Topological aspects in solid state chemistry

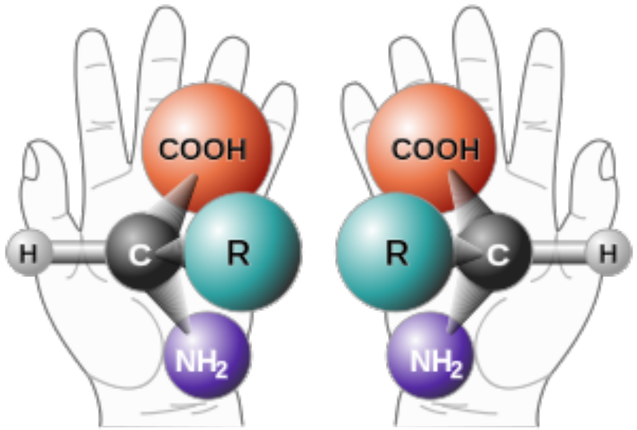
Claudia Felser

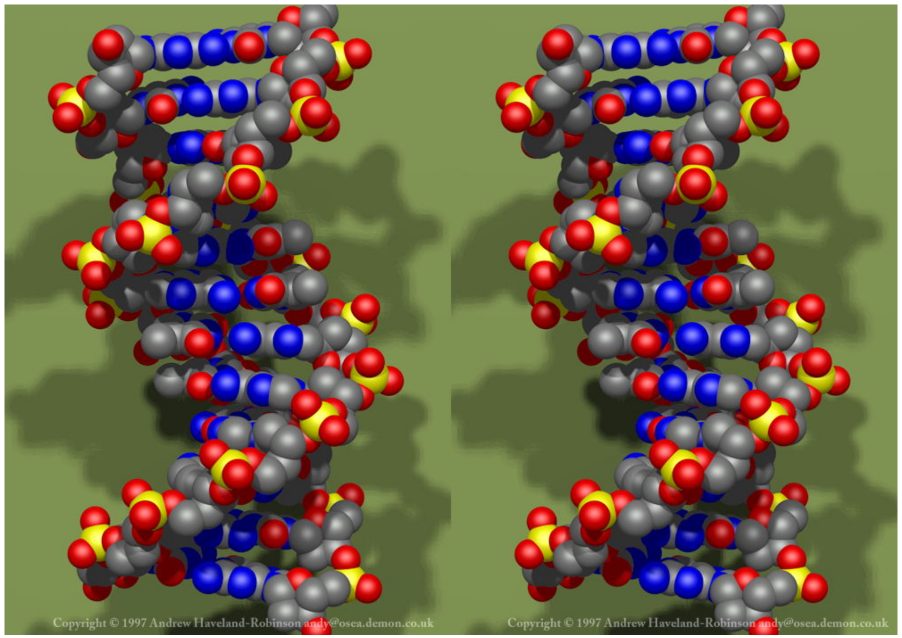
Topology

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

Topology in Chemistry

Molecules with different chiralities can have different physical and chemical properties

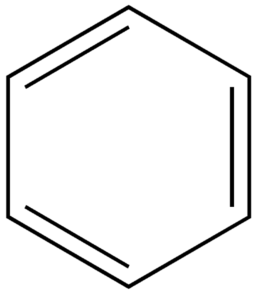


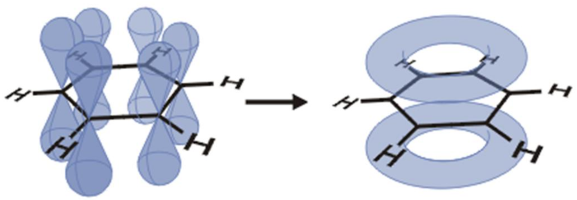


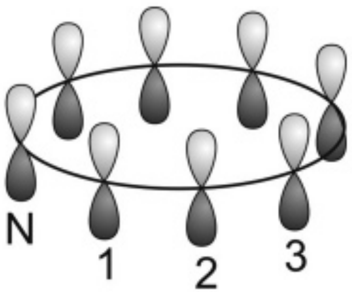
Topology in Chemistry

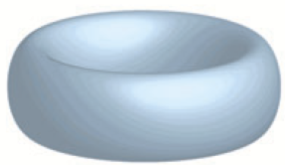
Aromatic compounds

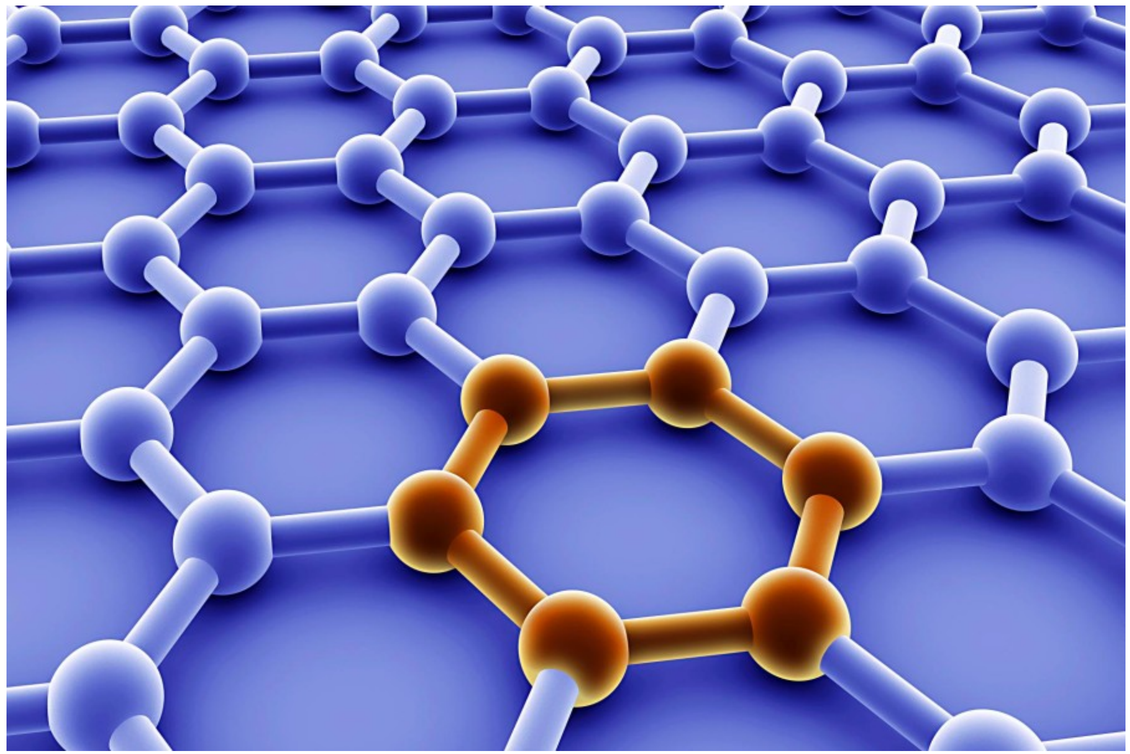
- Aromatic with (**4 n + 2) π-electrons**
- The symmetry counts



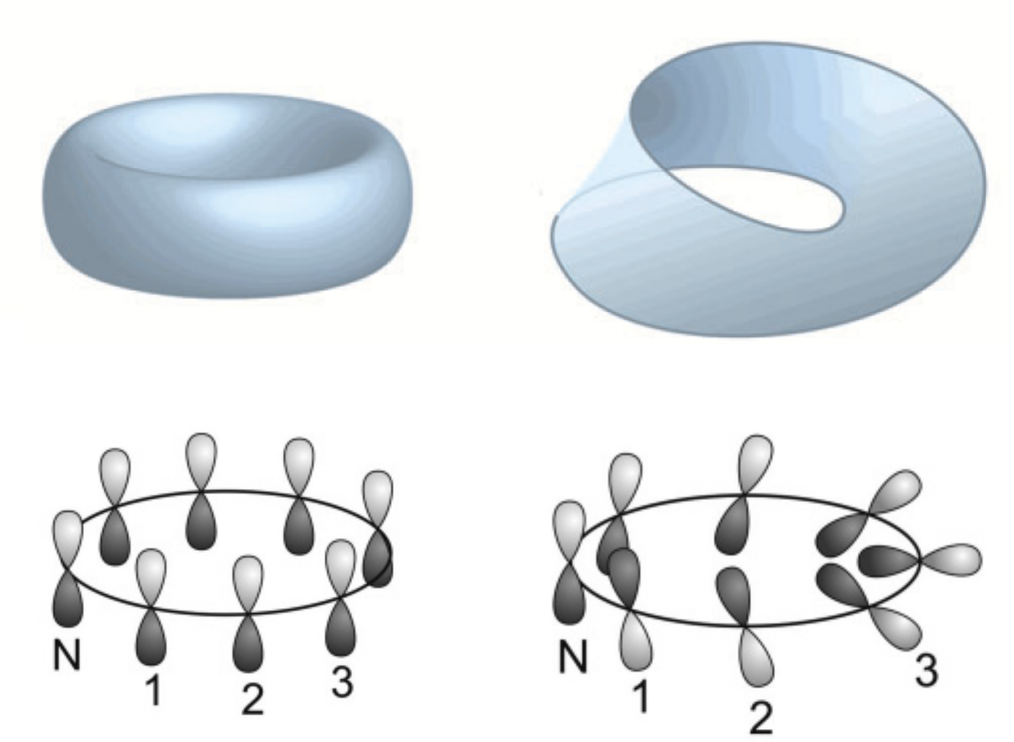








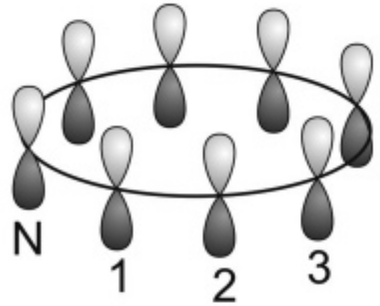
Topology in Chemistry



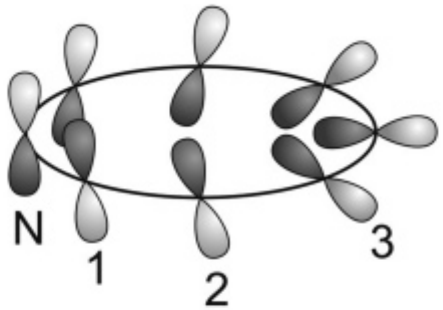
Magic electron numbers of π-electrons

Hückel:	**Möbius**
4n+2 aromatic	**4n aromatic**
4n antiaromatic	**4n+2 antiaromatic**

Hückel and Möbius Aromaticity



Möbius Annulenes



ORGANIC CHEMISTRY

Aromatics with a twist

Rainer Herges

The properties of flat aromatic molecules are well known to chemists, but some non-planar aromatics remain a mystery. A molecule that can twist into a Möbius band on command might shed light on their features.

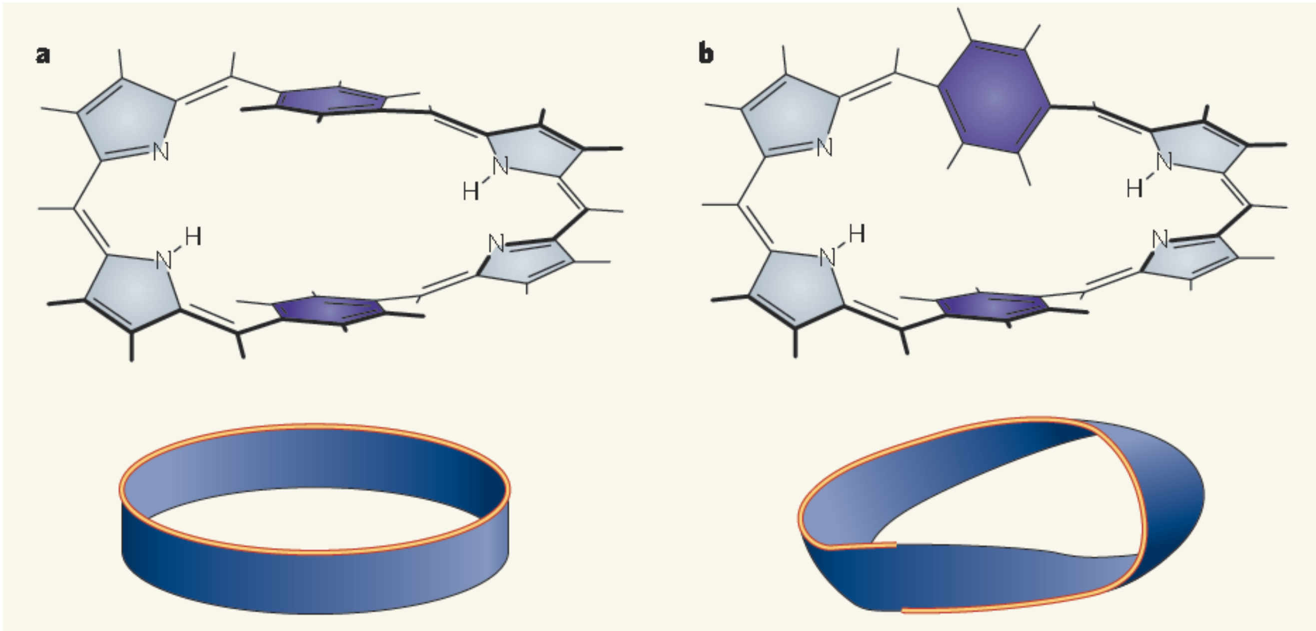
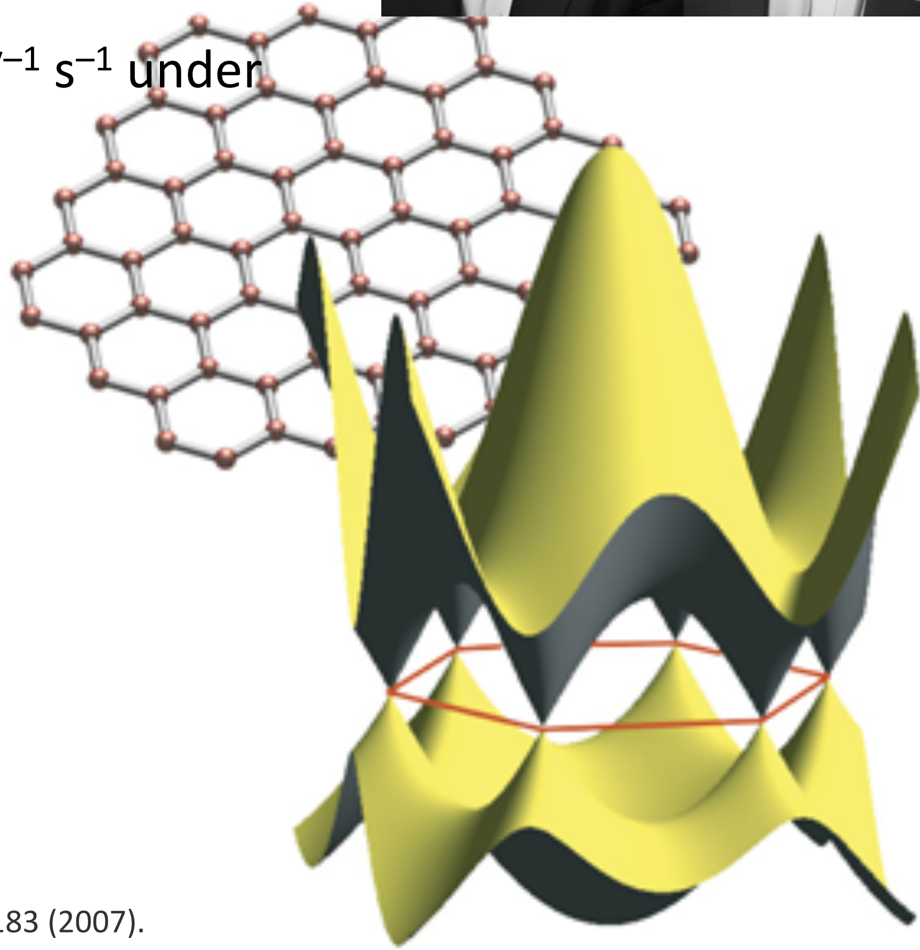
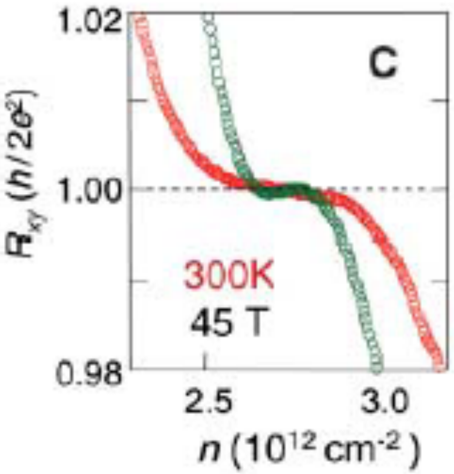


Figure 2 | A molecular topological switch. Latos-Grażyński and colleagues[1] have made a compound that is antiaromatic in nonpolar solvents, but not in polar solvents. **a**, In nonpolar solvents, the two benzene rings (purple) in the molecule are parallel, and the molecule is a two-sided, non-twisted band. **b**, In polar solvents, the upper benzene ring twists by 90°, so that the molecule becomes a one-sided, Möbius structure. This conformational change alters the aromaticity of the molecule.

Graphene

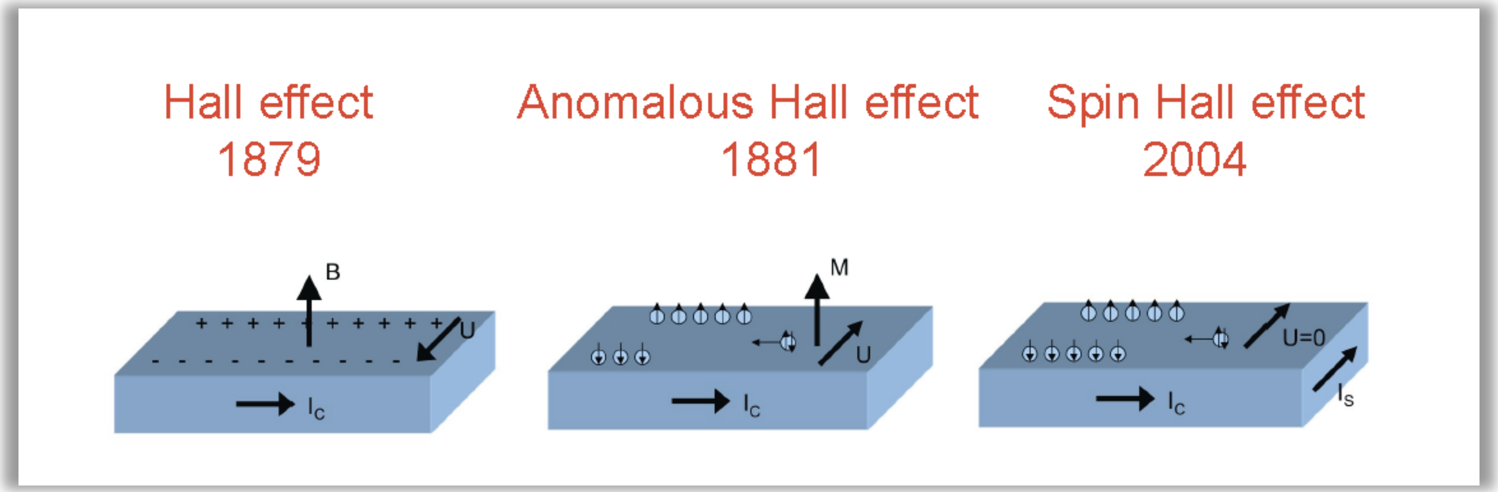
- Graphene's conductivity exhibits values close to the conductivity quantum e2/h per carrier type
- Graphene's charge carriers can be tuned continuously between electrons and holes in concentrations n = 10^{13} cm^{-2}
- Mobilities μ can exceed 15,000 cm^2 V^{-1} s^{-1} under ambient conditions
- InSb has μ ≈77,000 cm^2 V^{-1} s^{-1}

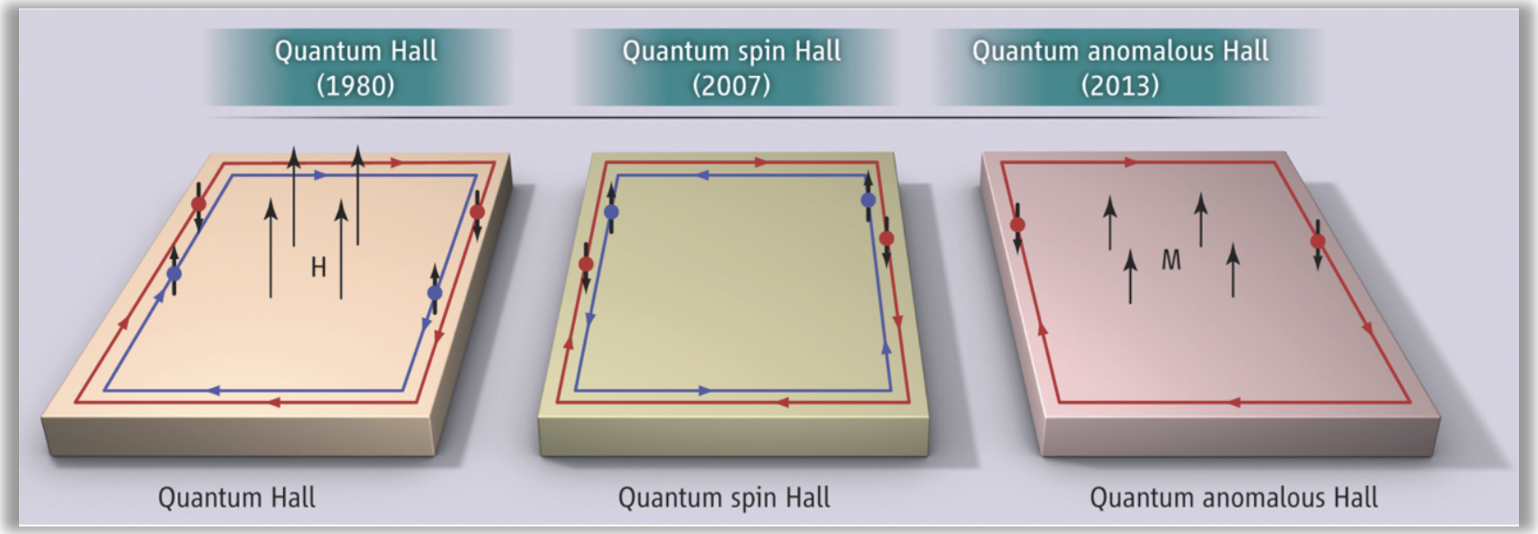




Geim, A. K. & Novoselov, K. S. The rise of graphene. Nature Mater. 6, 183 (2007).

Family of Quantum Hall Effects

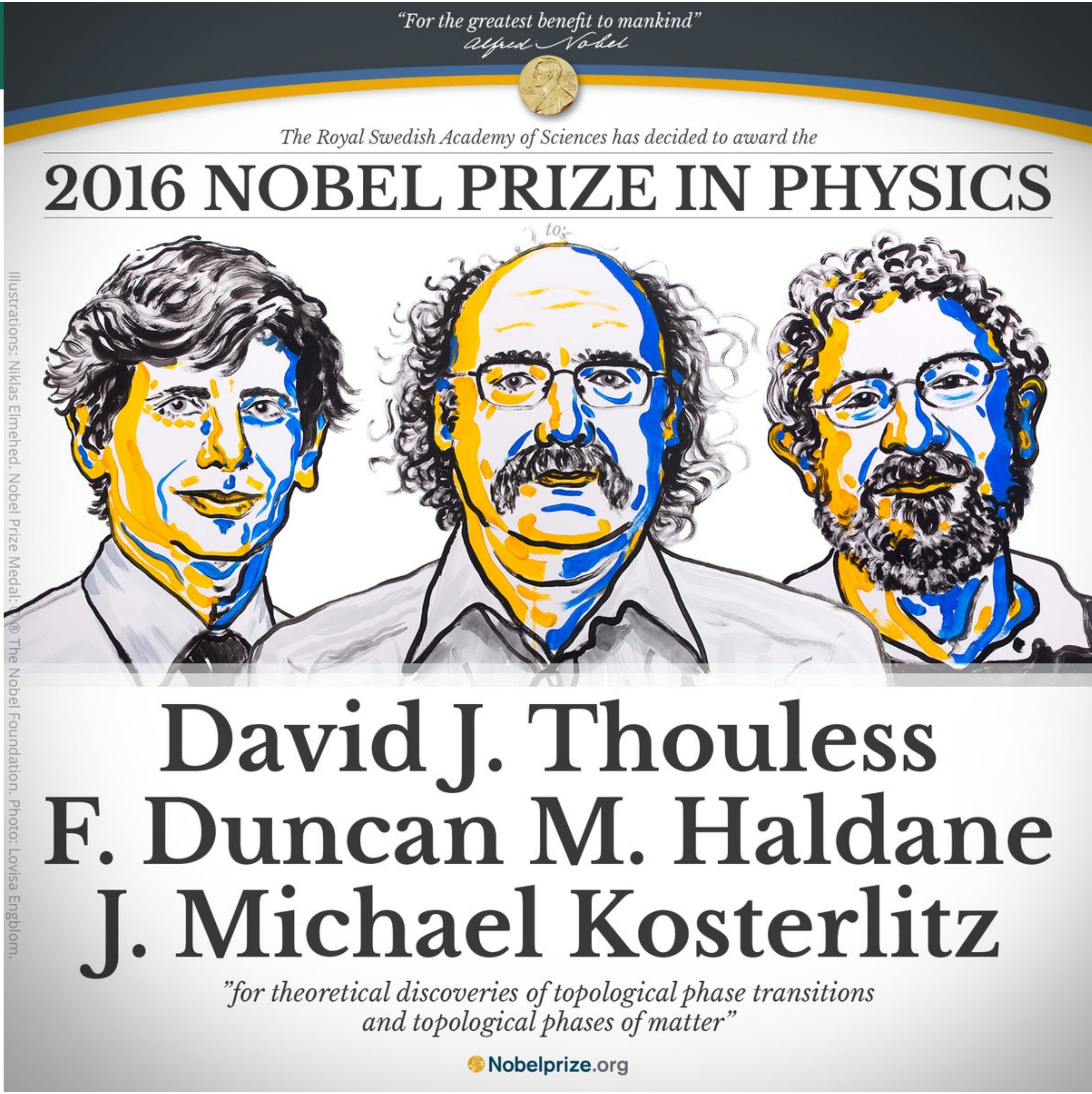




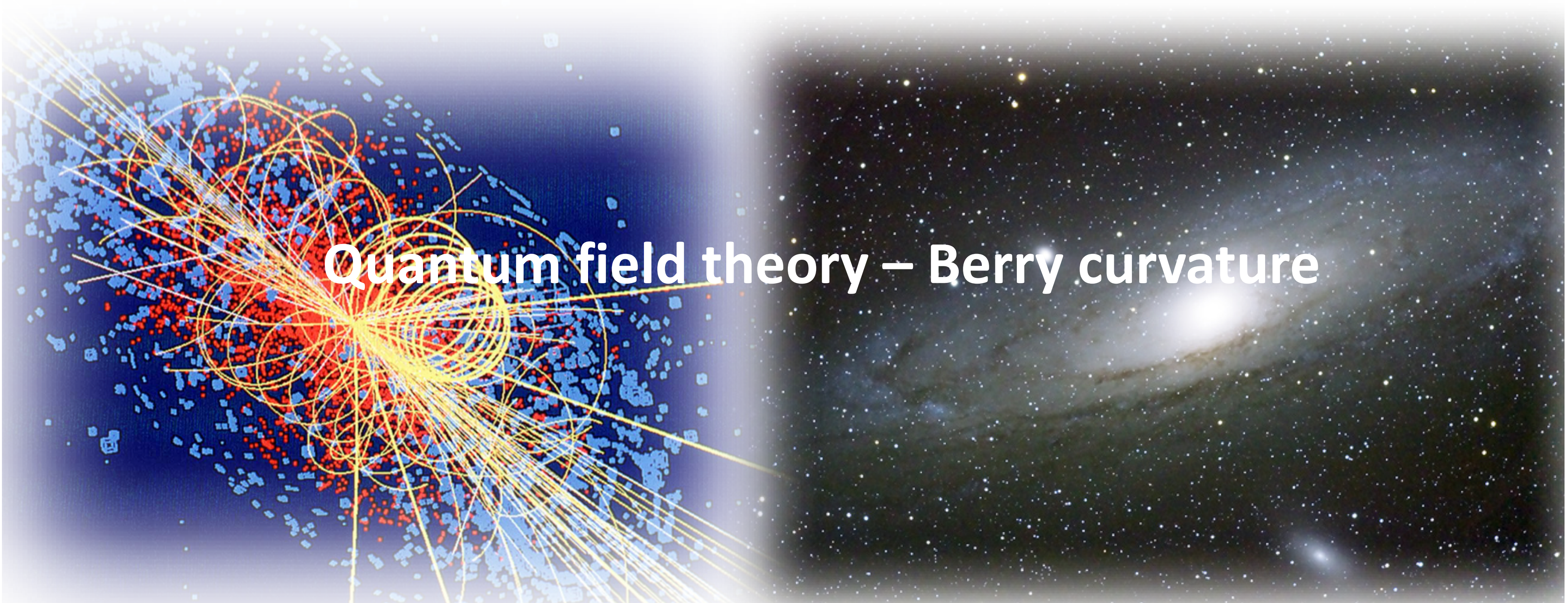
S Oh Science 340 (2013) 153

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


"For the greatest benefit to mankind"
Alfred Nobel
The Royal Swedish Academy of Sciences has decided to award the
2016 NOBEL PRIZE IN PHYSICS
to:
David J. Thouless
F. Duncan M. Haldane
J. Michael Kosterlitz
"for theoretical discoveries of topological phase transitions
and topological phases of matter"
Nobelprize.org
Illustrations: Niklas Elmehed. Nobel Prize Medal: ® The Nobel Foundation. Photo: Lovisa Engblom.

Particles – Universe –Condensed matter

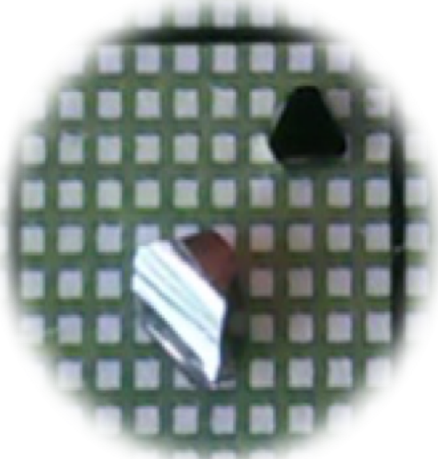


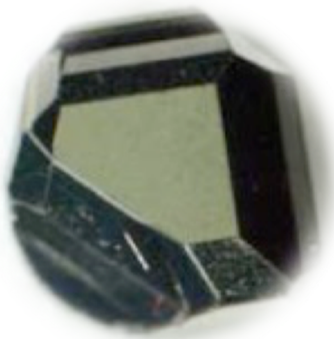
Dirac
Cd_3As_2
Guido Kreiner

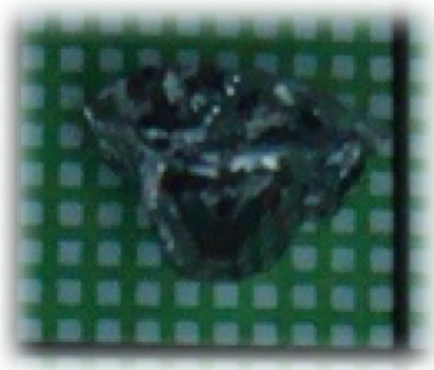
Higgs
$YMnO_3$
Lichtenberg Spaldin

Weyl
TaAs
Vicky Süss, Marcus Schmidt

Majorana
YPtBi
Chandra Shekhar







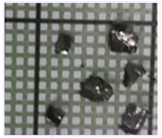
Topology - Electronic structure

Topology – interdisciplinary

Chemistry

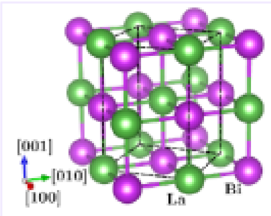
Real space - local

Crystals



LaBi

Crystal structure

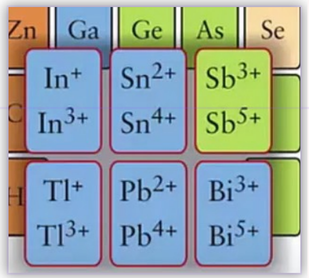


Position of the atoms

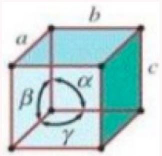
Orbitals

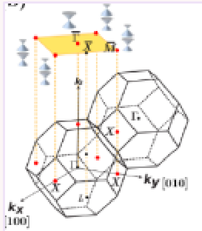
Check	WP	Representative
☐	8g	x,y,z
☐	4f	x,1/2,z
☐	4e	x,0,z
☑	4d	x,x,z
☑	2c	1/2,0,z
☐	1b	1/2,1/2,z
☑	1a	0,0,z

Inert pair effect

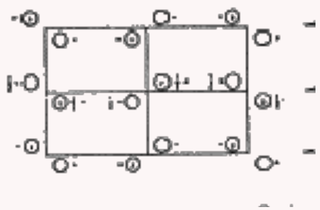


Symmetry





Local symmetry



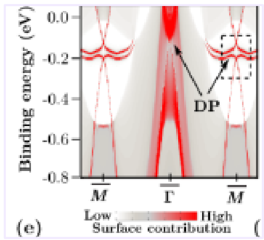
Relativistic effects

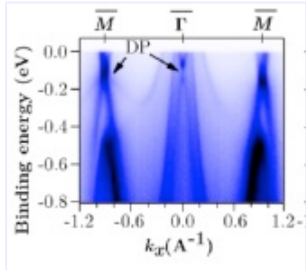
Physics

Recipro. space - delocalized

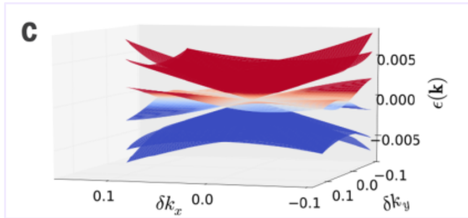
Brillouin zone

Electronic structure





Band connectivity

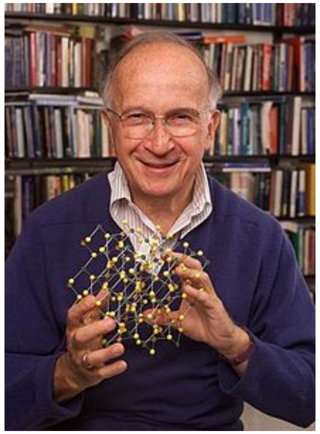


Darwin term

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

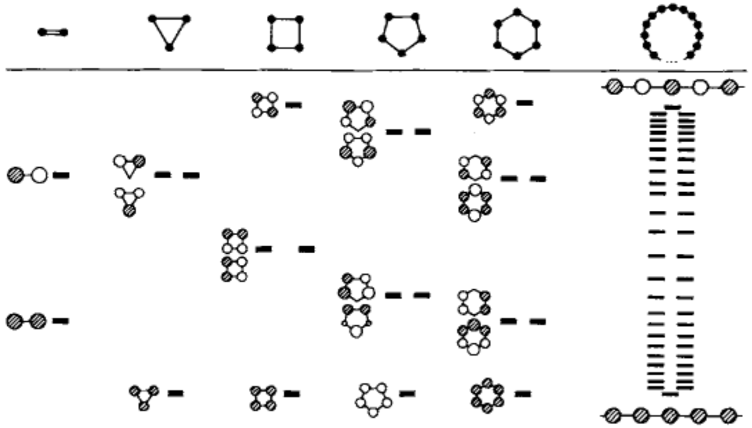
Barry Bradlyn, L. Elcoro, Jennifer Cano, M. G. Vergniory, Zhijun Wang, C. Felser, M. I. Aroyo, B. Andrei Bernevig, Nature (2017)

How to find a band structure



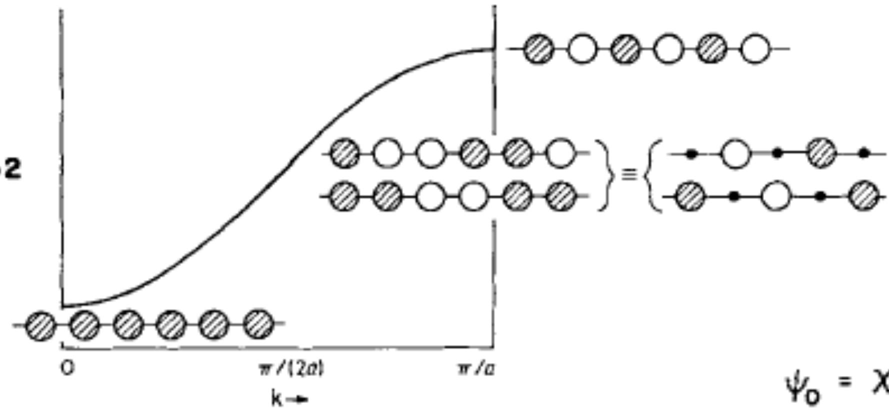
How Chemistry and Physics Meet in the Solid State

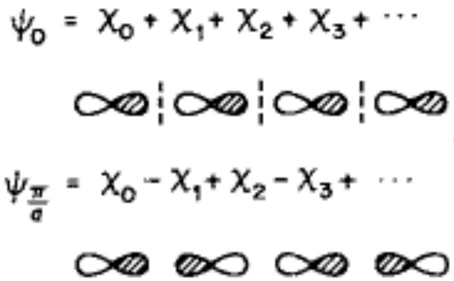
By Roald Hoffmann*



5

32





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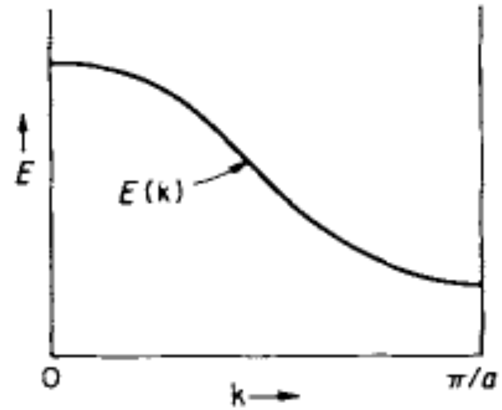
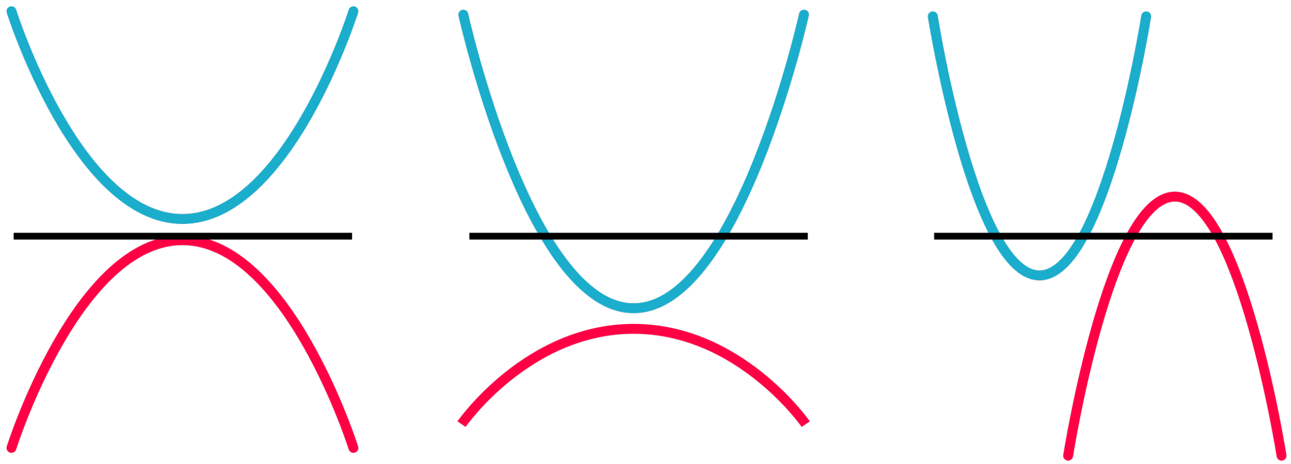


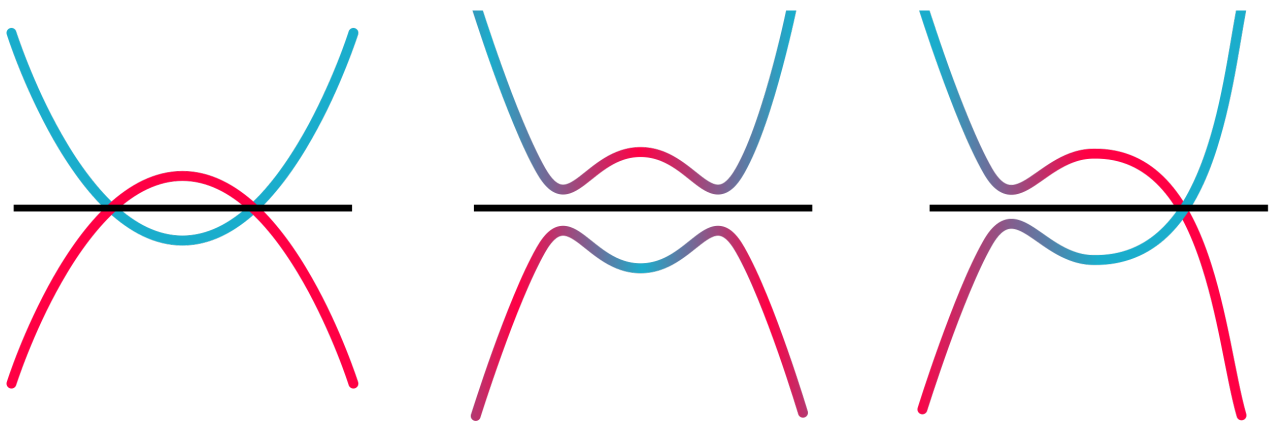
Hoffmann Angewandte. Chem. 26 (1987) 846

Insulator – Semiconductor – Metal

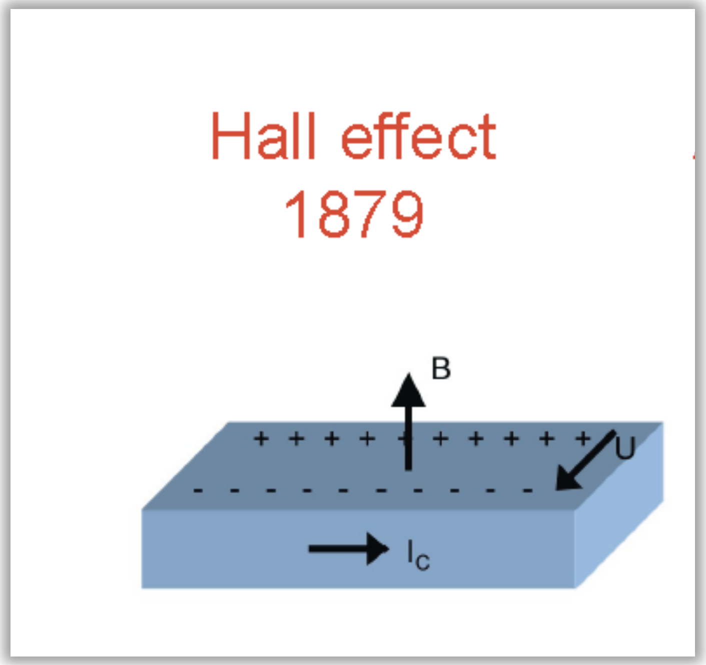
Insulator/Semiconductor Metal Semimetal

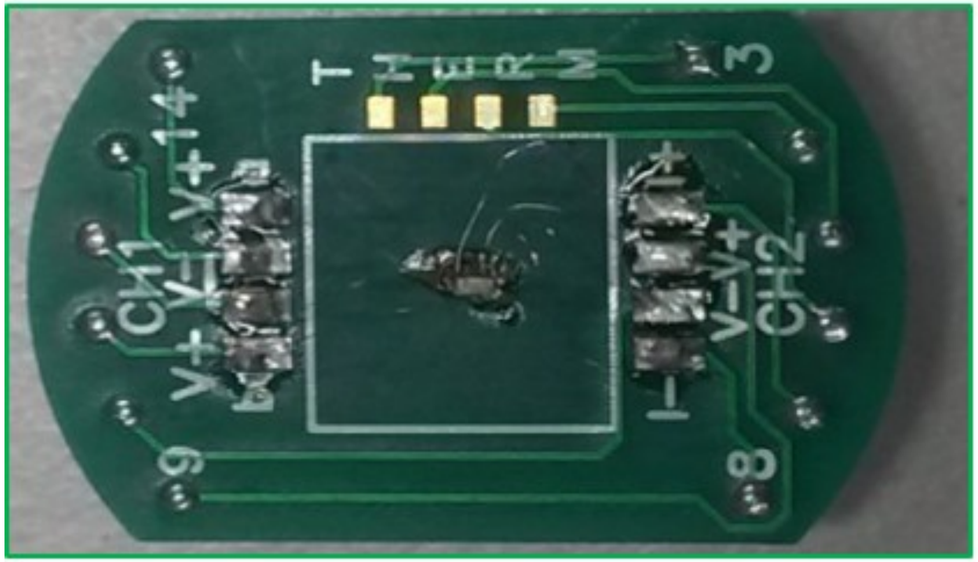


Topologcial Insulator/Semiconductor Dirac/Weyl-Semimetal



Resistance Measurement

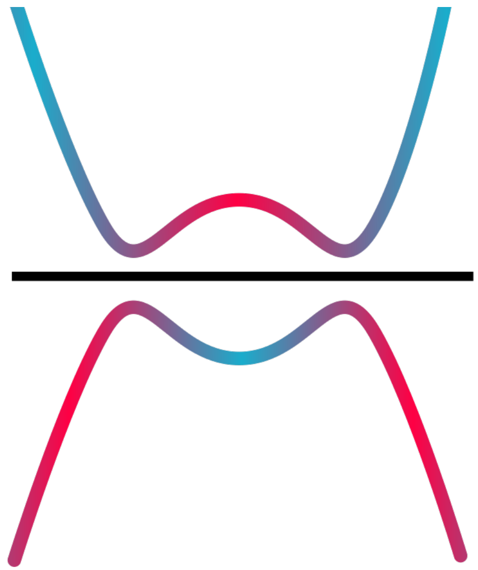




We measure the resistance without and with a magnetic field

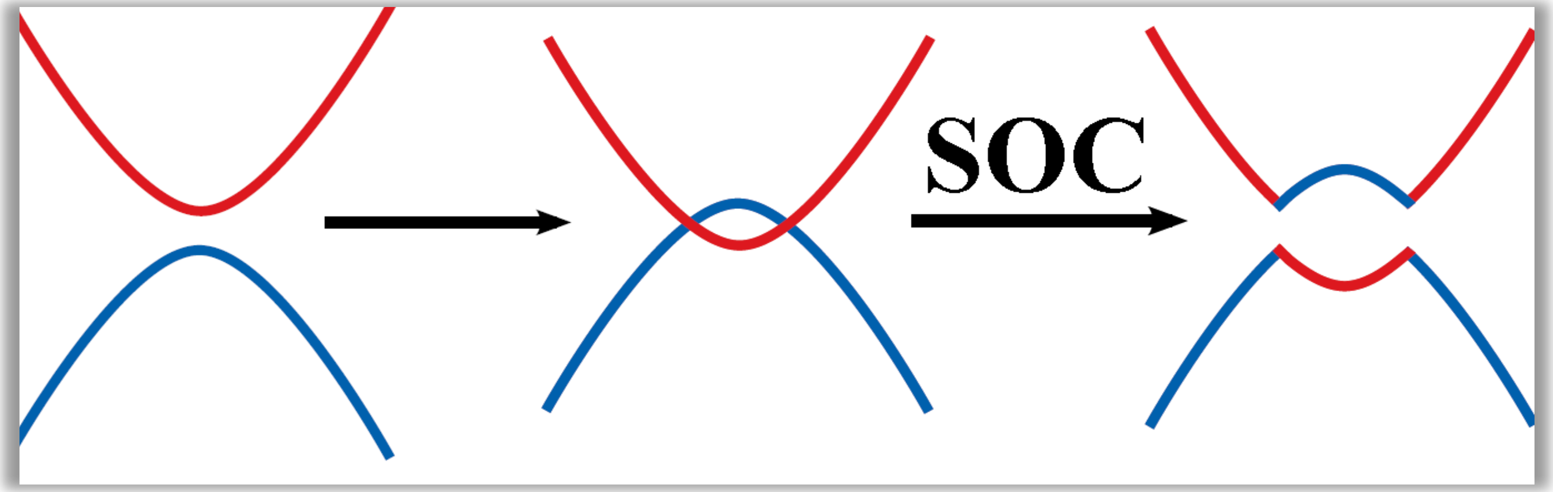
- ? Metal, semiconductor, or insulator
- ? Electron or hole conductivity
- ? Resistance in a magnetic field: Magnetoresistance

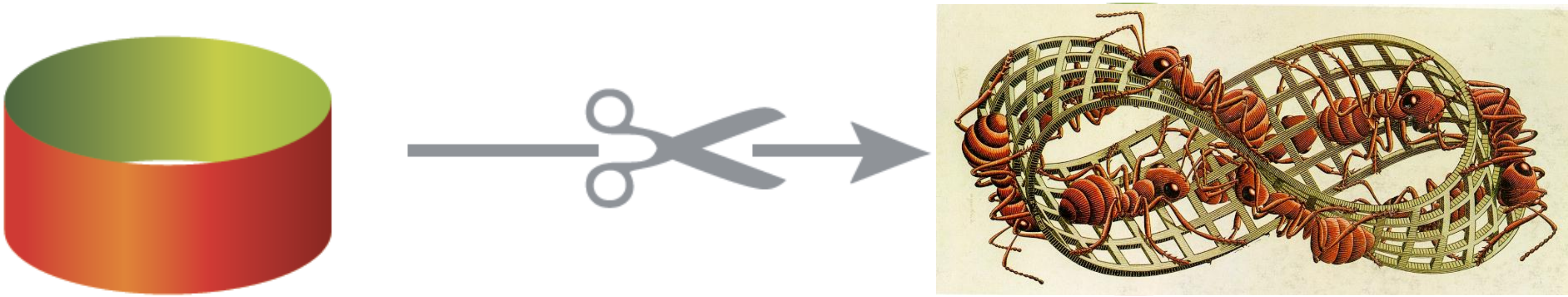
Topological Insulators



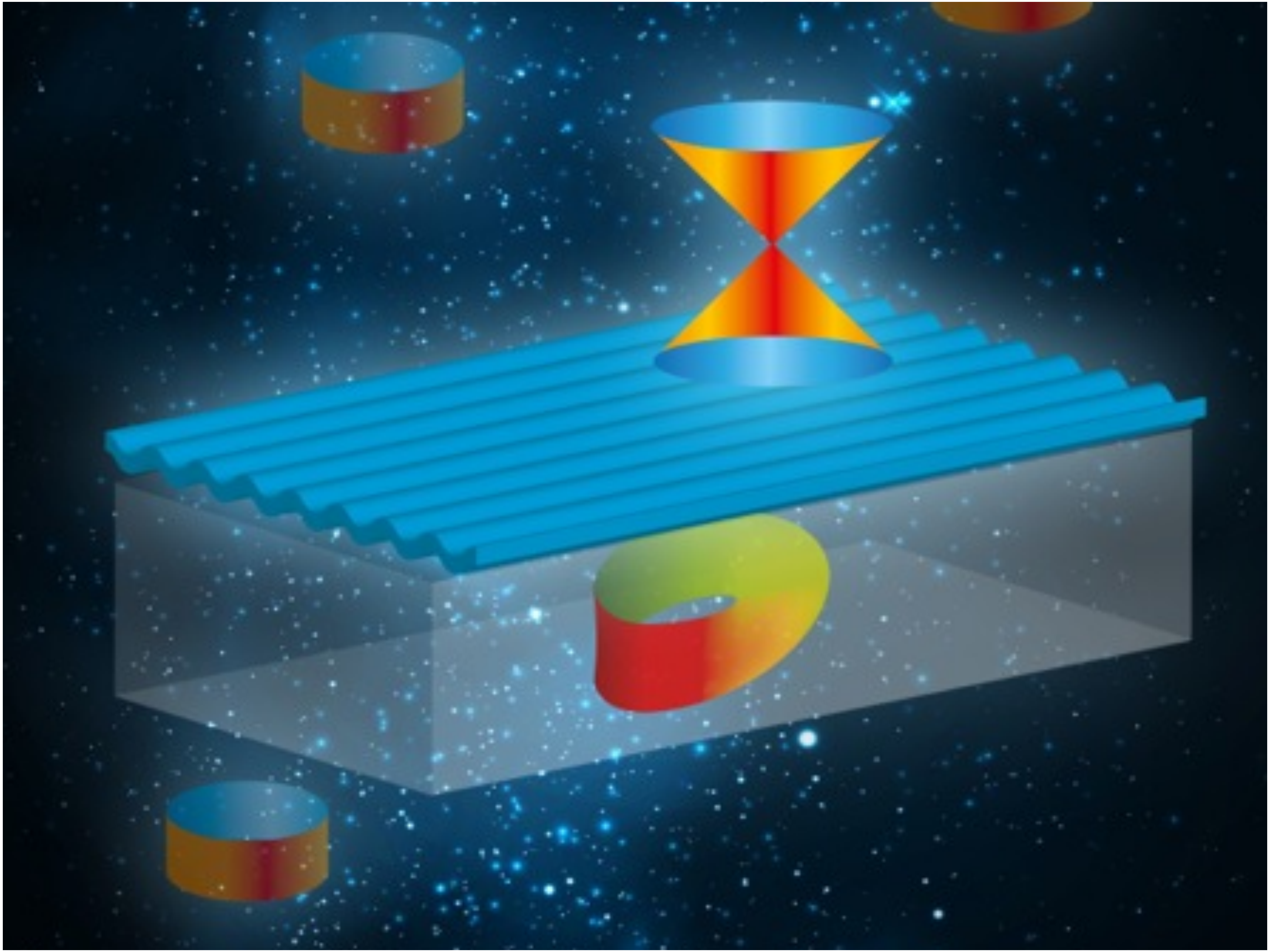
Trivial and Topological Insulators

Trivial semiconductor CdS	Topological Insulator Without spin orbit coupling	Topological Insulator Withspin orbit coupling





M. C. Escher



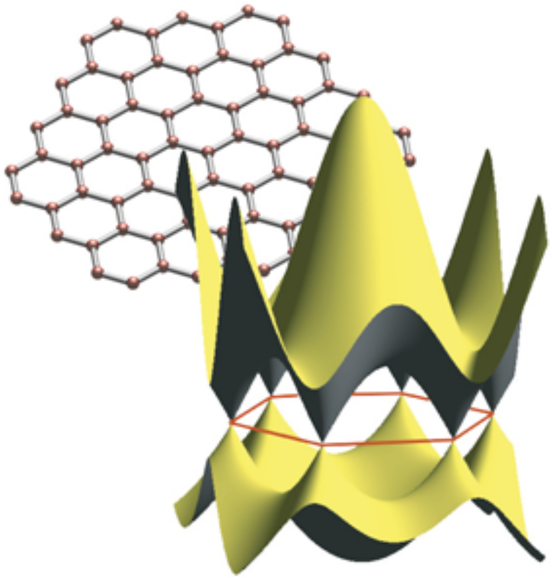
Topological Insulators

Z_2 Topological Order and the Quantum Spin Hall Effect

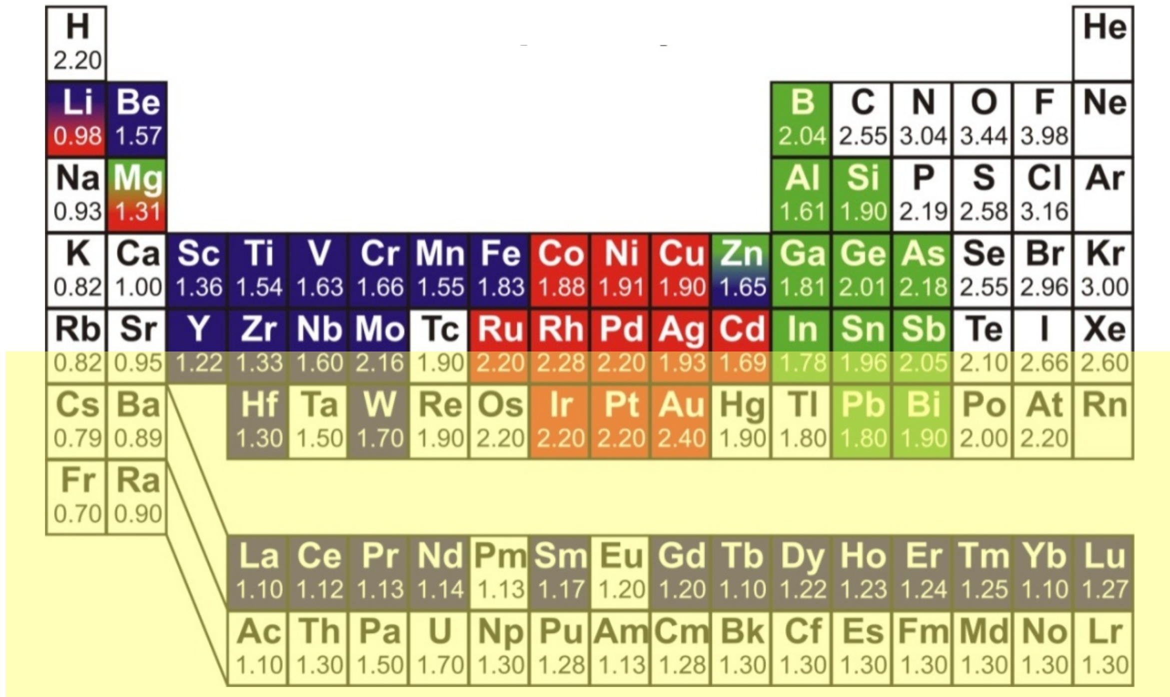
C. L. Kane and E. J. Mele
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
(Received 22 June 2005; published 28 September 2005)

The quantum spin Hall (QSH) phase is a time reversal invariant electronic state with a bulk electronic band gap that supports the transport of charge and spin in gapless edge states. We show that this phase is associated with a novel Z_2 topological invariant, which distinguishes it from an ordinary insulator. The Z_2 classification, which is defined for time reversal invariant Hamiltonians, is analogous to the Chern number classification of the quantum Hall effect. We establish the Z_2 order of the QSH phase in the two band model of graphene and propose a generalization of the formalism applicable to multiband and interacting systems.

