Weyl Semimetals

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Yulin Chen et al., Oxford; Kornelius Nielsch, IFW Dresden
S. S. P. Parkin et al., IBM Almaden, MPI Halle

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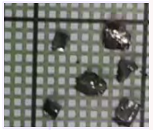
Alexander von Humboldt
Stiftung / Foundation

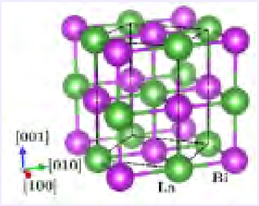
Topology – interdisciplinary

Chemistry	Physics
Real space - local	Recipro. space -deloc
Crystals	Brillouin zone

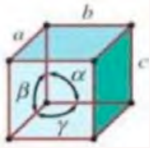


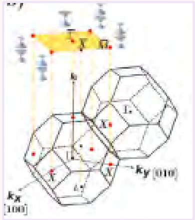
LaBi

Crystal structure

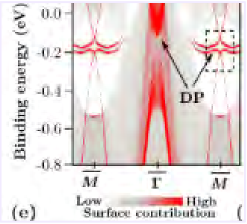


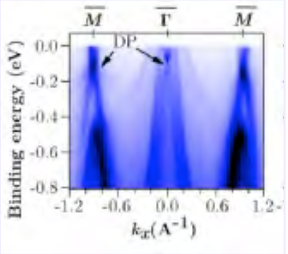
Symmetry





Electronic structure



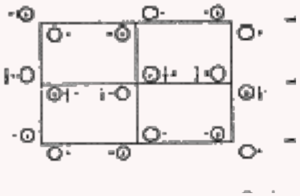


Position of the atoms

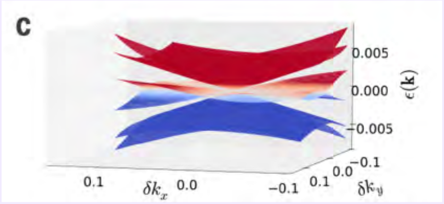
Orbitals

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

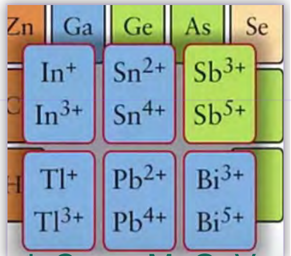
Local symmetry



Band connectivity



Inert pair effect



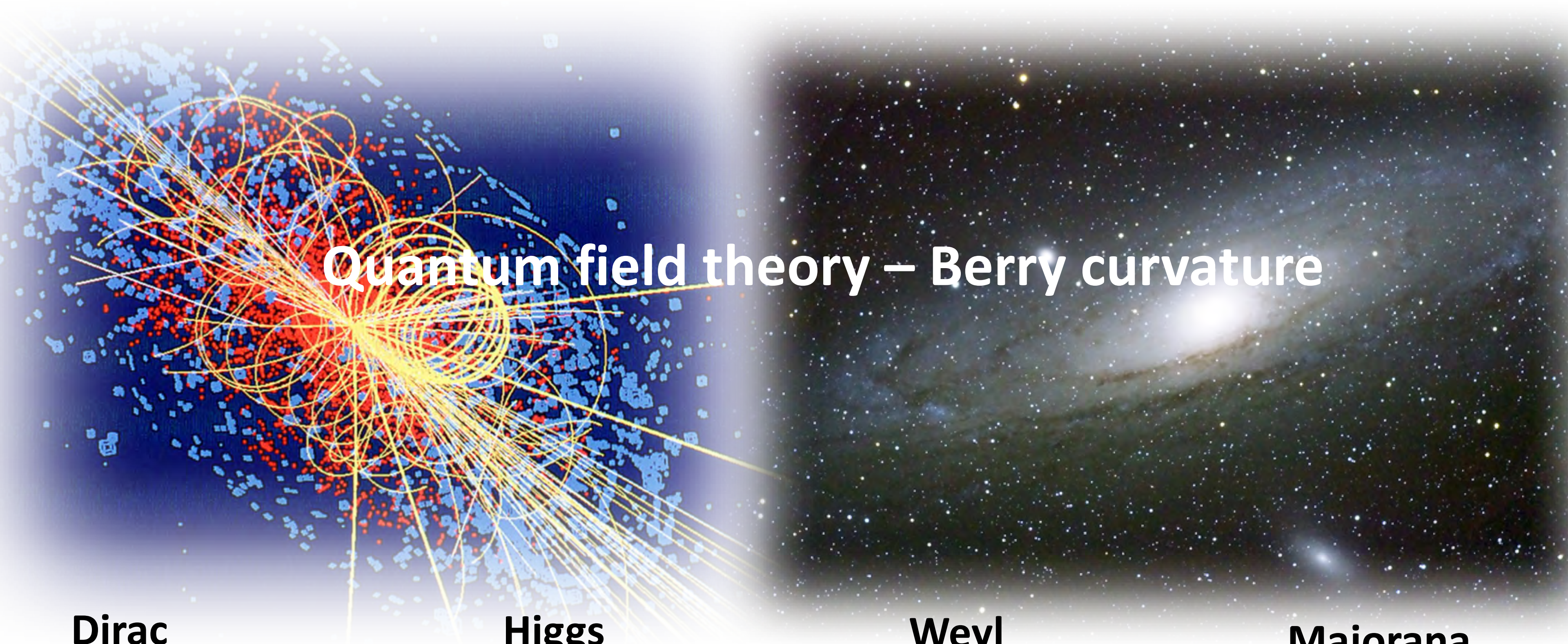
Relativistic effects

Darwin term

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

Barry Bradlyn, L. Elcoro, J. Cano, M. G. Vergniory, Z. Wang, C. Felser, M. I. Aroyo, B. A. Bernevig, Nature 547 (2017) 298

Particles – Universe –Condensed matter

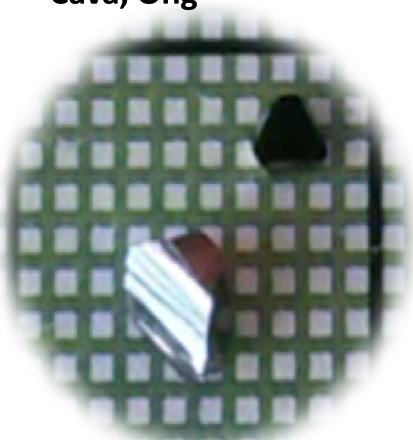


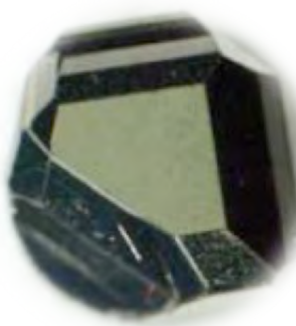
Dirac
Cd_3As_2
Cava, Ong

Higgs
$YMnO_3$
Lichtenberg Spaldin

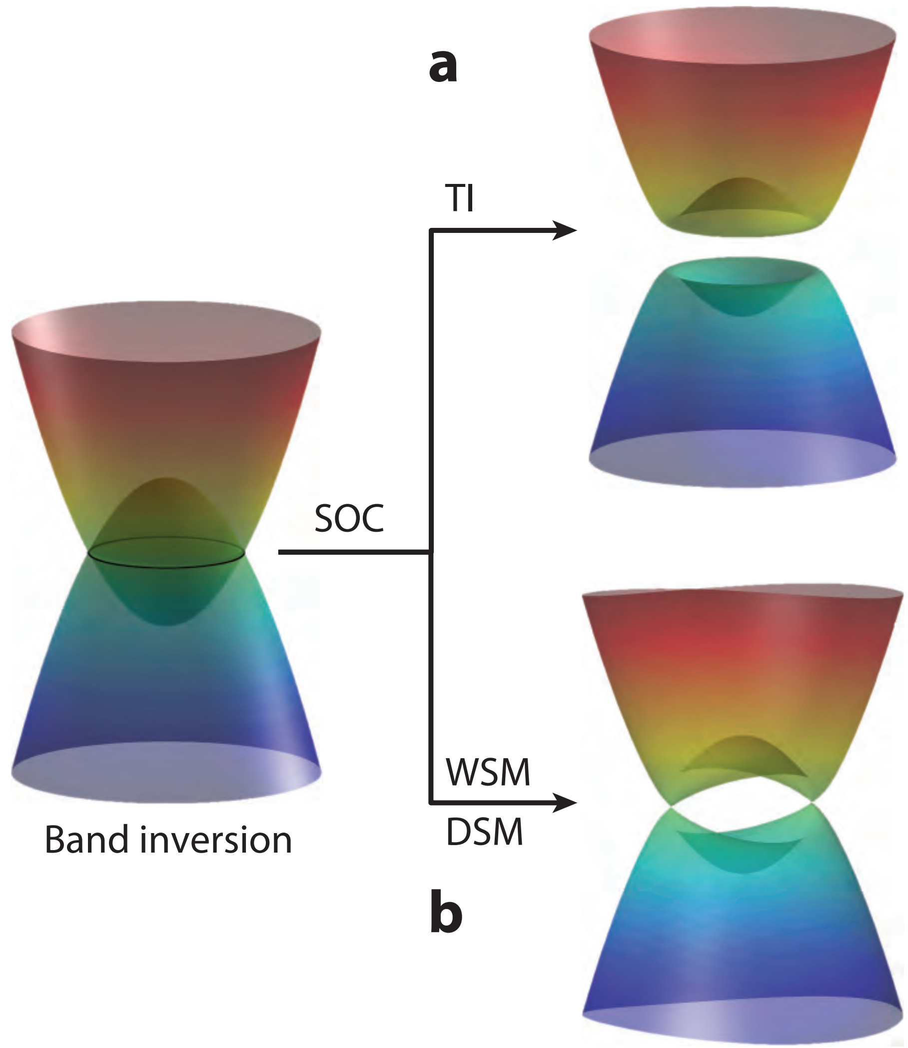
Weyl
NbP, WP2
Vicky Süss, Marcus Schmidt

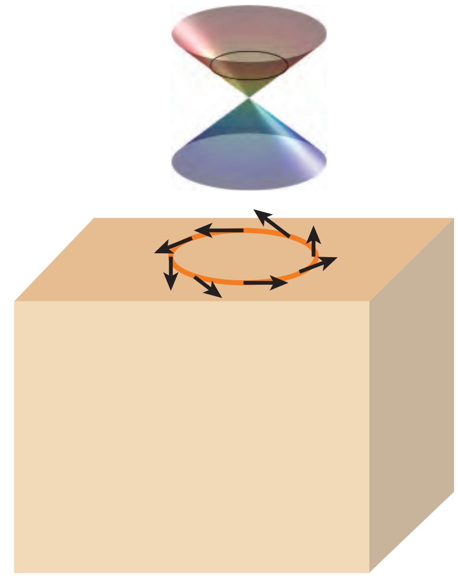
Majorana
YPtBi
Chandra Shekhar

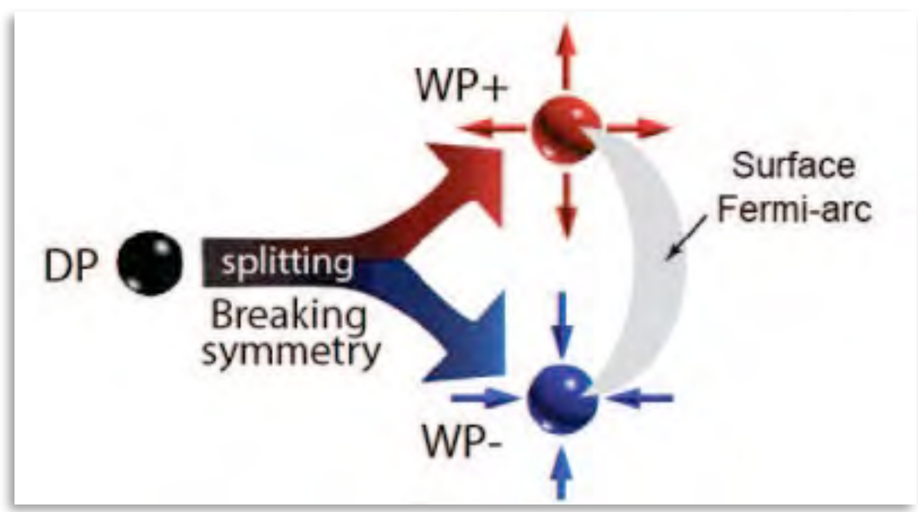




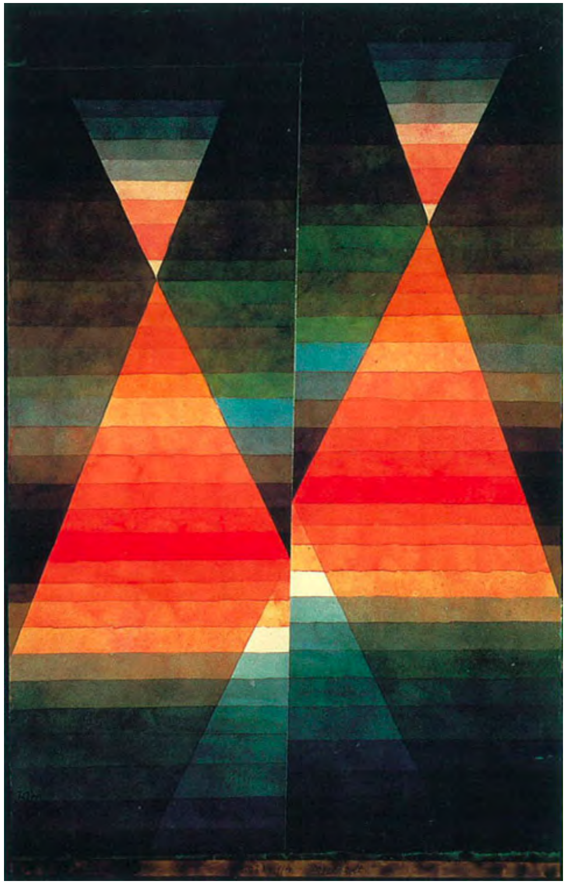
Weyl semimetals







Weyl Semimetals



Paul Klee

Weyl semimetals

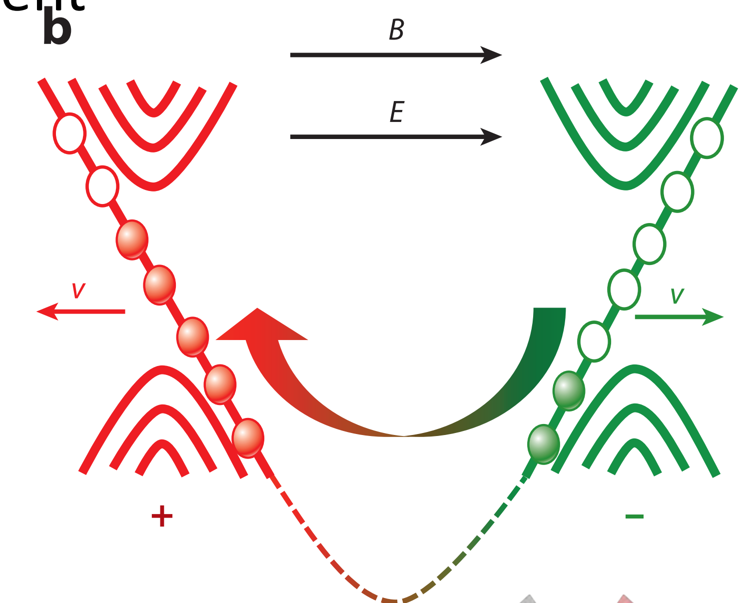
3D topological Weyl semimetals - breaking time reversal symmetry – in transport measurement
we should see:

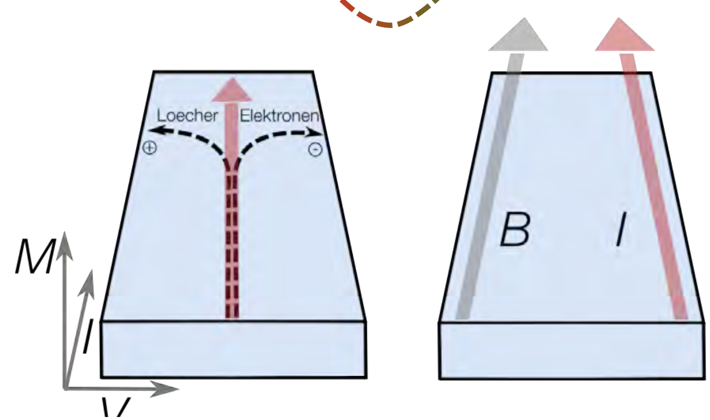
1. Fermi arc

2. Chiral anomaly

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

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



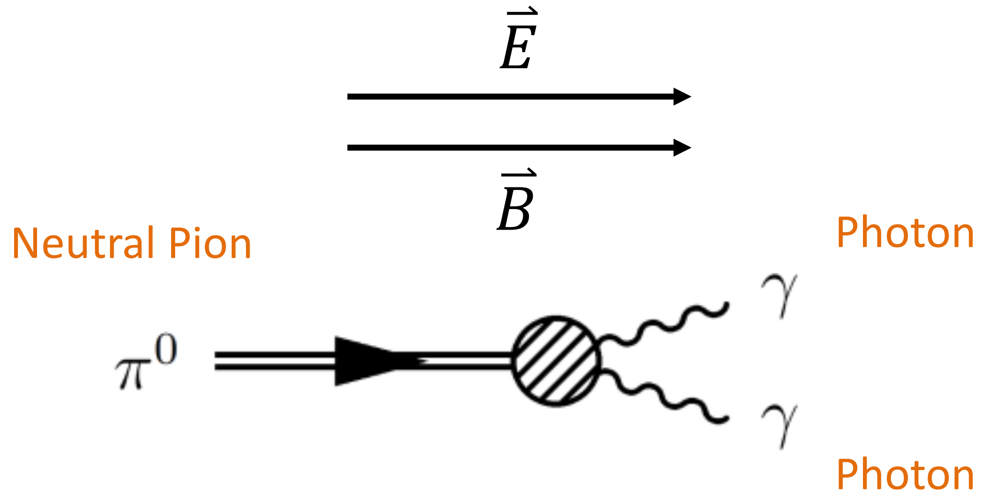


S. L. Adler, Phys. Rev. 177, 2426 (1969)
J. S. Bell and R. Jackiw, Nuovo Cim. A60, 47 (1969)
AA Zyuzin, AA Burkov - Physical Review B (2012)
AA Burkov, L Balents, PRL 107 12720 (2012)

Violation of chiral symmetry.

