近代物理专题讲座I

固体宇宙

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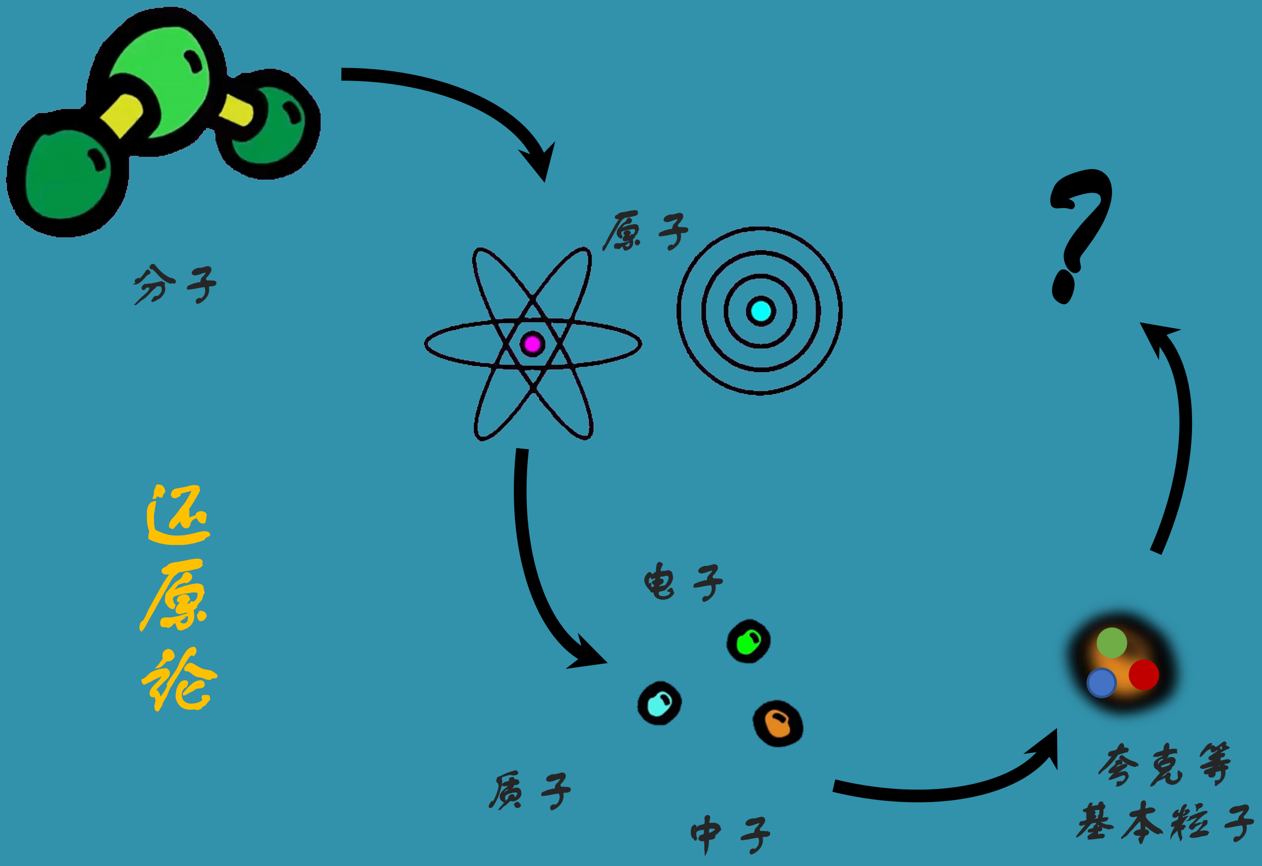
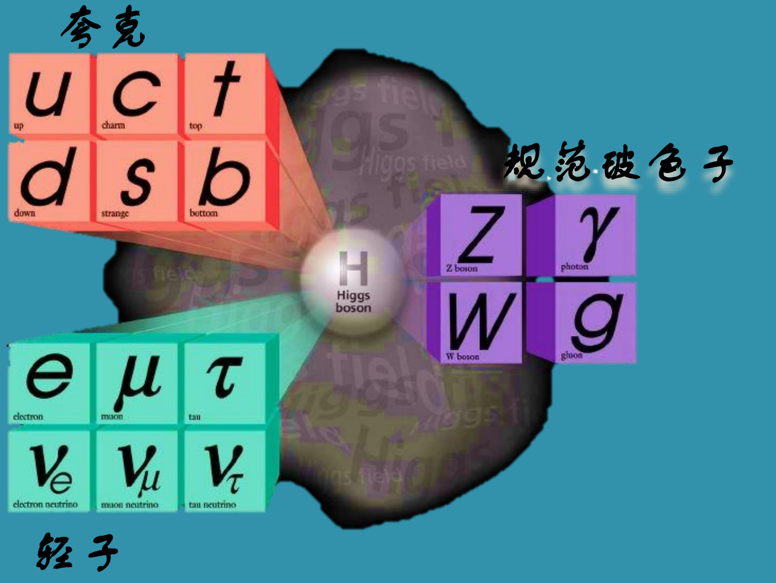
组成世界的粒子





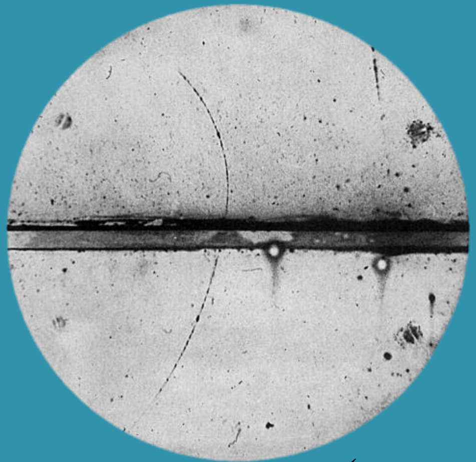
粒子物理学标准模型

17种基本粒子

宇宙中基本的粒子

狄拉克

$$\frac{1}{i}\gamma^{\mu}\partial_{\mu}\psi + m\psi = 0$$



正电子的发现（1932）

量子力学+相对论=狄拉克方程

计算出费米子能量为$E = \pm\sqrt{c^2p^2 + m^2}$

负的能量预言了反粒子。

狄拉克费米子的世界

这种反粒子与自身不同的费米子

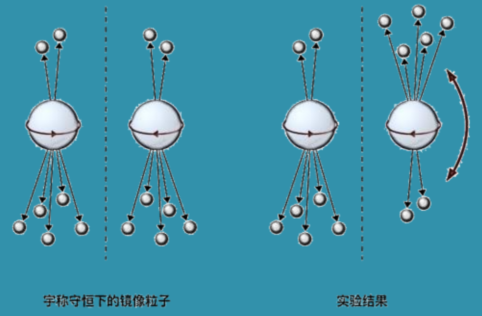
我们叫做狄拉克费米子。

宇宙中基本的粒子

外尔

$$\sigma^{\mu}\partial_{\mu}\psi = 0$$

外尔想到：当狄拉克费米子无质量时，狄拉克费米子可以视为左手的外尔费米子与右手的外尔费米子组合

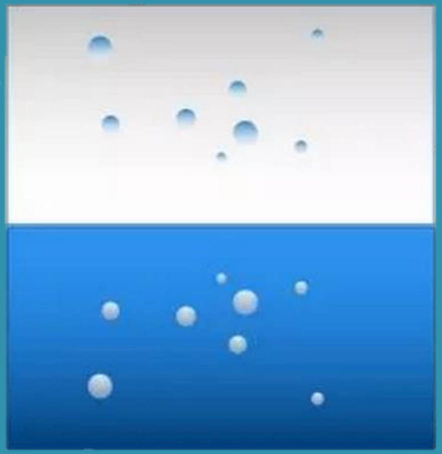


宇称不守恒

马约拉纳

$$i\partial\!\!\!/\psi - m\psi_c = 0$$

马约拉纳则构想了一种自己是自己的反粒子的费米子



马约拉纳费米子的世界

但到目前为止，宇宙中的基本粒子中只发现了狄拉克费米子！
我们将如何去发现新的粒子？

More Is Different

安德森

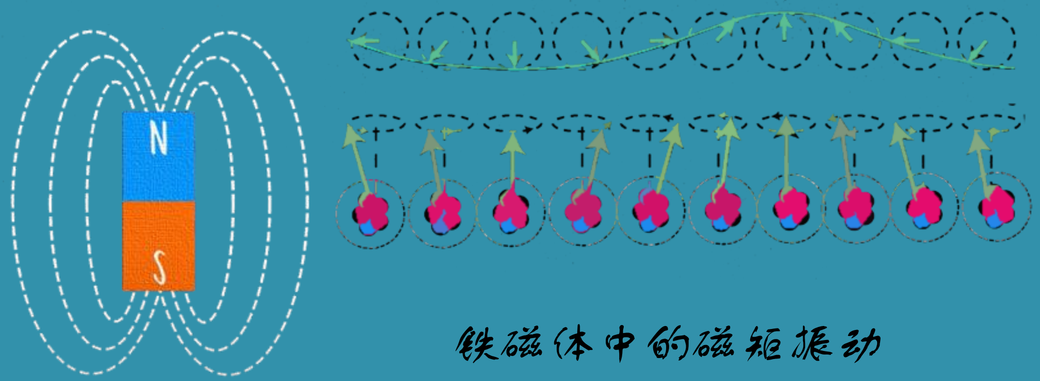
多者异也！

将所有事物还原为简单的基本定律的能力并不意味着从那些基本定律出发并重建整个宇宙的能力。

我们不断还原去得到最基本的粒子

从非常简单的相互作用之中展示出复杂的结构和模式（pattern）

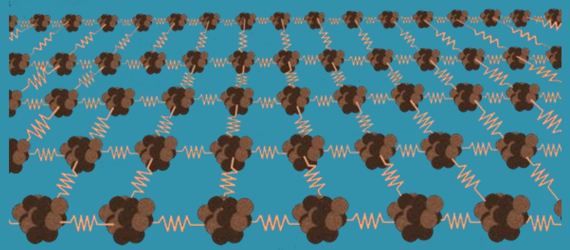
固体材料中有些集体行为。从大量基本粒子的复杂相互作用中产生，表现得像是一个粒子一样。



铁磁体中的磁矩振动

磁振子

magnon



晶格的振动

声子

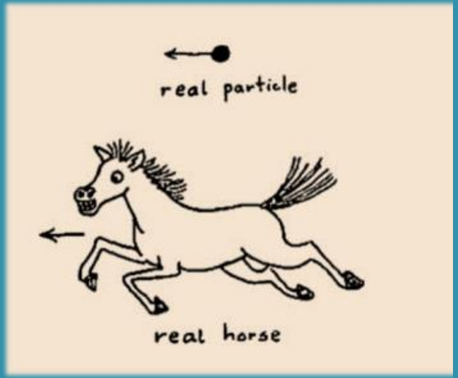
phonon

“准粒子”

什么是准粒子?

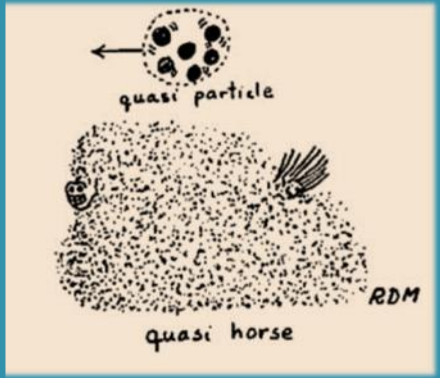
“基本”粒子

- 有固有的量子属性（质量，自旋，电荷）
- 遵从某一个物理方程

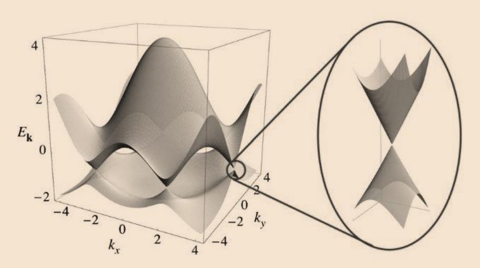


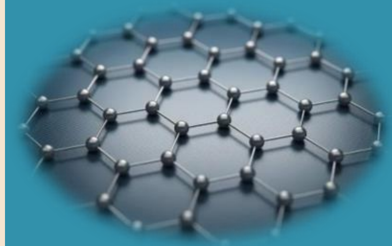
准粒子

- 也表现出固有的量子属性（质量，自旋，电荷）
- 也遵从与前者一样的物理方程



固体宇宙





无质量的狄拉克费米子

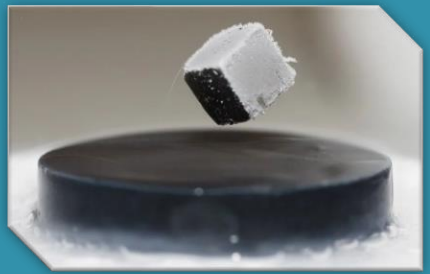
质量为0

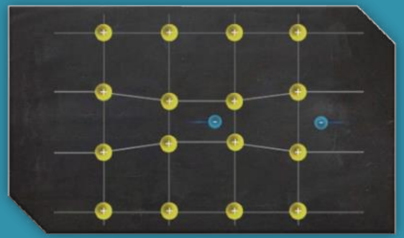
具有相对论的效应

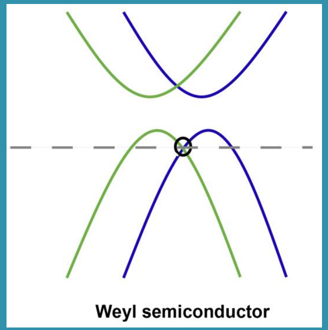
电子

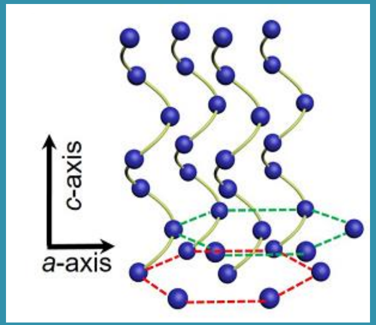
超流的玻色子——库伯对

- 超导的基础
- 无损耗的运动





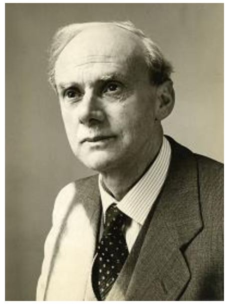




外尔费米子

我们的宇宙波澜壮阔，我们的材料也丰富多彩。同样的电子在不同的材料中，可以被“装饰”成各种各样不同的准粒子

Dirac & Weyl fermions

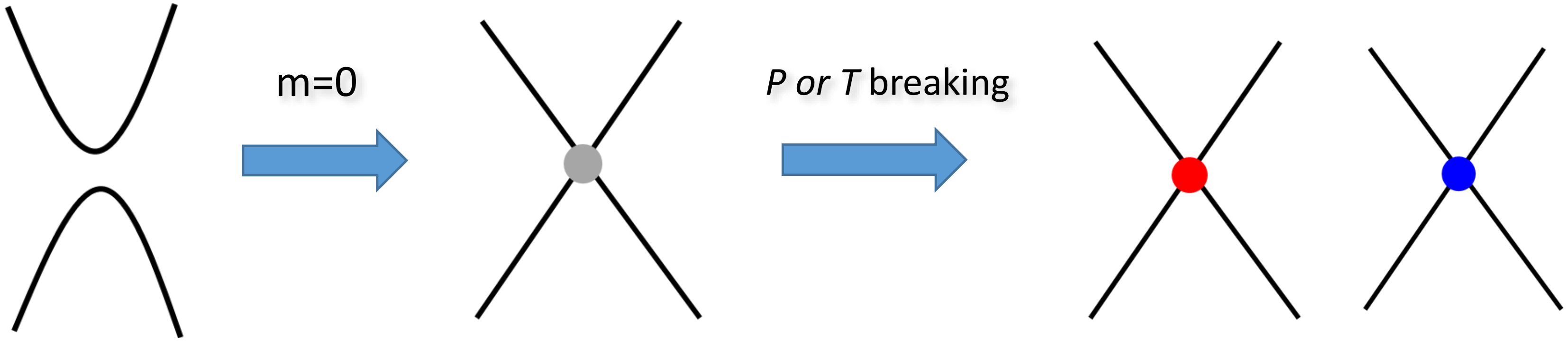


Paul Dirac

Hermann Weyl

(Massless) Dirac fermion

Weyl fermion



4 x 4 matrix

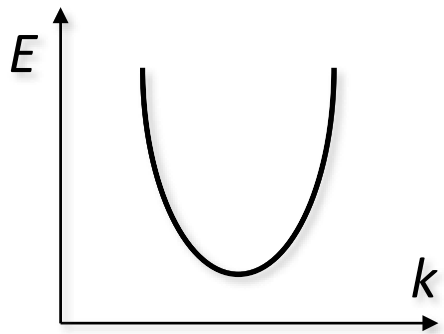
$$H = \begin{pmatrix} v\vec{\sigma}\cdot\vec{k} & \mathrm{m} \\ \mathrm{m} & -v\vec{\sigma}\cdot\vec{k} \end{pmatrix}$$

4 x 4 matrix

$$H = \begin{pmatrix} v\vec{\sigma}\cdot\vec{k} & 0 \\ 0 & -v\vec{\sigma}\cdot\vec{k} \end{pmatrix}$$

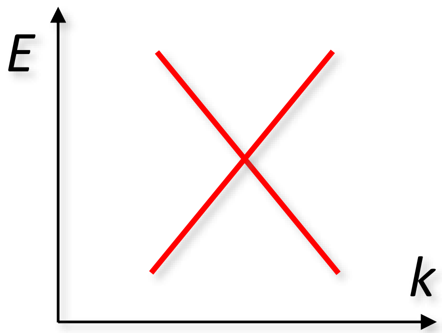
$$v\vec{\sigma}\cdot\vec{k} \qquad -v\vec{\sigma}\cdot\vec{k}$$

Band dispersions



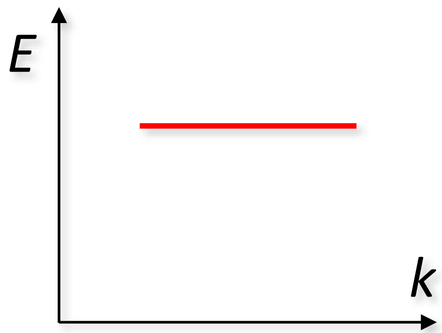
Parabolic $E \propto k^2$

m^*



Linear $E \propto k^1$

$m^* \rightarrow 0$

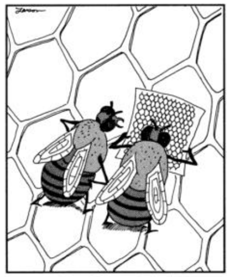


Flat $E \propto k^0$

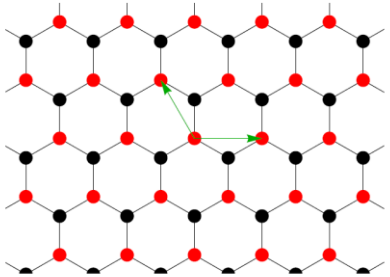
$m^* \rightarrow \infty$

Band design by controlling lattice geometry

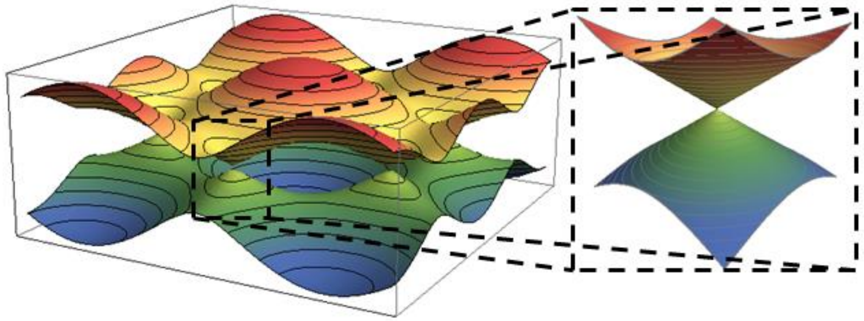
Honeycomb lattice



"Face it, Fred—you're lost!"



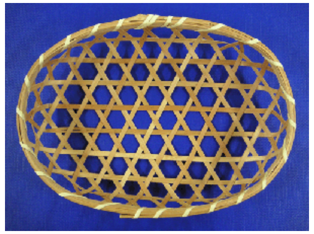
$$\hat{H} = -t\sum_i a^\dagger_{r_i} b_{r_i+e_1} - t\sum_i a^\dagger_{r_i} b_{r_i+e_2} - t\sum_i a^\dagger_{r_i} b_{r_i+e_3} + h.c.$$

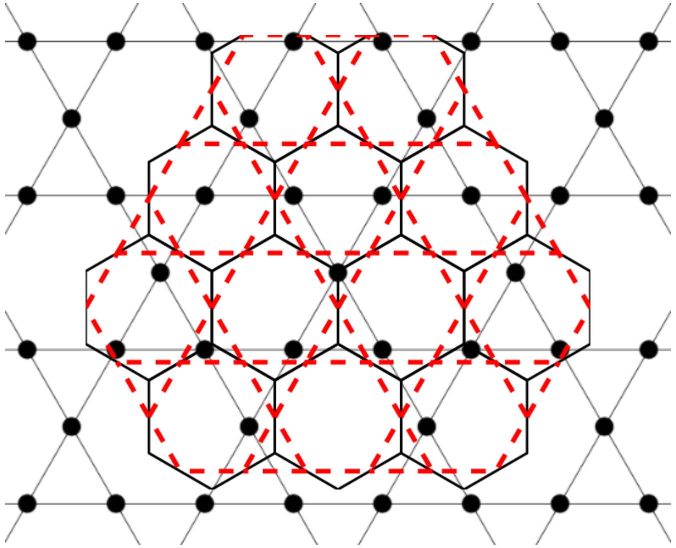


$$E_\pm(q) \approx \pm v_F|q| + O[(q/K)^2]$$
$$v_F = 3ta/2$$

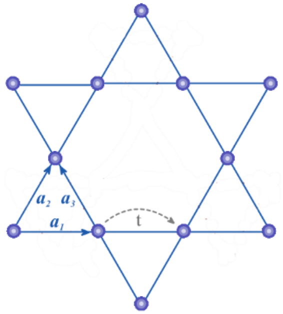
Kagome lattice: flat band & Dirac band

Kagome lattice





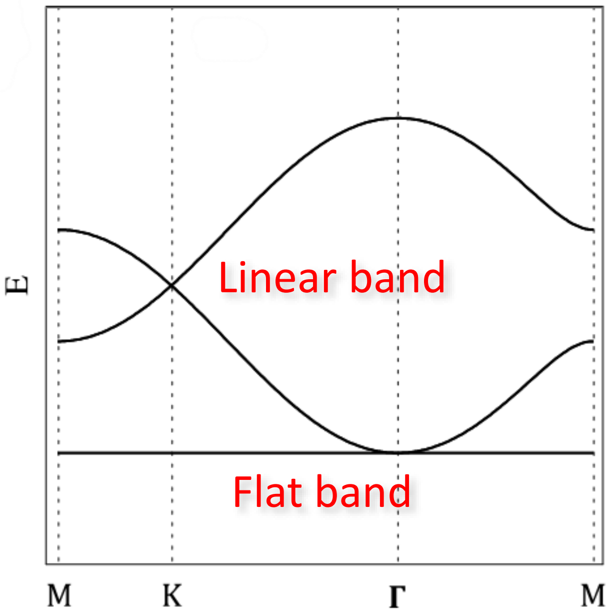
Tight-binding modeling



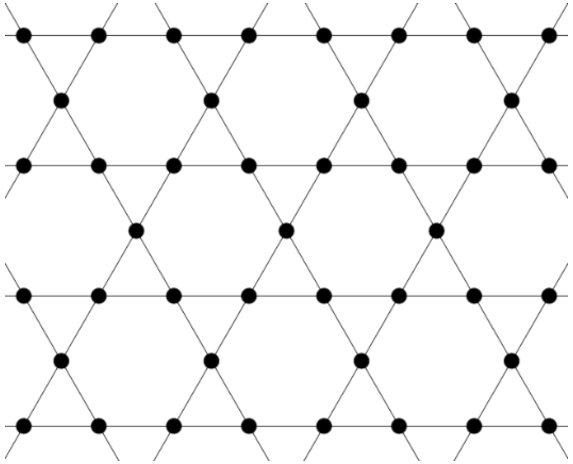
$$\hat{H} = t \sum_{<i,j>} (\hat{c}_i^{\dagger} \hat{c}_j + h.c.)$$

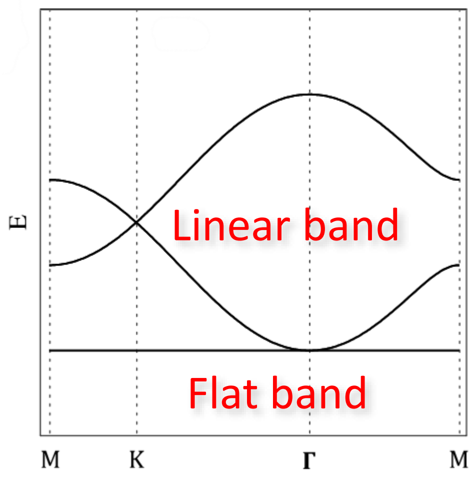
$$\epsilon_{\pm} = t[1 \pm \sqrt{4(\cos^2 k_1 + \cos^2 k_2 + \cos^2 k_3) - 3}]$$

$$\varepsilon = -2t$$



Kagome lattice: ideal platform to exploit rich physics



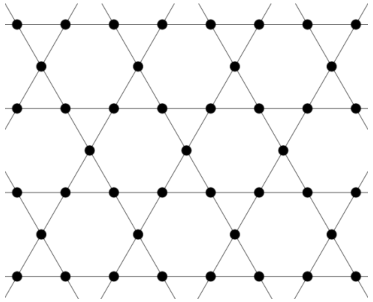


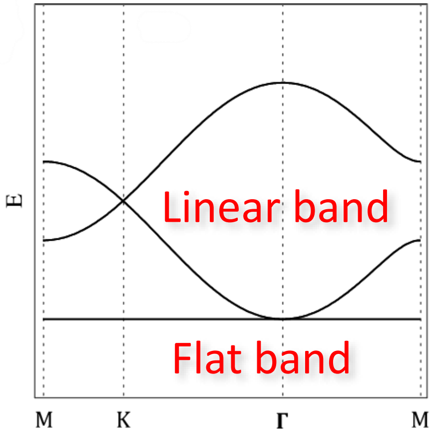
Linearly dispersive bands hosting massless fermions ➕ Flat bands hosting superheavy fermions

Topology, strong correlation, magnetism, relativity, …

Outline

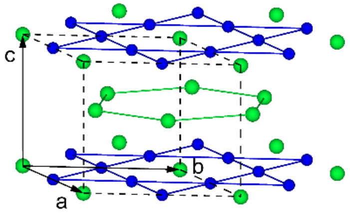
Novel properties in kagome lattices





- Antiferromagnetic Dirac semimetal

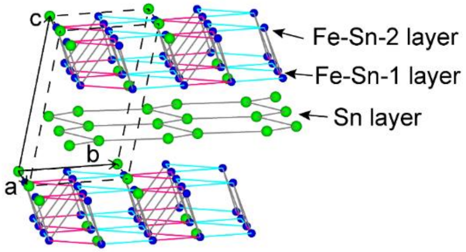
  PRB 102,155103 (2020)
  Editors' Suggestion



FeSn

- Flat band and HT ferromagnetism

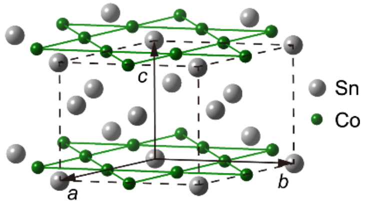
  PRL 121, 096401 (2018)
  Cover story, Editors' Suggestion



Fe_3Sn_2

- Flat band and anomalously giant magnetic & transport anisotropy

  PRL 128, 096601 (2022)



CoSn

Dirac Point and its protection

Four-fold degenerate Dirac points are unstable

Symmetry protection for Dirac point

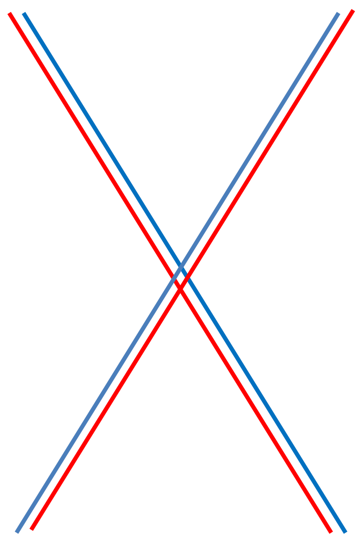
- Doubly degenerate band

  PT symmetry

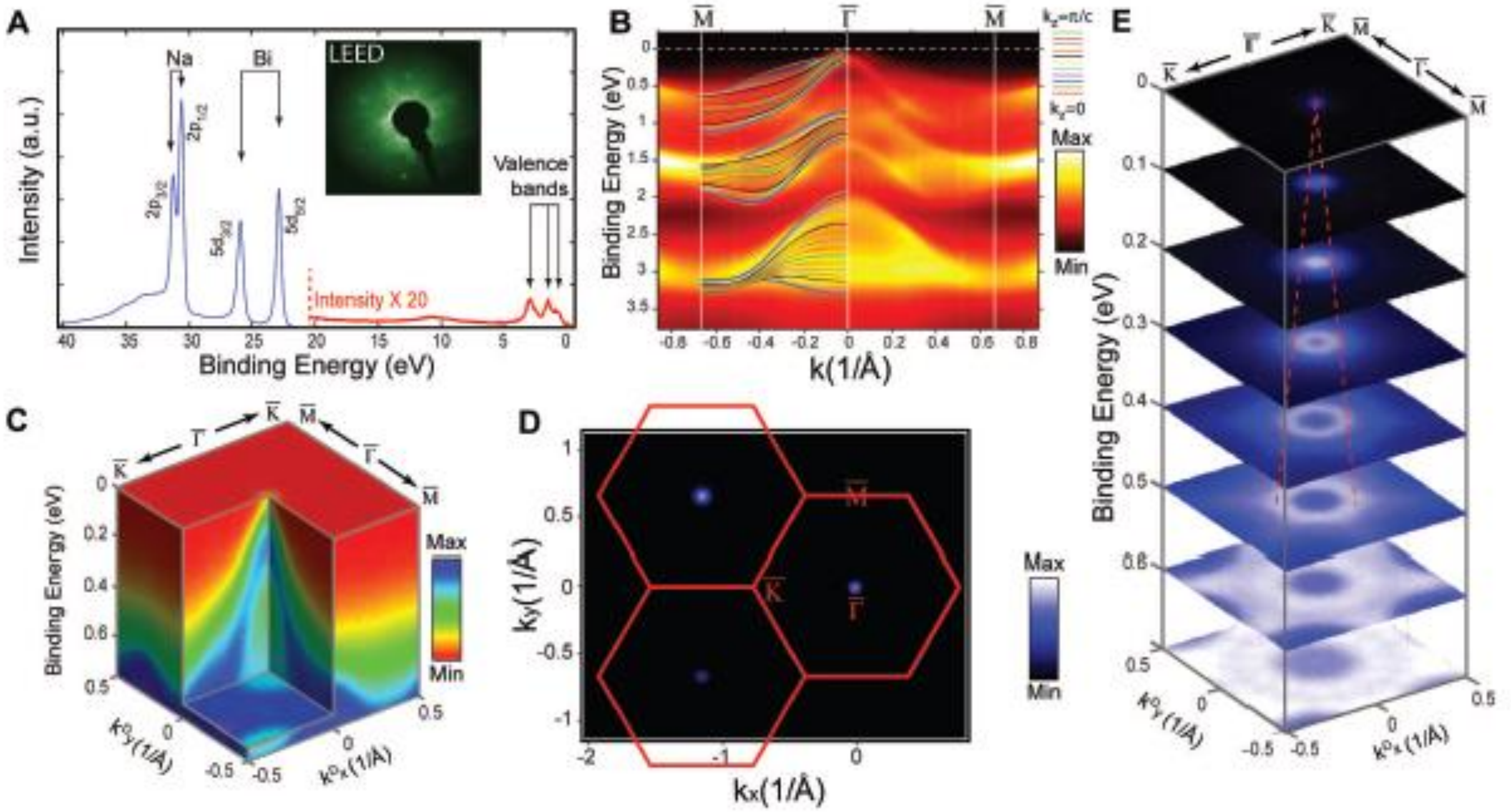
  P: space-inversion symmetry
  T: time-reversal symmetry

- Band crossing

  Non-symmorphic symmetry
  (Screw rotation or gliding mirror)



Previous demonstration of nonmagnetic Dirac semimetal



Nonmagnetic Na_3Bi with both *P* and *T* symmetries

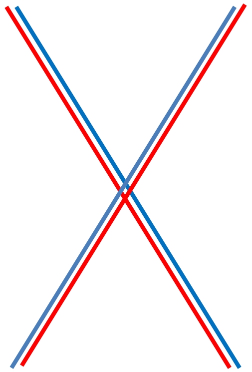
Liu *et al.*, Science 343, 864 (2014)

Magnetic Dirac semimetal?

