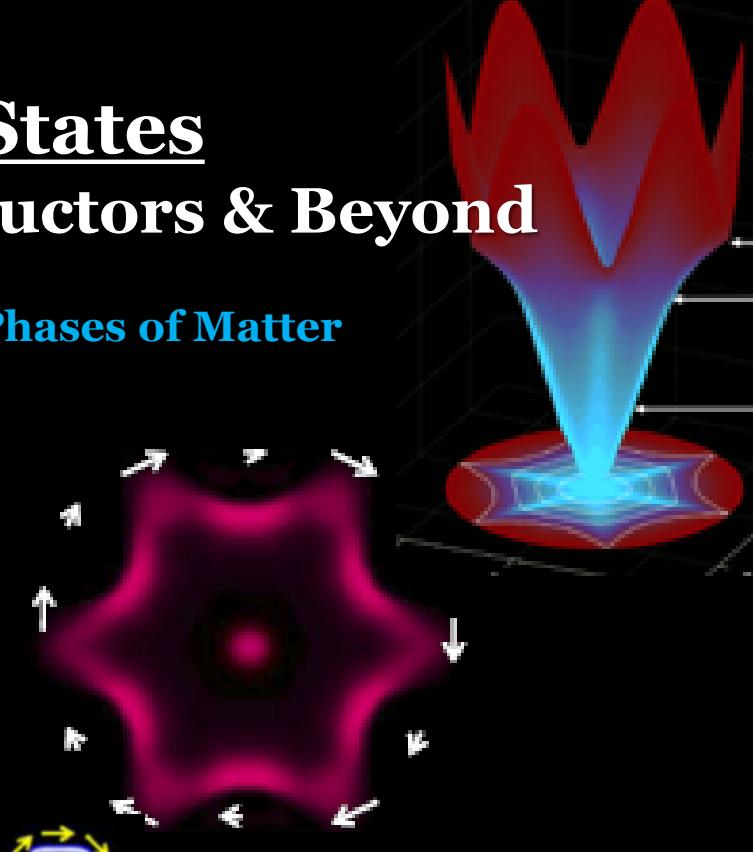
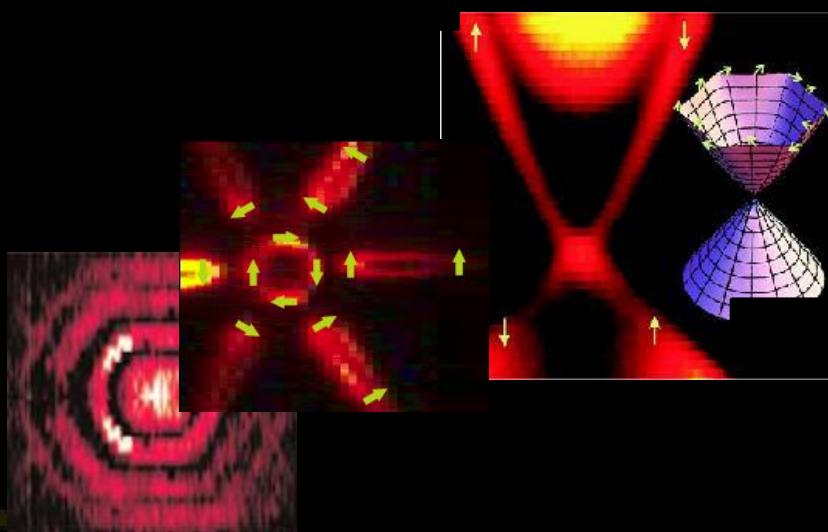


Topological Surface States

Topological Insulators, Superconductors & Beyond

NORDITA workshop on Topological Phases of Matter
Stockholm, Sweden
July 2012

M. Z. Hasan
Dept. of Physics, Princeton Univ.



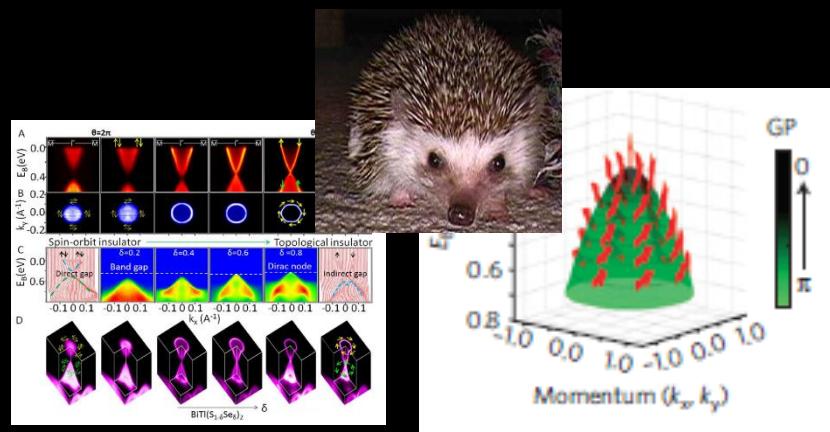
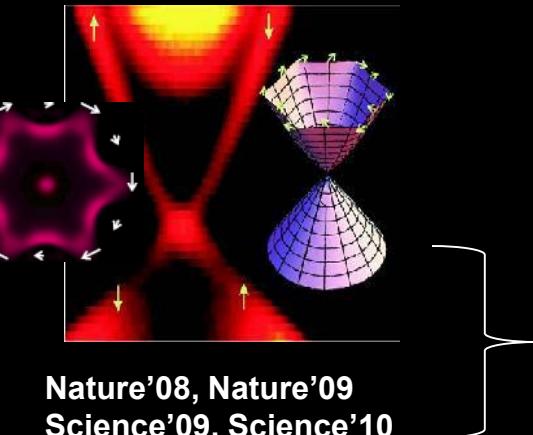
Overview of this talk

Z2 TI Brief Overview (Expts)
**Surface States as a Novel 2DEG
Topo-Phase-Transition**

Interaction effects?

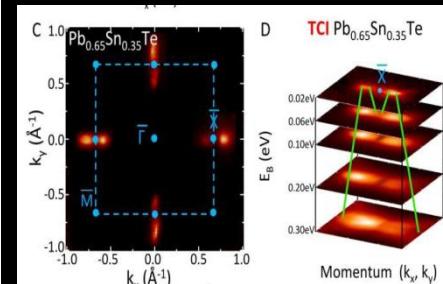
***Superconductivity, Ferromagnetism
Topo-Phase-Transition & Weyl Fermion?***

TI beyond Kane-Mele Z2 theory? TCI phases?



Science'11
Preprint'12

NatPhys'12
NatPhys'11, Preprint'12



Preprint '12 (arXiv)

Physics/Experiments Team

David Hsieh, Dong Qian, Andrew Wray, Yuqi Xia, SuYang Xu, MZH



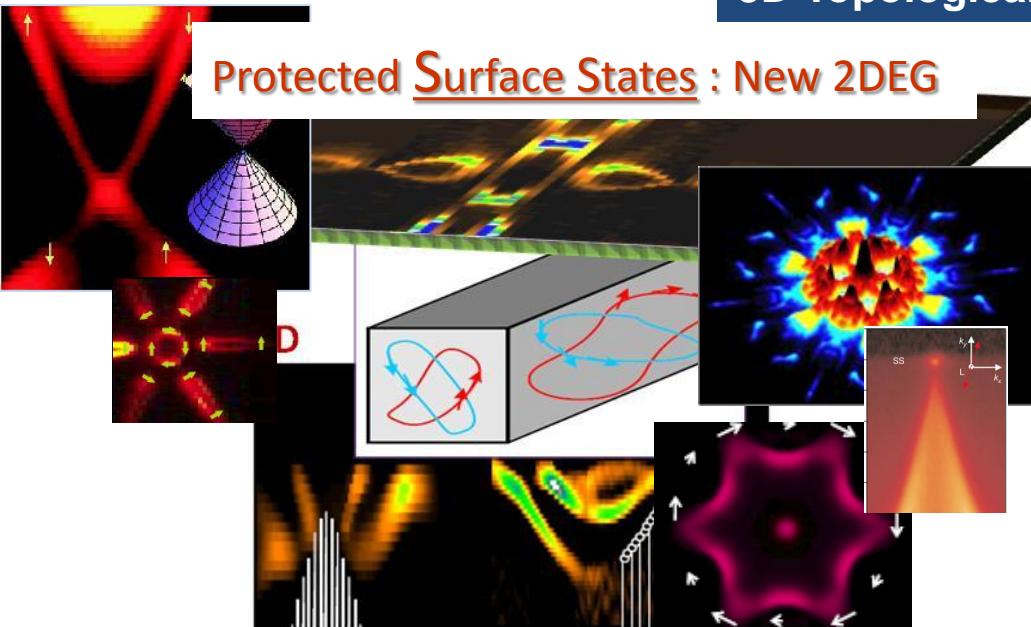
**M. Neupane,
C. Liu, Alexei Fedorov
H.K Mo (Berkeley)
at LBNL-ALS
J.H. Dil et.al.,
J. Osterwalder
at SLS/PSI (Zurich),
E. Vescovo (BNL
-Brookhaven)
J.Xiong & NP Ong
(Princeton)**

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

LDA/First-Principles: H. Lin, A. Bansil (NEU)

Topological Insulator

$\{v_o\}$ (Chern Parity invariants) Z_2 Kane-Mele & many others



3D Topological Insulators

Protected Surface States : New 2DEG

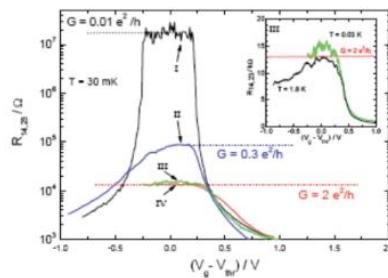
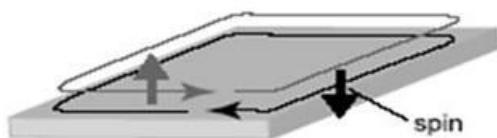
Quantum Hall Effect

v (Chern Number): Z (TKNN)

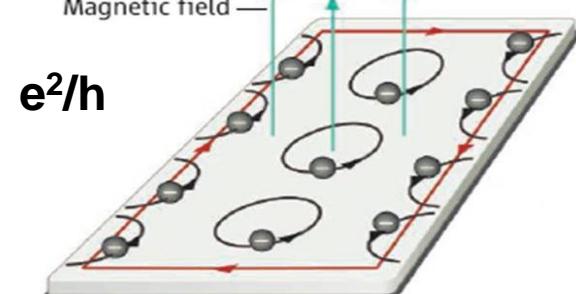


2D Topological Insulators

$2e^2/h$



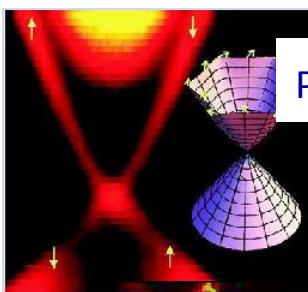
Edge States (1D) by TRS



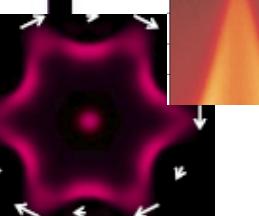
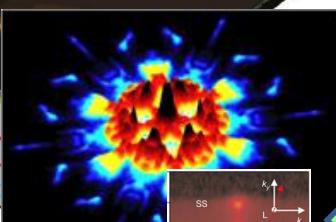
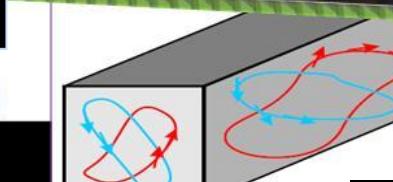
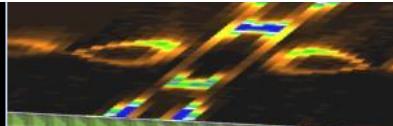
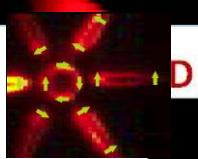
Chiral Edge States (1D)

Topological Insulator

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

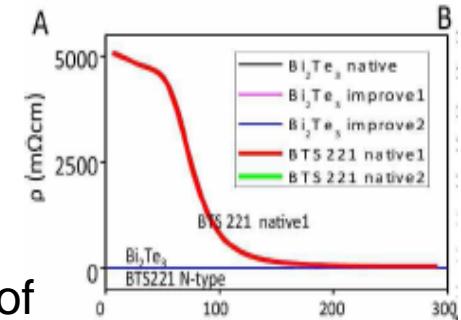


Protected Surface States :New 2DEG



3D Topological Insulators

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



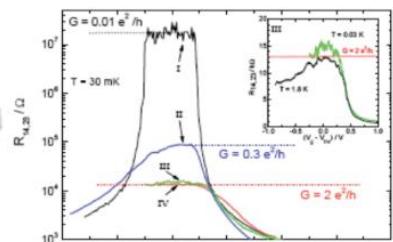
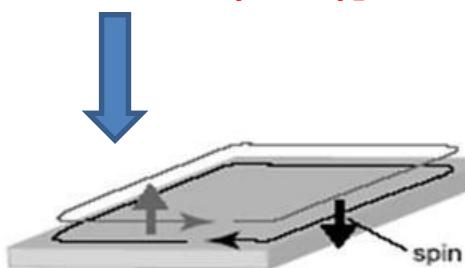
Proof of
topological nature of
Topological surface states

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

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

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

2D Topological Insulators



QSH edge States (1D) by TRS

Charge transport
Measurement of edge states
of quantum spin Hall

Experimental Challenge:

experimental “measure” of topological invariants ?
(no quantization of charge or spin transport)

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

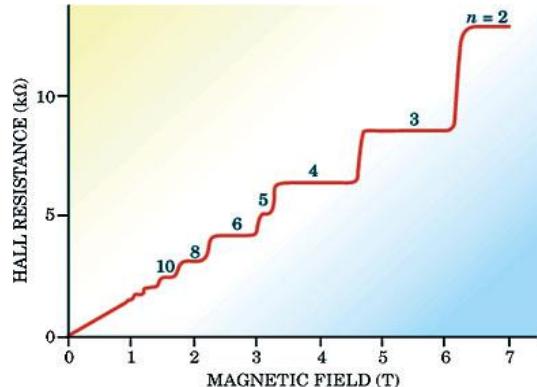
Experimentally IMAGE boundary/edge/surface states
Experimentally Probe BULK--BOUNDARY CORRESPONDENCE
Experimental prove “topological order”

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

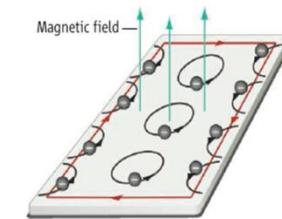
QHE phases

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

Topological quantum number



Transport



Topo Insulators

$$v_o = \Theta / \pi$$

$\Theta = \pi$ (odd)

$\Theta = 2\pi$ (even)

No quantized transport

via :

$$\{v_i\}$$

Topological quantum number

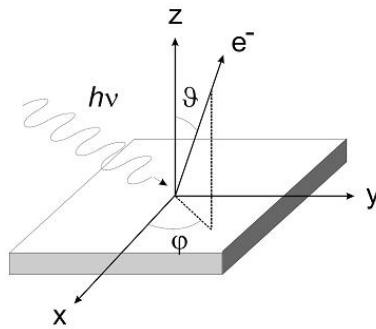
How to experimentally “measure” the topological quantum numbers (v_i) ?

4 TQNs → 16 distinct insulators

$\{v_0, v_1, v_2, v_3\}$
Topological “Order Parameters”

Spin-sensitive
Momentum-resolved
Edge vs. Bulk

Photoelectric Scattering Process

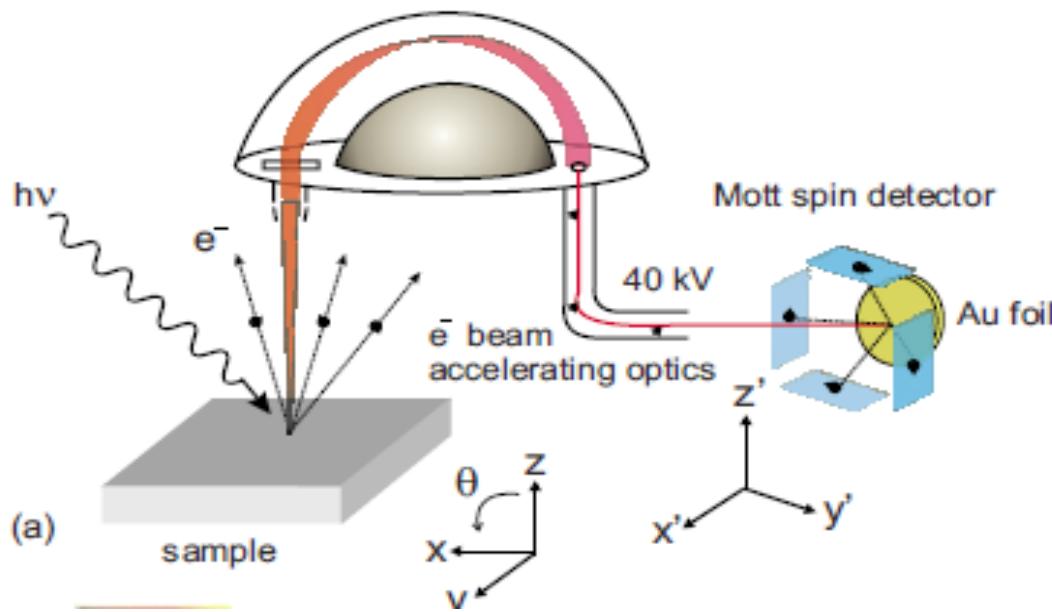
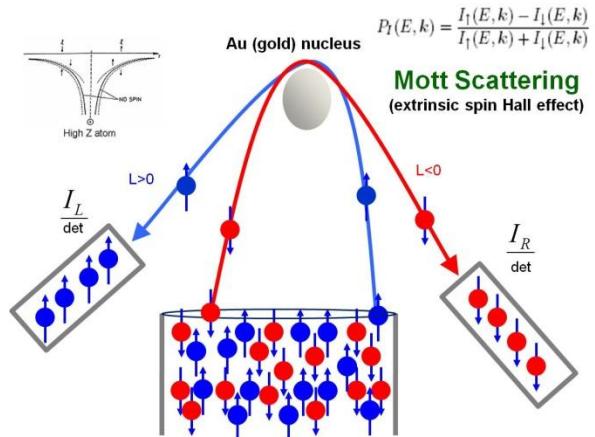


$$K_x = \frac{1}{\hbar} \sqrt{2mE_{kin}} \sin\vartheta \cos\varphi$$

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

$$K_z = \frac{1}{\hbar} \sqrt{2mE_{kin}} \cos\vartheta$$

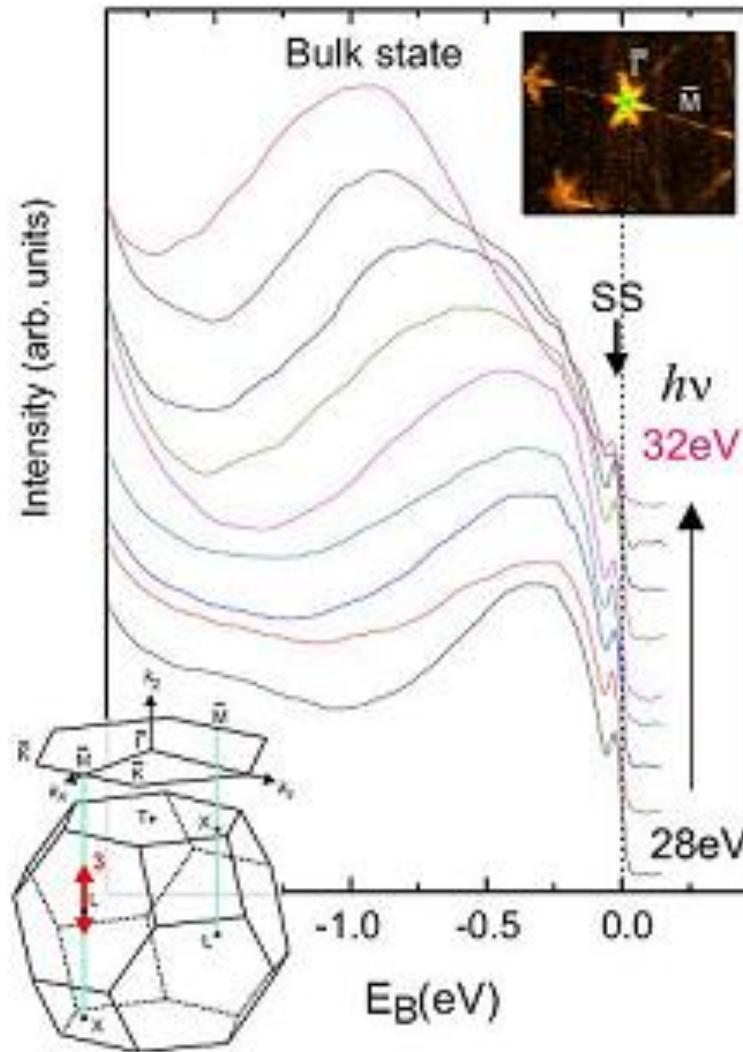
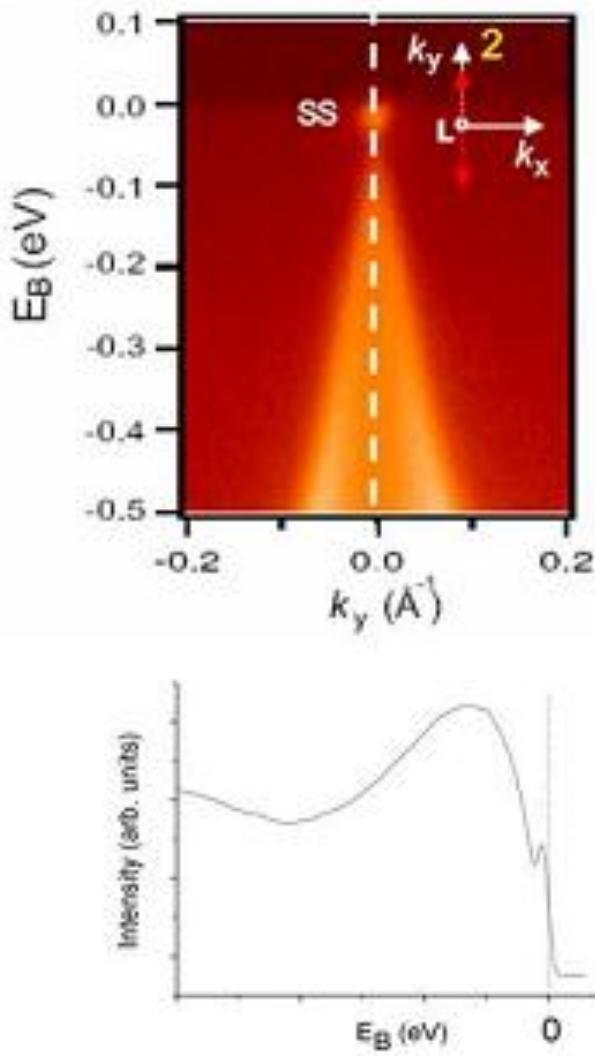
- By measuring electron intensity as a function of E_{kin} , ϑ and φ , a momentum resolved energy spectrum is obtained



