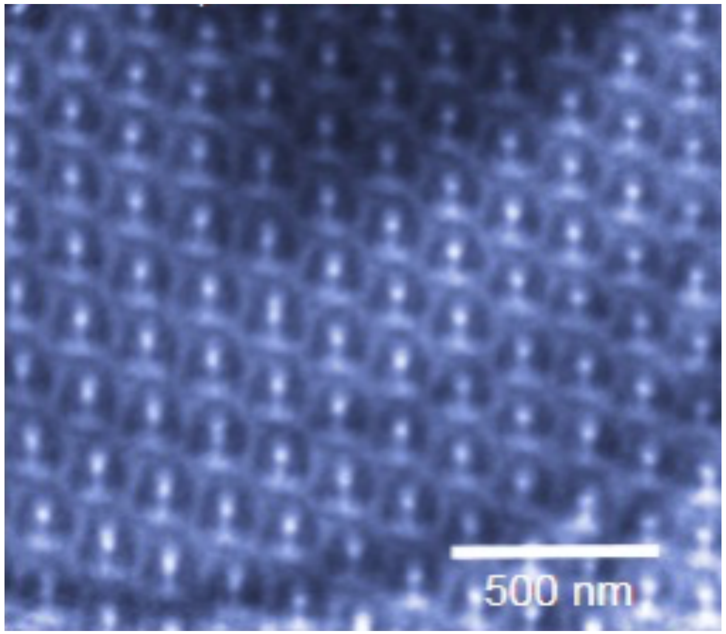
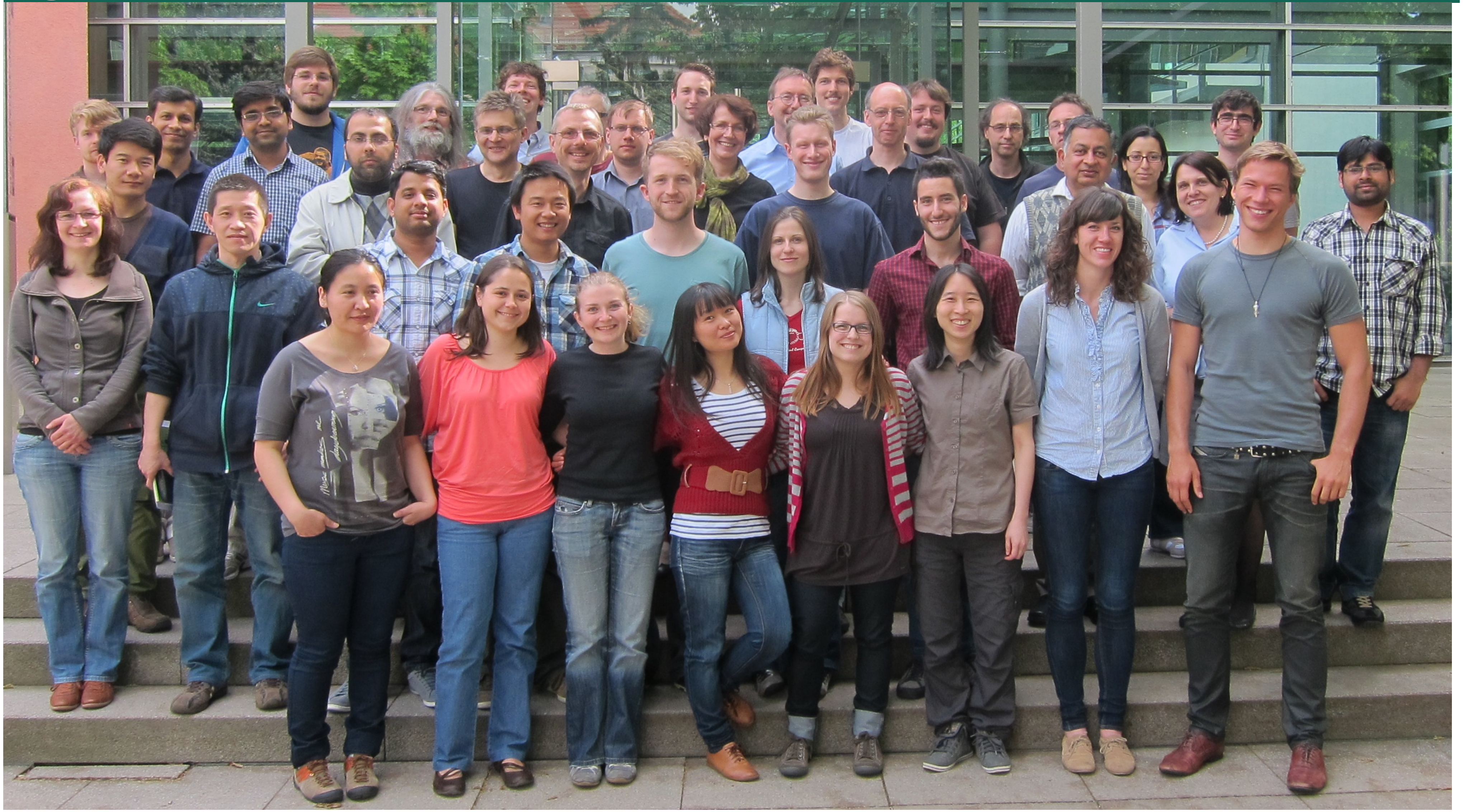
Topology, non-collinear spin structures and Skyrmions in Heusler compounds



Claudia Felser

Co-workers in Dresden and elsewhere

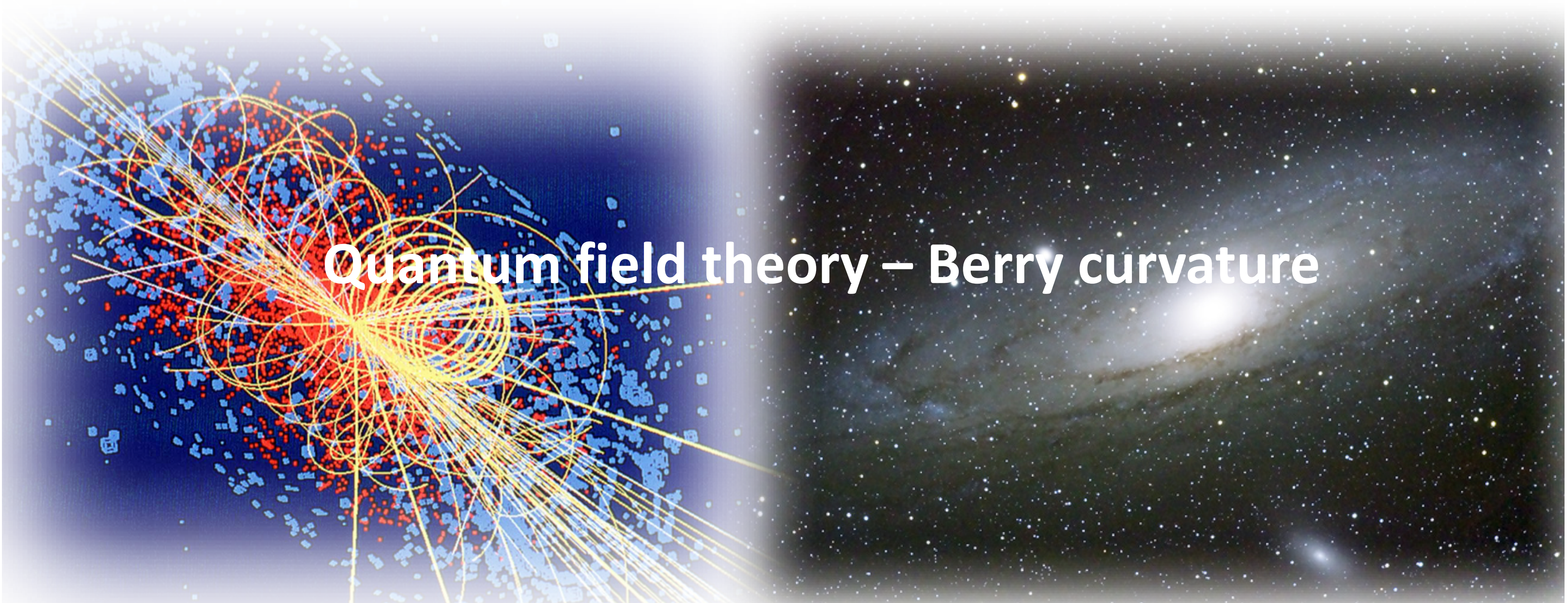


Andrei Bernevig, Princeton, CNR Rao, Bangalore, India
Uli Zeitler, et al. HFML - EMFL, Nijmegen; J. Wosnitza et al., HFML Rossendorf
Yulin Chen et al., Oxford; Günter Reiss, Bielfeld
S.C.Zhang et al. and A. Kapitulnik, Stanford
S. S. P. Parkin et al., IBM Almaden, MPI Halle

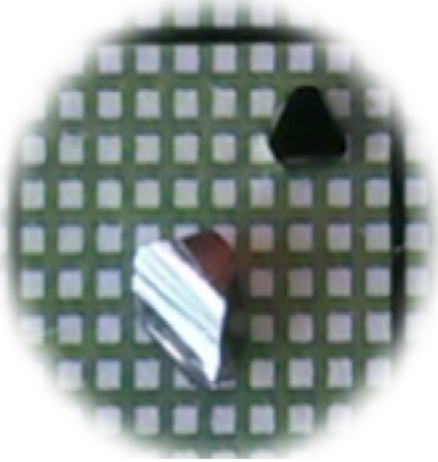
erc

Alexander von Humboldt
Stiftung/Foundation

Particles – Universe –Condensed matter

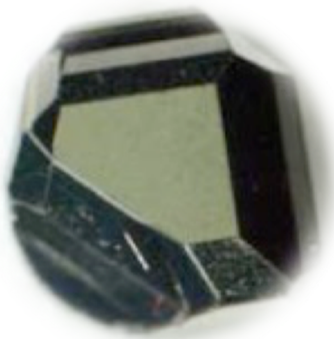


Dirac
Cd_3As_2
Guido Kreiner

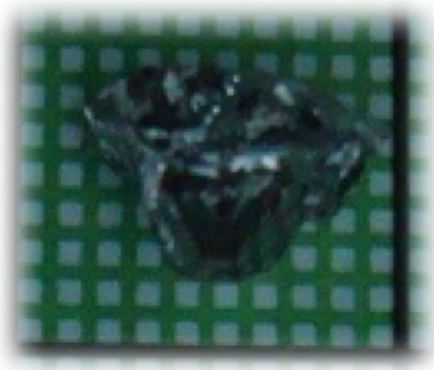


Higgs
$YMnO_3$
Lichtenberg Spaldin

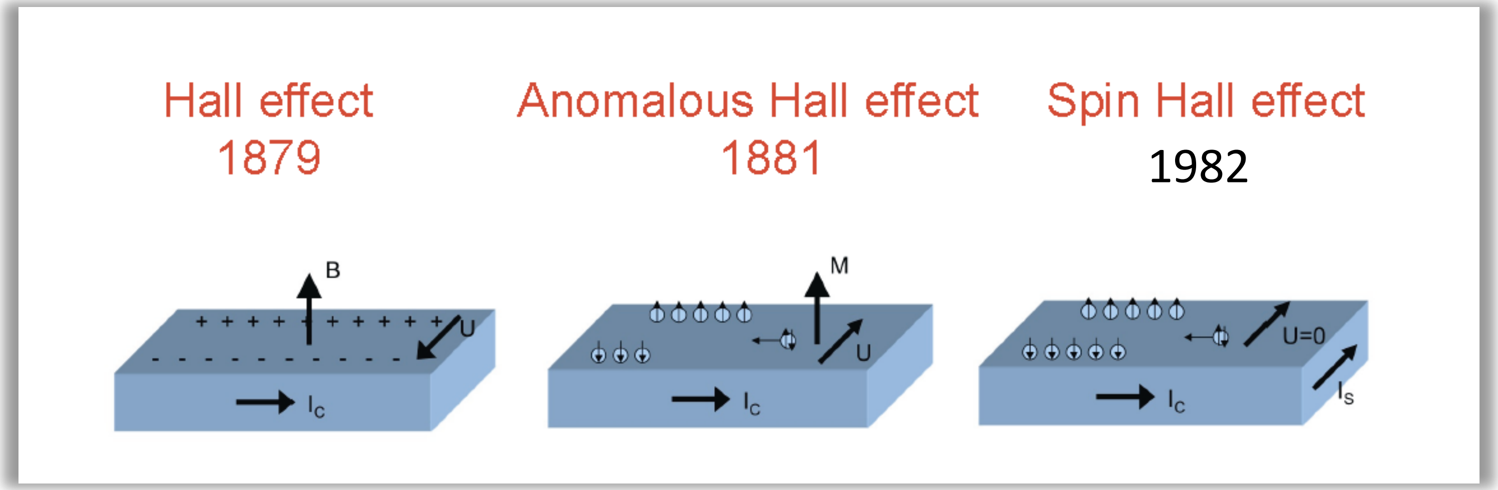
Weyl
TaAs
Vicky Süss, Marcus Schmidt

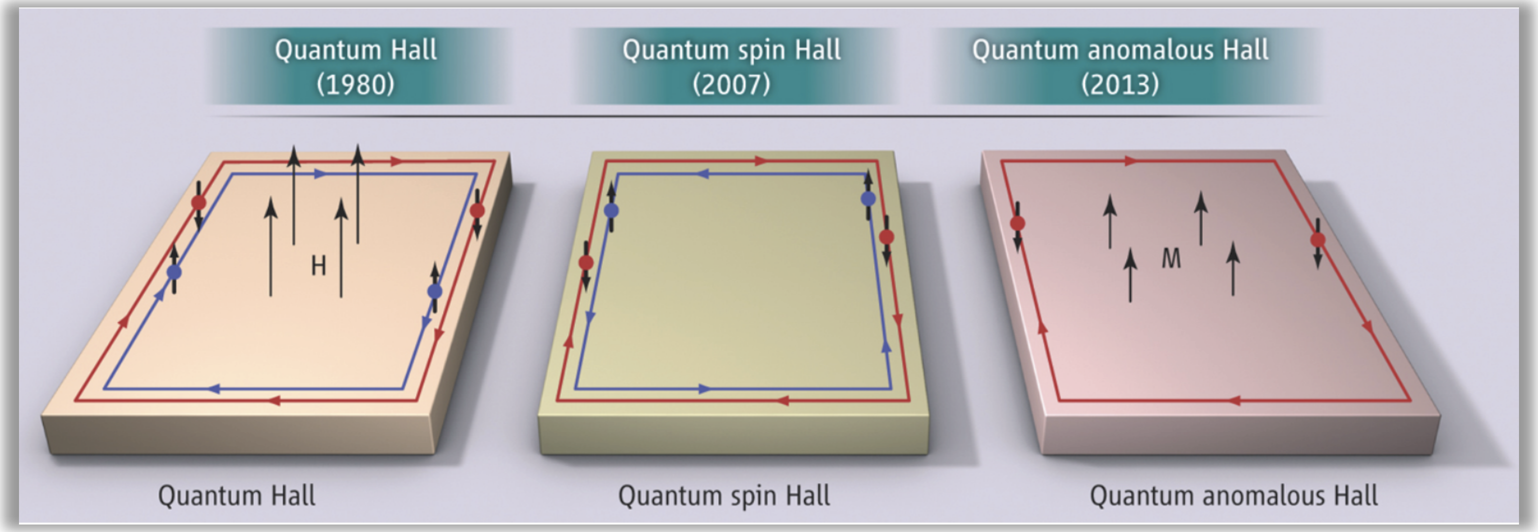


Majorana
YPtBi
Chandra Shekhar



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

Anomalous –Hall effect

REVIEWS OF MODERN PHYSICS, VOLUME 82, APRIL–JUNE 2010

Anomalous Hall effect

Naoto Nagaosa

Department of Applied Physics, University of Tokyo, Tokyo 113-8656, Japan and Cross-Correlated Materials Research Group (CMRG), and Correlated Electron Research Group (CERG), ASI, RIKEN, Wako, 351-0198 Saitama, Japan

Jairo Sinova

Department of Physics, Texas A&M University, College Station, Texas 77843-4242, USA and Institute of Physics ASCR, Cukrovarnická 10, 162 53 Praha 6, Czech Republic

Shigeki Onoda

Condensed Matter Theory Laboratory, ASI, RIKEN, Wako, 351-0198 Saitama, Japan

A. H. MacDonald

Department of Physics, University of Texas at Austin, Austin, Texas 78712-1081, USA

N. P. Ong

Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

(Published 13 May 2010)

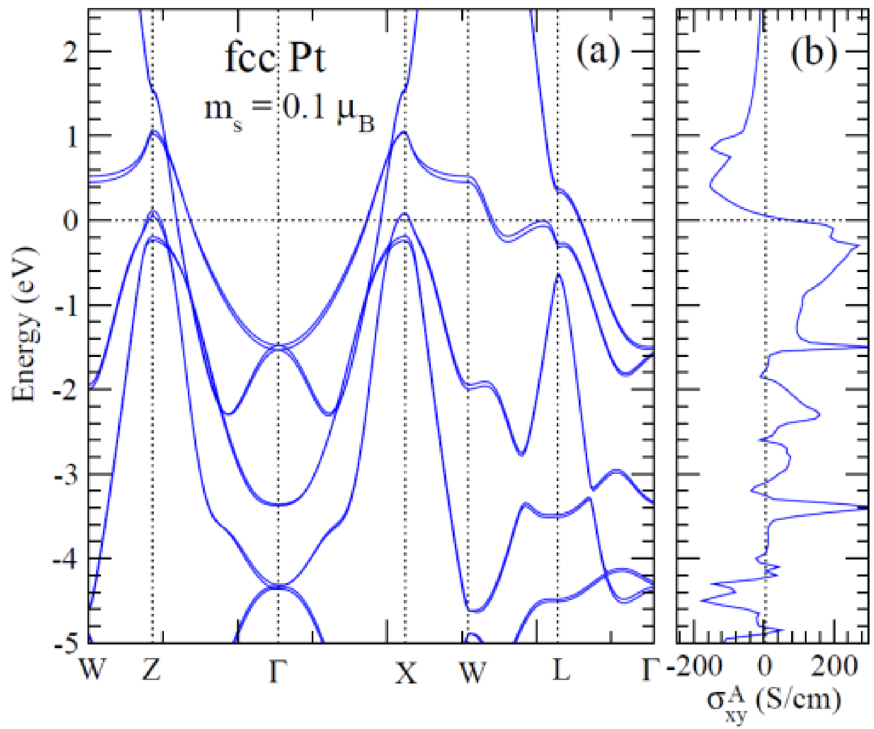
The anomalous Hall effect (AHE) occurs in solids with broken time-reversal symmetry, typically i ferromagnetic phase, as a consequence of spin-orbit coupling. Experimental and theoretical studie the AHE are reviewed, focusing on recent developments that have provided a more compl framework for understanding this subtle phenomenon and have, in many instances, repla controversy by clarity. Synergy between experimental and theoretical works, both playing a cru role, has been at the heart of these advances. On the theoretical front, the adoption of the Berry-ph concepts has established a link between the AHE and the topological nature of the Hall currents. the experimental front, new experimental studies of the AHE in transition metals, transition-m oxides, spinels, pyrochlores, and metallic dilute magnetic semiconductors have established system trends. These two developments, in concert with first-principles electronic structure calculatic strongly favor the dominance of an intrinsic Berry-phase-related AHE mechanism in meta ferromagnets with moderate conductivity. The intrinsic AHE can be expressed in terms of Berry-phase curvatures and it is therefore an intrinsic quantum-mechanical property of a perf crystal. An extrinsic mechanism, skew scattering from disorder, tends to dominate the AHE in hig conductive ferromagnets. The full modern semiclassical treatment of the AHE is reviewed wh incorporates an anomalous contribution to wave-packet group velocity due to momentum-space Be curvatures and correctly combines the roles of intrinsic and extrinsic (skew-scattering and side-jur scattering-related mechanisms. In addition, more rigorous quantum-mechanical treatments based

Intrinisic Hall

- Berry curvature
- Magnetisation?

Extrinsic Hall

- Skew scattering
- Side jumps

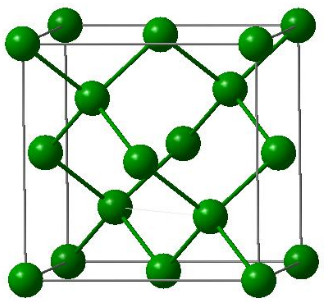


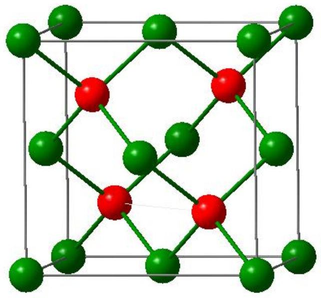
Anomalous Nernst and Hall effects in magnetized platinum and palladium

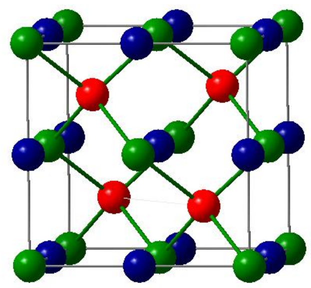
G. Y. Guo,[1,2,*] Q. Niu,[3,4] and N. Nagaosa[5,6]

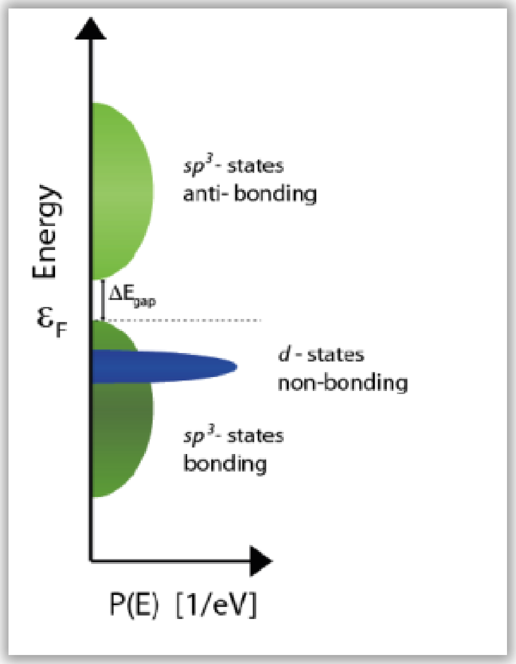
Heusler compounds

Diamond | **ZnS** | **Heusler XYZ $C1_b$**









Cd **Se**

$2 + 6 = 8$

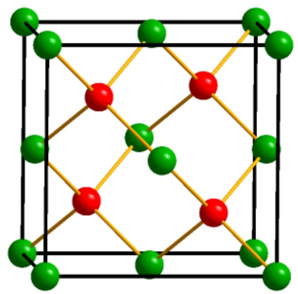
Li **Zn** **As**

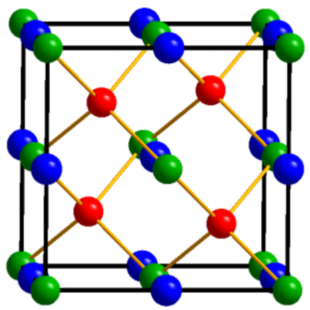
$1 + 2 + 5 = 8$

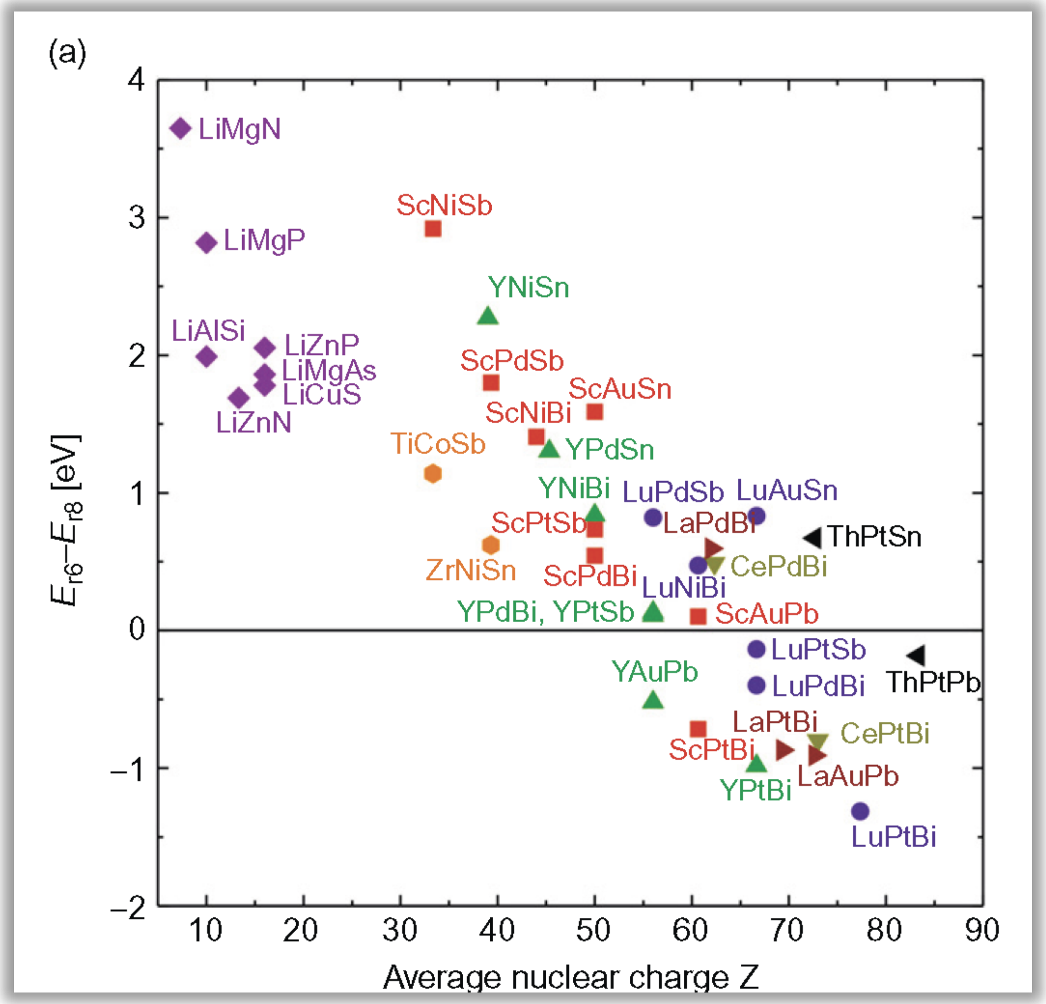
RE **Pt** **Bi**

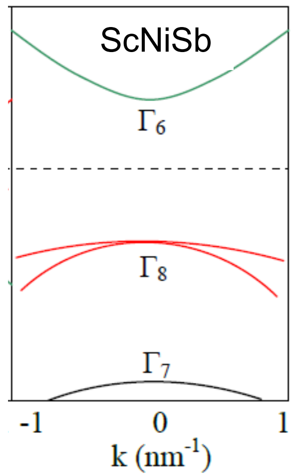
$3 + 10 + 5 = 18$

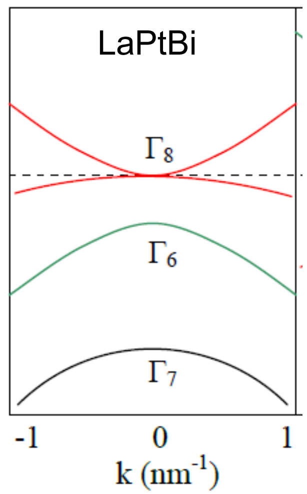
Predicting new compounds











S. Chadov et al., Nat. Mater. 9, 541 (2010).
H. Lin et al., Nat. Mater. 9, 546 (2010).

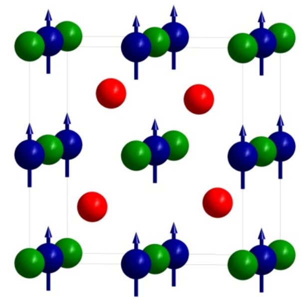
REPtBi …multifunctional topologic insulators

Magnetism and heavy fermion-like behavior in the RBiPt series

P. C. Canfield, J. D. Thompson, W. P. Beyermann, A. Lacerda, M. F. Hundley,
E. Peterson, and Z. Fisk
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

H. R. Ott
ETH, Zurich, Switzerland

J. Appl. Phys. **70** (10), 15 November 1991

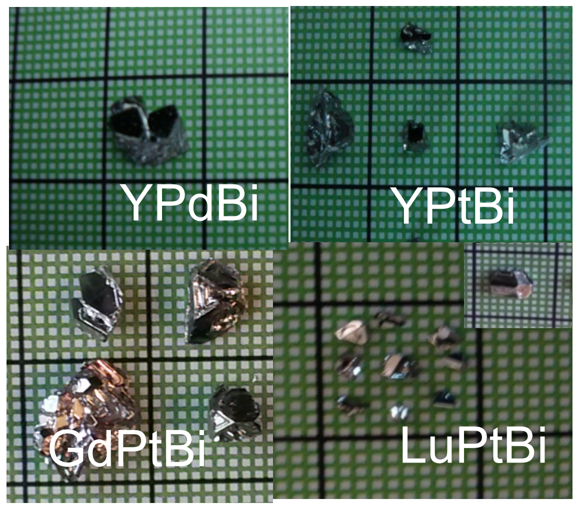


Multifunctional properties

- RE: Y, La, Lu, Er, … superconductivity
  RE: Gd, Tb, Sm Magnetism and TI
    - Antiferromagnetism with GdPtBi
- RE: Ce
    - complex behaviour of the Fermi surface
- RE: Yb Kondo insulator and TI
    - YbPtBi is a super heavy fermion with the highest γ value

