JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JÜLICH FORSCHUNGSZENTRUM

On the origins of transport in altermagnets

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Thanks


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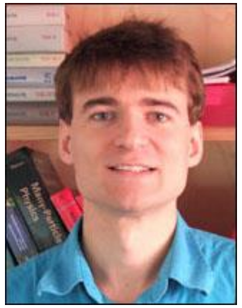
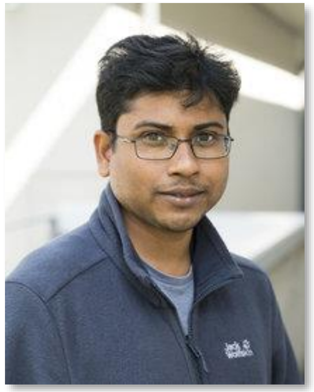

Frank Freimuth


Max Merte


Marjana Ležaić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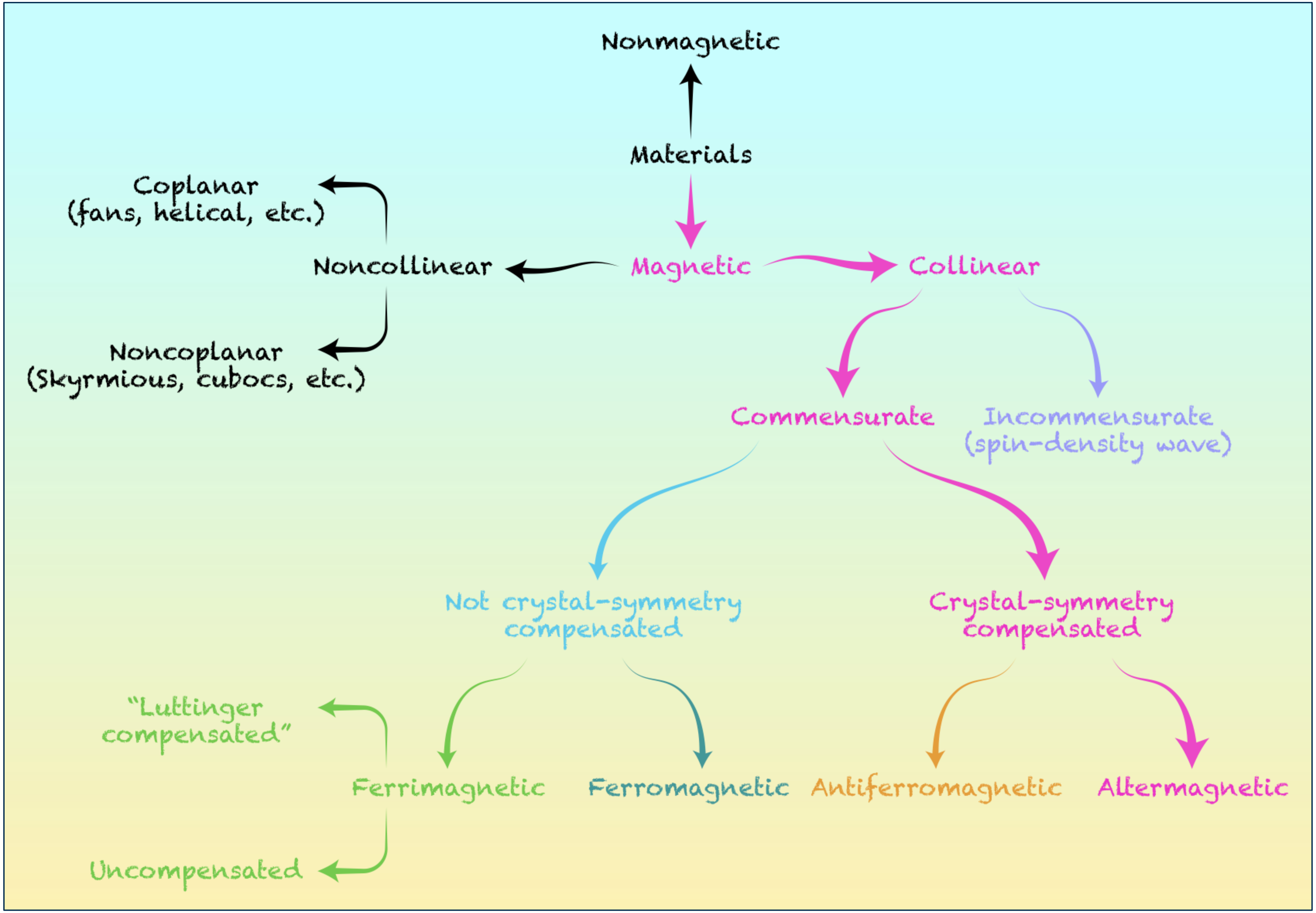
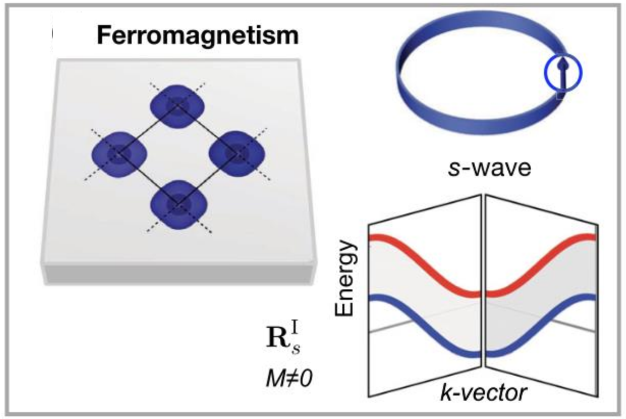
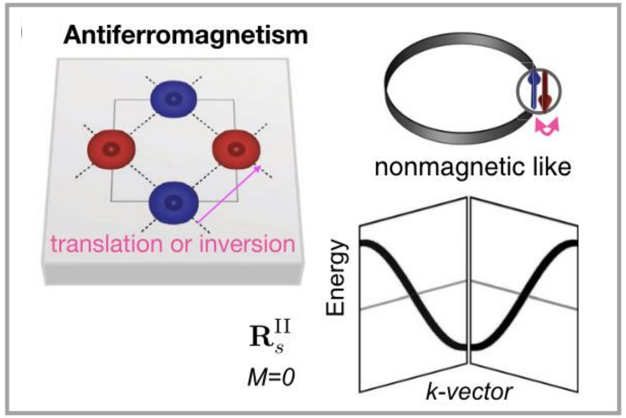


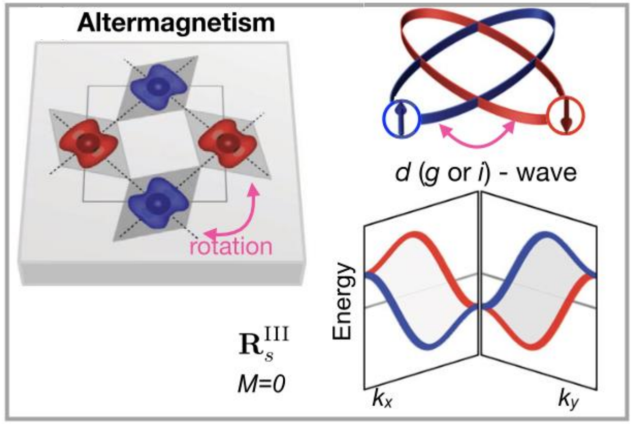
I. Mazin **PRX** 2022

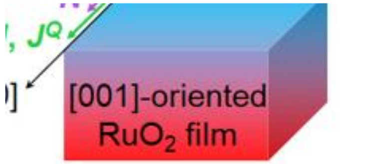
Altermagnetism

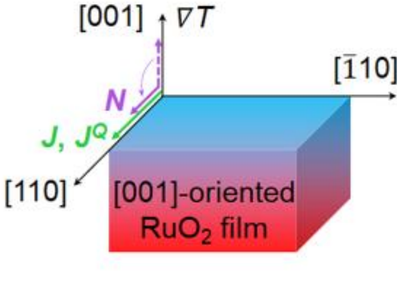
Šmejkal, Sinova & Jungwirth **PRX** 12, 031042 (2022); 12, 040501 (2022)
Libor Šmejkal *et al*. **Sci. Adv.** 6, eaaz8809 (2020)





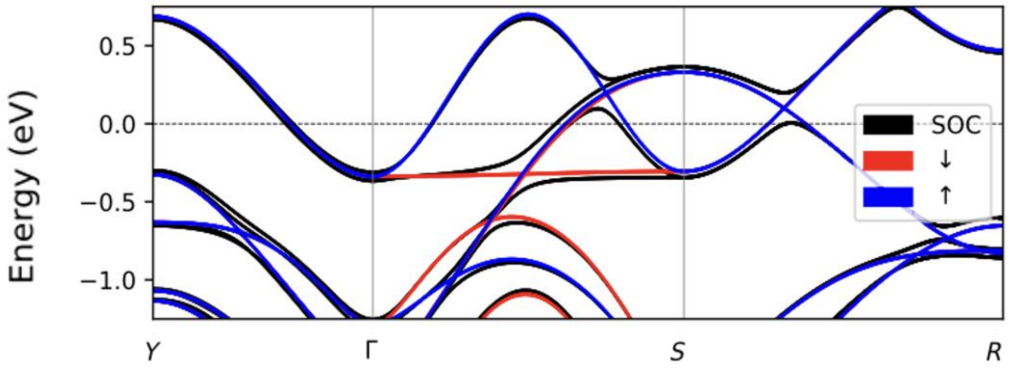






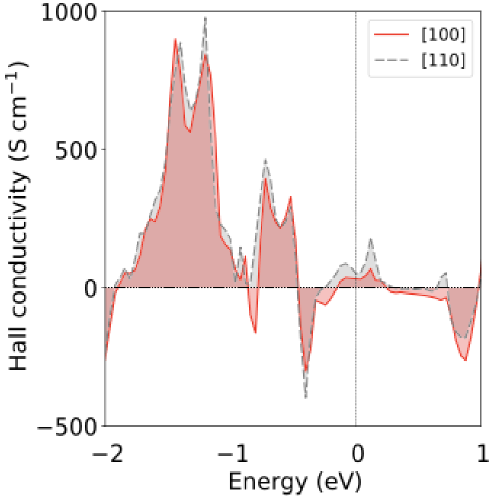
Prototype altermagnet: RuO_2

What drives transport in altermagnets microscopically?



