MAX PLANCK GESELLSCHAFT

TOPOLOGY IN THERMOELECTRIC MATERIALS

Claudia Felser

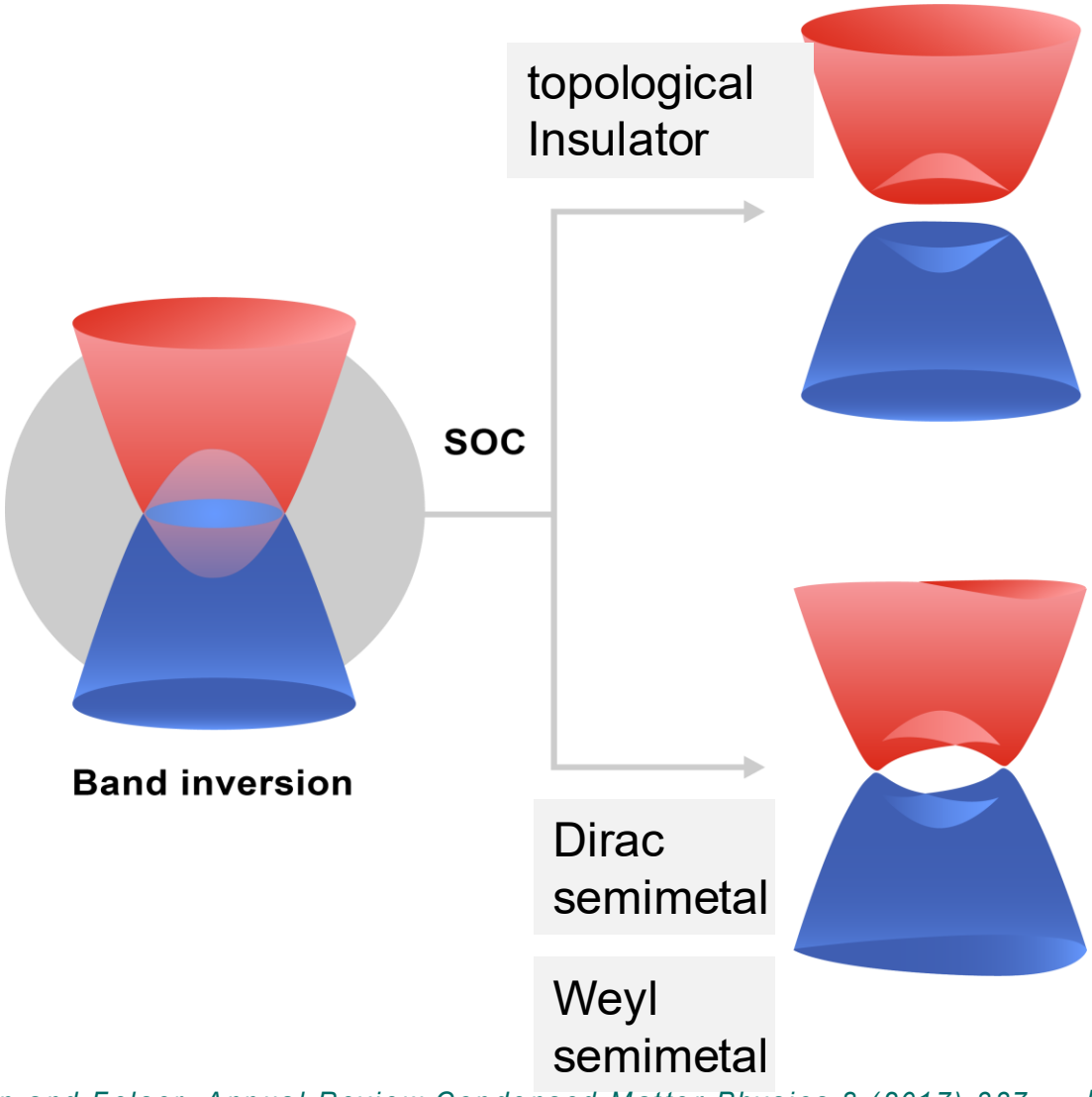
WILHELM UND ELSE HERAEUS-STIFTUNG

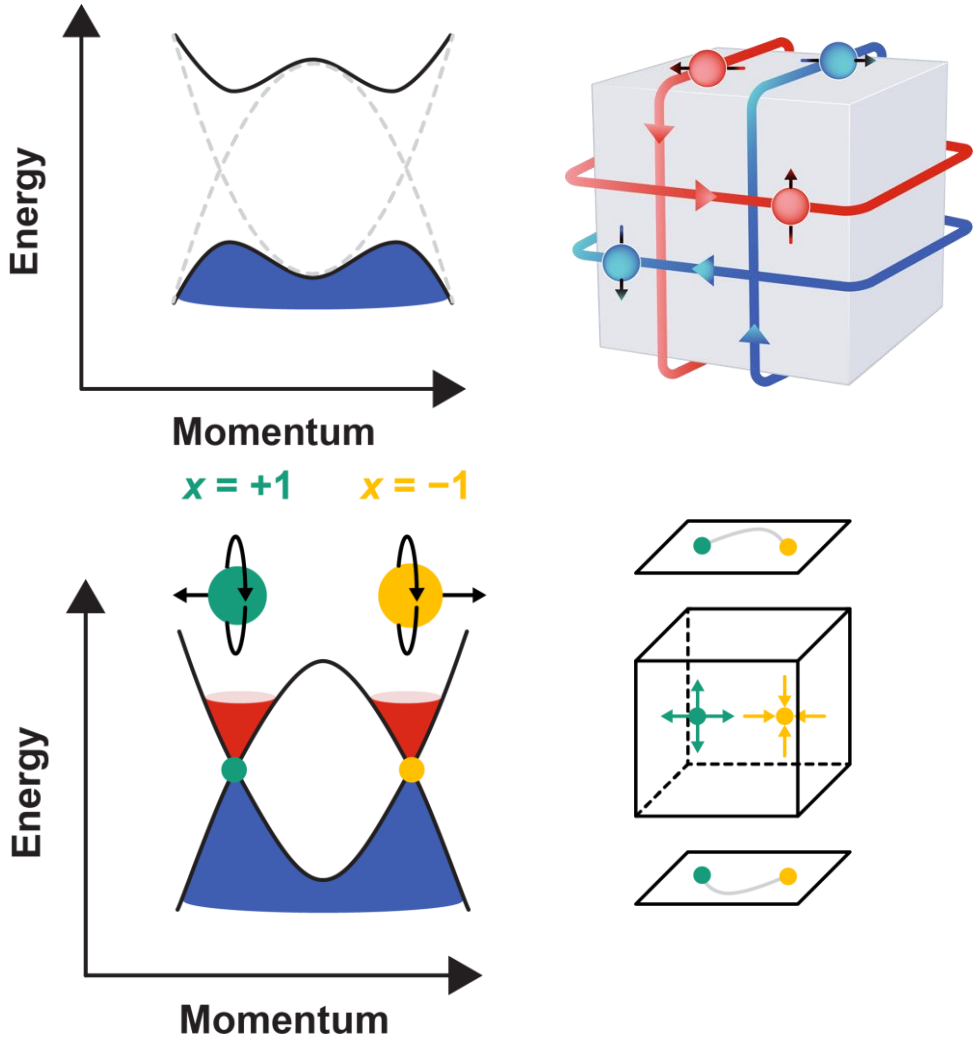
https://www.we-heraeus-stiftung.de/

SPIN PHENOMENA INTERDISCIPLINARY CENTER

SPICE

TOPOLOGY

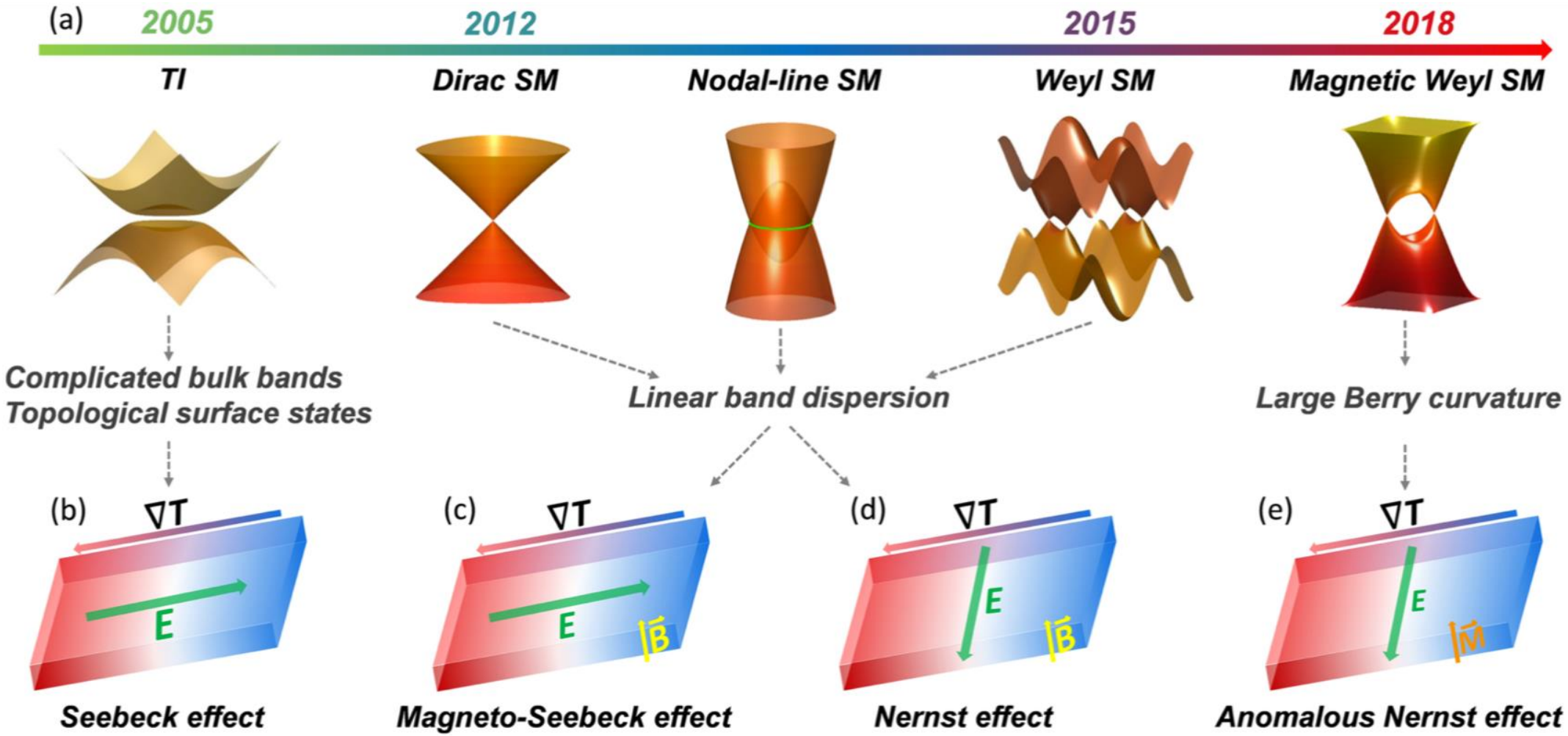




Yan and Felser, Annual Review Condensed Matter Physics 8 (2017) 337

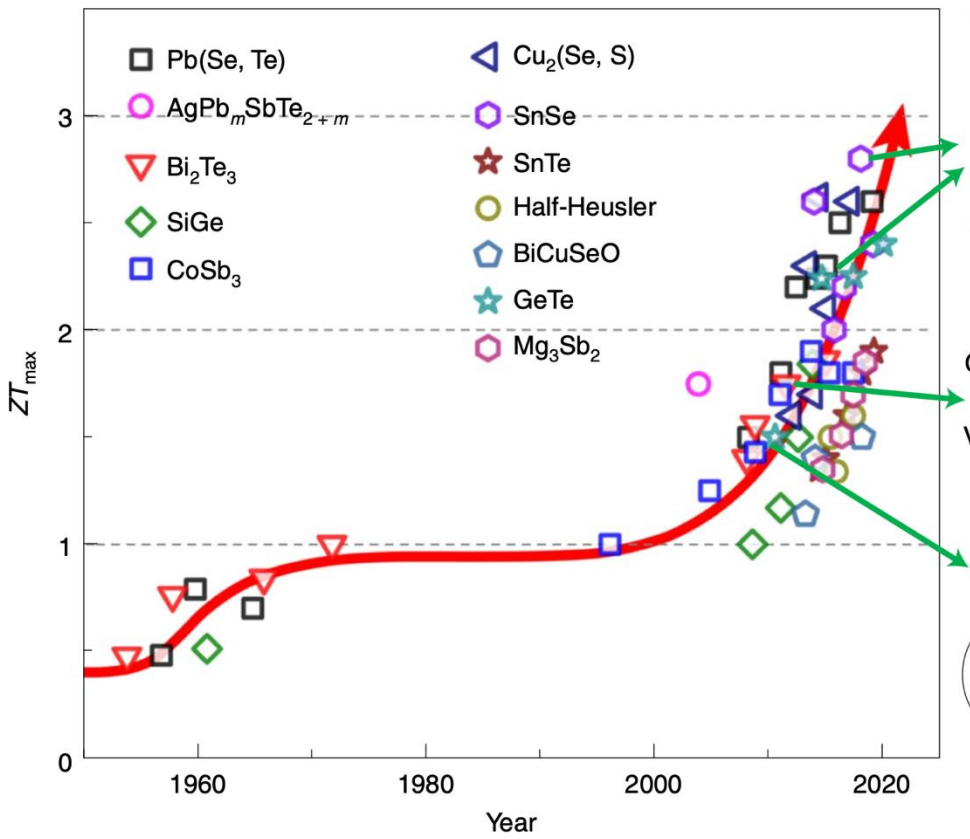
He, Toriyama, Snyder, Felser, Pan; MRS Bulletin 50 (2025) 1

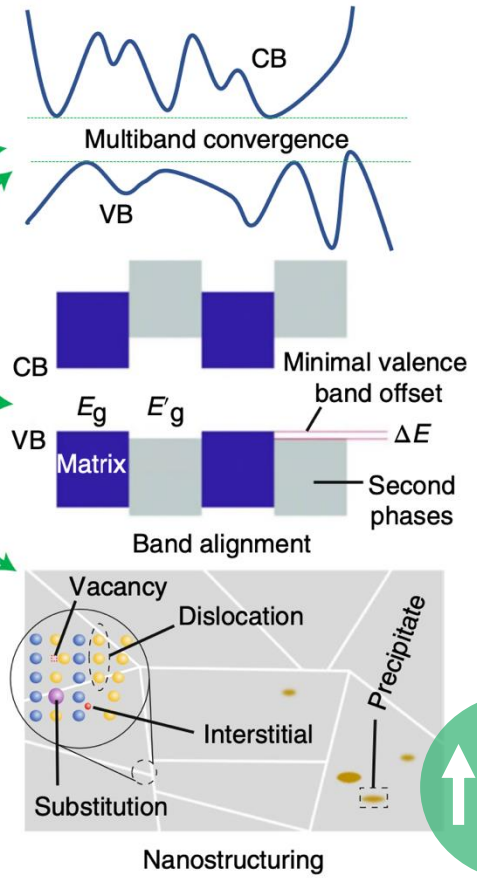
TOPOLOGY AND THERMOELECTRICS



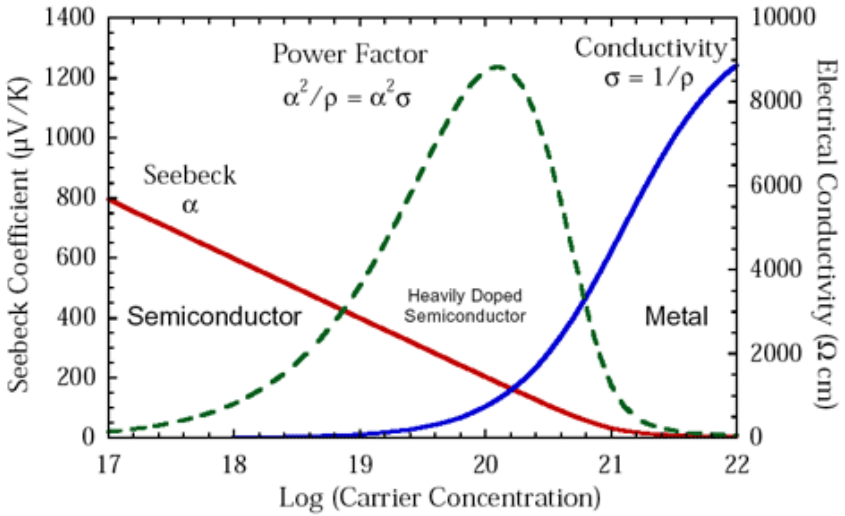
Fu et al., APL Mat. 8 (2020) 040913

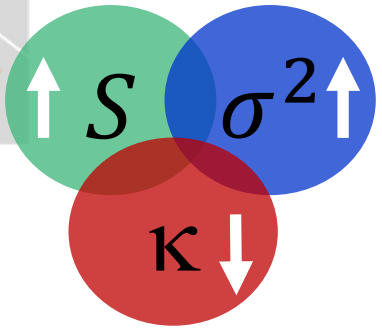
THERMOELECTRICS





$$ZT = \frac{S^2\sigma}{\kappa}T$$



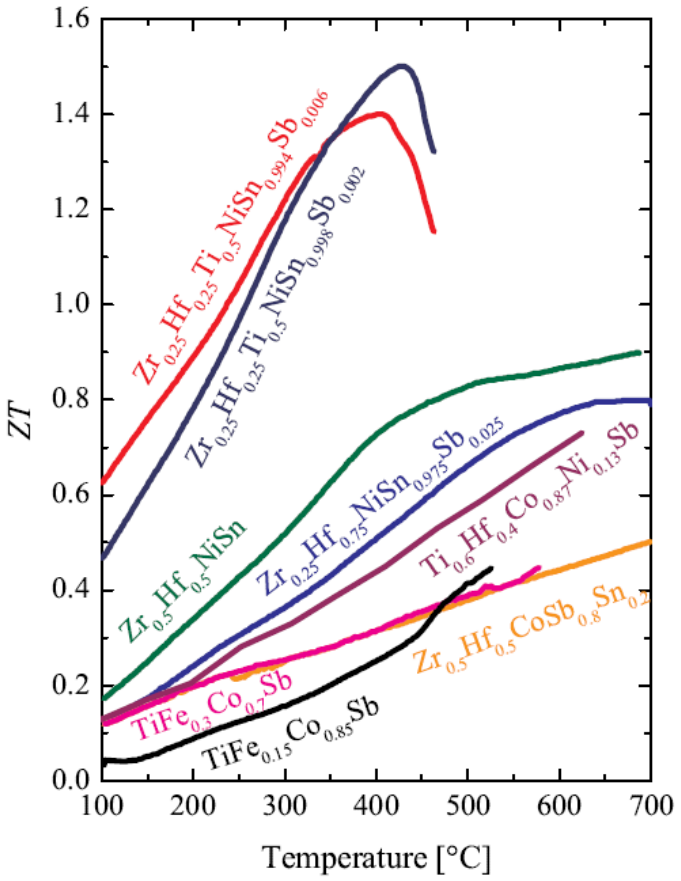


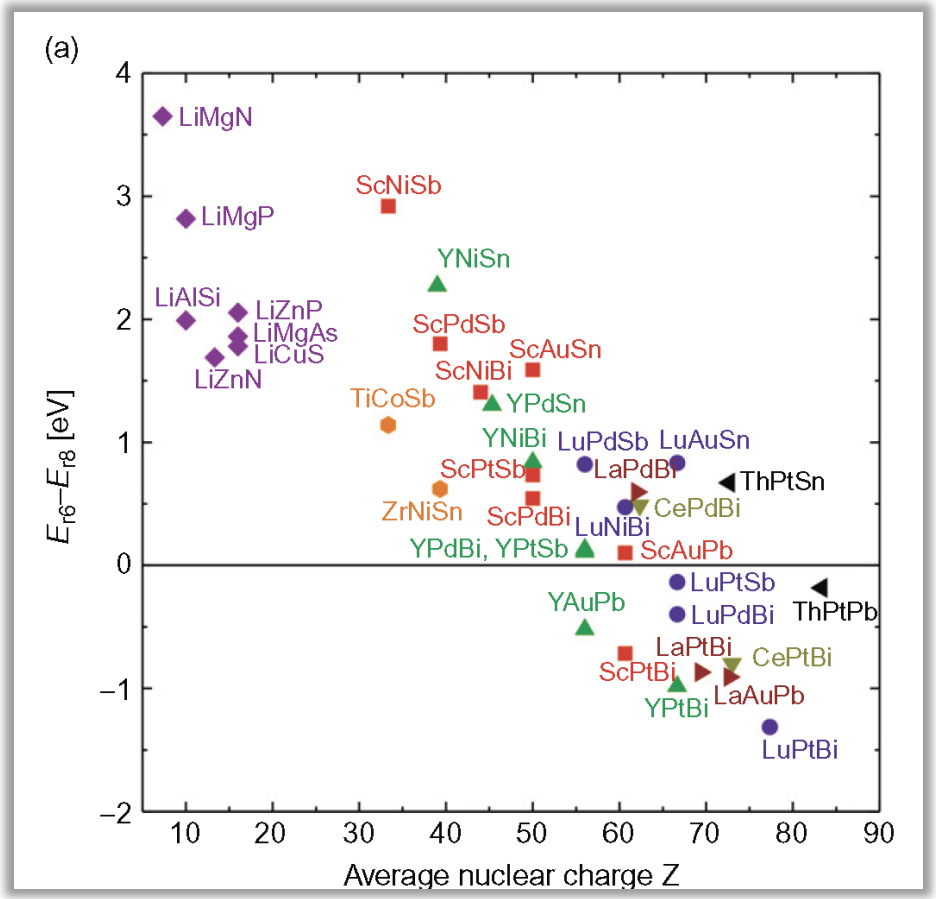
Key:

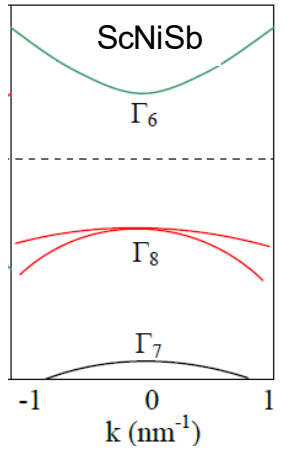
- **Increase Seebeck**
- Increase electrical conductivity
- Decrease thermal conductivity

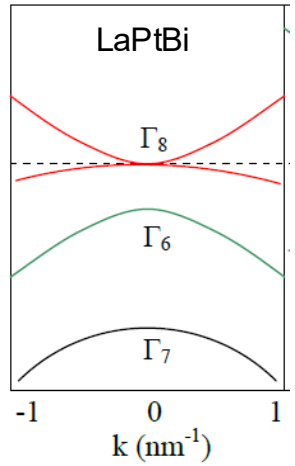
Qingyu Yan & Mercouri G. Kanatzidis Nat. Mat. 21, 503–513 (2022), J.Snyder, E. S. Toberer, Nat. Mat. 7 (2008) 105.

THERMOELECTRICS, TOPOLOGY AND HEUSLER





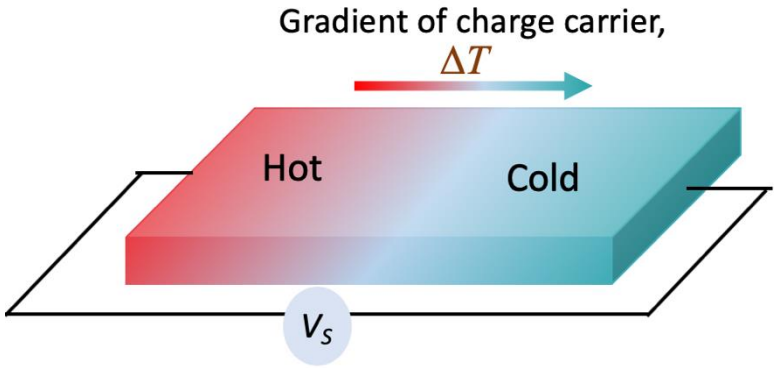


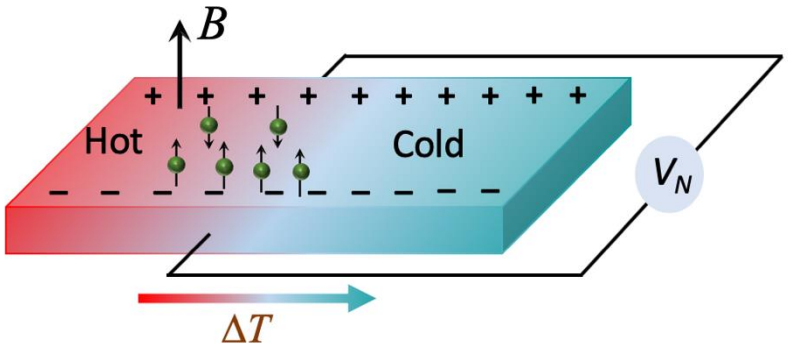


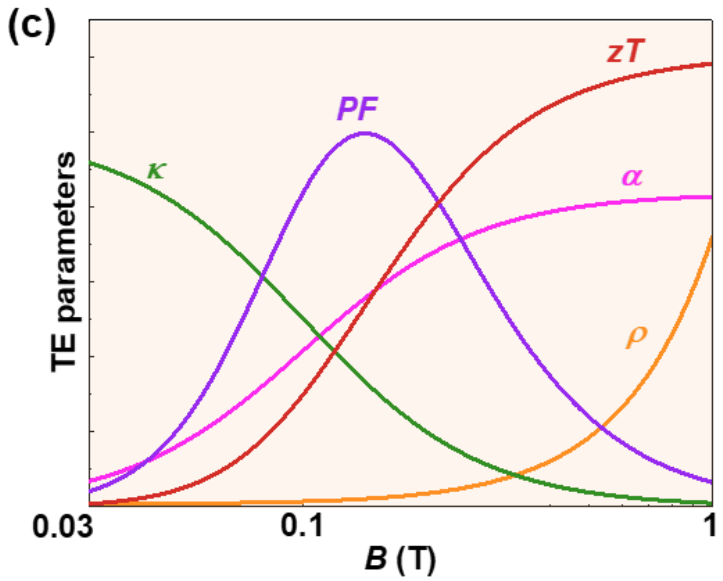
Ouardi et al. ,CF Phys. Rev. B 82 (2010) 085108
Ouardi et al. ,CF, APL 97 (2010) 252113
Patent Bosch, Mainz, US Patent DE 10 2010 029 968, 20,130,156,636,

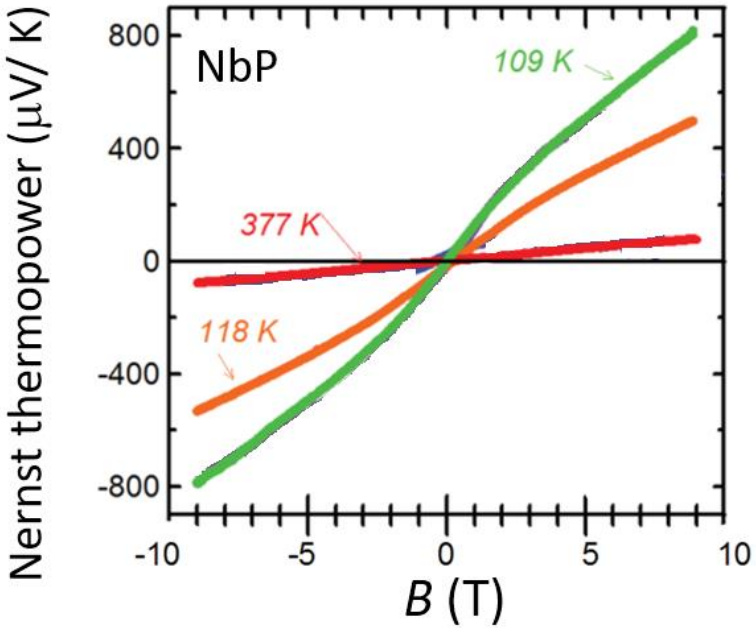
Graf, Felser, Parkin, Progress in Solid State Chemistry (2011)
Chadov, Qi, Kübler, Zhang, Felser Nature Mat. 9 (2010) 541

SEEBECK AND NERNST











J.Snyder, E. S. Toberer, Nat. Mat. 7 (2008) 105.

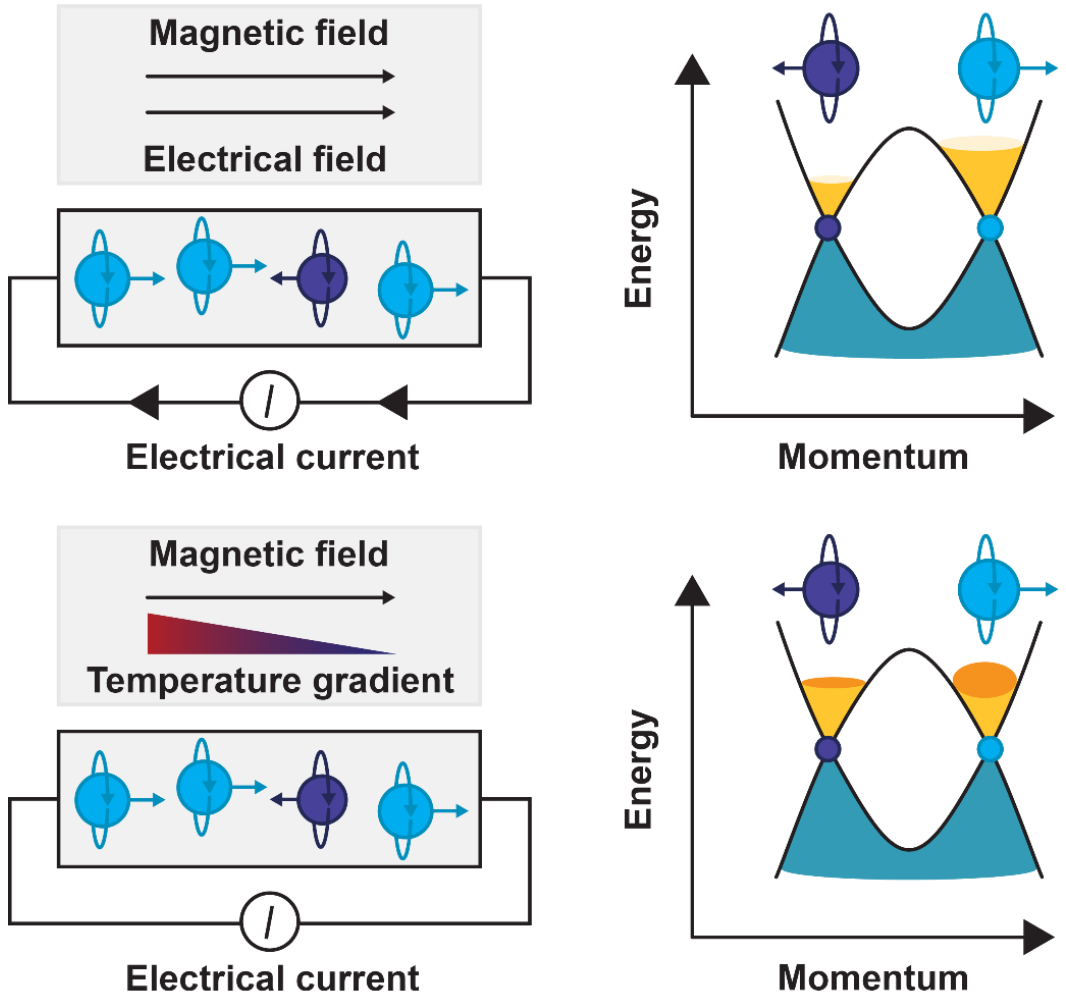
Sarah J. Watzman, et al., Physical Review B 97 (2018) 161404(R)

WEYL SEMIMETAL

3D topological Weyl - transport measurements:

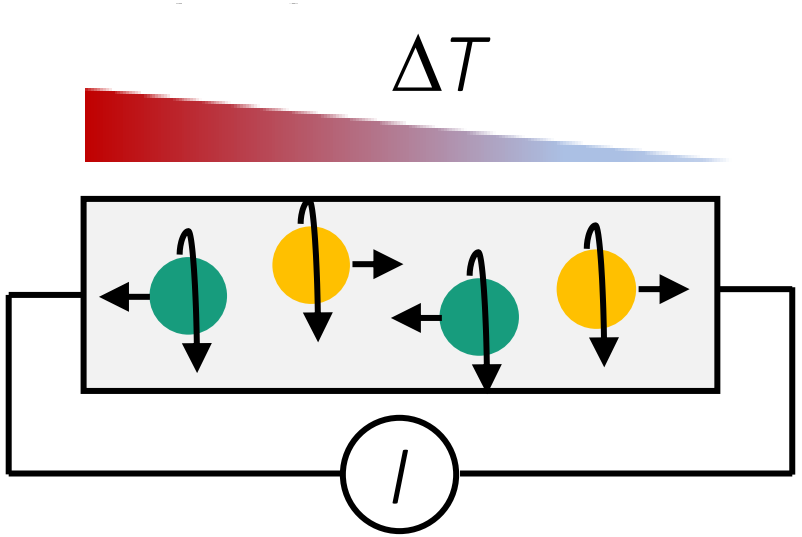
1. Weyl points
2. chiral anomaly
3. axial gravitational anomaly

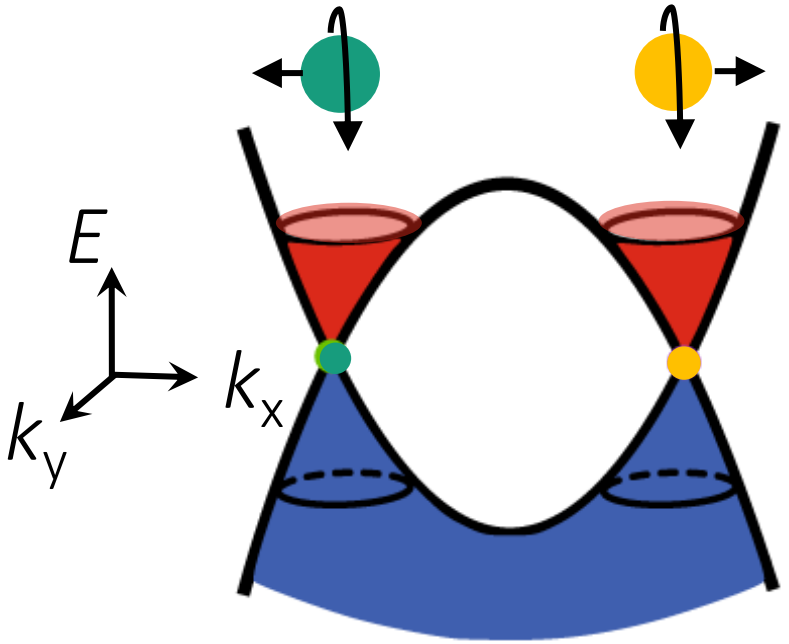
$$A = -\left(\frac{L^2}{2\pi\ell_B^2}\right)\left(\frac{Le\dot{k}_z}{2\pi}\right) = -V\frac{e^3}{4\pi^2\hbar^2}\mathbf{E}.\mathbf{B}$$



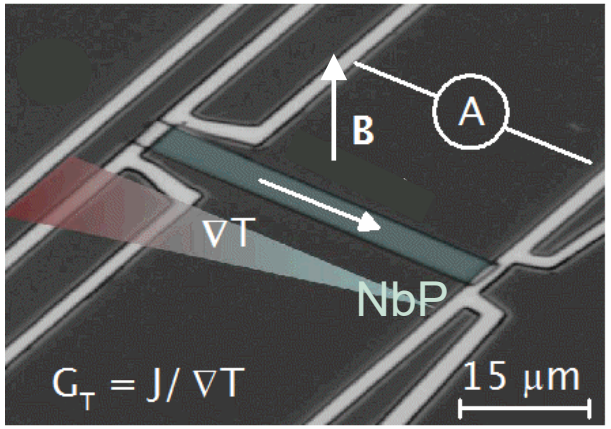
Johannes Gooth et al., Nature 547 (2017) 324

