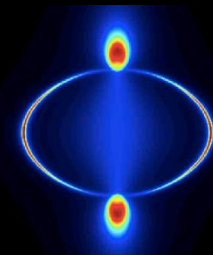
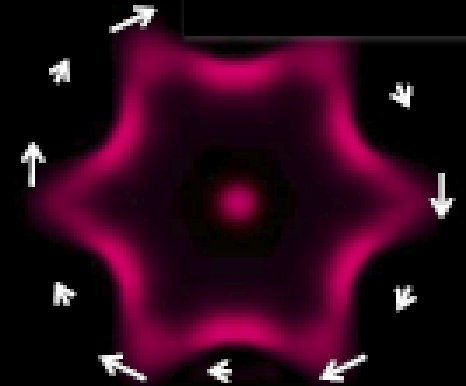
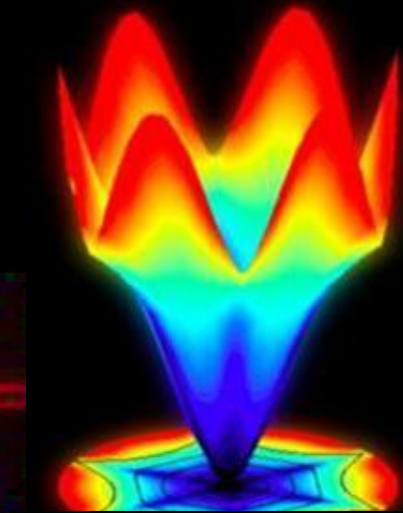
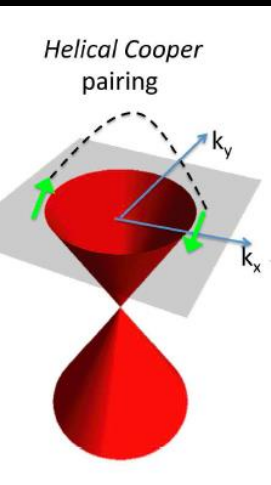


Topological Insulators 2D Topological Superconductors & Weyl Semimetals

M. Z. Hasan (Princeton)

Fine Theoretical Physics Institute
Workshop on Symmetry, Interactions & Topology
Minnesota, 2015



Supported by DOE, Moore Fdn, NSF

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

Experiments:

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

Sample Collaborations (on Superconductors, Weyl Semimetals)

SS: R. Sankar, F.-C. Chou (Taiwan)

SS: C. Zhang, Shuang Jia (Peking)

MBE: D. Zhang, A. Richardella, Nitin Samarth (PennState)

MBE/SolidState: Yong Chen et al (Purdue);

MBE: M. Brahlek, Bansal, S.-H. Oh (Rutgers)

TKI samples : Z. Fisk

National Lab Beamline Support

H.K. Mo, A. Wray, Z. Hussain, A. Fedorov et.al., (**LBNL/ALS-Berkeley**)

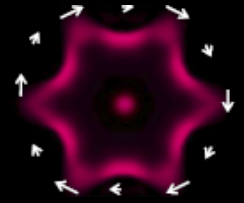
G. Landolt; B. Slomski; J.H. Dil, J. Osterwalder et.al., (**SLS/COPHEE**)

M. Leandersson; T. Balasubramanian et.al., (**MaxIII, Sweden**)

M. Hashimoto, D.H. Lu et.al., (**SSRL/Stanford**)

E. Vescovo (NSLS); Tomasz Durakiewicz (**Los Alamos**)

REVIEWS



Topo. Insulators & Topo. Superconductors

M.Z.H. and C.L. Kane

“Topological Insulators” (Topo. Superconductor is also in this review)

Rev. of Mod. Phys., (*RMP*) 82, 3045 (2010)

M.Z.Hasan and J.E. Moore

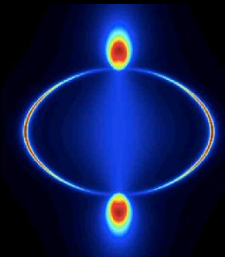
“Three Dimensional Topological Insulators”

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)



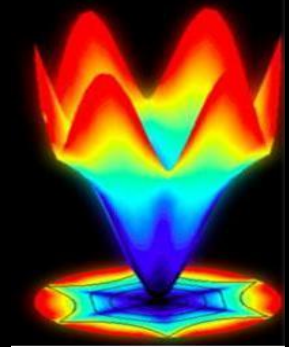
Weyl Semimetals (THEORY ONLY):

O. Vafek & A. Vishwanath

“Dirac Fermions in Solids (including Weyl Semimetals)”

Ann. Rev. of Cond. Mat. Phy., 5, 83 (2014)

AND many other recent excellent reviews...

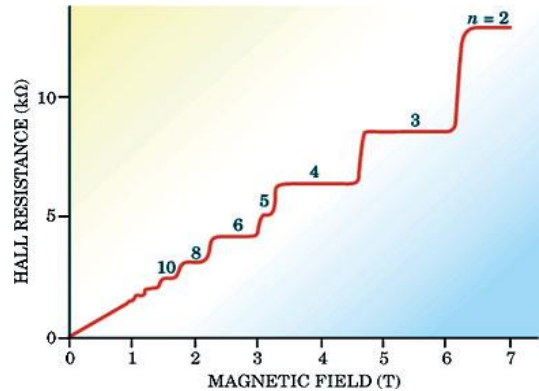


QHE phases (2D)

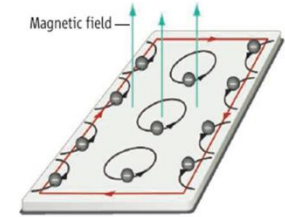
$$\sigma_{xy} = n e^2/h$$

↑
Chern no.

(D. Thouless et.al., M. Berry)



Transport



Topo Insulators

$$\nu_0 = \Theta_{ME}/\pi$$

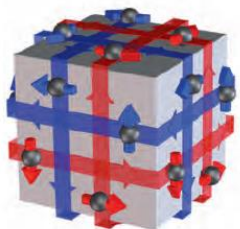
$\Theta = \pi$ (odd)

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

4 TQNs \rightarrow **15+1** distinct insulators

No quantized transport

via : $\{\nu_i\}$



$\{\nu_0, \nu_1, \nu_2, \nu_3\}$
Topological “Order Parameters”

Spin-sensitive
Momentum-resolved
Edge vs. Bulk

(Bulk-Boundary Correspondence)

No quantized transport via (topo. Invariants):

$$\{ v_i \}$$

KEY questions

Experimentally IMAGE

Boundary/surface states with Spin

Experimentally PROBE

CORRESPONDENCE, BULK — BOUNDARY

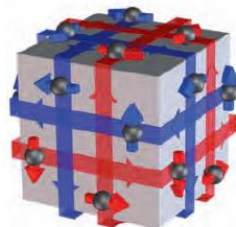
Experimental prove

“Z2 or SPT topological order”, Gapless throughout

Experimentally break symmetry (SPT)

Topo. protection must be lost !

Experimentally how does it arise from a Bloch band insulator ?



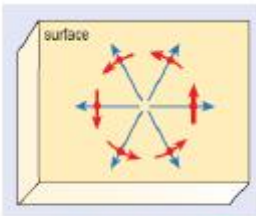
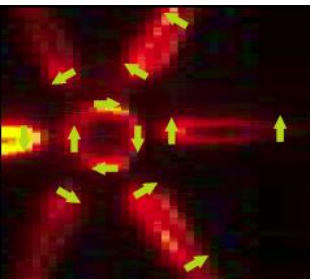
Spin-sensitive
Momentum-resolved
Edge vs. Bulk

Topo. Insulator → Most Researched Topo. Insulator

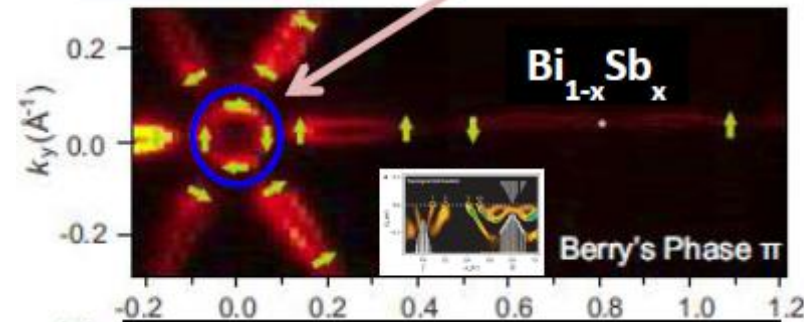


KITP Proceed. (2007)
 Hsieh et.al., NATURE 2008
 Hsieh et.al., SCIENCE 2009
Physics Today, April-2009

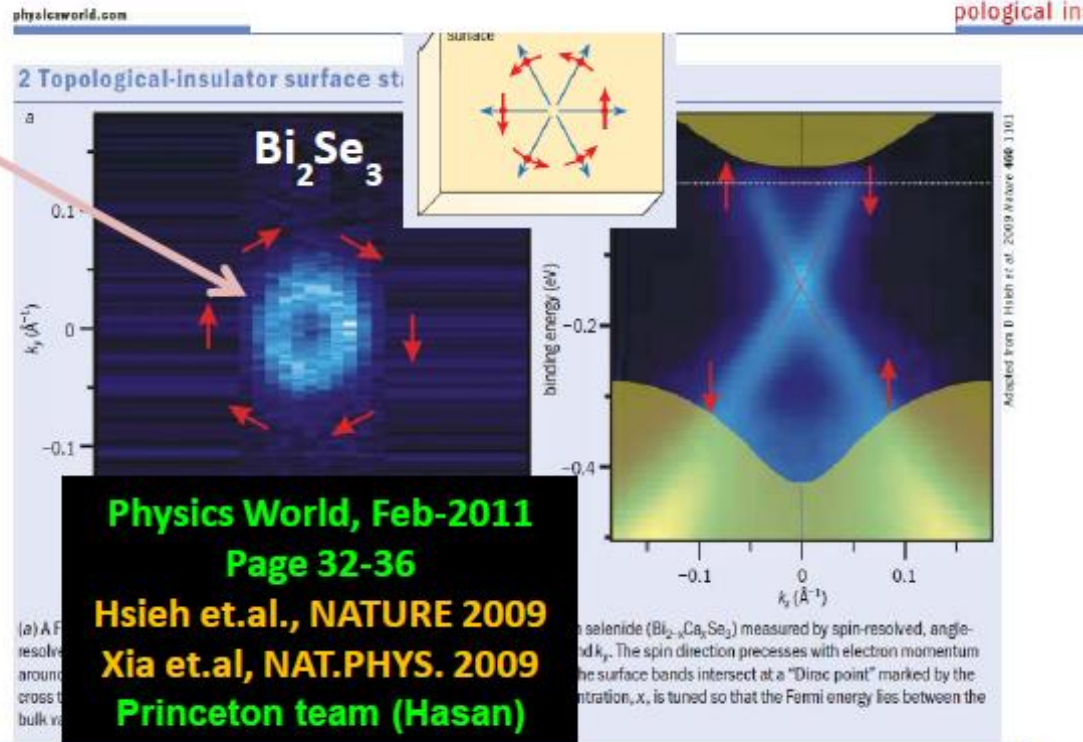
Xia et.al, NAT.PHYS. 2009 (arXiv 2008)
 Hsieh et.al., NATURE 2009
 Zhang et.al, NAT.PHYS. 2009
Physics World, Feb-2011



Dirac Cone



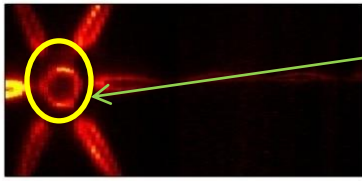
(a) **Physics Today, April 2009**
 "Search & Discovery" Page 12-13
 Topological Insulators ($\text{Bi}_{1-x}\text{Sb}_x$)
 Hsieh et.al., NATURE 2008
 Princeton team (Hasan)



(a) A Fermi level resolved ARPES intensity plot around the Dirac point of Bi_2Se_3 measured by spin-resolved, angle-resolved photoemission spectroscopy (ARPES). The spin direction precesses with electron momentum. The surface bands intersect at a "Dirac point" marked by the intersection, x , is tuned so that the Fermi energy lies between the bulk bands.
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)

Bi-Sb lead to the discovery of Bi_2X_3 class as TI ..

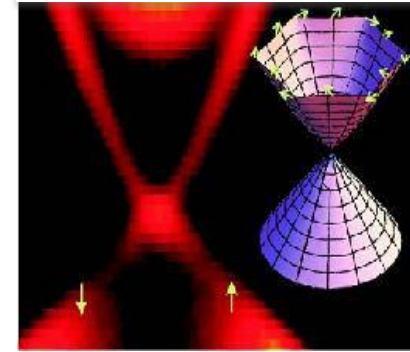
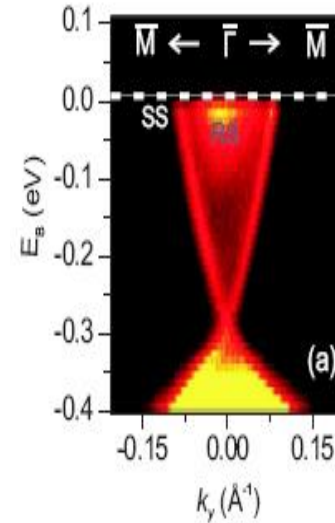
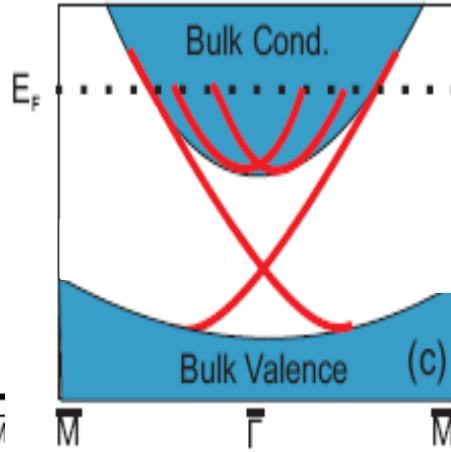
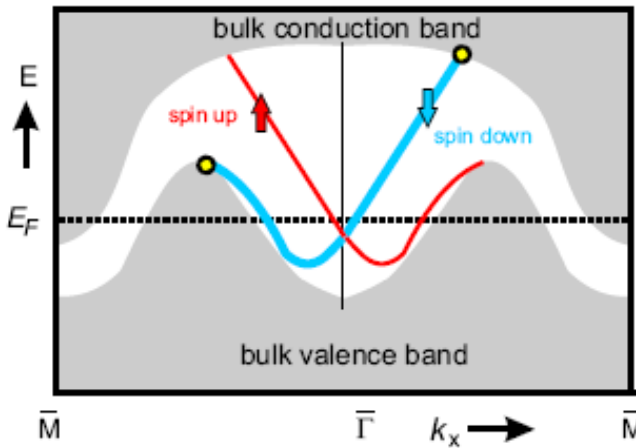
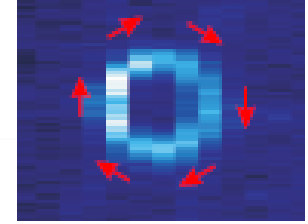


Single Dirac cone Bi-Sb

Bi-Sb \rightarrow Pure Sb

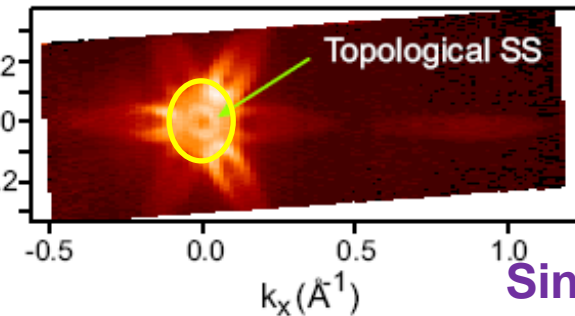


Bi_2Se_3



Topology in Bi-Sb [Hsieh et.al., 08]

Bi_2Se_3 class as TIs :



Xia, Hsieh et.al., **NATURE PHYS** 09, arXiv (2008)
and elaborated in Hsieh et.al. (MZH) **NATURE** 09

also

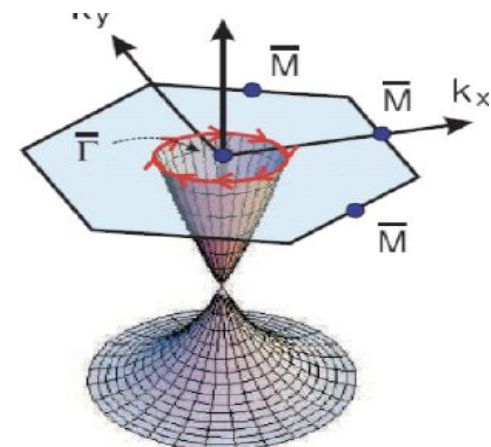
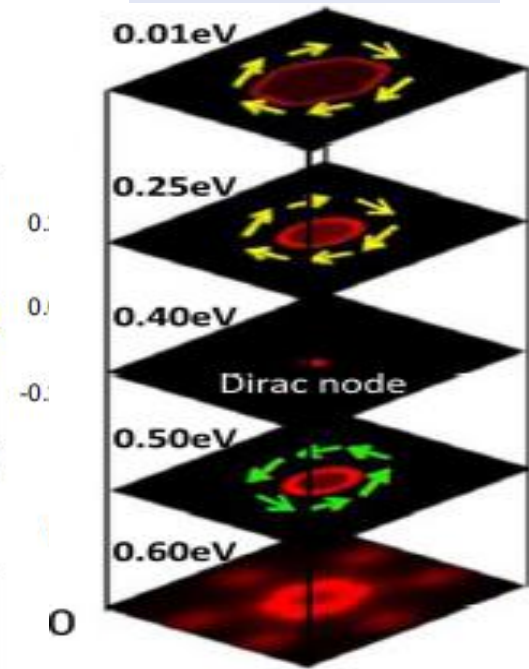
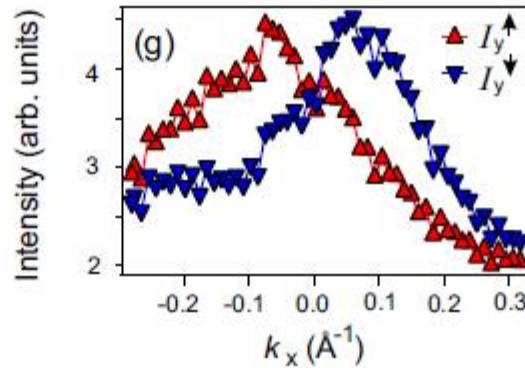
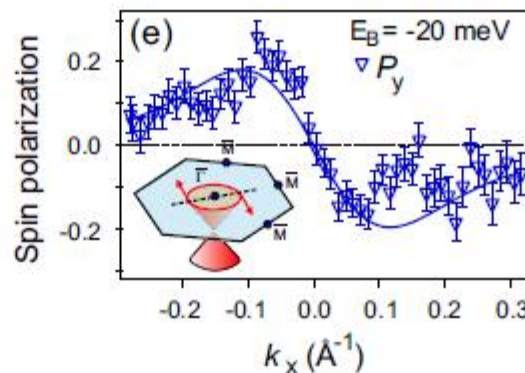
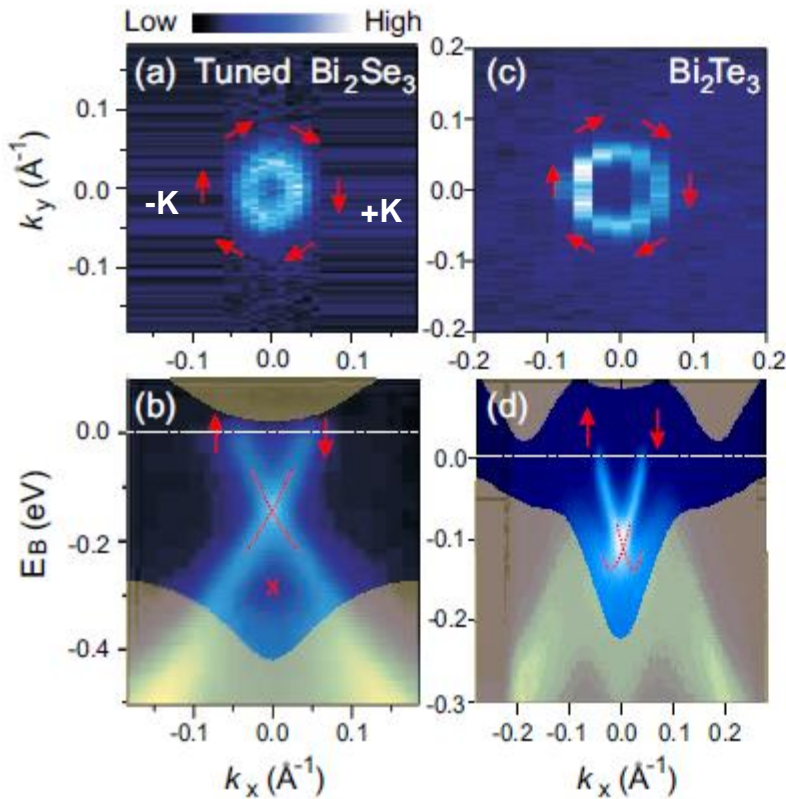
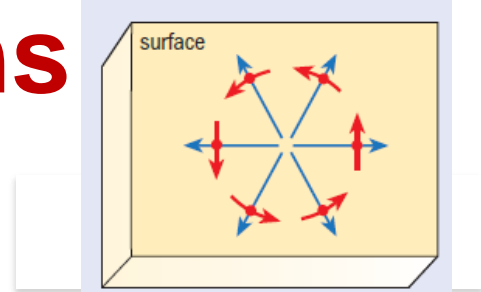
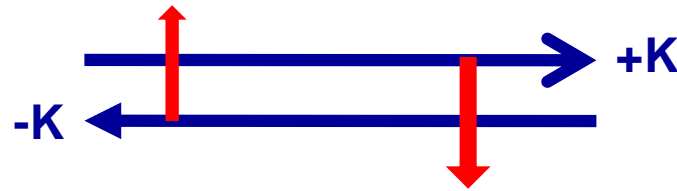
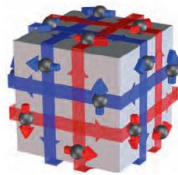
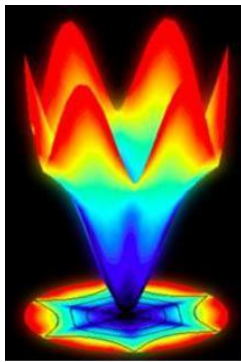
Zhang et.al. **NAT. PHYS** 09, Chen et.al.,(Zhang) **SCIENCE** '09
Hsieh et.al., **PhysRevLett** '09

Single Dirac cone in (Bi-Sb alloy)

\rightarrow Single Dirac cone ONLY in Bi_2Se_3 class

Helical Dirac fermions

One-to-One Spin-LinearMomentum Locking

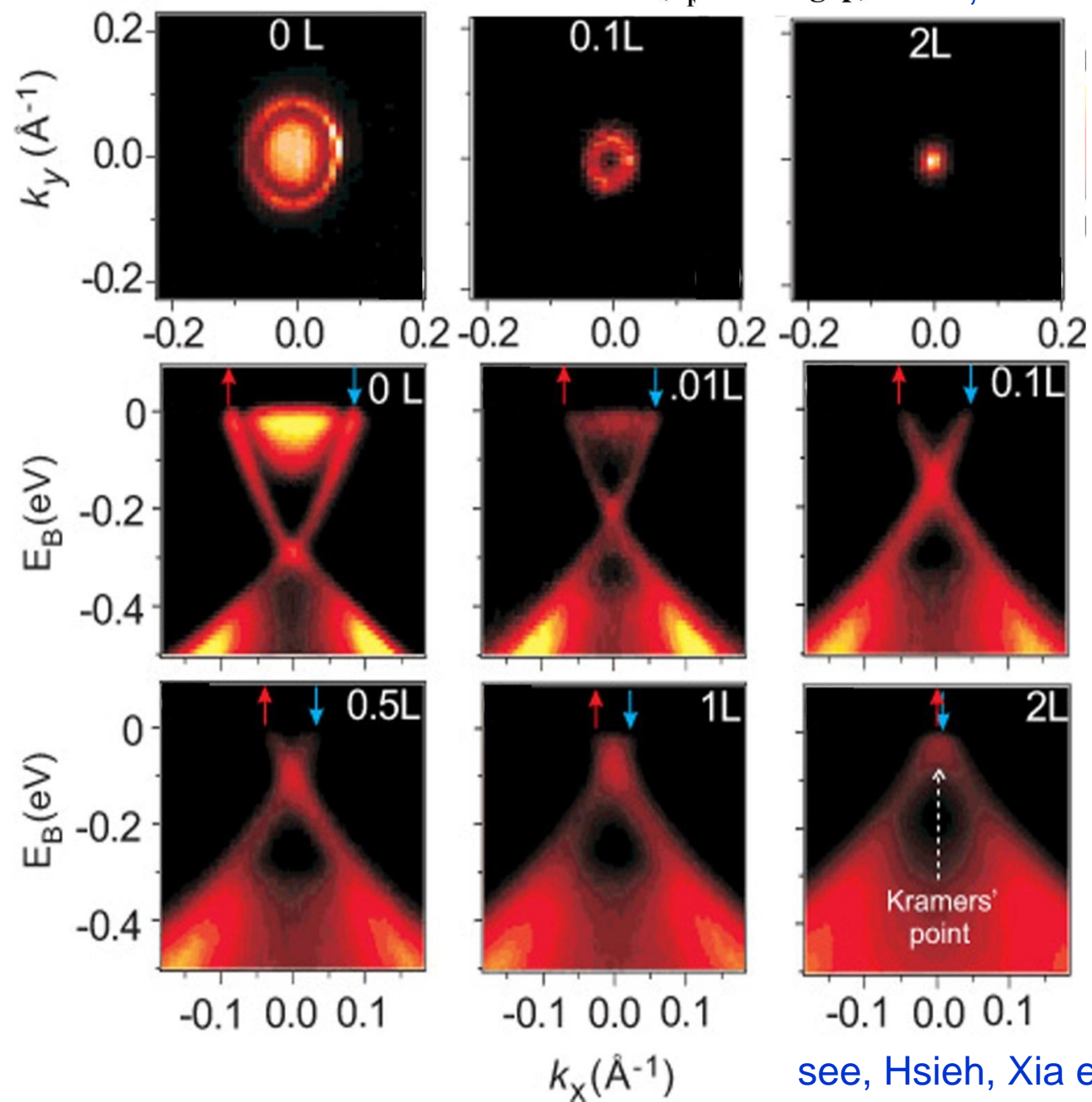


Berry's phase $\theta = \pi$
Invariant = $\theta/\pi = 1$

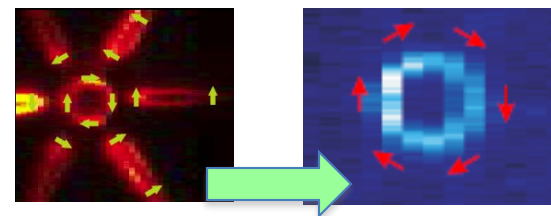
Insulating Topological Insulators

(E_F in bulk gap) see, Hsieh, Xia et.al., **Nature (2009)**

**Bulk Insulating
achieved
under UHV
conditions
(stable)**



Bi-Sb \rightarrow Bi₂X₃



see, Hsieh, Xia et.al., (MZH) **Nature (2009)**

(SPT or Z_2) Topo.Order at Room Temperature

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

Protected Surface States (New 2DEG)

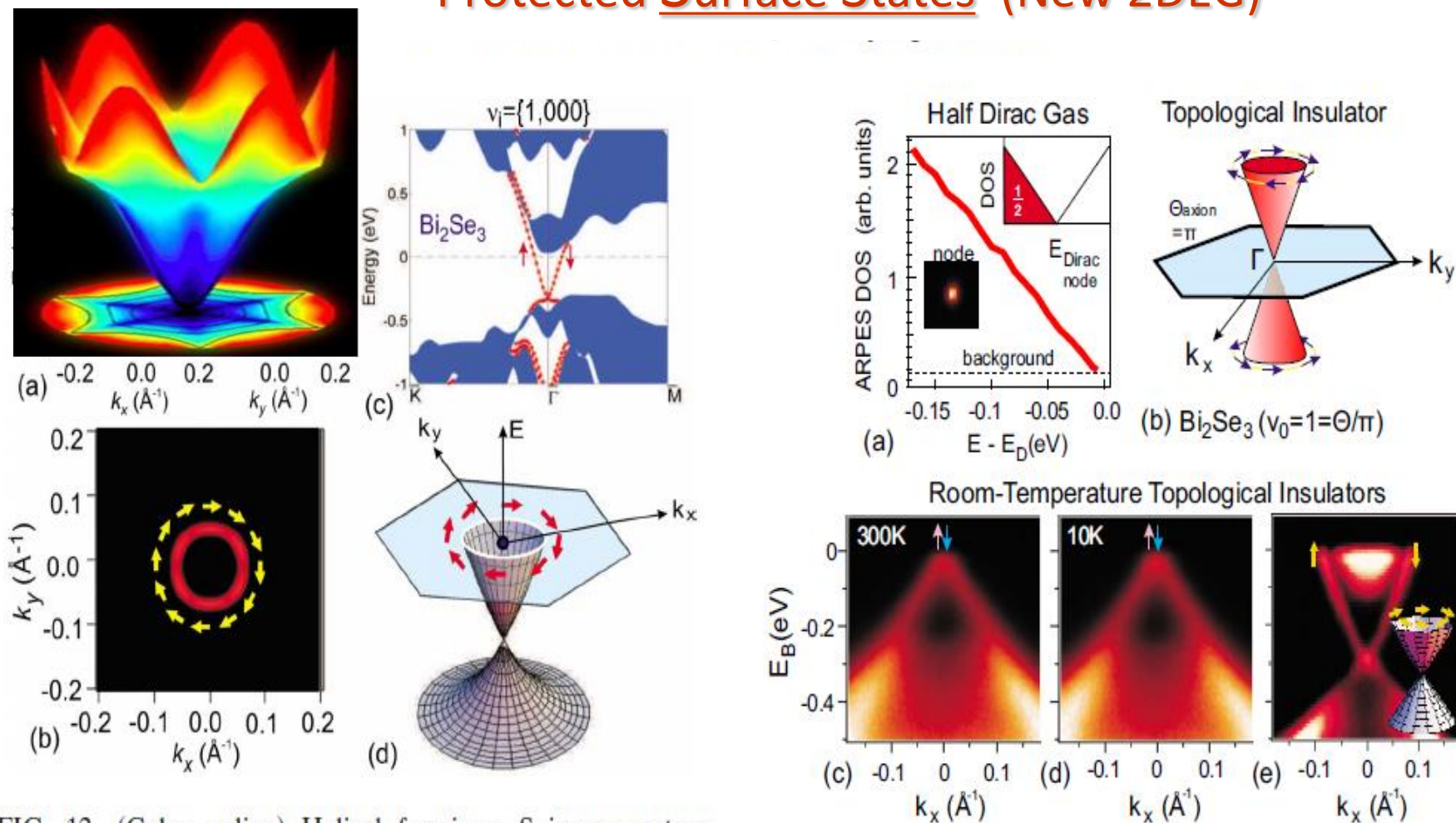
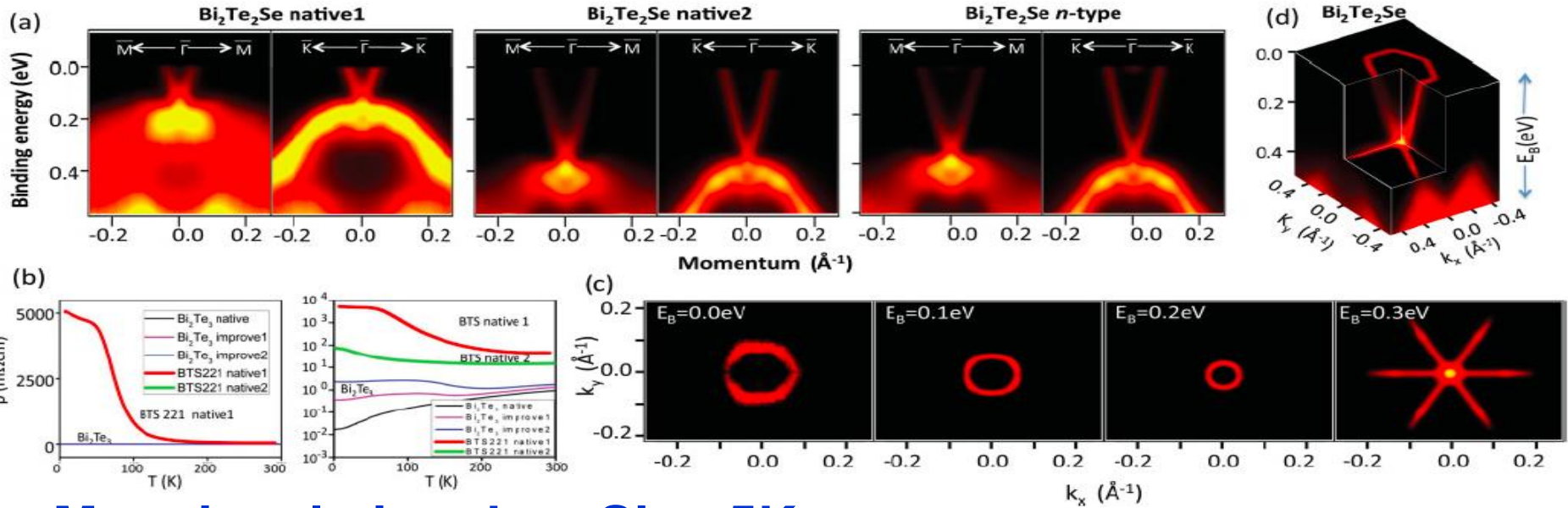


