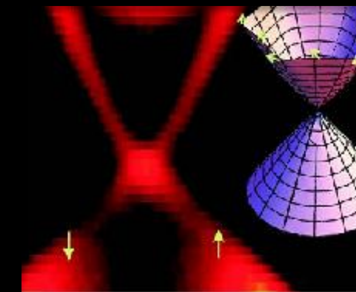
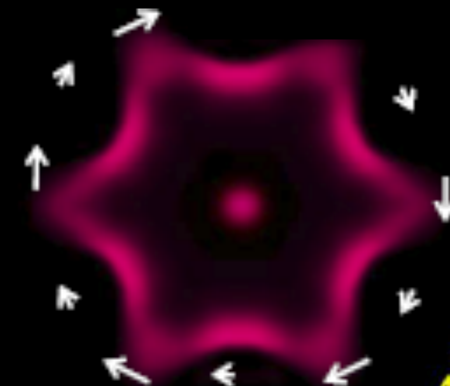
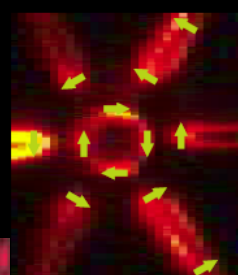
Topo. Superconductivity, Weyl fermions & Topo. Fermi arcs

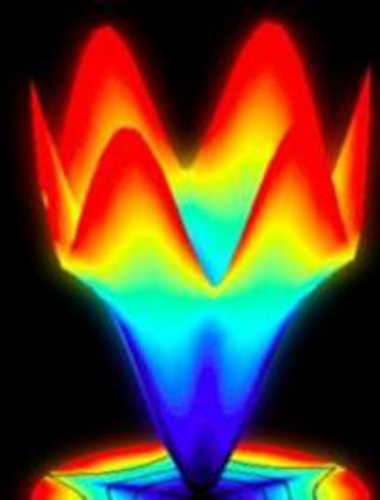
M. Zahid Hasan
Princeton University

Kavli Institute of Theoretical Physics (KITP)
Santa Barbara, California
July 2015

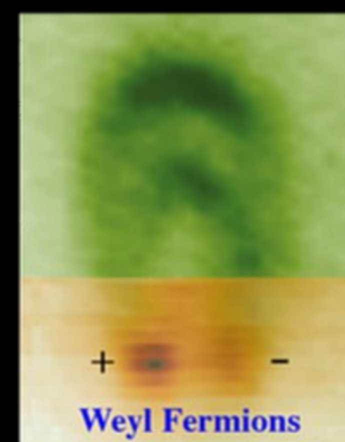


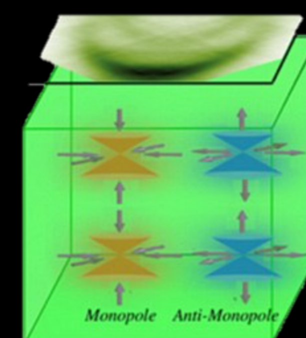


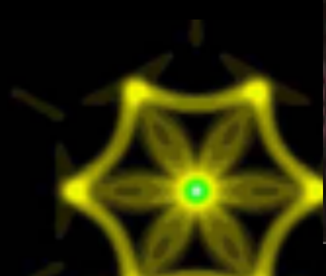


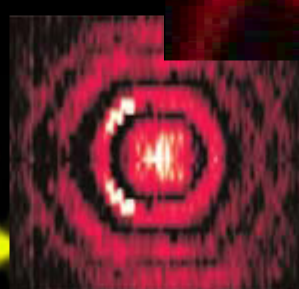


h-Dirac fermions





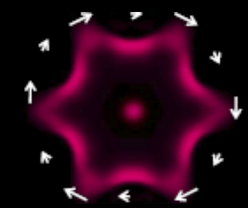




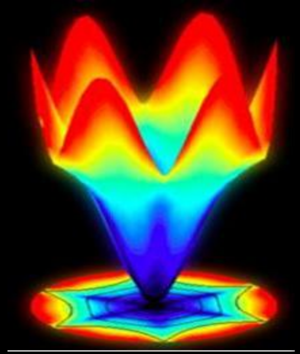
Cover Images: http://physics.princeton.edu/zahidhasangroup/

REVIEWS

(in chrono.order)



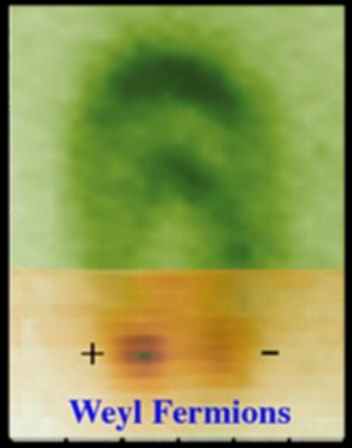
M.Z.H. and C.L. Kane
"Topological Insulators" (and Topological Superconductors)
Rev. of Mod. Phys., (RMP) 82, 3045 (2010)

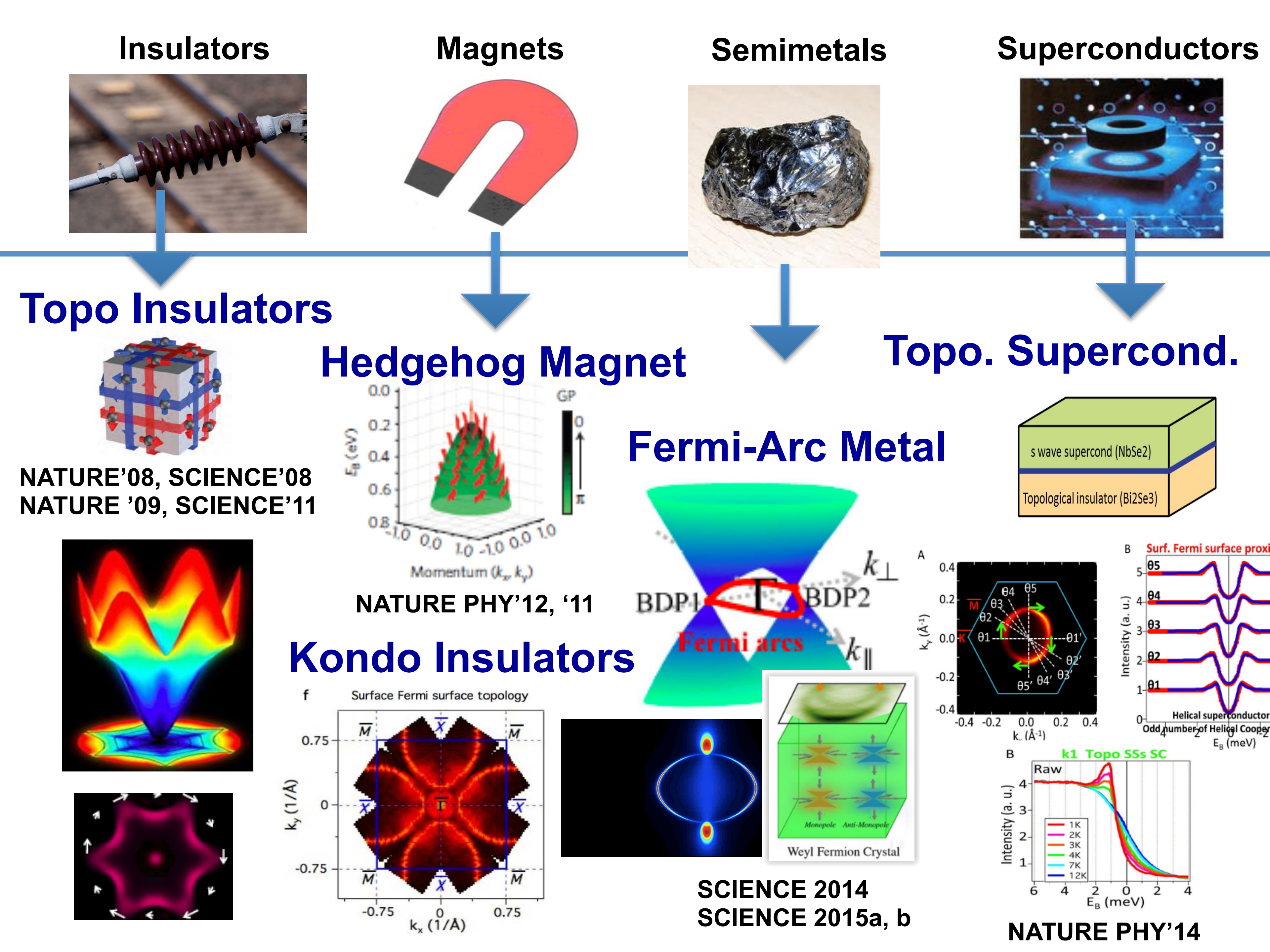


M.Z.Hasan and J.E. Moore
"Three Dimensional Topological Insulators"
Ann. Rev. of Cond. Mat. Phy., 2, 78 (2011)

X.L. Qi and S.-C. Zhang
"Topological Insulators and Superconductors"
Rev. of Mod. Phys., (RMP) 83, 1057 (2011)

AND many other recent excellent reviews…

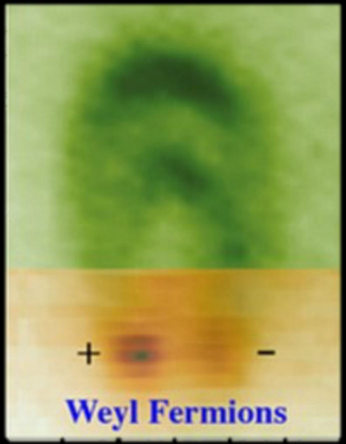



Insulators
Magnets
Semimetals
Superconductors
Topo Insulators
NATURE'08, SCIENCE'08
NATURE '09, SCIENCE'11
Hedgehog Magnet
Momentum (k_x, k_y)
GP
NATURE PHY'12, '11
Kondo Insulators
Surface Fermi surface topology
k_x (1/Å)
k_y (1/Å)
Fermi-Arc Metal
BDP1
BDP2
Fermi arcs
$k_\perp$
$k_\parallel$
Monopole
Anti-Monopole
Weyl Fermion Crystal
SCIENCE 2014
SCIENCE 2015a, b
Topo. Supercond.
s wave supercond (NbSe2)
Topological insulator (Bi2Se3)
Surf. Fermi surface proxi
Helical superconductor
k1 Topo SSs SC
Raw
1K
2K
3K
4K
7K
12K
E_B (meV)
Intensity (a. u.)
NATURE PHY'14

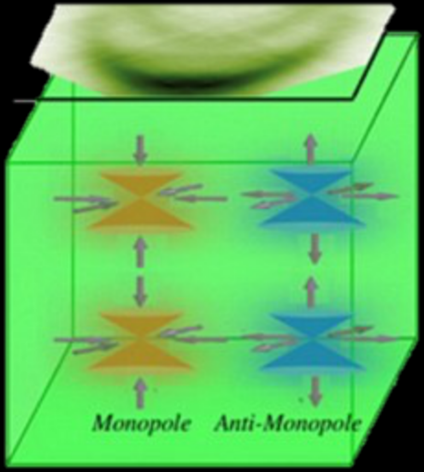
Weyl Fermions
&
Topological Fermi Arcs

M.Z. Hasan (Princeton)

Kavli Institute of Theoretical Physics (2015)



H. Weyl @ IAS-Princeton
(1933-54)



H. Weyl had a Princeton address in his ***1929 Weyl fermion*** paper!

H. Weyl, *Z. Phys.* **56**, 330–352 (1929).

Elektron und Gravitation. I.

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

(Eingegangen am 8. Mai 1929).

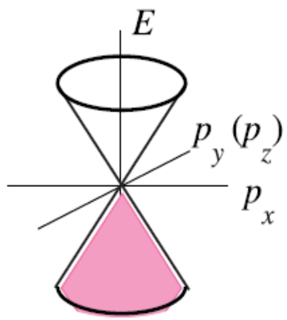
Einleitung. Verhältnis der allgemeinen Relativitätstheorie zu den quantentheoretischen Feldgleichungen des spinnenden Elektrons: Masse, Eichinvarianz, Fernparallelismus. Zu erwartende Modifikationen der Diracschen Theorie. — I. Zweikomponententheorie: Die Wellenfunktion ψ hat nur zwei Komponenten. — § 1. Bindung der Transformation der ψ an die Lorentztransformation des normalen

invarianz gab: die Elektrizität ein Begleitphänomen des materiellen Wellenfeldes und nicht der Gravitation.

Palmer Physical Laboratory, Princeton University, 19. April 1929.

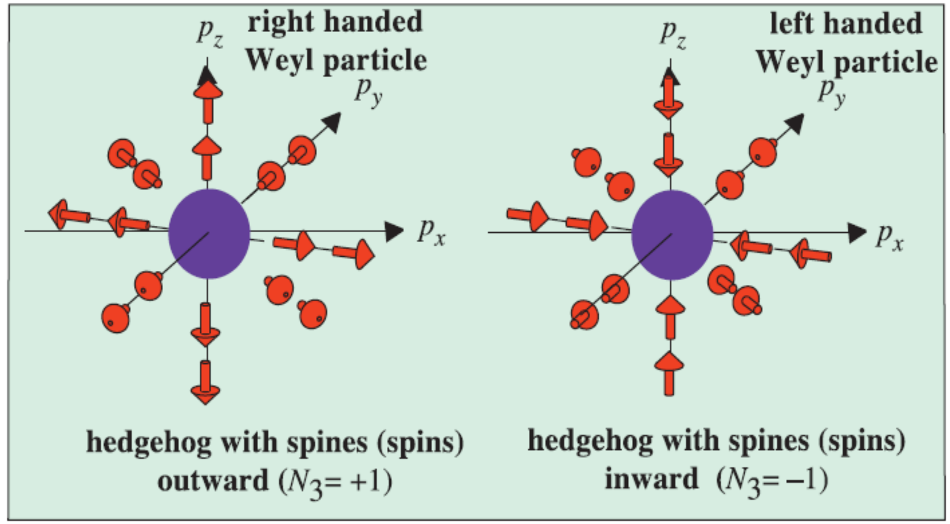
He was at the Institute for Adv. Studies (IAS) from 1933 to 1954

Weyl Fermions and Quantum Topology



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

Weyl particles in Standard Model - hedgehogs in p-space



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

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

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

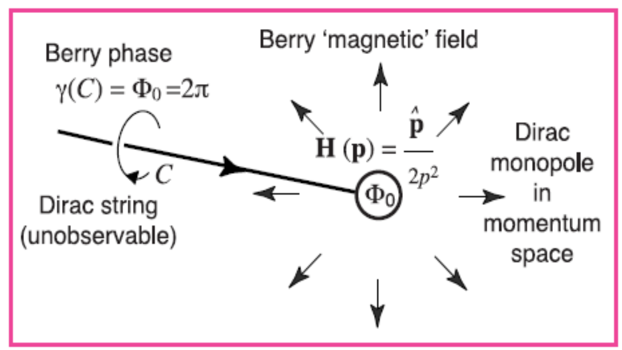
$H = -\,c\,\sigma \cdot \mathbf{p}$

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

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

over 2D surface
around Fermi point

p-space topological invariant
for Weyl particles

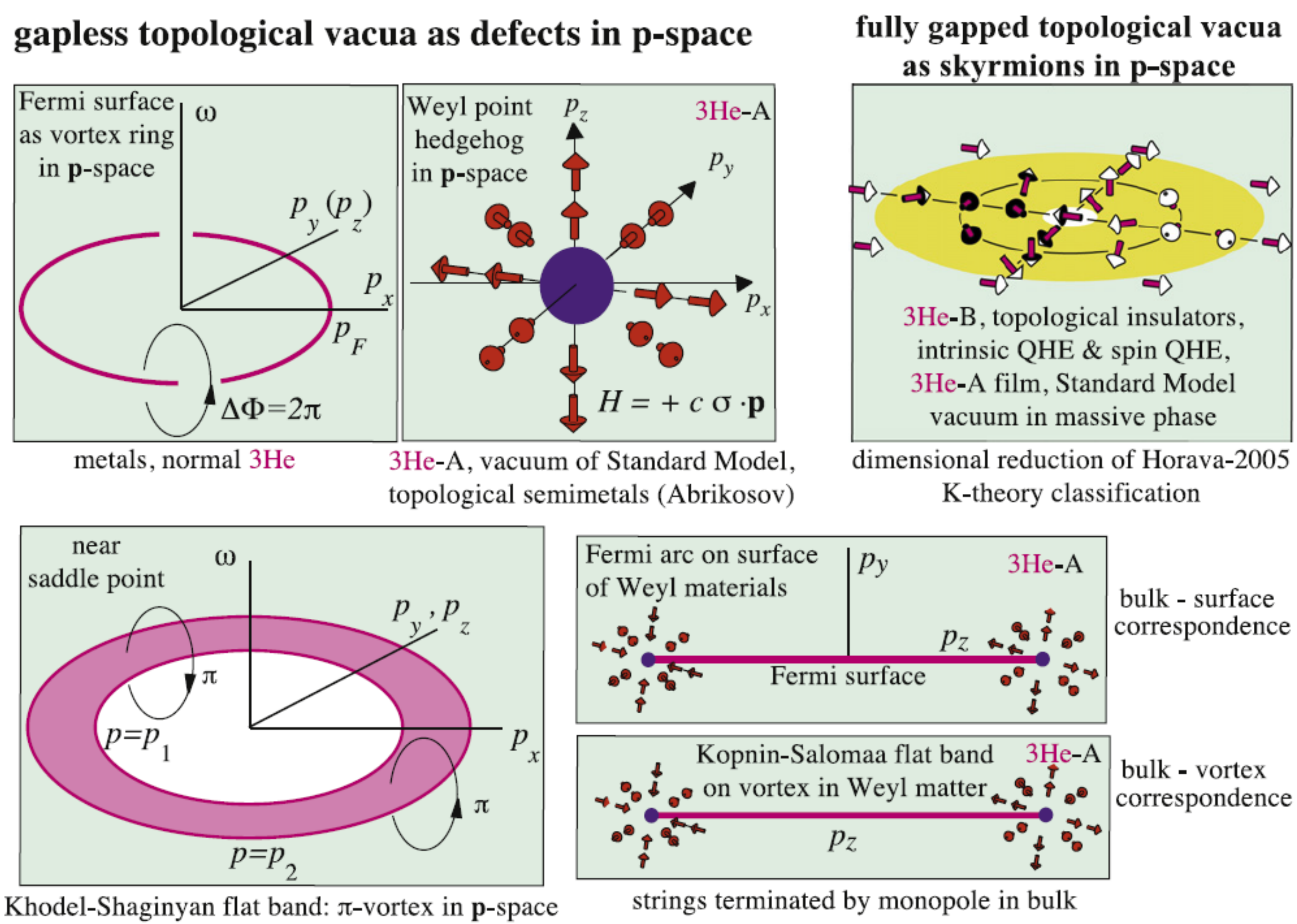


Weyl point: Berry-Dirac monopole in p-space

Theory: Weyl (1929), Volovik (1987, 2015); von Neumann & Wigner (1929)

M.Z. Hasan (Princeton) talk at KITP

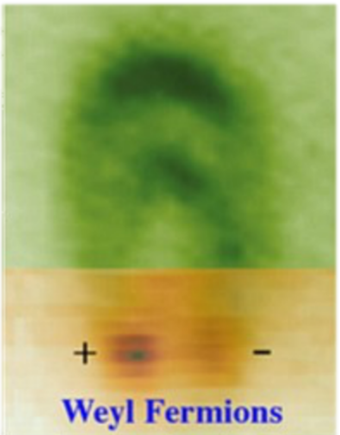
Weyl Fermions and Quantum Topology



Volovik, Phys. Scr. (2015)

M.Z. Hasan (Princeton) talk at KITP

Sciencexpress
Research Articles



Discovery of a Weyl Fermion semimetal and topological Fermi arcs

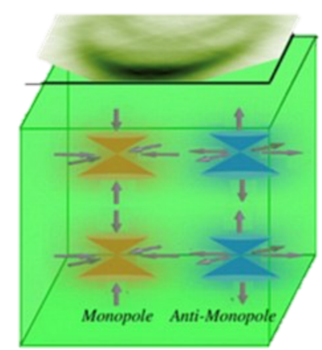
16th July, 2015

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*]



Fermi arc ("fractional" Fermi surfaces) in topological systems

Sciencexpress | Research Articles

Discovery of a Weyl Fermion semimetal and topological Fermi arcs

July 16th, 2015

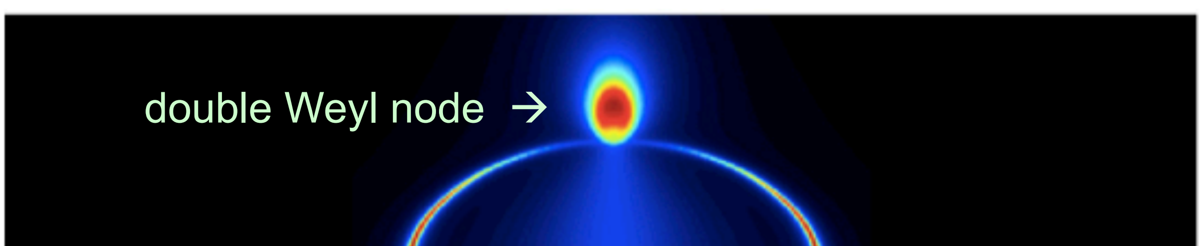
Su-Yang Xu,[1,2*] Ilya Belopolski,[1*] Nasser Alidoust,[1,2*] Madhab Neupane,[1,3*] Guang Bian,[1] Chenglong Zhang,[4] Raman Sankar,[5] Guoqing Chang,[6,7] Zhujun Yuan,[4] Chi-Cheng Lee,[6,7] Shin-Ming Huang,[6,7] Hao Zheng,[1] Jie Ma,[8] Daniel S. Sanchez,[1] BaoKai Wang,[6,7,9] Arun Bansil,[9] Fangcheng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

Sciencexpress | Reports

Observation of Fermi arc surface states in a topological metal

December, 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]†



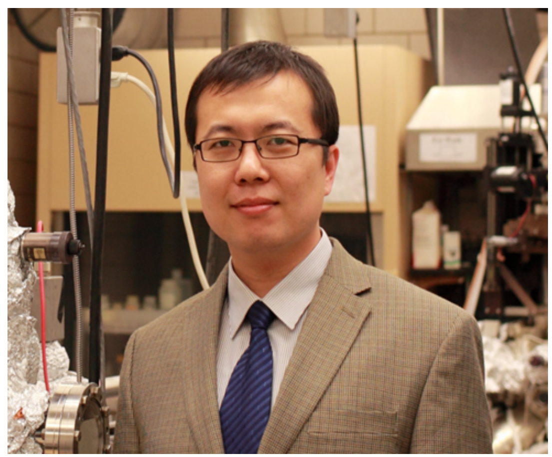
Princeton ARPES team

Suyang Xu

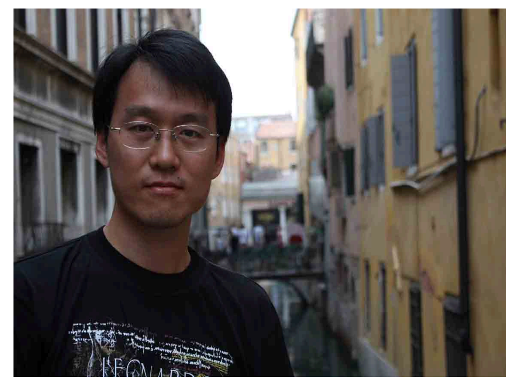
Ilya Belopolski

Nasser Alidoust

Madhab Neupane



Guang Bian



Hao Zheng

+ more …

Physics/Experiments/ARPES Team at Princeton

SuYang Xu, Chang Liu, N. Alidoust, M. Neupane, Ilya Belopolski
Pavel Shibayev, Daksh Sharma, MZH (Princeton)
(previously) D.Hsieh (CalTech), D.Qian (Shanghai), L.A.Wray (LBNL)

Sample chemistry/MBE Collaborations

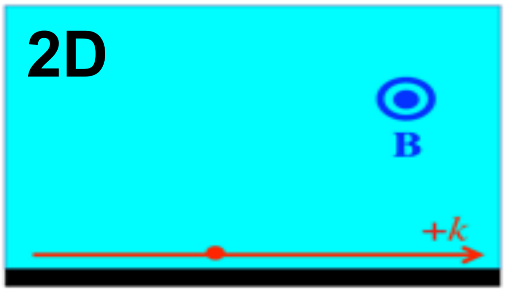
Solid-State: S. Jia, Y. Hor, R.J. Cava (PU Chemistry) F.C. Chou (Taiwan)
MBE films: D. Zhang, A. Richardella, Nitin Samarth (PennState)
MBE/SolidState: Yong Chen et al (Purdue);
MBE: M. Brahlek, Bansal, S.-H. Oh (Rutgers)
SSS: Morosan (Rice); TKI samples : Z. Fisk
Transport: J. Xiong, N.P. Ong (Princeton), L. Balicas (Florida)

