Topological Insulators & Superconductors

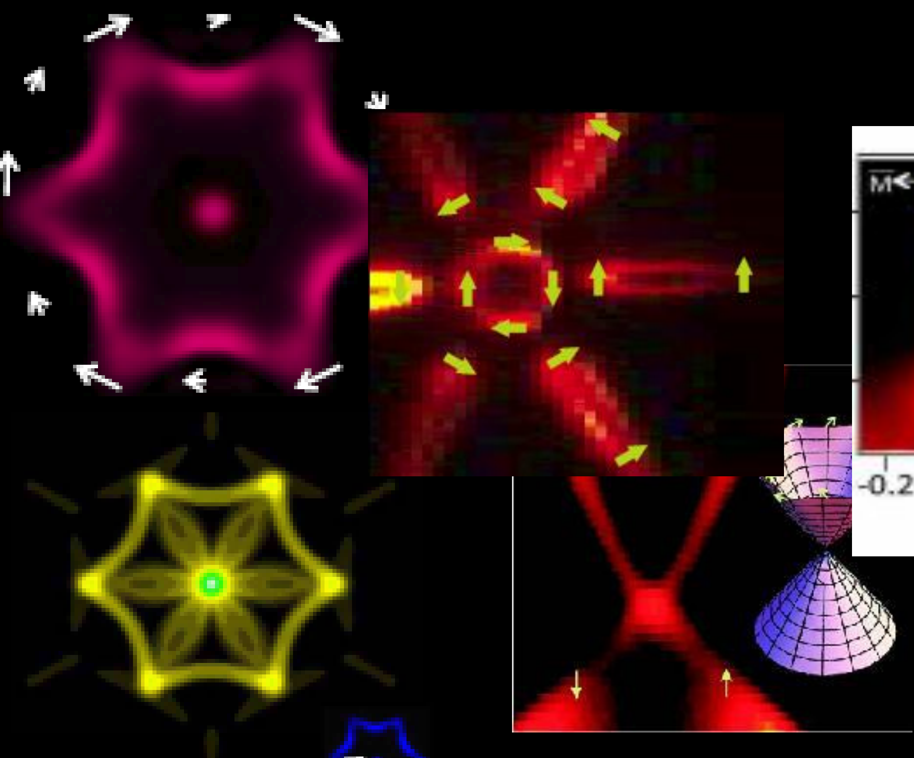
KITP Topomat-11

M. Z. Hasan
Joseph Henry Laboratories of Physics
PRINCETON UNIVERSITY

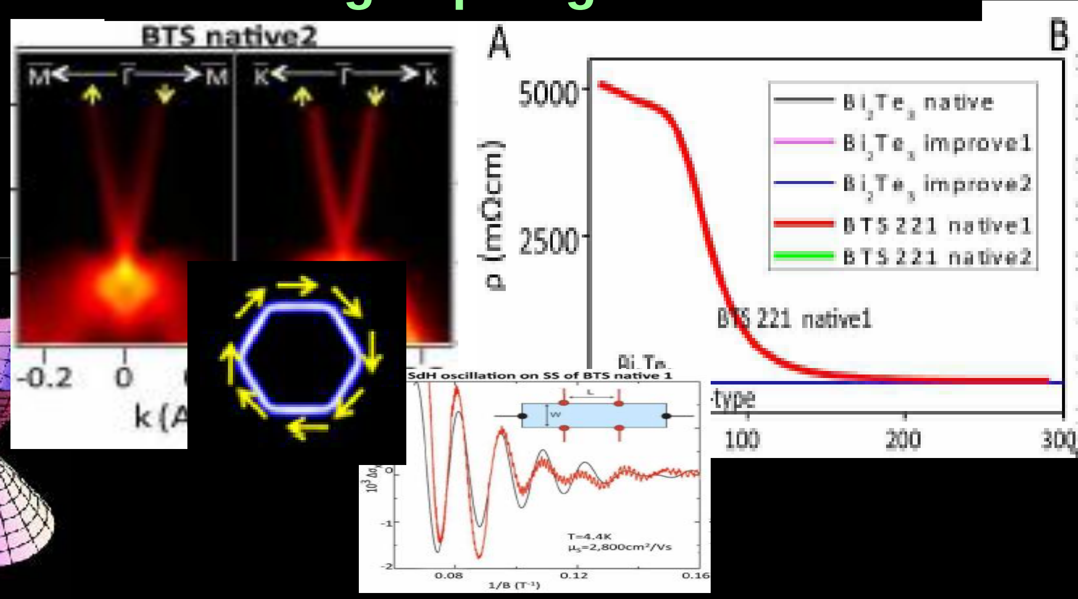
Review of our experimental works are included in:

Rev. of Mod. Phys. 82, 3045 (2010)
Ann.Review of CondMat Phys. 2, 55 (2011)

Mostly supported by U.S. DOE/BES



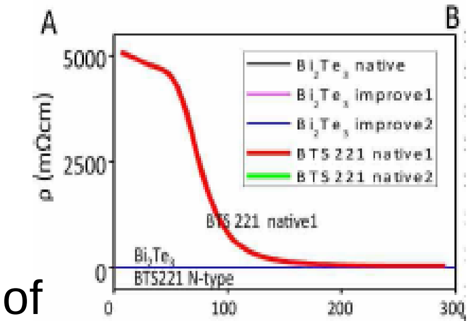
Insulating Topological Insulators



Topological Insulator

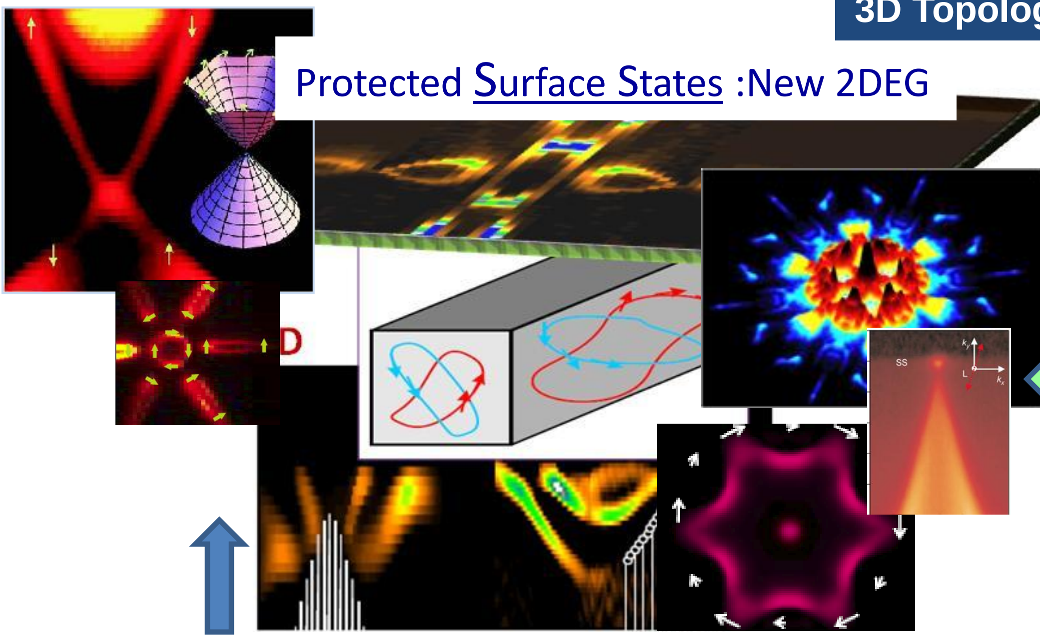
$\{\nu_o\}$ (Chern Parity invariants) Z_2 (Kane-Mele & many others '05-'09)

Bulk-Insulating 3D TI (>90% surface transport)



3D Topological Insulators

Protected Surface States :New 2DEG



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

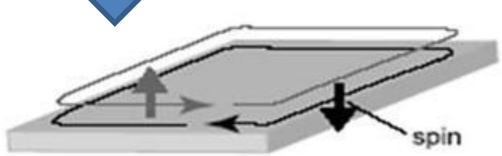
Hsieh et. Nature (2008) [Subm. 2007, Nov]

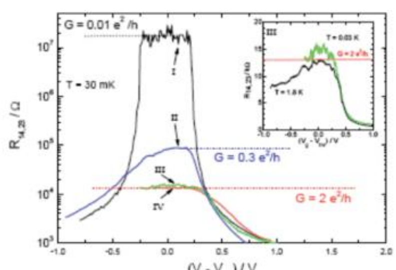
3D expts are neither derivatives nor extensions of 2D TI expts!

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

2D Topological Insulators

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

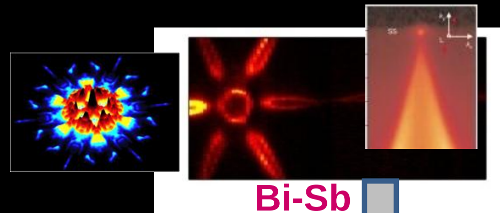




QSH edge States (1D) by TRS

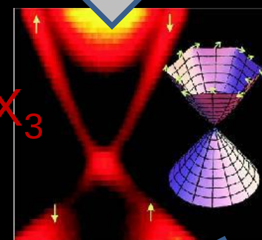
Charge transport Measurement of edge states of **quantum spin Hall**

Experiments on Topological Insulators (3D



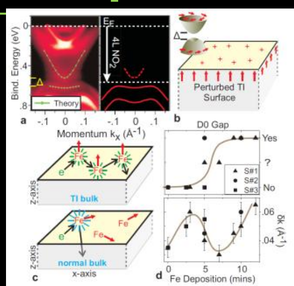
Hsieh et.al., NATURE 08 (sub. 2007)
Hsieh et.al., SCIENCE 09
Roushan et.al., NATURE 09

Bi_2X_3

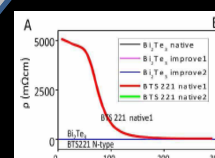


Xia et.al, 2008 (arXiv'08, KITP 08)
Xia et.al, 2009 (Nature Phys.)
Hsieh et.al., Nature 2009
Zhang et. NatPhy '09 & Chen et.al, Sci '09
and many others ..

Surface Magnetic Impurity Coulomb perturbation etc.

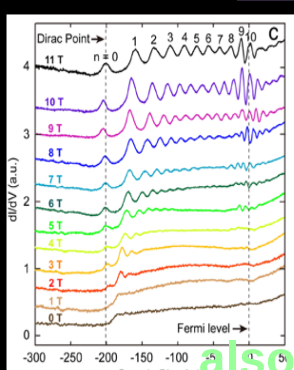


Xia et.al, arXiv. 2008
Wray et.al., Nat.Phys. 2010
Chen et.al, Science '10

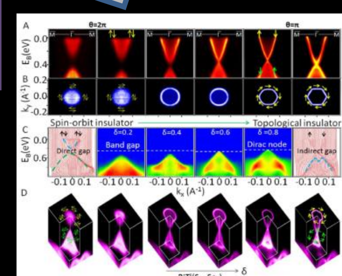


Quantum Hall effect

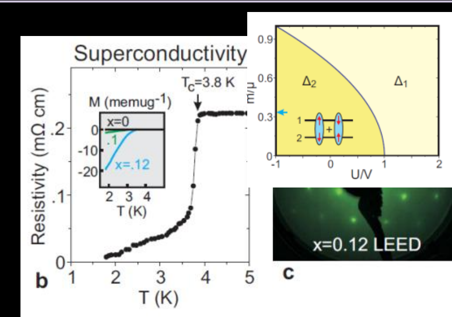
STM Landau quantization
Xue et.al., PRL 2010
Analytis et.al, NatPhys '10
Xiong et.al., arXiv'11



also Fractional QHE



Superconductivity



Hor et.al., PRL 2010
Wray et.al., Nat.Phys.20
Ando et.al, PRL '11

Topo.Phase Transition

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

<u>Three Myths </u>on Topological Insulators/Experiments:

1. Expts on 3D Topological Insulators are extensions and derivatives of quantum spin Hall effect of 2D topological insulators. **NO.**

3D-TI Spectroscopy/ARPES: Hsieh et. Nature (2008) [Subm. 2007, Nov]

2D-TI Charge-Transport/ Konig et. Science (2007)[Subm. 2007, June]

Two different types of experiments independently reported topological **<u>edge states</u>** and **<u>topological surface states</u>** (in addition, these two papers are a few months apart not several years). **Most people work on Surface States.** So 3D expts have been reproduced by many others…(>95% expt. papers are on 3D)

2. Transport in topological insulators are Z2 quantized.
   NO.
   Observation of spin-momentum locking ½ Dirac gas
   (or/and a topological phase transition) closes the case

This was first done in 3D topological insulators (spin in 2D QSH etc. came later)

3. MBE films of 3D Topological insulators are better than bulk insulating samples.
   NO!; Z2 Topological Proof does not require MBE films and Transport and has long been done (focus of this talk, also see reviews RMP 2010)
   Our Spectroscopy results show that no NEW topological information in gained in the best MBE films (nothing to do with quality of the films!!)
   Films may or may not (in future) help us observe proximity effects (many are working on this including our team ..)

Our experiments on Topological Surface States (new type of 2DEG)

KITP Online talks 2007-

1. **Robust & Protected** to alloying, Non-mag. disorder : ***Nature 08***
   TSS survive various bulk, surface doping, annealing disorders etc.
2. FS encloses **odd** no. of Dirac points (**1/4 Graphene**): ***Nature Phys 09***
3. Spin-Linear Momentum Locking (**Helical Fermions**): ***Nature 09***

   Room temperature topological order demonstration.
4. **Berry's phase** π around the Dirac cone pocket : ***Science 09***

   Nearly 100% spin polarized, Spins lie mostly in plane
5. Opposite to Anderson Localization ("**Anti-localization**"): ***Nature 09***
   STM(A.Y.)+Spin-ARPES(Z.H.) → Absence of backscattering
6. Dirac node is destroyed if TRI is broken (**Doping effect**): ***Nature 09***
   Magnetic impurity on the surface makes it a band insulator
7. **New platform** for topological quantum phenomena: ***NatureMat 10***
8. Magnetic doping on Topological Ins : ***Nature Phys 10***
9. Superconductivity in doped TI (**Superconduct**): ***Nature Phys 10***
10. New classes of Topological Ins (**New topo insulators**): ***Preprint 11***

Overview of this talk:

- **A new experimental approach to Topological phenomena**

- **Topological Insulator A new quantum phase of matter has been identified (bulk Topological-Insulator) whose surface is a** new type of 2DEG **(spin-momentum locked ½ Dirac gas) protected by time-reversal symmetry.**

  Bulk Insulating samples are now realized.

- Topological Phase Transition Spin-texture and half Dirac gas is one-to-one correlated with a topological (quantum) phase transition

  Bulk-boundary correspondence

- Superconductivity & Magnetism in Topological Insulators leading to new physics of competing order : Broken symmetry vs. Topo Order

- **Topological Superconductor** some results but more work..

Reviews summarizing our works along with theory:

M.Z.H. and C.L. Kane, Rev. of Mod. Phys. 82, 3045 (2010)

M.Z.H. and J.E. Moore, Ann.Review of CondMat Phys. 2, 55 (2011)

Physics/Experiments Team

D.Hsieh, D.Qian, L.A.Wray, Yuqi Xia, SuYang Xu, MZH

Alexei Fedorov
at LBNL-ALS
J.H. Dil et.al.,
J. Osterwalder
at SLS/PSI (Zurich),
E. Vescovo (BNL
-Brookhaven)
J.Xiong & NP Ong
(transport measurements)
(Princeton)

Bulk Crystals & Chemistry: S. Jia, Y. Hor, R.J. Cava (PU-Chem)
MBE samples: N. Samarth (PennState), Chen et.al., (Purdue)
Interface/Heterostructures : S. Oh (Rutgers)

LDA/Numerics: H. Lin, A. Bansil (NEU)

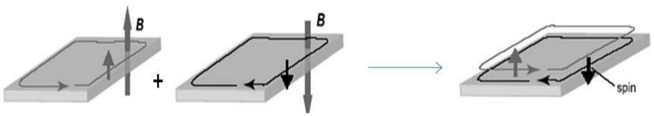
Topological Surface States

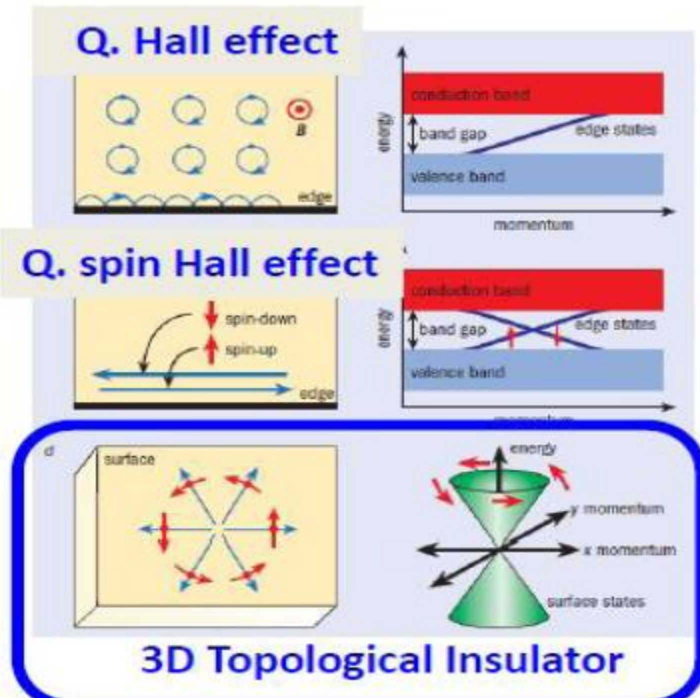
Topological insulators

This newly discovered phase of matter has become one of the hottest topics in condensed-matter physics. It is hard to understand – there is no denying it – but take a deep breath, as **Charles Kane** and **Joel Moore** are here to explain what all the fuss is about

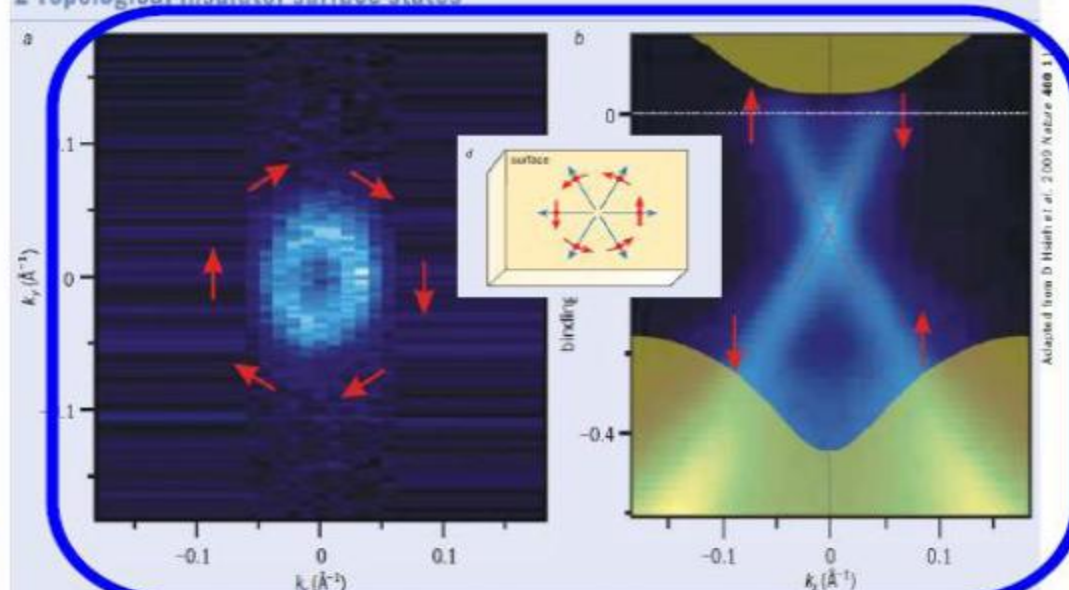
The first 3D topological insulator to be probed in this way was the semiconducting alloy bismuth antimonide (Bi_xSb_{1-x}), which had previously been predicted theoretically to be a topological insulator. In work published in 2008, a group from Princeton University led

Physics World February 2011





2 Topological-insulator surface states



(a) A Fermi-surface map for the surface of the topological insulator bismuth calcium ... ($Bi_{2-x}Ca_xSe_3$) measured by spin-resolved, angle-resolved photoemission spectroscopy as a function of the surface momentum, k_x an... spin direction precesses with electron momentum around the circular Fermi surface, and opposite momenta have opposite spin. (b) Th... e bands intersect at a "Dirac point" marked by the cross that is inside the bulk band gap at approximately 0.25 eV. The calcium concent... x, is tuned so that the Fermi energy lies between the

Experimental discovery

The first 3D topological insulator to be probed in this

n streaming QuickTime of the whole talk (high bandwidth).
right-click to

Novel Phases and Topological Excitations in Systems with Unusual Symmetries

File Edit View Window Help

KITP Mott Materials, 24 Oct 2007 10:30

Novel Phases and Topological Excitations in Systems with Unusual Symmetries

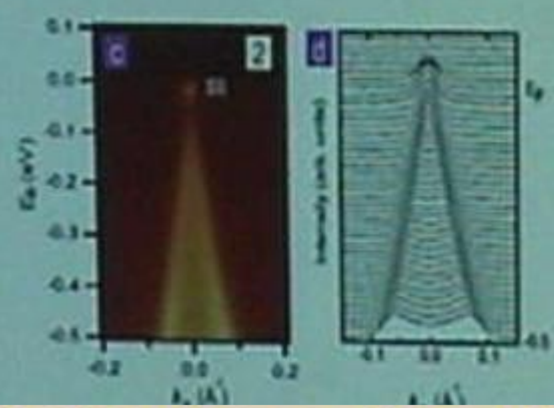
Zahid Hasan, Princeton

http://online.itp.ucsb.edu/online/motterials07/hasan/

A new Dirac point in condensed-matter

Bi(Sn)Sb thermoelectrics

Dirac-y physics beyond Graphene



Protected Surface States
= New 2DEG

KITP Mott Materials, 24 Oct 2007 10:30

Novel Phases and Topological Excitations in Systems with

Experimental Challenge:

How to experimentally "measure" topological invariants that do not give rise to quantization of charge or spin transport

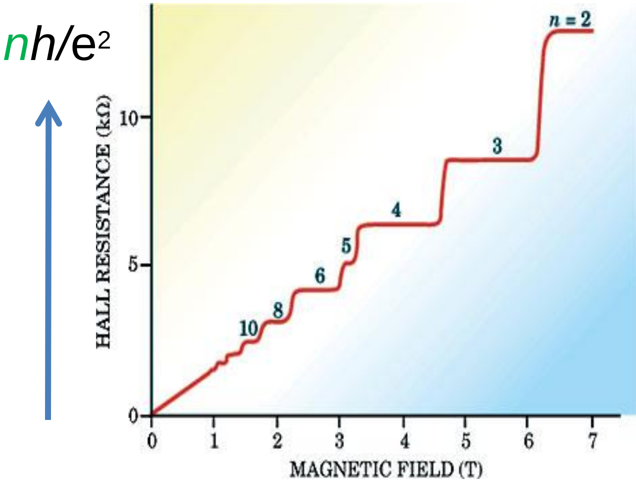
cannot be done via transport in Z2 topological insulators
(transport is still interesting and becoming possible)

Experimentally IMAGE (see) boundary/edge/surface states
Experimentally Probe BULK--BOUNDARY CORRESPONDENCE
Experimental prove "topological order"

Spectroscopy is capable of probing BULK--BOUNDARY correspondence, Determine the topological nature of boundary/surface states & experimentally prove "topological order"

(Chiral)Topological Insulator in 2D: Quantum Hall State

Thouless et.al, ('82)



Hall conductance:

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

n = Chern no. (**Edge** states)

Topological Quantum Number

Chern : Quantum version (Hilbert space) of Gauss-Bonnet formula

Topological Property

$$n = \frac{1}{2\pi}\int_{BZ} [\nabla_{\mathbf{k}} \times \mathbf{A}(k_x, k_y)]_z d^2\mathbf{k}$$

Berry curvature

$$\mathbf{A} = -i\langle u_{\mathbf{k}}|\nabla_k|u_{\mathbf{k}}\rangle$$

Electron-occupied **Bulk** bands

Finite n → **topologically "protected" edge-states**

Conventionally, Topological phenomena are probed via transport method (Von Klitzing & others..)
This amounts to measuring Chern numbers ***n*** (since σ_{xy} = ***n***e^2/h)
Chern numbers are the topological quantum numbers (TQN) in original landmark paper by Thouless et.al., (TKNN'82). This was before Berry's '84 paper.

A novel (non-conventional) experimental approach:
In Z2 Topological Insulators, a novel approach is needed since
Transport is not Z2 topologically quantized
In original Kane-Mele-Fu '05-'07 definition, topological order is described by parity based topological quantum numbers (TQN) $\{\nu_0, \nu_1 \nu_2 \nu_3\}$
doing transport is also interesting of course but cannot give us these $\{\nu_0, \nu_1 \nu_2 \nu_3\}$

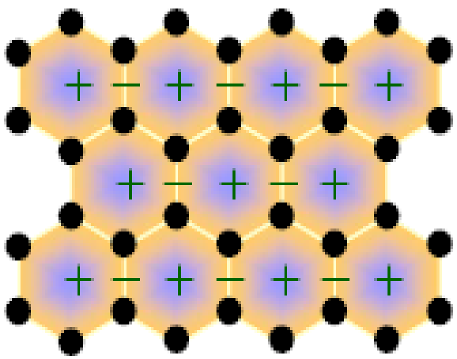
In a series of papers this non-conventional experimental (spectroscopy) approach is demonstrated in general terms for the first time (focus of this talk):

“Quantum Hall Effect” without Magnetic Field?

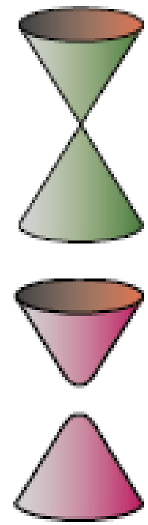
Haldane Model, PRL (1988)

Alternating field but net magnetic flux is zero

Bulk band-structure



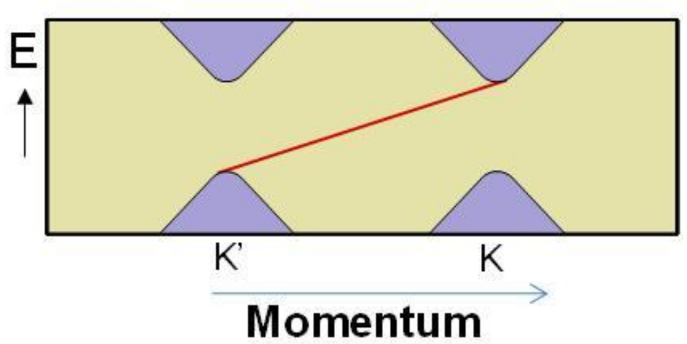
B(r) = 0
Zero gap,
Dirac point



Dirac point

B(r) ≠ 0
Energy gap
$\sigma_{xy} = e^2/h$

Massive Dirac particles



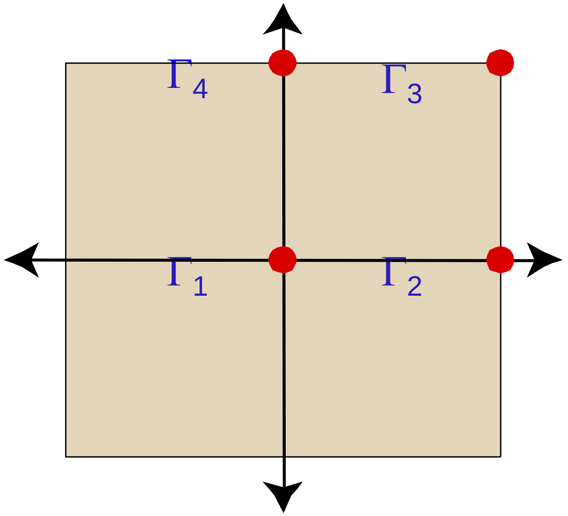
Edge structure

Chiral fermions

Kane & Mele and many others ('05-'09)

Spin-Orbit + Time-Reversal → Topological (Z_2) invariants :

Inversion Symmetry : **Parity of occupied Bloch states** at $\Gamma_{1,2,3,4}$



Bulk Brillouin Zone

$$P\left|\psi_n(\Gamma_i)\right\rangle = \xi_n(\Gamma_i)\left|\psi_n(\Gamma_i)\right\rangle$$

$$\xi_n(\Gamma_i) = \pm 1$$

$$(-1)^{\upsilon} = \prod_{i=1}^{4}\prod_{n}\xi_{2n}(\Gamma_i)$$

$\nu = 0$ or 1

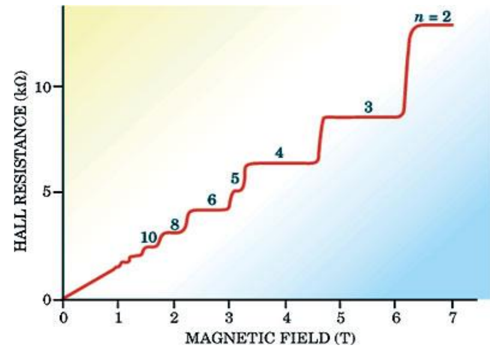
In 3D (8 bulk KPs) there are **4 Z_2 invariants: ($\nu_0 ; \nu_1\nu_2\nu_3$)** Characterizing the bulk. These determine how edge states Connect → 16 topological phases!!

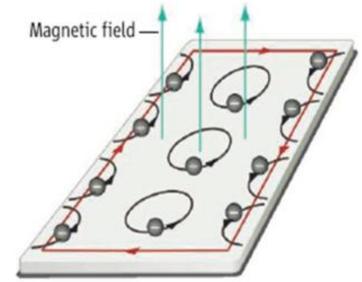
Challenge: How to experimentally "measure" these invariants or topological quantum numbers (ν_i) ?

QHE phases

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

Topological quantum number





Transport → n (Chern no.)

Spectroscopy → $\{\nu_i\}$ [Z_2 qtm no.]

Topo Insulators

$$\nu_o = \Theta/\pi$$

$\Theta=\pi$ (odd)

$\Theta=2\pi$ (even)

<u>No quantized transport</u>

via the Z_2 qtm no.:

$\{\nu_i\}$

Topological quantum number

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

4 TQNs → **16** distinct insulators

?