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

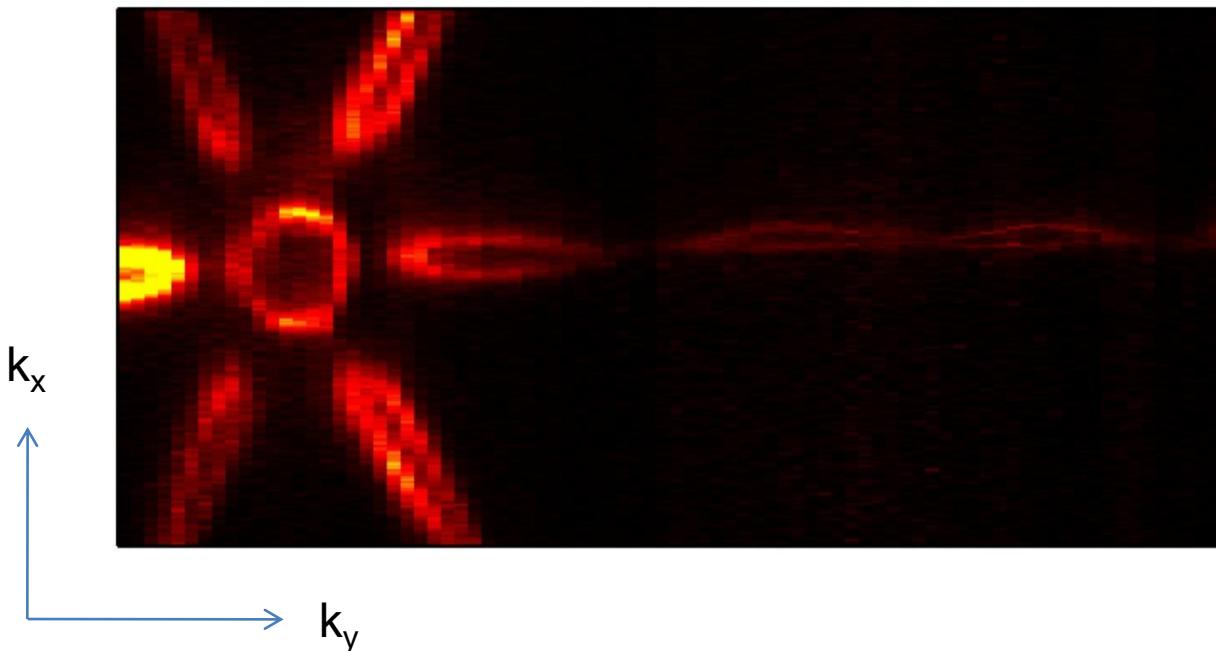
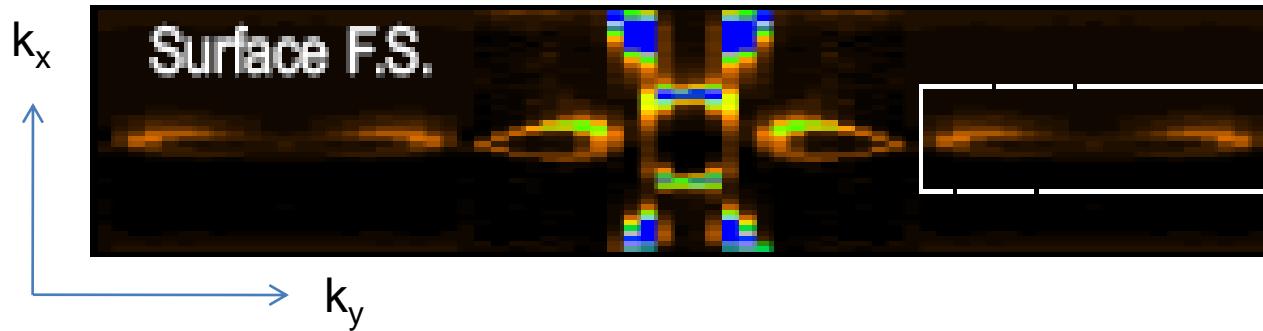
Band-structure of Bi(Sn)Sb semiconductors

Fu-Kane PRB'07 Prediction: Bi-Sb Z_2 non-trivial since Sb is non-trivial but Bi is trivial

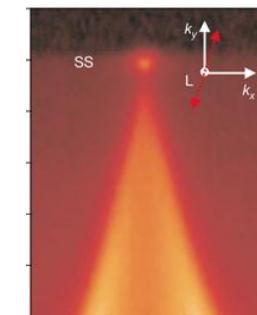


Protected Fermi surface on the surface on an insulator (first Topological Insulator (3D): Thermoelectric Bi(Sn)Sb alloy semiconductors)

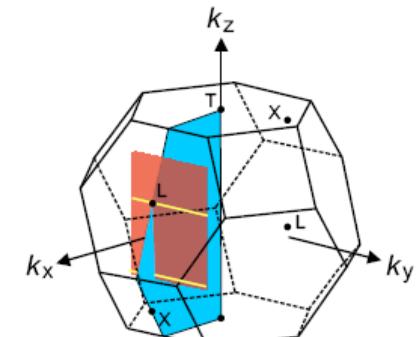
Z_2 non-triviality (theory) does not predict the actual Fermi surface



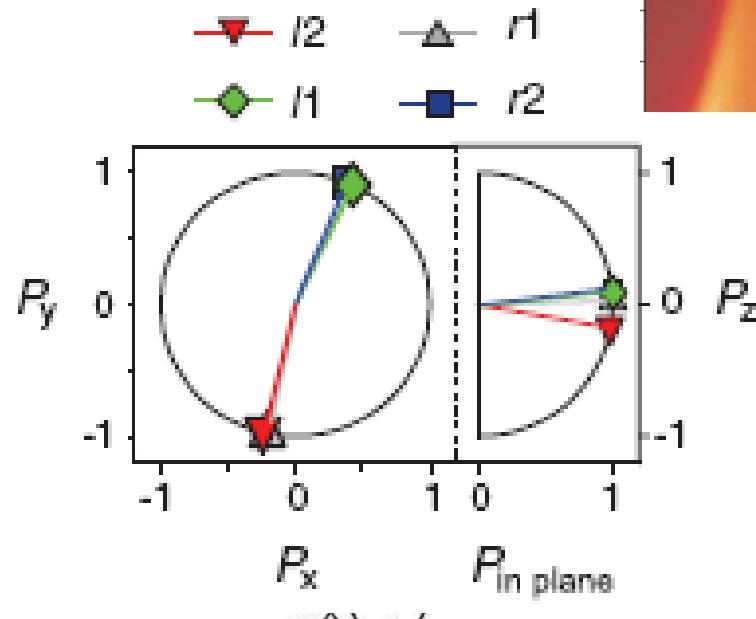
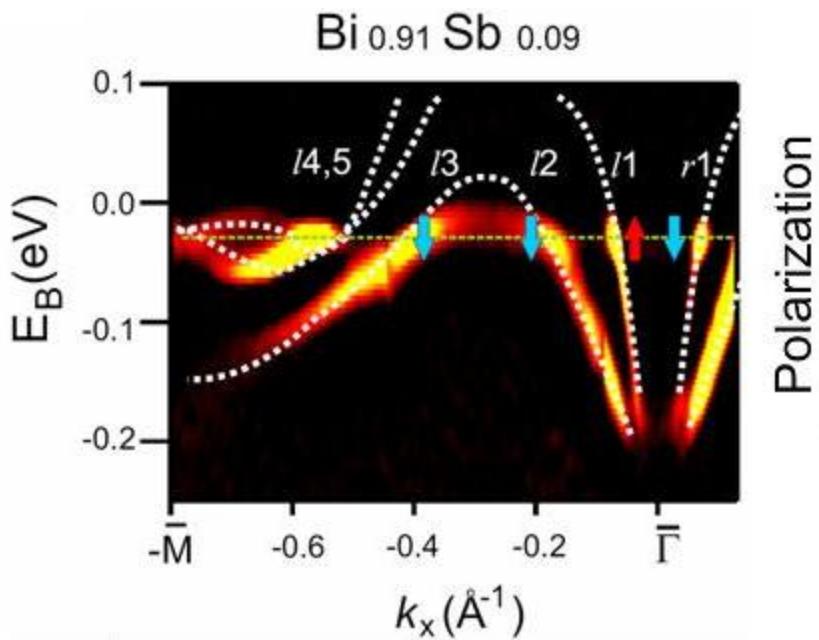
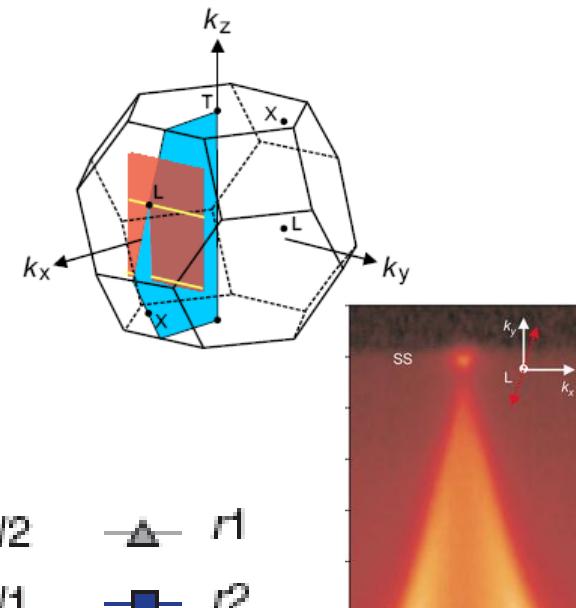
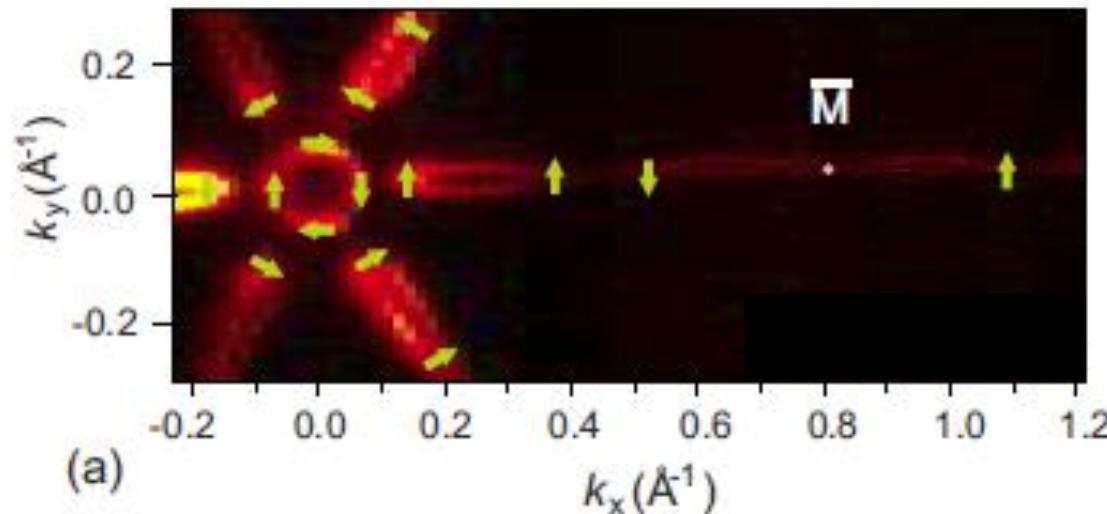
Dirac Fermion



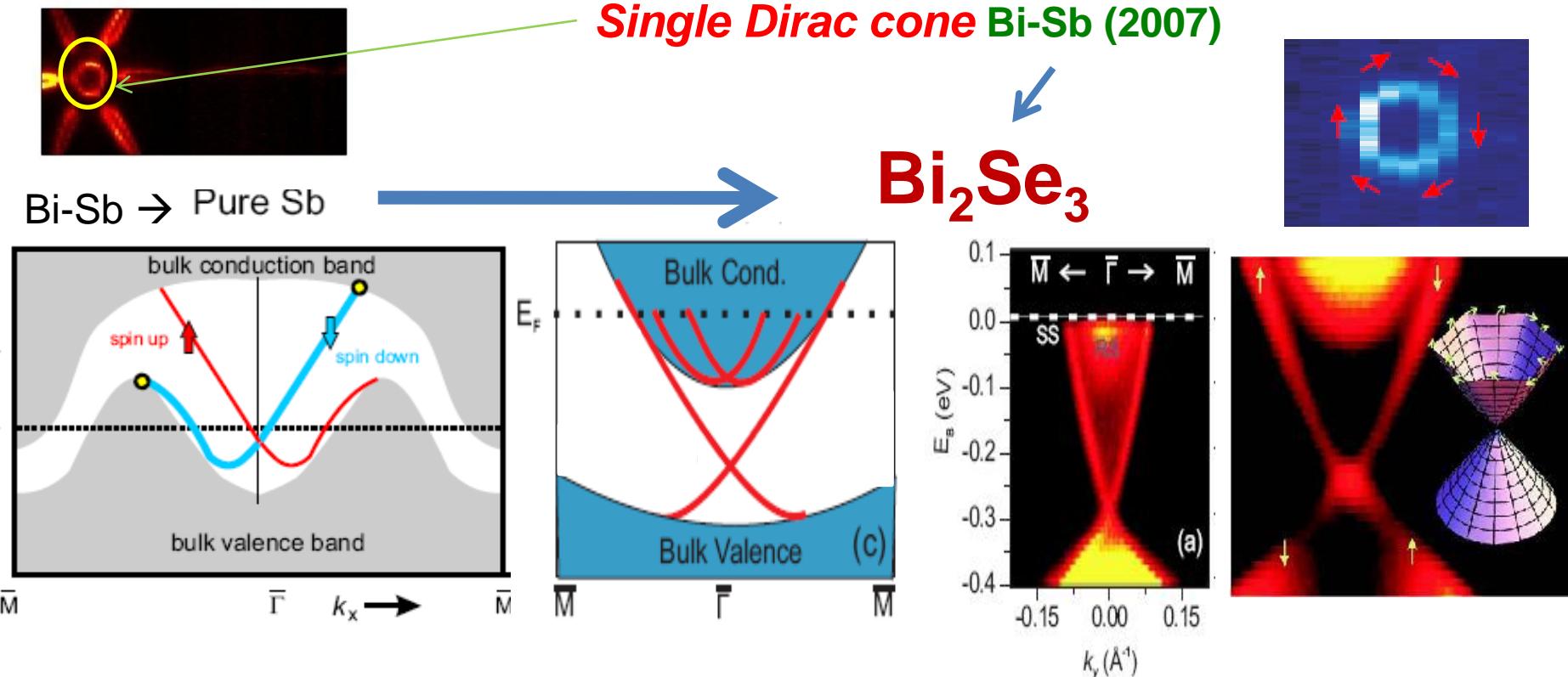
NATURE 08
KITP Proc. 2007



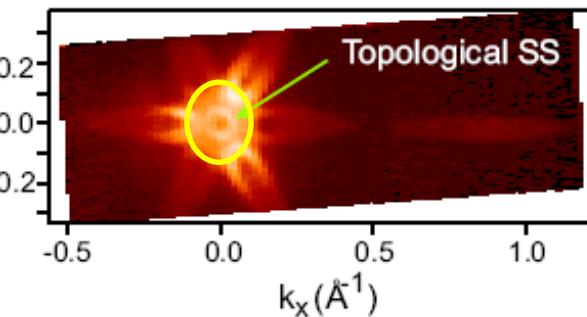
Spin Texture on the SS Fermi surface



Can we make a large-gap version of TI ..



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

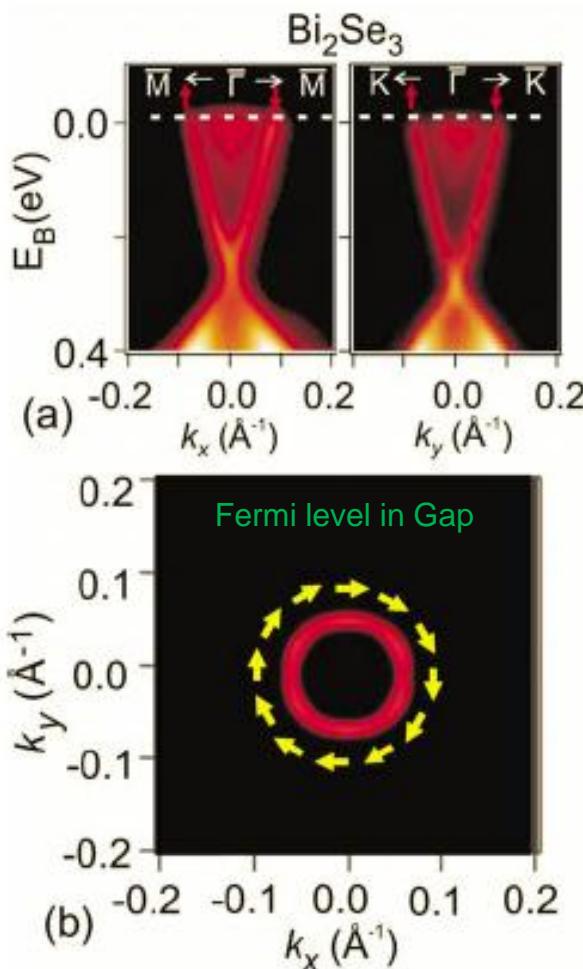


Bi₂Se₃ class as TIs :
Xia et.al., **NATURE PHYS** 09, arXiv (2008)
Hsieh et.al. **NATURE** 09
Zhang et.al. **NATURE PHYS** 09

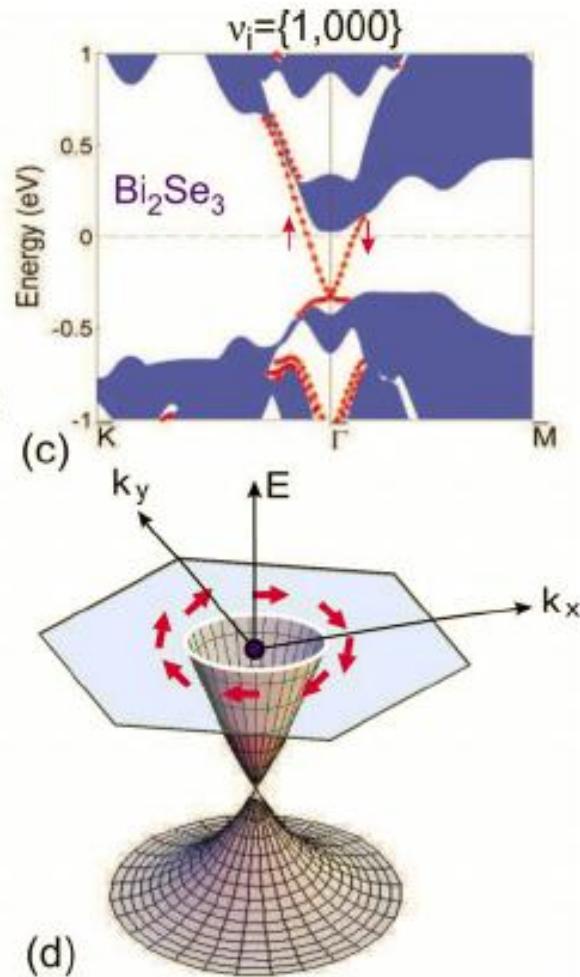
Single Dirac cone in (Bi-Sb alloy)
→ Single Dirac cone ONLY in Bi₂Se₃ class

Chirality change through the Dirac node

Left handed

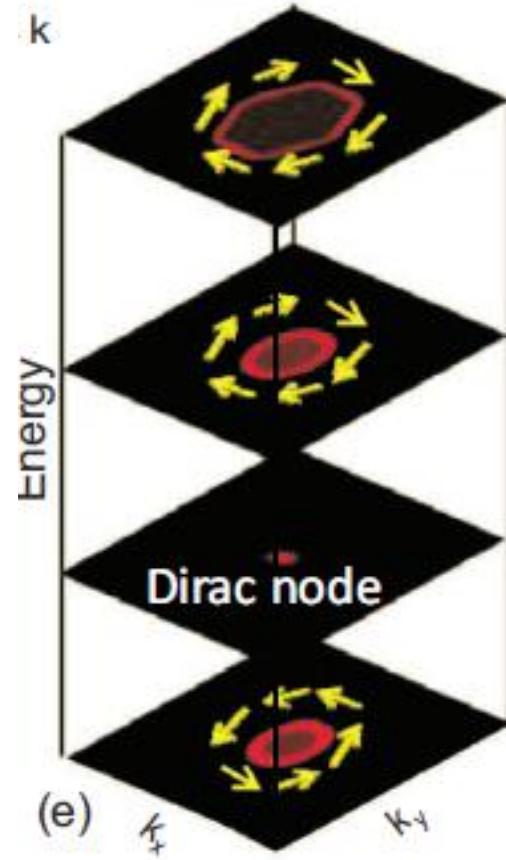


Spin-ARPES



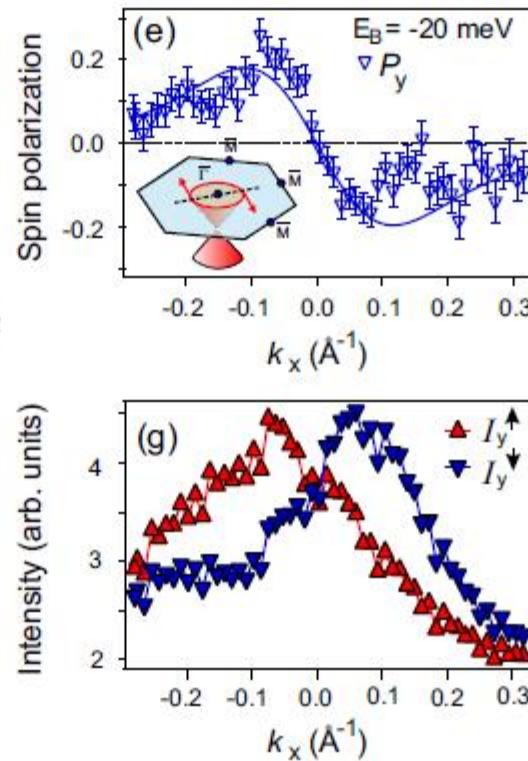
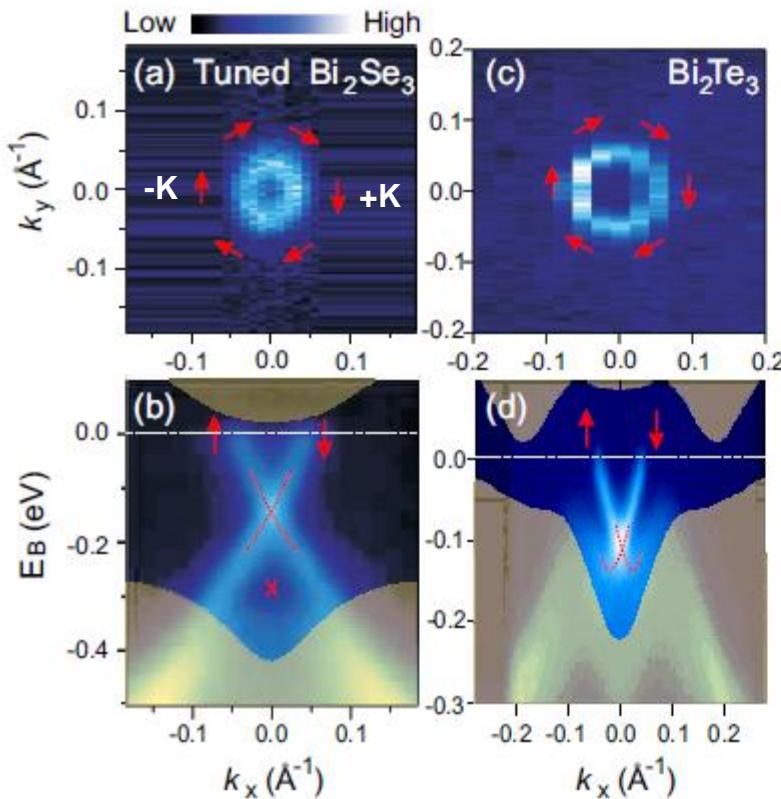
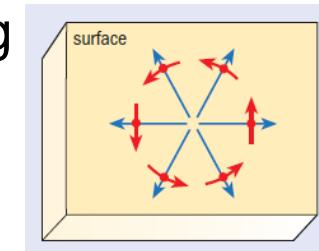
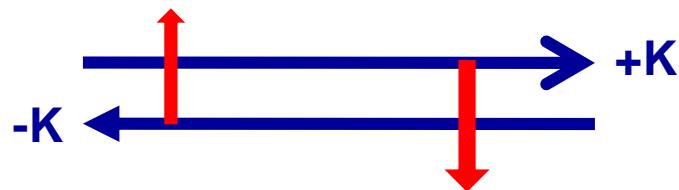
Nature (2009)