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

Pion decay:

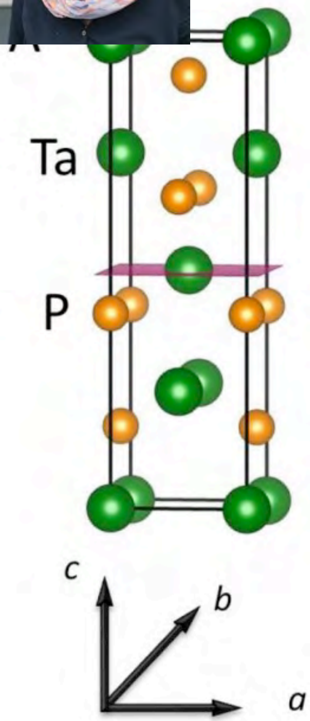


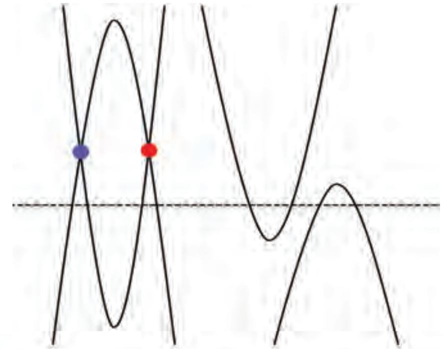
Electric charge: 0 | 0
Spin: half-integer | integer → Chiral anomaly

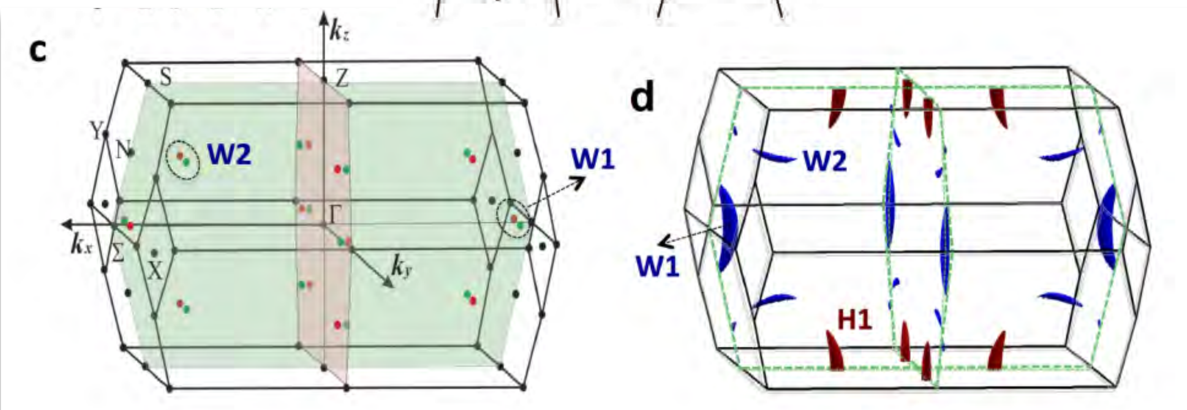
Adler, S. L. *Phys. Rev.* **177,** 5 (1969).
Bell, J. S. & Jackiw, R. *Nuovo Cim.* **A60,** 4 (1969)

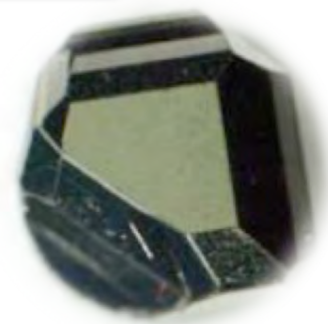
Weyl semimetals in non-centro NbP

NbP, NbAs,
TaP, TaAs









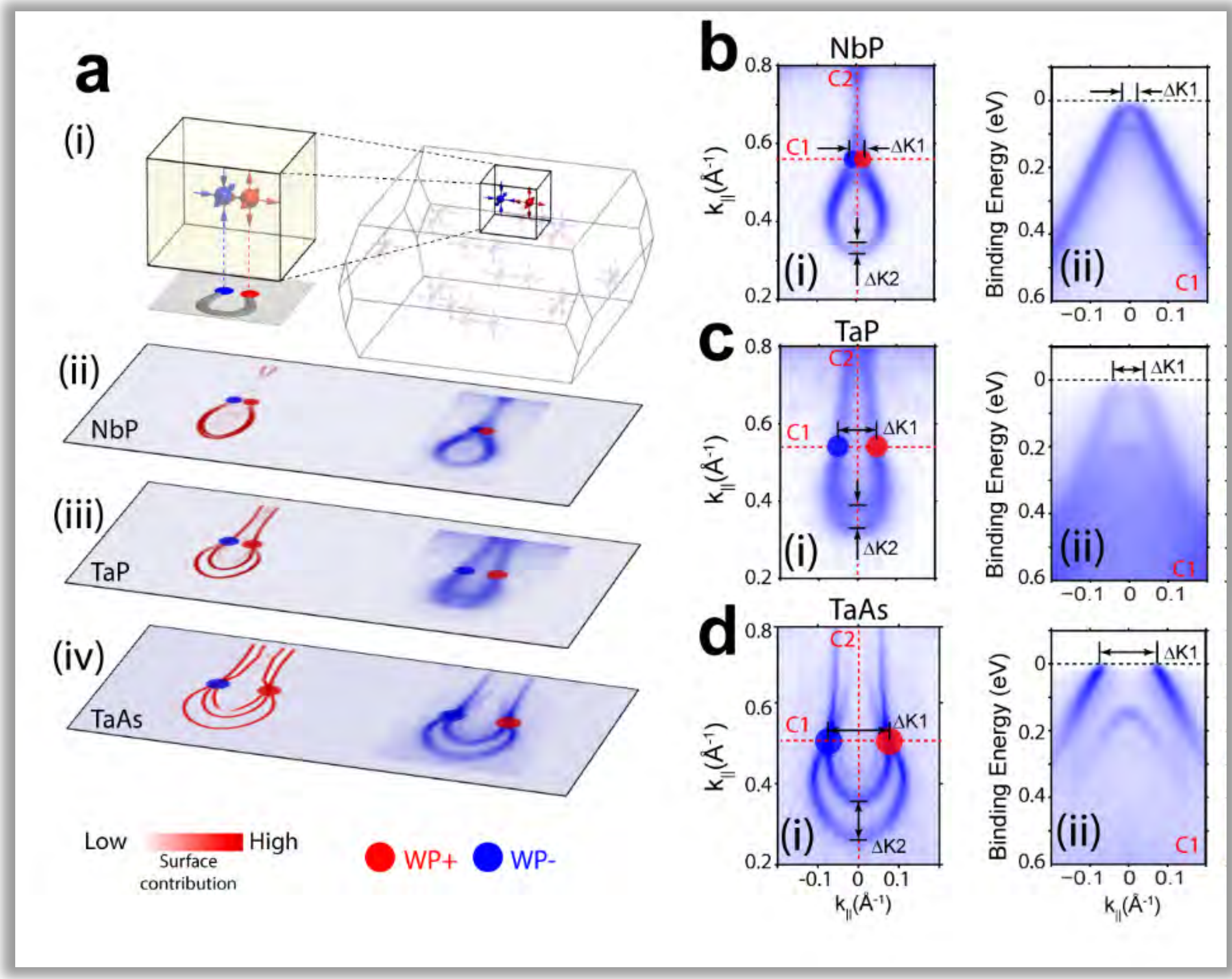
Shekhar, et al. , Nature Physics 11 (2015) 645,
Frank Arnold, et al. Nature Communication 7 (2016) 11615

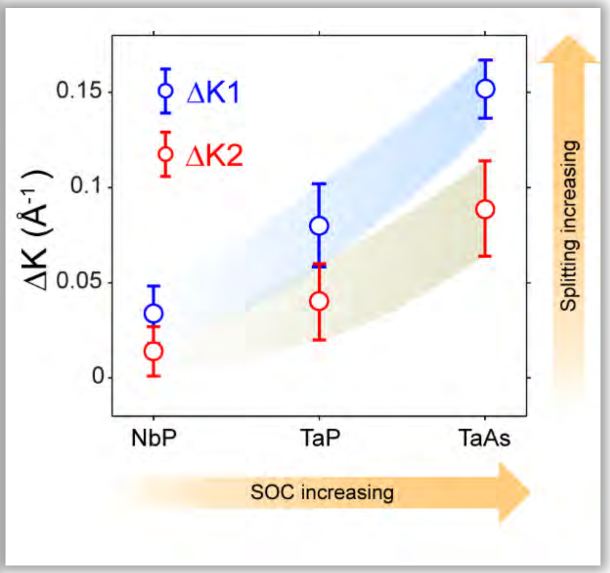
Weng, et al. Phys. Rev. X 5, 11029 (2015)
Huang et al. preprint arXiv:1501.00755

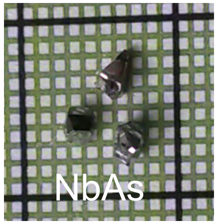
NbP, TaP, TaAs

Increasing spin orbit coupling increases – heavier elements

Distance between the Weyl points increases



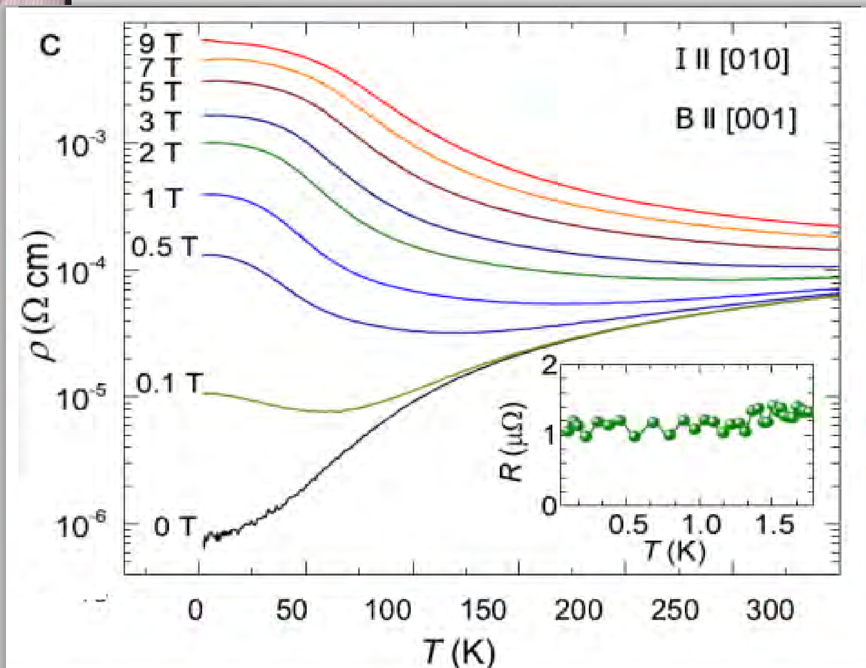


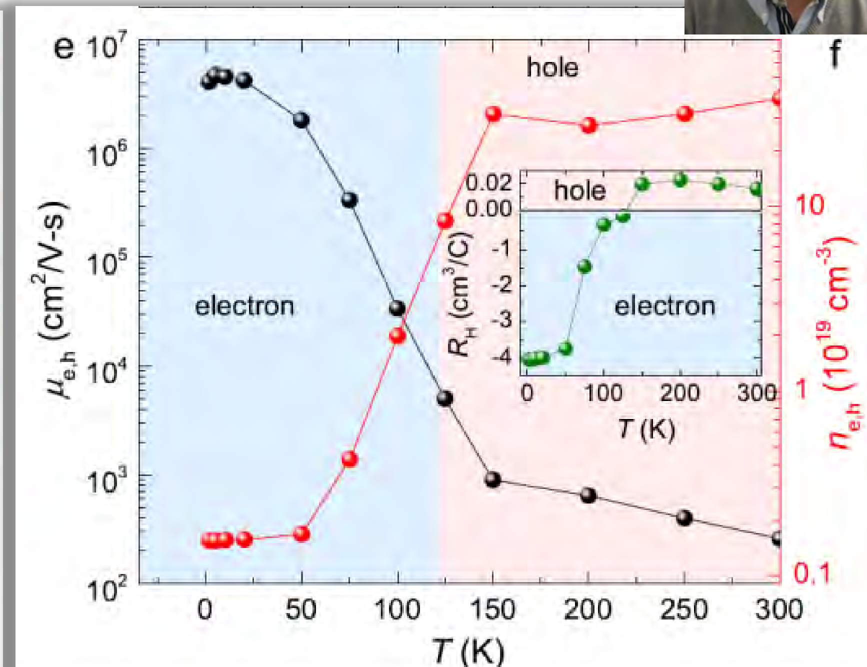


Z. K. Liu et al., Nature Mat. 15 (2016) 27

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

Weyl semimetals in non-centro NbP





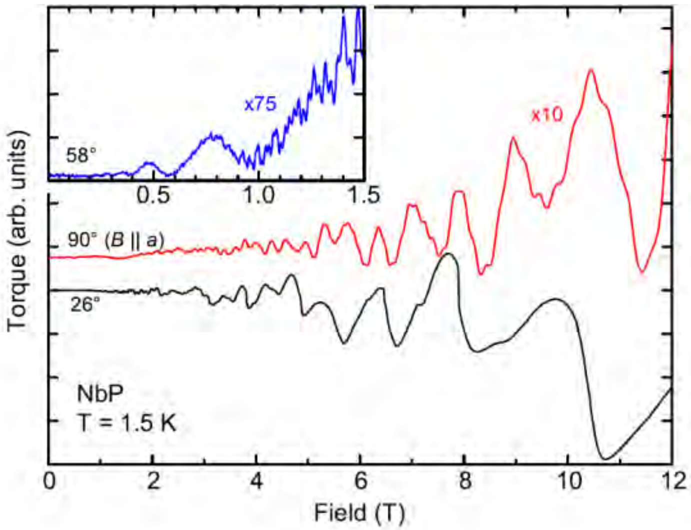
NbP is a topological Weyl semimetal

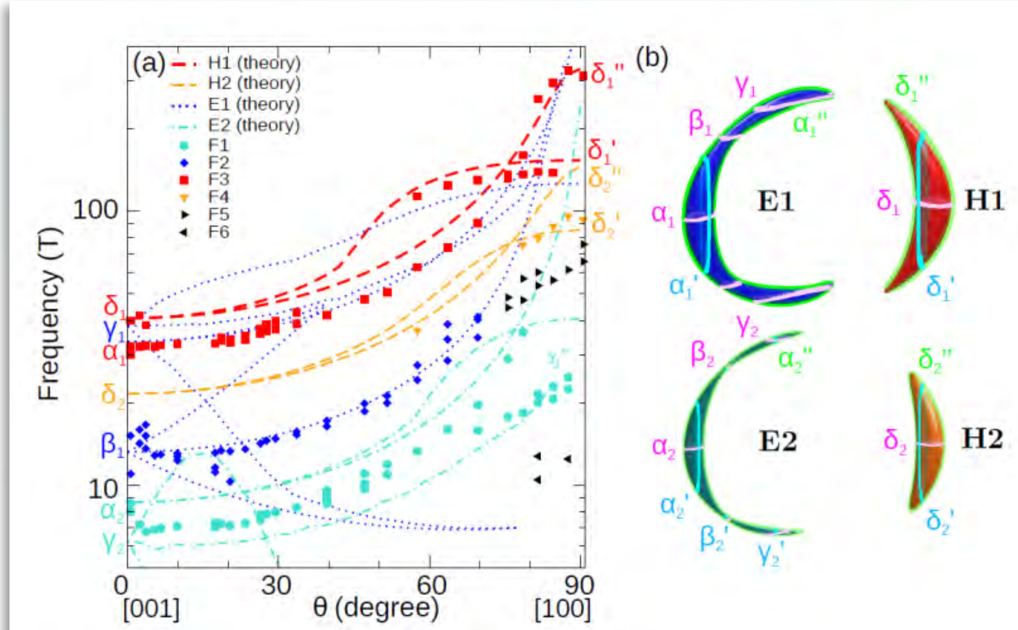
- with massless relativistic electrons
- extremely large magnetoresistance of **850,000%** at 1.85 K, 9T (250% at room temperature)
- an ultrahigh carrier mobility of **$5*10^6$ cm^2 / V s**

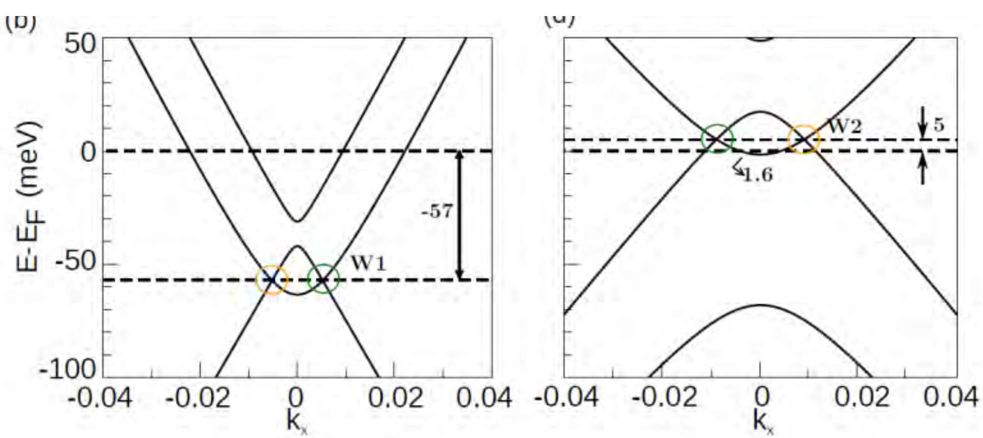
Shekhar, et al. , Nature Physics 11 (2015) 645,
Frank Arnold, et al. Nature Communication 7 (2016) 11615

