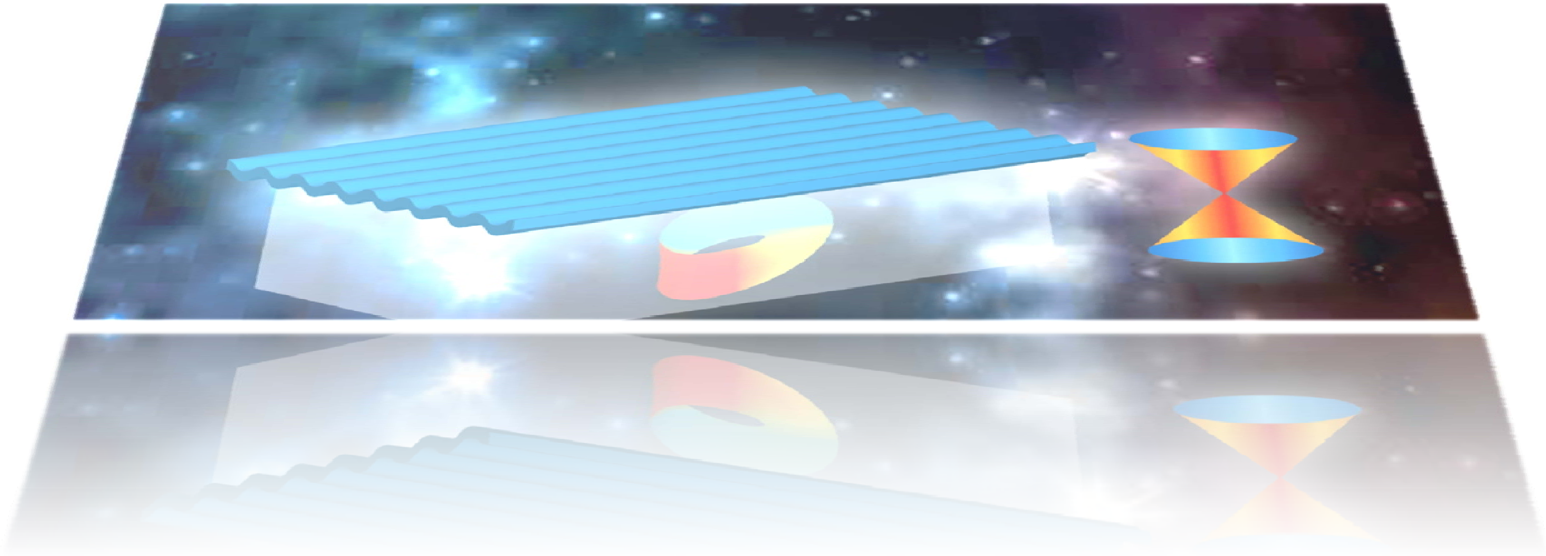
Topology – from the materials perspective



Special thanks to Binghai Yan, Shekhar Chandra, Lukas Müchler, Leslie Schoop, Stas Chadov, Sun Yan, Yulin Chen, Shoucheng Zhang, Stuart Parkin

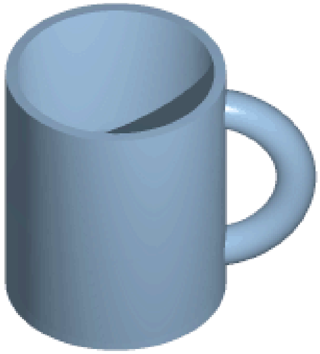
Claudia FELSER

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

Topological Insulators

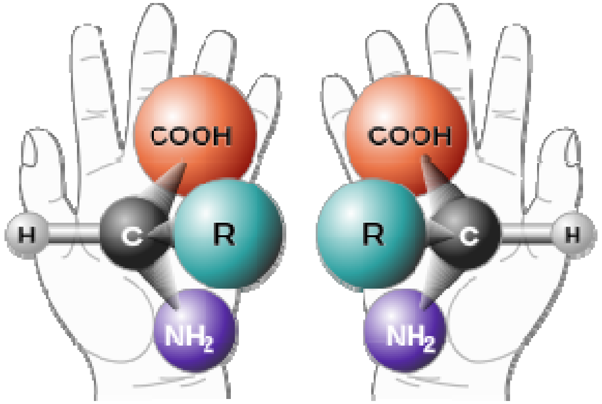
Topology

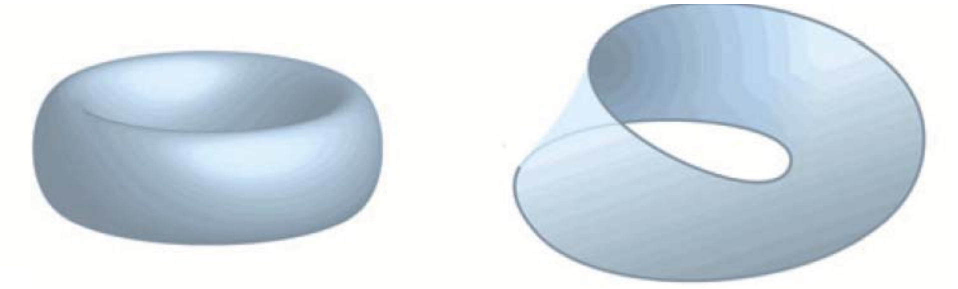


 $\cong$  $\ncong$  $\cong$ 

Topology in chemistry

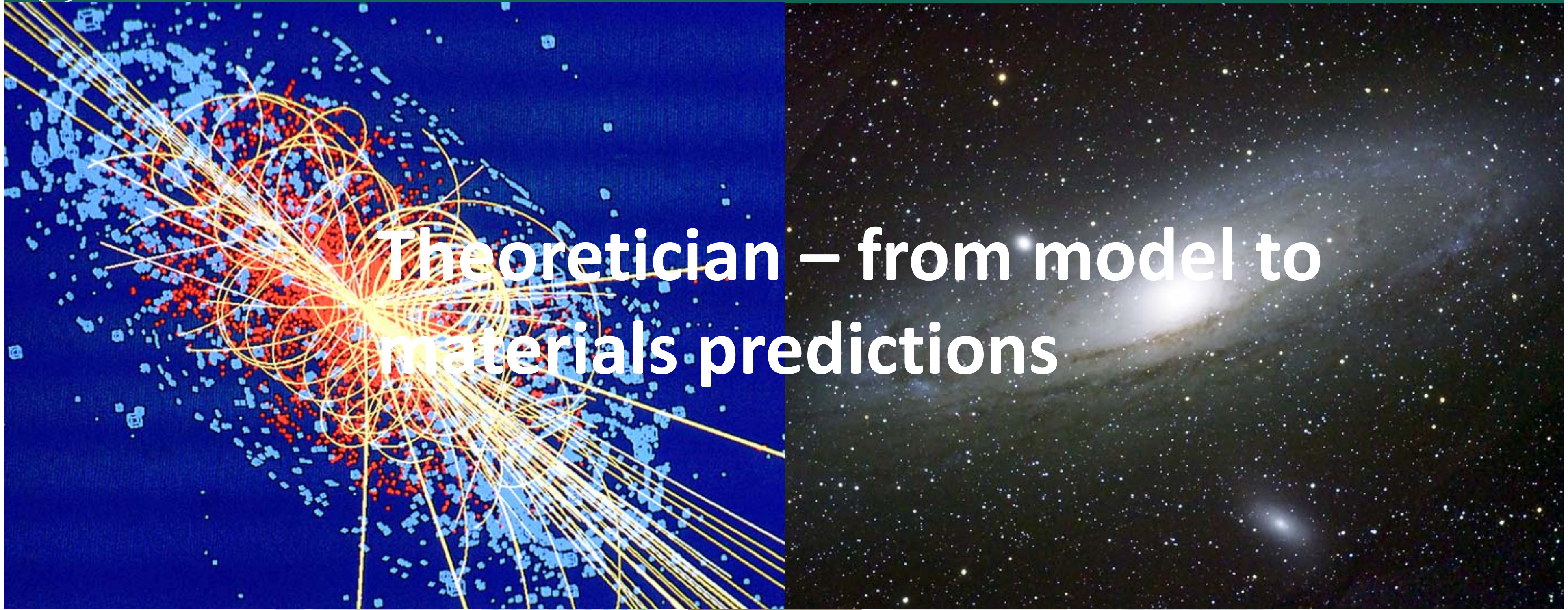
Molecules with different chiralities can have different physical and chemical properties



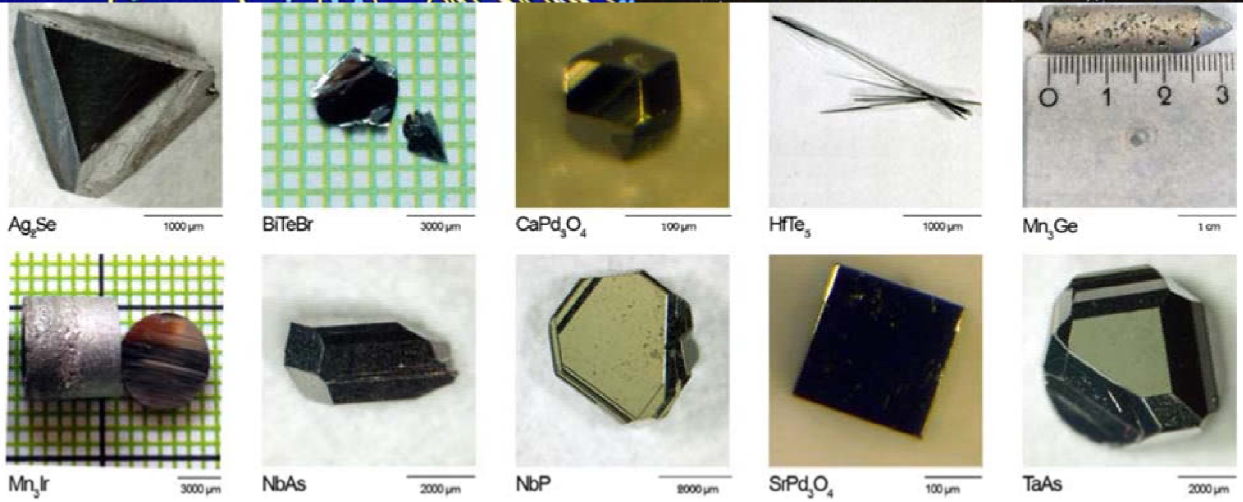


Topologically interesting compounds are 4n aromatics with Möbius geometry, whereas normal 4n compounds are anti-aromatic

Universe – particles – condensed matter



Theoretician – from model to materials predictions

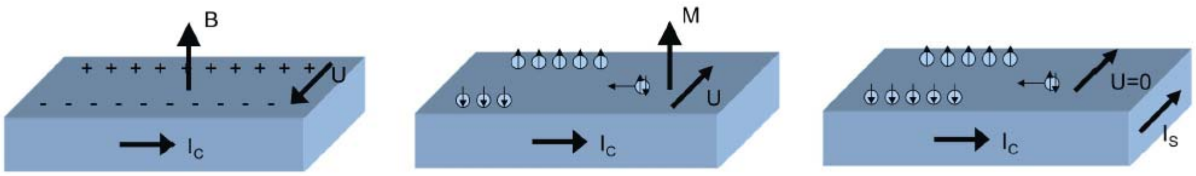


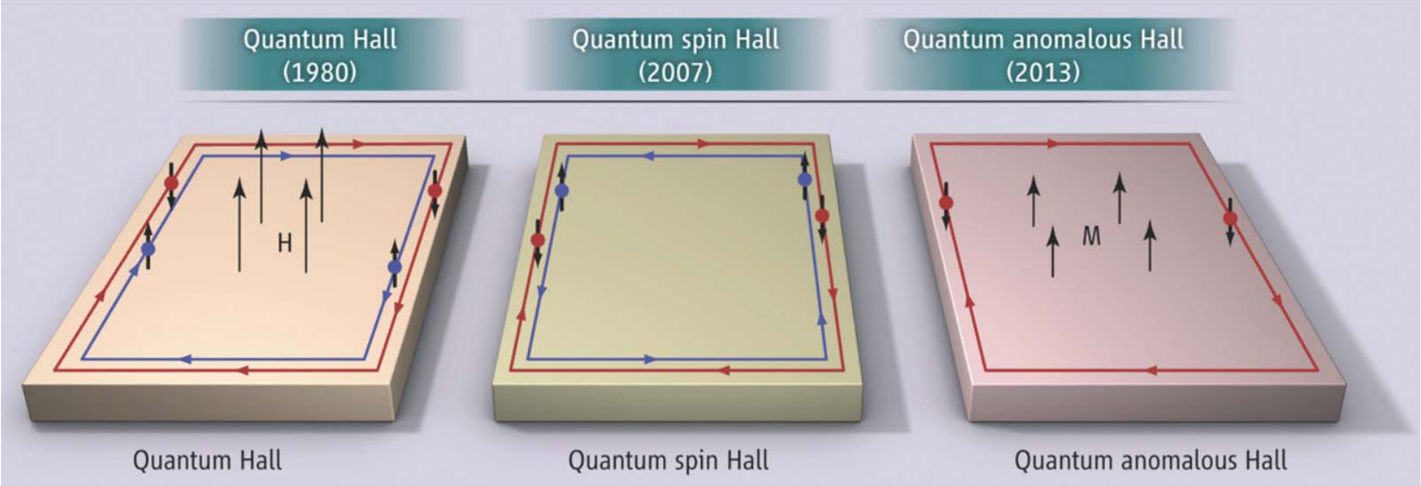
Family of quantum Hall effects

Hall effect
1879

Anomalous Hall effect
1881

Spin Hall effect
2004

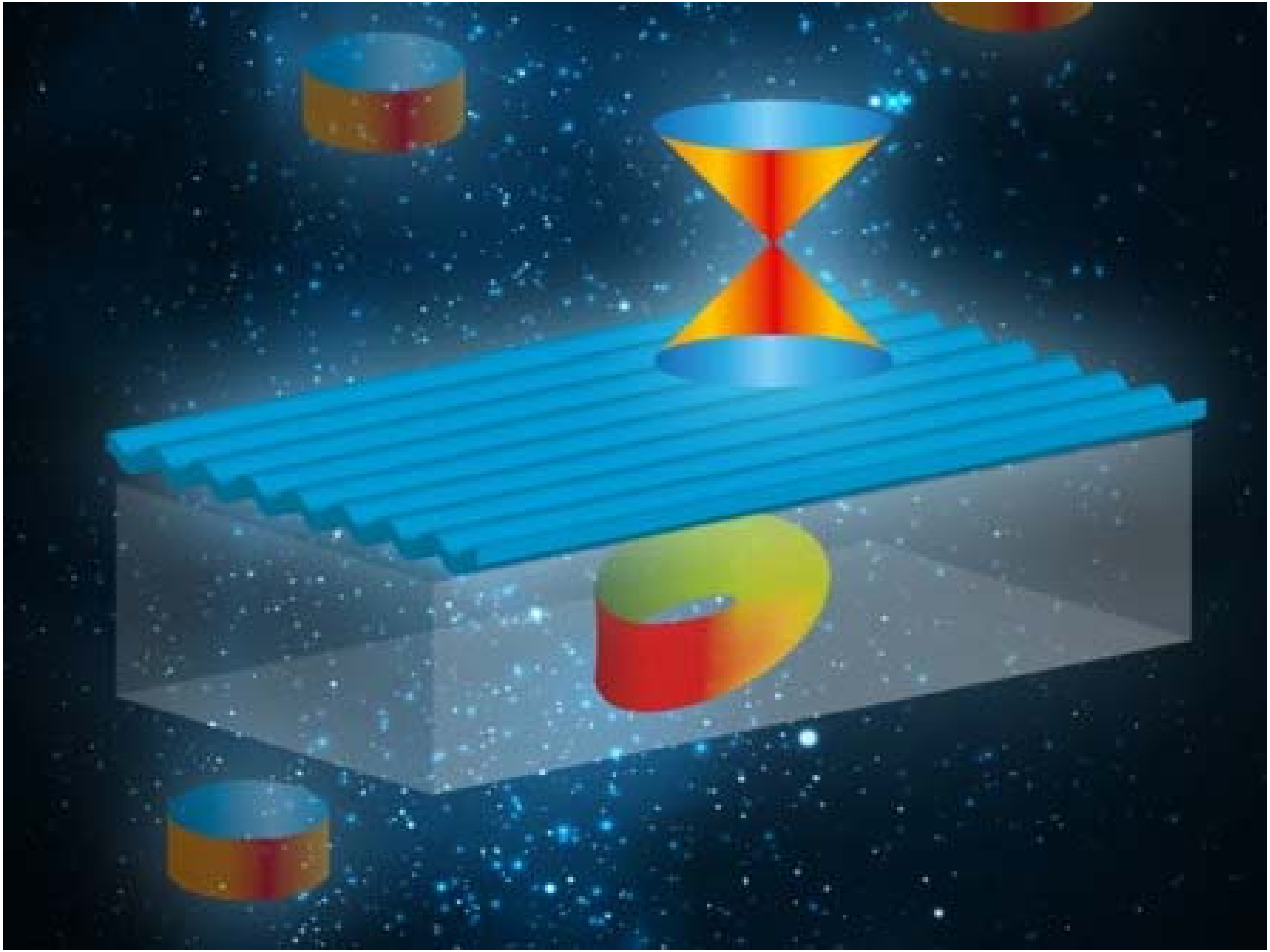




S Oh Science 340 (2013) 153

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

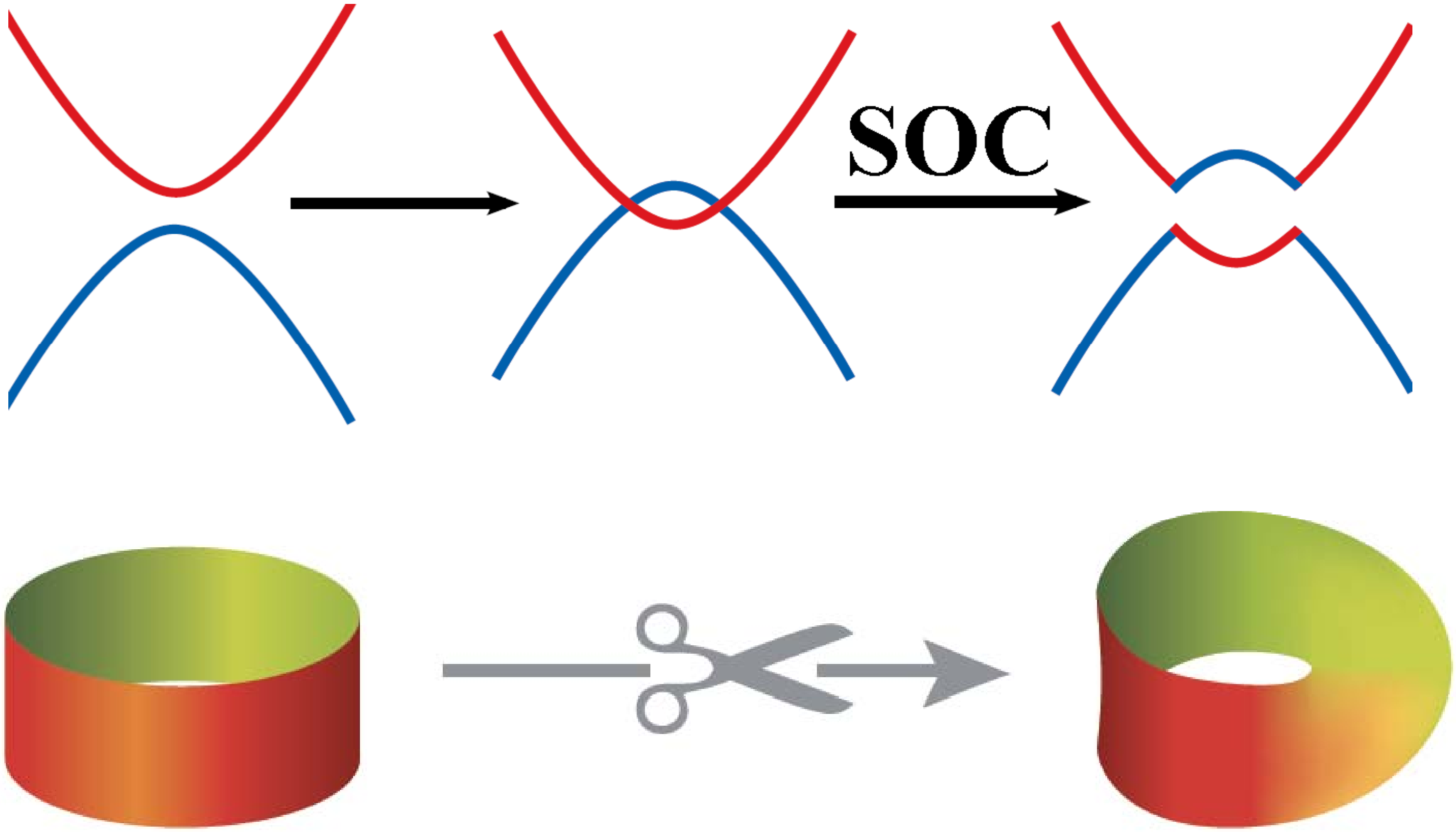


Trivial and topological insulators

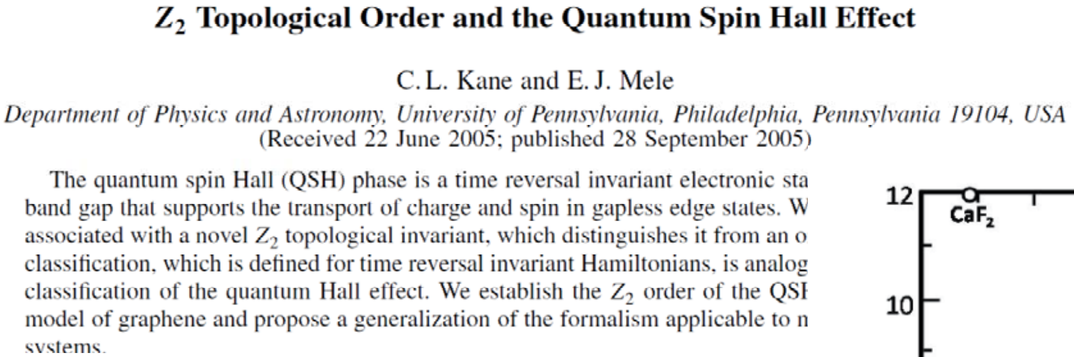
Trivial semiconductor
CdS

Topological Insulator
Without spin orbit coupling

Topological Insulator
Withspin orbit coupling



Topological insulator



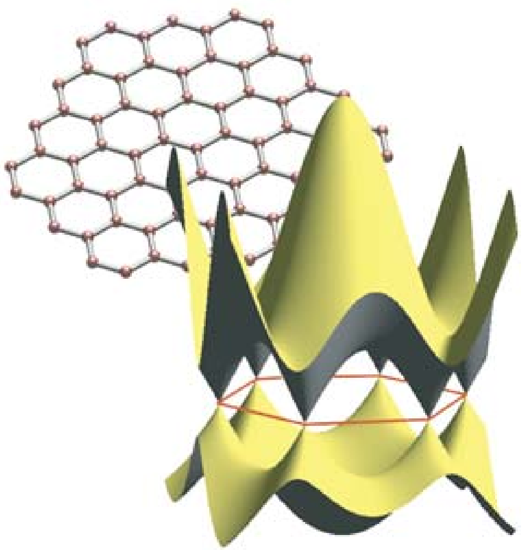
Z_2 Topological Order and the Quantum Spin Hall Effect

C. L. Kane and E. J. Mele

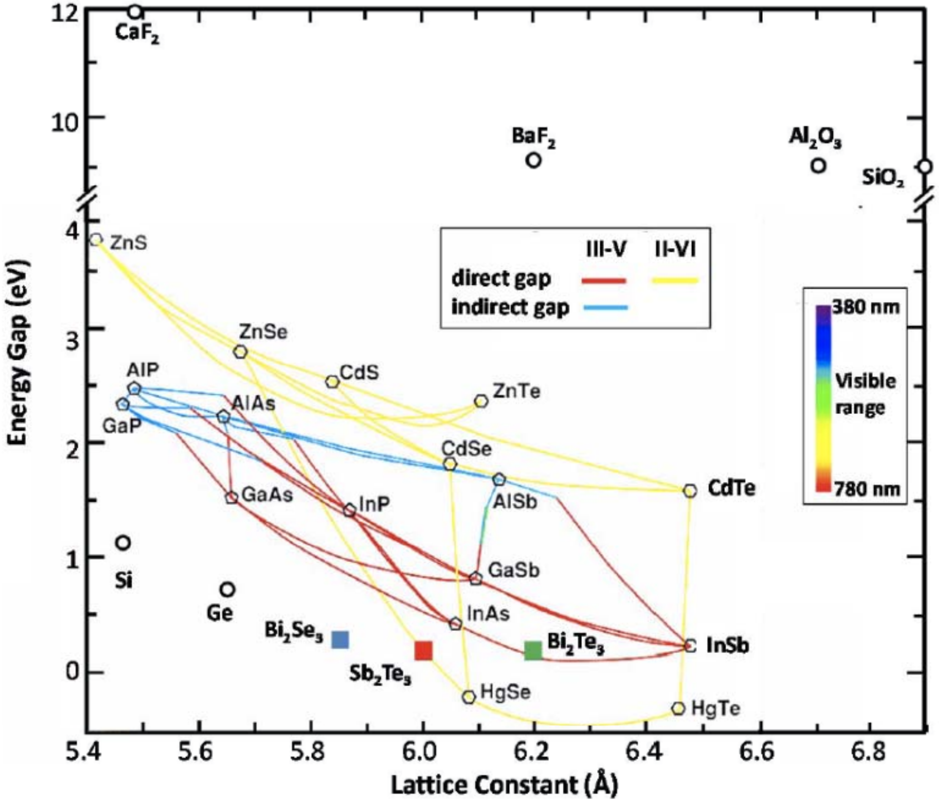
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

(Received 22 June 2005; published 28 September 2005)

The quantum spin Hall (QSH) phase is a time reversal invariant electronic sta band gap that supports the transport of charge and spin in gapless edge states. W associated with a novel Z_2 topological invariant, which distinguishes it from an o classification, which is defined for time reversal invariant Hamiltonians, is analog classification of the quantum Hall effect. We establish the Z_2 order of the QSI model of graphene and propose a generalization of the formalism applicable to n systems.