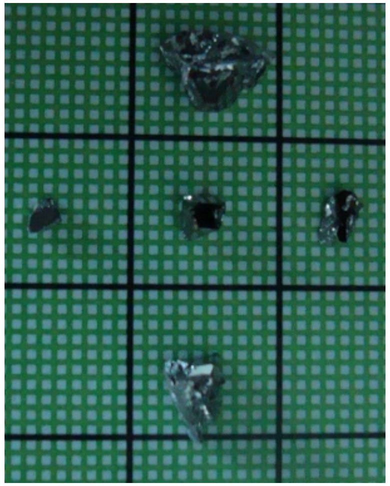
Pt — RE — Bi

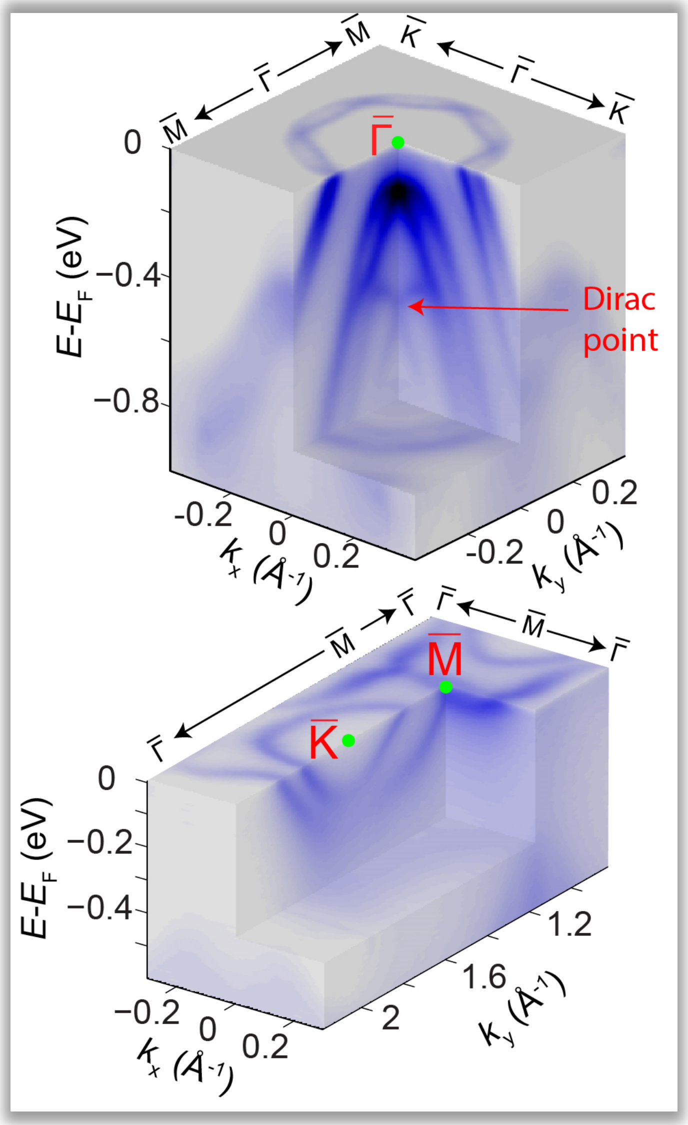
$10 + 3\ (+f^n) + 5 = 18$

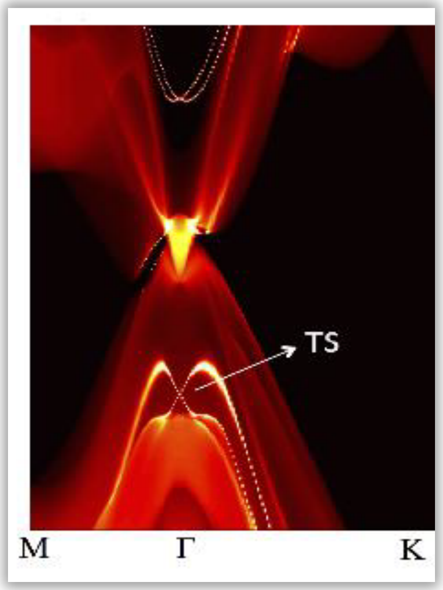


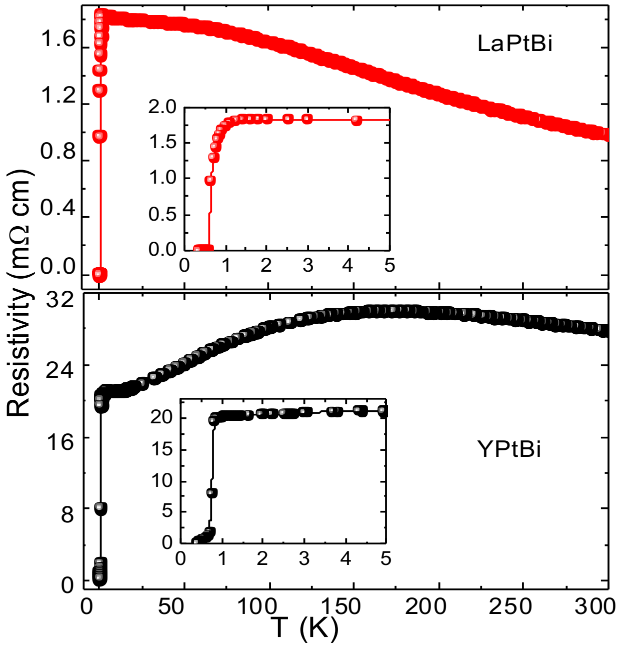
S. Chadov et al., Nat. Mater. 9, 541 (2010).
H. Lin et al., Nat. Mater. 9, 546 (2010).

ARPES of LnPtBi



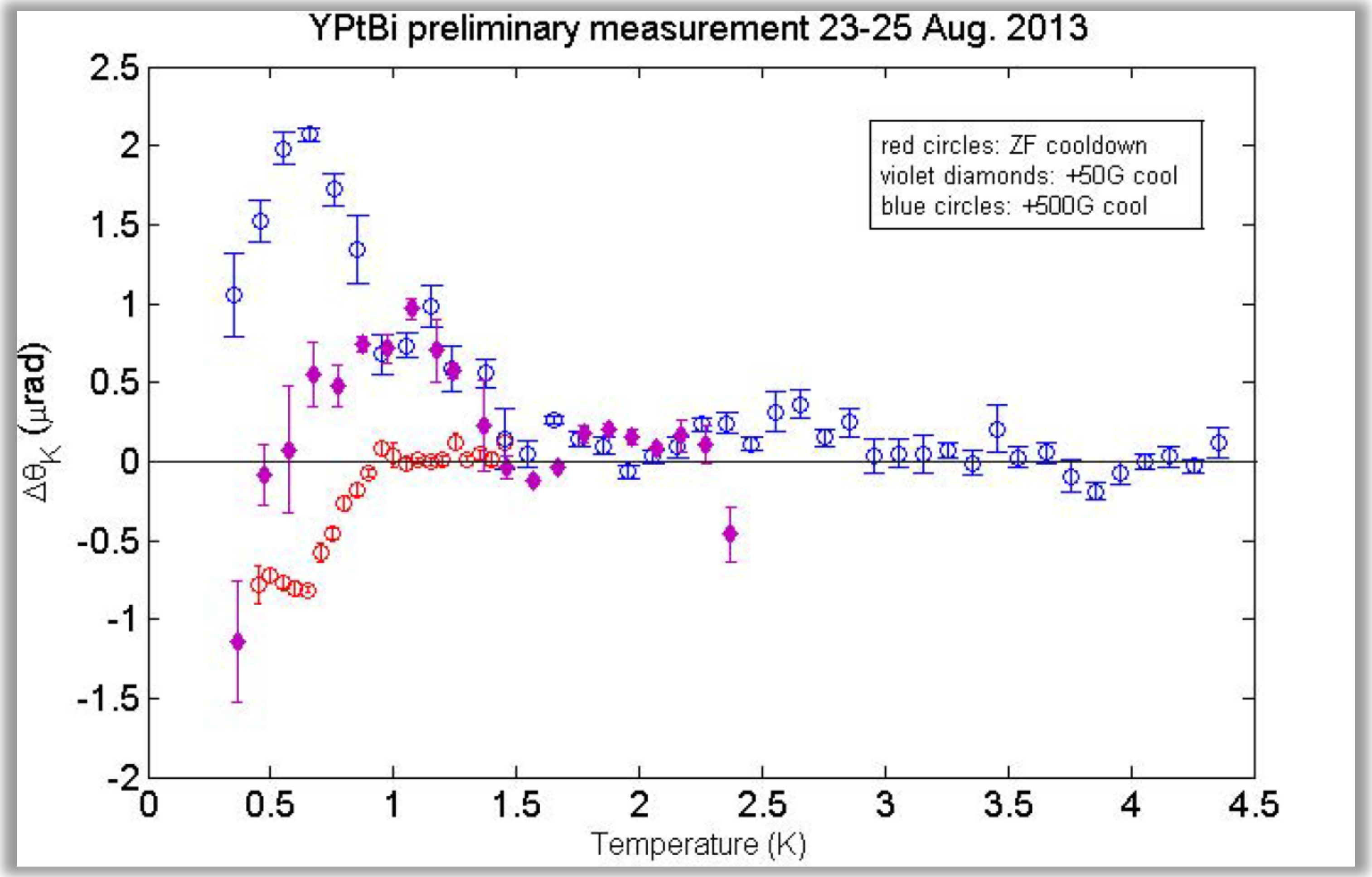






Z. K. Liu et al. Nature Com. 7 (2016) 12924
Shekhar et al. Phys. Rev. B 86 (2012) 155314

Kerr effect and unconventional SC

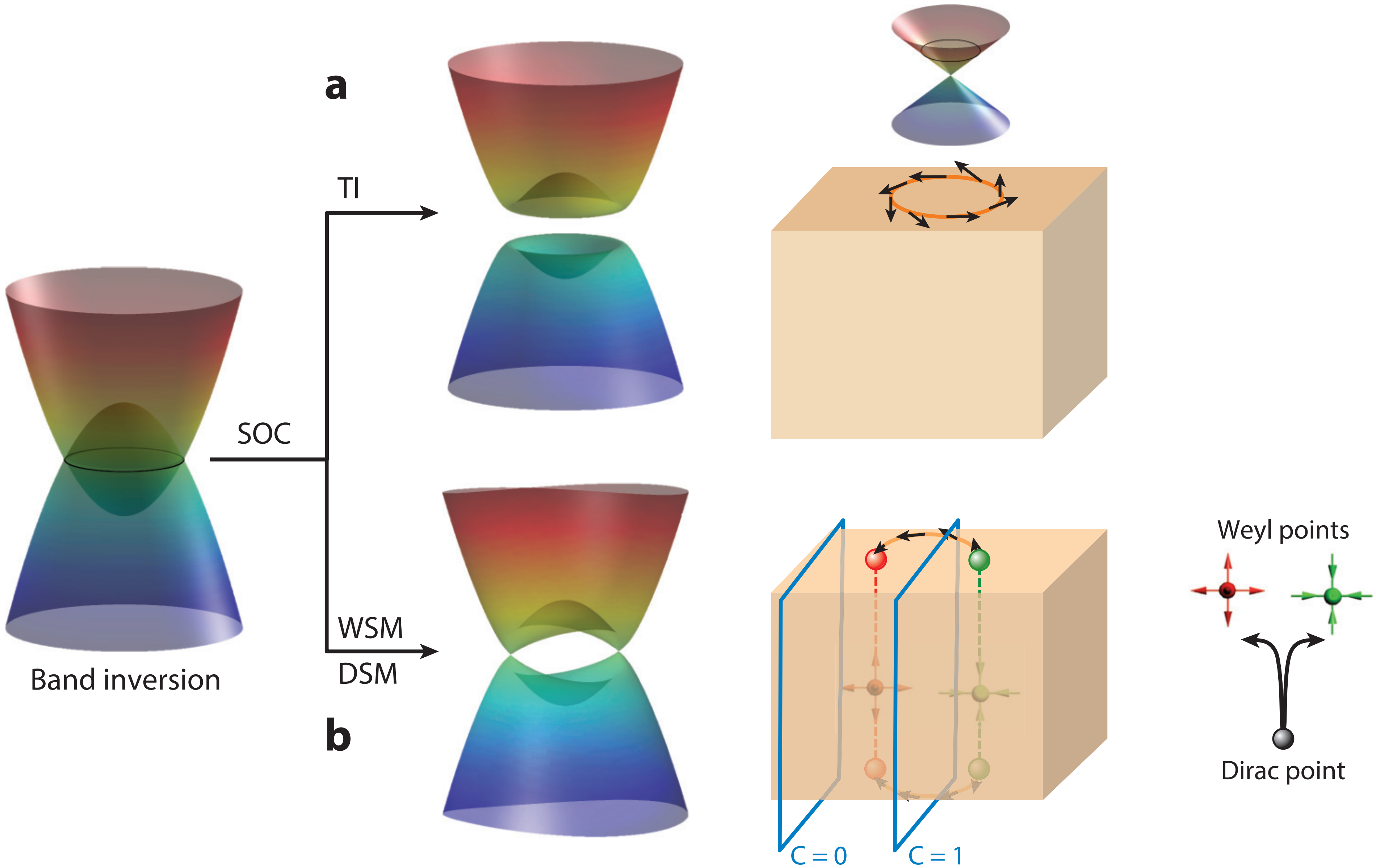


Kapitulnik, Shekhar, … Felser et al. unpublished

Weyl Semimetals

Breaking symmtery - TaAs

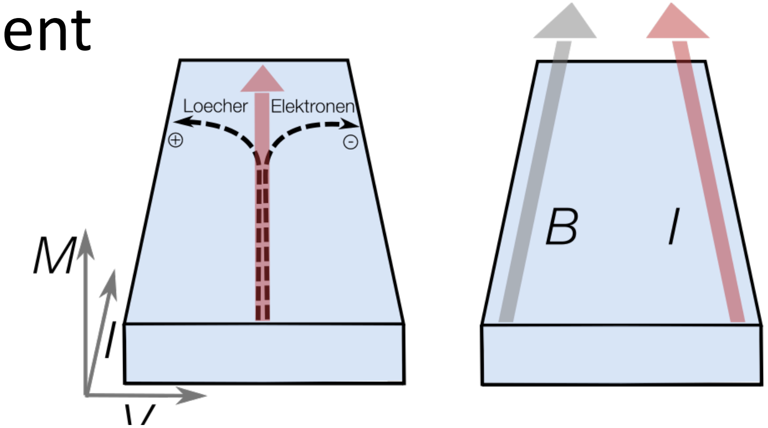
Weyl semimetals



Weyl semimetals

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

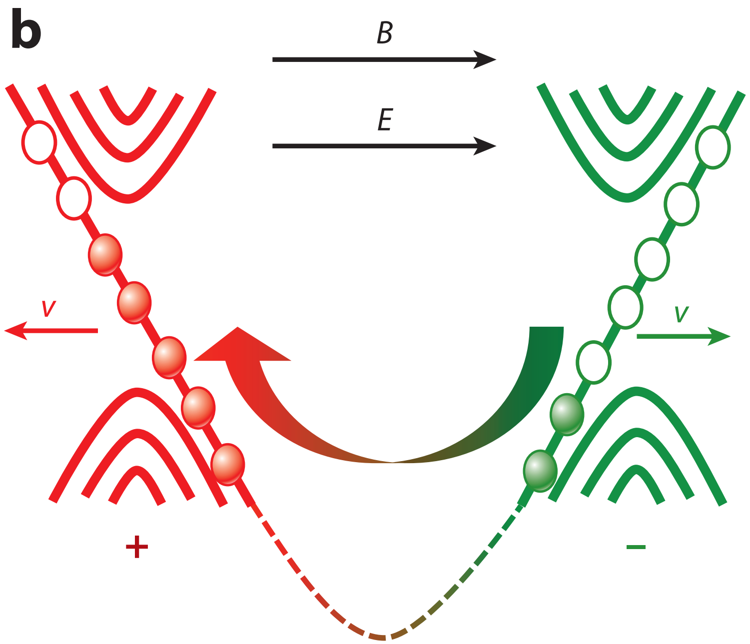
1. **Intrinsic anomalous Hall effect**



2. Chiral anomaly

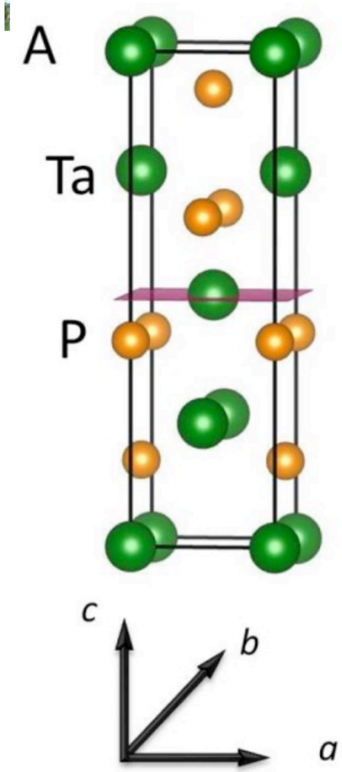
$$\partial_\mu j^\mu_\chi = \boxed{-}\chi \frac{e^3}{4\pi^2\hbar^2}\boldsymbol{E}\cdot\boldsymbol{B}$$

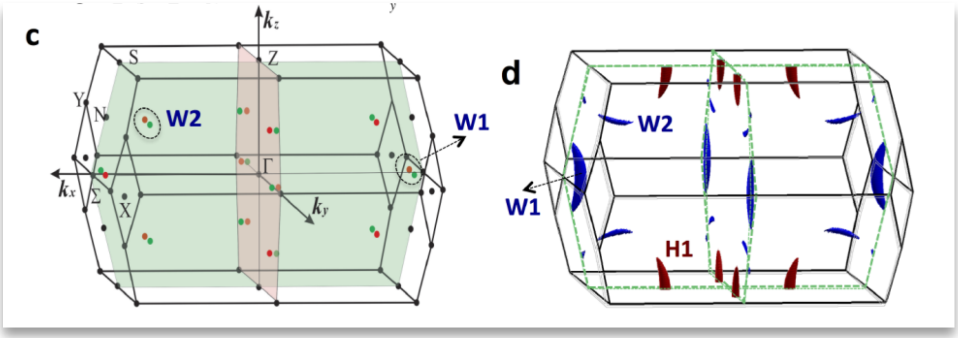
$$\sigma_a = \frac{e^3 v_f^3}{4\pi^2\hbar\mu^2 c}\boxed{B^2},$$

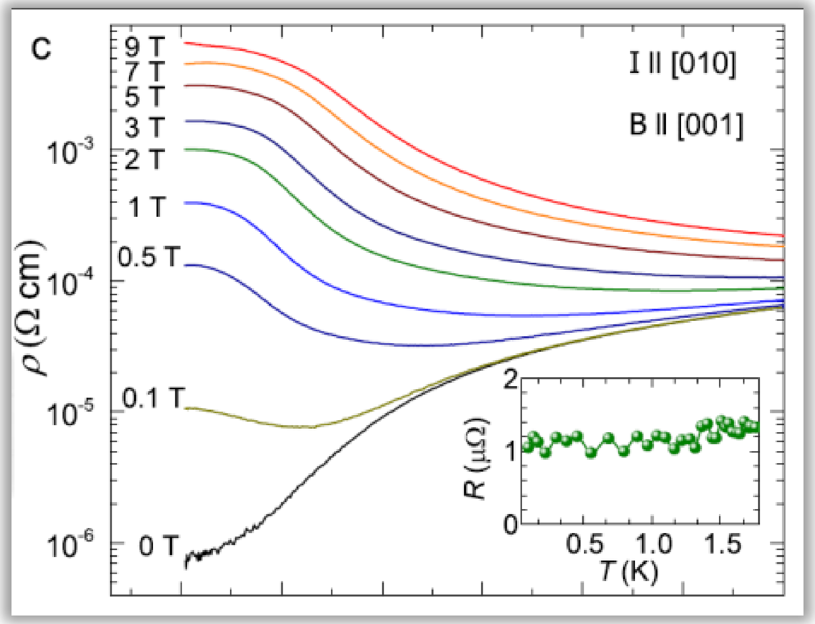


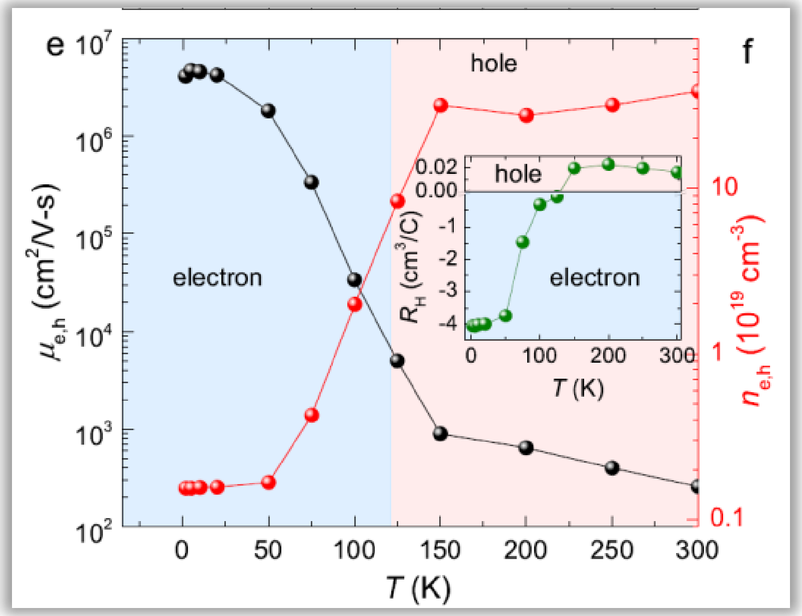
S. L. Adler, Phys. Rev. 177, 2426 (1969)
J. S. Bell and R. Jackiw, Nuovo Cim. A60, 47 (1969)
AA Zyuzin, AA Burkov - Physical Review B (2012)
AA Burkov, L Balents, PRL 107 12720 (2012)

Weyl semimetals in non-centro NbP









NbP is a topological Weyl semimetal

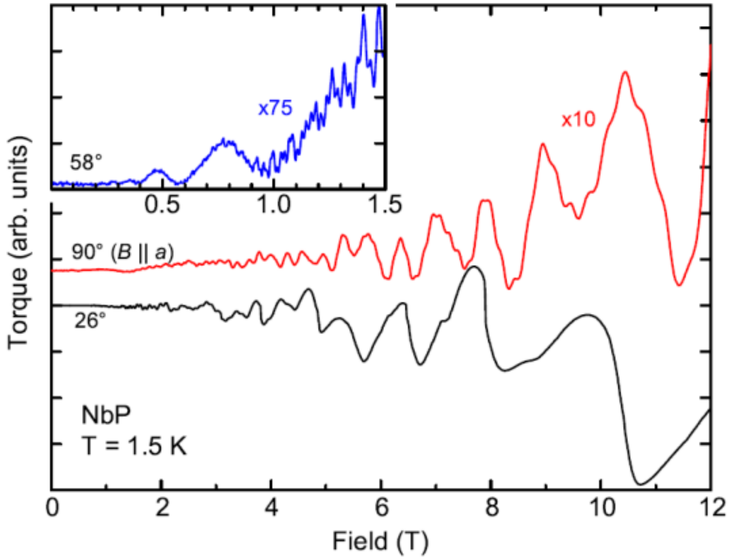
- with massless relativistic electrons
- extremely large magnetoresistance of **850,000%** at 1.85 K, 9T (250% at room temperature)
- an ultrahigh carrier mobility of **$5*10^6$ cm^2 / V s**

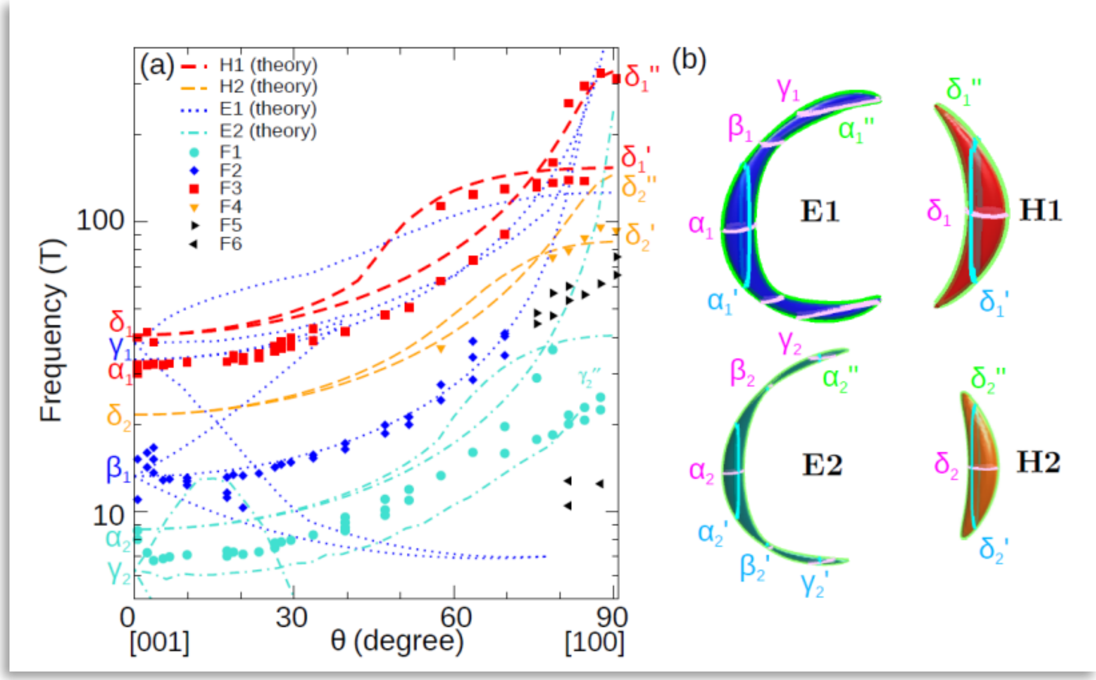
NbP, NbAs, TaP, TaAs

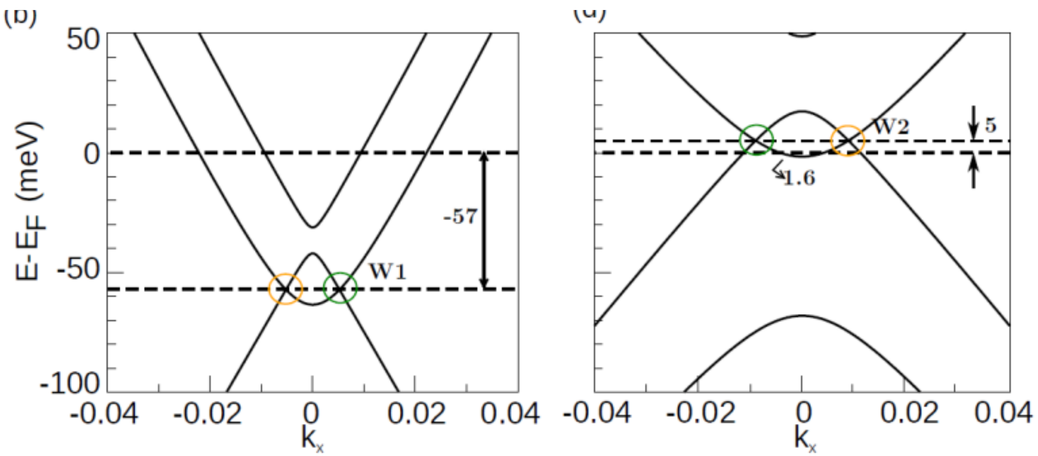
Shekhar, et al. , Nature Physics 11 (2015) 645,
Frank Arnold, et al. Nature Communication 7 (2016) 11615

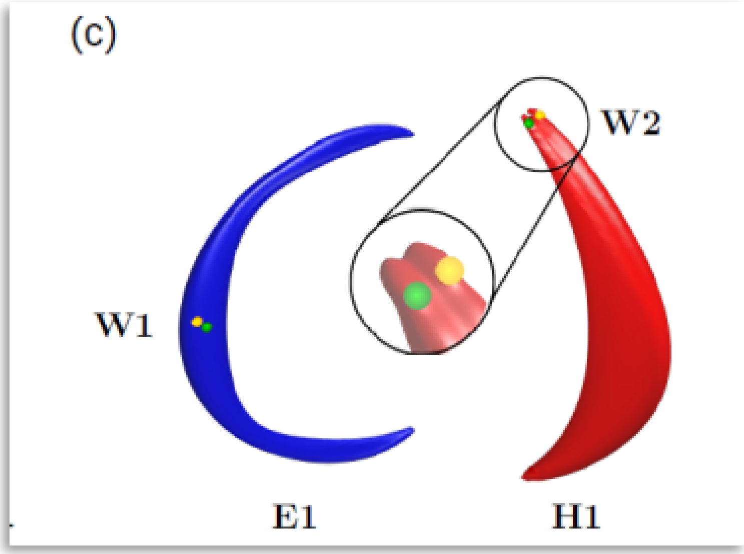
Weng, et al. Phys. Rev. X 5, 11029 (2015)
Huang . et al. preprint arXiv:1501.00755

