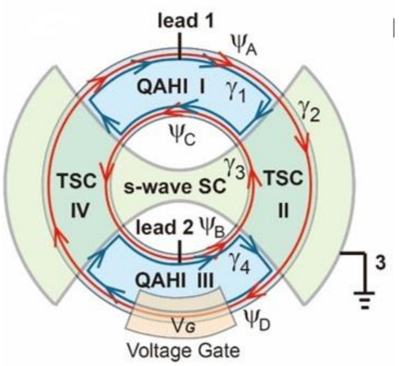
Magnetic Weyl Semimetals

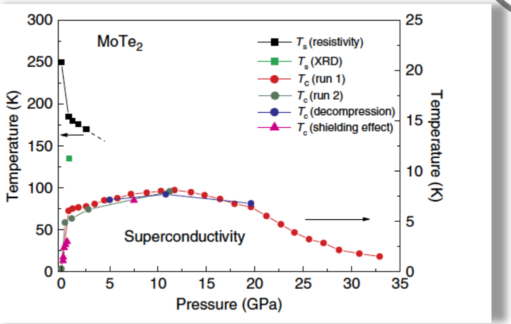
Claudia Felser

MAX-PLANCK-GESELLSCHAFT

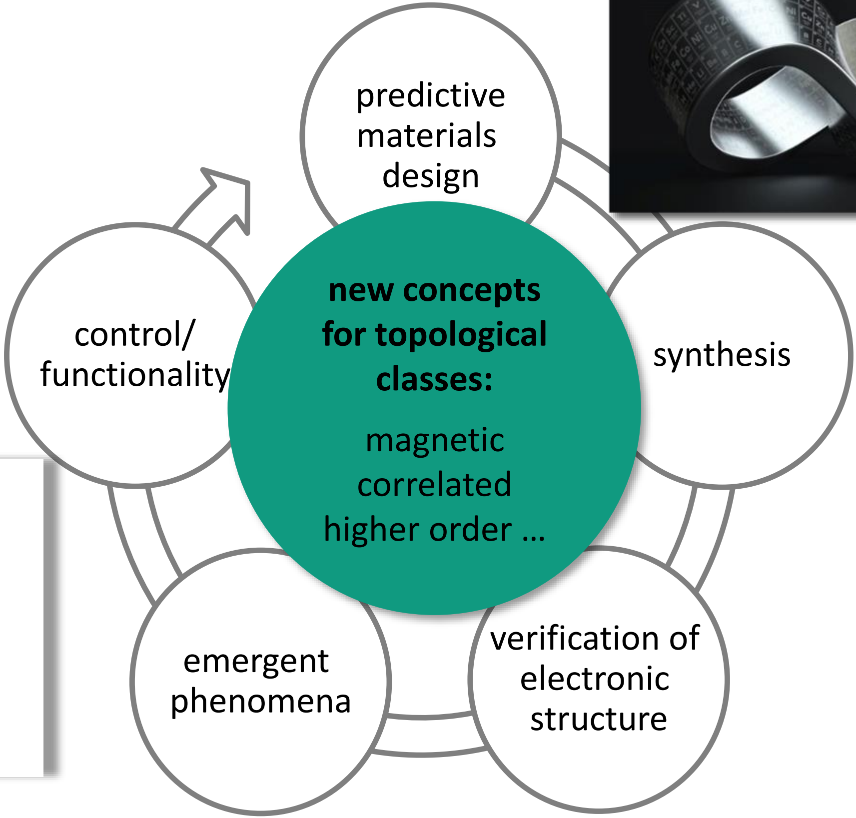
the concept



Lian, et al., PNAS 2018

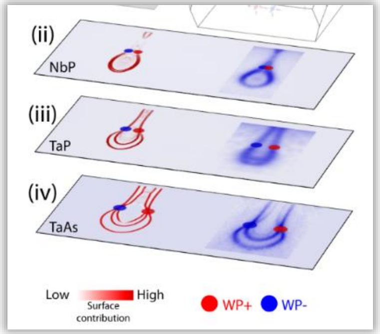


Qi et al. Nat. Com. (2016)



Topological quantum chemistry
Bradlyn, et al., Nature 2017
1807.10271, 1807.08756

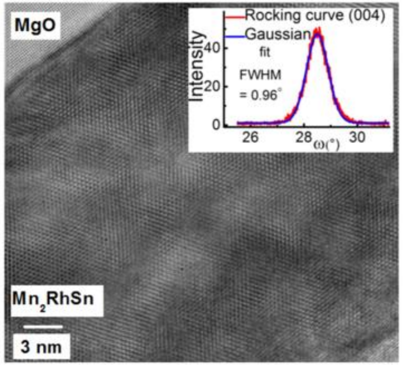
© Nature

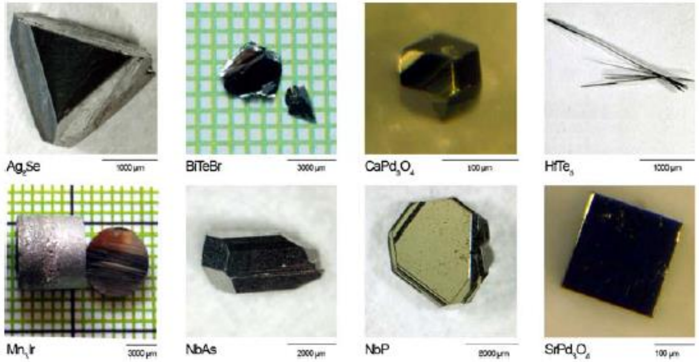


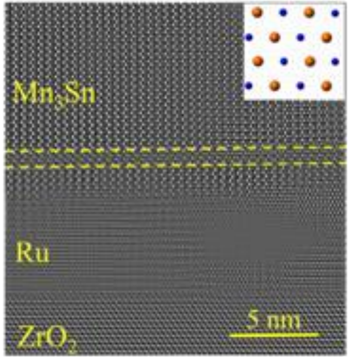
Liu et al. Nat. Mat. (2016)

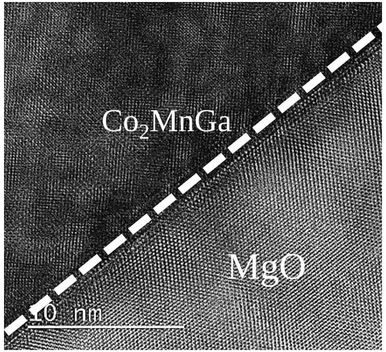
the materials

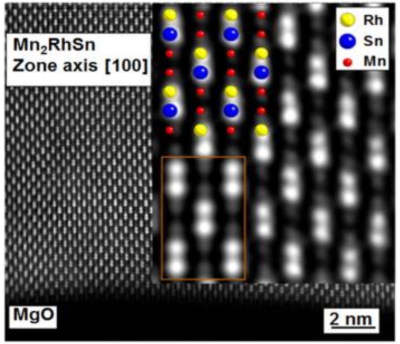
- **explorative search for new materials** & **predictive design**
- high quality **single crystal growth**
- **epitaxial growth** of ultrathin films and heterostructures
- **2D materials and micro/nano structures**



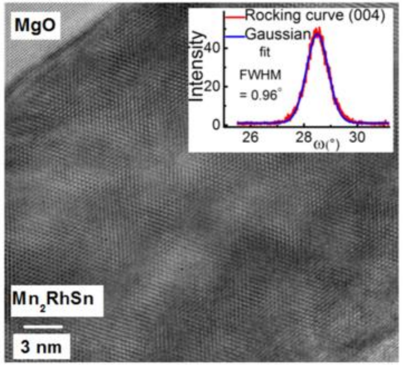


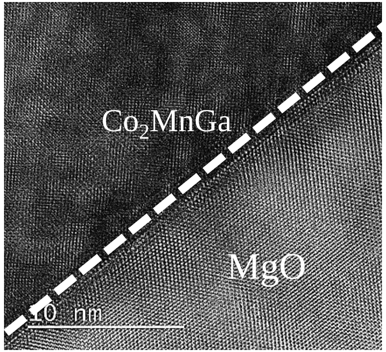


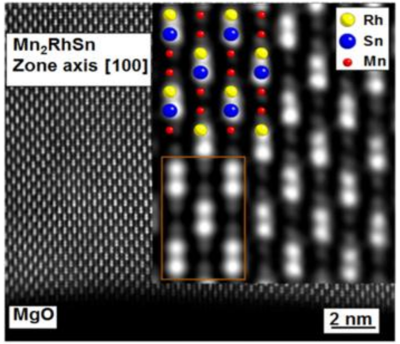


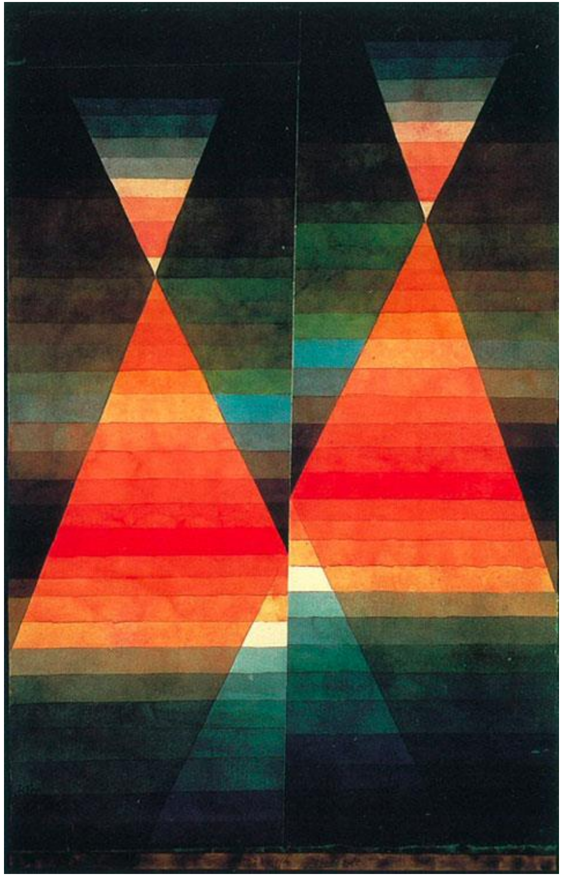


the materials





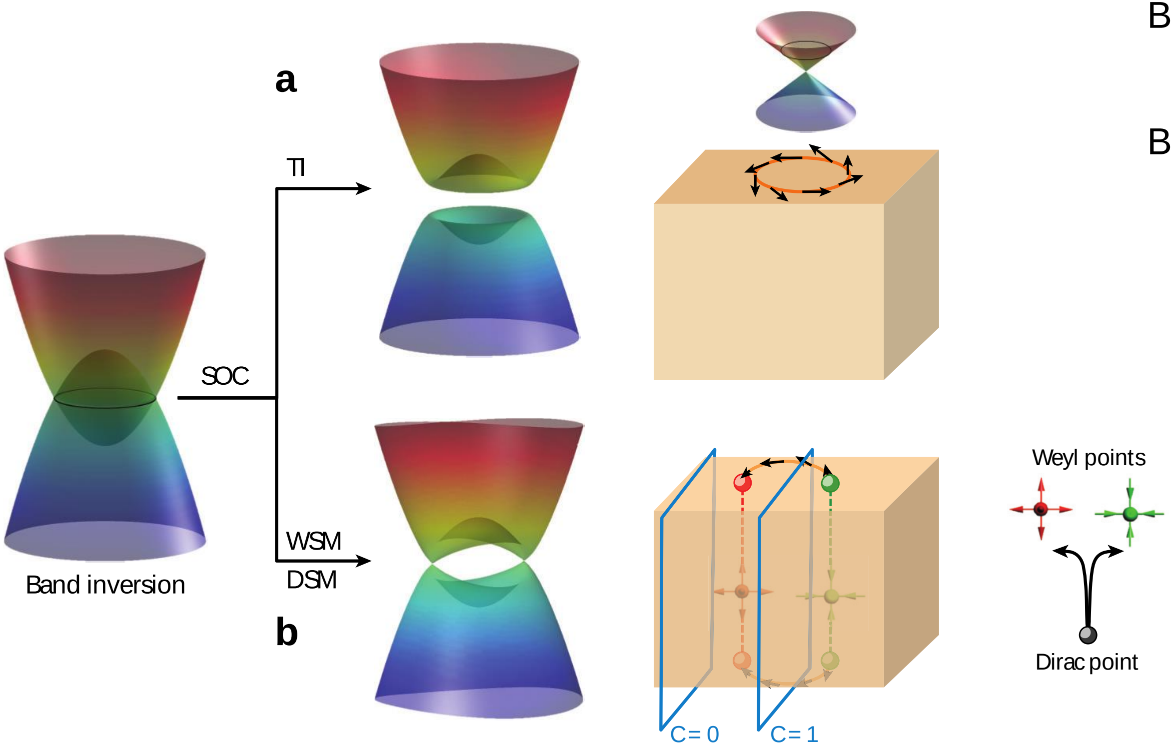




Weyl semimetals

Breaking time reversal symmetry

Weyl semimetals

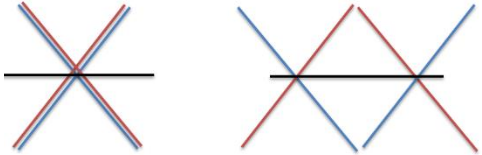


Breaking symmetry

- Inversion symmetry (Strain)

Breaking time reversal symmetry

- Magnetic field

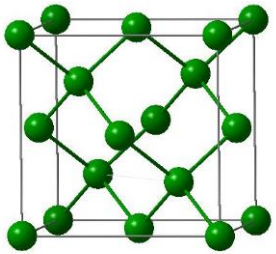


- Dirac points at high symmetry
- Weyl points at low symmetry
- **All crossings in ferromagnets: Weyl points**

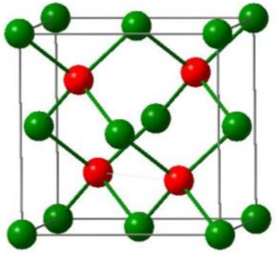
Binghai Yan and Claudia Felser, Annual Review in Condensed Matter 8 (2017) 337

the Heusler family

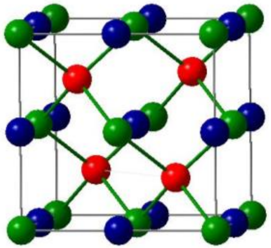
Diamond



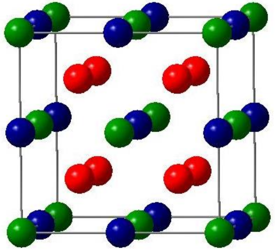
ZnS



Heusler XYZ $C1_b$



X_2YZ $L2_1$



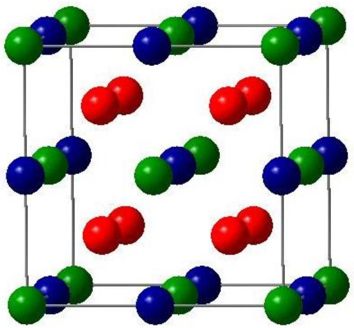
C 2.55	N 3.04
Si 1.90	P 2.19
Ge 2.01	As 2.18
Sn 1.96	Sb 2.05

