Weyl Semimetals

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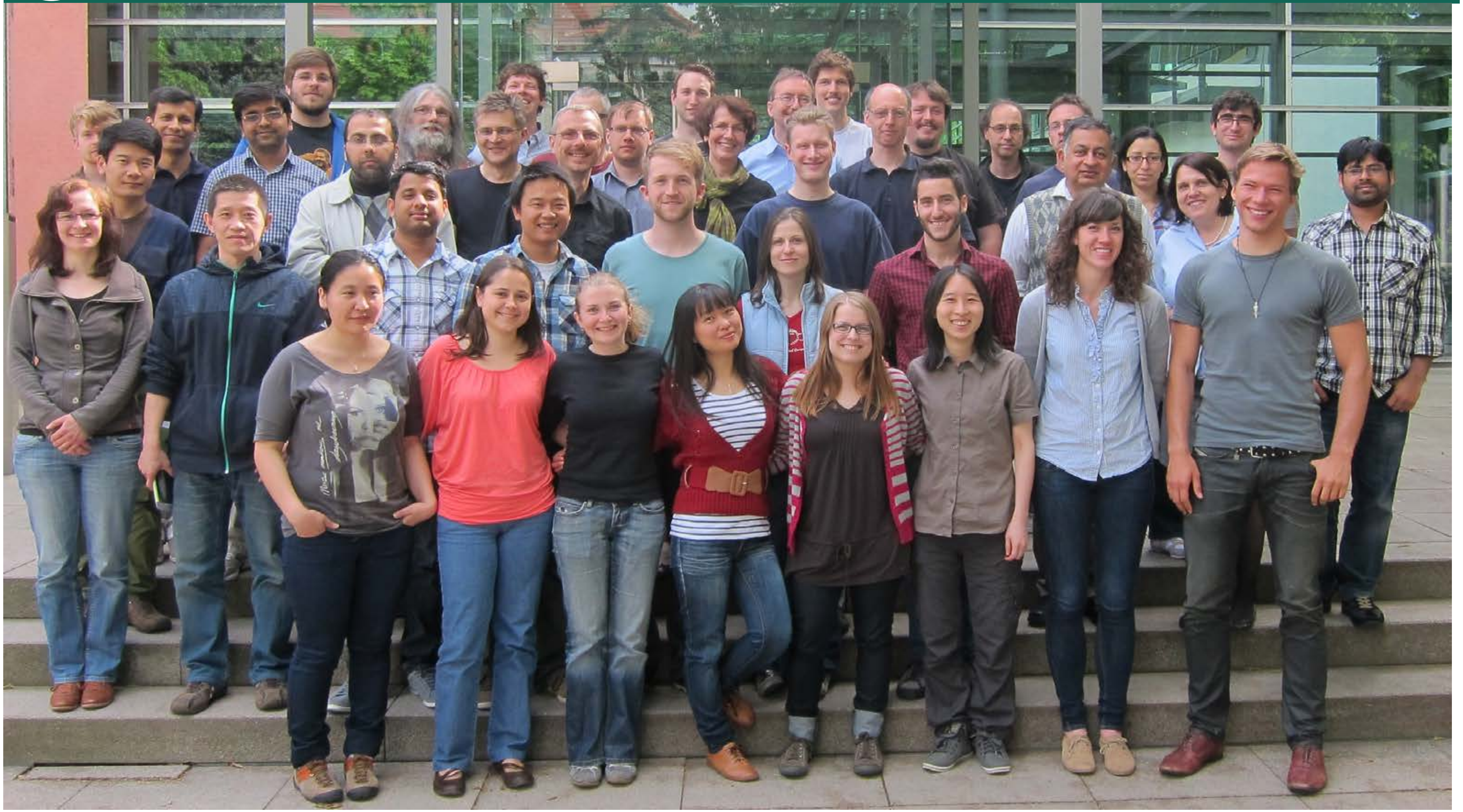
Claudia Felser, Johannes Gooth, Chandra Shekhar,
Nitesh Kumar and Yan Sun

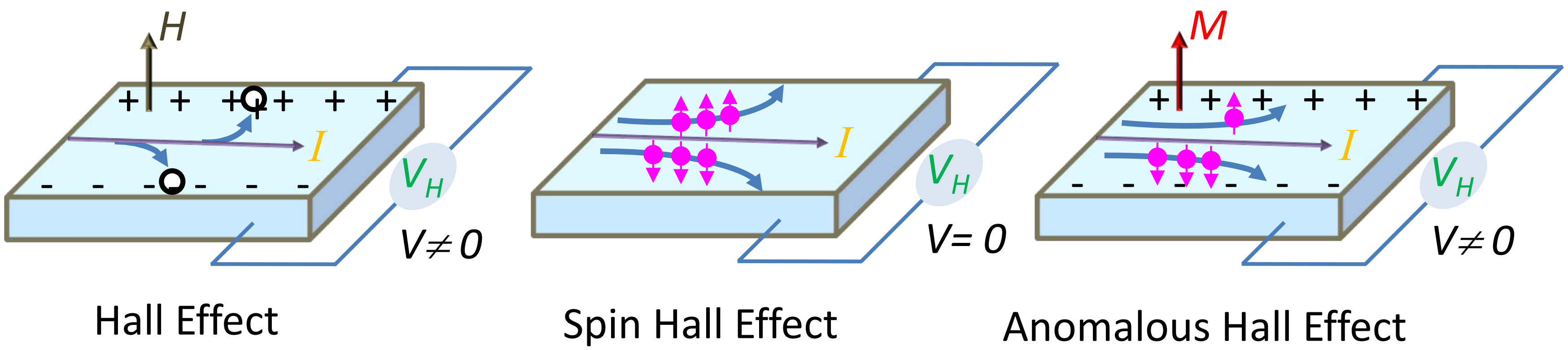
Co-workers in Dresden and elsewhere

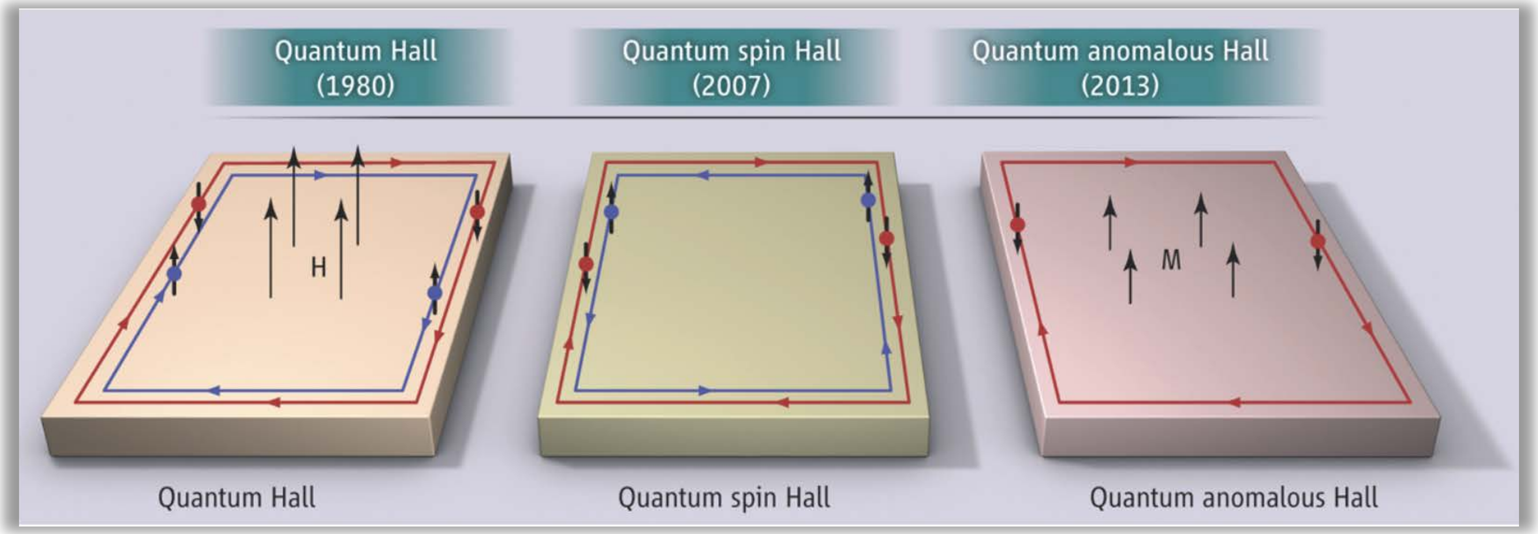


Kornelius Nielsch, IFW Dresden, Andrei Bernevig, Princeton, PIS ARPES team
Johannes Gooth, IBM Zürich
Uli Zeitler, et al. HFML - EMFL, Nijmegen; J. Wosnitza et al., HFML Rossendorf
Yulin Chen et al., Oxford;
S. S. P. Parkin et al., IBM Almaden, MPI Halle

Alexander von Humboldt Stiftung/Foundation

Family of Quantum Hall Effects





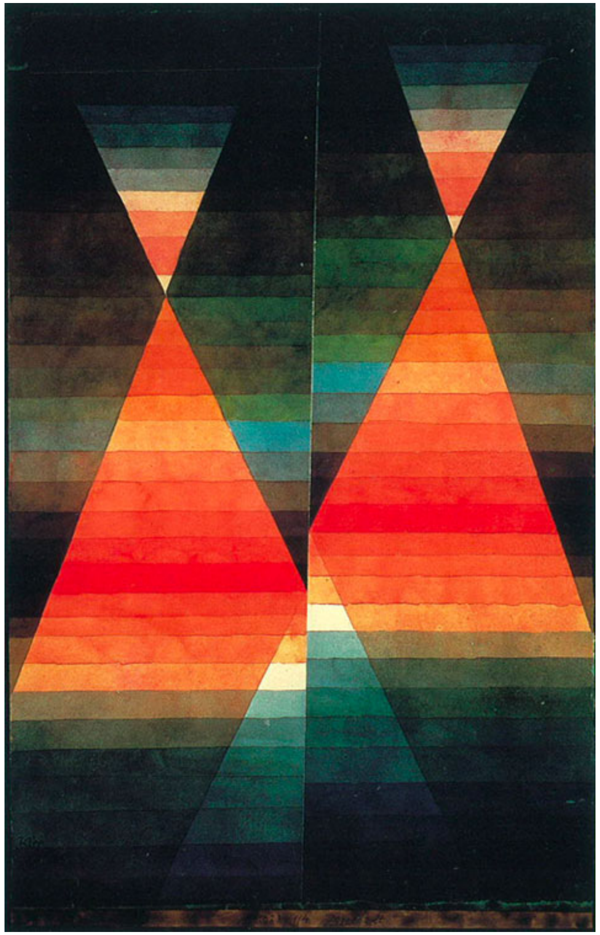
S Oh Science 340 (2013) 153

1985
Klaus von Klitzing
1998
Horst Ludwig Störmer and Daniel Tsui
2010
Andre Geim and Konstantin Novoselov

2016
David Thouless, Duncan Haldane und Michael Kosterlitz

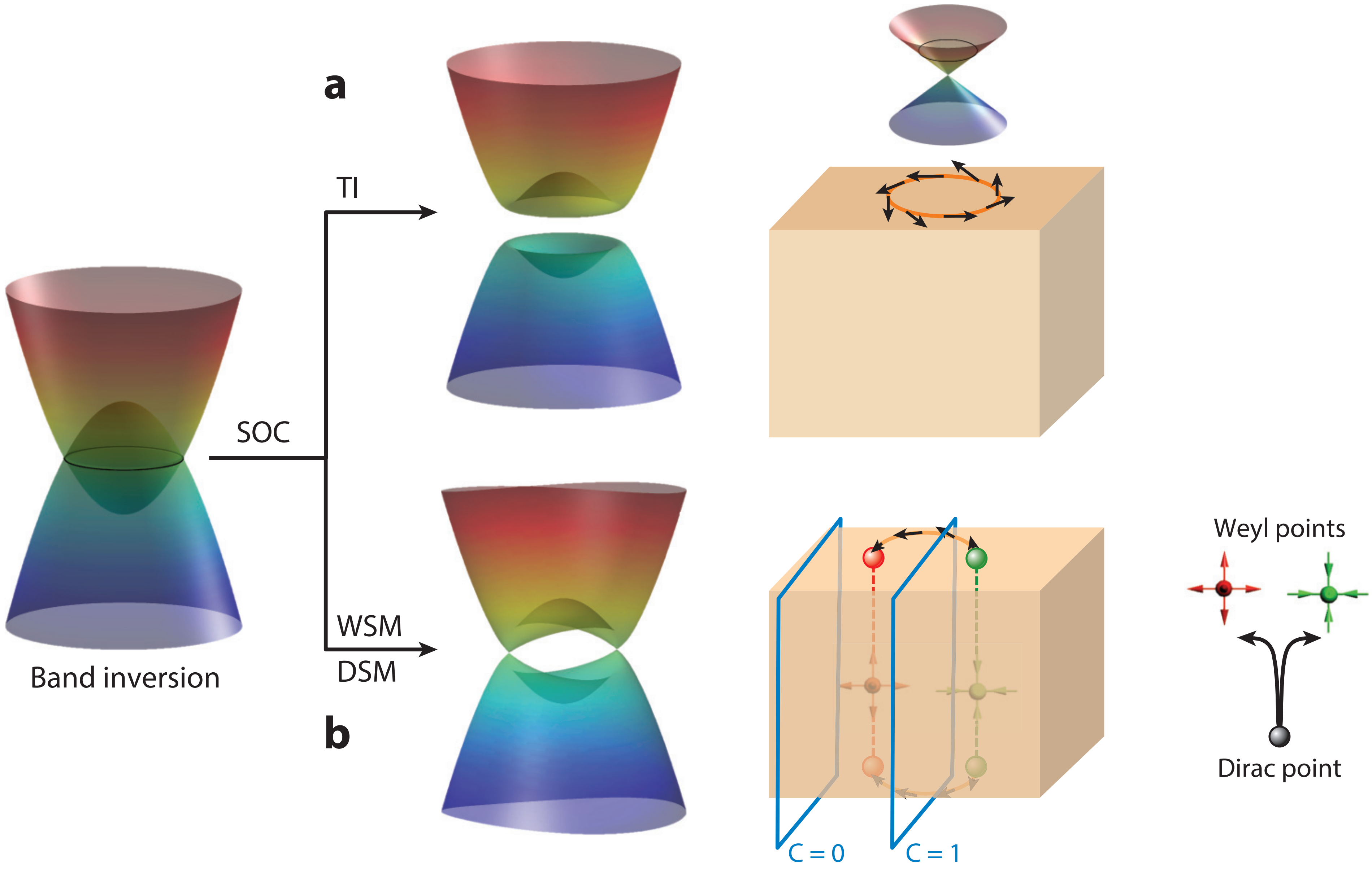
Weyl Semimetals

NbP, TaAs …

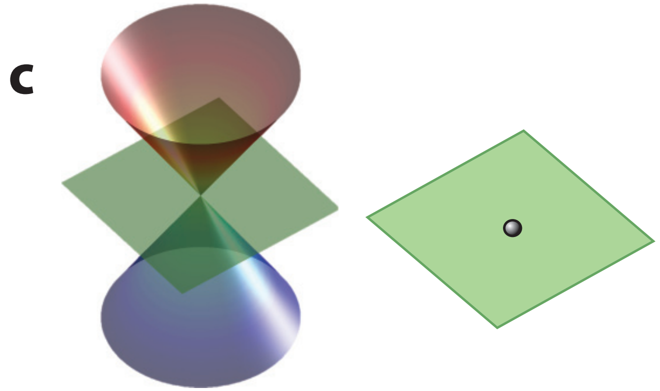


Paul Klee

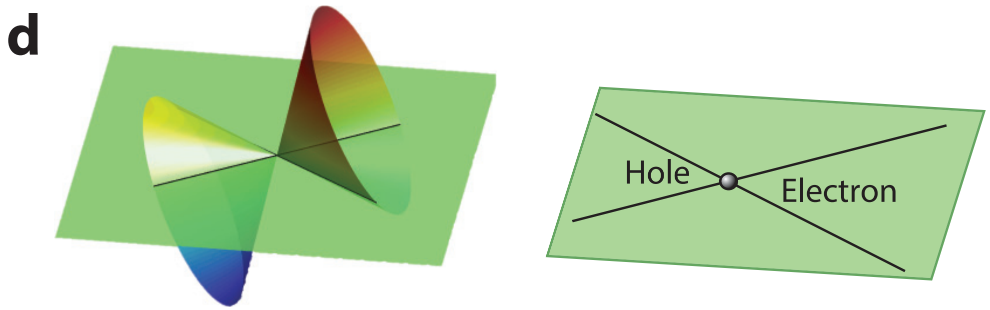
Weyl semimetals



Type I or II

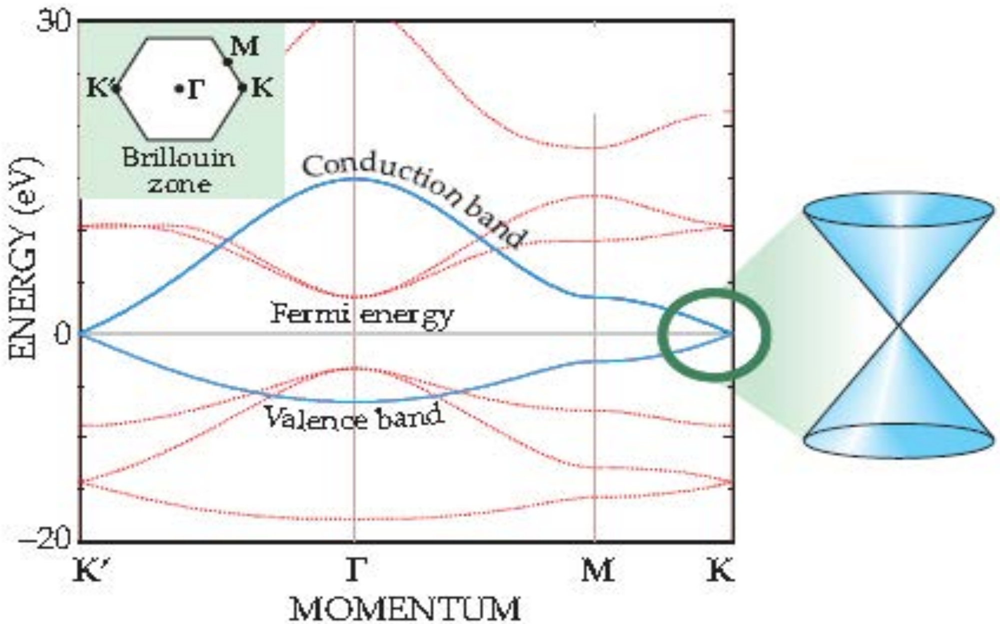


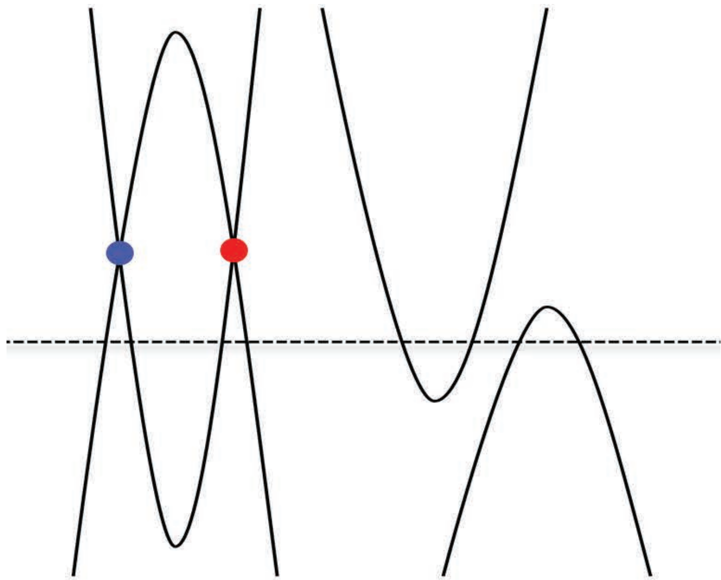
Type-I WSM



Type-II WSM

Graphene





A. K. Geim, A. H. MacDonald Physics Today, 08.(2007), 35-41

Shekhar, et al. , Nature Physics 11 (2015) 645

Weyl semimetals

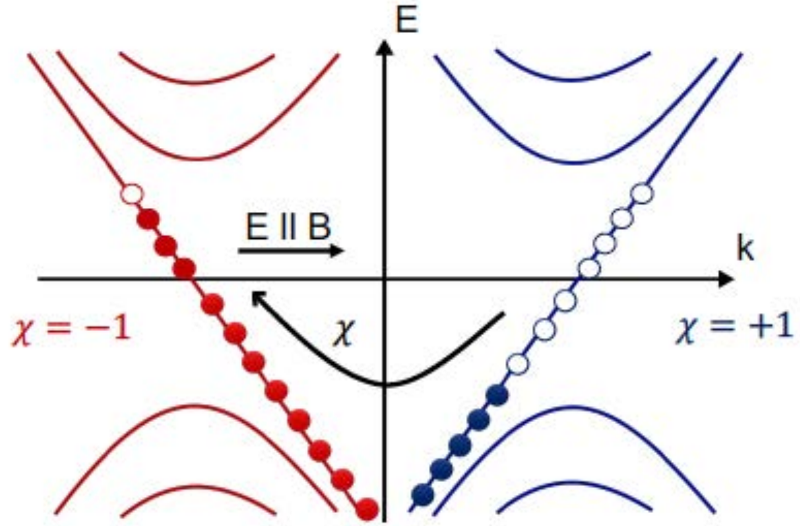
3D topological Weyl semimetals - breaking time reversal symmetry – in transport measurement we should see:

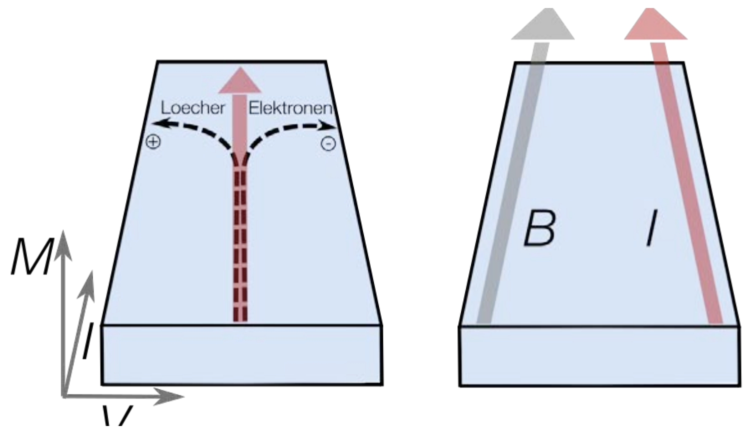
1. **Fermi arc**

2. Chiral anomaly

$$\partial_\mu j^\mu_\chi = \boxed{-}\chi \frac{e^3}{4\pi^2\hbar^2} \boldsymbol{E} \cdot \boldsymbol{B}$$

$$\sigma_a = \frac{e^3 v_f^3}{4\pi^2 \hbar \mu^2 c} \boxed{B^2},$$





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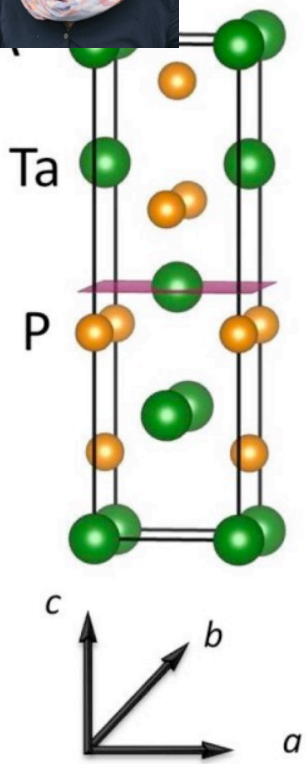
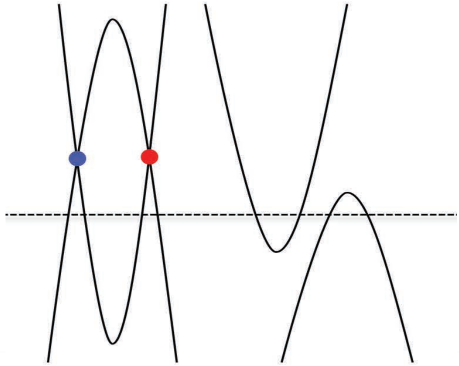
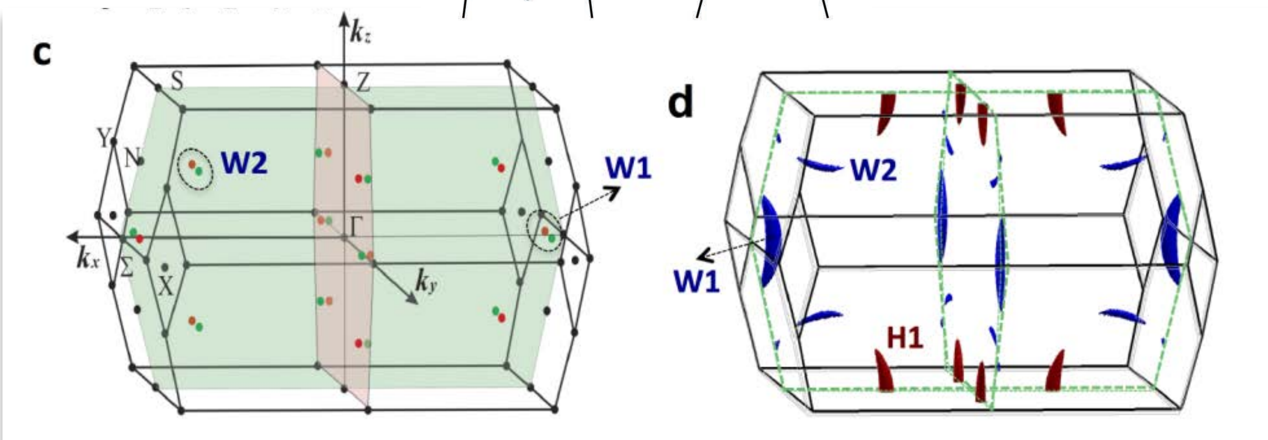
J. S. Bell and R. Jackiw, Nuovo Cim. A60, 47 (1969)
AA Zyuzin, AA Burkov - Physical Review B (2012)
AA Burkov, L Balents, PRL 107 12720 (2012)