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

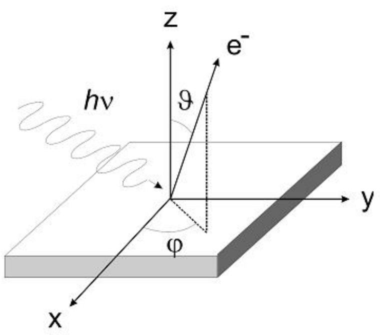
Topological "Order Parameters"

Spin-sensitive

Momentum-resolved

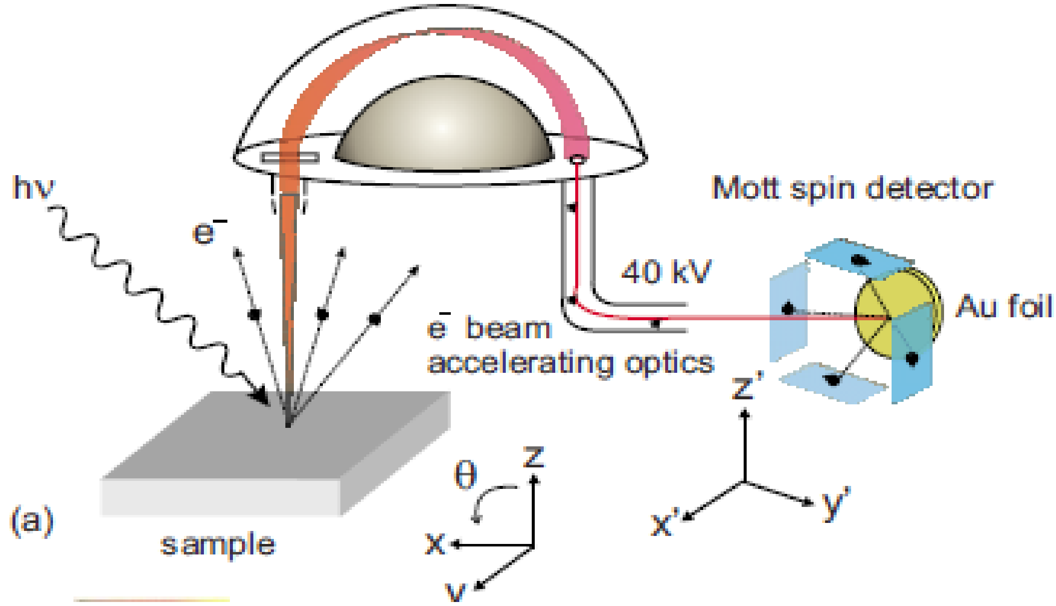
Edge vs. Bulk correspondence

Photoelectric Scattering Process



$$K_x = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\cos\varphi$$
$$K_y = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\sin\varphi$$
$$K_z = \frac{1}{\hbar}\sqrt{2mE_{kin}}\cos\vartheta$$

- By measuring electron intensity as a function of E_{kin}, ϑ and φ, a momentum resolved energy spectrum is obtained



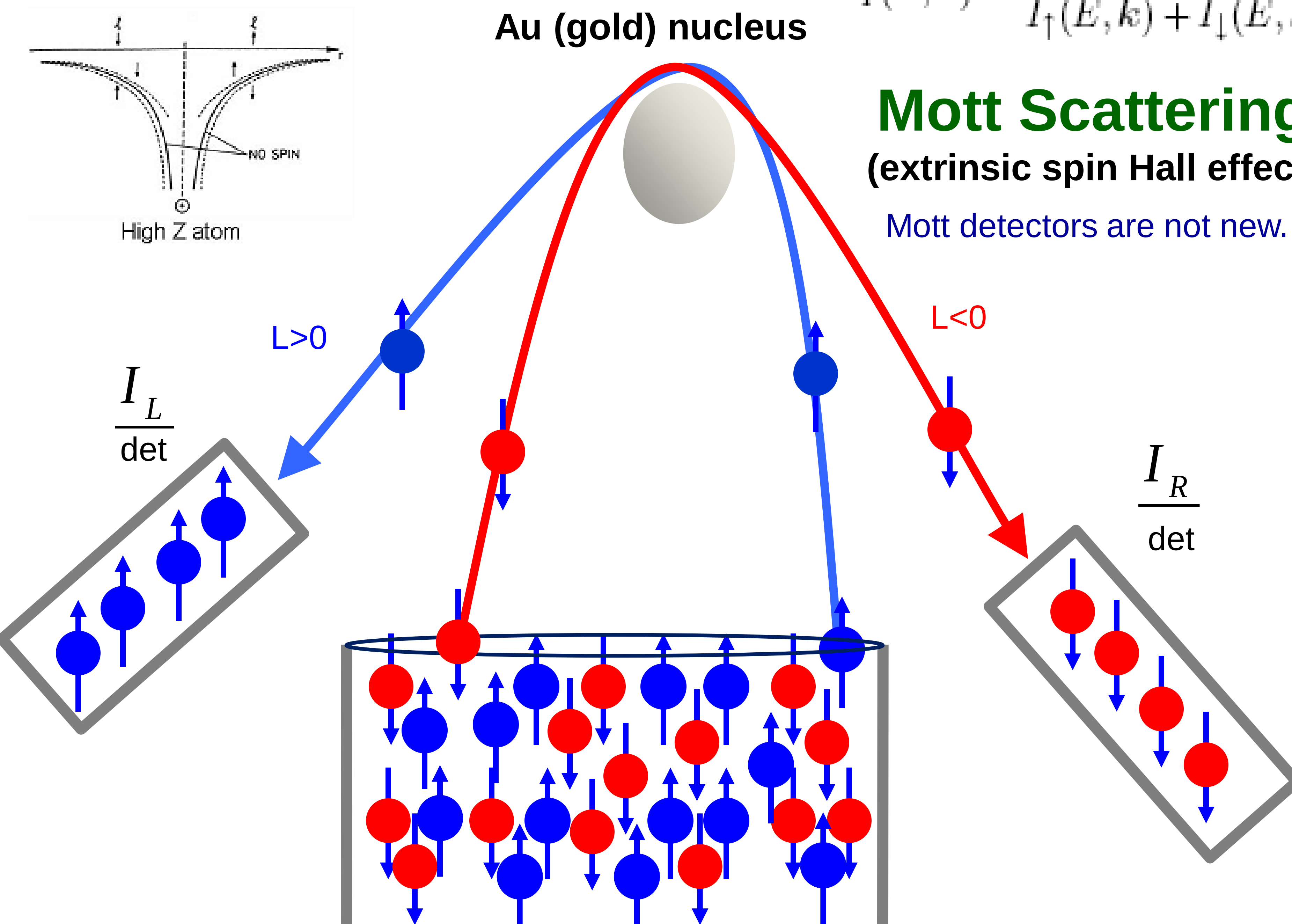
ALS & SLS set-ups (2008)

$$P_I(E,k) = \frac{I_\uparrow(E,k) - I_\downarrow(E,k)}{I_\uparrow(E,k) + I_\downarrow(E,k)}$$

Mott Scattering

(extrinsic spin Hall effect)

Mott detectors are not new.



Challenge:

How to experimentally "measure" topological invariants that do not give rise to quantization of charge or spin transport

cannot be done via transport in Z2 topological insulators
(transport is still interesting and becoming possible)

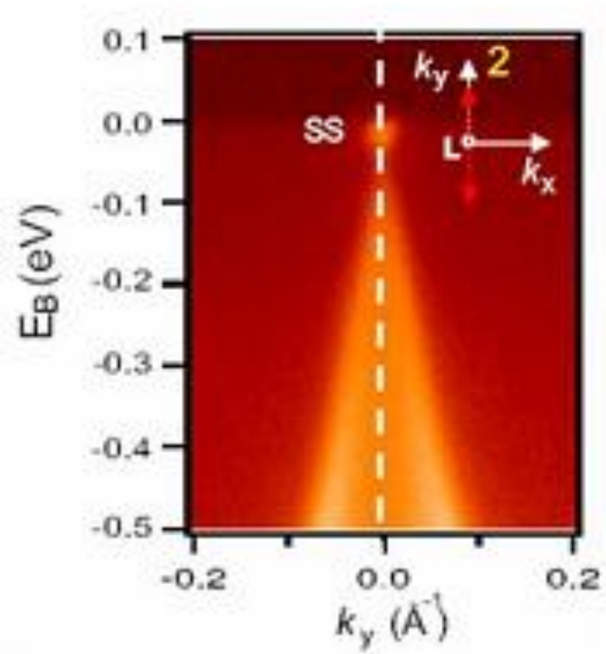
Experimentally IMAGE (see) boundary/edge/surface states
Experimentally Probe BULK--BOUNDARY CORRESPONDENCE
Experimental prove "topological order"

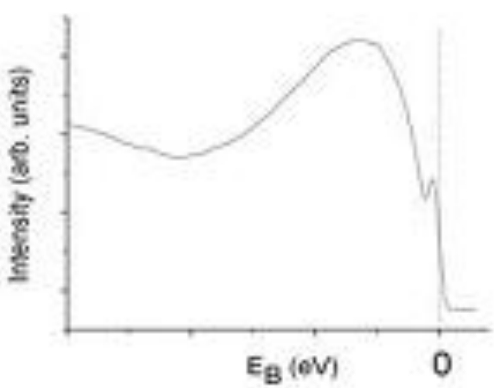
Spectroscopy is capable of probing
BULK--BOUNDARY correspondence,
Determine the topological nature of boundary/surface states &
experimentally prove "topological order"

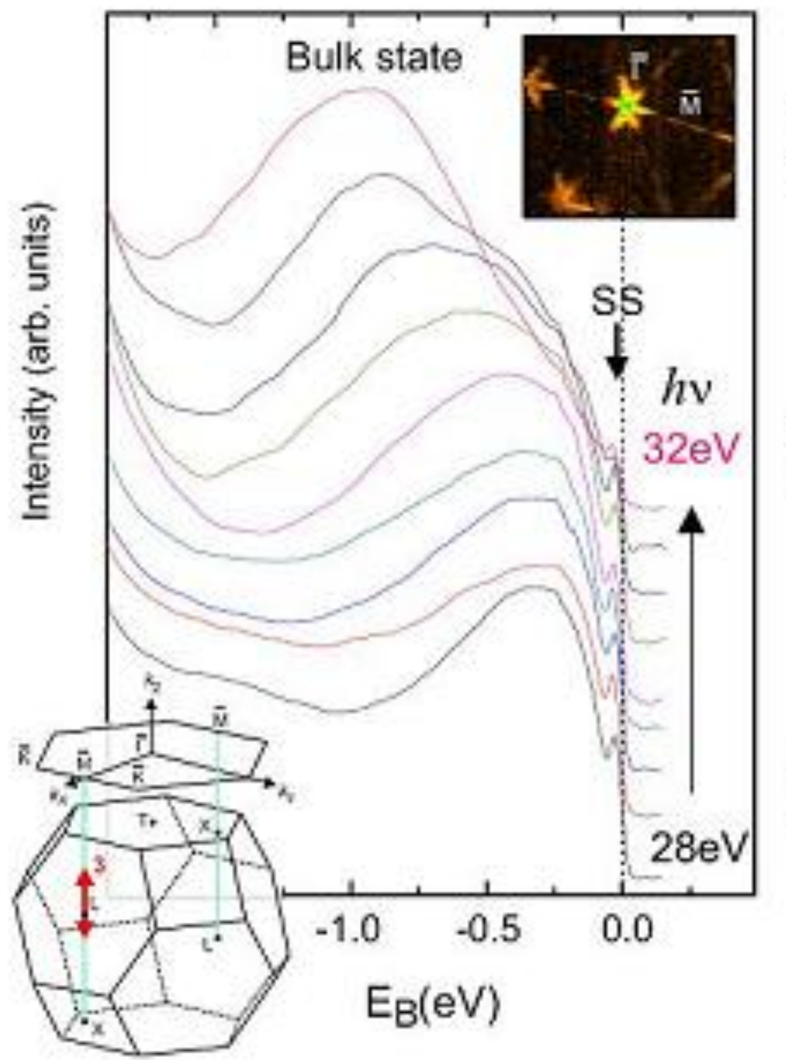
How to isolate intrinsic Bulk(3D) vs. Surface(2D) states ?

Band-structure of Bi(Sn)Sb semiconductors KITP '07

Fu-Kane PRB'07 Prediction: Bi-Sb Z2 non-trivial since Sb is non-trivial but Bi is trivial





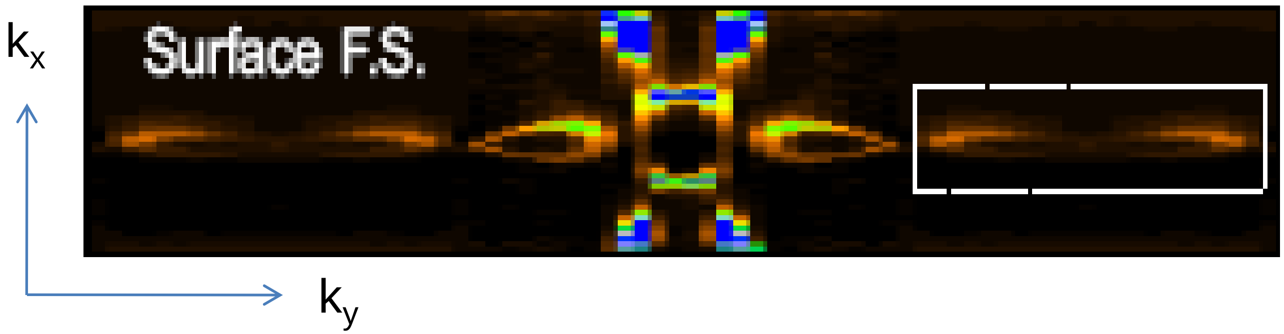


Hsieh et.al., NATURE 08, KITP Proc. (2007)

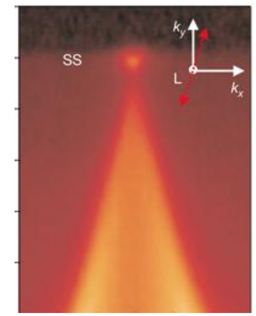
Protected Fermi surface on the surface on an insulator

(first Topological Insulator (3D): Thermoelectric Bi(Sn)Sb alloy semiconductors)

Z2 non-triviality does not predict the actual Fermi surface

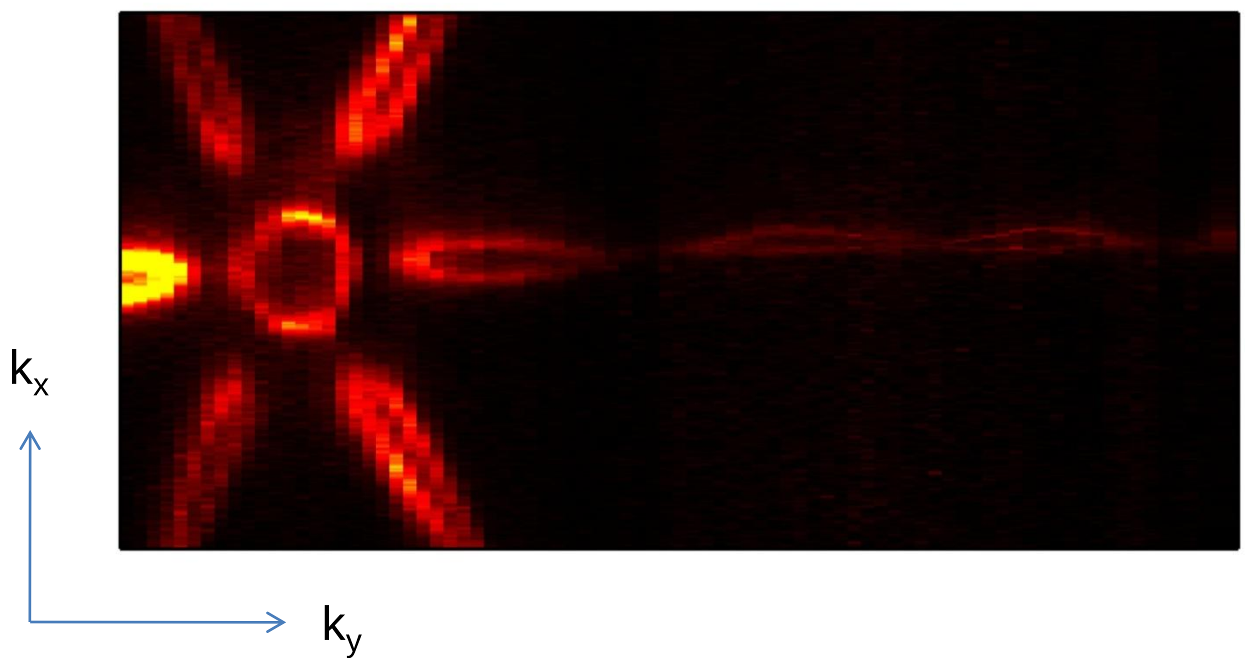


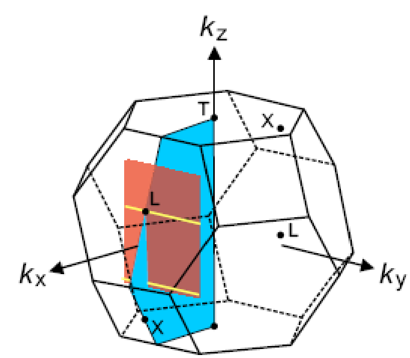
Dirac Fermion



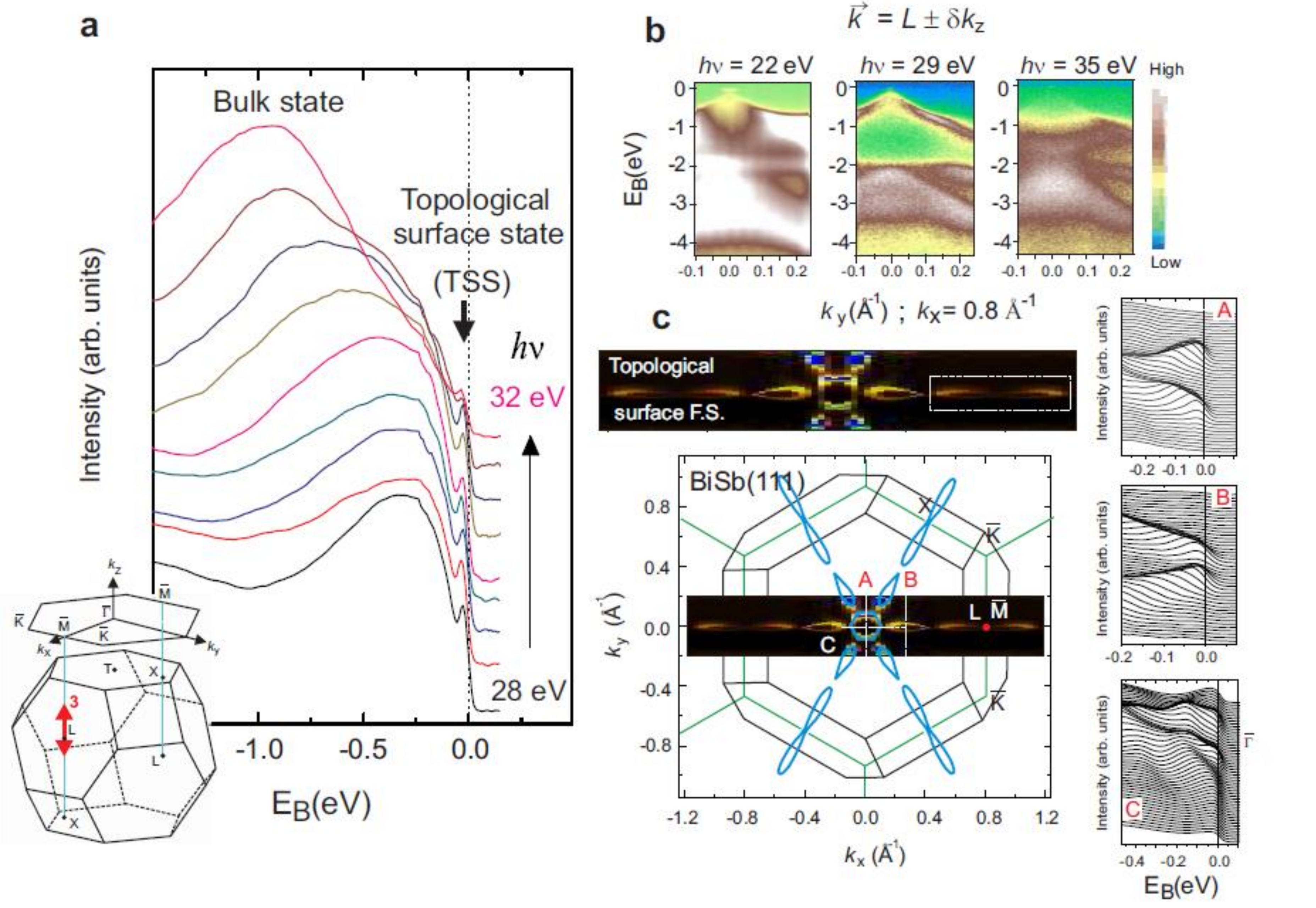
NATURE 08

KITP Proc. 2007



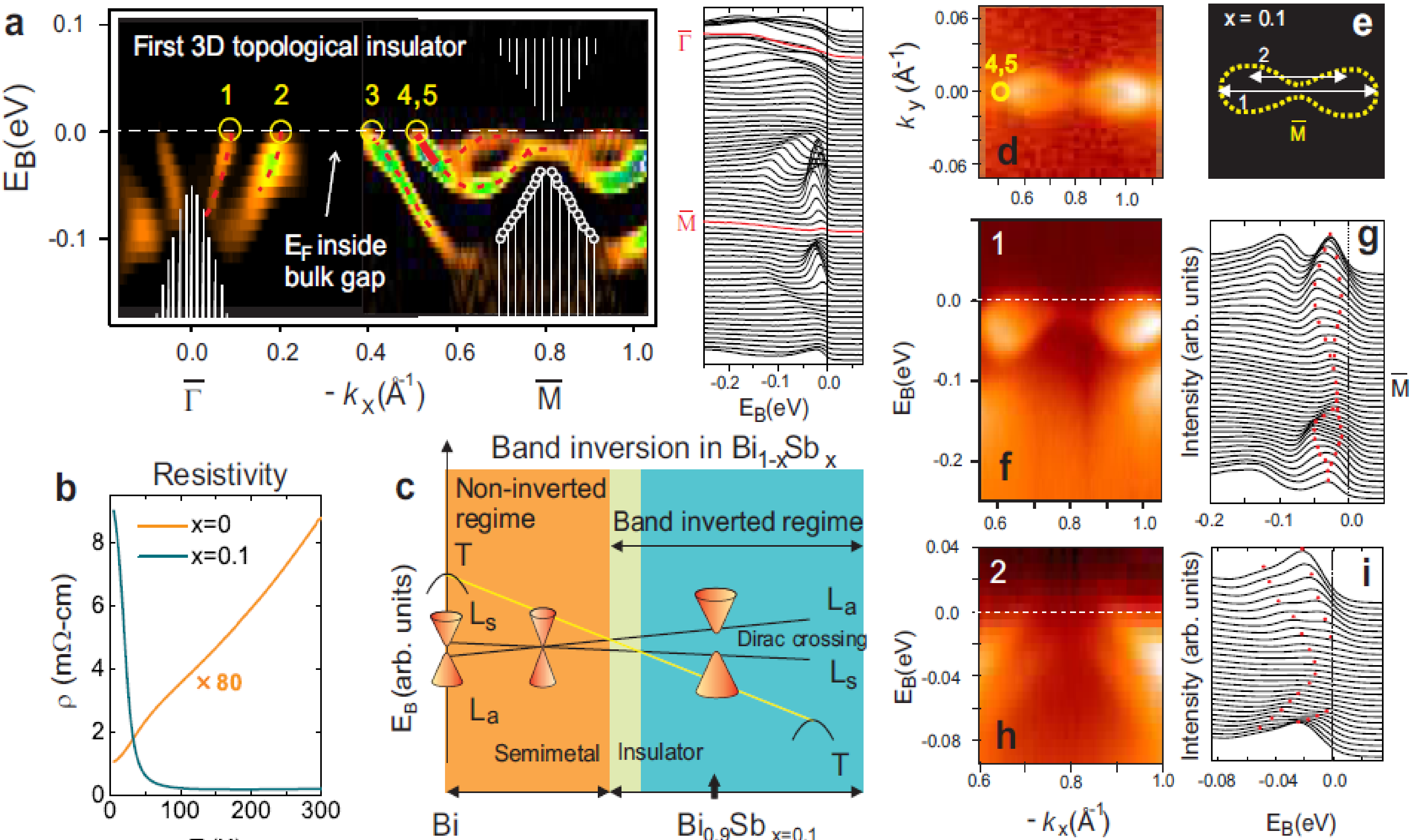


NATURE 08

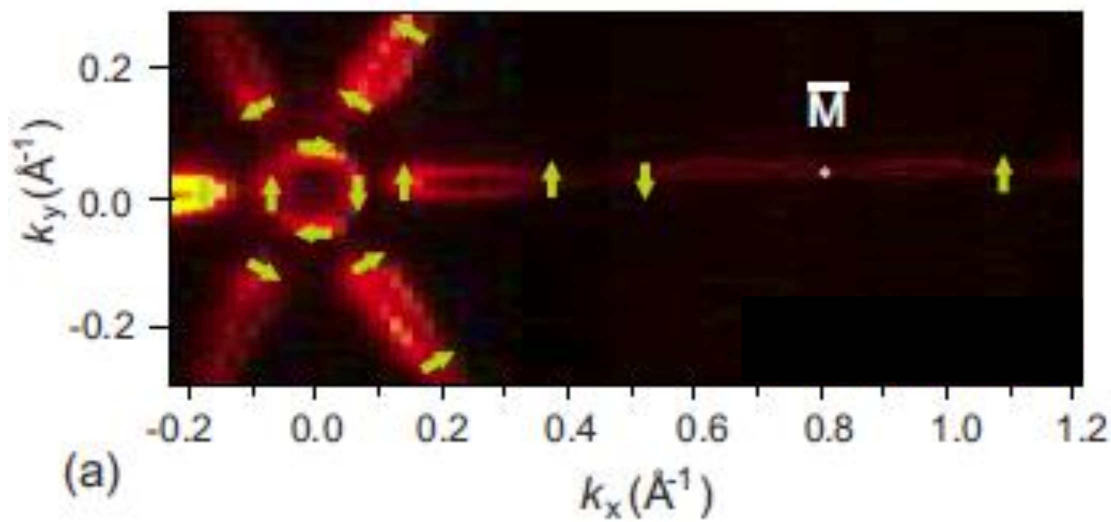


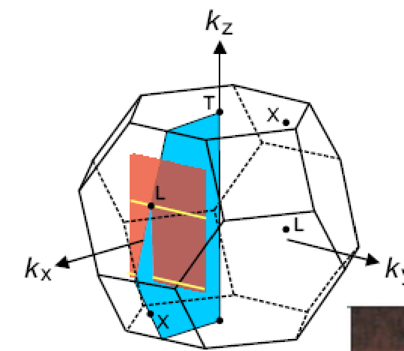
a
Bulk state
Topological
surface state
(TSS)
hν
32 eV
28 eV
Intensity (arb. units)
-1.0
-0.5
0.0
E_B(eV)
b
k = L ± δk_z
hν = 22 eV
hν = 29 eV
hν = 35 eV
High
Low
E_B(eV)
c
k_y(Å^-1) ; k_x = 0.8 Å^-1
Topological
surface F.S.
BiSb(111)
A
B
C
L
M
X
K
k_x (Å^-1)
k_y (Å^-1)
E_B(eV)

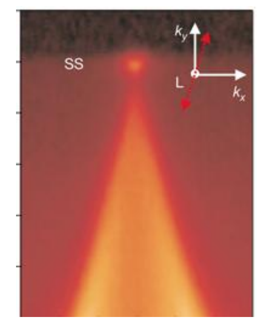
First 3D topological insulator with E_F inside bulk gap