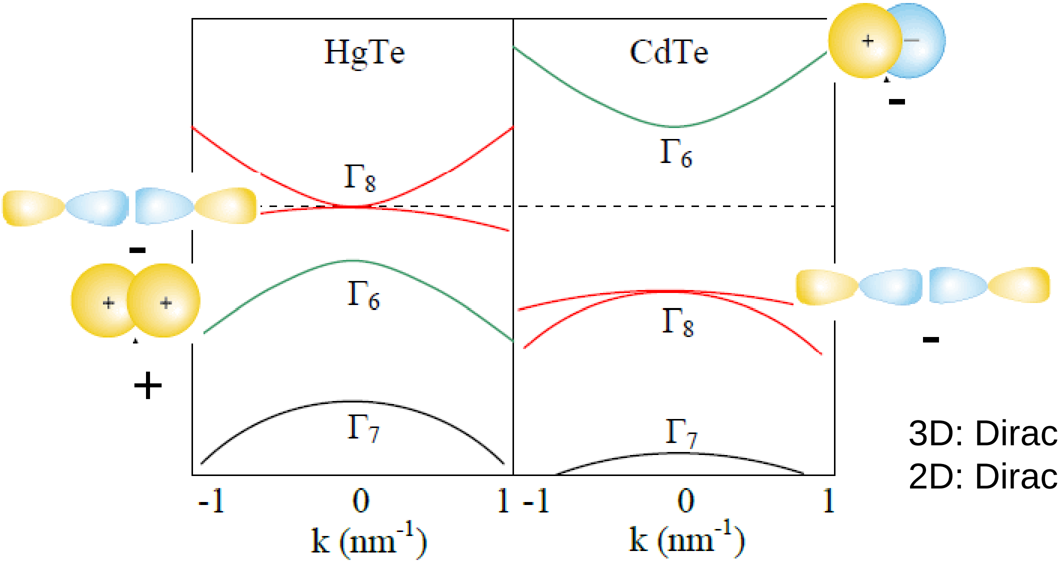
First prediction in graphene by Kane

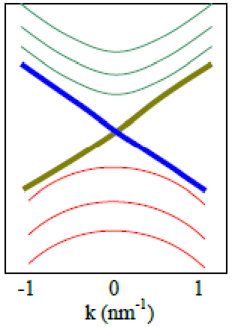


Kane and Mele, PRL 95, 146802 (2005)
Bernevig, et al., Science 314, 1757 (2006)
Bernevig, S.C. Zhang, PRL 96, 106802 (2006)
König, et al. Science 318, 766 (2007)

First success

Quantum Spin Hall Effect and Topological Phase Transition in HgTe Quantum Wells
B. Andrei Bernevig, *et al.*
Science **314**, 1757 (2006);
DOI: 10.1126/science.1133734





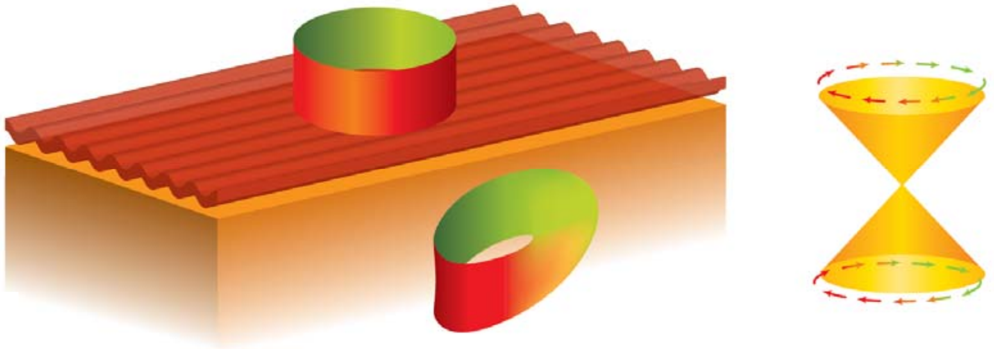
3D: Dirac cone on the surface
2D: Dirac cone in quantum well

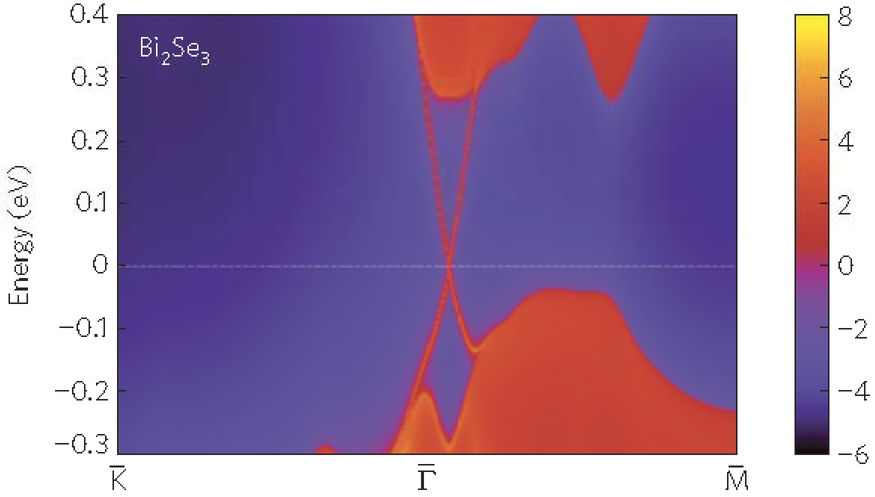
Theory and experiment

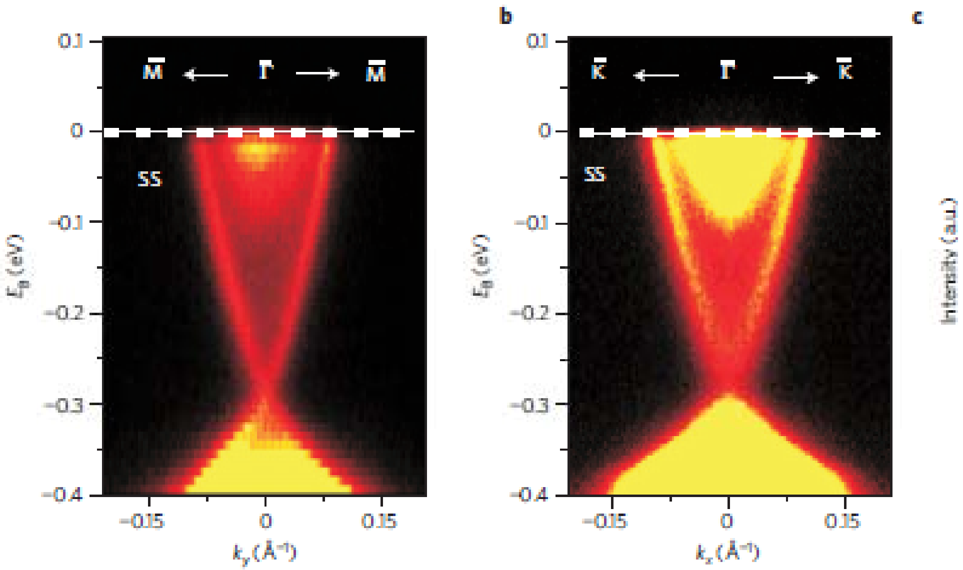
3D Topological Insulators

Bi-Sb alloys

Bi_2Se_3 and relatives







Moore and Balents, PRB 75, 121306(R) (2007)
Fu and Kane, PRB 76, 045302 (2007)
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Hsieh, et al., Science 323, 919 (2009)
Xia, et al., Nature Phys. 5, 398 (2009); Zhang, et al., Nature Phys. 5, 438 (2009)

Materials

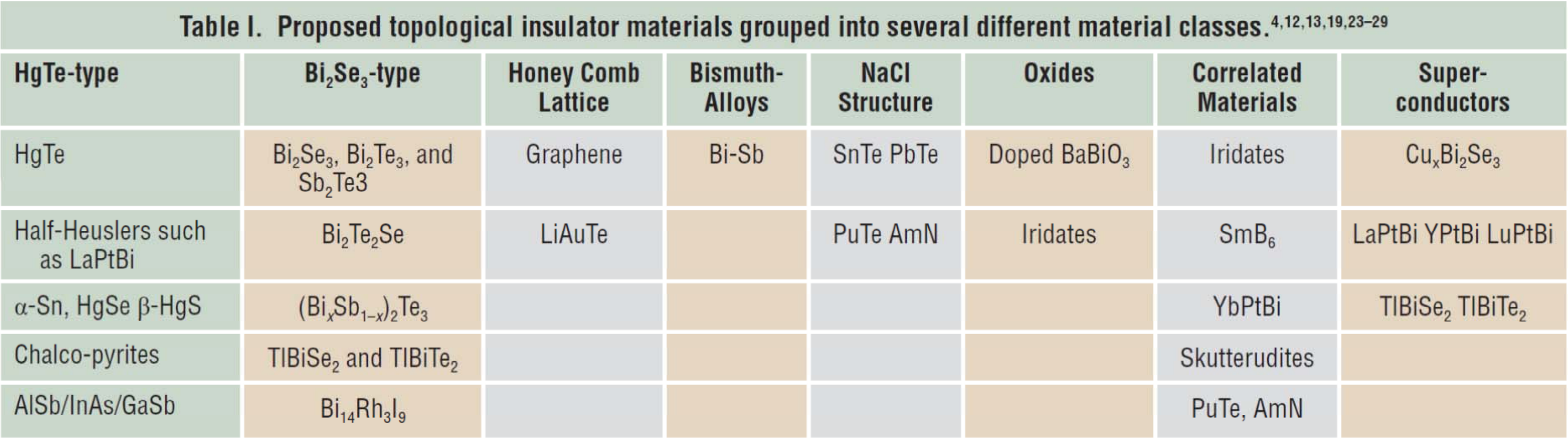


Table I. Proposed topological insulator materials grouped into several different material classes.[4,12,13,19,23–29]

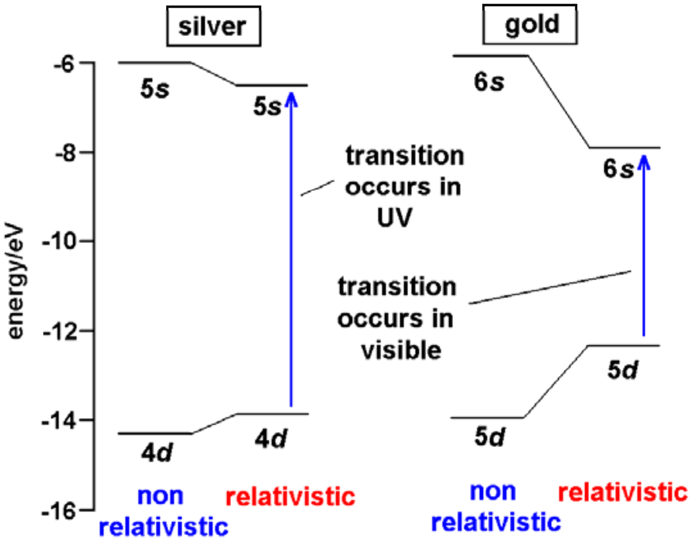
HgTe-type	Bi_2Se_3-type	Honey Comb Lattice	Bismuth-Alloys	NaCl Structure	Oxides	Correlated Materials	Super-conductors
HgTe	Bi_2Se_3, Bi_2Te_3, and Sb_2Te3	Graphene	Bi-Sb	SnTe PbTe	Doped $BaBiO_3$	Iridates	$Cu_xBi_2Se_3$
Half-Heuslers such as LaPtBi	Bi_2Te_2Se	LiAuTe		PuTe AmN	Iridates	SmB_6	LaPtBi YPtBi LuPtBi
α-Sn, HgSe β-HgS	$(Bi_xSb_{1-x})_2Te_3$					YbPtBi	$TlBiSe_2$ $TlBiTe_2$
Chalco-pyrites	$TlBiSe_2$ and $TlBiTe_2$					Skutterudites	
AlSb/InAs/GaSb	$Bi_{14}Rh_3I_9$					PuTe, AmN	

Claudia Felser and Xiao-Liang Qi , Guest Editors, MRS Bull. 39 (2014) 843.

Tl^{+1} Sn^{2+} Bi^{+3}

Inert pair effect

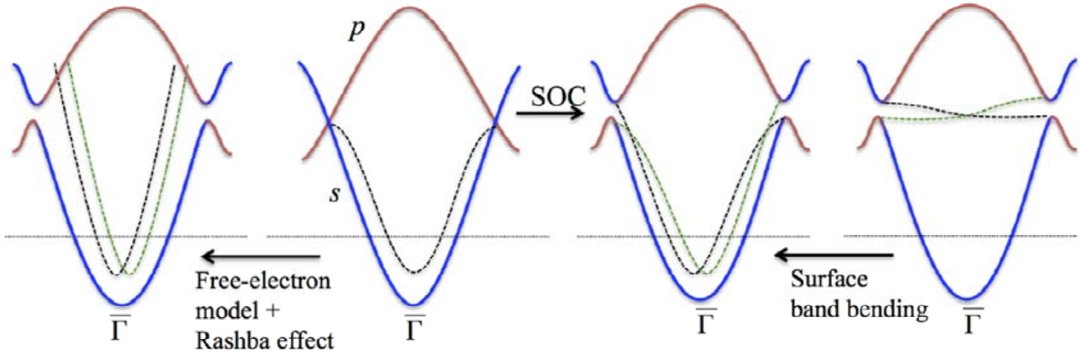
Rewriting the text book: Au



AUGUST 15, 1939 PHYSICAL REVIEW VOLUME 56

On the Surface States Associated with a Periodic Potential

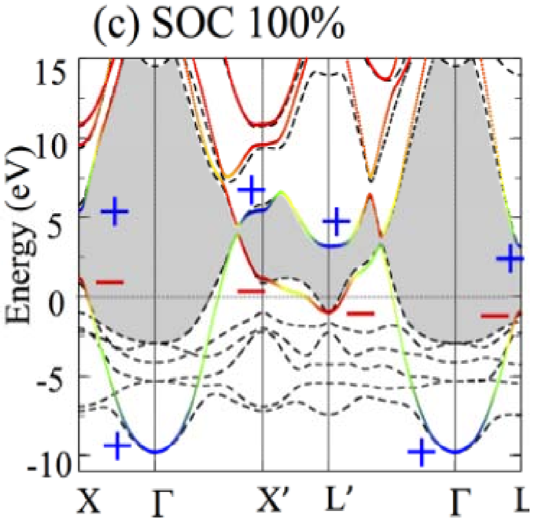
William Shockley
Bell Telephone Laboratories, New York, New York
(Received June 19, 1939)

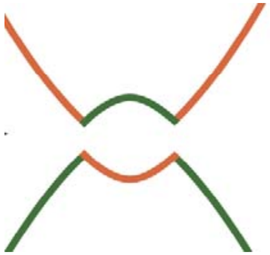


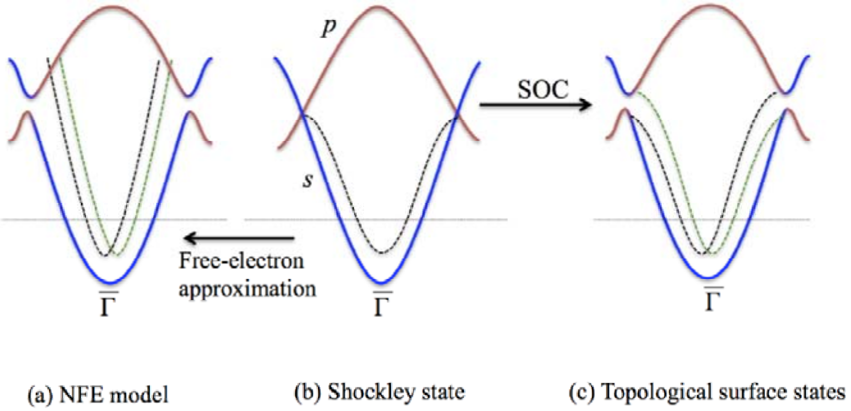
(a) NFE model (b) Shockley state (c) Topological state (d) Topological state

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

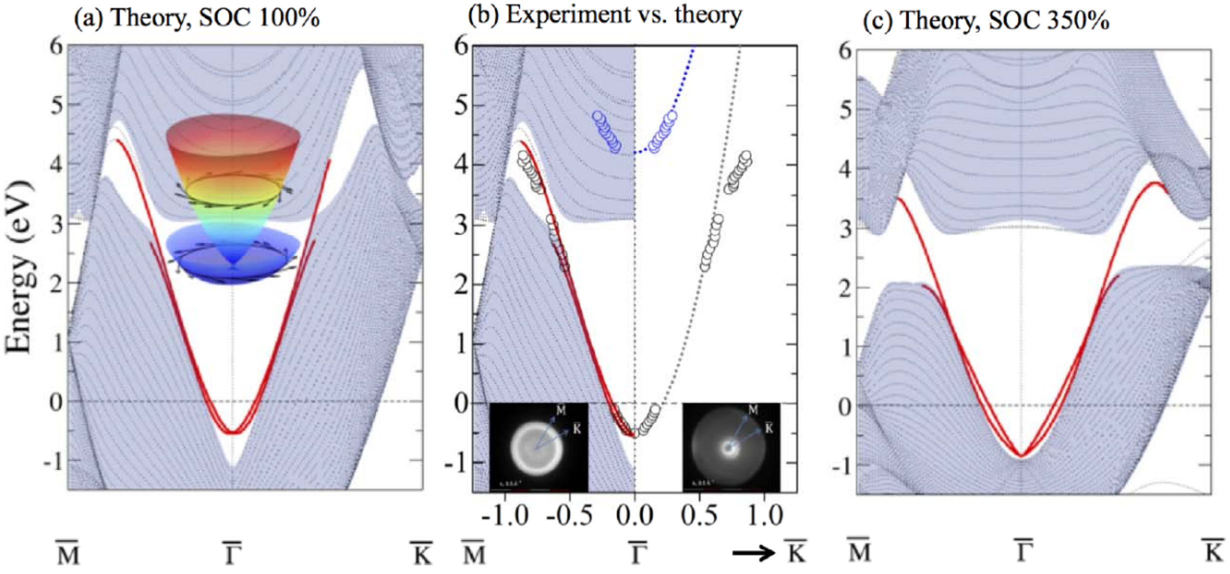
Rewriting the text book: Au







(a) NFE model (b) Shockley state (c) Topological surface states

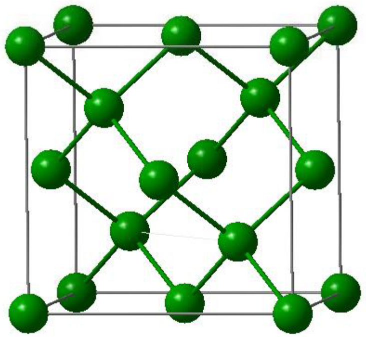


Cs^+Au^-

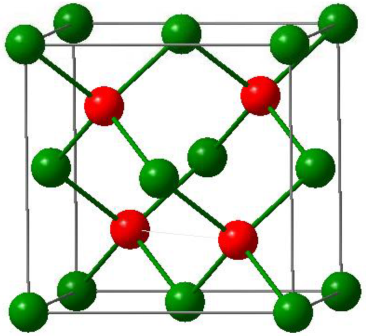
Binghai Yan at al., Nature Communication 6 (2015) 10167

Heusler compounds

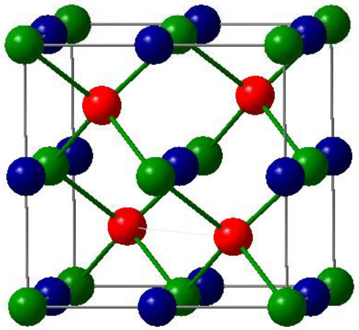
Diamond



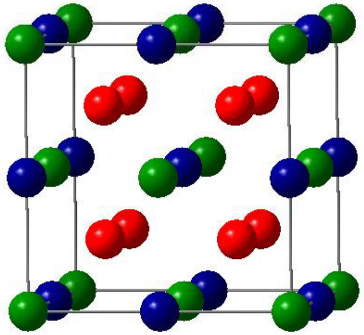
ZnS

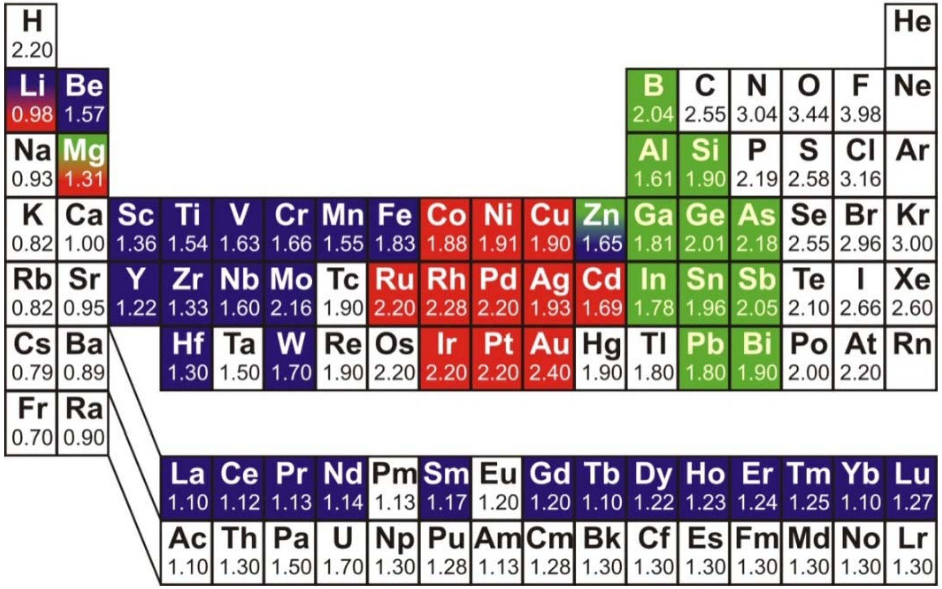


Heusler XYZ $C1_b$



X_2YZ $L2_1$

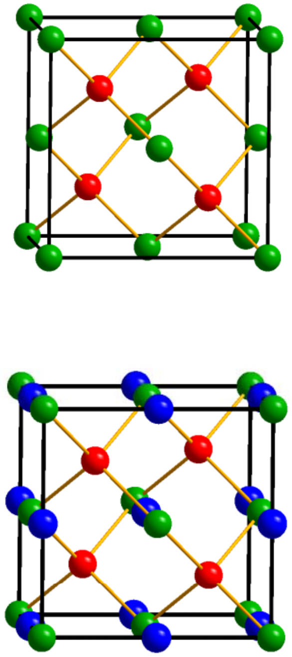


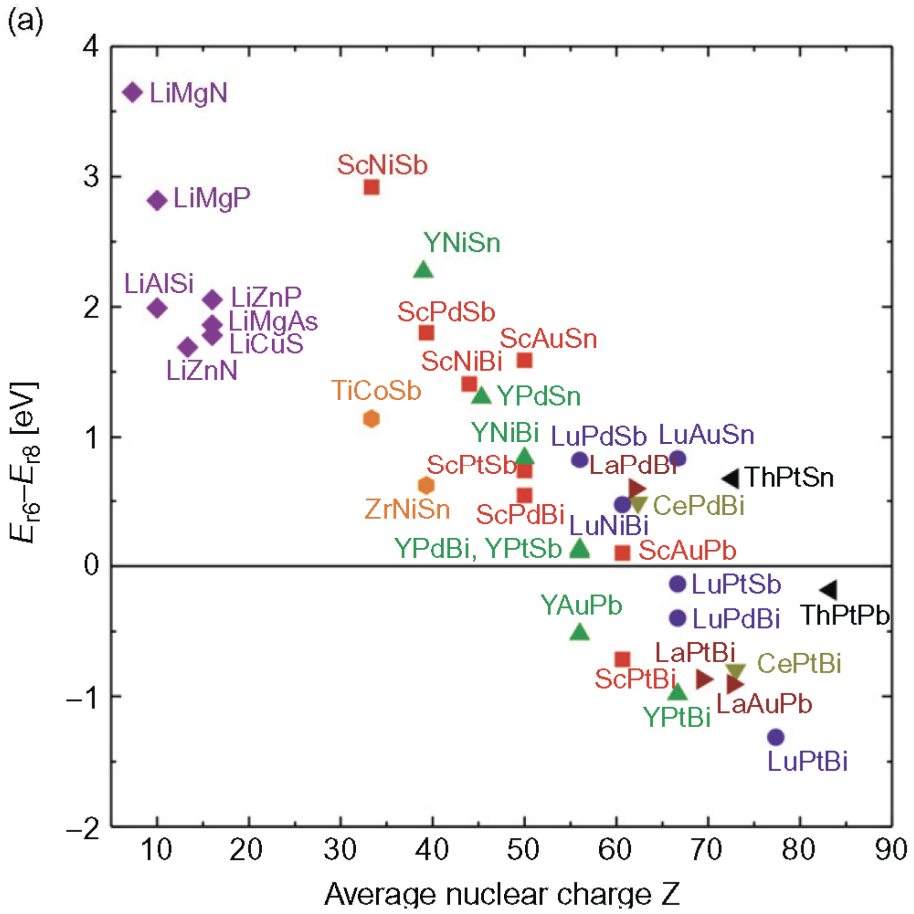


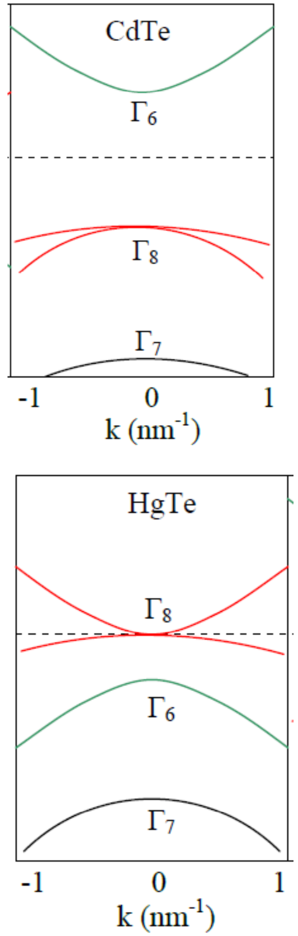
H 2.20																	He
Li 0.98	Be 1.57											B 2.04	C 2.55	N 3.04	O 3.44	F 3.98	Ne
Na 0.93	Mg 1.31											Al 1.61	Si 1.90	P 2.19	S 2.58	Cl 3.16	Ar
K 0.82	Ca 1.00	Sc 1.36	Ti 1.54	V 1.63	Cr 1.66	Mn 1.55	Fe 1.83	Co 1.88	Ni 1.91	Cu 1.90	Zn 1.65	Ga 1.81	Ge 2.01	As 2.18	Se 2.55	Br 2.96	Kr 3.00
Rb 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 T, Felser C, Parkin SSP, IEEE TRANSACTIONS ON MAGNETICS 47 (2011) 367
Graf T, Felser C, Parkin SSP, Progress in Solid State Chemistry Chemistry 39 (2011) 1

Predicting new compounds

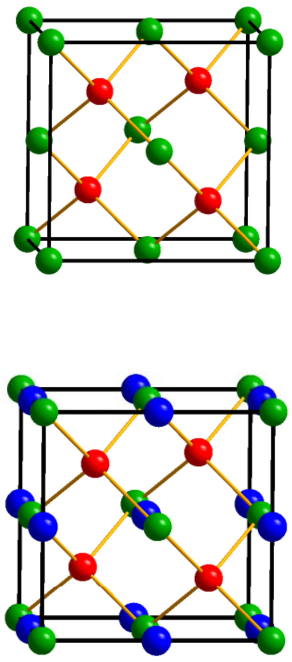


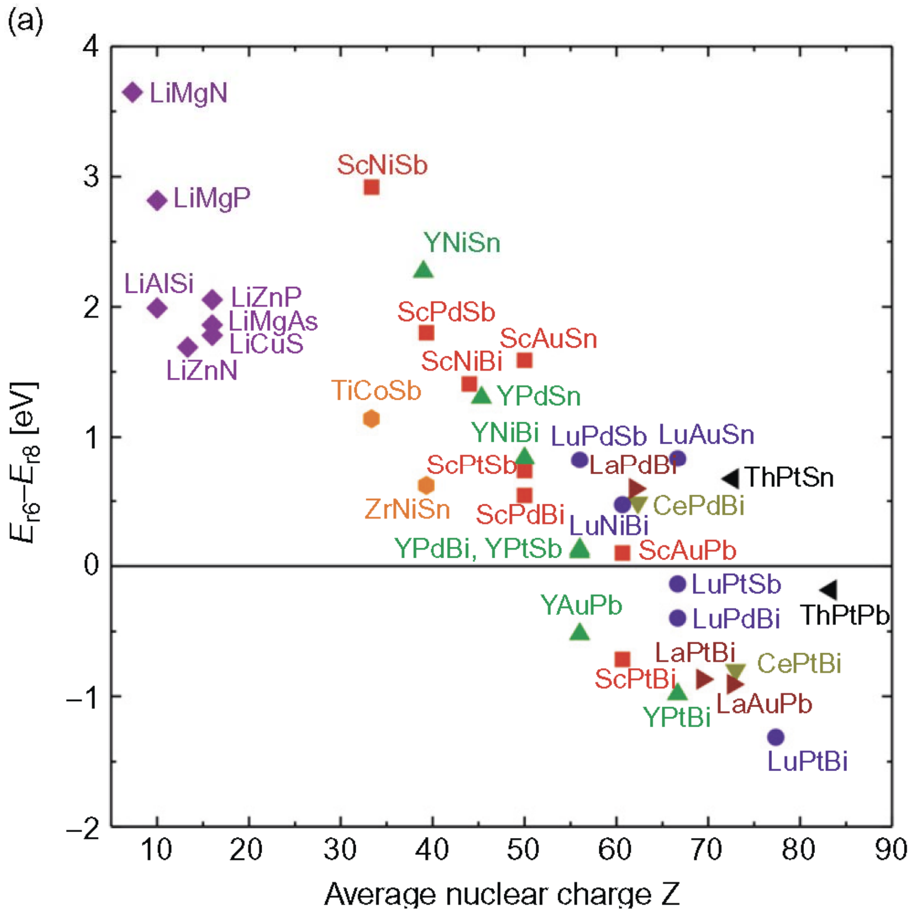


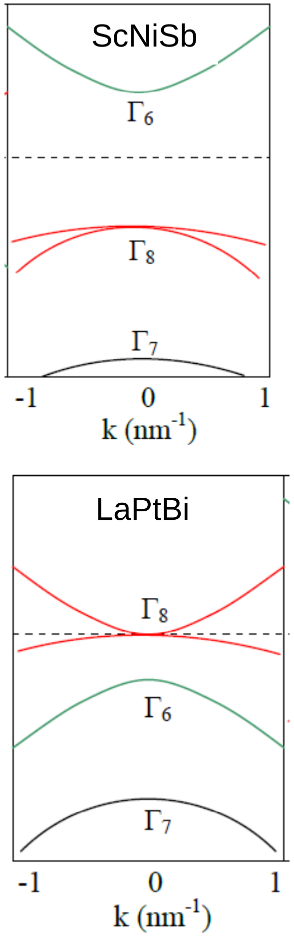


S. Chadov et al., Nat. Mater. 9, 541 (2010).
H. Lin et al., Nat. Mater. 9, 546 (2010).

Predicting new compounds

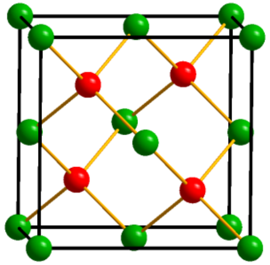






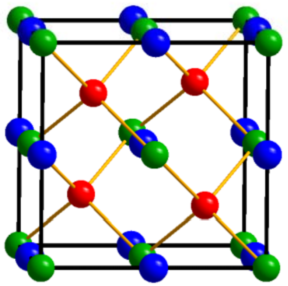
S. Chadov et al., Nat. Mater. 9, 541 (2010).
H. Lin et al., Nat. Mater. 9, 546 (2010).

