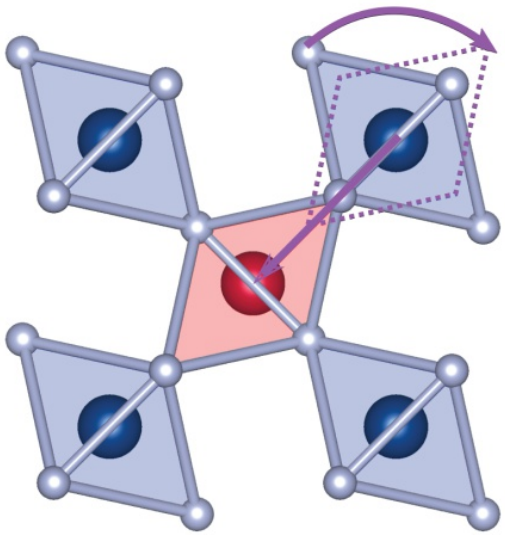
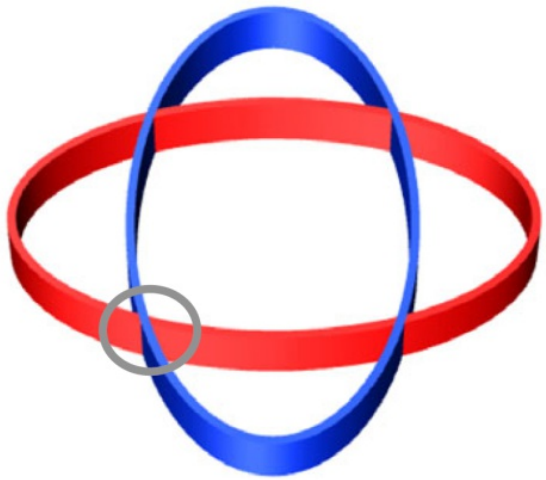
Altermagnetic, or not?

Alexander Tsirlin

Felix Bloch Institute for Solid State Physics
Leipzig University, Germany



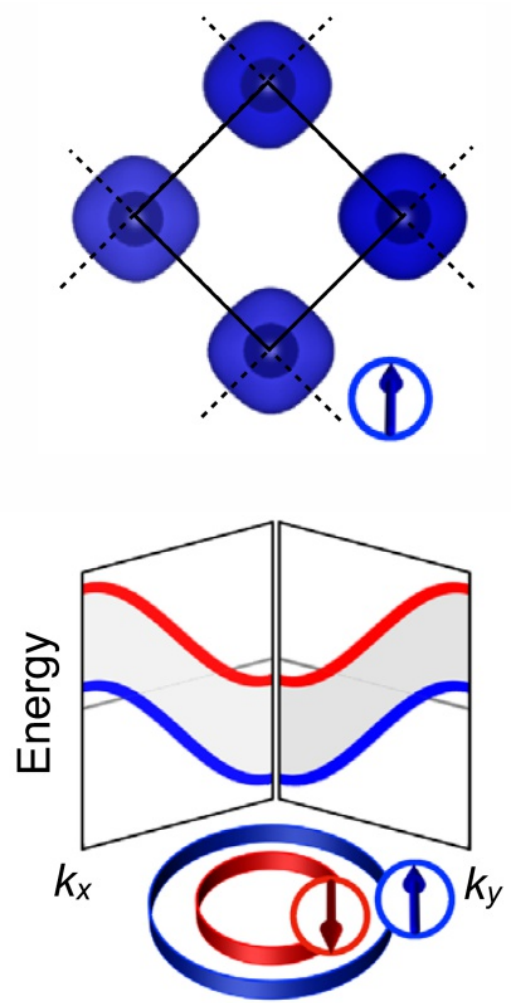


University of Warsaw

April 4, 2025

UNIVERSITÄT LEIPZIG

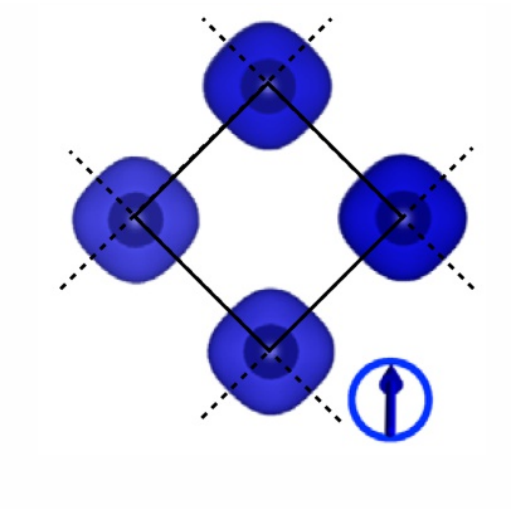
Images from: L. Šmejkal *et al.* PRX 12, 031042 (2022)

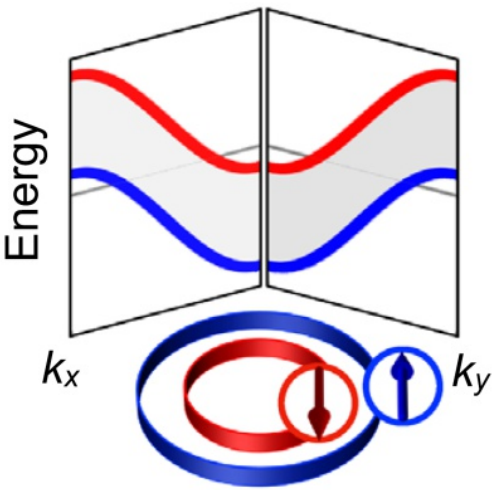


Ferromagnet

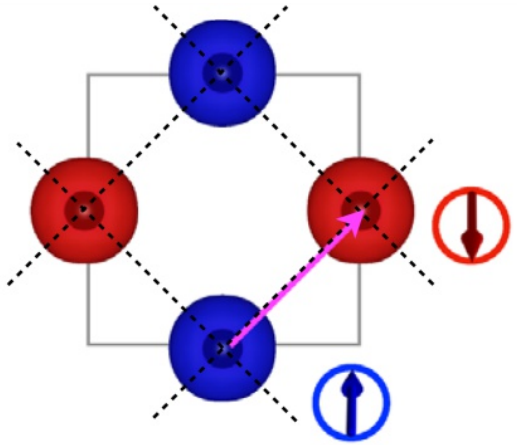
New class of magnets?

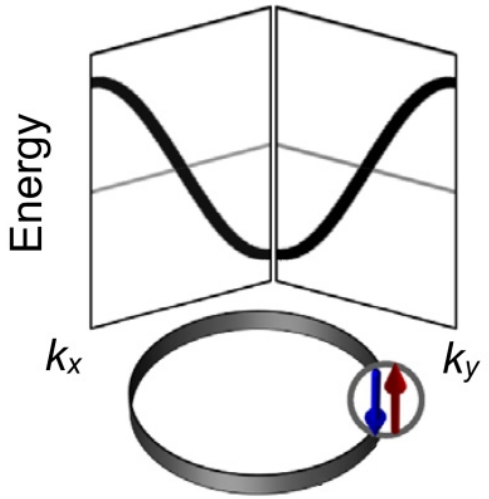
Images from: L. Šmejkal *et al.* PRX 12, 031042 (2022)





Ferromagnet

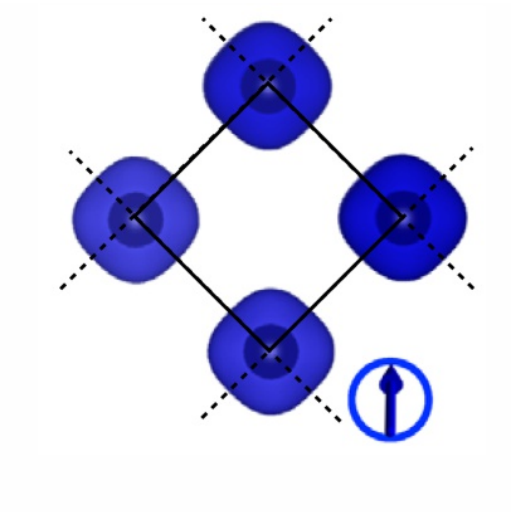


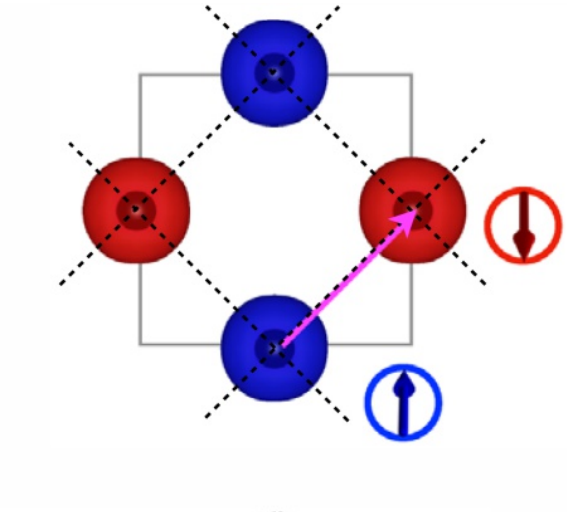


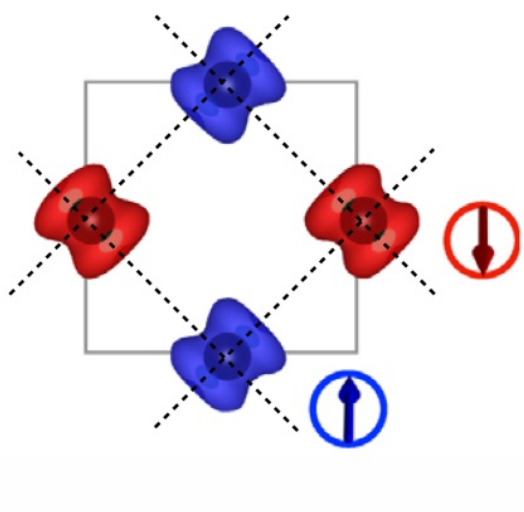
Antiferromagnet

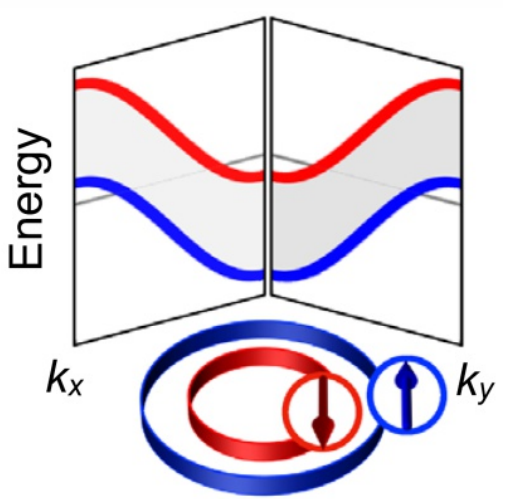
New class of magnets?

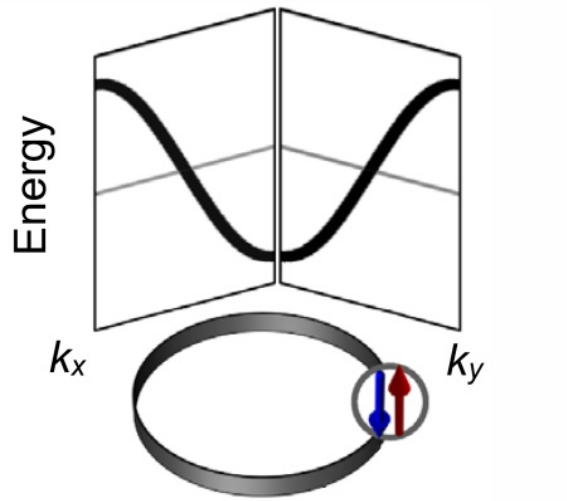
Images from: L. Šmejkal *et al.* PRX 12, 031042 (2022)