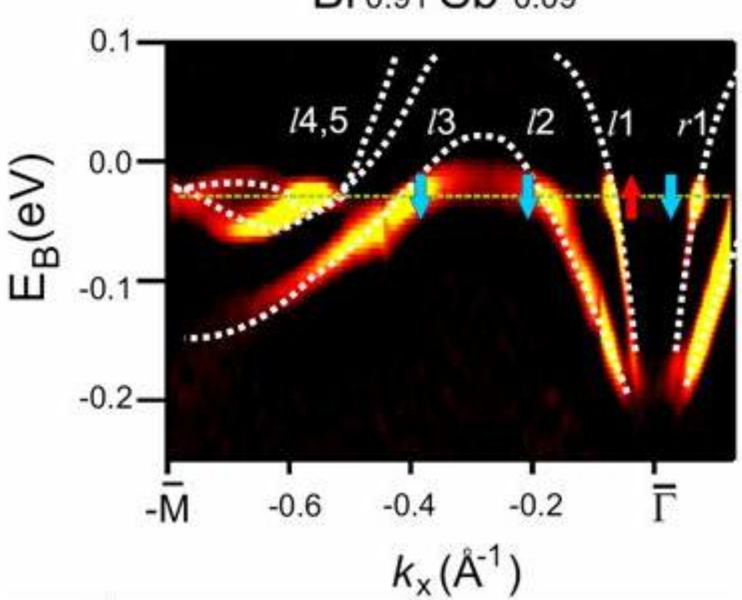


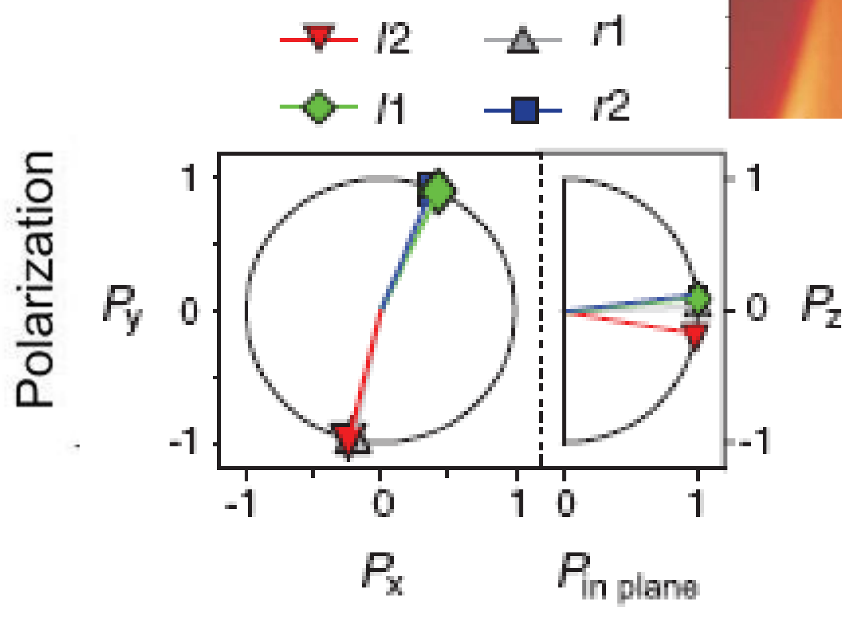
Spin Texture on the Fermi surface



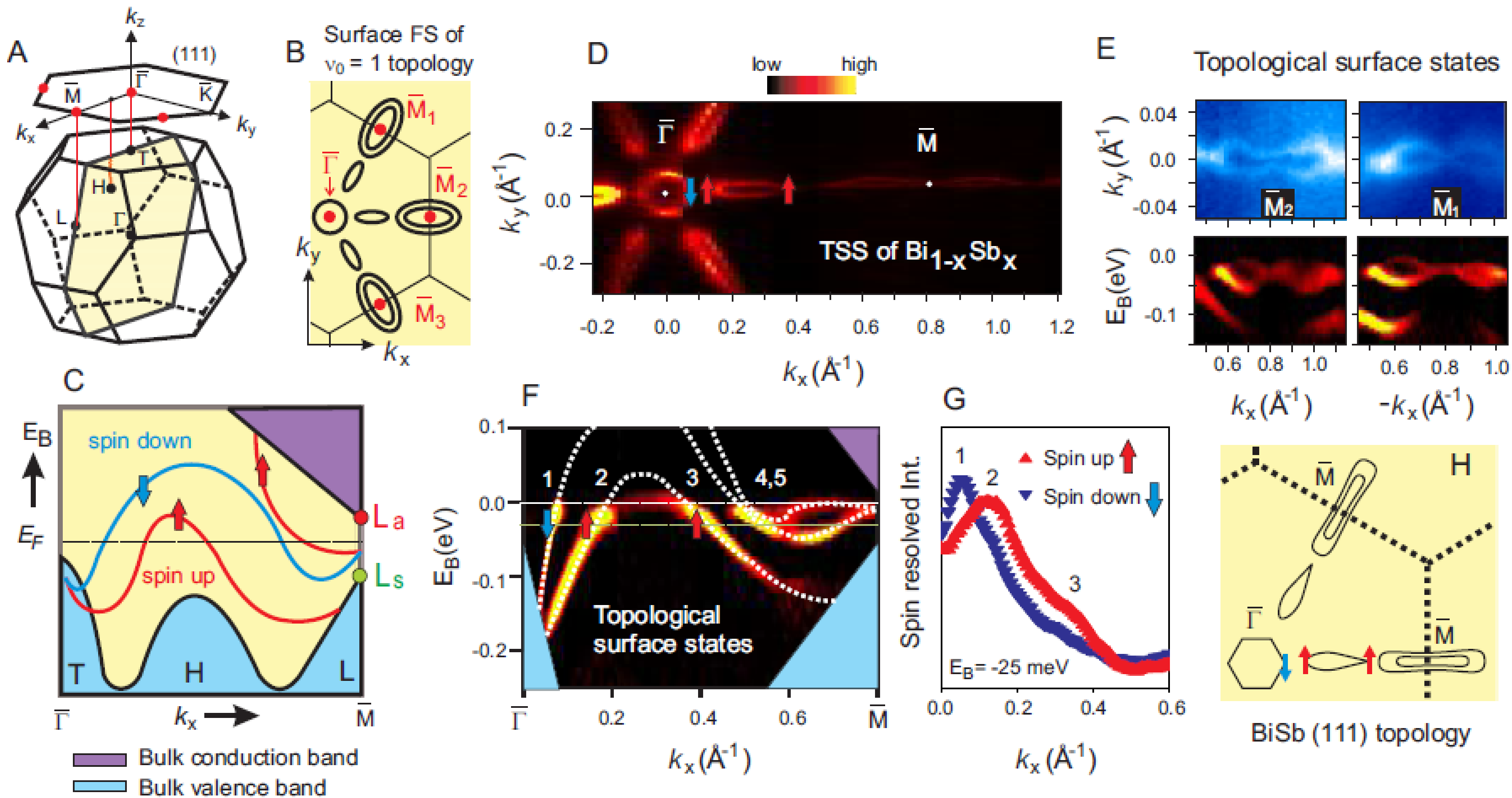




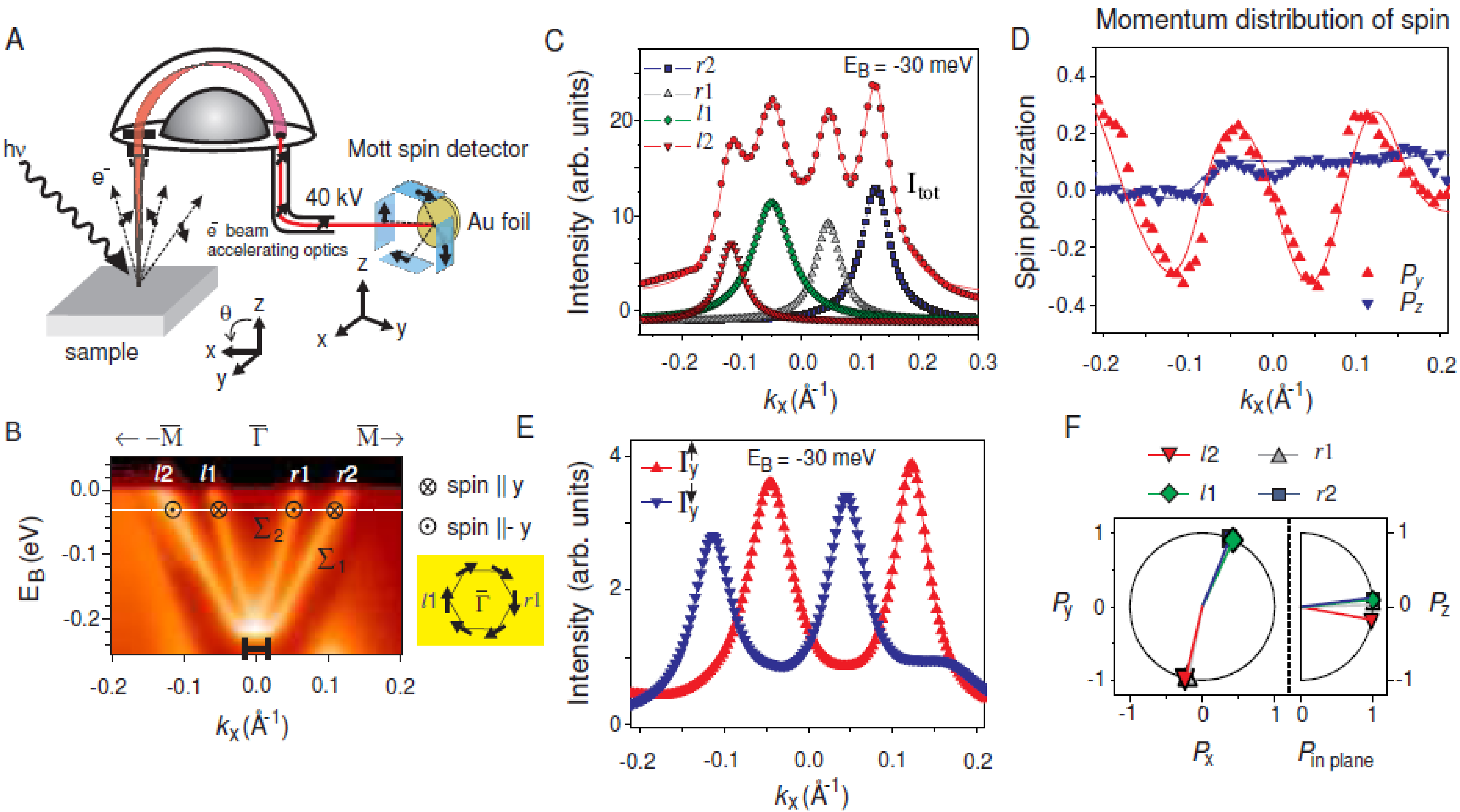




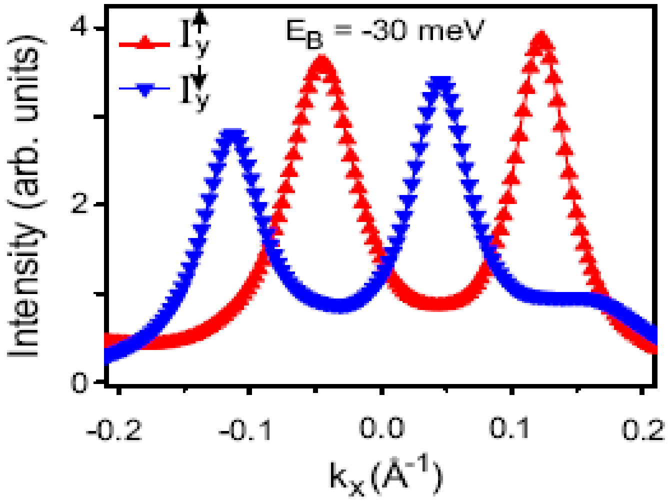
Topological spin textures



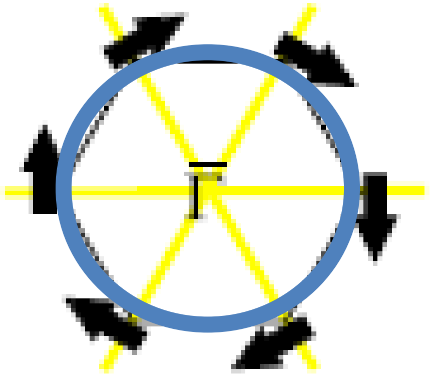
Topological spin textures



Time-Reversal, Spin Chirality & Berry's Phase



Spin-ARPES

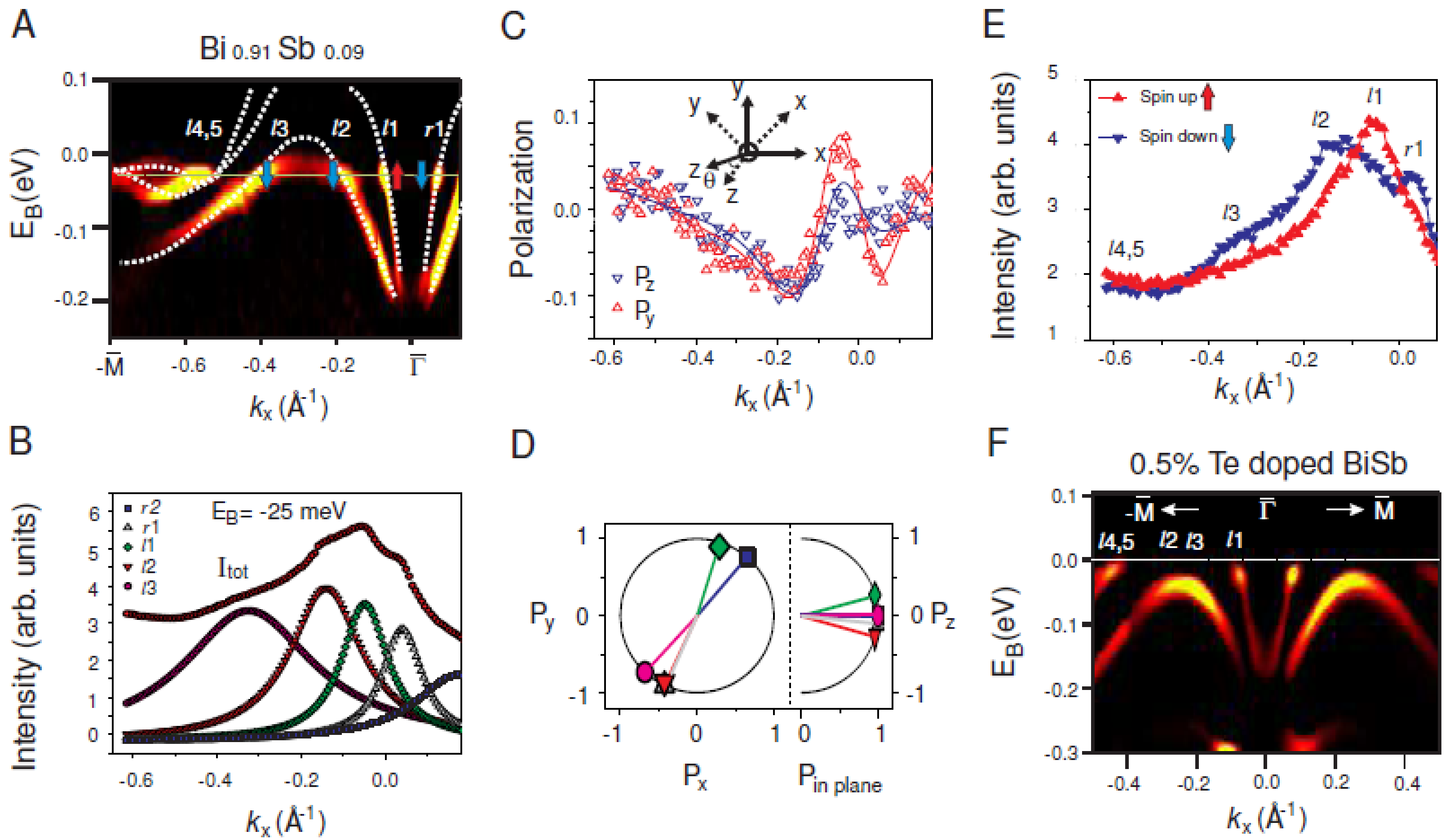


-> Anti-localization

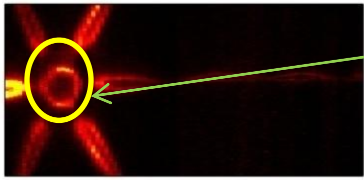
$$e^{i\phi(\Gamma)} = \exp i \oint_{\Gamma} \mathcal{A}_\mu dg^\mu \quad = -1$$

$$\oint_{\Gamma} \mathcal{A}_\mu(\boldsymbol{g}) = -i\langle\Psi(\boldsymbol{g})|\partial_\mu\Psi(\boldsymbol{g})\rangle \sim \pi$$

Topological spin textures

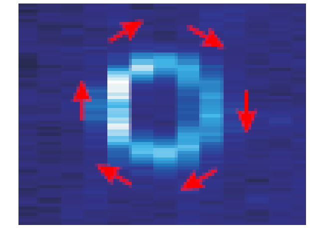


Can we make a large-gap version of TI ?



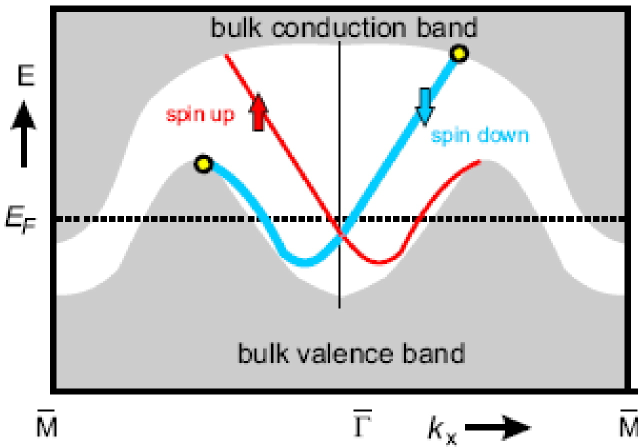
Single Dirac cone **Bi-Sb (2007)**

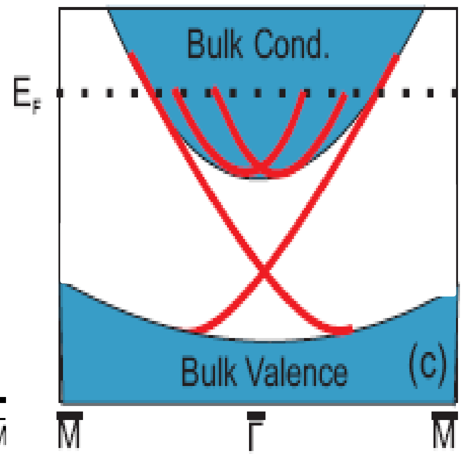
Bi-Sb → Bi2Se3

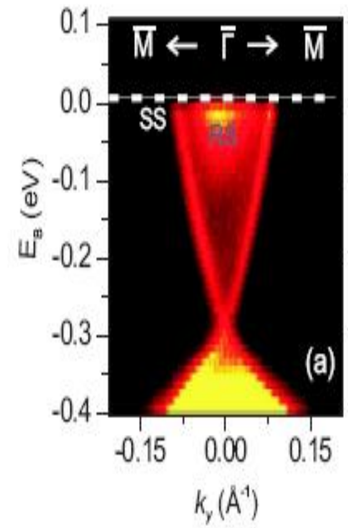


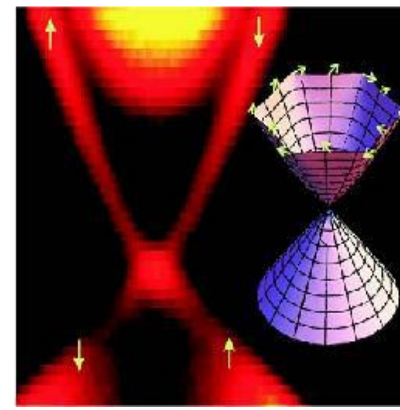
Bi-Sb → Pure Sb

Bi_2Se_3

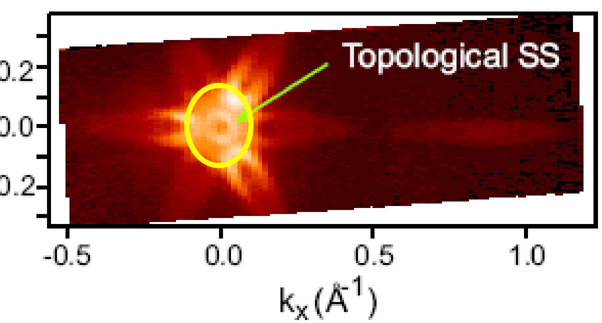








Topology in Bi-Sb [Hsieh et.al., 08]



Bi_2Se_3 class as TIs : KITP Proc. 08

Xia et.al., **NATURE PHYS** 09, arXiv (2008)

Spin (topo order) : **NATURE** 09

Zhang et.al. **NATURE PHYS** 09

Single Dirac cone in (Bi-Sb alloy)

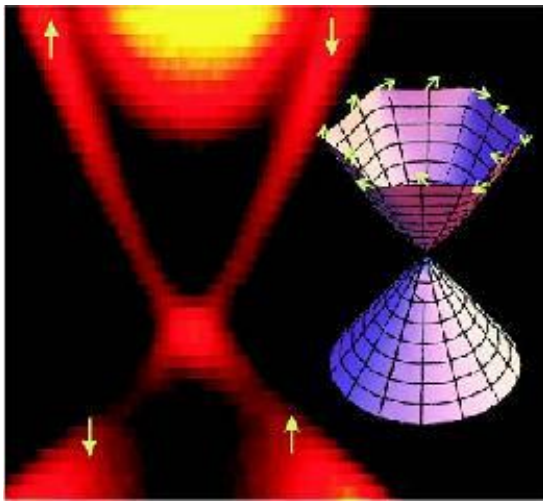
→ Single Dirac cone ONLY in Bi_2Se_3 class

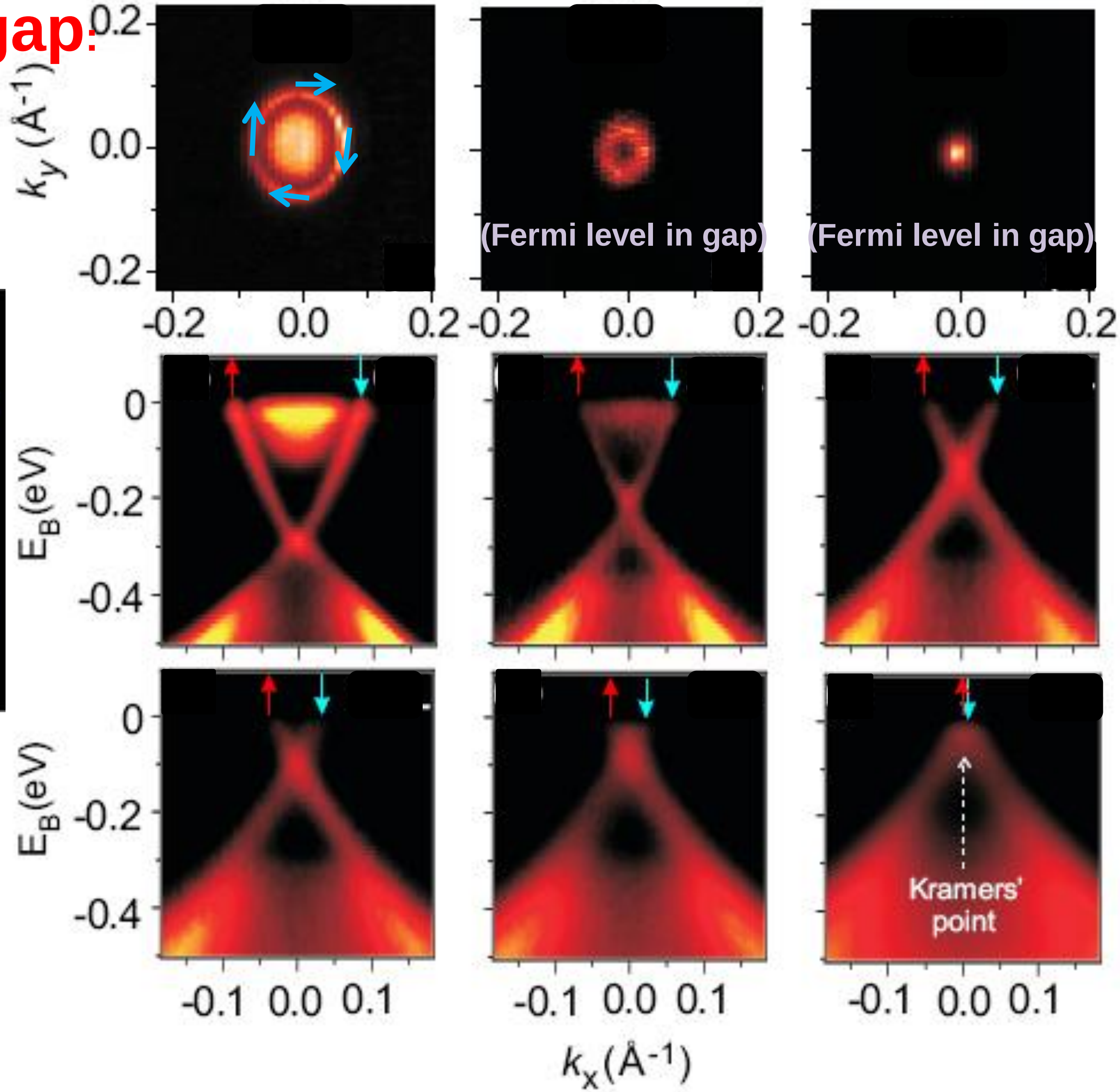
Manipulation & control of TI surface states

Fermi level in gap:

Nature09, Science09

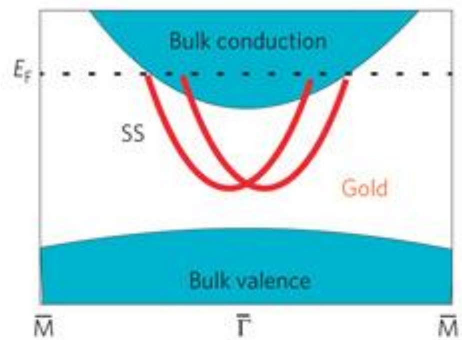
"TOPOLOGICAL Graphene"

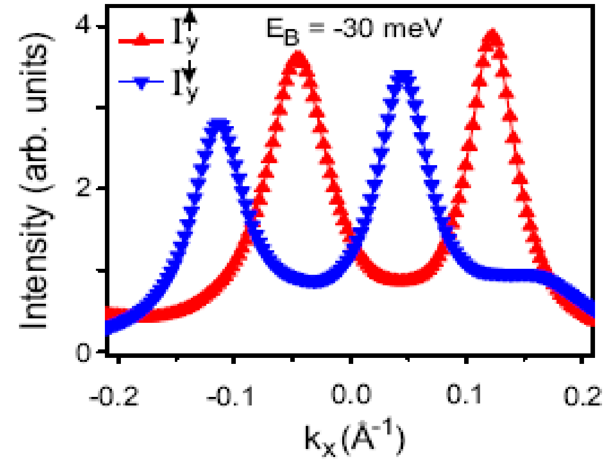




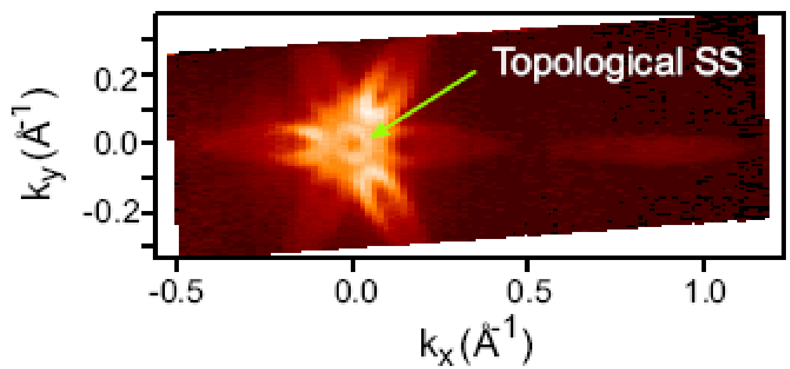
Electrical Gating is also possible

Trivial Surface States (Rashba type)