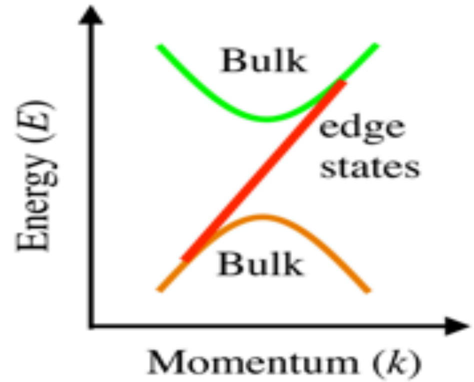
National Lab Beamline Support+Collaborators

H.K. Mo, A. Wray, Z. Hussain, A. Fedorov et.al., (LBNL/ALS-Berkeley)
G. Landolt; B. Slomski; J.H. Dil, J. Osterwalder et.al., (SLS/COPHEE)
M. Leandersson; T. Balasubramanian; A. Preobrajenski (MaxIII)
M. Hashimoto, D.H. Lu et.al., (SSRL/Stanford)
E. Vescovo (NSLS); Tomasz Durakiewicz (Los Alamos)
S. Barriga; D. Marchenko; A. Varykhalov; O. Rader (BESSY);
T. Kondo, S. Shin (ISSP and Univ. of Tokyo)

Lets focus on (band) ***INSULATORS*** first

1
Invaritant

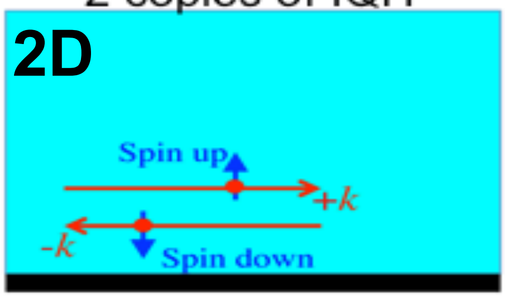


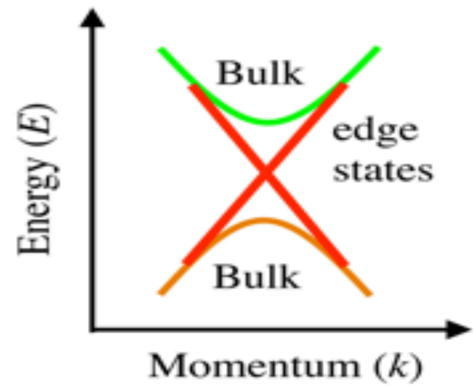


Quant. Hall physics

2 copies of IQH

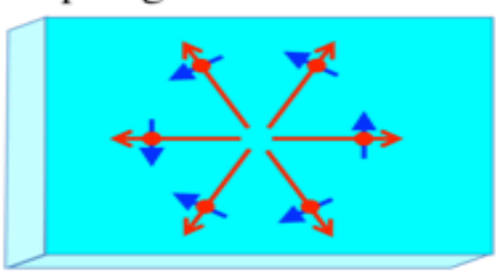
1
Invaritant

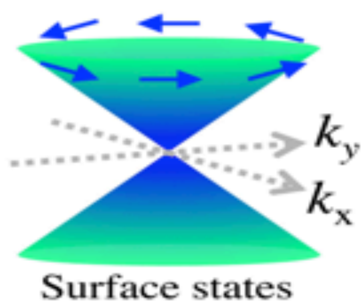


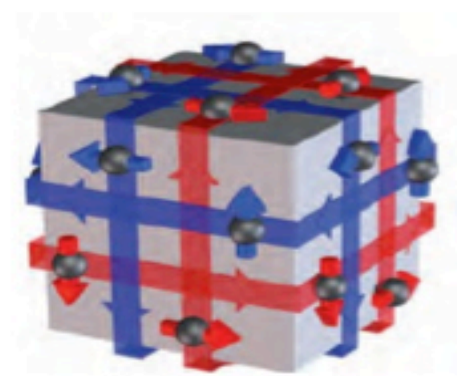


Topological Surface States

4
InvaritantS



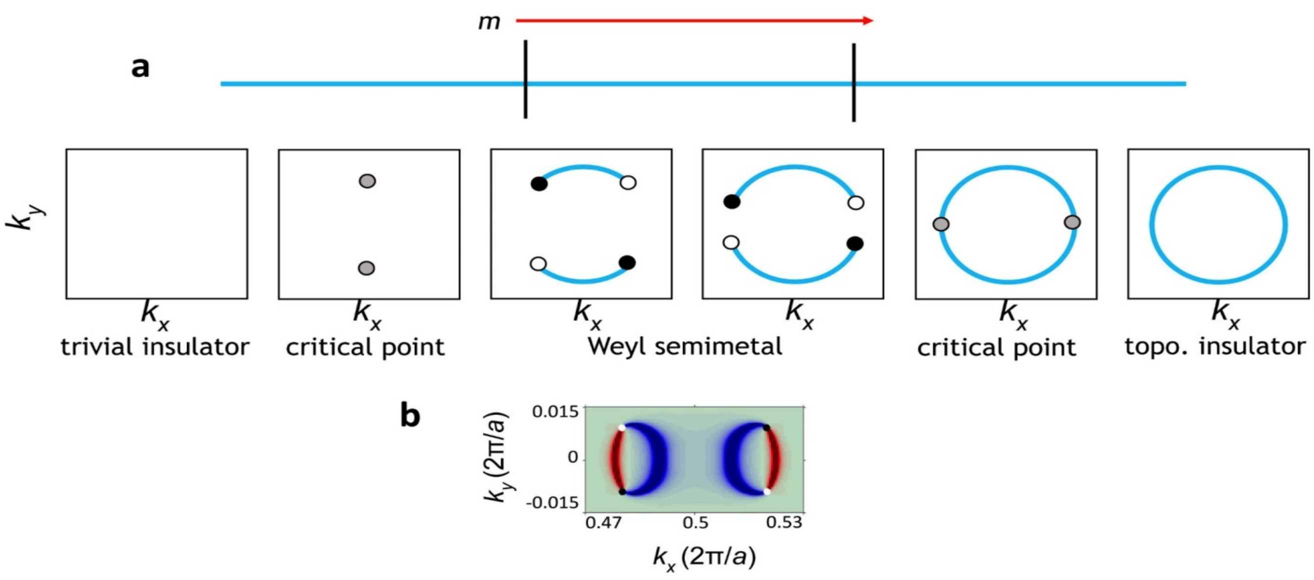




3D **Topo. Insulator**

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

Phase Diagram of Topological Matter and Experimental Realizations



nature COMMUNICATIONS

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

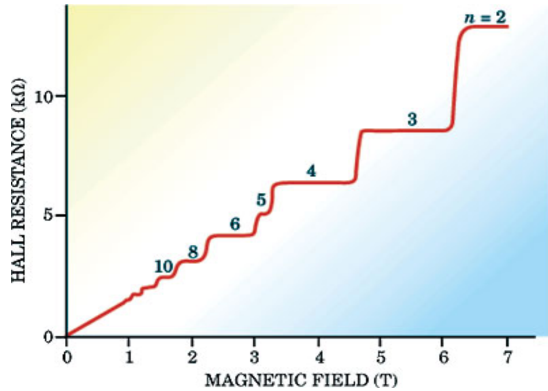
Shin-Ming Huang[1,2,*], Su-Yang Xu[3,4,*], Ilya Belopolski[3,4,*], Chi-Cheng Lee[1,2], Guoqing Chang[1,2], BaoKai Wang[1,2,5], Nasser Alidoust[3,4], Guang Bian[3], Madhab Neupane[3,4,6], Chenglong Zhang[7], Shuang Jia[7,8], Arun Bansil[5], Hsin Lin[1,2] & M. Zahid Hasan[3,4,9]

QHE phases (2D)

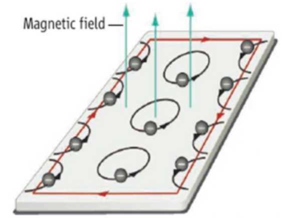
$\sigma_{xy} = \mathbf{n}e^2/h$

↑

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

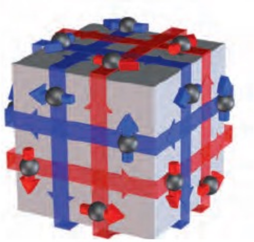
$\{\nu_0, \nu_1\ \nu_2\ \nu_3\}$

Topological "order parameters!"

No quantized transport

via : $\{\nu_i\}$

↑



?

Spin-sensitive

Momentum-resolved

Edge vs. Bulk

(Bulk-Boundary Correspondence)

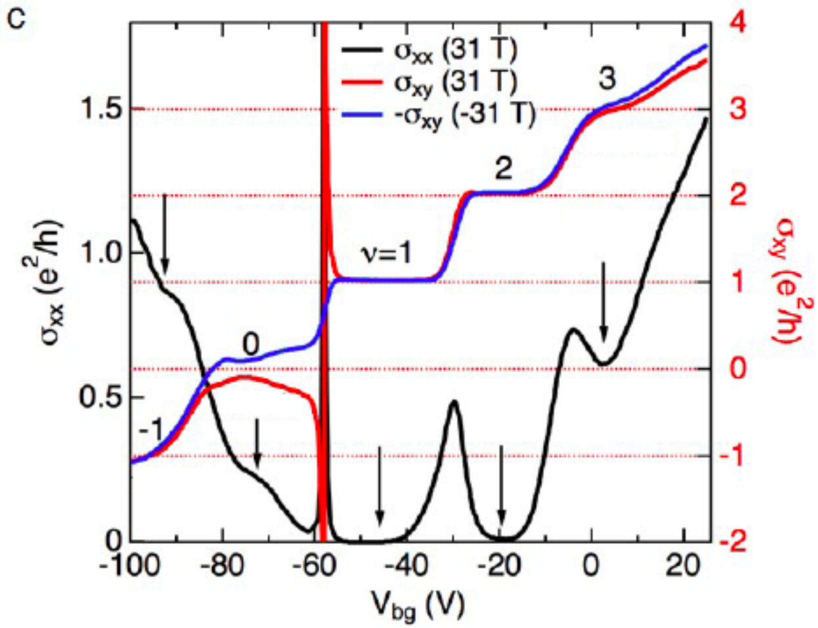
Lets look at <u>transport</u> first

Bulk insulating (intrinsic) Topological insulators exist.

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

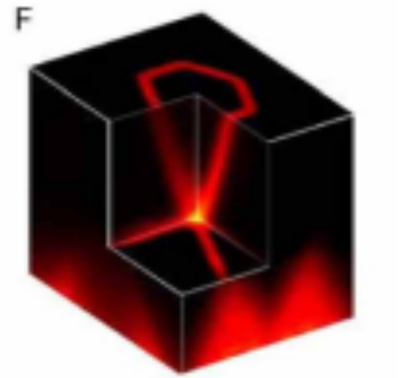
QHE for a 3D **Topo.Insulator** : Bi(Sb/Te)Se2

Transport



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

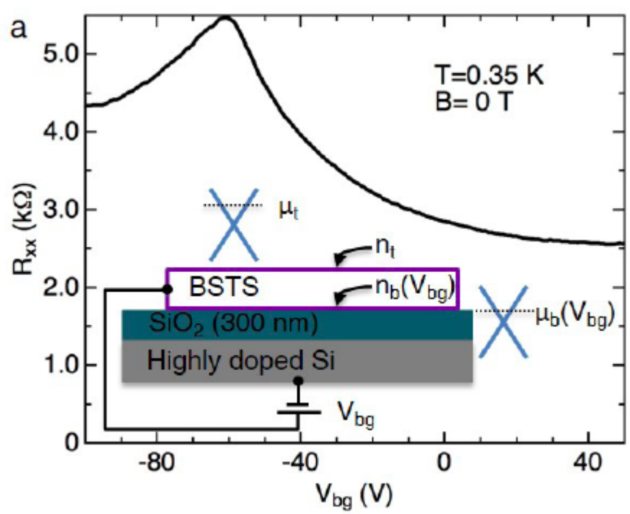
Nature Physics (2014)

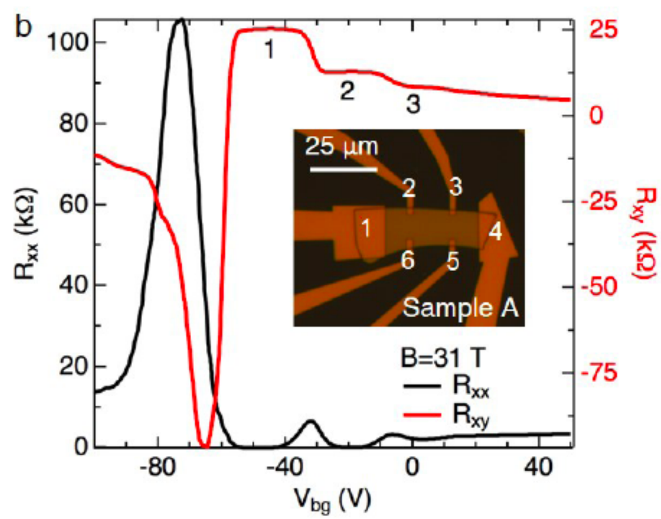


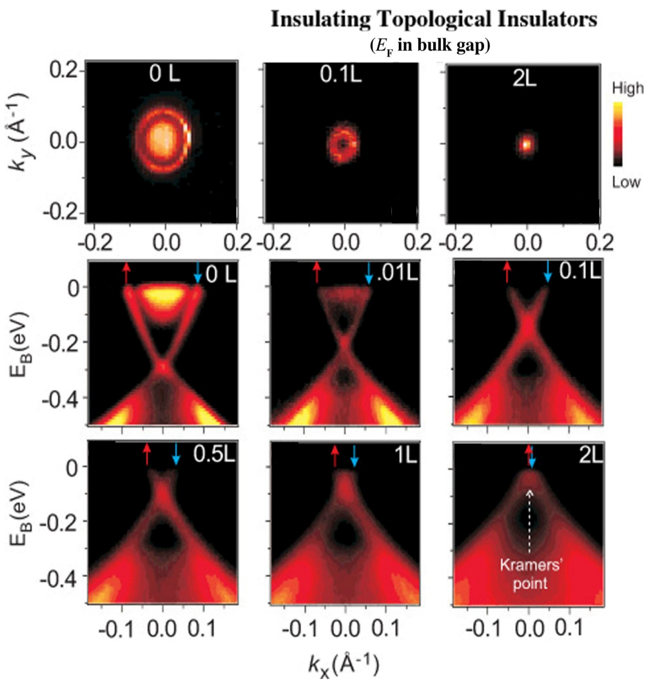
TI = 2 surf's(Top + Bot.) of Dirac gas

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

only Integer QHE !

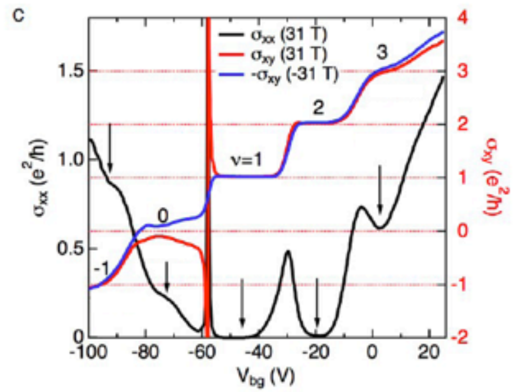






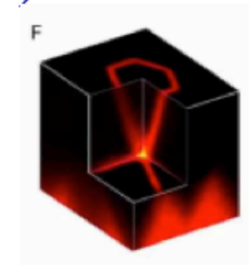
QHE for a 3D **Topo.Insulator** : Bi(Sb/Te)Se2

Transport



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

Nature Physics (2014)



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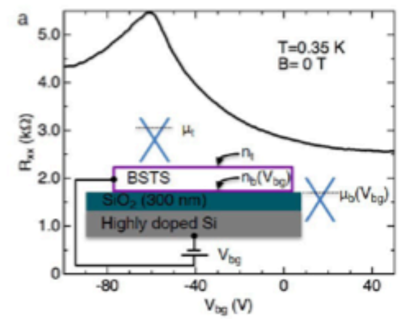
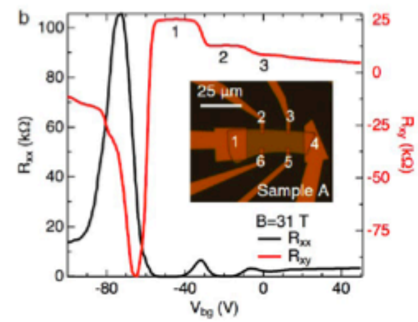
only Integer QHE !

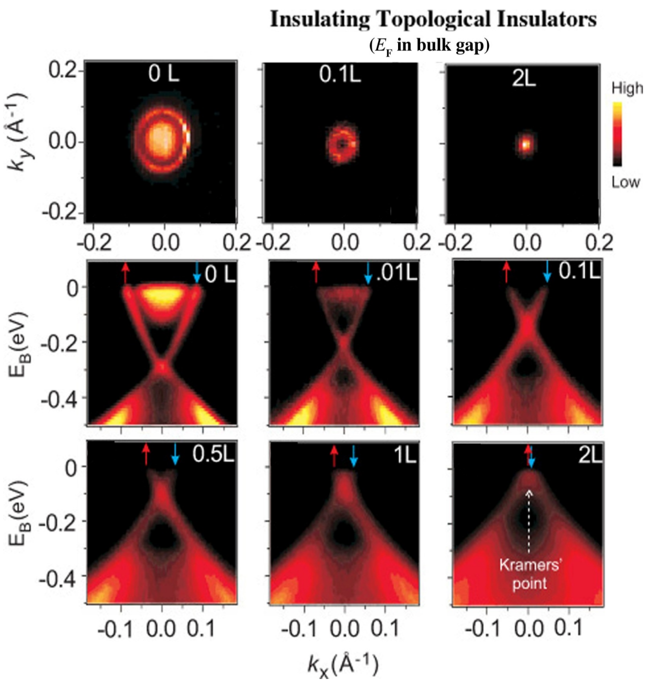




Yes!

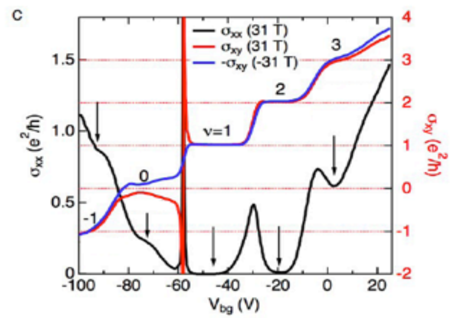
Bulk insulating (intrinsic)
Topological insulators exist.

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



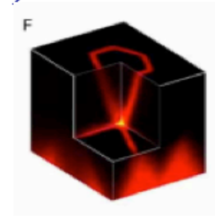
QHE for a 3D **Topo.Insulator** : Bi(Sb/Te)Se2

Transport



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

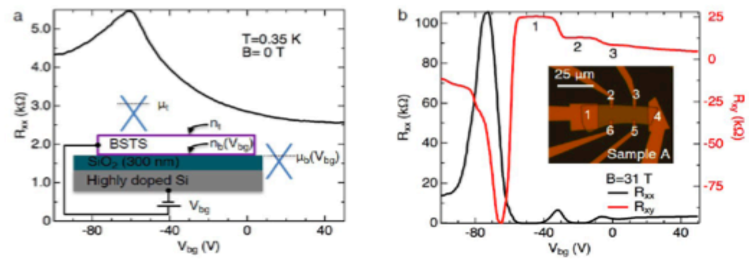
Nature Physics (2014)



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

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

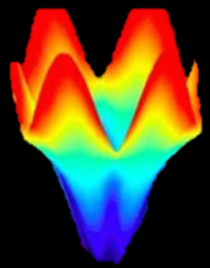
only Integer QHE !



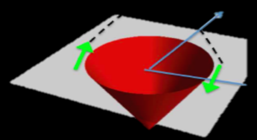
Since the bulk is intrinsically insulating in these topo.insulators, it is possible to observe topo. surface state transport in the form of QHE (since QHE is only possible with 2D electron syst. like 2DEG or 2D surface states).

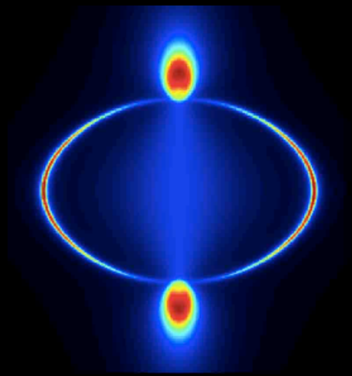
BUT by looking at the transport data alone one cannot tell if topo. Insulators are a new states of matter (?) since transport (QHE) do not couple to the Z_2 invariants directly.

Measurements of Z_2 invariants were done (first) by SPECTROSCOPIES
Thus it is ARPES that provided the first proof of Z_2 topology of insulators introduced by Kane & Mele.



Topo. Insulator



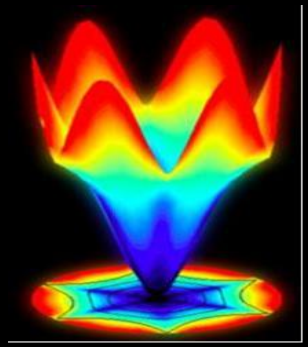


Topo. Superconductors
Helical Pairing

Majorana

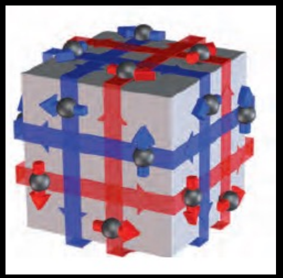
Weyl Semimetals
Topological Fermi Arcs

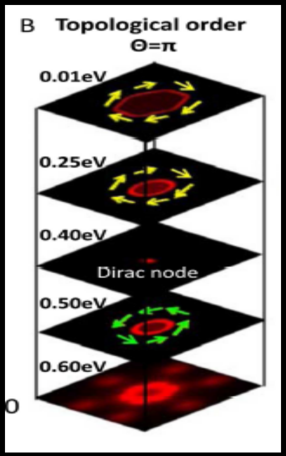
Weyl Fermion



Topological Insulators

A New Form of Quantum Matter





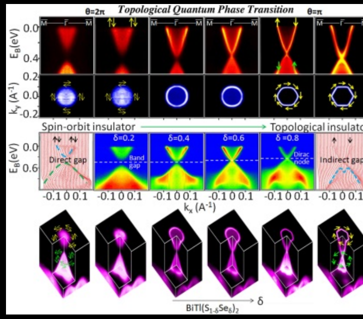
1. Surface States exist and locate inside the bandgap and ½ metallic throughout (**Nature' 08,** submit. **2007**)

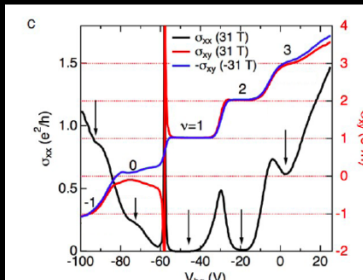
2. Spin - Momentum Locking (Spin-Texture, Berry's phase) (**Nature' 09, Science' 09**)

3. Topo Phase transition (BI to TI) via spin-orbit tuning (**Science' 10-11**)

4. Robust up to room temperature (**Nature' 09**)

5. Absence of backscatt. by Spin-Texture (**Nature' 09**)



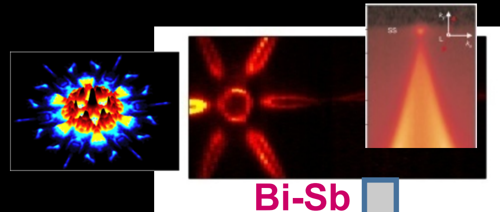


M.Z.H. & CL Kane, Rev. Mod. Phys. 82, 3045 (2010)

Experiments on Topo.Insulators (3D)

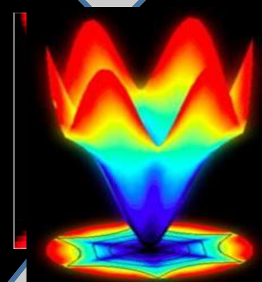
500+

Papers on Bi-based TIs



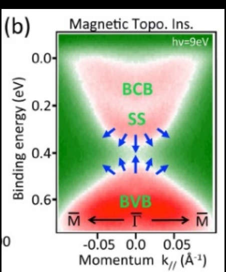
Hsieh et.al., NATURE 08 (sub. 2007)
Hsieh et.al., SCIENCE 09
Roushan et.al., NATURE 09

