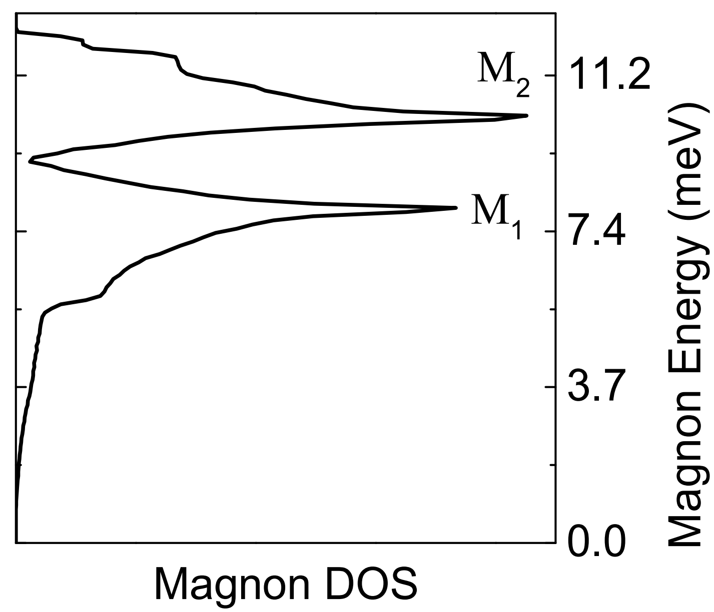
Extended Data Fig. 1: Raman spectra taken at 12 K at zero field in the σ^+/σ^+ polarization channel. Multiple magnons (Γ_1, Γ_1, M_1, M_2), phonons (A_g, E_g), a spin-orbit exciton (SOE) and a zone-folded phonon (ZFP) are observed. Asterisks are laser noise lines.

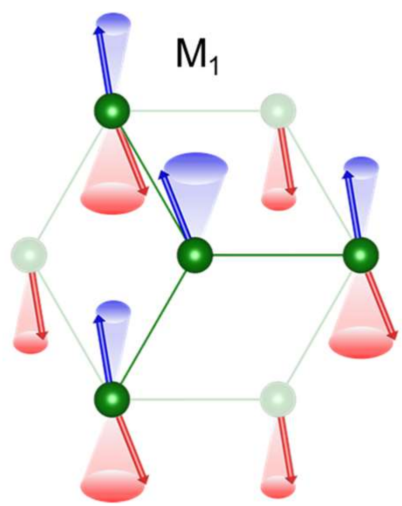
Dirac Magnon Dispersion



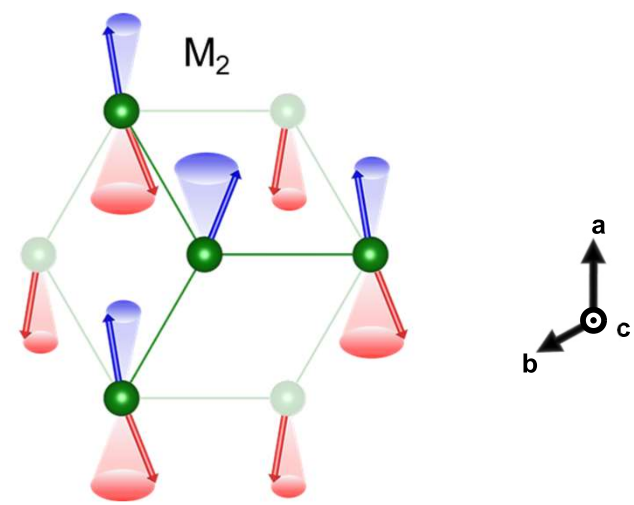
Dirac Magnon Dispersion





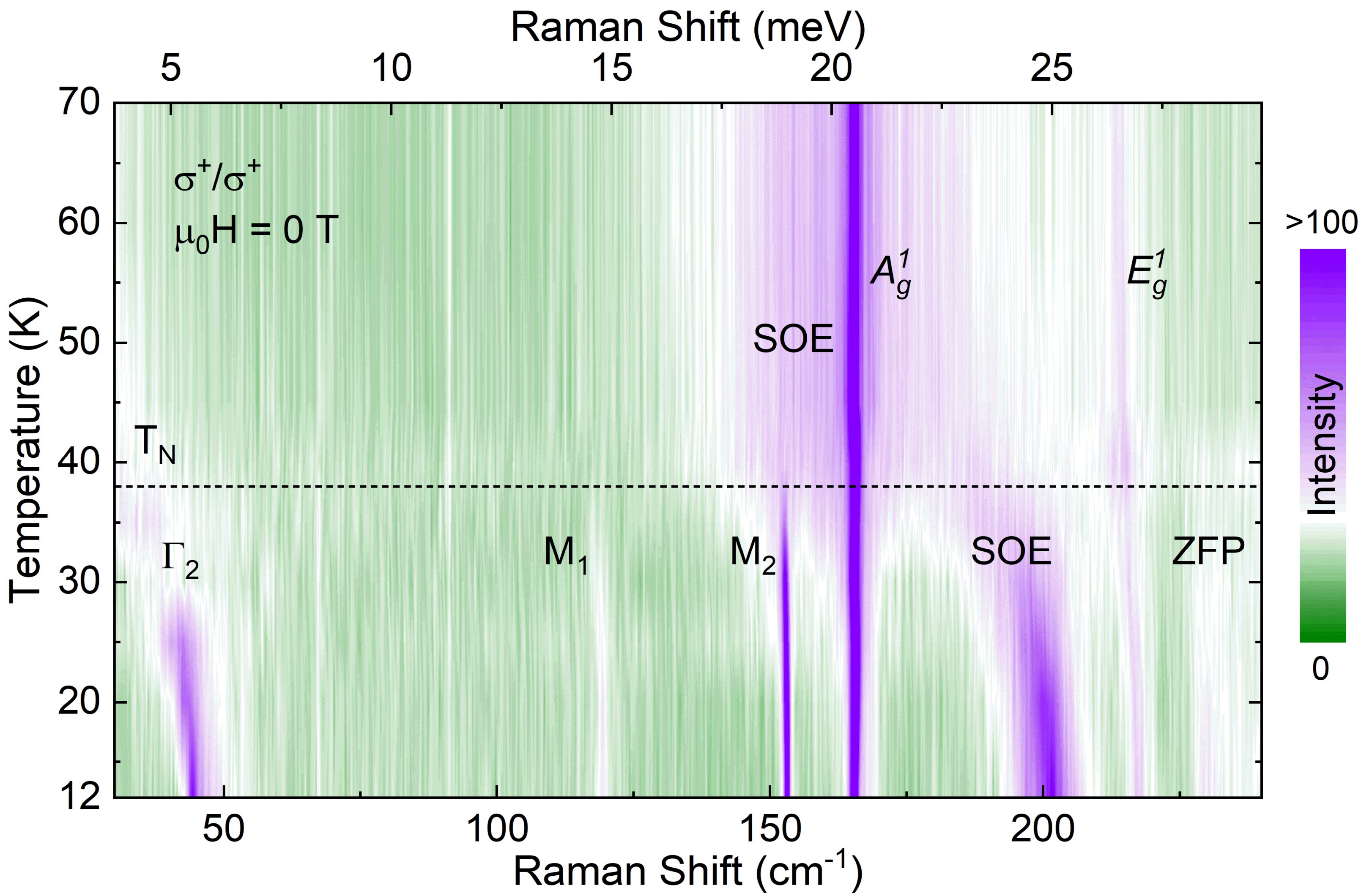


Acoustic mode
(in-phase precession)