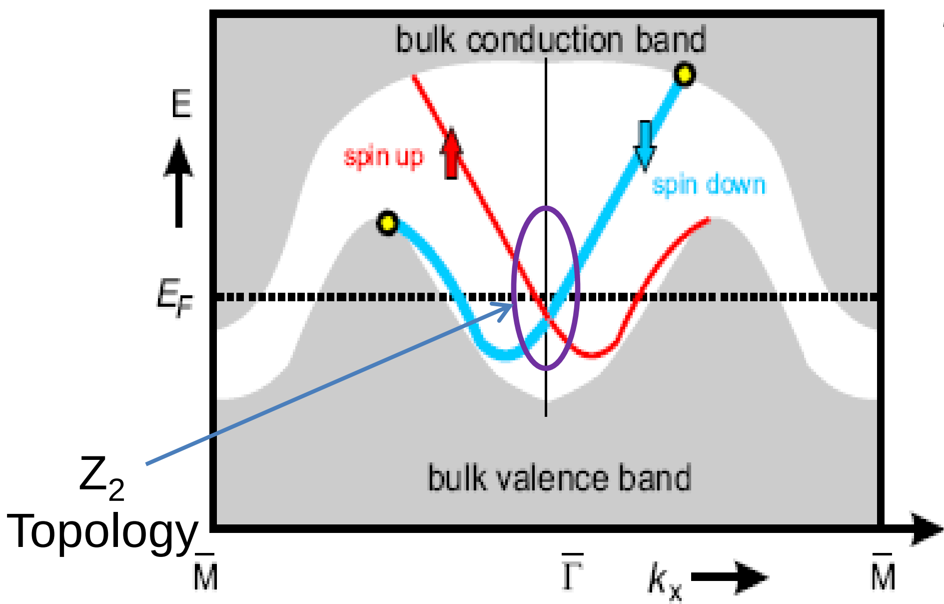


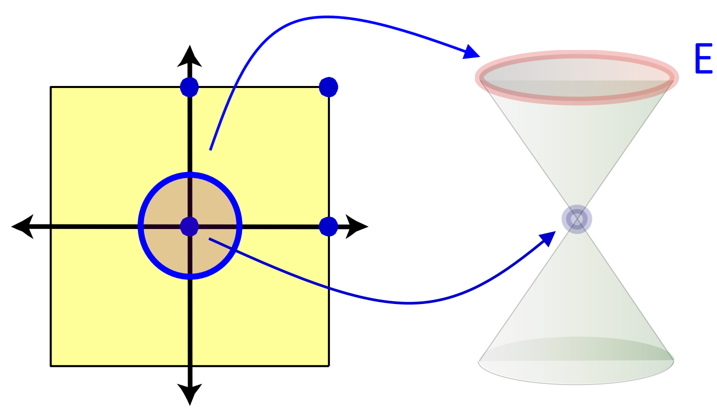


Sb



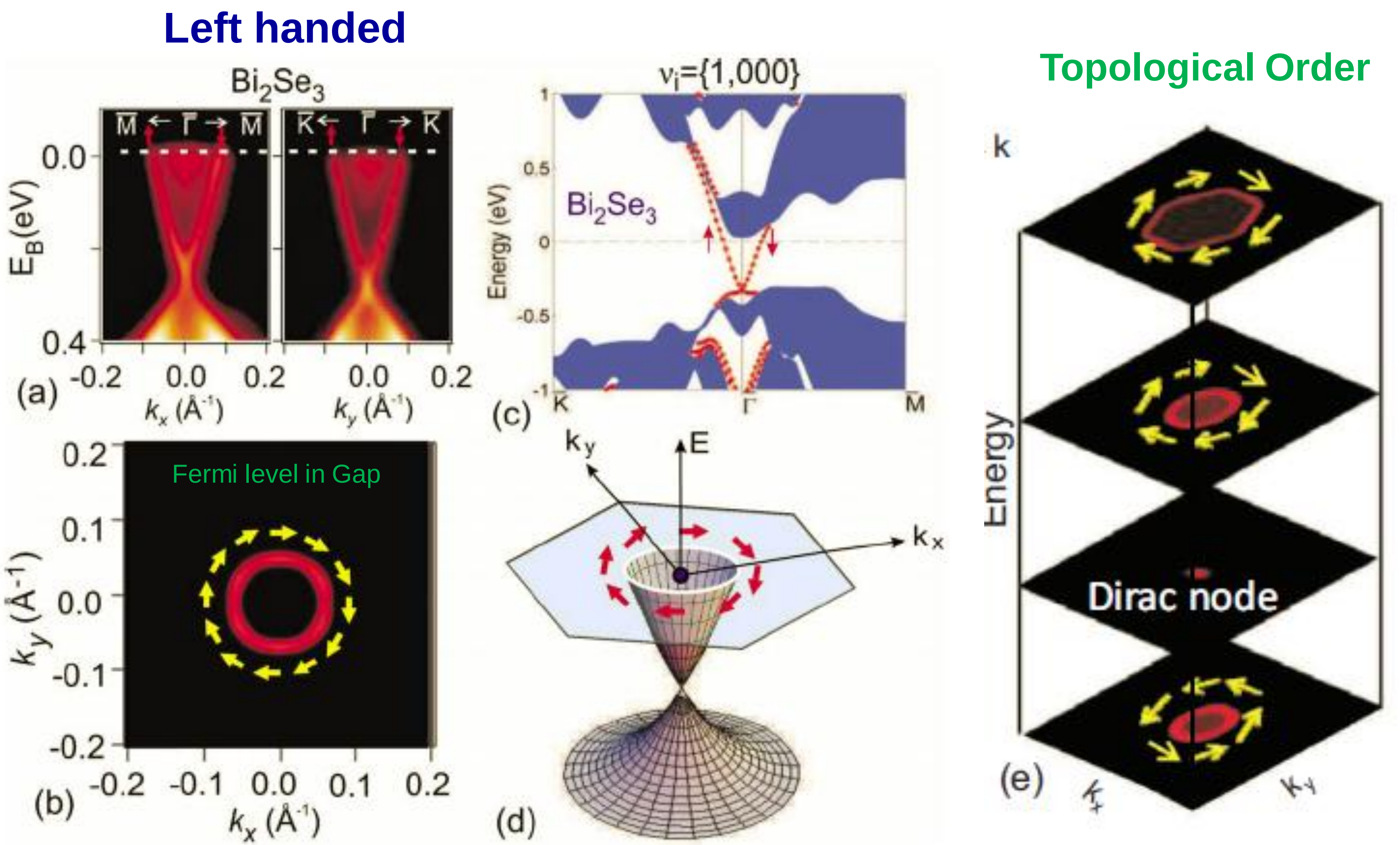
Topological Surface States



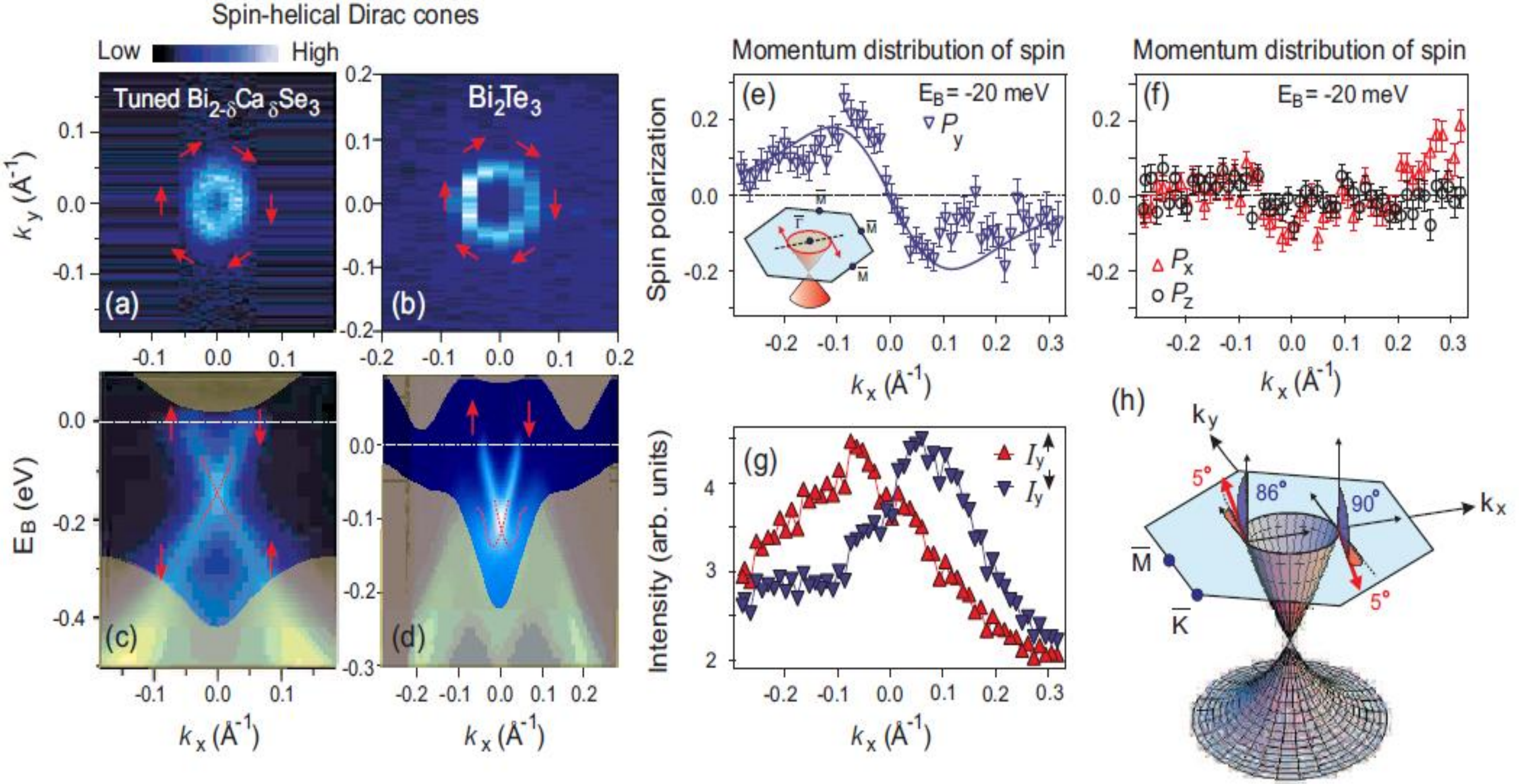


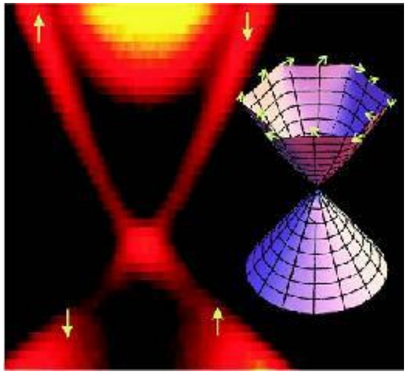
Hsieh et.al., SCIENCE 09

Chirality *inversion* through the Dirac node



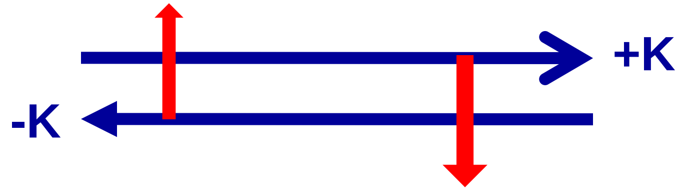
Topological spin textures

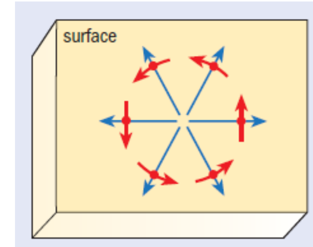


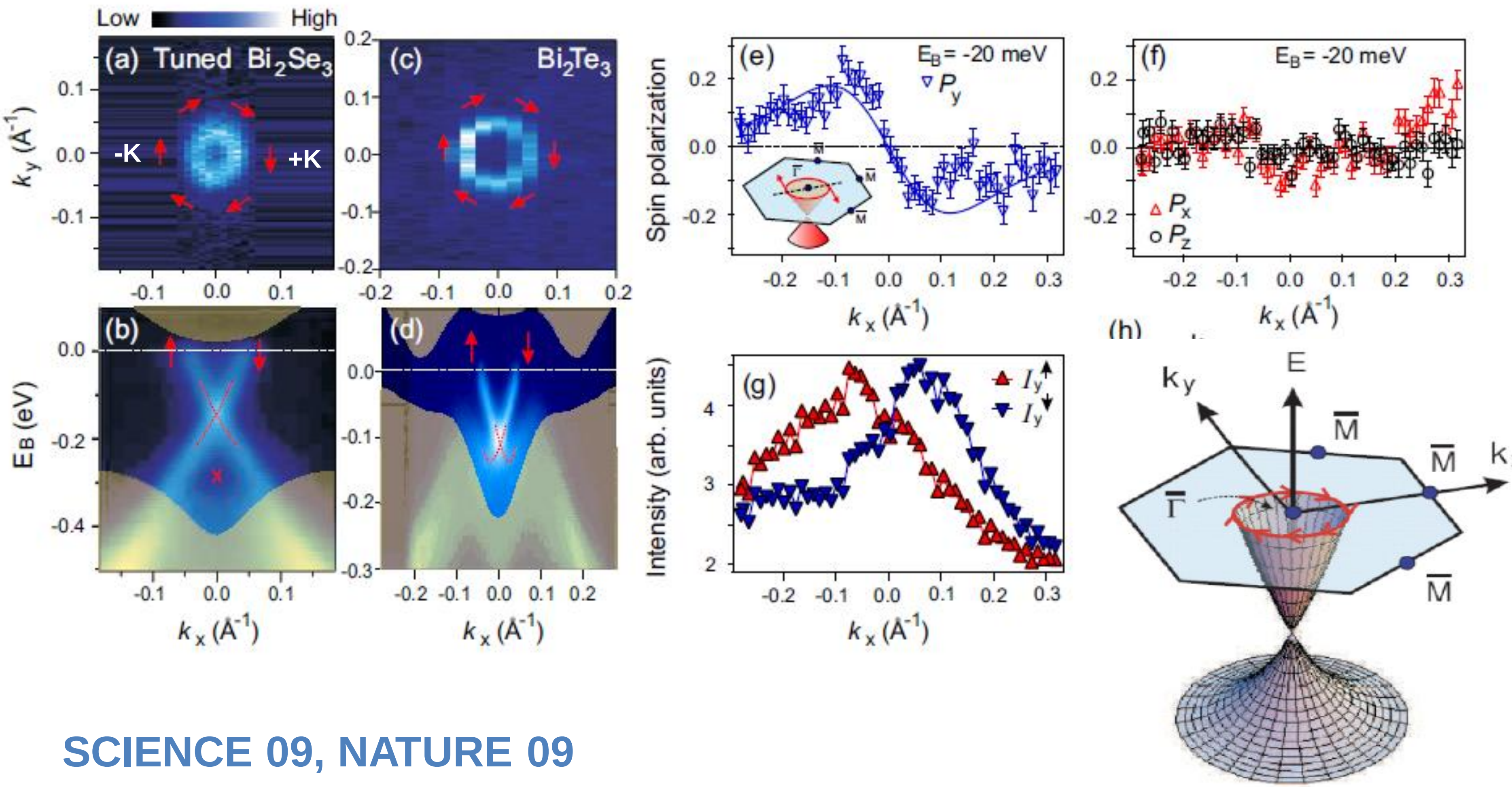


Helical Dirac fermions

One to One Spin-LinearMomentum Locking

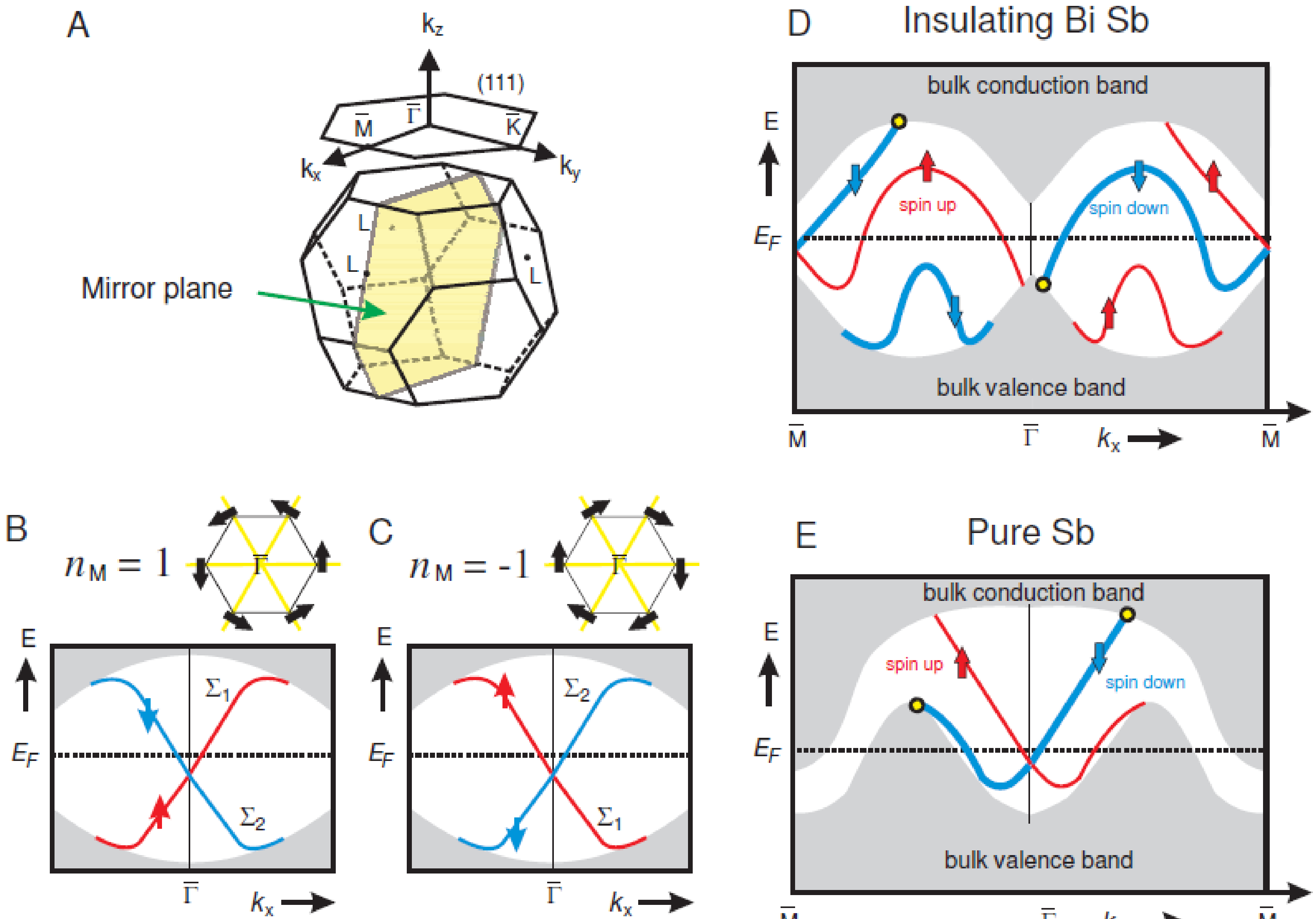






SCIENCE 09, NATURE 09

Measurement of Mirror Chern number

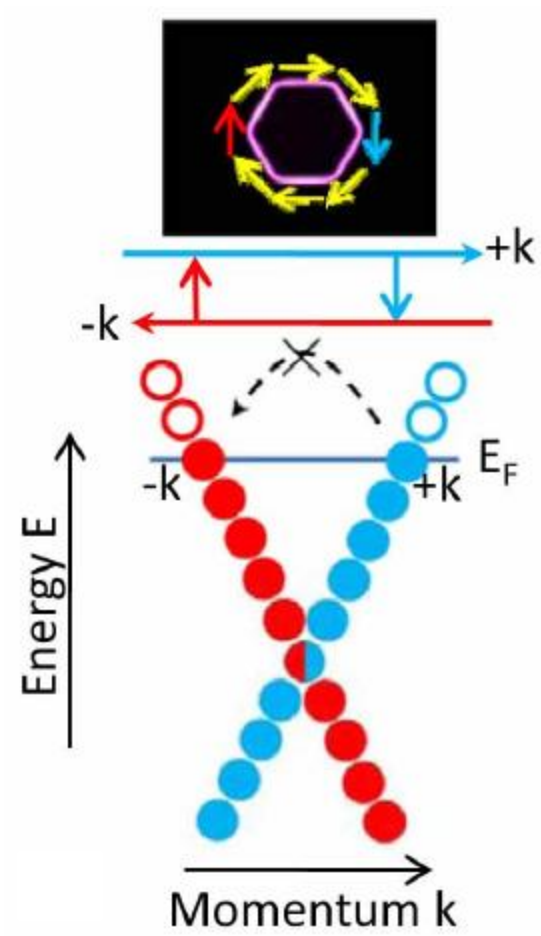


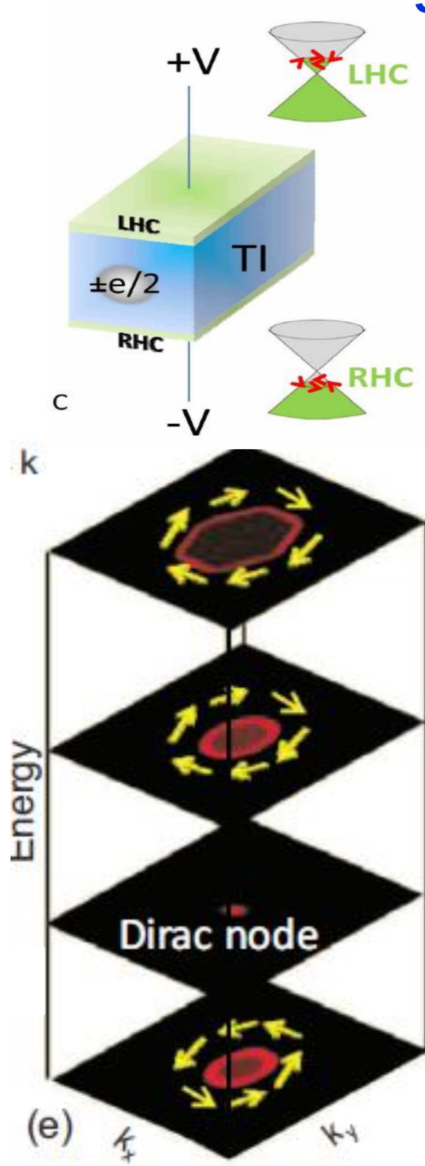
Hsieh et.al., SCIENCE 09

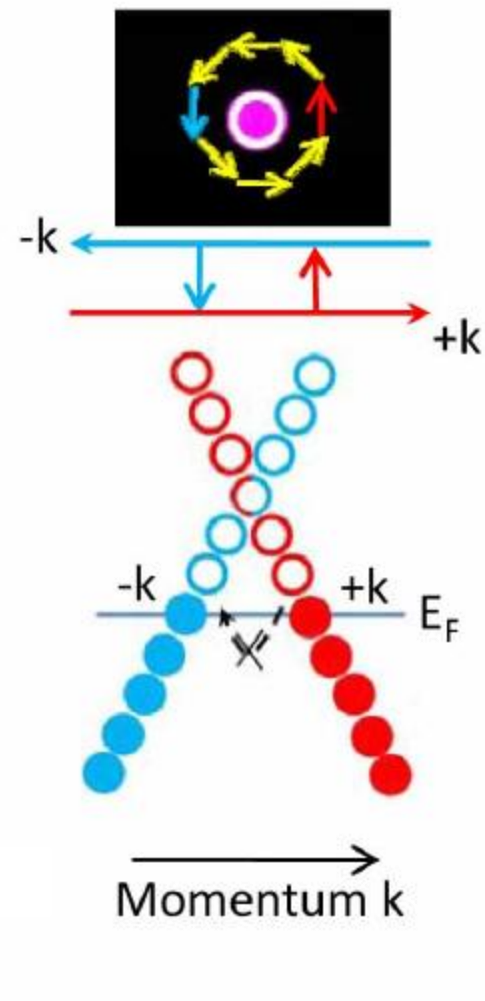
Chirality inversion as a function of binding energy..

SuYang Xu *et.al.*, SCIENCE ’11

Spin-ARPES

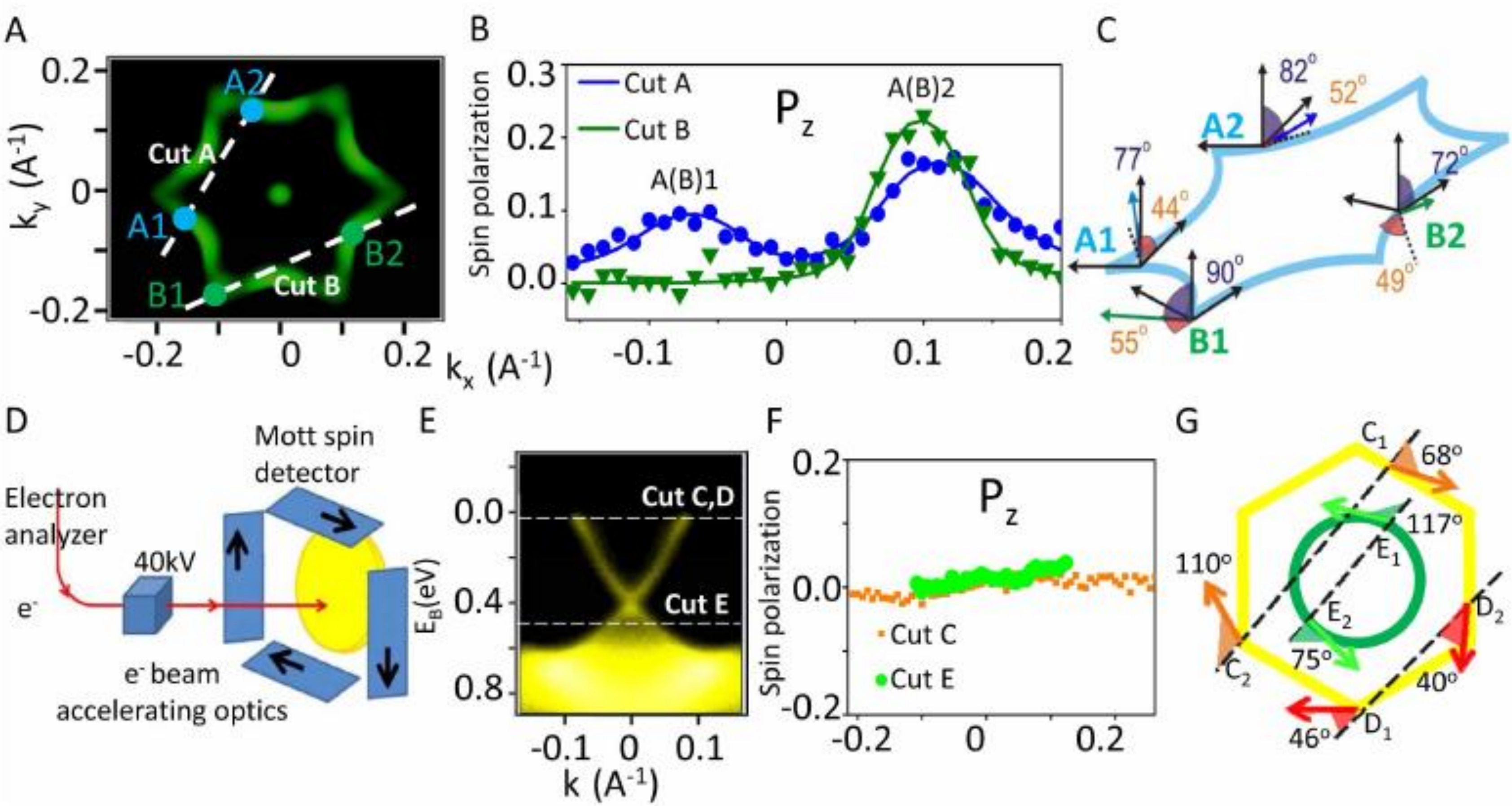


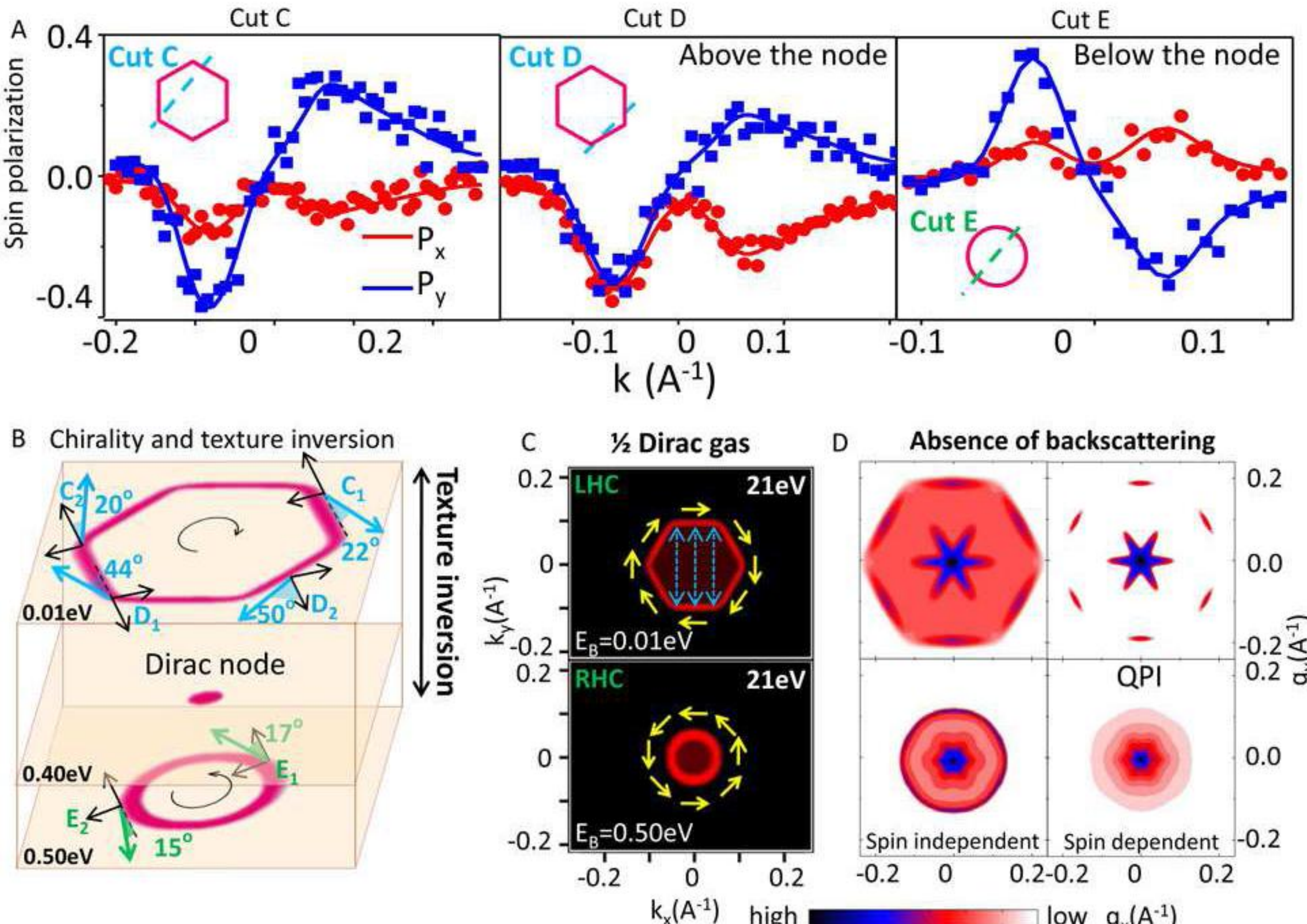




Out-of-plane Spin-Texture

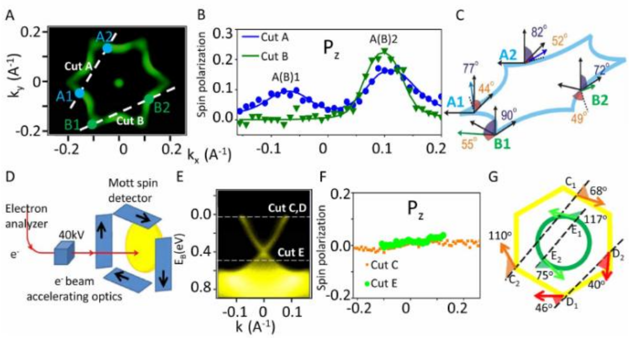
SuYang Xu *et.al.*, SCIENCE

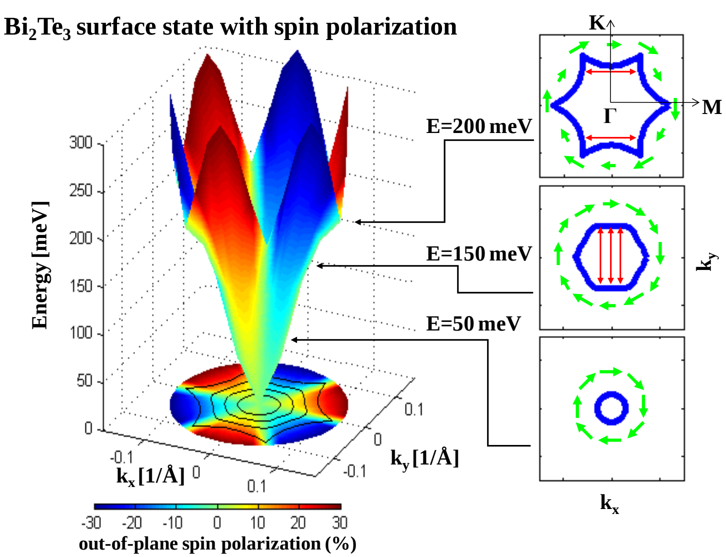


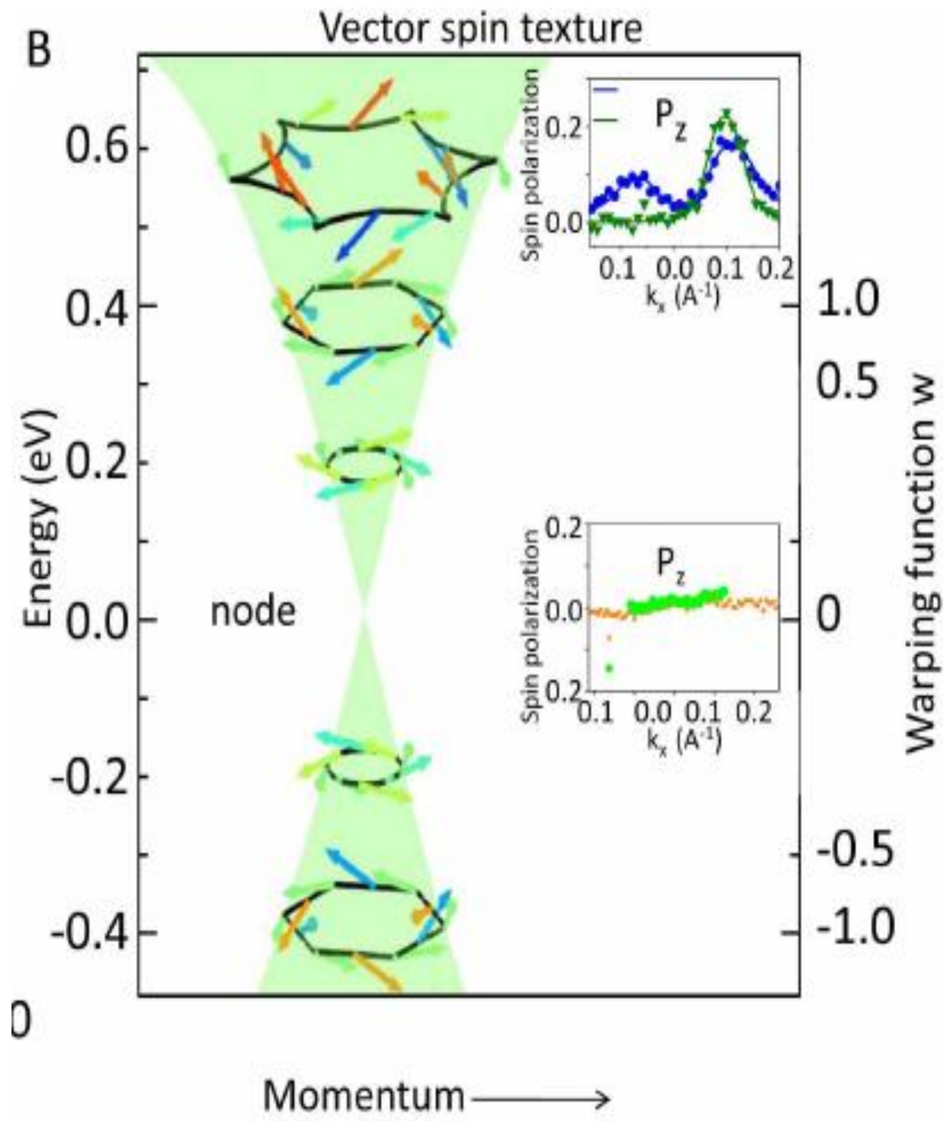

A
Cut C
Cut D
Cut E
Above the node
Below the node
Spin polarization
P_x
P_y
k (A^-1)
B
Chirality and texture inversion
Texture inversion
C_1
C_2
20°
22°
44°
D_1
D_2
50°
0.01eV
Dirac node
17°
E_1
E_2
15°
0.40eV
0.50eV
C
½ Dirac gas
LHC
21eV
E_B=0.01eV
RHC
21eV
E_B=0.50eV
k_y(A^-1)
k_x(A^-1)
D
Absence of backscattering
QPI
Spin independent
Spin dependent
high
low
q_x(A^-1)
q_y(A^-1)

