Relaxation dynamics in topological insulators

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SOCSIS, 07/02/2016

Collaborators

- ***ARPES Experiments***

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- ***Synchrotron Beam Line Assistance***

S.-K. Mo, J. D. Denlinger, A. Fedorov : **Advanced Light Source, LBNL; Stanford Synchrotron Radiation Lightsource, Stanford, CA**; **Swiss Light Source, PSI**

Laser based TR-ARPES

T. Kondo, Y. Ishida, S. Shin (ISSP, University of Tokyo, Japan)

- ***Crystal Growth***

Robert Cava (Princeton University, Chemistry), E. D. Bauer (Los Alamos National Laboratory)

D. Kaczorowski (Polish Academy of Science), N. Samarth (Penn State)

F.C. Chou (Taiwan), D.J. Kim, Z. Fisk (University of California at Irvine)

- ***Theory and Calculations***

T. Rahman group (University of Central Florida), **Jianxin Zhu** (LANL), T.-R. Chang, T.-H. Jeng (National Tsing Hua University, Taiwan), **H. Lin** (NUS), **A. Bansil** (Northeastern University)

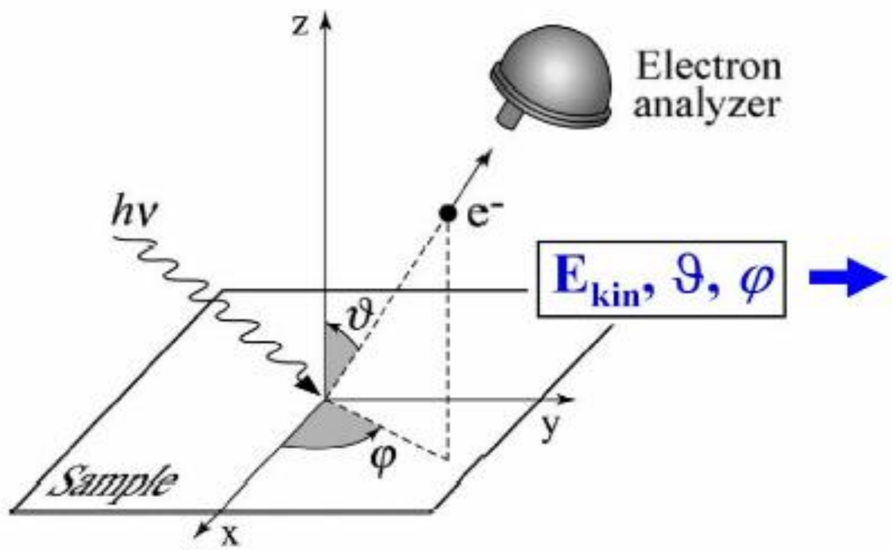
Outline

Photoemission studies of topological insulators and beyond

- Introduction: Photoemission & topological insulators
- Binary and ternary topological insulators – time-resolved phenomena
- New topological phases – 3D Dirac, Weyl and nodal phases

Technique: Photoemission

Angle-resolved Photoemission Spectroscopy (ARPES)



$$\mathbf{K} = \mathbf{p}/\hbar = \sqrt{2m\boldsymbol{E}_{\boldsymbol{kin}}}/\hbar$$

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

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

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

Vacuum		Conservation laws		Solid
E_{kin}	→	$E_{kin} = h\nu - \lvert E_B \rvert - \Phi$	→	E_B
$\vec{K}$		$\vec{K} = \vec{k} + \cancel{\vec{k}_{photon}}$		$\vec{k}$

momentum conservation

ARPES “sees” electrons

ARPES measures spectral function

$$I(\vec{k},\omega) = I_0(\vec{k},\nu,\vec{A})f(\omega)A(\vec{k},\omega)$$

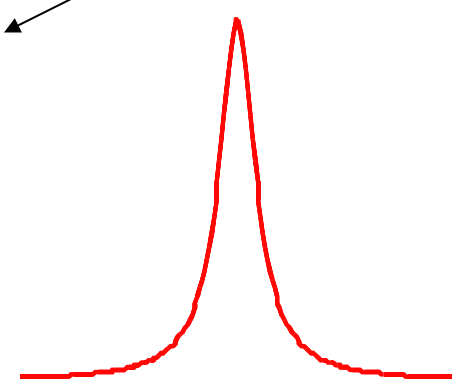
$$A(k,\omega) = \frac{1}{\pi}\mathrm{Im}\left(G(k,\omega)\right)$$

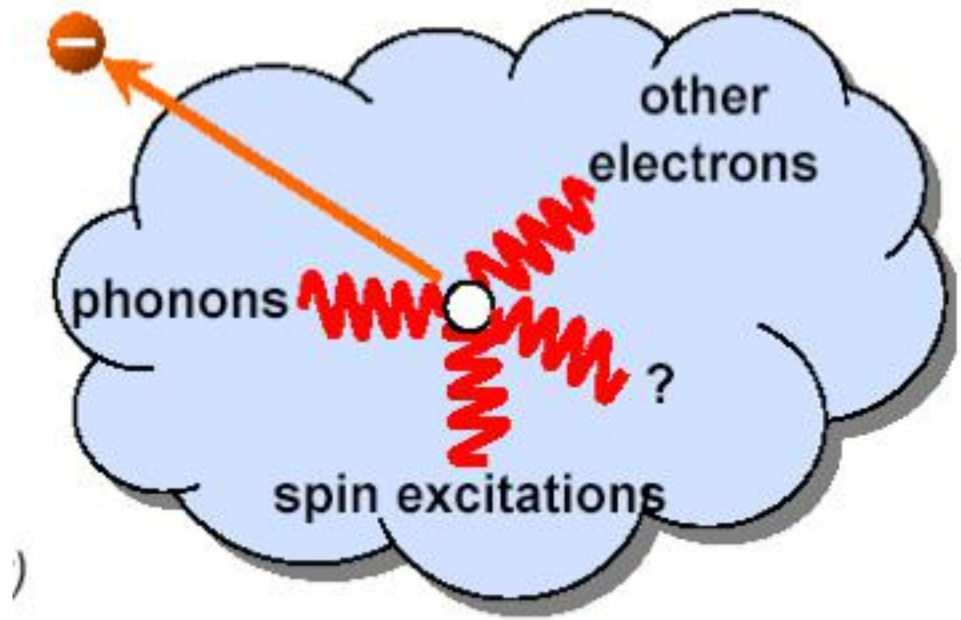
$$G(k,\omega) = \frac{1}{\omega - \varepsilon_k - \Sigma(k,\omega)}$$

self energy

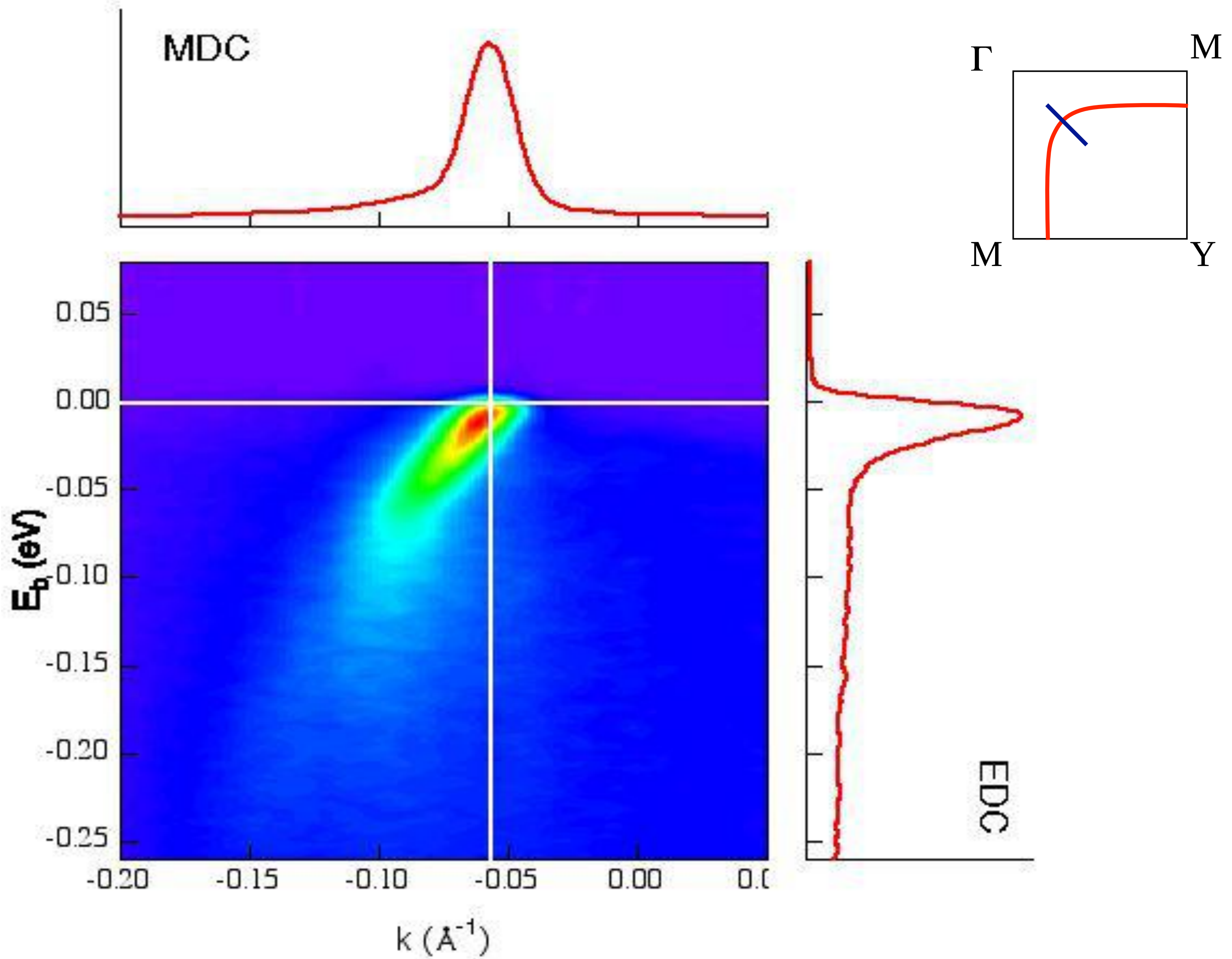
$$A(k,\omega) = \frac{1}{\pi}\frac{\Sigma''(k,\omega)}{\left[\omega - \varepsilon_k - \Sigma'(k,\omega)\right]^2 + \left[\Sigma''(k,\omega)\right]^2}$$

Γ

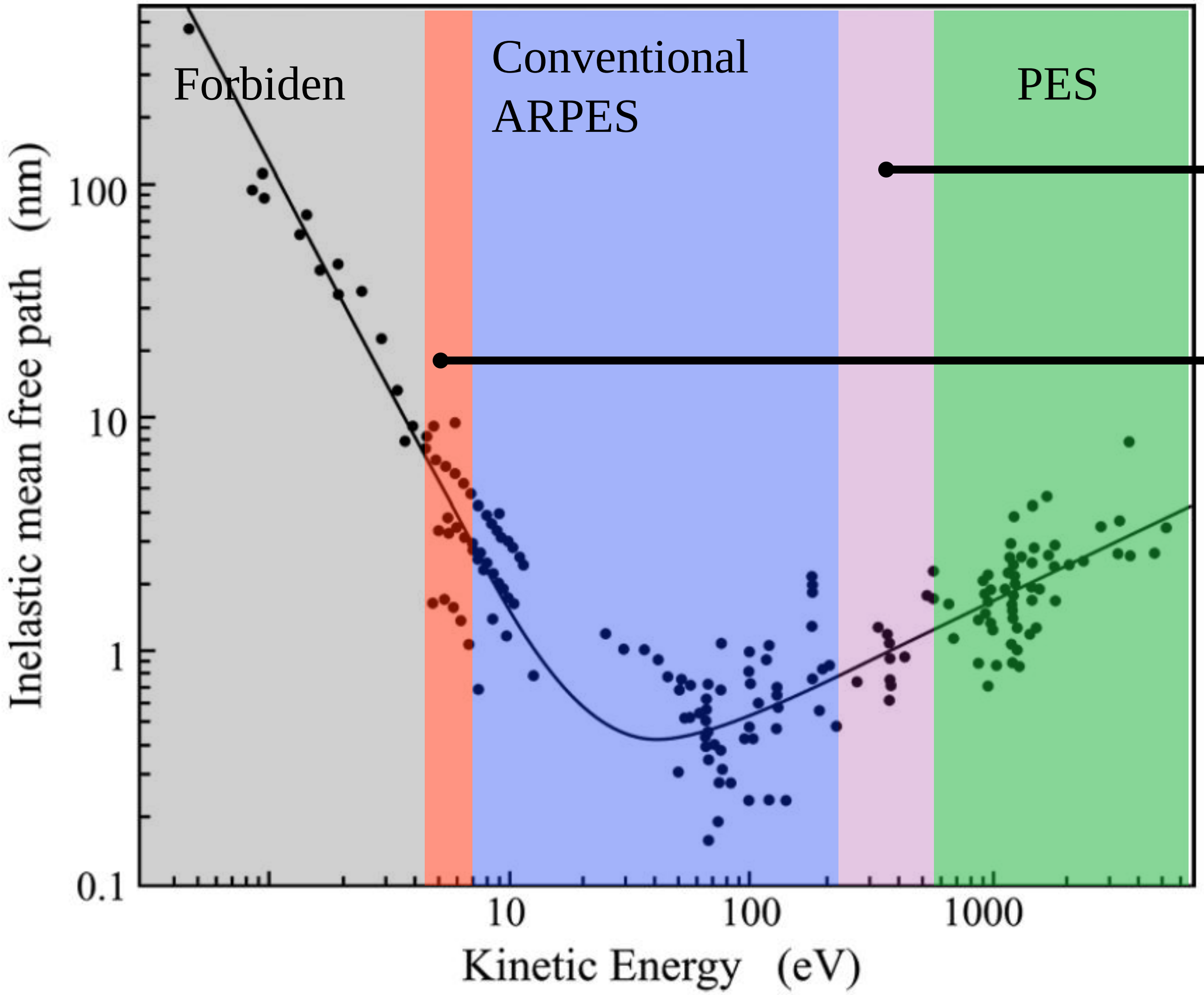




ARPES SPECTRA



Surface probe



Low resolution

ARPES + PES

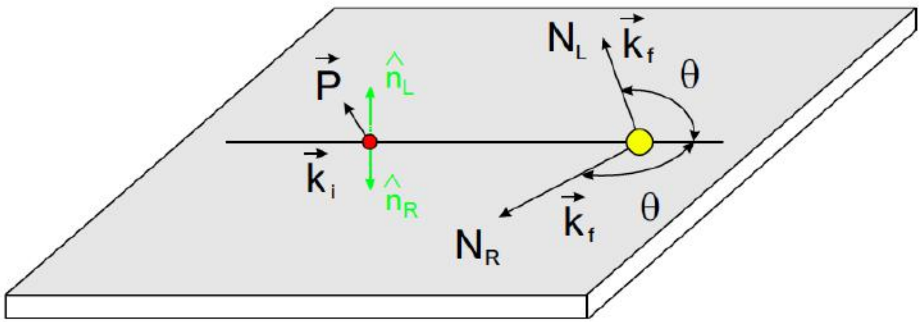
New!

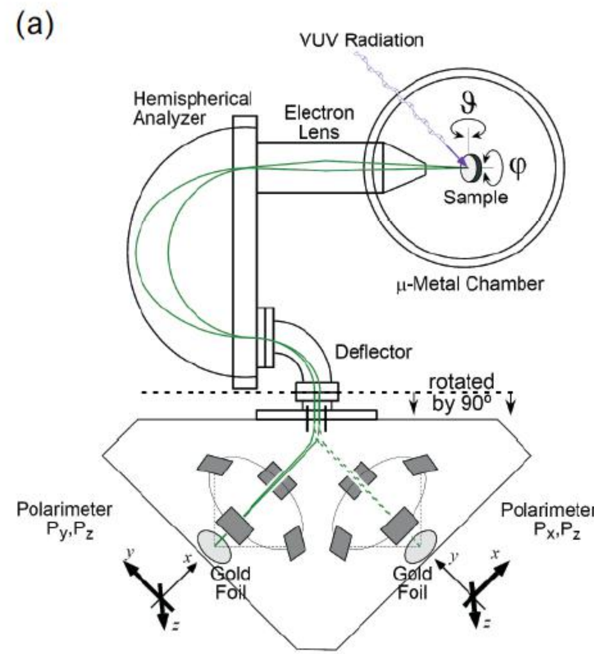
Laser-ARPES

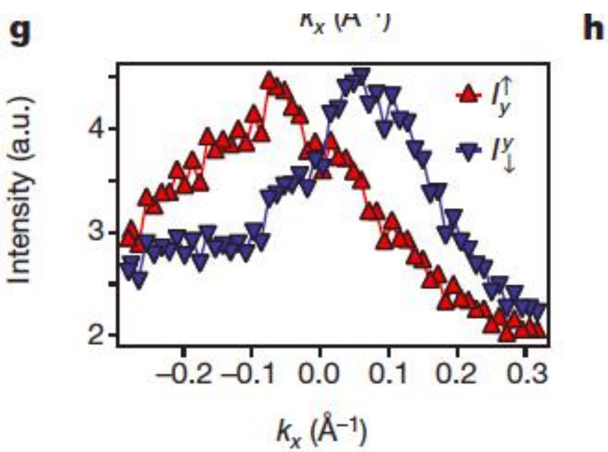
- *High resolution (E ~ 4meV)*
- *Low temperature (T ~ 6K)*
- *d/f selectivity*

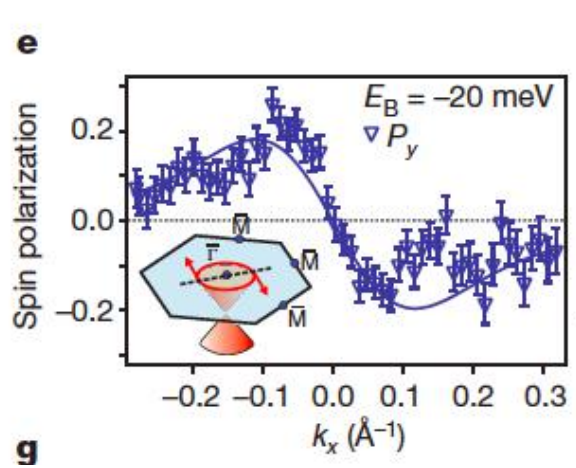
Seah *et al.*, Surf. Interface Anal. **1**, 2 (1979).

Spin-resolved ARPES



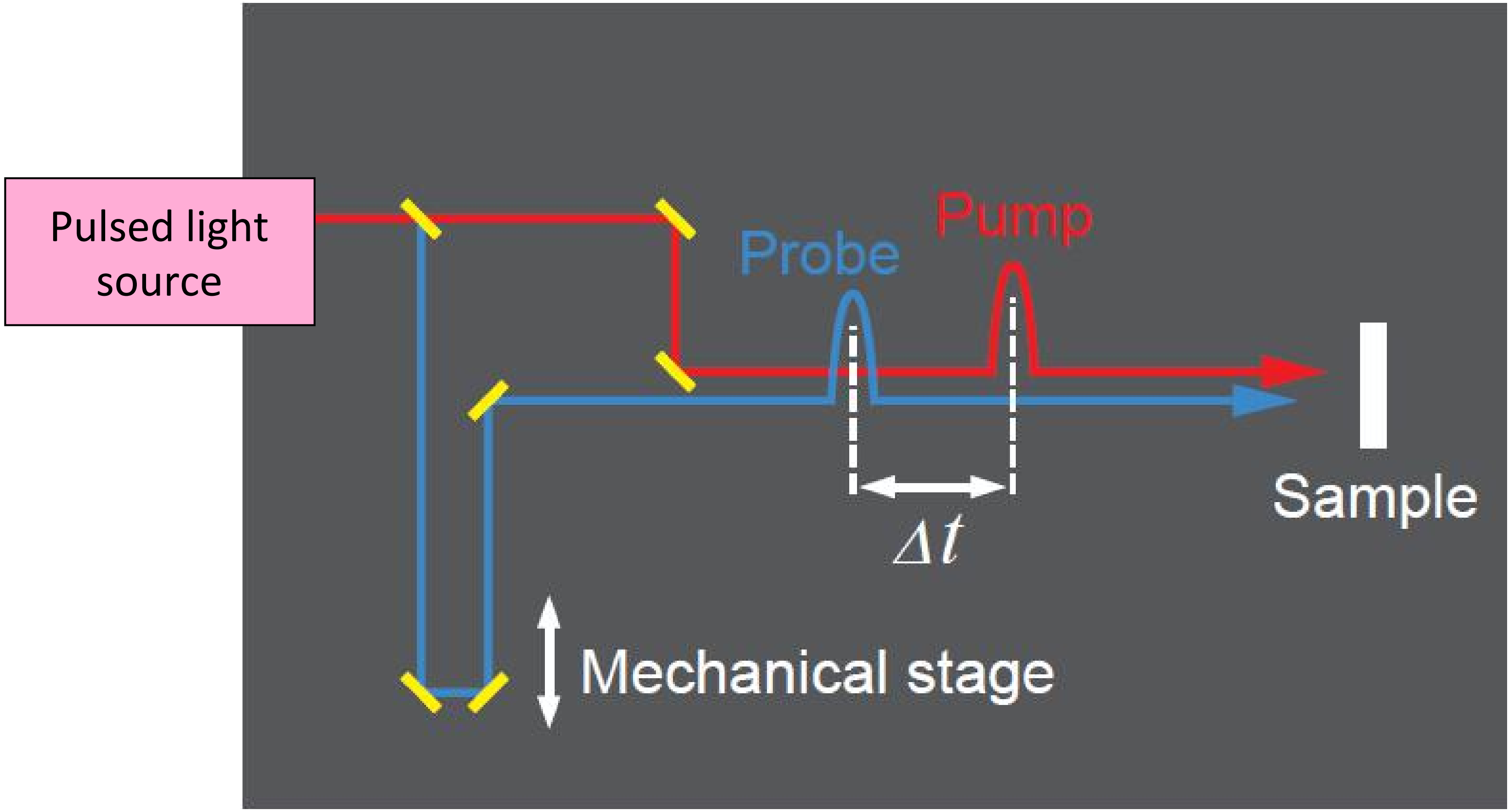






Hsieh, *et al.*, (2009);

Time-resolved spectroscopy

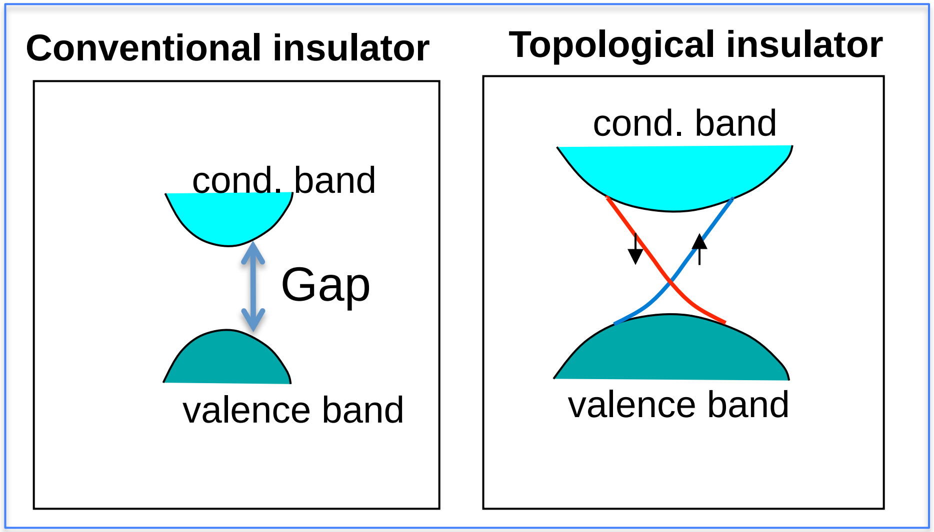


Pump-probe spectroscopy:

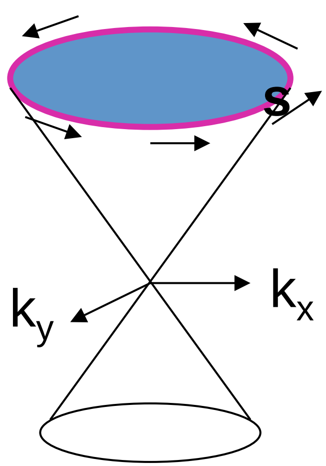
Pump pulse initiates the dynamics, and probe pulse snapshots the transient.