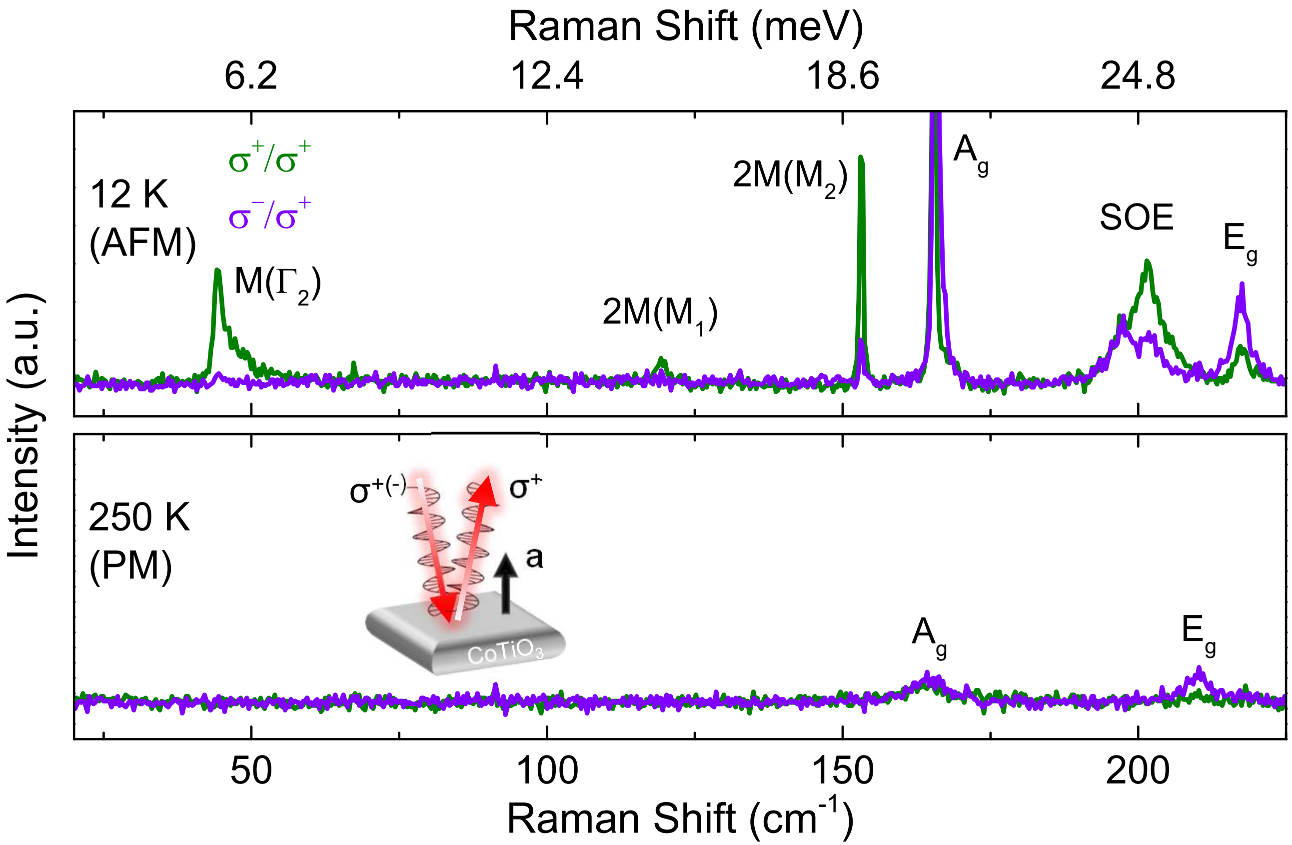
Optical mode
(out-of-phase precession)

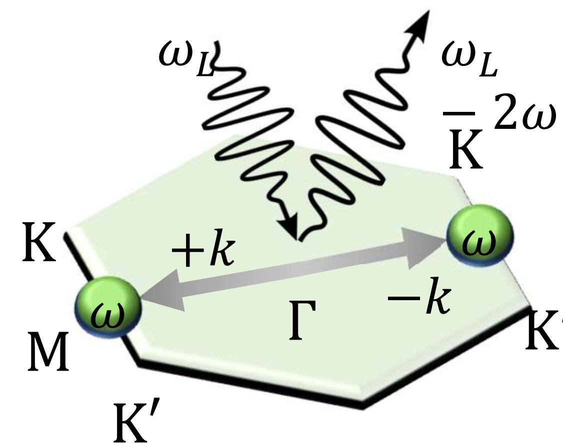
Identifying phonons and magnons



Multiple magnon peaks are observed below Néel temperature (~38 K)