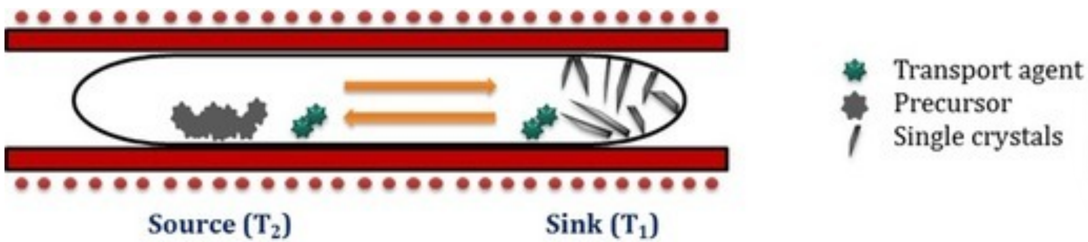
Weyl semimetals in non-centro NbP

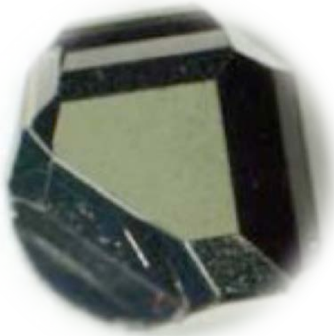
NbP, NbAs,
TaP, TaAs









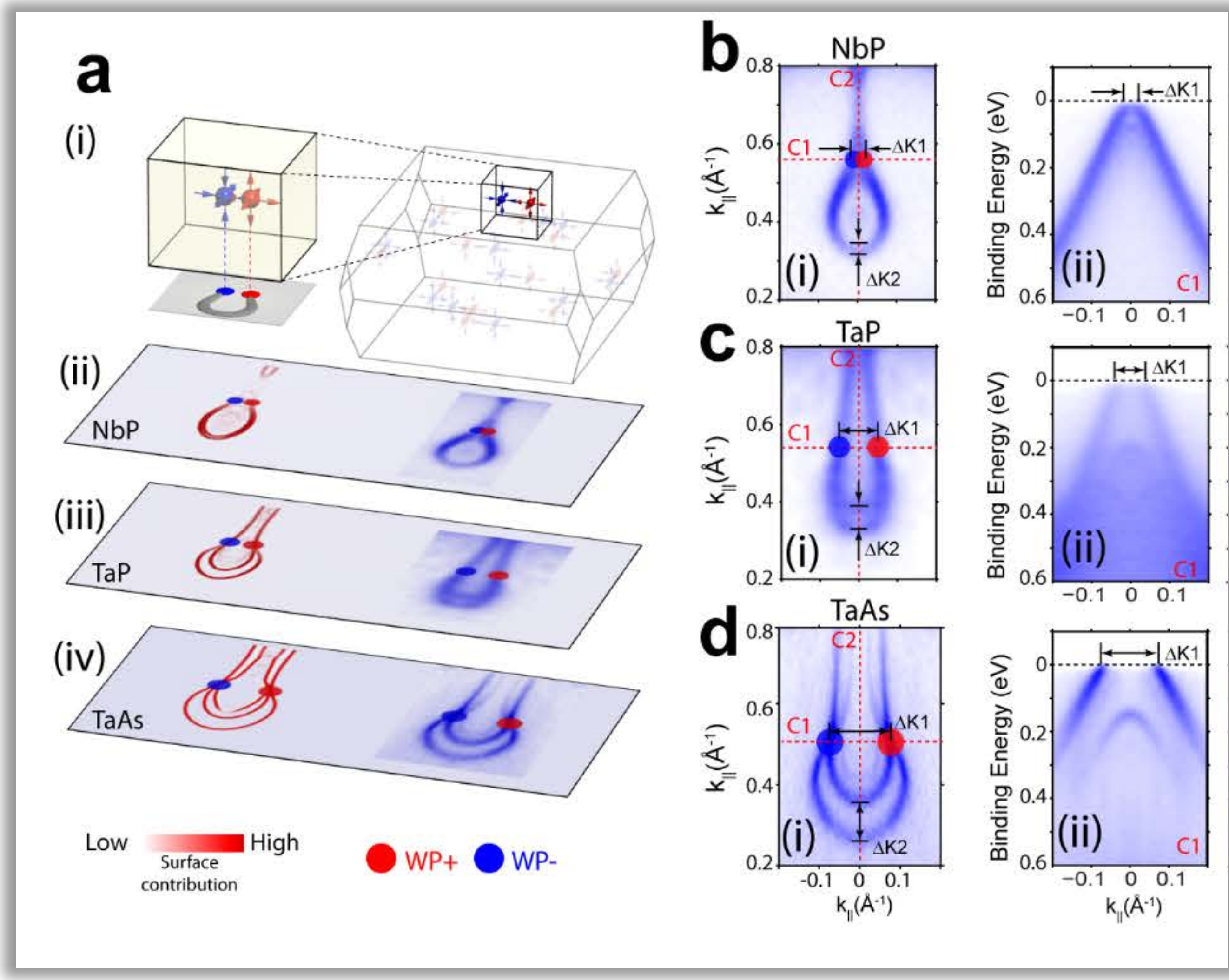


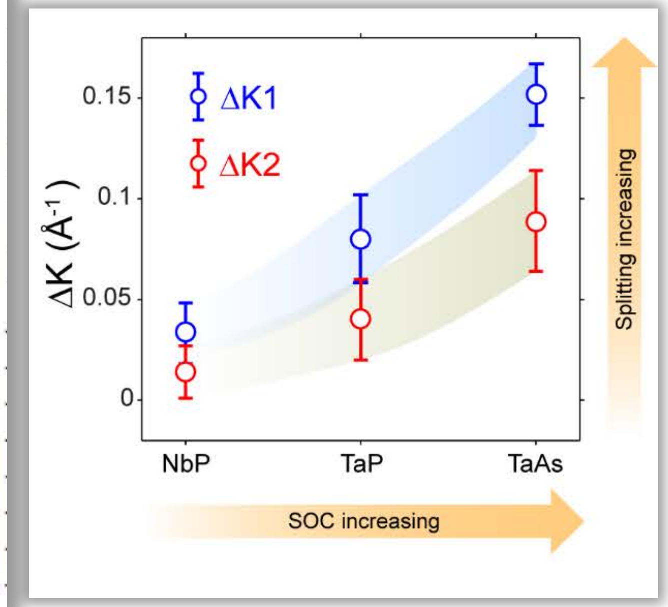
Shekhar, et al. , Nature Physics 11 (2015) 645,
Frank Arnold, et al. Nature Communication 7 (2016) 11615

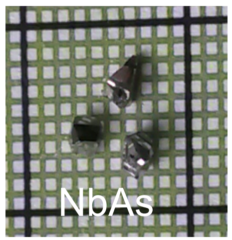
Weng, et al. Phys. Rev. X 5, 11029 (2015)
Huang et al. preprint arXiv:1501.00755

NbP, TaP, TaAs

Increasing spin orbit coupling increases –
heavier elements
Distance between the Weyl points increases

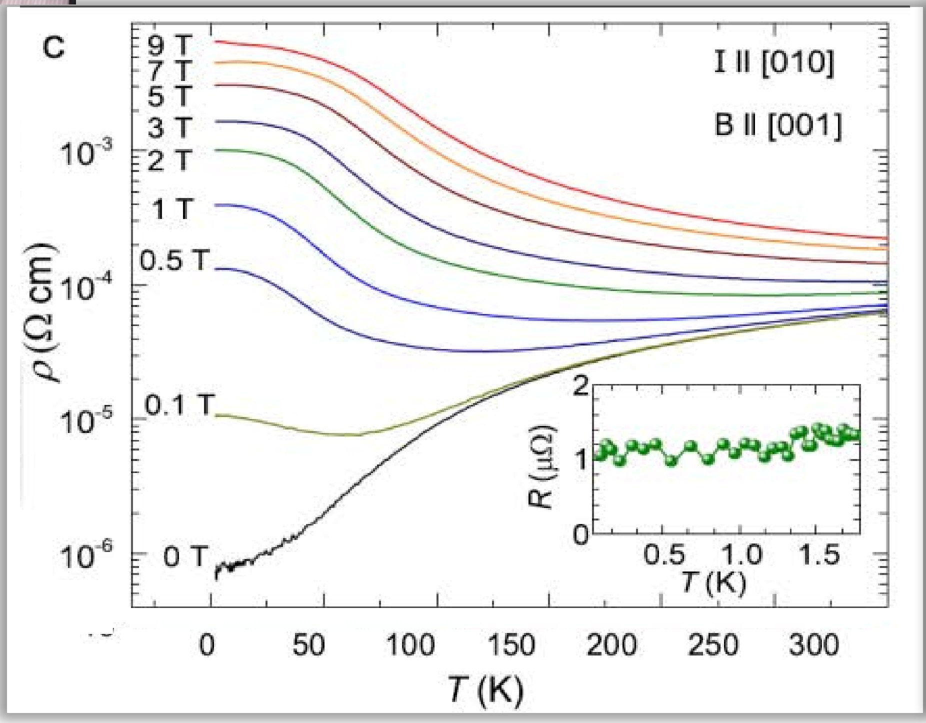


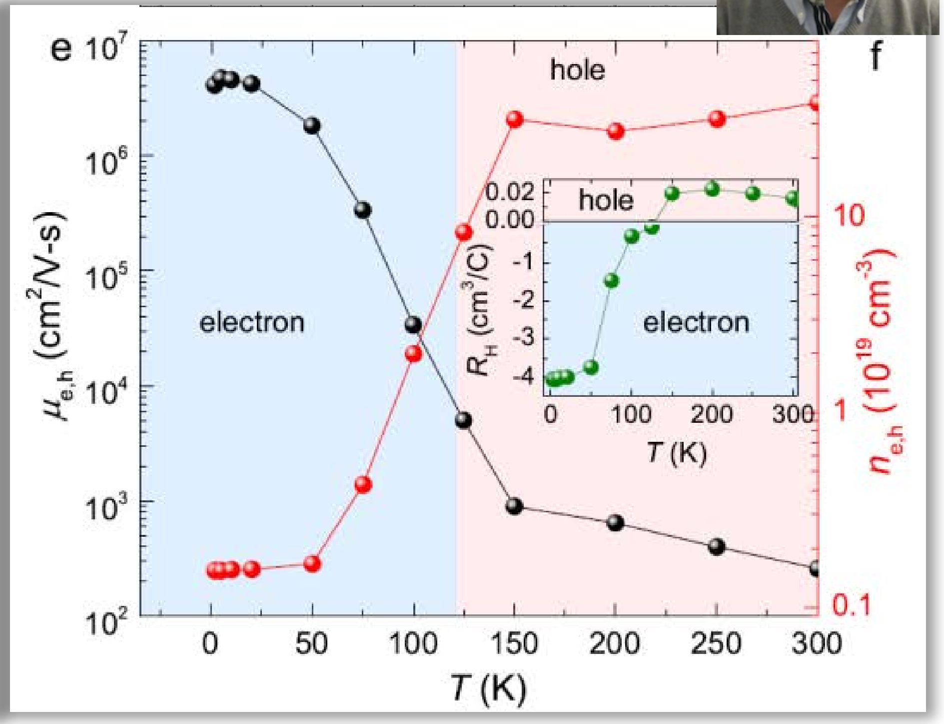




Z. K. Liu et al., Nature Mat. 15 (2016) 27
Yang, et al. Nature Phys. 11 (2015) 728

Weyl semimetals in non-centro NbP





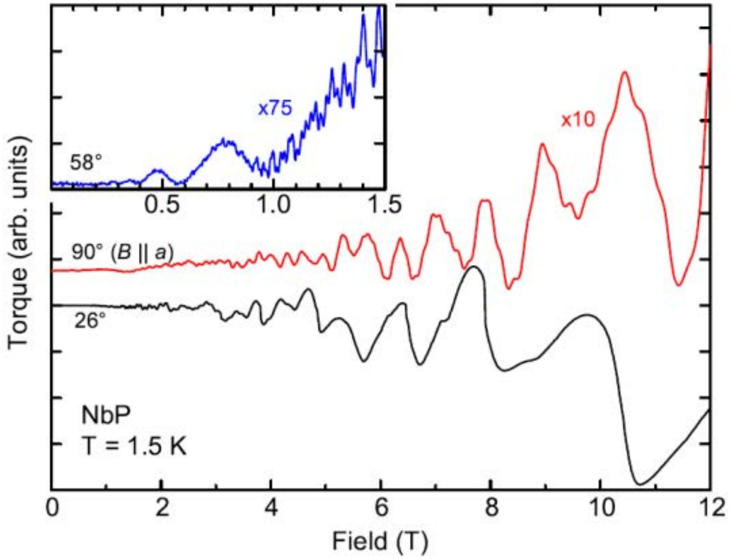
NbP is a topological Weyl semimetal

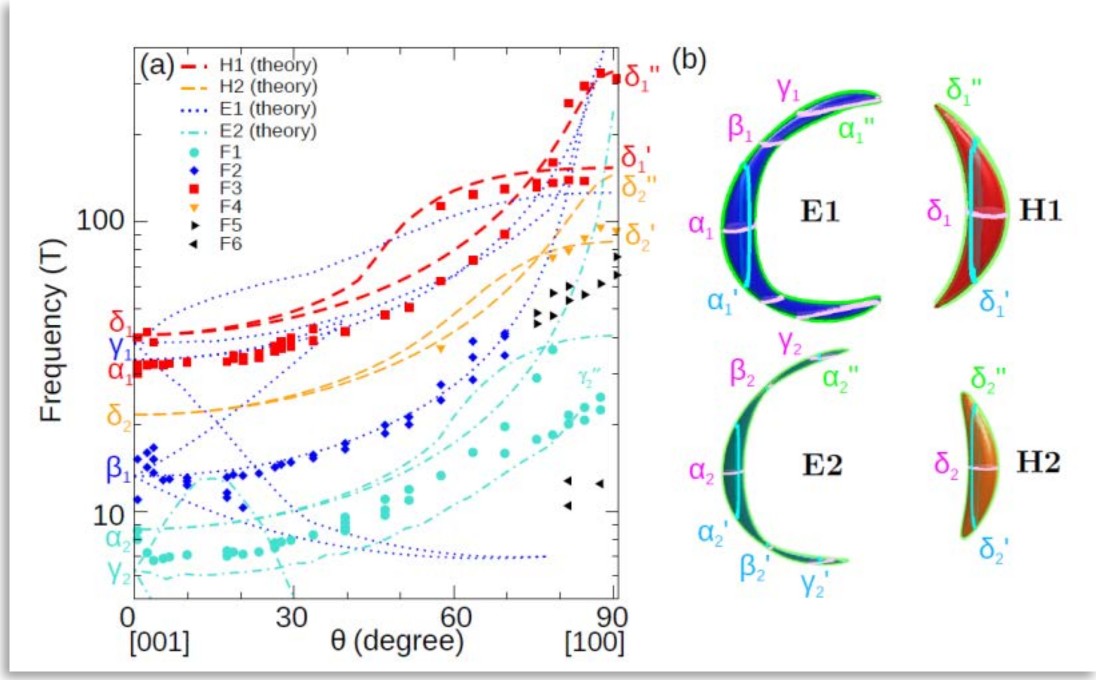
- with massless relativistic electrons
- extremely large magnetoresistance of **850,000%** at 1.85 K, 9T (250% at room temperature)
- an ultrahigh carrier mobility of **$5*10^6$ cm^2 / V s**

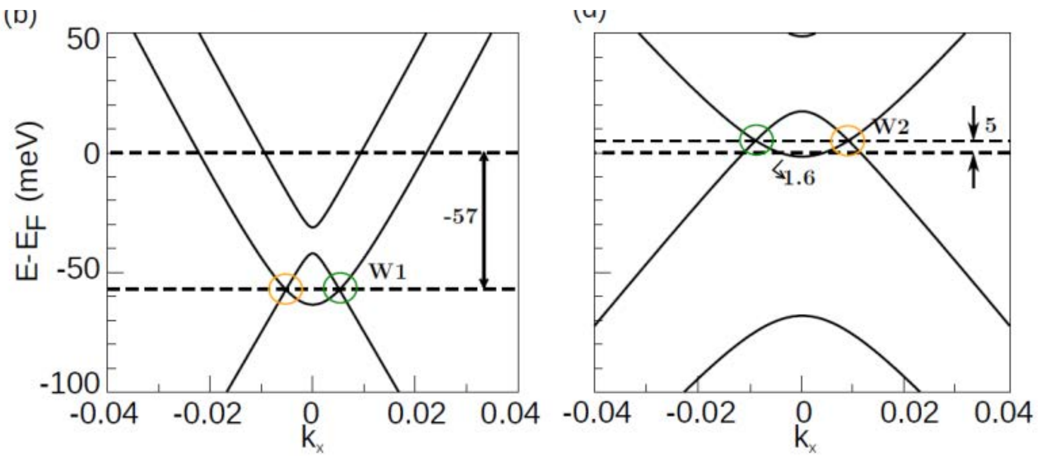
Shekhar, et al. , Nature Physics 11 (2015) 645,
Frank Arnold, et al. Nature Communication 7 (2016) 11615

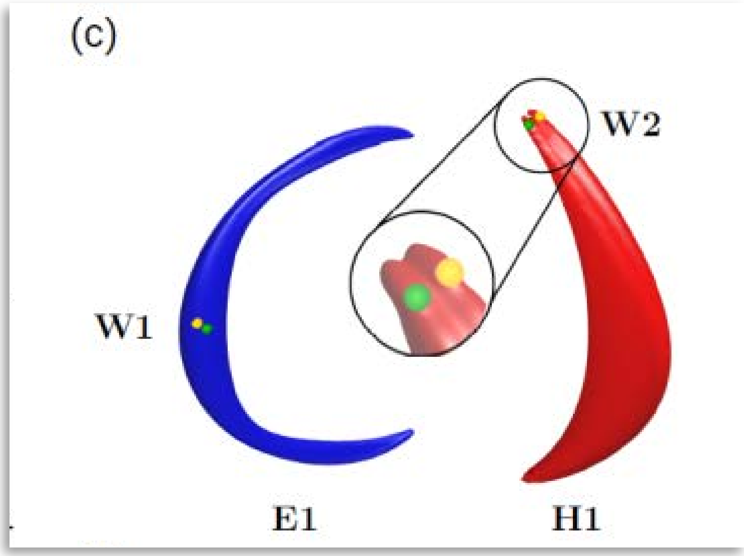
Weng, et al. Phys. Rev. X 5, 11029 (2015)
Huang . et al. preprint arXiv:1501.00755

NbP and the Fermi surface



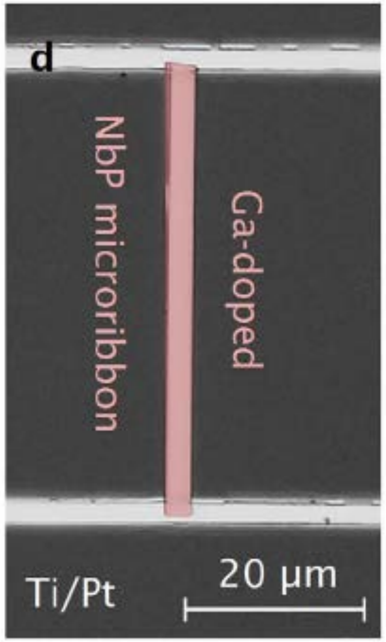


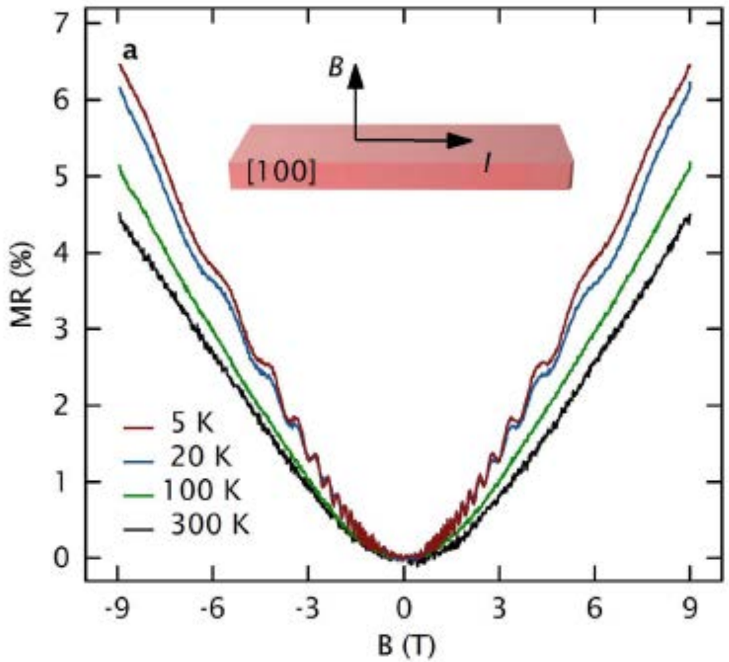


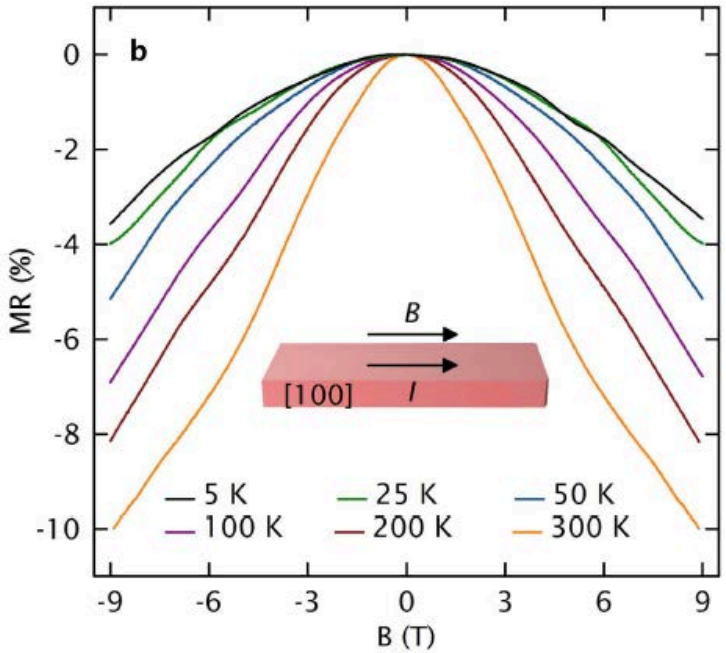


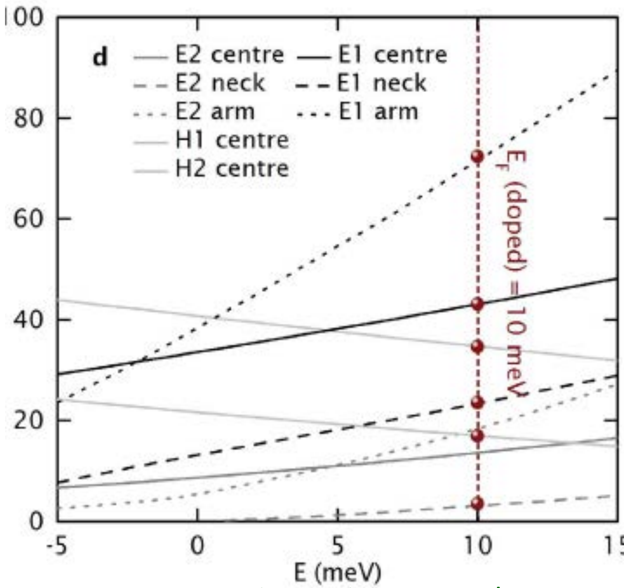
Klotz et al. Physical Review B 93 (2016) 121105(R)

Chiral Anomaly









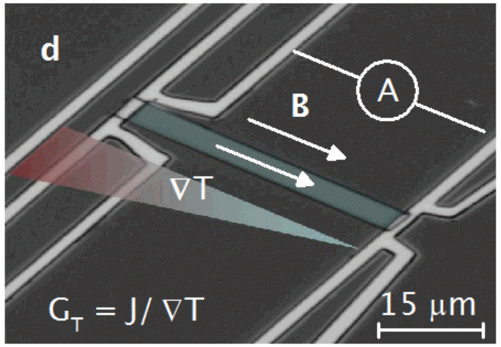
Ga-doping relocate the Fermi energy in NbP close to the W2 Weyl points

Therefore we observe a negative MR as a signature of the chiral anomaly the, NMR survives up to room temperature

Anna Corinna Niemann, Johannes Gooth et al. Scientific Reports 7 (2017) 43394 doi:10.1038/srep4339 preprint arXiv:1610.01413

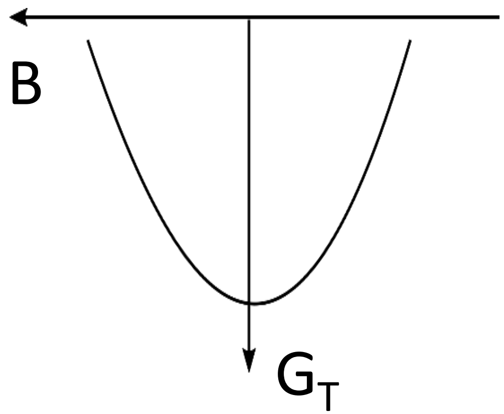
Experimental signatures for the mixed axial-gravitational anomaly in Weyl semimetals

- In solid state physics, mixed axial-gravitational anomaly can be identified by a positive magneto-thermoelectric conductance (PMTG) for ΔT ll B.



