ARPES investigations of bulk insulating topological insulators

Mark S. Golden
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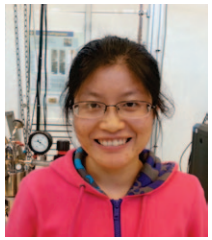
Thanks to

Yingkai Huang

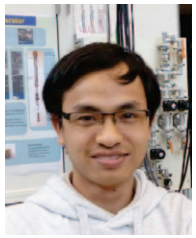
Dong Wu

Anne de Visser



Yu Pan

Huib Luigjes



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Nick de Jong

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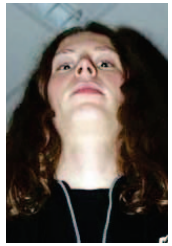


Erik Slooten

Ming Shi

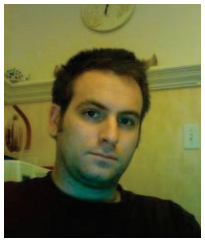
Andrei Varykhalov

+ Emile Rienks

Jeroen Goedkoop

Jochem Kaas

Jiri Oen



Steve Johnston

NWO

FOM

What's special about topological insulators ?

Highly original & deep insights from theoretical physics

Difficult, yet possible experimental challenges: 'doable' on a 5-10(+) year scale

New 'elementary' particle, new superconductors

fault tolerant quantum computation

nature International weekly journal of science

NATURE | NEWS

Google and NASA snap up quantum computer

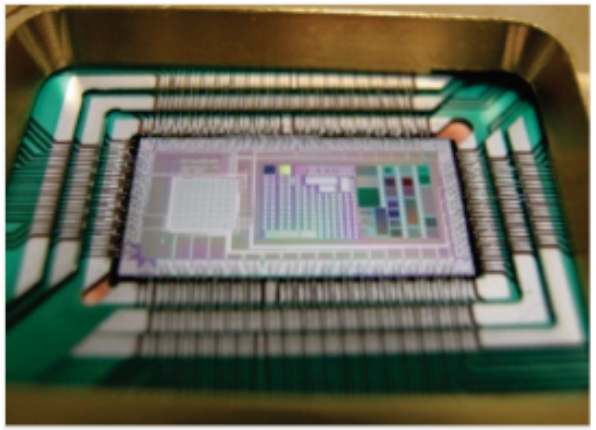
D-Wave machine to work on artificial-intelligence problems.

Nicola Jones

16 May 2013

D-Wave, the small company that sells the world's only commercial quantum computer, has just bagged an impressive new customer: a collaboration between Google, NASA and the non-profit Universities Space Research Association.

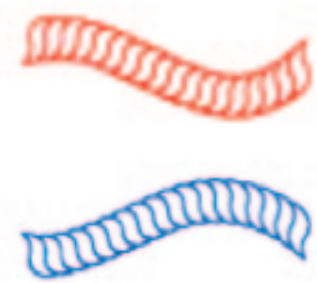
The three organizations have joined forces to install a D-Wave Two, the computer company's latest model, in a facility launched by the collaboration — the Quantum Artificial Intelligence Lab at NASA's Ames Research Center in Moffett Field, California. The lab will explore areas such as machine learning —

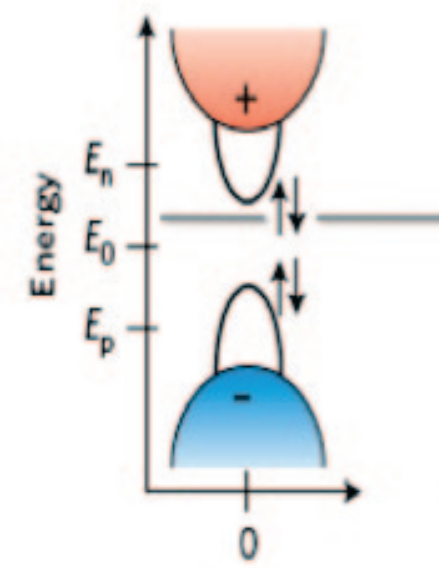


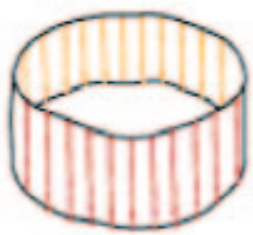
The D-Wave Two quantum computer has a 512-qubit processor (pictured) that can do some calculations thousands of times faster than conventional computers.

D-WAVE

Surface states



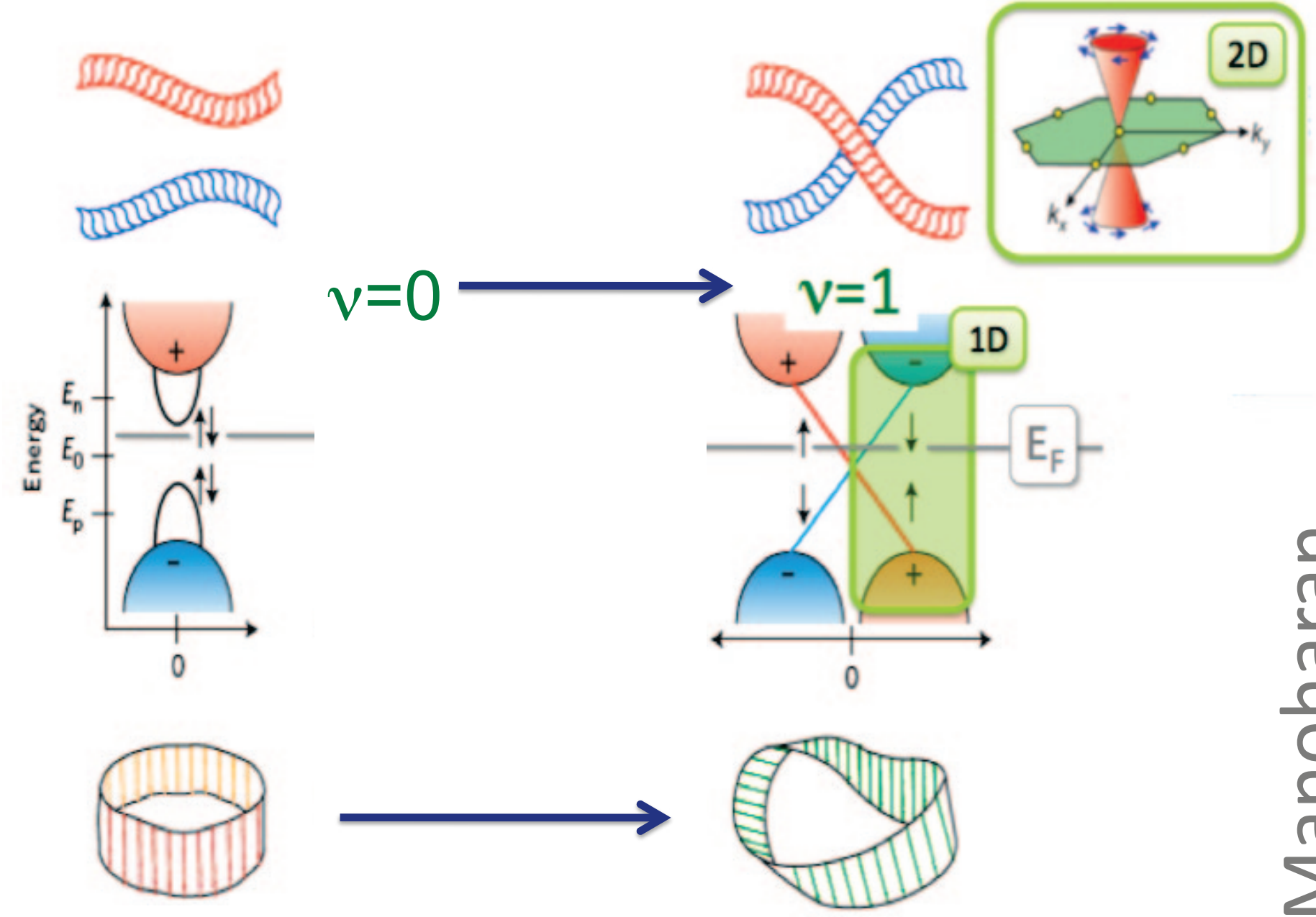




- regular band structure:
  no twist
- surface states in gap:
  spin degenerate
- they can cross E_F, but
  can be gapped

Manoharan

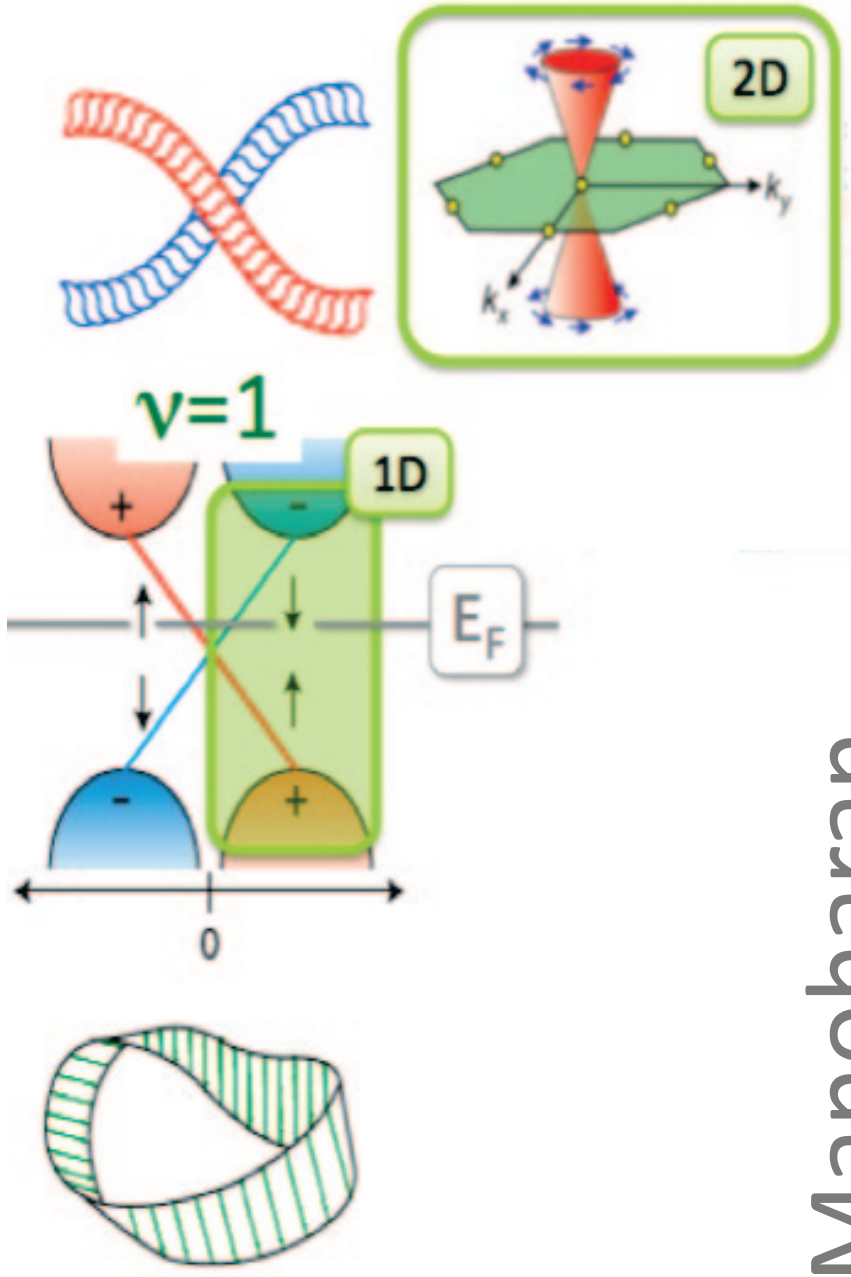
Add a twist to the band structure



Manoharan

Edge states in topological insulators

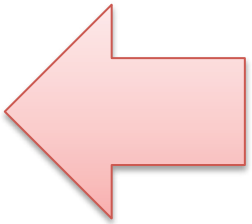
- e.g. 2D surface of 3D TI
- live in the gap:
  100% spin polarized
- they can't not cross E_F
  topological
  protection