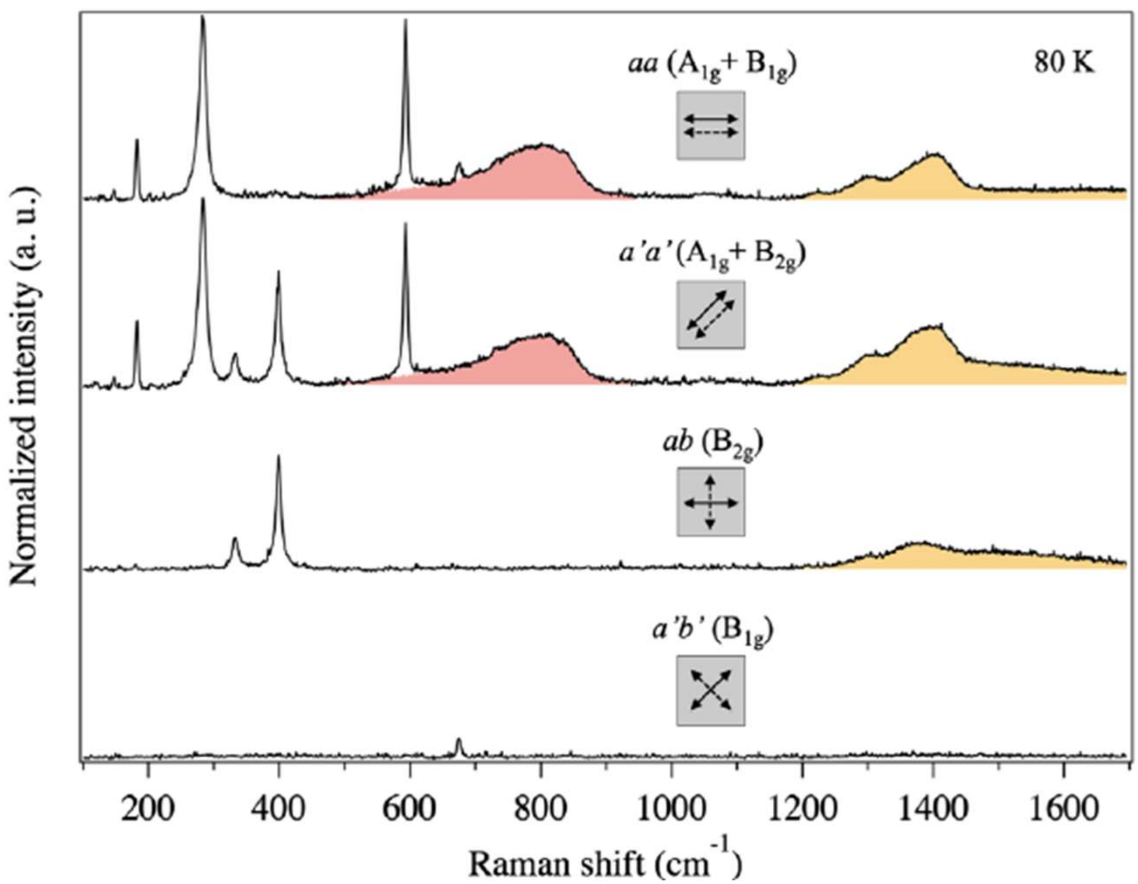
2-magnon resonance





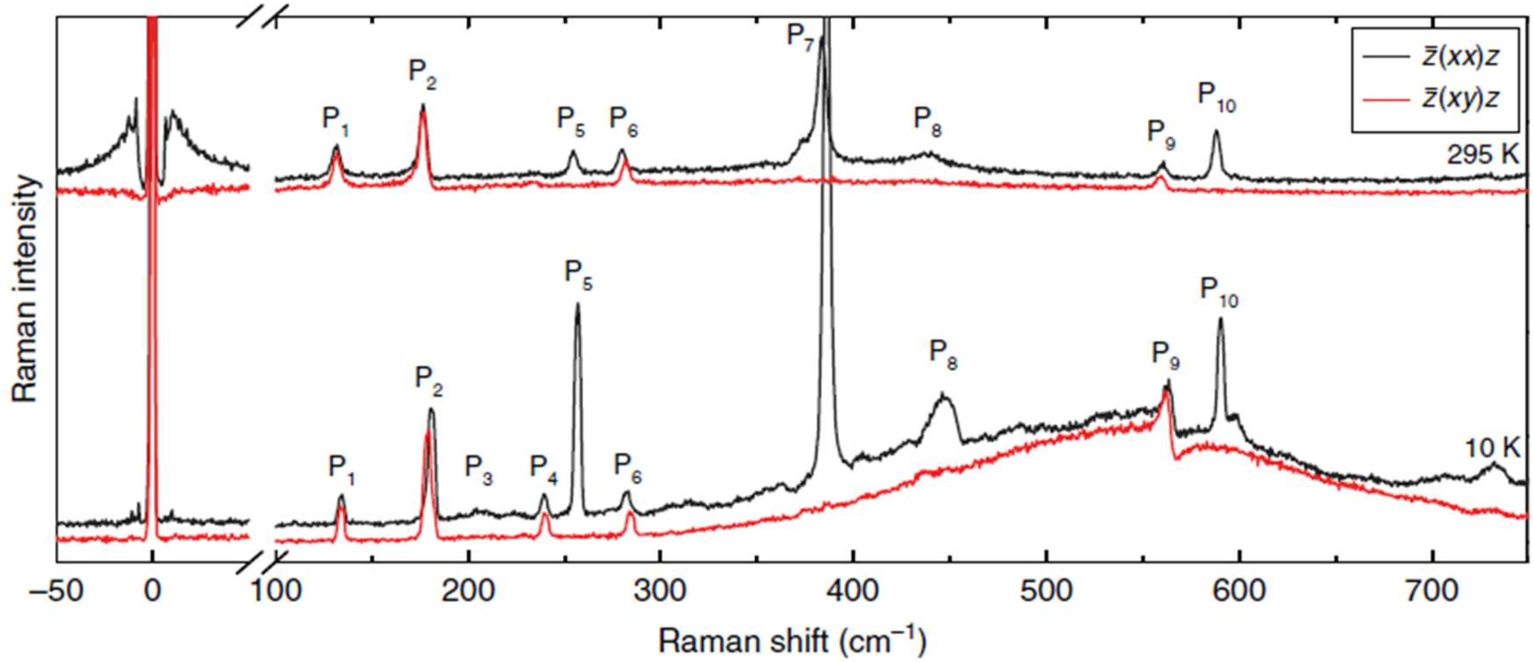
Large magnon DOS at $M_{1,2}$ contributes to 2-magnon Raman signal with from the zone-boundary

2-magnon resonance in other materials



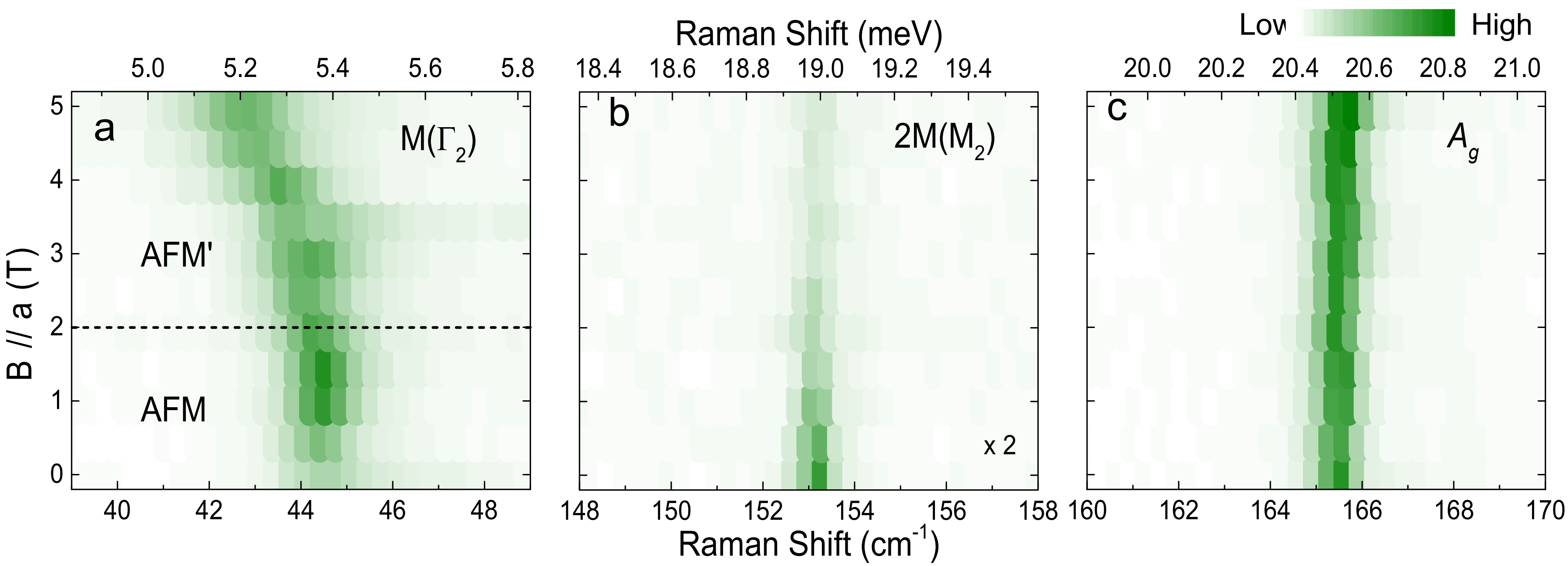
$Sr_3Ir_2O_7$, PRL, 125, 087202, 2020

2-magnon resonance in other materials



$NiPS_3$, Nat. Comm, 10, 345, 2019

Magnetic field dependence

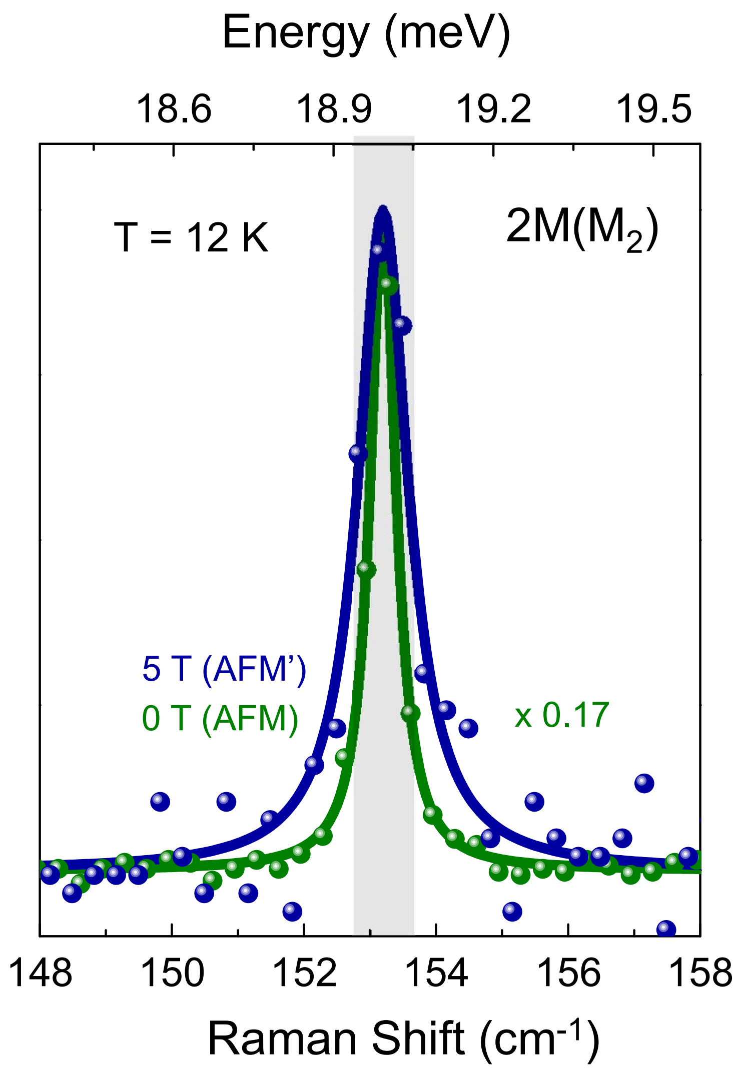


Zone-centered magnon, $M(\Gamma_2)$: peak center is nearly constant at AFM, red shift at AFM'

