NEW YORK UNIVERSITY

CQP Center for Quantum Phenomena

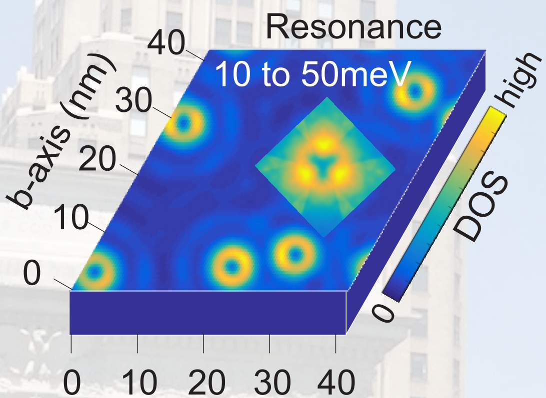
上海纽约大学 NYU SHANGHAI

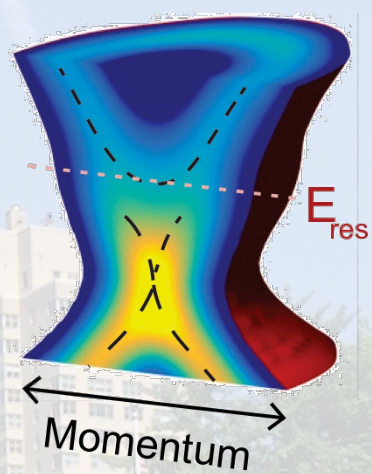
The birth of new particles from structure and disorder at a topological insulator surface

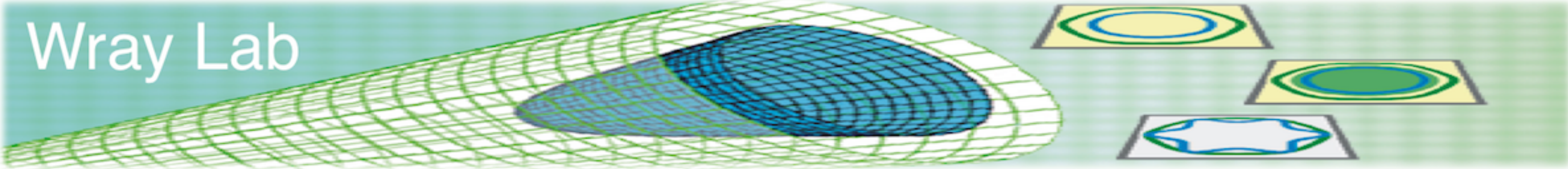
L. Andrew Wray

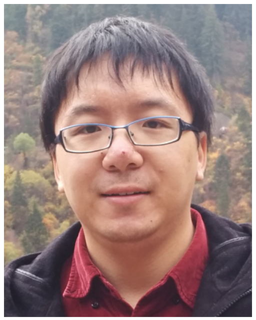
Center for Quantum Phenomena & NYU-ECNU Joint Physics Research institute,

Physics Department, New York University





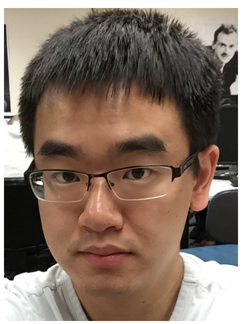




Lin Miao, postdoc

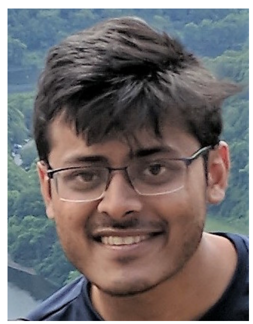
Yishuai Xu

Erica Kotta

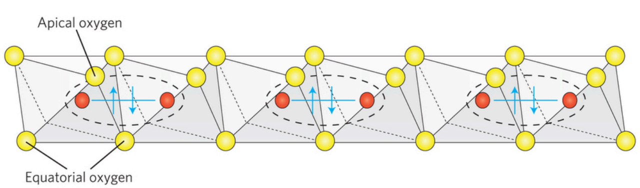


Haowei He

Divyanshi Sar



Rourav Basak



RIXS, XAS and ARPES on **strongly correlated materials** and **topologically ordered materials**

ALS
Jonathan Denlinger
Yi-De Chuang
Wanli Yang
MAESTRO collaboration

UCSD
Sheng Ran
Brian Maple

Purdue
Guodon Jiang
Rudro Biswas

NIST/UMD
Nick Butch

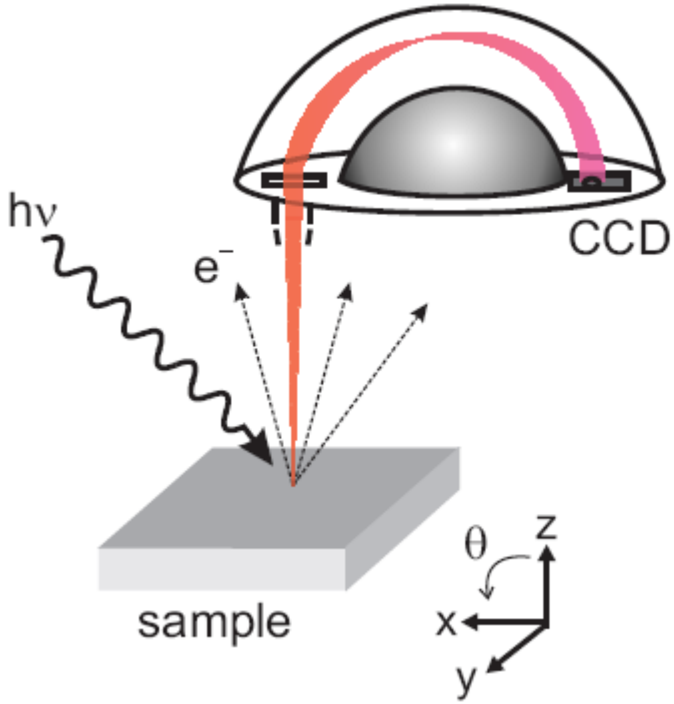
Rutgers
Wenhan Zhang
Weida Wu
Gabriel Kotliar

NSLS-II
Ignace Jarrige
Yilin Wang

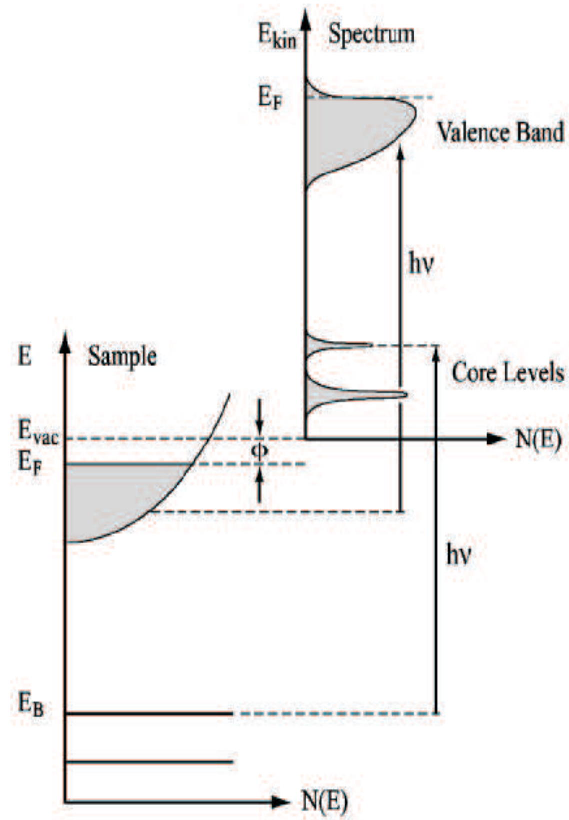
MIT
Takehito Suzuki
Joe Checkelsky

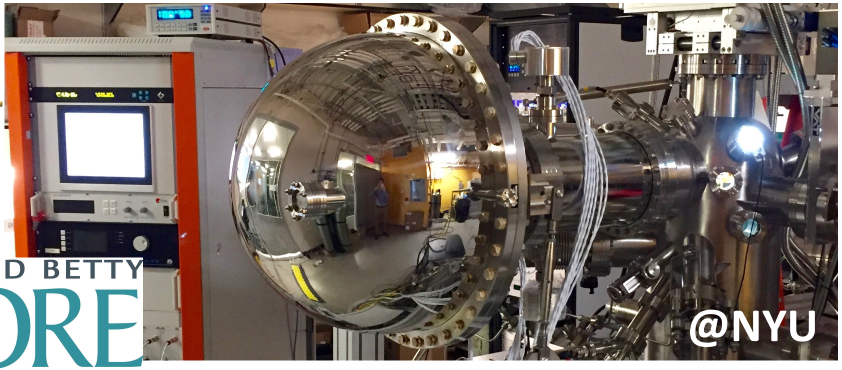
MS&T
Yew San Hor

Angle Resolved Photoemission (ARPES)



