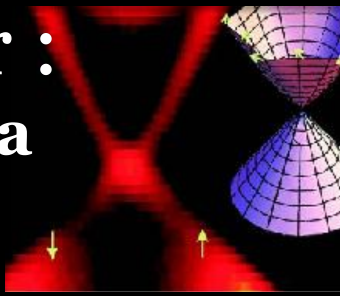
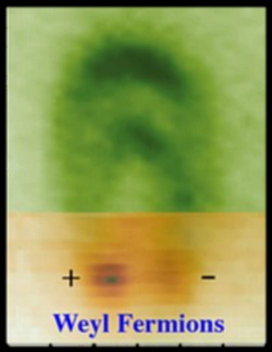
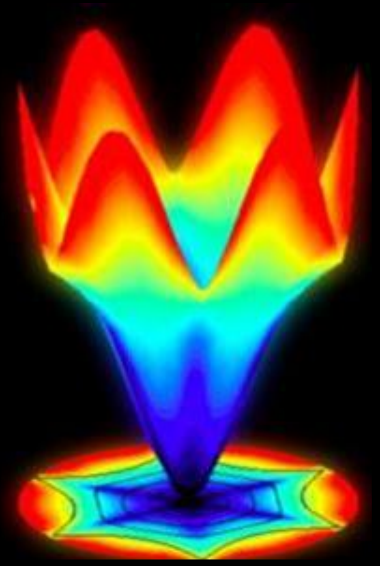
New Topological Phases of Matter :
Platform for emergent Dirac, Majorana and Weyl fermions

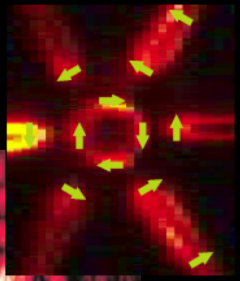


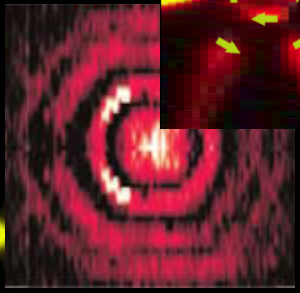
Physics Colloquium
California Inst. of Technology
October, 2016

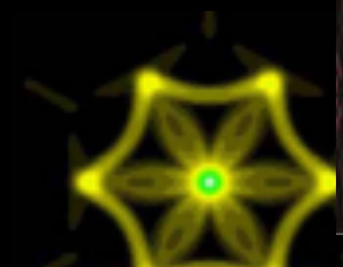


M.Z. Hasan
Princeton Univ.









Topological Phases Theory:

Thouless et.al., PRL 1982; Laughlin, PRL 1983

Haldane, PRL 1983 (SPT) & Haldane, PRL 1988 (QAHE)

Kane, Mele; PRL 2005, *Kane, Mele, Fu*; PRL 05 -> PRL 07

and many others….

Experiments :

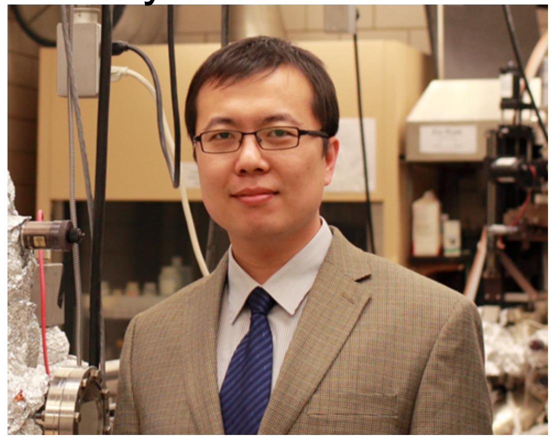
2D :	*von Klitzing et.al.,* PRL 1980	Int. **QHE**
	Tsui et.al., PRL 1982	Frq. QHE
	Konig et.al, (Molenkamp) Sci' 2007	Spin QHE
	Chang et.al., (Q.Xue) Science 2013	Anom **QHE**
3D:	*Hsieh et., (MZH)* KITP'2007, Nature 2008	**TSS, TI (3D-TI)**
	Xu et.al., (MZH) Science'15, Science 2015	**FermiArc, Weyl**
	and others…	

+ Superconductivity

ARPES team on Topo. Fermions (Weyl, Dirac, TNL)

Weyl-Semimetals + Superconductivity **TNL**-Semimetals **Dirac**-Semimetals

Su-Yang Xu

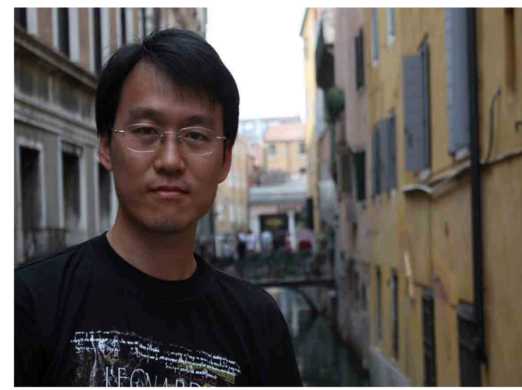


Guang Bian

Madhab Neupane

Ilya Belopolski

Nasser Alidoust



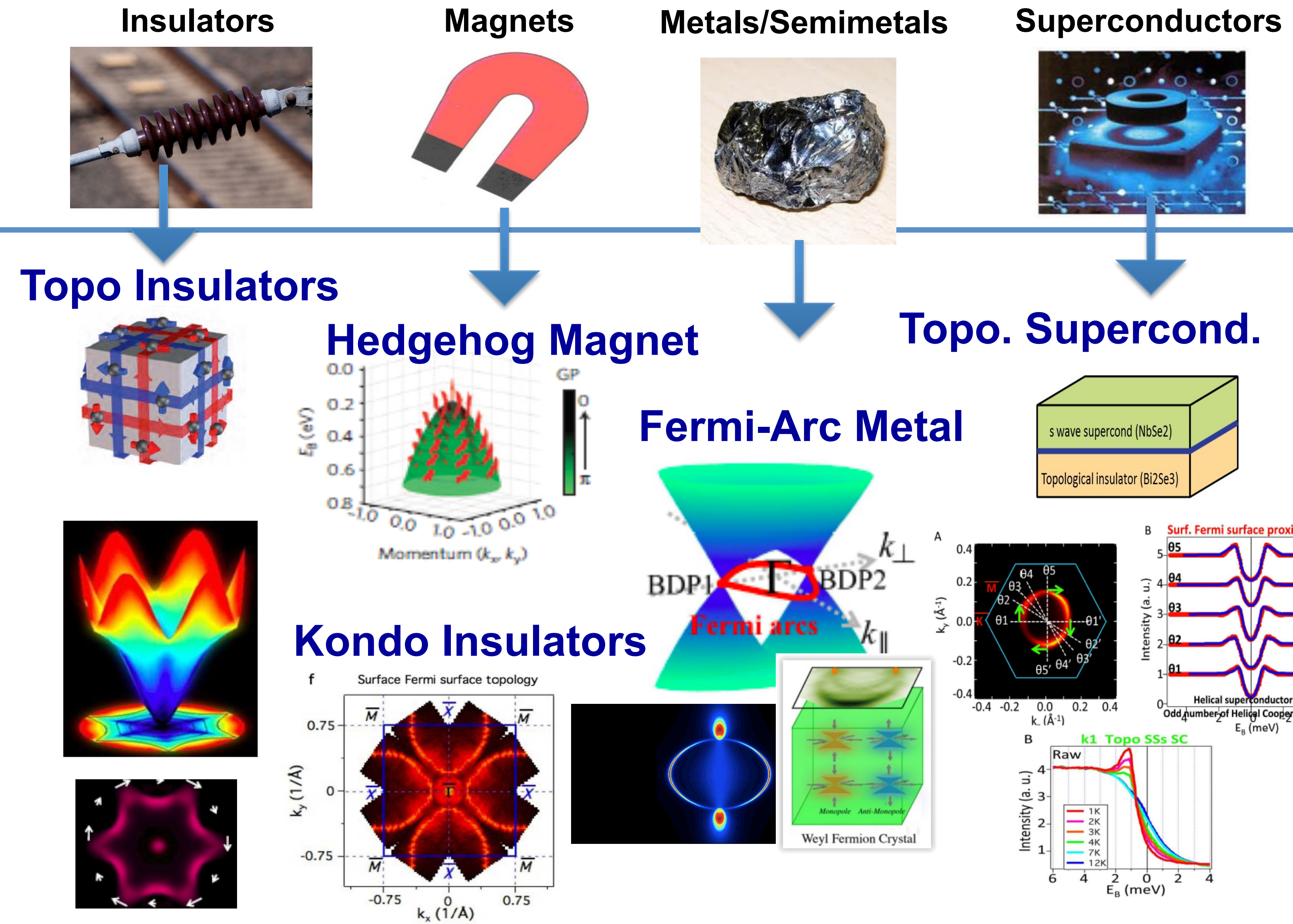
Hao Zheng

S. Xu, G. Bian, M. Neupane, I. Belopolski, N. Alidoust, H. Zheng C. Liu, D. Sanchez

(previously) D.Hsieh (CalTech), L.A.Wray (SLAC/NYU), D.Qian (Shanghai)

Samples: R. Sanker (India), C. Zhang, Shuang Jia (Peking), F.C Chou (Taiwan)

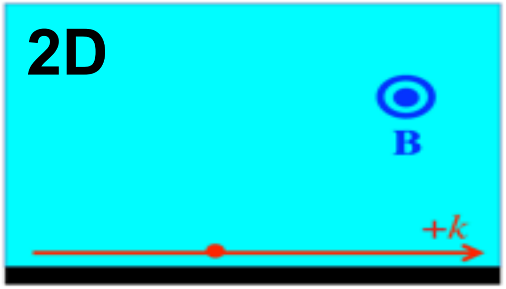
FP/DFT: G. Bian, S. Xu, I. Belopolski, MZH + A. Bansil (NEU), S. Huang, H. Lin (NUS)

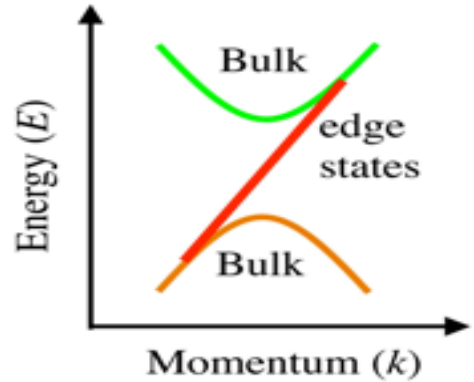

Insulators
Magnets
Metals/Semimetals
Superconductors
Topo Insulators
Hedgehog Magnet
Fermi-Arc Metal
Topo. Supercond.
Kondo Insulators
GP
Momentum (k_x, k_y)
E_B (eV)
BDP1
BDP2
Fermi arcs
$k_\perp$
$k_\parallel$
s wave supercond (NbSe2)
Topological insulator (Bi2Se3)
Surface Fermi surface topology
k_y (1/Å)
k_x (1/Å)
Monopole
Anti-Monopole
Weyl Fermion Crystal
Surf. Fermi surface proxi
Helical superconductor
Odd number of Helical Cooper
Intensity (a. u.)
E_B (meV)
k1 Topo SSs SC
Raw
1K
2K
3K
4K
7K
12K

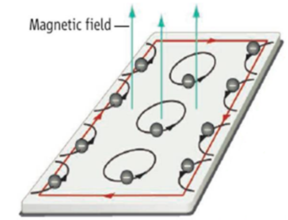
Non-trivial insulators

σ_{xy} = **n**e²/h

1 Invariant





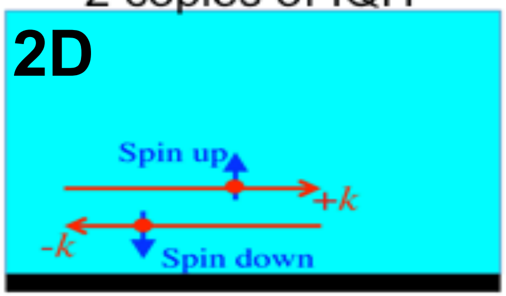


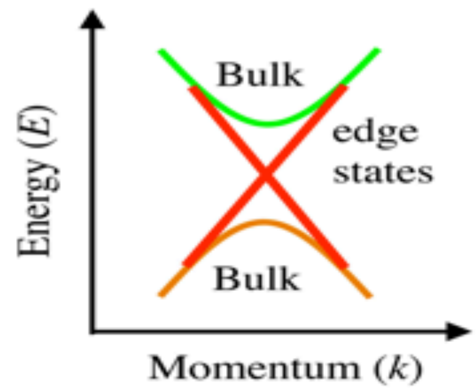
Quant. Hall physics

Haldane + spin-orbit

2 copies of IQH

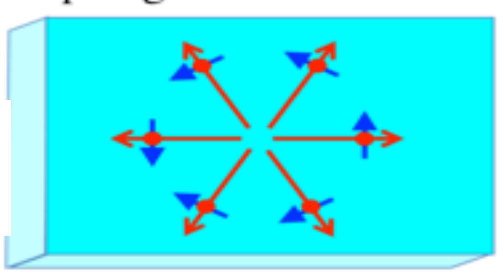
1 Invariant

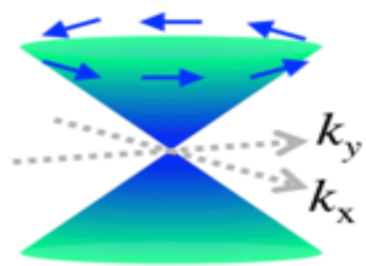




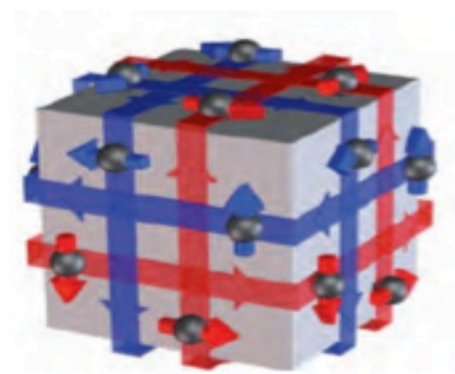
Topological Surface States

4 Invariant





Surface states



3D **Topo. Insulator**

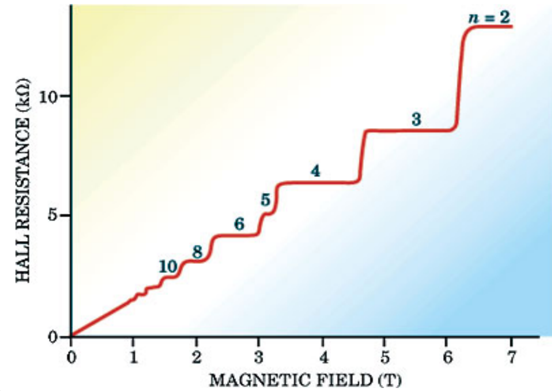
3D TI is a novel topological state
first NON-quantHall-like topological matter

QHE phases (2D)

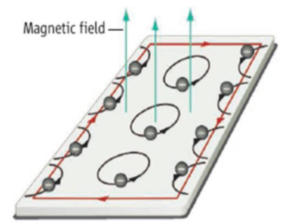
$\sigma_{xy} = \mathbf{n}e^2/h$

↑

Chern no.
(D. Thouless et.al., M. Berry)



Transport



Topo Insulators

$\nu_o = \Theta_{ME}/\pi$

$\Theta=\pi$ (odd)

How to experimentally "measure" the topological quantum numbers (ν_i) ?

4 TQNs → **15+1** distinct insulators

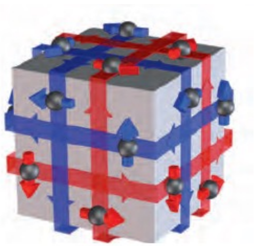
$\{\nu_0, \nu_1\ \nu_2\ \nu_3\}$

Topological "order parameters!"

No quantized transport

via : $\{\nu_i\}$

↑



?

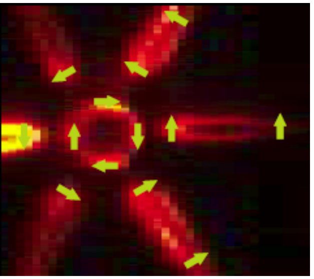
Spin-sensitive

Momentum-resolved

Edge vs. Bulk

(Bulk-Boundary Correspondence)

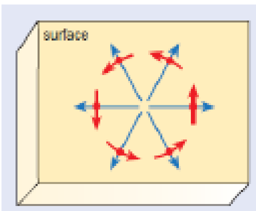
Topo. Insulator → Most Researched Topo. Insulator



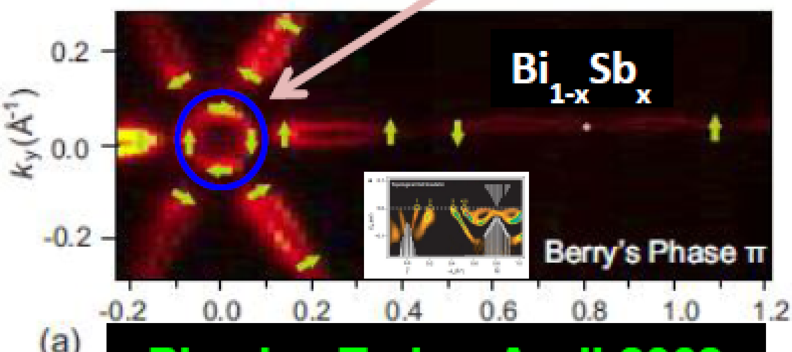
$Bi_{1-x}Sb_x$ → Bi_2Se_3 class

KITP Proceed. (2007)
Hsieh et.al., NATURE 2008
Hsieh et.al., SCIENCE 2009
Physics Today, April-2009

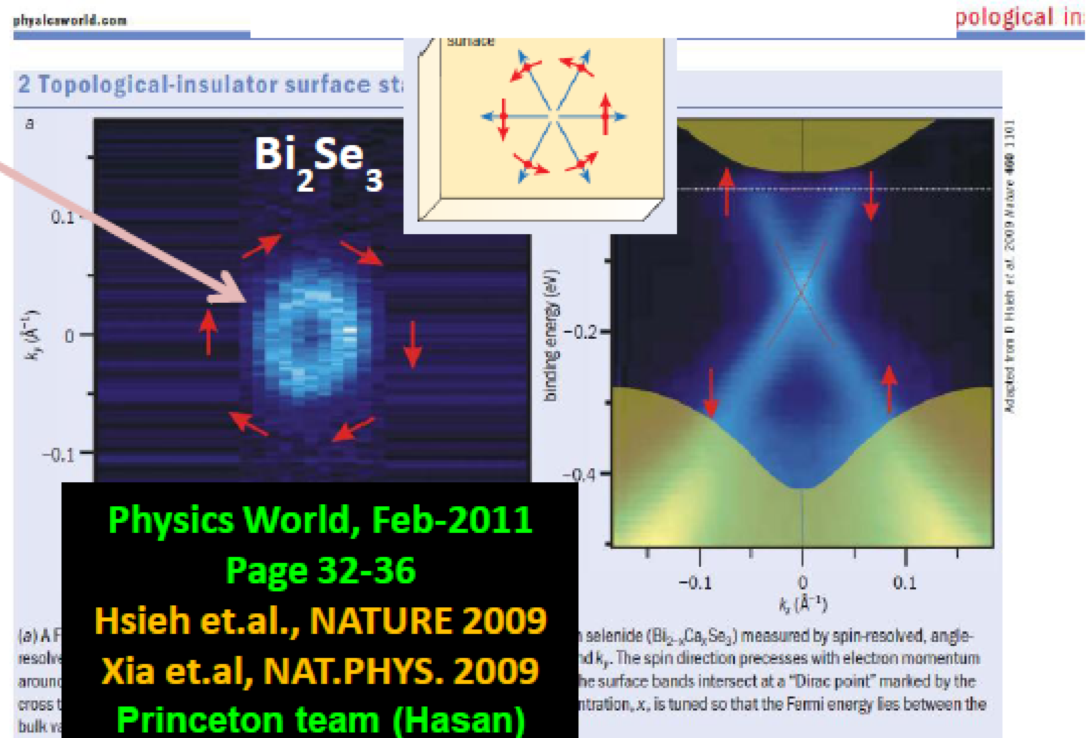
Xia et.al, NAT.PHYS. 2009 (arXiv 2008)
Hsieh et.al., NATURE 2009
Zhang et.al, NAT.PHYS. 2009
Physics World, Feb-2011



Dirac Cone



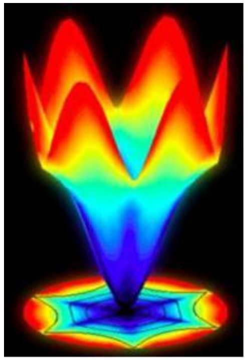
Physics Today, April 2009
"Search & Discovery" Page 12-13
Topological Insulators ($Bi_{1-x}Sb_x$)
Hsieh et.al., NATURE 2008
Princeton team (Hasan)



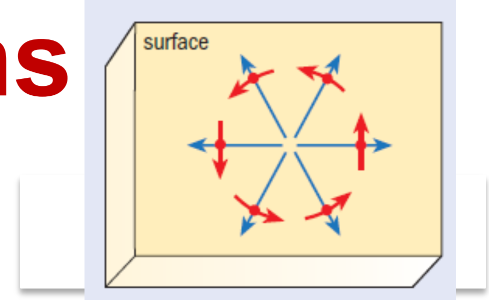
Physics World, Feb-2011
Page 32-36
Hsieh et.al., NATURE 2009
Xia et.al, NAT.PHYS. 2009
Princeton team (Hasan)

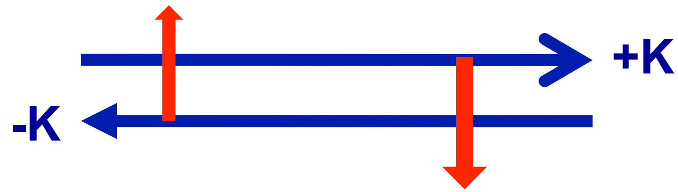
3D TI: More than **500** Expt's Papers (arXiv)

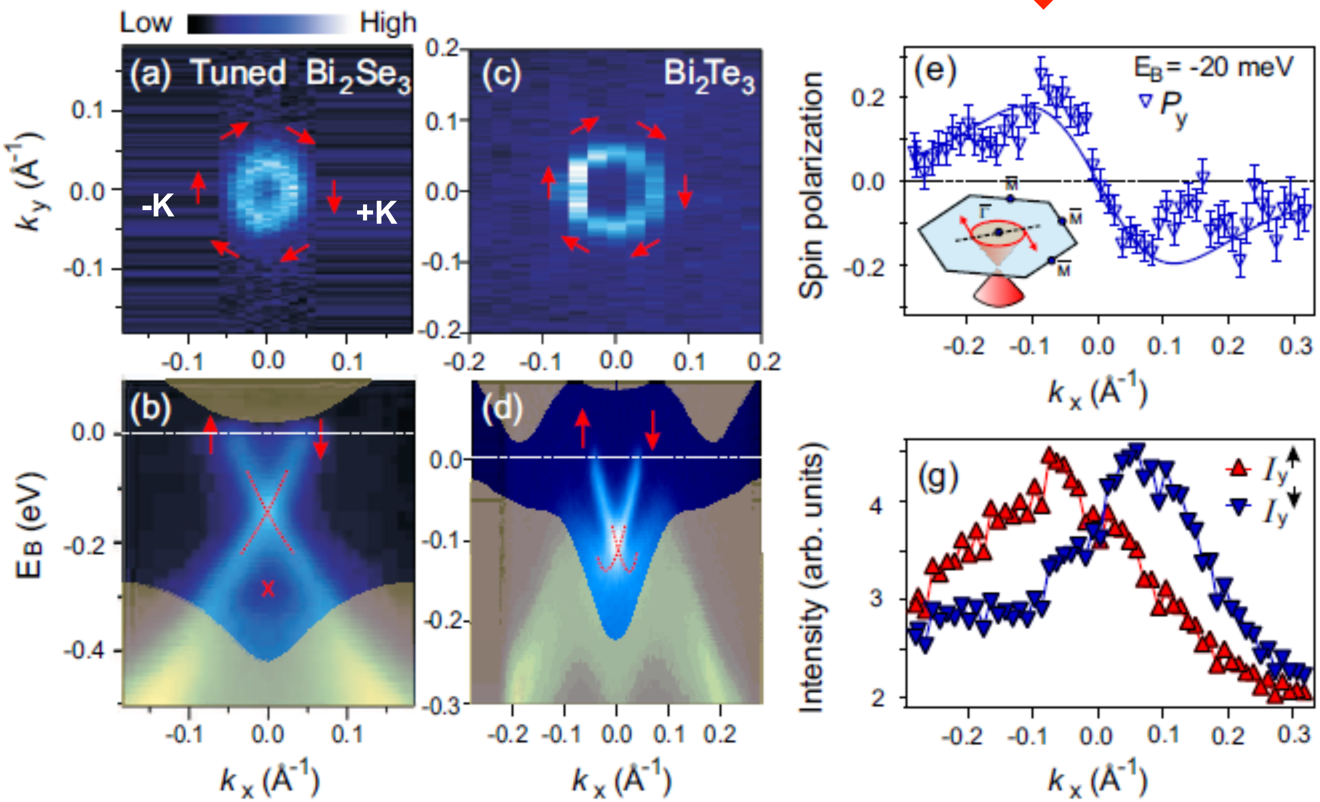
Helical Dirac fermions

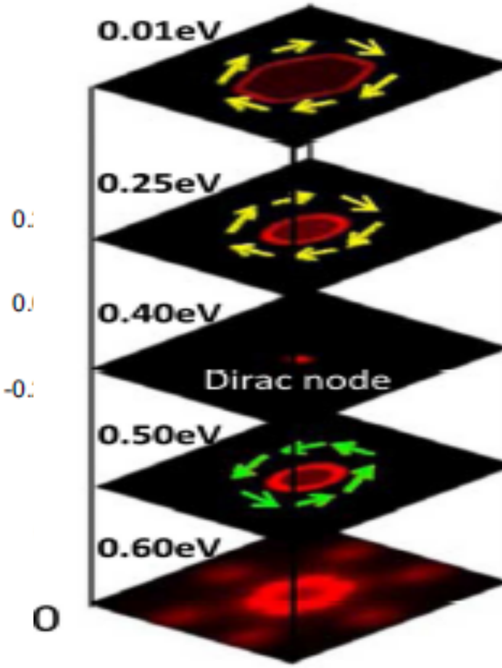


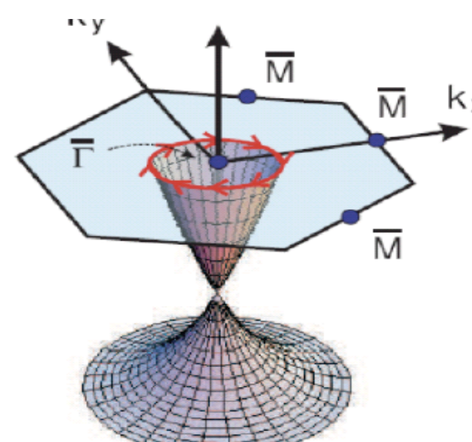
One-to-One Spin-LinearMomentum Locking









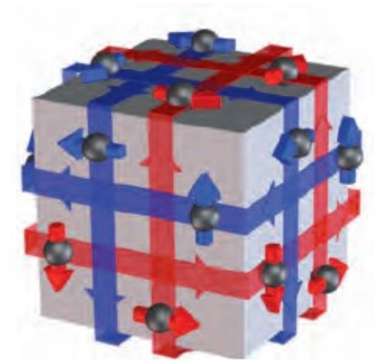


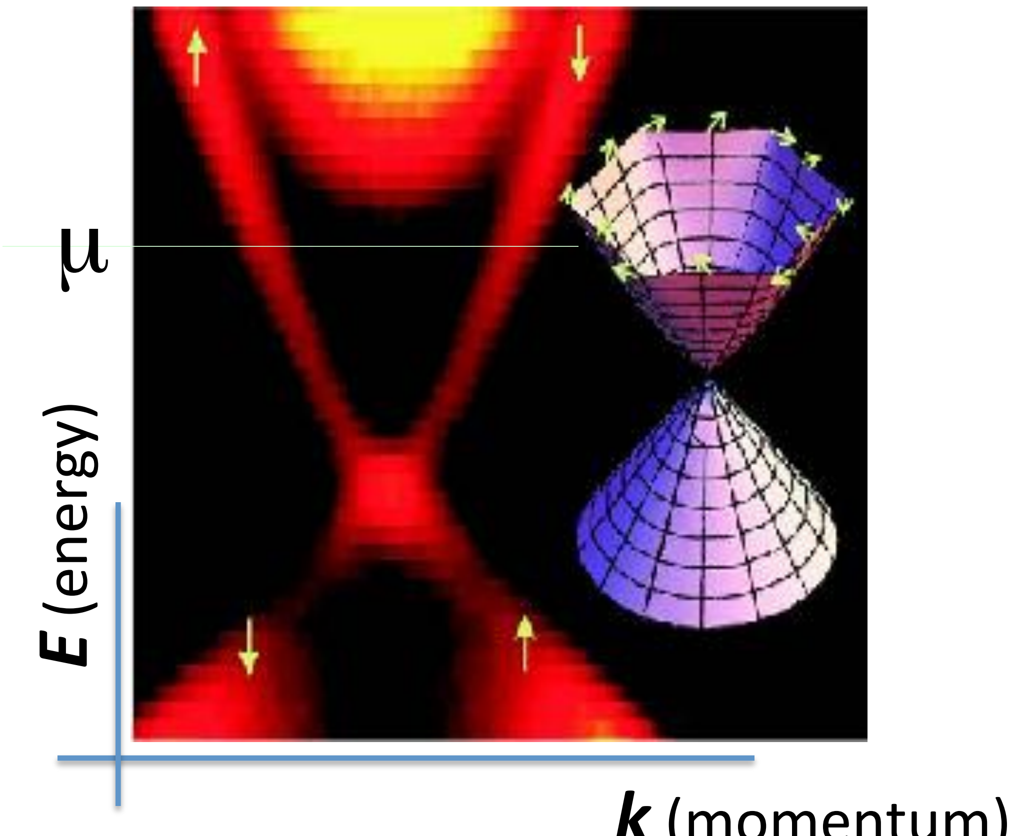
Berry's phase $\theta = \pi$

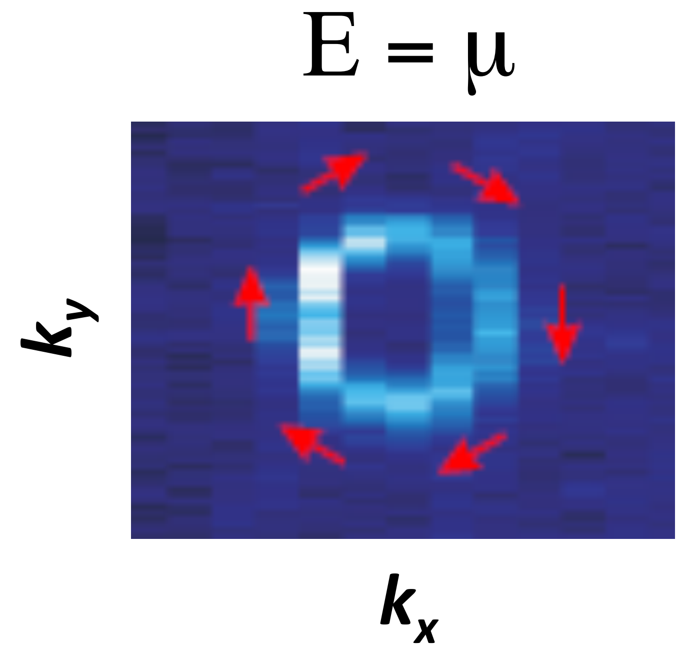
Invariant = $\theta/\pi = 1$

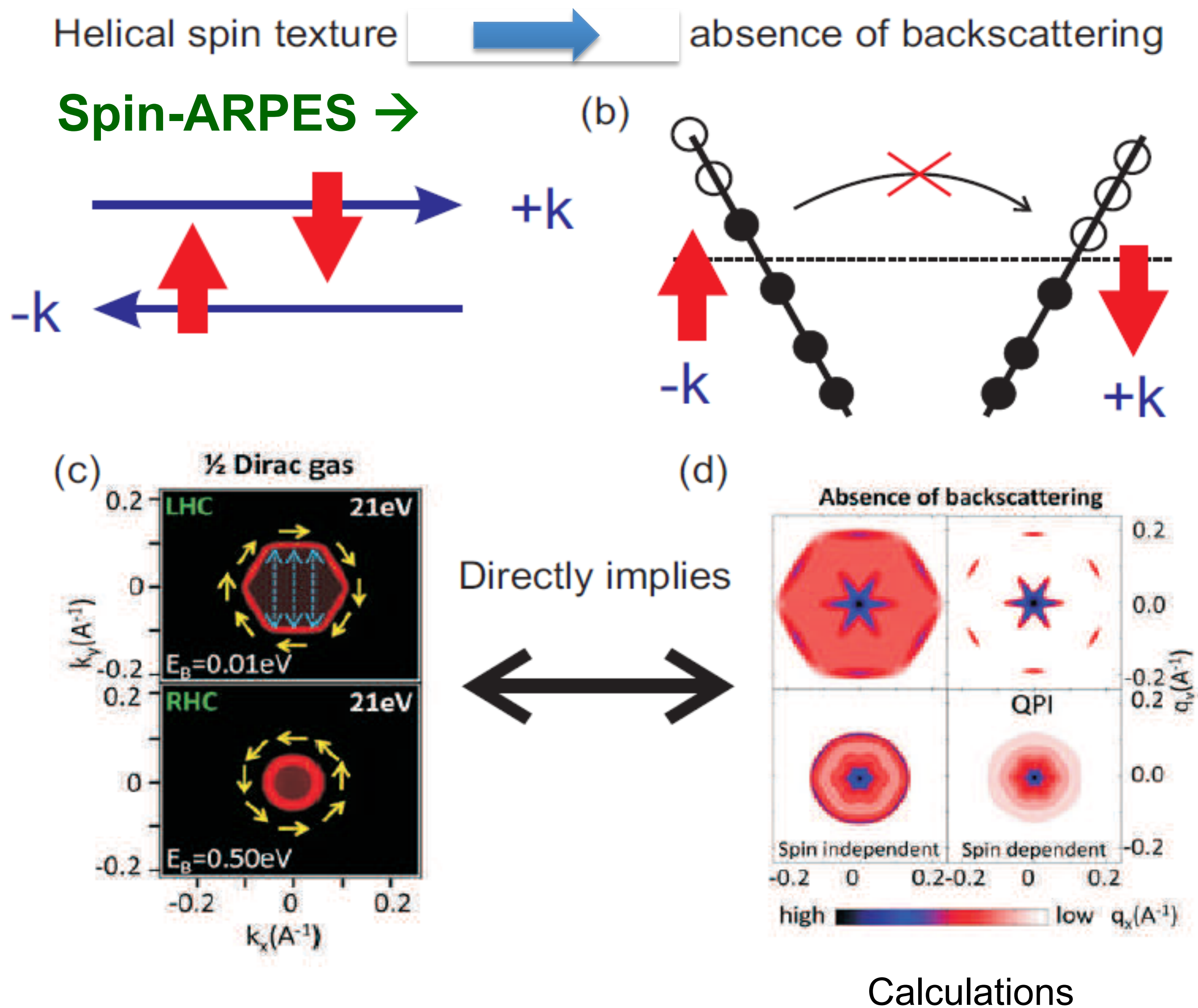
Hsieh, Qian, Wray et.al., (MZH) Nature'08, Science'09, Nature'09