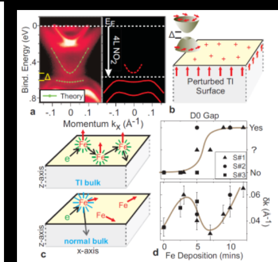
Bi_2X_3



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

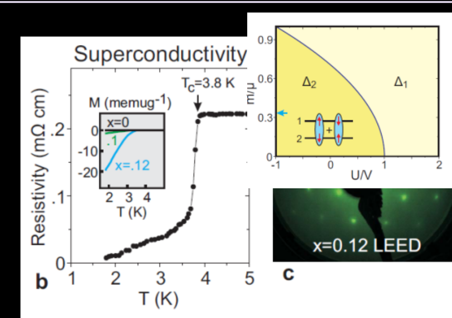
Magnetic TI





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

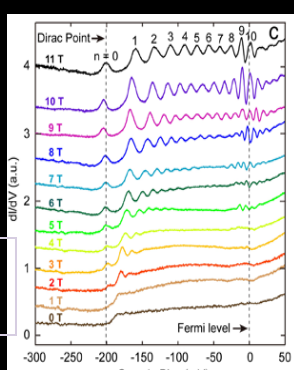
Superconductivity

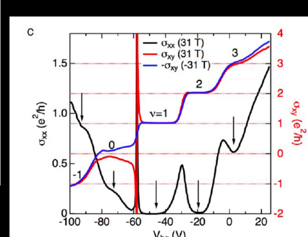


Hor et.al., PRL 2
Wray et.al., Nphy
Ando et.al, PRL

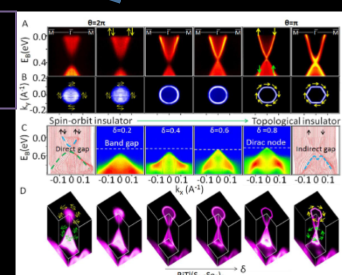
Quantum Hall effect

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





QAHE



Topo. Q. Phase Transition

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

Topo. Kondo Insulators

T-breaking topo. Superconductors

V. Mourik *et al.*, *Science* **336**, 1003 (2012). Delft group
L. Rokhinson *et al.*, *Nature Phys.* (2012). Purdue group
Das *et al.*, *Nature Phys.* **8**, 887 (2012). Israel group
…….more on nanowires…
S. Nadj-Perge *et al.*, *Science* **346**, 602 (2014) STM

These are analogs of Quantum Hall fluids (T-breaking, chiral)

How about the Z_2 Topo. Insulators (Helical)

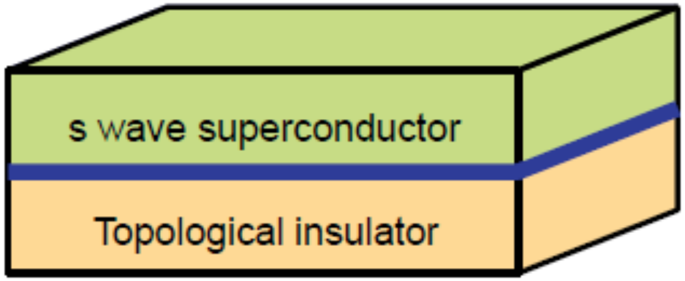
Goals: Not just ZBP but observe:

1. **Helical Cooper Pairing**
2. **Topo. SC gap**
3. **Order parameter (p + ip)**

Majorana Platform

Superconducting Proximity Effect

Fu, Kane PRL 08

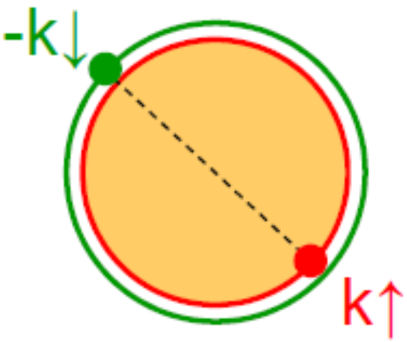


Surface states acquire superconducting gap Δ due to Cooper pair tunneling

BCS Superconductor :

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

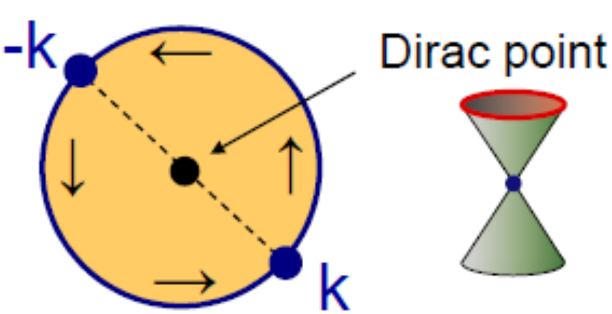
(s-wave, singlet pairing)



Superconducting surface states

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

(s-wave, singlet pairing)

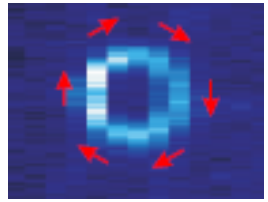


Half an ordinary superconductor
Highly nontrivial ground state

Slide from C. Kane

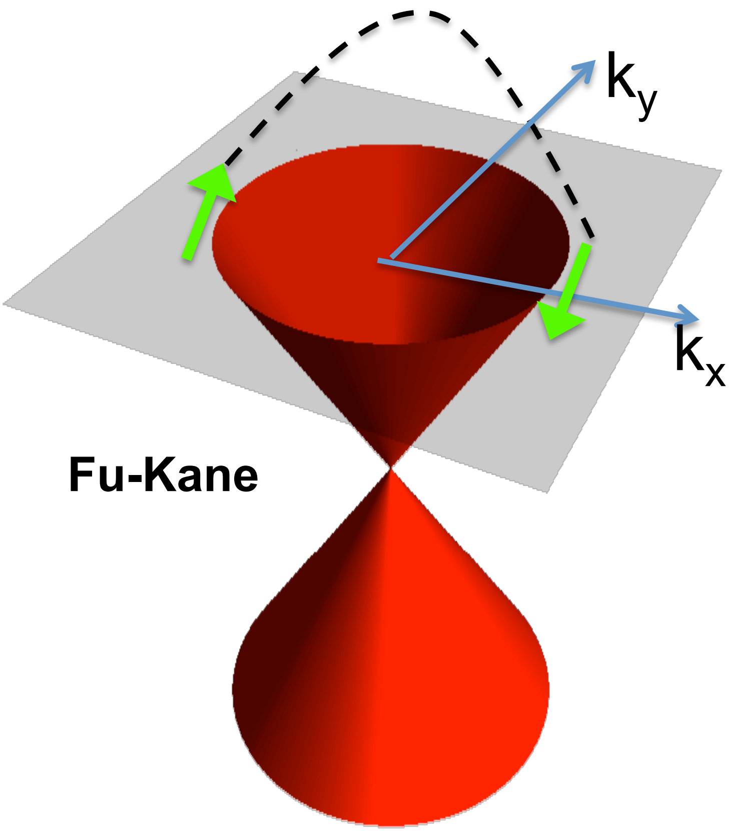
Topo. Superconductors

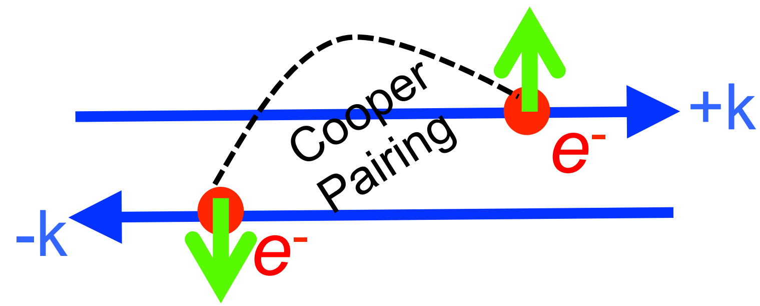
Helical pairing,
(*Singlet+Triplet*)



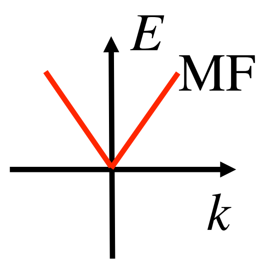
Topo.SC/SF : He3(B)

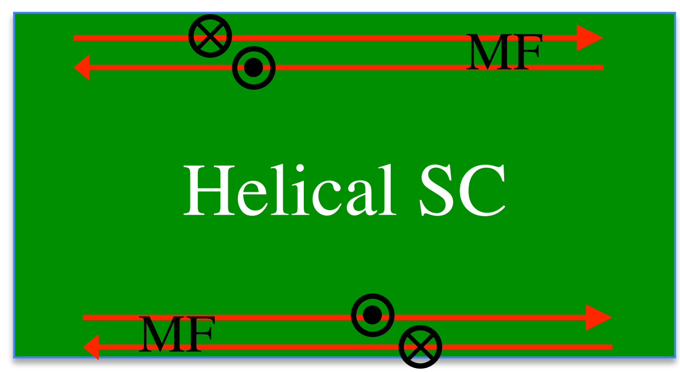
***Helical* SC,**
Odd number of *Helical* pairing





Fu-Kane



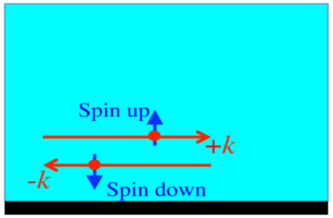


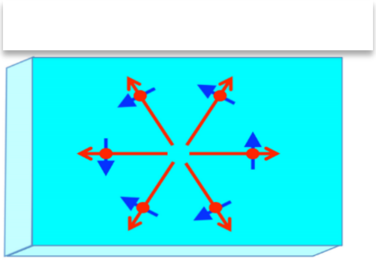
Topo. SF/SC: Volovik; Kitaev, Moore-Read; Roy; Sato; Fu-Kane, many others

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

MBE growth

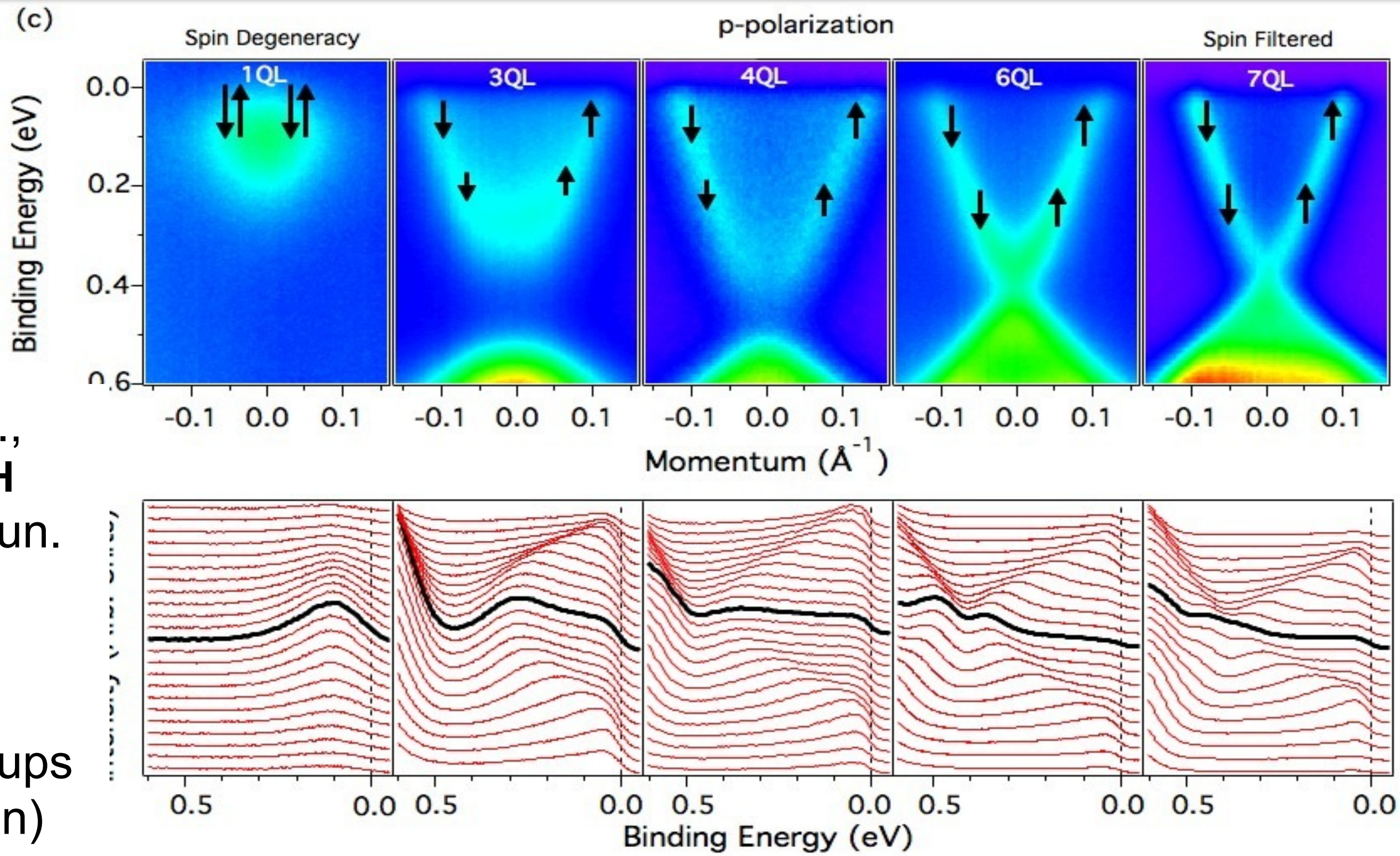
Spin changes
as one 2D -> 3D
3D → 2D (BULK)





2D ⟷ 3D

1 QL



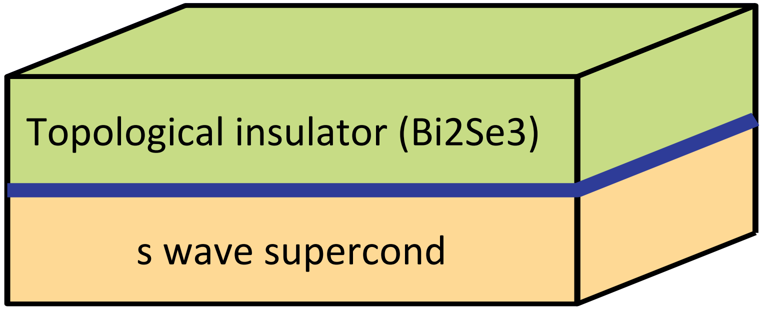
7 QL

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

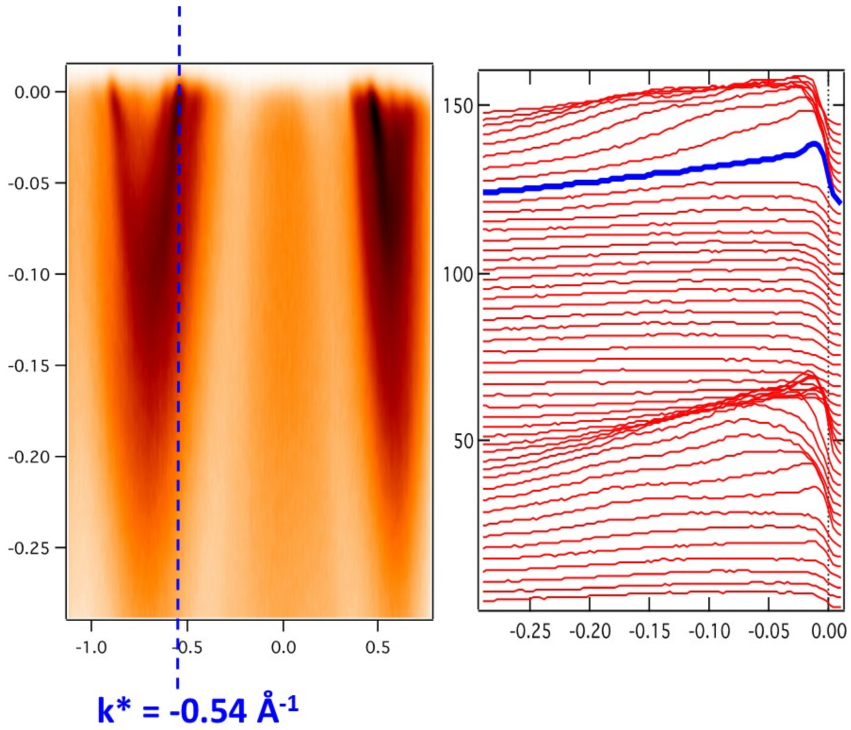
Work by
Xue & Jia groups
'12 (w/out Spin)

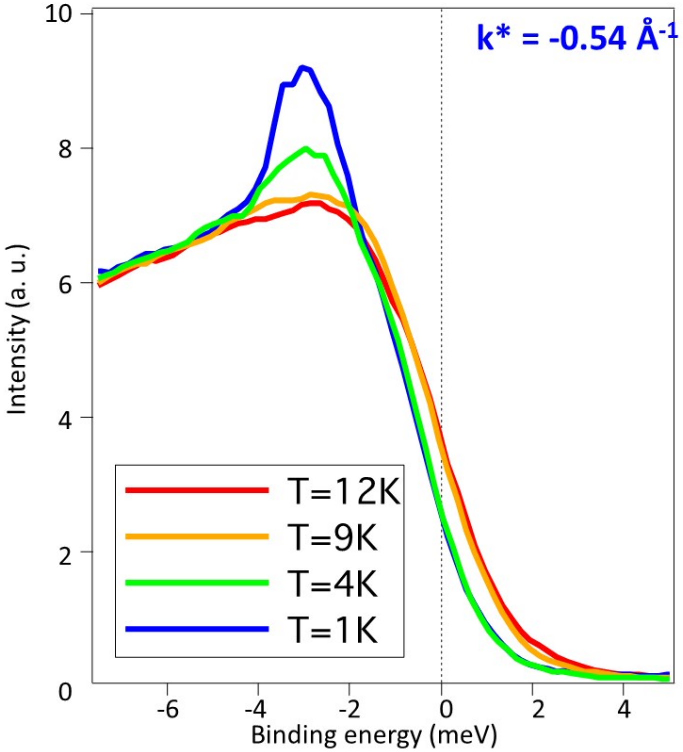
Make a Topological Superconductor: Superconducting Heterostructures

Guiding principle : spin-texture evolution

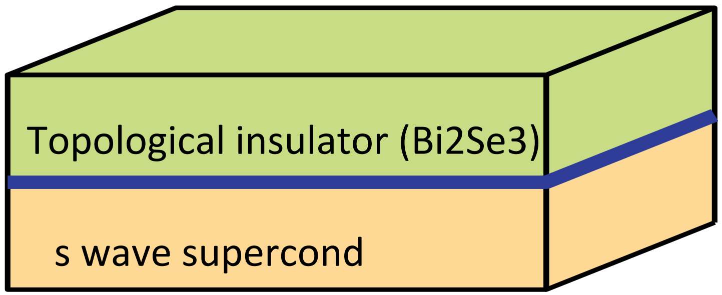


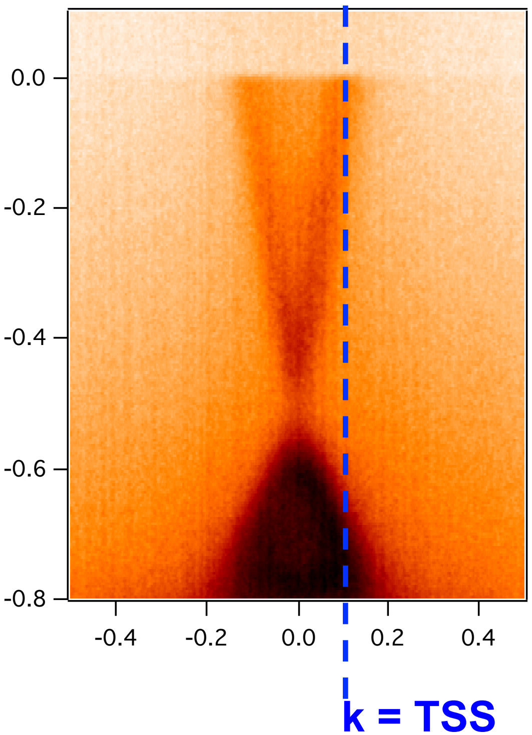
Spin-ARPES Observation of Proximity effect SC/Bi2Se3 Interface ?