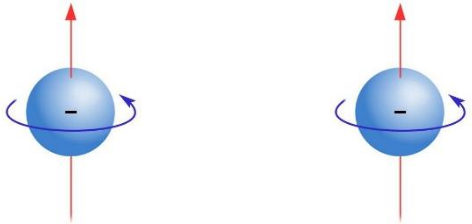
- Doubly degenerate band

  P and *T* symmetries absent separately

  Combined *PT* symmetry survived

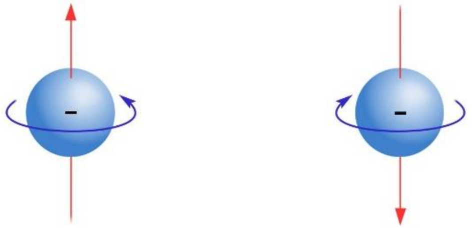


Ferromagnetic



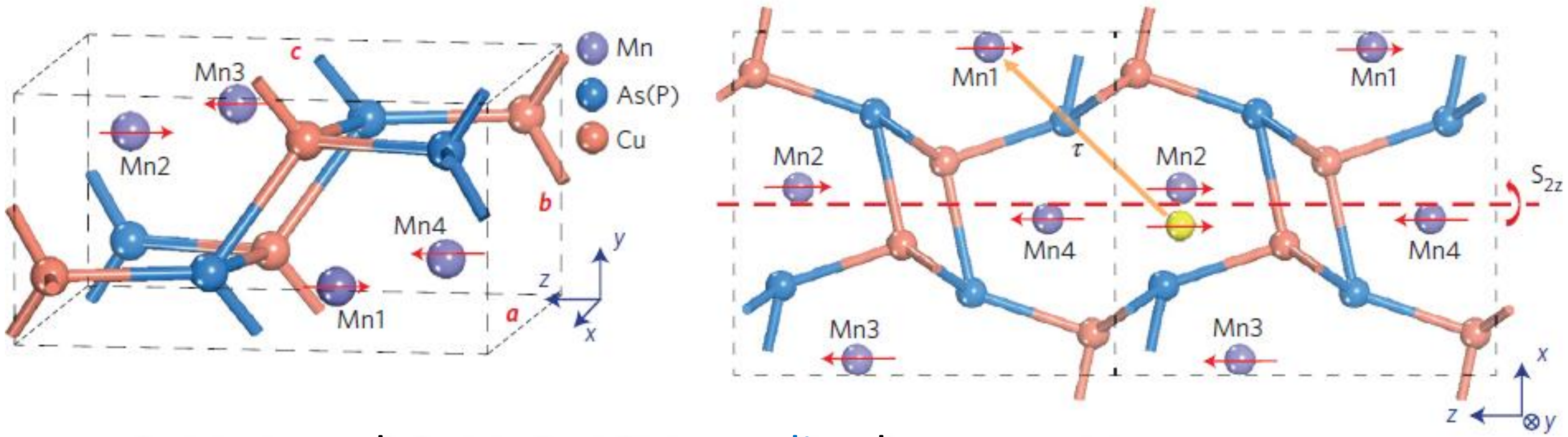
PT symmetry broken

Antiferromagnetic



PT symmetry possibly survived

3D antiferromagnetic Dirac semimetal: theory



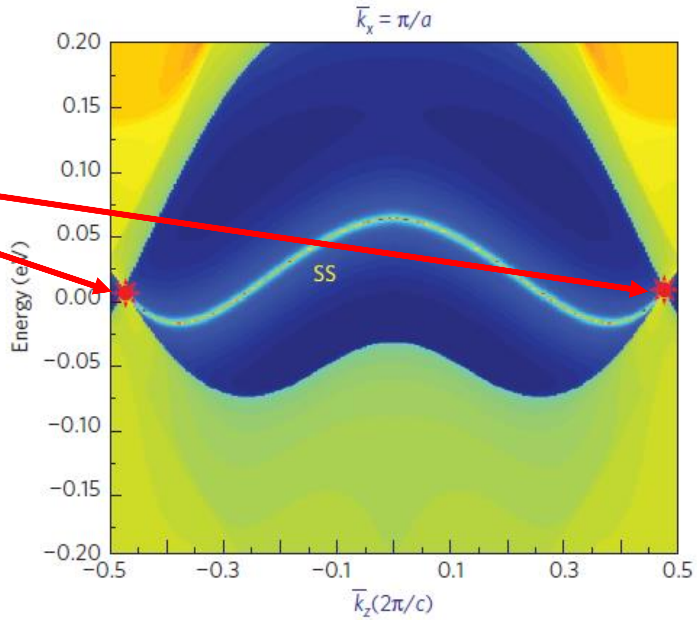
CuMnAs and CuMnP: AFM coupling between Mn atoms

Dirac points

Protected by $PT + S_{2z}$ symmetries

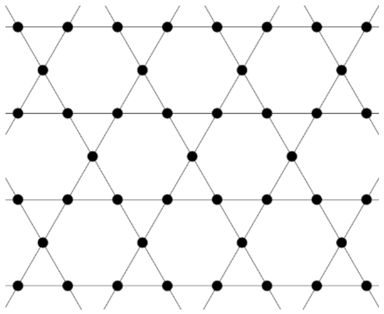
Non-symmorphic symmetry

Experimentally not validated

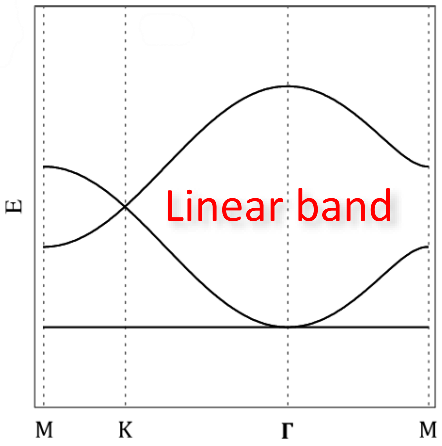


Zhang *et al.*, Nat.Phys.12, 1100 (2016)

Magnetic Dirac semimetal in kagome compounds?



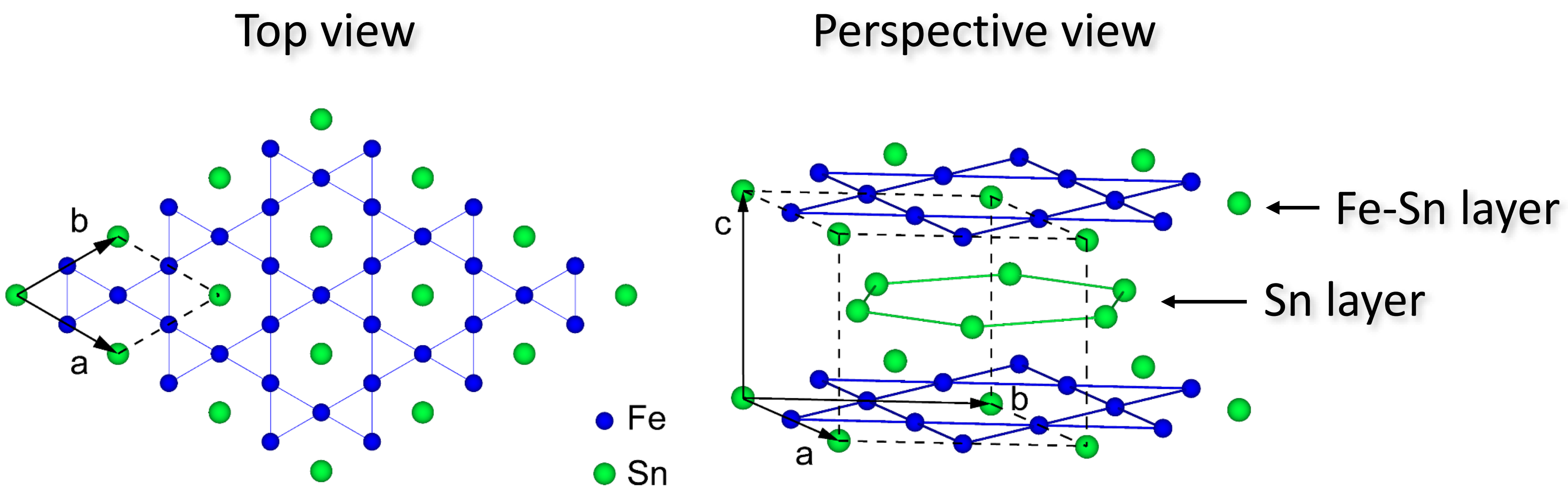
Kagome lattice



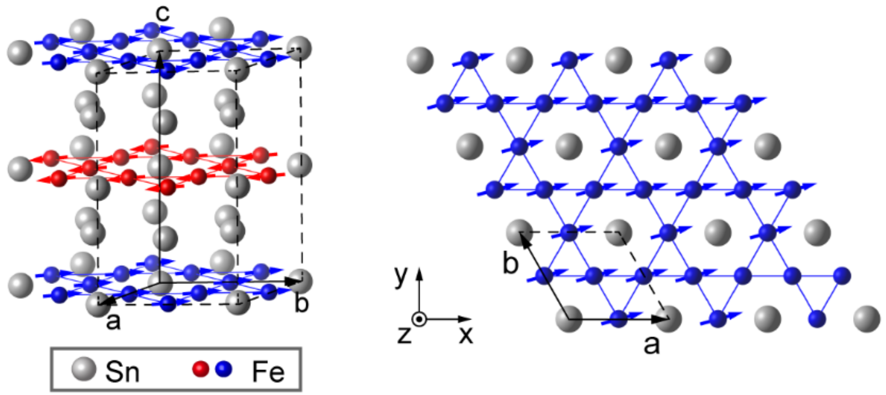
Antiferromagnetic kagome lattice:

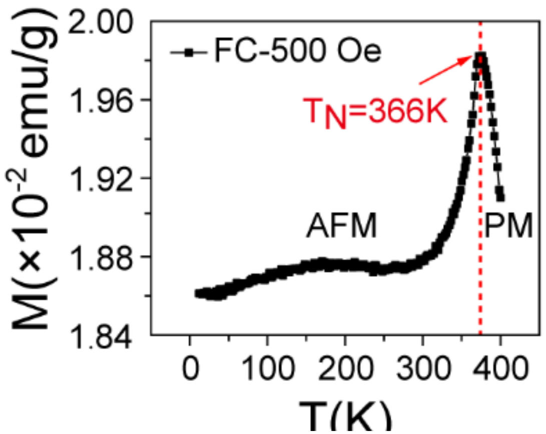
An ideal platform to exploit massless Dirac fermions

Antiferromagnetic kagome compound FeSn



Antiferromagnetism and symmetry

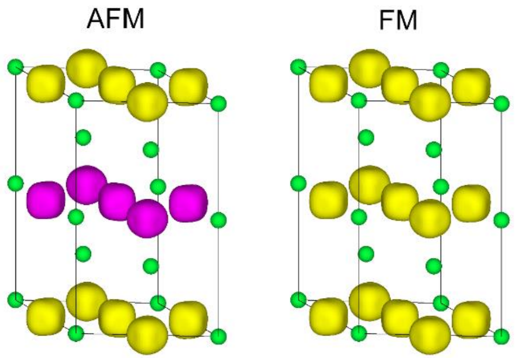




Spins in plane, along [3.73 1 0]

L Häggström et al. Phys Scripta,11,47-54 (1975)

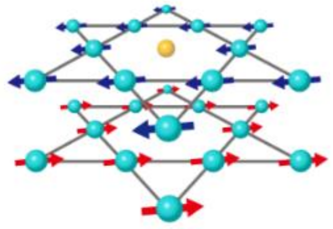
S K Kulshreshtha et al. J.Phys.F:metal Phys,11,281 (1981)

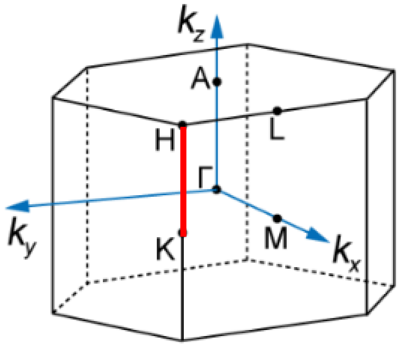


ΔE_{AFM-NM}= -2.328 (eV/u.c) ΔE_{FM-NM}= -2.280 (eV/u.c)

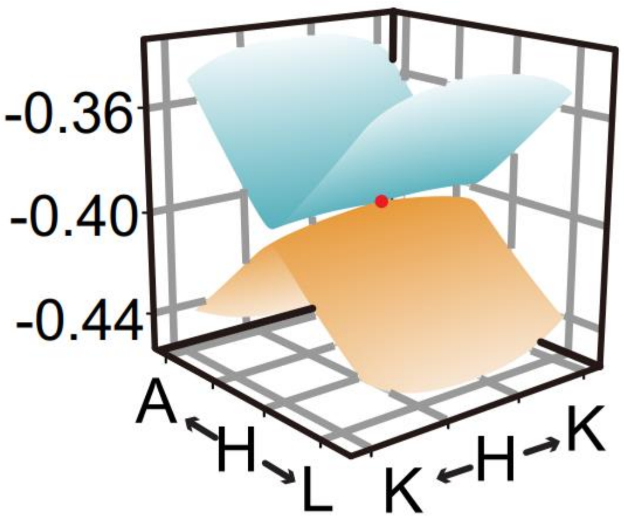
- Néel temperature 366 K
- In-plane FM order, out-of-plane AFM order
- *T* and *P* broken
- Combined *PT* symmetry survived

Band structure of FeSn bulk: theory



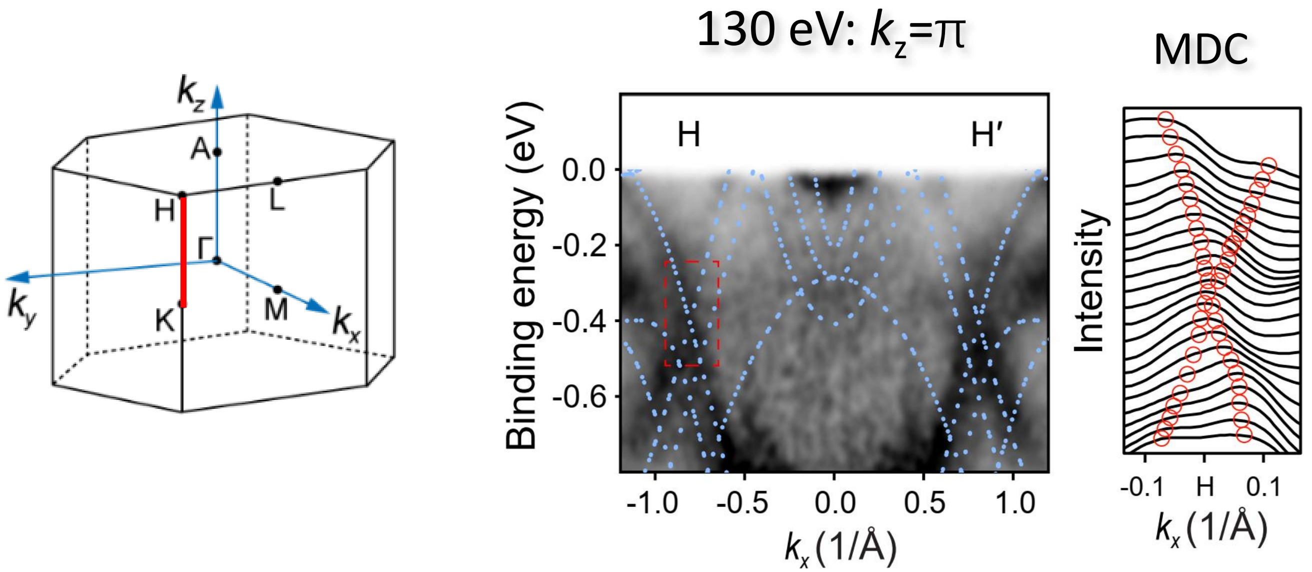


With SOC



- Gap opening along the nodal line (<30 meV)
- Dirac point at H protected by *PT* and S_{2z} (screw rotation) symmetries

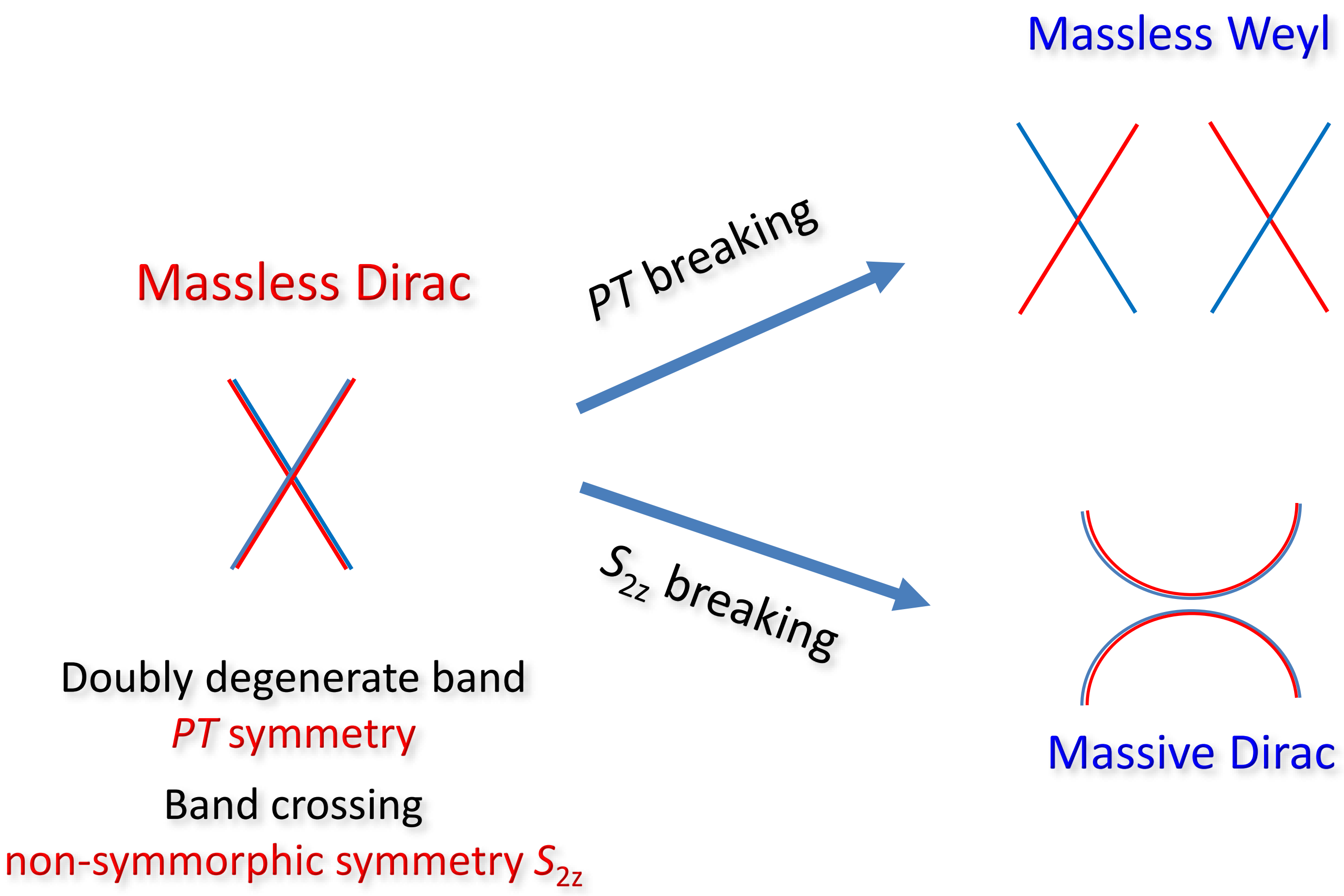
Dirac bands in FeSn: ARPES



Dirac points at H/H’ around 0.4 eV below E_F

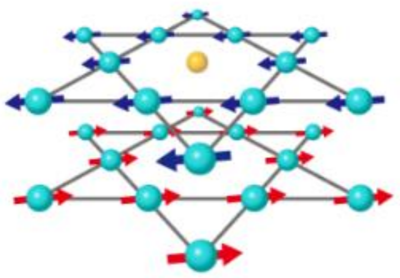
Symmetry ⟺ Topology

Symmetry control induced topological phase transition

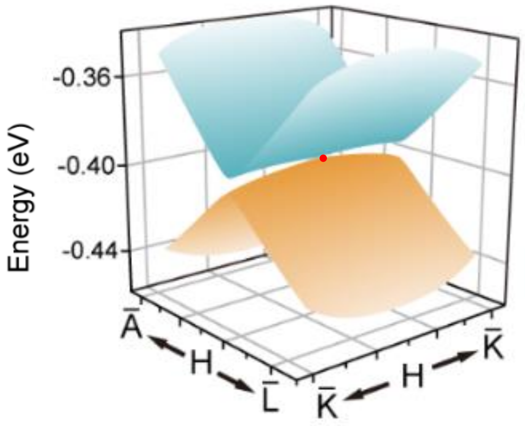


S_{2z} symmetry breaking: spin reorientation

Spin in-plane

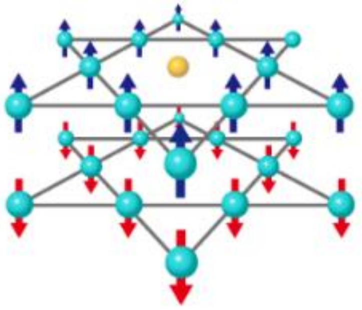


S_{2z} symmetry

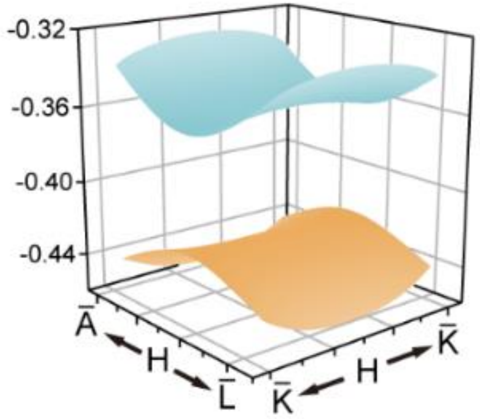


Massless Dirac fermion

Spin out-of-plane



S_{2z} symmetry broken

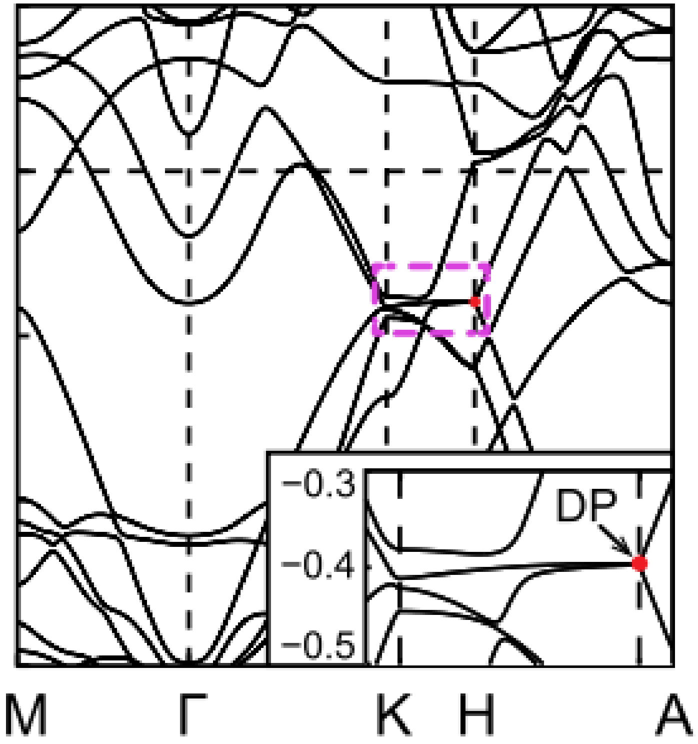


Gap of 70 meV

Massive Dirac fermion

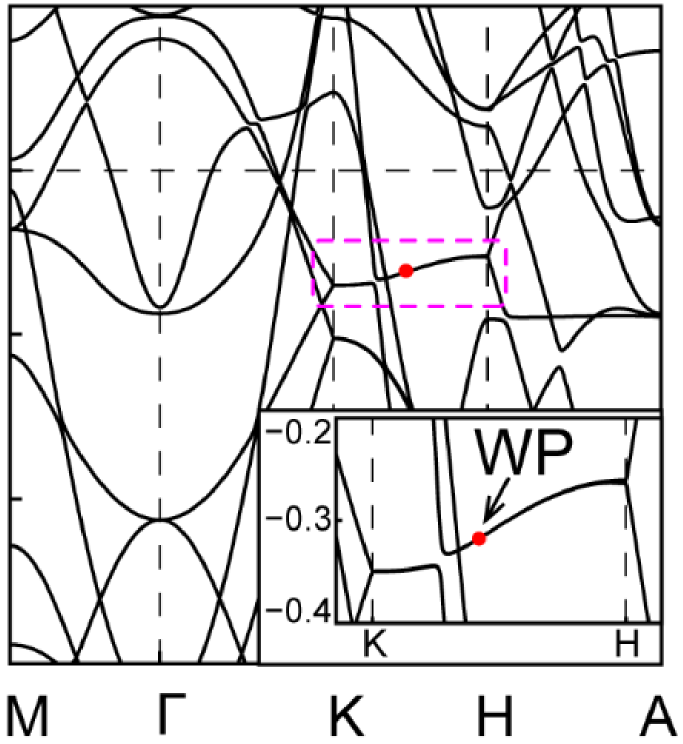
PT symmetry breaking: ferromagnetization

AFM



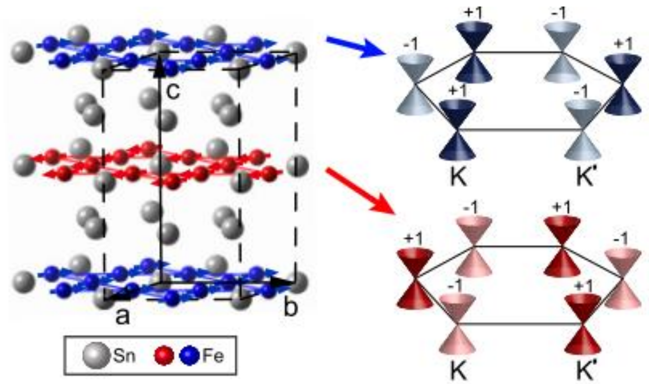
Dirac fermion

FM

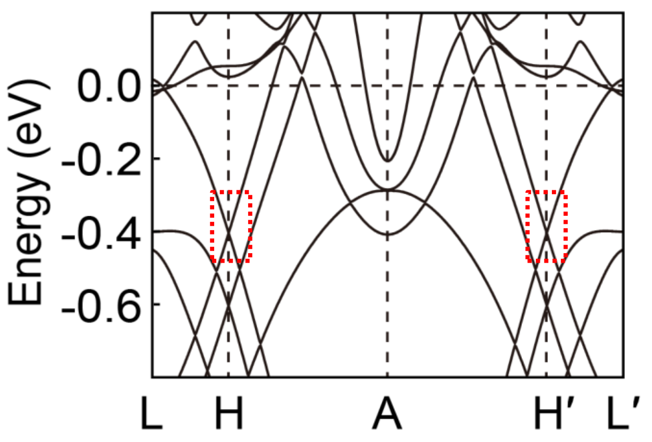


Weyl fermion

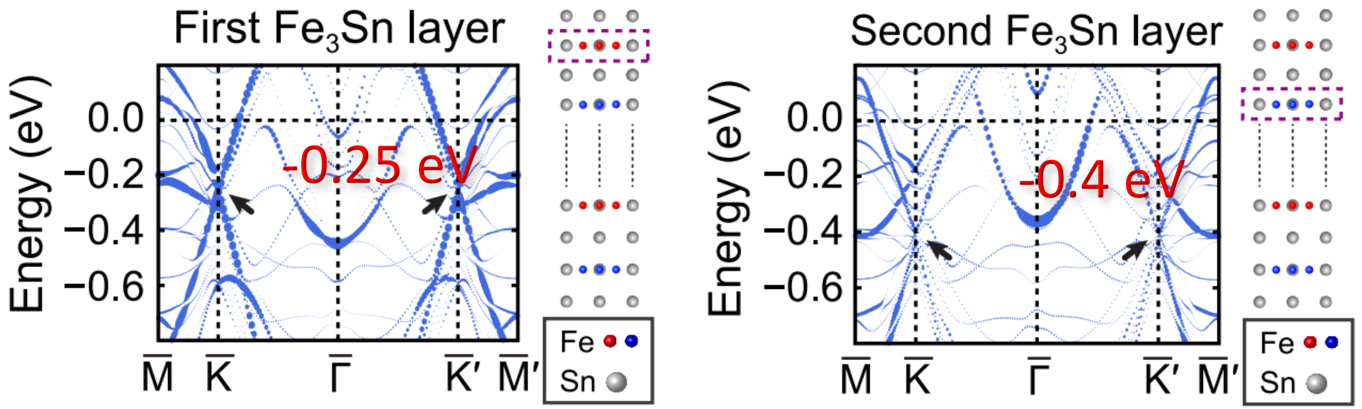
PT symmetry breaking: surface Stark effect



A Dirac point composed of a pair of Weyl points with opposite chirality residing in adjacent Fe_3Sn kagome layers



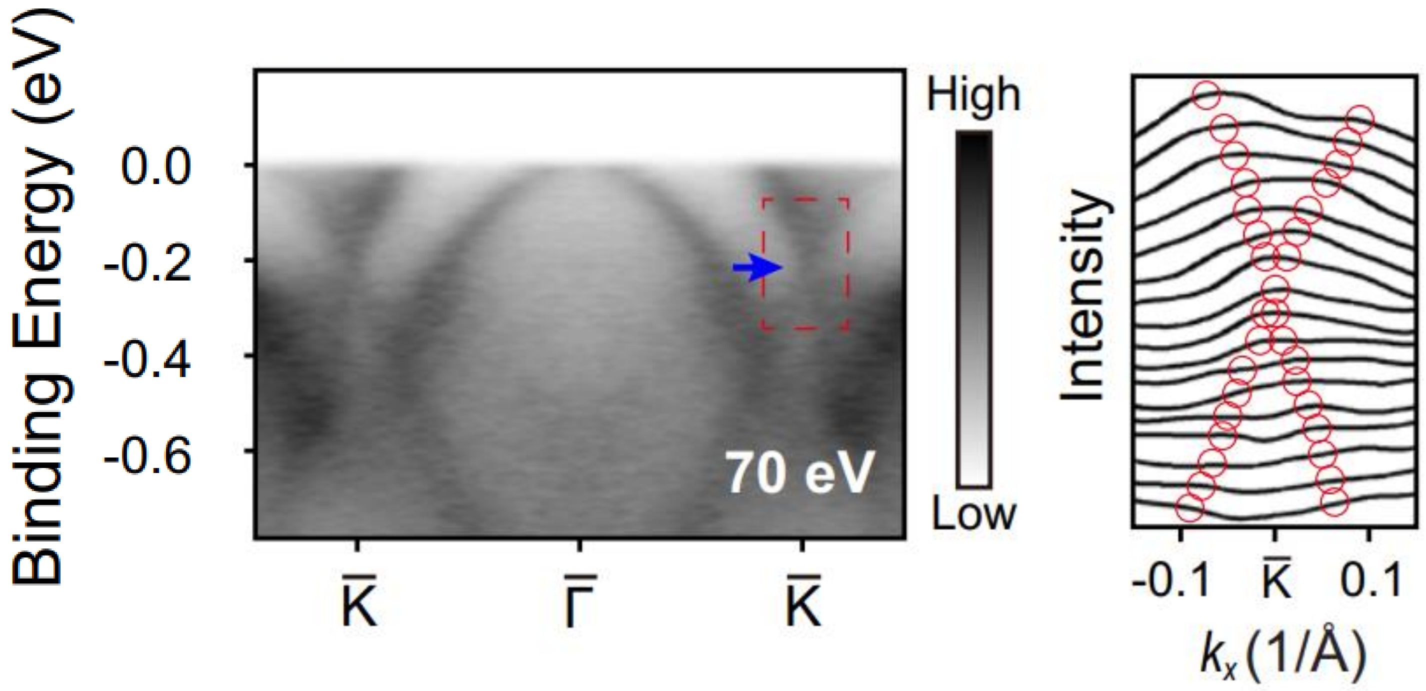
Dirac bands



Real-space separated Weyl-like bands

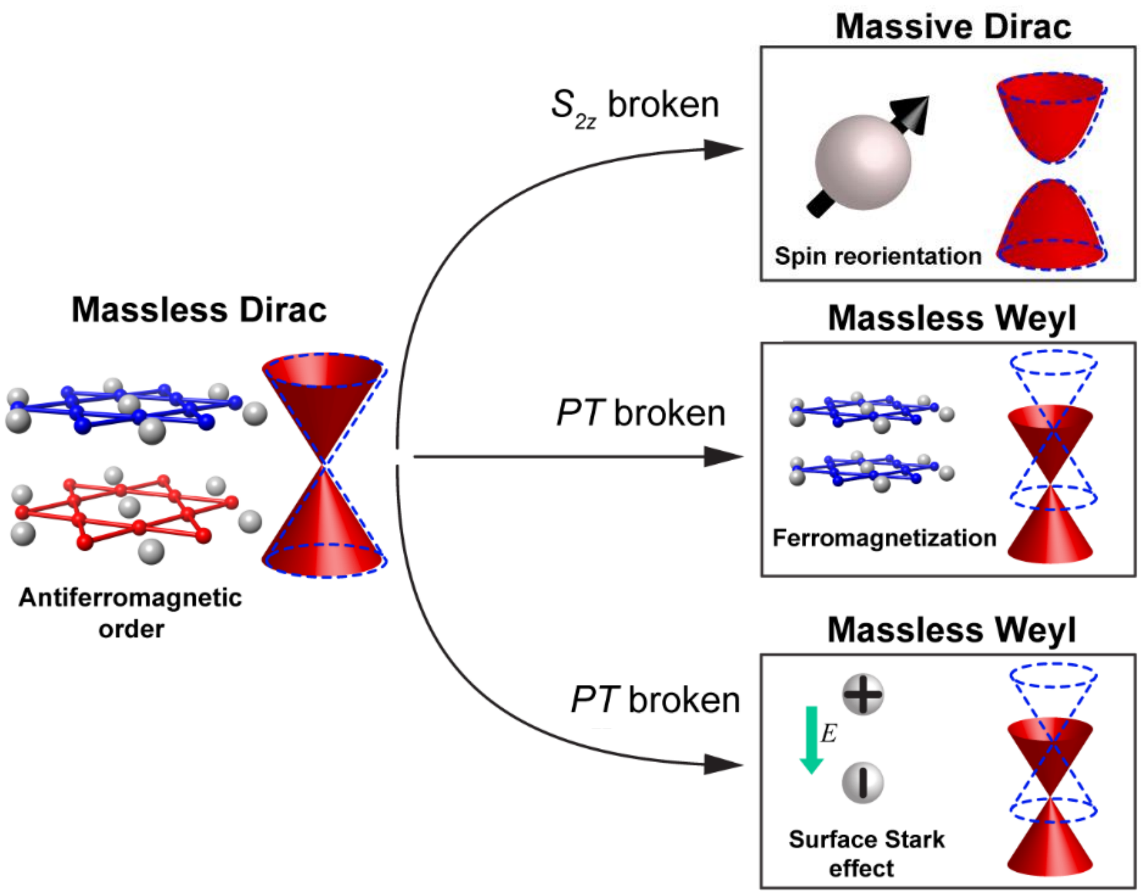
Surface potential breaking the *PT* symmetry
Paired Weyl points residing in the first and second Fe_3Sn layers no longer degenerate in energy