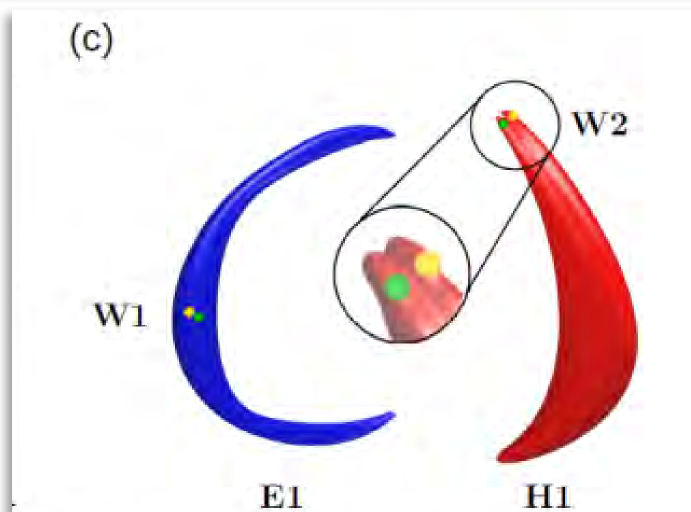
Weng, et al. Phys. Rev. X 5, 11029 (2015)
Huang . et al. preprint arXiv:1501.00755

NbP and the Fermi surface



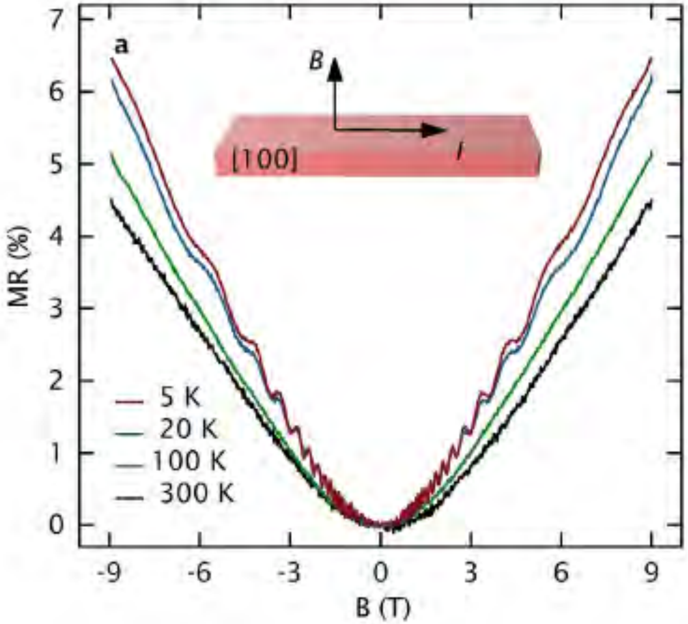


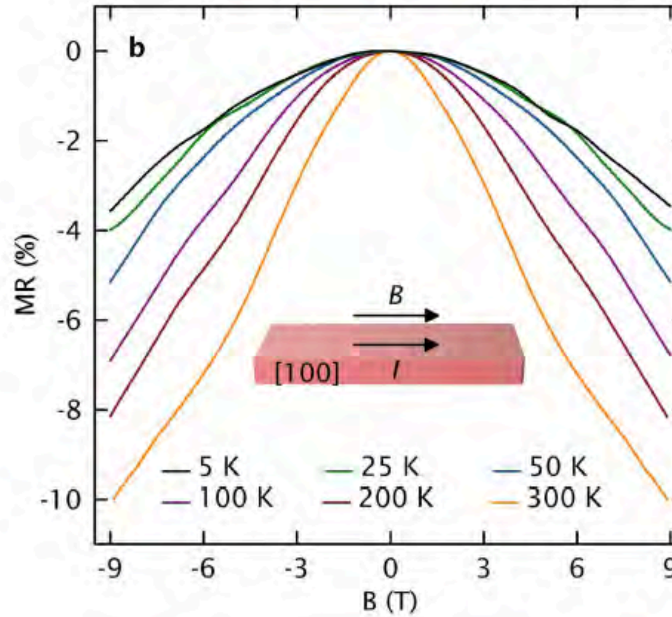


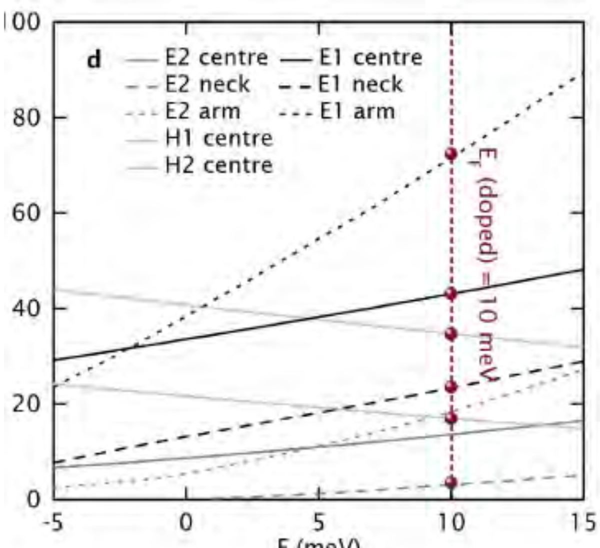


Klotz et al. Physical Review B 93 (2016) 121105(R)

Chiral Anomaly





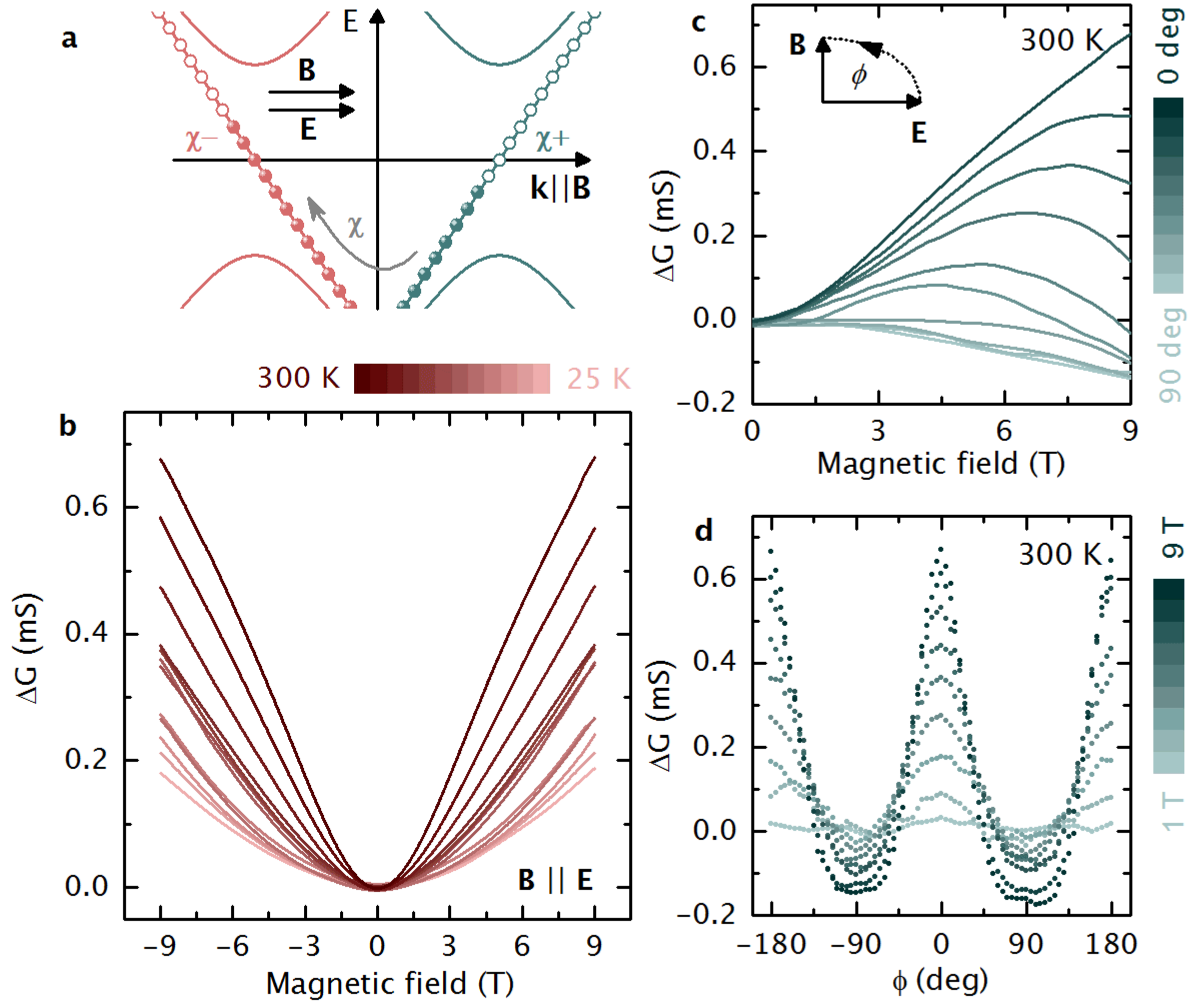


Ga-doping relocate the Fermi energy in NbP close to the W2 Weyl points

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

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

Longitudinal magneto-transport – E||B

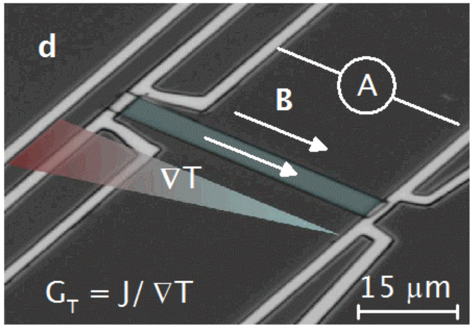


The PMC is locked to E||B, as expected for Chiral anomaly.

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

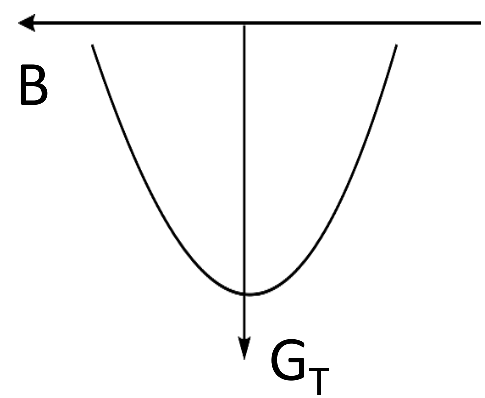
Experimental signatures for the mixed axial-gravitational anomaly in Weyl semimetals

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



- Low fields: quadratic

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

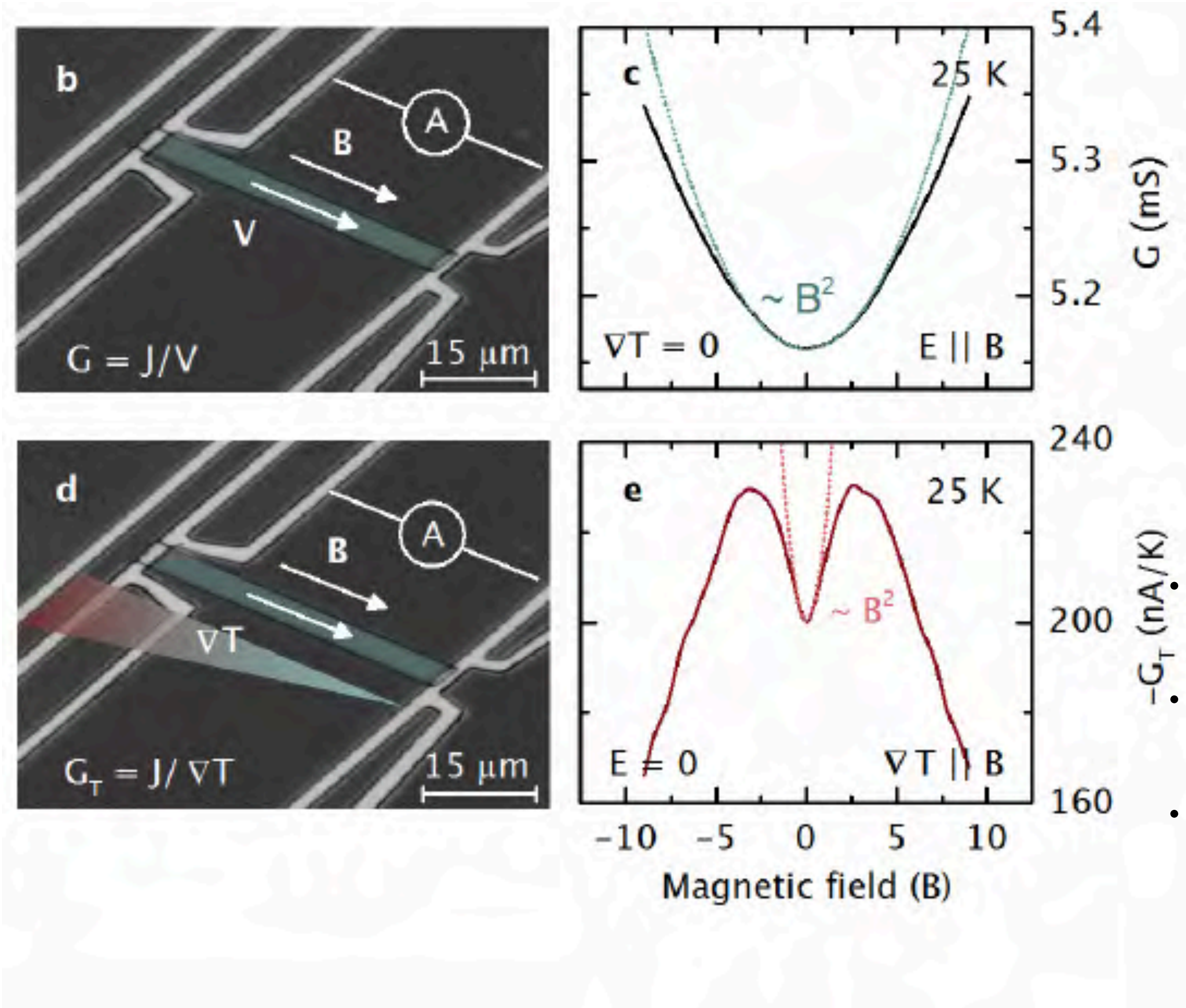


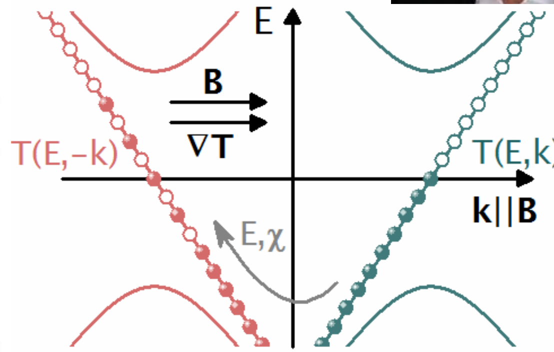
- High fields: deminishes

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

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

Gravitational Anomaly



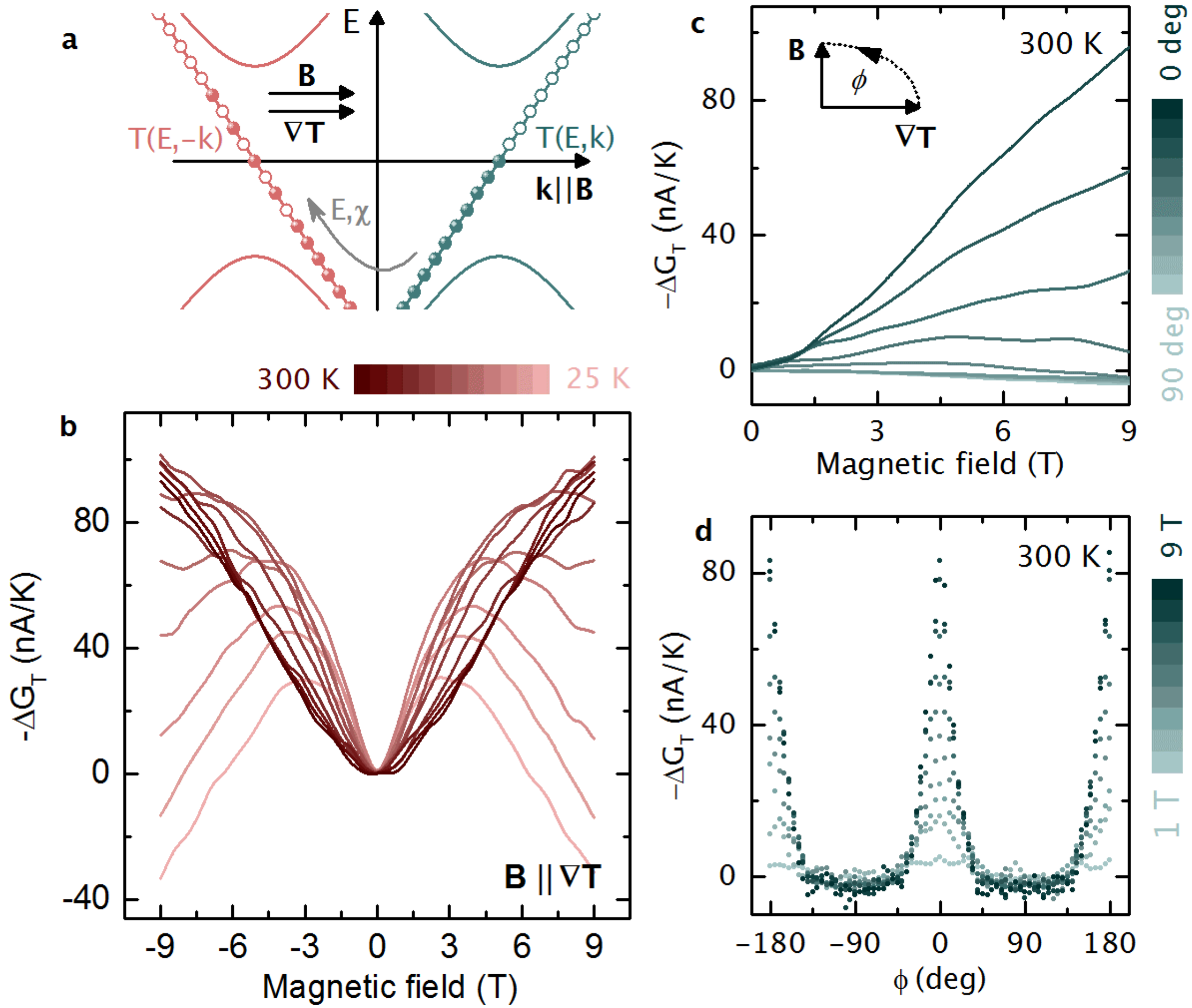


- Landsteiner, et al. Gravitational anomaly and transport phenomena. Phys. Rev. Lett. 107, 021601 (2011). URL
- Jensen, et al. Thermodynamics, gravitational anomalies and cones. Journal of High Energy Physics 2013, 88 (2013).
- Lucas, A., Davison, R. A. & Sachdev, S. Hydrodynamic theory of thermoelectric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