Electronic structure



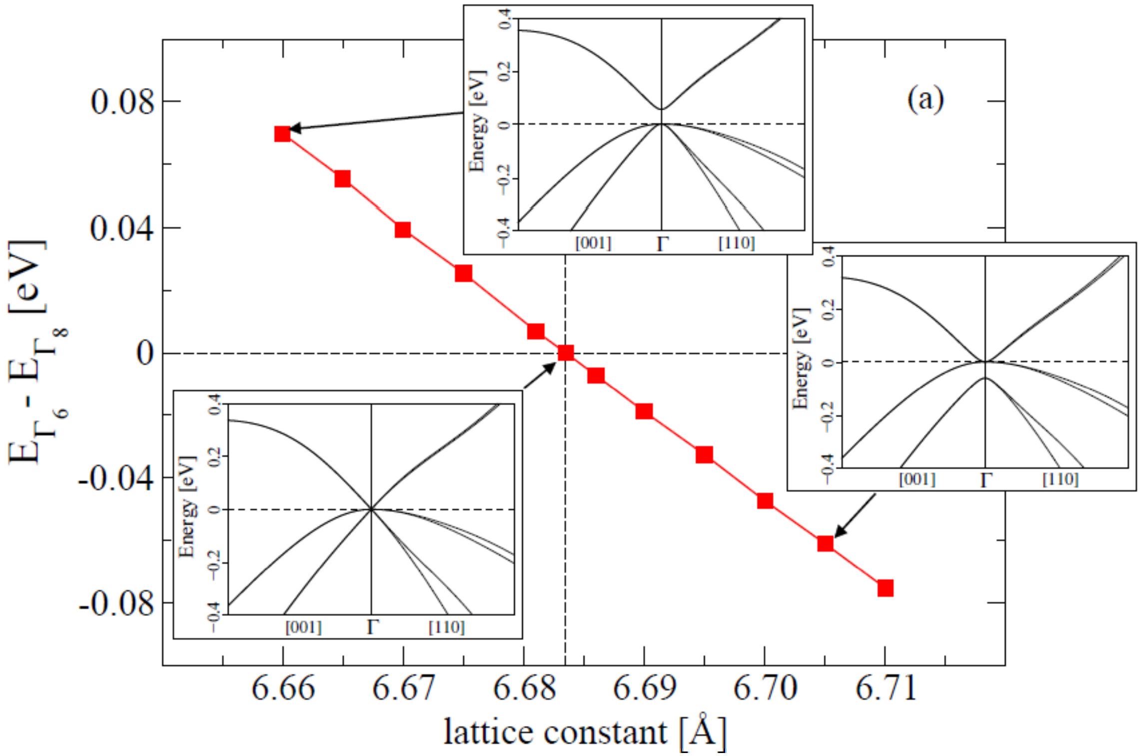
CdTe

HgTe



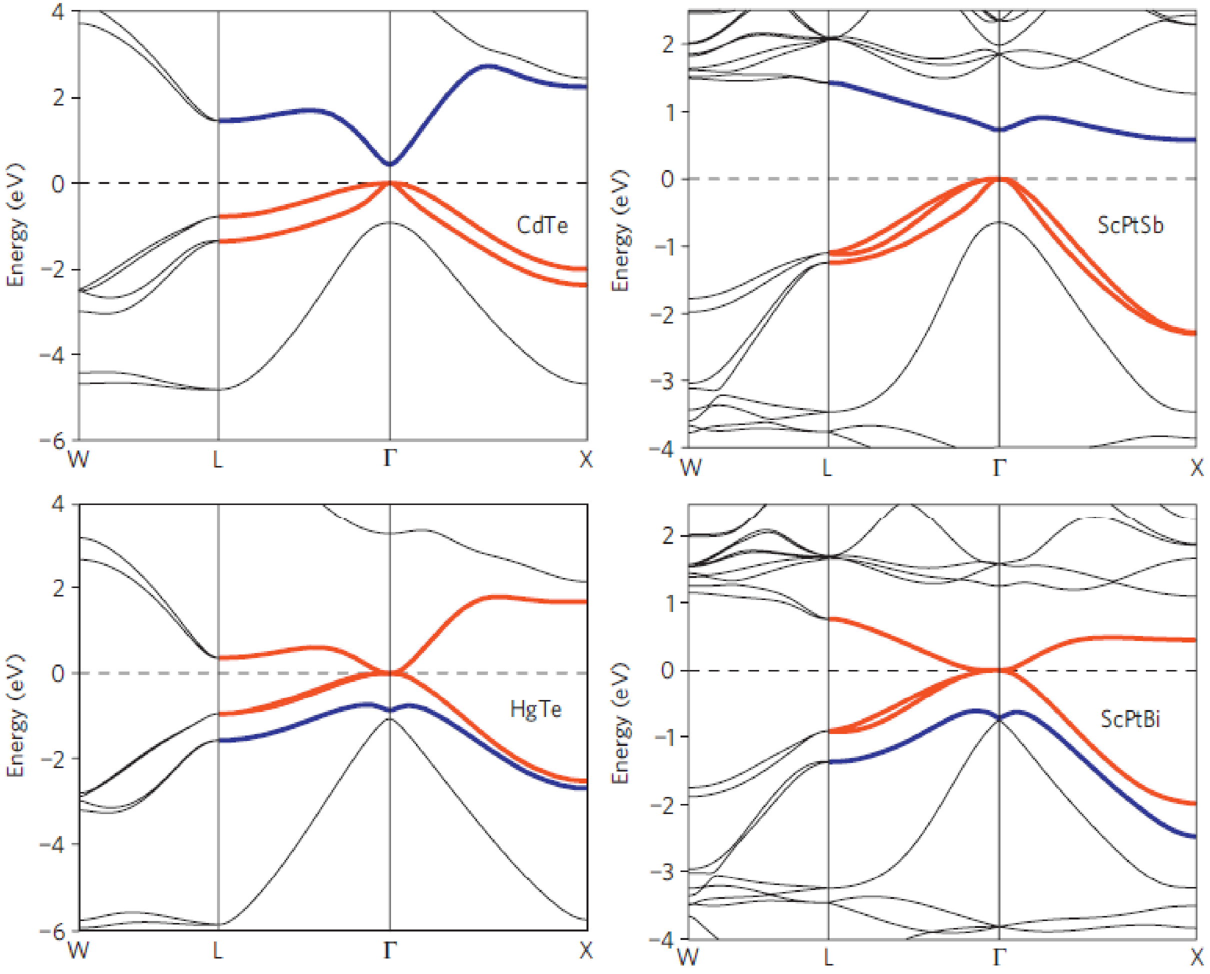
ScPtSb

ScPtBi



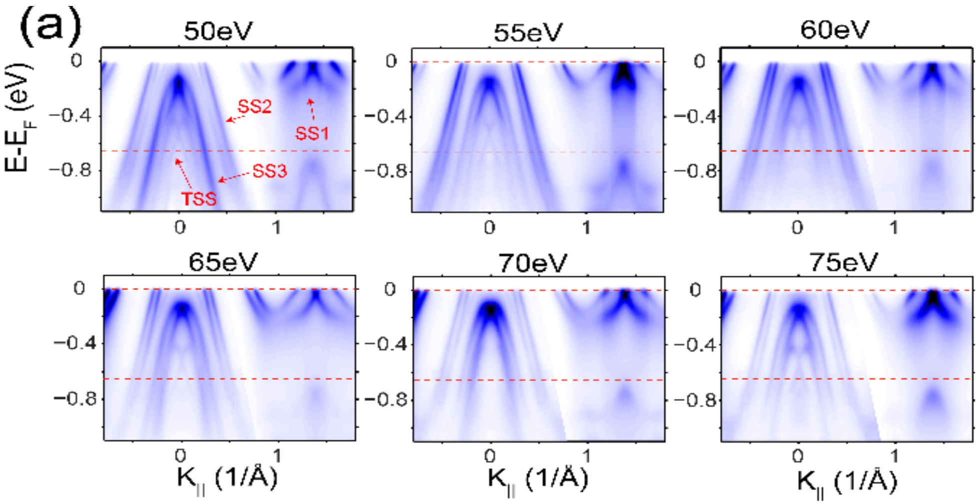
Chadov, Qi, Kübler, Zhang, Felser Nature Mat. 9 (2010) 541, arXiv:1003.0193

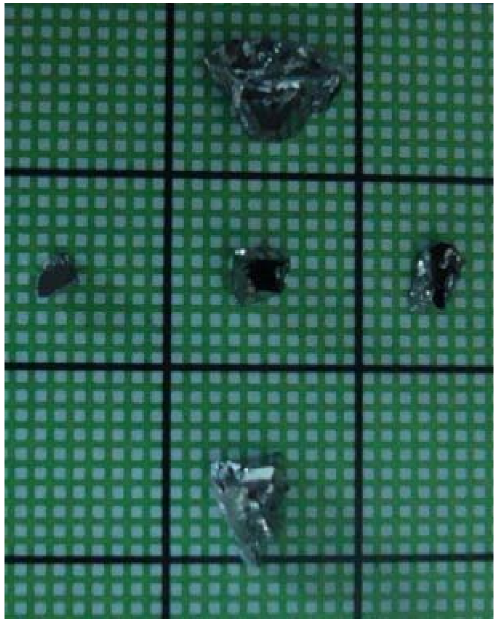
Electronic structure

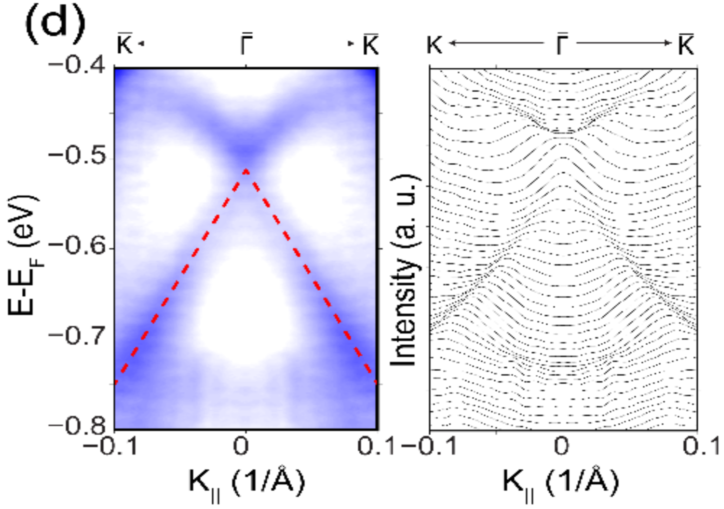


S. Chadov et al., Nat. Mater. 9, 541 (2010).
H. Lin et al., Nat. Mater. 9, 546 (2010).

ARPES of LnPtBi

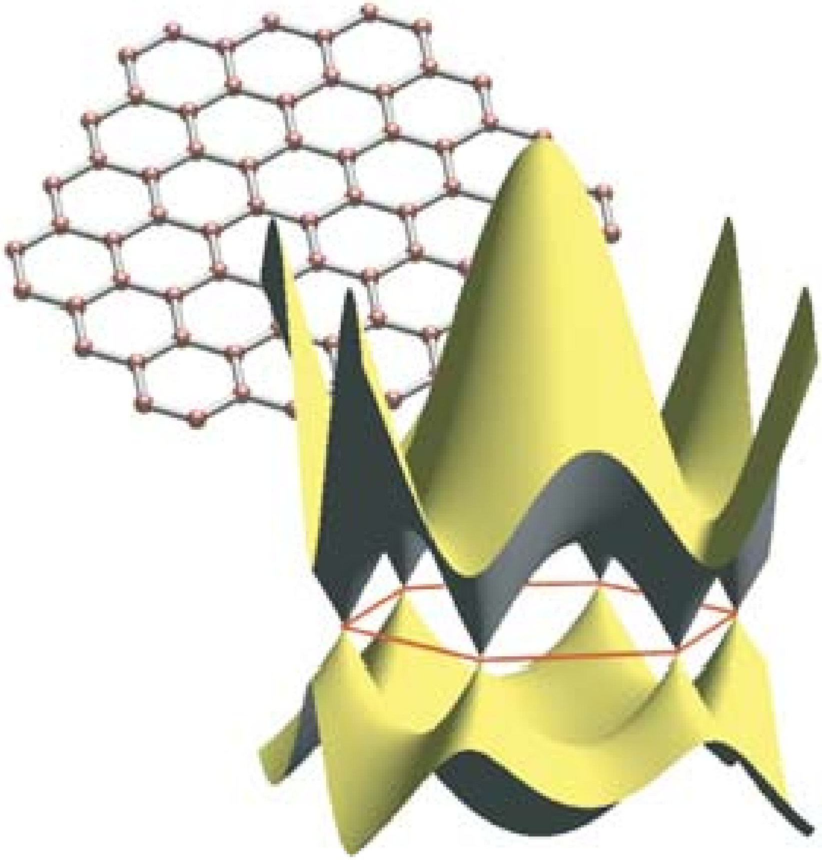


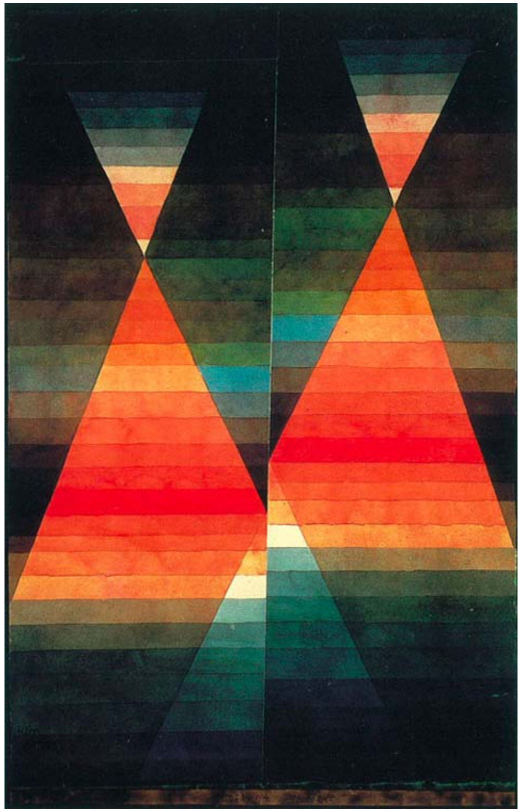




Z. K. Liu et al. Nature Com. 7 (2016) 12924

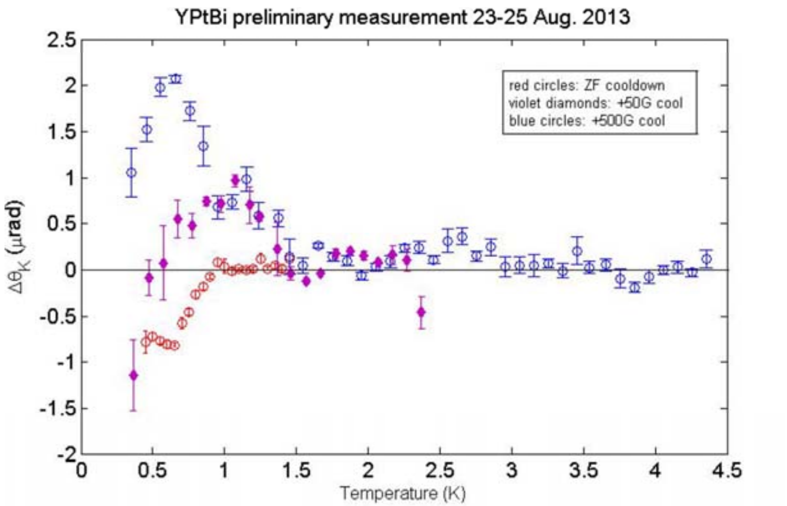
Dirac and Weyl semimetals

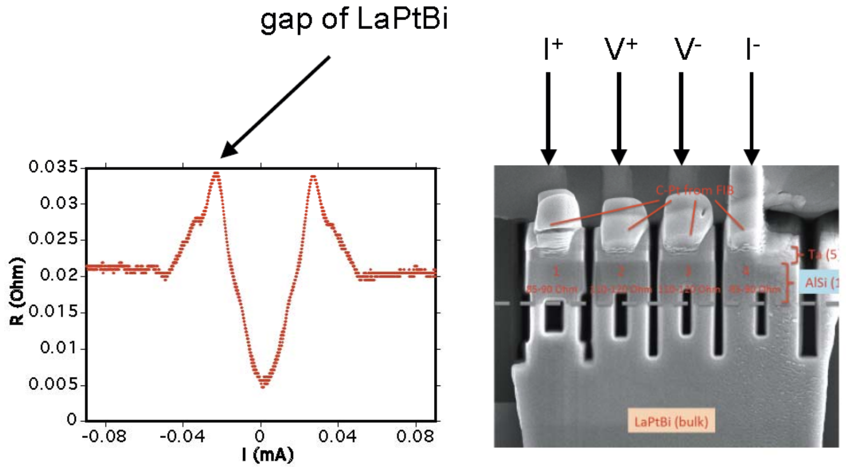


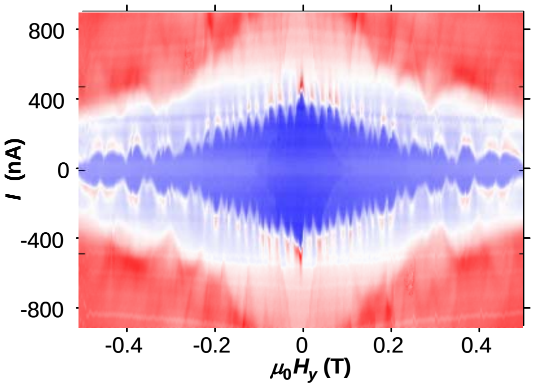


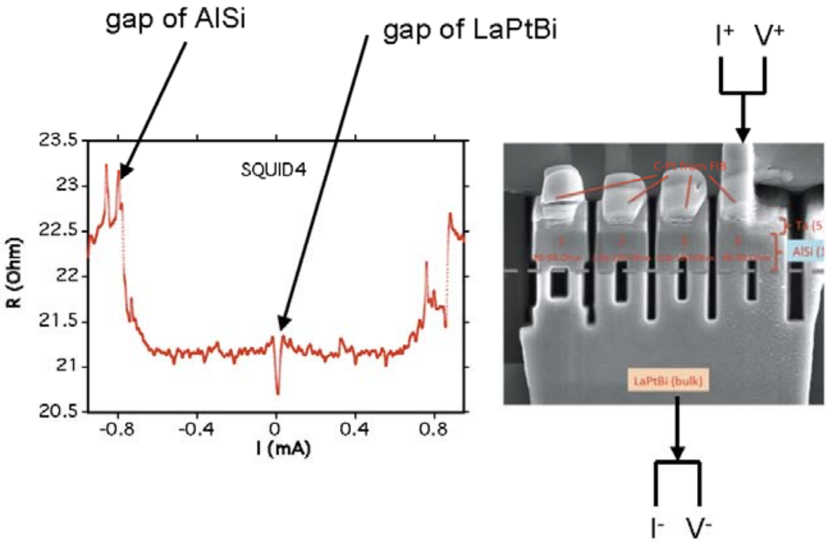
Paul Klee

Hunting Majorana









The nontrivial Josephson coupling leads to a current-flux relation with a **half period** in a superconducting quantum interference device geometry

R. Klett, K. Rott, G. Reiss, C. Shekhar, W. Wernsdörfer D. Ebke, C. Felser, in preparation

YPtBi

RESEARCH ARTICLE

SUPERCONDUCTORS

Topological *R*PdBi half-Heusler semimetals A new family of noncentrosymmetric magnetic superconductors

Yasuyuki Nakajima,[1] Rongwei Hu,[1] Kevin Kirshenbaum,[1] Alex Hughes,[1] Paul Syers,[1] Xiangfeng Wang,[1] Kefeng Wang,[1] Renxiong Wang,[1] Shanta R. Saha,[1] Daniel Pratt,[2] Jeffrey W. Lynn,[2] Johnpierre Paglione[1]*

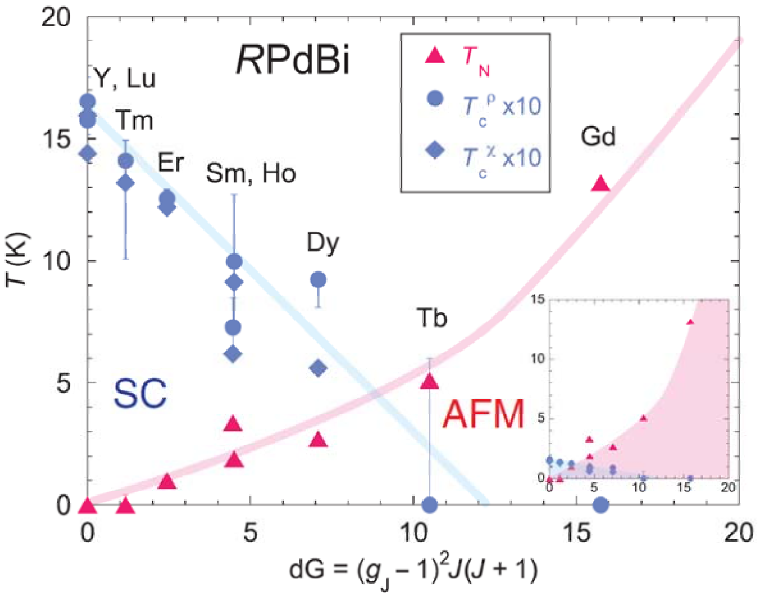


Fig. 5. Phase diagram of *R*PdBi series, indicating evolution of superconducting and antiferromagnetic ground states as a function of de Gennes factor dG = $(g_J - 1)^2 J(J + 1)$. The superconducting transition T_c

PRL **116,** 177001 (2016) PHYSICAL REVIEW LETTERS

Pairing of $j = 3/2$ Fermions in Half-Heusler Superconductors

P. M. R. Brydon,[1,2,*] Limin Wang,[3] M. Weinert,[4] and D. F. Agterberg[4]

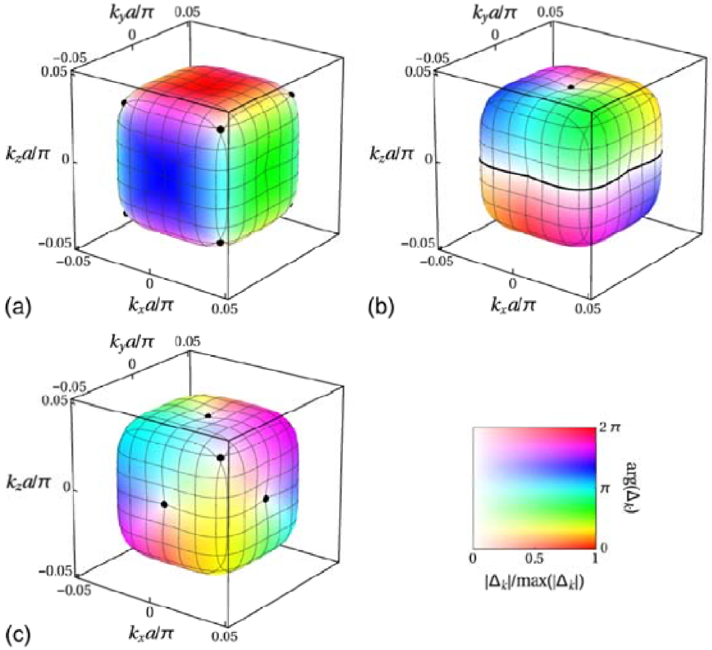
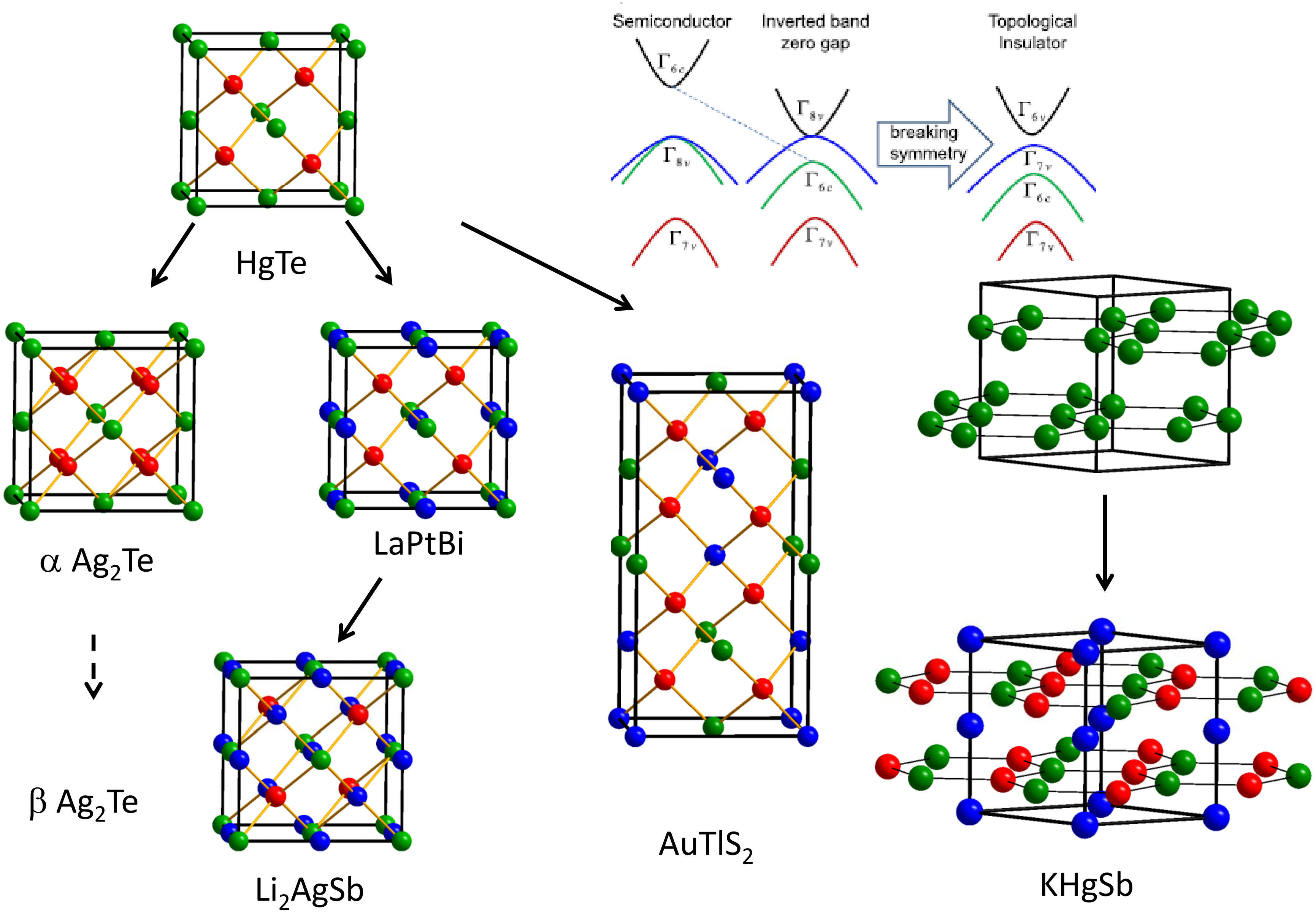


FIG. 4. Time-reversal symmetry-breaking quintet pairing states: (a) the E pairing state; (b) the T_2 pairing state with $\mathbf{l} = (1, i, 0)$; (c) the T_2 pairing state with $\mathbf{l} = (1, -e^{2\pi i/3}, e^{4\pi i/3})$. The color indicates the phase while the saturation gives the gap magnitude. Black points or lines indicate nodes of the gap.