Crystal Hall effect

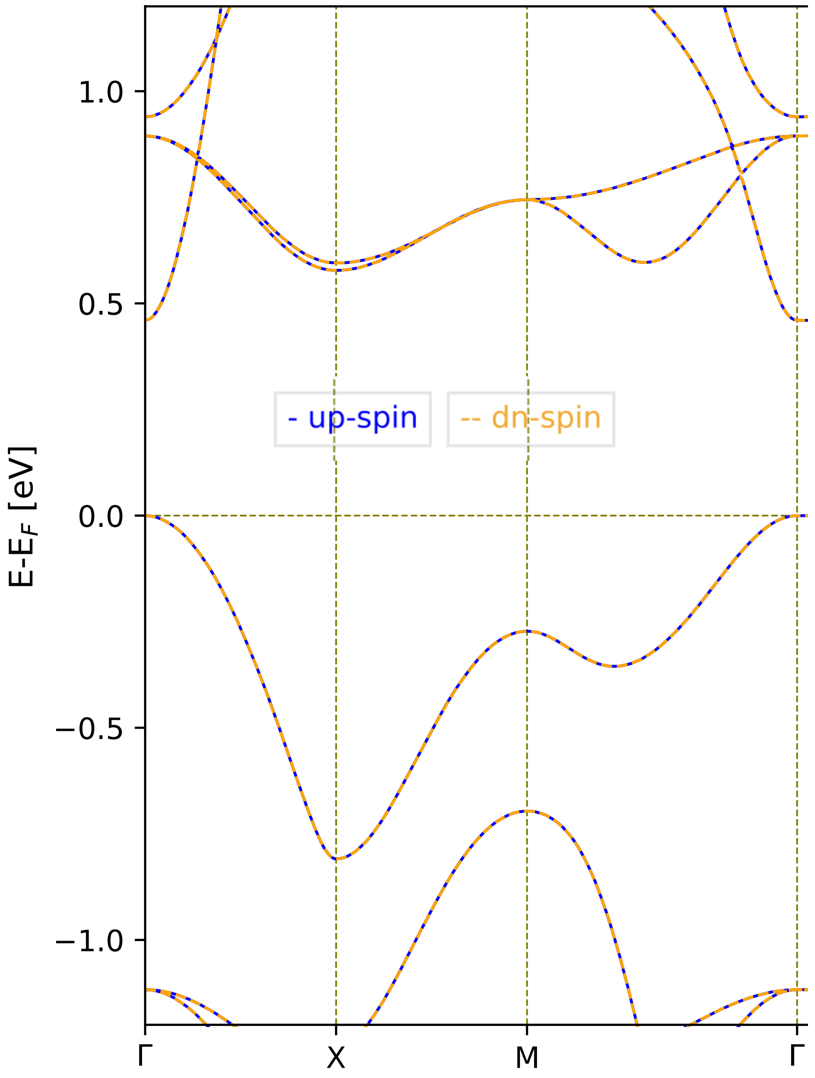
odd in crystal chirality

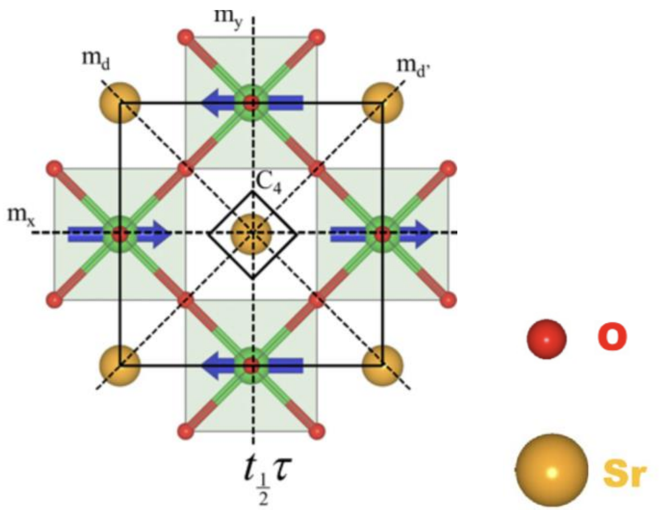


A case of $SrRuO_3$

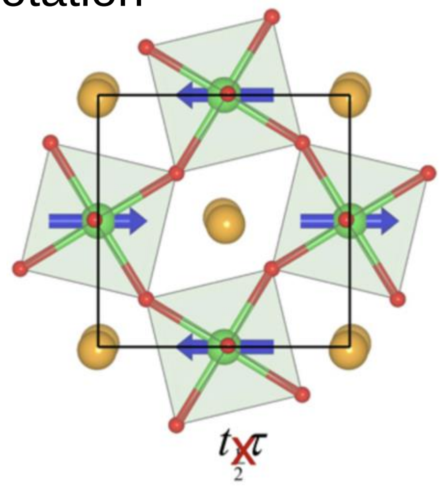
Samanta, Lezaic, Freimuth, Blügel, YM, JAP **127**, 213904 (2020)

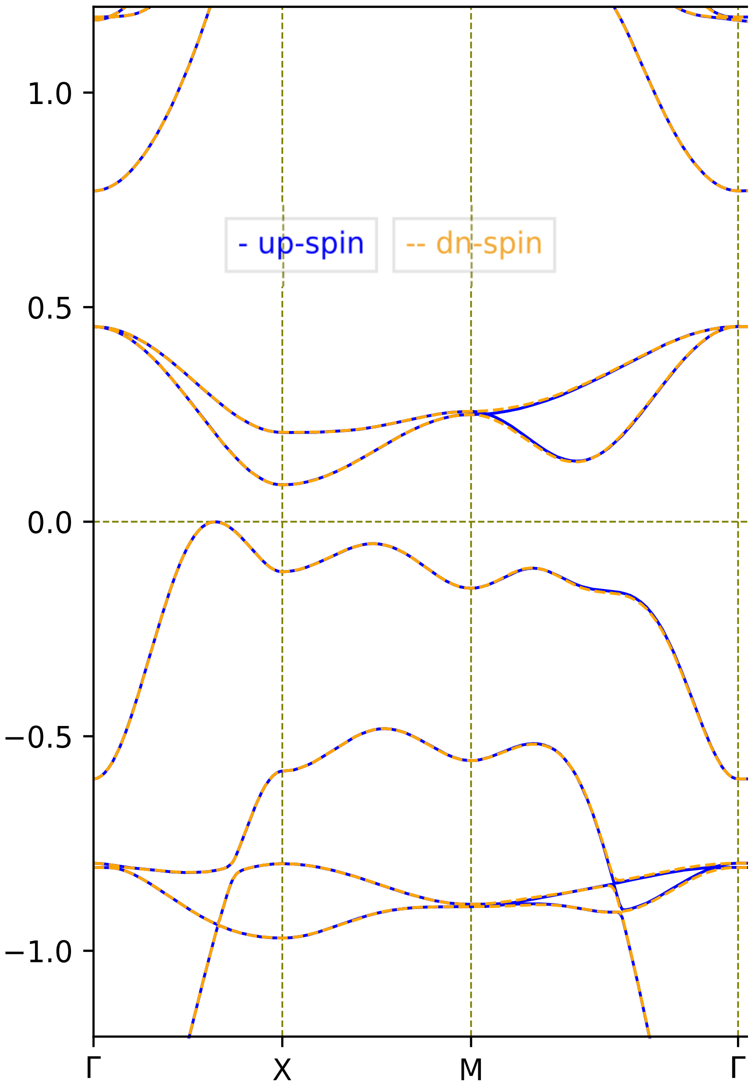
Antiferromagnetic up to 4 monolayers
Xia et al. PRB 79 (2009)