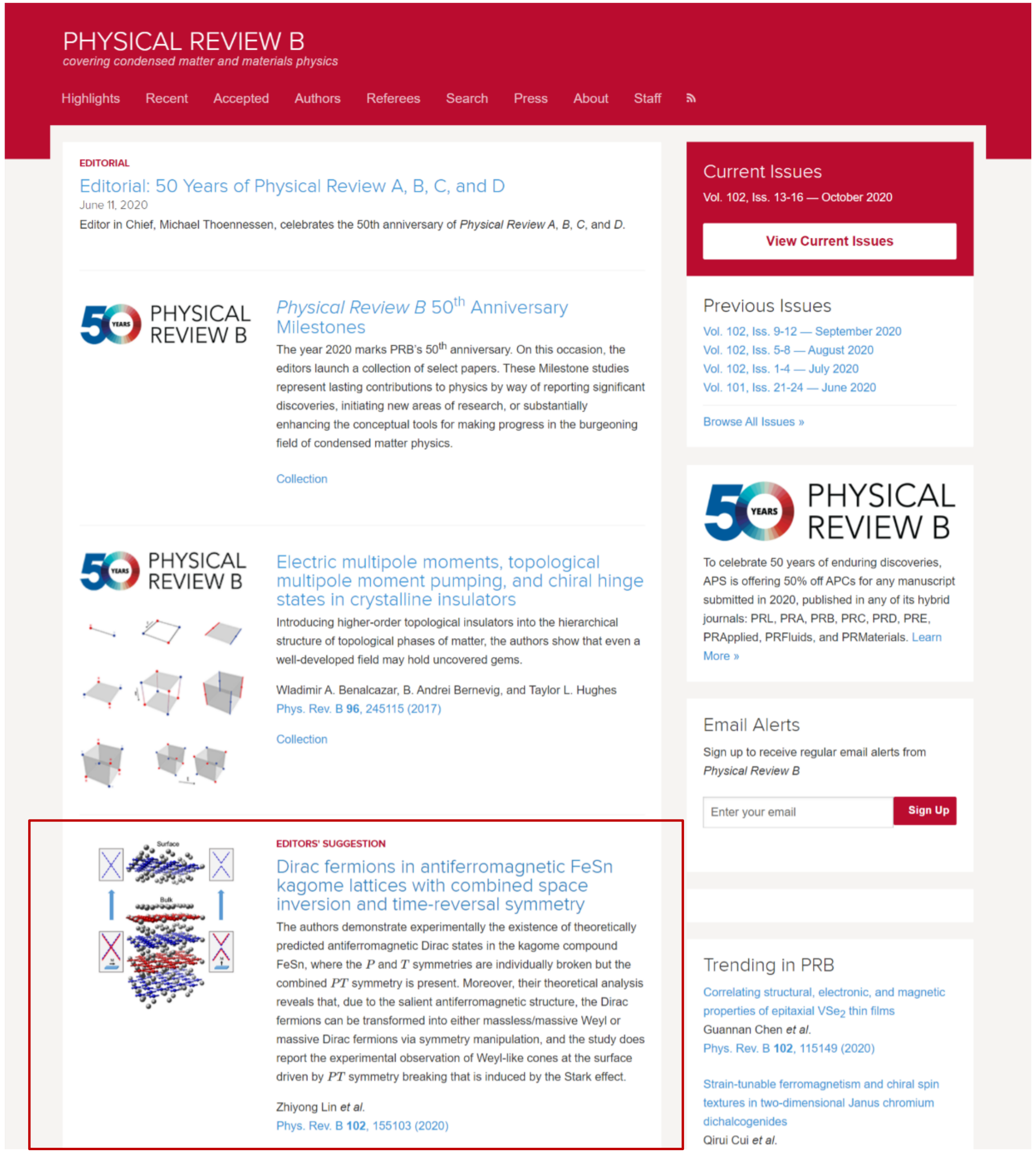
Experimental verification of 2D Weyl-like states at the surface



➢ Band crossing at K̄ point around -0.21 eV

Symmetry breaking induced topological phase transitions





PHYSICAL REVIEW B
covering condensed matter and materials physics

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EDITORIAL
Editorial: 50 Years of Physical Review A, B, C, and D
June 11, 2020
Editor in Chief, Michael Thoennessen, celebrates the 50th anniversary of *Physical Review A, B, C,* and *D*.

Physical Review B 50th Anniversary Milestones
The year 2020 marks PRB's 50th anniversary. On this occasion, the editors launch a collection of select papers. These Milestone studies represent lasting contributions to physics by way of reporting significant discoveries, initiating new areas of research, or substantially enhancing the conceptual tools for making progress in the burgeoning field of condensed matter physics.
Collection

Electric multipole moments, topological multipole moment pumping, and chiral hinge states in crystalline insulators
Introducing higher-order topological insulators into the hierarchical structure of topological phases of matter, the authors show that even a well-developed field may hold uncovered gems.
Wladimir A. Benalcazar, B. Andrei Bernevig, and Taylor L. Hughes
Phys. Rev. B **96**, 245115 (2017)
Collection

EDITORS' SUGGESTION
Dirac fermions in antiferromagnetic FeSn kagome lattices with combined space inversion and time-reversal symmetry
The authors demonstrate experimentally the existence of theoretically predicted antiferromagnetic Dirac states in the kagome compound FeSn, where the P and T symmetries are individually broken but the combined PT symmetry is present. Moreover, their theoretical analysis reveals that, due to the salient antiferromagnetic structure, the Dirac fermions can be transformed into either massless/massive Weyl or massive Dirac fermions via symmetry manipulation, and the study does report the experimental observation of Weyl-like cones at the surface driven by PT symmetry breaking that is induced by the Stark effect.
Zhiyong Lin *et al.*
Phys. Rev. B **102**, 155103 (2020)

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PHYSICAL REVIEW B
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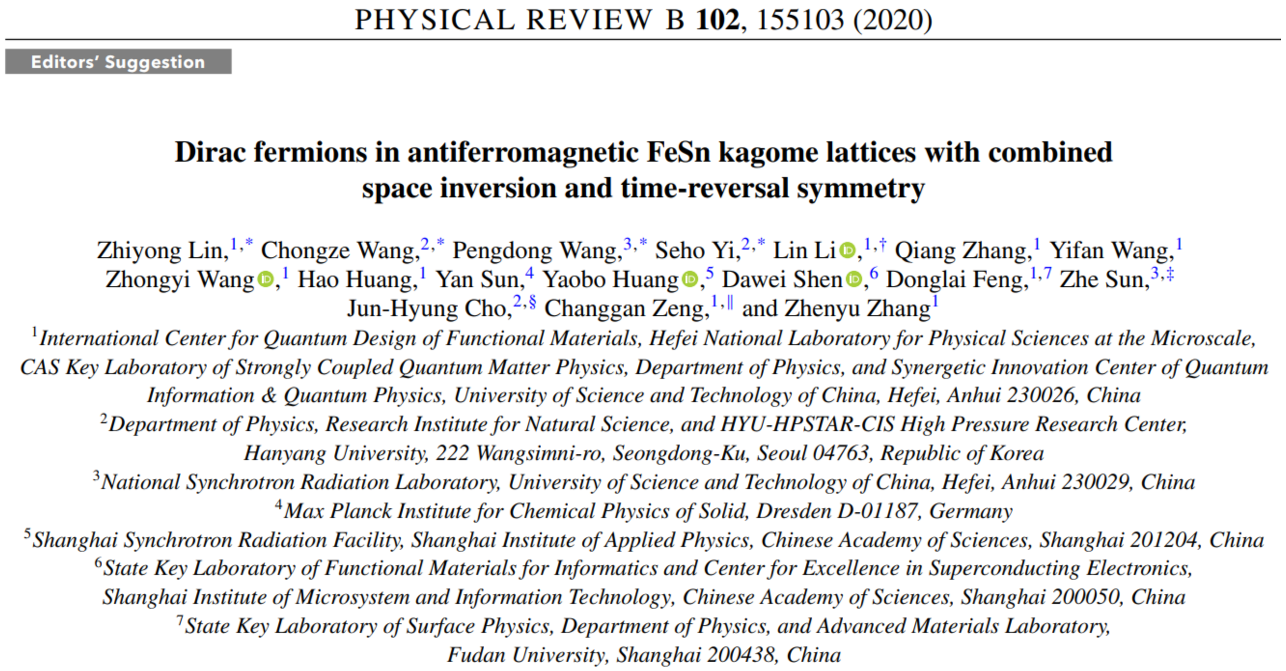
Trending in PRB
Correlating structural, electronic, and magnetic properties of epitaxial VSe_2 thin films
Guannan Chen *et al.*
Phys. Rev. B **102**, 115149 (2020)

Strain-tunable ferromagnetism and chiral spin textures in two-dimensional Janus chromium dichalcogenides
Qirui Cui *et al.*



PHYSICAL REVIEW B **102**, 155103 (2020)

Editors' Suggestion

Dirac fermions in antiferromagnetic FeSn kagome lattices with combined space inversion and time-reversal symmetry

Zhiyong Lin,[1,*] Chongze Wang,[2,*] Pengdong Wang,[3,*] Seho Yi,[2,*] Lin Li,[1,†] Qiang Zhang,[1] Yifan Wang,[1] Zhongyi Wang,[1] Hao Huang,[1] Yan Sun,[4] Yaobo Huang,[5] Dawei Shen,[6] Donglai Feng,[1,7] Zhe Sun,[3,‡] Jun-Hyung Cho,[2,§] Changgan Zeng,[1,||] and Zhenyu Zhang[1]

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[2]*Department of Physics, Research Institute for Natural Science, and HYU-HPSTAR-CIS High Pressure Research Center, Hanyang University, 222 Wangsimni-ro, Seongdong-Ku, Seoul 04763, Republic of Korea*
[3]*National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei, Anhui 230029, China*
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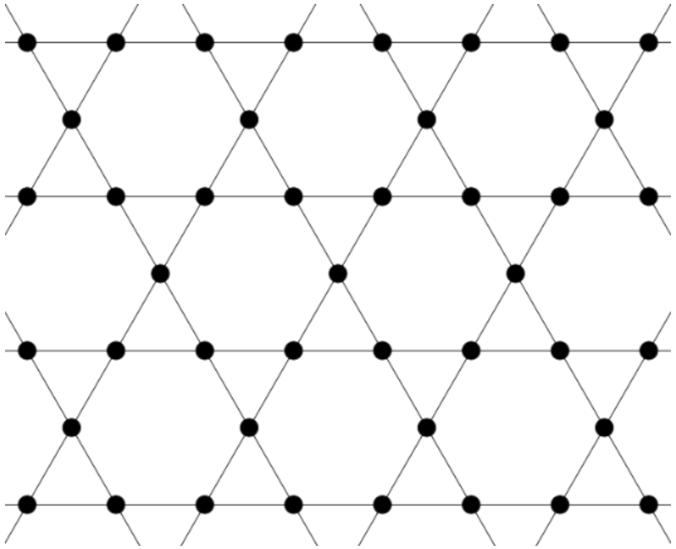
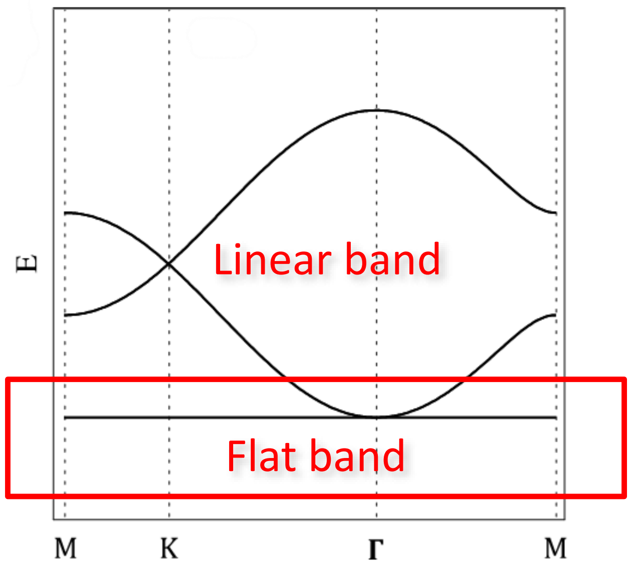
[5]*Shanghai Synchrotron Radiation Facility, Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201204, China*
[6]*State Key Laboratory of Functional Materials for Informatics and Center for Excellence in Superconducting Electronics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China*
[7]*State Key Laboratory of Surface Physics, Department of Physics, and Advanced Materials Laboratory, Fudan University, Shanghai 200438, China*

Lin *et al.*, Phys. Rev. B 102, 155103 (2020)

Editors' Suggestion





Linear band
Flat band
E
M
K
Γ
M

Flat band induced emergent effects: theory

In a flat band, the kinetic energy of electrons is quenched, this highly degenerate energy level becomes an ideal platform to achieve strongly correlated electronic states

Ferromagnetism

J. Phys. A: Math. Gen. **24** (1991) L73–L77. Printed in the UK

LETTER TO THE EDITOR

Ferromagnetic ground states for the Hubbard model on line graphs

A Mielke

Institut de Physique Théorique, Ecole Polytechnique Fédérale de Lausanne, PHB-Ecublens, CH-1015 Lausanne, Switzerland

Mielke *et al.*, J.Phys.A:Math.Gen.24, L73 (1991)

Wigner crystalization

PRL **99,** 070401 (2007) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2007

Flat Bands and Wigner Crystallization in the Honeycomb Optical Lattice

Congjun Wu,[1,2] Doron Bergman,[3] Leon Balents,[3] and S. Das Sarma[4]

[1]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
[2]*Department of Physics, University of California, San Diego, California 92093, USA*
[3]*Department of Physics, University of California, Santa Barbara, California 93106, USA*
[4]*Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
(Received 8 February 2007; published 16 August 2007)

Wu et al.,PRL.99,070401 (2007)

High-temperature FQHE

Selected for a Viewpoint in *Physics*
PRL **106,** 236802 (2011) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2011

High-Temperature Fractional Quantum Hall States

Evelyn Tang,[1] Jia-Wei Mei,[1,2] and Xiao-Gang Wen[1]

[1]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Institute for Advanced Study, Tsinghua University, Beijing, 100084, People's Republic of China*
(Received 14 December 2010; published 6 June 2011)

We show that a suitable combination of geometric frustration, ferromagnetism, and spin-orbit interactions can give rise to nearly flatbands with a large band gap and nonzero Chern number. Partial filling of the flatband can give rise to fractional quantum Hall states at high temperatures (maybe even room temperature). While the identification of material candidates with suitable parameters remains open, our work indicates intriguing directions for exploration and synthesis.

Wen et al.,PRL.106,236802 (2011)

Bose-Einstein condensation

PHYSICAL REVIEW B **82**, 184502 (2010)

Bose condensation in flat bands

Sebastian D. Huber and Ehud Altman

Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot 76100, Israel
(Received 27 July 2010; published 2 November 2010)

Huber et al.,PRB.82,184502 (2010)

High temperature superconductivity

VOLUME 84, NUMBER 1 PHYSICAL REVIEW LETTERS 3 JANUARY 2000

Superconductivity from Flat Dispersion Designed in Doped Mott Insulators

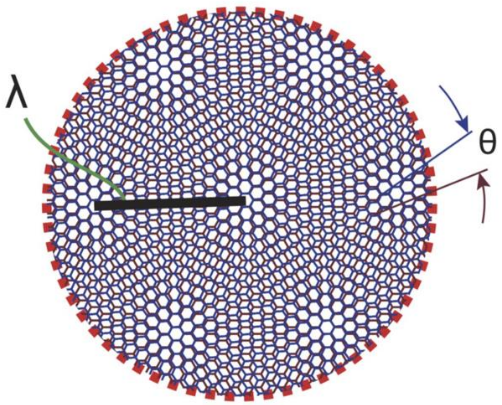
Masatoshi Imada[1] and Masanori Kohno[2]

[1]*Institute for Solid State Physics, University of Tokyo, Roppongi, Minato-ku, Tokyo 106-8666, Japan*
[2]*Mitsubishi Research Institute, Inc., Ootemachi, Chiyoda-ku, Tokyo, 100-8141, Japan*
(Received 23 June 1999)

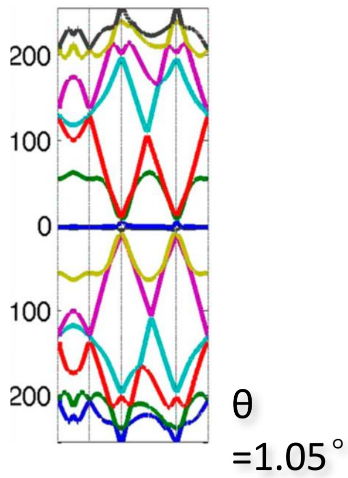
Imada et al.,PRL.84,143 (2000)

Fascinating flat band physics in magic-angle twisted bilayer graphene

Twisted bilayer graphene

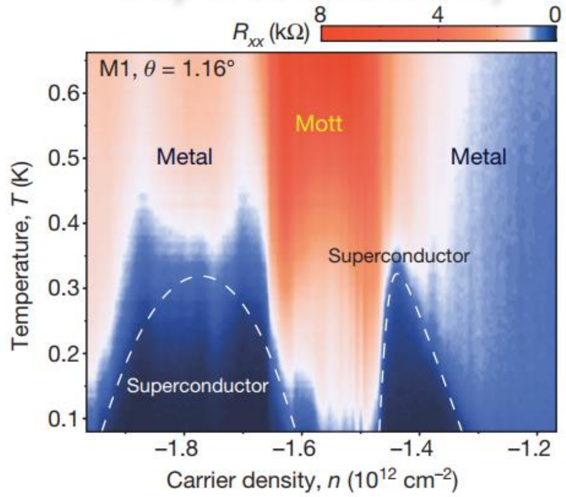


Band structure



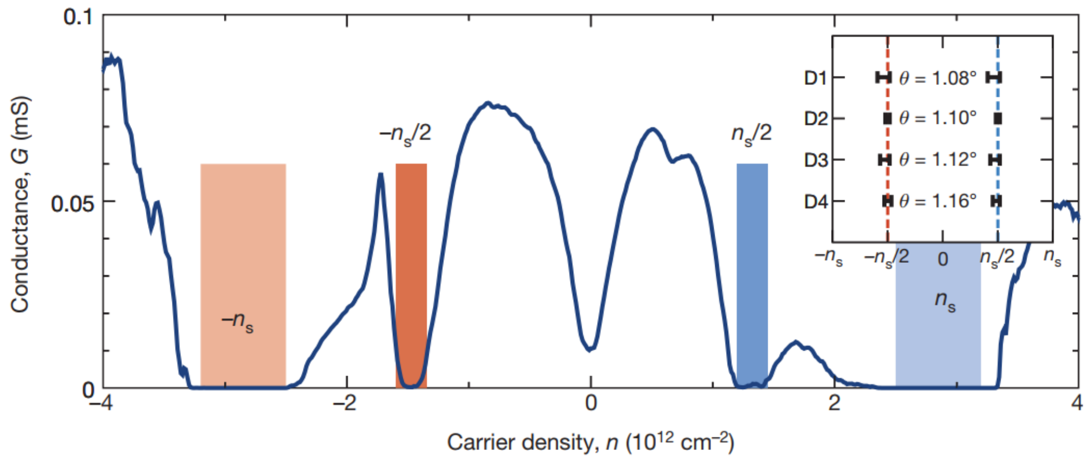
MacDonald *et al.*, PNAS 108, 12233 (2011)

Superconductivity



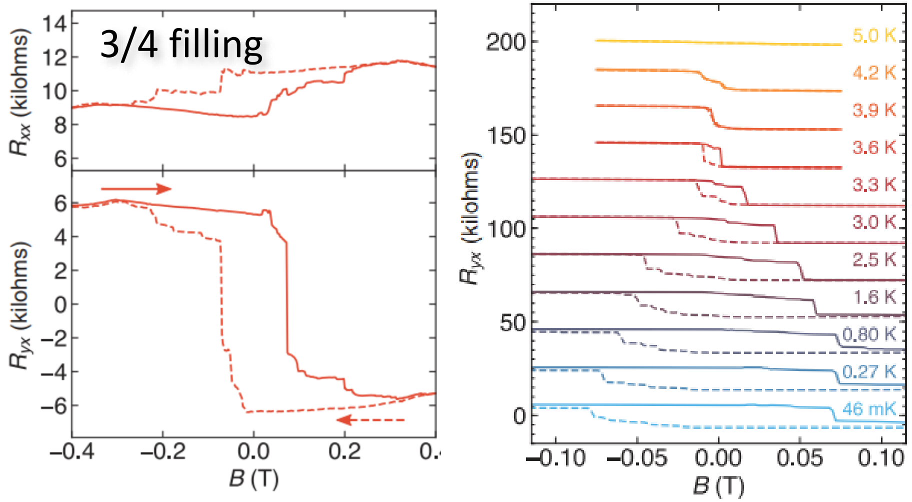
Cao *et al.*, Nature. 556, 43 (2018)

Correlated insulator



Cao *et al.*, Nature. 555, 80 (2018)

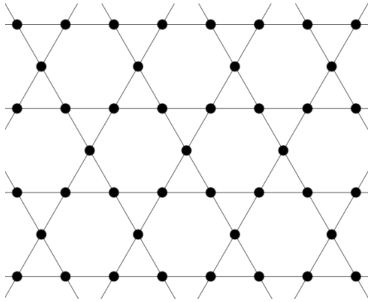
Ferromagnetism

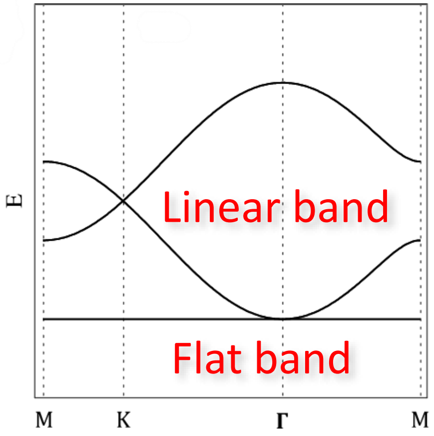


Sharpe *et al.*, Science. 365, 605 (2019)

Outline

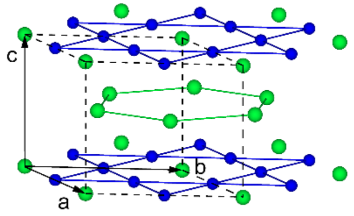
Novel properties in kagome lattices





- Antiferromagnetic Dirac semimetal

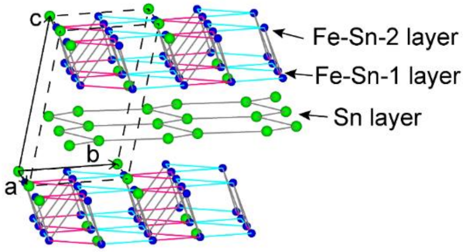
  PRB 102,155103 (2020)
  Editors' Suggestion



FeSn

- Flat band and HT ferromagnetism

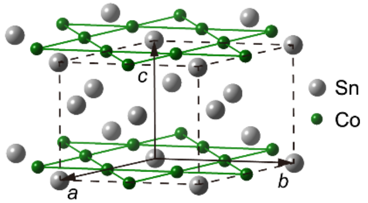
  PRL 121, 096401 (2018)
  Cover story, Editors' Suggestion



Fe_3Sn_2

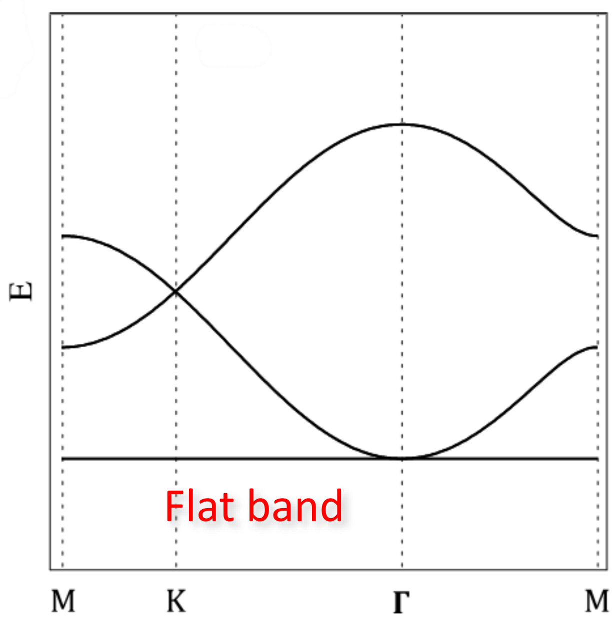
- Flat band and anomalously giant magnetic & transport anisotropy

  PRL 128, 096601 (2022)



CoSn

Understanding the flat band in kagome lattice

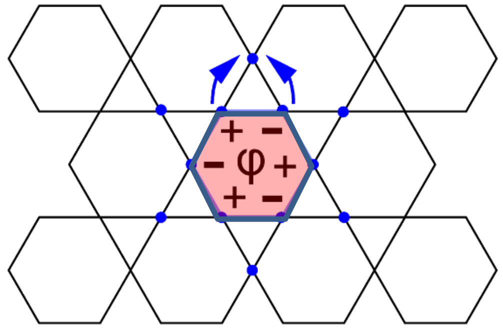


Bloch state of the flat band

$$\psi_k = (\sin k_3\,, -\sin k_2\,, \sin k_1)^T$$

In real space

$$\psi_{\mu\sigma} = \frac{1}{\sqrt{6}} \sum_{i \in \mu} (-1)^i d_{i\sigma}^\dagger \, |0\rangle$$

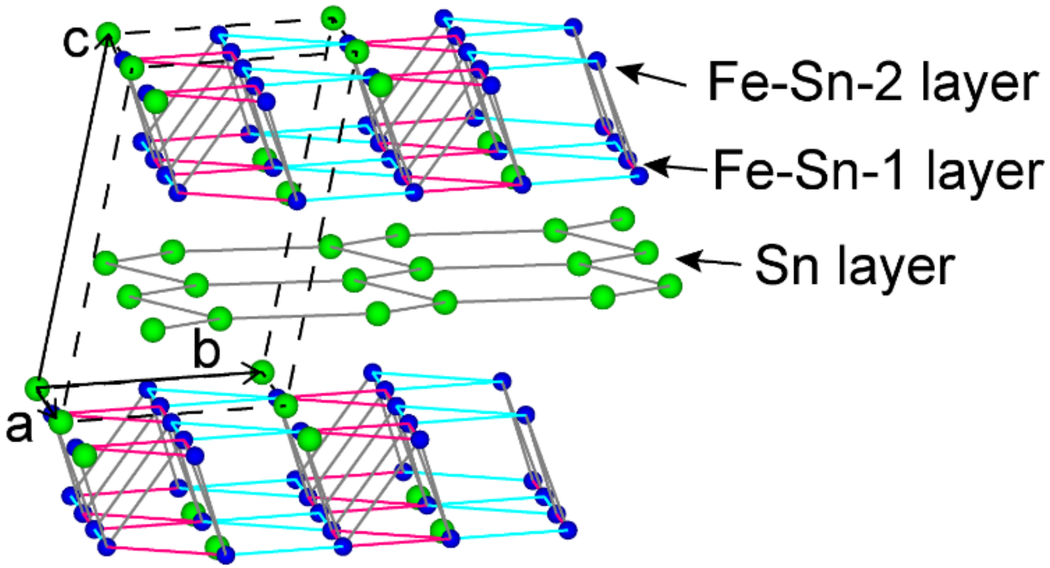


- Wavefunction alternates its sign around the six vertices in each hexagon
- Flat band arises from the local destructive interference of the Bloch wave functions

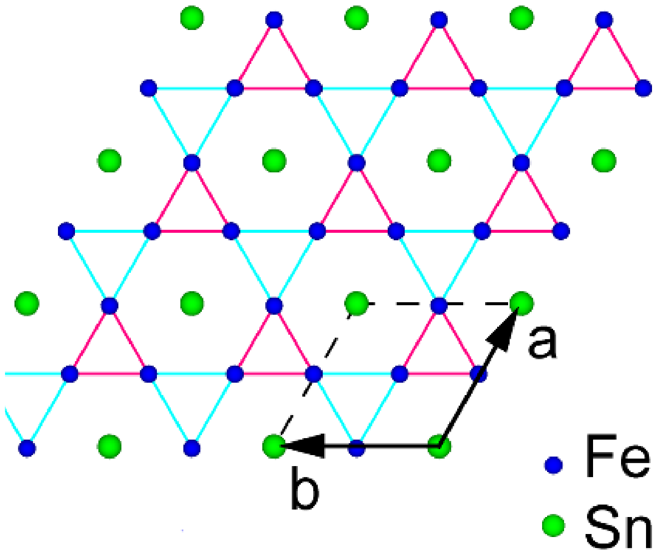
Definitive experimental demonstration of flat bands in kagome lattice remains to be accomplished

Ferromagnetic kagome compound Fe_3Sn_2

Perspective view

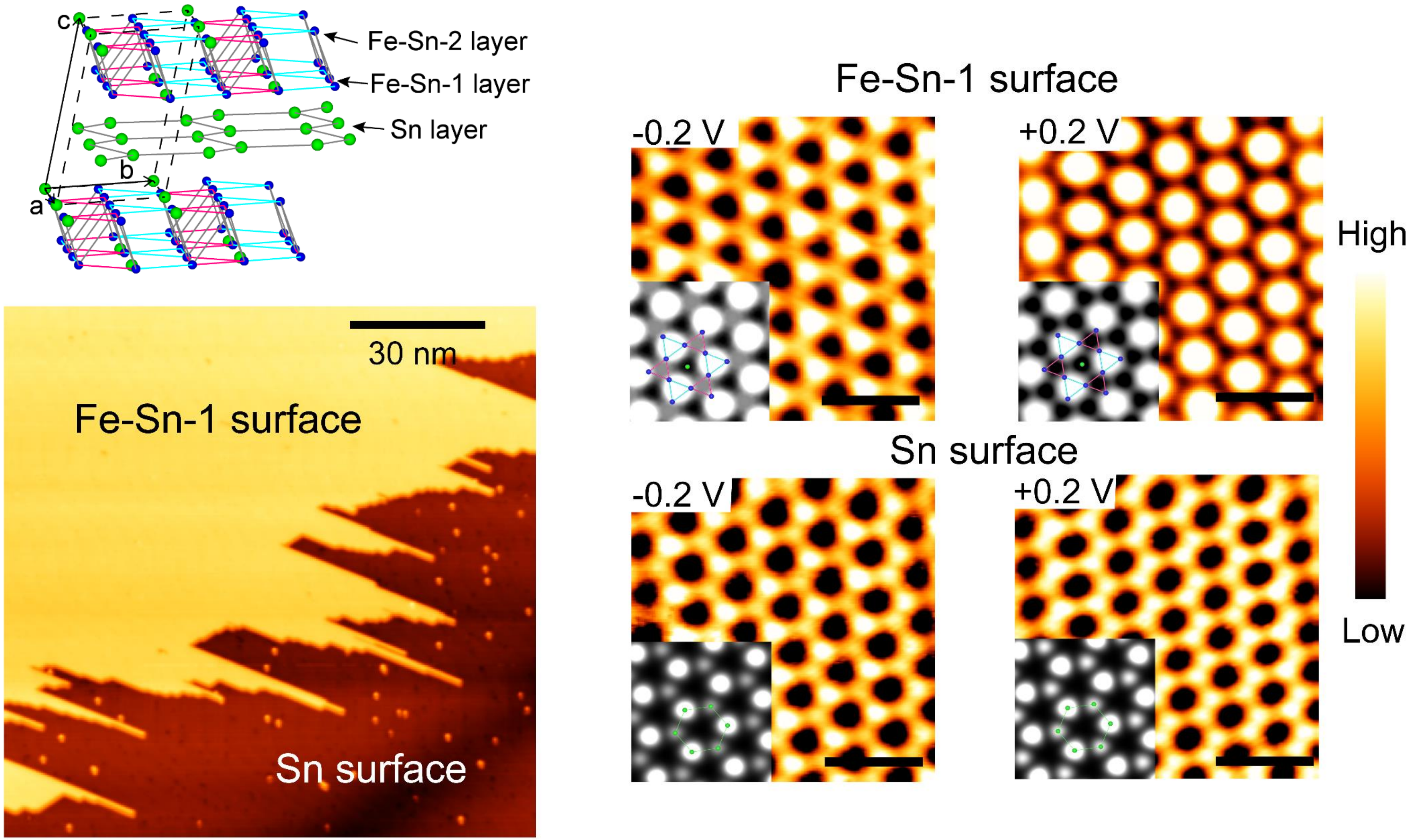


Top view



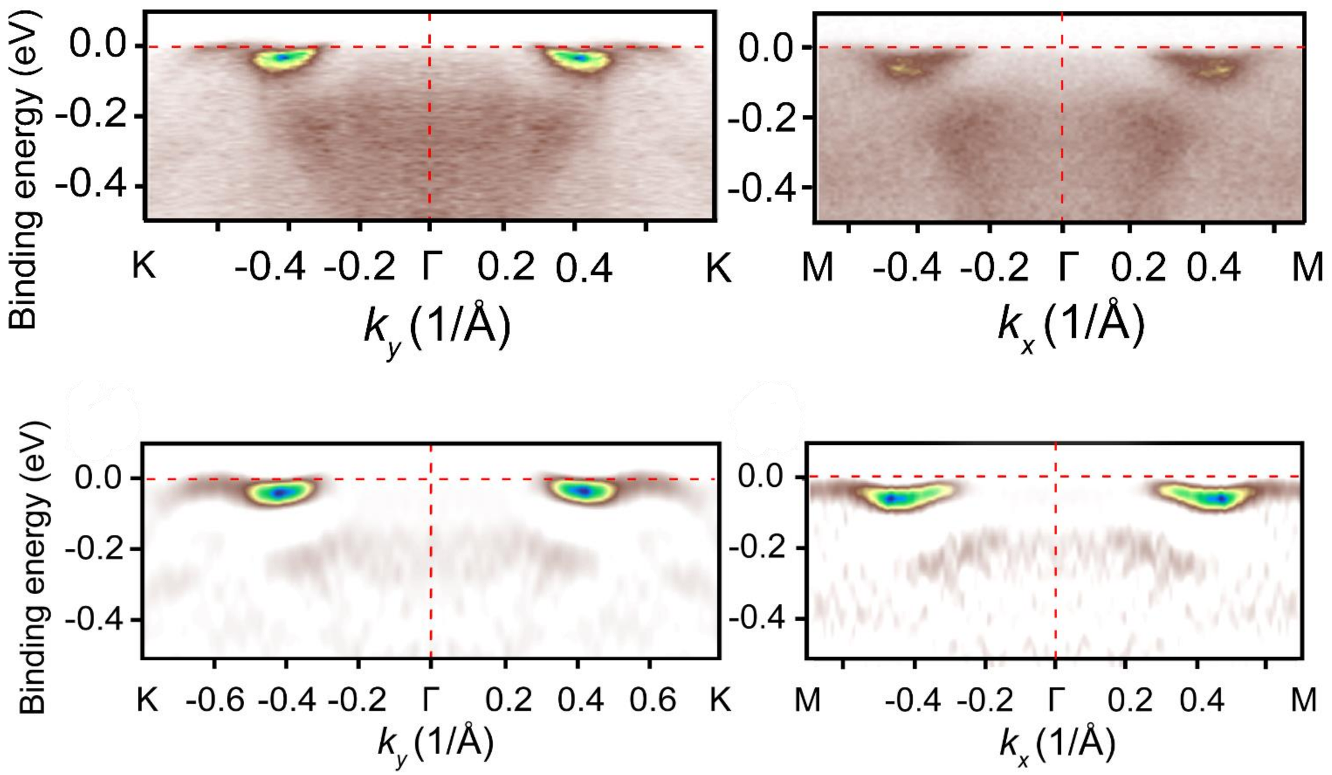
Fe atoms form quasi-2D kagome lattice in each Fe-Sn layer