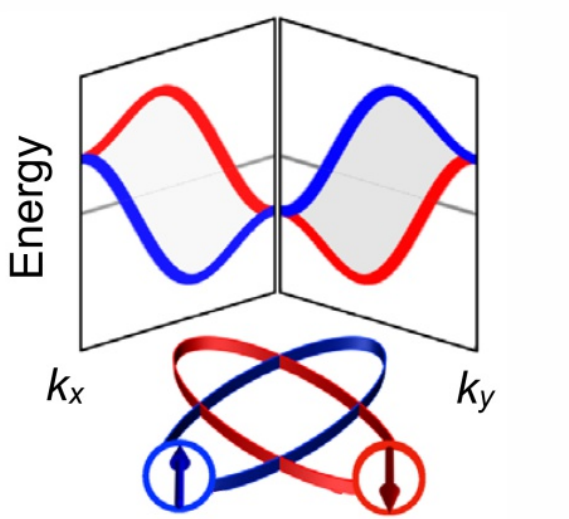












Ferromagnet

Antiferromagnet

Altermagnet

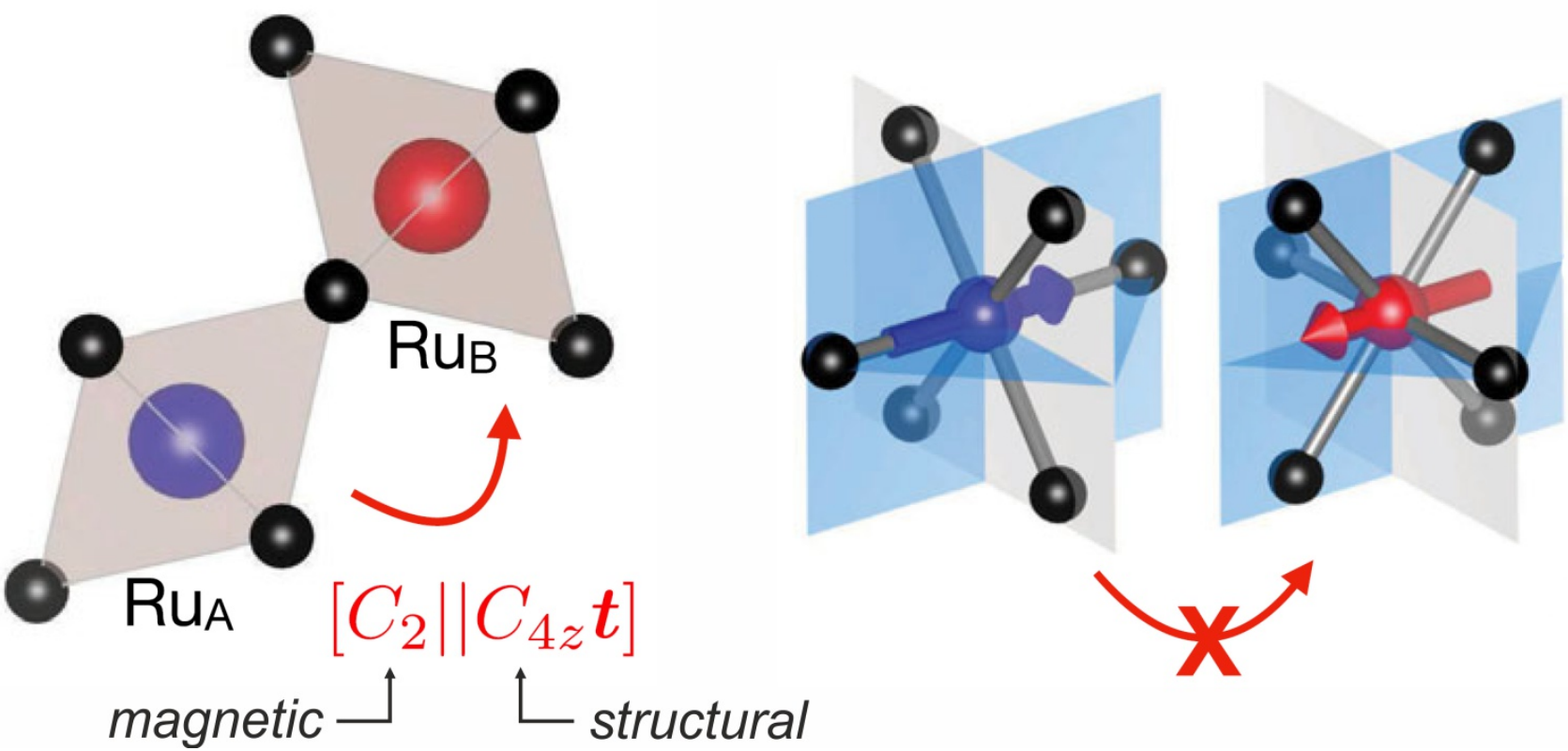
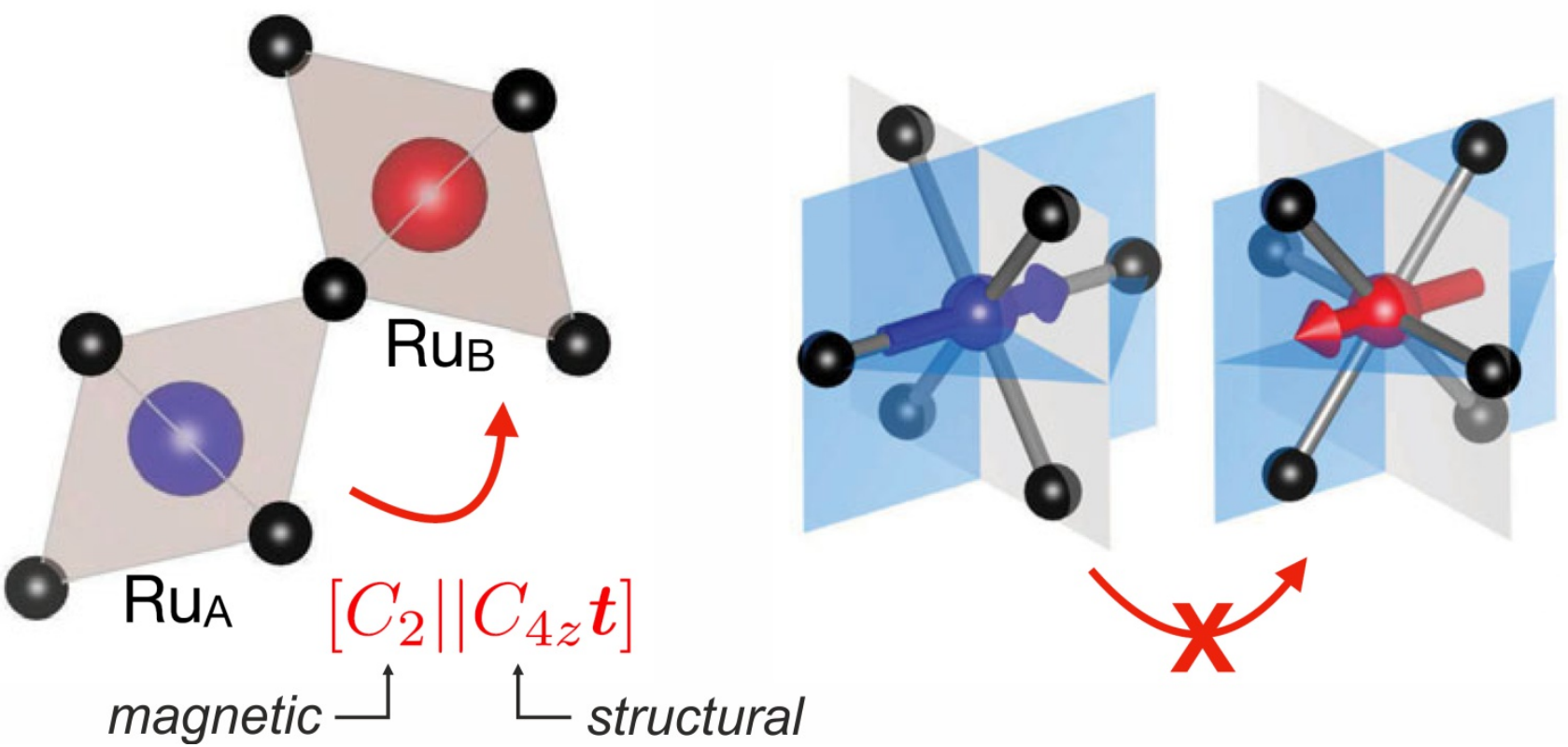


Image from: L. Šmejkal *et al.* PRX 12, 040501 (2022)



210 out of 230 space groups allow altermagnetism

Full list (incl. Wyckoff positions): H. Schiff *et al.* arXiv:2412.18025

Image from: L. Šmejkal *et al.* PRX 12, 040501 (2022)

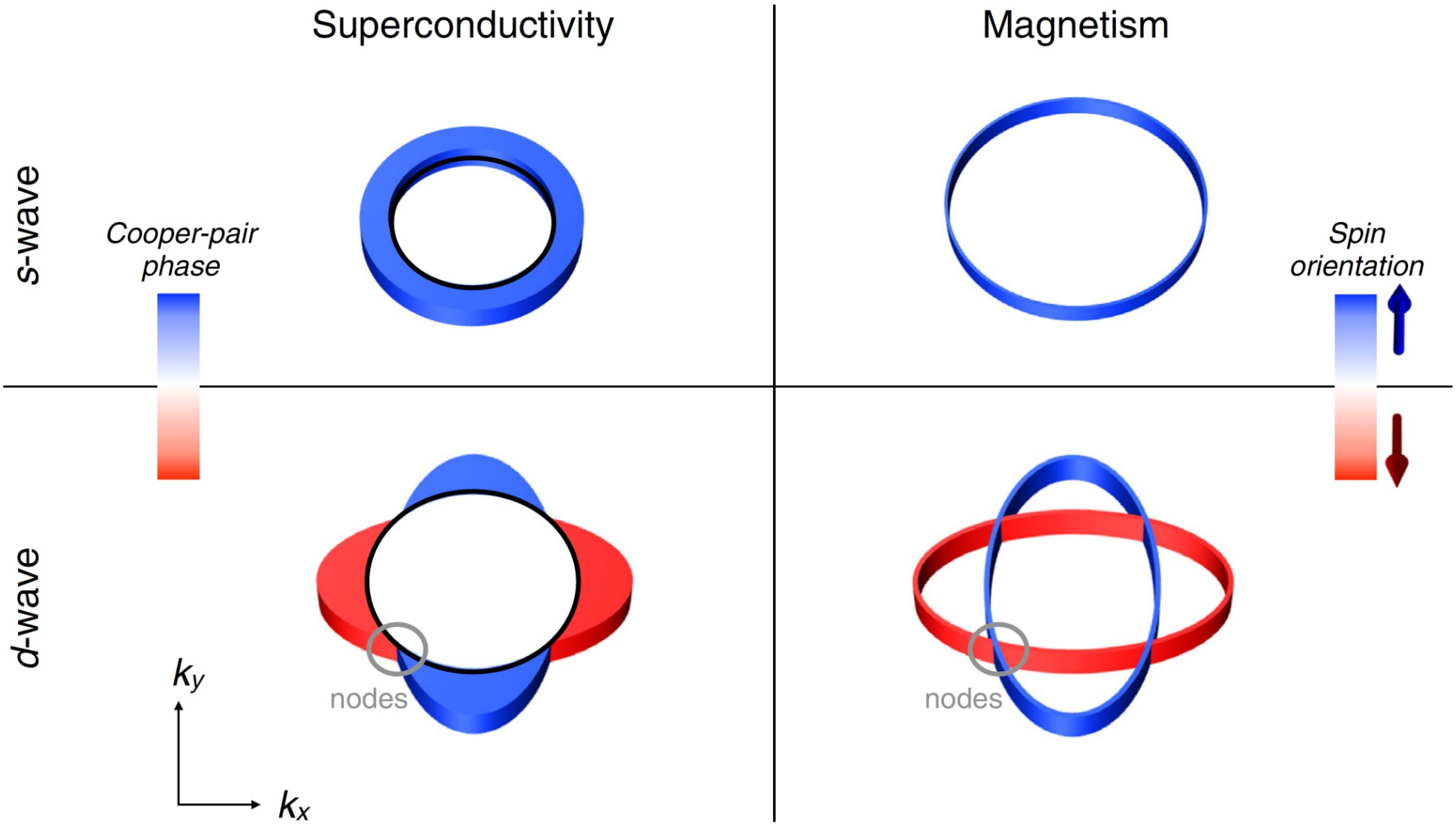


Image from: L. Šmejkal *et al.* PRX 12, 040501 (2022)

Discovery?

Libor Šmejkal
MPI PKS, Dresden

Jairo Sinova
Uni Mainz

Tomáš Jungwirth
Charles University, Prague

Discovery?

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PHYSICAL REVIEW X **12,** 040002 (2022)

Editorial: Altermagnetism—A New Punch Line of Fundamental Magnetism

Evgeny Turov

(1924–2007)

If an antiferromagnet shows phenomena typical of materials with a net magnetization, its symmetry must allow ML-term in thermodynamic potential, and

$$M_i = D_{ik} L_k$$

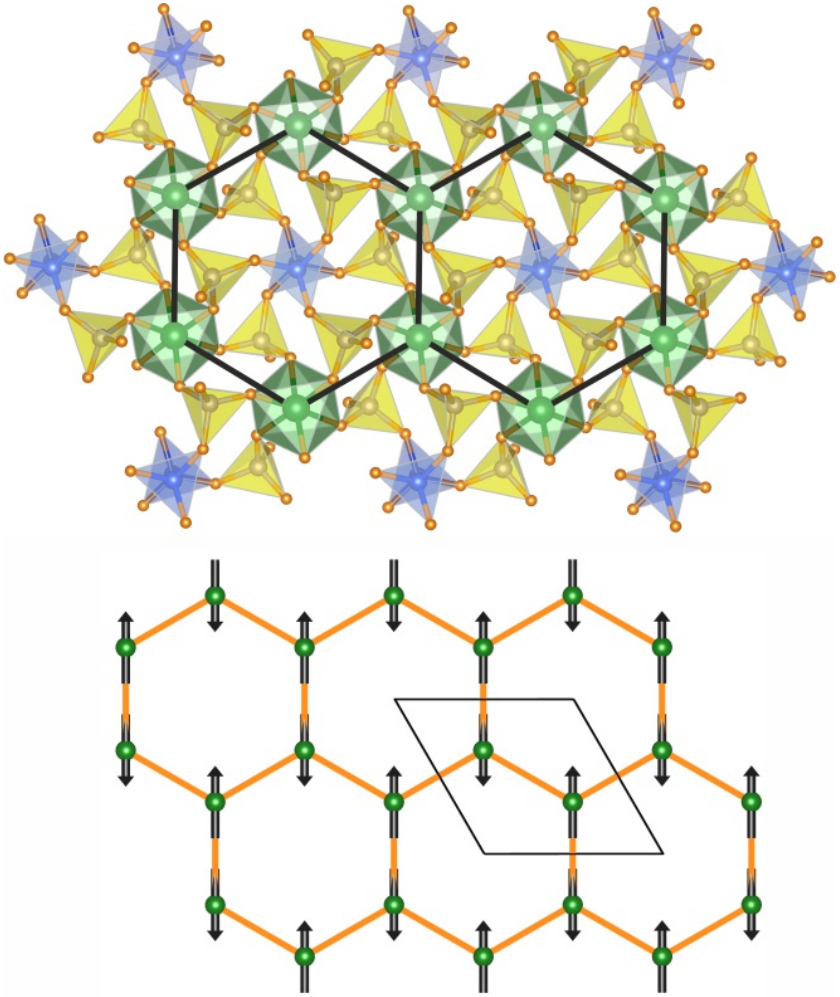
(**M** – magnetization, **L** – Néel vector)

More in the talks by Alexei Kimel (Radboud University, Nijmegen):

https://www.youtube.com/watch?v=_KkG2qkiQdM

Agnostic view of altermagnetism

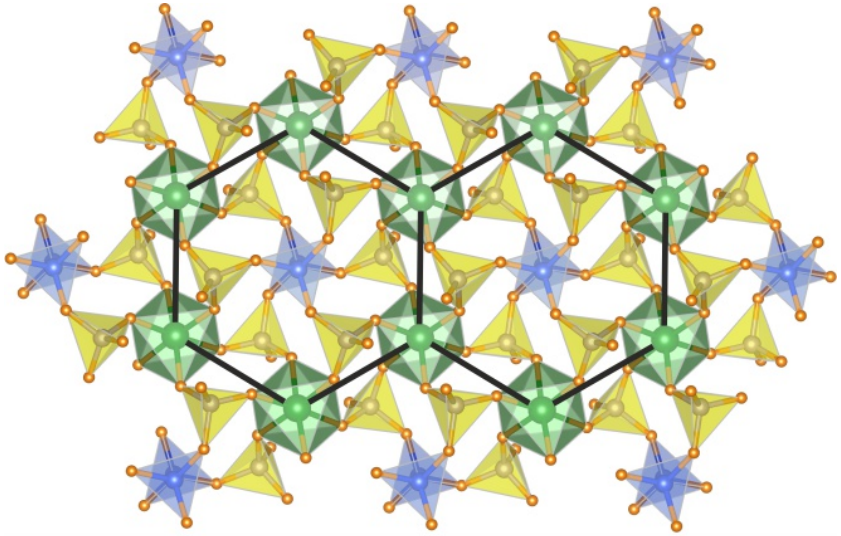
Image credit:
Jennifer Fowlie

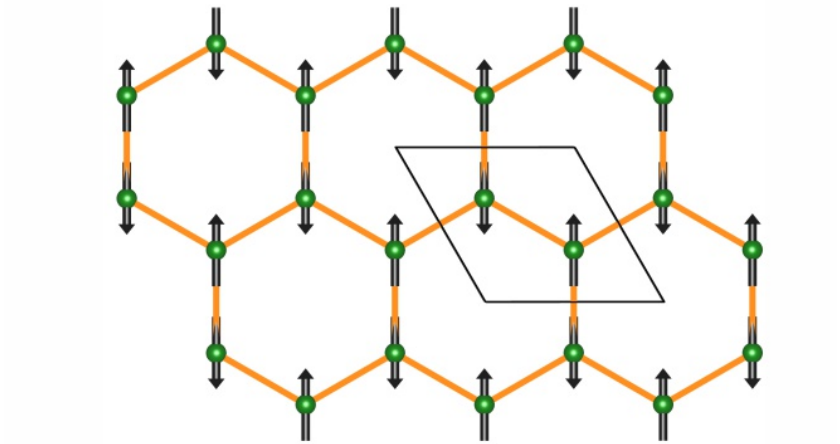


$MoSiP_3O_{11}$ (nn honeycomb)

D.I. Badrtdinov, AT *et al.* PRB 104, 094428 (2021)

Altermagnets everywhere





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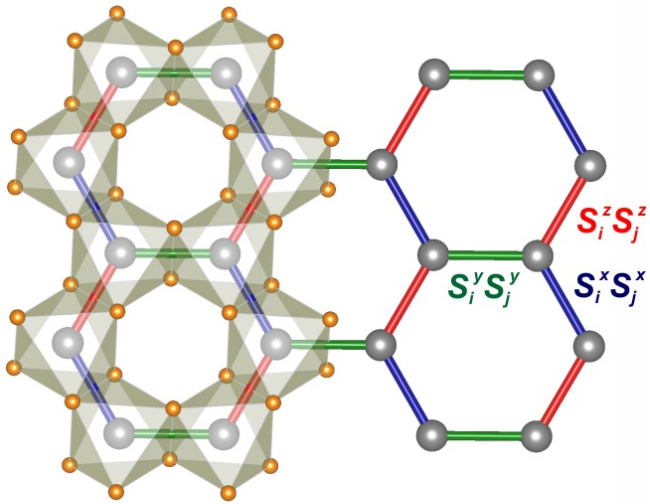
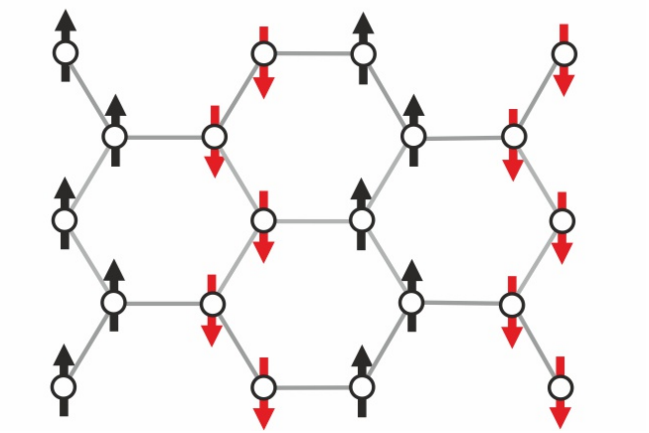


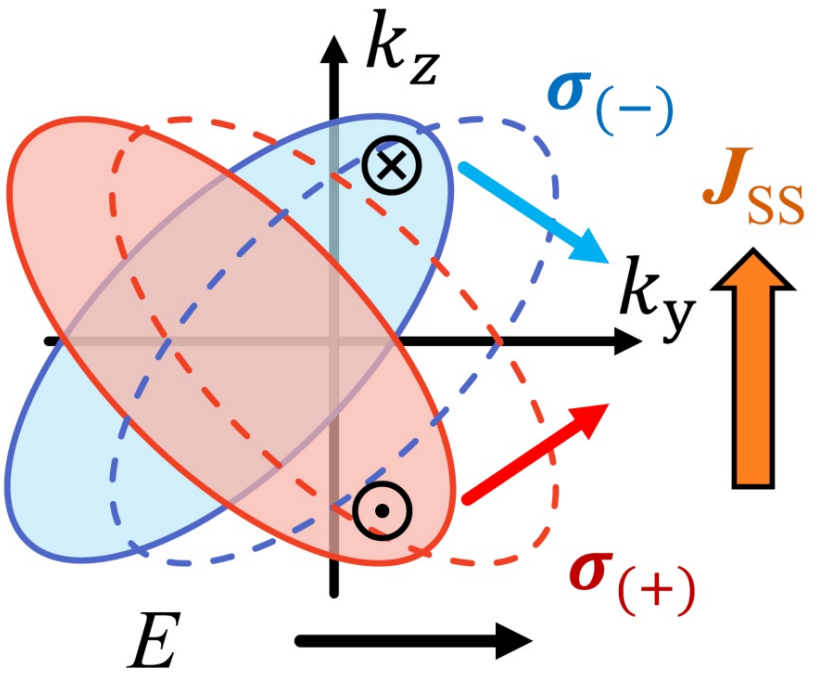


α-$RuCl_3$ (Kitaev)

S. Widmann, AT *et al.* PRB 99, 094415 (2019)

S. Bachus, AT *et al.* PRL 125, 097203 (2020)

Why thinking about altermagnetism?