Heavy insulating elements



First prediction in graphene by Kane



$\lambda_{SOC} \sim Z^2$ **for valence shells**

Kane and Mele, PRL 95, 146802 (2005)

Topological Insulators

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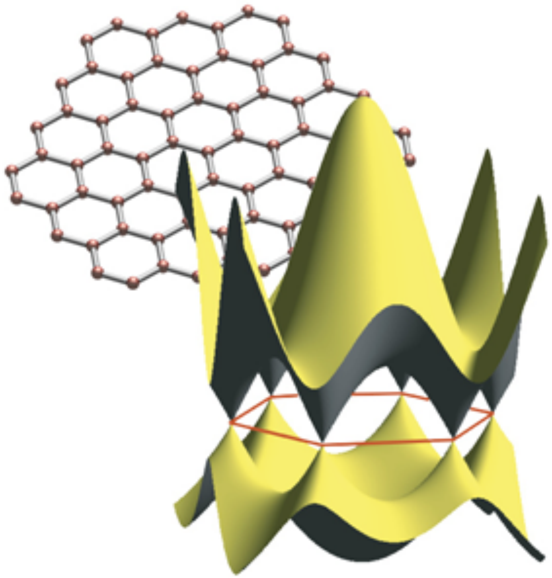
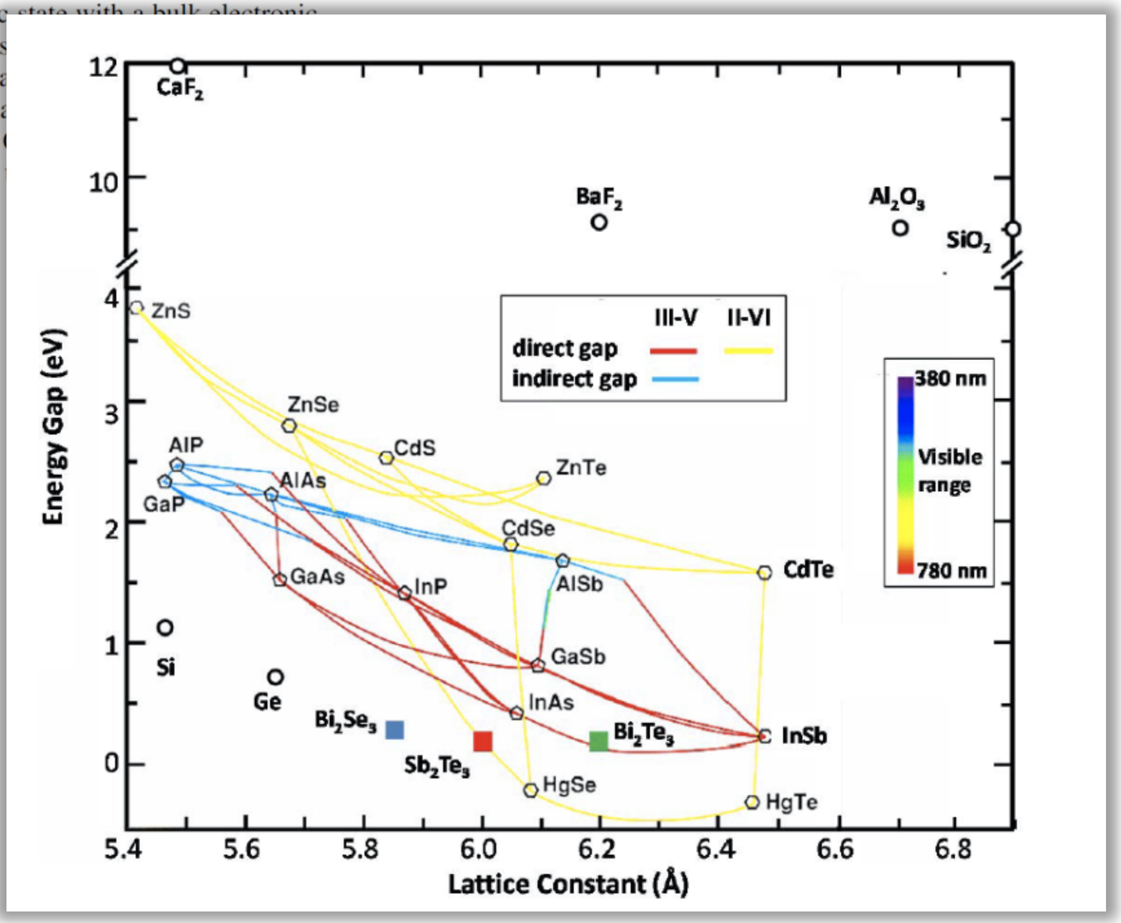
associated with a novel Z_2 topological invariant, which distinguishes it from
classification, which is defined for time reversal invariant Hamiltonians, is an
classification of the quantum Hall effect. We establish the Z_2 order of the
model of graphene and propose a generalization of the formalism applicable
systems.

Heavy insulating binaries



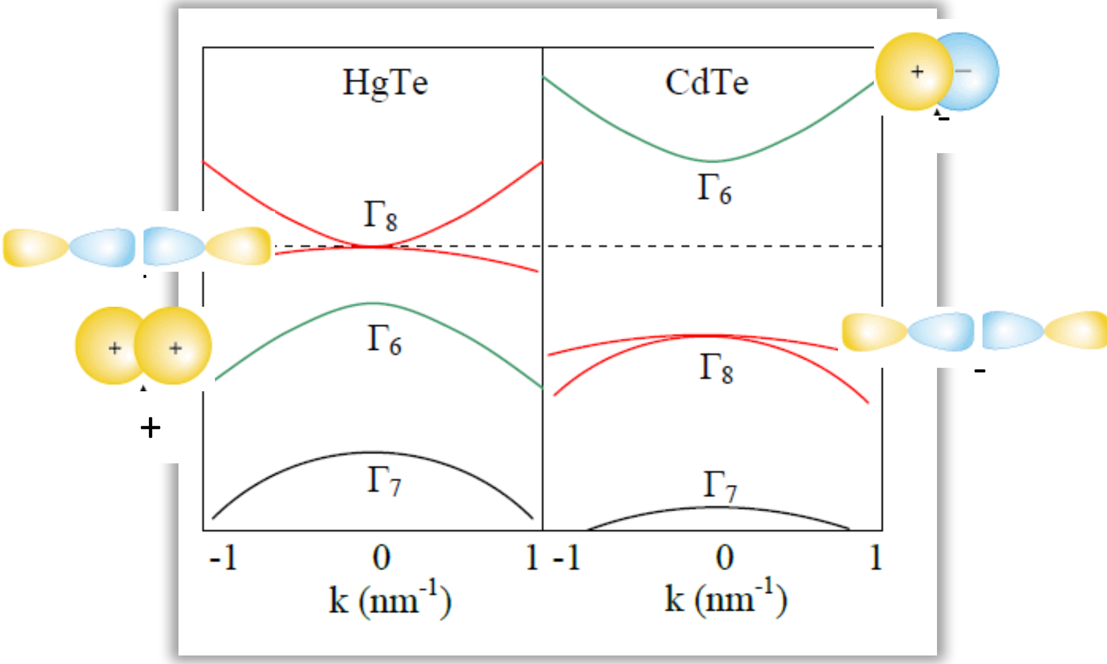
First prediction in graphene by Kane

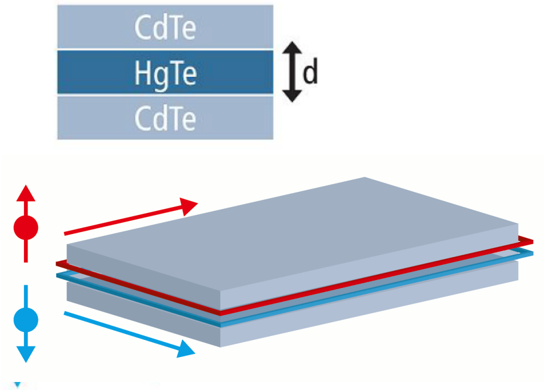


Kane and Mele, PRL 95, 146802 (2005)
Bernevig, et al., Science 314, 1757 (2006)
Bernevig, S.C. Zhang, PRL 96, 106802 (2006)
König, et al. Science 318, 766 (2007)

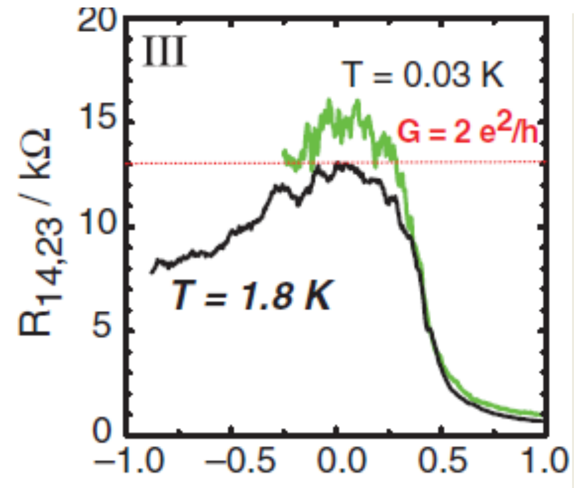
Quantum Spin Hall

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



Inert pair effect

Bernevig,et al., Science 314, 1757 (2006)
Bernevig, S.C. Zhang, PRL 96, 106802 (2006)
König, et al. Science 318, 766 (2007)

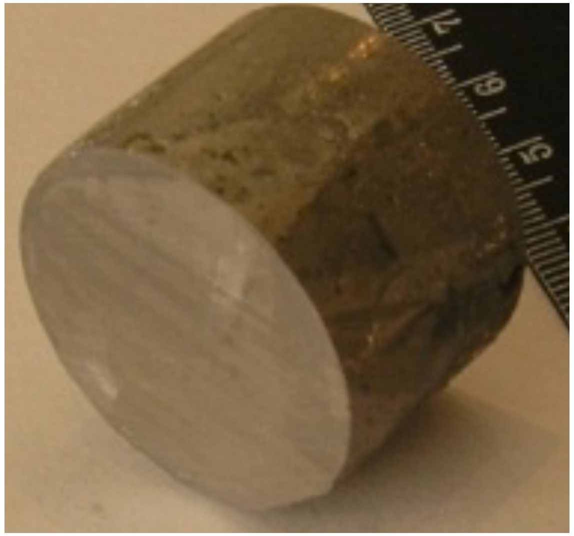
Stau im Mikrochip heute

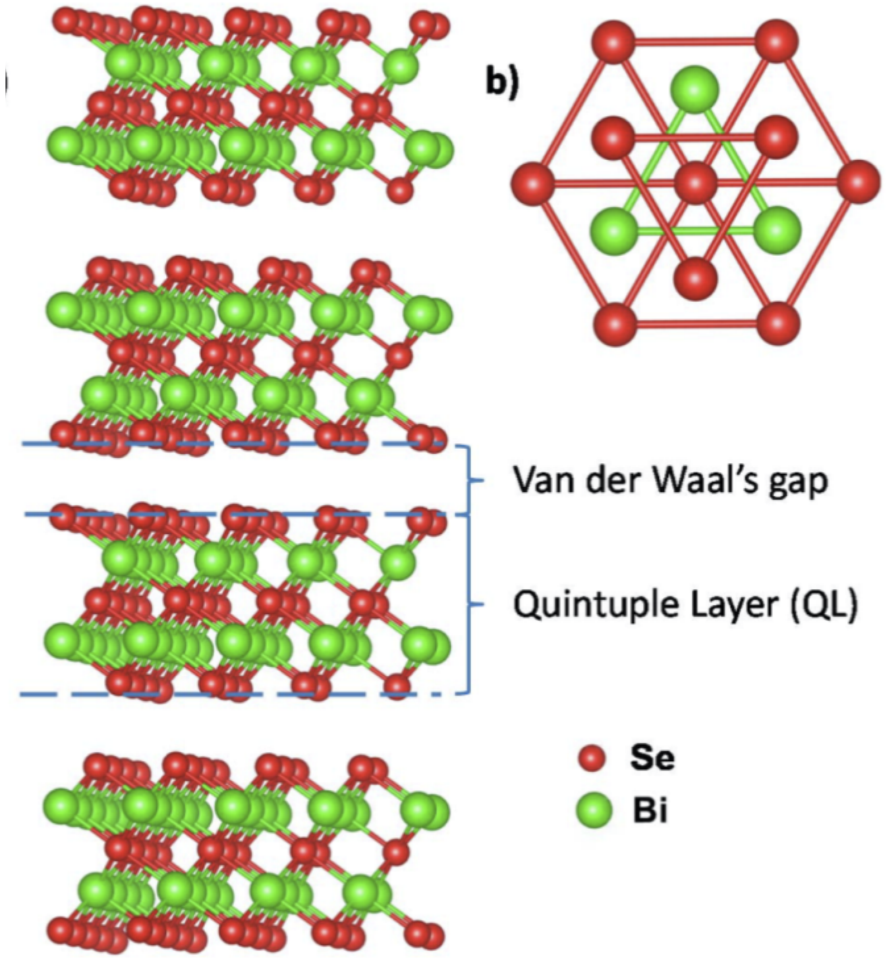
Chip-Autobahn in der Zukunft

Topologische Isolatoren

Bi-Sb Legierungen

Bi_2Se_3 und verwandte Strukturen





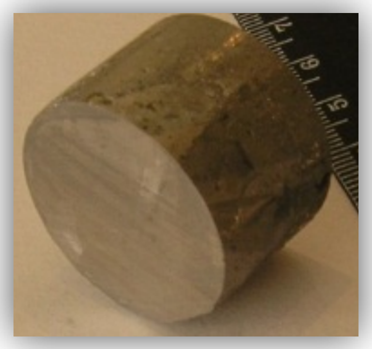
Moore and Balents, PRB 75, 121306(R) (2007)
Fu and Kane, PRB 76, 045302 (2007)
Murakami, New J. Phys. 9, 356 (2007)
Hsieh, et al., Science 323, 919 (2009)
Xia, et al., Nature Phys. 5, 398 (2009); Zhang, et al., Nature Phys. 5, 438 (2009)

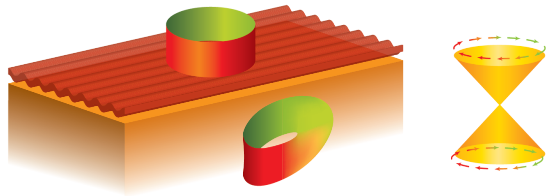
3D Topological Insulator

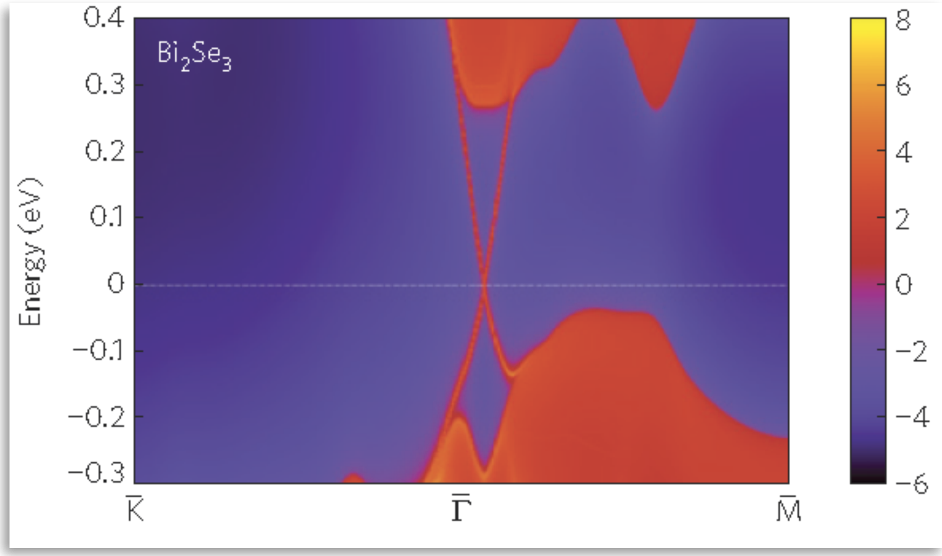
3D topological insulators

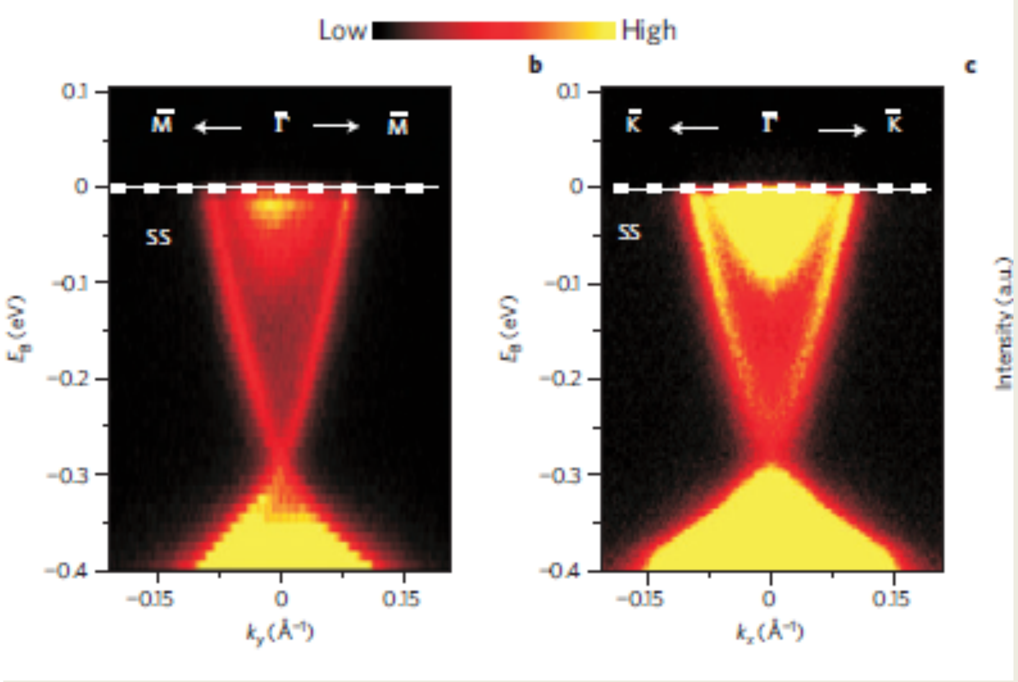
Bi-Sb alloy

Bi_2Se_3 and relatives









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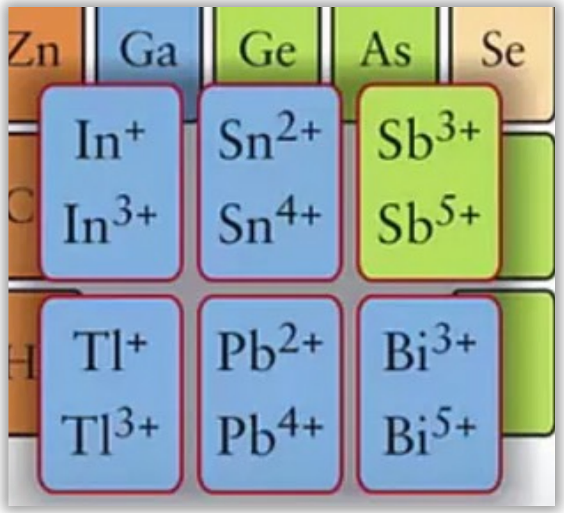
Fu and Kane, PRB 76, 045302 (2007)
Murakami, New J. Phys. 9, 356 (2007)
Hsieh, et al., Science 323, 919 (2009)
Xia, et al., Nature Phys. 5, 398 (2009); Zhang, et al., Nature Phys. 5, 438 (2009)

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.

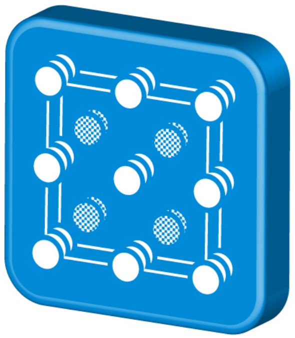
Tl^{+1} Sn^{2+} Bi^{+3}

Inert pair effect

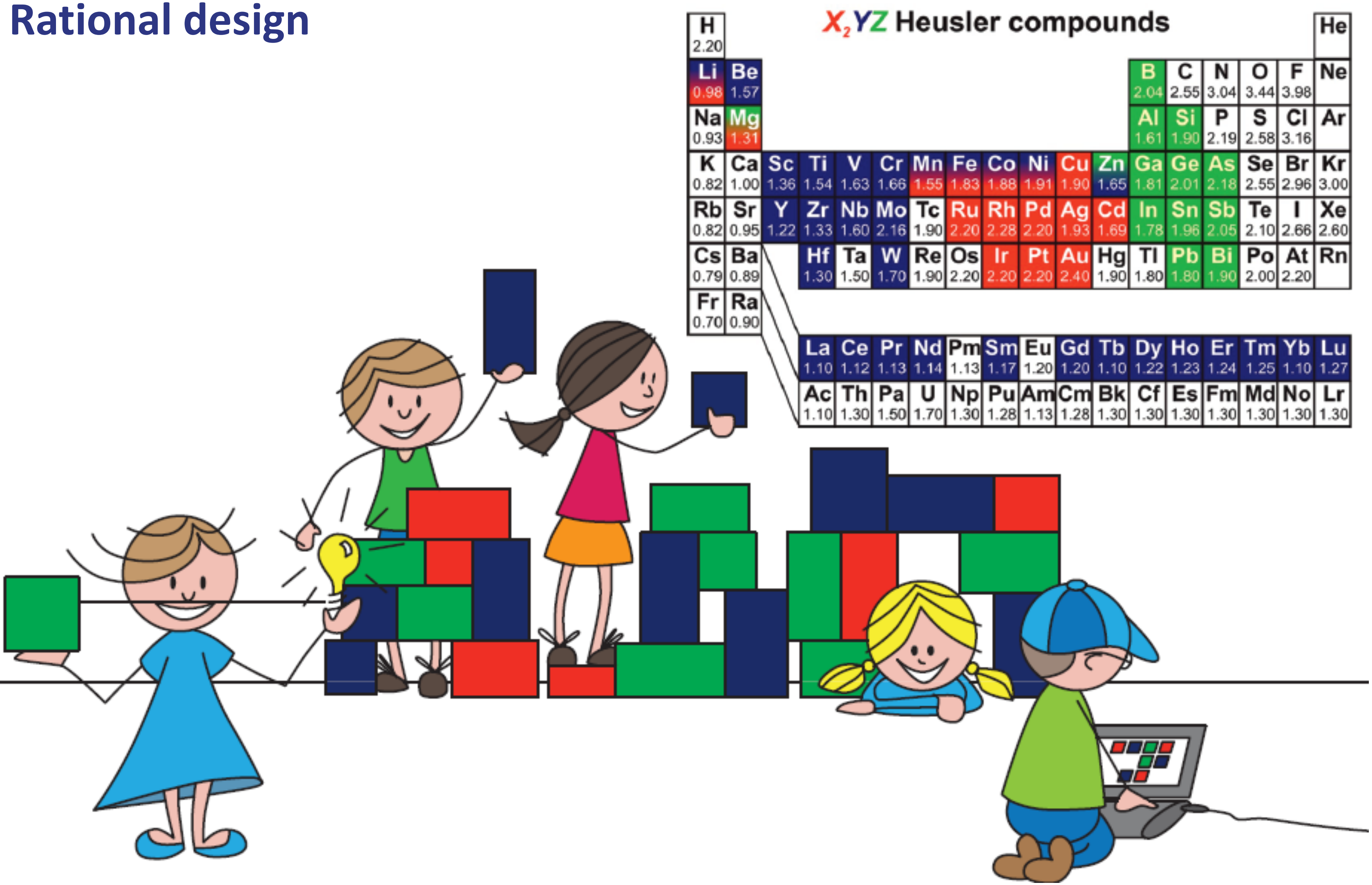
Design scheme: topological insulator

- Semiconductor or Insulator
- Band inversion – e.g. inert pair effect

The „Designer“-Material

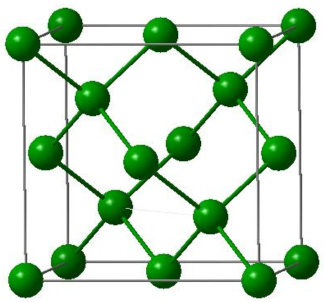


Rational design

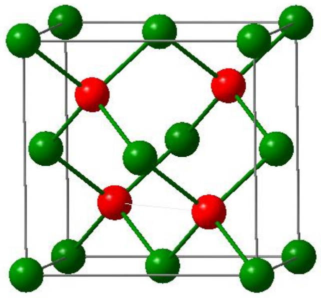


Heusler compounds

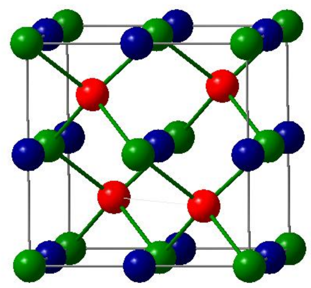
Diamond

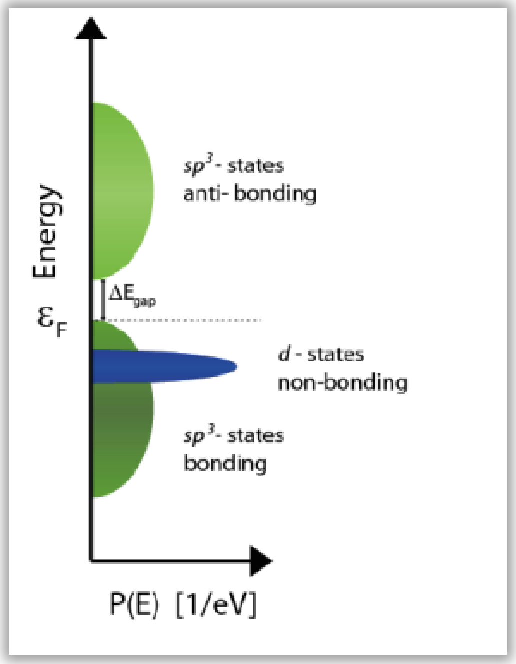


ZnS



Heusler XYZ $C1_b$





Cd Se

2 + 6 = 8

Li Zn Sb

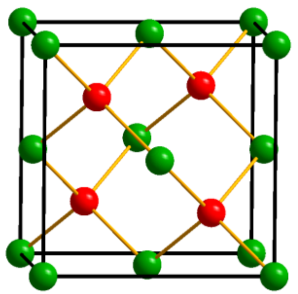
1 + 2 + 5 = 8

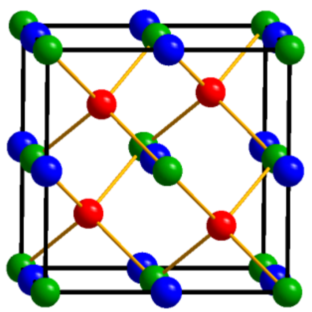
RE Pt Bi

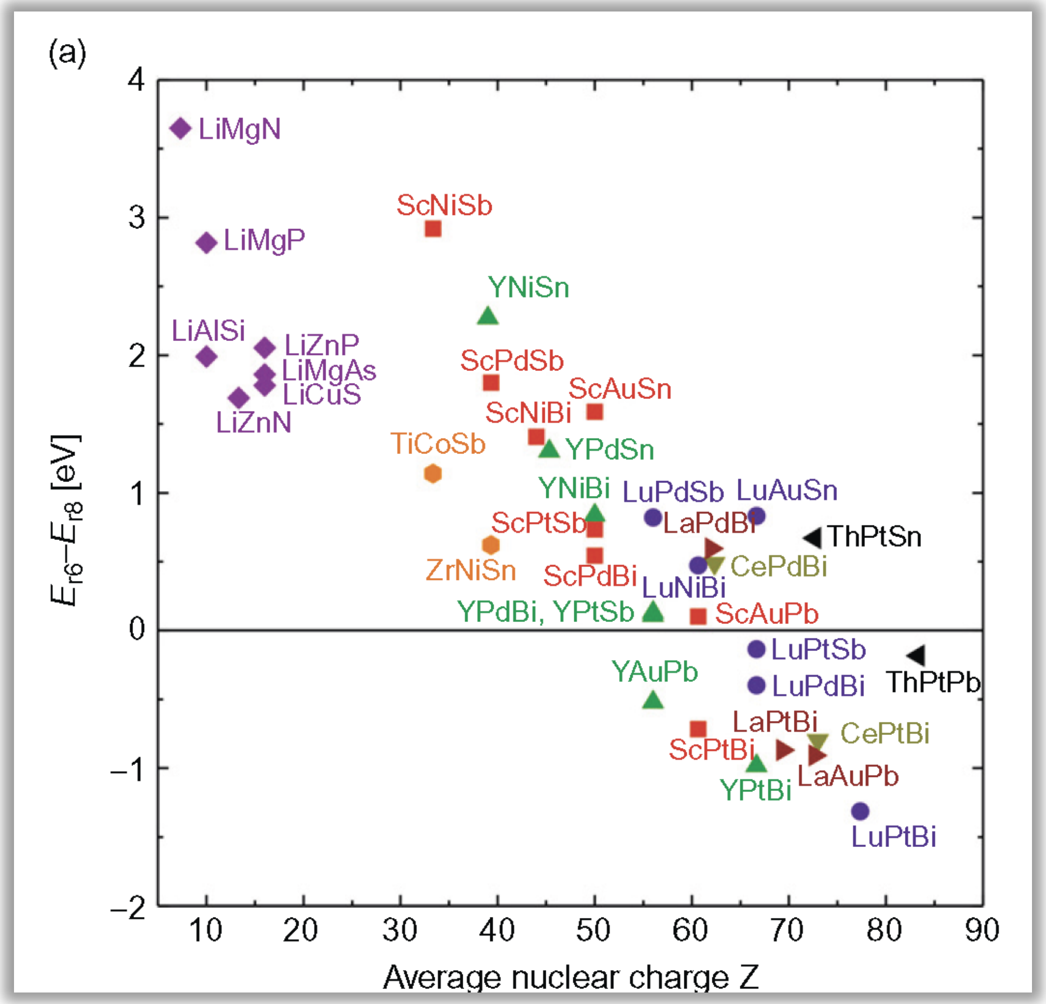
3 + 10 + 5 = 18

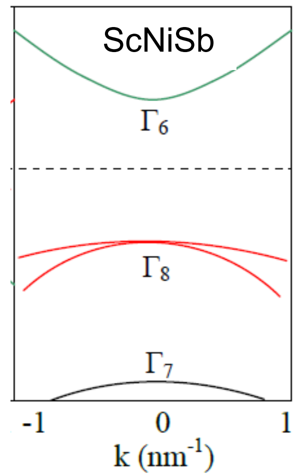

Periodensystem der Elemente
Heusler-Verbindungen: X_2YZ

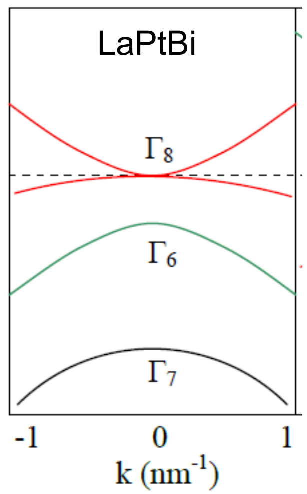
Predicting new compounds











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

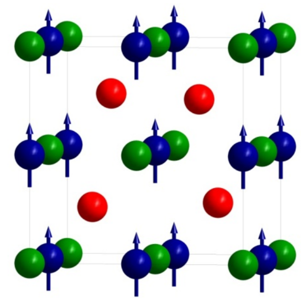
REPtBi …multifunctional topologic insulators

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

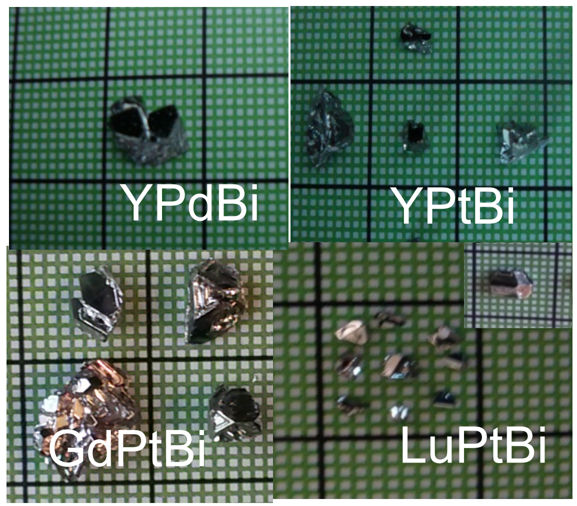
J. Appl. Phys. **70** (10), 15 November 1991



Multifunctional properties

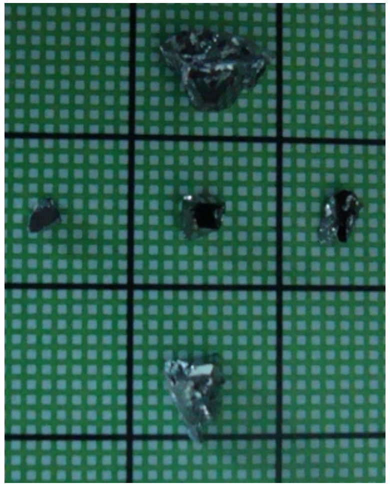
- RE: Y, La, Lu, Er, … superconductivity
  RE: Gd, Tb, Sm Magnetism and TI
  - Antiferromagnetism with GdPtBi
- RE: Ce
  - complex behaviour of the Fermi surface
- RE: Yb Kondo insulator and TI
  - YbPtBi is a super heavy fermion with the highest γ value

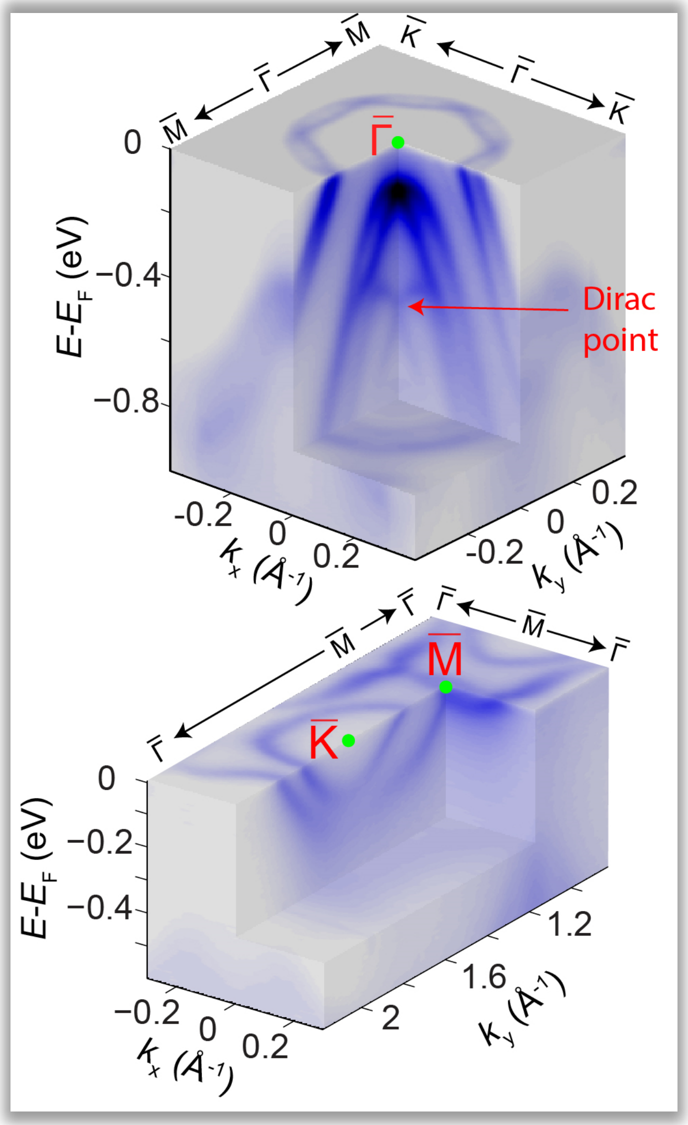
$$10 + 3\ (+f^n) + 5 = 18$$

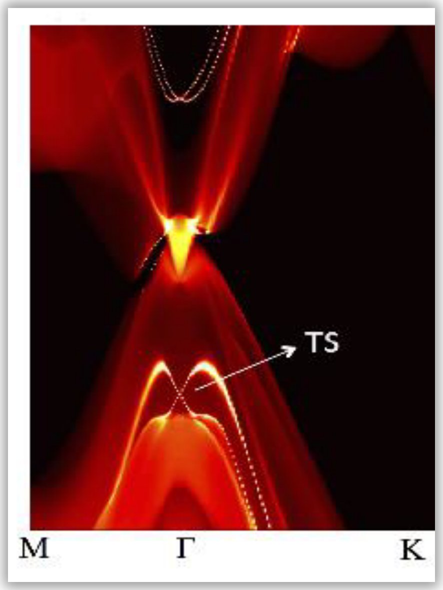


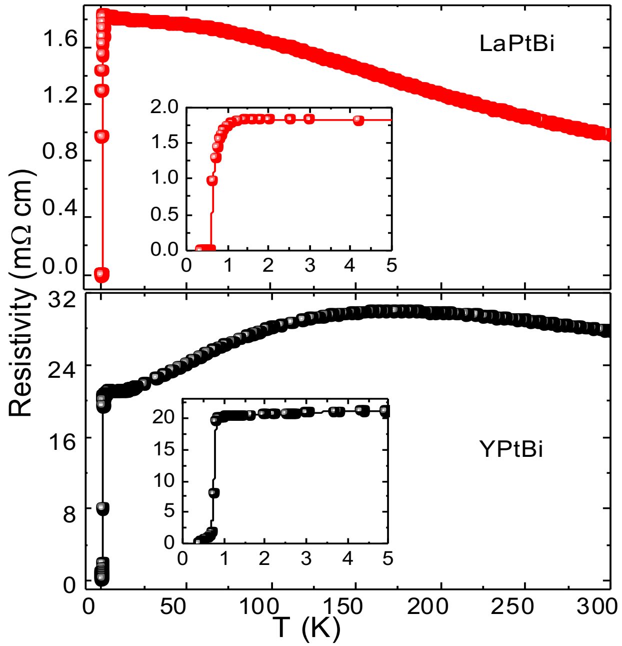
S. Chadov et al., Nat. Mater. 9, 541 (2010).
H. Lin et al., Nat. Mater. 9, 546 (2010).

ARPES of LnPtBi





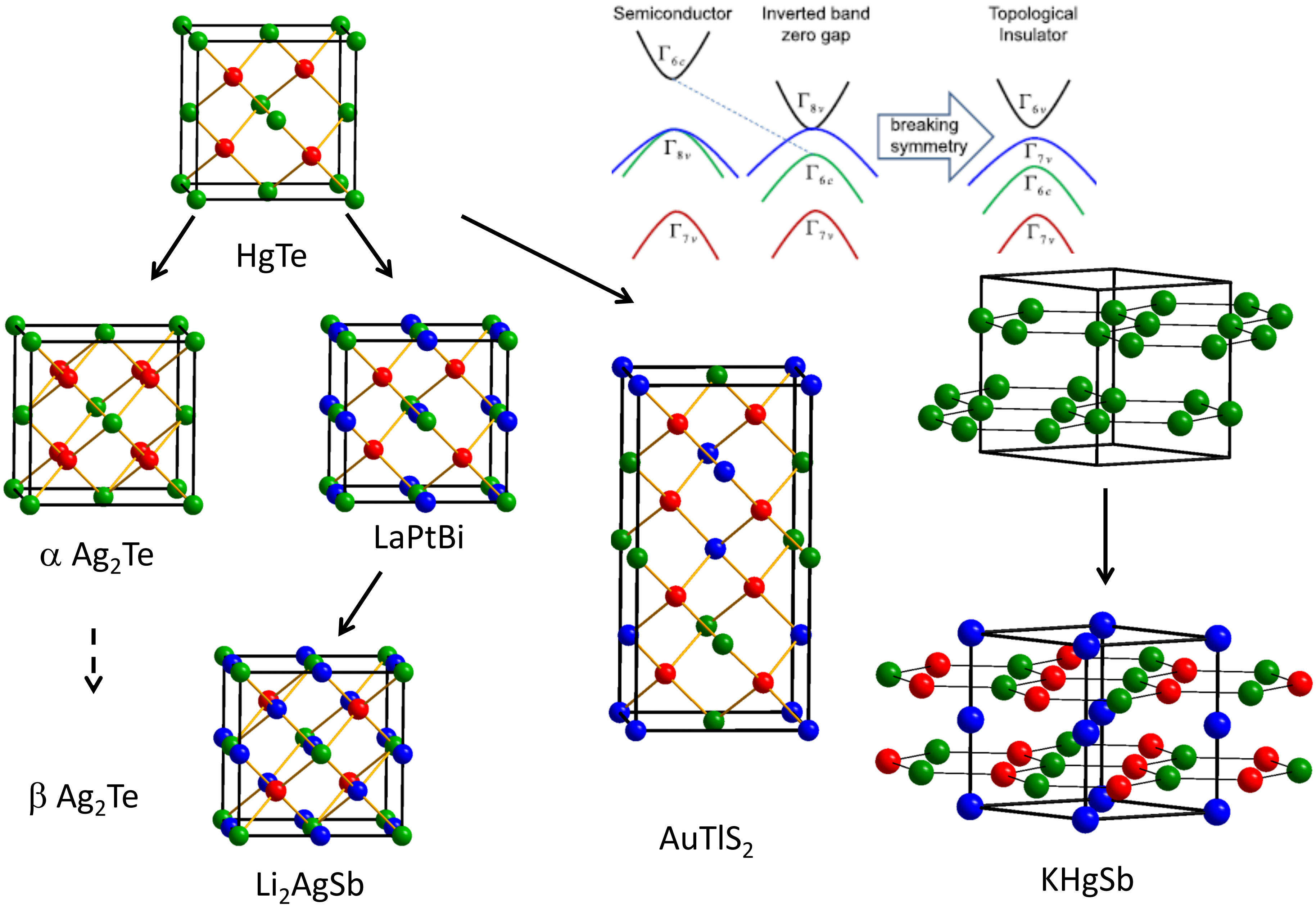




Z. K. Liu et al. Nature Com. 7 (2016) 12924

Shekhar et al. Phys. Rev. B 86 (2012) 155314

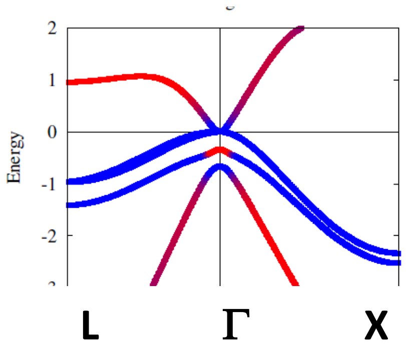
Structure to Property



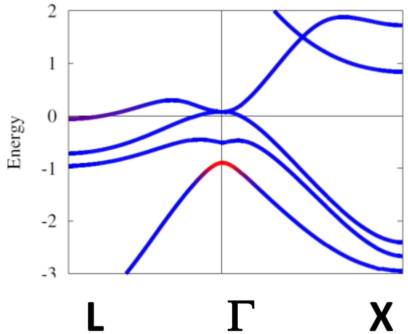
Müchler, et al., Angewandte Chemie 51 (2012) 7221.