Manoharan

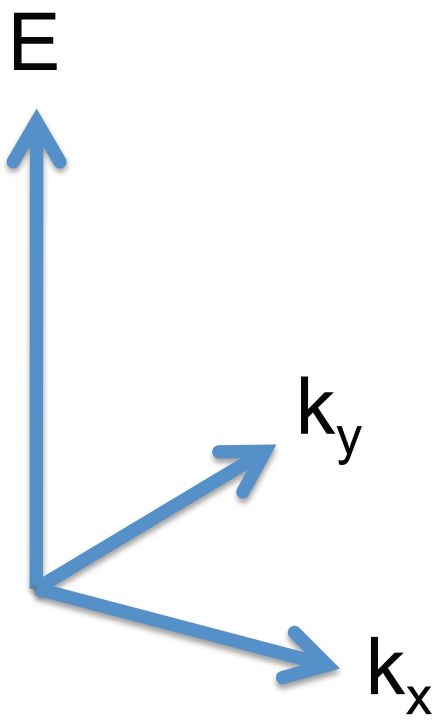
Overview

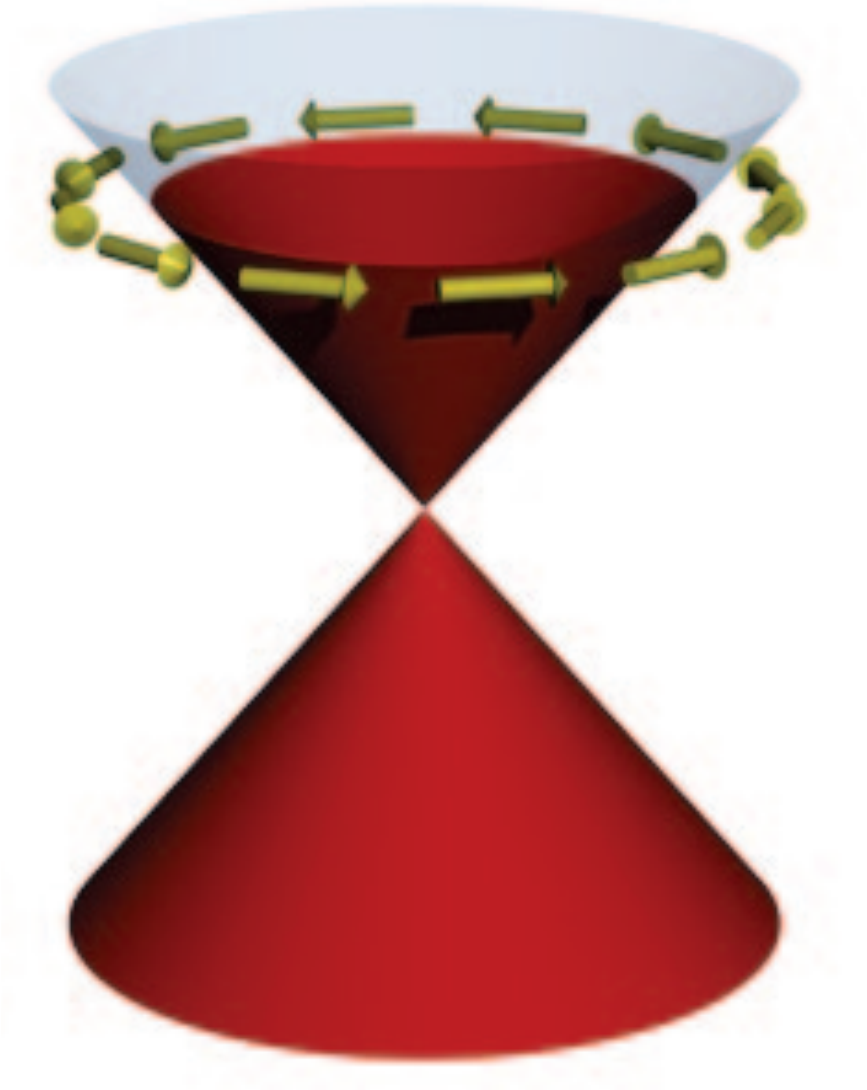
- hitchhiker's guide to TIs
- spectroscopy and microscopy of topological surface states



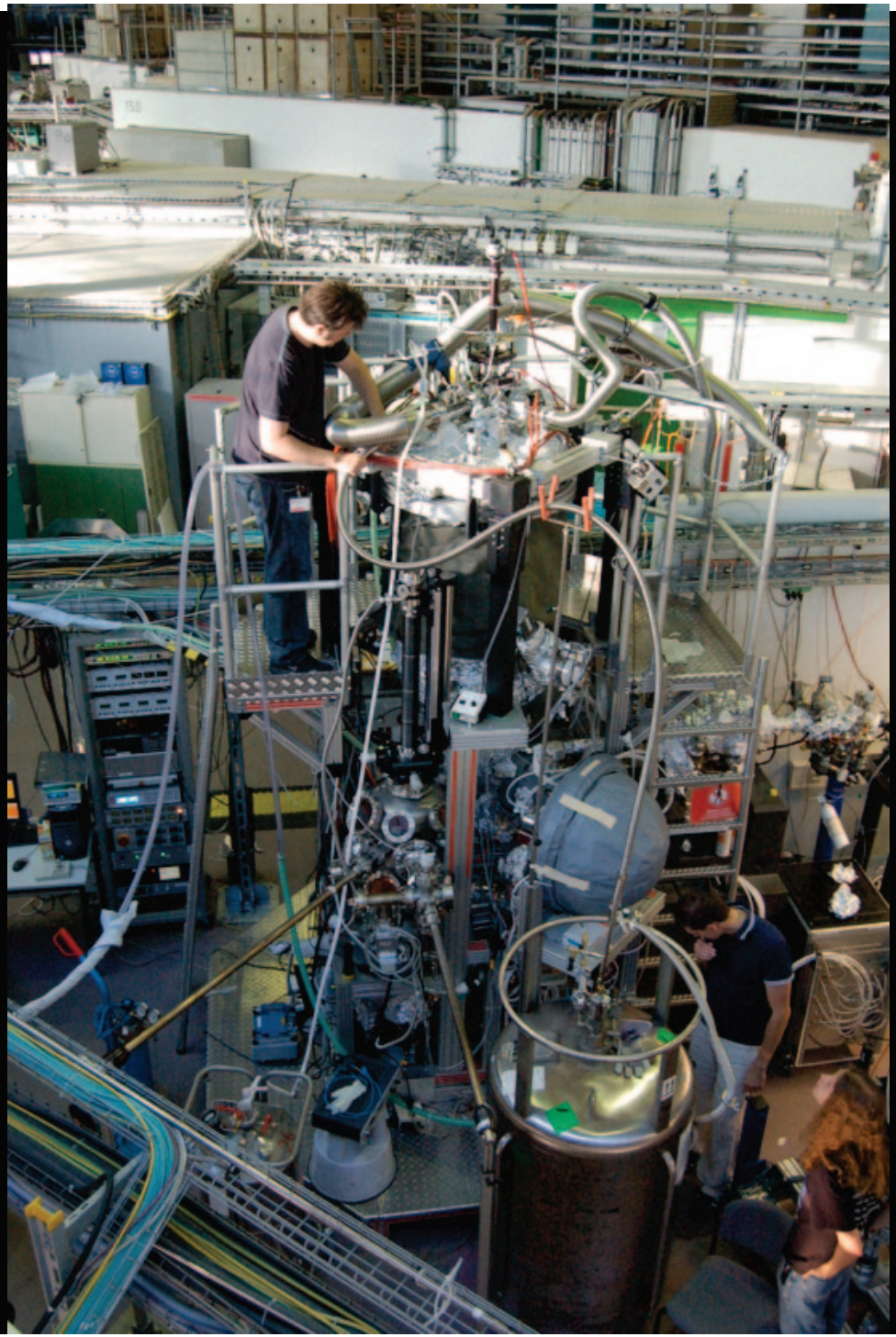
- towards 3D topological *insulators*

Dirac fermions with helical spin structure





Pic: Marcel Franz (UBC)



ARPES: gives birth to the 3D TI field

nature

LETTERS

Experimental Realization of a Three-Dimensional Topological Insulator, Bi_2Te_3

July 2009

epl A Letters Journal Exploring the Frontiers of Physics

March 2008

EPL, 81 (2008) 57006
doi: 10.1209/0295-5075/81/57006

www.epljournal.org

Spin-orbit interaction effect in the electronic structure of Bi_2Te_3 observed by angle-resolved photoemission spectroscopy

H.-J. Noh[1,2(a)], H. Koh[2], S.-J. Oh[2], J.-H. Park[3], H.-D. Kim[4], J. D. Rameau[5,6], T. Valla[5], T. E. Kidd[5], P. D. Johnson[5], Y. Hu[5] and Q. Li[5]

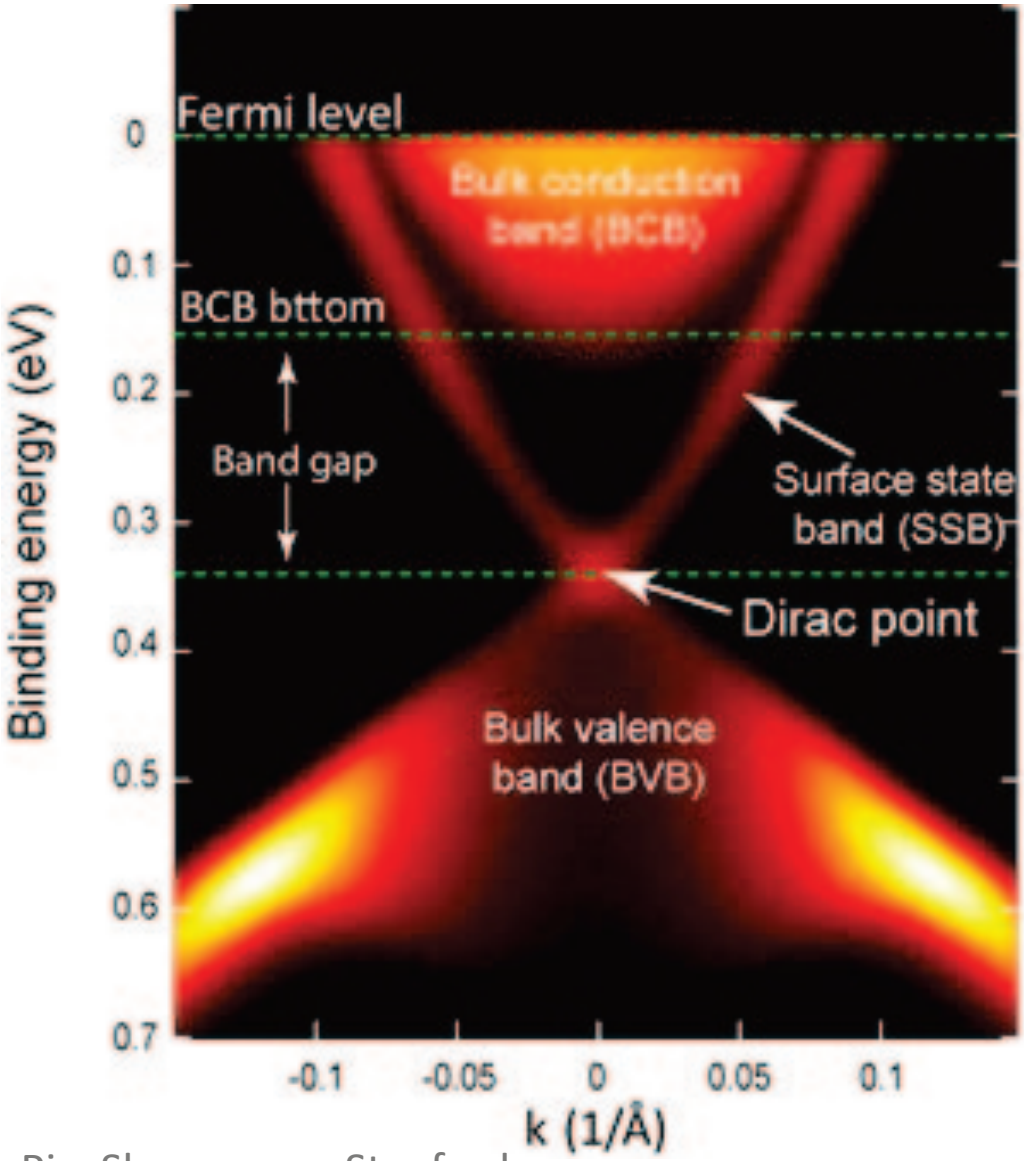
A topologically orde
that evades the con
matter. Exotic spin-t
have been speculate
spin-sensitive measu
polarimetry, we prol
numbers are comple
method to Sb and B
properties. These re
collectively carrying

Observation of a large-gap topological-insulator class with a single Dirac cone on the surface

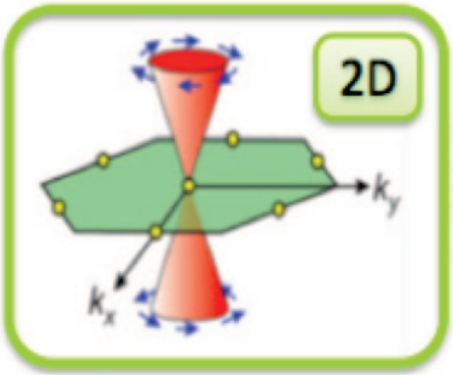
Feb 200

Y. Xia[1,2], D. Qian[1,3], D. Hsieh[1,2], L. Wray[1], A. Pal[1], H. Lin[4], A. Bansil[4], D. Grauer[5], Y. S. Hor[5], R. J. Cava[5] and M. Z. Hasan[1,2,6]*

Dirac cones in experiment (in odd number quantities)