Fe_3Sn_2 surfaces



Two surface Terminations: Fe-Sn-1 and Sn layers

ARPES results

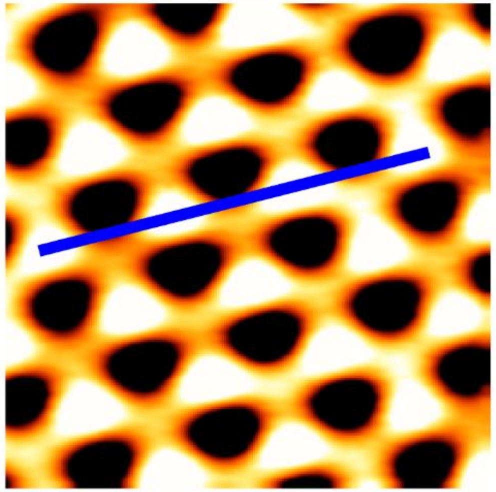


Second derivatives

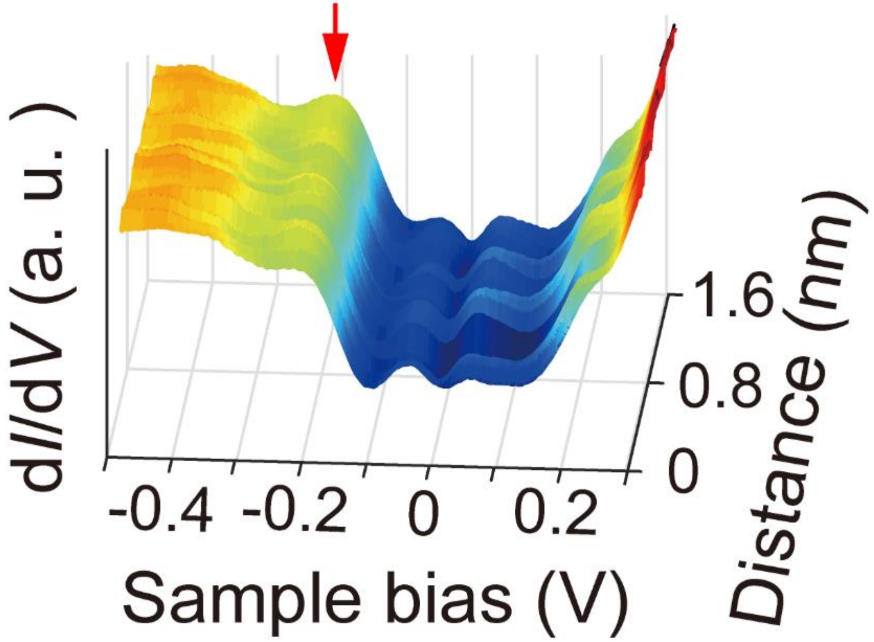
Photon energy 35 eV, surface sensitive

A nearly dispersionless surface flat band at ~ 0.2 eV below E_F

Scanning tunneling spectra on the Fe-Sn-1 surface



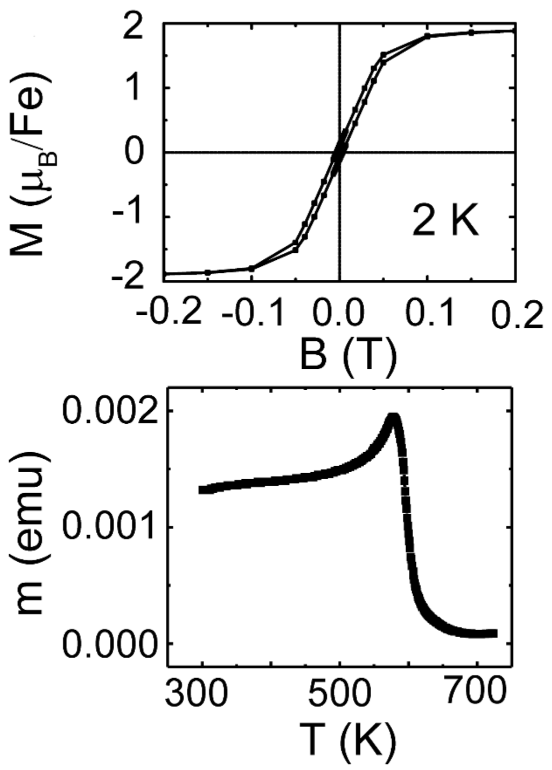
Fe-Sn-1 surface



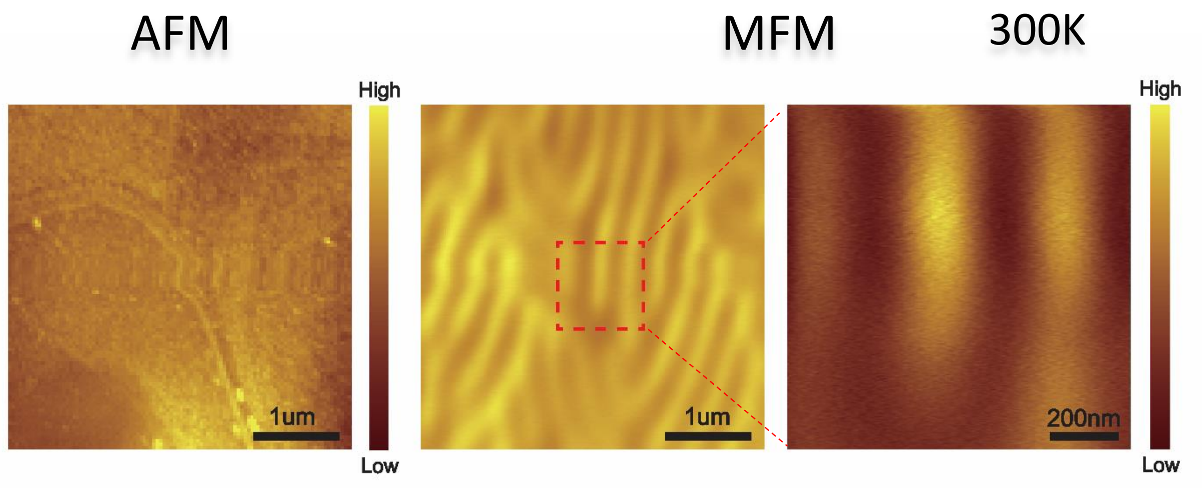
- DI/dV spectra: a prominent peak at ~-0.2 eV
- Consistent with ARPES observation of a flat band at ~-0.2 eV

Ferromagnetism of Fe_3Sn_2

Bulk



Surface

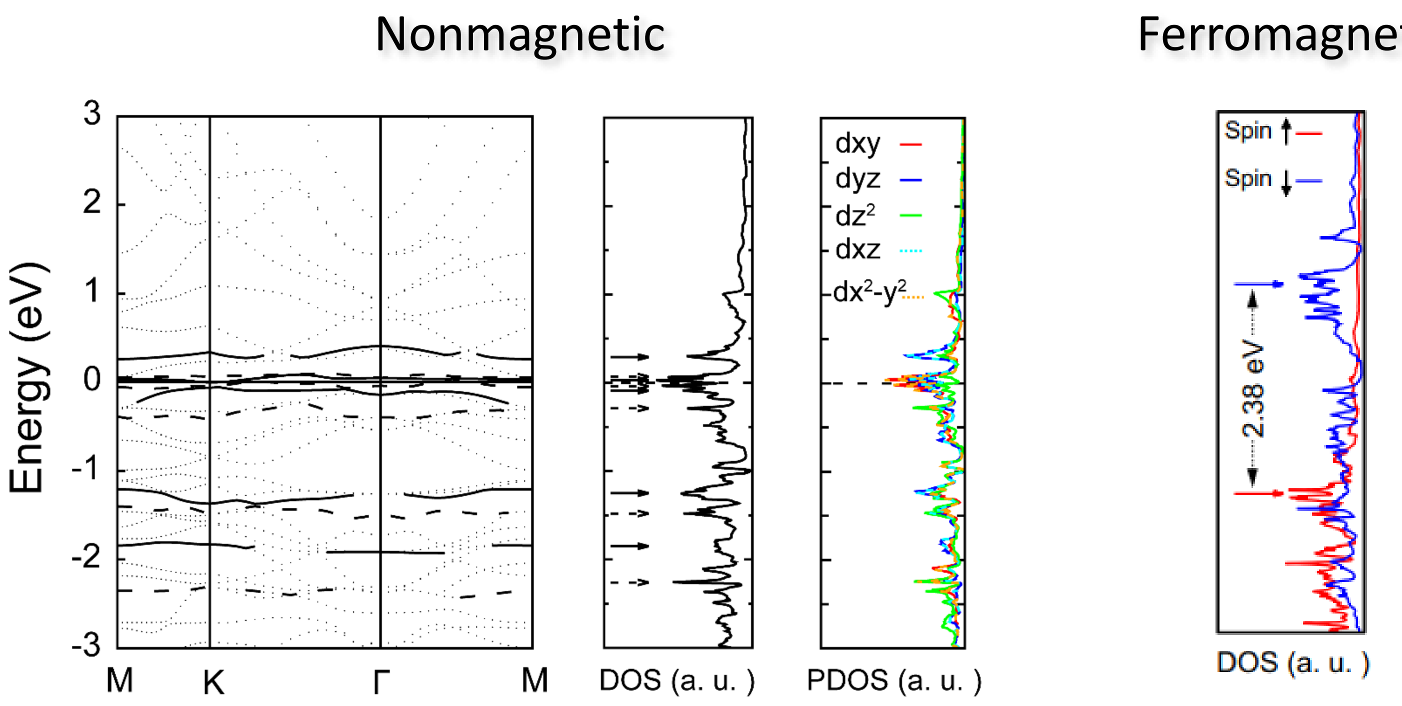


- $M_s = 1.94\ \mu_B$ (2 K)
- $T_c \sim 610$ K

Ferromagnetic behavior observed

- in Fe_3Sn_2 bulk by VSM
- near the surface by MFM

Ferromagnetic state vs nonmagnetic state



- Nonmagnetic state: Several nearly flat bands near E_F
- Ferromagnetic state: A splitting of ~2.4 eV between the majority- and minority-spin bands
- Ferromagnetic configuration is more stable than the nonmagnetic one by 2.8 eV per unit cell

Stoner criterion

Stoner criterion of ferromagnetism:

$$U \cdot n(E_F) > 1$$

- U: Coulomb interaction energy
- $n(E_F)$: density of states at the Fermi level

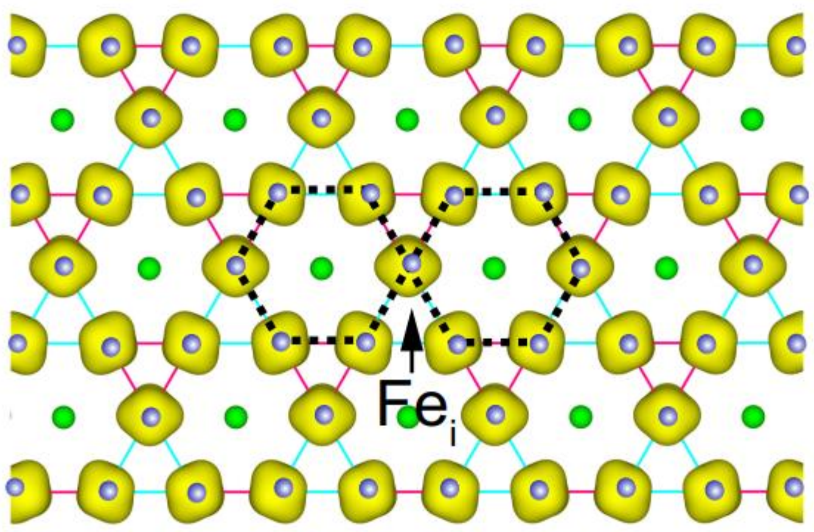
Fe_3Sn_2

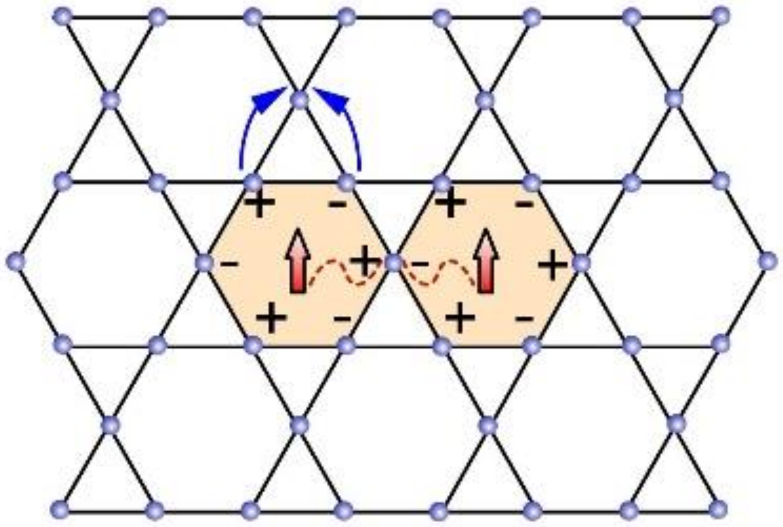
- ➢ Effective on-site Coulomb interaction *U* within the hexagonal cell ~1.15 eV
- ➢ High DOS of the flat bands at the Fermi level for the nonmagnetic state

⬇

Ferromagnetic order

FM Mechanism of Fe_3Sn_2: a real space picture





- Local spin polarization due to the intramolecular exchange of localized electrons around each hexagon
- Such spin moments coupled with each other via the intermolecular correlation through a unique network of the hexagons

Ferromagnetism in 2D van der Waals crystals

LETTER

doi:10.1038/nature22060

Discovery of intrinsic ferromagnetism in two-dimensional van der Waals crystals

Cheng Gong[1]*, Lin Li[2]*, Zhenglu Li[3,4]*, Huiwen Ji[5], Alex Stern[2], Yang Xia[1], Ting Cao[3,4], Wei Bao[1], Chenzhe Wang[1], Yuan Wang[1,4], Z. Q. Qiu[3], R. J. Cava[5], Steven G. Louie[3,4], Jing Xia[2] & Xiang Zhang[1,4]

$Cr_2Ge_2Te_6$

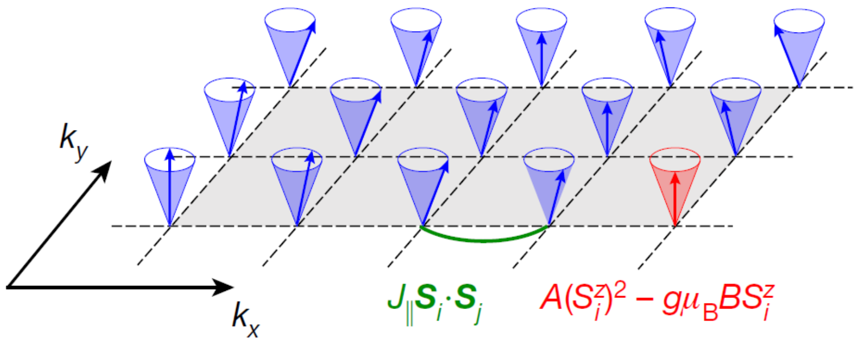
LETTER

doi:10.1038/nature22391

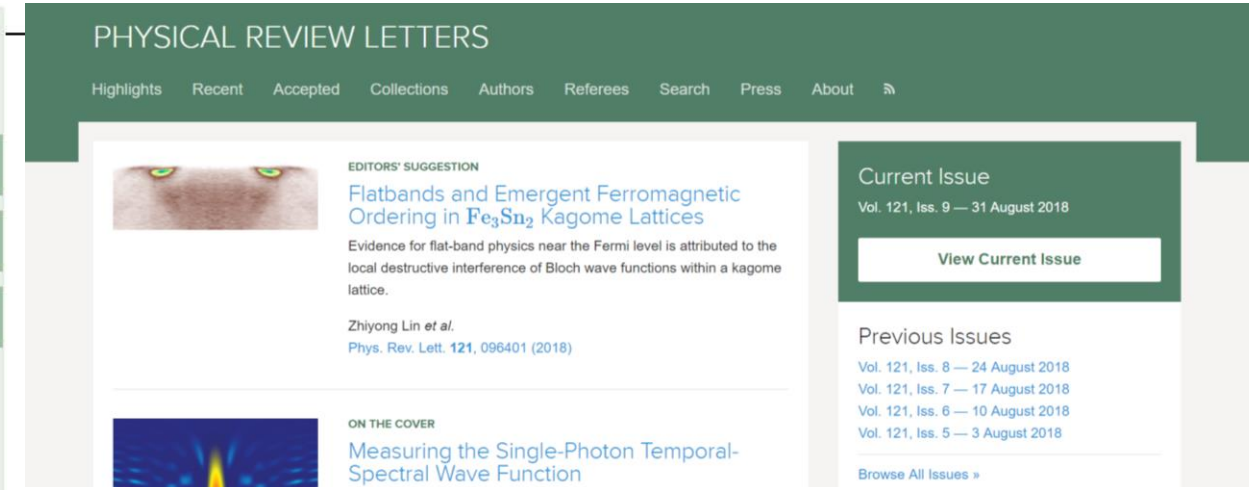
Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit

Bevin Huang[1]*, Genevieve Clark[2]*, Efrén Navarro-Moratalla[3]*, Dahlia R. Klein[3], Ran Cheng[4], Kyle L. Seyler[1], Ding Zhong[1], Emma Schmidgall[1], Michael A. McGuire[5], David H. Cobden[1], Wang Yao[6], Di Xiao[4], Pablo Jarillo-Herrero[3] & Xiaodong Xu[1,2]

CrI_3



Magnetic atoms are ferromagnetically coupled with the interelectronic exchange J



adiabatic

PHYSICAL REVIEW LETTERS **121**, 096401 (2018)

Editors' Suggestion

Flatbands and Emergent Ferromagnetic Ordering in Fe_3Sn_2 Kagome Lattices

Zhiyong Lin,[1,2] Jin-Ho Choi,[3] Qiang Zhang,[1,2] Wei Qin,[1] Seho Yi,[3] Pengdong Wang,[4] Lin Li,[1,2] Yifan Wang,[1,2] Hui Zhang,[1,2] Zhe Sun,[4] Laiming Wei,[1,2] Shengbai Zhang,[1,5] Tengfei Guo,[1,6,7] Qingyou Lu,[1,6,7] Jun-Hyung Cho,[1,3,†] Changgan Zeng,[1,2,*] and Zhenyu Zhang[1]

[1]*International Center for Quantum Design of Functional Materials (ICQD), Hefei National Laboratory for Physical Sciences at the Microscale, and Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*
[2]*CAS Key Laboratory of Strongly-Coupled Quantum Matter Physics, and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*
[3]*Department of Physics and HYU-HPSTAR-CIS High Pressure Research Center, Hanyang University, 17 Haengdang-Dong, SeongDong-Ku, Seoul 133-791, Korea*
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[5]*Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York 12180, USA*
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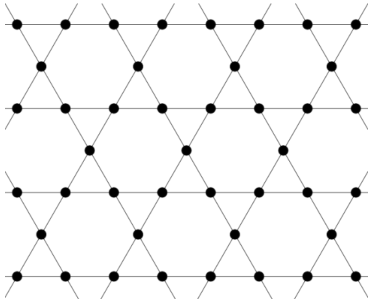
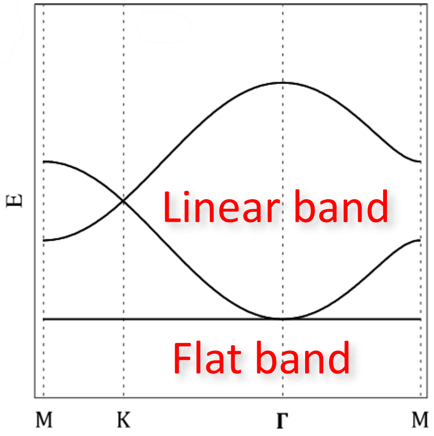
[7]*Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China*

Lin *et al.*, Phys. Rev. Lett. 121, 096401 (2018)   Editors' suggestion, highlighted on the cover

Outline

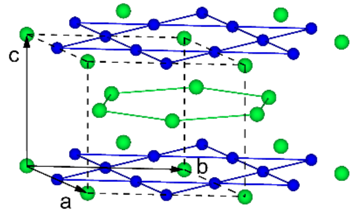
Novel properties in kagome lattices





- ➢ Antiferromagnetic Dirac semimetal

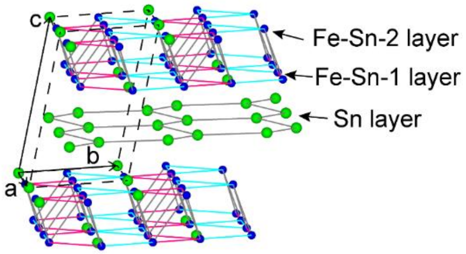
  PRB 102,155103 (2020)
  Editors' Suggestion



FeSn

- ➢ Flat band and HT ferromagnetism

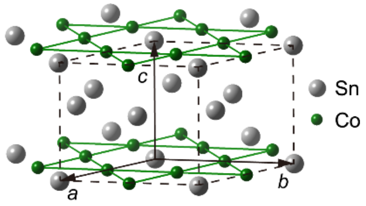
  PRL 121, 096401 (2018)
  Cover story, Editors' Suggestion



Fe_3Sn_2

- ➢ Flat band and anomalously giant magnetic & transport anisotropy

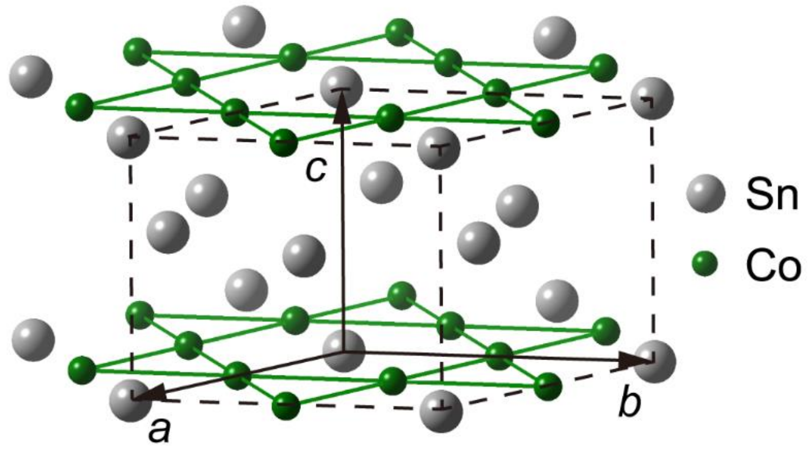
  PRL 128, 096601 (2022)



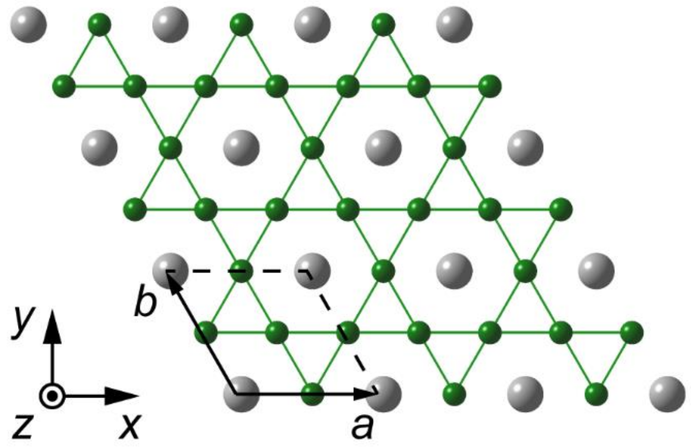
CoSn

Paramagnetic kagome compound CoSn

Perspective view

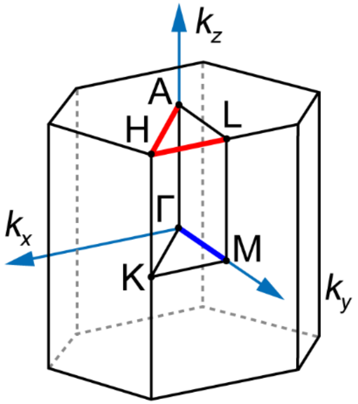


Top view

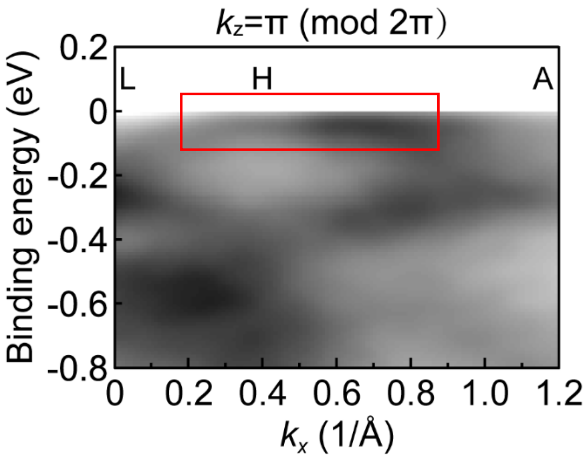


Paramagnetism: to exclude any effect from long-range magnetic order

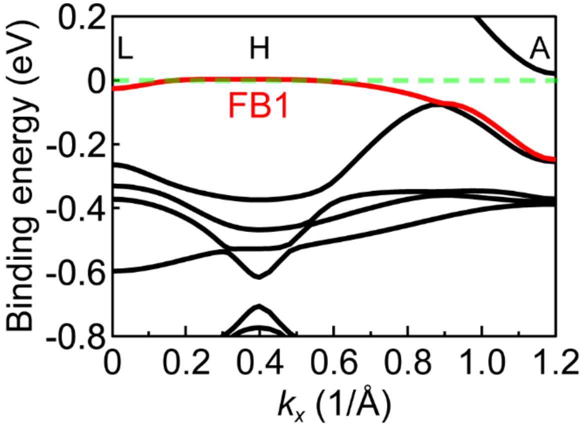
Band structure of CoSn



ARPES



DFT

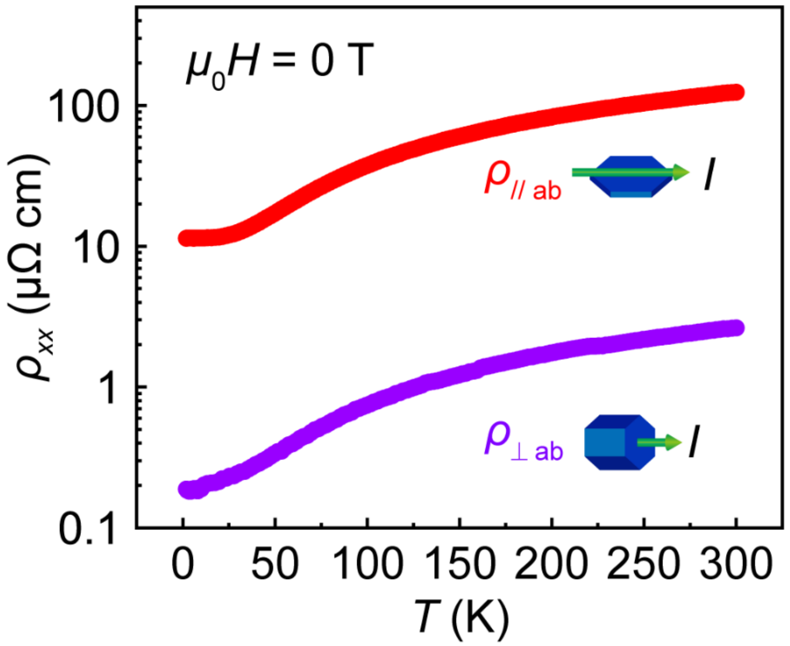


- Nearly dispersionless flat band around E_{F}
- Band width smaller than 0.1 eV

Anomalously giant electronic transport anisotropy

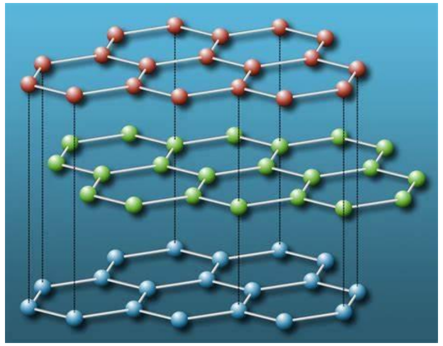
Quasi-2D kagome lattice

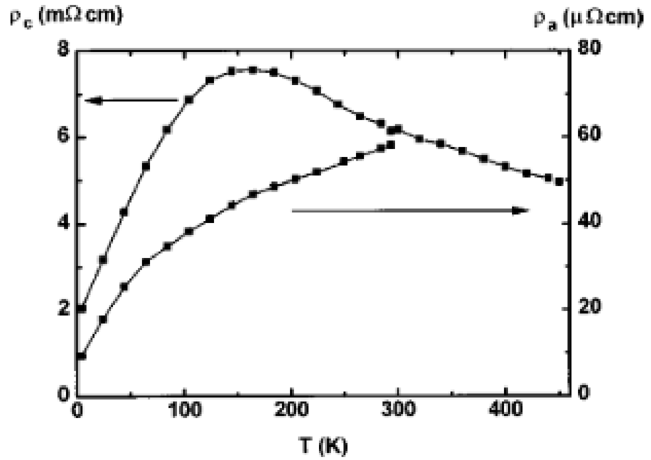
$$\rho_{//ab} \gg \rho_{\perp ab}$$



Conventional quasi-2D materials

$$\rho_{//ab} \ll \rho_{\perp ab}$$





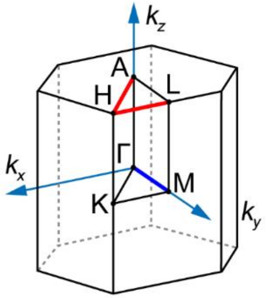
$$\frac{\rho_{//ab}}{\rho_{\perp ab}} \approx 5\times10^{-3}$$

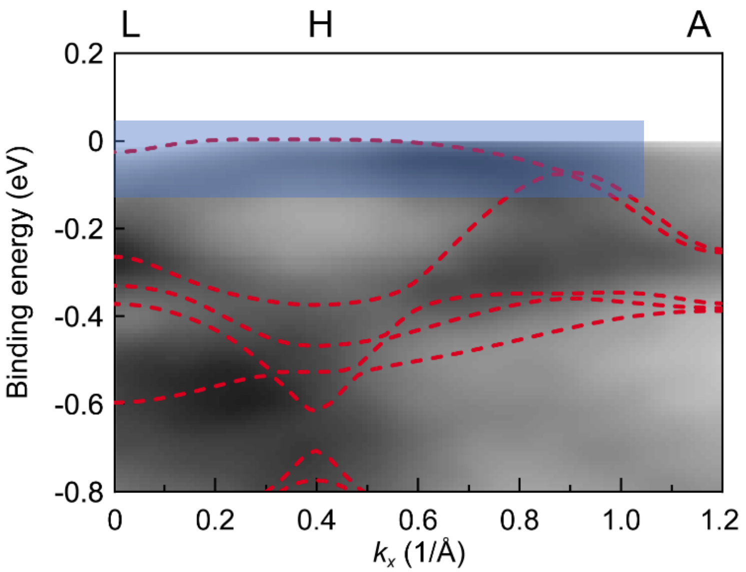
Edman *et al.*, Phys. Rev. B 57, 6227 (1998)