FIG. 12. (Color online) Helical fermions: Spin-momentum

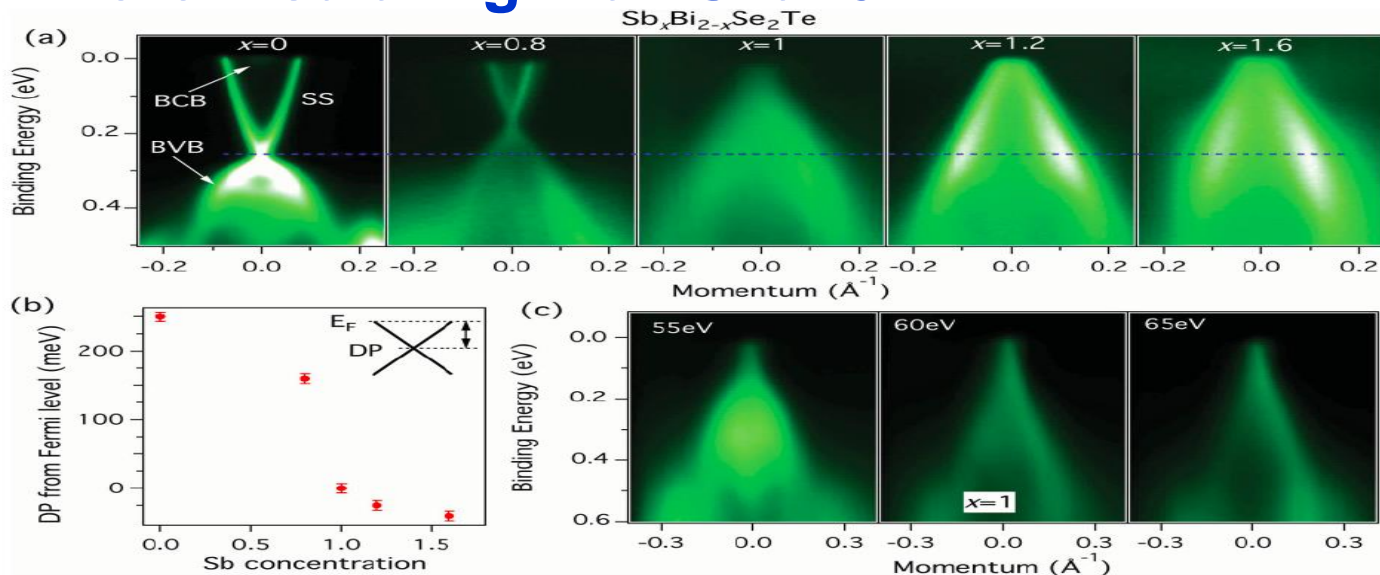
Hsieh, Qian, Wray, Xia et.al., Nature'08, Science'09, Nature'09

band-structure engineering (via ARPES and growth)

→ Highly Bulk Insulating BiTS (stable)



More insulating than Si at 5K



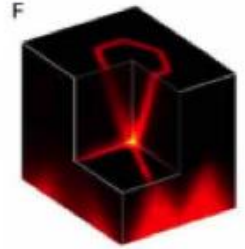
PRB'10
Taskin,
Ando et.al.

and

PRB'11
Xu et.al,
(princeton)

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

Transport

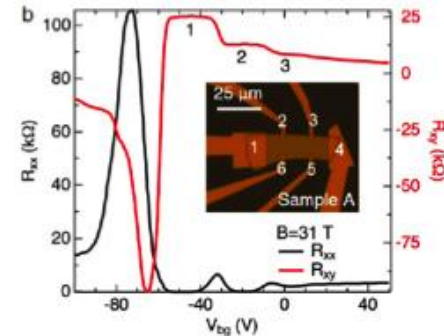
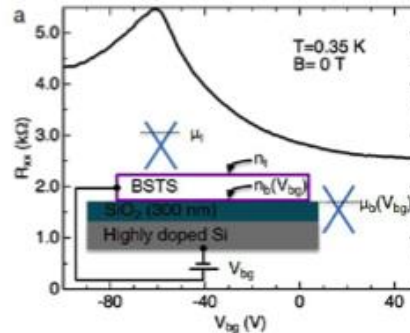
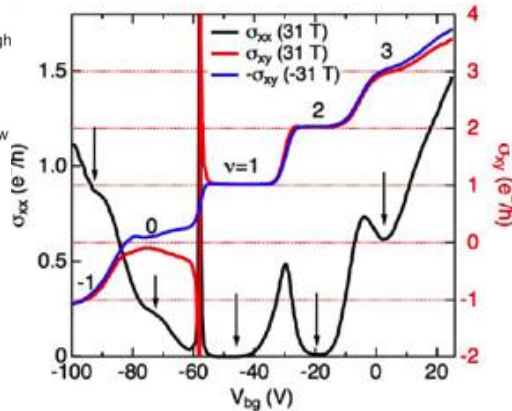
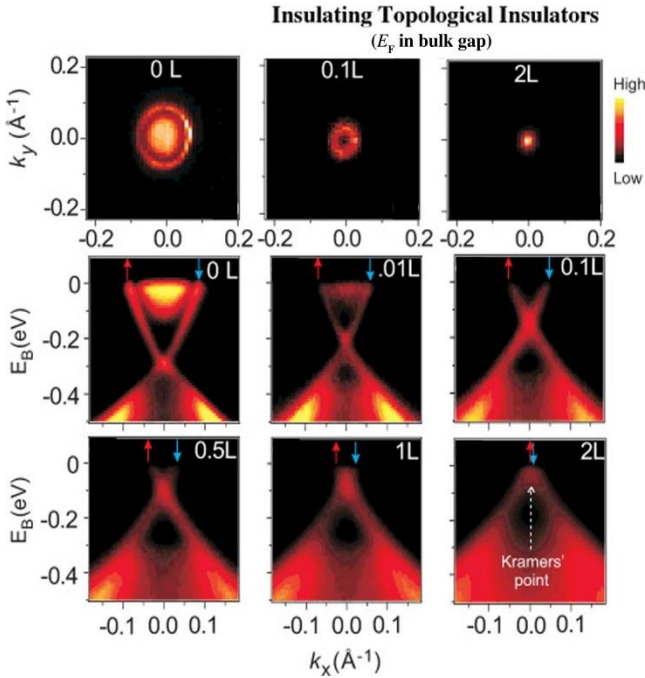


Purdue & Princeton
(Xu et.al, Hasan & Chen)
Magnet Lab in Florida

Nature Physics (2014)

TI = 2 surf's (Top + Bot.) of Dirac gas
LL = $(n_t + 1/2) + (n_b + 1/2) = n_t + n_b + 1$

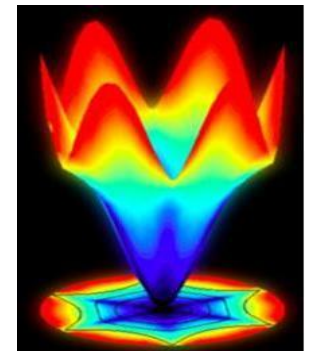
only Integer QHE !



Yes!

Bulk insulating (intrinsic)
Topological insulators exist
(outside UHV also).

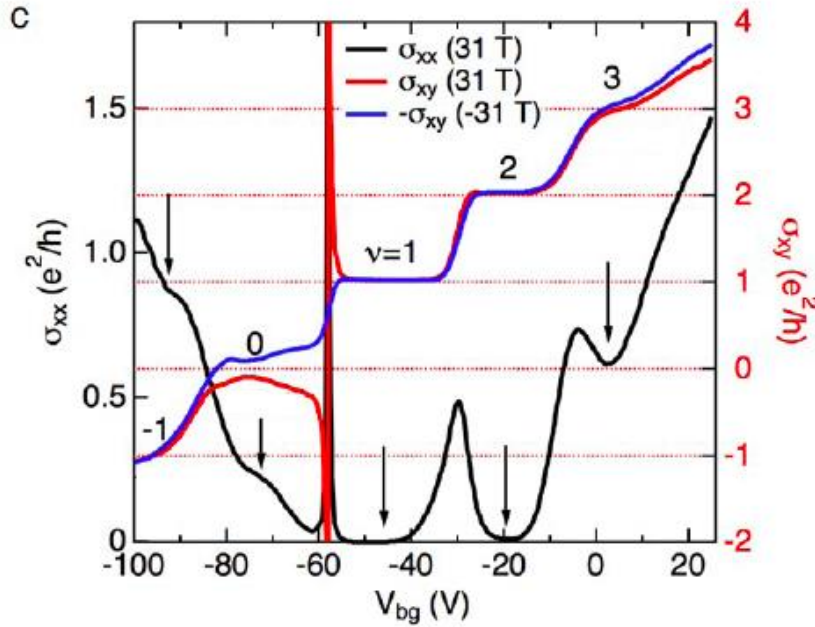
Latest paper : Xu et.al, Nature Physics (2014)



3D Topo. Insulators

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

Transport

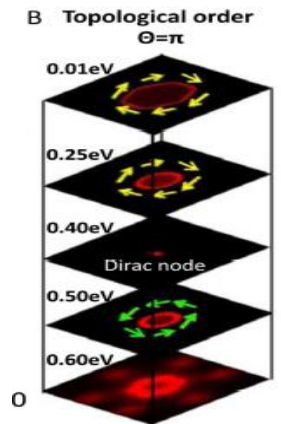
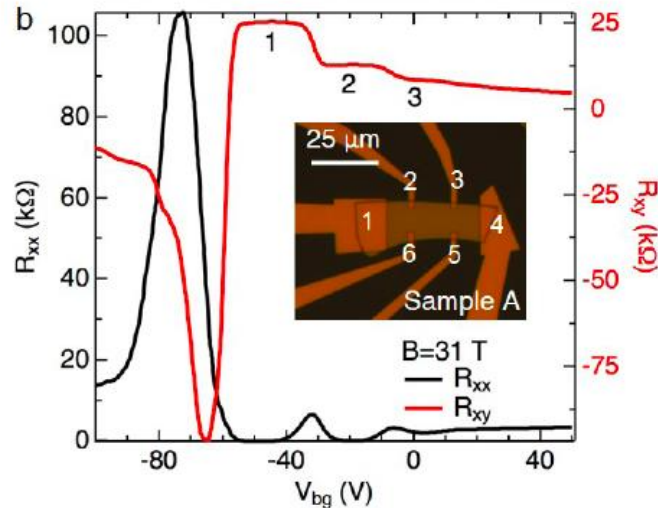
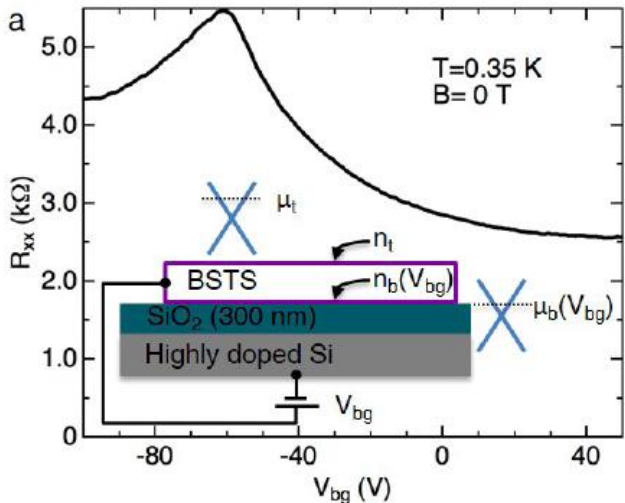
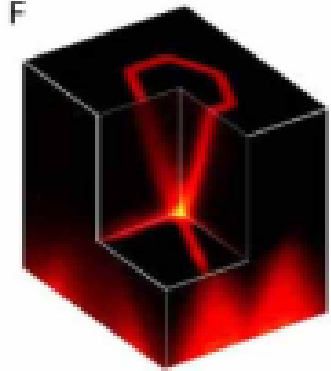


Princeton & Purdue
 Xu *et.al*, MZH & Yong Chen
Nature Physics (2014)
 10th Nov '14

only Integer QHE !

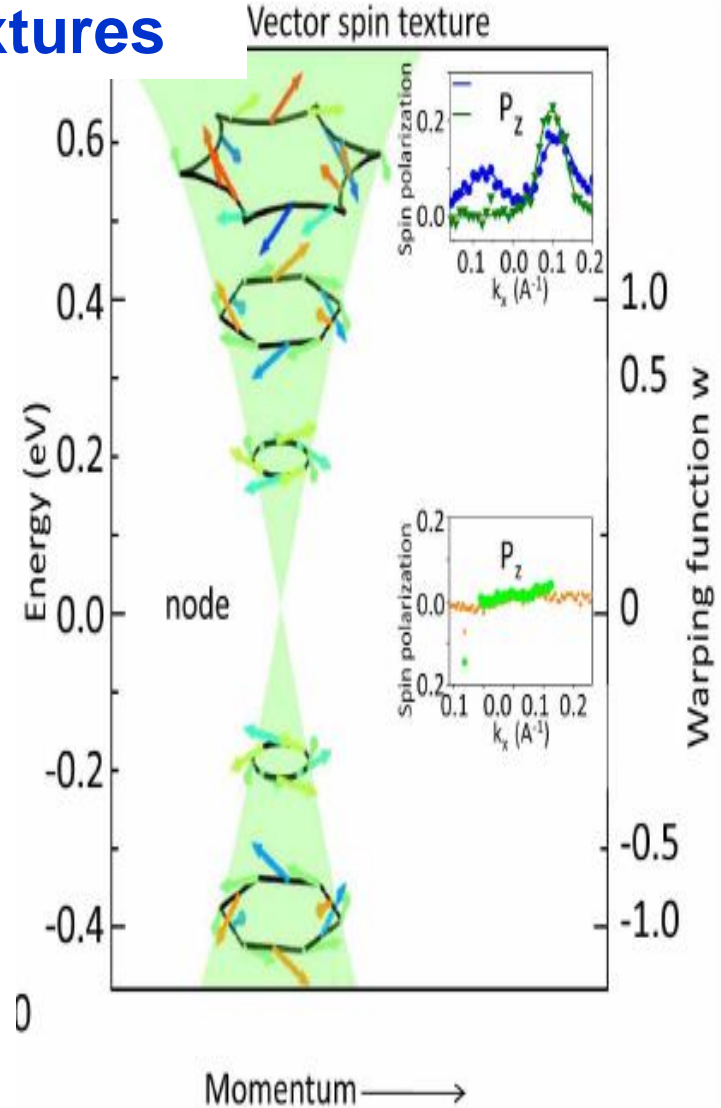
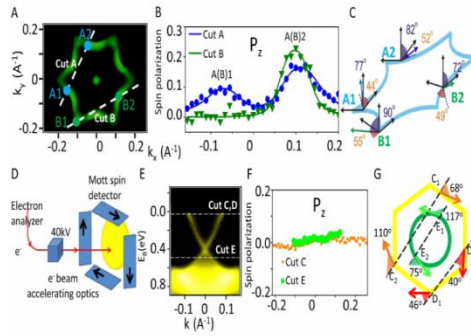
TI = 2 surf's (Top + Bot.) of Dirac gas
 $LL = (n_t + 1/2) + (n_b + 1/2) = n_t + n_b + 1$

ARPES

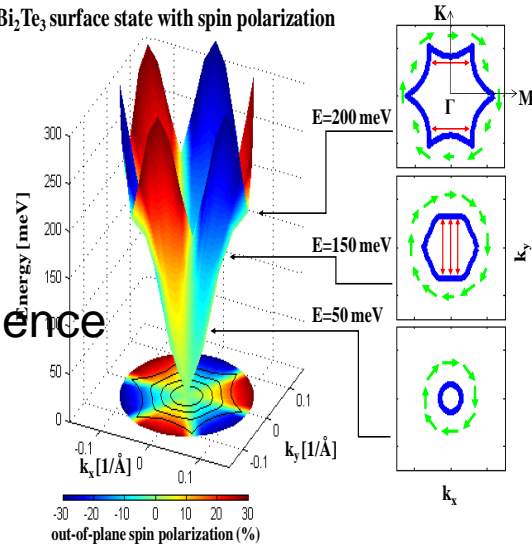


Evolution of Out-of-plane Spin-Texture

3D Vectorial Spin Textures



Bi₂Te₃ surface state with spin polarization



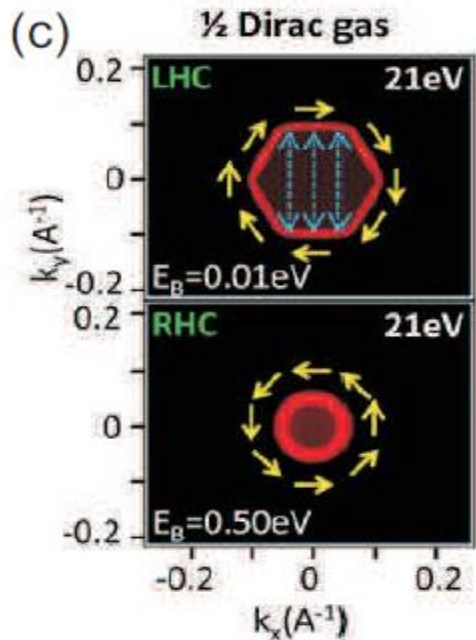
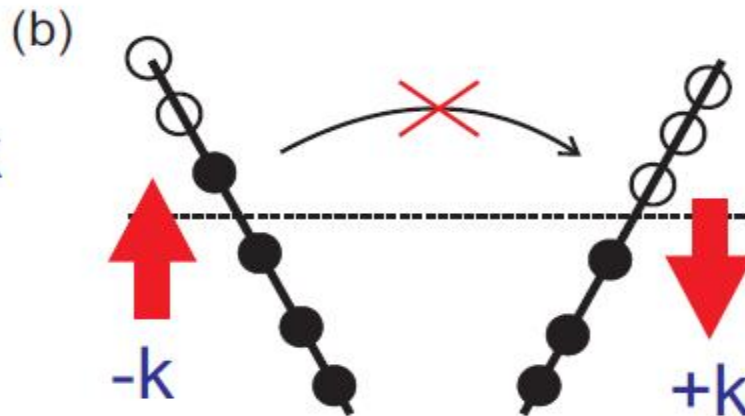
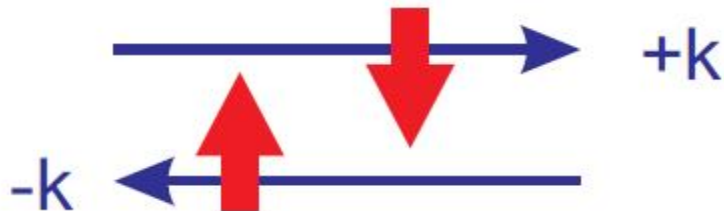
Bulk-Boundary
correspondence

Calculation : MZH, Lin et.al. (2009)

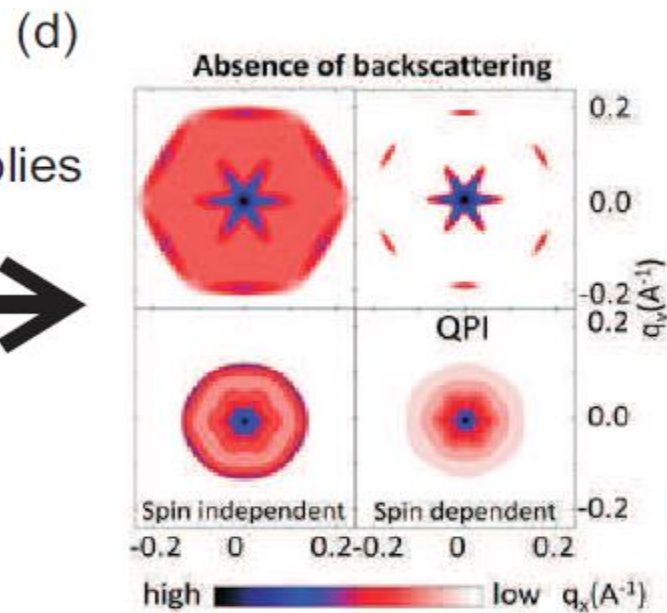
SuYang Xu et.al., (MZH) SCIENCE '11

Helical spin texture ➔ absence of backscattering

Spin-ARPES ➔



Directly implies



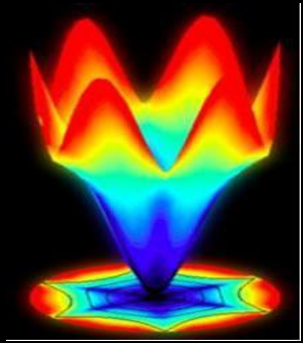
QPI

in

STM



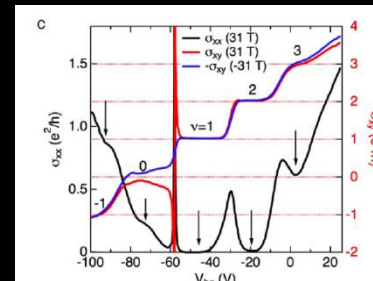
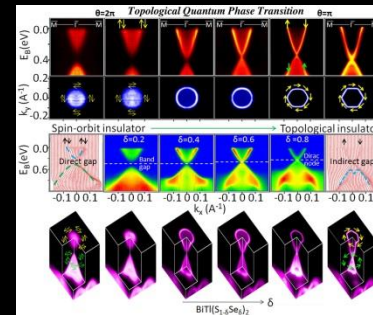
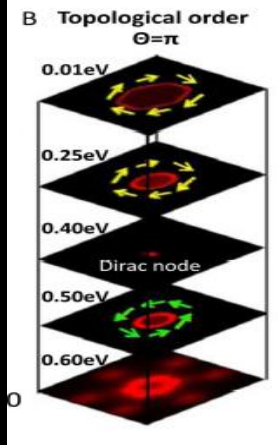
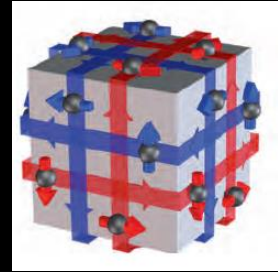
- Roushan et.al.,(Yazdani) Nature'09, Alpichshev et.al., (Kapitulnik) PRL'10, □ Zhang et.al., (Xue) PRL'10, Xu et.al., (MZH & Madhavan) Science'11, '09 & Sci'13



Topological Insulators

A New Form of Quantum Matter

1. Surface States exist and locate inside the bandgap and $\frac{1}{2}$ 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**)

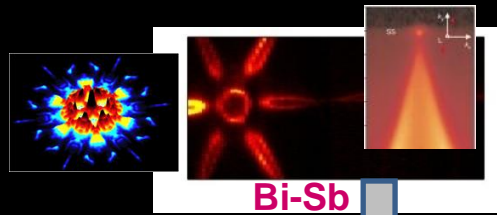


M.Z.H. & CL Kane, Rev. Mod. Phys. 82, 3045 (2010)

Experiments on Topo. Insulators (3D)

500+

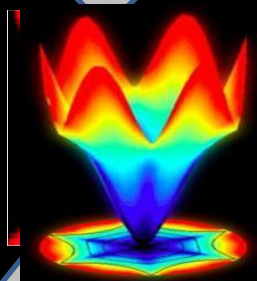
Papers on Bi-based TIs



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

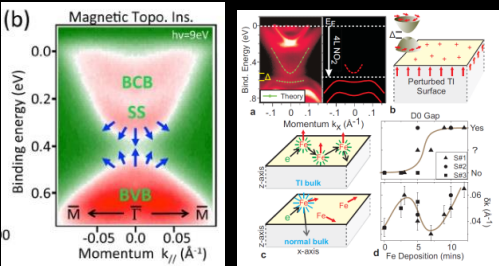
Magnetic TI

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

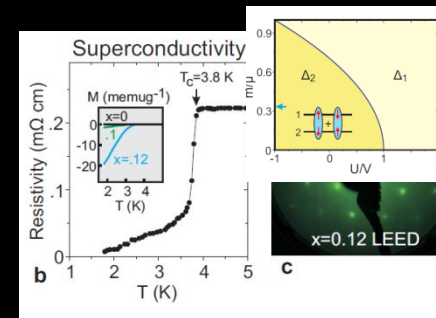
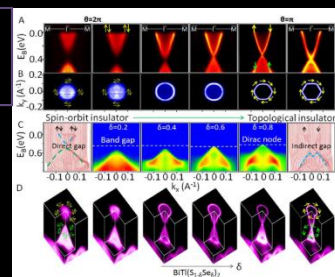
Superconductivity



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



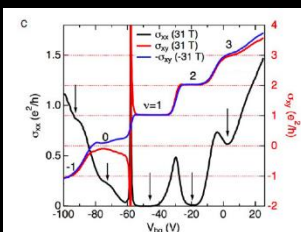
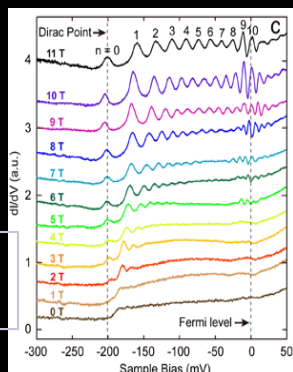
Hor et.al., PRL 2008
 Wray et.al., Nph 2009
 Ando et.al, PRL 2008

Topo. Q. Phase Transition

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

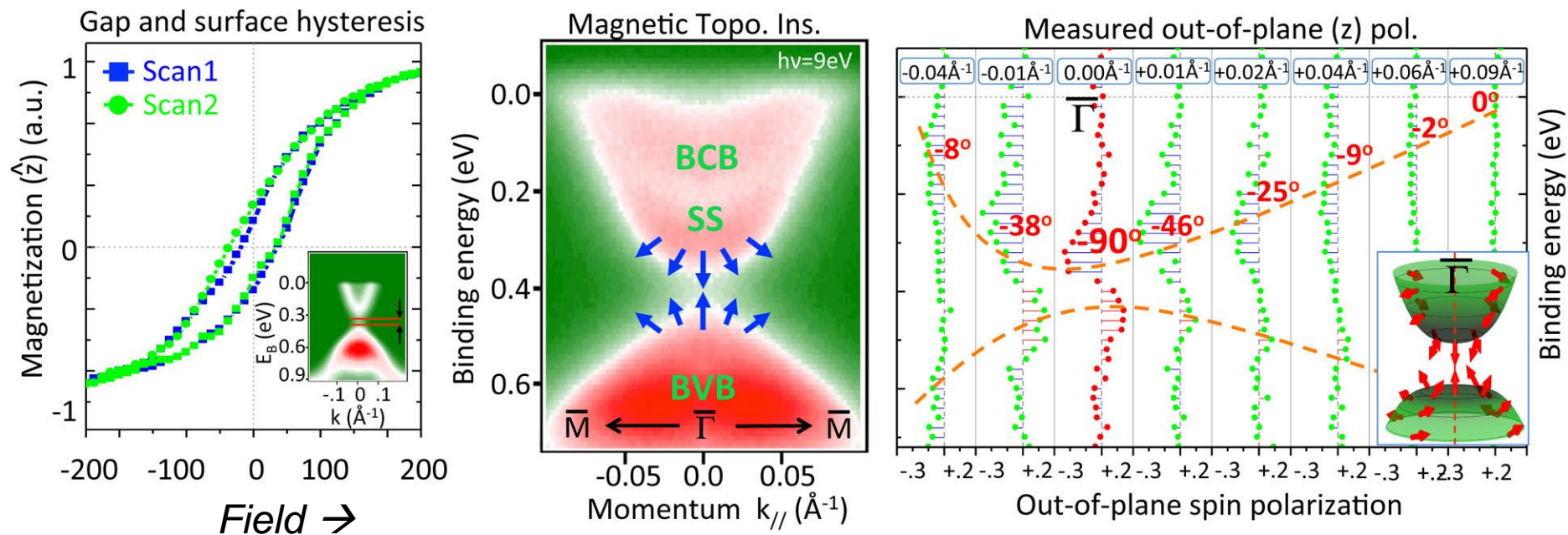
Topo. Kondo Insulators

QAHE

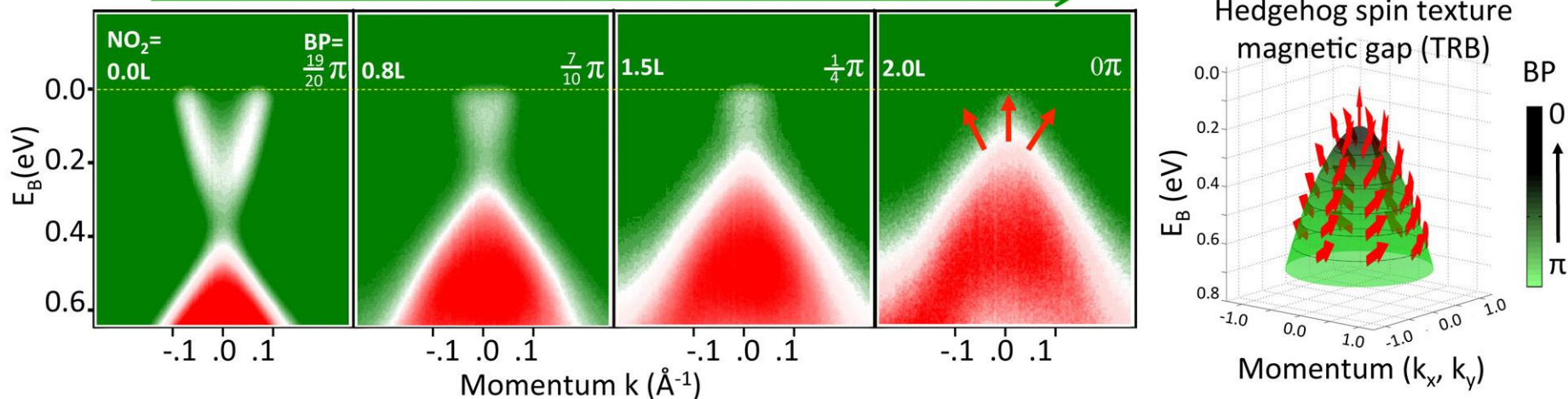


Hedgehog Magnets

Mn, V or Cr doping into Bi-TS (3D-TI) family → **Magnetic TI**



Surface gating to set chemical potential inside the magnetic gap \rightarrow

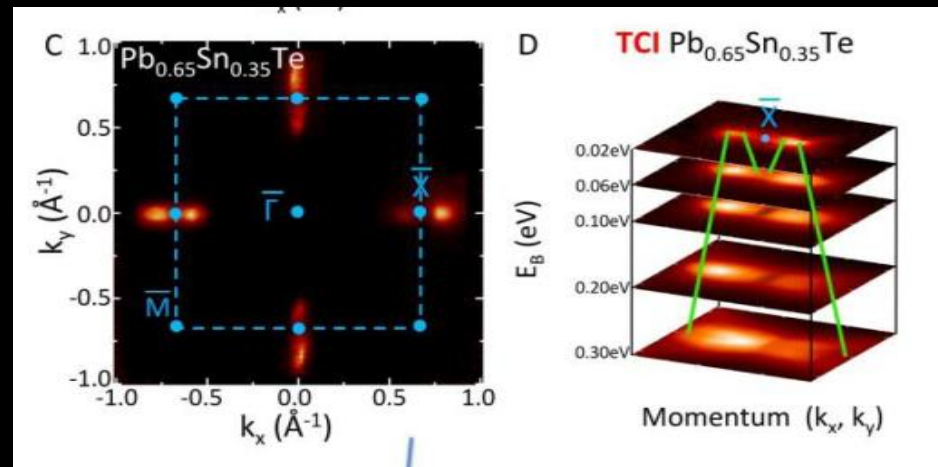


Topo Insulators beyond Z_2 or TRI

TR invariance \leftrightarrow SG symmetry (TCI)

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

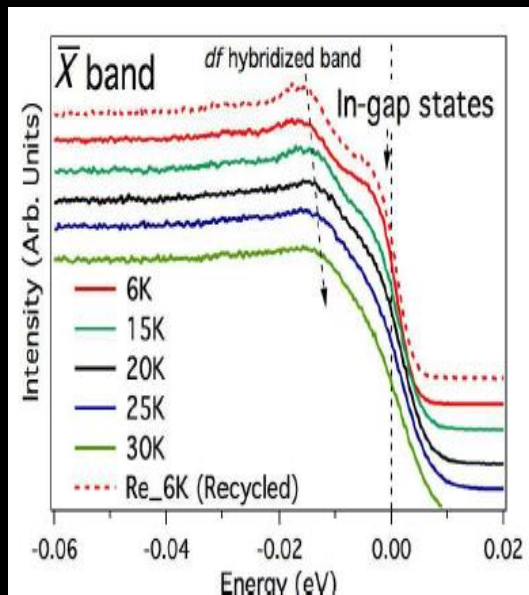
Mirror Chern no. measured in Bi-Sb;
Hsieh, Xia, et.al., (Kane & MZH) SCIENCE' 09



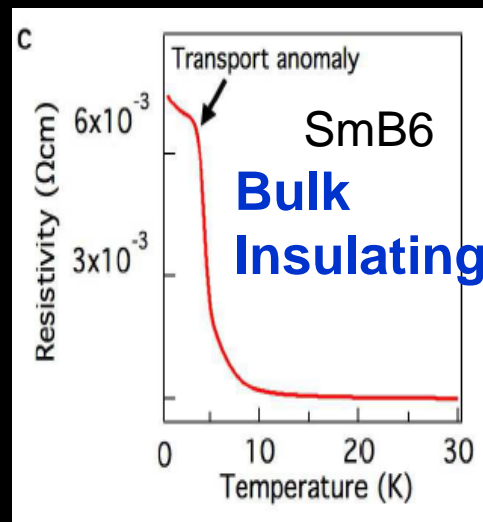
Topo Kondo Insulators

Kondo gap hosts topological surface states?