H 2.20																	He
Li 0.98	Be 1.57											B 2.04	C 2.55	N 3.04	O 3.44	F 3.98	Ne
Na 0.93	Mg 1.31											Al 1.61	Si 1.90	P 2.19	S 2.58	Cl 3.16	Ar
K 0.82	Ca 1.00	Sc 1.36	Ti 1.54	V 1.63	Cr 1.66	Mn 1.55	Fe 1.83	Co 1.88	Ni 1.91	Cu 1.90	Zn 1.65	Ga 1.81	Ge 2.01	As 2.18	Se 2.55	Br 2.96	Kr 3.00
Rb 0.82	Sr 0.95	Y 1.22	Zr 1.33	Nb 1.60	Mo 2.16	Tc 1.90	Ru 2.20	Rh 2.28	Pd 2.20	Ag 1.93	Cd 1.69	In 1.78	Sn 1.96	Sb 2.05	Te 2.10	I 2.66	Xe 2.60
Cs 0.79	Ba 0.89		Hf 1.30	Ta 1.50	W 1.70	Re 1.90	Os 2.20	Ir 2.20	Pt 2.20	Au 2.40	Hg 1.90	Tl 1.80	Pb 1.80	Bi 1.90	Po 2.00	At 2.20	Rn
Fr 0.70	Ra 0.90																
			La 1.10	Ce 1.12	Pr 1.13	Nd 1.14	Pm 1.13	Sm 1.17	Eu 1.20	Gd 1.20	Tb 1.10	Dy 1.22	Ho 1.23	Er 1.24	Tm 1.25	Yb 1.10	Lu 1.27
			Ac 1.10	Th 1.30	Pa 1.50	U 1.70	Np 1.30	Pu 1.28	Am 1.13	Cm 1.28	Bk 1.30	Cf 1.30	Es 1.30	Fm 1.30	Md 1.30	No 1.30	Lr 1.30

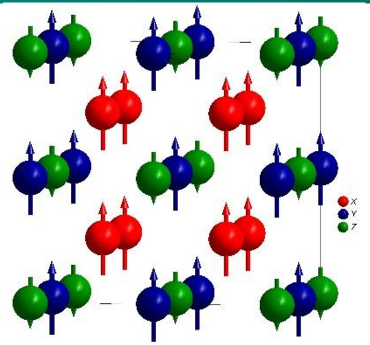
Graf, Felser, Parkin, IEEE TRANSACTIONS ON MAGNETICS 47 (2011) 367
Graf, Felser, Parkin, Progress in Solid State Chemistry Chemistry 39 (2011) 1

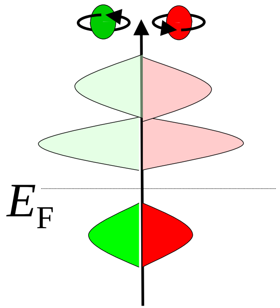
from semiconductors to half metals

X_2YZ



- magic valence electron number: 24
- valence electrons = 24 + magnetic moments

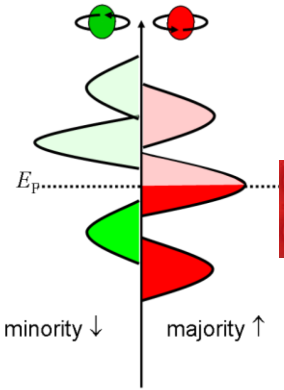




Fe_2 | V | Al

Co_2 | Mn | Ga

2 * 8 + 5 + 3 = 24

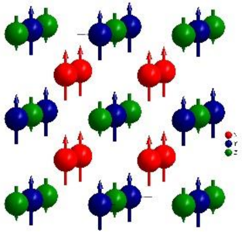


2 * 9 + 7 + 3 = 24 + 4

Kübler *et al.*, PRB **28**, 1745 (1983)
de Groot RA, et al. PRL **50** 2024 (1983)
Galanakis *et al.*, PRB **66**, 012406 (2002)

Kandpal et al., J. Phys. **D 40** (2007) 1507
Balke *et al.* Solid State Com. **150** (2010) 529
Kübler *et al.*, Phys. Rev. B **76** (2007) 024414

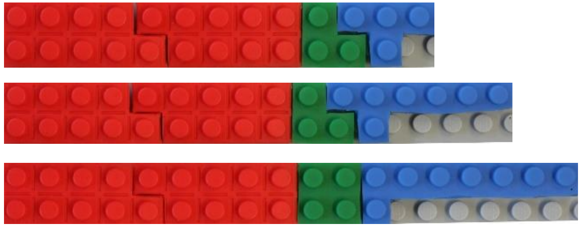
X_2YZ

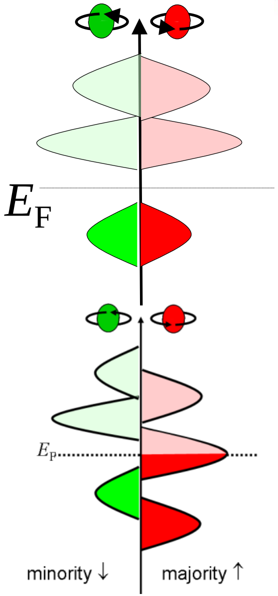


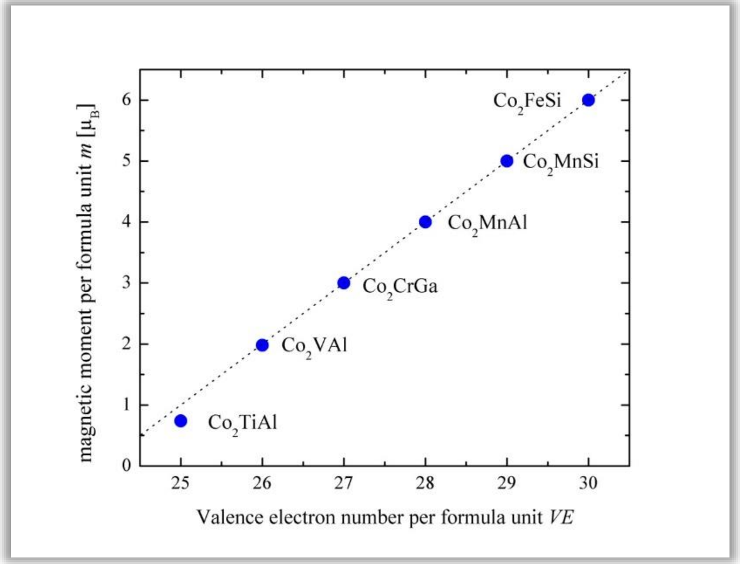
Co_2TiAl: $2\times9 + 4 + 3 = 25$ Ms = $1m_B$

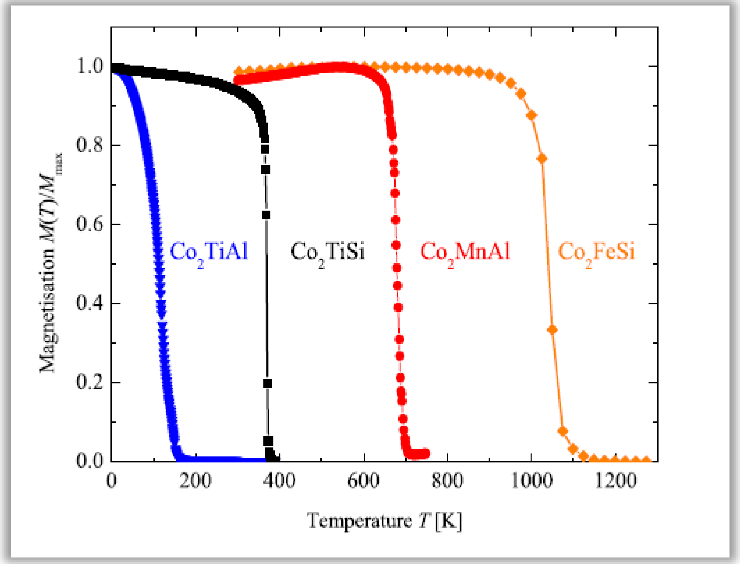
Co_2MnGa: $2\times9 + 7 + 3= 28$ Ms = $4m_B$

Co_2FeSi: $2\times9 + 8 + 4 = 30$ Ms = $6m_B$









Kübler *et al.*, PRB **28**, 1745 (1983)
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Heusler and Weyl

Breaking symmetry

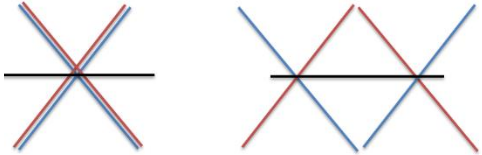
- Inversion symmetry (Strain)

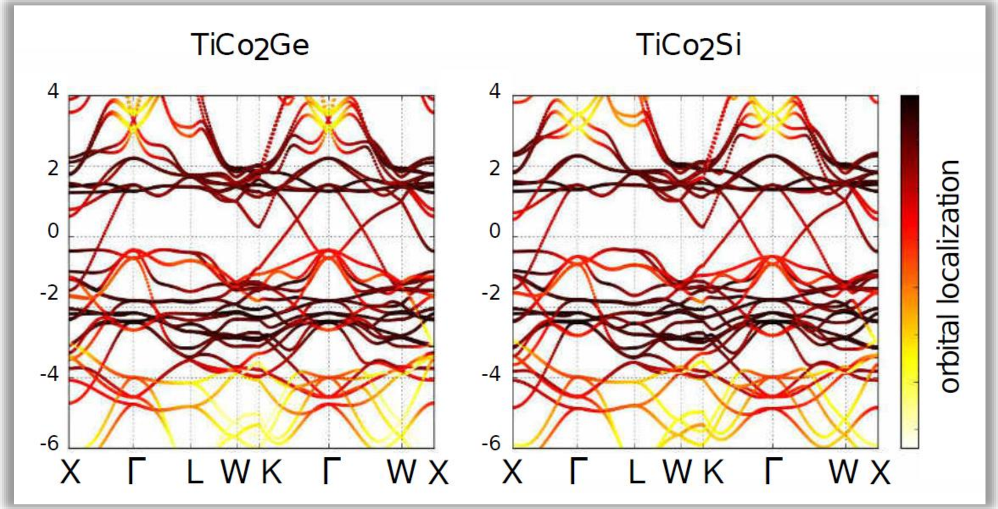
Breaking time reversal symmetry

- Magnetic field

Co_2TiSn

Co_2TiSi: $2\times9 + 4+ 4 = 26$ $M_s = 2\mu_B$





- Dirac points at high symmetry
- Weyl points at low symmetry
- All crossings in ferromagnets:

Weyl points

Binghai Yan Claudia Felser,
Annual Review in Condensed Matter 8 (2017) 337

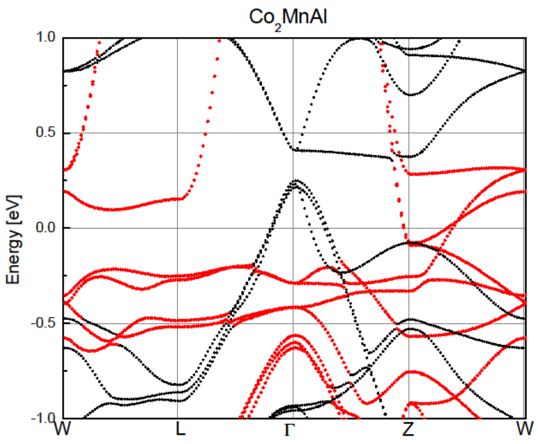
Zhijun Wang, et al., arXiv:1603.00479
Guoqing Chang et al., arXiv:1603.01255

Heusler, Weyl and Berry

Giant AHE in Co_2MnAl

$$\sigma_{xy} = 1800\,\mathrm{S/cm}\ \text{calc.}$$

$$\sigma_{xy} \approx 2000\,\mathrm{S/cm}\ \text{meas.}$$



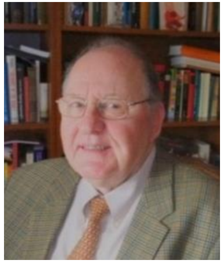
$$\sigma^{A}_{xy}(\mu) = ie^2 \left(\frac{1}{2\pi}\right)^3 \int_k dk \sum_{E(n,k)<\mu} f(n,k,\mu)\Omega_{n,xy}(k),$$

Compound[a]	N_V	a (nm)	M^{exp}	M^{calc}	σ_{xy}	P (%)
Co_2VGa	26	0.5779	1.92	1.953	66	65
Co_2CrAl	27	0.5727	1.7	2.998	438	100
Co_2VSn	27	0.5960	1.21	1.778	−1489	35
Co_2MnAl	28	0.5749	4.04	4.045	1800	75
Rh_2MnAl	28	0.6022		4.066	1500	94
Mn_2PtSn[b]	28	0.4509 (1.3477)		6.66	1108	91
Co_2MnSn	29	0.5984	5.08	5.00	118	82
Co_2MnSi	29	0.5645	4.90	4.98	228	100

$$\rho^{M}_{xy} = \left(\alpha\rho_{xx} + \beta\rho^{2}_{xx}\right)\boldsymbol{M}.\ ???$$

Kübler, Felser, PRB 85 (2012) 012405
Vidal et al Appl.Phys.Lett. 99 (2011) 132509
Kübler, Felser, EPL 114 (2016) 47005.