Photoemission: Einstein 1906



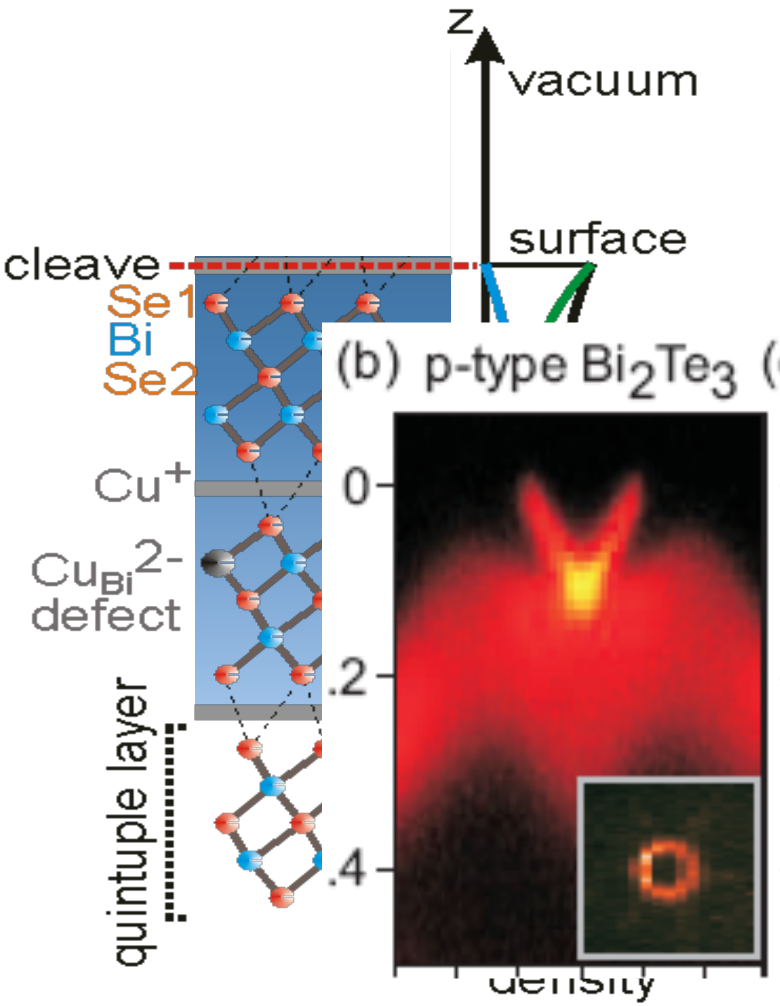


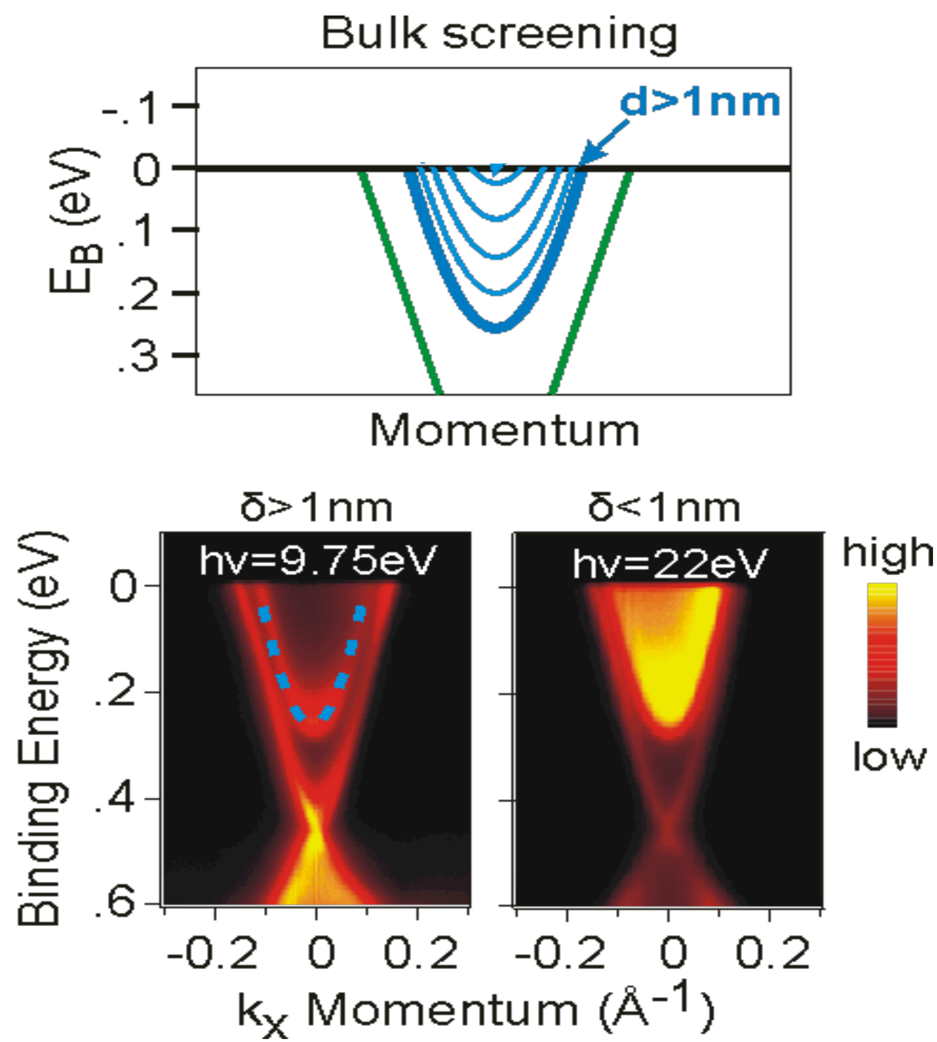
Reveals electron-derived 'quasiparticles' inside materials:

- **Band structure**
- **Topological surface states**
- **Majorana Fermions**

GORDON AND BETTY MOORE FOUNDATION

Photoemission on a TI (ARPES)





LAW PRB 2011

Phase Transitions and Electronic Topology

The Nobel Prize in Physics 2016

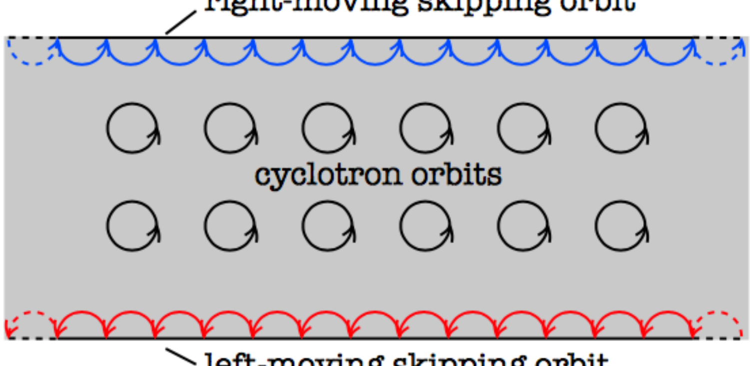
Photo: A. Mahmoud
David J. Thouless
Prize share: 1/2

Photo: A. Mahmoud
F. Duncan M. Haldane
Prize share: 1/4

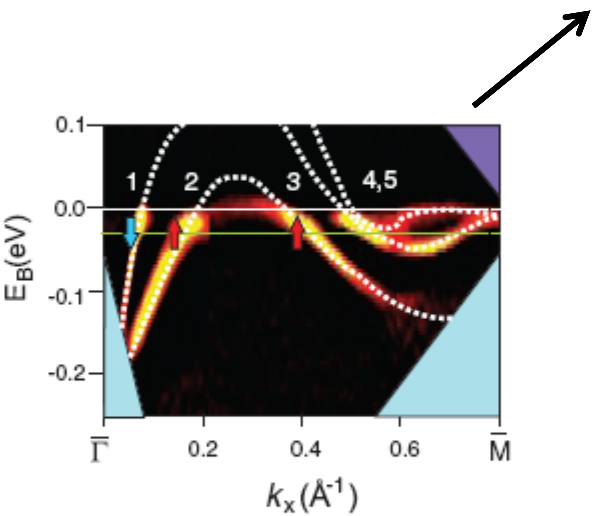
Photo: A. Mahmoud
J. Michael Kosterlitz
Prize share: 1/4

The Nobel Prize in Physics 2016 was awarded with one half to David J. Thouless, and the other half to F. Duncan M. Haldane and J. Michael Kosterlitz *"for theoretical discoveries of topological phase transitions and topological phases of matter"*.

Bulk-Boundary Correspondence
Quantum Hall Edge States



History of 3D Topological Matter



2005: Theoretical prediction of the Z2 TI phase (C.L. Kane and E.J. Mele *PRL 2005*)

2006-2007: Achievement of a 2D TI phase in HgTe (B.A. Bernevig, T.L. Hughes, S.-C. Zhang, *SCIENCE 2006*, M. König et al. *SCIENCE 2007*)

2007-2009: First discovery of a 3D TI ($Bi_{1-x}Sb_x$ alloy, L. Fu et al. PRL 2007, **D. Hsieh**, LAW, *et al*. **Zahid Hasan** group *NATURE 2008, SCIENCE 2009*)

2008: Discovery of the M_2X_3 TI class (Y. Xia, arXiv 2008, H.-J. Zhang et al. NATURE 2009, D. Hsieh *et al. NATURE 2009*)

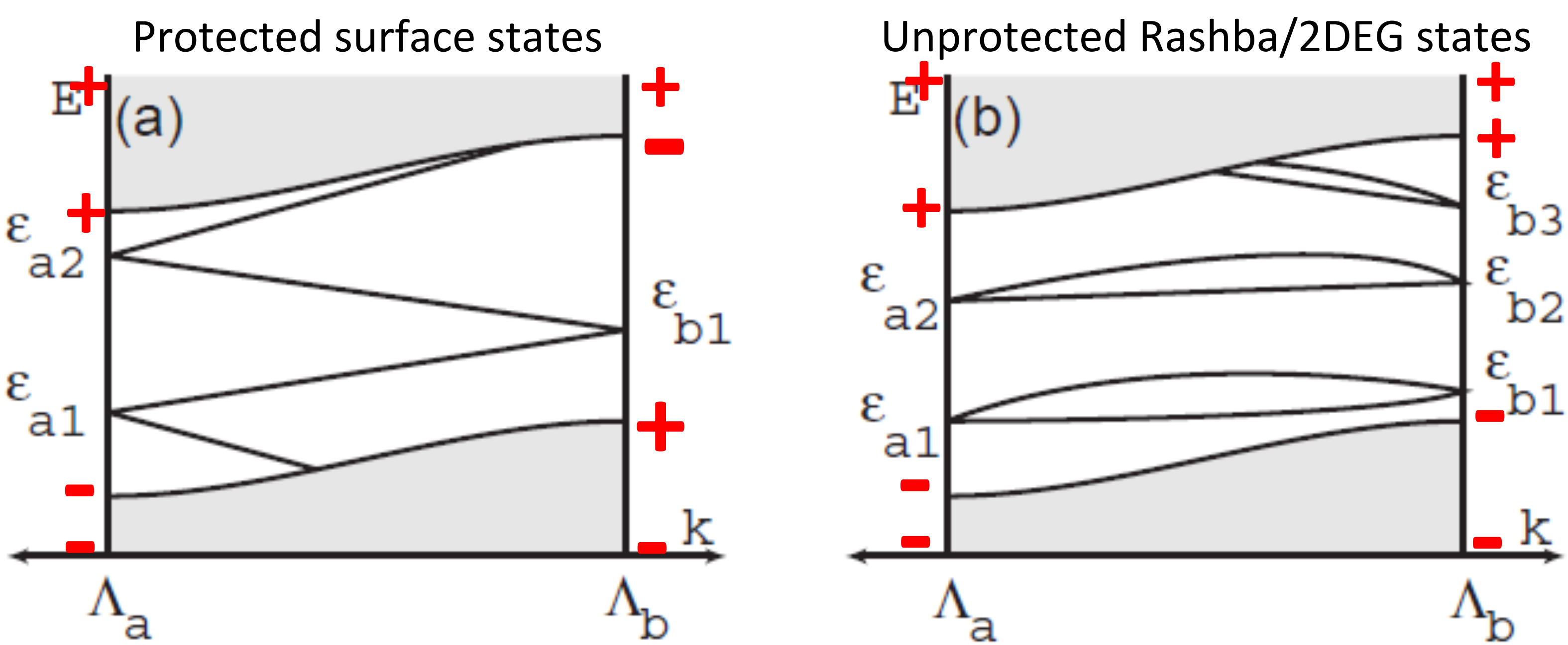
2010: Symmetry breaking: Observation of unconventional superconductivity in $Cu_xBi_2Se_3$, magnetism in $Mn_xBi_{2-x}Te_3$ (LAW et al. Nat. Phys. 2010, Y.-S. Hor et al. PRB 2010)

2011-2012: Discovery of "Topological Crystalline Insulators" (L. Fu *et al.*, PRL 2011; T. Hsieh *et al.*, Nat. Comm. 2012, S. Xu, LAW *et al.*, Nat Comm 2012)

2010-present: Higher order topological insulators, Weyl, Dirac, nodal line topological semimetals, many new materials

Surface states and Kramers Points

2 scenarios (i.e. Z_2)