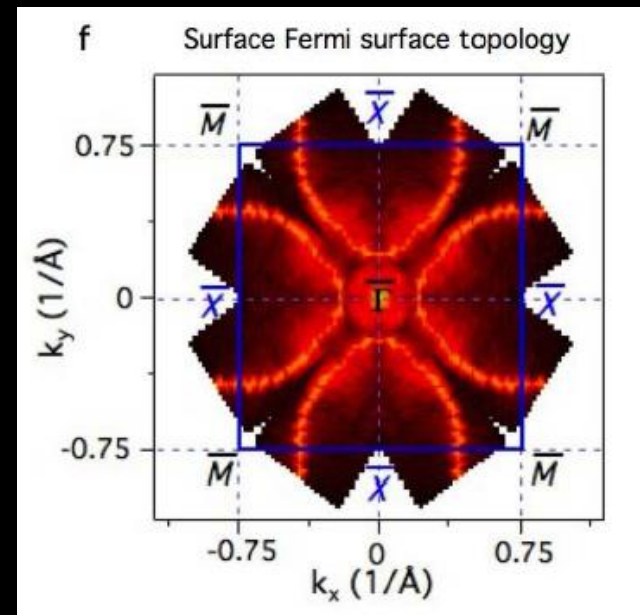
Theory : Dzero et.al, PRL '12



Neupane et.al., '13

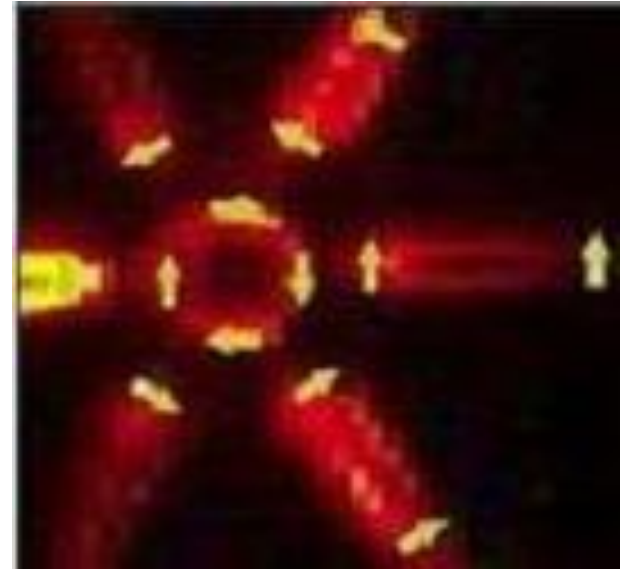
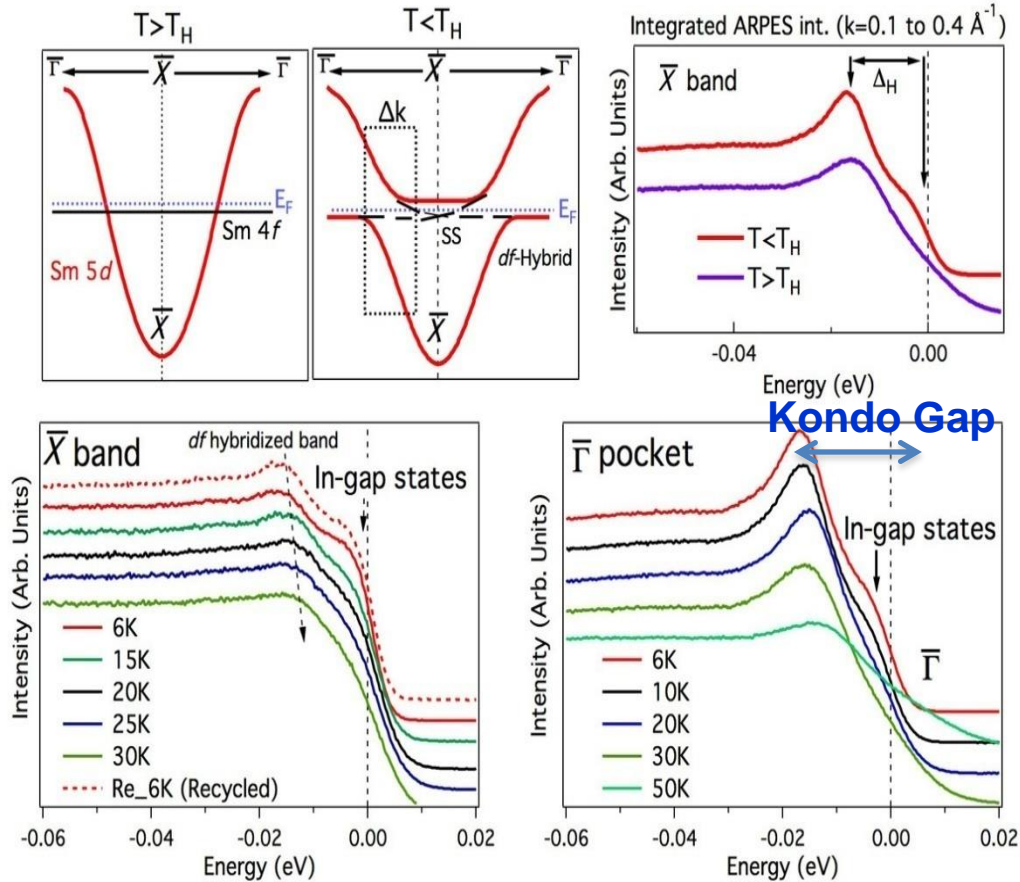


Known from 1960s !

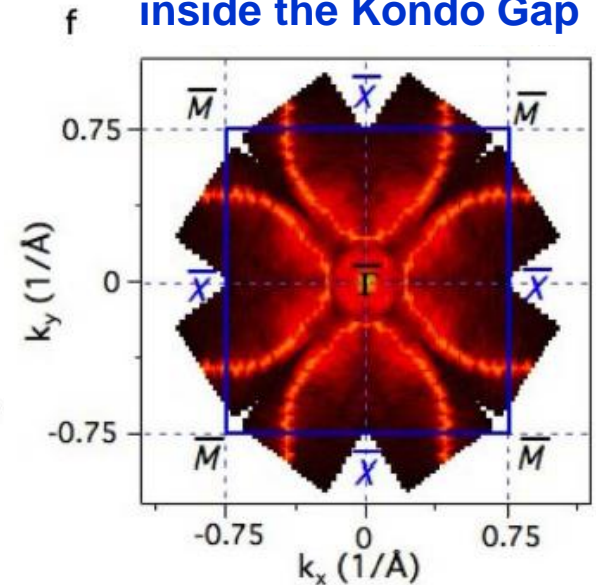


Neupane et.al., '13

Topo.Kondo Insulators



Fermi surface topology inside the Kondo Gap

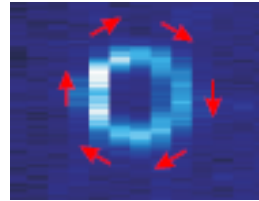


Neupane et.al., (MZH) '13

Transport : Bulk insulating with SS transport !
 J. Allen group (1990s) and others since 1960s
 Xia et.al., SciRep'13 and Wolgast et.al., PRB'13
ARPES:
 Hasan group'13; Feng group'13 and others

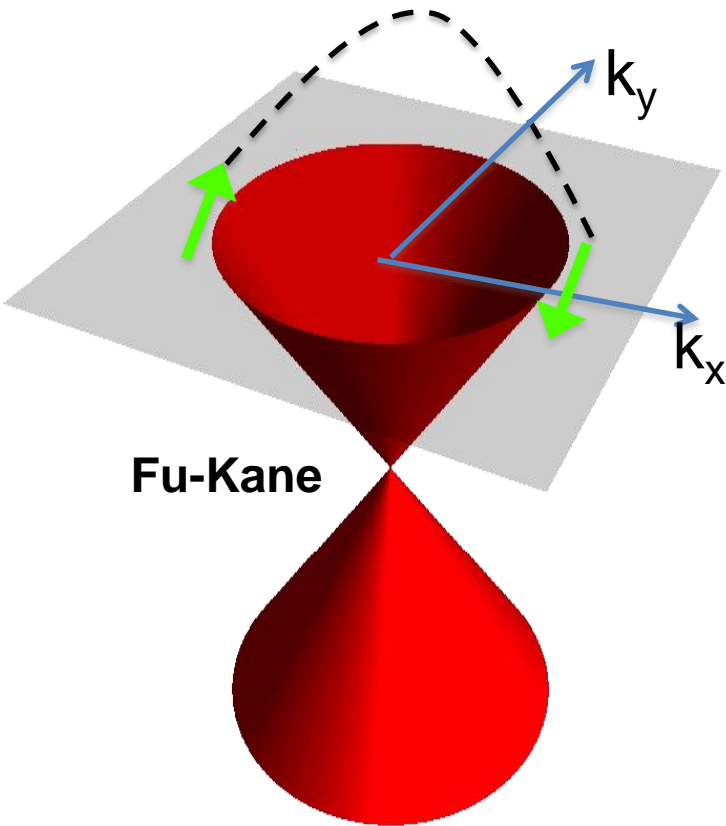
Topo. Superconductors

Helical pairing,
(Singlet+Triplet)

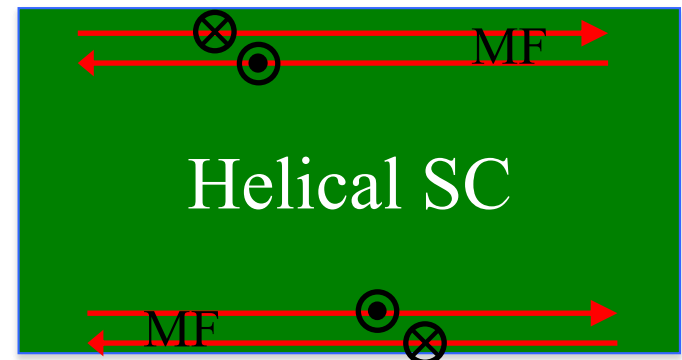
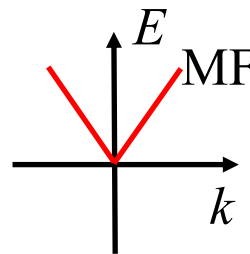
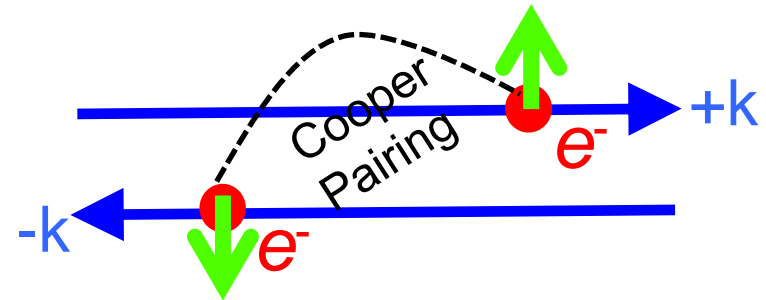


Topo.SC/SF : He3(B)

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



Fu-Kane



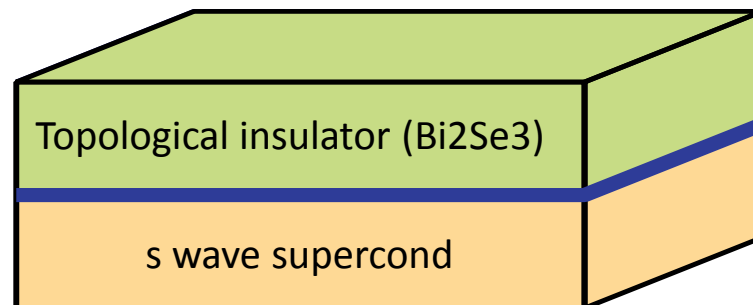
Topo. SF/SC: Volovik; Kitaev, Moore-Read; Roy; Sato; Fu-Kane, many others

Make a Topological Superconductor: Superconducting Heterostructures?

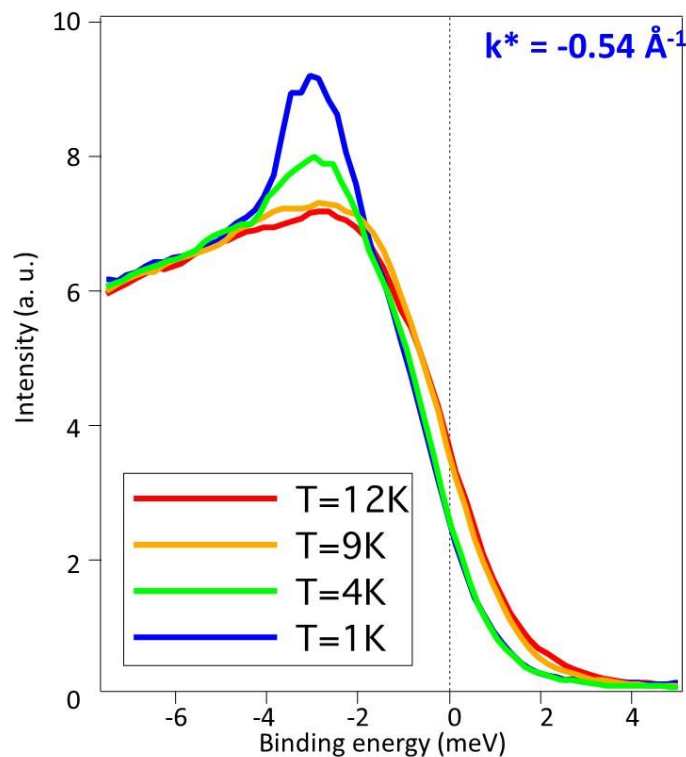
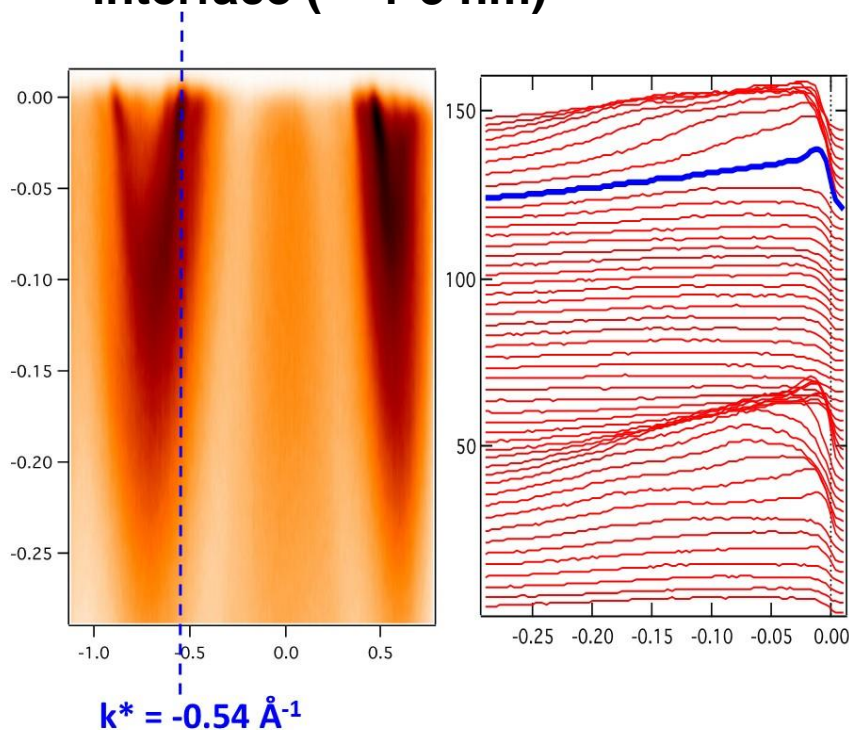
Recent Results

STM work by **Jia group** (Shanghai)
PRL'14

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



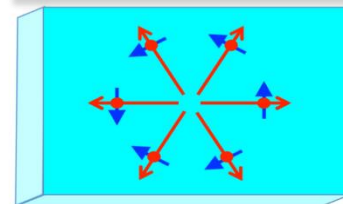
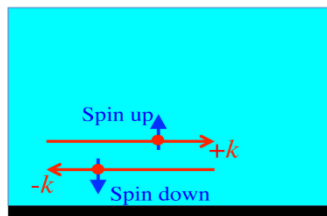
ARPES can look at the buried interface ($\sim 1-3$ nm)



3D to 2D Topo. Insulators : $\text{Bi}_2(\text{Se/Te})_3$

MBE growth

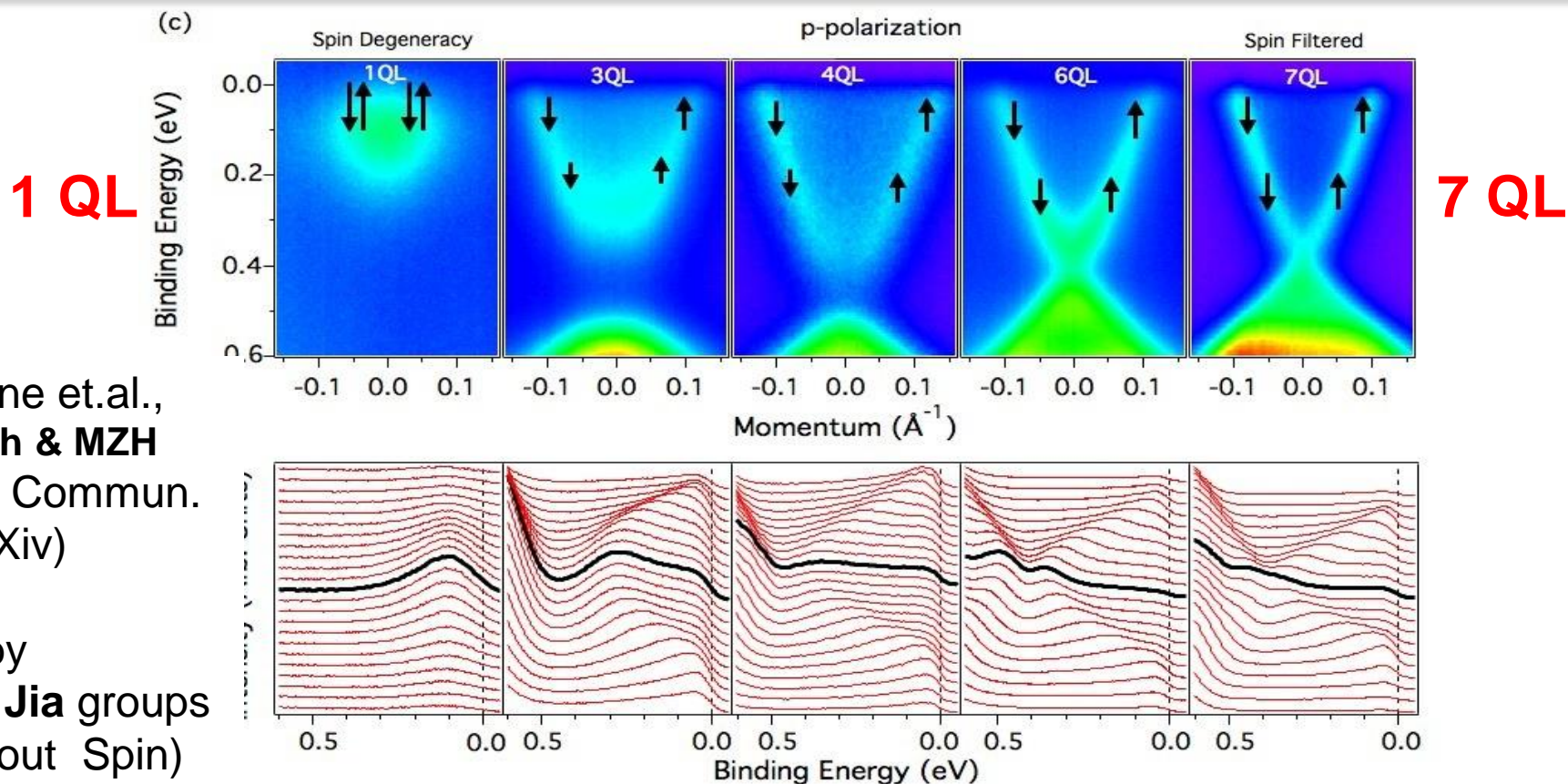
Spin changes
as one 2D \rightarrow 3D
3D \rightarrow 2D (BULK)



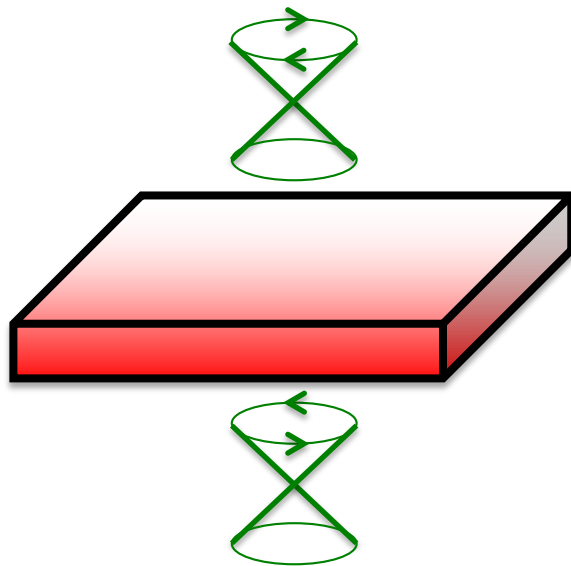
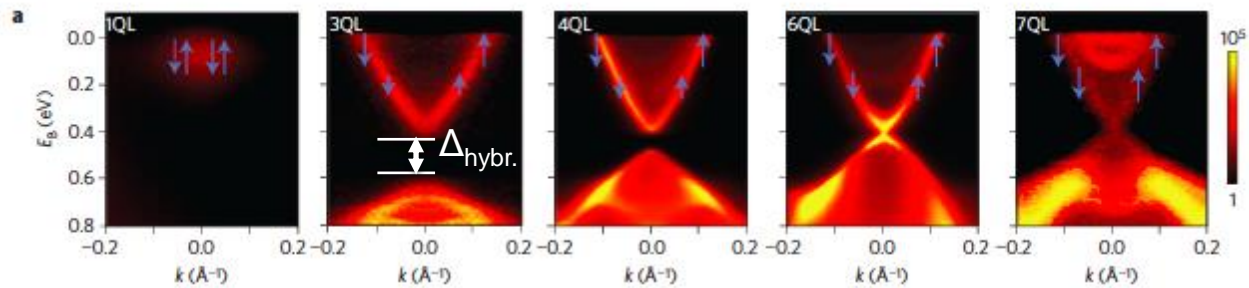
2D



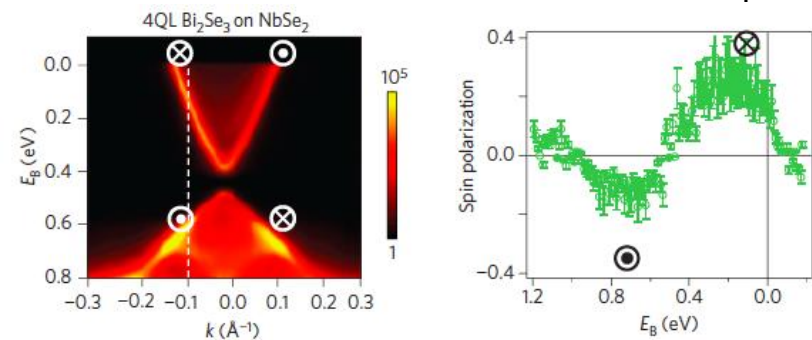
3D



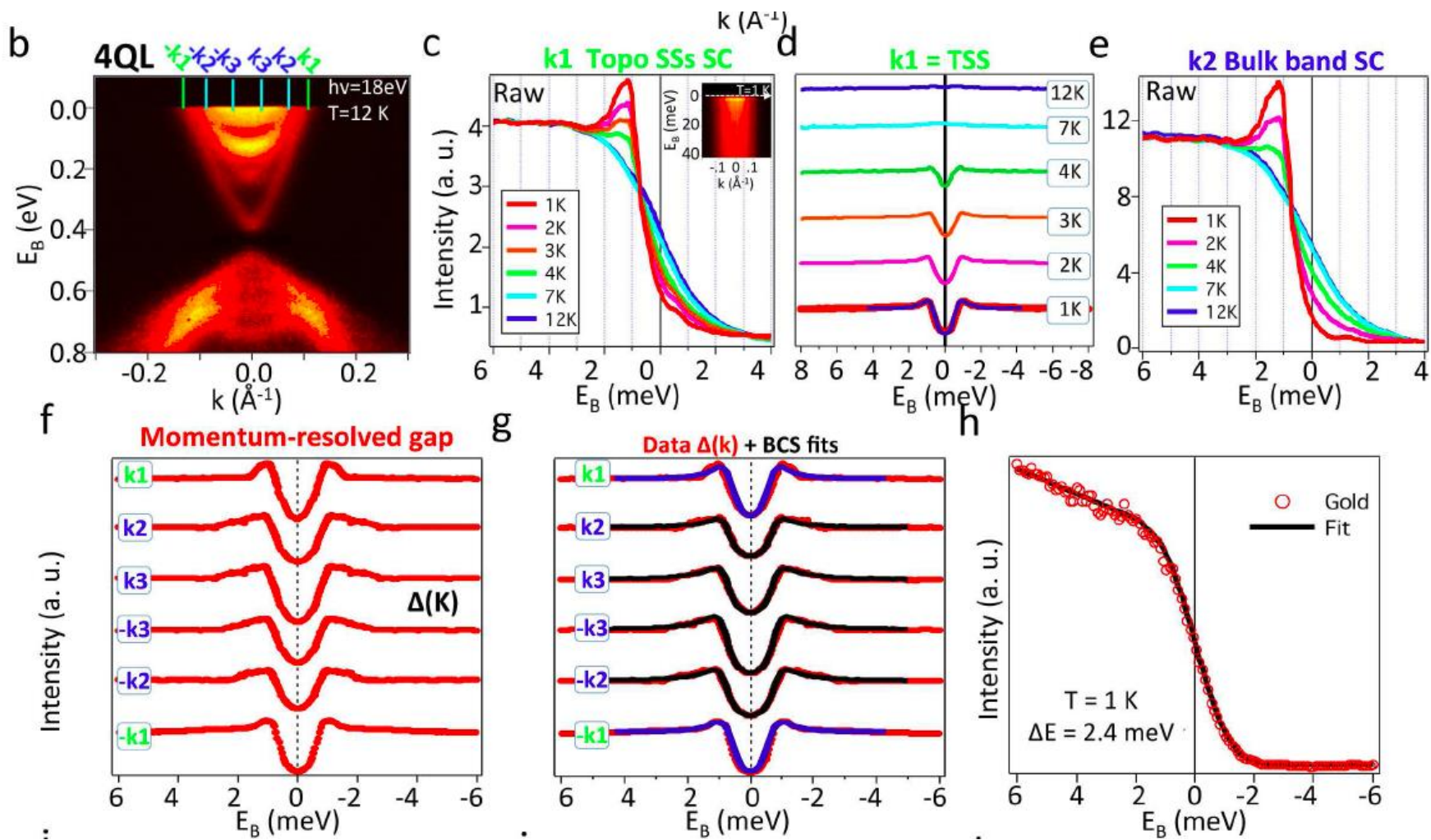
TI film thickness progression



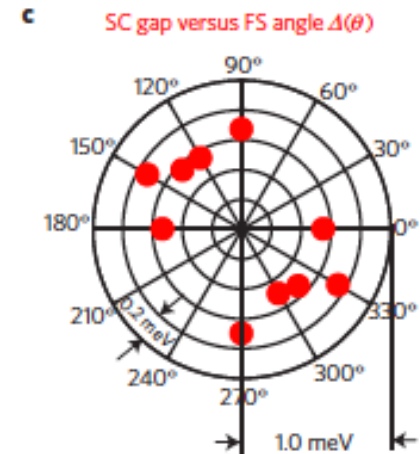
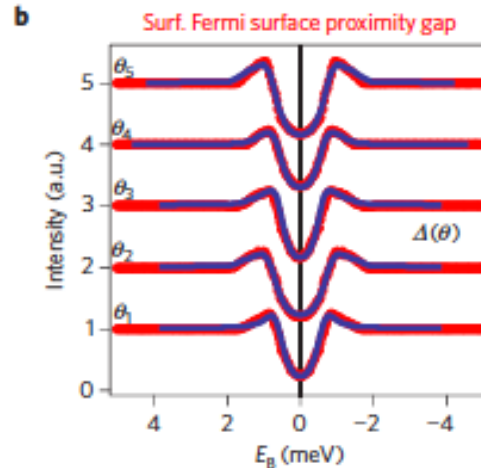
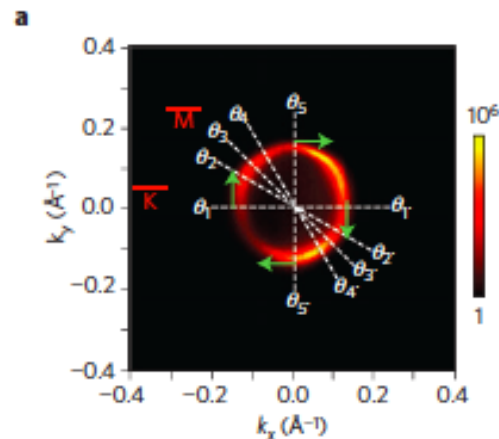
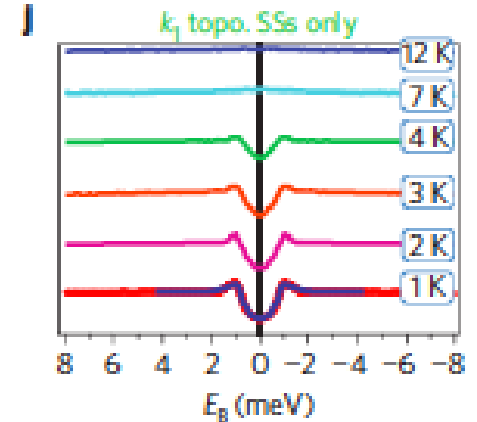
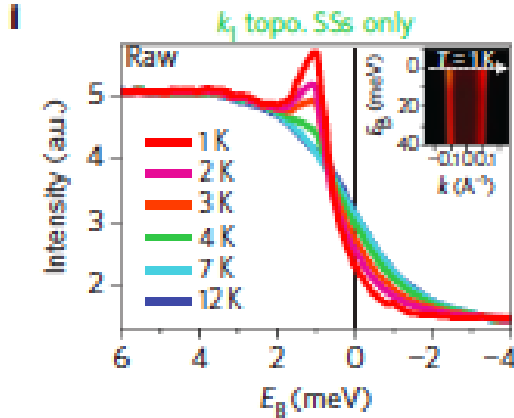
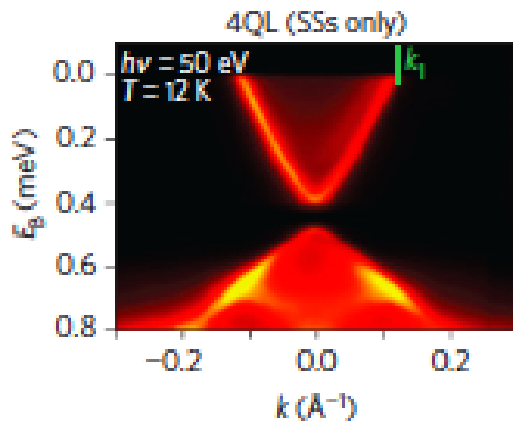
Spin-momentum locked at E_F