Heusler, Weyl and Berry



Giant AHE in Co_2MnAl

$$\sigma_{xy} = 1800\,\mathrm{S/cm}\ \ \text{calc.}$$

$$\sigma_{xy} \approx 2000\,\mathrm{S/cm}\ \ \text{meas.}$$

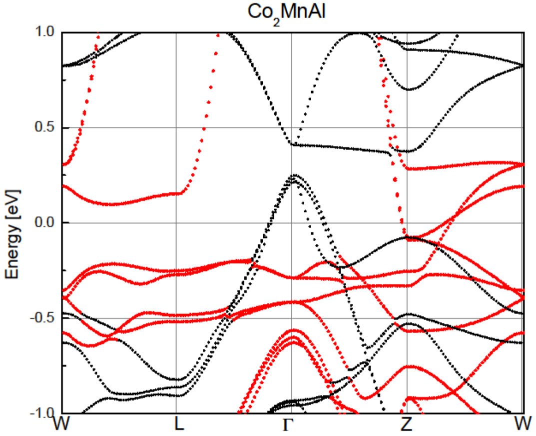
Co_2MnGa

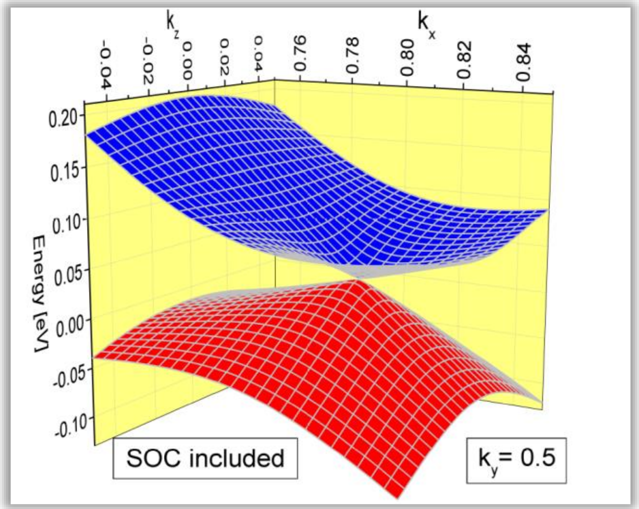
PHYSICAL REVIEW B **85**, 012405 (2012)

Berry curvature and the anomalous Hall effect in Heusler compounds

Jürgen Kübler[1,*] and Claudia Felser[2]

$$\sigma_{xy}^{A}(\mu) = ie^{2}\ \left(\frac{1}{2\pi}\right)^{3}\int_{k} dk \sum_{E(n,k)<\mu} f(n,k,\mu)\Omega_{n,xy}(k),$$





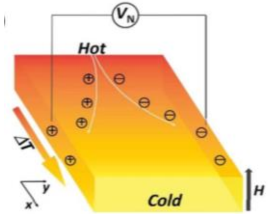
Kübler, Felser, PRB 85 (2012) 012405
Vidal et al., Appl. Phys. Lett. 99 (2011) 132509

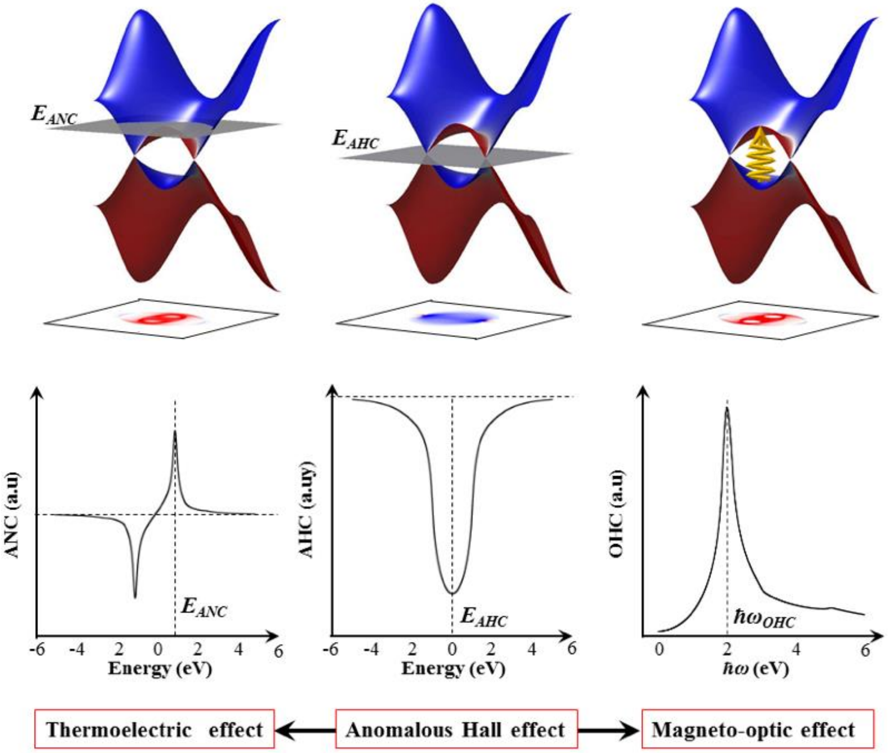
Kübler, Felser, EPL 114 (2016) 47005.

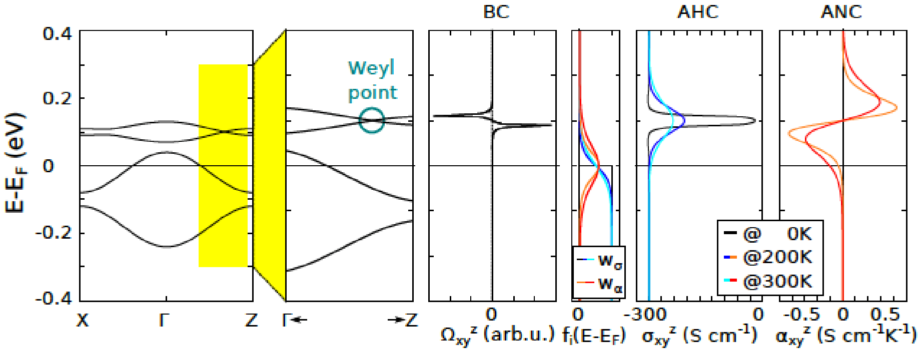
Berry curvature design

Berry curvature design
- giant spin Hall
- giant anomalous Hall
- giant topological Hall
- giant anomalous Nernst

Nernst effect



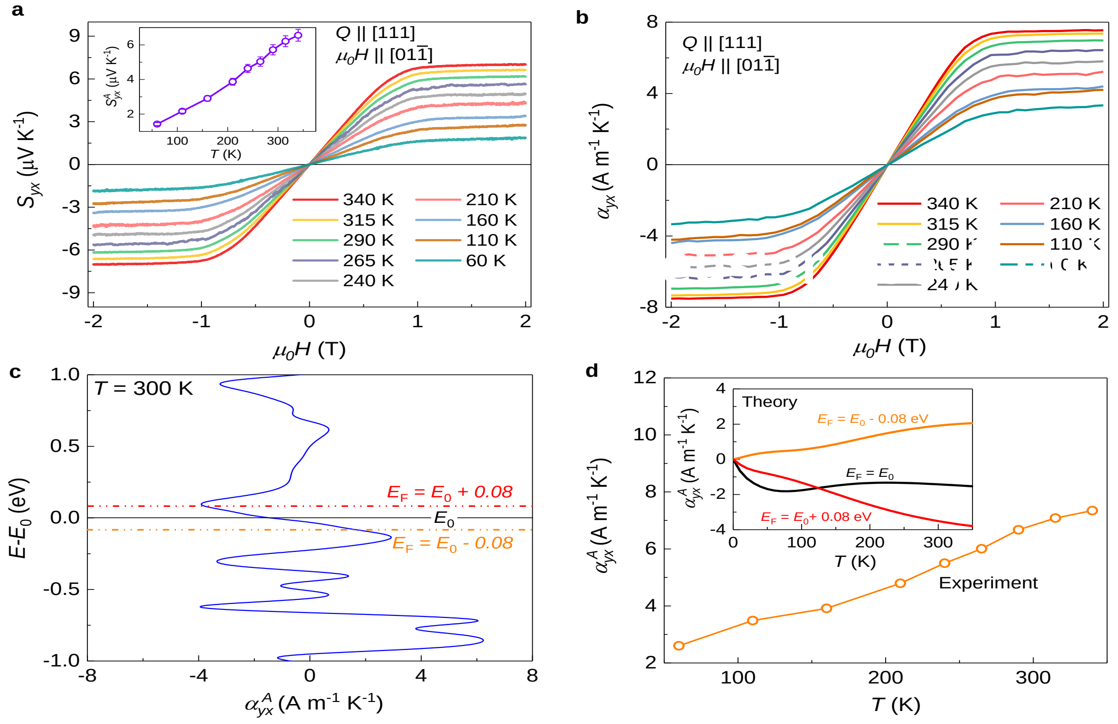


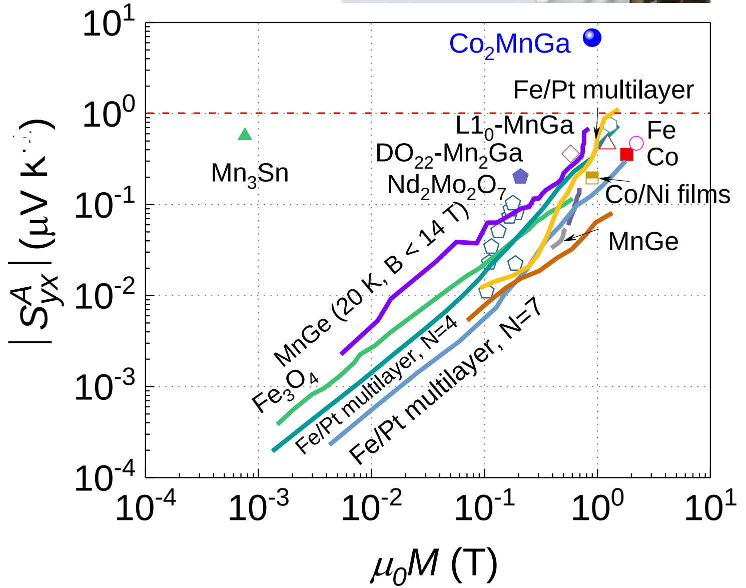


J. Noky et al., Phys. Rev. B 98, 241106(R) (2018), arXiv:1807.07843, arXiv:1806.06753

Nernst effect

Co_2MnGa

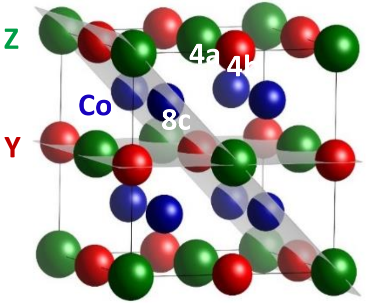




J. Noky et al., Phys. Rev. B 98, 241106(R) (2018)

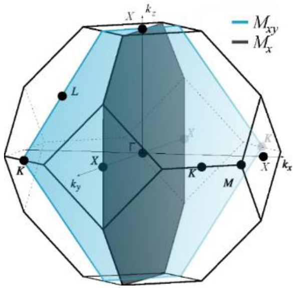
Satya N. Guin, et al., NPG Asia Mater. 11, 16 (2019), arXiv:1806.06753
Sakain et al. Nature Physics 2018

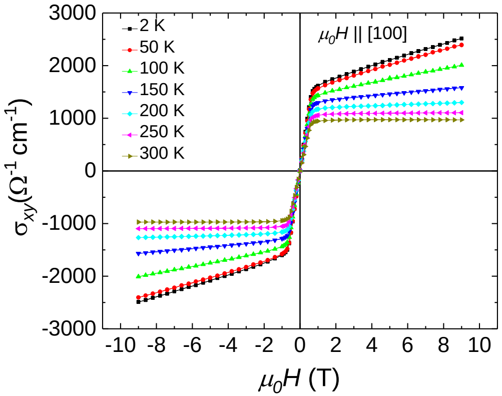
Heusler, Weyl and Berry

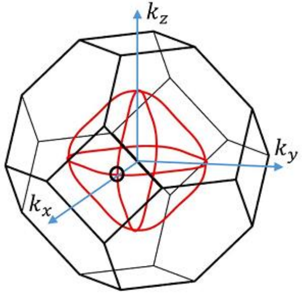


Co_2YZ (Y = IVB or VB; Z = IVA or IIIA)

$L2_1$ space group 225 ($Fm\bar{3}m$)

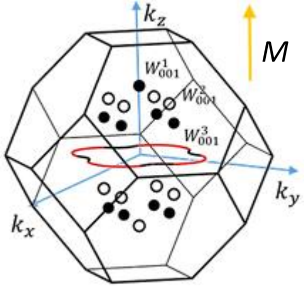






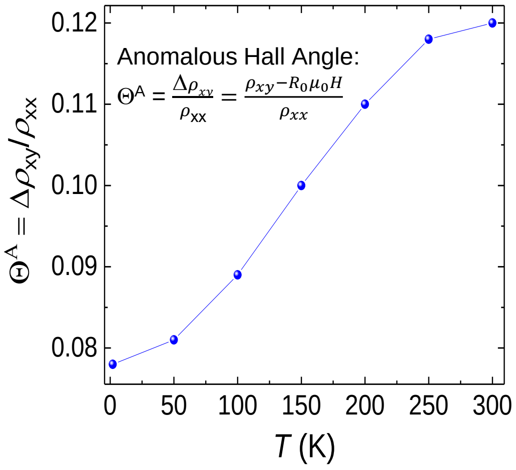
With SOC

Symmetry and electronic structures depend on the magnetization direction



Without SOC

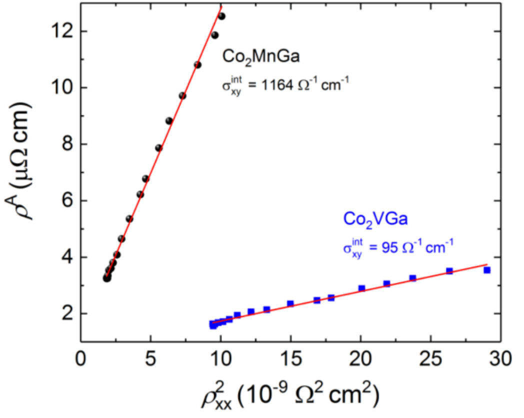
Phys. Rev. Lett. 117, 236401 (2016)
Sci. Rep. 6, 38839 (2016)

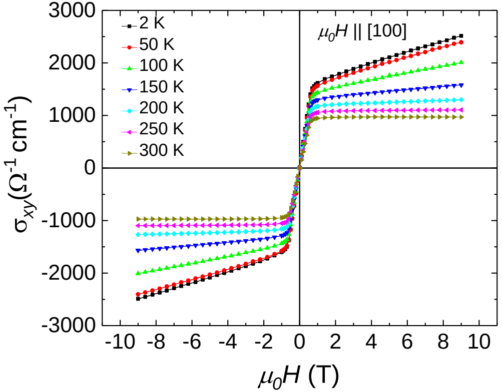


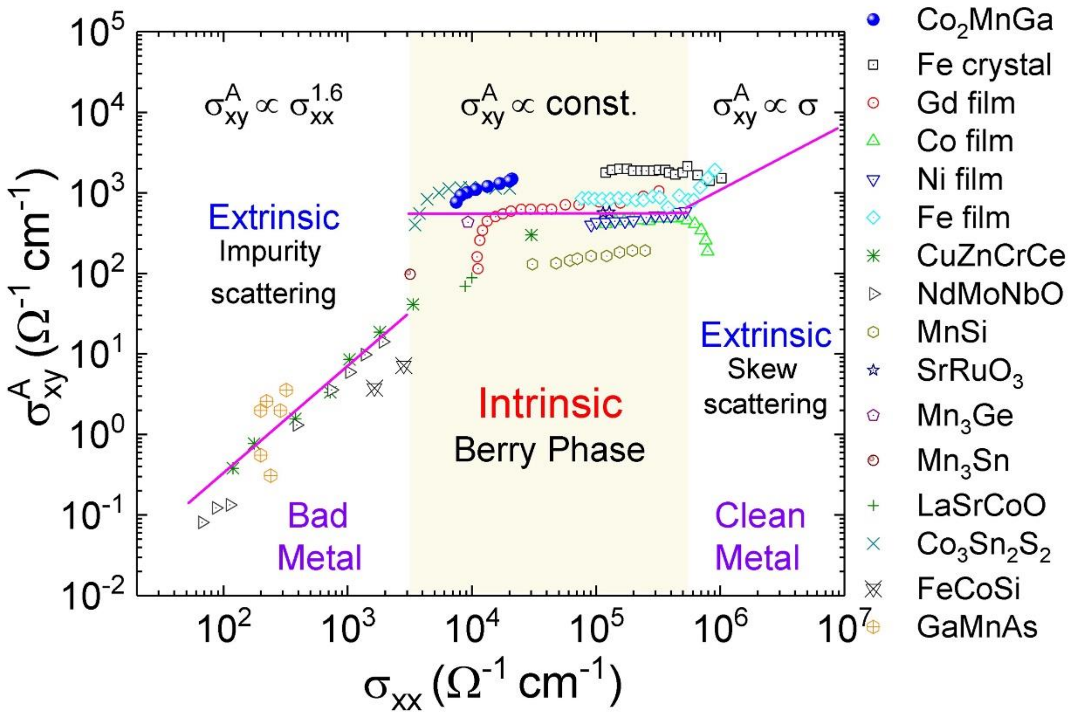
- nodal line is formed in the plane when bands of opposite mirror eigenvalues cross.
- Mirror planes are related to each other by the rotations