NbP and the Fermi surface



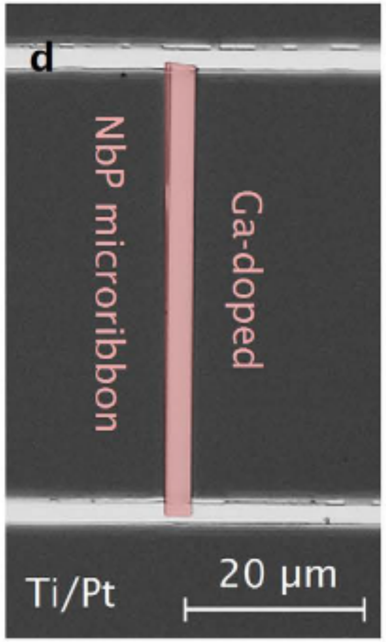


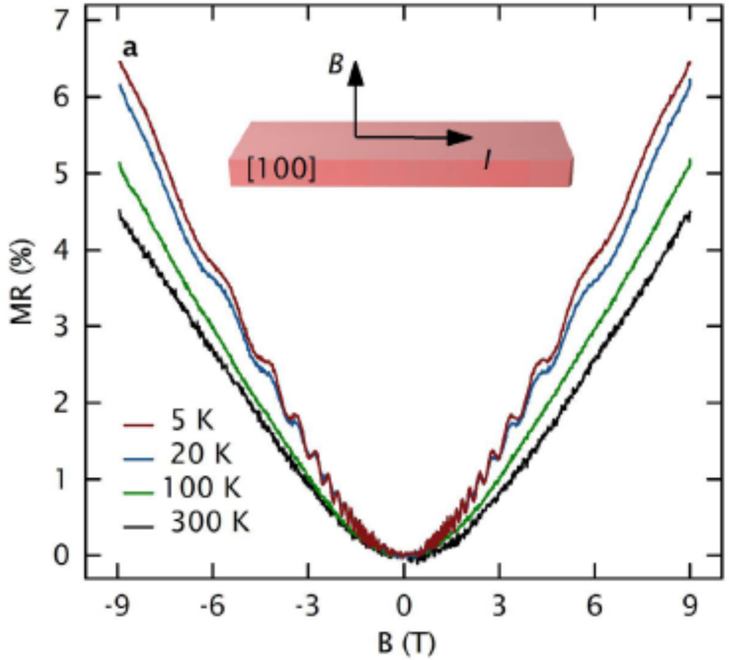


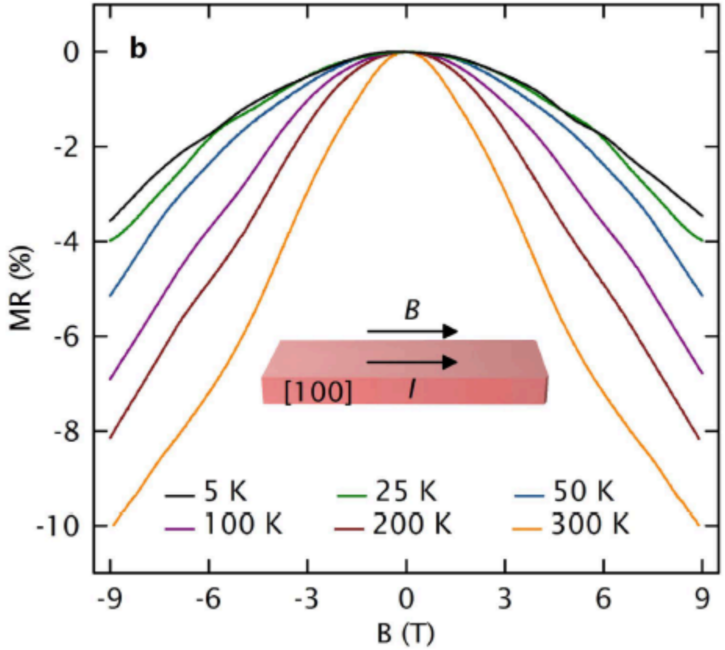


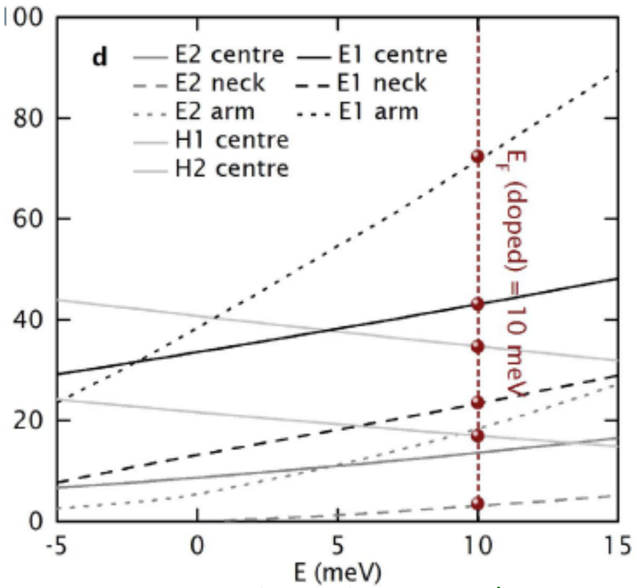
Klotz et al. Phys. Rev. Lett. 2016

Chiral Anomaly





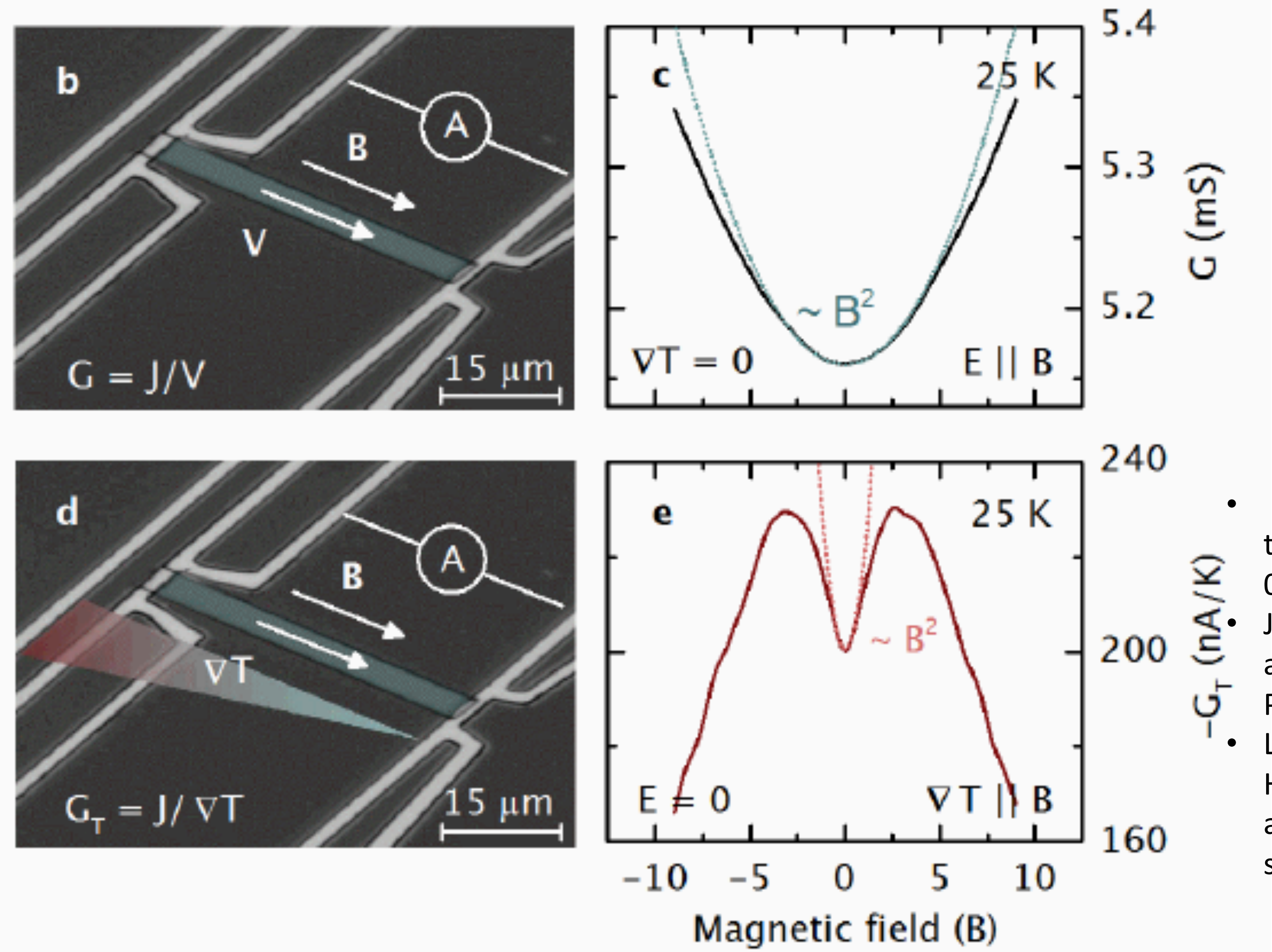




Ga-doping relocate the Fermi energy in NbP close to the W2 Weyl points
Therefore we observe a negative MR as a signature of the chiral anomaly the, NMR survives up to room temperature

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

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).

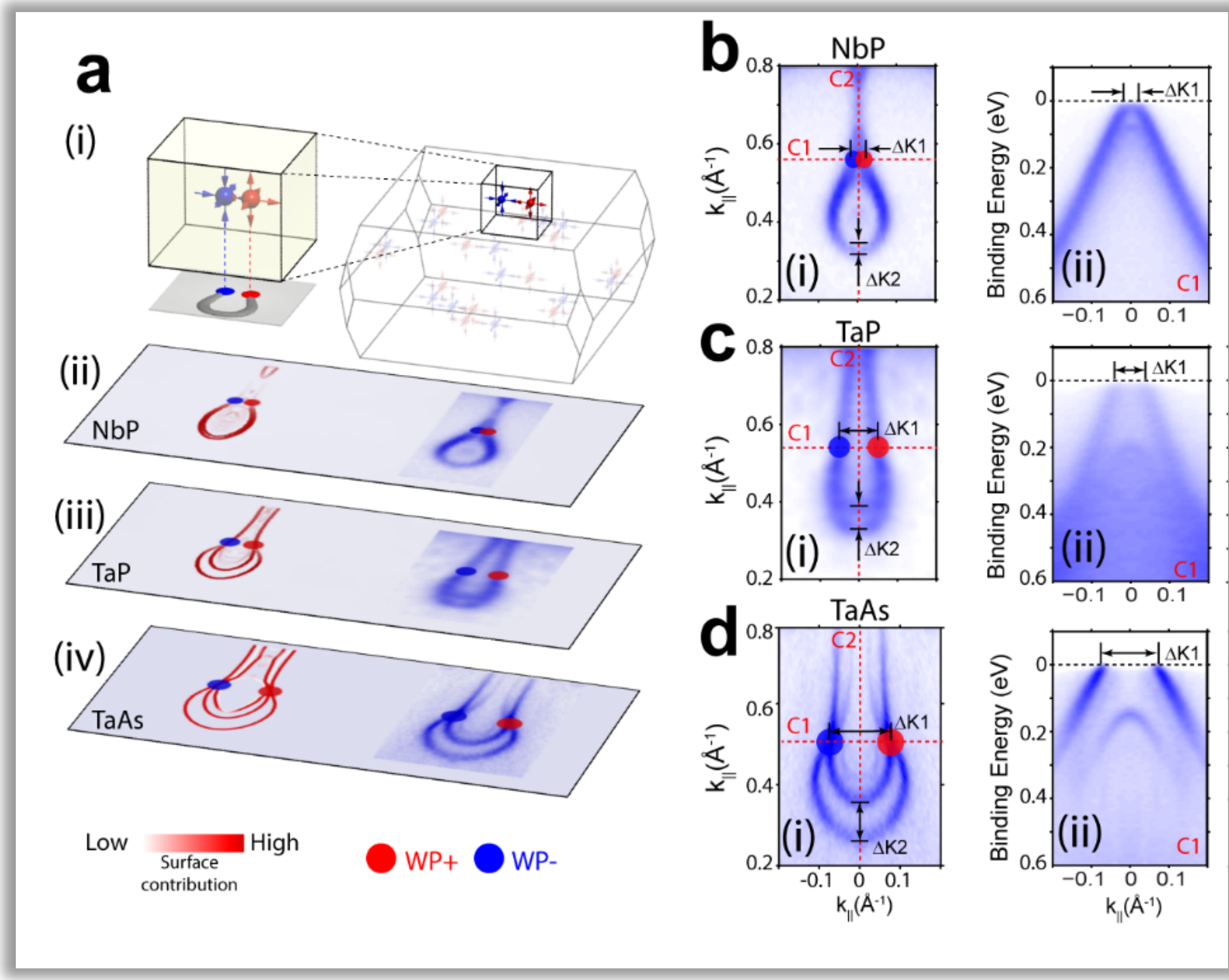
A positive longitudinal magnetothermoelectric conductance (PMTC) in the Weyl semimetal NbP for collinear temperature gradients and magnetic fields that vanishes in the ultra quantum limit.

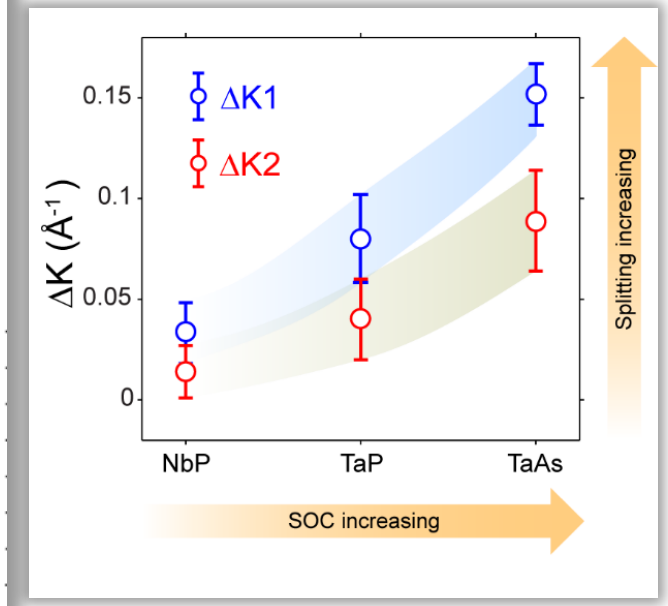
Johannes Gooth et al. Experimental signatures of the gravitational anomaly in the Weyl semimetal NbP, preprint arXiv:1703.10682

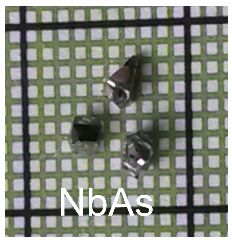
NbP, TaP, TaAs

Increasing spin orbit coupling increases – heavier elements

Distance between the Weyl points increases



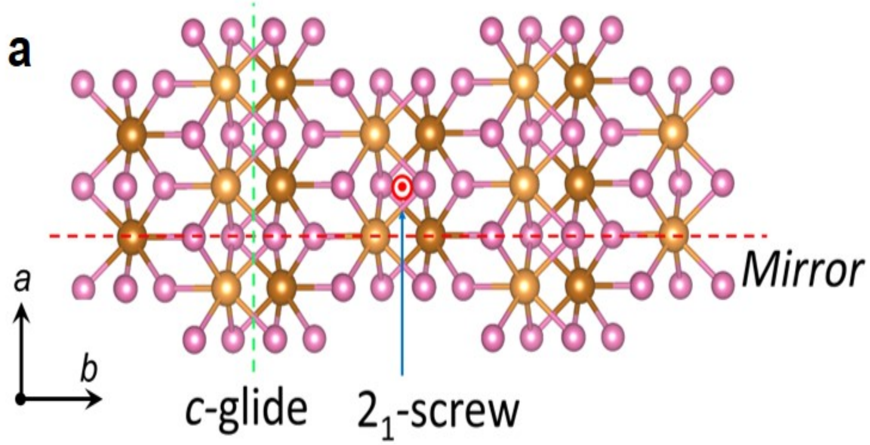


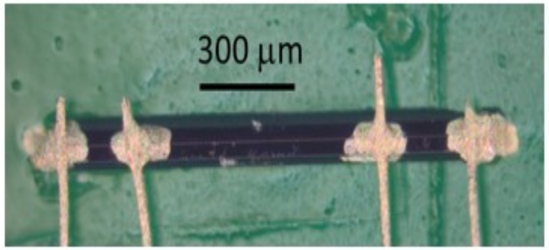


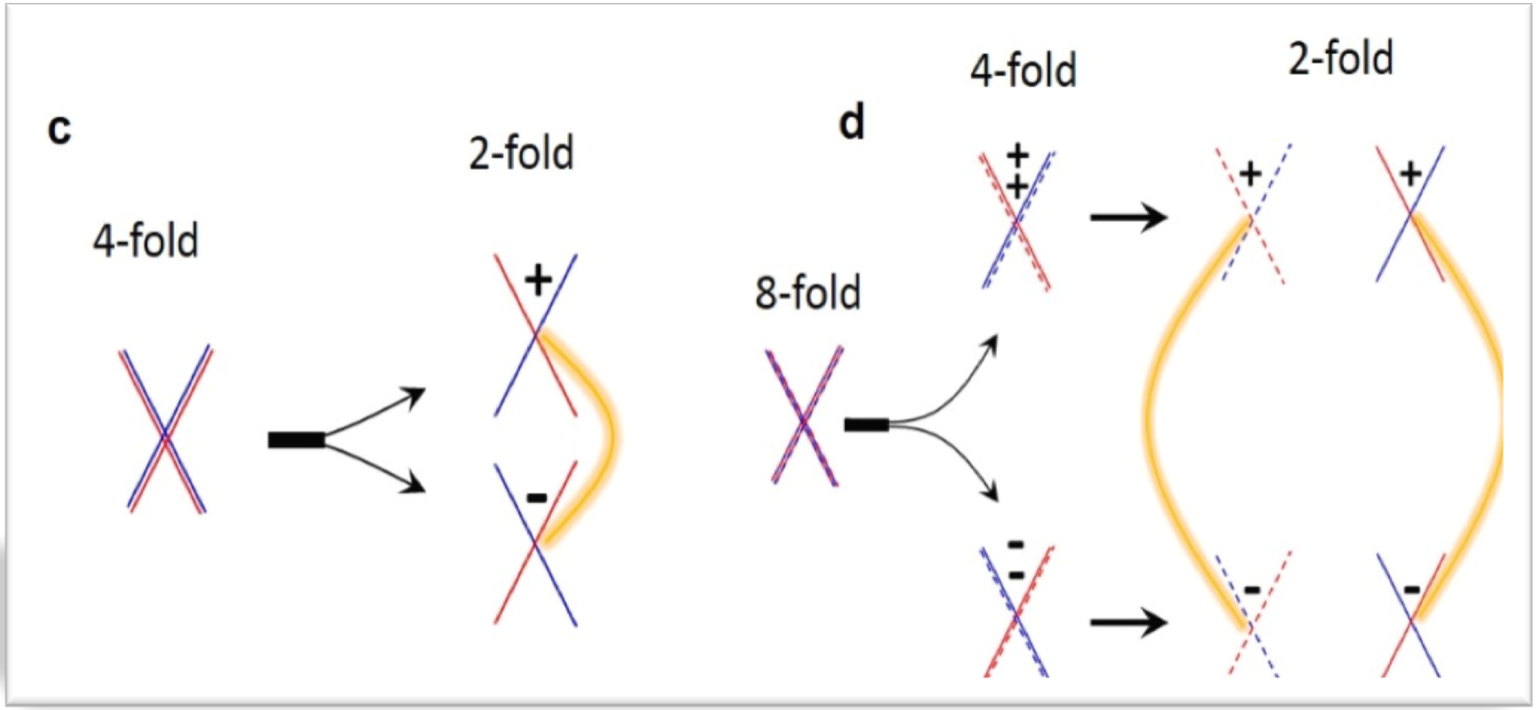
Z. K. Liu et al., Nature Mat. 15 (2016) 27

Yang, et al. Nature Phys. 11 (2015) 728

WP_2 protected Weyl

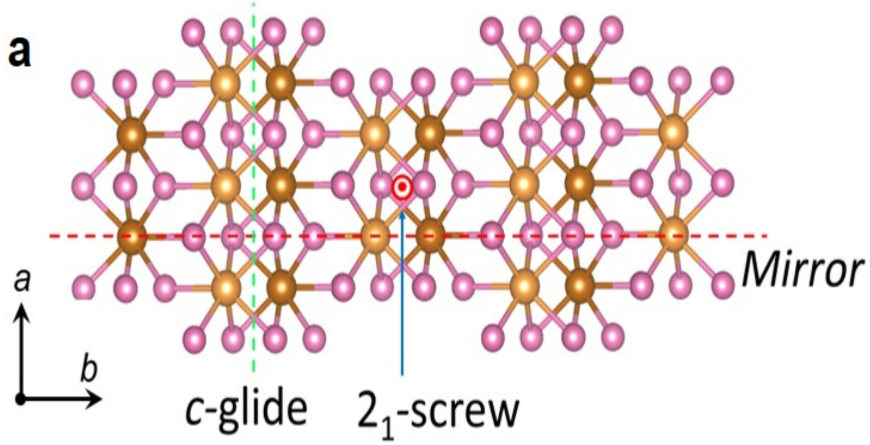


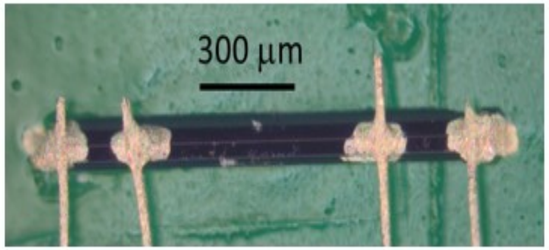


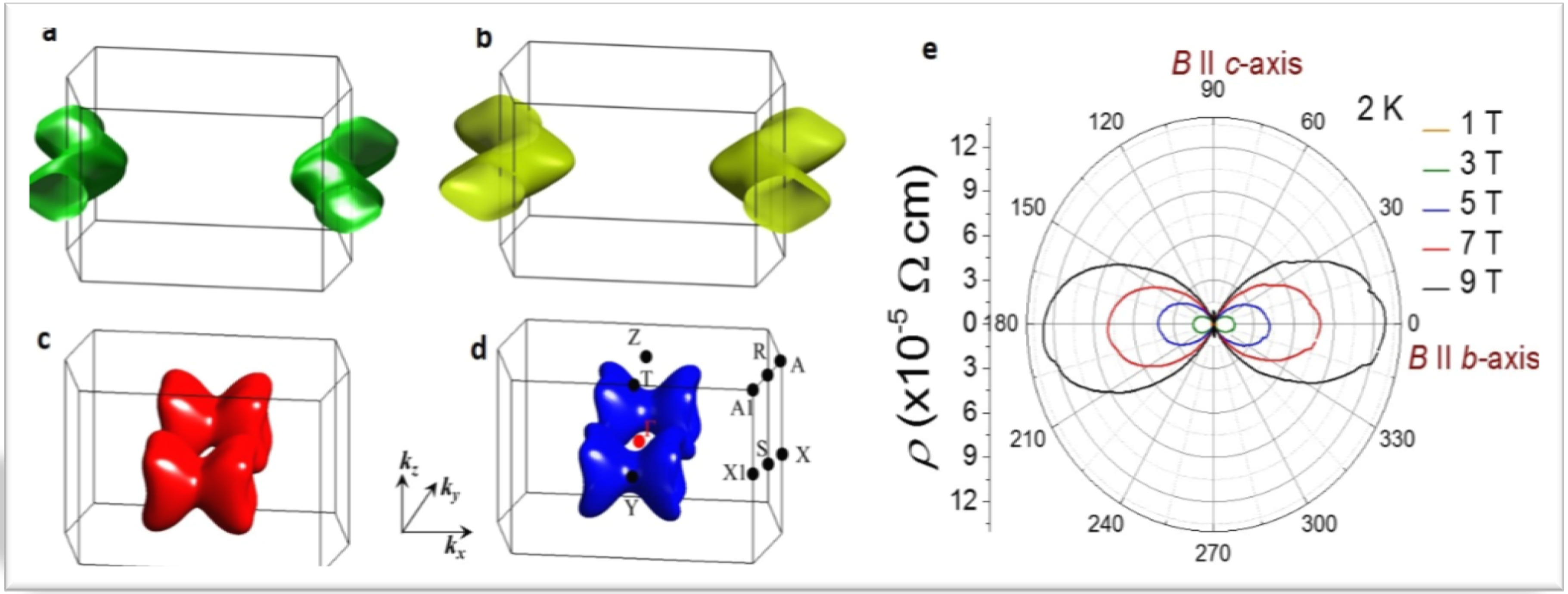


Prediction: G. Autès, et al.; Phys. Rev. Lett. 117 (2016) 066402 Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; **arXiv:1703.04527**

WP_2 protected Weyl



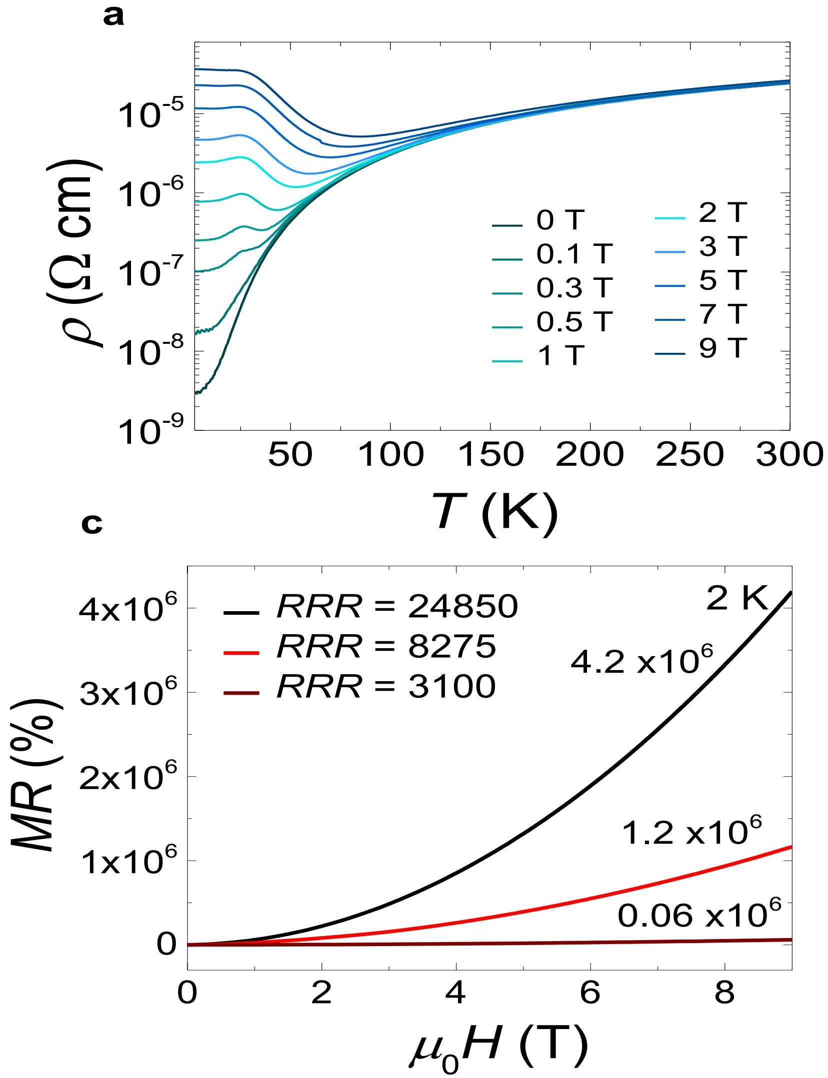


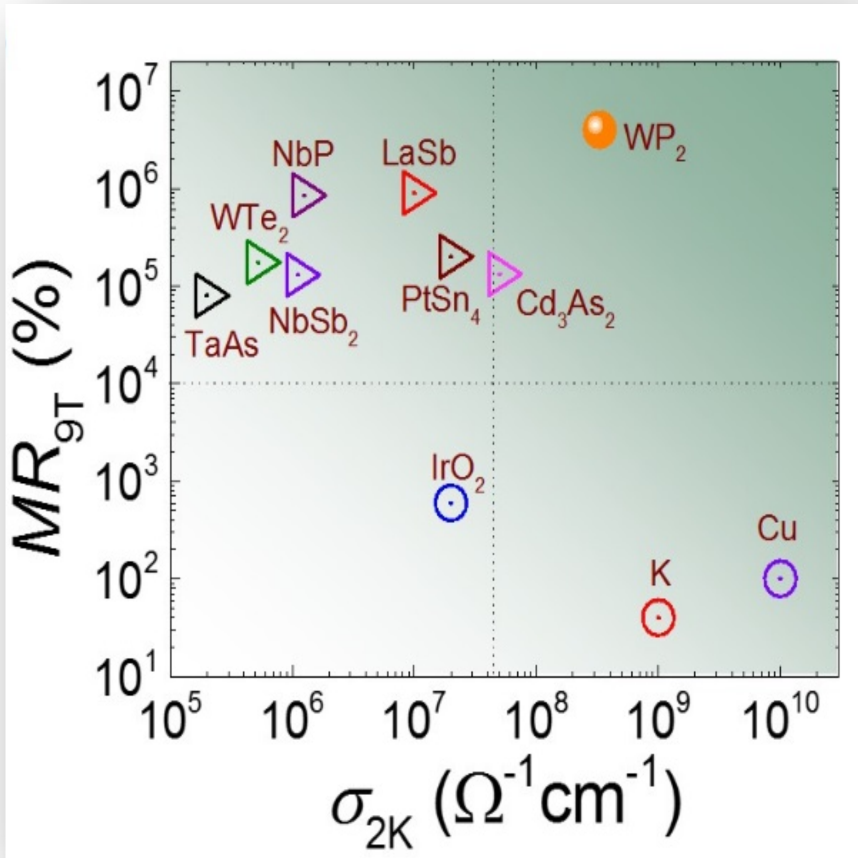


Prediction: G. Autès, et al.; Phys. Rev. Lett. 117 (2016) 066402 Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; **arXiv:1703.04527**

WP_2 protected Weyl

Magnetotransport in a novel Weyl WP_2





Prediction: G. Autès, et al.; Phys. Rev. Lett. 117 (2016) 066402 Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; **arXiv:1703.04527**

Weyl Semimetals

Magnetically induced

REPtBi ...multifunctional topologic insulators

Magnetism and heavy fermion-like behavior in the RBiPt series

P. C. Canfield, J. D. Thompson, W. P. Beyermann, A. Lacerda, M. F. Hundley, E. Peterson, and Z. Fisk
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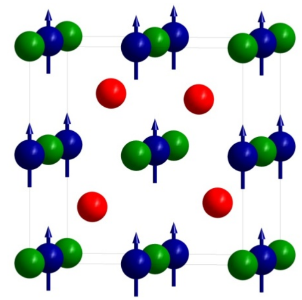
H. R. Ott
ETH, Zurich, Switzerland