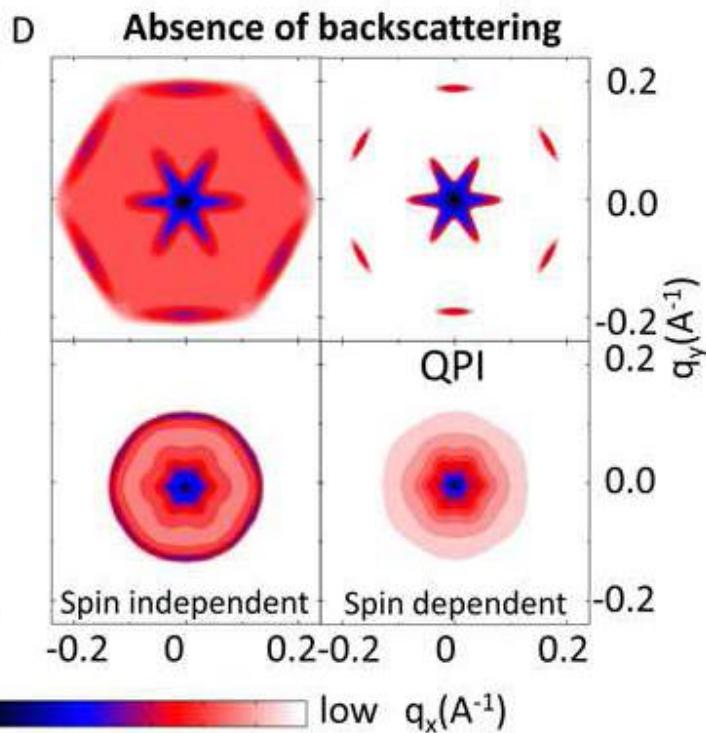
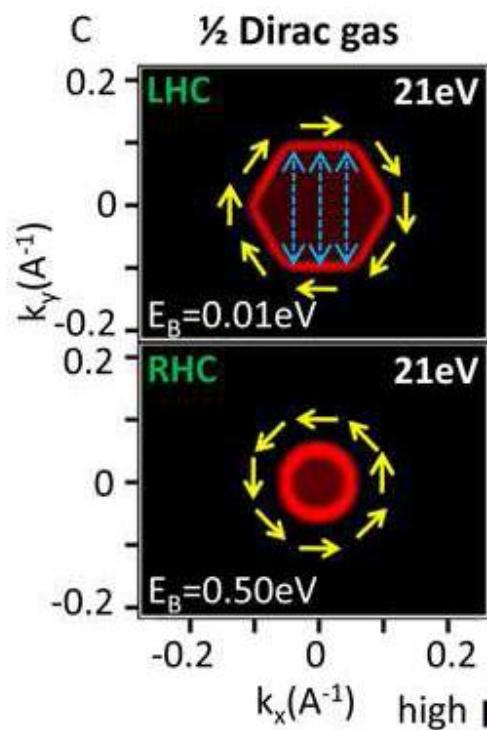
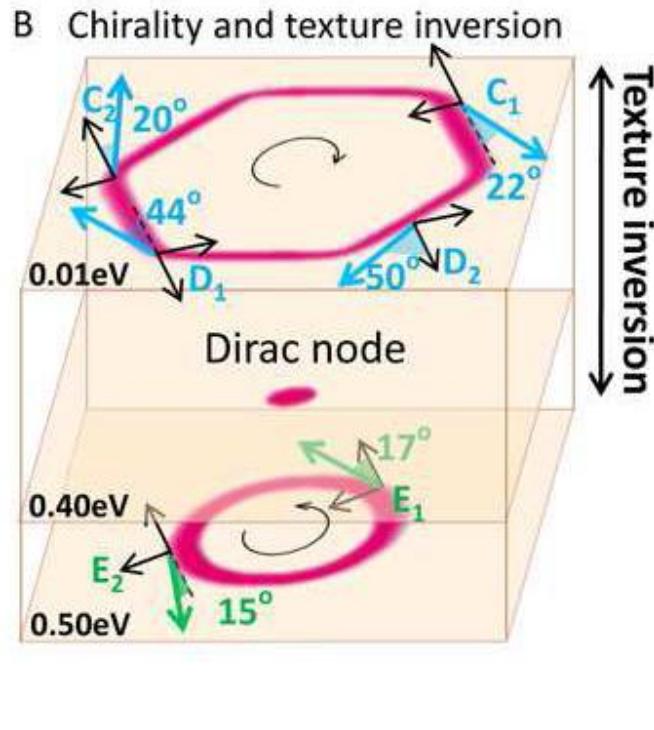
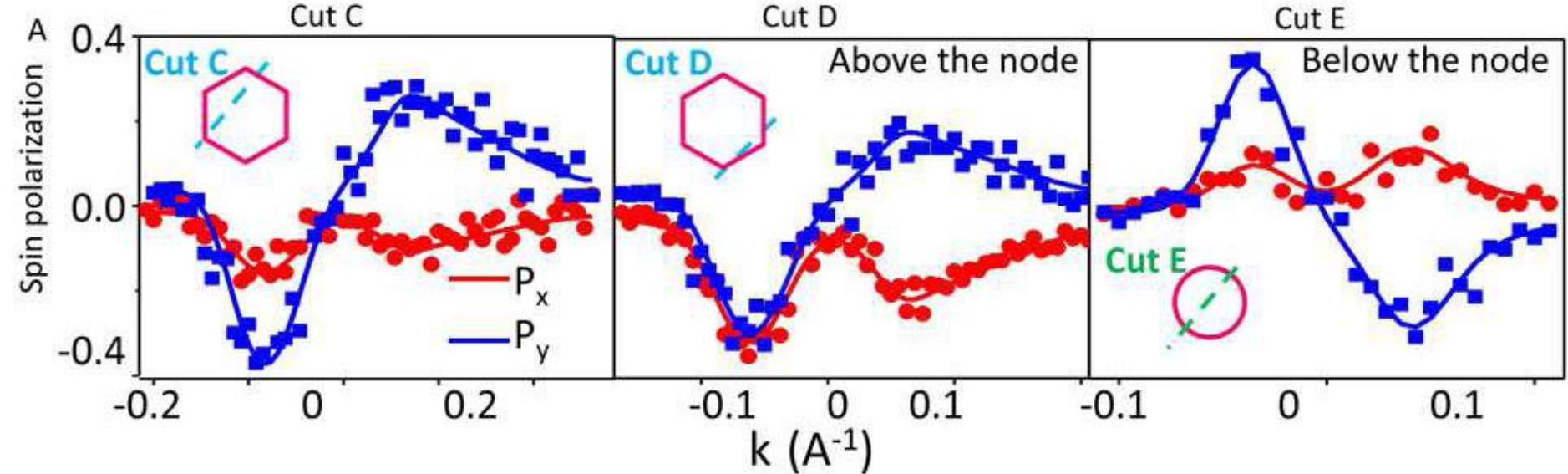
Topological Order



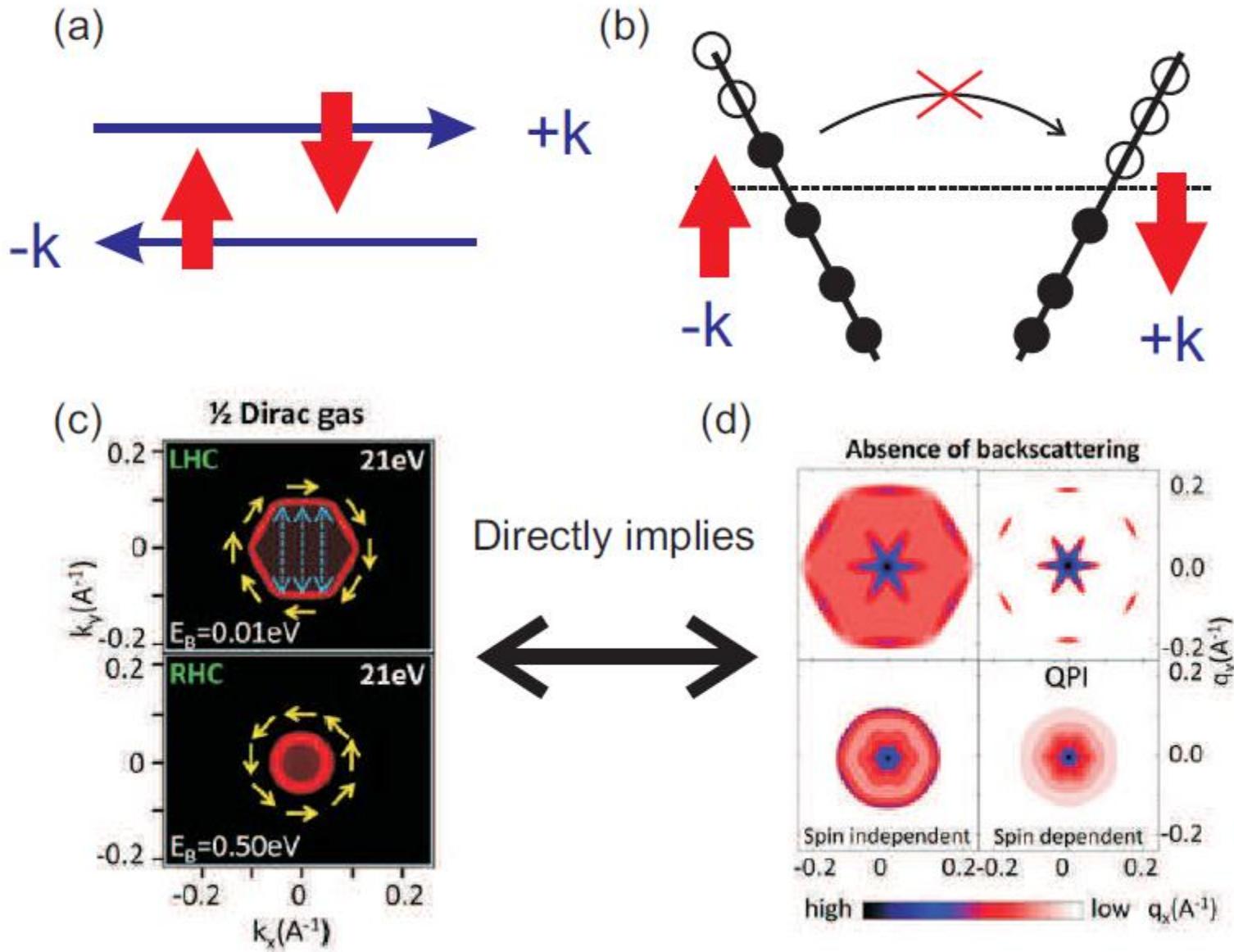
Helical Dirac fermions

One to One Spin-LinearMomentum Locking

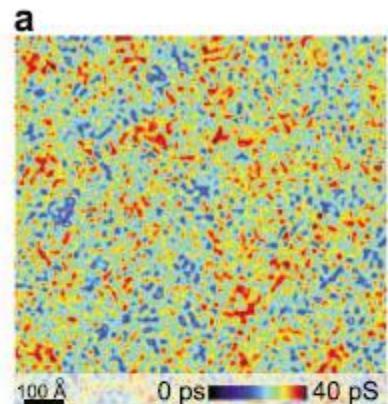




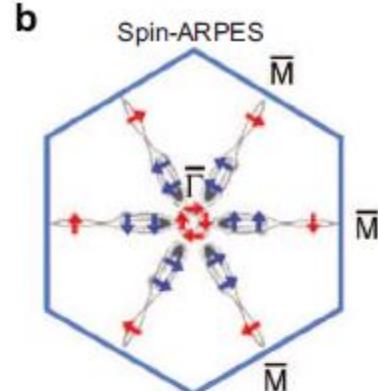
Helical spin texture directly implies absence of backscattering



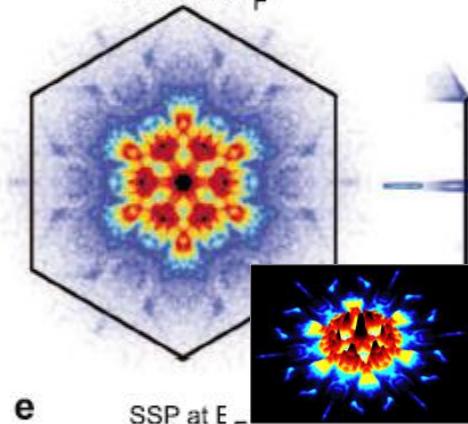
STM (Roushan et.al.)



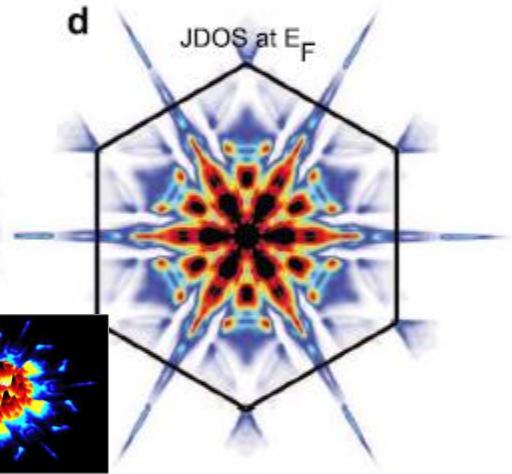
Spin-ARPES (Hsieh et.al.)



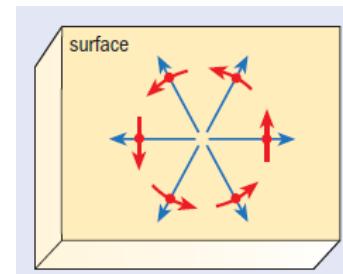
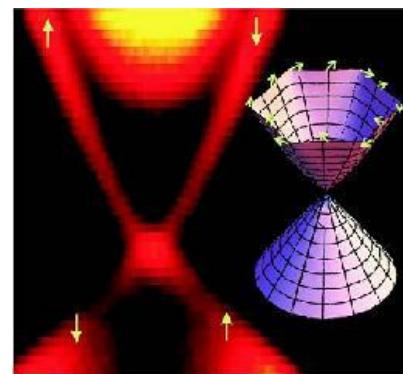
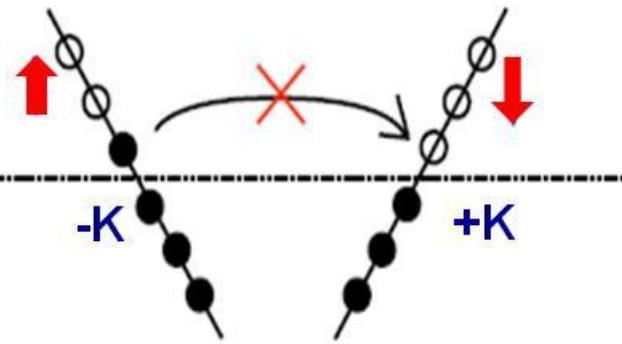
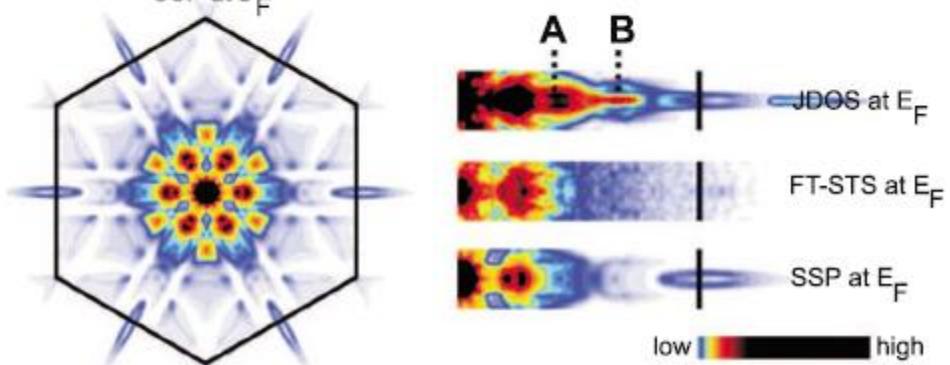
c FT-STS at E_F



d JDOS at E_F



e SSP at E_F



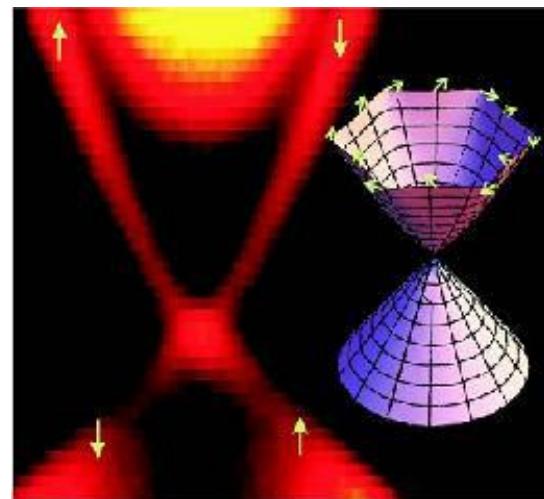
Spin-Independent

Spin-Dependent

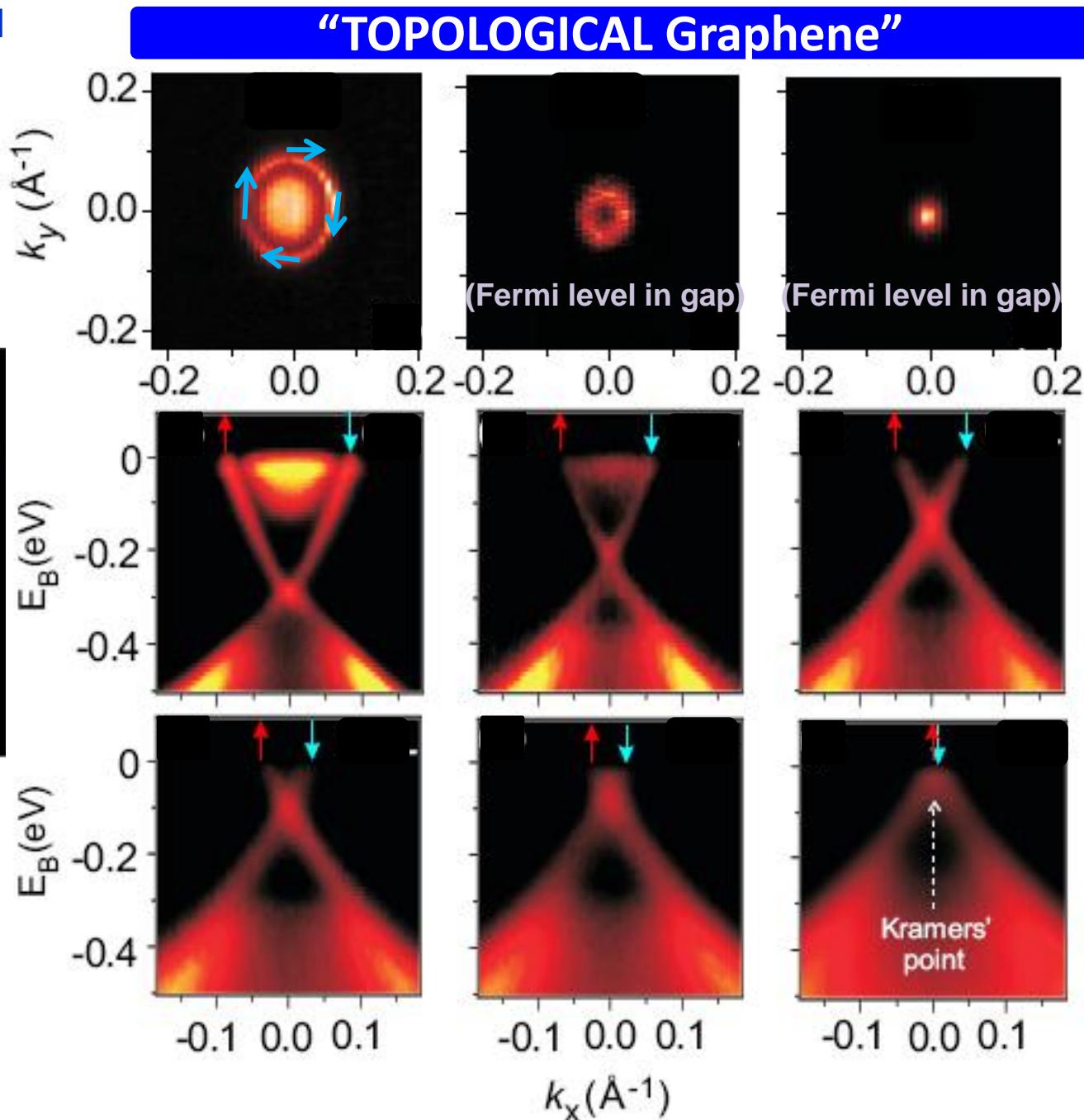
Roushan et.al., NATURE 09 & Others

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

“TOPOLOGICAL Graphene”