Struktur und elektronische Struktur

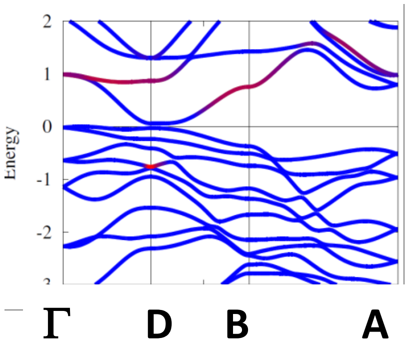
HgTe



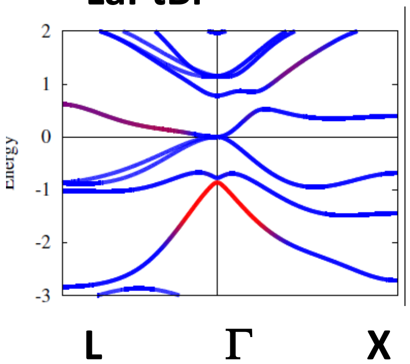
α Ag_2Te



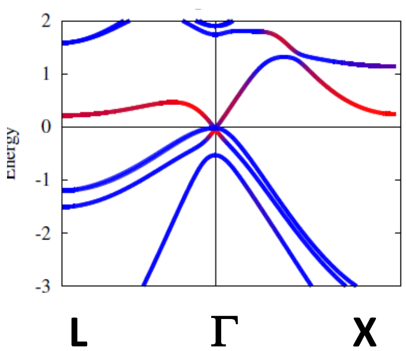
β Ag_2Te



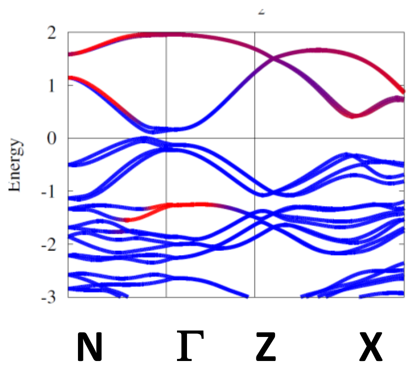
LaPtBi



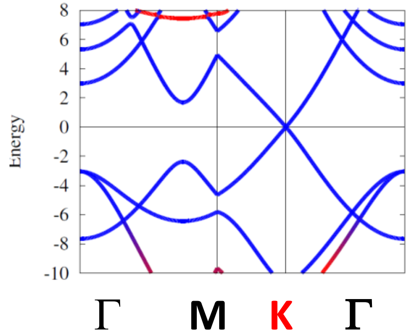
Li_2AgSb



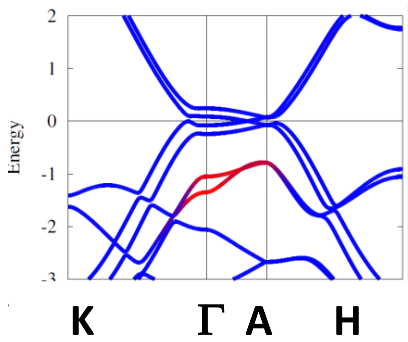
$AuTlTe_2$



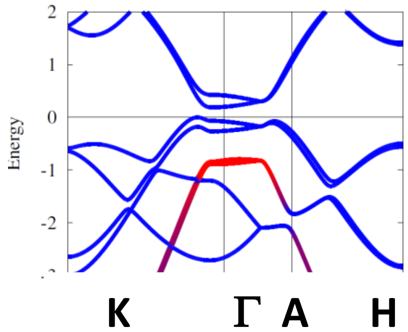
Graphite



LiAuTe

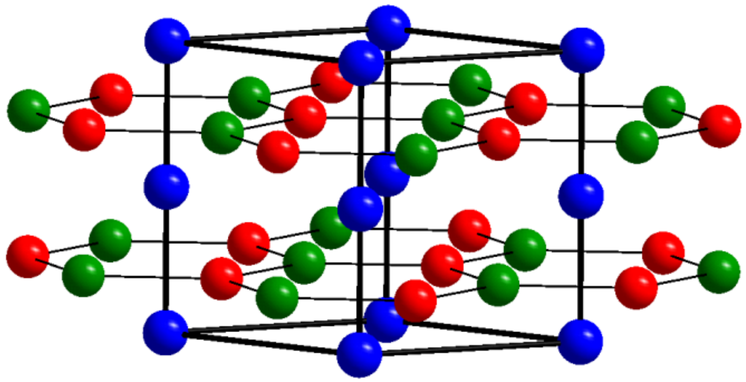


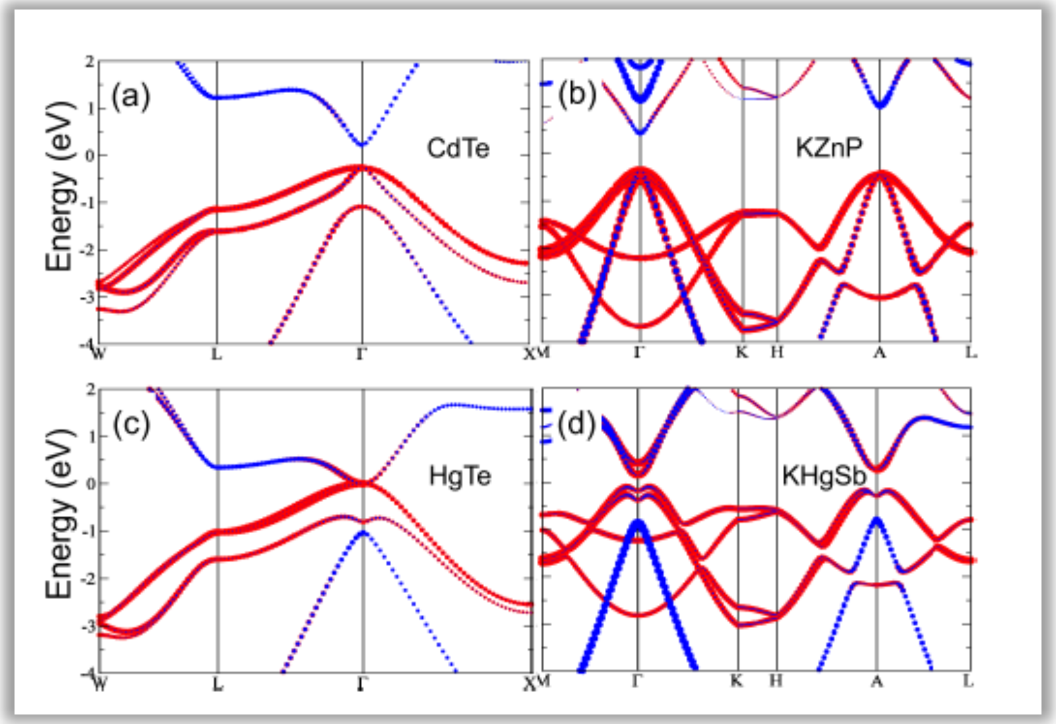
KHgSb



Müchler, et al., Angewandte Chemie 51 (2012) 7221.

Honeycomb from sp^3 to sp^2

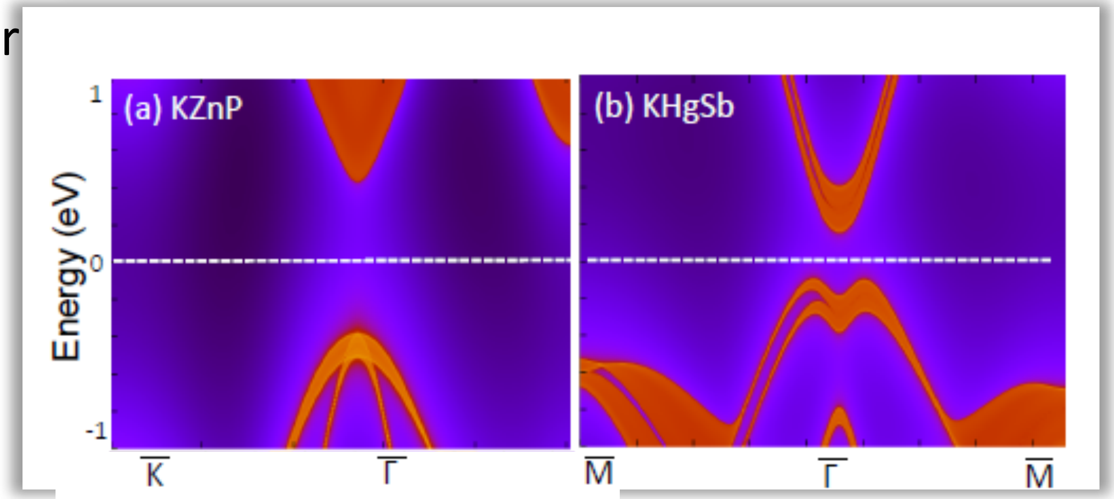




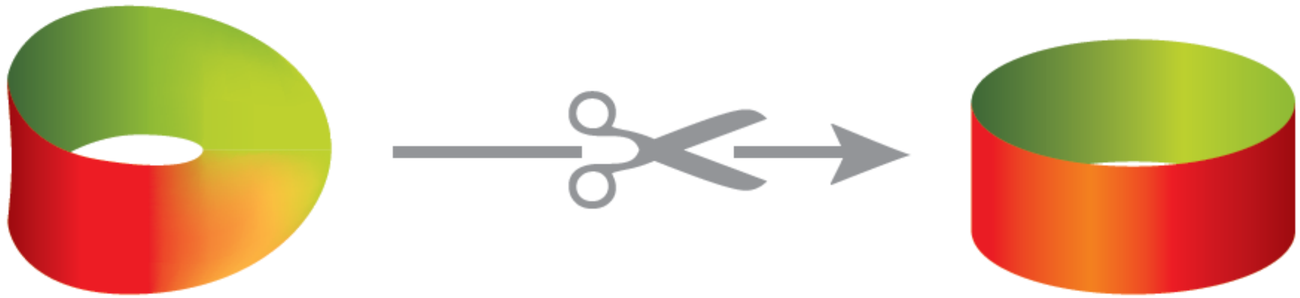
Band inversion is found in the heavier compounds

No surface state? Why ?

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

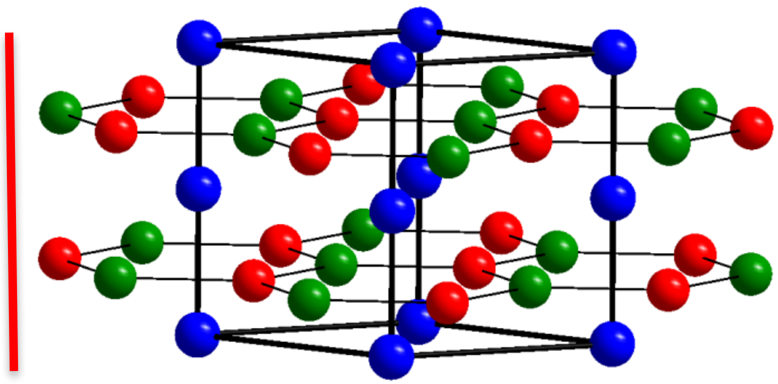


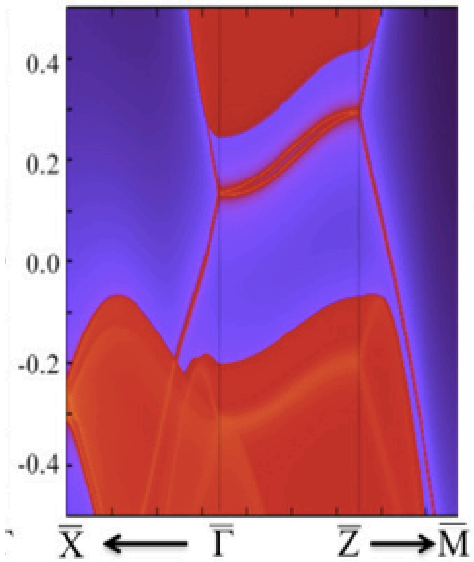
Zhang, Chadov, Müchler, Yan, Qi, Kübler, Zhang, Felser, Phys. Rev. Lett. 106 (2011) 156402 arXiv:1010.2195v1 a)

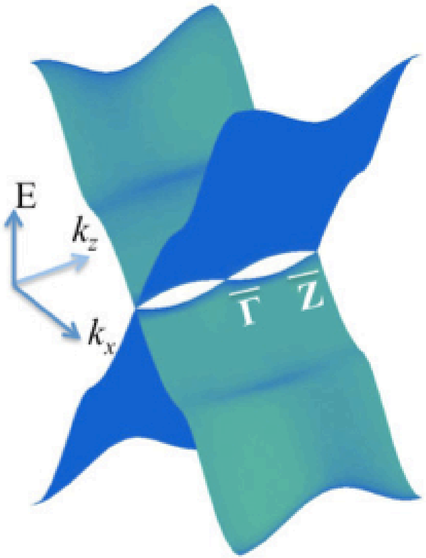


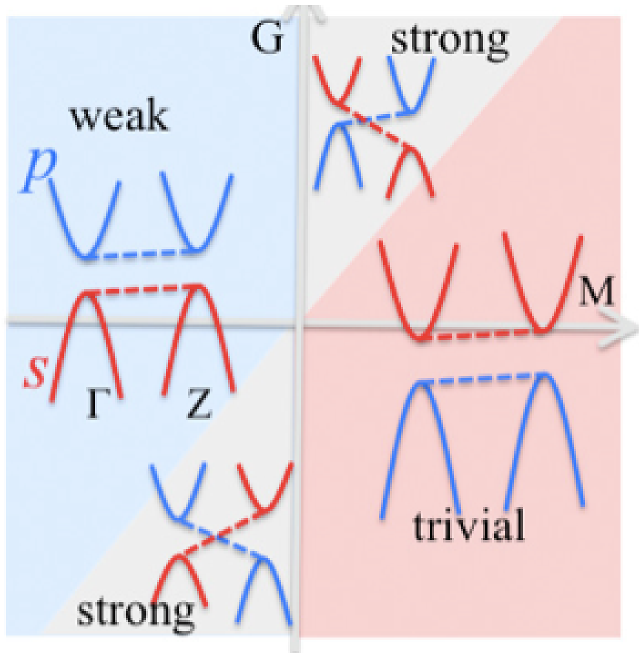
b)

Honeycomb: Weak TI









KHgSb	KHgAs	KHgP
NaHgSb	NaHgAs	NaHgP
LiHgSb	LiHgAs	LiHgP
KCdSb	KCdAs	KCdP
NaCdSb	NaCdAs	NaCdP
LiCdSb	LiCdAs	LiCdP

KAuTe	KAuSe
NaAuTe	NaAuSe
LiAuTe	LiAuSe
KAgTe	KAgSe
NaAgTe	NaAgSe
LiAgTe	LiAgSe

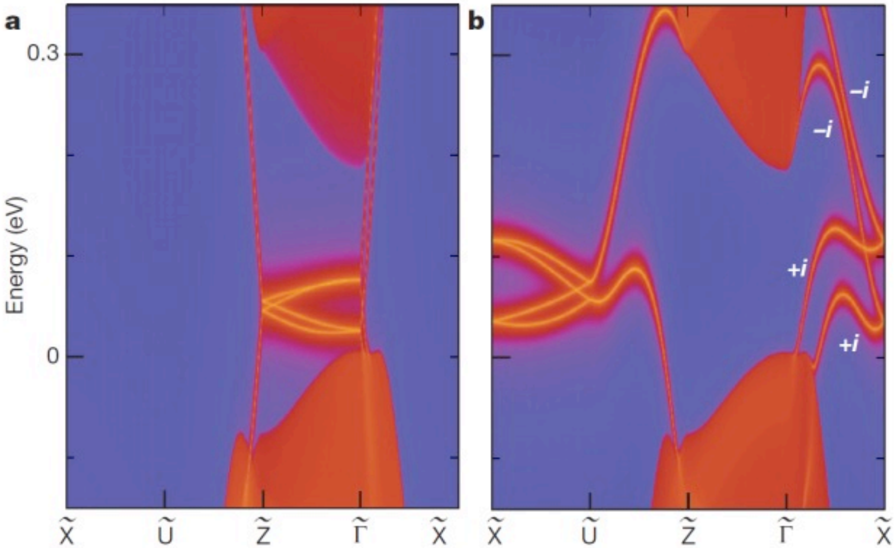
Yan, Müchler, Felser, Physical Review Lett. 109 (2012) 116406

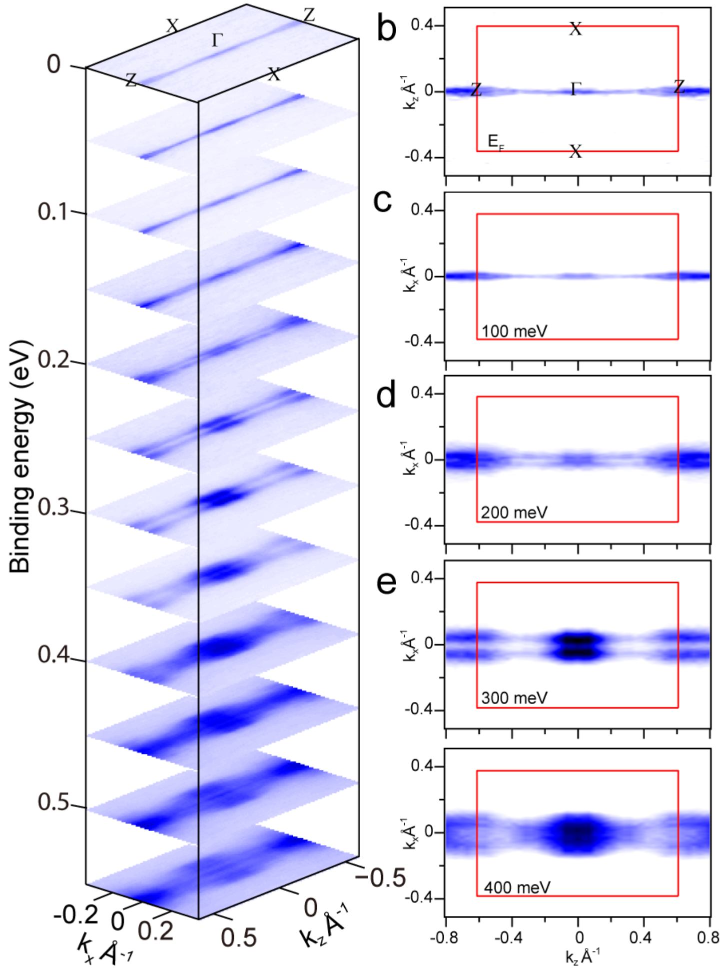
Hourglass

ARTICLE

Hourglass fermions

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





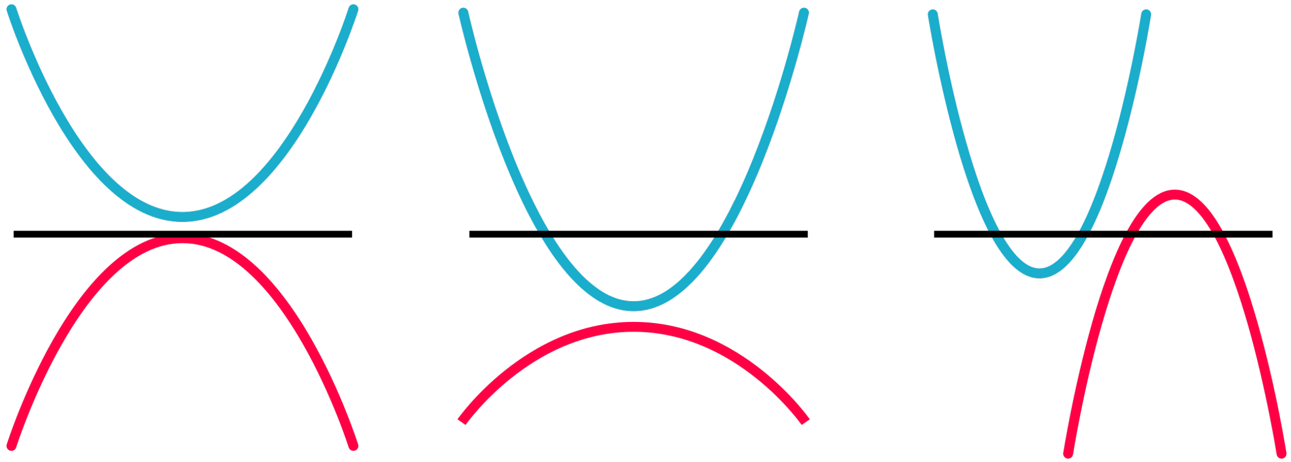
Wang et al. Nature 2016

unpublished results

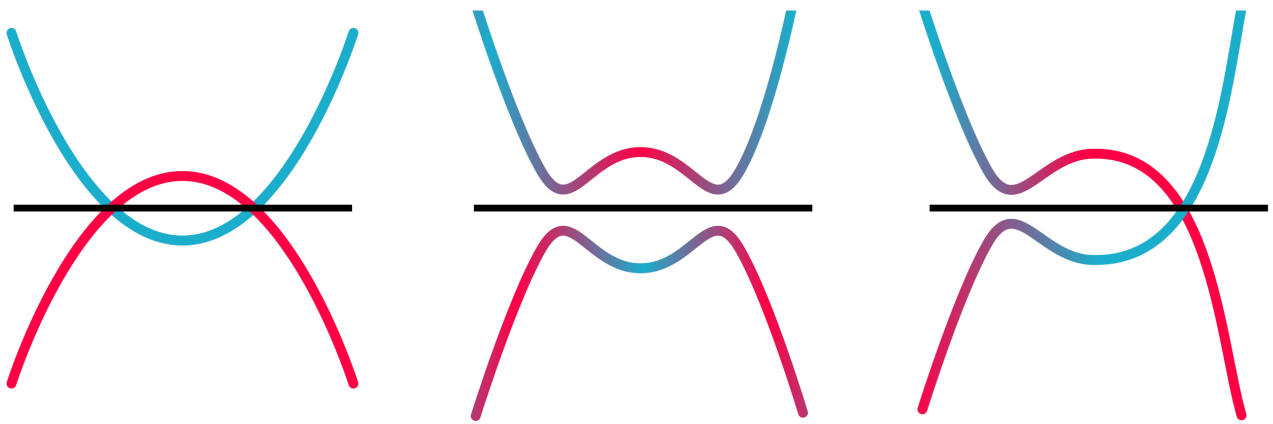
Dirac - Weyl Semimetals

Insulator – semiconductor – Metal

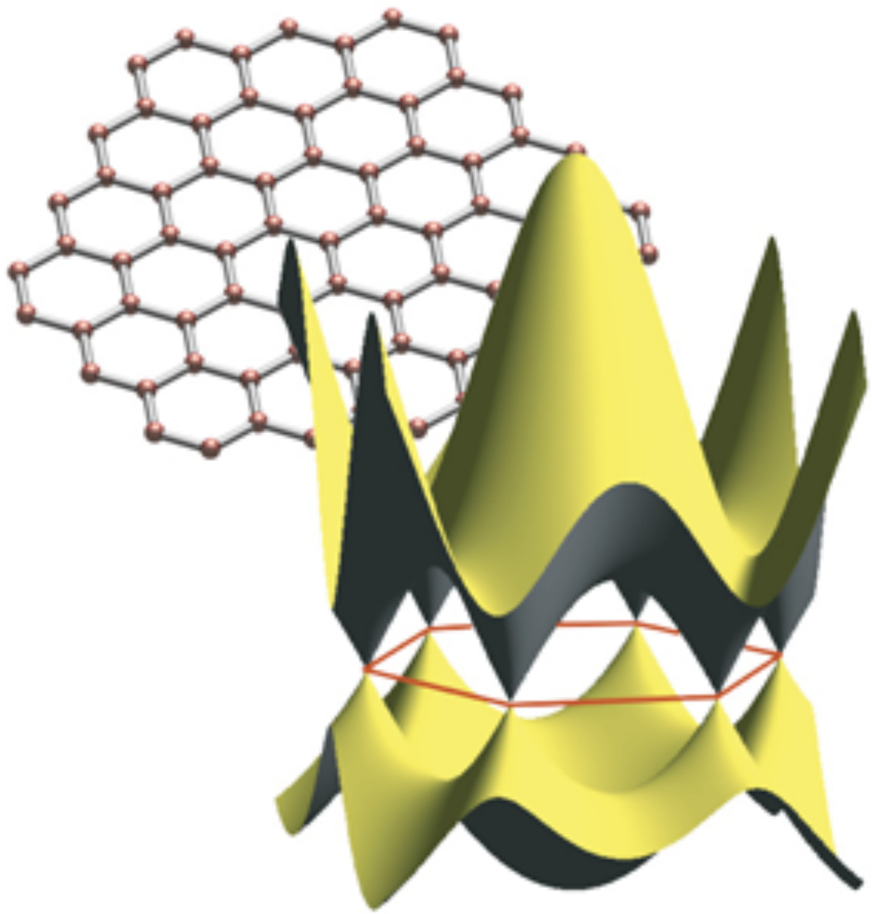
Insulator/Semiconductor – Metal – Semimetal

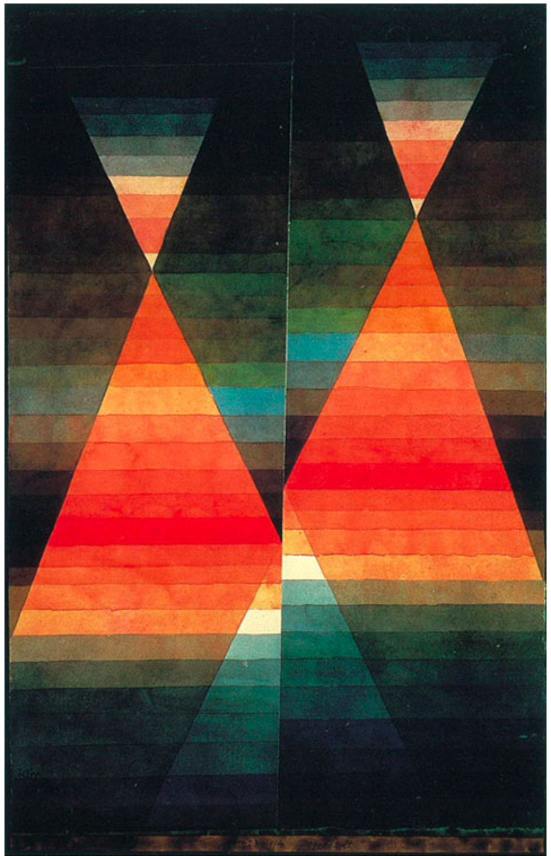


Topologcial Insulator/Semiconductor – Dirac/Weyl Semimetal



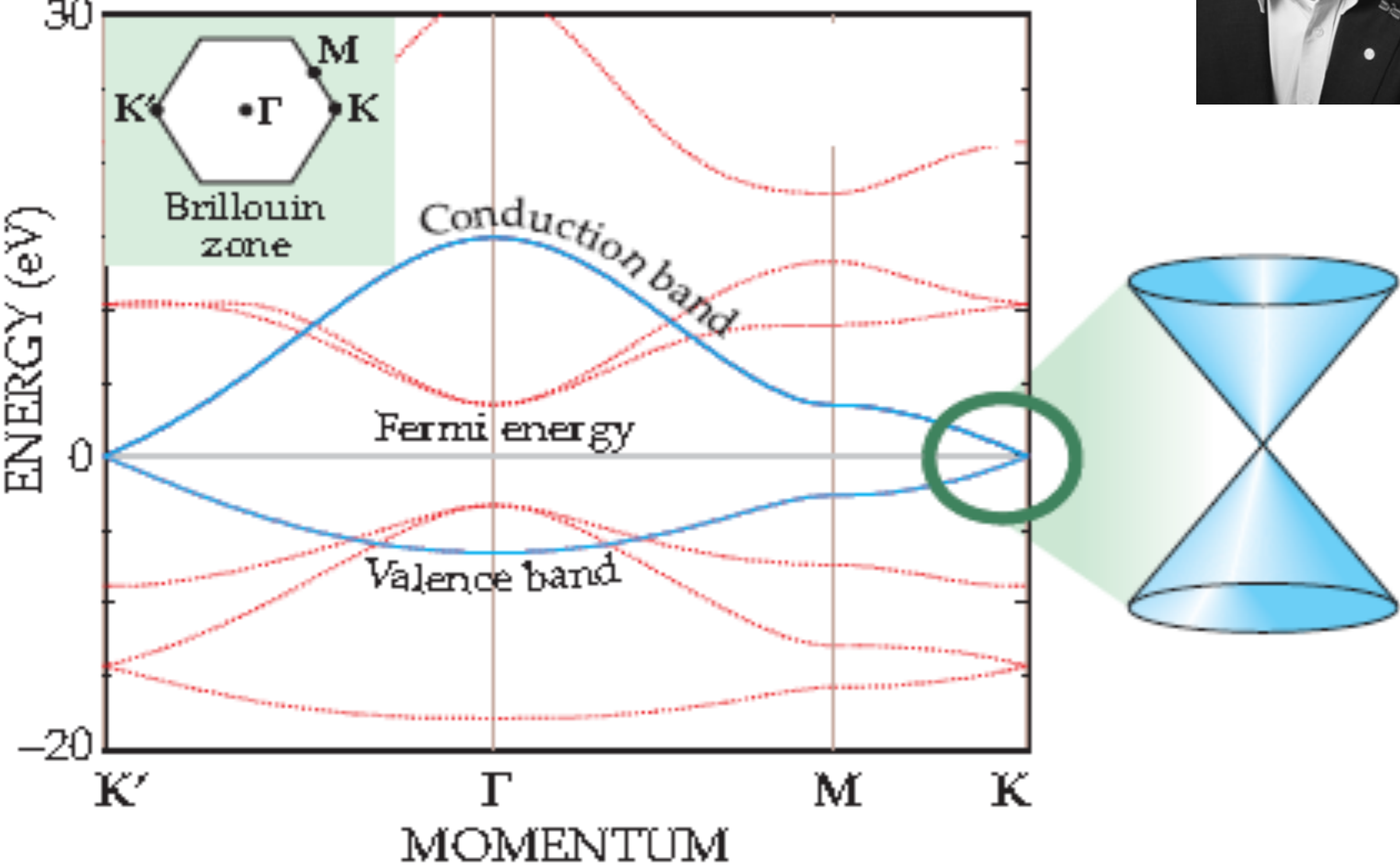
Dirac and Weyl semimetals





Paul Klee

Graphene

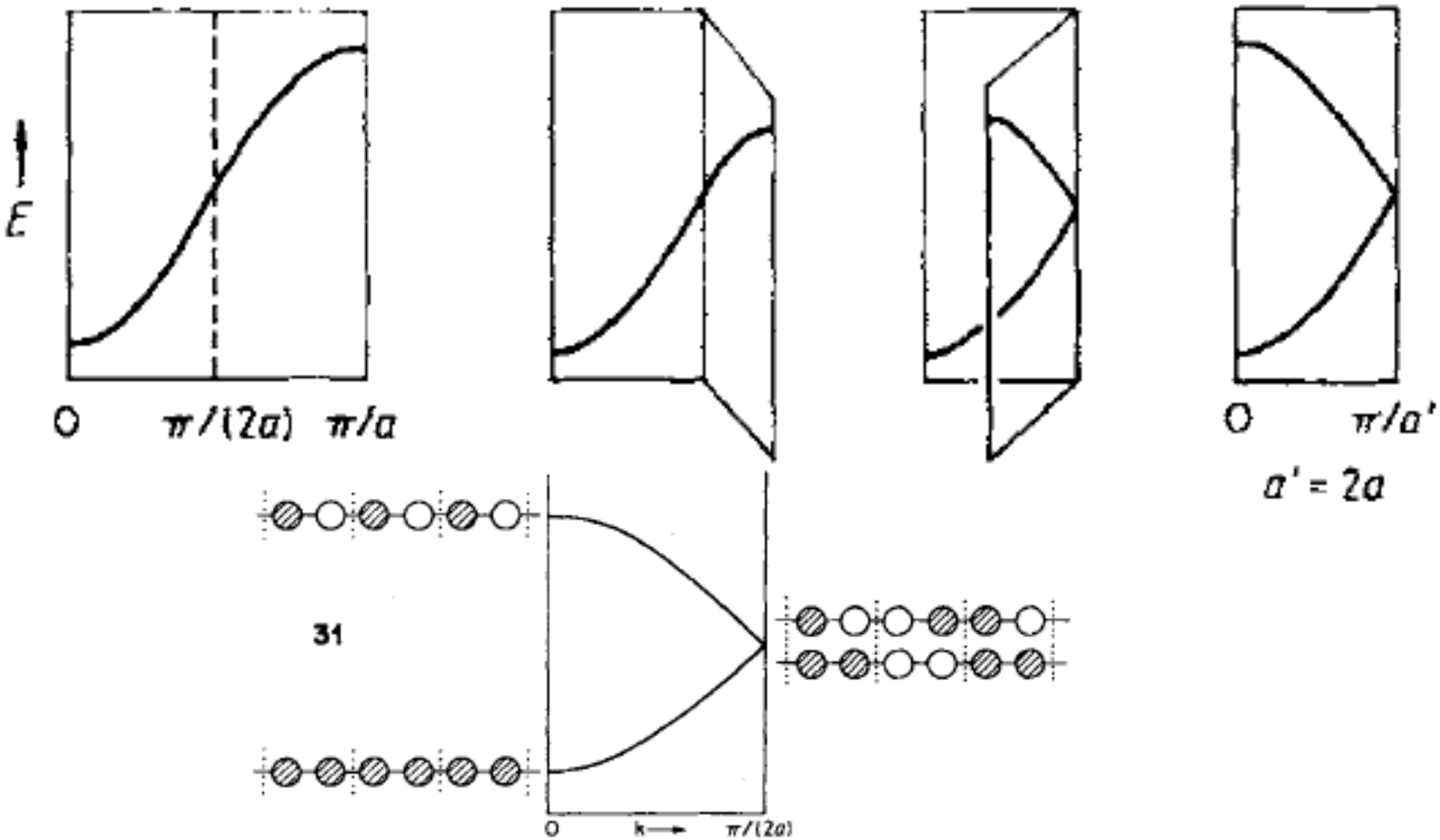


Geim, A. K. & Novoselov, K. S. The rise of graphene. Nature Mater. 6, 183 (2007).

Dirac and Weyl

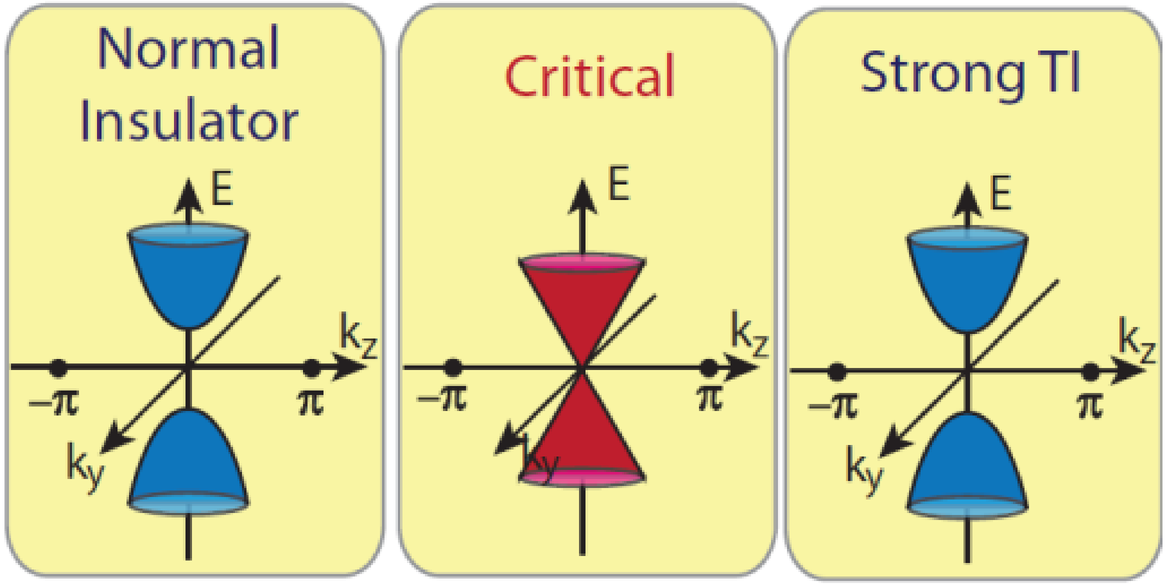
How Chemistry and Physics Meet in the Solid State

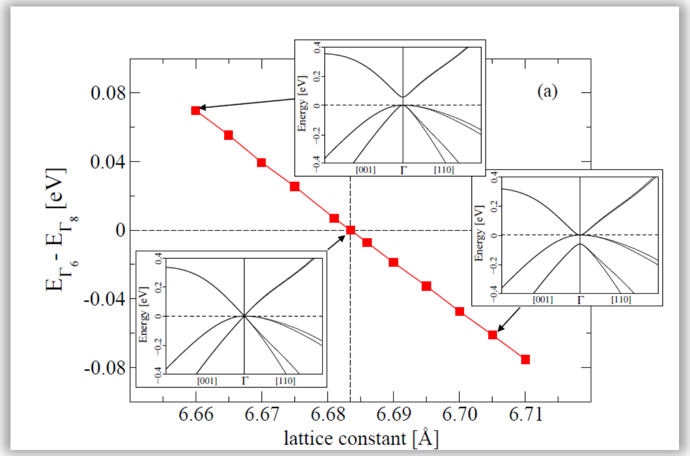
By Roald Hoffmann*



Hoffmann Angewandte. Chem. 26 (1987) 846

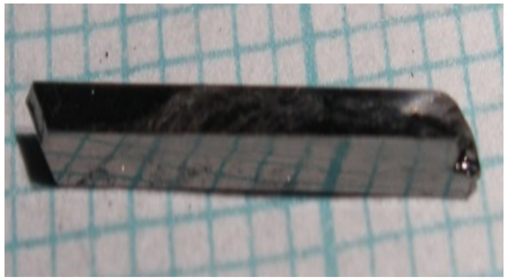
Dirac semimetals





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

3D Dirac Cd_3As_2

Cd_3As_2—A Noncubic Semiconductor with Unusually High Electron Mobility*

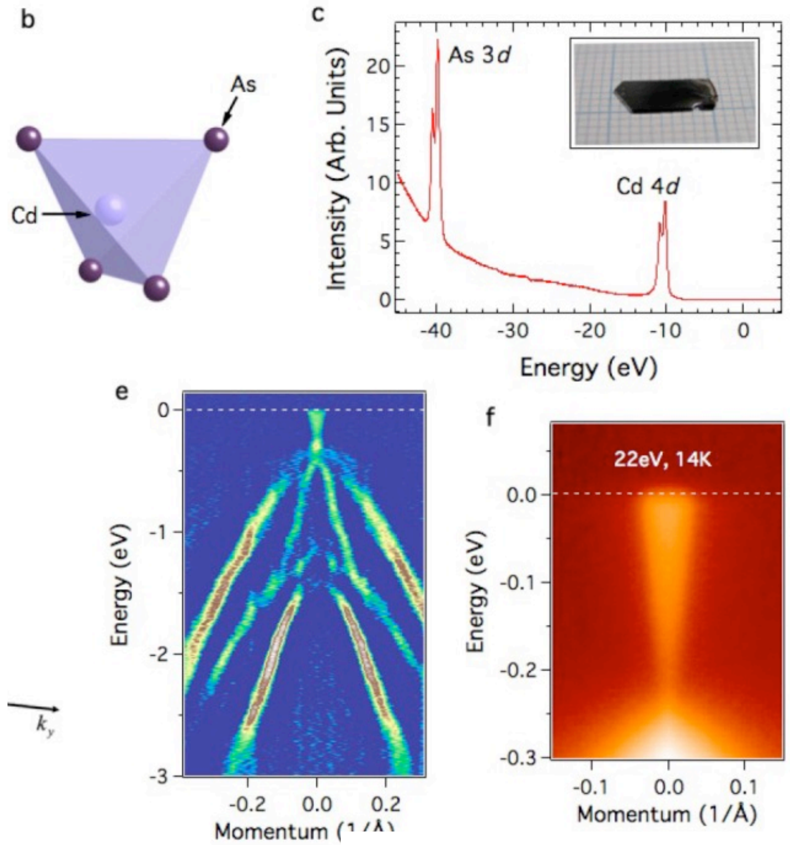
ARTHUR J. ROSENBERG AND THEODORE C. HARMAN
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts

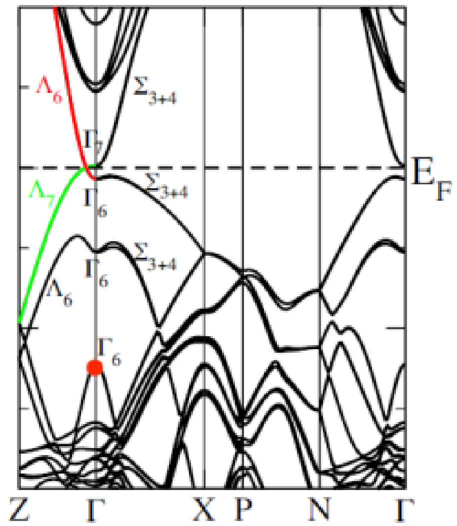
(Received June 17, 1959)

IN all reported studies of electron transport in solids, the electron mobility at room temperature determined by galvanomagnetic or drift experiments has been found to exceed 10 000 cm^2/volt-sec in but four materials, namely, the compounds InSb, InAs, HgSe, and HgTe at accessible purities [Table I(A)]. Each

TABLE I. Electron Hall mobility at 300°K.[a]

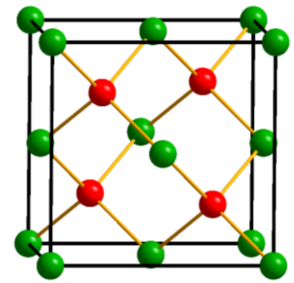
Material	Carrier concentration, cm^{-3}	Hall mobility, cm^2/volt-sec
A. Highest measured values		
InSb	2×10^{16}	63 000[b]
InAs	1.7×10^{16}	30 000[c]
HgSe	4×10^{17}	18 000[d]
HgTe	2.6×10^{17}	19 000[e]
B. Measured values at 4×10^{18} carriers/cm^3		
InSb		8000[f]
InAs		7000[g]
HgSe		6000[d]
Cd_3As_2		10 000





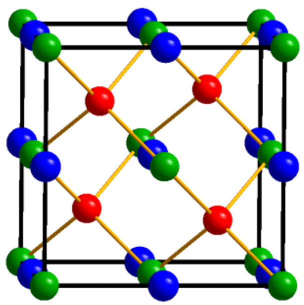
Arthur J. Rosenberg and Theodore C. Harman Journal of Applied Physics 30, 1621 (1959)
Wang, Z. J., Weng, H. M., Wu, Q. S., Dai, X. & Fang, Z., *Phys. Rev. B* 88, 125427 (2013).
Liu, Z. K. *et al*. *Nature Mater.* 13, 677-681 (2014).

Electronic structure



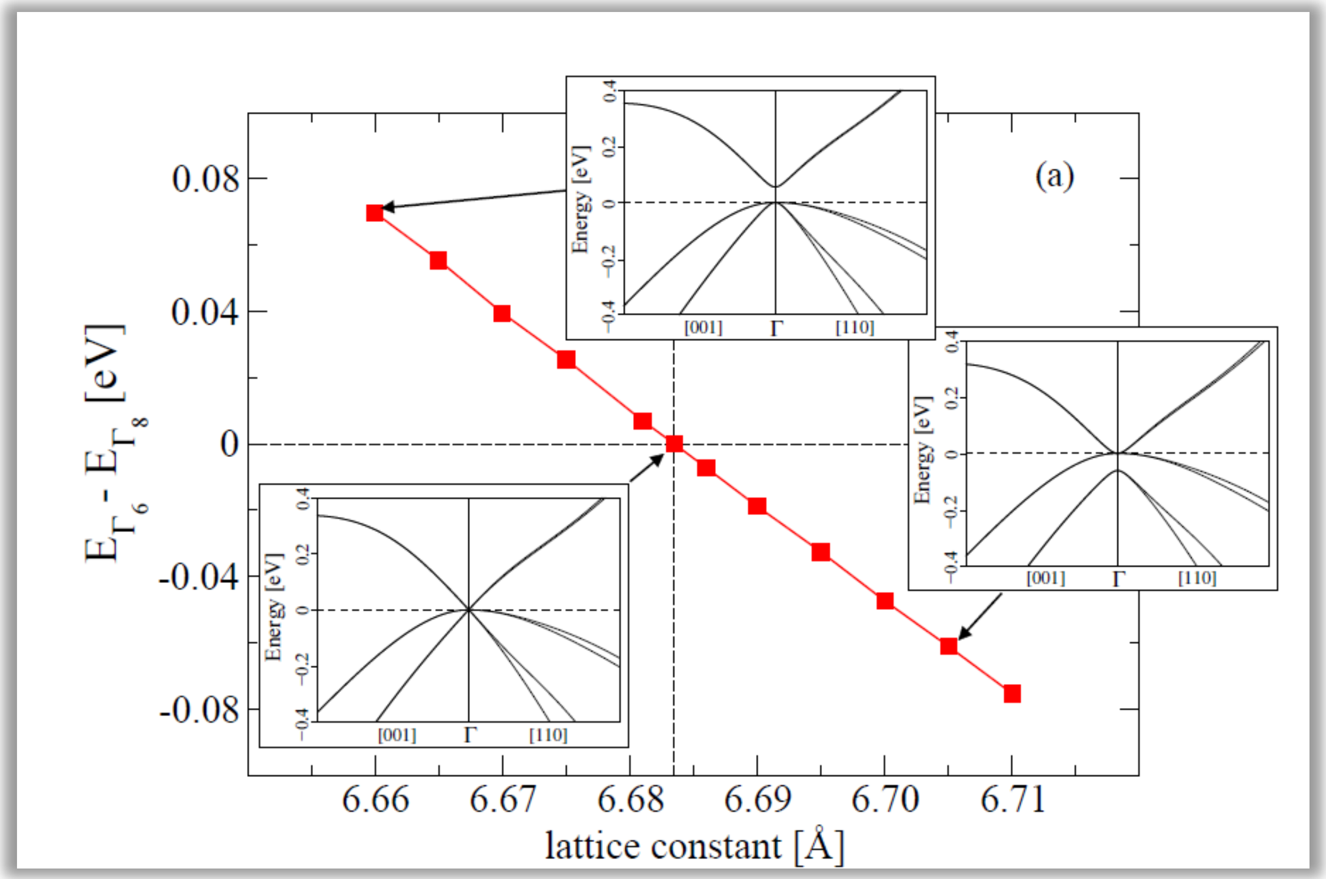
CdTe

HgTe



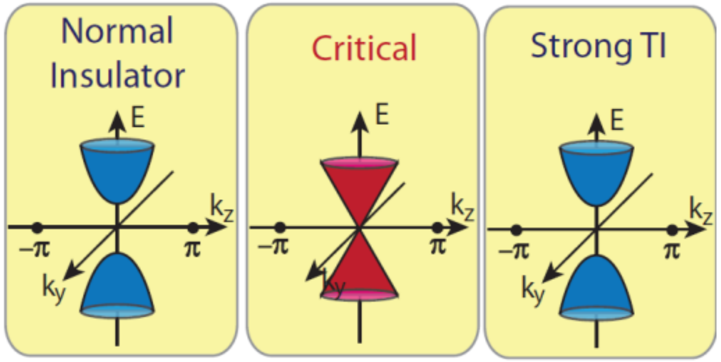
ScPtSb

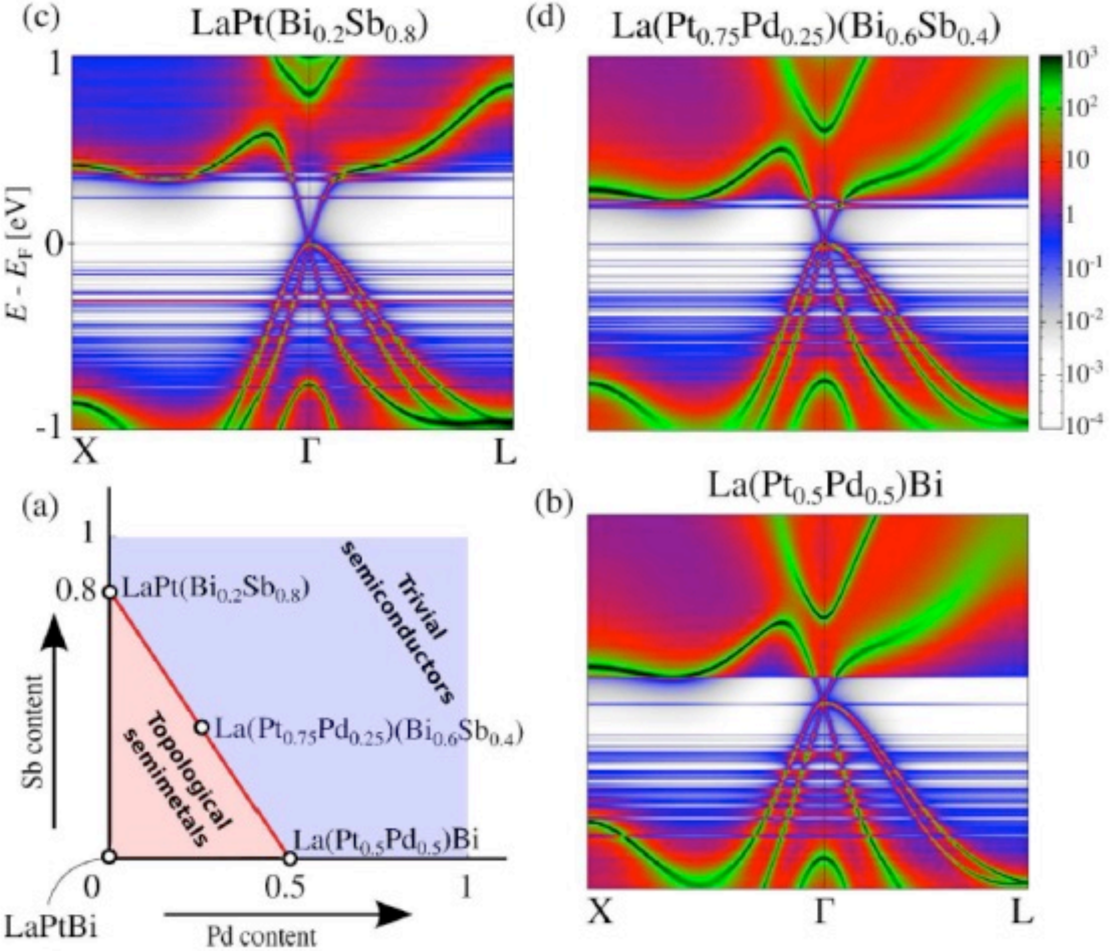
ScPtBi



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

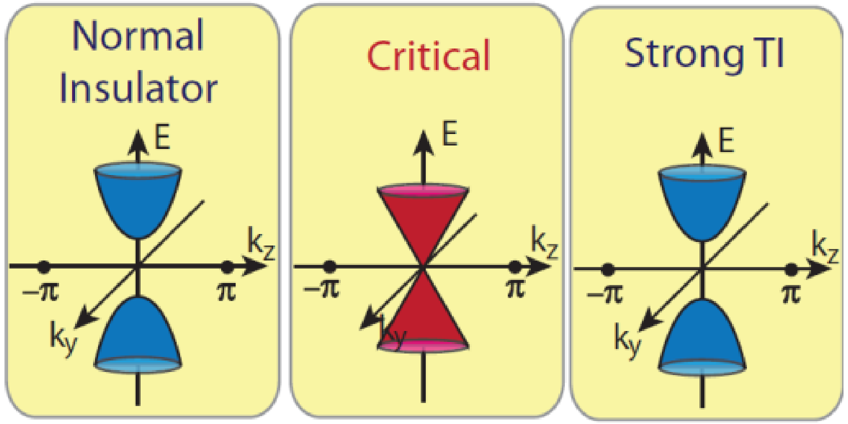
Application Spin Hall Effect

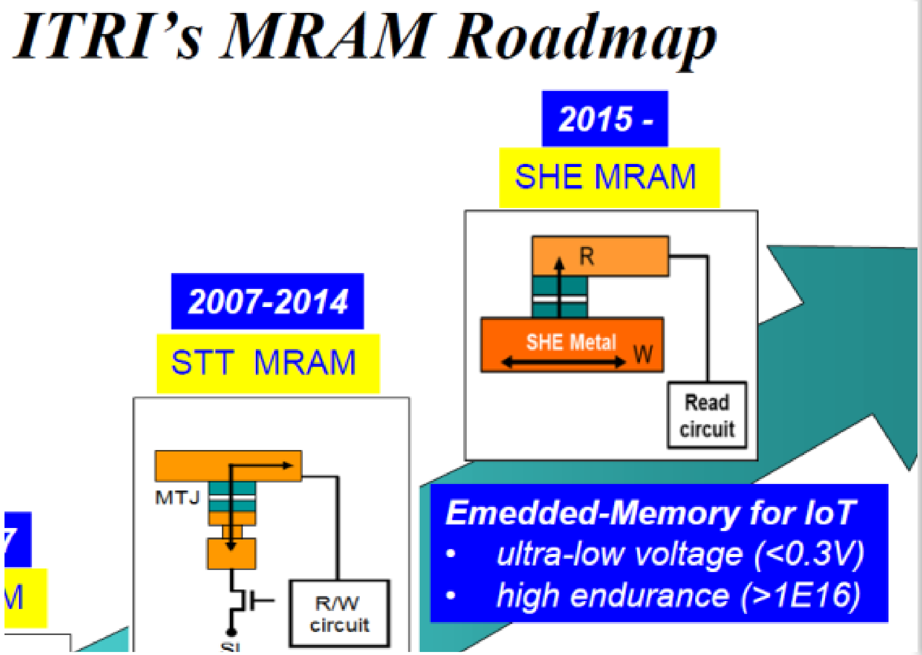


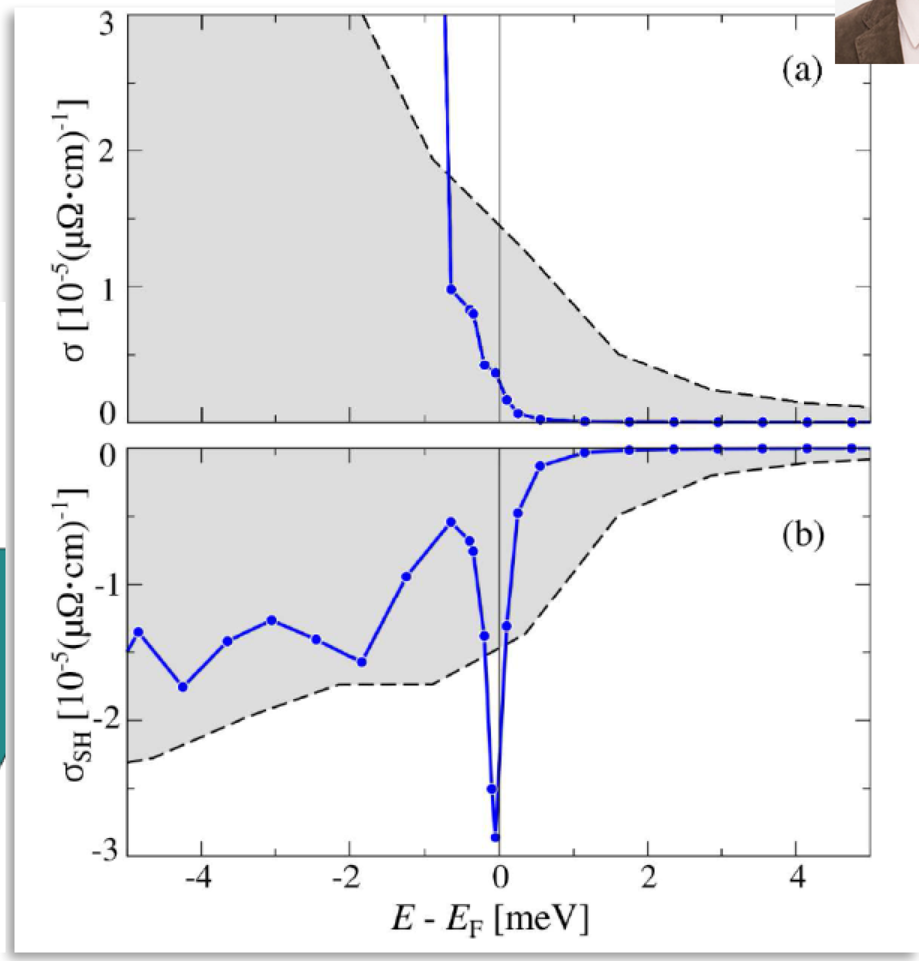


K. Chadova, et al., Phys. Rev. B 93 (2016) 195102 preprint: arXiv:1510.06935

Application Spin Hall Effect



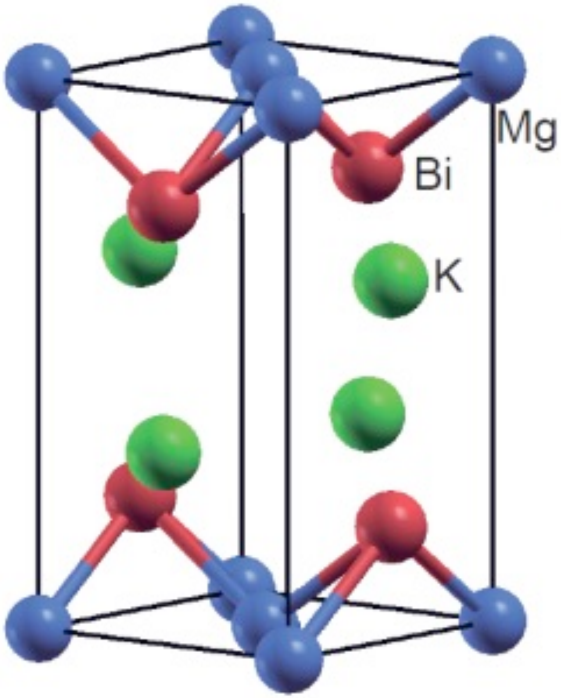




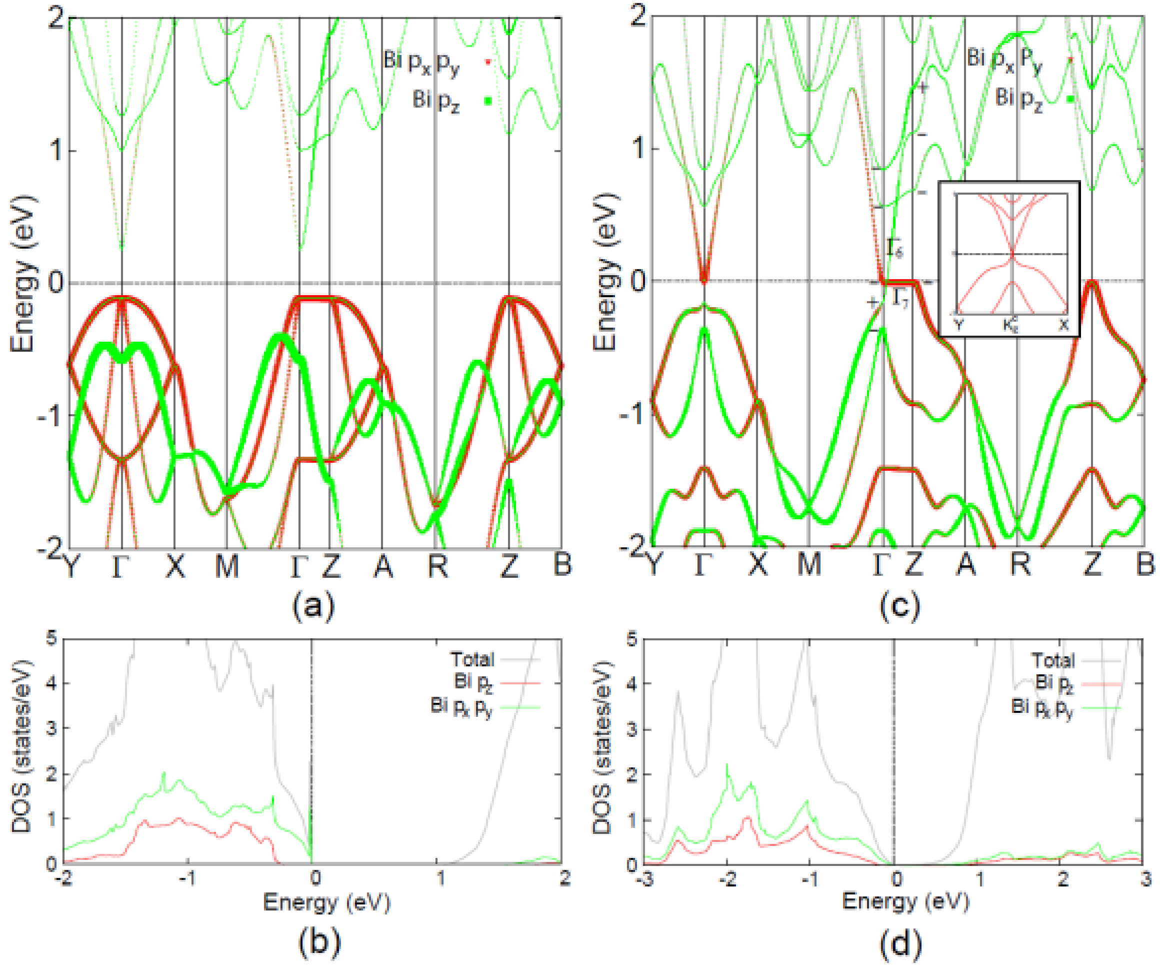
K. Chadova, et al., Phys. Rev. B 93 (2016) 195102 preprint: arXiv:1510.06935