Structure to Property



HgTe

α Ag_2Te

LaPtBi

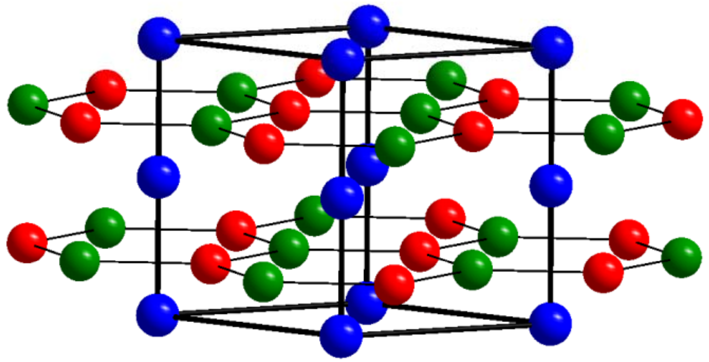
β Ag_2Te

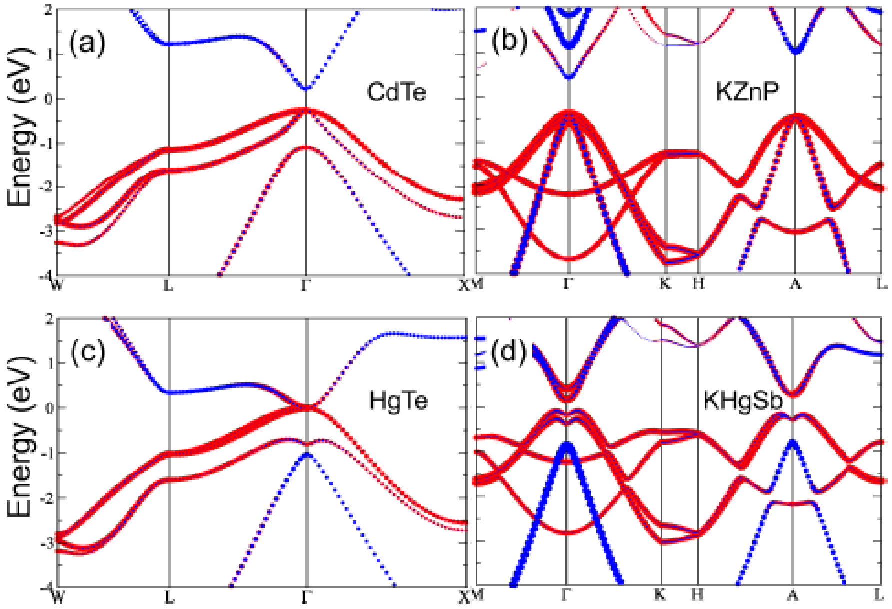
Li_2AgSb

$AuTlS_2$

KHgSb

Honeycomb from sp3 to sp2

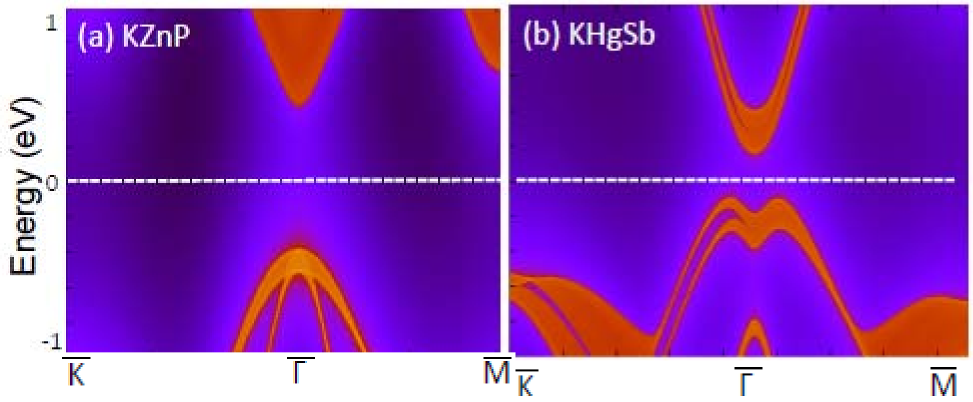




Band inversion is found in the heavier compounds

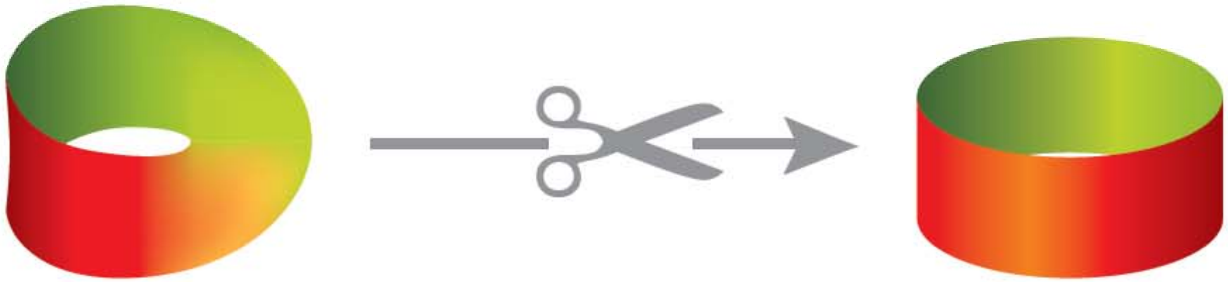
No surface state? Why ?

➡ Interaction between the two layers in the unit cell and two Dirac Cones

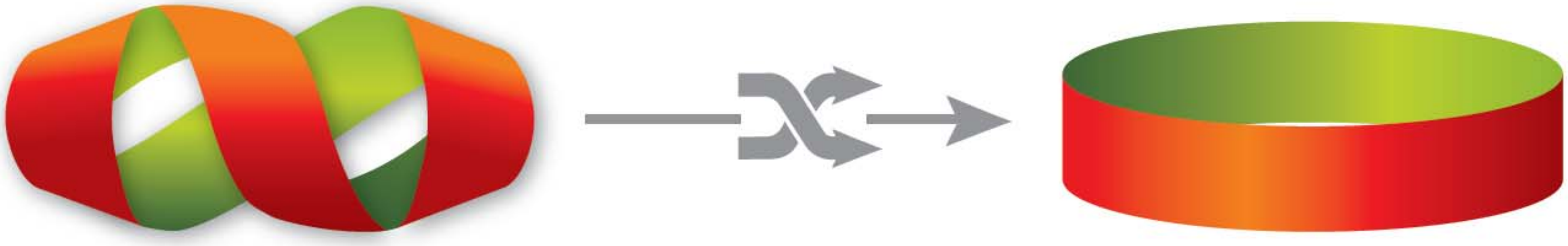


Zhang, Chadov, Müchler, Yan, Qi, Kübler, Zhang, Felser, Phys. Rev. Lett. 106 (2011) 156402 arXiv:1010.2195v1

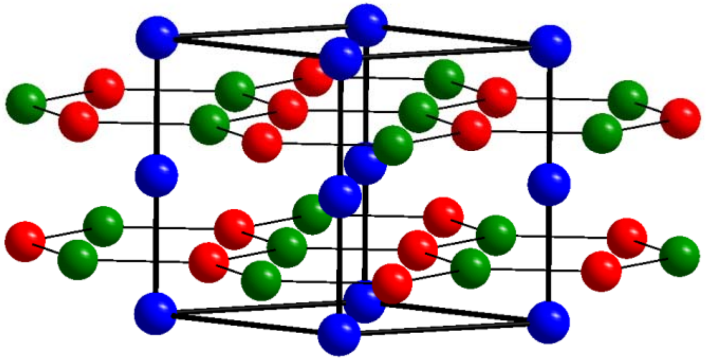
a)

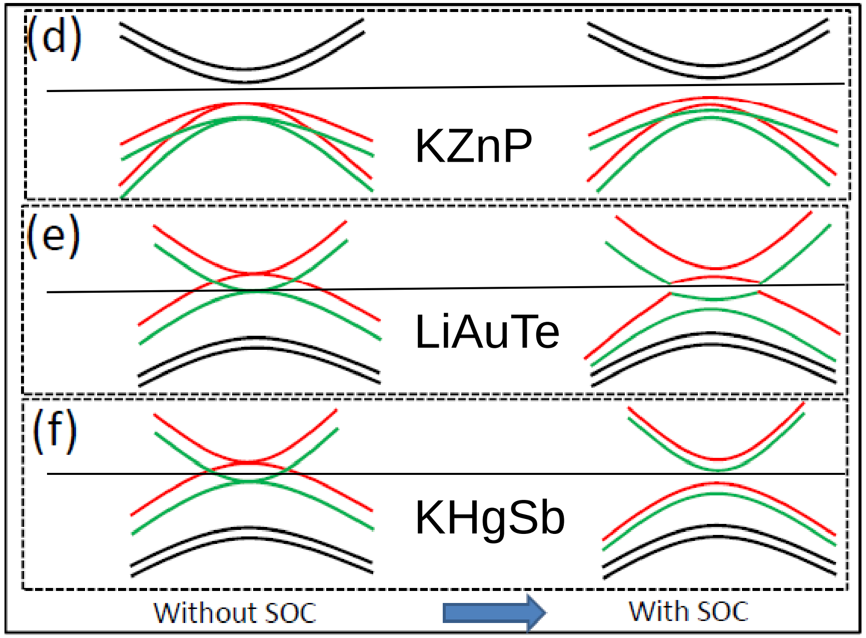


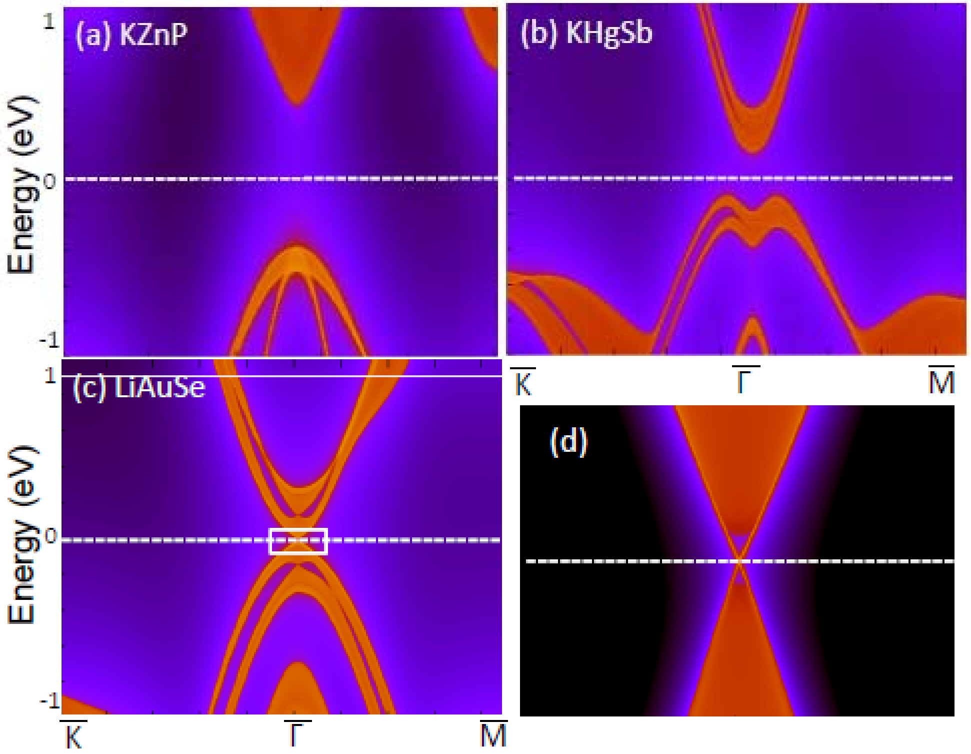
b)



Honeycomb from sp3 to sp2

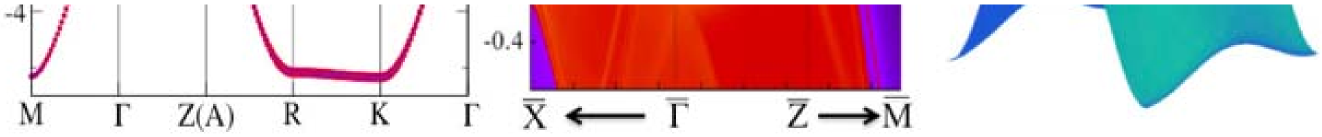


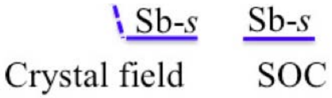


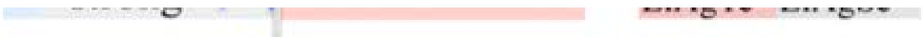


Zhang, Chadov, Müchler, Yan, Qi, Kübler, Zhang, Felser, Phys. Rev. Lett. 106 (2011) 156402 arXiv:1010.2195v1

Honeycomb: Weak TI







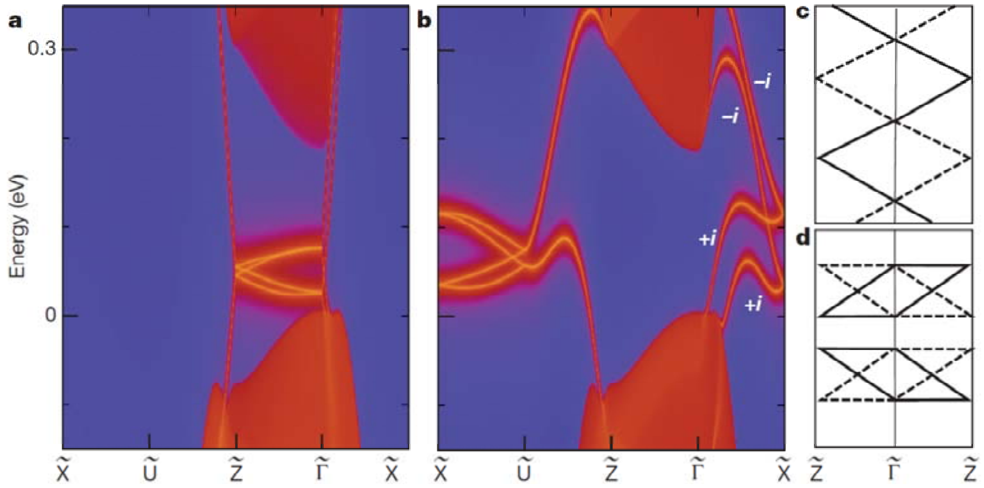
Yan, Müchler, Felser, Physical Review Lett. 109 (2012) 116406

Hourglass

ARTICLE

Hourglass fermions

Zhijun Wang[1]*, A. Alexandradinata[1,2]*, R. J. Cava[3] & B. Andrei Bernevig[1]

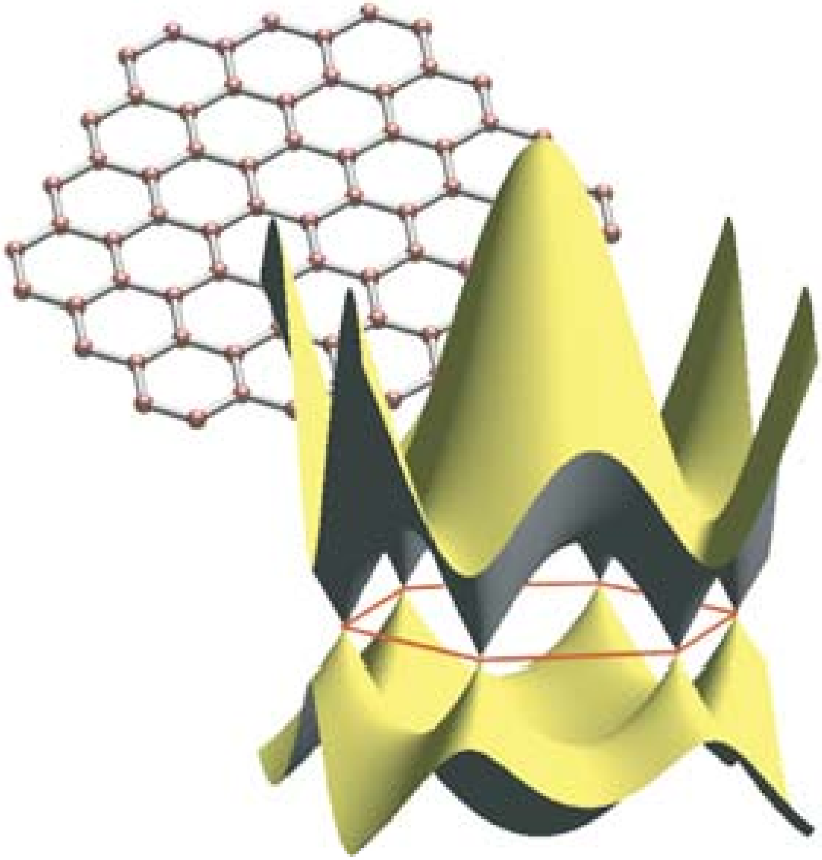


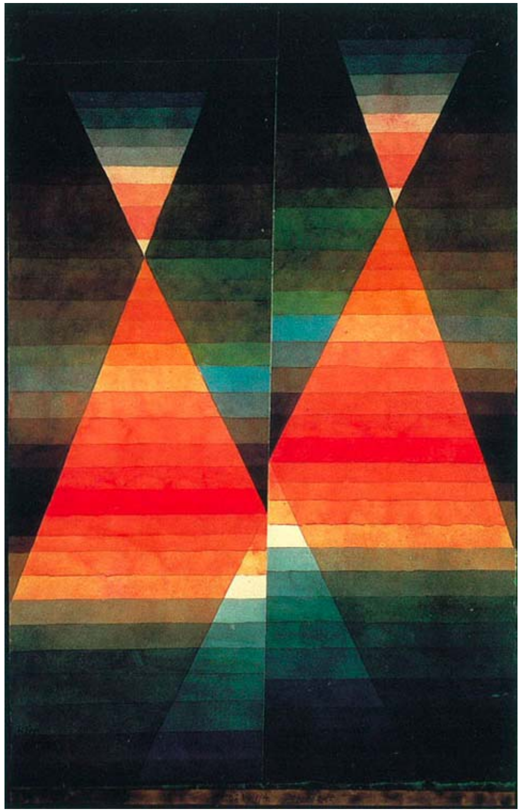
Wang et al. Nature 2016

Weyl Semimetals

Breaking symmtery - TaAs

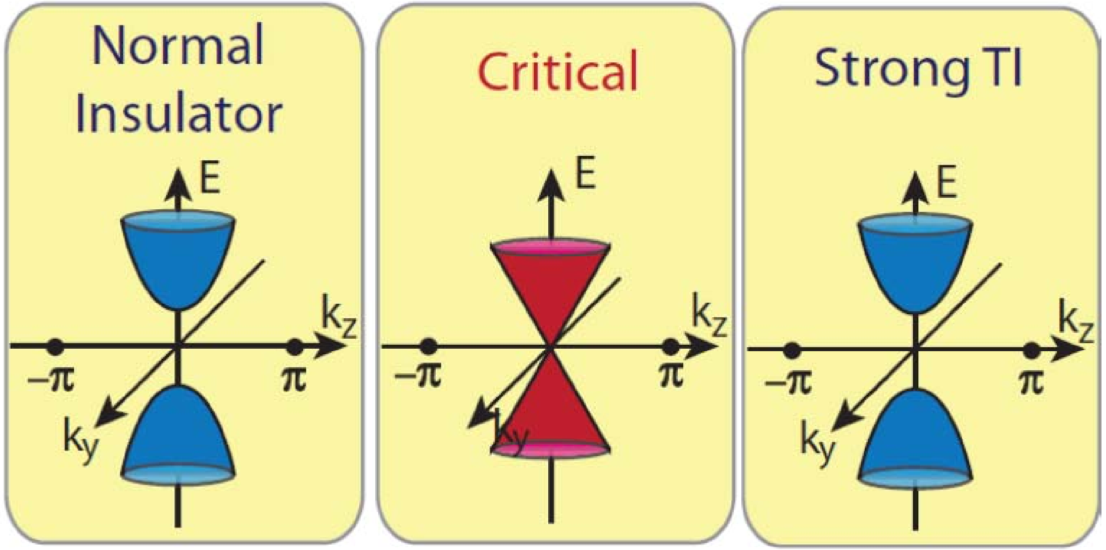
Dirac and Weyl semimetals



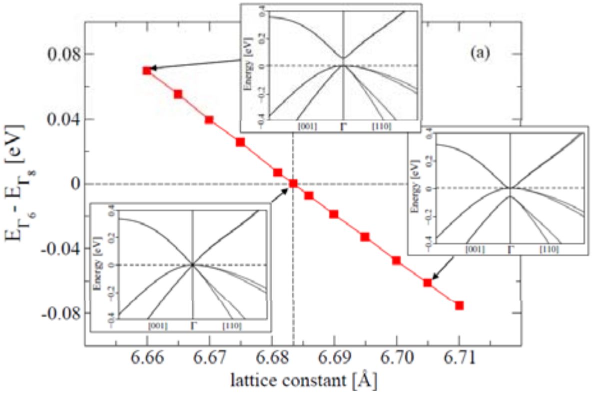


Paul Klee

Dirac semimetals



Bohm-Jung Yang and Naoto Nagaosa, arXiv:1404.0754




nature COMMUNICATIONS

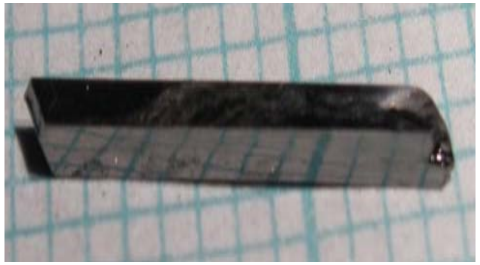
ARTICLE

Received 2 Dec 2013 | Accepted 2 Apr 2014 | Published 7 May 2014

DOI: 10.1038/ncomms4786

Observation of a three-dimensional topological Dirac semimetal phase in high-mobility Cd_3As_2

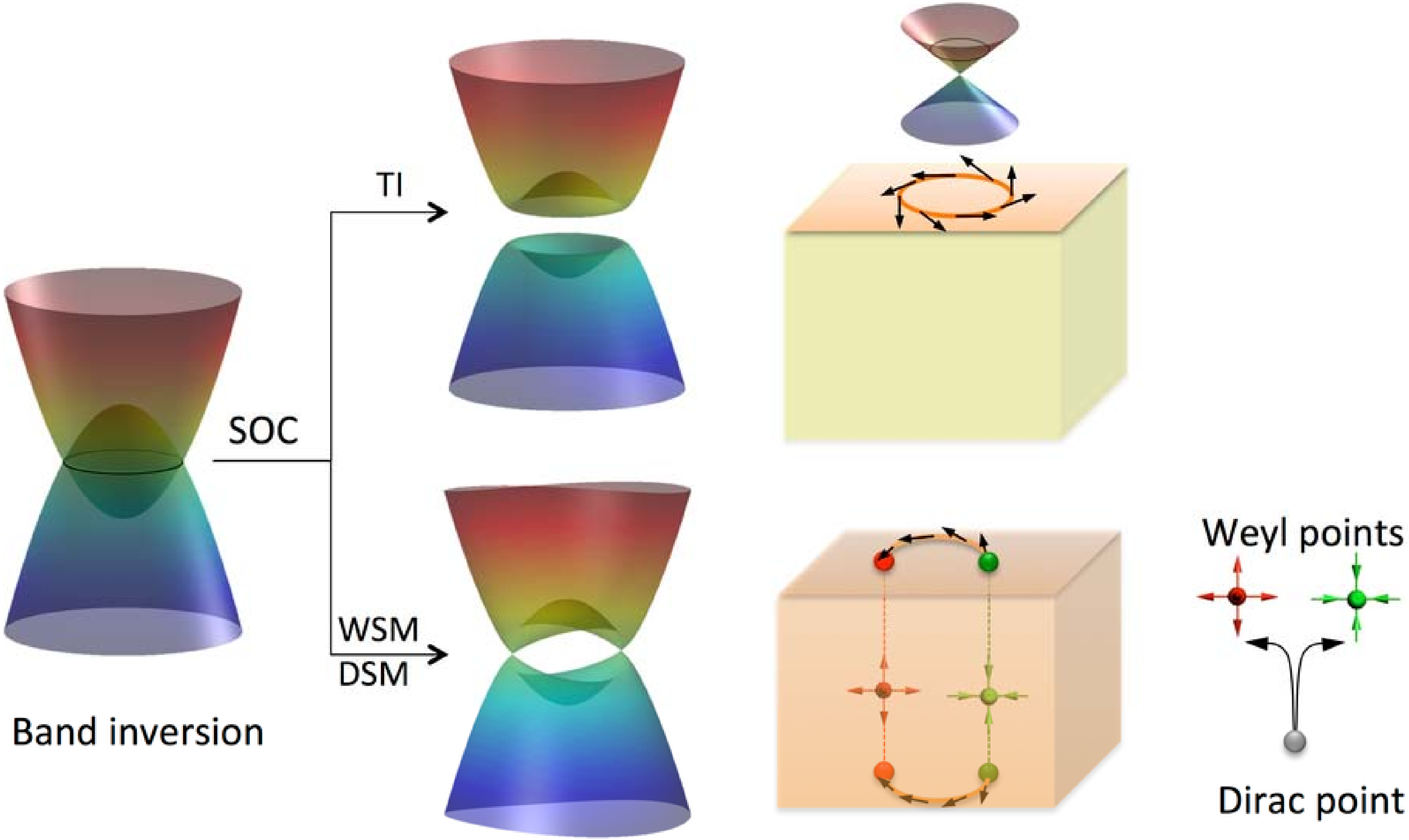
Madhab Neupane[1,*], Su-Yang Xu[1,*], Raman Sankar[2,*], Nasser Alidoust[1], Guang Bian[1], Chang Liu[1], Ilya Belopolski[1], Tay-Rong Chang[3], Horng-Tay Jeng[3,4], Hsin Lin[5], Arun Bansil[6], Fangcheng Chou[2] & M. Zahid Hasan[1,7]



Science AAAS

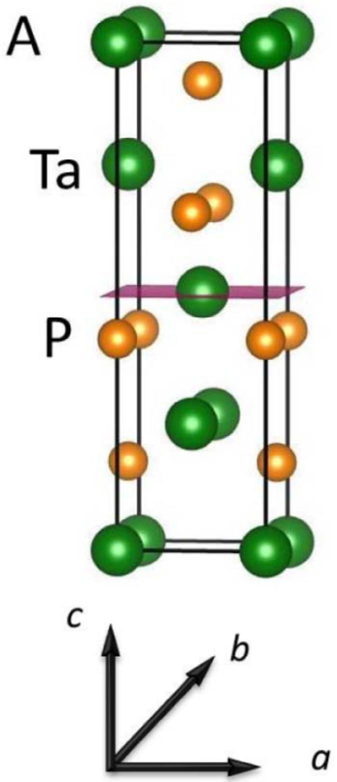
Observation of Fermi arc surface states in a topological metal
Su-Yang Xu *et al.*
Science **347**, 294 (2015);
DOI: 10.1126/science.1256742