Evolution of Out-of-plane Spin-Texture

3D Vectorial Spin Textures



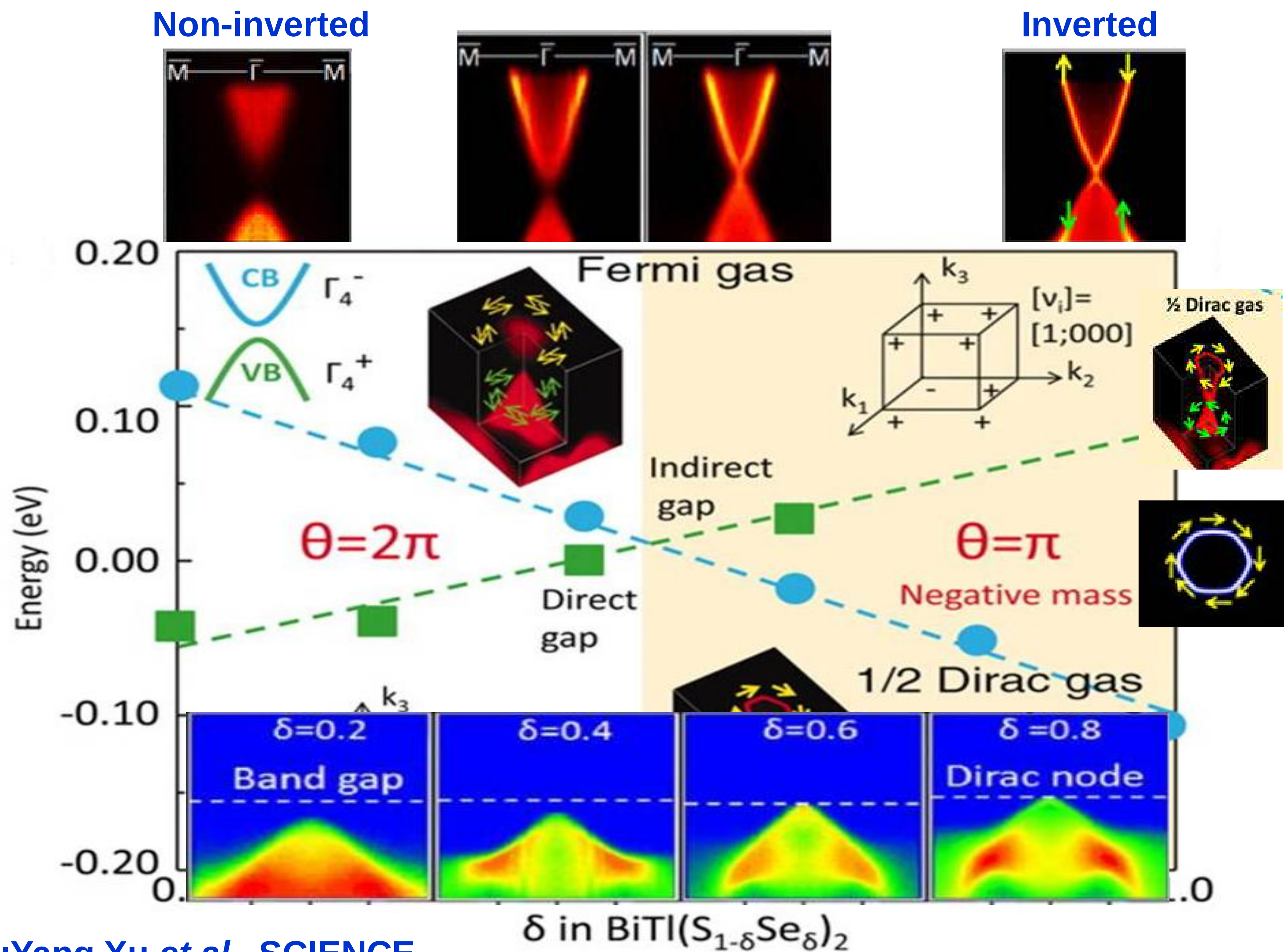




Calculation : MZH, Lin et.al. (2009)

Hsieh et.al., NATURE ‘09, SuYang Xu *et.al.*, SCIENCE ‘11

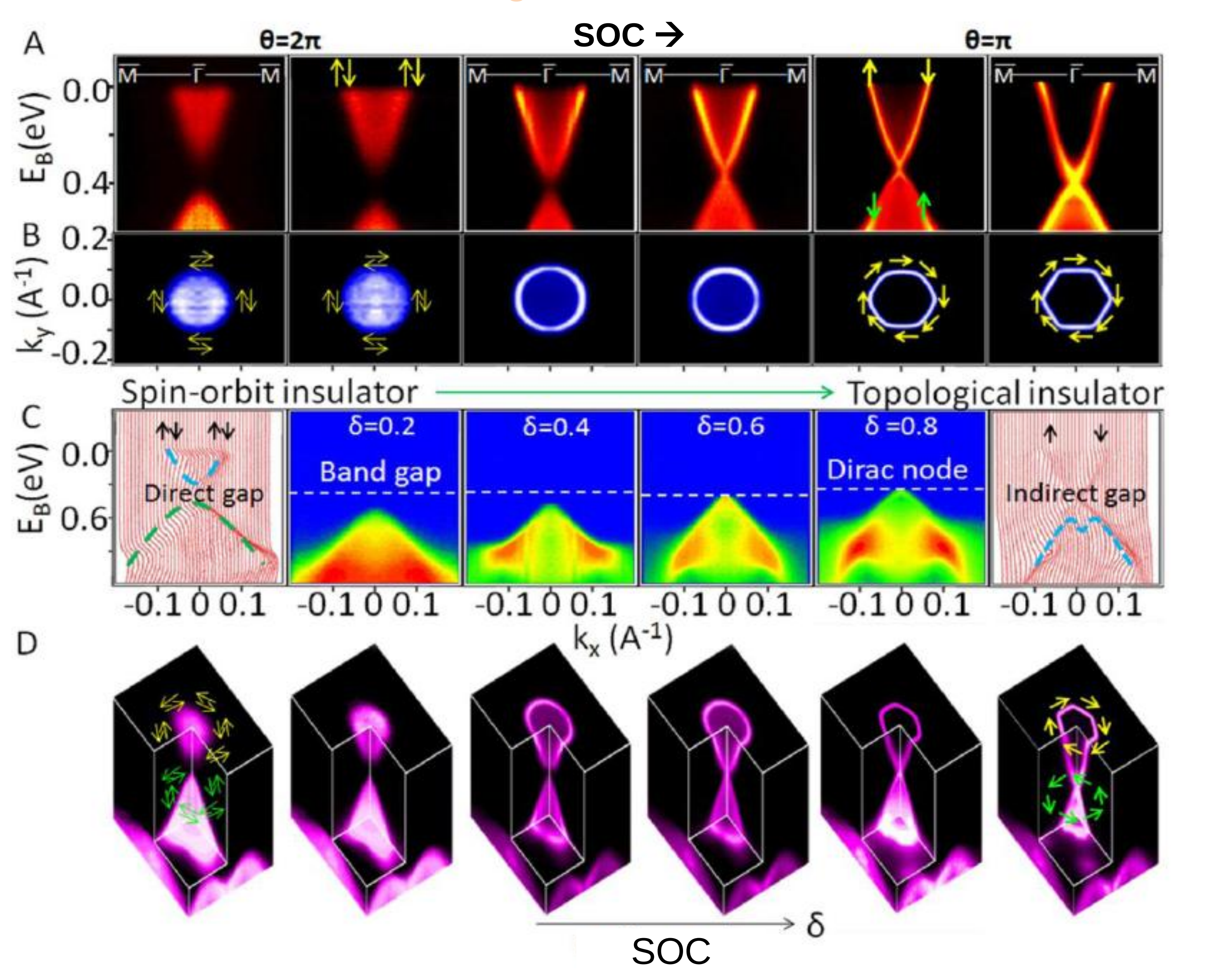
Band inversion and Topological Phase Transition



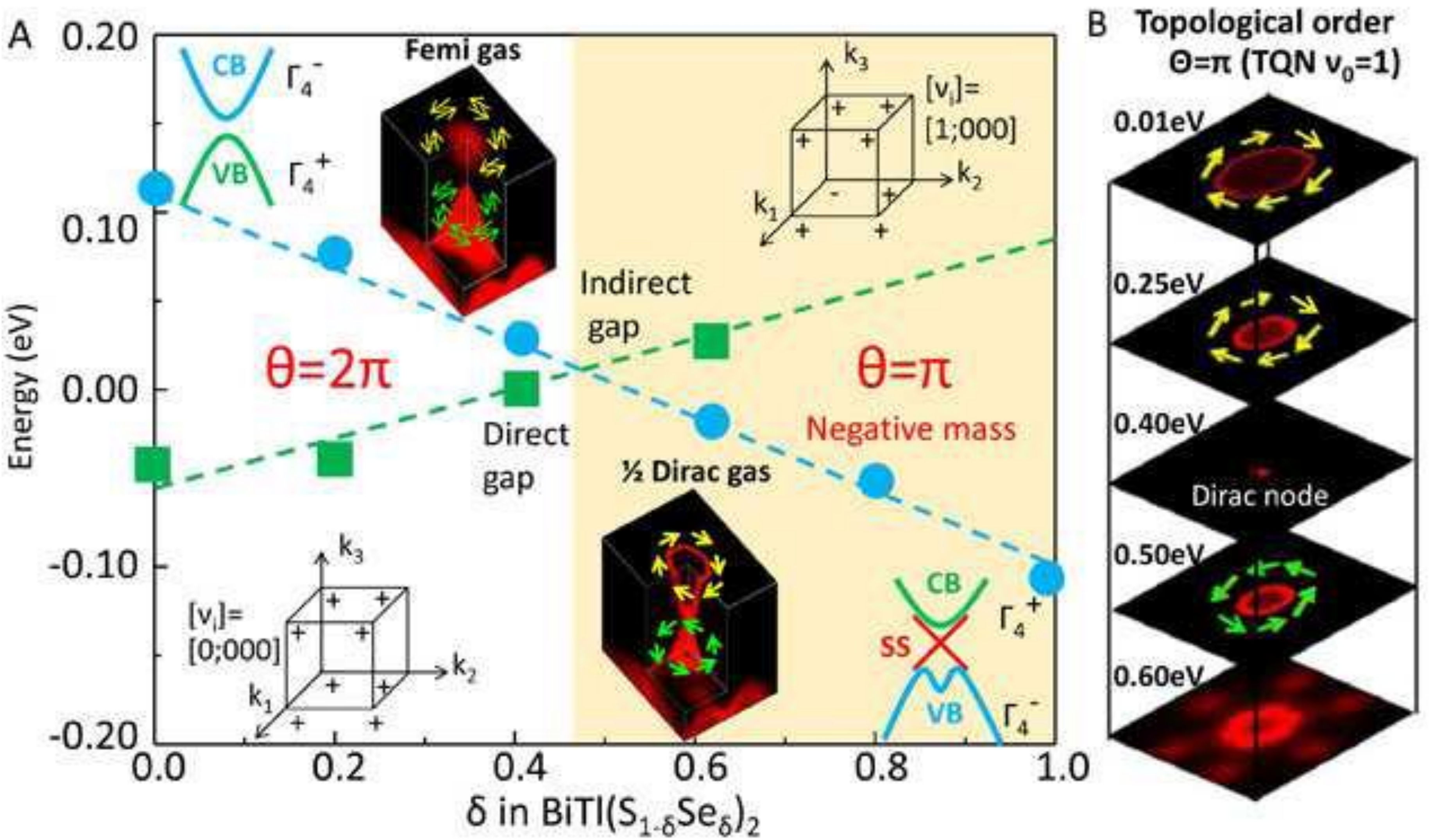
SuYang Xu *et.al.*, SCIENCE

Topological phase Transition (topo-QPT)

Su-Yang Xu et.al., SCIENCE

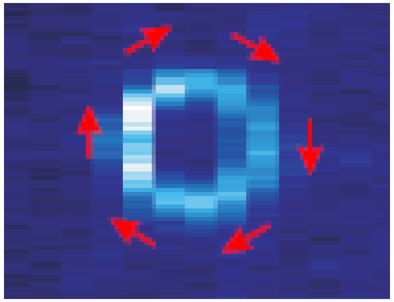


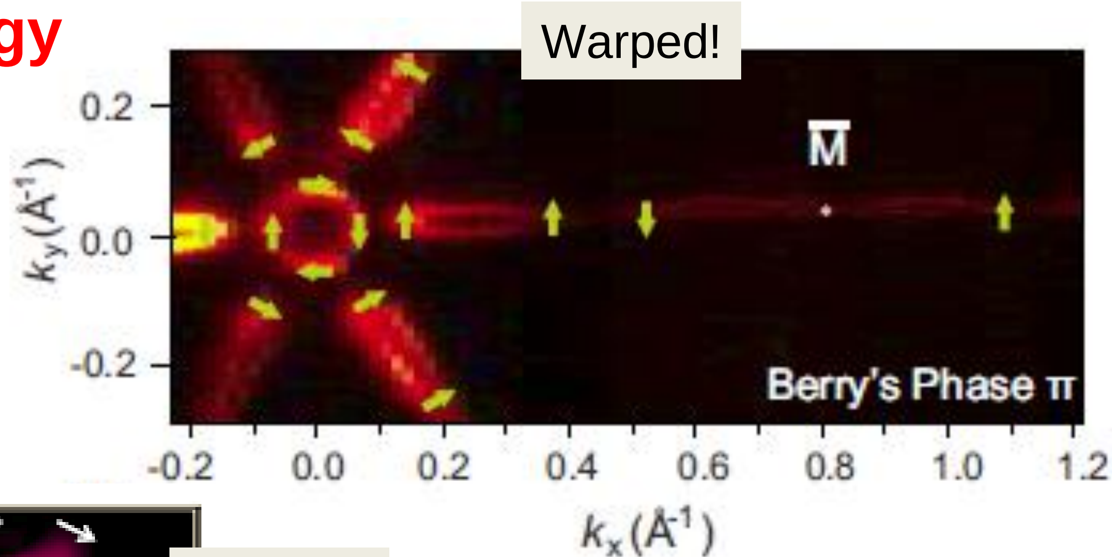
Phase Diagram of a Topological Insulator

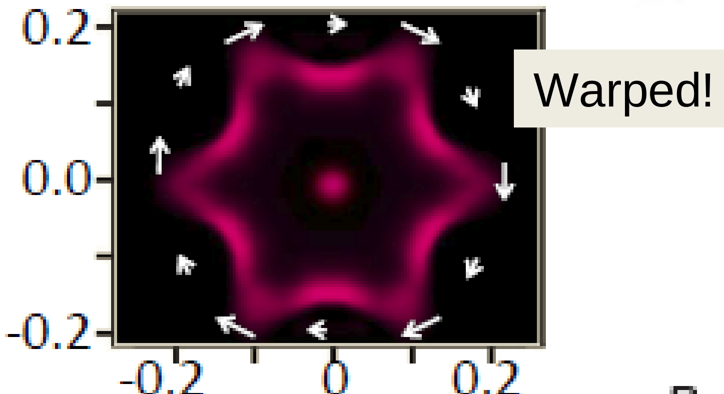


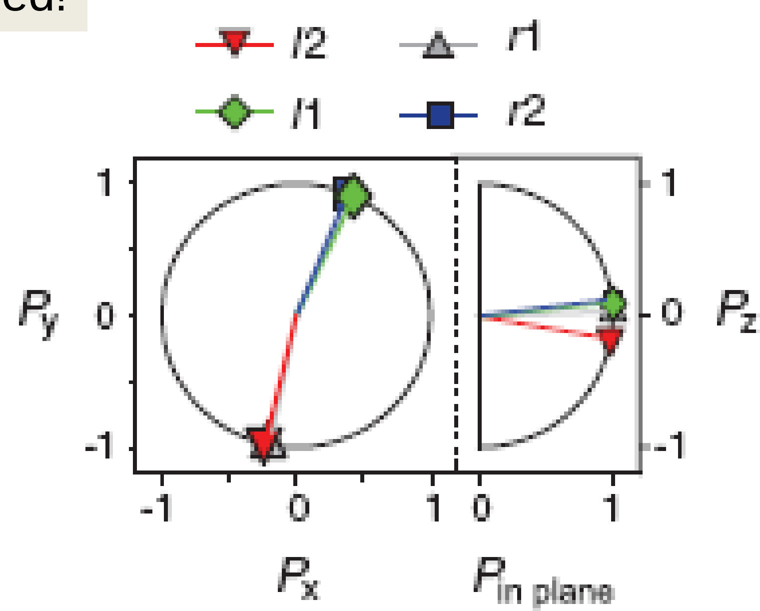
Many Spin-textures possible in TIs

Geometry vs. **Topology**







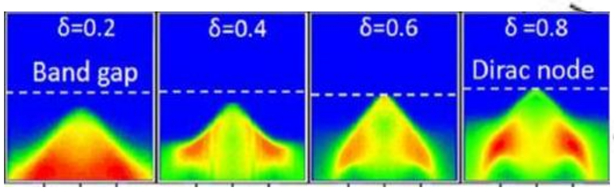


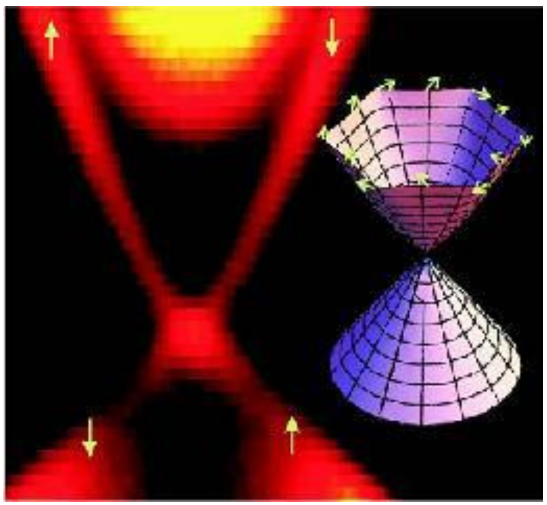
Always Berry's Phase = π

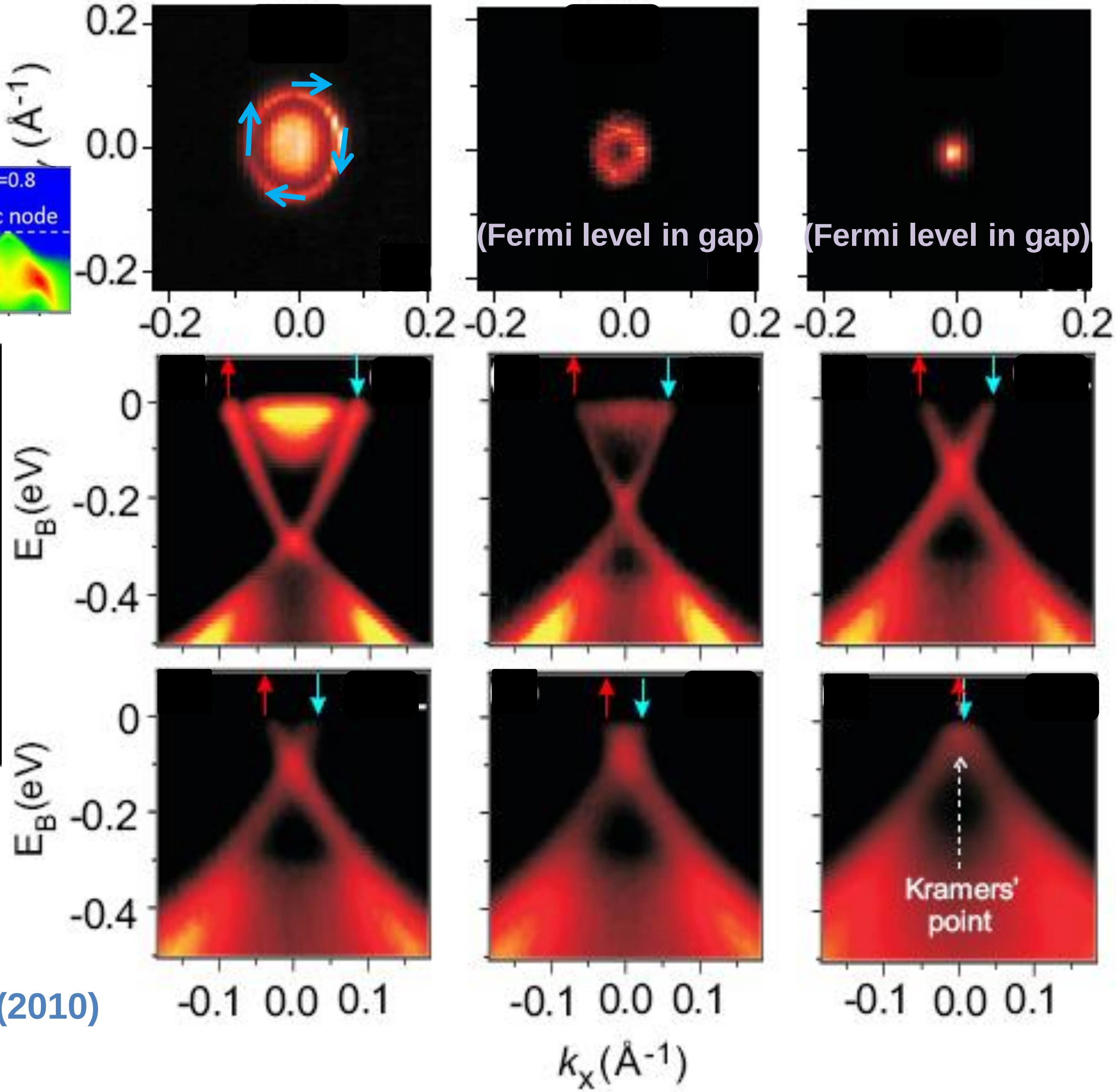
Topological Invariant = Phase/π = 1

Manipulation & control of TI surface states (Fermi level in gap):
(Nature09, Science09)

"TOPOLOGICAL Graphene"



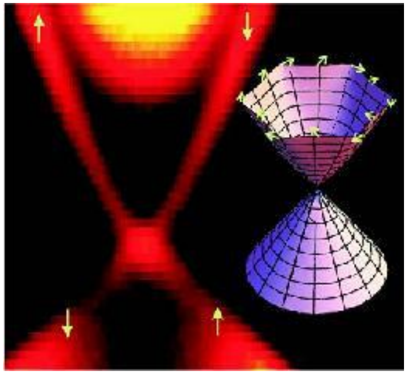




Electrical Gating is also possible

Also chemical gating
Wray et.al., Nature Phys (2010)

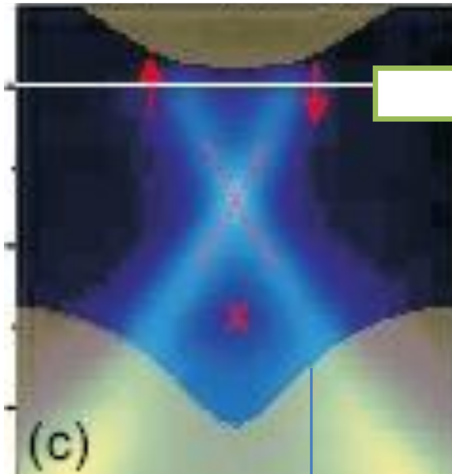
Spin-texture → Absence of Backscattering



Spin-ARPES Data

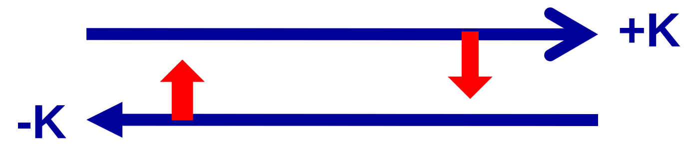
NATURE 09

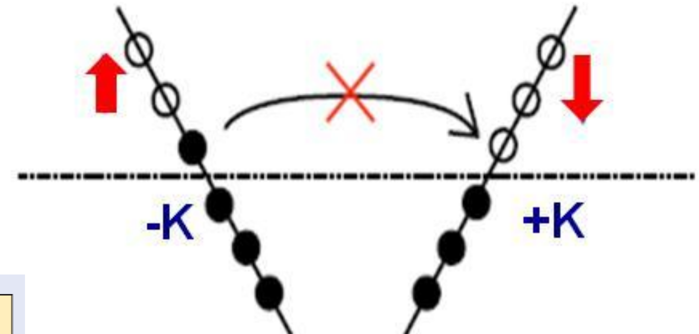
(Fermi level in gap)

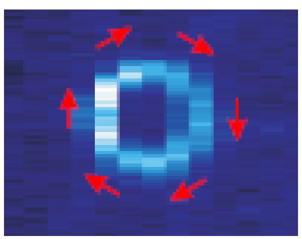


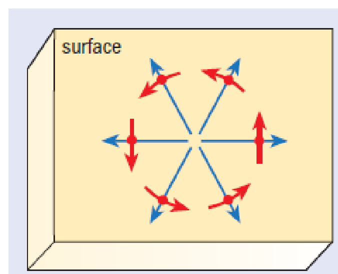
-K

+K









Electrons cannot go from –k to +k

No “U” turn!