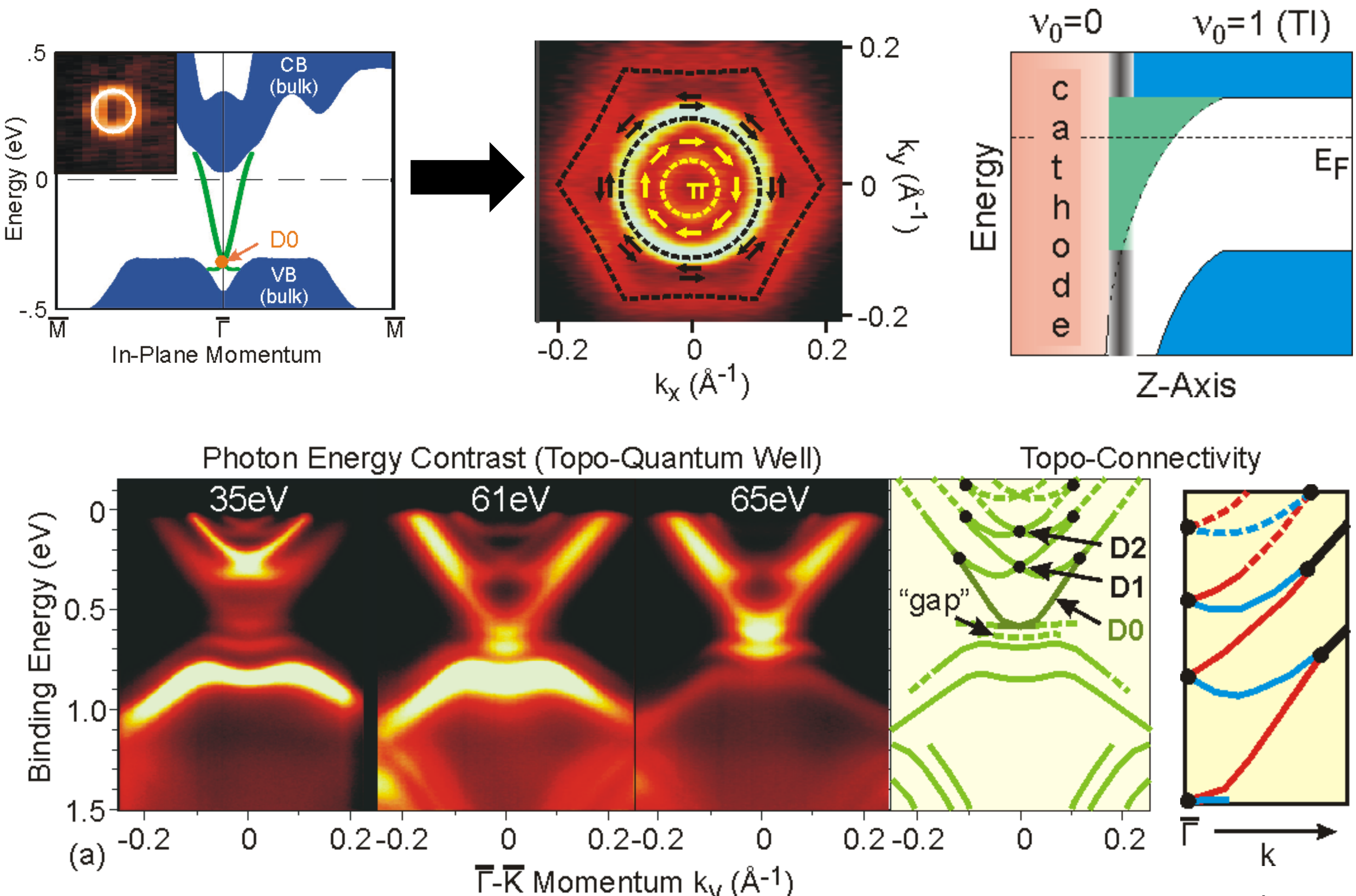


Fu PRL 2007

• *Terminology: All 2DEG's and Rashba states are "surface states", with respect to topology.*

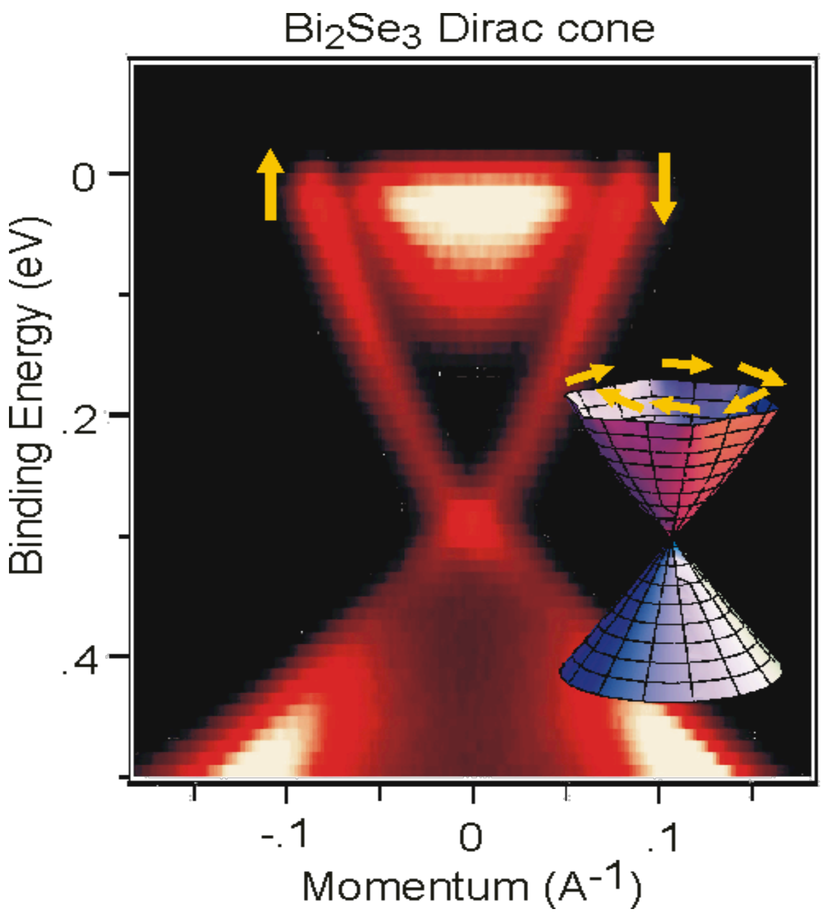
①

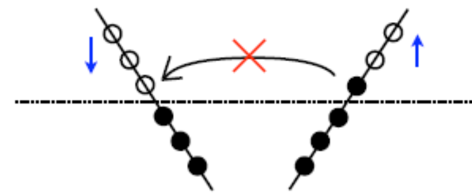
Topological connections



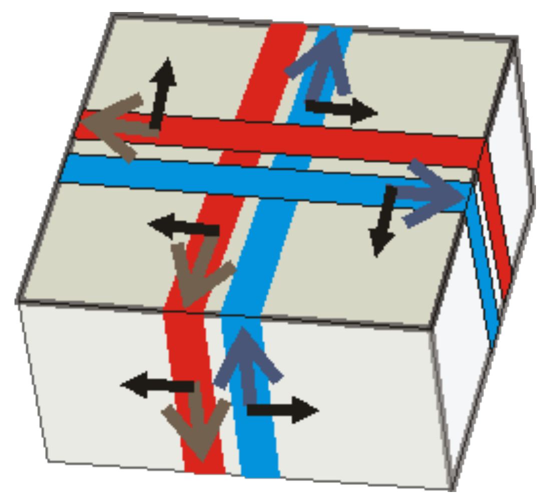
LAW Nat. Phys. 2011

Bi_2Se_3: a single Dirac cone TI





No backscattering!

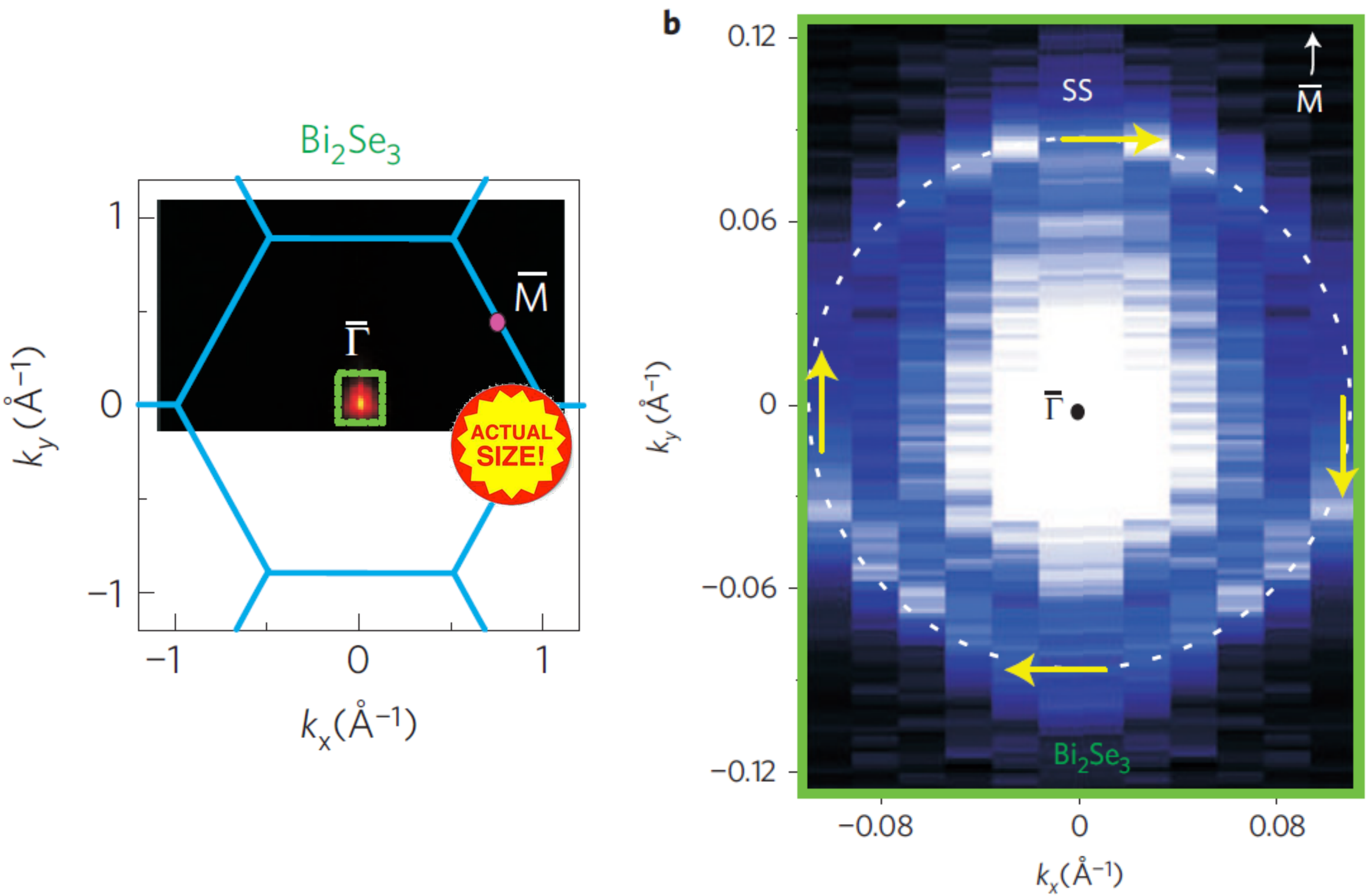


A 3D insulator, wrapped in a 2D metal

Y. Xia, LAW, M. Z. Hasan et al. Nat. Phys. *2009*

TI surface electrons are also protected from Anderson localization (See papers by Konig, Fu, Ostrovsky, Ryu)

Not many electrons are involved (usually)



Y. Xia, Nat. Phys. 2009

More Is Different

Broken symmetry and the nature of
the hierarchical structure of science.

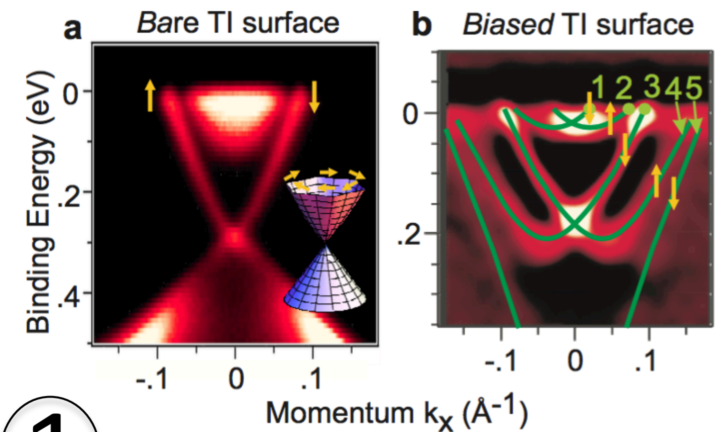
P. W. Anderson

Science ***177****, 393 (1972)*

A big question: What do we get from adding topological bulk-boundary correspondence to the many-body principles and states that we already know?