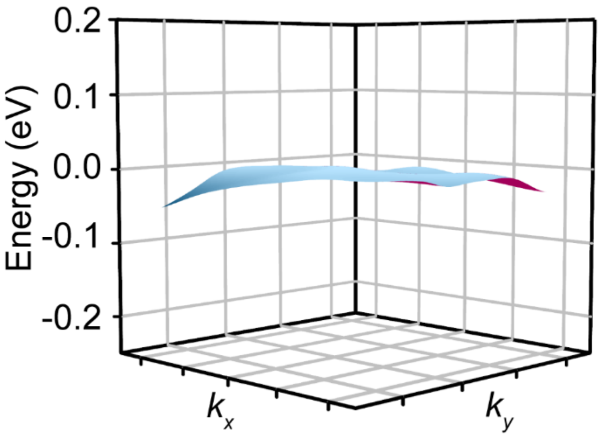
- Metallic *RT* behavior
- In-plane resistivity much larger than out-of-plane resistivity

Anomalously giant anisotropy: $\frac{\rho_{//ab}}{\rho_{\perp ab}} \approx 60$ at 2 K

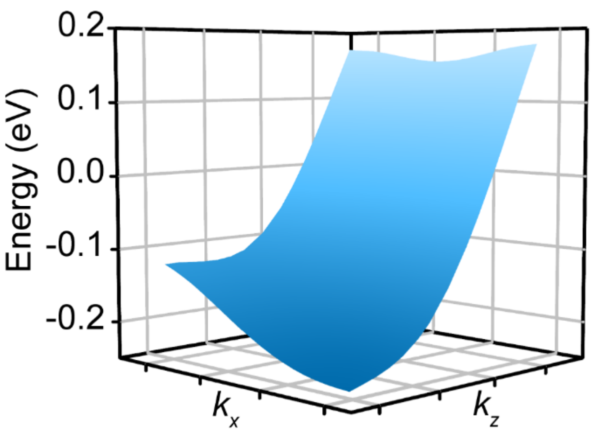
Flat band mechanism







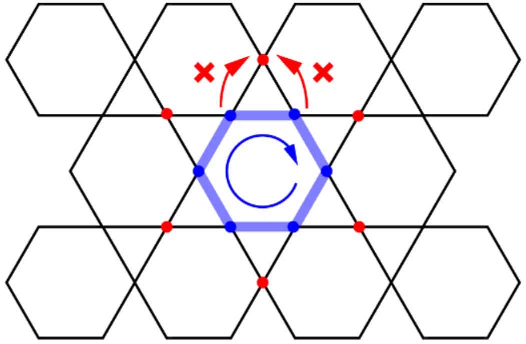
K_x-k_y plane: flat



k_z direction: dispersive

Flat band in k_x-k_y plane → In-plane m^* much larger than out-of-plane m^* $\frac{m^*_{\text{L-H}}}{m^*_{\Gamma\text{-A}}} \approx 34$ → $\rho_{//ab} \gg \rho_{\perp ab}$

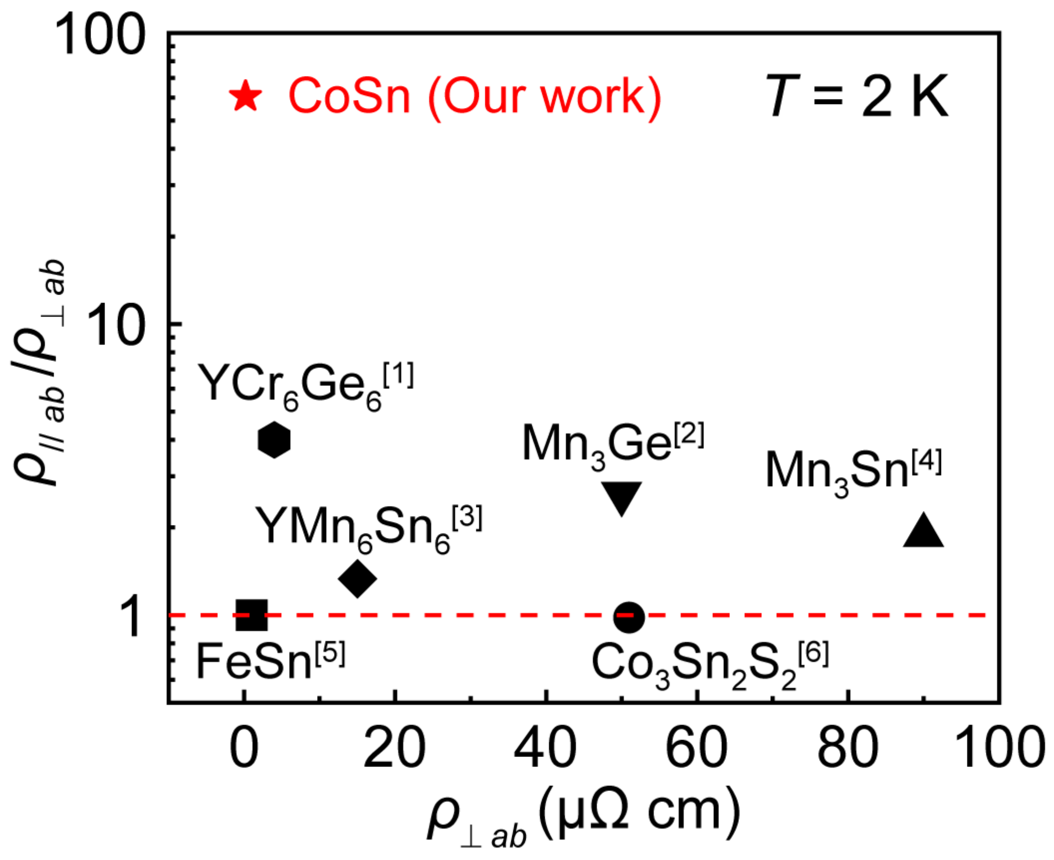
$\sigma = ne^2\tau/m^*$



At the atomic scale:
Self-localization of the flat band electrons in each hexagon

Comparison with other kagome compounds

$\rho_{//ab} > \rho_{\perp ab}$



Why much larger anomalous resistivity anisotropy in CoSn?

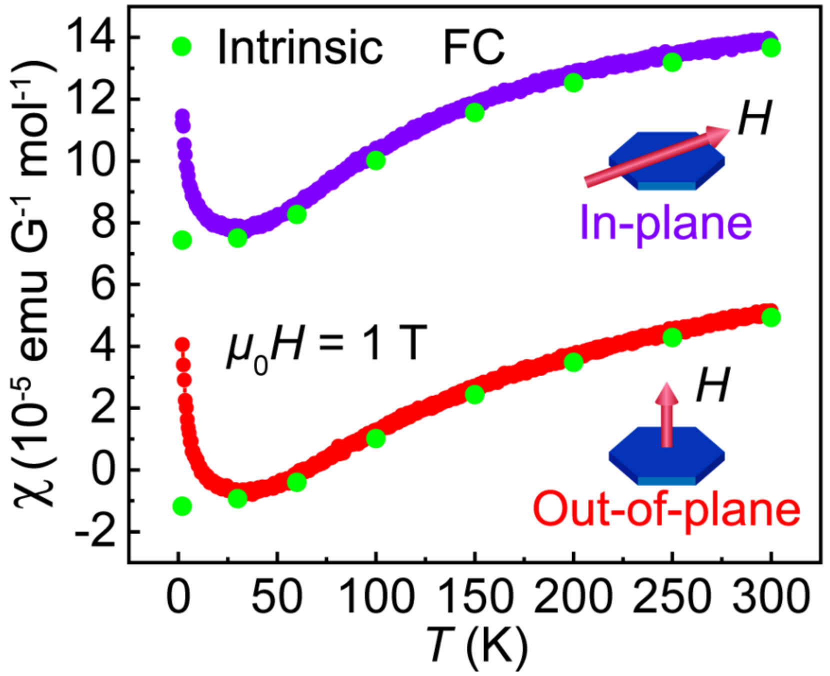
- Flat bands locate just around the Fermi level
- No long-range magnetic order

1. arXiv: 1906. 07140 (2019)
2. Phys. Rev. Appl. 5, (2016)
3. Phys. Rev. B 103, 014416 (2021)
4. arXiv: 1902. 06601, (2019)
5. J. Phys. Soc. Jpn. 88, (2019)
6. Sci. Adv. 5, 9867, (2019)

Anomalous diamagnetism along the perpendicular direction

Absence of long-range magnetic order

Superior to investigate the intrinsic magnetic properties of kagome lattice



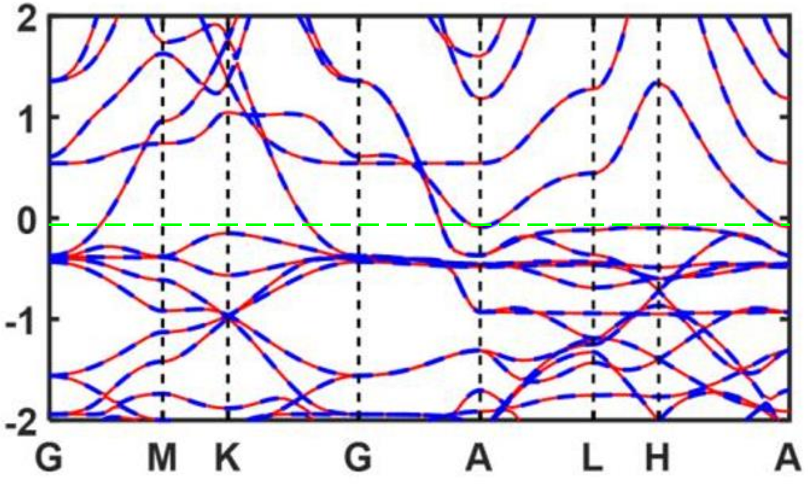
- Pauli paramagnetism, with magnetic-impurity contribution below 36 K
- Giant magnetic anisotropy:

  $\Delta\chi = \chi_{\perp ab} - \chi_{//ab} = -8.6\times10^{-5}$ emu·G^{-1}·mol^{-1}
- Additional diamagnetism along the out-of-plane direction

Flat band contributed orbital diamagnetism in CoSn

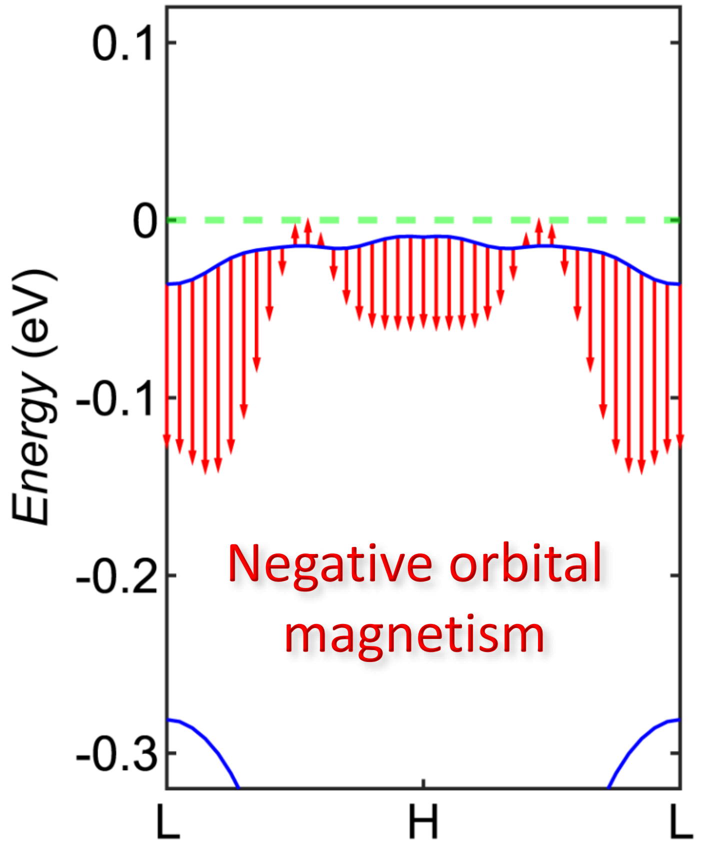
Red: DFT

Blue: Wannier



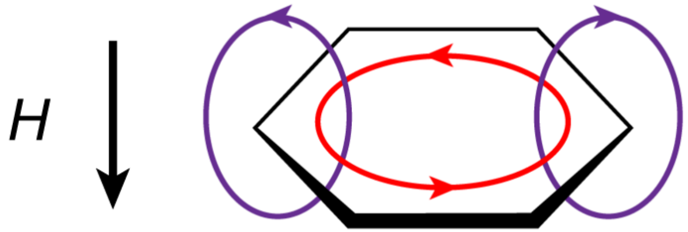
The magnetic moment is calculated by:

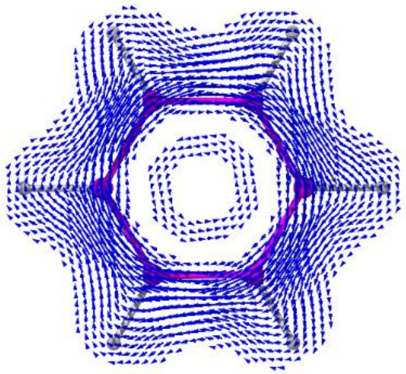
$$
\begin{aligned}
m_n(\mathbf{k}) &= \frac{-ie}{2\hbar} \times \langle \nabla_{\mathbf{k}} u_n(\mathbf{k}) | \times [H(\mathbf{k}) - E_{n,\mathbf{k}}] | \nabla_{\mathbf{k}} u_n(\mathbf{k}) \rangle \\
&= \frac{e}{2\hbar} \times \mathrm{Im} \langle \nabla_{\mathbf{k}} u_n(\mathbf{k}) | \times [H(\mathbf{k}) - E_{n,\mathbf{k}}] | \nabla_{\mathbf{k}} u_n(\mathbf{k}) \rangle \\
&= \frac{e}{2\hbar} \times \mathrm{Im} \sum_{m} \langle \nabla_{\mathbf{k}} u_n(\mathbf{k}) \mid u_m(\mathbf{k}) \rangle \times \langle u_m(\mathbf{k}) | [H(\mathbf{k}) - E_{n,\mathbf{k}}] | \nabla_{\mathbf{k}} u_n(\mathbf{k}) \rangle \\
&= \frac{e}{2\hbar} \times \mathrm{Im} \sum_{m} \sum_{t} \langle \nabla_{\mathbf{k}} u_n(\mathbf{k}) \mid u_m(\mathbf{k}) \rangle \times \langle u_m(\mathbf{k}) | [H(\mathbf{k}) - E_{n,\mathbf{k}}] | u_t(\mathbf{k}) \rangle \langle u_t(\mathbf{k}) \mid \nabla_{\mathbf{k}} u_n(\mathbf{k}) \rangle \\
&= \frac{e}{2\hbar} \times \mathrm{Im} \sum_{m \neq n} \langle \nabla_{\mathbf{k}} u_n(\mathbf{k}) \mid u_m(\mathbf{k}) \rangle \times [E_{m,\mathbf{k}} - E_{n,\mathbf{k}}] \langle u_m(\mathbf{k}) \mid \nabla_{\mathbf{k}} u_n(\mathbf{k}) \rangle \\
&= \frac{e}{2\hbar} \mathrm{Im} \sum_{m \neq n} \frac{\langle u_{n,\mathbf{k}} | (\nabla_{\mathbf{k}} H(\mathbf{k})) | u_{m,\mathbf{k}} \rangle \times \langle u_{m,\mathbf{k}} | (\nabla_{\mathbf{k}} H(\mathbf{k})) | u_{n,\mathbf{k}} \rangle}{E_{m,\mathbf{k}} - E_{n,\mathbf{k}}}
\end{aligned}
$$



Real-space scenario for the flat-band negative magnetism

Orbital diamagnetism in benzene ring

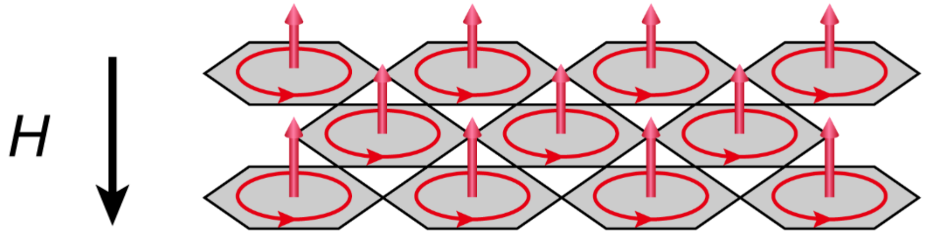




Aromatic molecule

In kagome lattice, flat-band electrons are sel-localized in the hexagons, similar to the benzene case

Orbital diamagnetism in kagome lattice



PHYSICAL REVIEW LETTERS **128,** 096601 (2022)

Flat-Band-Induced Anomalous Anisotropic Charge Transport and Orbital Magnetism in Kagome Metal CoSn

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Summary

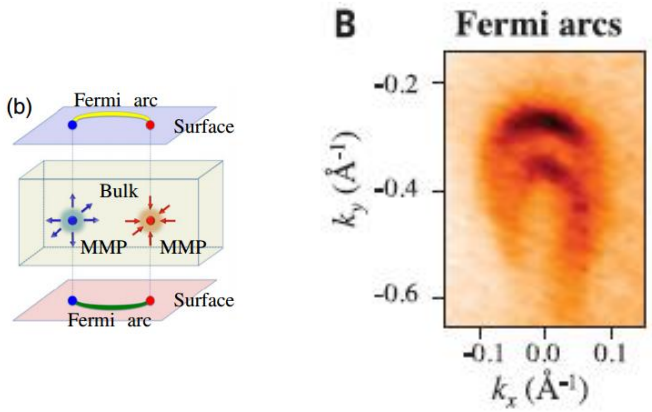
Kagome lattice:

- Rich Dirac/Weyl & flat-band physics
- Ideal platform to exploit novel magnetic, topological and strongly correlated physics
- New-concept applications: topological spintronic devices


KAGOME
野菜生活
100
1食分の野菜
KAGOME
野菜生活
100
Energy Roots
1食分の野菜
ポリフェノール
KAGOME
野菜生活
100
季節限定
夏みかんミックス
KAGOME
野菜生活
100
季節限定
佐藤錦ミックス
KAGOME
野菜生活
100
季節限定
白桃ミックス
KAGOME
野菜生活
100
季節限定
瀬戸内
柑橘ミックス

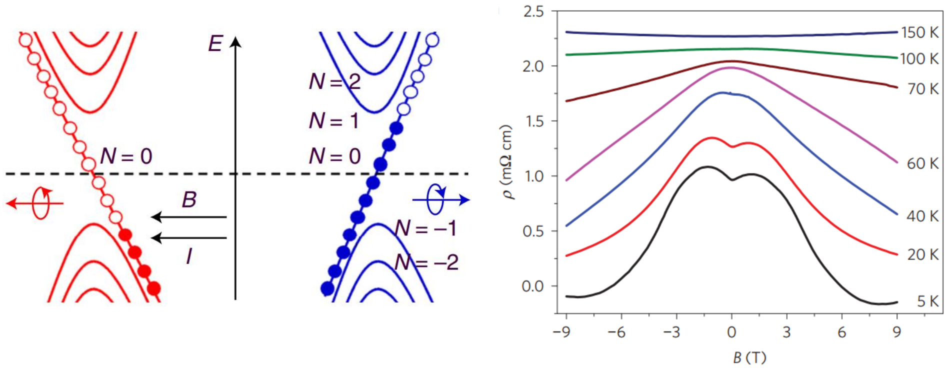
Intriguing Weyl physics

- Open Fermi arcs



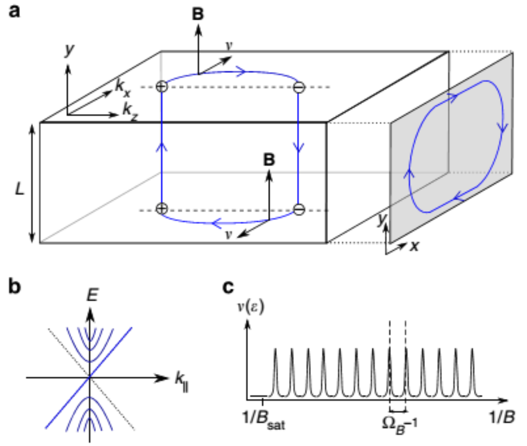
S. Y. Xu *et al.,* Science 349, 613 (2015)

- Chiral anomaly



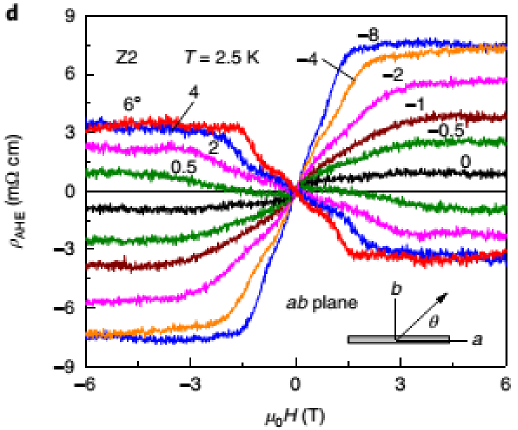
Q. Li *et al.,* Nat. Phys. 12, 550 (2016)

- Fermi arcs
→ Quantum oscillations



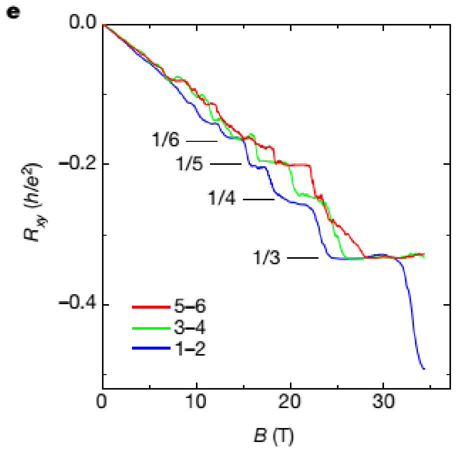
Andrew C. Potter *et al.,* Nat. Commun. 5, 5161 (2014)

- Large Berry curvature
→ AHE



T. Liang *et al.,* Nat. Phys. 14, 451-455 (2018)

- Weyl orbits→ 3D QHE



C. Zhang *et al.,* Nature 565, 331 (2019)

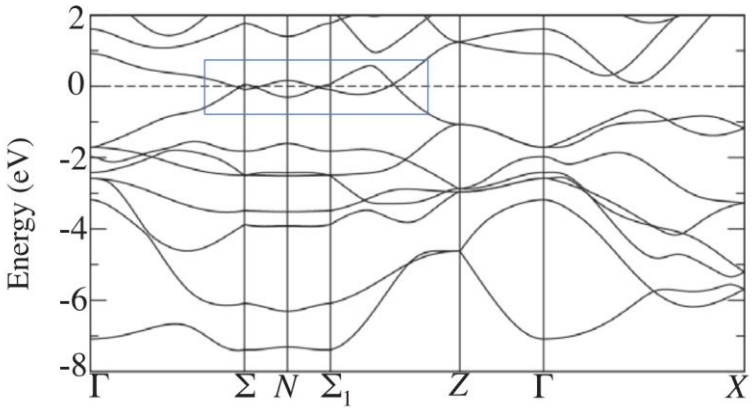
Typical systems

TaAs family

P breaking

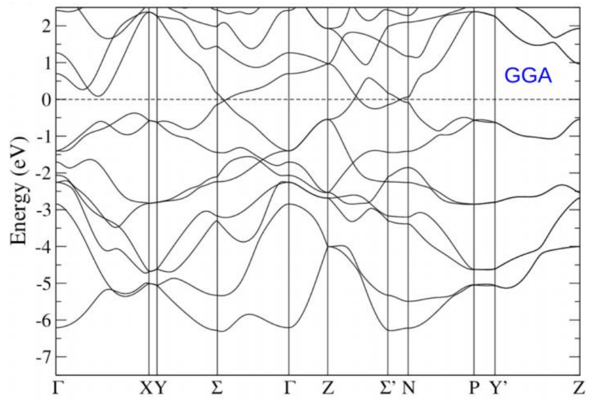
All semimetals !

TaAs



S. Xu, *et al.*, Science 349, 6248 (2015)

NbAs

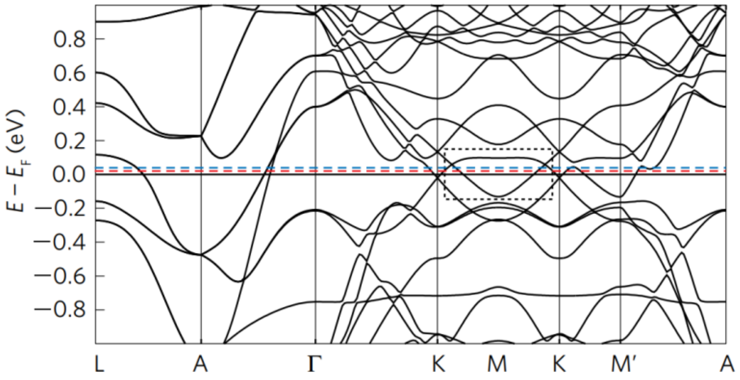


C. Lee, *et al.*, Phys. Rev. B 92, 235104 (2015)

Magnetic systems

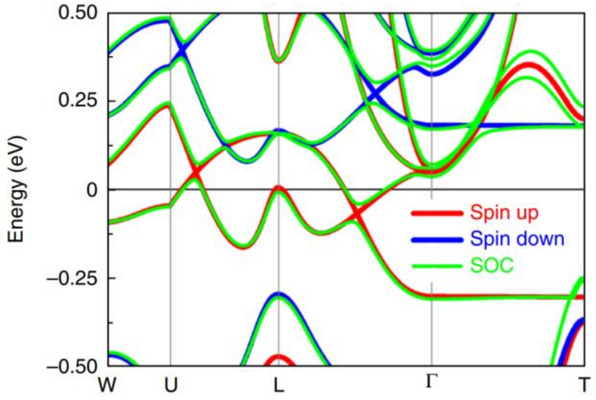
T breaking

Mn_3Sn (AFM)



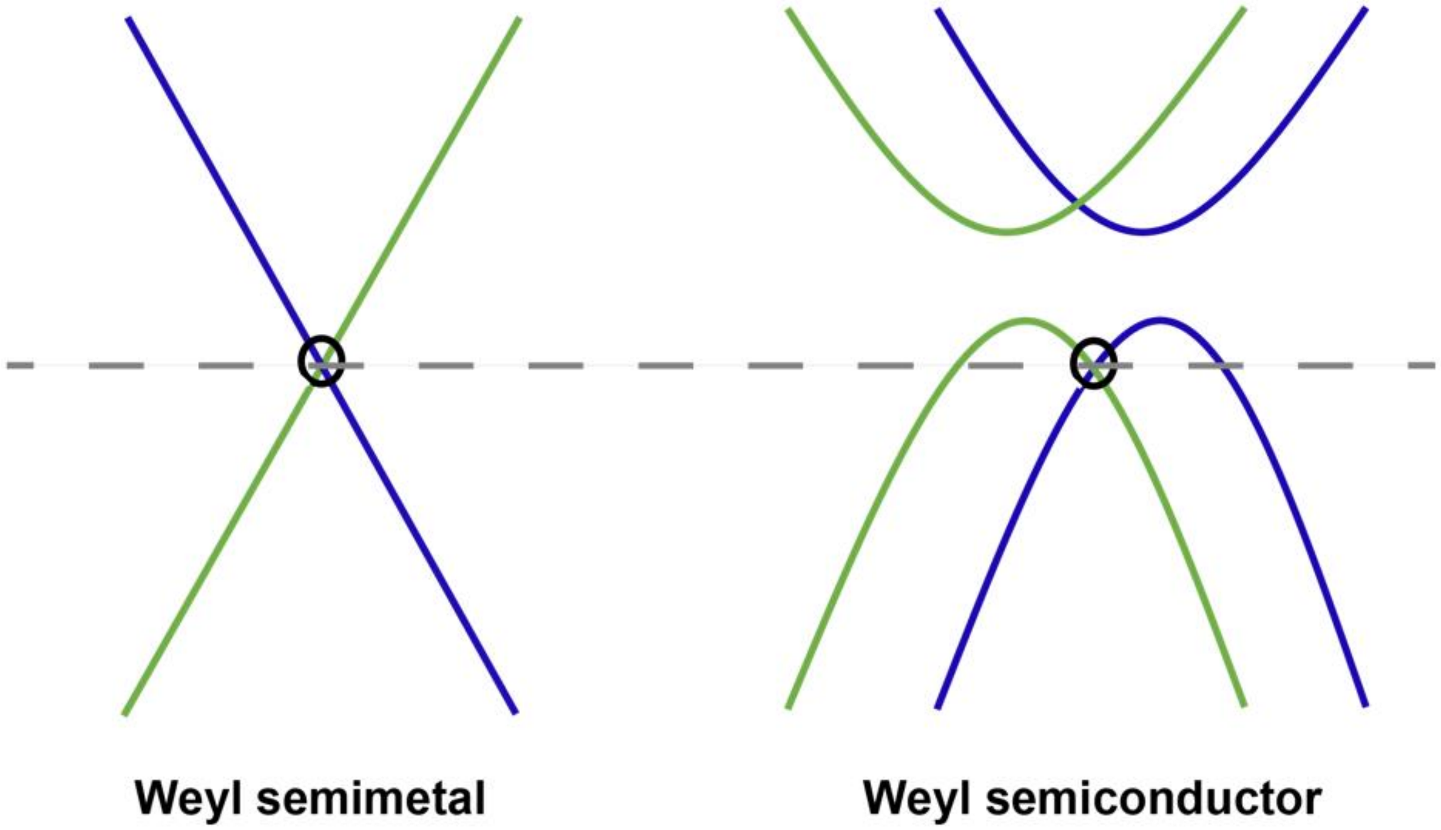
K. Kuroda, *et al.*, Nat. Mater. 16,1090 (2017)

$Co_3Sn_2S_2$ (FM)

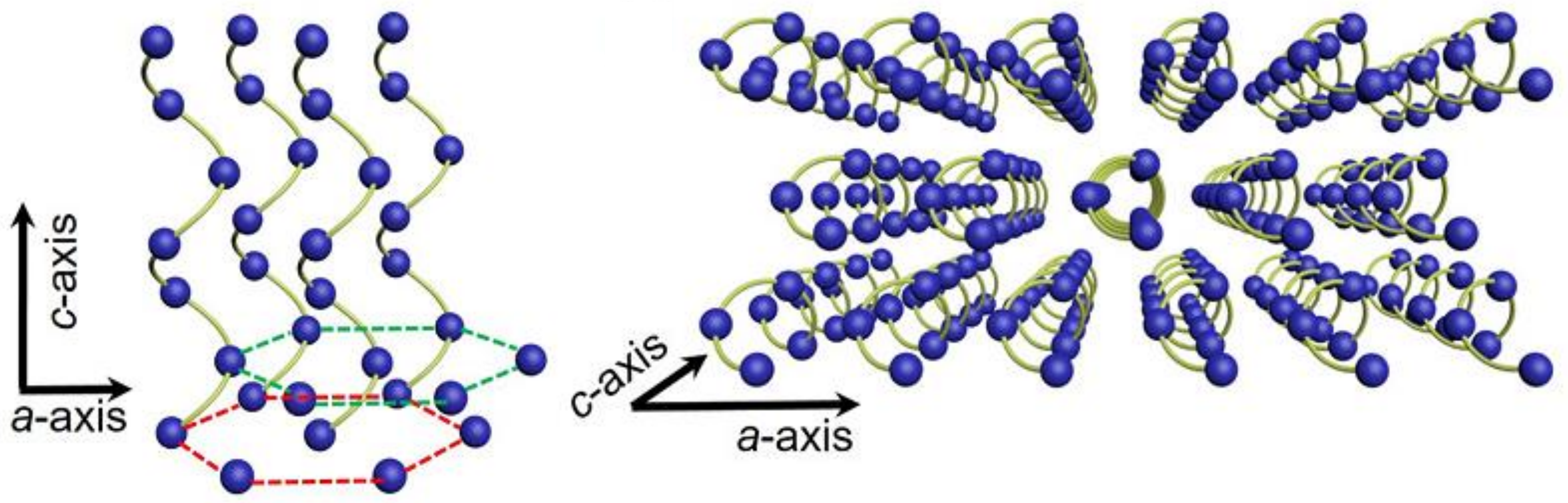


E. Liu, *et al.*, Nat. Phys. 14, 1125 (2018)

Weyl semiconductor?