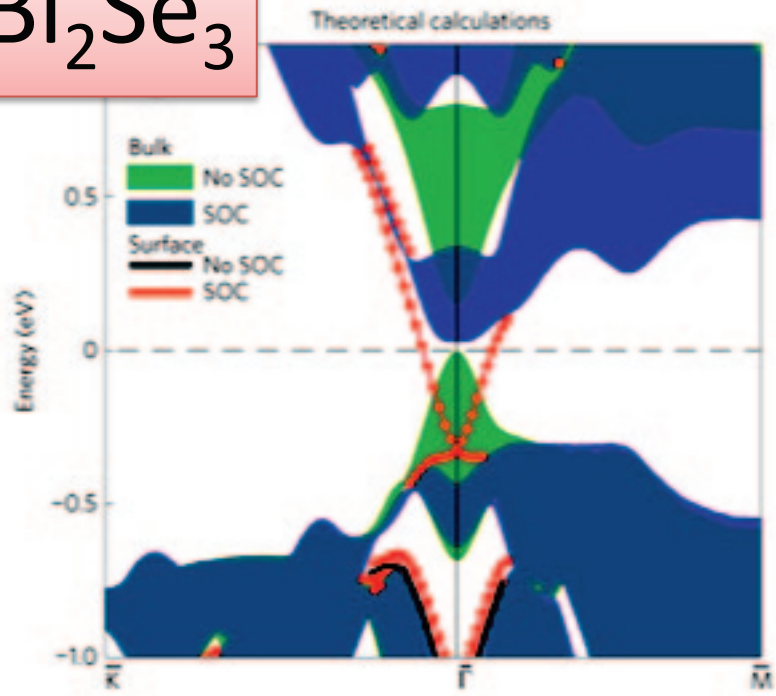


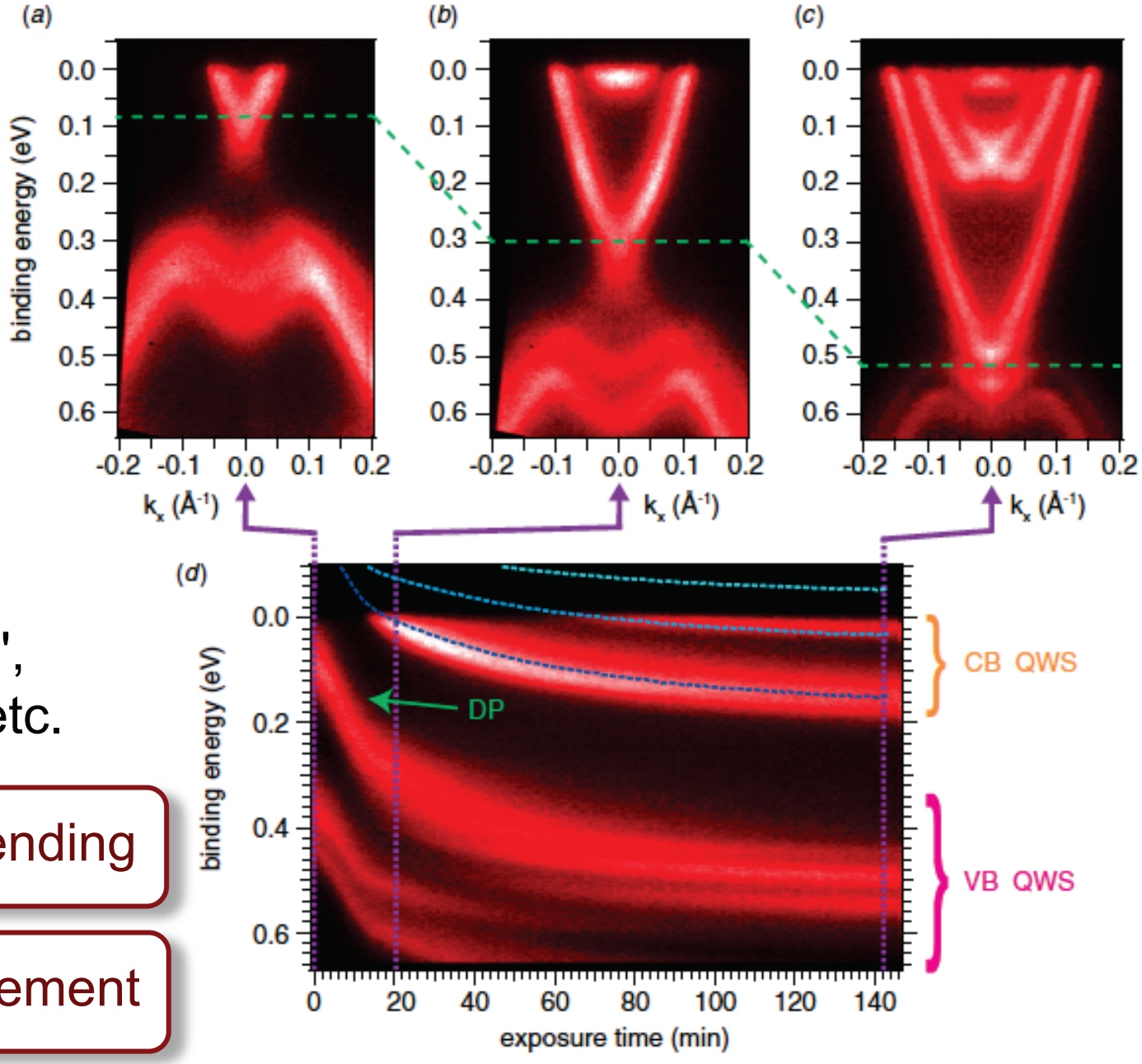
Pic: Shen group, Stanford



e.g. Xia et al (Princeton), Nature Physics **5**, 398 (2009)

Bi_2Se_3





'vacuum',
CO, K, etc.

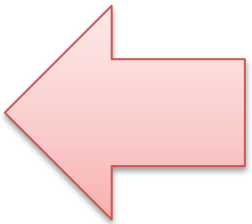
band bending

q-confinement

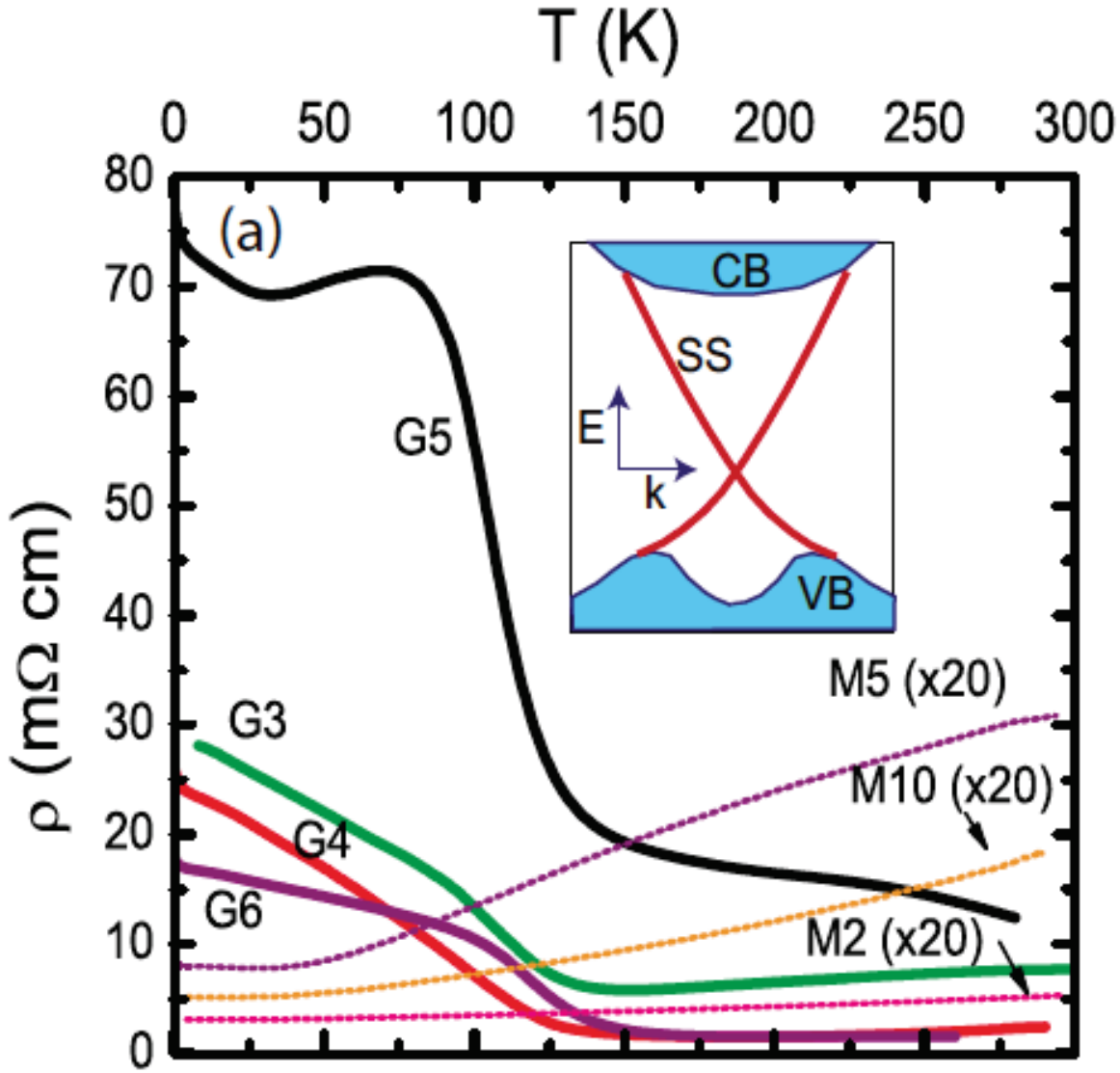
Figure 8. ARPES spectra acquired during the controlled dose of CO on Ca-doped Bi_2Se_3($h\nu = 16$ eV). The acquisition and dosing was

Overview

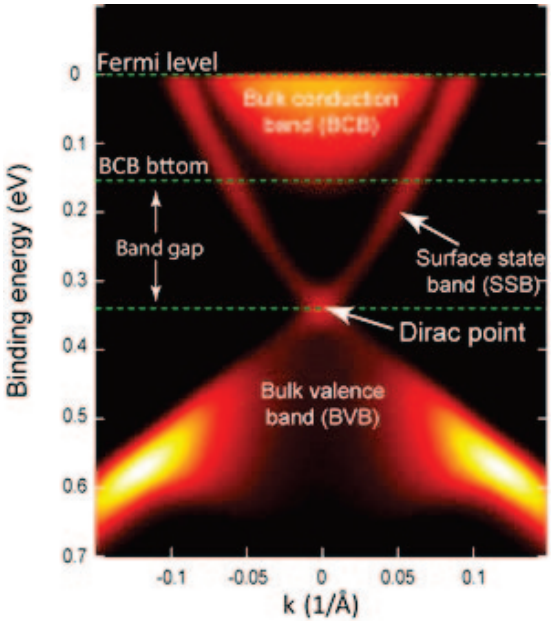
- hitchhiker's guide to TIs
- spectroscopy and microscopy of topological surface states
- towards 3D topological *insulators*



Bi_2Se_3: bulk is not very insulating



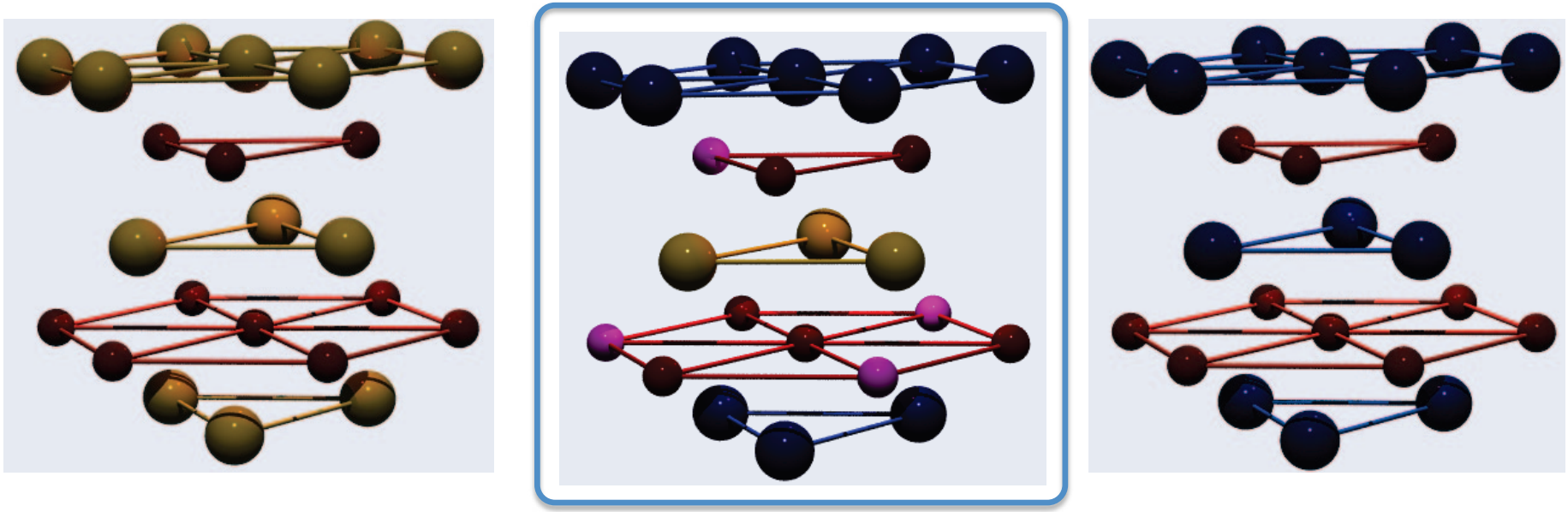
- Se vacancies
- in Bi_2Te_3: also Bi – Te antisite defects