Helical Dirac fermions

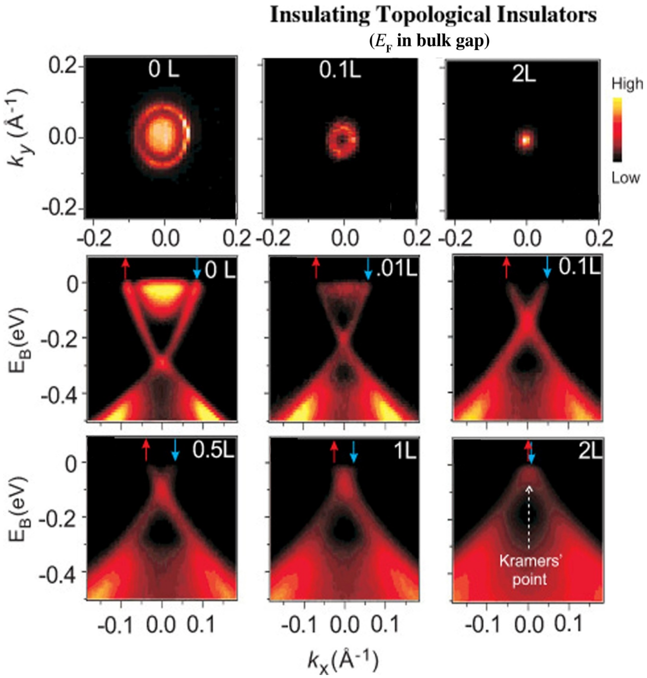






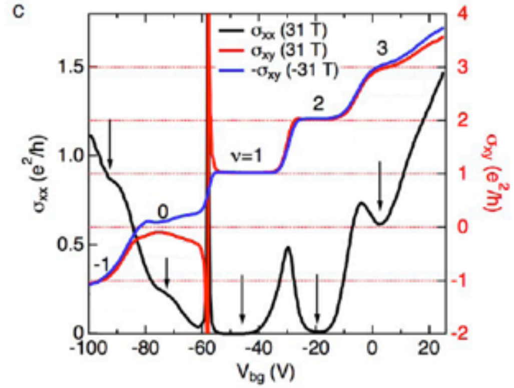


Helical spin texture
absence of backscattering
Spin-ARPES →
(b)
+k
-k
-k
+k
(c)
½ Dirac gas
LHC
21eV
E_B=0.01eV
RHC
21eV
E_B=0.50eV
0.2
0
-0.2
-0.2
0
0.2
$k_y(A^{-1})$
$k_x(A^{-1})$
Directly implies
(d)
Absence of backscattering
QPI
Spin independent
Spin dependent
0.2
0.0
-0.2
$q_y(A^{-1})$
-0.2
0
0.2
high
low
$q_x(A^{-1})$
Calculations



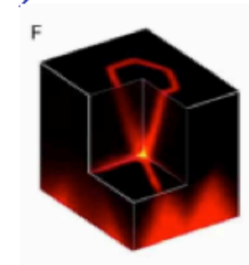
QHE for a 3D Topo.Insulator : Bi(Sb/Te)Se2

Transport



Purdue & Princeton
(Xu et.al, Hasan & Chen)
Magnet Lab in Florida

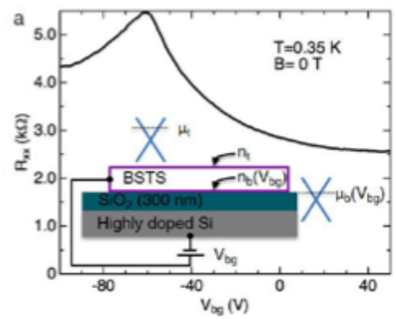
Nature Physics (2014)

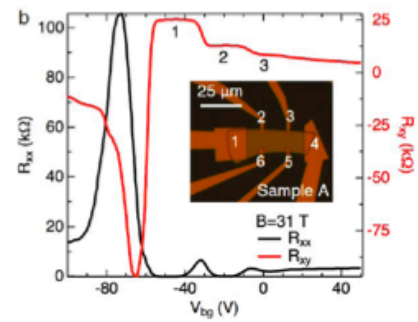


TI = 2 surf's(Top + Bot.) of Dirac gas

LL = $(n_t+1/2)+(n_b+1/2)=n_t+n_b+1$

only Integer QHE !





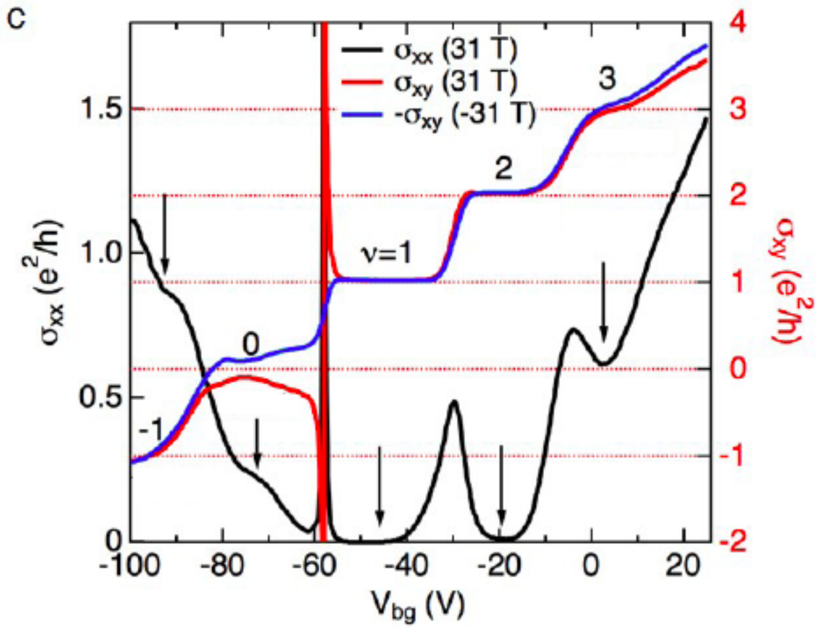
Bulk insulating (intrinsic)
Topological insulators exist.

Latest paper : Xu *et.al*, Nature Physics (2014)

QHE for a 3D **Topo.Insulator** : Bi(Sb/Te)Se2

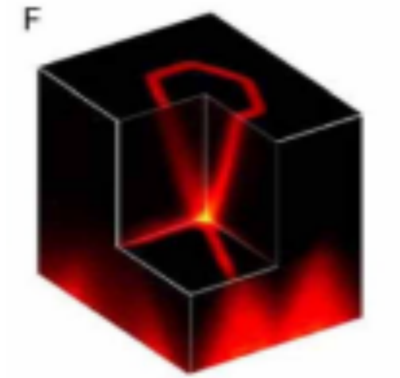
Transport

ARPES+Transport



Purdue & Princeton
(Xu et.al, Hasan & Chen)
Magnet Lab in Florida

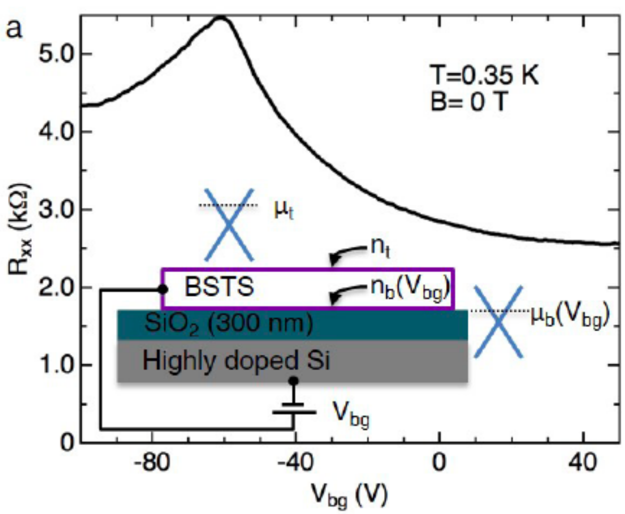
Nature Physics (2014)

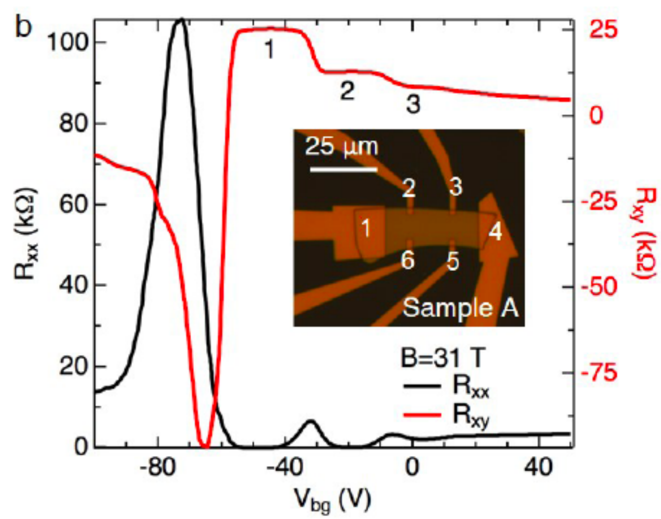


TI = 2 surf's(Top + Bot.) of Dirac gas

$$\mathbf{LL = (n_t+1/2)+(n_b+1/2)=n_t+n_b+1}$$

only Integer QHE !





(SPT or Z_2) Topo.Order at Room Temperature

QH-like topological effect at 300K, No magnetic field

Protected Surface States (New 2DEG)

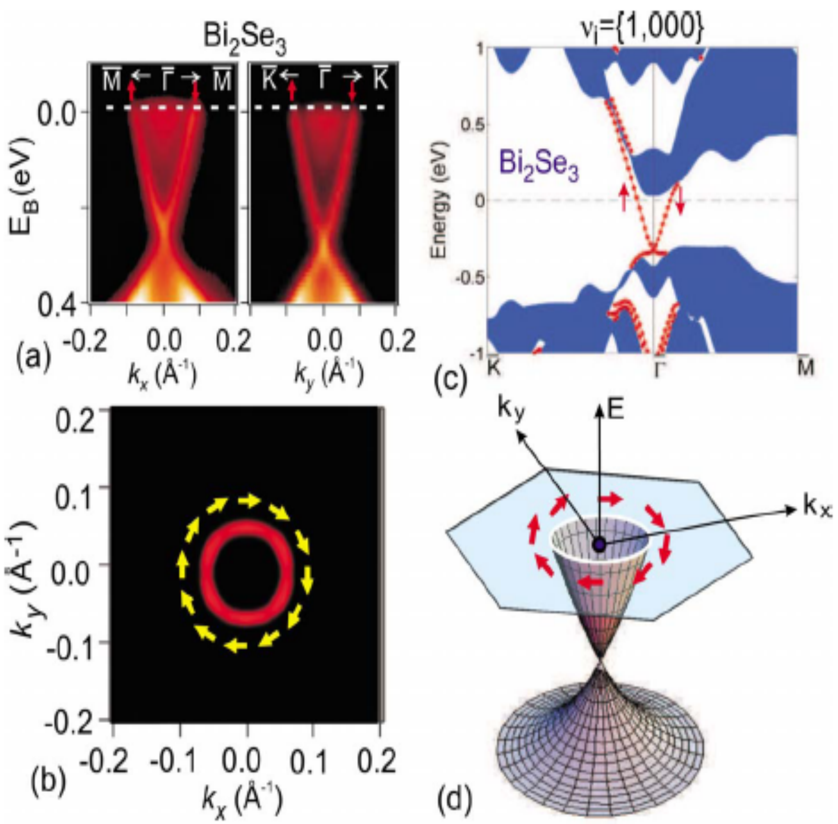
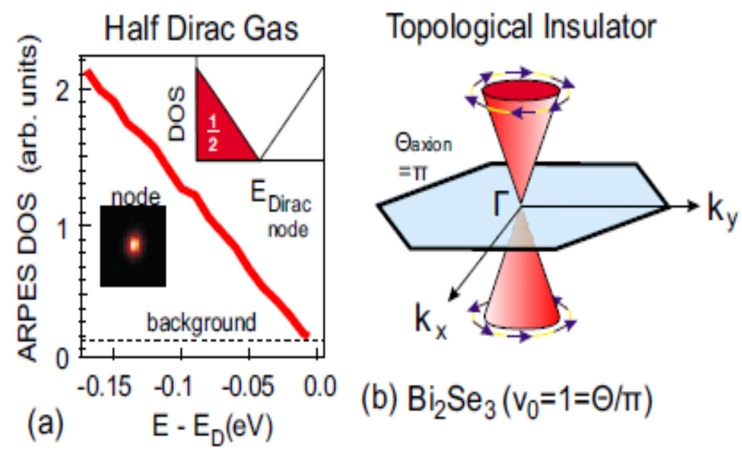
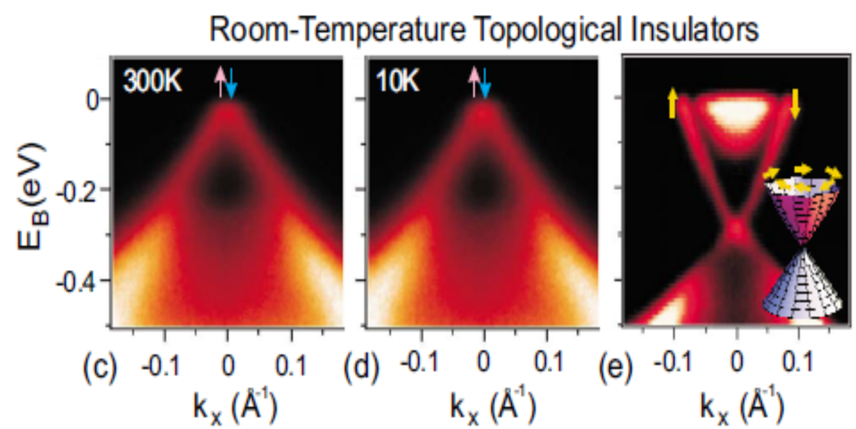


FIG. 12. (Color online) Helical fermions: Spin-momentum



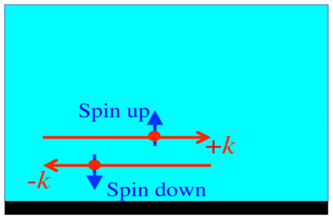


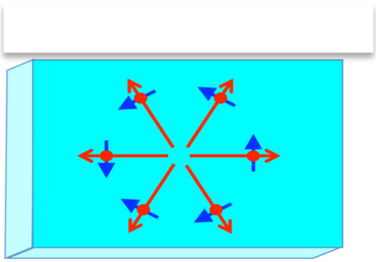
Hsieh, Qian, Wray, Xia et.al., Nature'08, Science'09, Nature'09

3D to 2D Topo. Insulators : $Bi_2(Se/Te)_3$

MBE growth

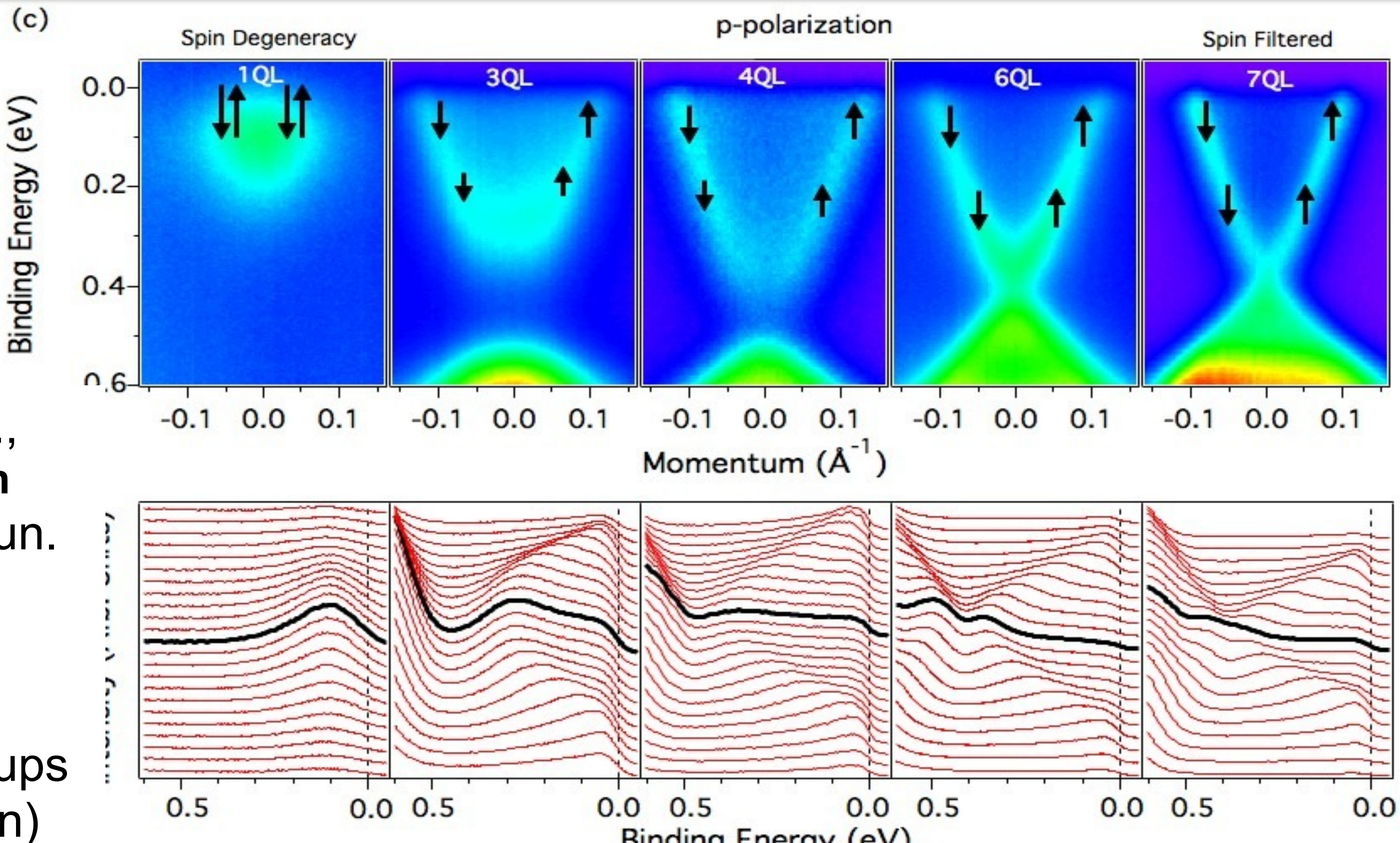
Spin changes
as one 2D -> 3D
3D → 2D (BULK)





2D ⟷ 3D

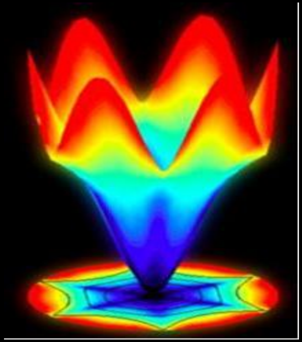
1 QL



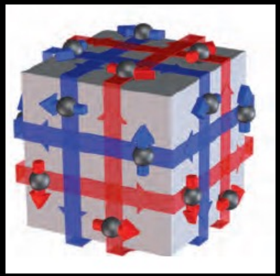
7 QL

Neupane et.al.,
MZH & Samarth
Nature Commun.
'13 (arXiv)

Work by
Xue & Jia groups
'12 (w/out Spin)

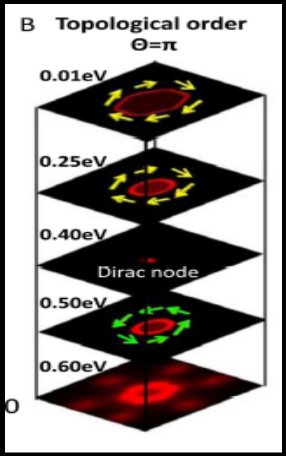


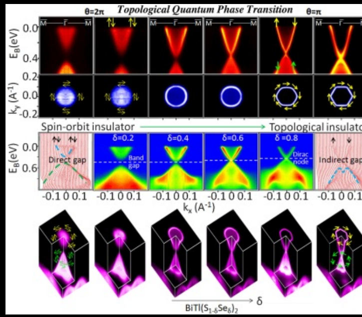
Gapped topological states:
Topological Insulators

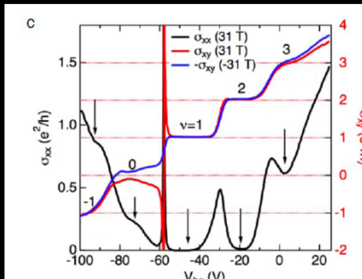


methodology to probe topo.matter……..

1. Surface States exist and locate inside the bandgap and ½ metallic throughout (**Nature' 08,** submit. **2007**)
2. Spin - Momentum Locking (Spin-Texture, Berry's phase) (**Nature' 09, Science' 09**)
3. Topo Phase transition (BI to TI) via spin-orbit tuning (**Nature Physics, Science' 10-11**)
4. Robust up to room temperature (**Nature' 09**)
5. Absence of backscatt. by Spin-Texture (**Nature' 09**)





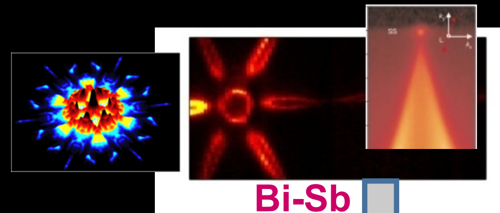


Th+Expts: MZH & Kane, Rev. Mod. Phys. 82, 3045 (2010)

Experiments on Topo.Insulators (3D)

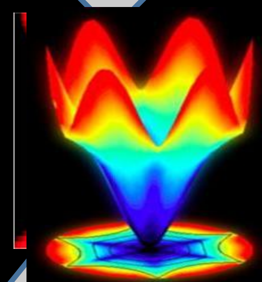
500+

Papers on Bi-based TIs



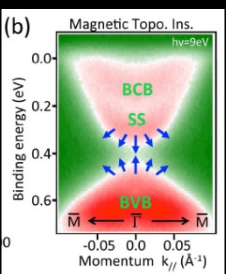
Hsieh et.al., NATURE 08 (sub. 2007)
Hsieh et.al., SCIENCE 09
Roushan et.al., NATURE 09

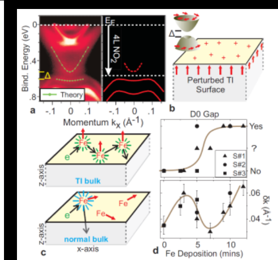
Bi_2X_3



Xia et.al, 2008 (arXiv'08, KITP 08)
Xia et.al, 2009 (Nature Phys.) and
Hsieh et.al., Nature 2009
Chen et.al, Sci '09, Zhang et. NatP '09

Magnetic TI

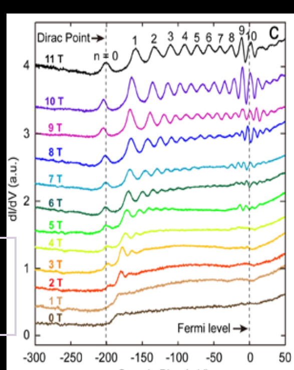


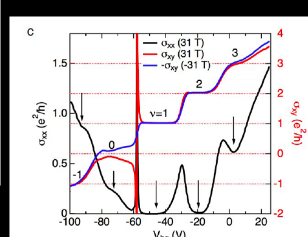


Xia et.al, arXiv. 2008
Wray et.al., Nat.Ph'10
Chen et.al, Science '10

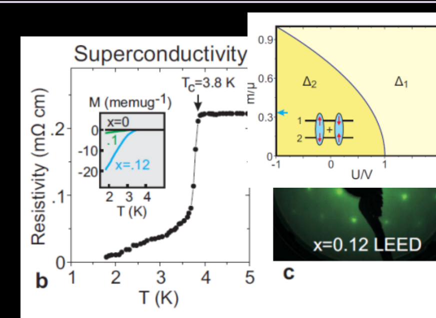
Quantum Hall effect

STM Landau quantization
Xue et.al., PRL 2010
Analytis et.al, NatPhys '10
Xiong et.al., arXiv'11



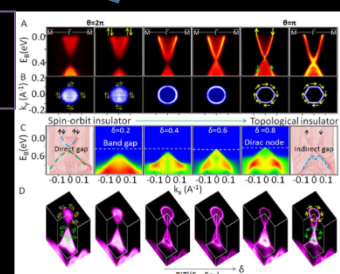


Superconductivity



Hor et.al., PRL 2
Wray et.al., Nphy
Ando et.al, PRL

Topo. Q. Phase Transition



S.-Y. Xu et.al., 2011
Science '11, arXiv'11

QAHE

Topo. Kondo Insulators

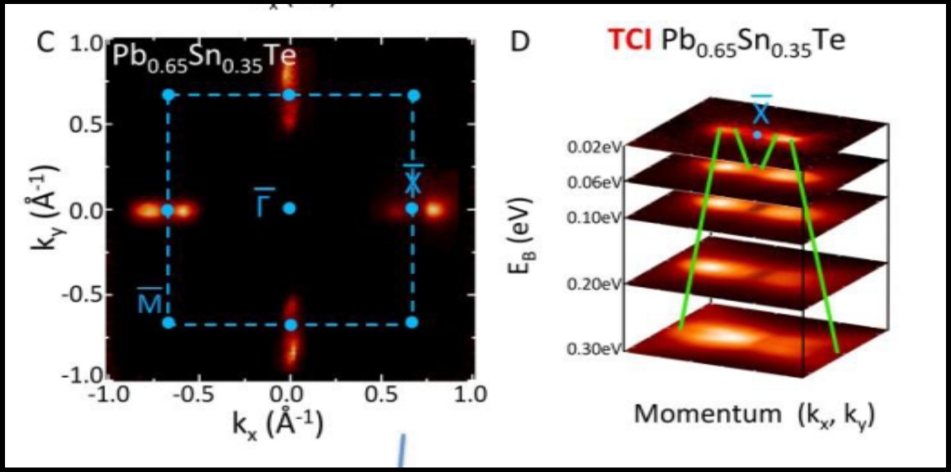
Topo Insulators beyond Z_2 or TRI

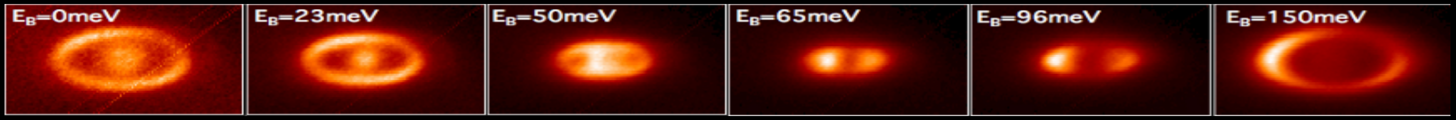
TR invariance ← → SG symmetry (TCI)

PbSnTe and theory : Fu-Kane '07; Fu '11, Lin-Bansil-Fu et.al., '12

PbSnTe

Mirror Chern no. measured in Bi-Sb;
Hsieh, Xia, et.al., (Kane & Hasan) SCIENCE' 09



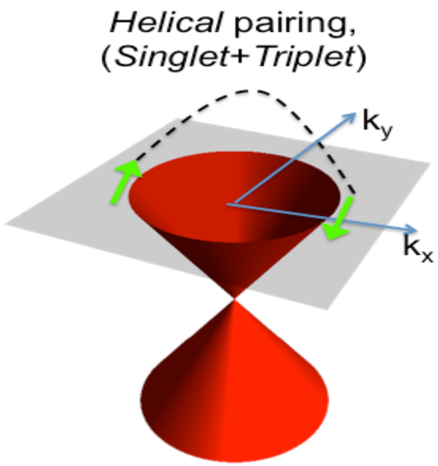


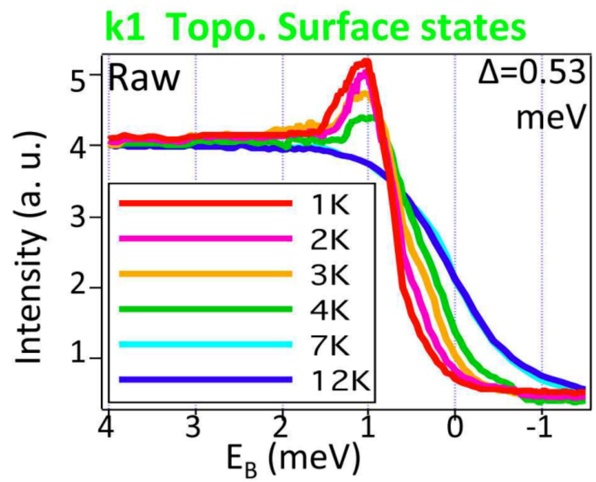
More Gapped topological states:

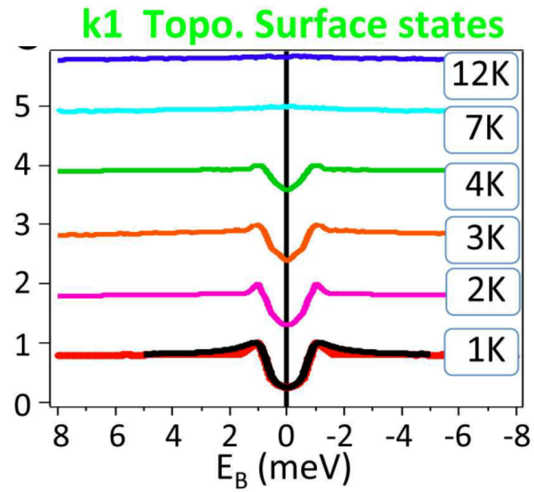
ARPES ⟷ MBE Growth

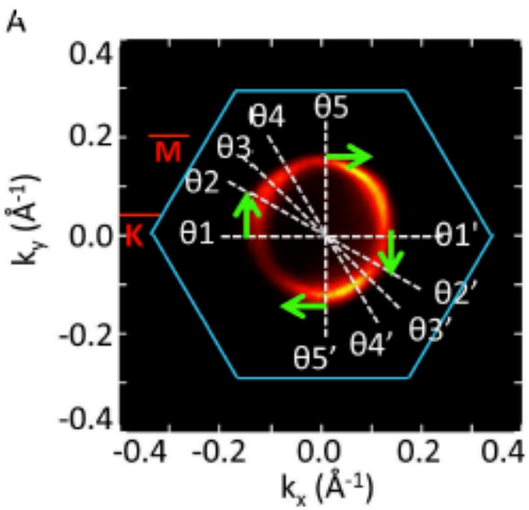
Feedback Loop

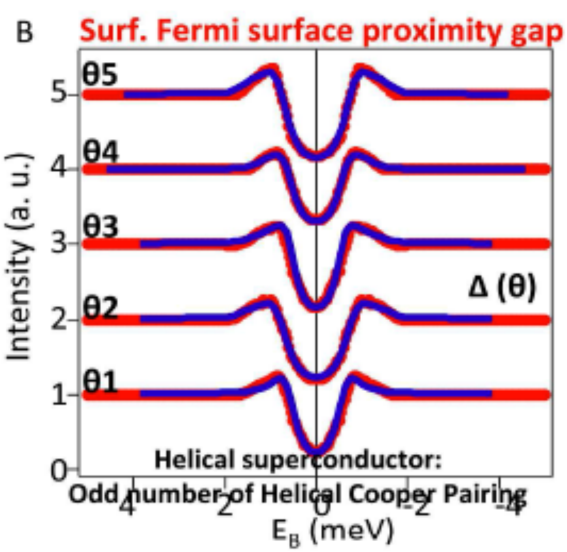
2D Topo. (Helical) Superconductor

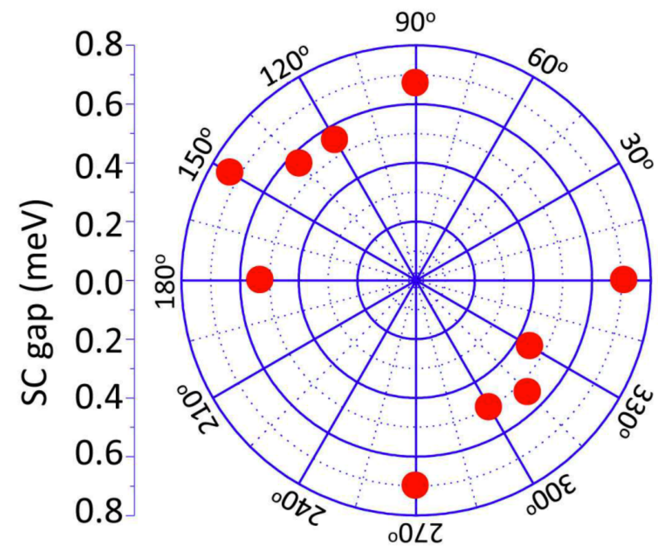










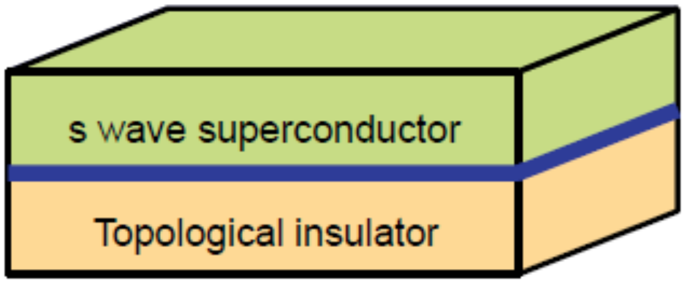


S. Xu, C. Liu *et.al.,* (MZH) Nature Phys (2014)

Majorana Platform

Superconducting Proximity Effect

Fu, Kane PRL 08

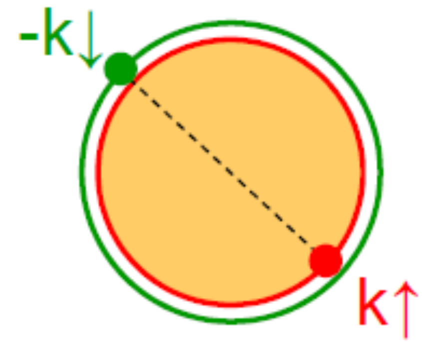


Surface states acquire superconducting gap Δ due to Cooper pair tunneling

BCS Superconductor :

$$\left\langle c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow} \right\rangle \propto \Delta e^{i\varphi}$$

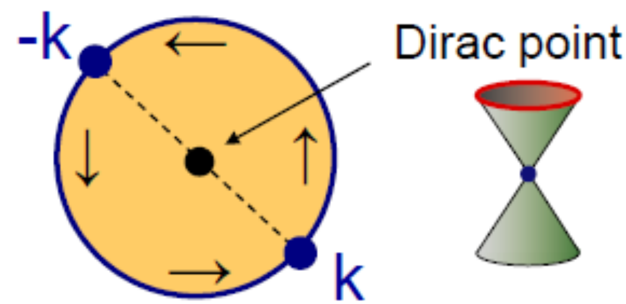
(s-wave, singlet pairing)



Superconducting surface states

$$\left\langle c^\dagger_{k} c^\dagger_{-k} \right\rangle \propto \Delta_{\text{surface}} e^{i\varphi}$$

(s-wave, singlet pairing)

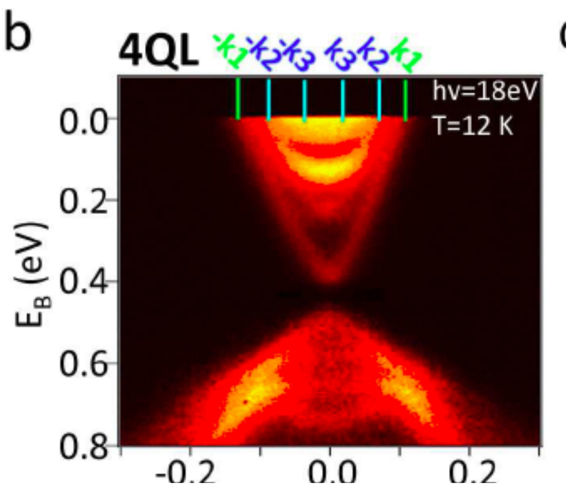


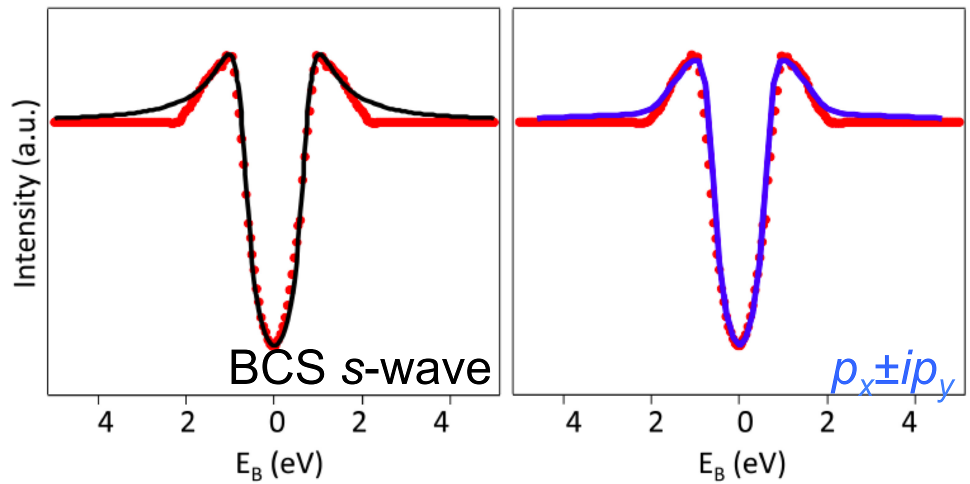
Half an ordinary superconductor
Highly nontrivial ground state

Slide from C. Kane

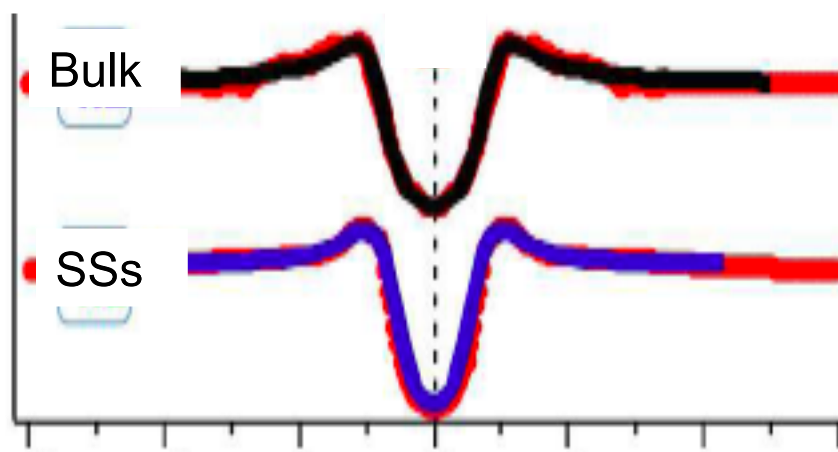
SC gap fitting
Surafce $p_x \pm ip_y$; Bulk band: *s*-wave

<u>Surface state gap fitting</u>





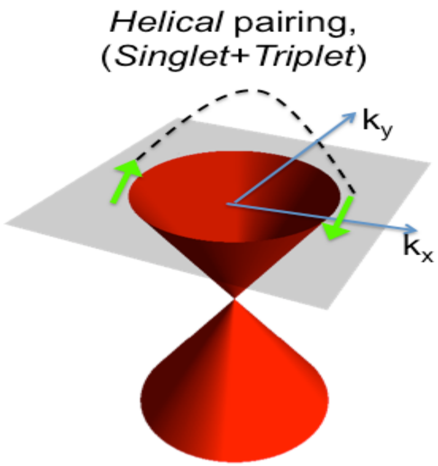
<u>Surface *vs* bulk gap fitting</u>

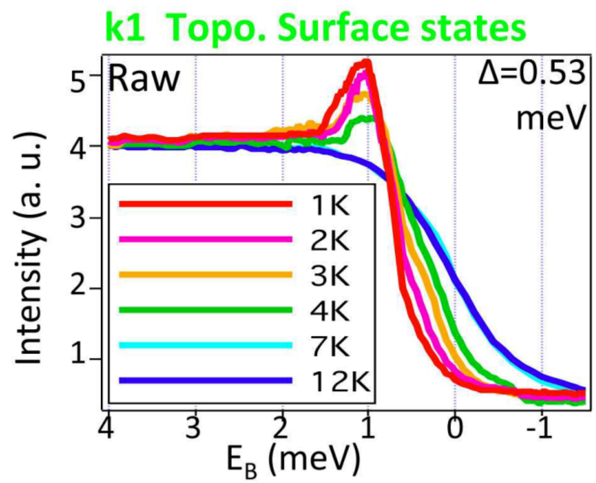


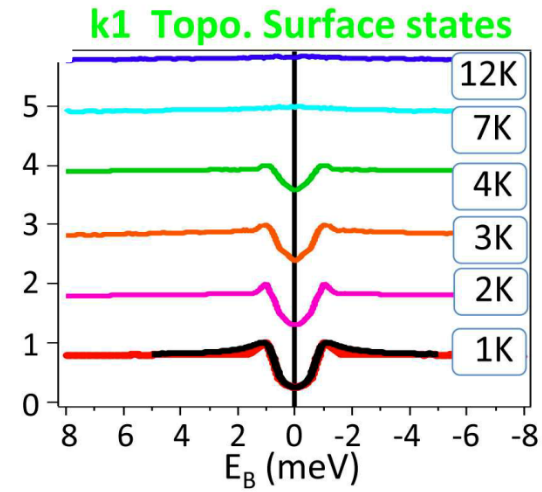
2D Topo. Superconductor

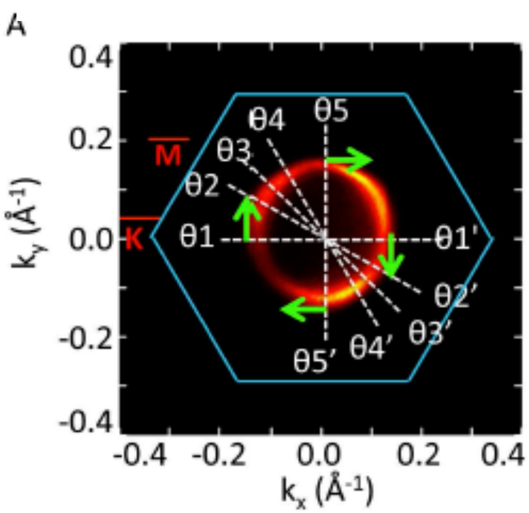
ARPES ⟷ MBE Growth

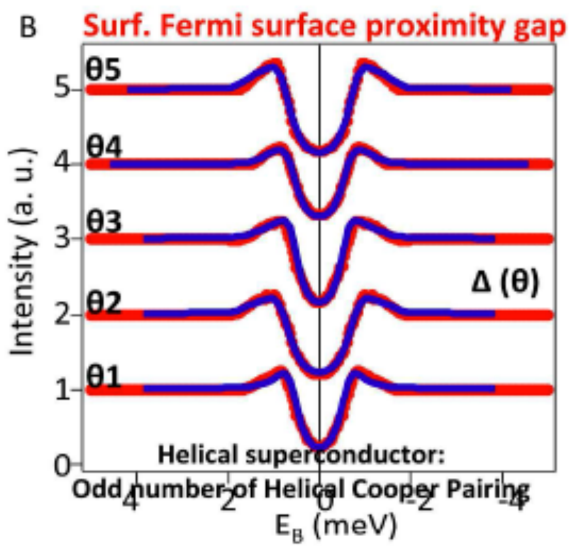
Feedback Loop

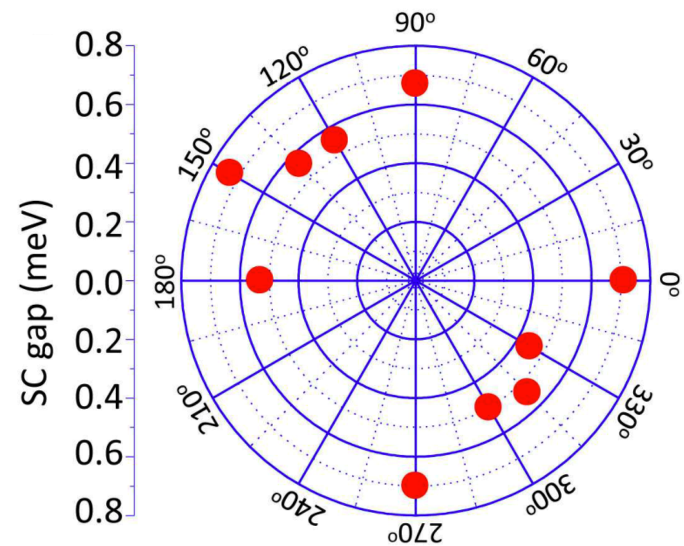






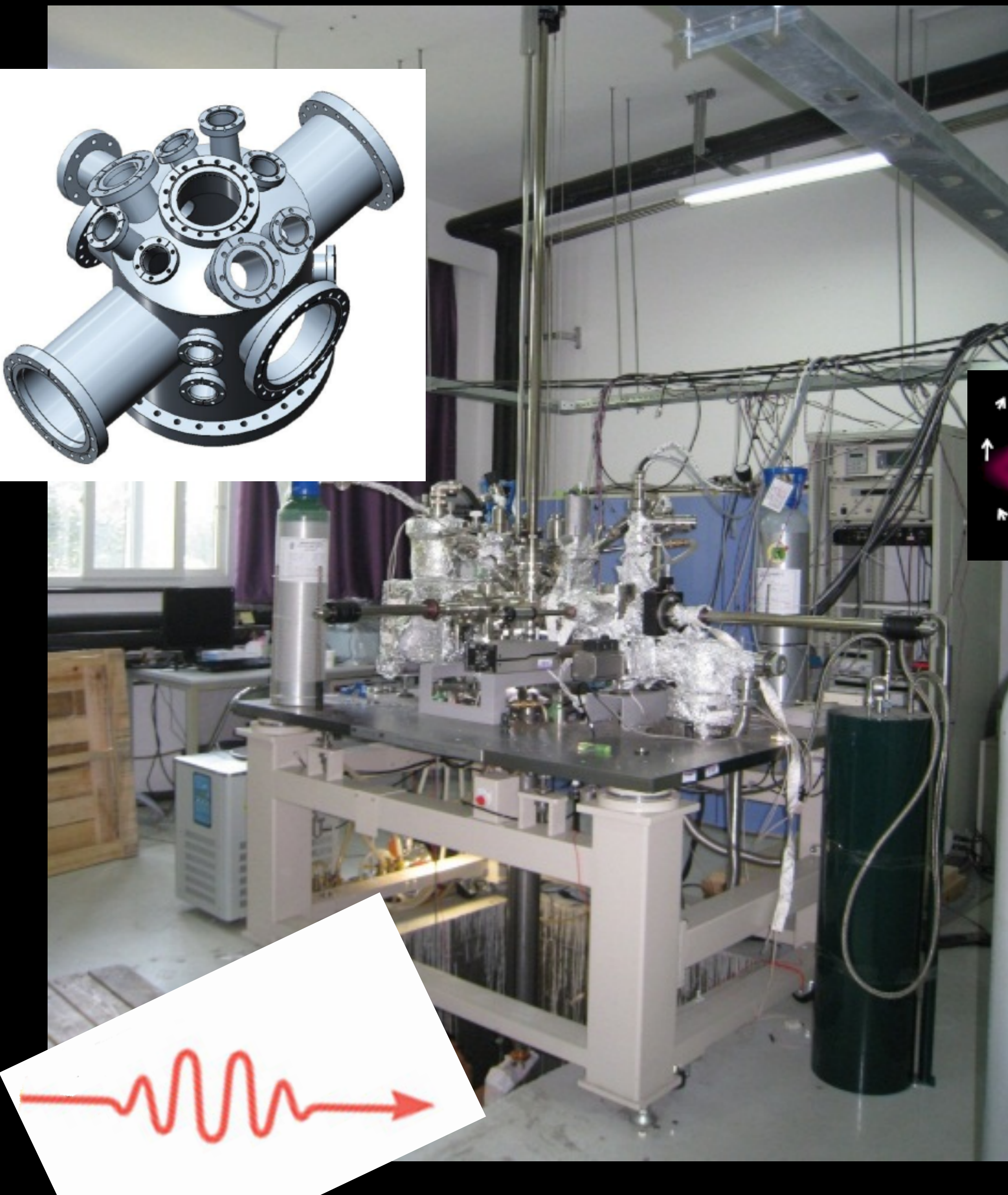


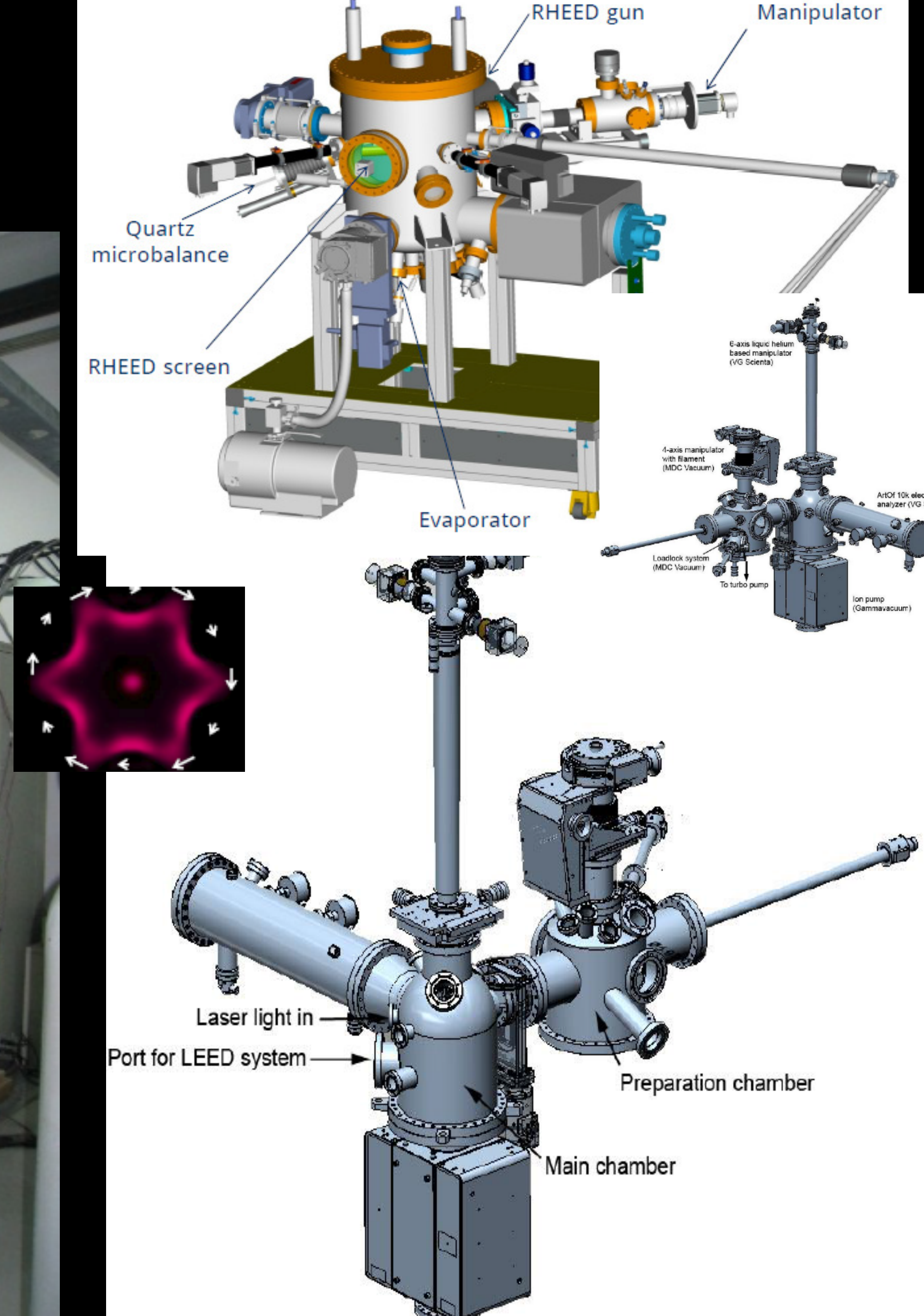




S. Xu, C. Liu et.al., (MZH) Nature Phys (2014)

MBE-STM (+ HR ARPES)
Under construction

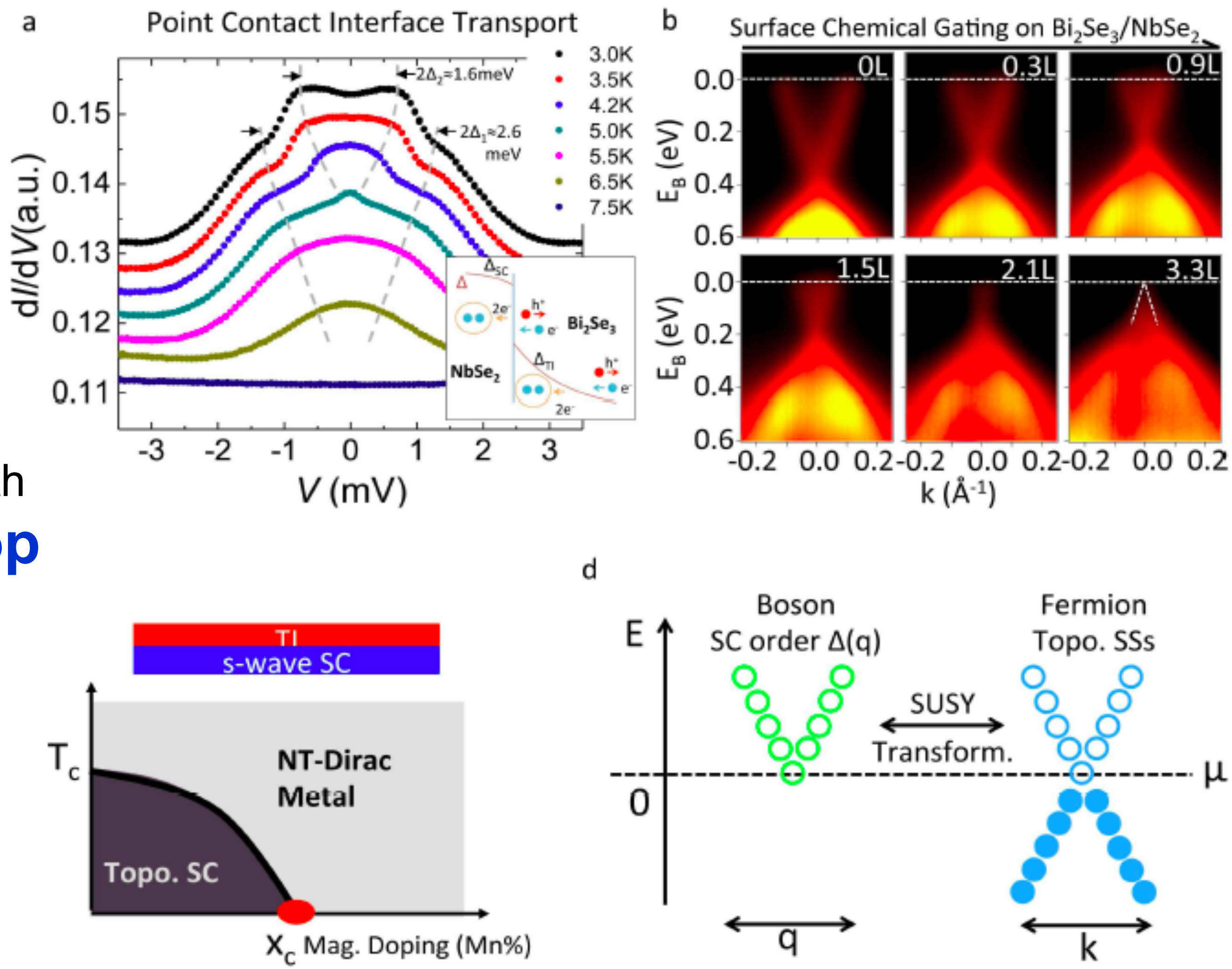




Samples can be driven near a Critical Point

(Emergent SuperSymmetry in theory)

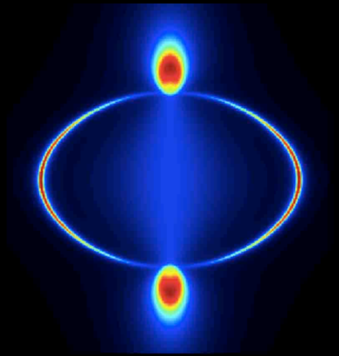
see prediction by Grover, Vishwanath et.al., Science'14



ARPES ⟷ Growth

Feedback Loop

S. Xu, et.al., (MZH) Nature Phys (2014)

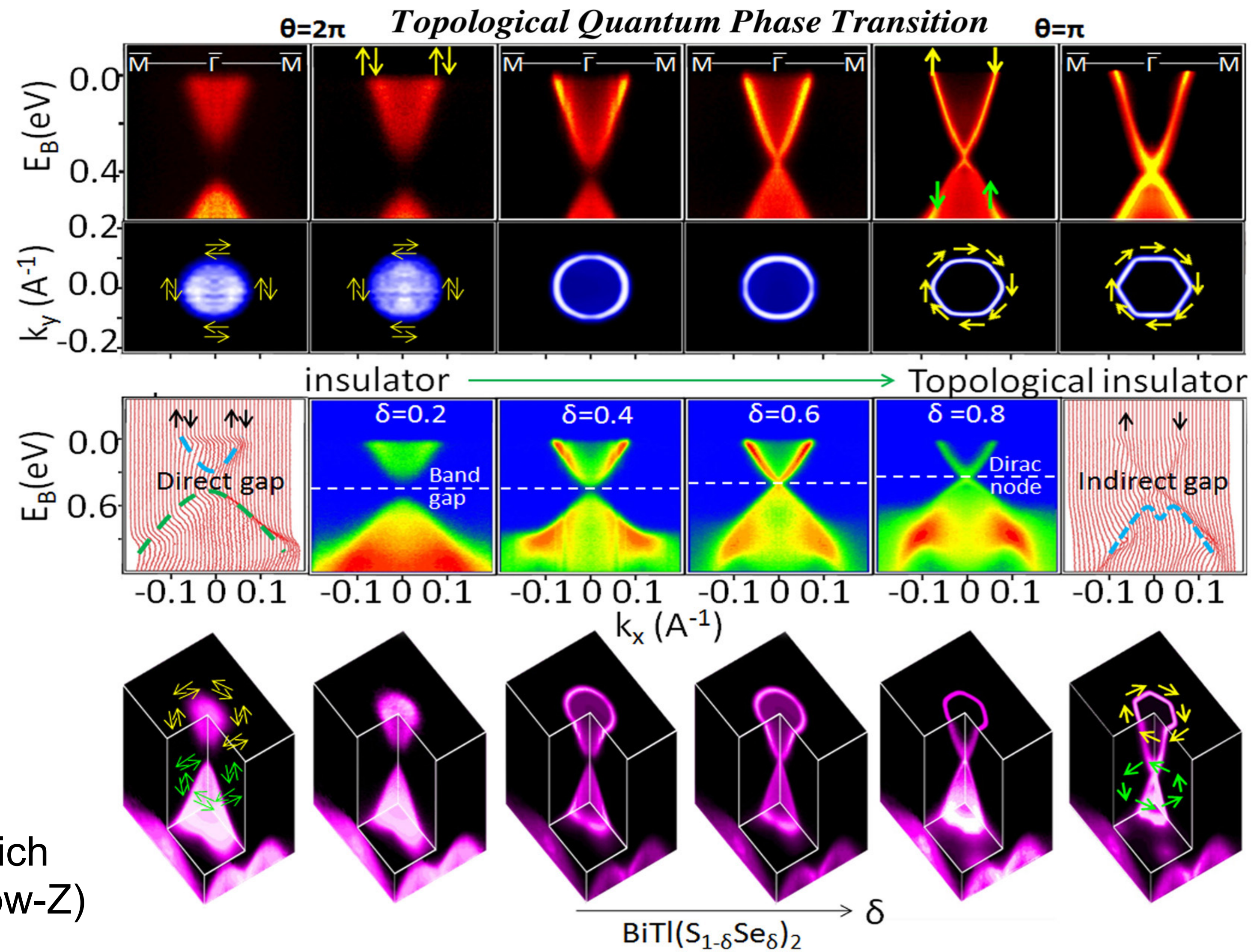


Can gapless systs be topological?

bulk Gapless *but* protected surface sates

3+1 D

Imaging a Topo. Insulator being born out of a Bloch Insulator as SOC is tuned



S rich (Low-Z)

Se rich (High-Z)

S.Y. Xu, Y. Xia, L. Wray *et.al.*, (MZH) Science '11

Elektron und Gravitation. I.

Von **Hermann Weyl** in Princeton, N. J.

(Eingegangen am 8. Mai 1929).