- Low fields: quadratic

$$G_T = d_{\text{th}} + c_2 a_\chi a_g B_\parallel^2$$

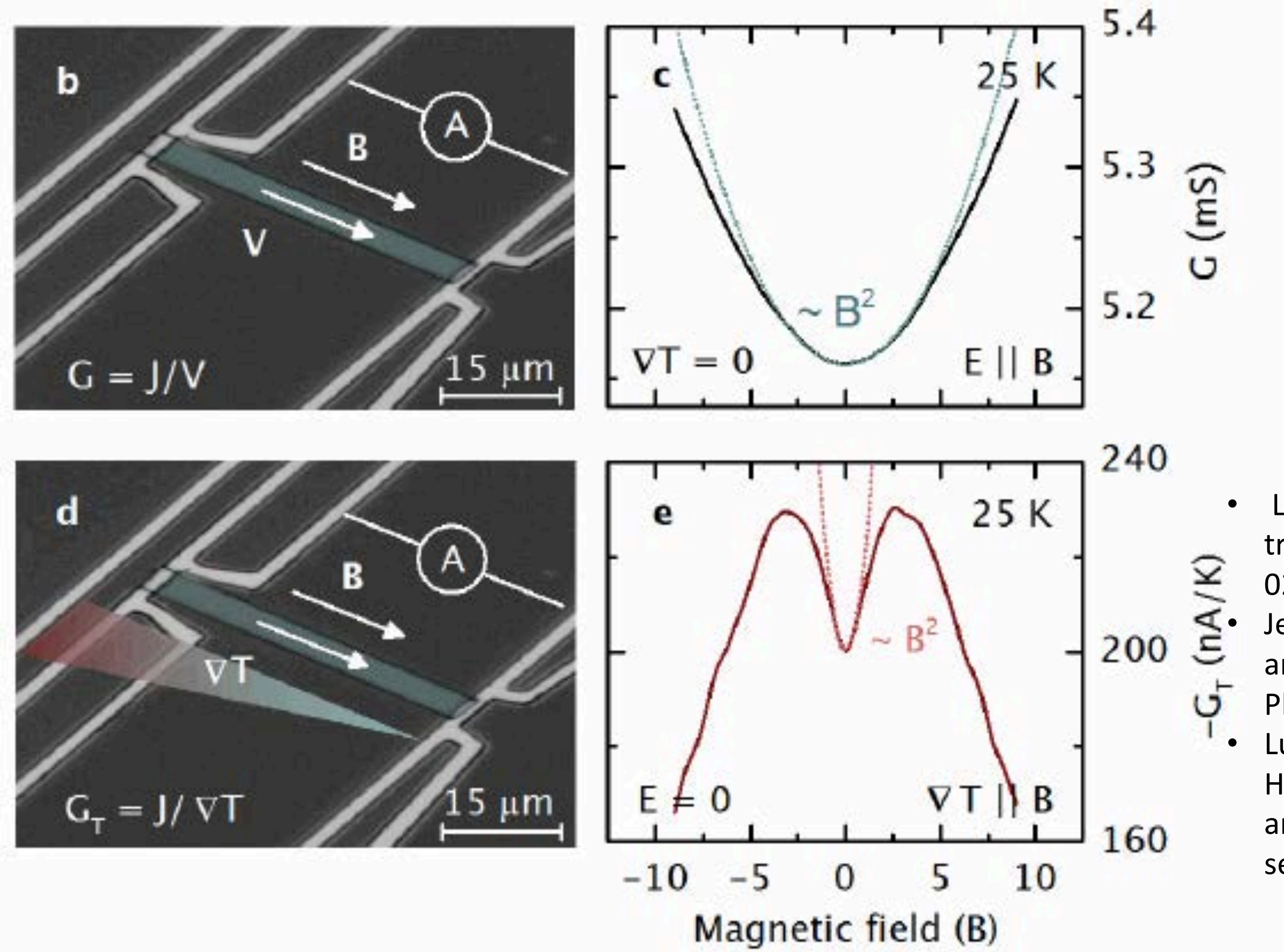


- High fields: deminishes

- ΔT ll B dictates sensitivity on alignement of B and ΔT.

[Lucas, *et al. Proceedings of the National Academy of Sciences* **113,** 9463 (2016)]

Gravitational Anomaly

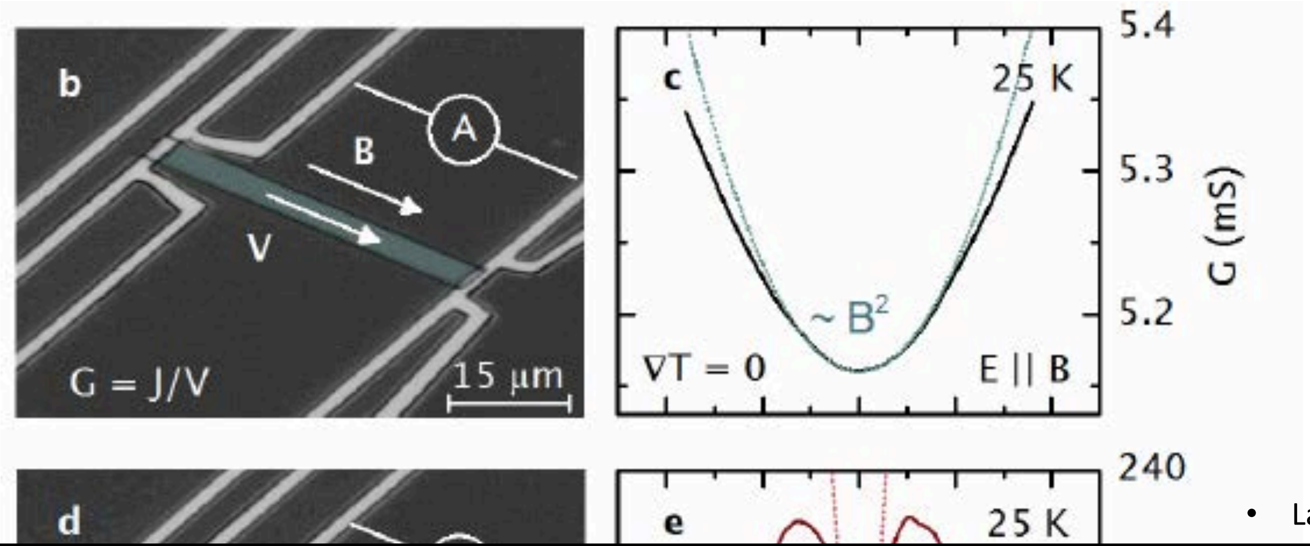


- Landsteiner, et al. Gravitational anomaly and transport phenomena. Phys. Rev. Lett. 107, 021601 (2011). URL
- Jensen, et al. Thermodynamics, gravitational anomalies and cones. Journal of High Energy Physics 2013, 88 (2013).
- Lucas, A., Davison, R. A. & Sachdev, S. Hydrodynamic theory of thermoelectric transport and negative magnetoresistance in weyl semimetals. PNAS 113, 9463–9468 (2016).

A positive longitudinal magneto-thermoelectric conductance (PMTC) in the Weyl semimetal NbP for collinear temperature gradients and magnetic fields that vanishes in the ultra quantum limit.

Johannes Gooth et al., Nature 547 (2017) 324 arXiv:1703.10682

Gravitational Anomaly



- Landsteiner, et al. Gravitational anomaly and

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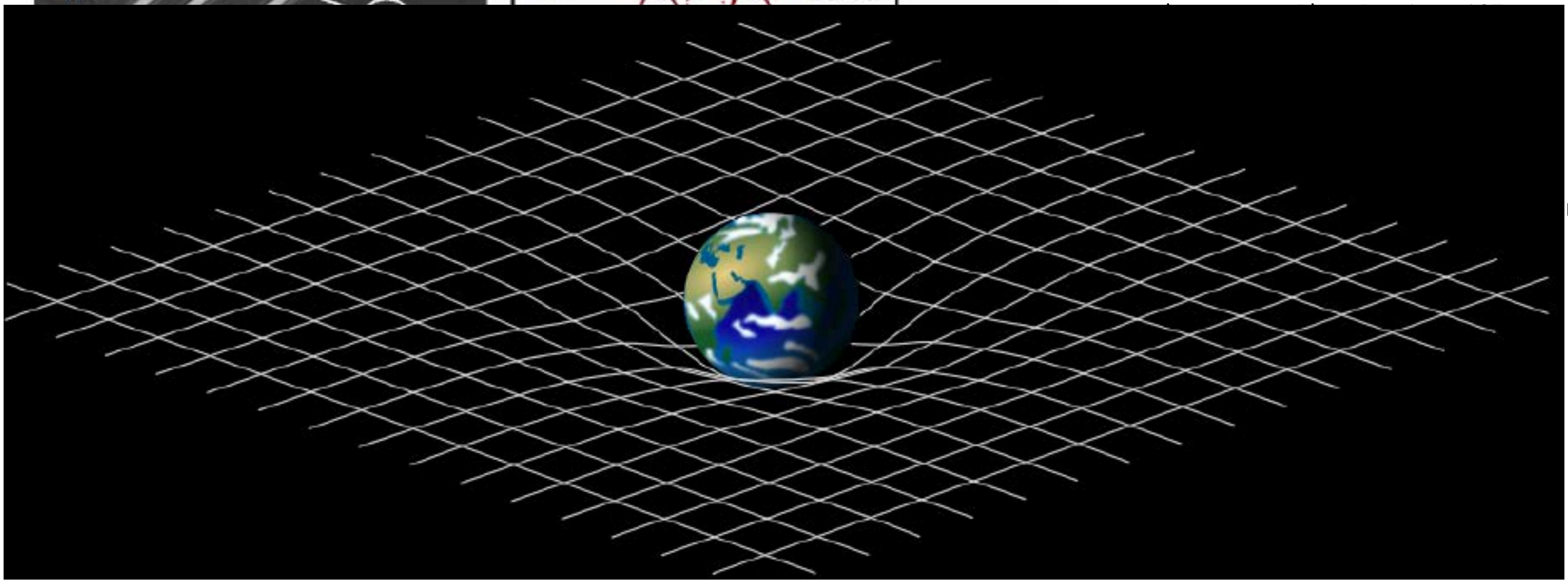
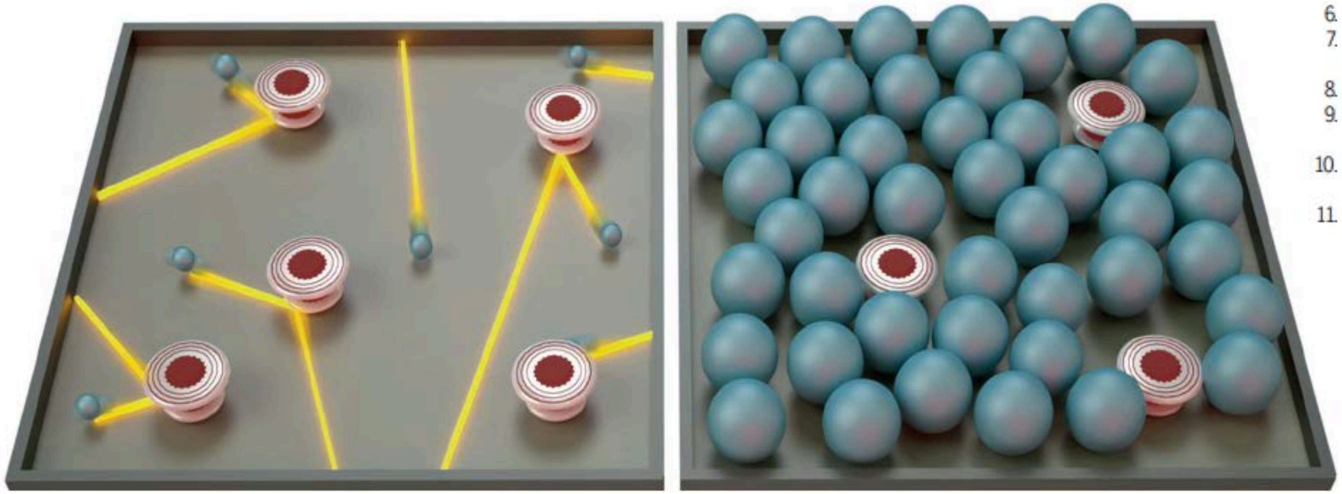


Hydrodynamics

PHYSICS

Electrons go with the flow in exotic material systems

Electronic hydrodynamic flow—making electrons flow like a fluid—has been observed



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- Hydrodynamic electron fluid is defined by momentum-conserving electron-electron scattering
- Violation of Wiedeman-Franz law
- Viscosity-induced shear forces making the electrical resistivity a function of the channel width

High mobility wires

PHYSICAL REVIEW B VOLUME 51, NUMBER 19 15 MAY 1995-I

Hydrodynamic electron flow in high-mobility wires

M. J. M. de Jong* and L. W. Molenkamp†

Philips Research Laboratories, 5656 AA Eindhoven, The Netherlands

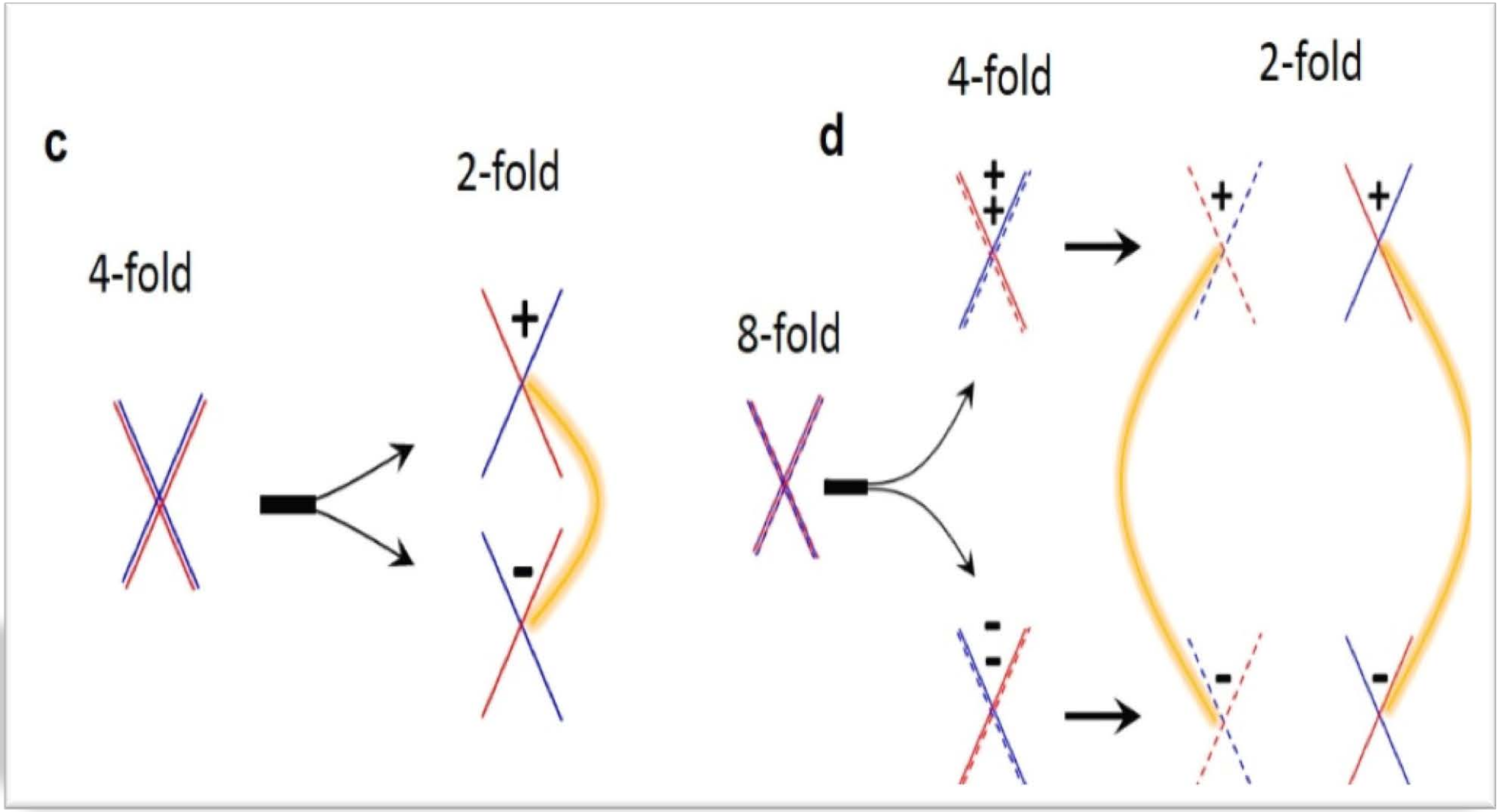
(Received 24 October 1994)

Hydrodynamic electron flow is experimentally observed in the differential resistance of electrostatically defined wires in the two-dimensional electron gas in (Al,Ga)As heterostructures. In these experiments current heating is used to induce a controlled increase in the number of electron-electron collisions in the wire. The interplay between the partly diffusive wire-boundary scattering and the electron-electron scattering leads first to an increase and then to a decrease of the resistance of the wire with increasing current. These effects are the electronic analog of Knudsen and Poiseuille flow in gas transport, respectively. The electron flow is studied theoretically through a Boltzmann transport equation, which includes impurity, electron-electron, and boundary scattering. A solution is obtained for arbitrary scattering parameters. By calculation of flow profiles inside the wire it is demonstrated how normal flow evolves into Poiseuille flow. The boundary-scattering parameters for the gate-defined wires can be deduced from the magnitude of the Knudsen effect. Good agreement between experiment and theory is obtained.

Weyl Semimetals

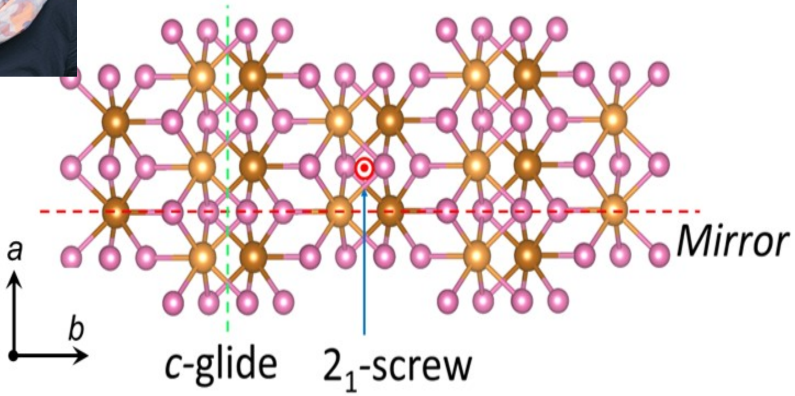
WP2

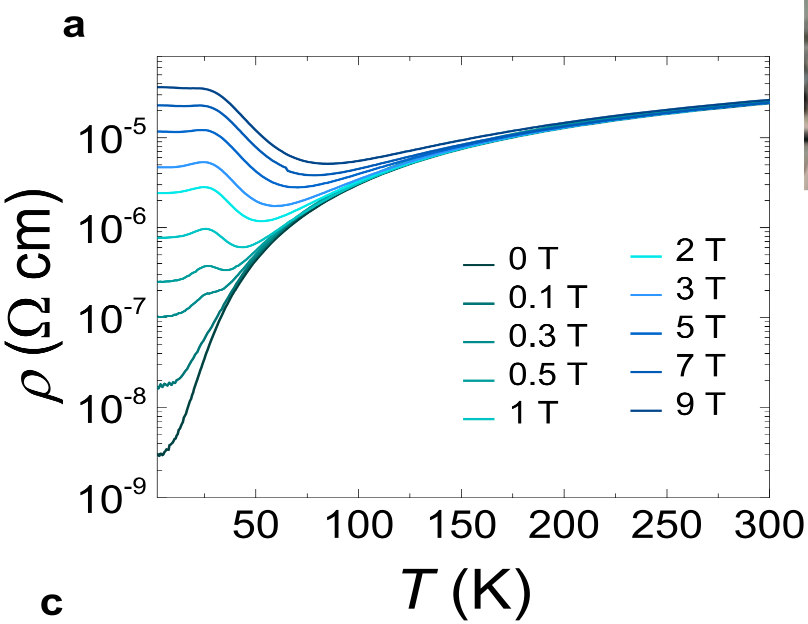
WP_2 protected Weyl

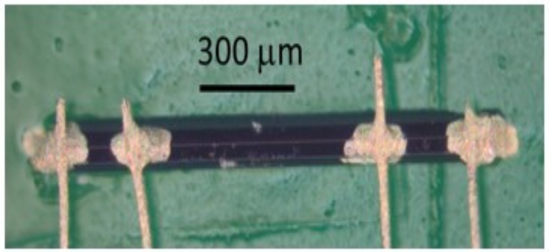


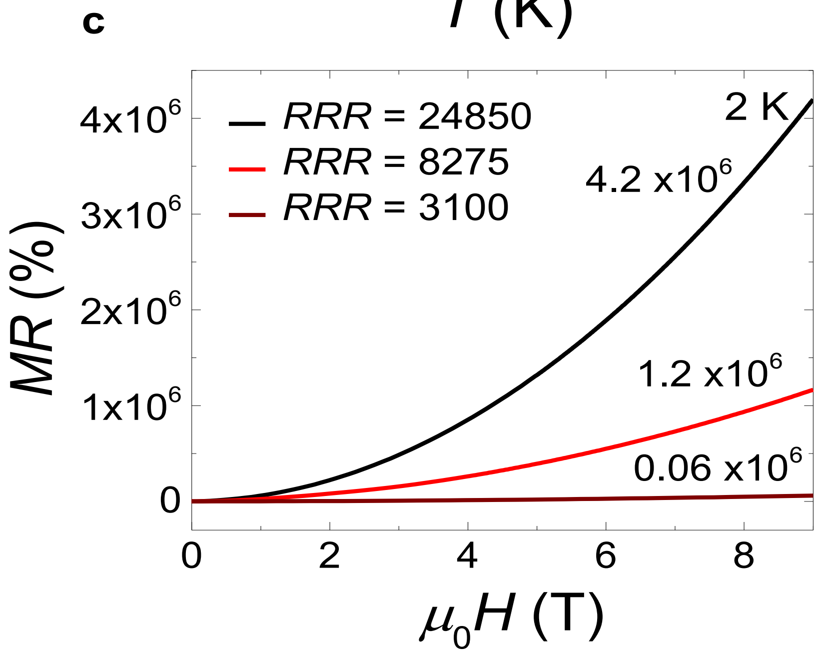
Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; arXiv:1703.04527

WP_2 protected Weyl





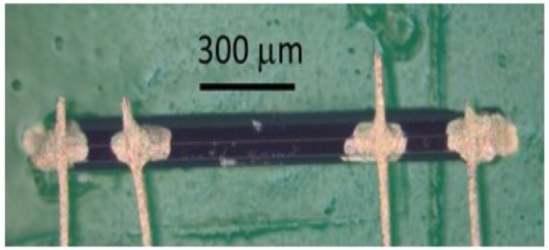




Nitesh, et al., Nature Com. accepted arXiv:1703.04527

Macroscopic mean free path

Compound	ρ (Ωcm)	l (μm)	μ ($cm^2V^{-1}s^{-1}$)	n (cm^{-3})
MoP	6×10^{-9}	11	2.4×10^4	2.9×10^{22}
WP_2	3×10^{-9}	530	4×10^6	5×10^{20}
WC	0.35×10^{-6}		$\sim1\times10^4$	4×10^{20}
$PtCoO_2$	40×10^{-9}	5	0.7×10^4	2.2×10^{22}
$PdCoO_2$	9×10^{-9}	20	$2.8x10^4$	2.4×10^{22}



WC J. B. He et al. arXiv:1703.03211
Pallavi Kushwaha, et al. Sci. Adv.1 (2015) e150069
P. Moll Science 351, (2016) 1061

Chandra Shekhar et al. arXiv:1703.03736
Nitesh, et al.; arXiv:1703.04527

Hydrodynamics

PRL **118**, 226601 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Hydrodynamic Electron Flow and Hall Viscosity

Thomas Scaffidi,[1] Nabhanila Nandi,[2] Burkhard Schmidt,[2] Andrew P. Mackenzie,[2,3] and Joel E. Moore[1,4]

In the ballistic regime ($w << l_{er}, l_{mr}$): $\rho \sim w^{-1}$

Hydrodynamic effects become dominant

- electron-electron scattering $l_{er} << w << l_{mr}$,
- with electron-electron scattering length $l_{er} = v_F \tau_{er}$
- w the sample width,
- $l_{mr} = v_F \tau_{mr}$ the mean free path and v_F the Fermi velocity