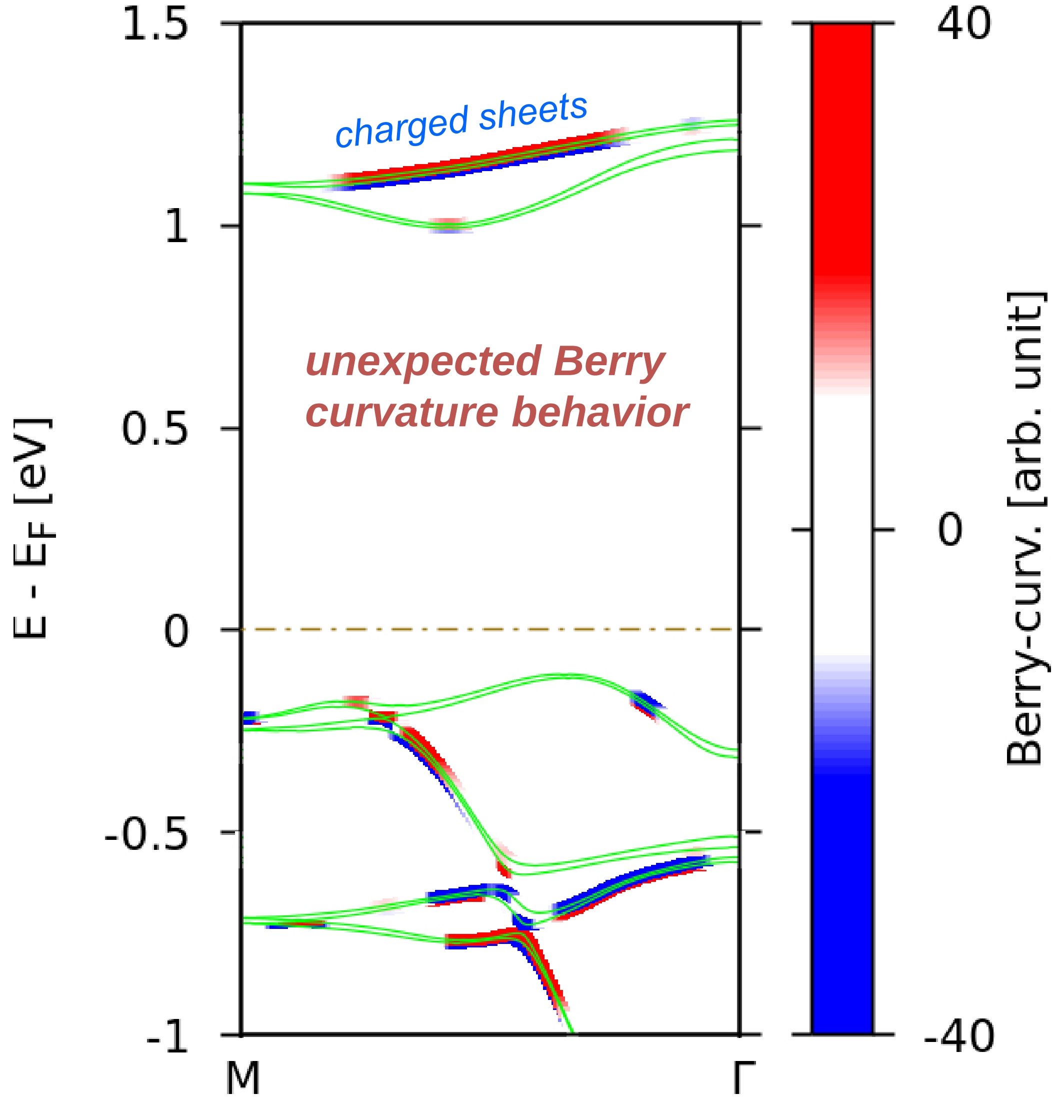
7º-rotation

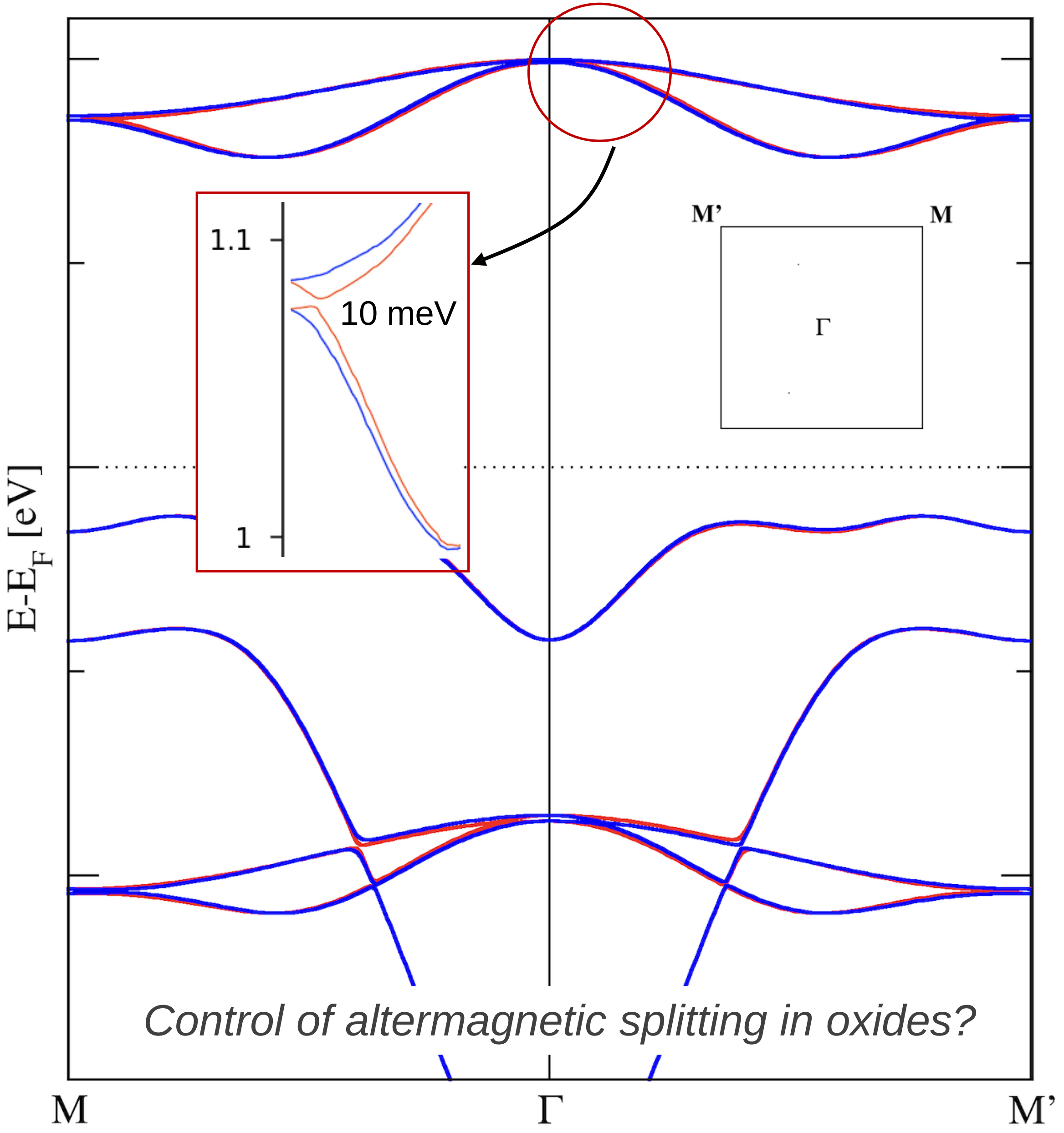




A case of $SrRuO_3$

Samanta, Lezaic, Freimuth, Blügel, YM, JAP **127**, 213904 (2020)





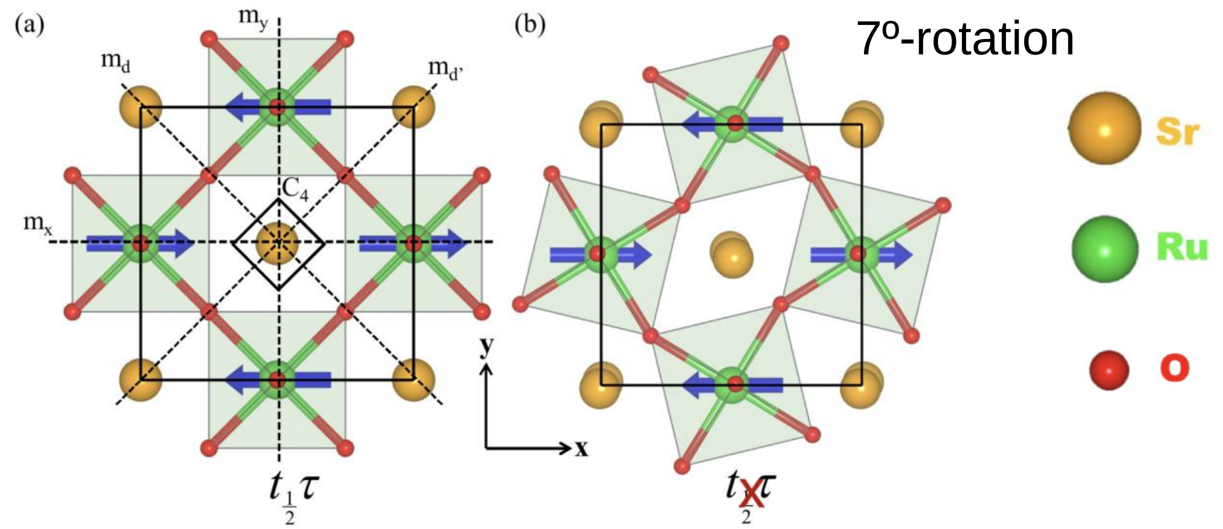
A case of $SrRuO_3$

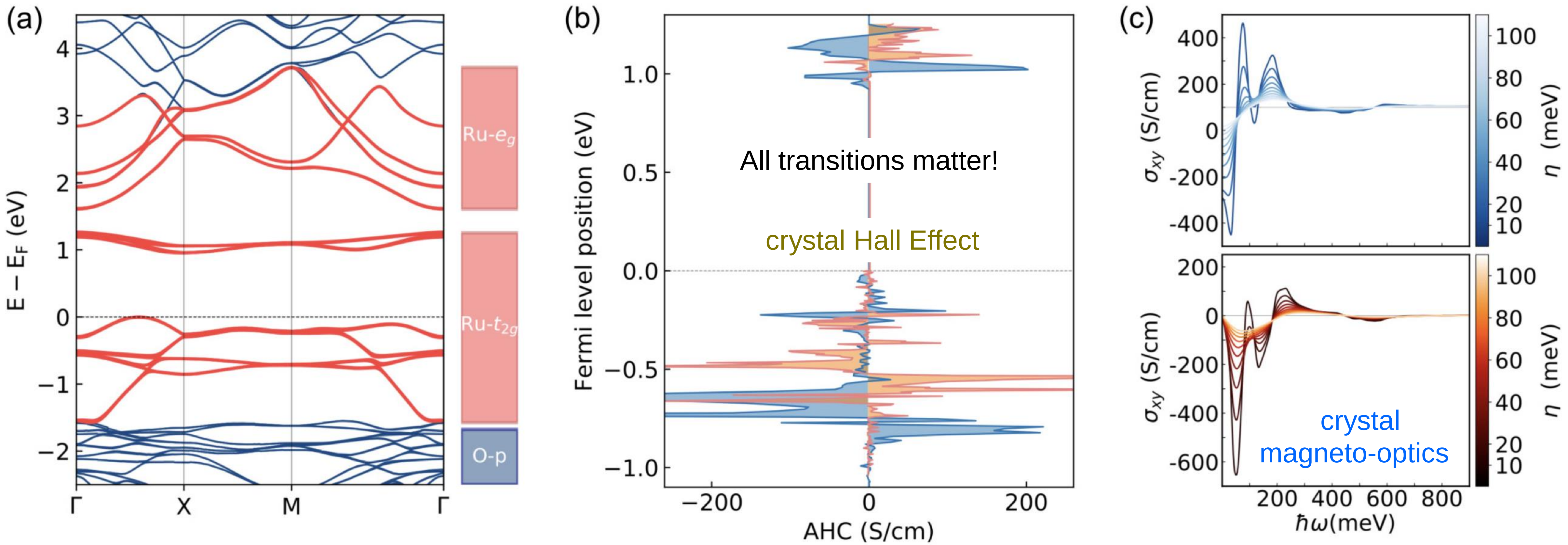
Samanta, Lezaic, Freimuth, Blügel, YM, JAP **127**, 213904 (2020)

Large ***crystal Hall effect***

crystal magneto-optical effect

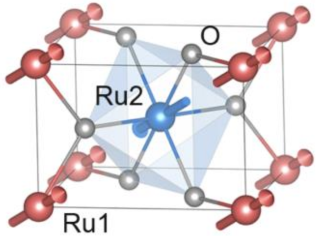
upon a “mininal” octahedral distortion





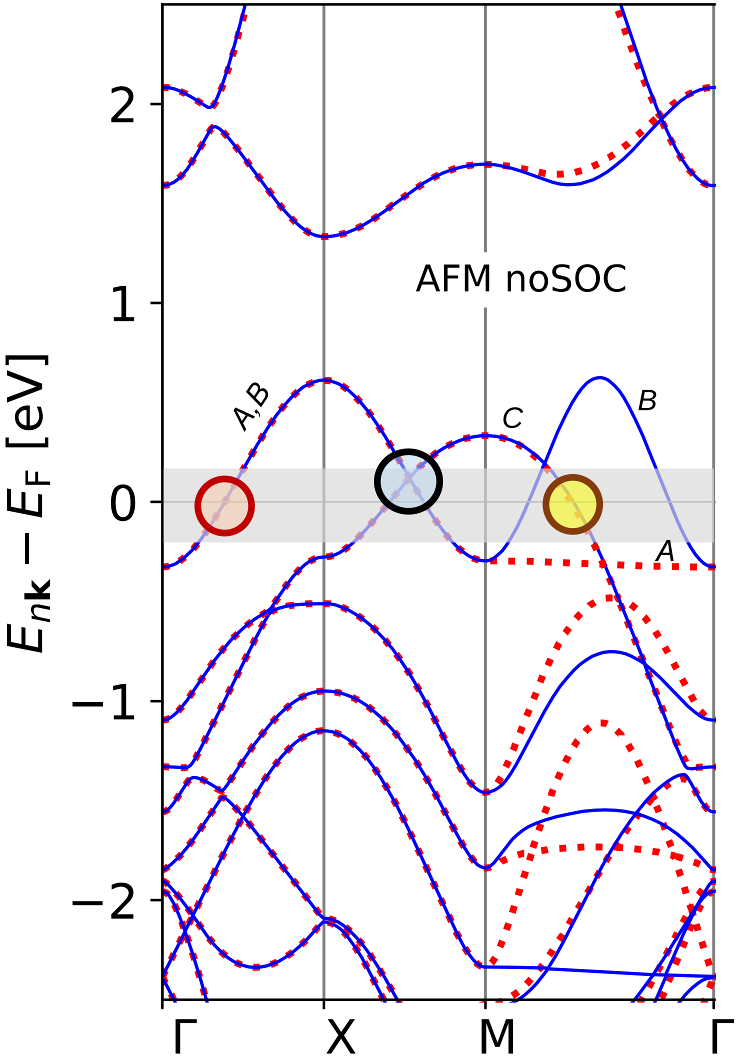
Band Topology of RuO_2

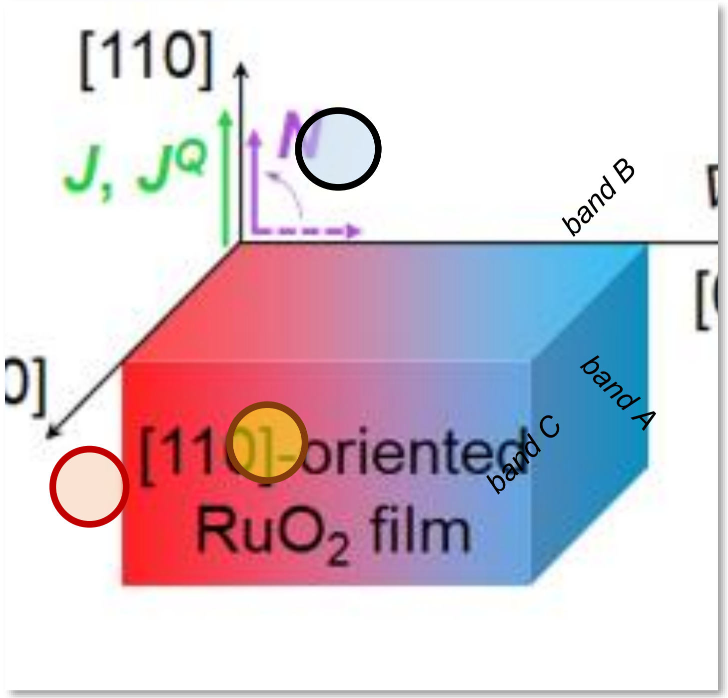
Zhou, Feng, LS, JS, YM et al., arXiv:2305.01410