Zone-boundary magnons, $2M(M_2)$: peak centers are constant but intensity drops

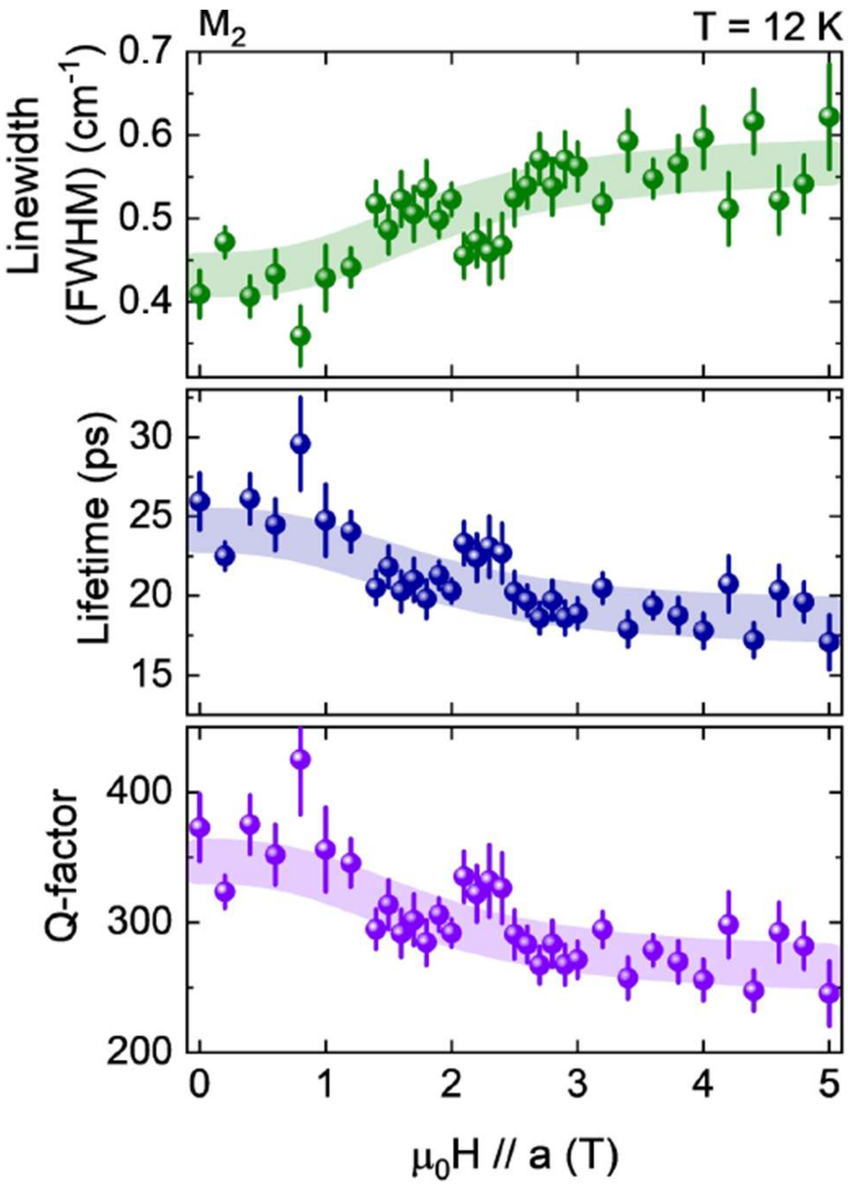
Phonon: both frequency and intensity stay constant

Long-lived Dirac magnon



- Measured linewidth is limited by instrumental resolution
- Magnon linewidth increases in the AFM' phase

Long-lived Dirac magnon: magnetic field dependence

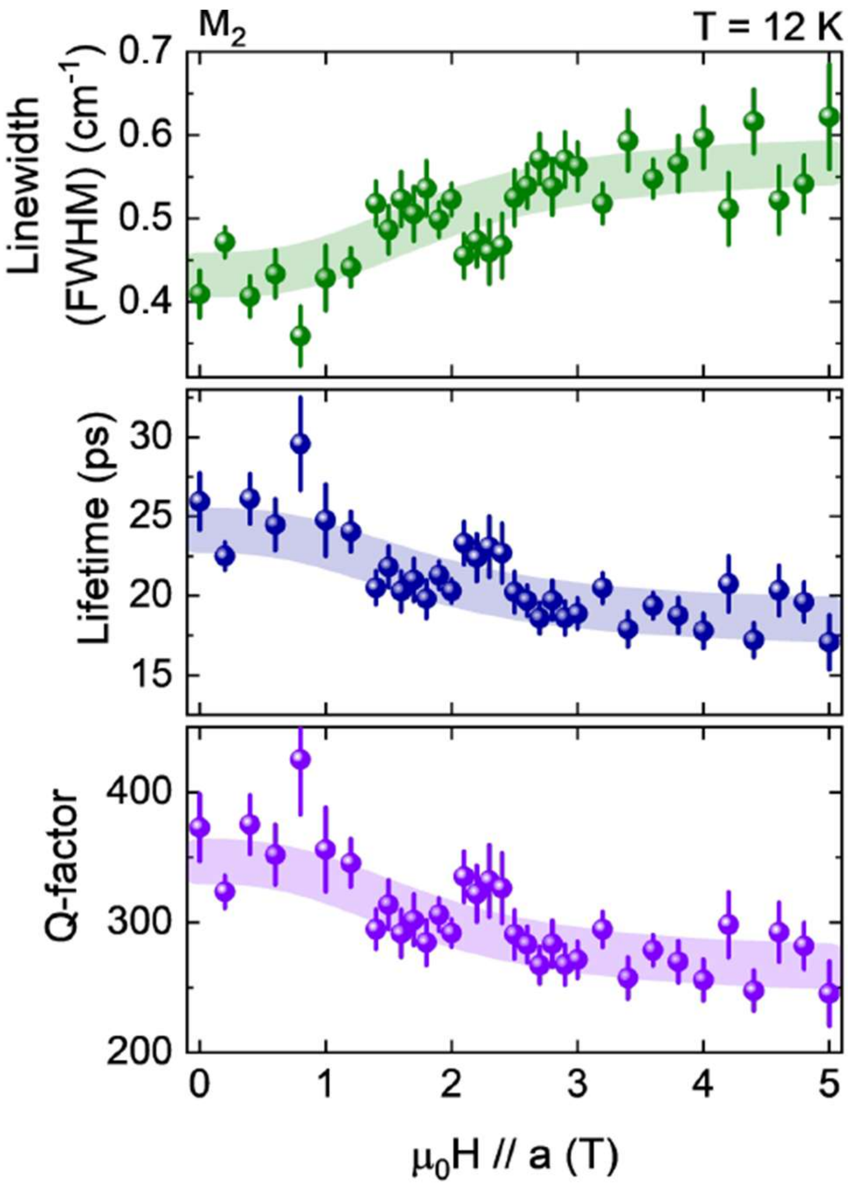


- 2M excitation comparison with other AFM materials

- Linewidth
  $CoTiO_3$ (~ 0.46 cm^{-1}), KMnF3 (~ 10 cm^{-1}),
  $(La_{1-x}Sr_x)_2CuO_4$ (~ 1000 cm^{-1}),
  NiPS3 (~ 200 cm^{-1})

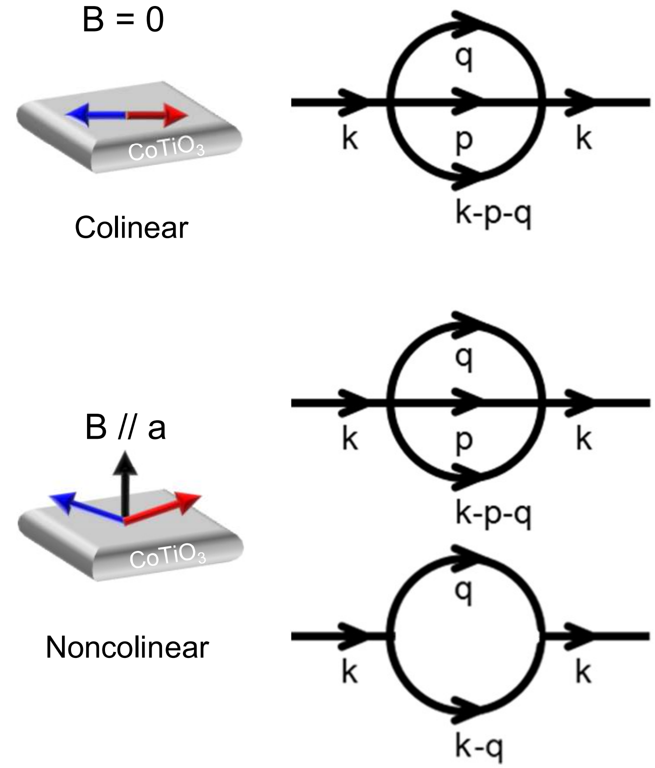
- Q-factor ($\omega/\Delta\omega$)
  $CoTiO_3$ (> 300), NiO (~ 23),
  α−Fe2O3 (~ 30)