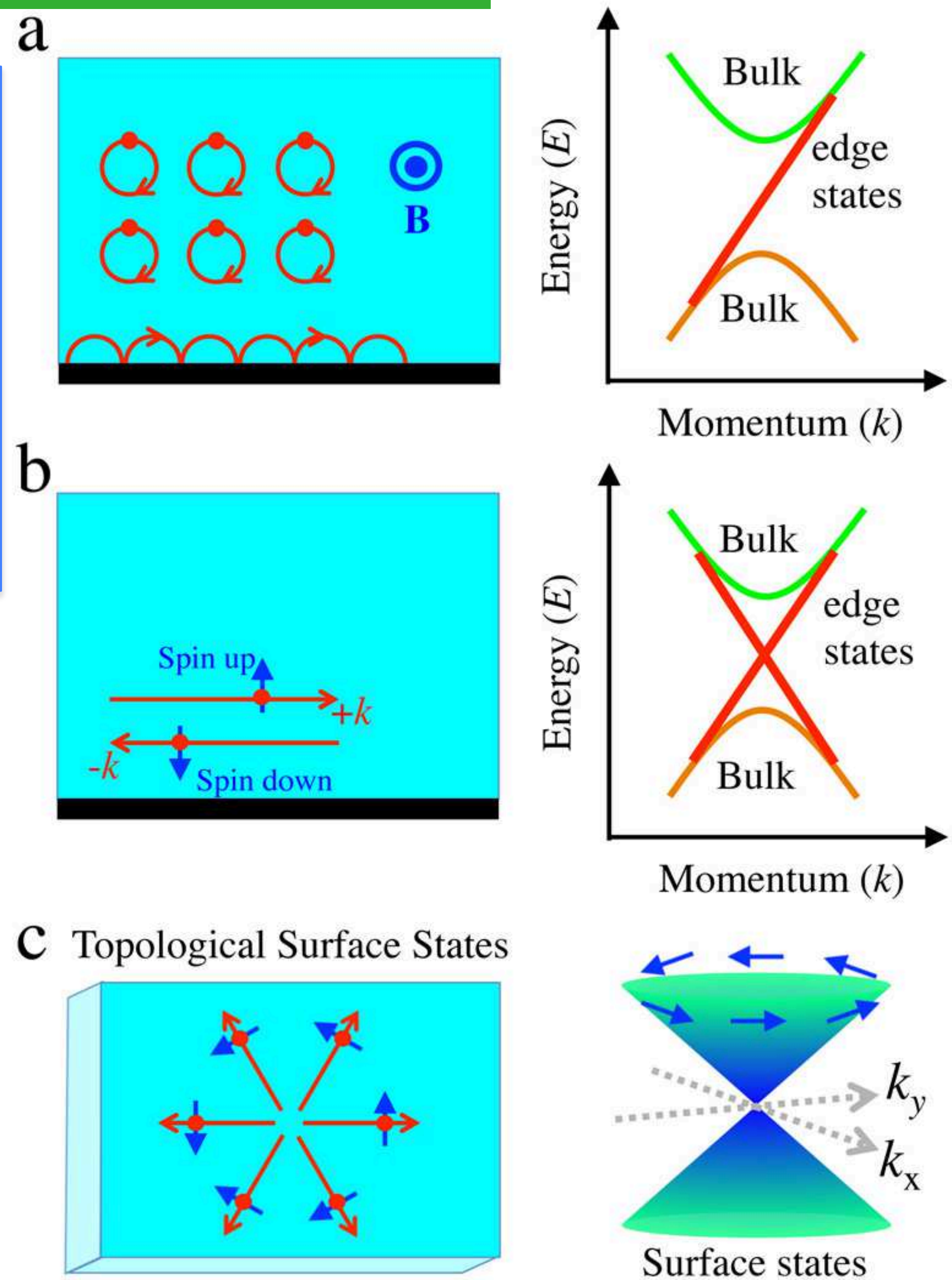
New class of insulator

Fu, Kane '06
Zhang et al. '06
Moore Balents '06
Xi, Hughes, Zhang '09

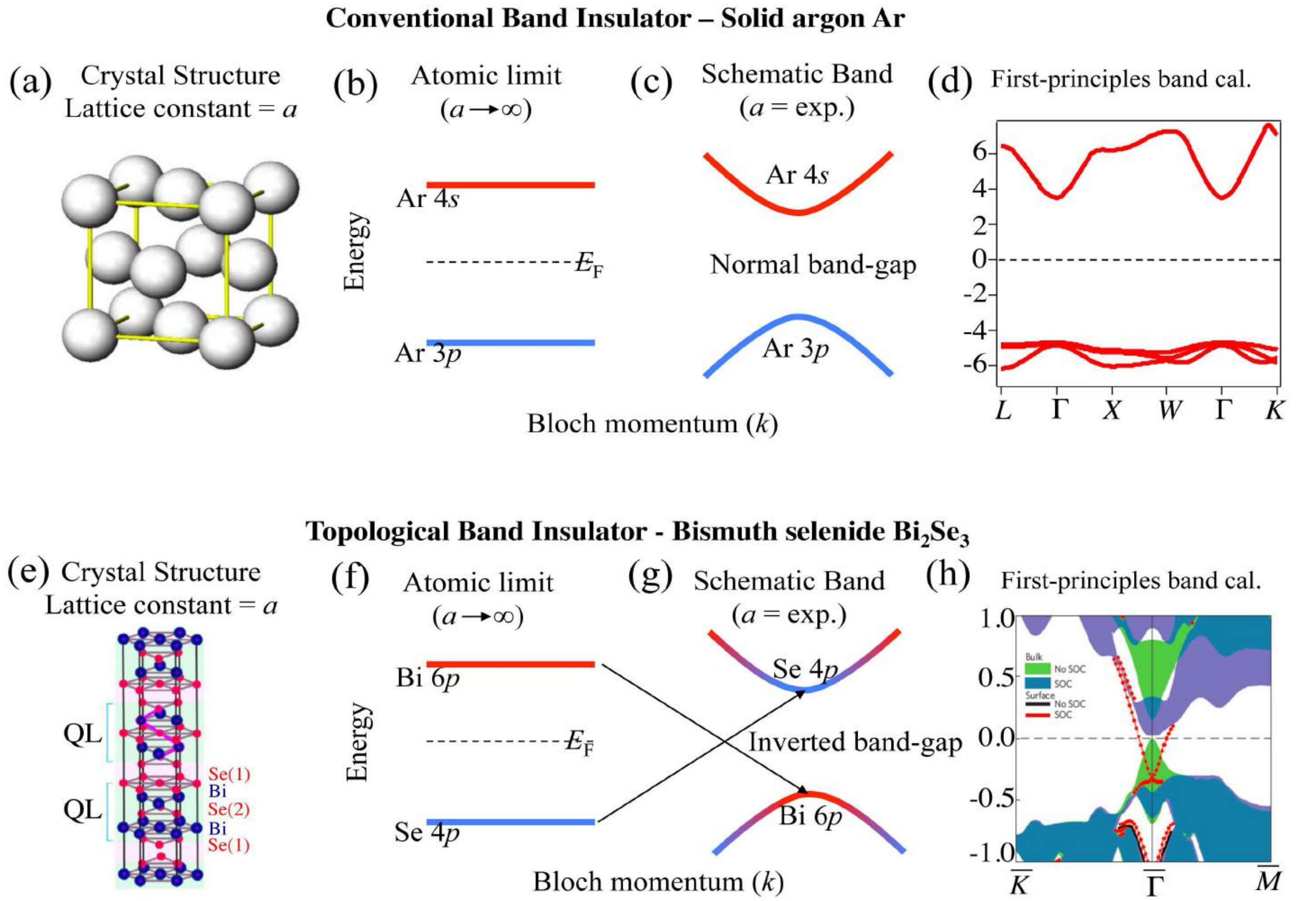


Surface state has
Dirac dispersion



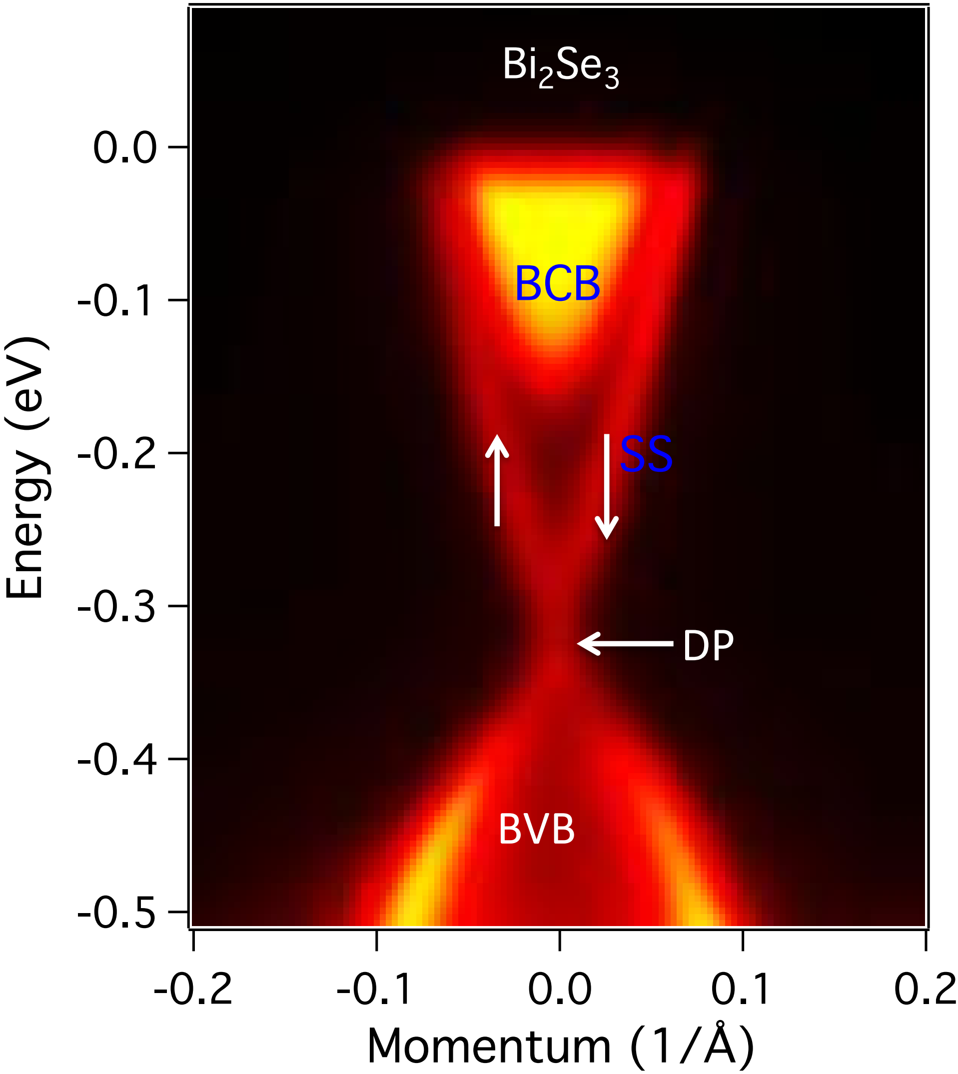


New class of insulator: TI



Topological Insulator

- ***DP***: *The two branches (left-moving and right moving) of the surface states cross, forming a surface Dirac point*
- ***In bulk gap:*** *The Dirac surface states span across the bulk energy gap, and connect the bulk conduction and the bulk valence bands each other, forming a surface Dirac point*
- ***Enclosing Kramers points***: *The surface state Fermi surfaces enclose the Kramers points of the surface BZ*
- ***Spin-momentum locking***: *The surface state spin is locked with its momentum*
- ***Odd number***: *There are an odd number of **robust** such spin-momentum locked surface state Fermi surfaces*

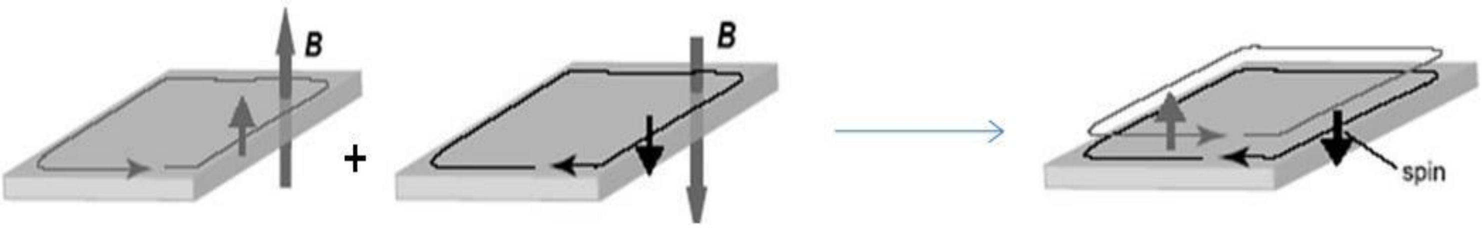


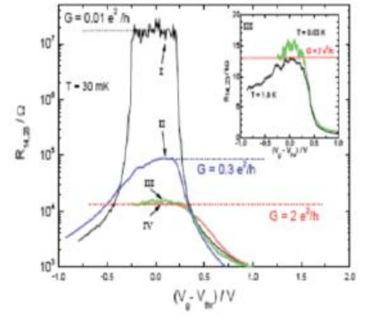
Experimental checklist

Experimental realization of TI

2D TI

Science 07 (subm. 2007)

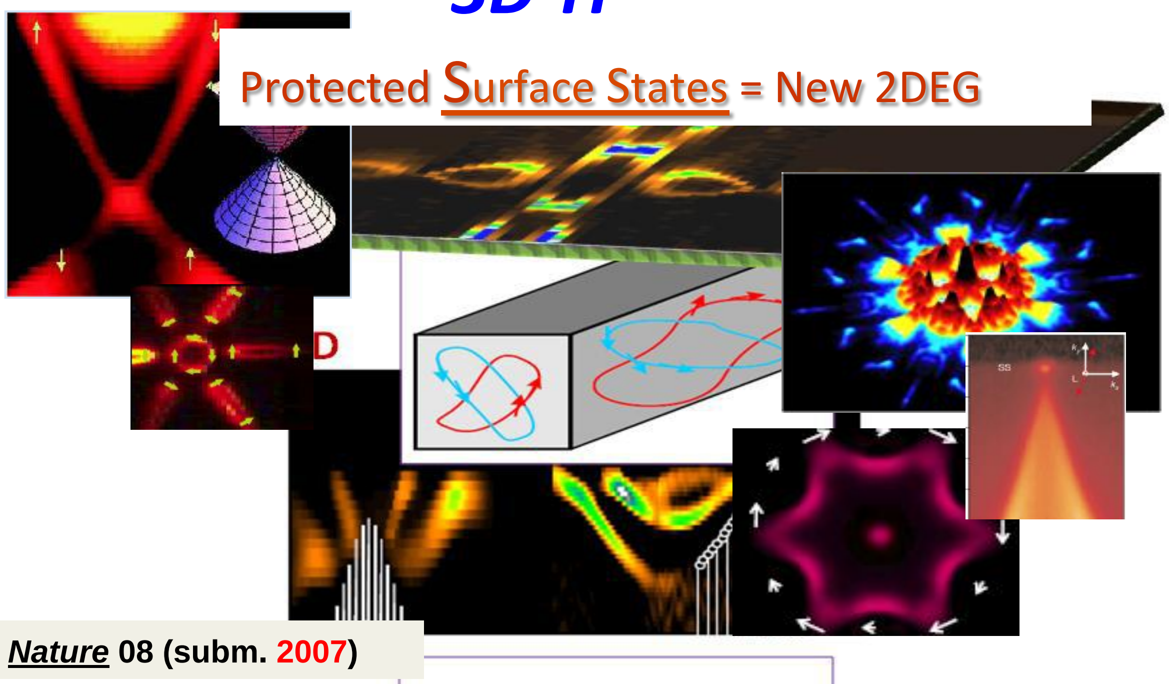




Edge States (1D) by TRS

3D TI

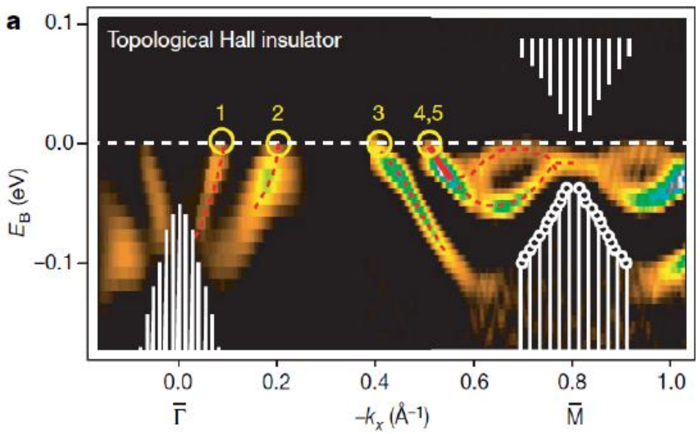
Protected Surface States = New 2DEG



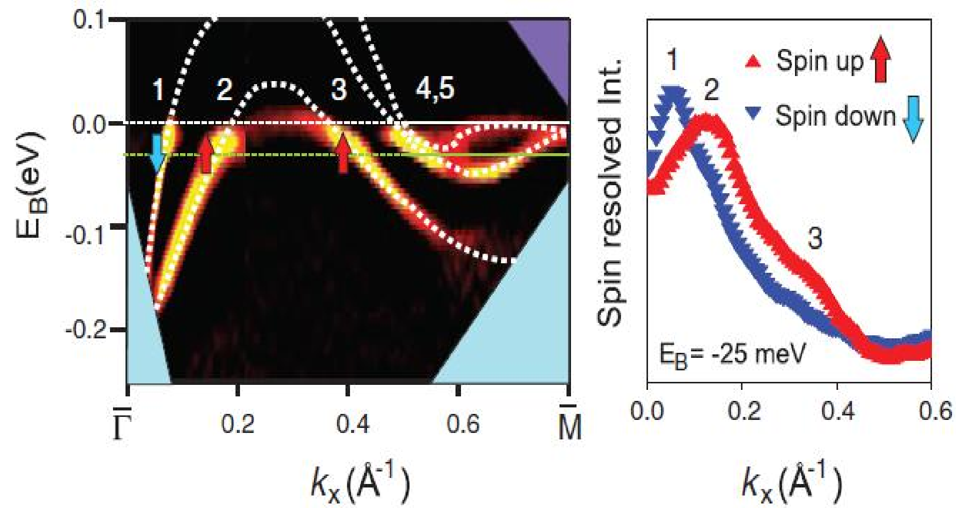
Nature 08 (subm. 2007)

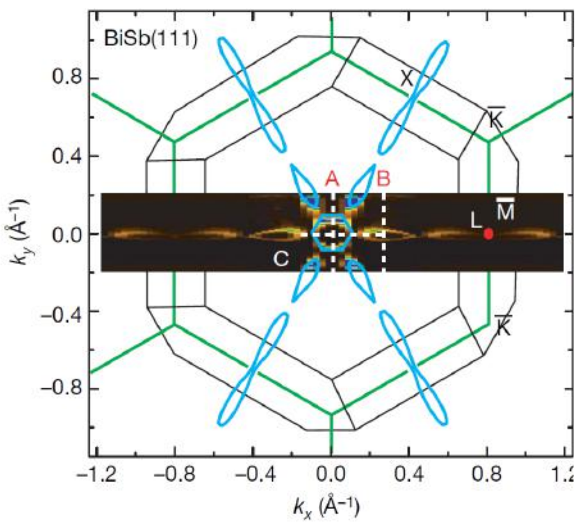
$Bi_{1-x}Sb_x$: the first discovered 3D TI

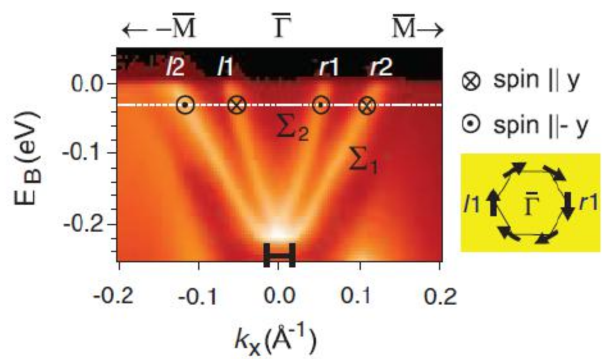
Odd number of Dirac cones

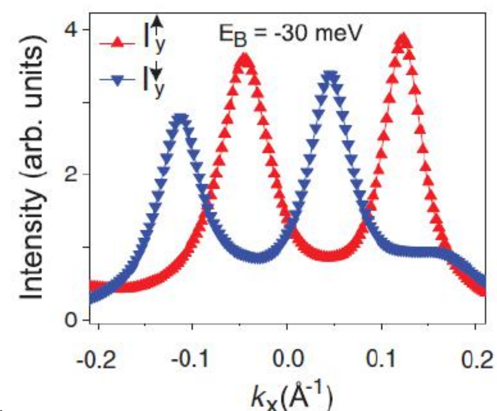


spin helical structure







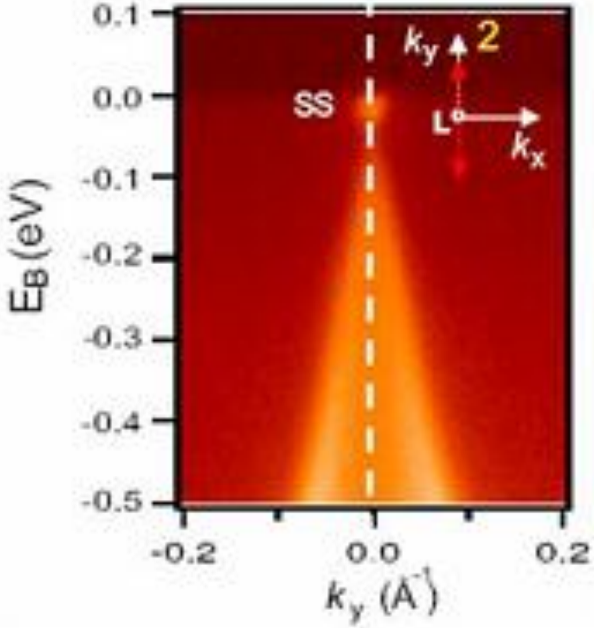


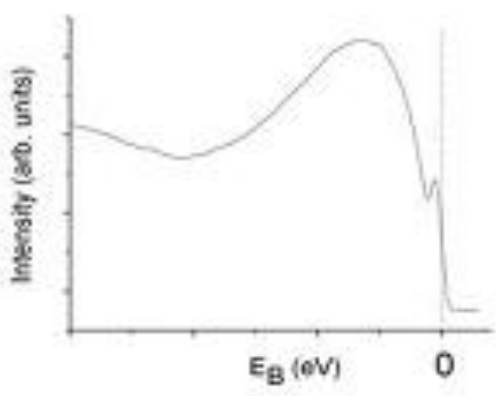
D. Hsieh *et al. Nature* **452**, 970 (2008);
D. Hsieh *et al. Science* **323**, 919 (2009)