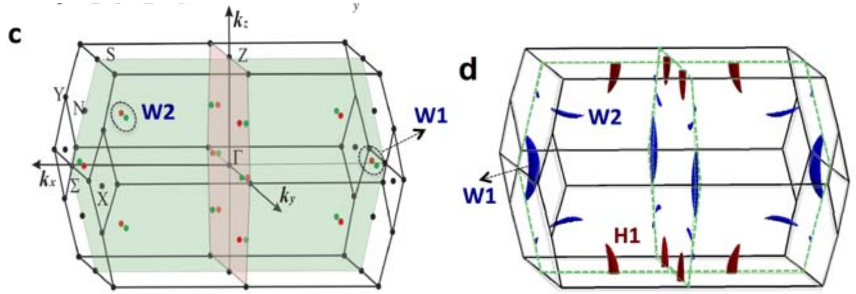
Weyl semimetals

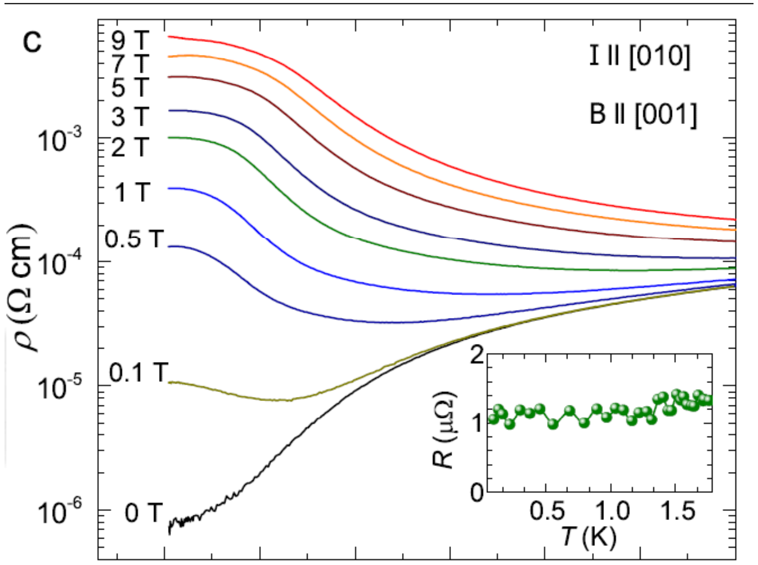


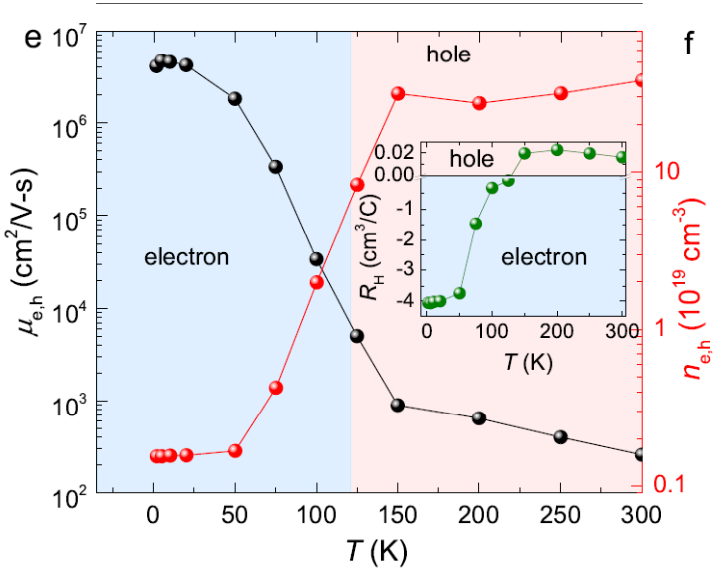
Weyl semimetals in non centro NbP

NbP, NbAs, TaP, TaAs









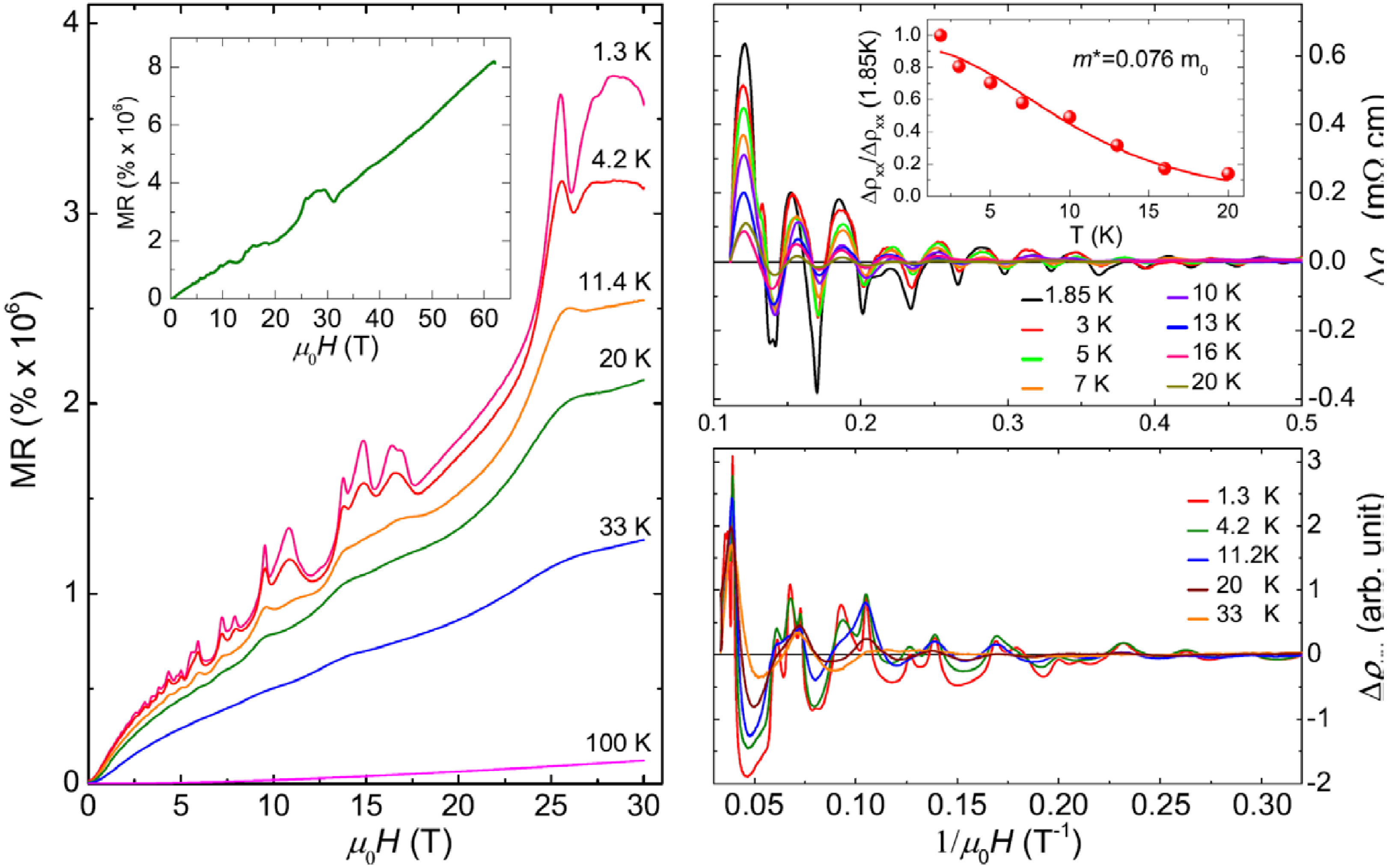
NbP is a topological Weyl semimetal

- 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

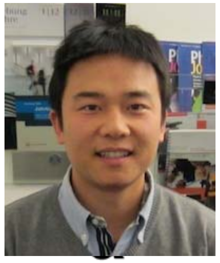
Weng, et al. Phys. Rev. X 5, 11029 (2015)
Huang . et al. preprint arXiv:1501.00755
Yang, et al. Nature Phys. 11 (2015) 728, preprint arXiv:1507.00521v1

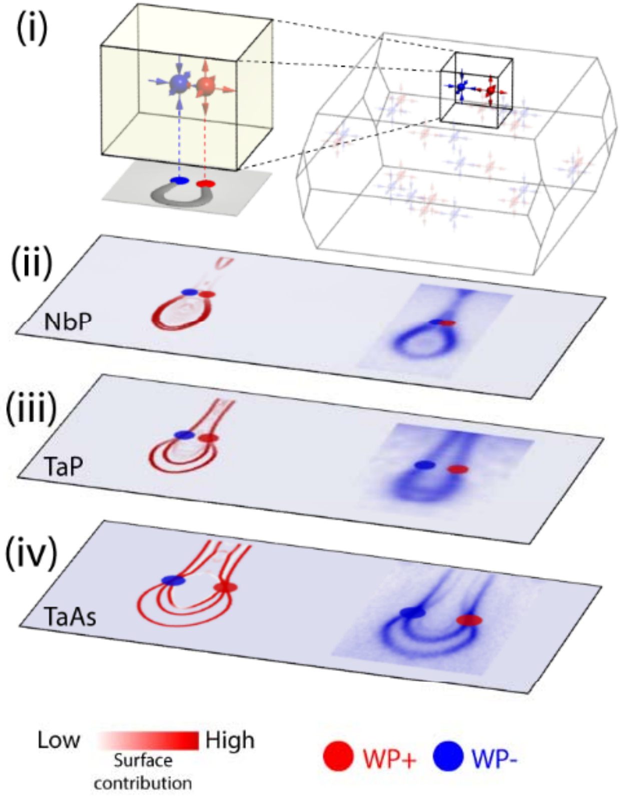
NbP quantum oscillations

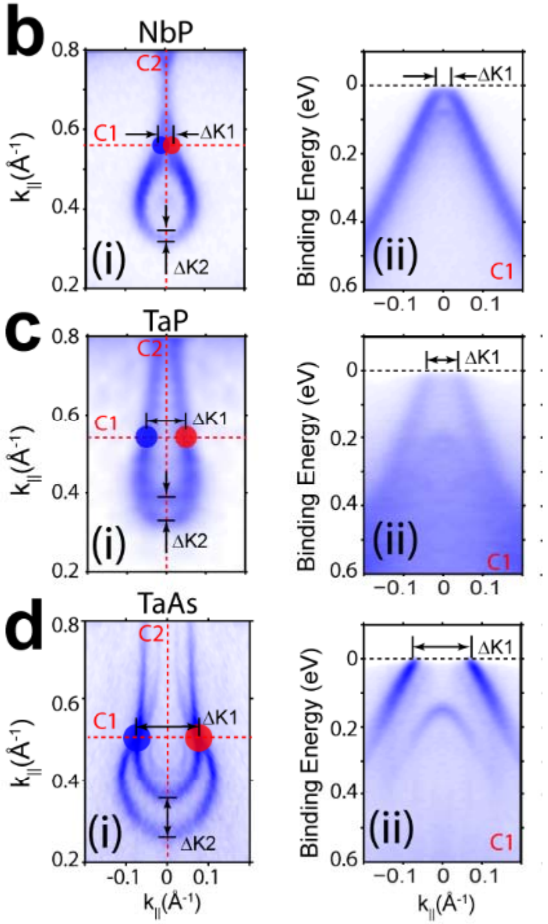


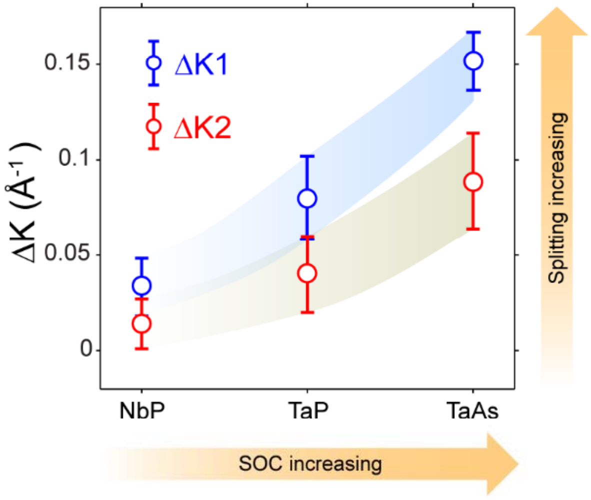
Shekhar, et al. , Nature Physics 11 (2015) 645, preprint arXiv:1502.04361

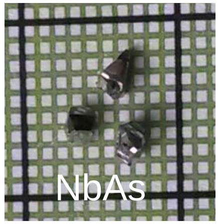
NbP, TaP, TaAs











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

MoS_2 : crystal field

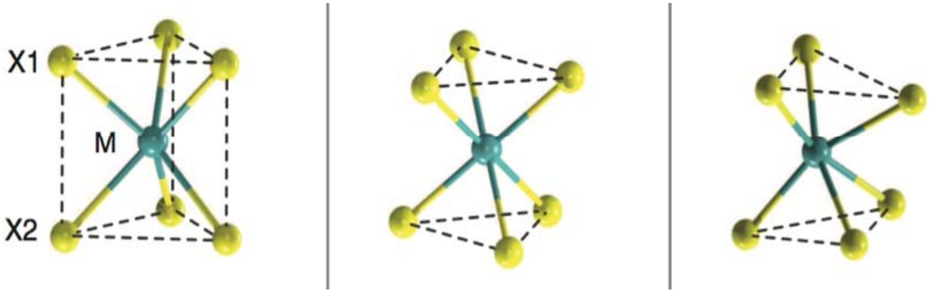
Mo^{4+} (d^2)

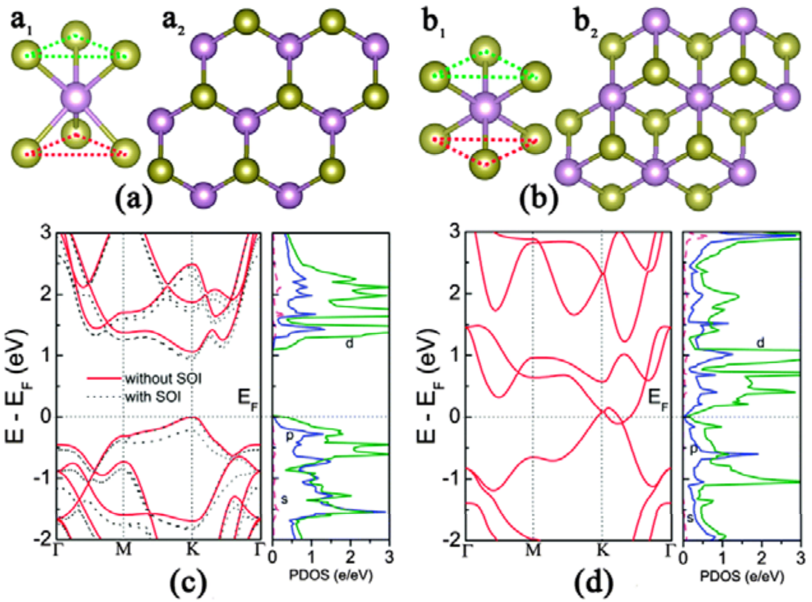
S^{2-} (s^2p^6)

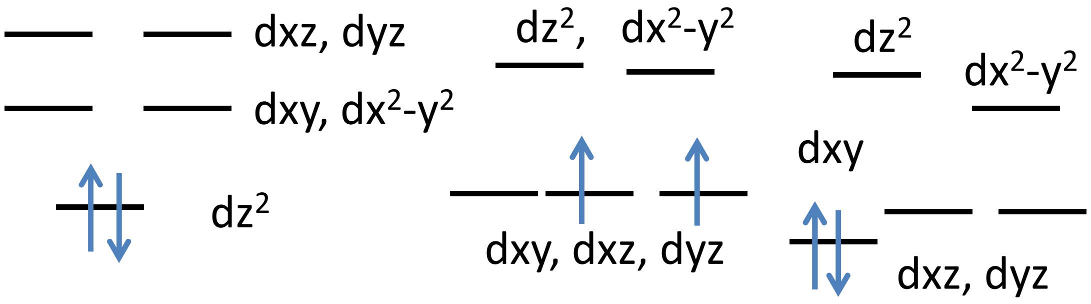
2 H

1T

1T', Td







dxz, dyz

dxy, dx^2-y^2

dz^2

dz^2, dx^2-y^2

dxy, dxz, dyz

dz^2

dx^2-y^2

dxy

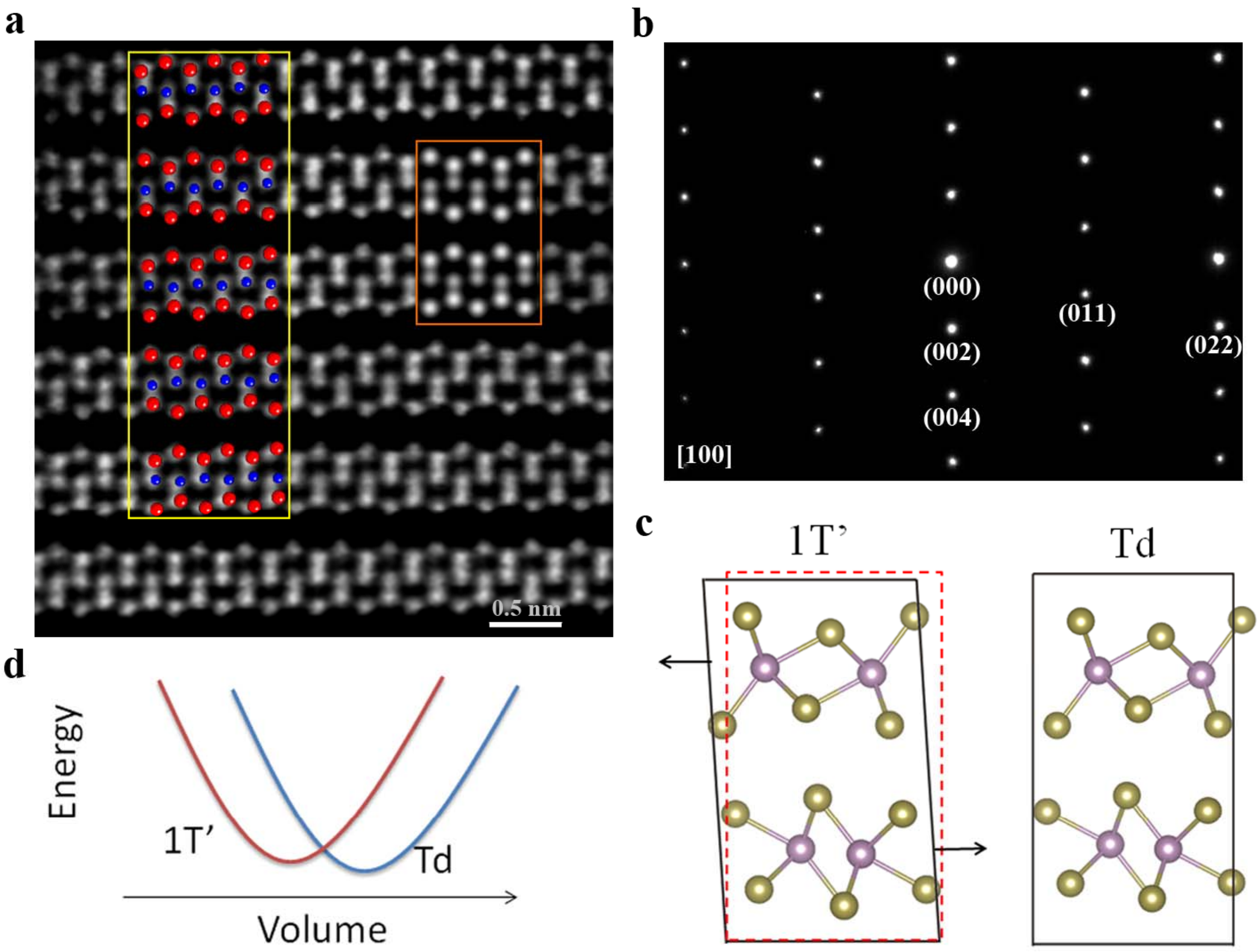
dxz, dyz

Semiconductor

Metal

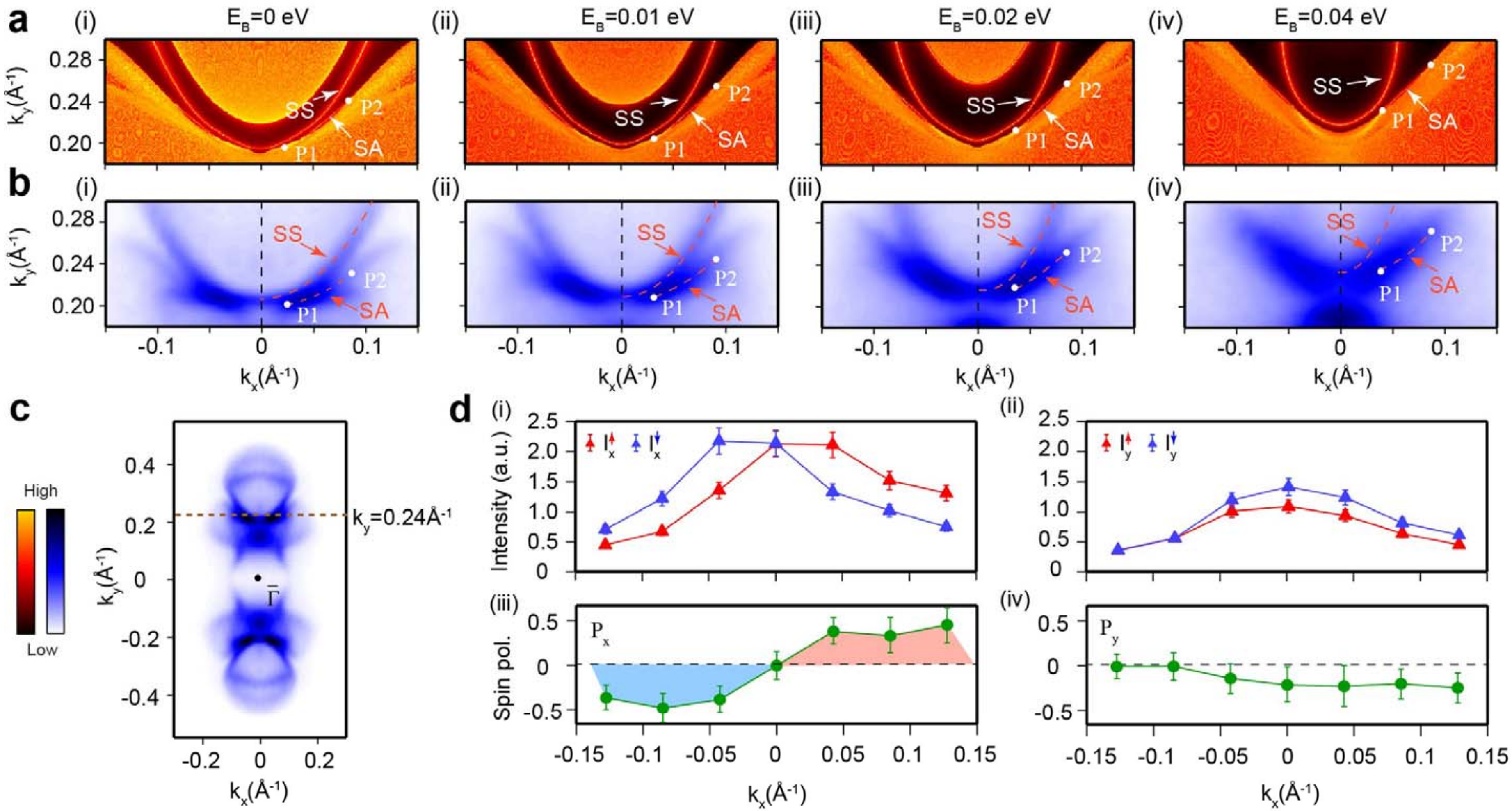
Semimetal

T_d-$MoTe_2$



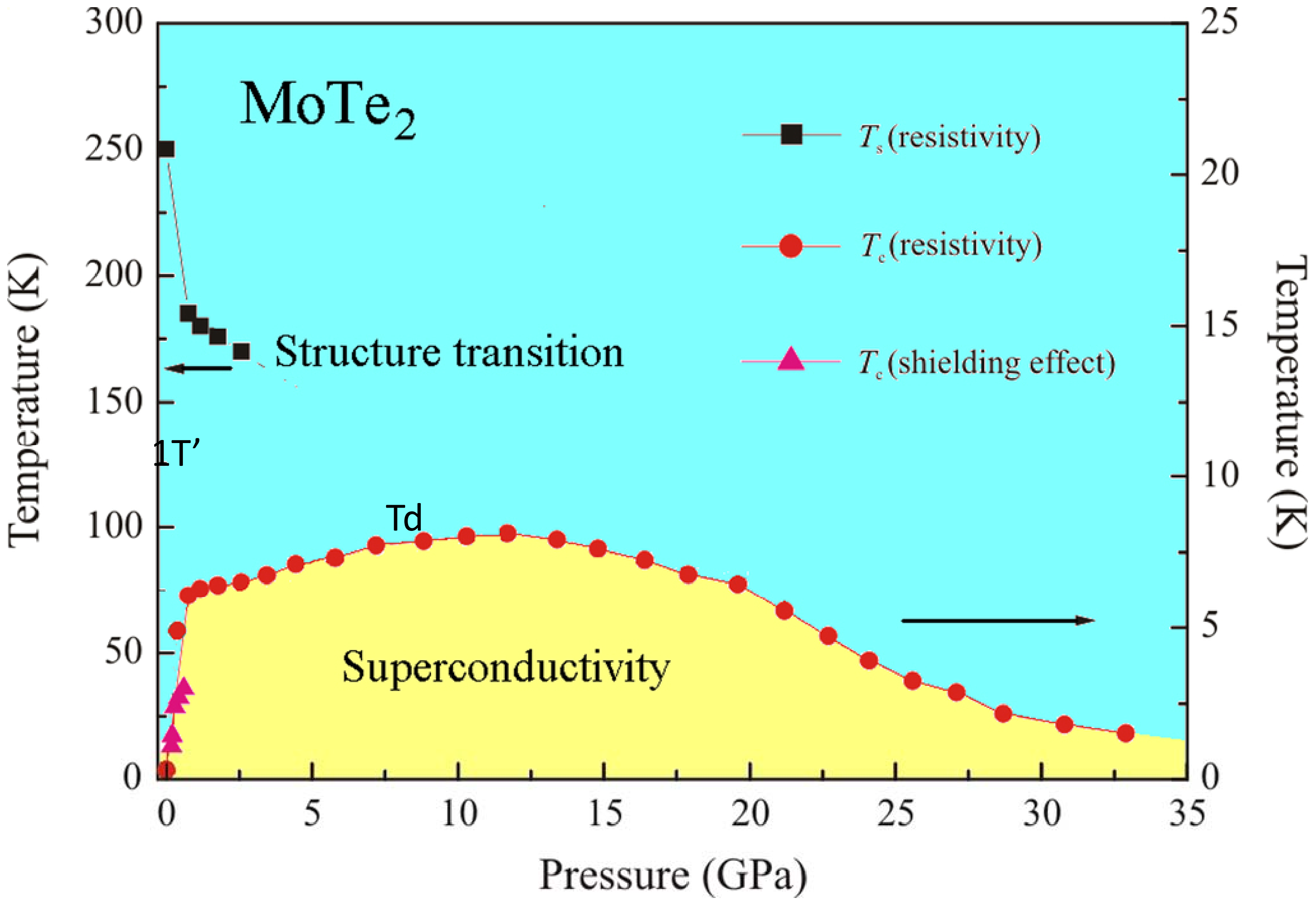
Y. Qi et al. Nature Com. 7 (2016) 11038, arXiv:1508.03502 (2015).

MoTe$_2$: Weyl Semimetal?