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

Johannes Gooth et al. Experimental signatures of the gravitational anomaly in the Weyl semimetal NbP, Nature (2017) arXiv:1703.10682

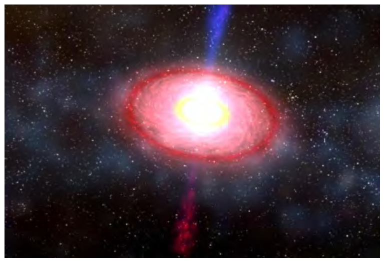
Longitudinal magneto-transport – E||B



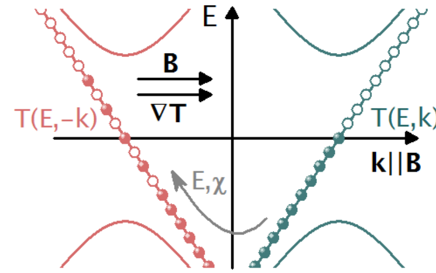
The PMTC is locked to ΔT||B, as expected for mixed-axial-gravitational anomaly.

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

Axial-gravitational anomaly



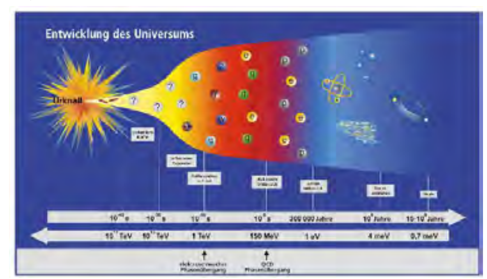
Neutron stars
(astronomy)



Positive MTG in Weyl semimetals
(solid state physics)

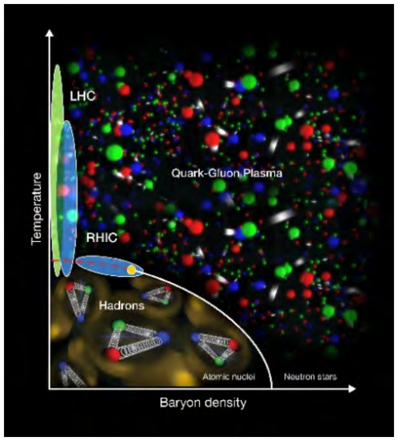
Mixed-axial-gravitational anomaly in AdS/CFT

Pion decay



Baryogenesis in early universe
(cosmology)

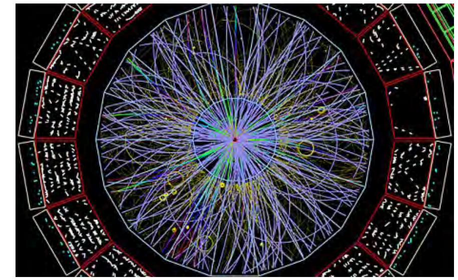
Holographic correspondence



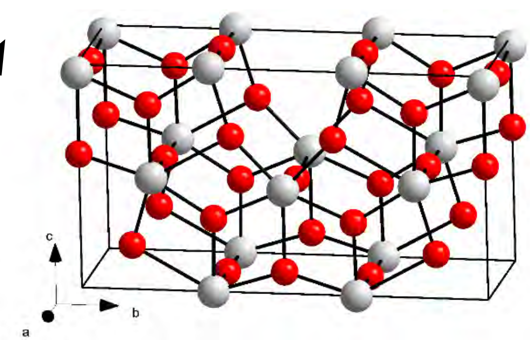
Baryogenesis
(cosmology)

Neutron stars
(astronomy)

Anti-de-Sitter space/
conformal field theory
(AdS/CFT)
correspondence



Quark-gluon plasma
(colliders)



Condensed matter

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

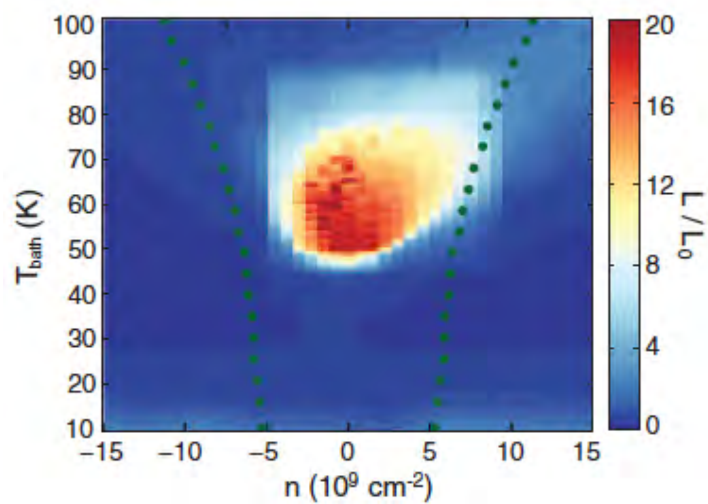
Negative local resistance caused by viscous electron backflow in graphene

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)

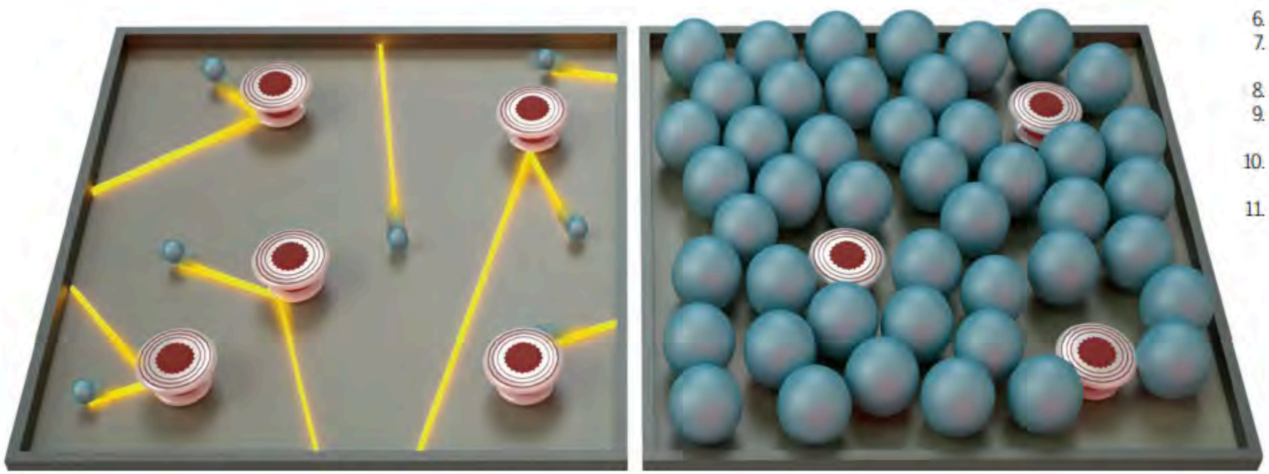
Hydrodynamic electron flow is experimentally observed in the differential resistance of electrostatically defined wires in the two-dimensional electron gas in (Al,Ga)As heterostructures. In these experiments current heating is used to induce a controlled increase in the number of electron-electron collisions 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.

Hydrodynamics

PHYSICS

Electrons go with the flow in exotic material systems

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



REFERENCES

1. J. Crossno, J. K. Shi, K. Wang, X. Liu, A. Harzheim, A. Lucas, S. Sachdev, P. Kim, T. Taniguchi, K. Watanabe, T. A. Ohki, K. C. Fong, *Science* **351**, 1058 (2016).
2. D. A. Bandurin, I. Torre, R. Krishna Kumar, M. Ben Shalom, A. Tomadin, A. Principi, G. H. Auton, E. Khestanova, K. S. Novoselov, I. V. Grigorieva, L. A. Ponomarenko, A. K. Geim, M. Polini, *Science* **351**, 1055 (2016).
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4. J. Zaanen, Y.-W. Sun, Y. Liu, K. Schalm, *Holographic Duality in Condensed Matter Physics* (Cambridge Univ. Press, 2015).
5. S. A. Hartnoll, P. K. Kovtun, M. Mueller, S. Sachdev, *Phys. Rev. B* **76**, 144502 (2007).
6. A. H. Castro Neto *et al.*, *Rev. Mod. Phys.* **81**, 109 (2009).
7. M. Mueller, J. Schmalian, L. Fritz, *Phys. Rev. Lett.* **103**, 025301 (2009).
8. M. S. Foster, I. L. Aleiner, *Phys. Rev. B* **79**, 085415 (2009).
9. A. Lucas, J. Crossno, K. C. Fong, P. Kim, S. Sachdev, http://arxiv.org/abs/1510.01738 (2015).
10. L. Levitov, G. Falkovich, http://arxiv.org/abs/1508.00836 (2015).
11. M. J. M. de Jong, L. W. Molenkamp, *Phys. Rev. B* **51**, 13389 (1995).

- 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

Weyl Semimetals

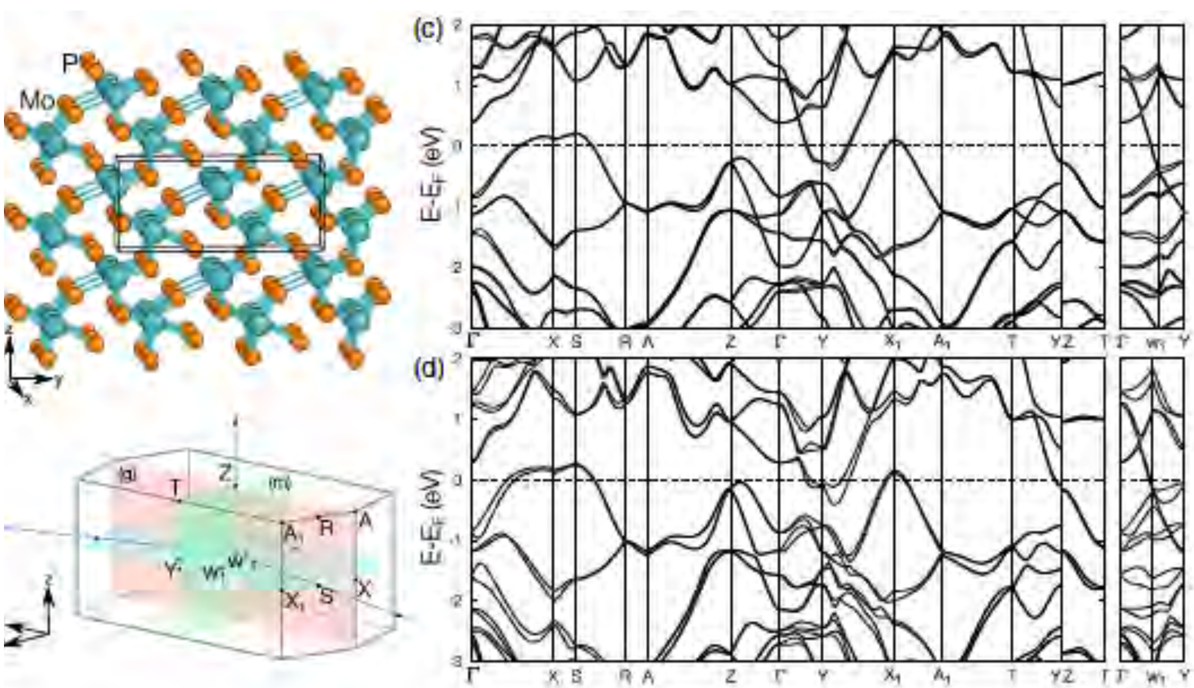
WP2

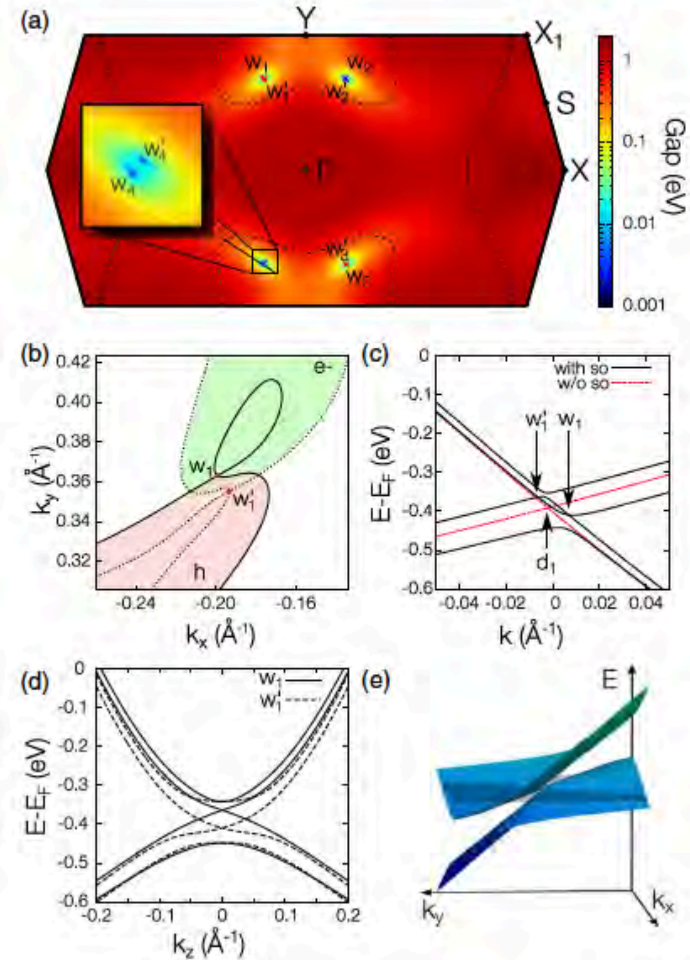
WP_2 protected Weyl

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)

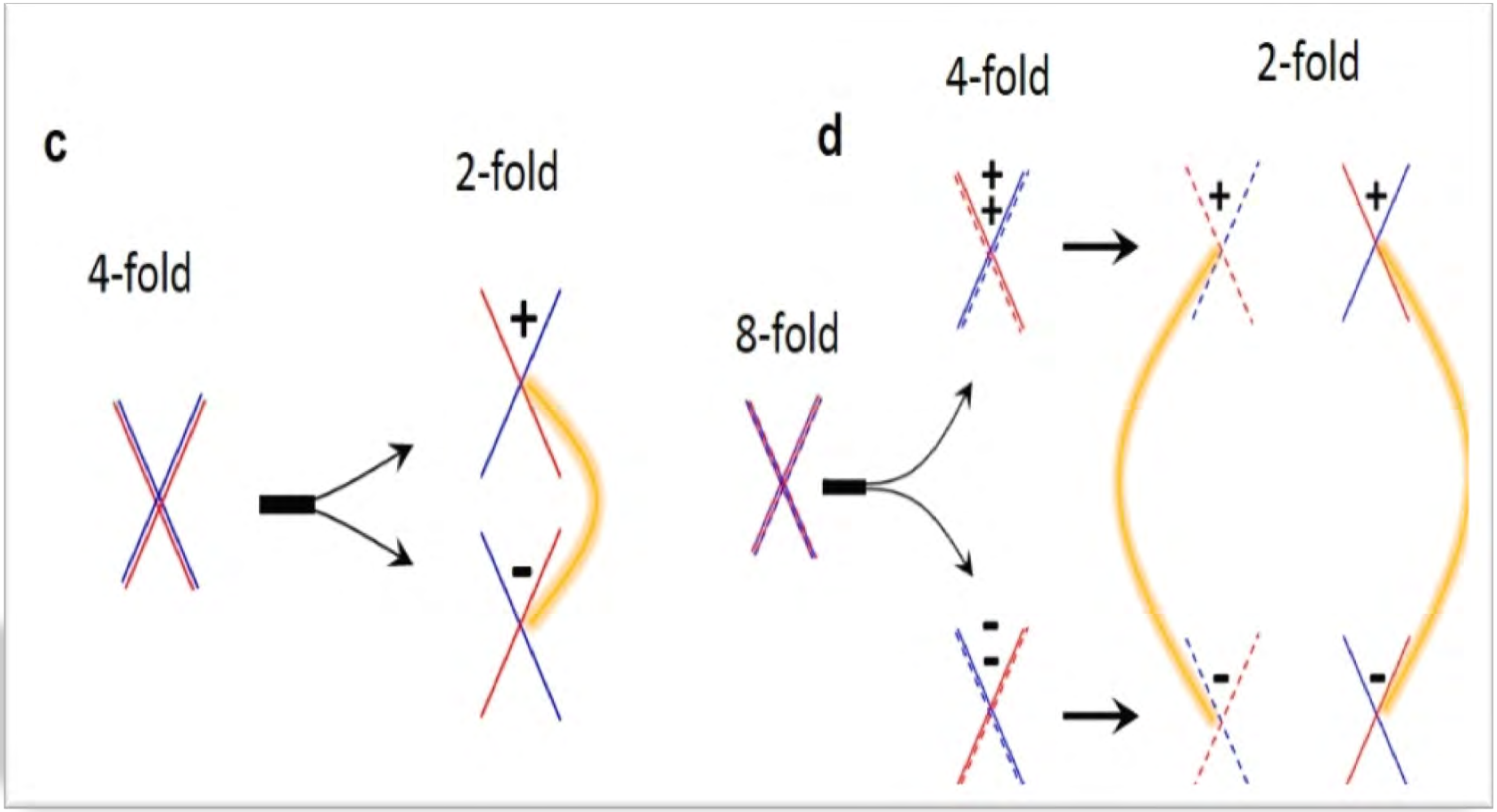
G. Autès,[1,2] D. Gresch,[3] M. Troyer,[3] A. A. Soluyanov,[3,4] and O. V. Yazyev[1,2]