Disrupting the system brings in-gap surprises

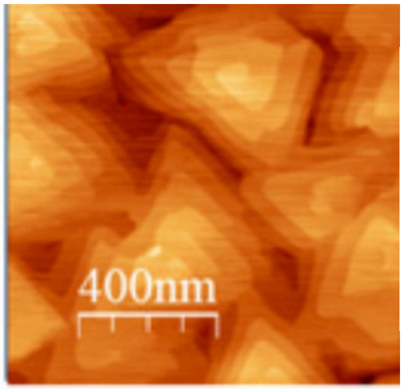
Gating creates new Dirac points



1

LAW Nat. Phys. 2011

Complex structure changes the game



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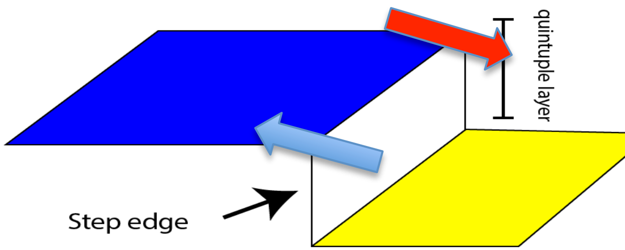
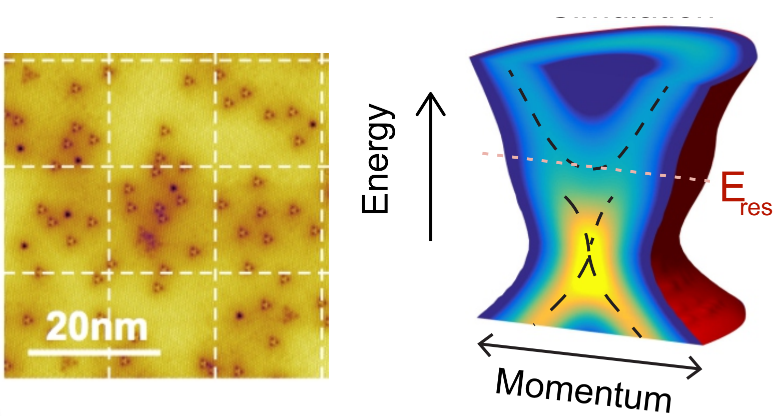


Miao, PNAS 2013; Xu, Miao, LAW in prep (2018)

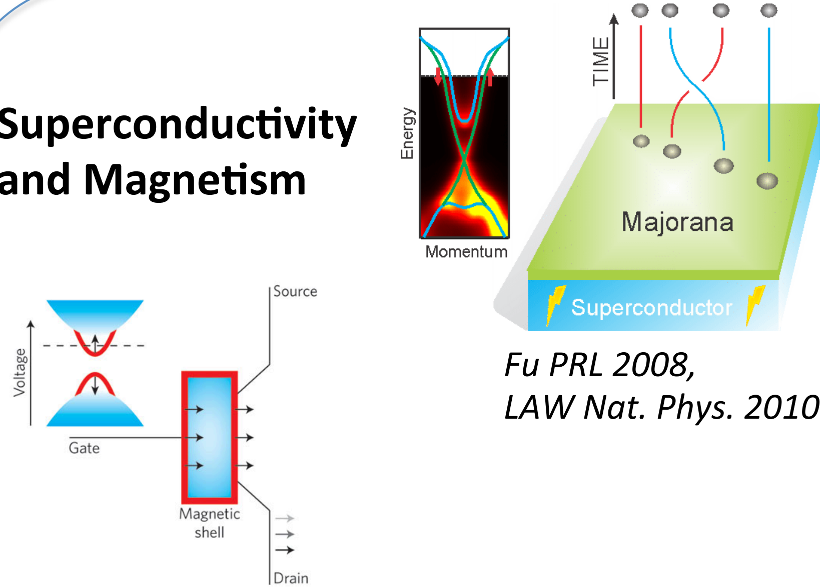
Defects create new band structure



2

Xu, Biswas, LAW Nat. Comm. 2017

Superconductivity and Magnetism



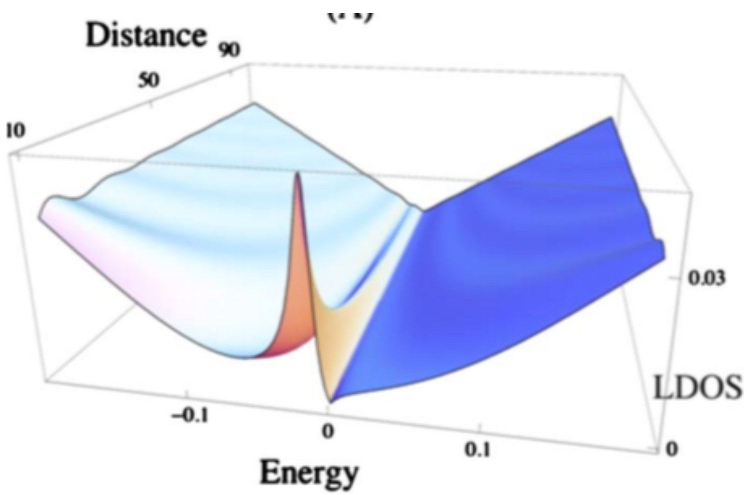
Fu PRL 2008, LAW Nat. Phys. 2010

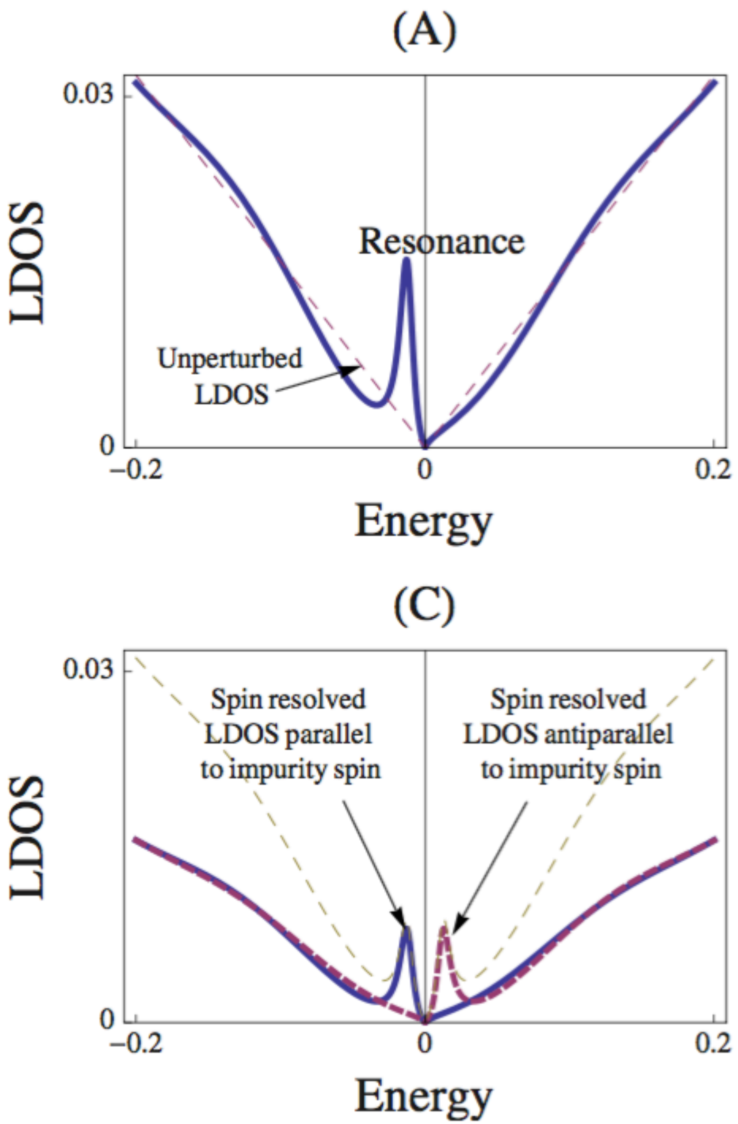
J. Checkelsky, Nat. Phys. 2012; News and Views by LAW

② The theory of in-gap states

$$\mathcal{H}_0 = \boldsymbol{\sigma} \cdot \boldsymbol{p}$$

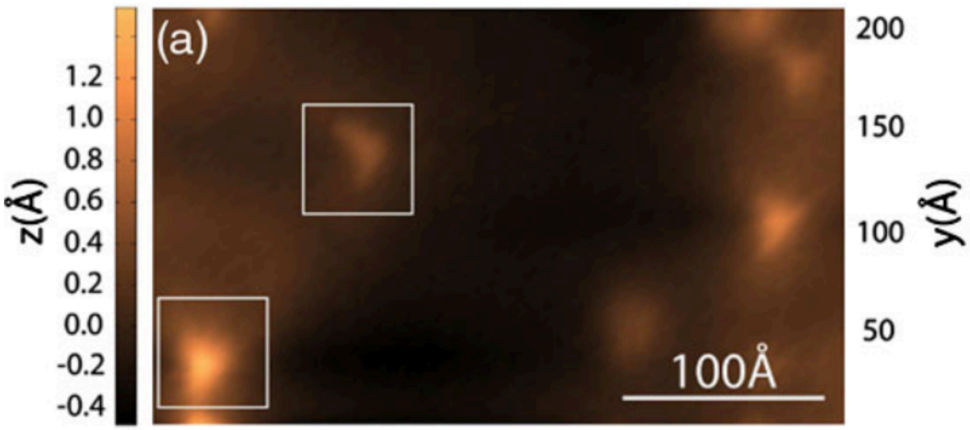
$$\hat{V}_{\text{pot}} = U\mathbb{I}\delta(\hat{\boldsymbol{r}}), \quad \hat{V}_{\text{mag}} = U\boldsymbol{S} \cdot \boldsymbol{\sigma}\delta(\hat{\boldsymbol{r}})$$

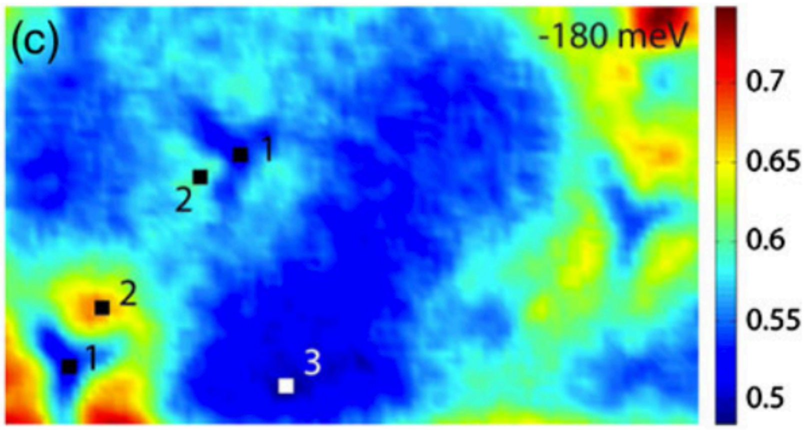




Biswas and Balatsky PRB 81, 233405 (2010)
See also work by A. Black-Schaffer and D. Yudin

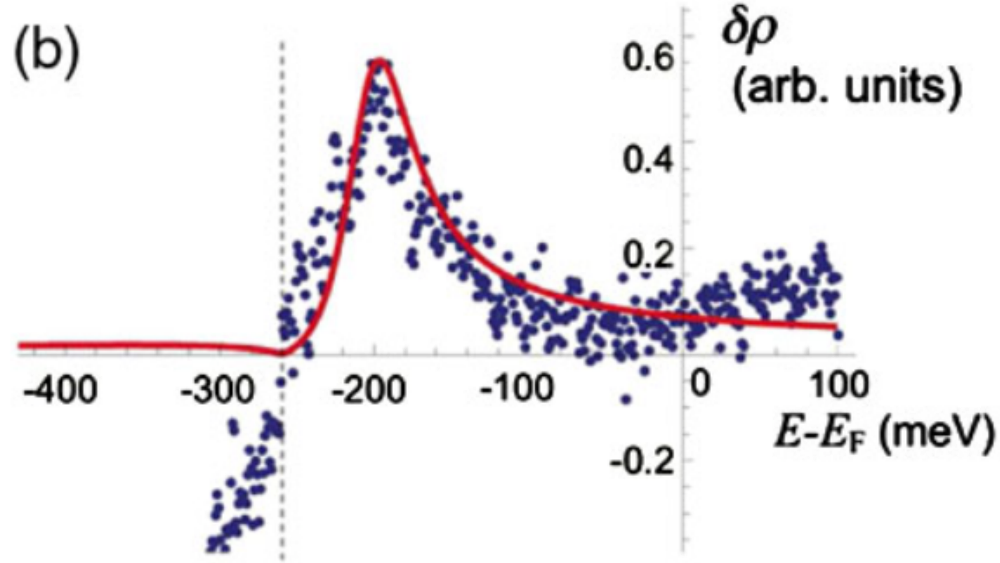
In-gap states "in practice"