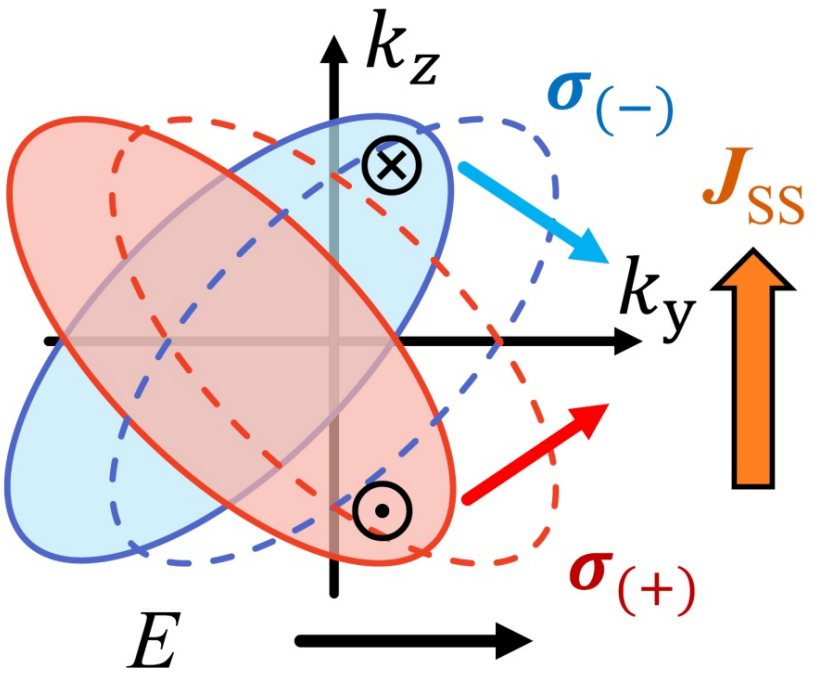
Band spin splitting has implications for transport:

– spin Hall effect

– anomalous Hall effect

Image from: C.T. Liao *et al.* PRL 133, 056701 (2024)

Why thinking about altermagnetism?



Band spin splitting has implications for transport:

– spin Hall effect

– anomalous Hall effect

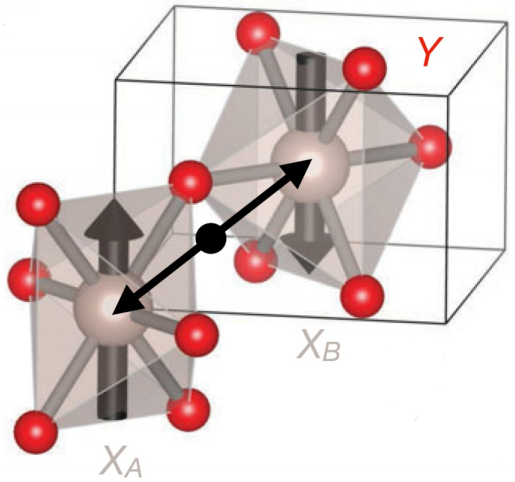
Practical altermagnets should be metallic

but most of the relevant materials are robust Mott insulators...

Image from: C.T. Liao *et al.* PRL 133, 056701 (2024)

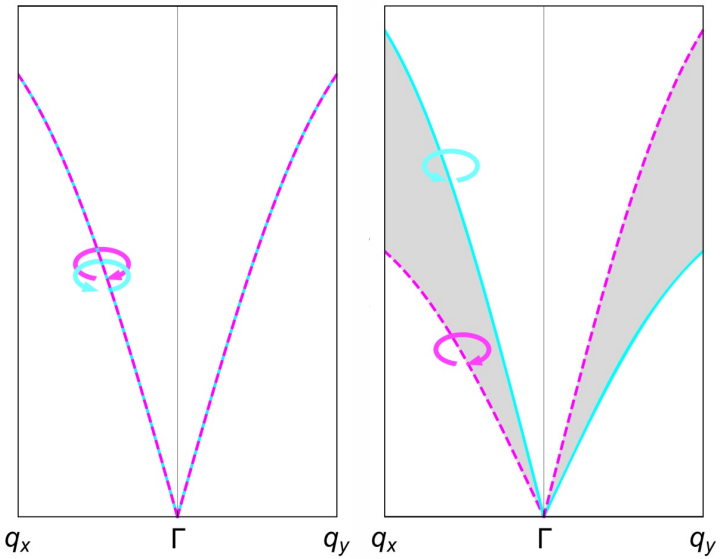
Metallic materials

importance of magnetic order,
and misleading insights from DFT



Insulating materials

splitting of magnon bands,
or not?



L. Šmejkal *et al.* PRX 12, 040501 (2022) and PRL 131, 256703 (2023)

Candidate materials

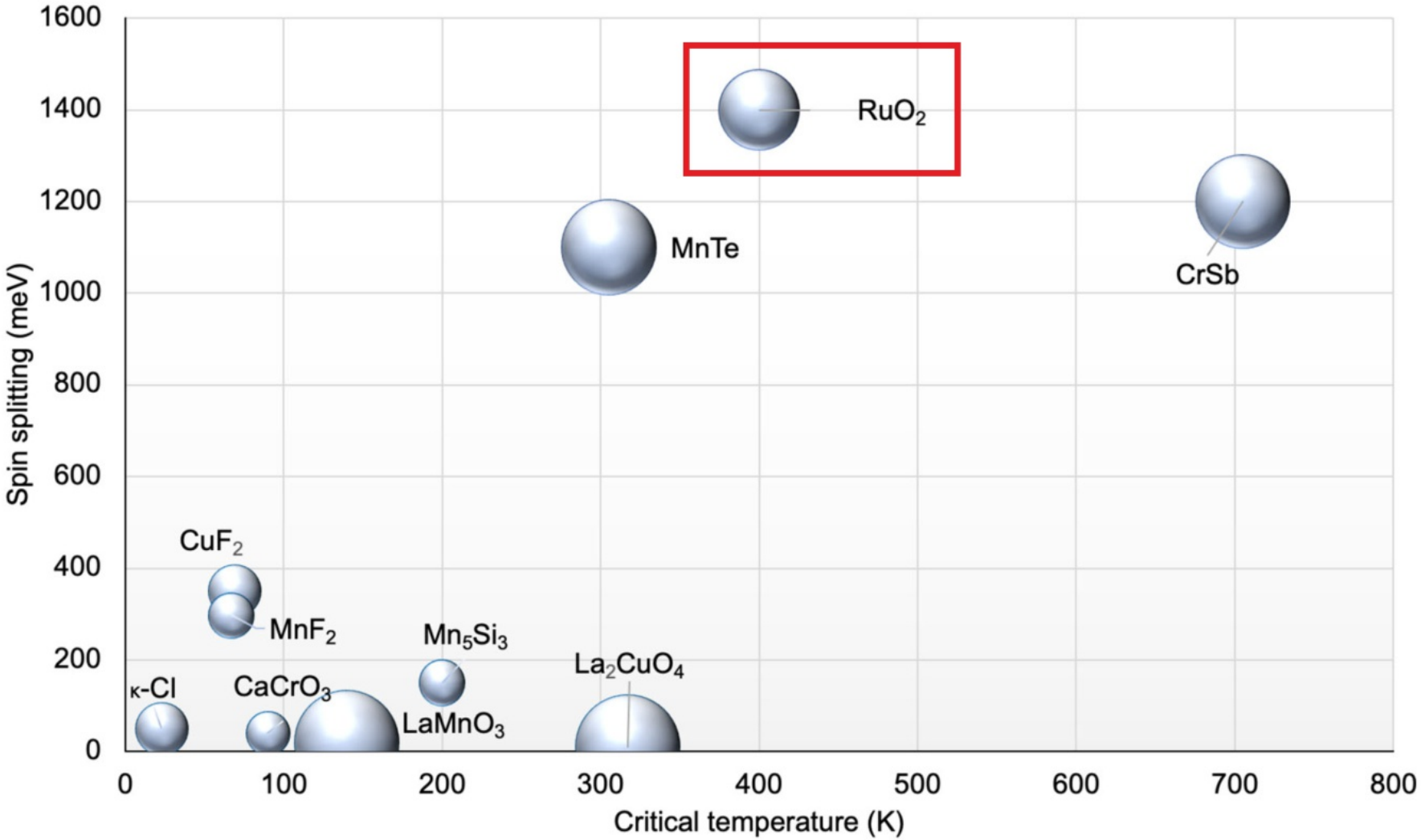


Image from: L. Šmejkal *et al.* PRX 12, 040501 (2022) [all numbers from DFT]

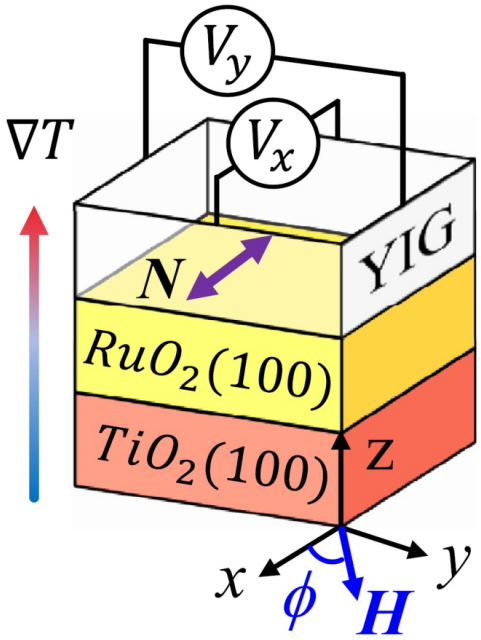
Checklist of altermagnetism:

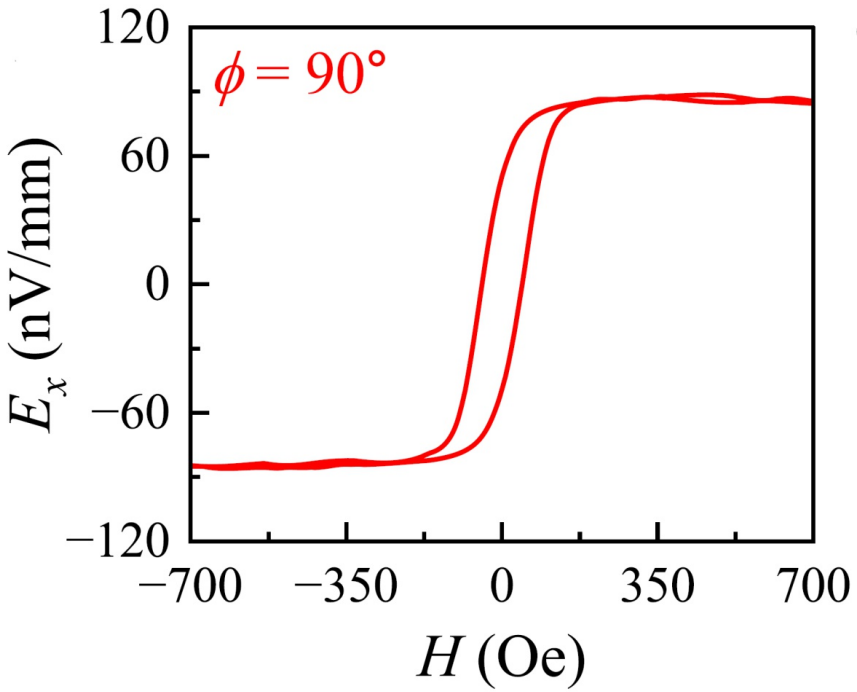
– spin splitting of the bands

– Hall responses (spin Hall, anomalous Hall)

– piezomagnetism

...





Charge-to-spin conversion

attributed to spin splitting of the bands

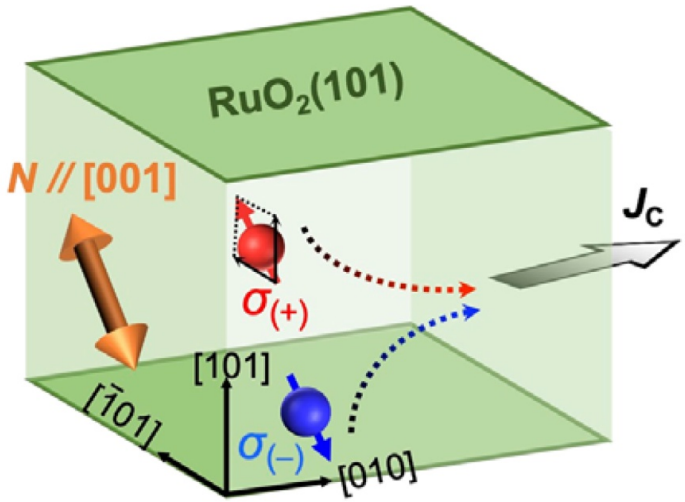
H. Bai *et al.* PRL 128, 197202 (2022)