J. Jiang, Z. K. Liu, Y. Sun, H. F. Yang, R. Rajamathi, Y. P. Qi, L. X. Yang, C. Chen, H. Peng, C.-C. Hwang, S. Z. Sun, S.-K. Mo, I. Vobornik, J. Fujii, S. S. P. Parkin, C. Felser, B. H. Yan, Y. L. Chen, preprint: arXiv: 1604.00139

$MoTe_2$



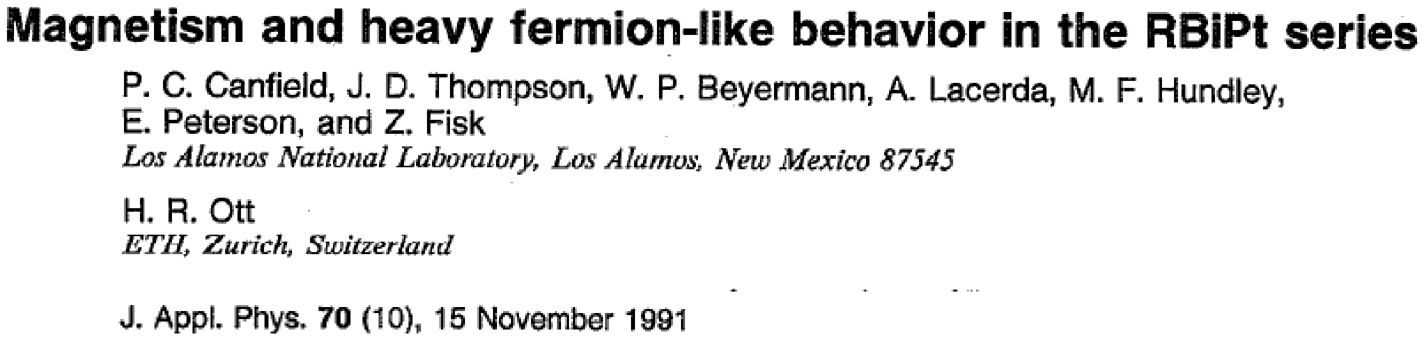
Y. Qi et al. Nature Com. 7 (2016) 11038, arXiv:1508.03502 (2015).

Magnetic Weyl Semimetals

Induced

Intrinsic

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

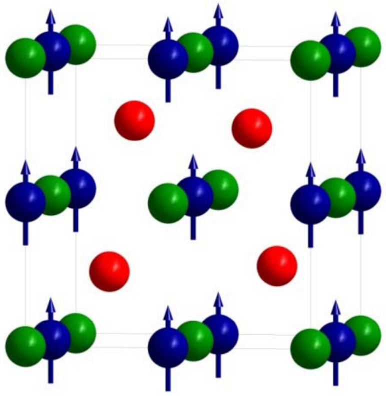
J. Appl. Phys. **70** (10), 15 November 1991

Multifunctional properties

- RE: Gd 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

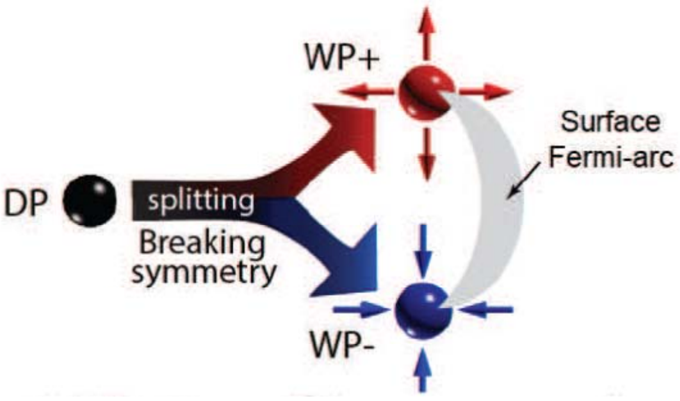
Pt — **RE** — **Bi**

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



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

Weyl semimetals



We need time reversal symmetry breaking
(Dirac points are at high symmetry points
Weyl points are not at high symmetry points)

- Structural distortion
- Application of magnetic field or magnetism

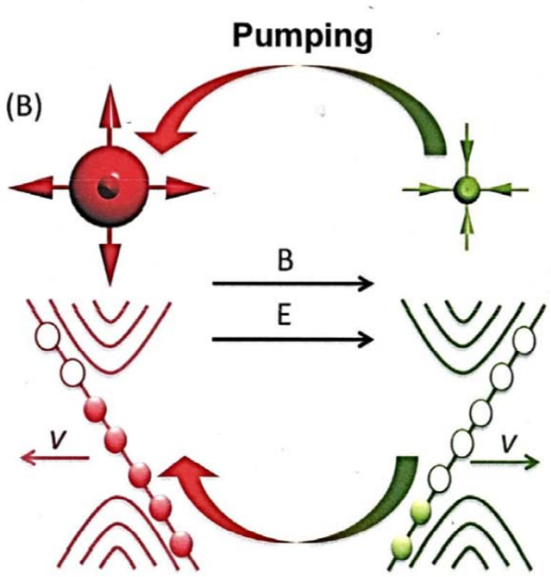
3D topological Weyl semimetals - breaking Time reversal symmetry – by transport

1. Intrinsic anomalous Hall effect

2. Chiral anomaly

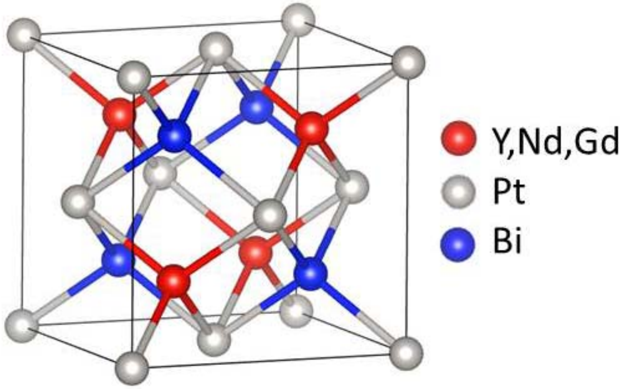
$$\partial_\mu j^\mu_\chi = -\chi \frac{e^3}{4\pi^2\hbar^2}\mathbf{E}\cdot\mathbf{B}$$

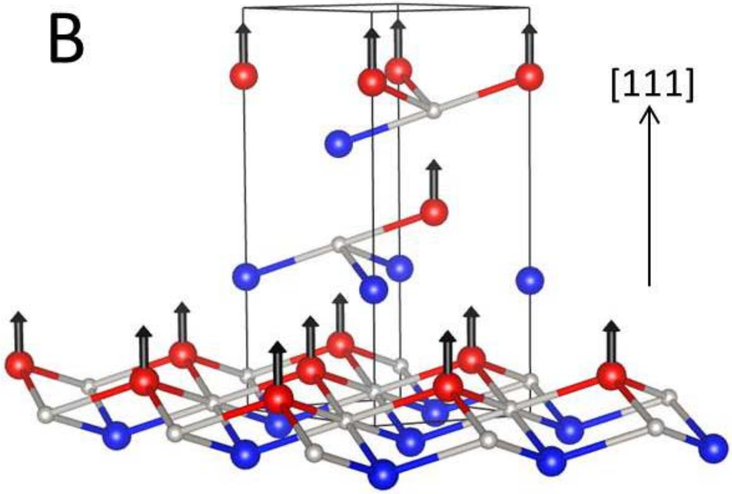
$$\sigma_a = \frac{e^3 v_f^3}{4\pi^2\hbar\mu^2 c} B^2,$$

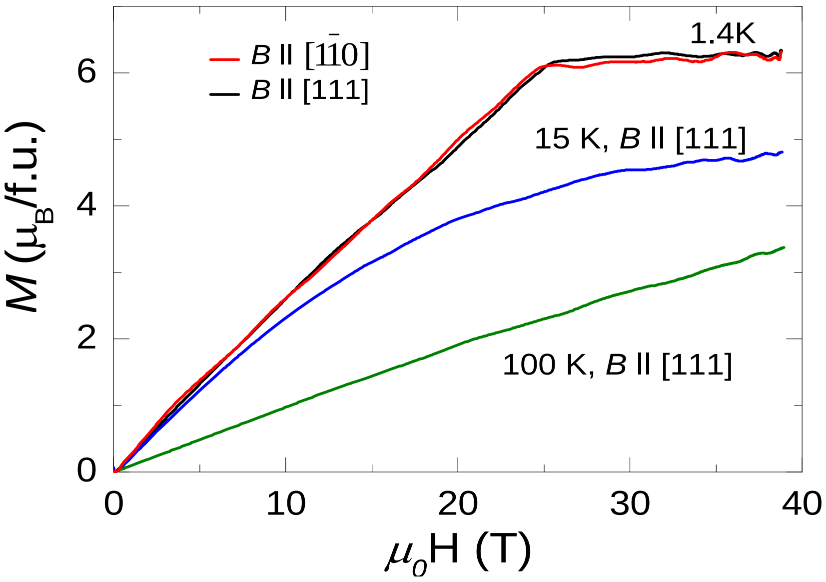


S. L. Adler, Phys. Rev. 177, 2426 (1969)
J. S. Bell and R. Jackiw, Nuovo Cim. A60, 47 (1969)
AA Zyuzin, AA Burkov - Physical Review B (2012)
AA Burkov, L Balents, PRL 107 12720 (2012)

GdPtBi is magnetic



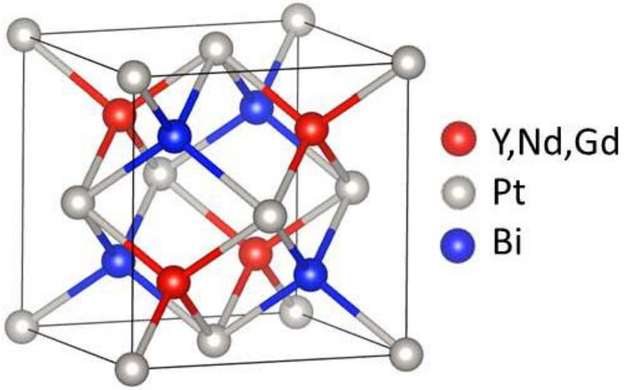


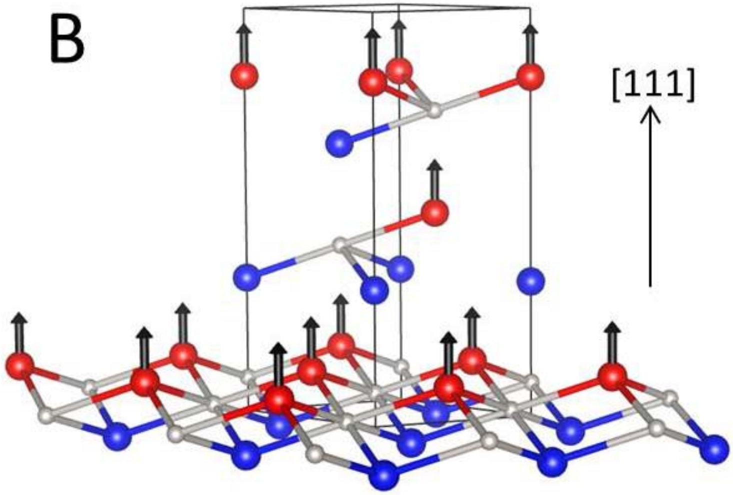


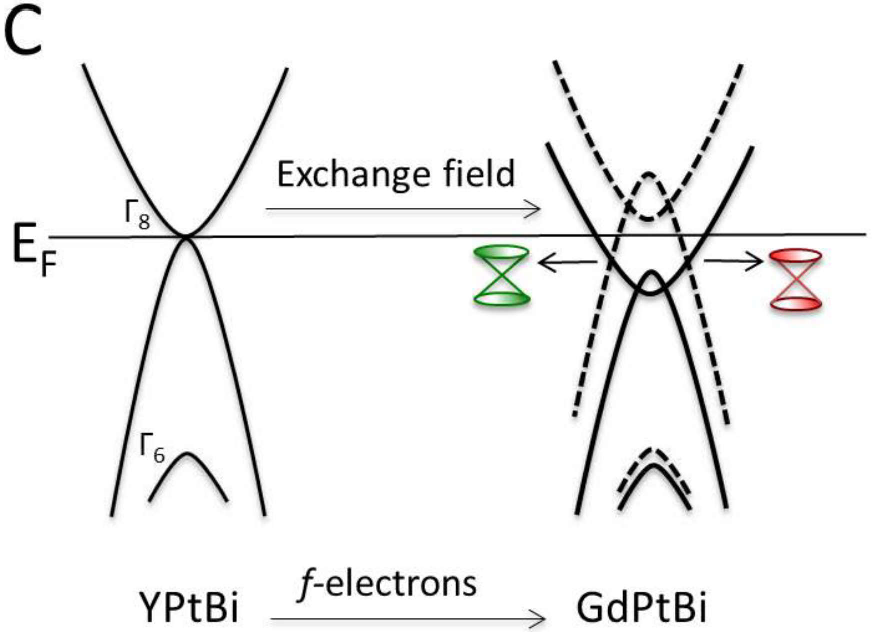
GdPtBi is an Antiferromagnet below 10 K
However it is very soft and the spins can be tuned in a magnetic field

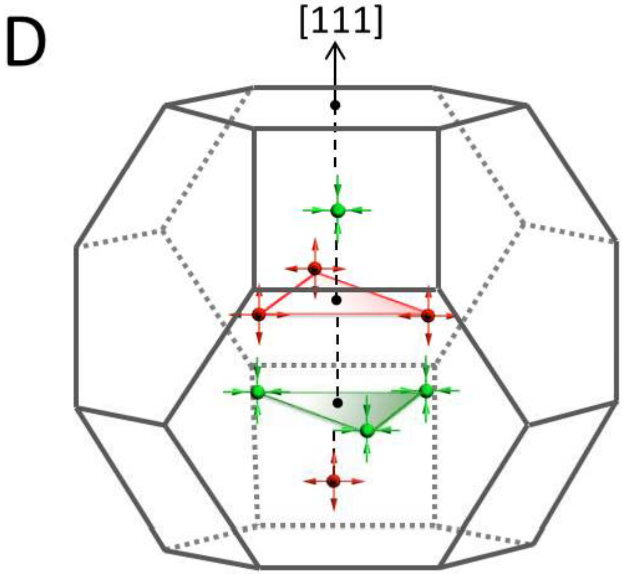
C. Shekhar et al., arXiv:1604.01641, (2016).

Weyl GdPtBi in a magnetic field





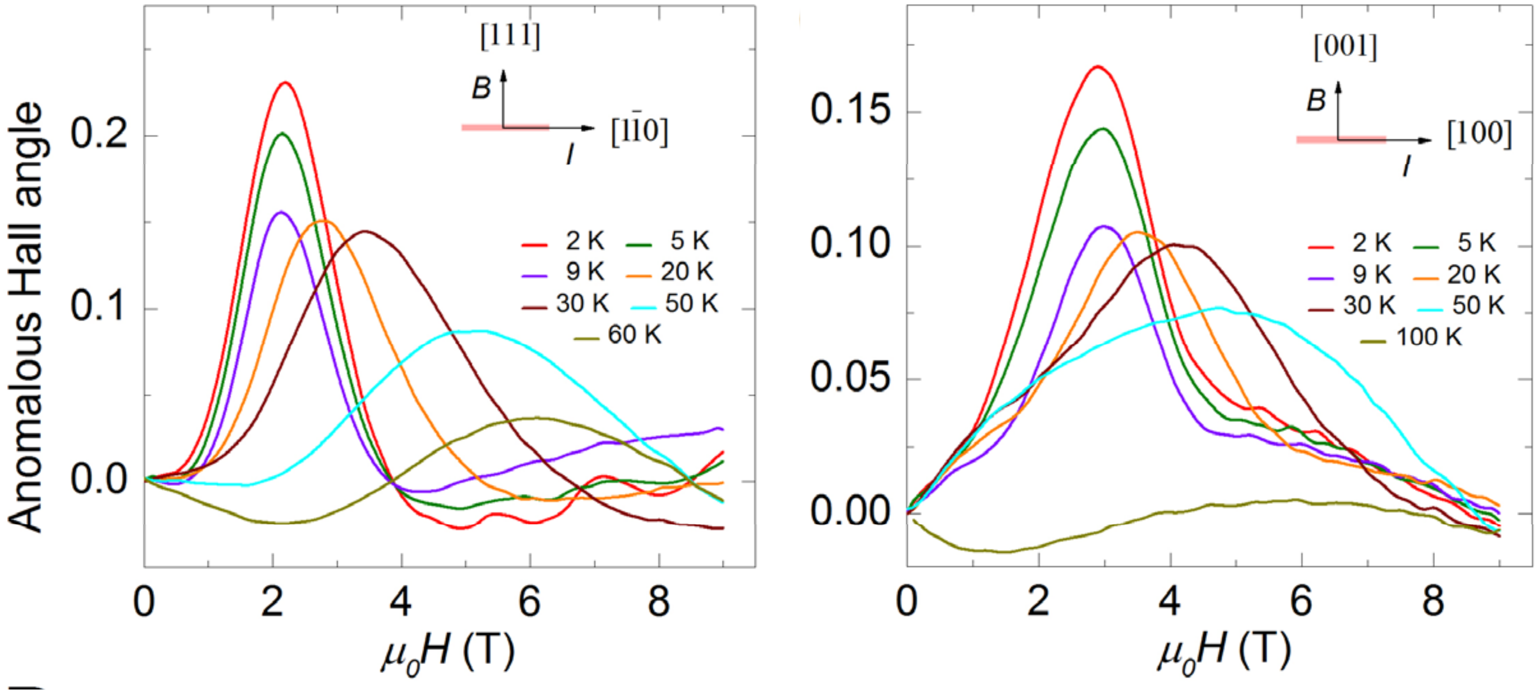




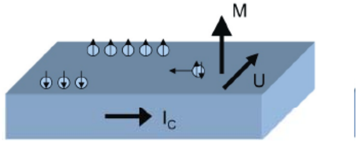
C. Shekhar et al., arXiv:1604.01641, (2016).

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

GdPtBi – Anomalous Hall Effect



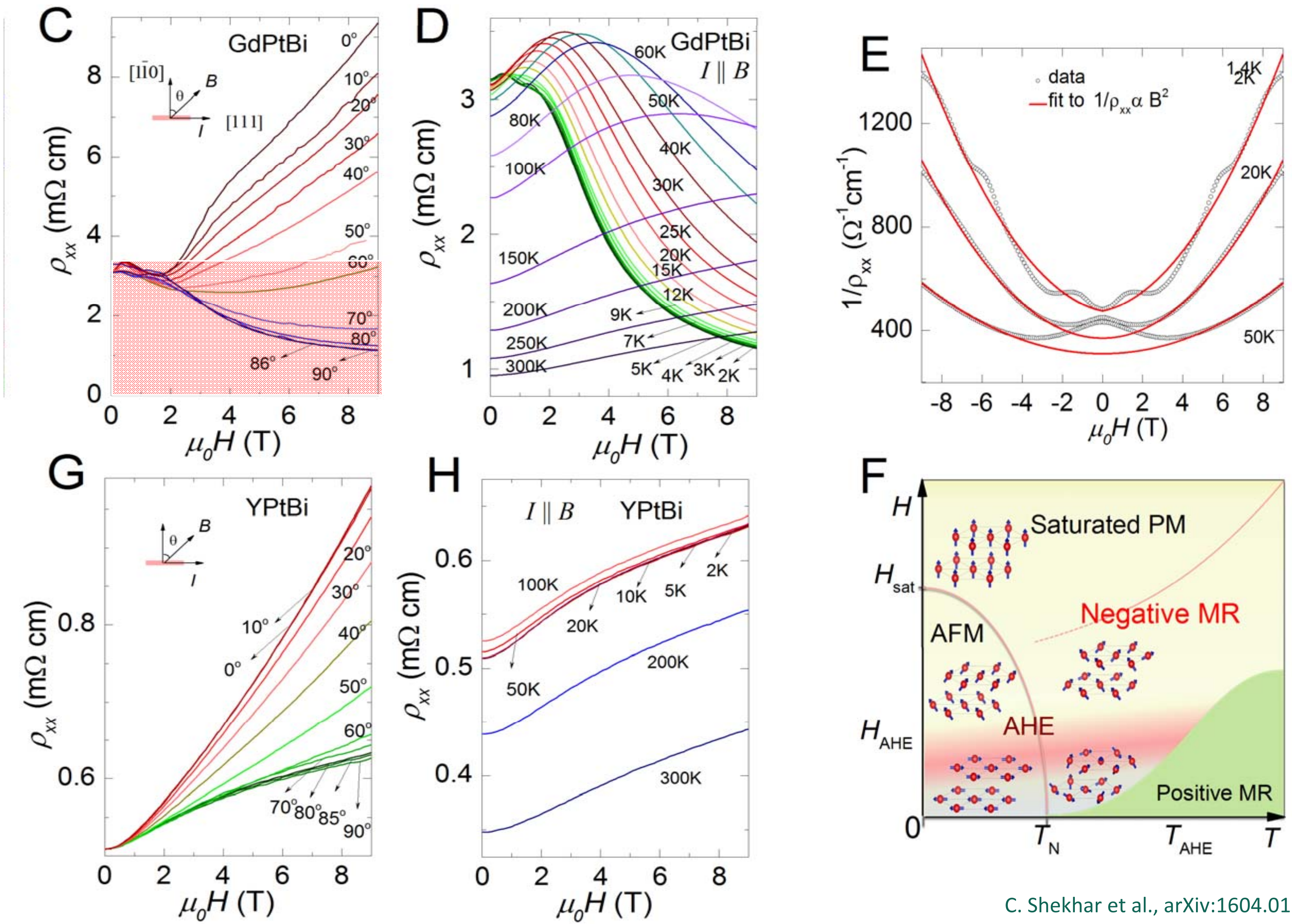
Anomalous Hall effect
1881



In ferromagnets an AHE scales with the magnetic moment
Antiferromagnet show no AHE
A Hall angle of 0.2 is exceptional – 1 would be the **Q**uantum AHE

T. Suzuki,… & J. G. Checkelsky, Nature Physics (2016) doi:10.1038/nphys3831
Shekhar et al., arXiv:1604.01641, (2016)

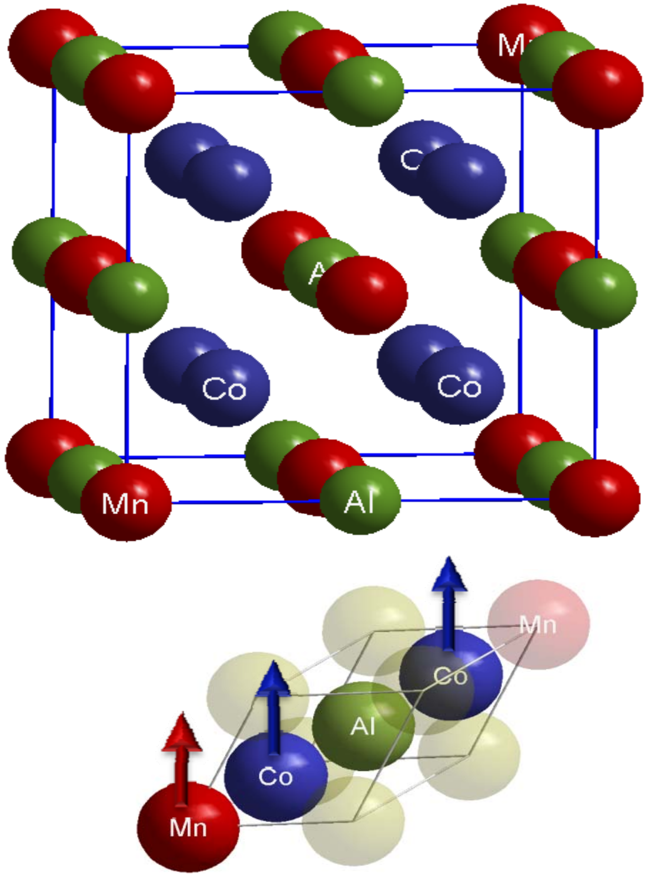
Chiral Anomaly – neg. quadratic MR

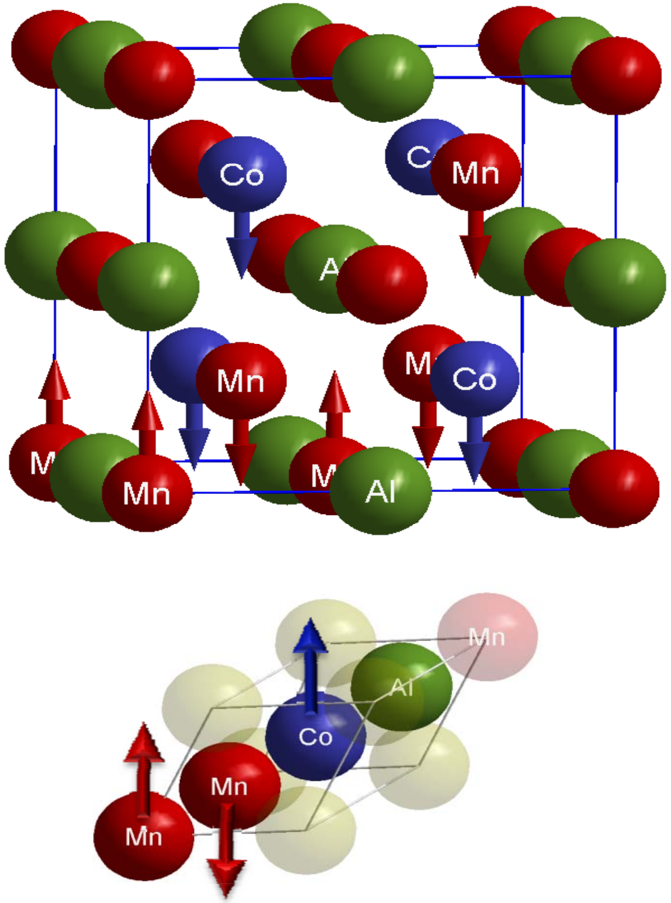


C. Shekhar et al., arXiv:1604.01641, (2016).

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

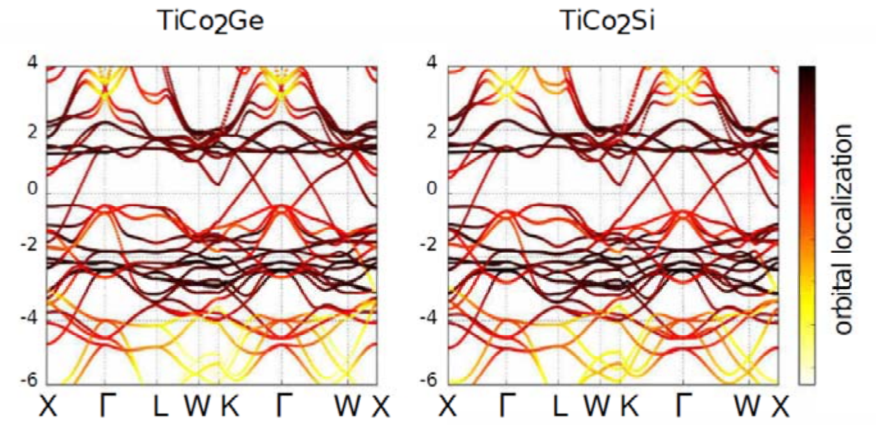
Magnetic Heusler compounds with and without inversion