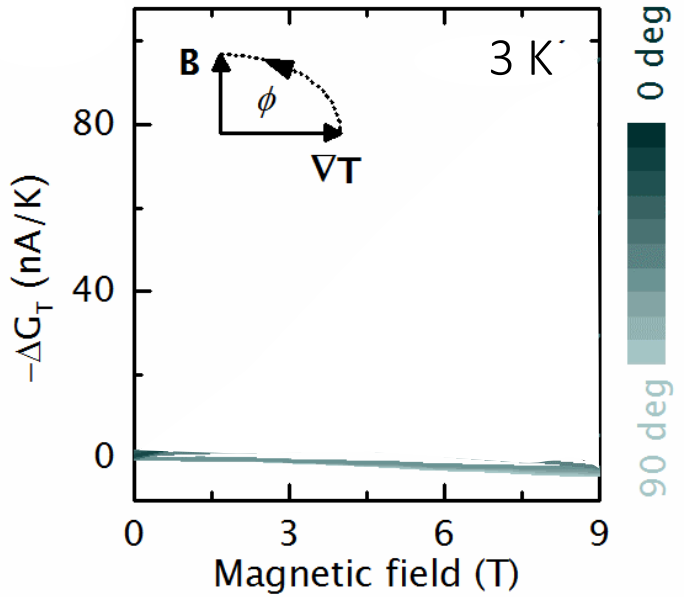
AXIAL GRAVIATIONAL ANOMALY





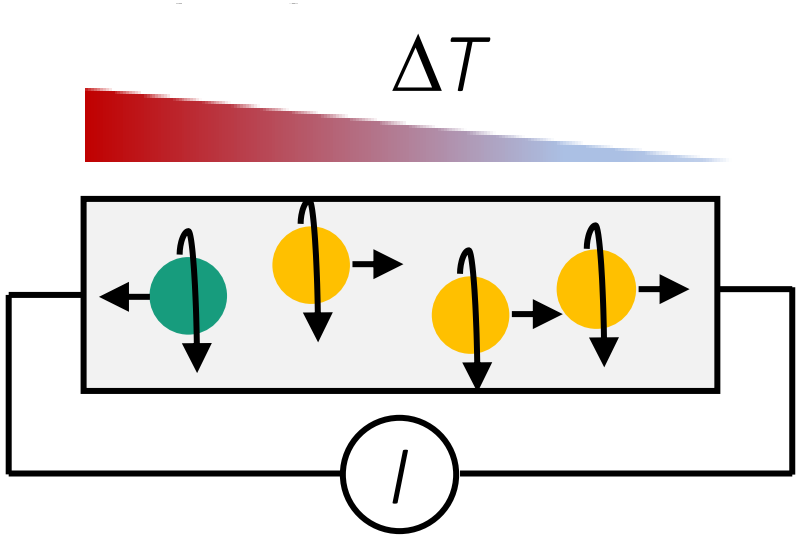
$\chi = +1 \quad \chi = -1$

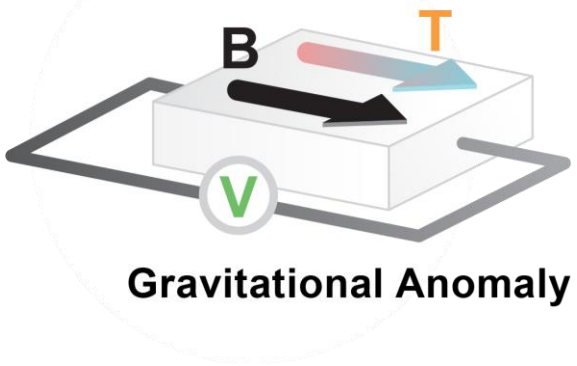


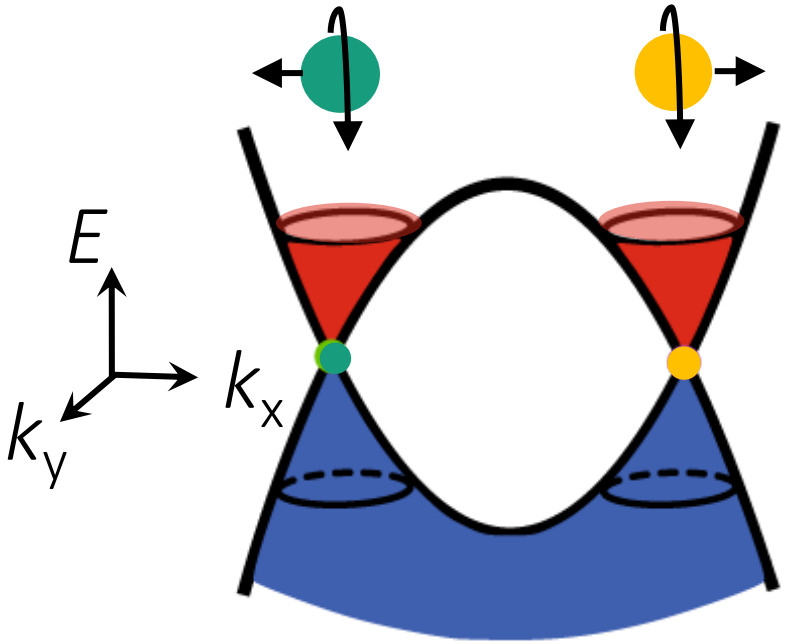


Johannes Gooth et al., Nature 547 (2017) 324

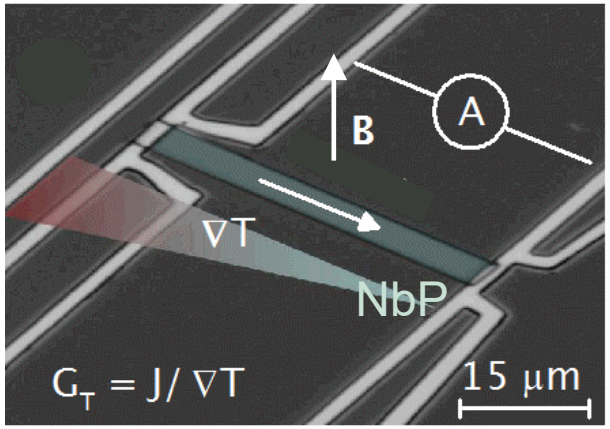
AXIAL GRAVIATIONAL ANOMALY

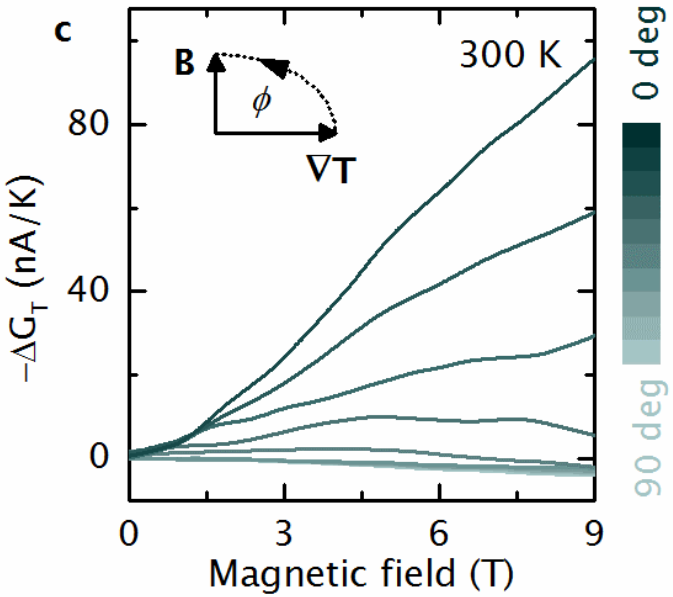






$\chi = +1$ $\chi = -1$

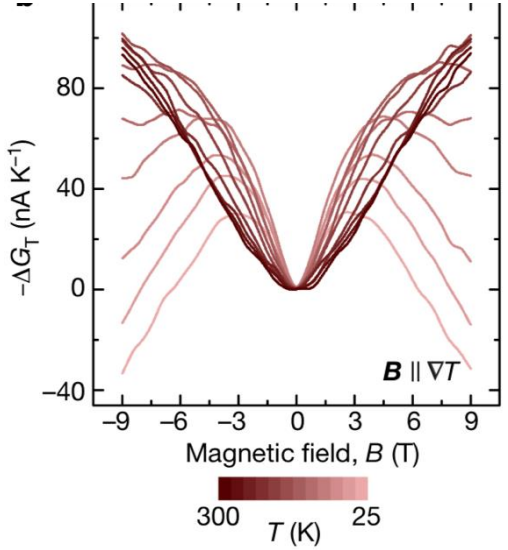


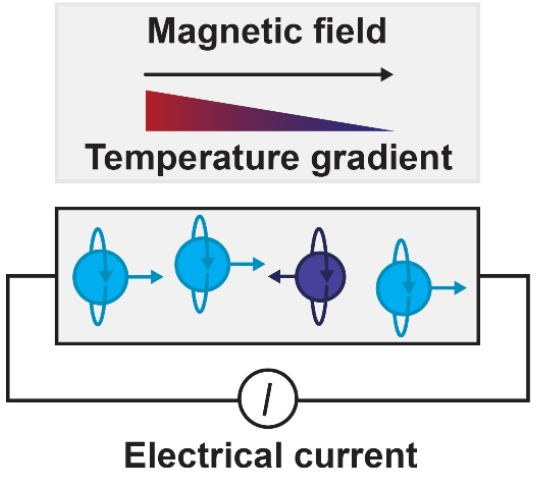


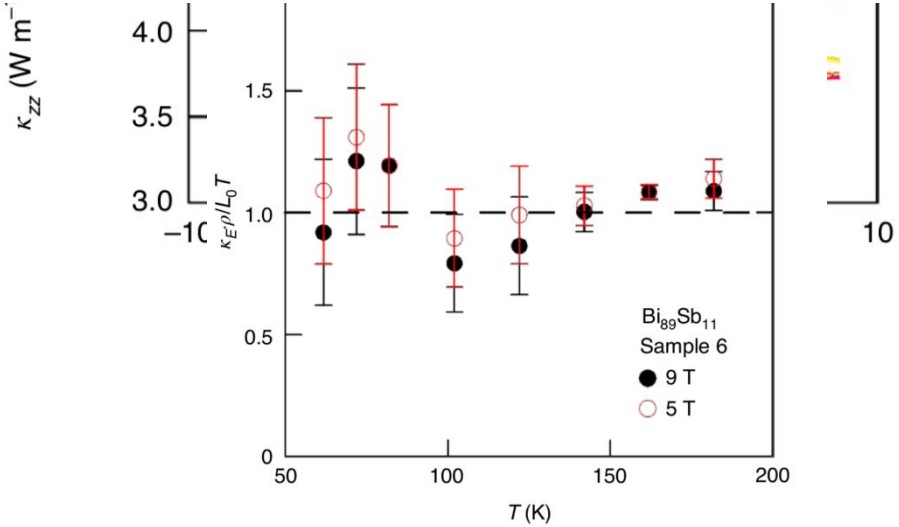
Johannes Gooth et al., Nature 547 (2017) 324

CHIRAL AND AXIAL GRAVITATIONAL ANOMALY

	Materials	S (μV/K)	α (A/mK)	ρ (μΩ cm)	κ (W/mK)
Ordinary Nernst	Bi	21700 at 5 T	/	/	/
	NbP	800 at 9 T	/	1140	438
	Cd_3As_2	129 at 3 T	/	300	2.44
	$ZrTe_5$	1902 at 13 T	/	98700	5.51
	Mg_2Pb	195 at 10 T	/	85.1	97.3
	$NbSb_2$	639 at 9 T	/	123	83.1
	WTe_2	7210 at 9 T	/	1717	114



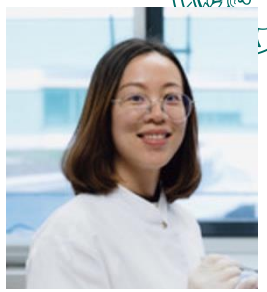


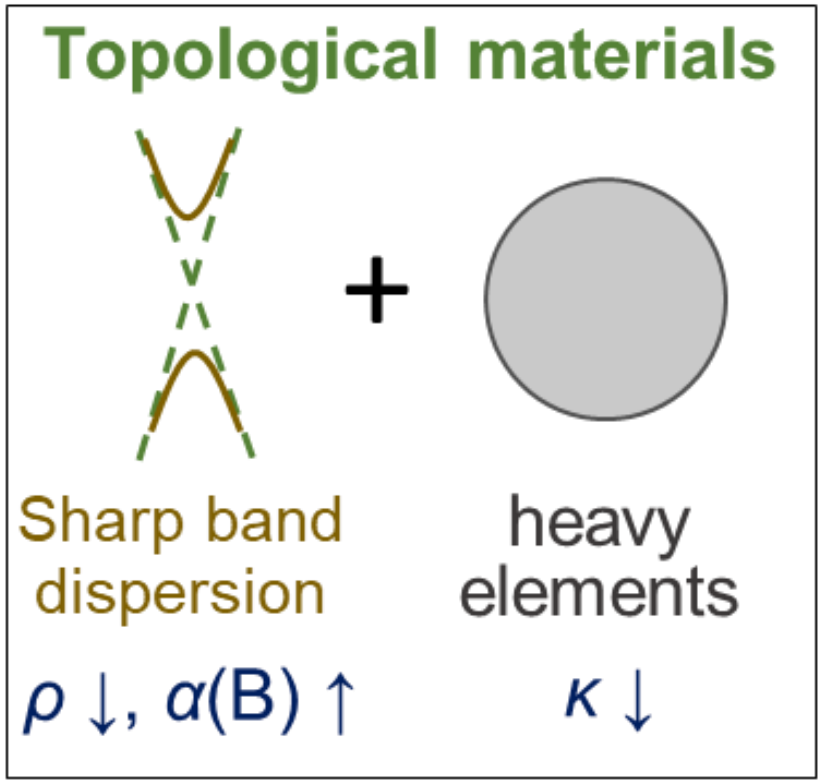


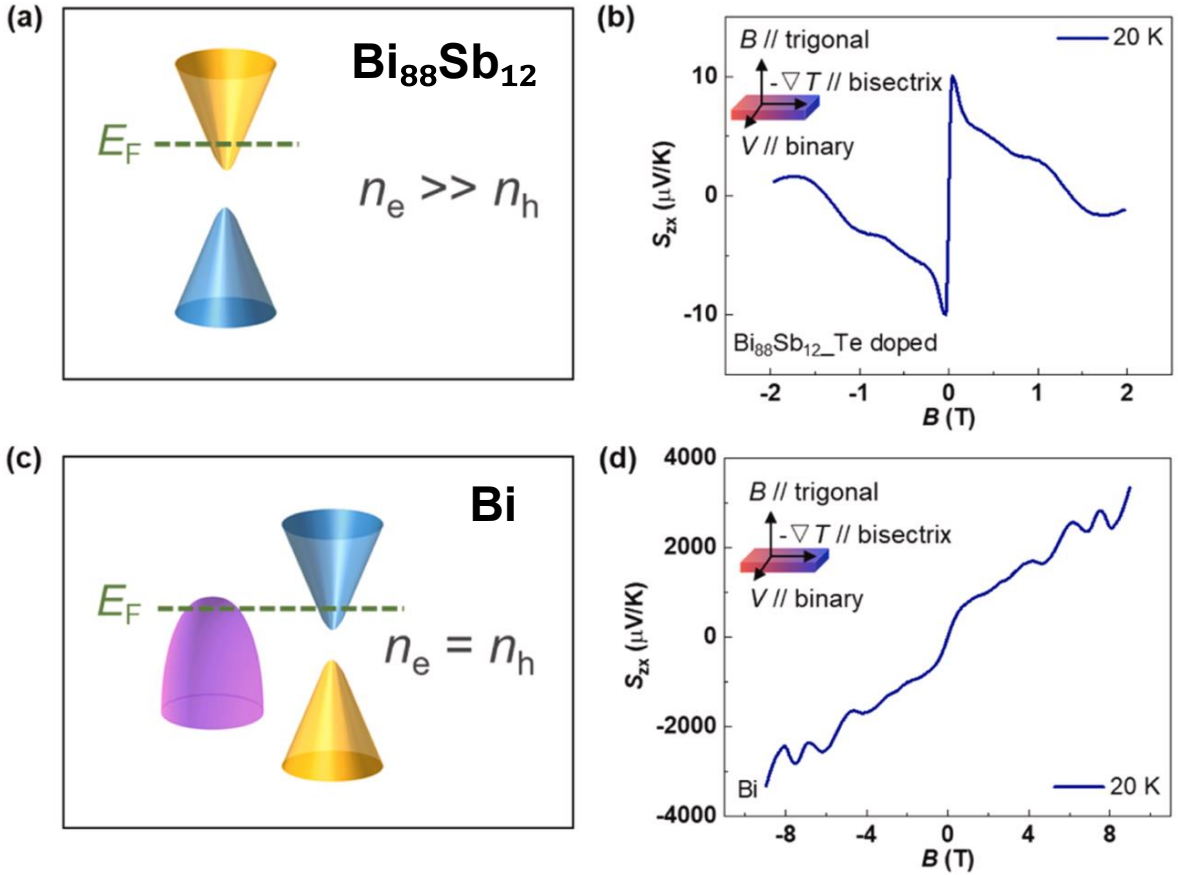
Johannes Gooth et al., Nature 547 (2017) 324.

Dung Vu, et al., Nature Materials 20 (2021) 1525–1531

MAGNETO SEEBECK EFFEKT



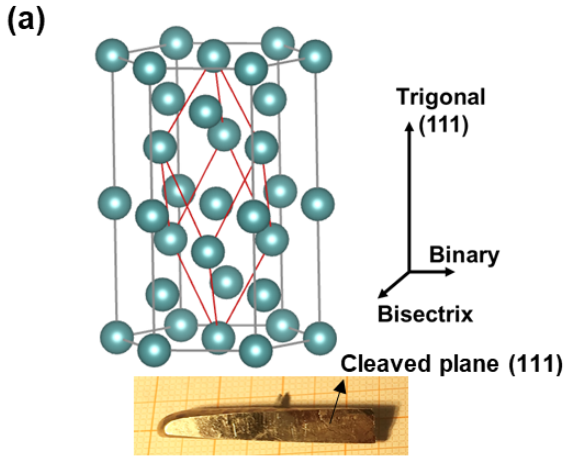


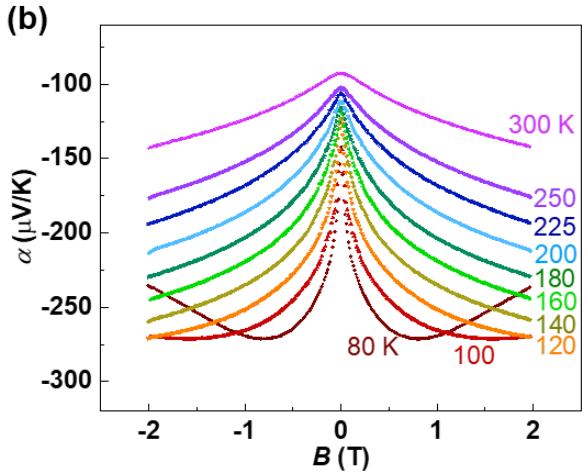


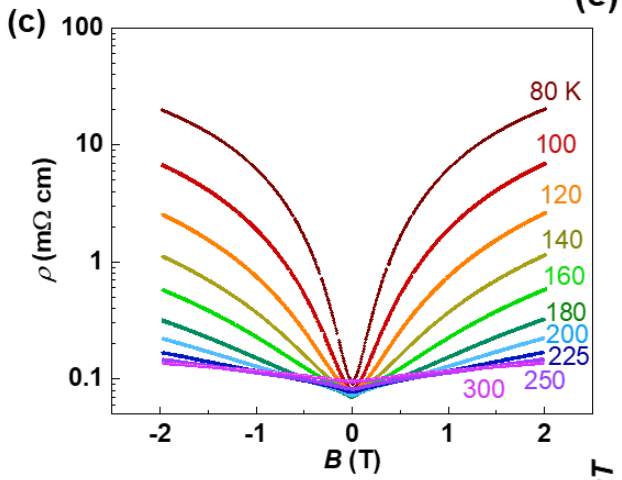
$Bi_{88}Sb_{12}$: carrier density around $10^{17}\ \mathrm{cm}^{-3}$ and mobility exceeding $4\times10^{5}\ \mathrm{cm}^{2}\mathrm{V}^{-1}\mathrm{s}^{-1}$ at 80 K

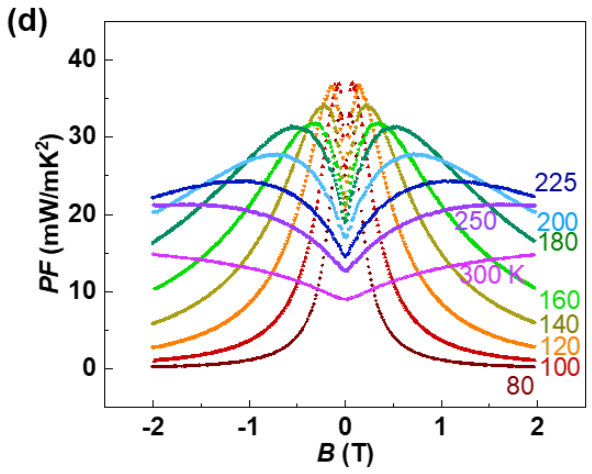
Y. Pan, B. He, F. Li, D. Chen, U. Burkhardt, C. Felser, Nature Materials 24 (2025) 76 and page 20, Pan et al., Next Energy 2 (2024) 100103