Einleitung. Verhältnis der allgemeinen Relativitätstheorie zu den quantentheoretischen Feldgleichungen des spinnenden Elektrons: Masse, Eichinvarianz, Fernparallelismus. Zu erwartende Modifikationen der Diracschen Theorie. —

, 1937 PHYSICAL REVIEW VOLUM

first Solid-State Weyl

Accidental Degeneracy in the Energy Bands of Crystals

Conyers Herring
Princeton University, Princeton, New Jersey

(Received June 16, 1937)

$$N_3 = \frac{1}{8\pi} e_{ijk} \int dS^i \, \hat{g} \cdot (\partial^j \hat{g} \times \partial^k \hat{g})$$

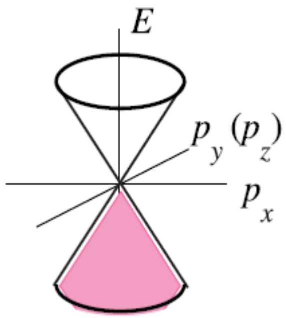
over 2D surface
around Fermi point

Topological classification (Volovik, Wan et.al., others…

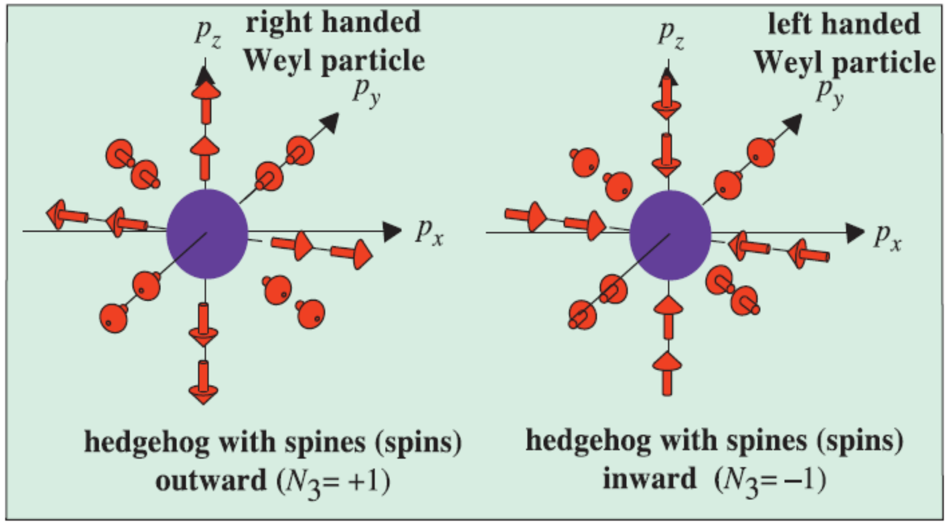
The circumstances are investigated under which two wave functions occurring in the Hartree r Fock solution for a crystal can have the same reduced wave vector and the same energy. It found that coincidence of the energies of wave functions with the same symmetry properties, well as those with different symmetries, is often to be expected. Some qualitative features

Weyl Fermions and Topo. Invariants

Weyl particles in Standard Model - hedgehogs in p-space



Weyl point:
conical (diabolical)
crossing point
in fermionic spectrum
in momentum space



$H = +c\,\sigma \cdot \mathbf{p}$
$\mathbf{g}(\mathbf{p}) = +c\mathbf{p}$

$$H = \sigma \cdot \mathbf{g}(\mathbf{p})$$

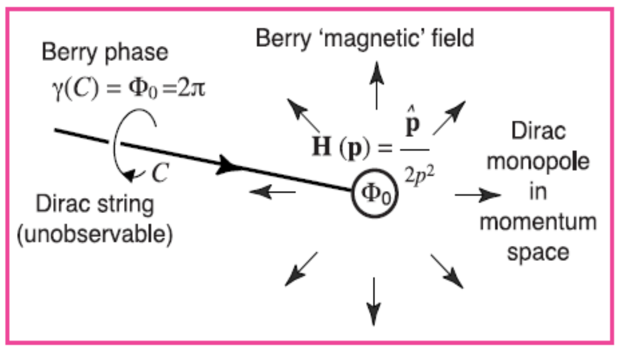
$H = -c\,\sigma \cdot \mathbf{p}$
$\mathbf{g}(\mathbf{p}) = -c\mathbf{p}$

All 3 Pauli Matrices
are used up in 3D
So gap opening is
not possible

$$N_3 = \frac{1}{8\pi}\, e_{ijk} \int dS^i\, \hat{\mathbf{g}} \cdot (\partial^j \hat{\mathbf{g}} \times \partial^k \hat{\mathbf{g}})$$

over 2D surface
around Fermi point

p-space topological invariant
for Weyl particles



Weyl point: Berry-Dirac monopole in p-space

Weyl (1929), Herring (1937), Nielsen-Ninomiya (1980s), Volovik (1987, 2003);

Weyl fermion in materials

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

Solid State quasiparticle Weyl

… in Crystals/SSP (1937-):
C. Herring (1937) [Princeton Univ.]
Abrikosov & Benelyavsky (1971)
Nielsen-Ninomiya (1983)
Volovik (2003)

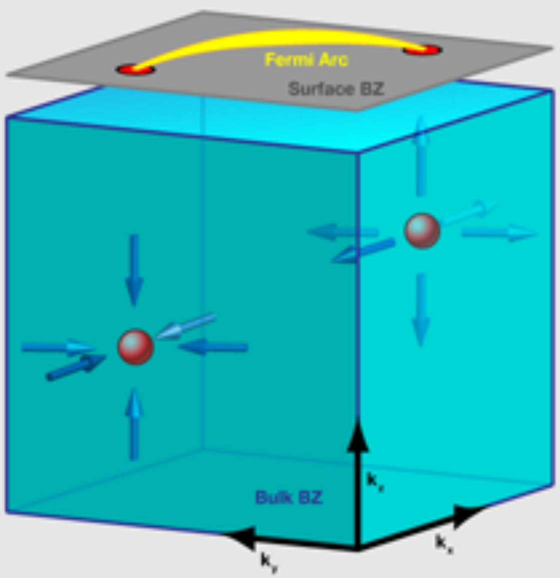
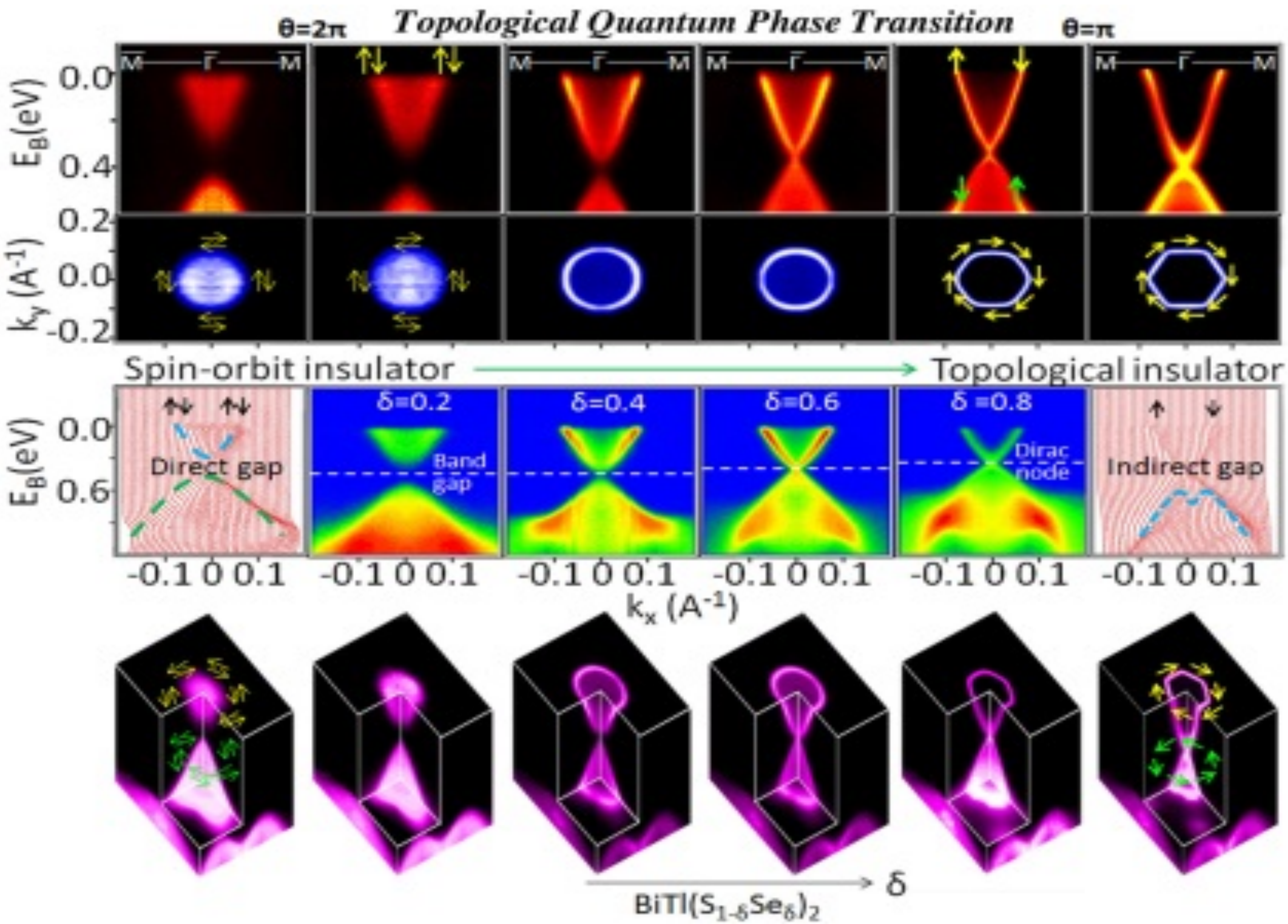


Image: Burkov & Balents *(2011)*

Murakami (2007), **Topo. Insulator connection…**
Wan, Turner, Vishwanath, Savrasov 2011 PRB
Y. Ran's group (boston) 2011 PRB
Iridate – spc. magnetic order etc.
Burkov, Balents et.al., 2011 PRL
TI/NI multilayers – fine tuning, magnetic order
Fang, Dai (also magnetic Hg-Cr-Se) 2012
Many more proposals on **magnetic compounds by many groups but all *T*-breaking**
But
no expt'l realization of these predictions

Early on I was interested in *I*-breaking Weyl
Singh et.al. (Lin, MZH & Bansil), **PRB 2012**

Xu et.al., Science (2011)



Wray: to magnetize the Dirac critical point

Neupane & Sankar: to magnetize Bi-Sb, Cd-As

Suyang Xu & Ilya: to search in the database to find I-broken materials

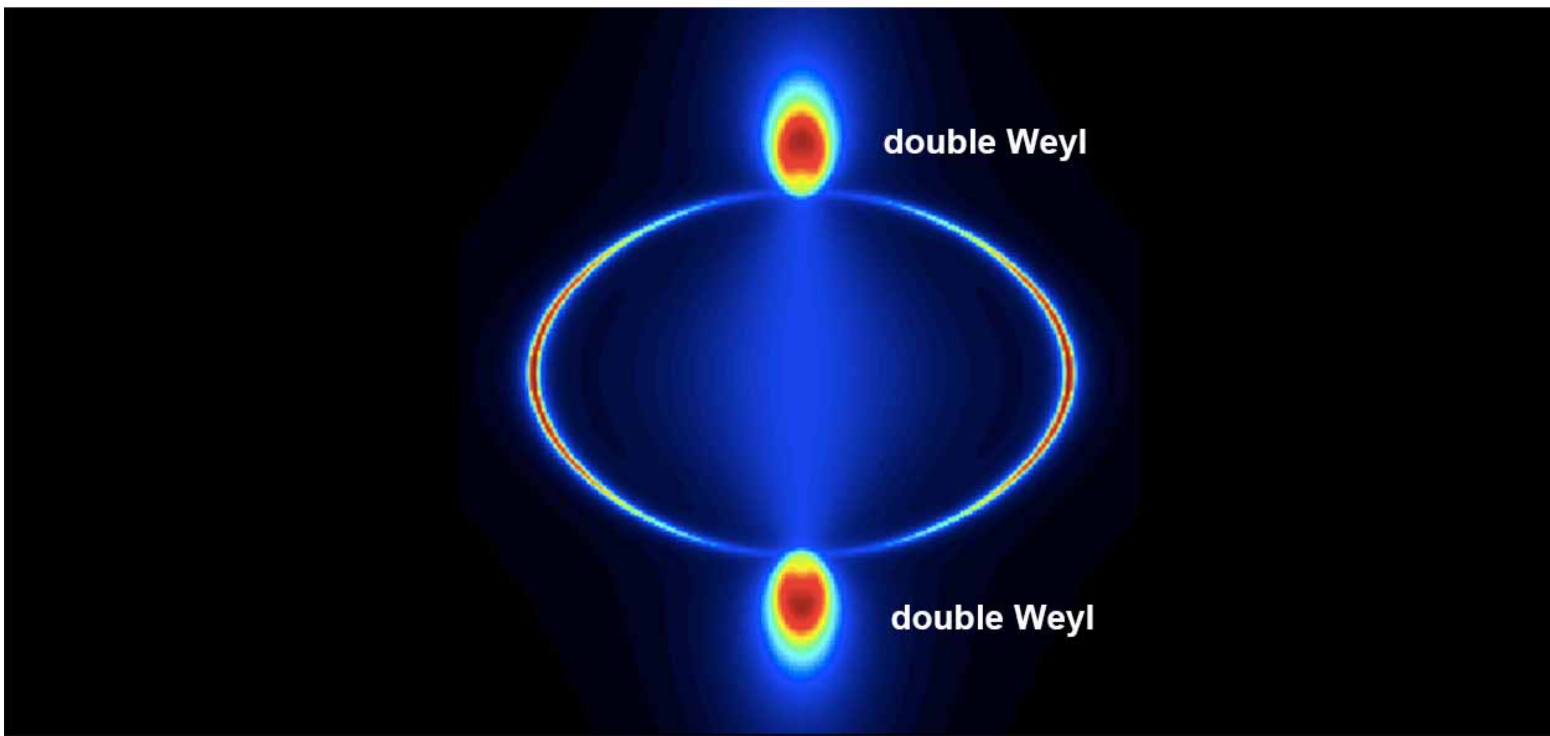
Science express

Reports

Observation of Fermi arc surface states in a topological metal

Publication date: December 18, 2014

Su-Yang Xu,[1,2*] Chang Liu,[1*] Satya K. Kushwaha,[3] Raman Sankar,[4] Jason W. Krizan,[3] Ilya Belopolski,[1] Madhab Neupan,e[1] Guang Bian,[1] Nasser Alidoust,[1] Tay-Rong Chang,[5] Horng-Tay Jeng,[5,6] Cheng-Yi Huang,[7] Wei-Feng Tsai,[7] Hsin Lin,[8] Pavel P. Shibayev,[1] Fangcheng Chou,[4] Robert J. Cava,[3] M. Zahid Hasan[1,2]†



Searching for compounds

Results: List View — # of Hits: 882

Select All | Deselect All | Show Detailed View | Show Synoptic View | Export Selected Data | Back to Query

Coll. Code	HMS	Struct. Form.	Struct. Type	Title	Authors	Reference
22347	P 1 21 1	Li2 (S O4) (H2 O)	Li2SO4H2O	Crystal structure of the monohydrate of lithium sulfate, Li2 S O4 H2 O	Rannev, N.V.; Datt, I.D.; Tovbis, A.B.; Ozerov, R.P.	Kristallografiya (1965) 10, p914-p915
23017	P 1 1 21	Li4 Zn (P O4)2		Crystal structure of lithium zinc orthophosphate Li4 Zn (P O4)2	Sandomirskii, P.A.; Simonov, M.A.; Belov, N.V.	Doklady Akademii Nauk SSSR (1976) 228, p344-p347
23021	P 1 1 21	Na.55 Cd2.45 P2 O7.45 (O H).55		Crystal Structure of Na, Cd- Phosphate Na1-x, Cdx Cd2 (P O4) (P O3+x (O H)1-x)	Ivanov, Yu.A.; Simonov, M.A.; Belov, N.V.	Doklady Akademii Nauk SSSR (1976) 228, p600-p602
23022	P 1 1 2	Ba3 Ge9 O20 (O H)2		Crystal Structure of Ba3 Ge9 O20 (O H)2	Malinovskii, Yu.A.; Pobedimskaya, E.A.; Belov, N.V.	Doklady Akademii Nauk SSSR (1976) 227, p1350-p1353
23150	P 1 21 1	H Br (H2 O)4		Hydrogen-Bond Studies. XXX. The Crystal Structure of Hydrogen Bromide Tetrahydrate, (H7O3)+ (H9O4)+ 2Br- .(H2O) (H2 O)	Lundgren, J.O.; Olovsson, I.	Journal of Chemical Physics (1968) 49, p1068-p1074
23841	P 1 21 1	P4 S5	P4S5	Refinement of the crystal structures of some phosphorus sulphides	Vos, A.; Olthof, R.; van Bolhuis, F.; Botterweg, R.	Acta Crystallographica (1,1948-23,1967) (1965) 19, p864-p867
23974	P 1 21 1	S3 N2 Cl2		The Crystal Structure of Chlorothiodiazyl Chloride, S3 N2 Cl2	Zalkin, A.; Hopkins, T.E.; Templeton, D.H.	Inorganic Chemistry (1966) 5, p1767-p1770
24848	P 1 21 1	N3 P3 Cl4 (Fe (C O)4)2		Synthesis of a Di-iron-spirocyclotriphosphazen and a Tri-iron-cluster-cyclotriphosphazene	Suszko, P.R.; Whittle, R.R.; Allcock, H.R.	Journal of the Chemical Society. Chemical Communications (1972-) (1982) 1982, p1344-p1344
25702	P 1 21 1	N H4 (P O S (N H2)2)		Die Kristallstruktur von Ammonium-diamidothiophosphat	Mootz, D.; Look, W.; Sassmannshauser G.	Zeitschrift fuer Anorganische und Allgemeine Chemie (1950) (DE) (1968) 358, p282-p295
26010	P 1 1 21	Ca2 (Nb2 O7)	La2Ti2O7(mP44	Compounds with perovskite-type slabs. III. The structure of a monoclinic modification of Ca2 Nb2 O7	Ishizawa, N.; Marumo, F.; Iwai, S.I.; Kimura, M.; Kawamura, T.	Acta Crystallographica B (24,1968-38,1982) (1980) 36, p763-p766

[FirstPage] [11-20] [21-30] [31-40] [41-50] **[51-60]** [61-70] [71-80] [81-90] [91-100] [LastPage]

Challenges in finding an I-breaking Weyl semimetal

- **>1000** I-breaking compounds entries (based on crystallographic library).
- **So many compounds have negative MR, transport does not help!!**
- **Weyl nodes at arbitrary *k* points**
- **Where is the Fermi level ?**
- **What is the cleaved surface potential?**
- **How to separate surface and bulk?**

Calculation/Prediction can <u>NOT</u> tell us that it will work

Experimentally! So many people predicted so many Weyl compounds

Searching for compounds

Results: List View # of Hits: 882

Select All | Deselect All | Show Detailed View | Show Synoptic View | Export Selected Data | Back to Query

Coll. Code	HMS	Struct. Form.	Struct. Type	Title	Authors	Reference
22347	P 1 21 1	Li2 (S O4) (H2 O)	Li2SO4H2O	Crystal structure of the monohydrate of lithium sulfate, Li2 S O4 H2 O	Rannev, N.V.; Datt, I.D.; Tovbis, A.B.; Ozerov, R.P.	Kristallografiya (1965) 10, p914-p915
23017	P 1 1 21	Li4 Zn (P O4)2		Crystal structure of lithium zinc orthophosphate Li4 Zn (P O4)2	Sandomirskii, P.A.; Simonov, M.A.; Belov, N.V.	Doklady Akademii Nauk SSSR (1976) 228, p344-p347
23021	P 1 1 21	Na.55 Cd2.45 P2 O7.45 (O H).55		Crystal Structure of Na, Cd- Phosphate Na1-x, Cdx Cd2 (P O4) (P O3+x (O H)1-x)	Ivanov, Yu.A.; Simonov, M.A.; Belov, N.V.	Doklady Akademii Nauk SSSR (1976) 228, p600-p602
23022	P 1 1 2	Ba3 Ge9 O20 (O H)2		Crystal Structure of Ba3 Ge9 O20 (O H)2	Malinovskii, Yu.A.; Pobedimskaya, E.A.; Belov, N.V.	Doklady Akademii Nauk SSSR (1976) 227, p1350-p1353
23150	P 1 21 1	H Br (H2 O)4		Hydrogen-Bond Studies. XXX. The Crystal Structure of Hydrogen Bromide Tetrahydrate, (H7O3)+ (H9O4)+ 2Br- .(H2O) (H2 O)	Lundgren, J.O.; Olovsson, I.	Journal of Chemical Physics (1968) 49, p1068-p1074
23841	P 1 21 1	P4 S5	P4S5	Refinement of the crystal structures of some phosphorus sulphides	Vos, A.; Olthof, R.; van Bolhuis, F.; Botterweg, R.	Acta Crystallographica (1,1948-23,1967) (1965) 19, p864-p867
23974	P 1 21 1	S3 N2 Cl2		The Crystal Structure of Chlorothiodiazyl Chloride, S3 N2 Cl2	Zalkin, A.; Hopkins, T.E.; Templeton, D.H.	Inorganic Chemistry (1966) 5, p1767-p1770
24848	P 1 21 1	N3 P3 Cl4 (Fe (C O)4)2		Synthesis of a Di-iron-spirocyclotriphosphazen and a Tri-iron-cluster-cyclotriphosphazene	Suszko, P.R.; Whittle, R.R.; Allcock, H.R.	Journal of the Chemical Society. Chemical Communications (1972-) (1982) 1982, p1344-p1344
25702	P 1 21 1	N H4 (P O S (N H2)2)		Die Kristallstruktur von Ammonium-diamidothiophosphat	Mootz, D.; Look, W.; Sassmannshauser G.	Zeitschrift fuer Anorganische und Allgemeine Chemie (1950) (DE) (1968) 358, p282-p295
26010	P 1 1 21	Ca2 (Nb2 O7)	La2Ti2O7(mP44	Compounds with perovskite-type slabs. III. The structure of a monoclinic modification of Ca2 Nb2 O7	Ishizawa, N.; Marumo, F.; Iwai, S.I.; Kimura, M.; Kawamura, T.	Acta Crystallographica B (24,1968-38,1982) (1980) 36, p763-p766

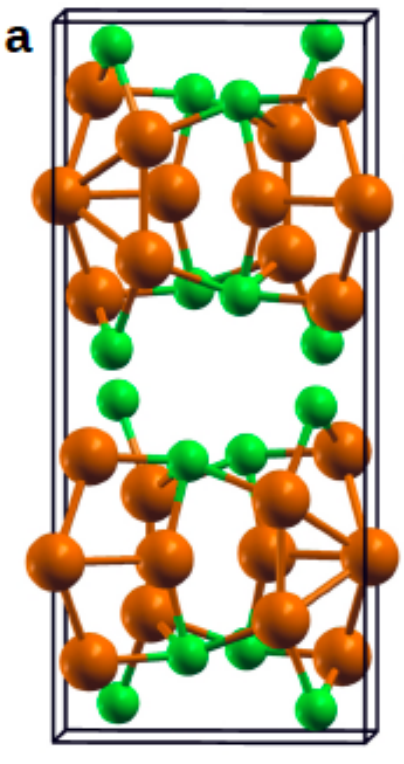
[FirstPage] [11-20] [21-30] [31-40] [41-50] **[51-60]** [61-70] [71-80] [81-90] [91-100] [LastPage]

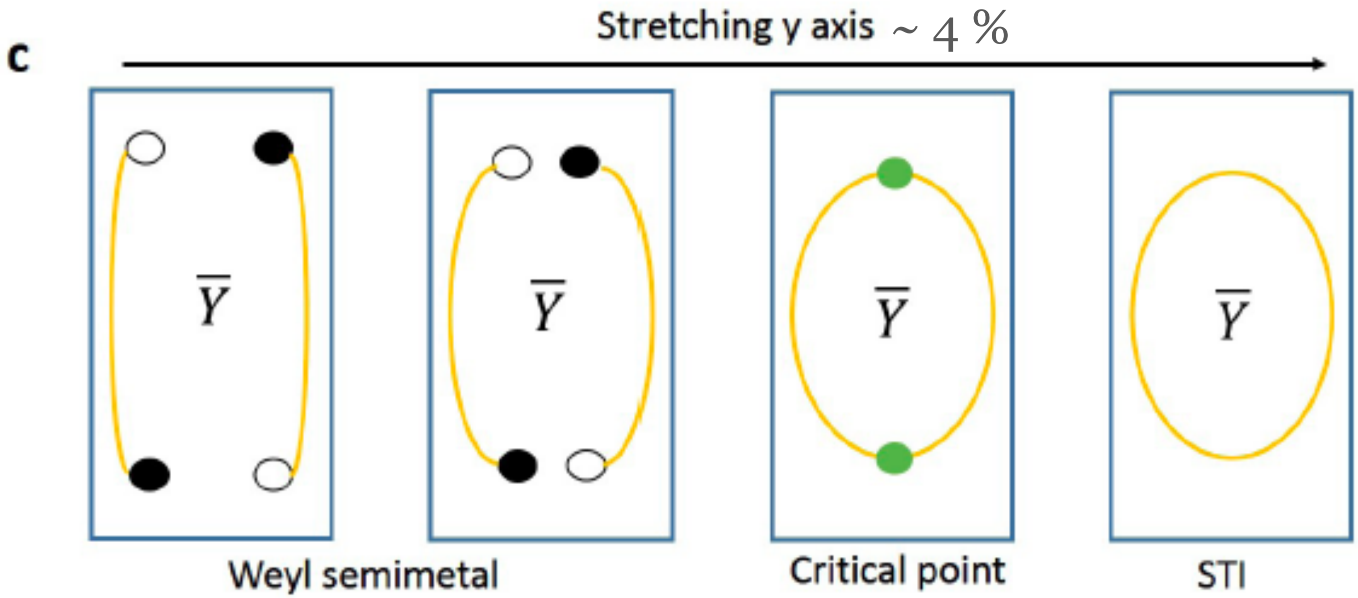
Conducted by Suyang Xu & Ilya Belopolski

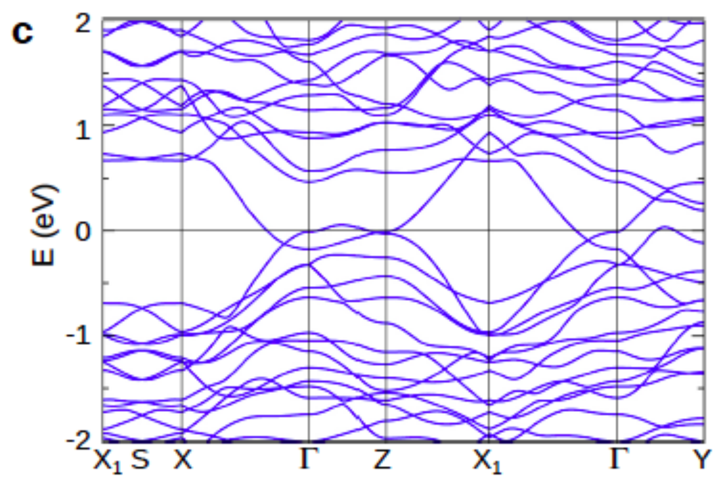
We found the TaAs, Ta3S2, Ta-Se-I class

Ta_3S_2 – Topo. Weyl to Insulator Transition

G. Chang*, **S.-Y. Xu*** *et al. http://arxiv.org/abs/1512.08781* (2015)







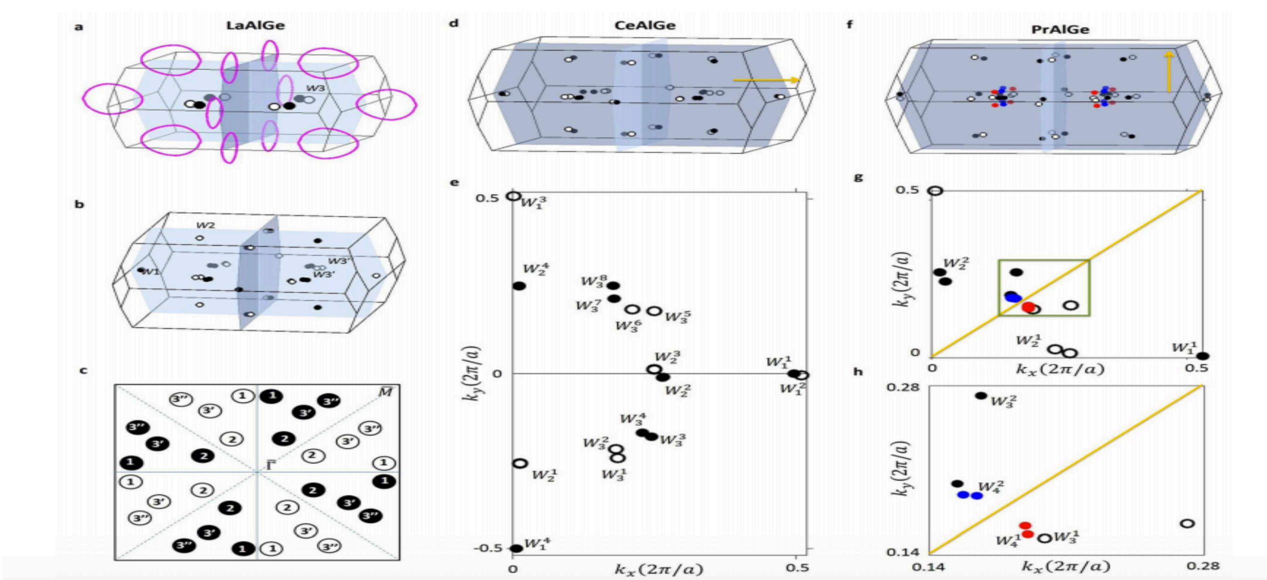
Theoretical Prediction

Theoretical prediction of magnetic and noncentrosymmetric Weyl fermion semimetal states in the R–Al–X family of compounds (R=rare earth, Al=aluminium, X=Si, Ge)

Guoqing Chang, Bahadur Singh, Su-Yang Xu, Guang Bian, Shin-Ming Huang, Chuang-Han Hsu, Ilya Belopolski, Nasser Alidoust, Daniel S. Sanchez, Hao Zheng, Hong Lu, Xiao Zhang, Yi Bian, Tay-Rong Chang, Horng-Tay Jeng, Arun Bansil, Han Hsu, Shuang Jia, Titus Neupert, Hsin Lin, M. Zahid Hasan

(Submitted on 7 Apr 2016 (v1), last revised 12 Apr 2016 (this version, v3))

Weyl semimetals are novel topological conductors that host Weyl fermions as emergent quasiparticles. While the Weyl fermions in high-energy physics are strictly defined as the massless solution of the Dirac equation and uniquely fixed by Lorentz symmetry, there is no such constraint for a topological metal in general. Specifically, the Weyl quasiparticles can arise by breaking either the space-inversion ($\mathcal{I}$) or time-reversal ($\mathcal{T}$) symmetry. They can either respect Lorentz symmetry (type-I) or strongly violate it (type-II). To date, different types of Weyl fermions have been predicted to occur only in different classes of materials. In this paper, we present a significant materials breakthrough by identifying a large class of Weyl materials in the RAlX (R=Rare earth, Al, X=Ge, Si) family that can realize all different types of emergent Weyl fermions ($\mathcal{I}$-breaking, $\mathcal{T}$-breaking, type-I or type-II), depending on a suitable choice of the rare earth elements. Specifically, RAlX can be ferromagnetic, nonmagnetic or antiferromagnetic and the electronic band topology and topological nature of the Weyl fermions can be tuned. The unparalleled tunability and the large number of compounds make the RAlX family of compounds a unique Weyl semimetal class for exploring the wide-ranging topological phenomena associated with different types of emergent Weyl fermions in transport, spectroscopic and device-based experiments.



Some examples of Weyl materials candidates :

$SrSi_2$: Huang, S.-Y. Xu, Belopolski *et al*. *PNAS* ***113***, *1180 (2015)*

(Quadratic double Weyl)

Ta_3S_2: *Chang, Xu,* Belopolski *et.al., http://arxiv.org/abs/1512.08781* (2015)

(Type II Weyl)

Co_2TiX (X=Si, Ge, and Sn):

Chang, Xu, Belopolski et.al, http://arxiv.org/abs/1603.01255 (Magnetic Weyl)

$Mo_xW_{1-x}Te/Se_2$: Chang, Xu, Belopolski et.al., *Nature Commun*. **7**, 10639 (2016)

More theoretical predictions forthcoming from our group..