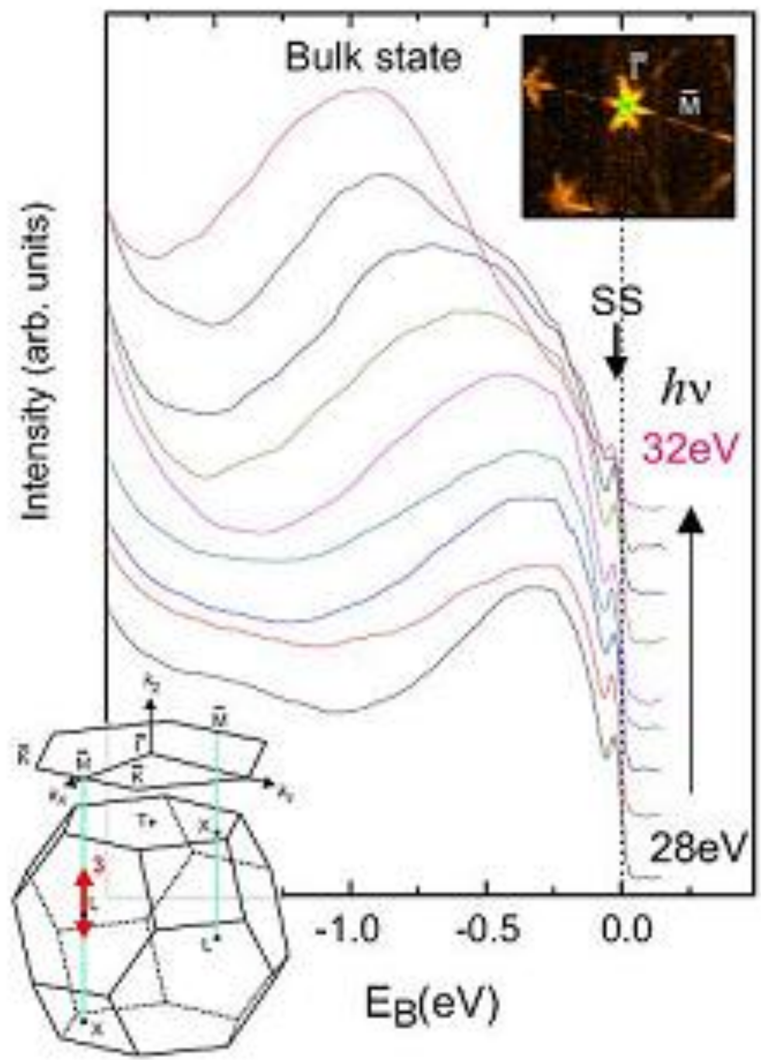
Surface vs bulk

Band-structure of BiSb semiconductors : ARPES view

Fu-Kane PRB'07 Bi-Sb

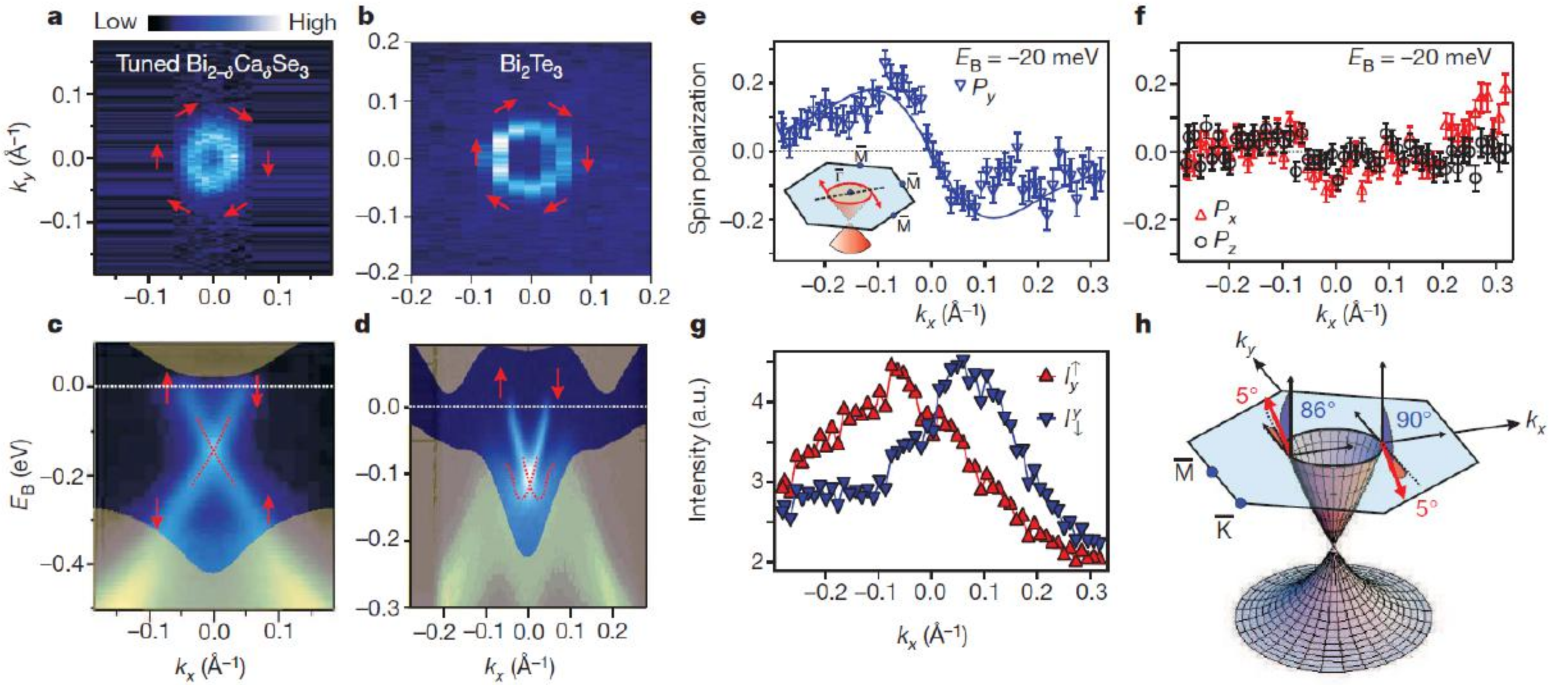




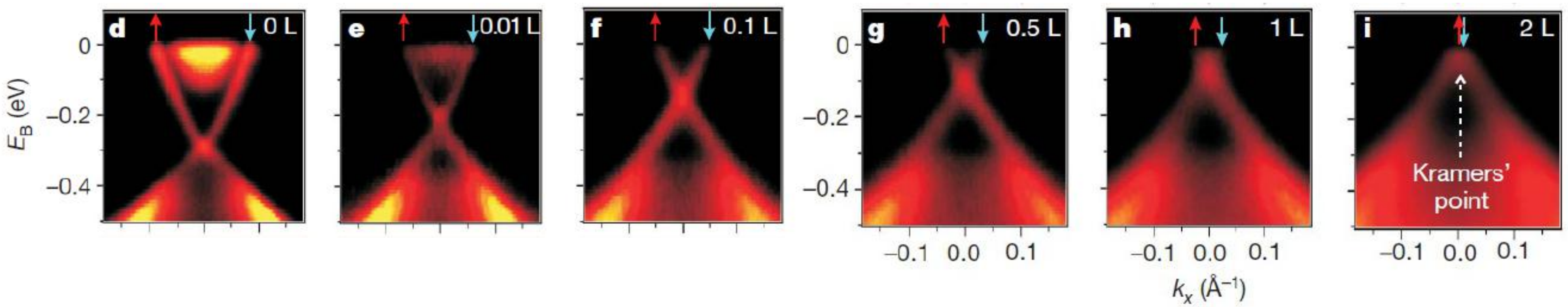


Bi_2Se_3- single Dirac cone TI

$Bi_2(Se/Te)_3$; Single Dirac cone and spin helical texture; stable at room T



Fermi level tunable by surface carrier deposition (NO_2 on $Bi_{2-x}Ca_xSe_3$)



D. Hsieh *et al. Nature* **460**, 1101 (2009), Y. Xia *et al. Nature Physics* **5**, 398 (2009), Y. L. Chen *et al. Science* **325**, 178 (2009)

Ternary Topological Insulators

Ternary Topological Insulators

Many Ternary TIs

- Several new topological insulator classes

- Gaps up to ~ 0.35 eV

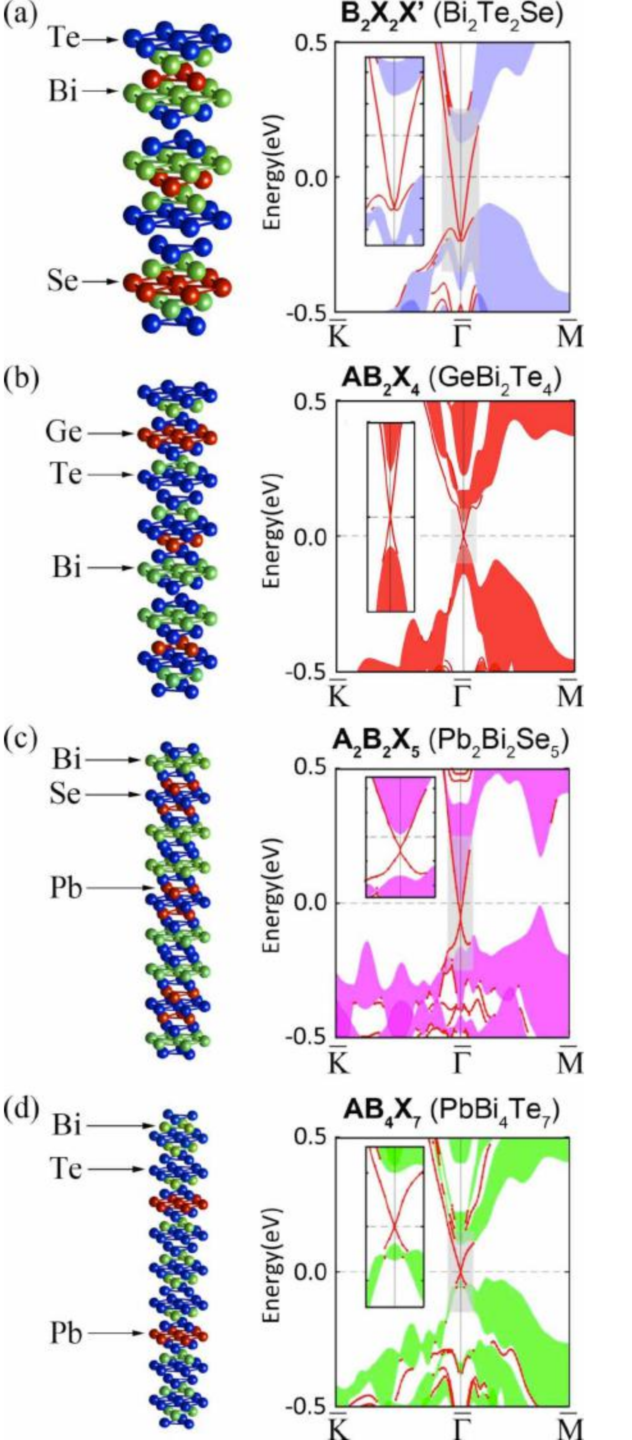
- New platforms to search for topological-superconductivity

- Single Dirac cone

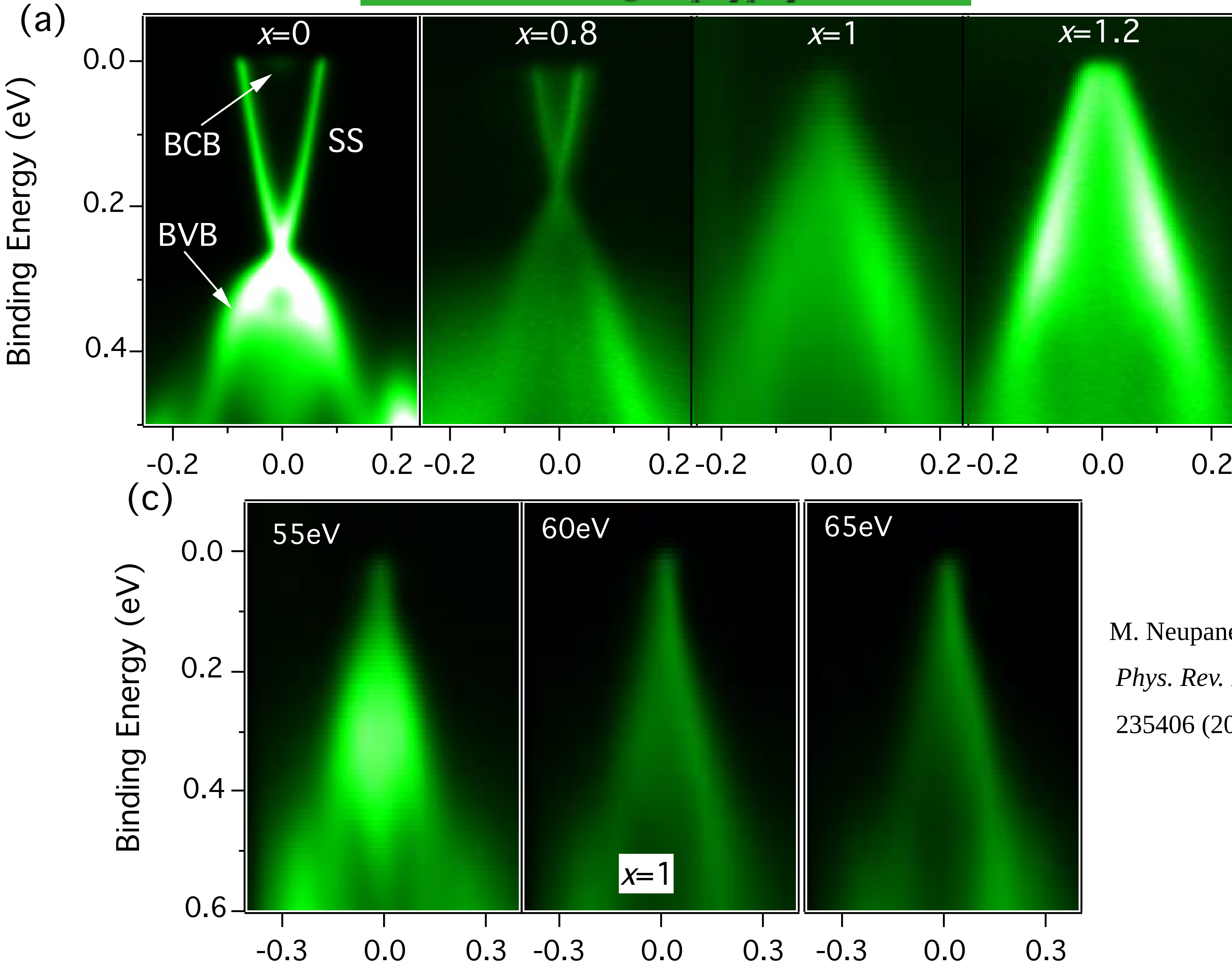
- Bulk insulating nature

M. Neupane *et al.*, *Phys. Rev. B* **85**, 235406 (2012)

Also see Z. Ren *et al.*, *Phys. Rev. B (R)* **82**, 241306 (R) (2010)