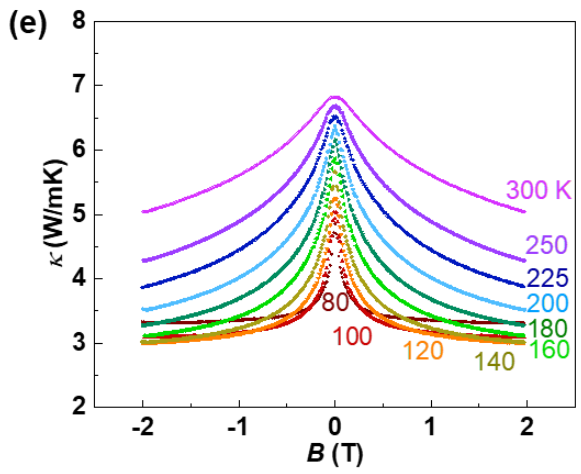
MAGNETO SEEBECK EFFEKT

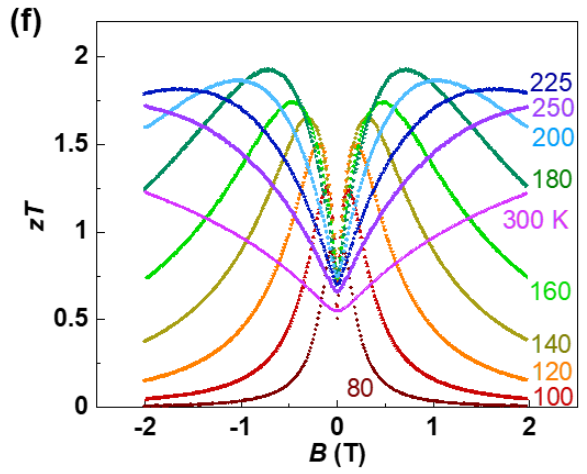


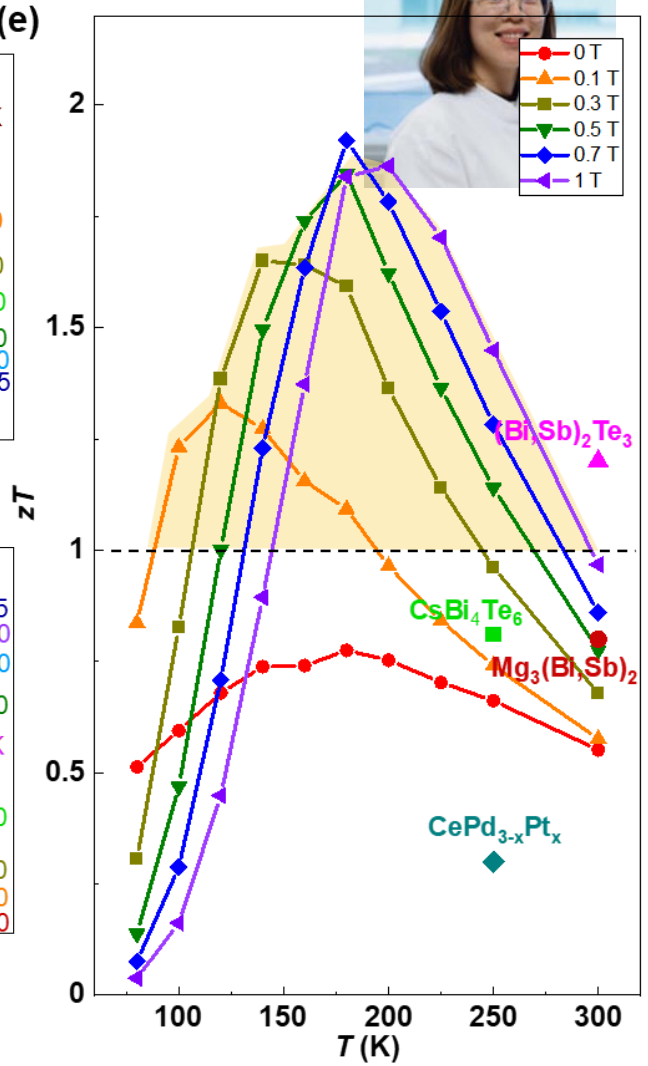








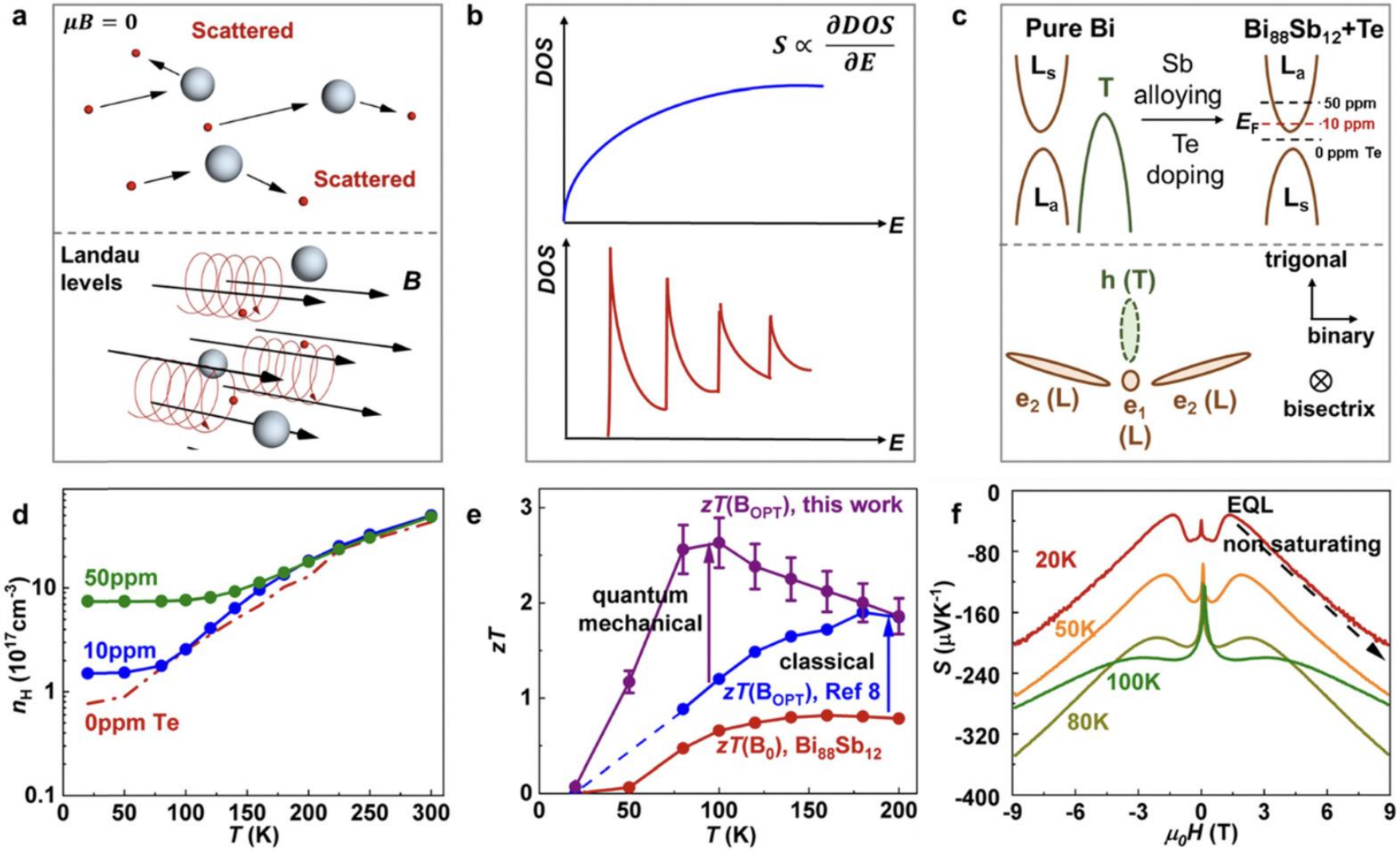




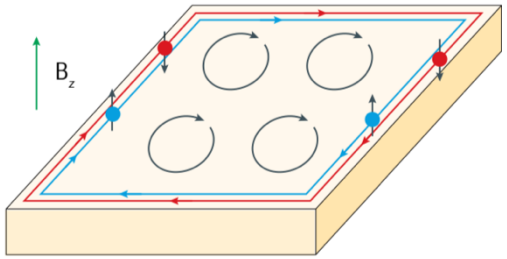
Y. Pan, B. He, F. Li, D. Chen, U. Burkhardt, C. Felser, Nature Materials 24 (2025) 76 and page 20

MAGNETO SEEBECK EFFEKT





Te doped $Bi_{88}Sb_{12}$



zT nearly 3

- small magnetic field 0.4 T
- Landau-quantized quantum regim
- max. 100 K

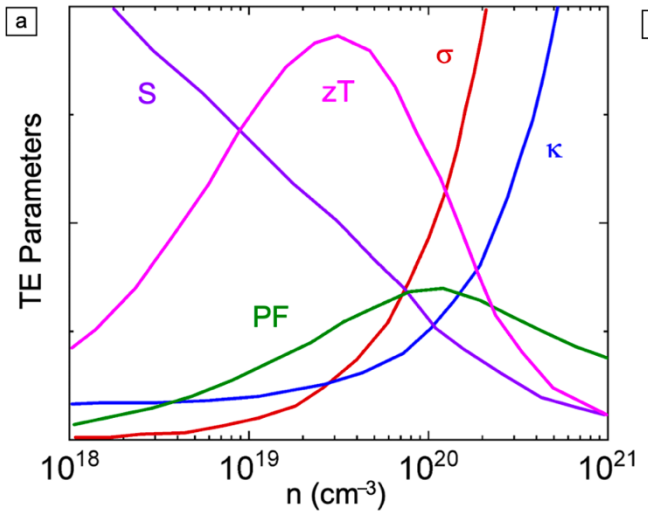
five times the zero-field value

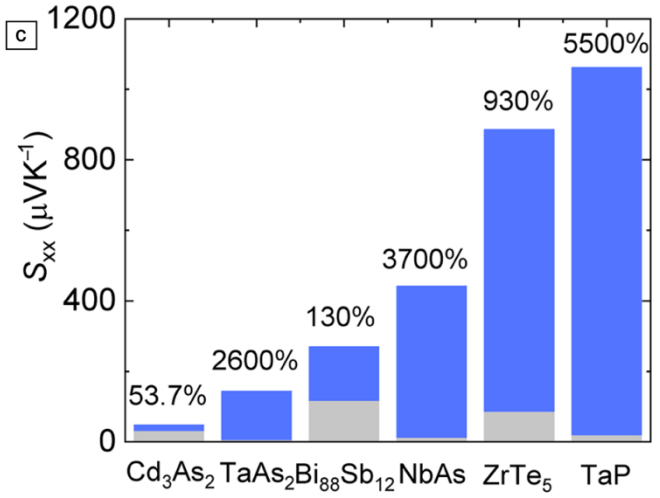
B. He, Energy Environ. Sci. 18 (2025) 3376–3384

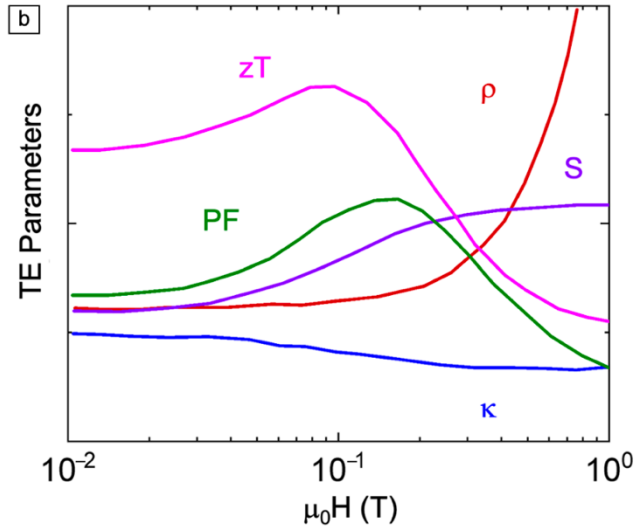
MAGNETO SEEBECK EFFEKT

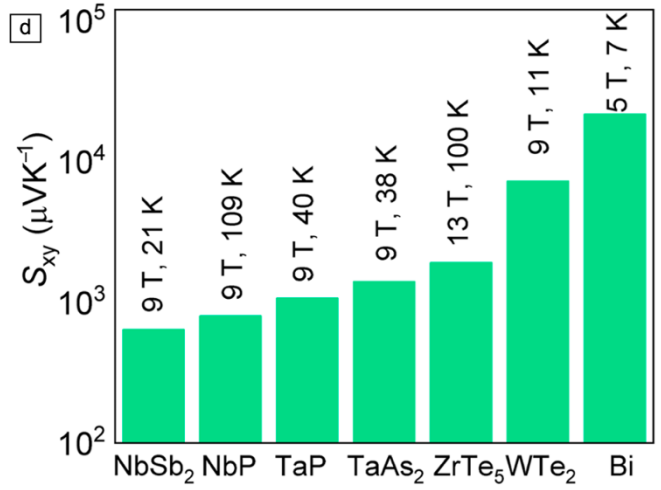


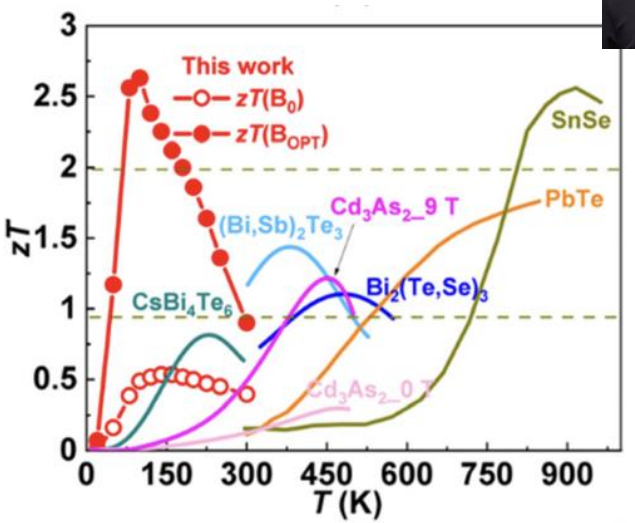
J.Snyder, E. S. Toberer, Nat. Mat. 7 (2008) 105.



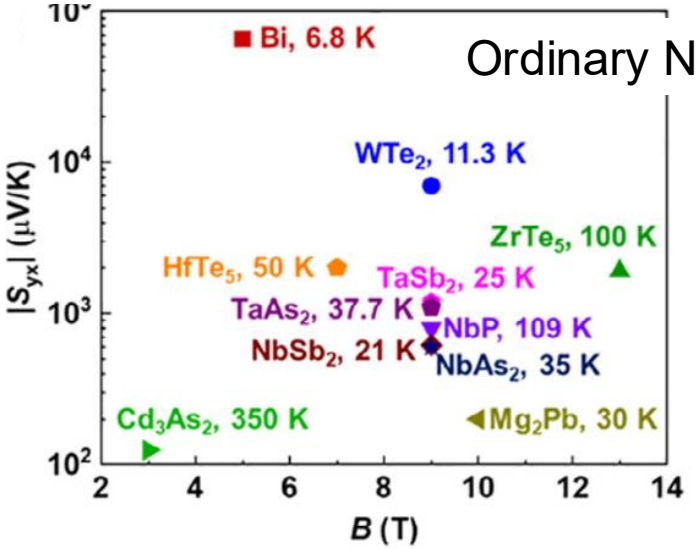






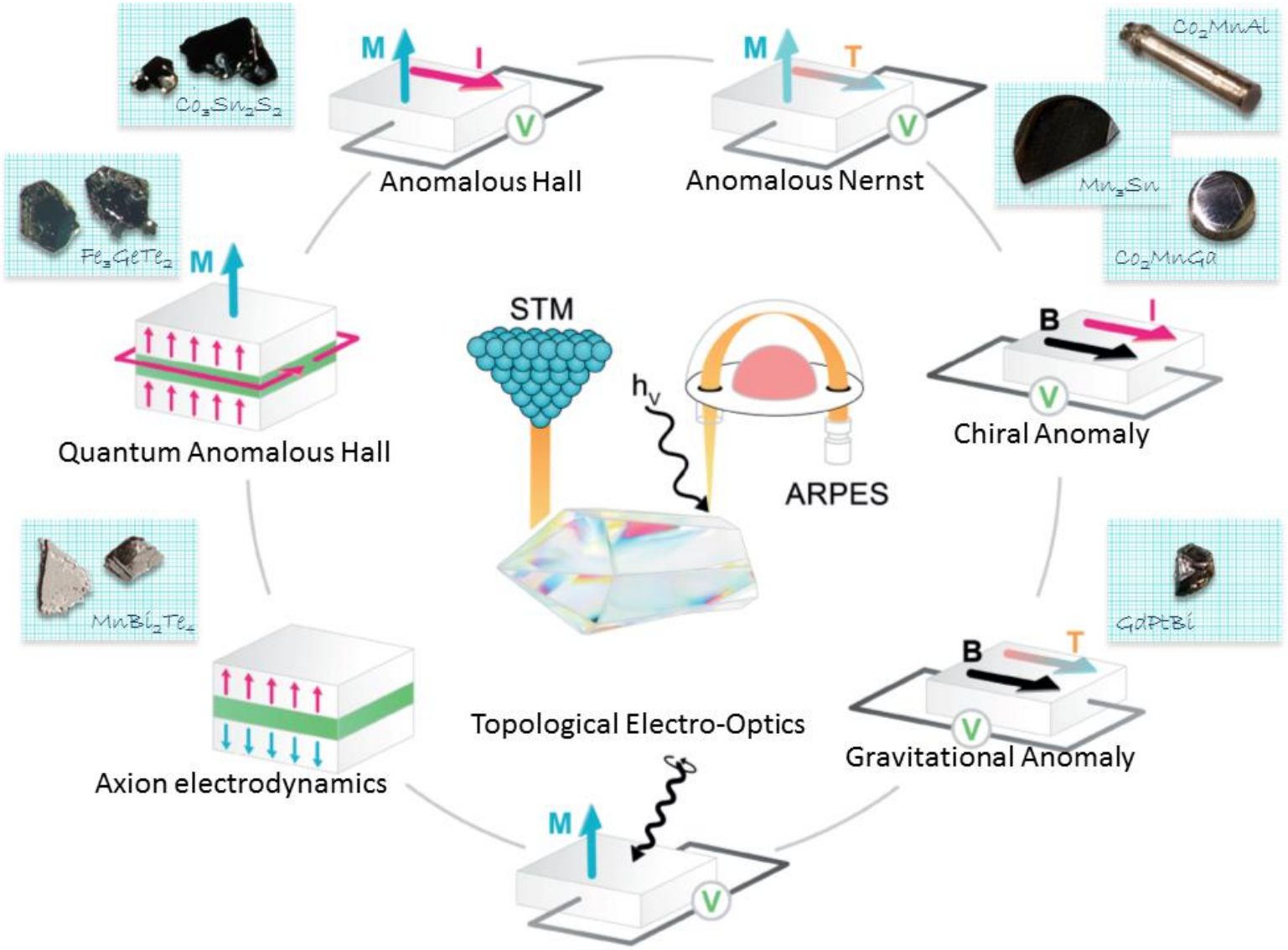


Ordinary Nernst



Bin He, Michael Toriyama, G. Jeffrey Snyder, Claudia Felser ##and Yu Pan, MRS Bulletin 50, 925–934 (2025).