S. Karube *et al.* PRL 129, 137201 (2022)

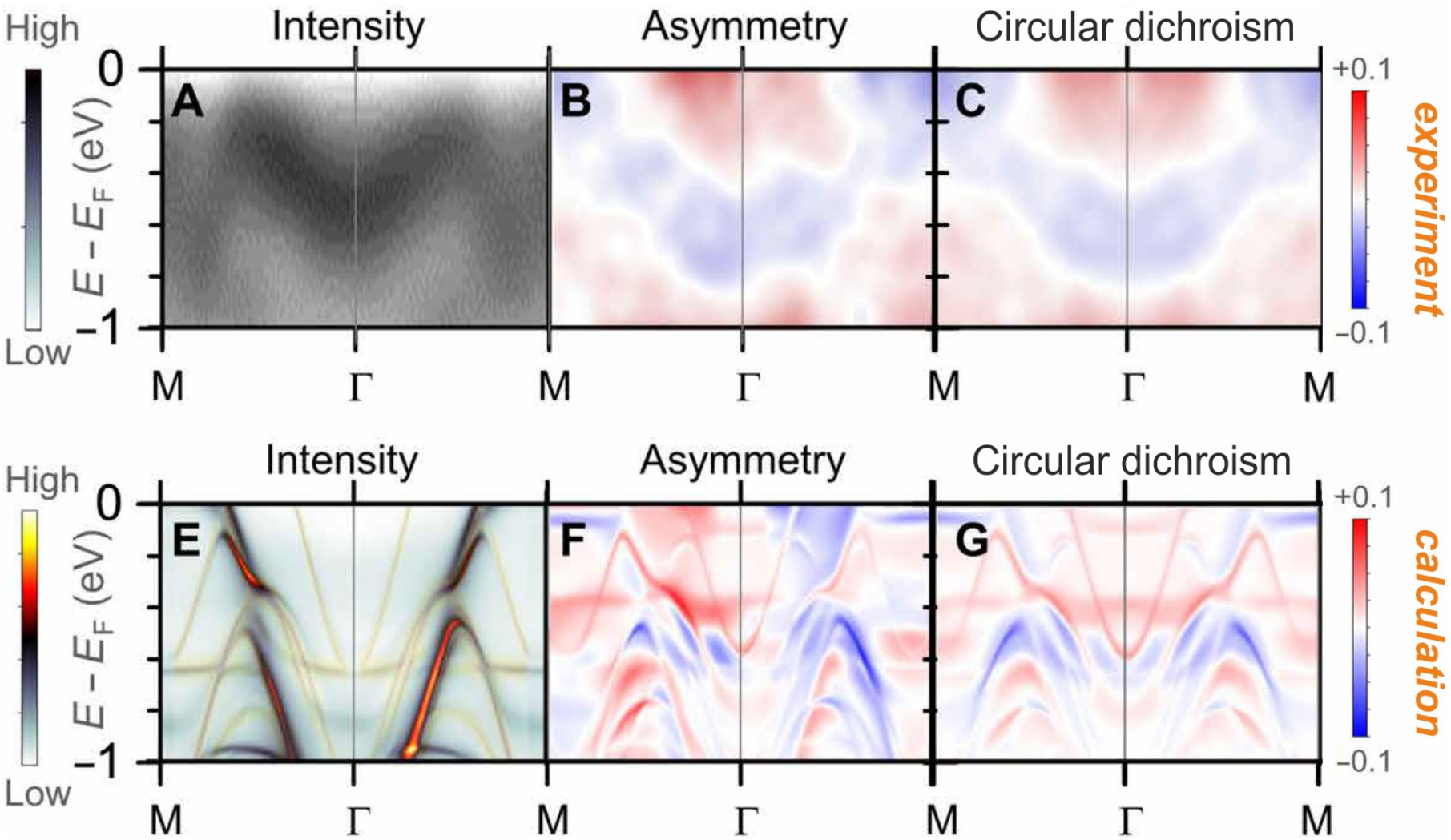
A. Bose *et al.* Nature Electronics 5, 267 (2022)

H. Bai *et al.* PRL 130, 216701 (2023)

C.-T. Liao *et al.* PRL 133, 056701 (2024)



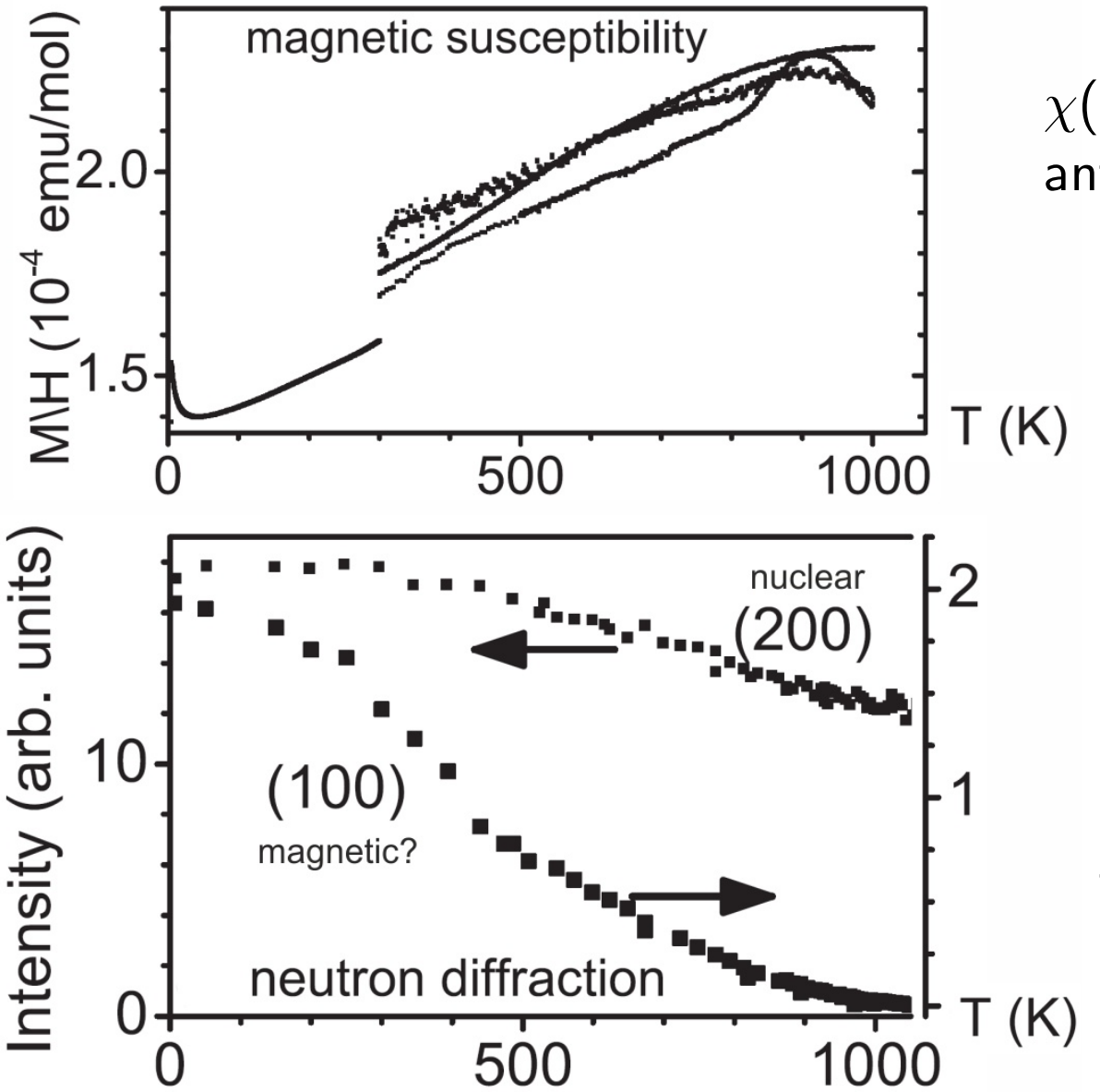
Signatures of altermagnetism



ARPES with polarization analysis to resolve the spin channels

O. Fedchenko *et al.* Sci. Advances 10, eadj4883 (2024)

"Signatures" of magnetic order

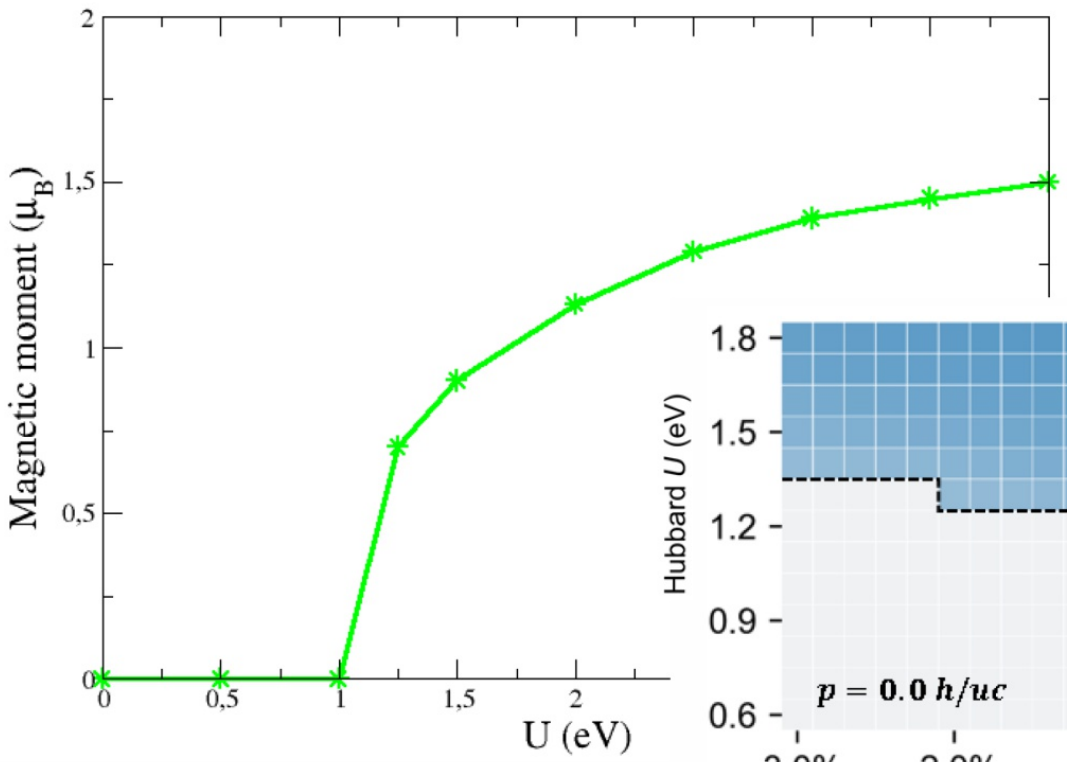


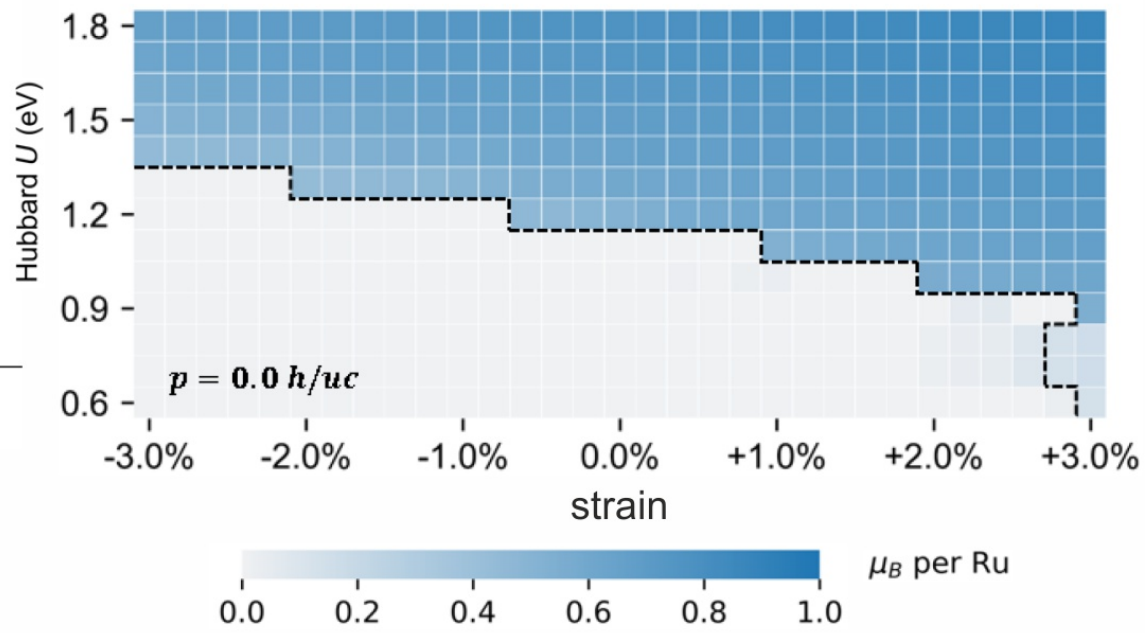
$\chi(T)$ increases as in an antiferromagnet at $T < T_N$

(100) peak is forbidden by symmetry

not purely magnetic, though...

T. Berlijn *et al.* PRL 118, 077201 (2017)





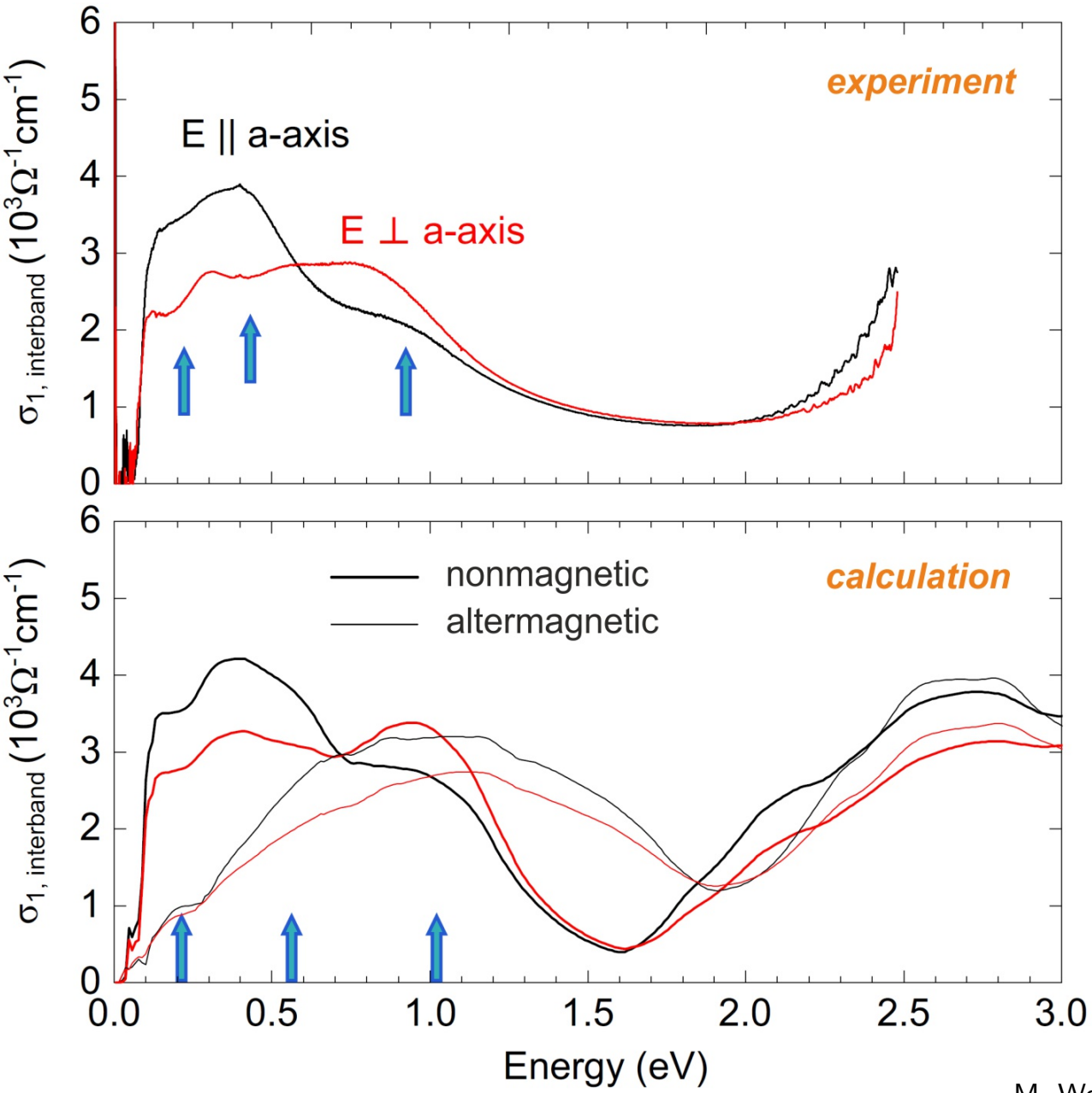
magnetically ordered state of RuO_2 unstable without correlations