Checkelsky et al, Phys. Rev. Lett. **103,** 246601, **(2009).**

Ternary 3D TI's: e.g. Bi_2Te_2Se and beyond

Bi_2Se_3 $Bi_xSb_{2-x}Te_{3-y}Se_y$ Bi_2Te_3

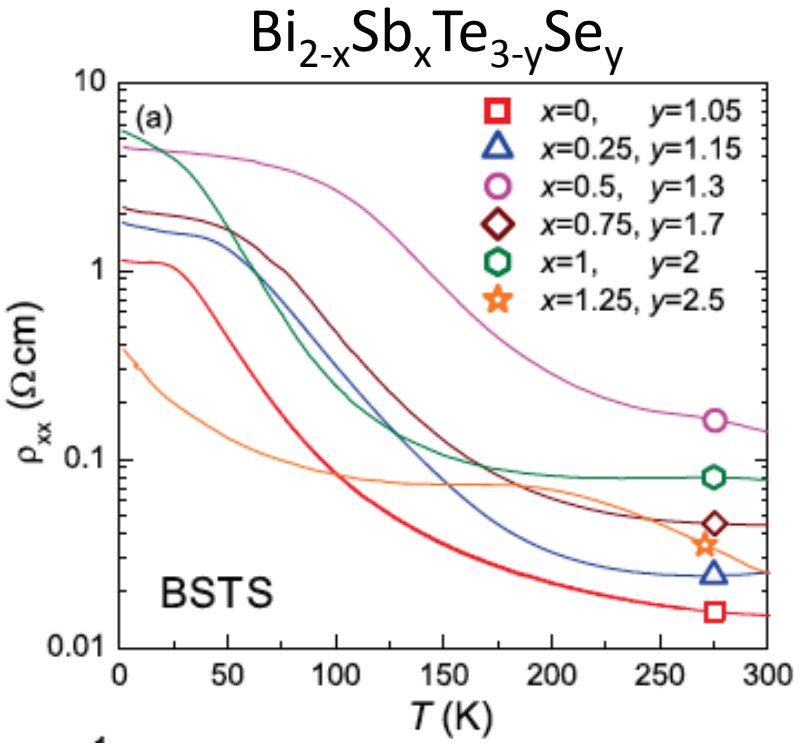


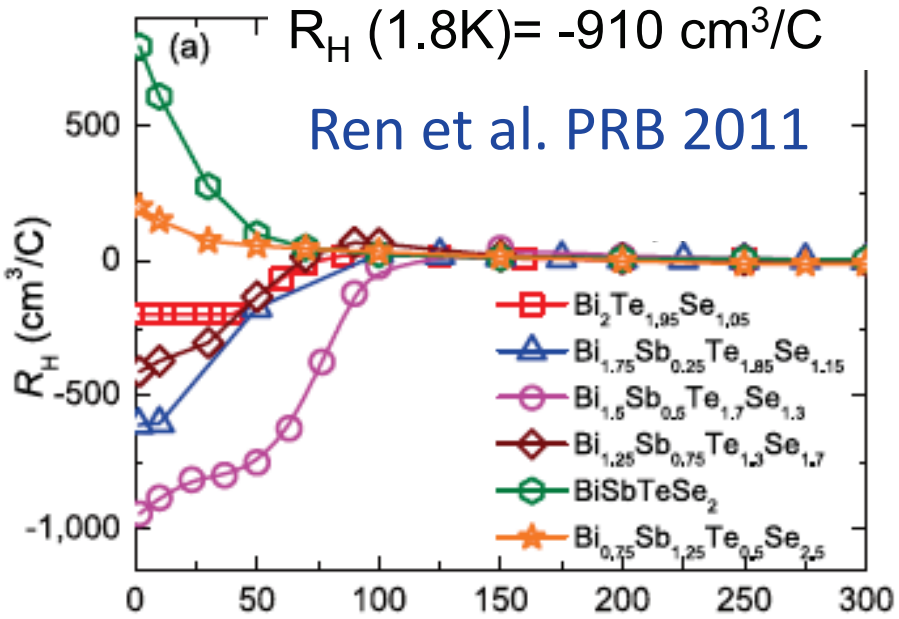
- Se stuck (strongly) between two Bi planes (less Se vacancies)
- strong Bi-Se bonding (less Bi-Te antisite defects)

Y. Ando group, Cava group

Yingkai Huang, Dong Wu

Ando group: quaternaries – Bi-Sb-Te-Se = BSTS

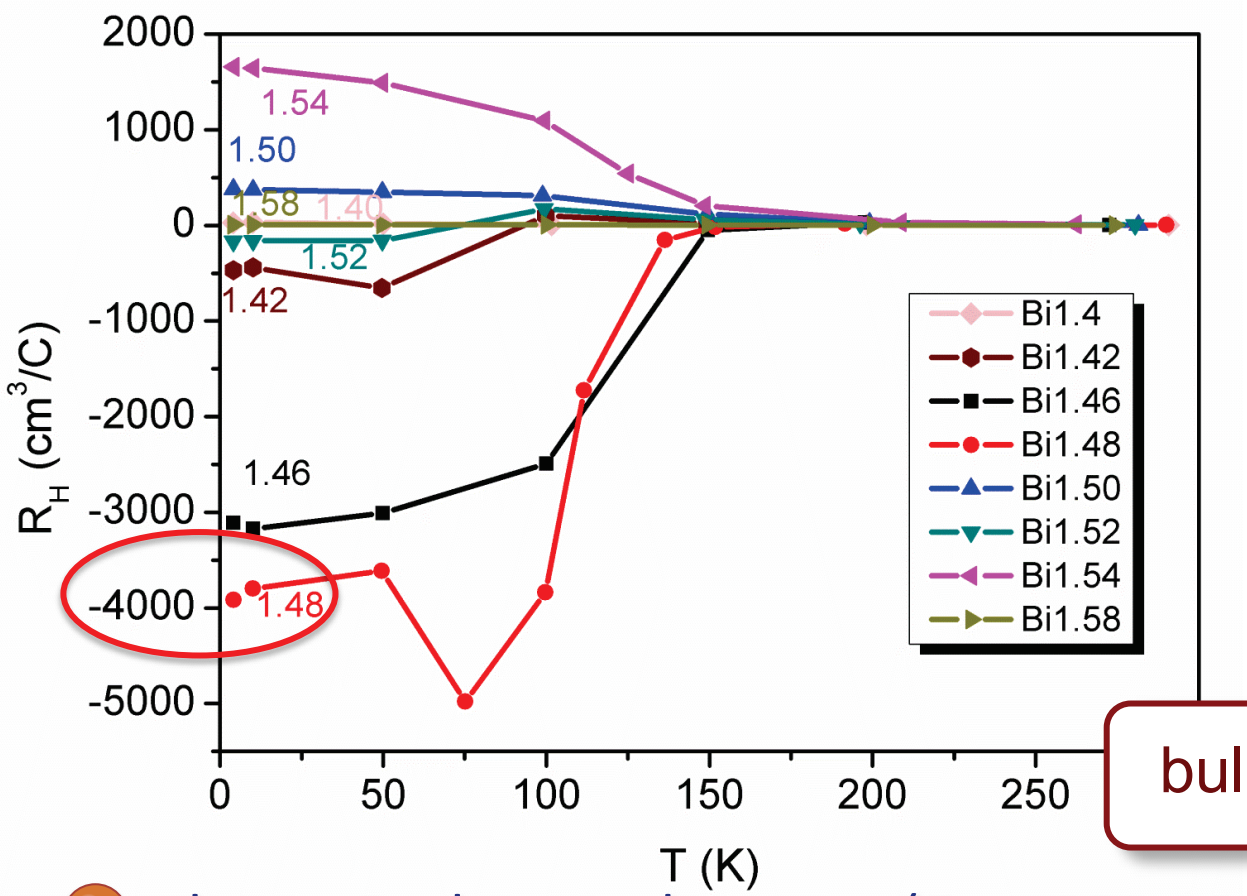




- significant improvements cf. Bi_2Se_3 and doped Bi_2Se_3
- resistivities close to 10 Ωcm
- low T Hall coefficient: -910 cm^3/C

also Cava group

$Bi_xSb_{2-x}Te_{1.7}Se_{1.3}$ – resistivity and Hall coefficient



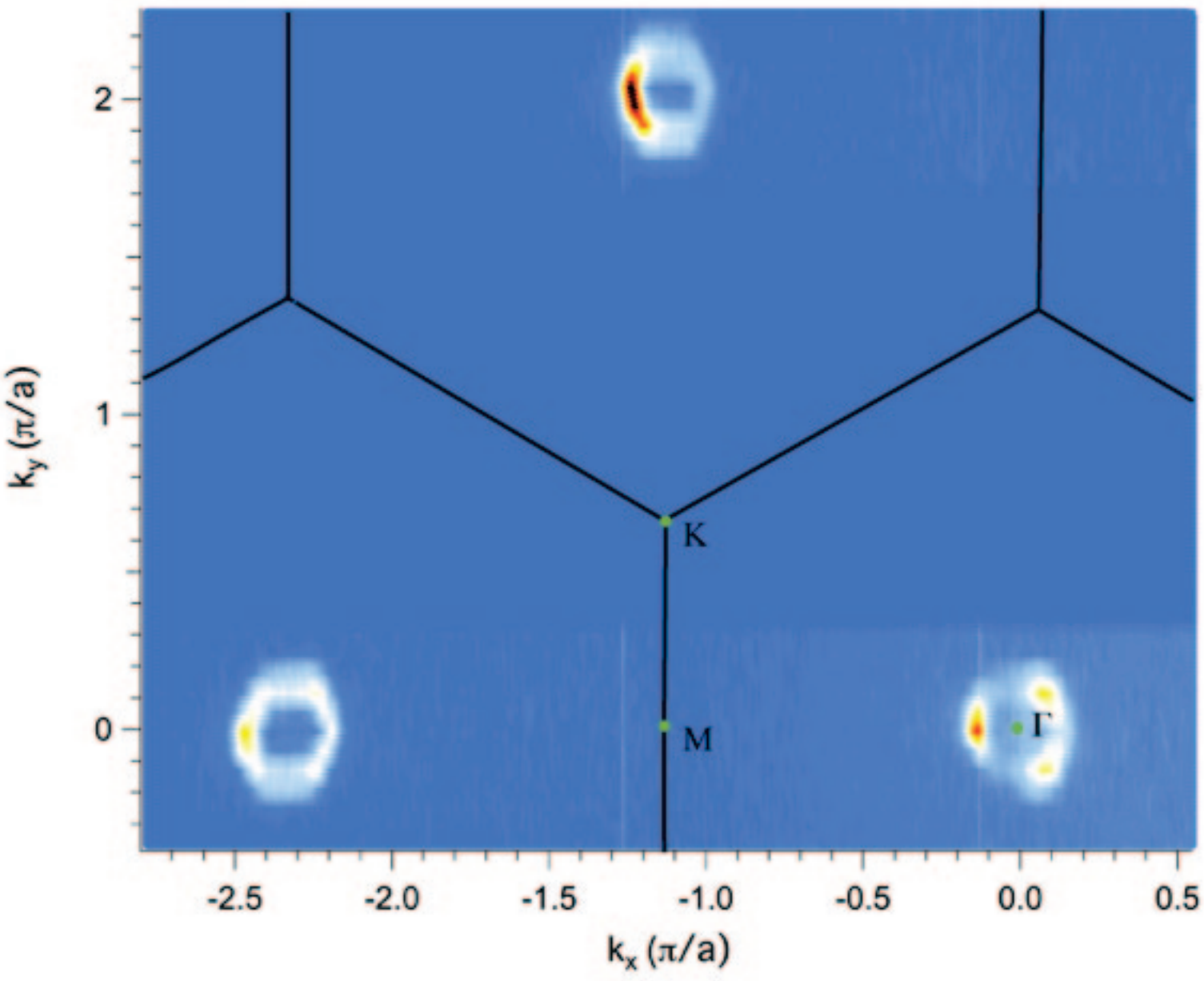
bulk insulating 3D TI's

- larger R_H than Osaka group (Ren, PRB 2011)
- higher surface conductance and lower bulk conductivity than Xia et al., PRB 2013 [Singapore]

→ G_s for d<1μm

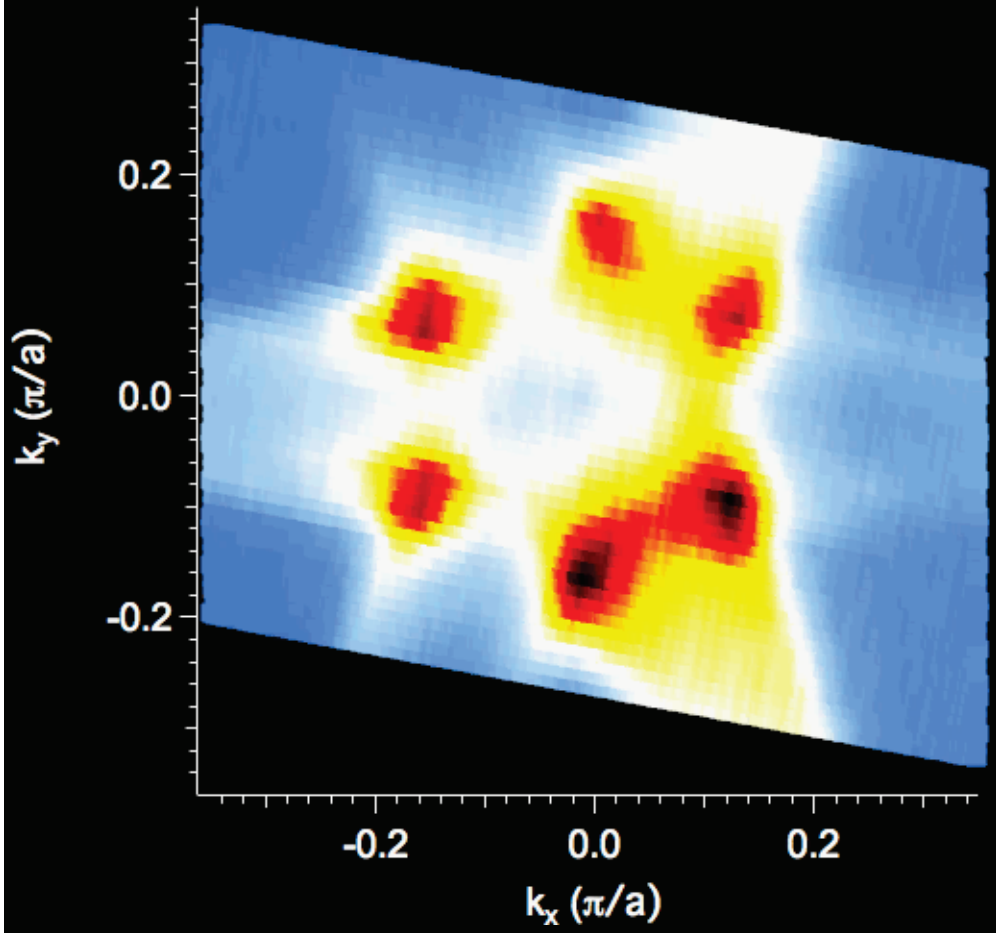
What do these quaternary 3D TI's look like in ARPES ?