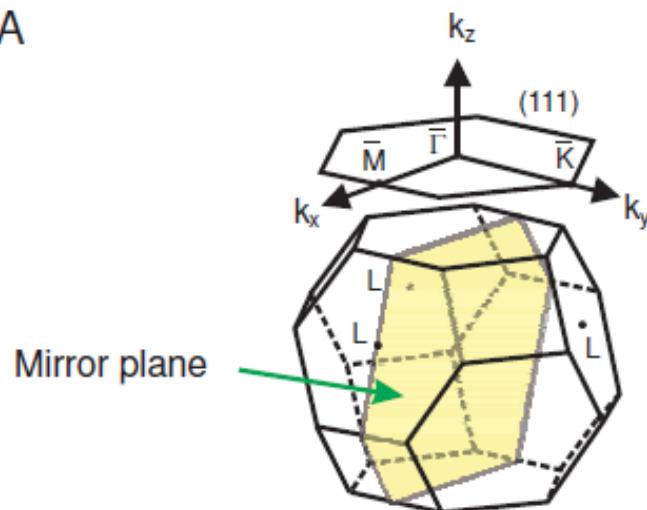


Electrical Gating
is also possible

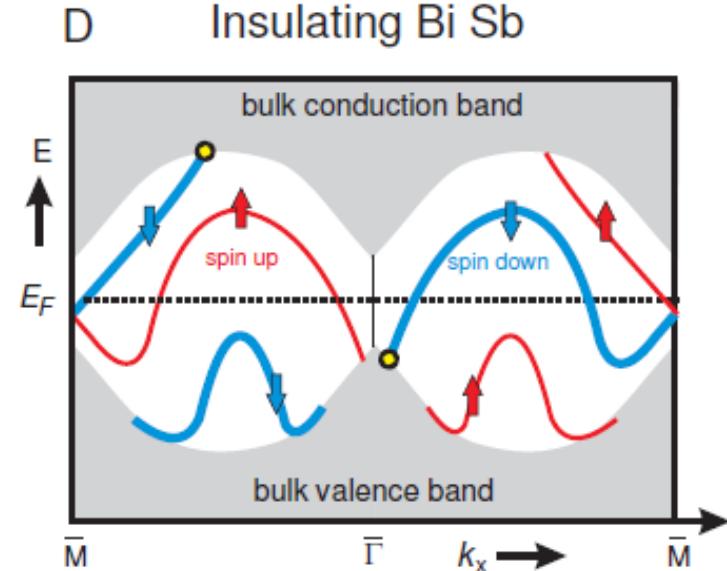


Mirror Chern number

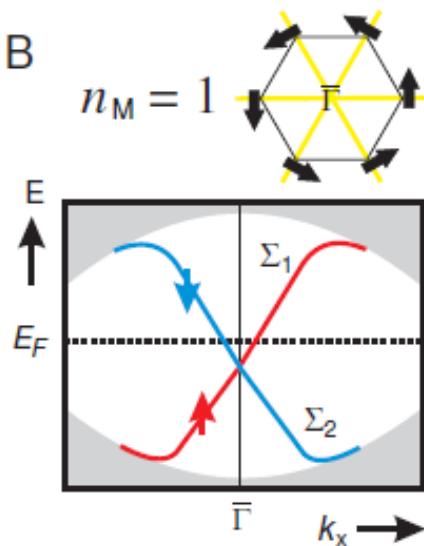
A



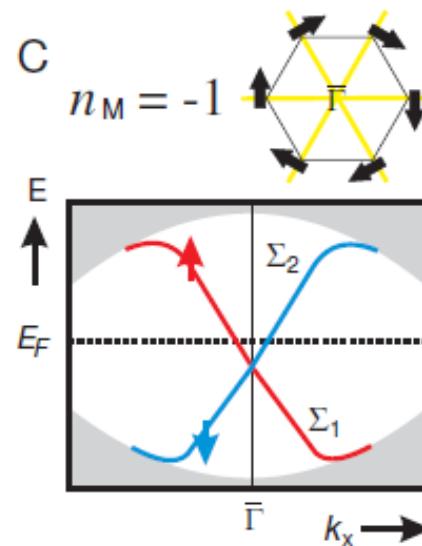
D



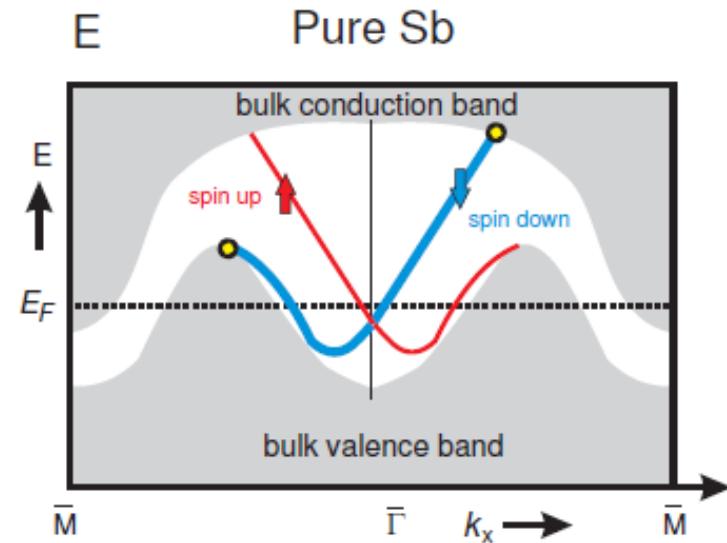
B



C

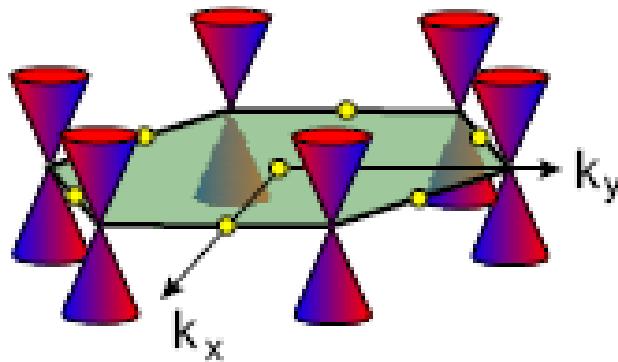


E



Graphene

Excellent Material Properties



Bulk band structure:
Dirac Fermion
is a BULK state

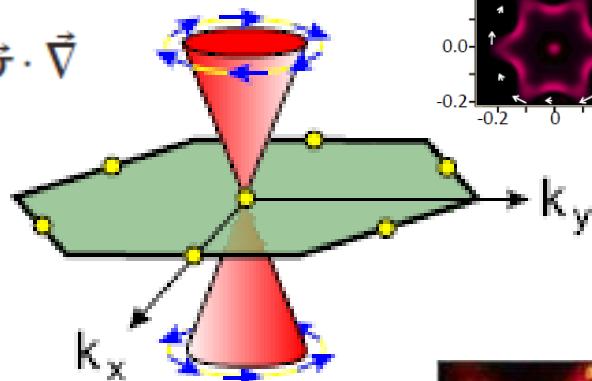
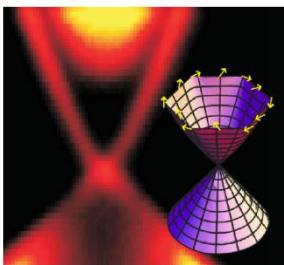
$$\sigma_{xy} = 2e^2/h$$

(q-Hall effect)

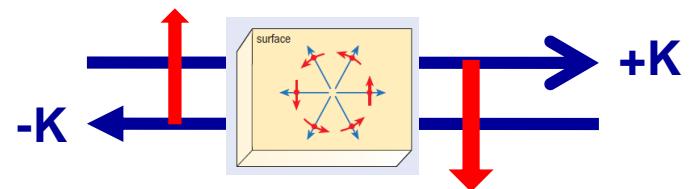
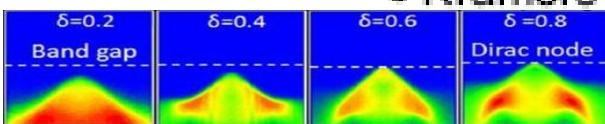
Topo Insulator

Chirality Inversion

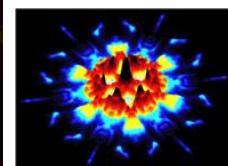
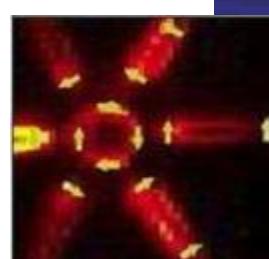
$$\mathcal{H}_{\text{surface}} = -i\hbar v_F \vec{\sigma} \cdot \vec{\nabla}$$



• Kramers' point



Protected Surface States : New 2DEG



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

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

Bi₂Se₃ : Topological Order at Room Temperature

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

Protected Surface States (New 2DEG)

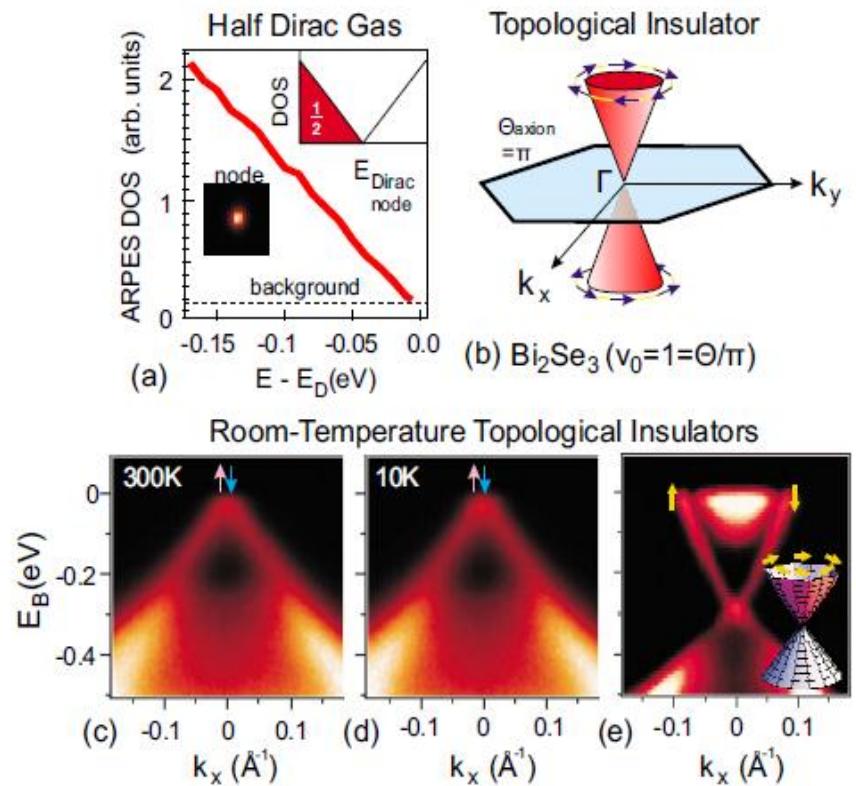
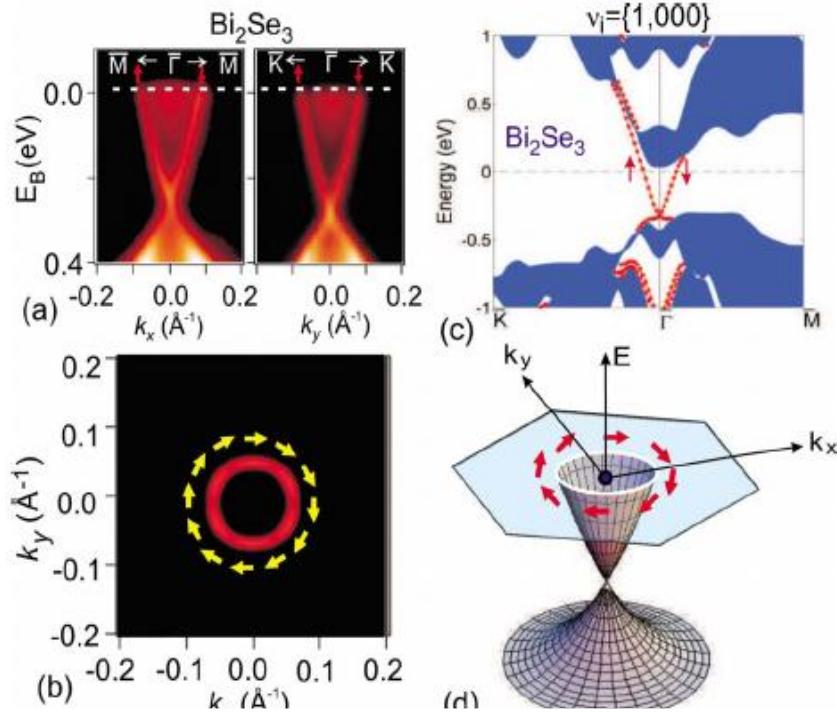
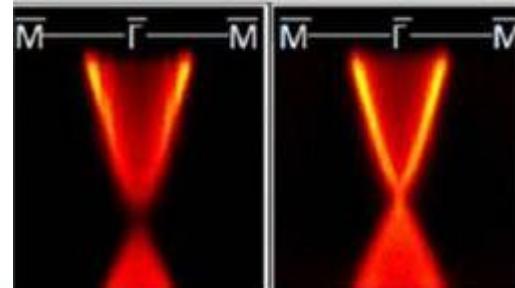
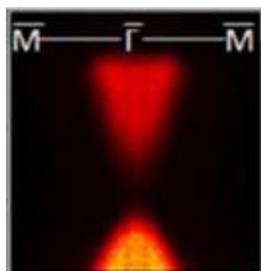


FIG. 12. (Color online) Helical fermions: Spin-momentum

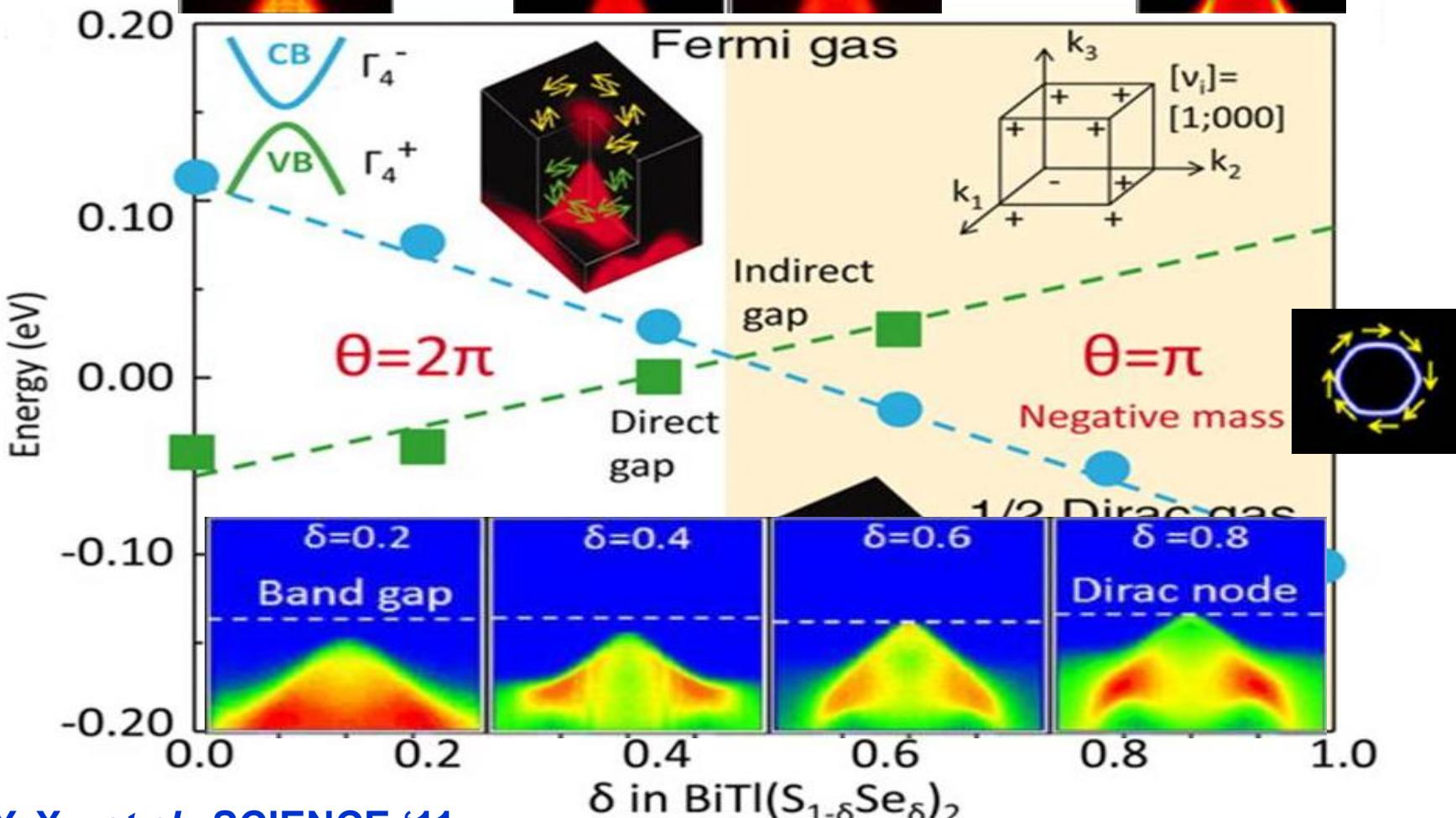
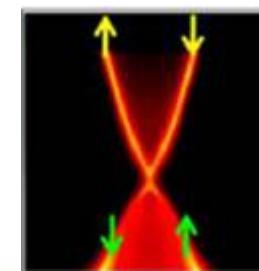
Weak electron-phonon coupling at 300K

Band inversion and Topological Phase Transition

Non-inverted

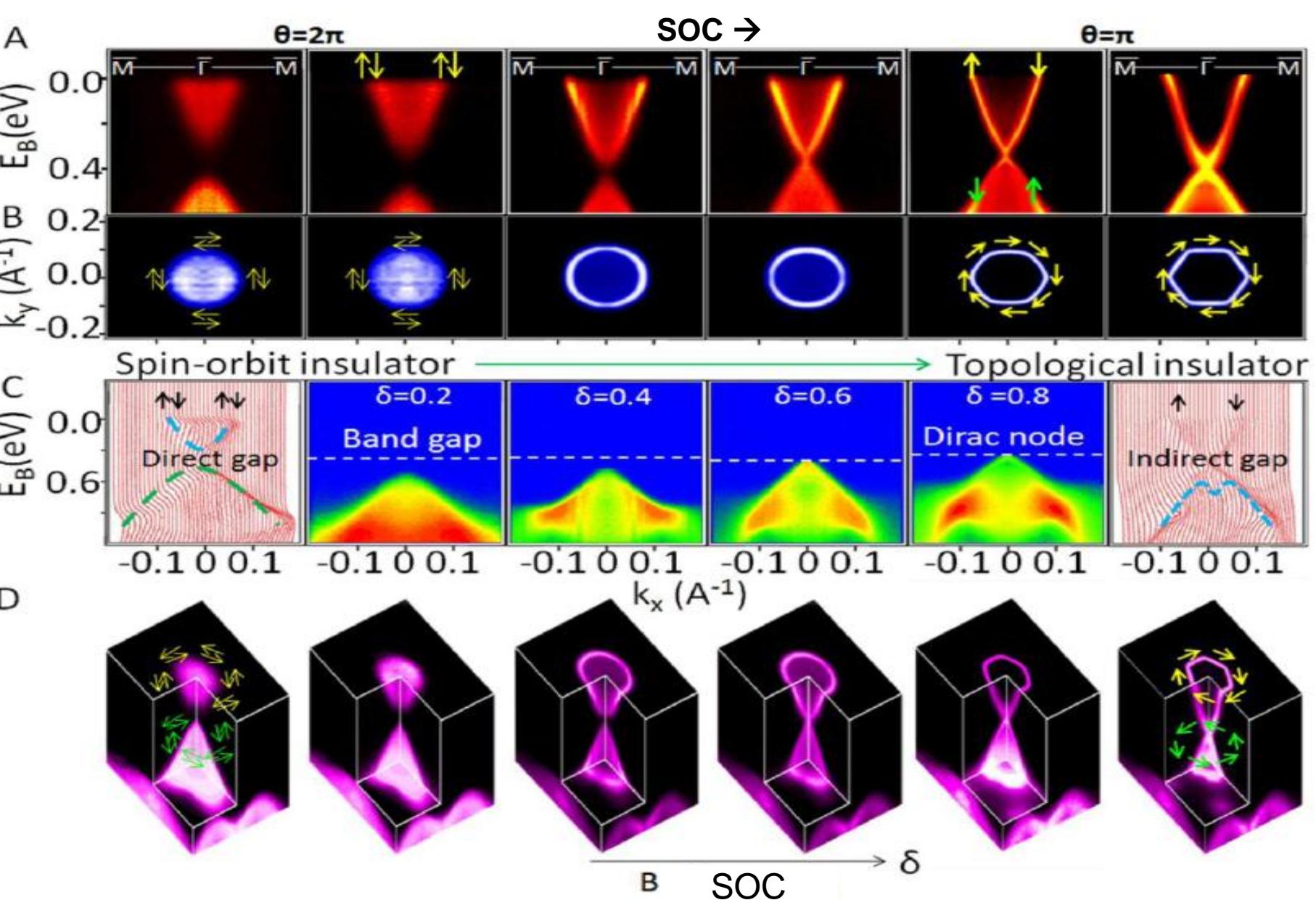


Inverted



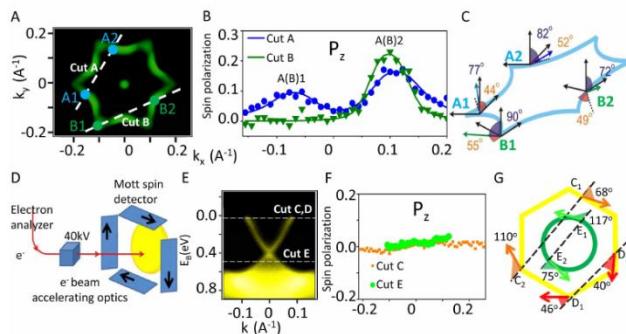
Topological phase Transition

Su-Yang Xu et.al., SCIENCE'11

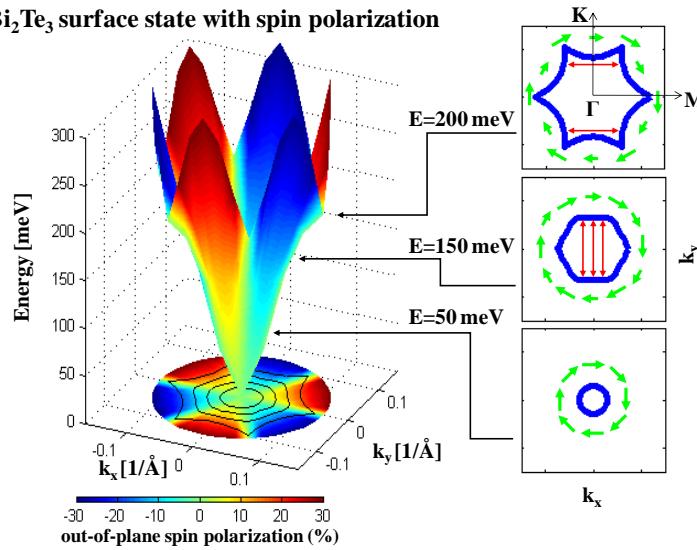


Evolution of Out-of-plane Spin-Texture

3D Vectorial Spin Textures

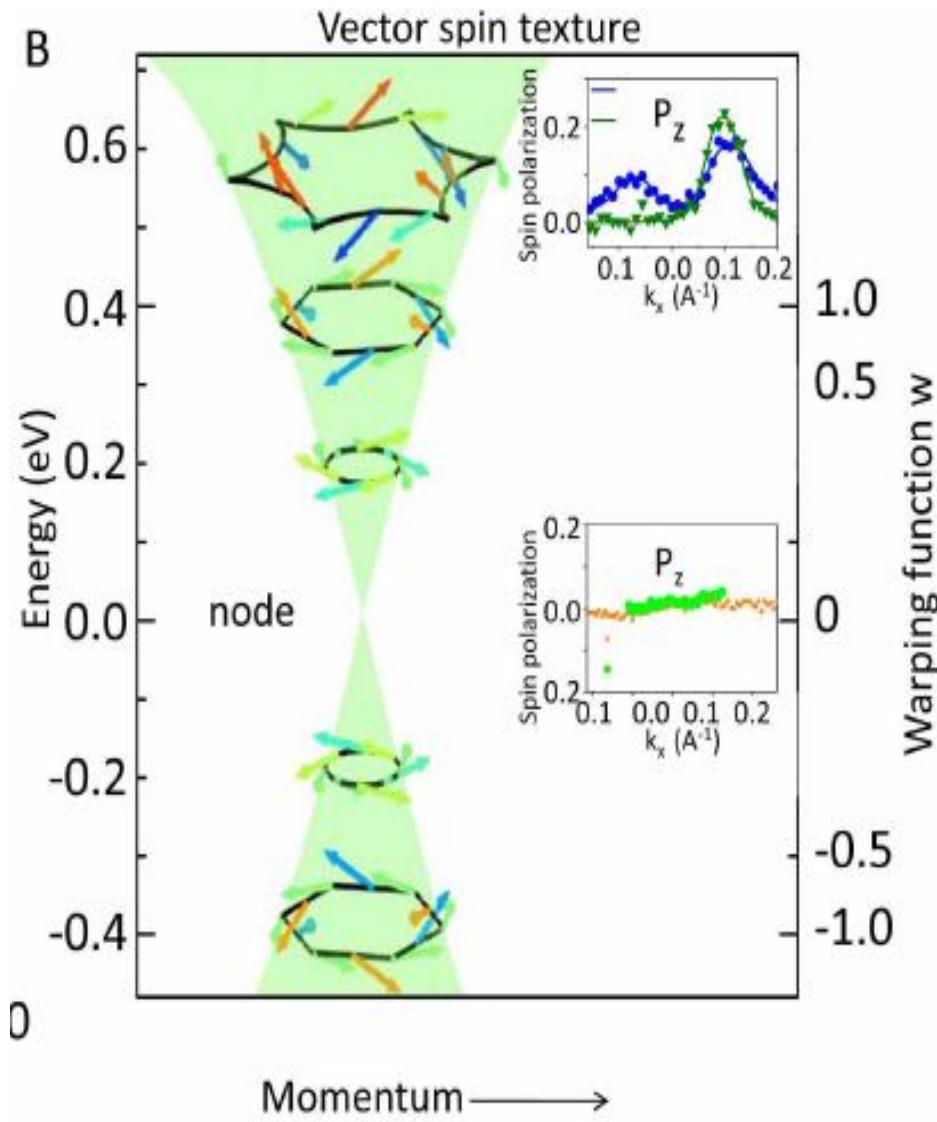


Bi_2Te_3 surface state with spin polarization



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

Hsieh et.al., NATURE '09, SuYang Xu et.al., SCIENCE '11



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**

Topo-insulators in nature

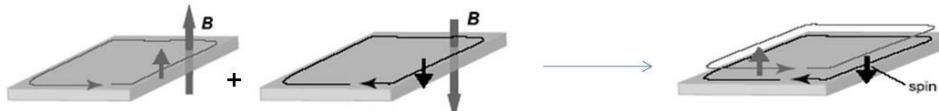
2D Topological Insulators: Ga(Al)As, Hg(Cd)Te

Quantum Hall state (Breaks T-invariance) IQH

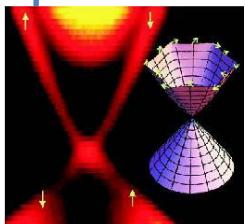
Cryogenic, Large Magnetic field, high-purity crystals

Quantum spin Hall state (Preserves T-invariance) → 2 IQH

Cryogenic, No Magnetic field, high-purity crystals,



3D Topological Insulators: Bi-Sb, Bi₂Se₃, Bi₂Te₂Se



Protected Surface States : New 2DEG

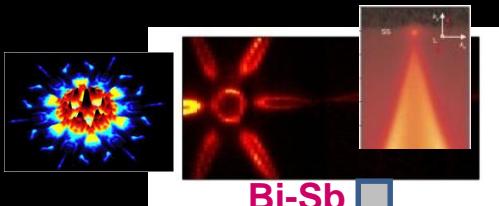
Topological insulator (Preserves T-invariance)

Room Temperature operation, No magnetic field, Dirty crystals?