all altermagnetic studies rely on DFT+U

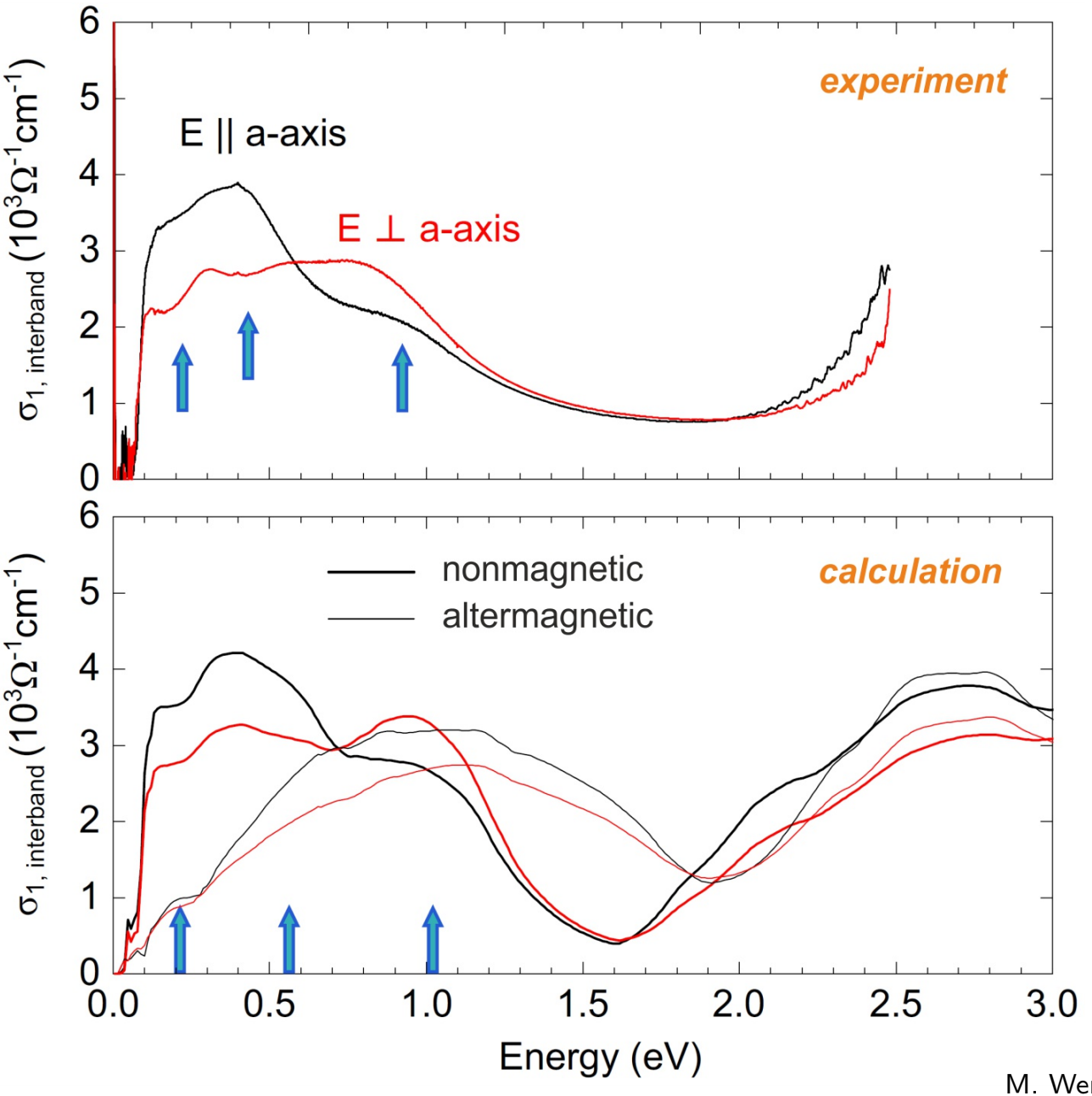
but is RuO_2 even correlated?

S. Brahimi *et al.* arXiv:2412.15377
Z. Qian *et al.* arXiv:2501.13616

Optical probe



M. Wenzel, AT *et al.* PRB 111, L041115 (2025)



Plasma frequencies

experiment

$E \parallel a$: 3.16 eV

$E \perp a$: 3.34 eV

DFT

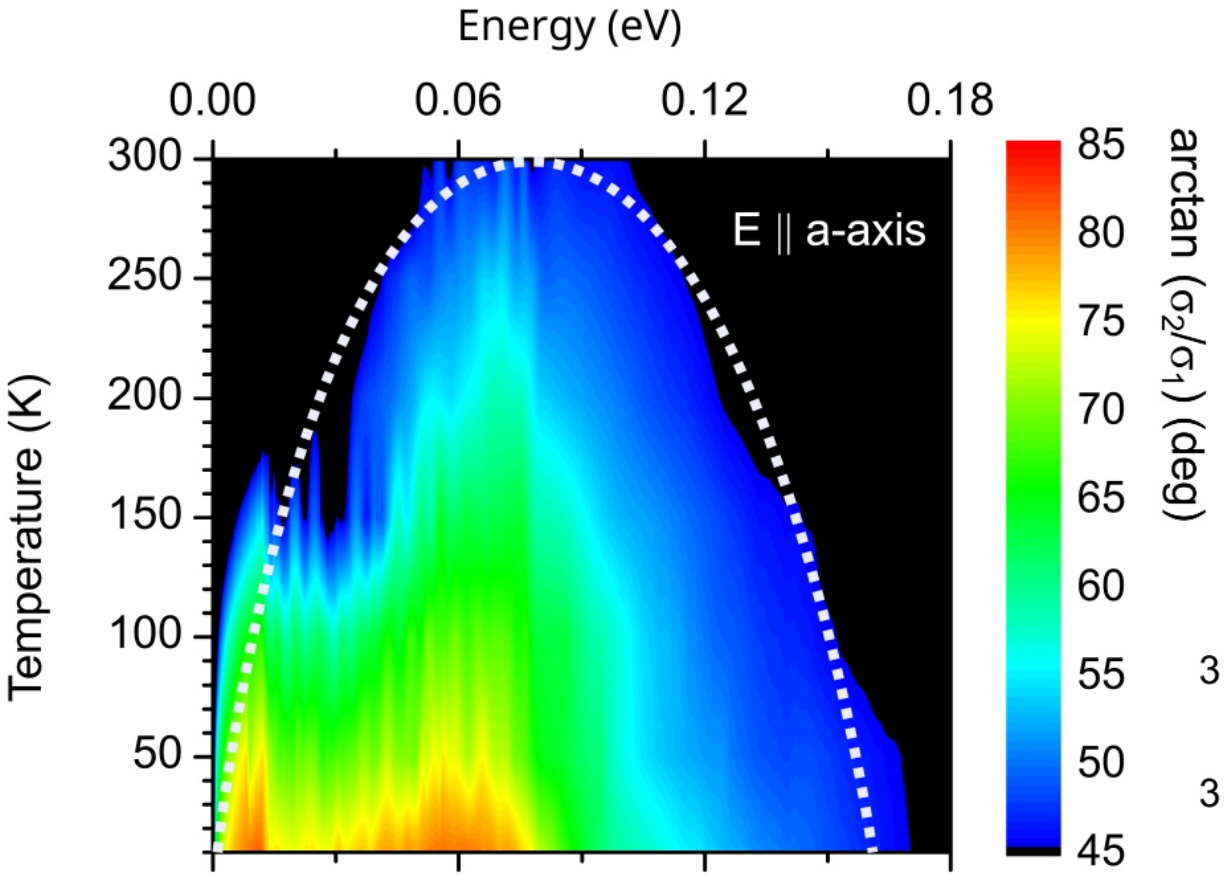
$E \parallel a$: 3.29 eV

$E \perp a$: 3.45 eV

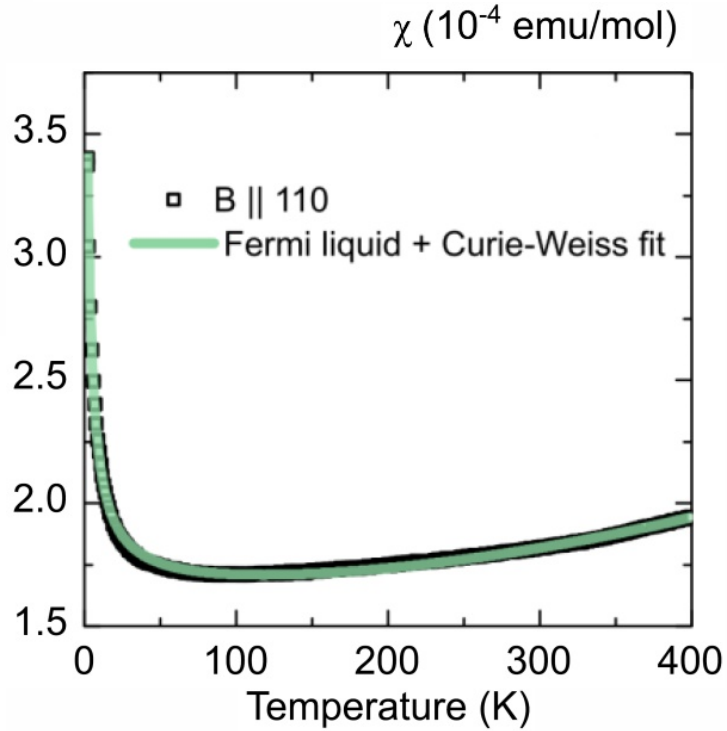
No correlations!

M. Wenzel, AT *et al.* PRB 111, L041115 (2025)

What about magnetism?



$$\sigma(\omega) = \sigma_1 + i\sigma_2$$



Conventional Fermi-liquid behavior

T^2 increase in the mag. susceptibility, as expected in a Fermi liquid

M. Wenzel, AT *et al.* PRB 111, L041115 (2025)

Bulk samples: no magnetic order

– ARPES [PRL 133, 176401 (2024)]
– neutron diffraction [npj Spintronics 2, 50 (2024)]
– μSR [PRL 132, 166702 (2024)]
– quantum oscillations [arXiv:2503.20621]
– optics [PRB 111, L041115 (2025)]

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Thin films: altermagnetism?

– spin Hall and anomalous Hall
– x-ray techniques (RXS, XMCD)
[PRL 122, 017202 (2019)]

$\times$ no magnetic order in μSR
$\times$ T_N unknown

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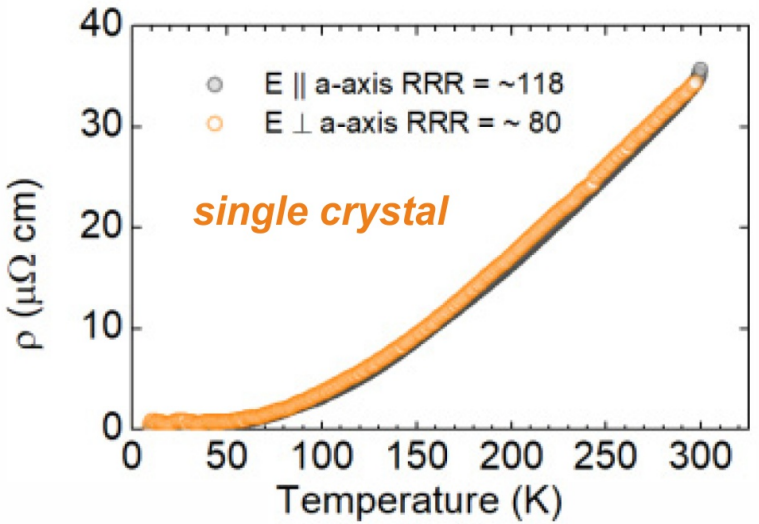
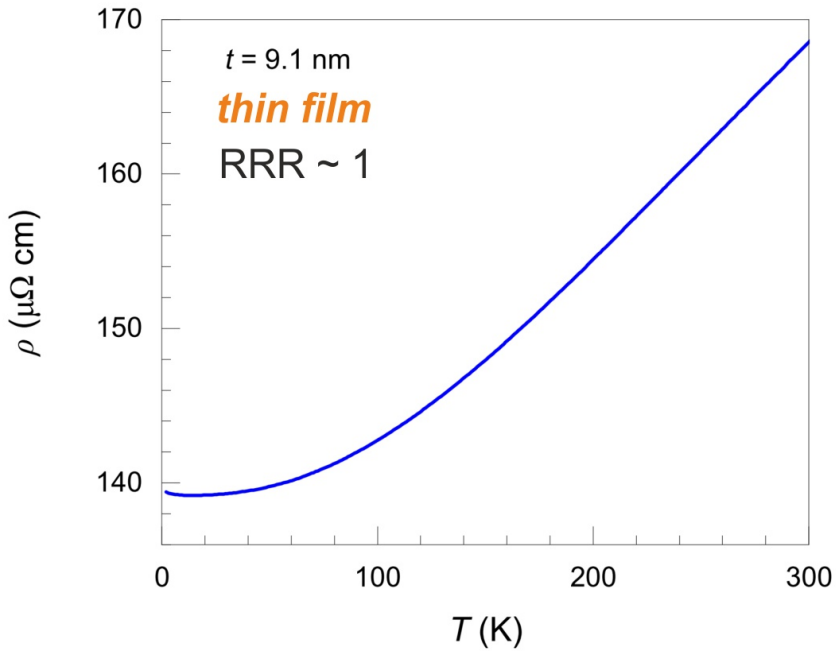


Thin films: altermagnetism?

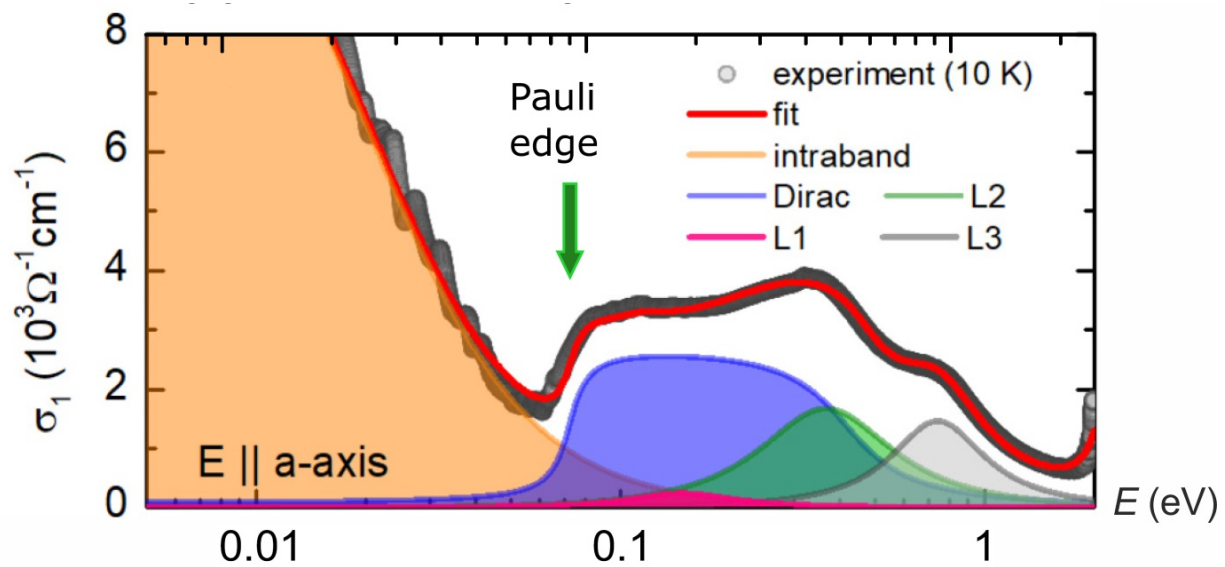
- spin Hall and anomalous Hall
- x-ray techniques (RXS, XMCD)
  [PRL 122, 017202 (2019)]

× no magnetic order in μSR
× T_N unknown
× very low RRR (defects...)