Three-dimensional Critical Dirac semimetal in KMgBi

Congcong Le,[1,*] Shengshan Qin,[1,*] Xianxin Wu,[1] Xia Dai,[1] Peiyuan Fu,[1] and Jiangping Hu[1,2,†]

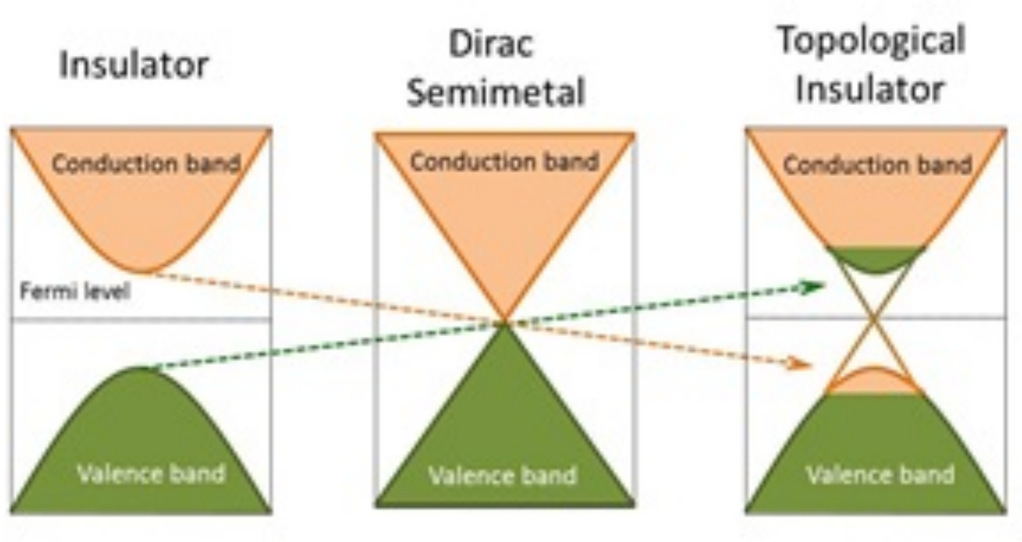


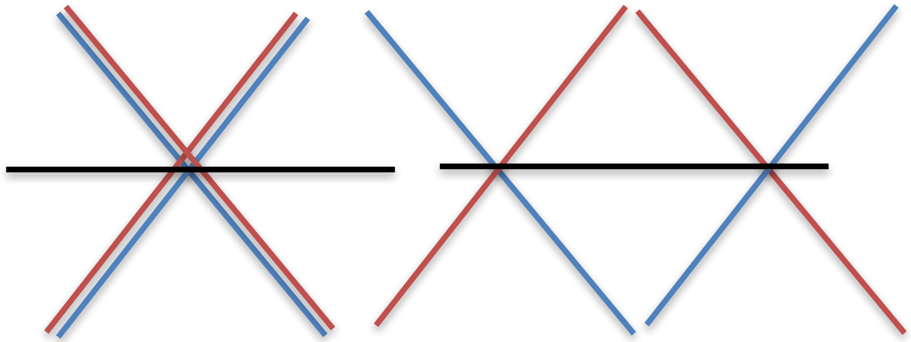
(a)



Insulator – semiconductor – metal

Topological Insulator/Semiconductor – Dirac/Weyl Semimetal –



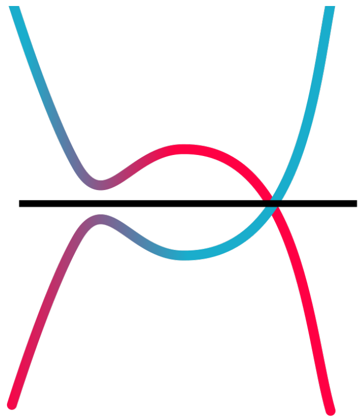


Dirac 4 folded Weyl 4 folded

degenerated

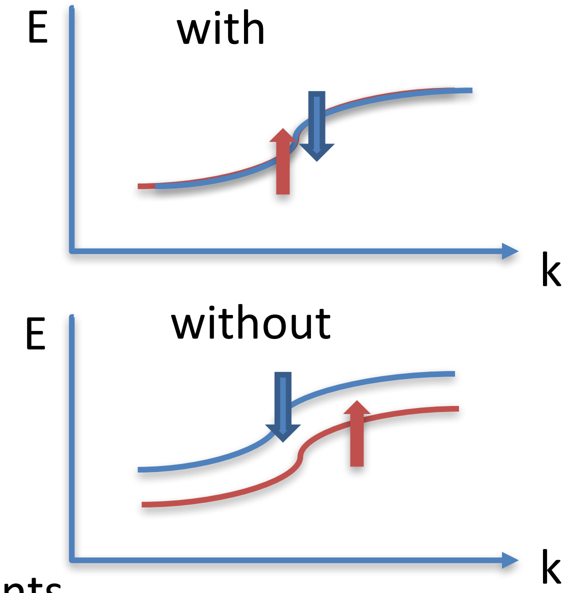
Weyl Semimetals

Breaking symmtery – NbP



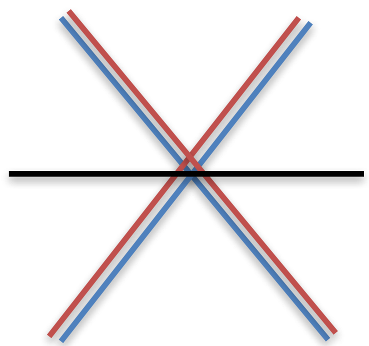
Weyl Semimetal

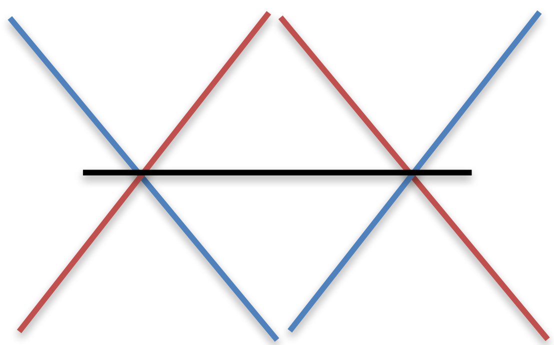
- Breaking symmetry
  - Inversion symmetry (Structural distortion)
- Breaking time reversal symmetry
  - Magnetic field

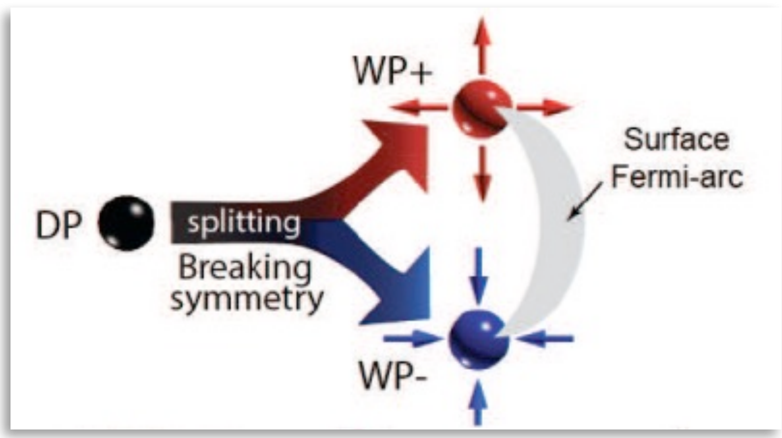


Dirac points are at high symmetry points

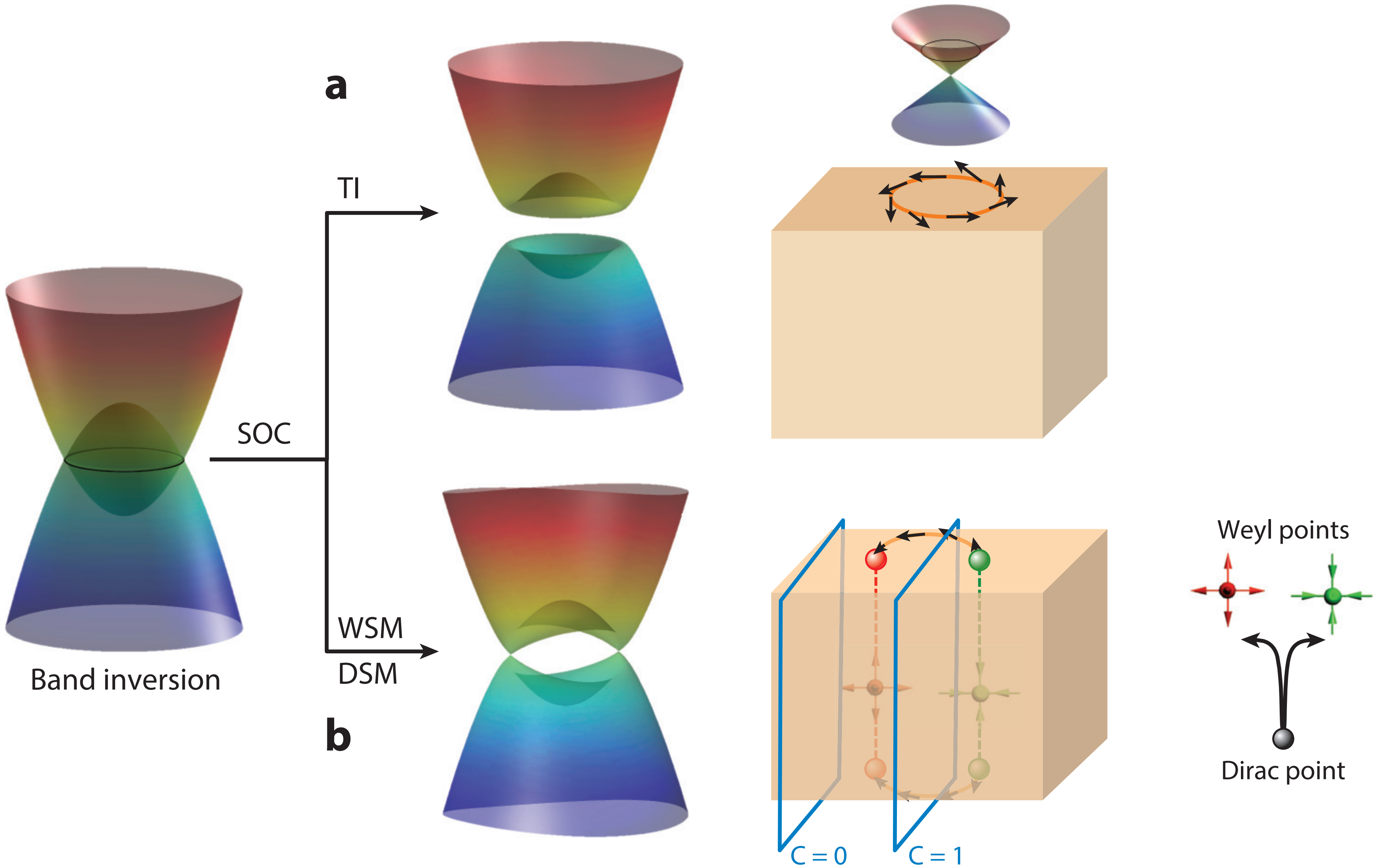
Weyl points are not at high symmetry points



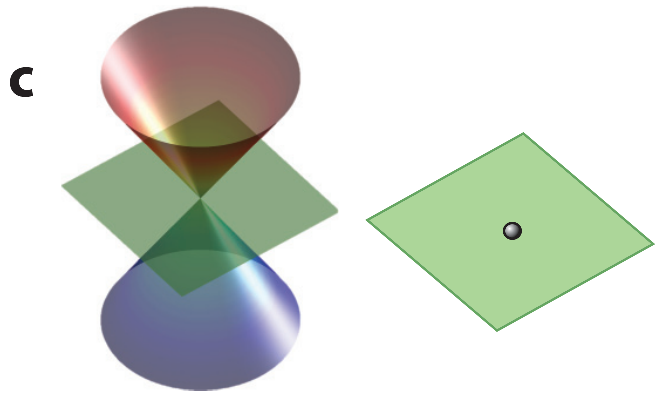




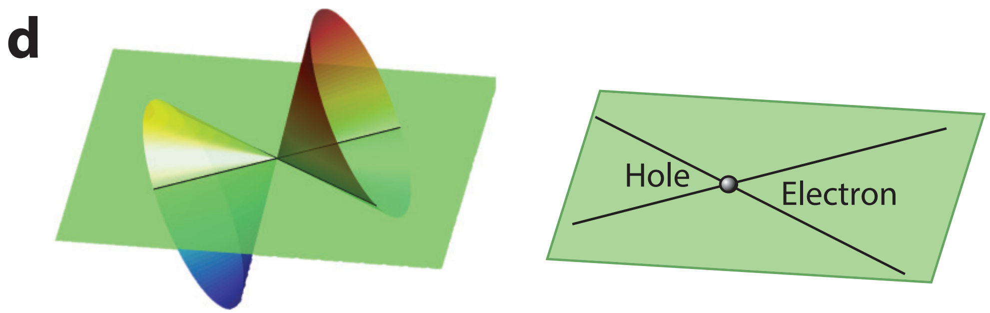
Weyl semimetals



Type I or II

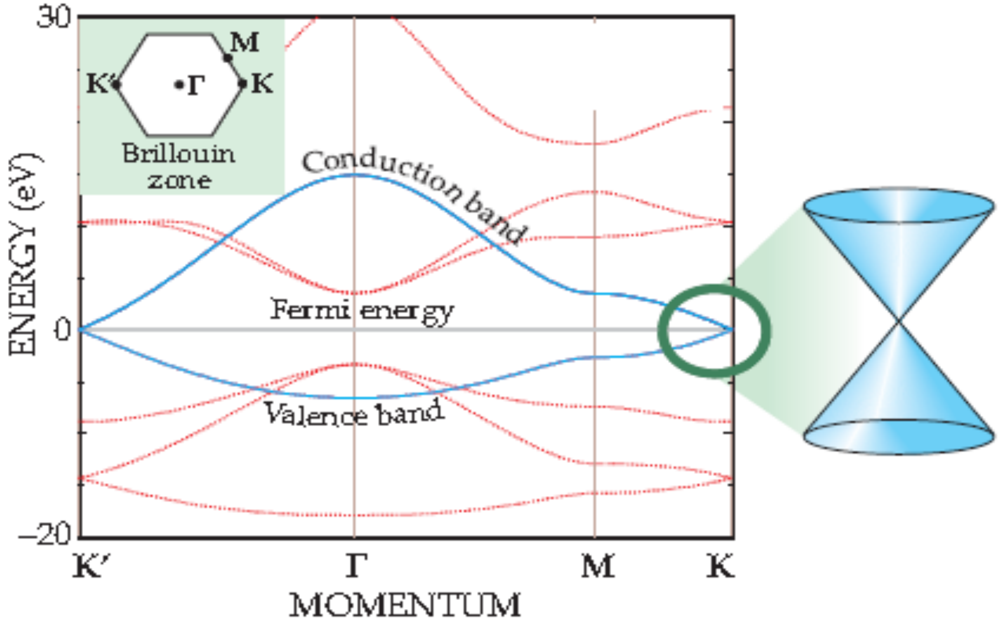


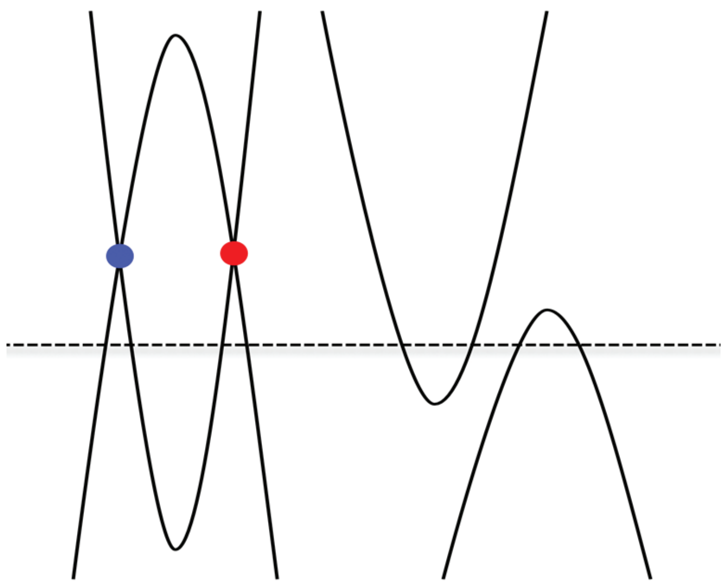
Type-I WSM



Type-II WSM

Graphene





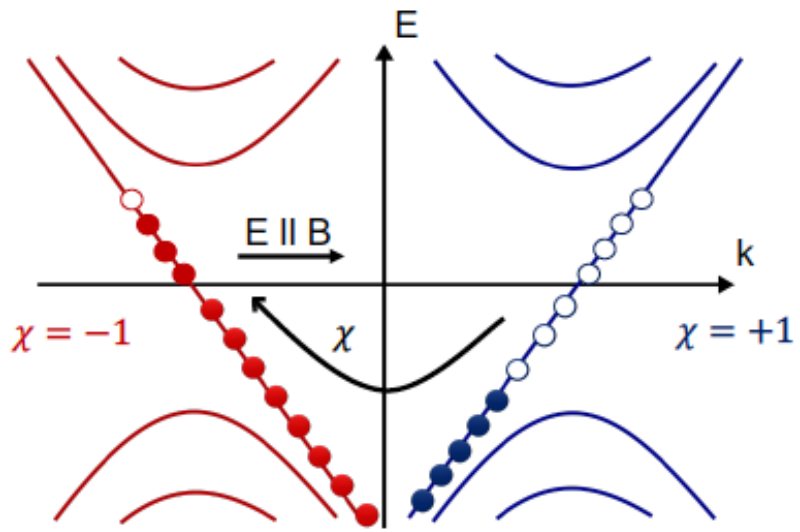
A. K. Geim, A. H. MacDonald Physics Today, 08.(2007), 35-41

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

Weyl semimetals

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

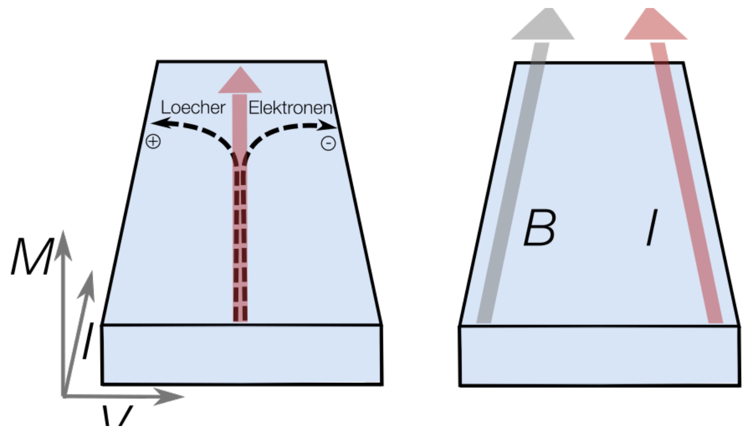
1. Fermi arc



2. Chiral anomaly

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

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



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)

Quantum anomaly in QED

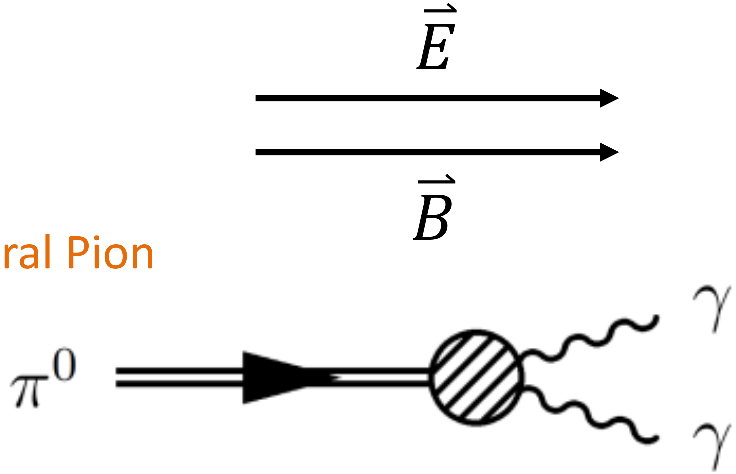
Violation of chiral symmetry.

In Quantum Electro Dynamics (relativistic quantum field theory) chiral charge conservation can be violated for massless fermions!

Pion decay:

Neutral Pion

Photon



Photon

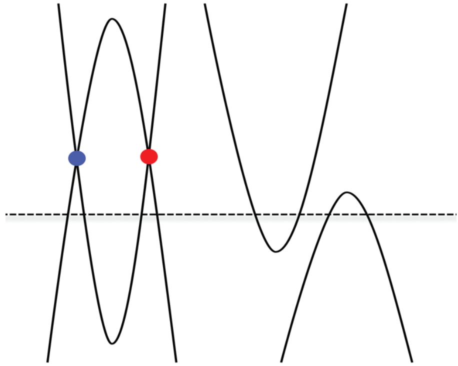
Electric charge: 0	0
Spin: half-integer	integer

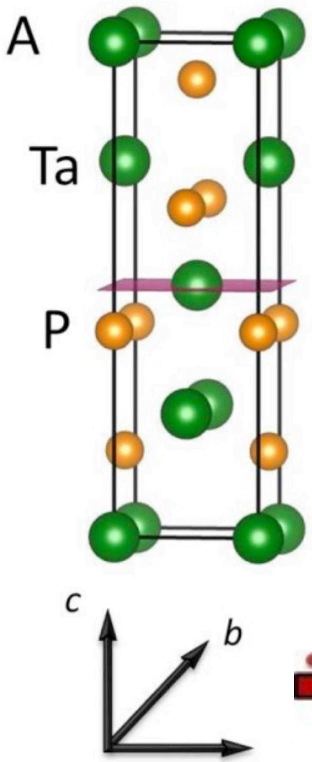
→ Chiral anomaly

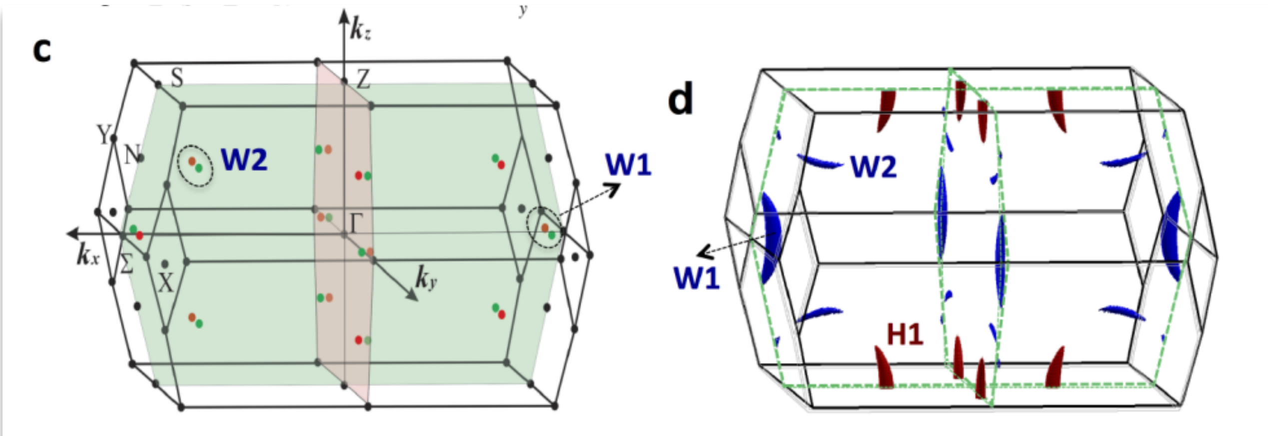
Adler, S. L. *Phys. Rev.* **177,** 5 (1969).
Bell, J. S. & Jackiw, R. *Nuovo Cim.* **A60,** 4 (1969).

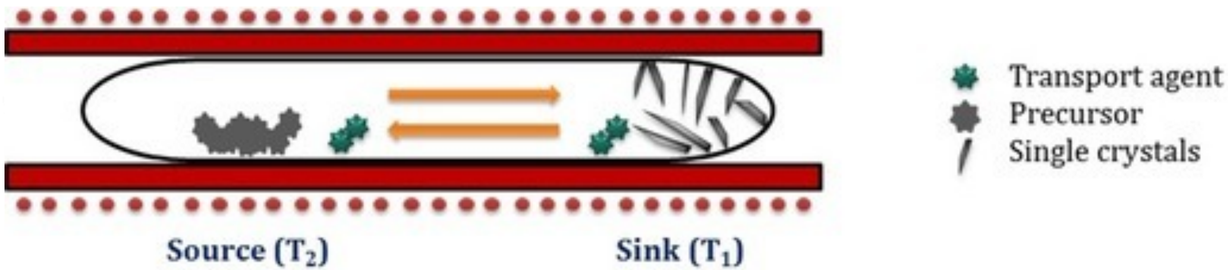
Weyl semimetals in non-centro NbP

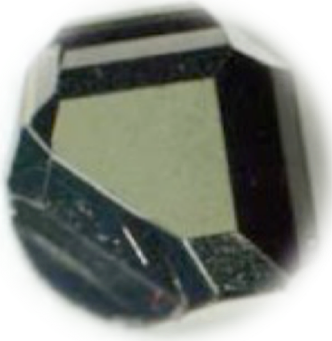
NbP, NbAs,
TaP, TaAs









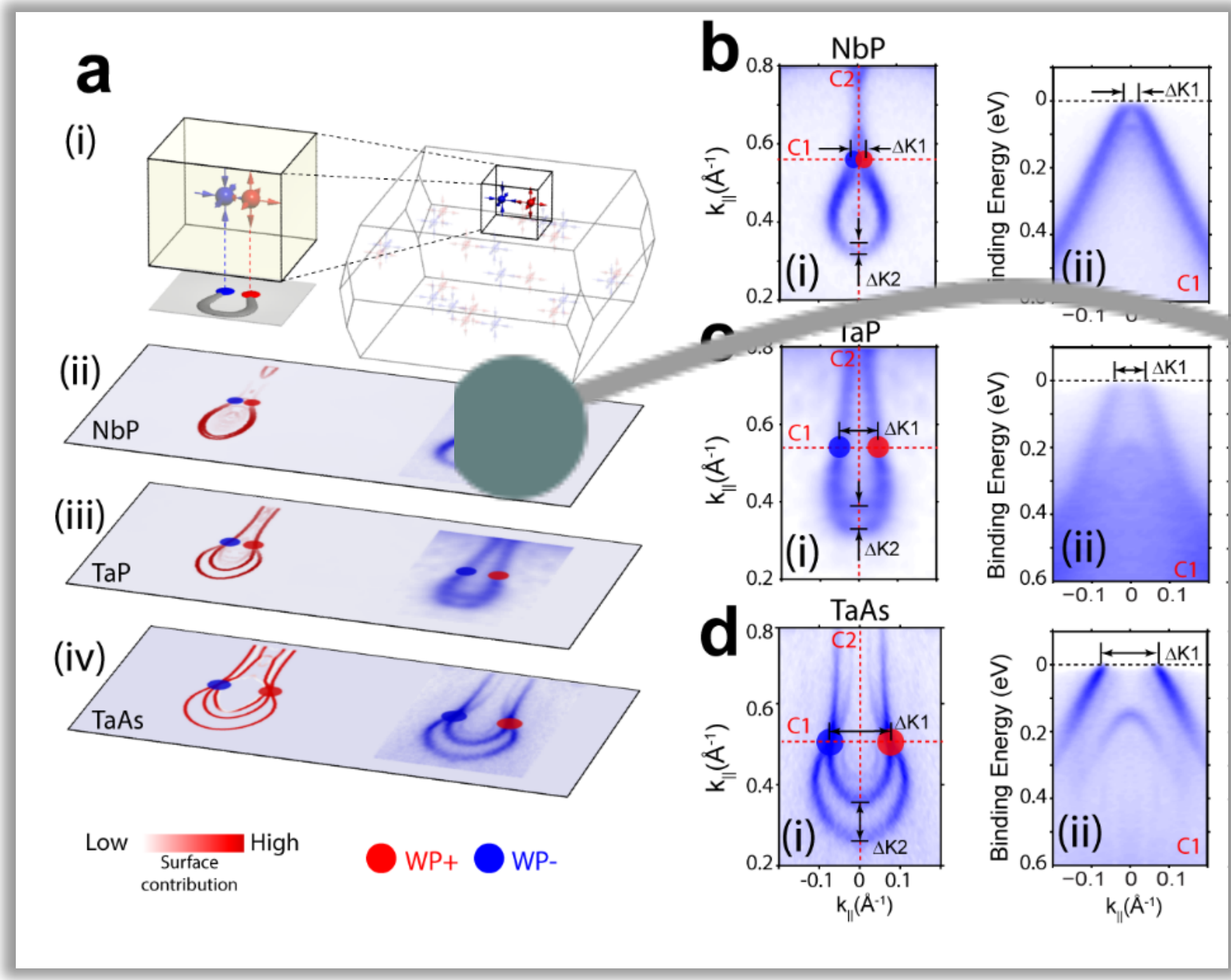


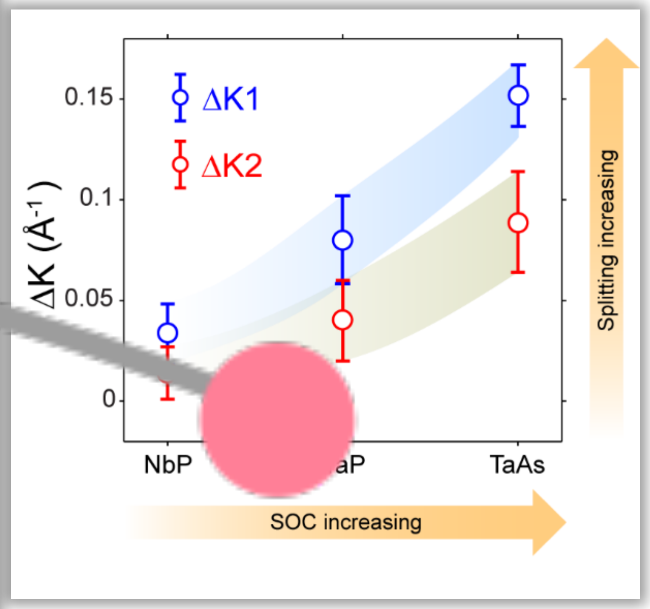
Shekhar, et al. , Nature Physics 11 (2015) 645,
Frank Arnold, et al. Nature Communication 7 (2016) 11615

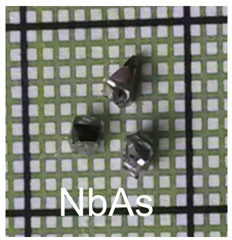
Weng, et al. Phys. Rev. X 5, 11029 (2015)
Huang et al. preprint arXiv:1501.00755

NbP, TaP, TaAs

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

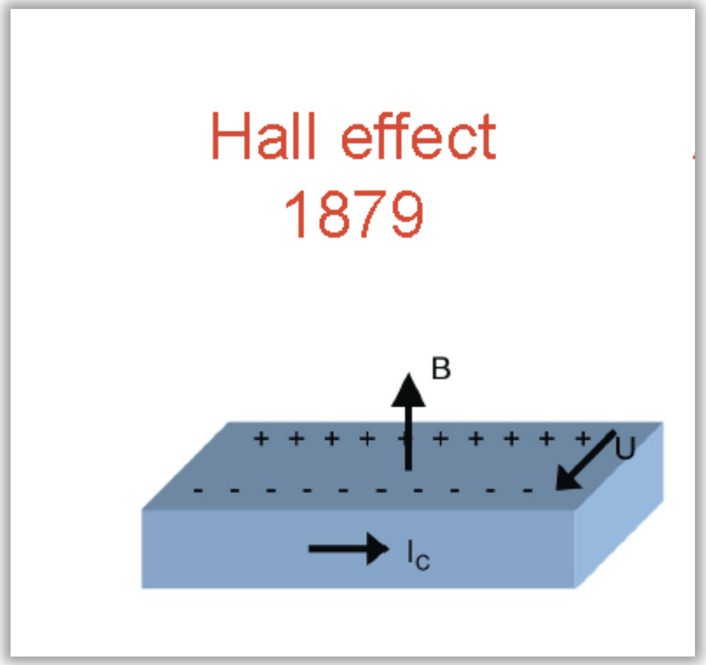


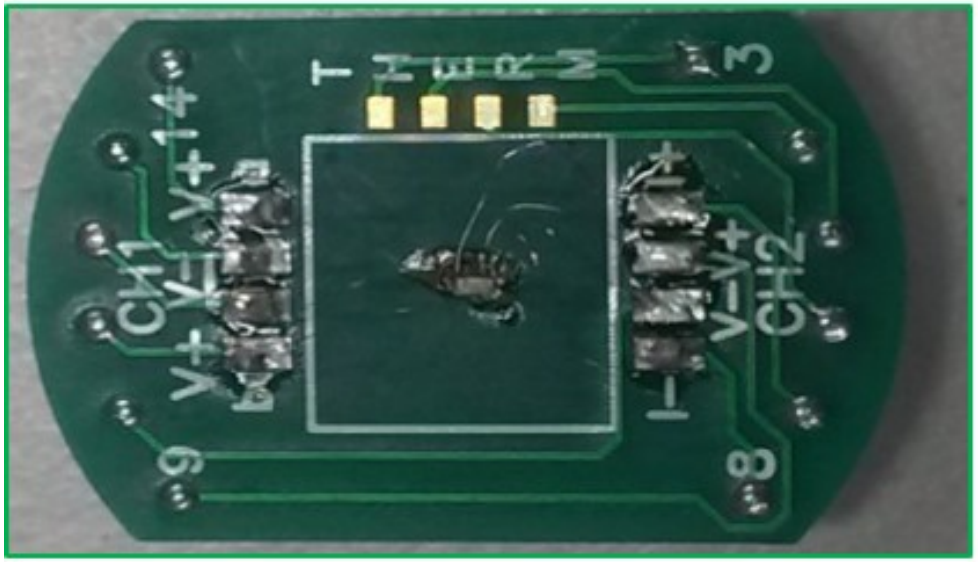




Z. K. Liu et al., Nature Mat. 15 (2016) 27
Yang, et al. Nature Phys. 11 (2015) 728

Resistance Measurement

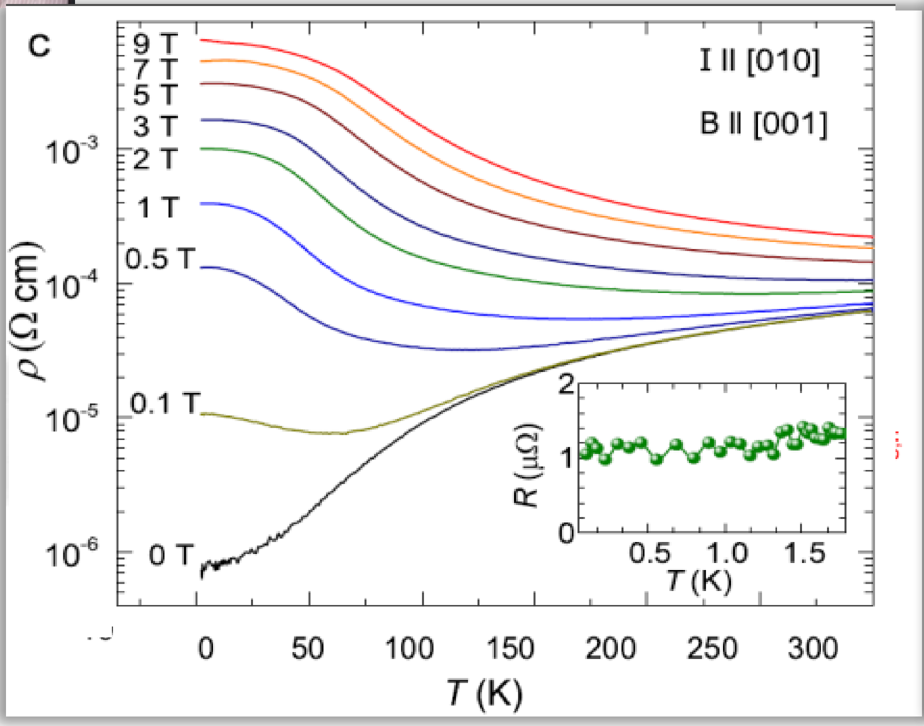


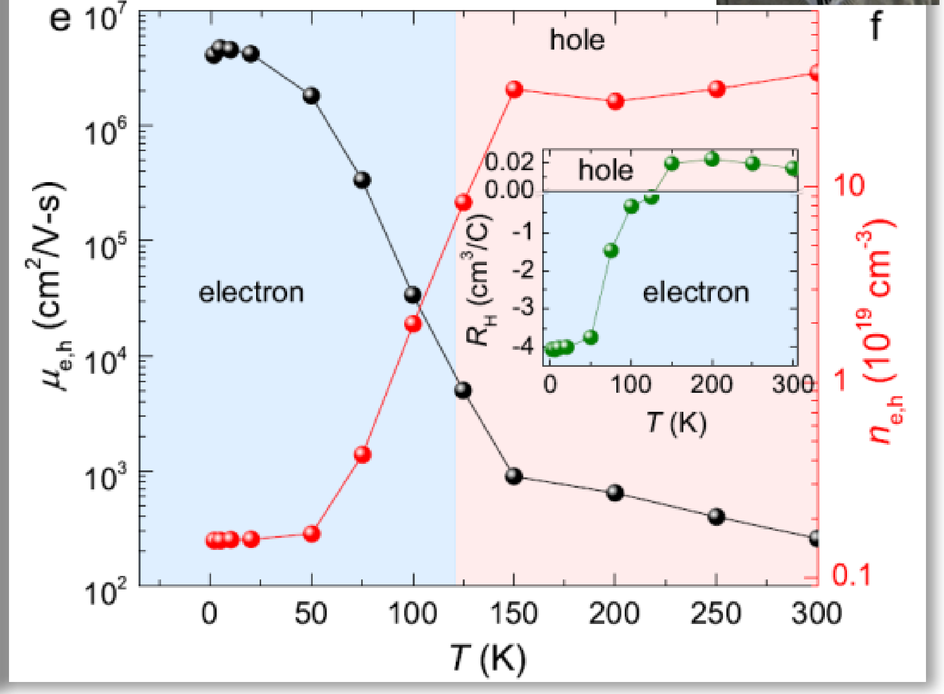


We measure the resistance without and with a magnetic field

- Metal, semiconductor, or insulator
- Electron or hole conductivity
- Resistance in a magnetic field: Magnetoresistance

Weyl Points in non-centro NbP





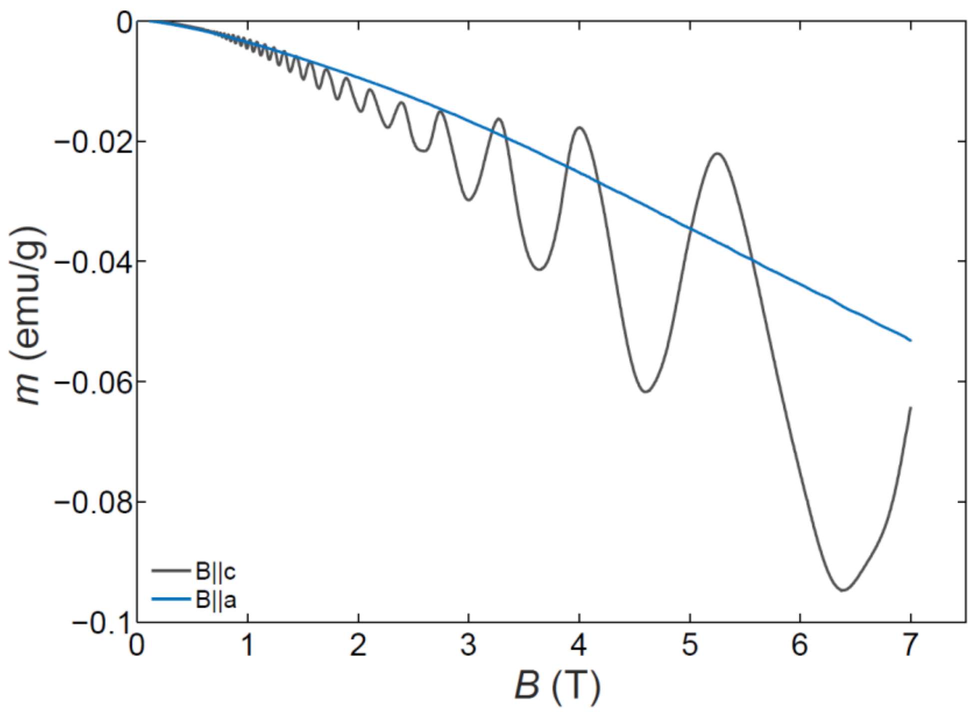
NbP is a topological Weyl semimetal

- 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

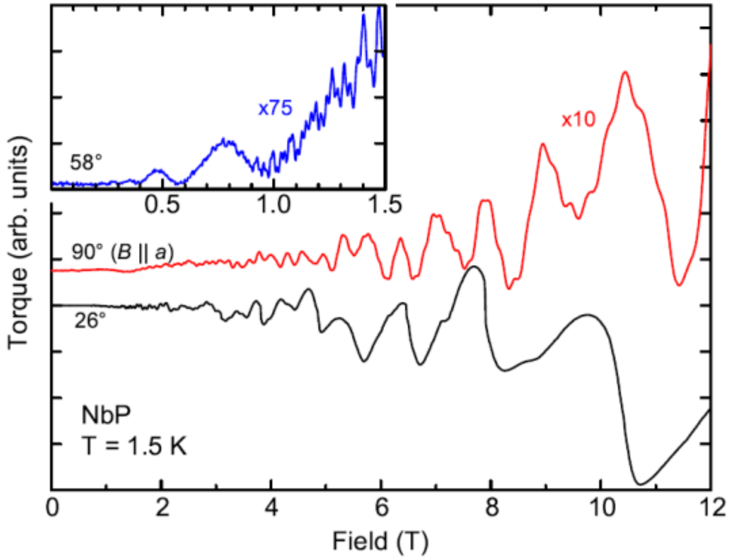
TaP Quantum Oscillations

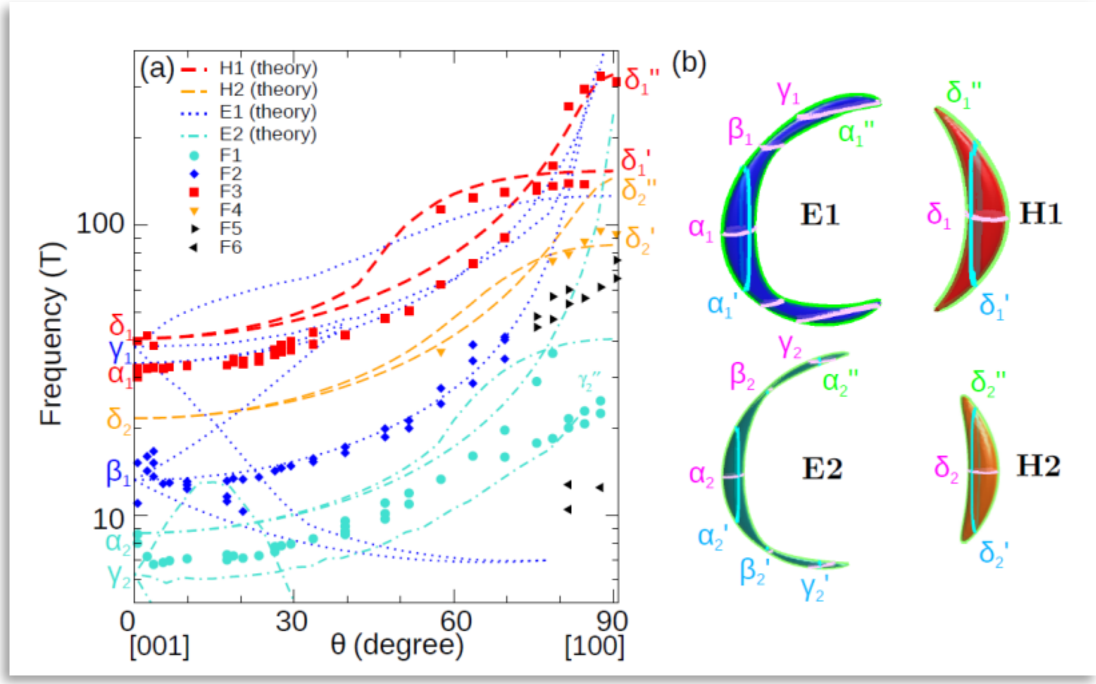


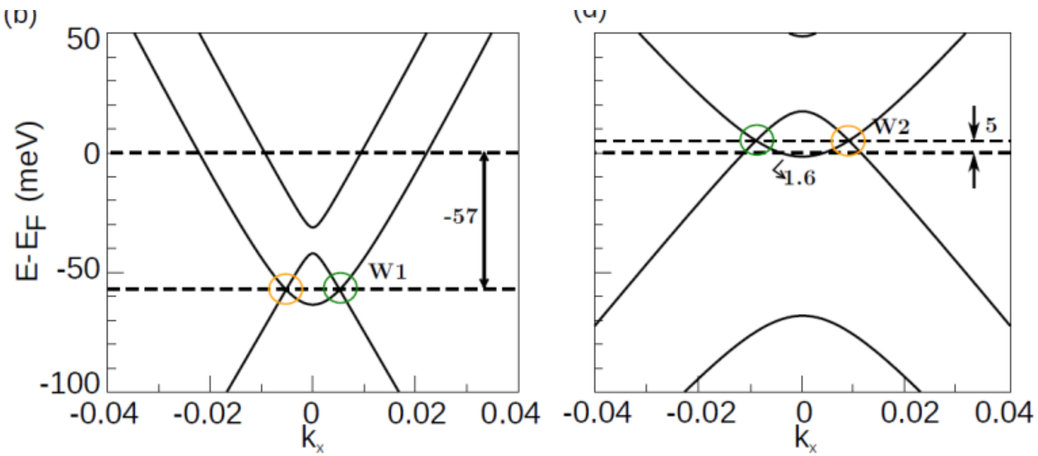
SQUID-VSM magnetization

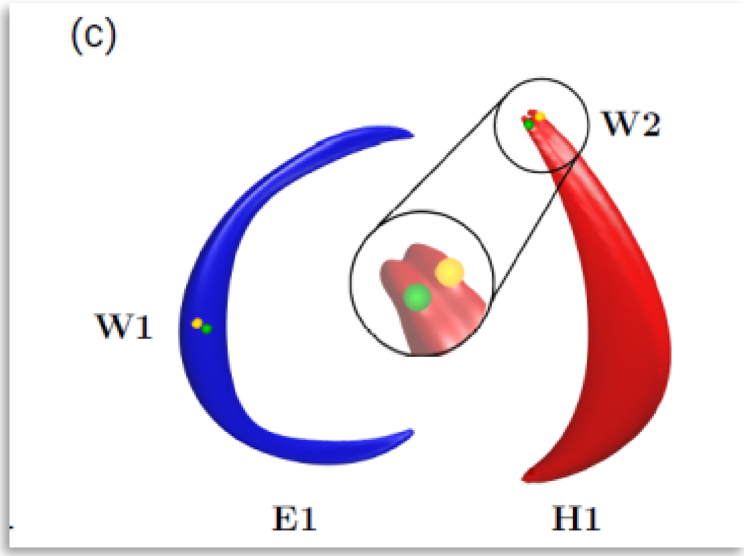
- In c-direction the diamagnetic magnetization is superimposed by quantum oscillations starting at 0.6 T
- In a-direction only weak quantum oscillations are visible
- The frequency proportional to the extremal Fermi surface perpendicular to ***B***