J. Appl. Phys. **70** (10), 15 November 1991

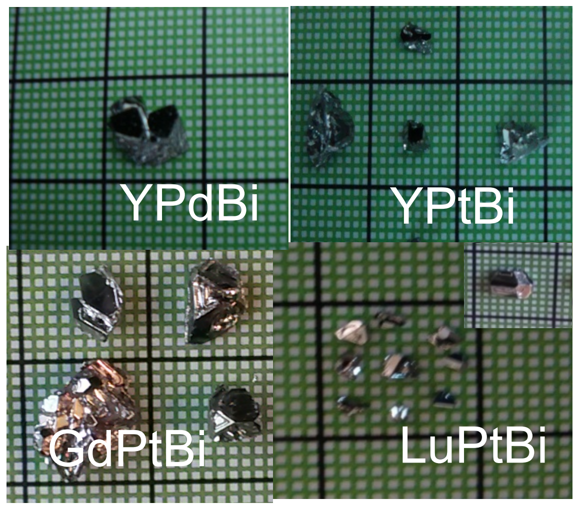


Pt — RE — Bi

$10 + 3\ (+f^n) + 5 = 18$

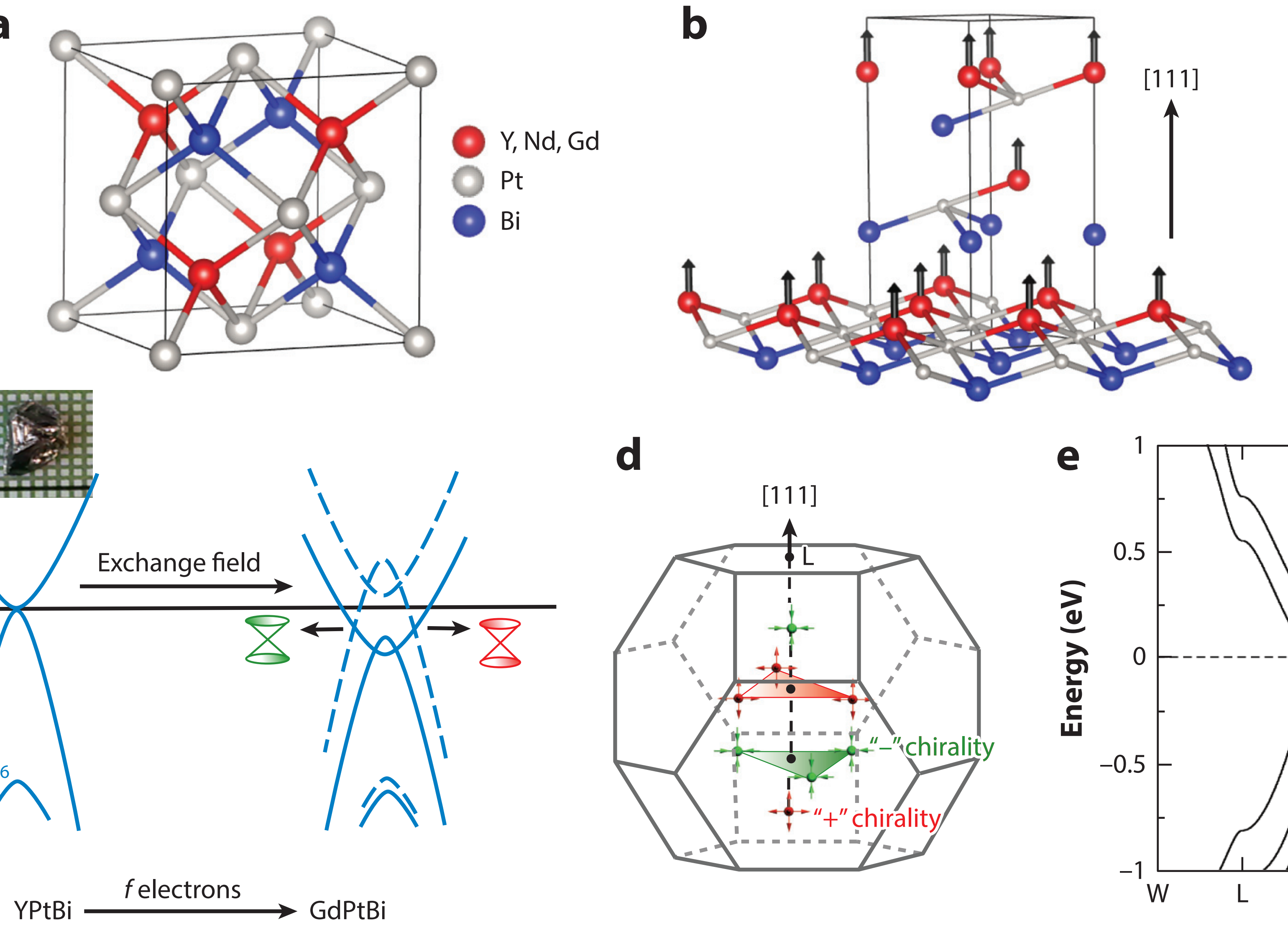
Multifunctional properties

- RE: Gd, Tb, Sm Magnetism and TI
  - Antiferromagnetism with GdPtBi
- RE: Ce
  - complex behaviour of the Fermi surface
- RE: Yb Kondo insulator and TI
  - YbPtBi is a super heavy fermion with the highest γ value



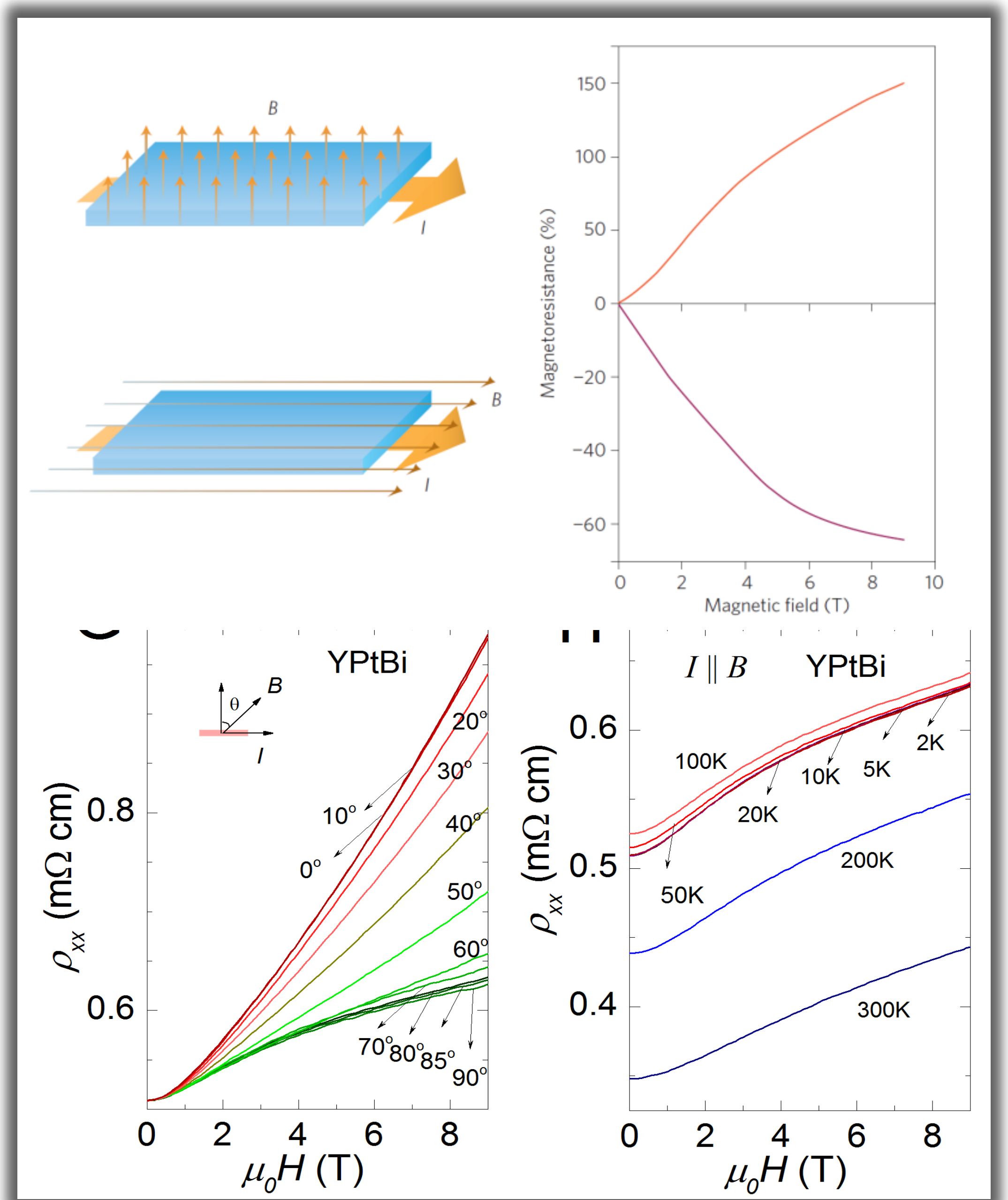
S. Chadov et al., Nat. Mater. 9, 541 (2010).
H. Lin et al., Nat. Mater. 9, 546 (2010).

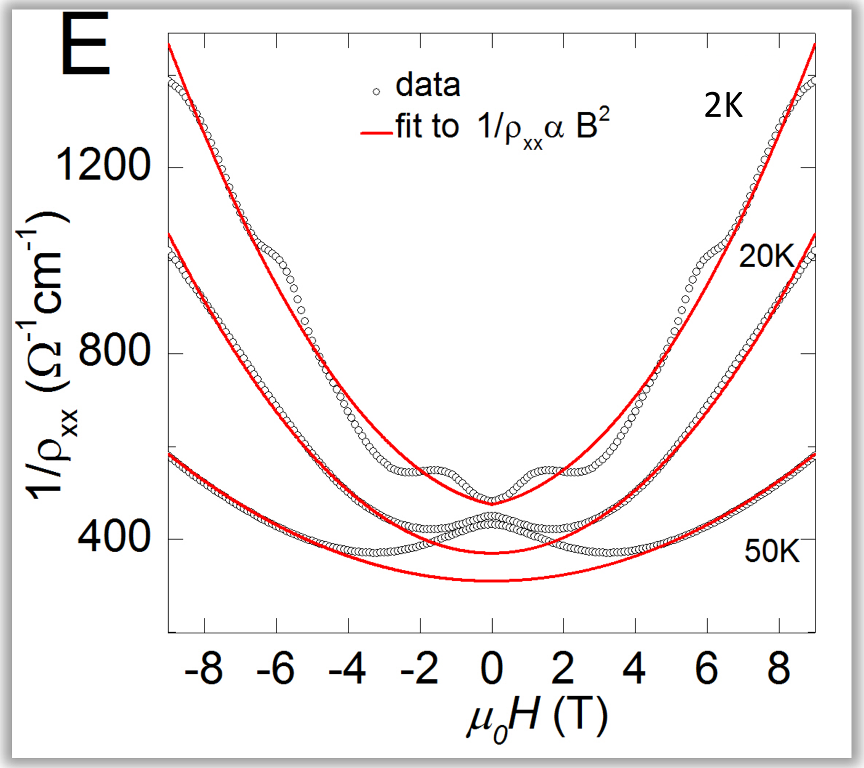
Weyl GdPtBi in a magnetic field



C. Shekhar et al., arXiv:1604.01641, (2016).
M. Hirschberger et al.,. Nature Mat. Online arXiv:1602.07219, (2016).

Chiral Anomaly – neg. quadratic MR



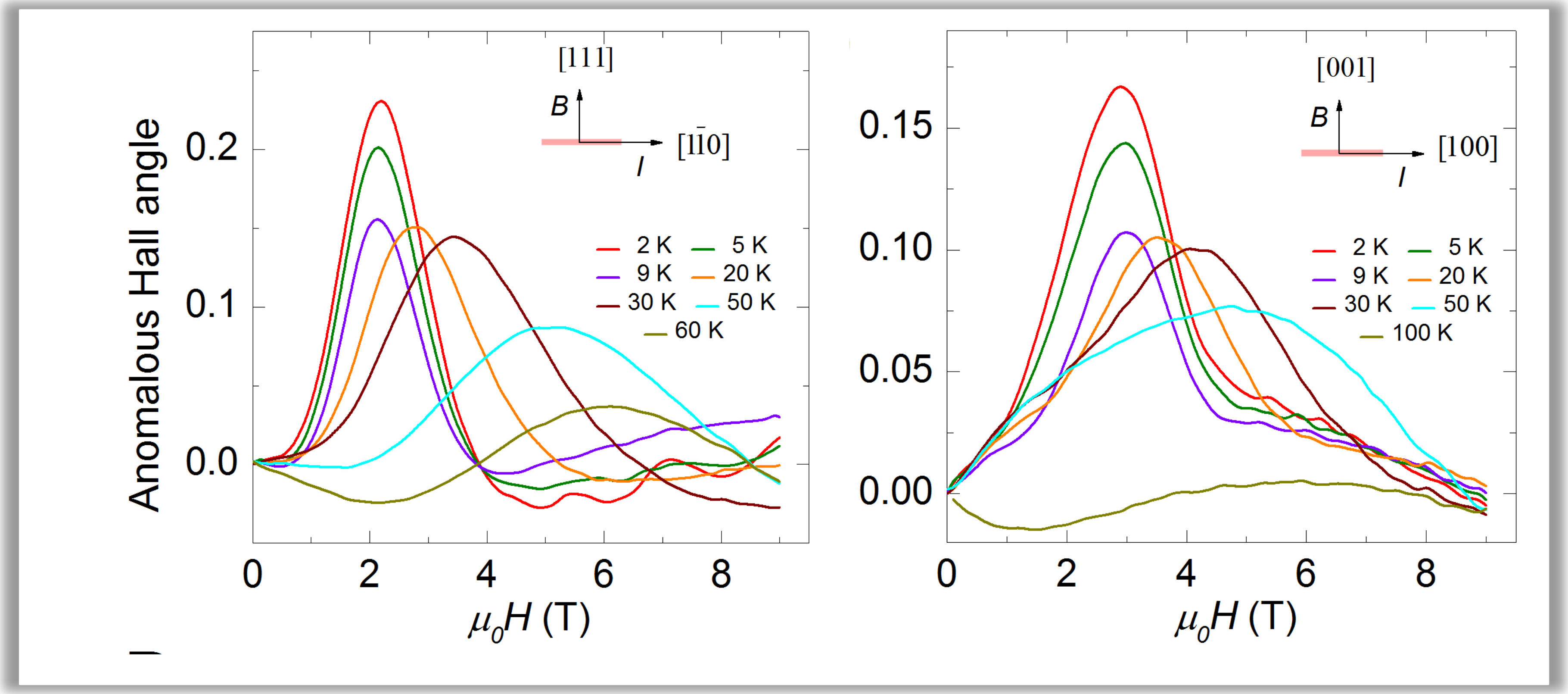


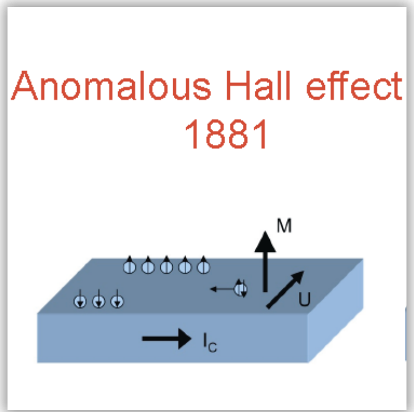
C. Shekhar et al., arXiv:1604.01641, (2016).

Claudia Felser and Binghai Yan, Nature Materials 15 (2016) 1149

M. Hirschberger et al. Nature Mat. online, arXiv:1602.07219, (2016).

GdPtBi – Anomalous Hall Effect





In Ferromagnets an AHE scales with the magnetic moment

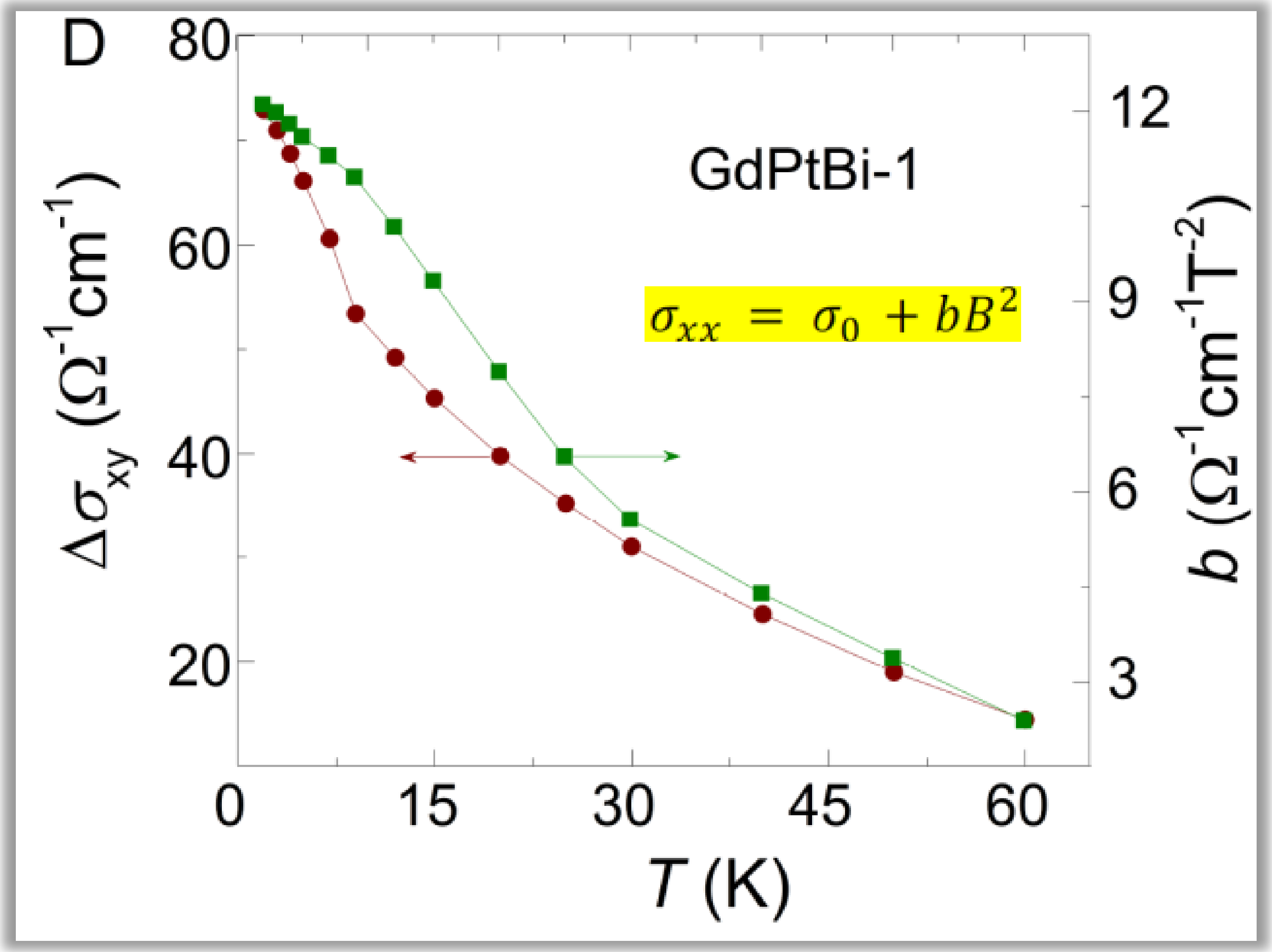
Antiferromagnets show no AHE

A Hall angle of 0.2 is exceptional high

Shekhar et al., arXiv:1604.01641, (2016).

T. Suzuki,… & J. G. Checkelsky, Nature Physics (2016) doi:10.1038/nphys3831

Chiral Anomaly – neg. quadratic MR

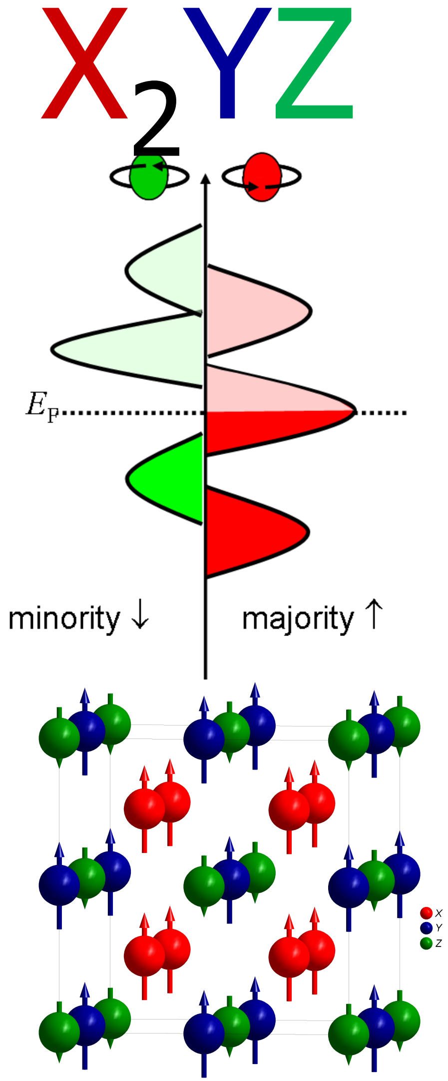


Claudia Felser and Binghai Yan, Nature Materials 15 (2016) 1149

C. Shekhar et al., arXiv:1604.01641, (2016).
M. Hirschberger et al. Nature Mat. online, arXiv:1602.07219, (2016).

Magnetic Weyl Semimetals

Materials: … to half metallic ferromagnets

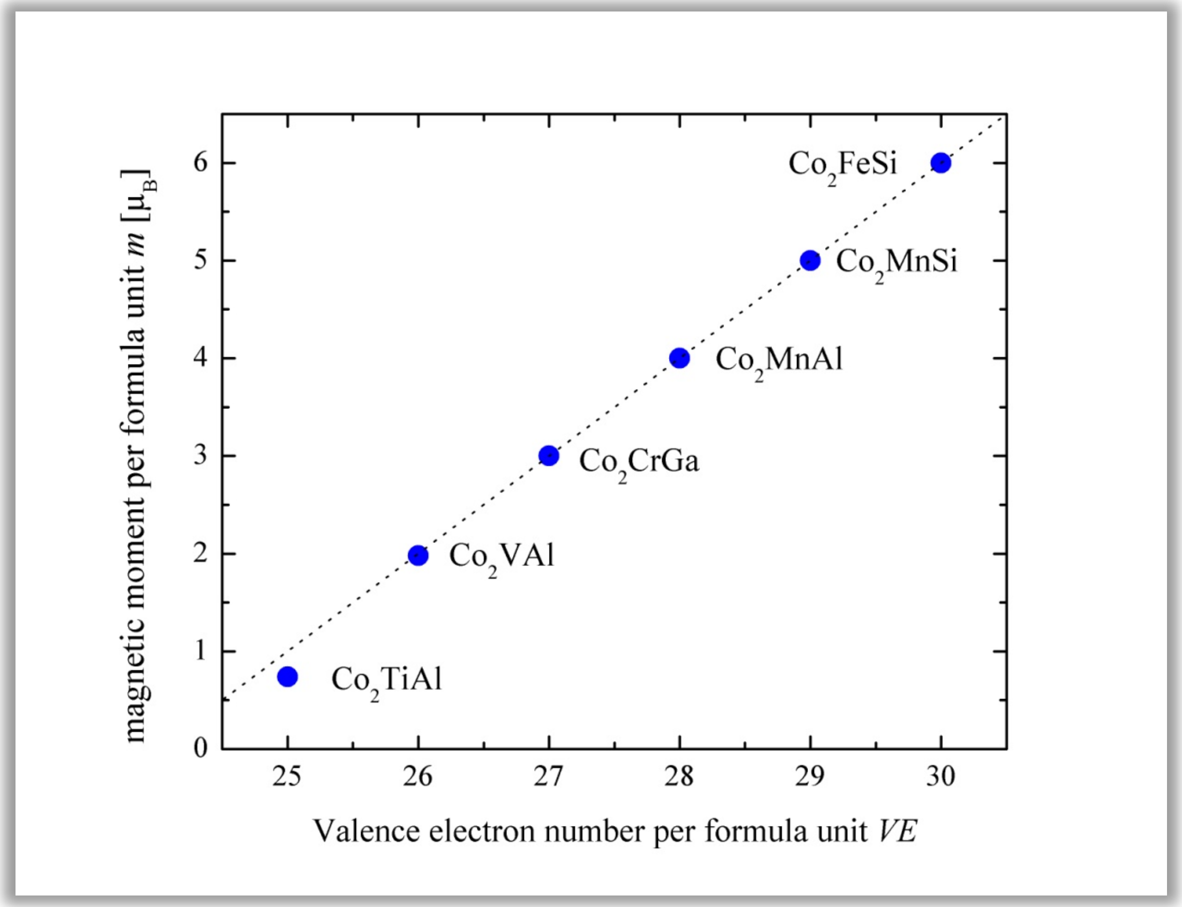


Kübler *et al.*, PRB **28**, 1745 (1983)
de Groot RA, et al. PRL **50** 2024 (1983)
Galanakis *et al.*, PRB **66**, 012406 (2002)

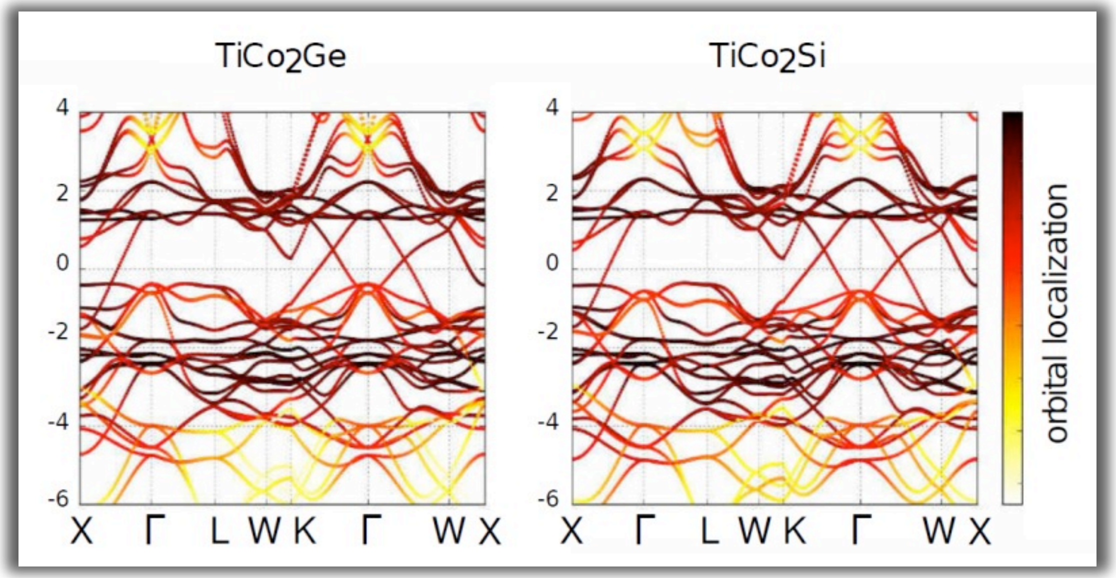
Example: Co_2MnSi

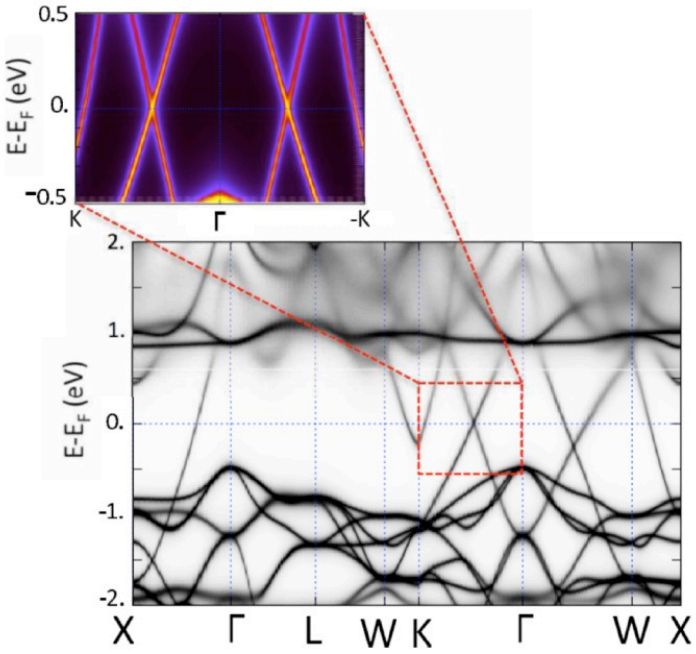
- magic valence electron number: 24
- valence electrons = 24 + magnetic moments

Co_2MnSi: $2\times9 + 7 + 4 = 29$ Ms = $5\mu_B$

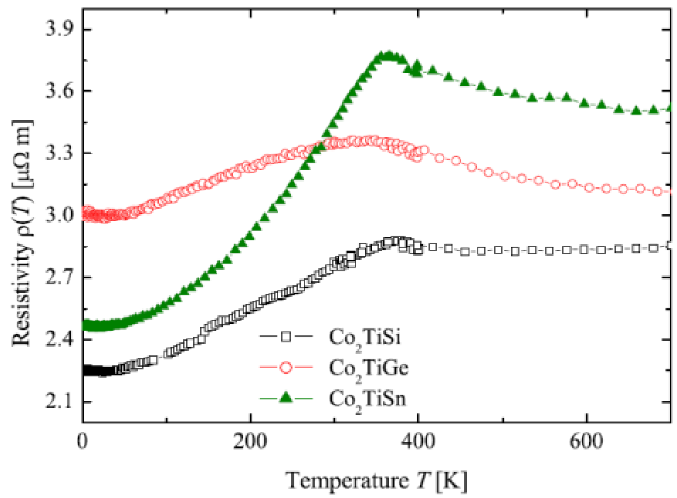


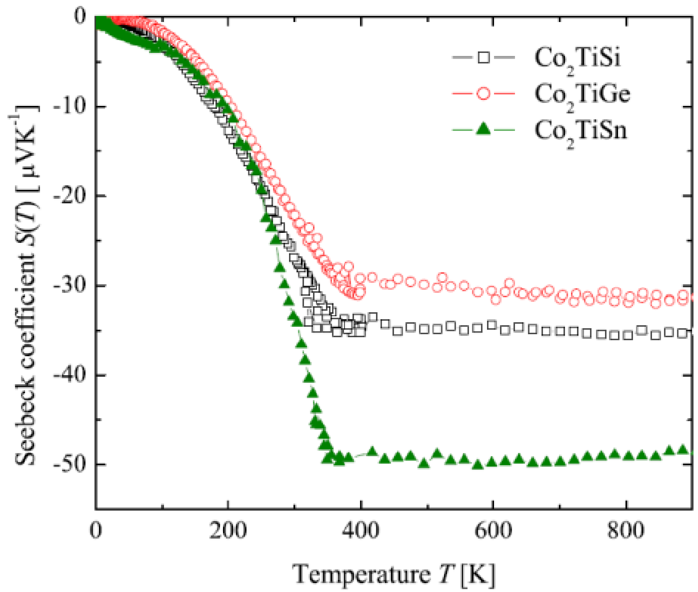
Weyl semimetals in Heusler compounds





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]

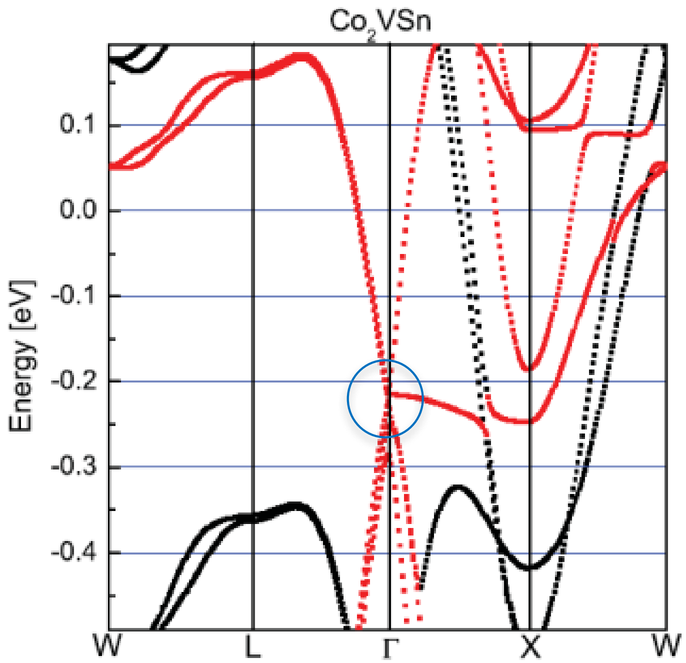
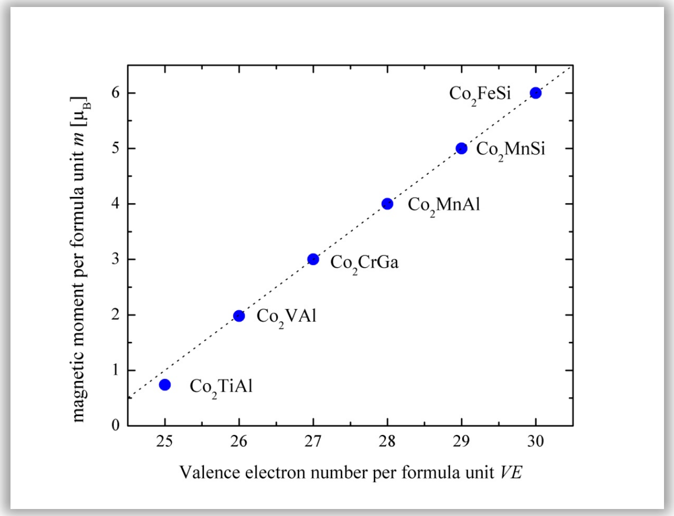


FIG. 4. (Color online) Band structure near the Fermi edge of Co_2VSn. Majority-spin electron states appear in red, minority-spin states in black. Note the Dirac cone at the Γ point at about −0.22 eV.