Long-lived Dirac magnon: magnetic field dependence



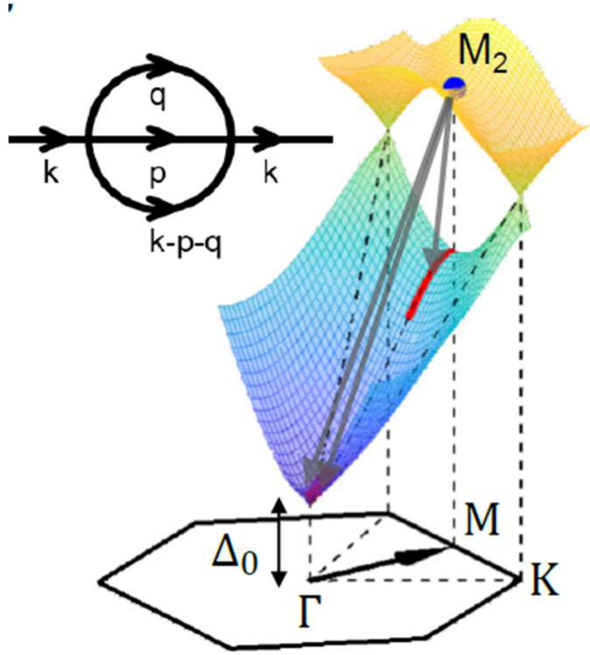
Additional 3 magnon scattering occurs in AFM’

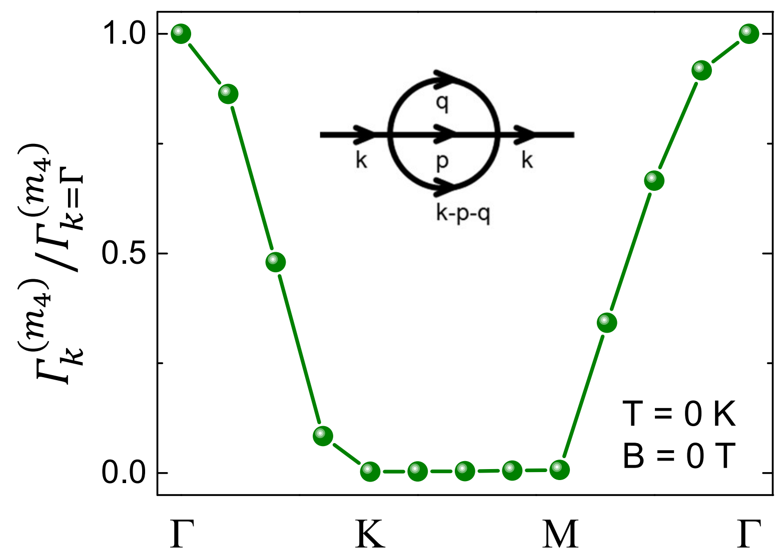
Magnon-magnon interaction
(Spontaneous decay)



Zhitomirsky and Chernyshev
RMP, 85, 219, 2013

Magnon damping mechanism: magnon-magnon interaction





$$H = \sum_{i\delta} J_1(S_i^x S_{i+\delta}^x + S_i^y S_{i+\delta}^y + \alpha S_i^z S_{i+\delta}^z) + \sum_{i\gamma} J_2(S_i \cdot S_{i+\gamma})$$

$$H = H_{(0)} + H_{(2)} + H_{(3)} + H_{(4)} + \cdots$$

- # of decay channels: Zone boundary << Zone centered magnons
- The gap at the Gamma point limits the phase space
- Lifetimes for zone-boundary magnons 2-3 orders of magnitude longer than those at the zone center

Beyond Linear Spin Wave Model

$$H = H^{(2)} + H^{(3)} + H^{(4)} + \cdots$$

PHYSICAL REVIEW X **11,** 021061 (2021)

Interaction-Stabilized Topological Magnon Insulator in Ferromagnets

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PHYSICAL REVIEW X **8,** 011010 (2018)

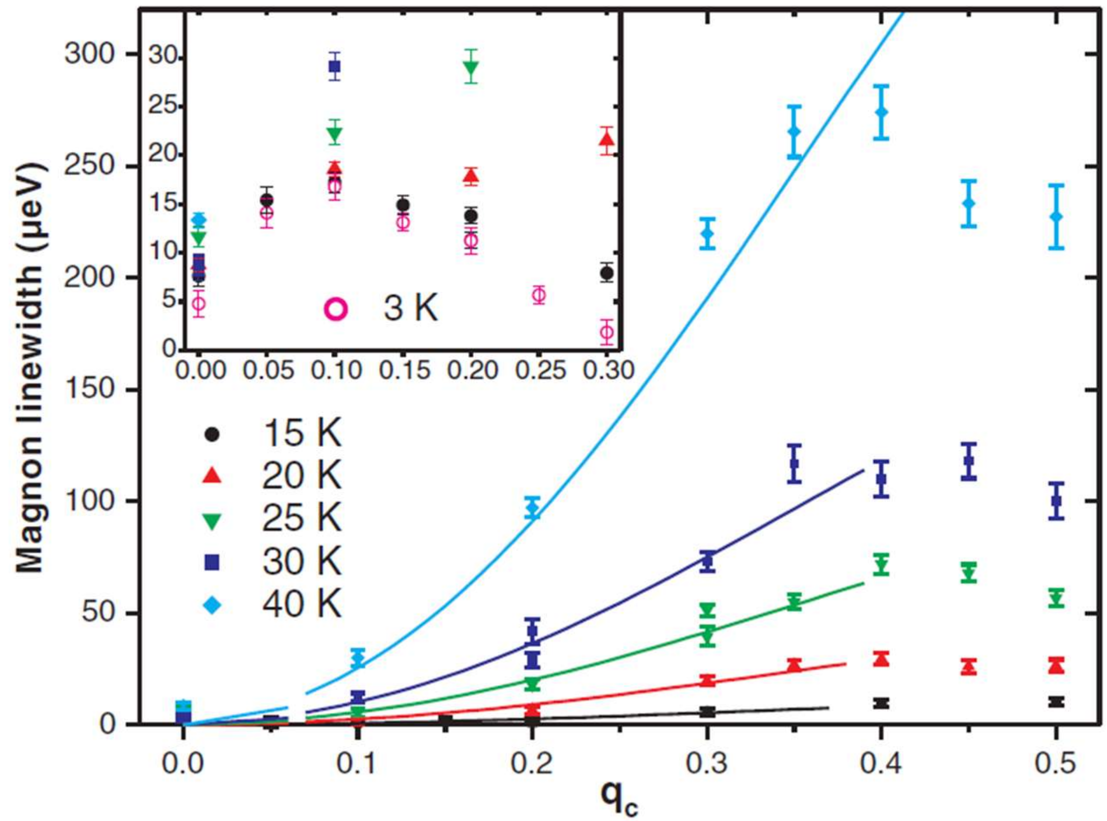
Dirac Magnons in Honeycomb Ferromagnets

Sergey S. Pershoguba,[1] Saikat Banerjee,[1,2,3] J. C. Lashley,[2] Jihwey Park,[4] Hans Ågren,[3]
Gabriel Aeppli,[4,5,6] and Alexander V. Balatsky[1,2,7]