NbP and the Fermi surface



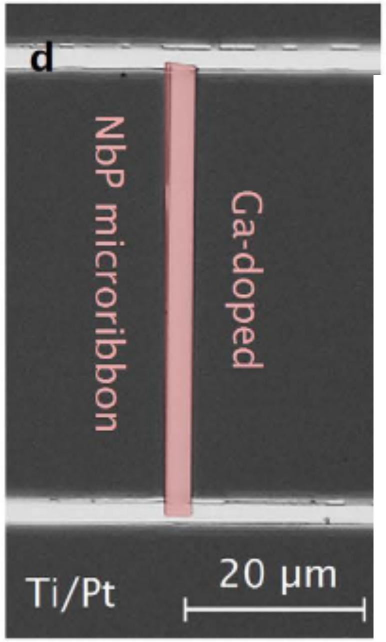


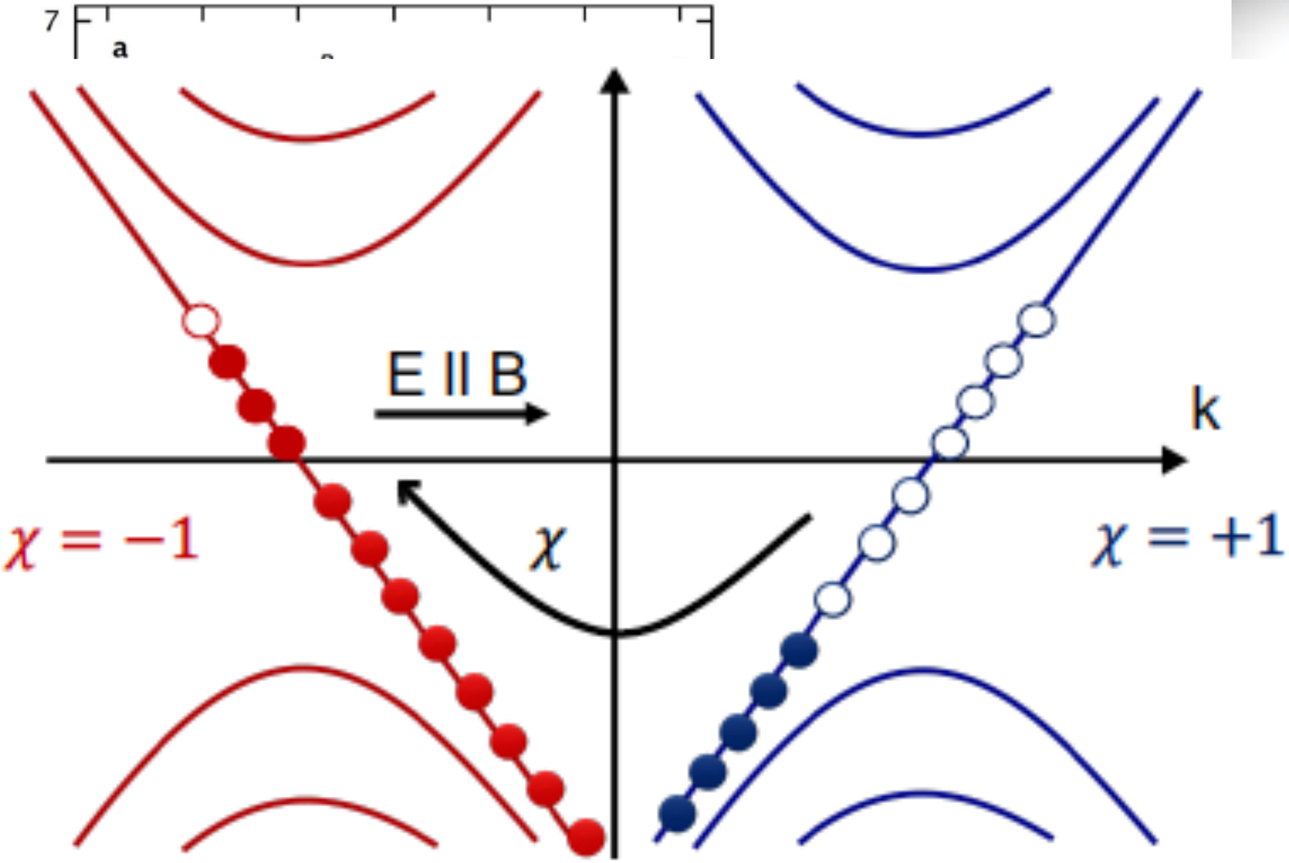


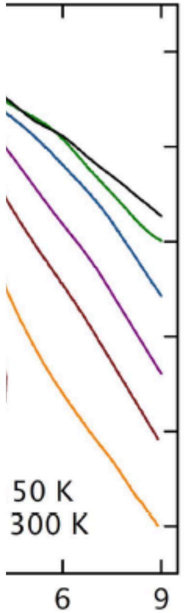


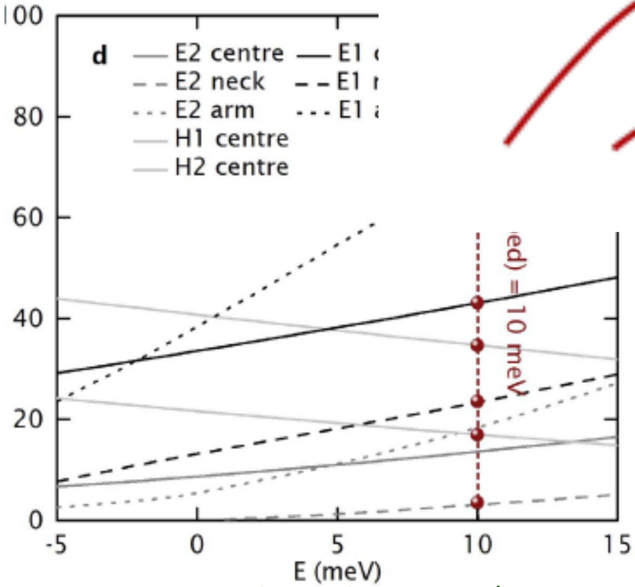
Klotz et al. Phys. Rev. Lett. 2016

Chiral Anomaly





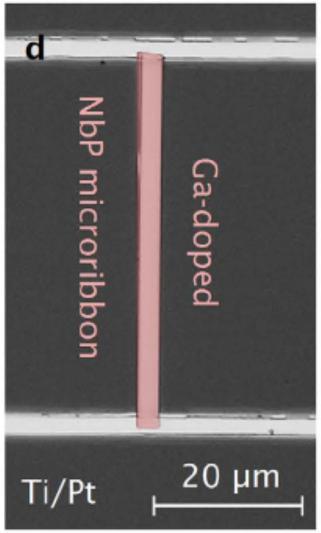


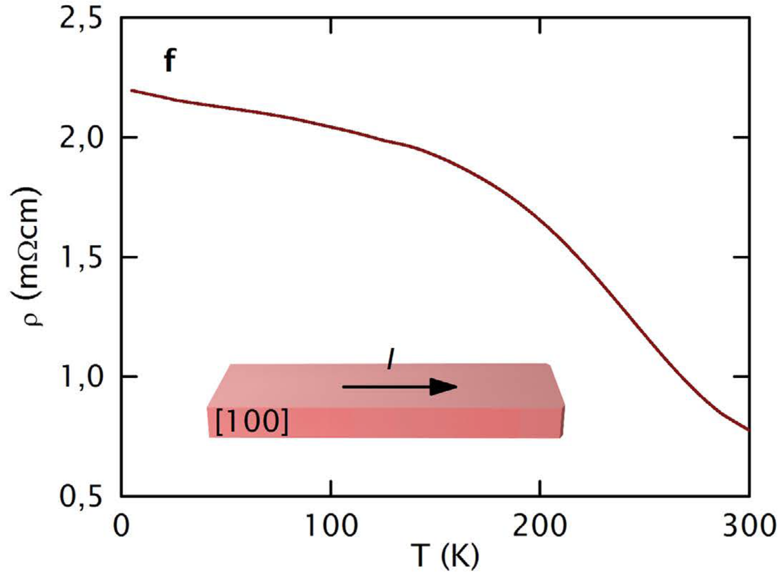


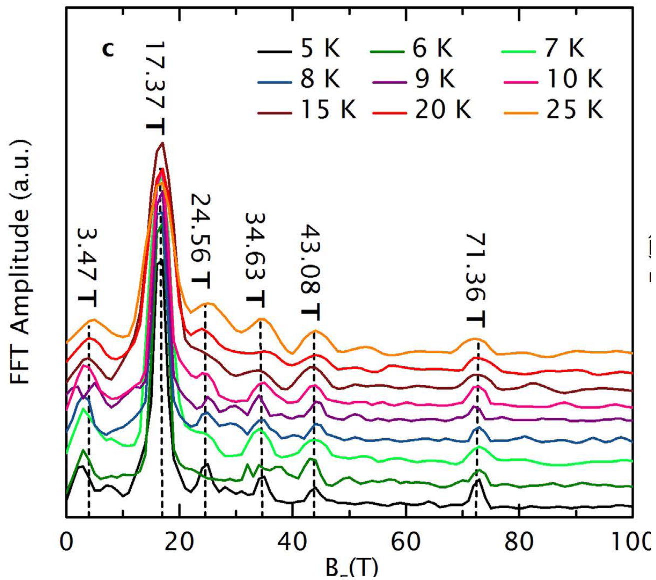
Ga-doping relocate the Fermi energy in NbP close to the W2 Weyl points
Therefore we observe a negative MR as a signature of the chiral anomaly the, NMR survives up to room temperature

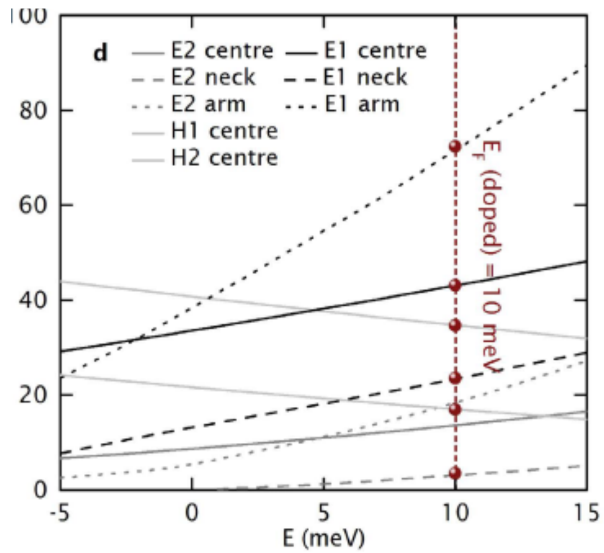
Anna Corinna Niemann, Johannes Gooth et al. Scientific Reports 7 (2017) 43394 doi:10.1038/srep4339 preprint arXiv:1610.01413

Chiral Anomaly









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

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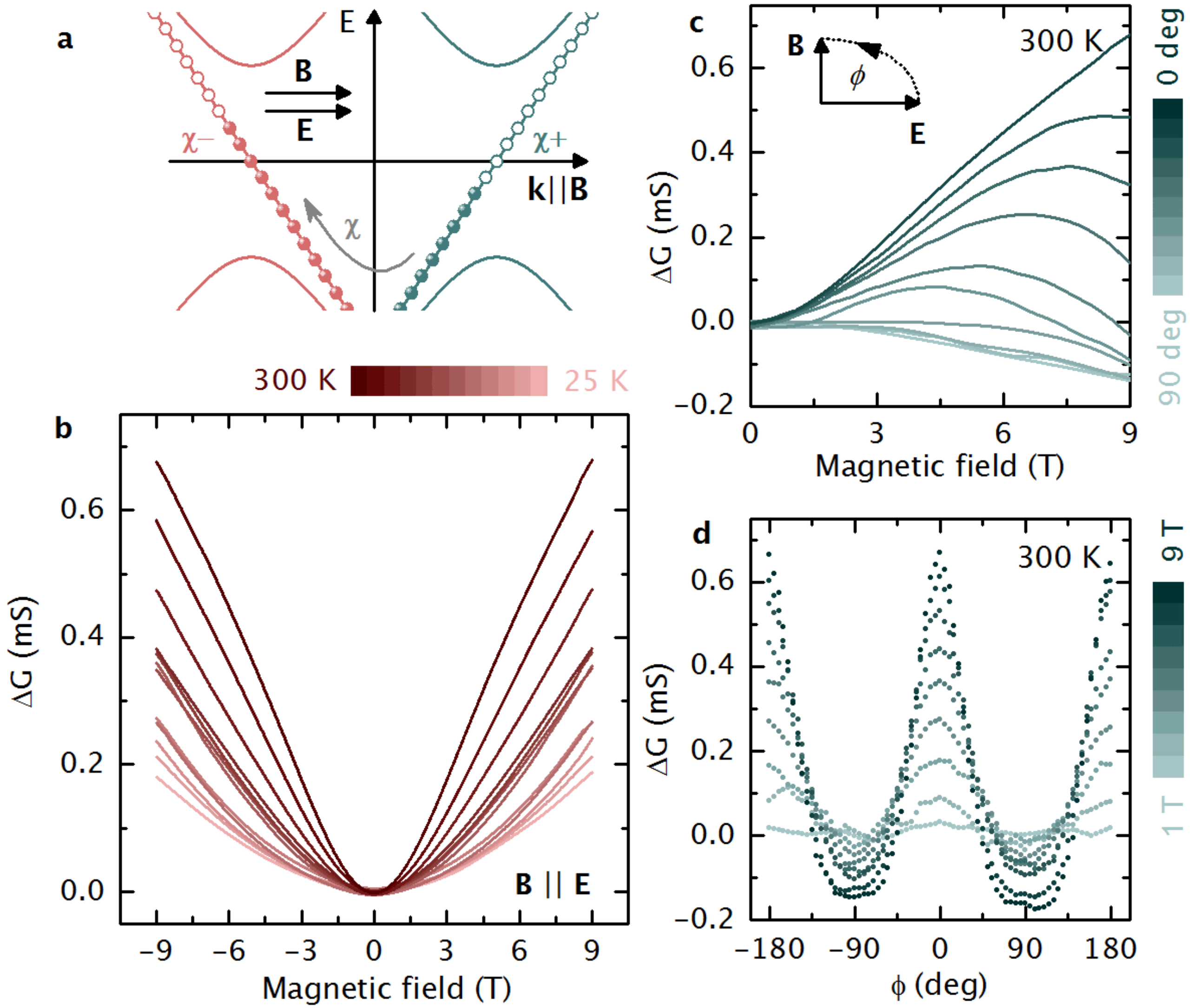
Longitudinal magneto-transport – E||B



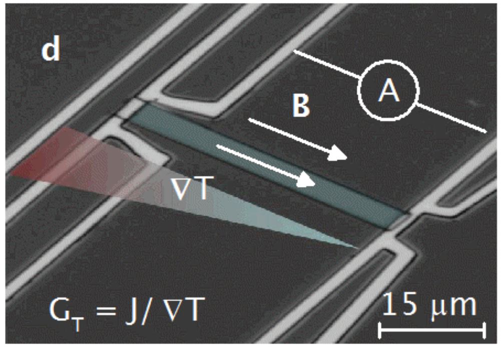
The PMC is locked to E||B, as expected for Chiral anomaly.

[Shekhar, C. et al. Nat. Phys. 11, 3372 (2015)]

Chiral Anomaly

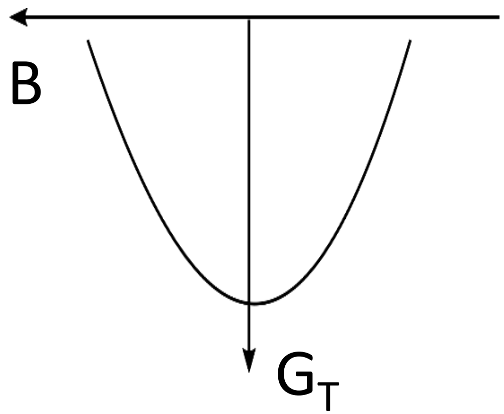
Experimental signatures for the mixed axial-gravitational anomaly in Weyl semimetals

- 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

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

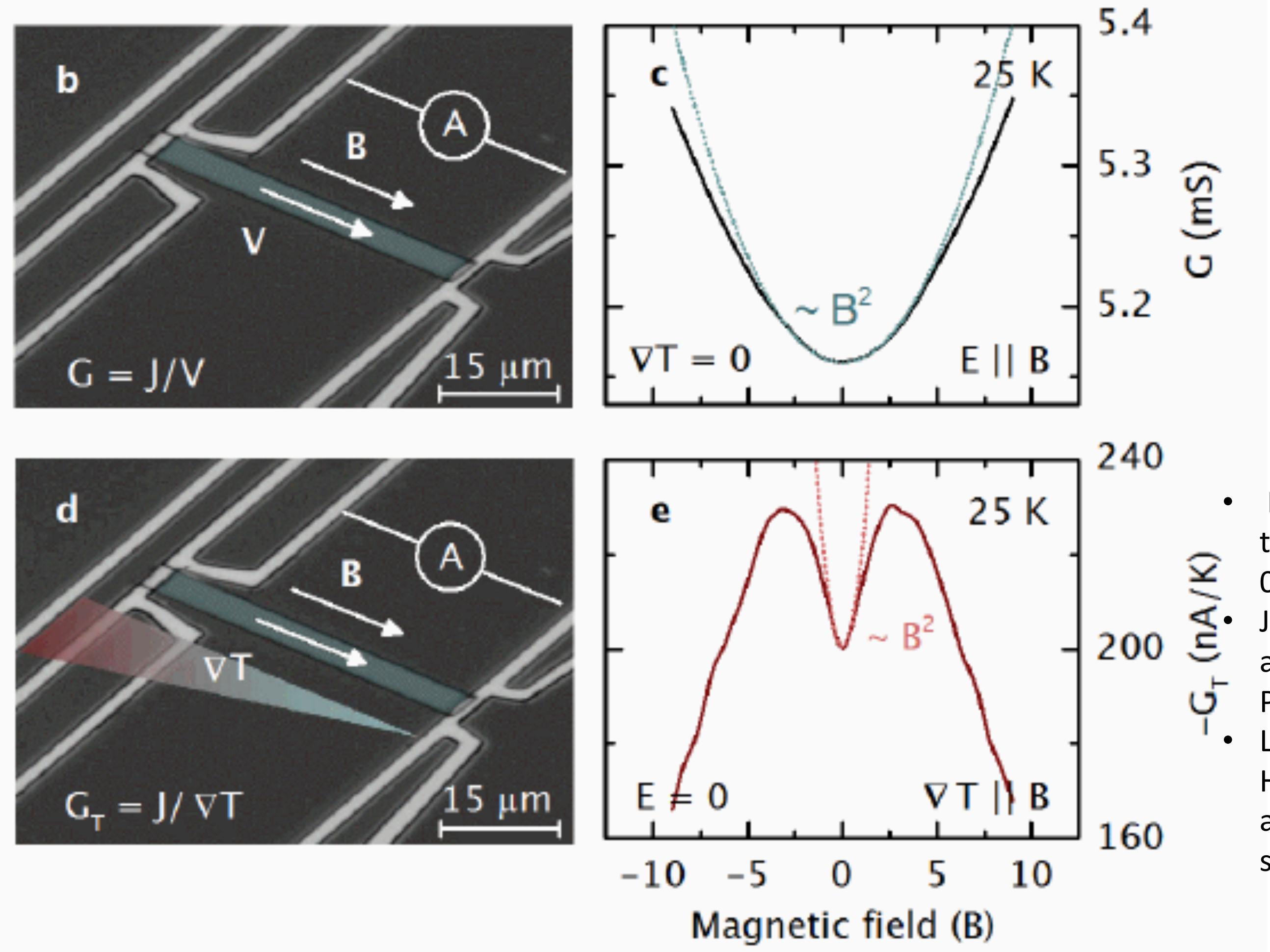


- High fields: deminishes

- 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



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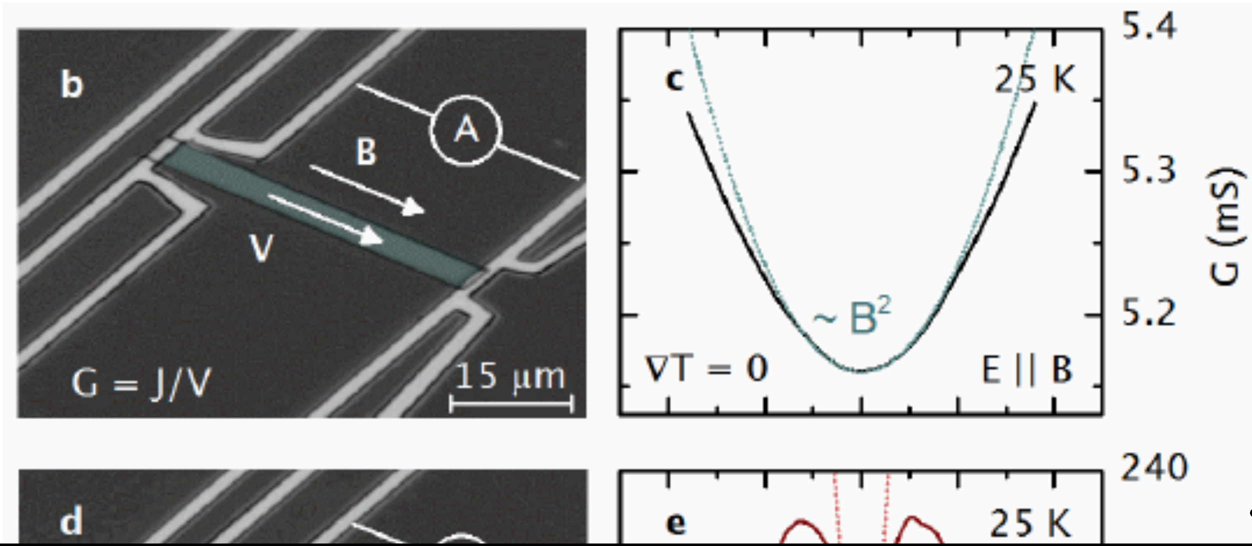
- Lucas, A., Davison, R. A. & Sachdev, S. Hydrodynamic theory of thermoelectric transport and negative magnetoresistance in weyl semimetals. PNAS 113, 9463–9468 (2016).

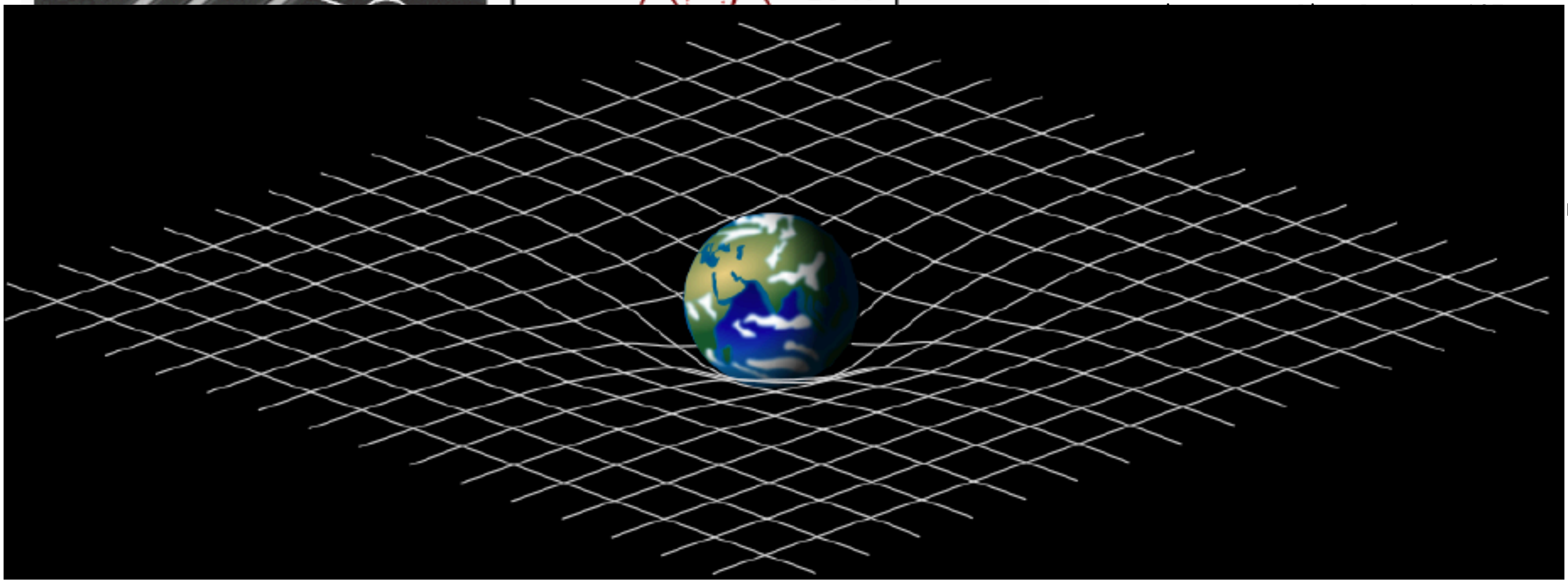
A positive longitudinal magneto-thermoelectric conductance (PMTC) in the Weyl semimetal NbP for collinear temperature gradients and magnetic fields that vanishes in the ultra quantum limit.

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

Gravitational Anomaly



- Landsteiner, et al. Gravitational anomaly and



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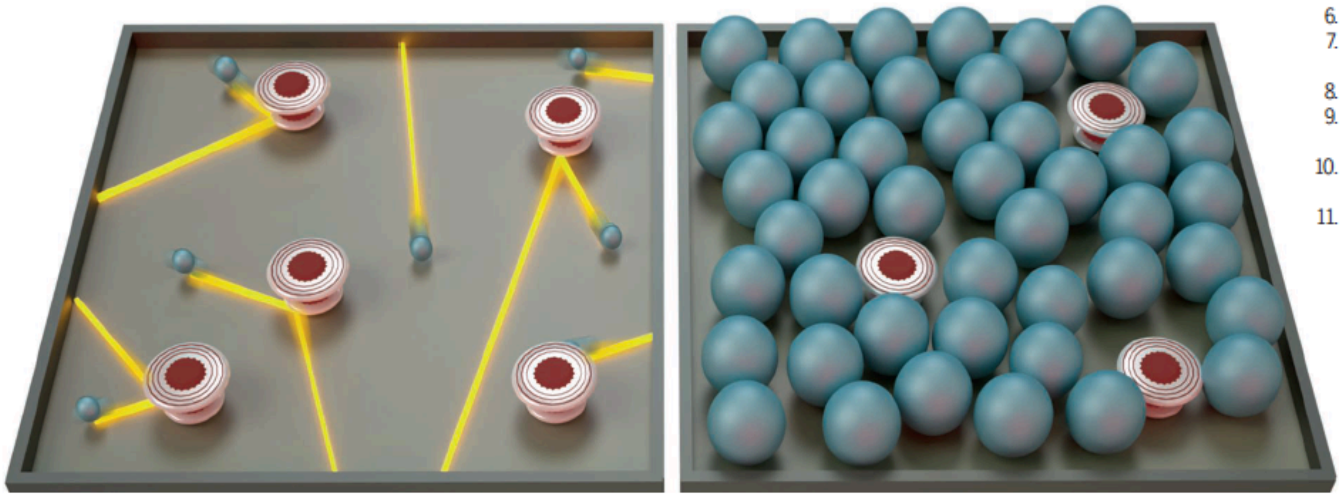
Hydrodynamics

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

Evidence for hydrodynamic electron flow in $PdCoO_2$

Philip J. W. Moll,[1,2,3] Pallavi Kushwaha,[3] Nabhanila Nandi,[3] Burkhard Schmidt,[3] Andrew P. Mackenzie[3,4*]

Experimental evidence that the resistance of restricted channels of the ultra-pure two-dimensional metal PdCoO2 has a large viscous contribution

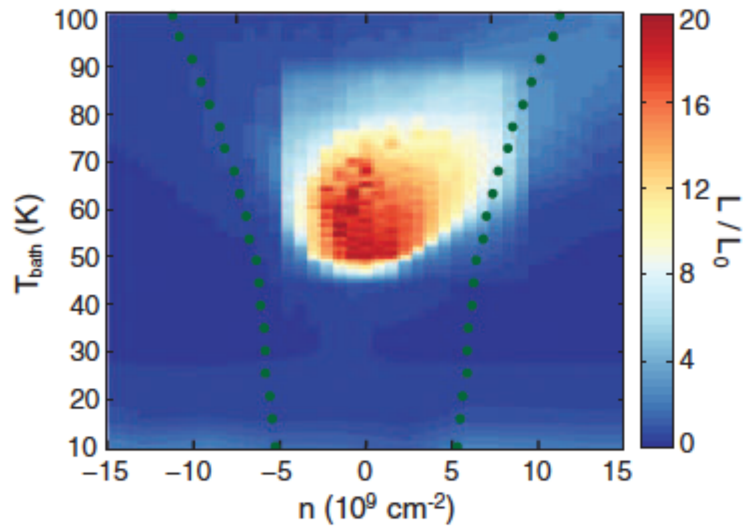
Negative local resistance caused by viscous electron backflow in graphene

D. A. Bandurin,[1] I. Torre,[2] R. Krishna Kumar,[1,3] M. Ben Shalom,[1,4] A. Tomadin,[5] A. Principi,[6] G. H. Auton,[4] E. Khestanova,[1,4] K. S. Novoselov,[4] I. V. Grigorieva,[1] L. A. Ponomarenko,[1,3] A. K. Geim,[1*] M. Polini[7*]

ELECTRON TRANSPORT

Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene

Jesse Crossno,[1,2] Jing K. Shi,[1] Ke Wang,[1] Xiaomeng Liu,[1] Achim Harzheim,[1] Andrew Lucas,[1] Subir Sachdev,[1,3] Philip Kim,[1,2*] Takashi Taniguchi,[4] Kenji Watanabe,[4] Thomas A. Ohki,[5] Kin Chung Fong[5*]



High mobility wires

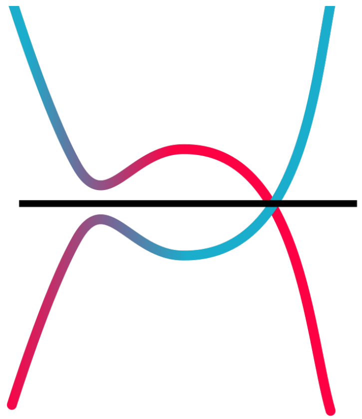
PHYSICAL REVIEW B VOLUME 51, NUMBER 19 15 MAY 1995-I

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.

A Better Weyl Semimetals

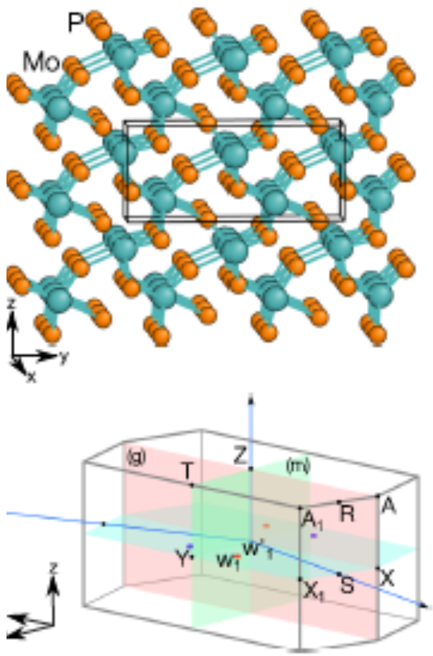


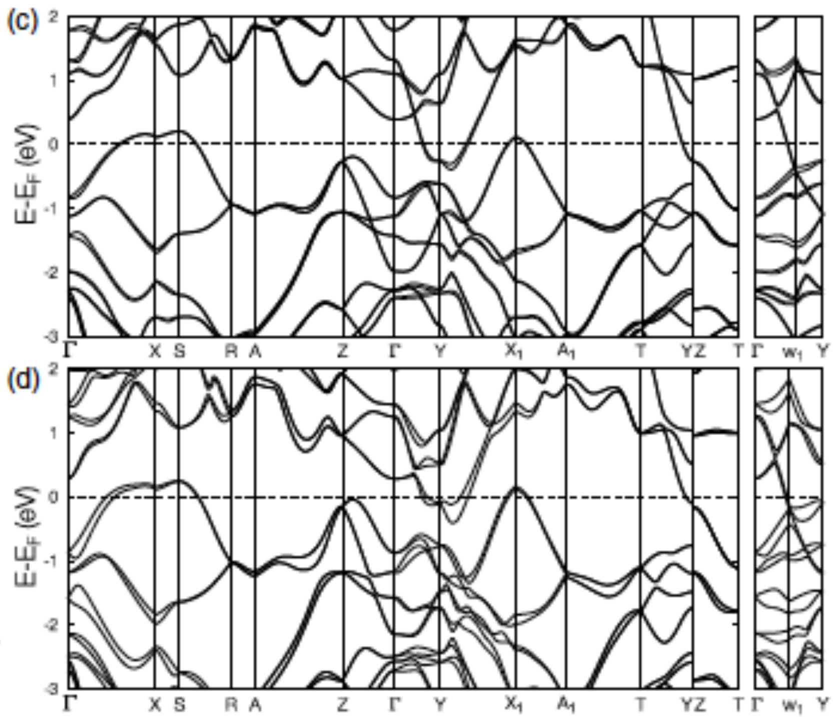
WP_2 protected Weyl

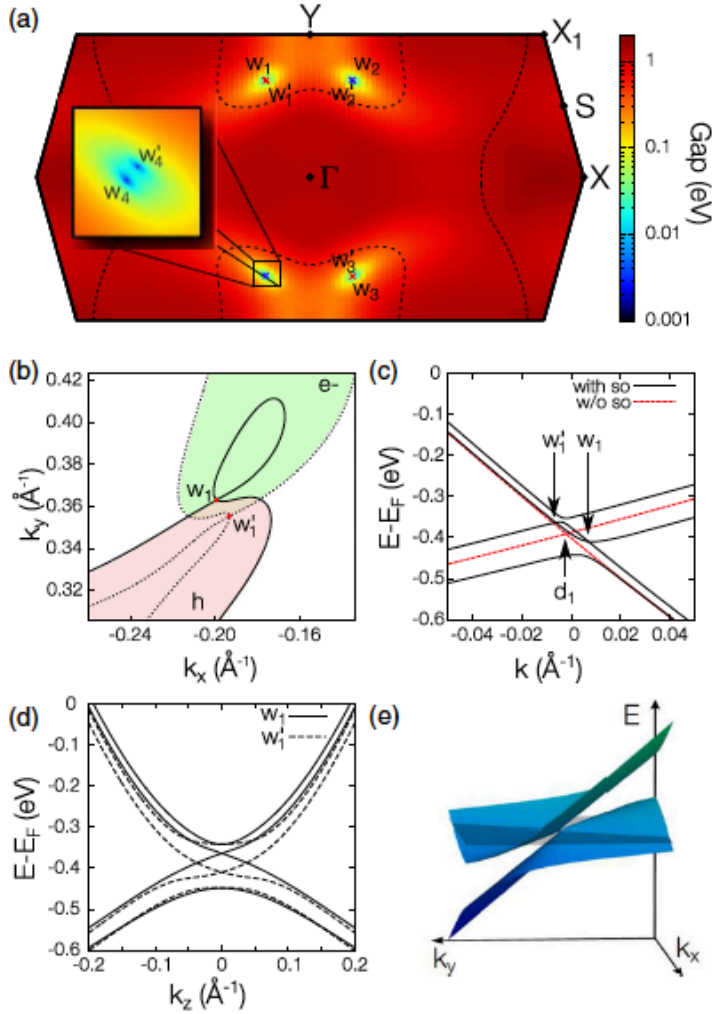
PRL 117, 066402 (2016) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2016

Robust Type-II Weyl Semimetal Phase in Transition Metal Diphosphides XP_2 (X = Mo, W)

G. Autès,[1,2] D. Gresch,[3] M. Troyer,[3] A. A. Soluyanov,[3,4] and O. V. Yazyev[1,2]

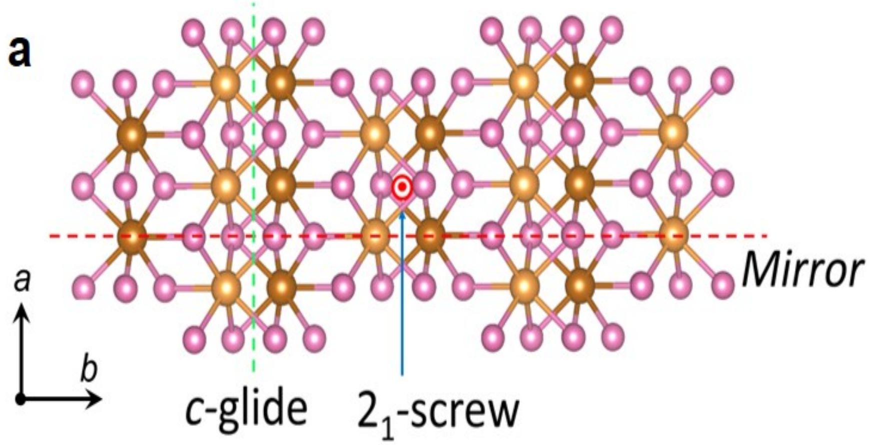


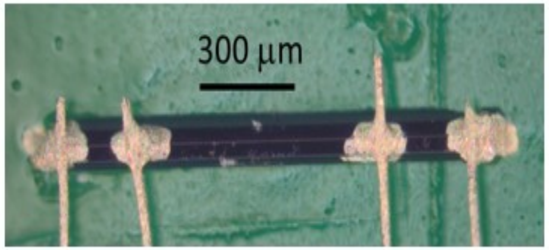


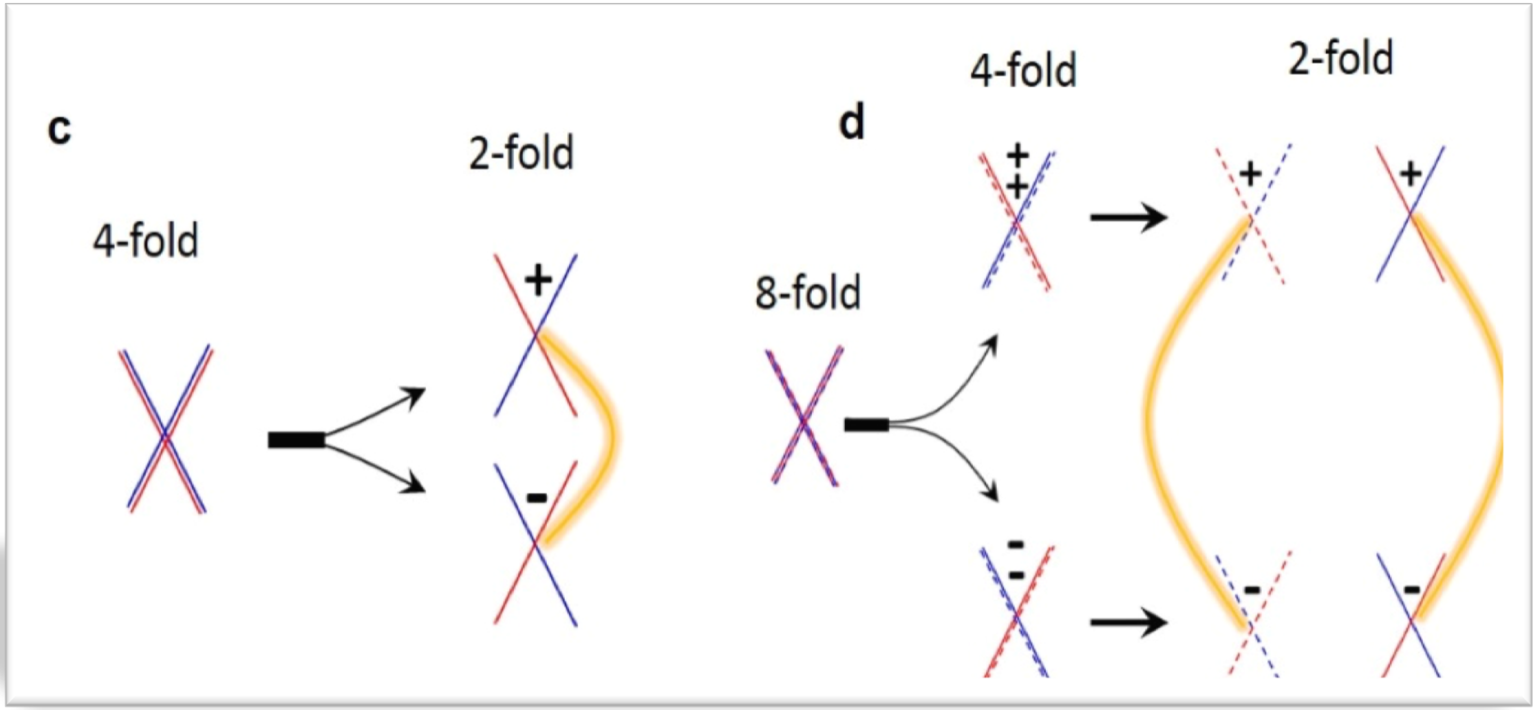


Prediction: G. Autès, et al.; Phys. Rev. Lett. 117 (2016) 066402

WP_2 protected Weyl

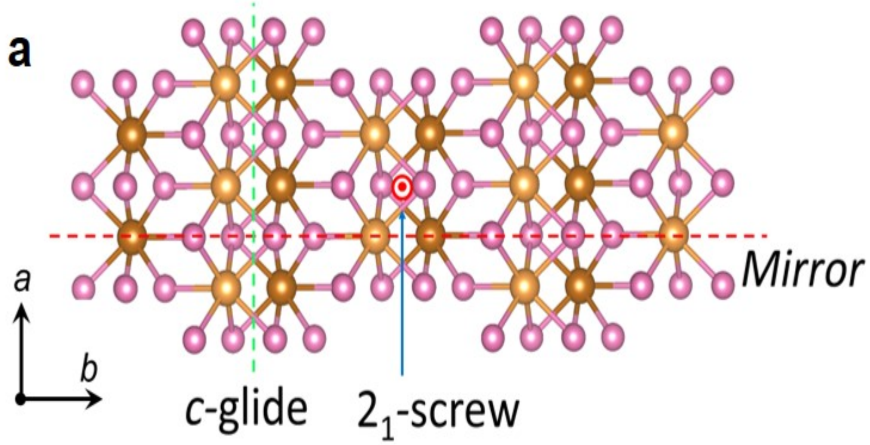


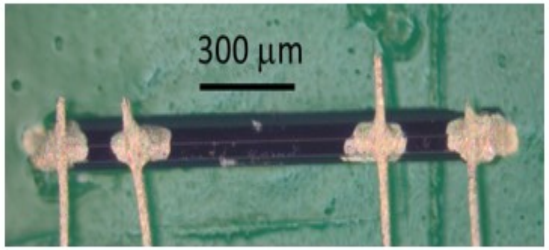


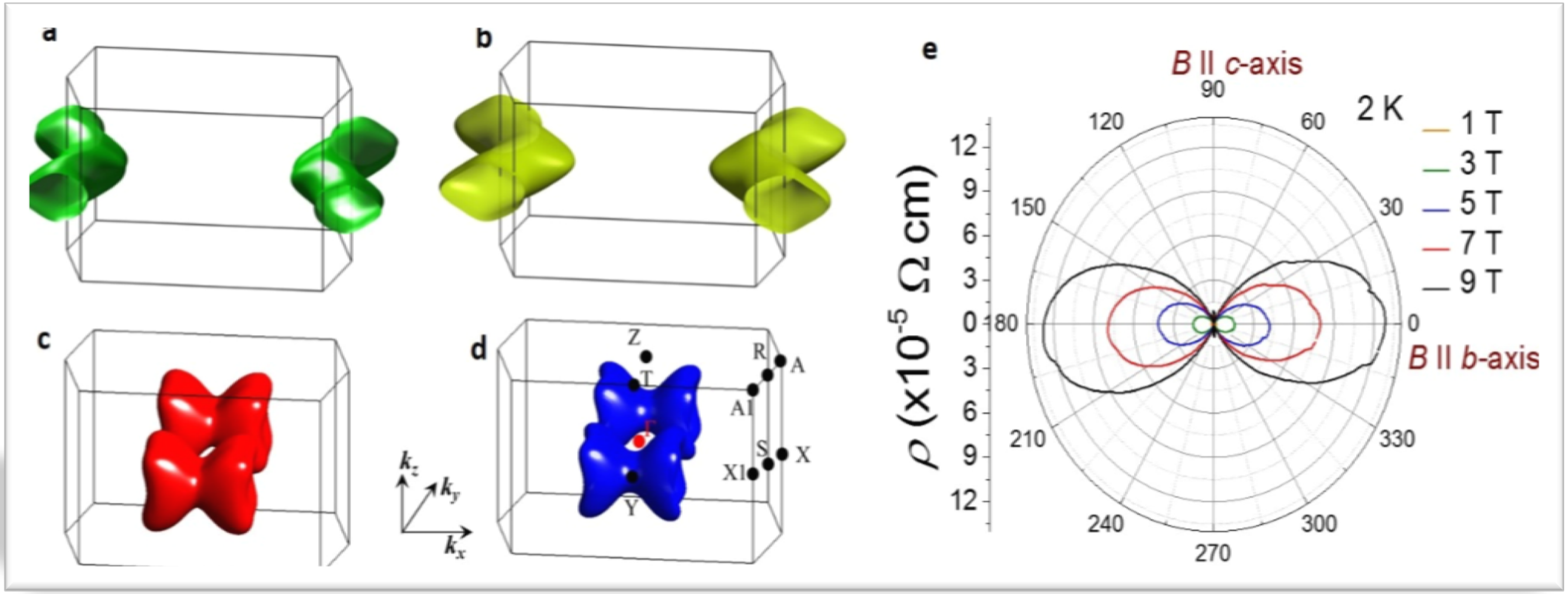


Prediction: G. Autès, et al.; Phys. Rev. Lett. 117 (2016) 066402 Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; **arXiv:1703.04527**

WP_2 protected Weyl

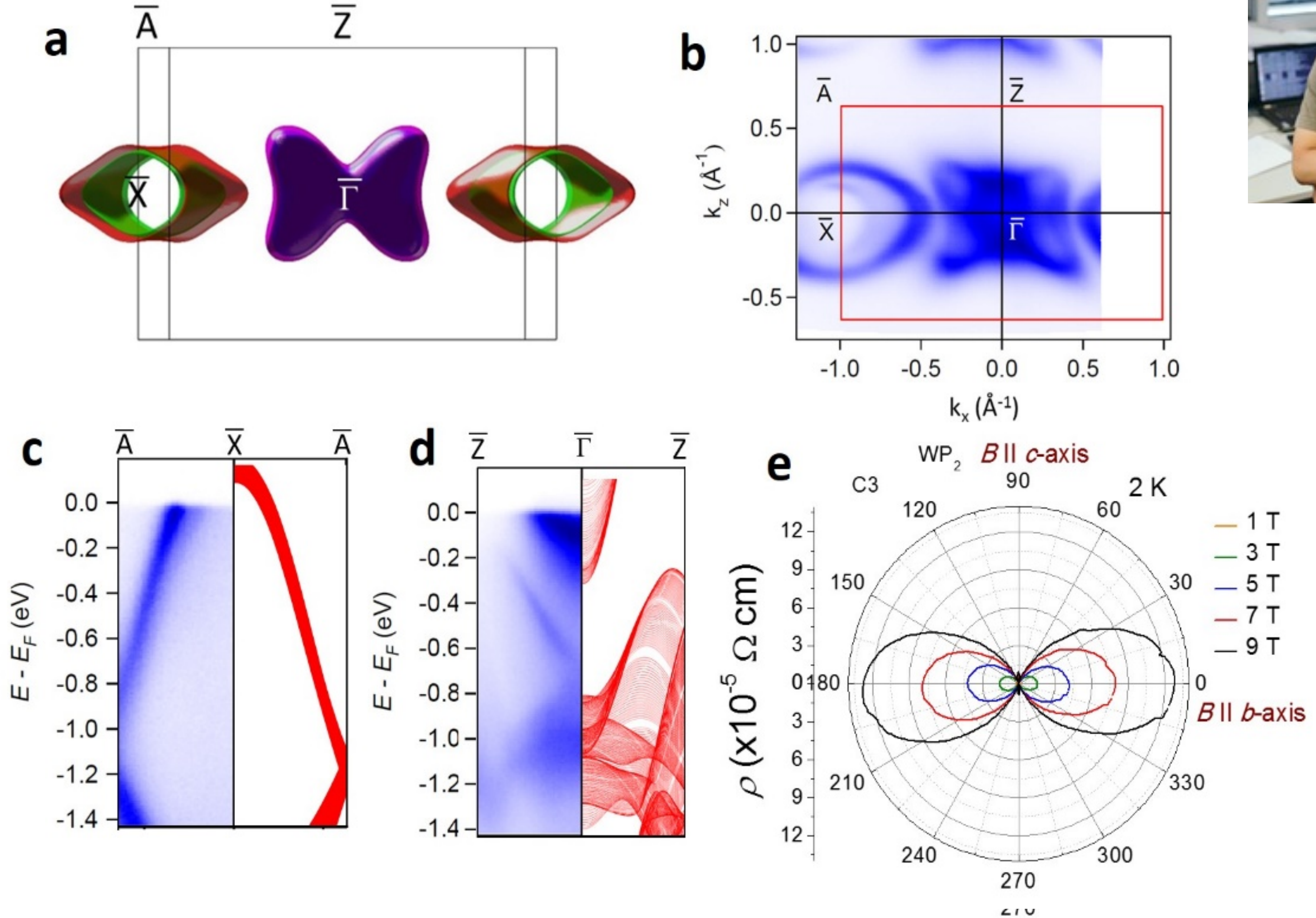






Prediction: G. Autès, et al.; Phys. Rev. Lett. 117 (2016) 066402 Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; **arXiv:1703.04527**