M. Wenzel, AT *et al.* PRB 111, L041115 (2025) and S.G. Jeong *et al.* arXiv:2501.11204

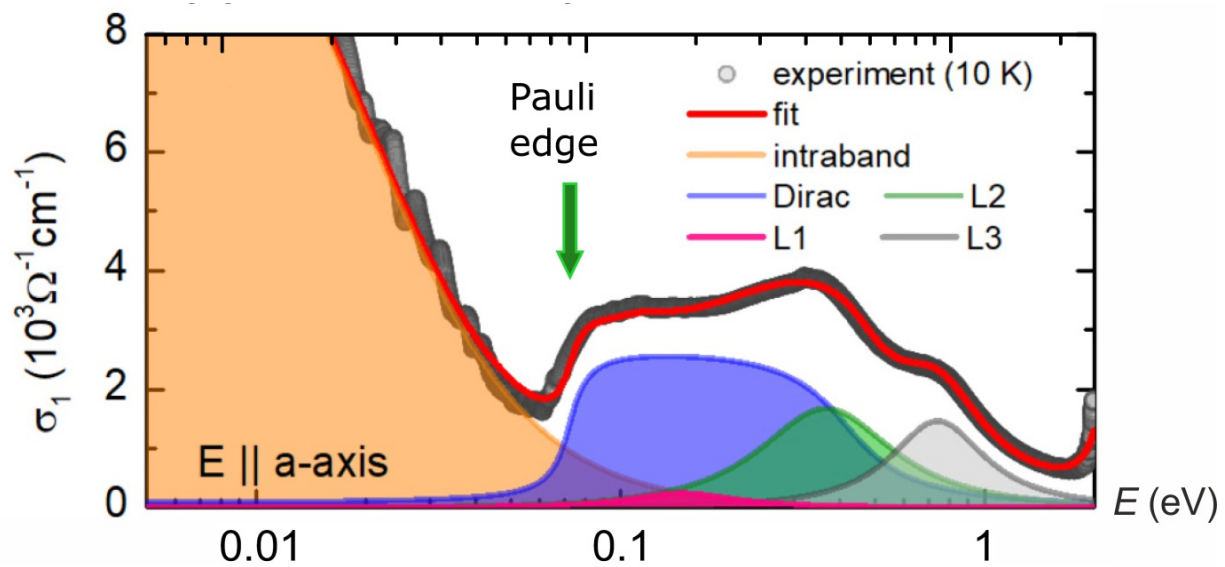
Low-energy features

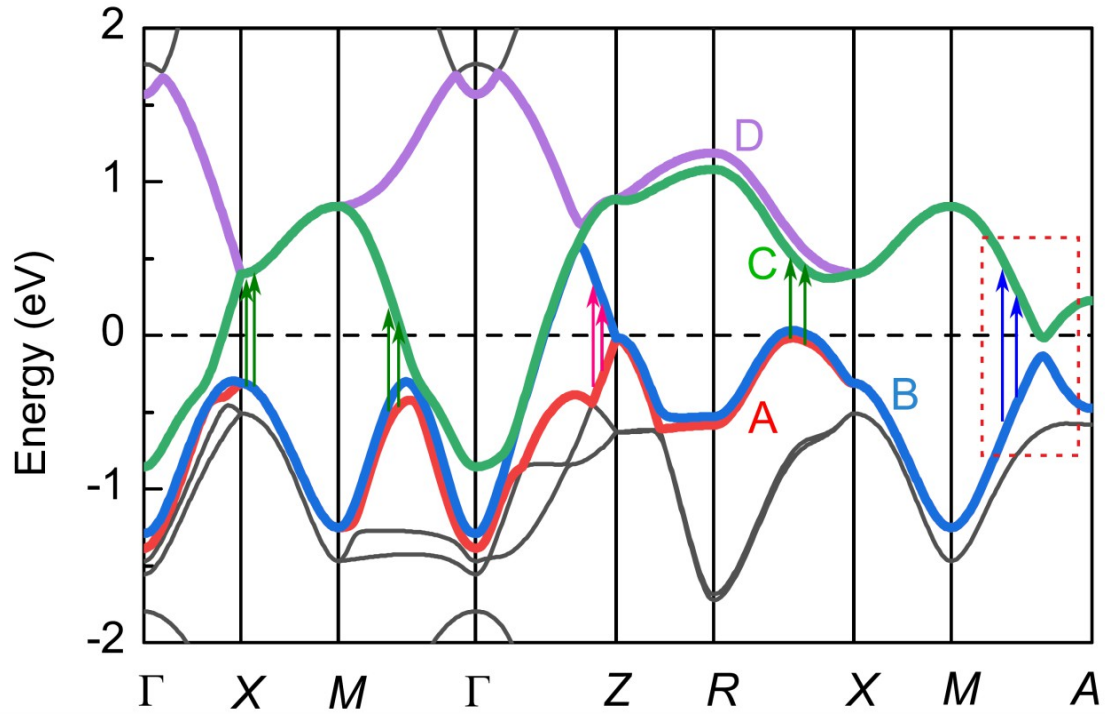


Step-like feature

M. Wenzel, AT *et al.* PRB 111, L041115 (2025)

Low-energy features





Step-like feature

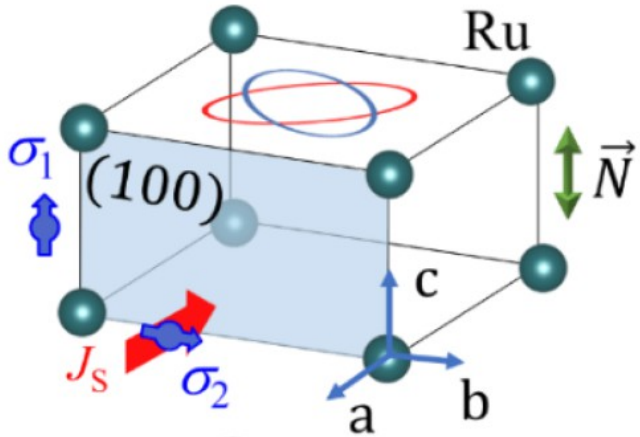
Dirac nodal line

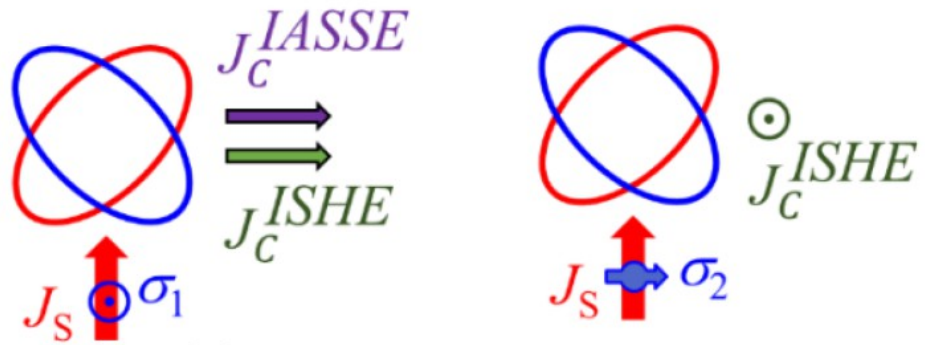
45 meV below the Fermi level

most relevant aspect of RuO_2!

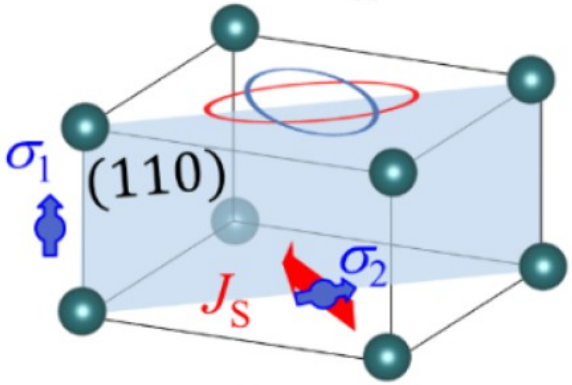
M. Wenzel, AT *et al.* PRB 111, L041115 (2025)

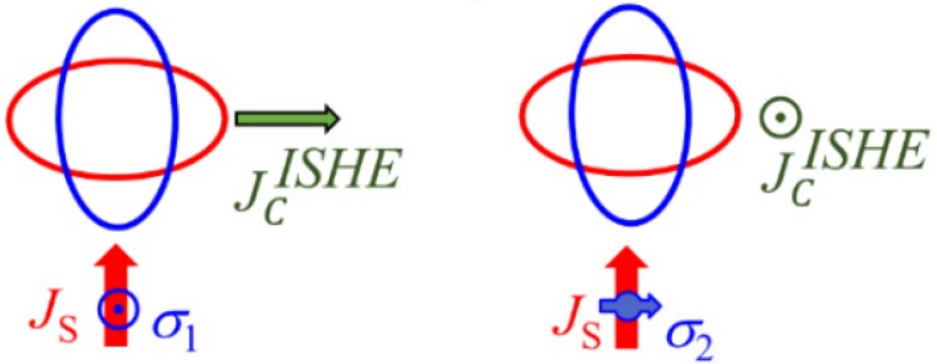
Spin Hall revisited

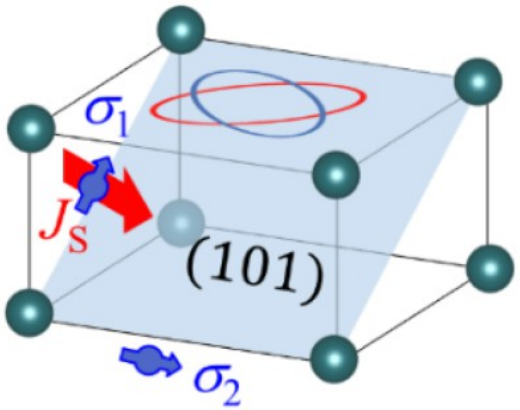


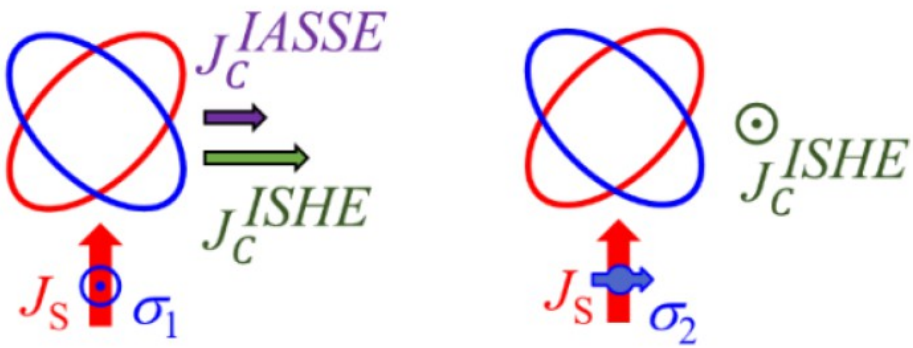


IASSE = band spin splitting
ISHE = inverse spin Hall



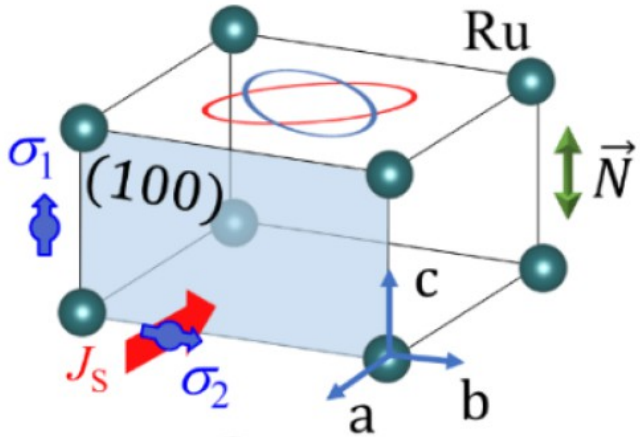


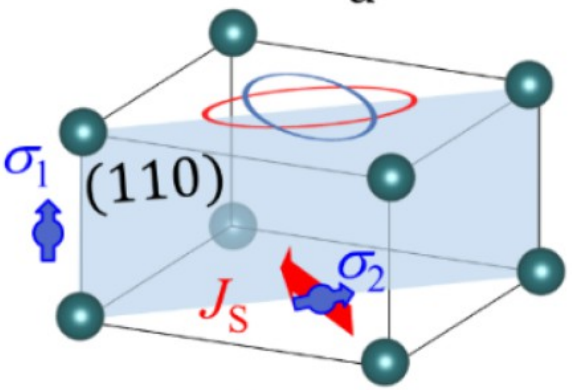


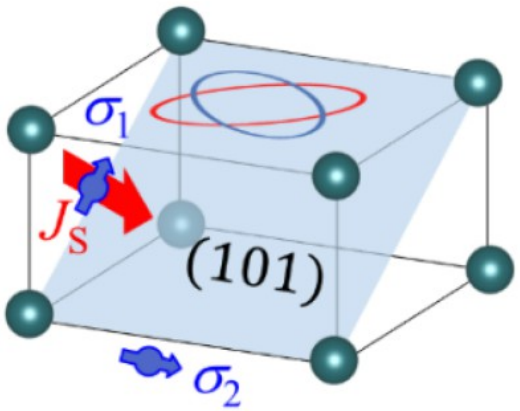


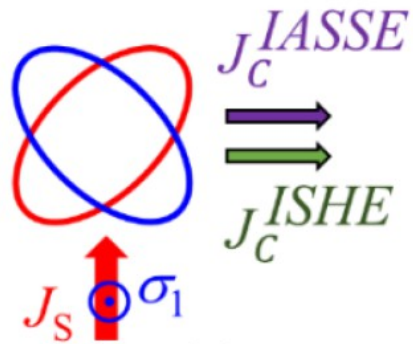
Y.-C. Wang *et al.* arXiv:2503.07985

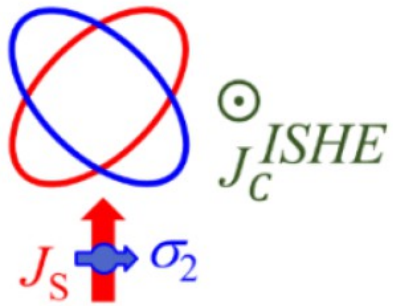
Spin Hall revisited



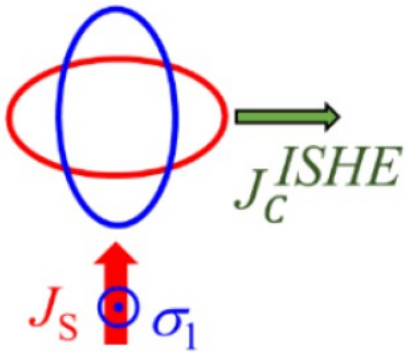


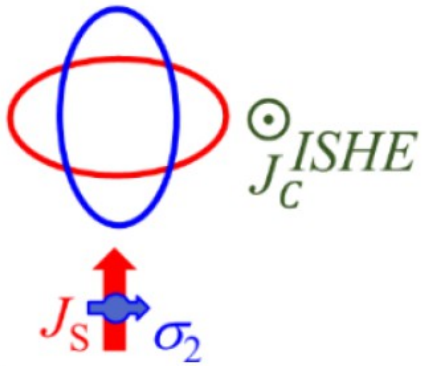


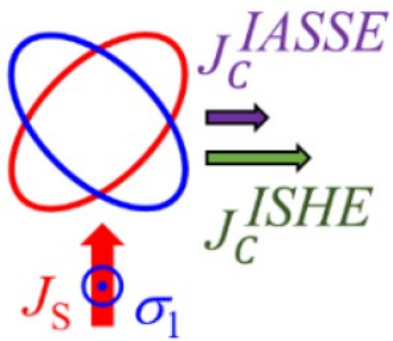


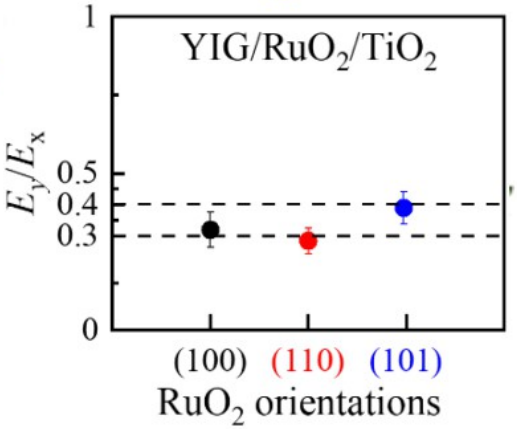


IASSE = band spin splitting
ISHE = inverse spin Hall









Y.-C. Wang *et al.* arXiv:2503.07985

Summary for RuO_2

Bulk RuO_2 is **not an altermagnet** (lacks magnetic order)

Spin-Hall effect is due to spin-orbit coupling ($4d$ electrons) and enhanced by the Dirac nodal line near E_F

spin splitting of the bands irrelevant (if present at all)