Spin-Wave Lifetimes Throughout the Brillouin Zone

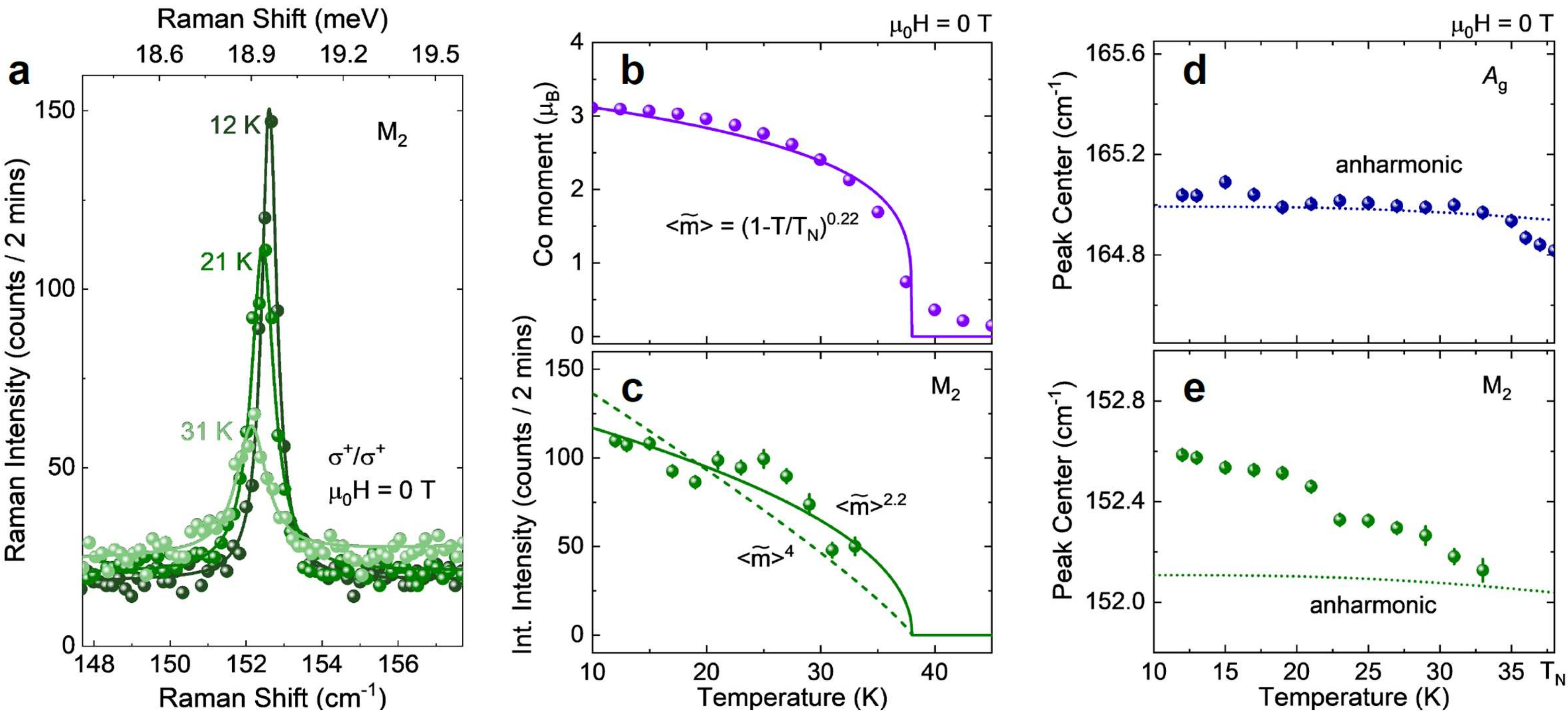
Science, 312, 1928, 2006

S. P. Bayrakci,[1*] T. Keller,[1,2] K. Habicht,[3] B. Keimer[1]

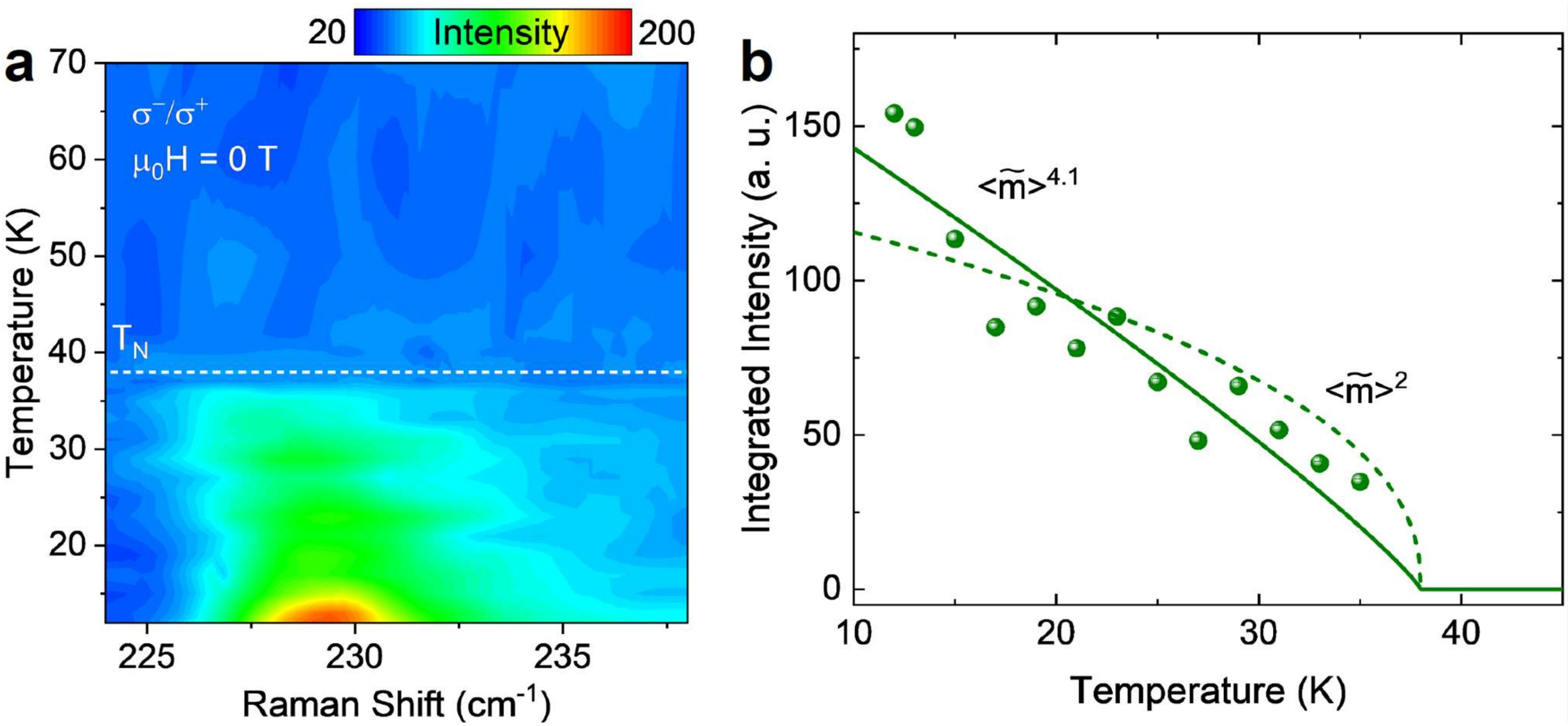


- Neutron echo experiment: MnF_2 linewidth ~ 0.1 cm-1
- Shorter lifetimes near zone boundary; lifetime quickly reduces at higher temperature

Temperature dependent intensity and frequency

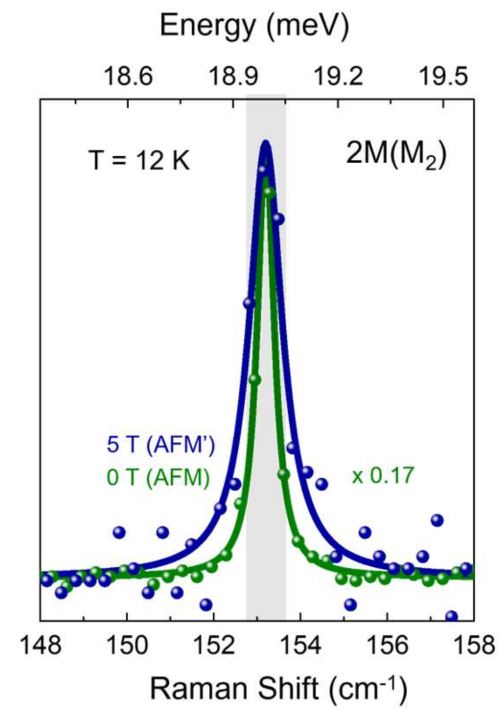


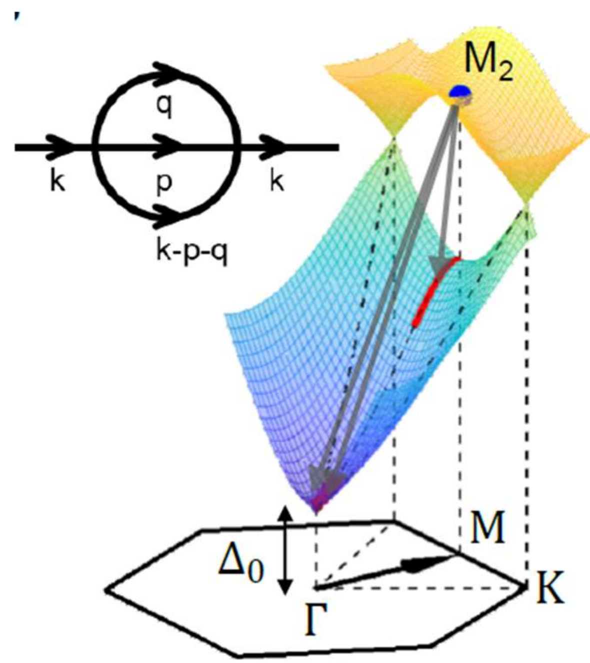
Zone-folded phonon?