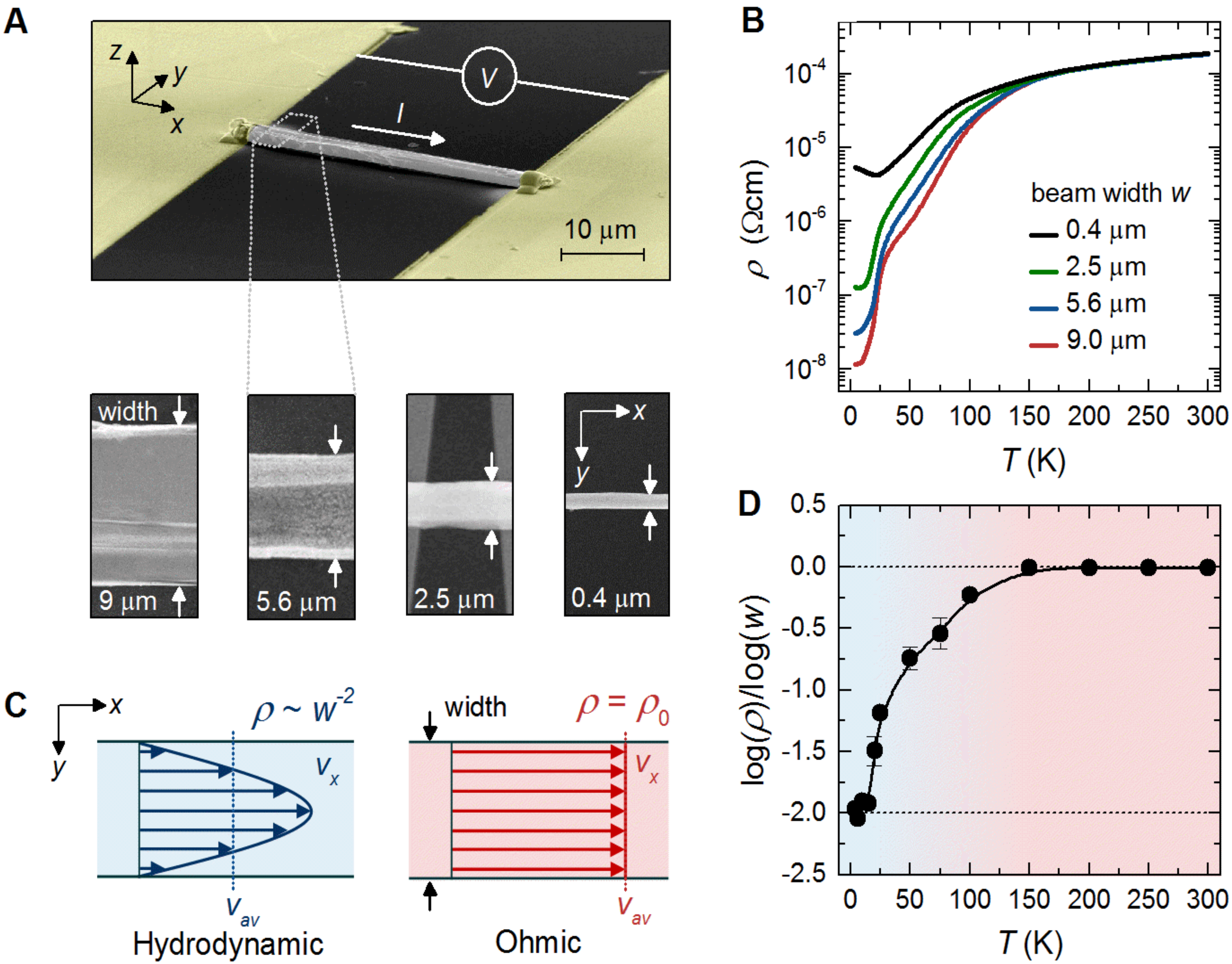
In the Navier-Stokes flow limit: $\rho = m^*/(e^2 n) \cdot 12 \eta w^{-2}$

R. N. Gurzhy, A. N. Kalinenko, A. I. Kopeliovich, Hydrodynamic effects in the electrical conductivity of impure metals. *Sov. Physics-JETP*. **69**, 863–870 (1989).

P. S. Alekseev, Negative magnetoresistance in viscous flow of two-dimensional electrons. *Phys. Rev. Lett.* **117** (2016).

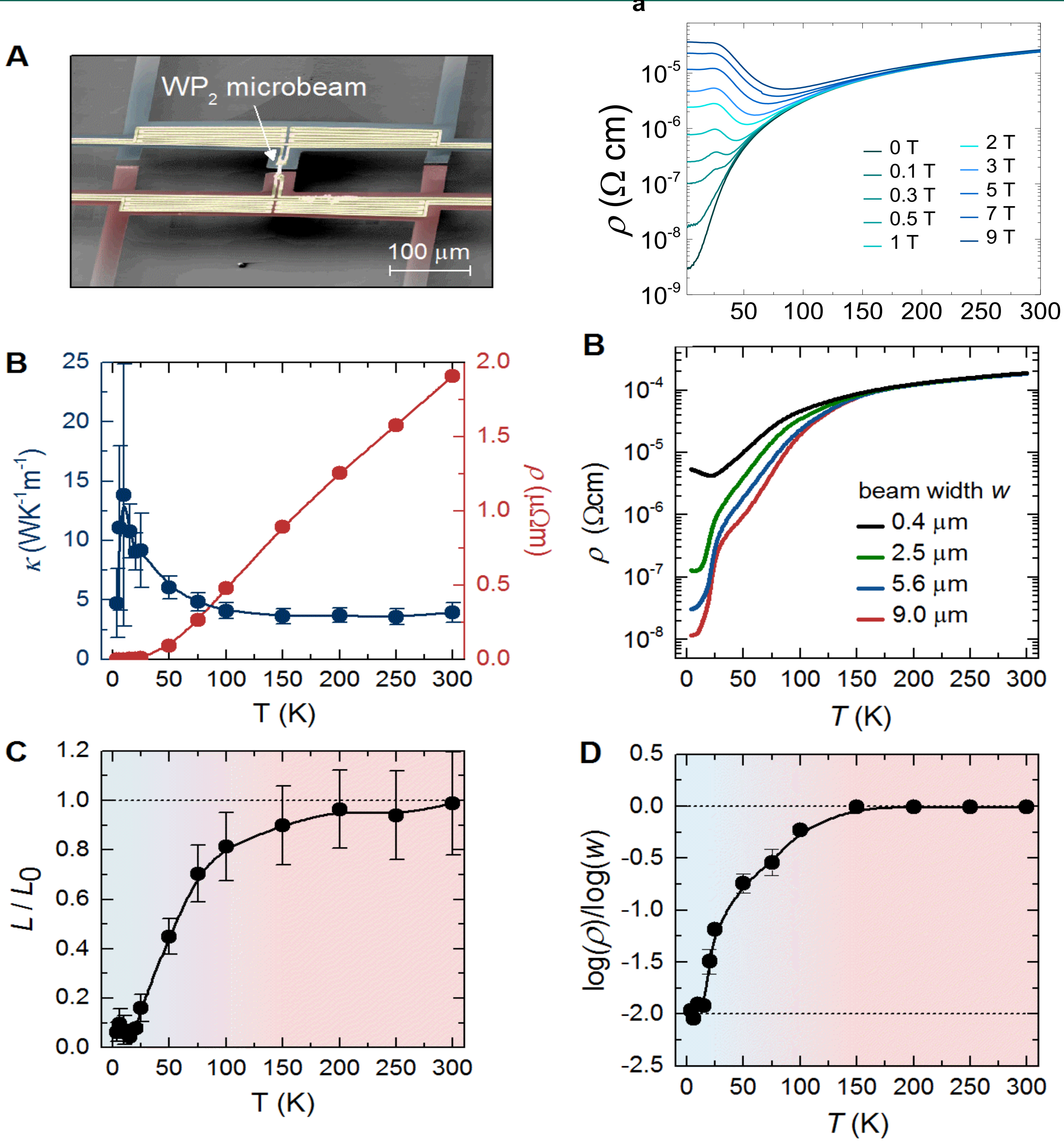
T. Scaffidi, N. Nandi, B. Schmidt, A. P. Mackenzie, J. E. Moore, Hydrodynamic Electron Flow and Hall Viscosity. *Phys. Rev. Lett.* **118**, 226601 (2017).

Hydrodynamic flow



J. Gooth et al. Science submitted, arXiv:1706.05925

Hydrodynamic flow



- Hydrodynamic electron fluid <15K
- conventional metallic state at T higher 150K

The hydrodynamic regime:

- a viscosity-induced dependence of the electrical resistivity on the square of the channel width

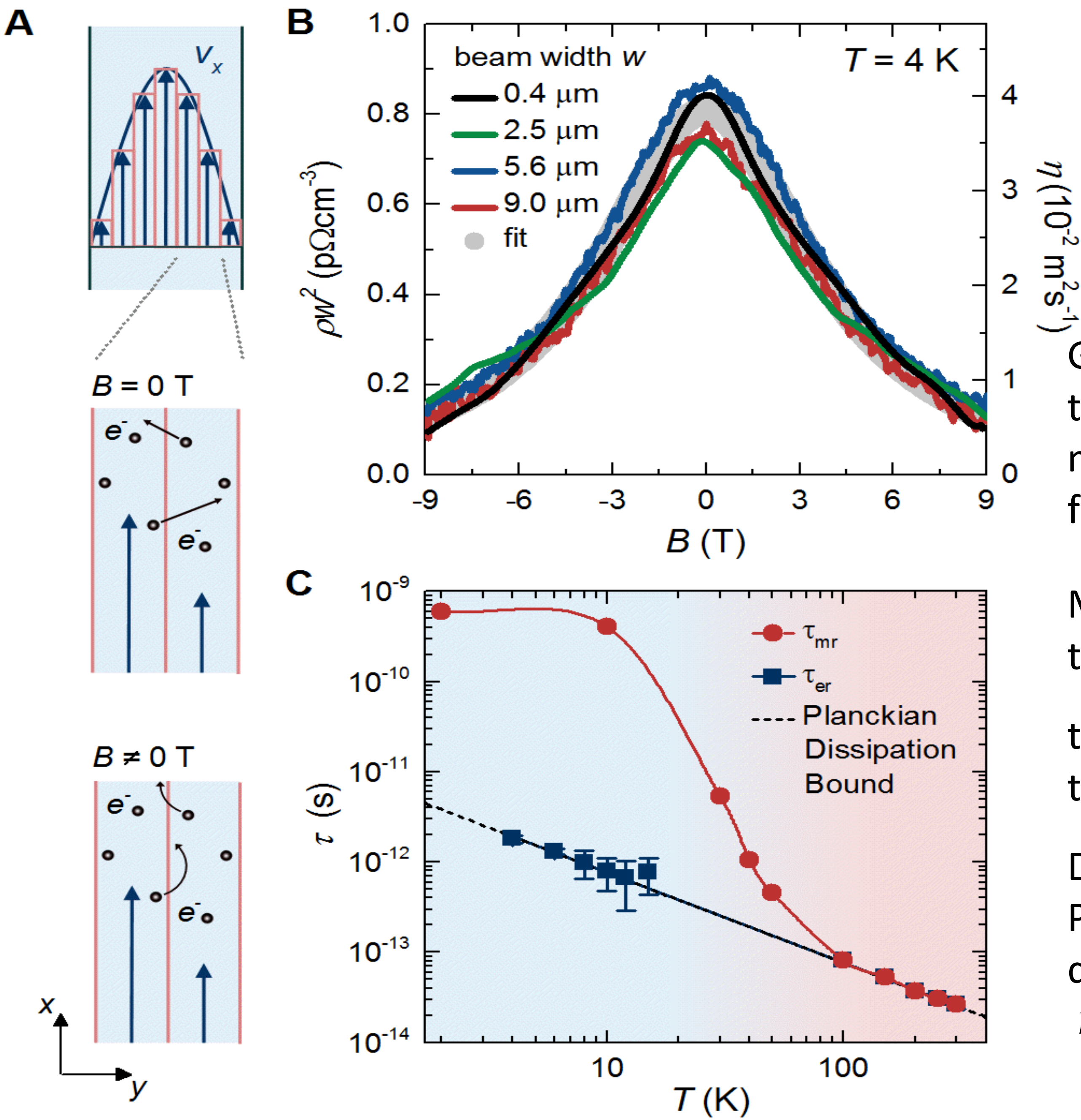
$$\rho = m^*/(e^2 n)\cdot 12\eta w^{-2}$$

- a strong violation of the

$$L \equiv \frac{\kappa}{\sigma T} = \frac{\pi^2}{3} \equiv L_0$$

J. Gooth et al. submitted, arXiv:1706.05925

Magnetohydrodynamics, Planckian bound of dissipation



Grey dots: the magnetohydrodynamic model in the Navier-Stokes flow limit

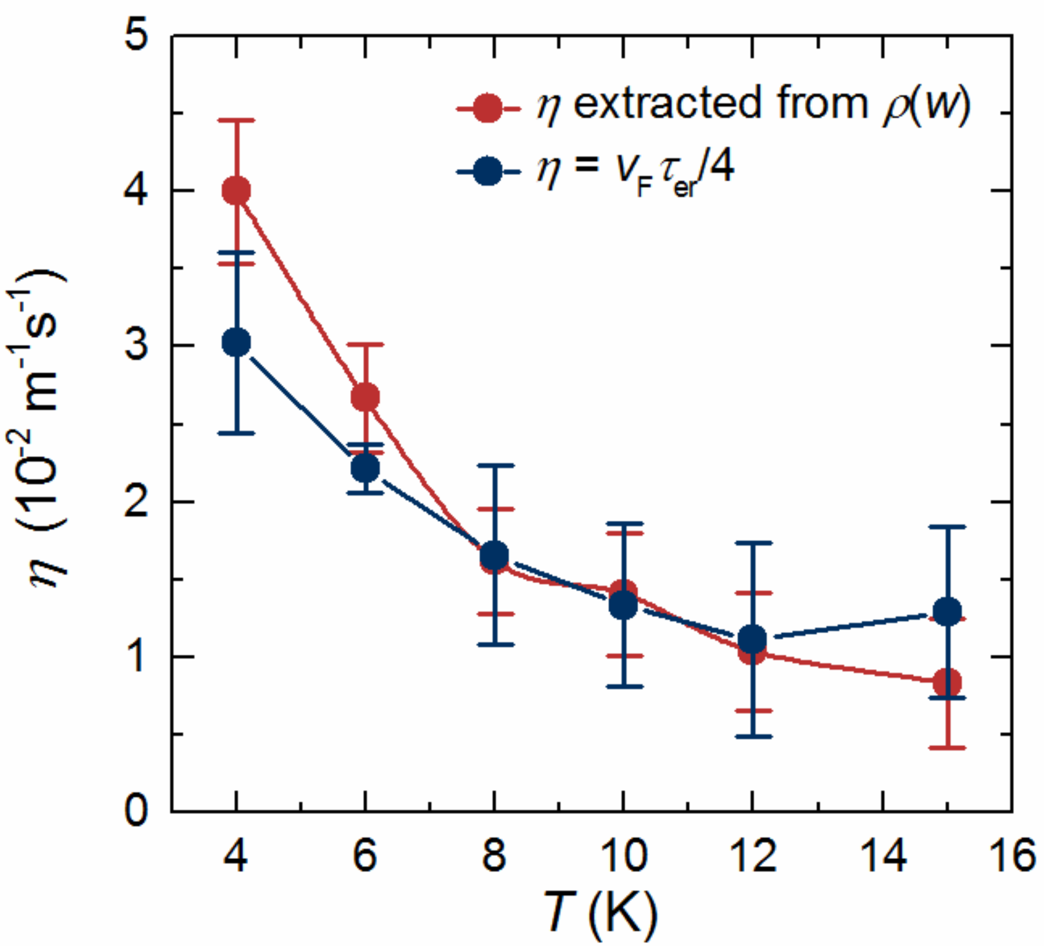
Momentum relaxation times t_{mr}

thermal energy relaxation times t_{er},

Dashed line marks the Planckian bound on the dissipation time $\tau_\hbar = \hbar/(k_B T)$.

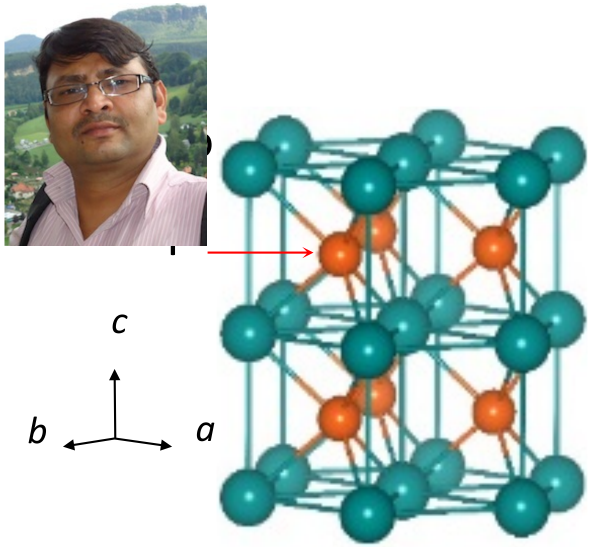
J. Gooth et al. submitted, arXiv:1706.05925

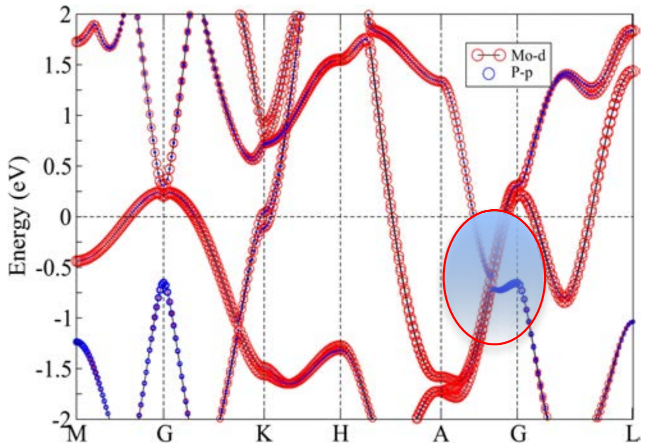
Viscosity of the electron fluid in WP_2

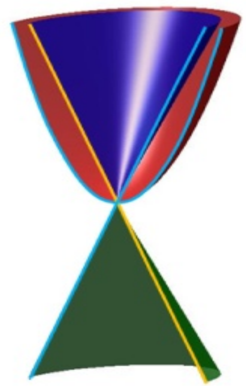


The dynamic viscosity is $\eta_D = 1\times10^{-4}$ kgm^{-1}s^{-1} at 4 K.

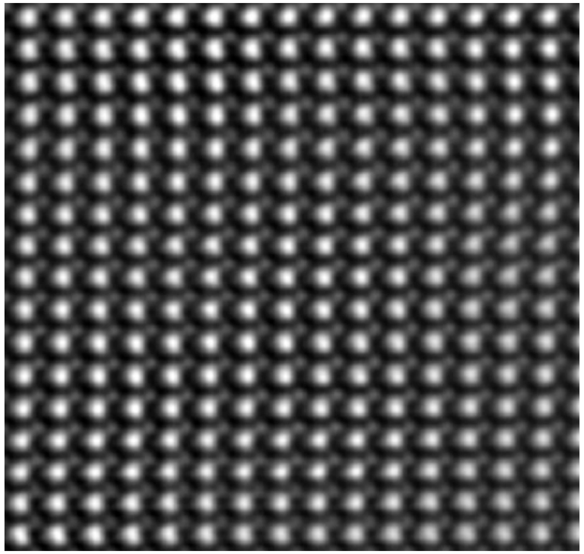
MoP better than Copper

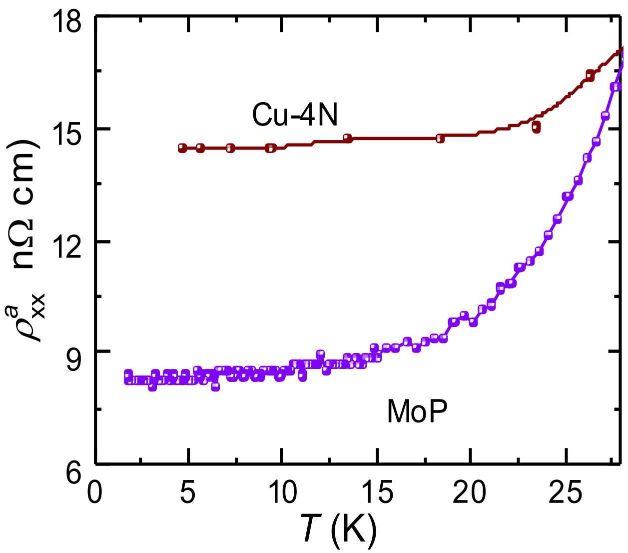


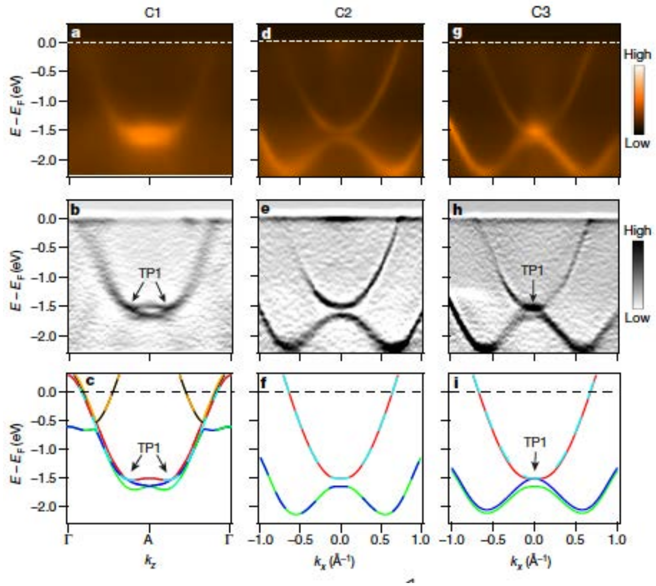




Triple-point





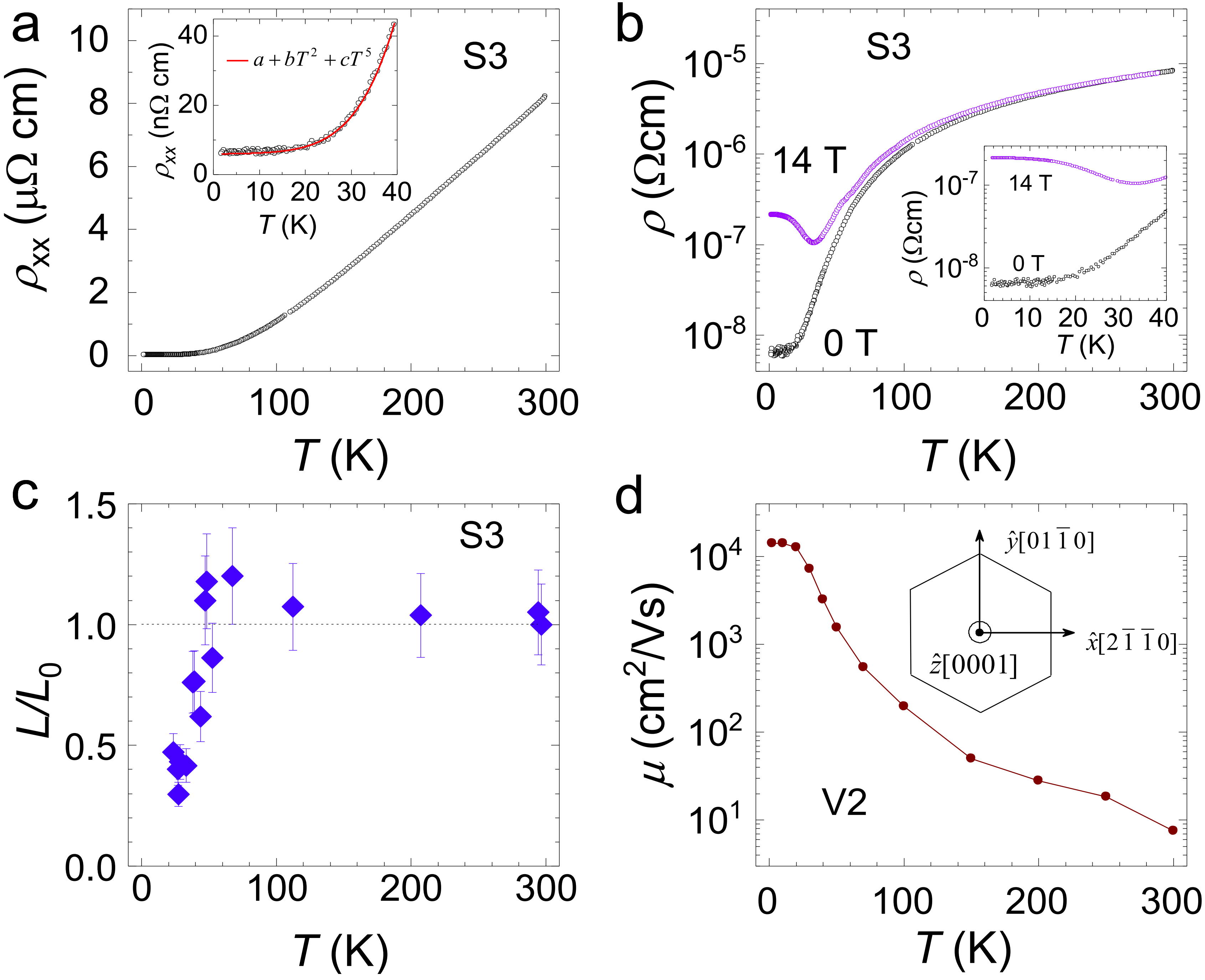


3D-Hydrodynamics ?