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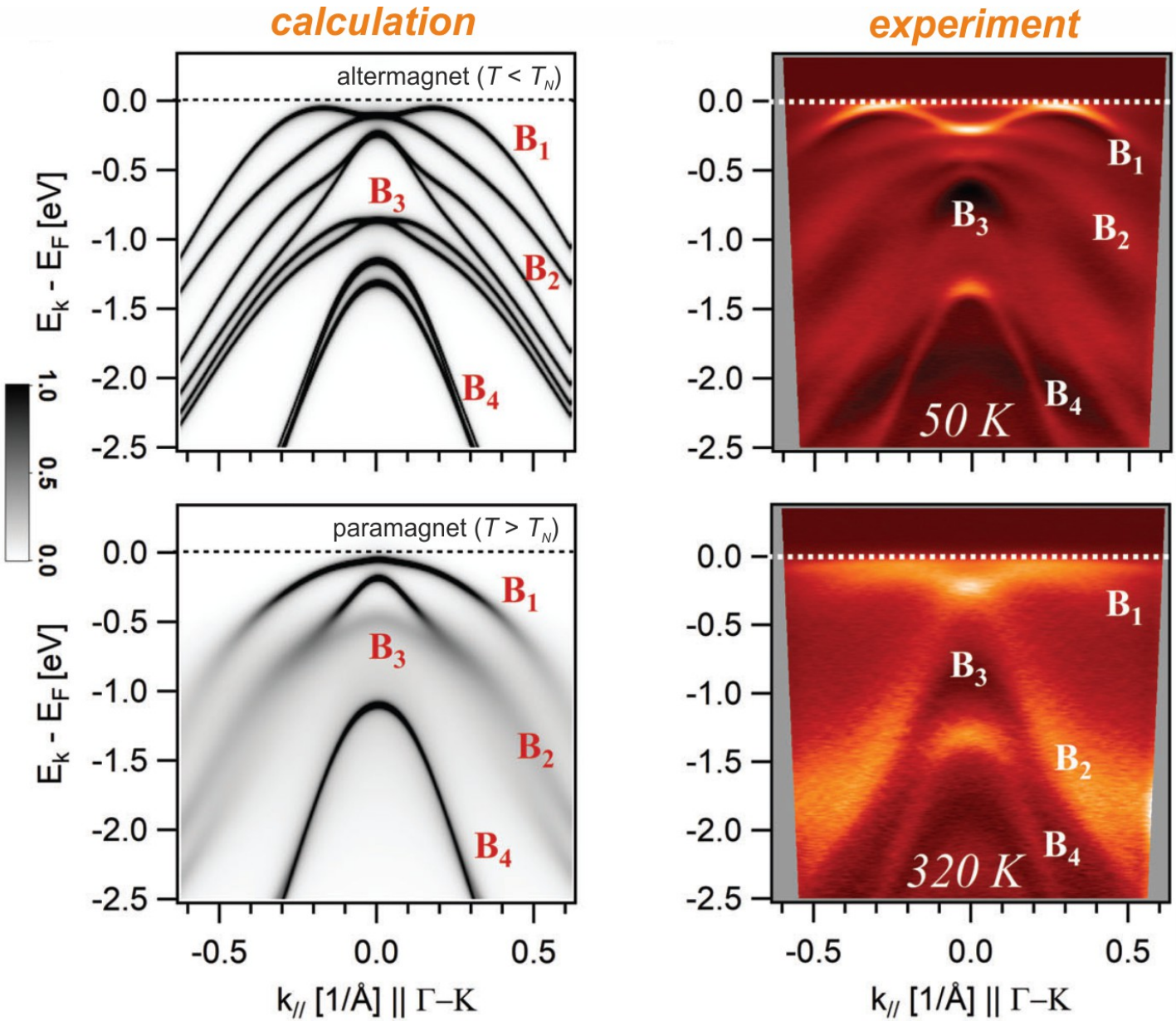
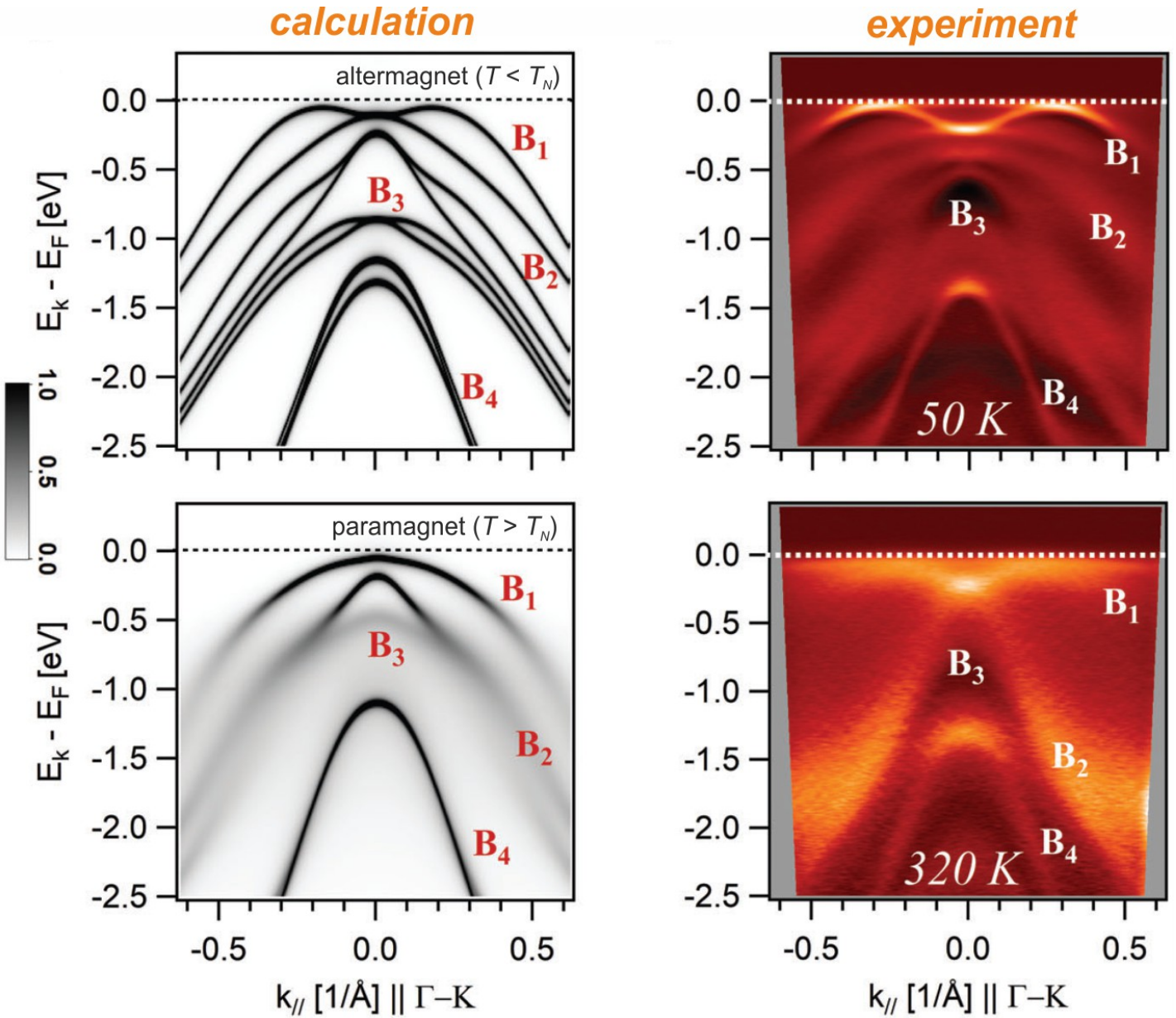
What is our next material candidate?

MnTe: true altermagnet



M. Hajlaoui *et al.* Adv. Mater. 36, 2314076 (2024)

MnTe: true altermagnet



but...

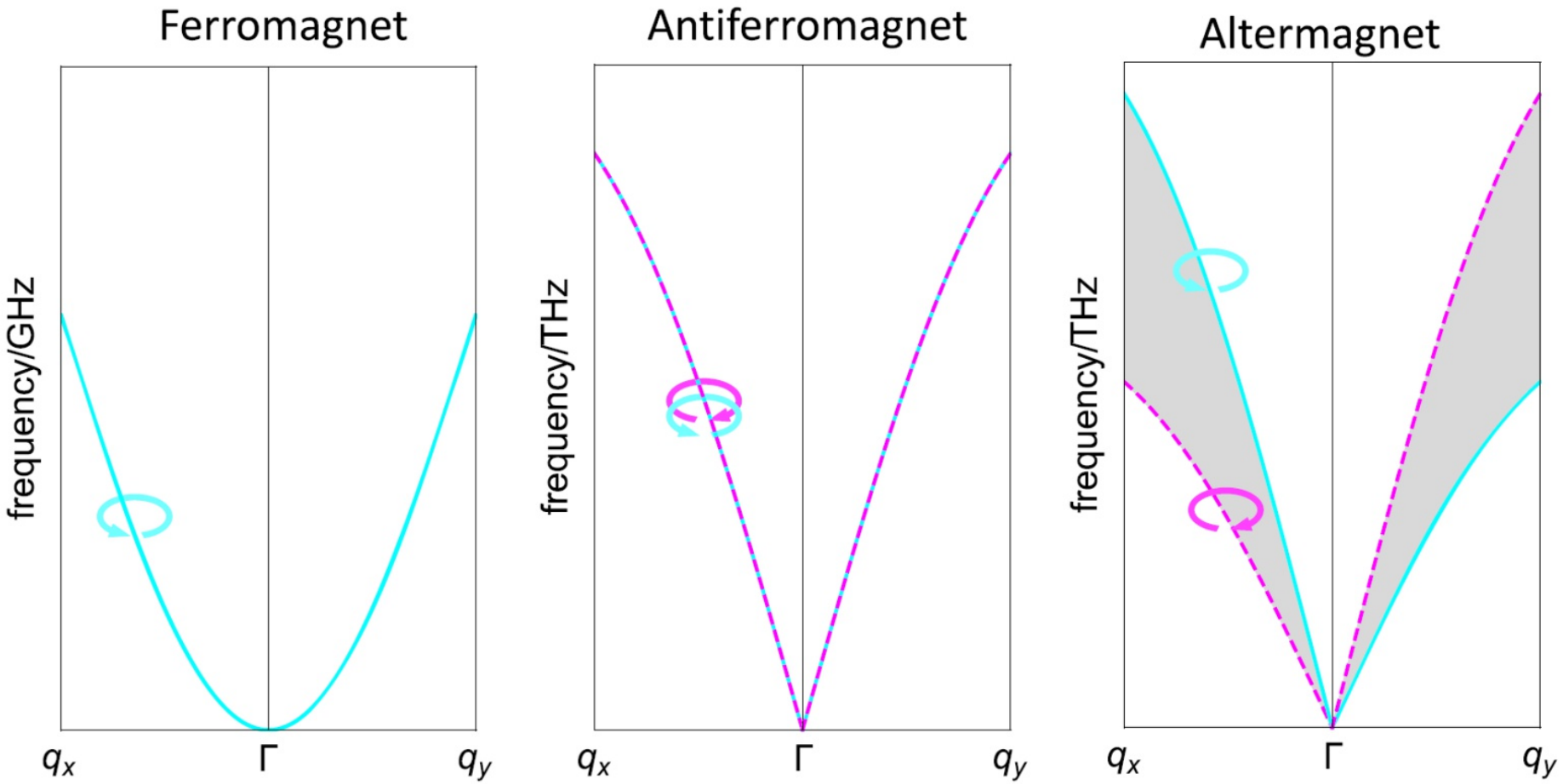
MnTe is semiconductor ($E_g \sim 1.25\,\mathrm{eV}$)

$$\sigma_{xy}^{\mathrm{AHE}} = 0.03\,\Omega^{-1}\,\mathrm{cm}^{-1}$$

very low...

M. Hajlaoui *et al.* Adv. Mater. 36, 2314076 (2024)

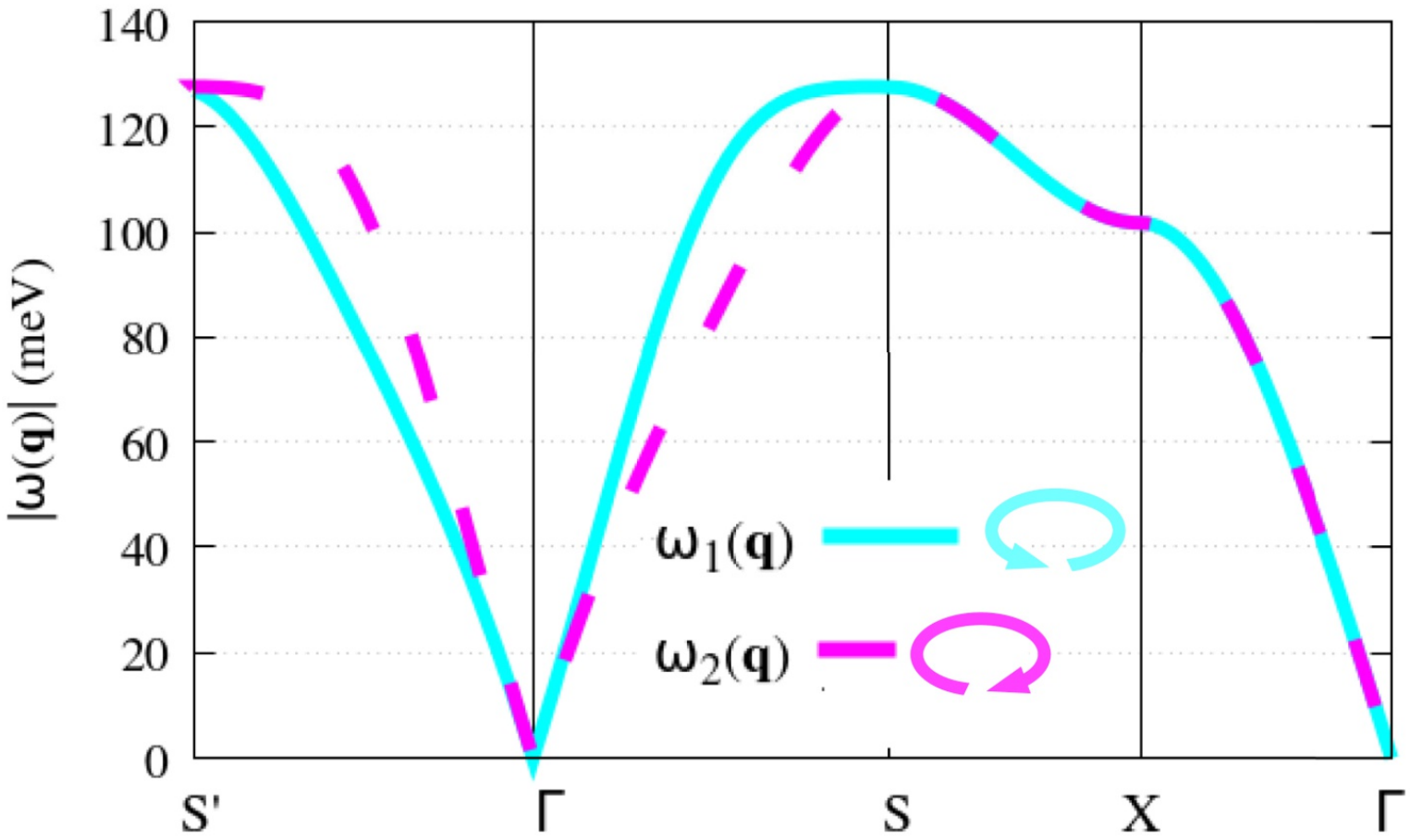
Chiral magnons



Degeneracy of AFM magnon modes is lifted away from $q = 0$

Image from: L. Šmejkal *et al.* PRL 131, 256703 (2023)

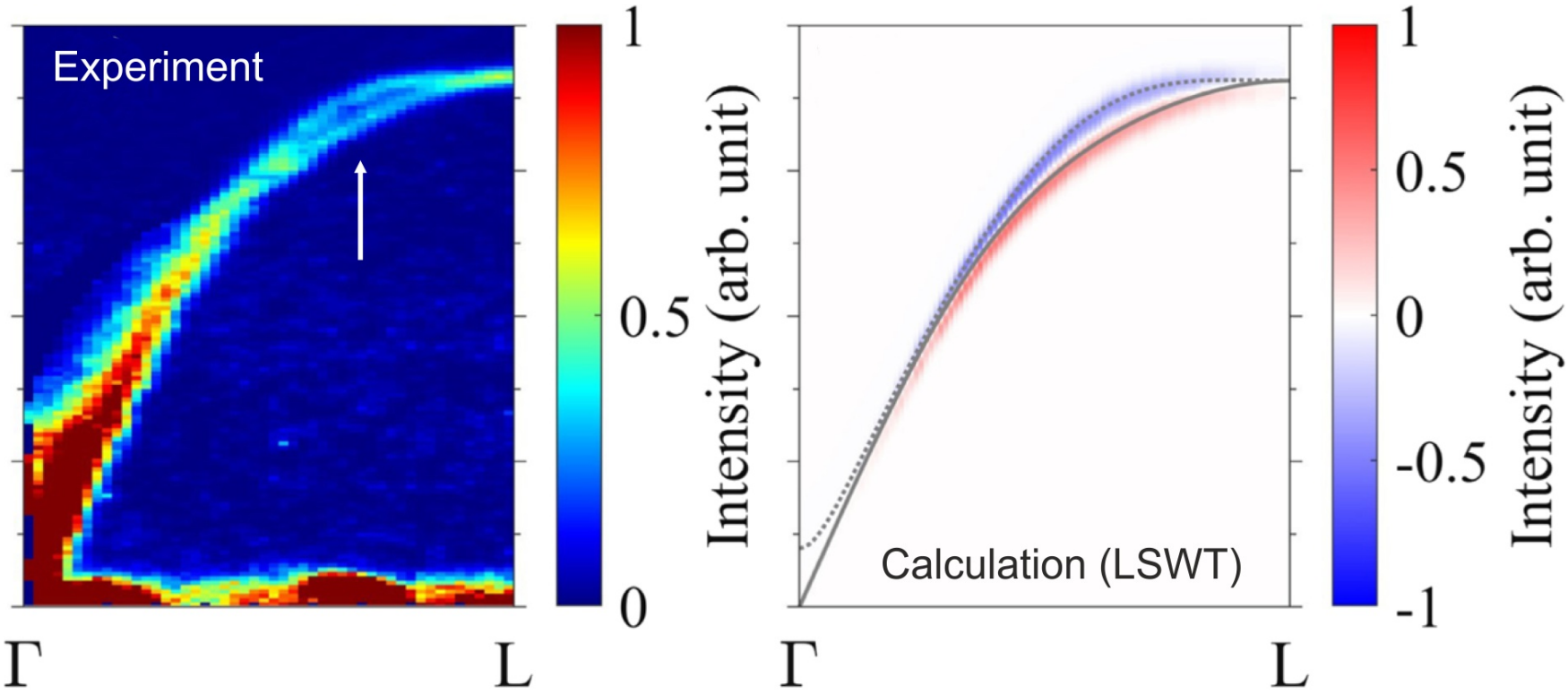
Prediction for RuO_2



but RuO_2 is nonmagnetic after all...