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

Superconductivity in doped topo insulator : Topo-Order & Broken-Symmetry

Experiments on Topological Insulators (3D)

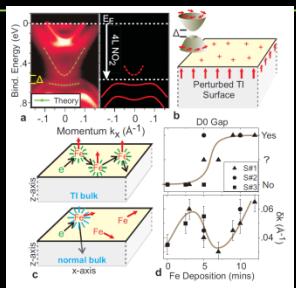


Hsieh et.al., NATURE 08 (sub. 2007)

Hsieh et.al., SCIENCE 09

Roushan et.al., NATURE 09

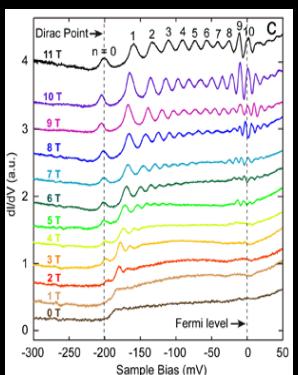
Surface Magnetic Impurity Coulomb perturbation etc.



Xia et.al, arXiv. 2008

Wray et.al., Nat.Phys. 2010

Quantum Hall effect

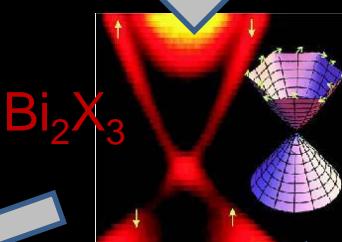


STM Landau quantization

Xue et.al., PRL 2010

Analytis et.al, NatPhys '10

Xiong et.al., arXiv'11

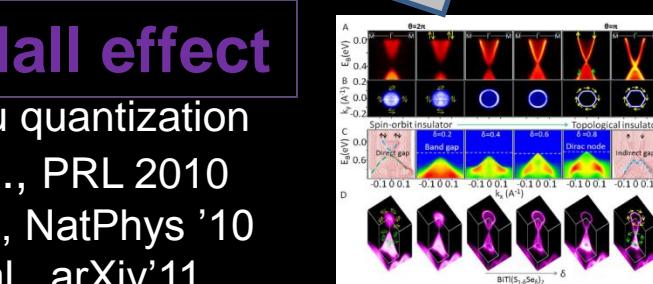
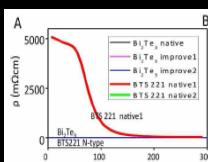


Xia et.al, 2008 (arXiv'08, KITP 08)

Xia et.al, 2009 (Nature Phys.)

Hsieh et.al., Nature 2009

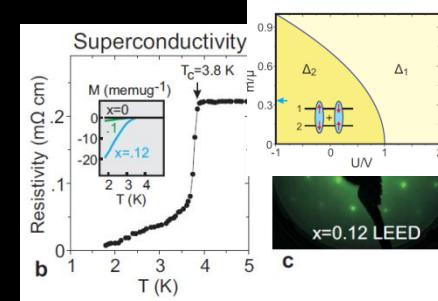
Chen et.al, Sci '09, Zhang et. NatP '09



Topo.Phase Transition

S.-Y. Xu et.al., 2011

Science '11, arXiv'11



Hor et.al., PRL 2010

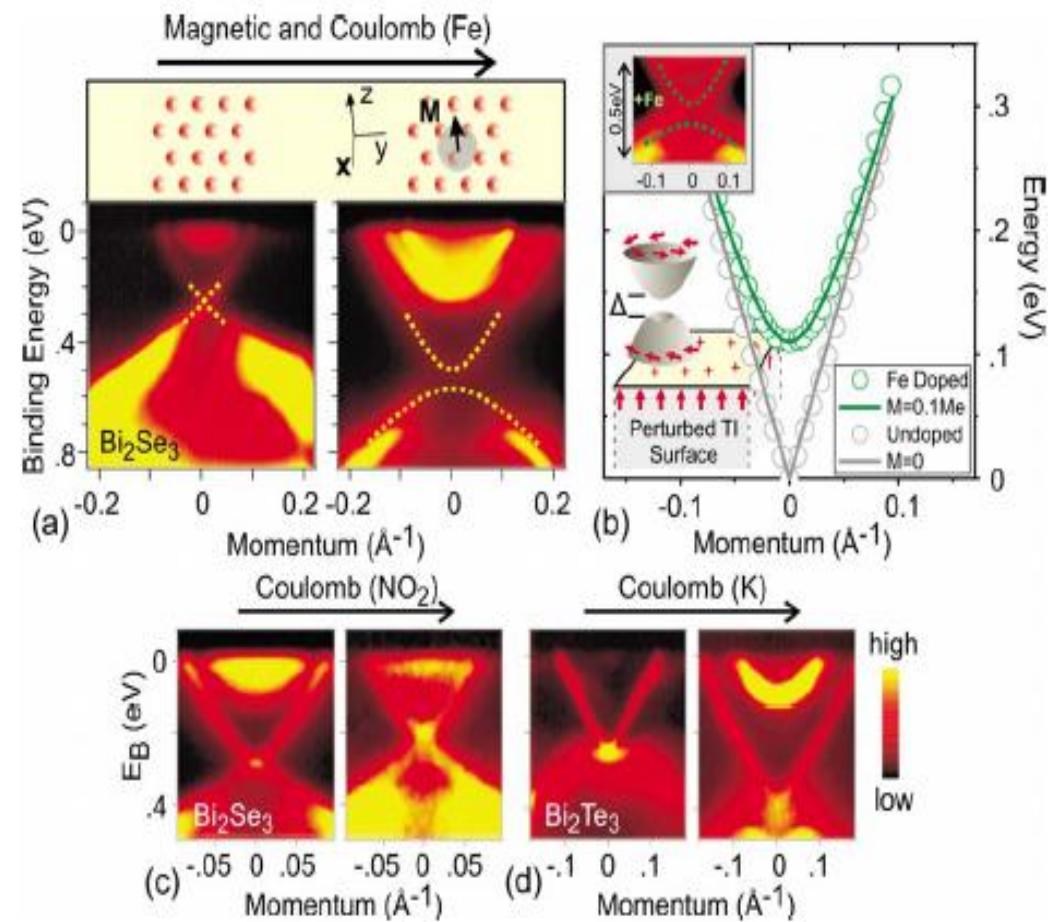
Wray et.al., Nat.Phys.20

Ando et.al, PRL '11

Surfaces under Coulomb, magnetic etc. perturbation

Surface Mobility Control

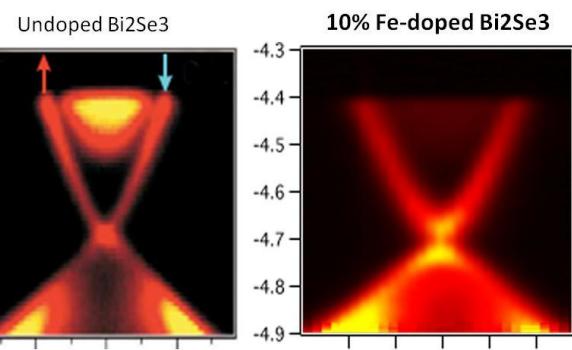
Magnetic perturbation is weak!



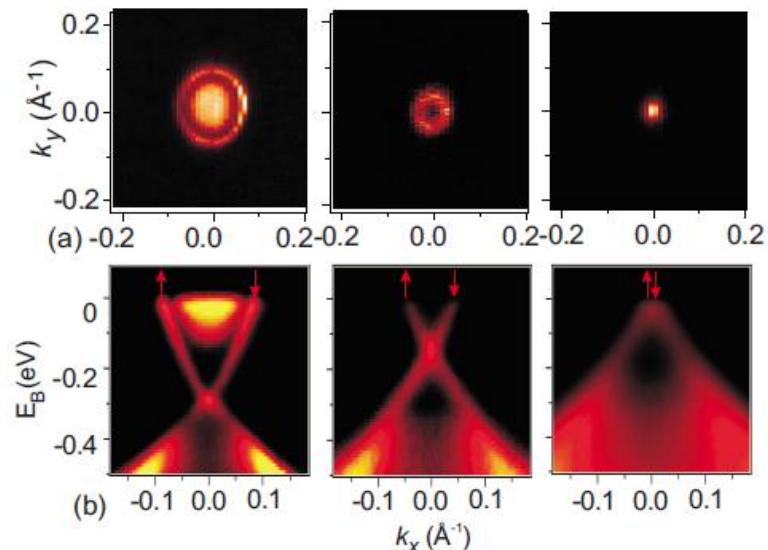
Wray et.al., Nature Physics (2010)

Surface interactions with adatoms, band bending,

Fe doping on Bi_2Se_3

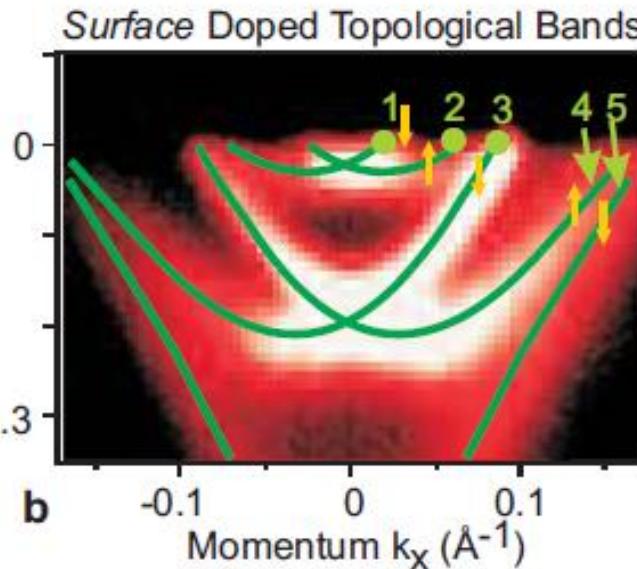
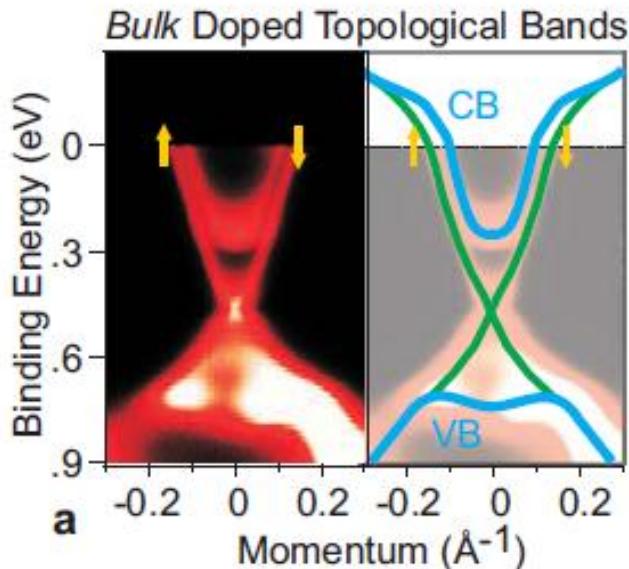


Non-mag doping

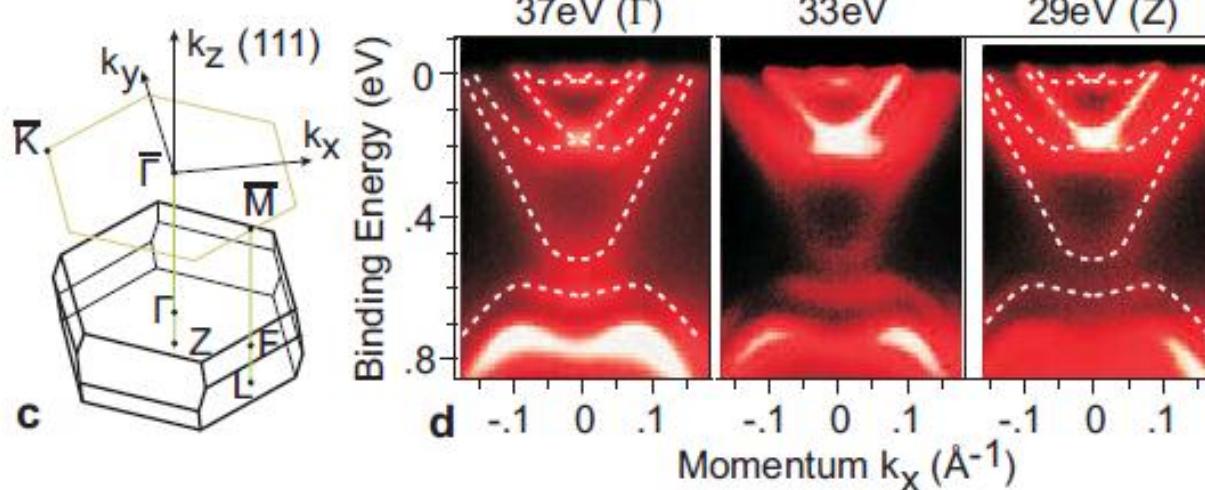


Hsieh et.al., Nature (2009)
Chen et.al., Science (2010)

Surface doping with Fe



**Band bending,
Rashba bands
+Topo Bands
→
Unique Rashba type
(5 Dirac cone -like FS)**



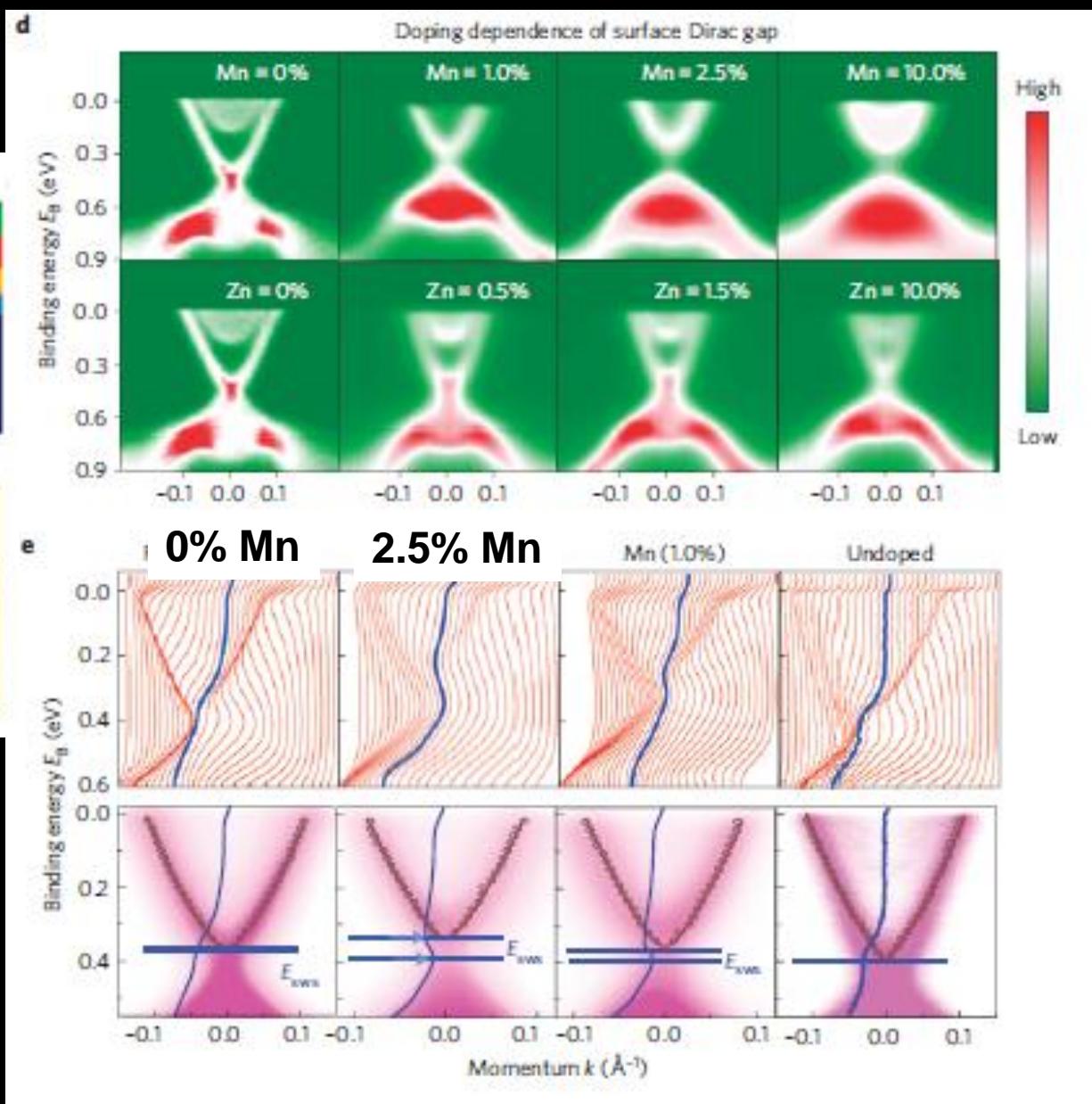
**Wray et.al.,
Nature Physics (2010)**

Magnetic vs. Non-magnetic doping (Mn)

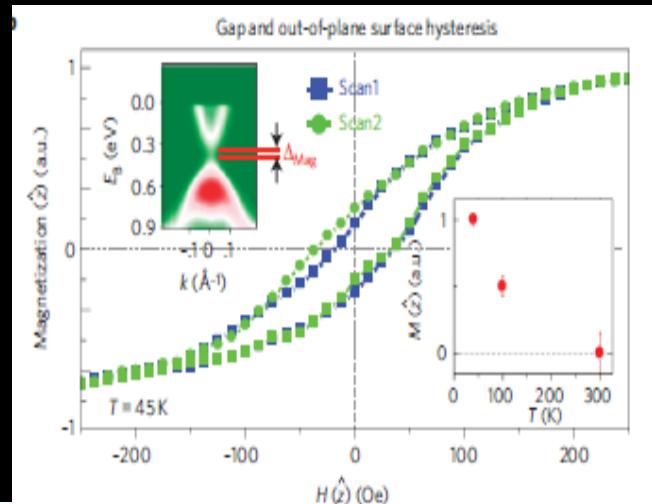
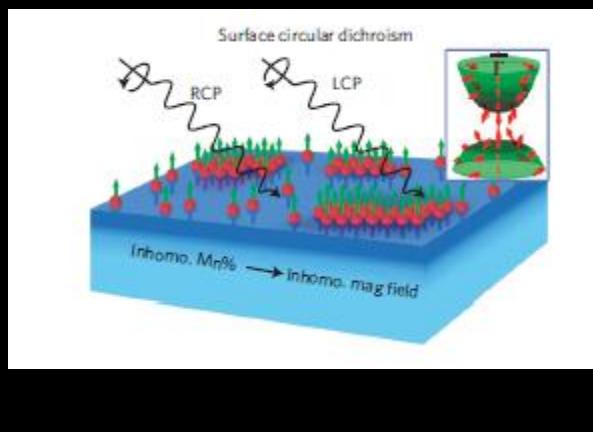
a