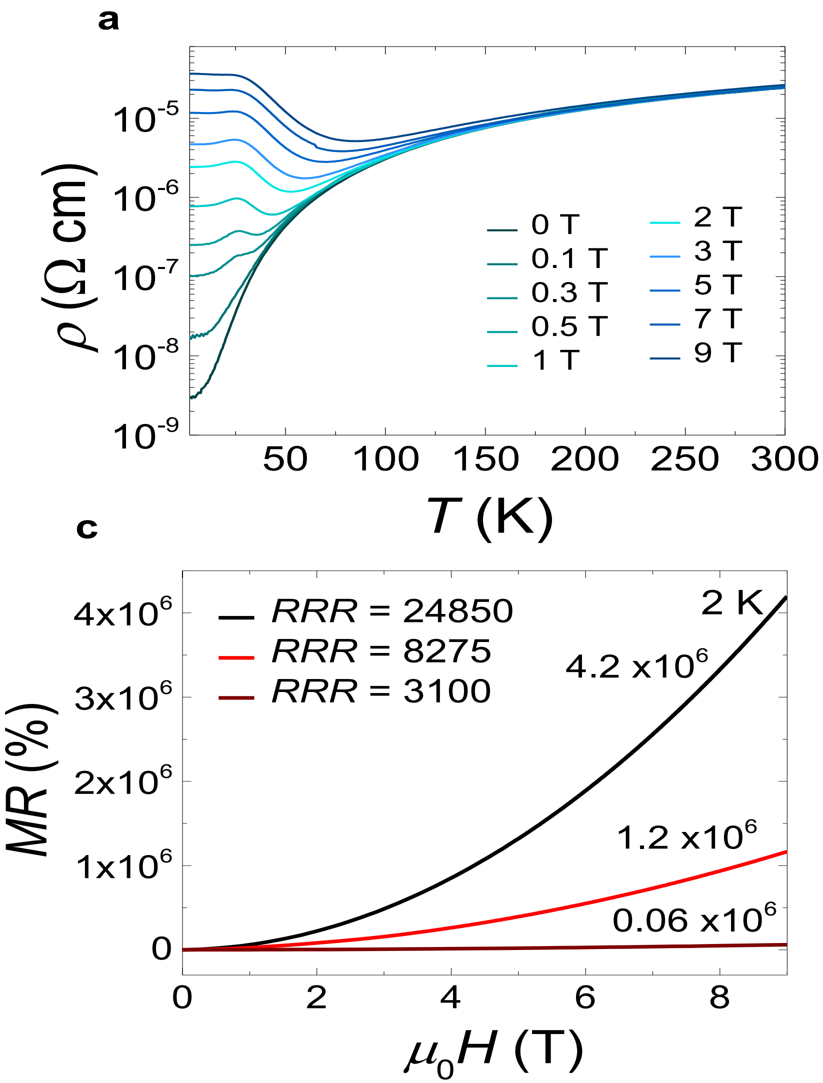
ARPES and the Band Structure

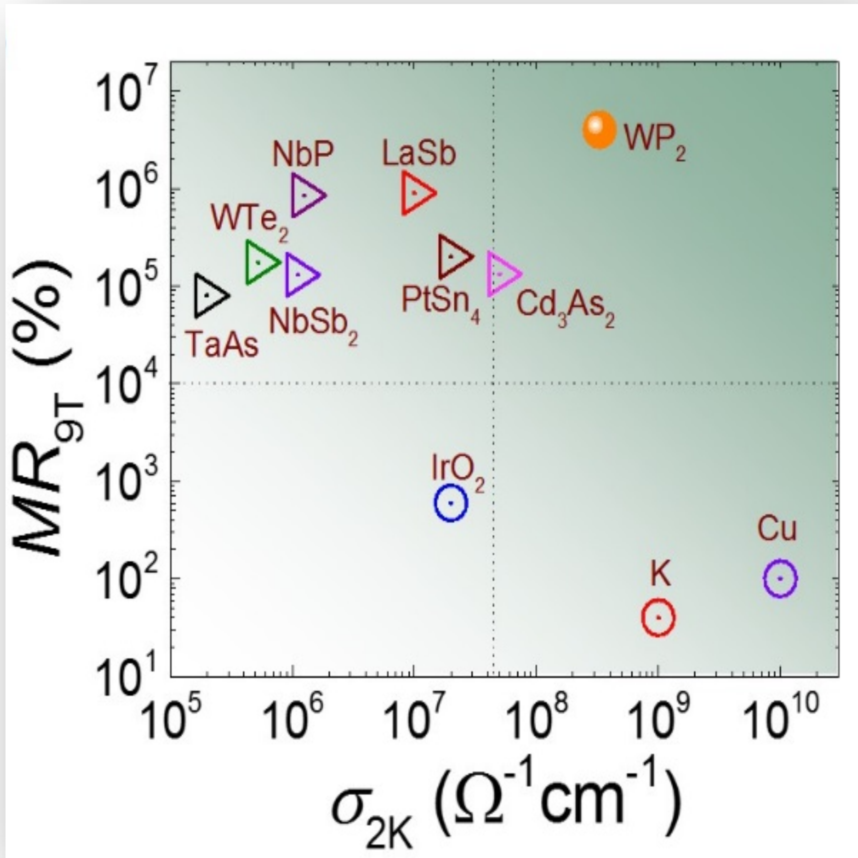


Photoemission, Nan Xu, Ming Shi, Paul Scherrer Institute, Swiss Light Source, CH-5232 Villigen PSI, Switzerland.
Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; arXiv:1703.04527

WP_2 protected Weyl

Magnetotransport in a novel Weyl WP_2

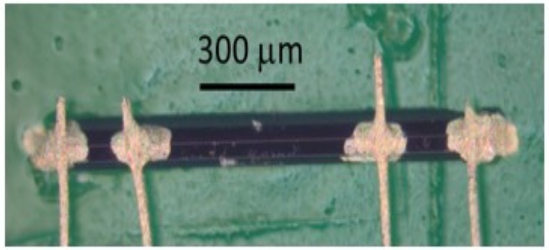




Prediction: G. Autès, et al.; Phys. Rev. Lett. 117 (2016) 066402 Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; **arXiv:1703.04527**

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

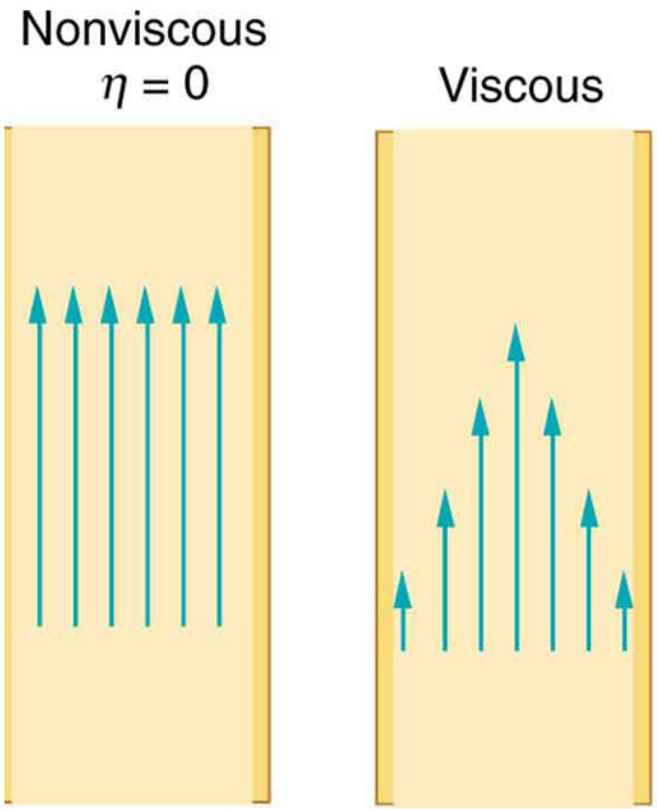
In the Navier-Stokes flow limit: $\rho = m^*/(e^2 n) \cdot 12\eta w^{-2}$

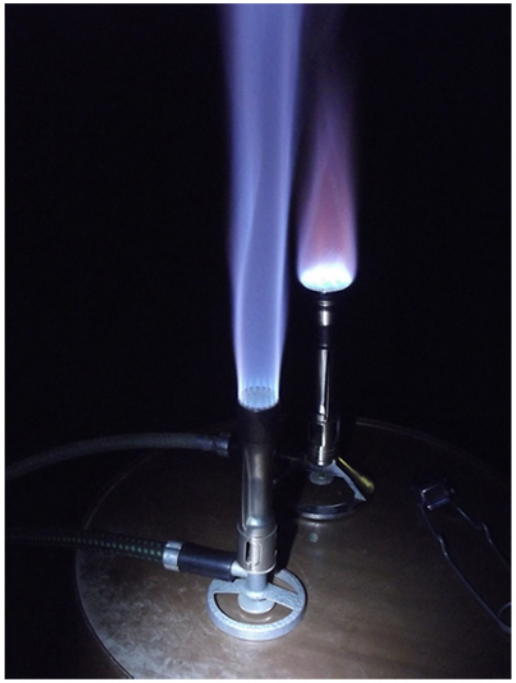
R. N. Gurzhy, A. N. Kalinenko, A. I. Kopeliovich, Hydrodynamic effects in the electrical conductivity of impure metals. *Sov. Physics-JETP*. **69**, 863–870 (1989).

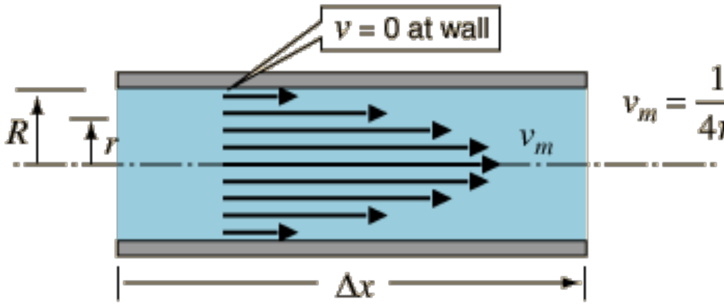
P. S. Alekseev, Negative magnetoresistance in viscous flow of two-dimensional electrons. *Phys. Rev. Lett.* **117** (2016).

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

Water, Gas or Electrons







$$v_m = \frac{1}{4\eta}\frac{\Delta P}{\Delta x}R^2$$

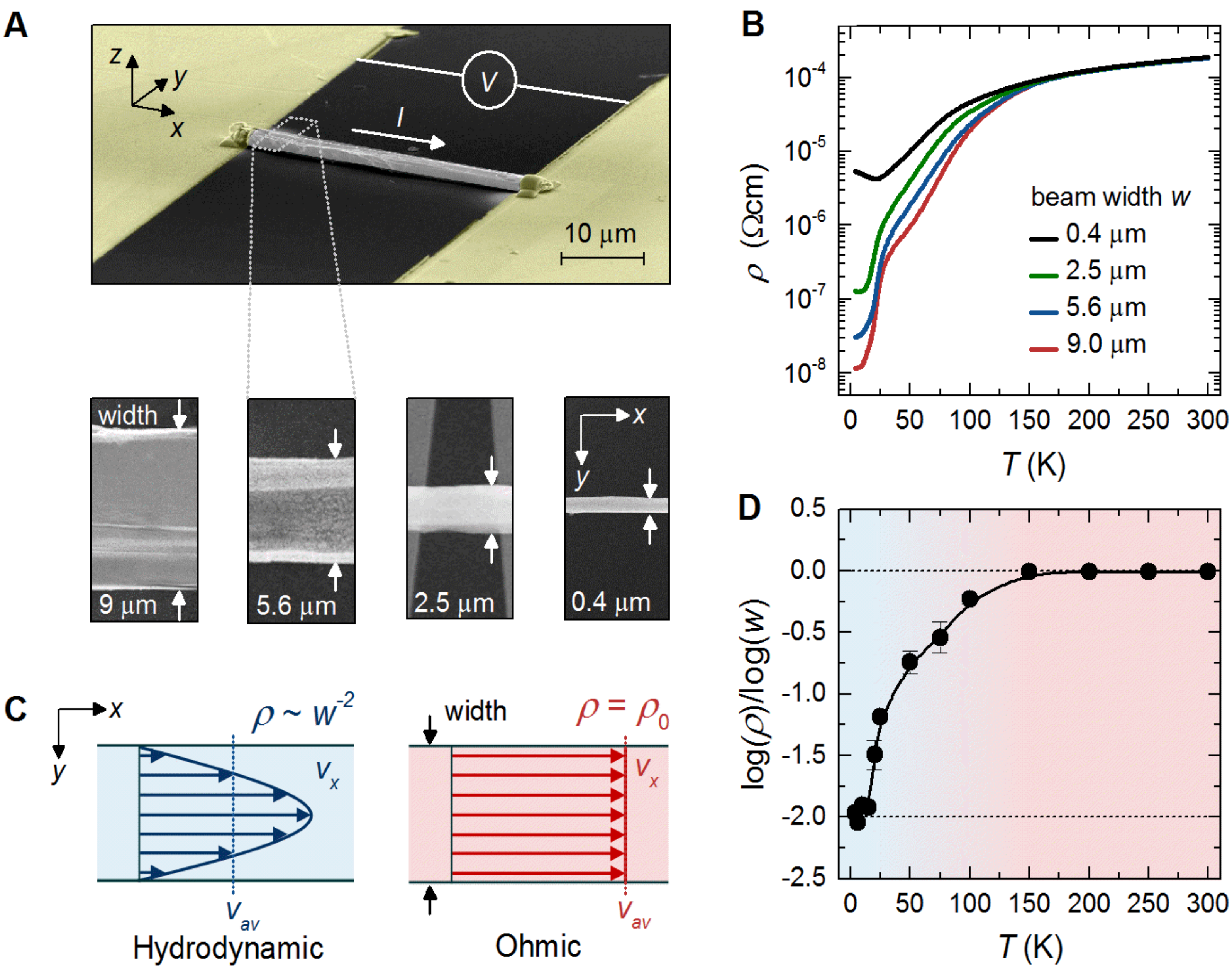
$\frac{\Delta P}{\Delta x}$ = pressure gradient

η = viscosity

$$v(r) = v_m\left(1 - \frac{r^2}{R^2}\right)$$

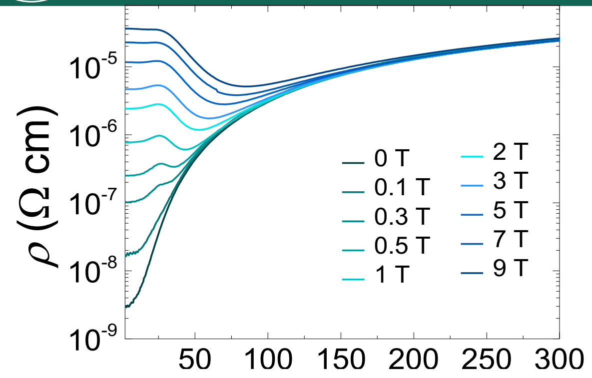
Velocity profile

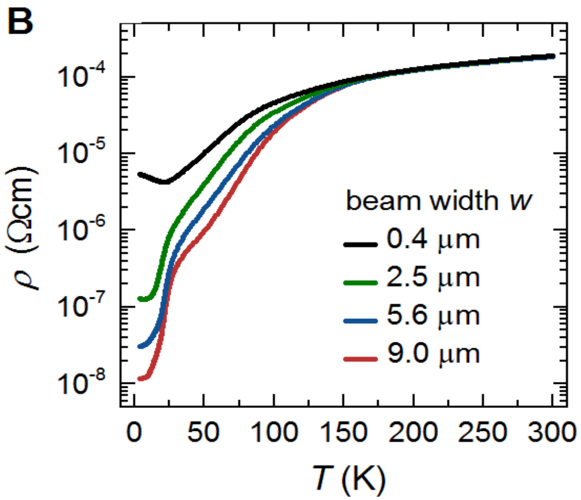
Hydrodynamic flow

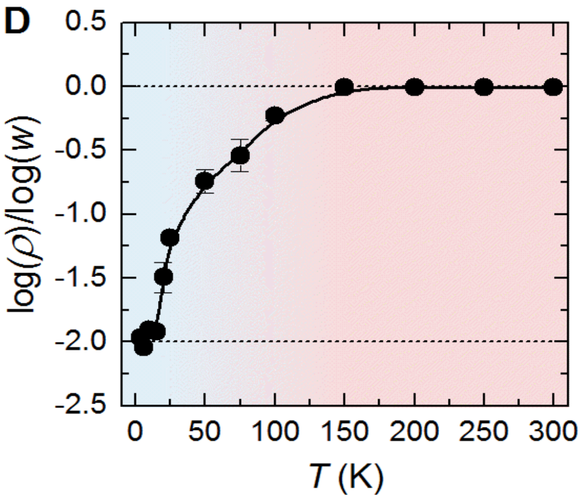


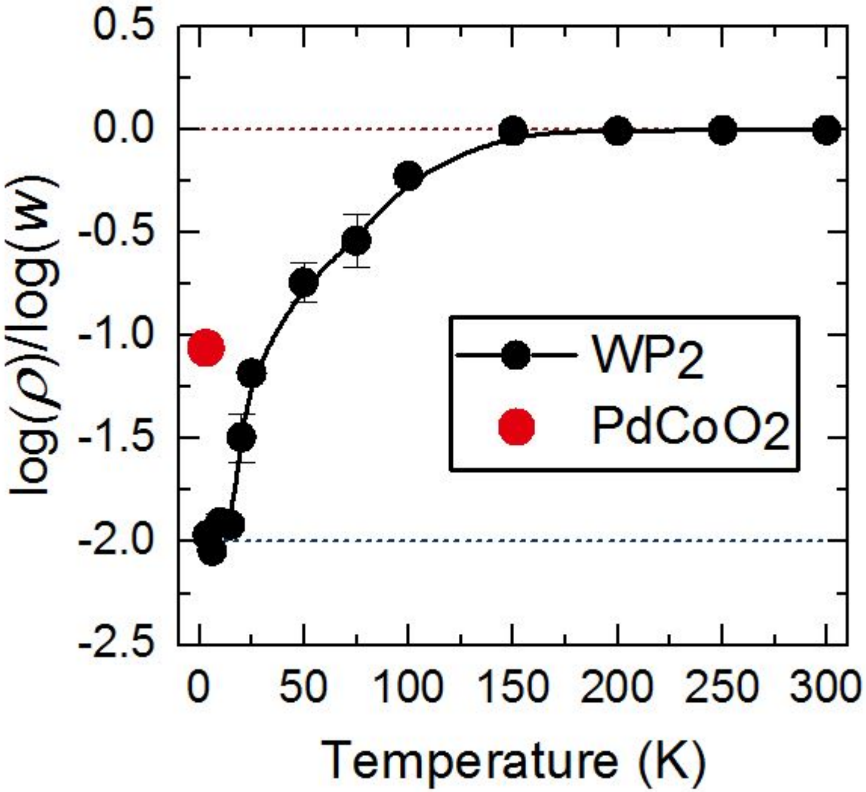
J. Gooth et al. submitted, arXiv:1706.05925

Hydrodynamic flow





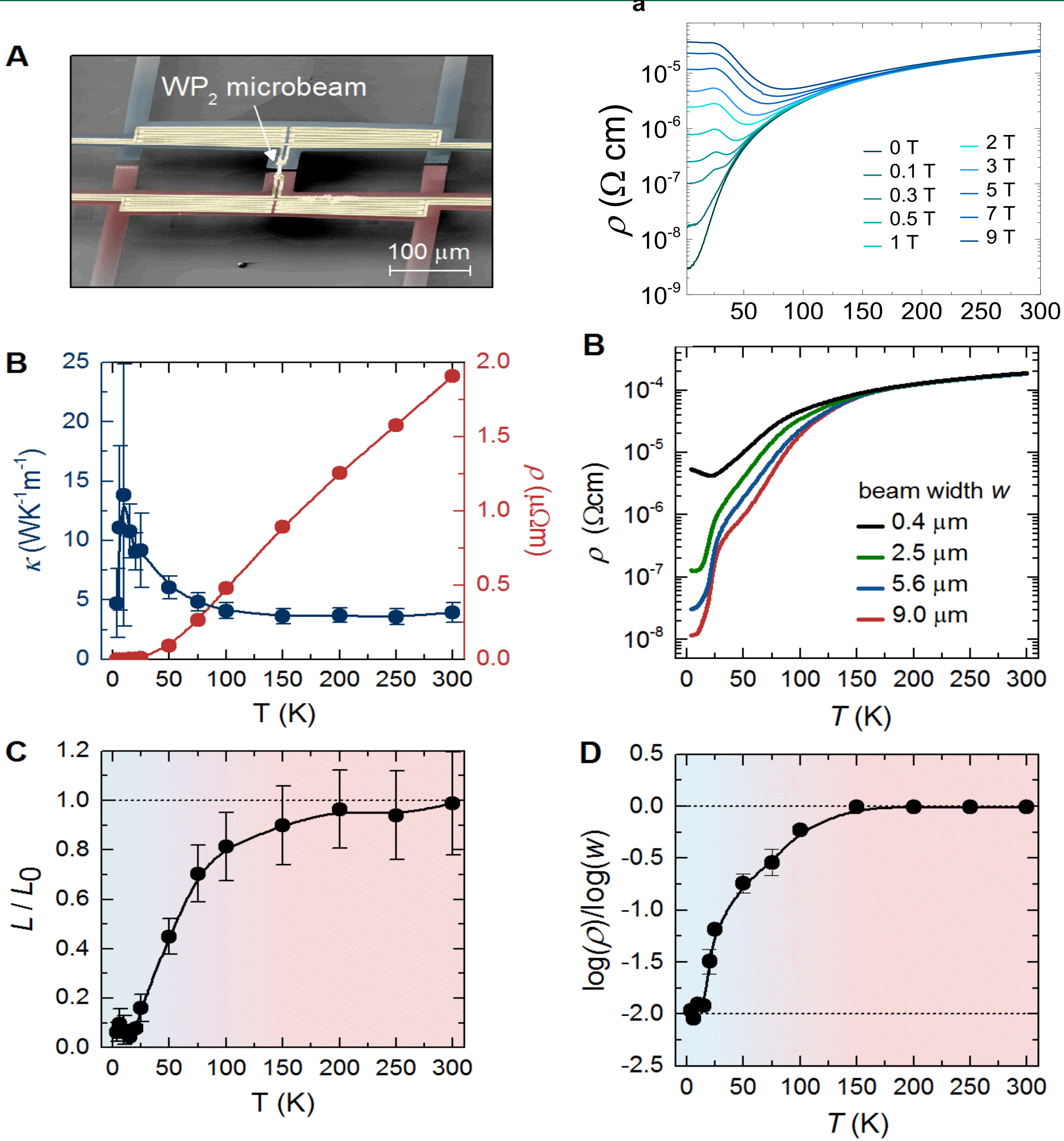




P. J. W. Moll *et al.*, *Science* 10.1126/science.aac8385 (2016).

J. Gooth et al. 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

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

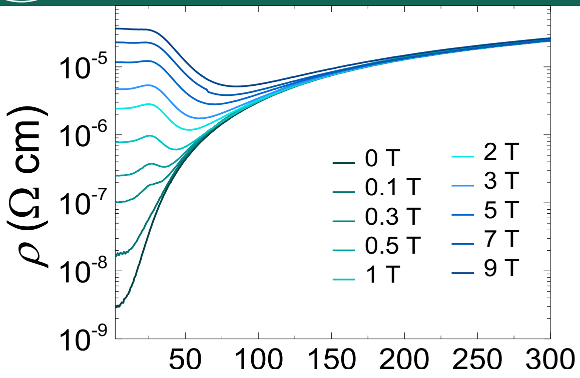
- a strong violation of the

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

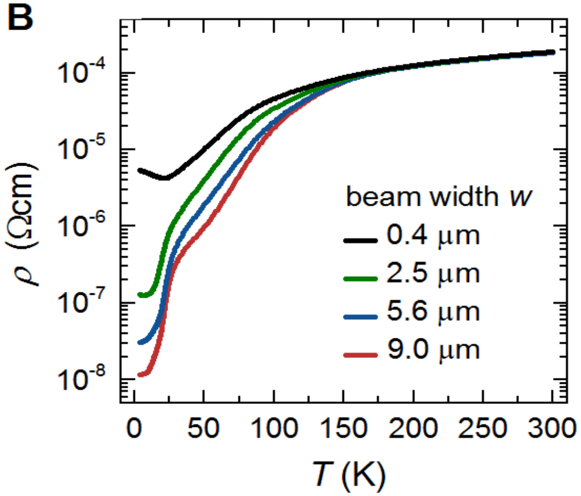
J. Gooth et al. submitted, arXiv:1706.05925

Hydrodynamic flow

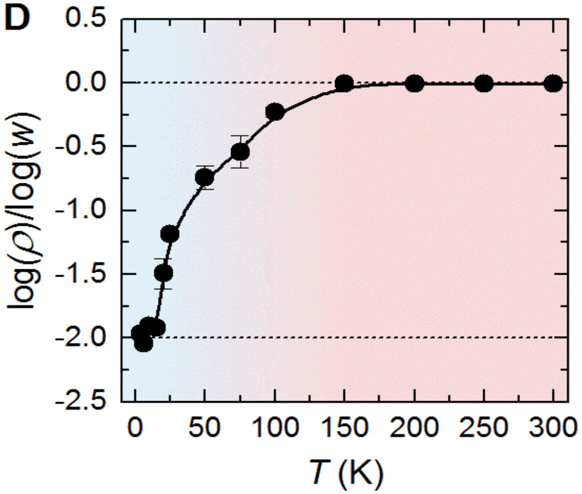
a



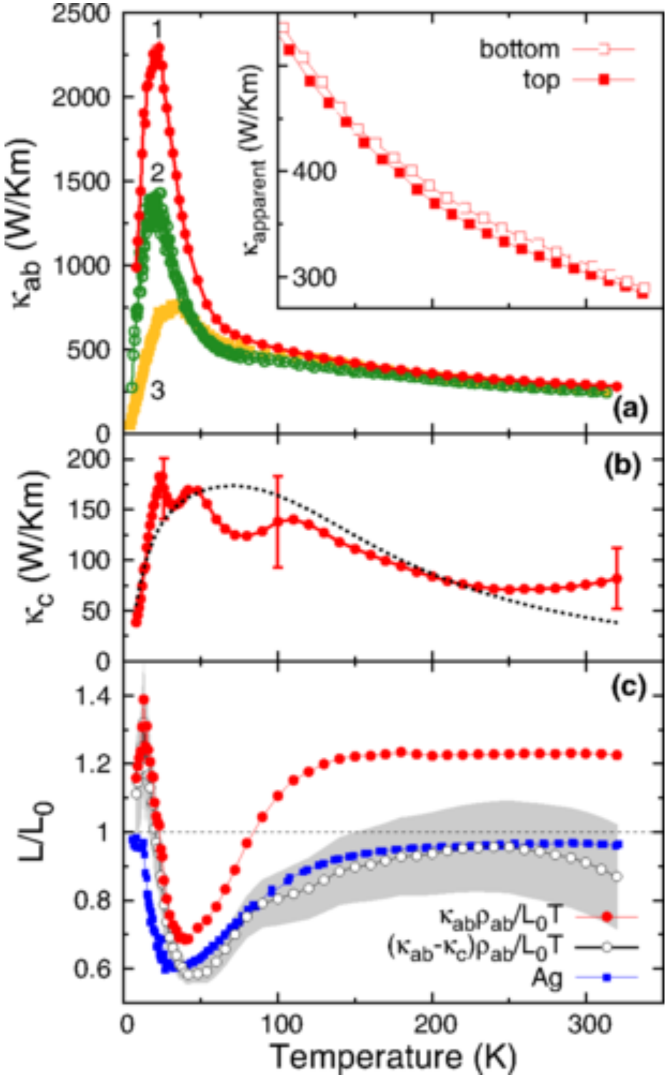
B

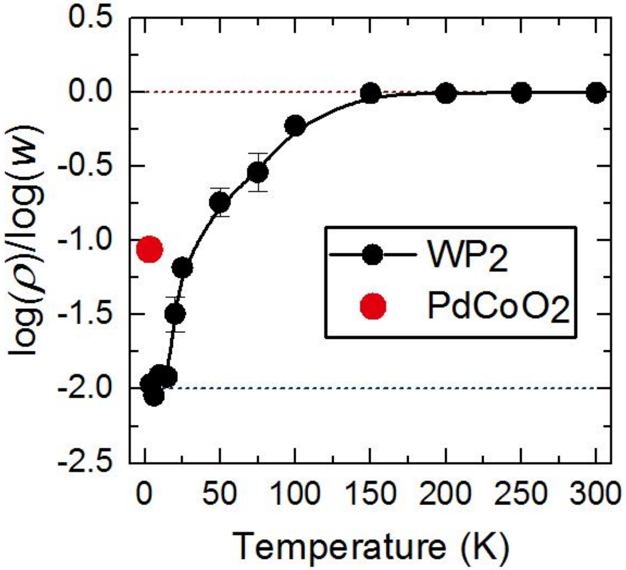


D



$PdCoO_2$





P. J. W. Moll *et al.*, *Science* 10.1126/science.aac8385 (2016)

R. Daou, et al. and Antoine Maignan, Phys. Rev. B 91, 041113(R) (2015)

J. Gooth et al. submitted, arXiv:1706.05925

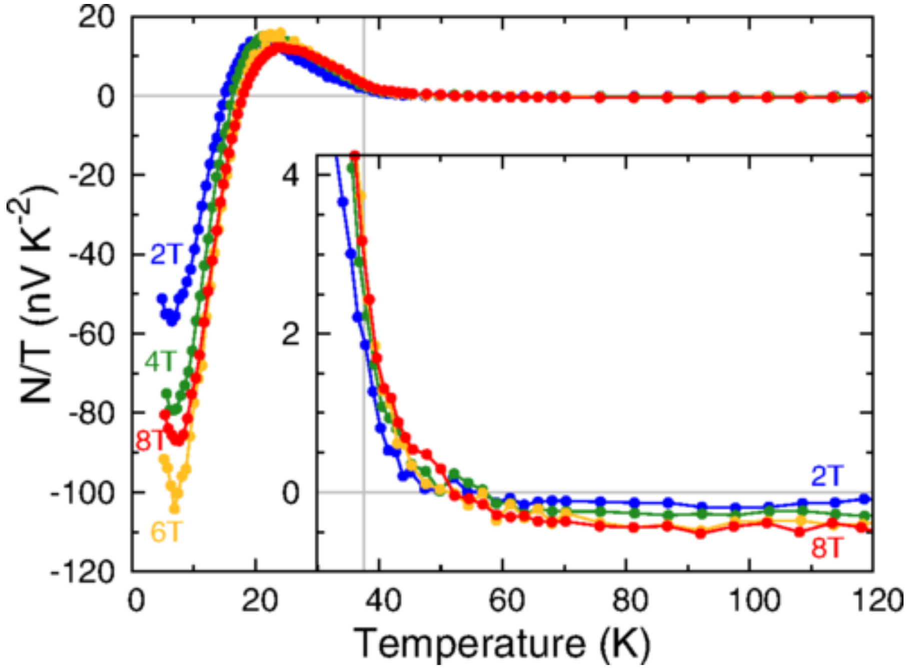
Giant Nernst – Topology - Hydrodynamic

Rep. Prog. Phys. **79** (2016) 046502 (23pp)
doi:10.1088/0034-4885/79/4/046502

Review

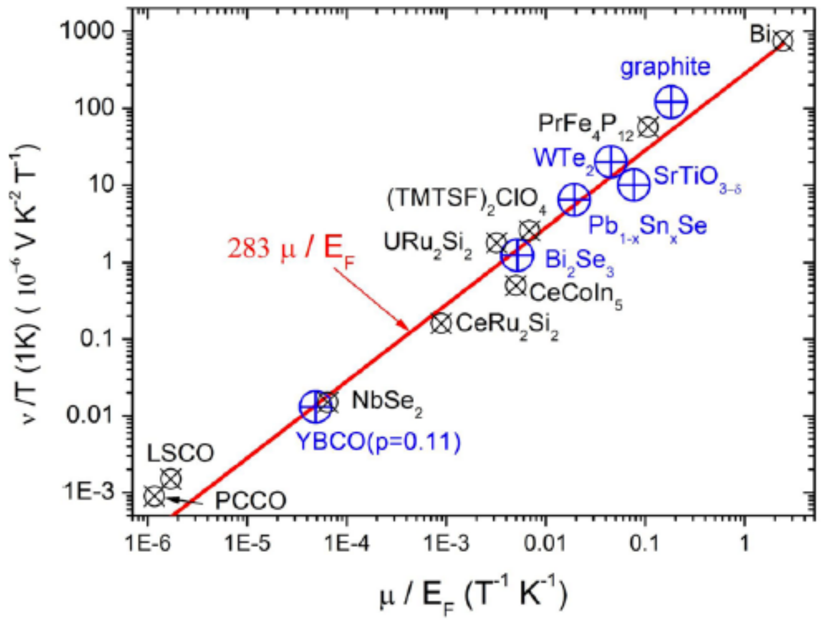
Nernst effect in metals and superconductors: a review of concepts and experiments

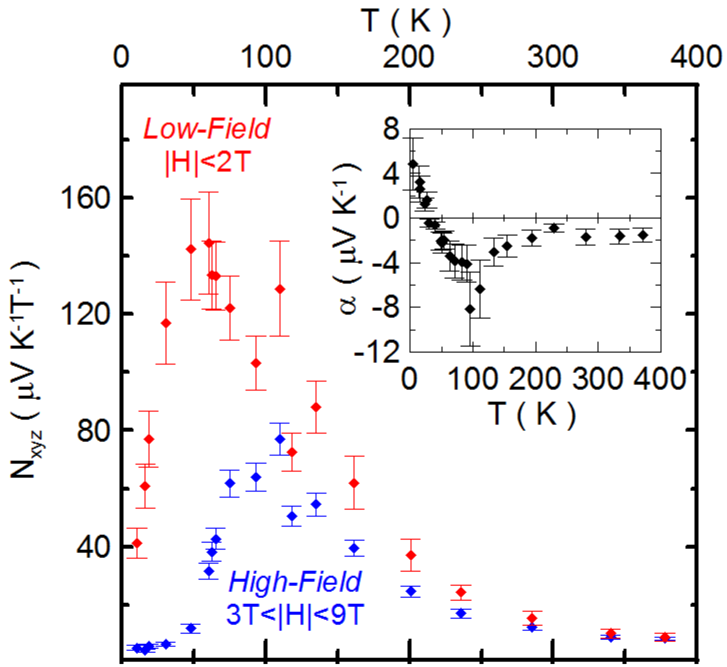
Kamran Behnia and Hervé Aubin



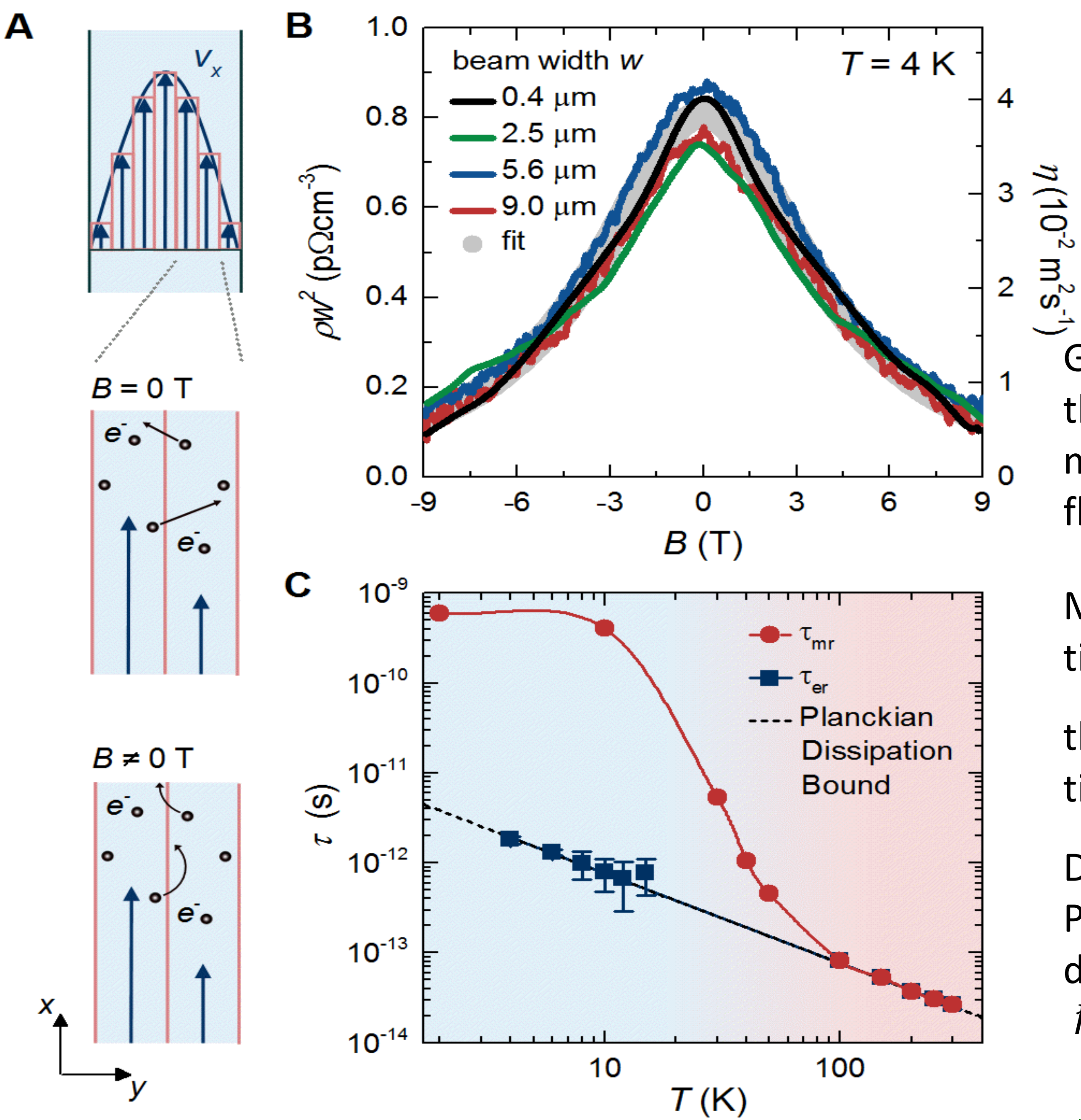
Ramzy Daou, Raymond Frésard, Sylvie Hébert, and Antoine Maignan, Phys. Rev. B 92, 245115 (2015)

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





Magnetohydrodynamics, Planckian bound of dissipation



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

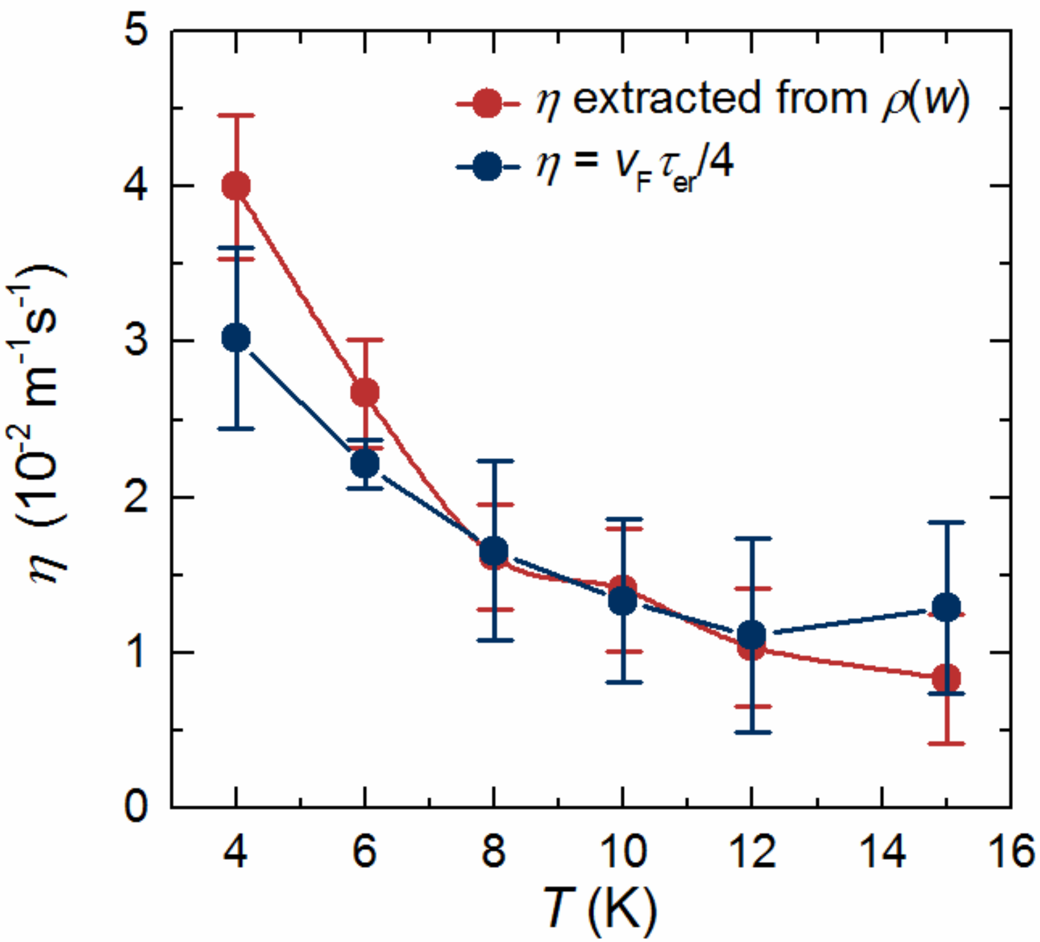
Momentum relaxation times t_{mr}

thermal energy relaxation times t_{er},

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

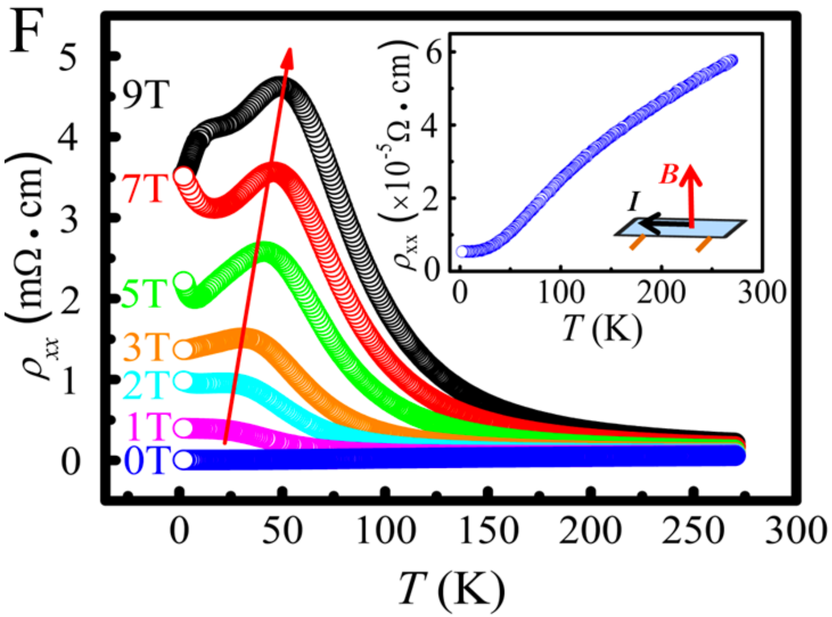
J. Gooth et al. submitted, arXiv:1706.05925

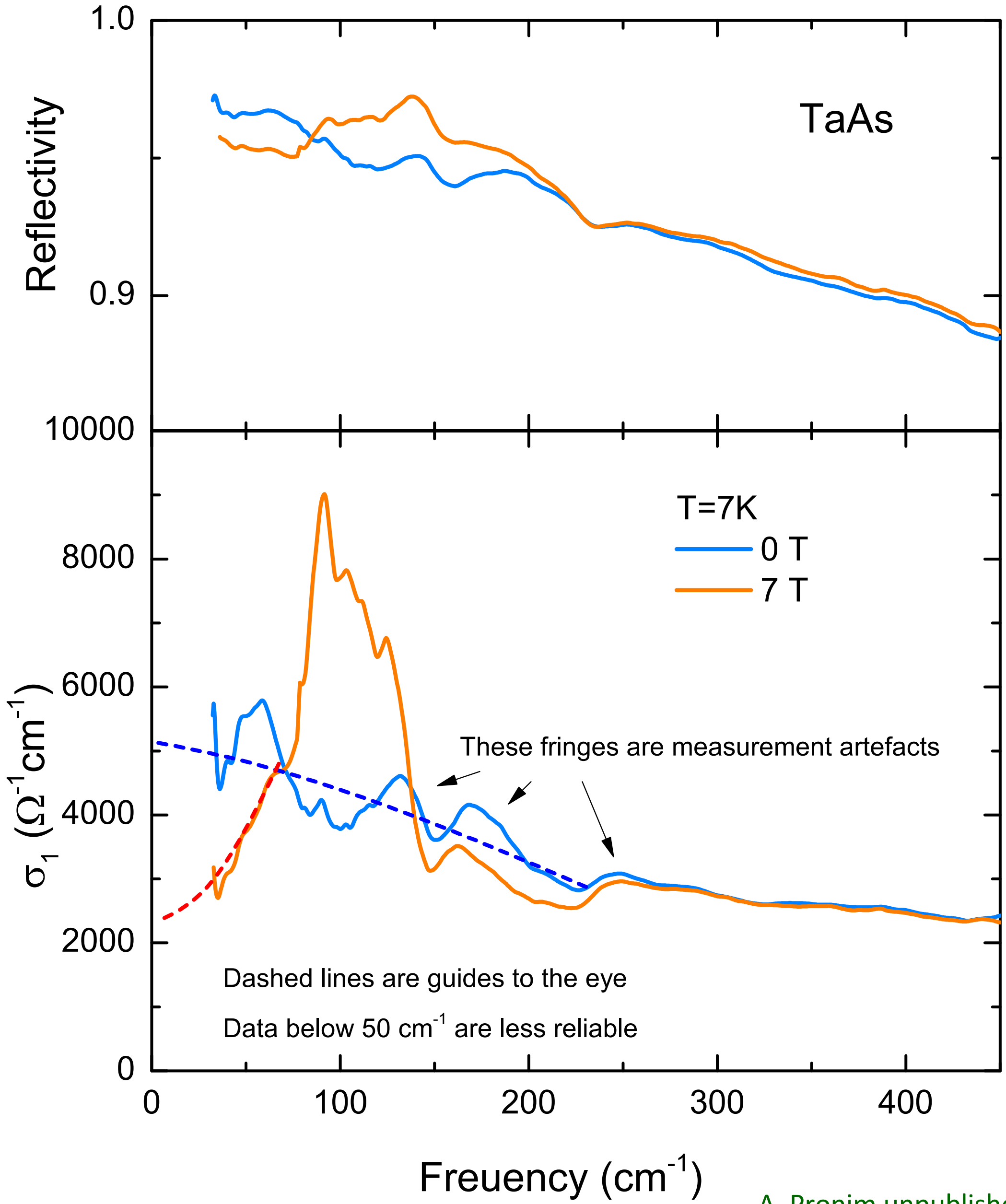
Viscosity of the electron fluid in WP_2



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

TaAs



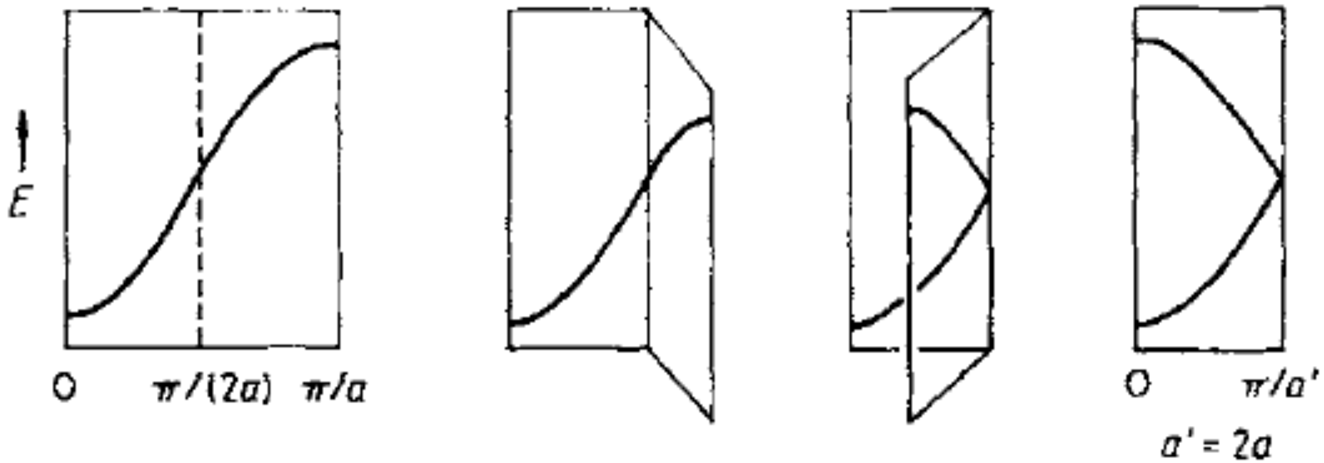


Huang et al. Phys. Rev. X 5, 031023 (2015)

A. Pronim unpublished

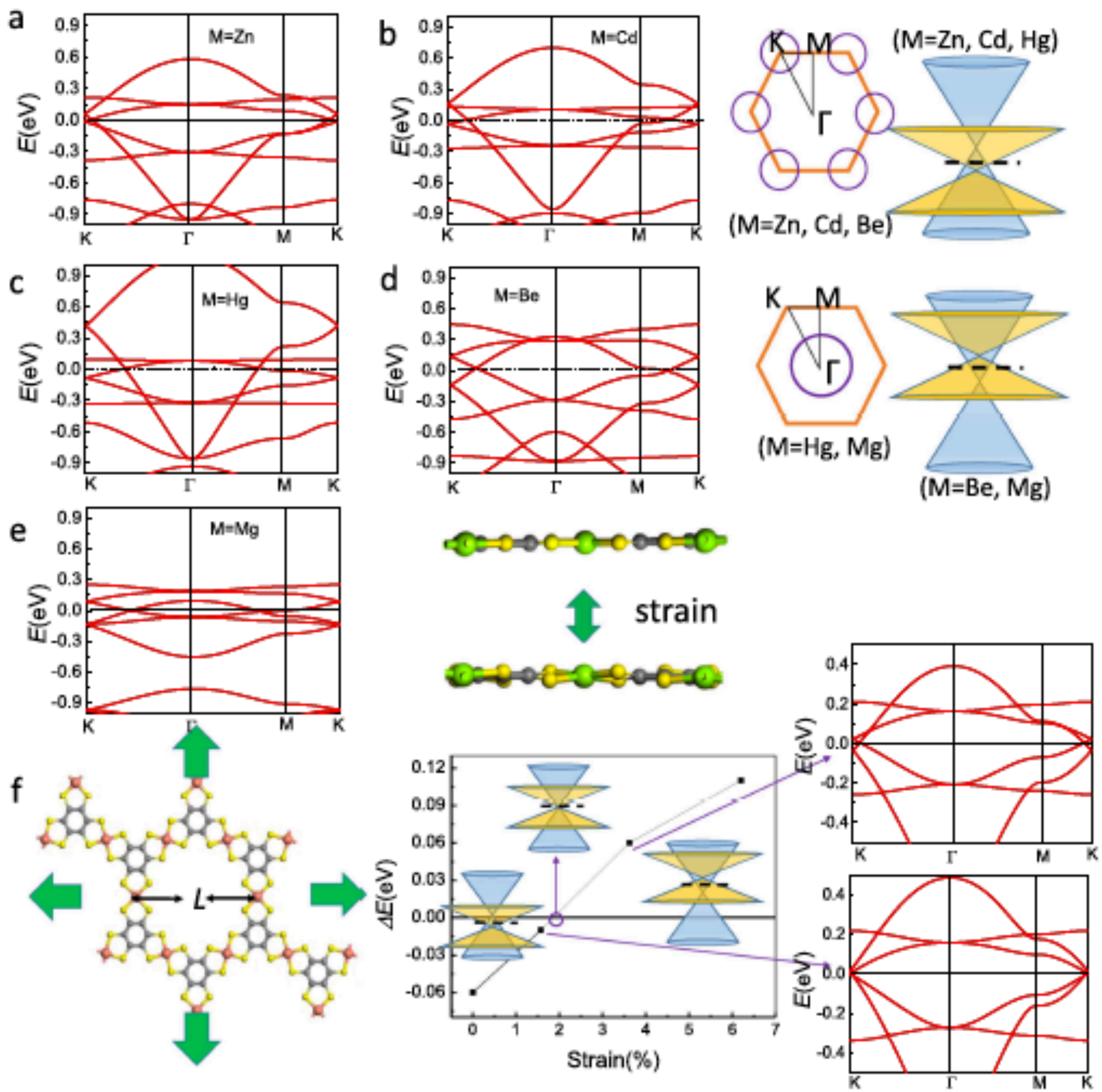
Design scheme: Dirac and Weyl

- Semimetal
- Band inversion – e.g. inert pair effect
- Crossing band due to enforced degeneration
- New quantum effects – electron liquid