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

The AHE depends only on the Berry curvature in Heusler compounds and not on the magnetic moment



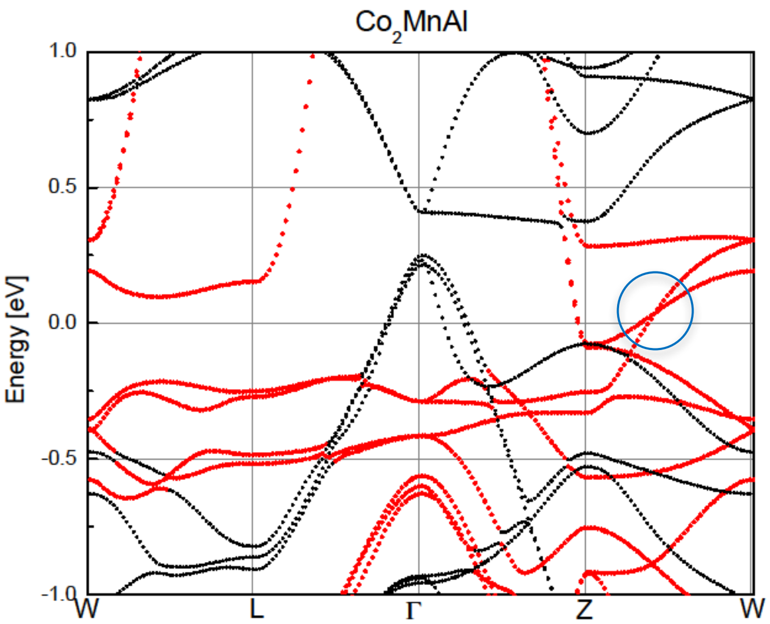
Kübler, Felser, PRB 85 (2012) 012405
Vidal et al Appl.Phys.Lett. 99 (2011) 132509
Kübler, Felser, EPL 114 (2016) 47005.

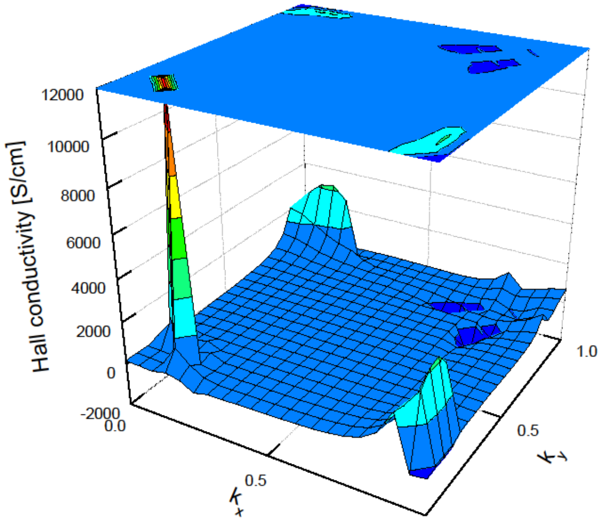
AHE in half metallic ferromagnets with Weyl

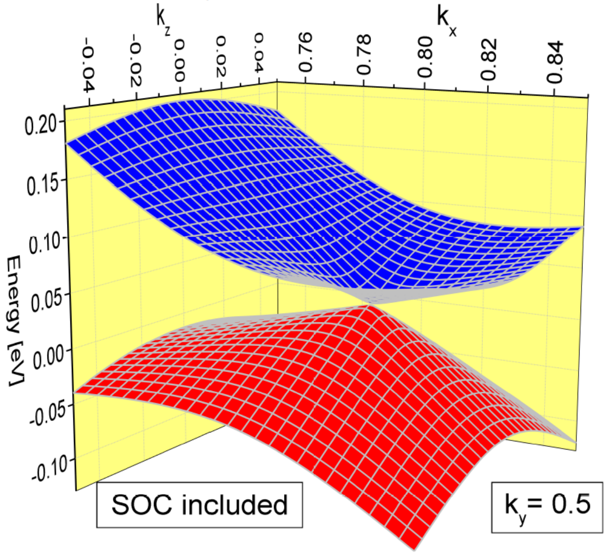
Giant AHE in Co_2MnAl

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

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



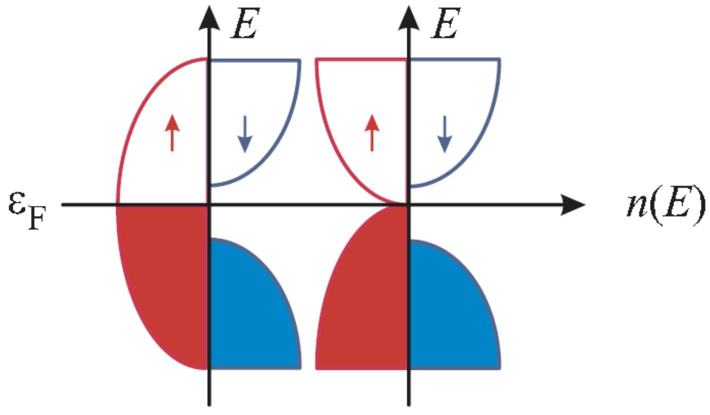




Weyl points are the origin for a large Berry phase and a Giant AHE

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

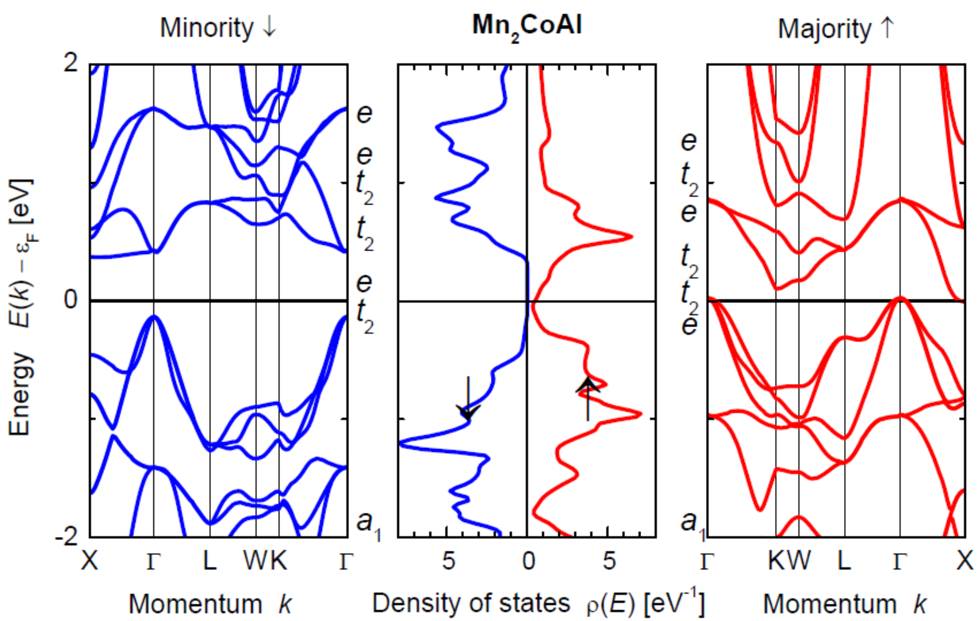
Spin gapless semiconductor Mn_2CoAl

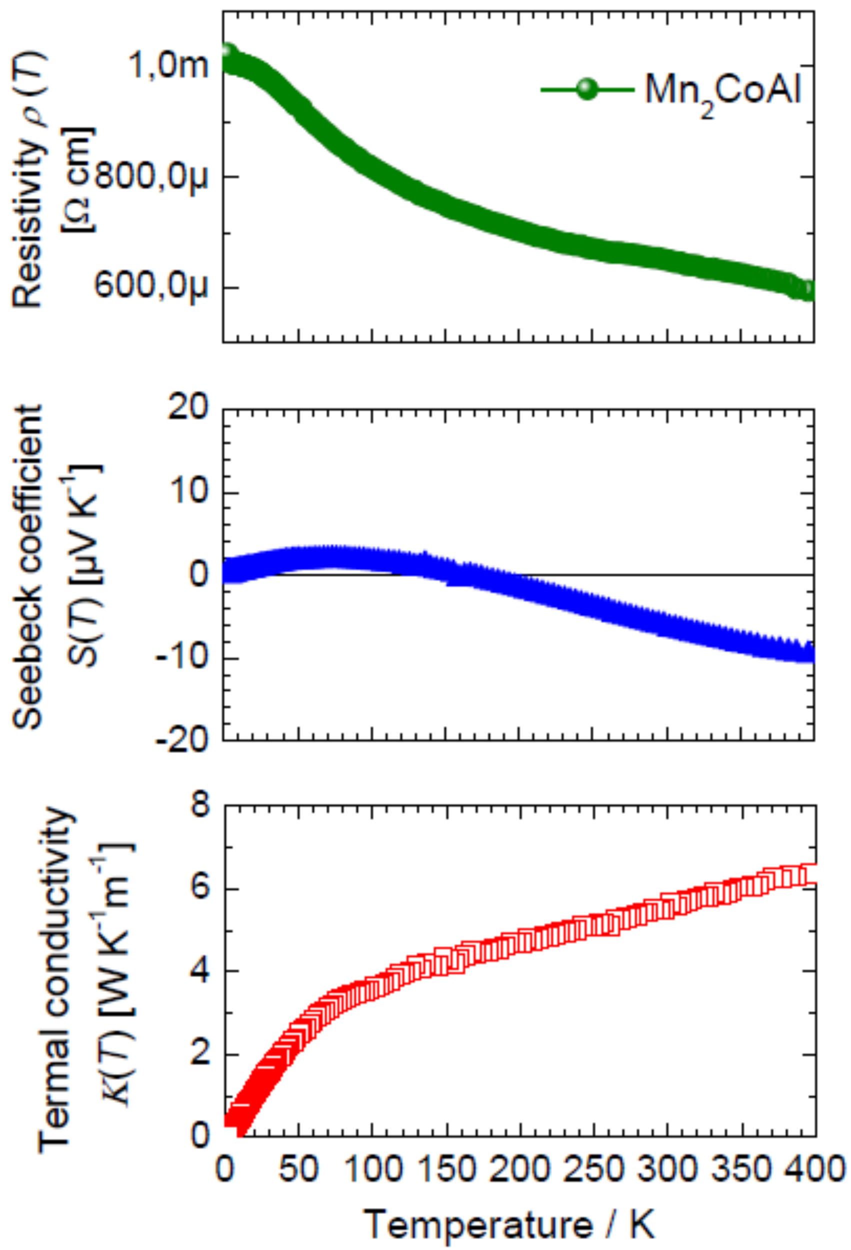


$2*7 + 9 + 3 = 26$. $m = 2\ \mu_B$

$T_C = 800$ K

Charge carrier ~ $10^{17} cm^{-3}$



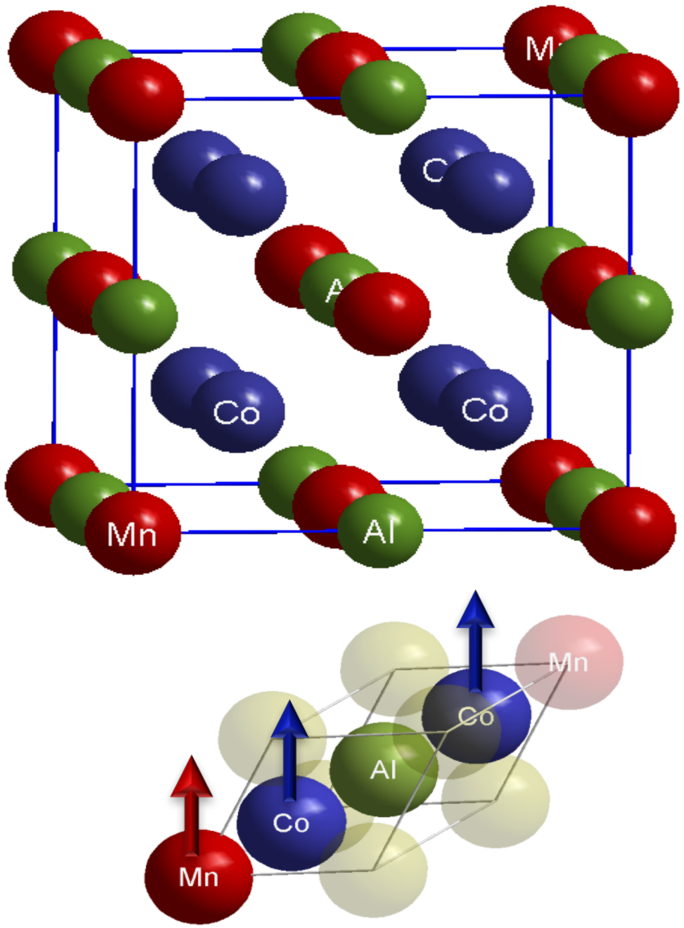


Wang PRL **100,** 156404 (2008)

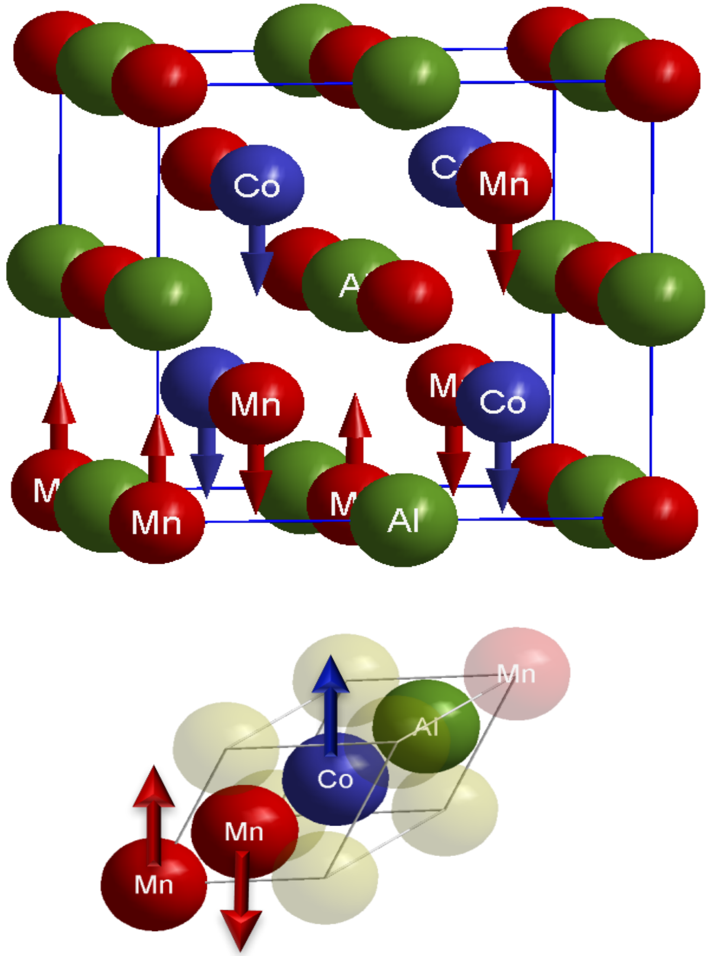
Ouardi et al., PRL 110 (2013) 100401

Magnetic Heusler compounds with and without inversion

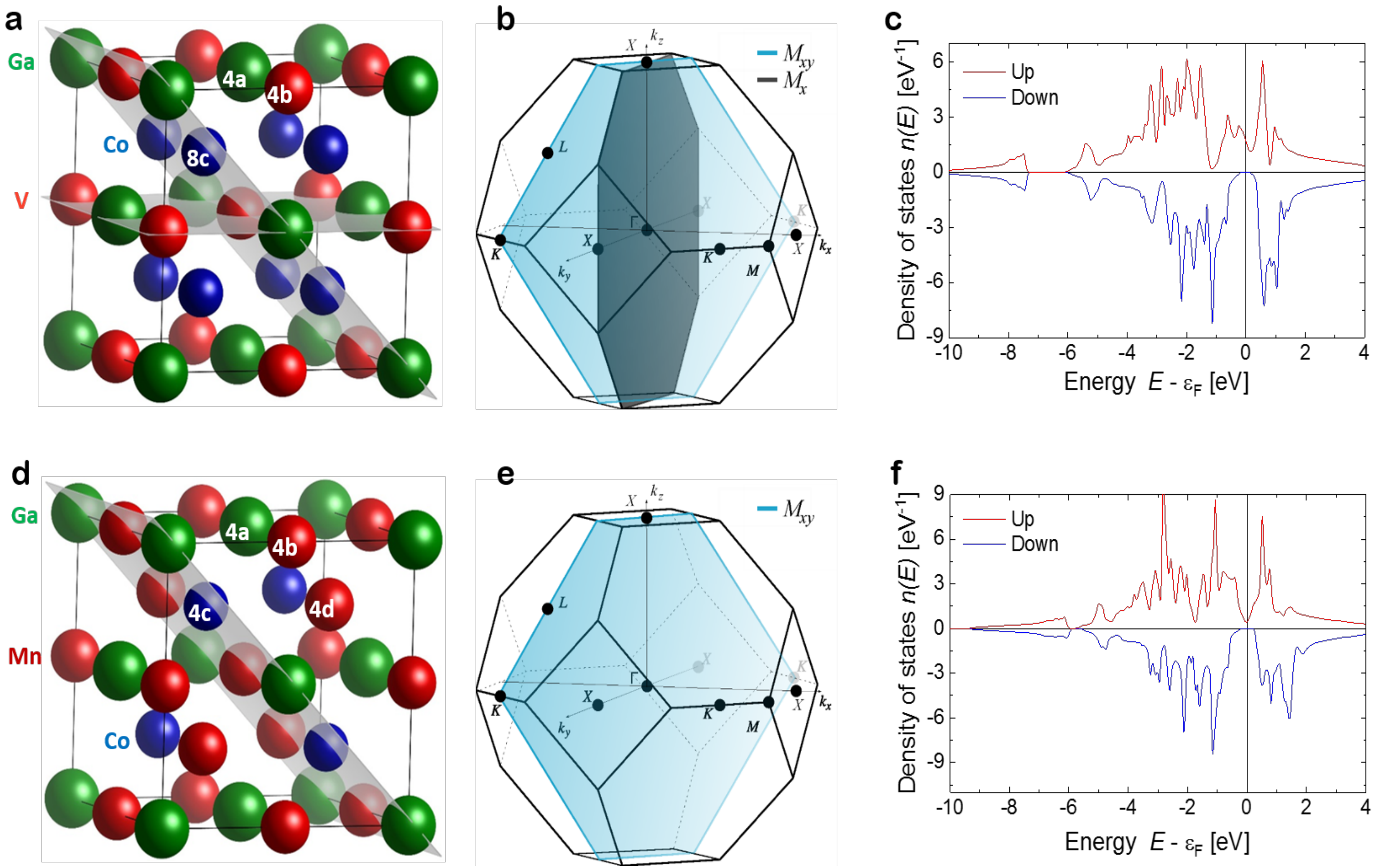
Co_2MnAl
$L2_1$ space group 225 ($Fm\bar{3}m$)



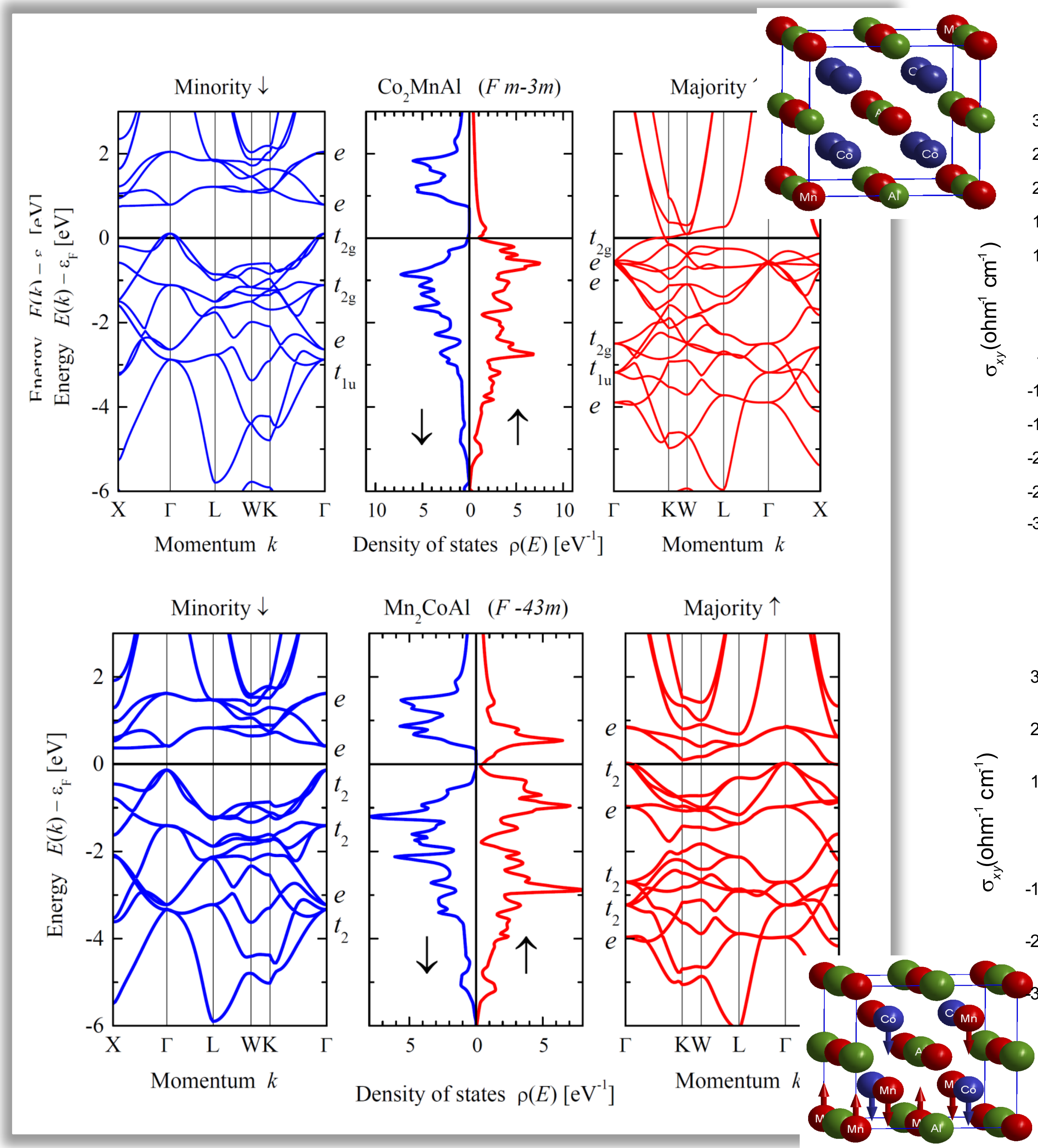
Mn_2CoAl
X space group 216 ($F\bar{4}3m$)