Searching for inversion-symm. breaking WSM

TaAs FP: Huang, S. Xu,(Lin & MZH) **Nat. Commun. 2015 (subm. Nov 2014)**

See also: FP: Weng et al., (Fang, IOP group) **PRX 2015 (subm. Jan 2015)**

nature COMMUNICATIONS

Similar cases: ZrTe, Ag2Se

Ta = $5d^3 6s^2$	Zr = $4d^2 5s^2$	Ag = $4d^{10} 5s^1$
As = $4s^2 4p^3$	Te = $5s^2 5p^4$	Se = $4s^2 4p^4$

(November 2014)

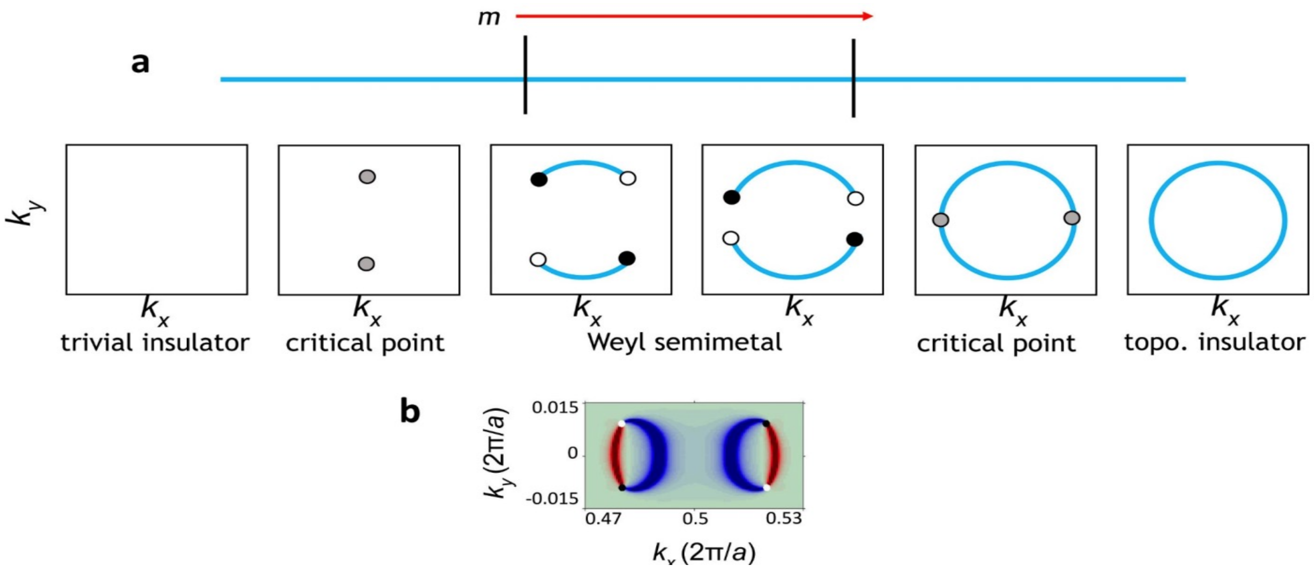
ARTICLE

Received 24 Nov 2014 | Accepted 30 Apr 2015 | Published 12 Jun 2015

DOI: 10.1038/ncomms8373 OPEN

A Weyl Fermion semimetal with surface Fermi arcs in the transition metal monopnictide TaAs class

Shin-Ming Huang[1,2,*], Su-Yang Xu[3,4,*], Ilya Belopolski[3,4,*], Chi-Cheng Lee[1,2], Guoqing Chang[1,2], BaoKai Wang[1,2,5], Nasser Alidoust[3,4], Guang Bian[3], Madhab Neupane[3,4,6], Chenglong Zhang[7], Shuang Jia[7,8], Arun Bansil[5], Hsin Lin[1,2] & M. Zahid Hasan[3,4,9]



nature COMMUNICATIONS

November 2014

Materials algorithm for finding Weyl

ARTICLE

Received 24 Nov 2014 | Accepted 30 Apr 2015 | Published 12 Jun 2015

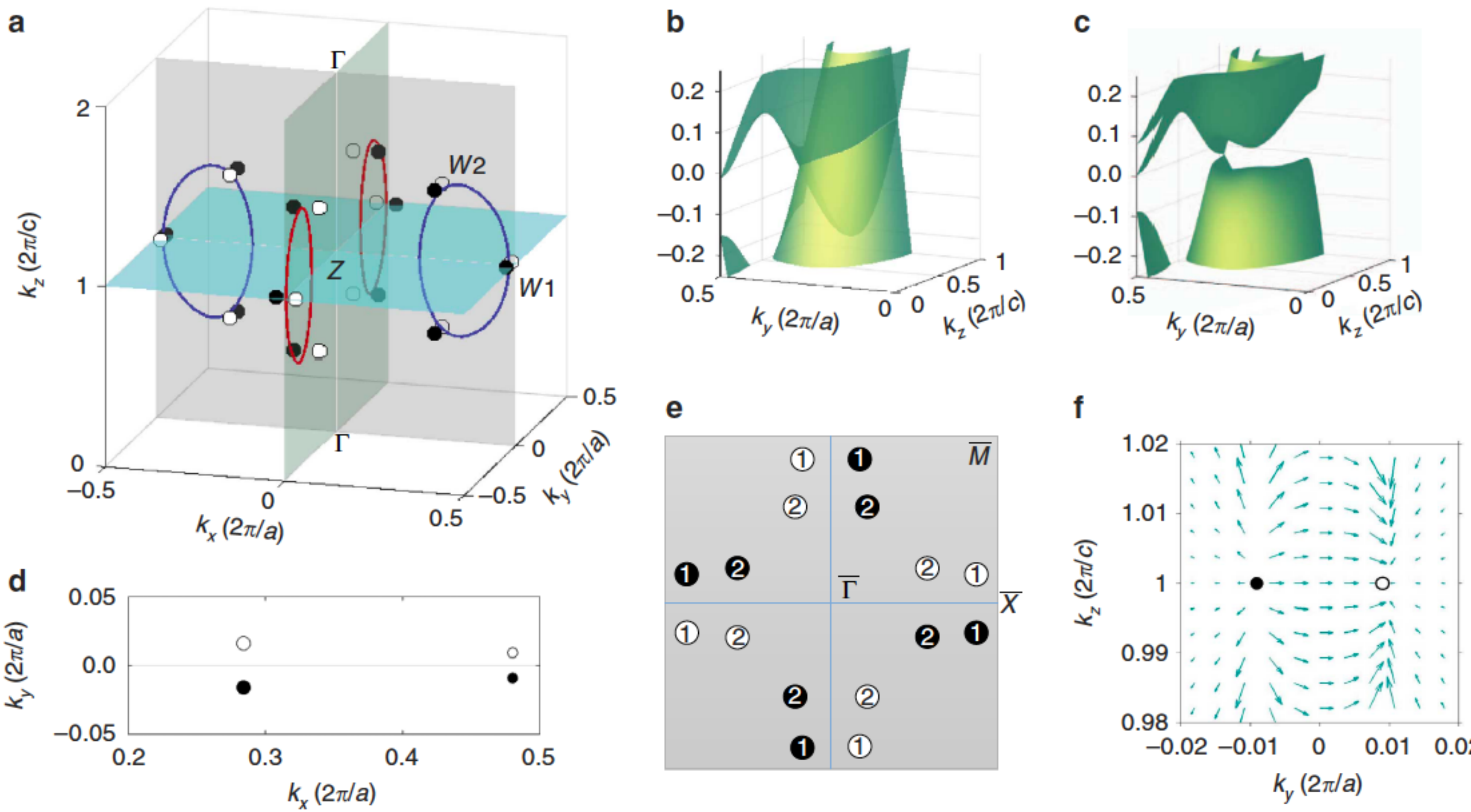
DOI: 10.1038/ncomms8373

OPEN

A Weyl Fermion semimetal with surface Fermi arcs in the transition metal monopnictide TaAs class

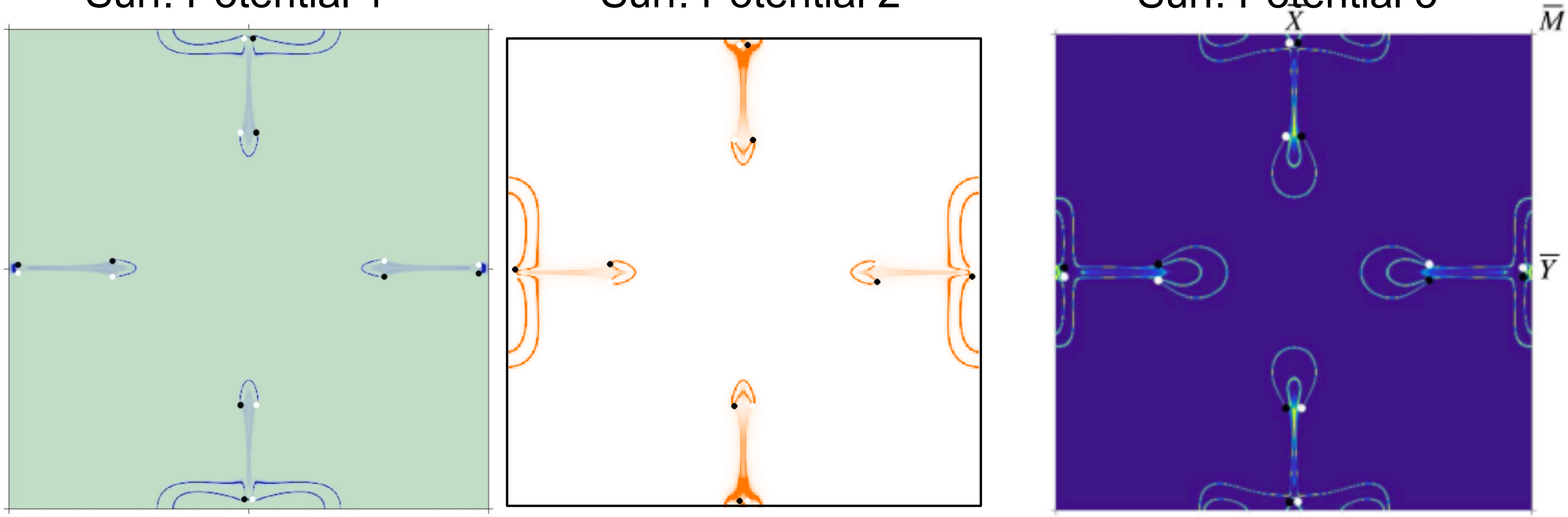
Shin-Ming Huang[1,2,*], Su-Yang Xu[3,4,*], Ilya Belopolski[3,4,*], Chi-Cheng Lee[1,2], Guoqing Chang[1,2], BaoKai Wang[1,2,5], Nasser Alidoust[3,4], Guang Bian[3], Madhab Neupane[3,4,6], Chenglong Zhang[7], Shuang Jia[7,8], Arun Bansil[5], Hsin Lin[1,2] & M. Zahid Hasan[3,4,9]

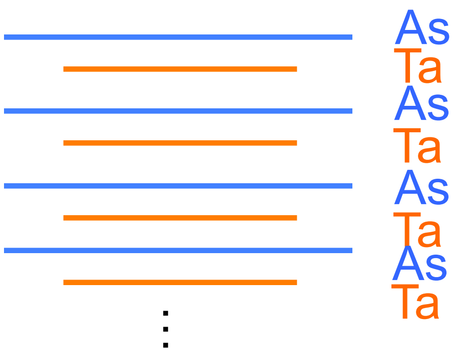
24 Weyl nodes in the bulk of TaAs, NbAs



Theory FIGURES from
S. Huang, Suyang Xu, Belopolski et.al., Nature Commun. 2015

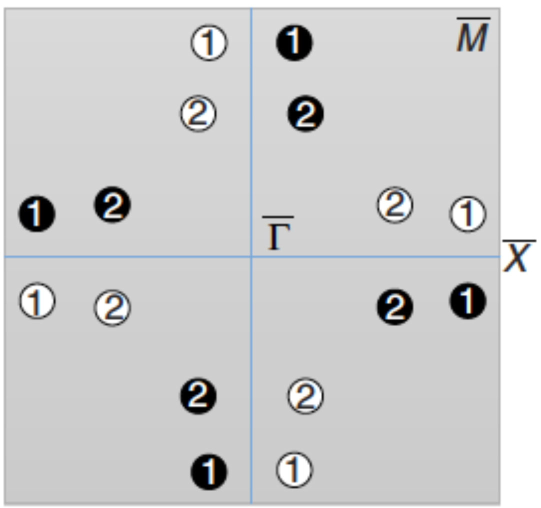
Surf. Potential 1 Surf. Potential 2 Surf. Potential 3



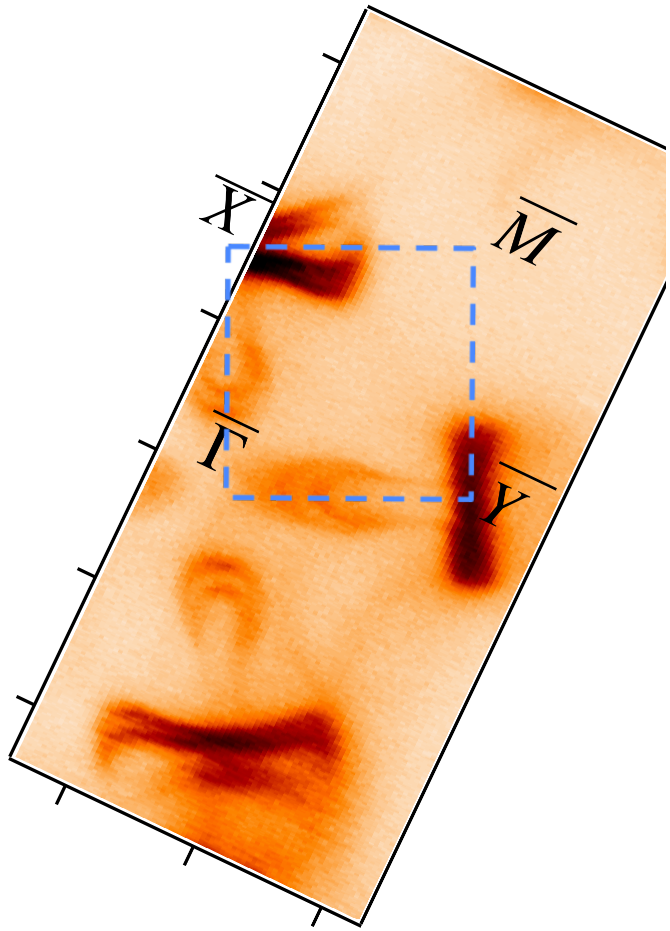


Ta 5*s* 5*d*, As 4*s*, 4*p*

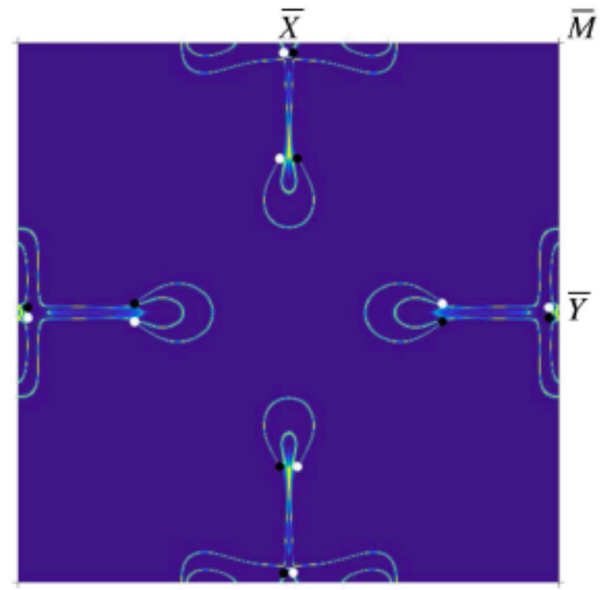
ARPES-1(low photon energies)



ARPES

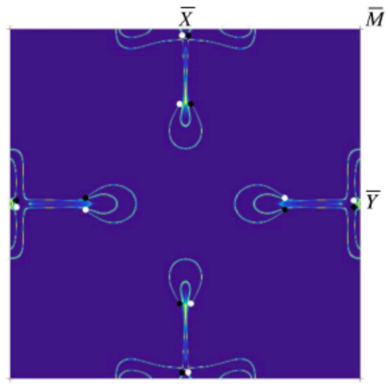


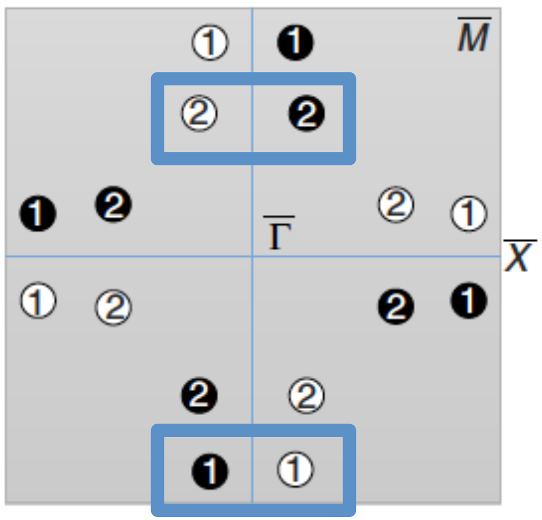
Calculation

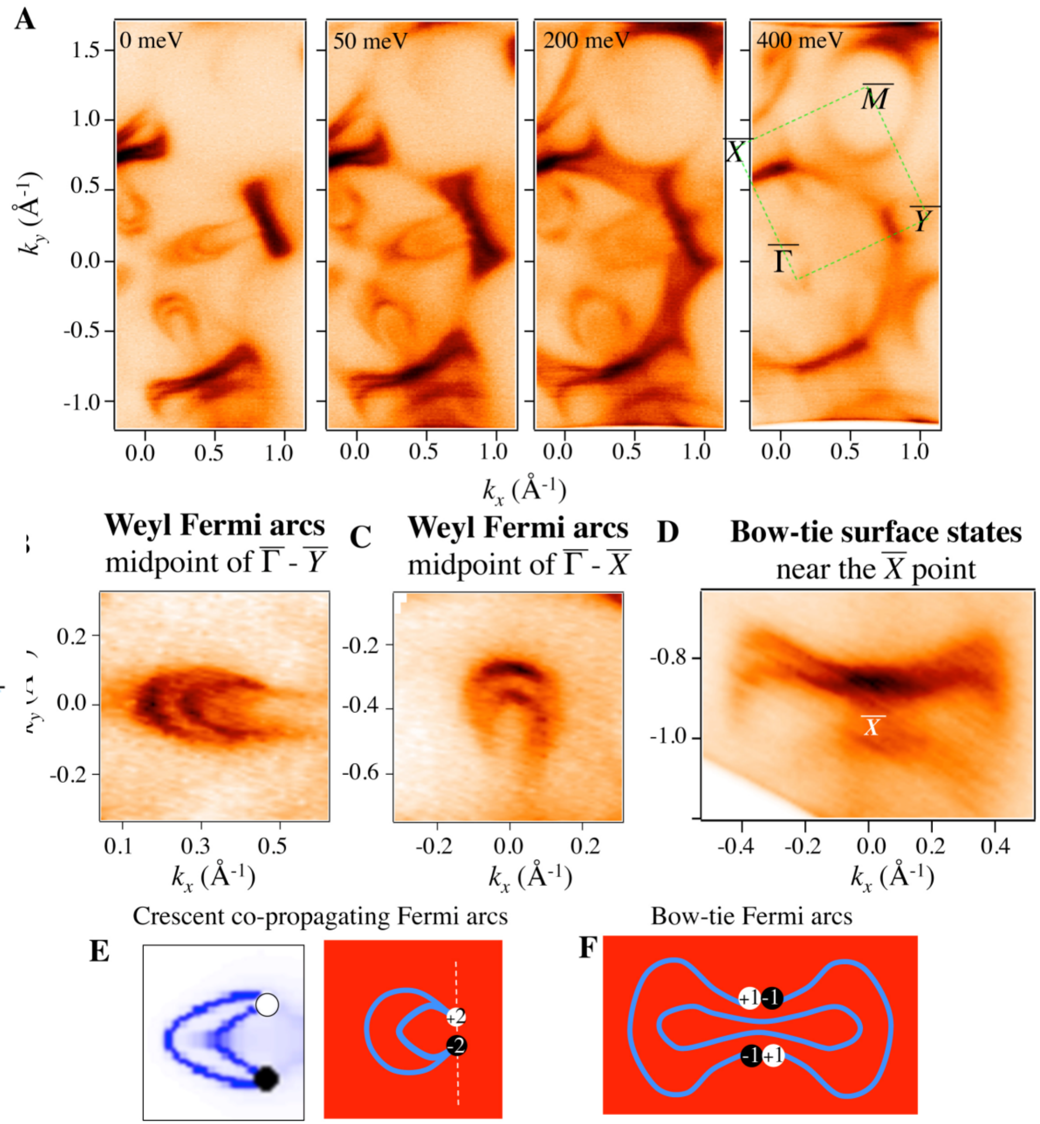


Weyl SM Data : Xu, Belopolski, et.al., Science, 349, 613 (2015)
Fermi arc Methods : Xu, Liu, Belopolski, et.al., Science, 347, 294 (2014) AOP

ARPES-1: Surface states





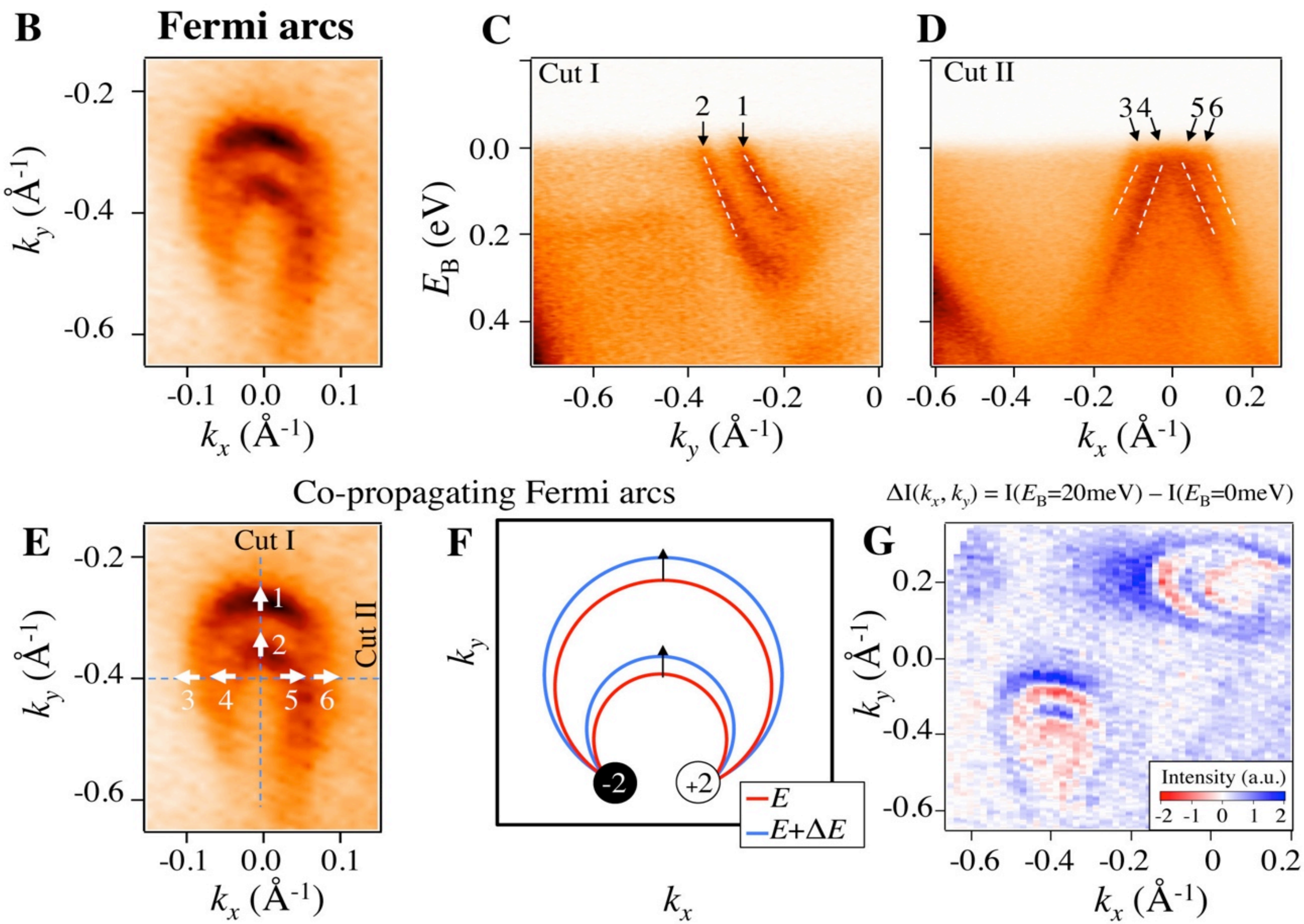


Weyl SM Data : Xu, Belopolski, et.al., Science, 349, 613 (2015)

Fermi arc Methods : Xu, Liu, Belopolski, et.al., Science, 347, 294 (2014) AOP

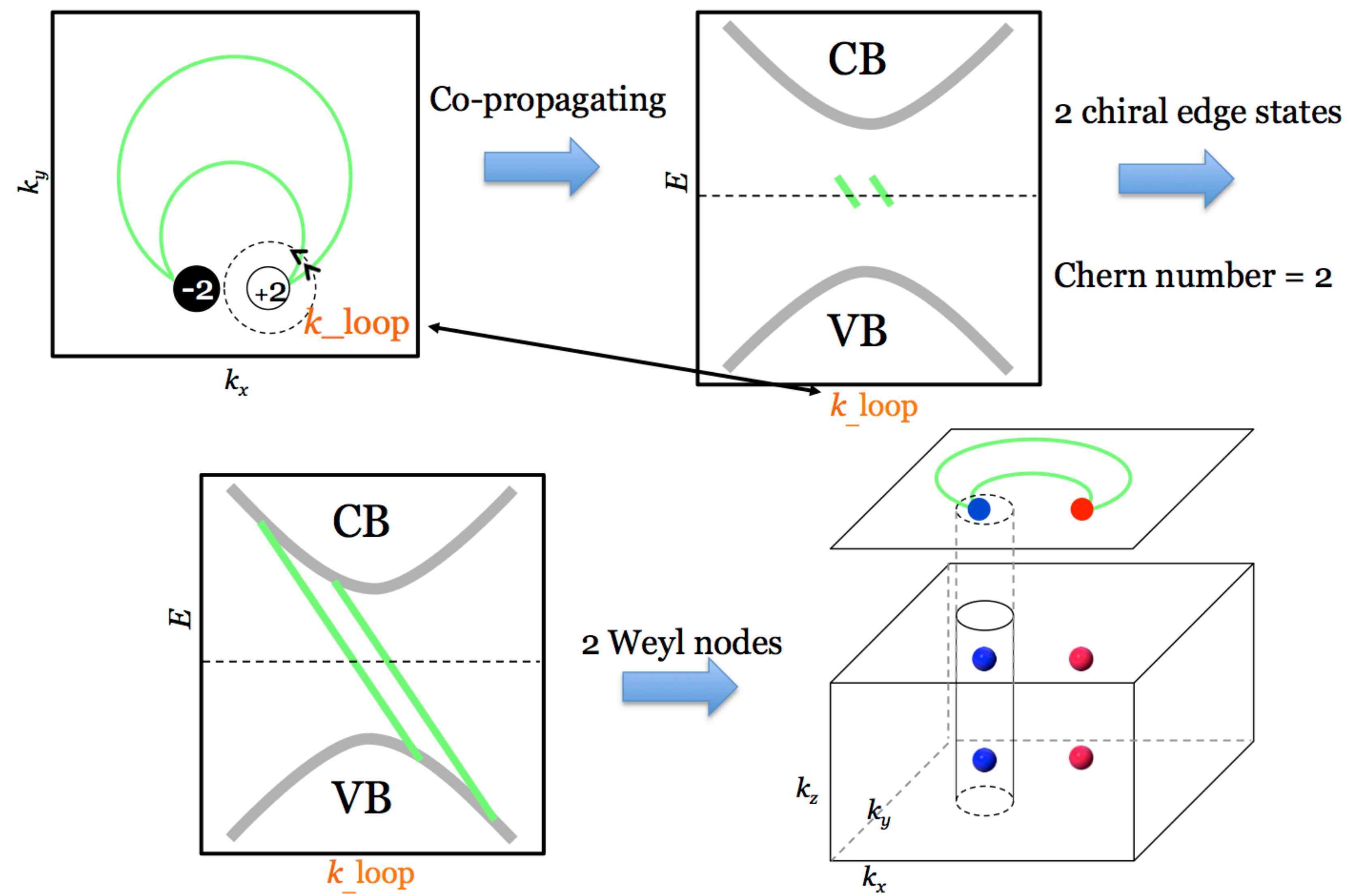
ARPES-1: Weyl Fermi surafces

Co-propagating



Weyl SM Data : Xu, Belopolski, et.al., Science, 349, 613 (2015)
Fermi arc Methods : Xu, Liu, Belopolski, et.al., Science, 347, 294 (2014) AOP

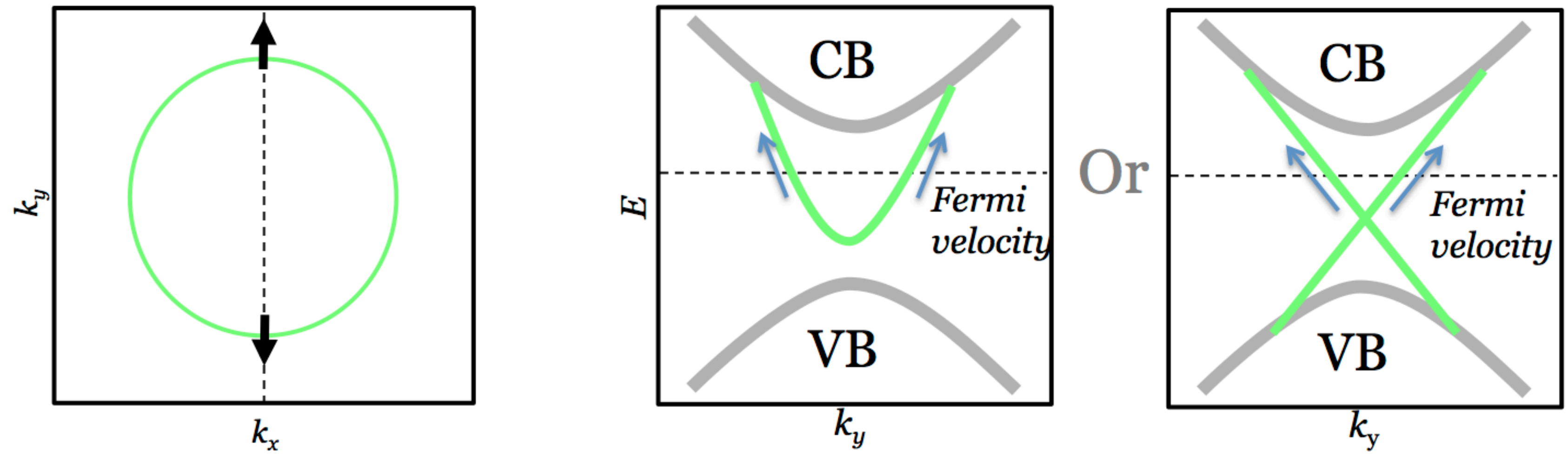
Weyl Fermi arcs – *Copropagating!*



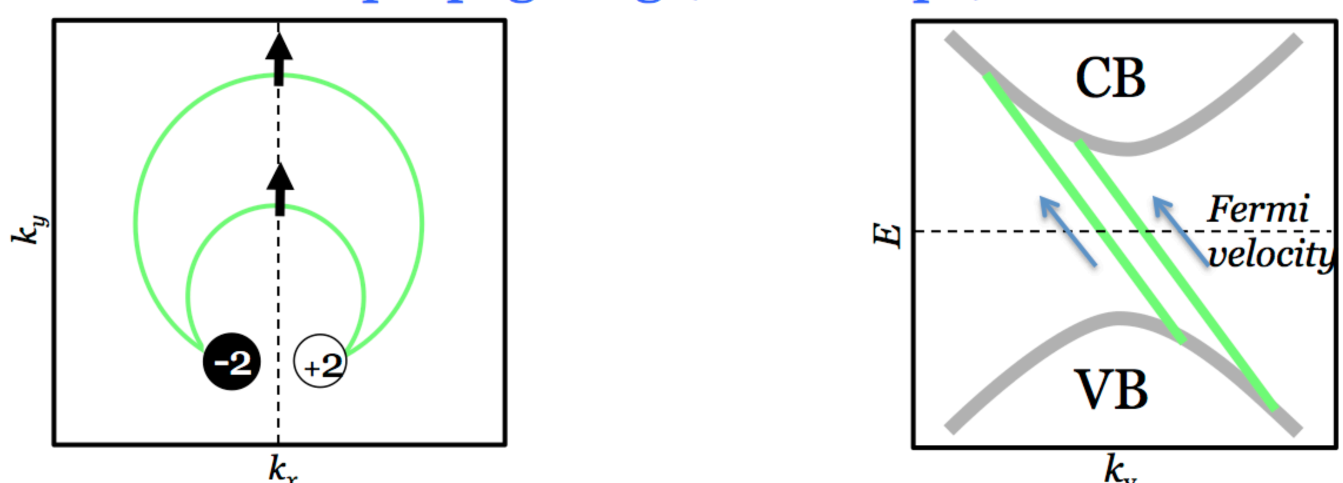
Weyl SM Data : Xu, Belopolski, et.al., Science, 349, 613 (2015)