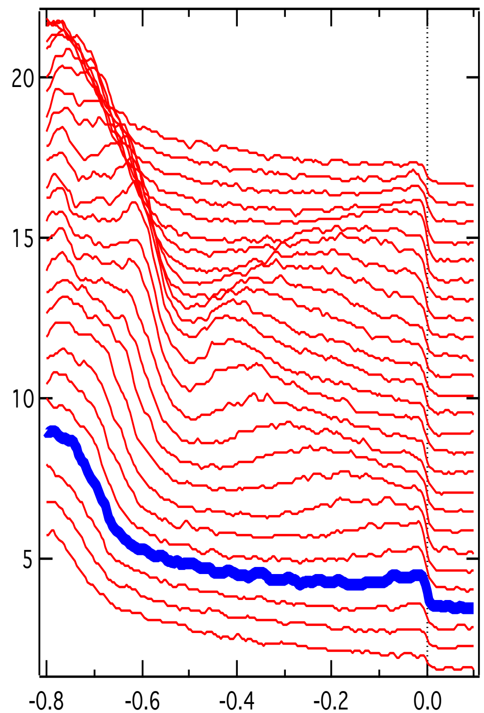


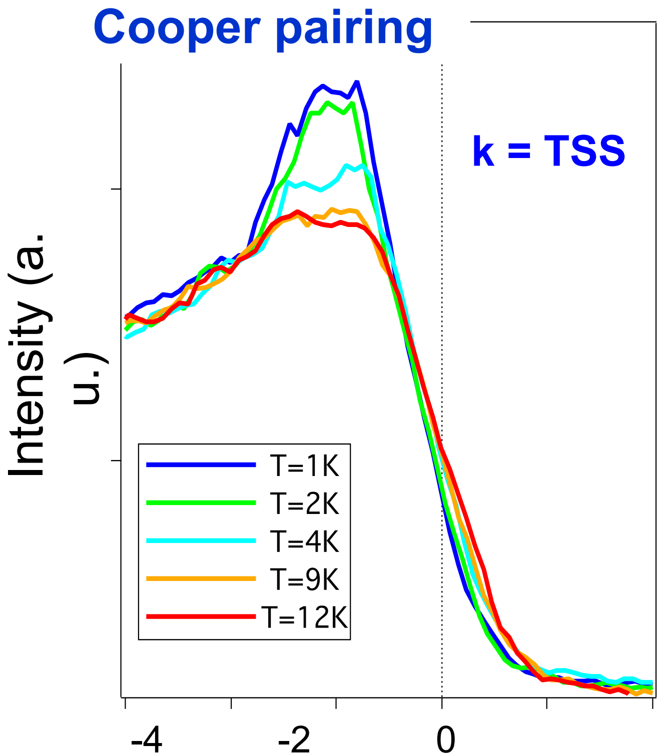


ARPES Observation of <u>Proximity effect</u> SC/Bi2Se3 Interface



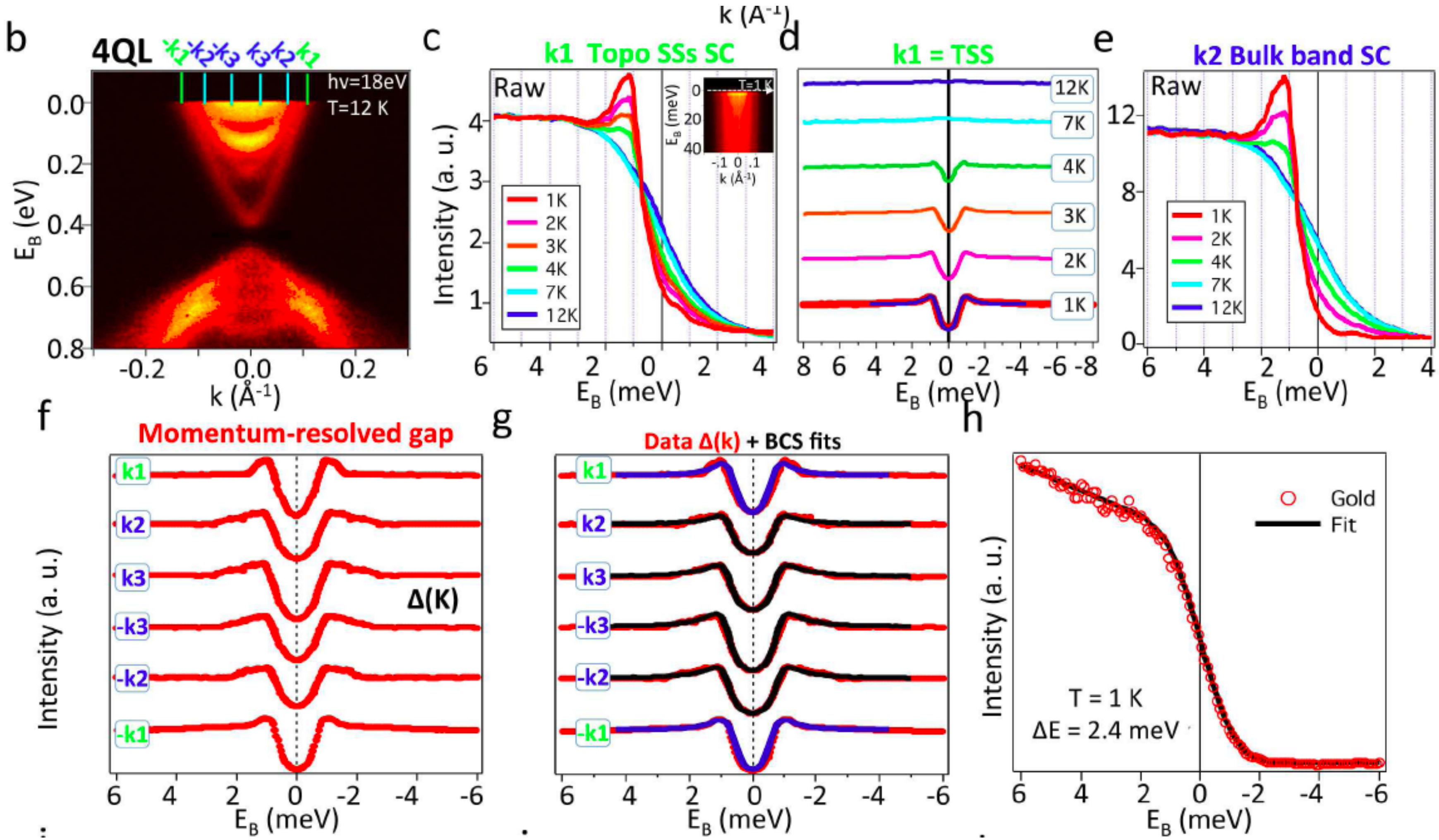






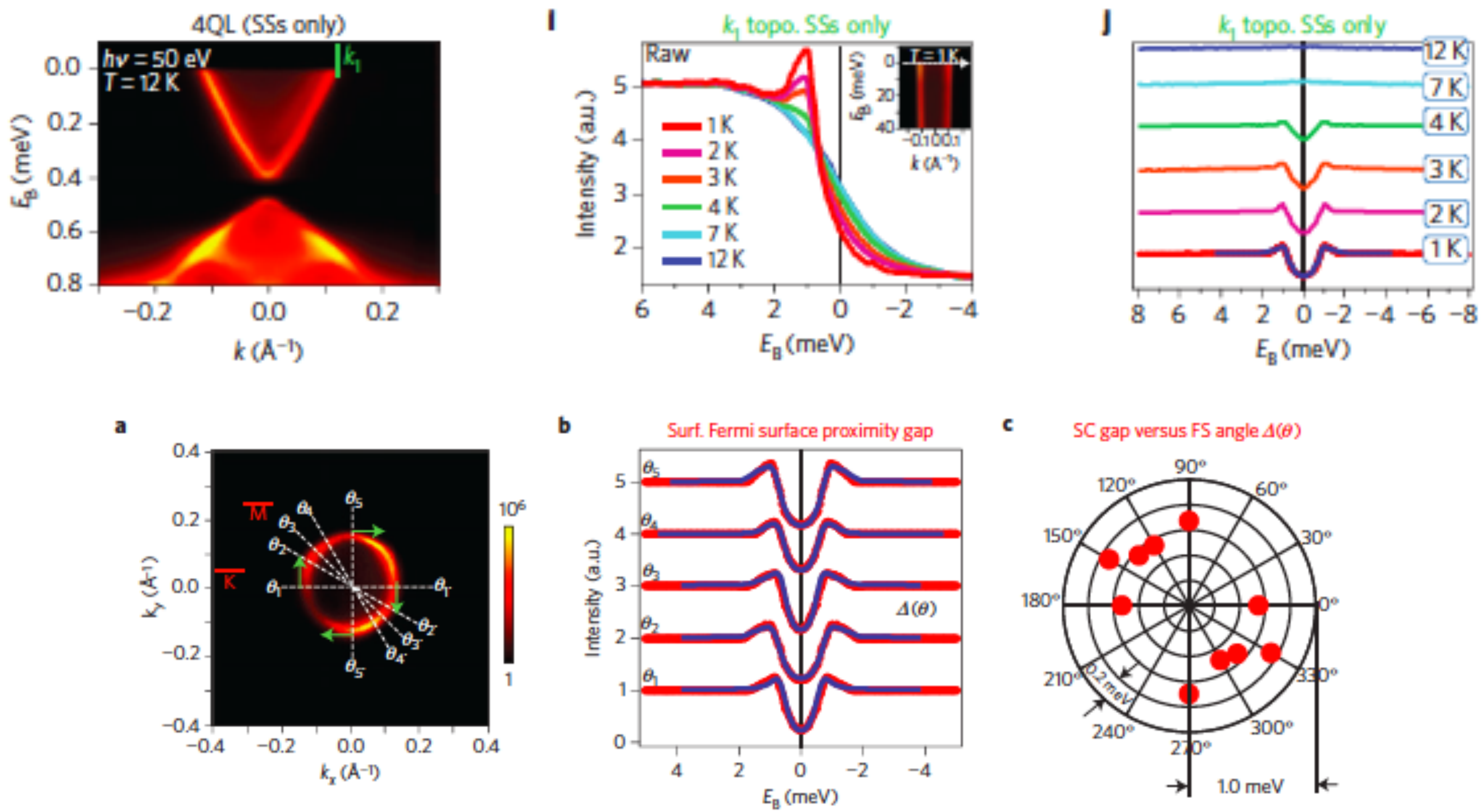
Data Images: http://physics.princeton.edu/zahidhasangroup/

Observation/demonstration of SC in the topo. Dirac SSs (Bi2Se3/NbSe2)



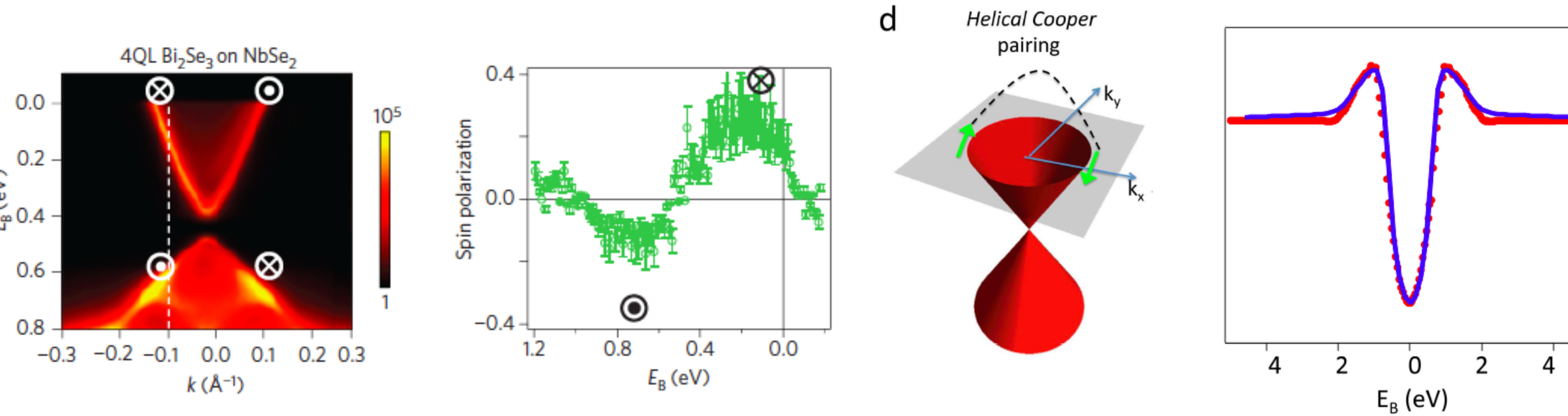
S.-Y. Xu, C. Liu *et al.*, *Nature Phys.* 10, 943 (2014).

Topo. Supercond. Gap ~ 1.5 meV (large!)



S.-Y. Xu, C. Liu *et al.*, *Nature Phys.* 10, 943 (2014).

Observation of SC in the Dirac SSs = Helical TSC

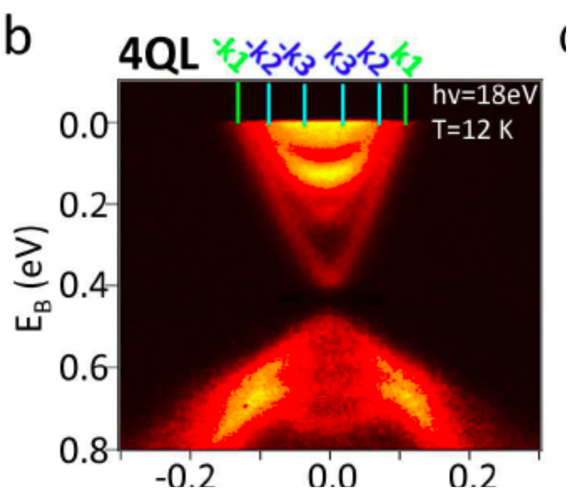


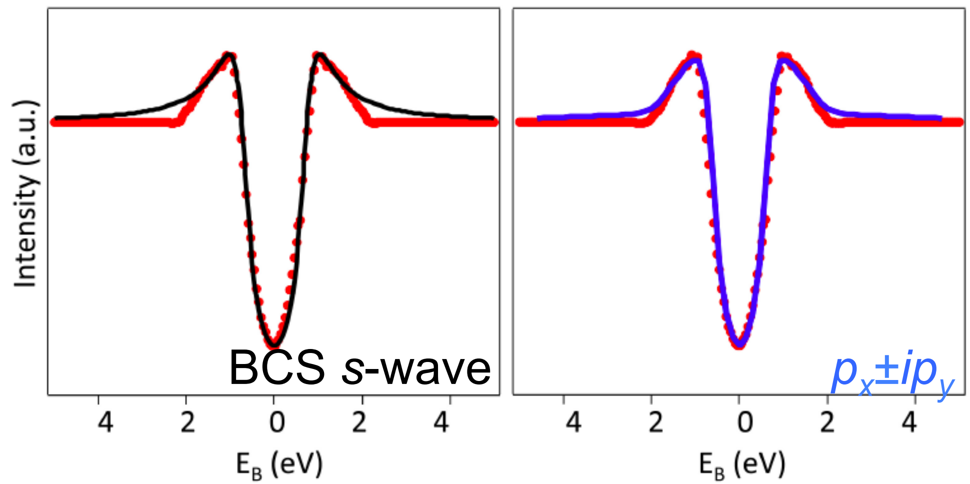
$$b_{\vec{k}} = e^{i\theta/2} c_{\vec{k},\uparrow} + e^{-i\theta/2} c_{\vec{k},\downarrow} \; (e^{i\theta} = \frac{1}{p}(p_x + ip_y))$$

$$\Delta(\vec{k})_{\text{helical SSs}} = b_{\vec{k}} b_{-\vec{k}} = [(\frac{1}{p}(p_x + ip_y))c_{\vec{k},\uparrow} c_{-\vec{k},\uparrow}] - [(\frac{1}{p}(p_x - ip_y))c_{\vec{k},\downarrow} c_{-\vec{k},\downarrow}]$$
$$- [c_{\vec{k},\uparrow} c_{-\vec{k},\downarrow} - c_{\vec{k},\downarrow} c_{-\vec{k},\uparrow}]$$

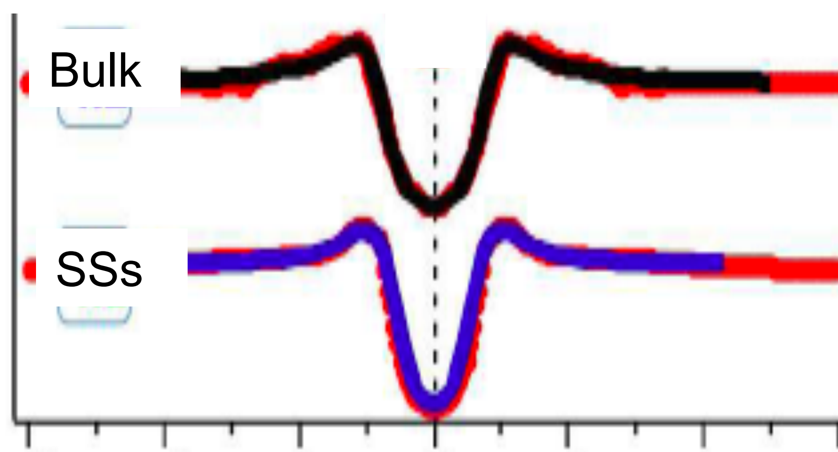
SC gap fitting
Surafce $p_x \pm ip_y$; Bulk band: *s*-wave

<u>Surface state gap fitting</u>





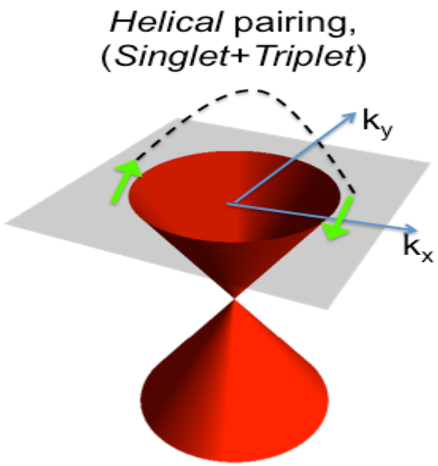
<u>Surface *vs* bulk gap fitting</u>

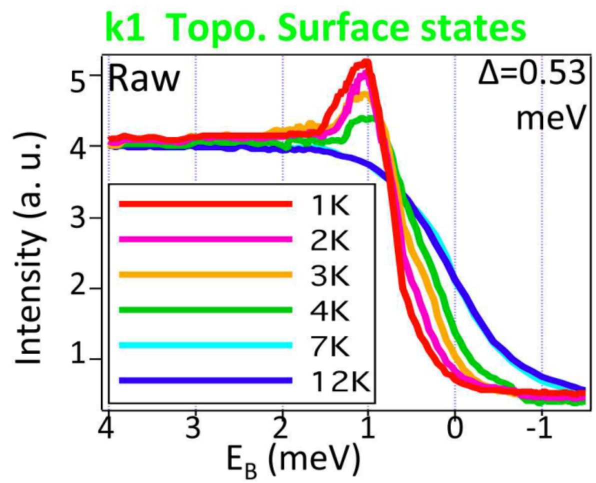


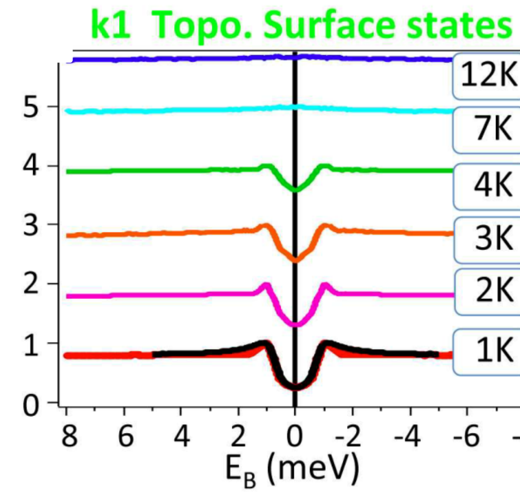
2D Topo. Superconductor

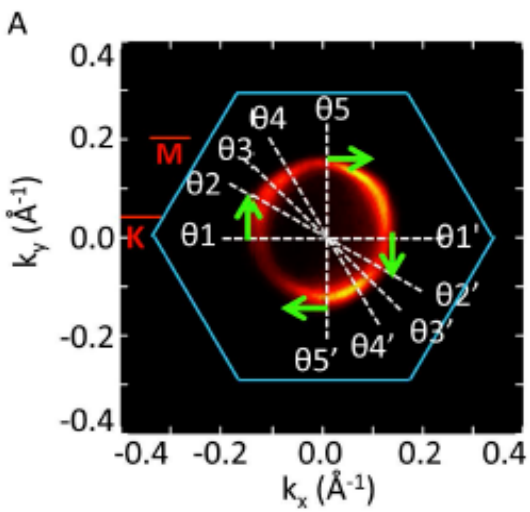
ARPES ⟷ MBE Growth

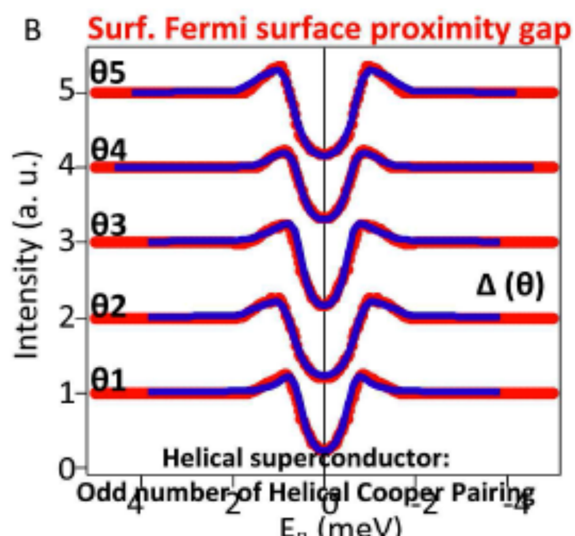
Feedback Loop!

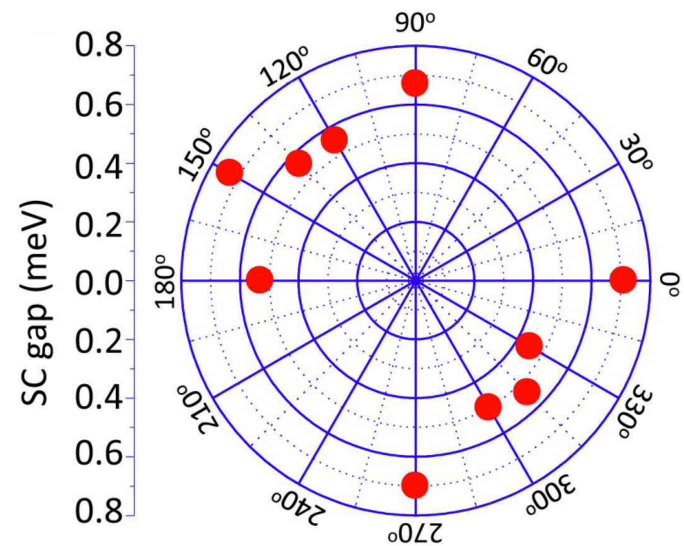










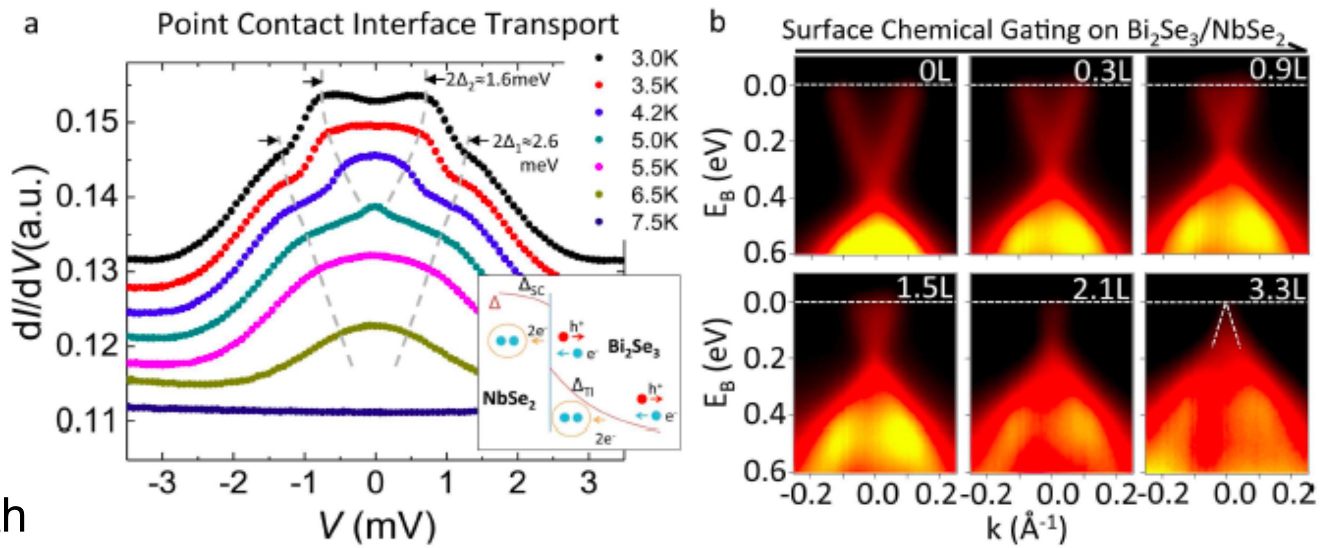


S. Xu, C. Liu et.al., (MZH) Nature Phys (2014)

Samples can be driven near a Critical Point

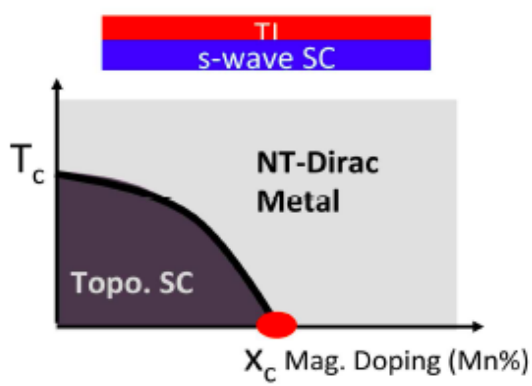
(Emergent SuperSymmetry in theory)

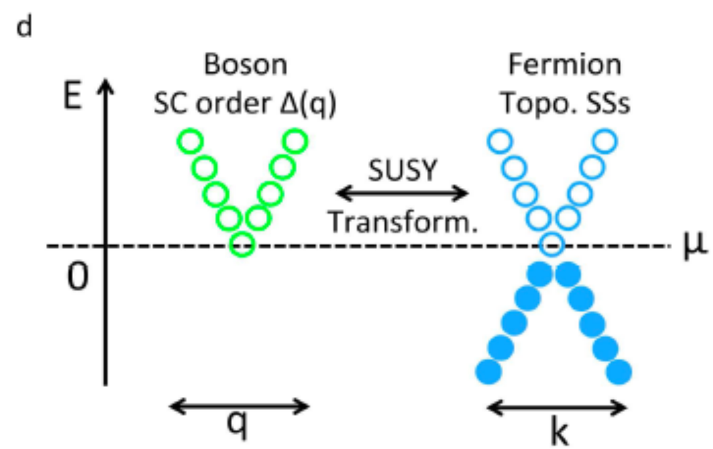
see prediction by Grover, Vishwanath et.al., Science'14



ARPES ⟷ Growth

Feedback Loop!



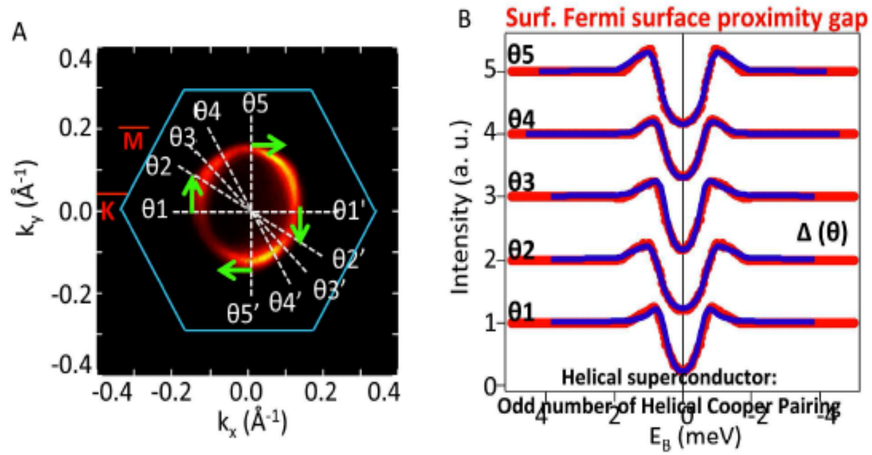


S. Xu, et.al., (MZH) Nature Phys (2014)

Search for TRI Topo. Superconductors ..

Natural Superconductor
(Majorana bound on the surface)

Engineering the Proximity effect



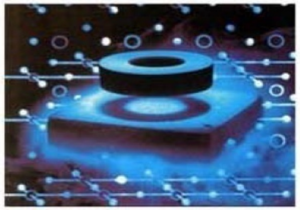
Centrosymmetric

$Cu_x(Bi_2Se_3)$	3.8K
$Pd_x(Bi_2Te_3)$	4.0K
$TlBiTe_2$	0.1K

Non-Centrosymmetric

LaPtBi	0.3K
Li_2Pt_3B	3.0K
$CePt_3Si$	0.7K

More..