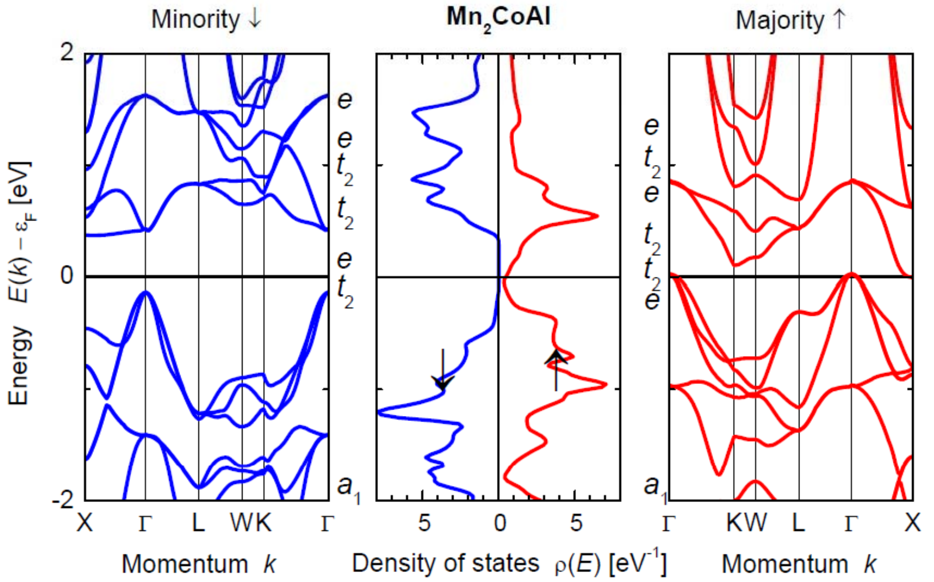


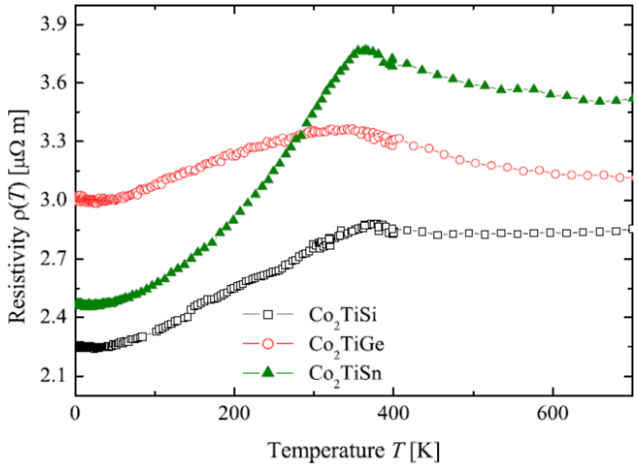


Magnetic Heusler compounds with and without inversion

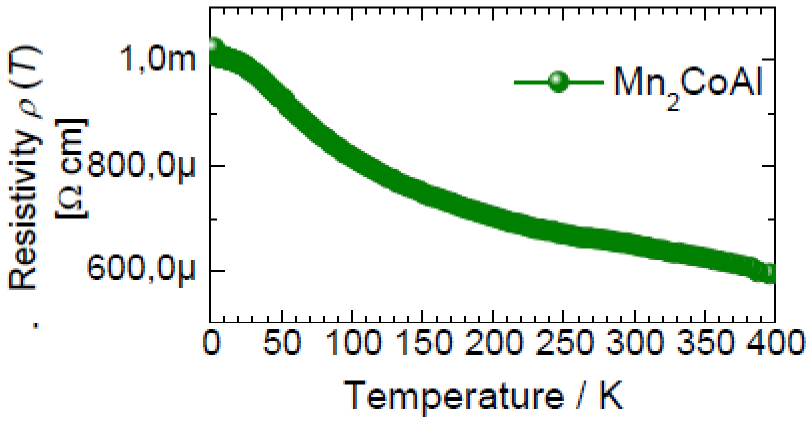
26 Valence electrons







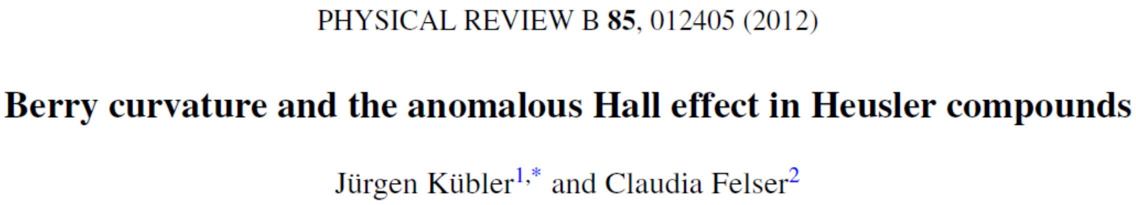
Zhijun Wang, et al., arXiv:1603.00479
Guoqing Chang et al., arXiv:1603.01255



Barth et al. PRB 81, 064404 2010

Ouardi et al., Phys. Rev. Lett. 110 (2013) 100401

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]

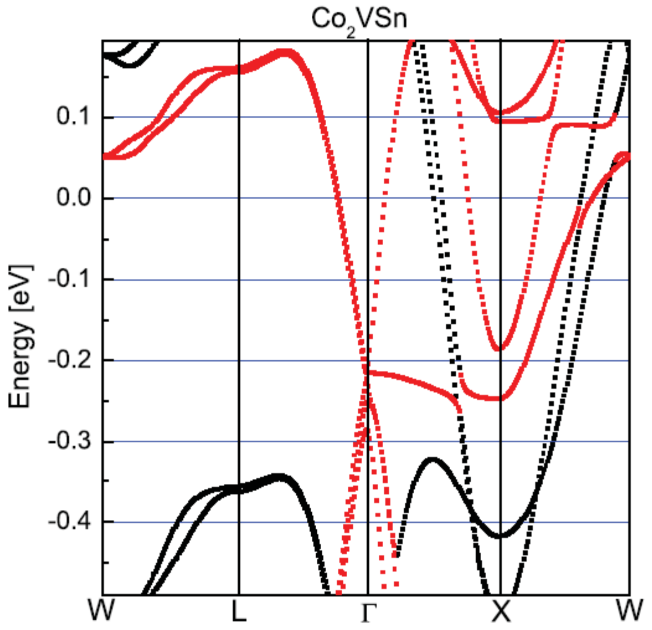
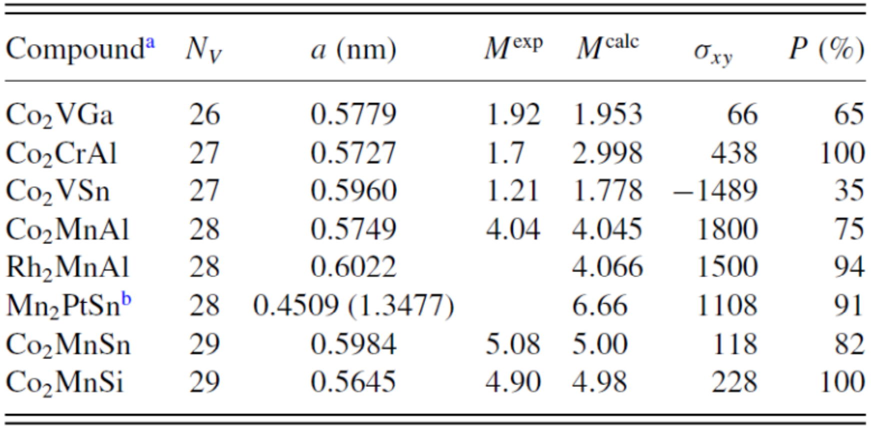


FIG. 4. (Color online) Band structure near the Fermi edge of Co_2VSn. Majority-spin electron states appear in red, minority-spin states in black. Note the Dirac cone at the Γ point at about −0.22 eV.



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

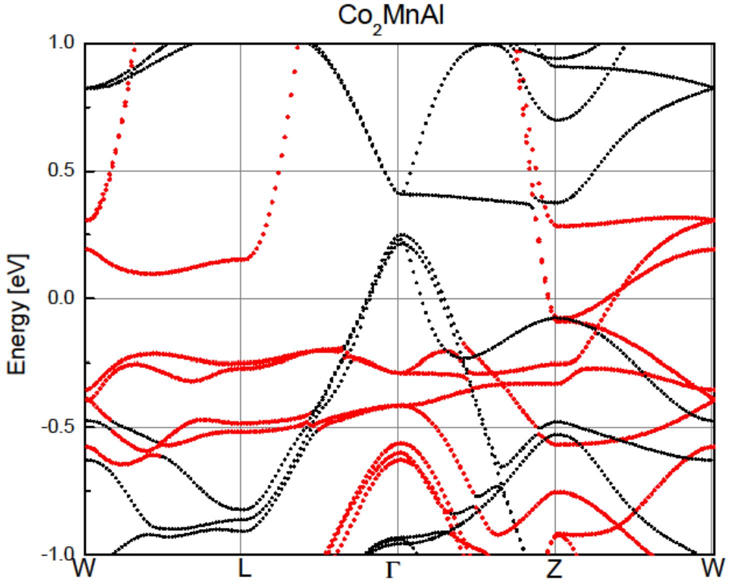
Kübler, Felser, PRB 85 (2012) 012405
Vidal et al Appl.Phys.Lett. 99 (2011) 132509
Kübler, Felser, Europhys. Lett. 114 (2016) 47005

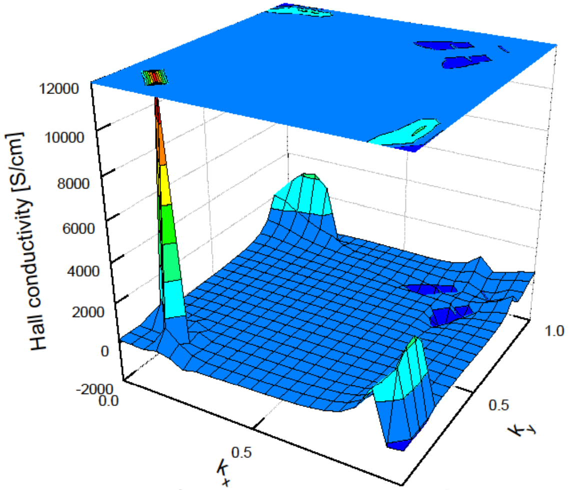
AHE in half metallic ferromagnets

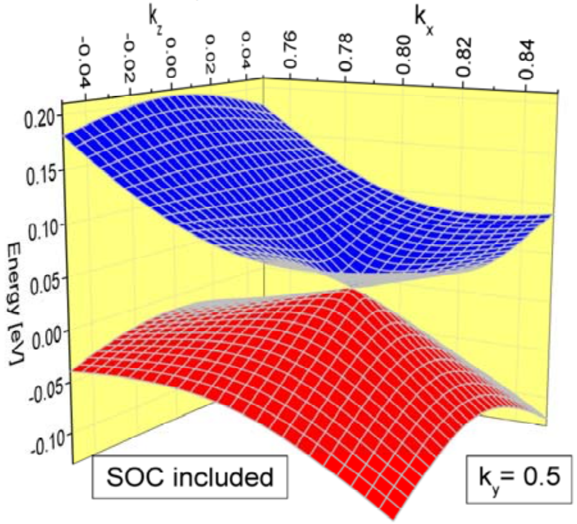
Giant AHE in Co_2MnAl

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

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



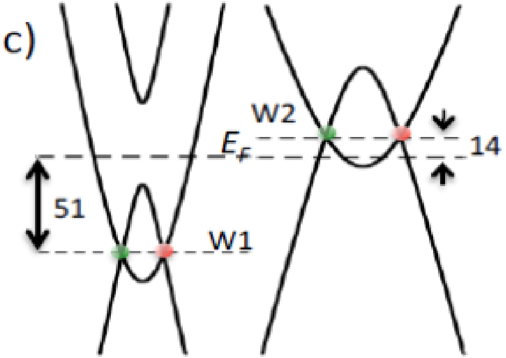


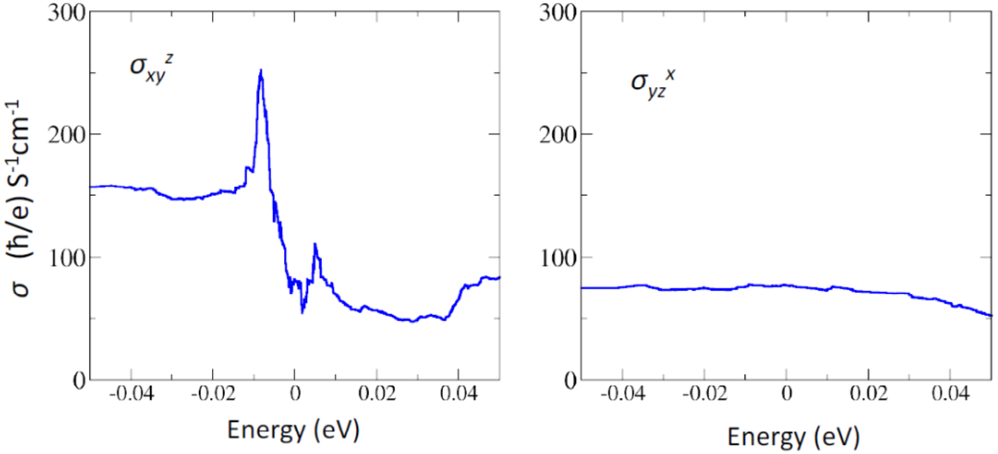


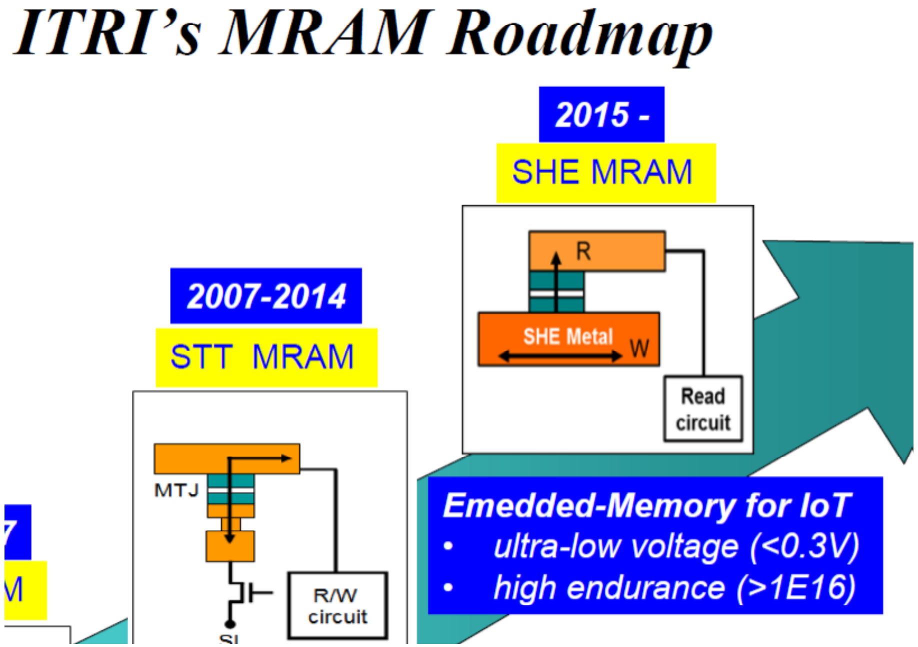
Weyl points are the origin for a large Berry phase and a Giant AHE

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

Application Spin Hall Effect

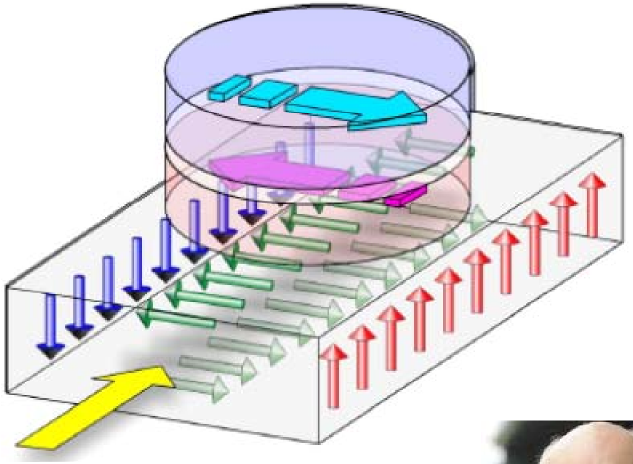




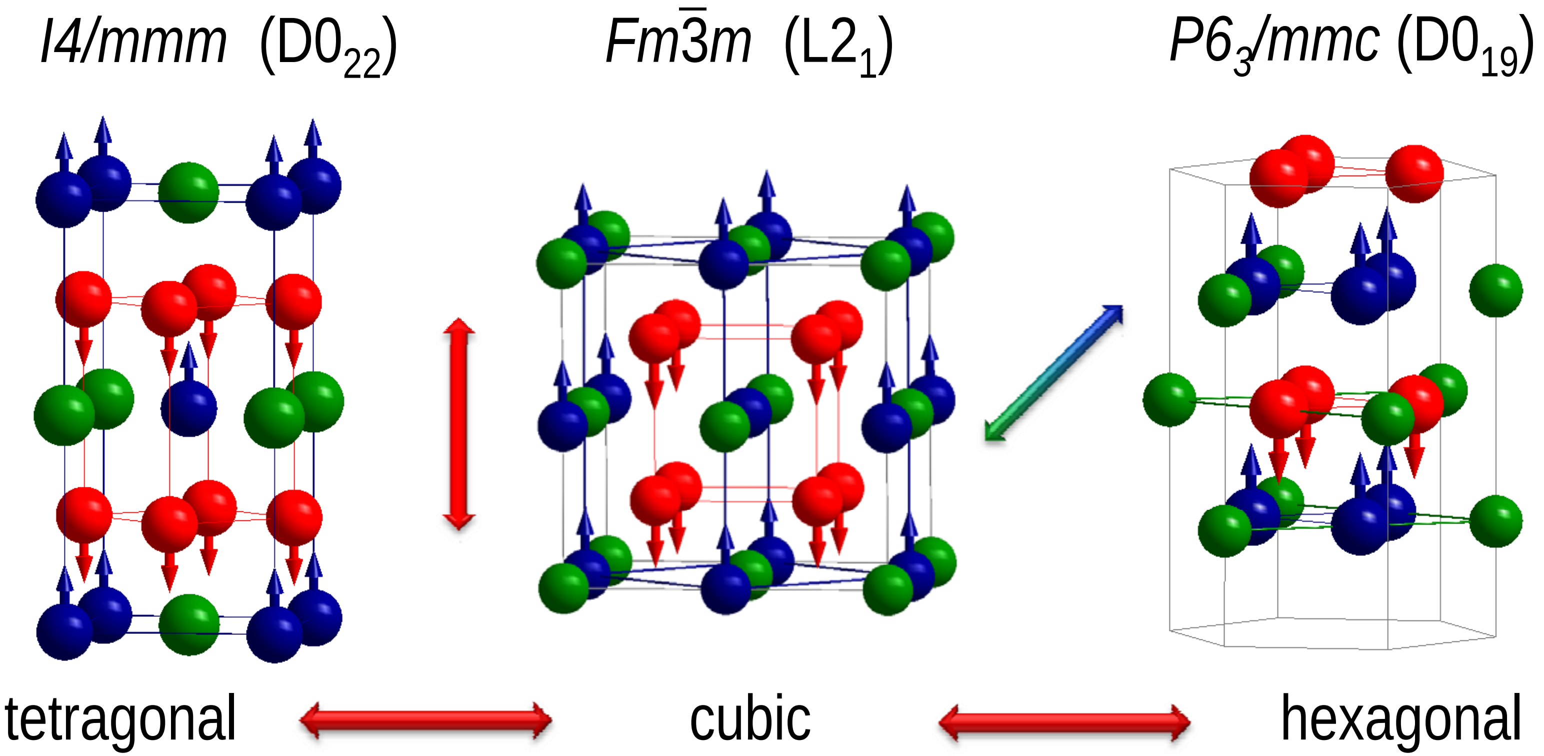


ITRI's MRAM Roadmap

Emedded-Memory for IoT
- ultra-low voltage (<0.3V)
- high endurance (>1E16)



Structural distortion of Heusler



$I4/mmm$ ($D0_{22}$)

$Fm\bar{3}m$ ($L2_1$)

$P6_3/mmc$ ($D0_{19}$)

tetragonal ⟷ cubic ⟷ hexagonal

Hexagonal Antiferromagnet

A Letters Journal Exploring the Frontiers of Physics

December 2014

EPL, **108** (2014) 67001
doi: 10.1209/0295-5075/108/67001

www.epljournal.org

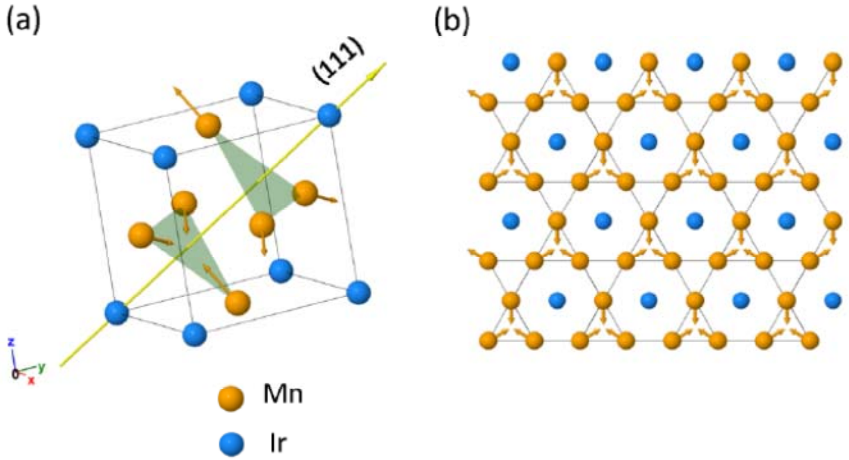
Non-collinear antiferromagnets and the anomalous Hall effect

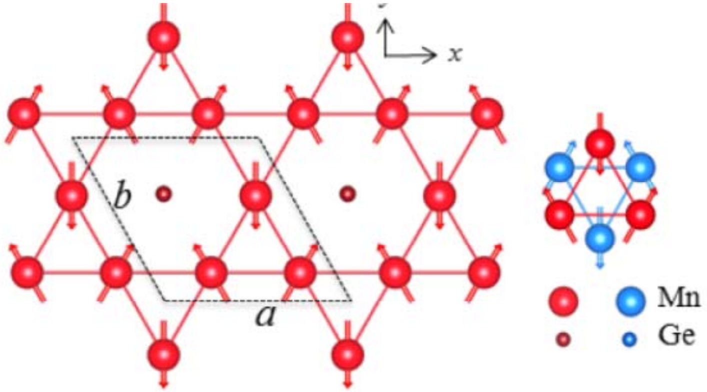
J. Kübler[1] and C. Felser[2]

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



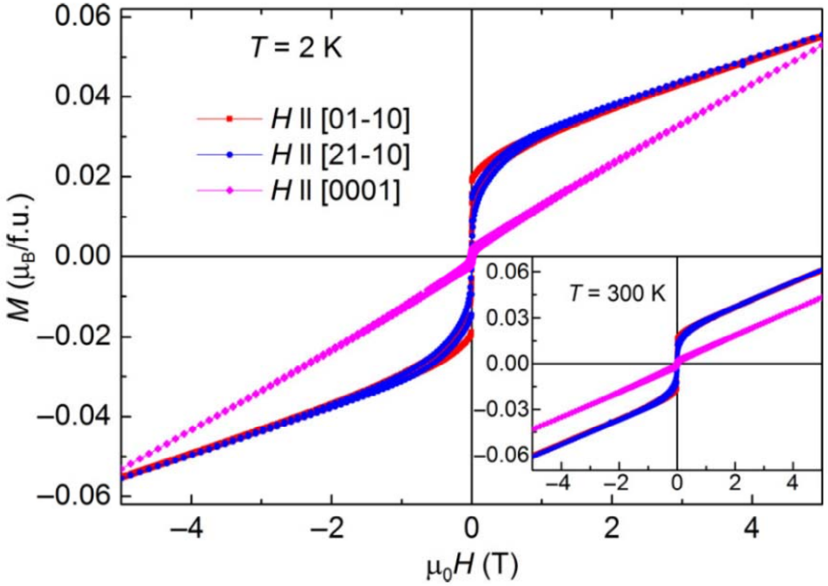


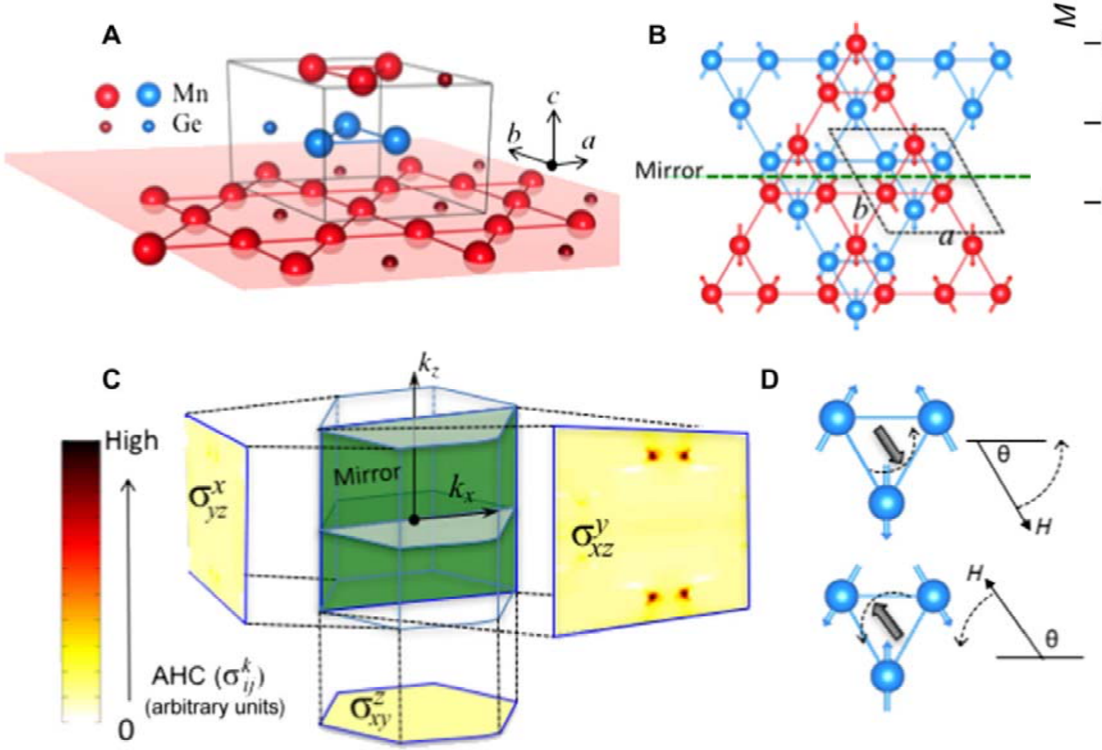
Chen, Niu, and MacDonald, Phys. Rev. Lett., 112 (2014) 017205

Kübler and Felser EPL 108 (2014) 67001

Non-collinear AFM in metallic Mn_3Ge

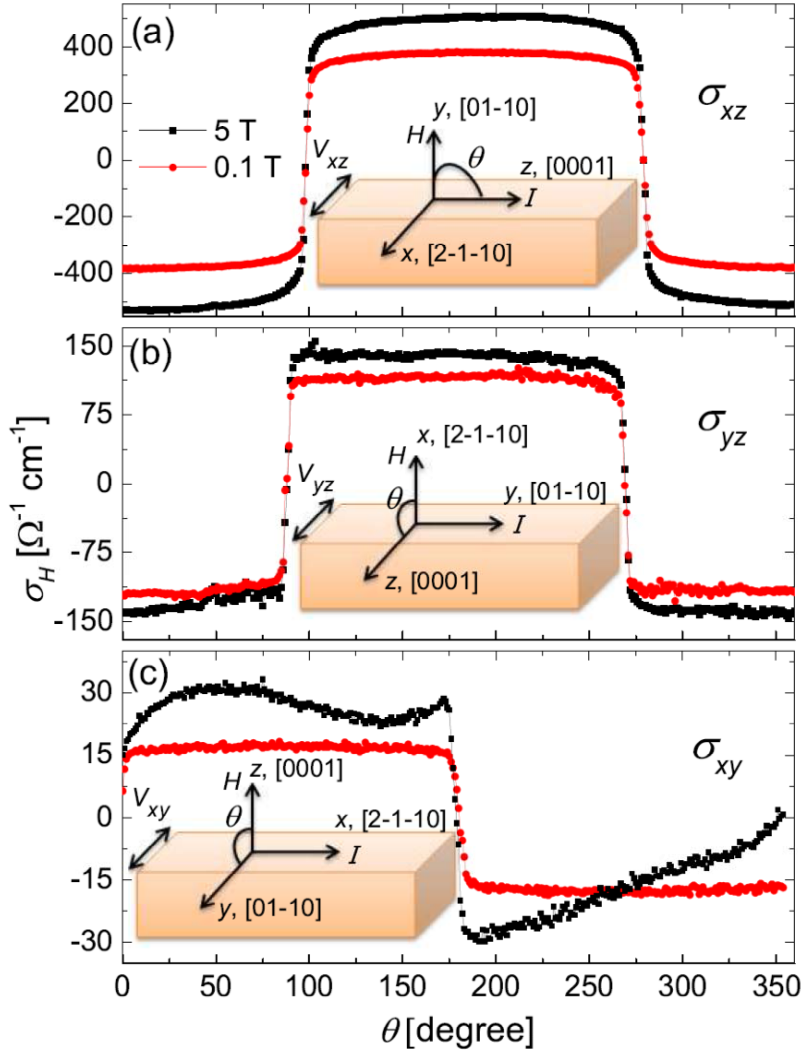
The anomalous Hall conductivities are normally assumed to be proportional to magnetization