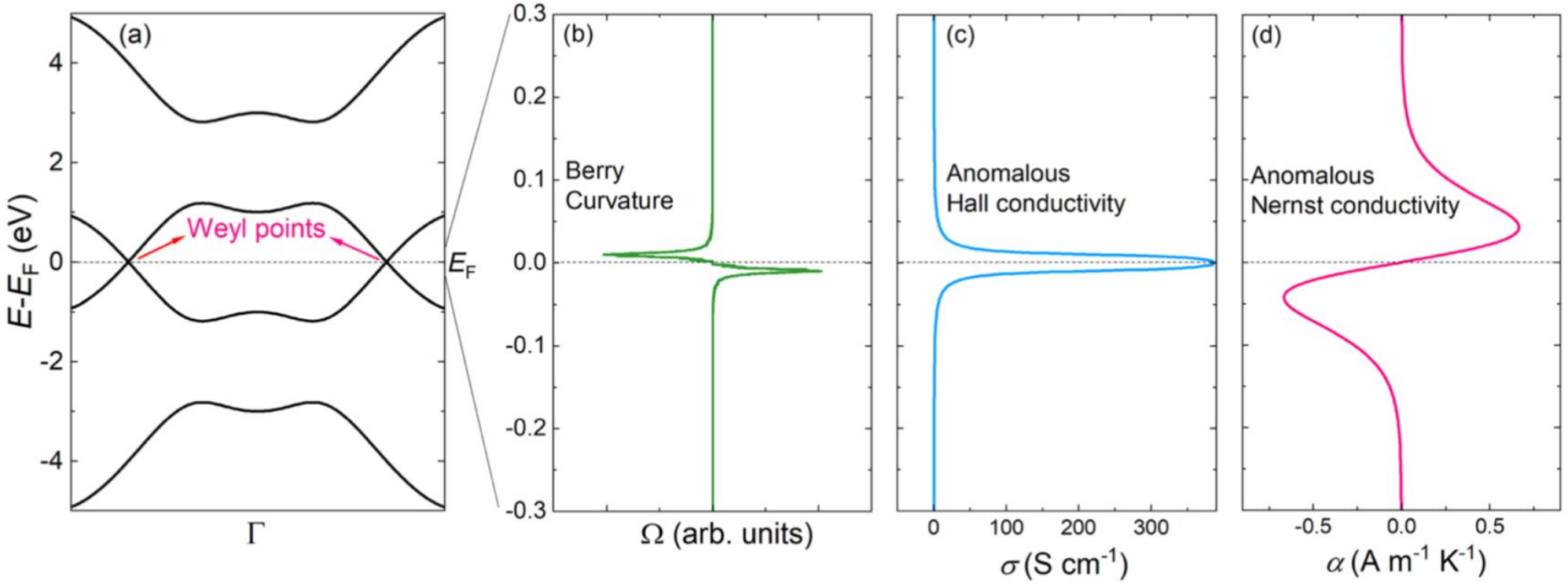
MAGNETIC TOPOLOGICAL MATERIALS



MAGNETIC TOPOLOGICAL MATERIALS

Berry curvature design

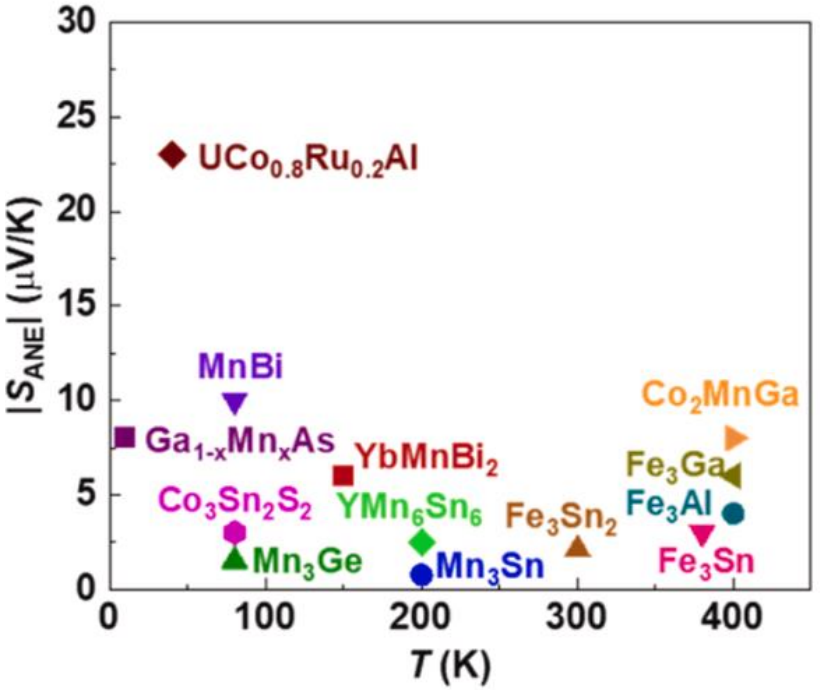
- giant anomalous Hall
- giant anomalous Nernst



J. Noky et al., Phys. Rev. B 98, 241106(R) (2018), arXiv:1807.07843, arXiv:1806.06753, Fu et al., APL Mat. 8 (2020) 040913

MAGNETIC TOPOLOGICAL MATERIALS

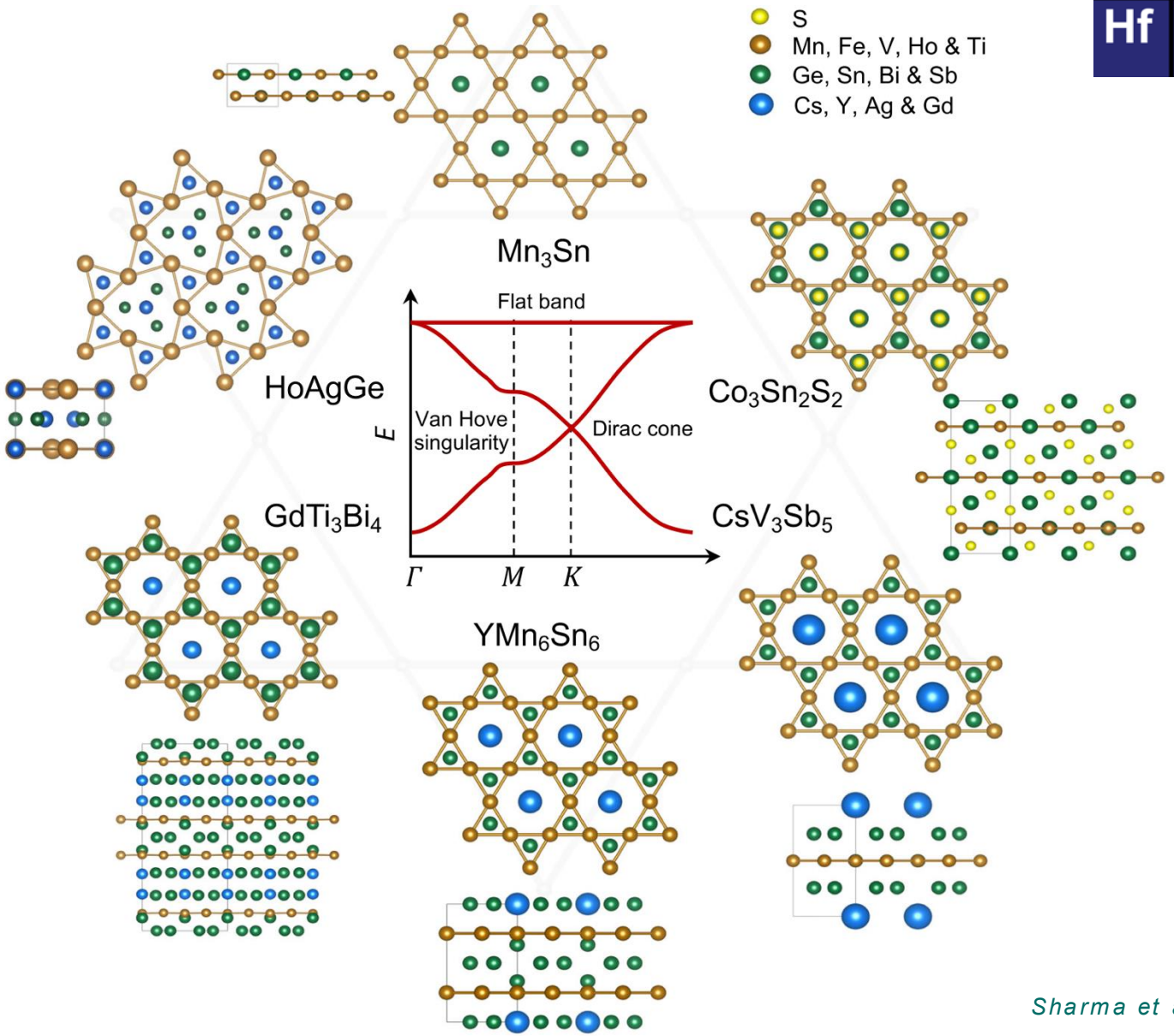
	Materials	S (μV/K)	α (A/mK)	ρ (μΩ cm)	κ (W/mK)
ONE	Bi	21700 at 5 T	/	/	/
	NbP	800 at 9 T	/	1140	438
	Cd_3As_2	129 at 3 T	/	300	2.44
	$ZrTe_5$	1902 at 13 T	/	98700	5.51
	Mg_2Pb	195 at 10 T	/	85.1	97.3
	$NbSb_2$	639 at 9 T	/	123	83.1
	WTe_2	7210 at 9 T	/	1717	114
ANE	$Ga_{1-x}Mn_xAs$	8 at 10 K	0.02	29100	/
	$Co_3Sn_2S_2$	3 at 80 K	0.84	137	6.7
	$UCo_{0.8}Ru_{0.2}Al$	23.5 at 41 K	14.7	136	10.6
	Co_2MnGa	7 at 335 K	7.4	136	20.4
	Fe_3Ga	6 at 400 K	4.2	100	21.5
	Fe_3Al	4.3 at 400 K	3	114	21.6
	MnBi	10 at 80 K	44	/	/
	Fe_3Sn_2	2.1 at 300 K	1	2000	8.1
	Fe_3Sn	3 at 380 K	2.2	90	/
	Mn_3Ge	0.5 at 300 K	0.22	250	7.2
	Mn_3Sn	1.5 at 65 K	1	140	10.8
	$YbMnBi_2$	5.8 at 160 K	0.37	1360	20.3
	YMn_6Sn_6	2.5 at 225 K	1.85	210	9.8



J. Guin, et al. Adv. Mater. 2019, 1806622, Manna et al., Phys. Rev. X 8 (2018) 041045, Ikhlas et al., Nat. Phys. 13, 1085 (2017).

KAGOME MATERIALS

Ti	V	Cr	Mn	Fe	Co	Ni	Cu
Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag
Hf	Ta	W	Re	Os	Ir	Pt	Au



Sharma et al., npj Quantum Materials 11, 55 (2026)

KAGOME - INSULATORS

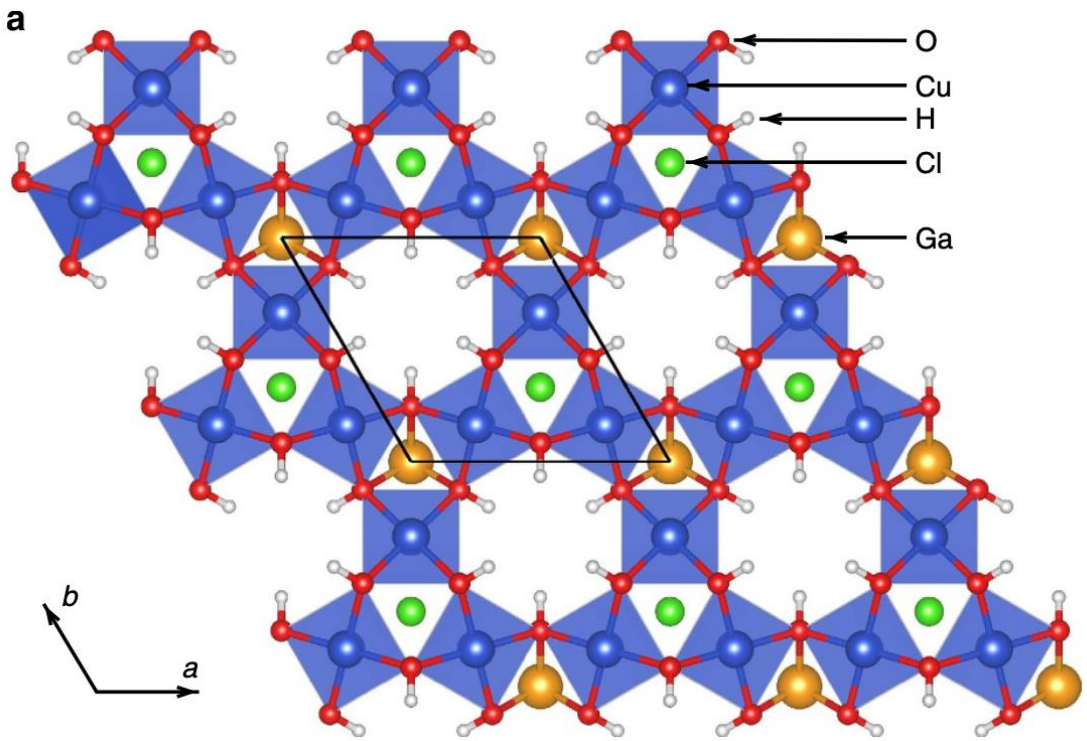
ARTICLE

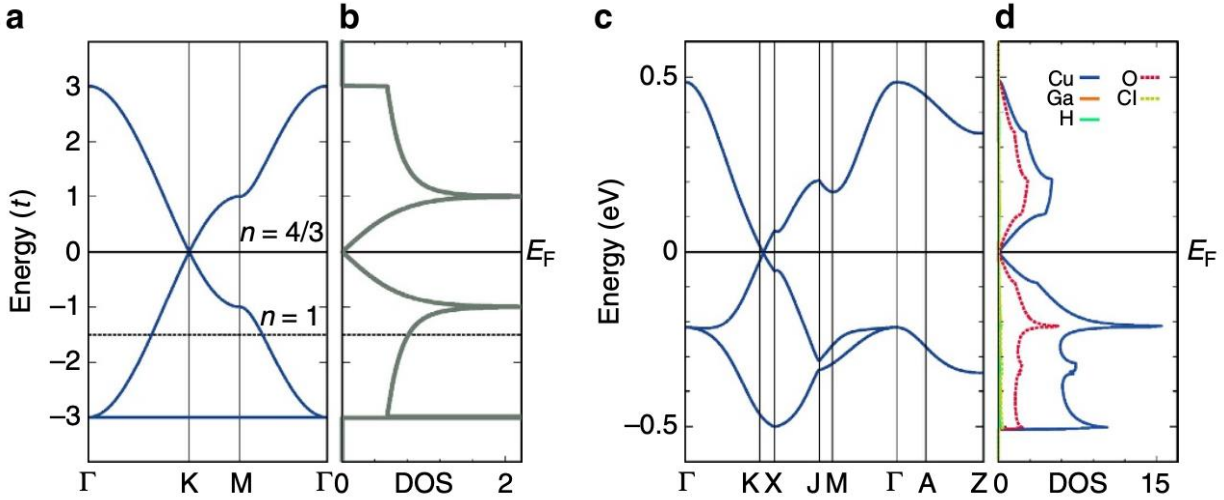
Received 11 Mar 2014 | Accepted 30 May 2014 | Published 1 Jul 2014

DOI: 10.1038/ncomms5261

Theoretical prediction of a strongly correlated Dirac metal

I.I. Mazin[1], Harald O. Jeschke[2], Frank Lechermann[3], Hunpyo Lee[2], Mario Fink[4], Ronny Thomale[4] & Roser Valentí[2]

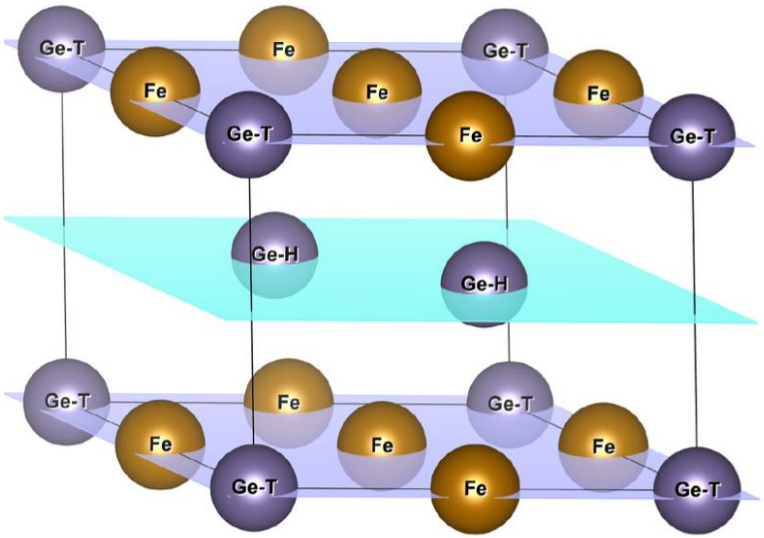




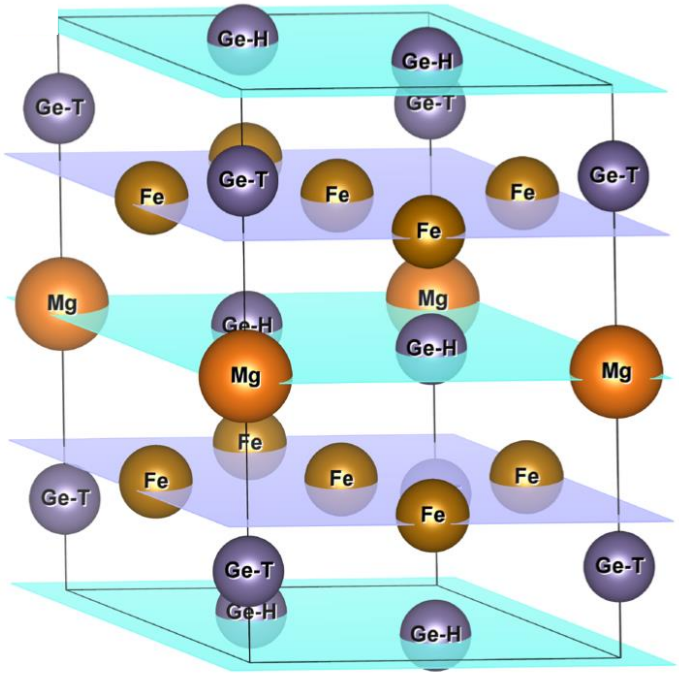
- Dirac cone,
- flat band, and
- van Hove singularity

KAGOME

FeGe



$MgFe_6Ge_6$



R = Li, Mg, Ca,rare earth metals;
M = V, Cr, Mn, Fe, Co, Ni; and
X = Ga, Ge, In, Sn, Sb etc

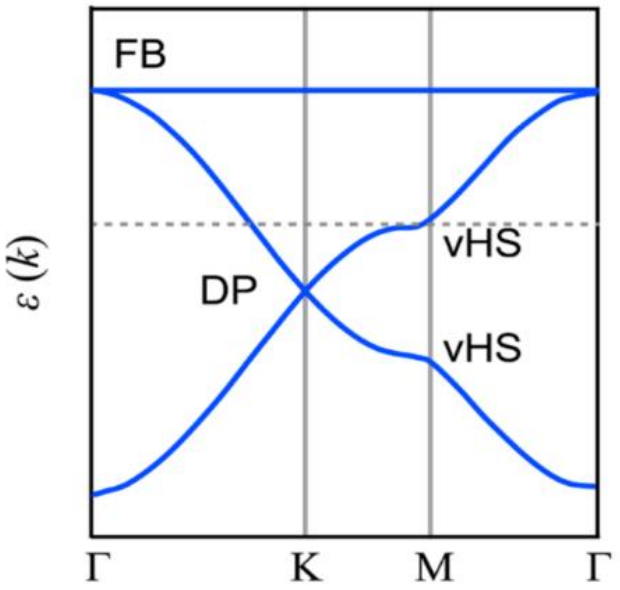
J. Alloys Compd.185, 99 (1992)

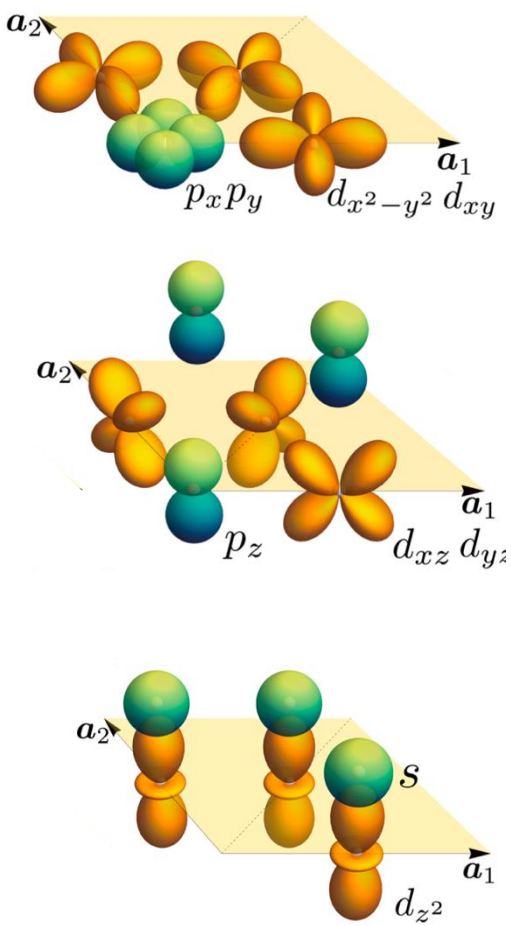
Yi Jiang, et al. Physical Review B 111 (2025) 125163, preprint arXiv:2311.09290