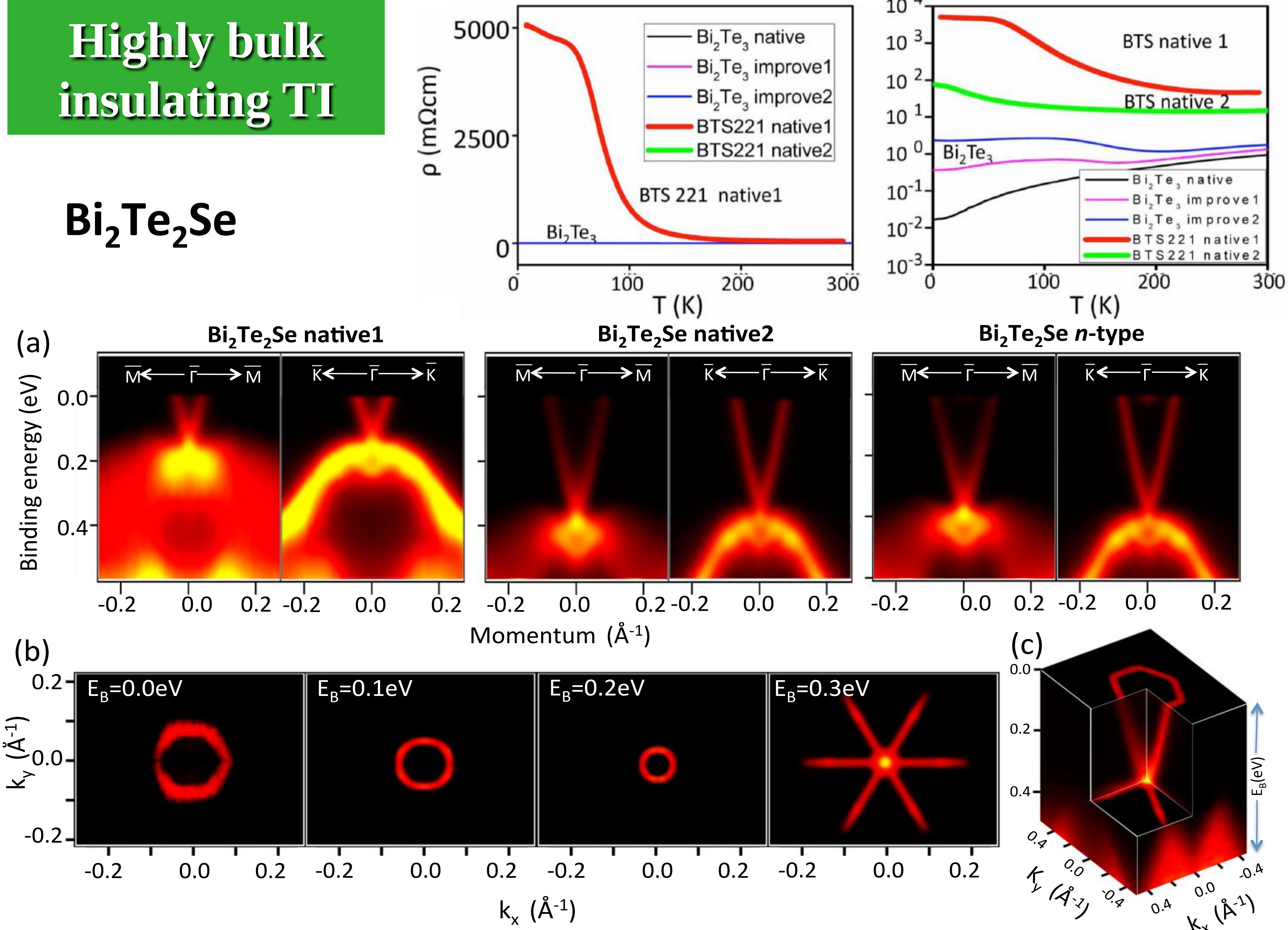
DP tuning: $Sb_xBi_{2-x}Se_2Te$



M. Neupane *et al.* *Phys. Rev. B* **85**, 235406 (2012)

Highly bulk insulating TI

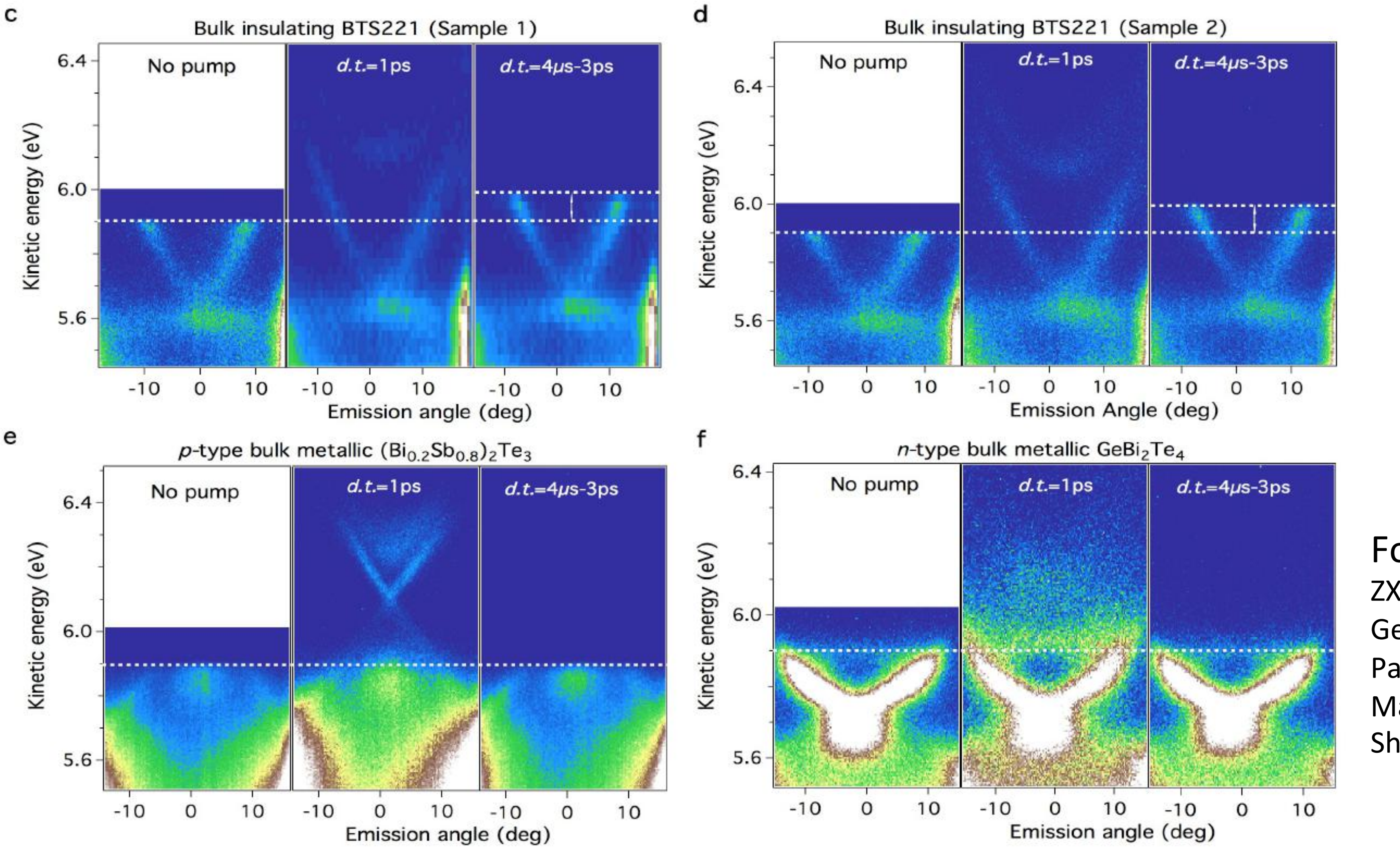
Bi_2Te_2Se



Z. Ren *et al.*, *Phys. Rev. B (R)* **82**, 241306 (R) (2010), M. Neupane *et al. Phys. Rev. B* **85**, 235406 (2012)

TrARPES on highly bulk insulating TI: Bi_2Te_2Se

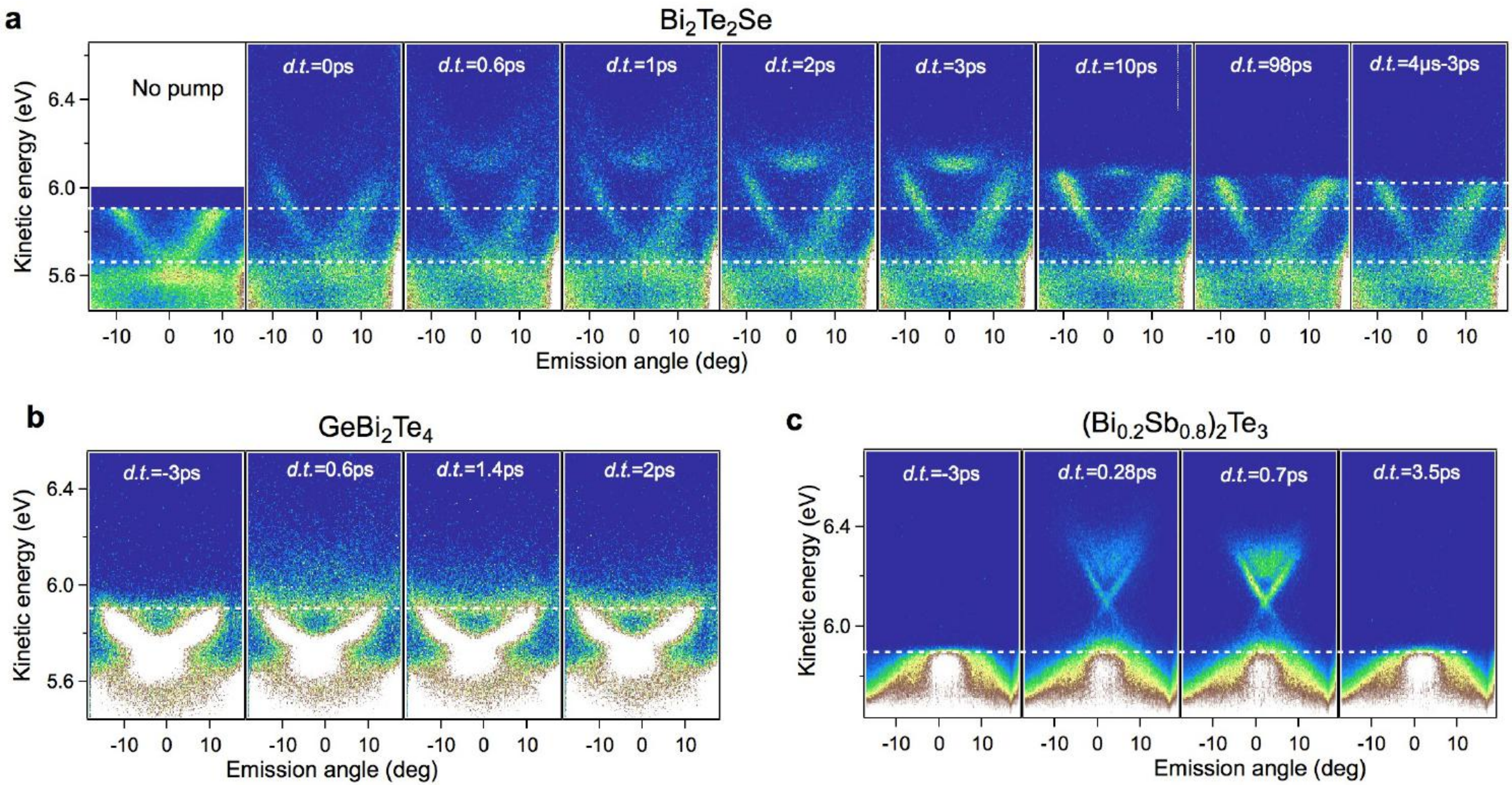
Gigantic surface life-time of an intrinsic topological insulator



For binary TIs
ZX Shen group
Gedik group
Parmigiani group
Marsi group
Shin group

M. Neupane *et al., Phys. Rev. Lett.* **115**, 116801 (2015).

Time-resolved spectra: Bulk insulating vs bulk metallic



M. Neupane *et al., Phys. Rev. Lett.* **115**, 116801 (2015).

Time-resolved spectra: time evolution

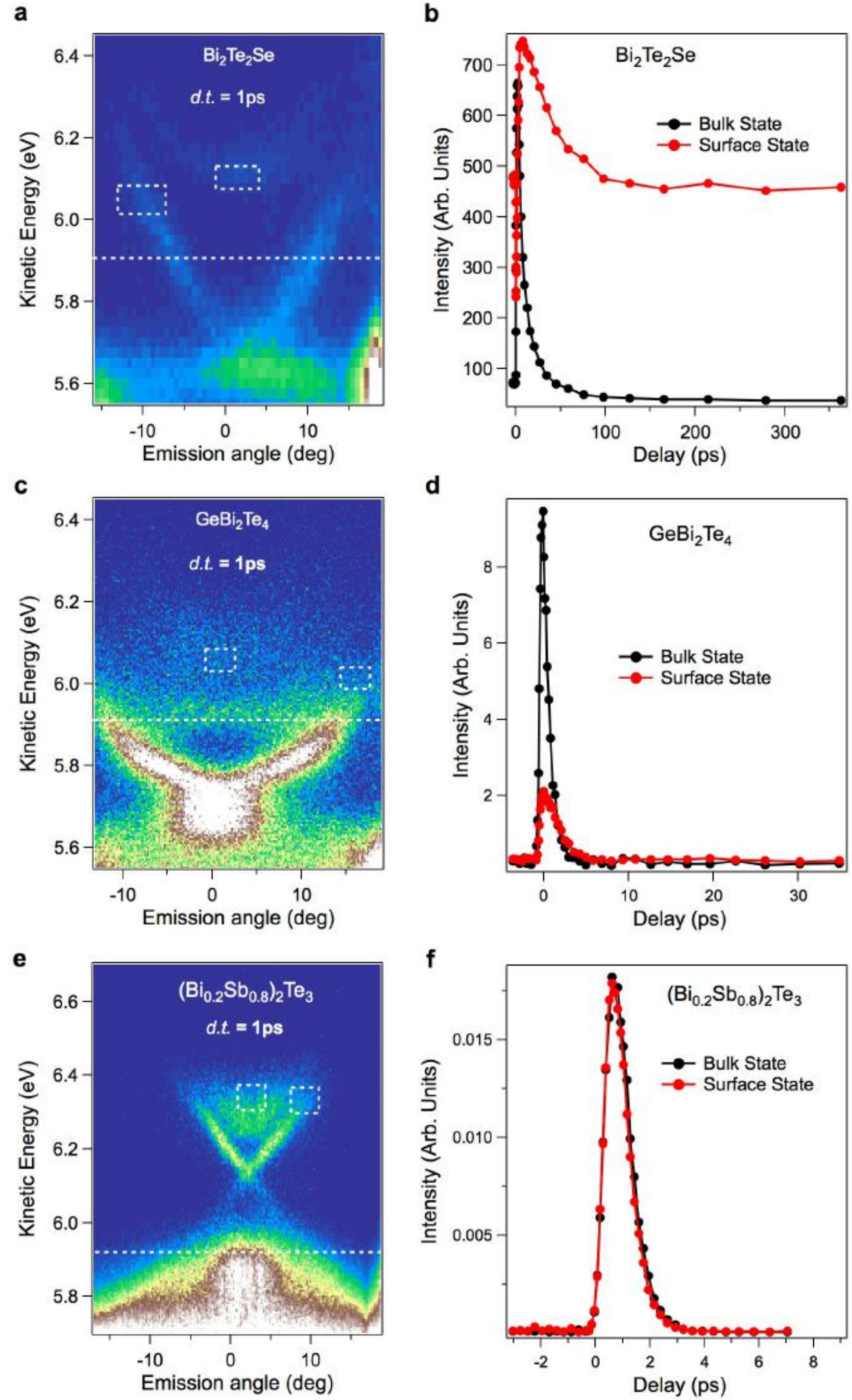
Bi_2Se_3/Bi_2Te_3 vs Bi_2Te_2Se

Bulk-metallic vs bulk-insulating TI

Pico-second vs Micro-second

Absence (SPV) vs presence (SPV)

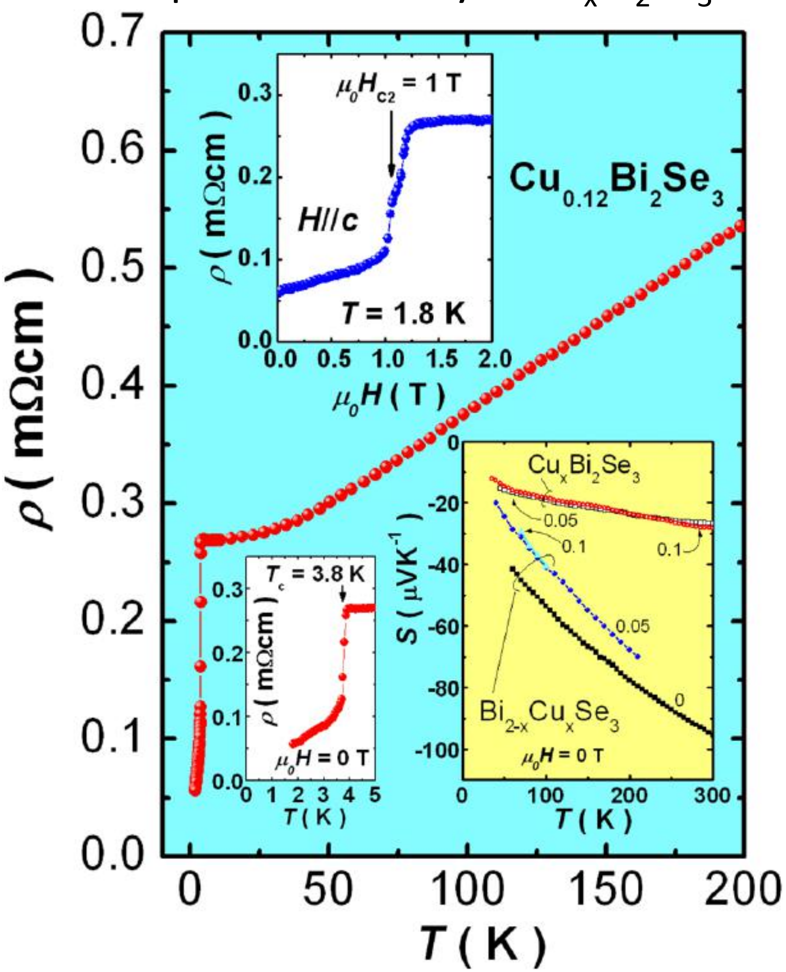
Charge relaxation: Exponential vs power law



M. Neupane *et al., Phys. Rev. Lett.* **115**, 116801 (2015).

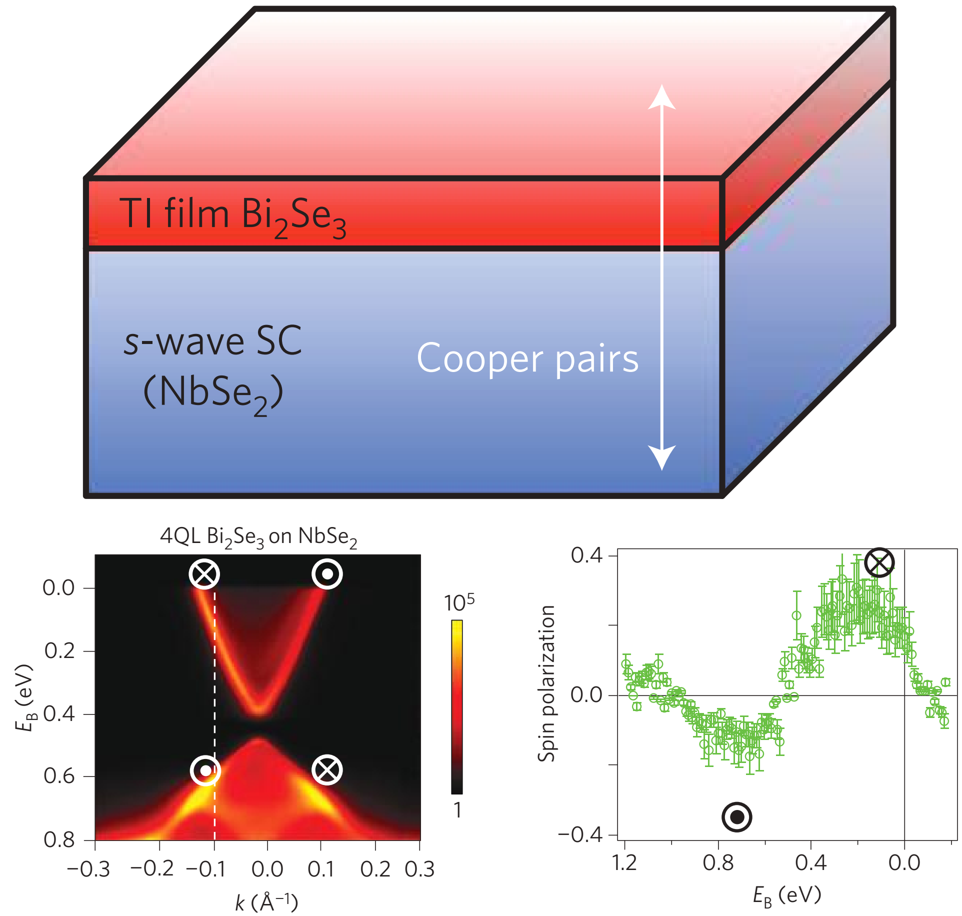
Relaxation dynamics in a superconducting topological insulator

Superconductivity in $Cu_xBi_2Se_3$



YS Hor *et al.*, *PRL* **104**, 057001 (2010)

Proximity induced superconductivity

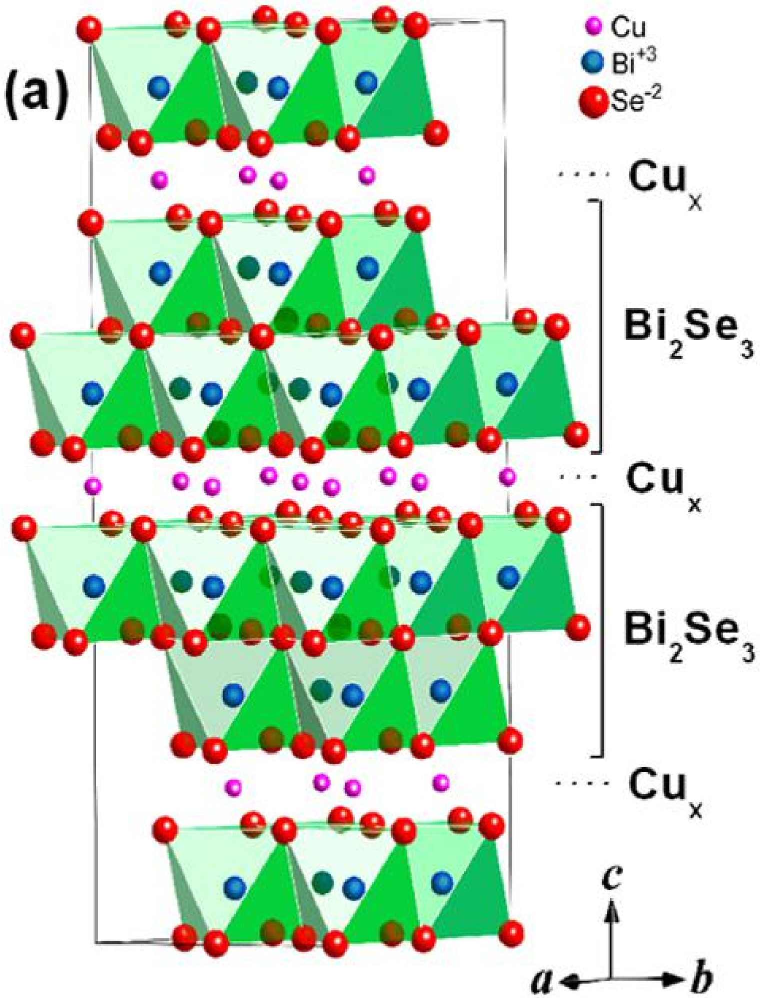


SY Xu *et al.*, *Nat. Phys.* **10**, 943 (2014)

Motivation:

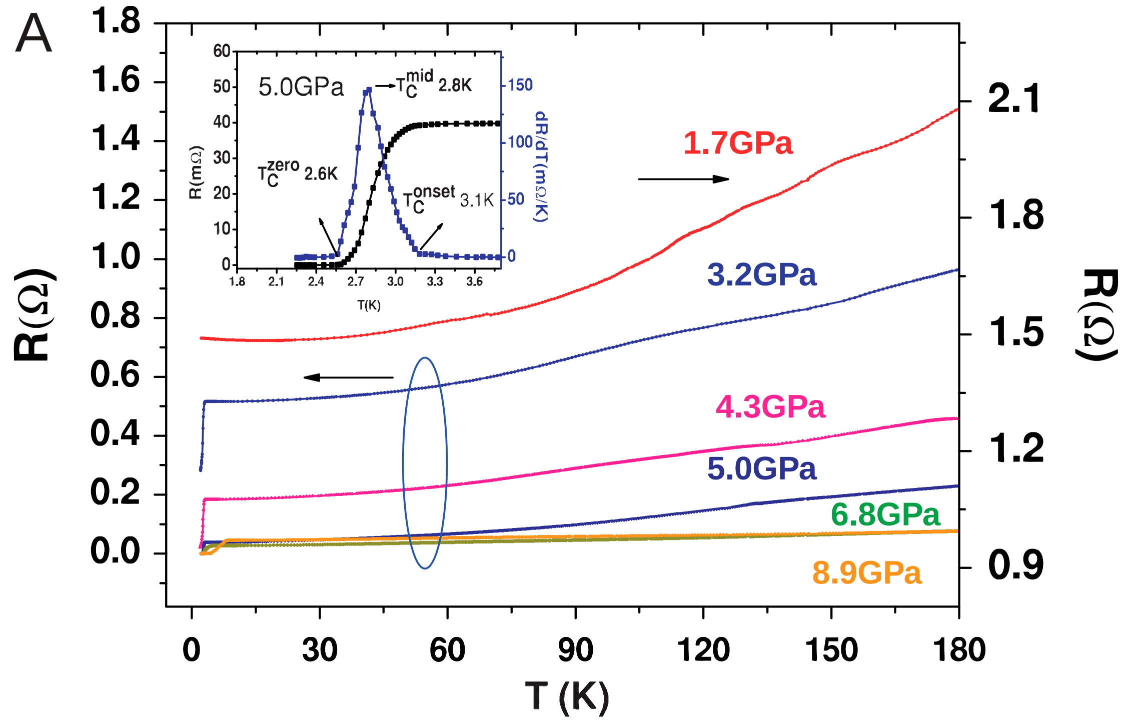
- **Search for a bulk topological superconductor**

Cu-intercalation



Y.S. Hor *et al., Phys. Rev. Lett.* 104, 05701 (2010).

Pressured induced SC on Bi_2Te_3



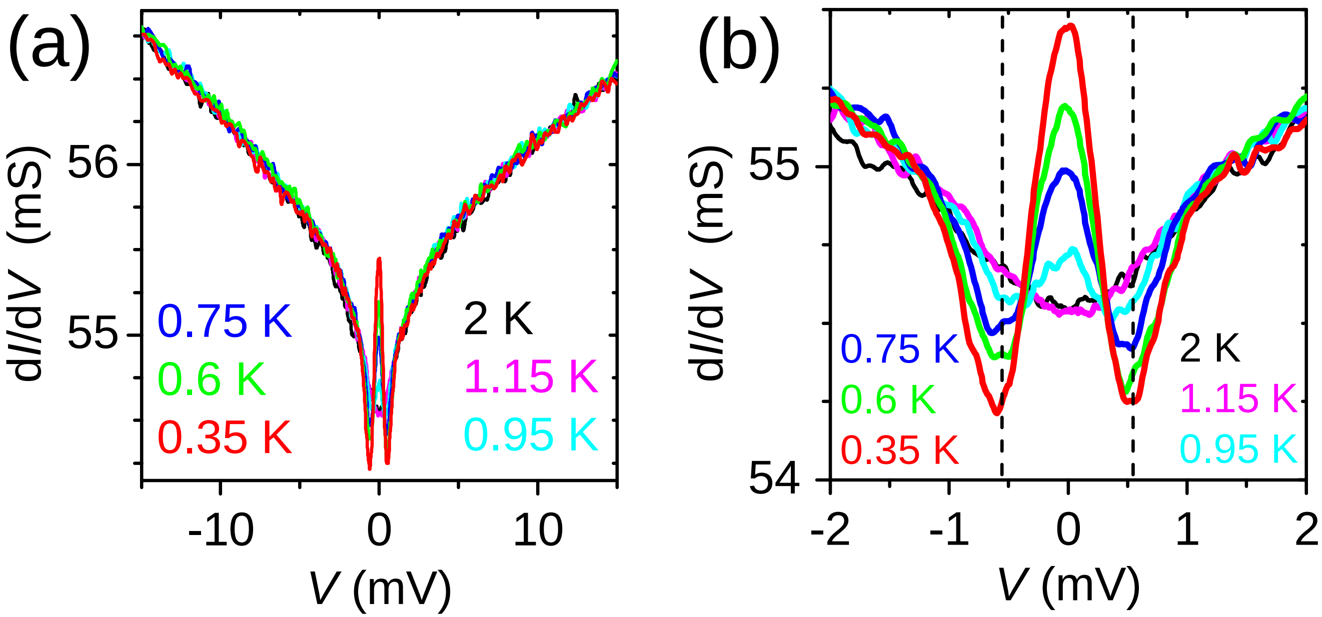
J. L. Zhang *et al., Proc. Natl. Acad. Sci*. **108**, 24 (2011).