Te: an ideal element Weyl semiconductor candidate

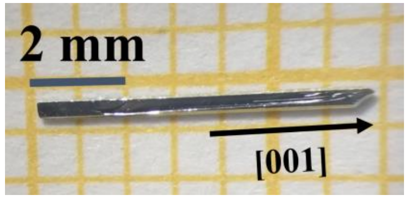


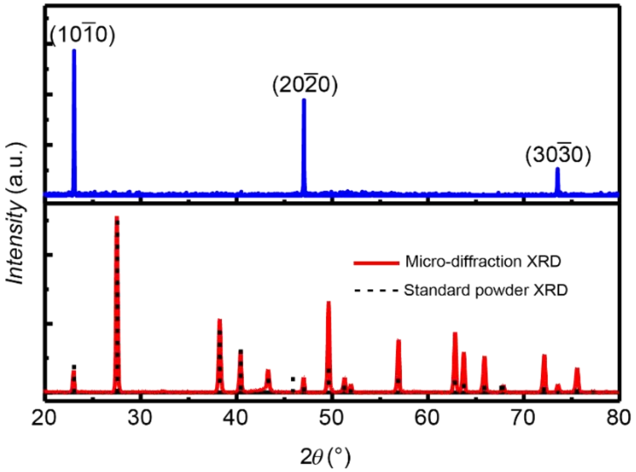
- Strong spin-orbit coupling
- Chiral structure without inversion symmetry
- Direct narrow band gap p-type semiconductor (0.38 eV)
- 1D helical vdW material

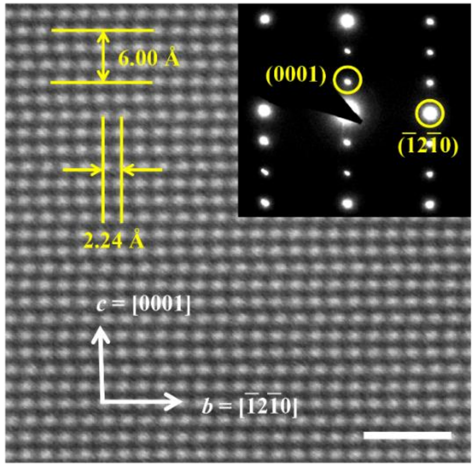
Structure

Rod-like crystals

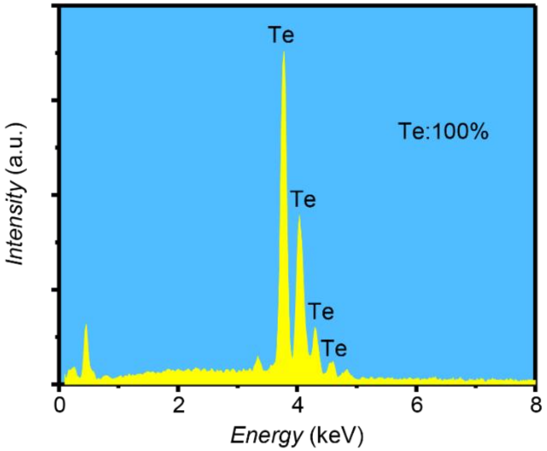
Physical vapor deposition

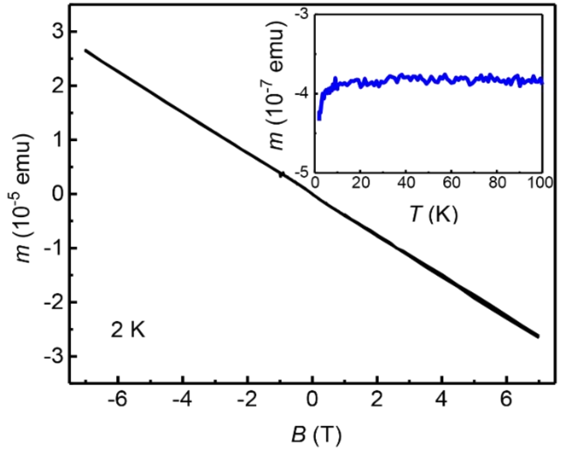




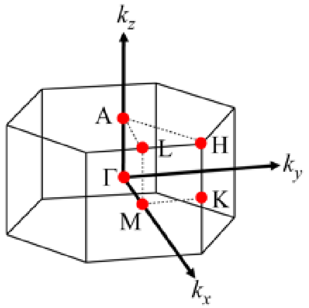


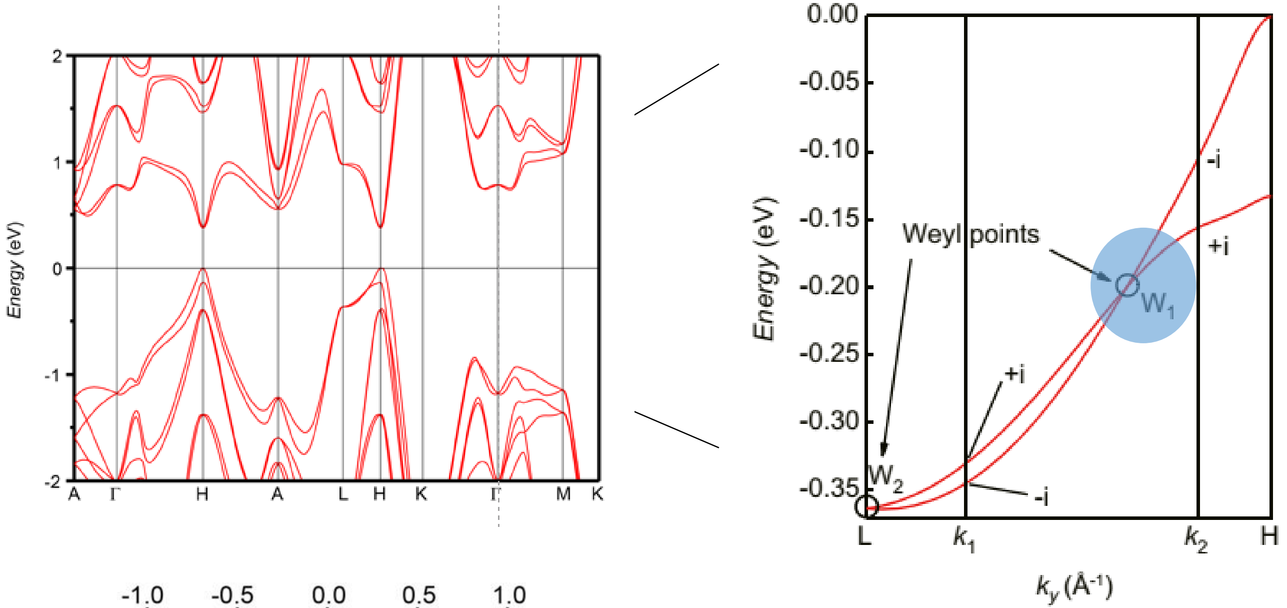
- Single crystalline
- No detectable impurities
- Non-magnetic

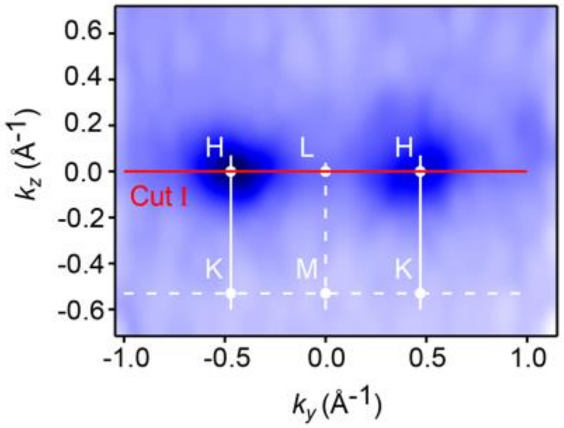


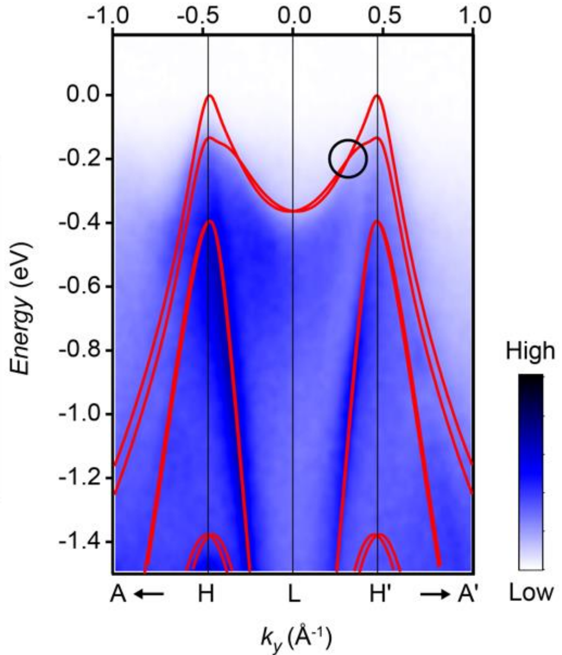


Band structure







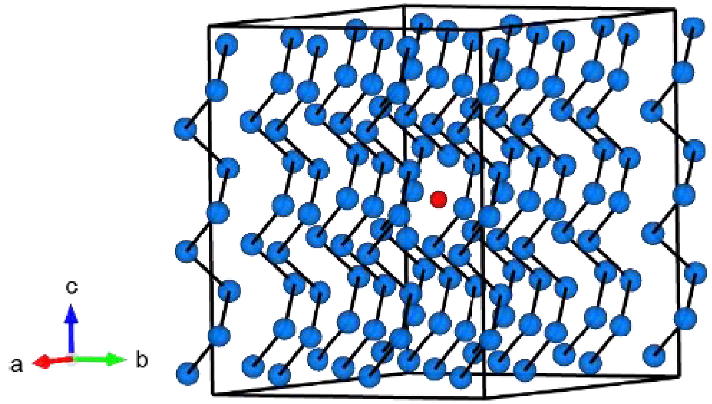


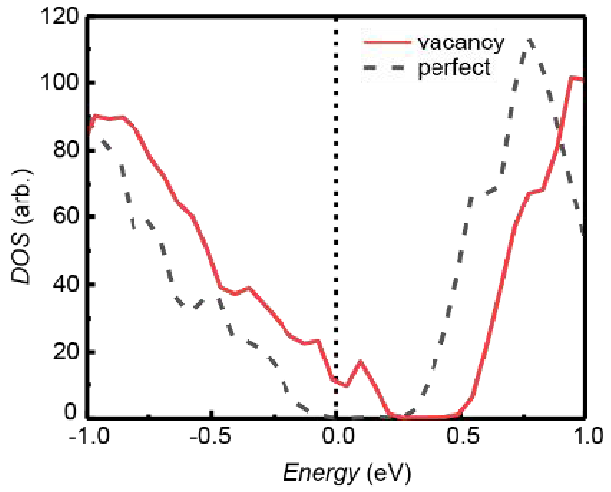
- ➢ Weyl points in VB
- ➢ Fermi level across VB (hole doping)

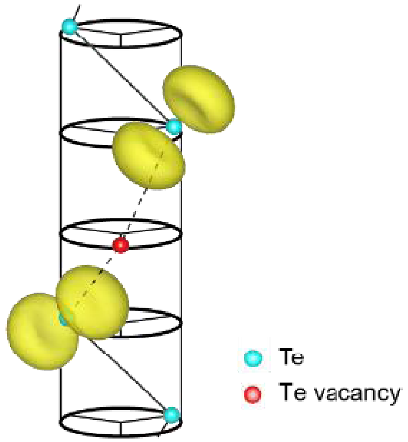
⇓

Promising to study Weyl physics

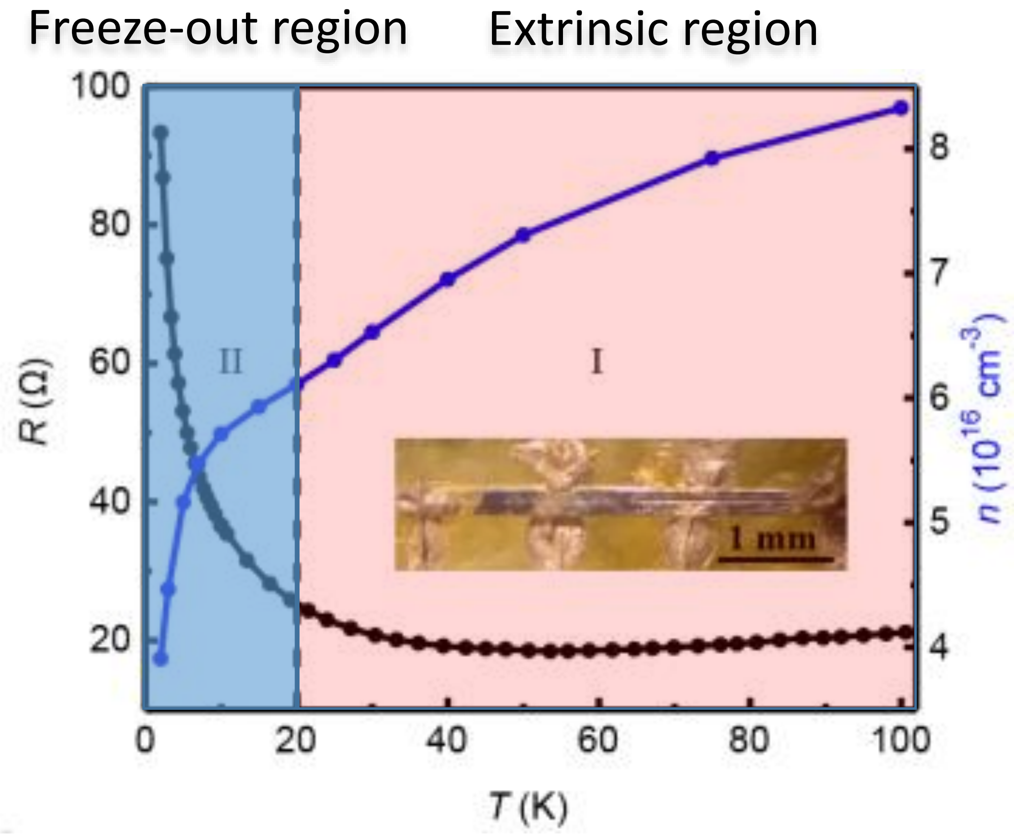
Vacancy-induced hole doping





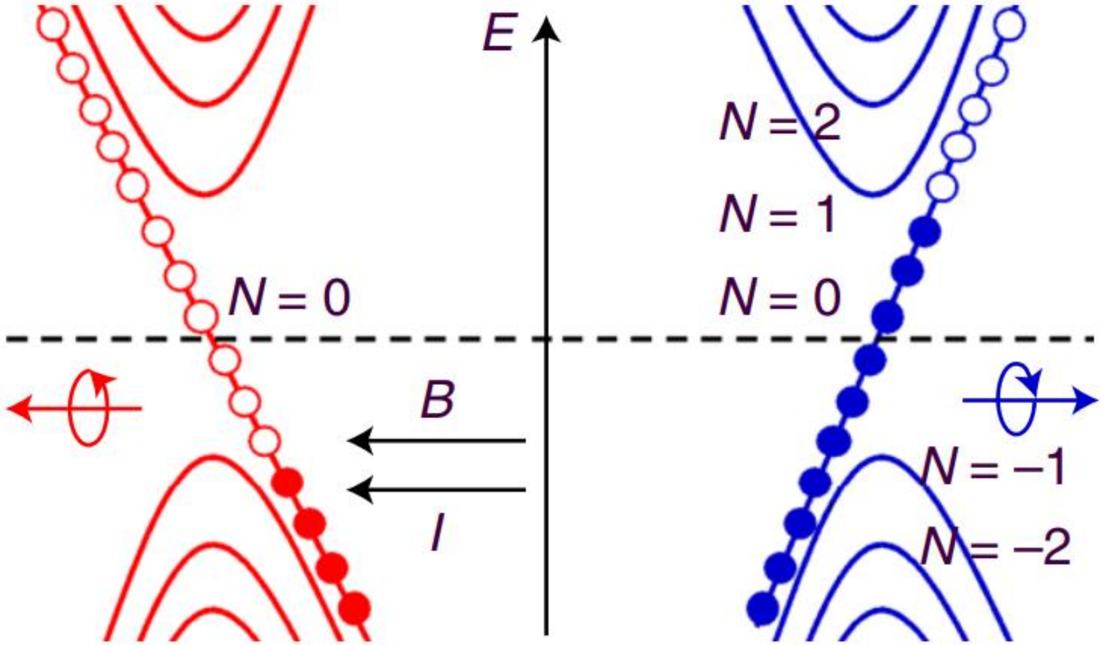


Basic transport characterization



- Typical transport behavior of doped semiconductor
- Relatively low carrier density

Negative MR effect: signatures of chiral anomaly

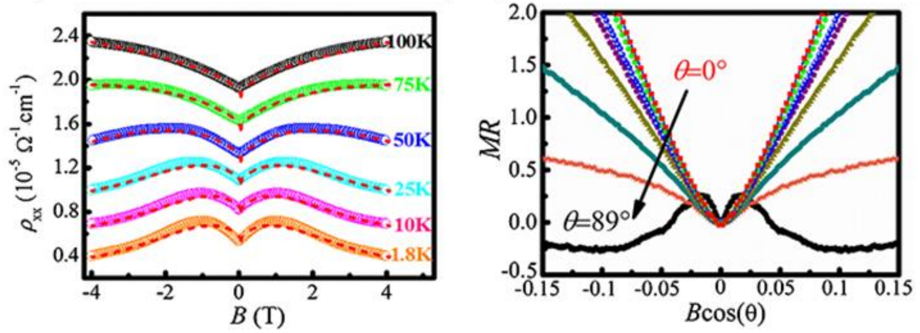


$$\sigma(B) = \sigma_0 + \frac{e^4 B^2 \tau_a}{4\pi^4 g(\epsilon_F)}$$

Nielsen & Ninomiya, Phys. Lett. B 130, 389 (1983)
Son & Spivak, Phys. Rev. B 89, 054202 (2013)

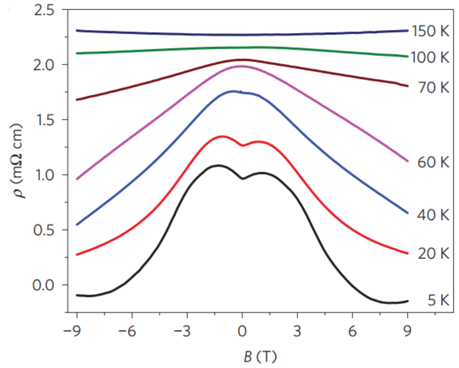
Negative MR effect: signatures of chiral anomaly

- TaAs



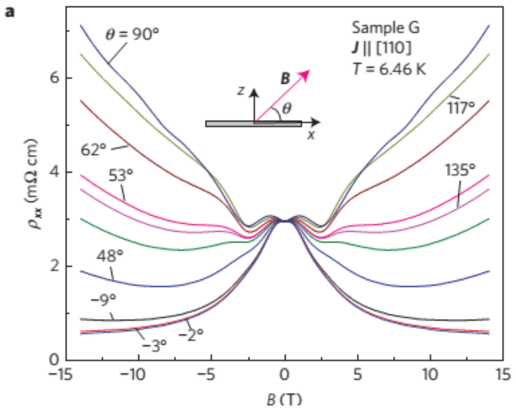
X. C. Huang *et al.,* PRX, 5, 031023 (2015)
C. L. Zhang *et al.,* Nat. Commun. 7,10735 (2015)

- $ZrTe_5$



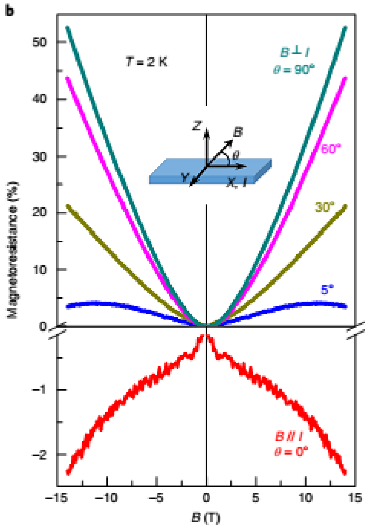
Q. Li, *et al.,* Nat. Phys. 12, 550 (2016)

- GdPtBi



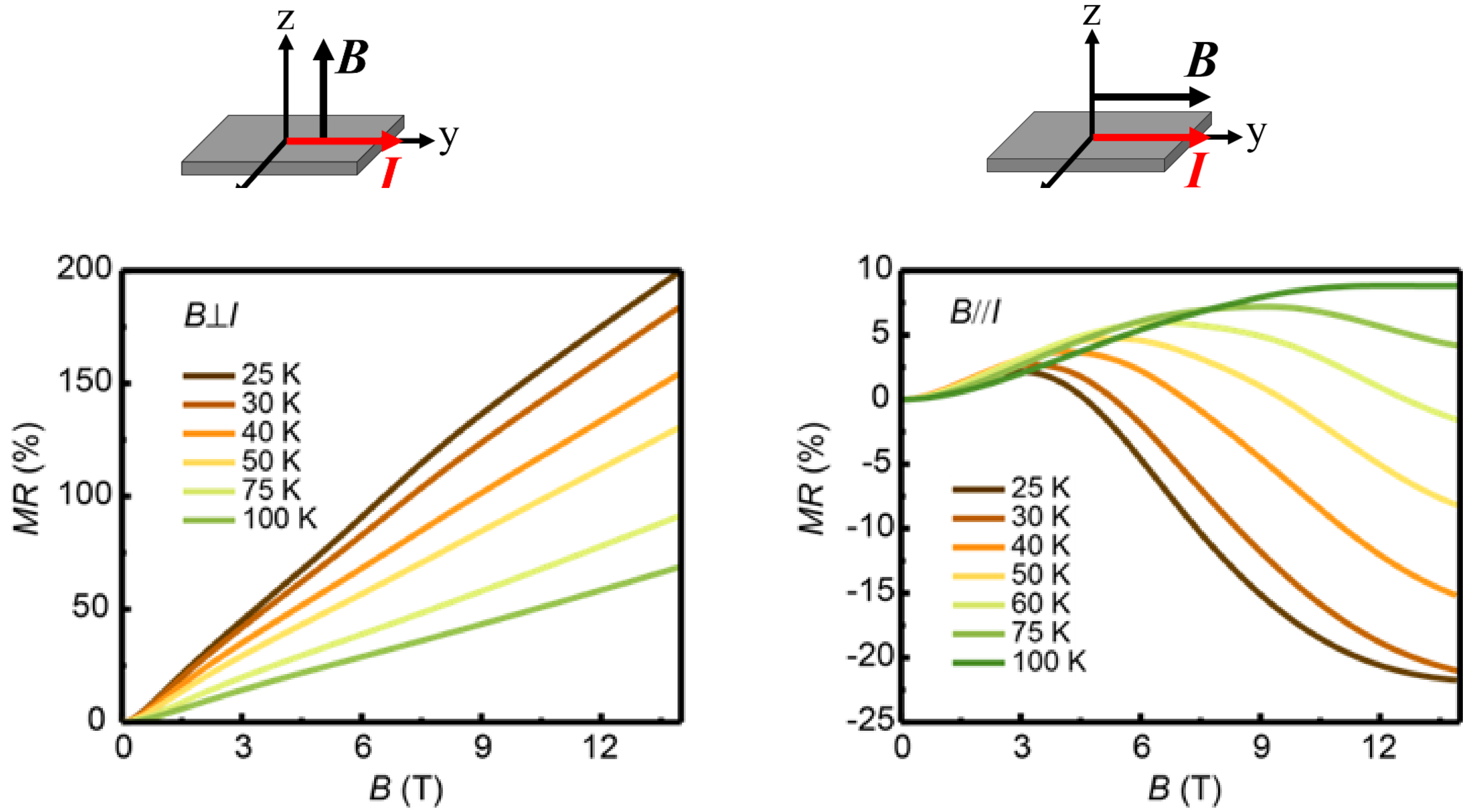
M. Hirschberger *et al.,* Nat. Mater. 15, 1161 (2016)

- $Co_3Sn_2S_2$



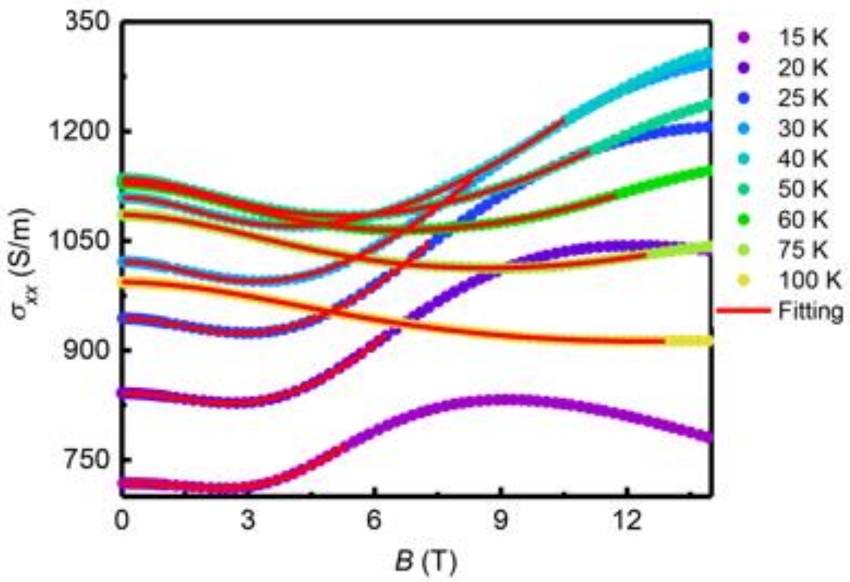
E. K. Liu. *et al.,* Nat. Phys. 14, 1125 (2018)

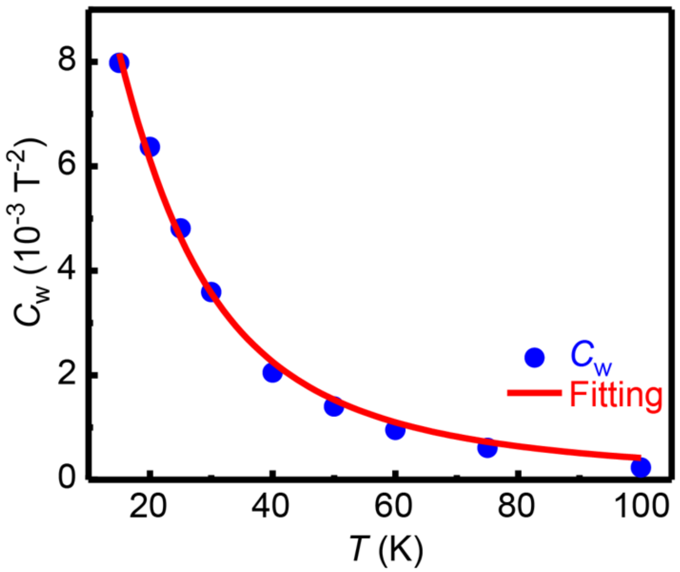
Negative MR when B//I



- NMR magnitude up to 22% at 14 T and 25 K
- Comparable to that for Weyl semimetals (WTe_2, $Co_3Sn_2S_2$)
- NMR degraded with increasing temperature due to the thermal effect but still observable up to ~100 K

Temperature dependence





$\sigma(B) = (1 + C_w B^2) \cdot \sigma_{WAL} + \sigma_N$

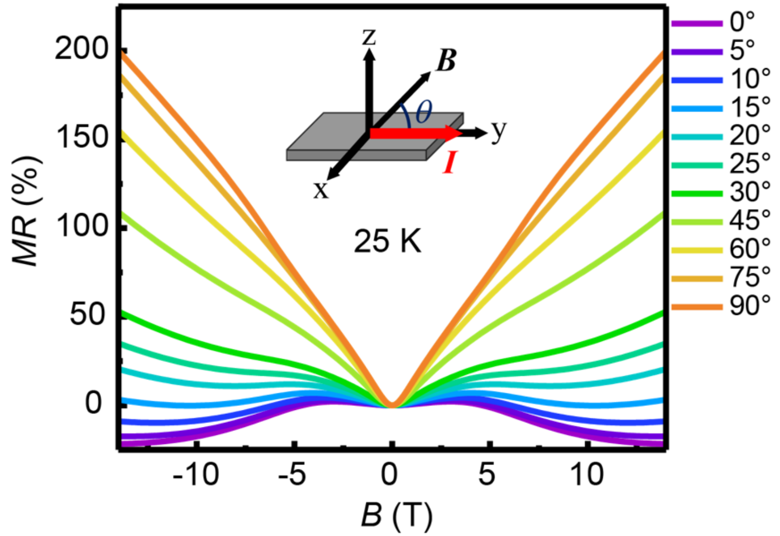
C_w: chiral coefficient, measuring chiral anomaly contribution to the conductivity

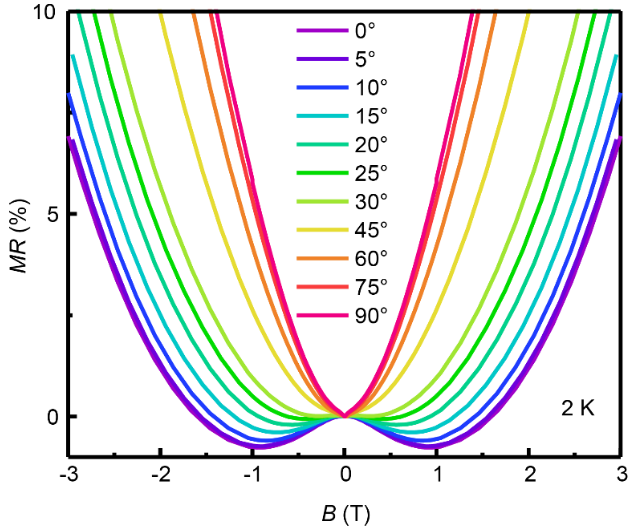
$C_w \propto v_F^3 \tau_v / (T^2 + \mu^2/\pi^2)$

Temperature dependence of the chiral anomaly

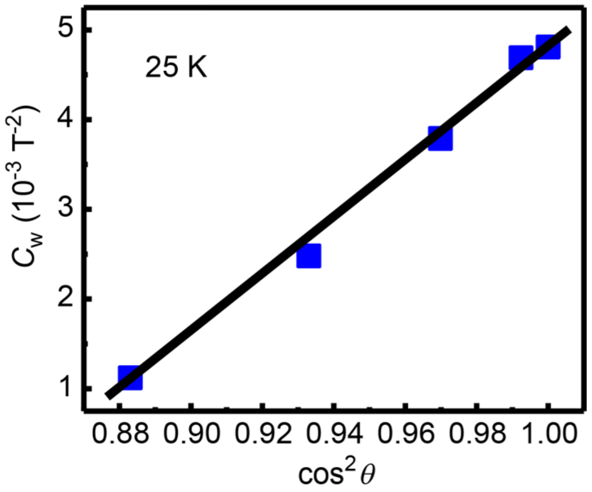
Consistent with the theory of chiral anomaly

Angle dependence





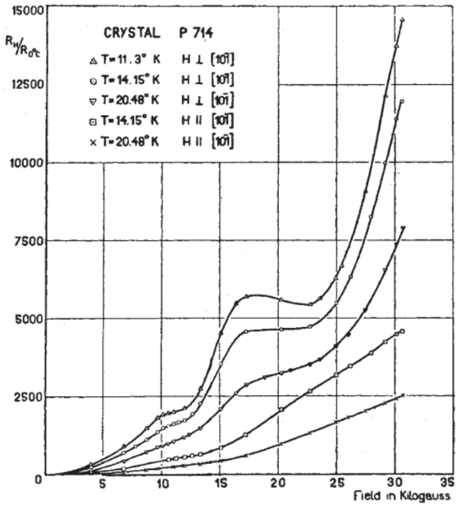
Negative MR when θ < 25 °



$C_w \propto \cos^2\theta$

Quantum oscillation zoom

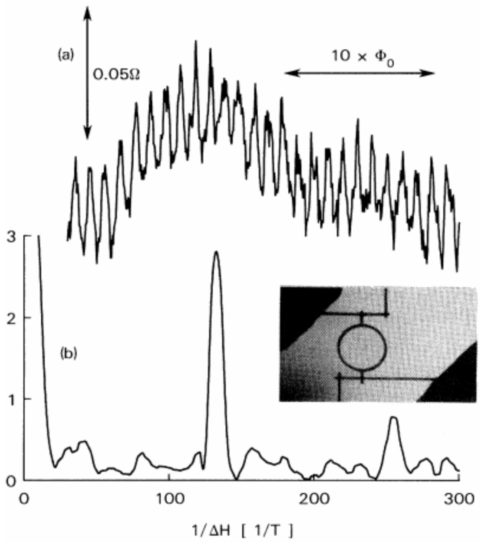
- 1/B



Shubnikov-de Haas (SdH)
(1930)

L. Schubnikow *et al.*, Nature 126, 500 (1930)

- B

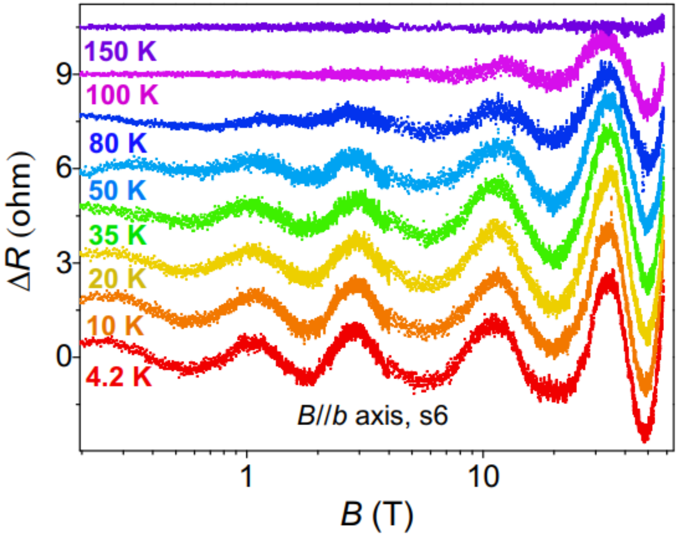


Aharonov–Bohm (AB)
(1985)

R. A. Webb *et al.*, Phys. Rev. Lett. 54, 2696 (1985)

- LogB

$ZrTe_5$ $HfTe_5$



Log-periodic oscillation
Jian Wang (2018)

H. Wang *et al.*, Sci. Adv. 4, eaau5096 (2018)
H. Wang *et al.*, Natl. Sci. Rev. 6, 914 (2019)

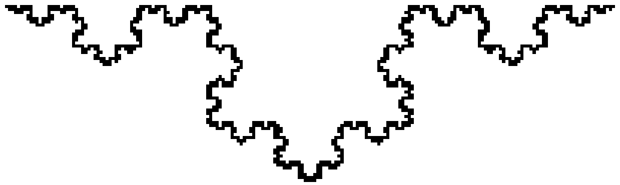
Log periodicity: signature of discrete scale invariance

Geometric series 1, 2, 4, 8, 16, … —Log→ 0, 1, 2, 3, 4, … Log periodicity

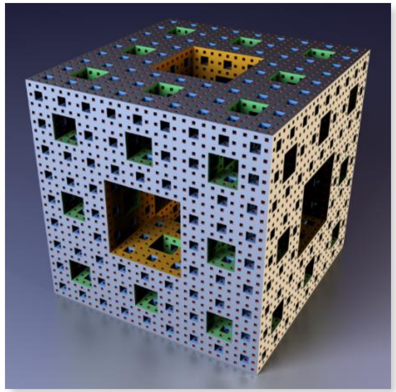
Discrete scale invariance (DSI)

Self reproduction for certain geometrical scaling factor

Matryoshka doll

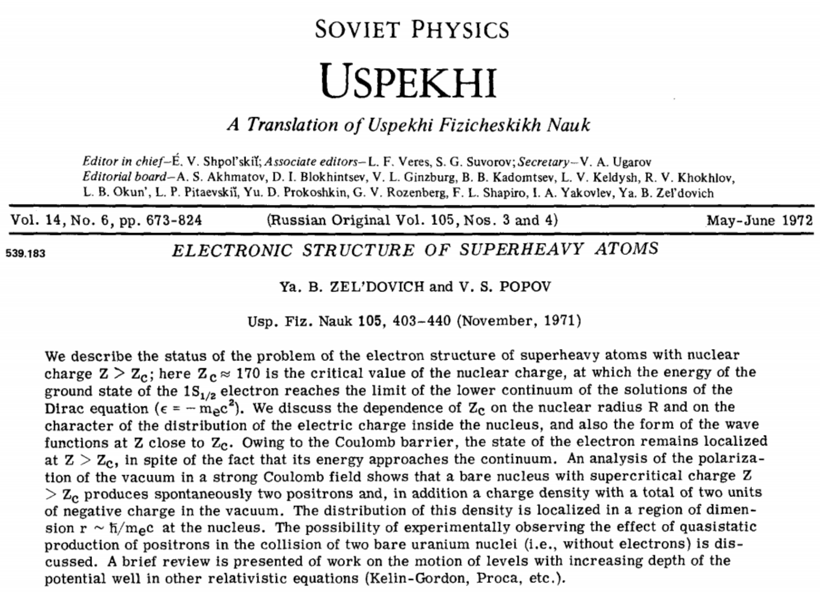


Koch curve



Menger sponge

Supercritical collapse


SOVIET PHYSICS

USPEKHI

A Translation of Uspekhi Fizicheskikh Nauk

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Vol. 14, No. 6, pp. 673-824 (Russian Original Vol. 105, Nos. 3 and 4) May-June 1972

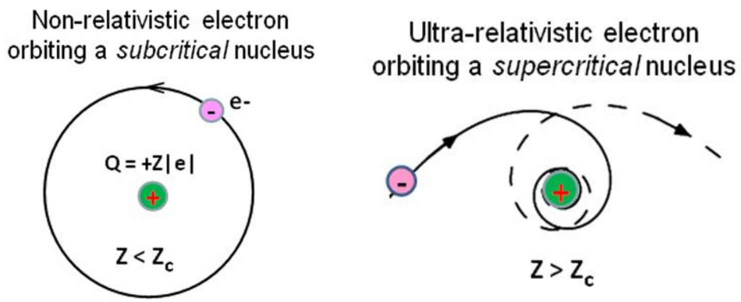
539.183

ELECTRONIC STRUCTURE OF SUPERHEAVY ATOMS

Ya. B. ZEL'DOVICH and V. S. POPOV

Usp. Fiz. Nauk 105, 403–440 (November, 1971)

We describe the status of the problem of the electron structure of superheavy atoms with nuclear charge $Z > Z_c$; here $Z_c \approx 170$ is the critical value of the nuclear charge, at which the energy of the ground state of the $1S_{1/2}$ electron reaches the limit of the lower continuum of the solutions of the Dirac equation ($\epsilon = -m_ec^2$). We discuss the dependence of Z_c on the nuclear radius R and on the character of the distribution of the electric charge inside the nucleus, and also the form of the wave functions at Z close to Z_c. Owing to the Coulomb barrier, the state of the electron remains localized at $Z > Z_c$, in spite of the fact that its energy approaches the continuum. An analysis of the polarization of the vacuum in a strong Coulomb field shows that a bare nucleus with supercritical charge $Z > Z_c$ produces spontaneously two positrons and, in addition a charge density with a total of two units of negative charge in the vacuum. The distribution of this density is localized in a region of dimension $r \sim \hbar/m_ec$ at the nucleus. The possibility of experimentally observing the effect of quasistatic production of positrons in the collision of two bare uranium nuclei (i.e., without electrons) is discussed. A brief review is presented of work on the motion of levels with increasing depth of the potential well in other relativistic equations (Kelin-Gordon, Proca, etc.).