2D Topo. Superconductor

by imaging of Helical Cooper Pairing

Fermi arc ("fractional" Fermi surfaces) in topological systems

Sciencexpress — Research Articles

Discovery of a Weyl Fermion semimetal and topological Fermi arcs

July 16th, 2015

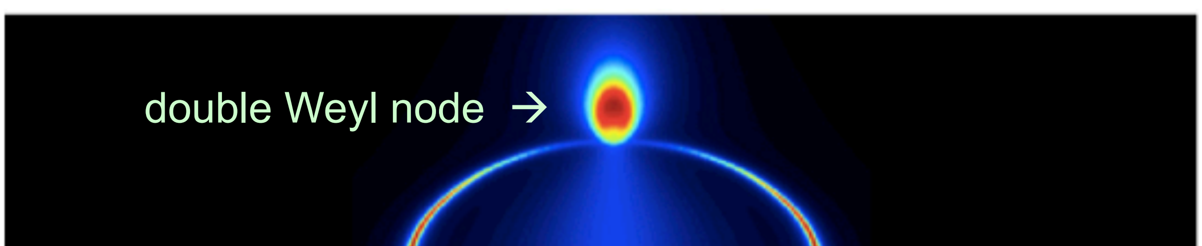
Su-Yang Xu,[1,2*] Ilya Belopolski,[1*] Nasser Alidoust,[1,2*] Madhab Neupane,[1,3*] Guang Bian,[1] Chenglong Zhang,[4] Raman Sankar,[5] Guoqing Chang,[6,7] Zhujun Yuan,[4] Chi-Cheng Lee,[6,7] Shin-Ming Huang,[6,7] Hao Zheng,[1] Jie Ma,[8] Daniel S. Sanchez,[1] BaoKai Wang,[6,7,9] Arun Bansil,[9] Fangcheng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

Sciencexpress — Reports

Observation of Fermi arc surface states in a topological metal

December, 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†]



Weyl spinors

The elements ψ_L and ψ_R are respectively the left and right handed Weyl spinors,

each with two components. Both have the form

$$\psi = \begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \chi e^{-i(\mathbf{k}\cdot\mathbf{r}-\omega t)} = \chi e^{-i(\mathbf{p}\cdot\mathbf{r}-Et)/\hbar}$$

Where $\chi = \begin{pmatrix}\chi_1\\ \chi_2\end{pmatrix}$ is a constant two-component spinor.

Since the particles are massless, i.e. $m = 0$, the magnitude of **p** relates directly to **k**

by the De Broglie relations as:

$$|\mathbf{p}| = \hbar|\mathbf{k}| = \hbar\omega/c \rightarrow |\mathbf{k}| = \omega/c$$

The equation can be written in terms of left and right handed spinors as:

$$\sigma^\mu\partial_\mu\psi_R = 0$$
$$\bar{\sigma}^\mu\partial_\mu\psi_L = 0$$

Weyl fermion in <u>THEORY</u>

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

H. Weyl (1929) at Princeton IAS (1933-55)
particle physics (Pauli, Yang-Lee, A. Salam..)

Solid State quasiparticle Weyl

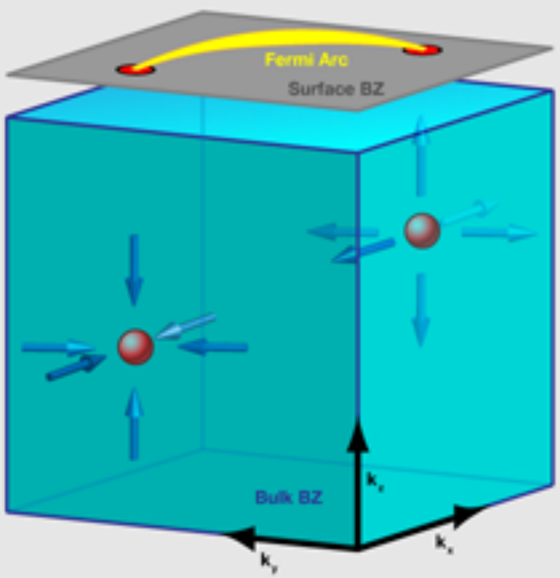


Image: L. Balents, *Physics (2011)*

Weyl Fermions in Crystals/SSP (1937-):
C. Herring (1937),
Abrikosov & Belyavosky (1971)
Nielsen-Ninomiya (1983)
Volovik (1998)
Murakami (2007),…more…
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

Many more proposals on magnetic compounds
also TI compounds by many groups
Including my group !
Singh et.al. (Lin, Hasan & Bansil), PRB 2012

Weyl fermions

H.Weyl 1929

Dirac equation *(natural units)*

$$(i\partial\!\!\!/ - m)\psi = 0$$

4×4

$\downarrow$ $m = 0$

Weyl equation

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

2×2

The chiral anomaly:
neutral pion decay

Weyl semimetals:

1. Provide the first ever realization of Weyl fermions in all physics
2. Extend the classification of topological phases of matter beyond insulators
3. Host Fermi arc surface states
4. Realize the condensed matter chiral anomaly
5. Many more exotic phenomena (both surf. & bulk!!!)

Murakami (2007), We (Lin & MZH) had a material proposal for that: **PRB (2012)**

FP-Calc._: Huang, Xu et.al., (Lin & MZH) **Nat. Commun. 2015** (subm. **Nov 2014**)

FP-Calc._: Weng et al., (IOP group, Dai, Fong) **PRX 2015** (subm. **Jan 2015**)

nature COMMUNICATIONS

Subm. last year (November 2014)

ARTICLE

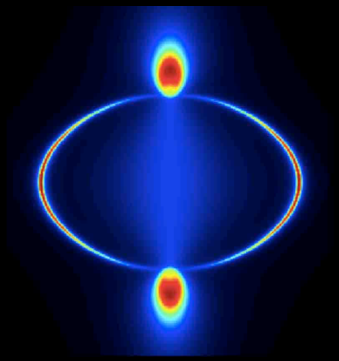
Received 24 Nov 2014 | Accepted 30 Apr 2015 | Published 12 Jun 2015

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]

Weyl fermions are massless chiral fermions that play an important role in quantum field theory but have never been observed as fundamental particles. A Weyl semimetal is an



Can metals be topological ?

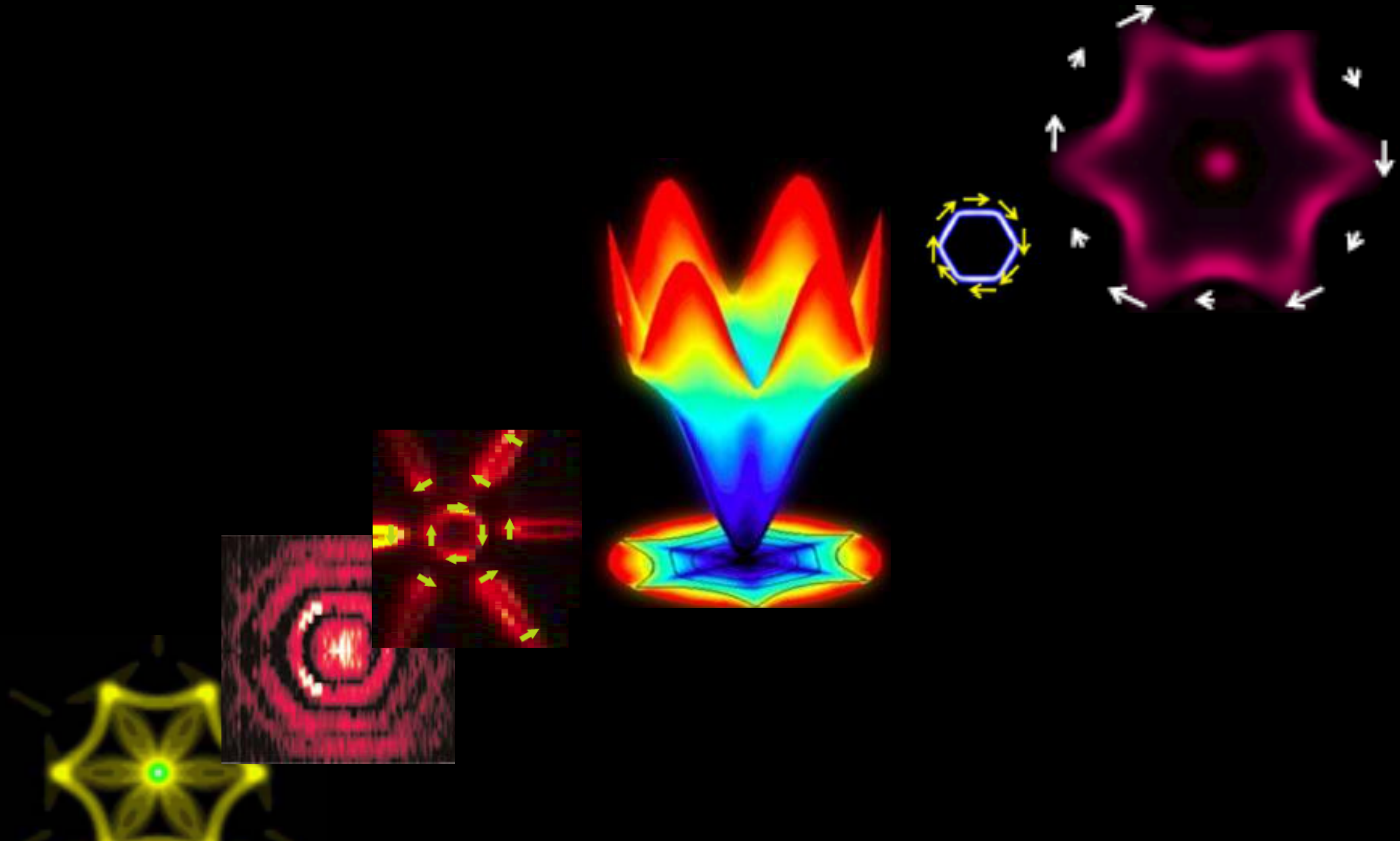
bulk Gapless *but* topological

Fermi arc metals

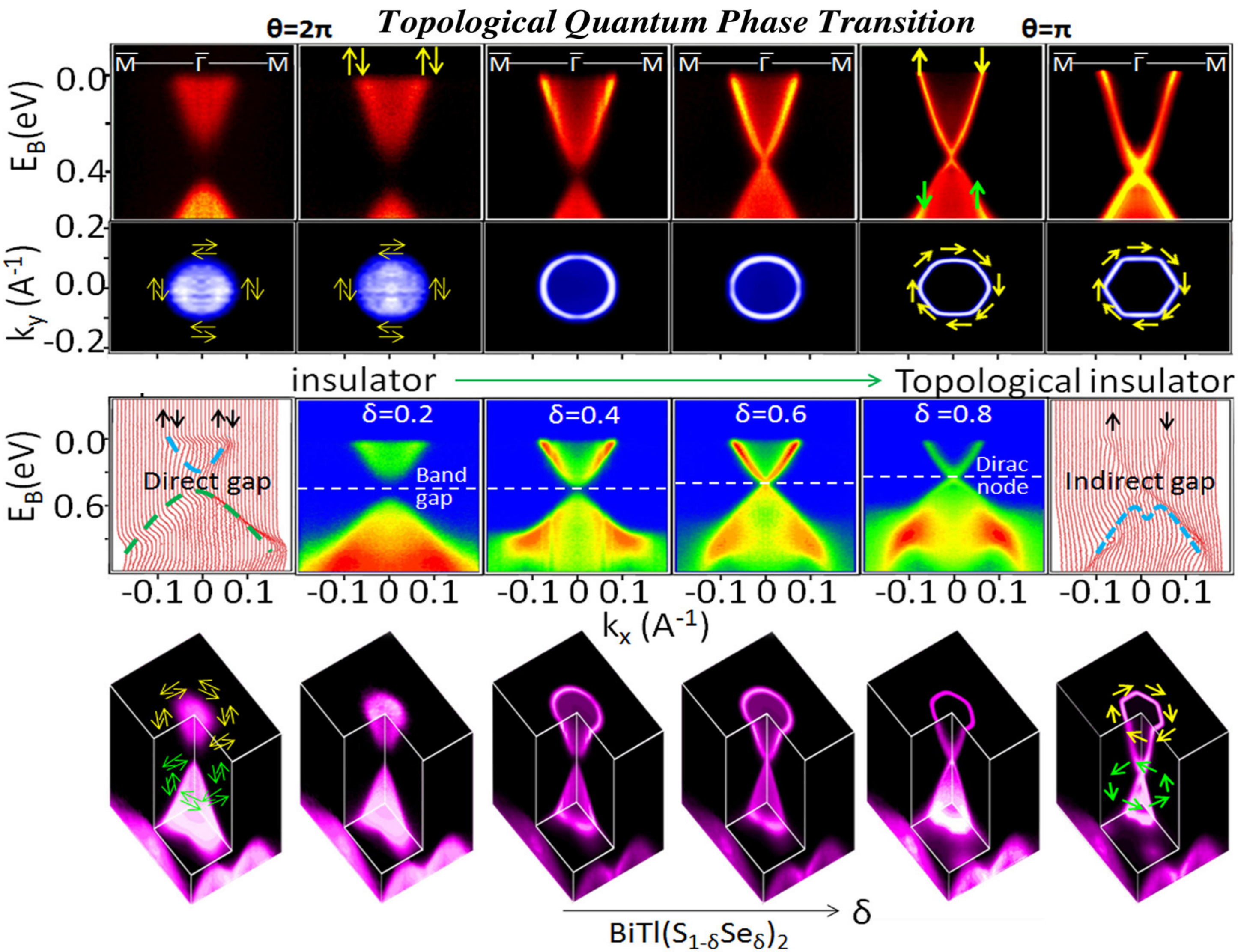
(iridates and other candidates)

Topological Phase Transition

M.Z.H. & CL Kane, Rev. Mod. Phys. 82, 3045 (2010)



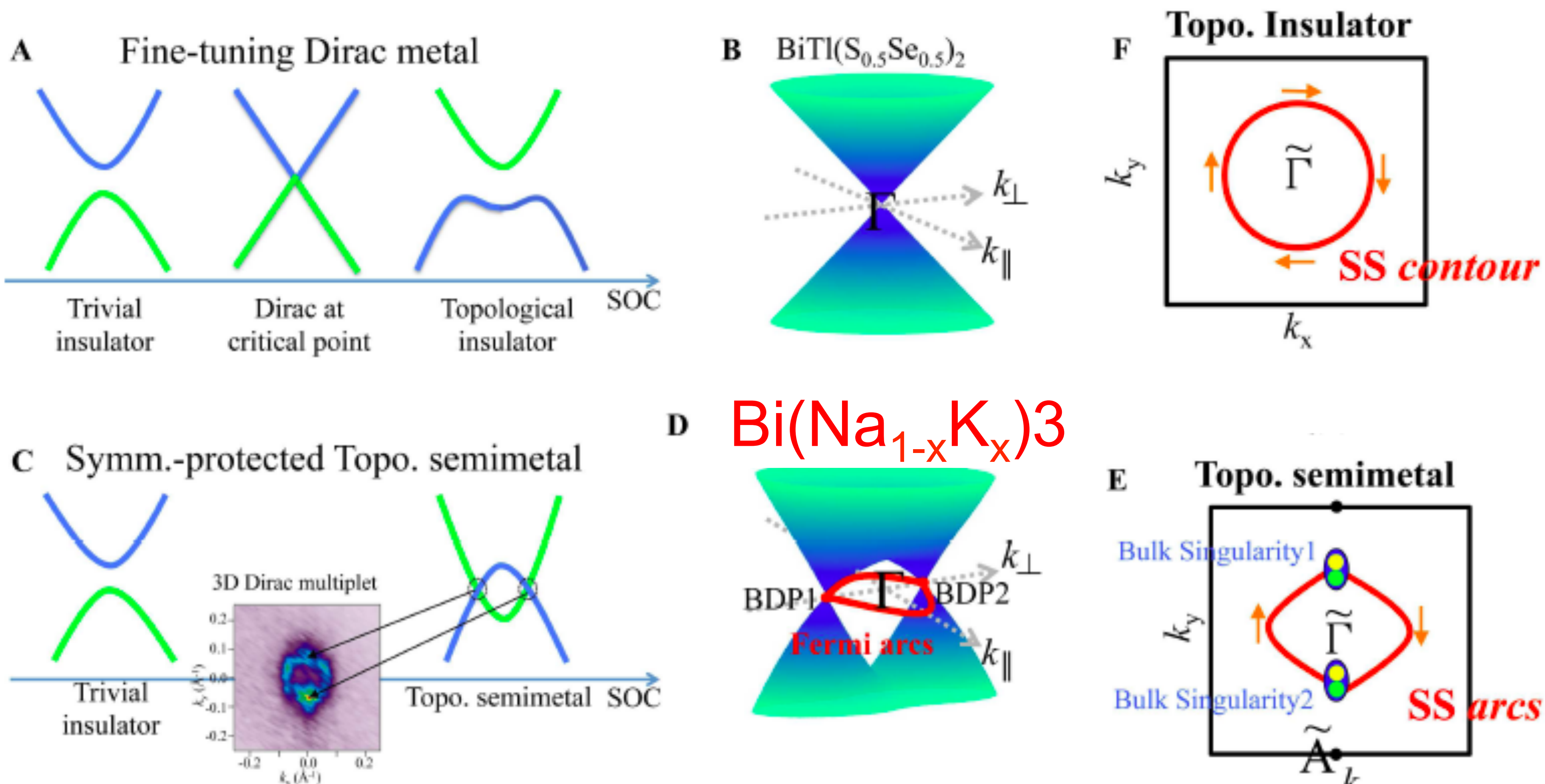
Imaging a Topo. Insulator being born out of a Bloch Insulator as SOC is tuned



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

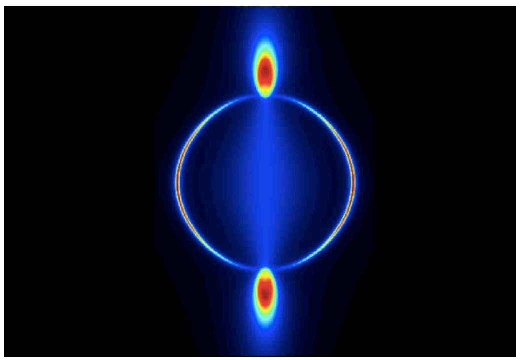
Fermi Arc SSs: Topo. Dirac semimetal

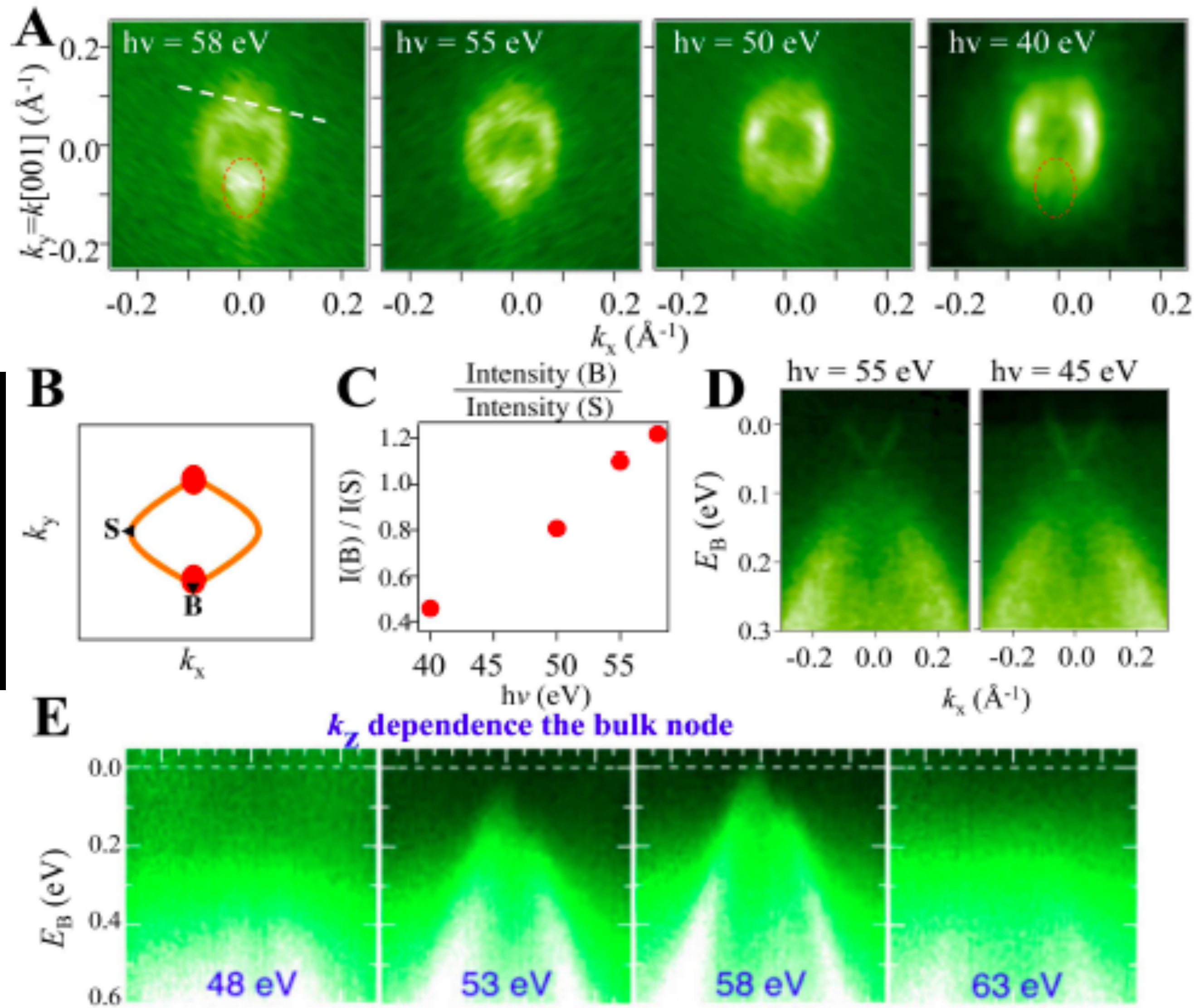
Bi-based (SOI) materials again



S. Xu *et.al., (MZH) Science (2014)* *Adv.OnLine*

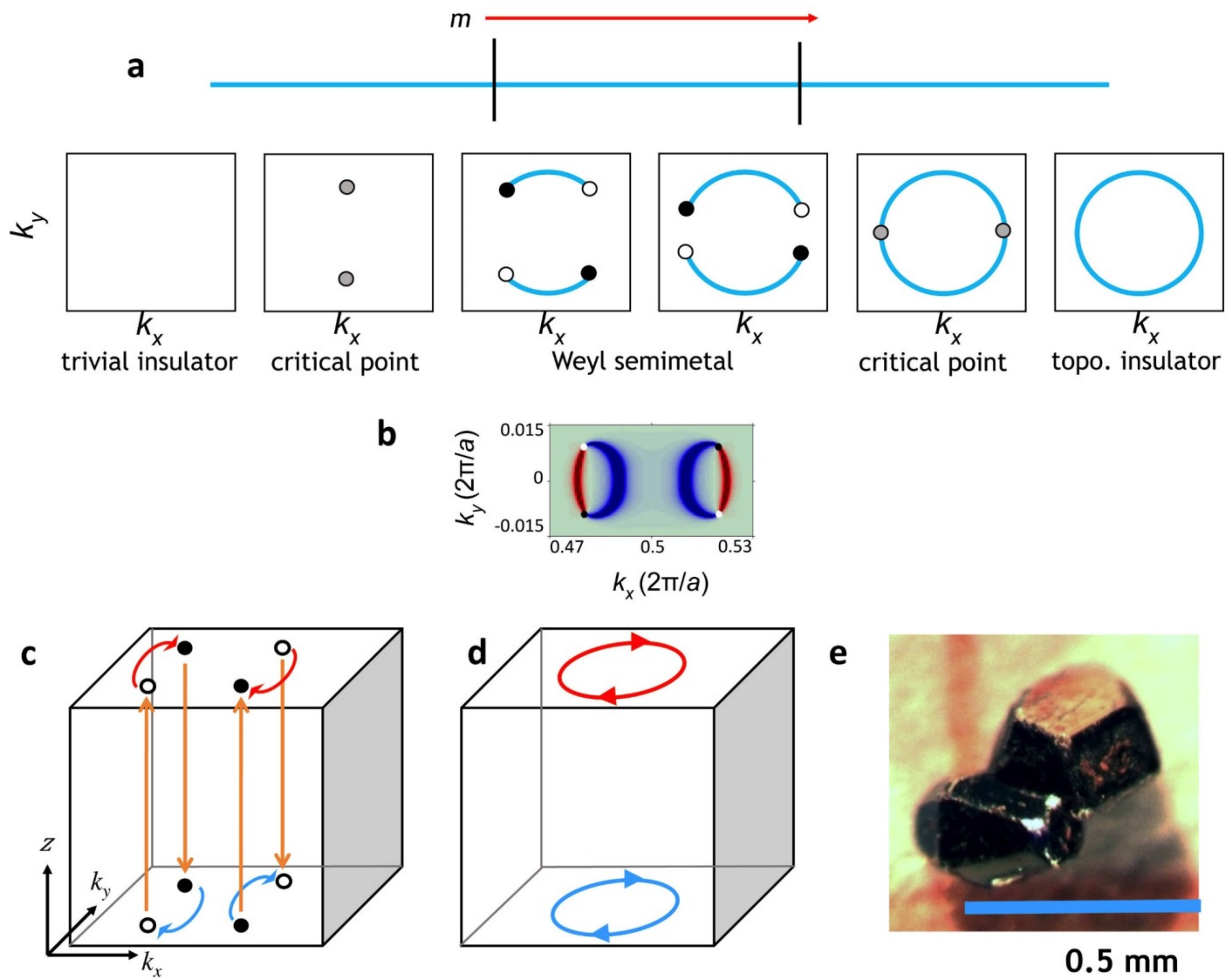
Fermi surface = 2 surface arcs + bulk Dirac nodes