- No crystal structure phase transition
- Tc ~3K between 3-6 GPa

Intercalation versus substitution

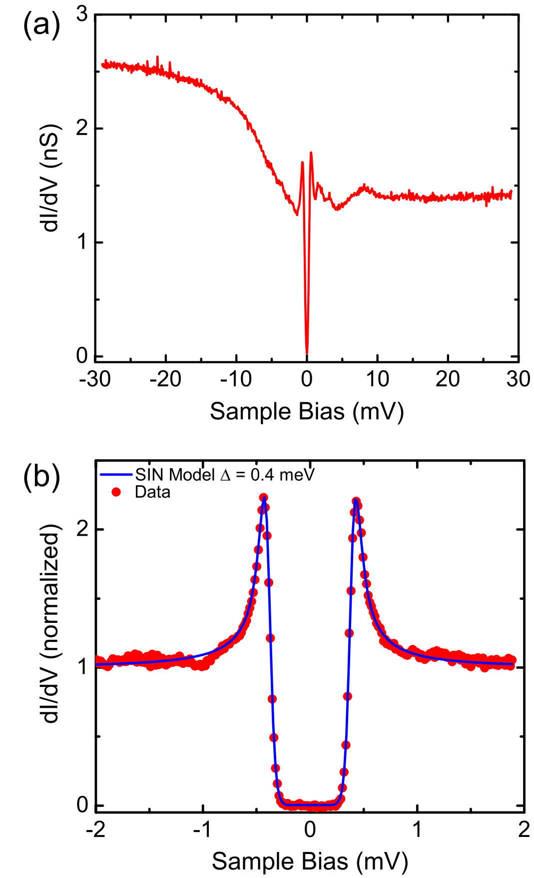
ZBP vs gap in $Cu_xBi_2Se_3$

Zero-biased conductance peak $Cu_xBi_2Se_3$ (x=0.3)



S. Sasaki et al., *Phys. Rev. Lett.* **107**, 217001 (2011).

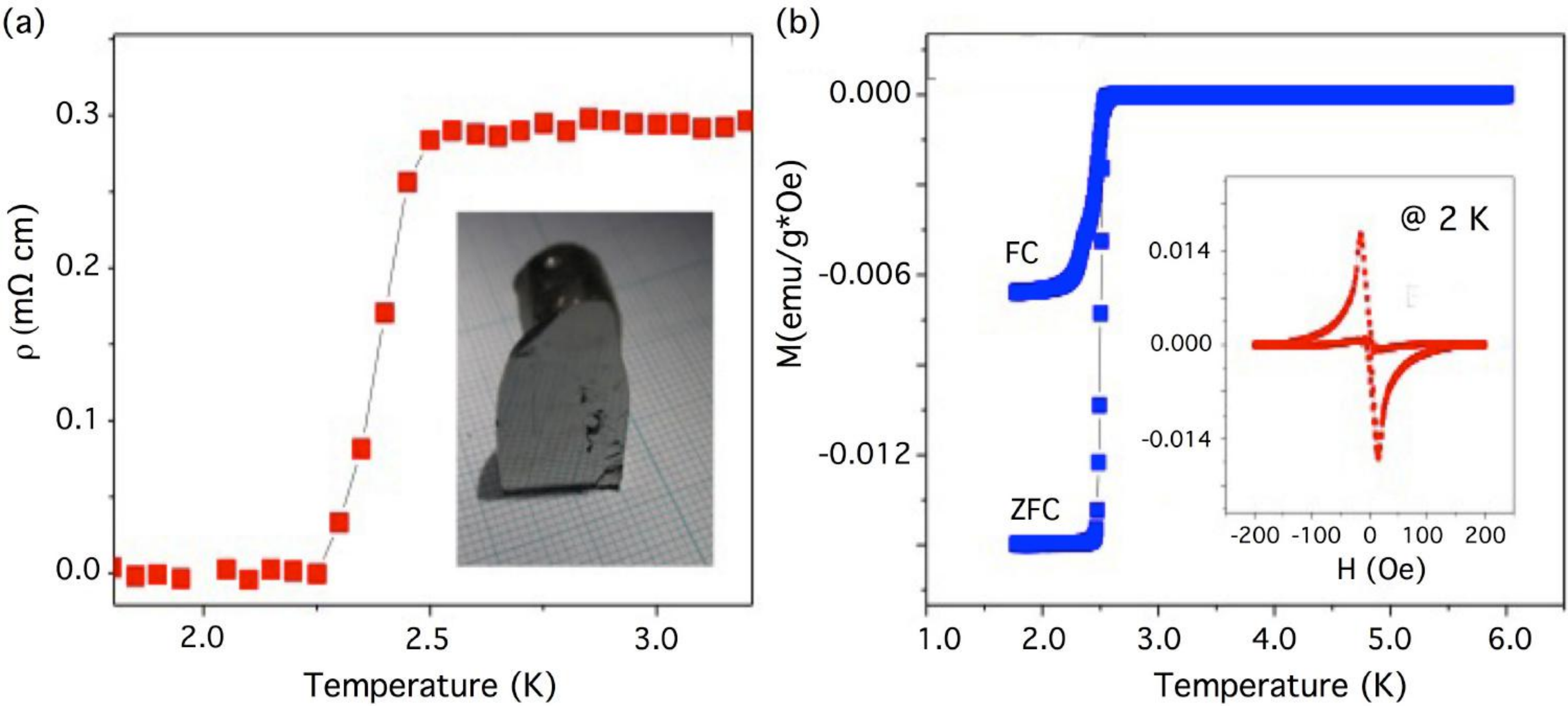
s-wave pairing gap



N. Levy *et al.*, *Phys. Rev. Lett.* 110, 117001 (2013).

Search for better candidates for TSC continue?

$Sr_{0.06}Bi_2Se_3$



M. Neupane *et al., Sci. Rep.* **6**, 22557 (2016)

- Tc~2.5K
- The shielding volume fraction at 0.5 K is about 90%.

Z. Liu *et al*., *Jour. Ame., Che. Soc.* **137**, 10512 (2015)
Shruti *et al.*, arXiv:1505.05394v1 (2015)

Tc ~2.9 K for $Sr_{0.1}Bi_2Se_3$

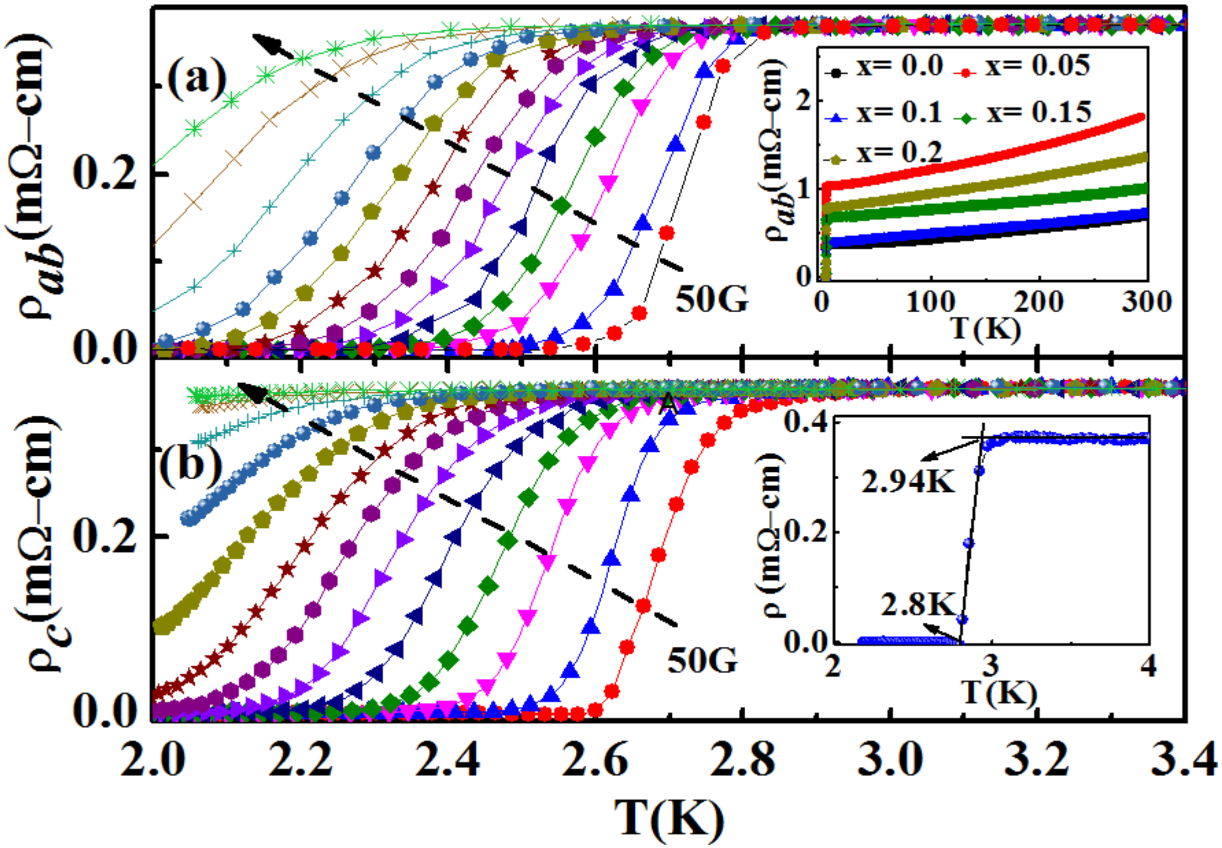
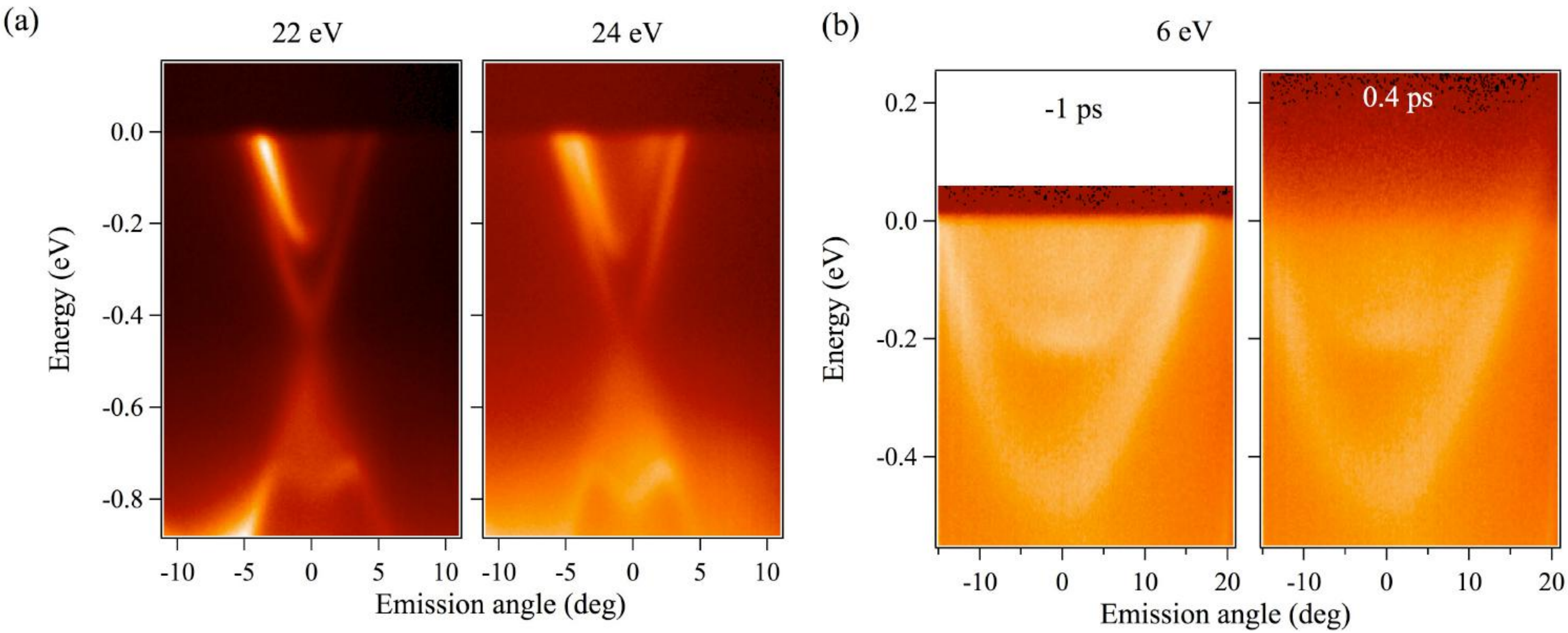


Figure 3. The resistivity as a function of magnetic field applied parallel to *ab* plane (a) and parallel to *c*-axis (b) is plotted for $Sr_{0.1}Bi_2Se_3$. External field H = 0.005, 0.02, 0.05, 0.08, 0.11, 0.14, 0.17, 0.20, 0.24, 0.28, 0.34, 0.42 and 0.50 T. Inset in (a) shows the resistivity behaviour from 2 K to 300 K. Inset in (b) shows the expanded view of the superconducting transition.

Shruti *et al.*, (2015)

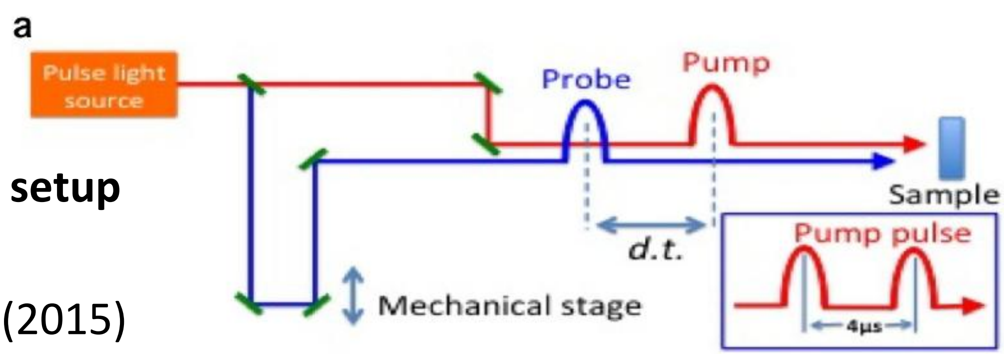
ARPES dispersion maps of $Sr_{0.06}Bi_2Se_3$



- Dirac point is located about 450 meV below the Fermi level.
- Coexistence of the topological surface states and a 2D states.
- 2D quantum well state is a generic property of the Sr intercalated topological insulator Bi_2Se_3.

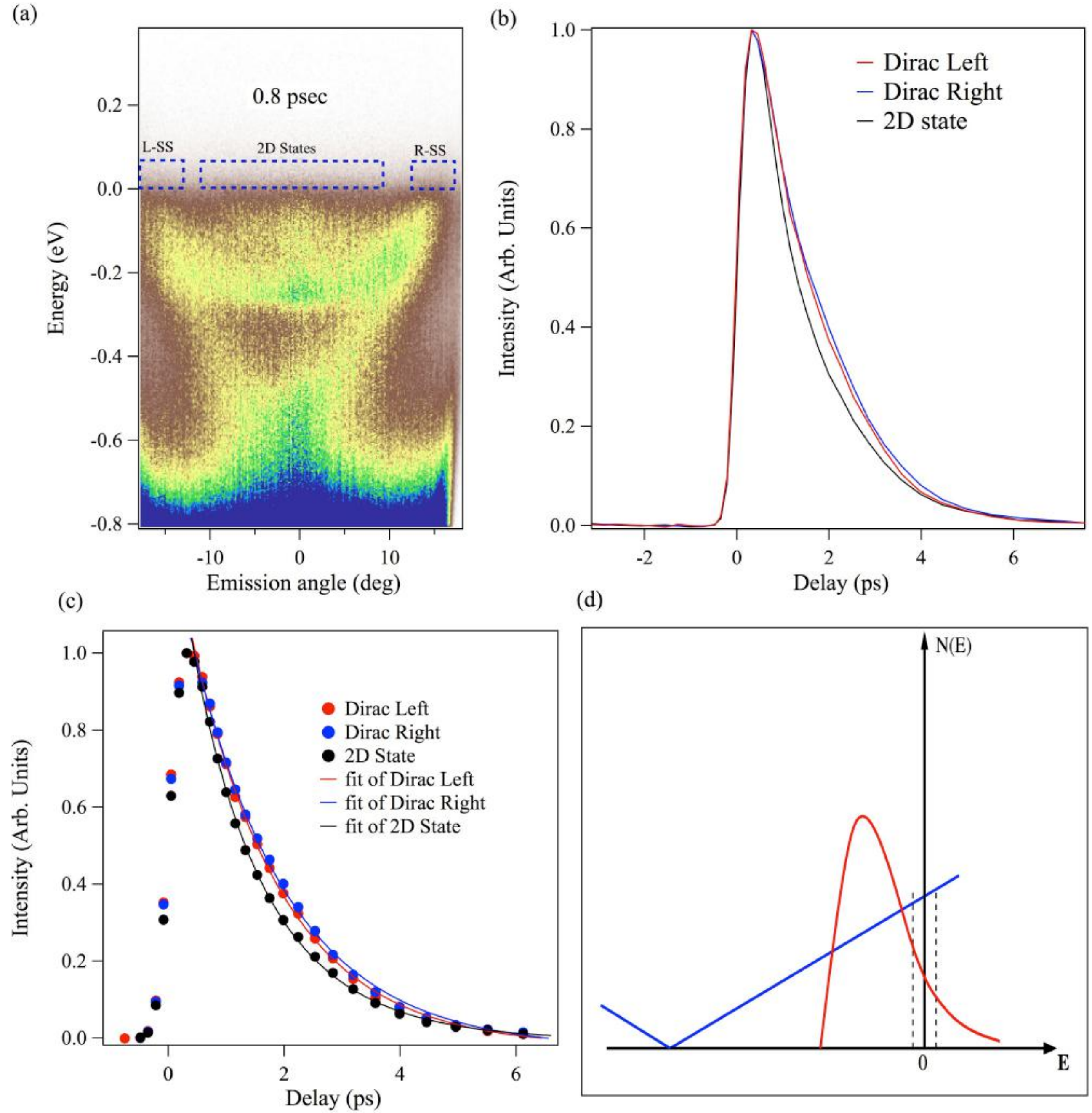
M. Neupane *et al.* (2016)

Pump probe setup



For normal ARPES, also see
C.Q. Han *et al*, *Appl. Rev. Lett.* 1**07**, 171602 (2015)

TR-ARPES result

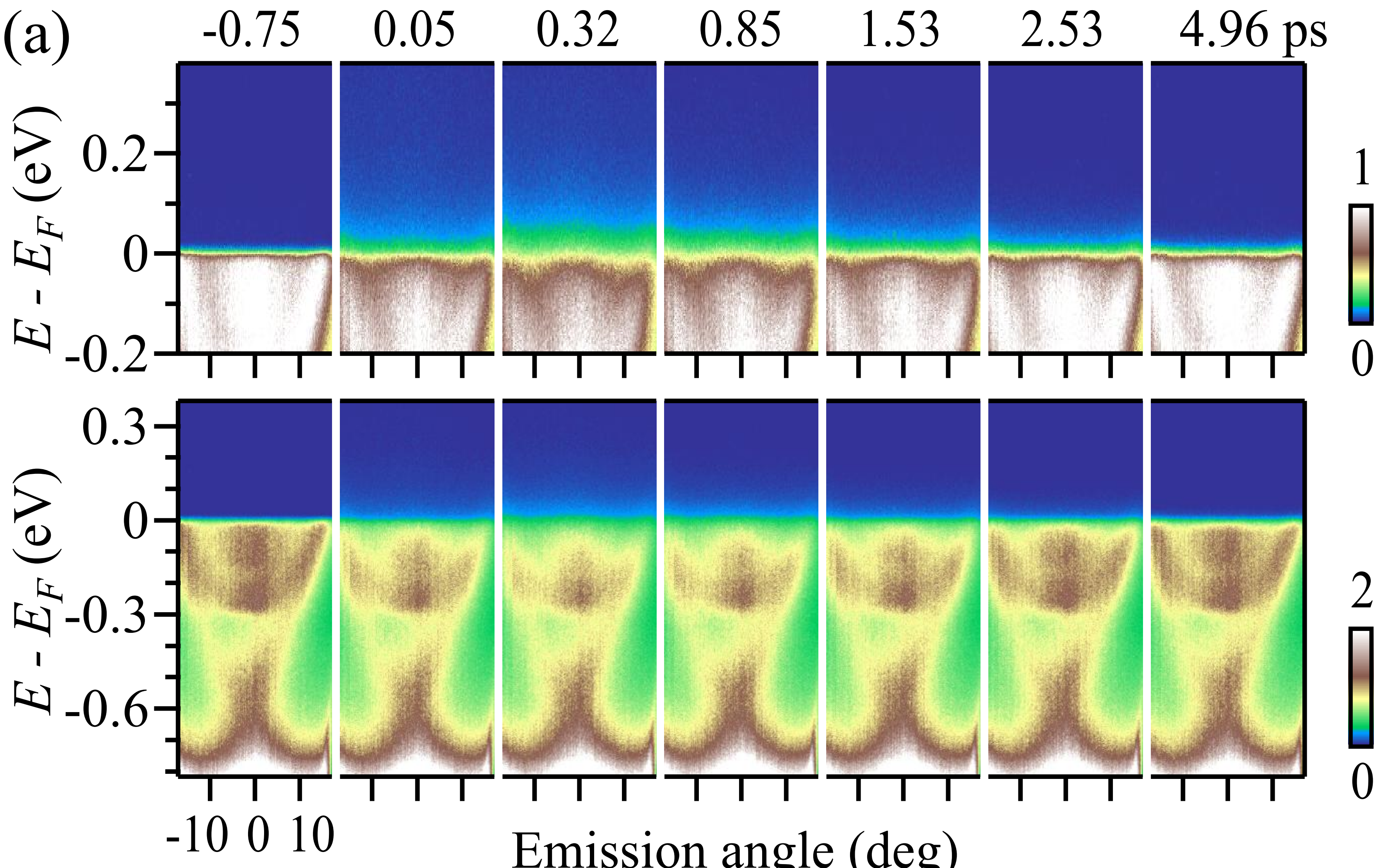


- Both relax within 5 ps
- Different decay dynamics
- Short lifetime

Spread of the intensity into the unoccupied side is less pronounced

M. Neupane *et al., Sci. Rep.* **6**, 22557 (2016)

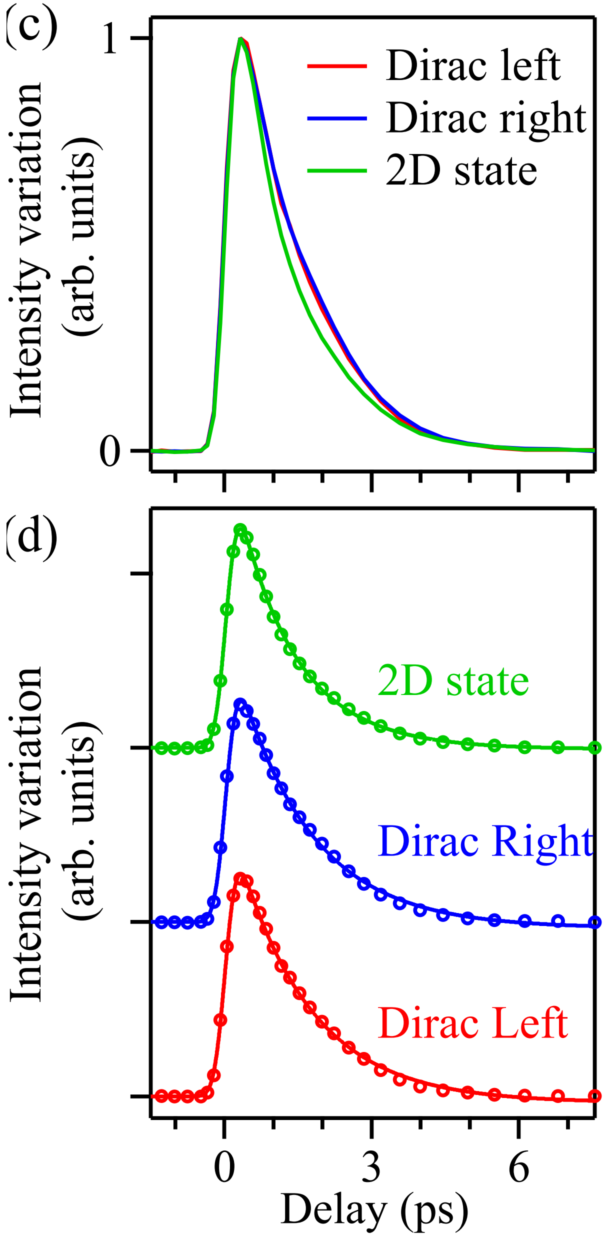
Carrier evolution

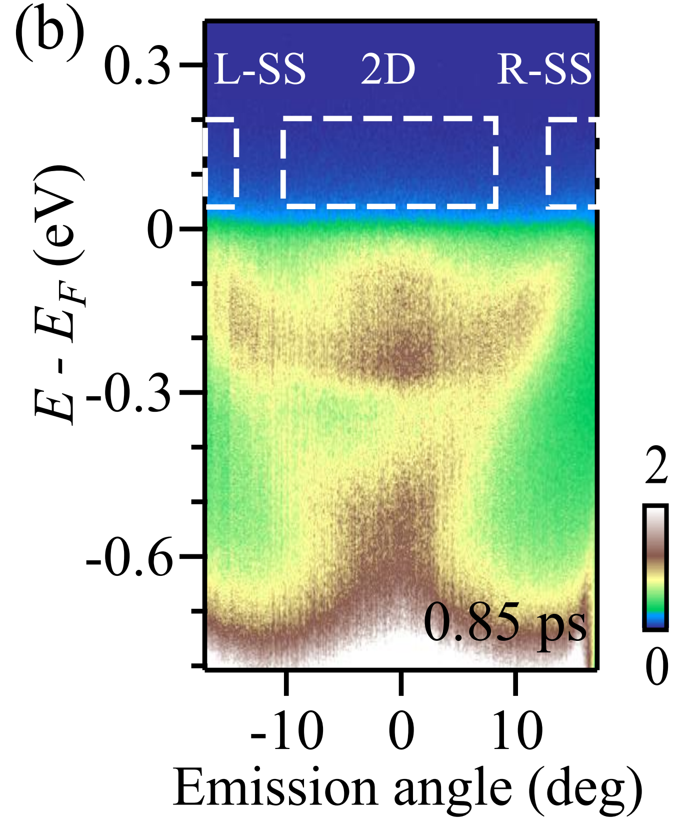


M. Neupane *et al., Sci. Rep.* **6**, 22557 (2016)

- Both (2D and TI SSs) relax within 5 ps
- Short lifetime
- Spread of the intensity into the unoccupied side is less pronounced (metallic)