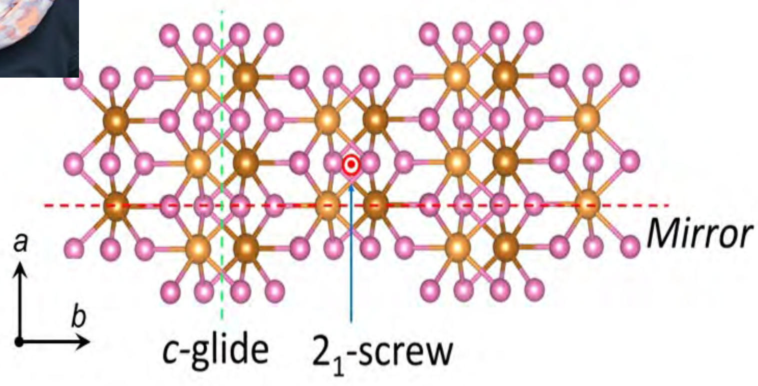
Prediction: G. Autès, et al.; Phys. Rev. Lett. 117 (2016) 066402

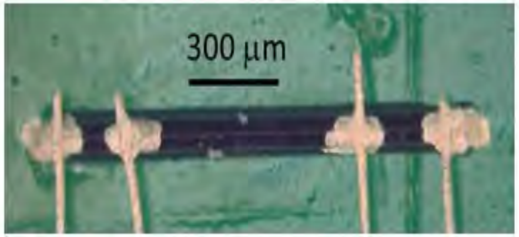
WP_2 protected Weyl

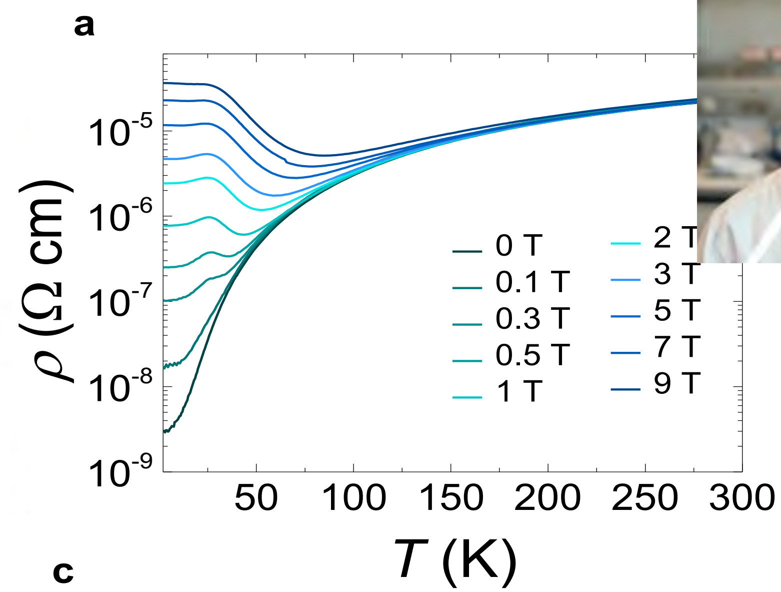


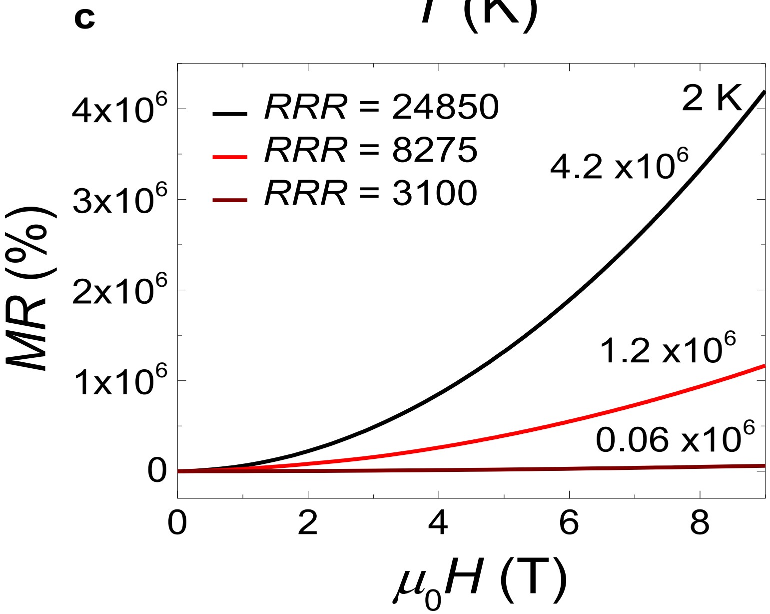
Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; arXiv:1703.04527

WP$_2$ protected Weyl



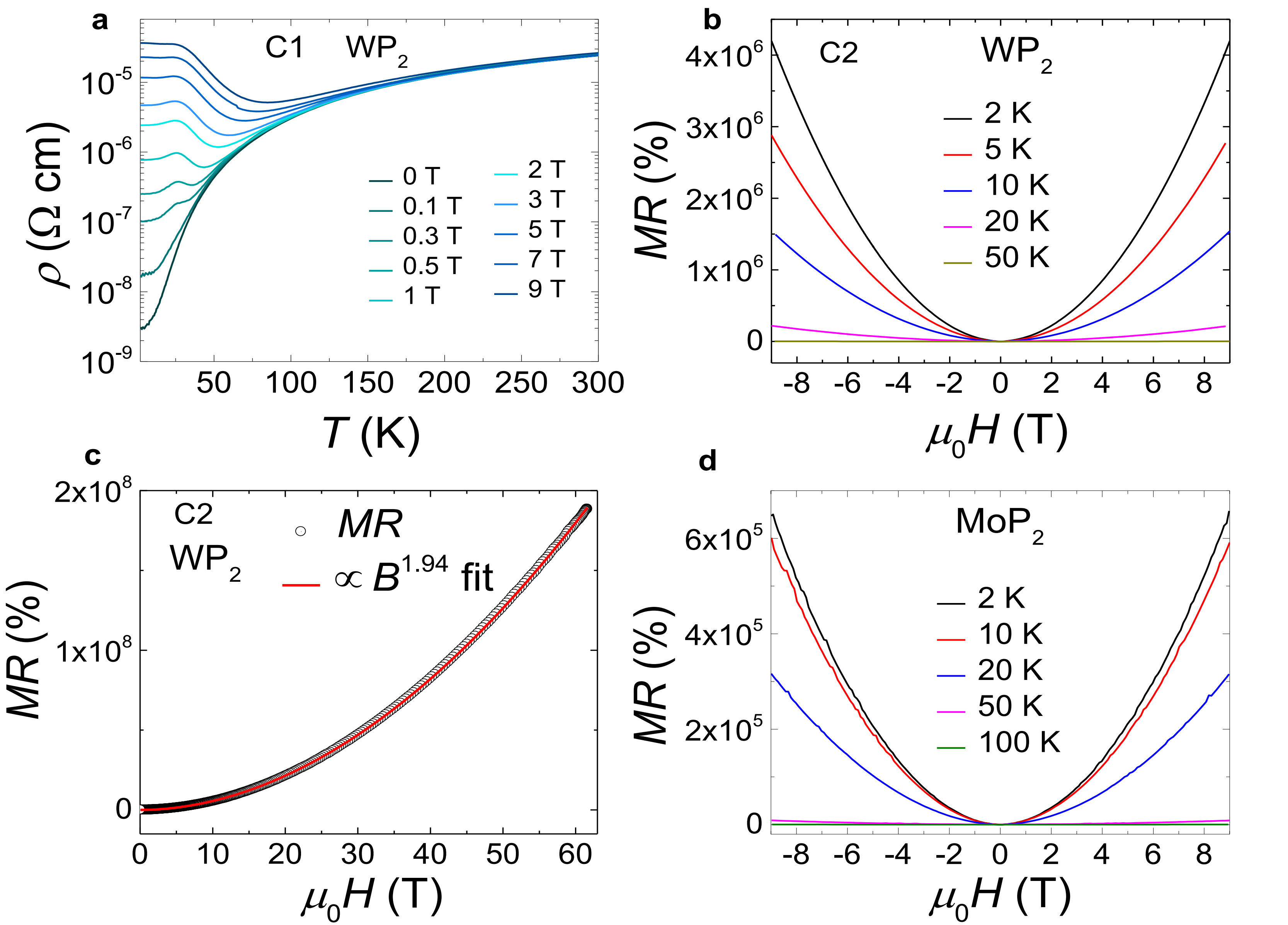






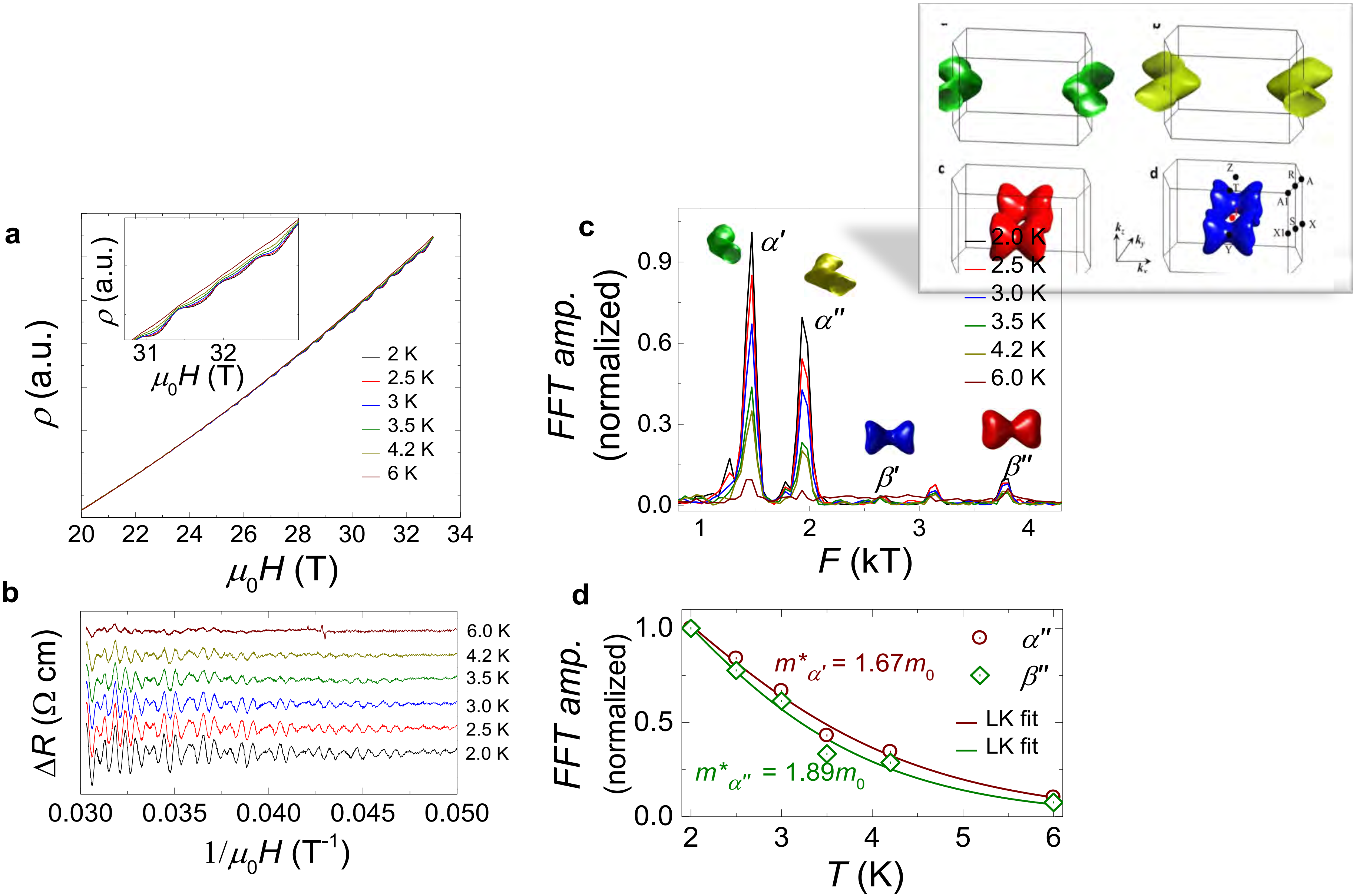
Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; arXiv:1703.04527

MoP_2 and WP_2



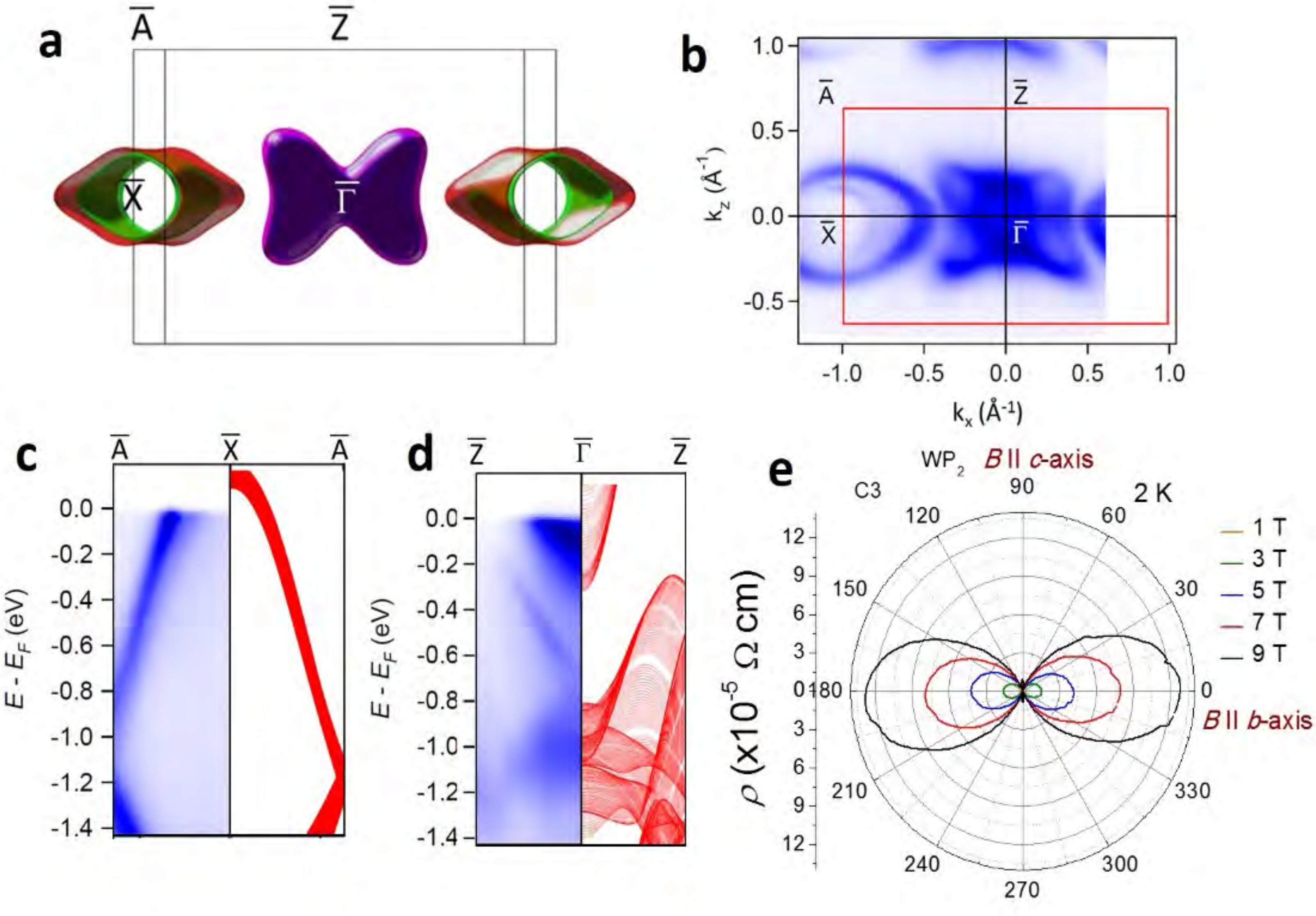
Extremely high magnetoresistance and conductivity in the type-II Weyl semimetal WP2, Nitesh, et al.; arXiv:1703.04527