Hoffmann Angewandte. Chem. 26 (1987) 846

Conetronics in 2D Metal-Organic Frameworks



Wu et al. 2D Mater. 4 (2017) 015015 arXiv:1606.04094

Topological Metals

Weyl Semimetals
Magnetically induced

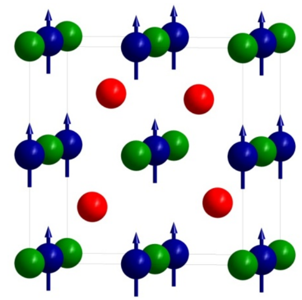
REPtBi ...multifunctional topologic insulators

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
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

H. R. Ott
ETH, Zurich, Switzerland

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

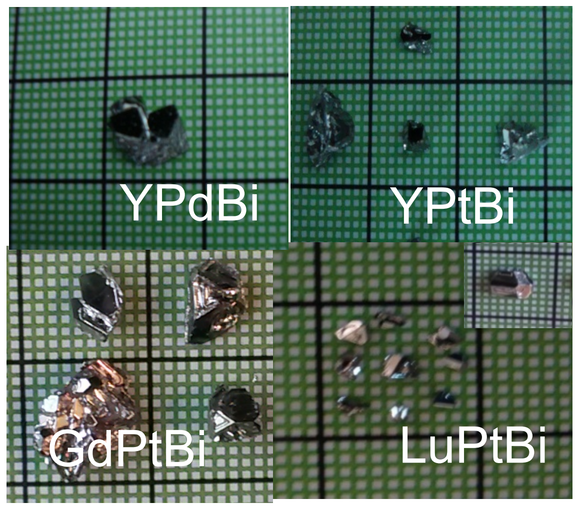


Multifunctional properties

- RE: Gd, 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**

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

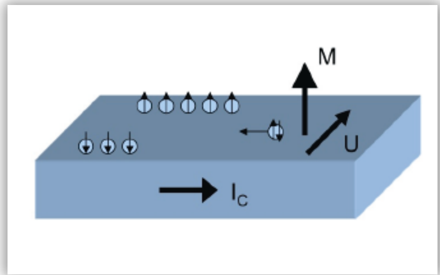


S. Chadov et al., Nat. Mater. 9, 541 (2010).
H. Lin et al., Nat. Mater. 9, 546 (2010).

Weyl semimetals

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

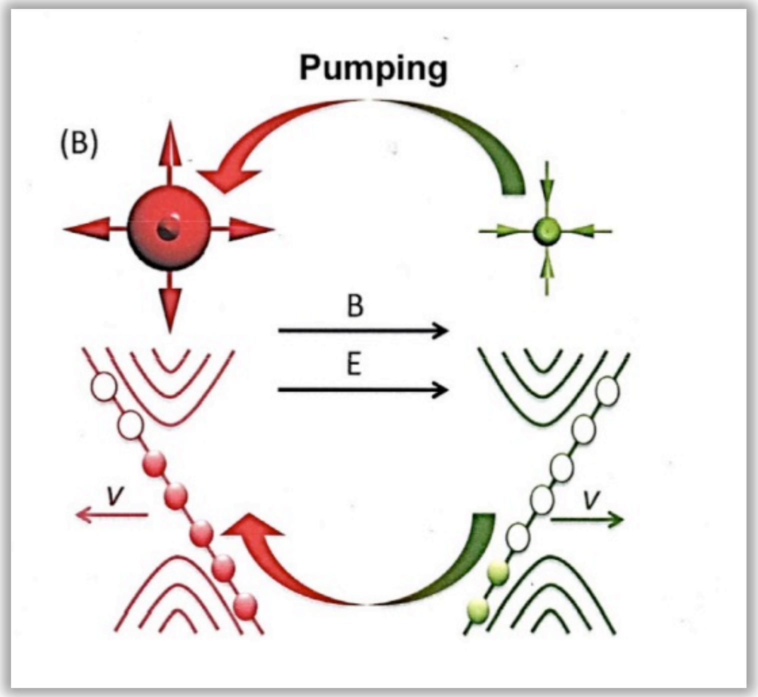
1. Intrinsic anomalous Hall effect



2. Chiral anomaly

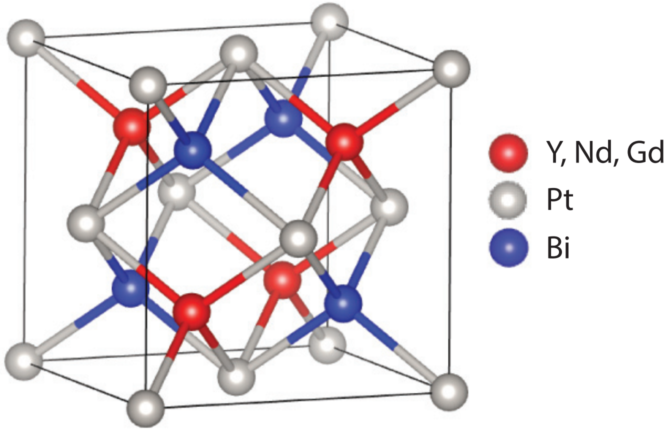
$$\partial_\mu j^\mu_\chi = -\chi \frac{e^3}{4\pi^2\hbar^2} \boldsymbol{E} \cdot \boldsymbol{B}$$

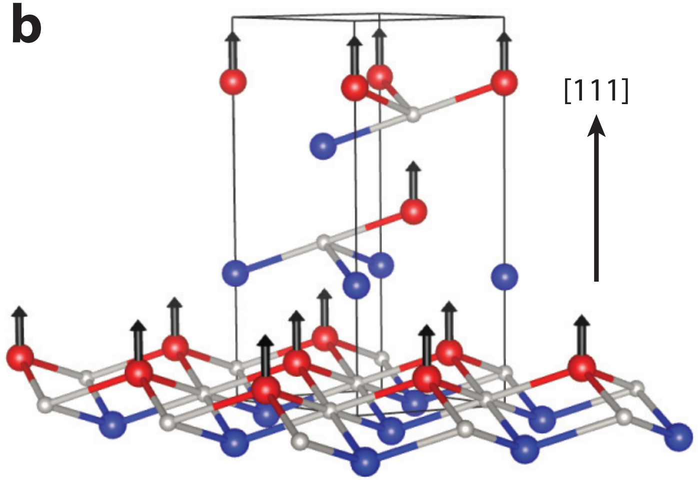
$$\sigma_a = \frac{e^3 v_f^3}{4\pi^2 \hbar \mu^2 c} B^2,$$

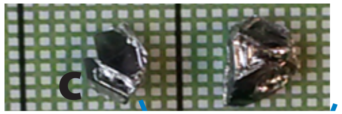


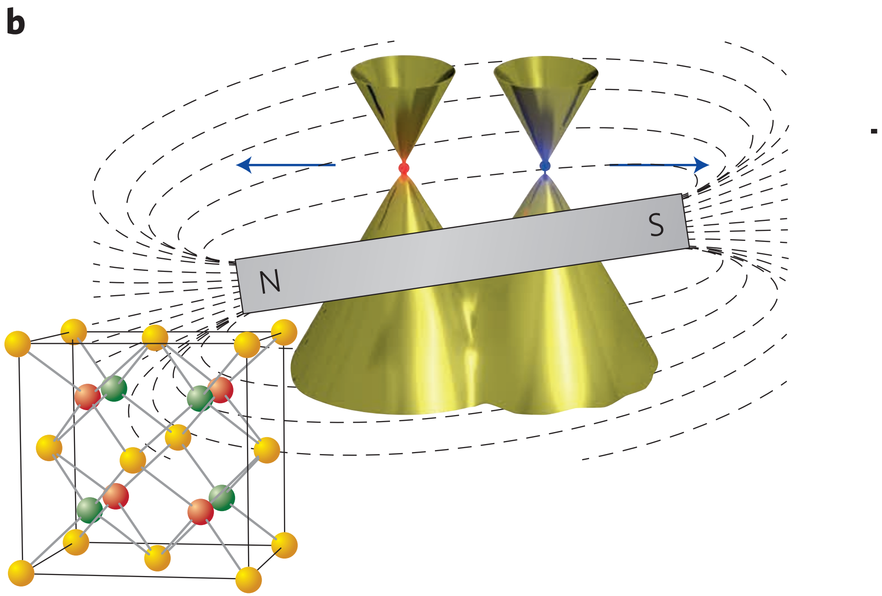
S. L. Adler, Phys. Rev. 177, 2426 (1969)
J. S. Bell and R. Jackiw, Nuovo Cim. A60, 47 (1969)
AA Zyuzin, AA Burkov - Physical Review B (2012)
AA Burkov, L Balents, PRL 107 12720 (2012)

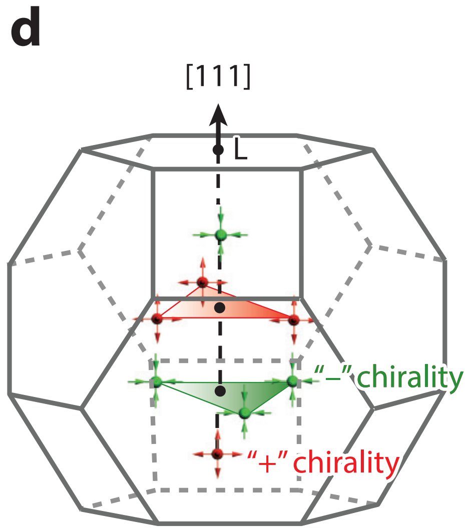
Weyl GdPtBi in a magnetic field

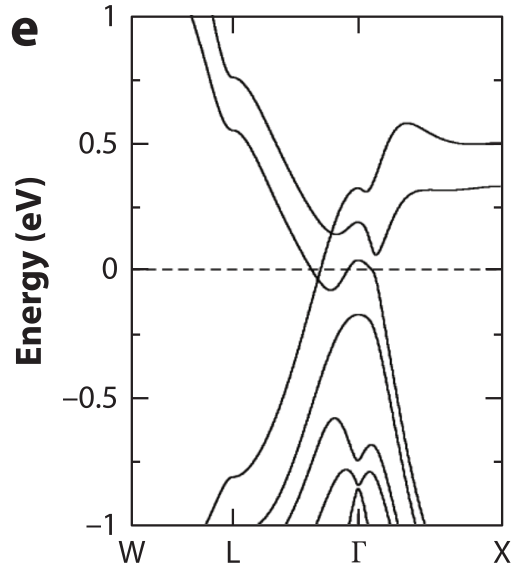








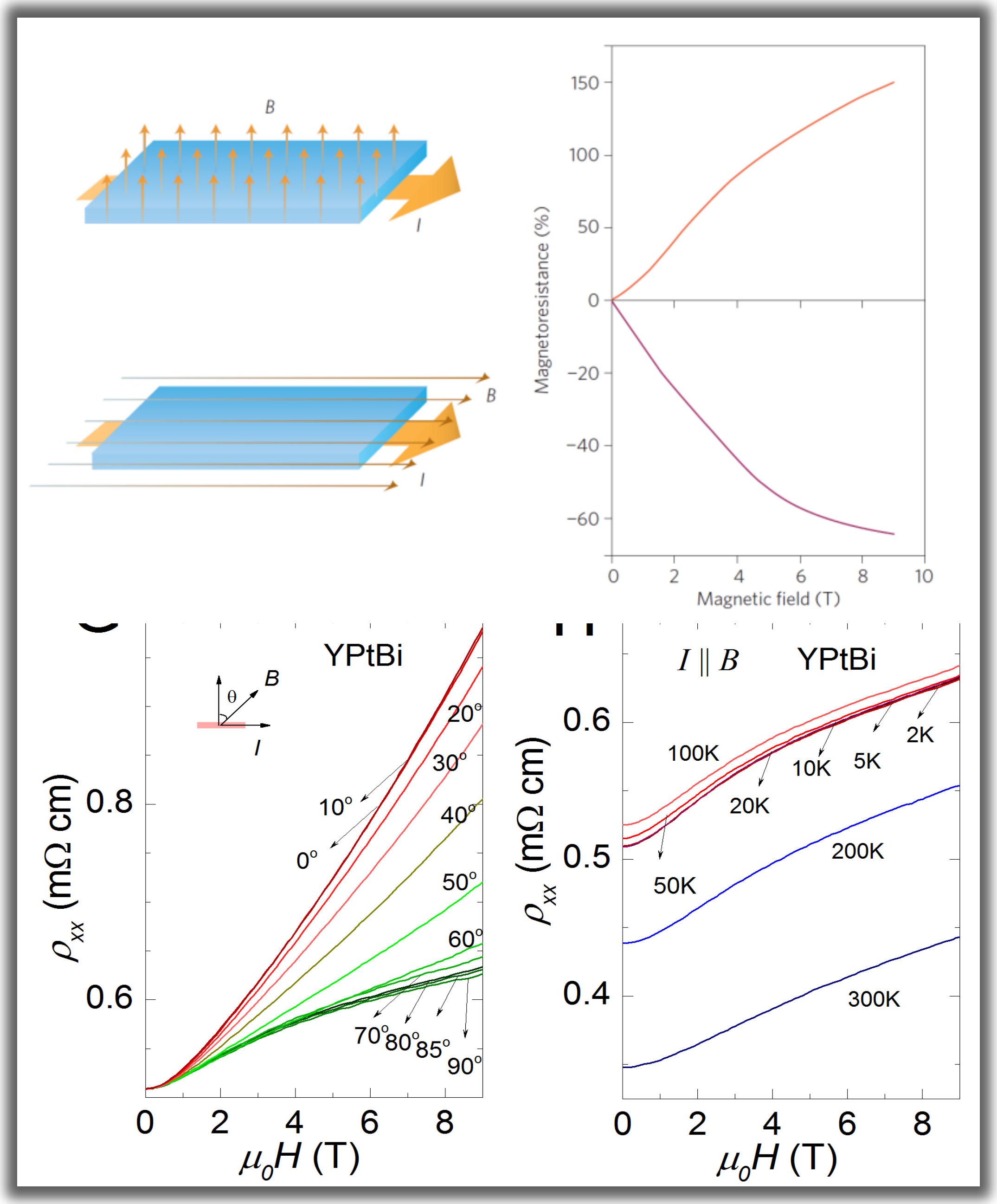


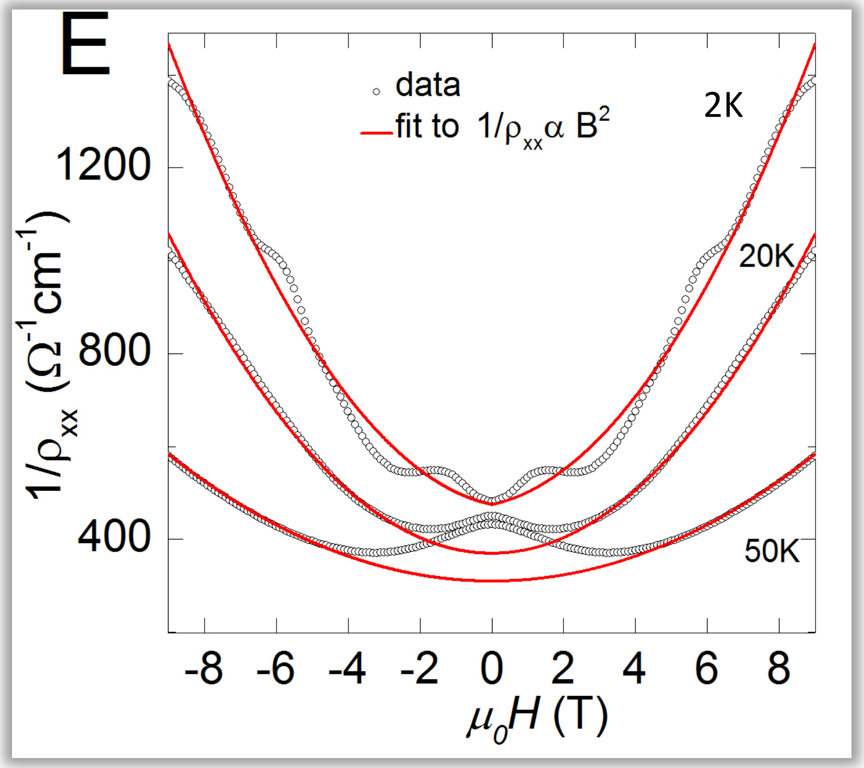


C. Shekhar et al., arXiv:1604.01641, (2016).

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

Chiral Anomaly – neg. quadratic MR



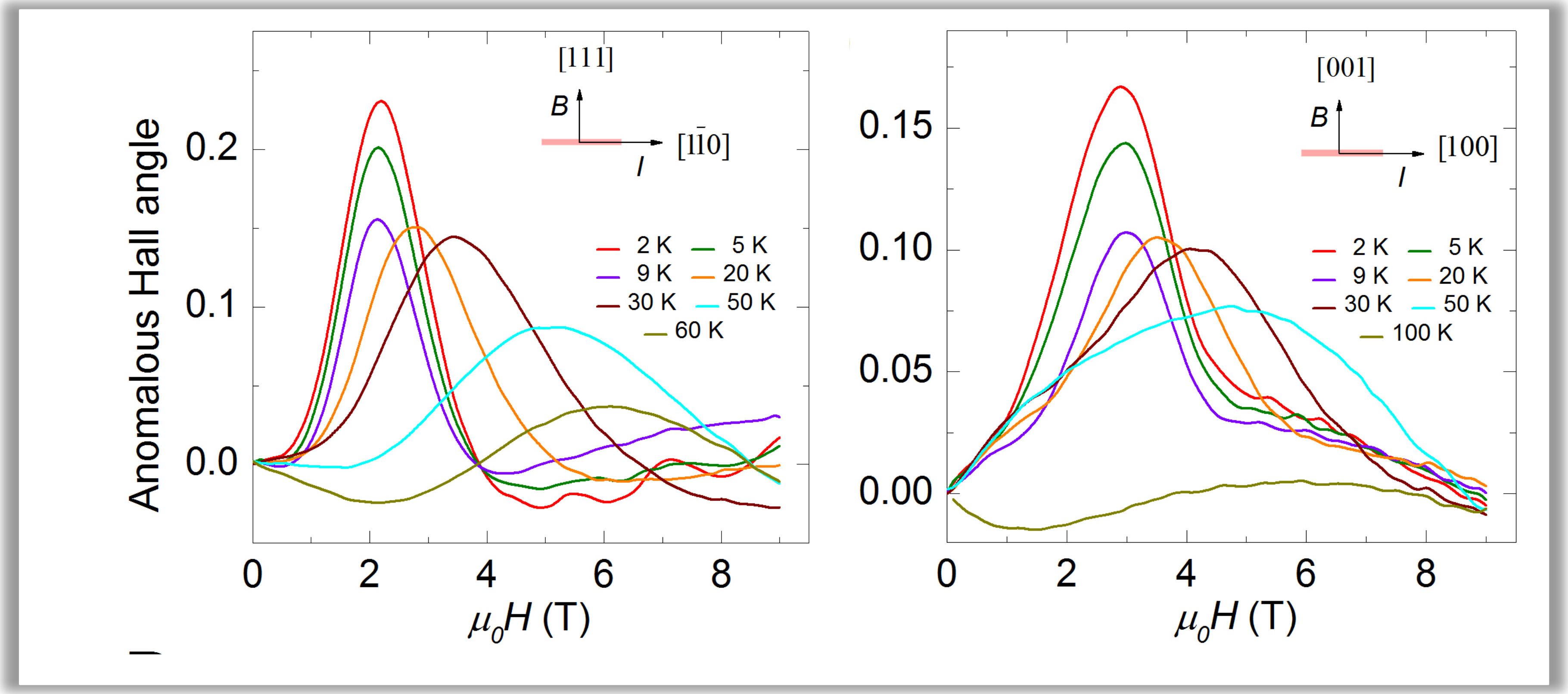


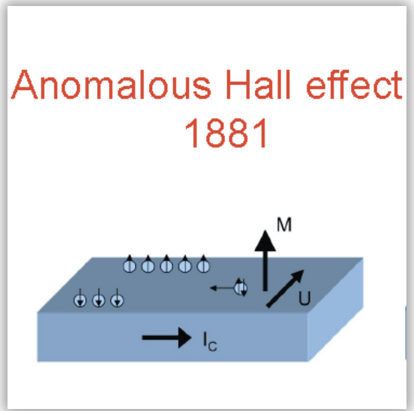
Claudia Felser and Binghai Yan, Nature Materials 15 (2016) 1149

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

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

GdPtBi – Anomalous Hall Effect

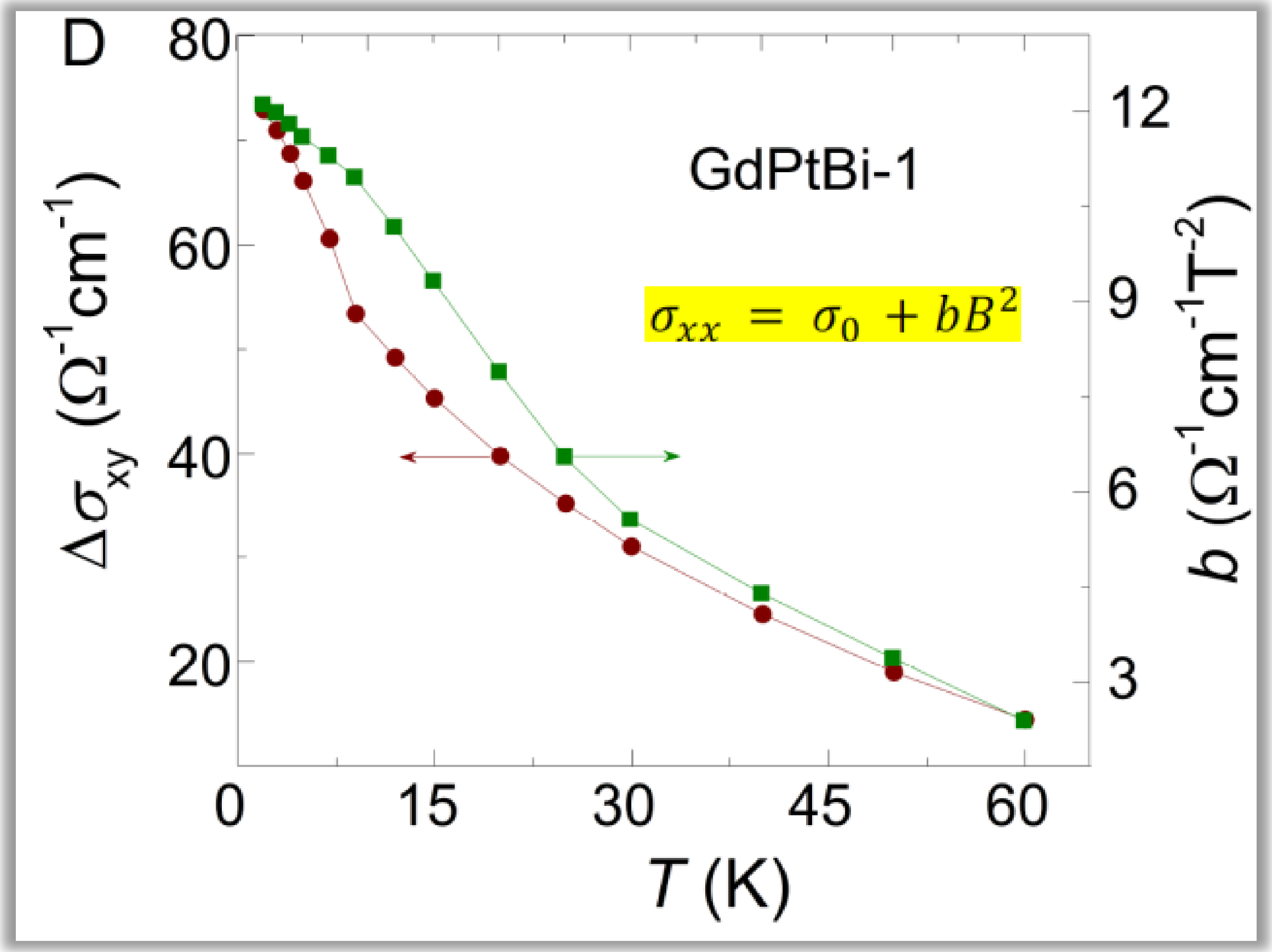




In Ferromagnets an AHE scales with the magnetic moment
Antiferromagnets show no AHE
A Hall angle of 0.2 is exceptional high

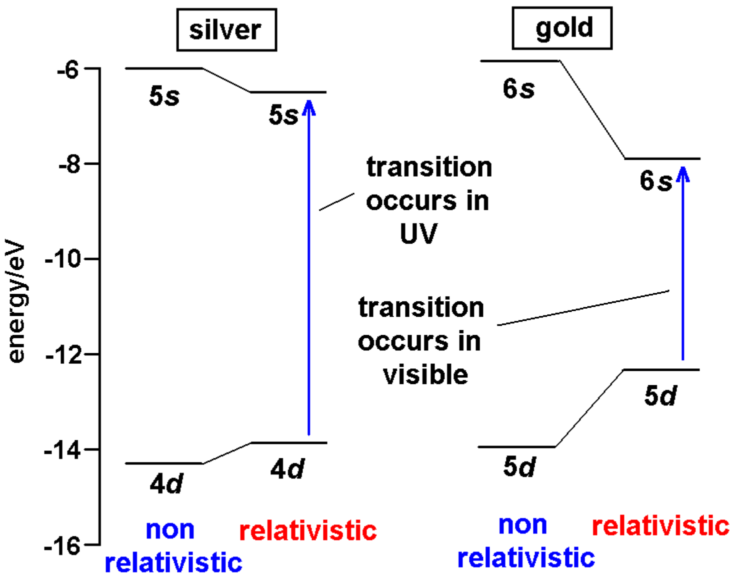
Shekhar et al., arXiv:1604.01641, (2016).
T. Suzuki,… & J. G. Checkelsky, Nature Physics (2016) doi:10.1038/nphys3831

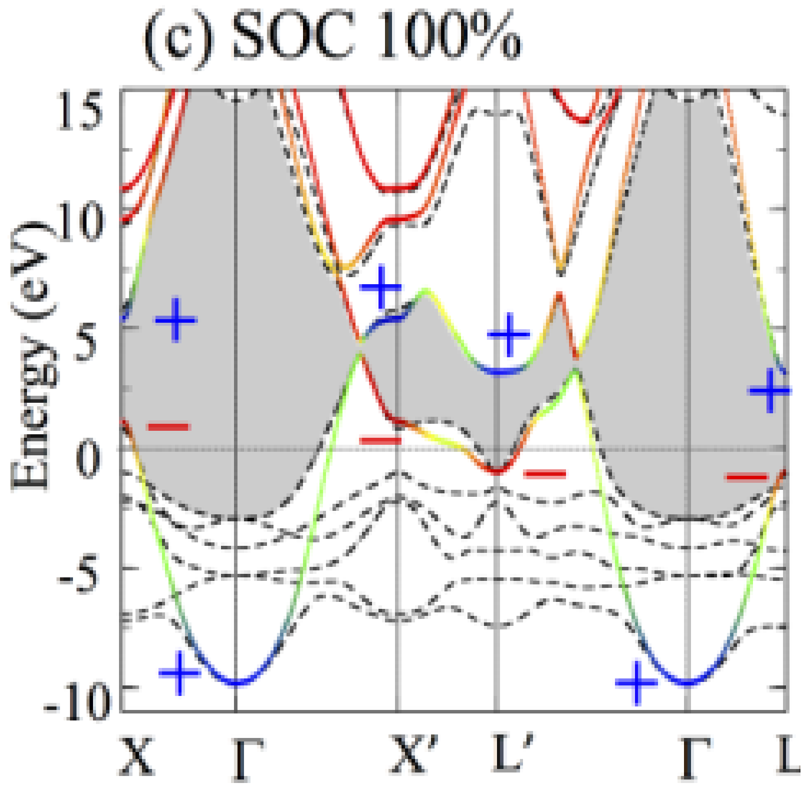
Chiral Anomaly – neg. quadratic MR

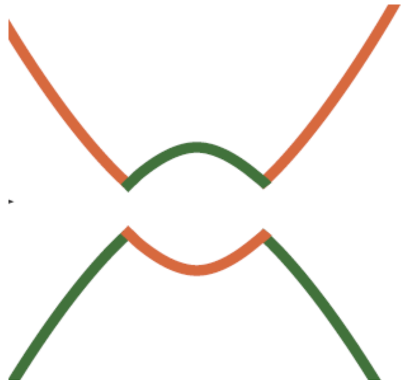


C. Shekhar et al., arXiv:1604.01641, (2016).
M. Hirschberger et al. Nature Mat. online, arXiv:1602.07219, (2016).
Claudia Felser and Binghai Yan, Nature Materials 15 (2016) 1149

Rewriting the text book: Au

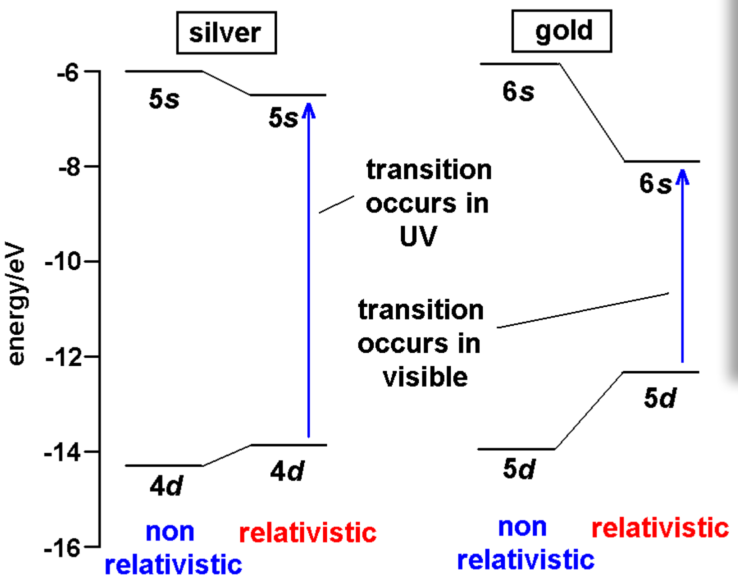






Binghai Yan at al., Nature Communication 6 (2015) 10167

Rewriting the text book: Au

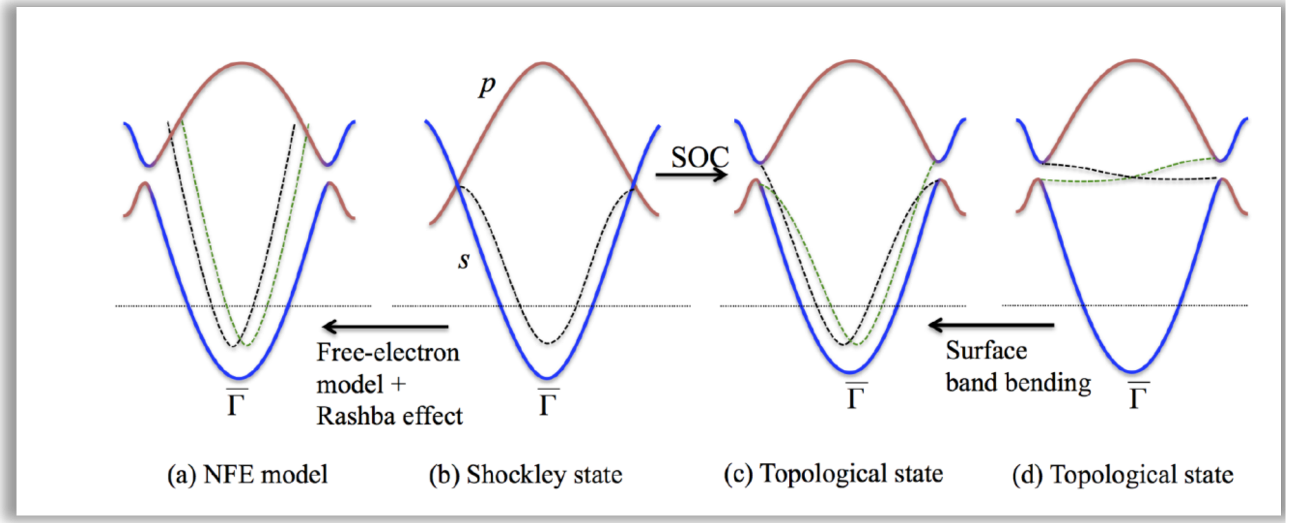


AUGUST 15, 1939 PHYSICAL REVIEW VOLUME 56

On the Surface States Associated with a Periodic Potential

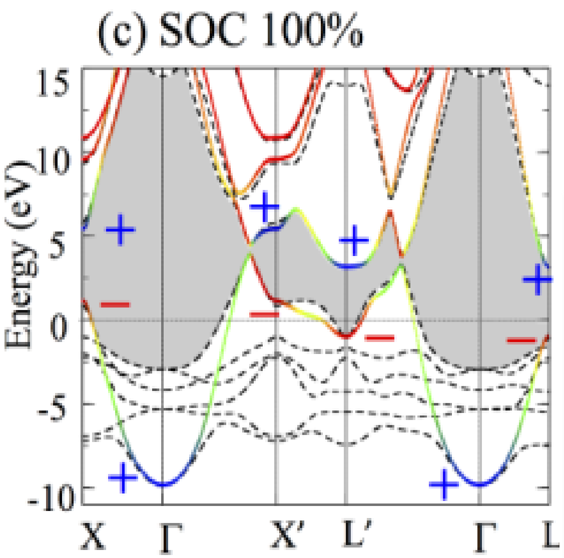
WILLIAM SHOCKLEY
Bell Telephone Laboratories, New York, New York

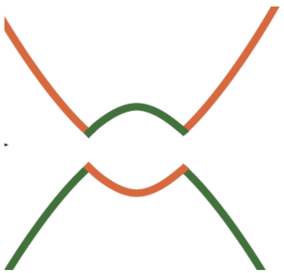
(Received June 19, 1939)

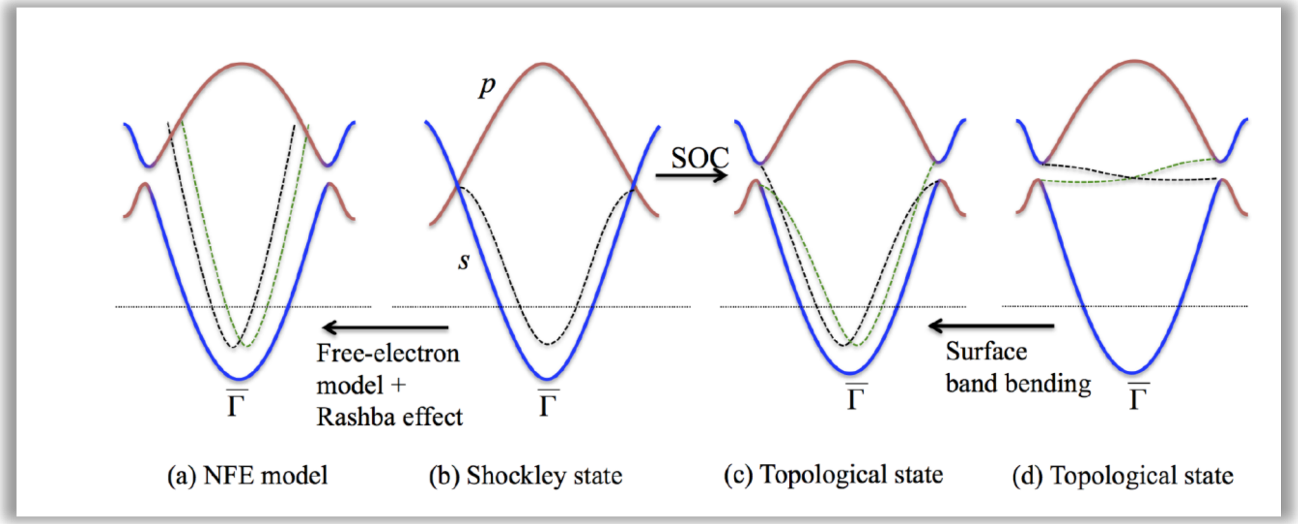


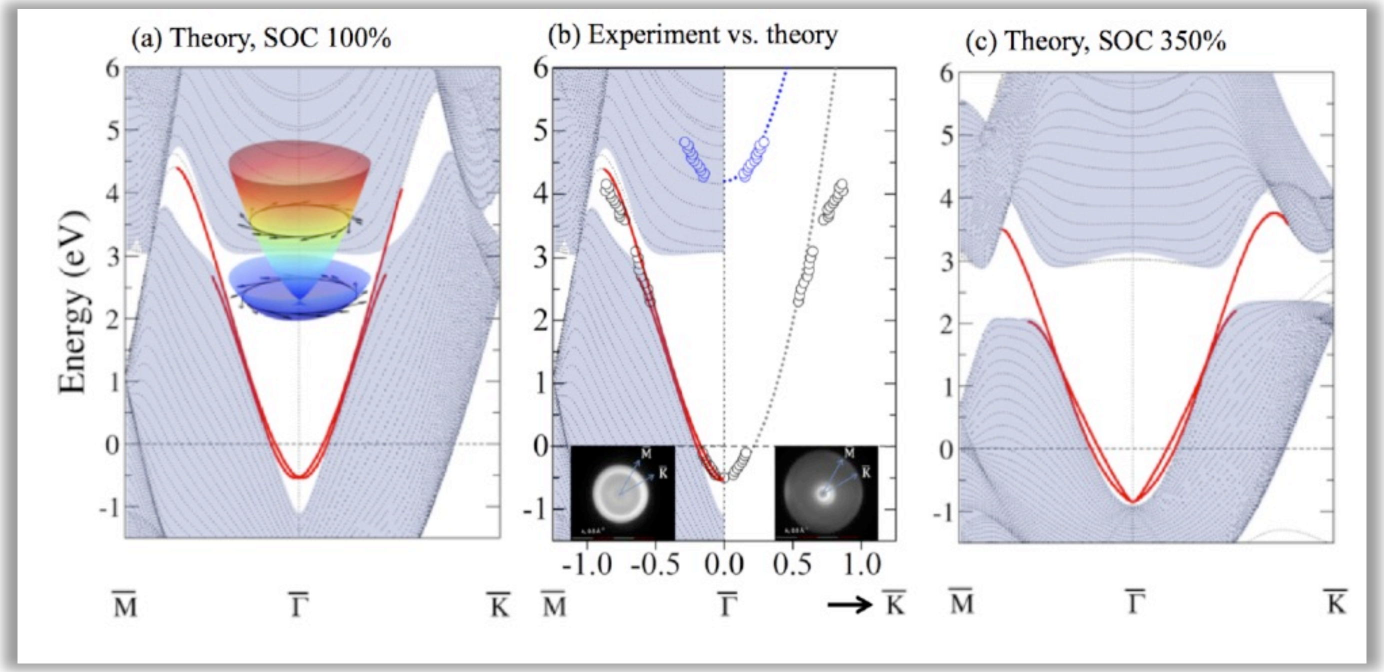
Binghai Yan at al., Nature Communication 6 (2015) 10167

Rewriting the text book: Au





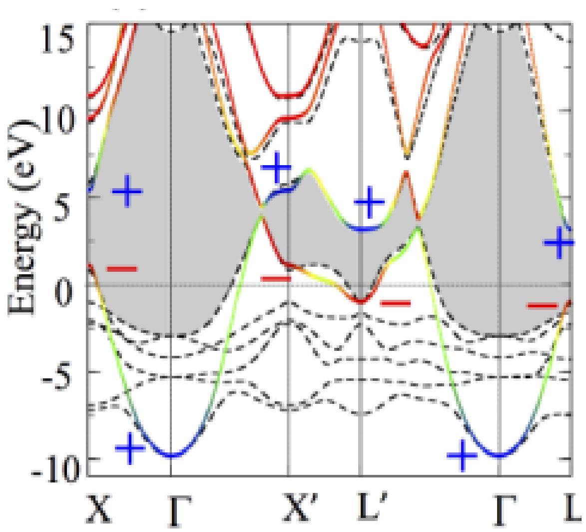


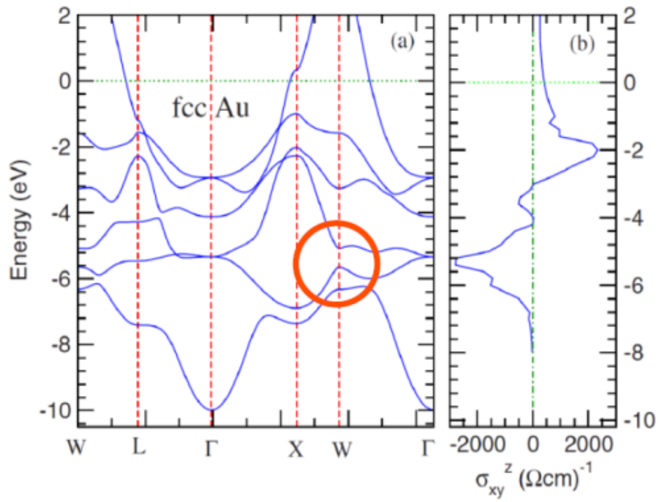


Cs^+Au^-

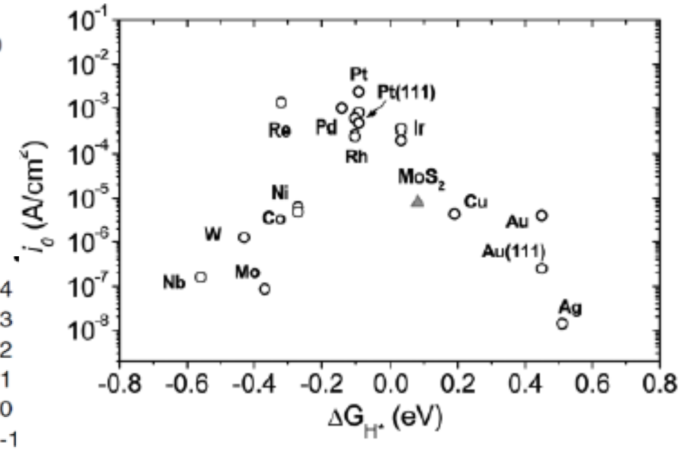
Binghai Yan at al., Nature Communication 6 (2015) 10167

Berry Phase of Au-Pt- Spin Hall Effect



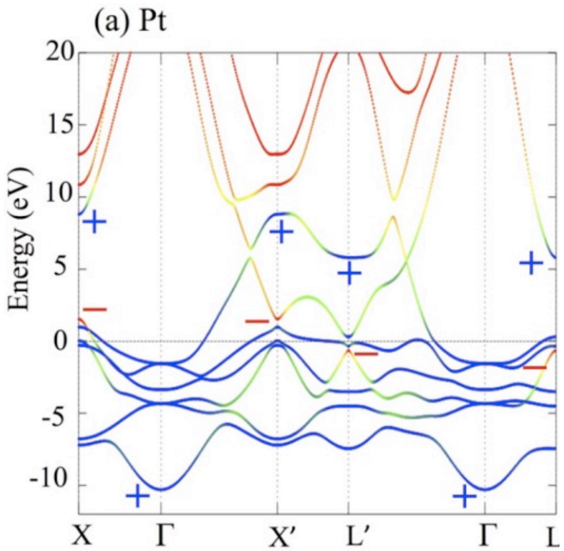


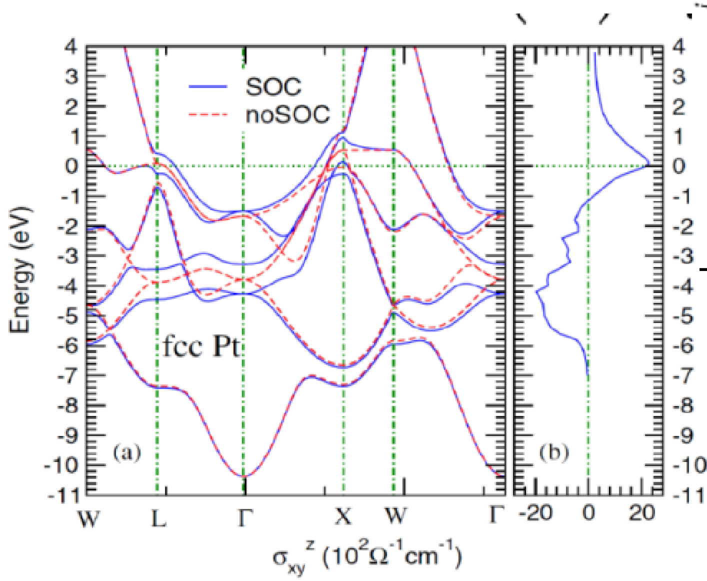
Inert pair effect



T. F. Jaramillo et al. Science 317, 100 (2007)

Au: **400** $\frac{\hbar}{e}\,(\Omega\ cm)^{-1}$

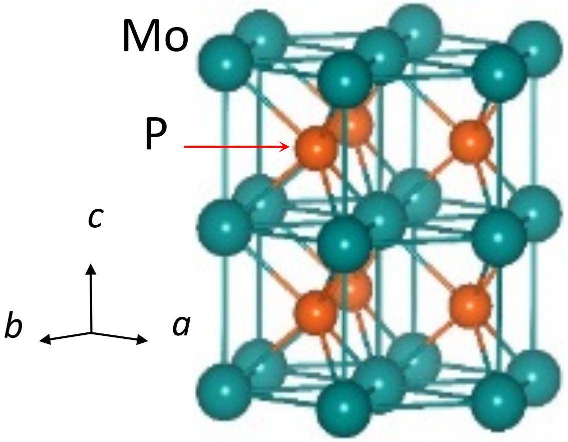


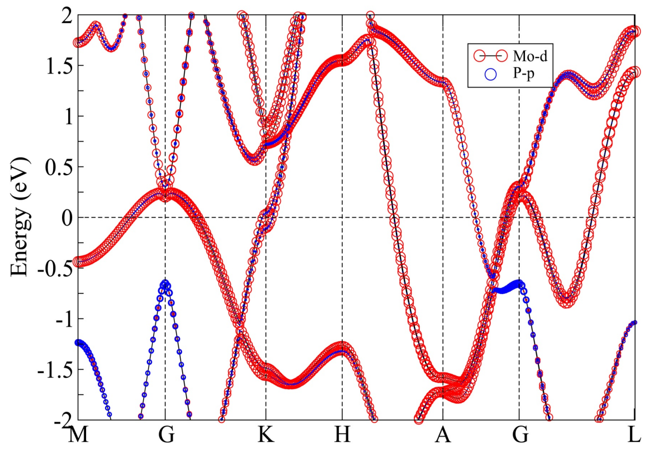


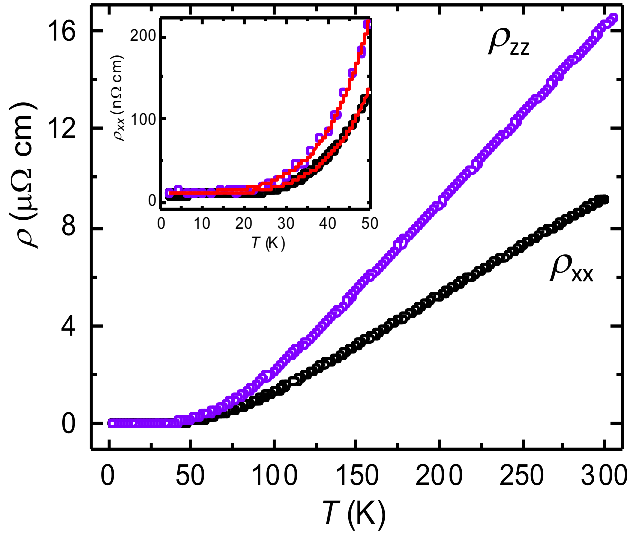
Guo et al., PRL 100, 096401 (2008)
J. Appl. Phys. 105, 07C701 (2009)

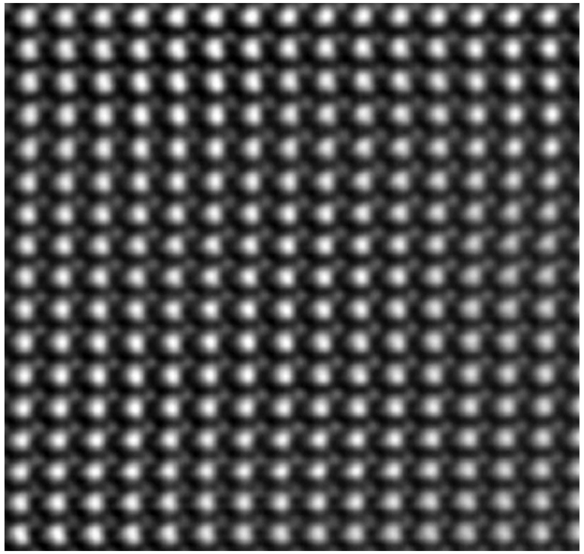
Pt: **2000** $\frac{\hbar}{e}\,(\Omega\ cm)^{-1}$