Observation of SC in the Dirac SSs



Observation of SC in the Dirac SSs

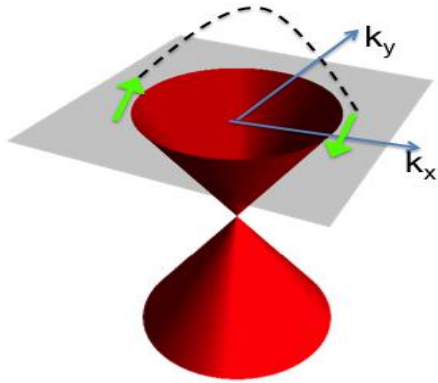


2D Topo. Superconductor via the proximity effect (Fu-Kane type)

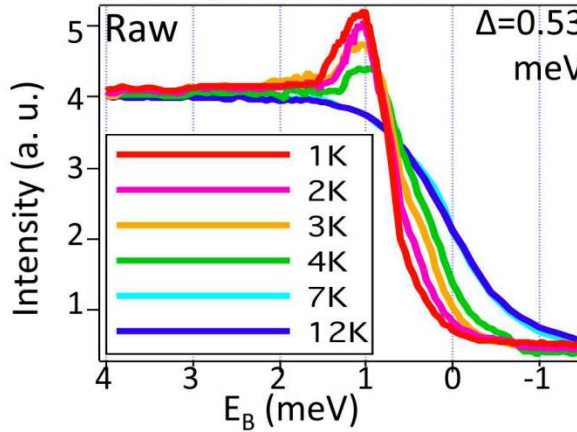
ARPES \longleftrightarrow MBE Growth

Feedback Loop!

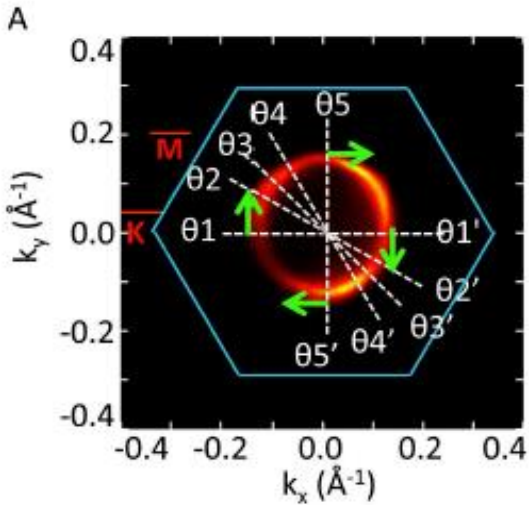
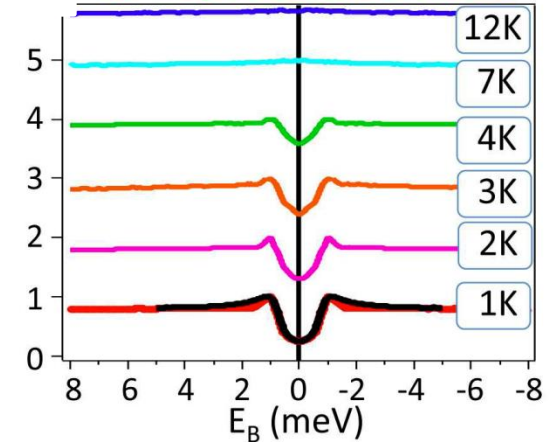
Helical pairing,
(Singlet+Triplet)



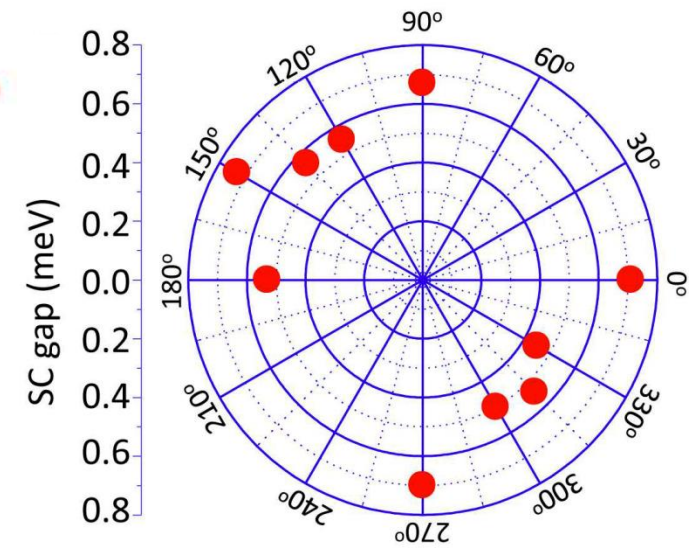
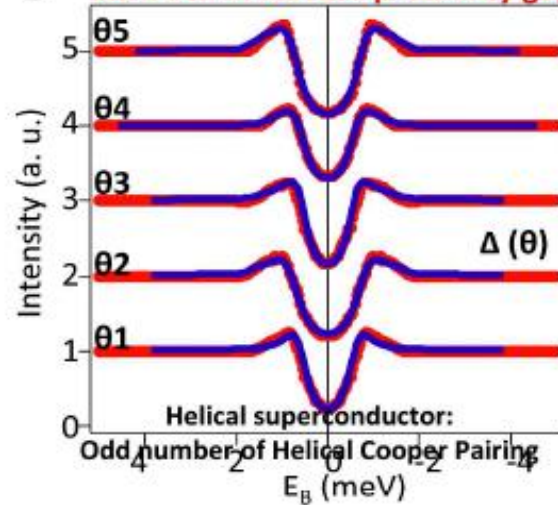
k1 Topo. Surface states



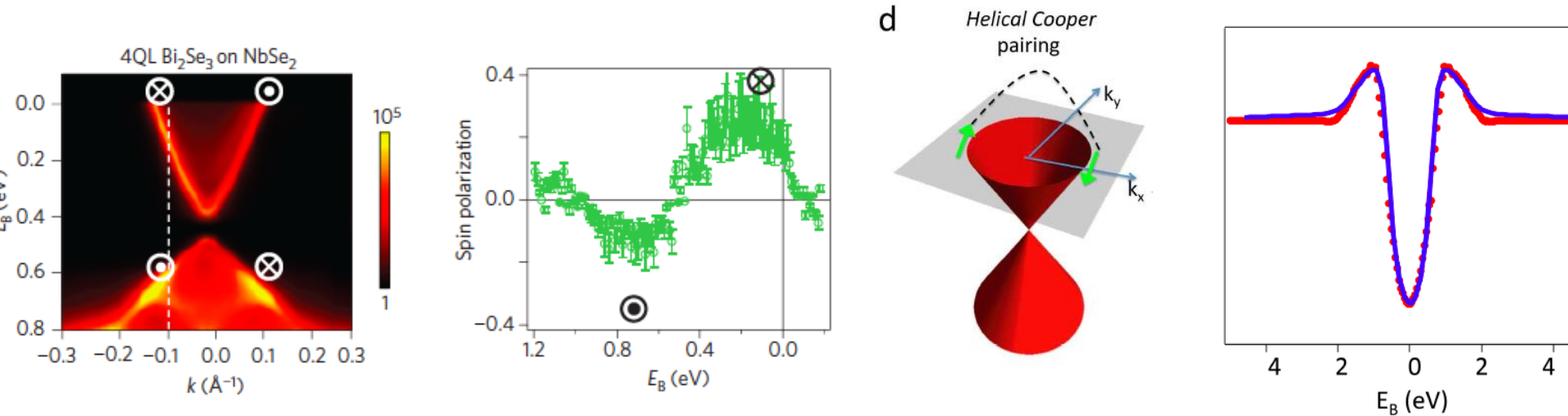
k1 Topo. Surface states



B Surf. Fermi surface proximity gap



Observation of SC in the Dirac SSs = Helical TSC



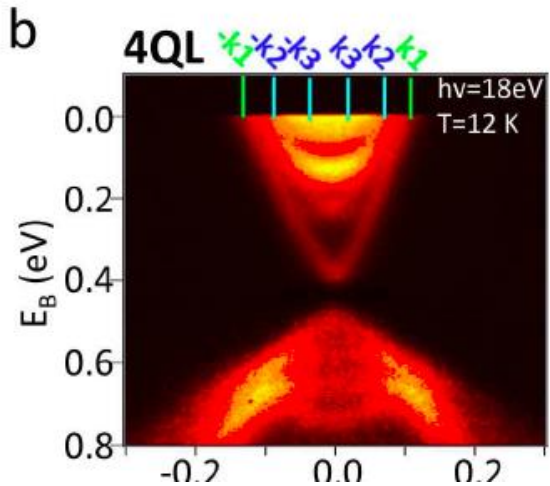
$$b_{\vec{k}} = e^{i\theta/2} c_{\vec{k},\uparrow} + e^{-i\theta/2} c_{\vec{k},\downarrow} \quad (e^{i\theta} = \frac{1}{p}(p_x + ip_y))$$

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

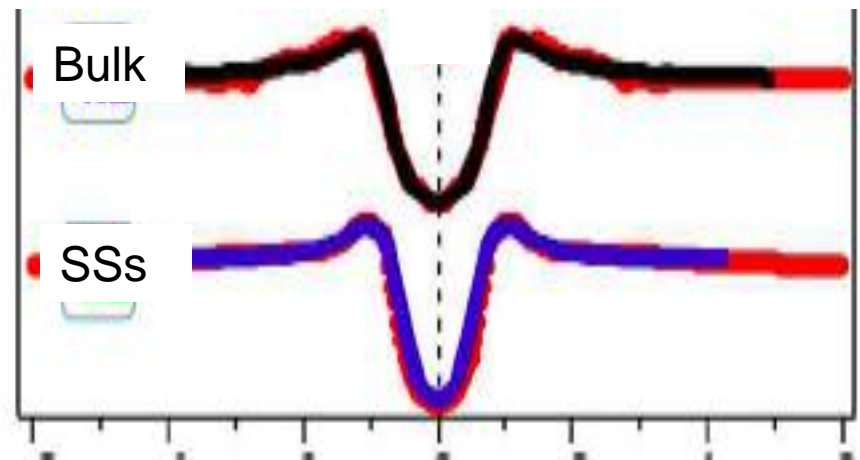
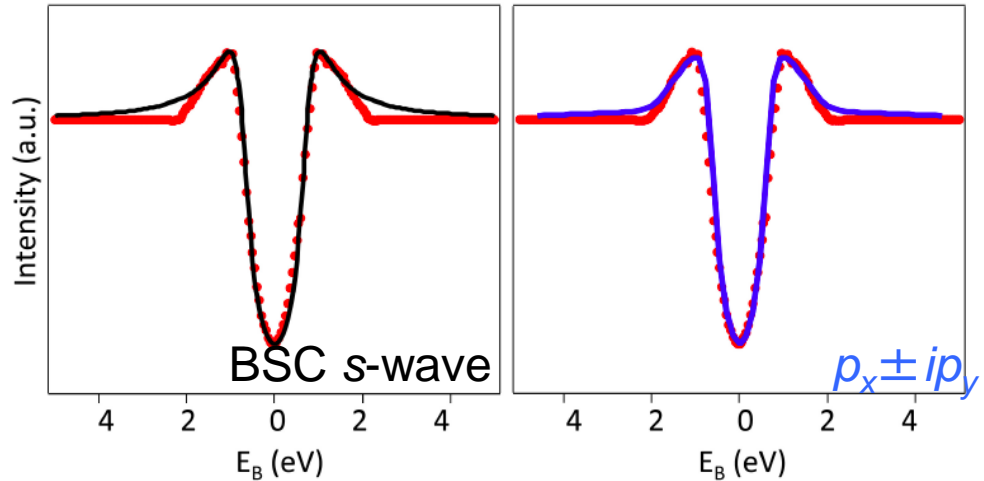
SC gap fitting

Surface $p_x \pm ip_y$; Bulk band: s-wave

Surface state gap fitting



Surface vs bulk gap fitting

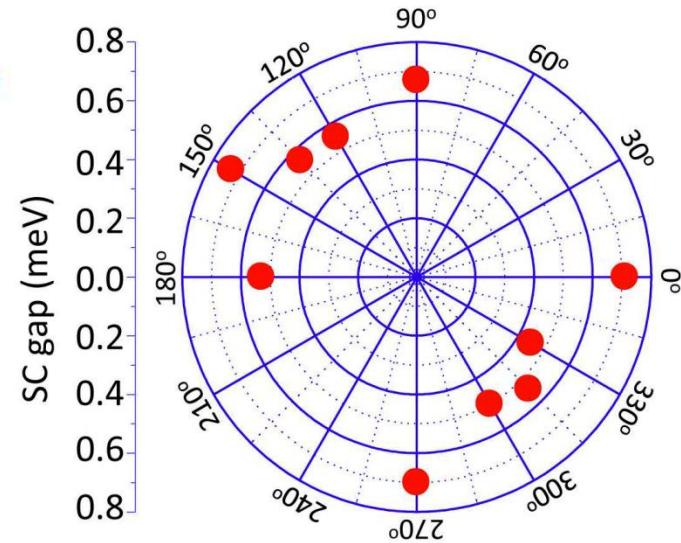
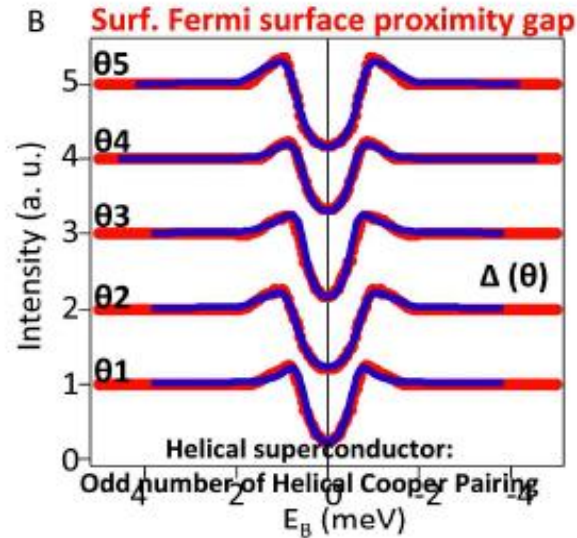
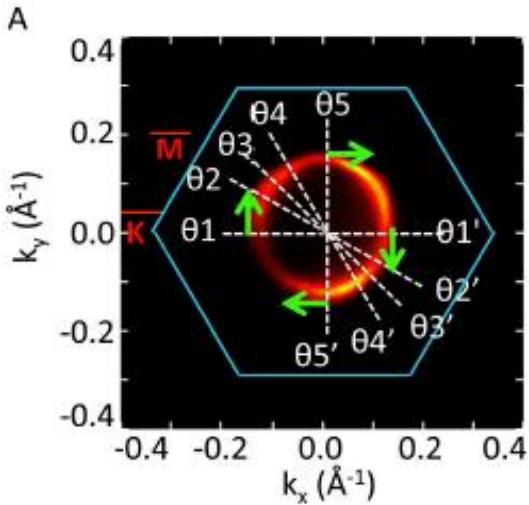
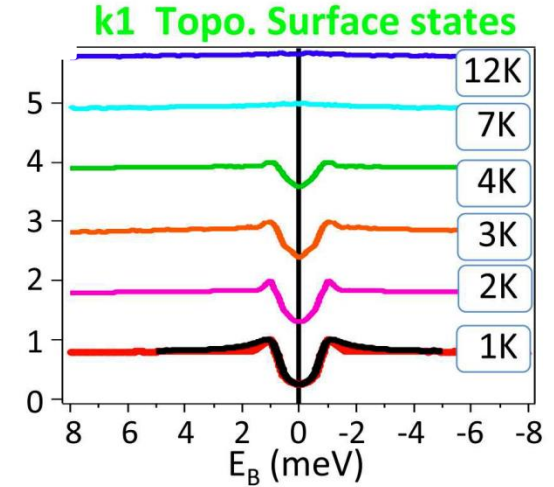
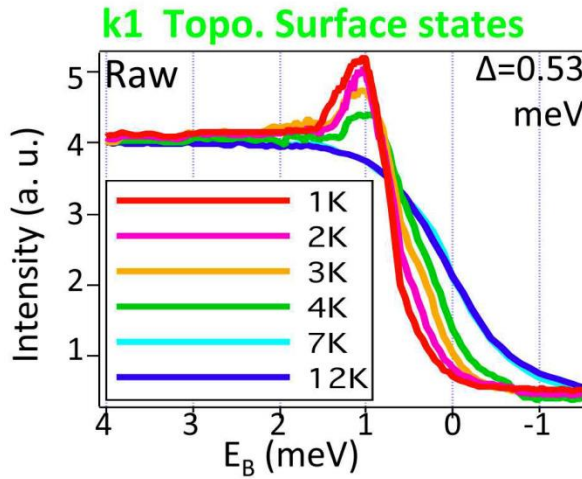
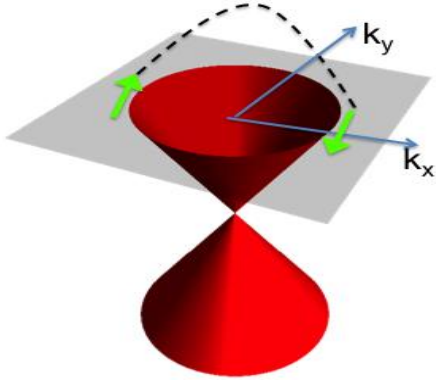


2D Topo. Superconductor

ARPES \longleftrightarrow MBE Growth

Feedback Loop!

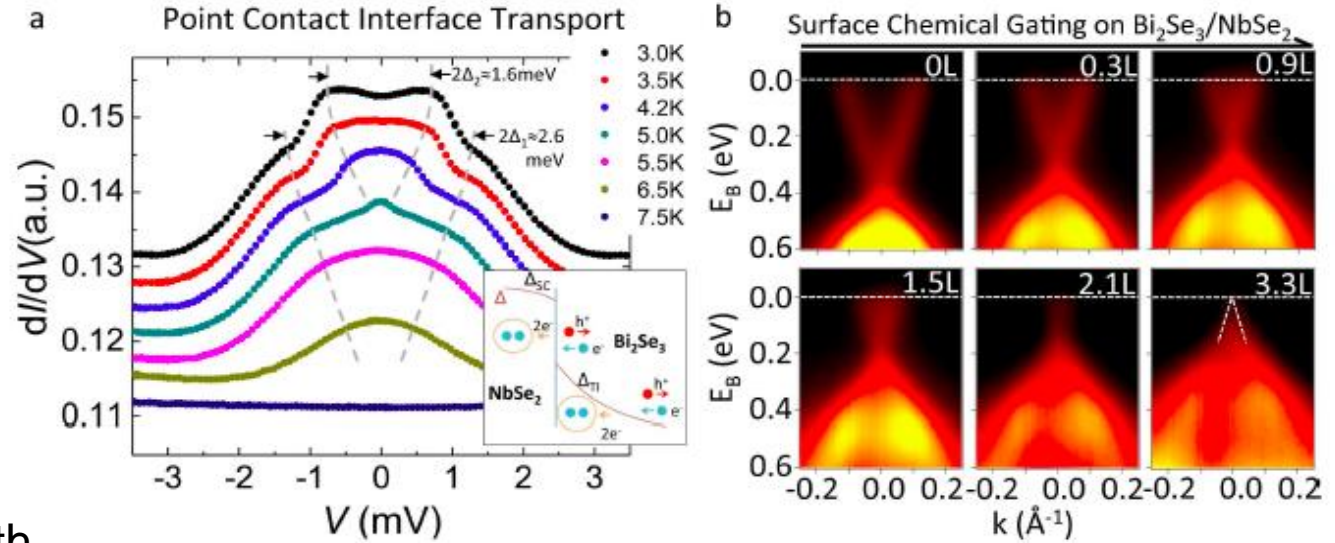
Helical pairing,
(Singlet+Triplet)



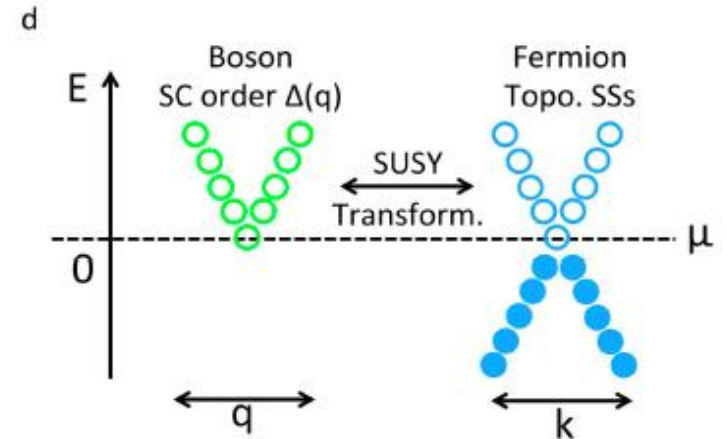
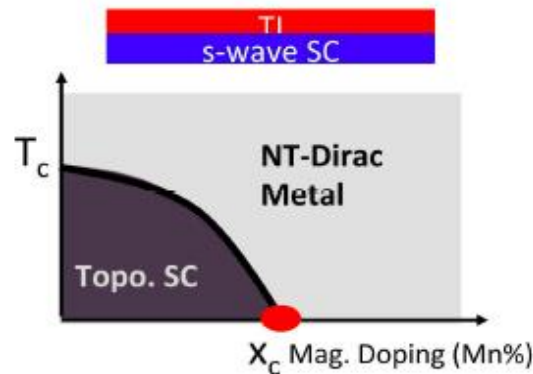
S. Xu, et.al., (MZH) Nature Phys (2014)

Samples can be driven near Emergent SuperSymmetry

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



ARPES \leftrightarrow Growth
Feedback Loop!



Search for TRI Topo. Superconductors ..

Natural Superconductor

(Majorana bound on the surface)

Centrosymmetric

$\text{Cu}_x(\text{Bi}_2\text{Se}_3)$ 3.8K

$\text{Pd}_x(\text{Bi}_2\text{Te}_3)$ 4.0K

TlBiTe_2 0.1K

Non-Centrosymmetric

LaPtBi 0.3K

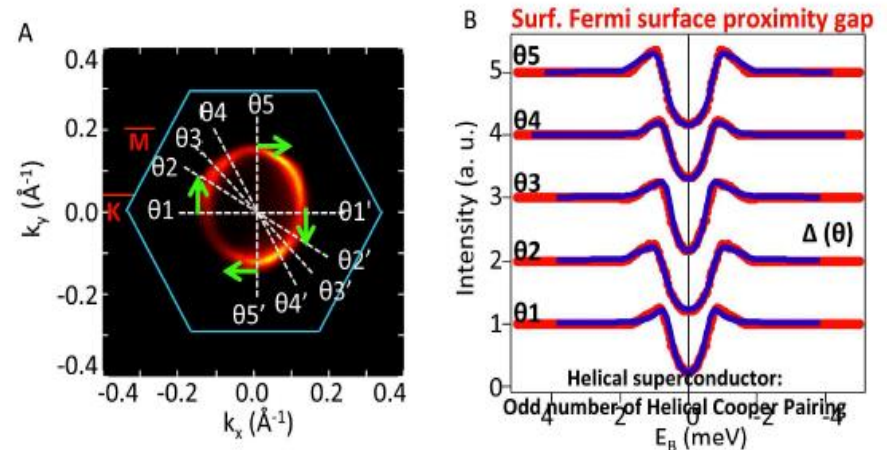
$\text{Li}_2\text{Pt}_3\text{B}$ 3.0K

CePt_3Si 0.7K

More..



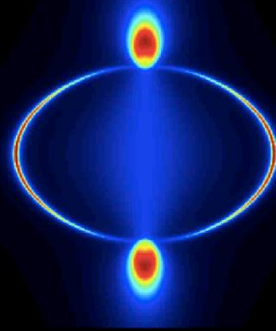
Engineering the Proximity effect



2D Topo. Superconductor

by imaging of Helical Cooper Pairing

S. Xu et.al., Nature Physics (2014)



Can metals be topological ?

bulk Gapless *but* topological

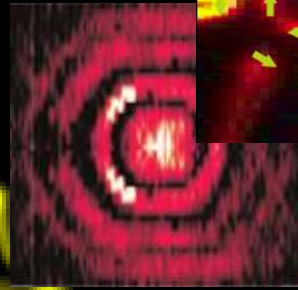
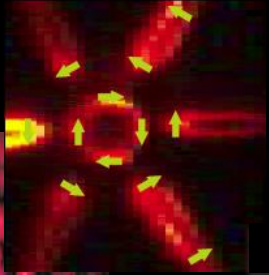
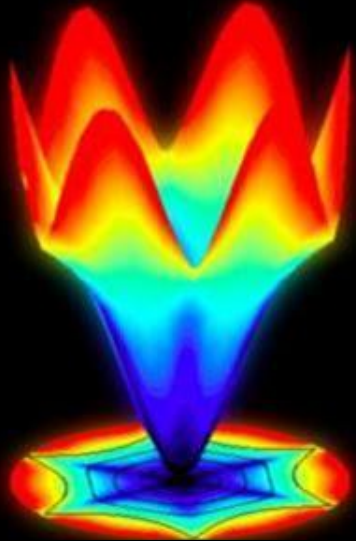
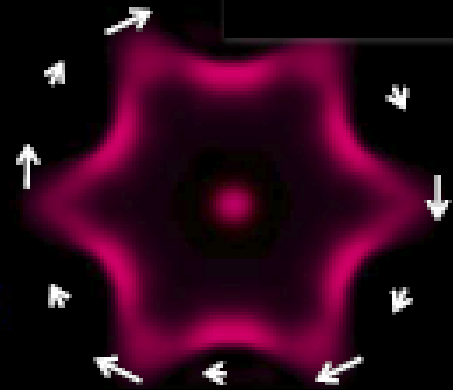
Wan, Turner, Vishwanath *et.al.*, '11

Fermi arc metals

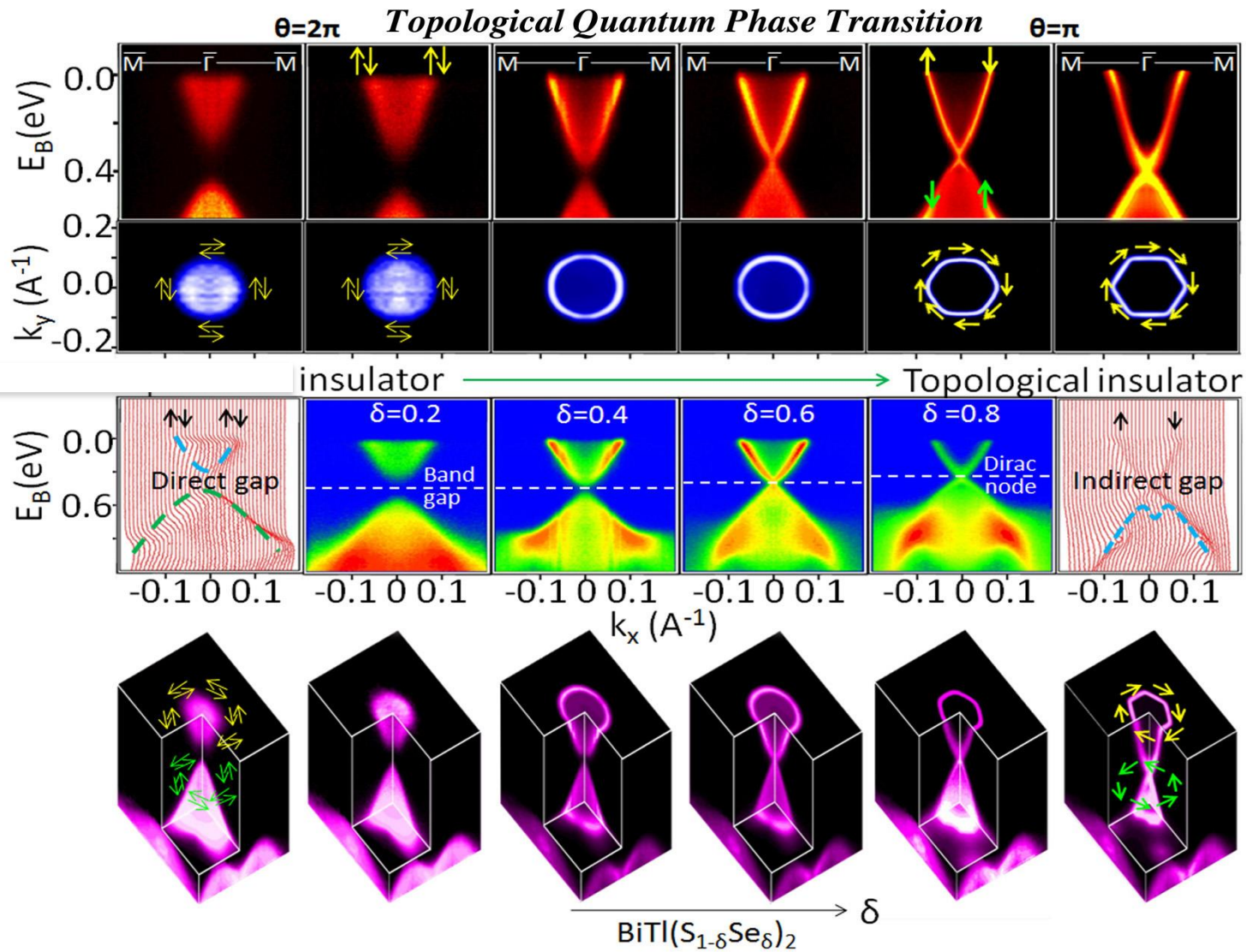
(iridates and other candidates)