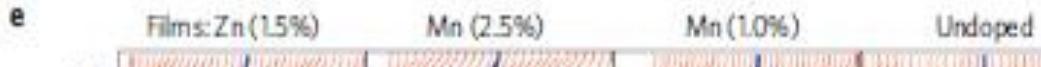
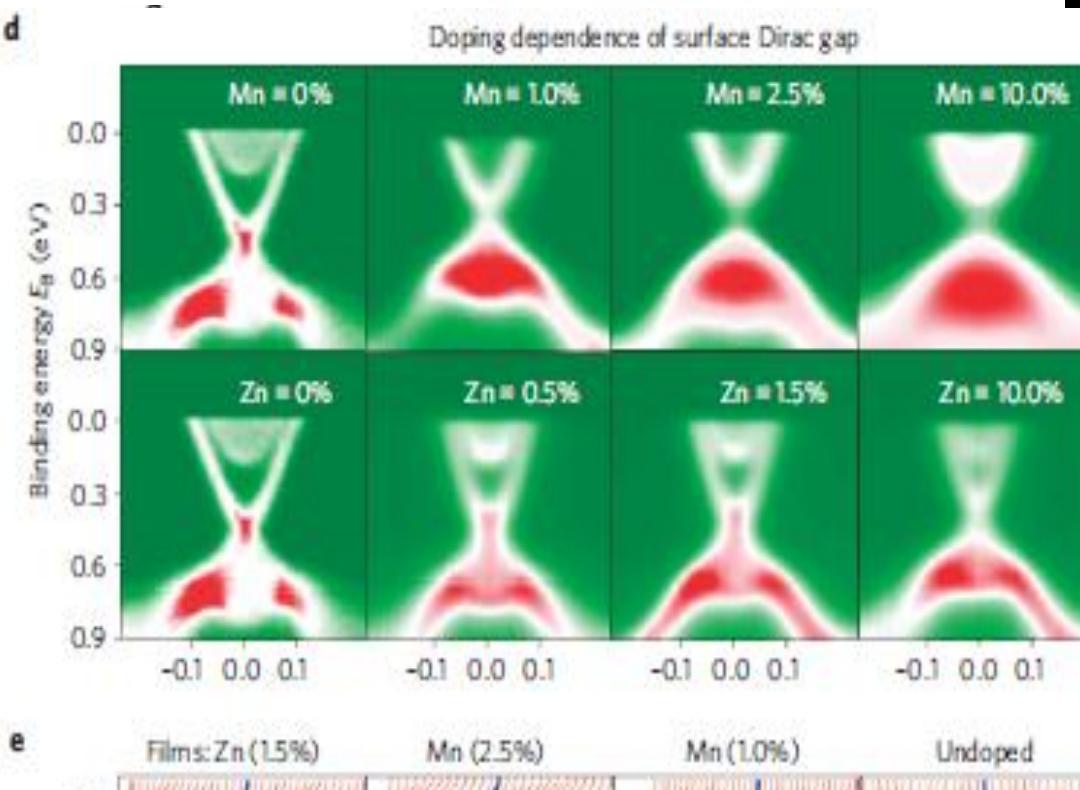
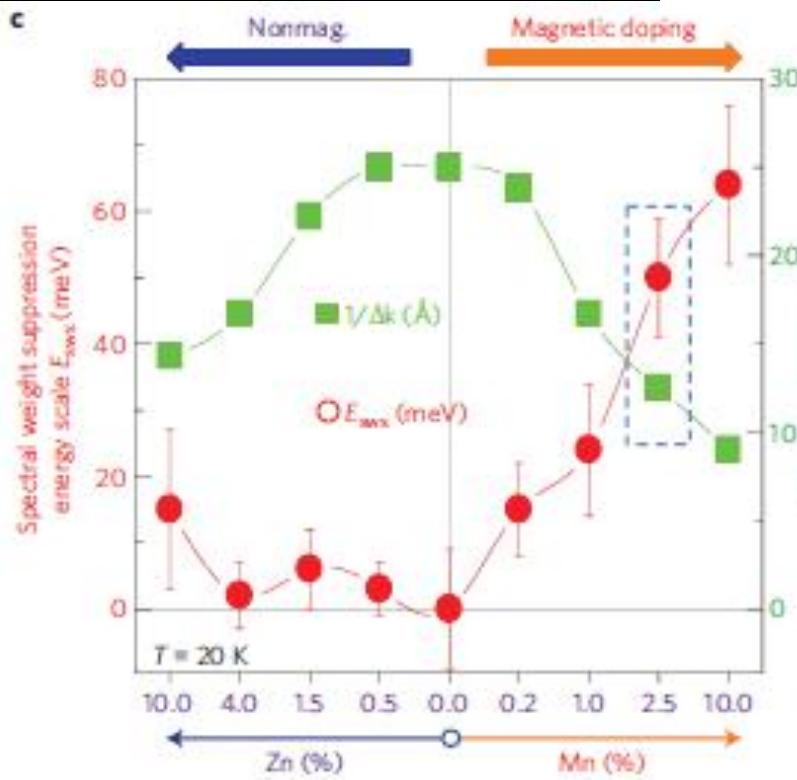
b



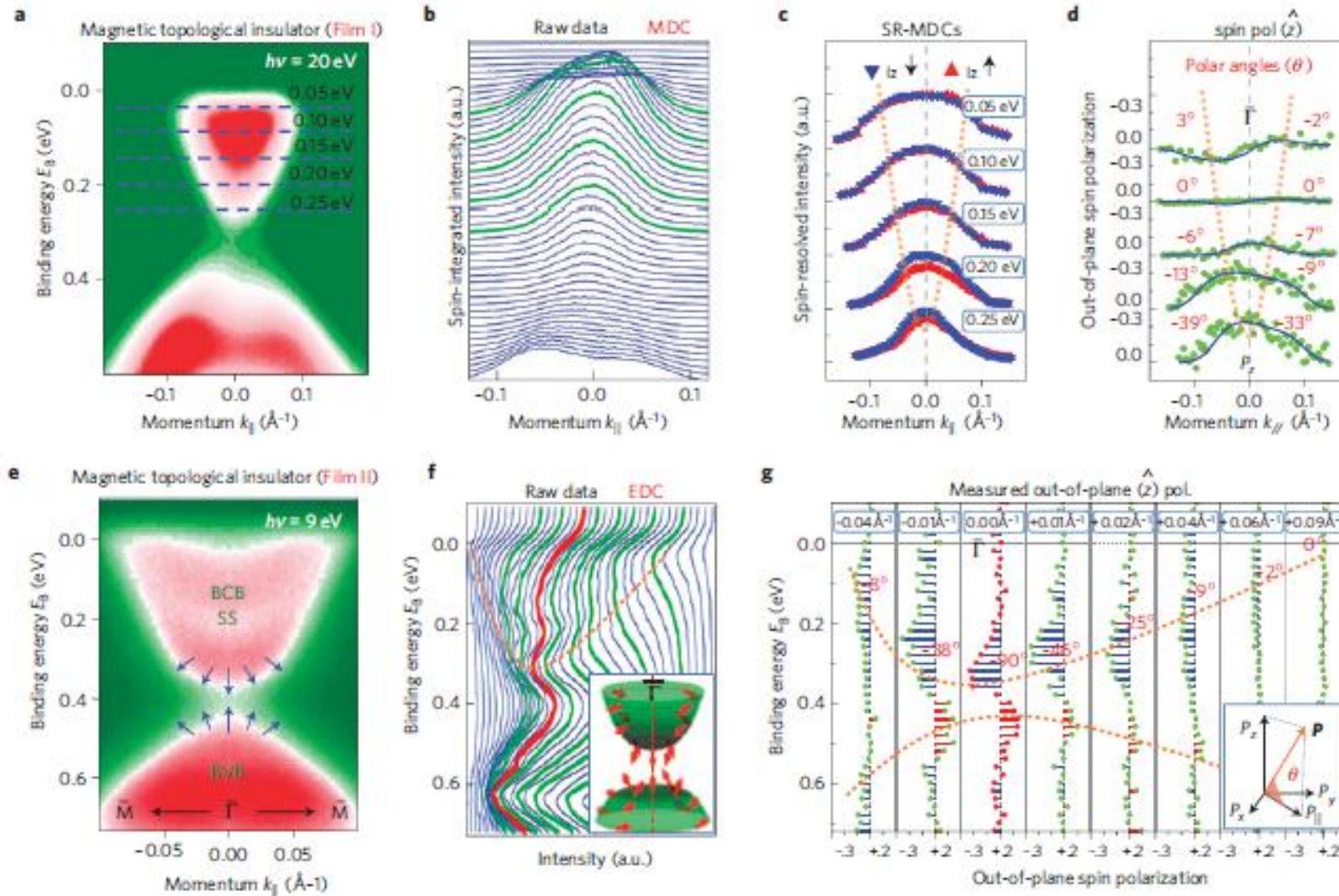
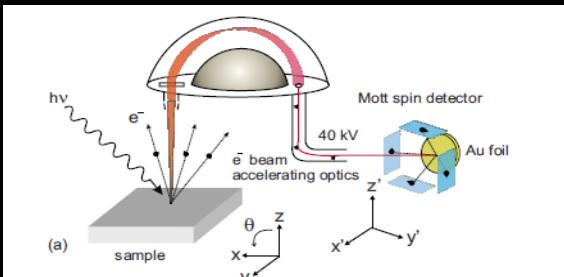
Resonant (Circular Pol.) X-ray Scattering + ARPES

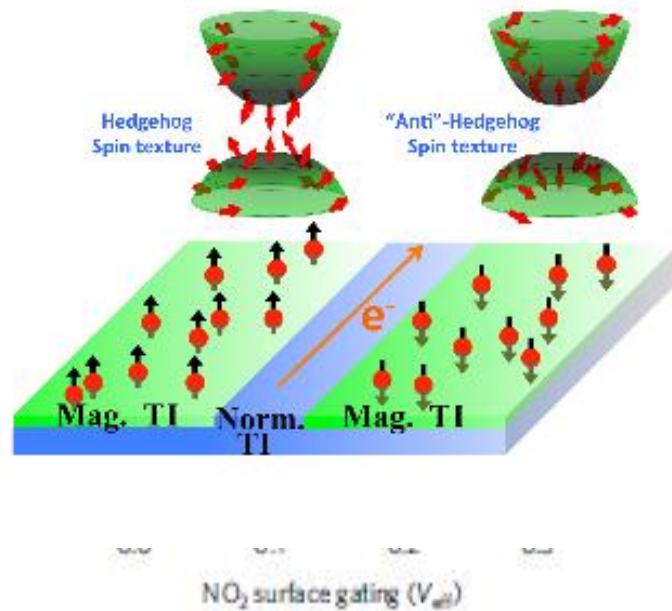
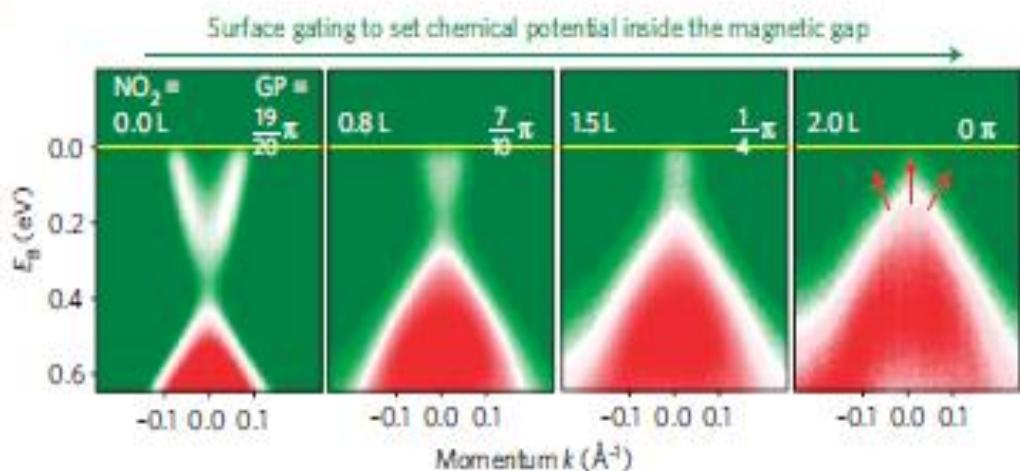
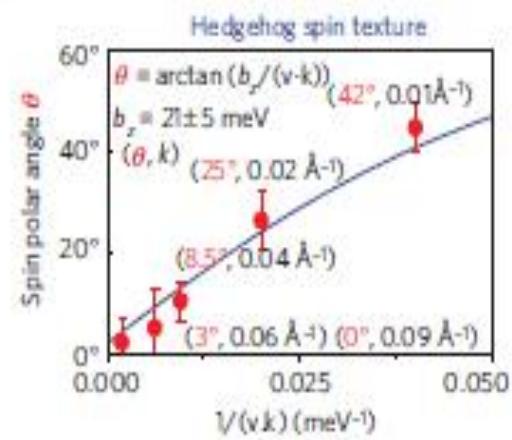
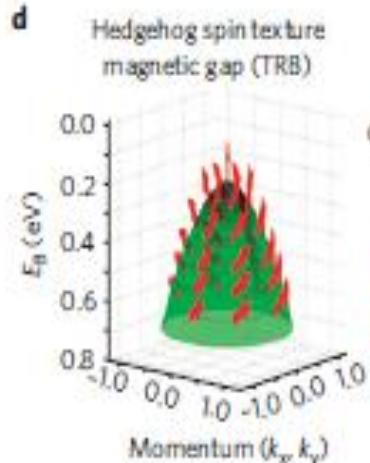
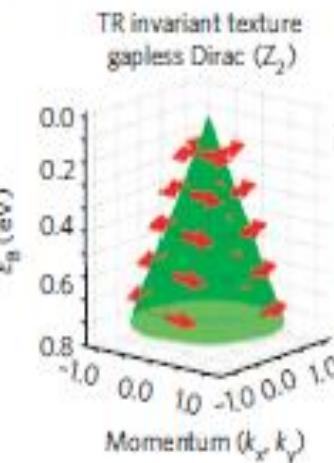
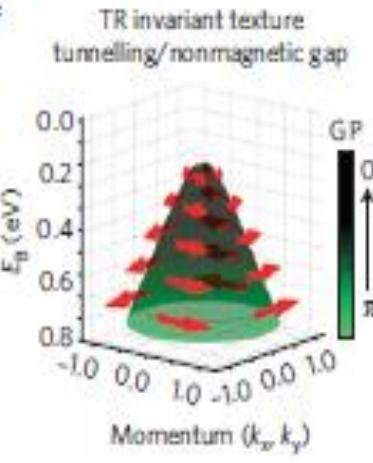


S.-Y. Xu et.al.,
Nature Physics
(2012)



Mott det ARPES



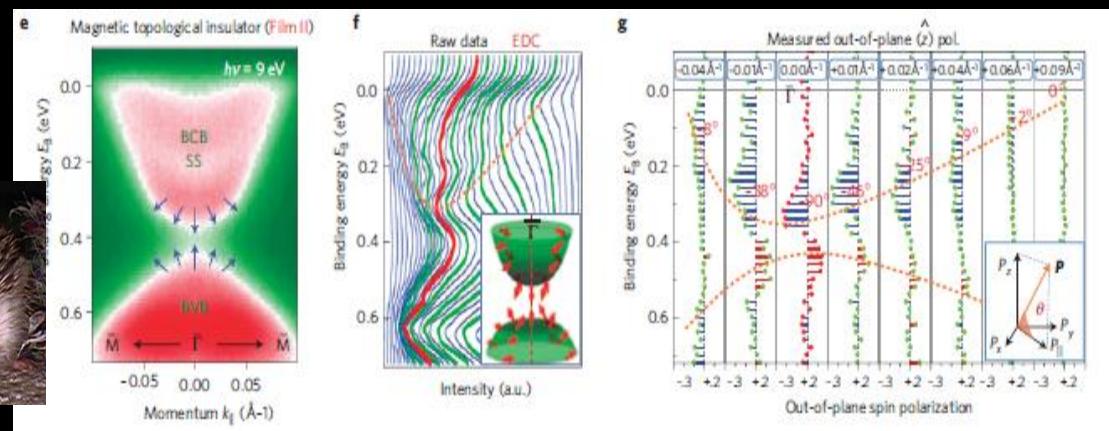
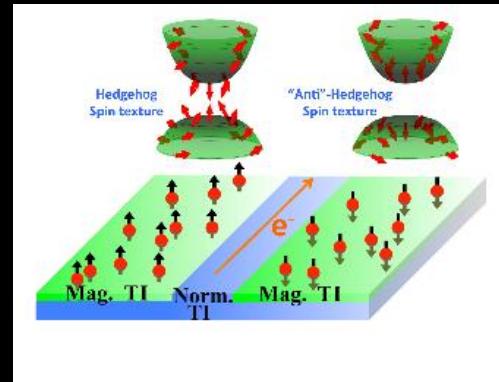
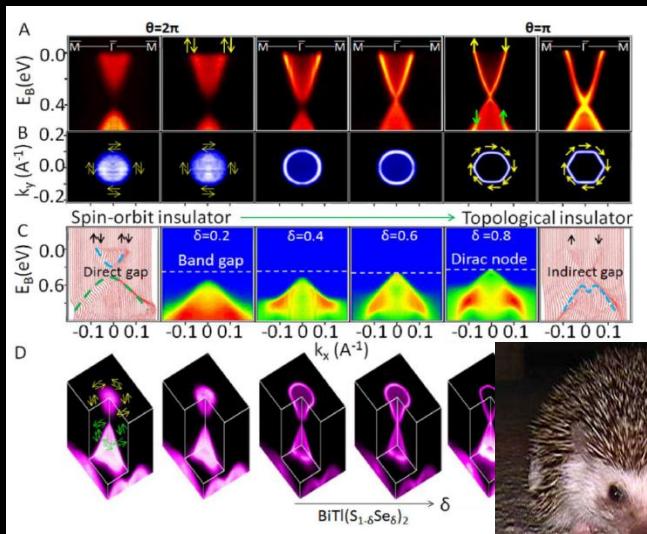
a**c****d****e****f**

S.-Y. Xu *et.al.*,
Nature Physics
(2012)

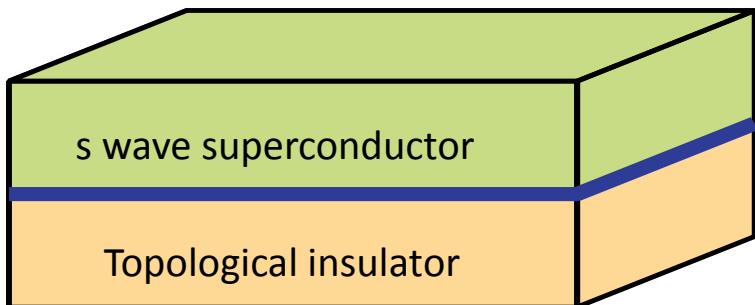
Route to Weyl Fermions & other cool stuff..

Topo-Ins. near criticality TI → NI (Xu et.al., Science 2011)

Magnetize it (Ferromagnetic) (Xu et.al., Nat. Phys. 2012)



STI/Superconduct interface



2D interface state with energy gap and exotic topological order

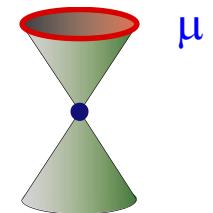
Resembles 2D spinless p_x+ip_y superconductor but does not violate time reversal symmetry

Fu-Kane proposal

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

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 $\nu=5/2$ FQHE, Sr_2RuO_4 , cold atoms, etc

Topological Surface States: Superconductivity in doped topological insulators

Wray et.al., Nature Physics (2010)

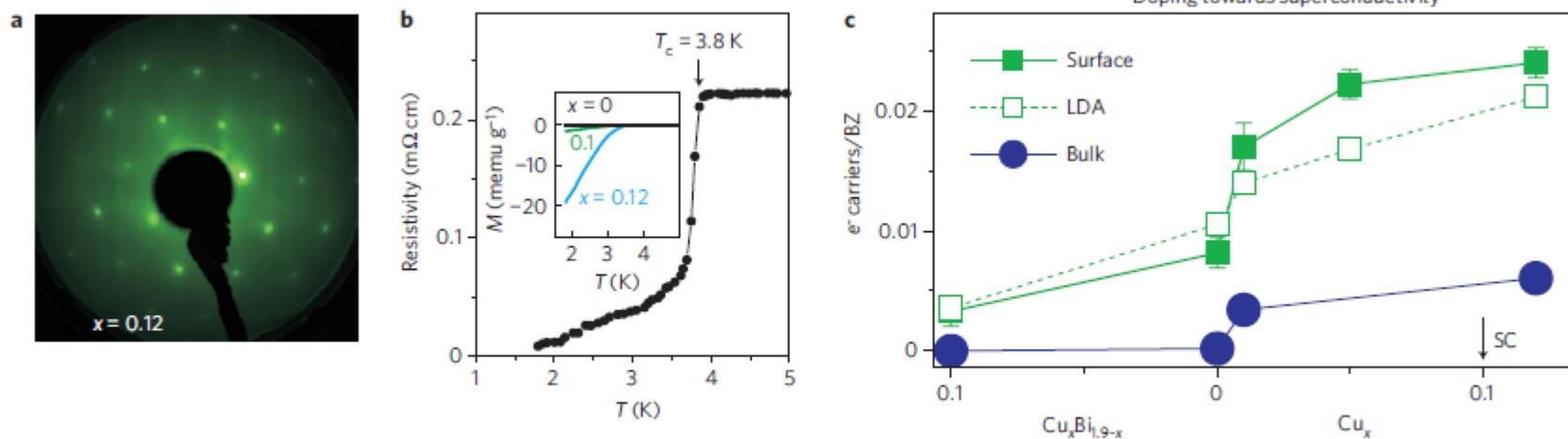
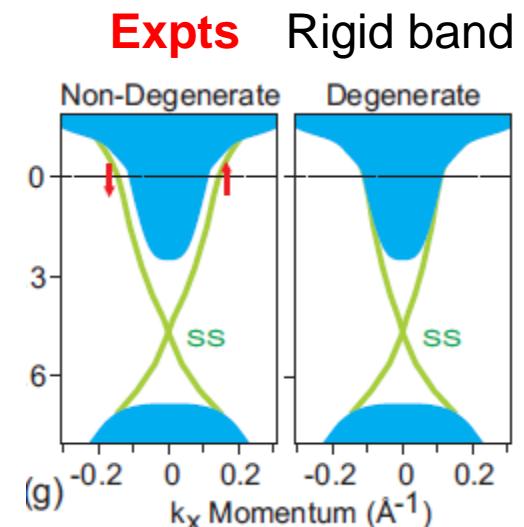
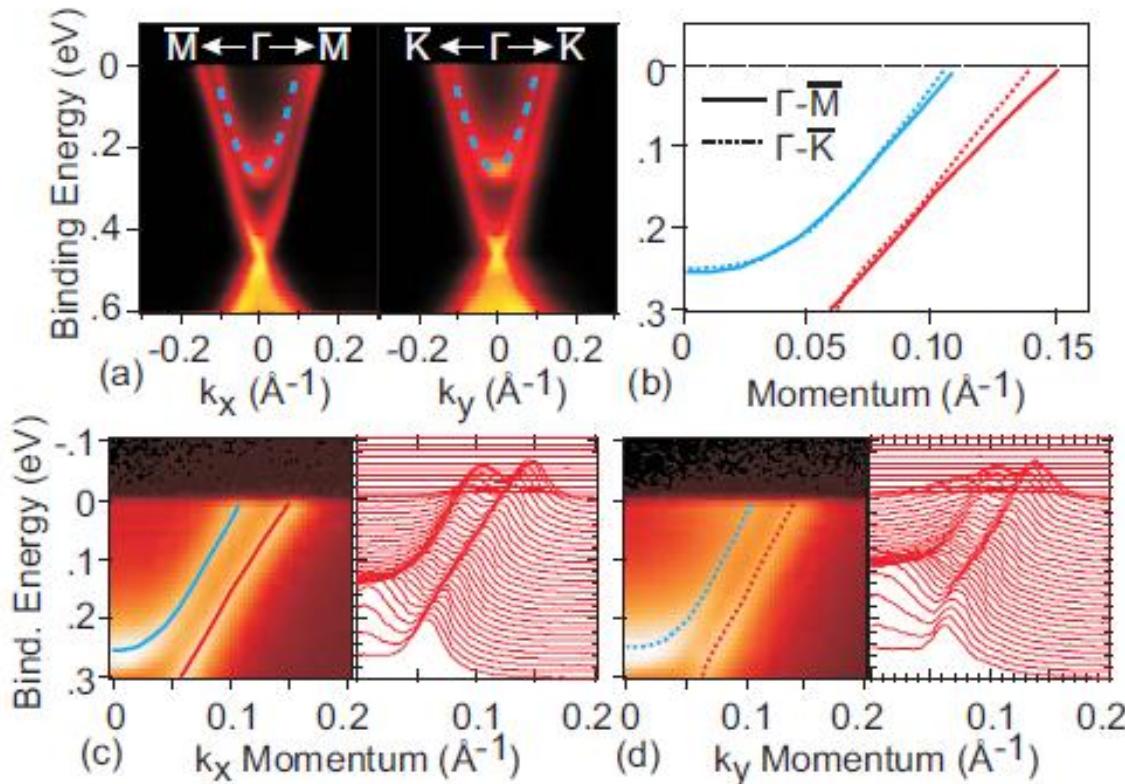