Critical condition: $Z\alpha > 1$

$\alpha = e^2/4\pi\varepsilon_0\hbar v$ = 1/137

Vacuum fine-structure constant

$Z_c = 170$


What Don't We Know?

At *Science*, we tend to get excited about new discoveries that lift the veil a little on how things work, from cells to the universe. That puts our focus firmly on what has been added to our stock of knowledge. For this anniversary issue, we decided to shift our frame of reference, to look instead at what we *don't* know: the scientific puzzles that are driving basic scientific research.

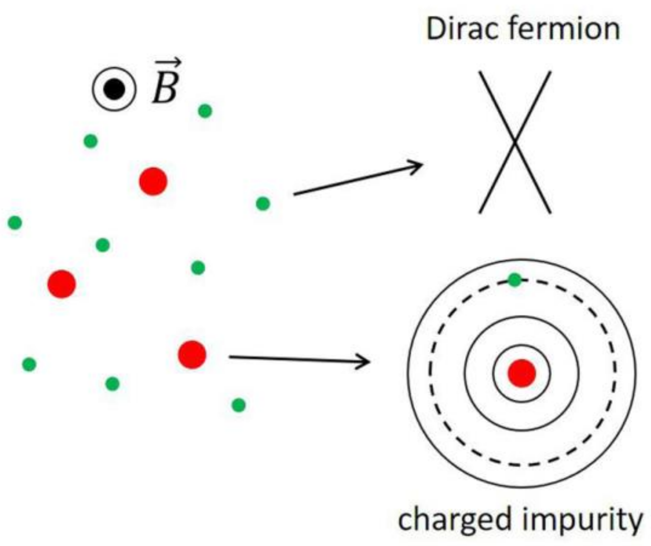
We began by asking *Science*'s Senior Editorial Board, our Board of Reviewing Editors, and our own editors and writers to suggest questions that point to critical knowledge gaps. The ground rules: Scientists should have a good shot at answering the questions over the next 25 years, or they should at least know how to go about answering them. We intended simply to choose 25 of these suggestions and turn them into a survey of the big questions facing science. But when a group of editors and writers sat down to select those big questions, we quickly realized that 25 simply wouldn't convey the grand sweep of cutting-edge research that lies behind the responses we received. So we have ended up with 125 questions, a fitting number for *Science*'s 125th anniversary.

First, a note on what this special issue is not: It is not a survey of the big societal challenges that science can help solve, nor is it a forecast of what science might achieve. Think of it instead as a survey of our scientific ignorance, a broad swath of questions that scientists themselves are asking. As Tom Siegfried puts it in his introductory essay, they are "opportunities to be exploited."

We selected 25 of the 125 questions to highlight based on several criteria: how fundamental they are, how broad-ranging, and whether their solutions will impact other scientific disciplines. Some have few immediate practical implications—the composition of the universe, for example. Others we chose because the answers will have enormous societal impact—whether an effective HIV vaccine is feasible, or how much the carbon dioxide we are pumping into the atmosphere will warm our planet, for example. Some, such as the nature of dark energy, have come to prominence only recently; others, such as the mechanism behind limb regeneration in amphibians, have

Are there stable high-atomic-number elements?
A superheavy element with 184 neutrons and 114 protons should be relatively stable, if physicists can create it.

Supercritical collapse in Dirac/Weyl systems



Relativistic particles

$v_F << c$ ⇨ $\alpha >> 1/137$

⇩

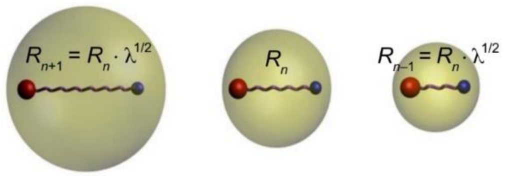
$Z\alpha > 1$

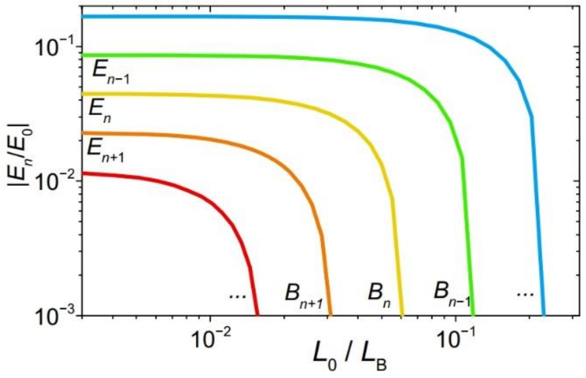
Relativistic quasiparticles (*e.g.* Dirac/Weyl fermions)

Opposite charge centers

} Coulomb attraction → Two-body **quasi-bound states**

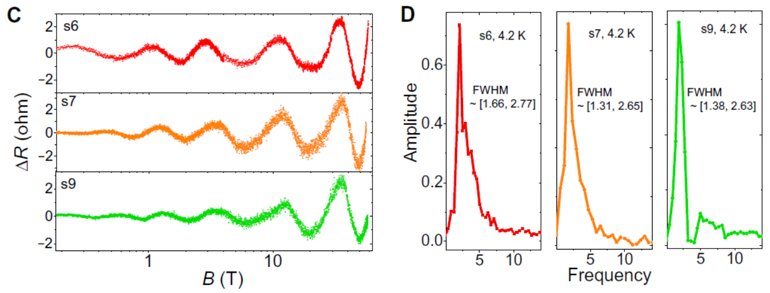
Quasi-bound states in Dirac/Weyl systems





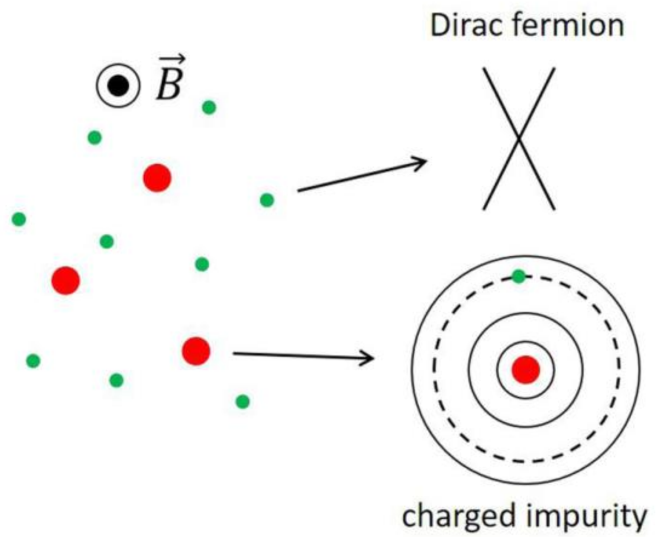
- Relativistic energy–momentum dispersion relation of a Dirac/Weyl band
- Solving Dirac/Weyl equation under the supercritical collapse condition
- Energy levels of quasi-bound states in geometric series → DSI

- Quasi-bound states passing the Fermi level with varying magnetic field
- Resonant scattering between the free carriers and quasi-bound states
- Log-periodic oscillation in transport



H. Wang *et al.*, Sci. Adv. **4**, eaau5096 (2018)

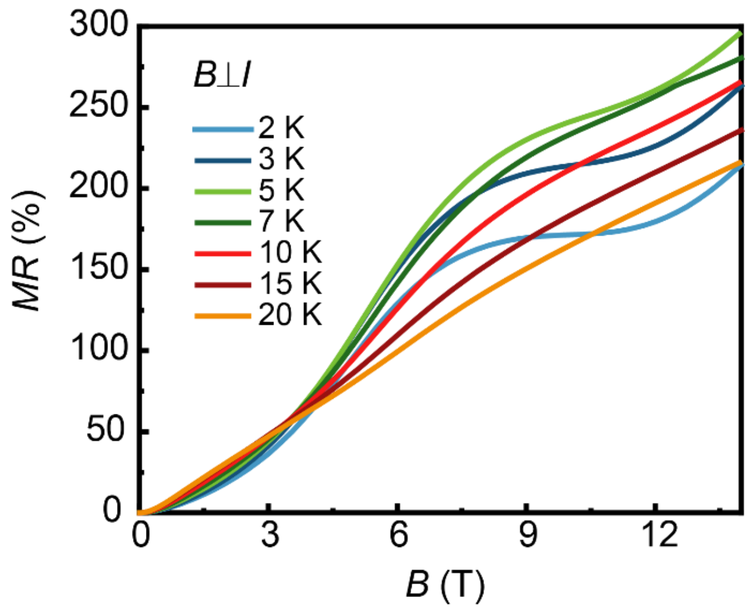
LogB oscillation in Te?



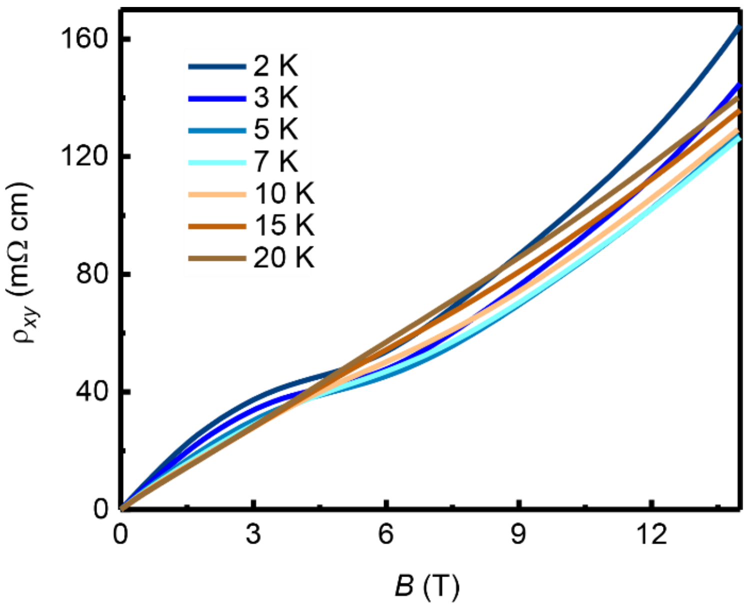
- Weyl band (relativistic holes)
- Te vacancy (negative chage center)
- Much smaller Fermi velocity than c ➡ Supercritical collapse criteria
- Low carrier density ➡ Quantum limit

Unusual oscillations in MR & Hall data

- MR



- Hall



- Oscillations beyond the quantum limit

Quantum limit: all carriers condensed to the lowest Landau level

Quantum limit： $B_Q = (2\pi^4)^{1/3}\hbar n^{2/3}/e$

- End of SdH oscillations
- 4.4 T for this Te sample ($n = 3.9 \times 10^{16} cm^{-3}$ at T=2 K)

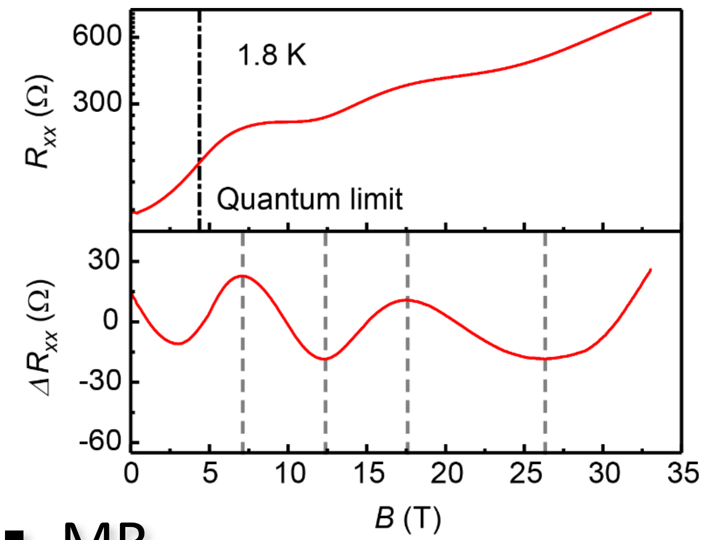
High magnetic field facilities

Steady High Magnet Field Facility
CHMFL, Hefei

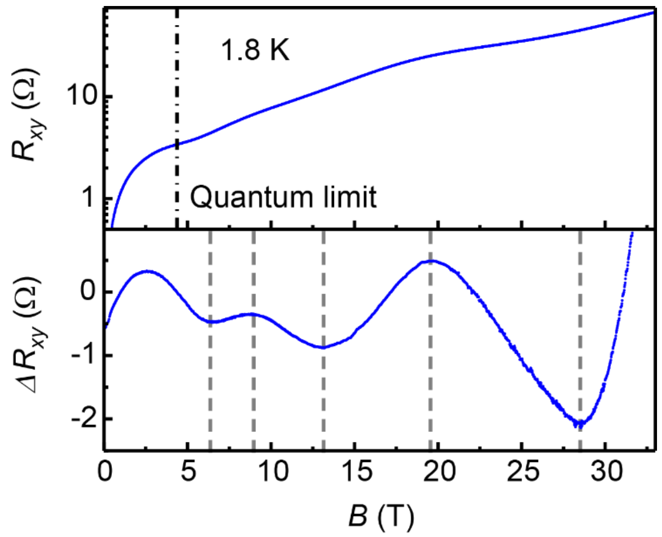
Pulsed High Magnetic Field Facility
WHMFC, Wuhan

Oscillations

- MR

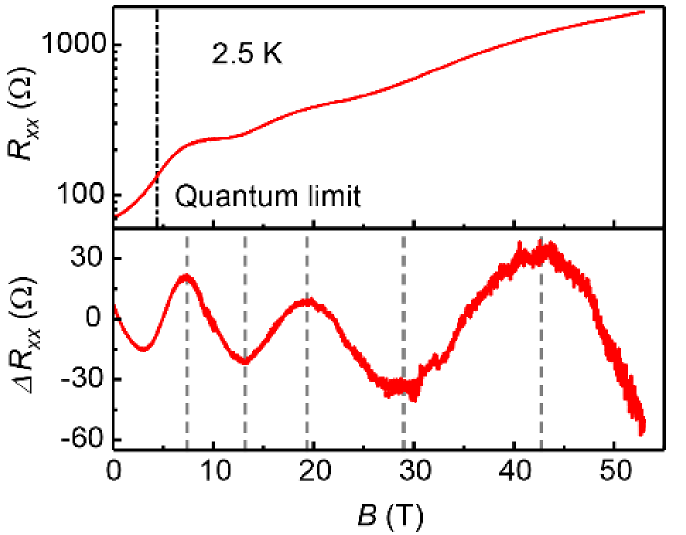


- Hall



SHMFF

- MR



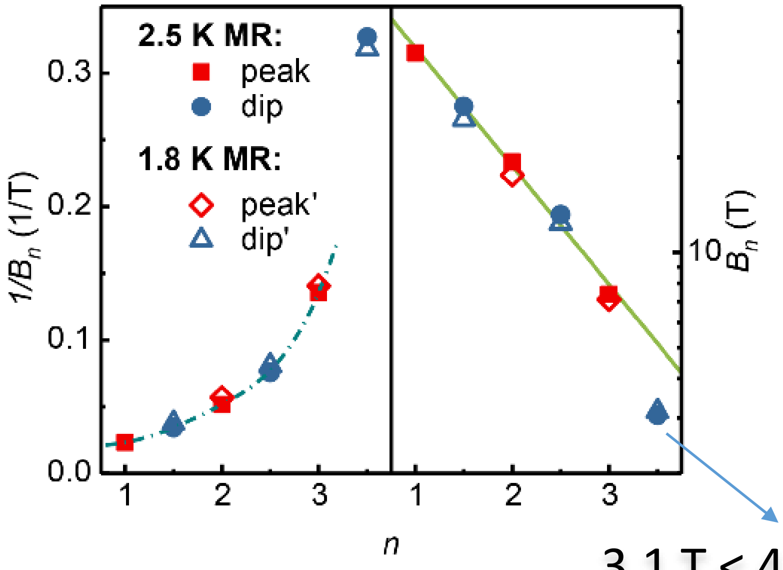
PHMFF

Interval between peaks/valleys grows larger as B increases

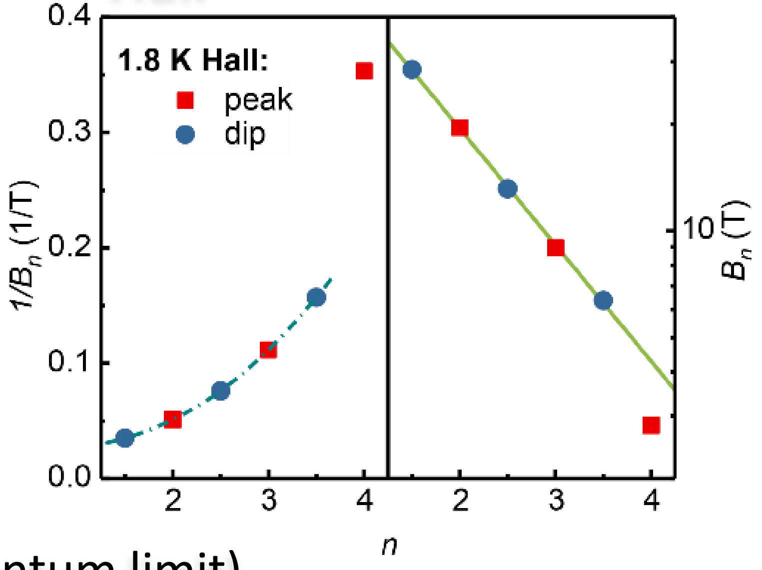
1/B？ logB？

LogB oscillations

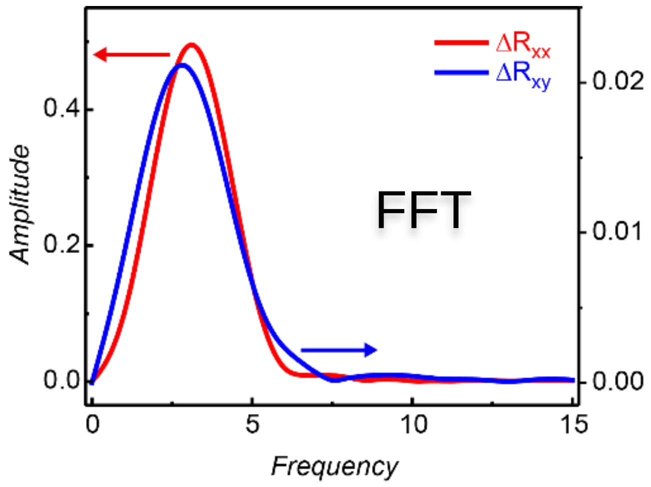
- MR



- Hall



3.1 T < 4.4 T (quantum limit)

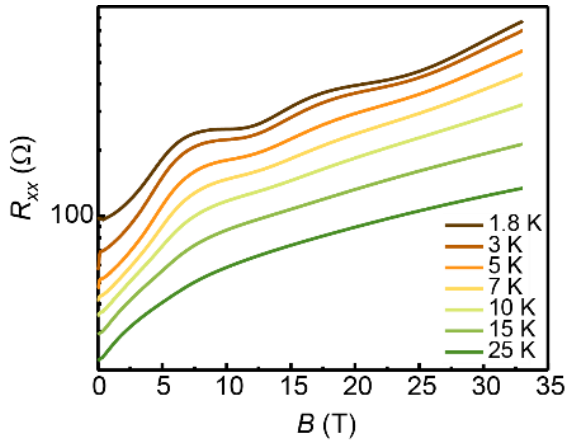


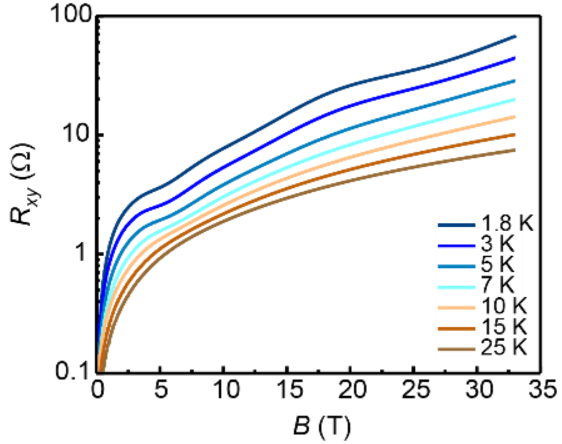
MR *vs* Hall oscillations

- the same period

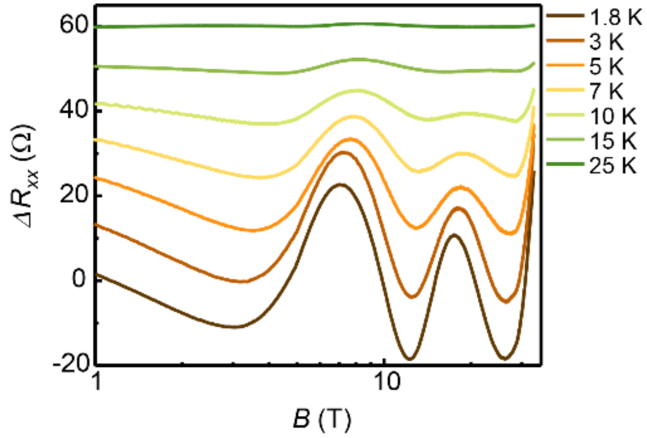
Temperature dependence

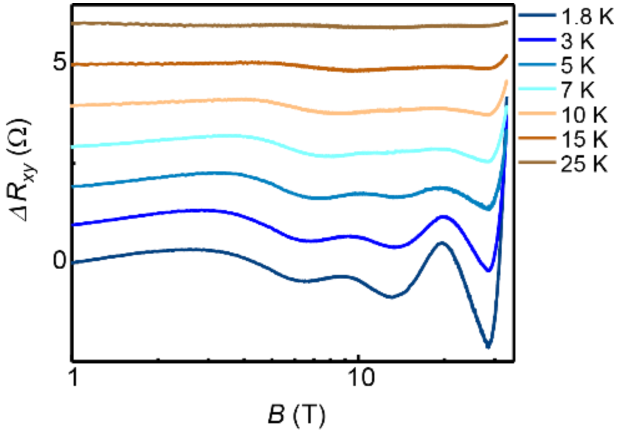
- Raw data





- Background subtraction



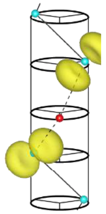


Oscillation suppressed with increasing temperature

- Thermionic excitation → Weakened Coulomb attraction
- Increased carrier density →Reinforced Coulomb screening effect

Mechanism

Weyl fermions in valence band



Negative charge centers
(Te vacancies)

Coulomb attraction →

Two-body
quasi-bound states

DSI scale factor： $\lambda = B_n/B_{n+1}$ (estimated from the log-period)

In theory， $\lambda = e^{2\pi/s_0}$, $s_0 = \sqrt{(Z\alpha)^2 - \kappa^2} = \sqrt{\alpha^2 - 1}$ (for Z=1, κ=$\pm$1)

Fine-structure constant $\alpha = e^2/4\pi\varepsilon_0\hbar v_F$ v_F : Fermi velocity

Te crystal： $\lambda \sim 2.33$ $\alpha \sim 7.5 >> 1/137$ $v_F \sim 2.9\times10^5$ m/s

Supercritical condition ($Z\alpha > 1$) → Quasi-bound states with DSI

Zhang *et al.*, PNAS 117, 11337 (2020)

Magnetotransport signatures of Weyl physics and discrete scale invariance in the elemental semiconductor tellurium

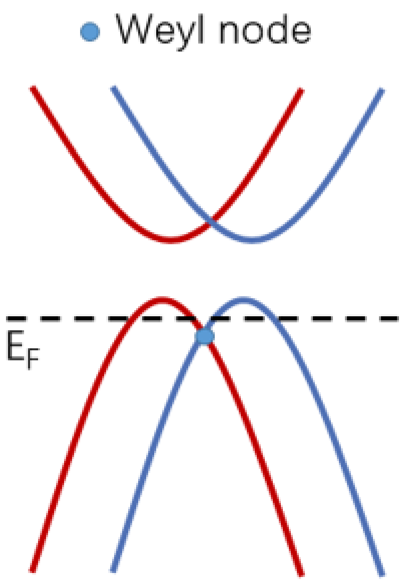
Nan Zhang[a,b,c,1], Gan Zhao[a,b,1], Lin Li[a,b,c,1,2], Pengdong Wang[d], Lin Xie[e], Bin Cheng[a,b,c], Hui Li[f], Zhiyong Lin[a,b,c], Chuanying Xi[g], Jiezun Ke[h], Ming Yang[h], Jiaqing He[e], Zhe Sun[d], Zhengfei Wang[a,b,2], Zhenyu Zhang[a,b], and Changgan Zeng[a,b,c,2]

[a]International Center for Quantum Design of Functional Materials, Hefei National Laboratory for Physical Sciences at the Microscale, University of Science and Technology of China, 230026 Hefei, Anhui, China; [b]Synergetic Innovation Center of Quantum Information & Quantum Physics, University of Science and Technology of China, 230026 Hefei, Anhui, China; [c]Chinese Academy of Sciences Key Laboratory of Strongly Coupled Quantum Matter Physics, Department of Physics, University of Science and Technology of China, 230026 Hefei, Anhui, China; [d]National Synchrotron Radiation Laboratory, University of Science and Technology of China, 230029 Hefei, Anhui, China; [e]Department of Physics, Southern University of Science and Technology, 518055 Shenzhen, China; [f]Institutes of Physical Science and Information Technology, Anhui University, 230601 Hefei, Anhui, China; [g]High Magnetic Field Laboratory, Chinese Academy of Sciences, 230031 Hefei, Anhui, China; and [h]Wuhan National High Magnetic Field Center, Huazhong University of Science and Technology, 430074 Wuhan, China

Zhang *et al.*, PNAS 117, 11337 (2020)

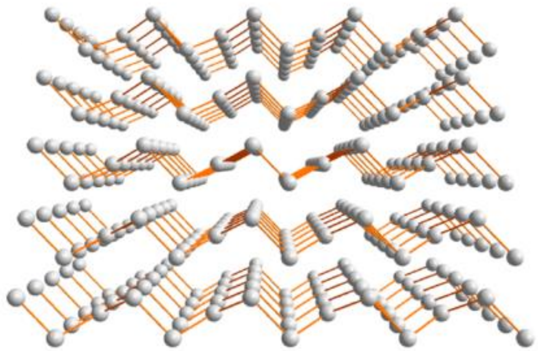
From bulk to 2D Weyl semiconductor

- Weyl semiconductor hosting Weyl fermions



Fermi level shifting
Band gap tuning
…

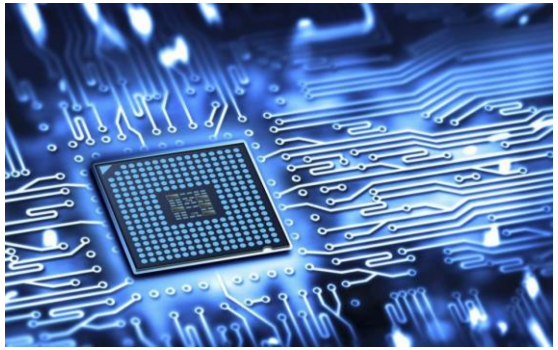
▪ 2D Te



- Further exploring Weyl physics
- Developing topological semiconductor devices

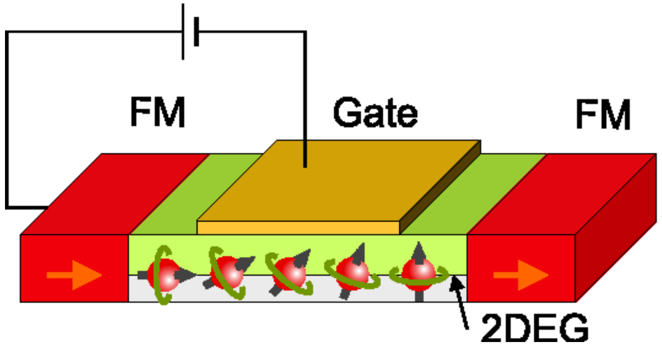
New degree of freedom→ New-concept device