Manna et al., Phys. Rev. X 8 (2018) 041045, arXiv:1712.10174

Heusler, Weyl and Berry

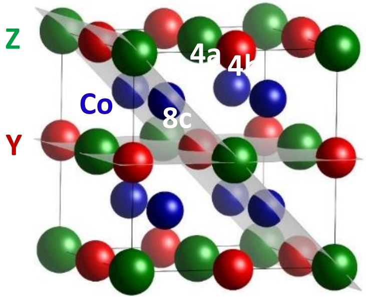


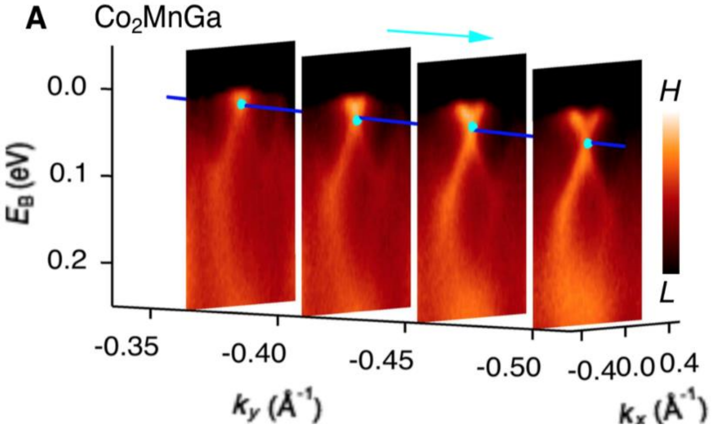




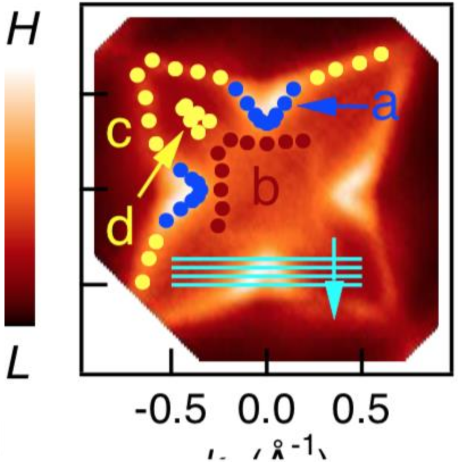
Manna et al., Phys. Rev. X 8 (2018) 041045, arXiv:1712.10174

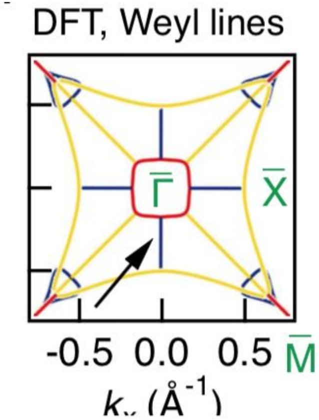
Co_2MnGa – ferromagnetic nodal line

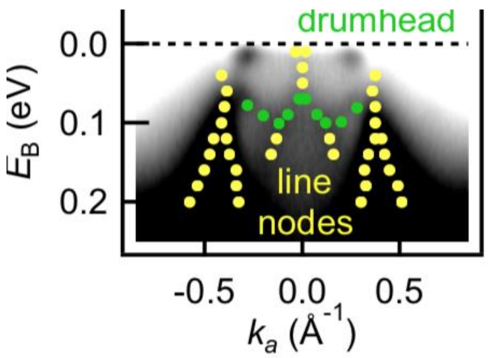


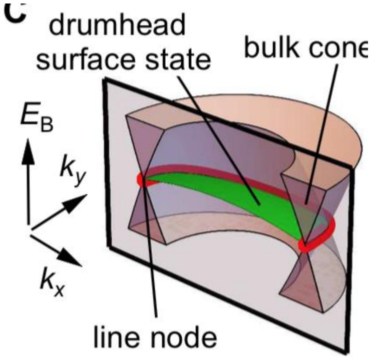


Series of ARPES cuts through the candidate line node



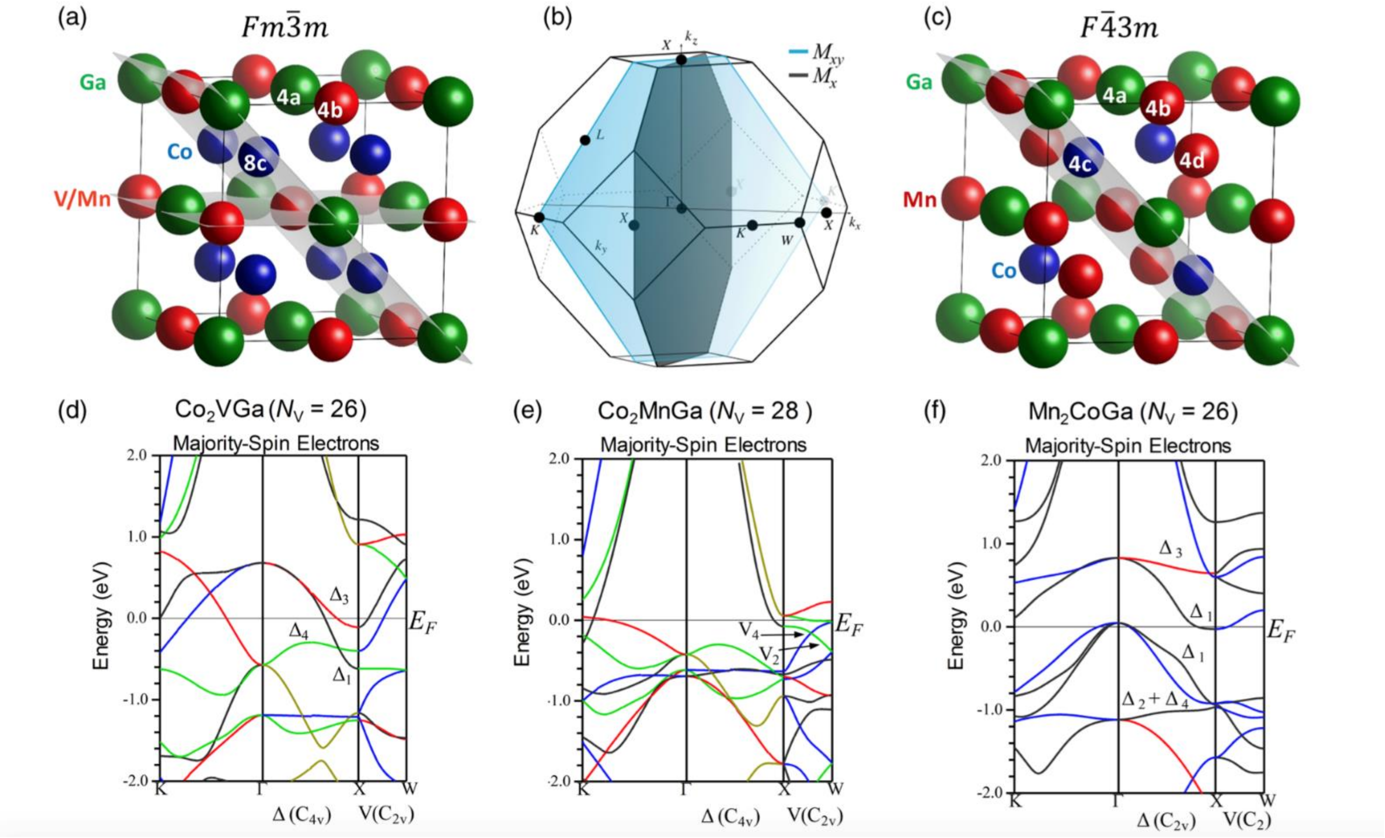






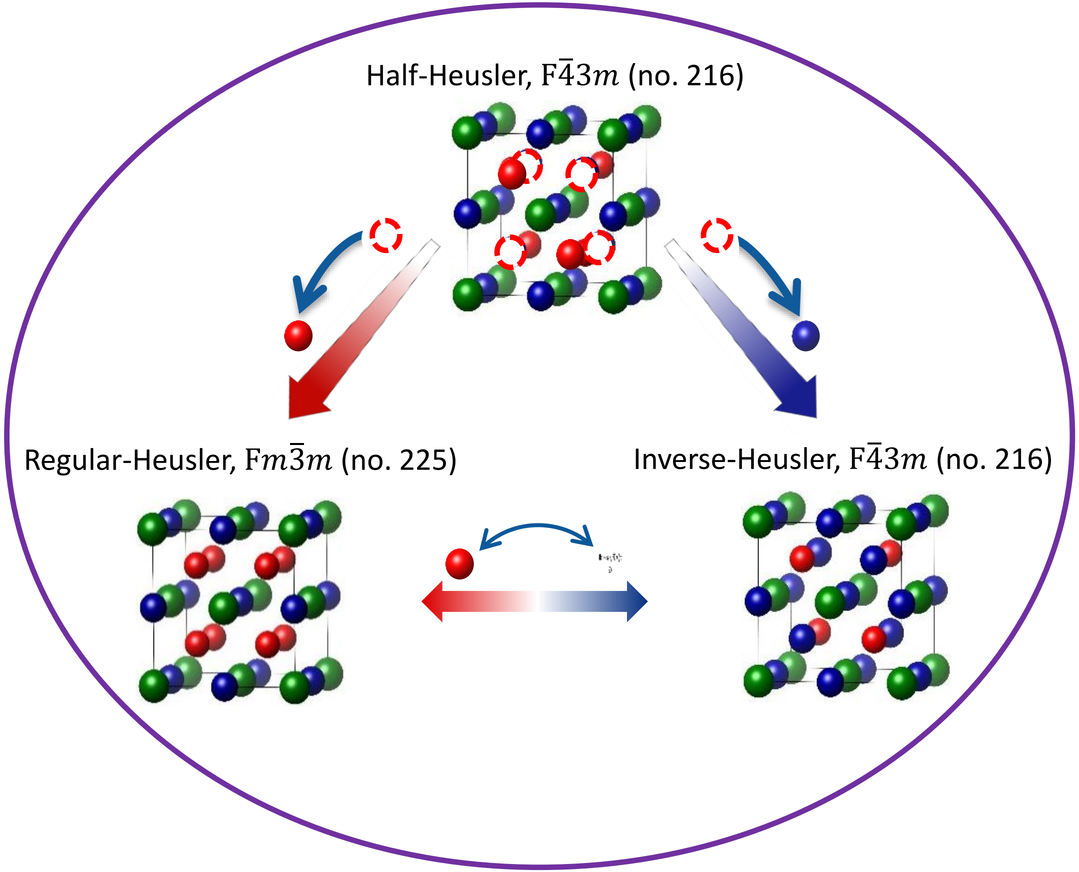
Belopolski, et al., Science accepted (2019) preprint arXiv:1712.09992

Heusler, Weyl and Berry



Manna et al., Phys. Rev. X 8 (2018) 041045, arXiv:1712.10174

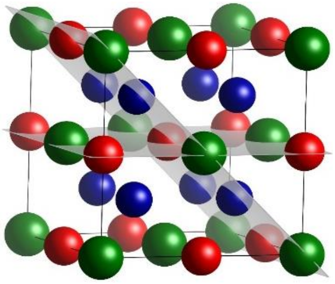
no inversion symmetry
topology !

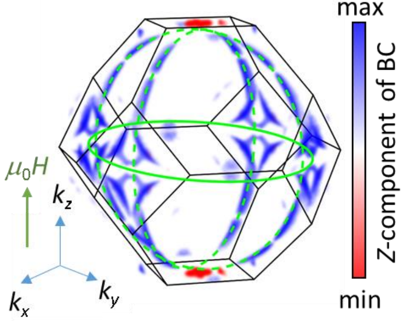


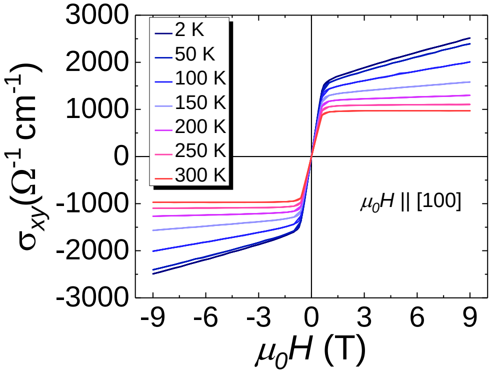
Heusler, Weyl and Berry

playing with symmetry: from Weyl to spingapless semiconductor

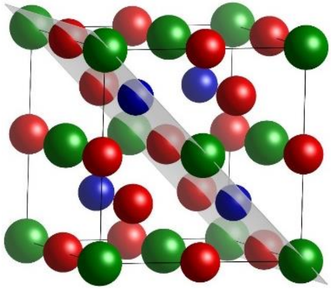
Co_2MnGa

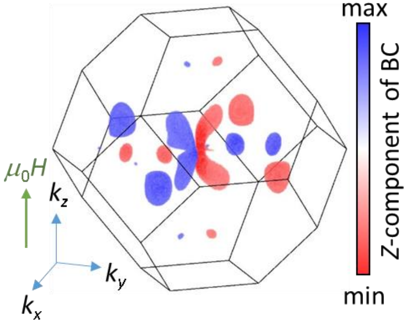


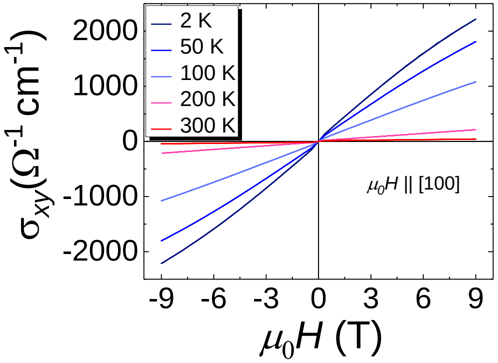




Mn_2CoGa





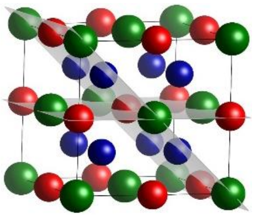


Manna et al., Phys. Rev. X 8 (2018) 041045, arXiv:1712.10174

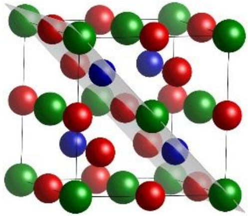
Heusler, Weyl and Berry

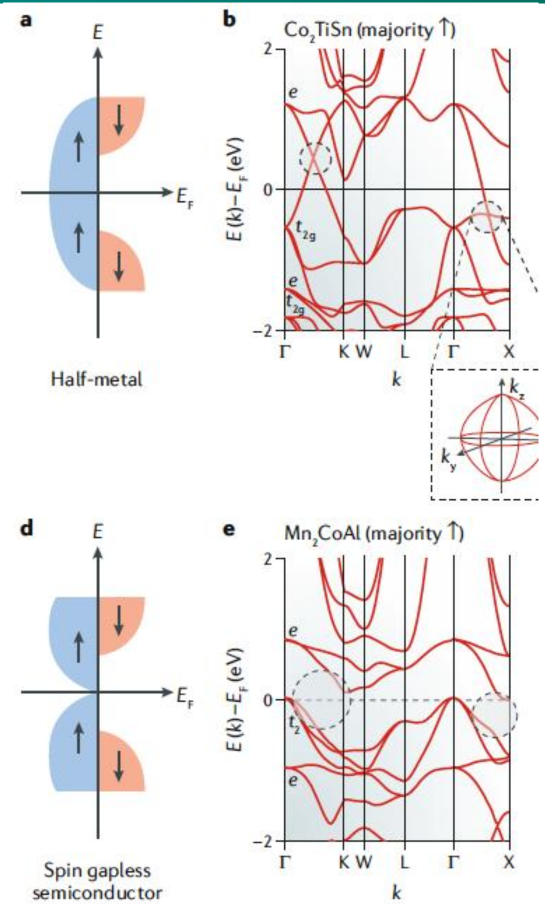
playing with symmetry: from Weyl to spingapless semiconductor