Chandra Shekhar et al. arXiv:1703.03736

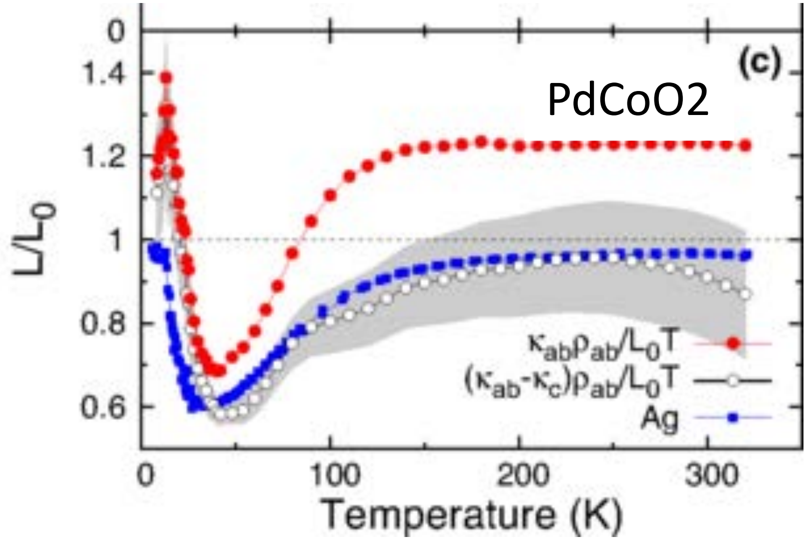
B. Q. Lv, Z.-L. Feng & Q.-N. Xu et al. Nature 546, (2017) 627

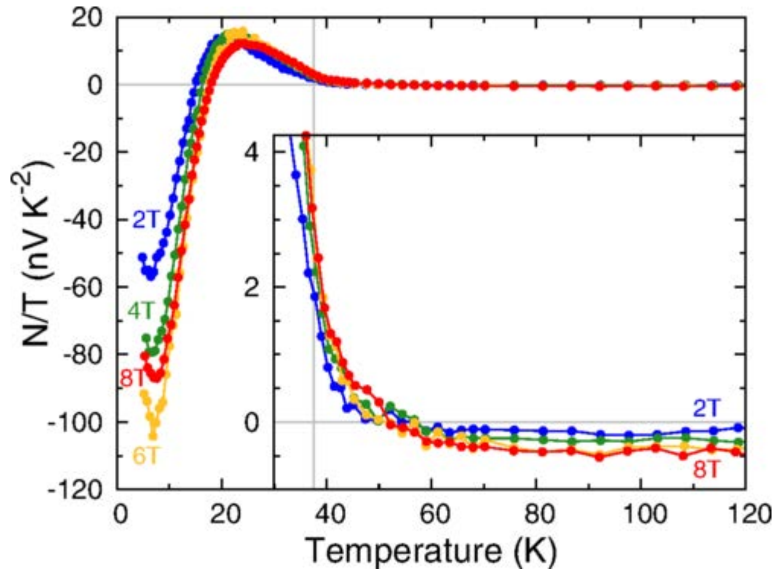
MoP – low T transport



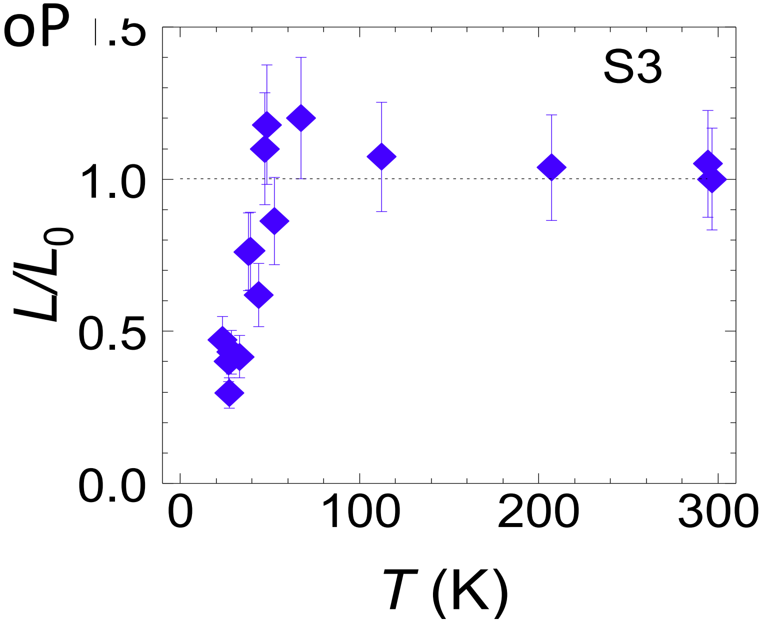
Violation of the Wiedemann-Franz law

$$L \equiv \frac{\kappa}{\sigma T} = \frac{\pi^2}{3} \equiv L_0$$

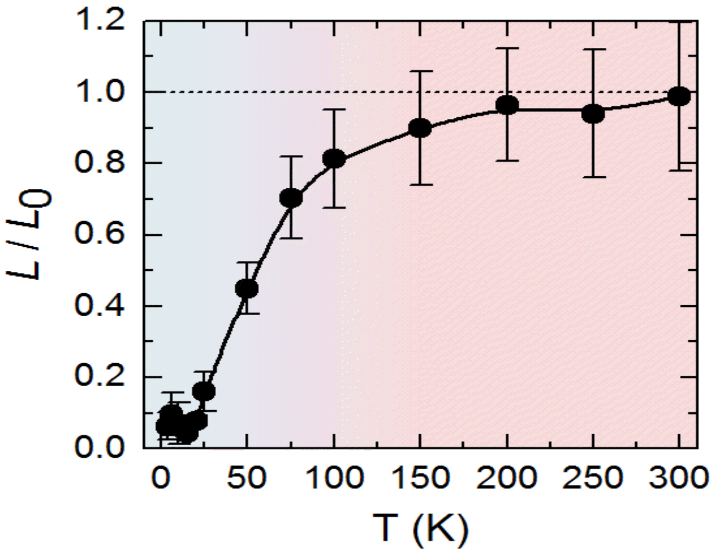




MoP

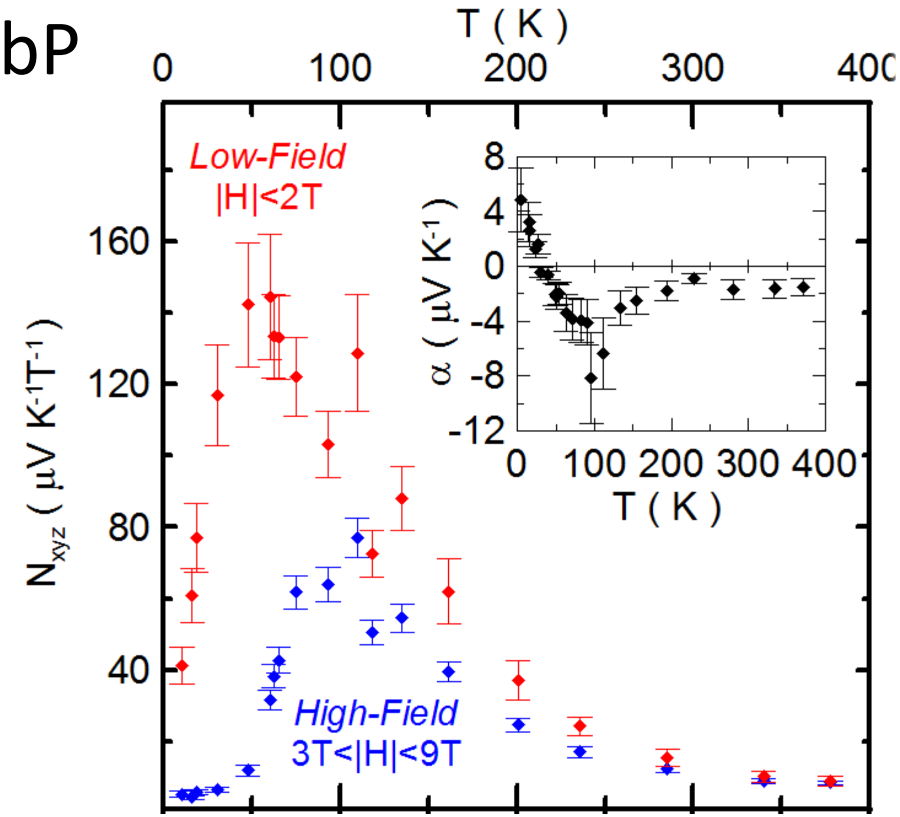


WP_2



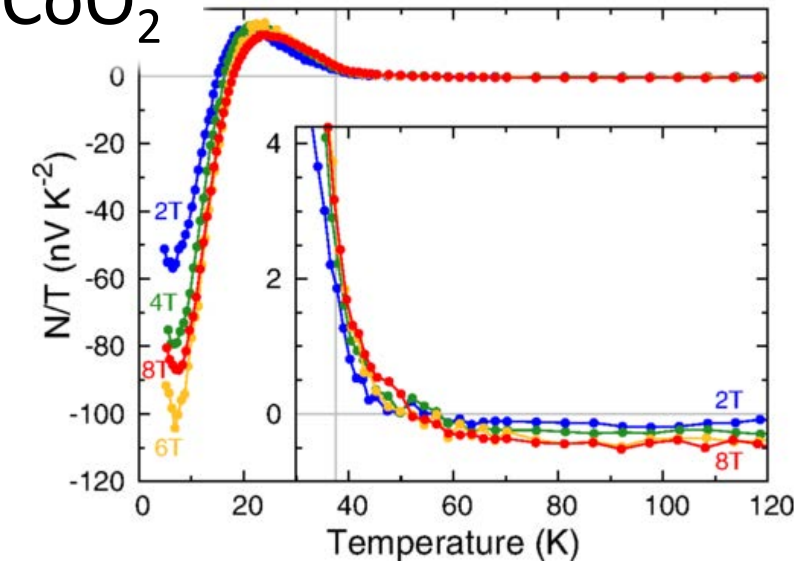
Giant Nernst – Topology - Hydrodynamic

NbP



Sarah J. Watzman, et al. preprint arXiv:1704.02241

$PdCoO_2$



Ramzy Daou, Raymond Frésard, Sylvie Hébert, and Antoine Maignan, Phys. Rev. B 92, 245115 (2015)

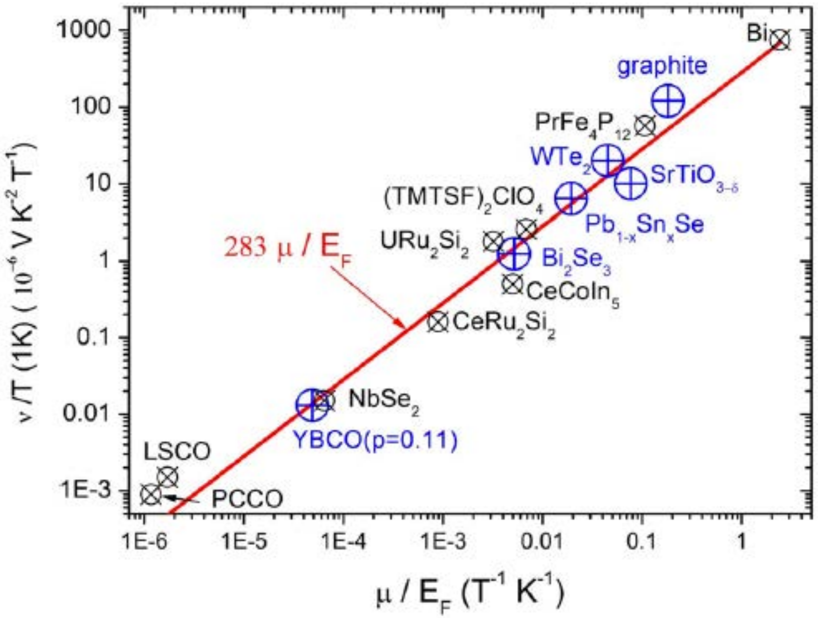
Rep. Prog. Phys. **79** (2016) 046502 (23pp)

doi:10.1088/0034-4885/79/4/046502

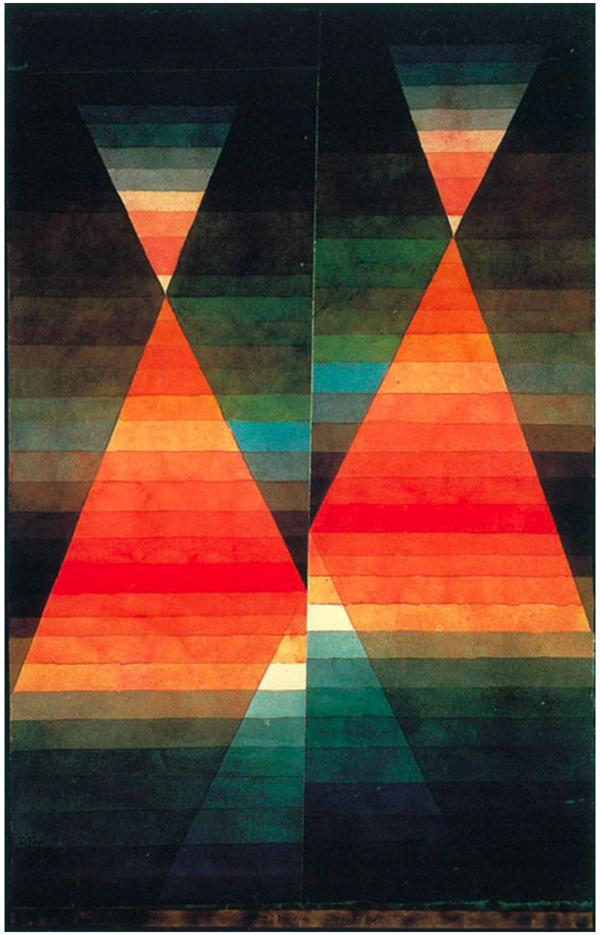
Review

Nernst effect in metals and superconductors: a review of concepts and experiments

Kamran Behnia and Hervé Aubin

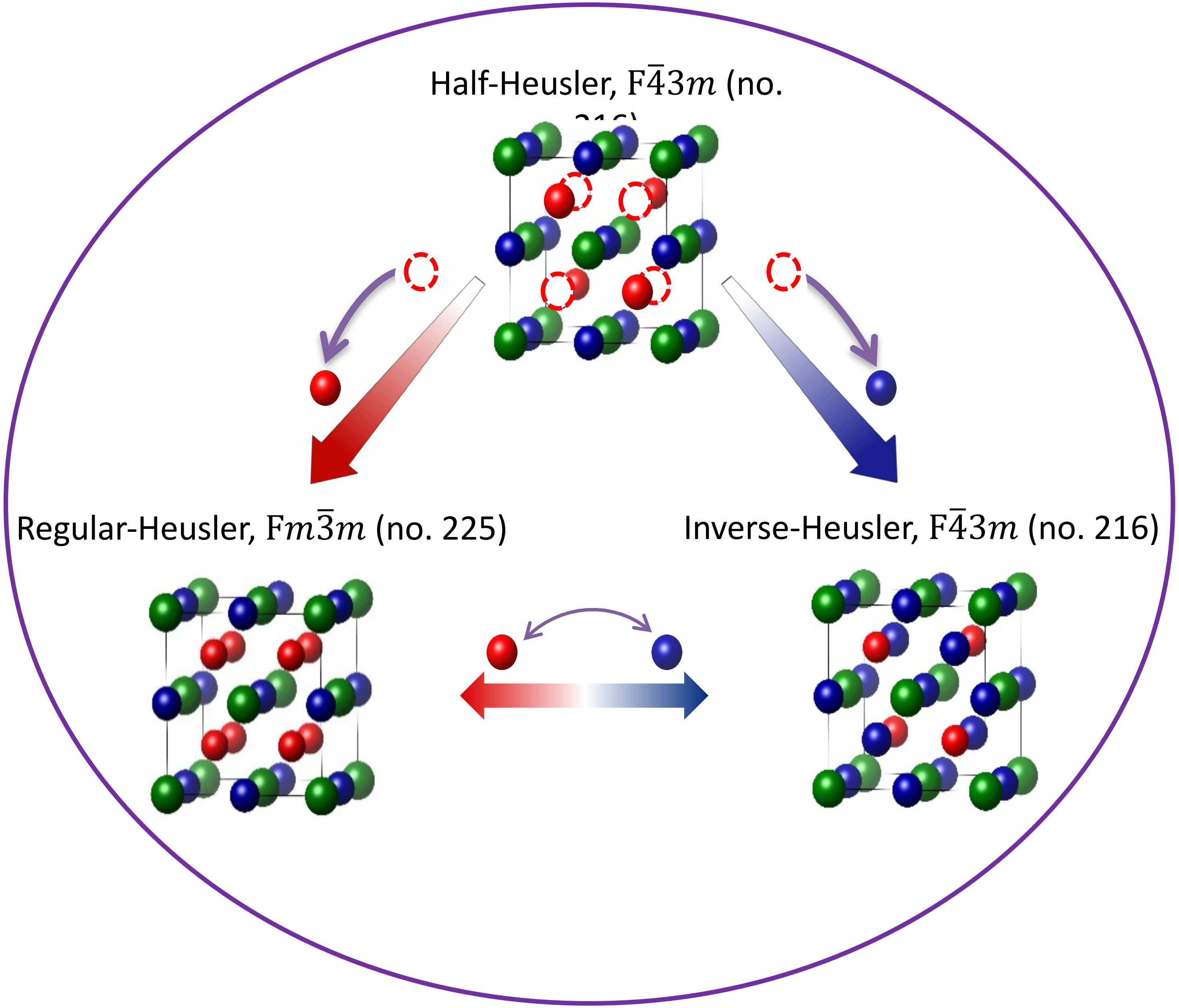


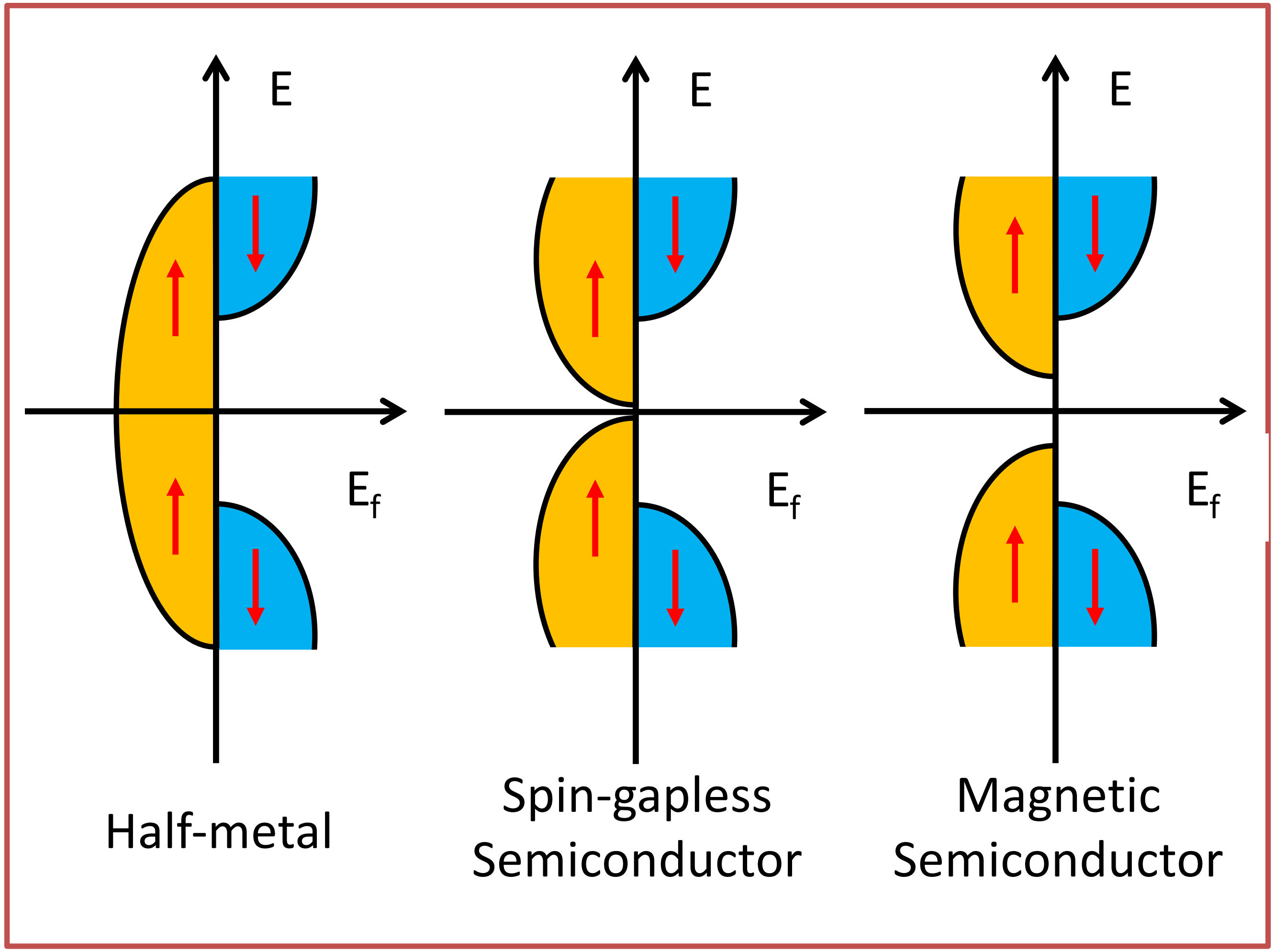
Magnetic Weyl Semimetals



Paul Klee

Tuning the symmetry




E
E
E
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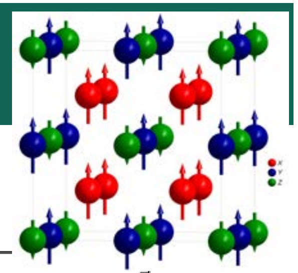
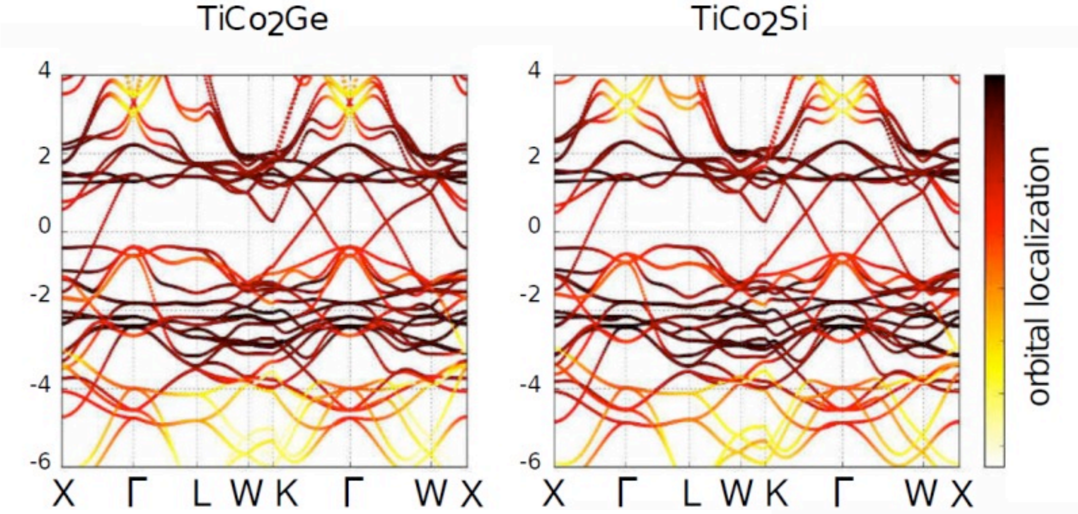
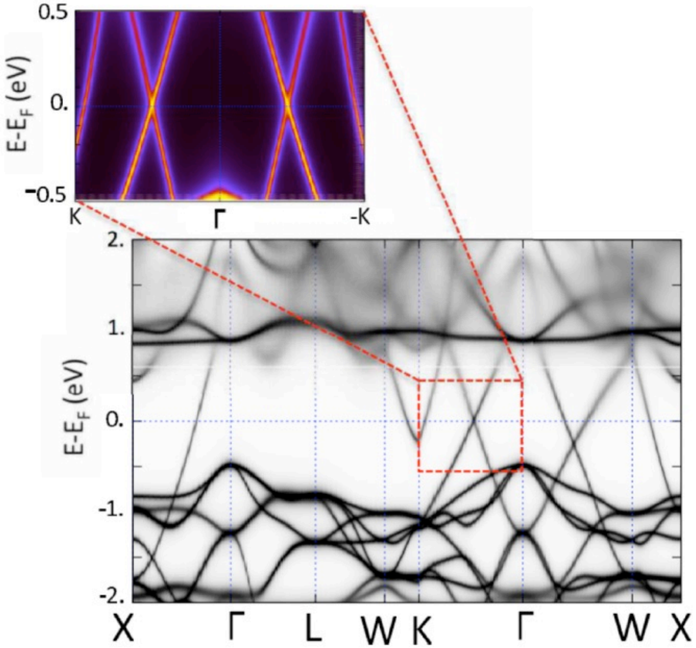
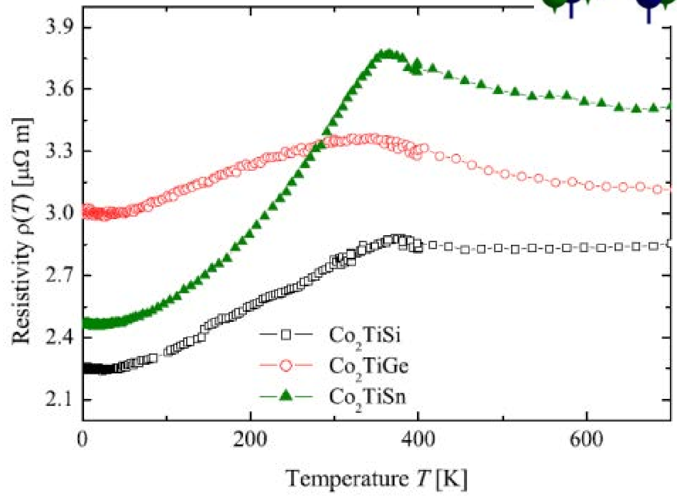
E_f
Half-metal
Spin-gapless Semiconductor
Magnetic Semiconductor