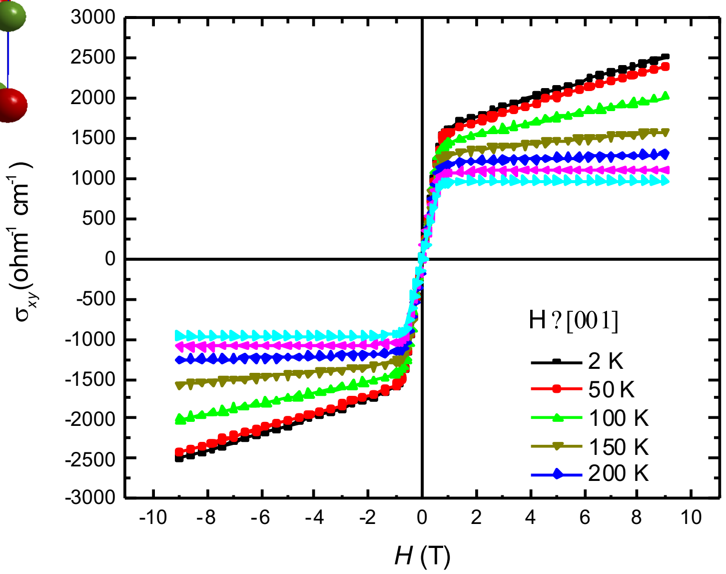


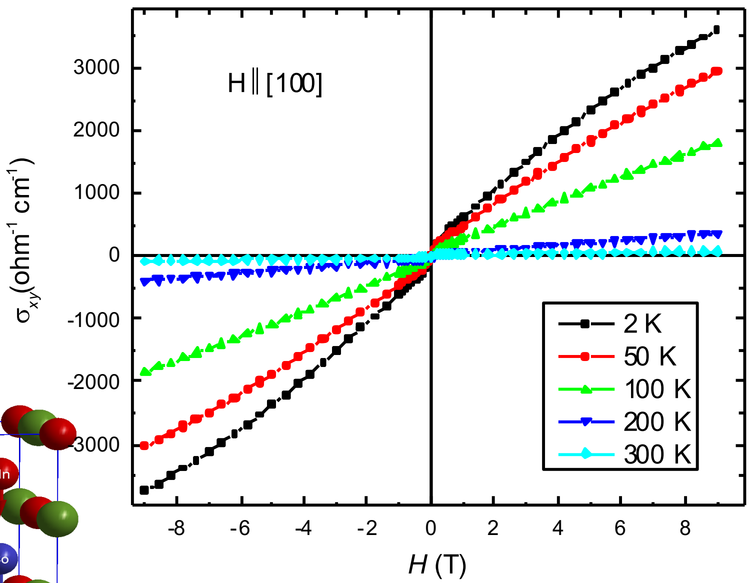
From Gap to Weyl



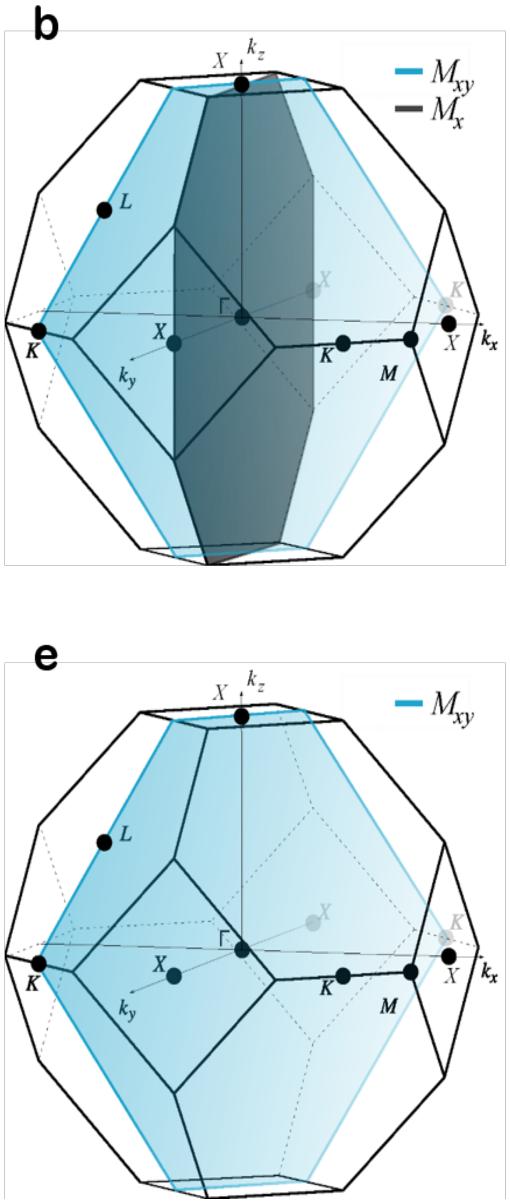
Weyl or Spingapless

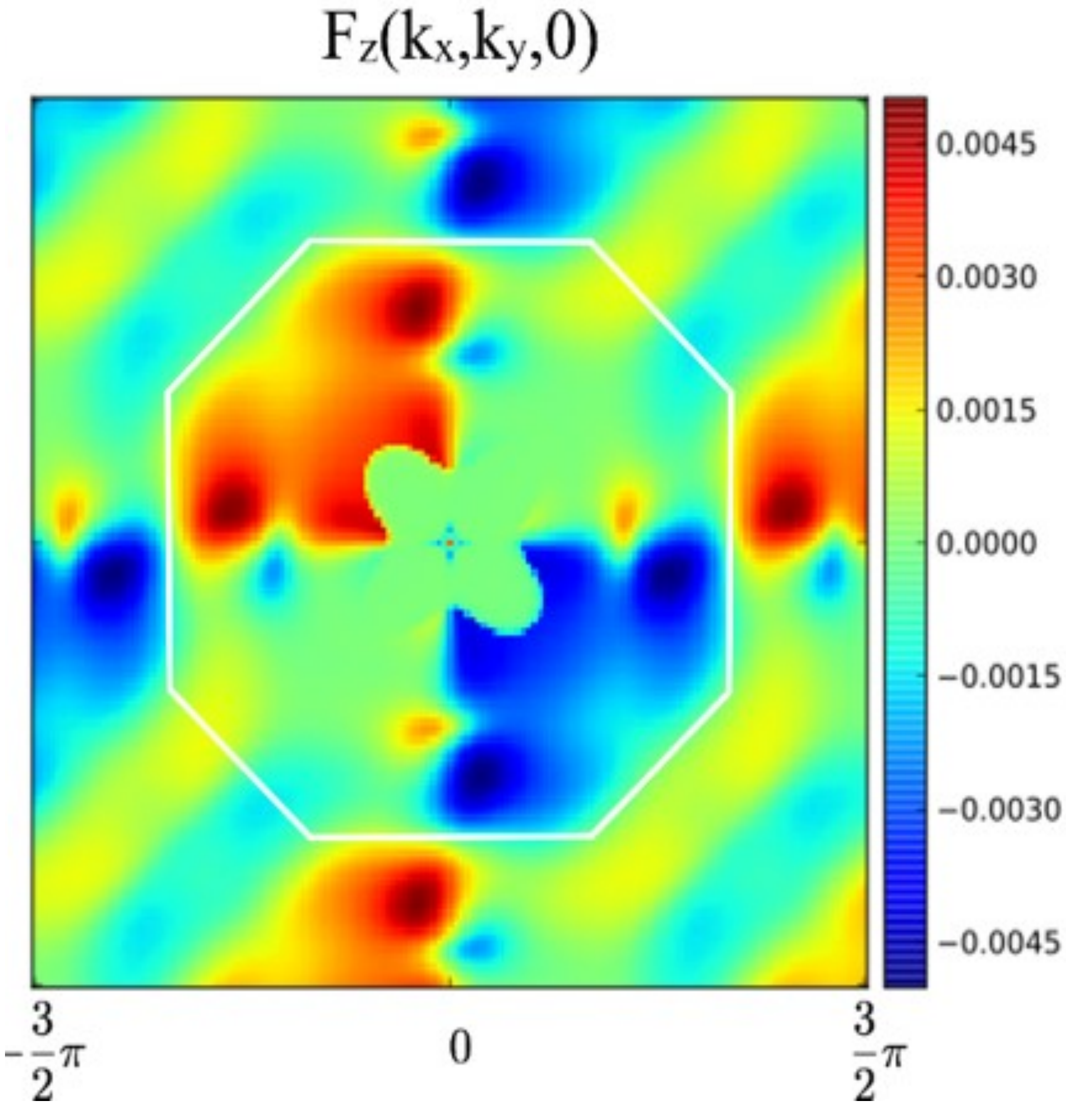






From Gap to Weyl





More semiconductors

26

Mn2CoAl

CoMn2Al

CoFeCrAl

CoMnCrSi

CoFeVSi

FeMnCrSb

18

V_3Al

21

FeVTiSi

CoVScSi

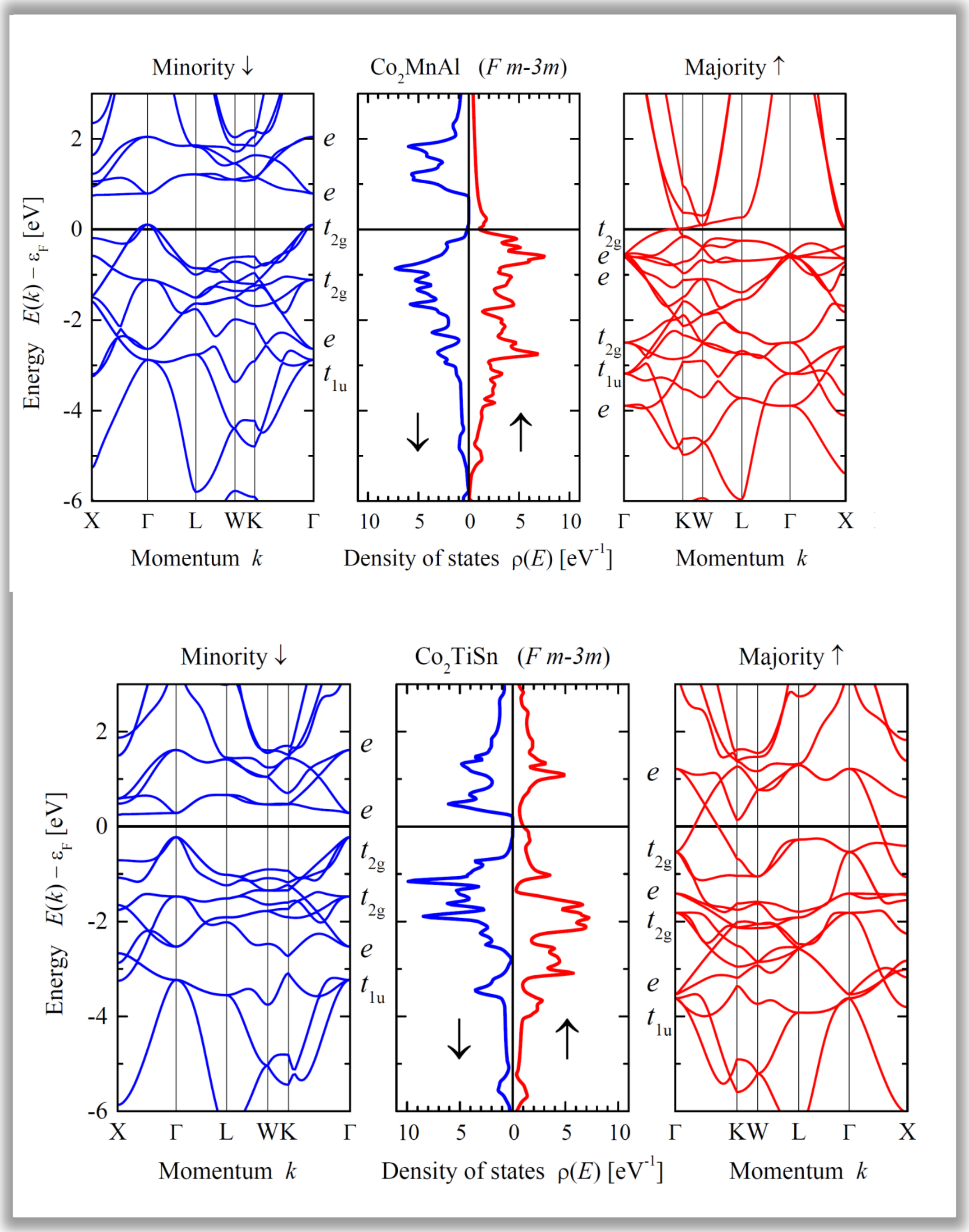
FeCrScSi

FeVTiSi

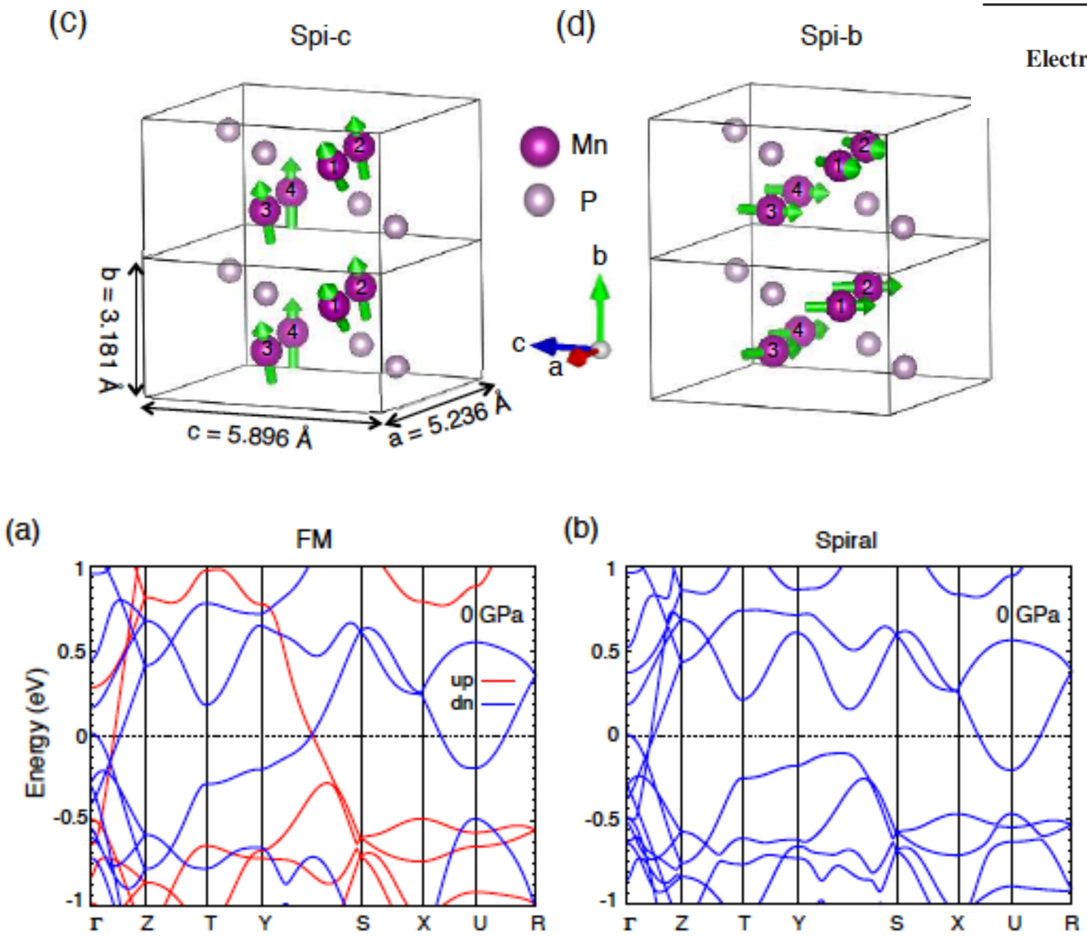
FeMnScAl

28

CoFeMnSi



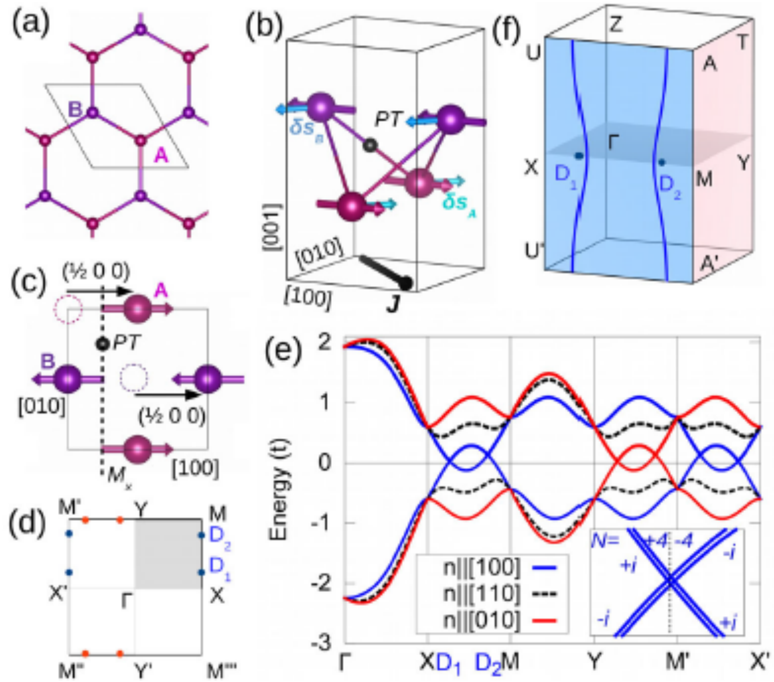
MnP and CuMnAs



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]

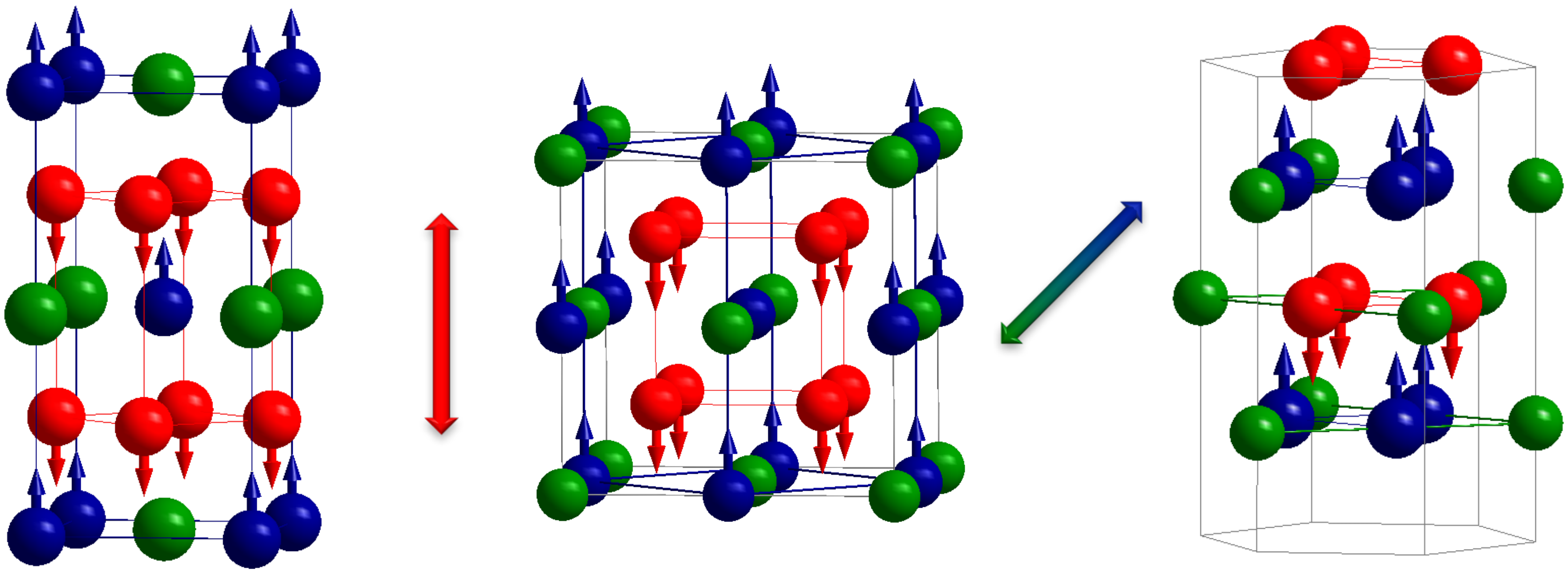


First-principles calculations of the magnetic and electronic structures of MnP under pressure

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,*]

Structural distortion

$I4/mmm$ ($D0_{22}$) $Fm\bar{3}m$ ($L2_1$) $P6_3/mmc$ ($D0_{19}$)



tetragonal ⟷ cubic ⟷ hexagonal

Out of plane M
Compensated ferrimagnets
Permament magnets
Non-collinear magnetism
Topological Hall effect
Skyrmions

Half metallic ferro/i
Spin gapless
mag. semiconductors
compensated ferrim. …

Phase transitions

- Magn. shape memory
- Magnetocalorics – CDW
- Multiferroics

Out of plane M
STT-RAM
Permanent magnets
Antiferromagnets: Mn_3Ge
Ferromagnets: Fe_3Sn
Anomalous Hall effect
Spin reorientation transition?

Hexagonal Antiferromagnet

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

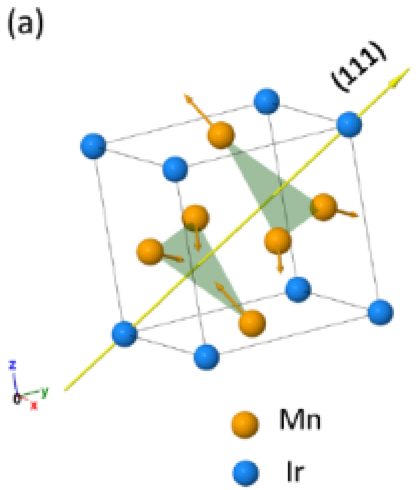
Non-collinear antiferromagnets and the anomalous Hall effect

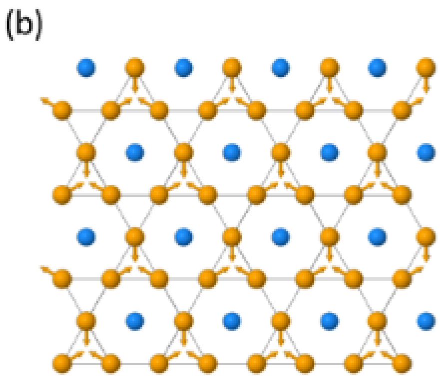
J. KÜBLER[1] and C. FELSER[2]

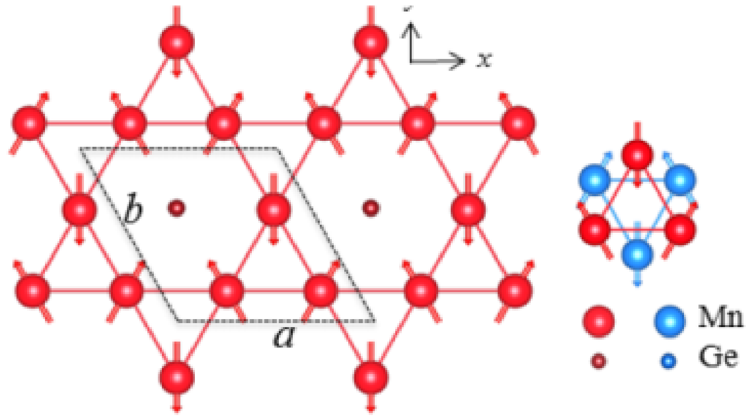
PRL **112,** 017205 (2014) PHYSICAL REVIEW LETTERS week ending 10 JANUARY 2014

Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism

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



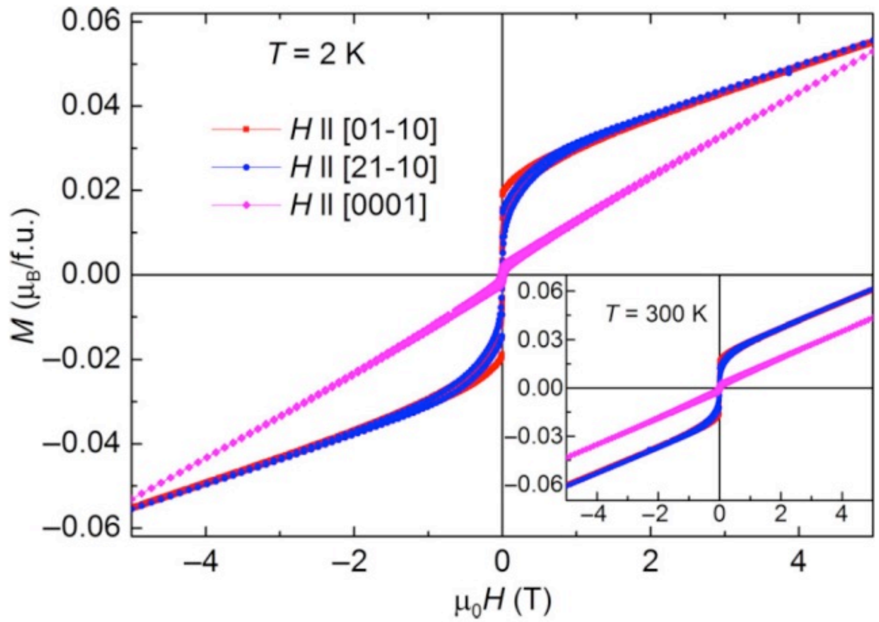


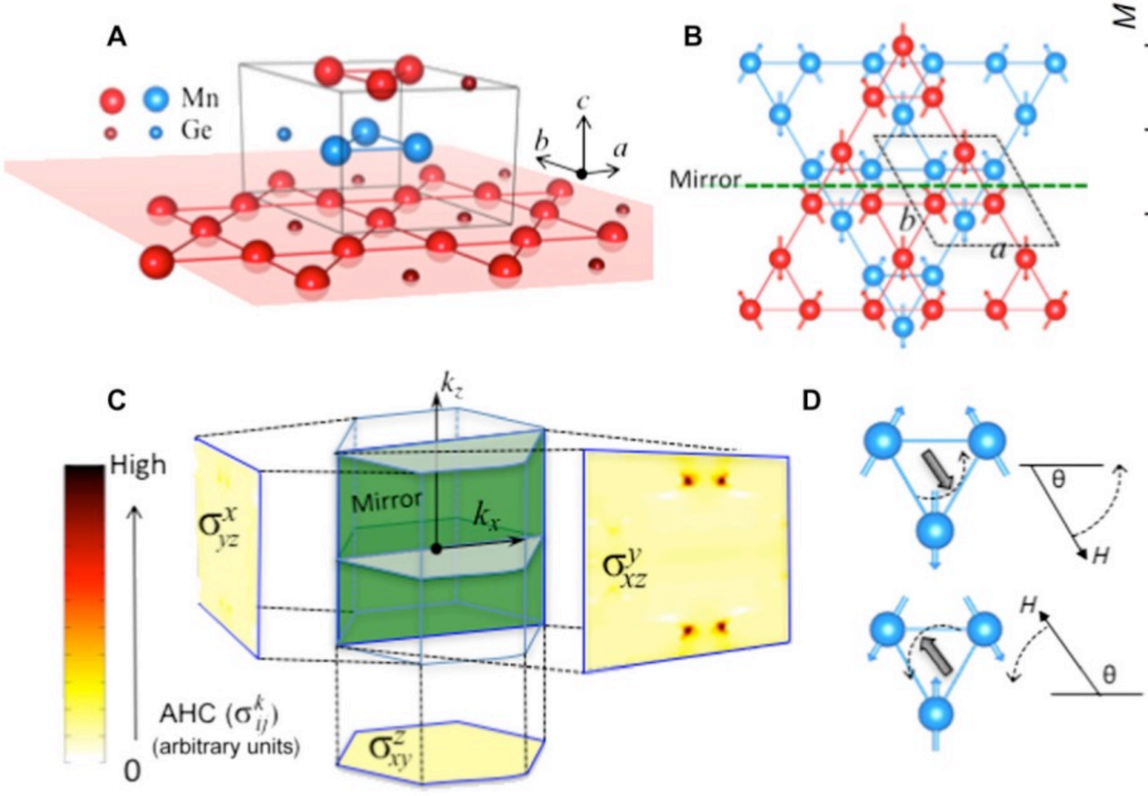


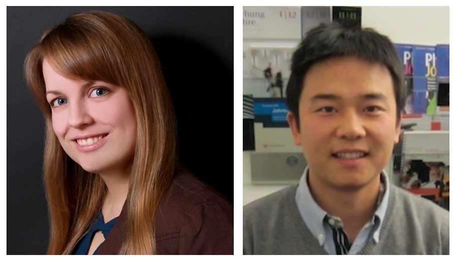
Chen, Niu, and MacDonald, Phys. Rev. Lett., 112 (2014) 017205
Kübler and Felser EPL 108 (2014) 67001

Non-collinear AFM in metallic Mn_3Ge

The anomalous Hall conductivities are normally assumed to be proportional to magnetization

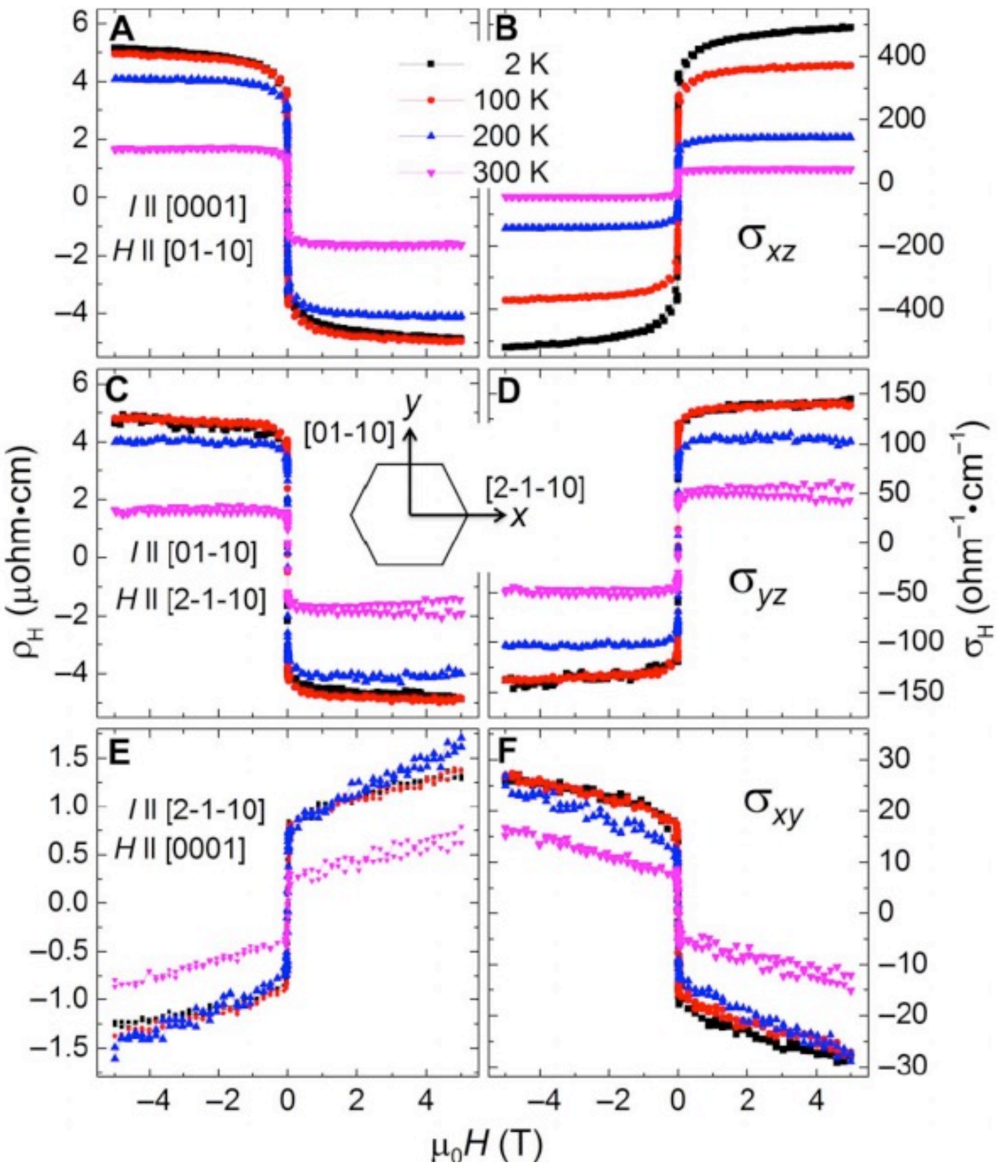






Kübler and Felser EPL 108 (2014) 67001
Nayak et al. preprint: arXiv:1511.03128, Science Advances 2 (2016) e1501870

Non-collinear AFM Mn_3Ge/Mn_3Sn

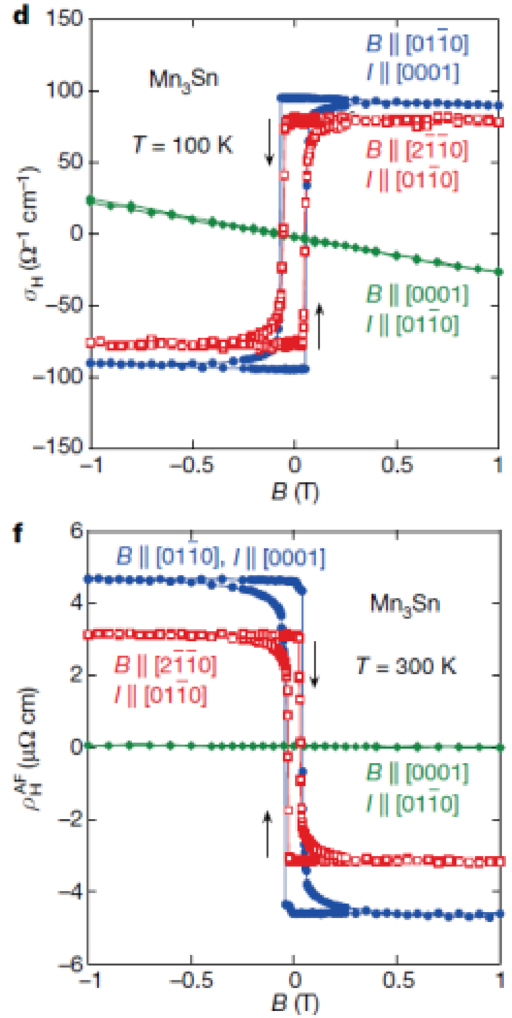


LETTER

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]

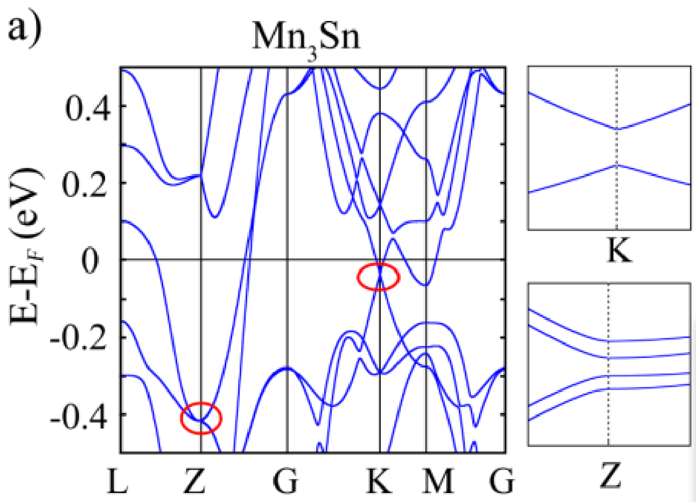


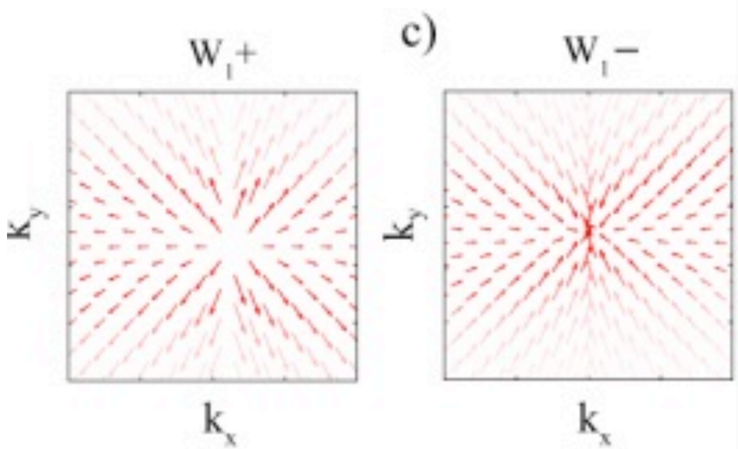
Nayak et al. preprint: arXiv:1511.03128, Science Advances 2 (2016) e1501870