Topological Phase Transition & Dirac Semimetals

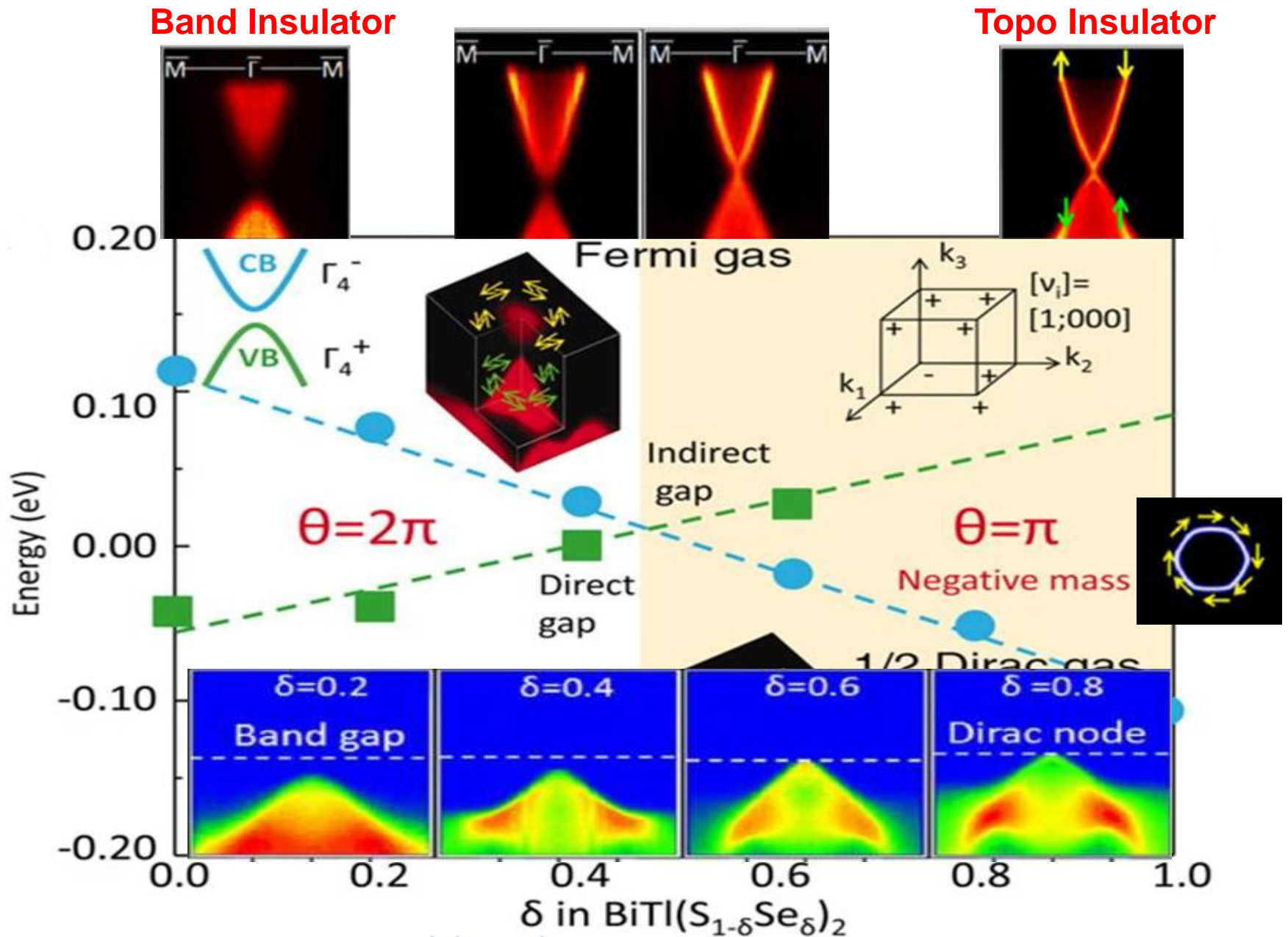
M.Z.H. & CL Kane, Rev. Mod. Phys. 82, 3045 (2010)

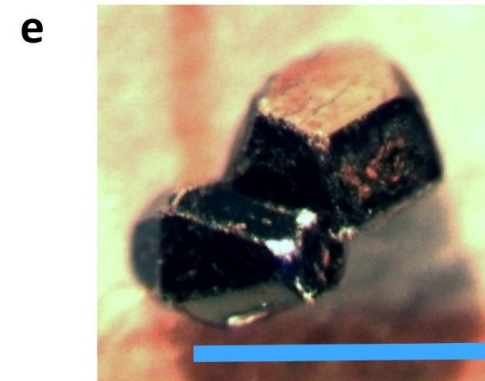
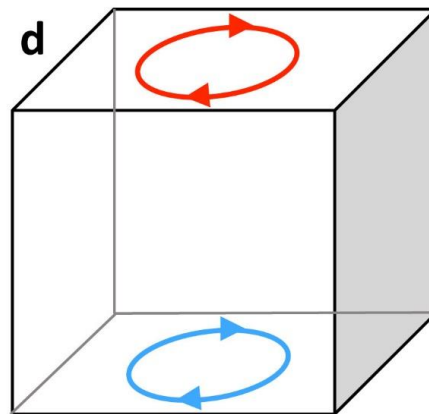
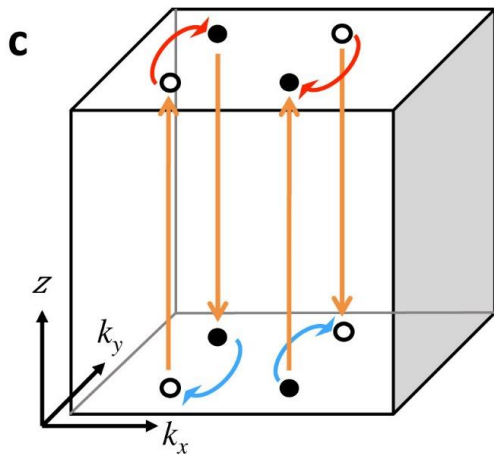
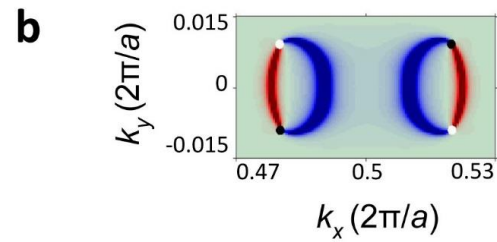
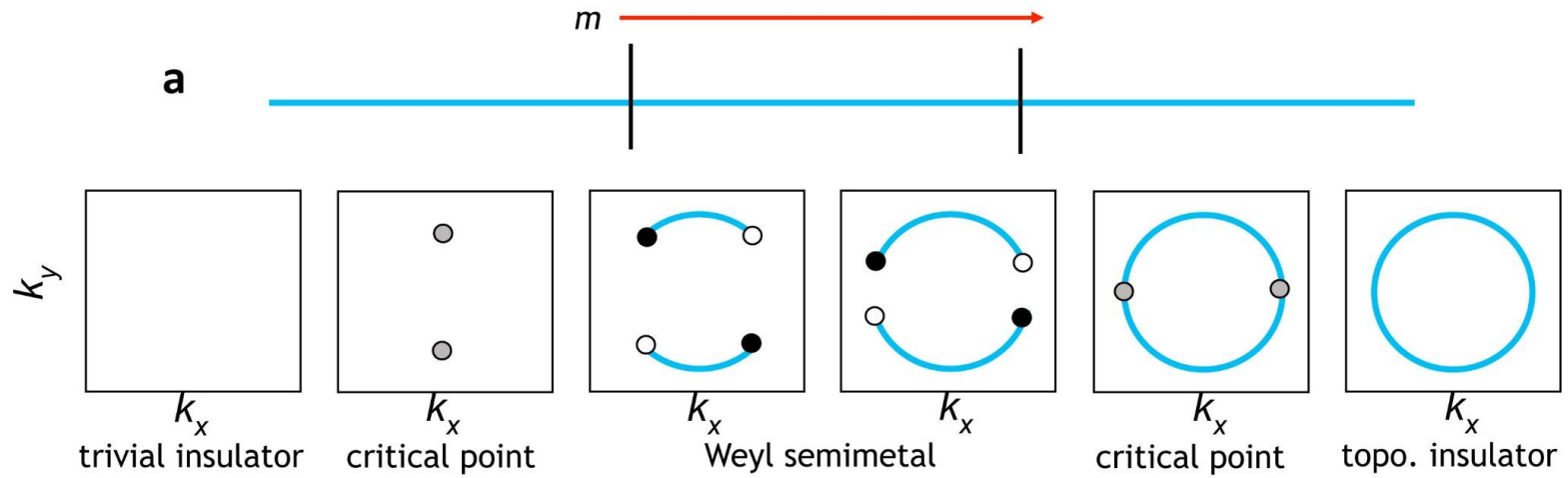


Imaging a Topo. Insulator being born out of a Bloch Insulator as SOC is tuned



Bulk-Boundary Correspondence

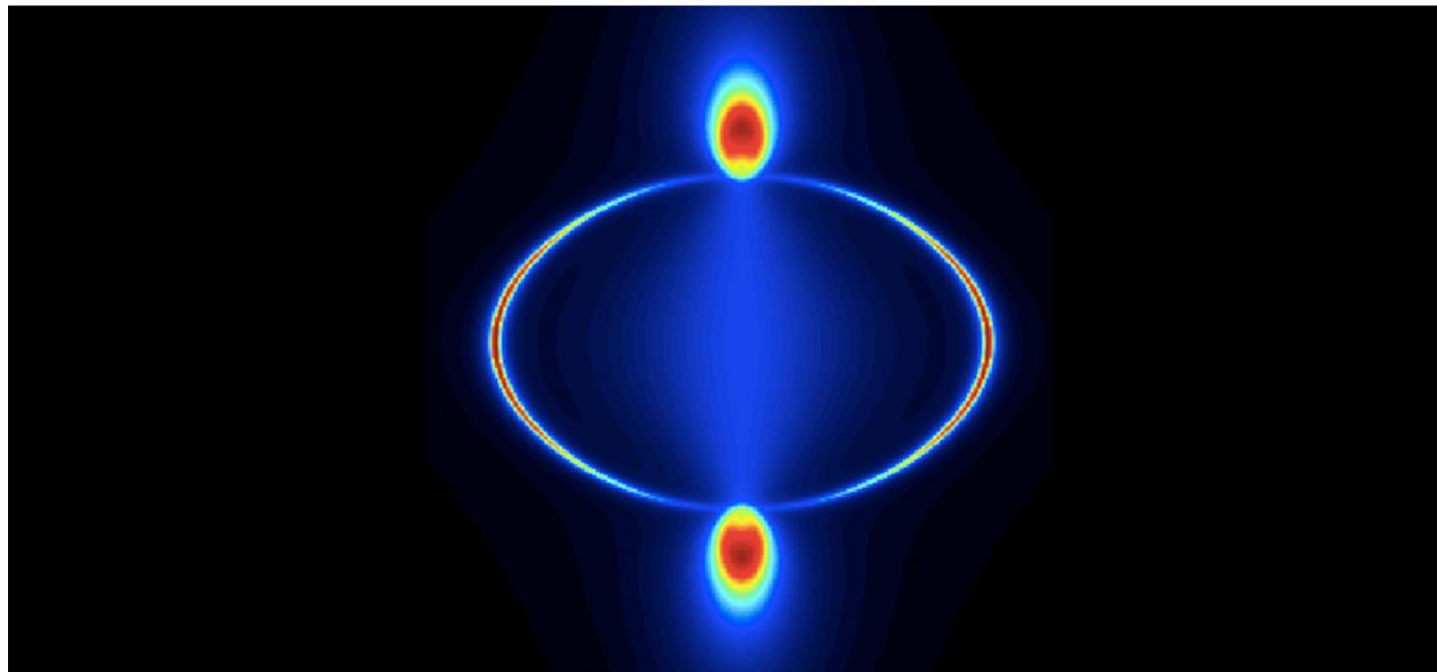




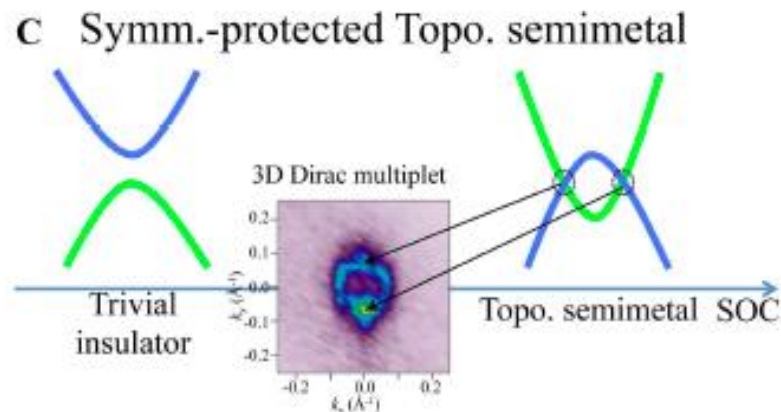
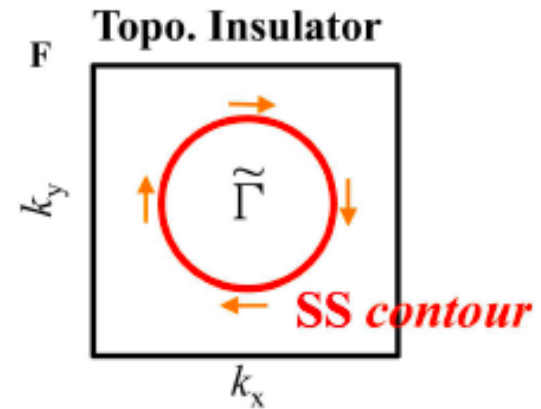
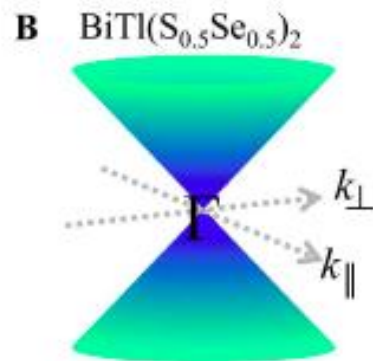
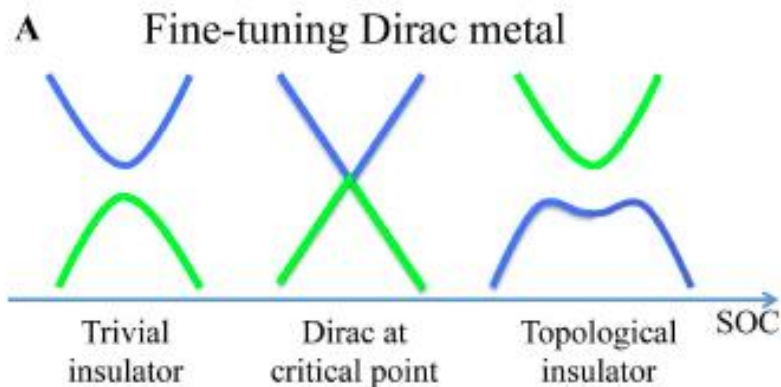
0.5 mm

Observation of Fermi arc surface states in a topological metal

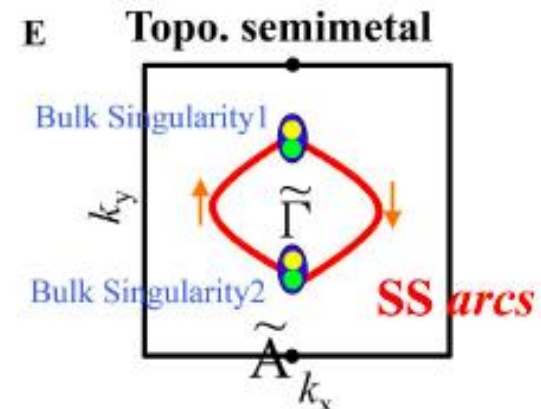
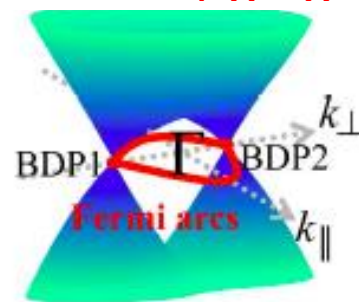
Su-Yang Xu,^{1,2*} Chang Liu,^{1*} Satya K. Kushwaha,³ Raman Sankar,⁴ Jason W. Krizan,³ Ilya Belopolski,¹ Madhab Neupane,^{e1} Guang Bian,¹ Nasser Alidoust,¹ Tay-Rong Chang,⁵ Horng-Tay Jeng,^{5,6} Cheng-Yi Huang,⁷ Wei-Feng Tsai,⁷ Hsin Lin,⁸ Pavel P. Shibayev,¹ Fangcheng Chou,⁴ Robert J. Cava,³ M. Zahid Hasan^{1,2†}



Fermi Arc SSs: Topo. semimetal Bi-based materials again !

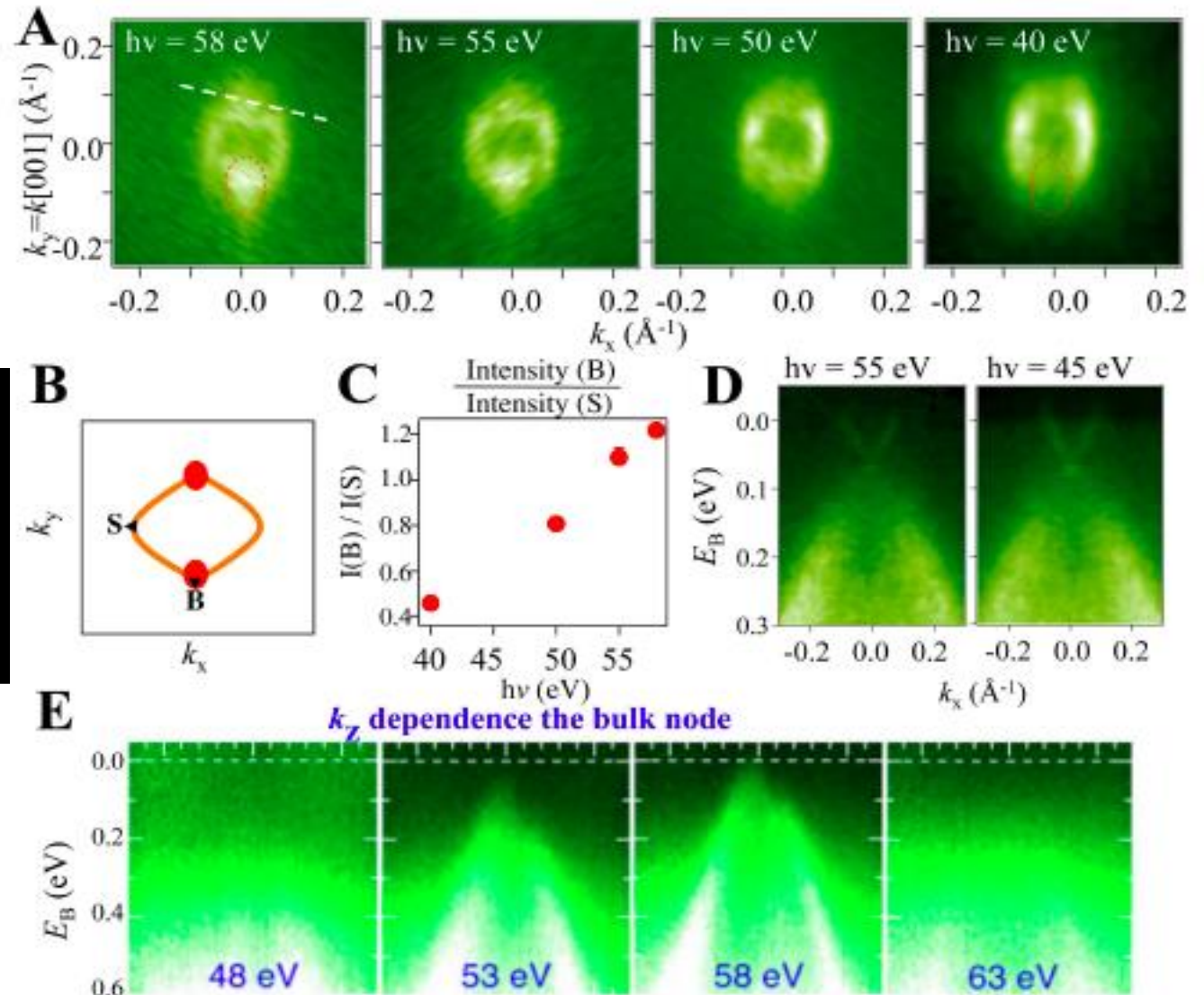


D $\text{Bi}(\text{Na}_{1-x}\text{K}_x)_3$



S. Xu et.al., (MZH) Science (AOP, 2014)

Fermi surface = 2 surface arcs + bulk Dirac nodes



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

A Weyl Semimetal

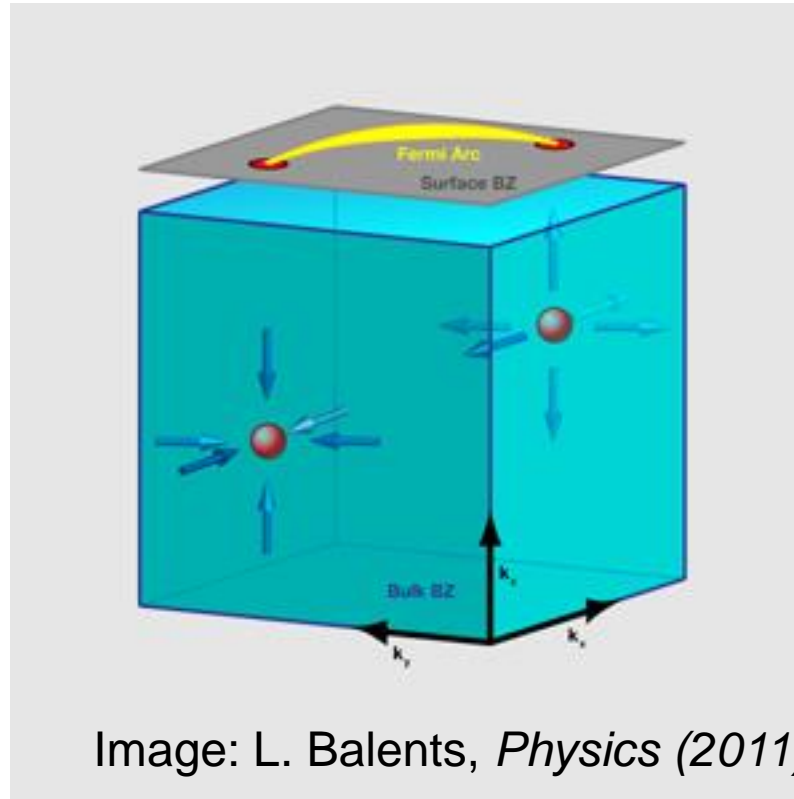
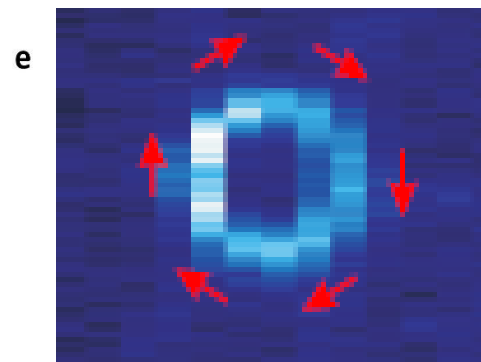
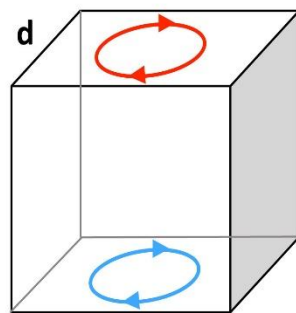
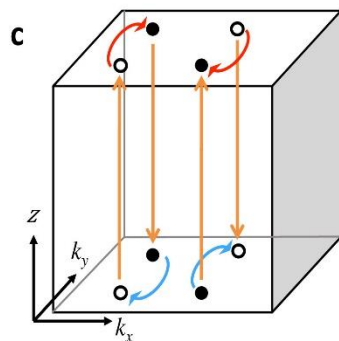
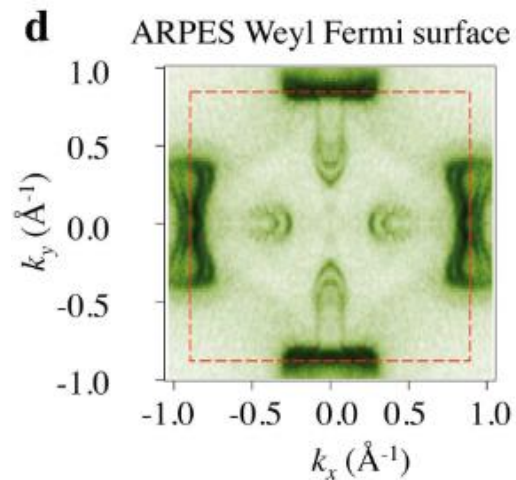
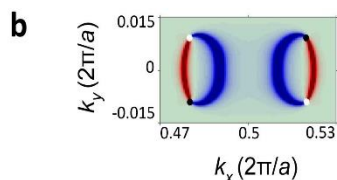
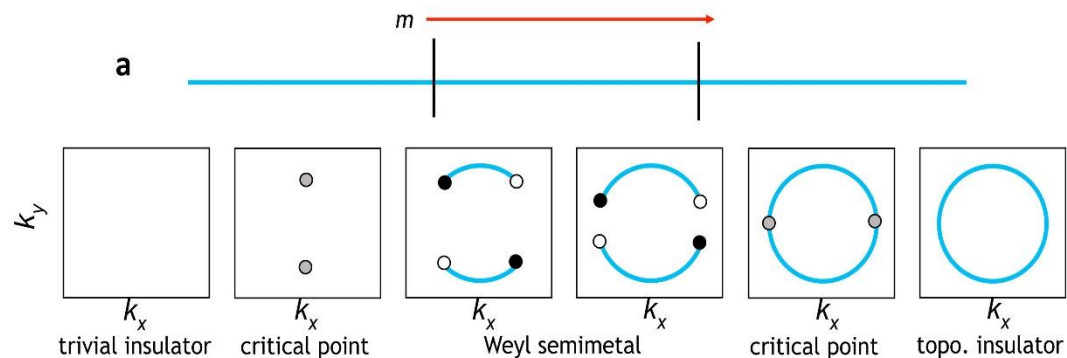


Image: L. Balents, *Physics* (2011)

Wan, Turner, Vishwanath et.al., '11 PRB
Burkov, Balents et.al., '11 PRL
and others

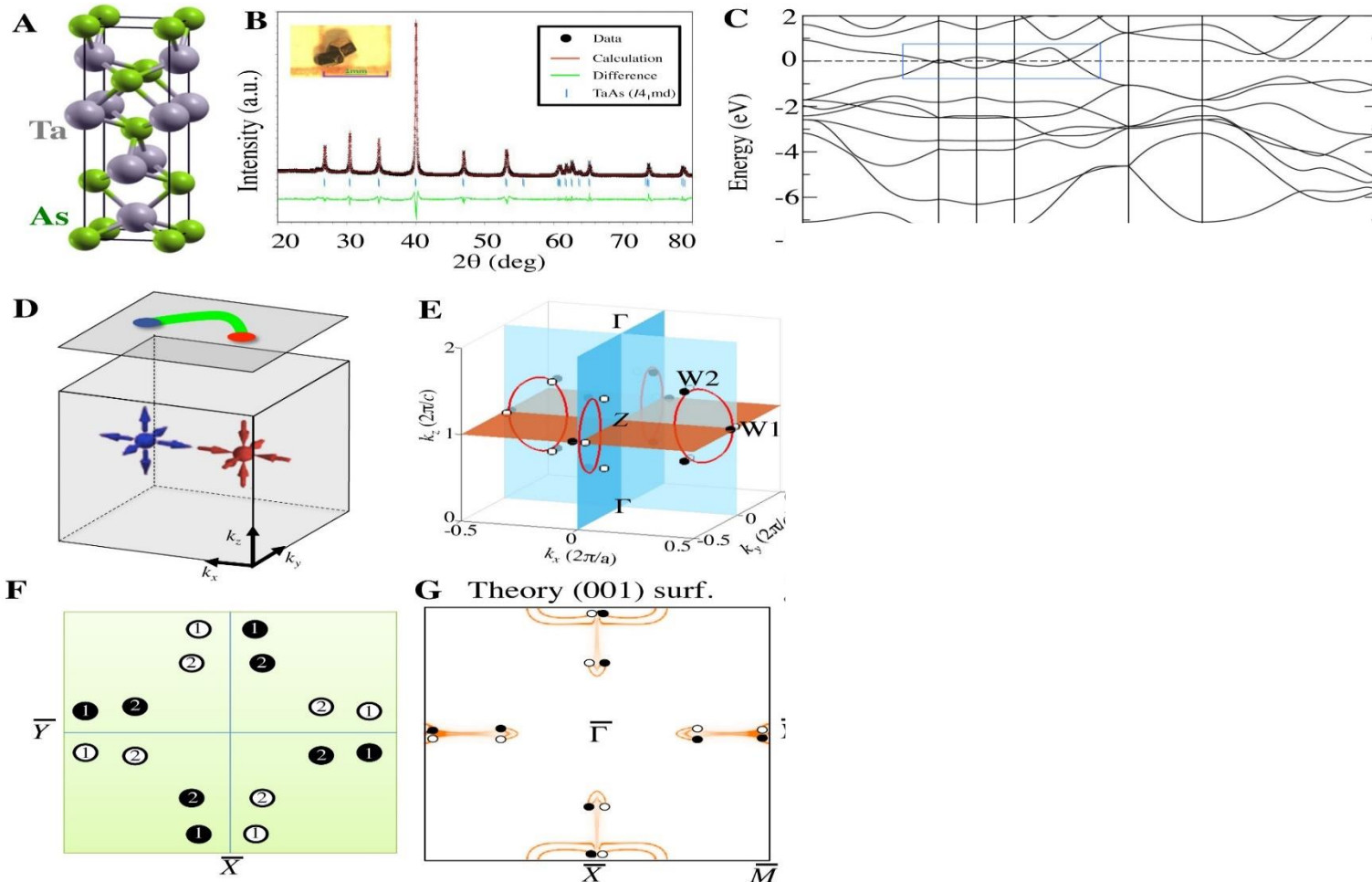
FP/Theory: Huang, Xu, Belopolski et.al.,(Lin & MZH) **Nature Commun.** (in press) '15
ARPES Expts: Xu, Belopolski, et.al., (MZH) **Science** (in review) 2015