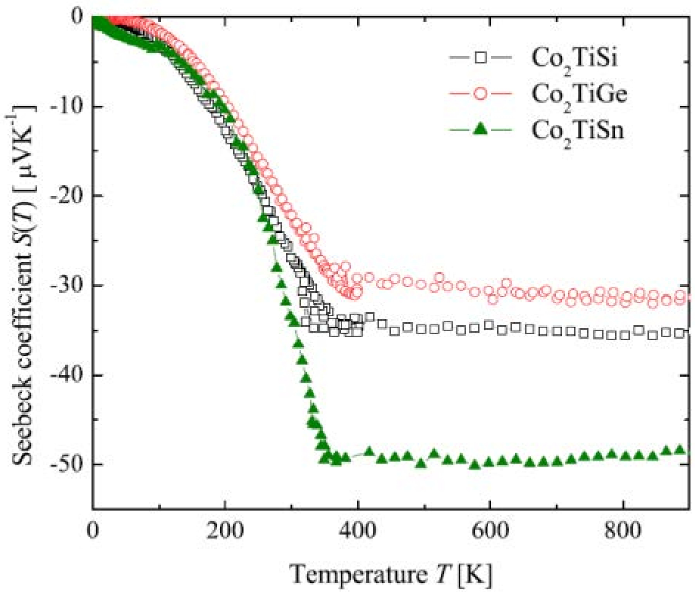
Weyl semimetals with 26 VEC











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

Barth et al. PRB 81, 064404 2010

AHE in half metallic ferromagnets

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

Berry curvature and the anomalous Hall effect in Heusler compounds

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

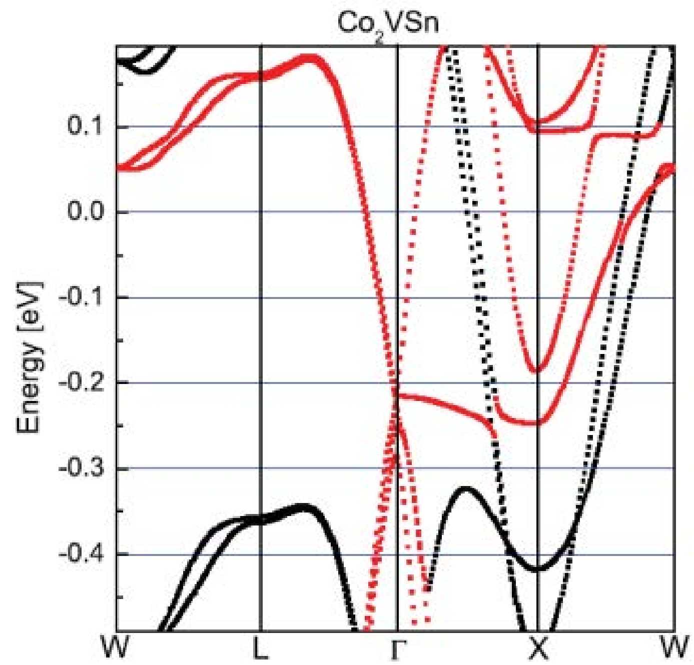
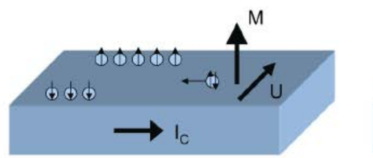


FIG. 4. (Color online) Band structure near the Fermi edge of Co_2VSn. Majority-spin electron states appear in red, minority-spin states in black. Note the Dirac cone at the Γ point at about −0.22 eV.

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

Anomalous Hall effect
1881



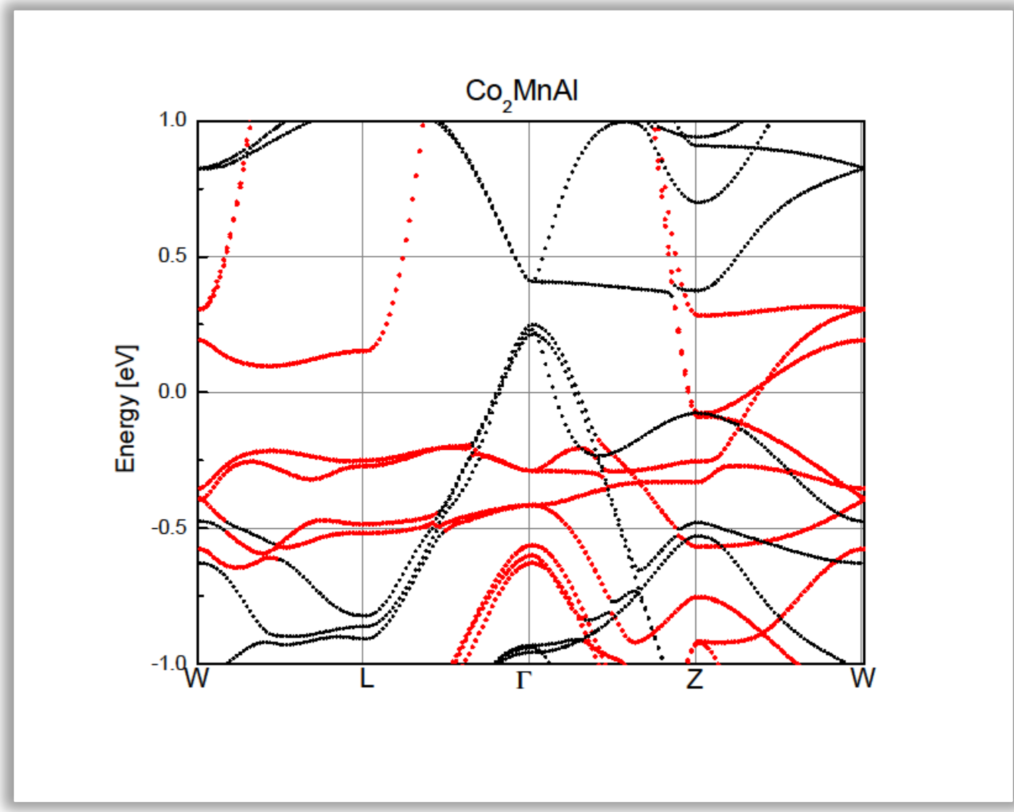
Kübler, Felser, PRB 85 (2012) 012405

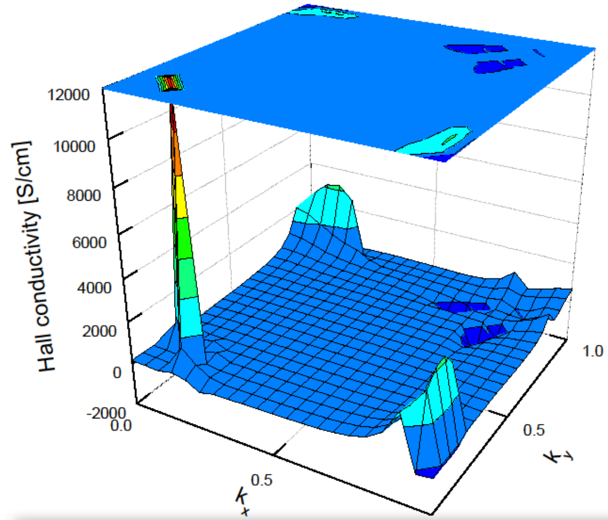
AHE in half metallic ferromagnets

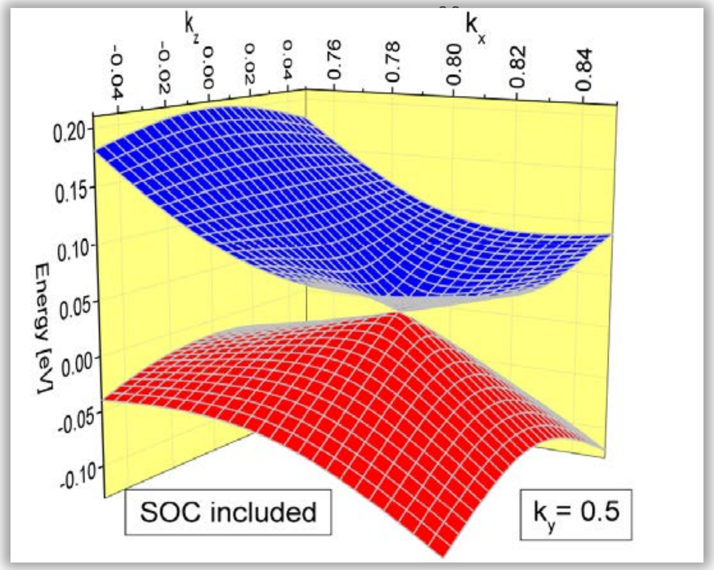
Giant AHE in Co_2MnAl

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

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



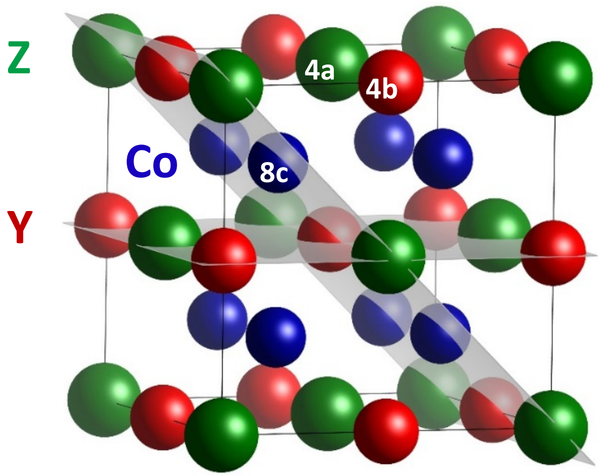




Kübler, Felser, PRB 85 (2012) 012405
Vidal et al. APL. 99 (2011) 132509
Kübler, Felser, EPL 114 (2016) 47005.

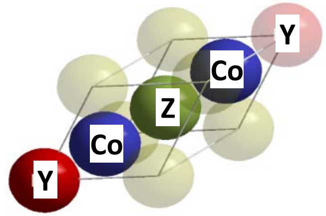
Weyl points are the origin for a large Berry phase and a Giant AHE

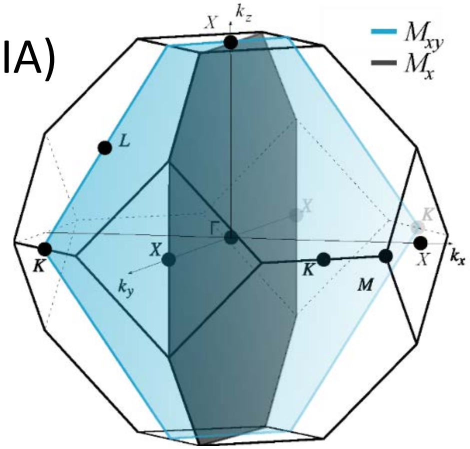
Weyl Fermion in Regular Heusler

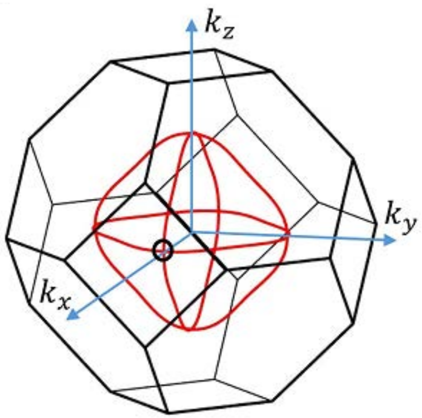


Co_2YZ (Y = IVB or VB; Z = IVA or IIIA)

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



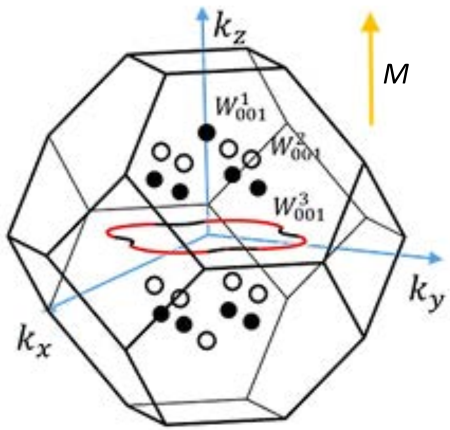




Without SOC

With SOC

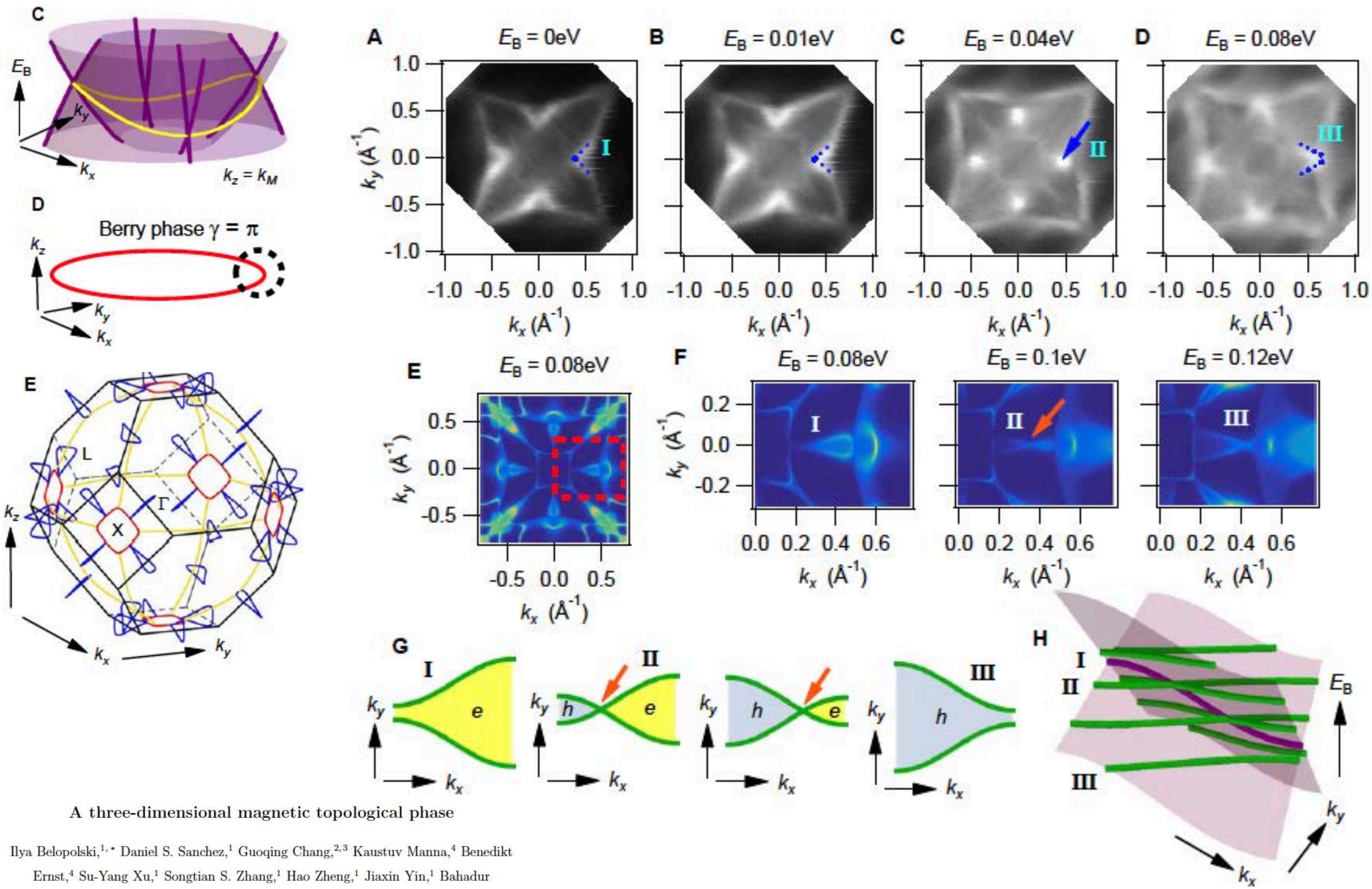
Symmetry and electronic structures depend on the magnetization direction



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

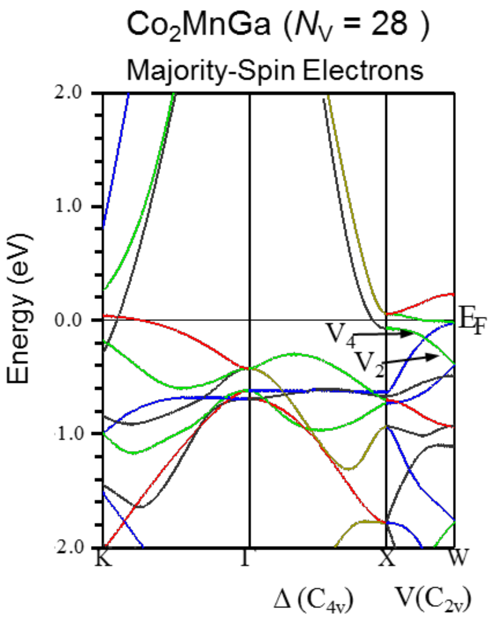
Berry and Heusler –and ARPES

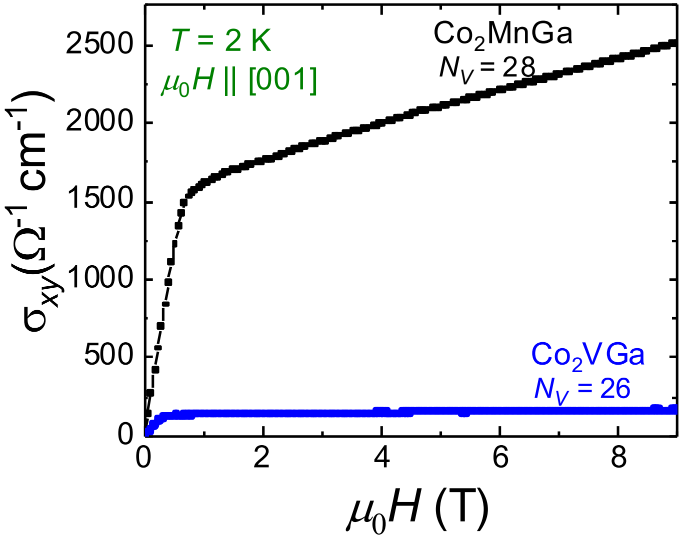


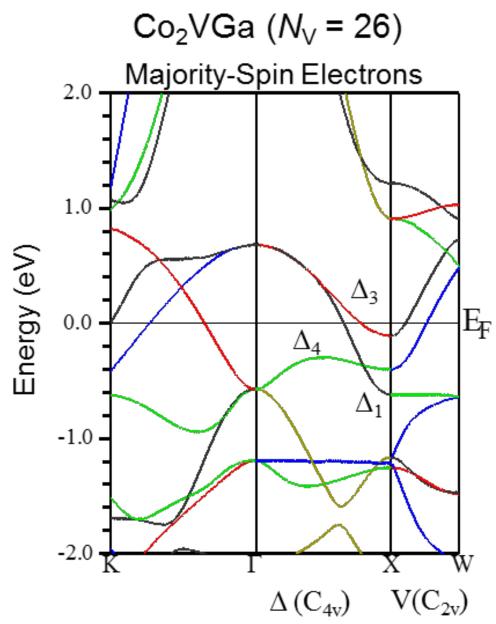
A three-dimensional magnetic topological phase

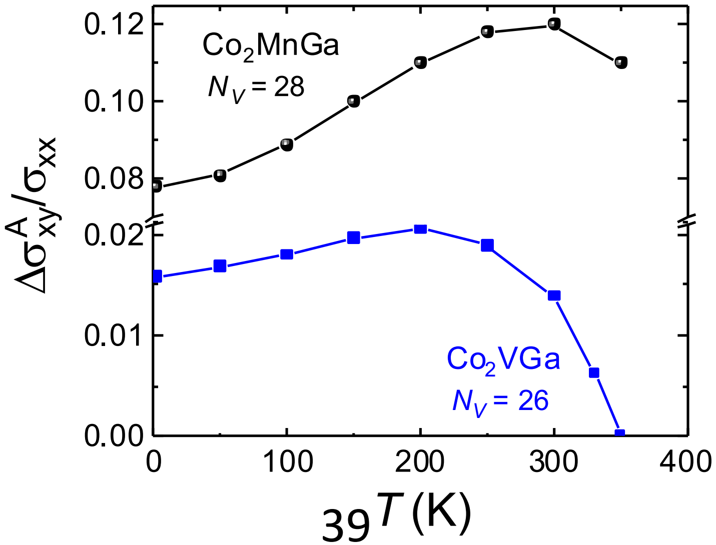
Ilya Belopolski,[1,*] Daniel S. Sanchez,[1] Guoqing Chang,[2,3] Kaustuv Manna,[4] Benedikt Ernst,[4] Su-Yang Xu,[1] Songtian S. Zhang,[1] Hao Zheng,[1] Jiaxin Yin,[1] Bahadur Singh,[2,3] Guang Bian,[5] Daniel Multer,[1] Xiaoting Zhou,[2,3] Shin-Ming Huang,[6] Baokai Wang,[7] Arun Bansil,[7] Hsin Lin,[2,3] Claudia Felser,[4] and M. Zahid Hasan[1,8,9,†]

How much Topology Influences the Anomalous Hall Effect?