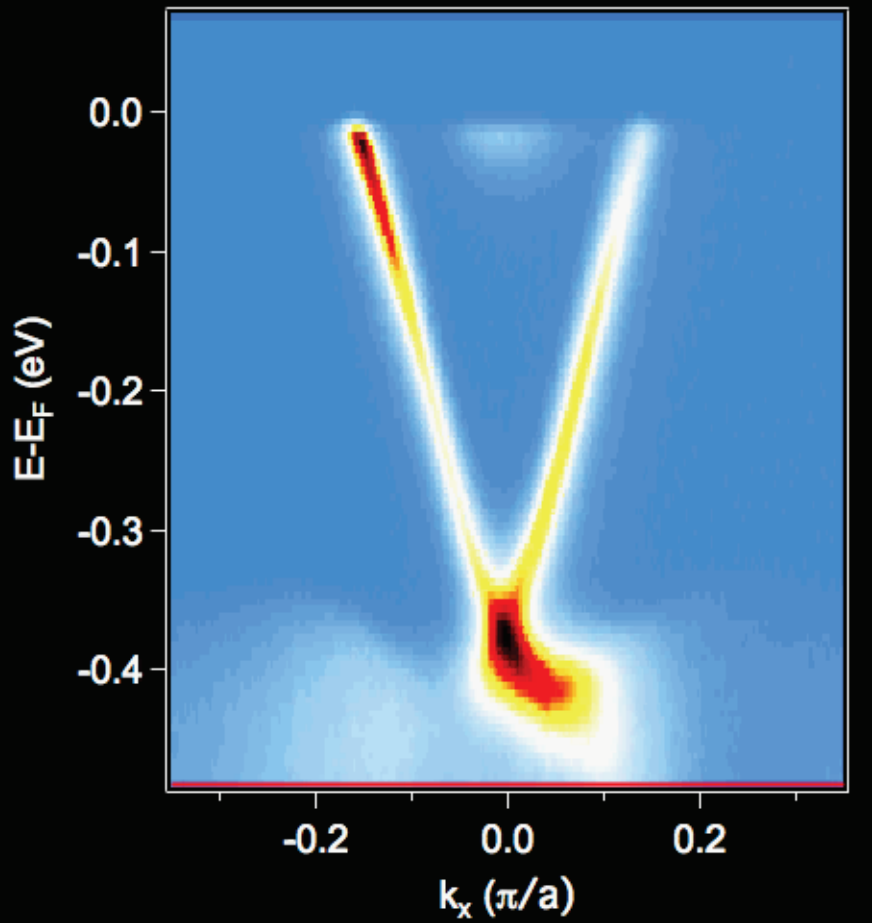
One cone per Brillouin zone: Bi_2Te_2Se is a strong TI



Nick de Jong, MSc thesis: SLS data.

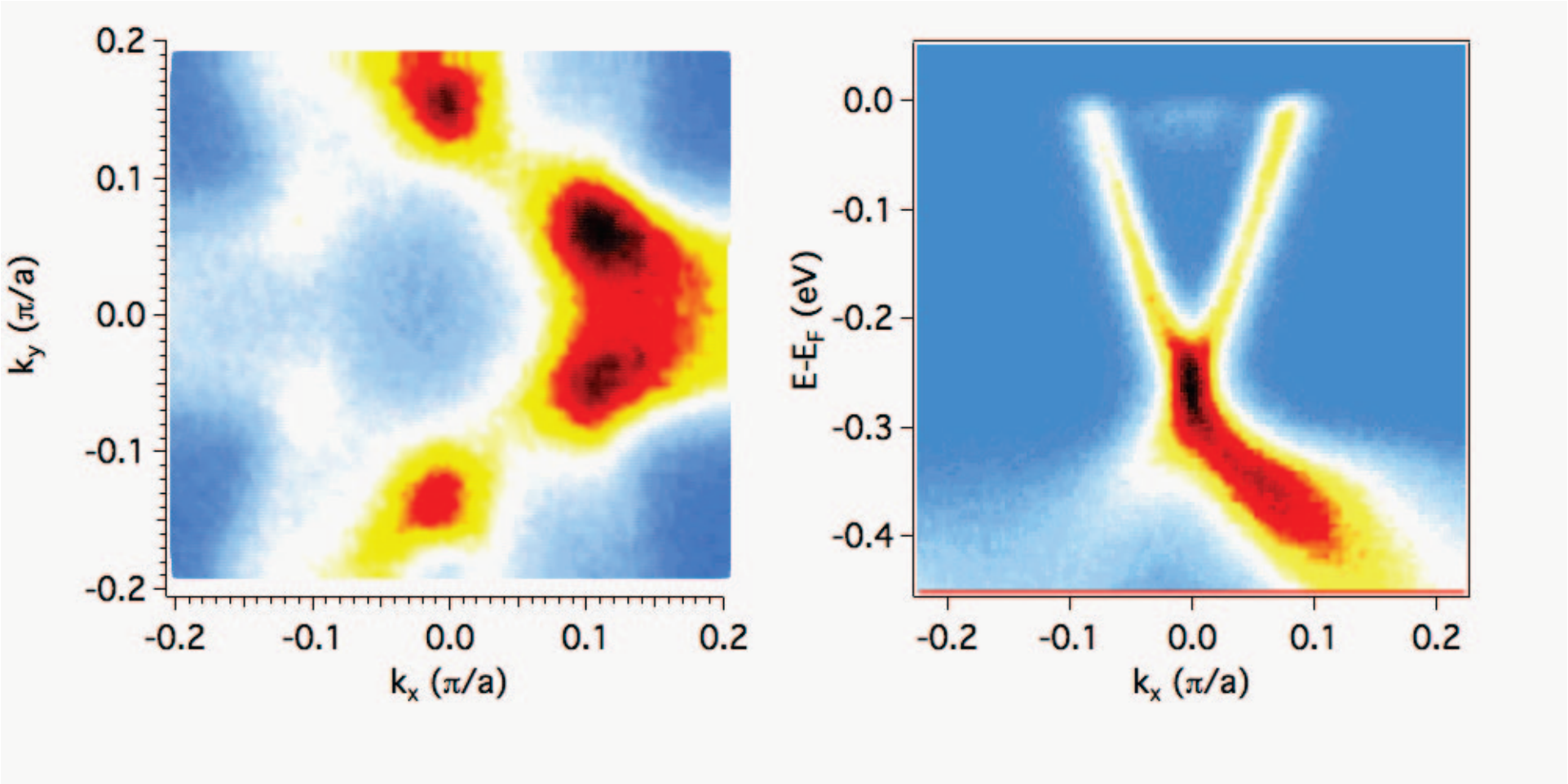
Bi_2Te_2Se





data: deJong & vHeumen @Swiss Light Source

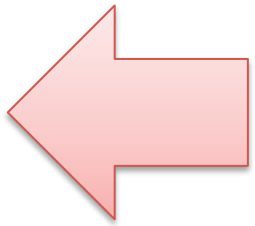
Mapping the cone in $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$



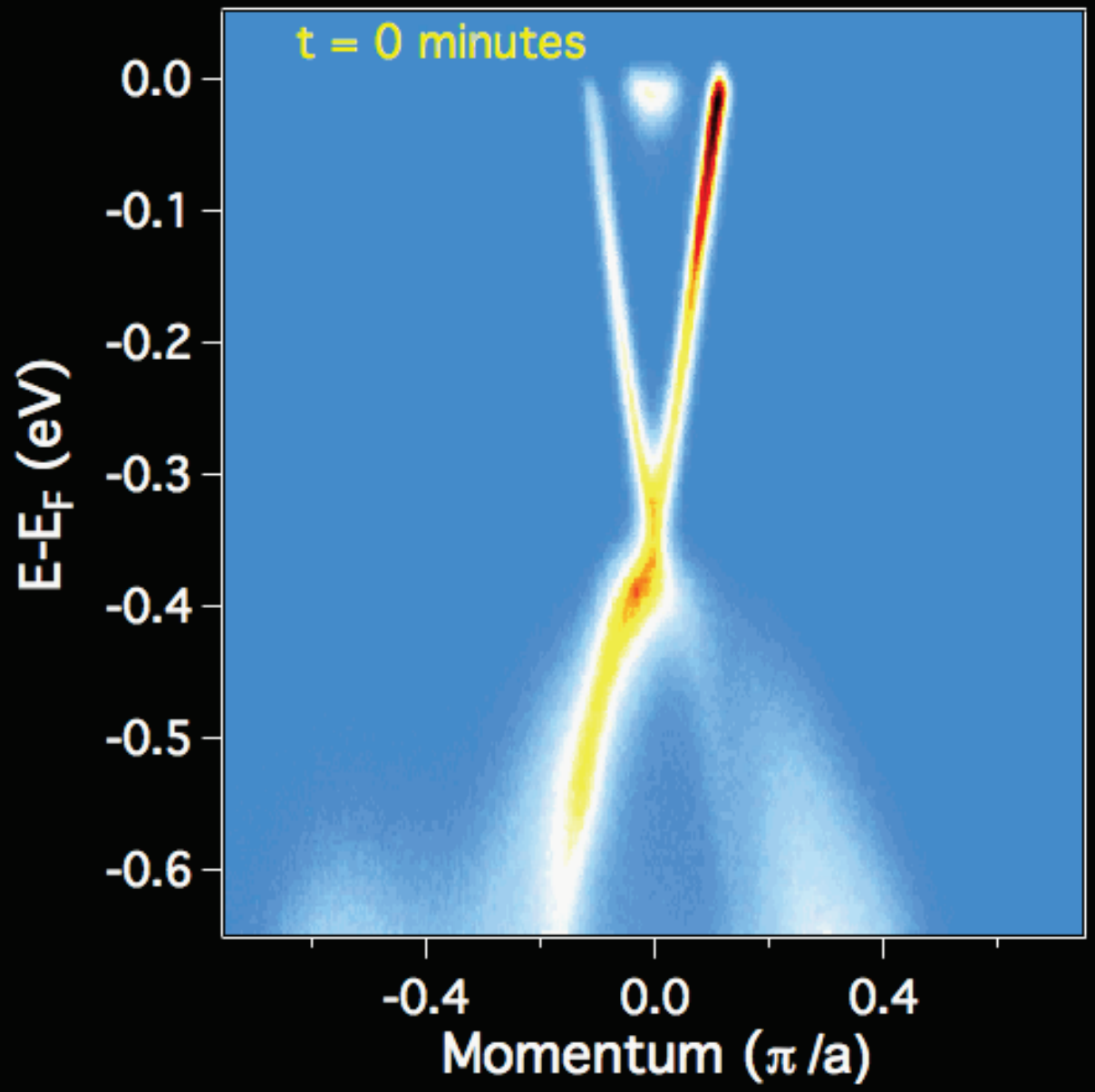
data: v.Heumen @ Swiss Light Source

Overview

- hitchhiker's guide to TIs
- spectroscopy and microscopy of topological surface states
- towards 3D topological *insulators*
- surprises in the time dependence in ARPES of insulating TI's

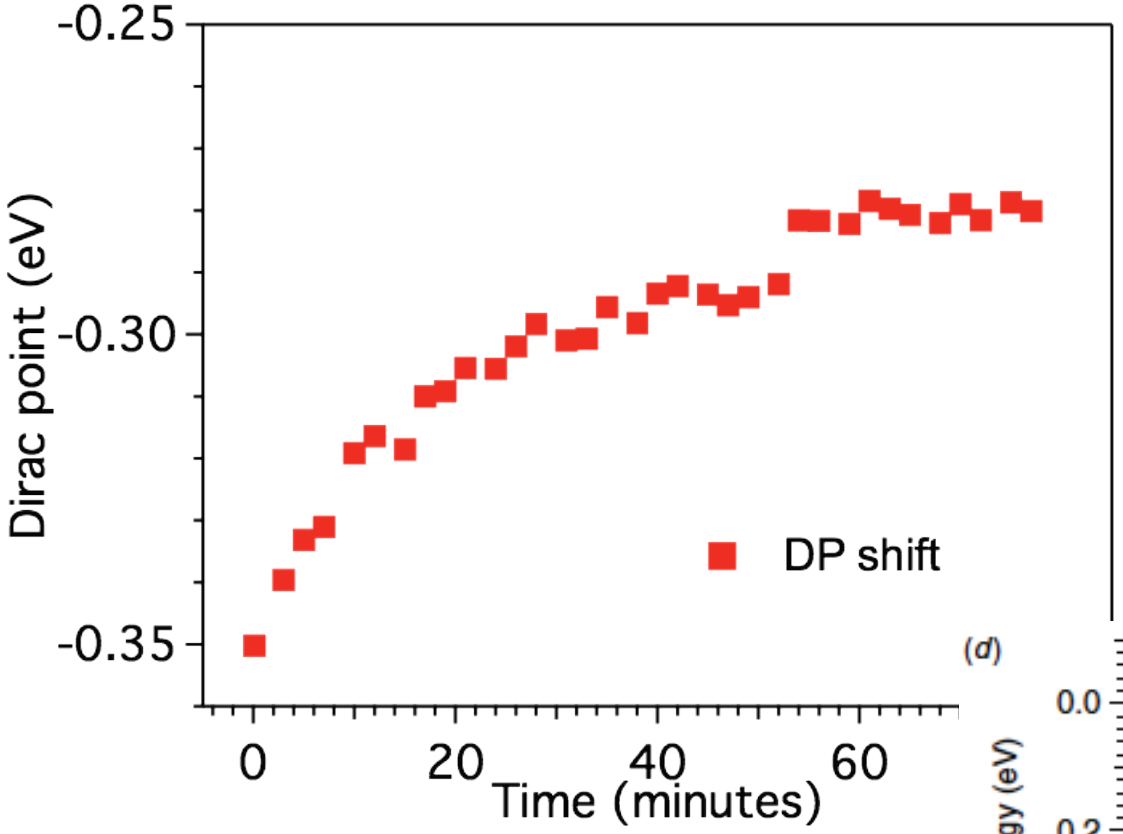


$Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$: as a function of time in the beam