Decay channels





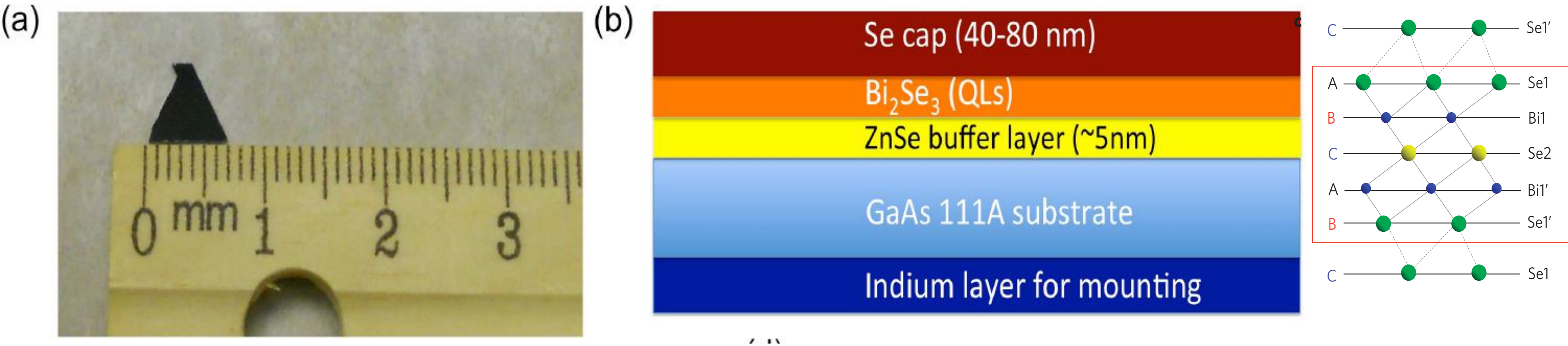
Band	Decay constants (ps)	r^2	Amplitude (A)
L-SS	$\tau_1 = \tau_2$=1.58	0.99	A=1.382
R-SS	$\tau_1 = \tau_2$ =1.69	0.99	A=1.347
2D state	τ_1=0.70 and τ_2=1.46	0.99	A1=0.33, A2=1.14

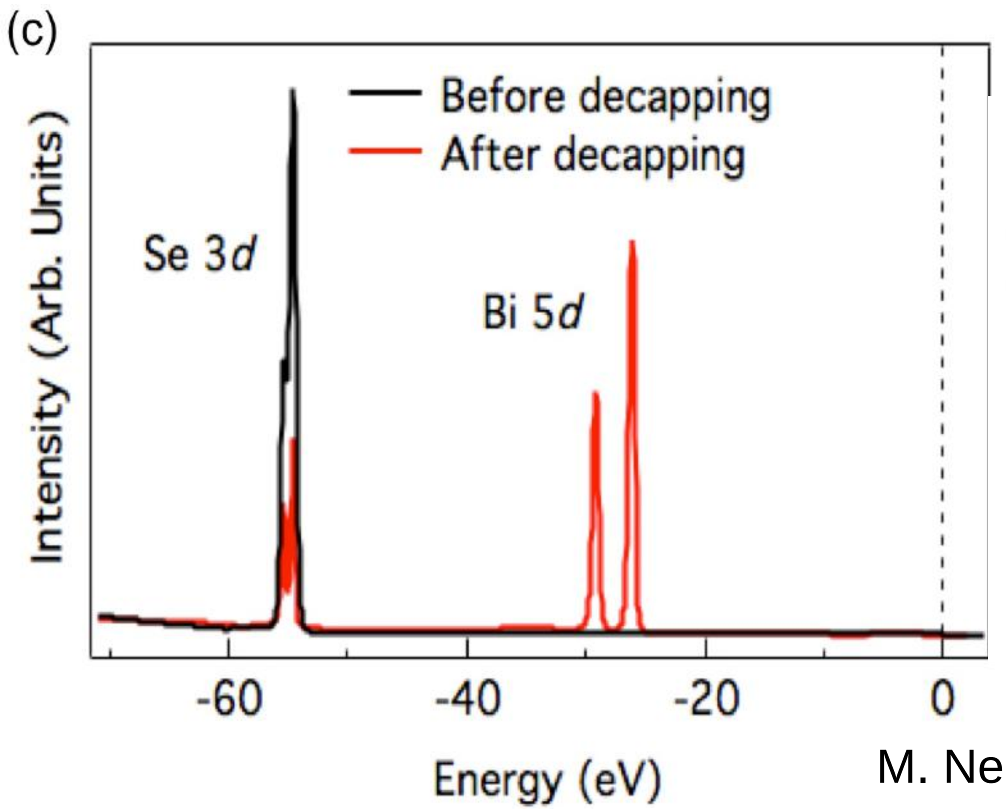
M. Neupane *et al., Sci. Rep*. **6**, 22557 (2016)

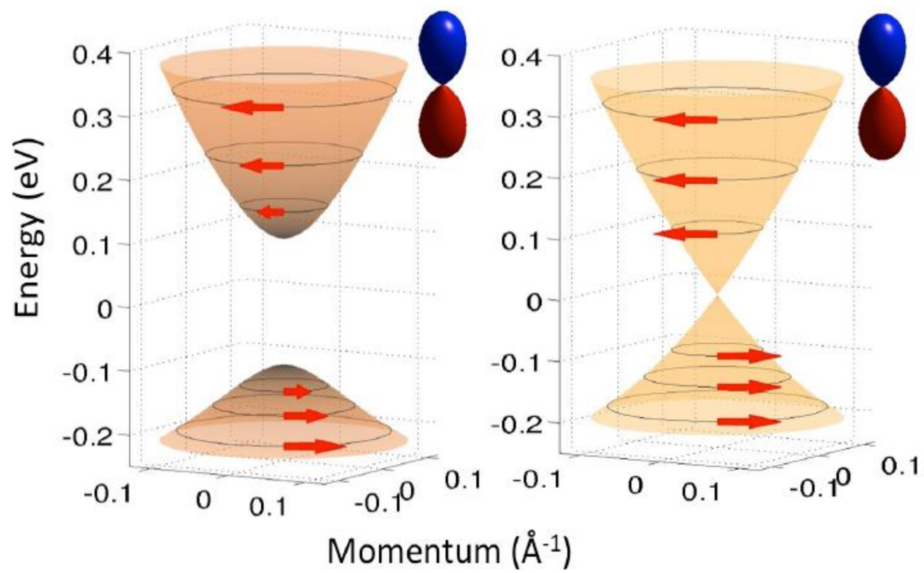
- Single and double exponential decay fitting functions
- TSS: single decay function; 2D states: double decay function

Thin films based TIs:

Ultrathin Bi_2Se_3 TI films

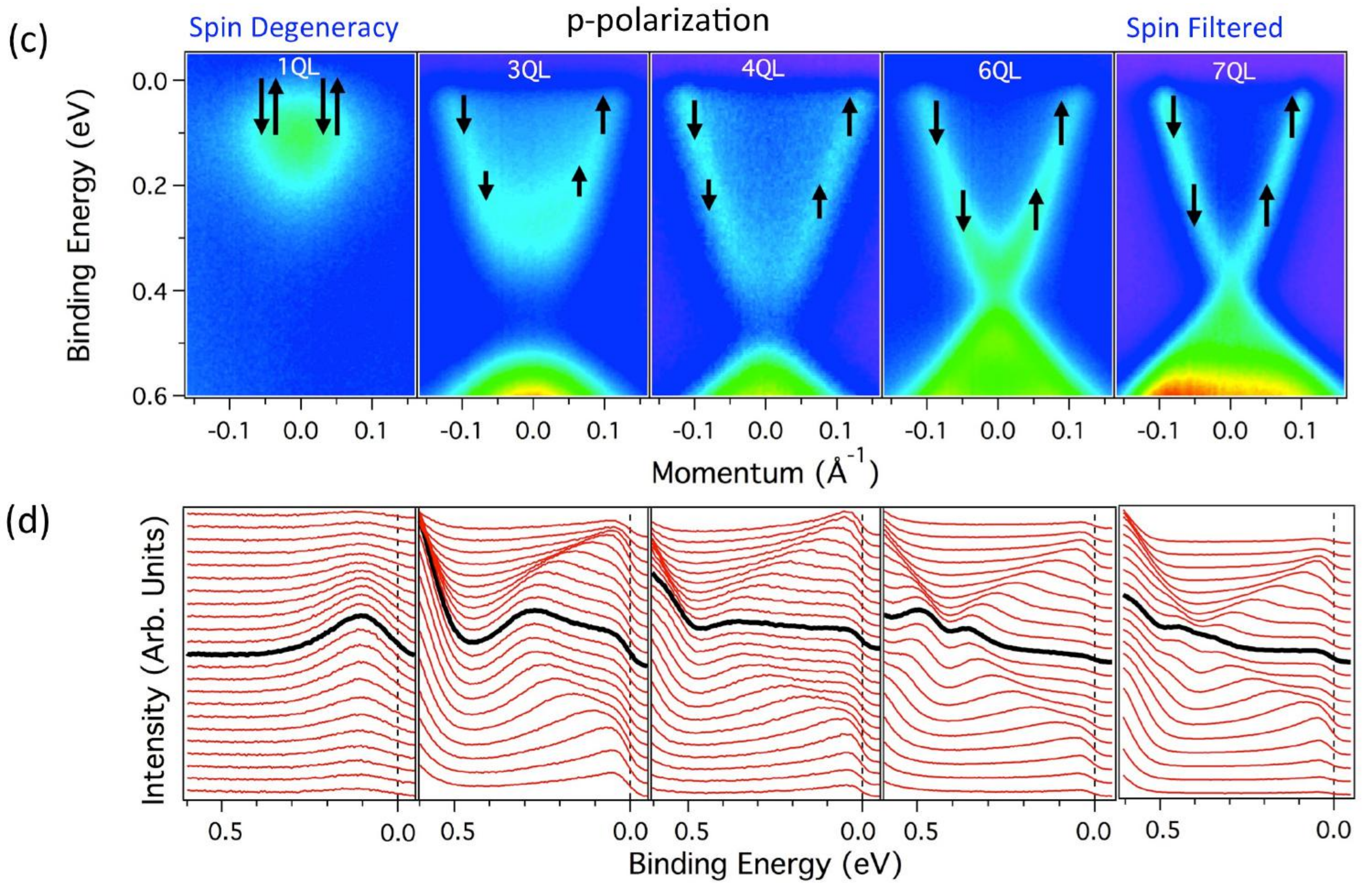






M. Neupane *et al.*, *Nat. Commun.* **5,** 4841 (2014)

Quantum tunneling modulated spectra: ultrathin Bi_2Se_3 TI films



M. Neupane *et al.*, *Nat. Commun*. **5,** 4841 (2014)   Y. Zhang *et al., Nat. Phys*. **6,** 584 (2010)

nature COMMUNICATIONS

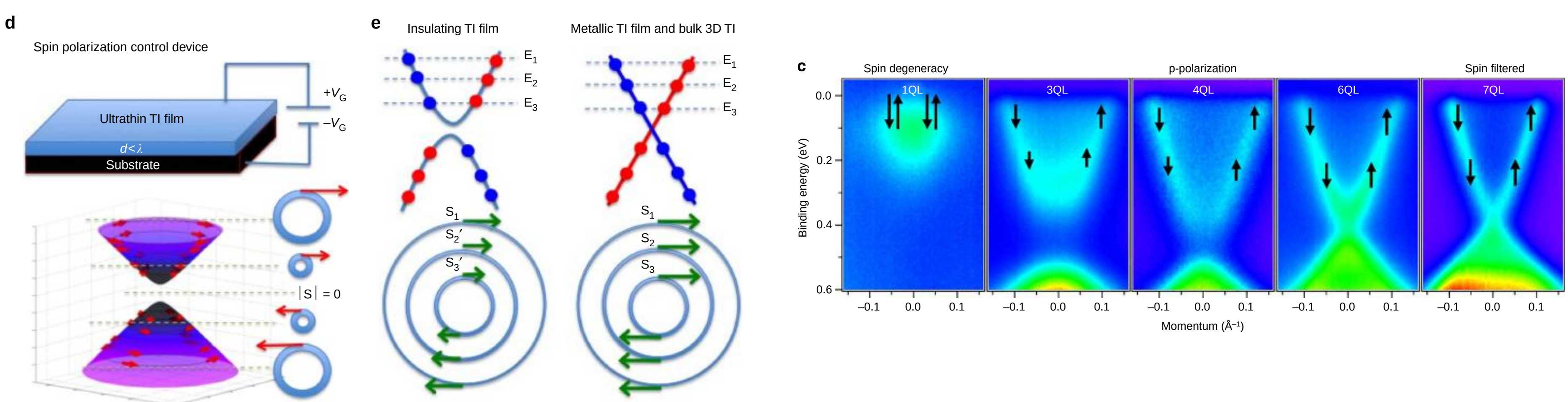
ARTICLE

Received 10 Nov 2013 | Accepted 9 Apr 2014 | Published 12 May 2014

DOI: 10.1038/ncomms4841

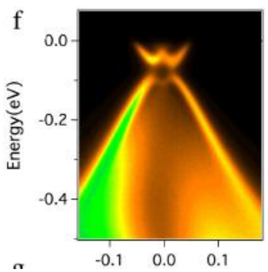
Observation of quantum-tunnelling-modulated spin texture in ultrathin topological insulator Bi_2Se_3 films

Madhab Neupane[1], Anthony Richardella[2], Jaime Sánchez-Barriga[3], SuYang Xu[1], Nasser Alidoust[1], Ilya Belopolski[1], Chang Liu[1], Guang Bian[1], Duming Zhang[2], Dmitry Marchenko[3,4], Andrei Varykhalov[3], Oliver Rader[3], Mats Leandersson[5], Thiagarajan Balasubramanian[5], Tay-Rong Chang[6], Horng-Tay Jeng[6,7], Susmita Basak[8], Hsin Lin[9], Arun Bansil[8], Nitin Samarth[2] & M. Zahid Hasan[1,10]



New topological phases beyond TIs

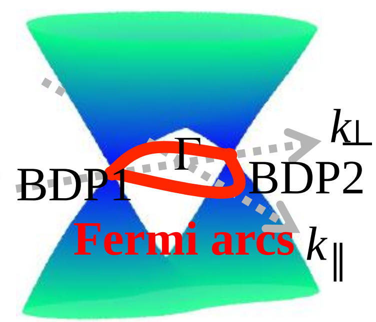
Topo. Crystalline Ins. (TCI)



Protected by symmetries beyond TR-symm.?

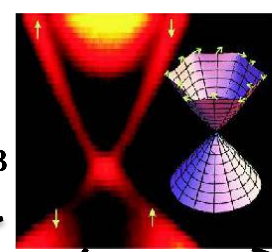
Topo. Dirac & Weyl Semimetal

SOC does not open full bulk gap? Topological semimetals?



TI

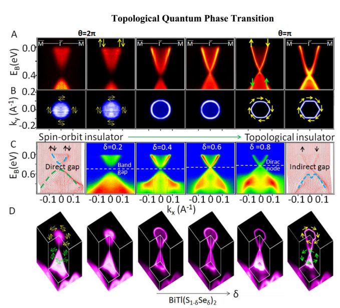
Bi_2Se_3



Superconductivity
Magnetism

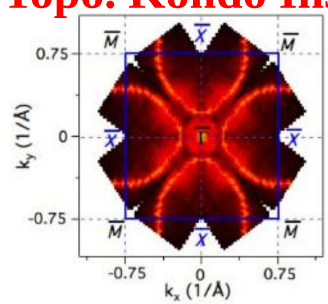
Trivial to TI
Band inversion

Topo. Phase Transition (TPT)

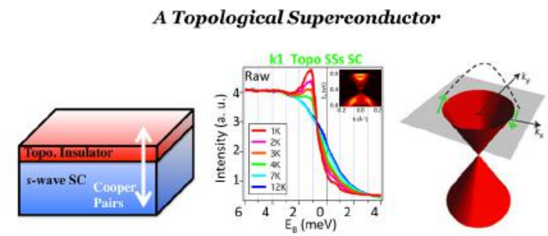


Interaction?

Topo. Kondo Ins. (TKI)



Topo. Superconductor (TSC)
Mag. TI (MTI)



New topological phases beyond TIs

<u>Topo. Kondo Ins.</u>

Neupane, *et al.*, *Nature Commun.* **4**, 2991 (2013).
Neupane *et al.*, *PRL* (2015).

<u>Correlated TI:</u>

Neupane *et al.*, *PRL* (2015).
Neupane *et al.*, arXiv:1411.0302 (2014), in review

<u>Topo. Dirac, Wely & nodal Semimetal</u>

Neupane *et al.*, *Nature Commun.* **5**, 4786 (2014).
Neupane *et al.*, *PR*B *(R)* (2015)

<u>Topo. Phase Transition</u>

Xu**, Neupane** *et al.*, *Nature Commun.* (2015).
Xu *et al.*, *Science* **332**, 560-564 (2011).

<u>Topo. Crystalline Ins.</u>

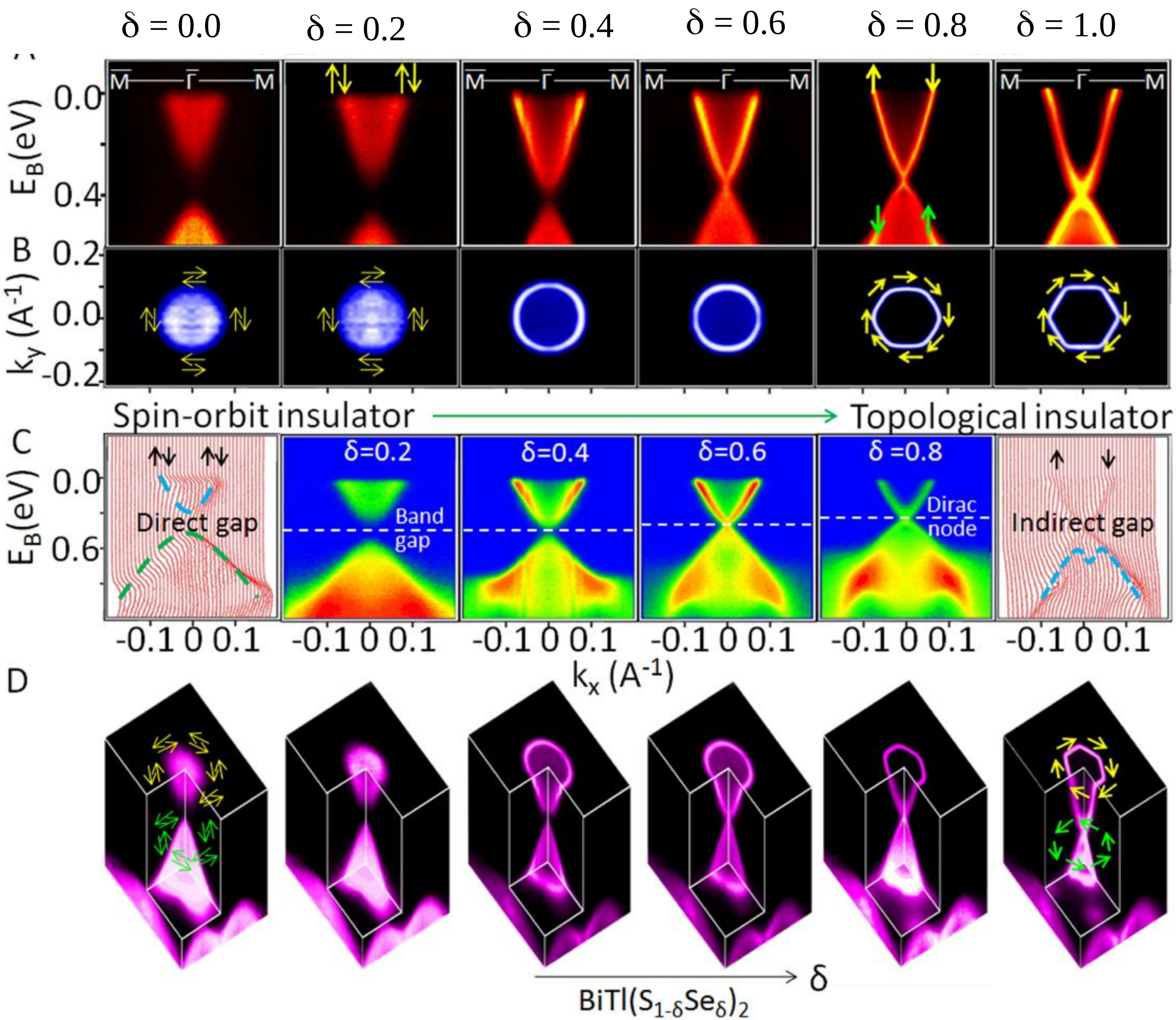
Neupane, *et al.*, *PRB* (2015); arXiv:1403.1560 (2014).
Xu, Liu**, Neupane** *et al.*, *Nature Commun.* **3**, 1192 (2012).