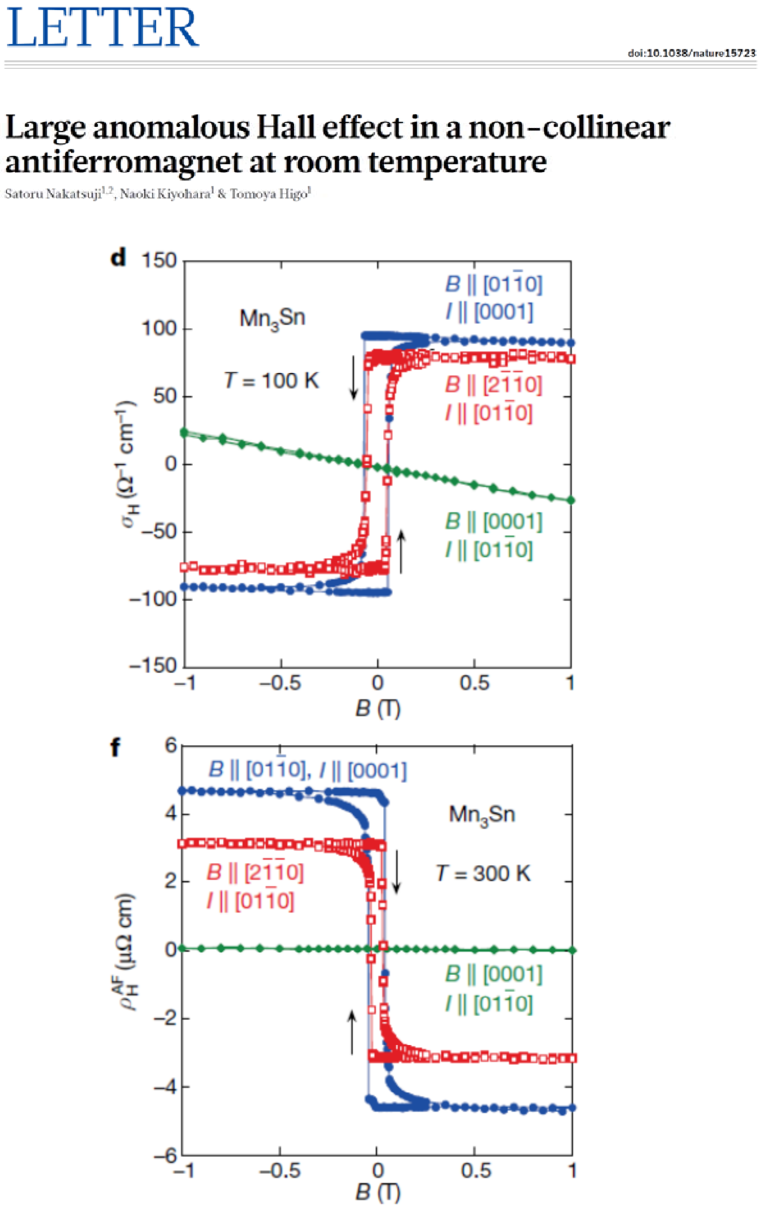




Kübler and Felser EPL 108 (2014) 67001

Non-collinear AFM Mn_3Ge/Mn_3Sn




LETTER

doi:10.1038/nature15723

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

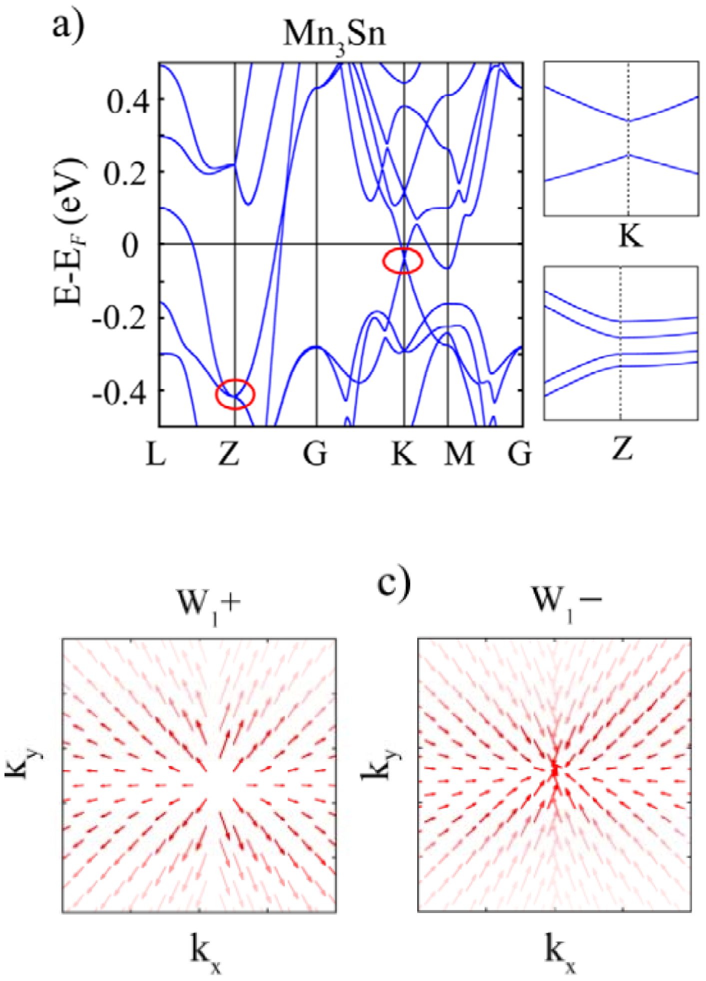
Satoru Nakatsuji[1,2], Naoki Kiyohara[1] & Tomoya Higo[1]

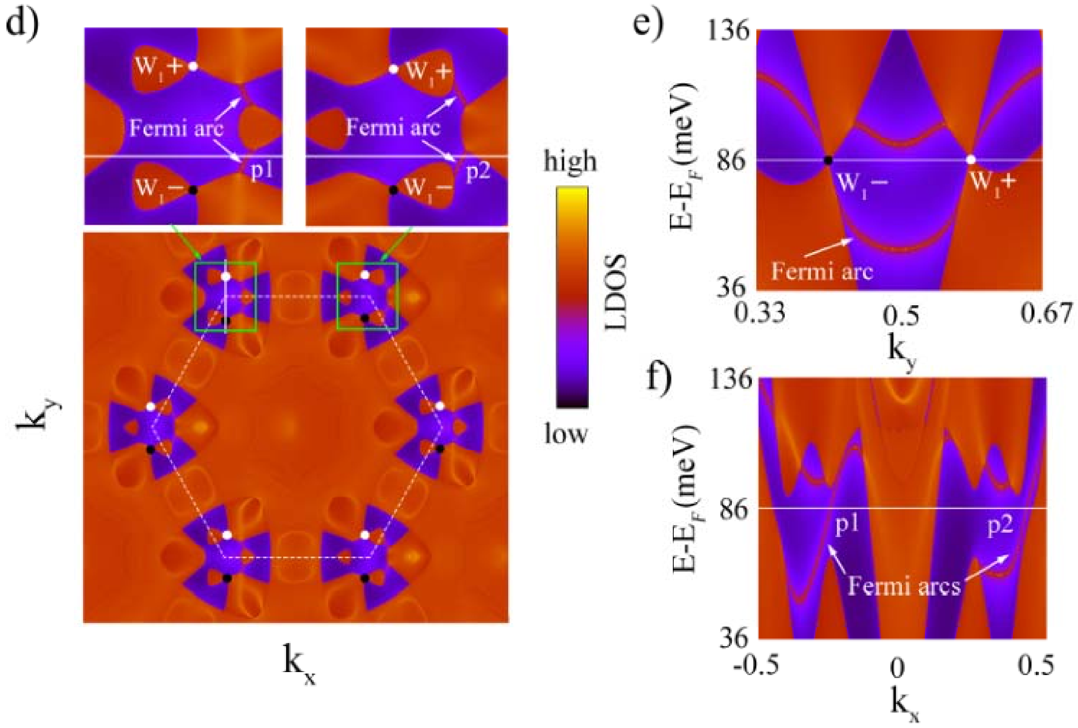
Nayak et al. preprint: arXiv:1511.03128, Science Advances in print

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

Universe – applying a lattice

Bringing order to the expanding fermion zoo

Carlo Beenakker Commentary
Heisenberg (1930): We observe space as a continuum, but we might entertain the thought that there is an underlying lattice and that space is actually a crystal. Which particles would inhabit such a lattice world? Werner Heisenberg *Gitterwelt* (lattice world) hosted electrons that could morph into protons, photons that were not massless, and more peculiarities that compelled him to abandon “this completely crazy idea”

New Fermions

RESEARCH

RESEARCH ARTICLE SUMMARY

TOPOLOGICAL MATTER

Beyond Dirac and Weyl fermions: Unconventional quasiparticles in conventional crystals

Barry Bradlyn,* Jennifer Cano,* Zhijun Wang,* M. G. Vergniory, C. Felser, R. J. Cava, B. Andrei Bernevig†

Fermions in condensed-matter systems are not constrained by Poincare symmetry. Instead, they must only respect the crystal symmetry of one of the 230 space groups. Hence, there is the potential to find and classify free fermionic excitations in solid-state systems that have no high-energy counterparts.

What comes next? Magnetic Space groups

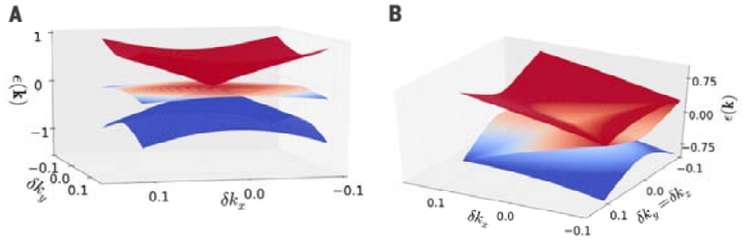
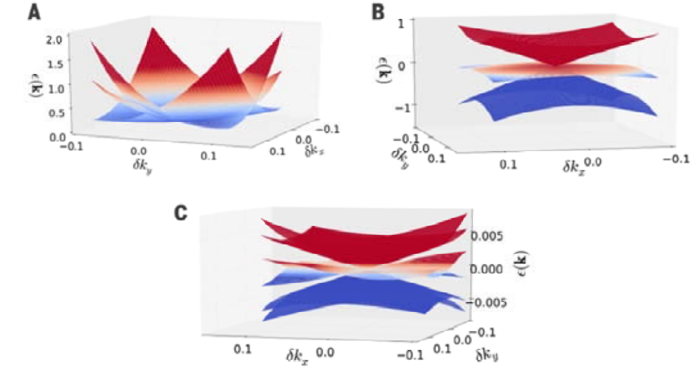
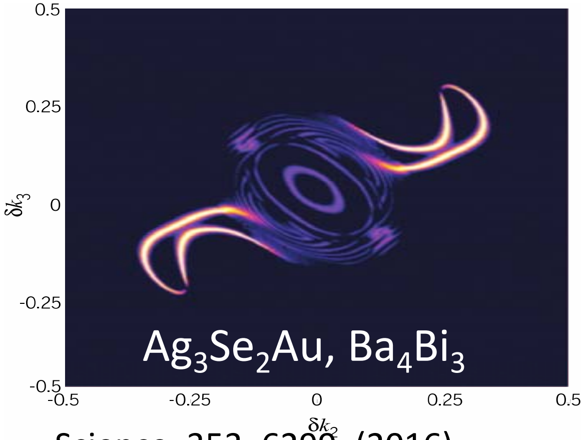


Fig. 1. Energy dispersion near a threefold degeneracy at the *P* point. (**A** and **B**) Shown are threefold degenerate points in (A) SGs 199 and 214 and (B) SG 220. In the latter case, pairs of bands remain degenerate in energy along the high-symmetry lines $|\delta k_x| = |\delta k_y| = |\delta k_z|$.

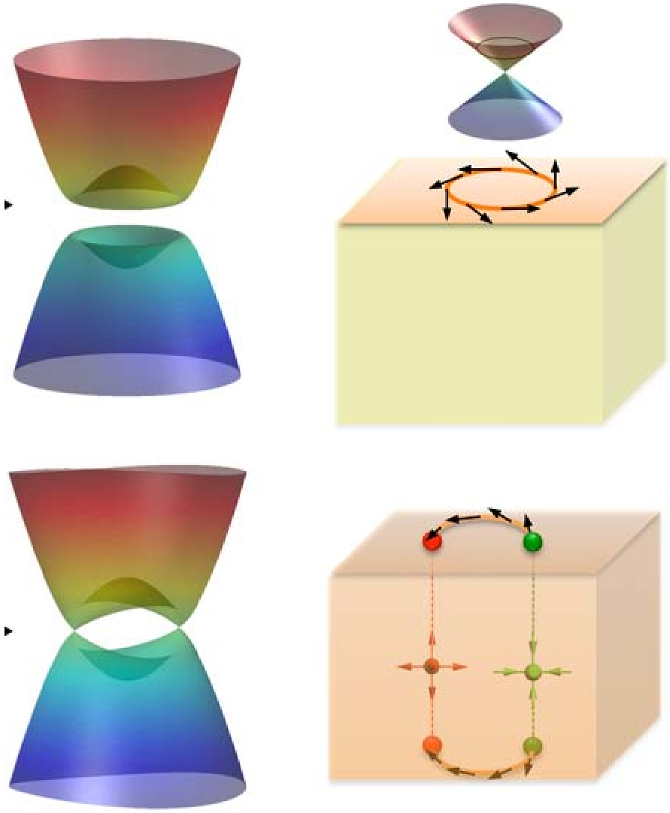




Science, 353, 6299, (2016)

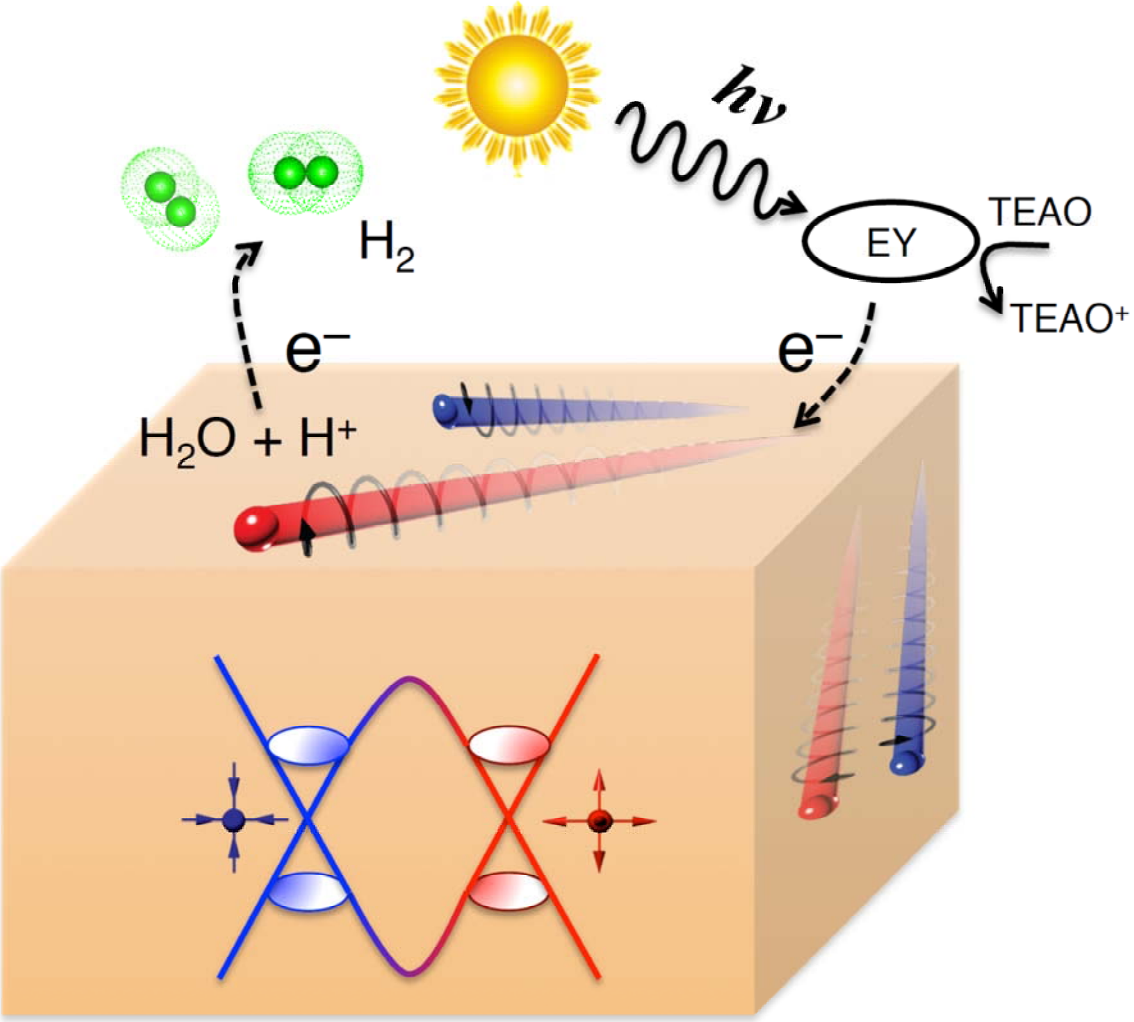
Can we do something useful- Catalysis

- Dirac and Weyl semimetals
  - Linear bands – electron and holes with **high mobilties**
  - High mobility of electrons and holes – reduces the probabilty of recombination of electron hole pairs in redox reaction
  - Toplogical connection between the two surfaces via Fermi arcs

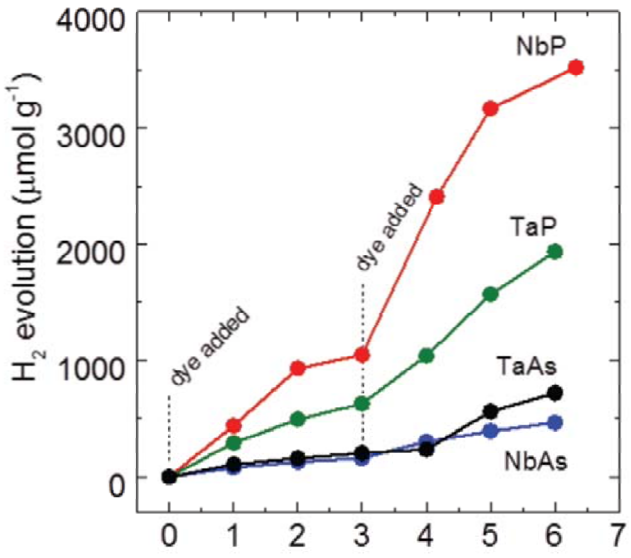


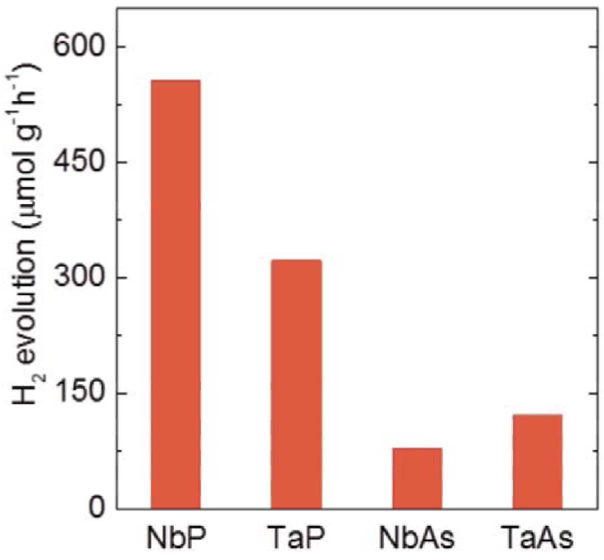
Catalysis

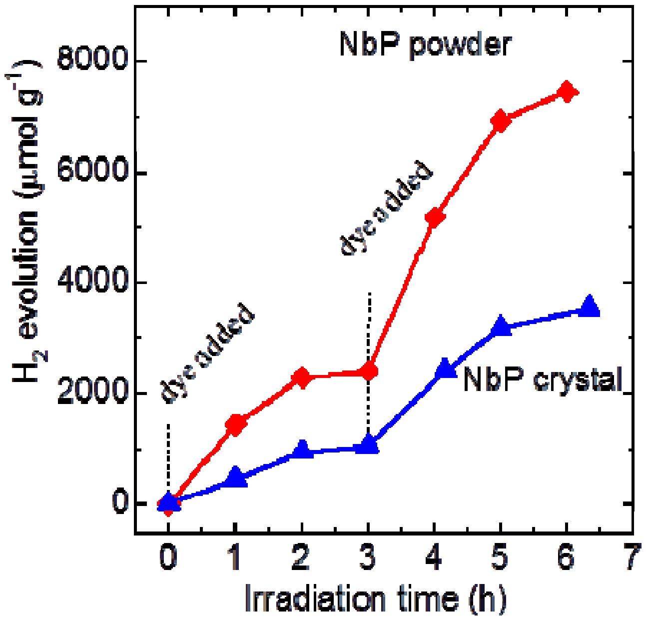
Hydrogen evolution reaction

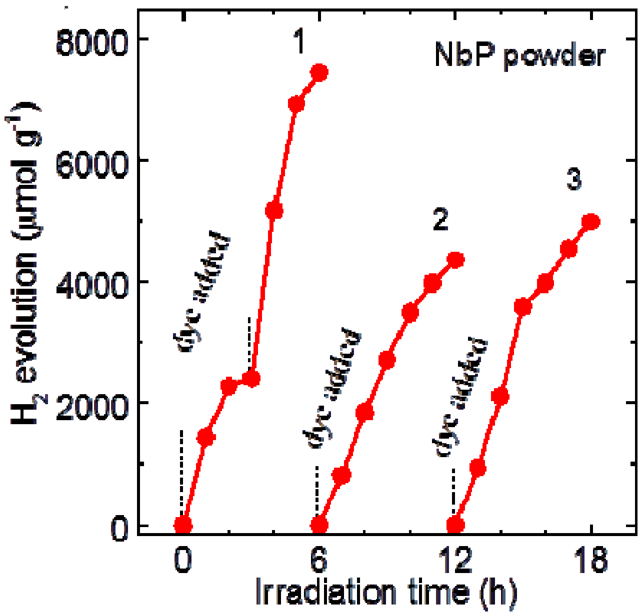


Weyl and catalysis



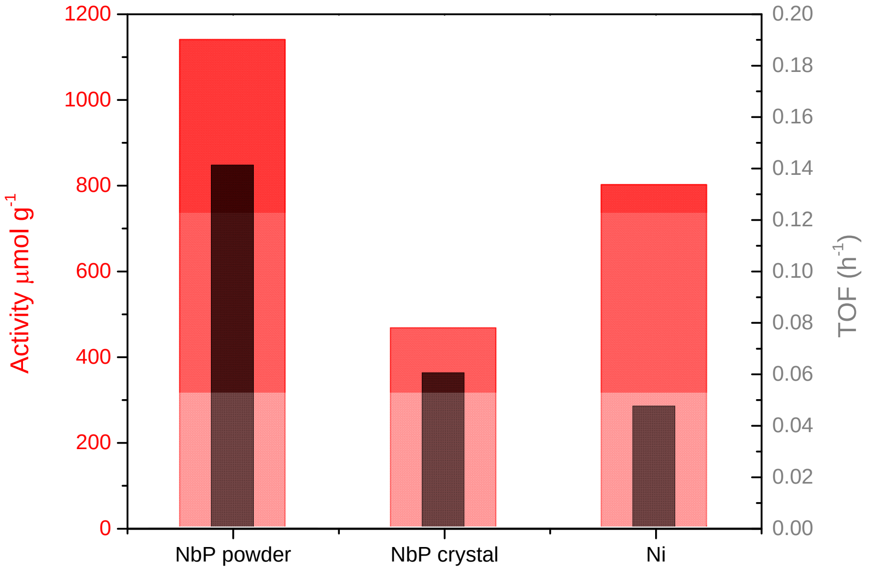


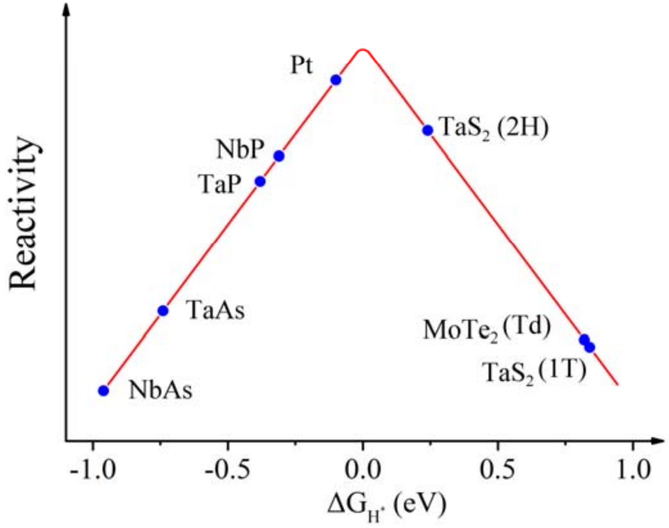


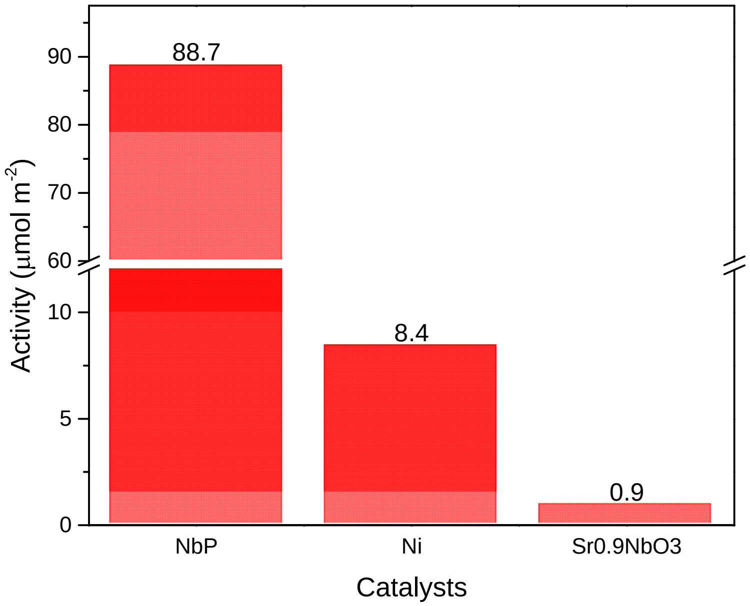


Comparison with other catalysts

Materials	Gibbs free energy (ΔGH^* (eV))
NbP	-0.31
TaP	-0.38
TaAs	-0.74
NbAs	-0.96
Pt	-0.1
Ni (111)	-0.27
2H-TaS_2	0.24
1T-TaS2	0.82
Td-$MoTe_2$	0.84
2H-MoS_2	2.19







Summary

Solid State Chemistry can have an impact on topological effects

- Topological insultors (Oxides, correlated systems)
- Weyl and Dirac semimetals
- ..

Applications in

- Electronics AHE SHE QAHE
- chemistry (catalysis)

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