WP_2 protected Weyl



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

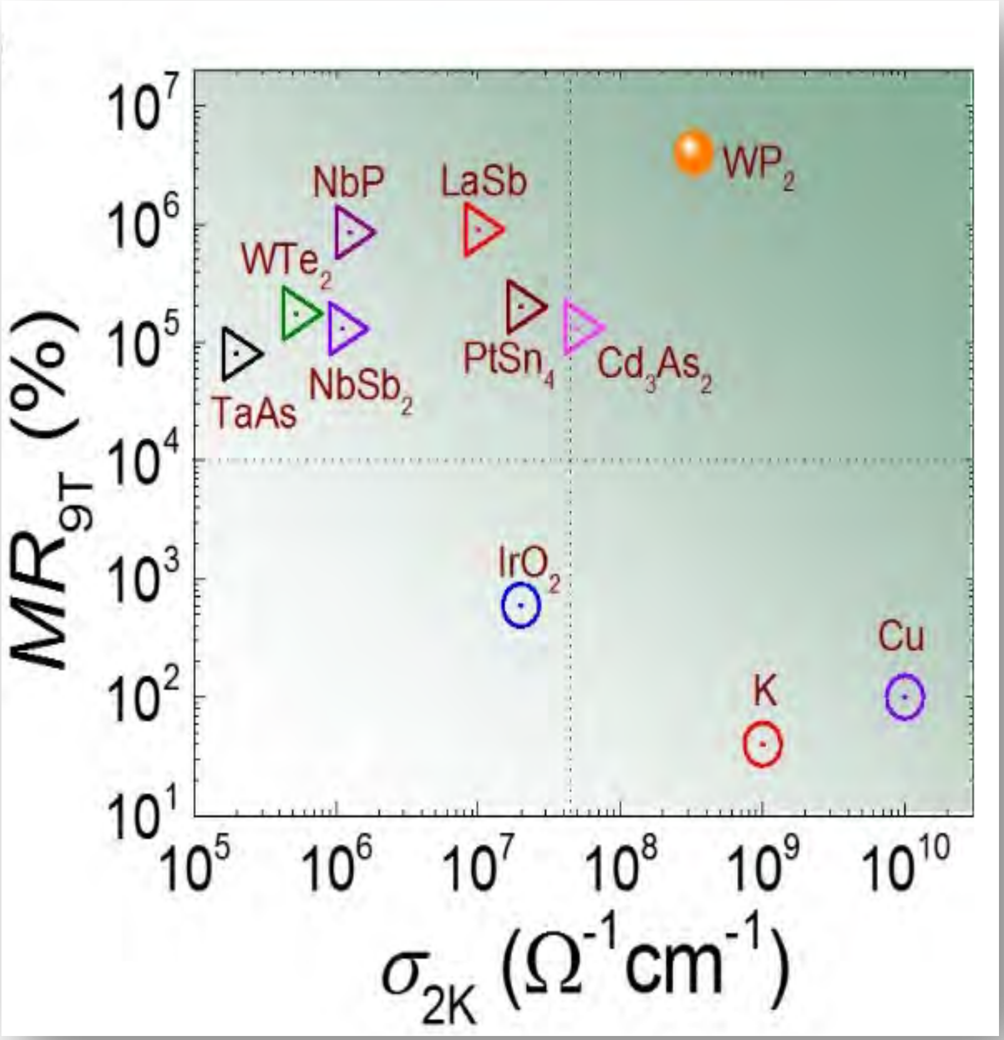
ARPES and the band structure



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



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}
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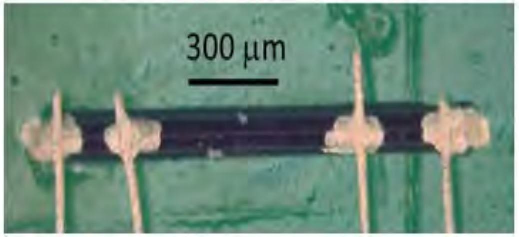


WC J. B. He et al. arXiv:1703.03211
Pallavi Kushwaha, et al. Sci. Adv.1 (2015) e150069
P. Moll Science 351, (2016) 1061

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

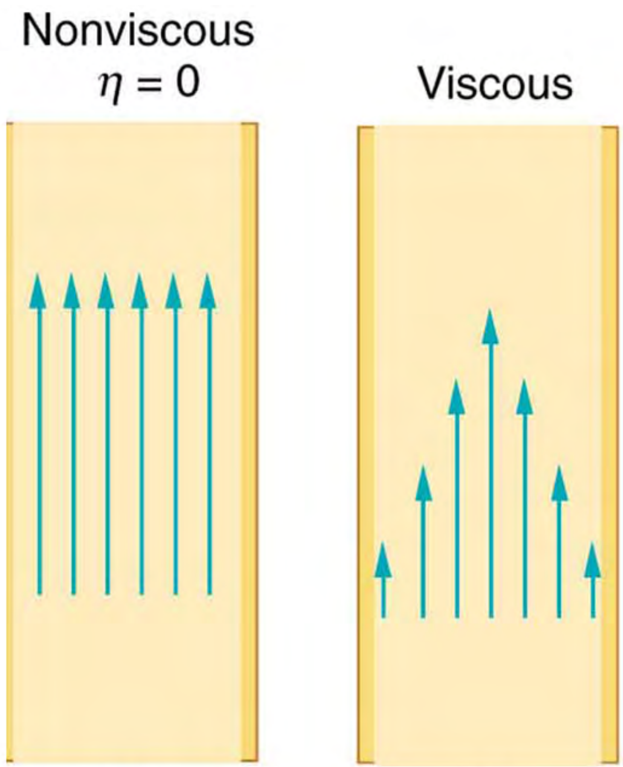
In the Navier-Stokes flow limit: $\rho = m^*/(e^2 n) \cdot 12 \eta w^{-2}$

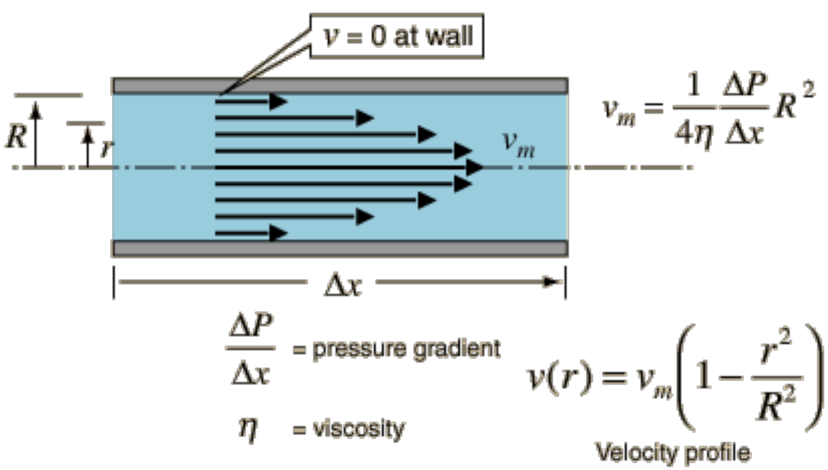
R. N. Gurzhy, A. N. Kalinenko, A. I. Kopeliovich, Hydrodynamic effects in the electrical conductivity of impure metals. *Sov. Physics-JETP*. **69**, 863–870 (1989).

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

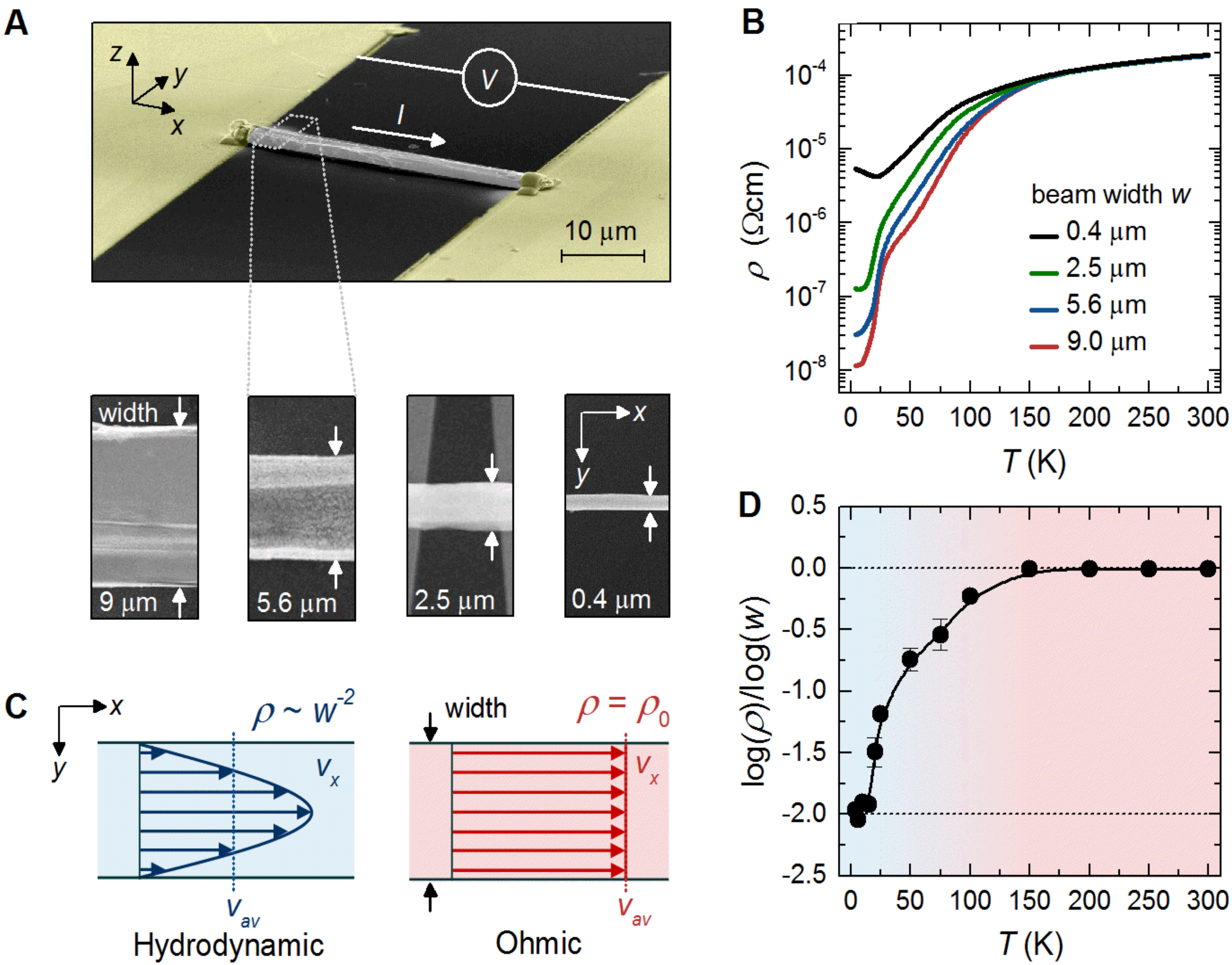
T. Scaffidi, N. Nandi, B. Schmidt, A. P. Mackenzie, J. E. Moore, Hydrodynamic Electron Flow and Hall Viscosity. *Phys. Rev. Lett.* **118**, 226601 (2017).

Water, Gas or Electrons



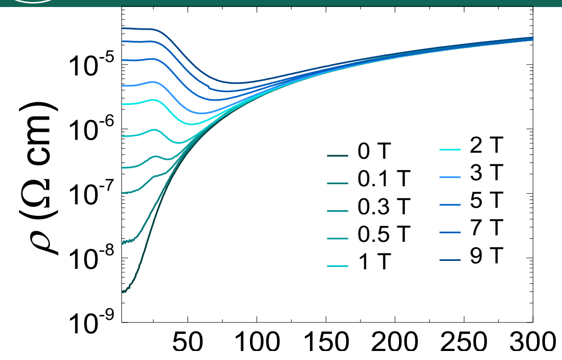


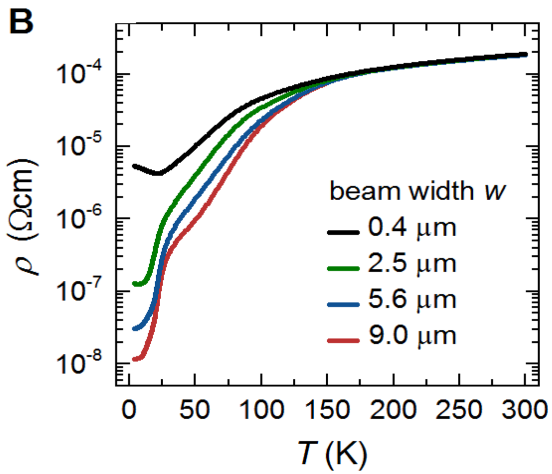
Hydrodynamic flow

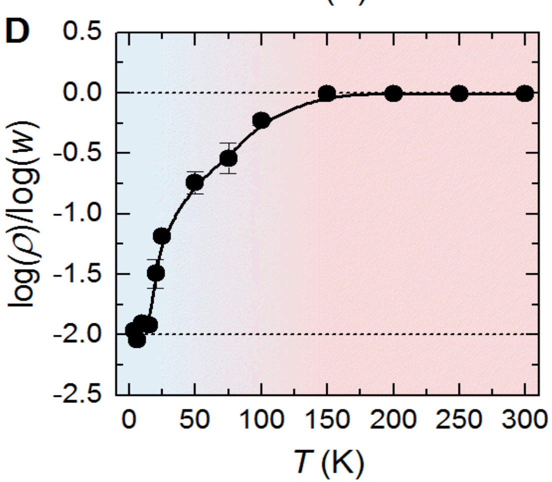


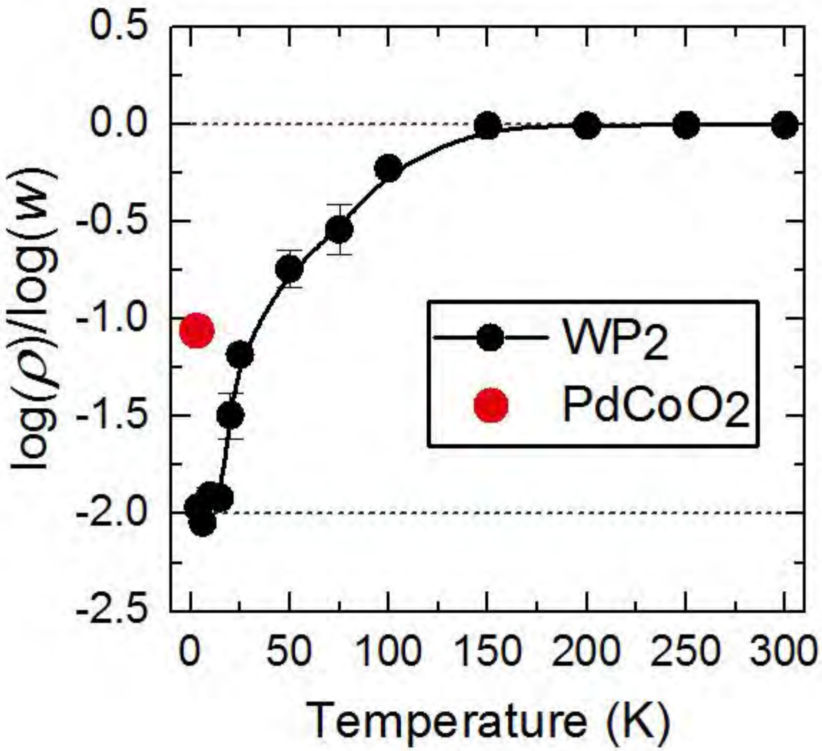
J. Gooth et al. preprint, arXiv:1706.05925

Hydrodynamic flow





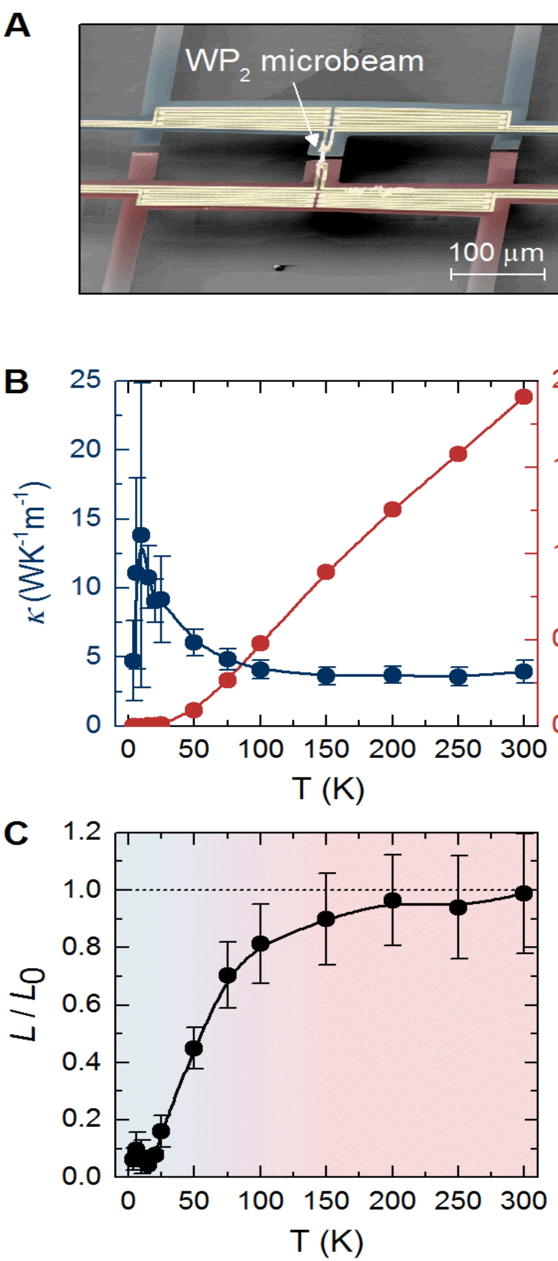


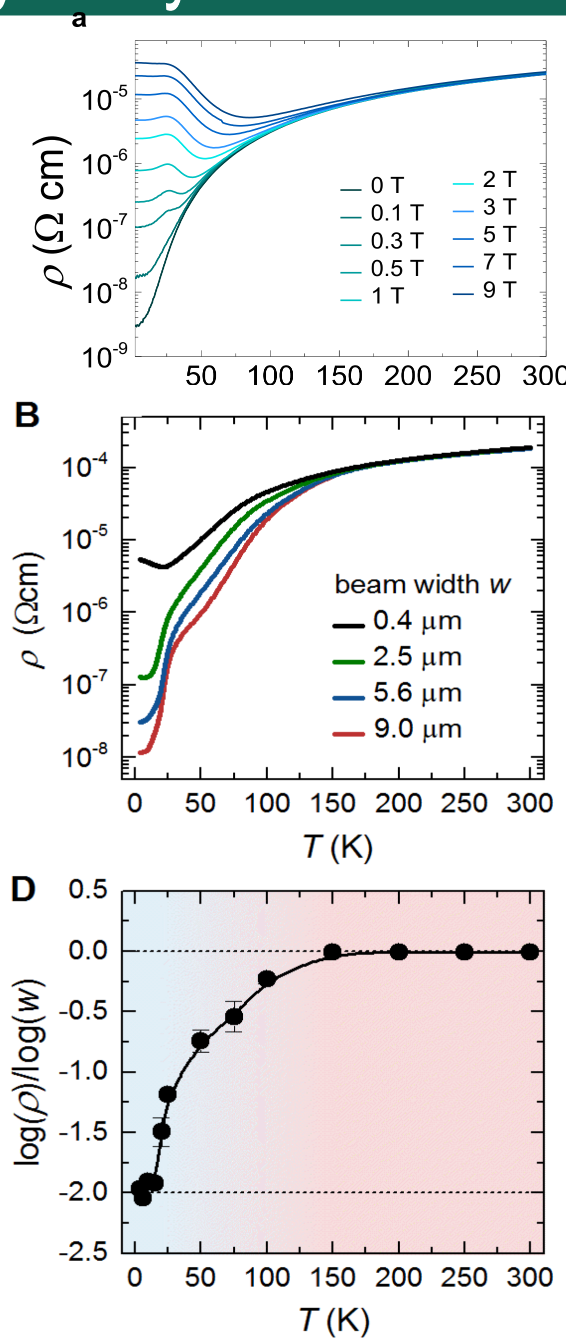


P. J. W. Moll *et al.*, *Science* 10.1126/science.aac8385 (2016).

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
- But independent of the thermal conductivity