Image from: L. Šmejkal *et al.* PRL 131, 256703 (2023)

Magnon splitting: MnTe

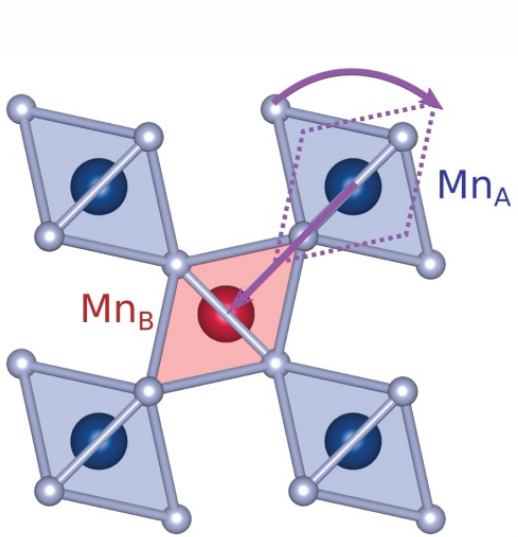


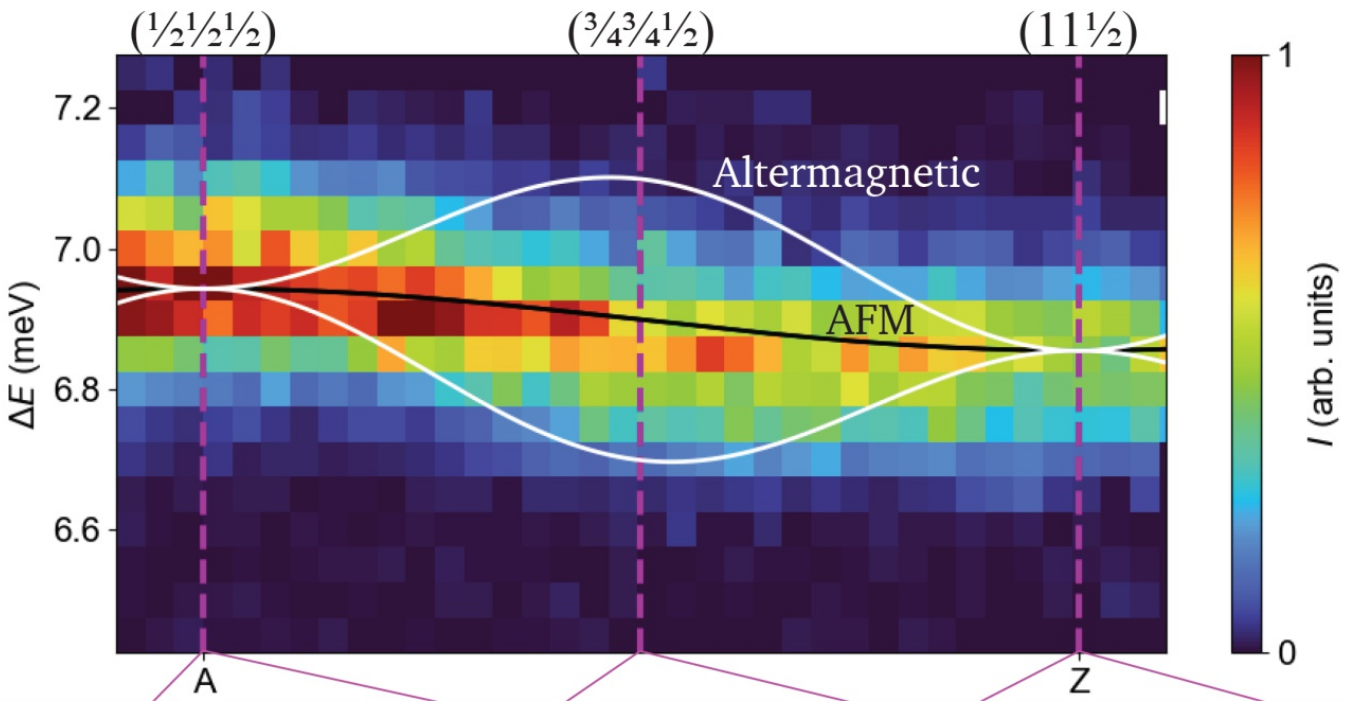
Splitting is there! (magnitude: up to 2 meV)

Probe of magnon chirality by RIXS: D. Jost *et al.* arXiv:2501.17380

Images from: Z. Liu *et al.* PRL 133, 156702 (2024)

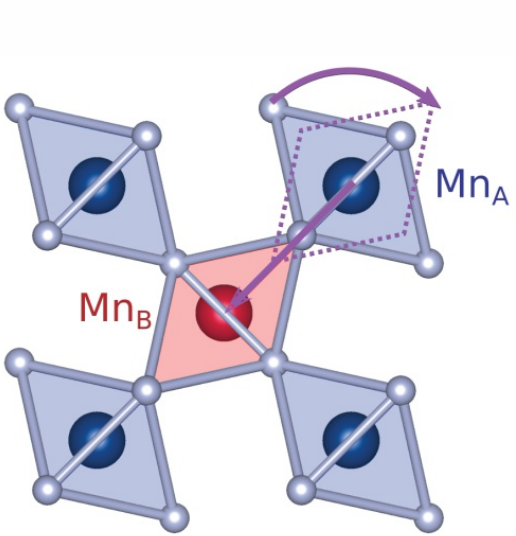
MnF_2: no magnon splitting...

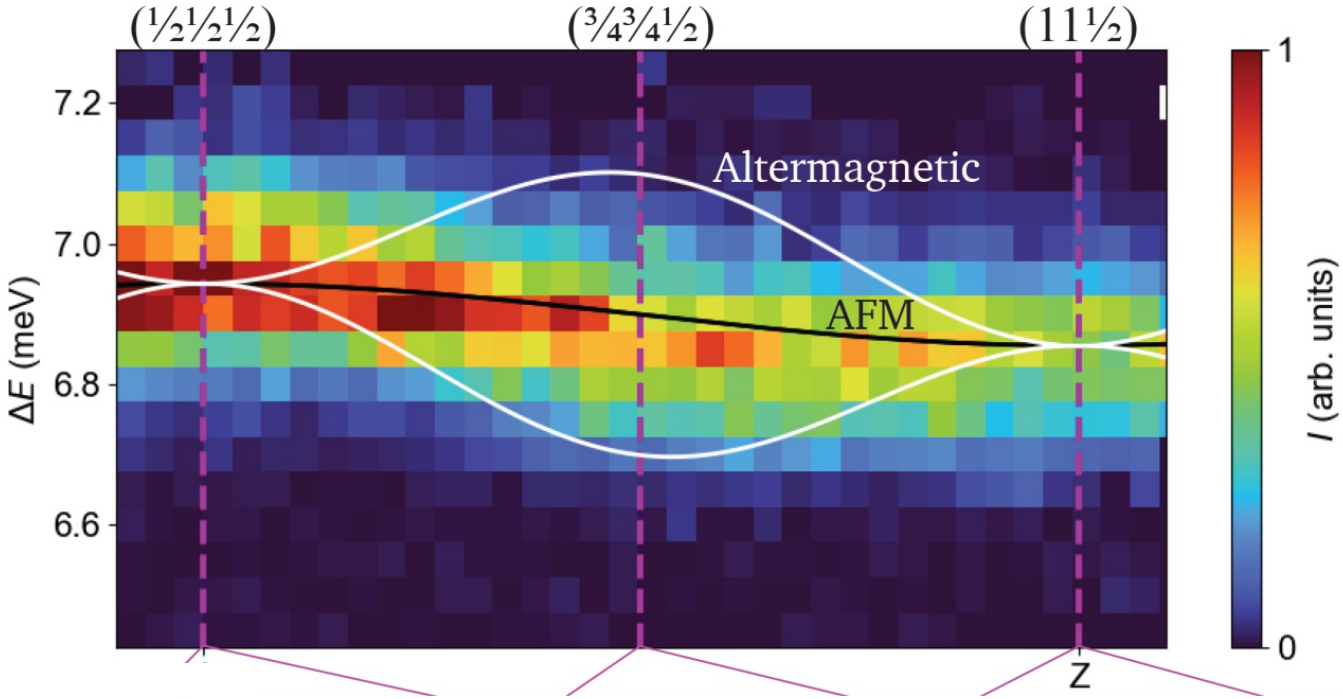


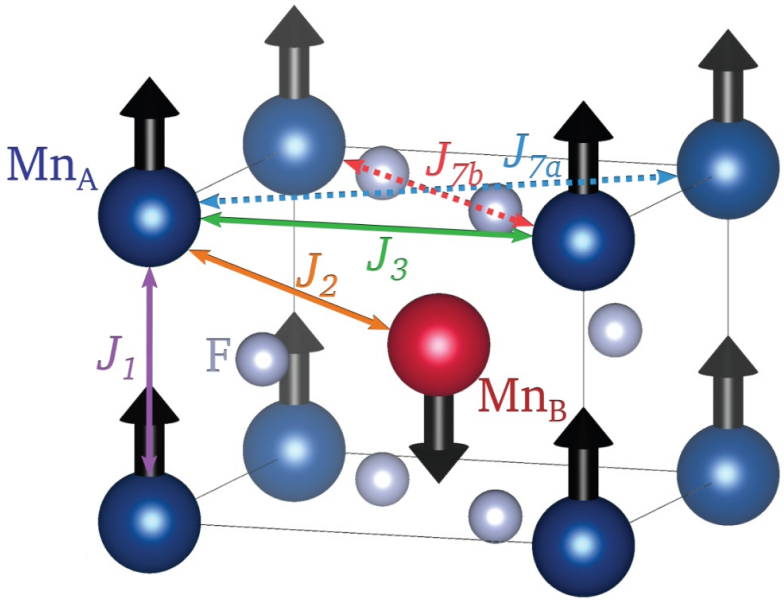


V.C. Morano *et al.* arXiv:2412.03545

MnF_2: no magnon splitting...





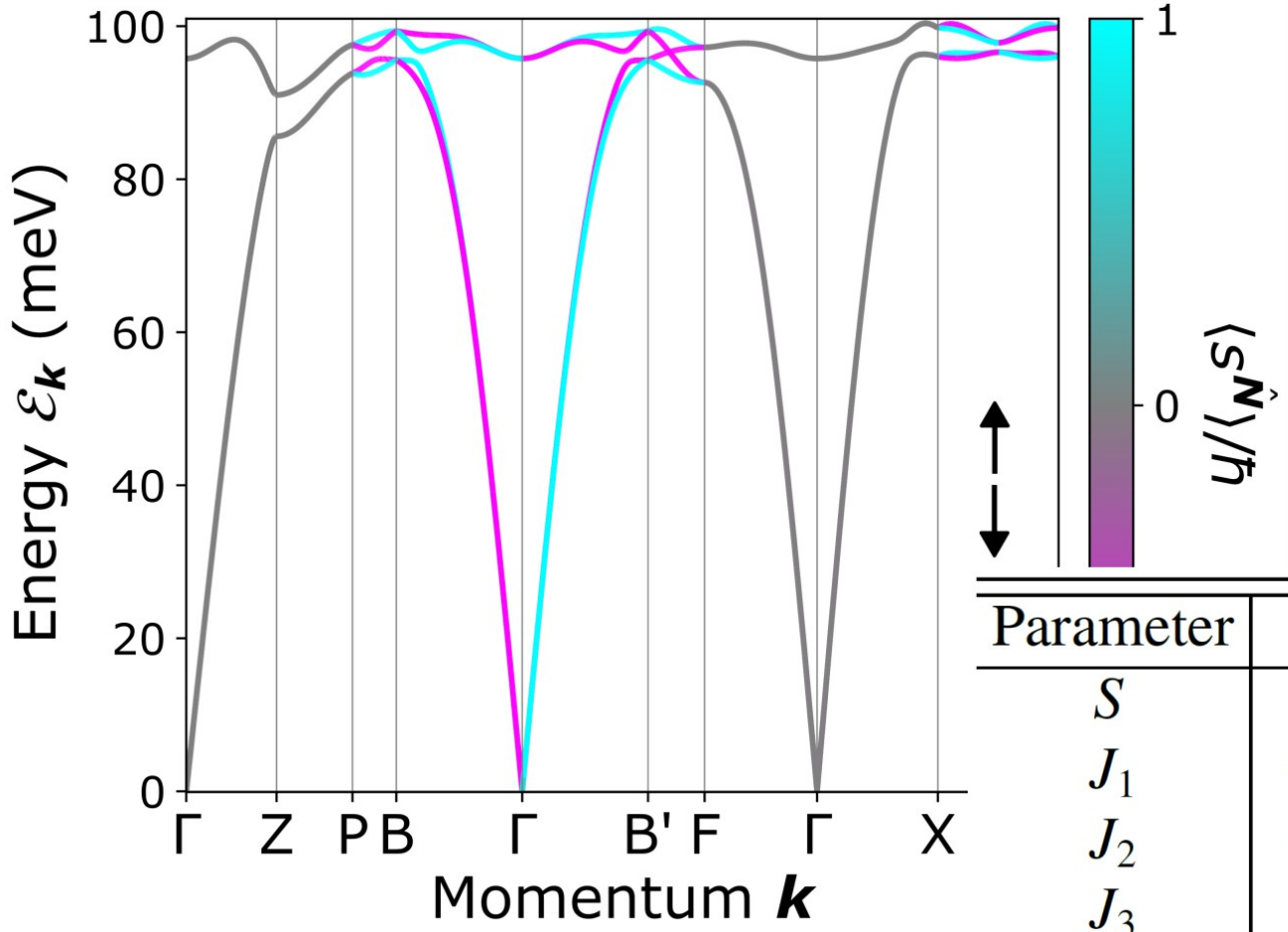


Spin lattice has a higher symmetry than the crystal itself

Magnons would be split by J_{7a} and J_{7b}, but these couplings are negligible

V.C. Morano *et al.* arXiv:2412.03545

Hematite (Fe_2O_3)



Parameter	Value	Unit
S	5/2	
J_1	−0.98212	meV
J_2	−0.16856	meV
J_3	5.45240	meV
J_4	4.00760	meV
J_5	0.33712	meV
J_{13}	0.04000	meV
Δ	0.15000	meV

Tiny band splitting
from a rather irrelevant coupling

R. Hoyer *et al.* arXiv:2503.11623

Lots of materials with suitable symmetries,
but **symmetry is not all**

Promising transport properties may occur without altermagnetism
check that your favorite altermagnet is magnetically ordered

Splitting of magnon bands (chiral magnons) could be a hallmark,
if this splitting is what we are after

Experimental protocol for "genuine altermagnets" **still missing**

Smart ideas for **new mechanisms** of altermagnetism are desirable

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- Oleg Janson (IFW Dresden)