Co_2TiSn



Mn_2CoGa

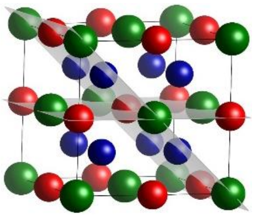


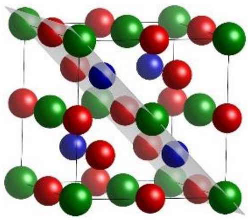


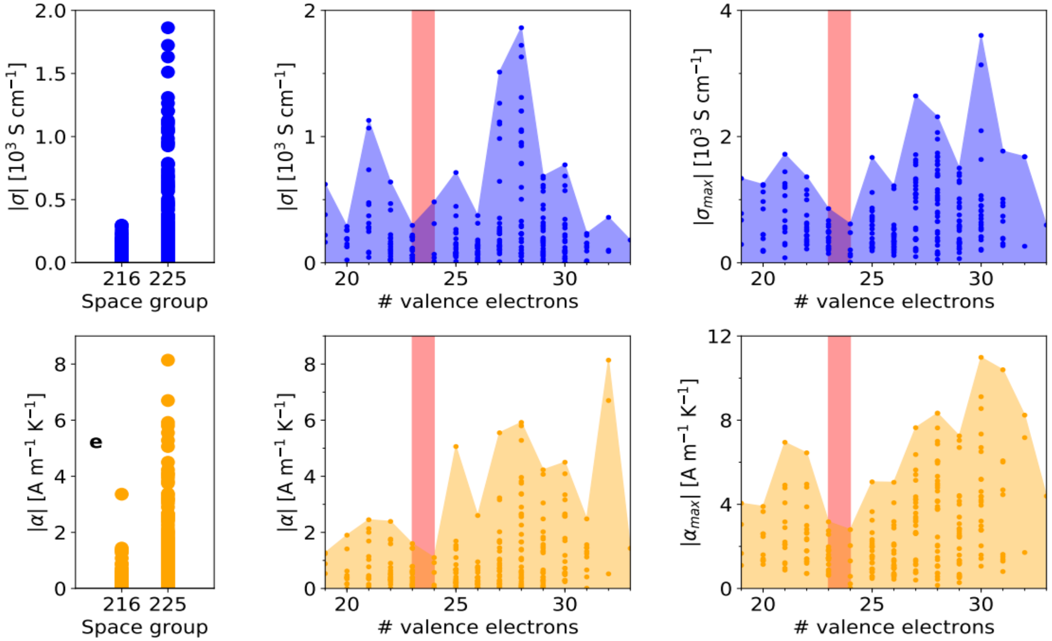
Ouardi, Fecher, Kübler, and Felser, Physical Review Letter 110 (2013) 100401
Manna et al., Phys. Rev. X 8 (2018) 041045, arXiv:1712.10174
Manna et al., Nature Review Materials, 3 (2018) 244 arXiv:1802.02838v1

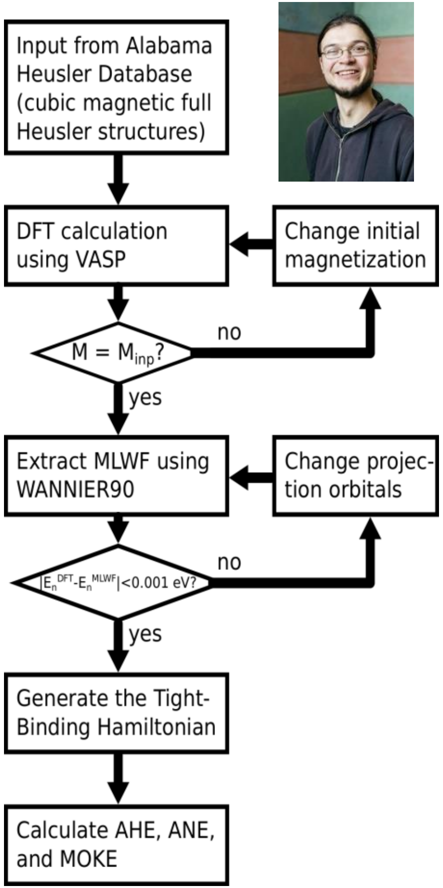
high through put

playing with symmetry:



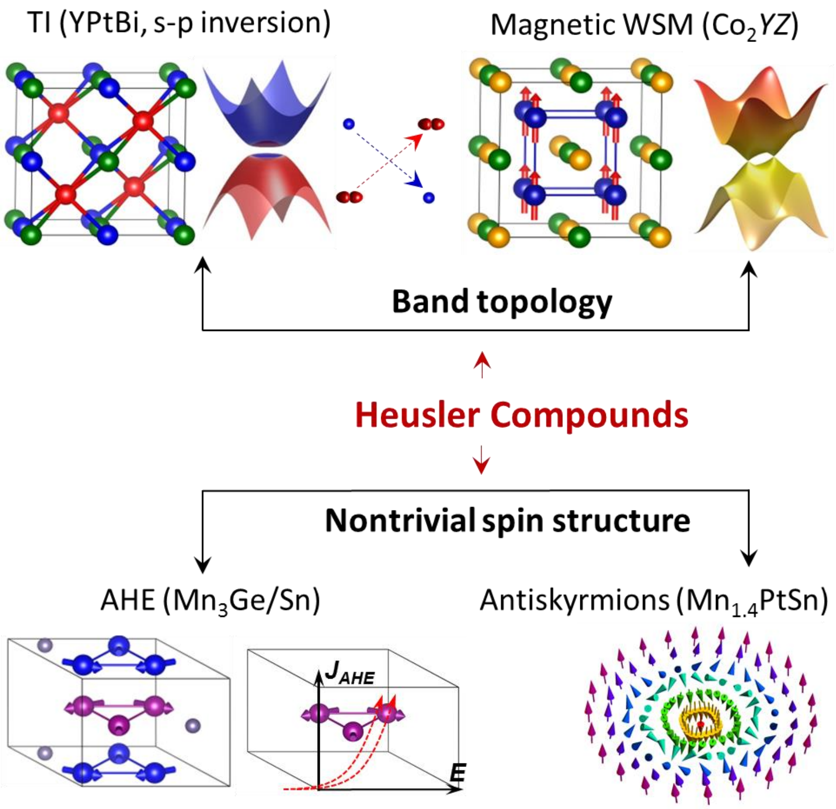


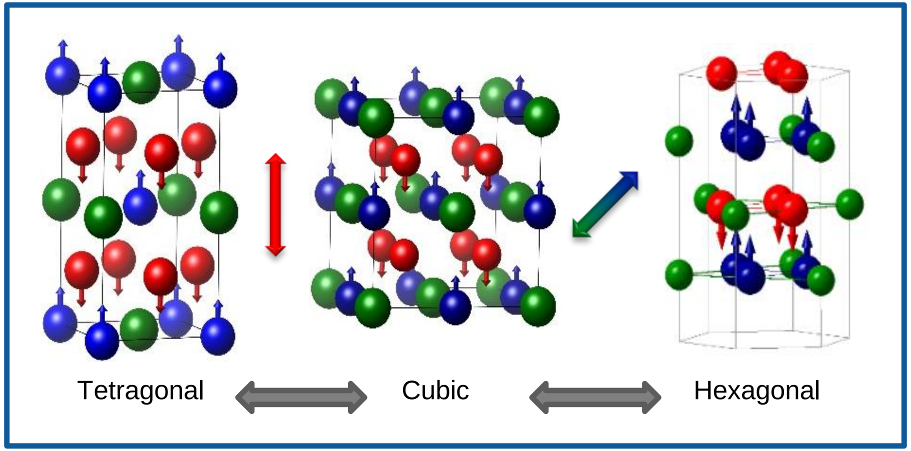




Noky et al., in submitted

Heusler, Weyl and Berry





Mn_3Ga Mn_3Ge Mn_3Sn

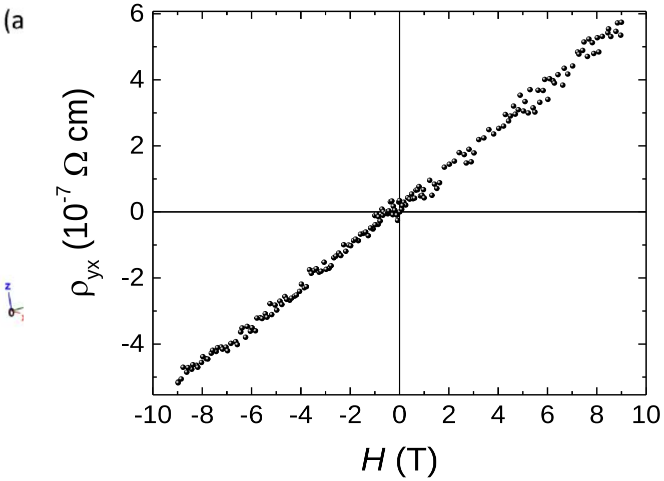
Manna et al., Nature Materials Review, 2018,

Heusler, Weyl and Berry

PRL 112, 017205 (2014) PHYSICAL REVIEW LETTERS week ending 10 JANUARY 20

Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism

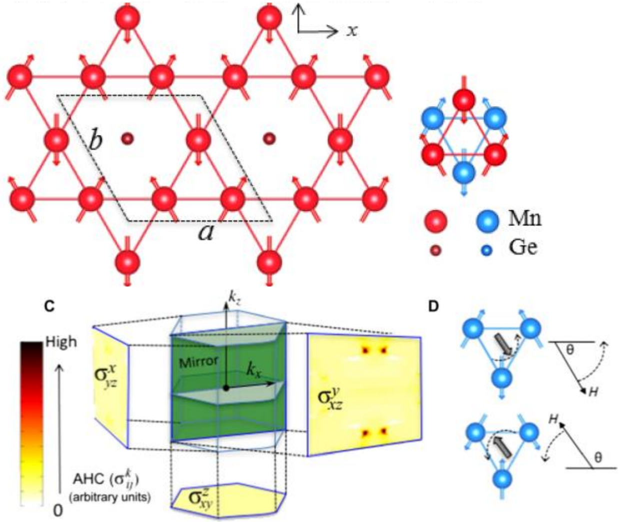
Hua Chen, Qian Niu, and A. H. MacDonald



epl A Letters Journal Exploring the Frontiers of Physics December 2014
EPL, 108 (2014) 67001 www.epljournal.org
doi: 10.1209/0295-5075/108/67001

Non-collinear antiferromagnets and the anomalous Hall effect

J. Kübler[1] and C. Felser[2]



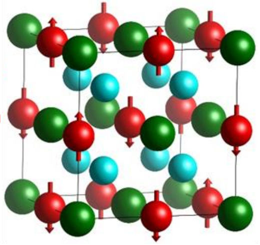
For the planar cases the AHC is connected with Weyl points in the energy- band structure.

Chen, Niu, and MacDonald, Phys. Rev. Lett., 112 (2014) 017205.

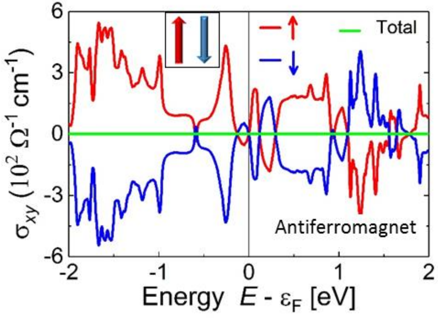
Kübler and Felser EPL 108 (2014) 67001

Heusler, Weyl and Berry

$$\sigma_{xy}^{A}(\mu) = ie^2 \left(\frac{1}{2\pi}\right)^3 \int_k dk \sum_{E(n,k)<\mu} f(n,k,\mu)\Omega_{n,xy}(k),$$

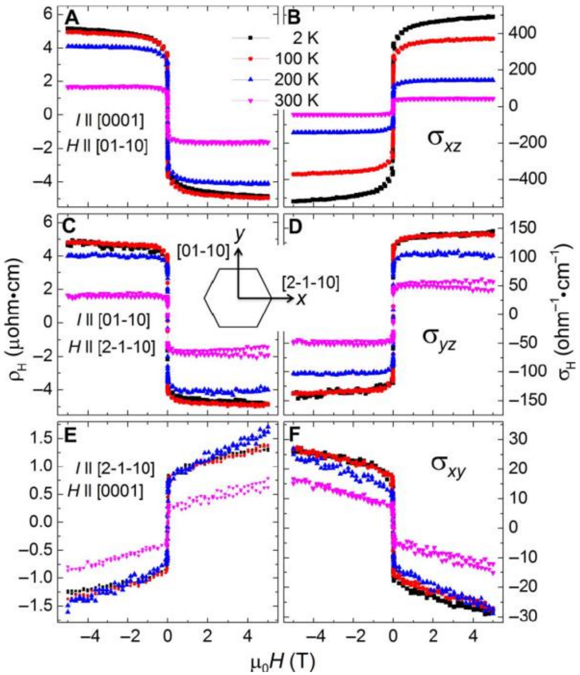


[Ru_2MnSi]



The anomalous Hall conductivity in an antiferromagnetic metal is zero

Mn_3Ge
Mn_3Sn

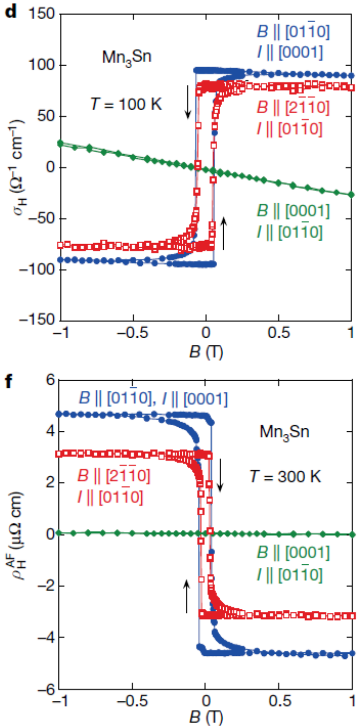


LETTER

doi:10.1038/nature15723

Large anomalous Hall effect in a non-collinear antiferromagnet at room temperature