S. Xu *et.al., (MZH) Science (2015)*

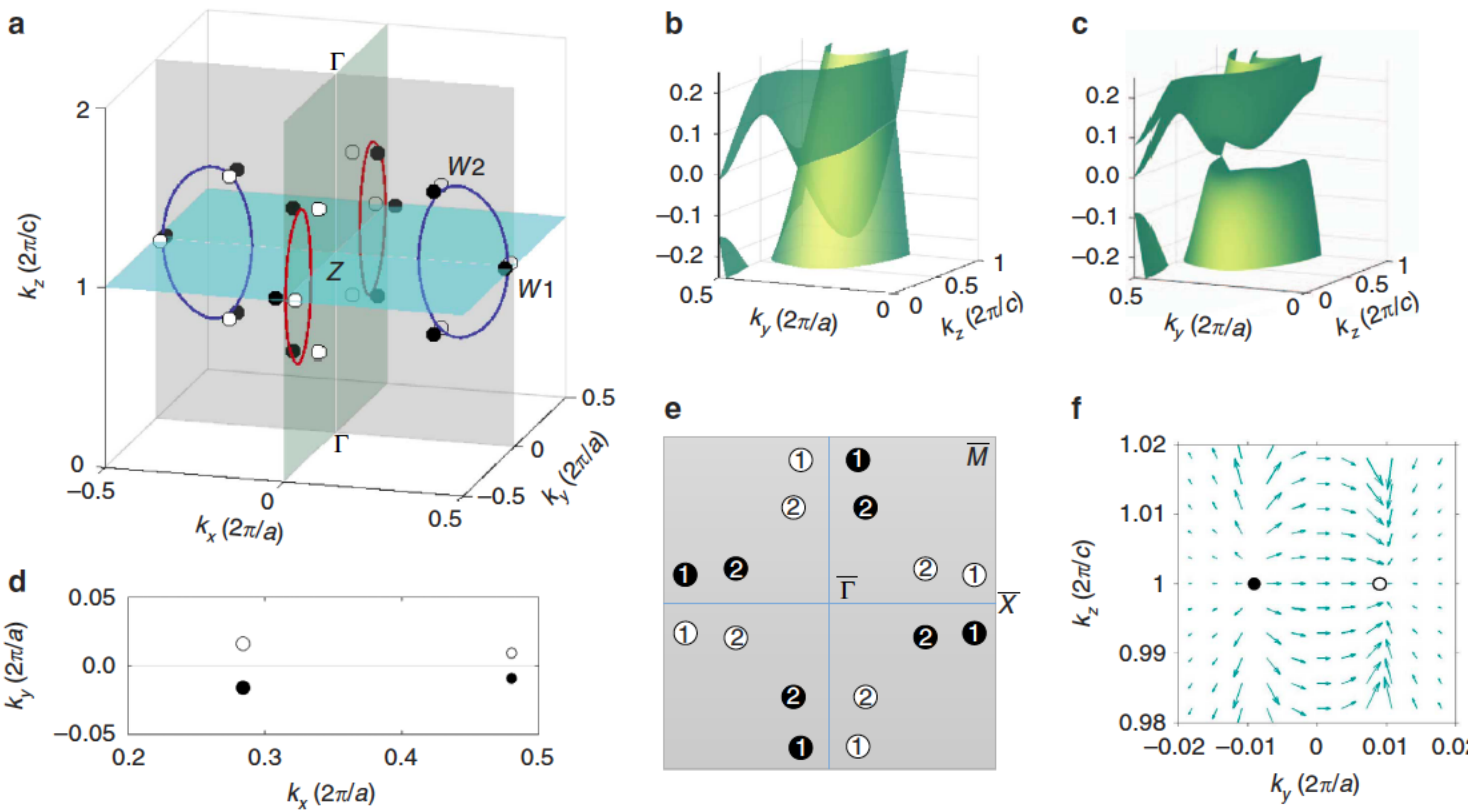
Phase Diagram of Topological Matter and Experimental Relaizations



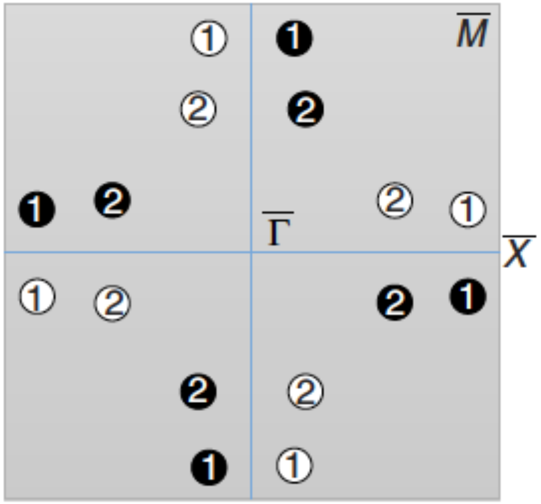
FP/Theory:
Huang, Xu, Belopolski et.al., (Lin & MZH) Nature Commun. 2015

24 Weyl nodes in the bulk of TaAs

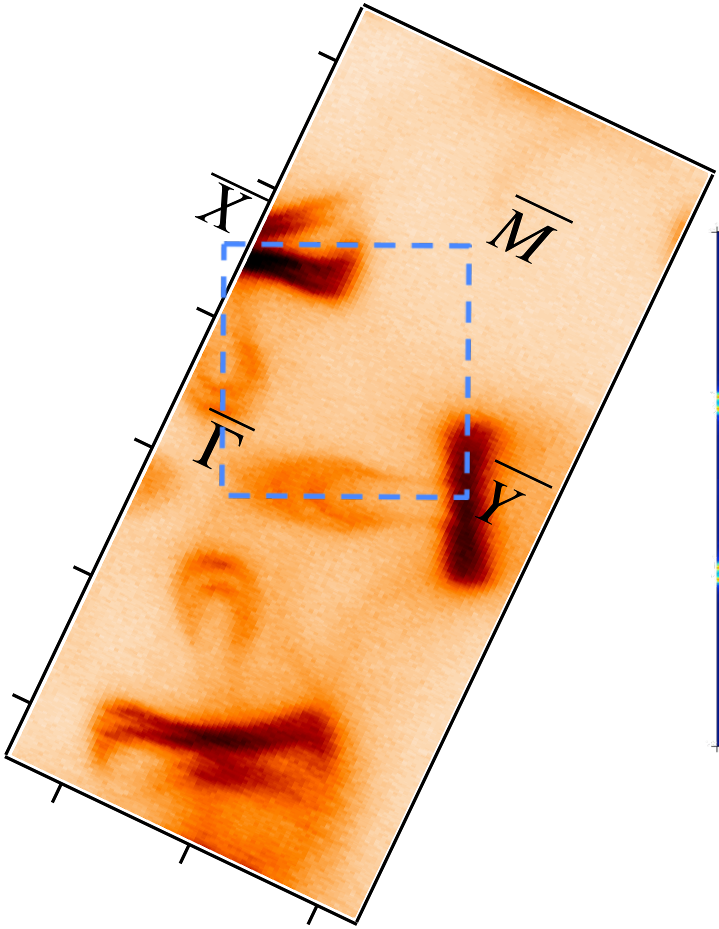
FIGURES from
Huang, Xu, Belopolski et.al., (Lin & MZH) Nature Commun. 2015



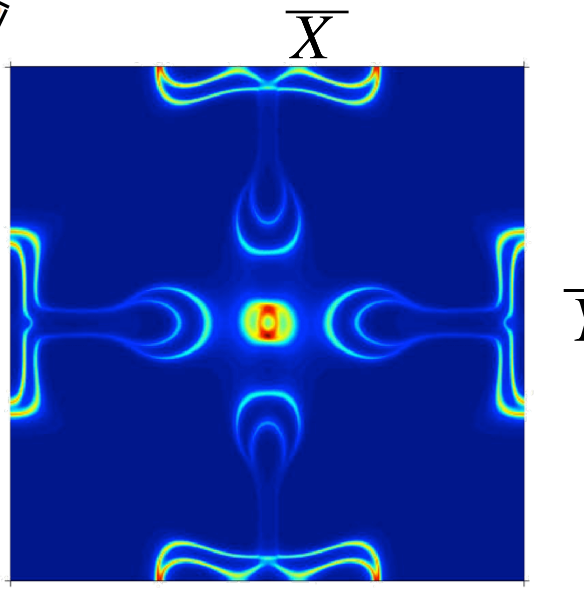
ARPES-1: Surface Fermi arcs



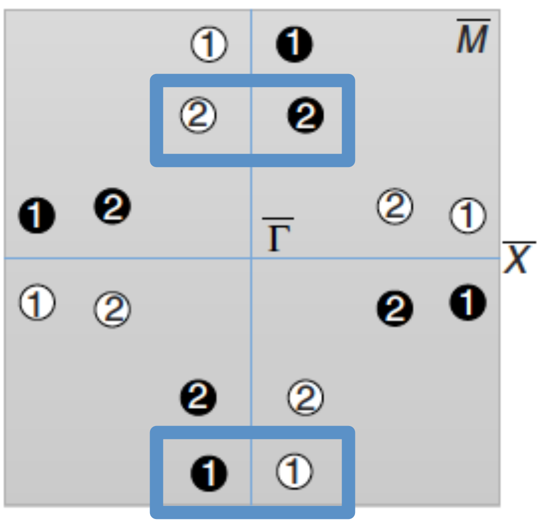
ARPES

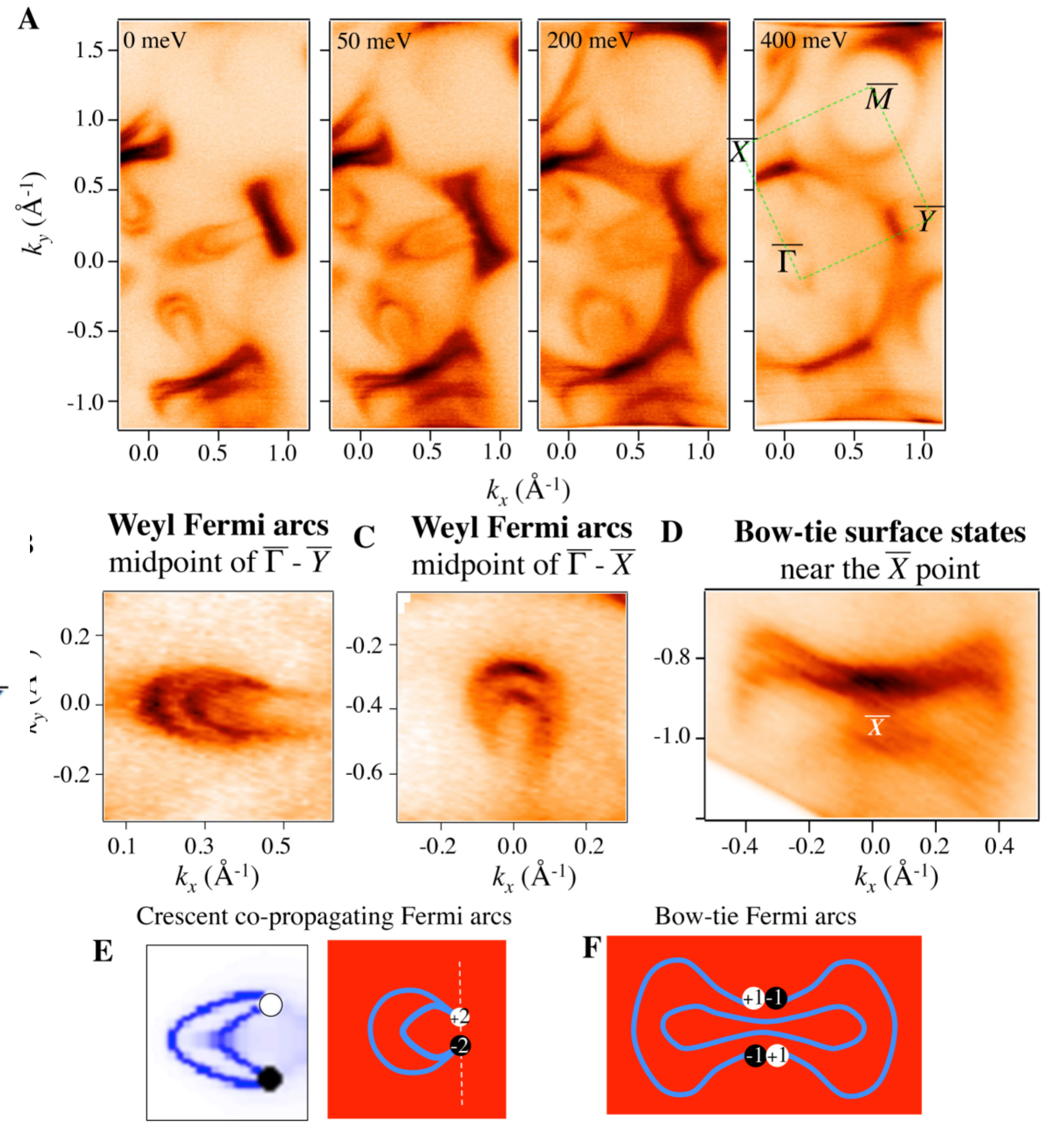


Calculation



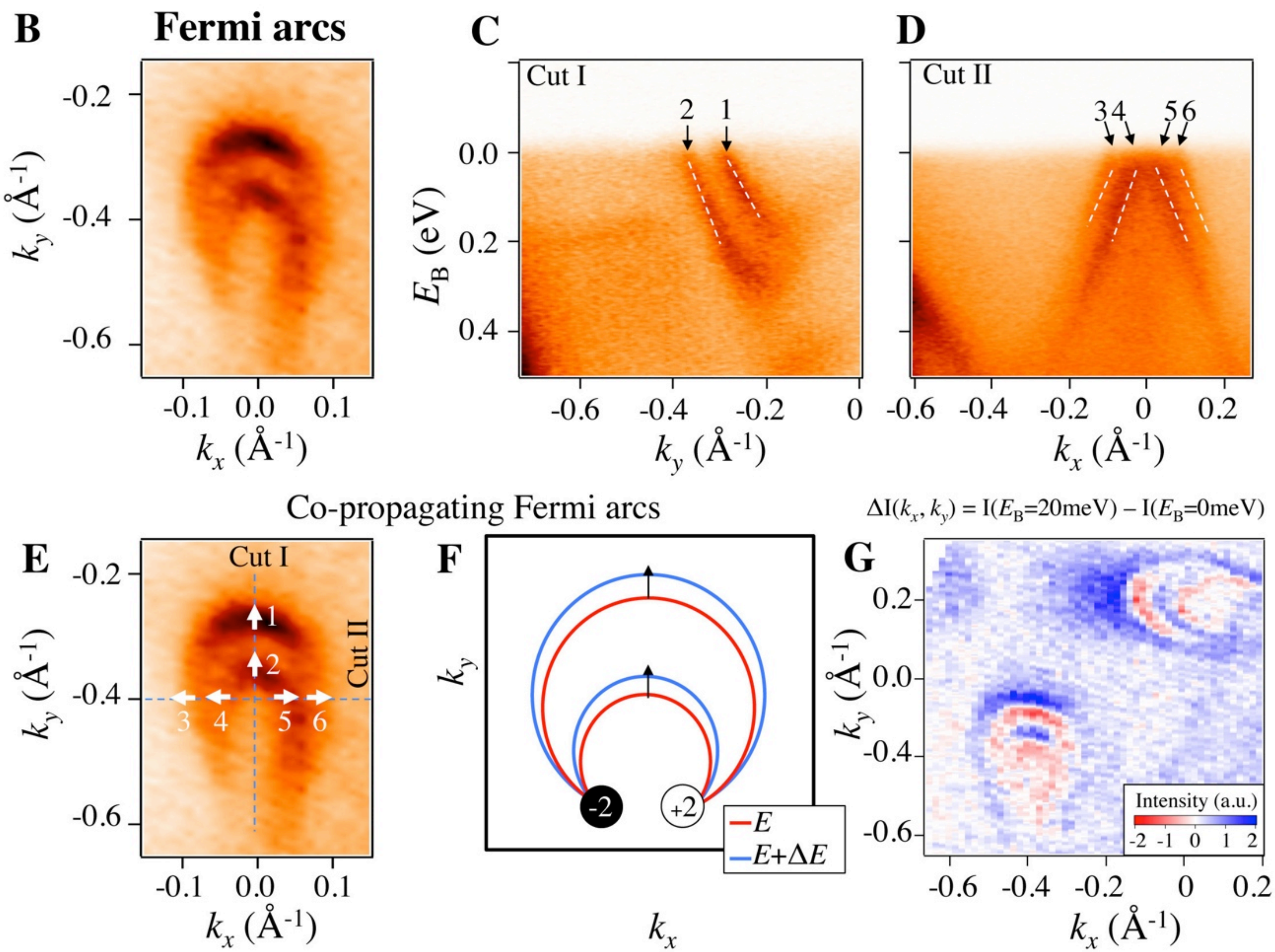
ARPES-1: Surface Fermi arcs



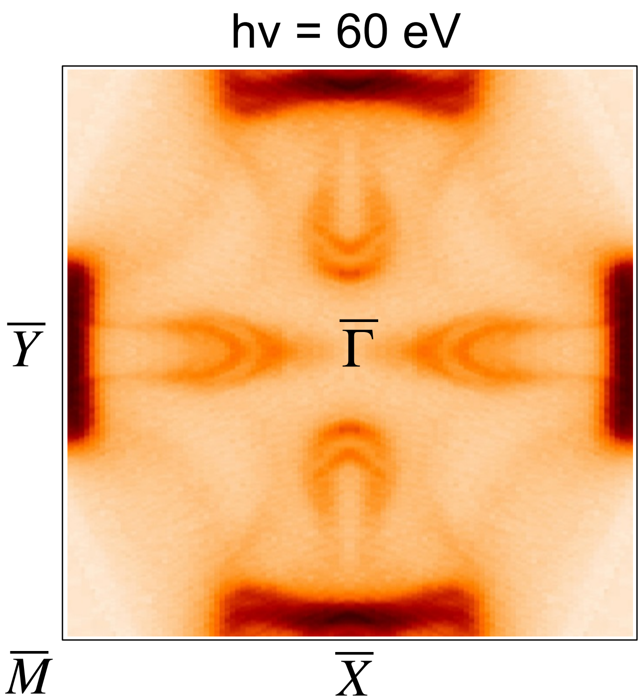


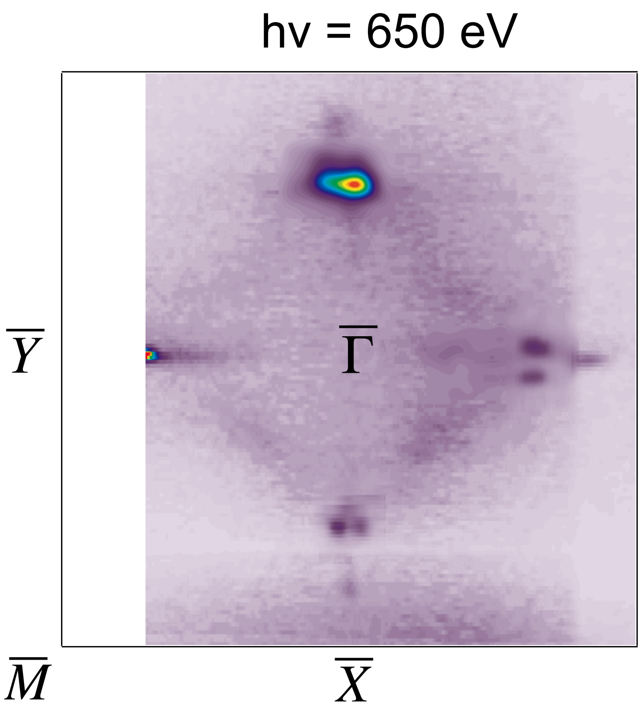
ARPES-1: Weyl Fermi arcs

Co-propagating



ARPES on Weyl Semimetal

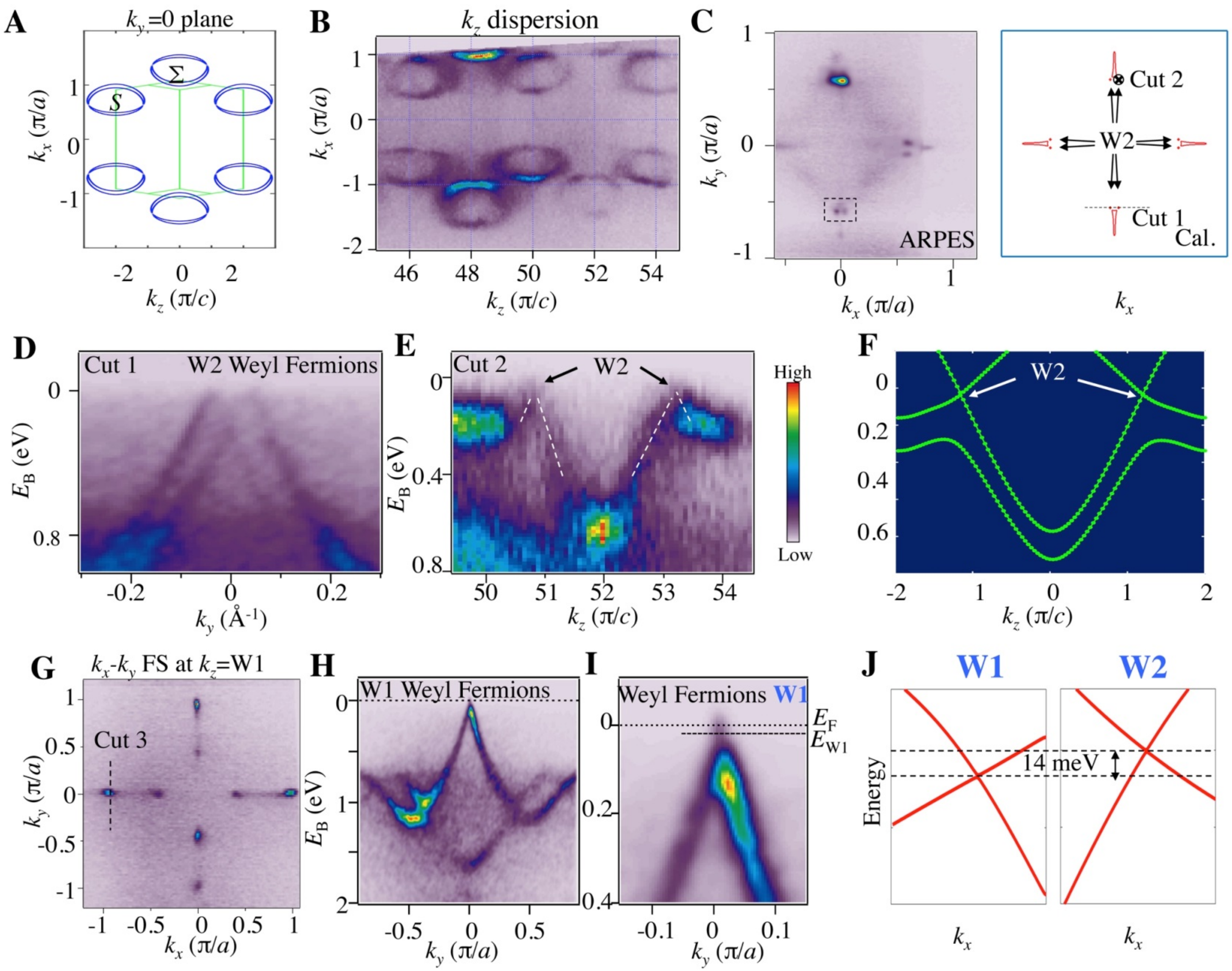




Low Photon Energy
(surface sensitive)

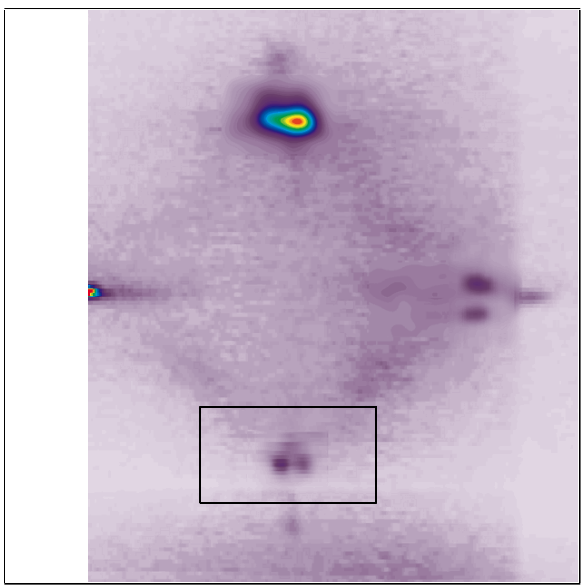
High Photon Energy
(Bulk sensitive)

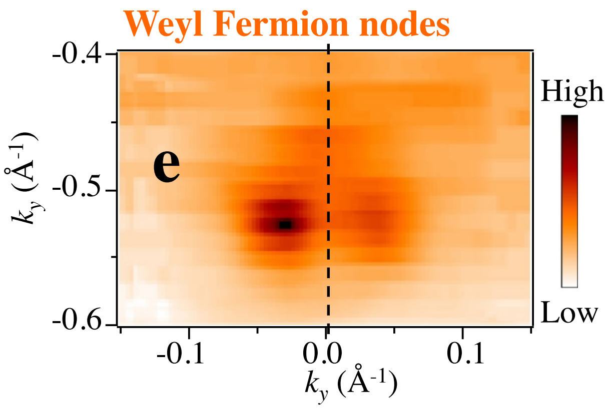
ARPES-2: Bulk Weyl fermions

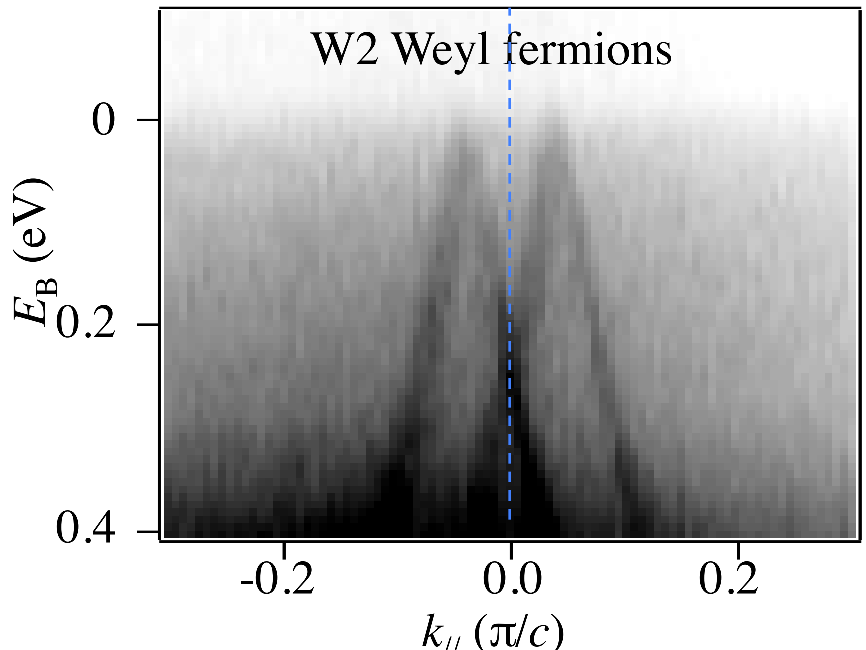


ARPES-2: Bulk Weyl fermions

Away from Kramers points or rotational axes!