Alpichshev, Biswas, Kaptiulnik PRL 2012

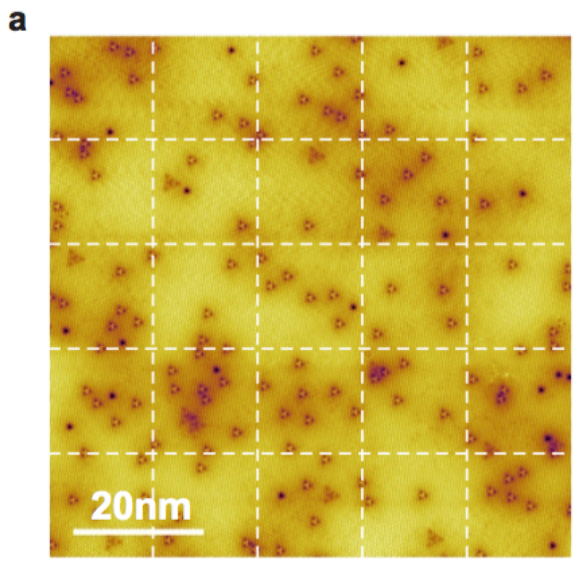
Local density of states:

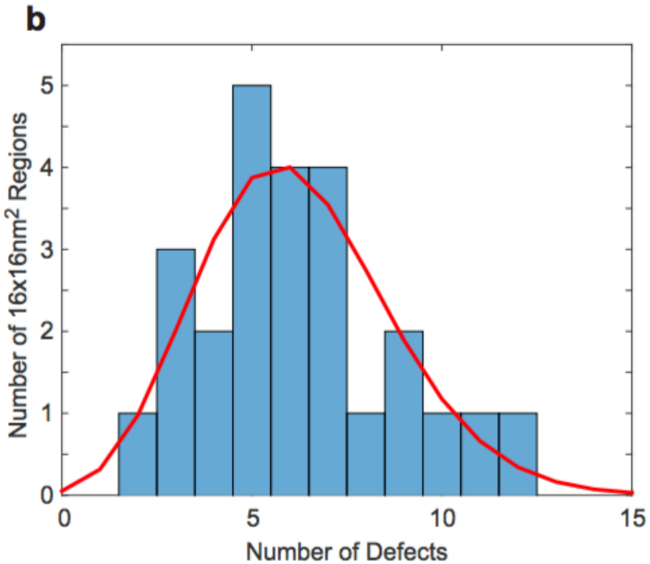


Is more different? (past experiments)

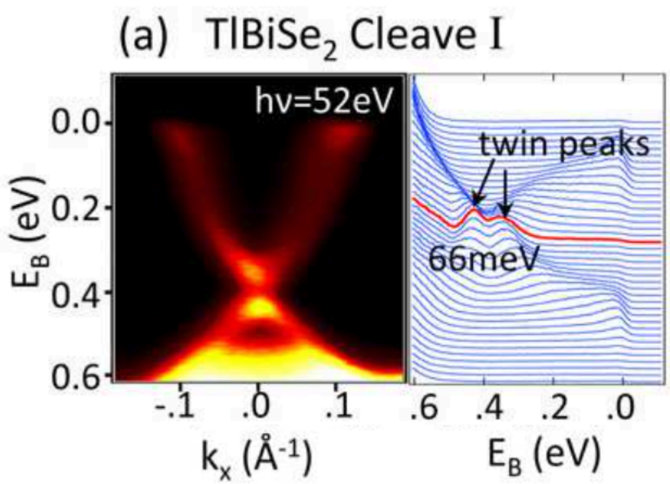
Selenium vacancies:
($Bi_2Se_{3-\delta}$)

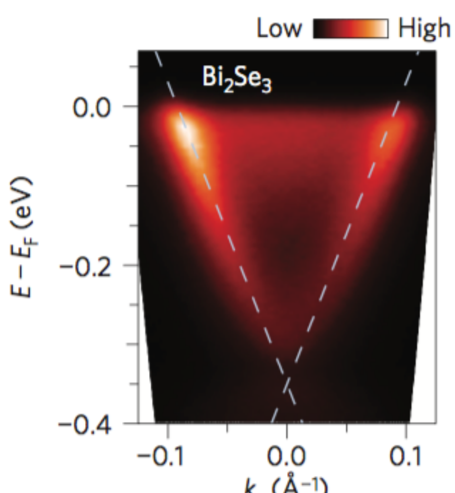
But real defect densities rarely exceed $N_d/N=0.001$!!!!!





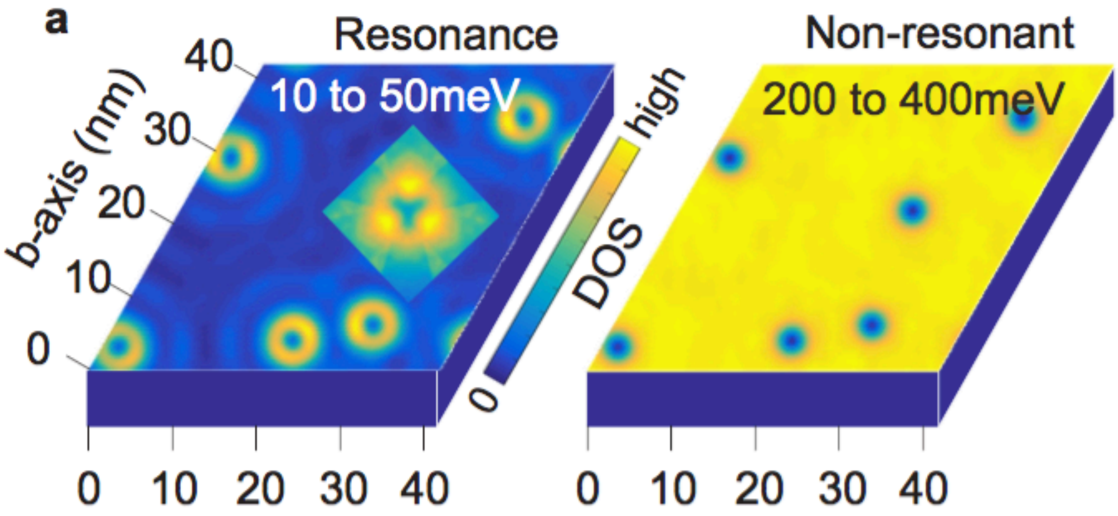
ARPES oddities:

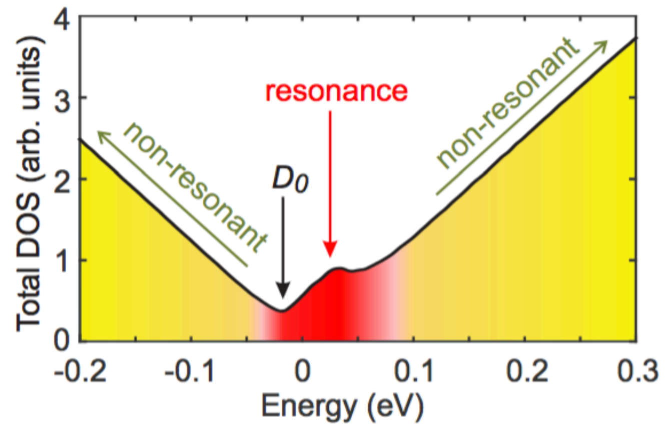




Jozwiak Nat. Phys. 2013

Is more different? (theory)



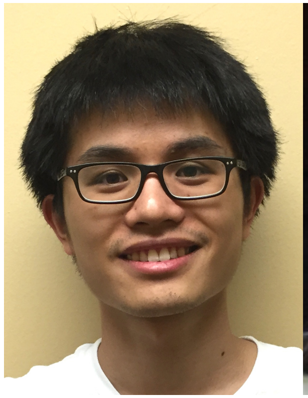


Xu, Chiu, Miao, Alpichshev, Kapitulnik, Biswas, LAW, Nat. Comm. 2017

These look like semiconductor impurity states, but...

(1) Why do they show up in total DOS, with $N_d/N=0.0006$?!

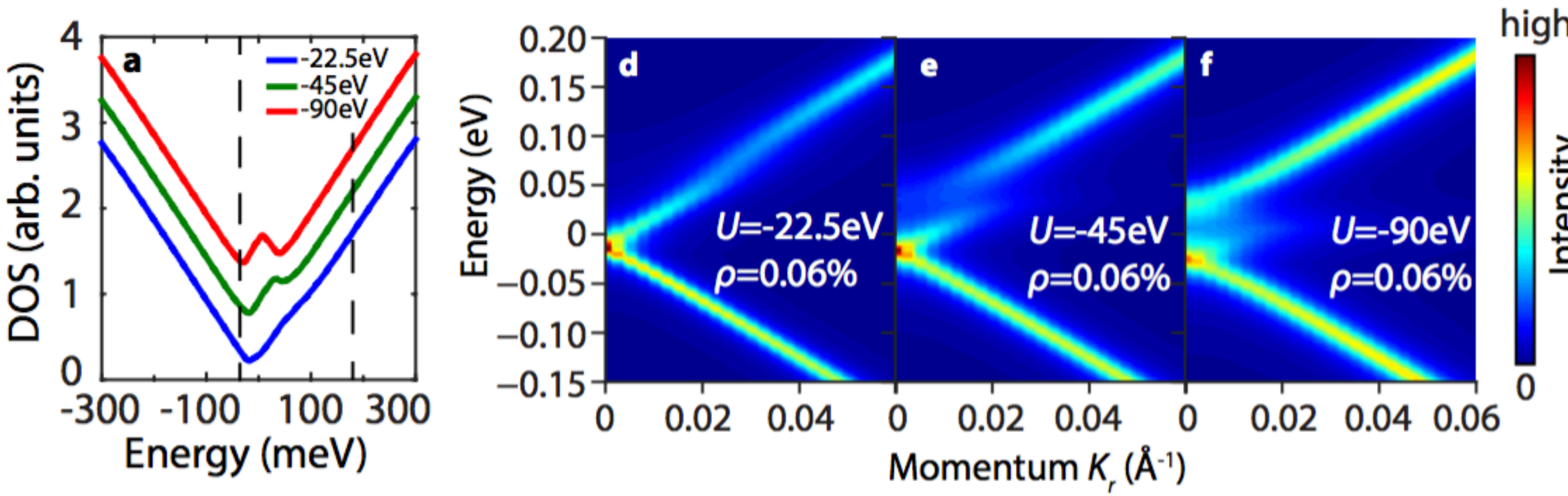
(2) Theoretically, they can't be localized?!