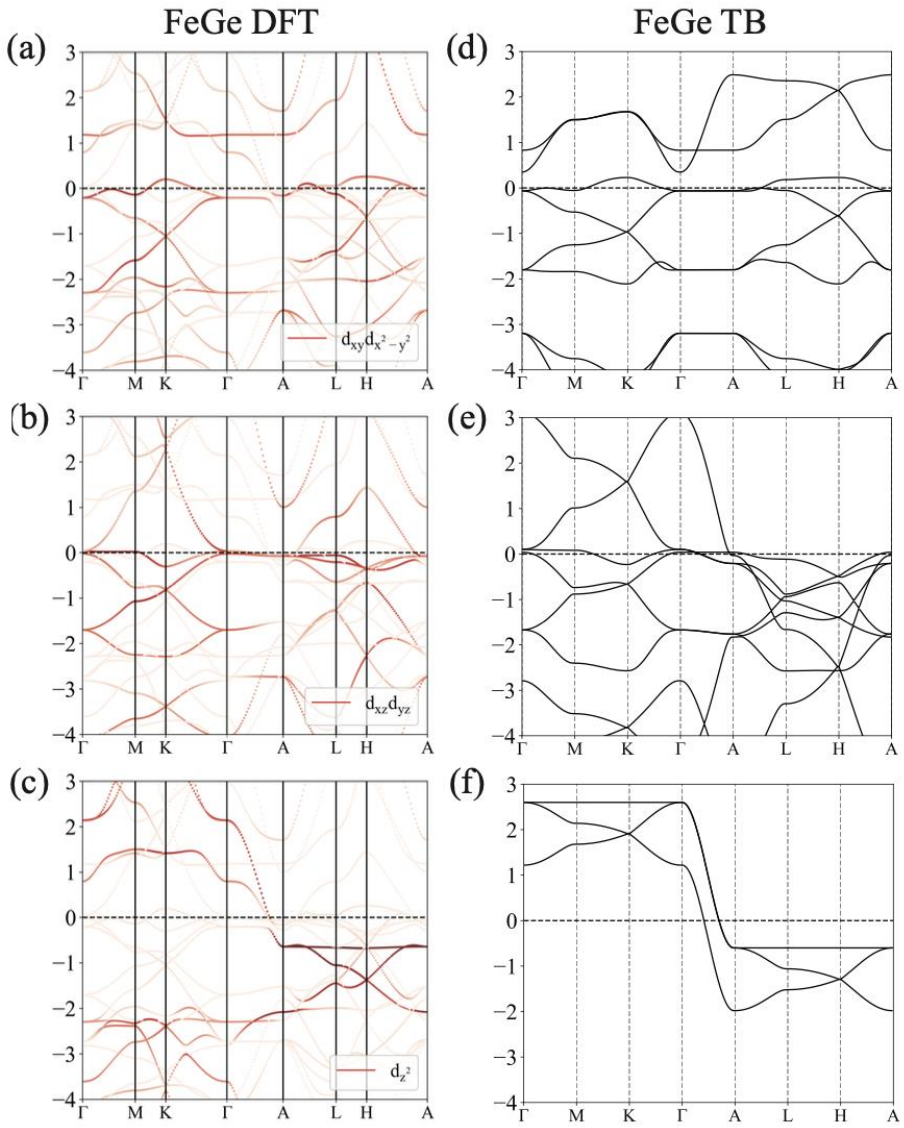
KAGOME

FeGe for every orbital sublattice the Kagome band structure fingerprint

FeGe



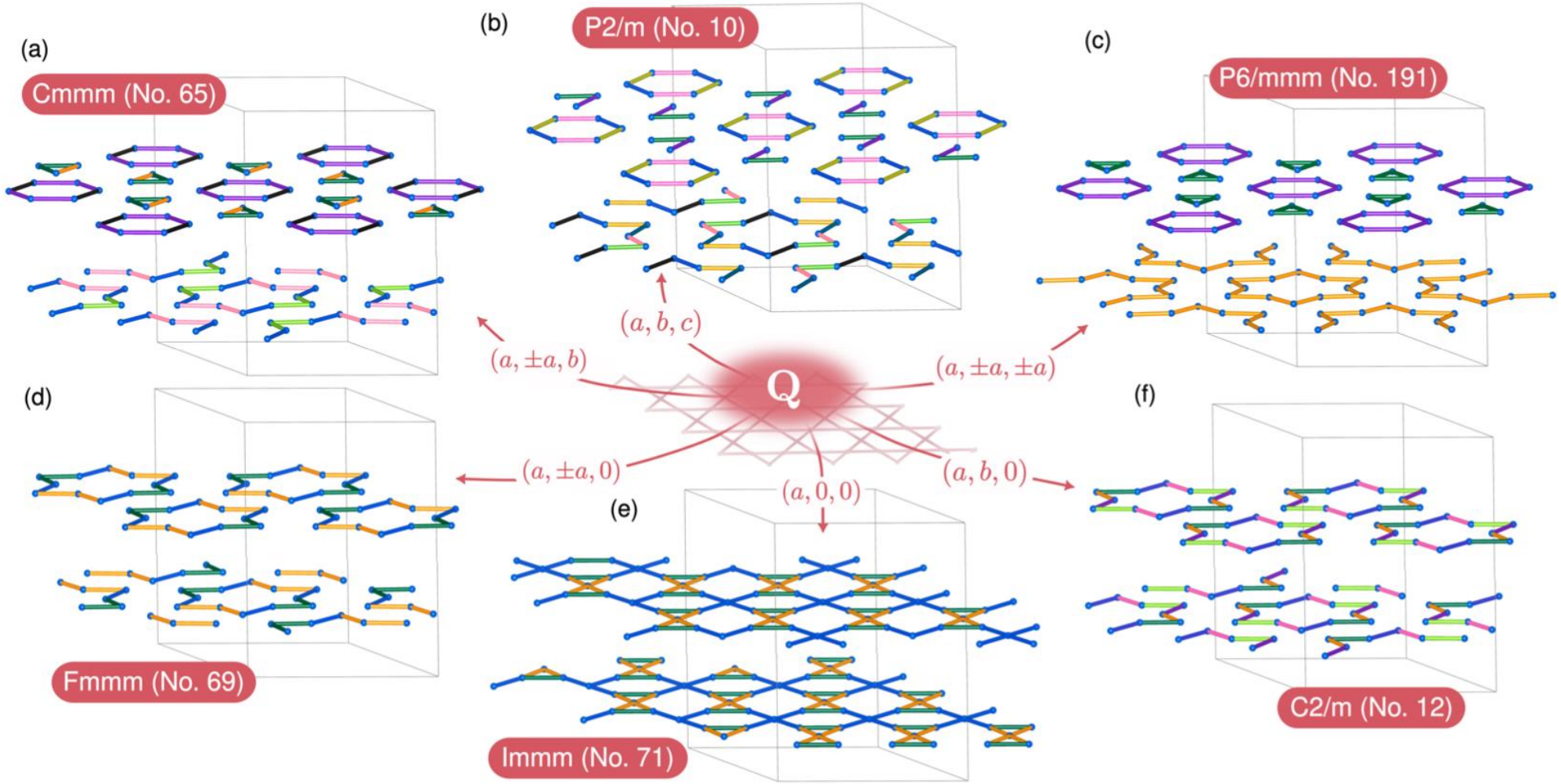




Yi Jiang, Haoyu Hu, Dumitru Călugăru, Claudia Felser, Santiago Blanco-Canosa, Hongming Weng, Yuanfeng Xu, B Andrei Bernevig, Physical Review B 111 (2025) 125163 preprint arXiv:2311.09290



STRUCTURAL DISTORTION



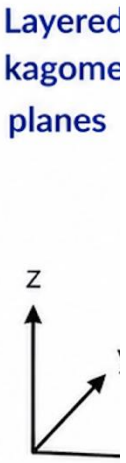
Gutierrez-Amigo,et al., Communications Materials 5 (2024) 234 preprint arXiv:2311.14112

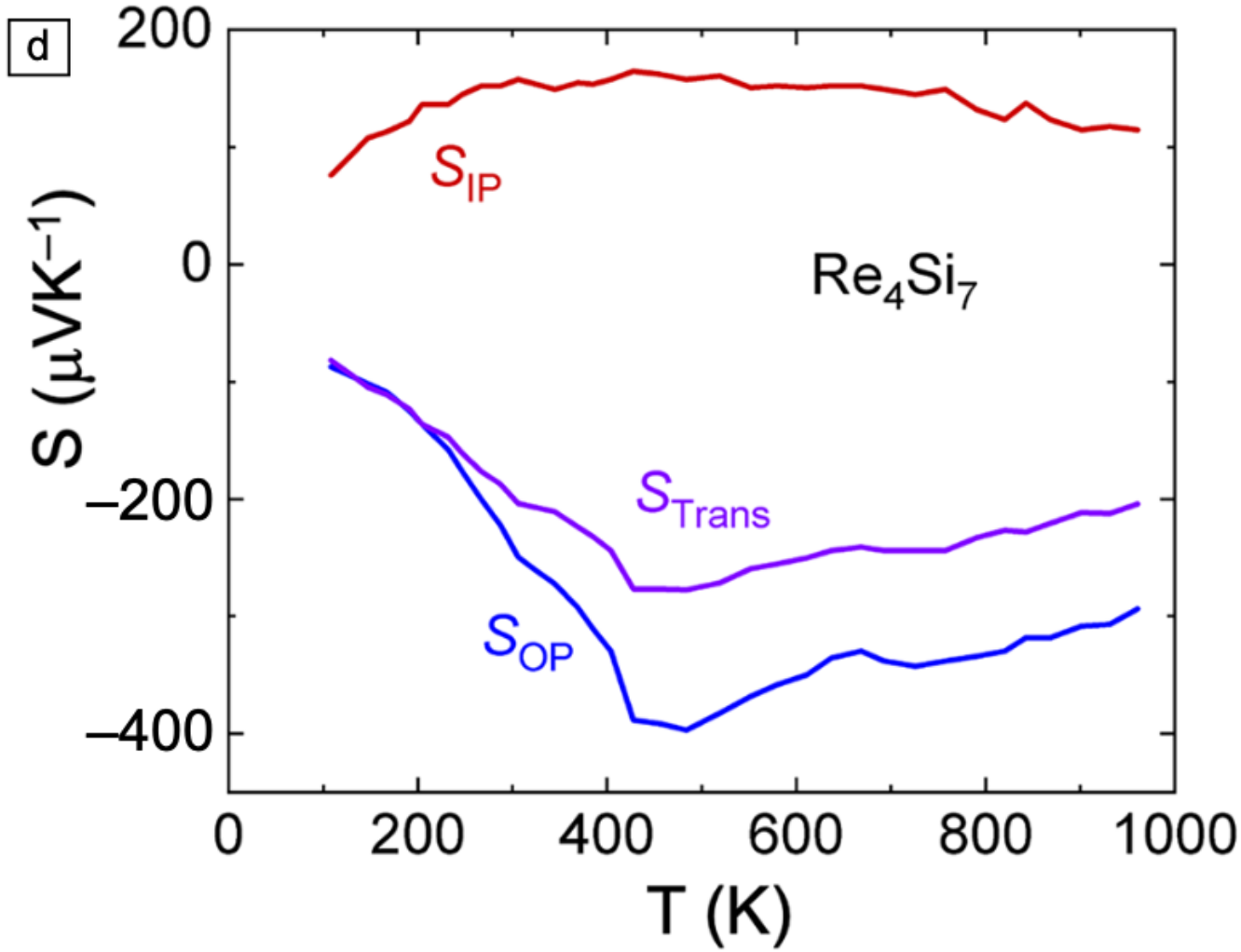


KAGOME AND GONIOPOLARITY

Goniopolarity: the same material shows different charge carrier polarity depending on the crystallographic direction:

- along one axis → **electron-like (n-type)**
- along another axis → **hole-like (p-type)**
- a **sign change of the Seebeck coefficient** depending on direction
- e.g. $S_x < 0$, $S_z > 0$



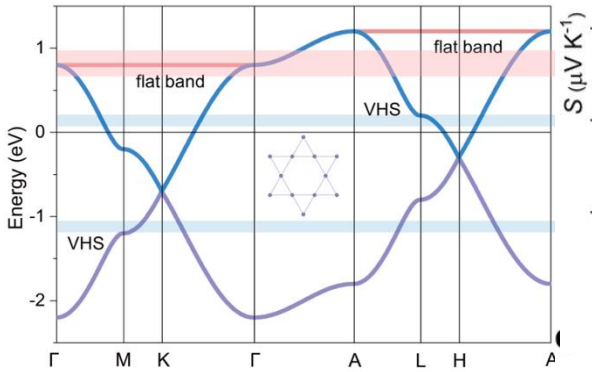


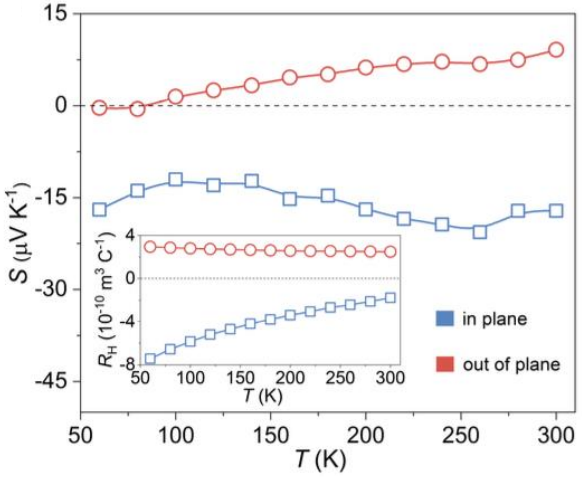
"flat bands and van Hove singularities … ge

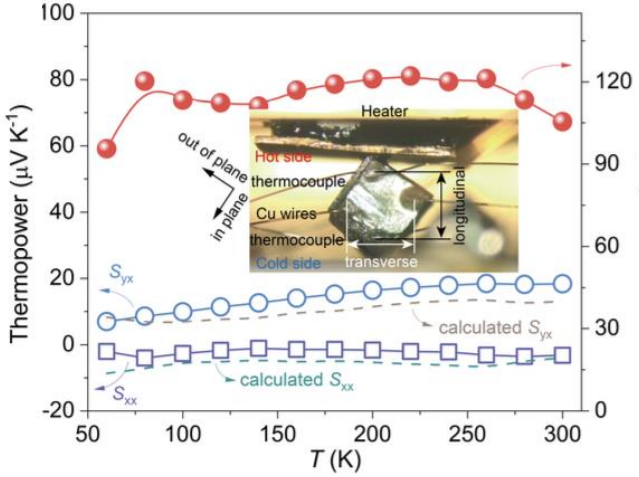
Bin He at al., Nature Materials 18 (2019) 568–572

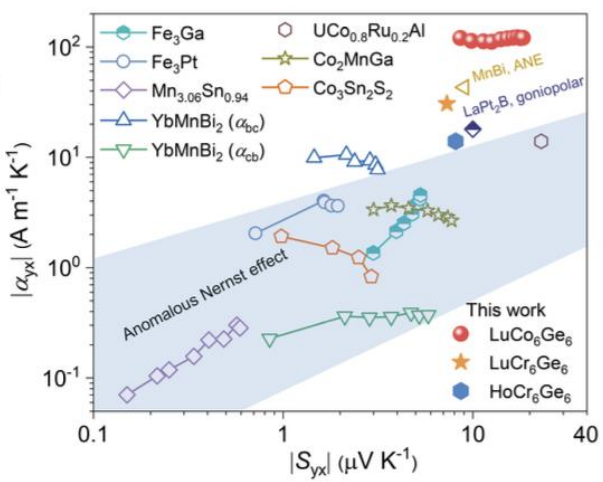
KAGOME AND GONIOPOLARITY

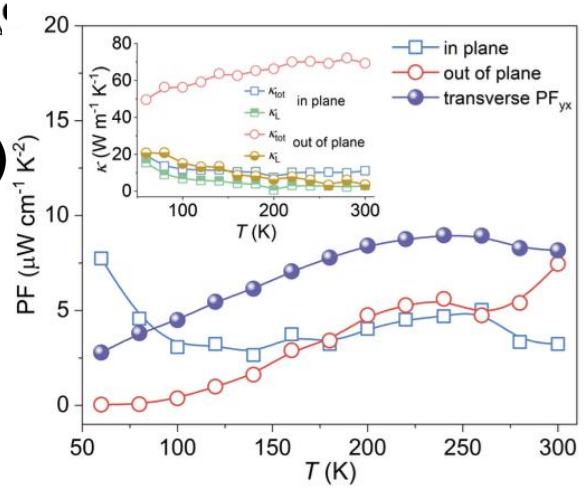
$LuCo_6Ge_6$

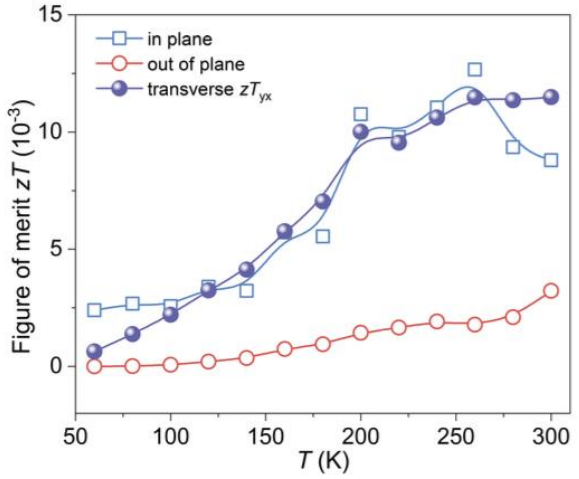


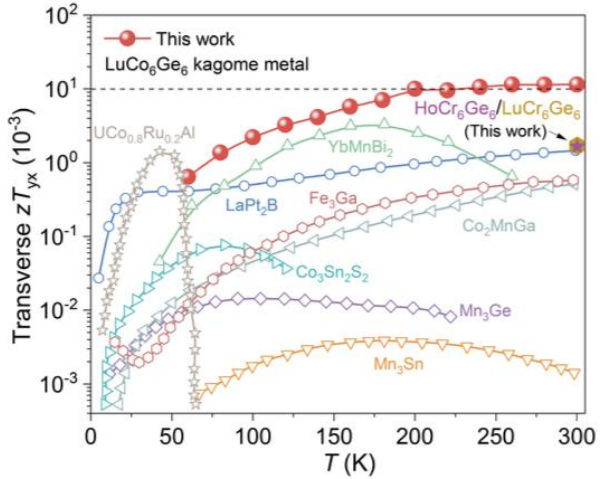












Experiment ($LuCo_6Ge_6$)
- S_{xz}=18.4μV/K (300 K)
- Zero magnetic field

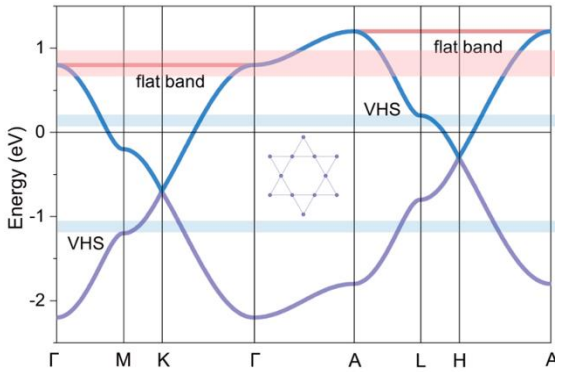
Transverse thermoelectricity without magnetism driven purely by band structure (fermiology)

The synergy of flat bands with high electrical conductivity yields values an order of magnitude greater

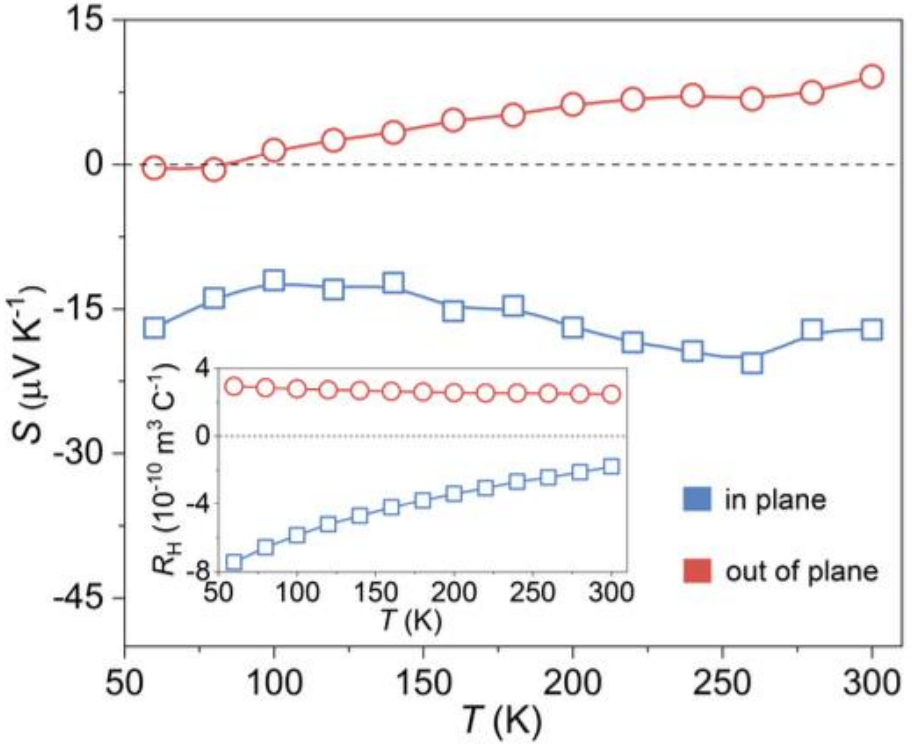
Haihua Hu, et al., Nature Materials (2026) https://doi.org/10.1038/s41563-026-02678-4