Phase Diagram of 3D Topo. States of Matter



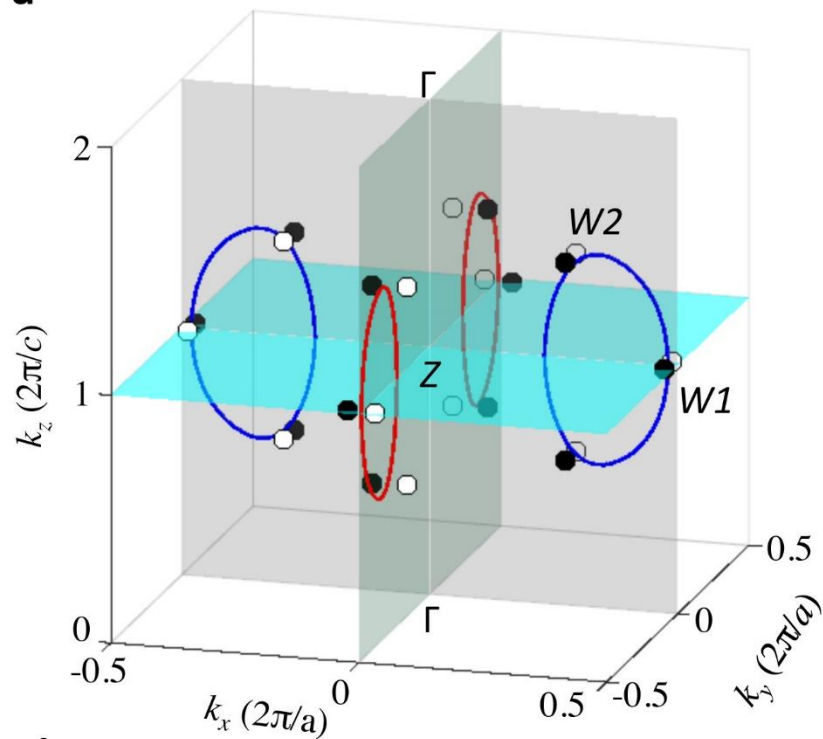
FP/Theory: Huang, Xu, Belopolski et.al.,(Lin & Hasan) **Nature Commun. (in press) '15**
also by Bernevig & Dai (2015)

ARPES Expts: TaAs: Xu, Belopolski, Alidoust et.al., (MZH) Science (in review) (2015)
also by Lv et.al, (Ding) 2015; NbAs: Xu, Belopolski, Alidoust et.al., (MZH) arXiv (2015)

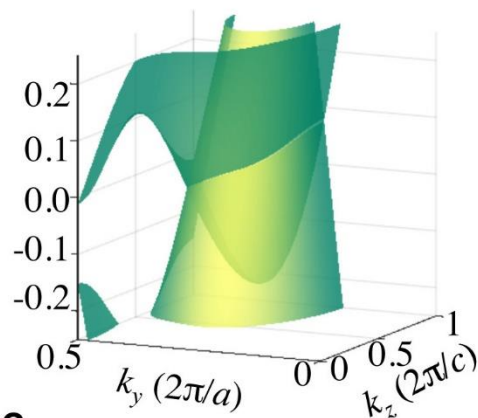


FP/Theory: Huang, Xu, Belopolski et.al.,(Lin & MZH) **Nature Commun. (in press) '15**
ARPES Expts: Xu, Belopolski, et.al., (MZH) **Science (in review) 2015**

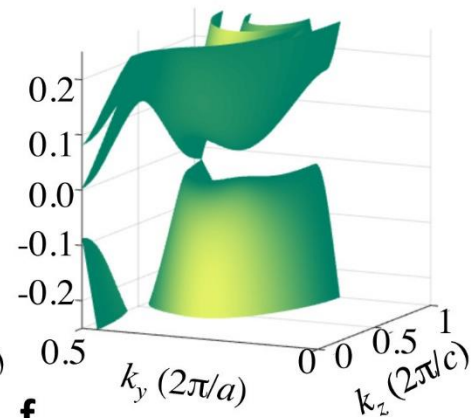
a



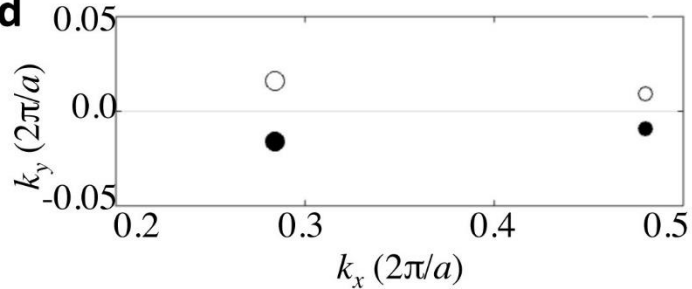
b



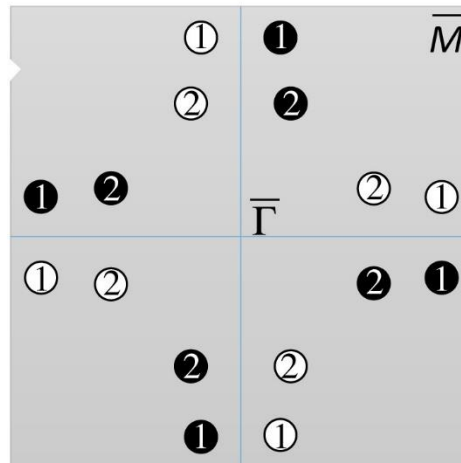
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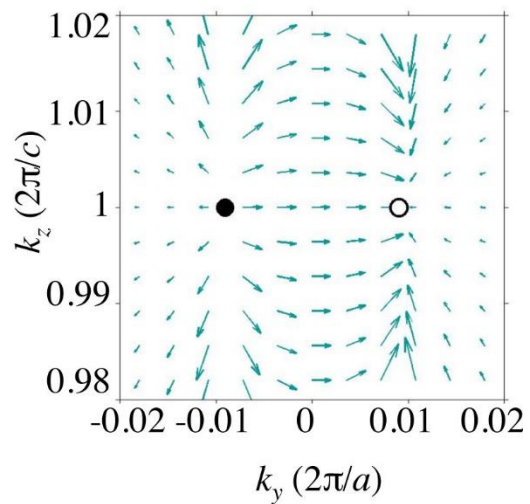
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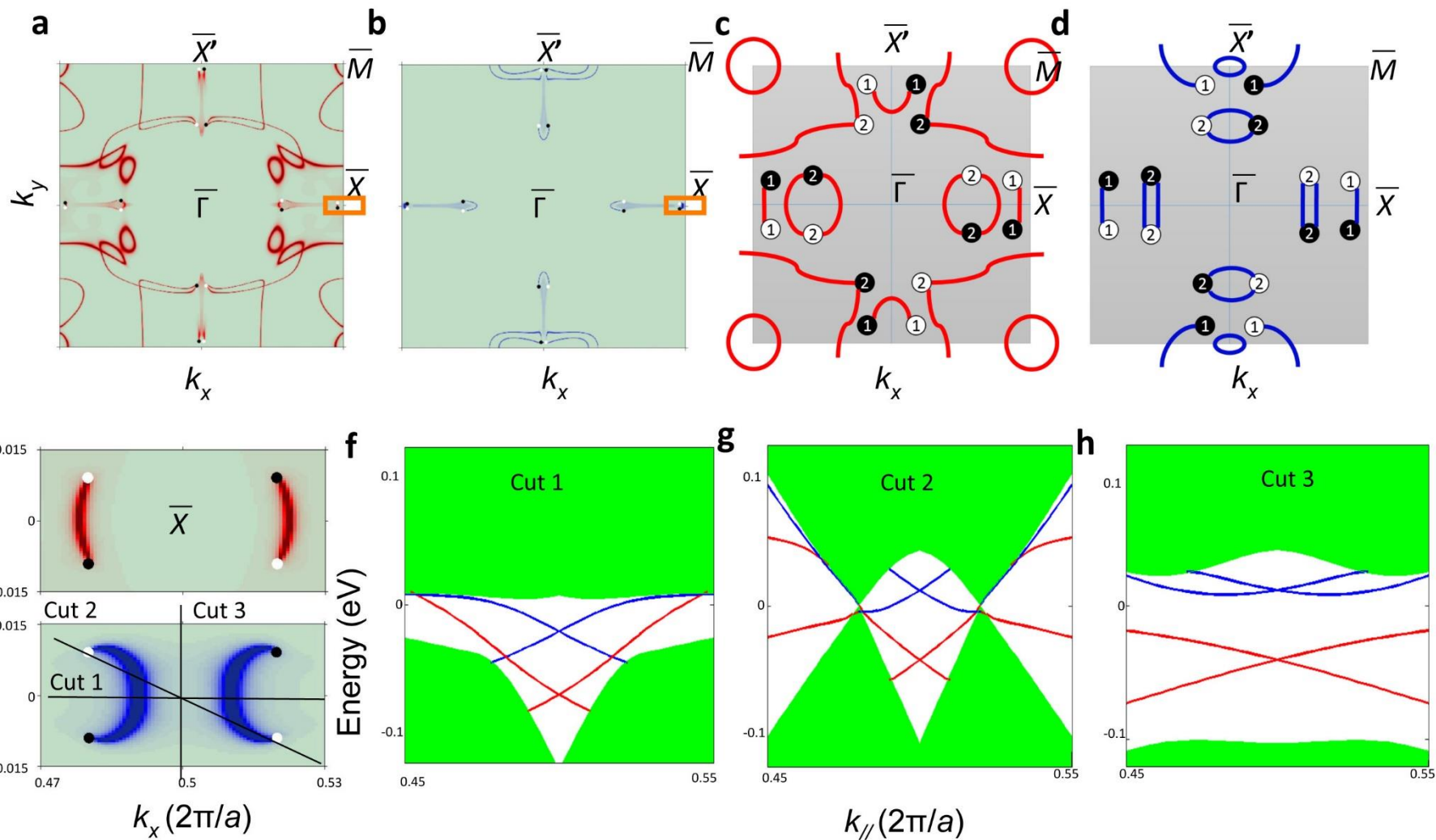
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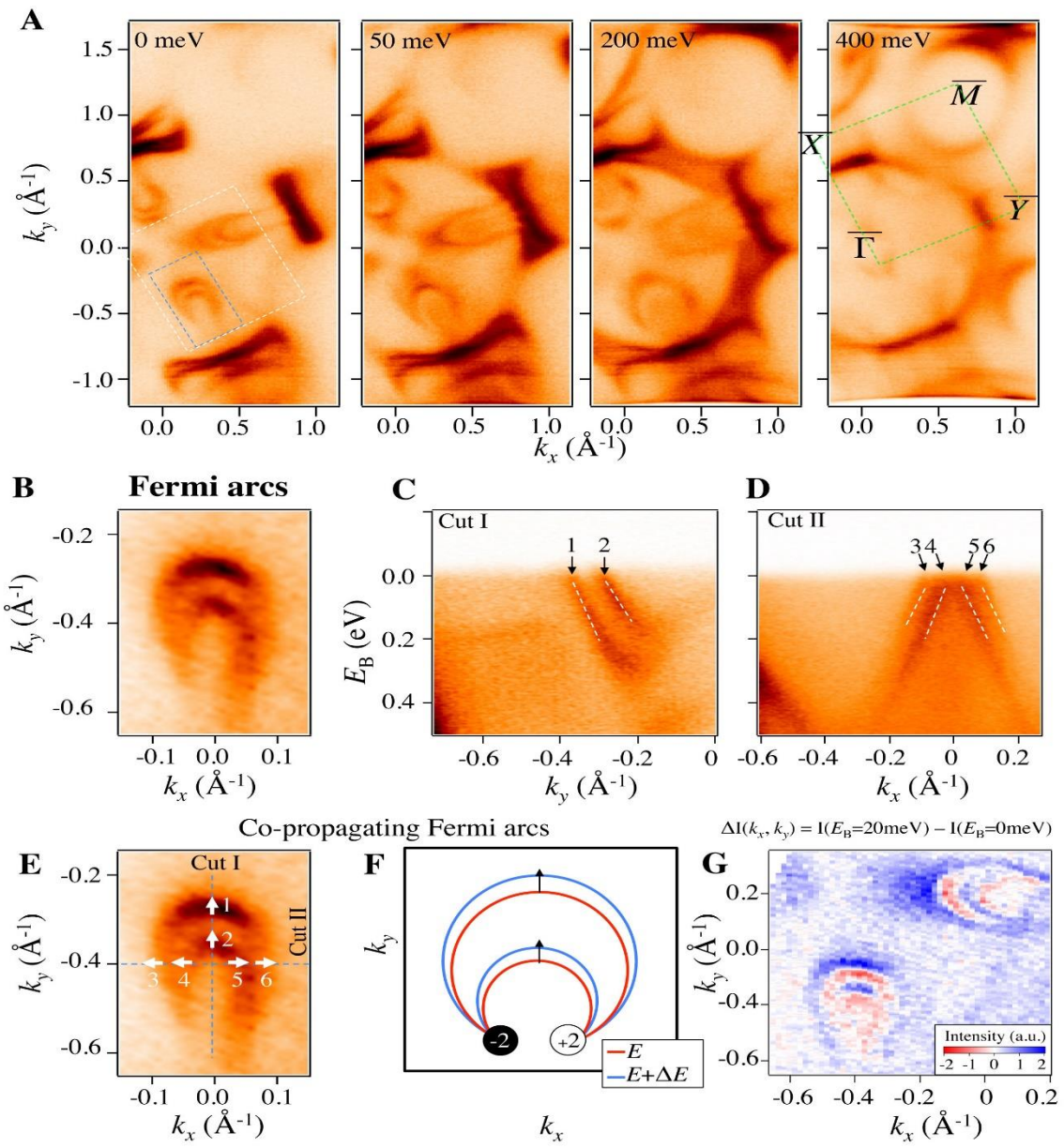
f



FP/Theory: Huang, Xu, Belopolski et.al.,(Lin & MZH) **Nature Commun. (in press) '15**
ARPES Expts: Xu, Belopolski, et.al., (MZH) **Science (in review) 2015**

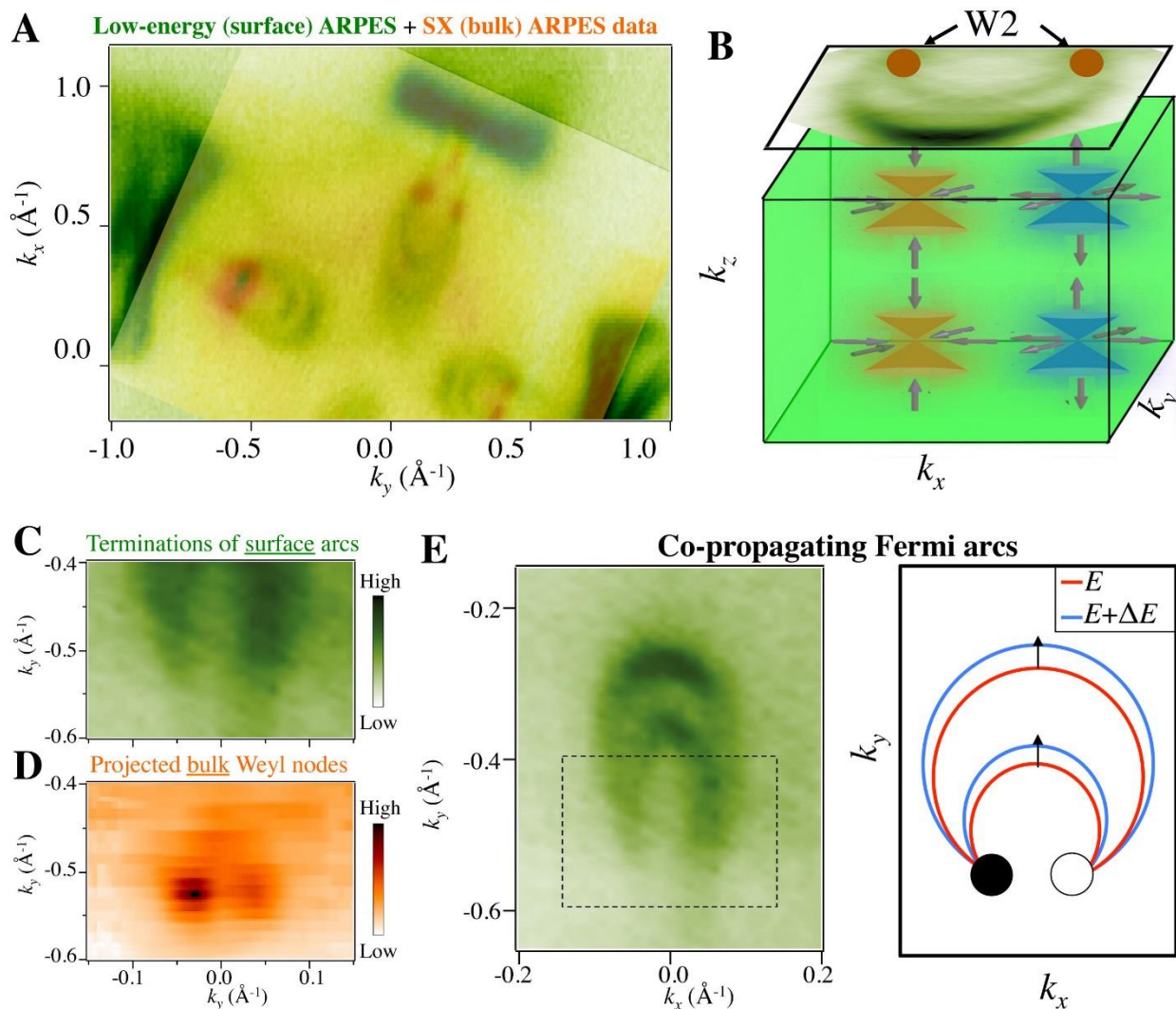


FP/Theory: Huang, Xu, Belopolski et.al.,(Lin & Hasan) **Nature Commun. (in press) '15**
ARPES Expts: Xu, Belopolski, Alidoust et.al., (MZH) Science (in review) 2015

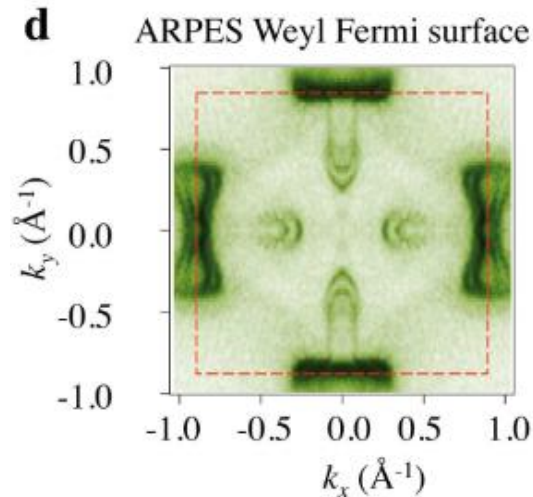
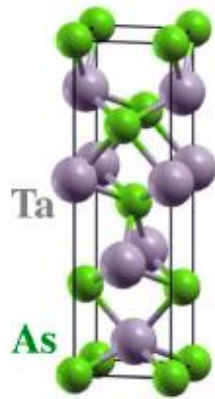


FP/Theory: Huang, Xu, Belopolski et.al.,(Lin & Hasan) **Nature Commun. (in press) '15**
ARPES Expts: Xu, Belopolski, Alidoust et.al., (MZH) **Science (in review) 2015**

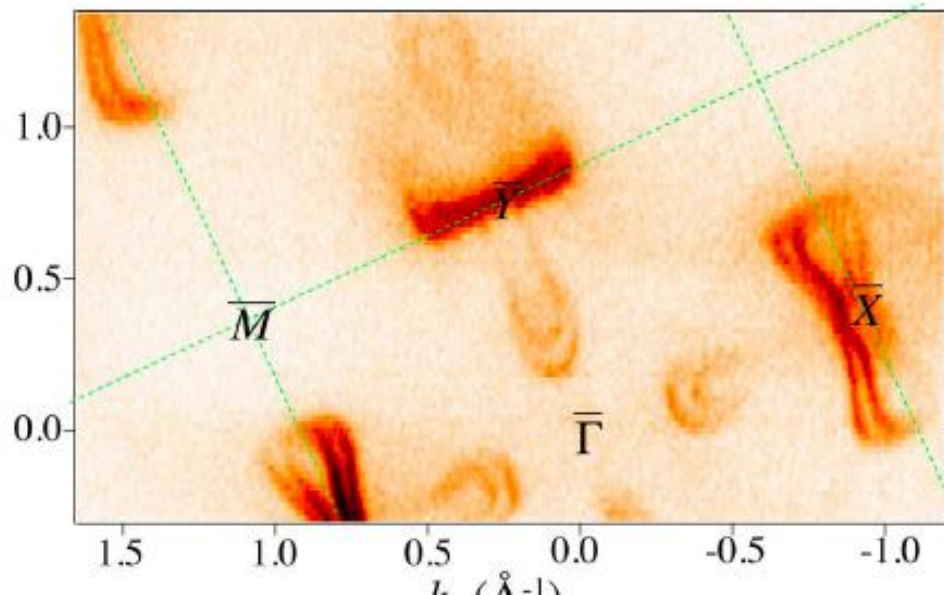
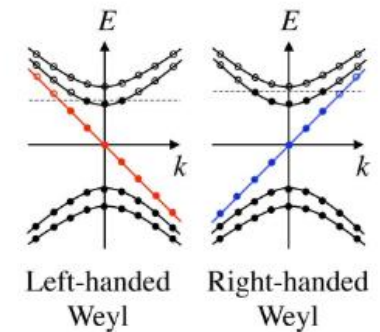
Weyl nodes and Fermi arcs in TaAs



A Weyl semimetals TaAs, NbAs



- Time-reversal invariant
- Inversion breaking
- 24 bulk Weyl points
- Weyl surface Fermi arcs



Weyl Semimetals : TaAs, NbAs and SrSi₂

Theory: An inversion breaking Weyl semimetal state in the TaAs material class; S.-M. Huang, S.-Y. Xu, I. Belopolski, C.-C. Lee, G. Chang, B. Wang, N. Alidoust, G. Bian, M. Neupane, A. Bansil, H. Lin, M. Z. Hasan

Paper: [arXiv:1501.00755](https://arxiv.org/abs/1501.00755)

ARPES Experiments: Experimental realization of a topological Weyl semimetal phase with Fermi arc surface states in TaAs

S.-Y. Xu, I. Belopolski, N. Alidoust, M. Neupane, C. Zhang, R. Sankar, S.-M. Huang, C.-C. Lee, G. Chang, B. Wang, G. Bian, H. Zheng, D. Sanchez, F.-C. Chou, H. Lin, S. Jia, M. Z. Hasan

Paper: [arXiv:1502.03807](https://arxiv.org/abs/1502.03807)

Transport Experiments: Tantalum Monoarsenide: an Exotic Compensated Semimetal; C. Zhang, Z. Yuan, S.-Y. Xu, Z. Lin, B.

Tong, M. Z. Hasan, J. Wang, C. Zhang, S. Jia

Paper: [arXiv:1502.00251](https://arxiv.org/abs/1502.00251)

Chiral Anomaly: 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

Paper: [arXiv:1503.02630](https://arxiv.org/abs/1503.02630)

Discovery of Weyl semimetal NbAs

S.-Y. Xu, N. Alidoust, I. Belopolski, C. Zhang, G. Bian, T.-R. Chang, H. Zheng, D. S. Sanchez, G. Chang, Z. Yuan, D. Mo, Y. Wu, L.

Huang, C.-C. Lee, S.-M. Huang, B. Wang, H.-T. Jeng, T. Neupert, A. Kaminski, H. Lin, S. Jia, and M. Z. Hasan

[arXiv:1504.01350](https://arxiv.org/abs/1504.01350)

A new type of Weyl semimetal with quadratic double Weyl fermions in SrSi₂

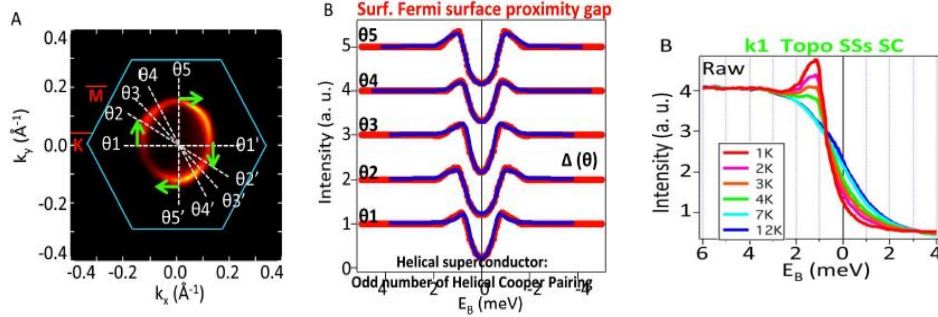
S.-M. Huang, S.-Y. Xu, I. Belopolski, C.-C. Lee, G. Chang, B. Wang, N. Alidoust, M. Neupane, H. Zheng, D. Sanchez, A. Bansil, G. Bian,

H. Lin, and M. Z. Hasan

[arXiv:1503.05868](https://arxiv.org/abs/1503.05868)

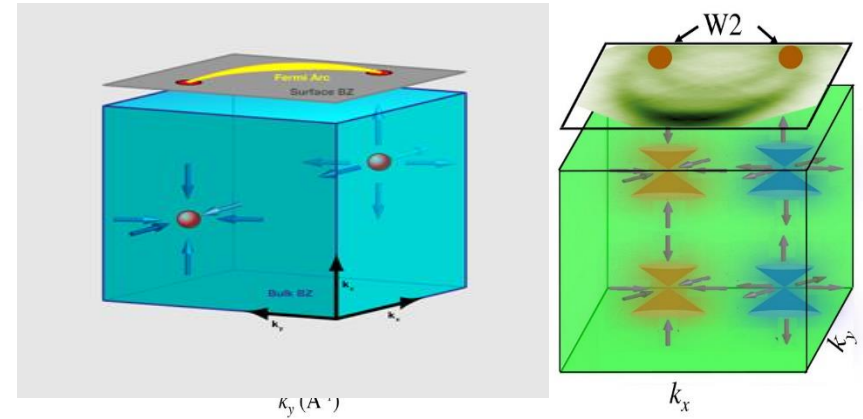
Topo. Insulator →

Topo. Superconductors

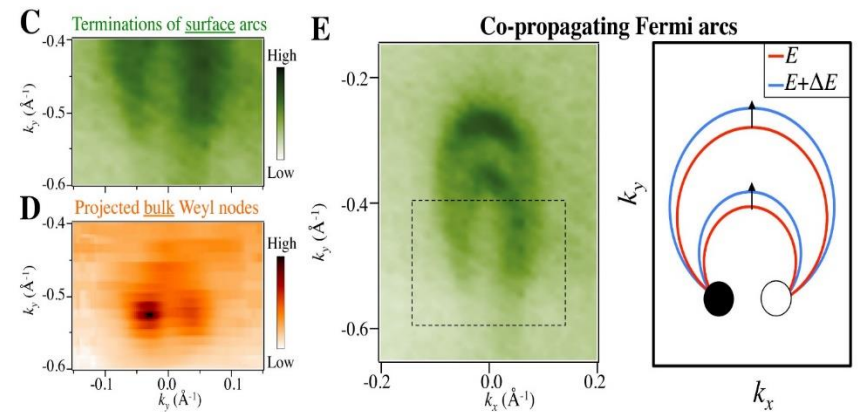
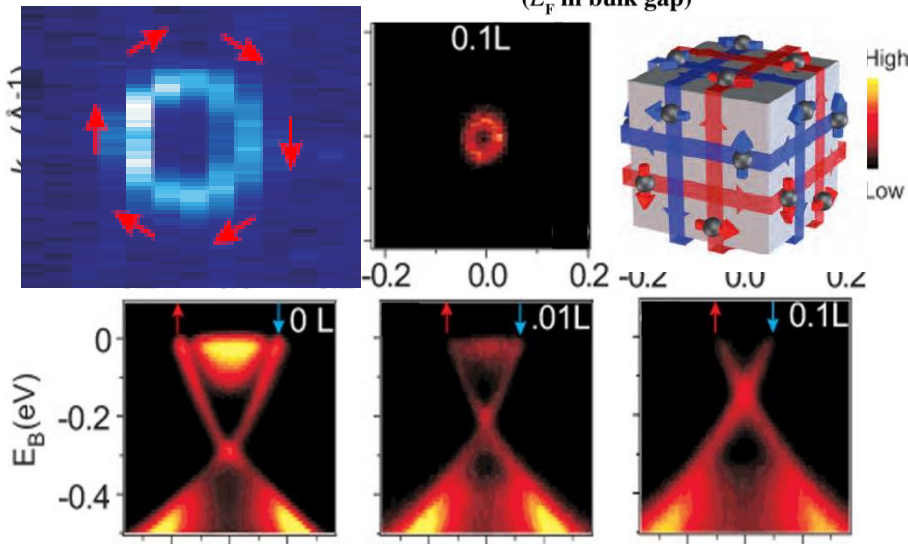


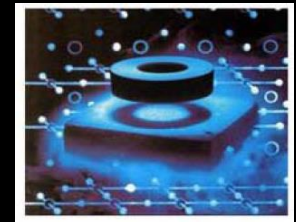
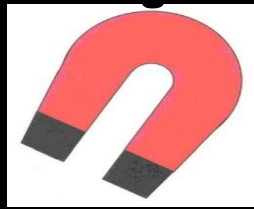
Topo. Phase Transition → WEYL Semimetals

Weyl nodes and Fermi arcs in TaAs



Insulating Topological Insulators
(E_F in bulk gap)



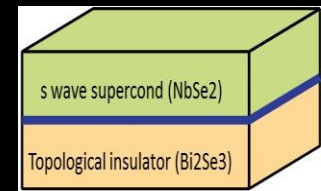
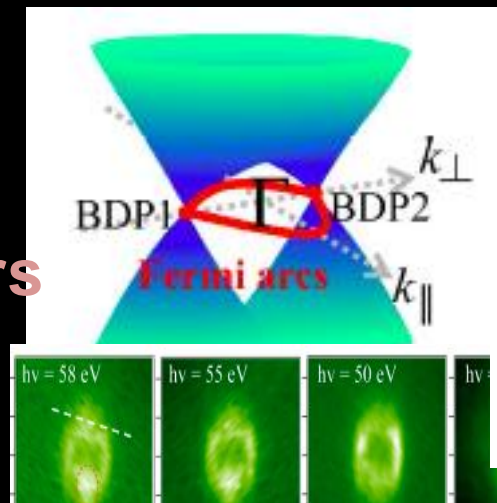
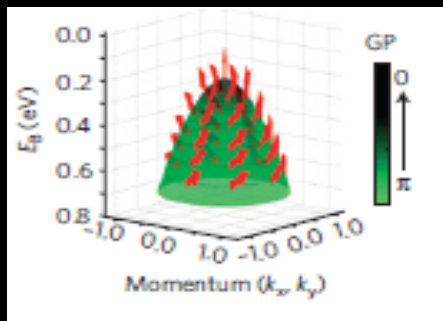
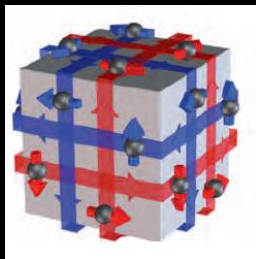