Dissipationless flow in 1D

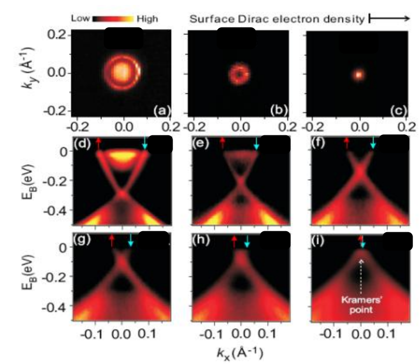
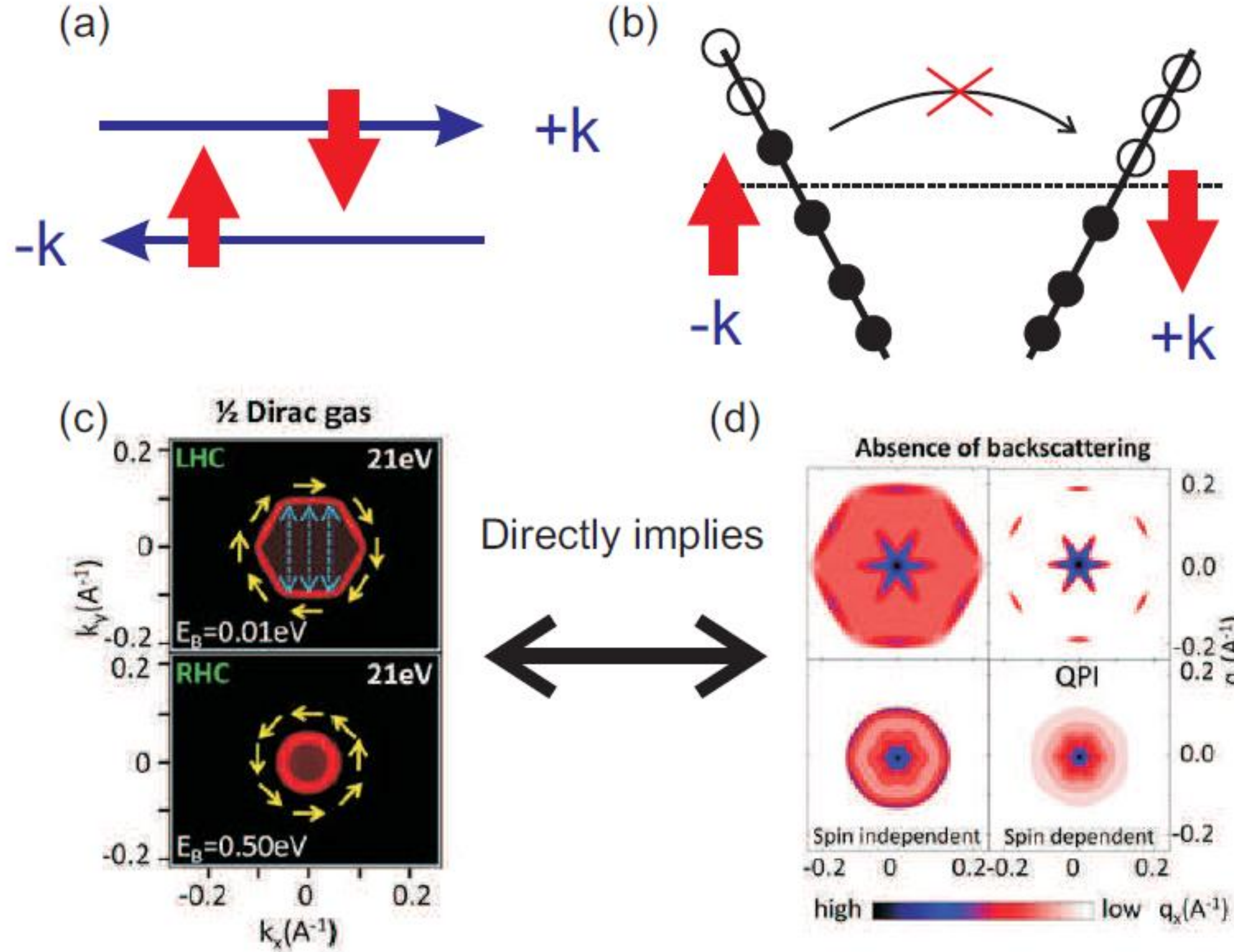
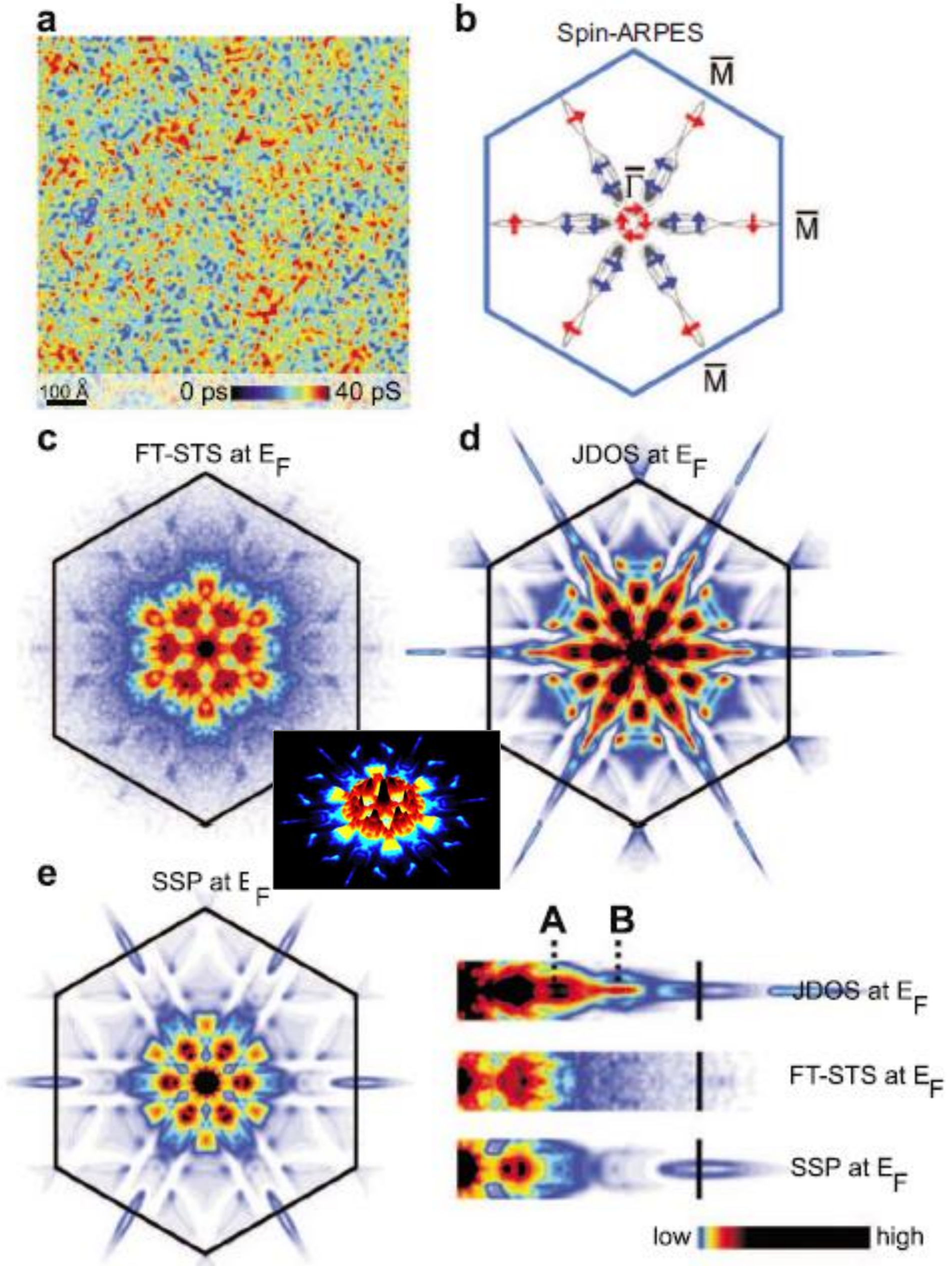


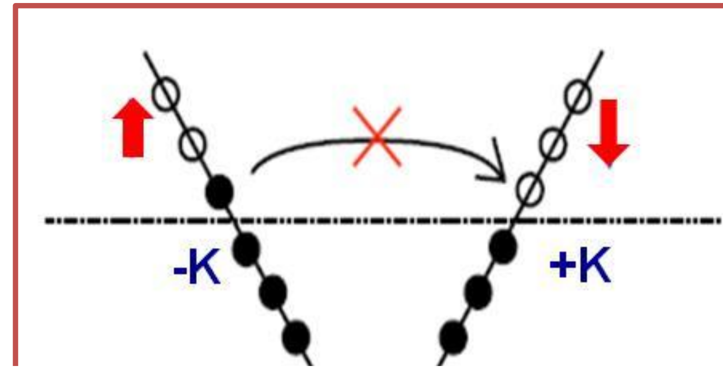
FIG. 3: M.Z. Hasan

Helical spin texture directly implies absence of backscattering

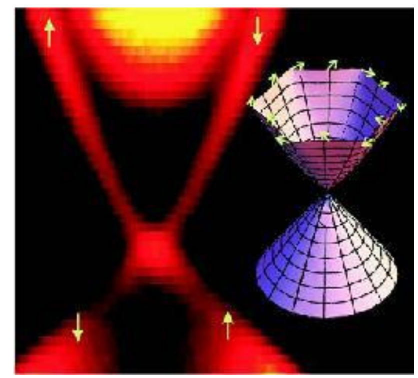


STM (Roushan et.al.) **Spin-ARPES (Hsieh et.al.)**

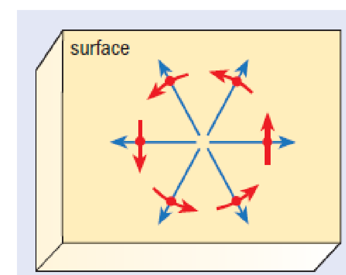




Spin-texture → Absence of Backscattering



Spin-**Independent**

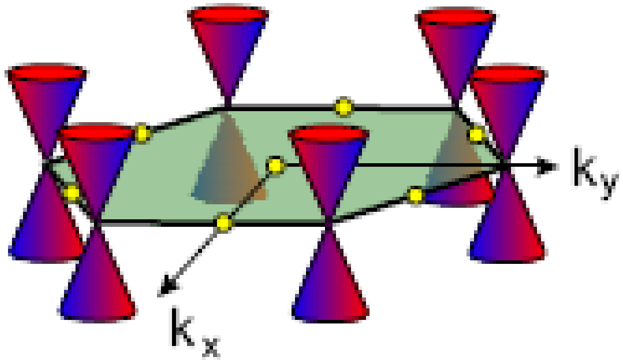


Spin-**Dependent**

Roushan et.al.,NATURE 09

Graphene

Excellent Material Properties



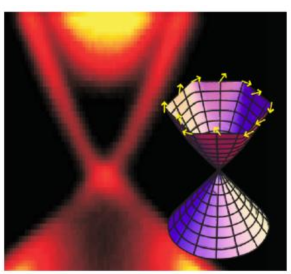
Bulk band structure:
Dirac Fermion
is a BULK state

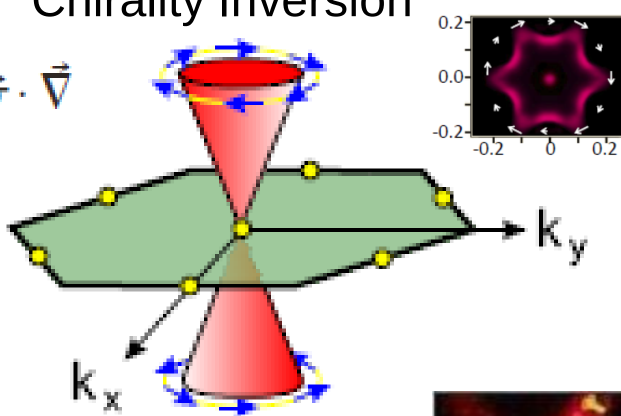
$\sigma_{xy} = 2e^2/h$
(q-Hall effect)

Topo Insulator

Chirality Inversion

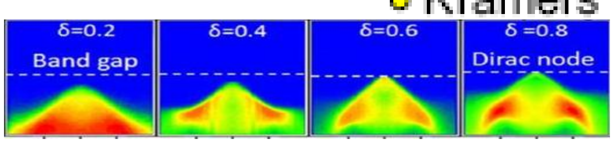
$$\mathcal{H}_{\text{surface}} = -i\hbar v_F \vec{\sigma} \cdot \vec{\nabla}$$

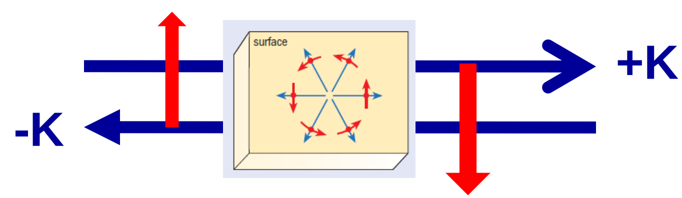




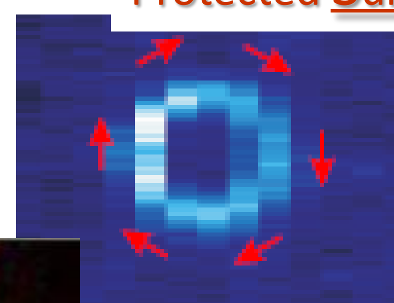
Bi_2Se_3

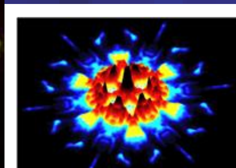
• Kramers' point





Protected Surface States : New 2DEG





Dirac Fermion
is a **boundary effect**
while the
BULK is insulating!

$\sigma_{xy} = e^2/2h = 1/4$

2 Classes of Topological Insulators

Spin-*k*(<u>Helical</u>) Locking, π-Berry's Phase, Half Fermi gas

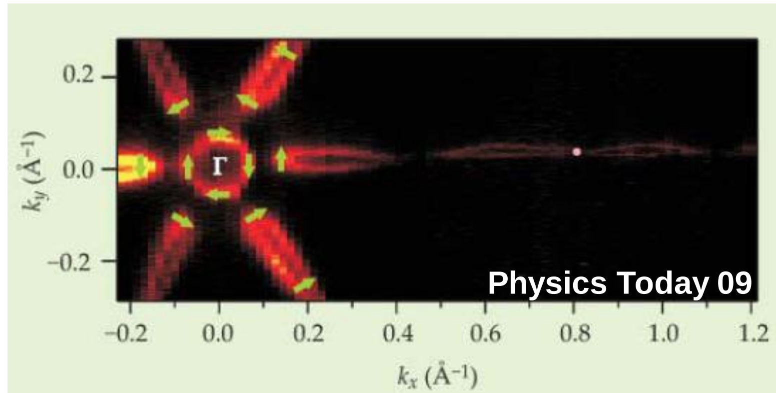
(1,*111*)

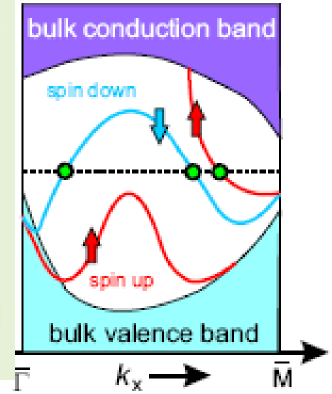
Bi-Sb class

Hsieh et., **Nature 08**

Hsieh et., **Science 09**

Roushan et., **Nature 09**





(1,*000*)

Bi_2Se_3

Bi_2X_3: Xia et. arXiv (08)

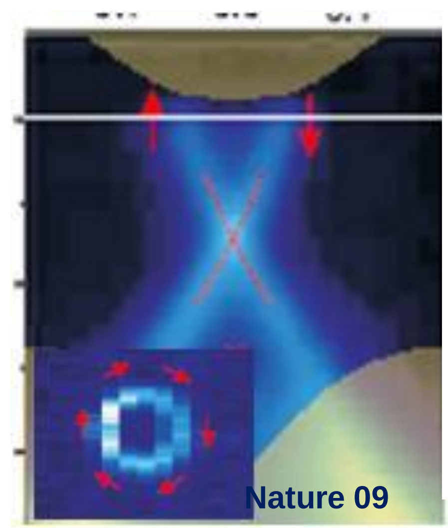
Nature Phys 09

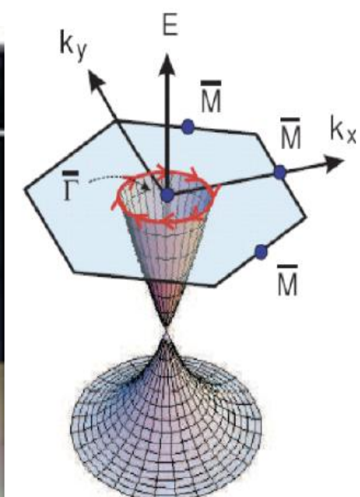
Sb_2Te_3: PRL 09

Bi_2Te_3(spin): Nature 09

Bi_2Te_3(w/o spin): Chen et. Sci09

Bi_2Se_3: Hsieh et., Nature 09



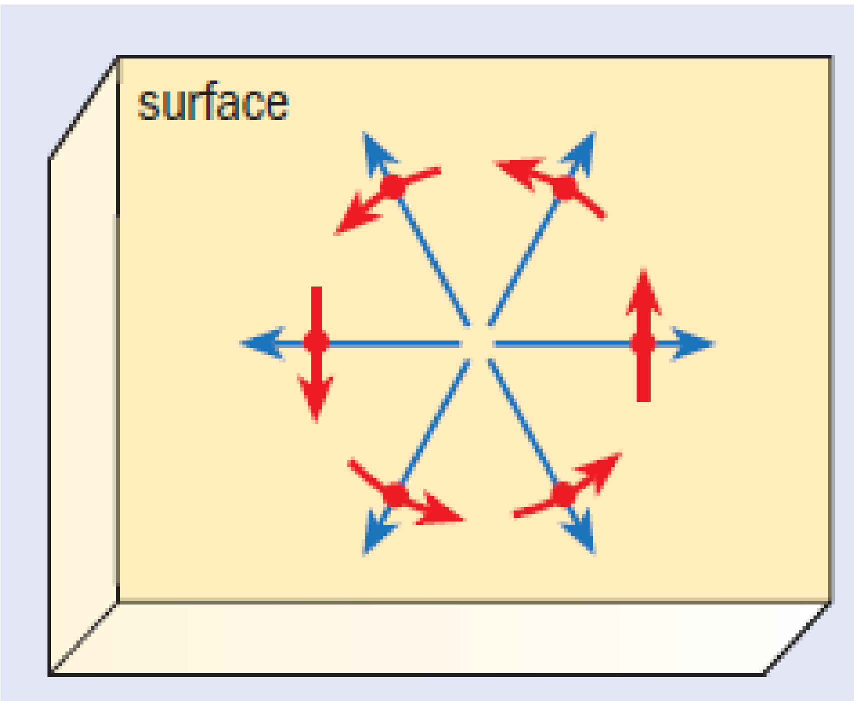


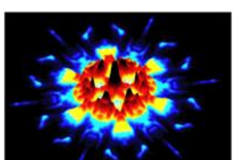
Ga(Al)As or Hg(Cd)Te limited to low-T (mK)

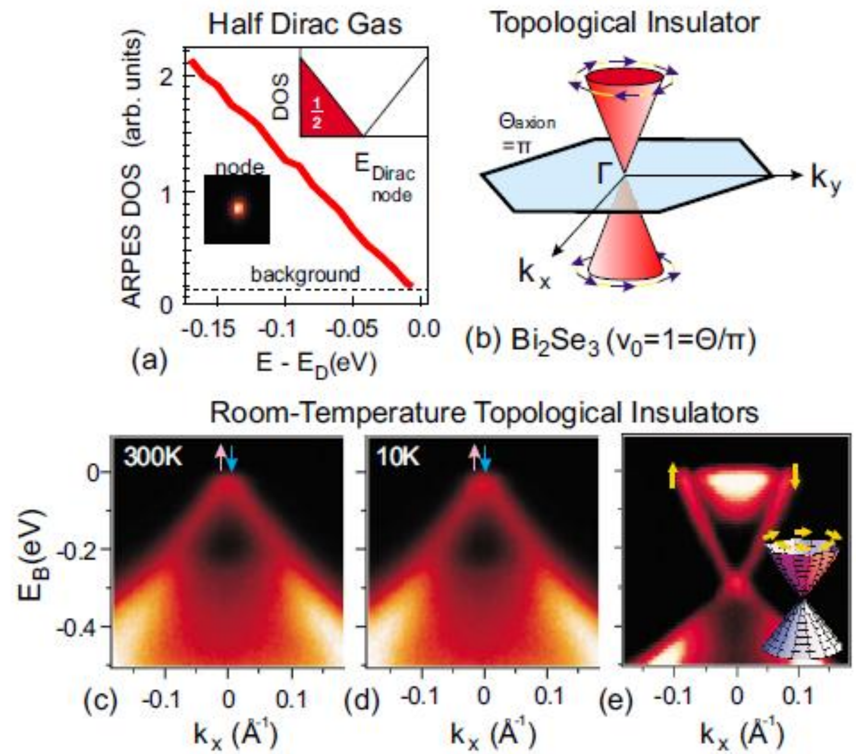
Bi_2Se_3 : Topological Order at Room Temperature

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

Protected Surface States (New 2DEG)





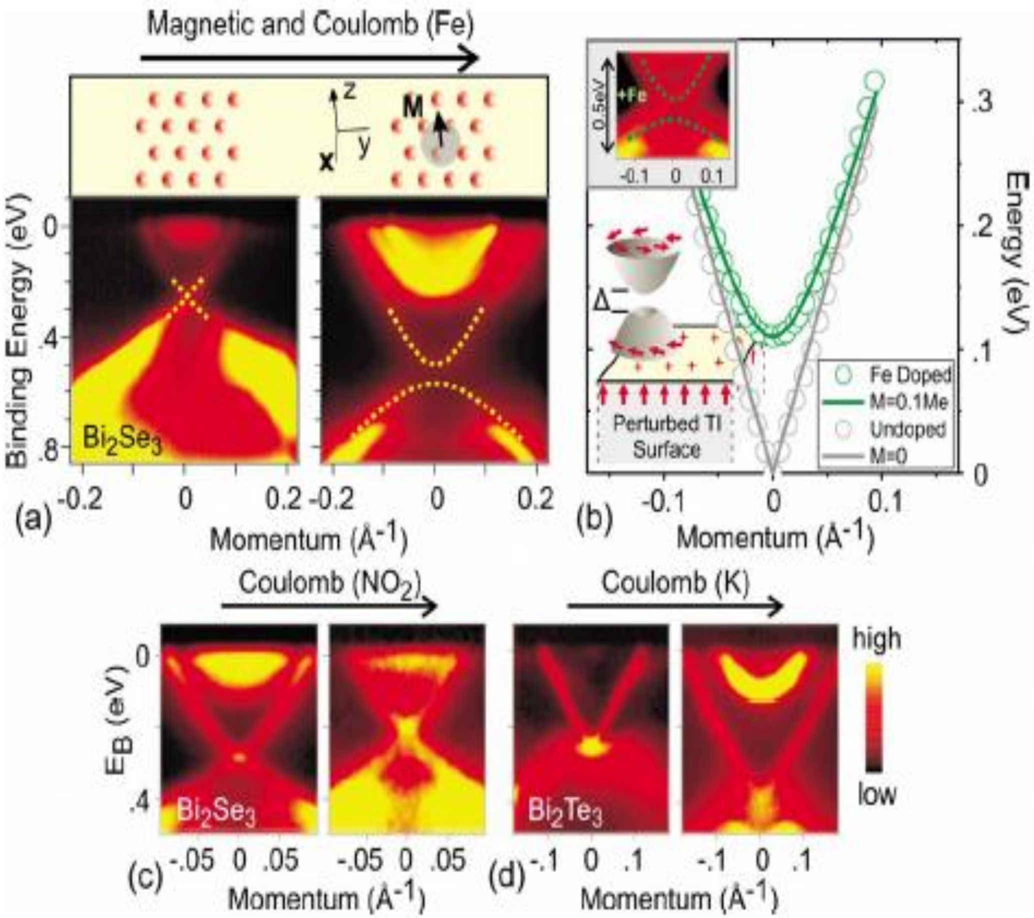


Hsieh *et.al.*, Nature '08, '09
Roushan *et.al.*, Nature '09, '10

Surfaces under Coulomb, magnetic etc. perturbation

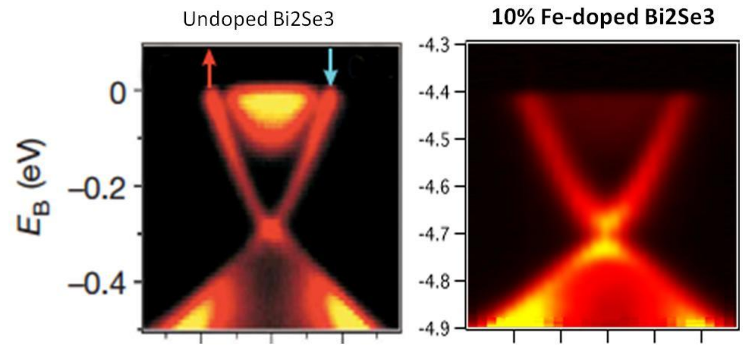
Surface Mobility Control

Magnetic perturbation is weak!

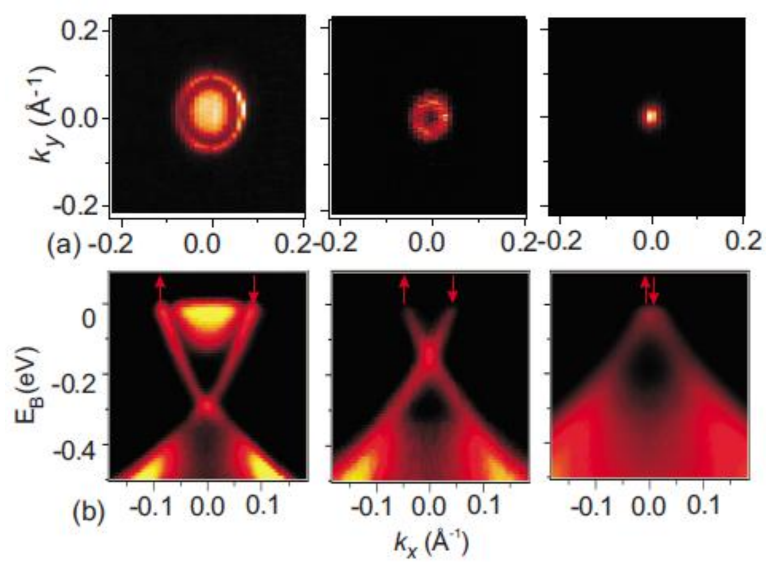


Wray et.al., Nature Physics (2010)

Fe doping on Bi2Se3



Carrier Control

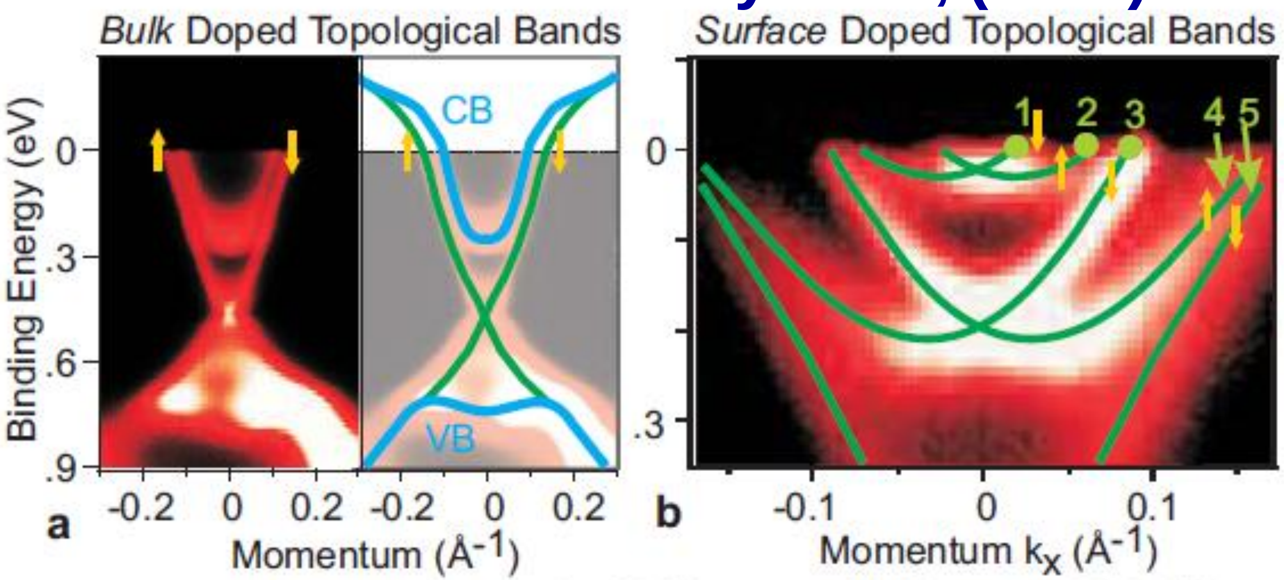


Nature (2009)

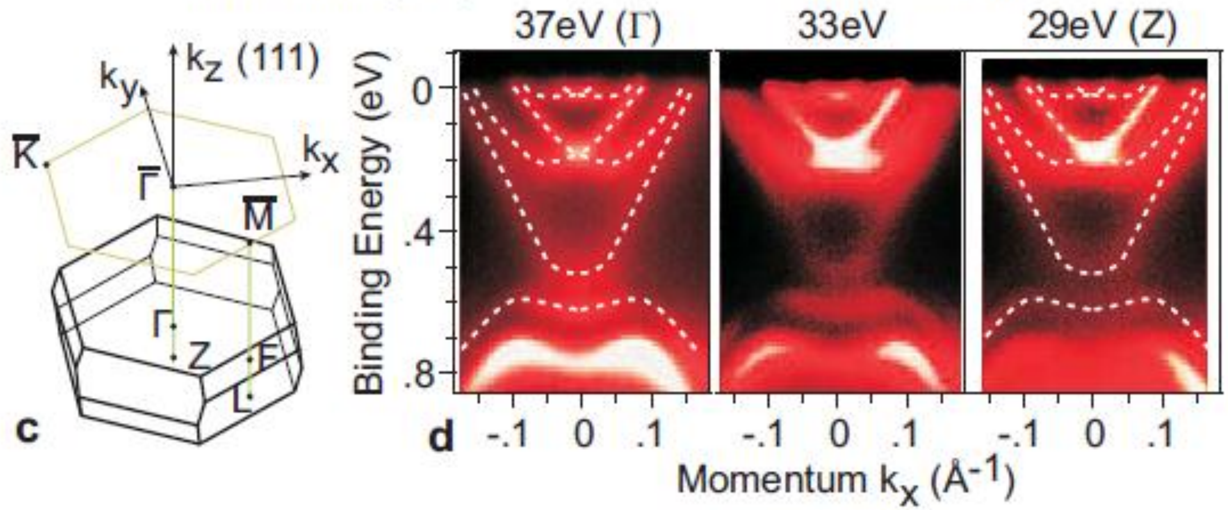
Surface interactions with adatoms, band bending, ….