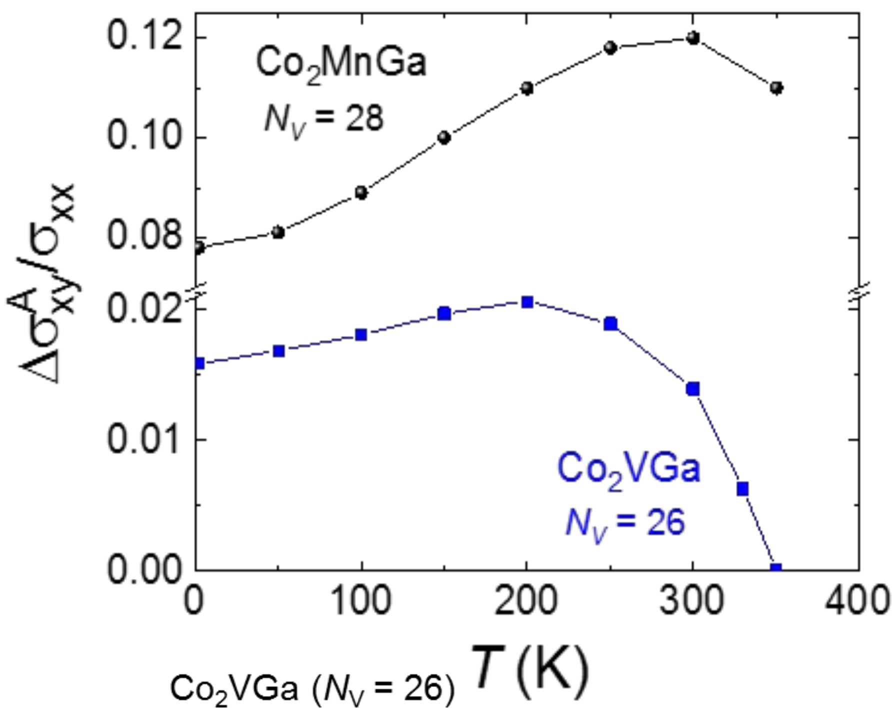








Large Anomalous Hall angle effect

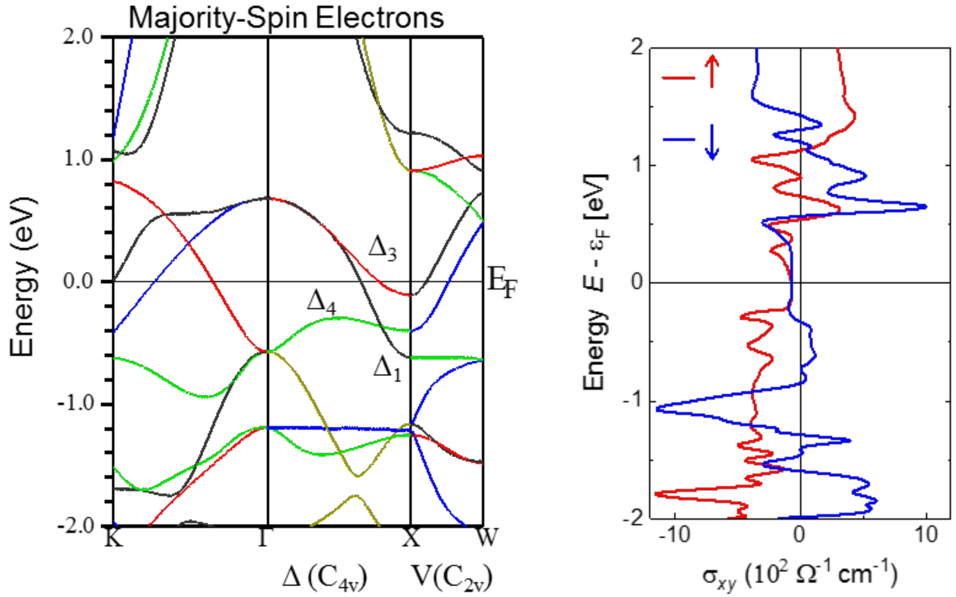


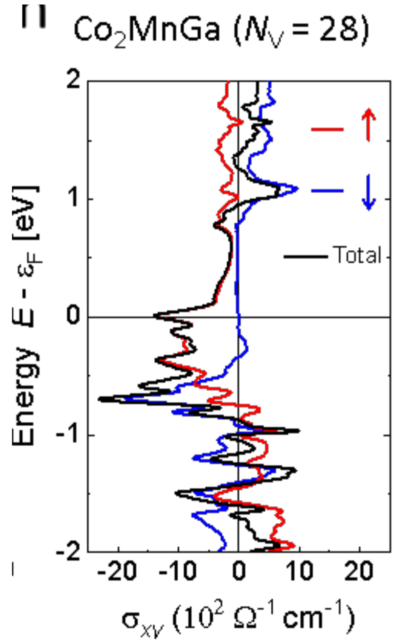
$$\Theta_{AHE} = \Delta\,\sigma_{xy}^{A} / \sigma_{xx}$$

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

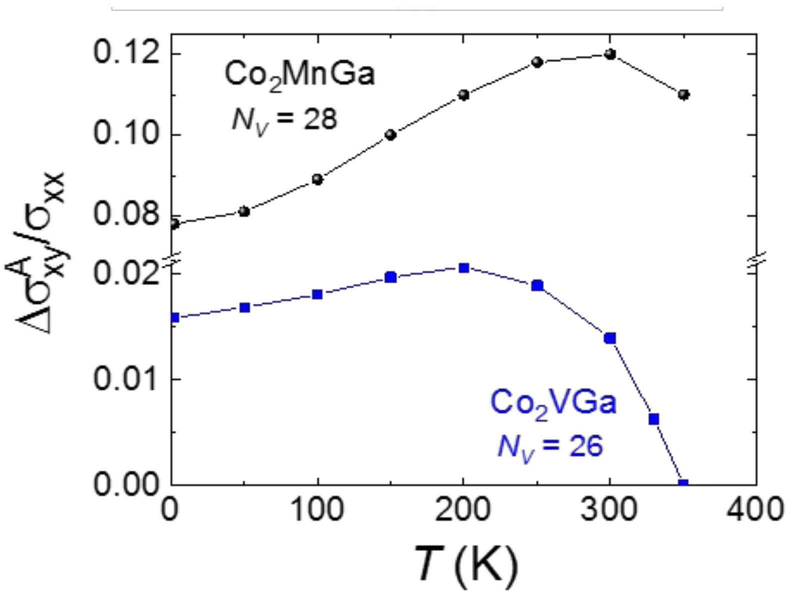
We are looking for a large Berry curvature
And a small charge carrier concentration

Goal: thin films for QAHE





Large Anomalous Hall angle effect



$$\Theta_{AHE} = \Delta\,\sigma_{xy}^A / \sigma_{xx}$$

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

We are looking for a large Berry curvature
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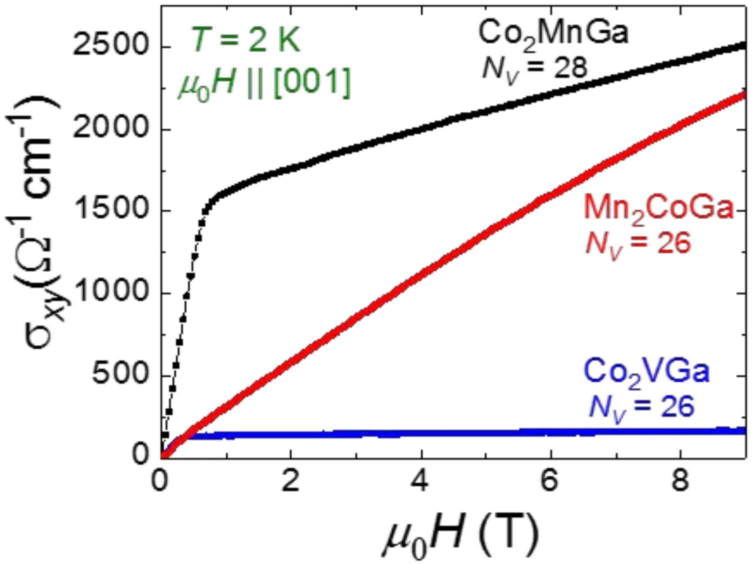
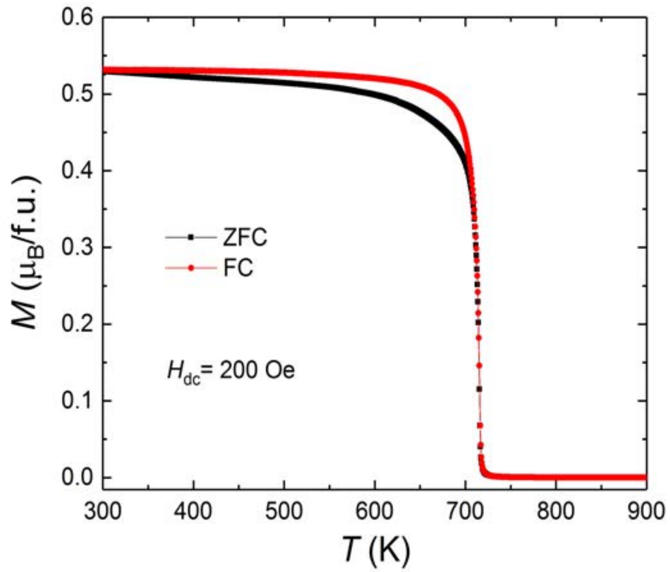
Goal: thin films for QAHE





More semiconductors

26

Mn2CoAl

CoMn2Al

CoFeCrAl

CoMnCrSi

CoFeVSi

FeMnCrSb

18

V_3Al

21

FeVTiSi

CoVScSi

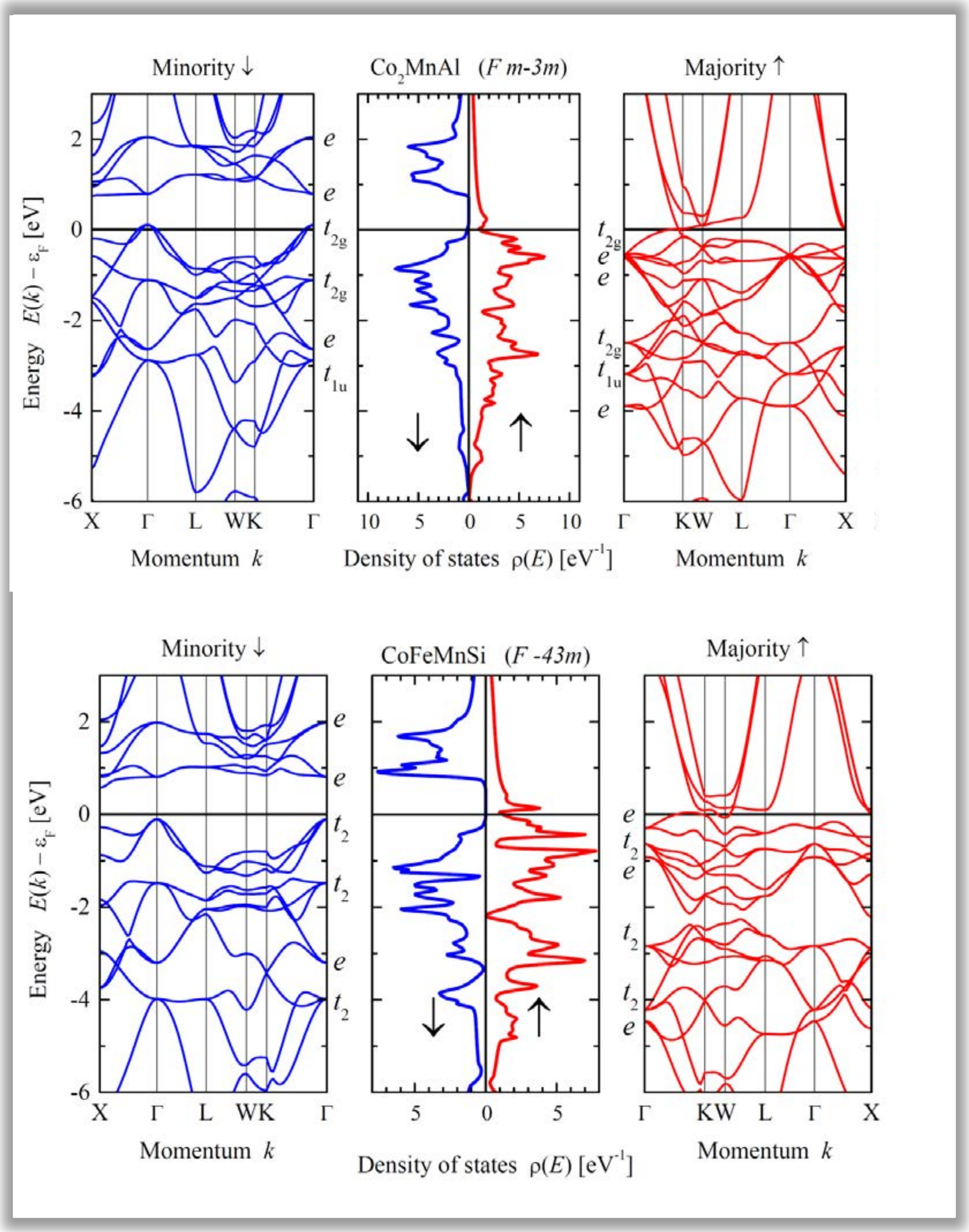
FeCrScSi

FeVTiSi

FeMnScAl

28

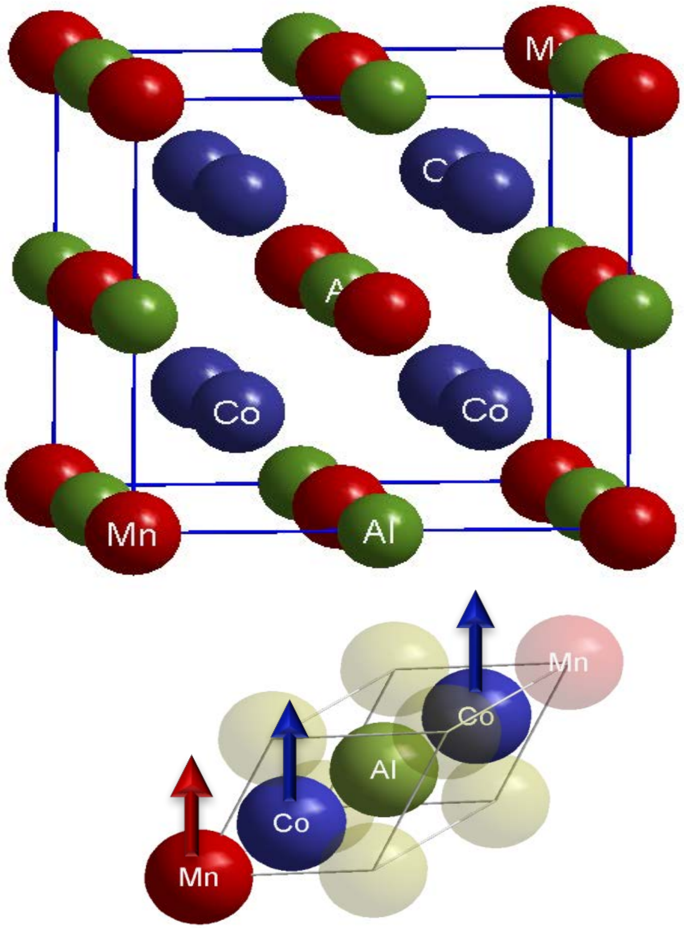
CoFeMnSi



Magnetic Heusler compounds with and without inversion

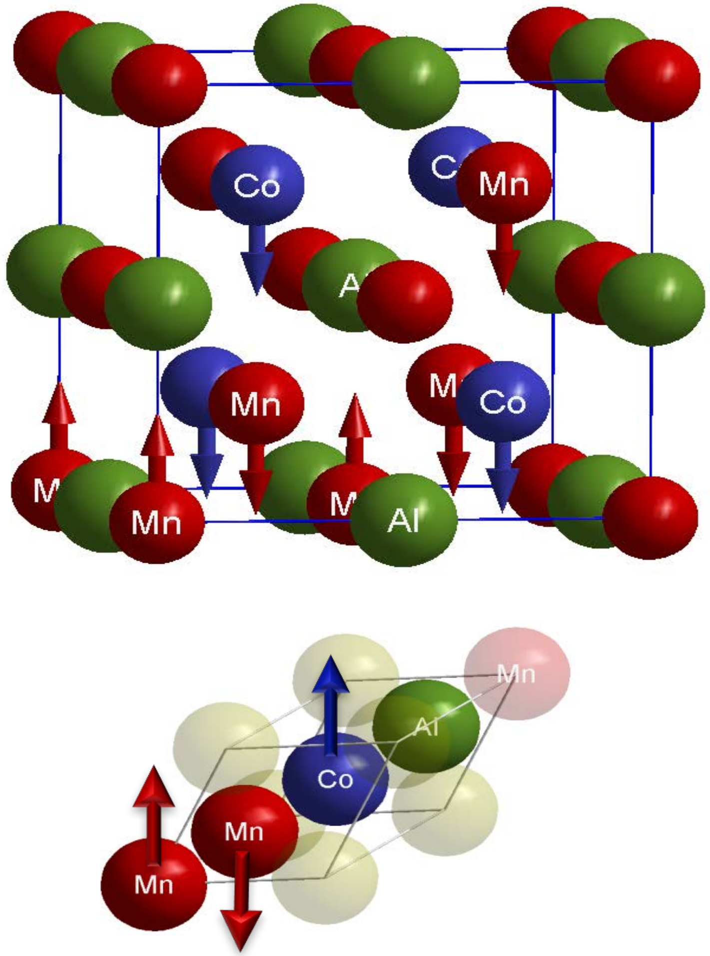
Co_2MnAl

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

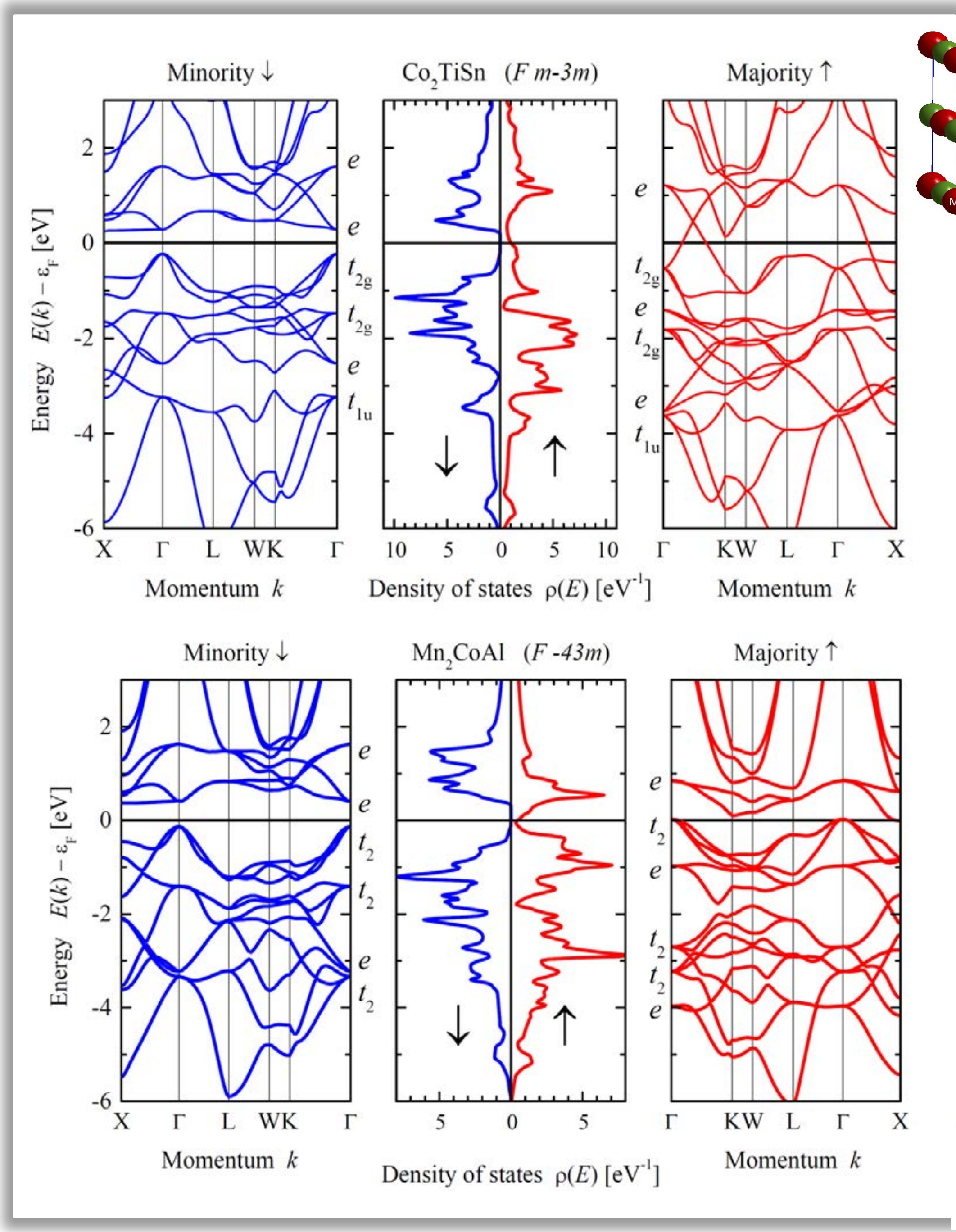


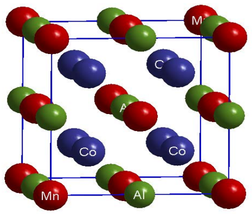
Mn_2CoAl

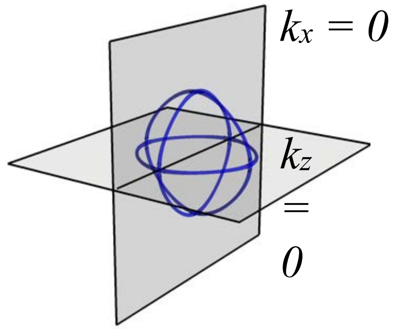
X space group 216 ($F\bar{4}3m$)