Satoru Nakatsuji[1,2], Naoki Kiyohara[1] & Tomoya Higo[1]



Nayak et al. arXiv:1511.03128, Science Advances 2 (2016) e1501870

Kiyohara, Nakatsuji, preprint: arXiv:1511.04619

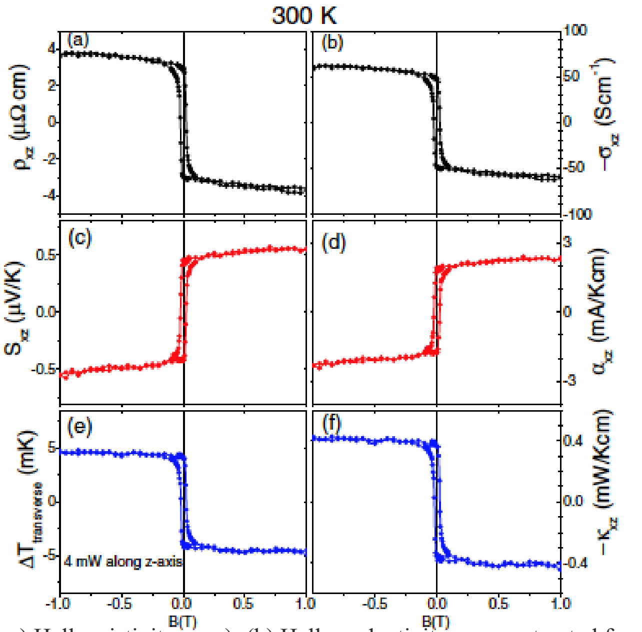
Nakatsuji, Kiyohara, & Higo, Nature, doi:10.1038/nature15723

Nernst effect in Mn_3Sn

PRL 119, 056601 (2017) PHYSICAL REVIEW LETTERS week ending 4 AUGUST 2017

Anomalous Nernst and Righi-Leduc Effects in Mn_3Sn: Berry Curvature and Entropy Flow

Xiaokang Li,[1] Liangcai Xu,[1] Linchao Ding,[1] Jinhua Wang,[1] Mingsong Shen,[1] Xiufang Lu,[1] Zengwei Zhu,[1,*] and Kamran Behnia[1,2,†]

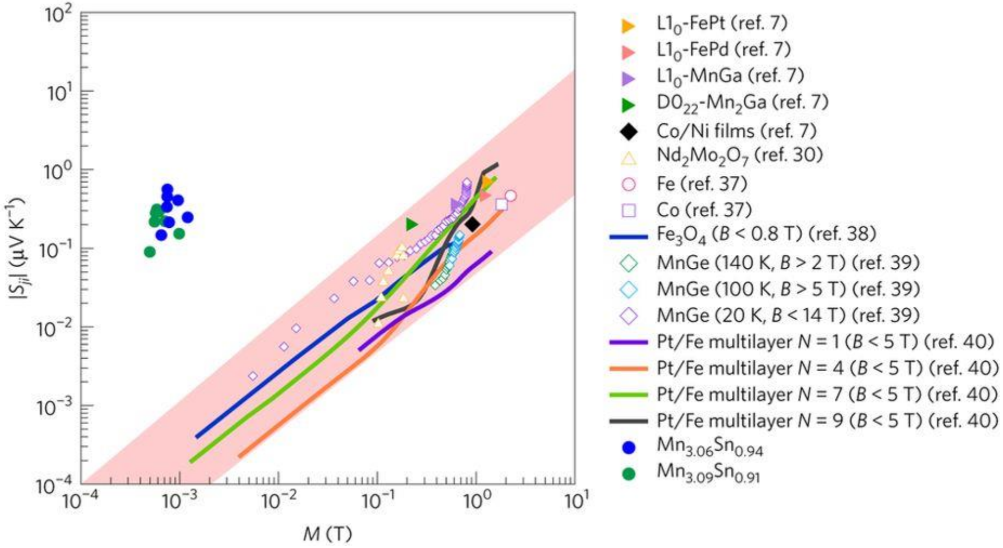


a) Hall resistivity, ρxz); (b) Hall conductivity, σxz, extracted from ρxz, ρxx, and ρzz; (c) Nernst signal, Sxz; (d) Transverse thermoelectric conductivity, αxz,

nature physics LETTERS
PUBLISHED ONLINE: 24 JULY 2017 | DOI: 10.1038/NPHYS4181

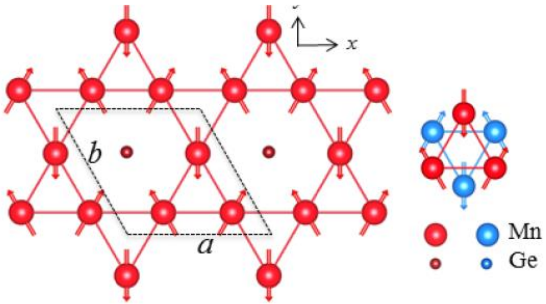
Large anomalous Nernst effect at room temperature in a chiral antiferromagnet

Muhammad Ikhlas[1†], Takahiro Tomita[1†], Takashi Koretsune[2,3], Michi-To Suzuki[2], Daisuke Nishio-Hamane[1], Ryotaro Arita[2,4], Yoshichika Otani[1,2,4] and Satoru Nakatsuji[1,4*]



Magnetization dependence of the spontaneous Nernst effect for ferromagnetic metals and Mn_3Sn

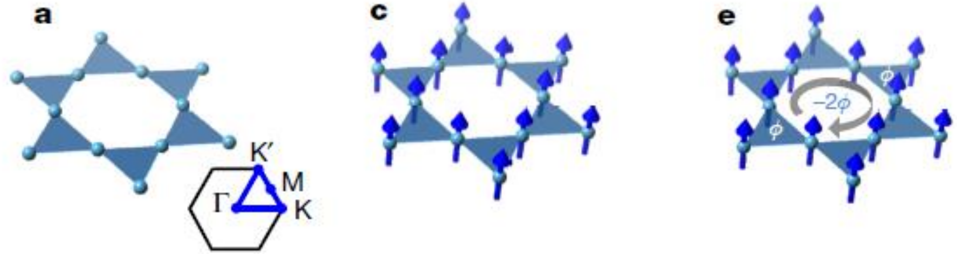
Kagome lattice



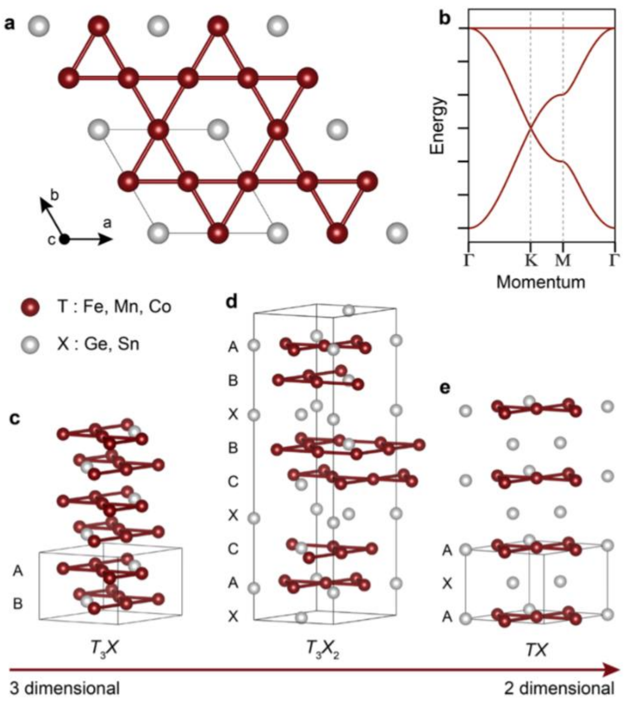
LETTER

doi:10.1038/nature25987

Massive Dirac fermions in a ferromagnetic kagome metal



Mn,Fe,Co



Nature, 2018, doi:10.1038/nature25987

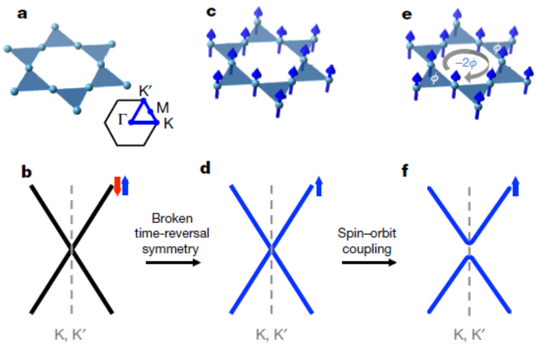
Kang et al., preprint arXiv:1906.02167

Kagome lattice

LETTER

doi:10.1038/nature25987

Massive Dirac fermions in a ferromagnetic kagome metal

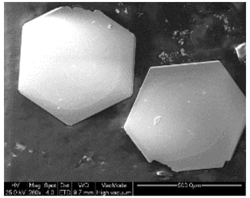


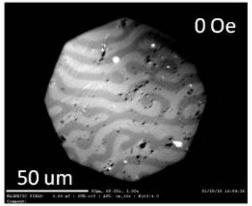
Fe_3Sn_2

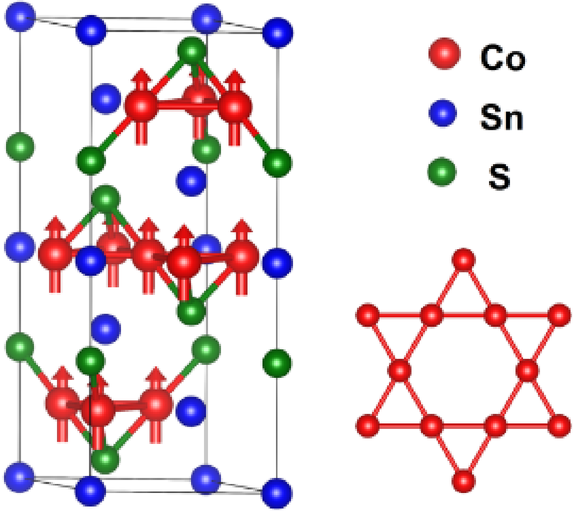
Nature, 2018, doi:10.1038/nature25987

Looking for Weyl fermions on a ferromagnetic Kagomé lattice with out of plane magnetisation.

$Co_3Sn_2S_2$

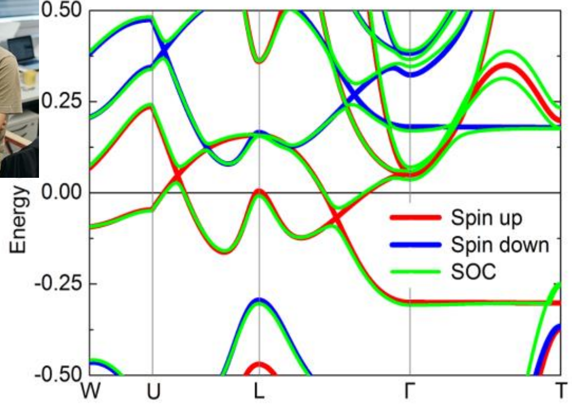


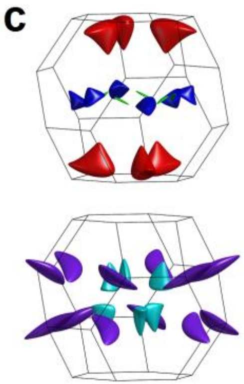




Enke Liu, et al. Nature Physics 14 (2018) 1125 , preprint arXiv:1712.06722

Weyl and Berry

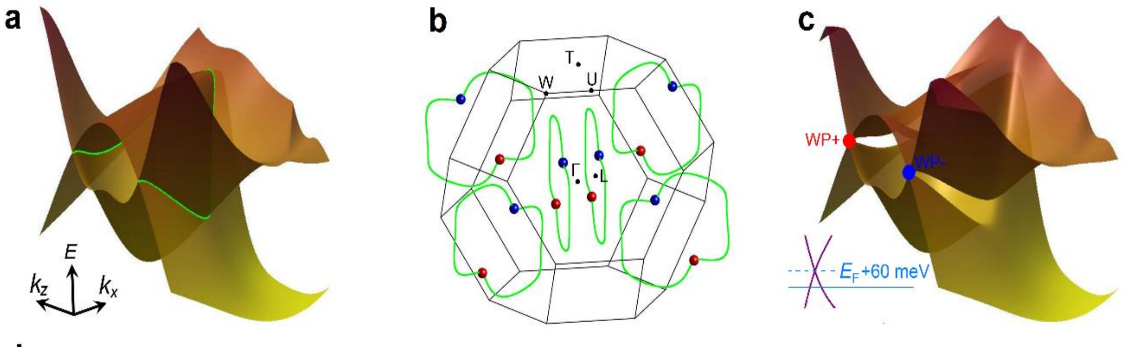


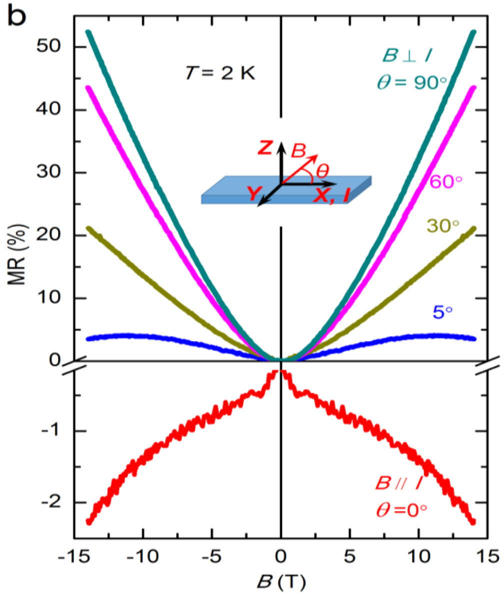


$Co_3Sn_2S_2$

Weyl points are close to EF
Hard magnetic behaviour

transport: chiral anomaly

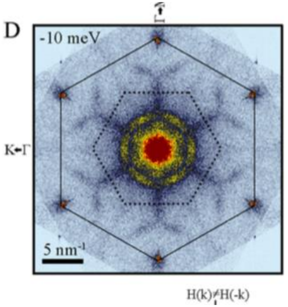


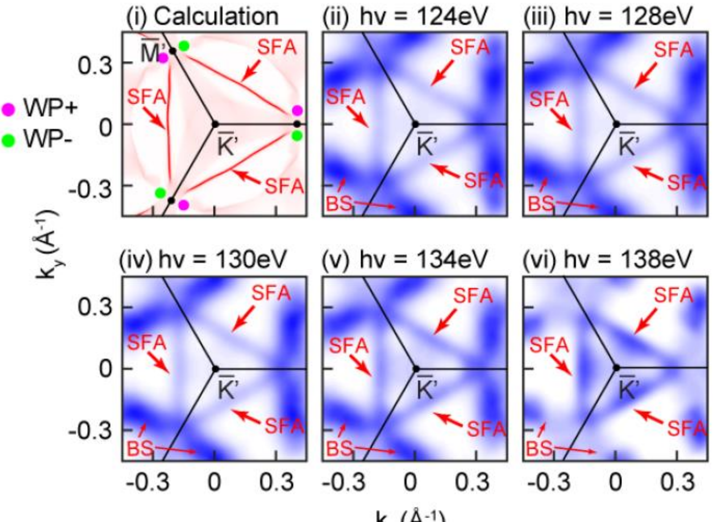


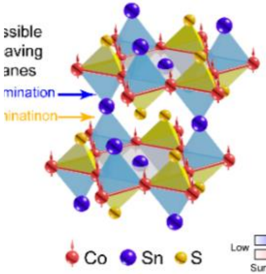
Liu, et al. Nature Physics 14 (2018) 1125 , preprint arXiv:1712.06722