Weyl Fermi arcs – *Copropagating!*

Counter-propagating (opposite slopes) ➡ Closed contour

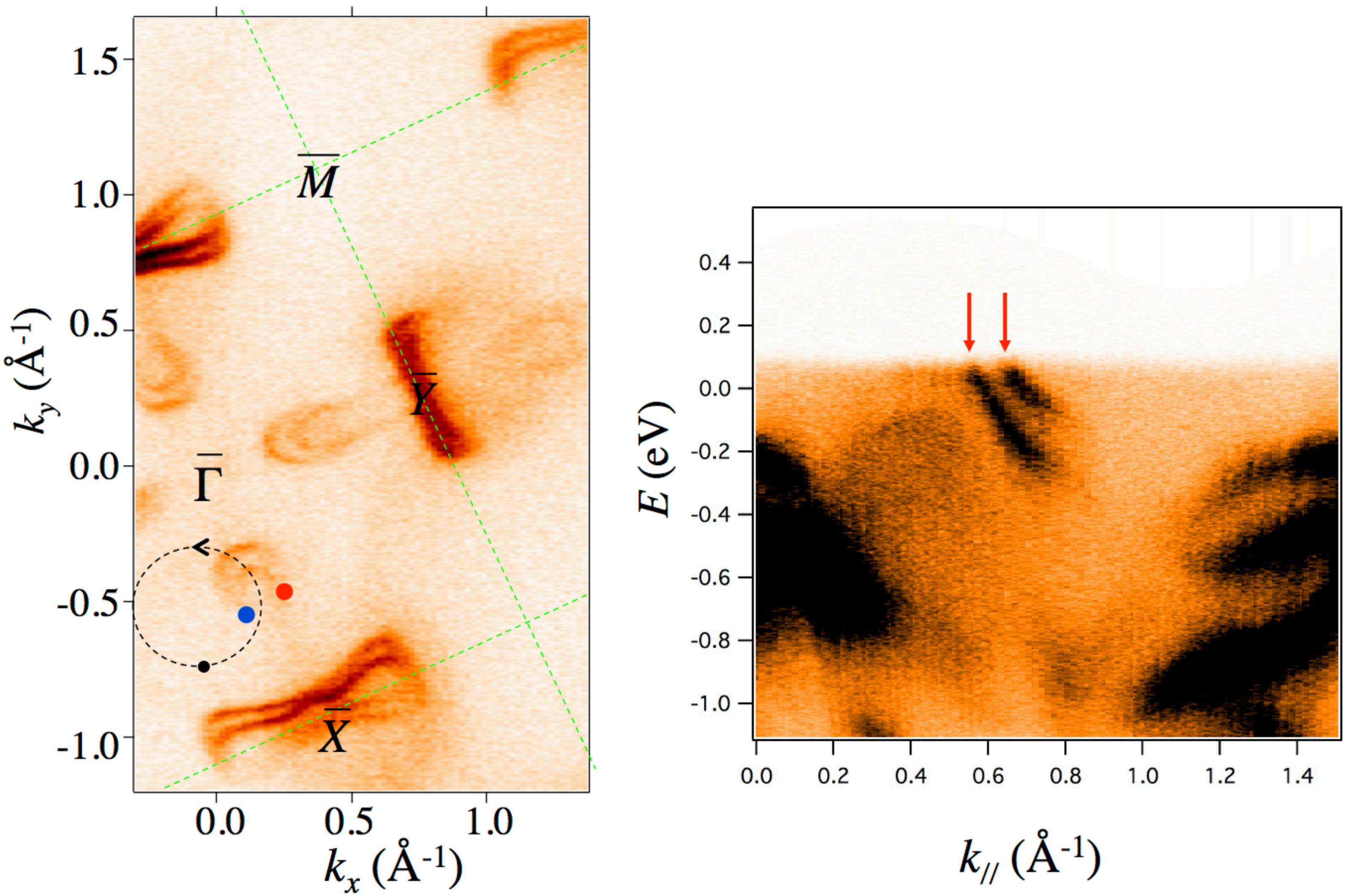


Co-propagating (same slope) ➡ Fermi arcs



Weyl SM Data : Xu, Belopolski, et.al., **Science, 349, 613 (2015)**
Fermi arc Methods : Xu, Liu, Belopolski, et.al., **Science, 347, 294 (2014)** AOP

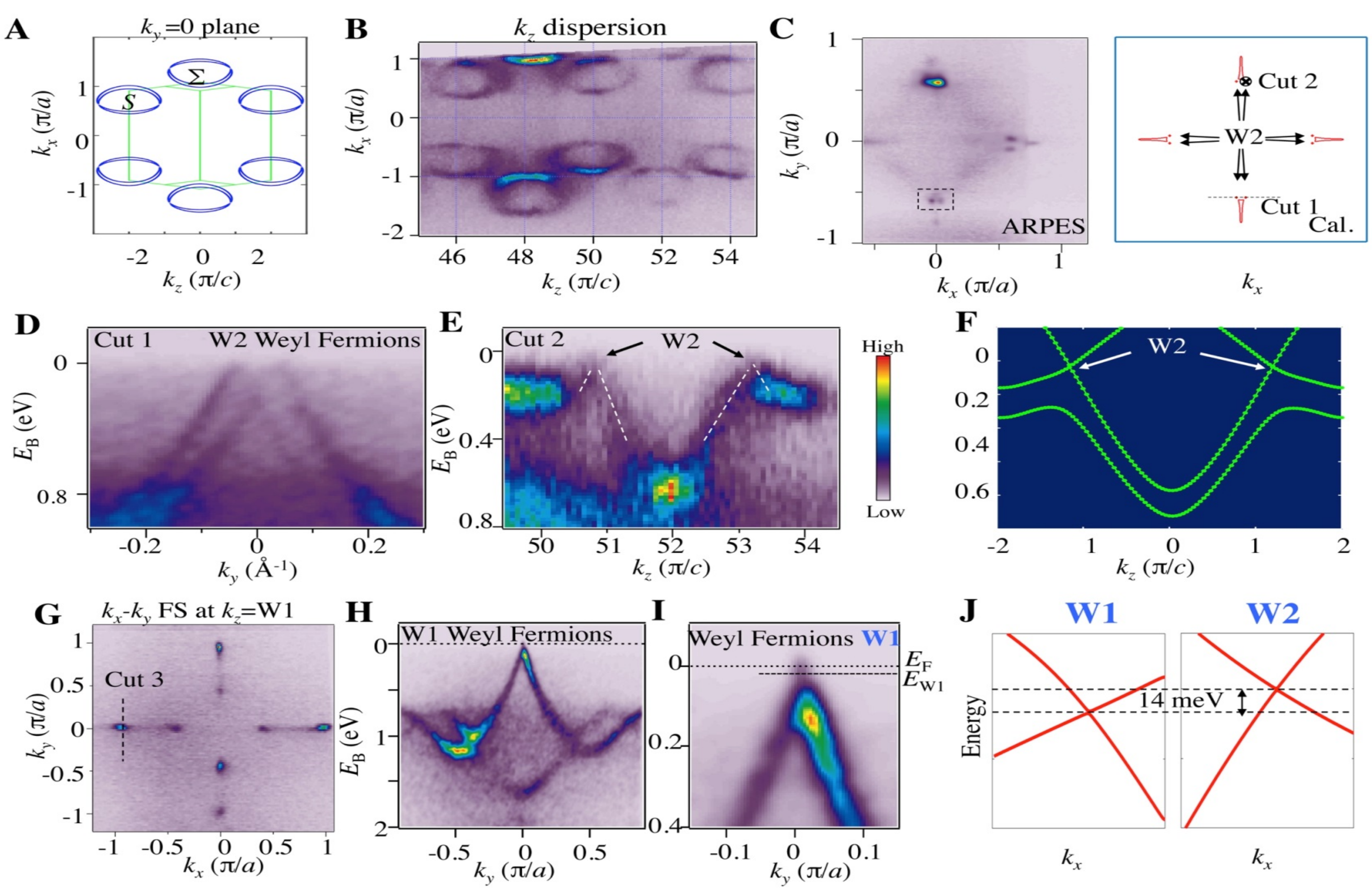
Weyl Fermi arcs – *Copropagating!*



Weyl SM Data : Xu, Belopolski, et.al., **Science, 349, 613 (2015)**

Fermi arc Methods : Xu, Liu, Belopolski, et.al., **Science, 347, 294 (2014)** AOP

ARPES-2: Bulk fermions

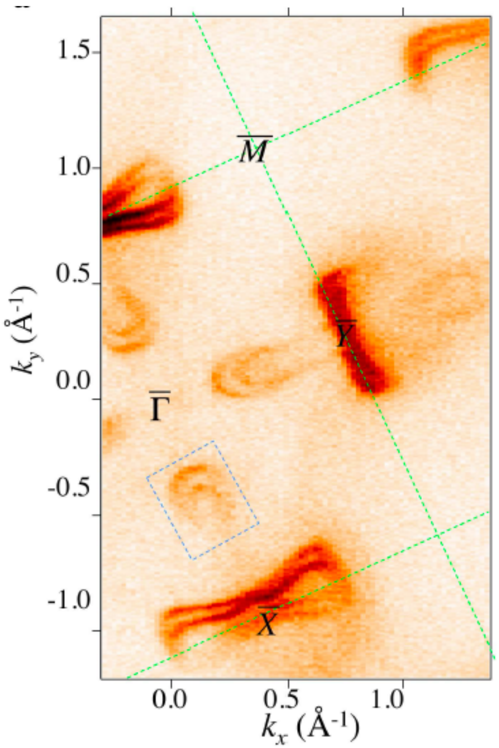


Weyl SM Data : Xu, Belopolski, et.al., Science, 349, 613 (2015)

Fermi arc Methods : Xu, Liu, Belopolski, et.al., Science, 347, 294 (2014) AOP

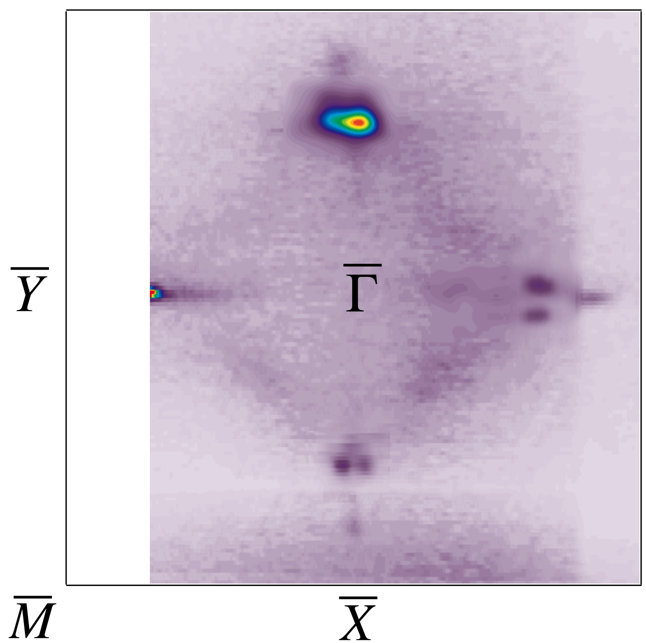
ARPES: Surface vs. Bulk

hv = 90 eV



Low Photon Energy
(surface sensitive)

hv = 650 eV

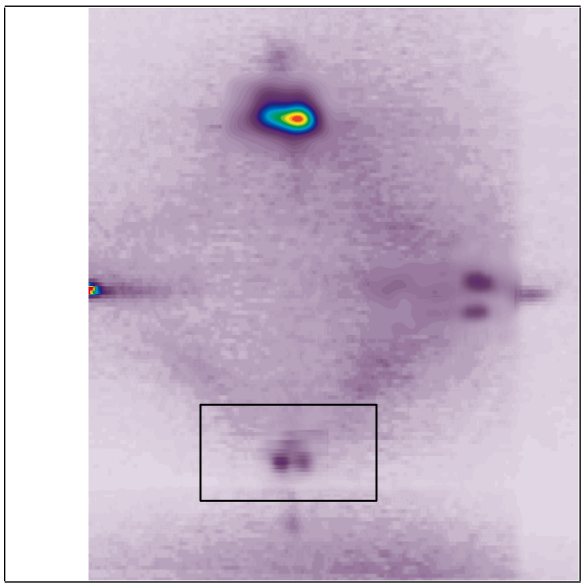


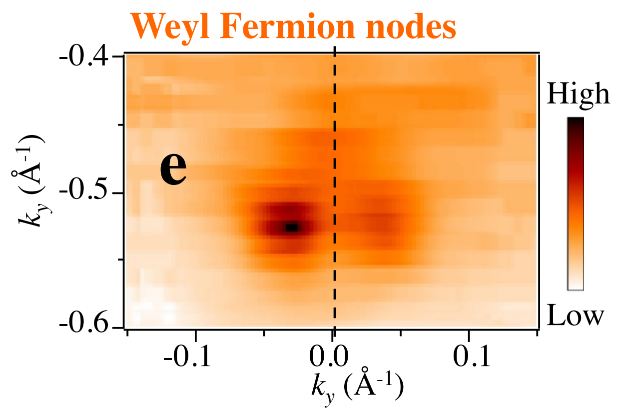
High Photon Energy
(Bulk sensitive)

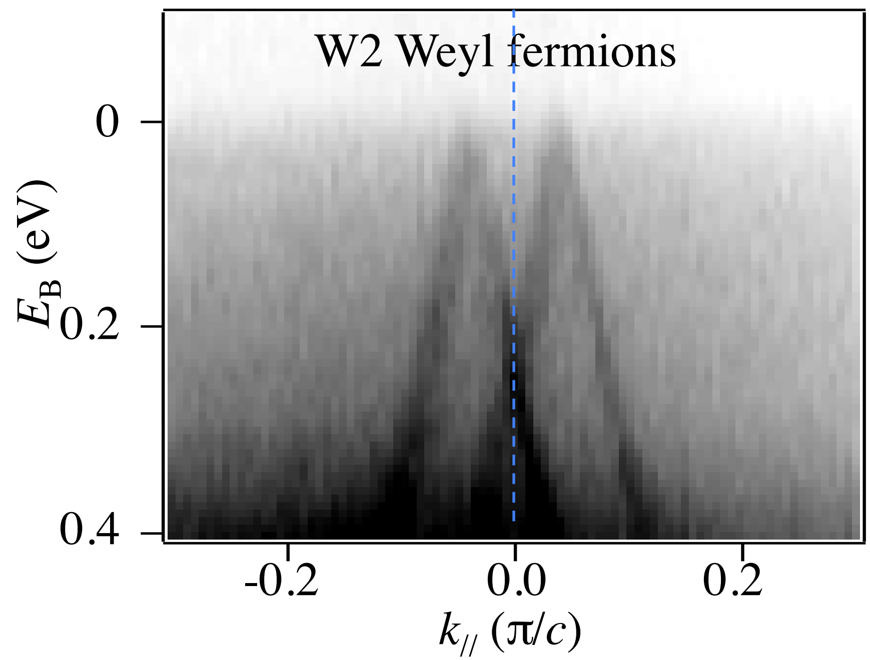
Weyl SM Data : Xu, Belopolski, et.al., **Science, 349, 613 (2015)**
Fermi arc Methods : Xu, Liu, Belopolski, et.al., **Science, 347, 294 (2014)** AOP

ARPES-2: Bulk Weyl fermions

Away from Kramers points or rotational axes





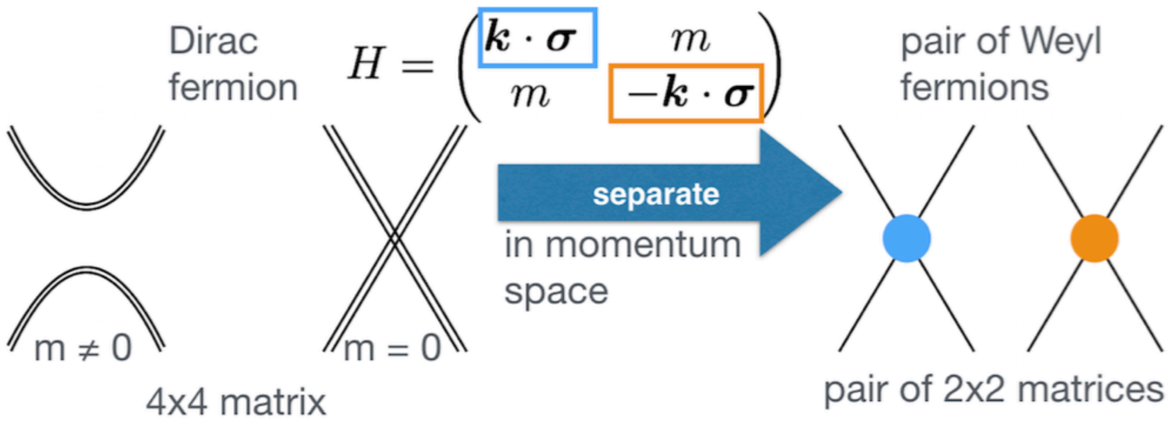


Weyl SM Data : Xu, Belopolski, et.al., Science, 349, 613 (2015)

Fermi arc Methods : Xu, Liu, Belopolski, et.al., Science, 347, 294 (2014) AOP

“Half” Fermions

Two ways to decompose a Dirac fermion



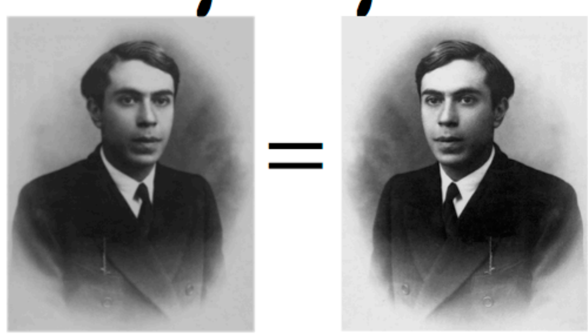
H.Weyl 1929

electron ~ 2 Majoranas

$$c = (\gamma + i\gamma')/2$$
$$c^\dagger = (\gamma - i\gamma')/2$$

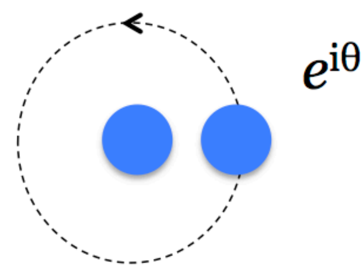
Majorana = anti-Majorana

$$\gamma = \gamma^\dagger$$



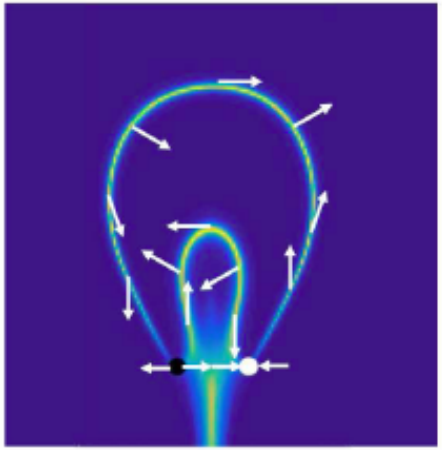
Ettore Majorana 1937

2 Majoranas ~
2-level system

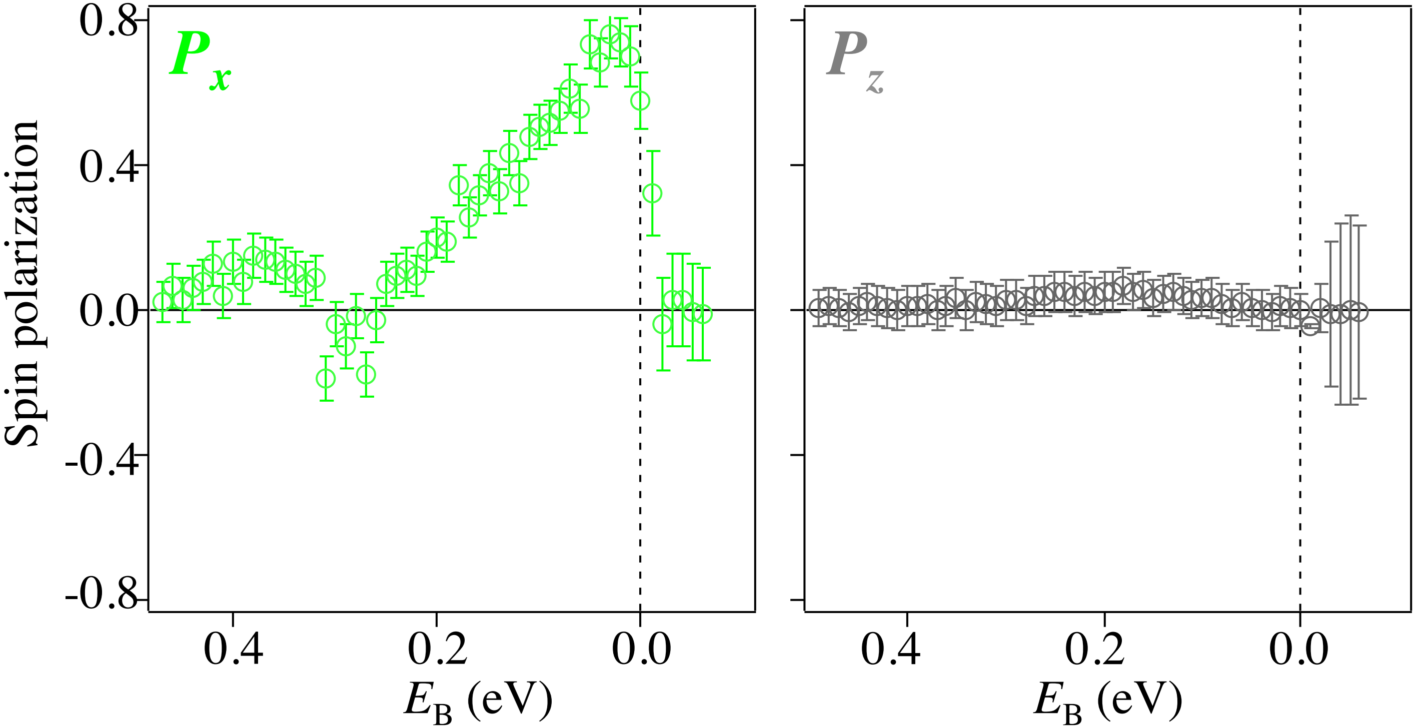


Spin polarization in TaAs > 80%

Measured spin texture



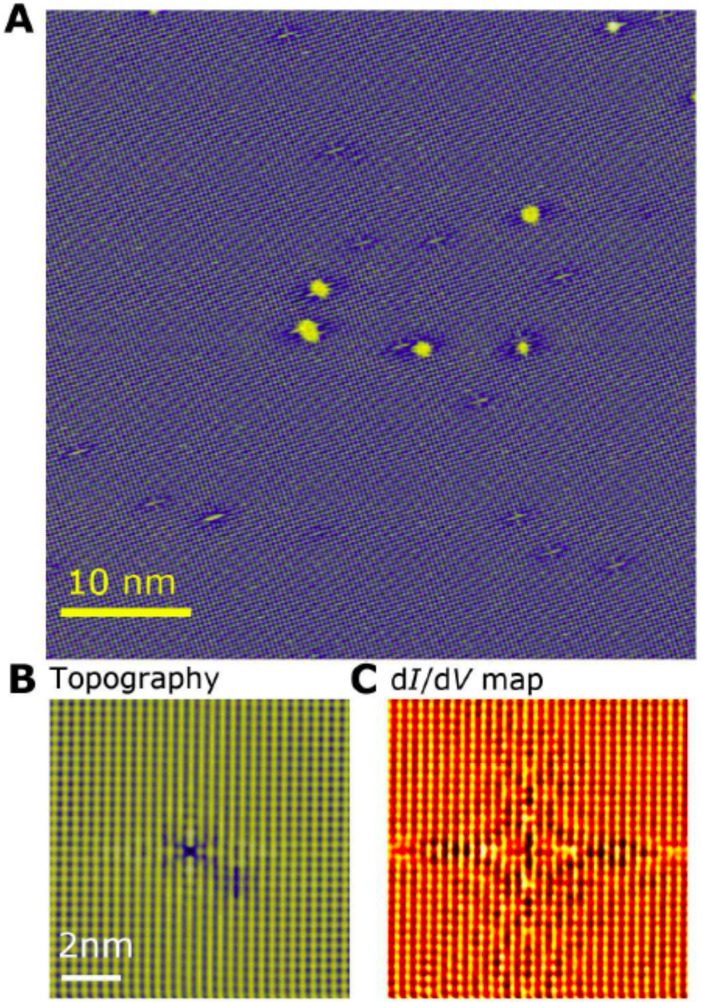
- Singly degenerate
- Spin pol. > 80%
- $P_z = 0$ (C_2T)

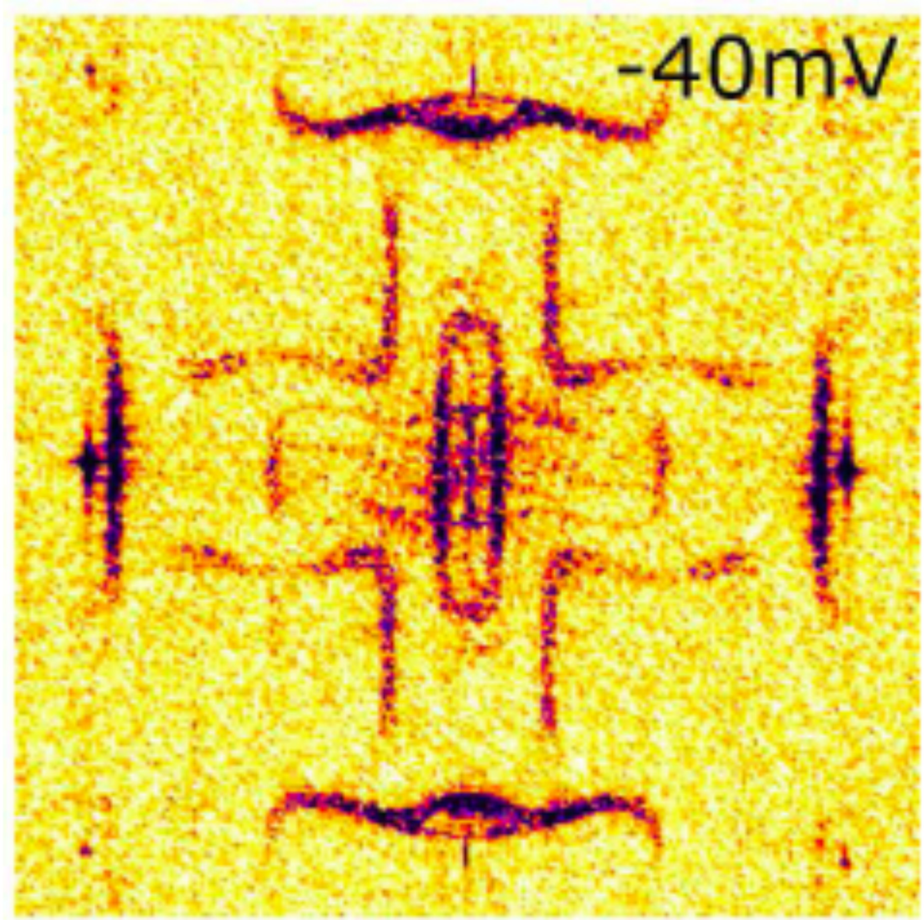


S.-Y. Xu *et al.*, http://arxiv.org/abs/1510.08430 (2015)

First STM images on Weyl

atomic resolution view of the surface

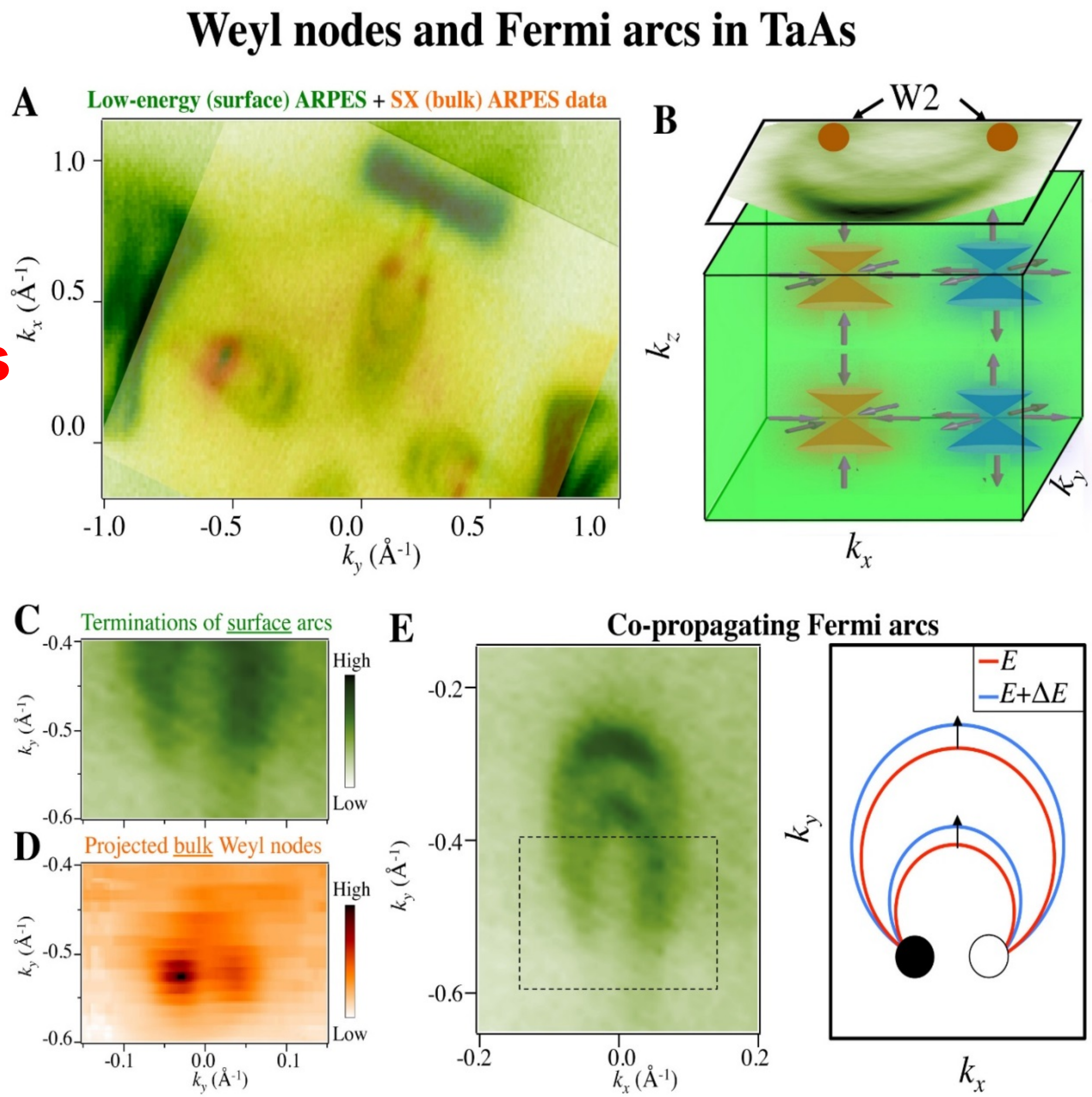




H. Zheng, S.-Y. Xu, *et al., (MZH)* (2015) ACS Nano

Weyl quasipaticles & Topological Fermi arcs

Weyl Semimetals



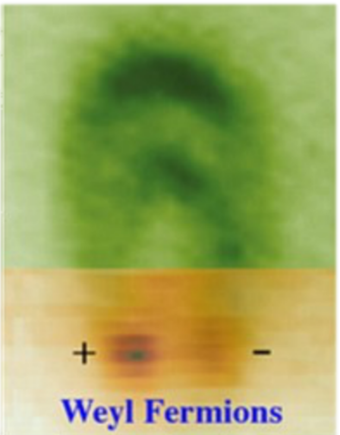
K-space: Monopole - Anti MP

Weyl Fermions

Fermi Arcs

Weyl SM Data : Xu, Belopolski, et.al., Science, 349, 613 (2015)
Fermi arc Methods : Xu, Liu, Belopolski, et.al., Science, 347, 294 (2014) AOP

Sciencexpress Research Articles



Discovery of a Weyl Fermion semimetal and topological Fermi arcs

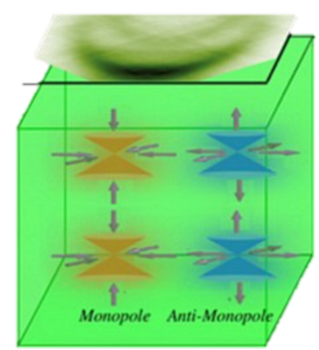
16th July, 2015

Su-Yang Xu,[1,2*] Ilya Belopolski,[1*] Nasser Alidoust,[1,2*] Madhab Neupane,[1,3*] Guang Bian,[1] Chenglong Zhang,[4] Raman Sankar,[5] Guoqing Chang,[6,7] Zhujun Yuan,[4] Chi-Cheng Lee,[6,7] Shin-Ming Huang,[6,7] Hao Zheng,[1] Jie Ma,[8] Daniel S. Sanchez,[1] BaoKai Wang,[6,7,9] Arun Bansil,[9] Fangcheng Chou,[5] Pavel P. Shibayev,[1,10] Hsin Lin,[6,7] Shuang Jia,[4,11] M. Zahid Hasan[1,2†]

nature physics
ARTICLES
PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NPHYS3437

Discovery of a Weyl fermion state with Fermi arcs in niobium arsenide

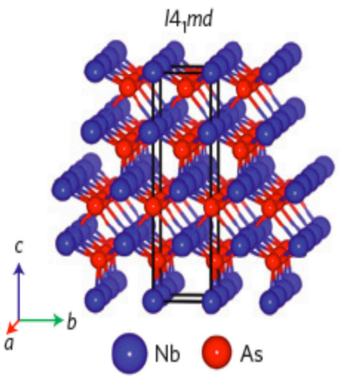
Su-Yang Xu[1,2†], Nasser Alidoust[1,2†], Ilya Belopolski[1,2†], Zhujun Yuan[3], Guang Bian[1], Tay-Rong Chang[1,4], Hao Zheng[1], Vladimir N. Strocov[5], Daniel S. Sanchez[1], Guoqing Chang[6,7], Chenglong Zhang[3], Daixiang Mou[8,9], Yun Wu[8,9], Lunan Huang[8,9], Chi-Cheng Lee[6,7], Shin-Ming Huang[6,7], BaoKai Wang[6,7,10], Arun Bansil[10], Horng-Tay Jeng[4,11], Titus Neupert[12], Adam Kaminski[8,9], Hsin Lin[6,7], Shuang Jia[3,13] and M. Zahid Hasan[1,2*]