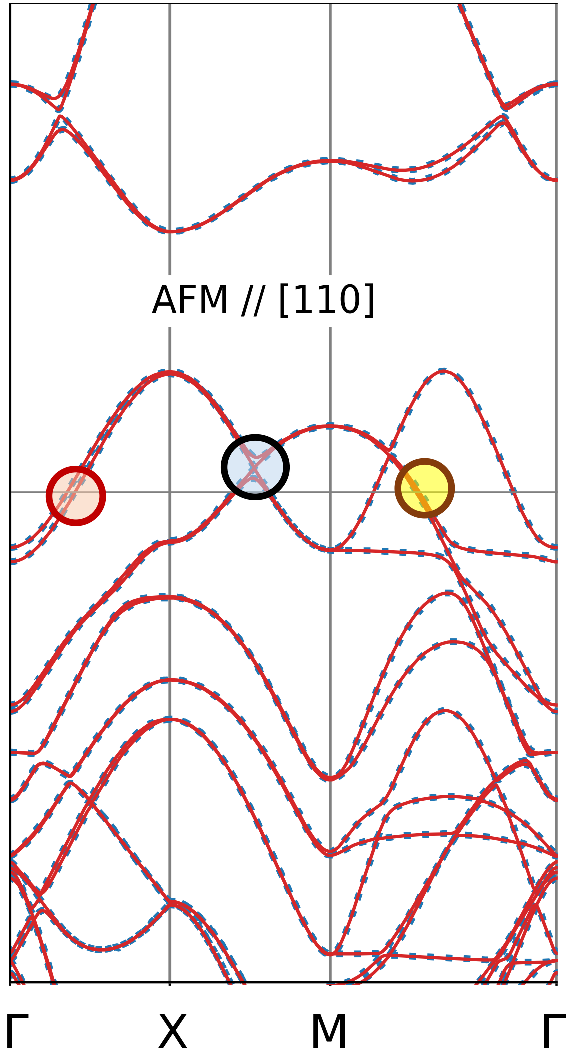


Bands A-B : **strong altermagnetism**

Bands C : **weak altermagnetism**







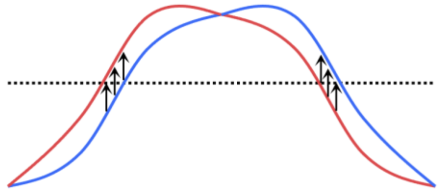
Type I : bands A/B – C

Type II : bands A – B

Type III : bands C

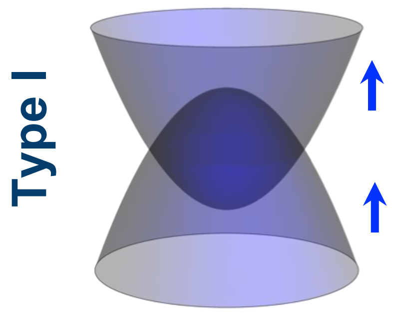
Altermagnetic Transitions

Zhou, Feng, LS, JS, YM et al., arXiv:2305.01410

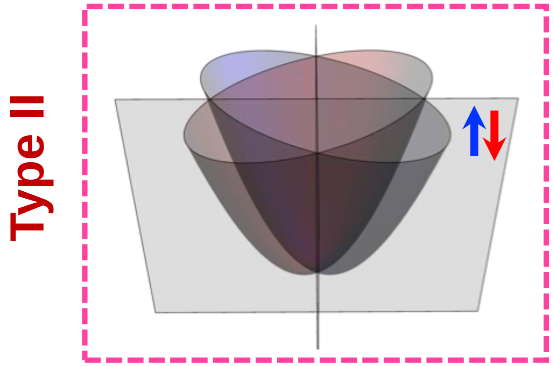


symmetry-enforced

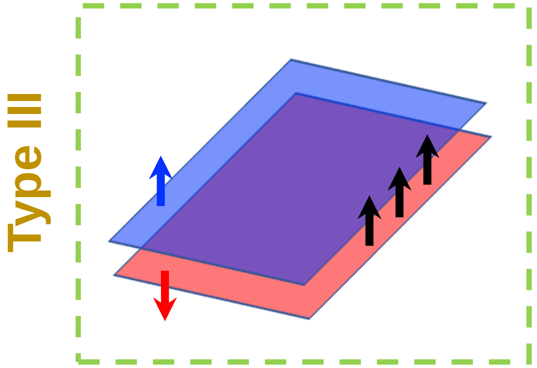
anisotropic exchange-originated



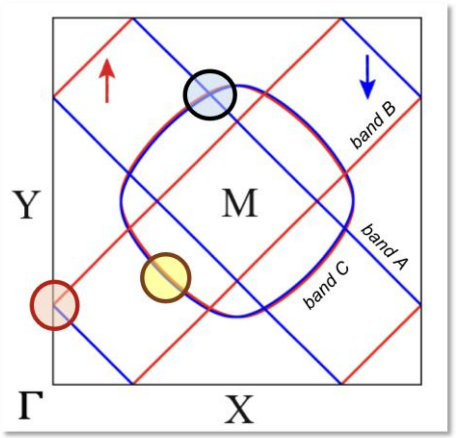
Weyl
pseudo-nodal lines



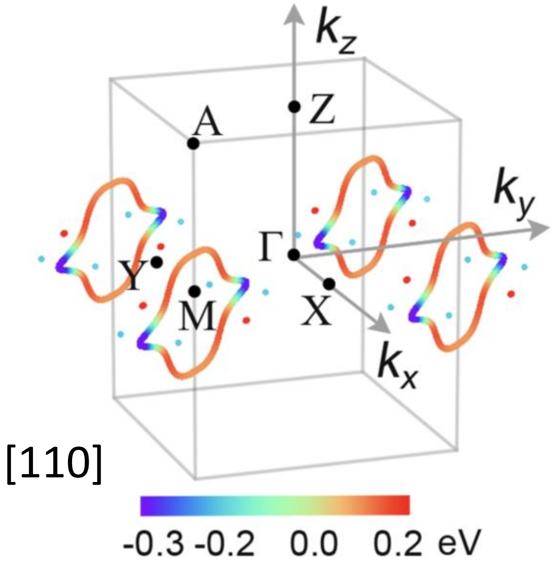
Strong altermagnetism
pseudo-nodal surfaces

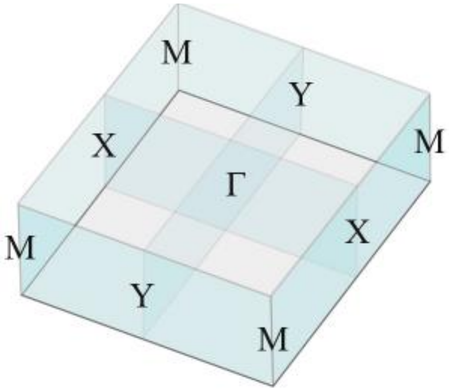


Ladder transitions
weak altermagnetism

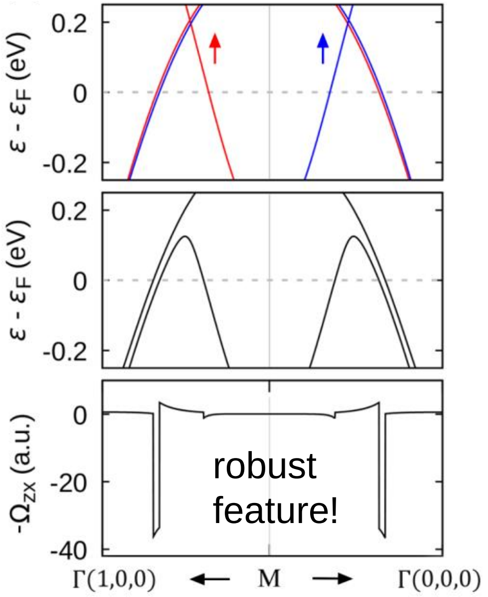


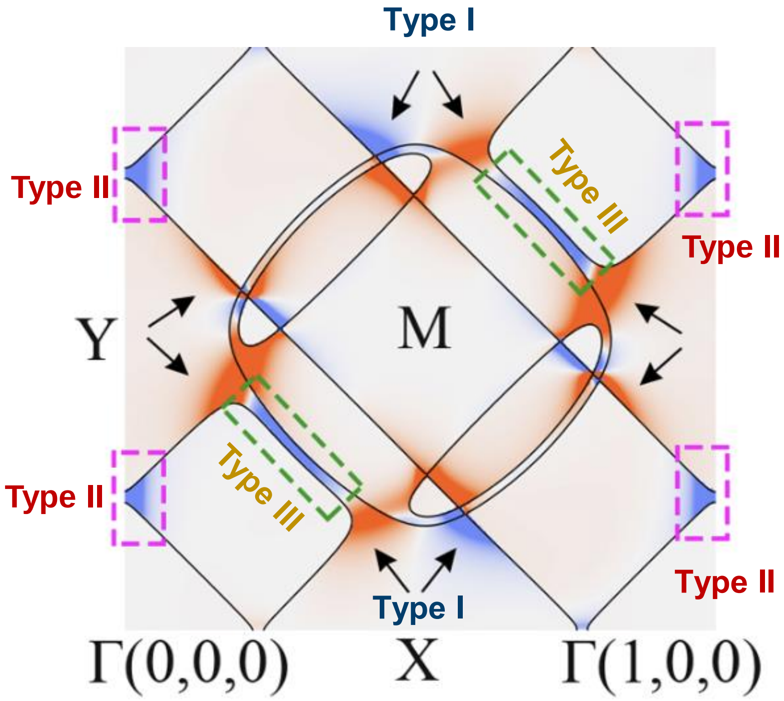
N || [110]





Type II and III :
altermagnetic!