Summary of Key Results

- Raman spectra reveal rich magnons and phonon modes (some chiral phonons) in CTO
- A long-lived mode attributed to zone-boundary magnons
  - Temperature dependent frequency and intensity
  - Comparison to neutron scattering experiments
  - Magnetic-field dependent linewidth
- Ruled out folded phonon interpretation
- Magnon-magnon interaction taken into account; Beyond single-particle band picture





Wishlist

- Long-lived magnons
- Dirac dispersion tunable in BZ

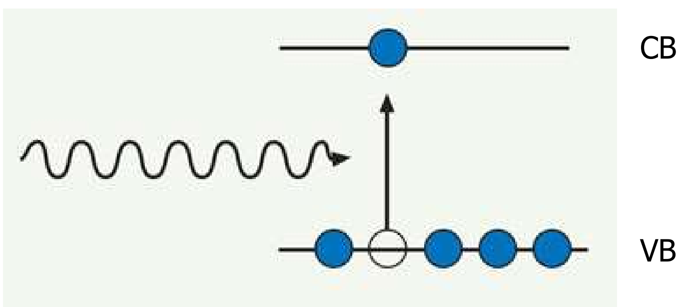
Lessons learned

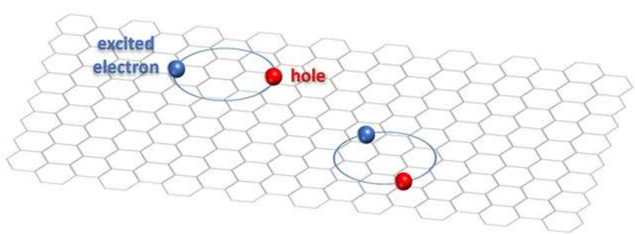
- Minimal magnon-phonon coupling
- AFM order and honeycomb spin lattice symmetry
- Magnon dispersion including topology and magnon gap at the zone center
- Magnetic anisotropy $$H = \sum J(S_i^x S_j^x + S_i^y S_j^y + \alpha S_i^z S_j^z)$$
- Small joint two-magnon density of states

	T_N (K)	T_C (K)	S	α	Magnetic configuration
$CoTiO_3$	38	–	1/2	0	A-type AFM
$CrCl_3$	14	17.2	3/2	1	A-type AFM
$CrBr_3$	–	32	3/2	1	FM
CrI_3	–	61	3/2	1	FM (bulk), A-type AFM (few-layer)
$CrGeTe_3$	–	63	3/2	1	FM
$CrSiTe_3$	–	33	3/2	1	FM
$FePS_3$	120	–	2	1	Zigzag AFM
$NiPS_3$	155	–	1	1	Zigzag AFM
$CoPS_3$	120	–	3/2	1	Zigzag AFM
$MnPS_3$	78	–	5/2	1	G-type AFM