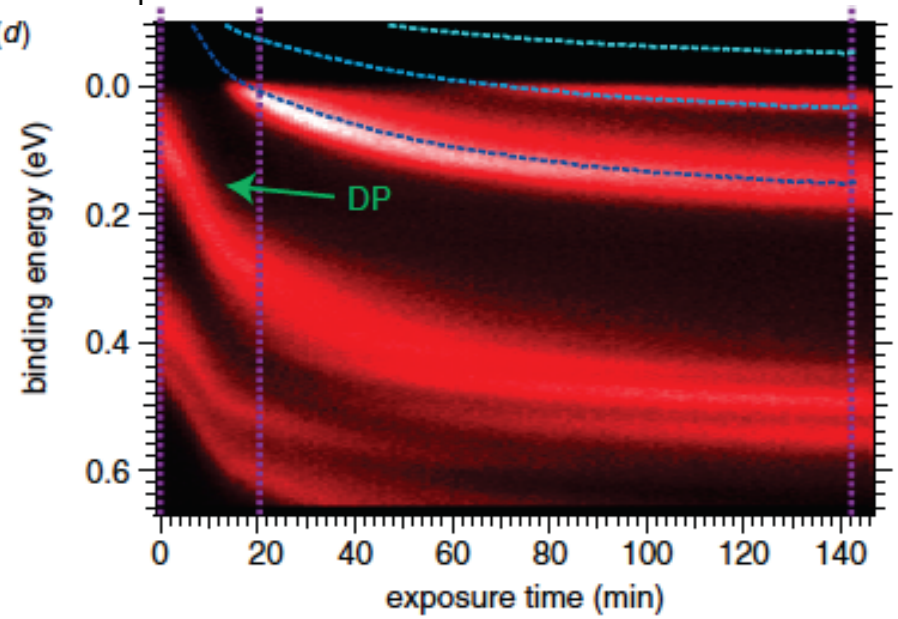
deJong, vHeumen @Swiss Light Source

$Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$: as a function of (photon) time

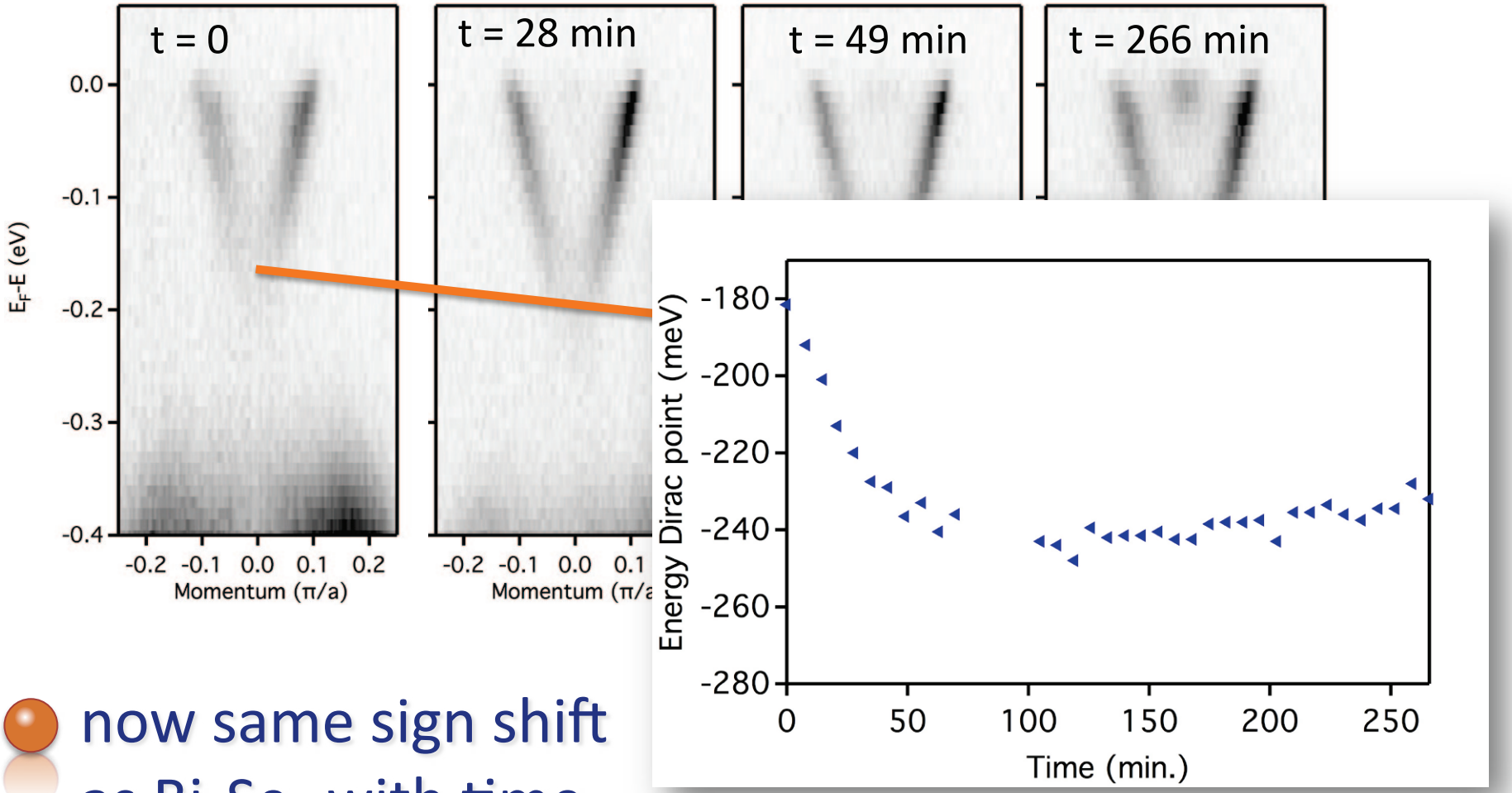


- opposite shift to Bi_2Se_3 with time

Marco Bianchi: CO exposure



$Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$: as a function of time – low flux



- now same sign shift as Bi_2Se_3 with time....

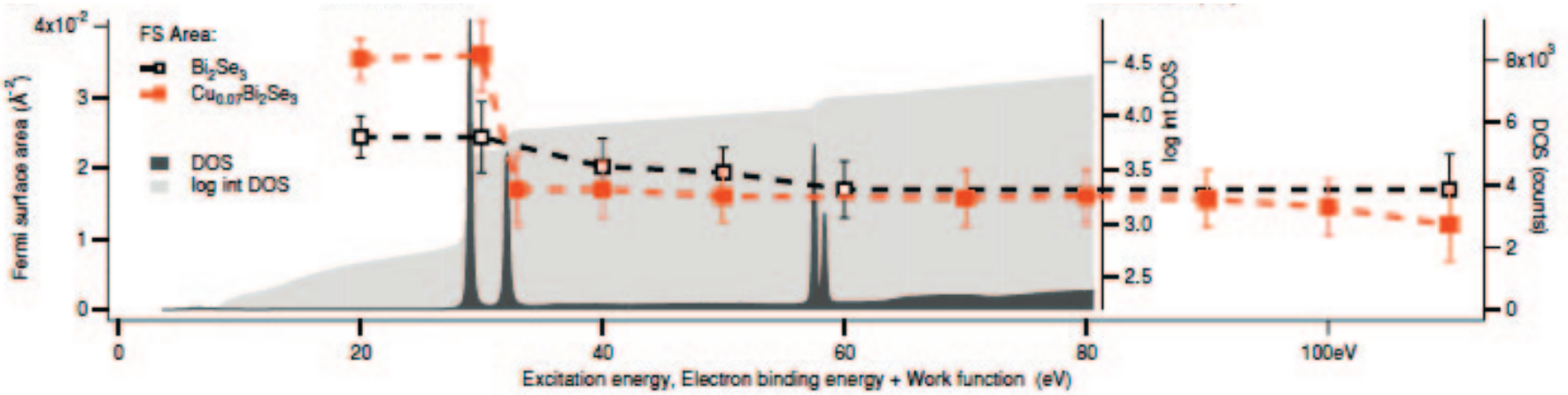
Flux reduced by factor 65

23 eV @ 16 K

Frantzeskakis, deJong @SLS

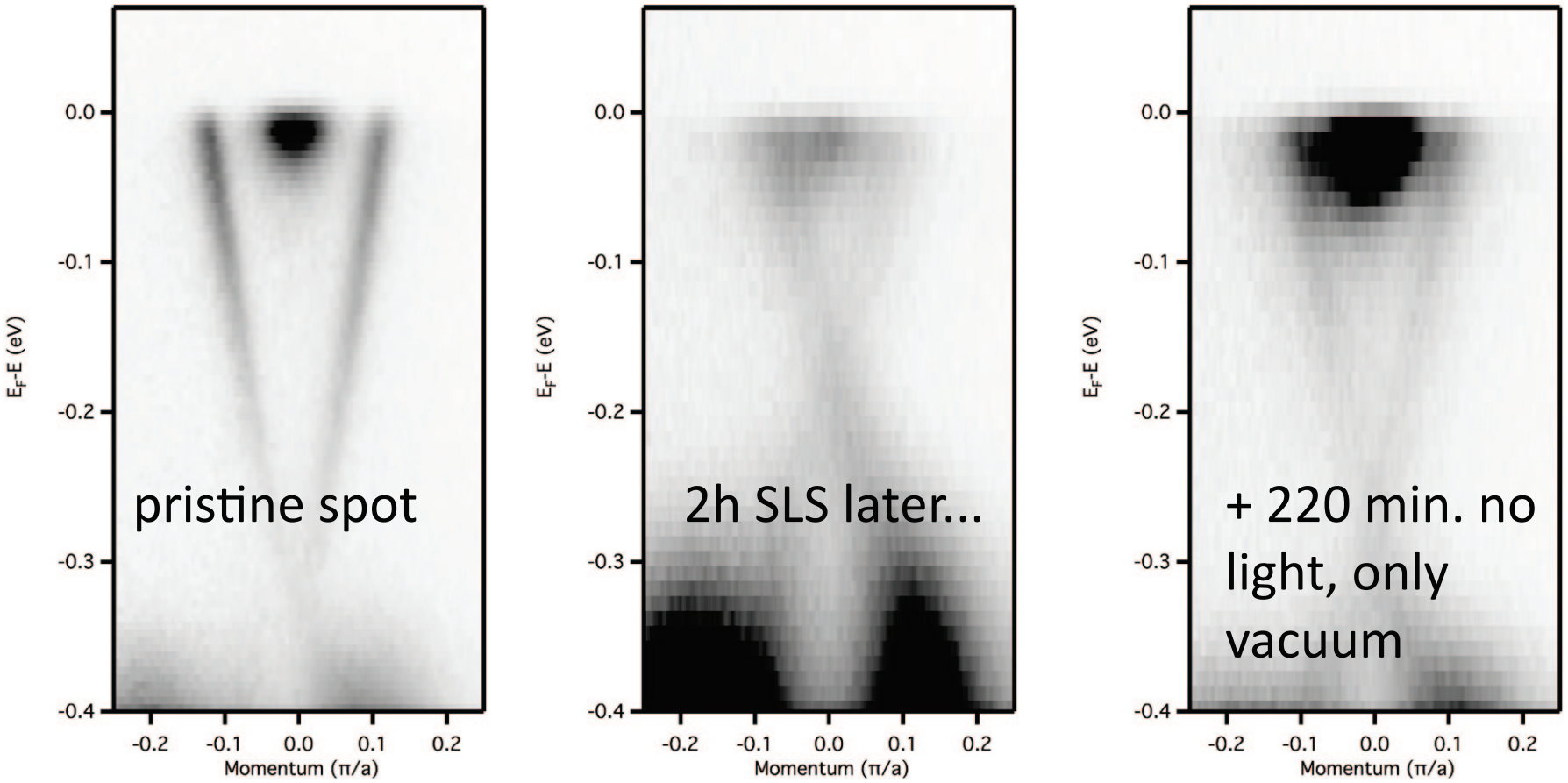
Very clear surface photovoltage

- e-h pairs from (very intense) photon beam reduce band bending at surface
- seen in $Cu_xBi_2Se_3$ by Kordyuk et al.