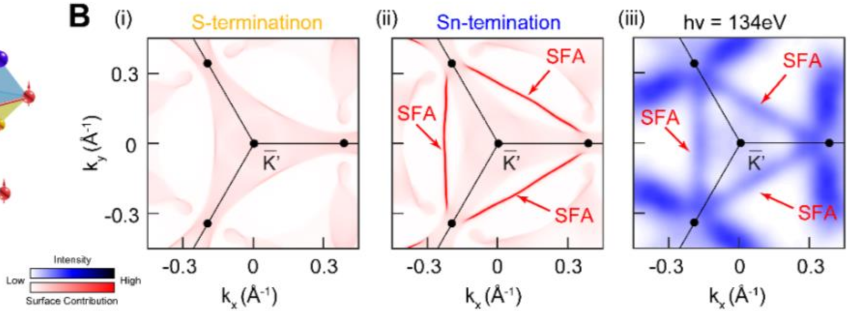
Weyl and Berry

STM and ARPES confirms Weyl and Fermiarcs









D. F. Liu, et al., Science 365 (2019) 1282

Morali et al., Science accepted , preprint arXiv:1903.00509

Weyl and Berry

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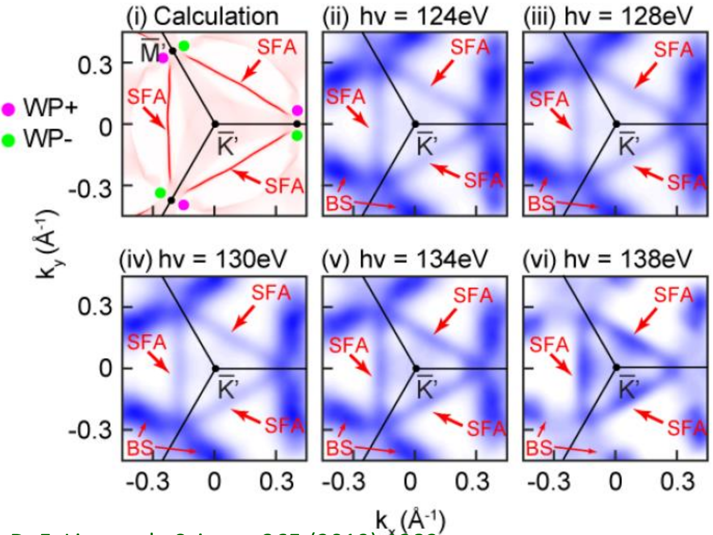
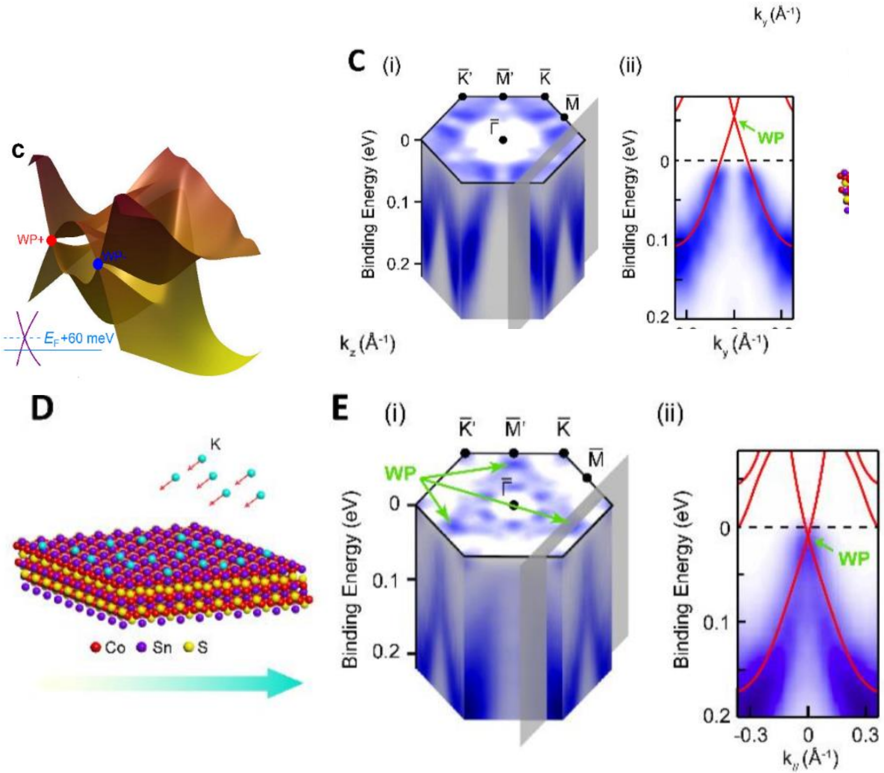
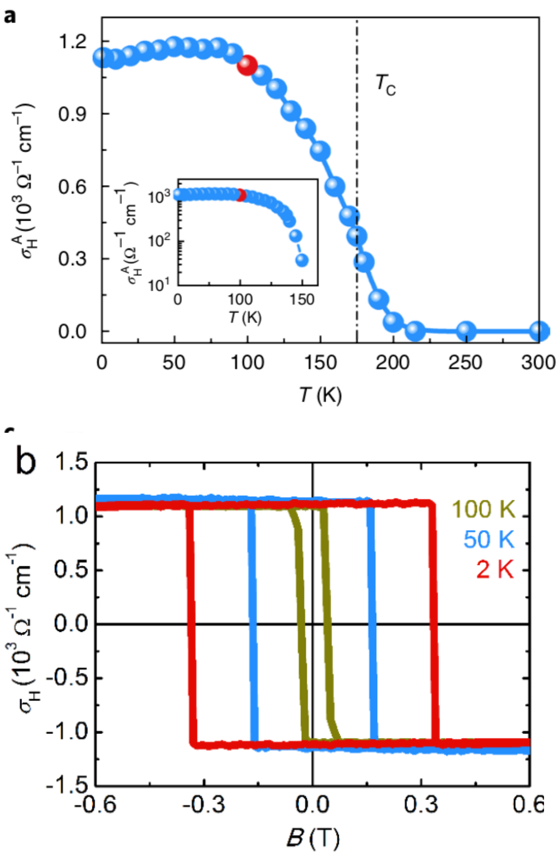
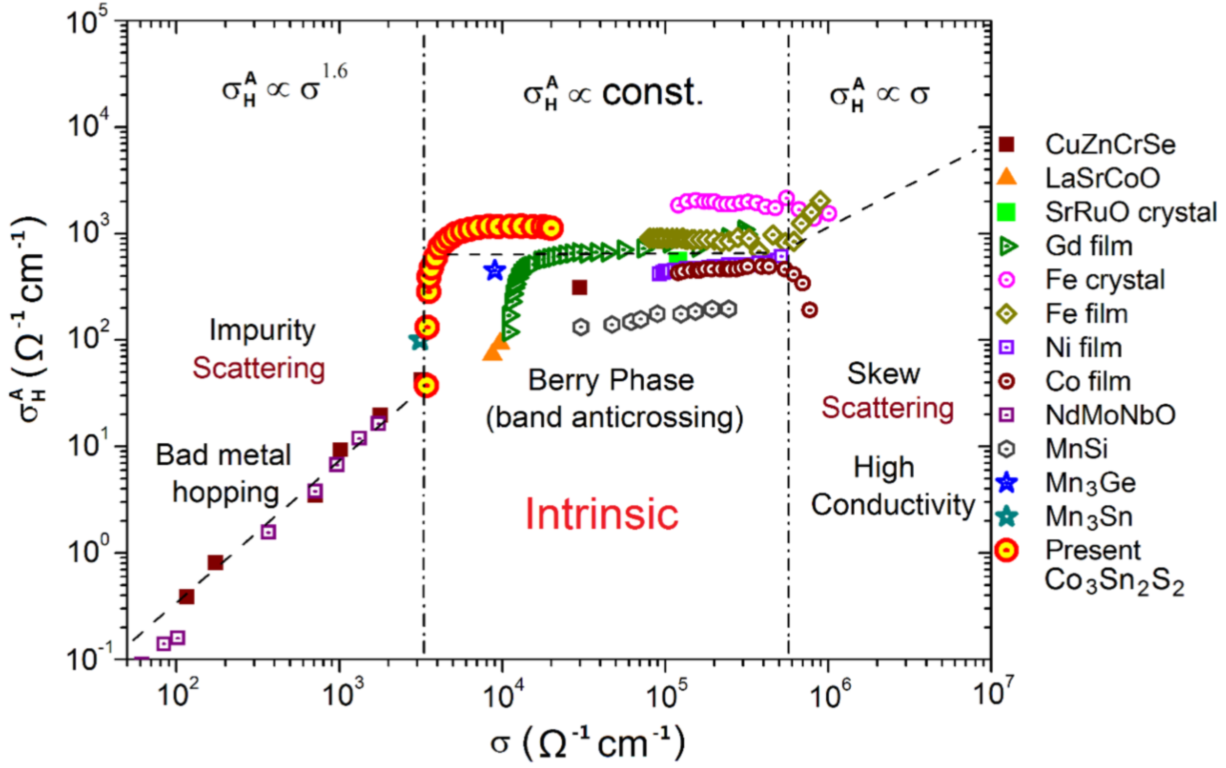




D. F. Liu, et al., Science 365 (2019) 1282

new transport properties





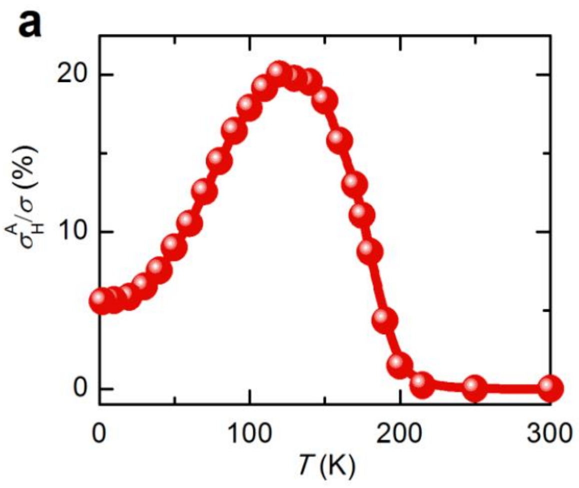
Liu, et al. Nature Physics 14 (2018) 1125 , Guin, et al. Adv. Mater. 2019, 1806622, arXiv:1712.06722, arXiv:1807.07843, arXiv:1806.06753

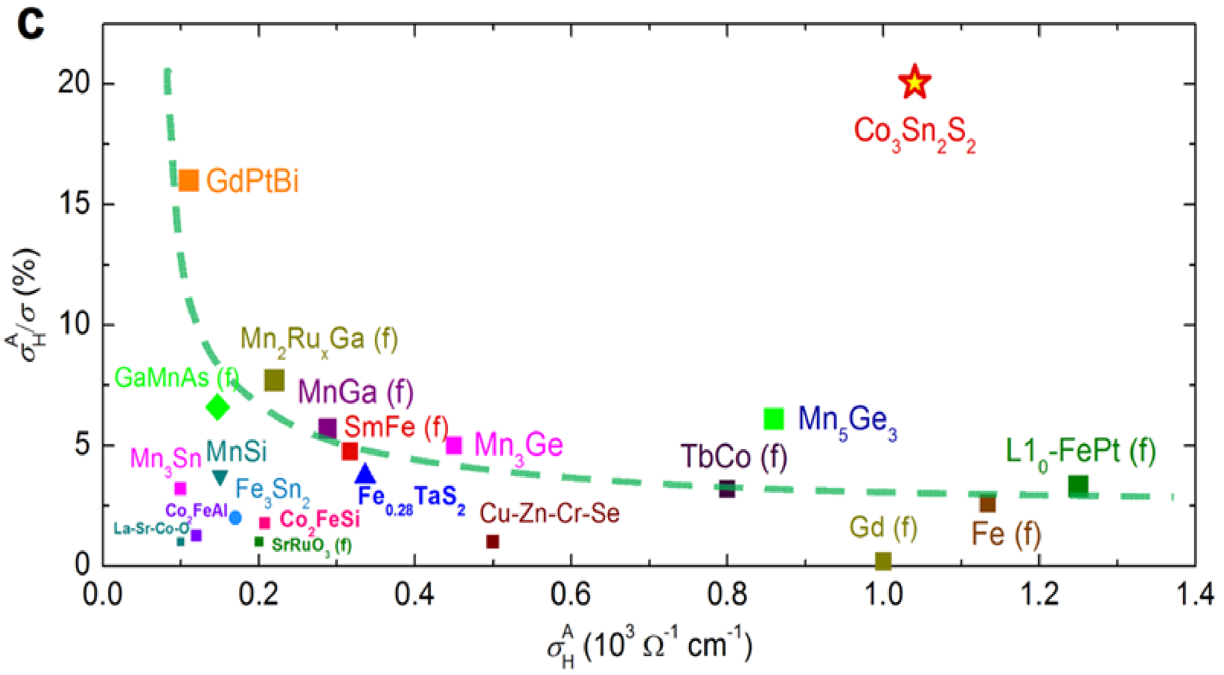
new transport properties

Berry curvature design
- giant anomalous Hall
- giant anomalous Nernst

$Co_3Sn_2S_2$
Mn_3Sn

Giant Hall Angle 20%





Liu, et al. Nature Physics 14 (2018) 1125 , Guin, et al. Adv. Mater. 2019, 1806622, arXiv:1712.06722, arXiv:1807.07843, arXiv:1806.06753

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$Co_3Sn_2S_2$
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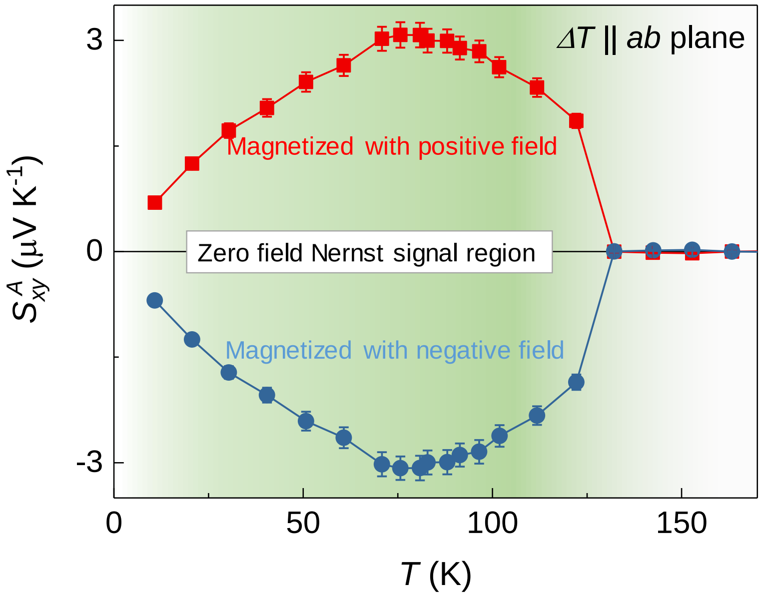