Spin-flip and spin-conserving AHE

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$$\mathbf{L}\cdot\mathbf{S} = L_{\hat{n}}S_{\hat{n}} + \frac{1}{2}\left(L^{+}_{\hat{n}}S^{-}_{\hat{n}} + L^{-}_{\hat{n}}S^{+}_{\hat{n}}\right) \Rightarrow \sigma_H = \sigma^{\uparrow} \pm \sigma^{\downarrow}?$$

- spin relaxation phenomena
- proper definition of the spin current

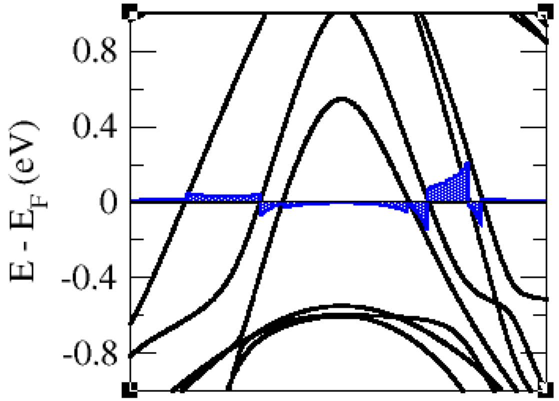
Shi *et al.*, PRL **96**, 76604 (2006)
Gradhand *et al.*, PRL **104**, 186403 (2010)

netic metals [4]). The second mechanism involves spin-orbit driven transitions between bands with similar dispersion which are split in energy across the Fermi level. We shall refer to them as ladder transitions. Both occur at low frequencies, of the order of the spin-orbit coupling strength.

Zhang, Freimuth, Blügel, Souza, Mokrousov, PRL **106**, 117202 (2011)

$$\sigma_z = \frac{e^2\hbar}{4\pi^3}\,\mathrm{Im}\int_{BZ} d\mathbf{k} \sum_{n,m}^{o,e} \frac{\langle\psi_{n\mathbf{k}}|v_x|\psi_{m\mathbf{k}}\rangle\langle\psi_{m\mathbf{k}}|v_y|\psi_{n\mathbf{k}}\rangle}{(\varepsilon_{m\mathbf{k}} - \varepsilon_{n\mathbf{k}})^2}$$

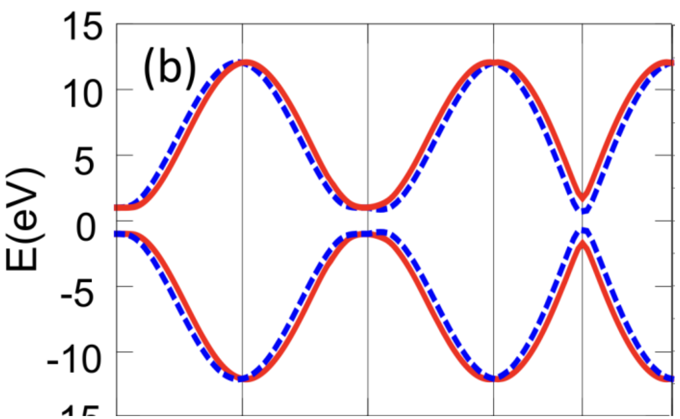
$L1_0$ FePt



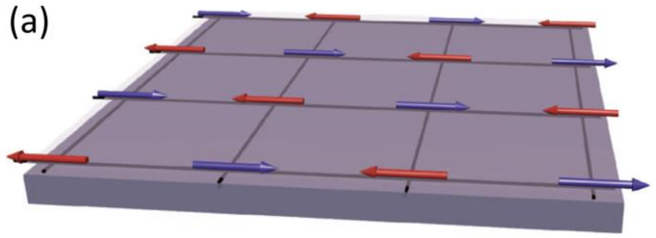
spin-flip only

spectral AHC

Psi-K Workshop, Halle, 2011



SOC ↔ crystal symmetry

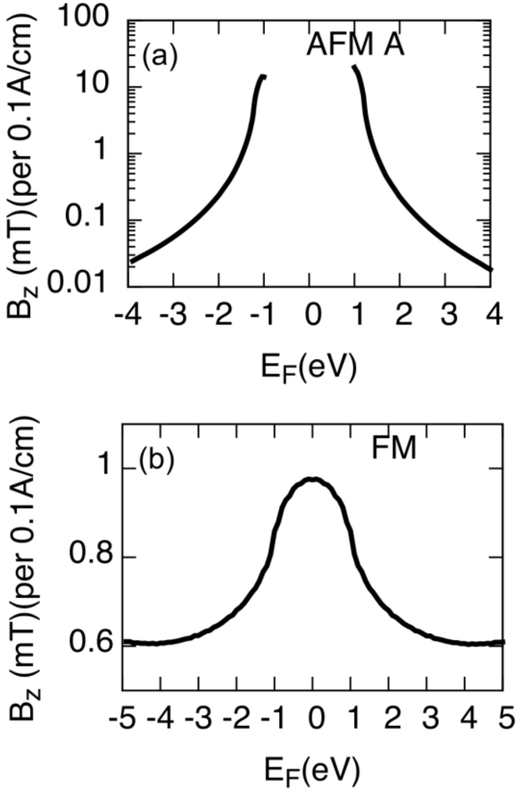


PRL 113, 157201 (2014) PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2014

Relativistic Néel-Order Fields Induced by Electrical Current in Antiferromagnets

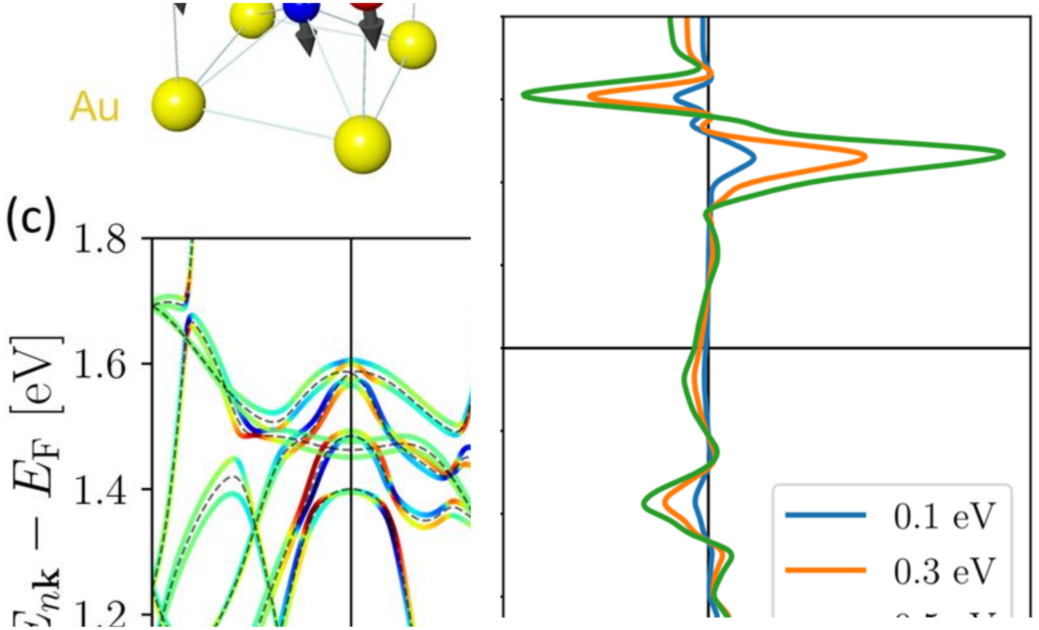
J. Železný,[1,2] H. Gao,[3] K. Výborný,[1] J. Zemen,[4] J. Mašek,[5] Aurélien Manchon,[6] J. Wunderlich,[1,7] Jairo Sinova,[8,1,3] and T. Jungwirth[1,9]

spin-axis angles, as shown in Figs. 3(e) and 3(f). Another important feature, illustrated in Figs. 4(a) and 4(b), is that the interband NSOT in the AFM can be significantly larger than its FM SOT counterpart. The interband nature of the term $\delta\vec{s}^{\text{inter}}$ from Eq. (5) implies that its magnitude is large when two subbands linked by spin-orbit coupling have a small energy spacing. In the calculations shown in Figs. 3(e) and



Chiral Hall effect in AFM can be gigantic

canting ↔ crystal symmetry



Ladder transitions are universal

Kipp, YM et al. Comm. Phys. **4**, 99 (2021)

Type II, III : Spin-flip Transitions

YM, Zhang, Freimuth et al., JPCM **25**, 163201 (2013)

$$\frac{\xi}{(\varepsilon_n^{(1)}-\varepsilon_m^{(1)})^2}\langle\psi^{\sigma'}_{n,0}|v_x|\psi^{\sigma}_{m,0}\rangle \times \sum_{l\neq n;\sigma''}\frac{\langle\psi^{\sigma''}_{l,0}|\mathbf{L}\cdot\mathbf{S}|\psi^{\sigma'}_{n,0}\rangle}{\varepsilon_{n,0}-\varepsilon_{l,0}}\langle\psi^{\sigma}_{m,0}|v_y|\psi^{\sigma''}_{l,0}\rangle$$