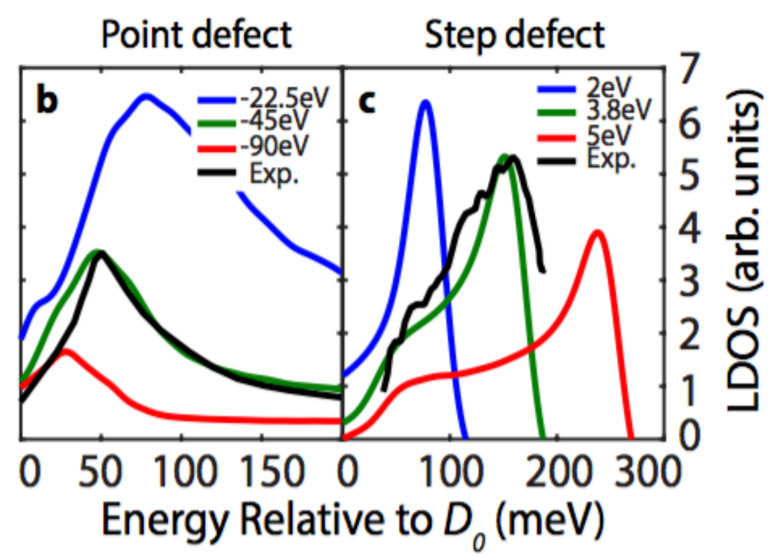
Yishuai Xu

Janet Chiu

What are the k-space implications?

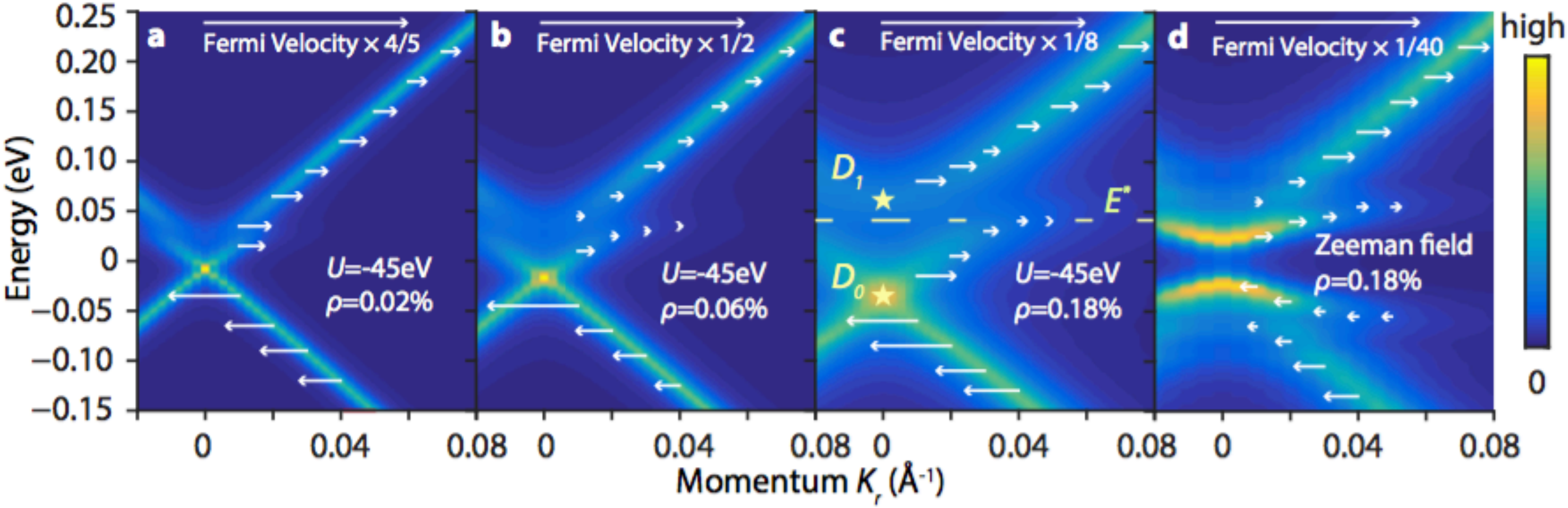


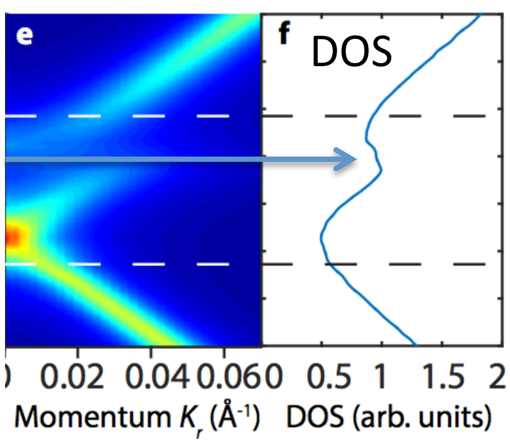
Does the theory still work?



A “Non-Topological” Quasiparticle?

To see this, you want 100nm + ~20meV resolution





A) Not a real gap (and no Luttinger theorem).

B) The constraints from band topology are also an open question.

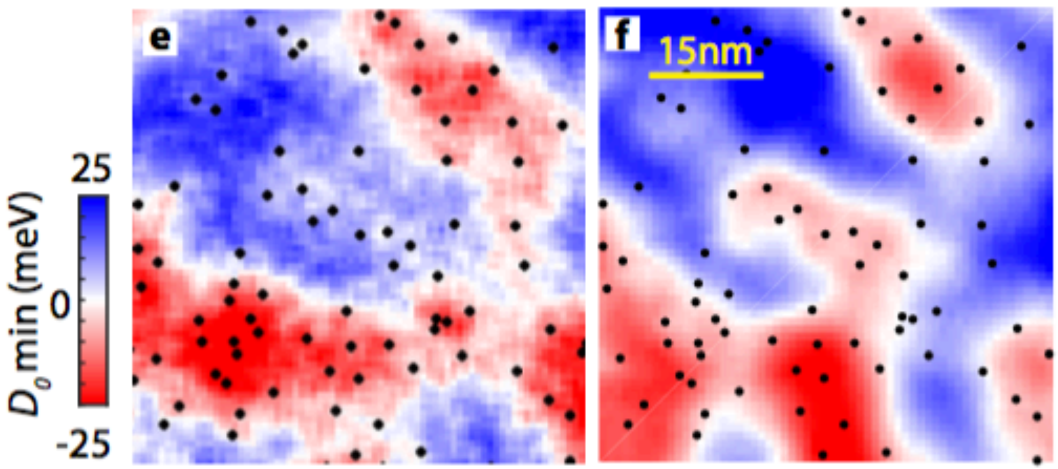
Twist velocity:

$$\mathbf{v}_\theta(\alpha) = \nabla_{\mathbf{K}_\theta} E_\alpha$$

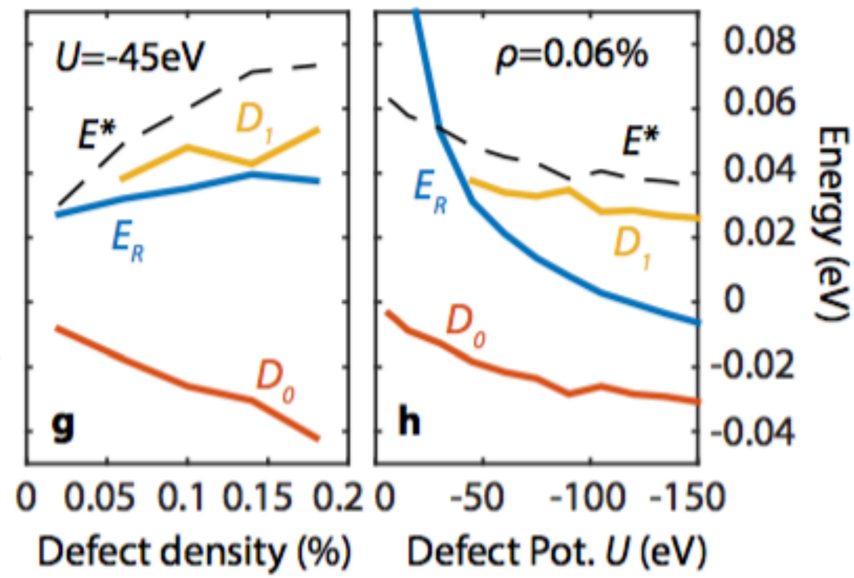
$$\mathbf{K}_\theta = \theta_x / L_x \hat{\mathbf{k}}_\mathbf{x} + \theta_y / L_y \hat{\mathbf{k}}_\mathbf{y}$$

What new principles does this bring into play?

To see *this*, you want 20nm resolution



STM from **Weida Wu** group (see Dai PRL **117**, 106401 [2016])



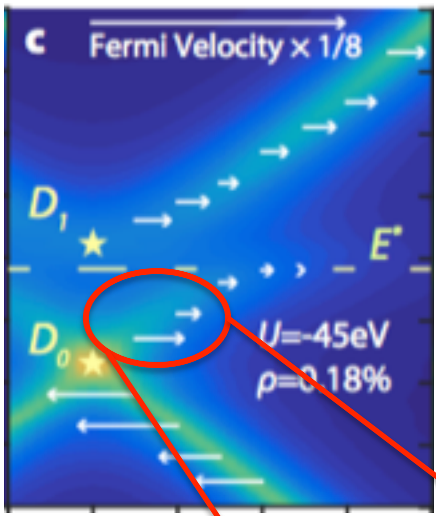
But! this defect density (~0.19%) has not been achieved in large single crystals!

$$N_E = \frac{\sqrt{3}a^2 N E^2}{4\pi {v_0}^2}$$

$$N_E = N_R \equiv 2\rho N$$

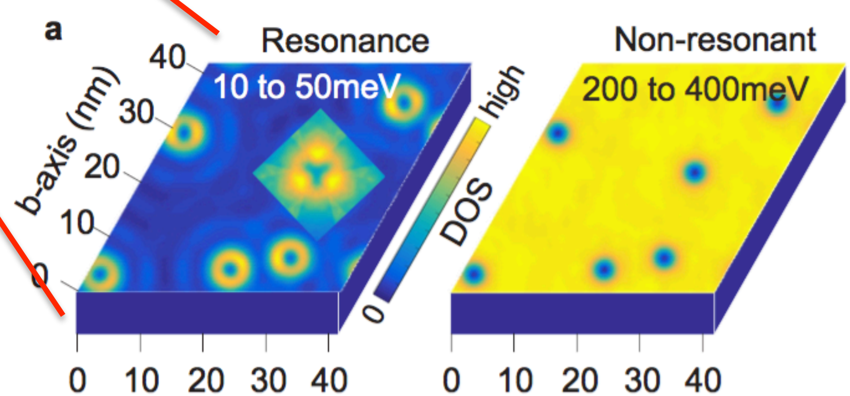
Density Threshold: $$E^* = \sqrt{\frac{8\pi {v_0}^2 \rho}{\sqrt{3}a^2}}$$

A Quasiparticle Without Translational Symmetry?