Topo Insulators

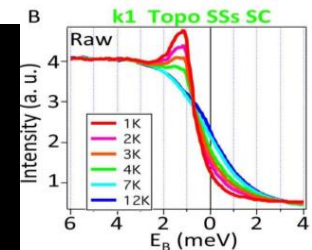
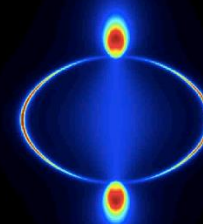
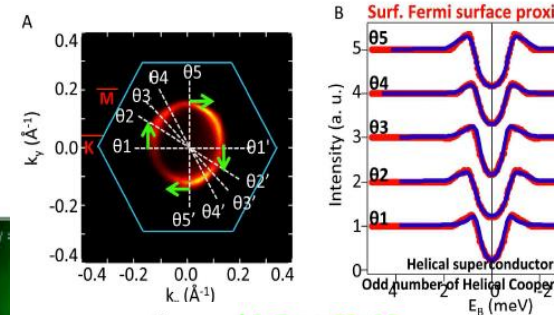
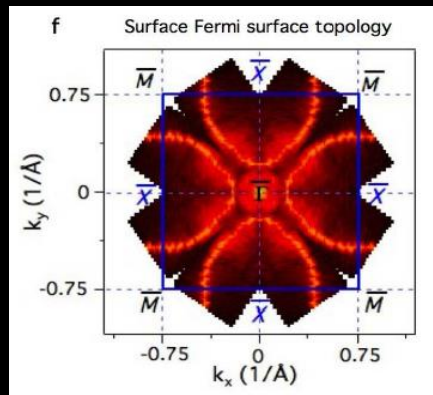
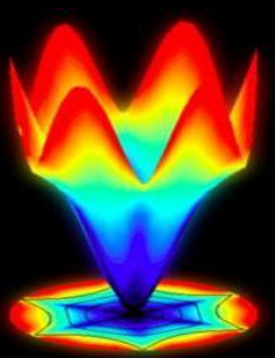
Hedgehog Magnet

Fermi-Arc Metal

Topo. Supercond



Kondo Insulators



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)

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

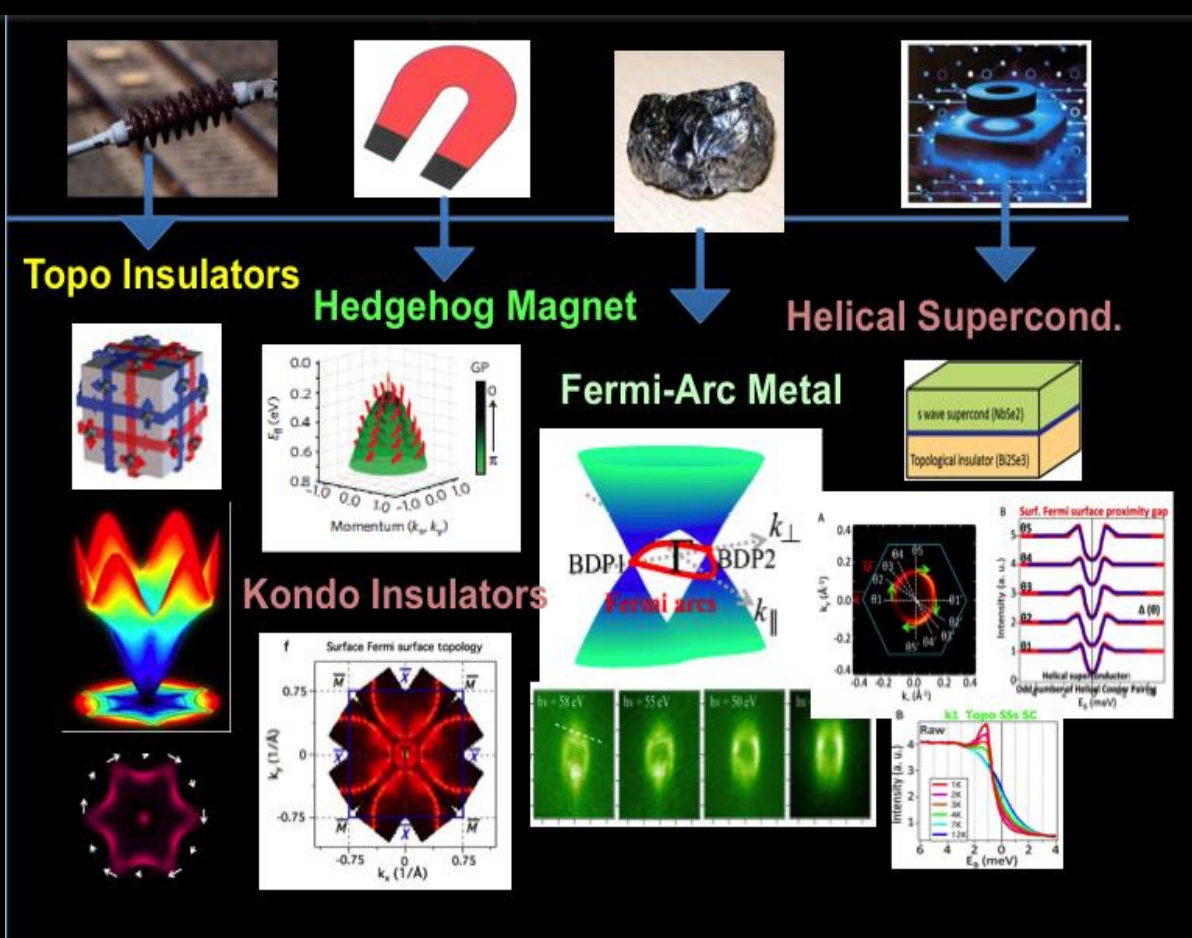
Science 2015

MZH and C.L. Kane

Rev. of Mod. Phys., (RMP) 82, 3045 (2010)

MZH and J.E. Moore

Ann. Rev. of Cond. Mat. Phys., 2, 78 (2011)



Topological Condensed Matter Physics

Thanks !

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]

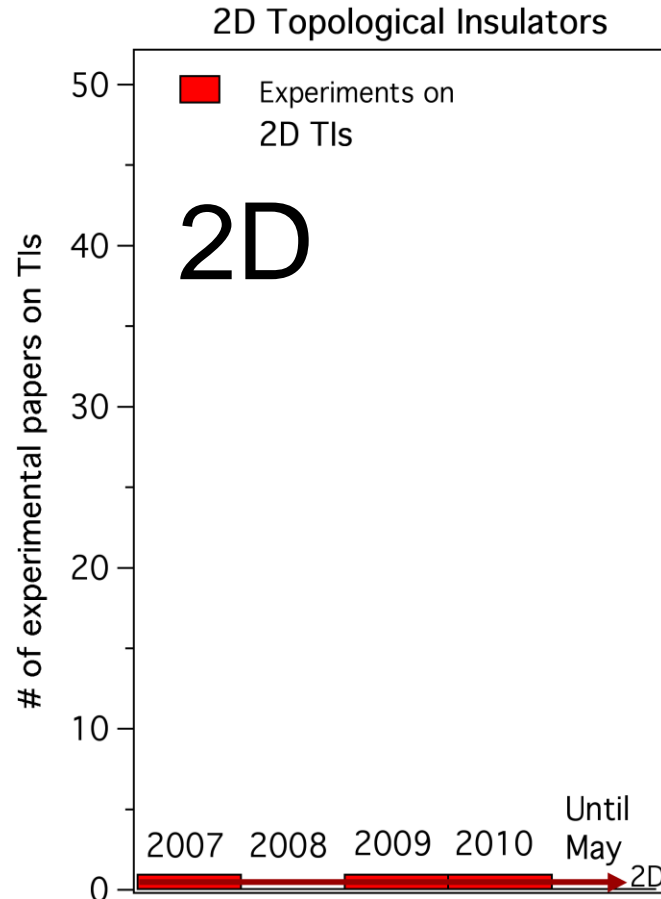
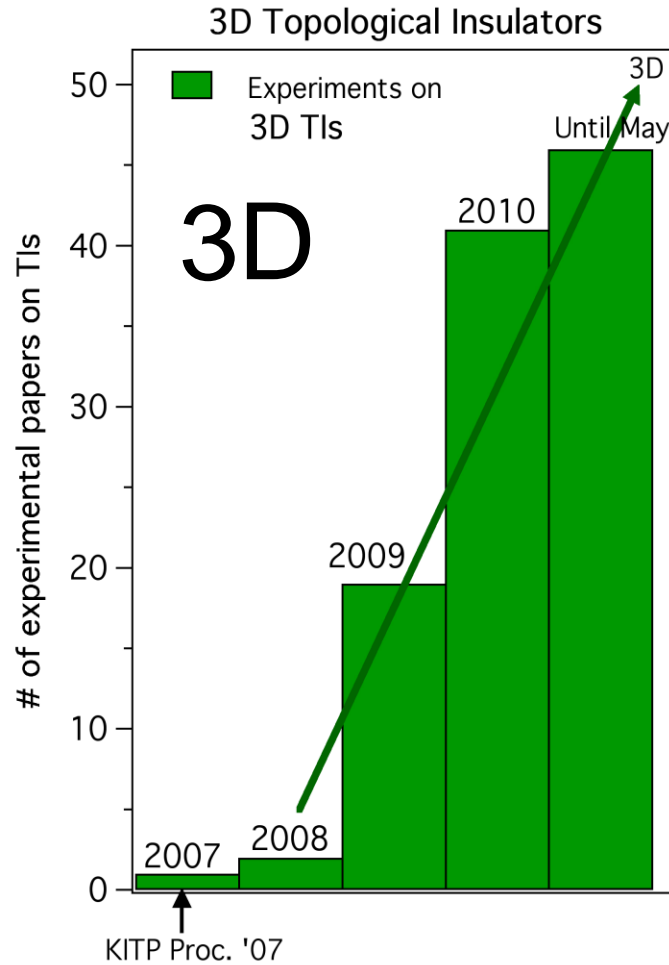
Y.Xia, D.Qian, L.A.Wray, D.Hsieh et al., [May '09] Sub. (2008) and extended version at
A tunable topological insulator in the spin helical Dirac transport regime
Nature 460, 1101 (2009); D.Hsieh, Y.Xia, D.Qian et.al., Submt.(2009) [Princeton]

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)

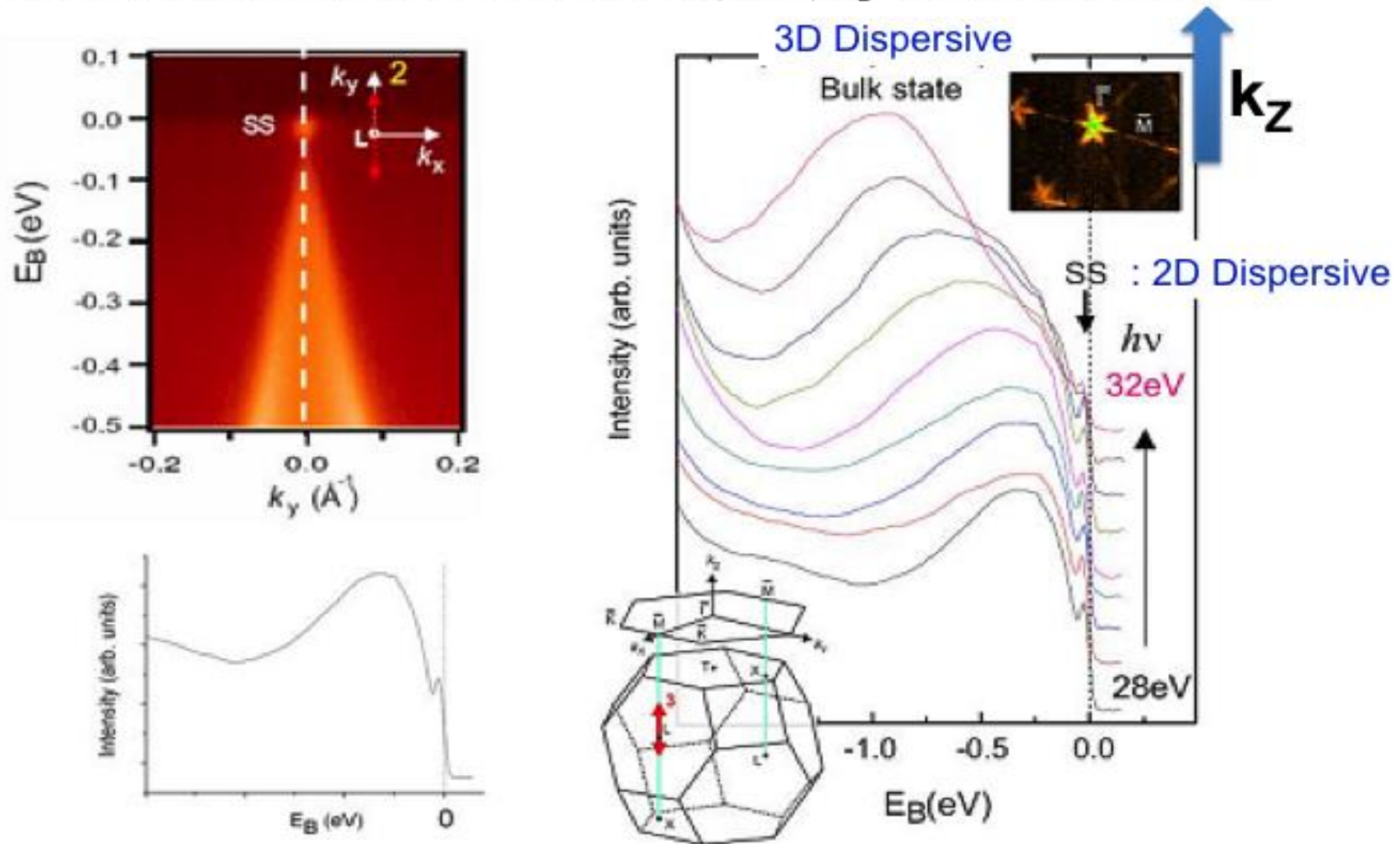
Distribution of experimental works in topo. Insulators (2007-2011)



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.)

Bi(Sn)Sb semiconductors with in-gap Fermi level

Band-structure of Bi(Sn)Sb semiconductors, 2005-07 thermoelectric, DOE Fu-Kane-Mele PRL/PRB'07 Prediction: Bi-Sb (no Sn) Z_2 non-trivial but what SS? grant



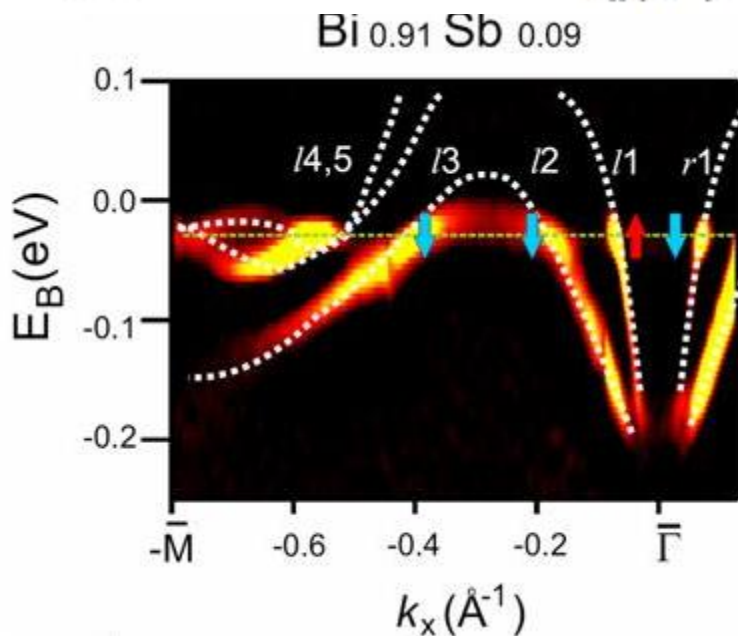
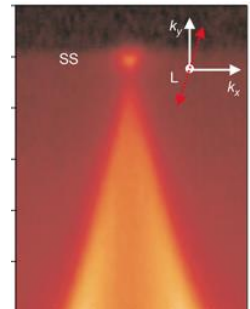
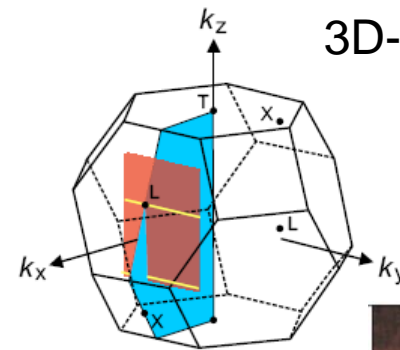
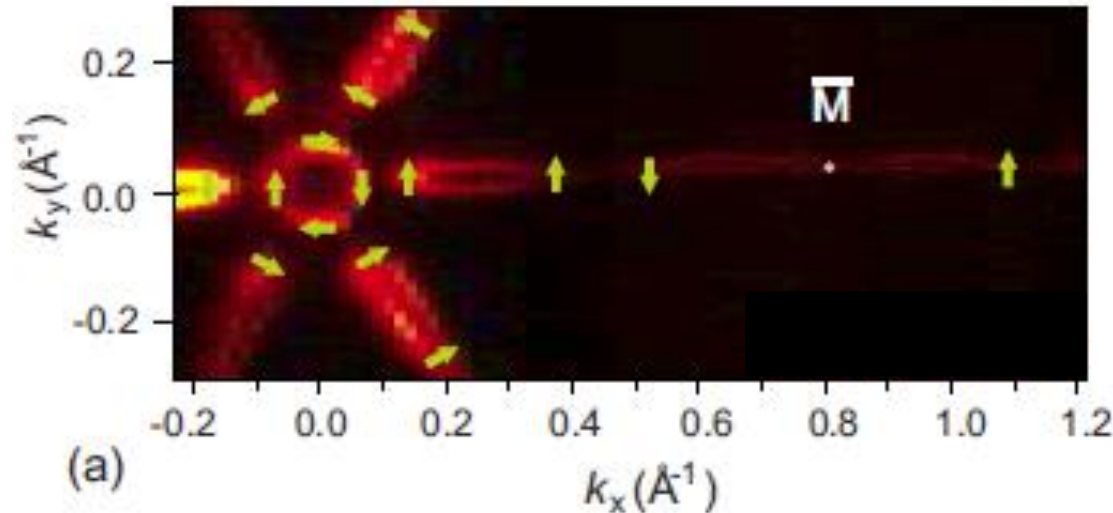
Hsieh, Qian, Xia, Wray, Hor, Cava, MZH NATURE 08 (submitted 2007), KITP Proc. (2007)

surface Fermi surface,

while E_f in bulk gap found to be spin-textured :

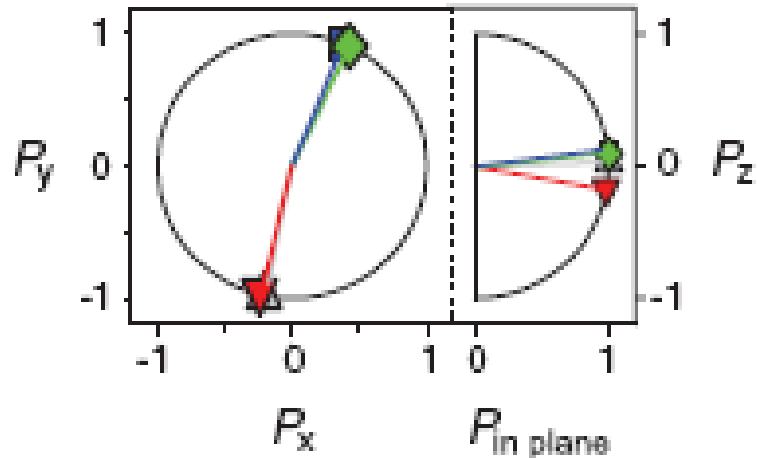
Phys.Today '09
 "Search & Discovery"

also first
 3D-Spin imaging



Polarization

- ▼ l2
- ◆ l1
- ▲ r1
- r2

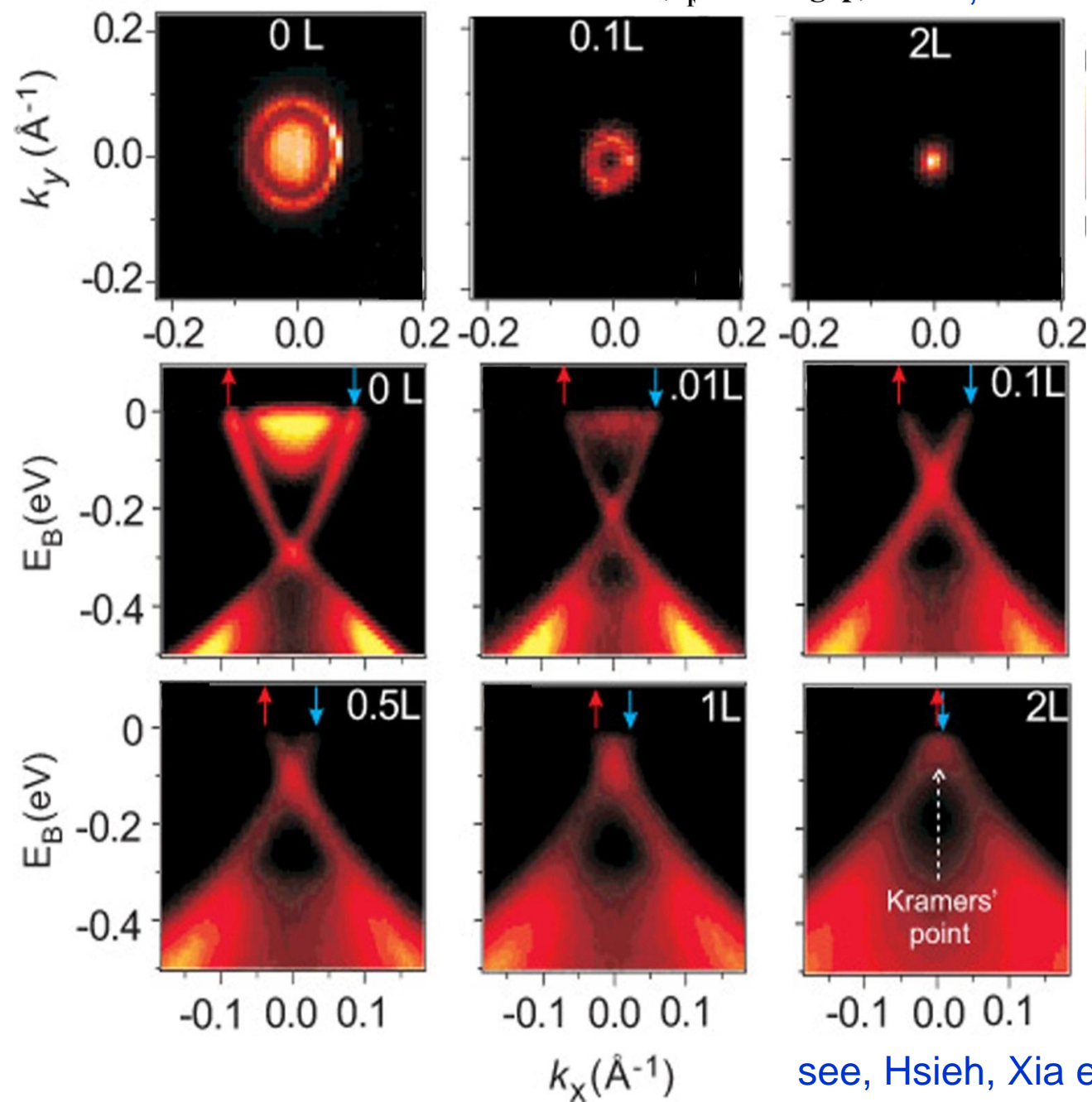


Hsieh, Qian, Xia et.al., (MZH) Nature 08, Science '09

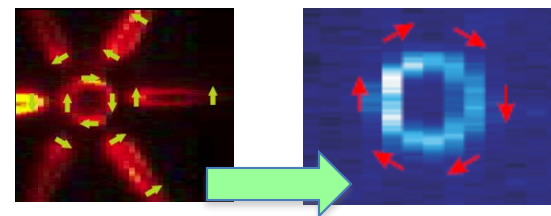
Insulating Topological Insulators

(E_F in bulk gap) see, Hsieh, Xia et.al., **Nature (2009)**

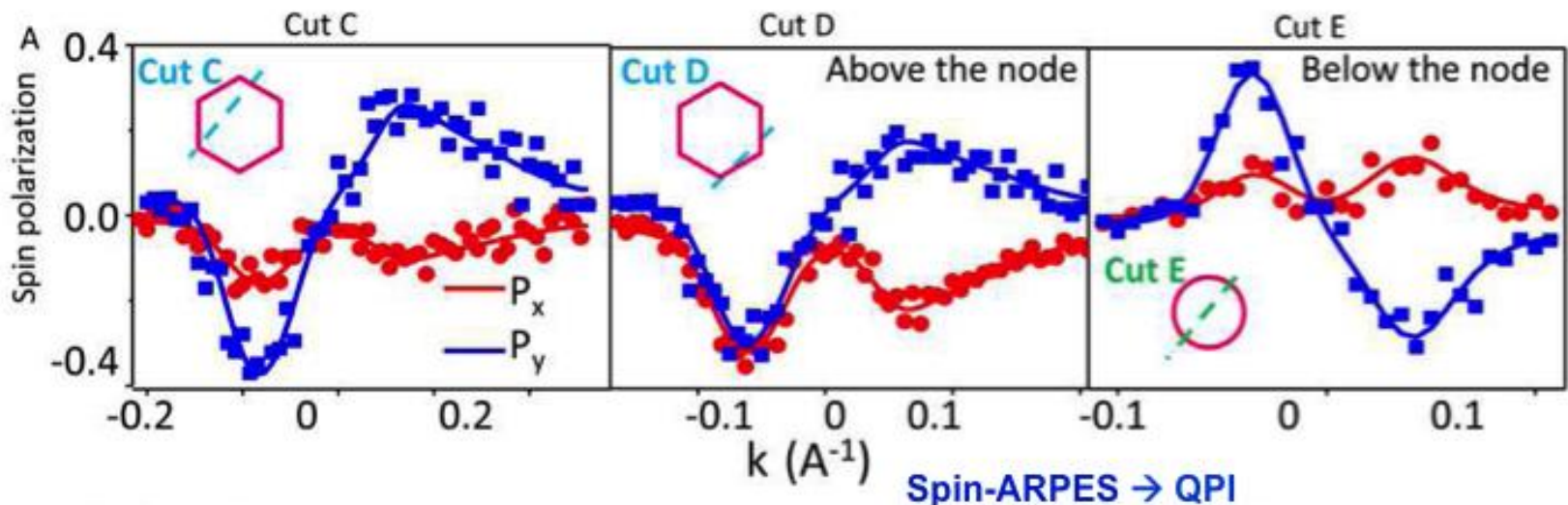
**Bulk Insulating
achieved
under UHV
conditions
(stable)**



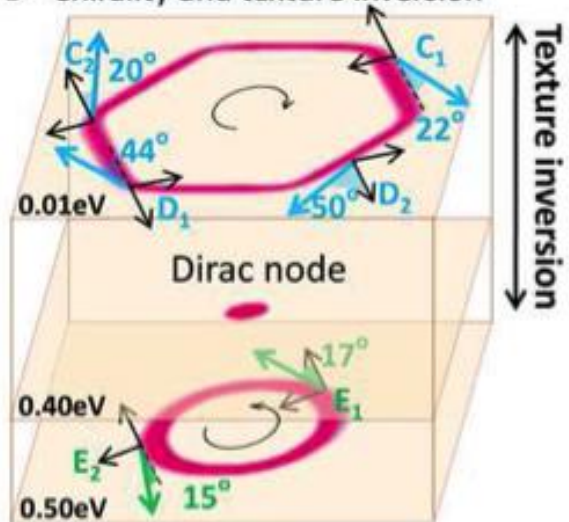
Bi-Sb \rightarrow Bi₂X₃



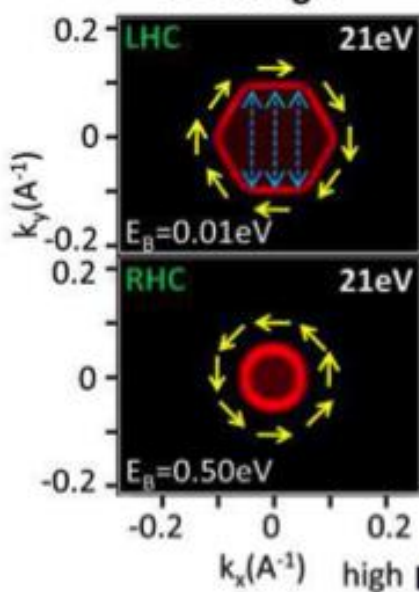
see, Hsieh, Xia et.al., (MZH) **Nature (2009)**



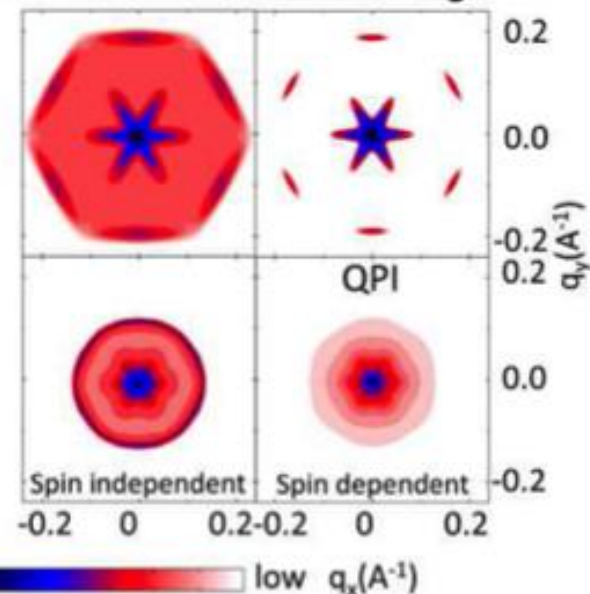
B Chirality and texture inversion



C $\frac{1}{2}$ Dirac gas



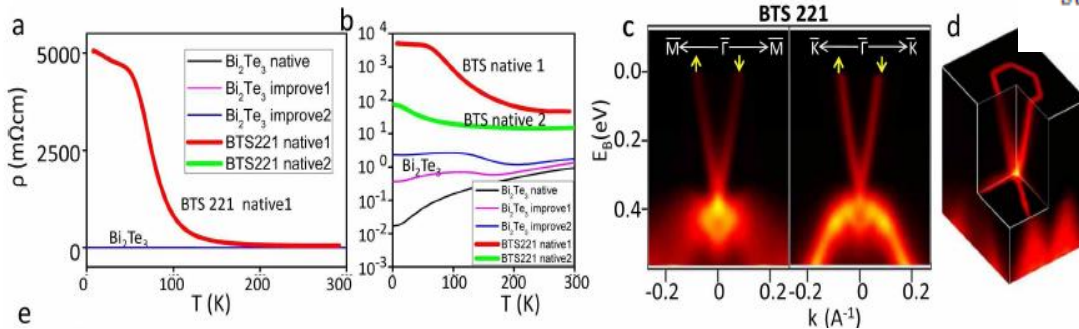
D Absence of backscattering



Hsieh, Qian, Wray, Xu et.al., (MZH) Nature'09 Science'11

Highly Bulk-Insulating Topological Insulators

Surface contribution to transport more than 90%
 Surface Mobility $\sim 3000 \text{ cm}^2/\text{Vs}$