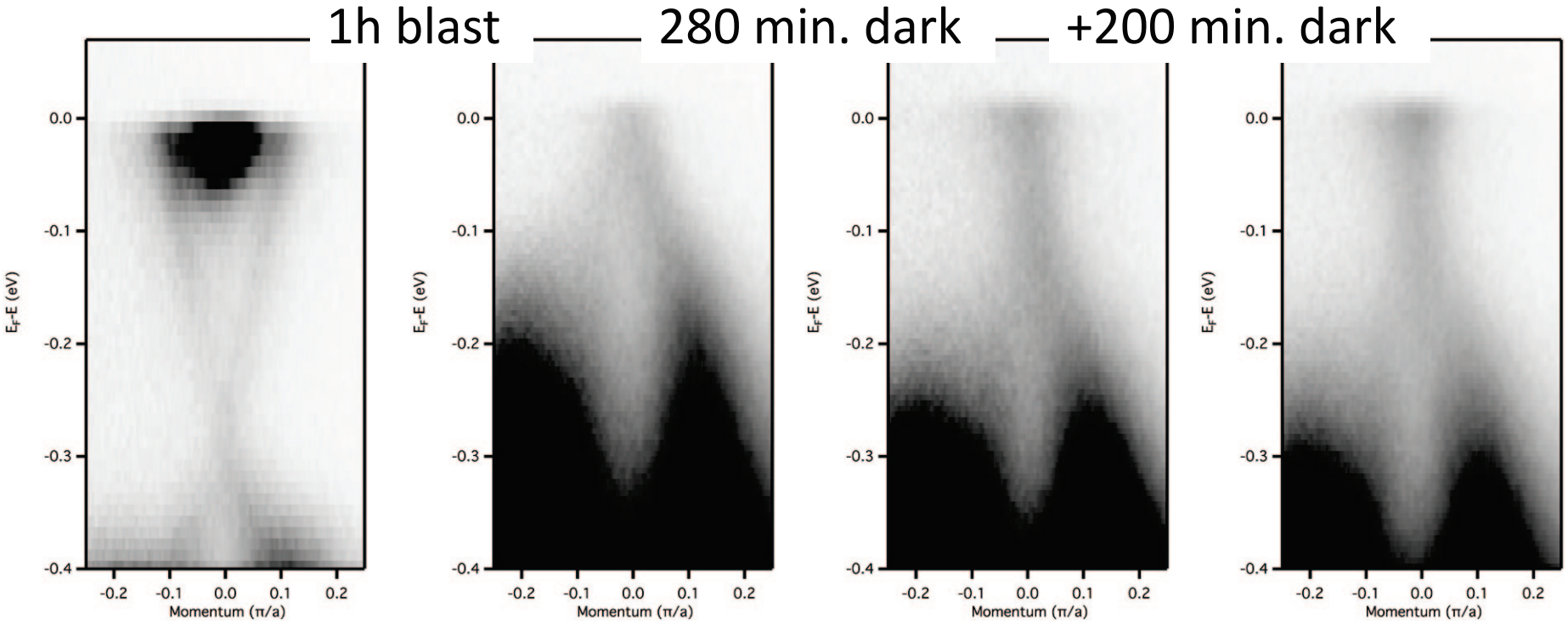
Kordyuk et al., PRB 2011

BSTS: vacuum shifts one way, photons the opposite



Frantzeskakis, deJong @SLS

BSTS: how far can we go? .....photon blasting

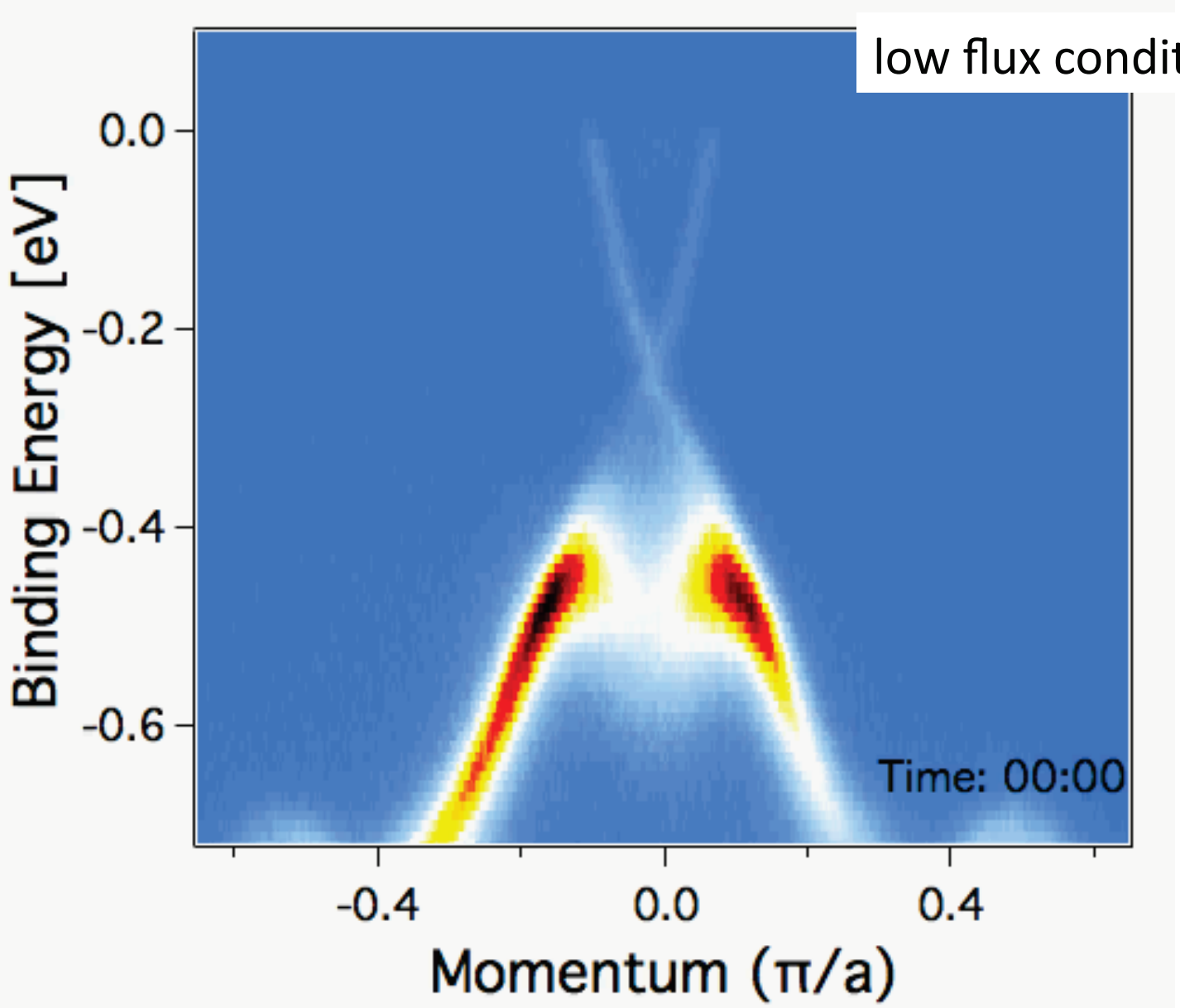


- total SPV (upward shift) exceeds 250 meV
- shift back starts once SR is off

Flux increased by factor 8
130 eV @ 16 K

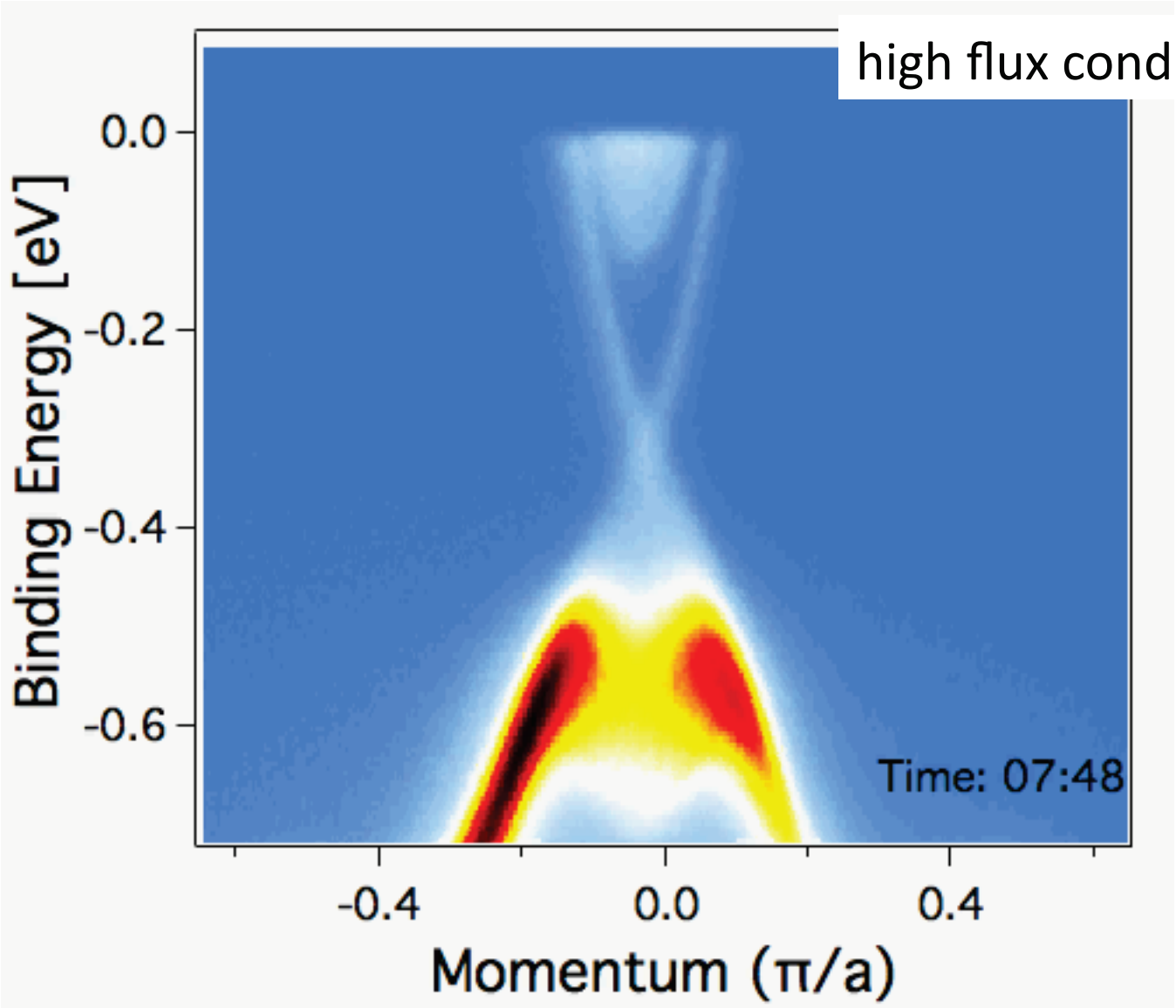
Frantzeskakis, deJong @SLS

Return to Bi_2Se_3



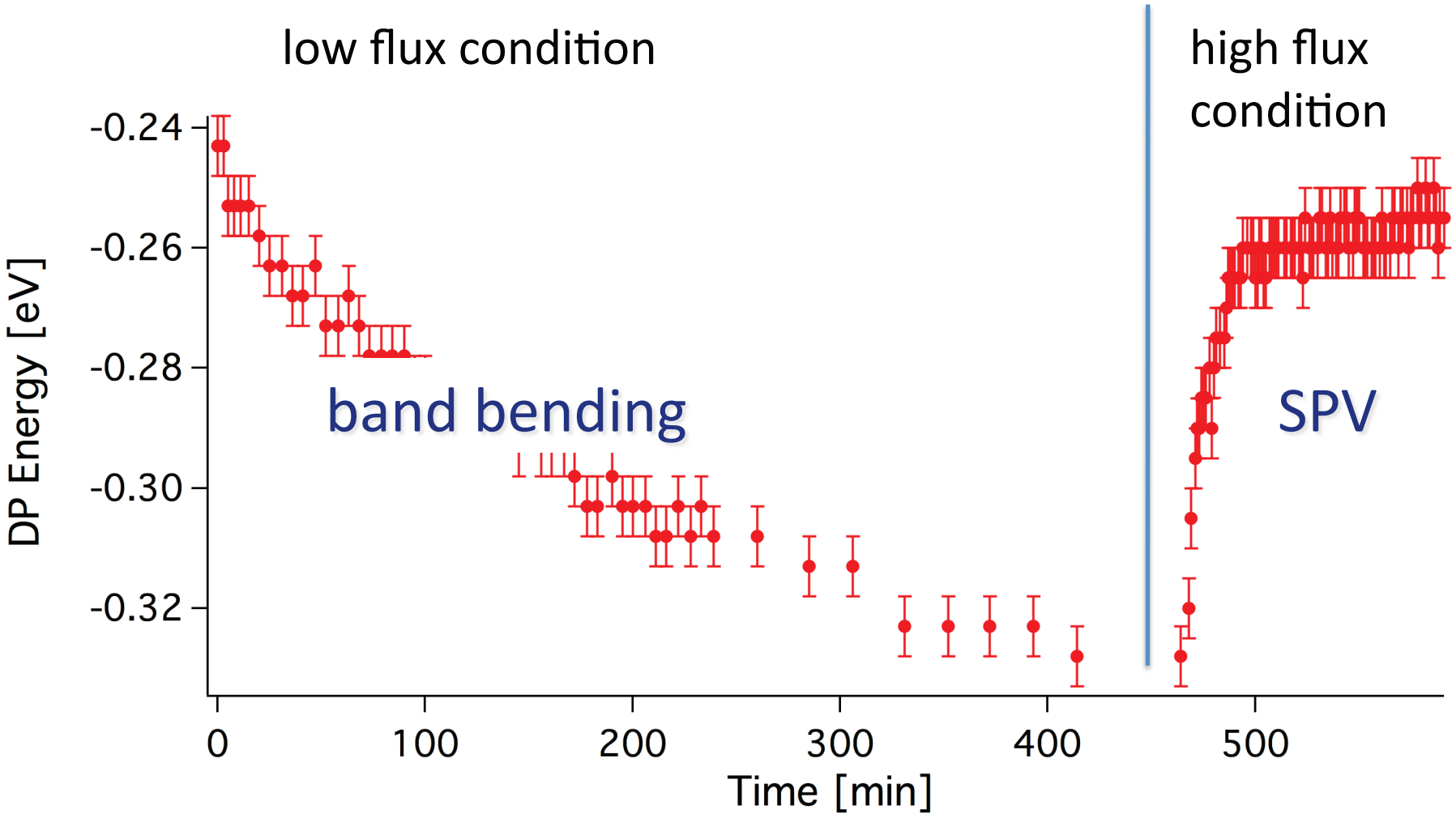
Frantzeskakis, deJong @SLS

Return to Bi_2Se_3



Frantzeskakis, deJong @SLS

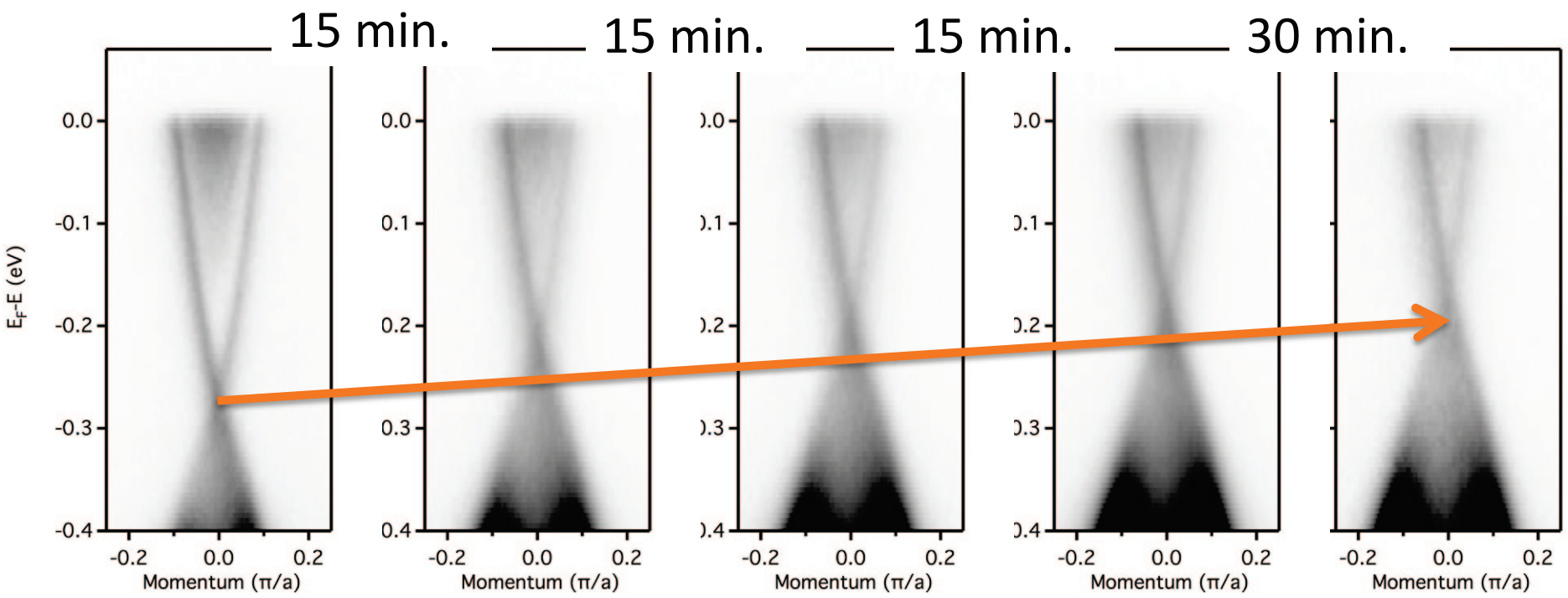
Return to Bi_2Se_3



- close to complete flattening of bands

Frantzeskakis, deJong @SLS

Bi_2Se_3: how far can we go? .....photon blasting



- total SPV (upward shift) 170 meV

Flux increased by factor 8
130 eV @ 16 K

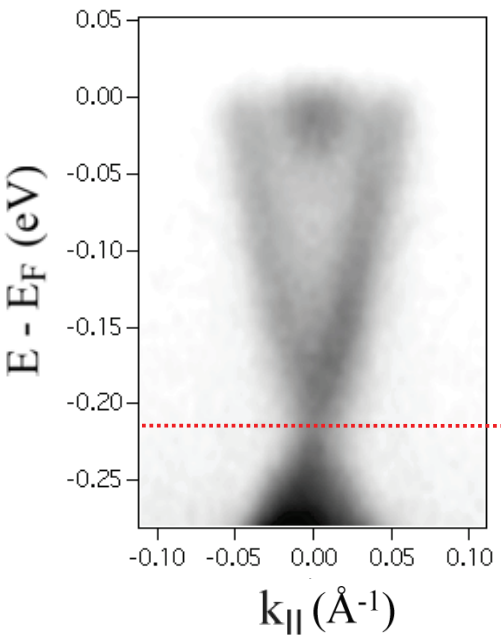
Frantzeskakis, deJong @SLS

Temperature dependence: Bi_2Se_3

27eV

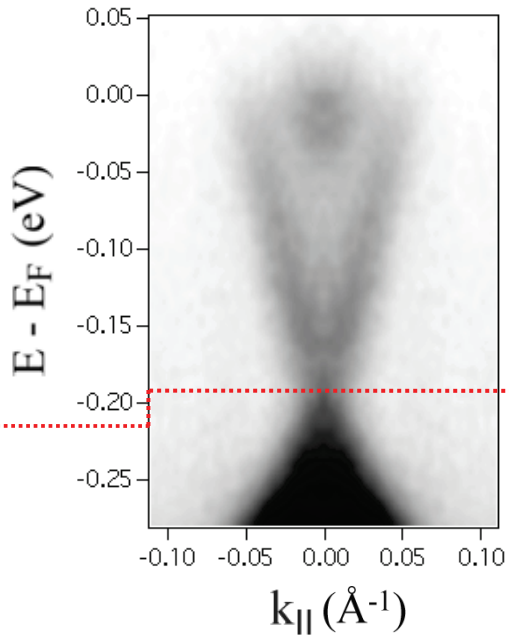
E_DP=219meV

T=36K



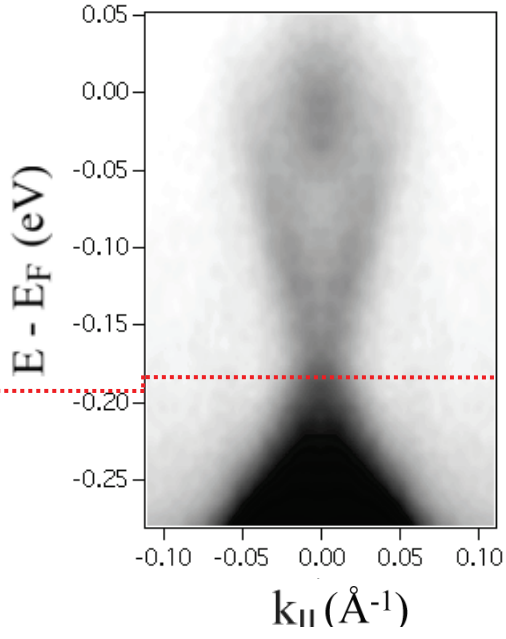
E_DP=197meV

T=170K



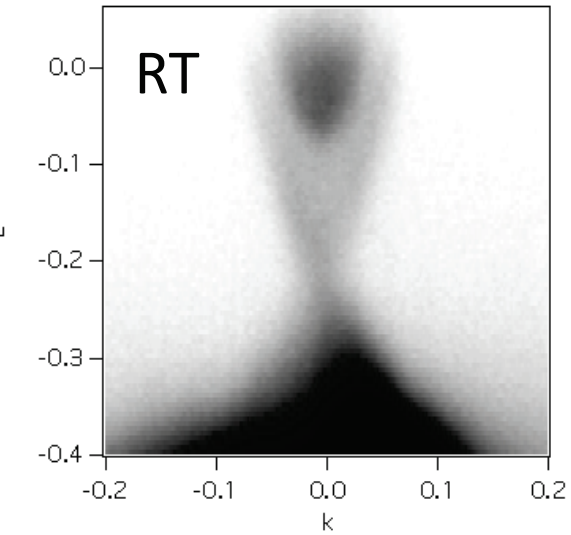
E_DP=188meV

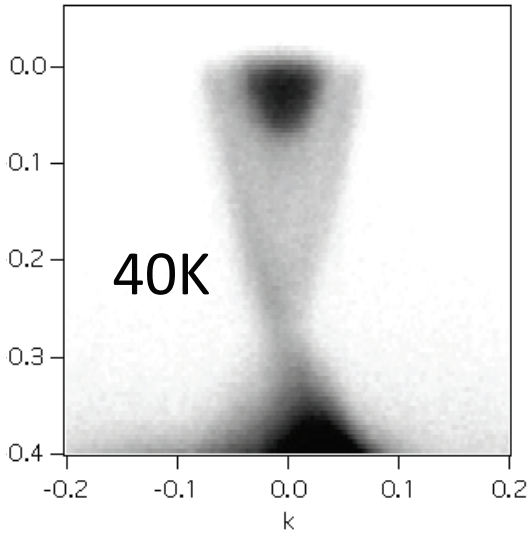