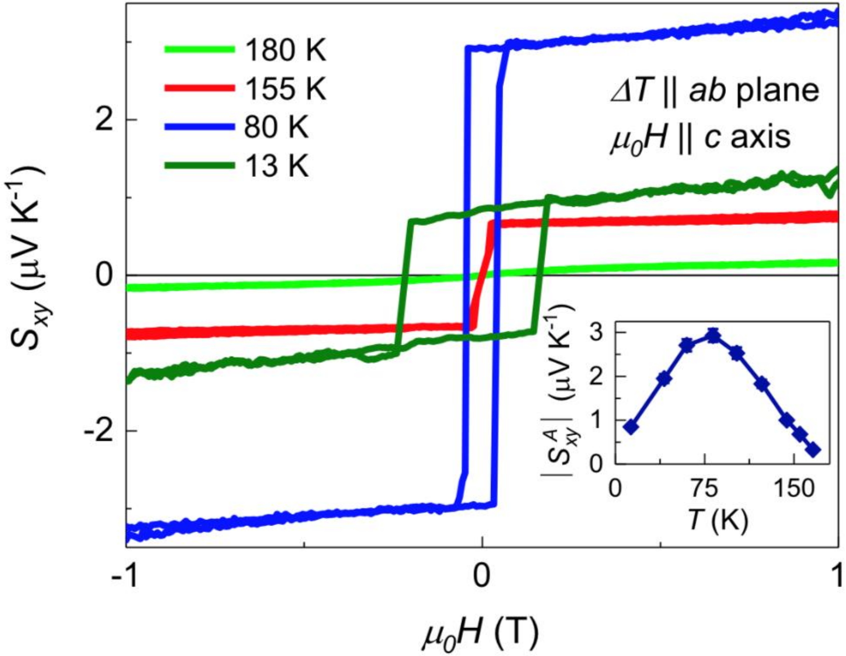

Guin, et al. Adv. Mater. 2019, 1806622, arXiv:1712.06722, arXiv:1807.07843, arXiv:1806.06753

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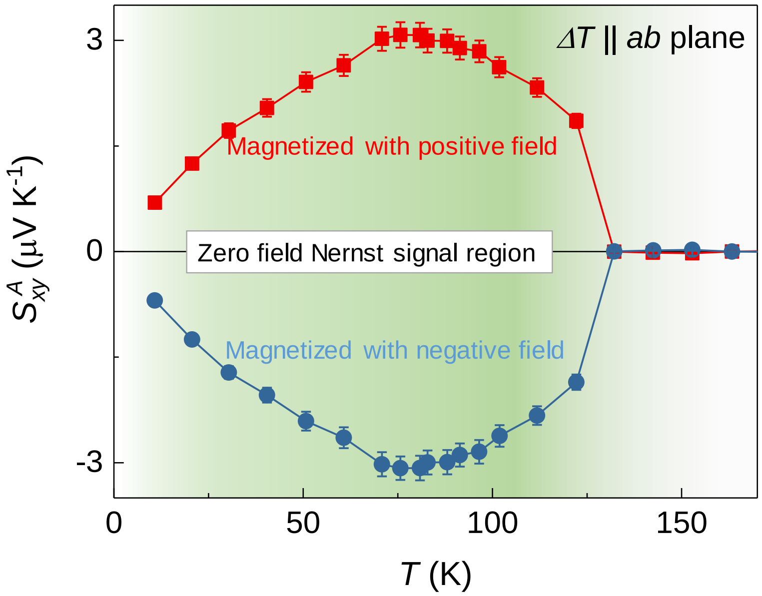
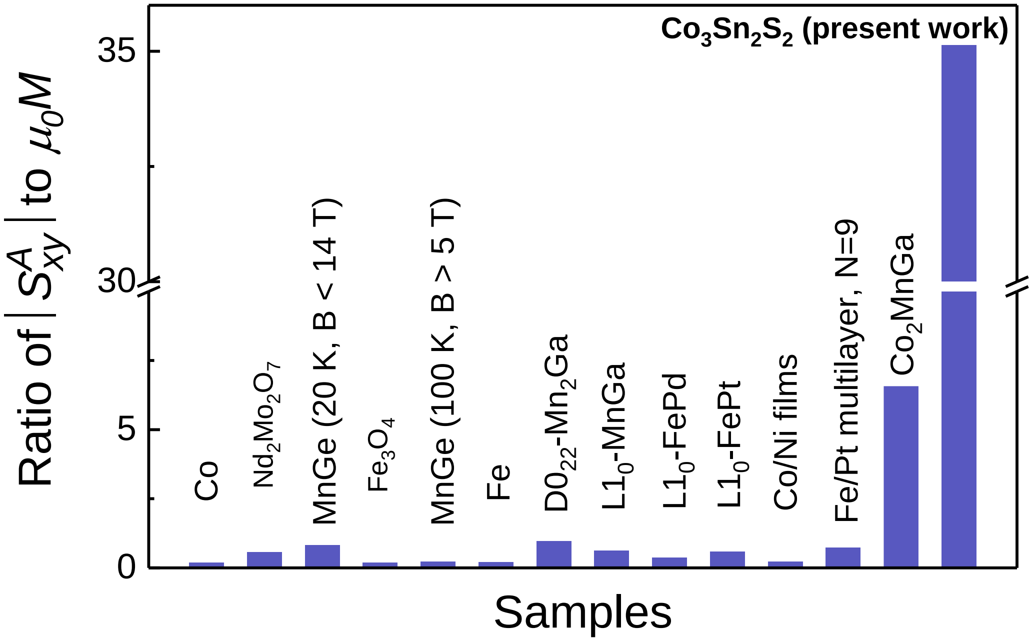
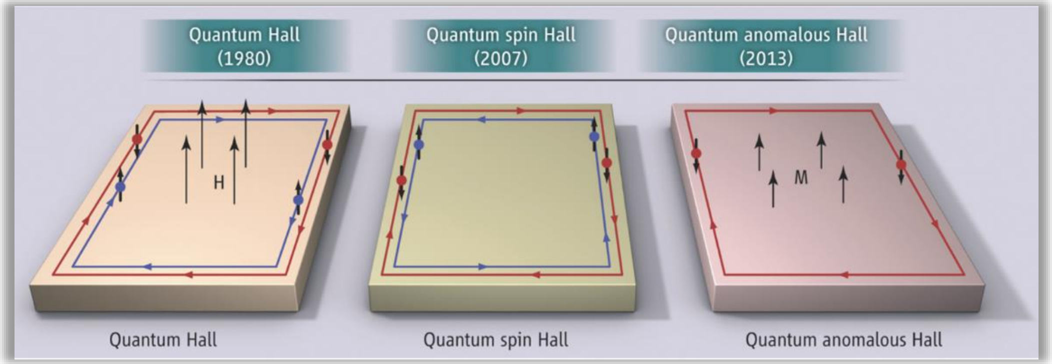
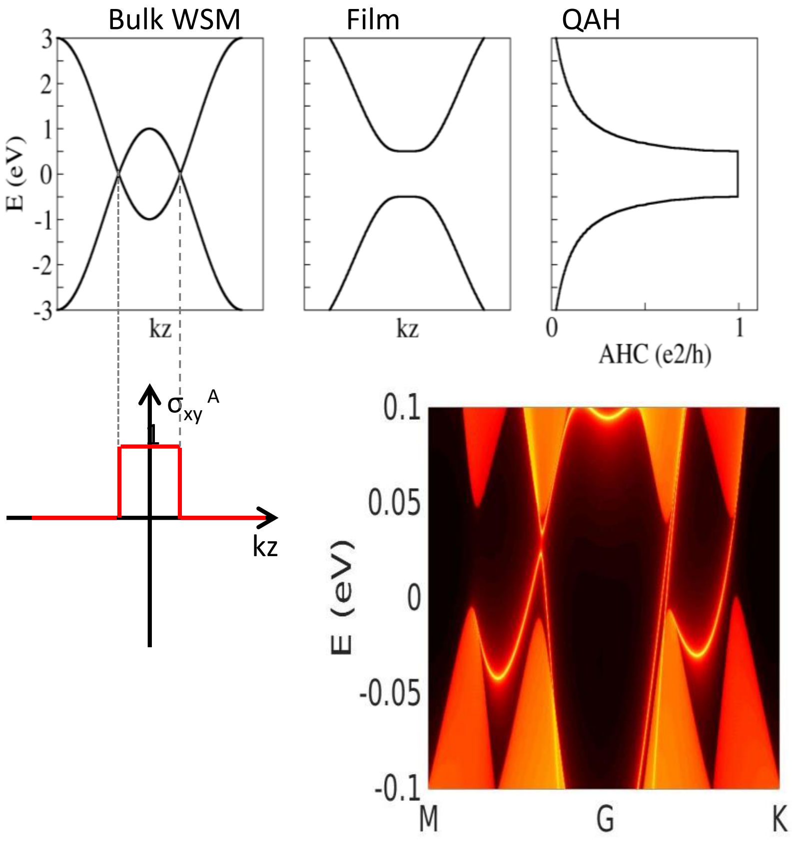




Guin, et al. Adv. Mater. 2019, 1806622, arXiv:1712.06722, arXiv:1807.07843, arXiv:1806.06753

quantum devices

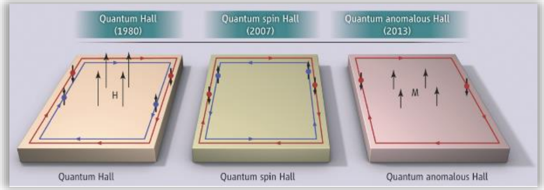


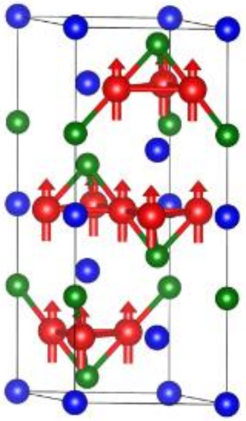


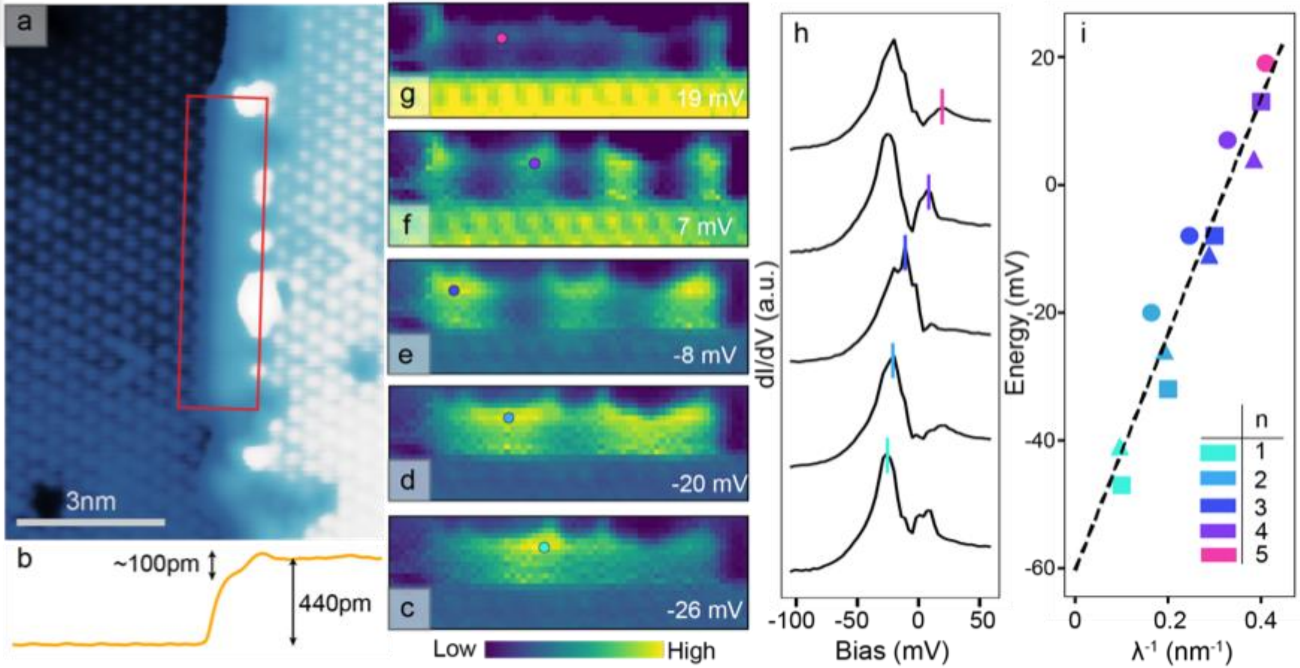
- Towards QAHE in MBE grown thin films.
- Magnetic Weyl for QAH effect in 2D

Qiunan Xu, Enke Liu, Wujun Shi, Lukas Muechler, Claudia Felser, Yan Sun, preprint arXiv:1712.08915

quantum anomalous Hall







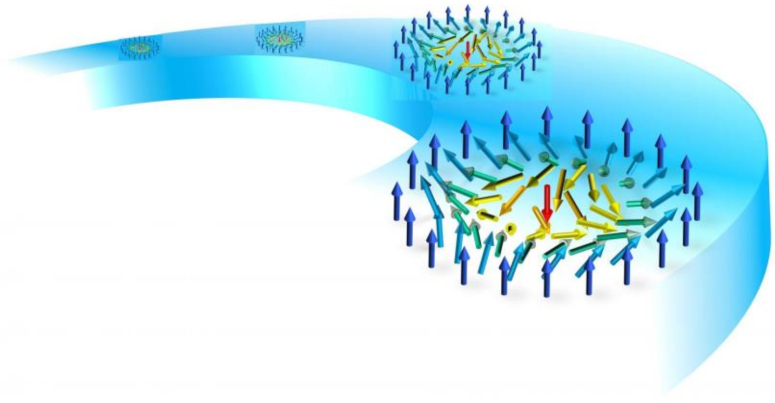
Sean Howard, Lin Jiao, Zhenyu Wang, Chandra Shekhar, Claudia Felser, Taylor Hughes3, Vidya Madhavan, submitted

vision

new physics

- Berry phase design of materials for energy conversion and Hall sensors
- Quantum anomalous Hall effect at room temperature
- Berry curvature design in real and reciprocal space
- devices made of thin films and crystals

- **potential applications**
- spintronics
    - Racetrack memory
    - Majorana fermions
    - Spin Hall based MRAM
    - antiferromagnetic Spintronics
    - Spincaloritronics
- quantum computing
- energy conversion



thank you for your attention

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