Surface doping with Fe

Wray et.al., (2011)



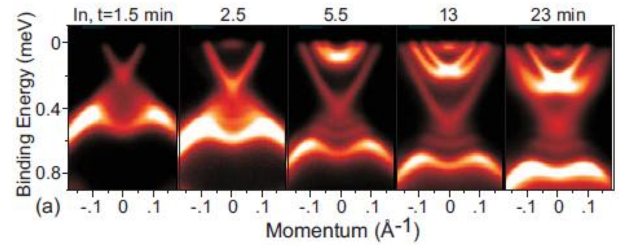
Rashba bands
+
Topo Bands
→
Unique Rashba type
(5 Dirac cone –like FS)



Wray et.al.,
Nature Physics (2010)

Topological nanoscale P-N interface

Wray et.al., (2011)



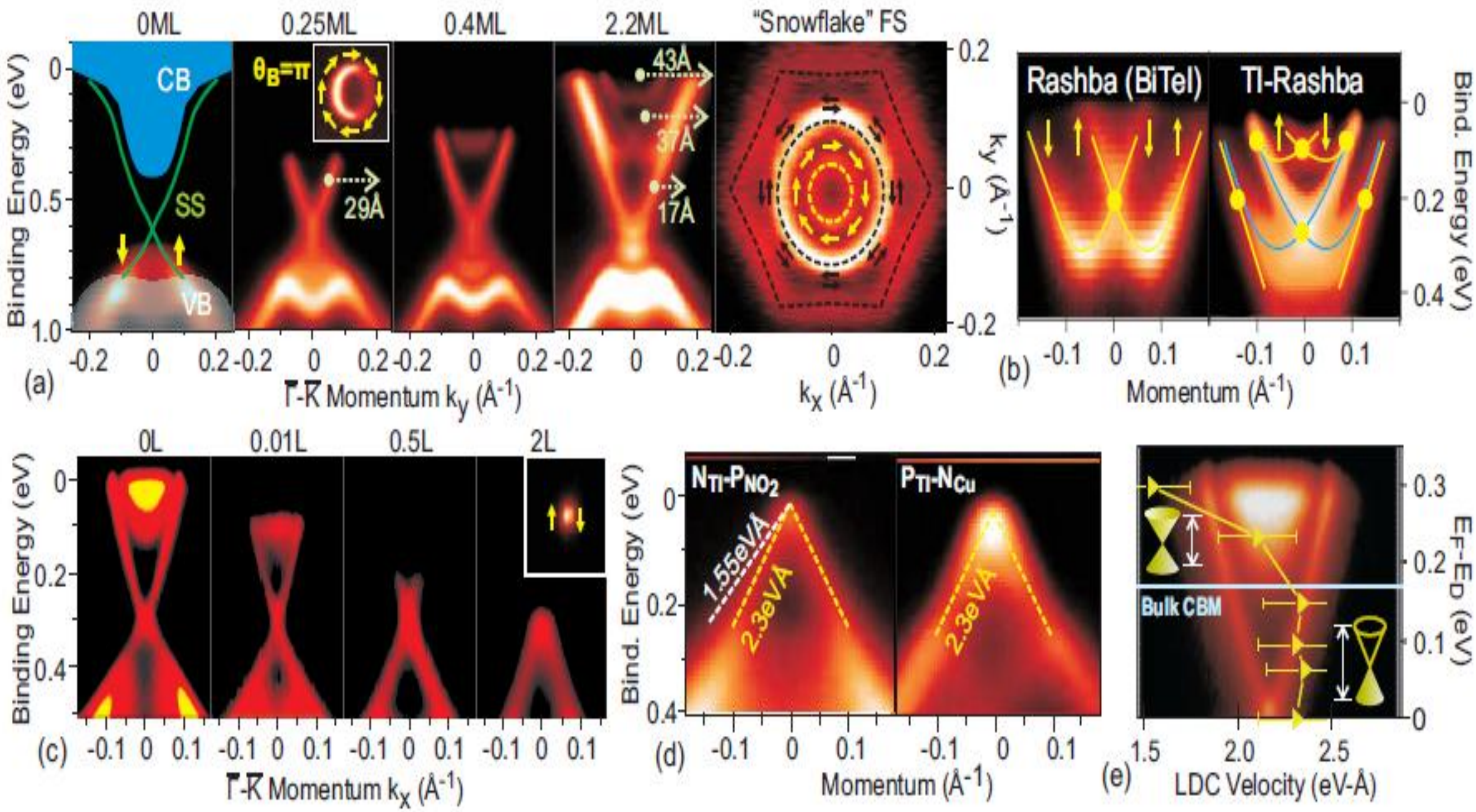


FIG. 2: Measuring topological nanoscale P-N interface electron dynamics: (a) Surface deposition of copper is shown

Topological nanoscale P-N interface

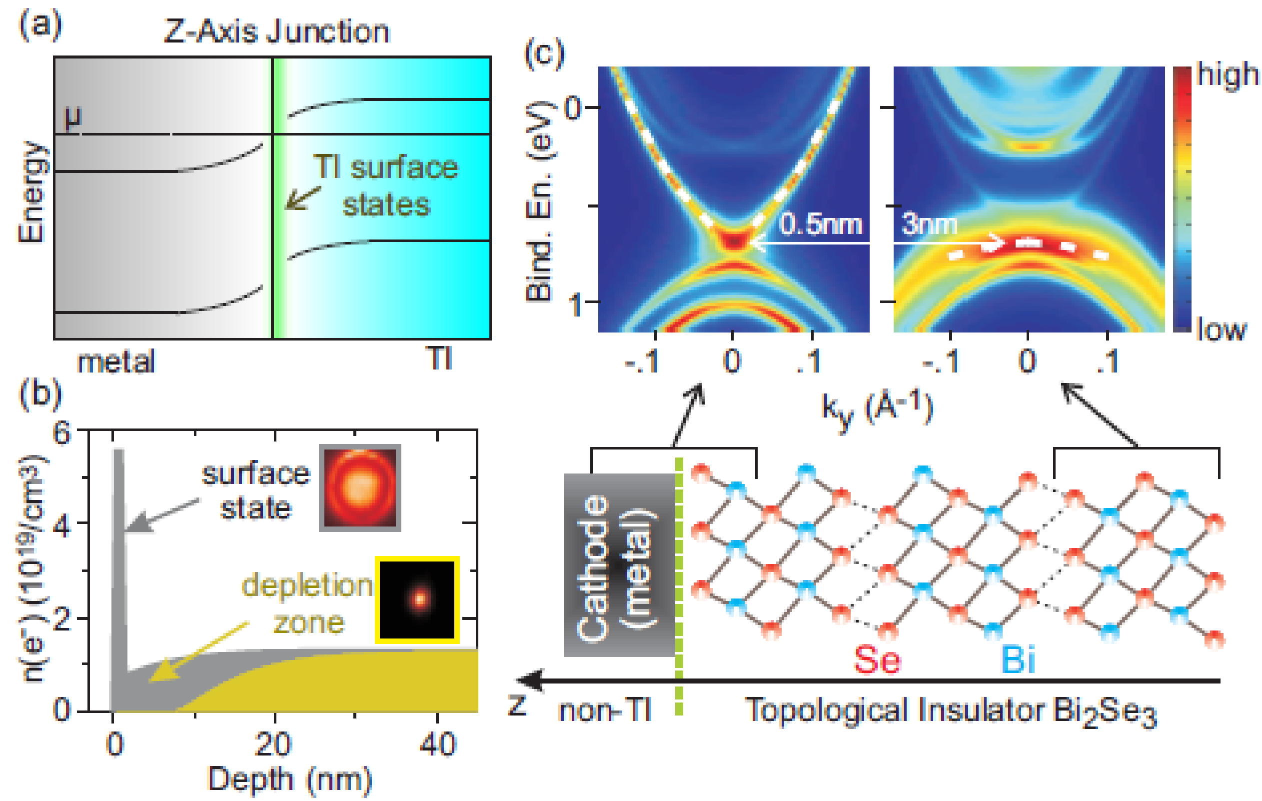


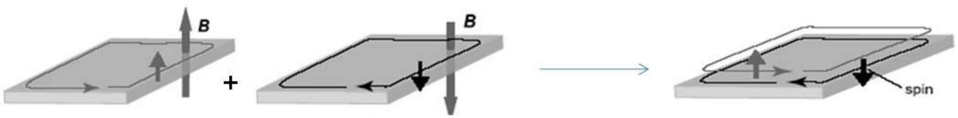
FIG. 4: **Combining electrostatics and electronic topology:** (a) A diagram illustrates conventional band bending in a junction, with a discontinuity due to the presence of topological surface states. (b) The electron density distribution is modeled for (gray) N-type as-grown Bi_2Se_3 and (gold) the

Wray et.al., (2011)

Topo-insulators in nature

2D Topological Insulators: Ga(Al)As, Hg(Cd)Te

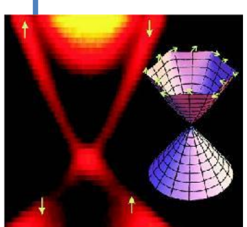
Quantum Hall state (Breaks T-invariance) IQH
Cryogenic, Large Magnetic field, high-purity crystals
Quantum spin Hall state (Preserves T-invariance) → 2 IQH
Cryogenic, No Magnetic field, high-purity crystals,



2 copies of IQH <-> QSH

No 3D quantum hall effect but there is a novel 3D topological insulator whose surface is topological metal (new type of 2DEG)

3D Topological Insulators: Bi-Sb, Bi_2Se_3, Bi_2Te_2Se, more

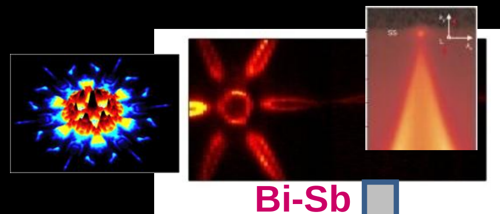


Protected Surface States : New 2DEG

Topological insulator (Preserves t-invariance)
Room Temperature operation, No magnetic field, High tolerance of dirt?

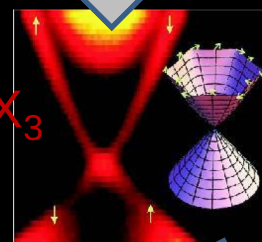
AFM/Magnetism in doped topo insulator : Topo-Order & Broken-Symmetry!
Superconductivity in doped topo insulator : Topo-Order & Broken-Symmetry!

Experiments on Topological Insulators (3D



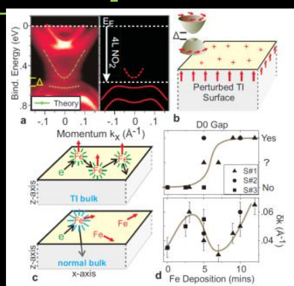
Hsieh et.al., NATURE 08 (sub. 2007)
Hsieh et.al., SCIENCE 09
Roushan et.al., NATURE 09

Bi_2X_3

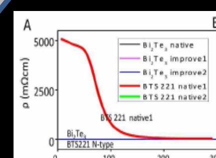


Xia et.al, 2008 (arXiv'08, KITP 08)
Xia et.al, 2009 (Nature Phys.)
Hsieh et.al., Nature 2009
Zhang et. NatPhy '09 & Chen et.al, Sci '09
and many others ..

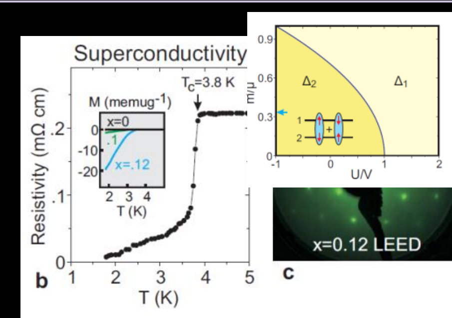
Surface Magnetic Impurity
Coulomb perturbation etc.



Xia et.al, arXiv. 2008
Wray et.al., Nat.Phys. 2010
Chen et.al, Science '10



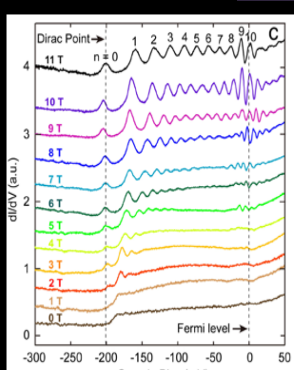
Superconductivity

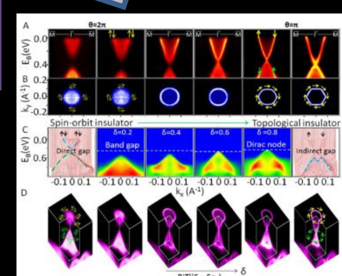


Hor et.al., PRL 2010
Wray et.al., Nat.Phys.20
Ando et.al, PRL '11

Quantum Hall effect

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



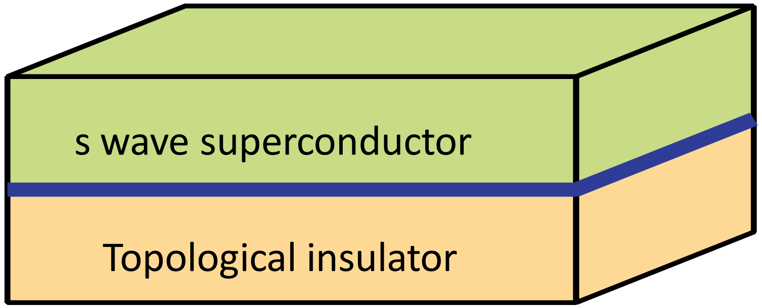


Topo.Phase Transition

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

also Fractional QHE

STI/Superconduct interface

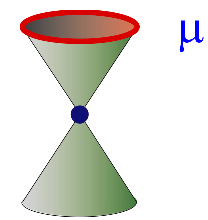


2D interface state with energy gap and exotic topological order

Resembles 2D spinless p_x+ip_y superconductor but does not violate time reversal symmetry

Fu-Kane proposal

$$H = \psi^\dagger(-iv\vec{\sigma}\cdot\vec{\nabla} - \mu)\psi + \Delta\psi_\uparrow^\dagger\psi_\downarrow^\dagger + \Delta^*\psi_\downarrow\psi_\uparrow$$



Dirac surface states (no spin degeneracy)

proximity induced superconductivity

Majorana bound state at a vortex : $\Delta = \Delta(r)e^{i\theta}$

- bound state solution to BdG equation at exactly zero energy
- $c_0 = c_0^\dagger$ (electron=hole) Majorana fermion = “1/2 a state”

Also predicted in ν=5/2 FQHE, Sr_2RuO_4, cold atoms, etc

$Cu_xBi_2Se_3$ (T_c ~ 3.8K) : **Hor et.al., PRL 2010**

nature physics
LETTERS
PUBLISHED ONLINE: 19 SEPTEMBER 2010 | DOI: 10.1038/NPHYS1762

Topological Surface States: Superconductivity in doped topological insulators

Wray et.al., Nature Physics (2010)

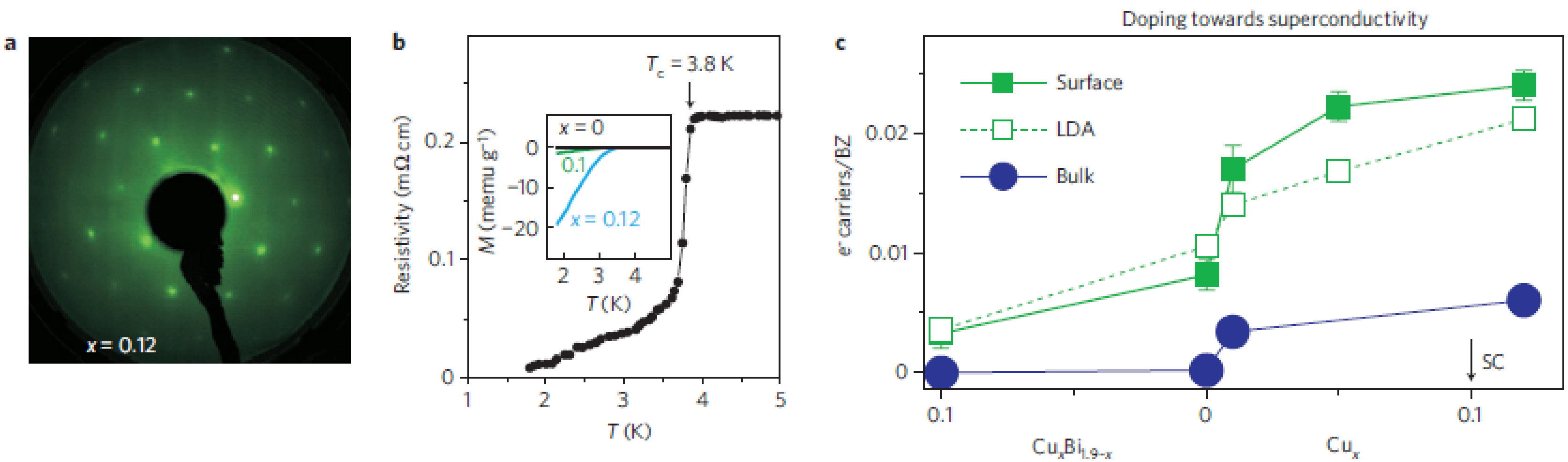
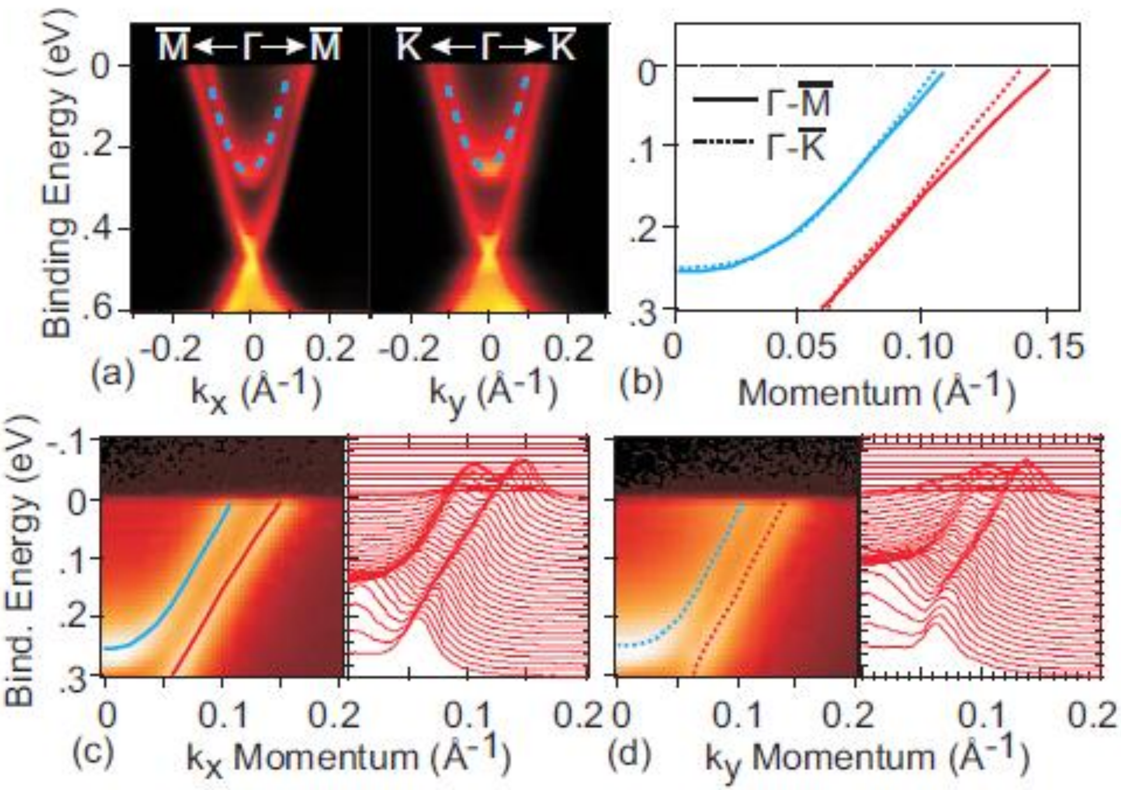
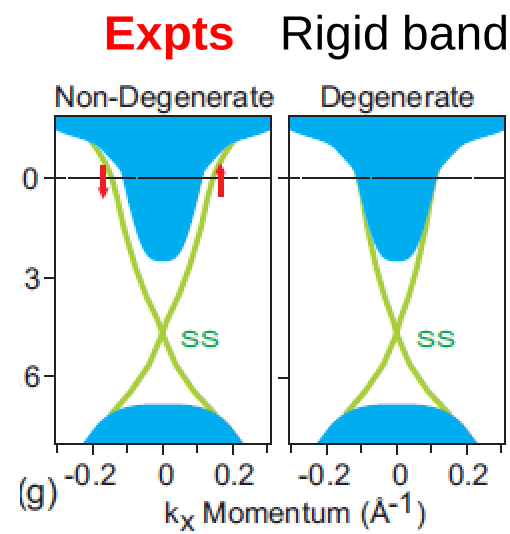


Figure 1 | Superconductivity in $Cu_xBi_2Se_3$ crystals. a, A low-energy electron diffraction image taken at 200 eV electron energy provides evidence for a well-ordered surface with no sign of superstructure modulation. **b**, Resistivity and magnetic susceptibility measurements for samples used in this study. Samples exhibit a superconducting transition at 3.8 K at optimal copper doping ($x = 0.12$). **c**, The number of charge carriers is calculated from the Luttinger count (Fermi surface area/Brillouin zone (BZ) area, ×2 for the doubly degenerate bulk band). Local density approximation (LDA) predictions show the carrier density obtained by aligning the local-density-approximation band structure with the experimentally determined binding energy of the Dirac point.

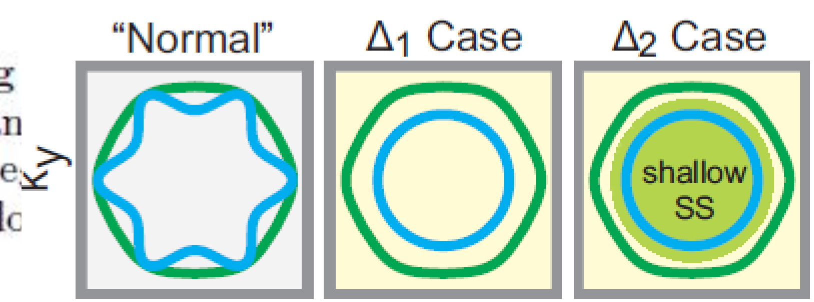
Surface States at superconducting composition

$Cu_xBi_2Se_3$ (T_c ~ 3.8K) : **Hor et.al., PRL 2010**

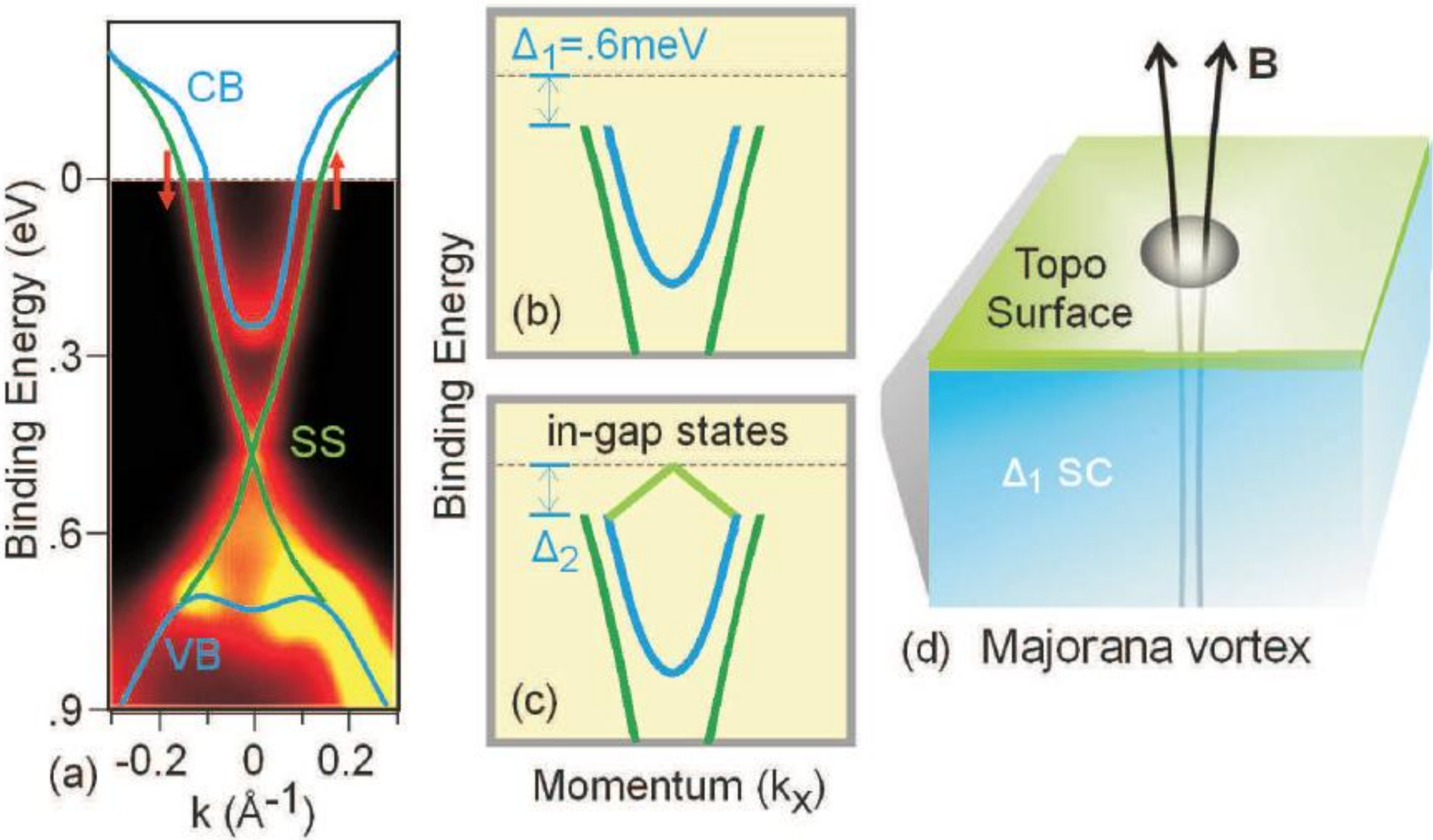




Band structure at superconducting sition: (a) Momentum dependence of the bulk an conduction bands in superconducting $Cu_{0.12}Bi_2Se$ sured through the 3D Brillouin zone center with lc



Wray et.al., Nature Physics (2010)

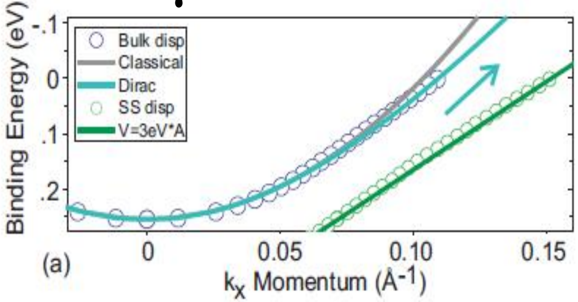


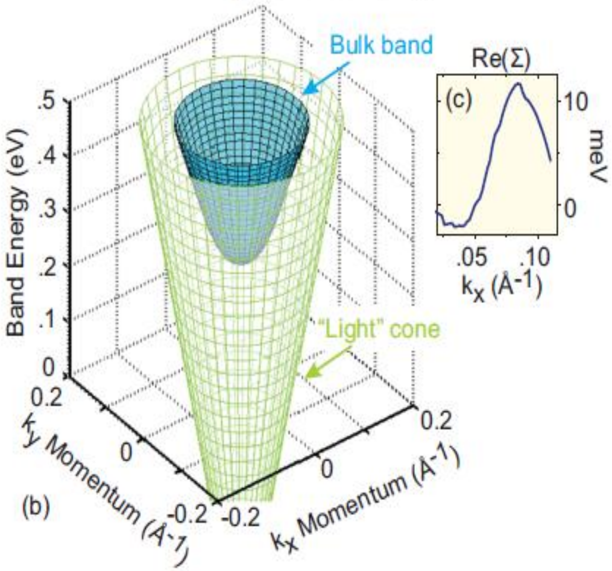
CB
SS
VB
Binding Energy (eV)
0
.3
.6
.9
(a)
-0.2
0
0.2
k (Å-1)
Δ1=.6meV
(b)
in-gap states
Δ2
(c)
Binding Energy
Momentum (kx)
B
Topo
Surface
Δ1 SC
(d) Majorana vortex

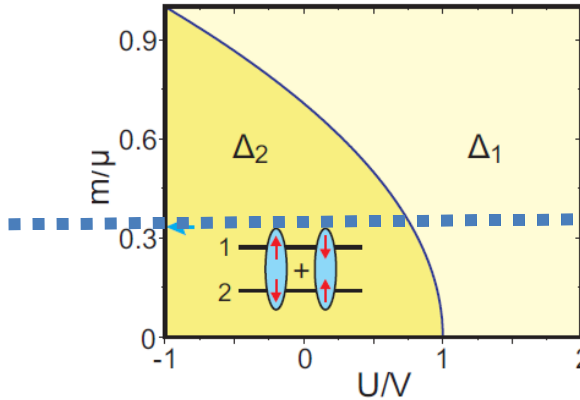
Topological Superconductor (TSC)?