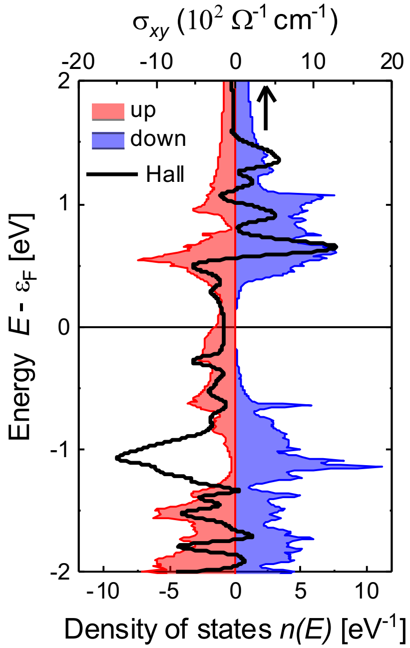


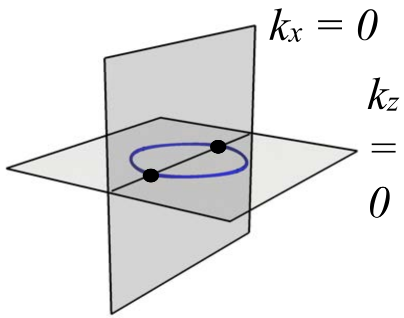
Weyl or Spingapless

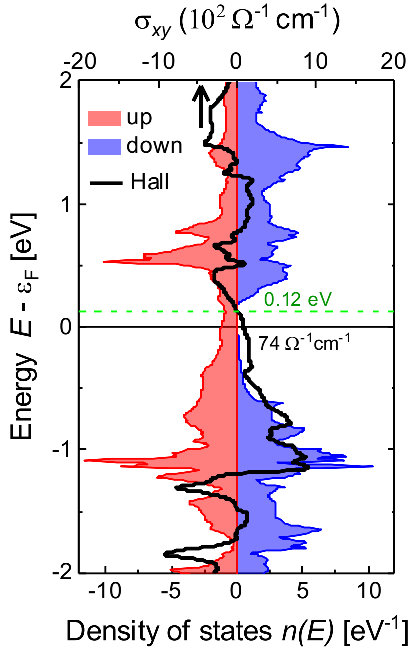


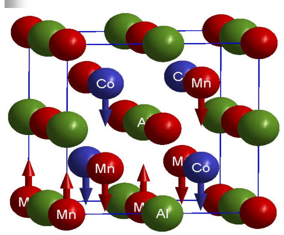




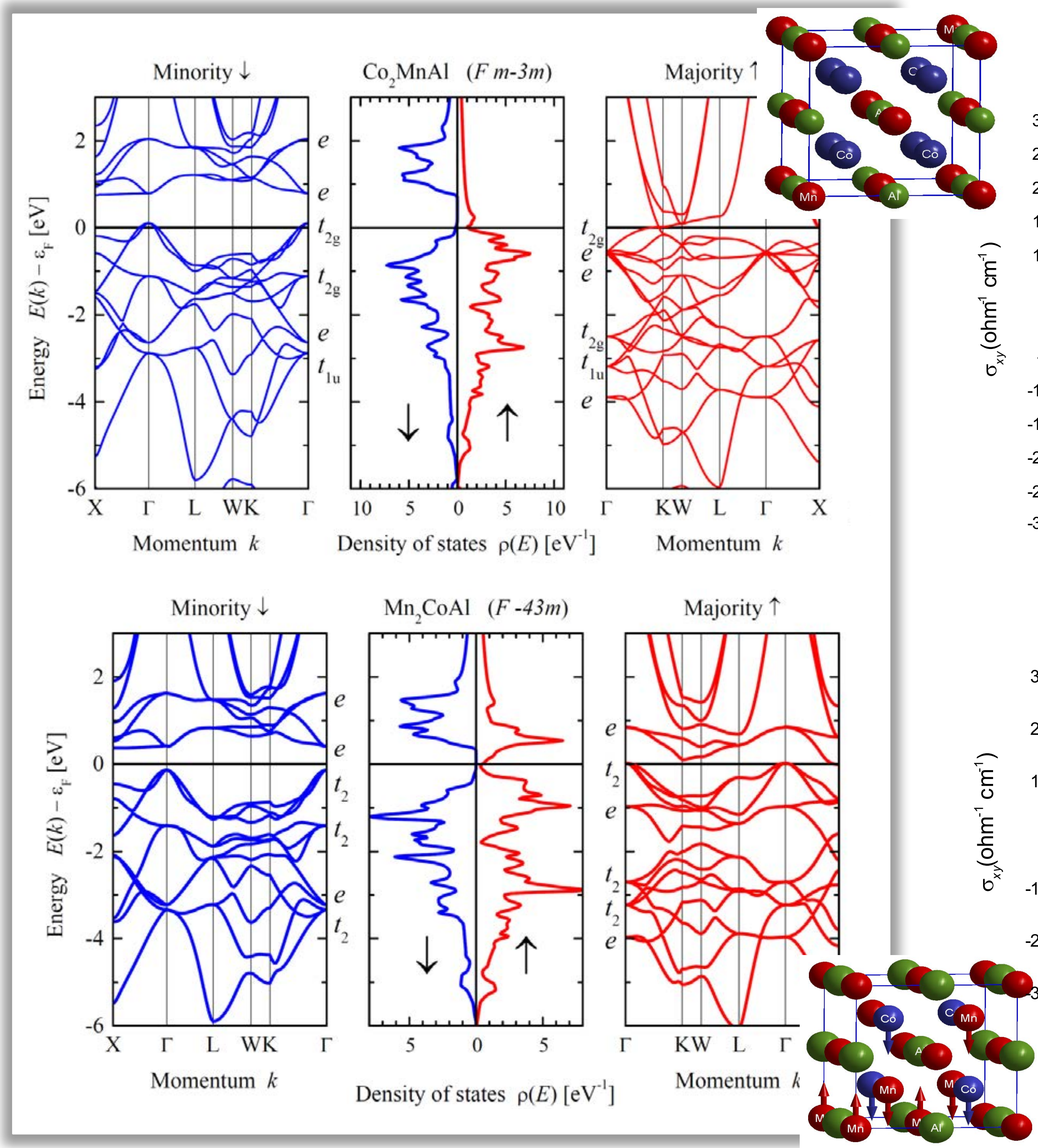


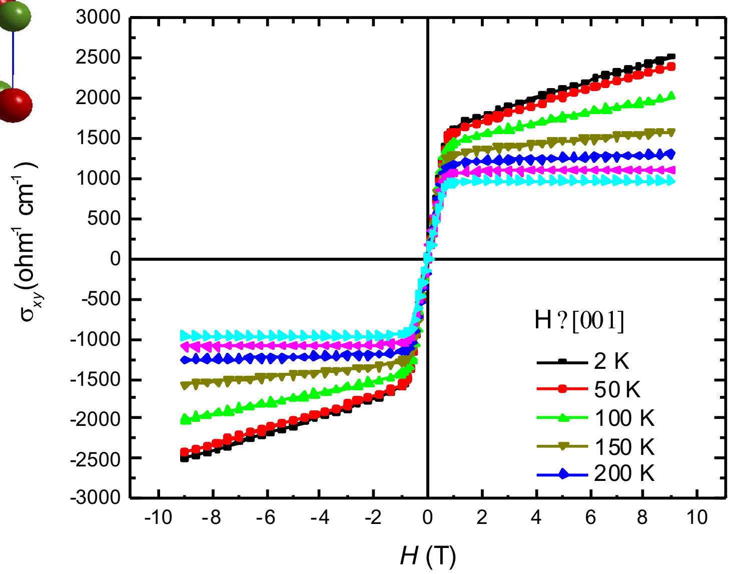


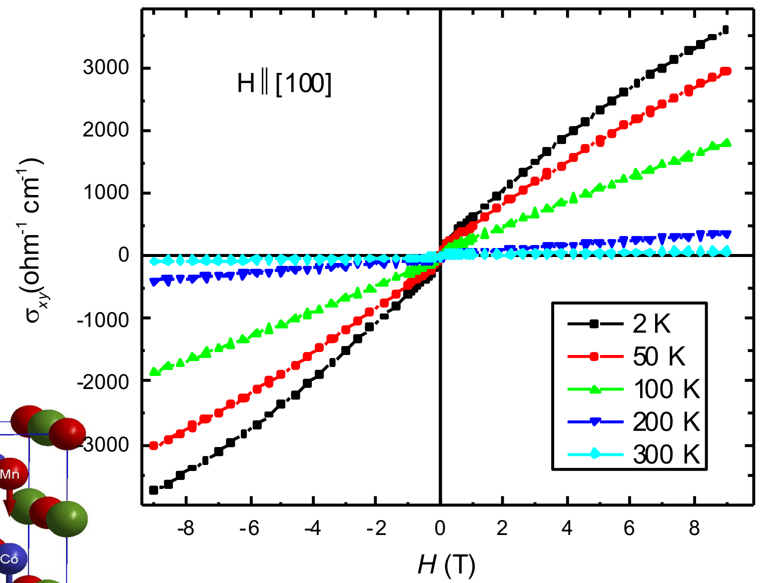




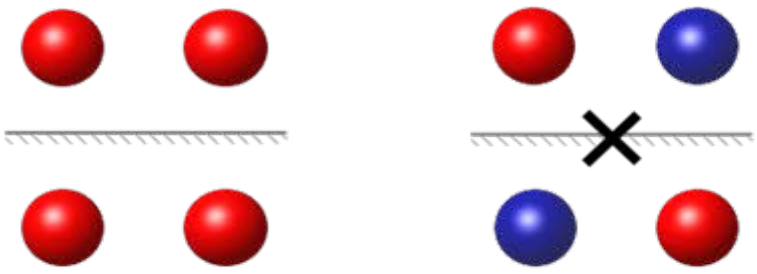
Weyl or Spingapless

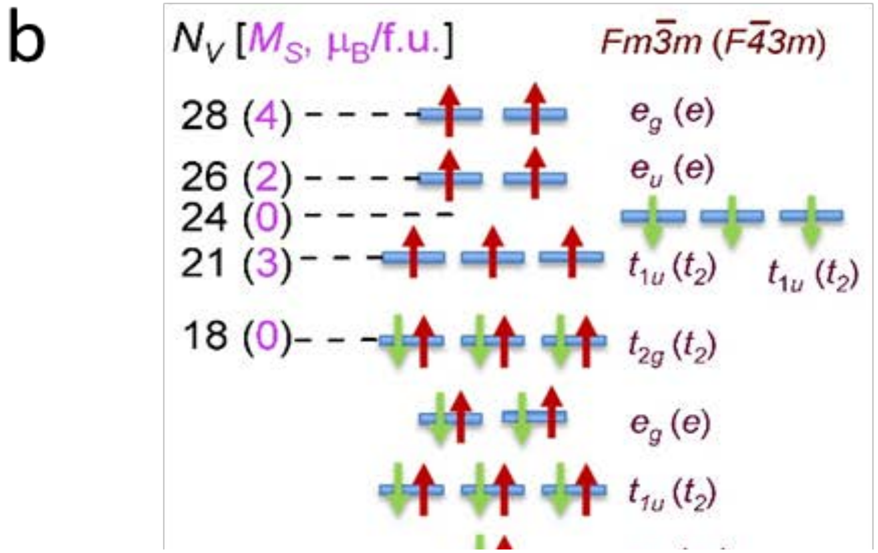


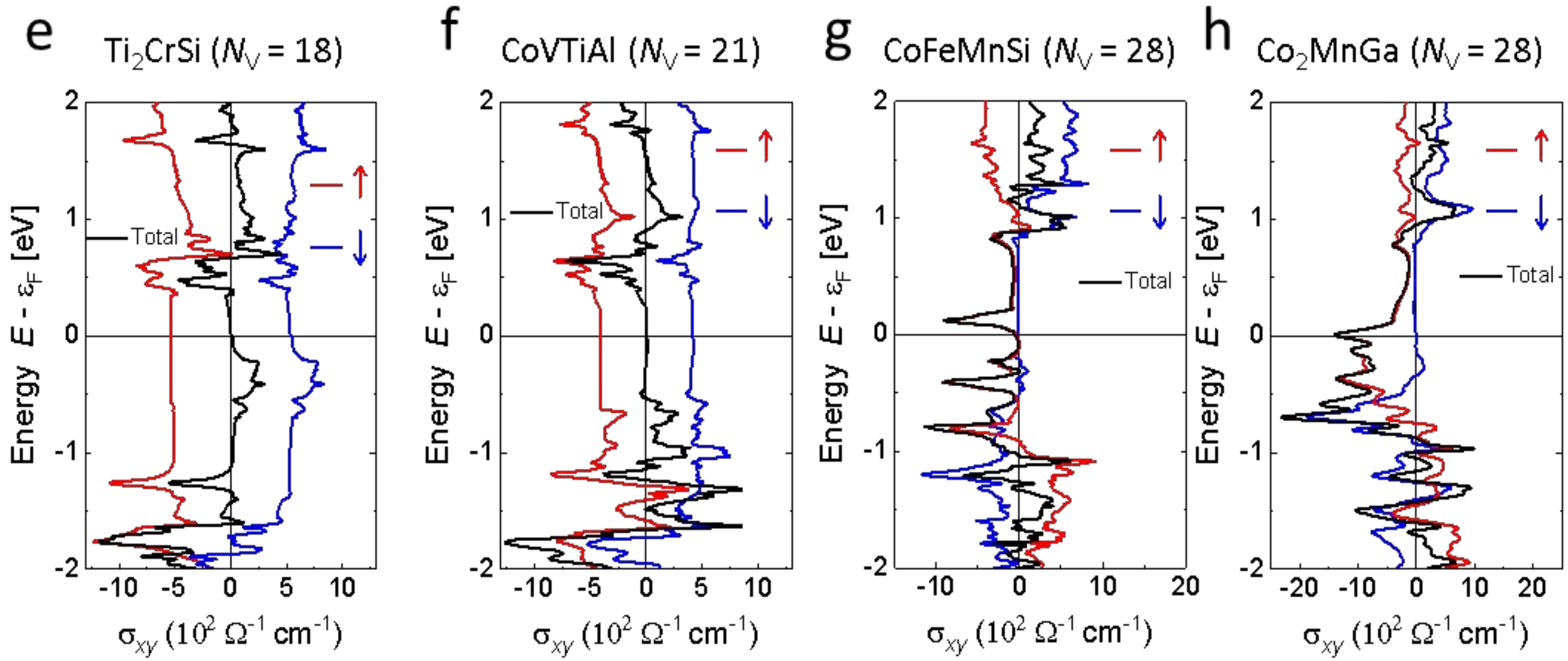




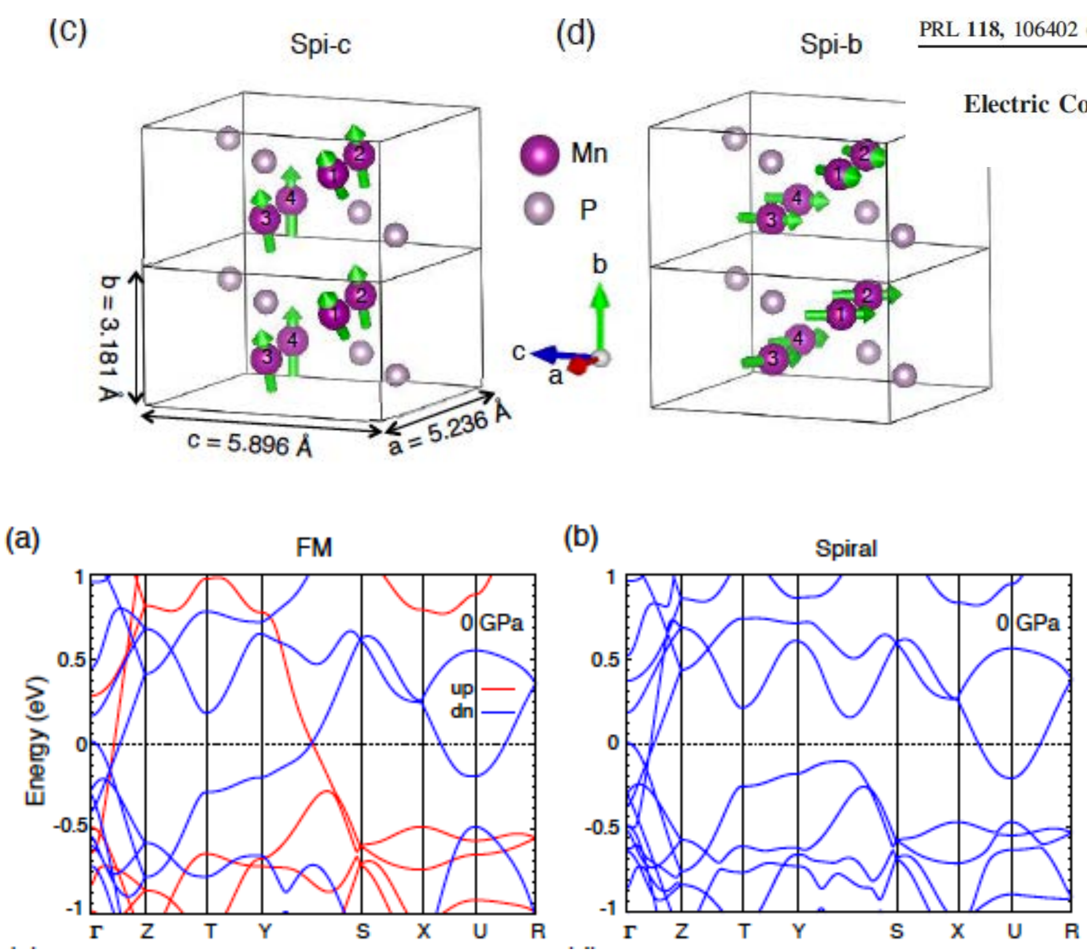
… more spin gapless







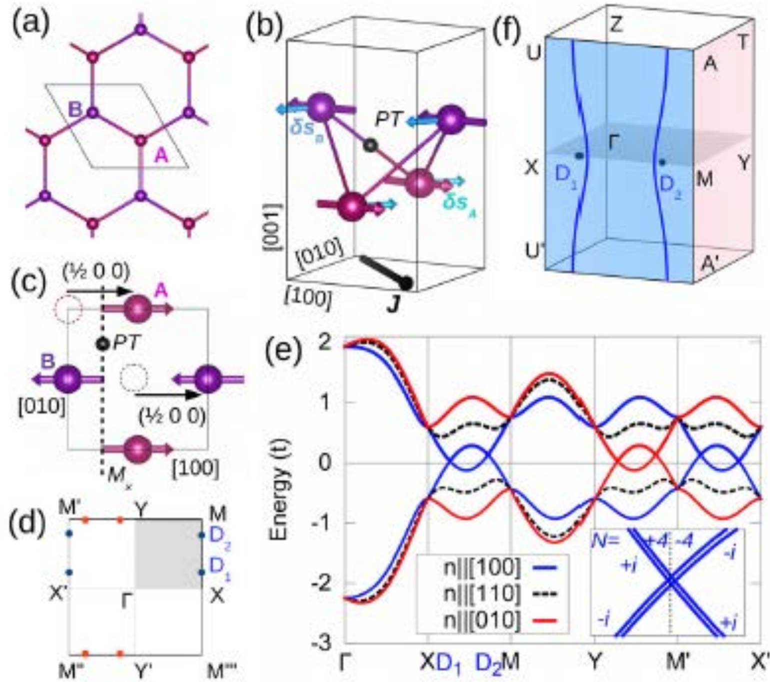
MnP and CuMnAs



PRL 118, 106402 (2017) PHYSICAL REVIEW LETTERS week ending 10 MARCH 2017

Electric Control of Dirac Quasiparticles by Spin-Orbit Torque in an Antiferromagnet

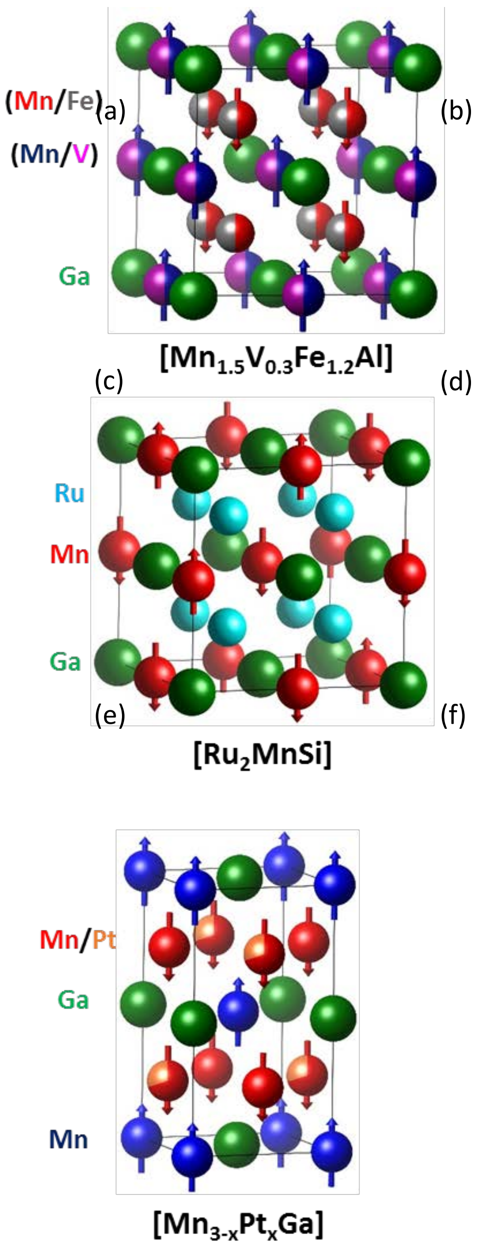
L. Šmejkal,[1,2,3] J. Železný,[4,1] J. Sinova,[2,1] and T. Jungwirth[1,5]

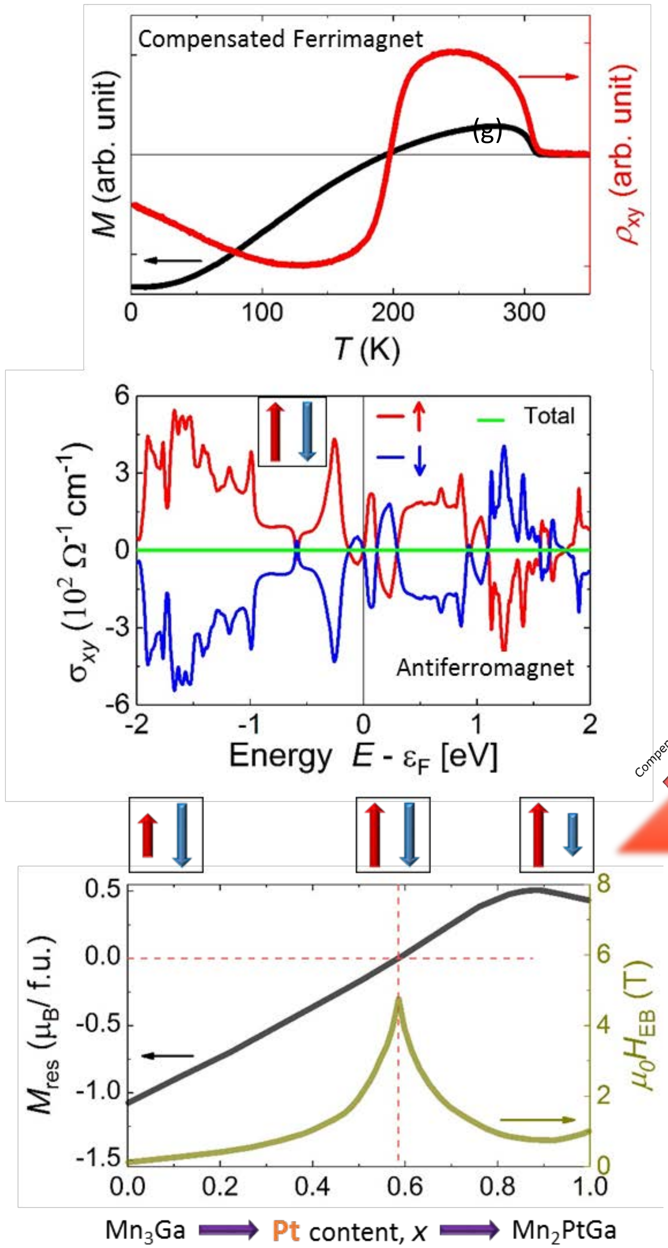


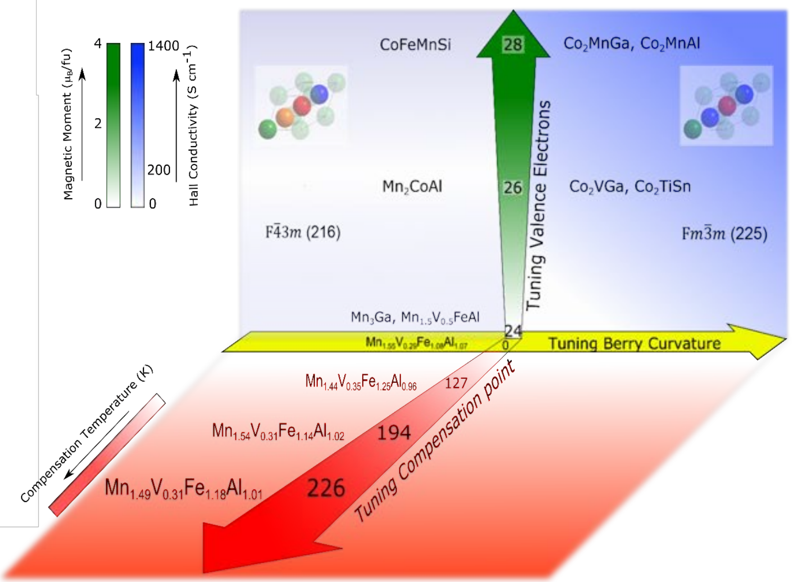
First-principles calculations of the magnetic and electronic structures of MnP under pressure

Yuanji Xu[1], Min Liu[1,2], Ping Zheng[1], Xiangrong Chen[2], Jin-guang Cheng[1], Jianlin Luo[1,3,4], Wenhui Xie[5] and Yi-feng Yang[1,3,4,*]

Artificial Antiferromagnets





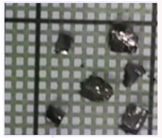


Topology – Chemistry

Chemistry

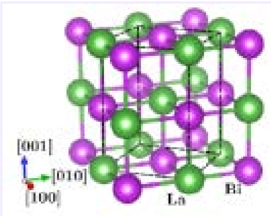
Real space - local

Crystals



LaBi

Crystal structure

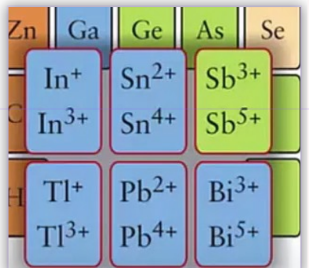


Position of the atoms

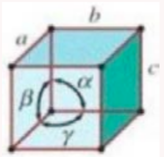
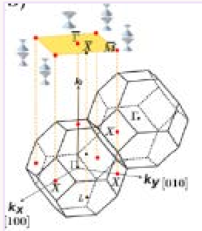
Orbitals

Check	WP	Representative
	8g	x,y,z
	4f	x,1/2,z
	4e	x,0,z
✓	4d	x,x,z
✓	2c	1/2,0,z
	1b	1/2,1/2,z
✓	1a	0,0,z

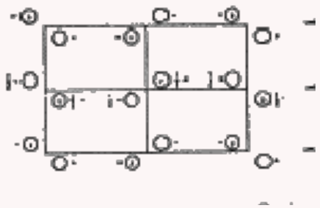
Inert pair effect



Symmetry

Local symmetry



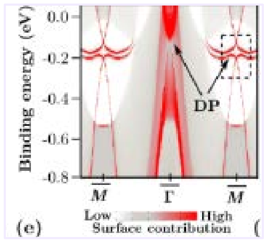
Relativistic effects

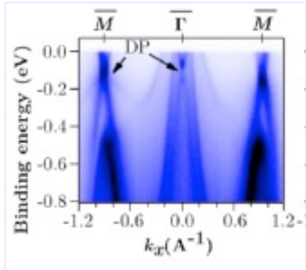
Physics

Recipro. space - delocalized

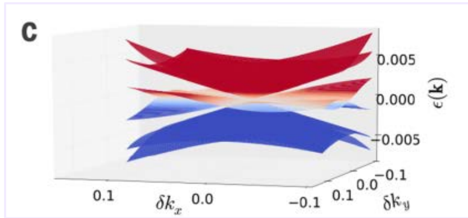
Brillouin zone

Electronic structure





Band connectivity



Darwin term

$$H_{\text{Darwin}} = \frac{\hbar^2}{8m_e^2c^2}(\Delta V)$$

B. Bradlyn, L. Elcoro, J. Cano, M. G. Vergniory, Z. Wang, C. Felser, M. I. Aroyo, B. Andrei Bernevig, Nature in press arXiv:1703.02050

Summary

The class of topological materials ranges from

- Topological insulators
- Dirac and Weyl semimetals
- New metallic Fermions

Non magnetic Weyl semimetals show Fermi arcs and a chiral anomaly

Electronic properties were studied extensively, while the thermal properties are still unexplored

Hydrodynamic flow of electrons might be more common in topological materials with high spin orbit coupling and can lead to new interesting applications

In magnetic Weyl semimetals the Berry curvature has impact on the classical properties and might lead to the identification of QAH with high Curie tempertature

Single Crystals available

BaCr2As2
BaCrFeAs2

CaPd3O4
SrPd3O4
BaBiO3

Bi2Te2Se
Bi2Te3
Bi2Se3
BiSbTe2S
BiTeI
BiTeBr
BiTeCl

LaBi, LaSb
GdBi, GdSb

HfSiS

Bi4I4

BaSn2

AlPt
GdAs
CoSi

MoP
WP

TaP
NbP
NbAs
TaAs
NbP-Mo
NbP-Cr
TaP-Mo
TaAsP

CrNb3S6
V3S4
Cd3As2

MnP
MnAs

MoSe2-xTex
MoTe2-xSex
MoTe2 (T´/2H)

PtTe2
PtSe2
PdTe2
PdSe2
OsTe2
RhTe2
TaTe2
NbTe2
WSe2
HfTe5
MoTe2
TaS2
PdSb2
CuxWTe2
FexWTe2
WTe2
Co0,4TaS2
Fe0,4TaS2

Ag2Se
IrO2
OsO2
ReO2
WP2
MoP2

VAl3
Mn3Ge
Mn3Ir
Mn3Rh
Mn3Pt
[illegible]

YPtBi
NdPtBi
GdPtBi
YbPtBi
ScPdBi
YPdBi
ErPdBi
GdAuPb
TmAuPb
AuSmPb
AuPrPb
AuNdPb
[illegible]
AuLuSn
AuYSn
ErAuSn
EuAuBi

CaAgAs

KMgSb
KMgBi
KHgSb
KHgBi
LiZnAs
LiZnSb

YbMnBi2
Ni2Mn1.4In0.6
YFe4Ge2

Mn1.4PtSn

CuMnSb
CuMnAs

Co2Ti0.5V0.5Sn
Co2VAl0.5Si0.5
Co2Ti0.5V0.5Si
Mn2CoGa
Co2MnGa
Co2Al9
Co2MnAl
Co2VGa0.5Si0.5
Co2TiSn
Co2VGa
Co2V0.8Mn0.2Ga
CoFeMnSi

Thank you!