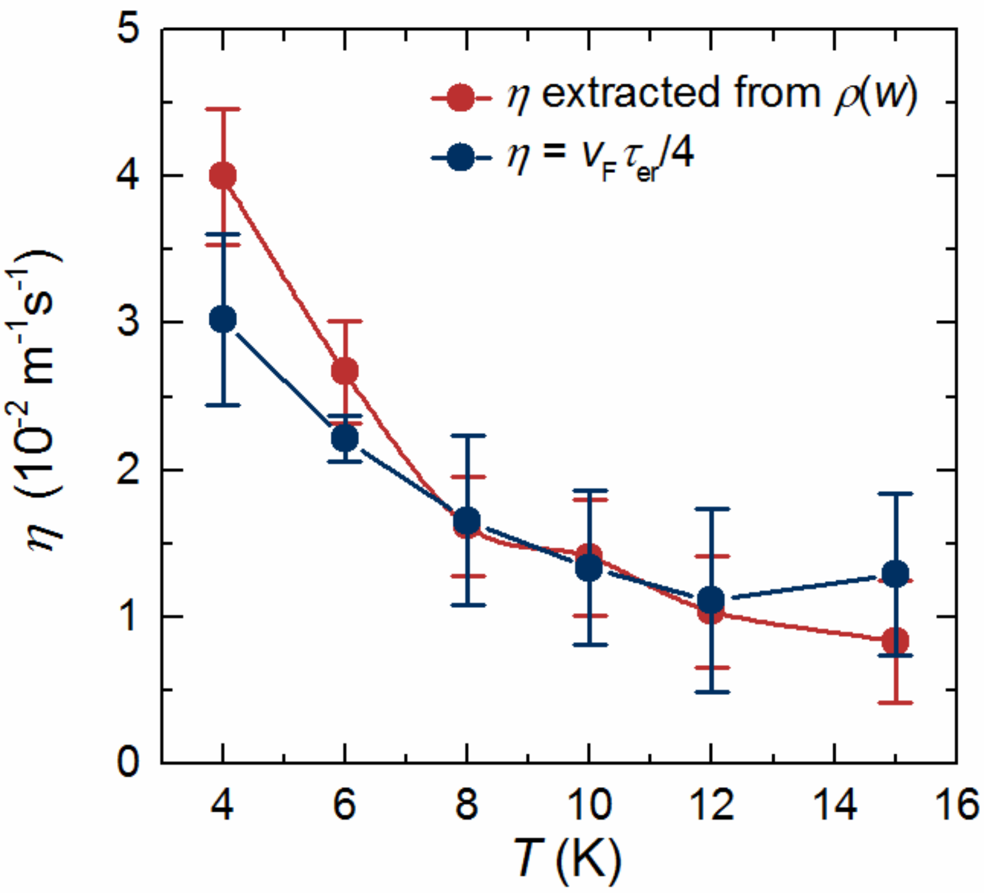
$$\rho = m^*/(e^2 n)\cdot 12\eta w^{-2}$$

- a strong violation of the Wiedemann-Franz law

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

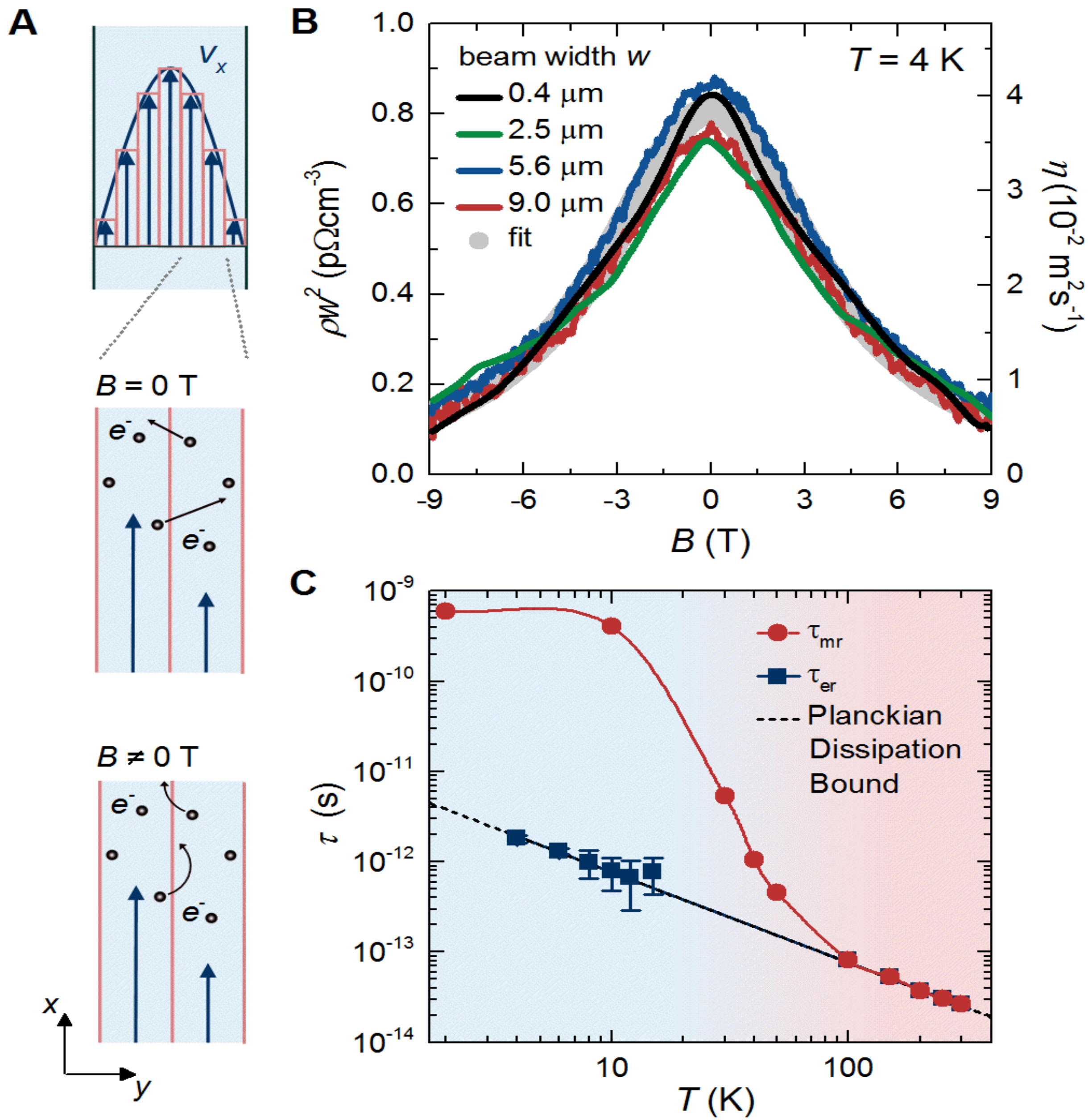
J. Gooth et al. submitted, arXiv:1706.05925

Viscosity of the electron fluid in WP_2



The dynamic viscosity is η_D = 1×10^{-4} kgm^{-1}s^{-1} at 4 K.

Magnetohydrodynamics, Planckian bound of dissipation



Grey dots: the magneto-hydrodynamic model in the Navier-Stokes flow limit

Momentum relaxation times t_{mr}

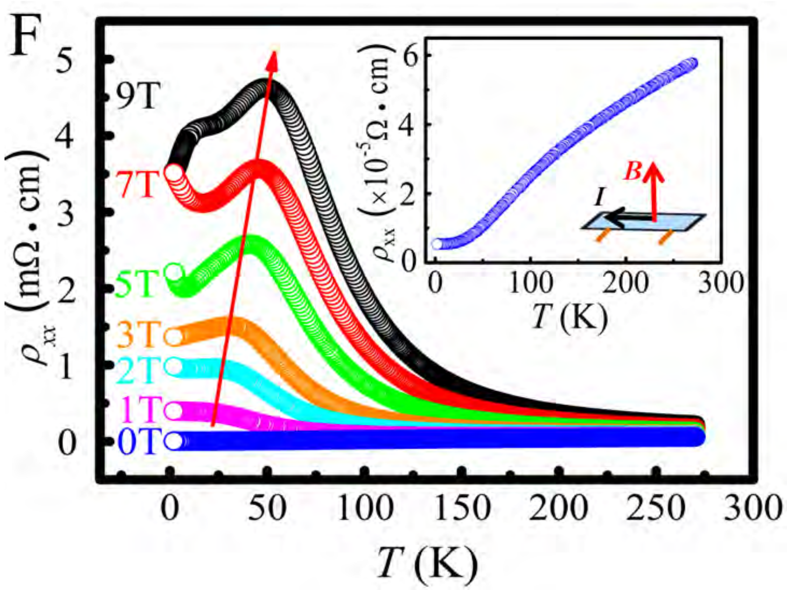
Thermal energy relaxation times t_{er},

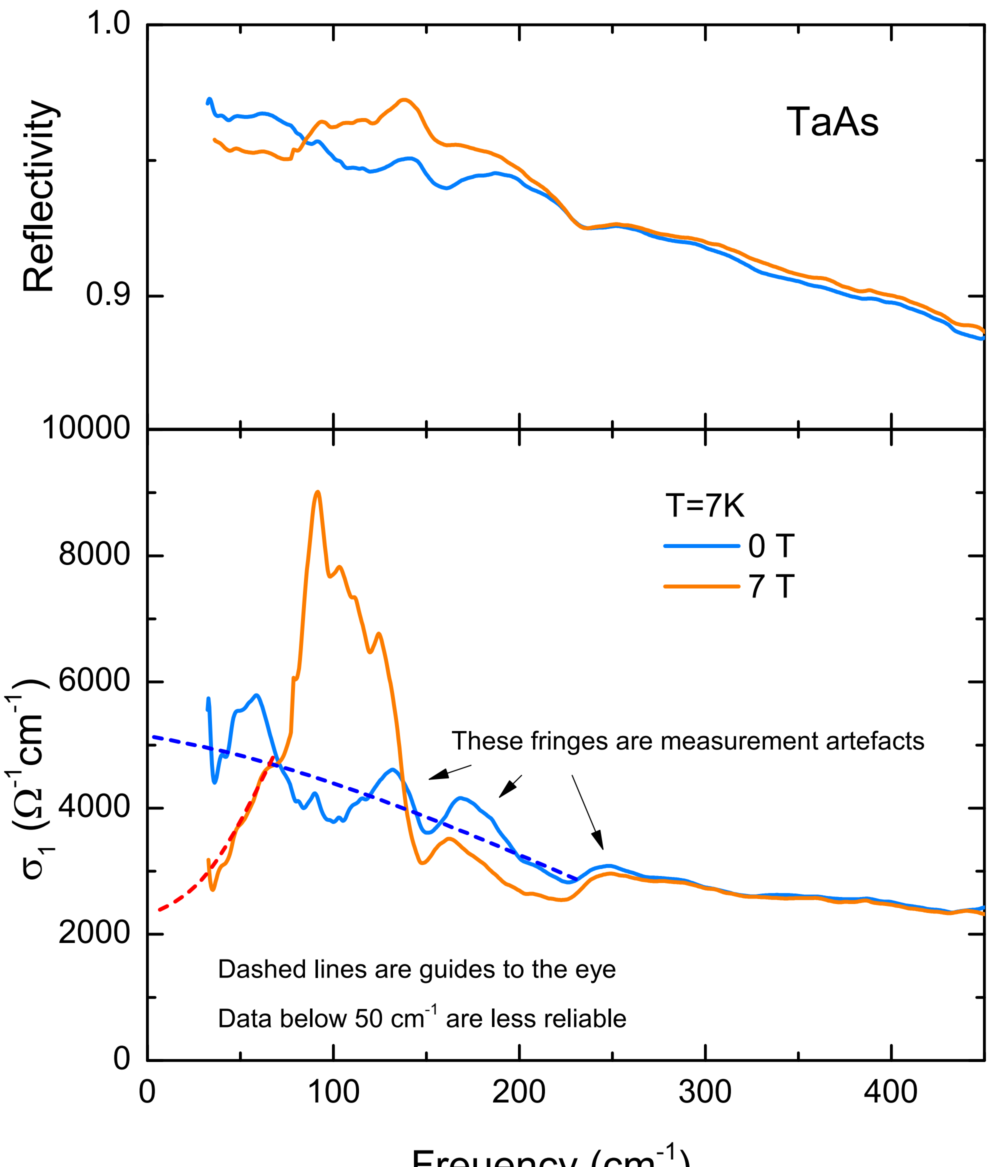
Dashed line marks the Planckian bound on the dissipation time $\tau_\hbar = \hbar/(k_B T)$.

Both times saturate the bound posed by the uncertainty principle at all temperatures

J. Gooth et al. submitted, arXiv:1706.05925

TaAs



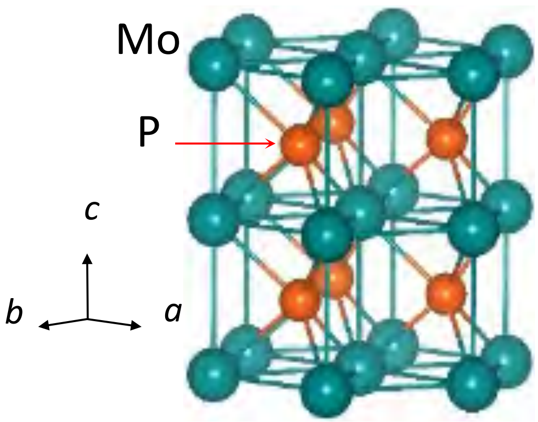


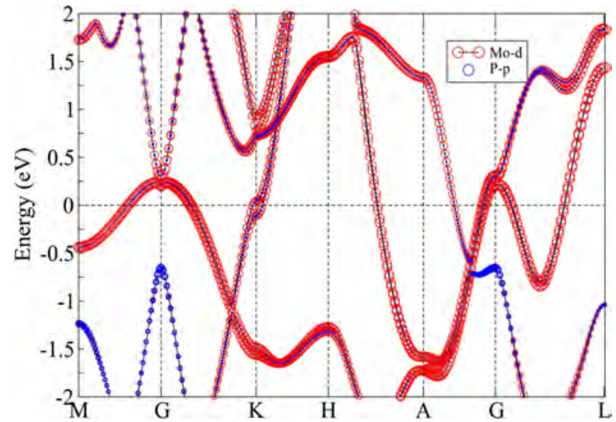
Huang et al. Phys. Rev. X 5, 031023 (2015)