Kitaev/Ludwig D3 class of TSC (proposed by Fu & Berg 09)

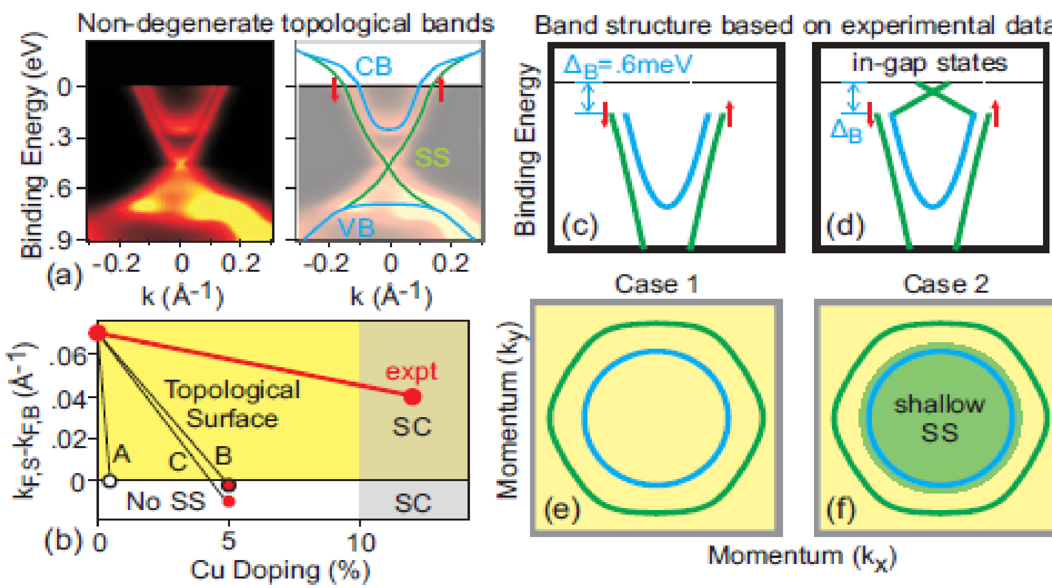
m/μ from ARPES







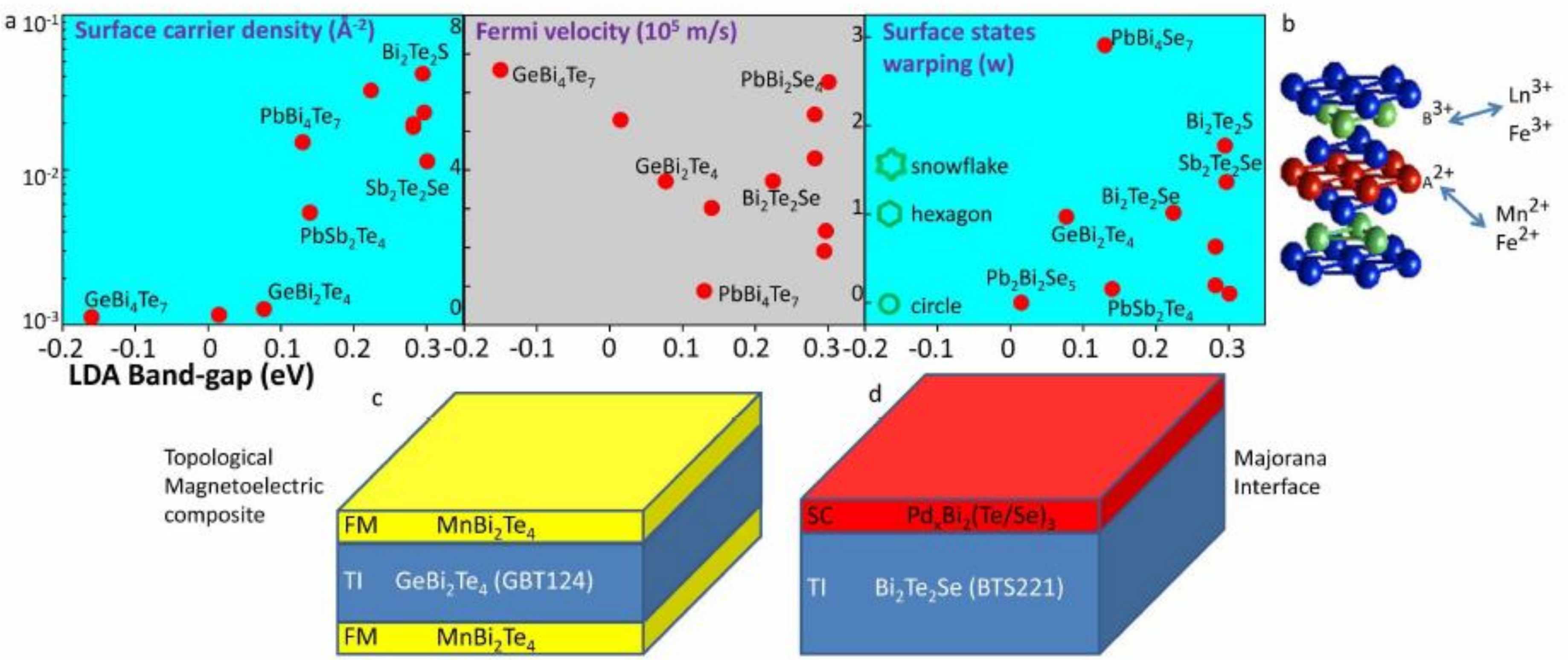
If **ODD** parity → TSC
[analog of SF He-3(B)]



Wray et.al., Nature Physics (2010)

Path to Topological Devices?

Some of the materials are reported at
[S.-Y. Xu et.al., arXiv:1007.5111v1]

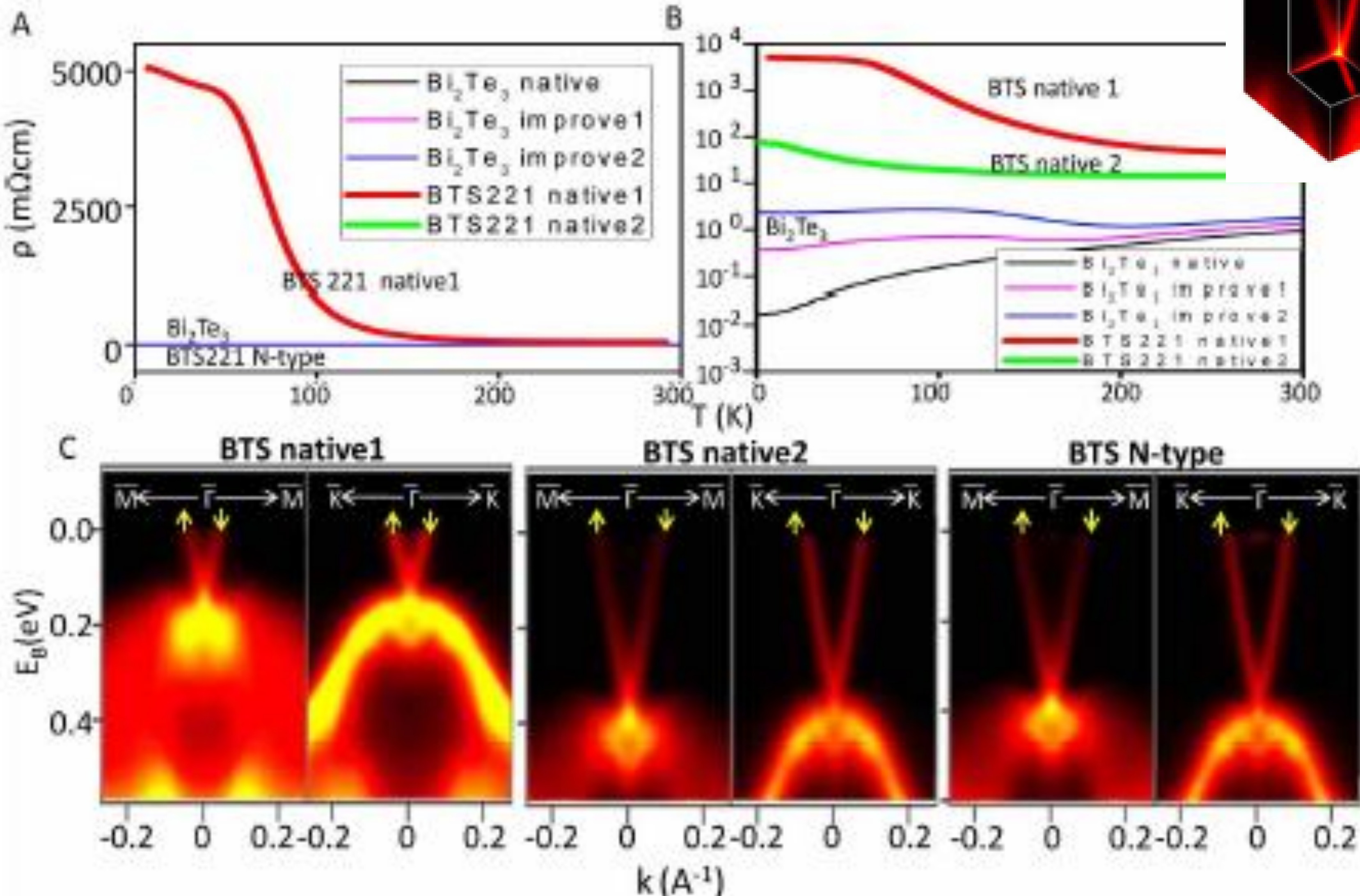


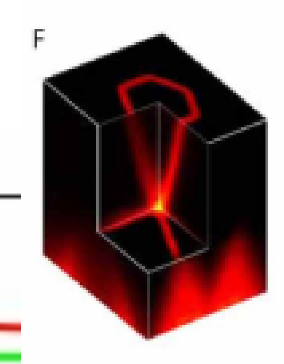
Magnetoelectric interface

Majorana interface

$Bi_2Te_2Se_1$ (more insulating than Si at 4K)

5 Ohm-cm (more insulating than Si at low-T)





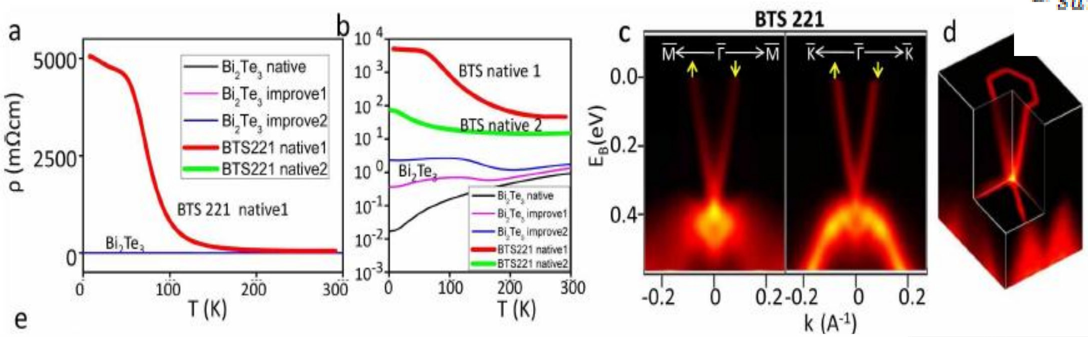
S.-Y. Xu et.al., preprint (2010)

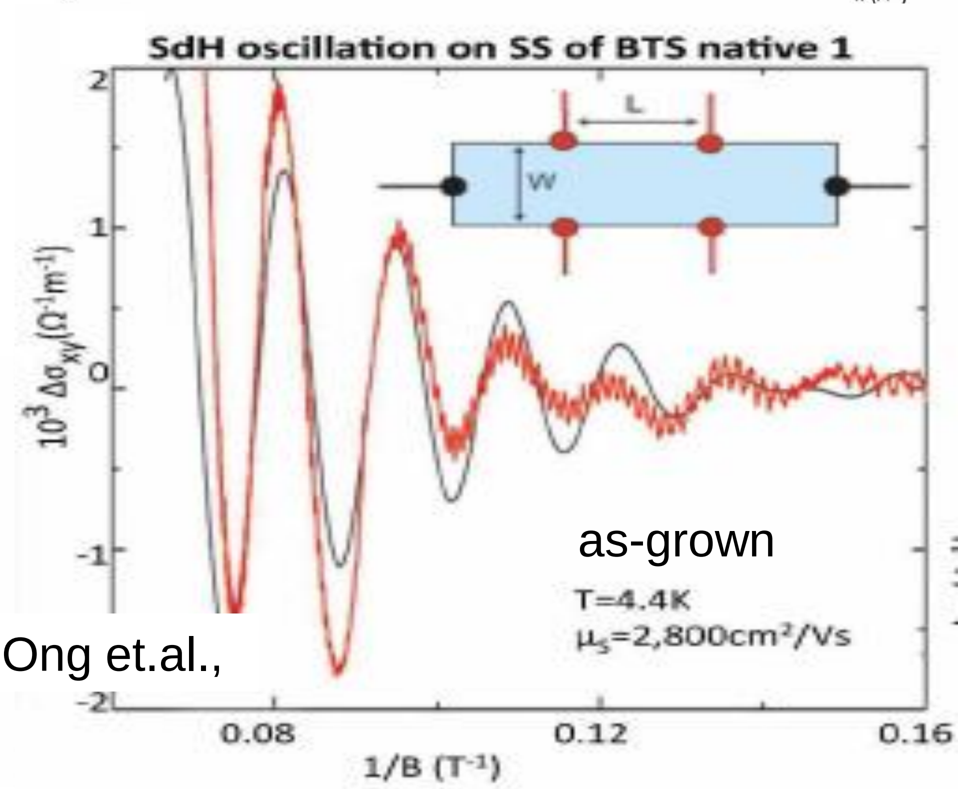
Highly Bulk-Insulating Topological Insulators

Surface contribution to transport more than 90%
Surface Mobility ~ 3000 cm^2/Vs

S.-Y. Xu et.al., preprint (2010)

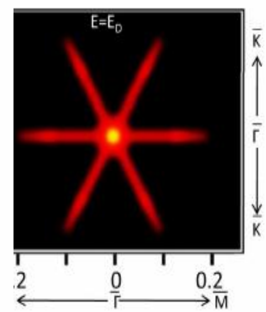
$$G_{surface}(T \sim 0) = (e^2/h)k_F L = (e^2/h)k_F v_F \tau$$





as-grown

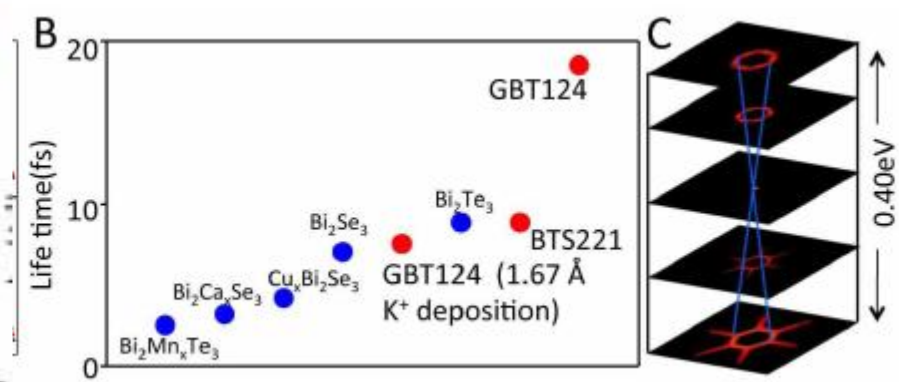
Ong et.al.,



even
Bulk crystals > 5 Ohm-cm

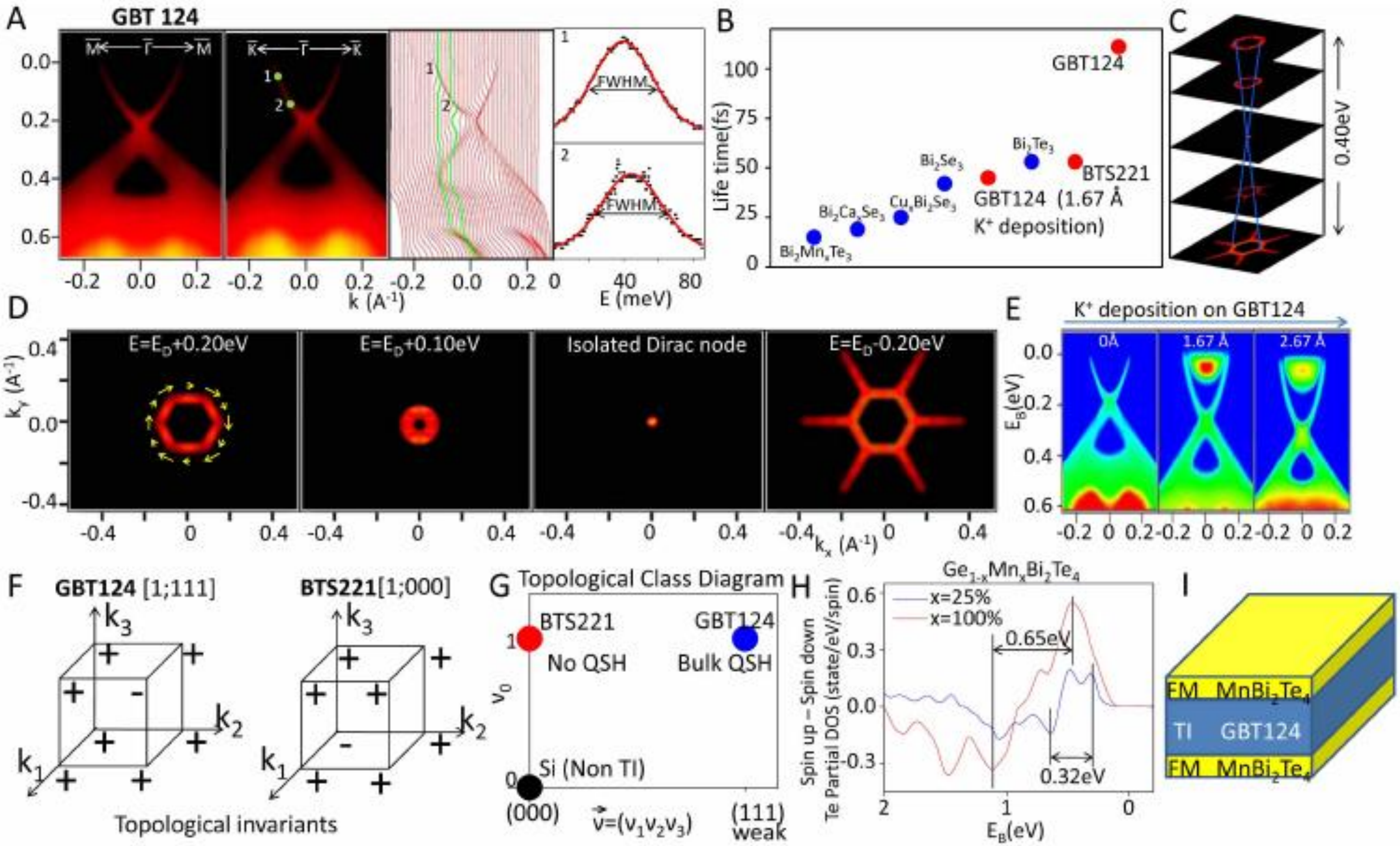
100-nm Film equivalents
~ 10^{10} carriers

Very large Gap ~ 200 meV
(unlike HgTe)

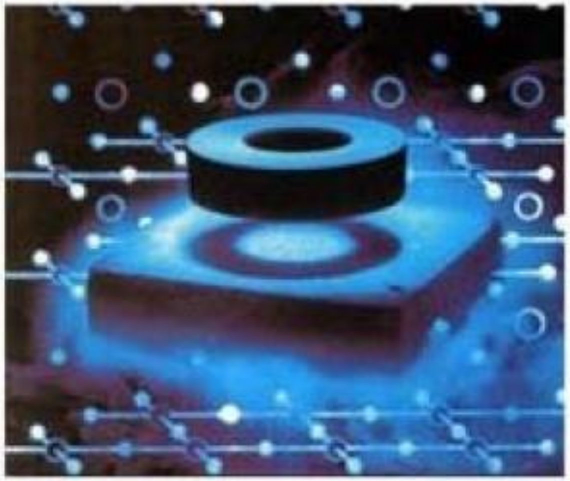


Very long quasiparticle life-time ..

S.-Y. Xu et.al., preprint (2010)



Candidate Topological Superconductors ..



Centrosymmetric

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

Non-Centrosymmetric

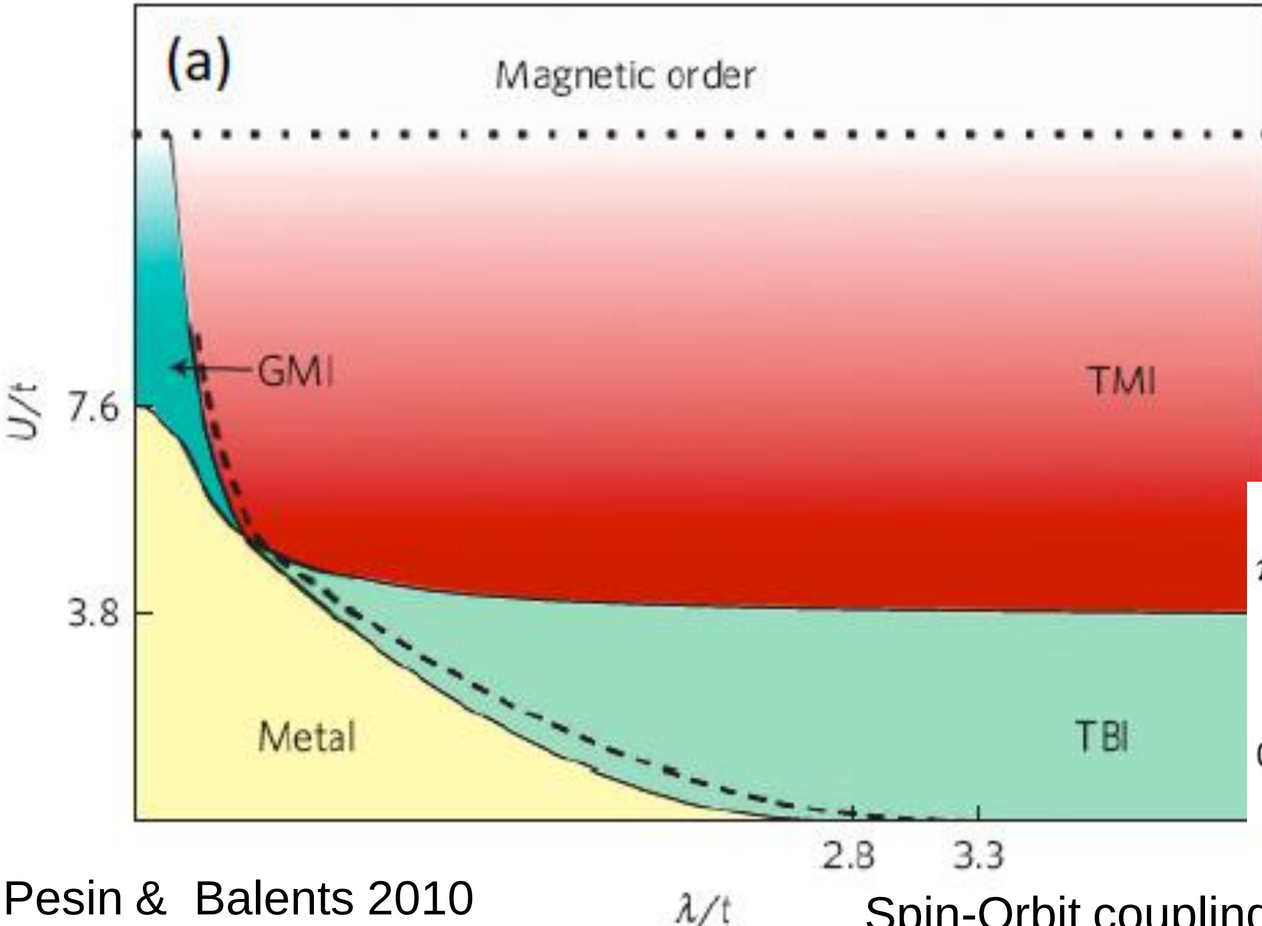
LaPtBi	0.3K
Li_2Pt_3B	3.0K
$CePt_3Si$	0.7K

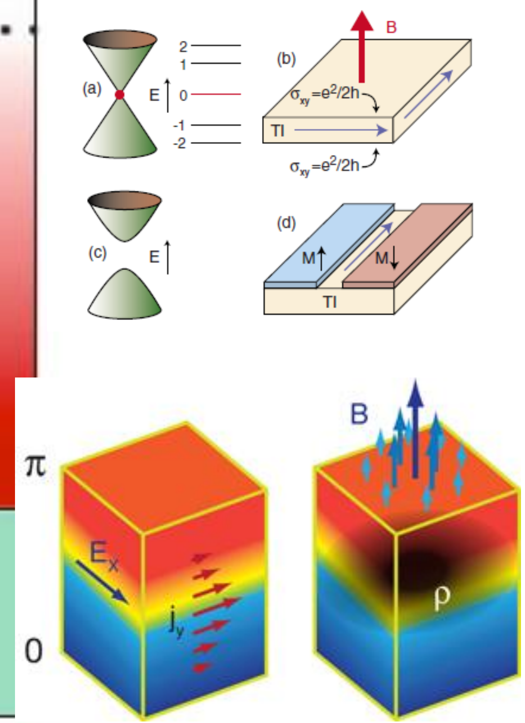
Topo (Band) Insulator → Topo Mott insulator (TMI)

Emergent physics in TMI

5d -Oxides

Coulomb Interaction





Pesin & Balents 2010

Spin-Orbit coupling

Conclusions :

- **A new experimental approach to Topological phenomena**

- **Topological Insulator A new quantum phase of matter has been identified (bulk Topological-Insulator) whose surfac[e] is a** new type of 2DEG **(spin-momentum locked ½ Dirac gas) protected by time-reversal symmetry.**

  Bulk Insulating samples are now realized.

- Topological Phase Transition Spin-texture and half Dirac gas is one-to-one correlated with a topological (quantum) phase transition

  Bulk-boundary correspondence

- Superconductivity & Magnetism in Topological Insulators leading to new physics of competing order : Broken symmetry vs. Topo Order

- **Topological Superconductor** some results but more work..

Reviews summarizing our works along with theory:

M.Z.H. and C.L. Kane, Rev. of Mod. Phys. 82, 3045 (2010)

M.Z.H. et.al., http://xxx.lanl.gov/abs/1105.0396 (2011) [New Review]

Reference list (Experiments on bulk Topological Insulators and Superconductors in this talk)

A Topological Dirac insulator in a Quantum Spin Hall phase (Experimental observation of the first 3D TI : Topological Order in bulk solids), D. Hsieh, D. Qian, L. Wray, Y. Xia, Y.S. Hor, R. J. Cava, M.Z. Hasan
Hsieh *et.al.*, Nature 452, 970-974 (2008). [Submitted in 2007]

Observation of unconventional quantum spin-textures (non-trivial Berry's phase) in topological Insulators (First spin-sensitive study of quantum spin Hall/topological insulator physics) D. Hsieh, Y. Xia, L. Wray, D. Qian, A. Pal, J. H. Dil, F. Meier, J. Osterwalder, G. Bihlmayer, Y. S. Hor, R. J. Cava **C.L. Kane**, and **M.Z. Hasan**.
Hsieh *et.al.*, Science 323, 919-922 (2009).

Observation of a large-gap topological-insulator class (Bi2Se3 class) with a single-Dirac-cone on the surface, Y. Xia, L. Wray, D. Qian, D. Hsieh, A. Pal, H. Lin, A. Bansil, D. Grauer, Y. Hor, R.J. Cava, M.Z. Hasan
Xia *et.al.*, Nature Physics 5, 398-402 (2009).

A tunable topological insulator in the spin-Helical Dirac transport regime, D. Hsieh, Y. Xia, D. Qian, L. Wray, J. H. Dil, F. Meier, L. Patthey, J. Osterwalder, A.V. Fedorov, H. Lin, D. Grauer, Y.S. Hor, R.J. Cava, M.Z. Hasan
Hsieh *et.al.*, Nature 460, 1101-1005 (2009).

Topological surface states protected from backscattering by chiral spin texture P. Roushan, J. Seo, C. V. Parker, Y. S. Hor, D. Hsieh, D. Qian, A. Richardella, M. Z. Hasan, R. J. Cava, A. Yazdani
Roushan *et.al.*, Nature 460, 1106-1009 (2009).

A topological insulator surface under strong Coulomb, magnetic and disorder perturbations, L.A. Wray, S. Xu, Y. Xia, D. Qian, H. Lin, A. Bansil, Y. Hor, R.J. Cava, M.Z.Hasan
Wray *et.al.*, Nature Physics 7, 32-36 (2010).

Observation of topological order in a superconducting doped topological insulator, L.A. Wray, S. Xu, Y. Xia, D. Qian, H. Lin, A. Bansil, Y. Hor, R.J. Cava, M.Z. Hasan
Wray *et.al.*, Nature Physics 6, 855-859 (2010).

Topological Insulators: Rev. of Mod. Phys. 82, 3045 (2010)

<u>Three Myths</u> on Topological Insulators/Experiments:

1. Expts on 3D Topological Insulators are extensions and derivatives of quantum spin Hall effect of 2D topological insulators. **NO.**

3D-TI Spectroscopy/ARPES: Hsieh et. Nature (2008) [Subm. 2007, Nov]

2D-TI Charge-Transport/ Konig et. Science (2007)[Subm. 2007, June]

Two different types of experiments independently reported topological **<u>edge states</u>** and **<u>topological surface states</u>** (in addition, these two papers are a few months apart not several years). **Most people work on Surface States.** So 3D expts have been reproduced by many others…(>95% expt. papers are on 3D)

2. Transport in topological insulators are Z2 quantized.
   NO.
   Observation of spin-momentum locking ½ Dirac gas
   (or/and a topological phase transition) closes the case

This was first done in 3D topological insulators (spin in 2D QSH etc. came later)

3. MBE films of 3D Topological insulators are better than bulk insulating samples.
   NO!; Z2 Topological Proof does not require MBE films and Transport and has long been done (focus of this talk, also see reviews RMP 2010)
   Our Spectroscopy results show that no NEW topological information in gained in the best MBE films (nothing to do with quality of the films!!)
   Films may or may not (in future) help us observe proximity effects (many are working on this including our team ..)

Thanks !

General Reading on Topological Surface States

"Search & Discovery": PHYSICS TODAY '09 (April)
Feature article: PHYSICS TODAY '10 (January)
News: PHYSICS TODAY '09 (August)

NEW SCIENTIST '10 (July)
SCIENTIFIC AMERICAN '10

Sorry for the Priority issues!

Reviews :

M.Z.H and C.L. Kane, Rev. of Mod. Phys. 82, 3045 (2010)
M.Z.H and J.E. Moore, Ann. Rev. of Cond. Mat. Phys. 2, 55 (2011)
X.-L. Qi and S.-C. Zhang Rev. of Mod. Phys. (in press) (2011)