T=300K



Overnight @RT: measure pristine spot.

The cool (in dark): then re-measure





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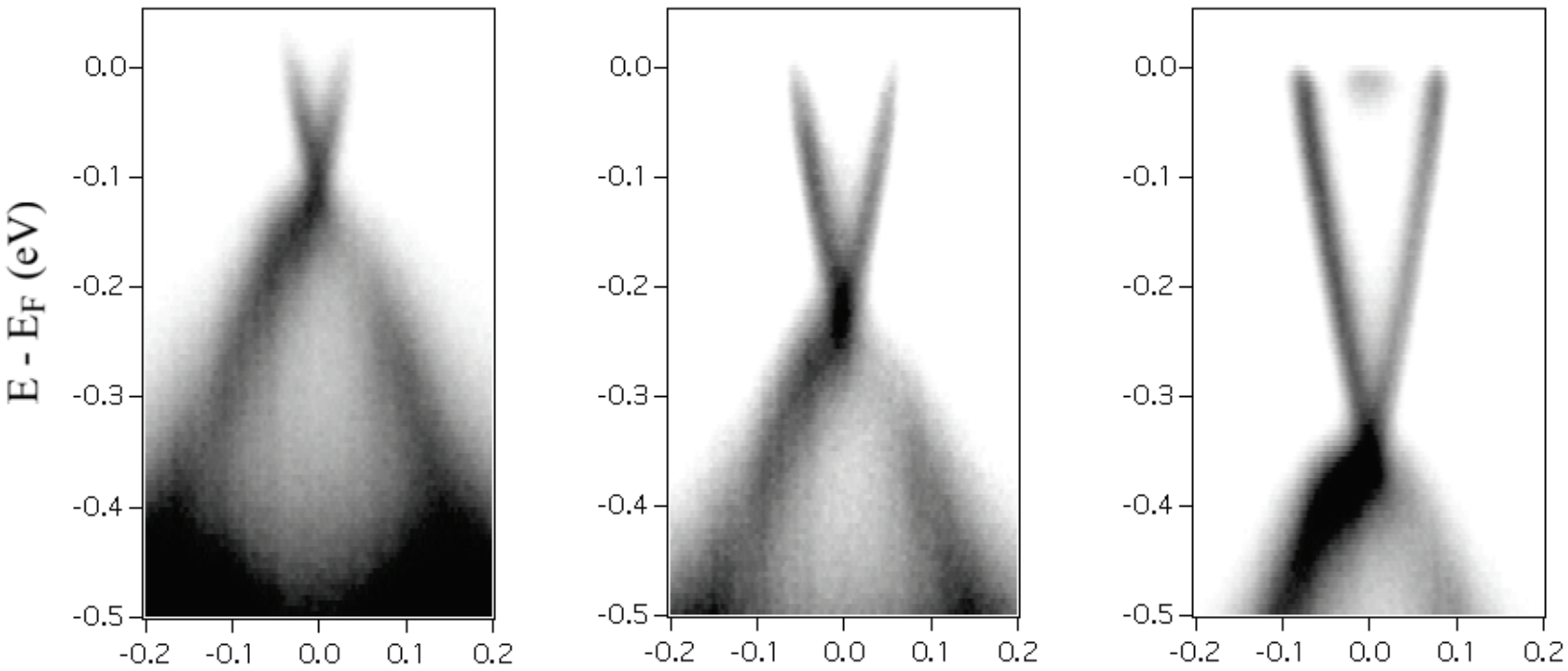
Temperature dependence: BSTS

27eV

10mins after cleave
RT; not exposed to hv

15h after cleave
RT; not exposed to hv

cooling down to 40K
Delta_E DP is 125meV



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Summary

- good progress → bulk insulating 3D TI's
- clear surface photovoltage:
  → faster when more insulating

  none seen for Bi_2Te_3, also no T-dep of BB
- downward band bending:
  → faster for more insulating
  → stronger at low T

clear correlations between transport properties and ARPES behaviour

Thanks to

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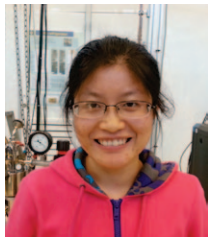
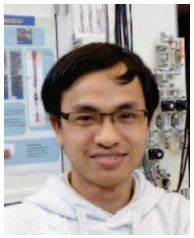
Dong Wu

Anne de Visser



Yu Pan

Huib Luigjes



Bay Tran

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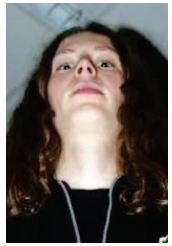

Erik Slooten

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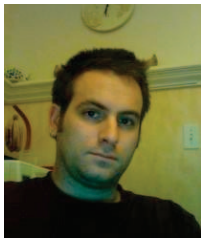

Steve Johnston

NWO

FOM