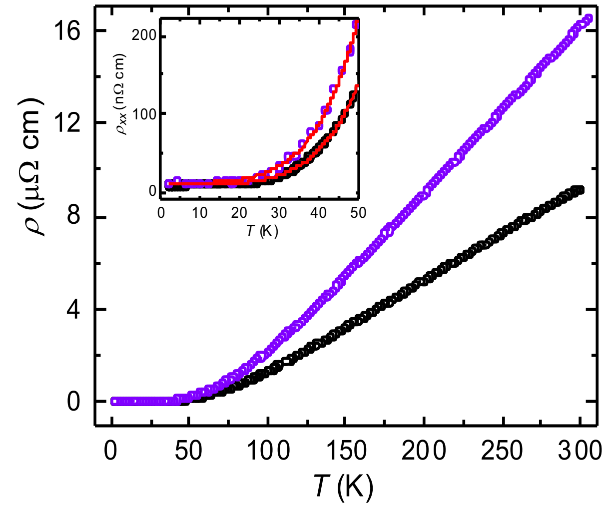
A. Pronim unpublished

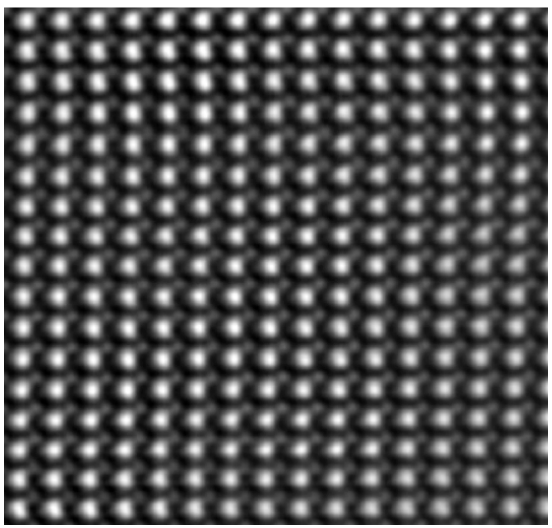
Topological Metals

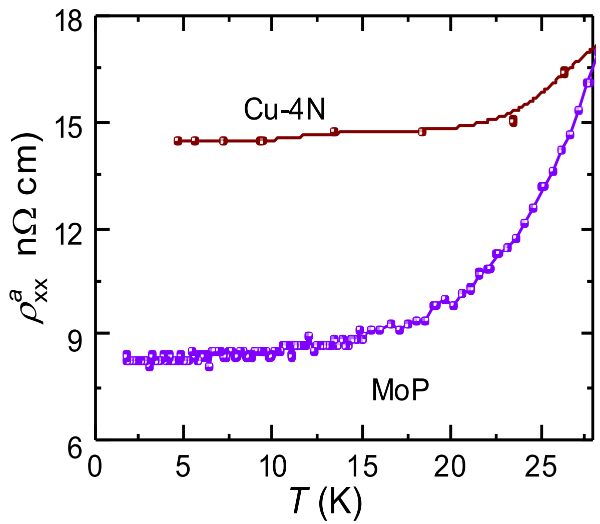
MoP better than Copper

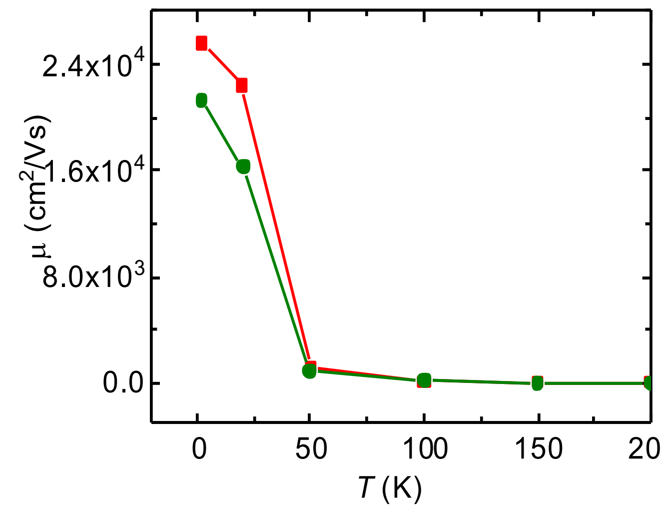








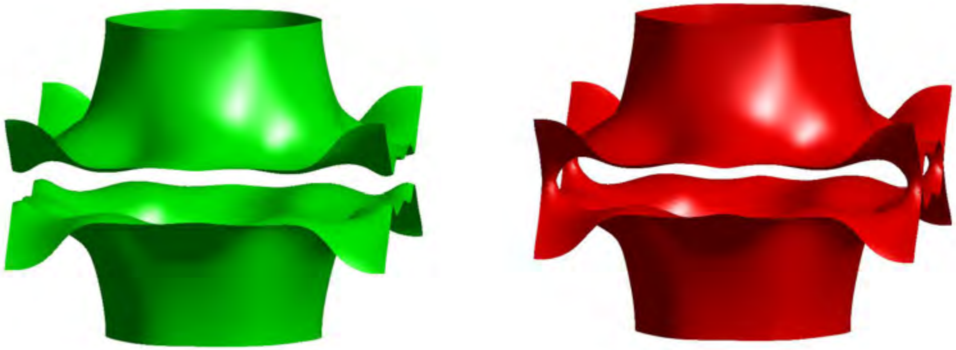




3D-Hydrodynamics ?

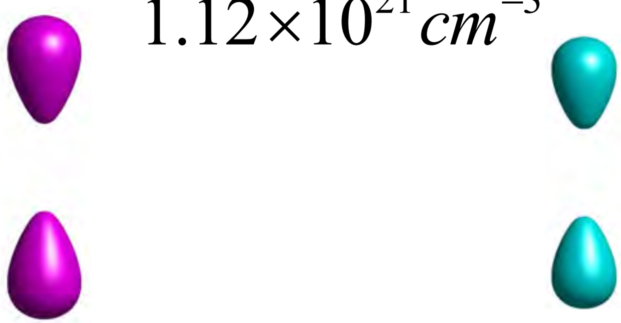
Chandra Shekhar et al. arXiv:1703.03736

Fermi surfaces



$2.7 \times 10^{22}\, cm^{-3}$

$1.12 \times 10^{21}\, cm^{-3}$



$2.57 \times 10^{20}\, cm^{-3}$

Experimental measurement is around

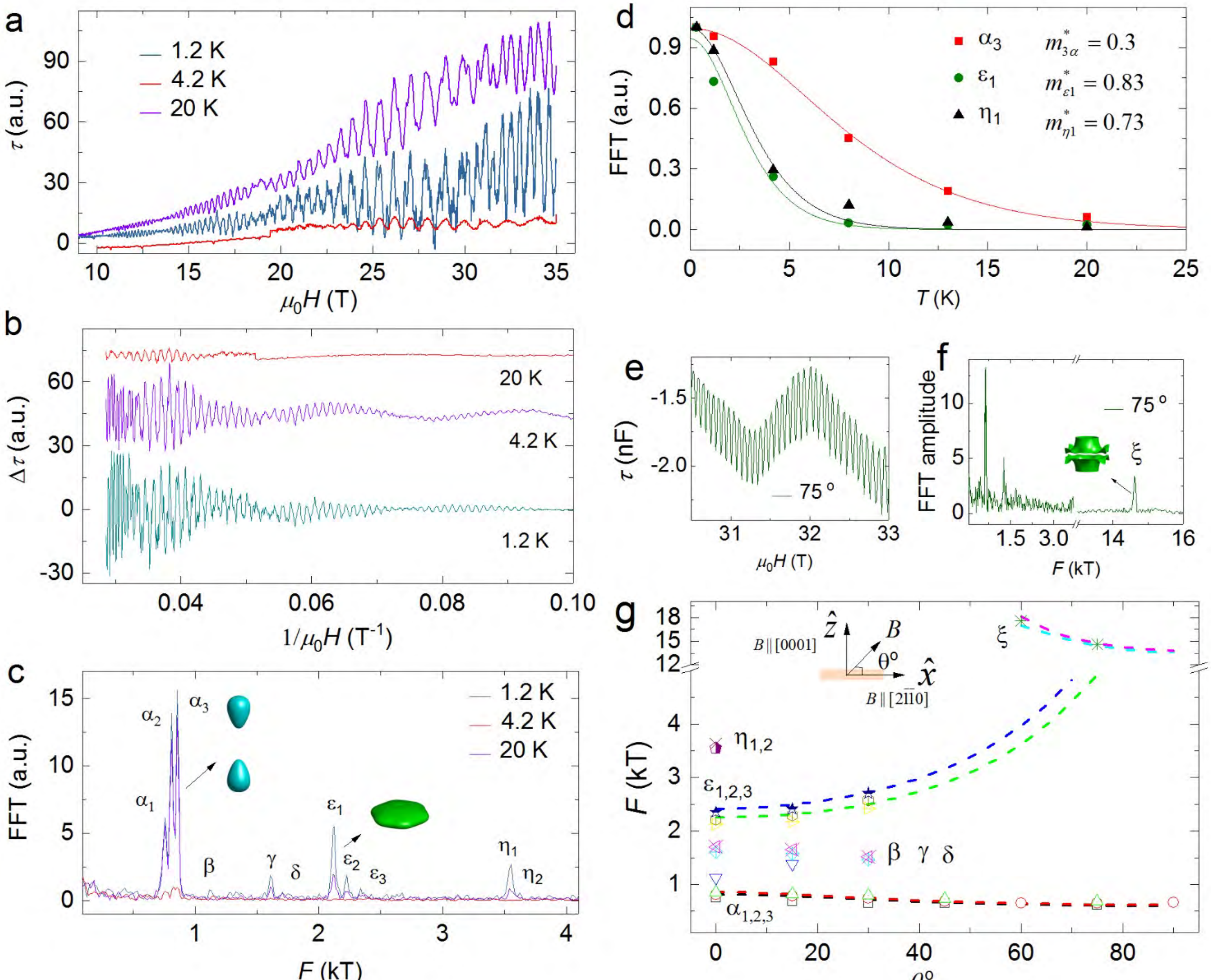
$3.2 \times 10^{22}\, cm^{-3}$ at 2K

Experiment and calculation have the same order of magnitude

Charge carriers are mainly from the open Fermi surface

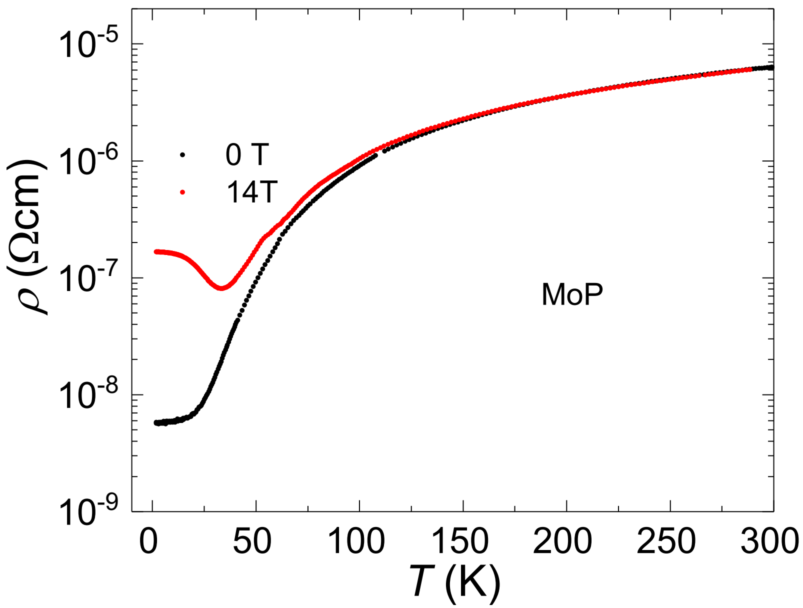
Chandra Shekhar et al. arXiv:1703.03736

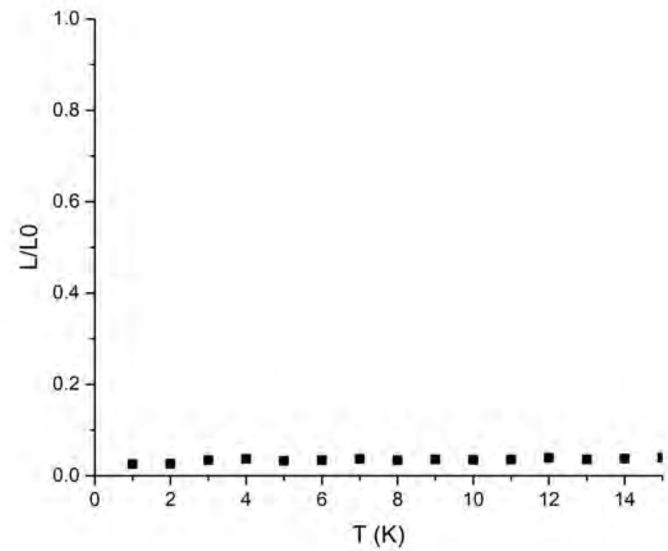
Quantum Oscillations



Chandra Shekhar et al. arXiv:1703.03736

Hydrodynamic





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

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

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

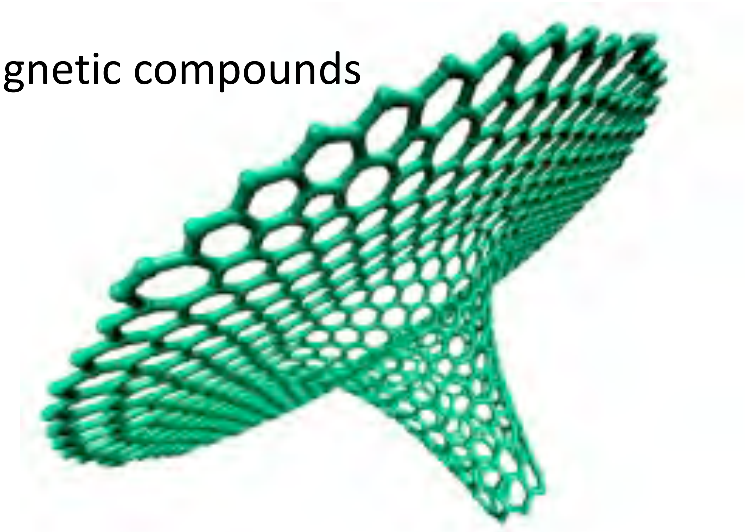
Summary

Fermi arcs and and a chiral anomaly in magneto-transport are signatures of Weyl semimetals

We found new magneto thermal transport properties in Weyl semimetals and topological metals which can be explained by hydrodynamic flow of the electrons

These phenomena are also found in magnetic compounds

… much more to do!



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]
AuLuSn
AuYSn
ErAuSn
EuAuBi

CaAgAs

KMgSb
KMgBi
KHgSb
KHgBi
LiZnAs
LiZnSb

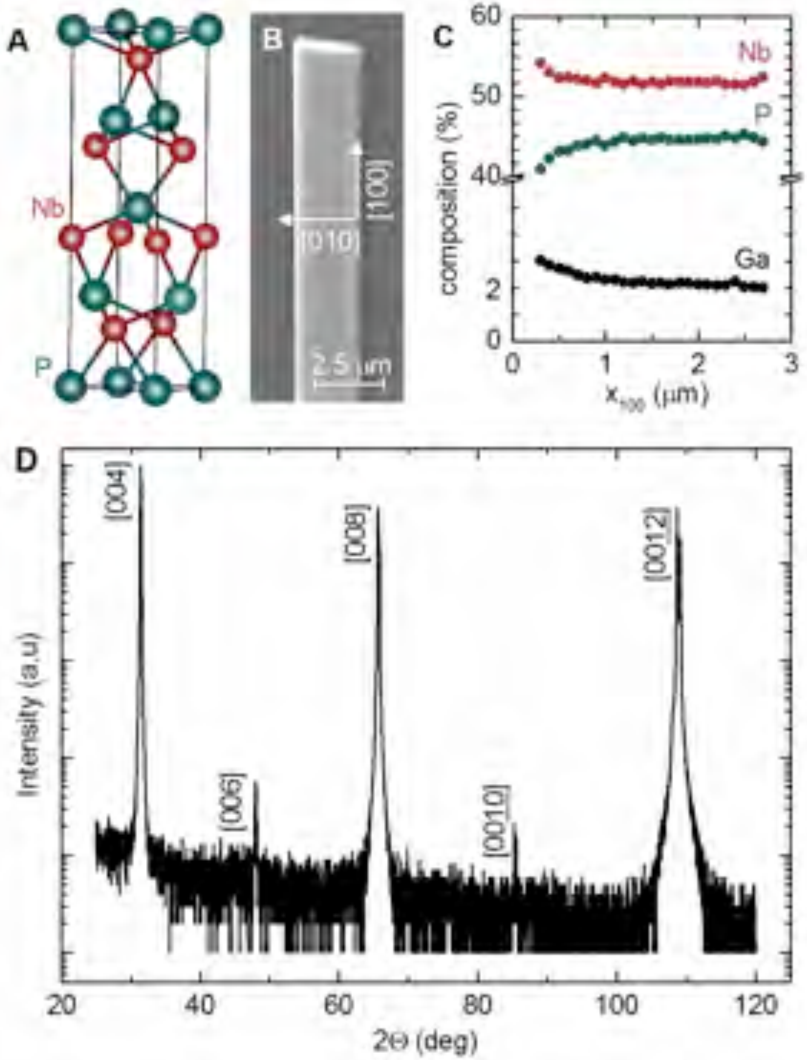
YbMnBi2
Ni2Mn1.4In0.6
YFe4Ge2

Mn1.4PtSn

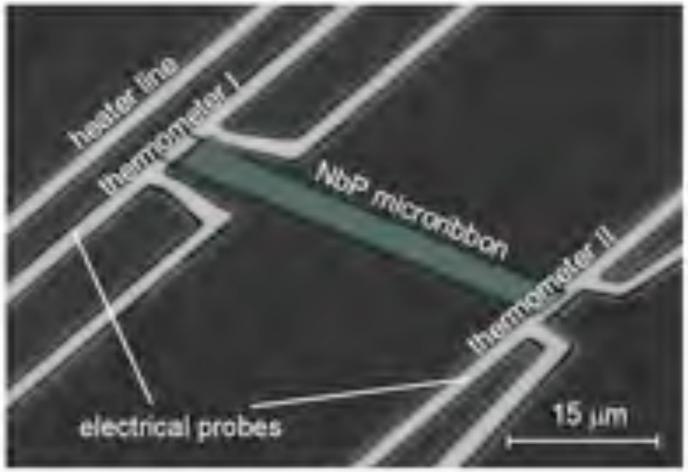
CuMnSb
CuMnAs

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

Thank you!



A
Nb
P
B
[100]
[010]
2.5 µm
C
Nb
P
Ga
composition (%)
x_{100} (µm)
D
[004]
[006]
[008]
[0010]
[0012]
Intensity (a.u)
2Θ (deg)



heater line
thermometer I
NbP microribbon
thermometer II
electrical probes
15 µm