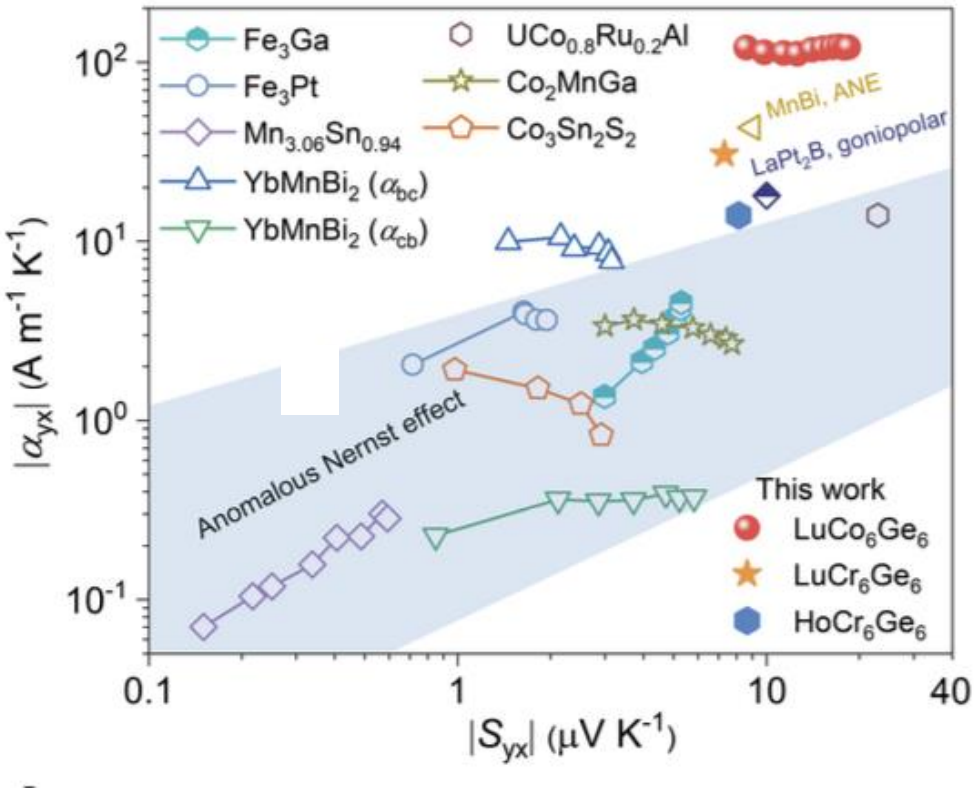
KAGOME AND GONIOPOLARITY

$LuCo_6Ge_6$



Experiment ($LuCo_6Ge_6$)
- S_{xz}=18.4μV/K (300 K)
- Zero magnetic field





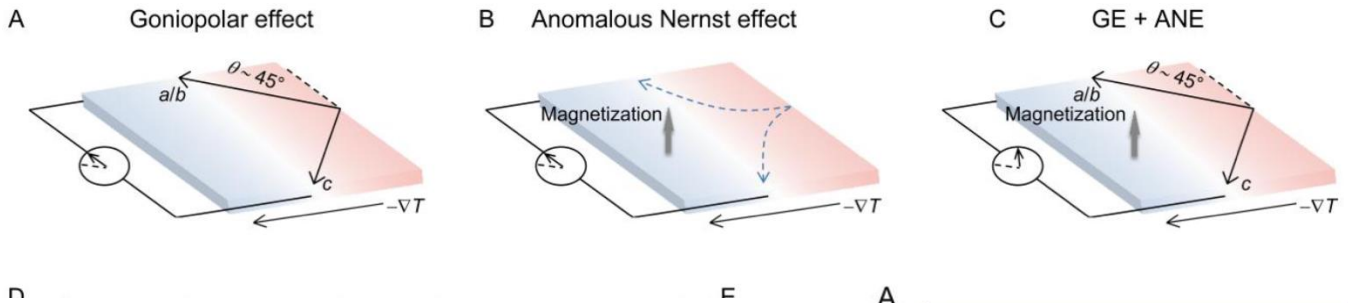
Transverse thermoelectricity without magnetism driven purely by band structure (fermiology)

The synergy of flat bands with high electrical conductivity yields values an order of magnitude greater

Haihua Hu, et al., Nature Materials (2026) https://doi.org/10.1038/s41563-026-02678-4

KAGOME AND GONIOPOLARITY

$MgMn_6Sn_6$



Two transverse mechanisms

1. Anomalous Nernst effect (ANE)

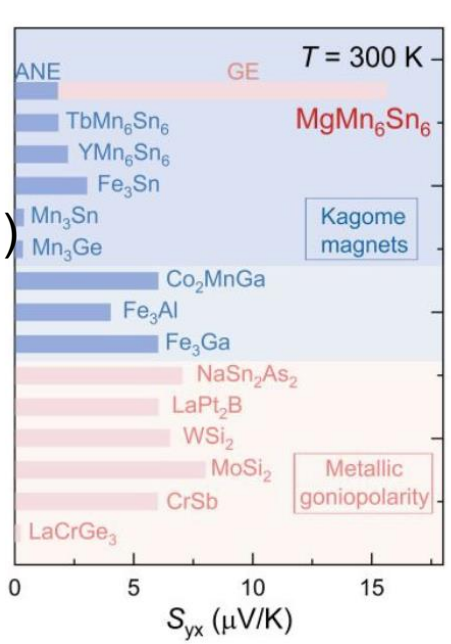
- From Berry curvature (SOC + magnetism)
- S_{yx}~1.8 μV/KSyx~1.8μV/K at 300 K

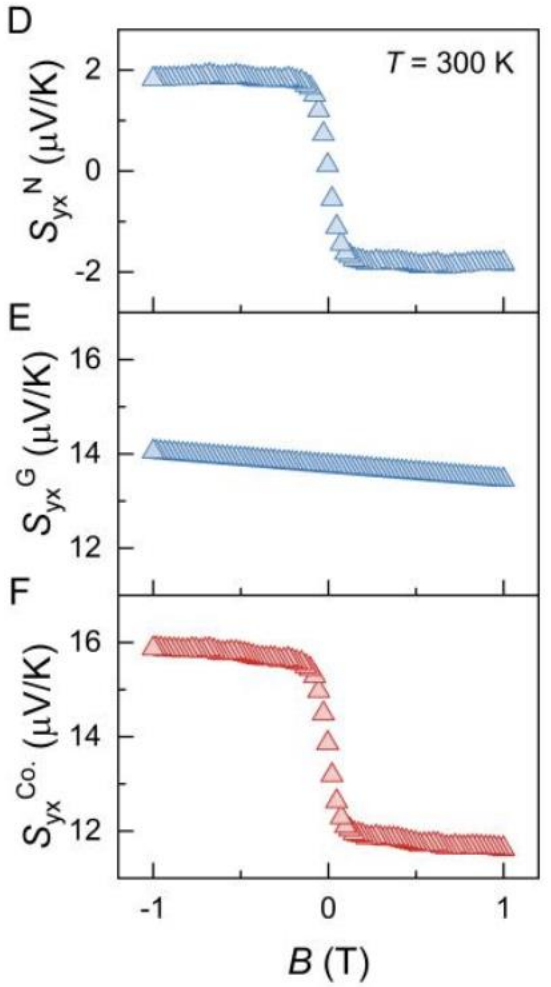
2. Goniopolar effect (GE)

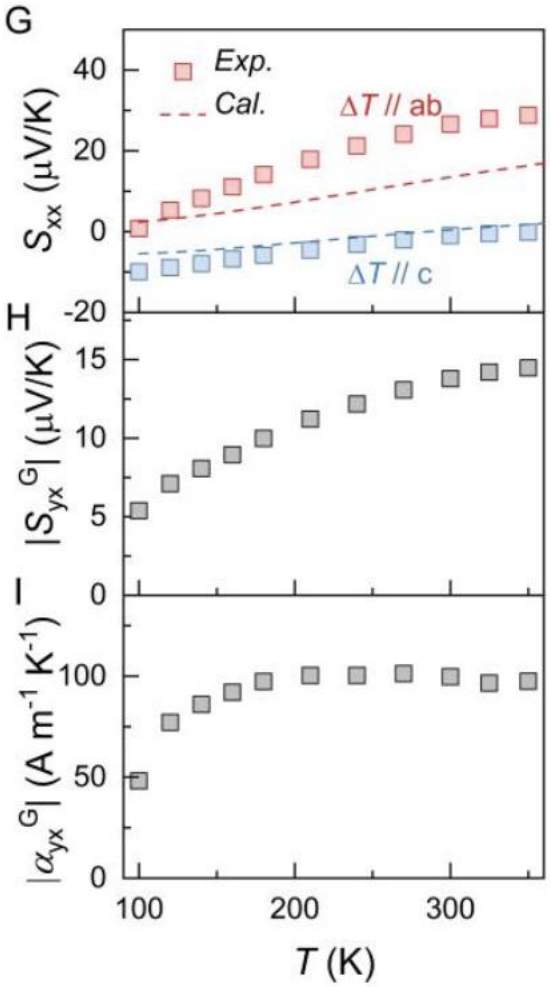
- Direction-dependent Seebeck: Sxx≠Szz
- Rotating heat flow ⇒ transverse voltage

GE + ANE **add constructively**

- ⟶ S_{yx}total≈15.6μV/K

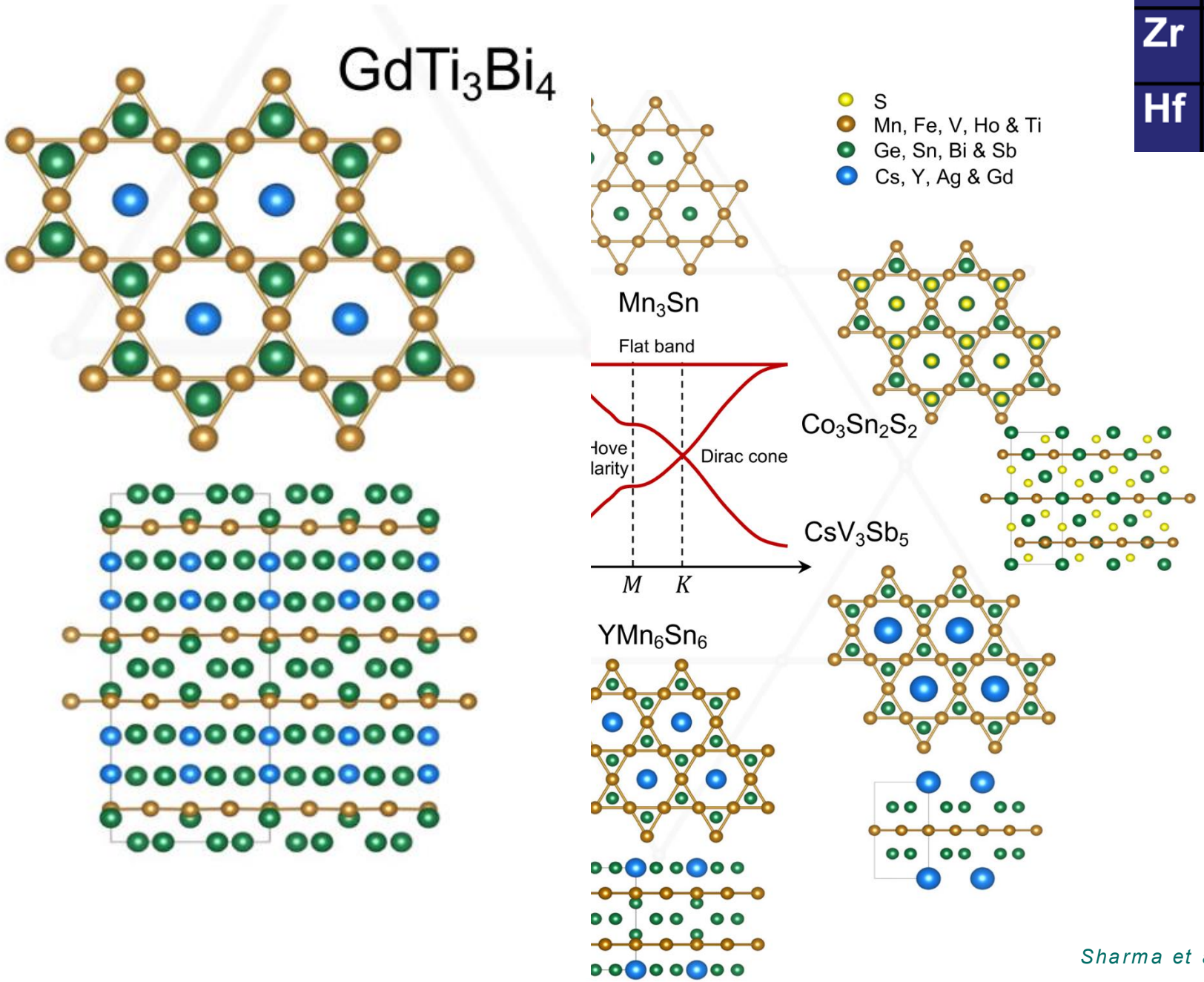






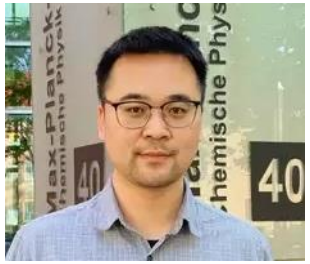
Honghui Wang, et al., Advanced Materials (2026) e74839

Ti	V	Cr	Mn	Fe	Co	Ni	Cu
Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag
Hf	Ta	W	Re	Os	Ir	Pt	Au

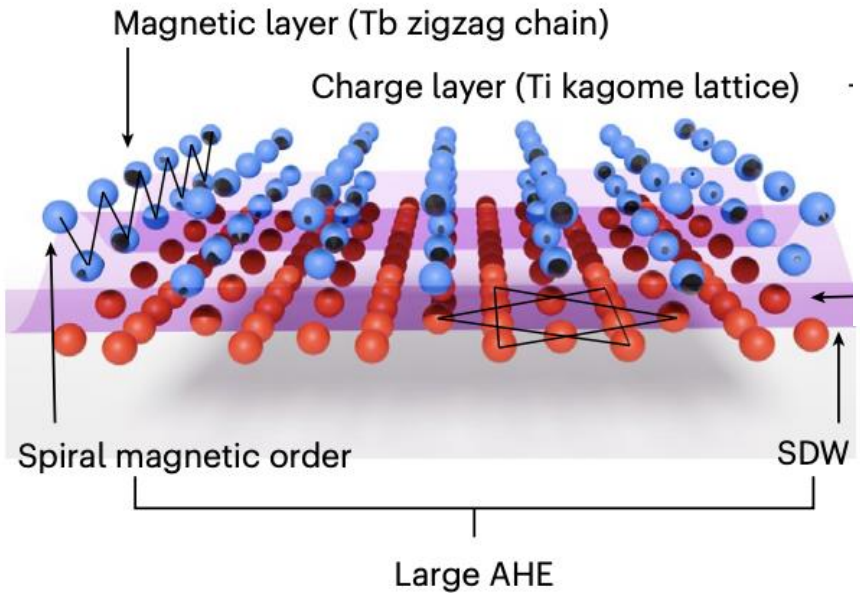


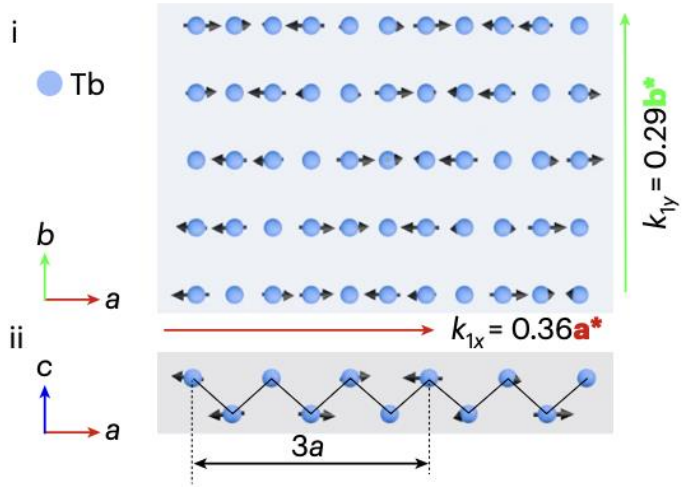
Sharma et al., npj Quantum Materials 11, 55 (2026)

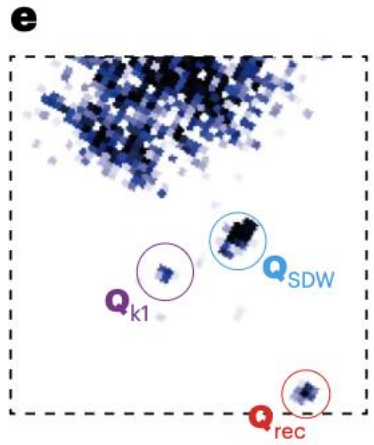
INTERWOVEN MAGNETISM INDUCES A SPIN DENSITY WAVE



$TbTi_3Bi_4$







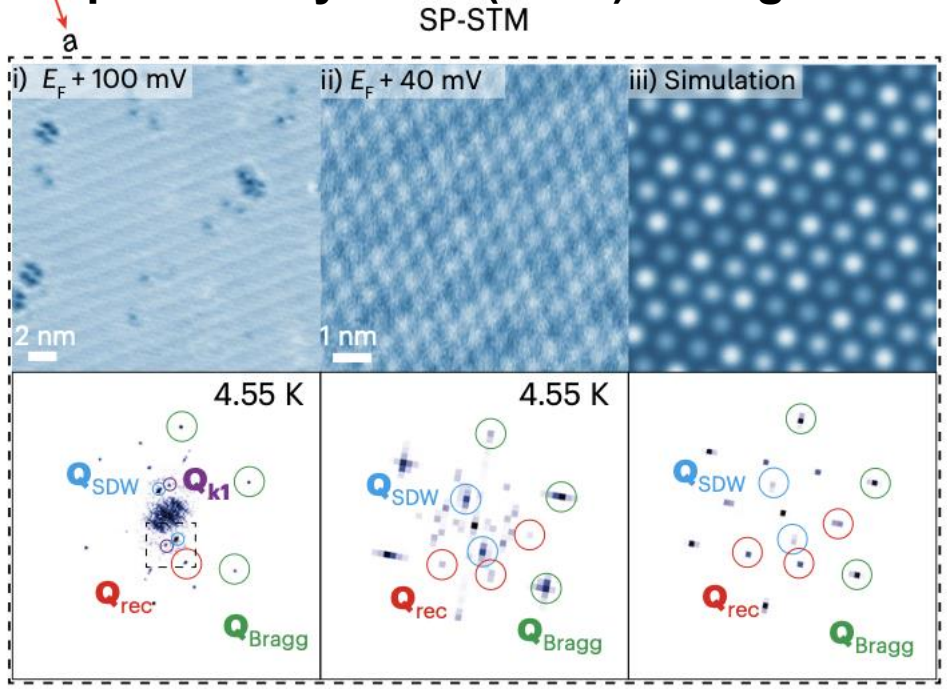
Key observation

Real-space modulation with wavevector

Q = (1/3, 0, 0)

Appears only below $T_N \approx 20\ K$

Spin density wave (SDW) emerges



Material design

Tb zigzag chains (local moments)

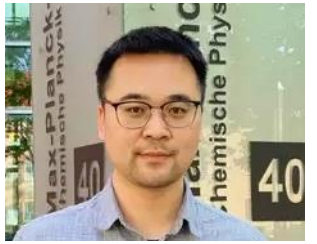
Ti kagome layers (itinerant electrons)