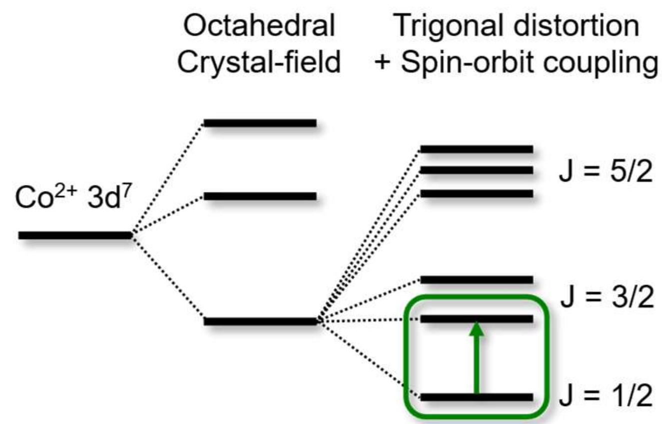
Topological SOE

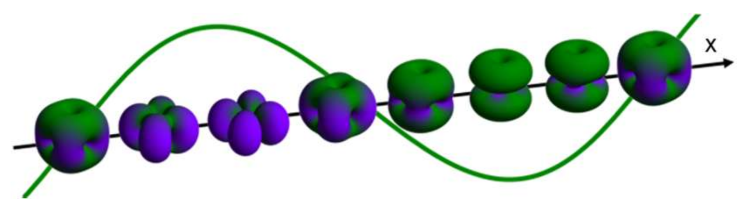
Excitons



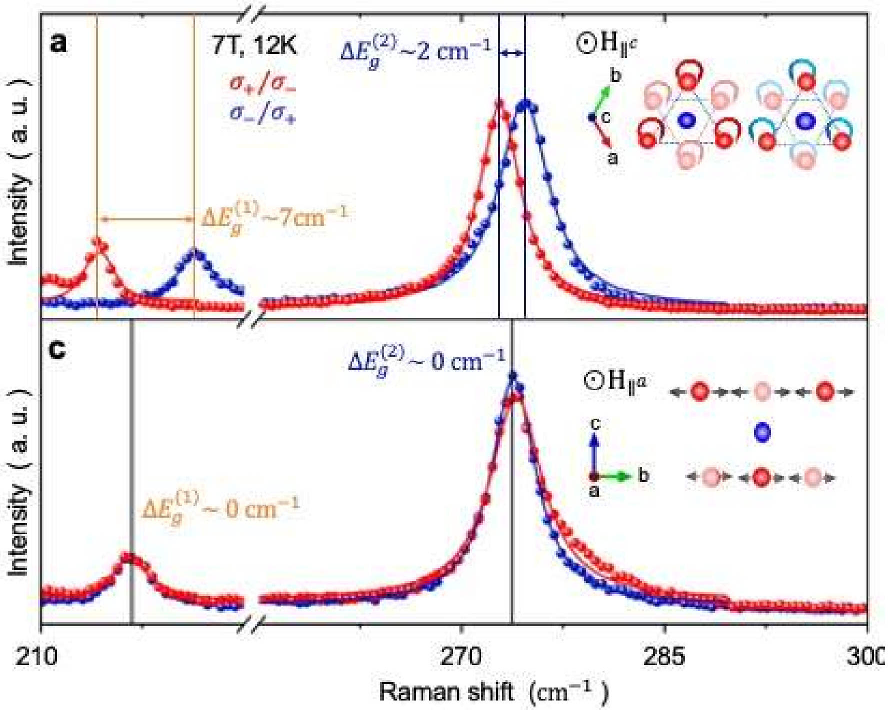


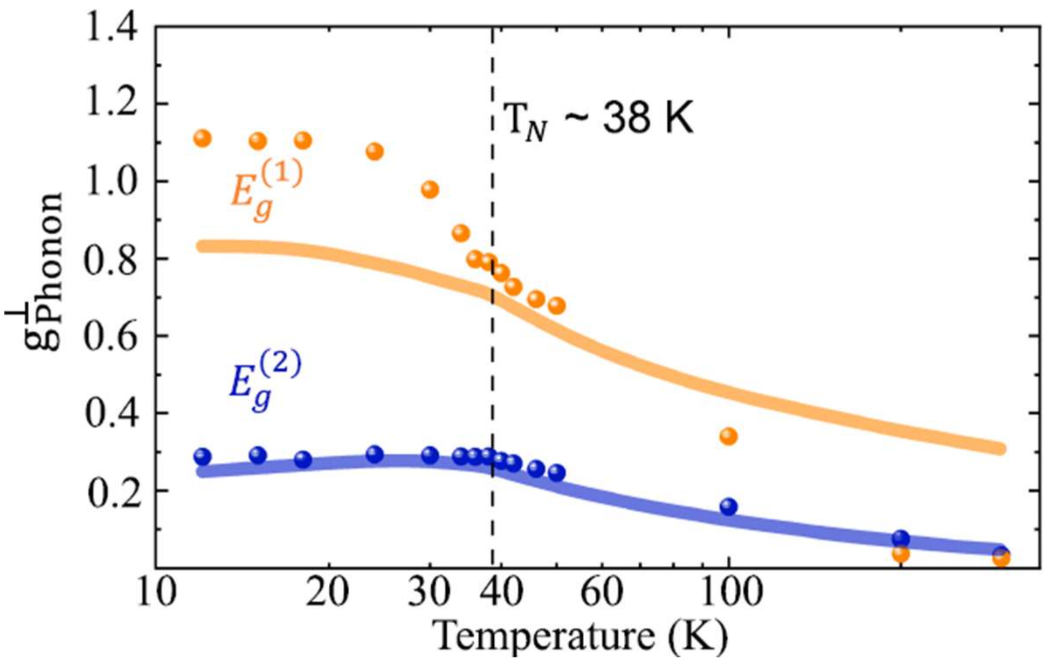
Spin-orbit excitons





Phonon chirality from coupling to SOE

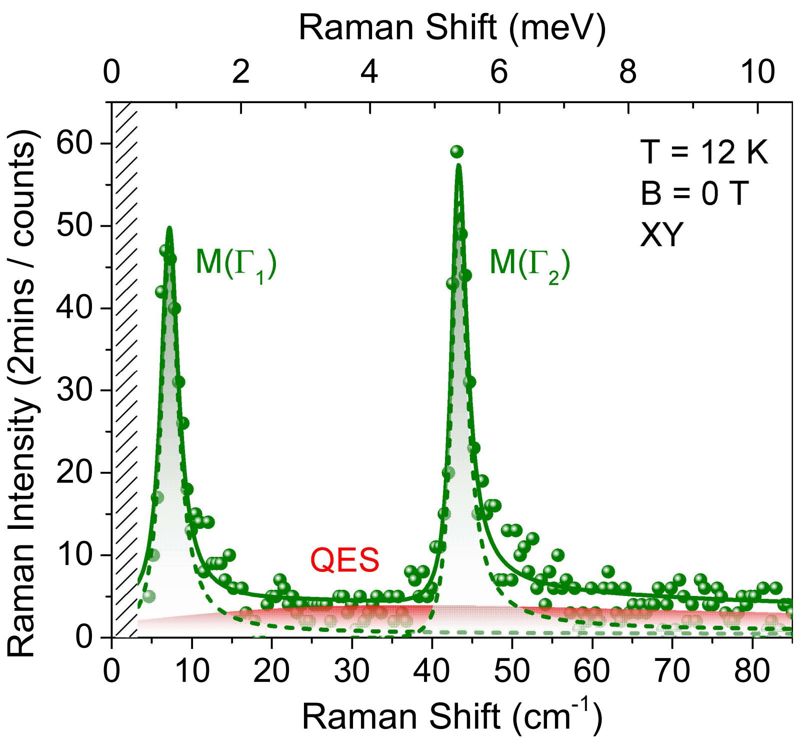


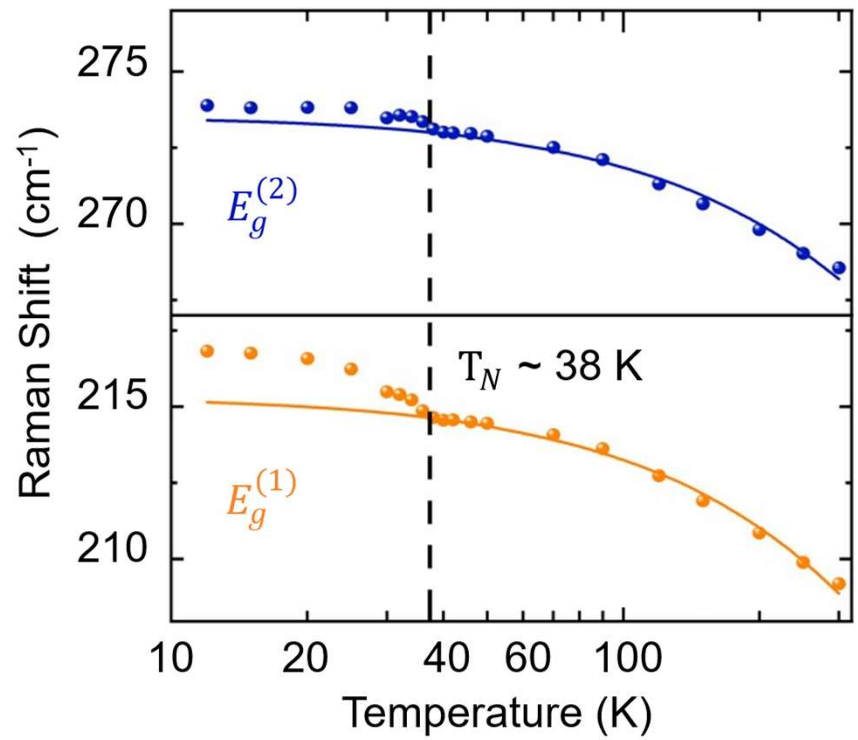


- Circular ionic motion leads to underestimate of phonon g factor
- Coupling to electrons:
  - phonon induced adiabatic evolution of electron states;
  - phonon induced mixing of electron states

PNAS 2024, 121, e2304360121
https://doi.org/10.1073/pnas.2304360121

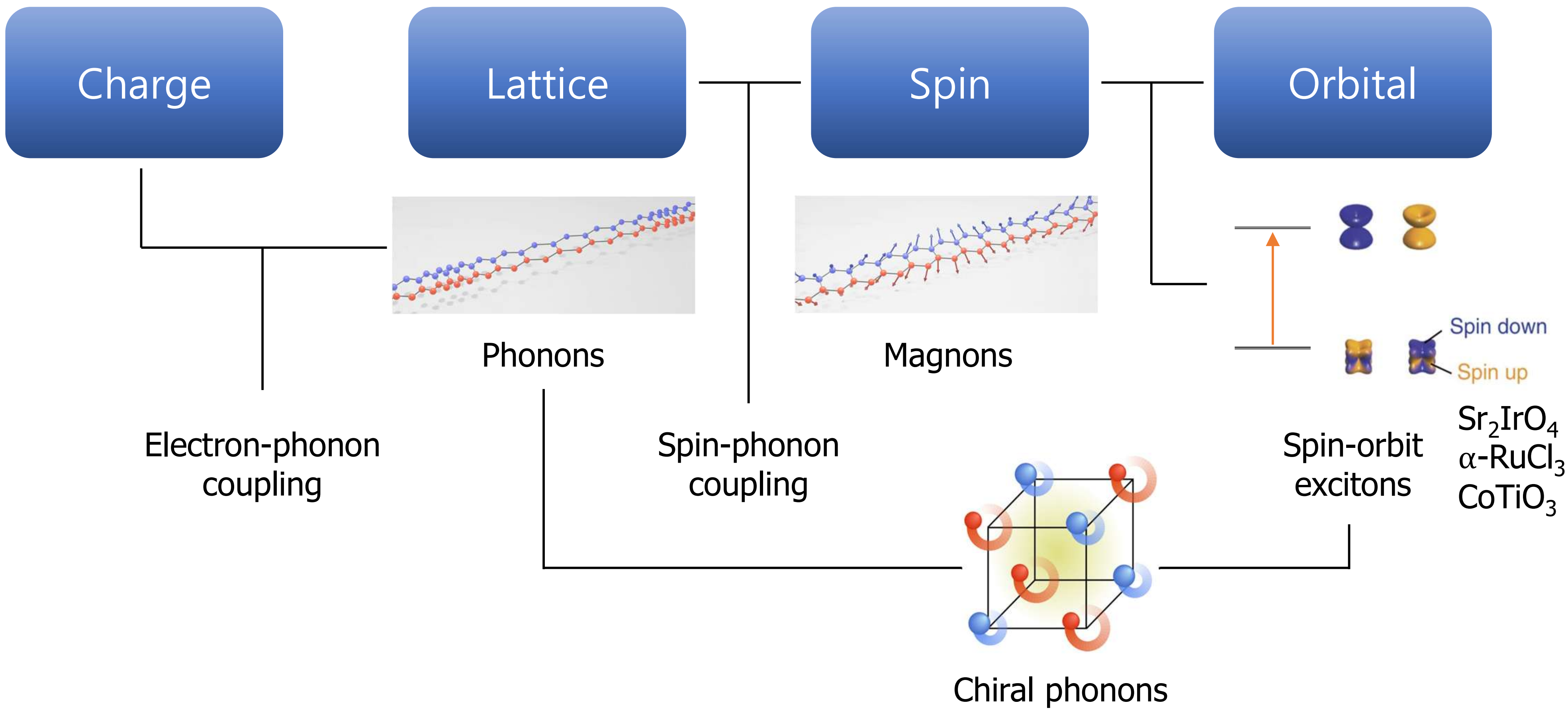
Magnon gap due to spin-lattice coupling





Zone-center magnon gap: lattice distortion induces symmetry breaking and enables higher order spin-spin coupling

Collective excitations and their coupling



Thank you for your attention!

Humboldt fellowship applicants welcomed

The University of Texas at Austin
Department of Physics
College of Natural Sciences