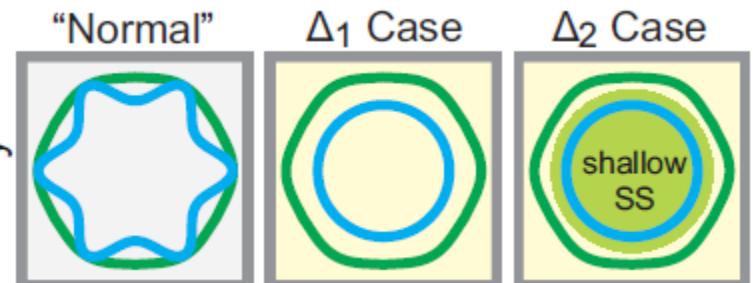
Figure 1 | Superconductivity in $Cu_xBi_2Se_3$ crystals. **a**, A low-energy electron diffraction image taken at 200 eV electron energy provides evidence for a well-ordered surface with no sign of superstructure modulation. **b**, Resistivity and magnetic susceptibility measurements for samples used 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, $\times 2$ 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

$\text{Cu}_x\text{Bi}_2\text{Se}_3$ ($T_c \sim 3.8\text{K}$) : Hor et.al., PRL 2010



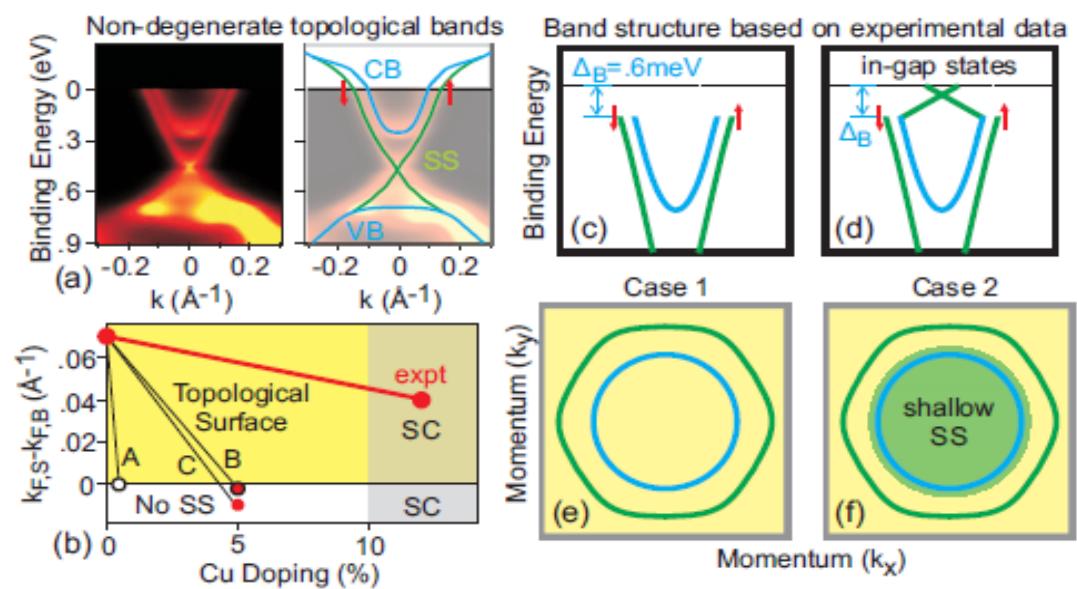
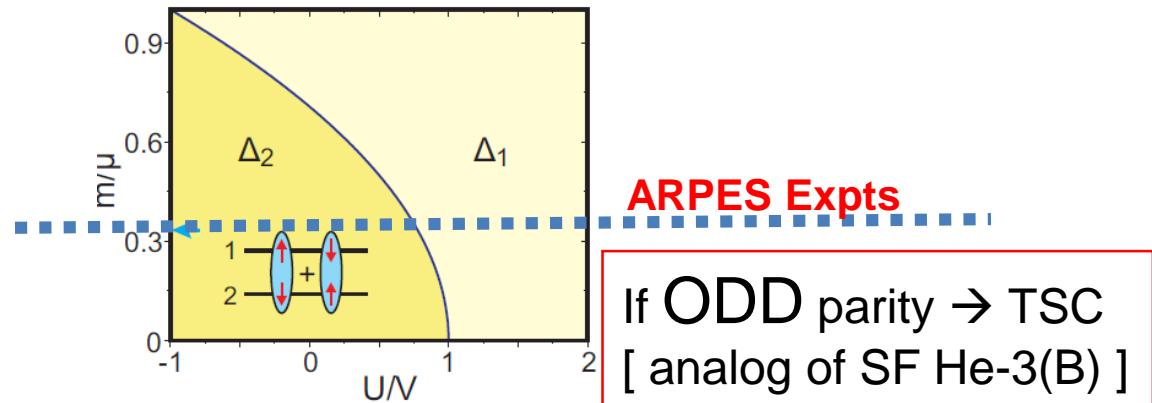
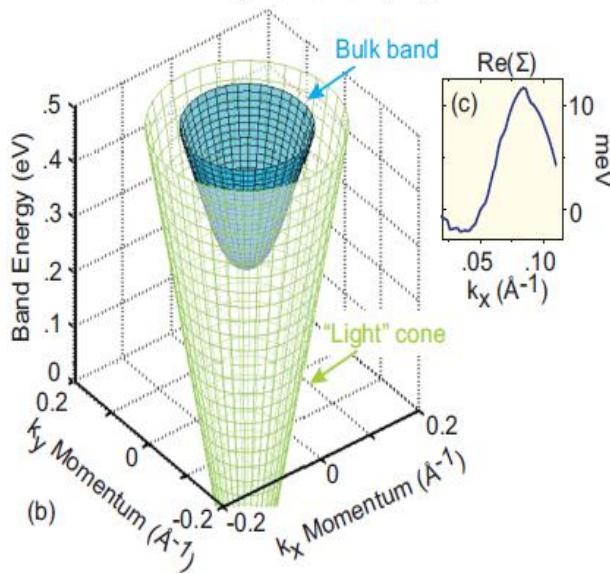
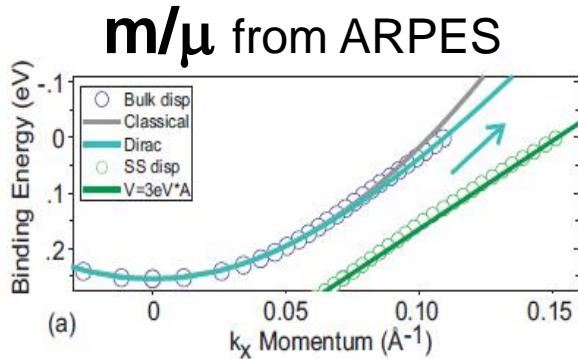
Band structure at superconducting composition: (a) Momentum dependence of the bulk and conduction bands in superconducting $\text{Cu}_{0.12}\text{Bi}_2\text{Se}_3$ measured through the 3D Brillouin zone center with k_c



Wray et.al., Nature Physics (2010)

Topological Superconductor (TSC)?

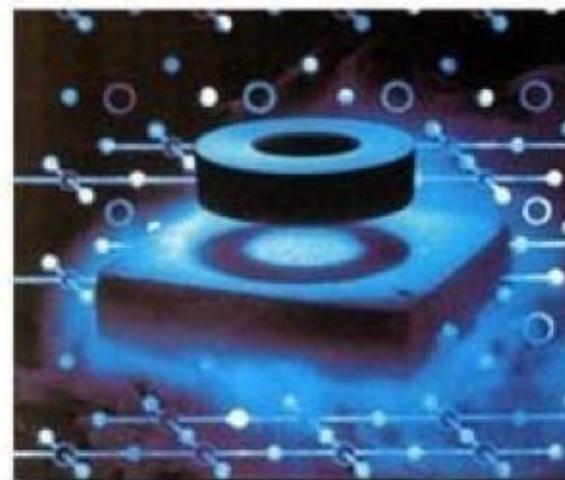
Kitaev/Ludwig D3 class of TSC (proposed by Fu & Berg 09)



Candidate Topological Superconductors ..

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



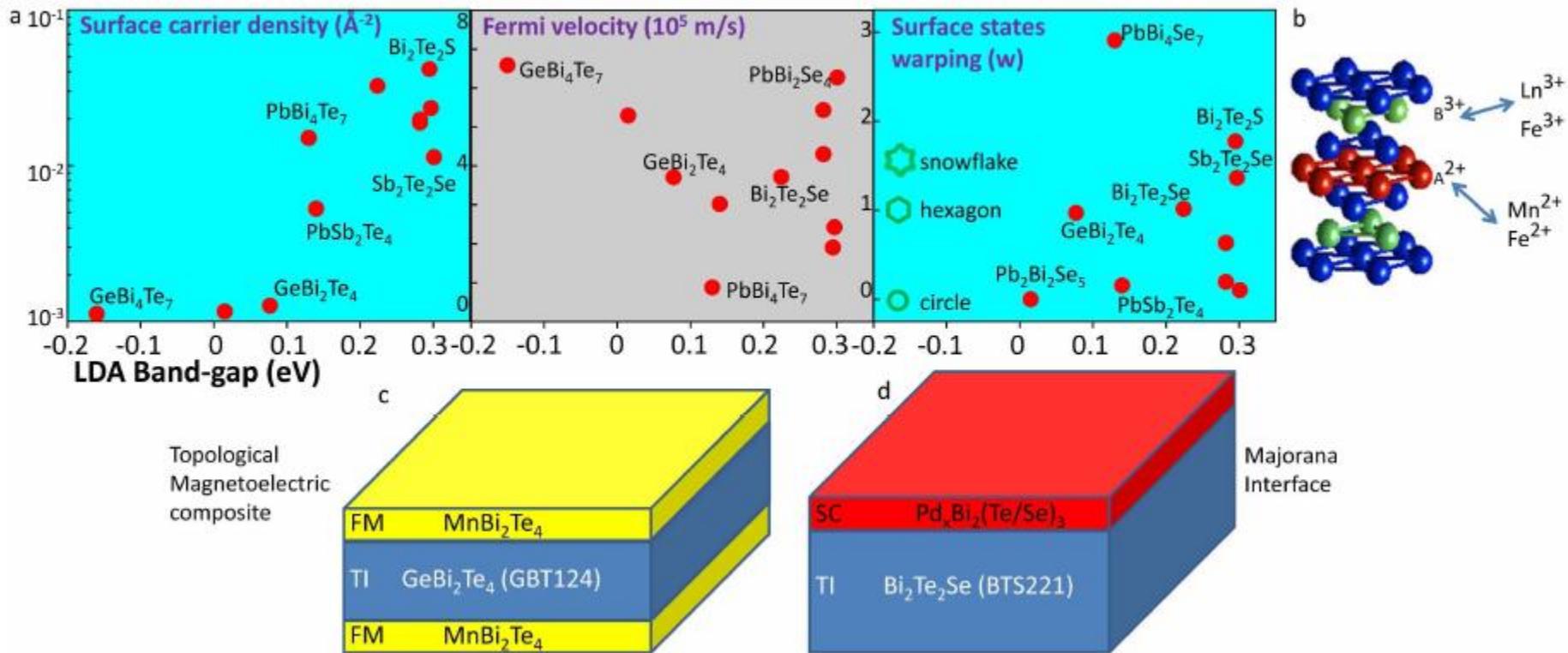
Non-Centrosymmetric

LaPtBi	0.3K
$\text{Li}_2\text{Pt}_3\text{B}$	3.0K
CePt_3Si	0.7K

Order parameter sym
must be determined

Path to Topological Devices?

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

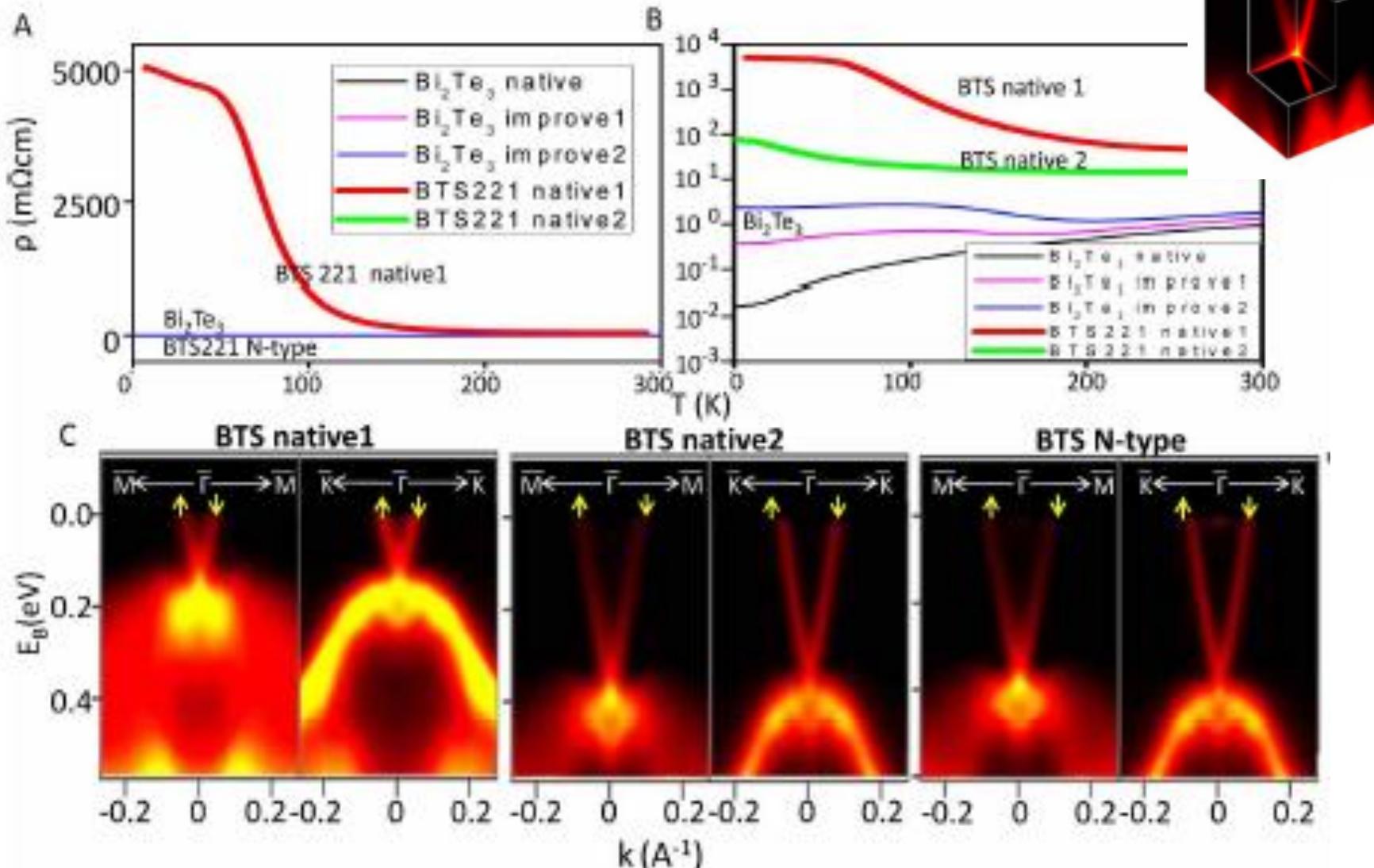


Magnetoelectric
interface

Majorana interface

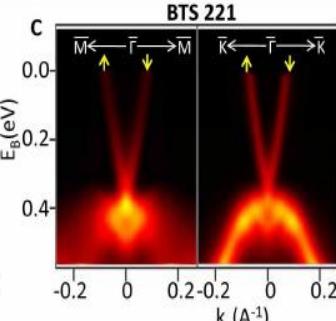
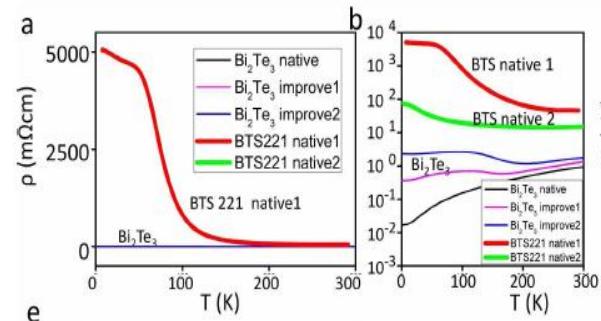
$\text{Bi}_2\text{Te}_2\text{Se}_1$ (more insulating than Si at 4K)

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



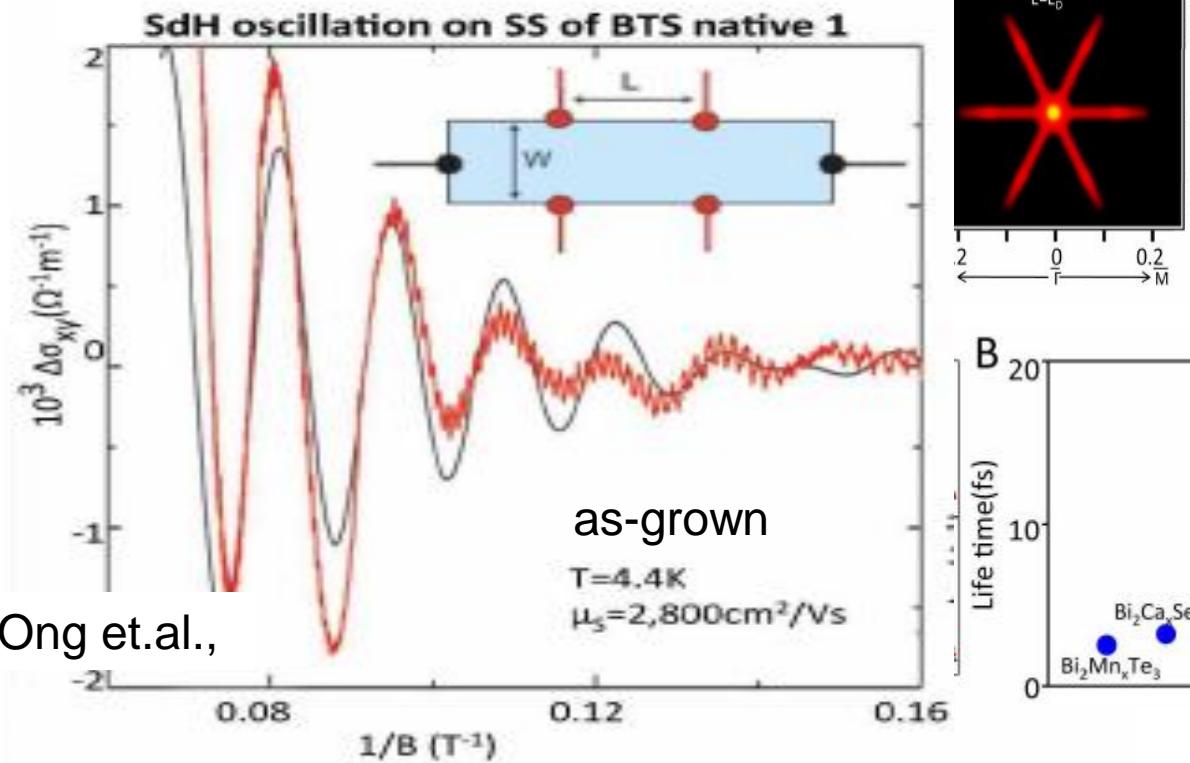
Highly Bulk-Insulating Topological Insulators

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



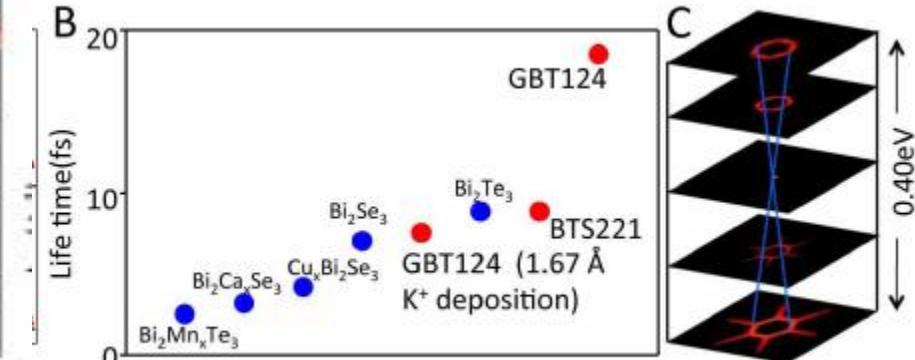
$$G_{\text{surface}}(T \sim 0) = (e^2/h)k_F L = (e^2/h)k_F v_F \tau$$

even
Bulk crystals > 5 Ohm-cm



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

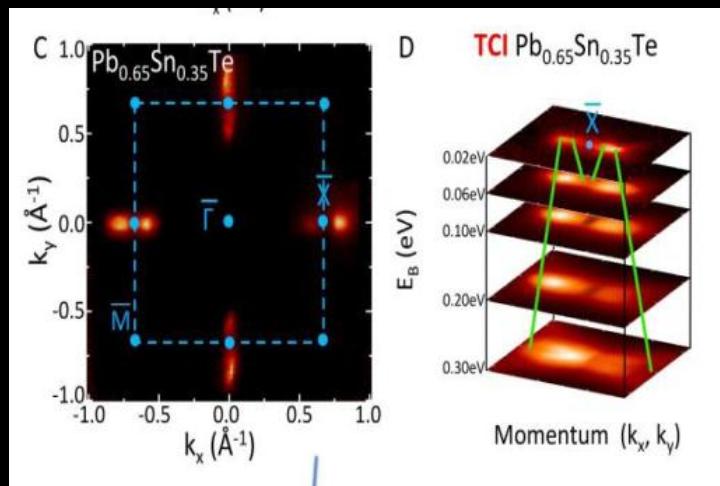
Very large Gap ~ 200 meV
(unlike HgTe)



Topo Insulators beyond Kane-Mele Z_2 theory ?