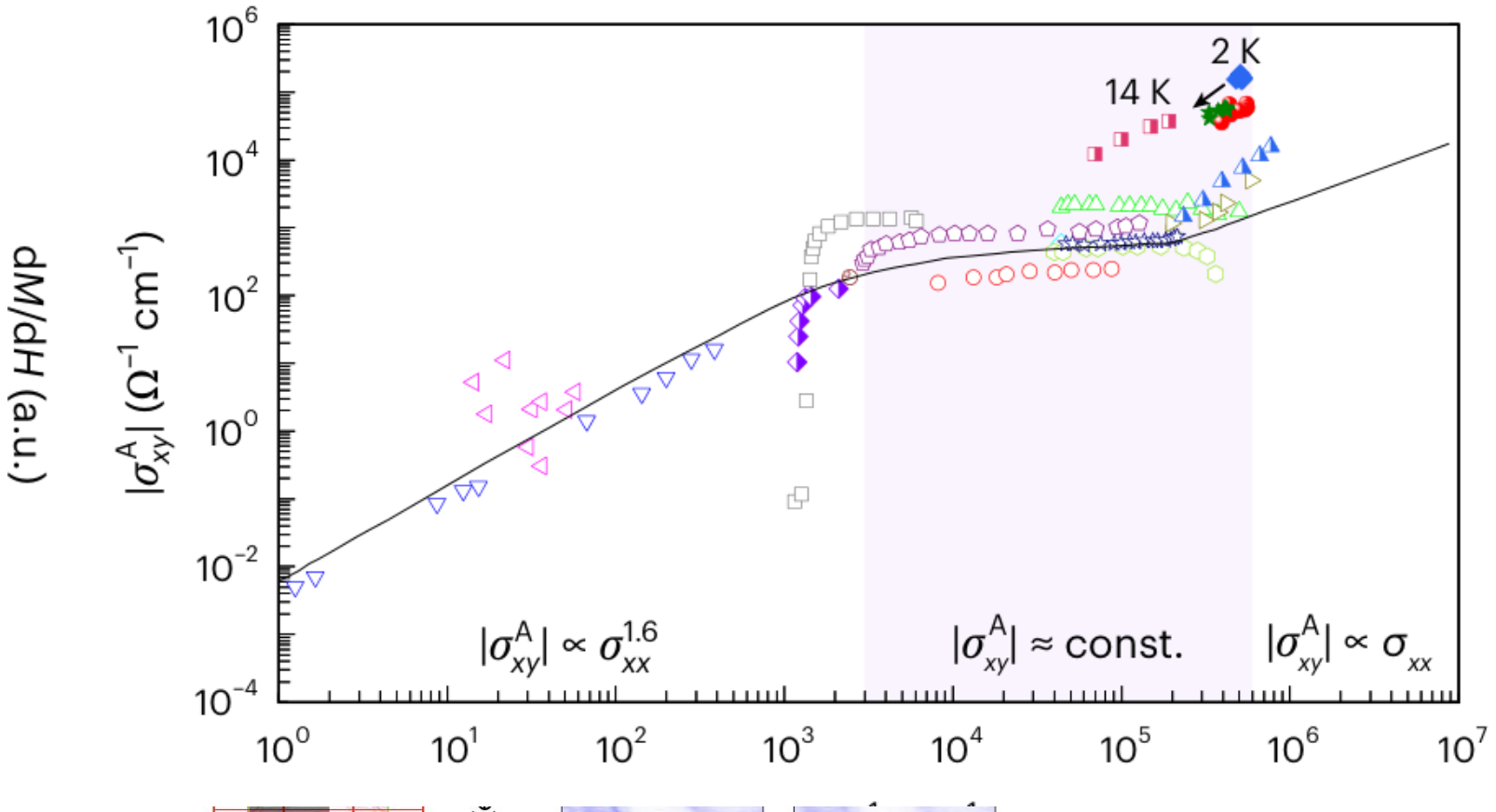
Magnetic ground state

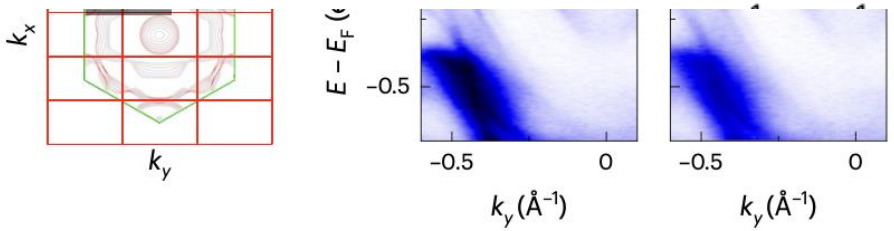
Complex spiral magnetic order (large Tb moments)

Erjian Cheng, et al., Nature Materials 25 (2026) 602, preprint arXiv:2409.01365

KAGOME AND BEYOND





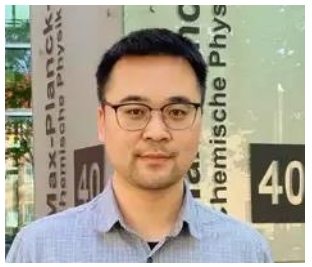


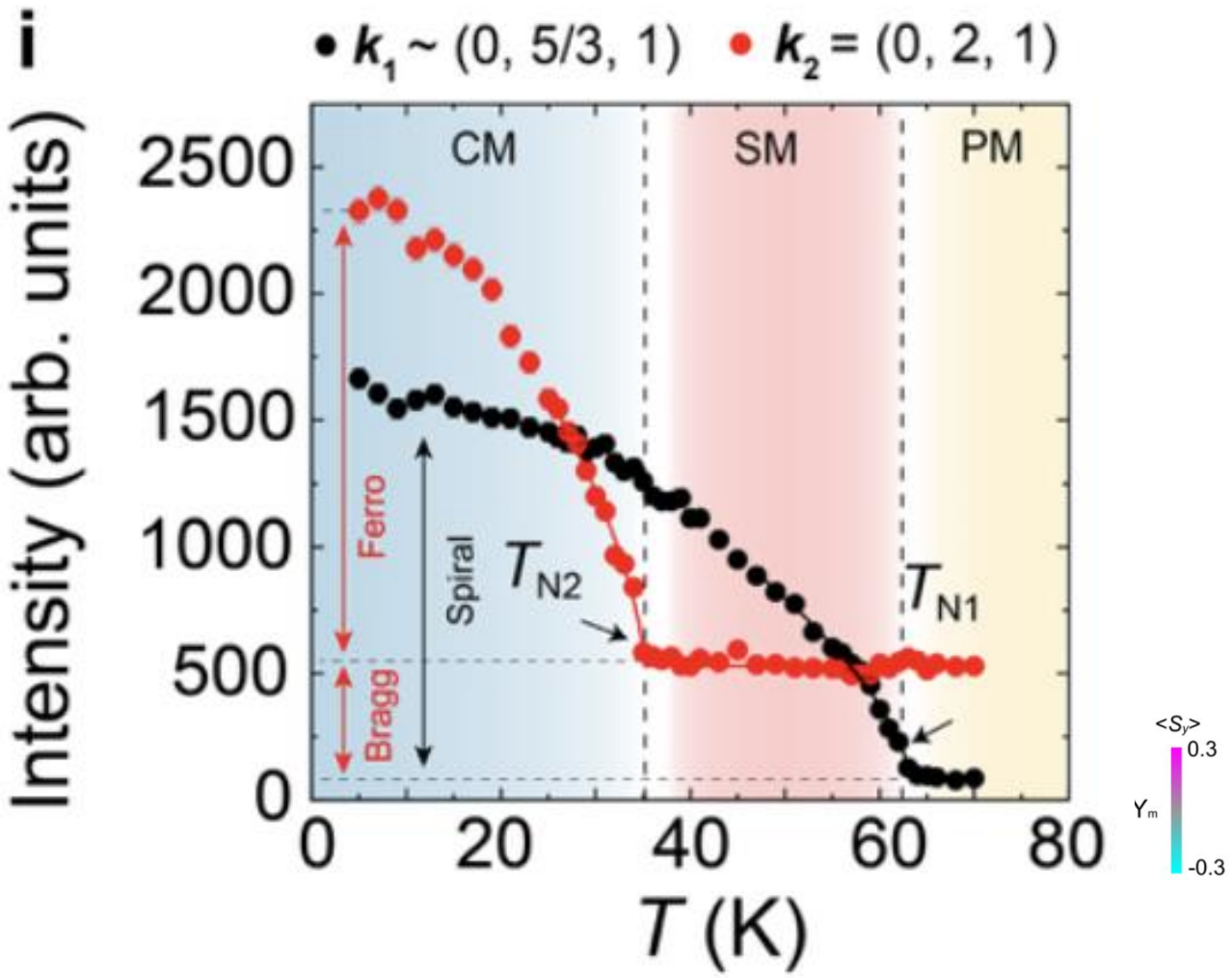
and electrons
Magnetism reconstructs the electronic bands

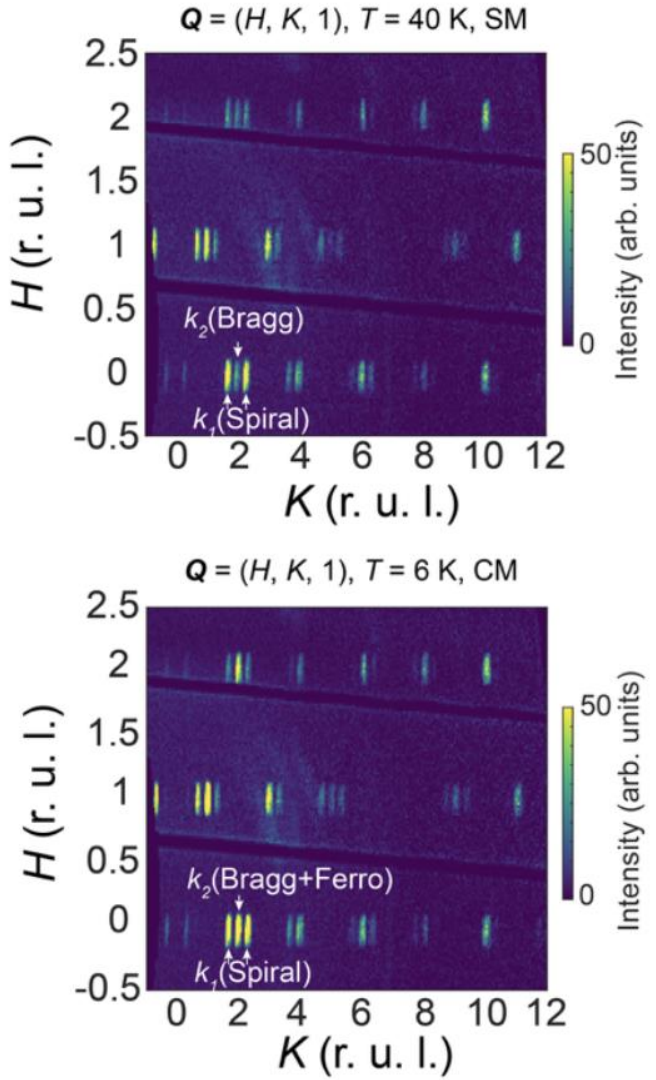
Erjian Cheng, et al., Nature Materials 25 (2026) 602, preprint arXiv:2409.01365

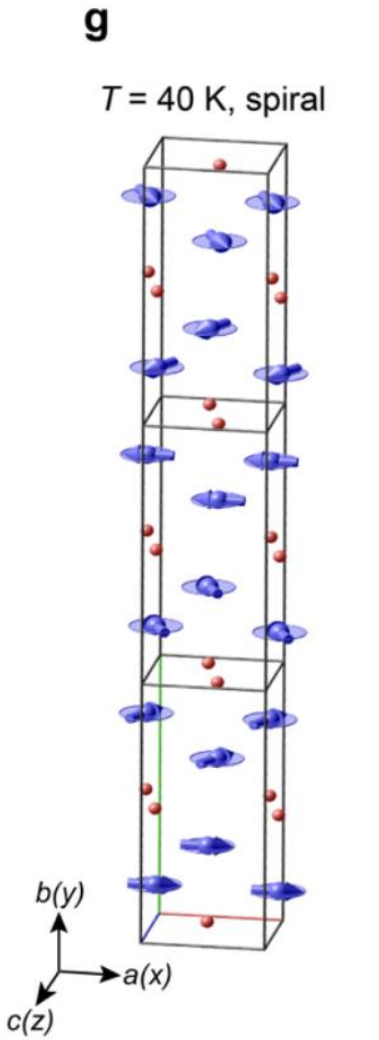
ALTERMAGNETISM



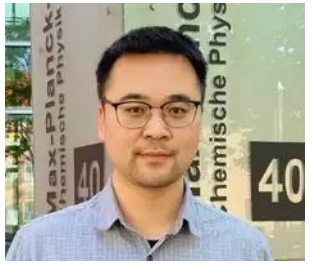








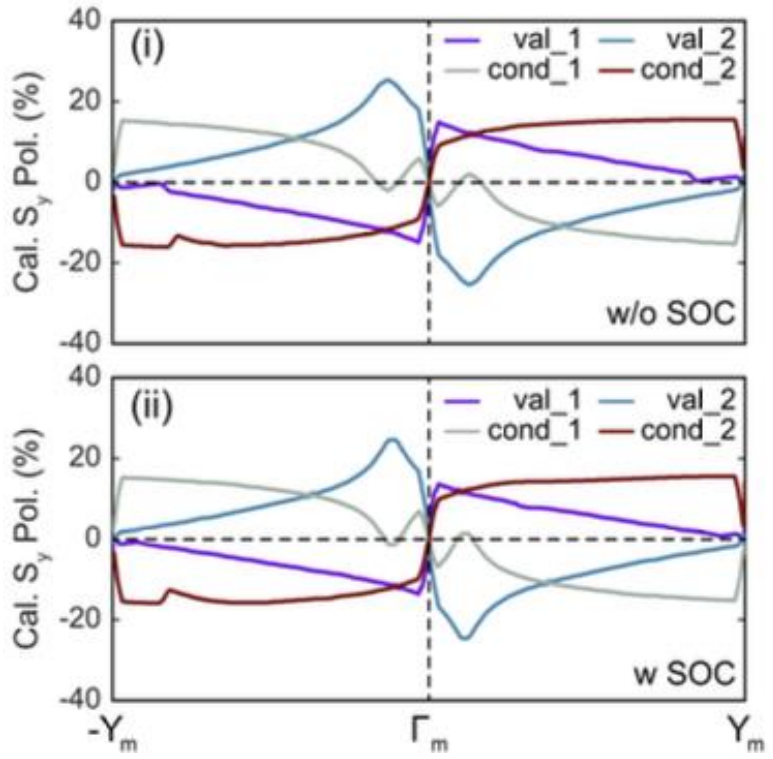
Erjian Cheng, et al., Nature under review

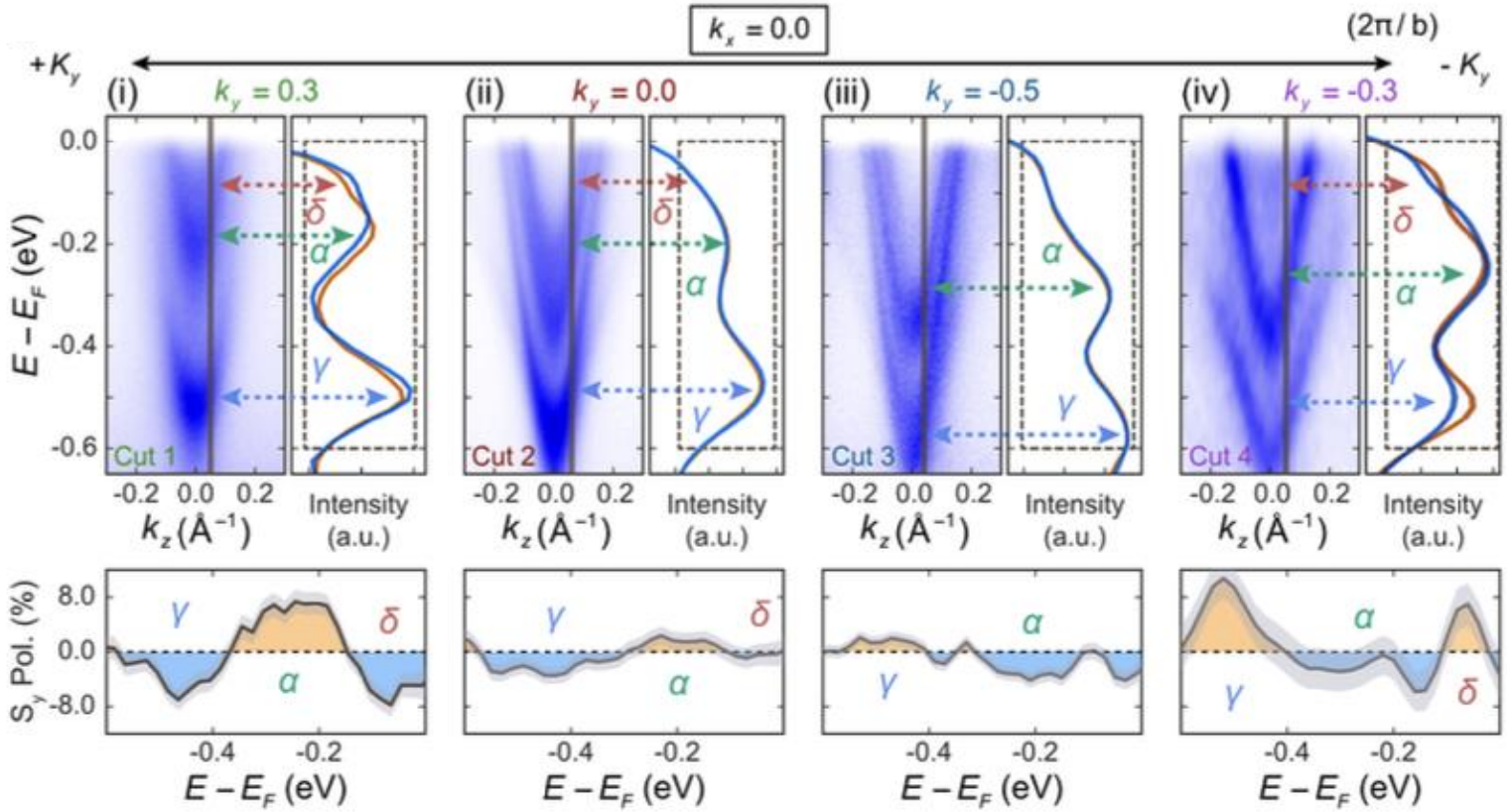



ALTERMAGNETISM

Direct observation of p-wave spin splitting

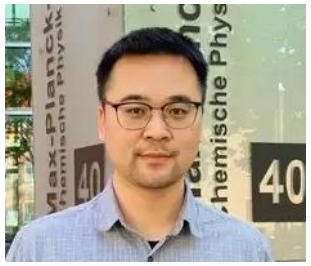
- **Odd-parity spin texture:** $S_y(+k_y) = -S_y(-k_y)$
- **Spin polarization suppressed at** $k_y = 0$ → symmetry-protected nodal plane
- **Experiment matches non-relativistic calculation** → exchange-driven p-wave magnetism, not SOC



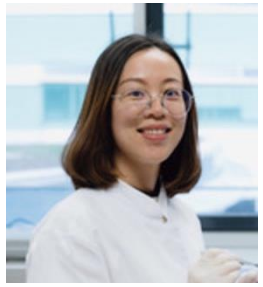


Erjian Cheng, et al., Nature under review

THANK YOU!



Erjian Cheng

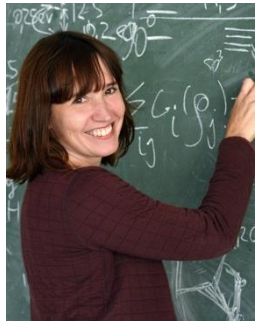


Yu Pan





Andrei Bernevig



Maia Vergniory

erc

Alexander von Humboldt
Stiftung/Foundation