$LS^{\uparrow\uparrow}$

1st order perturbation theory: purely spin-conserving

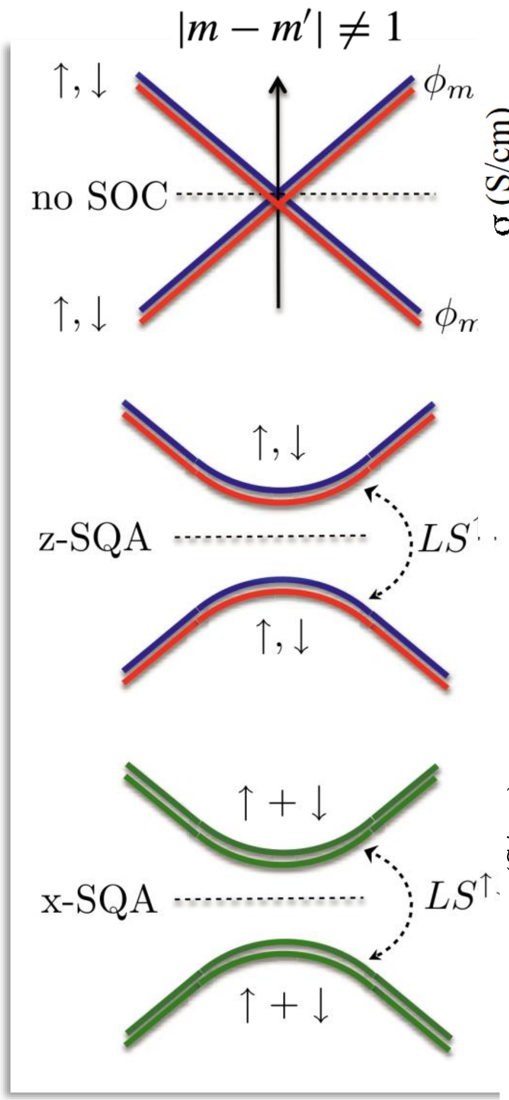
Strong anisotropy expected

Fermi surface, properties

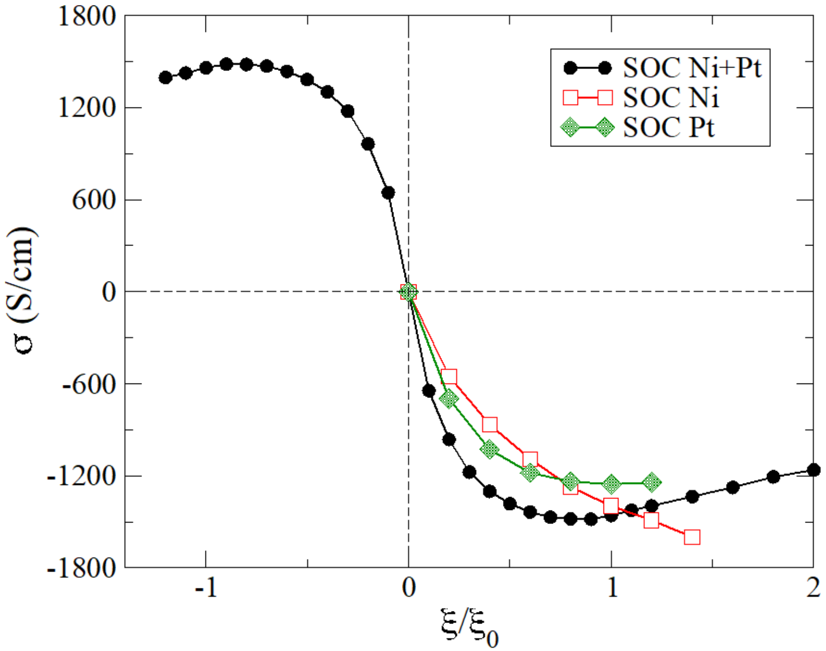
2nd order perturbation theory: purely spin-flip

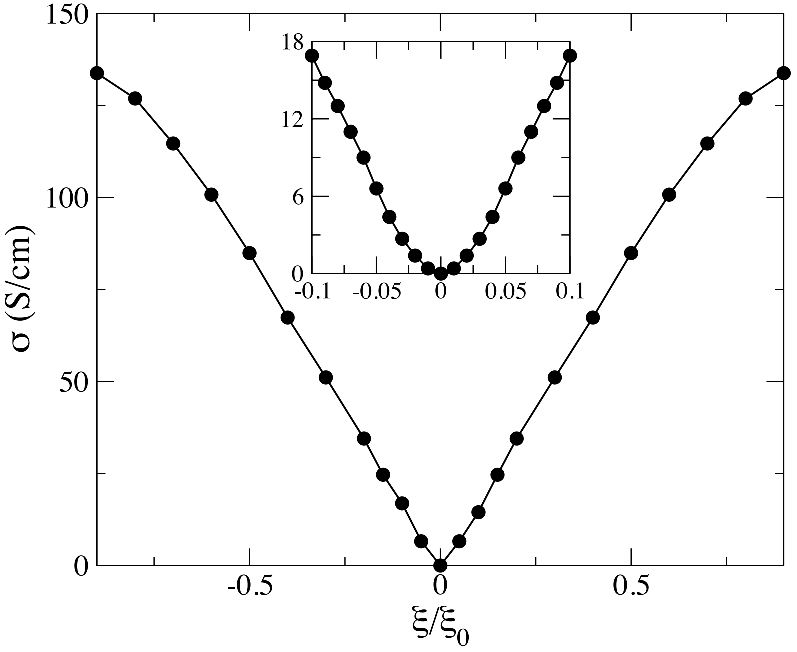
$$\frac{\xi^2}{(\varepsilon_n^{(1)}-\varepsilon_m^{(1)})^2}\sum_{p\neq m;\sigma'''}\frac{\langle\psi^{\sigma'''}_{p,0}|\mathbf{L}\cdot\mathbf{S}|\psi^{\sigma}_{m,0}\rangle}{\varepsilon_{m,0}-\varepsilon_{p,0}}\langle\psi^{\sigma'}_{n,0}|v_x|\psi^{\sigma'''}_{p,0}\rangle \times \sum_{l\neq n;\sigma''}\frac{\langle\psi^{\sigma''}_{l,0}|\mathbf{L}\cdot\mathbf{S}|\psi^{\sigma'}_{n,0}\rangle}{\varepsilon_{n,0}-\varepsilon_{l,0}}\langle\psi^{\sigma}_{m,0}|v_y|\psi^{\sigma''}_{l,0}\rangle$$

$LS^{\uparrow\downarrow}$



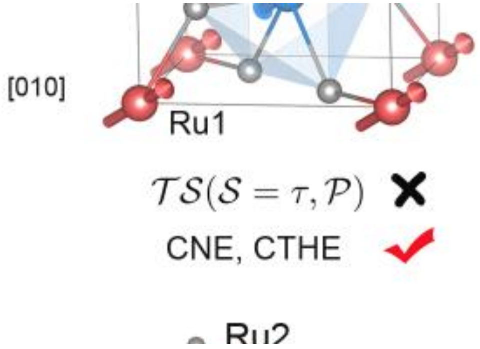
same energy & *k*

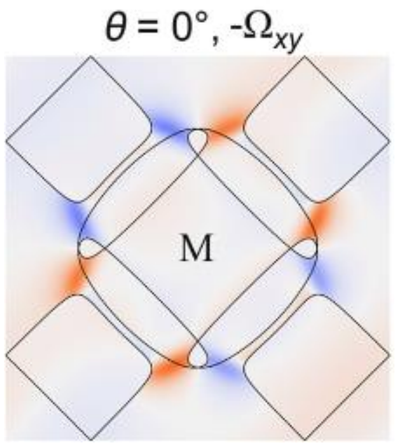


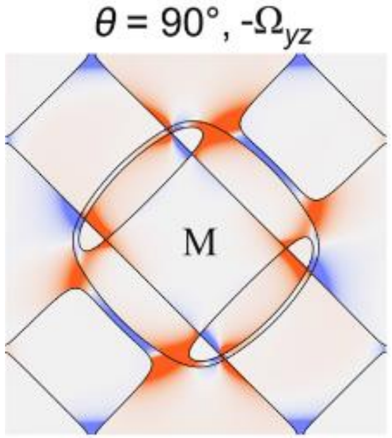


Anisotropy in RuO_2

Zhou, Feng, LS, JS, YM et al., arXiv:2305.01410

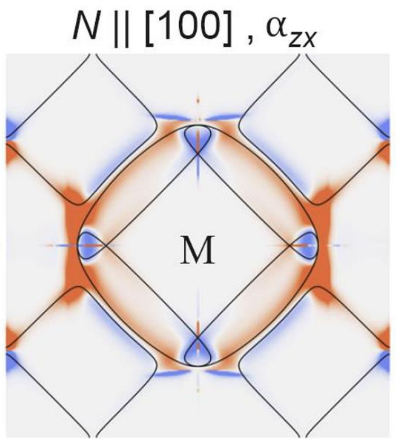




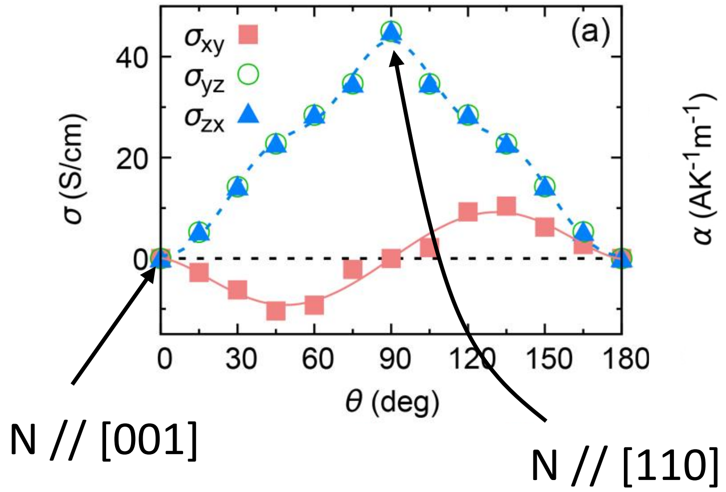


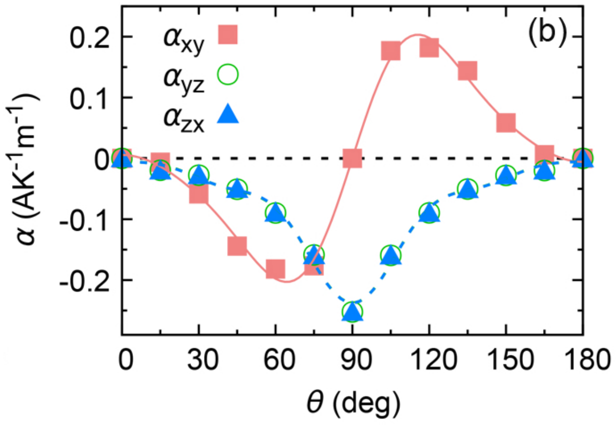
Access thermal phenomena:

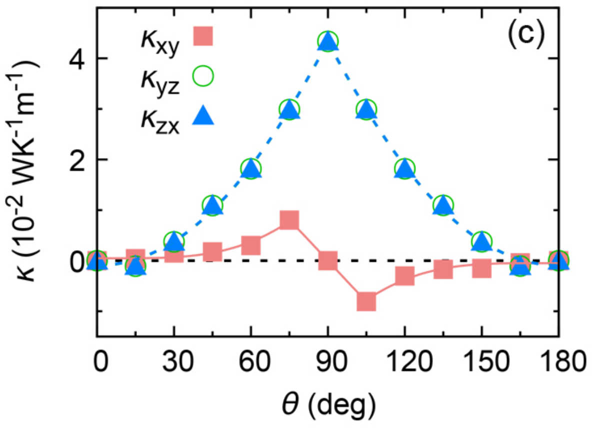
$$R_{ij}^{(n)} = \int_{-\infty}^{\infty} (\varepsilon-\mu)^n \left(-\frac{\partial f}{\partial \varepsilon}\right) \sigma_{ij}^{T=0}(\varepsilon) d\varepsilon$$

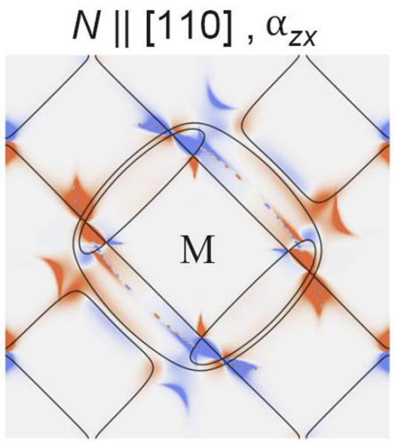


anomalous Hall conductivity	anomalous Nernst conductivity	anomalous thermal Hall conductivity
$\sigma_{ij} = R_{ij}^{(0)}$	$\alpha_{ij} = -R_{ij}^{(1)}/eT$	$\kappa_{ij} = R_{ij}^{(2)}/e^2T$
Crystal Hall effect	Crystal Nernst effect	Crystal thermal Hall effect









compare to **0.2 – 0.3** **1.5 – 4.5** in Mn_3X

Wiedemann-Franz Law

Zhou, Feng, LS, JS, YM et al., arXiv:2305.01410

Sommerfeld expansion $\sigma_{ij} \approx \sigma_{ij}^{T=0}(\mu)$ $\kappa_{ij} \approx \frac{\pi^2 k_B^2 T}{3e^2}\sigma_{ij}^{T=0}(\mu)$