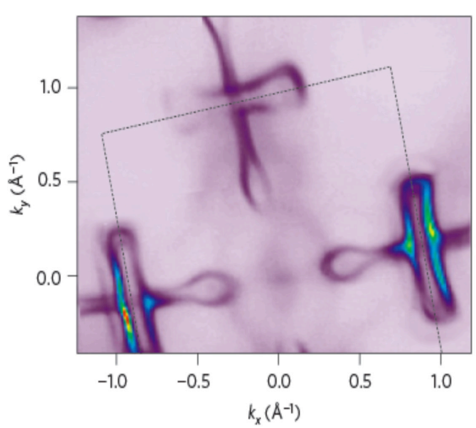


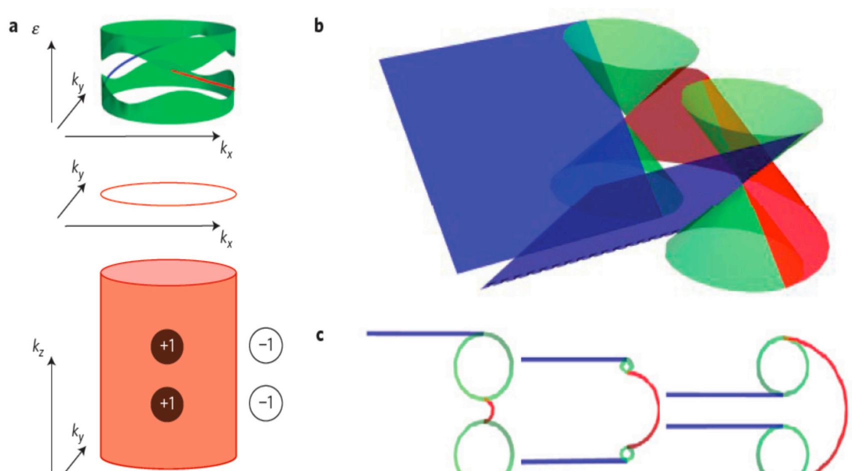
nature physics
ARTICLES
PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NPHYS3437

Discovery of a Weyl fermion state with Fermi arcs in niobium arsenide

Su-Yang Xu[1,2†], Nasser Alidoust[1,2†], Ilya Belopolski[1,2†], Zhujun Yuan[3], Guang Bian[1], Tay-Rong Chang[1,4], Hao Zheng[1], Vladimir N. Strocov[5], Daniel S. Sanchez[1], Guoqing Chang[6,7], Chenglong Zhang[3], Daixiang Mou[8,9], Yun Wu[8,9], Lunan Huang[8,9], Chi-Cheng Lee[6,7], Shin-Ming Huang[6,7], BaoKai Wang[6,7,10], Arun Bansil[10], Horng-Tay Jeng[4,11], Titus Neupert[12], Adam Kaminski[8,9], Hsin Lin[6,7], Shuang Jia[3,13] and M. Zahid Hasan[1,2*]



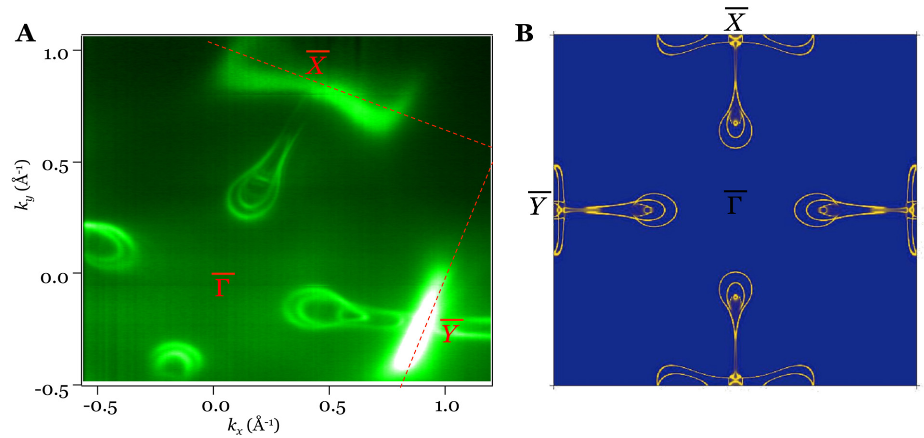


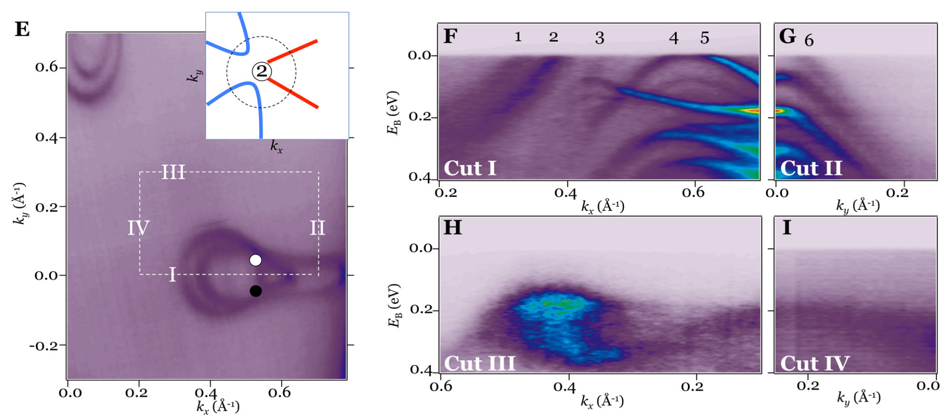


RESEARCH ARTICLE
Science Advances
Science advances 1, e1501092 (2015)
PHYSICS

Experimental discovery of a topological Weyl semimetal state in TaP

Su-Yang Xu,[1*†] Ilya Belopolski,[1*] Daniel S. Sanchez,[1*] Chenglong Zhang,[2] Guoqing Chang,[3,4] Cheng Guo,[2] Guang Bian,[1] Zhujun Yuan,[2] Hong Lu,[2] Tay-Rong Chang,[5] Pavel P. Shibayev,[1] Mykhailo L. Prokopovych,[6] Nasser Alidoust,[1] Hao Zheng,[1] Chi-Cheng Lee,[3,4] Shin-Ming Huang,[3,4] Raman Sankar,[7,8] Fangcheng Chou,[7] Chuang-Han Hsu,[3,4] Horng-Tay Jeng,[5,8] Arun Bansil,[9] Titus Neupert,[10] Vladimir N. Strocov,[6] Hsin Lin,[3,4] Shuang Jia,[2,11] M. Zahid Hasan[1,12†]





First Experimental Papers on Weyl physics

1. S. Xu et al (**Princeton**); *Science* 349, 617 (2015) Weyl fermion with Fermi arc

2. L. Lu et.al., (**MIT**); *Science* 349, 622 (2015) Weyl photonic (bosonic) crystal

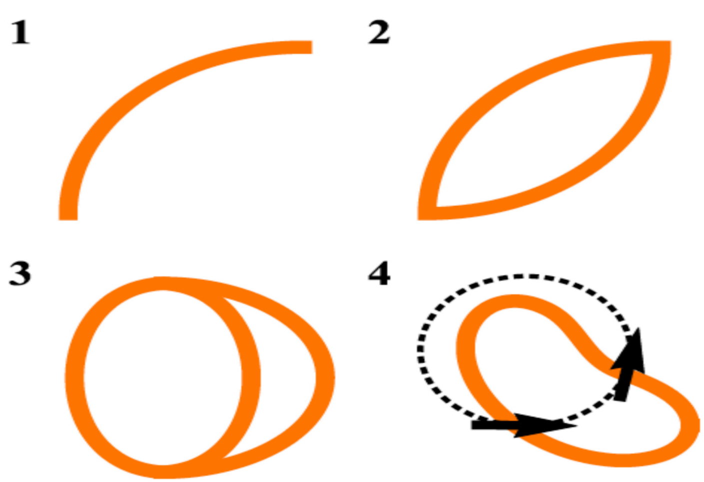
3. B. Lv et al (**IOP-China**) *Phy. Rev. X (2015)* Fermi arc

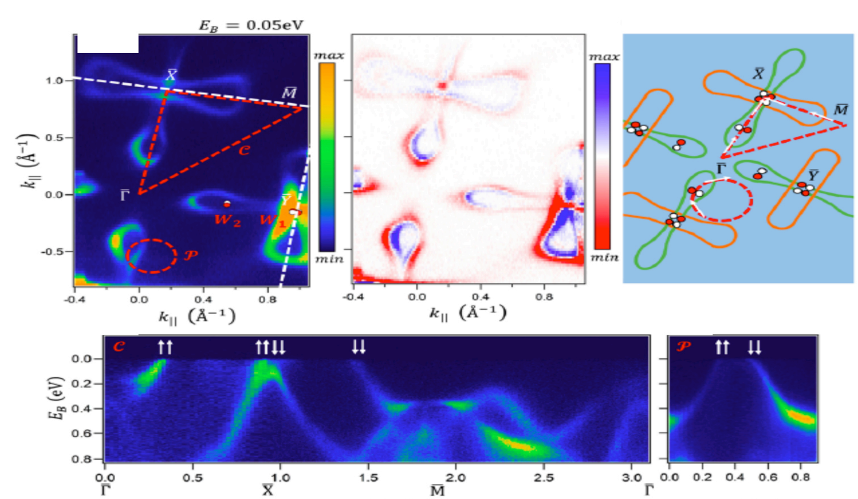
and now more ….(including a few from us)

PRL **116,** 066802 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Criteria for Directly Detecting Topological Fermi Arcs in Weyl Semimetals

Ilya Belopolski,[1,*] Su-Yang Xu,[1] Daniel S. Sanchez,[1] Guoqing Chang,[2,3] Cheng Guo,[4] Madhab Neupane,[5,6] Hao Zheng,[1] Chi-Cheng Lee,[2,3] Shin-Ming Huang,[2,3] Guang Bian,[1] Nasser Alidoust,[1] Tay-Rong Chang,[1,7] BaoKai Wang,[2,3,8] Xiao Zhang,[4] Arun Bansil,[8] Horng-Tay Jeng,[7,9] Hsin Lin,[2,3] Shuang Jia,[4] and M. Zahid Hasan[1,†]





nature COMMUNICATIONS

ARTICLE

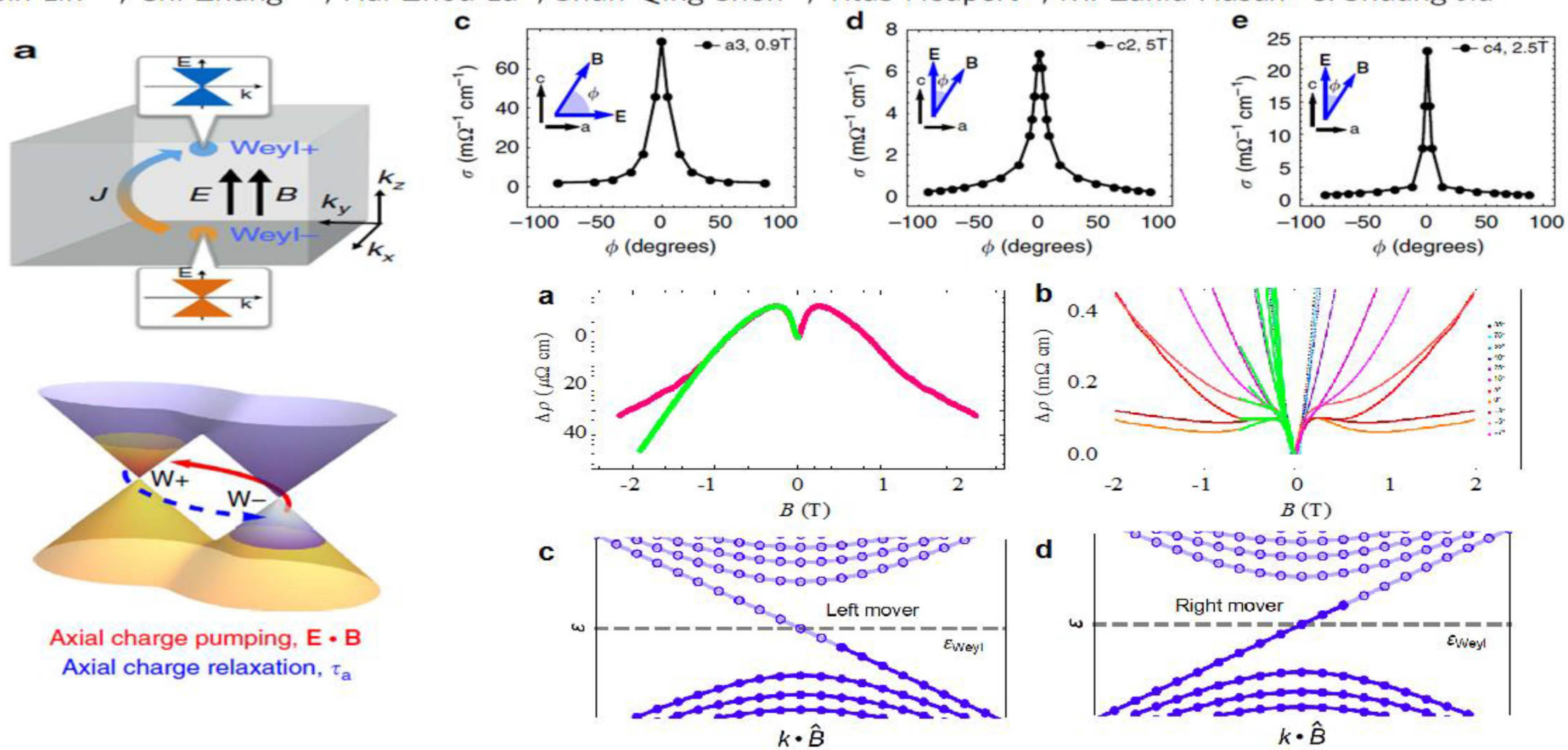
Received 18 Oct 2015 | Accepted 15 Jan 2016 | Published 25 Feb 2016

DOI: 10.1038/ncomms10735

OPEN

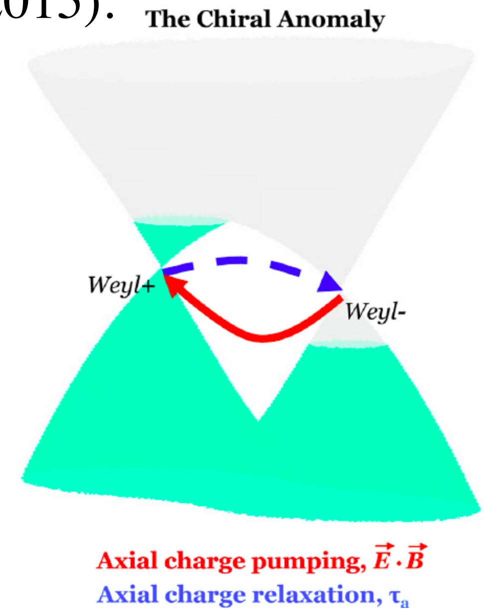
Signatures of the Adler–Bell–Jackiw chiral anomaly in a Weyl fermion semimetal

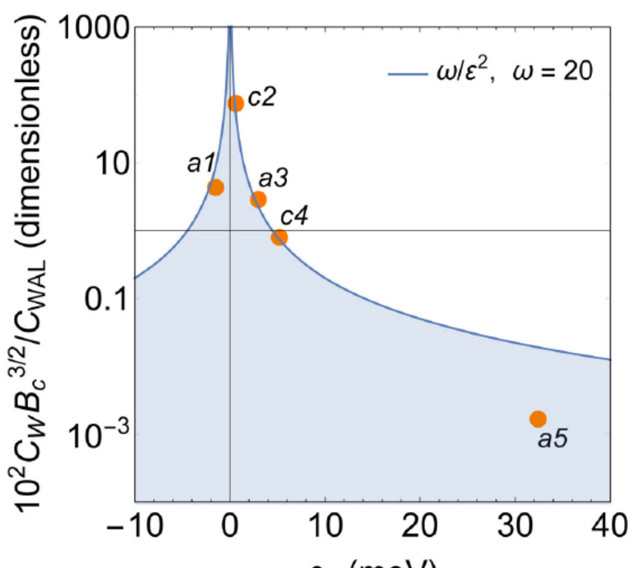
Cheng-Long Zhang[1,*], Su-Yang Xu[2,*], Ilya Belopolski[2,*], Zhujun Yuan[1,*], Ziquan Lin[3], Bingbing Tong[1], Guang Bian[2], Nasser Alidoust[2], Chi-Cheng Lee[4,5], Shin-Ming Huang[4,5], Tay-Rong Chang[2,6], Guoqing Chang[4,5], Chuang-Han Hsu[4,5], Horng-Tay Jeng[6,7], Madhab Neupane[2,8,9], Daniel S. Sanchez[2], Hao Zheng[2], Junfeng Wang[3], Hsin Lin[4,5], Chi Zhang[1,10], Hai-Zhou Lu[11], Shun-Qing Shen[12], Titus Neupert[13], M. Zahid Hasan[2] & Shuang Jia[1,10]

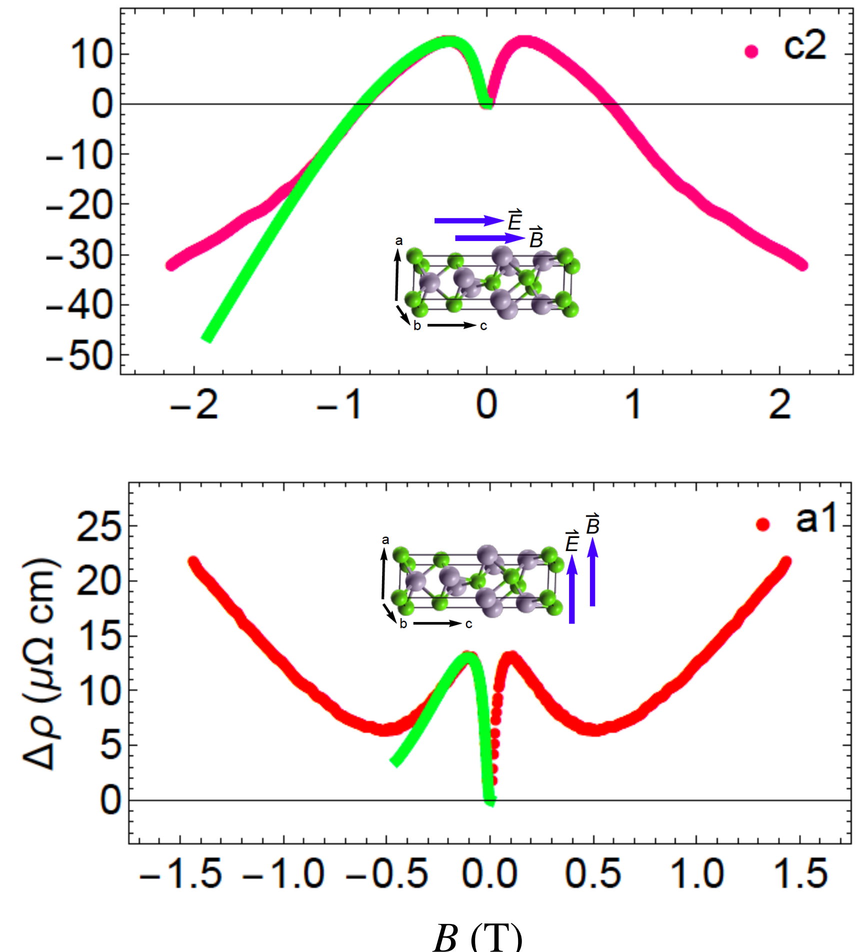


TaAs (WSM) chiral anomaly - $\boldsymbol{E \cdot B}$

C.L. Zhang, Su-Yang Xu, Belopolski, Jia *et al*. arxiv:1503.02630 (2015).



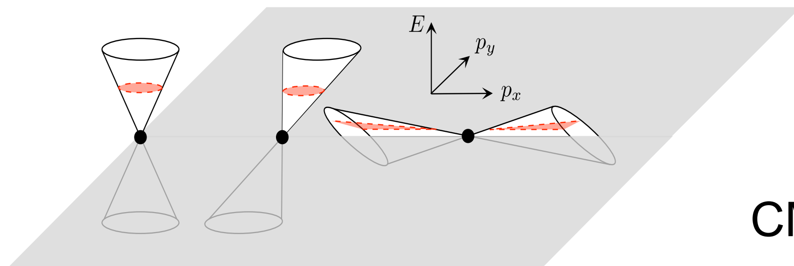




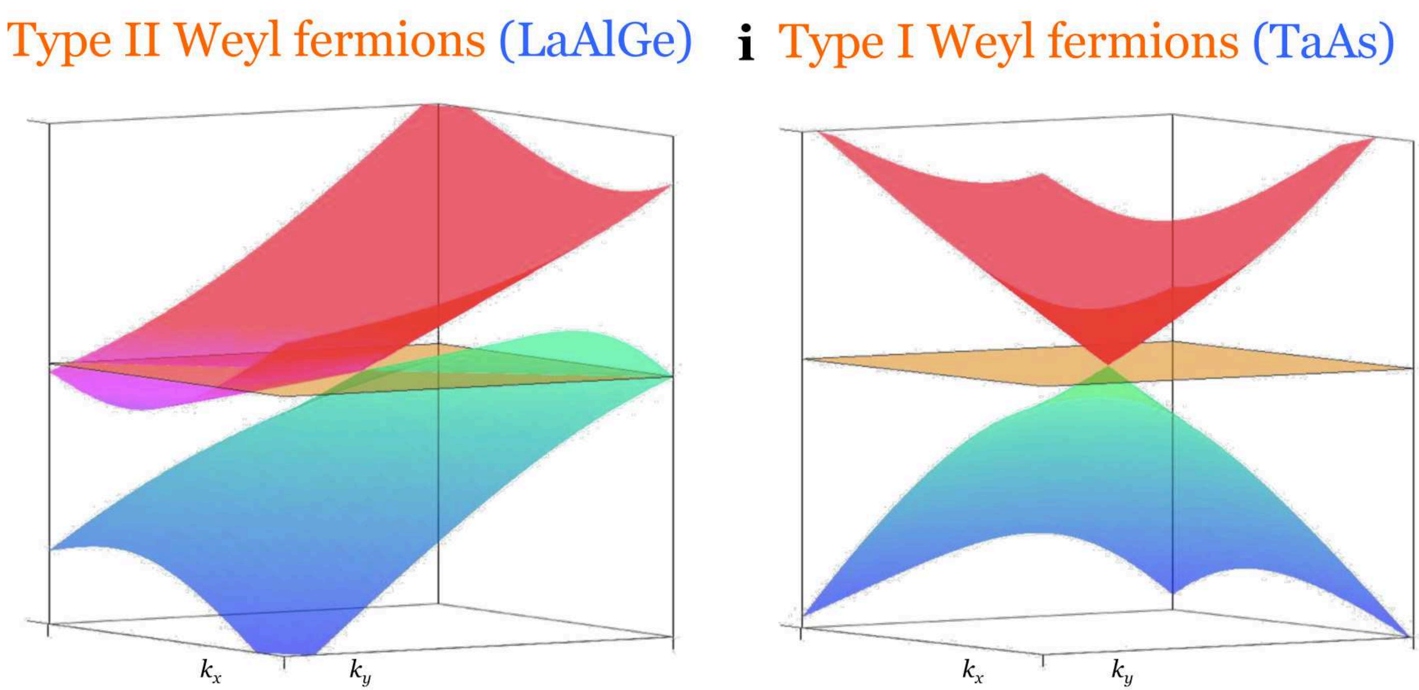
See also

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

Tilting the Weyl Cone: Lorentz-violation



CM-JC 2015



Lorentz violating tilt in Dirac & Weyl: Many theory papers at least since 1995
Type-II by Soluyanov, Bernevig et.al., (2015) and others

Discovery of Lorentz-violating Weyl fermion semimetal state in LaAlGe materials

Su-Yang Xu*,[1] Nasser Alidoust*,[1] Guoqing Chang*,[2,3] Hong Lu*,[4] Bahadur Singh*,[2] Ilya Belopolski,[1] Daniel S. Sanchez,[1] Xiao Zhang,[4,3] Guang Bian,[1] et.al.,

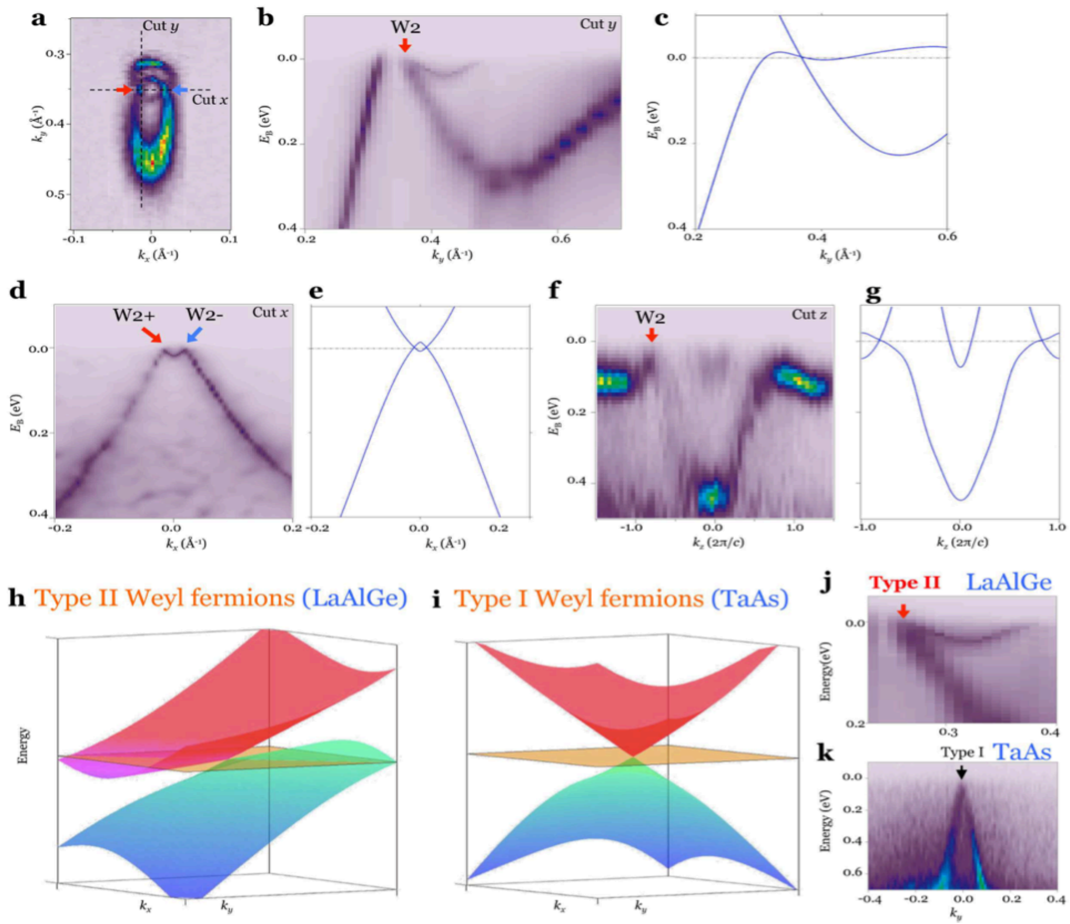
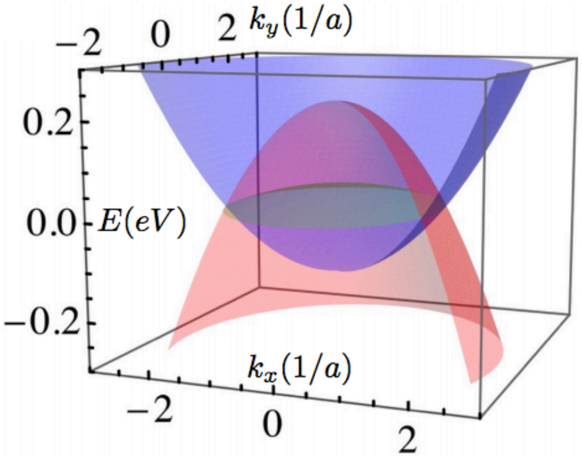


FIG. 3: **Type-II Weyl fermions in LaAlGe. a,** SX-ARPES-measured $k_x - k_y$ Fermi surface map in the region marked by the green rectangle in panel **c** of Fig. 2. **b,** Measured and **c,** calculated

Ta3S2 is also Lorentz-violating

Topological Nodal-Line Semimetals



nodal line

winding number

$$\gamma/\pi = \pm 1$$

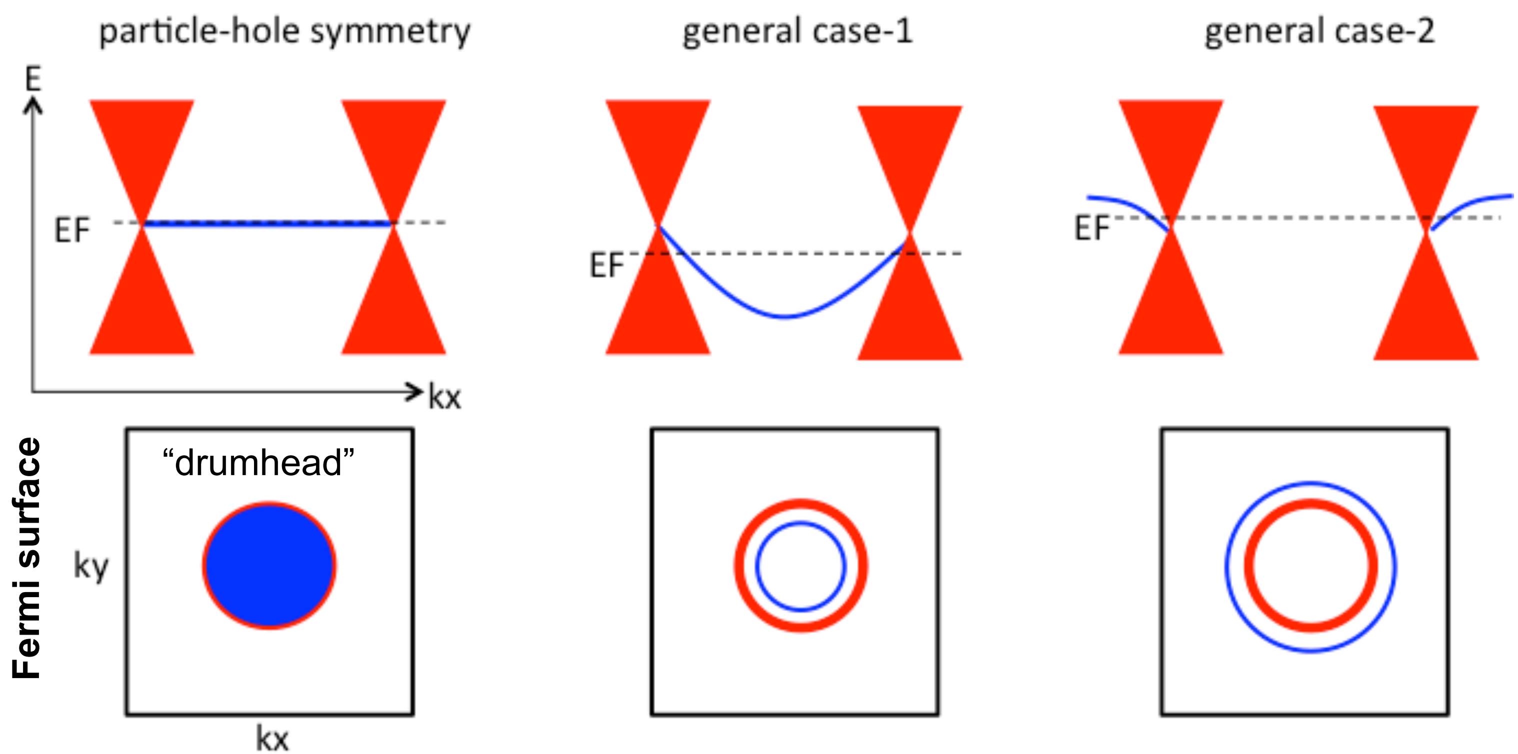
bulk-boundary correspondece

↓

topo. surface states

$$\gamma = i\oint_C \langle\psi(\mathbf{k})|\nabla\psi(\mathbf{k})\rangle \cdot \mathrm{d}\mathbf{k}$$