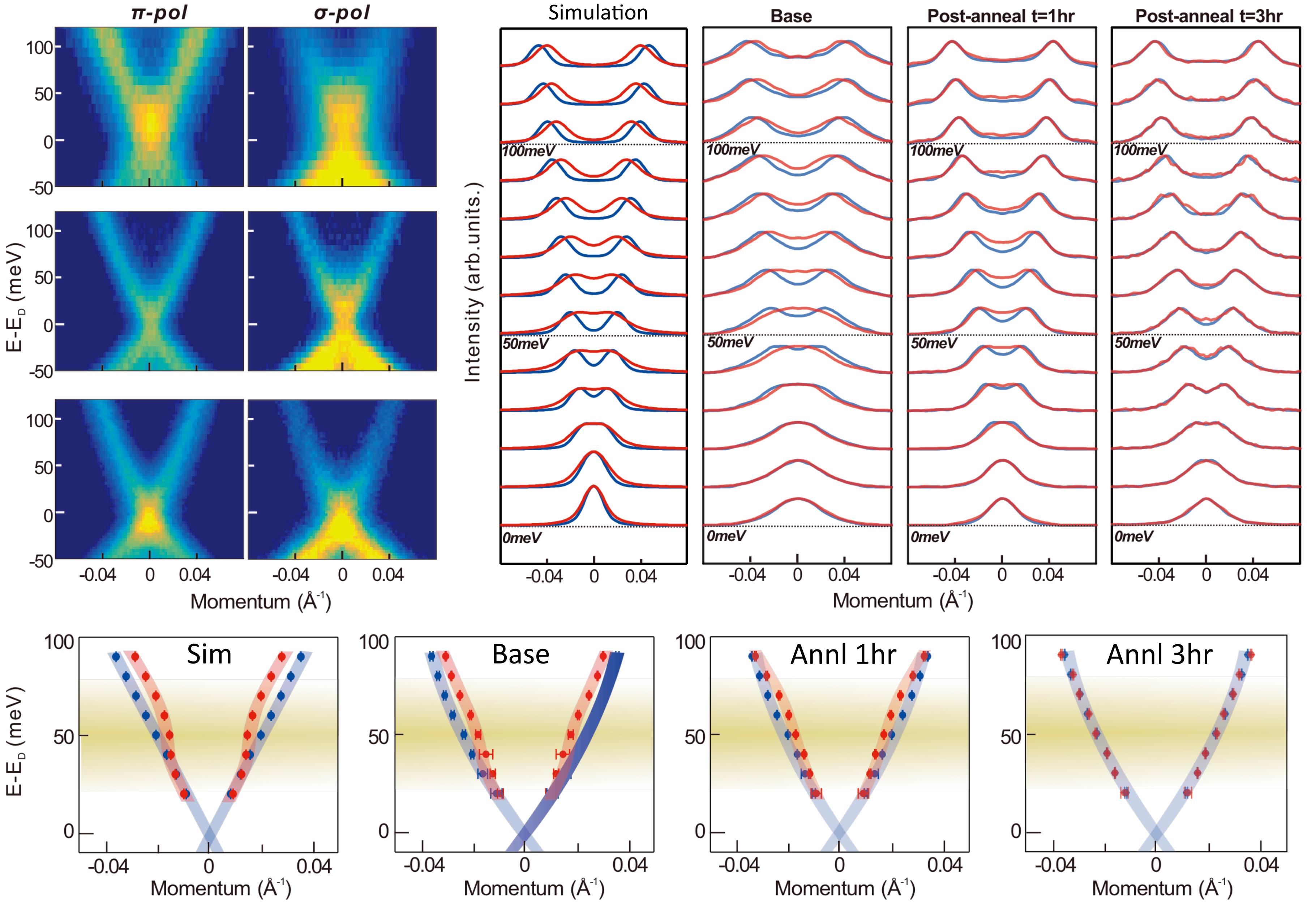


$$\mathbf{T}(x)=\exp(-ix\mathbf{P}/\hbar)$$

Normal states are either (near-) eigenstates of *both* translation (**T**) and momentum (**B**) symmetry, or *neither.*



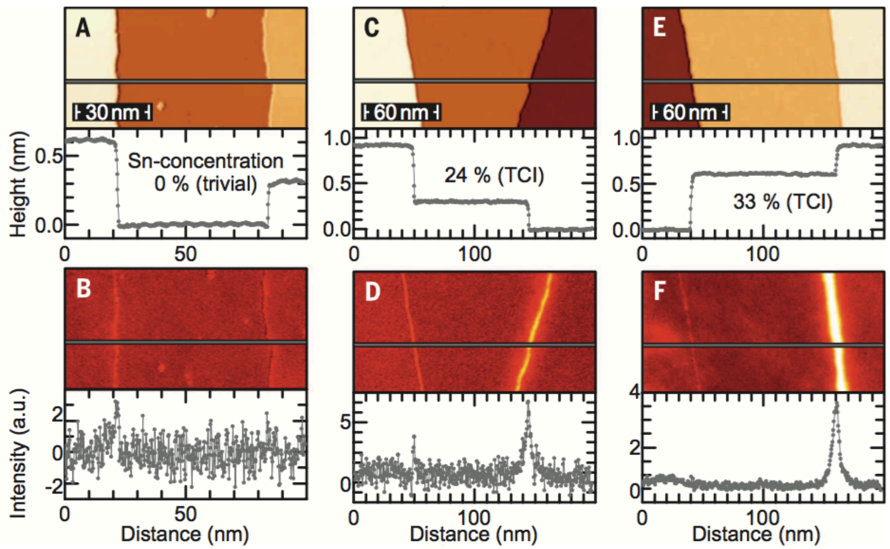
Post-Growth Sample Tuning



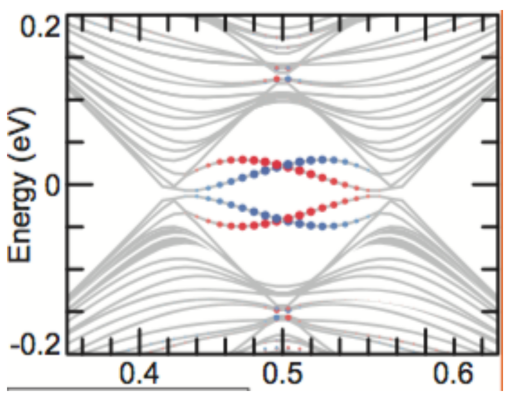
L. Miao, LAW, accepted for publication in Nature Partner Journals: Quantum Materials

③ Surface steps: on the edge of 'topological'

(semi-)topological T**C**I edge states

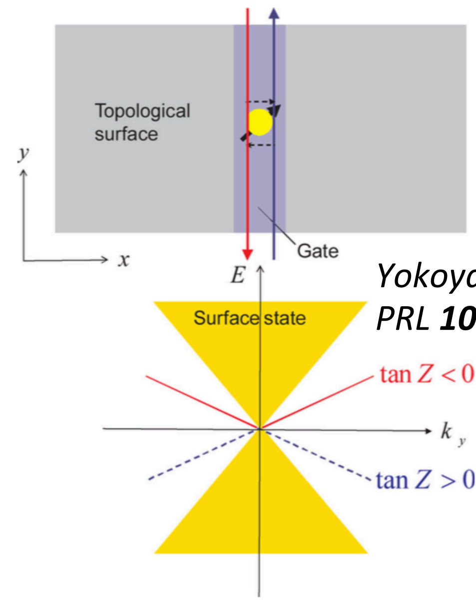


An even-odd 1D topological distinction unique to TCI

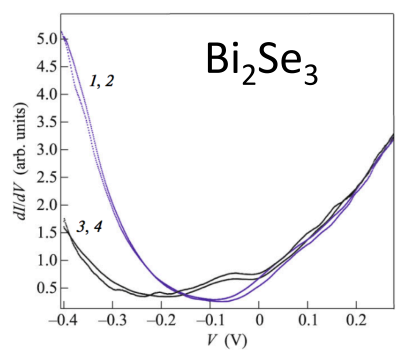


*Sessi et al, Science **354**, 1269 (2016)*

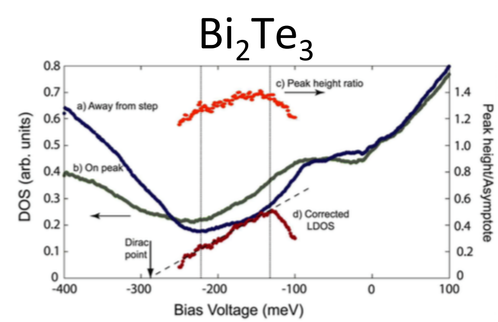
Dirac-connected states beneath a delta function potential



*Yokoyama, Balatsky, Nagaosa, PRL **104**, 246806 (2010)*

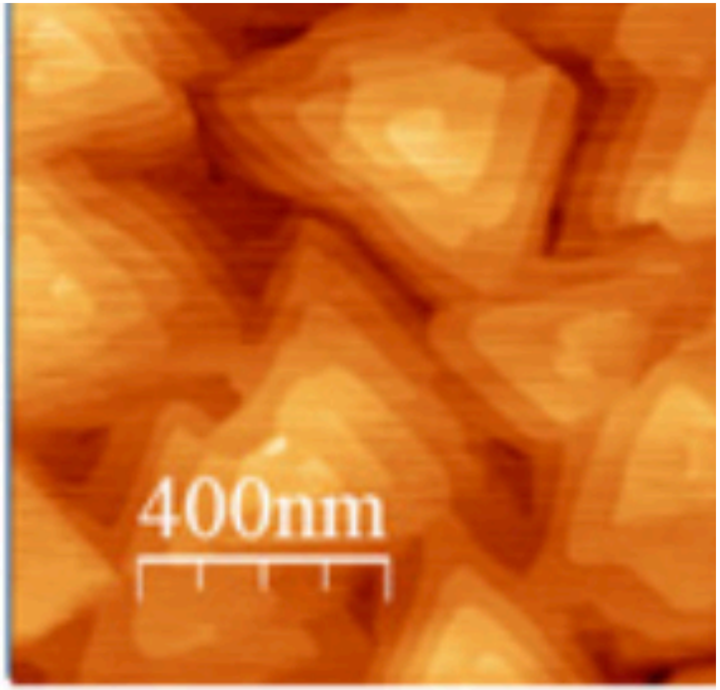


*Dmitriev, JETP Letters, **100**, 398 (2014)*

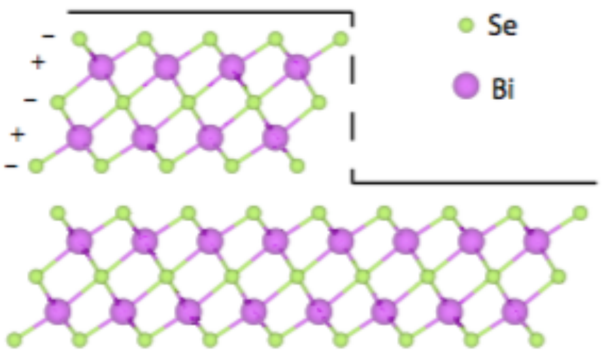


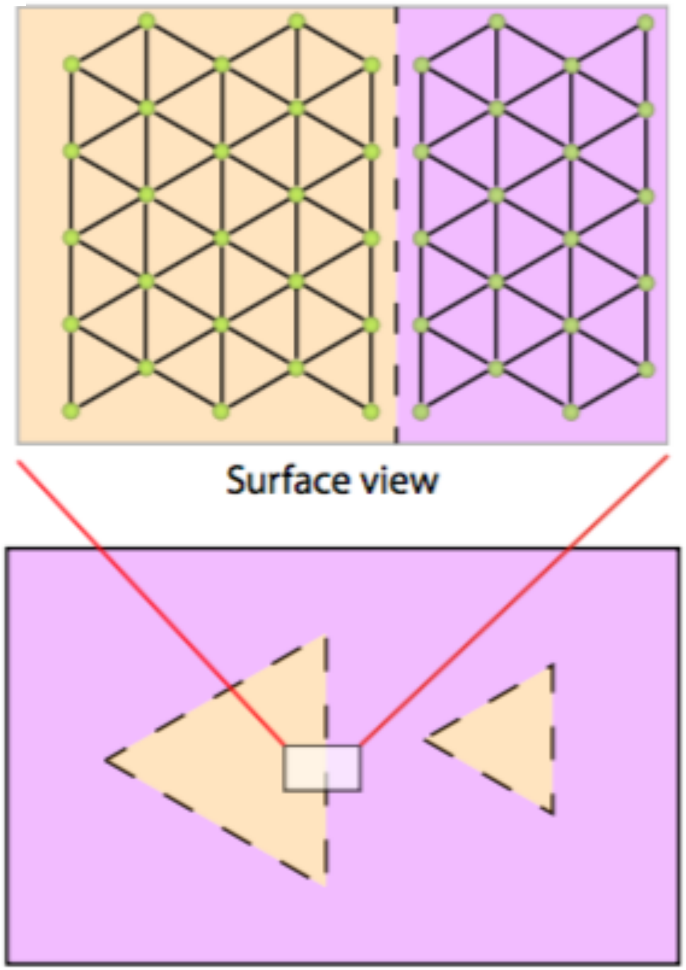
Alpischev, Kapitulnik PRB 84, 041104 (2011)