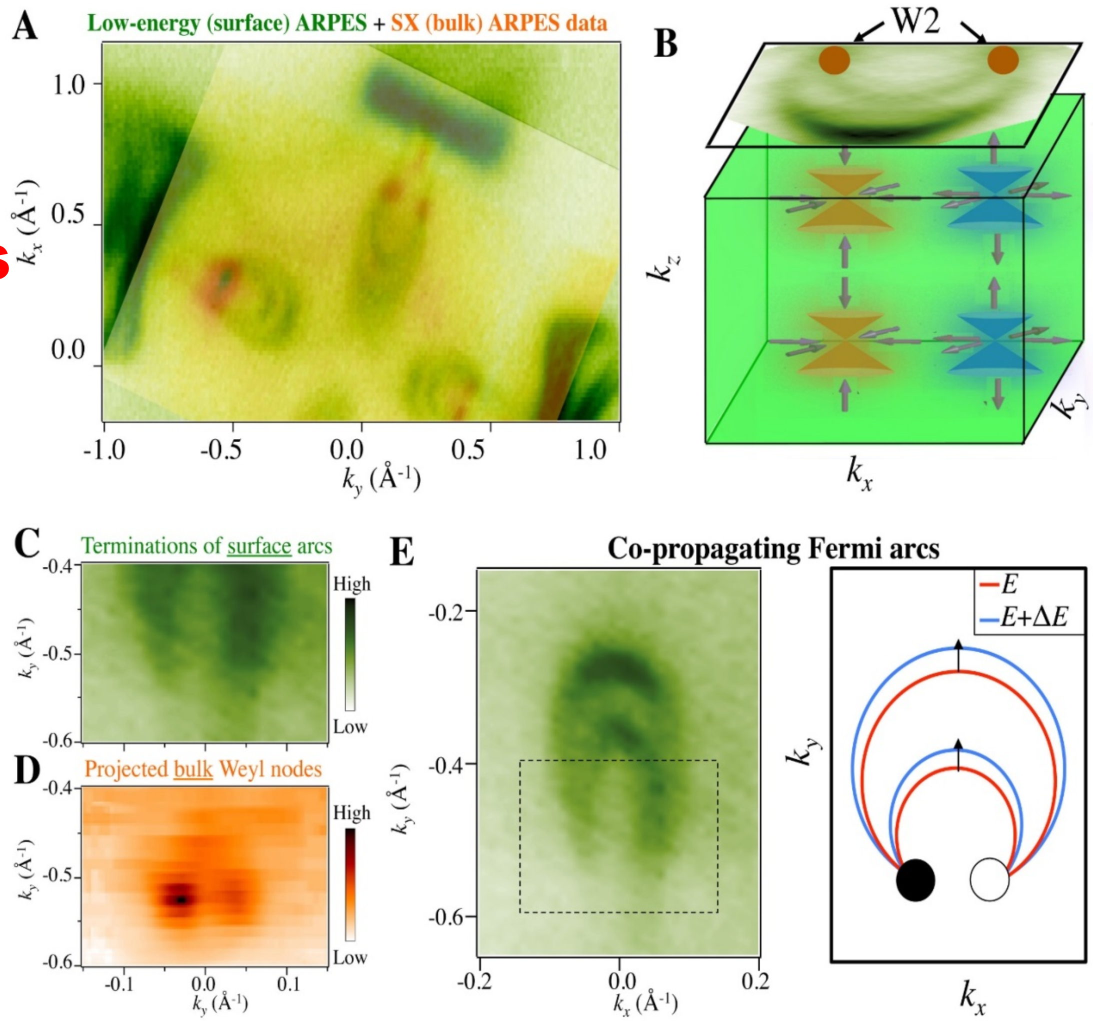


FP-Theory:Huang, Xu, Belopolski, Lin et. (MZH), **Nature Commun. 2015 (subm 2014)**
ARPES Expts & Theory: Hasan, Xu, Guang in **Proc. of Nobel Sympos. 2014 (2015)**
FP-Theory: Bernevig, Weng, Dai et.al., **Phys Rev. X 2015 (subm. 2015)**
ARPES Expts: Xu, Belopolski et.al., (MZH) **Science (July) 2015 (subm. Feb 2015)**

Weyl Fermion semimetals and Topological Fermi arcs

Weyl Semimetals

Monopole - Anti MP

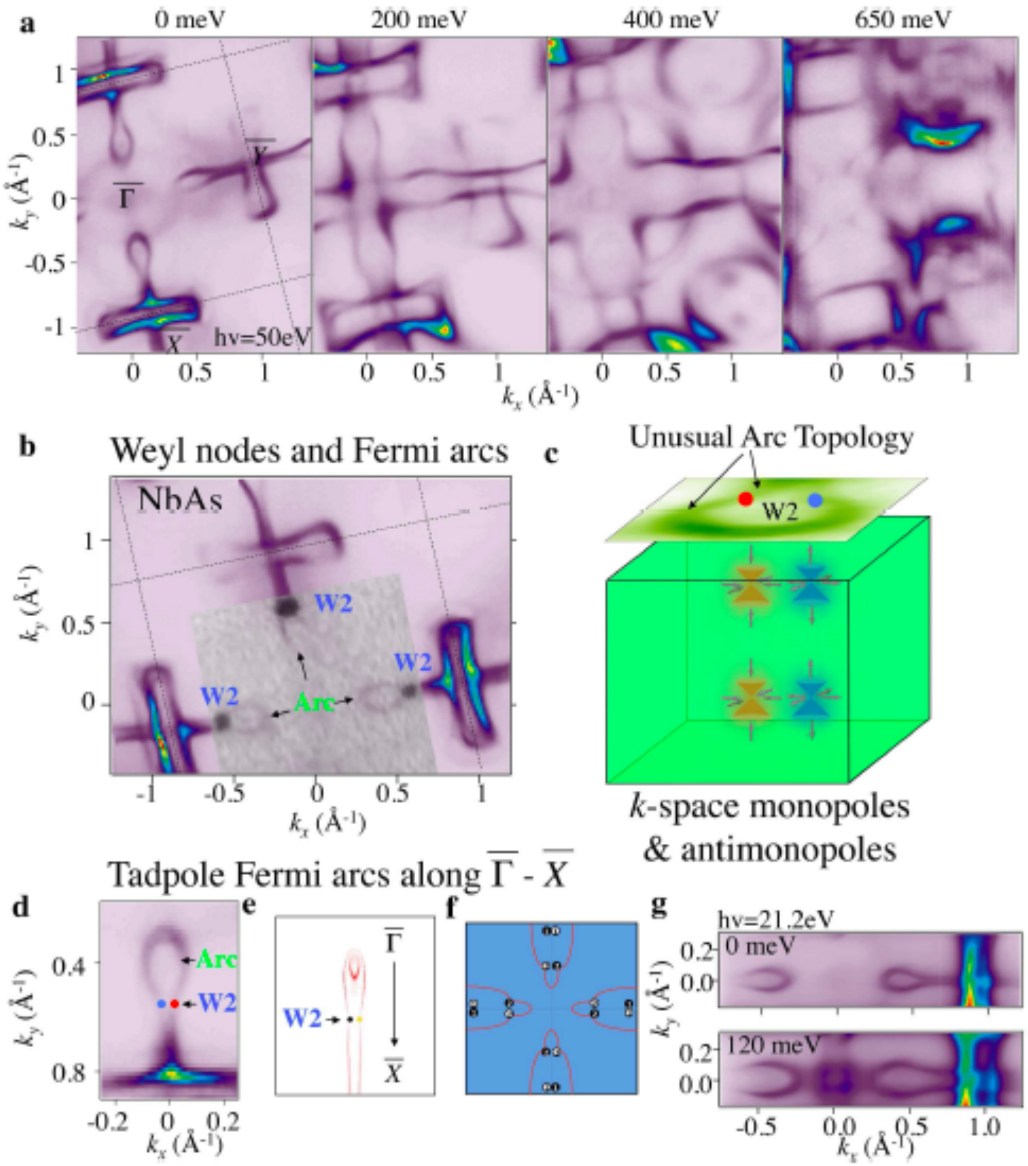


Weyl Fermions

Fermi Arcs

Discovery of the Weyl semimetal state with a new form of Fermi arcs in niobium arsenide (NbAs)

S.-Y. Xu et al., arXiv:1504.01350 (2015)



Sciencexpress Research Articles

Discovery of a Weyl Fermion semimetal and topological Fermi arcs

July 16th, 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

August, 2015

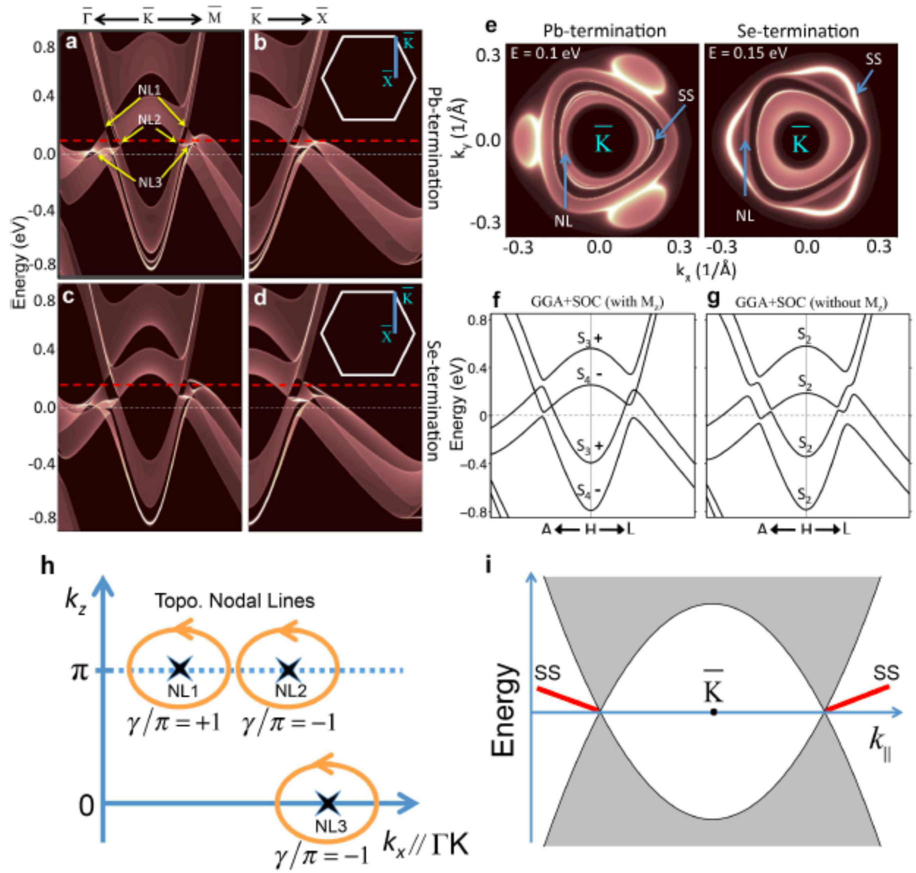
Discovery of a Weyl fermion state with Fermi arcs in niobium arsenide

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*]

Three types of fermions play a fundamental role in our understanding of nature: Dirac, Majorana and Weyl. Whereas Dirac

Topological Nodal-Line Fermions in the Non-Centrosymmetric Superconductor Compound $PbTaSe_2$

Guang Bian*,[1] Tay-Rong Chang*,[2,1] Raman Sankar*,[3] Su-Yang Xu*,[1] Hao Zheng*,[1] Titus Neupert,[1,4] Ching-Kai Chiu,[5] Shin-Ming Huang,[6,7] Guoqing Chang,[6,7] Ilya Belopolski,[1] Daniel S. Sanchez,[1] Madhab Neupane,[1] Nasser Alidoust,[1] Chang Liu,[1] BaoKai Wang,[6,7,8] Chi-Cheng Lee,[6,7] Horng-Tay Jeng,[2,9] Arun Bansil,[8] Fangcheng Chou,[3] Hsin Lin,[6,7] and M. Zahid Hasan†[1,10]

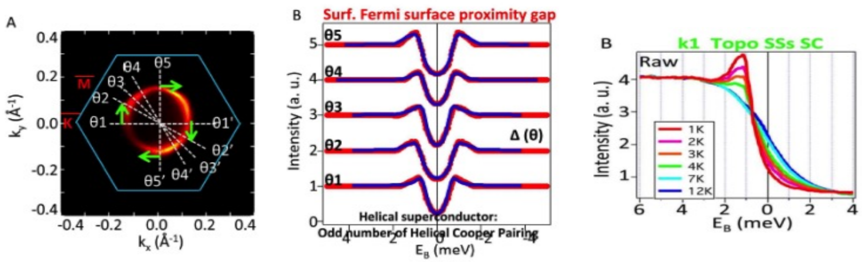


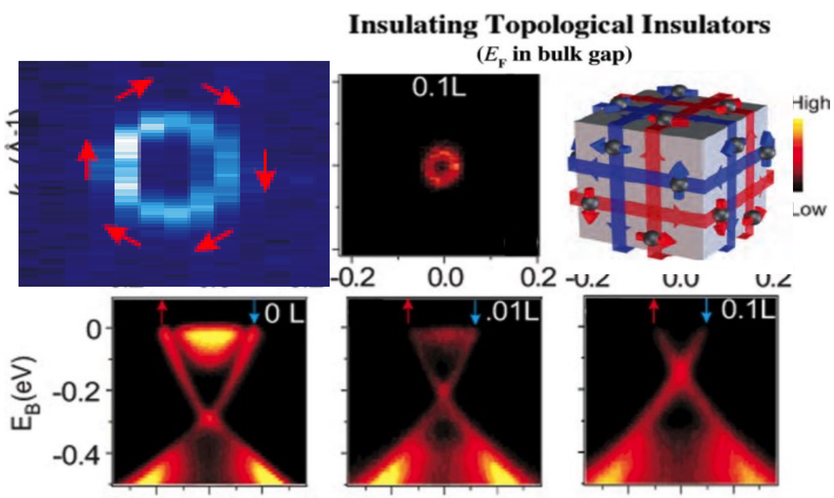
Conclusions & Outlook:

Topo.Insulator →

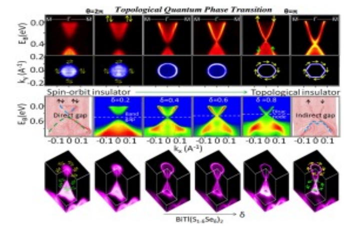
Helical Cooper Pairing

Topo. Superconductors



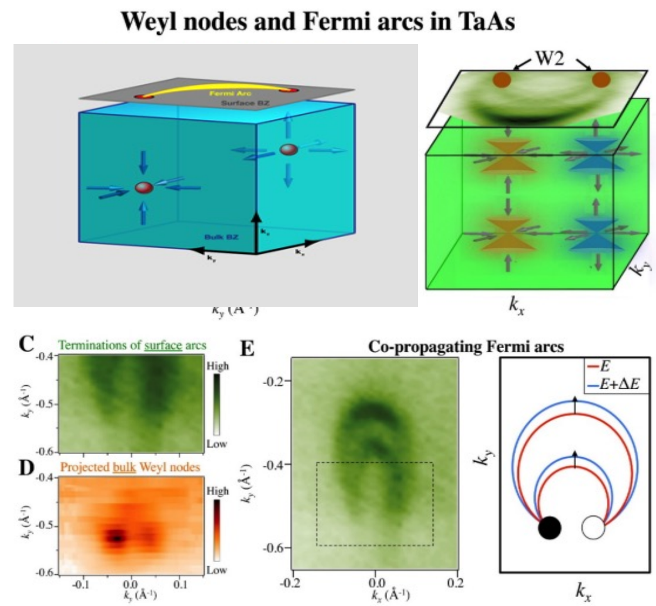


Weyl Fermion Semimetals & Fermi arcs



Topo. Phase Transition ->

WEYL Semimetals



Future: *New topo. supercond's, Weyl fermion materials, Line-node topo. semimetals… Topological quantum phase transitions, phase diagrams, novel excitations*

Thanks !

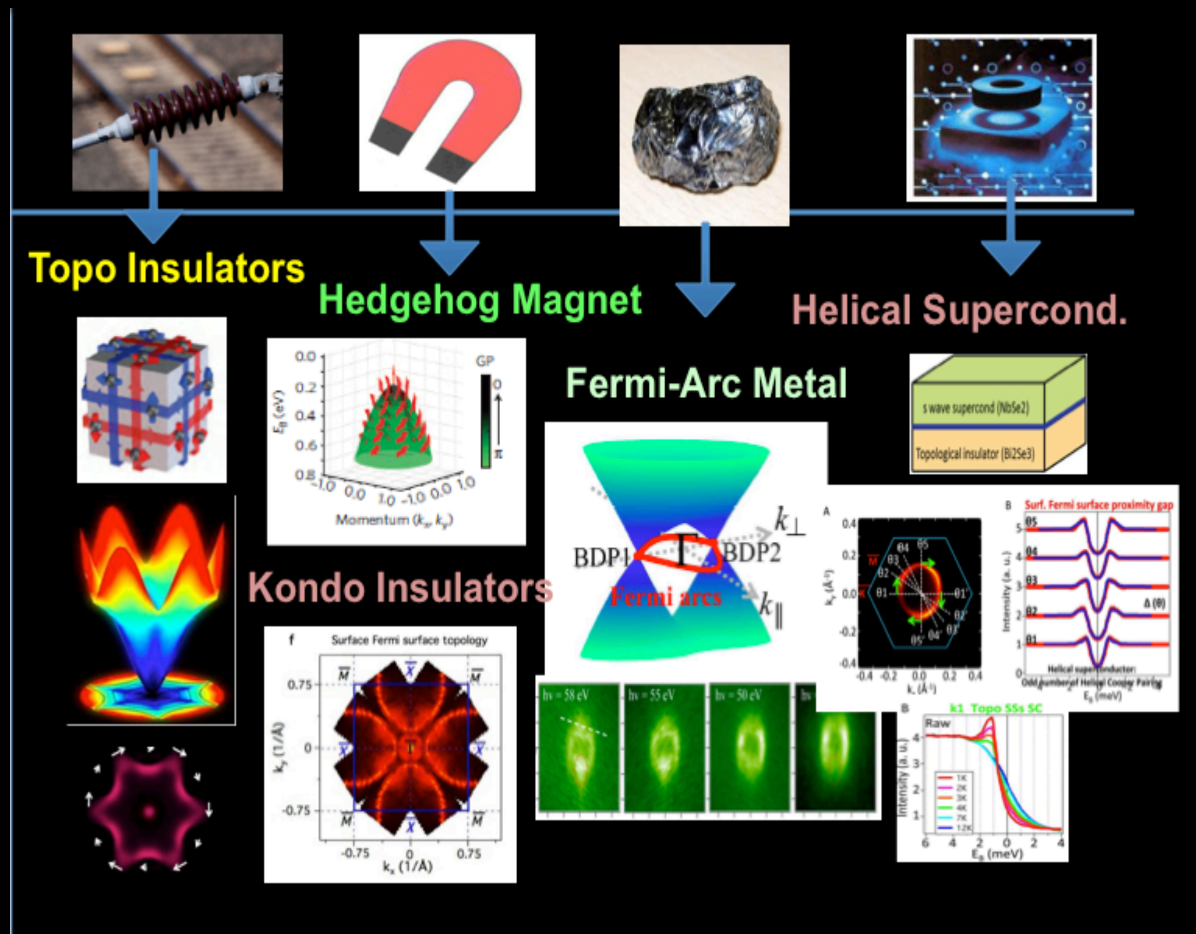
MZH, Xu, Neupane *Topo Insulators, Topo Cryst. Insulators & Topo Kondo Insulators*, arXiv(2014)
MZH, Xia, Hsieh, Wray *et.al.*, (Book ch.) ***Topological Insulators,*** Elsevier/Oxford (2013)

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)

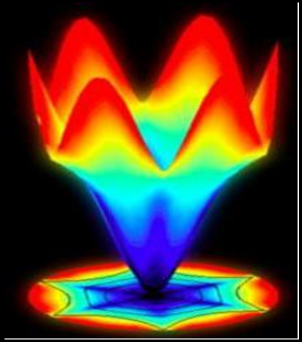
Nature '08 (sub. in 2007)
Science '09
Nature Phys. '09
Nature '09
PhyRevLett '09
Nature '09
Nature Phys. '10
PhyRevLett. '10
Nature Mat. '10

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 2015

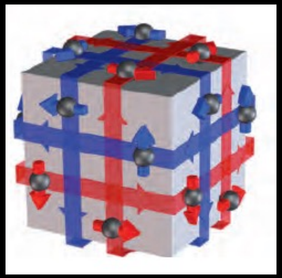


Topological Condensed Matter Physics

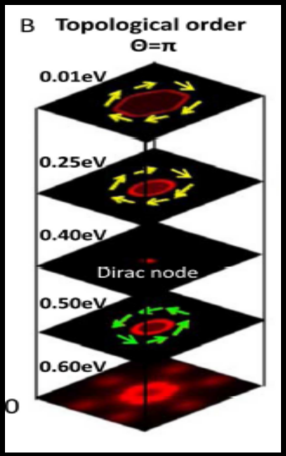


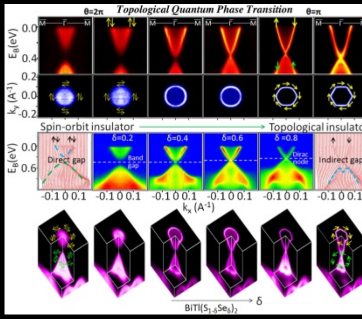
Topological Insulators

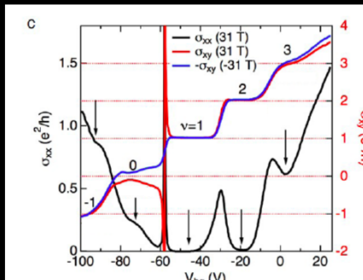
A New Form of Quantum Matter



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 (**Science' 10-11**)
4. Robust up to room temperature (**Nature' 09**)
5. Absence of backscatt. by Spin-Texture (**Nature' 09**)







M.Z.H. & CL Kane, Rev. Mod. Phys. 82, 3045 (2010)

First five experimental papers on 3DTI (Topological Insulators)