Semiconductor devices

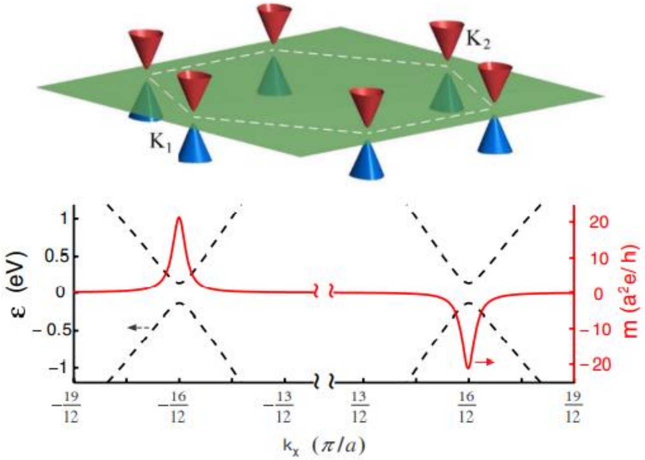


Charge

Spin



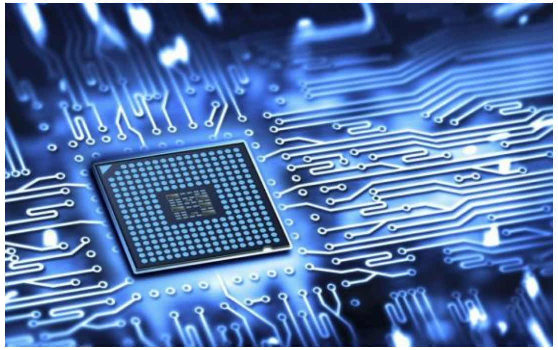
Valley



D. Xiao *et al.*, Phys. Rev. Lett. 99, 236809 (2007)

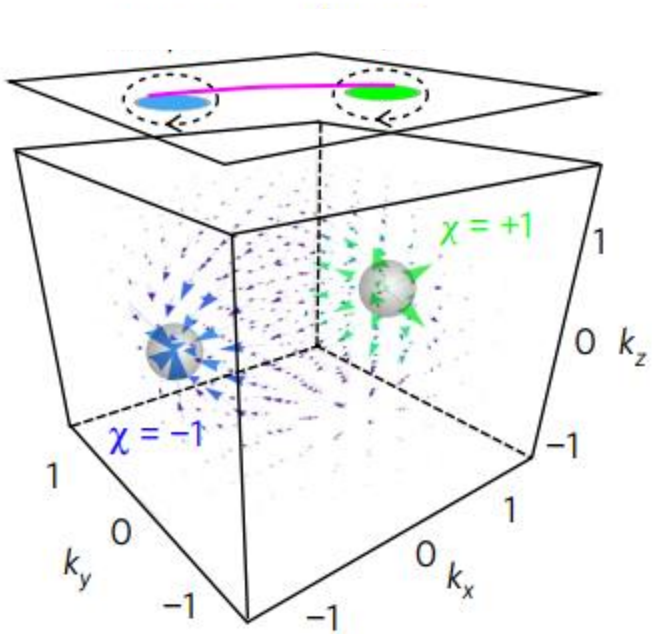
Utilizing chirality degree of freedom

Semiconductor devices



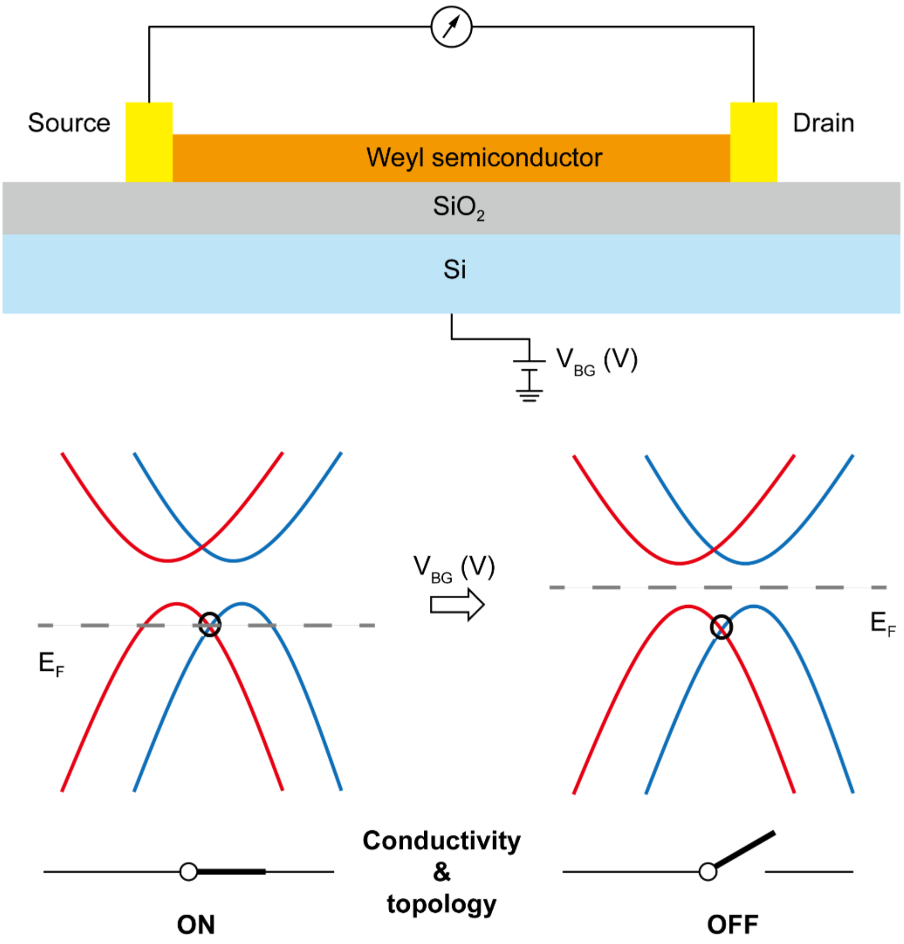
Charge

➕ Chirality



Q. Ma, *et al.,* Nat. Phys. 13, 842 (2017)

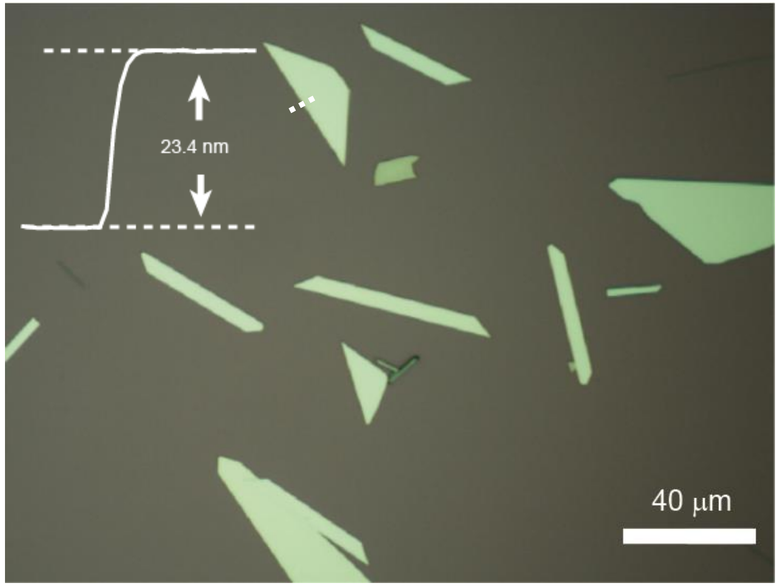
Topological field effect transistor (TFET)

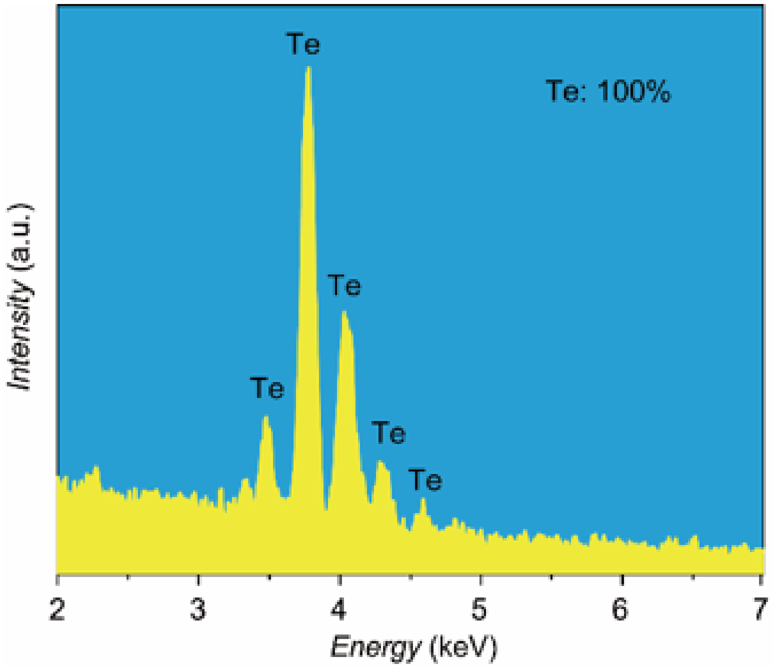


Dual switch of conducting- and topological states

Quasi-2D Te samples

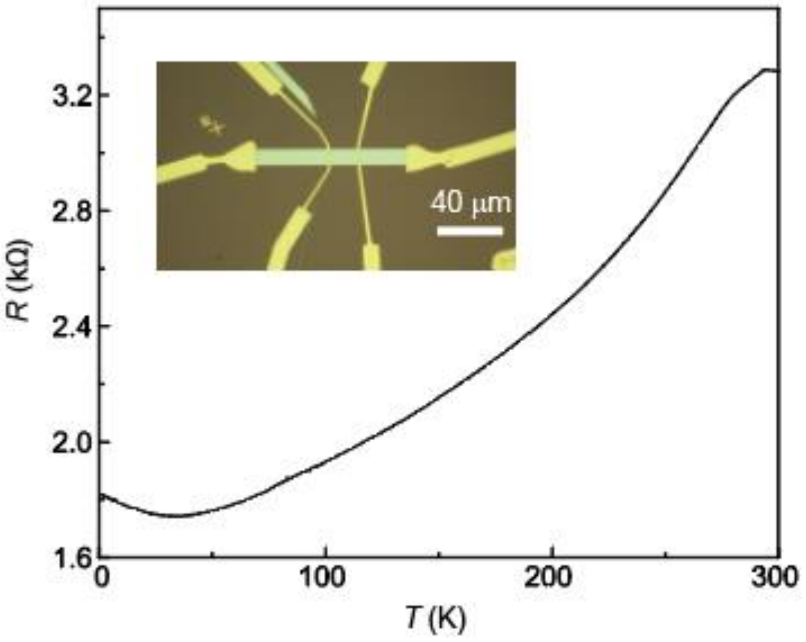
- Te nanoflakes grown using hydrothermal method



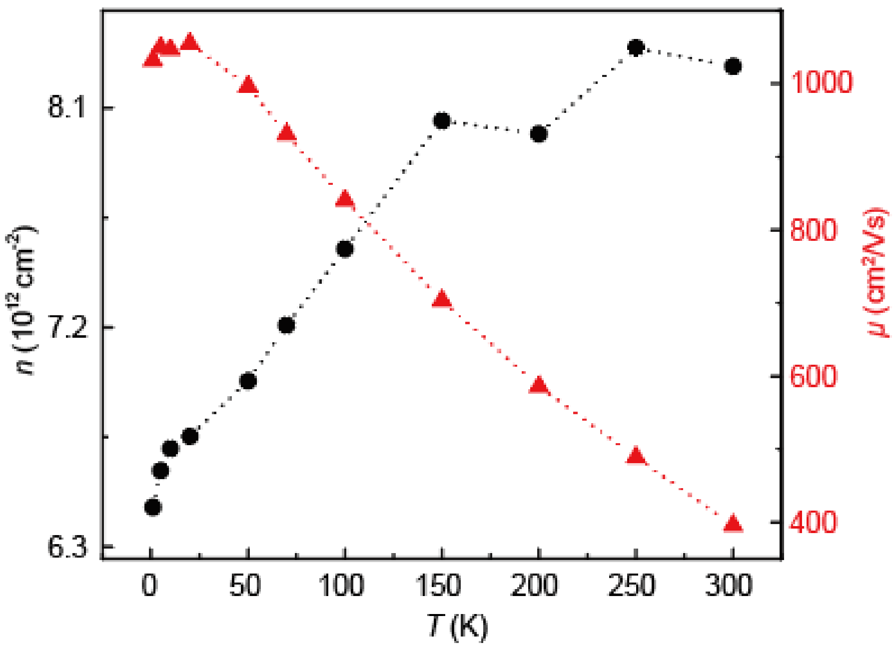


Basic transport characterizations

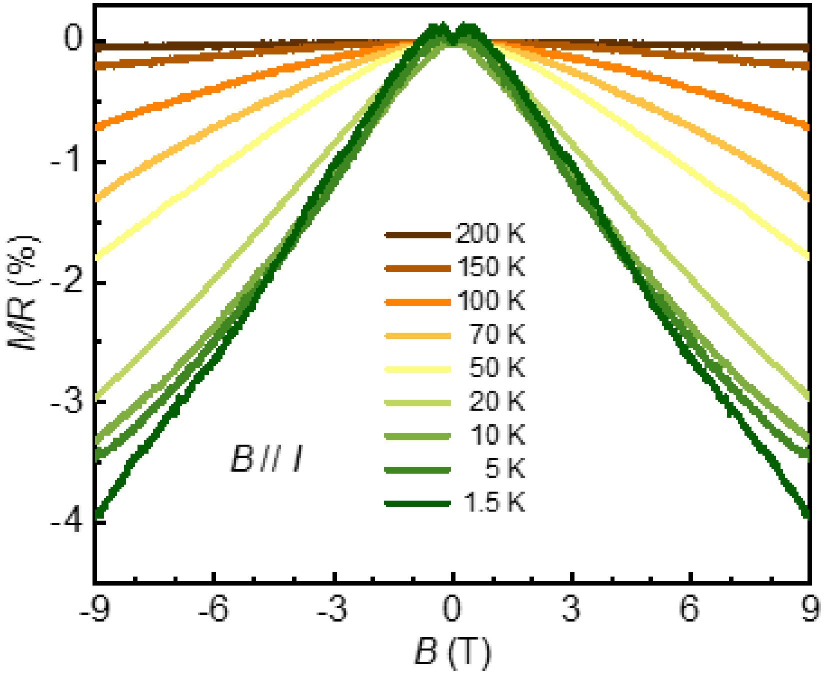
- *R*-*T* curves

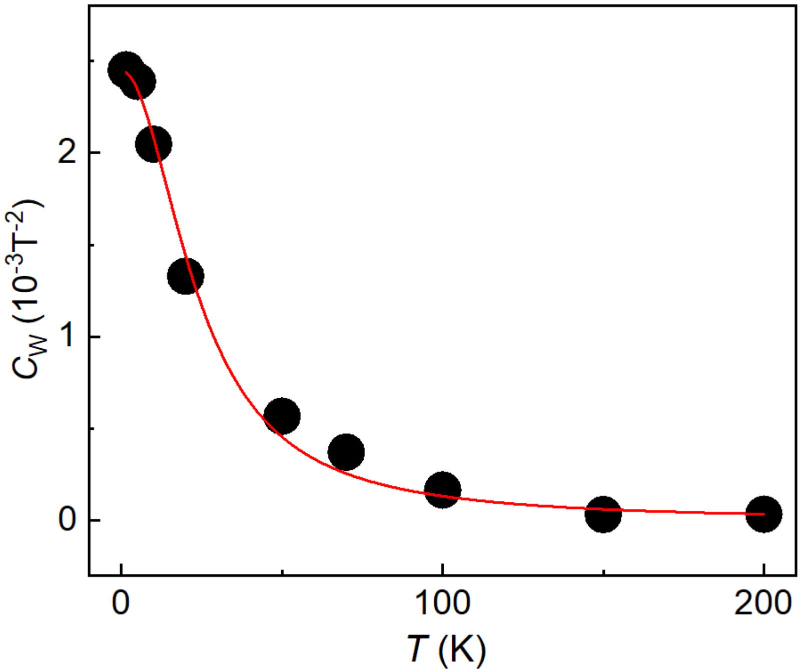


- Carrier density and mobility



Chiral-anomaly-induced negative MR when *B*//*I*



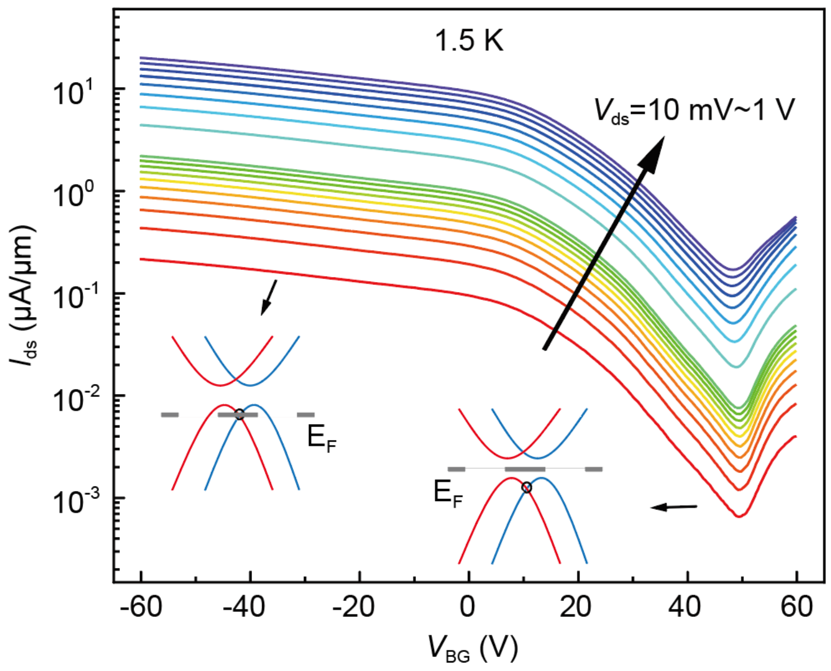


Negative MR

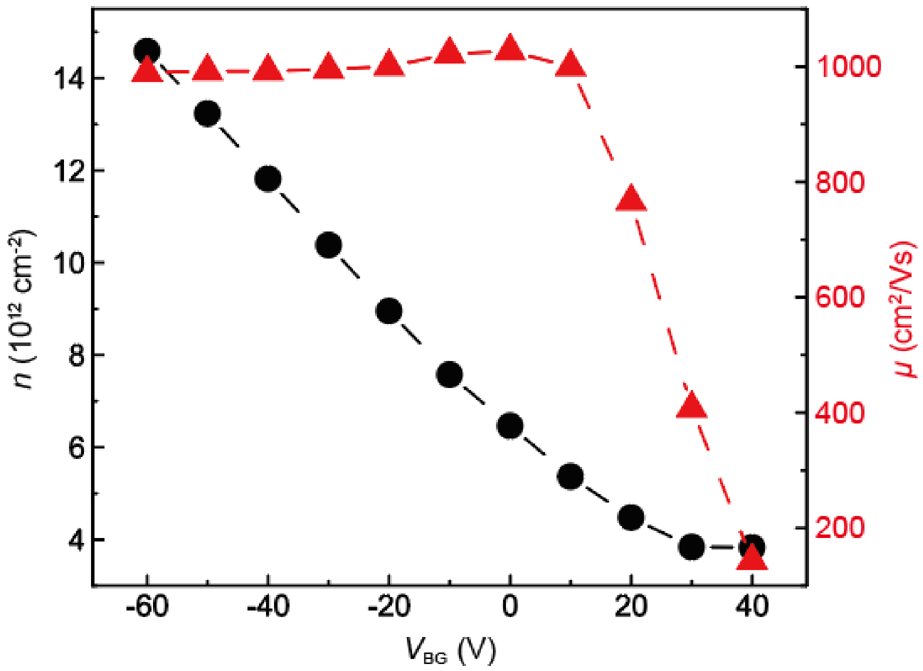
Fingerprint signature of chiral anomaly

$$C_W \propto \frac{v_F^3 \tau_V}{T^2 + \frac{\mu^2}{\pi^2}}$$

Field effect performance



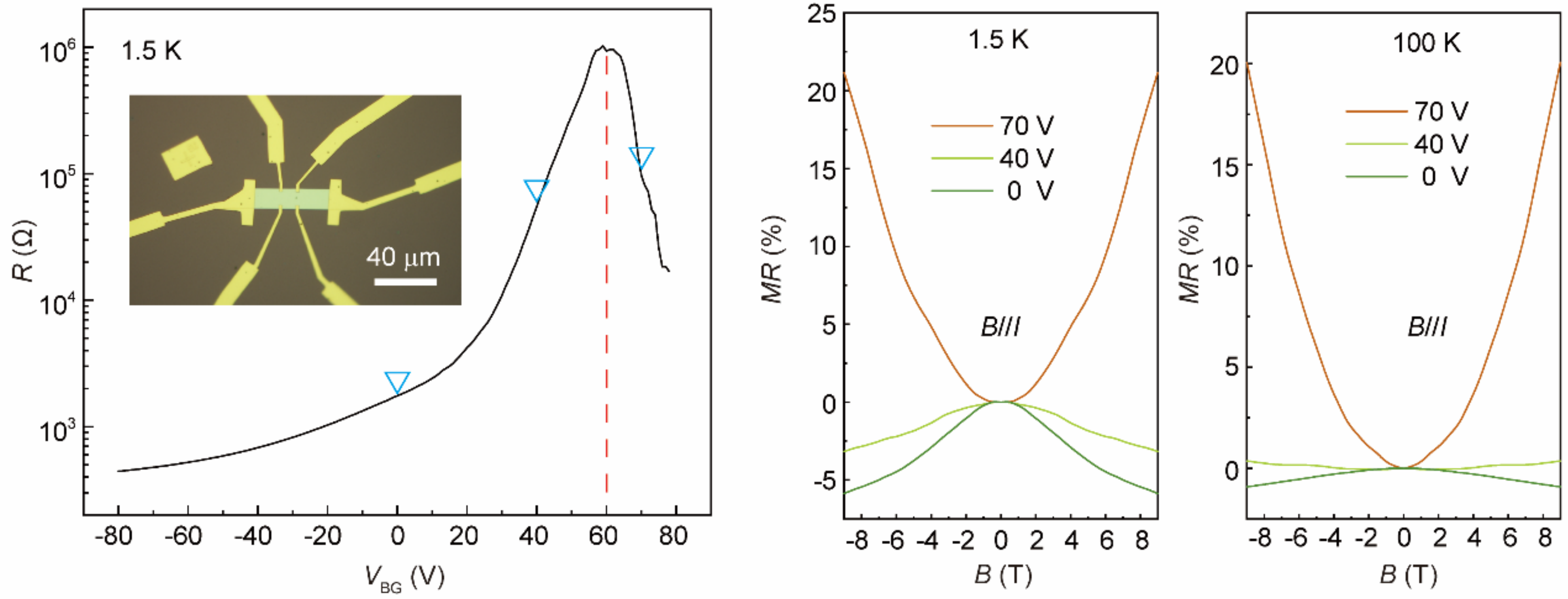
On/off current ratio ~ 3×10² (1.5 K)



High tunability of carrier density

- Effective tuning of the Fermi level (valence band → band gap)

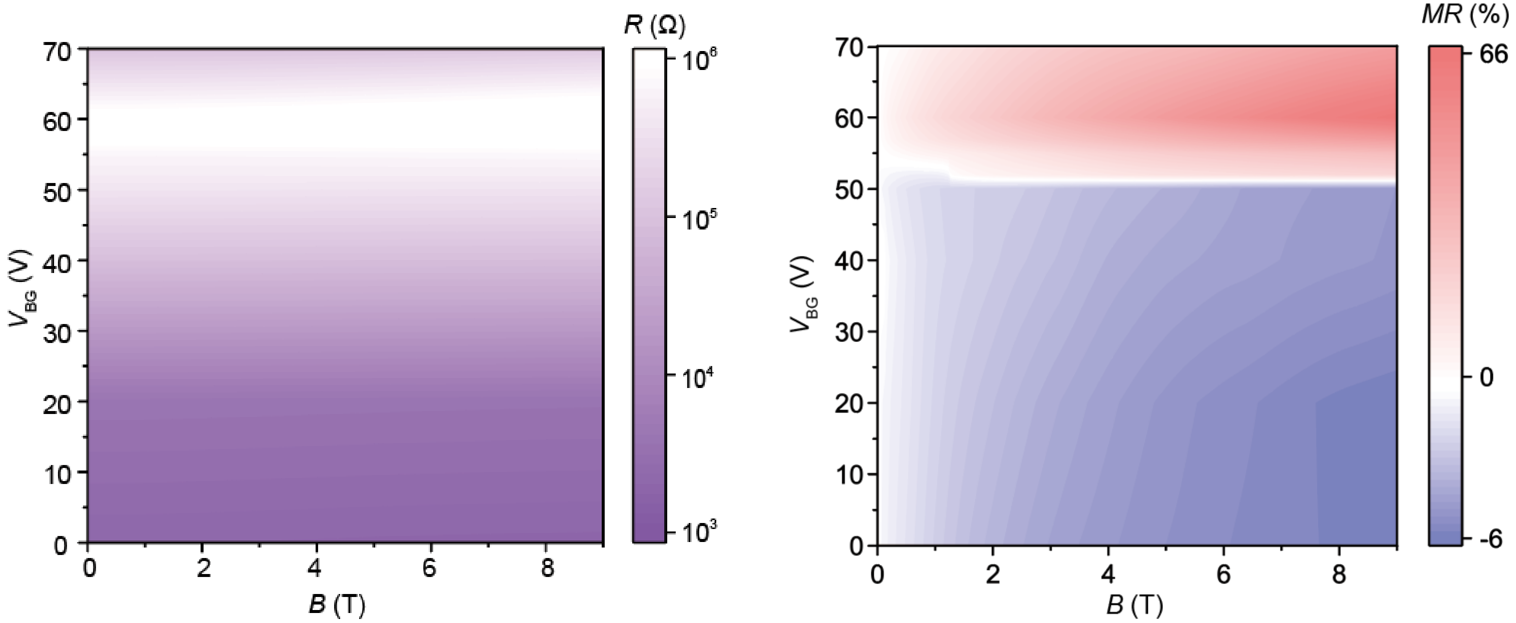
Dual switch of conducting- and topological states



Dual switch

- Conductivity: High ➡ Low
- Topology: Nontrivial ➡ trivial

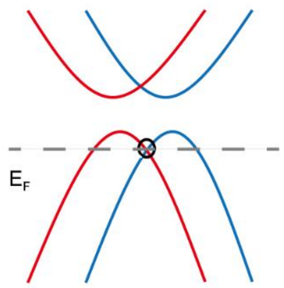
Dual switch of conducting- and topological states



- Three orders of magnitude change of resistance
- In-plane MR changes from negative (-5.8%) to positive (65.9%)

Intriguing functionality of the present TFET

Weyl semiconductor



Semiconductivity

- Conductivity on/off controlled by electrostatic field

chirality

- Topological nontrial/trivial states controlled by electrostatic field
- Chiral charge pumping control by parallel electric- and magnetic field

Hybrid device applications with multi-field control

PHYSICAL REVIEW APPLIED **17,** 054044 (2022)

Editors' Suggestion

Topological Field-Effect Transistor Based on Quasi-Two-Dimensional Tellurium Flakes

Bin Cheng,[1,2] Lin Li,[1,2,*] Nan Zhang,[1,2] Ling Zhang,[1,2] Xianglin Li,[1,2] Zhiyong Lin,[1,2] Hui Li,[3] Zhengfei Wang,[2] and Changgan Zeng[1,2,†]

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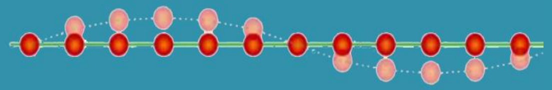
For semiconductors, adding a degree of freedom beyond charge, e.g., spin and valley, will lead to alternative physics and device applications. Here, we demonstrate that another electronic degree of freedom, the chirality of Weyl node, can be used in the Weyl semiconductor tellurium, a unique system harnessing intriguing Weyl physics and high tunability of the semiconductor. By constructing a field-effect device based on quasi-two-dimensional tellurium flakes, the Fermi level can be effectively tuned from the top of valence bands, where the Weyl nodes locate at, into the bandgap via electrostatic gating. In addition to a significant reduction of channel conductivity, a transition from chiral-anomaly-induced negative magnetoresistance to conventional positive magnetoresistance occurs at the same time, indicating complete suppression of the chirality-related topological transport. The simultaneous switch of both conducting and topological states is unprecedented in previous Weyl semimetals. Our findings pave the way for developing new-principle semiconductor devices with fascinating functionalities.

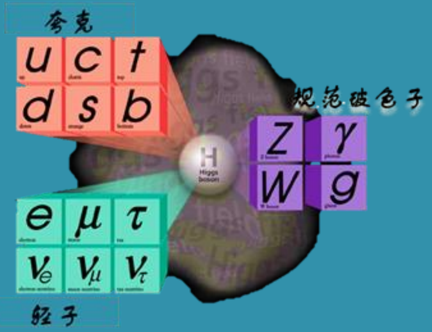
DOI: 10.1103/PhysRevApplied.17.054044

粒子—准粒子的相对性原理

粒子和准粒子的概念不是绝对的

晶格的振动——声子





标准模型

$10^{10}eV$

能量

$10^{-3}eV$

凝聚态中基本激发

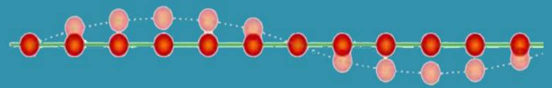
准粒子

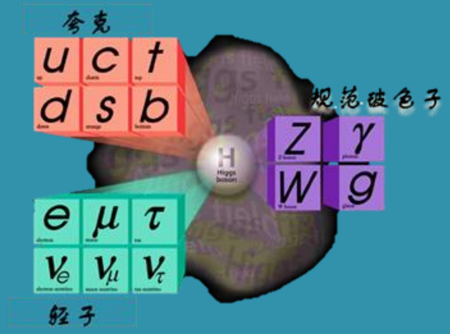
粒子

粒子—准粒子的相对性原理

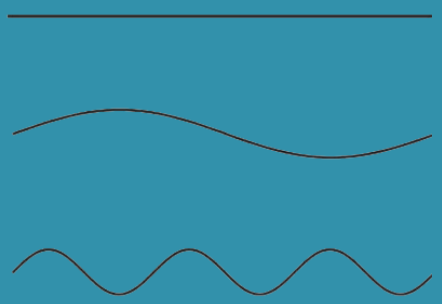
粒子和准粒子的概念不是绝对的

晶格的振动——声子





超弦的振动模式



标准模型

$10^{10}eV$

超弦理论的
普朗克能标
$10^{28}eV$

$10^{-3}eV$
凝聚态中
基本激发

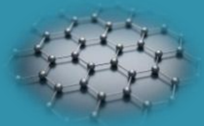
准粒子

而是取决于观察者的相对能量和长度尺度

粒子

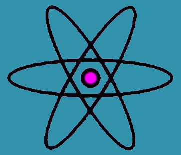
粒子—准粒子的相对性原理

石墨烯中的电子



meV

原子中的电子



eV

静止质量为0.511MeV电子

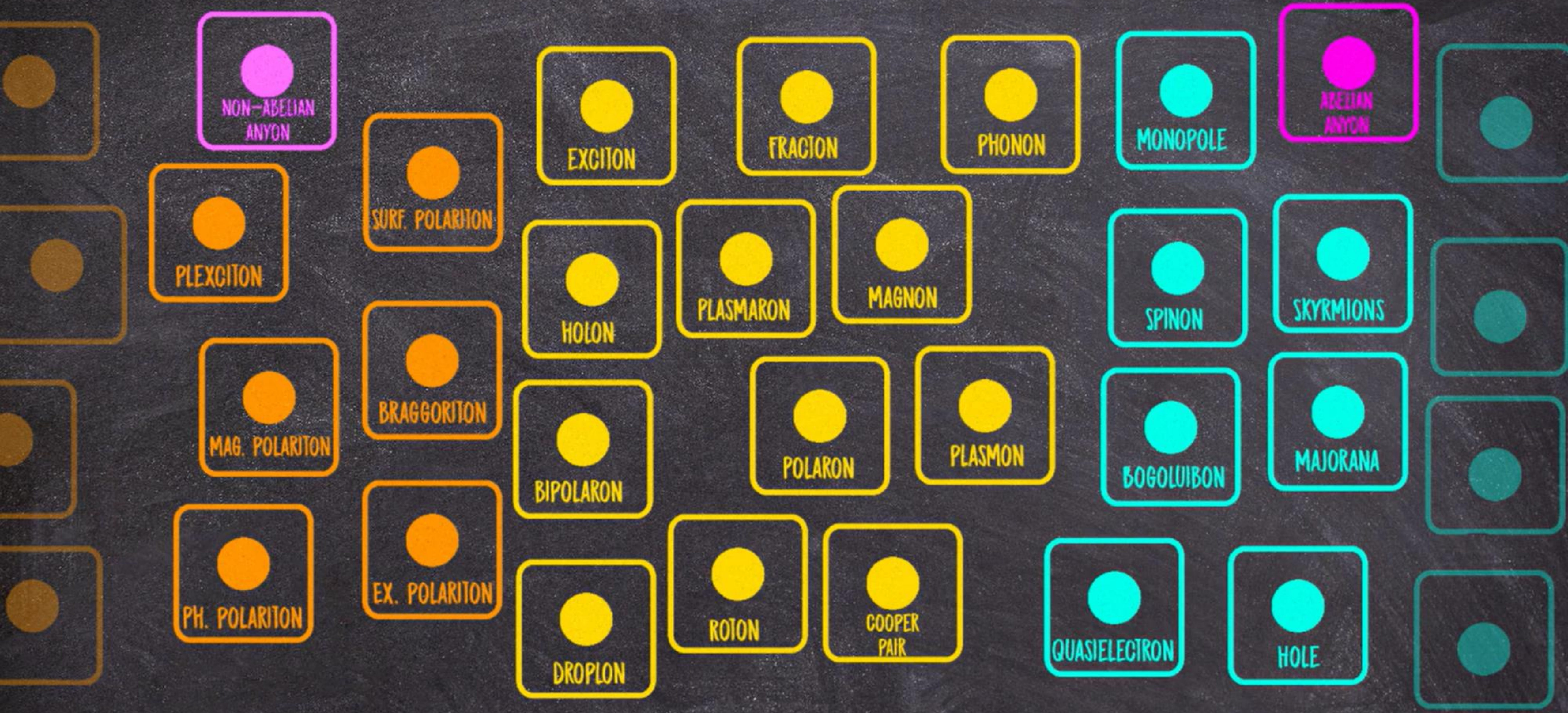
MeV

能量

相对论性狄拉克方程 ← 推导 非相对论的薛定谔方程 ← 推导 相对论性狄拉克方程

演生现象

有时准粒子可能比粒子本身更有趣



THE QUASI-PARTICLE ZOO

Auguries of Innocence （节选）

To see a world in a grain of sand
and a heaven in a wild flower
Hold infinite in the palm of your hand
and eternity in an hour

William Blake (1757-1827)

一沙一世界，一花一天堂。

无限掌中置，刹那成永恒。（徐志摩译）

"佛土生五色茎，
一花一世界，
一叶一如来"

《华严经》

創寰宇學府 育天下英才

UNIVERSITY OF SCIENCE AND
TECHNOLOGY OF CHINA

感謝垂听

敬请批评指正