<u>TSC and MTI</u>

Xu**…Neupane** *et al.*, *Nature Phys.* doi:10.1038/nphys3139 (2014).
Xu**, Neupane** *et al.*, *Nature Phys.* **8**, 616-622 (2012).

Topological Dirac semimetals

Band inversion and topological phase transition in $BiTl(S_{1-\delta}Se_{\delta})_2$



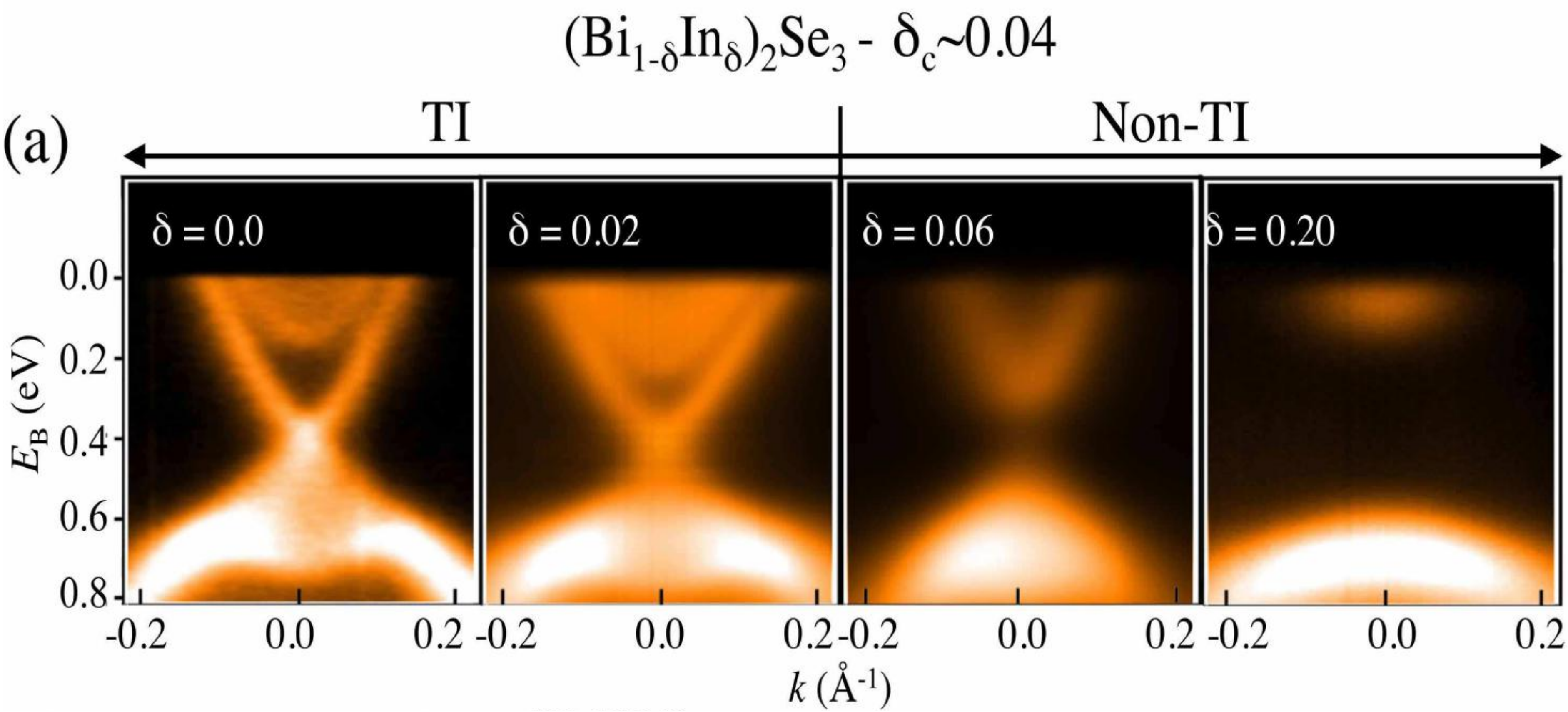
Band inversion happens at δ ~ 0.5;

Fermi gas → Dirac gas;

Spin degenerate → spin-momentum locked

Xu *et al.*, *Science* **332**, 560 (2011); Xu**, Neupane** *Nat. Comm.* (2015)

Topological phase transition in $(Bi_{1-\delta}In_{\delta})_2Se_3$



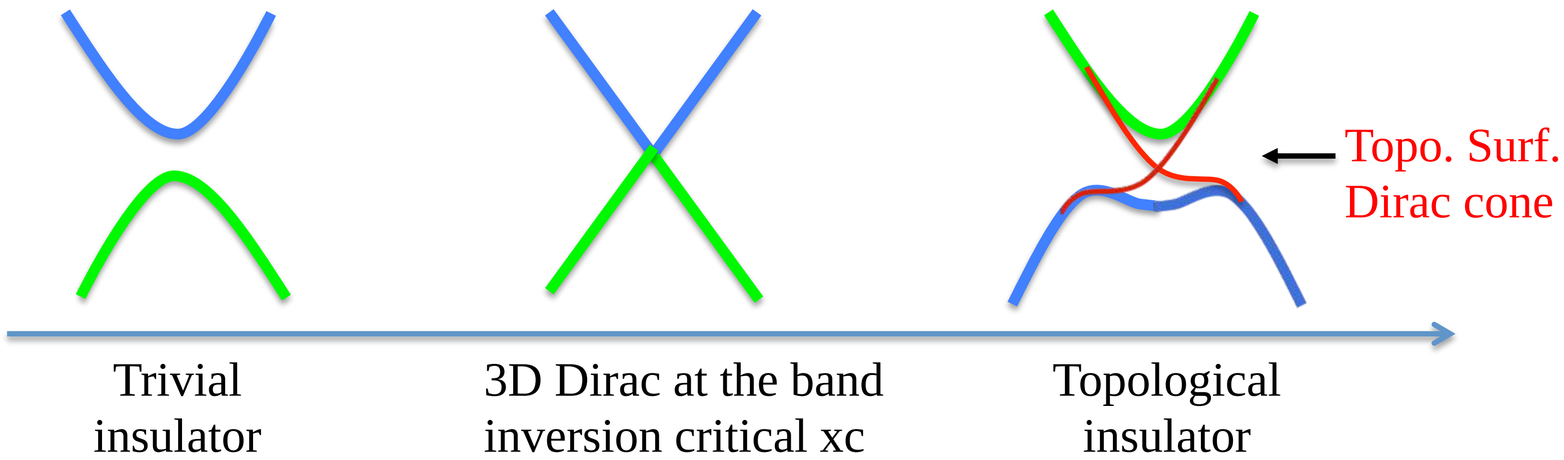
- Requires fine-tuning of the chemical doping
- Introduces chemical disorder into the system

The search for TBDS phase in stoichiometric materials continues ----

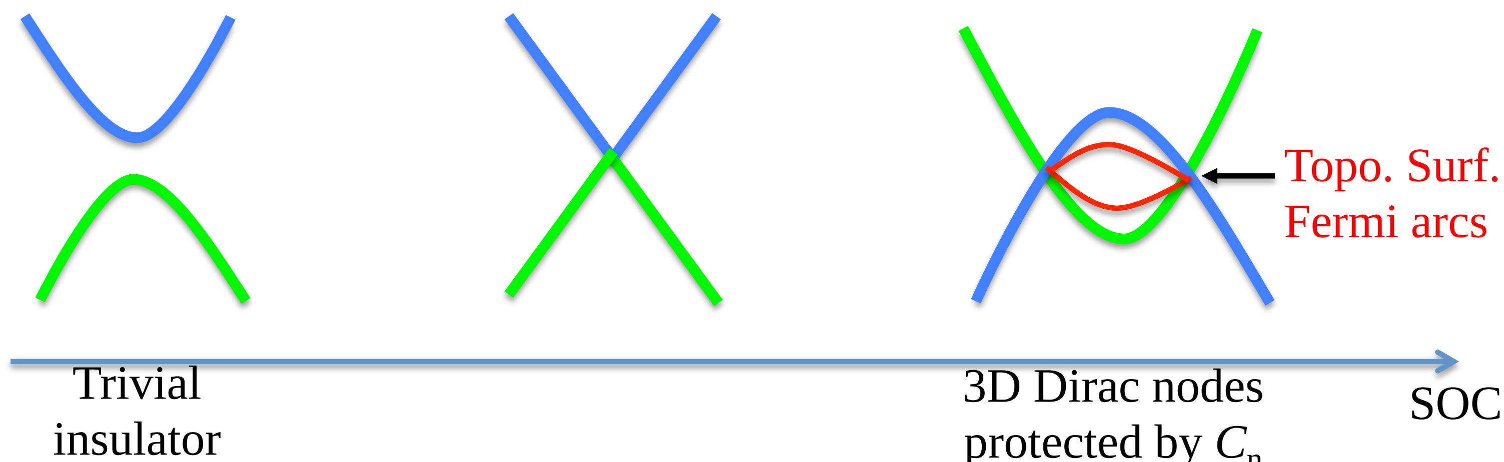
M. Brahlek,… **M. Neupane**, M. Z. Hasan, *Phys. Rev. Lett.* 109, 186403 (2012)

Topological Dirac semimetals

Band inversion in $BiTl(S_{1-\delta}Se_{\delta})_2$

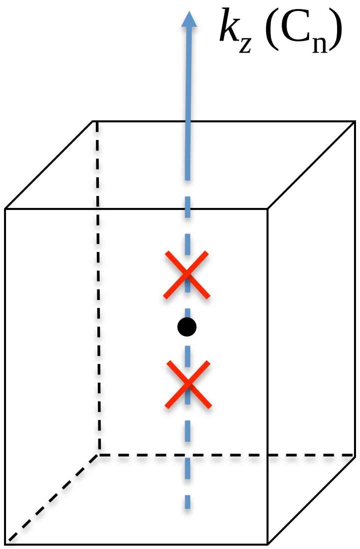


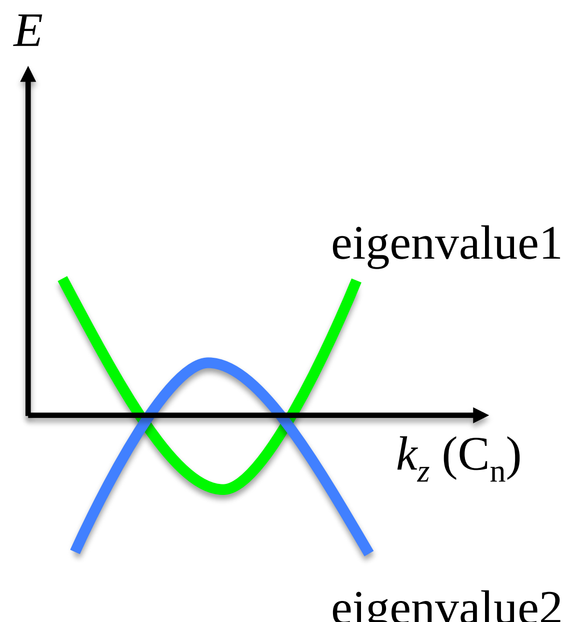
Topo. Dirac Semimetal

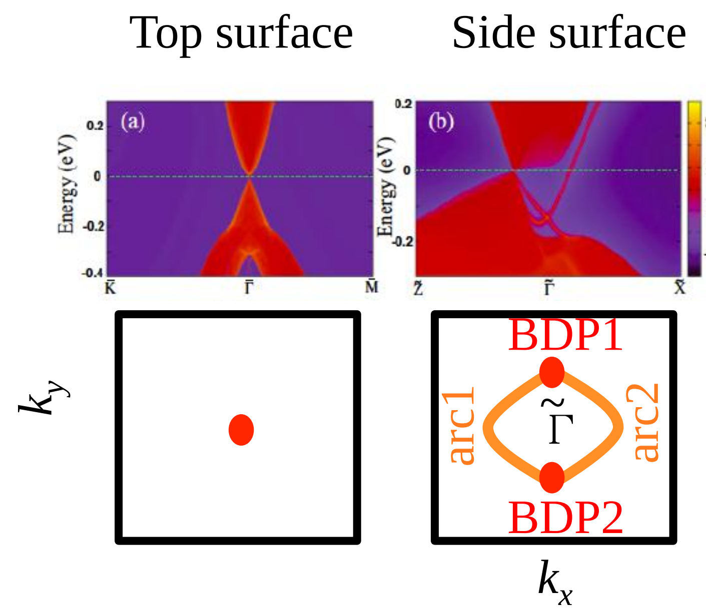


TDSM states protected by uniaxial rotational symmetries

Cd_3As_2





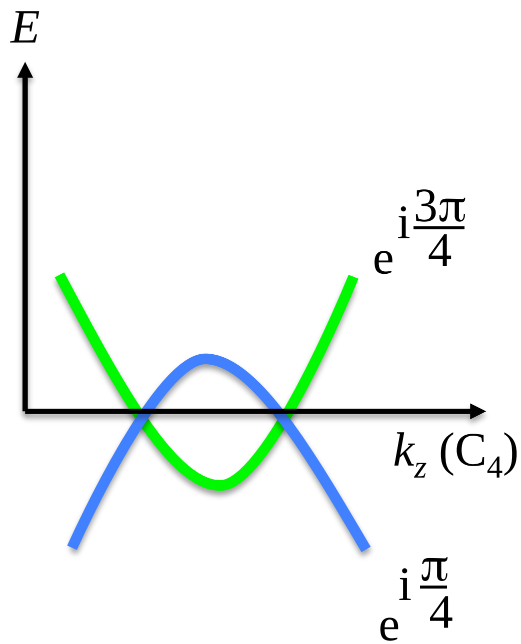


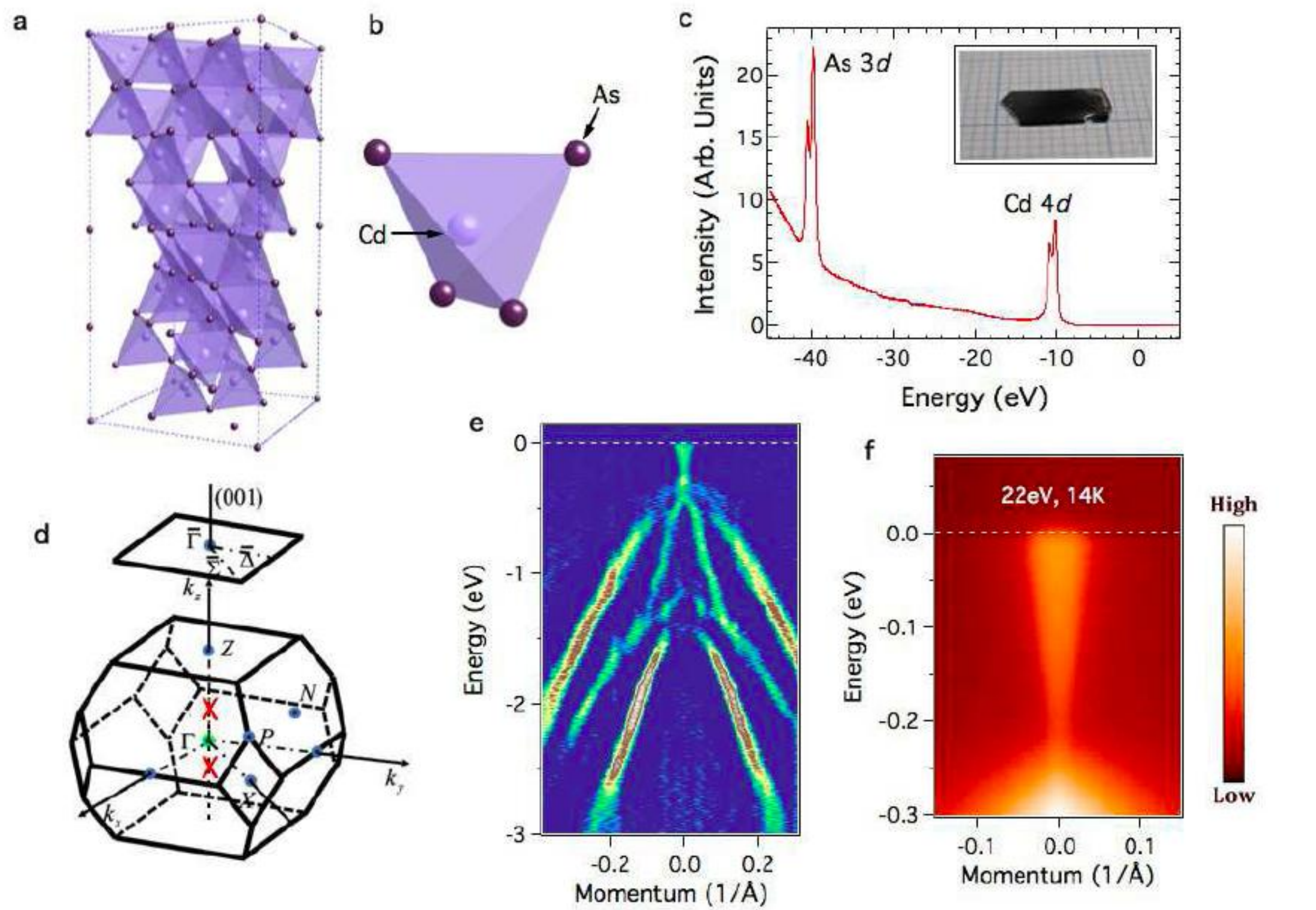
Wang *et al.*, *Phys. Rev. B* **85**, 195320 (2010)

For Na_3Bi, Z . Wang *et al.*, *Phys. Rev. B* **95**, 195320 (2011)

TDSM state in high mobility Cd_3As_2

3D analog of graphene





For Na_3Bi:

Z . Wang *et al., Phys. Rev. B* **95**, 195320 (2011)

Z.K. Liu *et al., Science* **343**, 864 (2014)

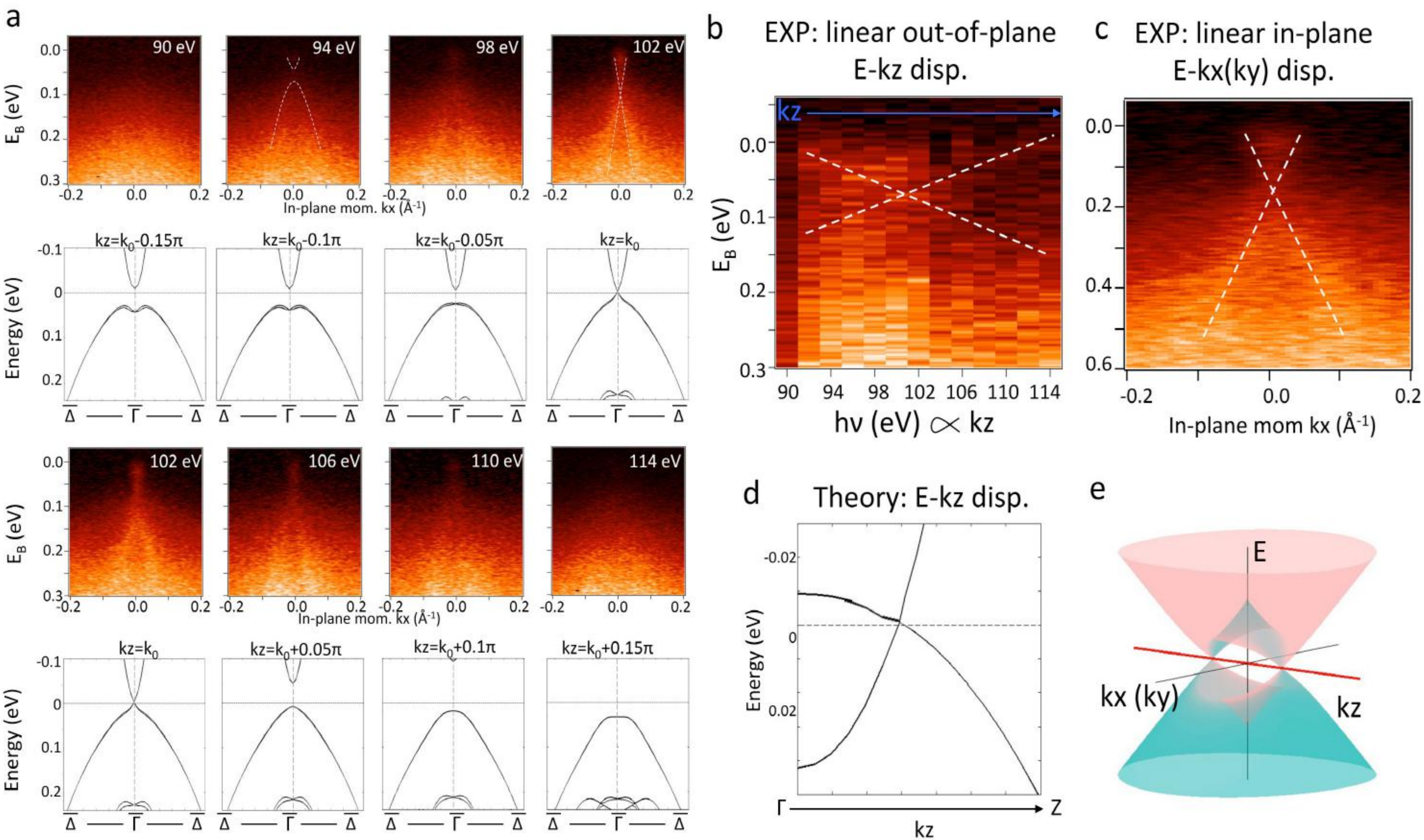
S.Y. Xu *et al., Science* **347**, 294 (2015)

M. Neupane *et al.*, *Nature Commun.* **5**, 4786 (2014).

S. Borisenko *et al, Phys. Rev. Lett*. **113,** 027603 (2014)

Z.K. Liu *et al., Nat. Mat.* **13**, 677 (2014)