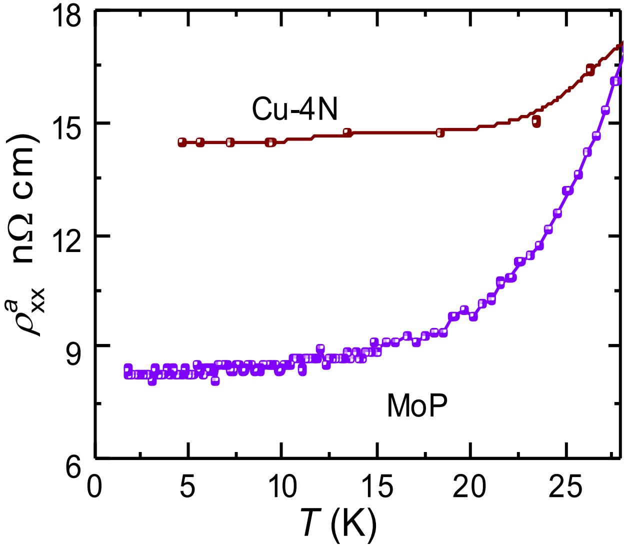
MoP better than Copper

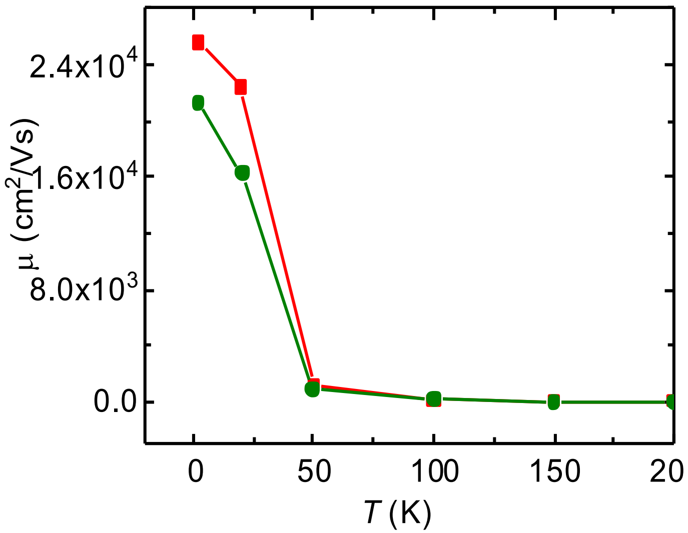






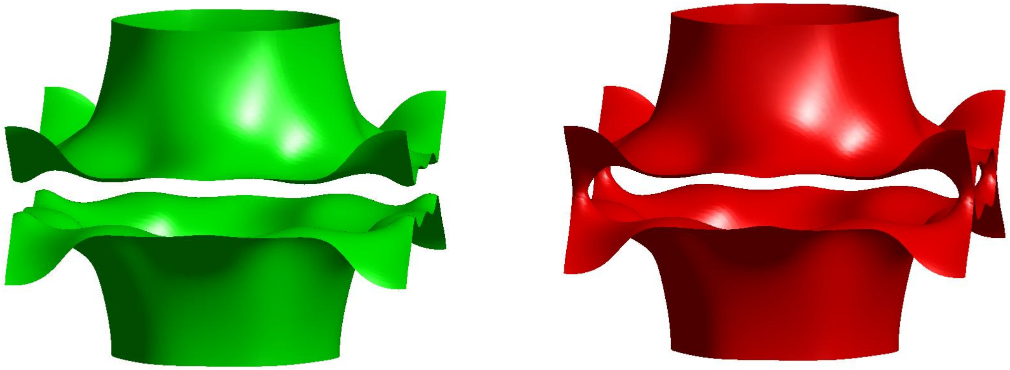






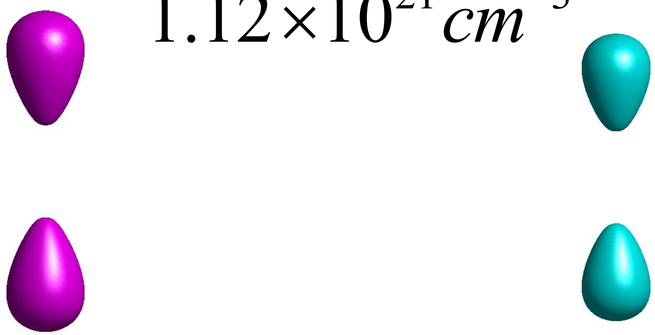
Chandra Shekhar et al. arXiv:1703.03736

Fermi surfaces

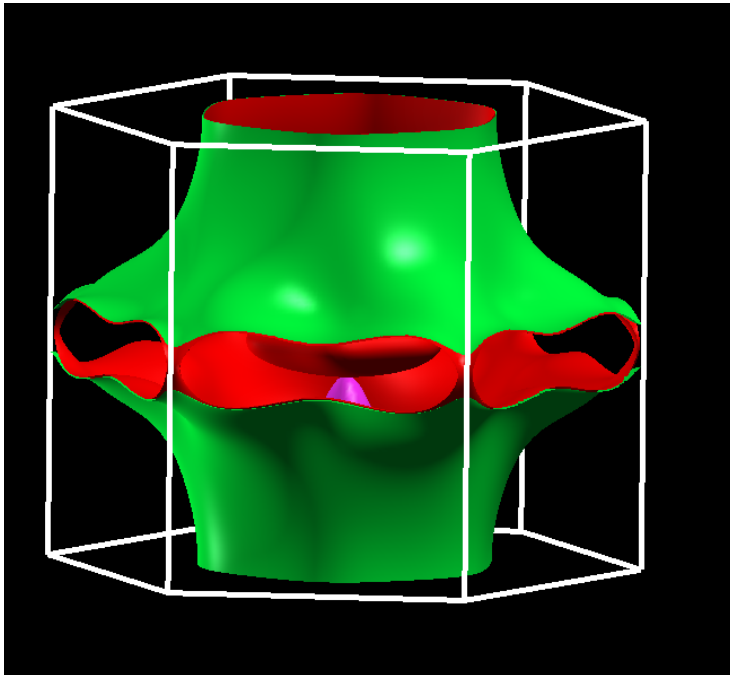


$$2.7\times10^{22}\,cm^{-3}$$

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



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



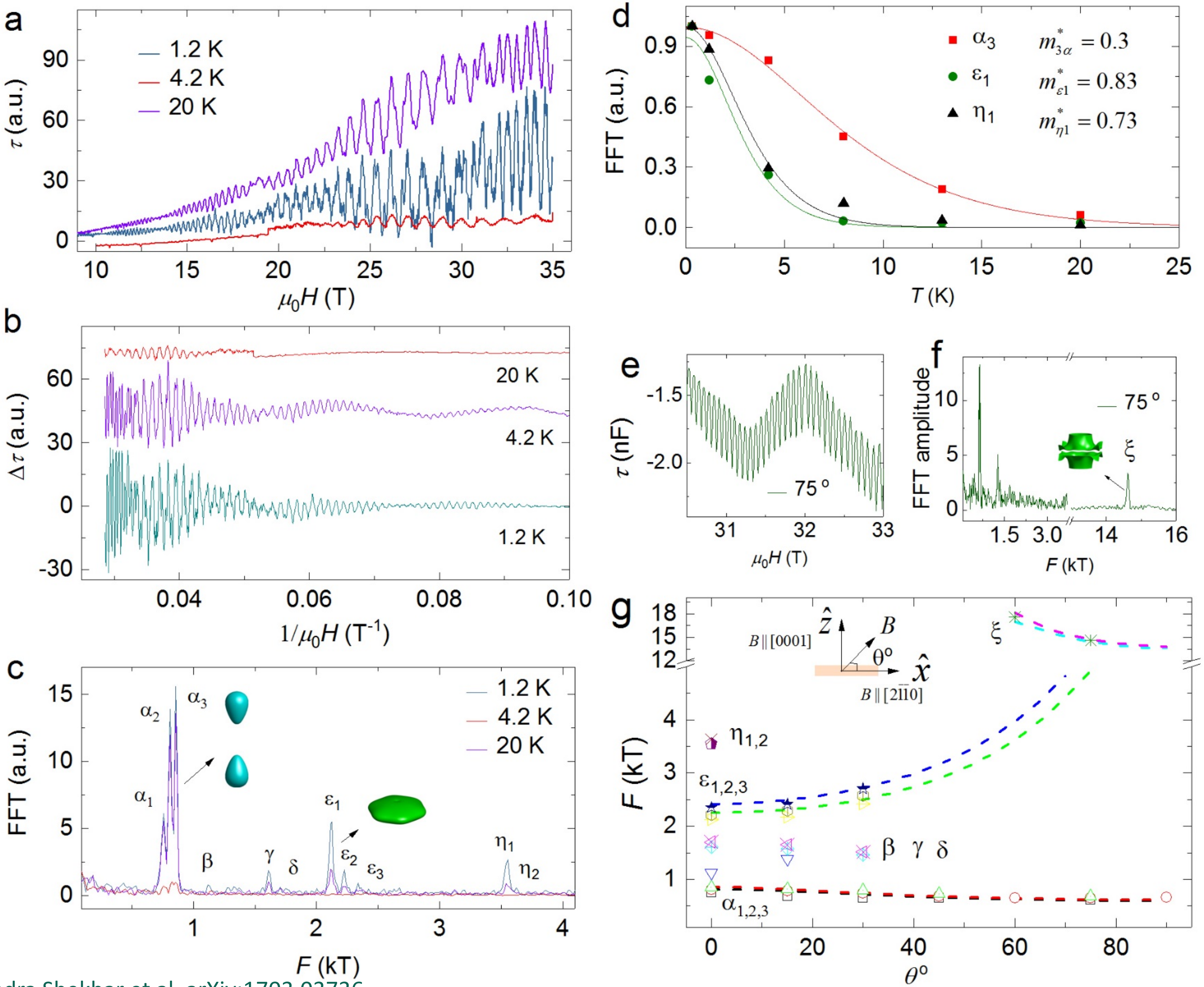
Charge carriers are mainly from the open Fermi surface

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

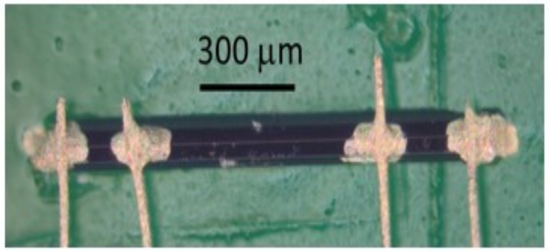
Quantum Oscillations



Chandra Shekhar et al. arXiv:1703.03736

Macroscopic Mean Free Path

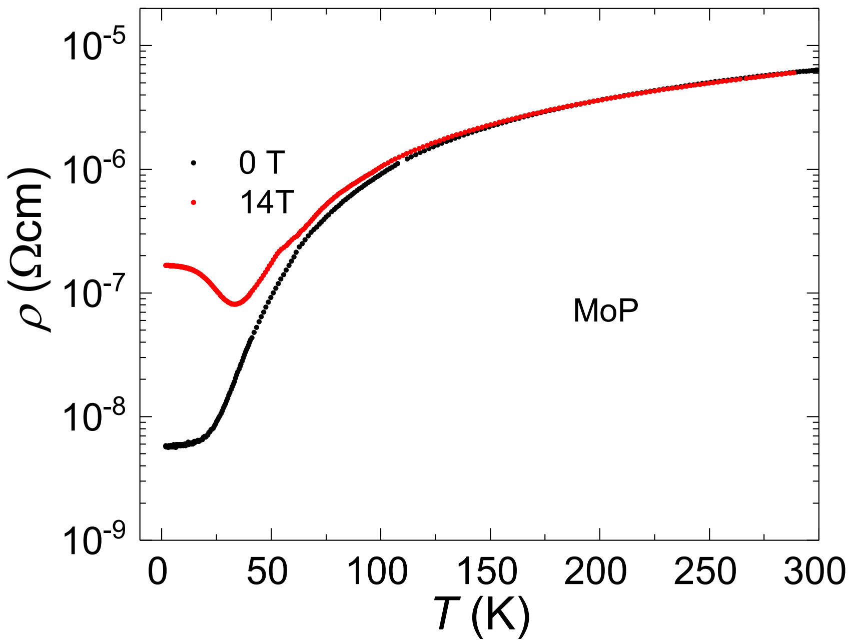
Compound	ρ (Ωcm)	l (μm)	μ ($cm^2V^{-1}s^{-1}$)	n (cm^{-3})
MoP	6×10^{-9}	11	2.4×10^{4}	2.9×10^{22}
WP_2	3×10^{-9}	530	4×10^{6}	5×10^{20}
WC	0.35×10^{-6}		$\sim1\times10^{4}$	4×10^{20}
$PtCoO_2$	40×10^{-9}	5	0.7×10^{4}	2.2×10^{22}
$PdCoO_2$	9×10^{-9}	20	$2.8x10^{4}$	2.4×10^{22}

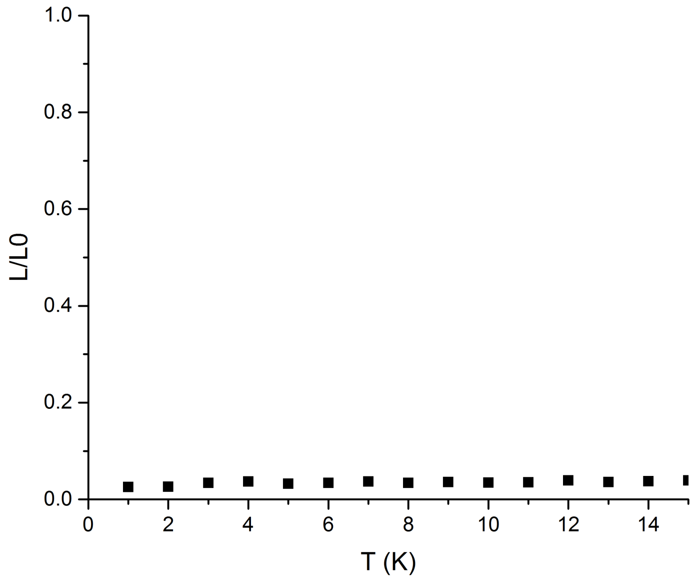


WC J. B. He et al. arXiv:1703.03211
Pallavi Kushwaha, et al. Sci. Adv.1 (2015) e150069
P. Moll Science 351, (2016) 1061

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

Hydrodynamic





- A strong violation of the Wiedemann-Franz law
- The Lorentz

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

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}
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$PdCoO_2$	9×10^{-9}	20	2.8×10^4	2.4×10^{22}

Chandra Shekhar et al. arXiv:1703.03736

What comes next?

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

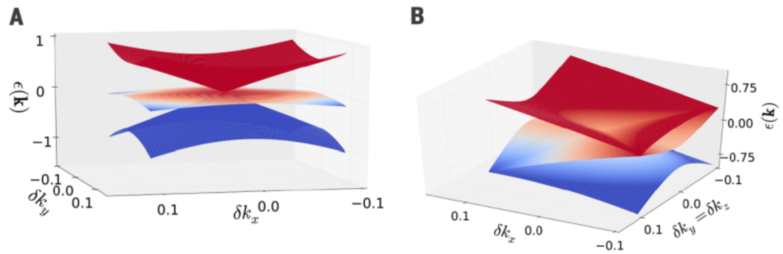
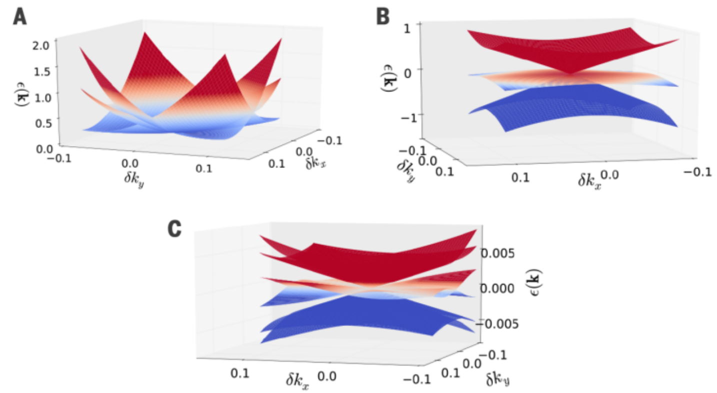
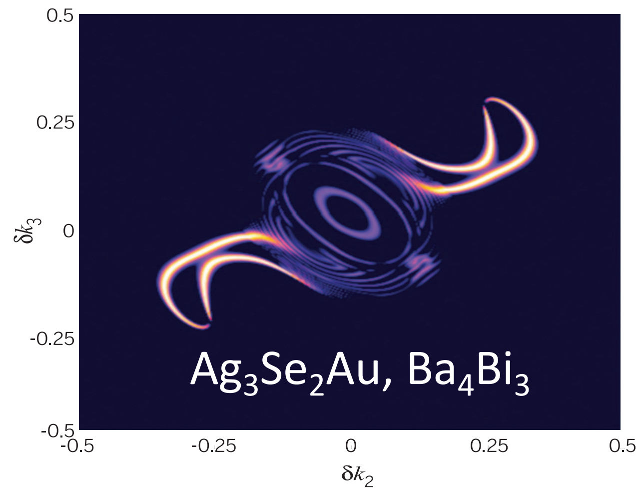


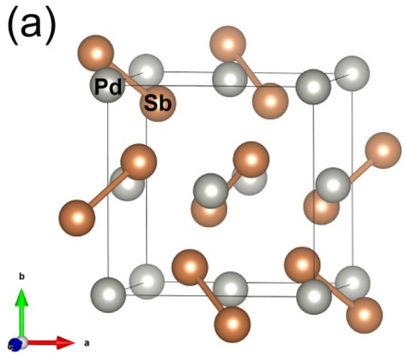
Fig. 1. Energy dispersion near a threefold degeneracy at the *P* point. (**A** and **B**) Shown are threefold degenerate points in (A) SGs 199 and 214 and (B) SG 220. In the latter case, pairs of bands remain degenerate in energy along the high-symmetry lines $|\delta k_x| = |\delta k_y| = |\delta k_z|$.

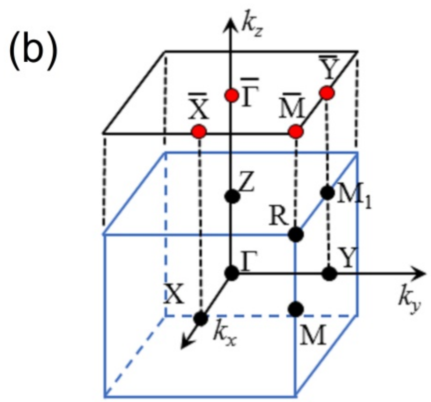


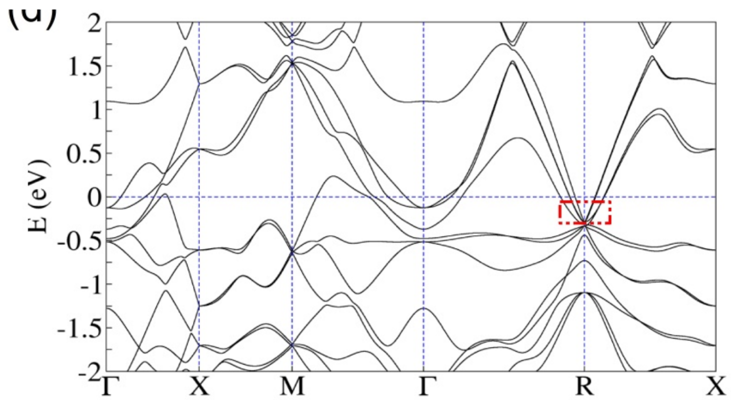


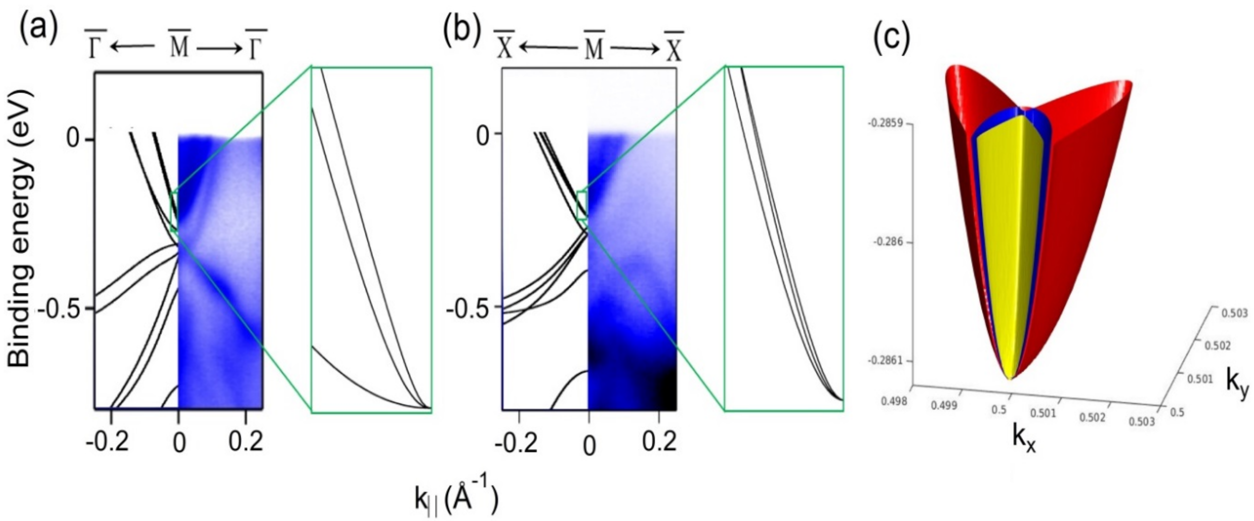
Science, 353, 6299, (2016)

Example: $PdSb_2$









6-fold fermions at the R point

Since SG 205 contains inversion symmetry, all bands are doubly degenerate

•non-symmorphic: elements with *fractional lattice translations* (157)

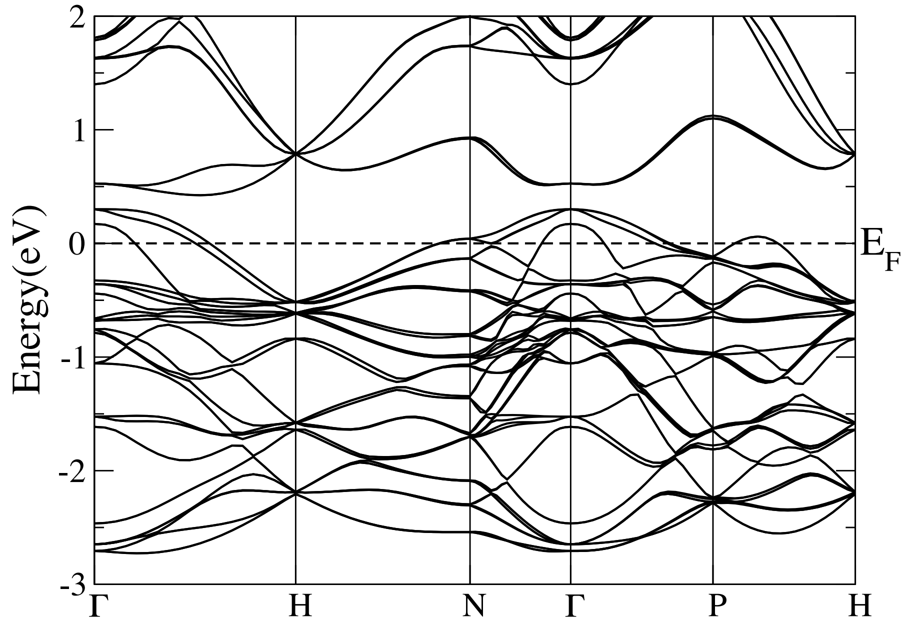
- Cubic crystal structure for high degenerations
- Non symmorphic is essential for stabilizing six- and eight-fold degenerate points.

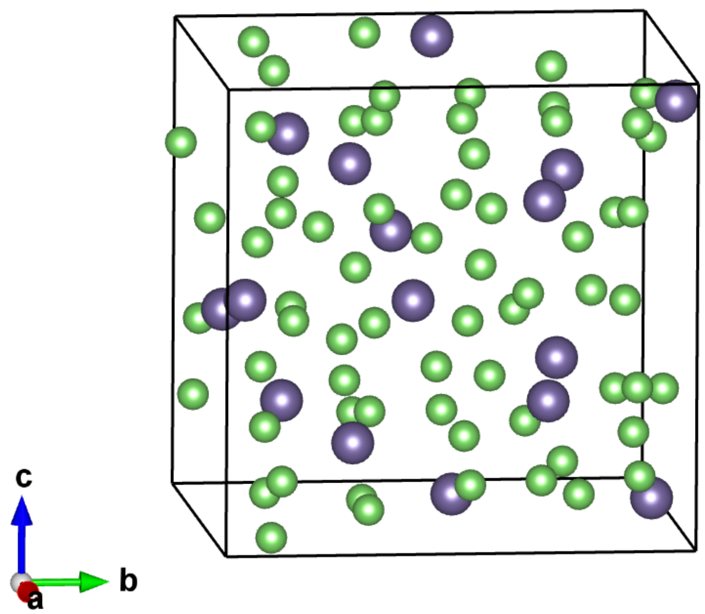
Novel Metals

- SG I-43d (220) has elementary band representations with *16* branches -> 16fold connected metal if topologically trivial

- Filling -1/8 (lowest filling possible in a material is 1/24)

- Examples in the $A_{15}B_4$ material class (Here $Li_{15}Ge_4$)





Universe – applying a lattice

Bringing order to the expanding fermion zoo

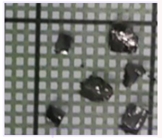
Carlo Beenakker Commentary
Heisenberg (1930): We observe space as a continuum, but we might entertain the thought that there is an underlying lattice and that space is actually a crystal. Which particles would inhabit such a lattice world? Werner Heisenberg *Gitterwelt* (lattice world) hosted electrons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

Topology – interdisciplinary

Chemistry

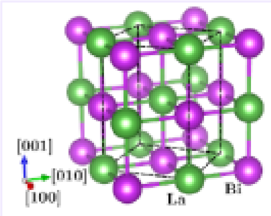
Real space - local

Crystals



LaBi

Crystal structure

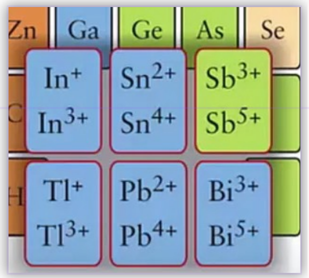


Position of the atoms

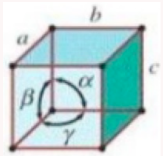
Orbitals

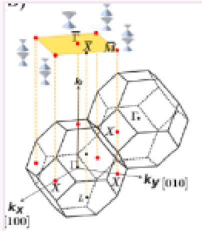
Check	WP	Representative
☐	8g	x,y,z
☐	4f	x,1/2,z
☐	4e	x,0,z
☑	4d	x,x,z
☑	2c	1/2,0,z
☐	1b	1/2,1/2,z
☑	1a	0,0,z

Inert pair effect

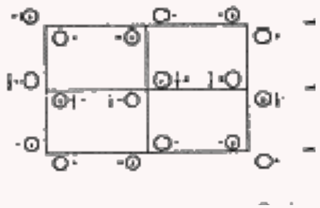


Symmetry





Local symmetry



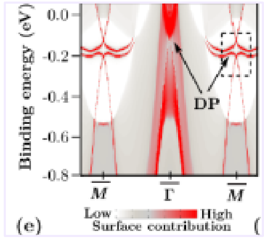
Relativistic effects

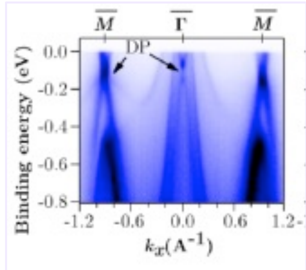
Physics

Recipro. space - delocalized

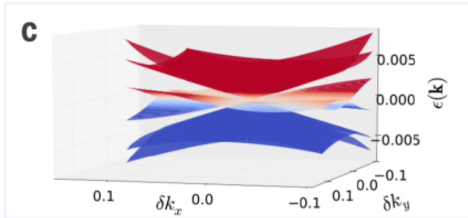
Brillouin zone

Electronic structure





Band connectivity

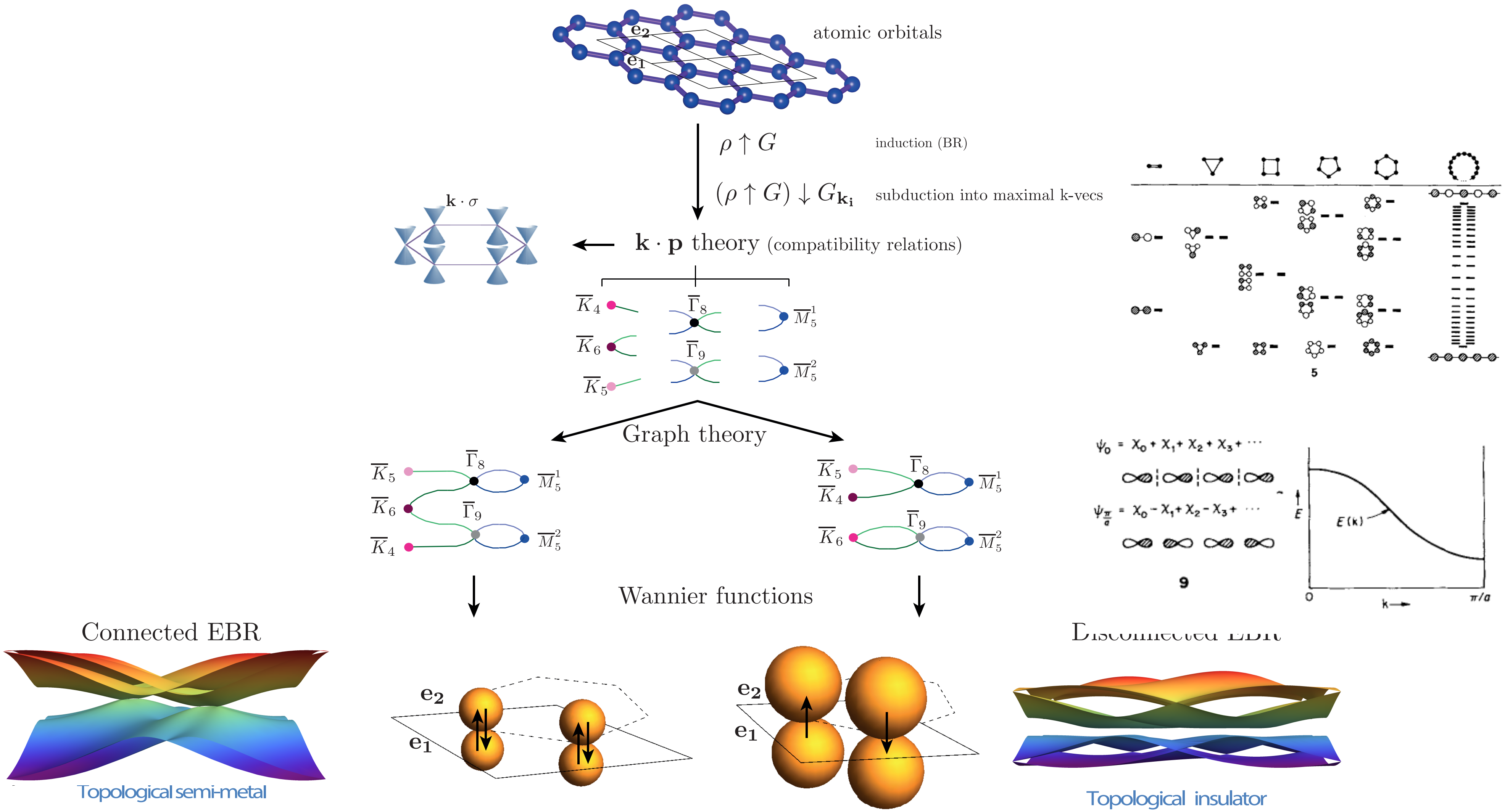


Darwin term

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

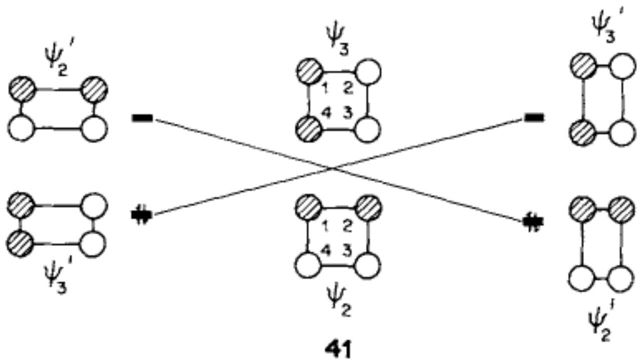
Barry Bradlyn, L. Elcoro, Jennifer Cano, M. G. Vergniory, Zhijun Wang, C. Felser, M. I. Aroyo, B. Andrei Bernevig, Nature (2017)

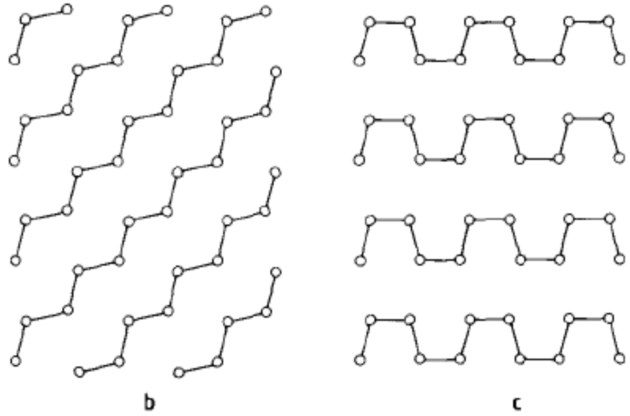
Translation

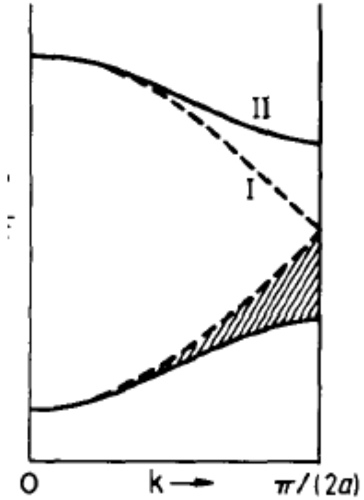


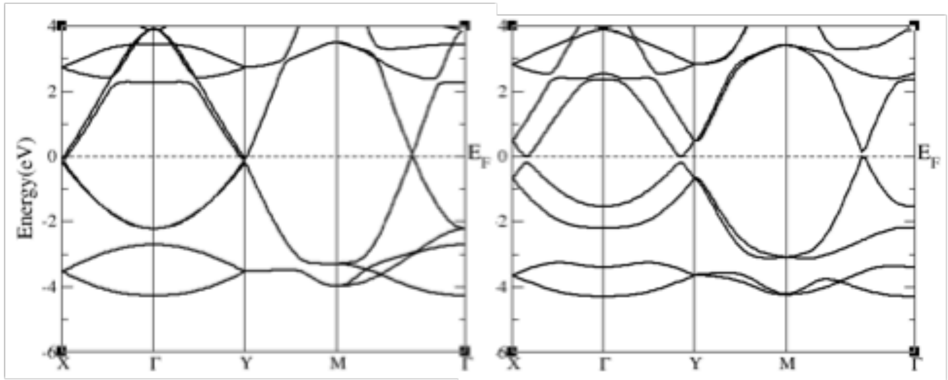
Barry Bradlyn, L. Elcoro, Jennifer Cano, M. G. Vergniory, Zhijun Wang, C. Felser, M. I. Aroyo, B. Andrei Bernevig, Nature (2017)

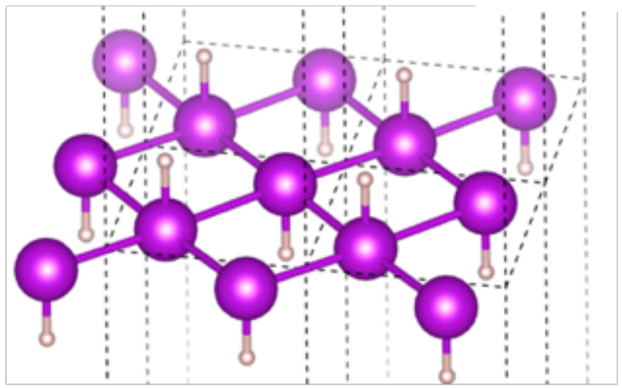
Square nets of electron doped Bi











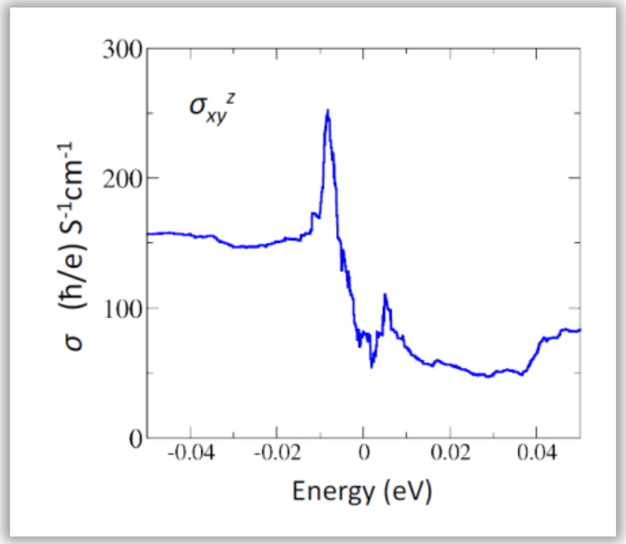
Square Nets of Main Group Elements in Solid-State Materials

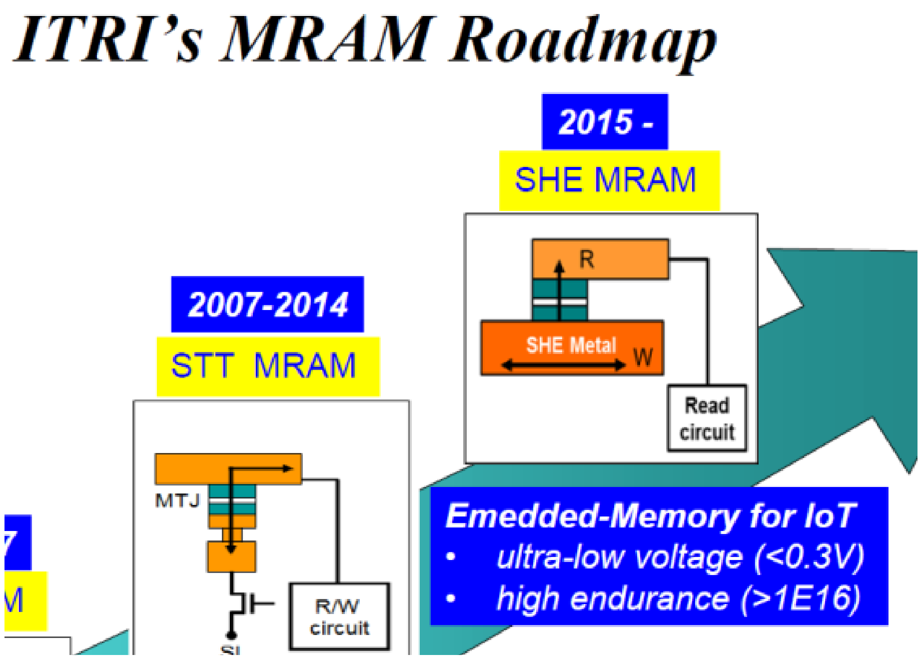
Wolfgang Tremel[1] and Roald Hoffmann*

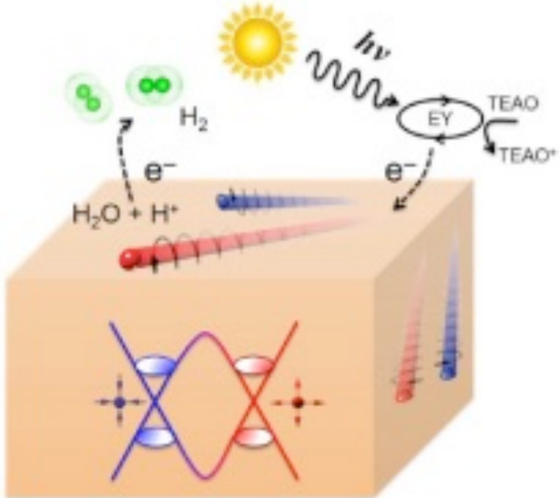
Contribution from the Department of Chemistry and Materials Science Center, Cornell University, Ithaca, New York 14853. *Received May 29, 1986*

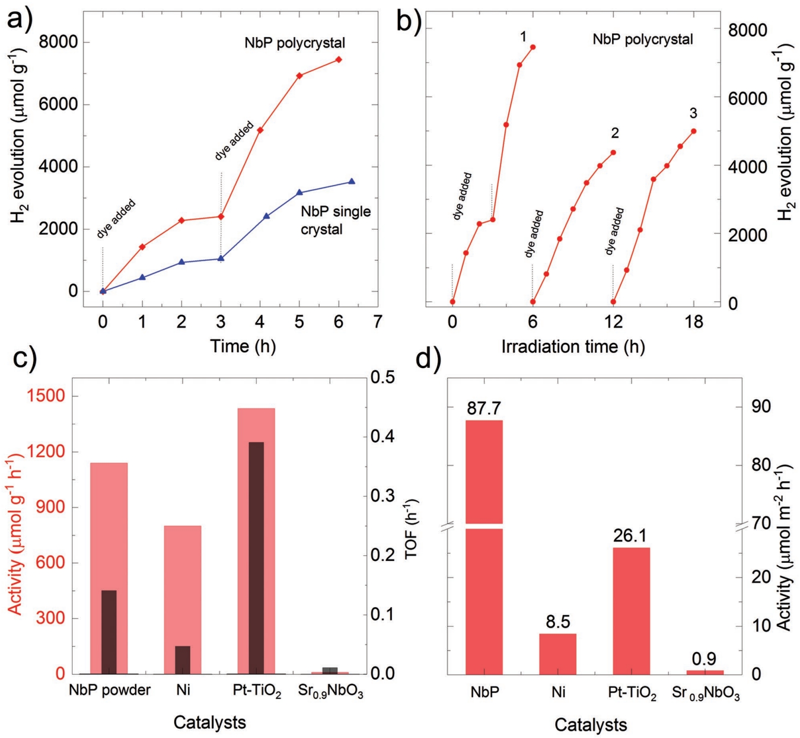
Barry Bradlyn, L. Elcoro, Jennifer Cano, M. G. Vergniory, Zhijun Wang, C. Felser, M. I. Aroyo, B. Andrei Bernevig, Nature (2017)

Application Spin Hall Effect and Catalysis









Yang Zhang, et al. PRB **95** (2017) 075128, preprint . arXiv:1610.04034
Yan Sun, et al. PRL 117 (2016) 146401 preprint arXiv:1604.07167

Catherine R. Rajamathiet al. and C.N.R. Rao, Advanced Materials 2017 preprint arXiv:1608.03783

Summary

Is there a relation between reciprocal and real space Berry curvature

Many materials proposed, only a few made

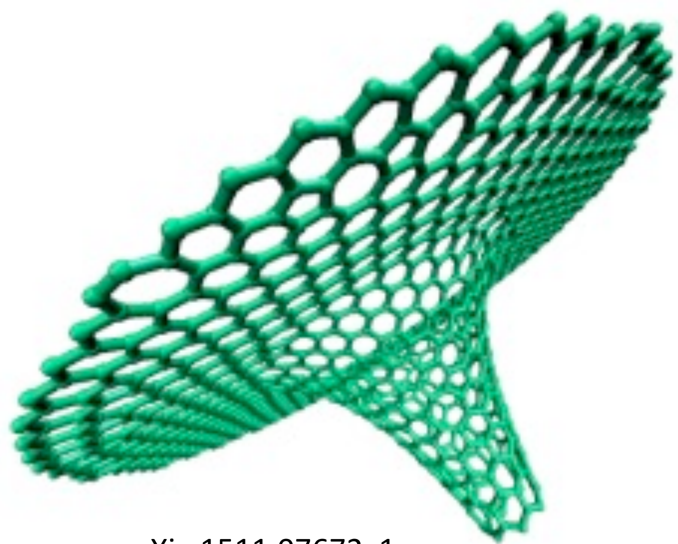
- More Weyl and Dirac semimetals
- More new Fermions
- High quality single crystals, defect free – or with defects
- Topological insulators in oxides, correlated systems
- Generalization of the concept
  - Magnetic Fermions
  - Thin films
  - Superconductors – Majorana
  - Chemical reactions
  - Phase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

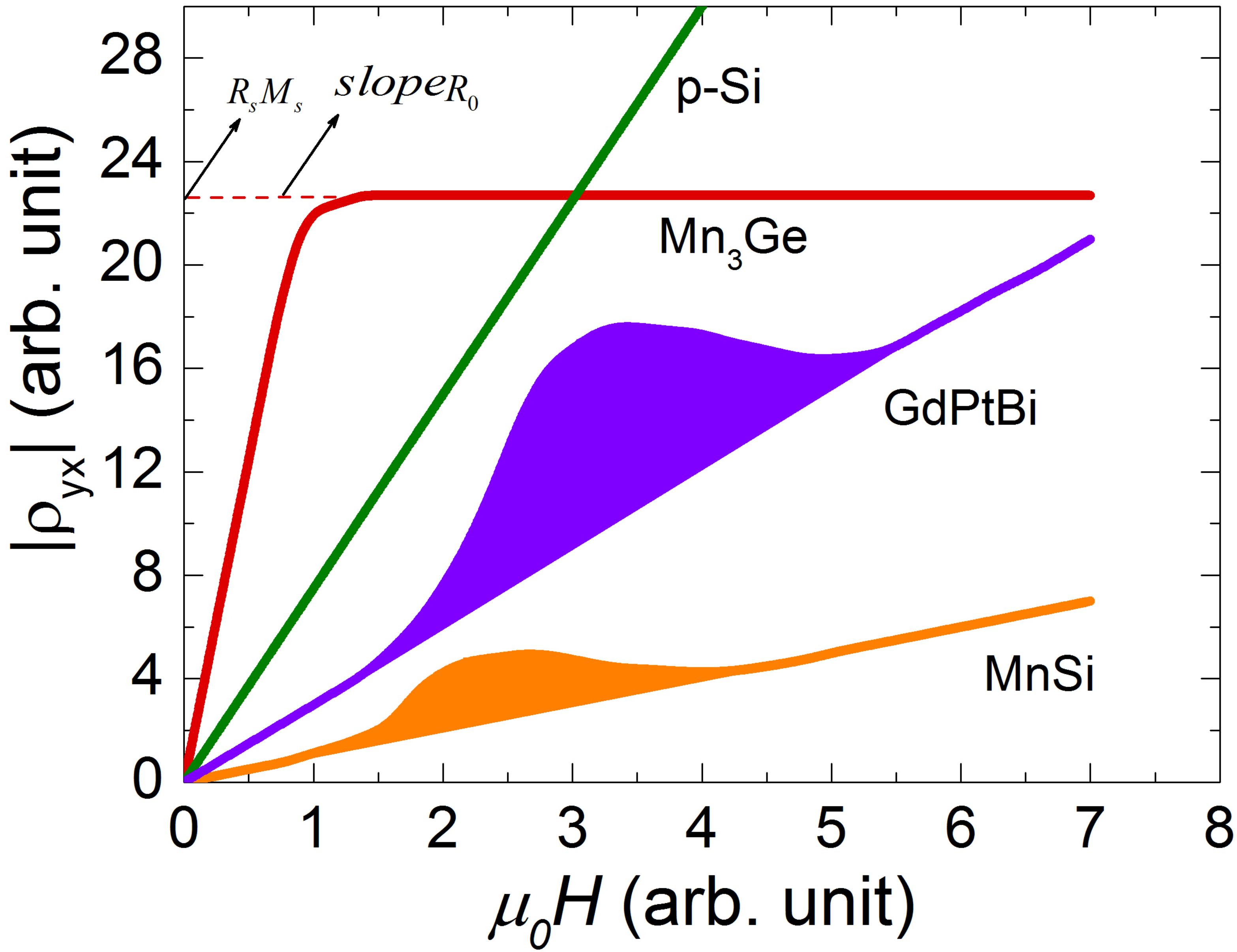
Mn1.4PtSn

CuMnSb
CuMnAs

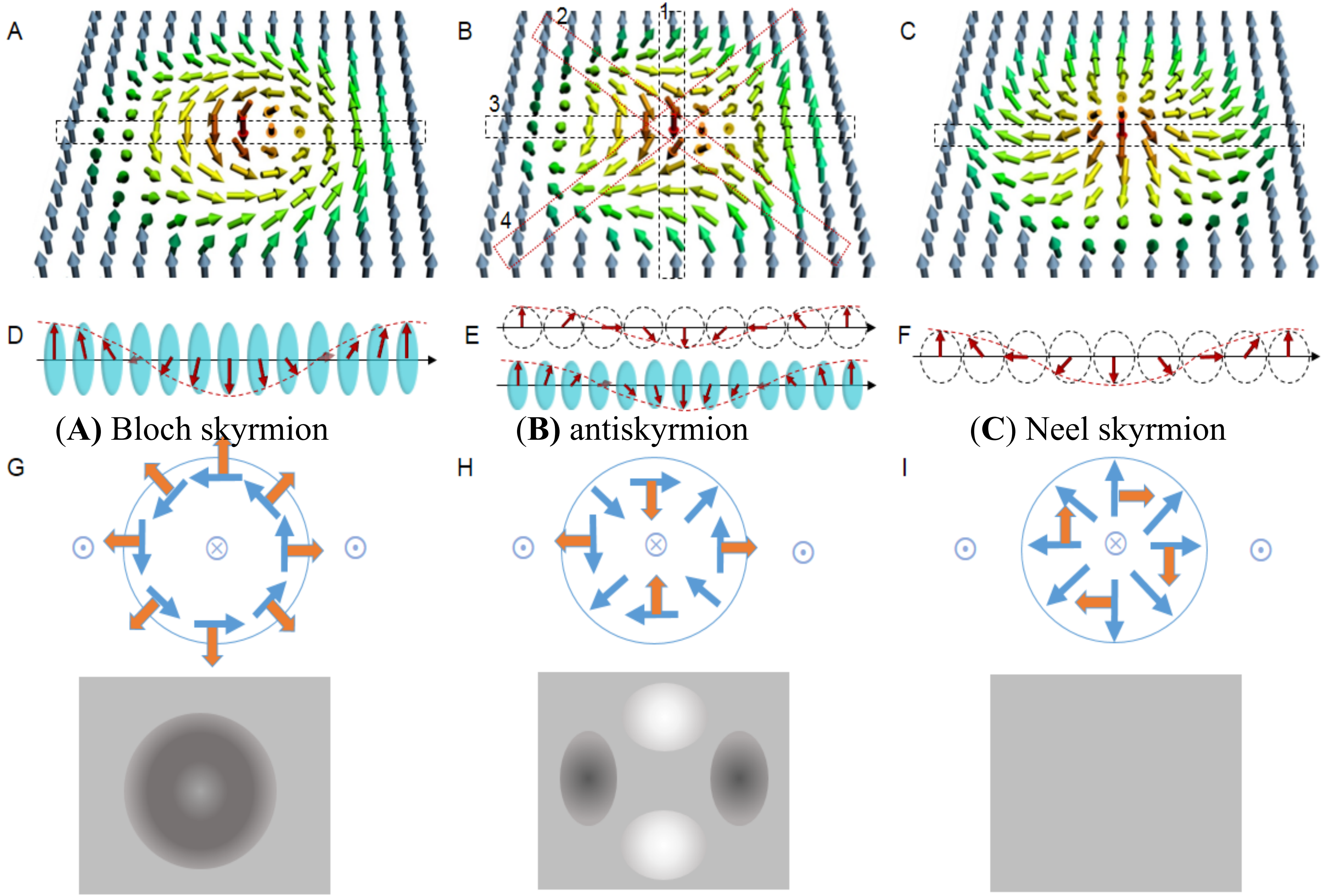
Co2Ti0.5V0.5Sn
Co2VAl0.5Si0.5
Co2Ti0.5V0.5Si
Mn2CoGa
Co2MnGa
Co2Al9
Co2MnAl
Co2VGa0.5Si0.5
Co2TiSn
Co2VGa
Co2V0.8Mn0.2Ga
CoFeMnSi

Thank you!

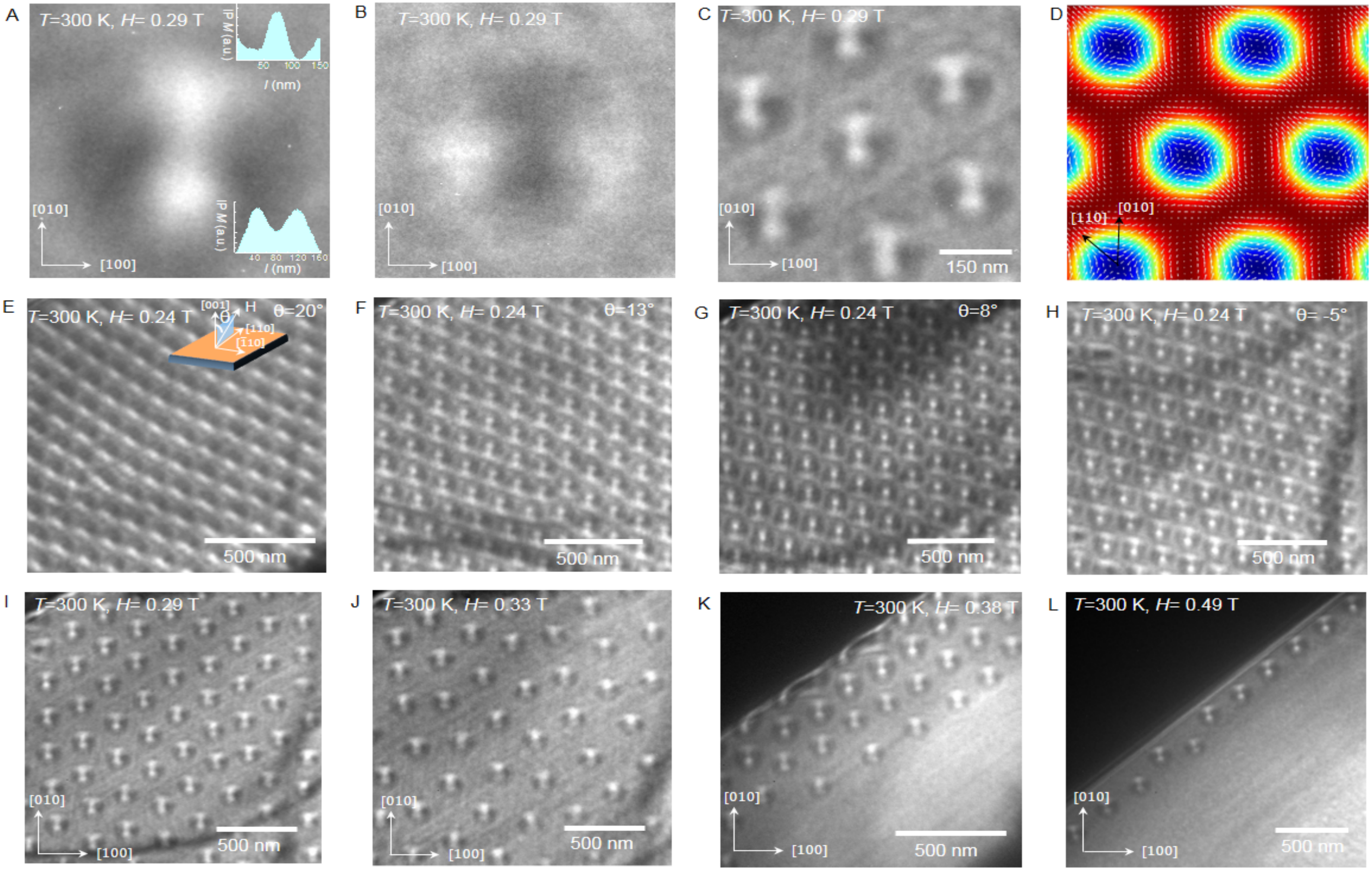
Anomalous Hall effect



Real space topology - Skyrmions



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



Nayak, et al. preprint arXiv:1703.01017

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