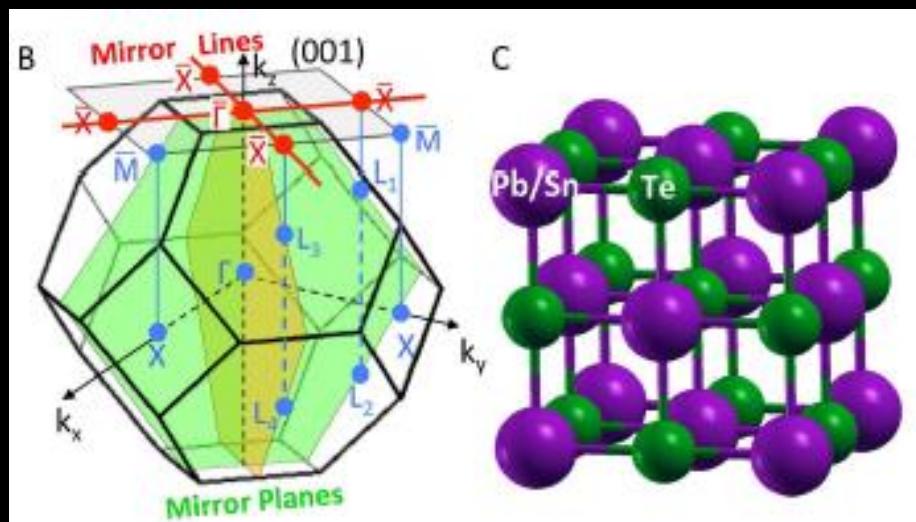
TR invariance \leftrightarrow SG symmetry (TCI)

Space group symmetry protected
topological insulators (Fu PRL'11)

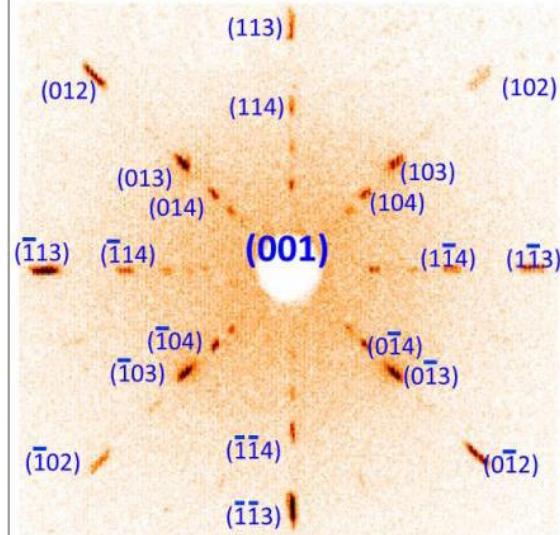


$\text{Pb}(1-x)\text{Sn}(x)\text{Te}$:

Space group symmetry protected topological insulators

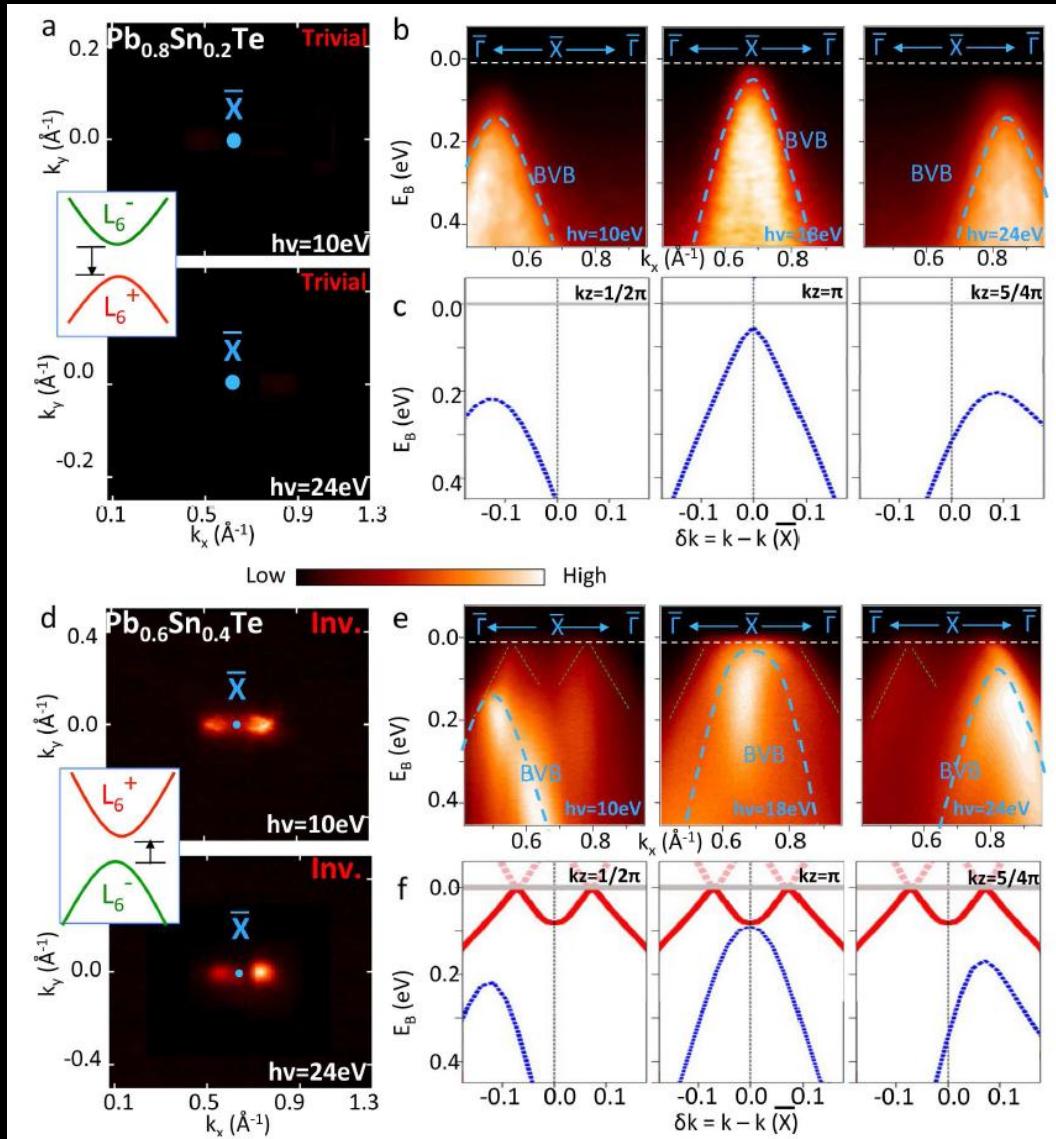


Ultra-fine alignment



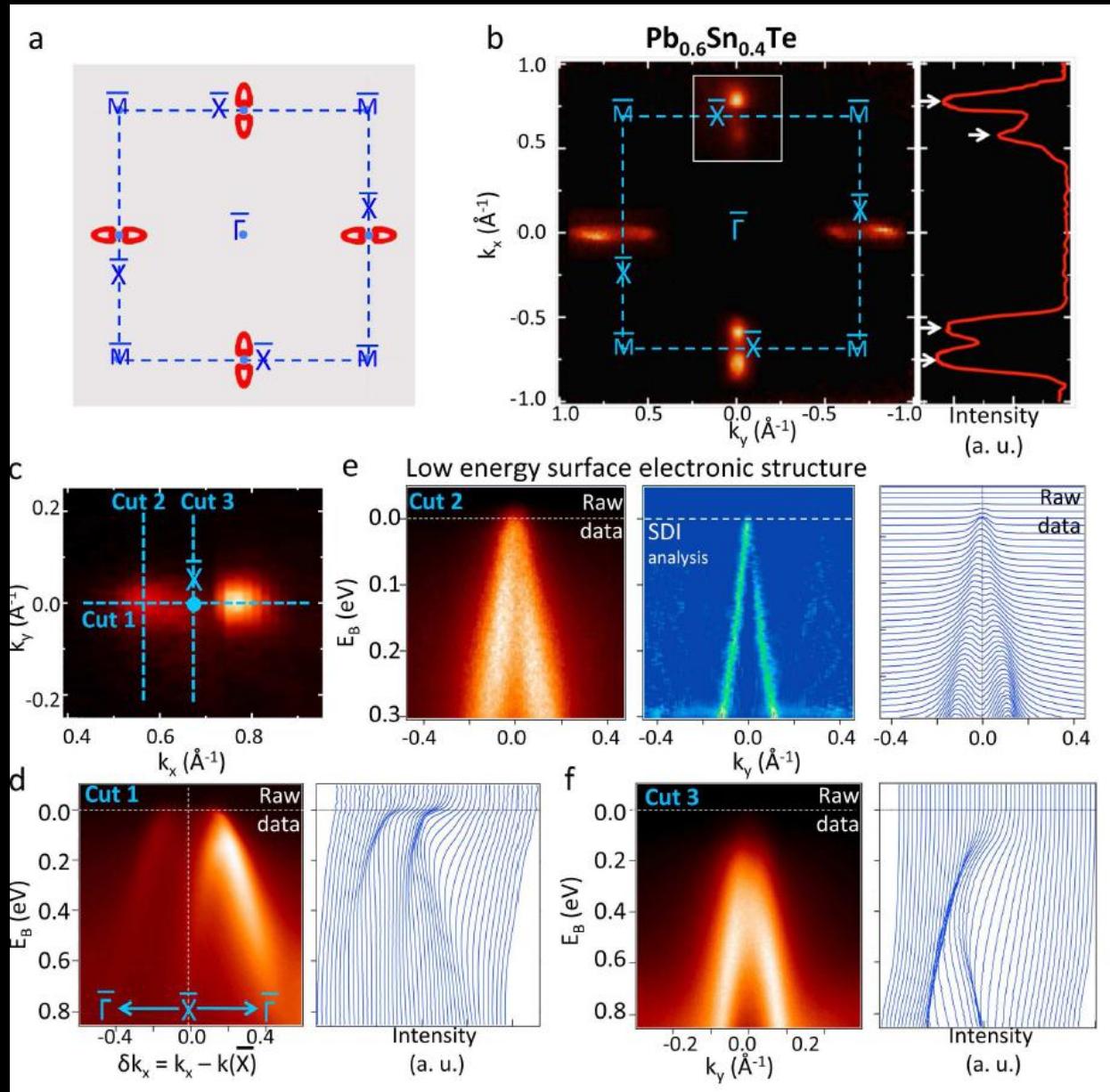
Pb(1-x)Sn(x)Te :

Space group symmetry protected topological insulators



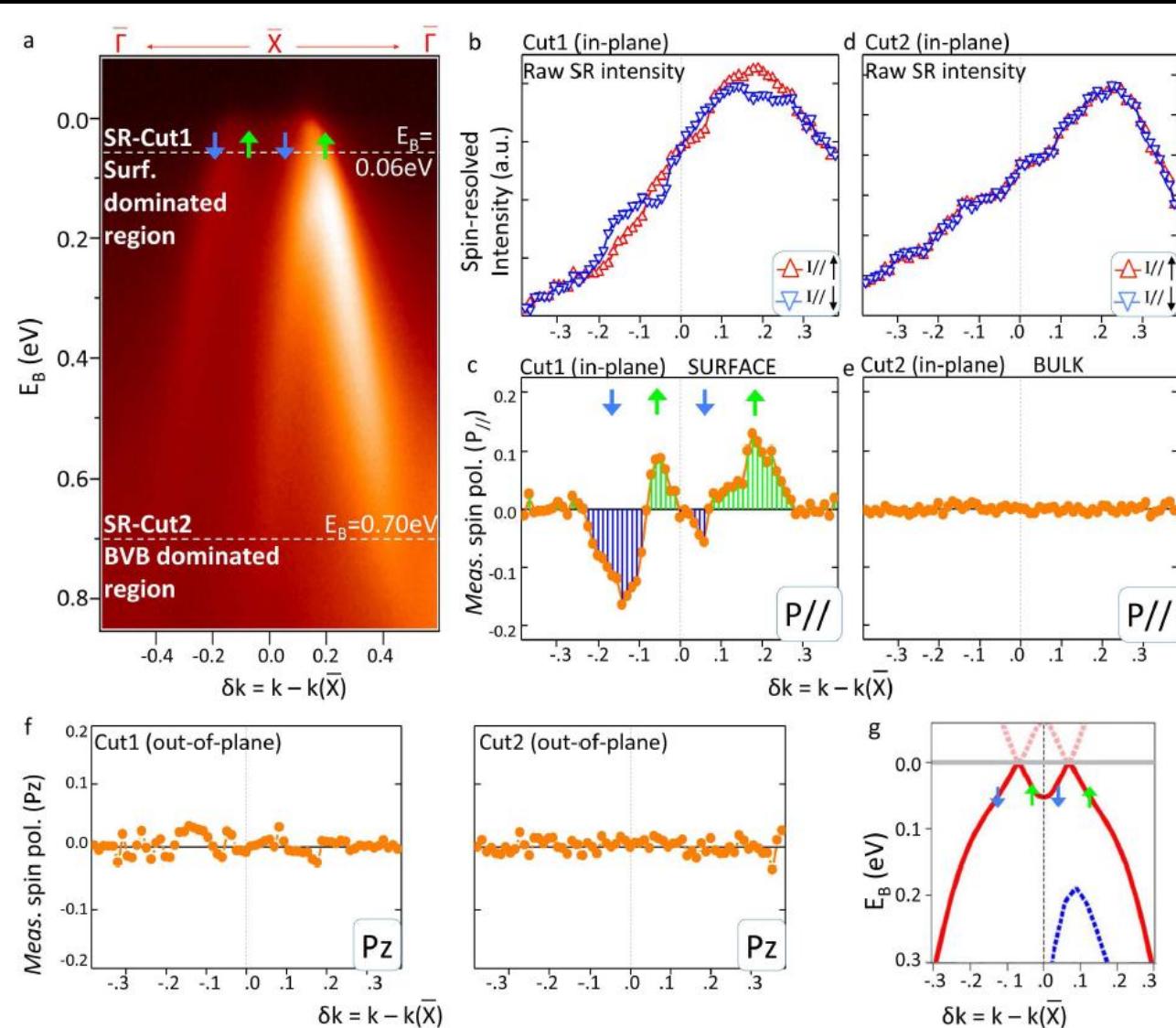
$\text{Pb}(1-x)\text{Sn}(x)\text{Te}$:

Space group symmetry protected topological insulators

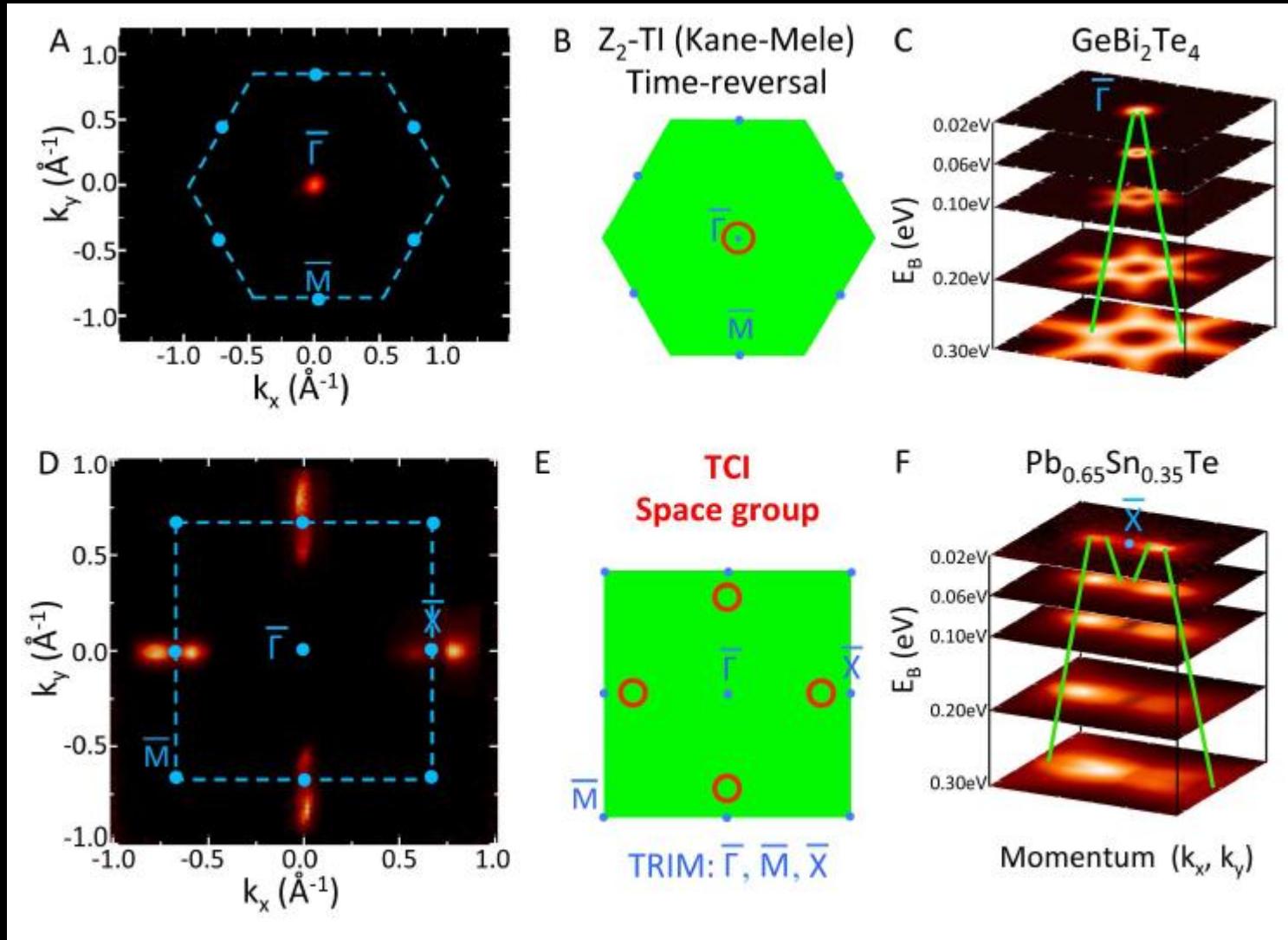


Pb(1-x)Sn(x)Te :

Space group symmetry protected topological insulators



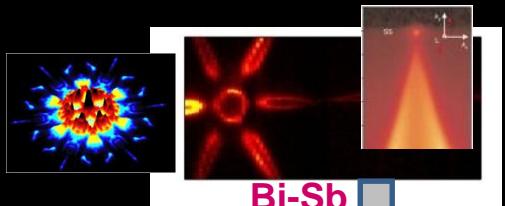
Topo Insulators beyond Z2 theory ?



S.-Y. Xu et.al.,
(2012)

Also see
Work by Story
and Ando grps
(arXiv)

Experiments on Topological Insulators (3D)

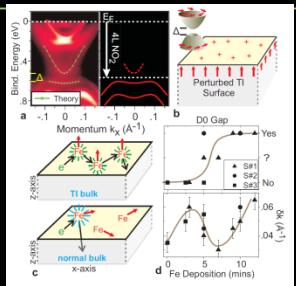


Hsieh et.al., NATURE 08 (sub. 2007)

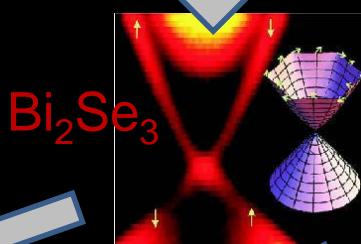
Hsieh et.al., SCIENCE 09

Roushan et.al., NATURE 09

Surface Magnetic Impurity Coulomb perturbation etc.



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

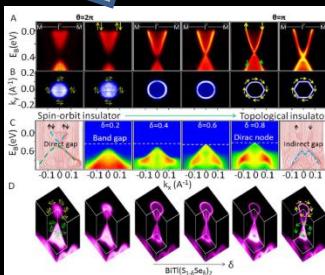
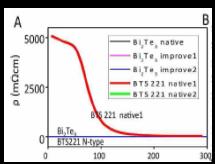


Xia et.al, 2008 (arXiv'08, KITP 08)

Xia et.al, 09 (Nat Phys.) & Hsieh et., Nature 09

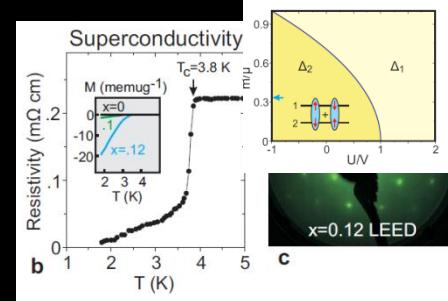
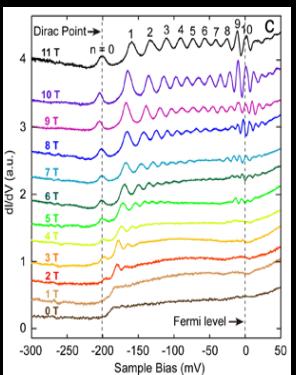
Zhang et. NatP '09 & Chen et.al, Sci '09,
many others

Superconductivity



STM Landau quantization

Xue et.al., PRL 2010
Analytis et.al, NatPhys '10
Xiong et.al., arXiv'11
+ others

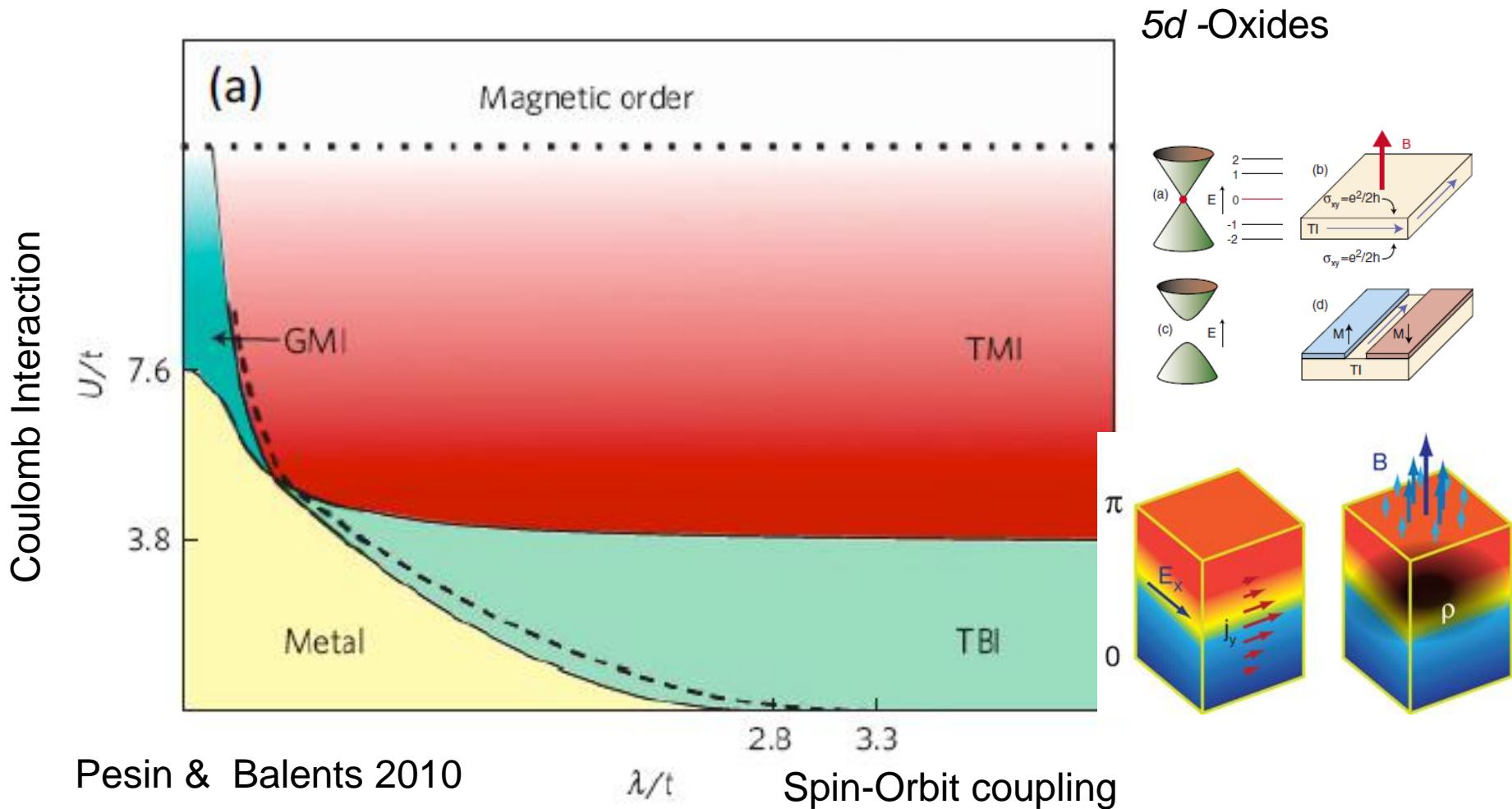


Hor et.al., PRL 2010
Wray et.al., Nat.Phys.20
Ando et.al, PRL '11

Topo.Phase Transition

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

Topo (Band) Insulator → Topo Mott insulator (TMI) Emergent physics in TMI



Conclusions

1. A novel experimental approach to Topological phenomena
2. **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 $\frac{1}{2}$ Dirac gas)
 - protected by time-reversal symmetry.

Bulk Insulating samples are now realized.
3. **Topological Phase Transition** Spin-texture and half Dirac gas is one-to-one correlated with a topological (quantum) phase transition
Bulk-boundary correspondence
4. **FerroMagnetism in Topological Insulators**
new physics of competing order : Broken symmetry vs. Topo Order
5. Topological Superconductors: some results but a lot more work..
6. Route to Weyl Fermions (Future)
7. TIs protected by SGS (Topo Cryst. Insulators)

Items 1) &2) : MZH & CL Kane Rev. Mod. Phys. 82, 3045 (2010)
(also reviews by others including Qi&Zhang (2011))

Items 3)-7) are new frontiers (interactions + New Topo Phases!)

Thanks!