Lorentz ratio: $L_{ij} = \kappa_{ij}/\sigma_{ij}T,$ *Sommerfeld constant*

$$L_{ij}(T \to 0) = L_0 = \pi^2 k_B^2/3e^2$$

inelastic

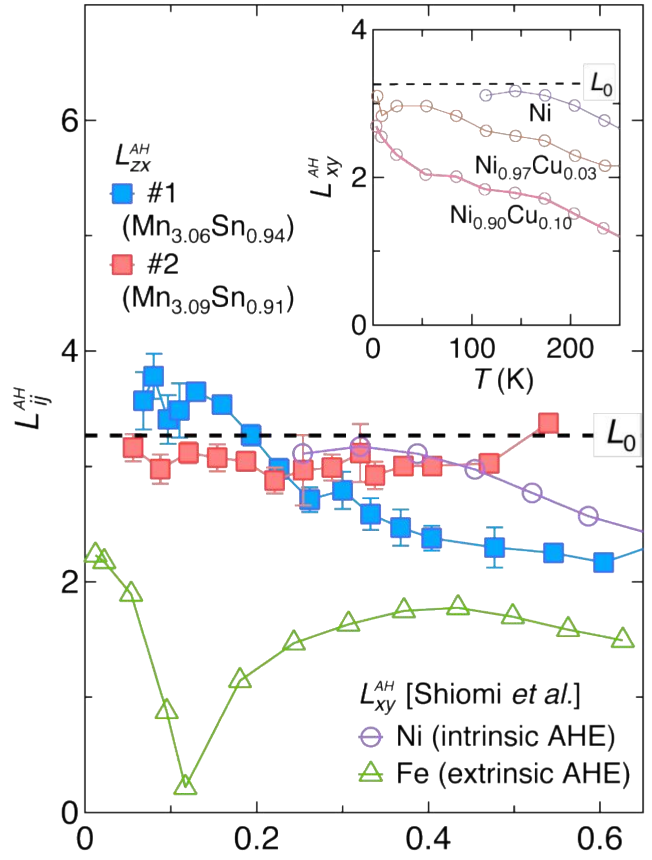
Traditionally believed to give an estimate for extrinsic / intrinsic origins

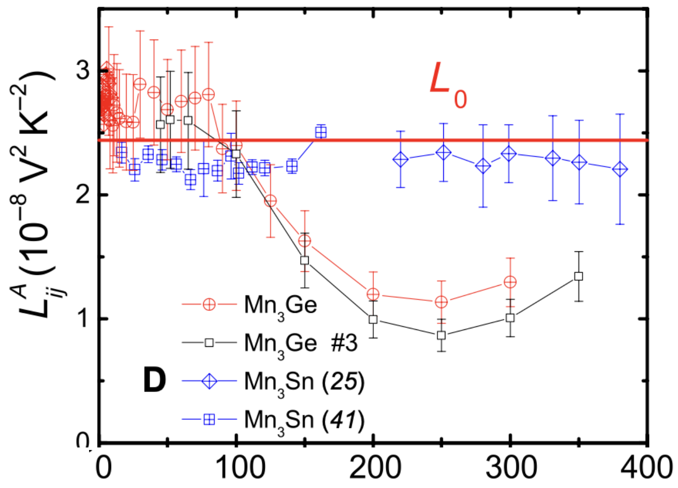
small-angle inelastic scattering has stronger impact on heat flow than electron momentum flow [Ziman, 1972]

Mn_3Sn and Mn_3Ge: intrinsic by far, negligible inelastic scattering

Where does WF law violation come from?

Sugii et al. arXiv:1902.06601 (2019)





Wiedemann-Franz Law Violation

Zhou, Feng, LS, JS, YM et al., arXiv:2305.01410

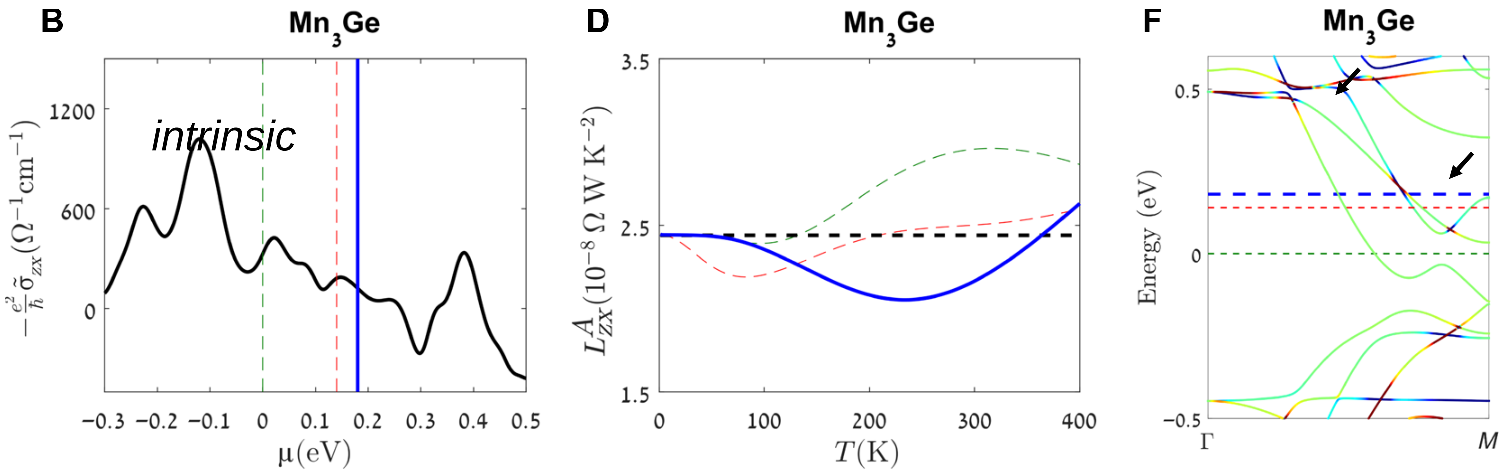
At T = 0 pondering function gives WF law: $$F_n(\varepsilon) = \left(\frac{\varepsilon - \mu}{k_B T}\right)^n \frac{\partial f}{\partial \varepsilon}$$

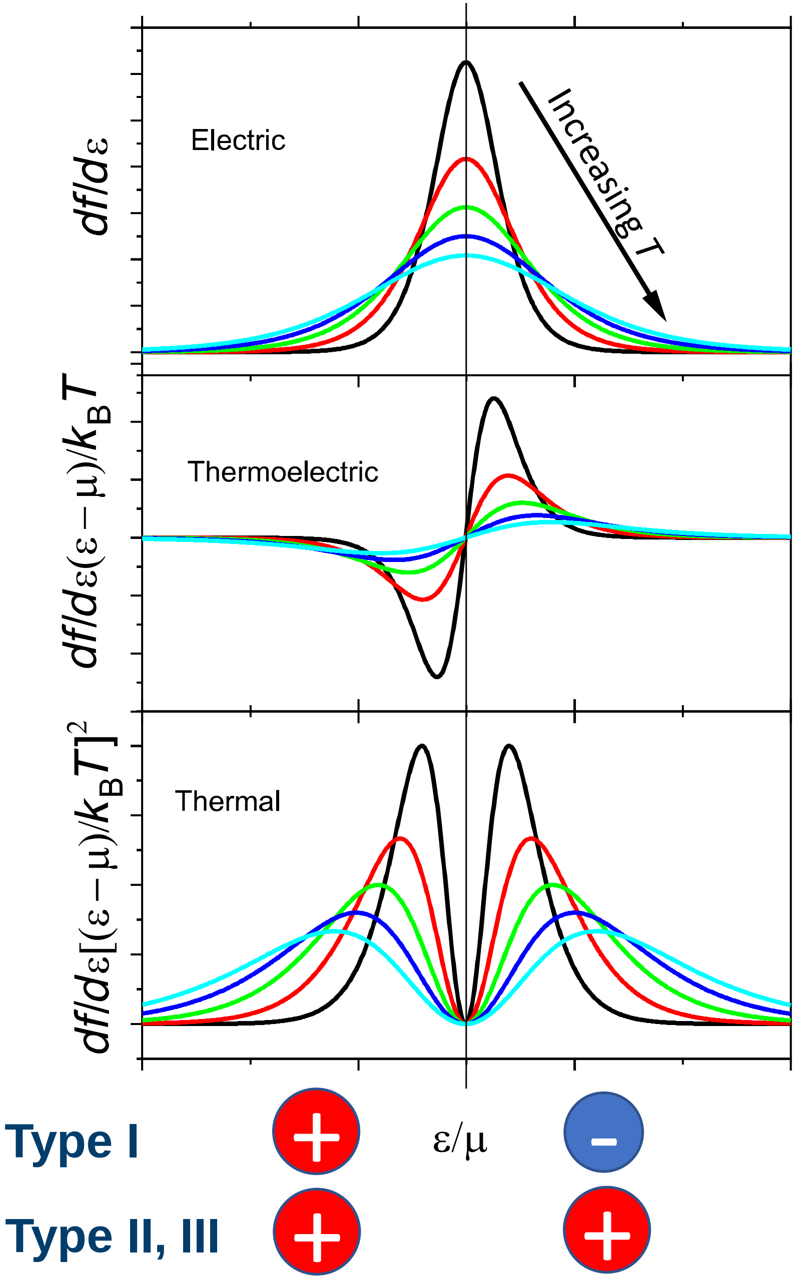
WF law deviations can be caused by pondering function

Purely antisymmetric AHC around the chemical potential:

WF law is satisfied

WF nodes in Mn_3Sn

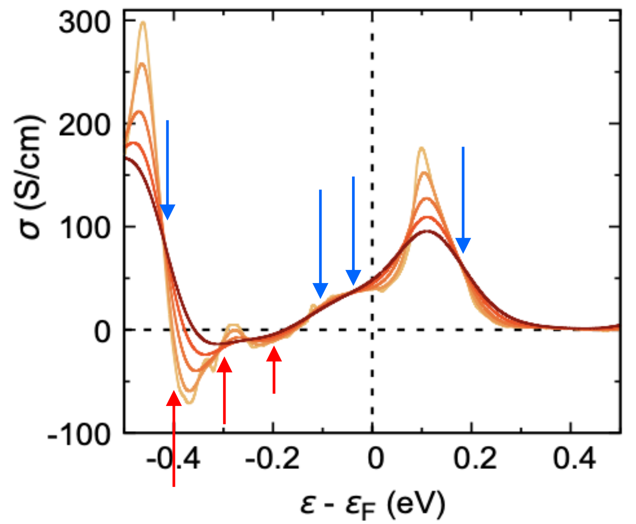


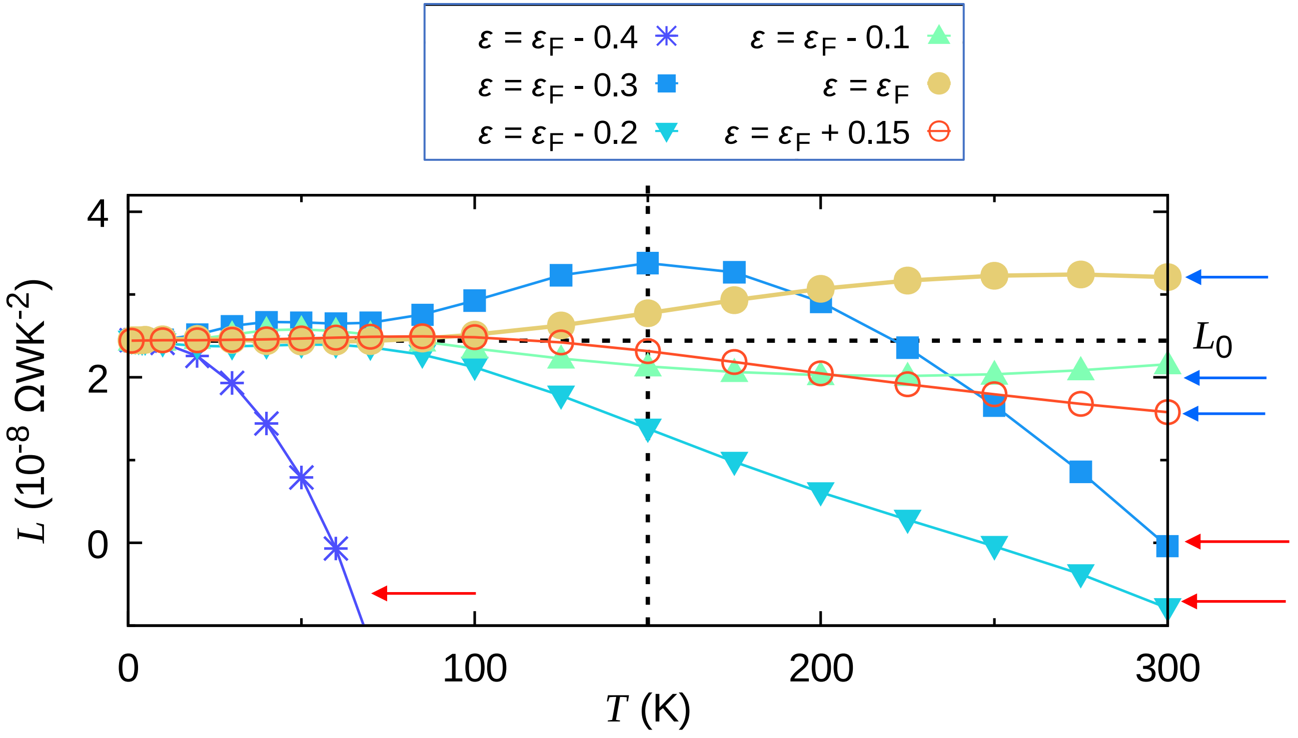


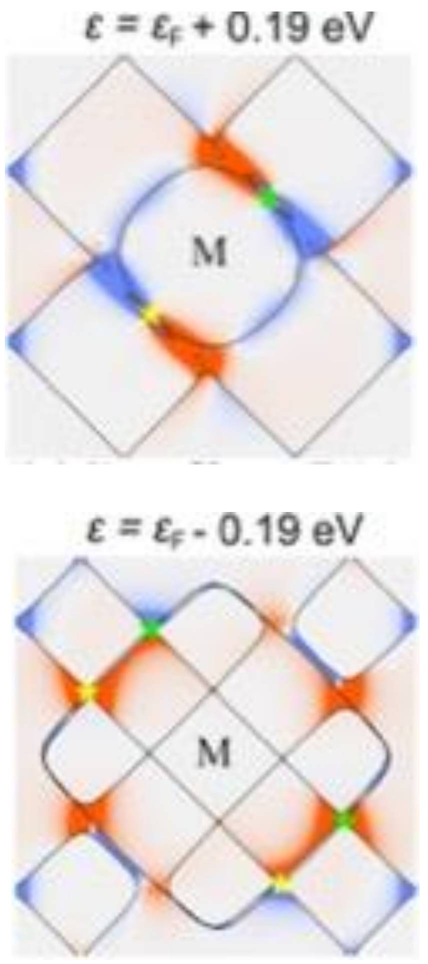
Xu et al. Sci. Adv. **6**, eaaz3522 (2020)

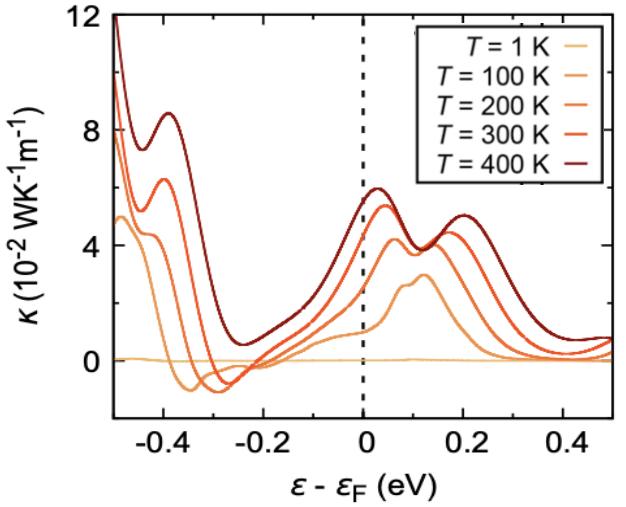
Wiedemann-Franz Law in RuO_2

Zhou, Feng, LS, JS, YM et al., arXiv:2305.01410









WF ratio is very sensitive to band filling

Use WF law to identify the type of transitions?

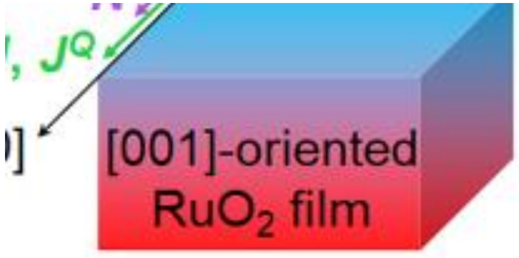
Anisotropy of electrical & thermal transport:

position and character of different types of features?

Photophysics with RuO_2?

Adamantopoulos, YM, WF, LS, JS et al. (2023)

actually has inversion symmetry…



PHYSICAL REVIEW LETTERS **130**, 166302 (2023)

Time-Reversal-Even Nonlinear Current Induced Spin Polarization

Cong Xiao,[1,2,*,†] Weikang Wu,[3,*] Hui Wang,[4,*] Yue-Xin Huang,[4,*] Xiaolong Feng,[4] Huiying Liu,[5,4,‡] Guang-Yu Guo,[6,7,§] Qian Niu,[8] and Shengyuan A. Yang[4]

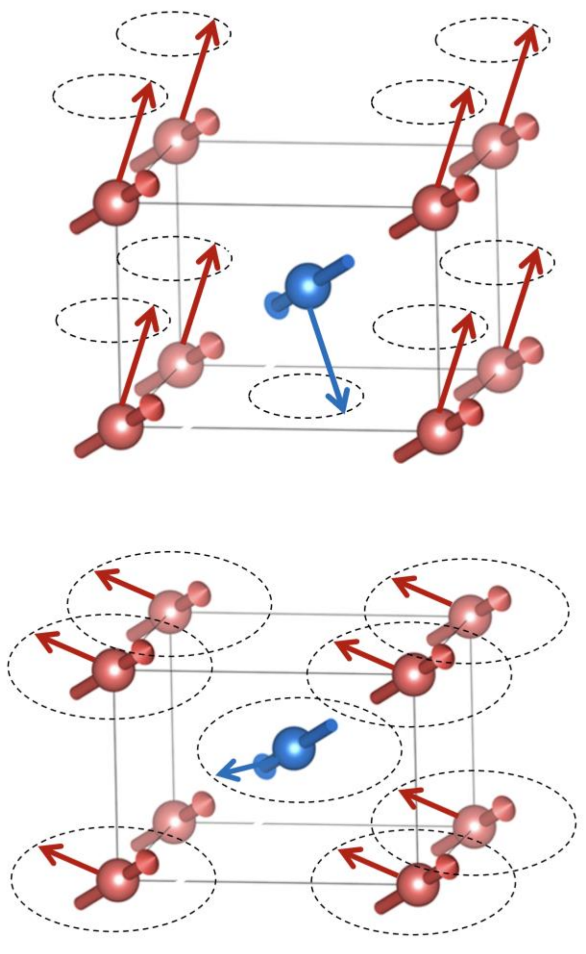
Linear *in electric field*	✓	✗	✗
Quadratic *in electric field (photo)*	✗	✓	✓
	*Orbital **Hall*** *Spin **Hall*** *Anomalous **Hall***	*Orbital, spin **accumulation***	***Torques***

Photo Orbital Magnetism : RuO_2

Adamantopoulos, YM, WF, LS, JS et al. (2023)

Strong canting in RuO_2

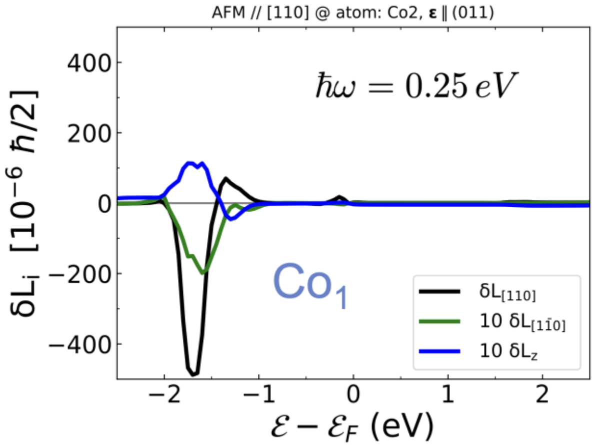
Giant induced moments in CoF_2

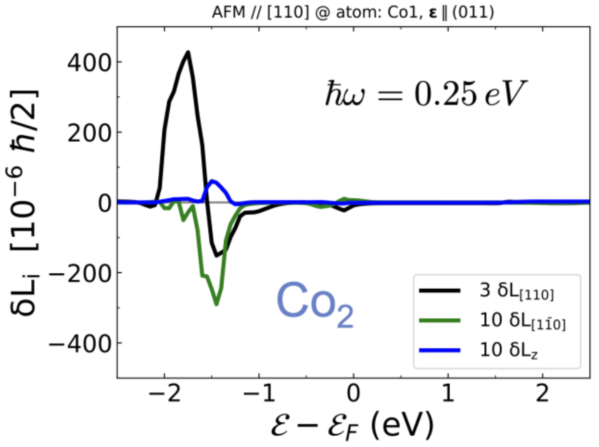


Poster session

RuO_2

CoF_2





Outlook

- ✓ Clearly, altermagnets combine properties of FMs, *PT*-AFMs, and NC-AFMs
- ✓ Crystal symmetries play a role in classification of topological features / excitations
- ✓ Electrically and thermally altermagnets are not worse than (e.g.) Mn_3X type
- ✓ Canting properties in ground state and out of equilibrium: anisotropic!

  may give a handle on dynamics driven by magnetic field
- ✓ Expect some exciting orbital properties
- ✓ Sublattice-dependent currents and response may be more relevant
- ✓ Interplay of structural and magnetic chirality: new ideas for magno-phononics?