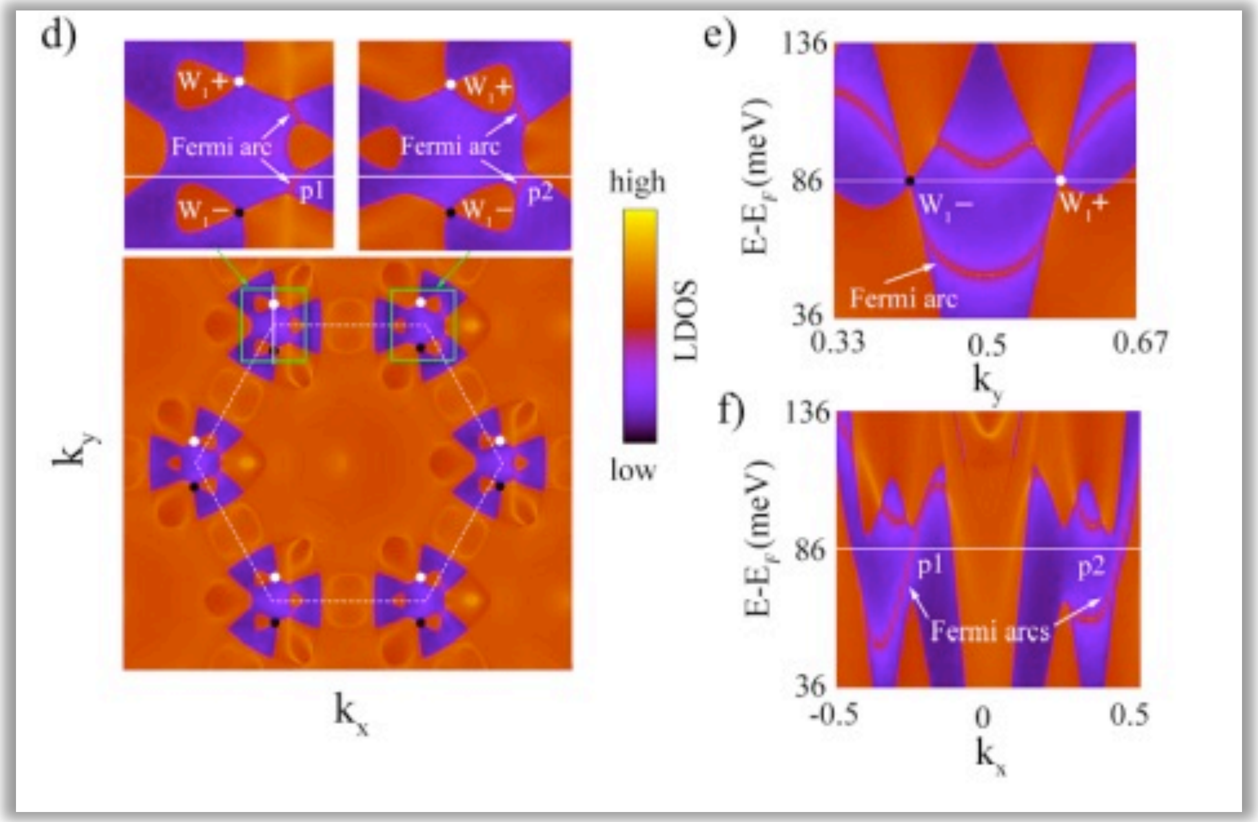
Kiyohara, Nakatsuji, preprint: arXiv:1511.04619,

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

Fermiarcs in the Weyl AFM

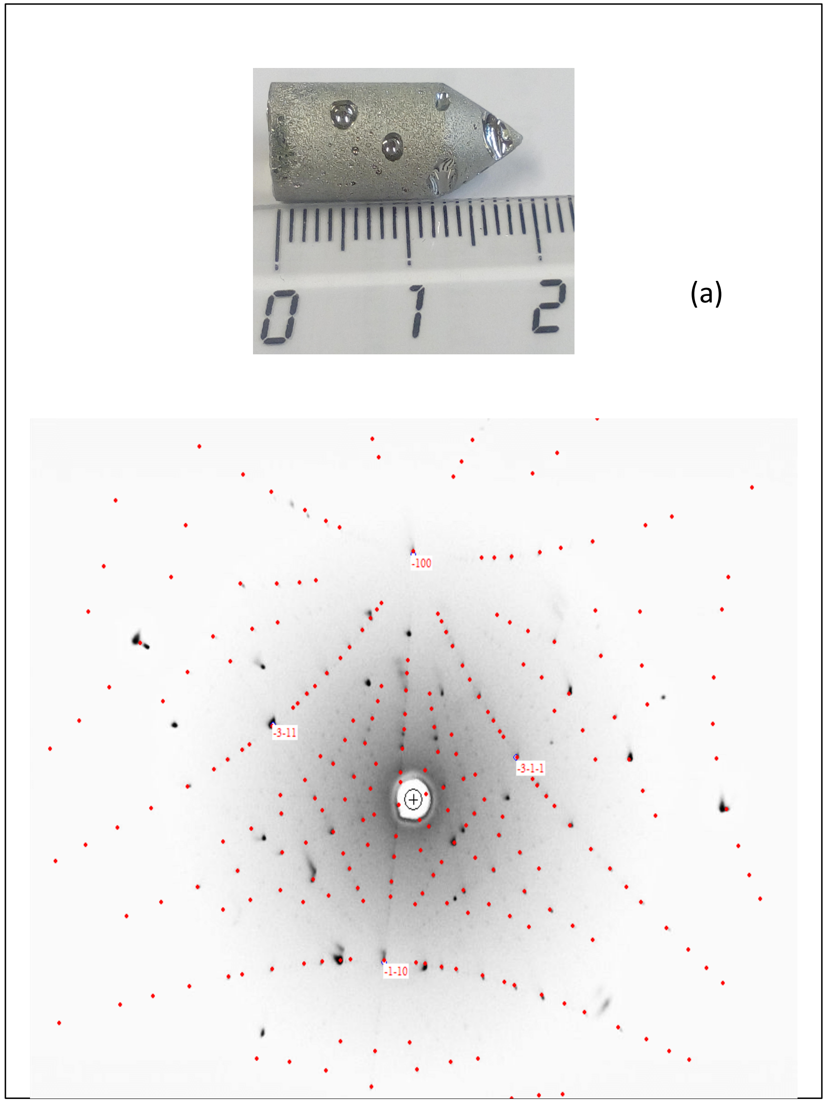


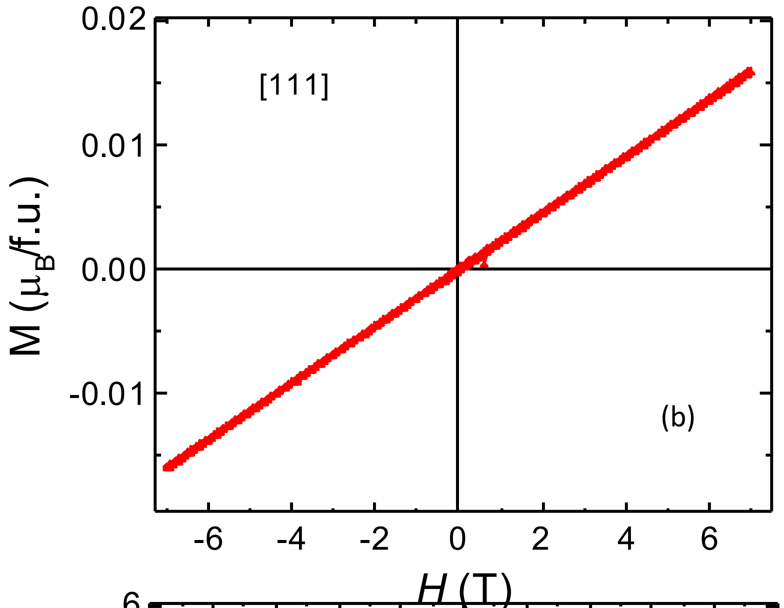


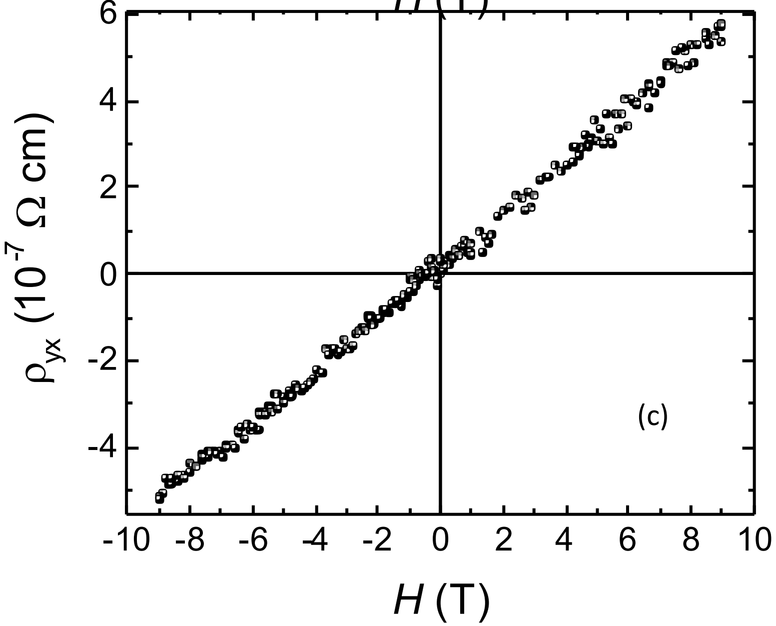


Hao Yang, et al. , preprint: arXiv:1608.03404

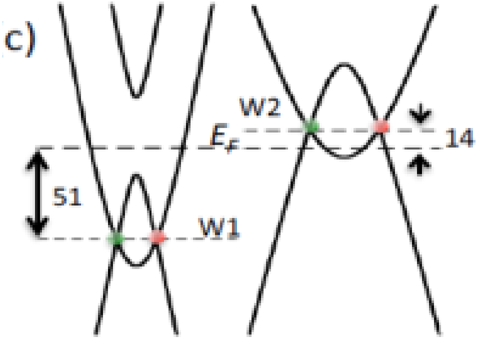
Mn_3Ir – no AHE

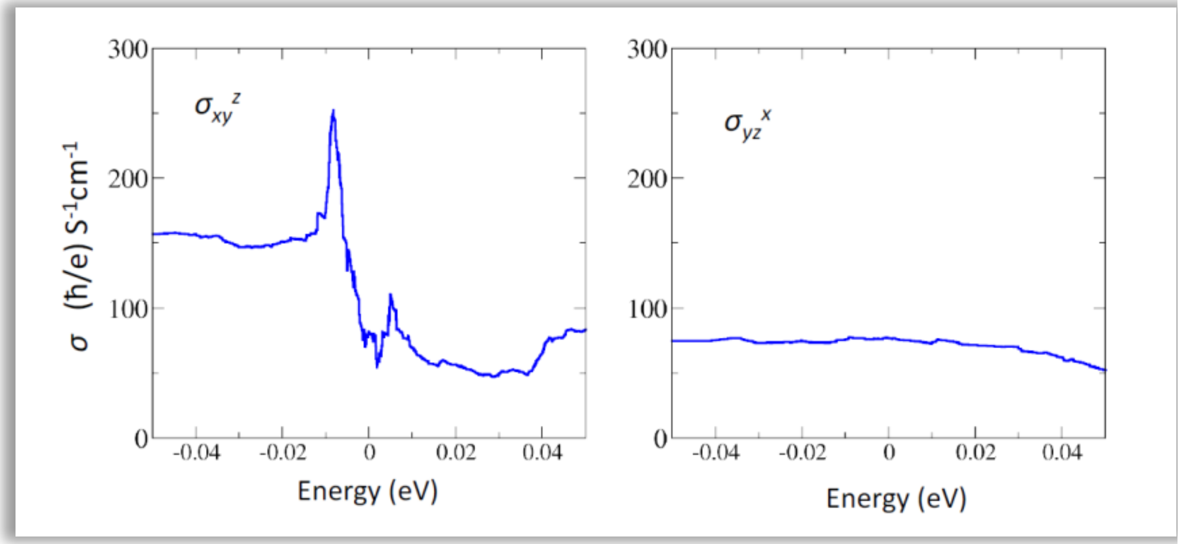

0
1
2
(a)
-100
-3-11
-3-1-1
-1-10


[111]
(b)
M (μB/f.u.)
H (T)
0.02
0.01
0.00
-0.01
-6
-4
-2
0
2
4
6


(c)
ρyx (10-7 Ω cm)
H (T)
6
4
2
0
-2
-4
-10
-8
-6
-4
-2
0
2
4
6
8
10

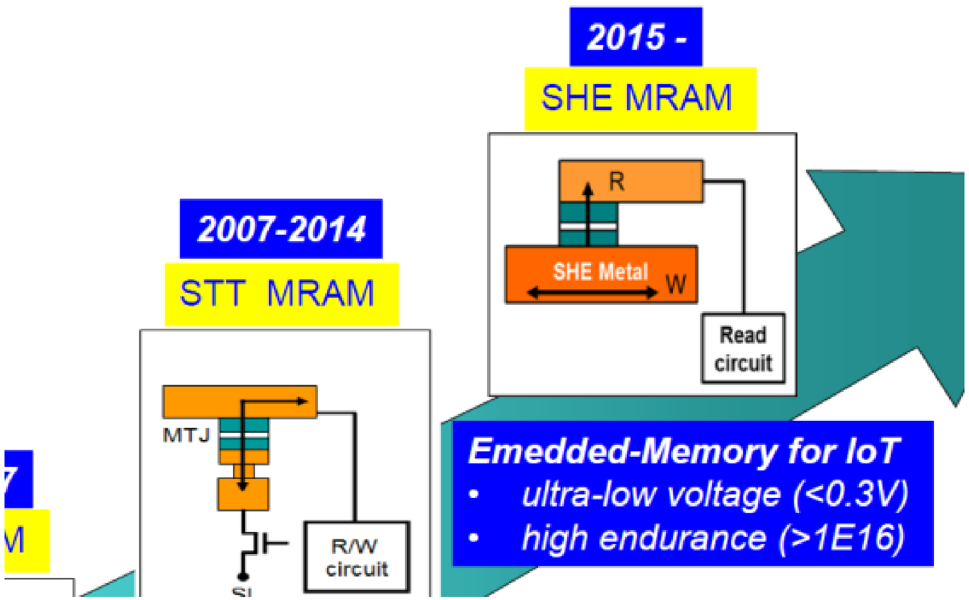
Application Spin Hall Effect

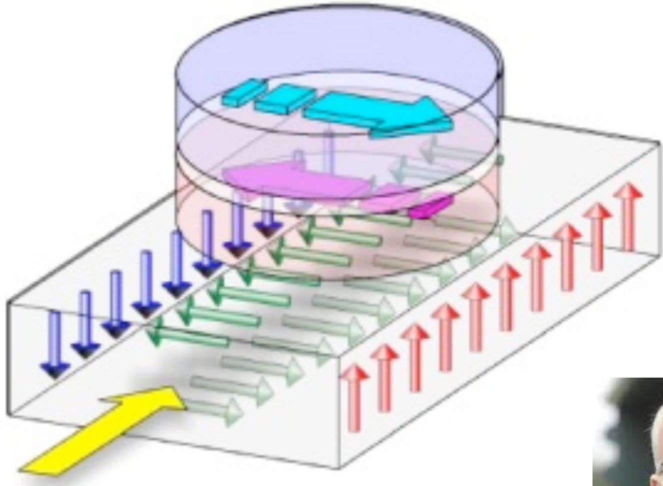




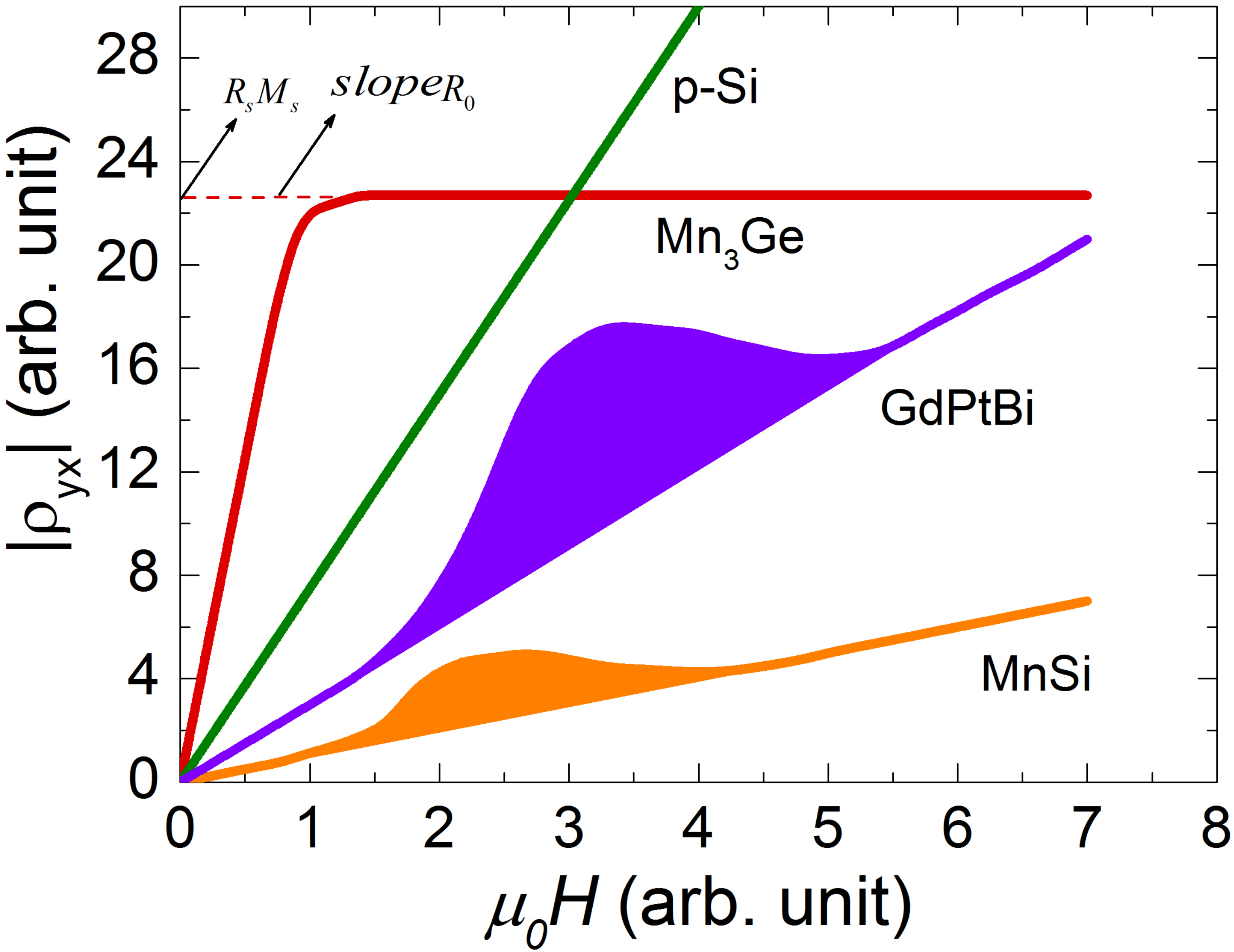
Yan Sun et al., Physical Review Letter 117 (2016) 146401

ITRI's MRAM Roadmap



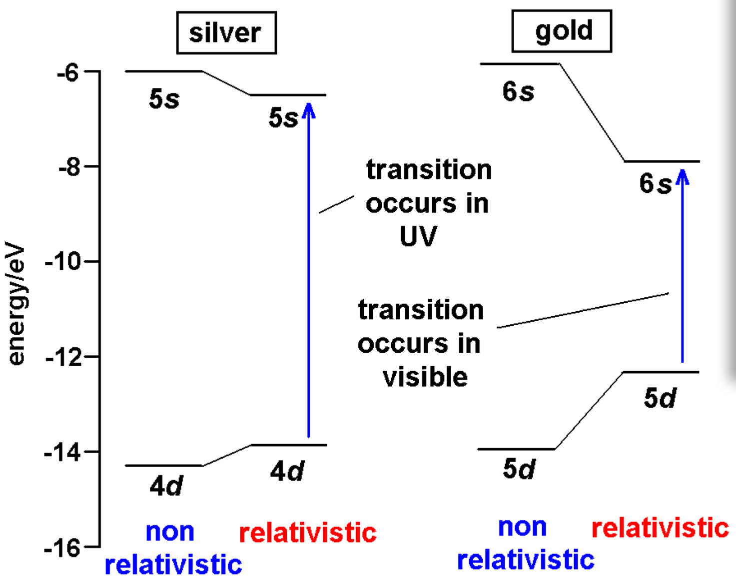


Anomalous Hall effect



Topological Metals

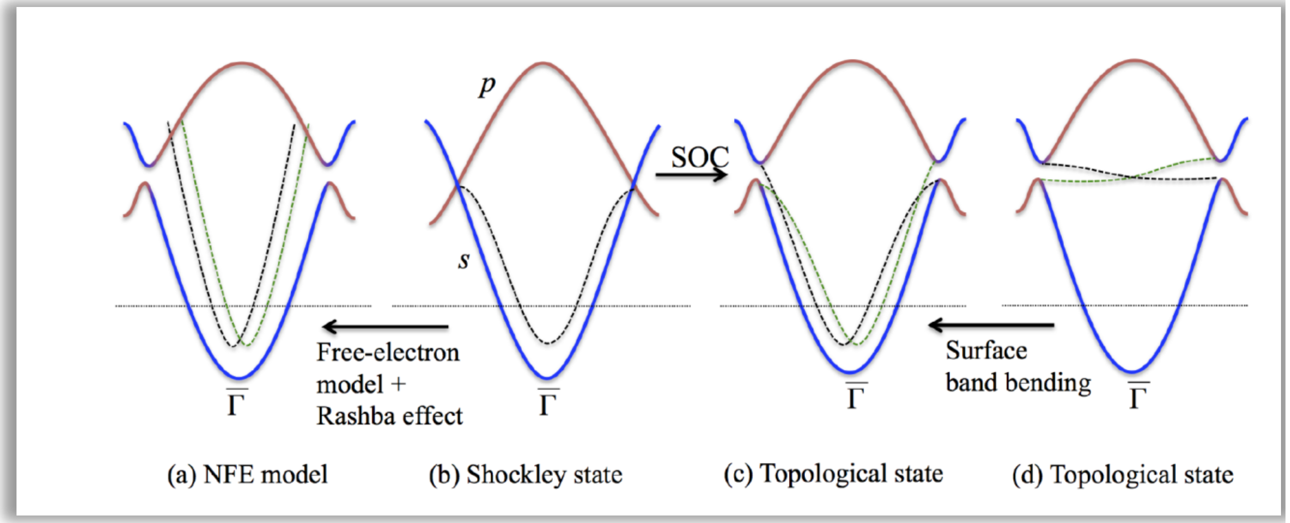
Rewriting the text book: Au



AUGUST 15, 1939 PHYSICAL REVIEW VOLUME 56

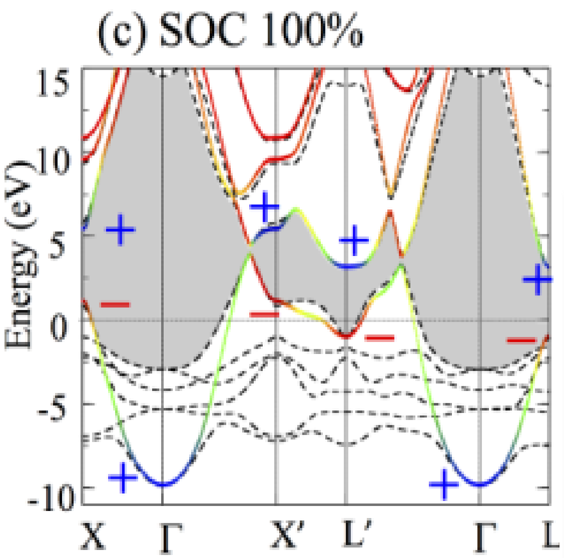
On the Surface States Associated with a Periodic Potential

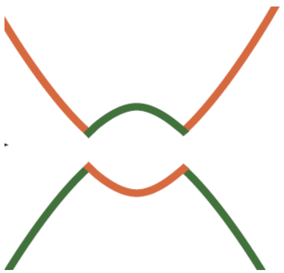
WILLIAM SHOCKLEY
Bell Telephone Laboratories, New York, New York
(Received June 19, 1939)

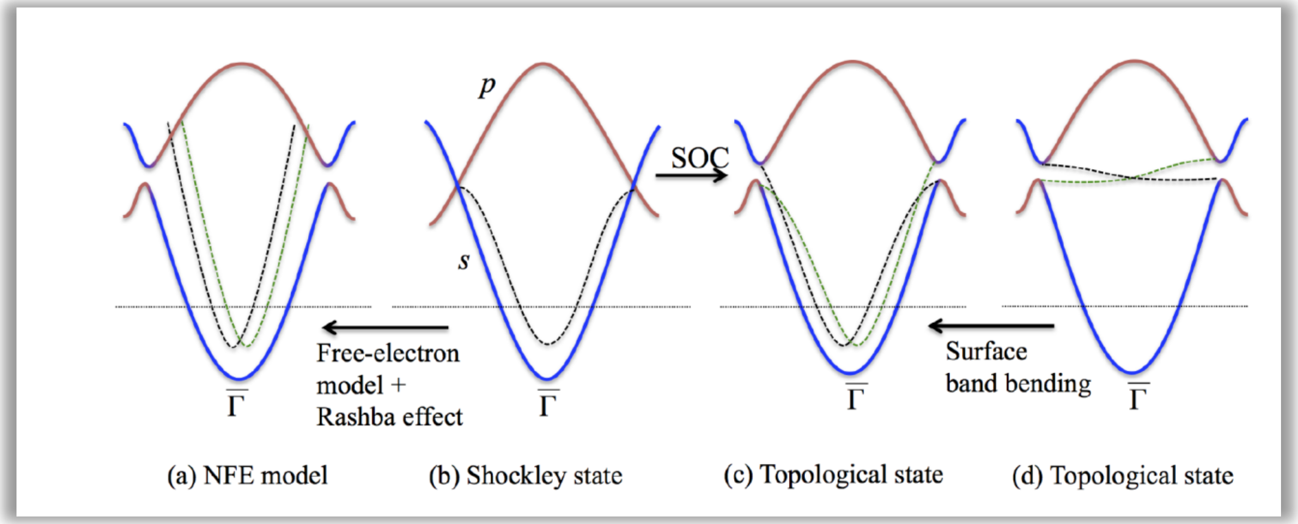


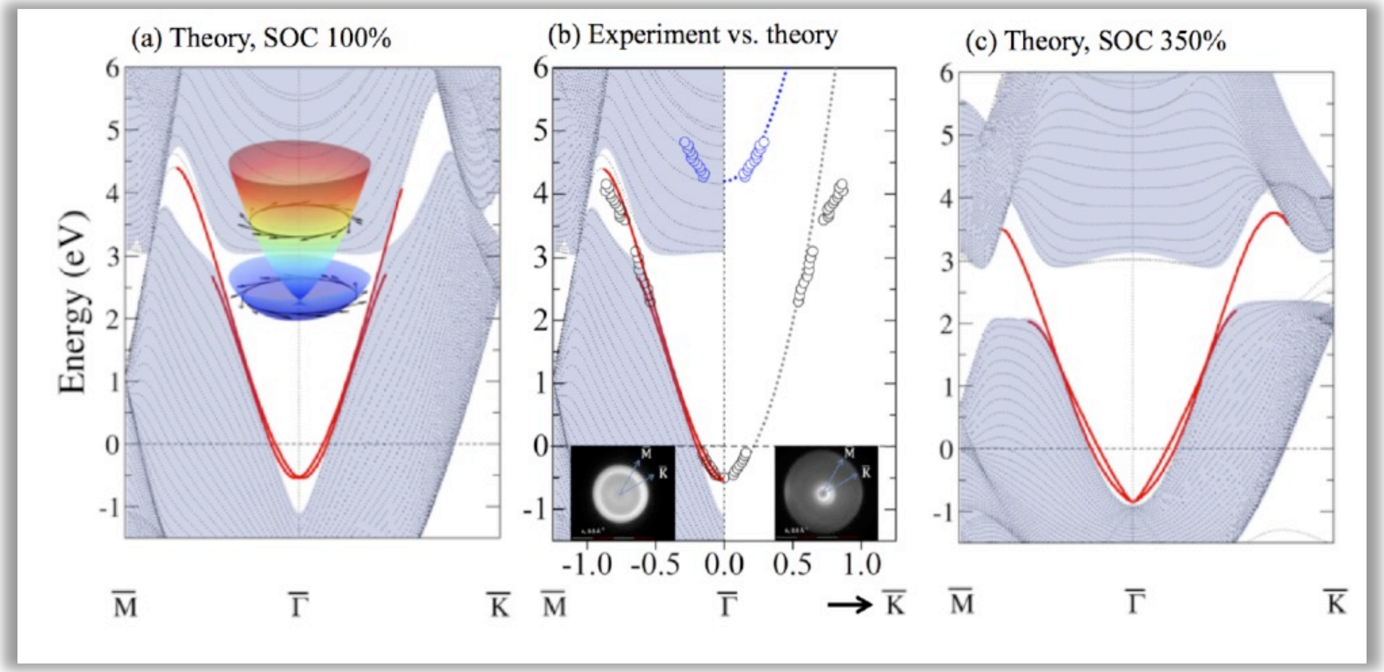
Binghai Yan at al., Nature Communication 6 (2015) 10167