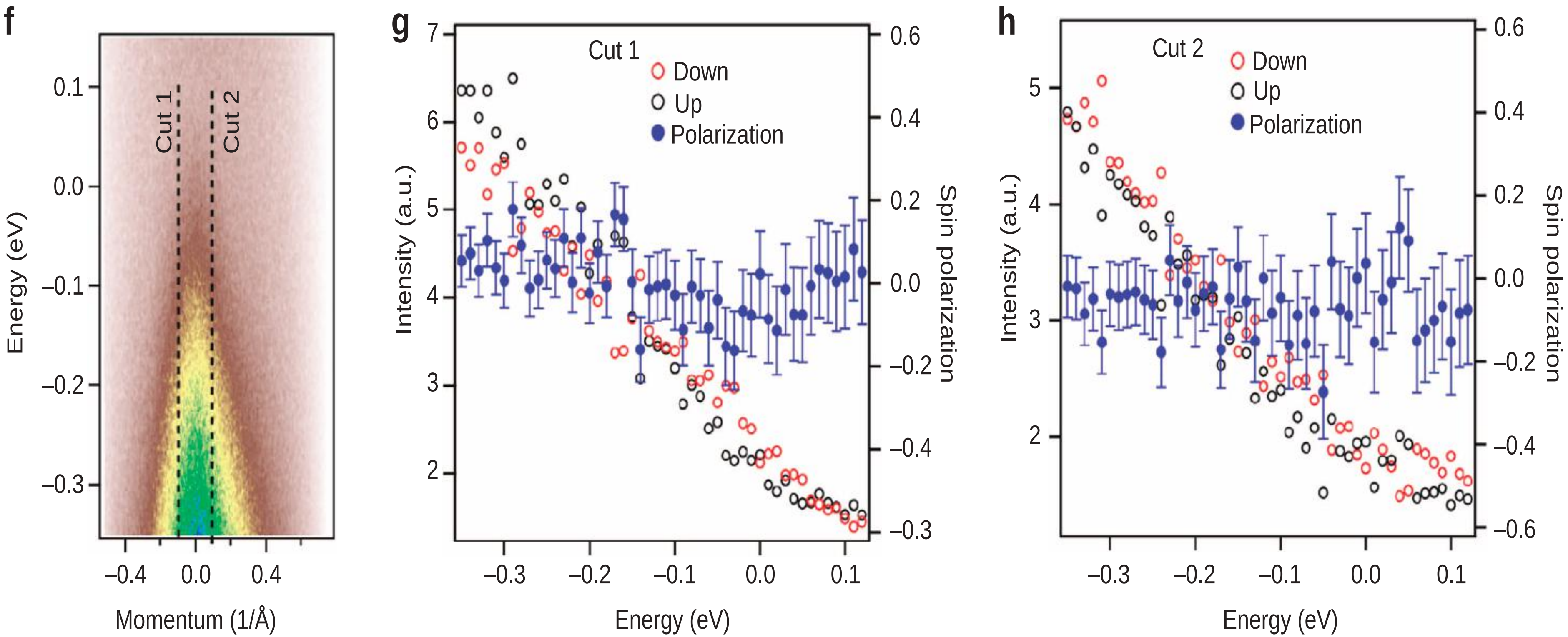
3D band dispersion: Cd_3As_2



M. Neupane *et al.*, *Nature Commun.* **5**, 4786 (2014).

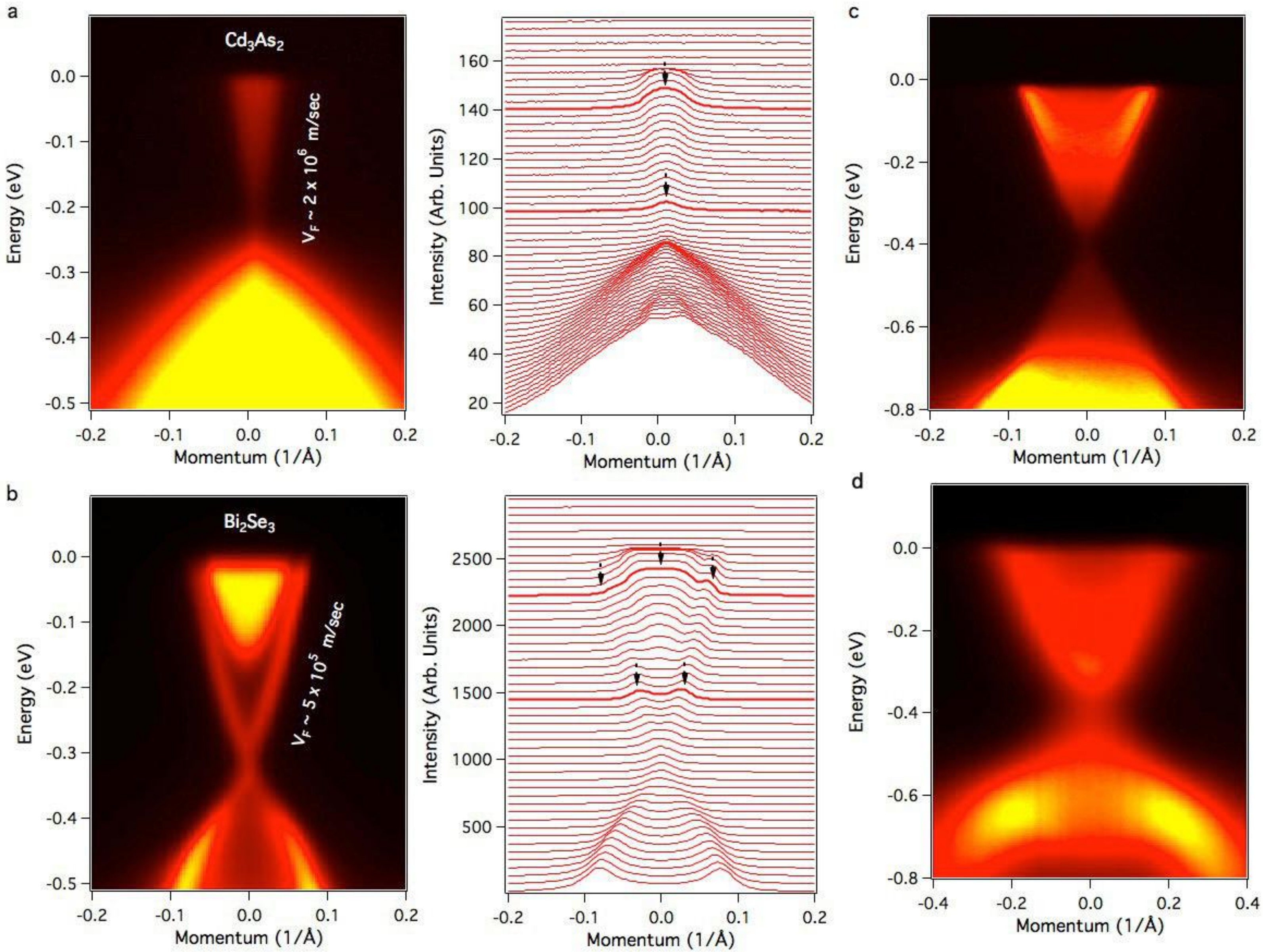
3D band dispersion: Cd_3As_2

Spin-degenerate property: bulk Dirac cone



M. Neupane *et al*., *Nature Commun*. **5**, 4786 (2014).

2D vs 3D Dirac semimetals



$BiTl(S_{1-\delta}Se_{\delta})_2$

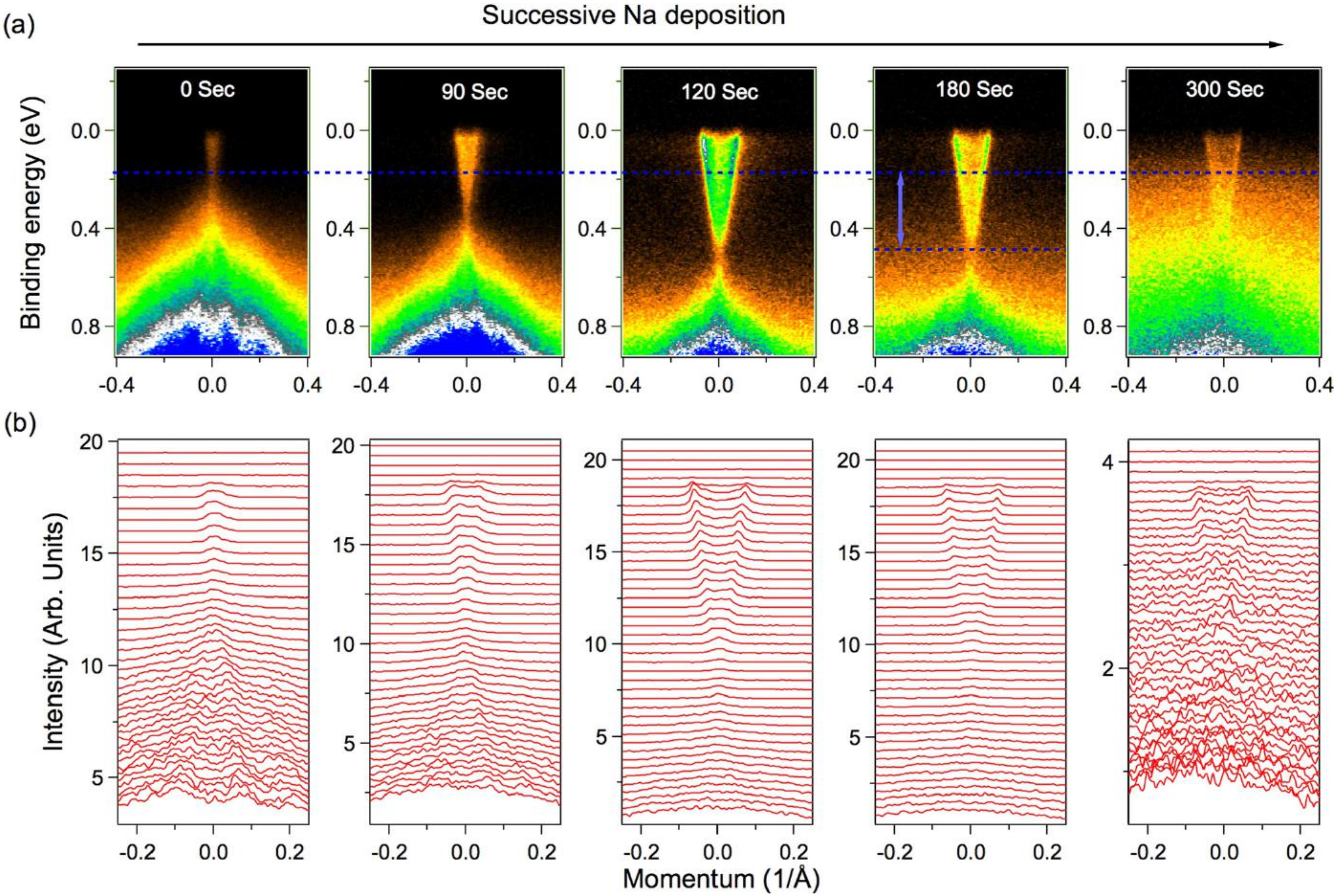
$\delta = 0.5$

$(Bi_{1-x}In_x)_2Se_3$

$\delta = 0.04$

M. Neupane *et al.*, *Nature Commun.* **5**, 4786 (2014).

Surface deposition



M. Neupane *et al.*, *Phys. Rev. B* **91**, 241114 (R) (2015)

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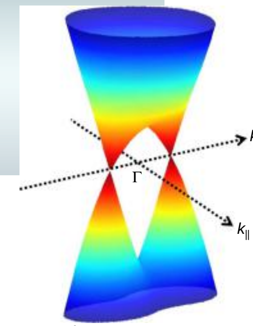
Received 2 Dec 2013 | Accepted 2 Apr 2014 | Published 7 May 2014

DOI: 10.1038/ncomms4786

3D Dirac semimetal (Cd_3As_2, Na_3Bi)



Observation of a three-dimensional topological Dirac semimetal phase in high-mobility Cd_3As_2

Madhab Neupane[1,*], Su-Yang Xu[1,*], Raman Sankar[2,*], Nasser Alidoust[1], Guang Bian[1], Chang Liu[1], Ilya Belopolski[1], Tay-Rong Chang[3], Horng-Tay Jeng[3,4], Hsin Lin[5], Arun Bansil[6], Fangcheng Chou[2] & M. Zahid Hasan[1,7]

Conclusions:

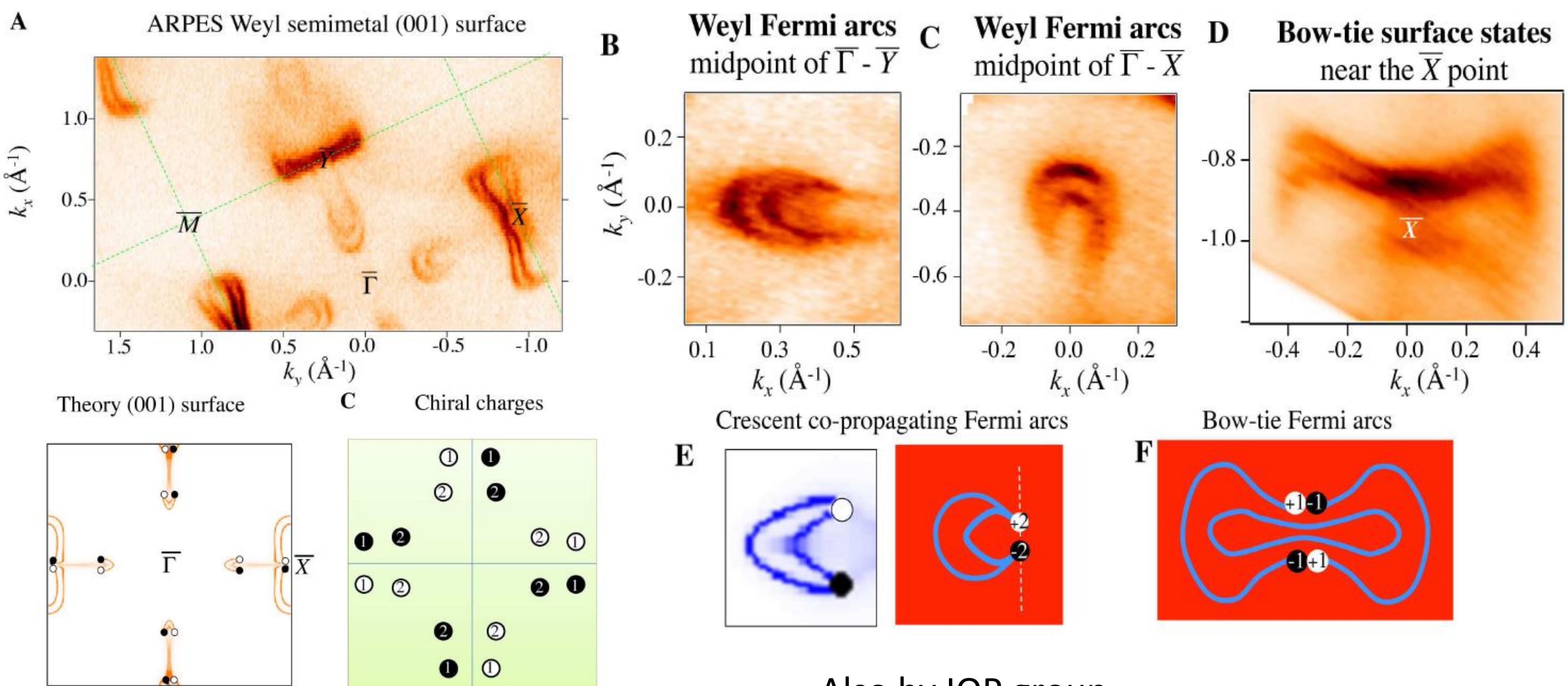
- Experimental observation of the bulk Dirac semimetal phase in Cd_3As_2
- High Fermi velocity
- 3D BDS phase in stoichiometric compound
- ***Basis for Weyl semimetal phase: break symmetry (TR and IS)***

Sciencexpress Research Articles

Discovery of a Weyl Fermion semimetal and topological Fermi arcs

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

correspondence in a topological phase. In contrast to topological insulators where only the surface states are interesting (*21*, *22*), a Weyl semimetal features unusual band structure in the bulk and on the surface. The Weyl fermions in the bulk are predicted to provide a condensed matter realization of the chiral anomaly, giving rise to a negative magnetoresistance under parallel electric and



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PHYSICAL REVIEW B **93**, 201104(R) (2016)

Observation of topological nodal fermion semimetal phase in ZrSiS

Madhab Neupane,[1,*] Ilya Belopolski,[2] M. Mofazzel Hosen,[1] Daniel S. Sanchez,[2] Raman Sankar,[3] Maria Szlawska,[4] Su-Yang Xu,[2] Klauss Dimitri,[1] Nagendra Dhakal,[1] Pablo Maldonado,[5] Peter M. Oppeneer,[5] Dariusz Kaczorowski,[4] Fangcheng Chou,[3] M. Zahid Hasan,[2] and Tomasz Durakiewicz[6]

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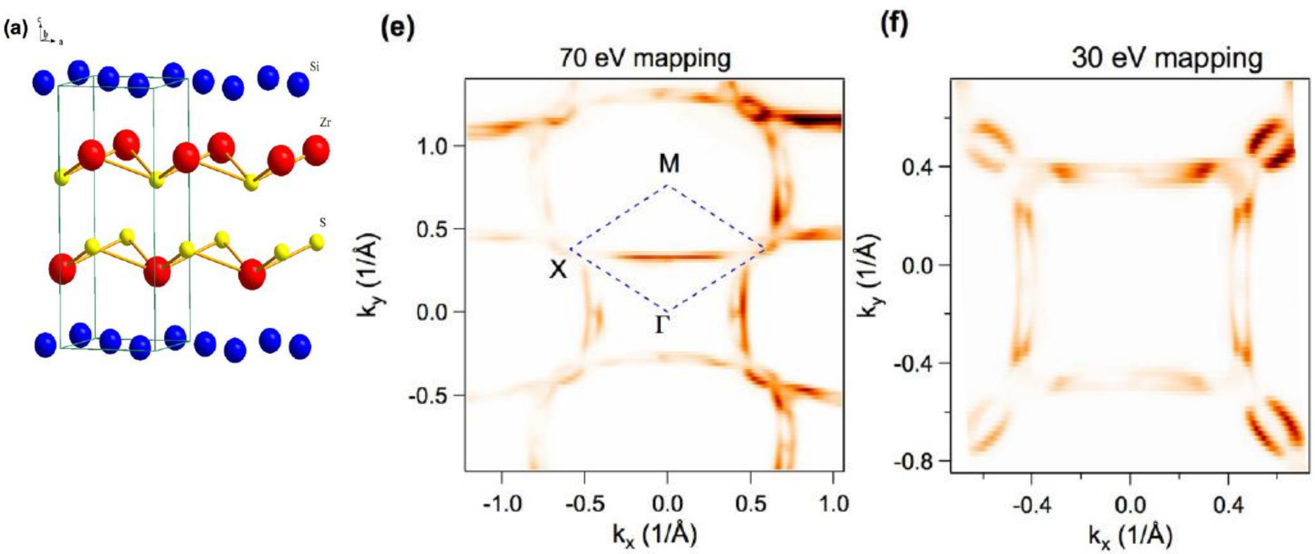
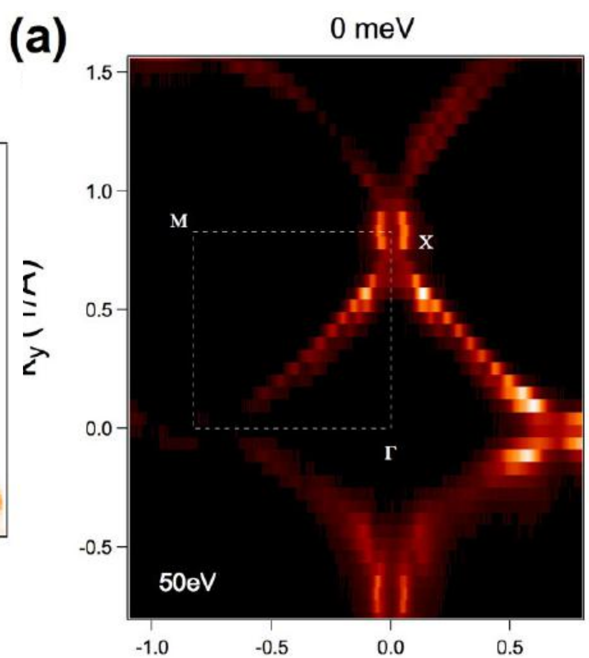
[2]*Joseph Henry Laboratory and Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[3]*Center for Condensed Matter Sciences, National Taiwan University, Taipei 10617, Taiwan*
[4]*Institute of Low Temperature and Structure Research, Polish Academy of Sciences, 50-950 Wroclaw, Poland*
[5]*Department of Physics and Astronomy, Uppsala University, P.O. Box 516, S-75120 Uppsala, Sweden*
[6]*Condensed Matter and Magnet Science Group, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

(Received 4 March 2016; published 11 May 2016)





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Journal of Physics: Condensed Matter

J. Phys.: Condens. Matter **28** (2016) 23LT02 (5pp)

doi:10.1088/0953-8984/28/23/23LT02

Letter

Observation of Dirac-like semi-metallic phase in NdSb

Madhab Neupane[1,5], M Mofazzel Hosen[1], Ilya Belopolski[2], Nicholas Wakeham[3], Klauss Dimitri[1], Nagendra Dhakal[1], Jian-Xin Zhu[4], M Zahid Hasan[2], Eric D Bauer[3] and Filip Ronning[3]

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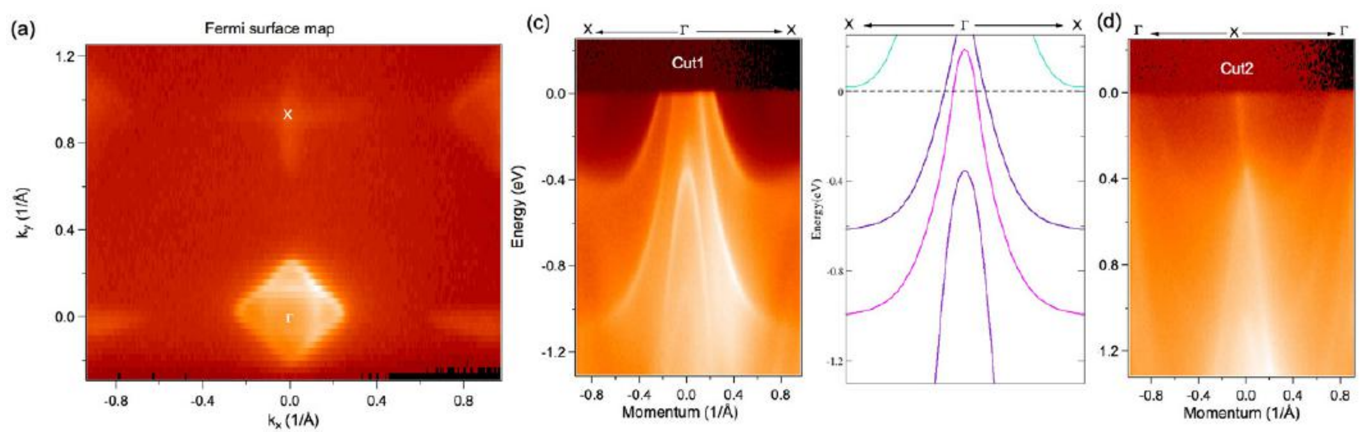
[2] Joseph Henry Laboratory and Department of Physics, Princeton University, Princeton, NJ 08544, USA
[3] Condensed Matter and Magnet Science Group, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[4] Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA



Thank you!