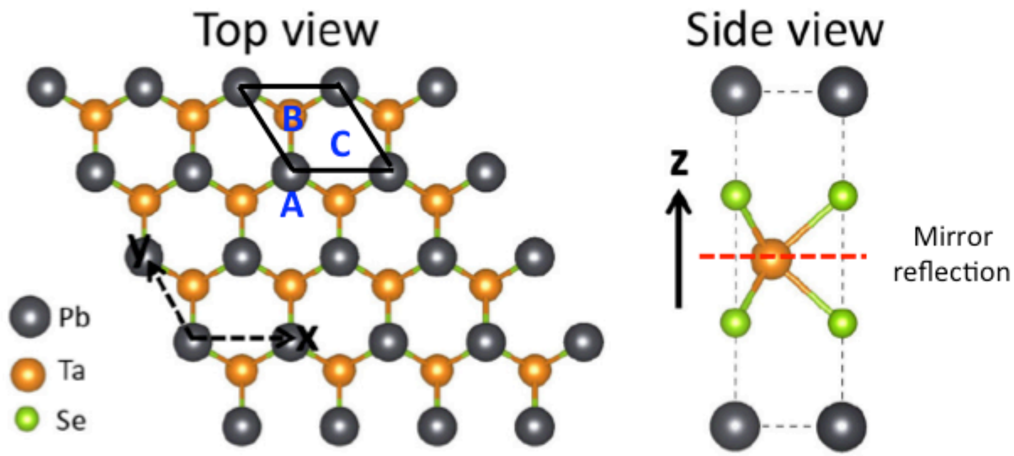
Chan *et al.*, arXiv:1510.02759 (2015)



Topological Nodal-Line Semimetals: $PbTaSe_2$

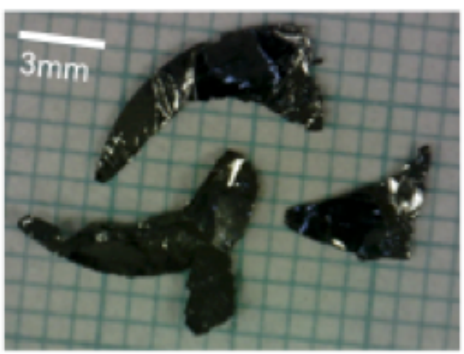
Theory & Experiments

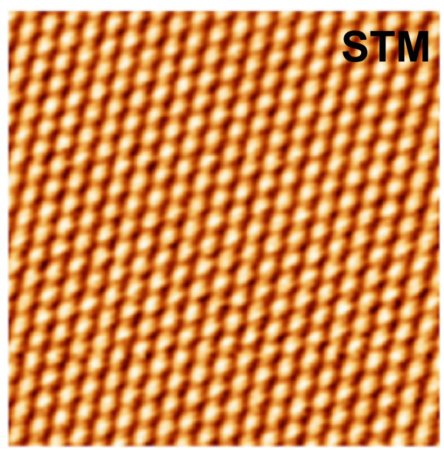
$PbTaSe_2$: **G. Bian**, T.-R. Chang, R. Sankar *et al.*, (MZH) *Nature Commun.* **7**:10556 (2016)

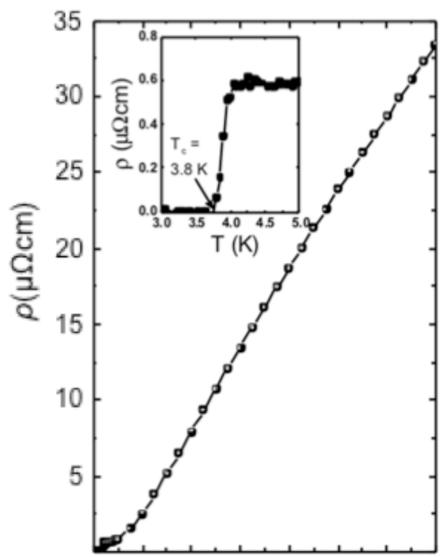


Space group: P-6m2 (# 187)
a=b= 3.44 Å
c= 9.35 Å

Bond-length
Pb-Se = 2.90 Å
Ta-Se = 2.66 Å

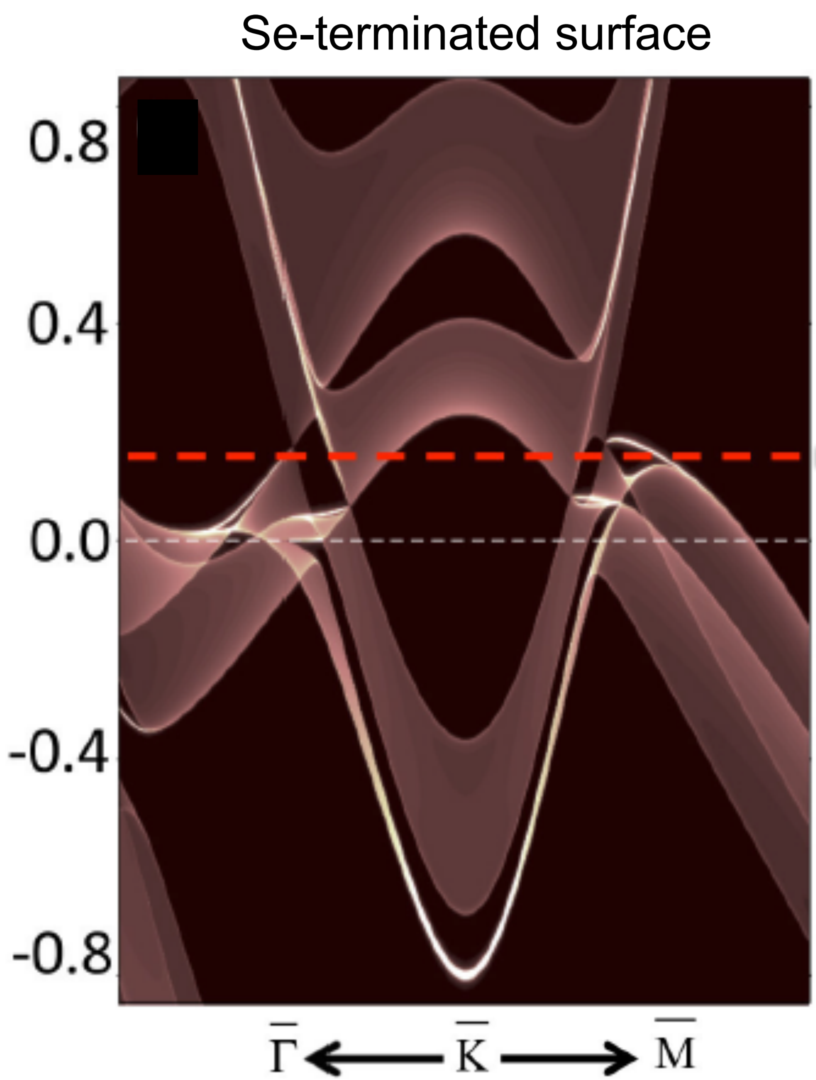


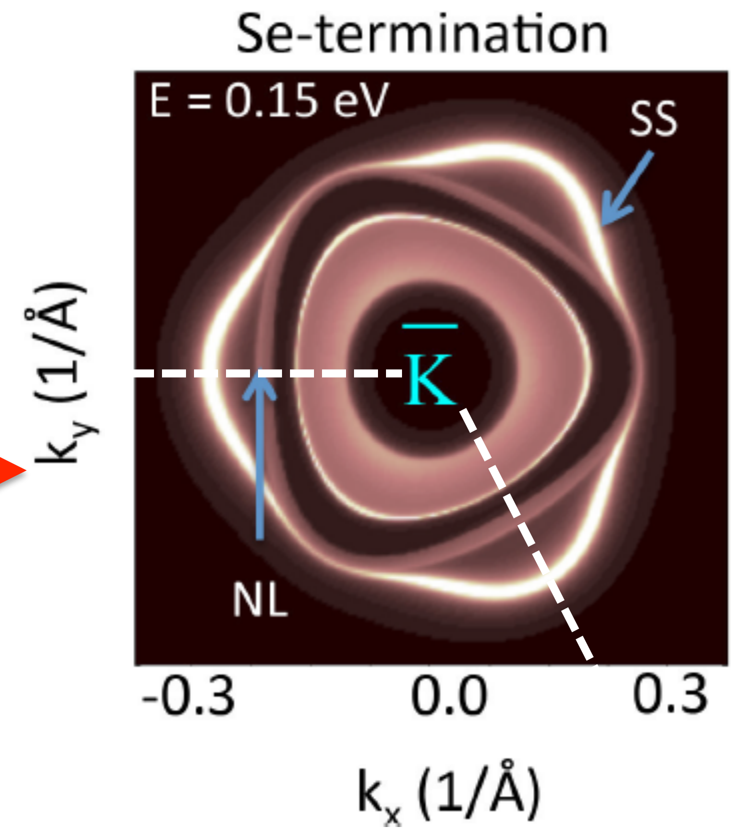




Superconducting!

Topological Nodal-Line Semimetals: $PbTaSe_2$





Experimental goals:

A. **Crossing of Pb and Ta bands**

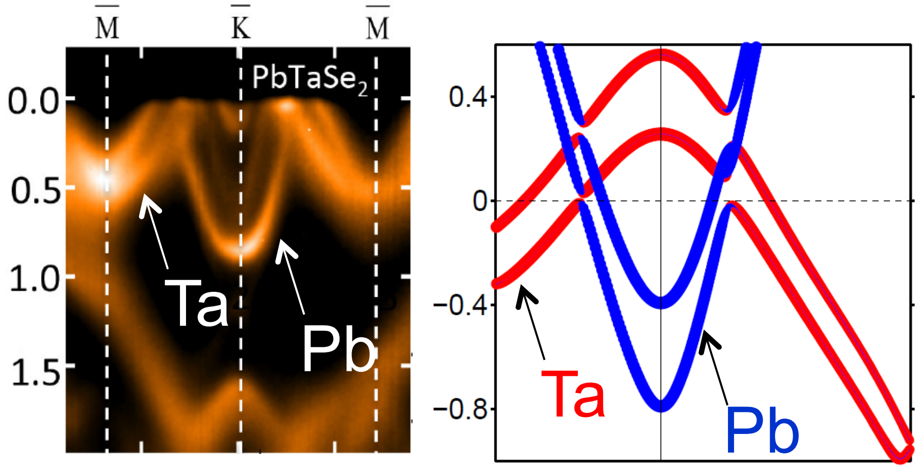
B. **Ring-shaped bulk Fermi surface**

C. **Surface states**

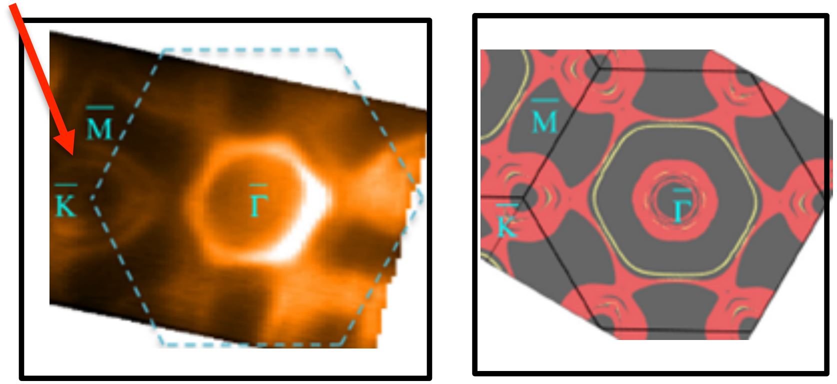
Topological Nodal-Line Semimetals: $PbTaSe_2$

A

Pb and Ta bands



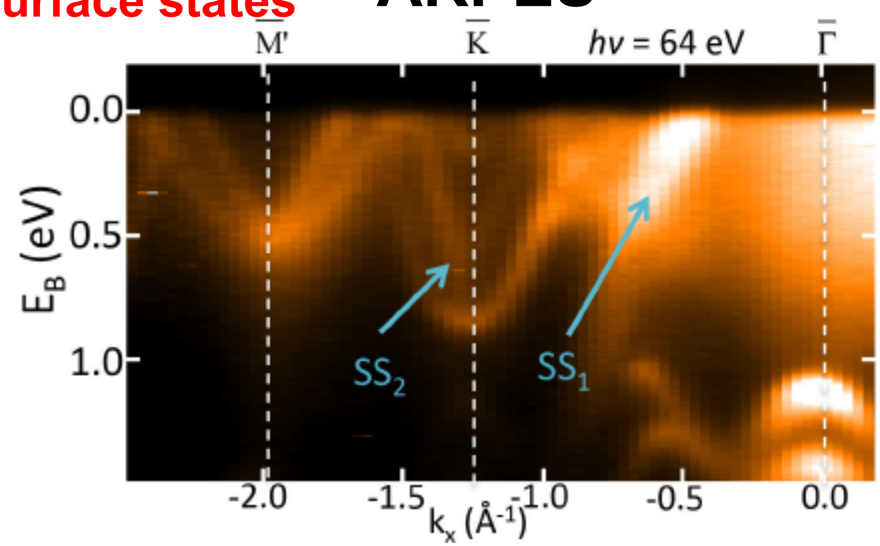
B **Bulk Fermi ring**



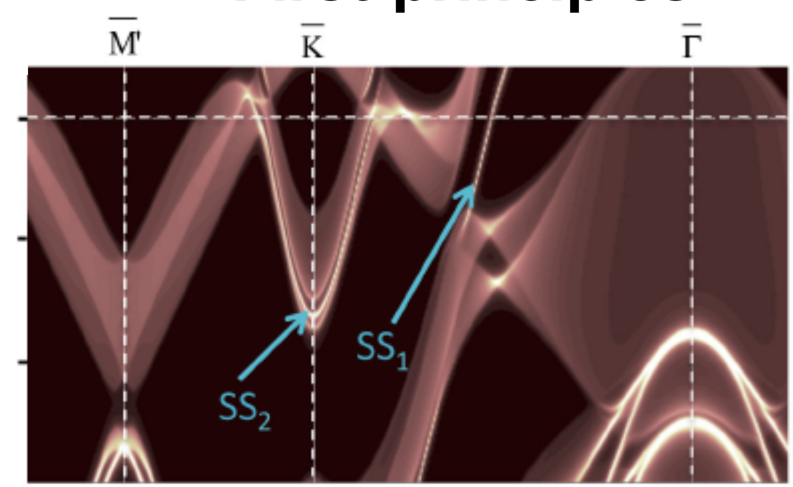
C

Surface states

ARPES



First-principles

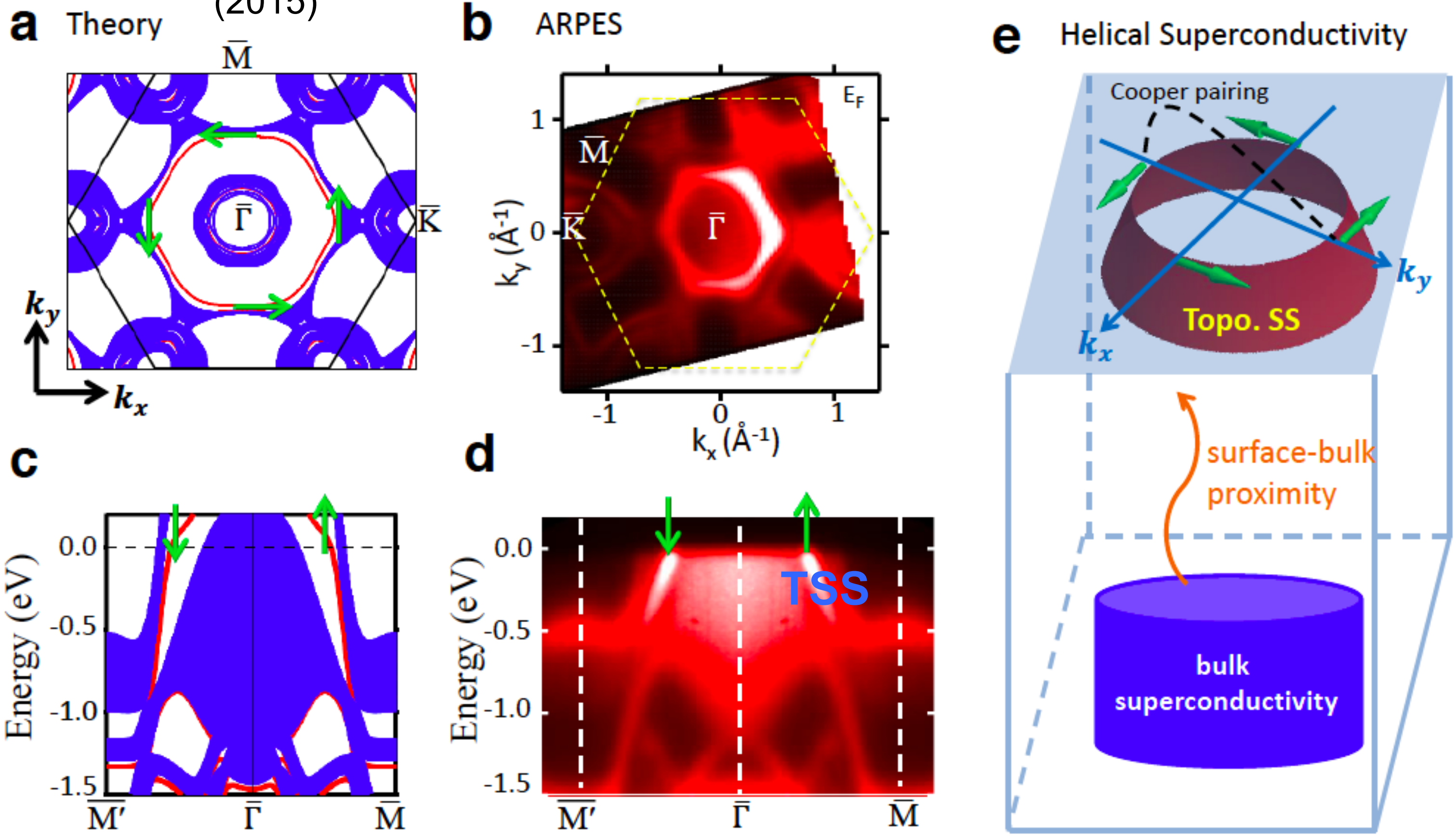


Topological Nodal-Line Semimetals: $PbTaSe_2$

$PbTaSe_2$: **Superconductivity T_c= 3.8 K** **proximity effect** → **Surface topological superconductivity**

Nontrivial Z_2, topological surface states

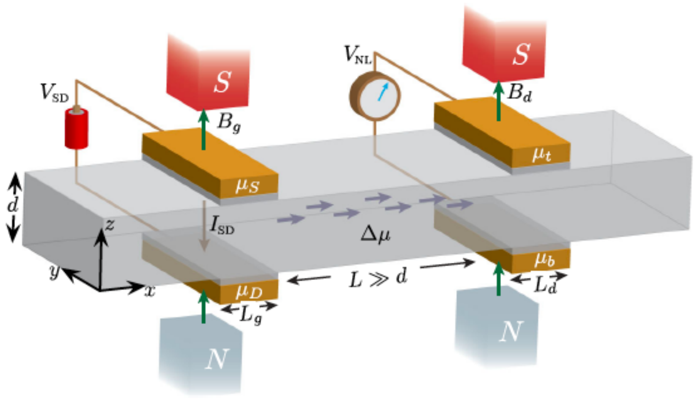
T.-R. Chang*, P.-J. Chen*, G. Bian* *et al.*, (MZH) arXiv:1511.06231 (2015)



G. Bian, T.-R. Chang *et al.*, (MZH) arXiv:1508.07521 for nodal lines in $TlTaSe_2$

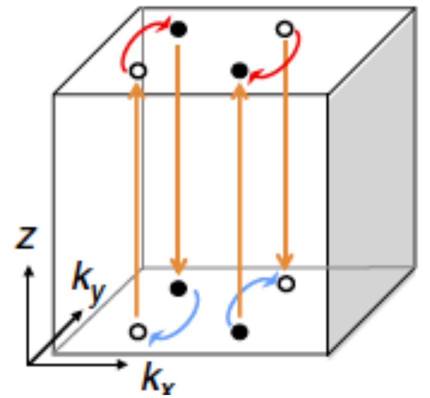
Future Weyl devices

Nonlocal transport



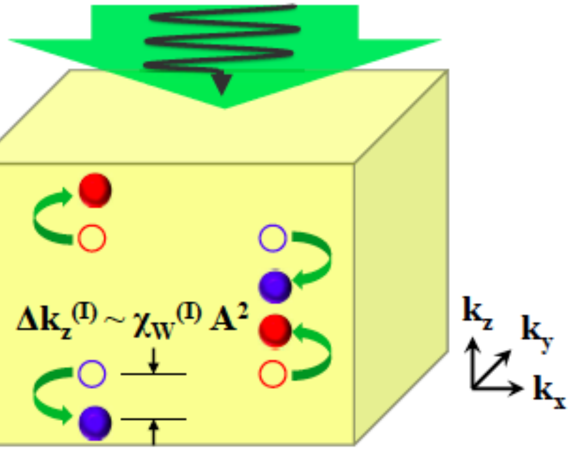
Parameswaran *et al*. *PRX* (2014)

Fermi arc transport

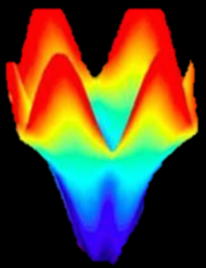


Potter *et al*. *Nature Commun*. (2014)
Huang, SYX *et al*. *Nature Commun*. (2015)

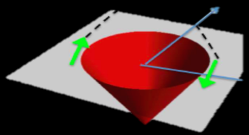
Chiral photon driven AHE

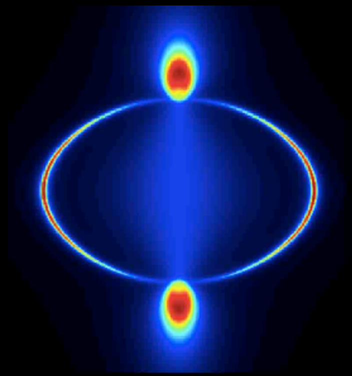


C.-K. Chan *et al*. arxiv:1509.05400 (2015).



Topo. Insulator



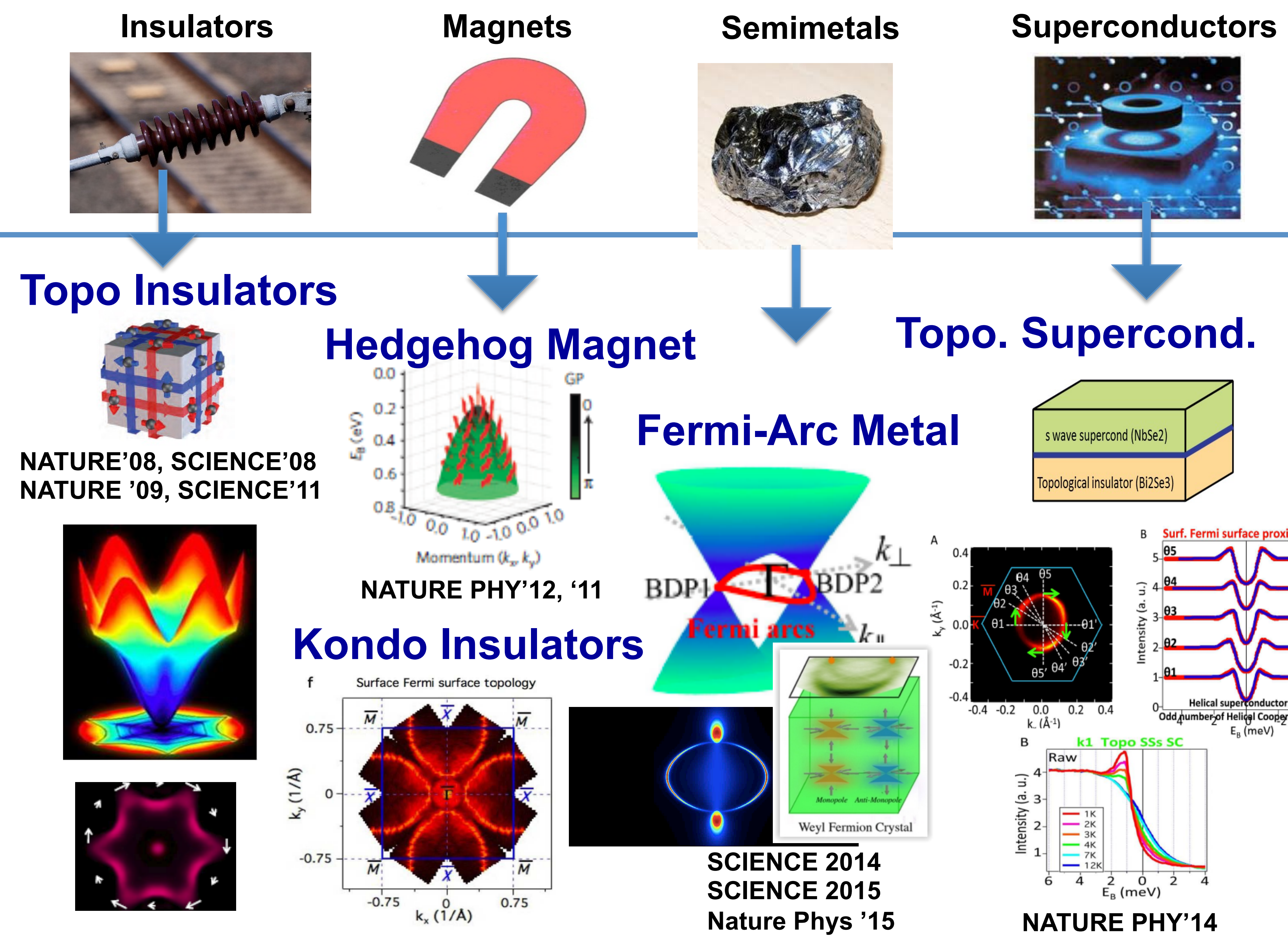


Topo. Superconductors
Helical Pairing

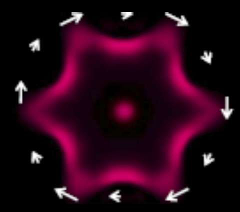
Majorana

Weyl Semimetals
Topological Fermi Arcs

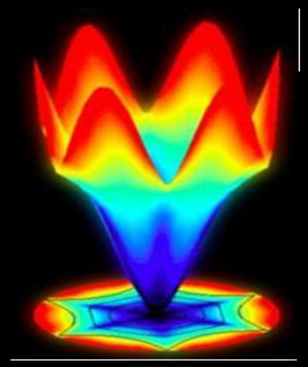
Weyl Fermion & TNL Fermion
Weyl Superconductors (topological)
Weyl - Majorana


Insulators
Magnets
Semimetals
Superconductors
Topo Insulators
NATURE'08, SCIENCE'08
NATURE '09, SCIENCE'11
Hedgehog Magnet
Momentum
NATURE PHY'12, '11
Kondo Insulators
Surface Fermi surface topology
Fermi-Arc Metal
BDP1
BDP2
Fermi arcs
Monopole
Anti-Monopole
Weyl Fermion Crystal
SCIENCE 2014
SCIENCE 2015
Nature Phys '15
Topo. Supercond.
s wave supercond (NbSe2)
Topological insulator (Bi2Se3)
Surf. Fermi surface proxi
Helical superconductor
k1 Topo SSs SC
Raw
NATURE PHY'14

REVIEWS



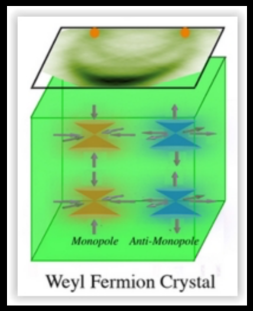
M.Z.H. and C.L. Kane
Colloq.: “Topological Insulators” (& Superconductors)
Rev. of Mod. Phys., (RMP) 82, 3045 ***(2010)***



M.Z.H. and J.E. Moore
“Three Dimensional Topo. Insulators”
Ann. Rev. of Cond. Mat. Phys., 2, 78 ***(2011)***

M.Z.H., D. Hsieh, Y. Xia, L. Wray
“Topological Surface States”
book Chapter in “Topological Insulators” (2013)

M.Z H., S.-Y. Xu & I. Belopolski
“Weyl Fermions and Topological Semimetals” ***(2016)***
Ann. Rev. of Cond. Mat. Phys., **(in press)**



Thanks !

MZH, Xu, Neupane *Topo Insulators, Topo Cryst. Insulators & Topo Kondo Insulators*, arXiv(2014)

MZH, Xia, Hsieh, Wray *et.al.*, (Book ch.) ***Topological Insulators,*** Elsevier/Oxford (2013)

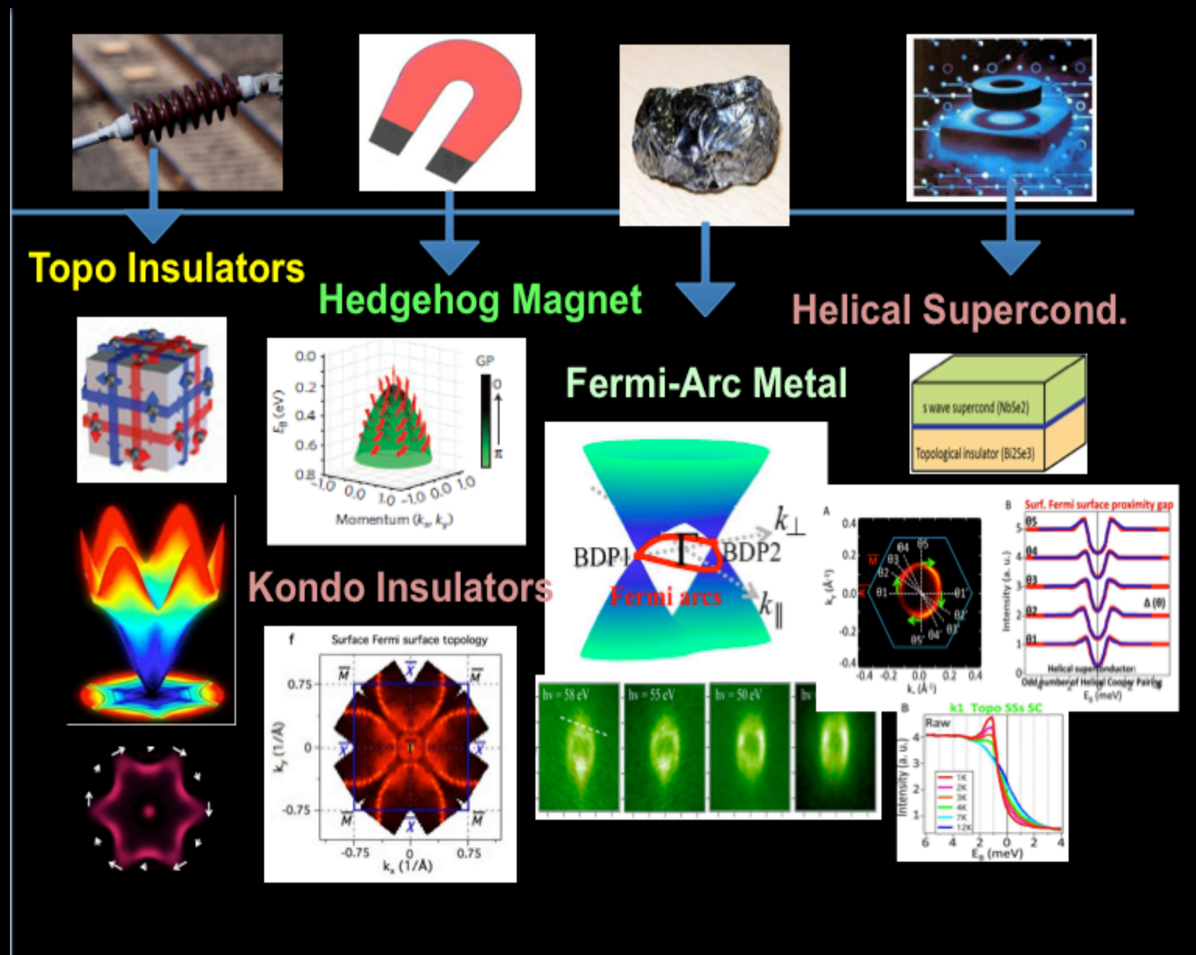
MZH and C.L. Kane ***Rev. of Mod. Phys., (RMP)*** 82, 3045 (2010)

MZH and J.E. Moore ***Ann. Rev. of Cond. Mat. Phy.,*** 2, 78 (2011)

Nature '08 (sub. in 2007)
Science '09
Nature Phys. '09
Nature '09
PhyRevLett '09
Nature '09
Nature Phys. '10
PhyRevLett. '10
Nature Mat. '10

RevModPhys. ' 10
AnnRevCMP. '11

Nature Phys. '11
PhyRevLett.' 12
Nature Comm.' 12
Science '11
Nature Phys.' 12
Nature Comm.' 13
Science '13
Nature Comm.' 14a
Nature Comm.' 14b
Nature Comm.' 14c
Nature Phys' 14
Nature Phys' 14
Science 2014
Science 2015
Science Adv '15
Nature Phys' 15



Topological Condensed Matter Physics