Rewriting the text book: Au









$Cs^{+}Au^{-}$

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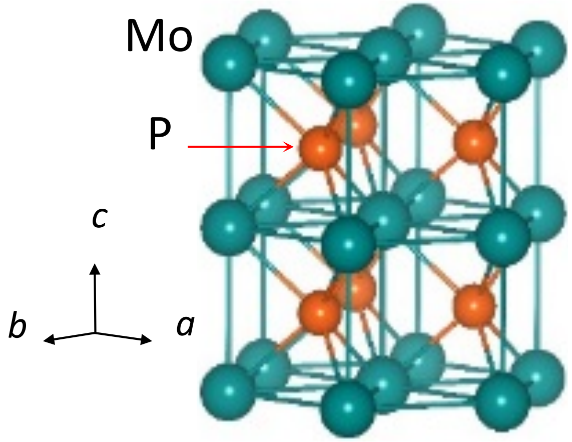
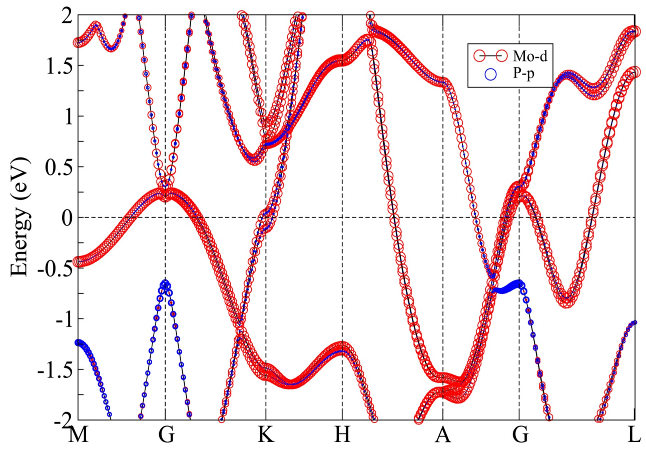
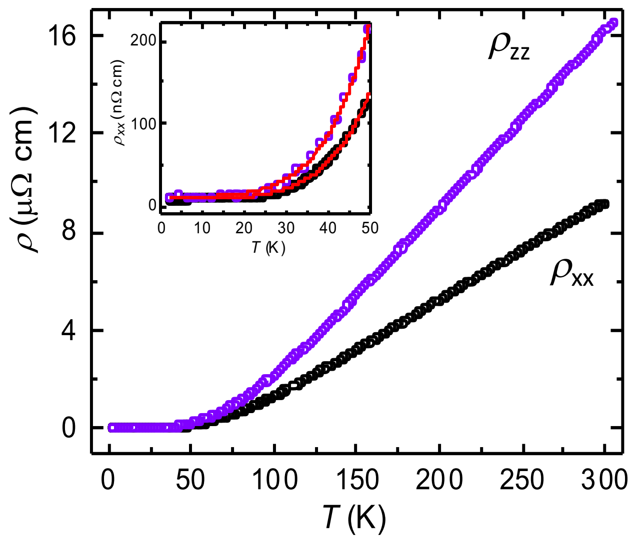
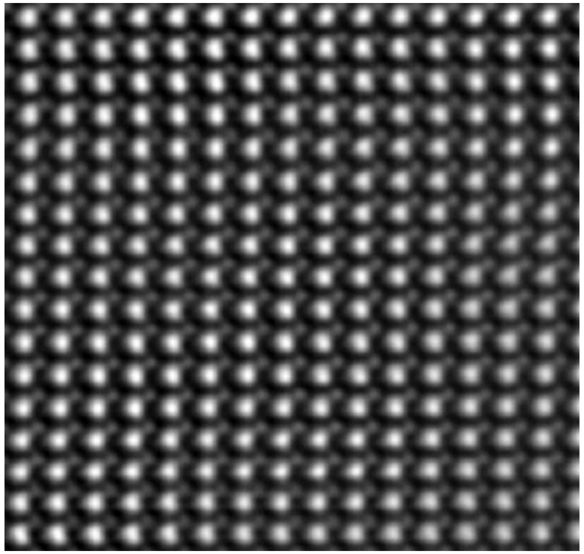
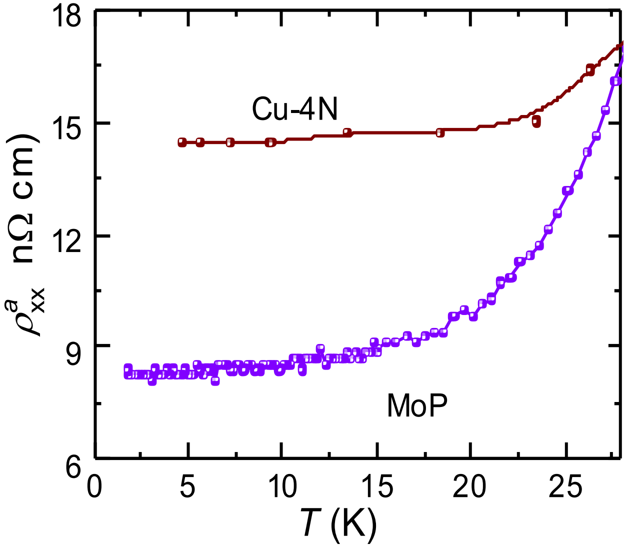
MoP better than Copper

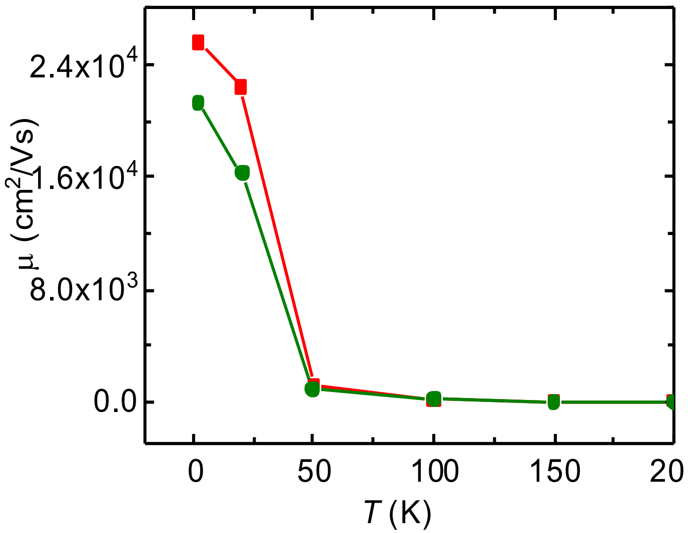






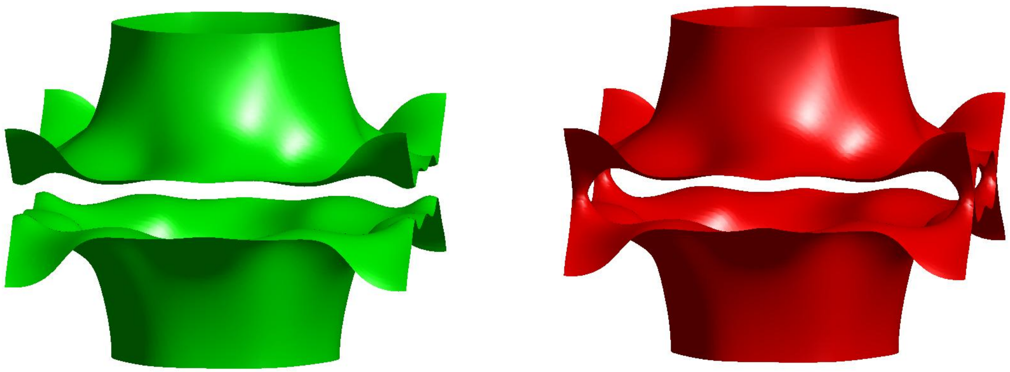






Chandra Shekhar et al. arXiv:1703.03736

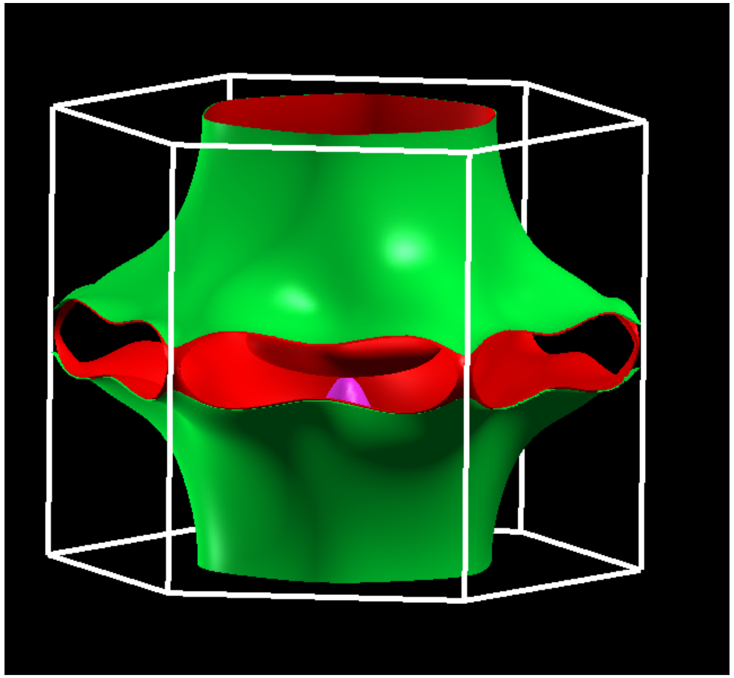
Fermi surfaces



$$2.7\times10^{22}\,cm^{-3}$$

$$1.12\times10^{21}\,cm^{-3}$$

$$2.57\times10^{20}\,cm^{-3}$$



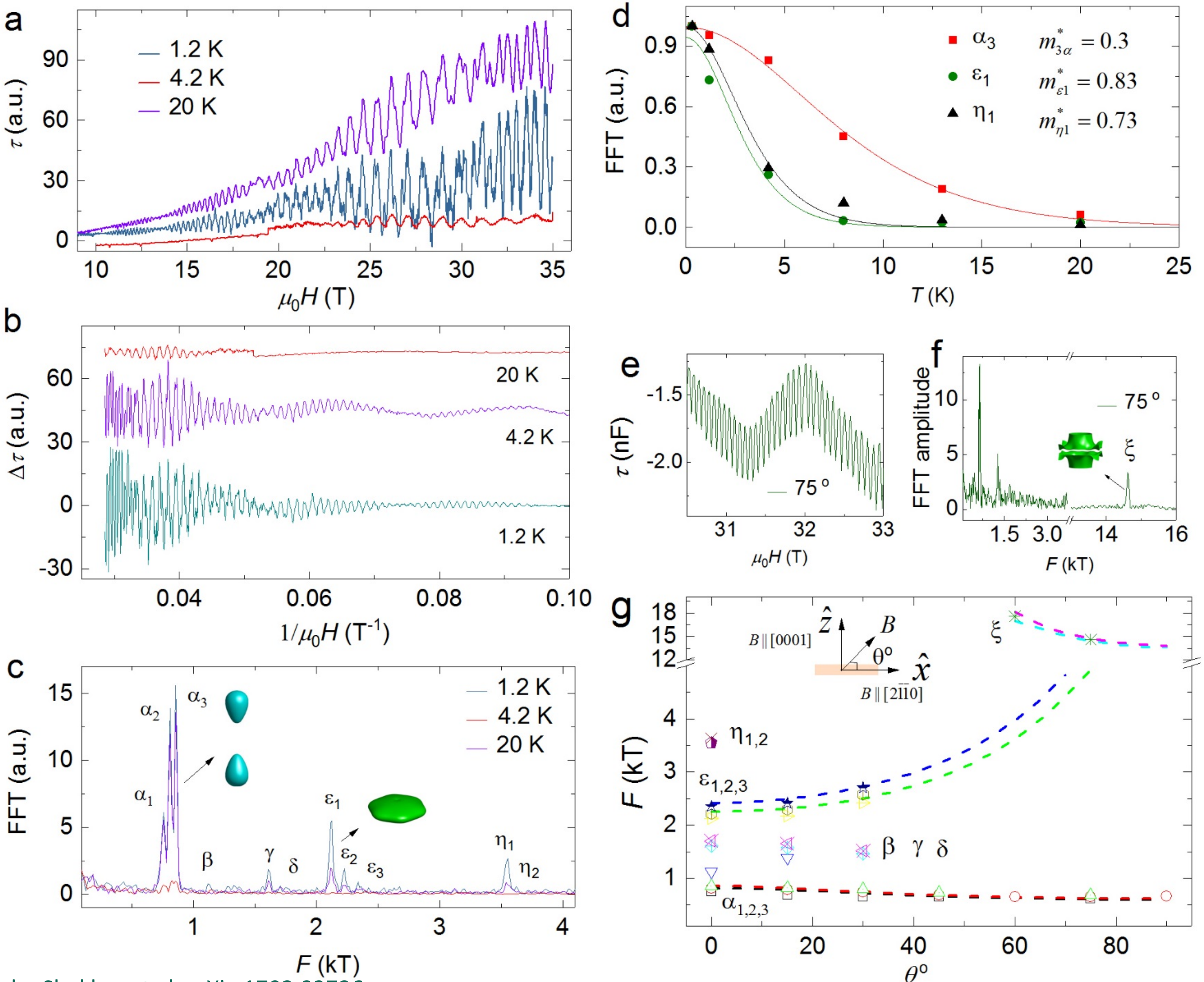
Charge carriers are mainly from the open Fermi surface

Experimental measurement is around $3.2\times10^{22}\,cm^{-3}$ at 2K

Experiment and calculation have the same order of magnitude

Chandra Shekhar et al. arXiv:1703.03736

Quantum Oscillations



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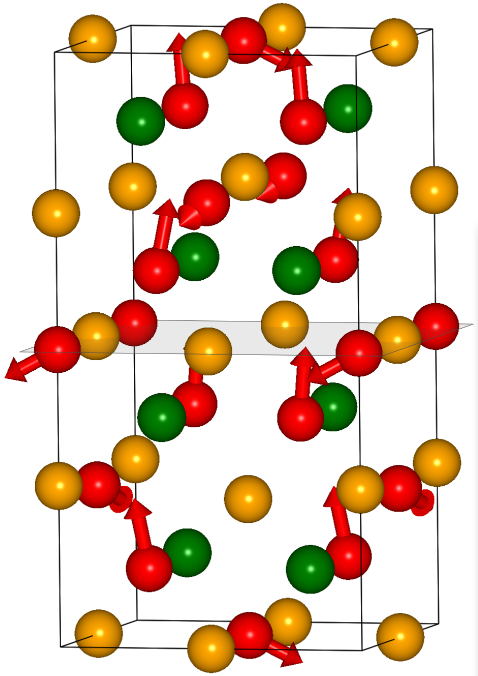
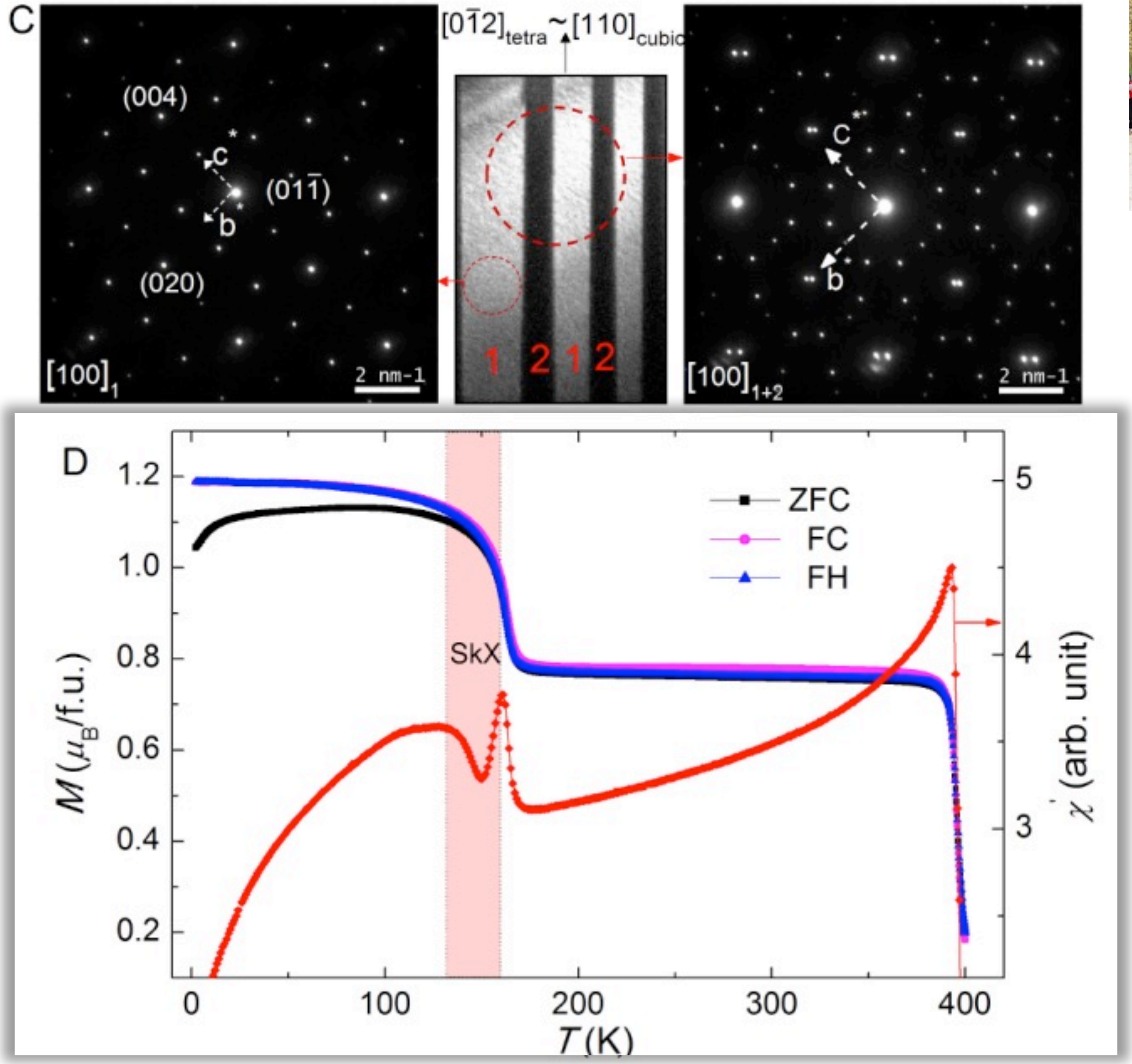
Skyrmions

Real space Berry curvature

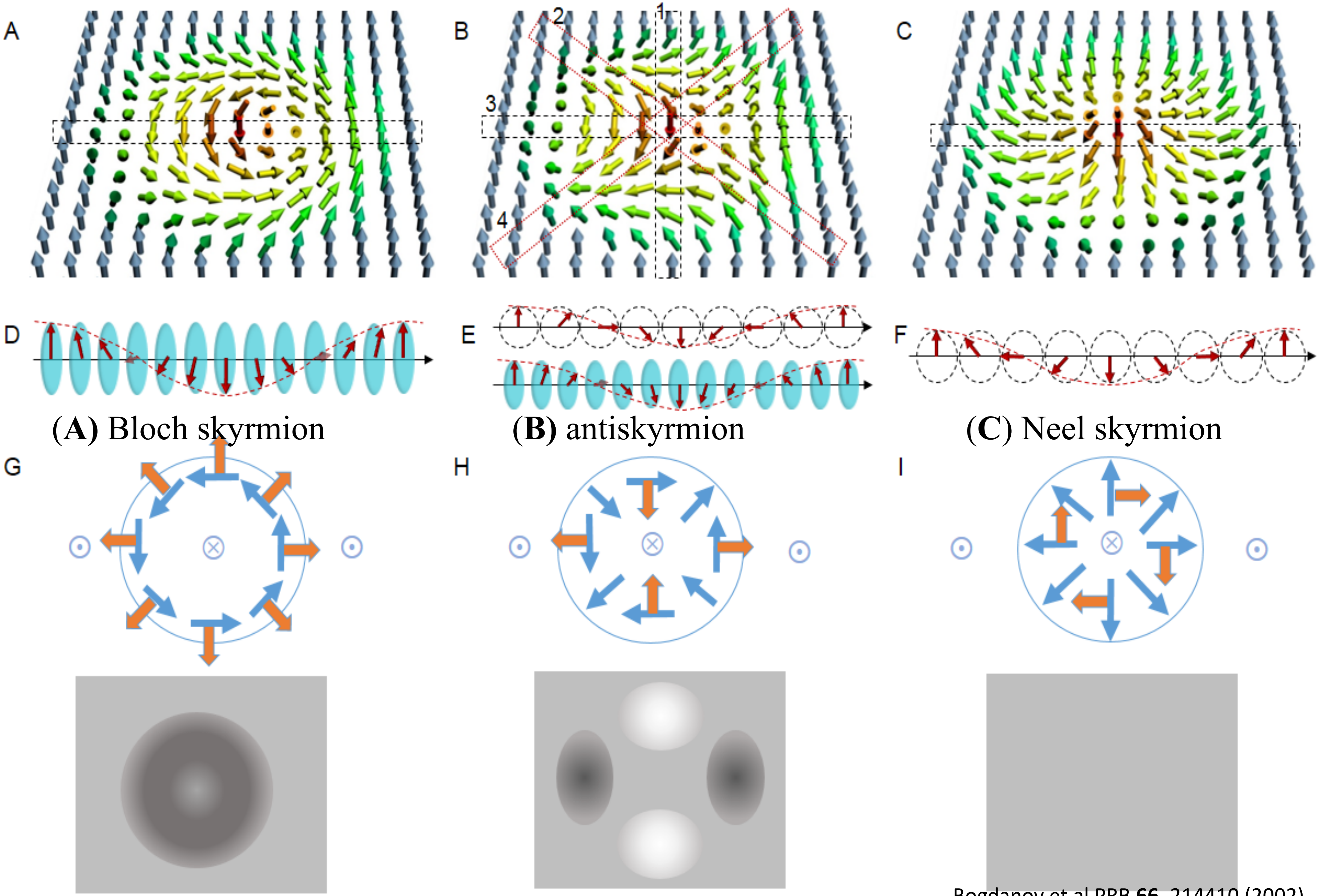
Mn-Pt-Sn – non collinear





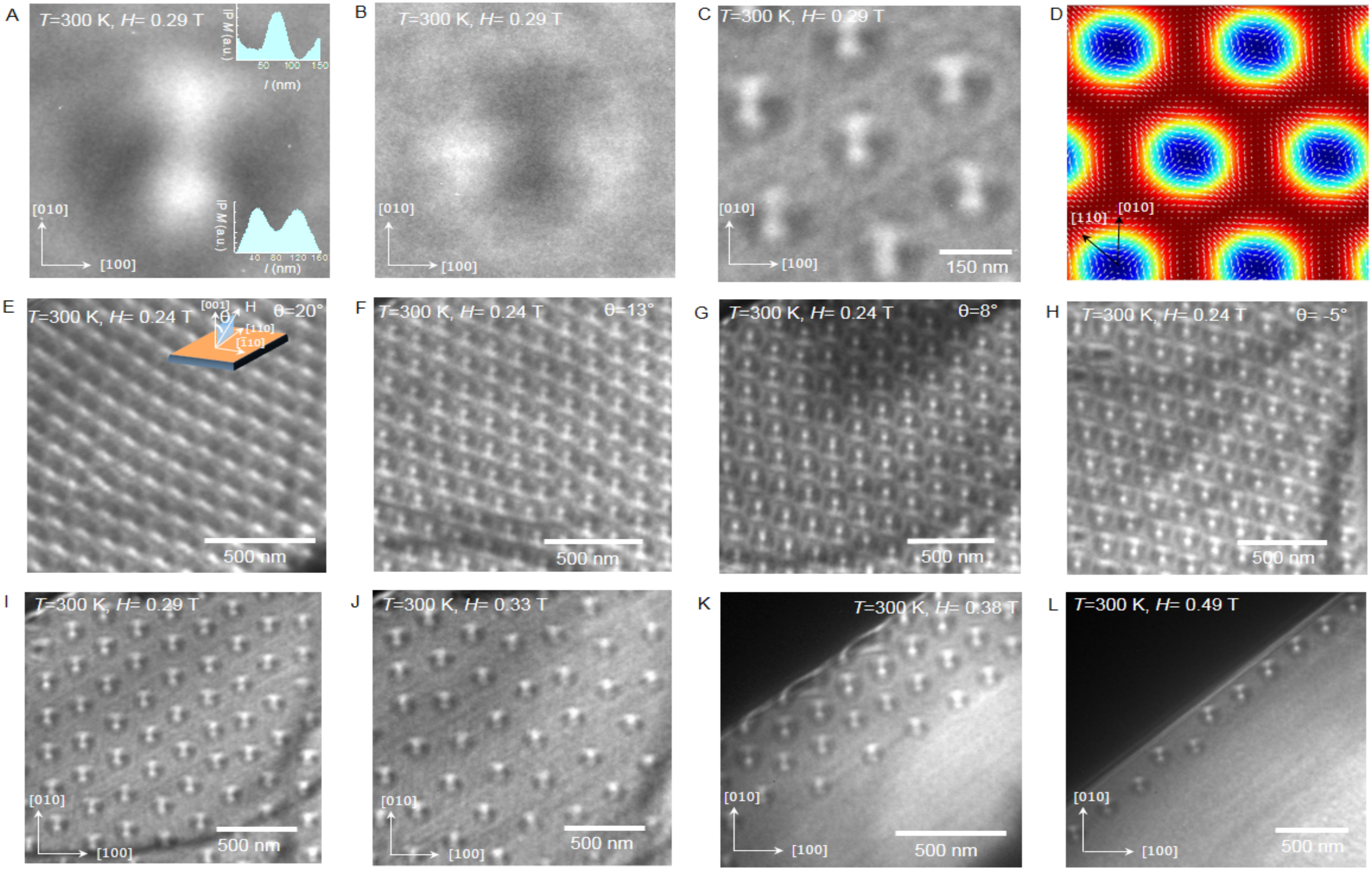
Nayak, et al. preprint arXiv:1703.01017

Real space topology - Skyrmions



Bogdanov et al PRB **66**, 214410 (2002)

$Mn_{1.4}Pt_{0.9}Pt_{0.1}Sn$: Anti-Skyrmions

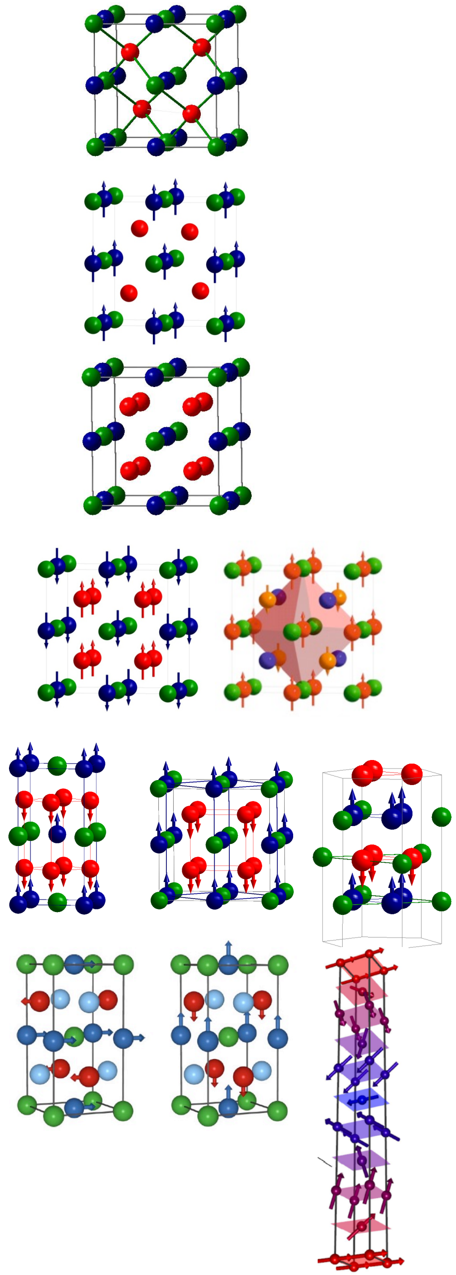


Nayak, et al. preprint arXiv:1703.01017

Bogdanov et al PRB **66**, 214410 (2002)

Tunability of Heusler compounds

- Tuning the band gap
- Tuning spin orbit coupling
  - Trivial and topological Heusler
- Adding spins
  - half metals,magnetic semiconductors
  - Weyl semimetals
- Localized and delocalized spins
- Tuning the magnetic sublattices
  - ferro to ferri: Compensated ferrimagnets
  - Centro and non-centro symmetric Weyl
  - Adding anisotropy
  - lattice distortion via van Hove and Jahn Teller
- In and out of plane magnetization
- Non collinear spin structures and frustration
  - Dzyaloshinskii-Moriya
  - Berry phase in antiferromagnets
  - Skyrmions



Summary

Is there a relation between reciprocal and real space Berry curvature

Many materials proposed, only a few made

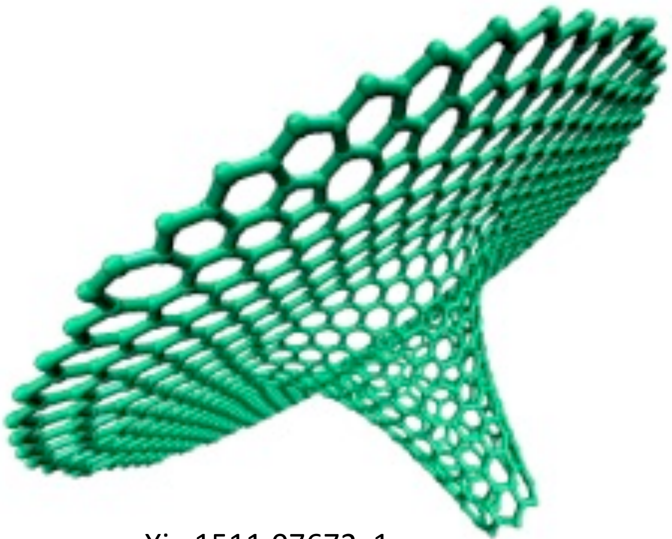
- More Weyl and Dirac semimetals
- More new Fermions
- High quality single crystals, defect free – or with defects
- Topological insulators in oxides, correlated systems
- Generalization of the concept
  - Magnetic Fermions
  - Thin films
  - Superconductors – Majorana
  - Chemical reactions
  - Phase transitions

New properties

- Thermal (magneto) transport
- (Magneto) optical properties …
- Devices

Applications

- Electronics
- Chemistry (Catalysis) …



arXiv:1511.07672v1

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]
[illegible]uLuSn
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!