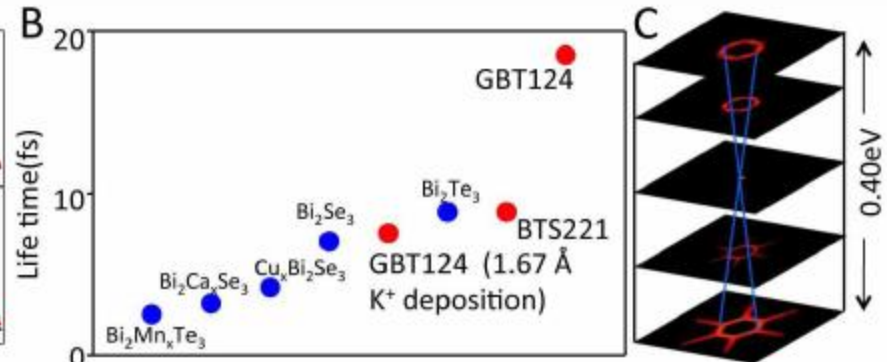
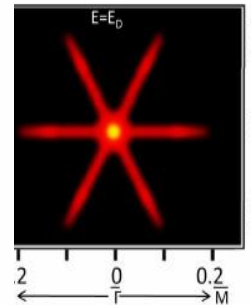
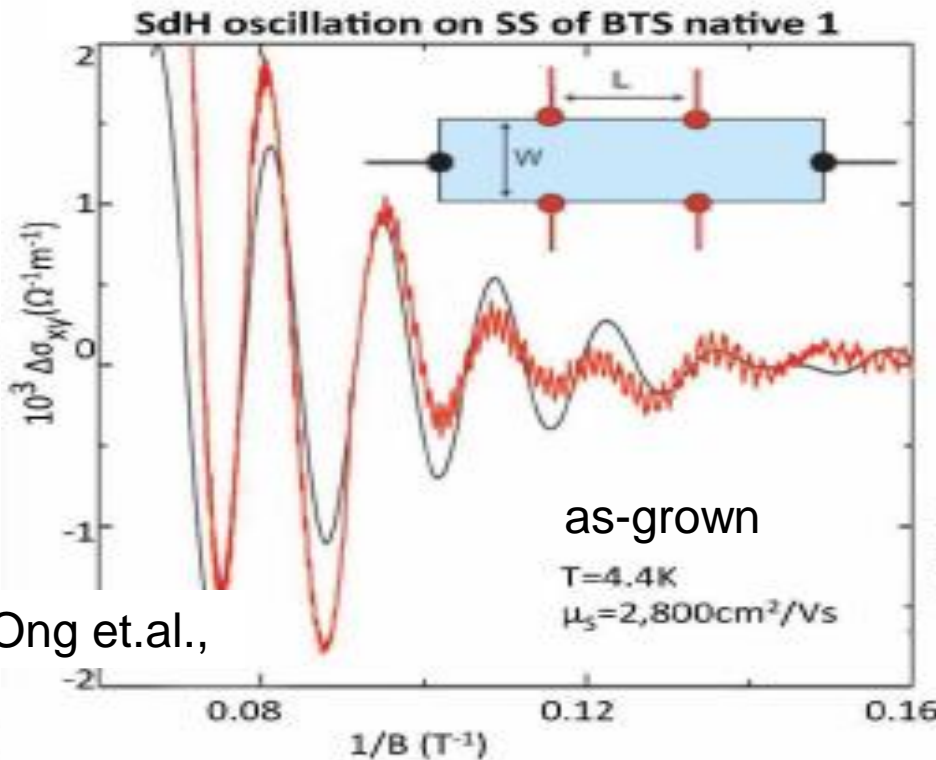


$$G_{\text{surface}}(T \sim 0) = (e^2/h)k_F L = (e^2/h)k_F v_F \tau$$

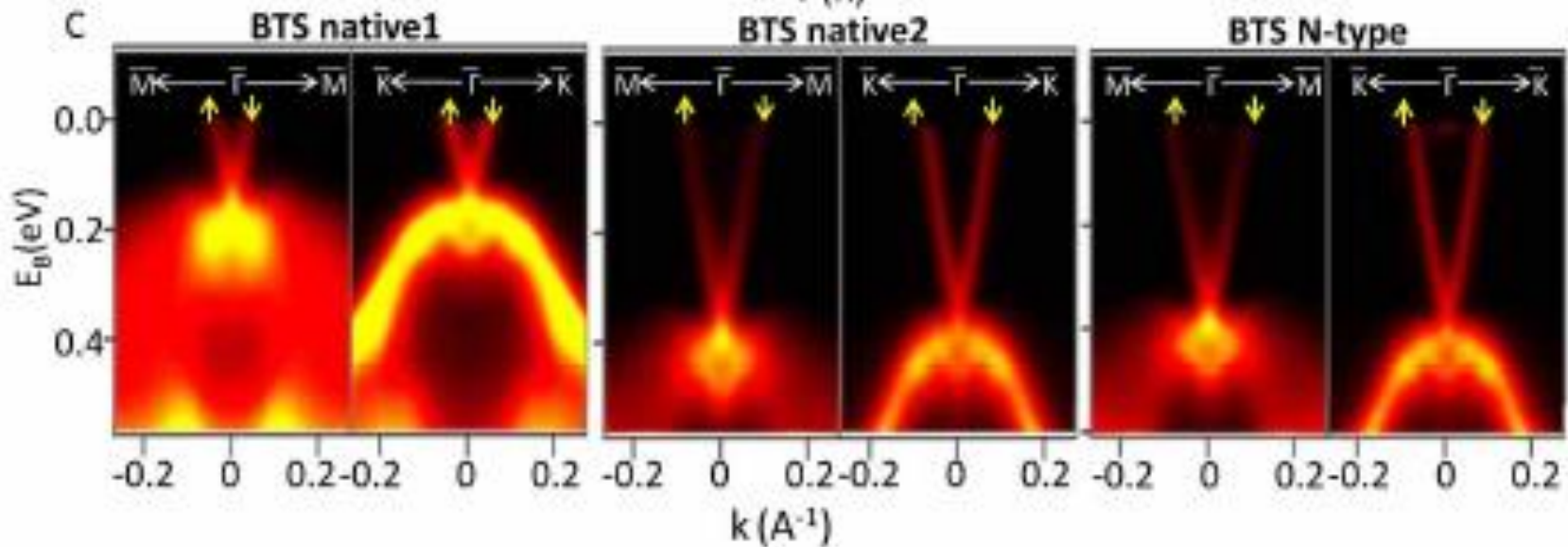
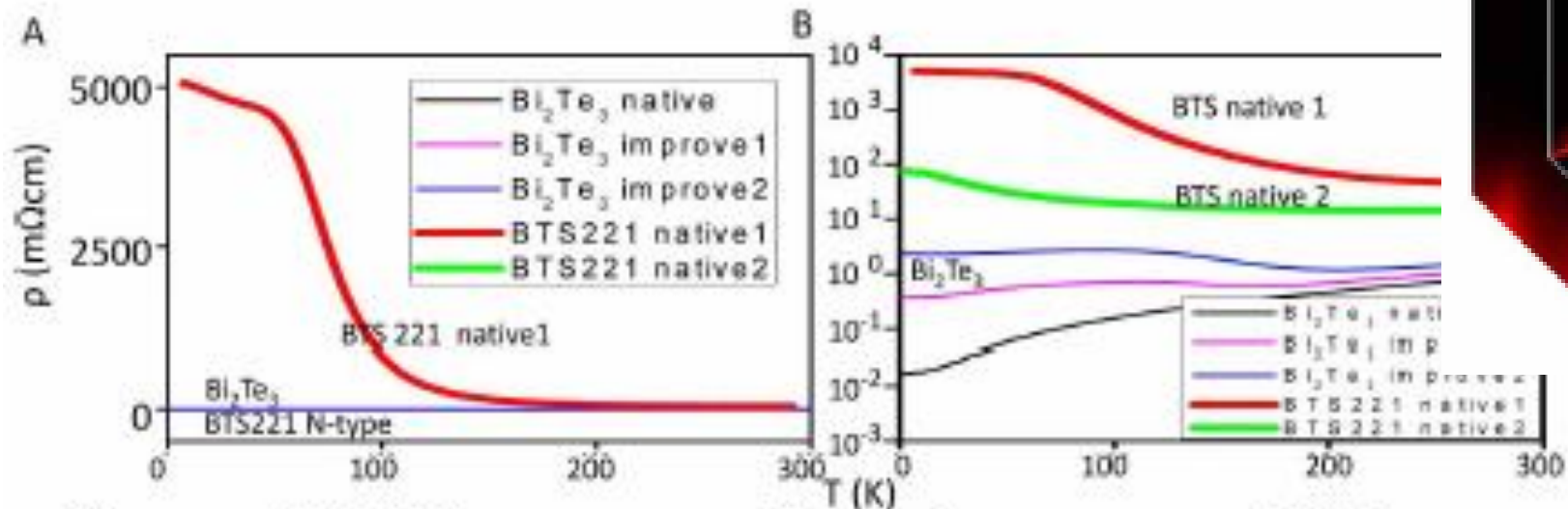
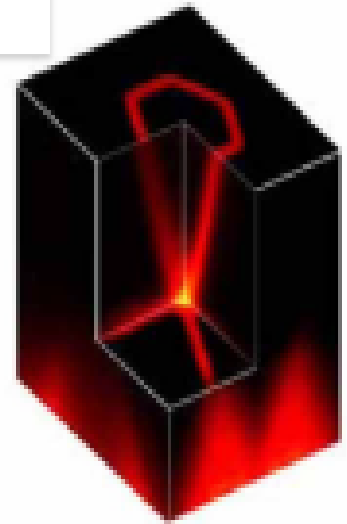
even
 Bulk crystals $> 5 \text{ Ohm-cm}$

100-nm Film equivalents
 $\sim 10^{10}$ carriers

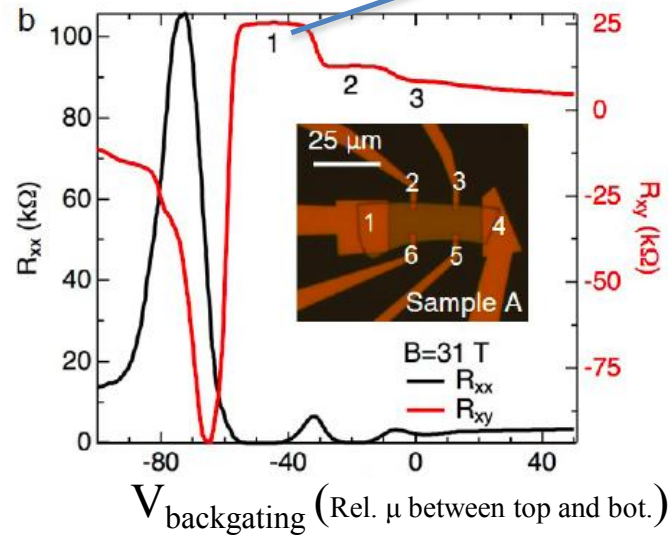
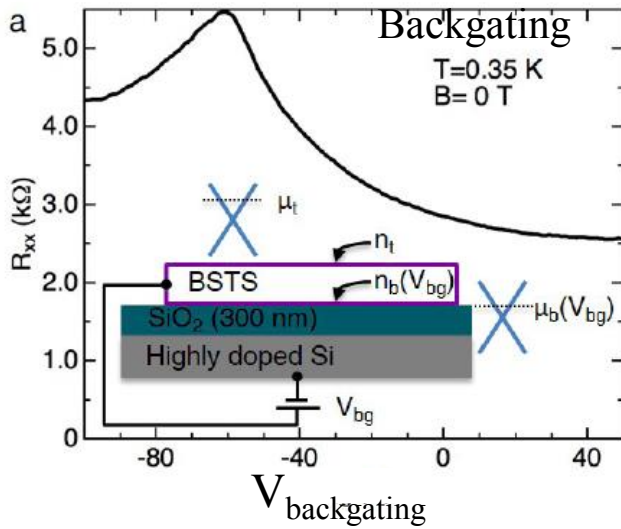
Very large Gap $\sim 200 \text{ meV}$
 (unlike HgTe)



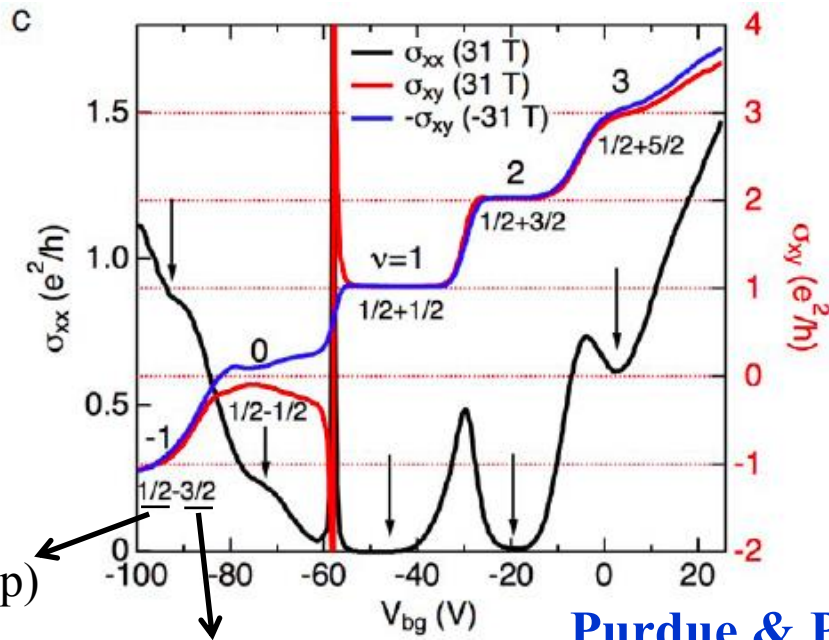
Mix Bi-Sb and Bi₂(Te/Se)₃ -> BTS, BSTS
 (more bulk insulating than Si at 4K)



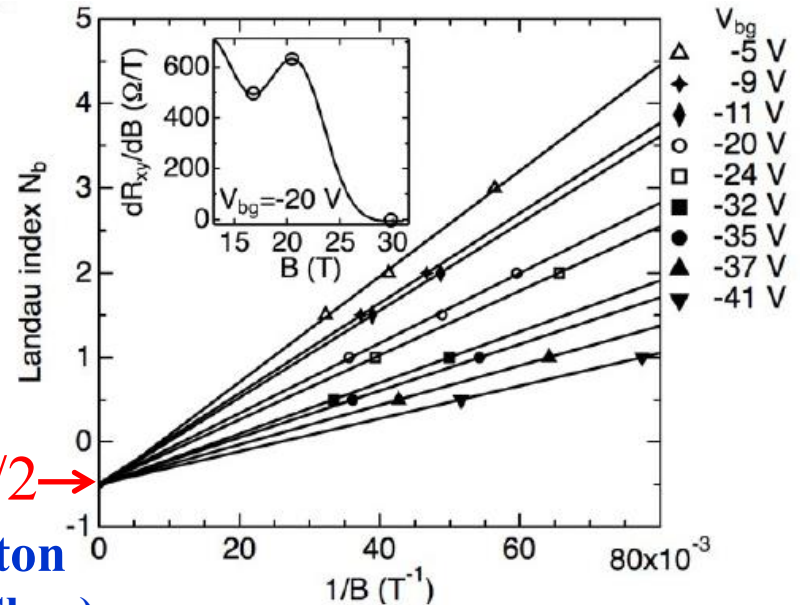
Experimental Setup: BiSbTeSe_2



Observ. of Quant. Hall Plateaus



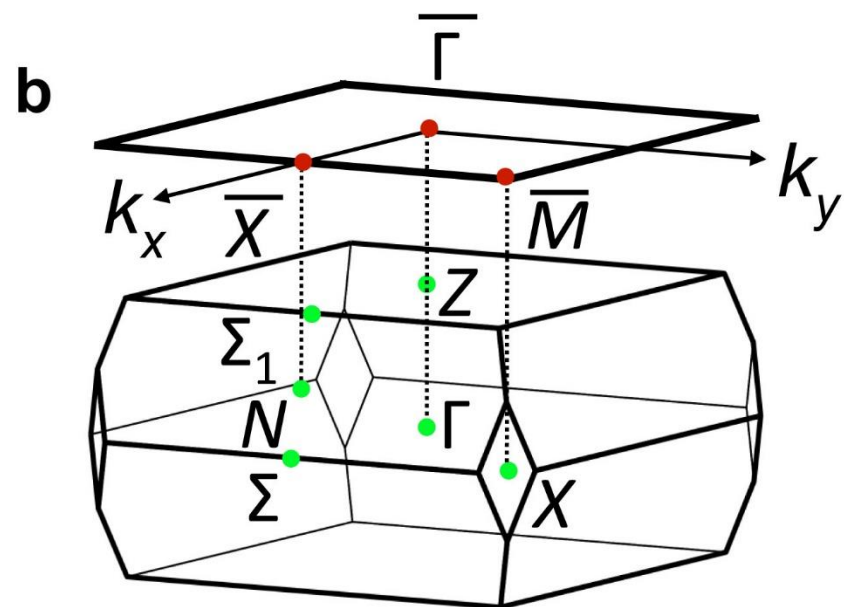
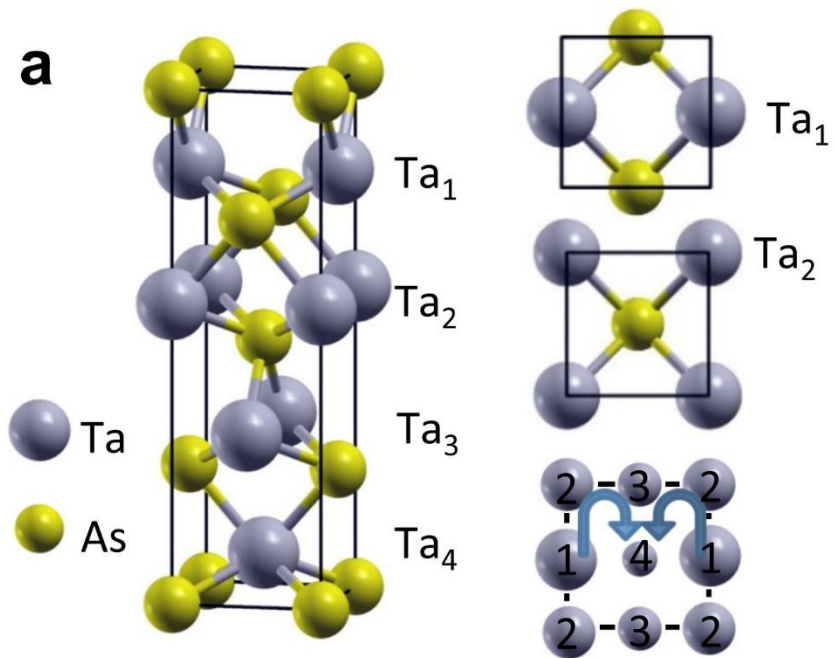
LL \rightarrow Dirac dispersion

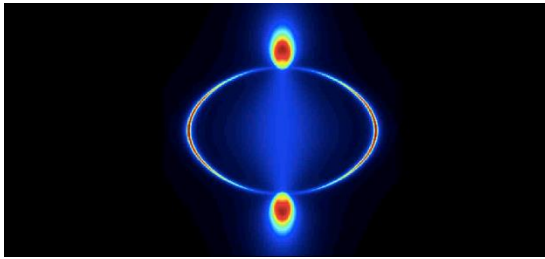


Purdue & Princeton
 (Xu et.al, Hasan & Chen)

$\frac{1}{2}$ (top)

$-3/2$ (bot. tuned by BG)





Recent **Experimentally focused** reviews:

Topo. Insulators, Topo. Crystalline Insulators & Topo. Dirac Semimetals and Topological Kondo Insulators

MZH., S.-Y. Xu, M. Neupane

[arXiv:1406.1040 \(2014\)](#)

[Published Book Chapter \(Weily & Sons, 2015\)](#)

Experimental Discoveries:

Topological Surface States - A New Type of 2D Electrons Systems

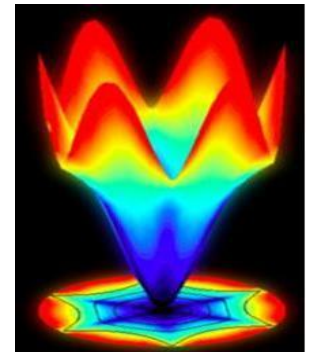
MZH., S.-Y. Xu, D. Hsieh, L. Wray, Y. Xia

[Book Chapter in Topological Insulators \(Elsevier\) \(2013\)](#)

Pre-2010 experimental works are at

MZH. and C. L. Kane

[Rev. Mod. Phys 82, 3045 \(2010\)](#)



Hedgehog Magnets →

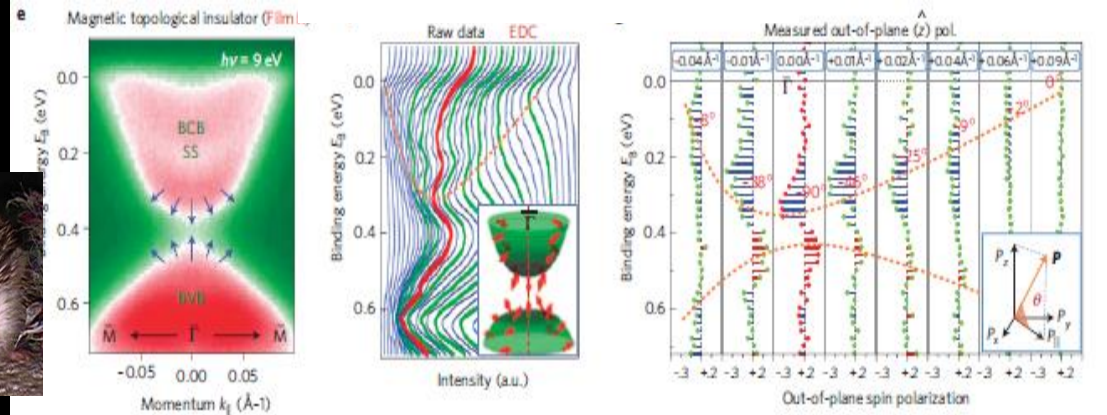
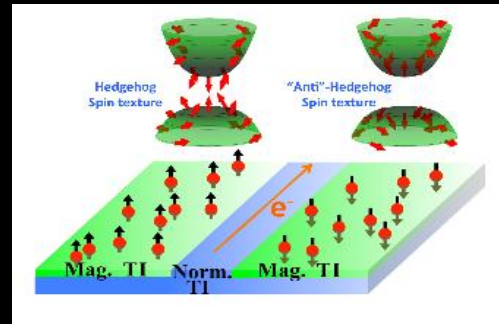
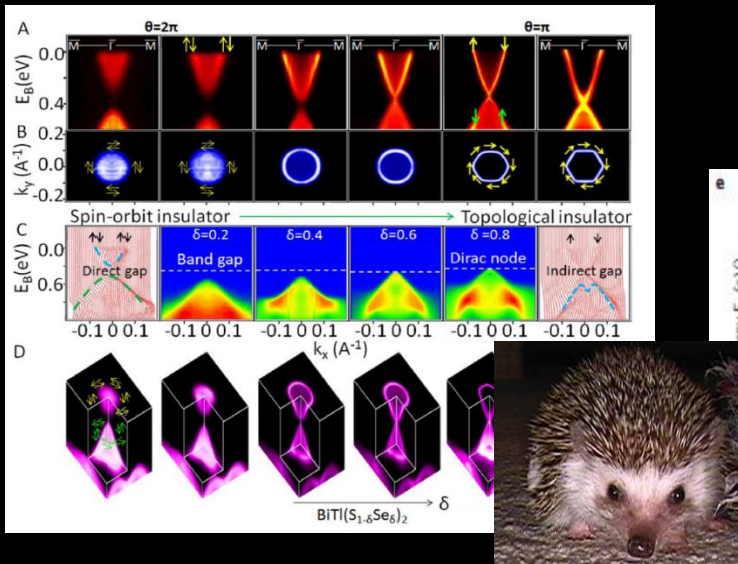
a route to Weyl Fermions & other cool stuff..

near criticality TI → NI

Xu et.al., (MZH) Science '11

magnetize it (Ferromagnetic)

Xu et.al., (MZH) Nat. Phys. '12

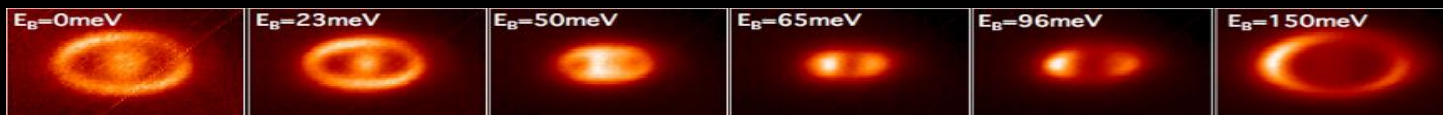
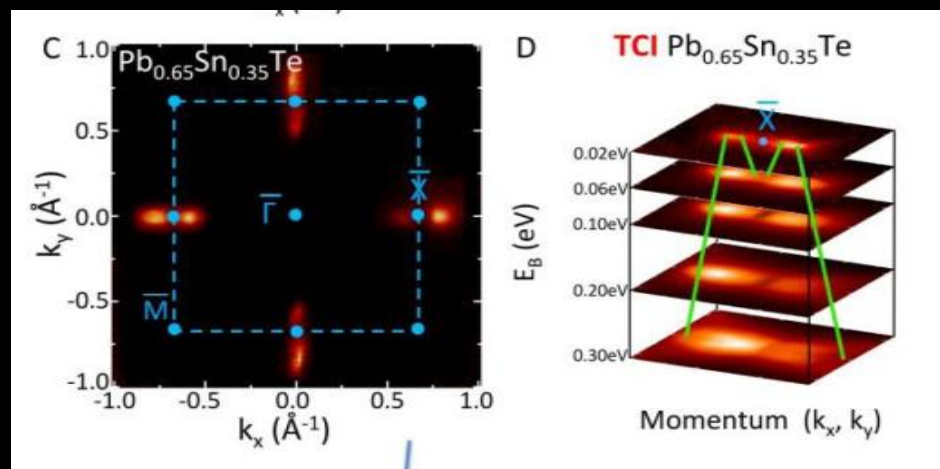


Topo Insulators beyond Z_2 or TRI

TR invariance \leftrightarrow SG symmetry (TCI)

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

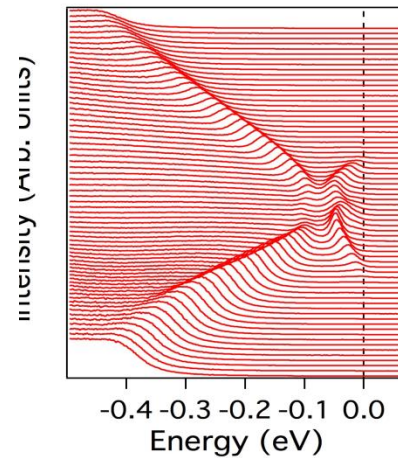
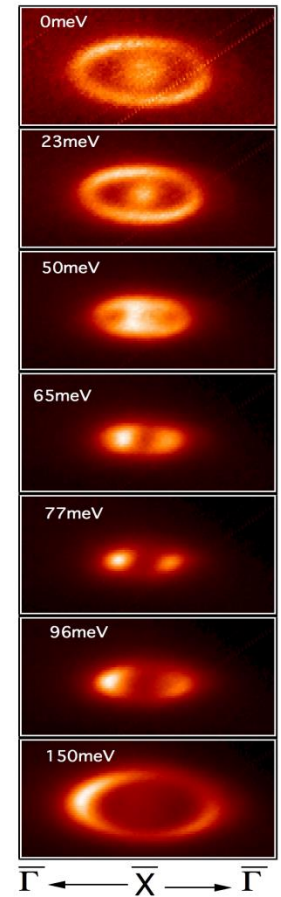
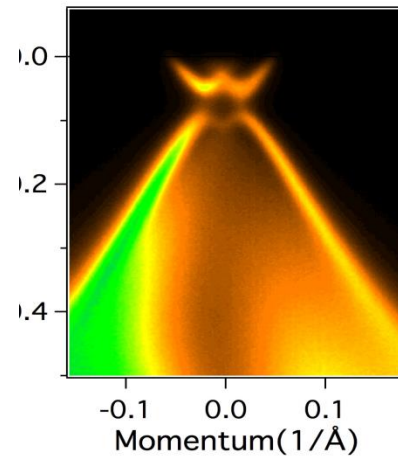
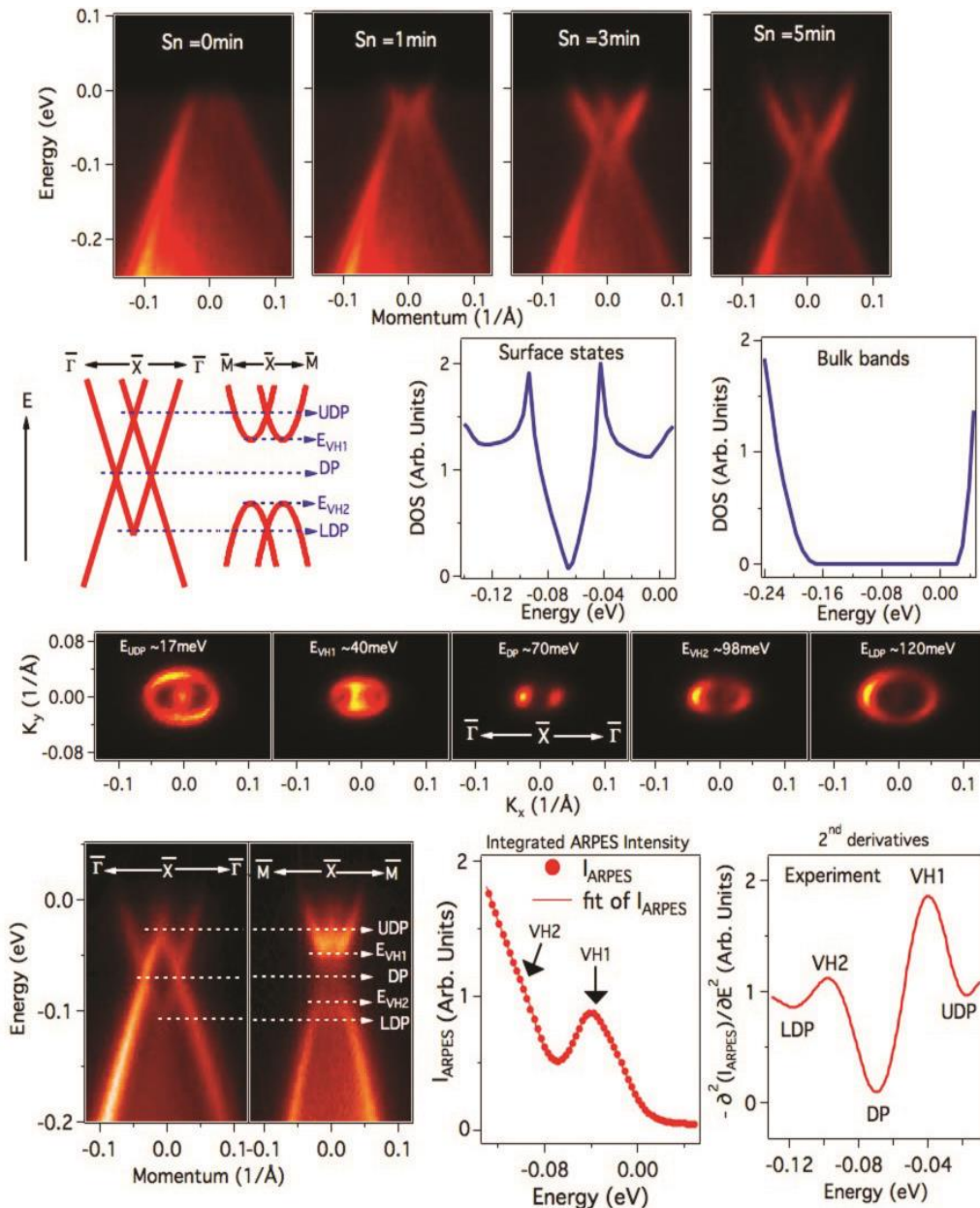
Mirror Chern no. measured in Bi-Sb;
Hsieh, Xia, et.al., (Kane & MZH) SCIENCE' 09



Lifshitz Transition \rightarrow Singularity \rightarrow

may lead to correlated electron pheno.

Pb_{1-x}Sn_xTe/Se



Okuda et.al., (MZH & VM) Science '13
 Neupane et.al., (MZH) 2013