A topological Dirac insulator in a quantum spin Hall phase [Princeton]
Nature 452, 970 (2008); D.Hsieh, D.Qian, Y.Xia et.al., [April, '08] Submt.(2007)

Observation of Unconventional Quantum Spin Textures in Topological Insulators
Science 323, 919 (2009); D.Hsieh, Y.Xia, L.A.Wray et al., [February, '09] Submt.(2008)

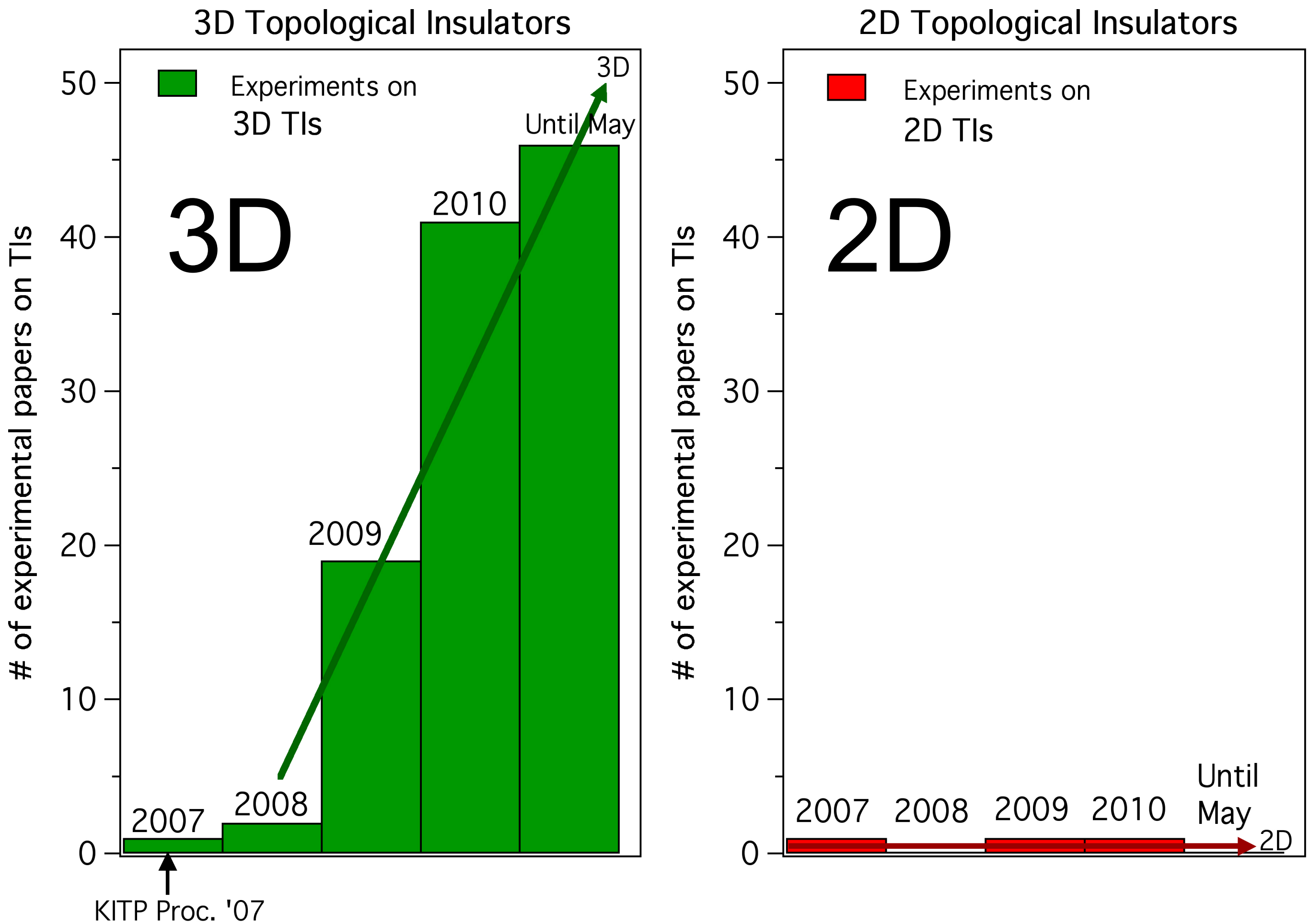
Observation of a large-gap topological-insulator class with a single Dirac cone on the surface
Nature Physics 5, 398 (2009); [Princeton]
Y.Xia, D.Qian, L.A.Wray, D.Hsieh et al., [May '09] Sub. (2008) and extended version at
A tunable topological insulator in the spin helical Dirac transport regime
Nature 460, 1101 (2009); D.Hsieh, Y.Xia, D.Qian et.al., Submt.(2009) [Princeton]

p-type Bi2Se3 for topological insulator and low-temperature thermoelectric applications.; **Phys.Rev.B 79, 195208 (2009)**;
Y.Hor, A.Richardella, Y.Xia, D.Hsieh et.al., [May '09] Submt.(2009) [Princeton]

Experimental Realization of a Three-Dimensional Topological Insulator. Bi2Te3
Science 325,178 (2009); Y.L.Chen, J.Analytis,.. S.-C. Zhang et al., [Stanford]
[June '09] Submt.(Mar. 2009)

See SCZ talk at this session.

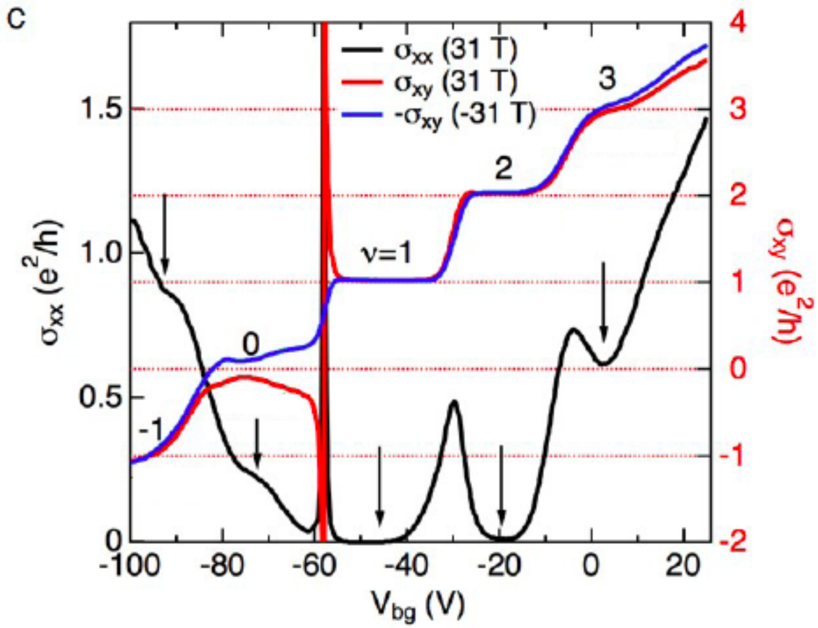
Distribution of experimental works in topo. Insulators (2007-2011)



Years	'Experimental papers on 2D TIs'	'Experimental papers on 3D TIs'
2011 (Until May)	0	46
2010	1	41
2009	1	19
2008	0	2
2007	1	1 (KITP Proc.)

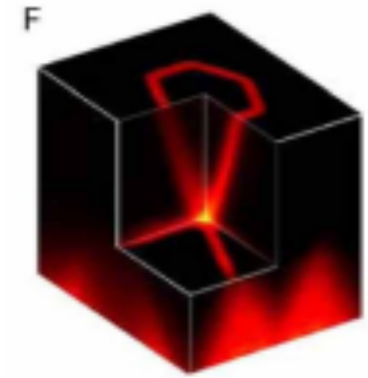
QHE for a 3D **Topo.Insulator** : Bi(Sb/Te)Se2

Transport



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

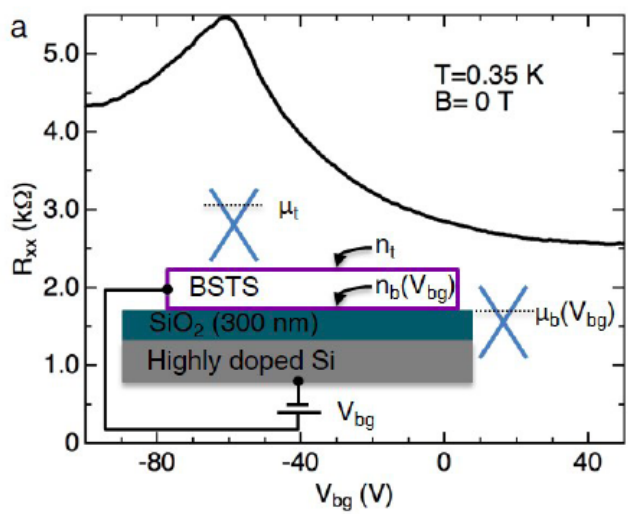
Nature Physics (2014)

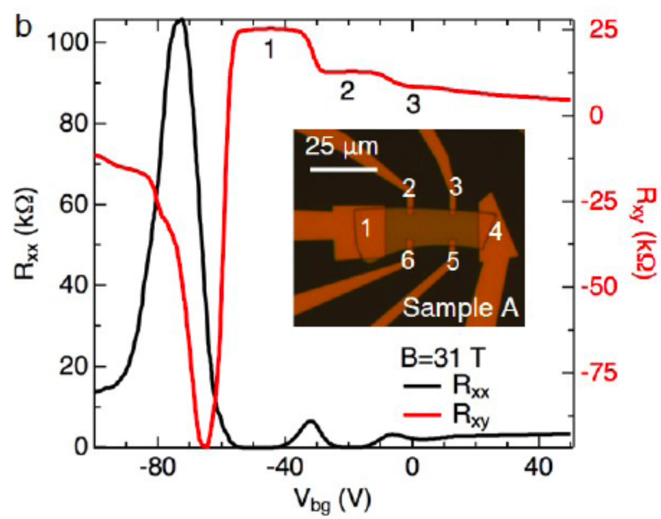


TI = 2 surf's(Top + Bot.) of Dirac gas

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

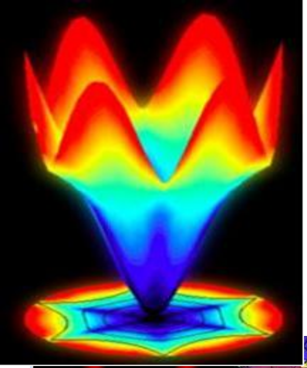
only Integer QHE !





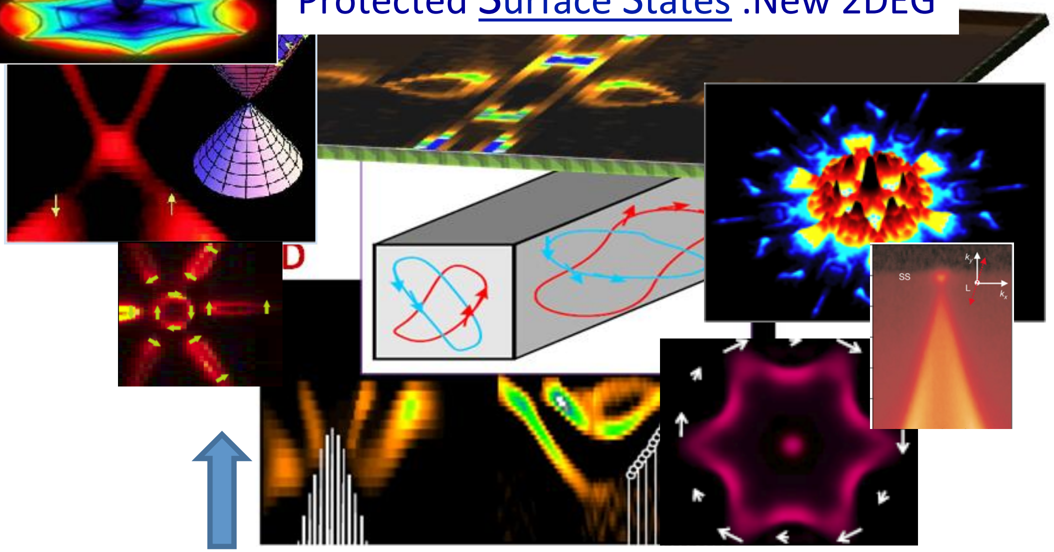
(SPT) Topological Insulators

$\{\nu_o\}$ (Chern Parity invariants) Z_2



3D Topological Insulators

Protected Surface States :New 2DEG



Proof of topological nature of **Topological surface states**

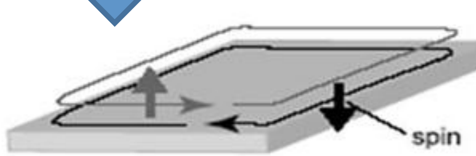
3D expts are neither derivatives nor extensions of 2D TI expts!

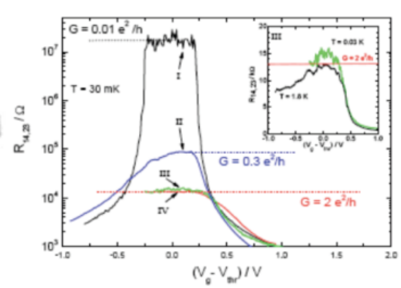
(also they are less than few months apart by the submission dates)

Hsieh et. Nature (2008) [Subm. 2007, Nov]

2D Topological Insulators

Konig et. Science (2007)[Subm. 2007, June]





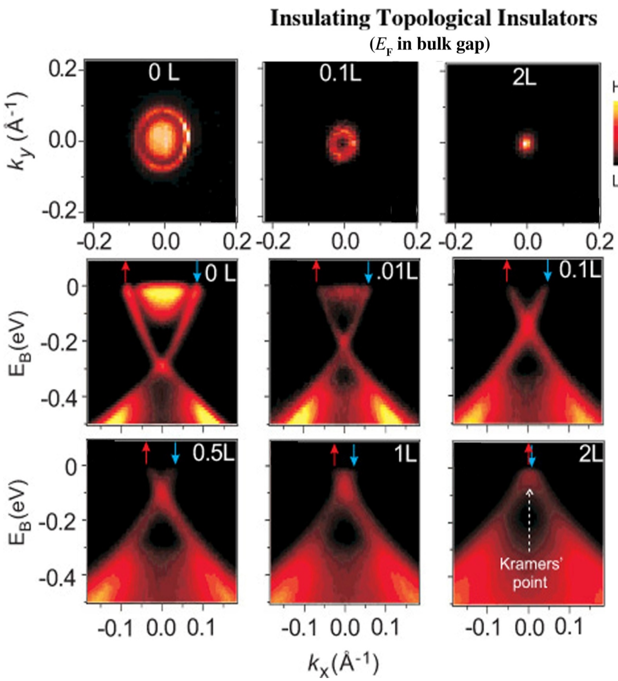
QSH edge States (1D) by TRS

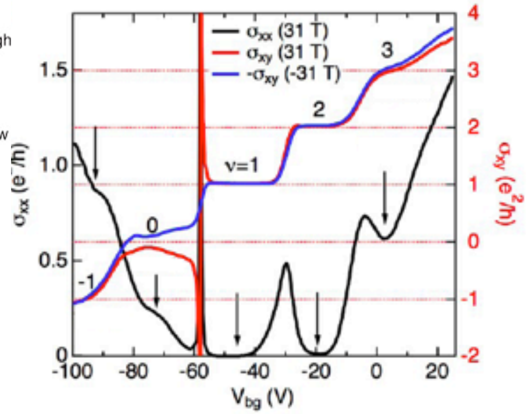
Charge transport Measurement of edge states of **quantum (spin) Hall**

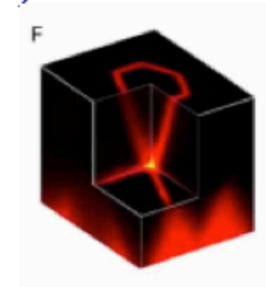
But no spin measurement was reported in 2007 as noted by the authors

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

Transport







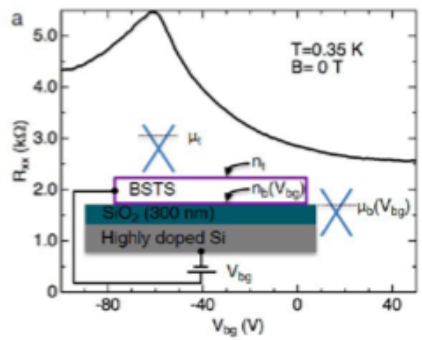
Purdue & Princeton
(Xu et.al, Hasan & Chen)
Magnet Lab in Florida

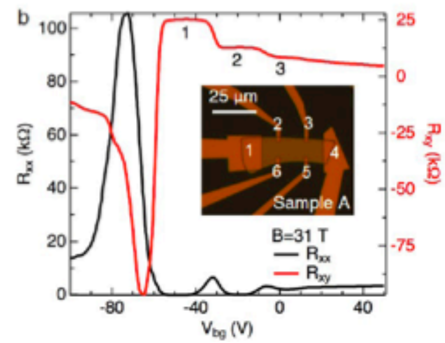
Nature Physics (2014)

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 !

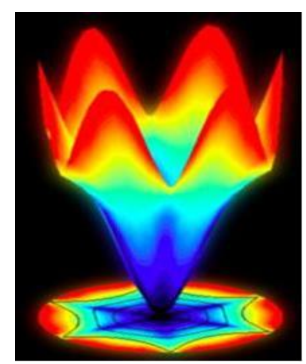




Yes!

Bulk insulating (intrinsic)
Topological insulators exist.

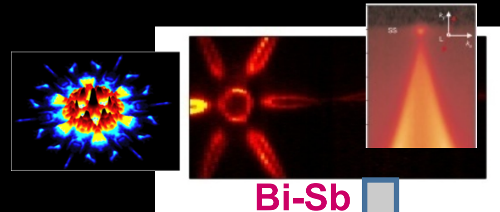
Latest paper : Xu *et.al*, Nature Physics (2014)



Experiments on Topo.Insulators (3D)

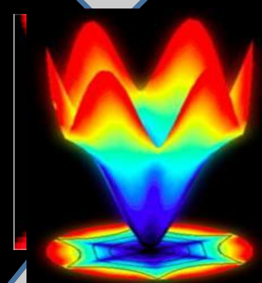
500+

Papers on Bi-based TIs



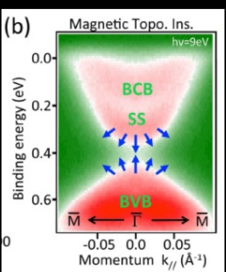
Hsieh et.al., NATURE 08 (sub. 2007)
Hsieh et.al., SCIENCE 09
Roushan et.al., NATURE 09

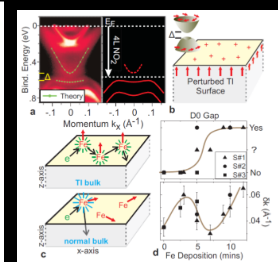
Bi_2X_3



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

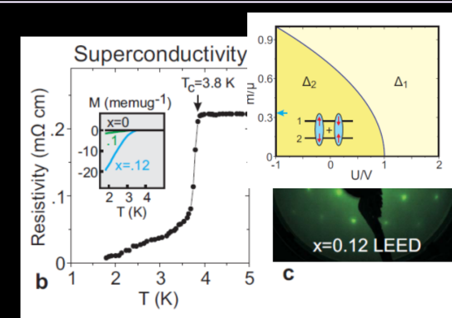
Magnetic TI





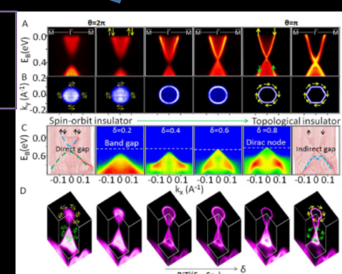
Xia et.al, arXiv. 2008
Wray et.al., Nat.Ph'10
Chen et.al, Science '10

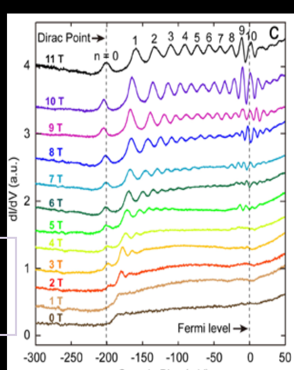
Superconductivity

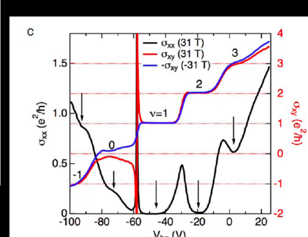


Quantum Hall effect

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







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

A Weyl Fermion semimetal with surface Fermi arcs in the transition metal monopnictide TaAs class; S.-M. Huang, S.-Y. Xu, I. Belopolski, C.-C. Lee, G. Chang, B. Wang, N. Alidoust, G. Bian, M. Neupane, C. Zhang, S. Jia, A. Bansil, H. Lin, M. Z. Hasan
Nature Commun. **6**:7373 (2015) (submitted Nov. 2014)

Discovery of a Weyl Fermion semimetal and topological Fermi arcs ; S.-Y. Xu, I. Belopolski, N. Alidoust, M. Neupane, G. Bian, C. Zhang, R. Sankar, G. Chang, Z. Yuan, C.-C. Lee, S.-M. Huang, H. Zheng, J. Ma, D. S. Sanchez, B. Wang, A. Bansil, F. Chou, P. P. Shibayev, H. Lin, S. Jia, and M. Z. Hasan
Science **349**, 613 (2015)

Discovery of a Weyl Fermion state with Fermi arcs in niobium arsenide ; S.-Y. Xu, N. Alidoust, I. Belopolski, Z. Yuan, G. Bian, T.-R. Chang, H. Zheng, V. Strocov, D. S. Sanchez, G. Chang, C. Zhang, D. Mou, Y. Wu, L. Huang, C.-C. Lee, S.-M. Huang, B. Wang, A. Bansil, H.-T. Jeng, A. Kaminski, H. Lin, S. Jia, and M. Z. Hasan
Nature Physics doi:10.1038/nphys3437 (2015)
NaturePhysics: "Discovery of a Weyl Fermion state"

Experimental discovery of a topological Weyl semimetal state in TaP ; S.-Y. Xu, I. Belopolski, D. S. Sanchez, C. Guo, G. Chang, C. Zhang, G. Bian, Z. Yuan, H. Lu, Yi. Feng, T.-R. Chang, P. P. Shibayev, M. L. Prokopovych, N. Alidoust, H. Zheng, C.-C. Lee, S.-M. Huang, R. Sankar, F. Chou, C.-H. Hsu, H.-T. Jeng, A, Bansil, T. Neupert, V. N. Strocov, H. Lin, S. Jia, M. Z. Hasan
arXiv:1508.03102 (2015)

Quantum Phase Transitions in Weyl Semimetal Tantalum Monophosphide ; C. Zhang, Z. Lin, C. Guo, S.-Y. Xu, C.-C. Lee, H. Lu, S.-M. Huang, G. Chang, C.-H. Hsu, H. Lin, L. Li, C. Zhang, T. Neupert, M. Z. Hasan, J, Wang, S. Jia
arXiv:1507.06301 (2015)

Arc-tunable Weyl Fermion metallic state in $Mo_xW_{1-x}Te_2$; T.-R. Chang, S.-Y. Xu, G. Chang, C.-C. Lee, S.-M. Huang, B. Wang, G. Bian, H. Zheng, D. S. Sanchez, I. Belopolski, N. Alidoust, M. Neupane, A. Bansil, H.-T. Jeng, H. Lin, M. Zahid Hasan
arXiv:1508.06723 (2015)

Fermi arc topology and interconnectivity in Weyl fermion semimetals TaAs, TaP, NbAs, and NbP ; C.-C. Lee, S.-Y. Xu, S.-M. Huang, D. S. Sanchez, I. Belopolski, G. Chang, G. Bian, N. Alidoust, H. Zheng, M. Neupane,B. Wang, A. Bansil, M. Z. Hasan, and H. Lin
arXiv:1508.05999 (2015)

Tantalum Monoarsenide: an Exotic Compensated (Weyl) Semimetal ; C. Zhang, Z. Yuan, S.-Y. Xu, Z. Lin, B. Tong, M. Z. Hasan, J. Wang, C. Zhang, S. Jia
arXiv:1502.00251

Observation of the Adler-Bell-Jackiw chiral anomaly in a Weyl semimetal ; C. Zhang, S.-Y. Xu, I. Belopolski, Z. Yuan, Z. Lin, B. Tong, N. Alidoust, C.-C. Lee, S.-M. Huang, H. Lin, M. Neupane, D. S. Sanchez, H. Zheng, G. Bian, J. Wang, C. Zhang, T. Neupert, M. Z. Hasan, S. Jia
arXiv:1503.02630

A new type of Weyl semimetal with quadratic double Weyl fermions in SrSi2
S.-M. Huang, S.-Y. Xu, I. Belopolski, C.-C. Lee, G. Chang, B. Wang, N. Alidoust, M. Neupane, H. Zheng, D. Sanchez, A. Bansil, G. Bian, H. Lin, and M. Z. Hasan
arXiv:1503.05868