Step edges on Bi_2Se_3

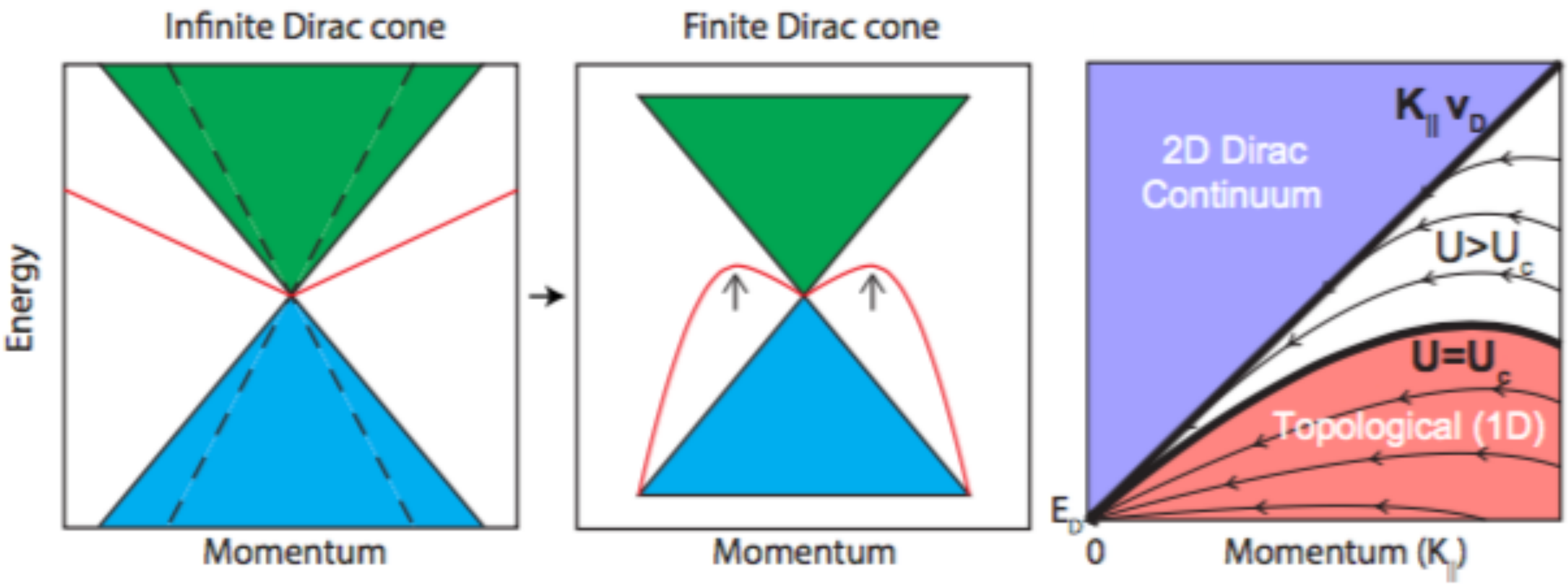


Teague et al., Solid State Comm. 152, 747 (2012)





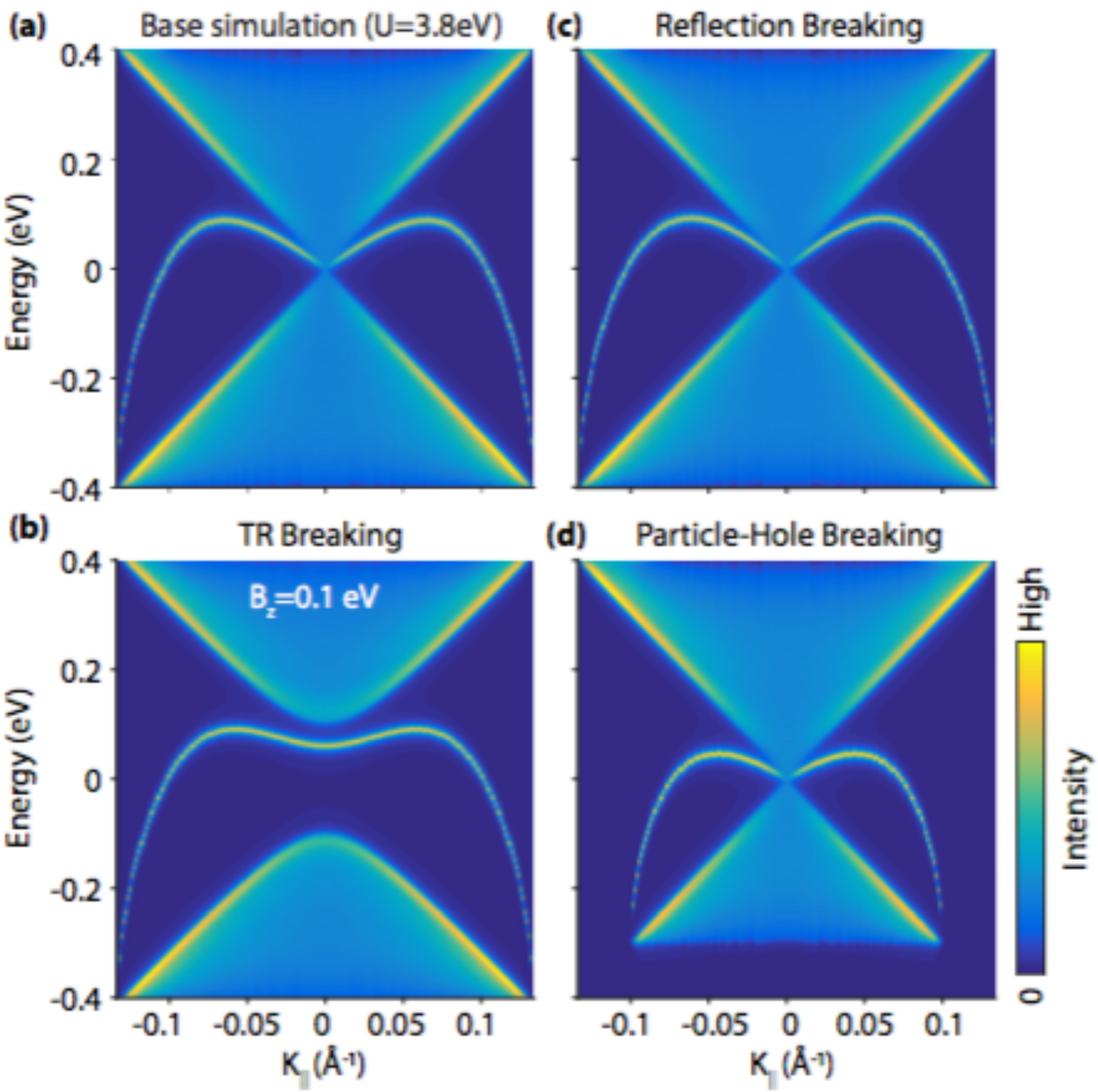
(anti-)Bound states of a 2D Weyl cone



$$H_T = v_D(\mathbf{k} \times \boldsymbol{\sigma})$$

Y. Xu, R. Biswas, LAW, submitted to N. J. Phys. 2018

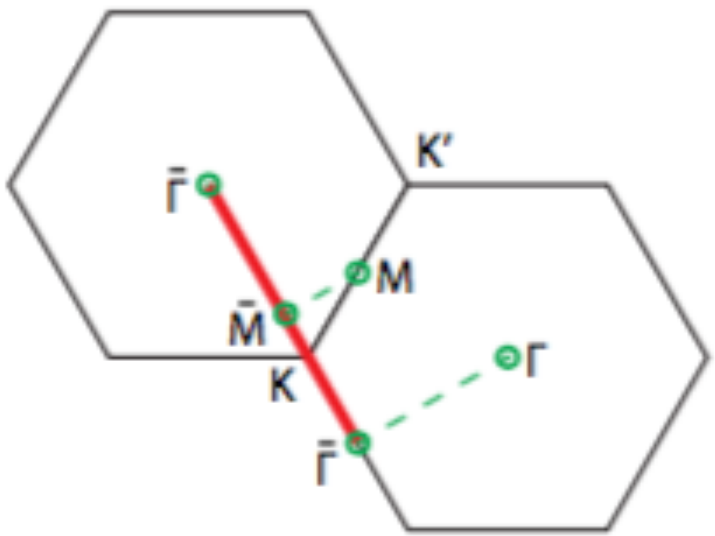
Symmetry protection

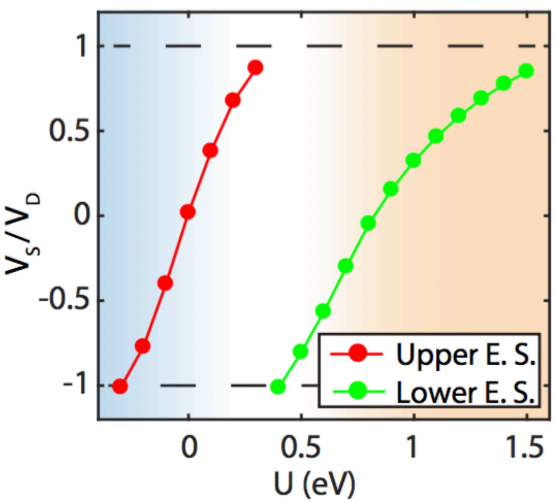


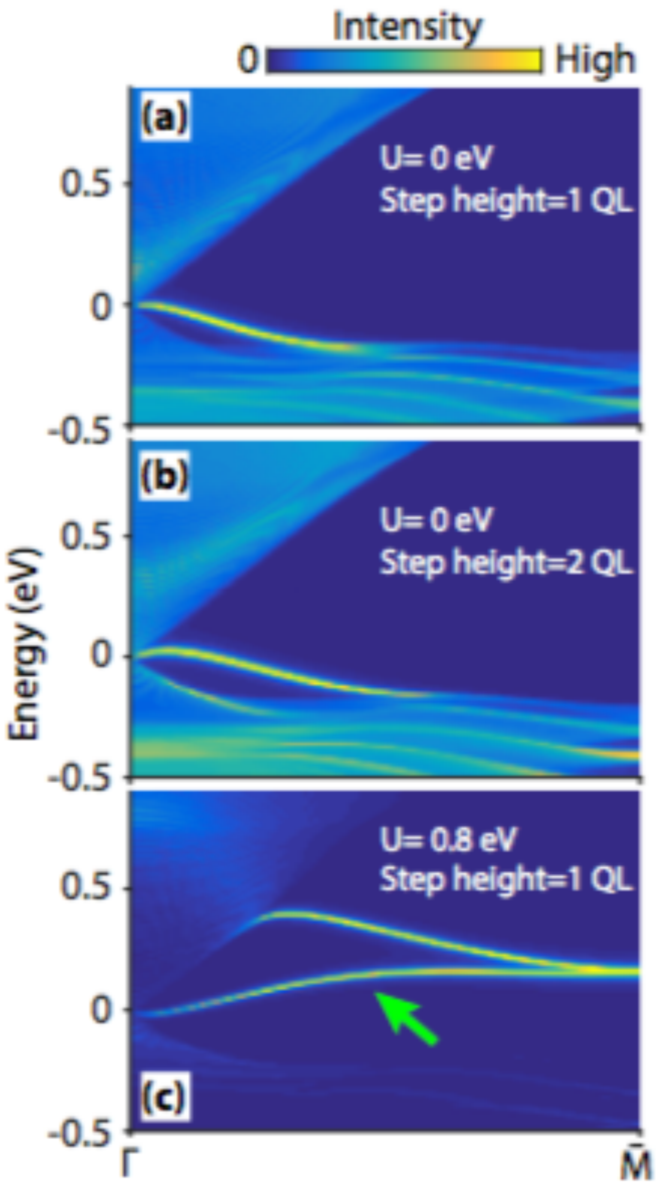
$$H_T = v_D(\mathbf{k} \times \boldsymbol{\sigma})$$

$$H_U = U \sum_{\alpha} n_{\alpha}$$

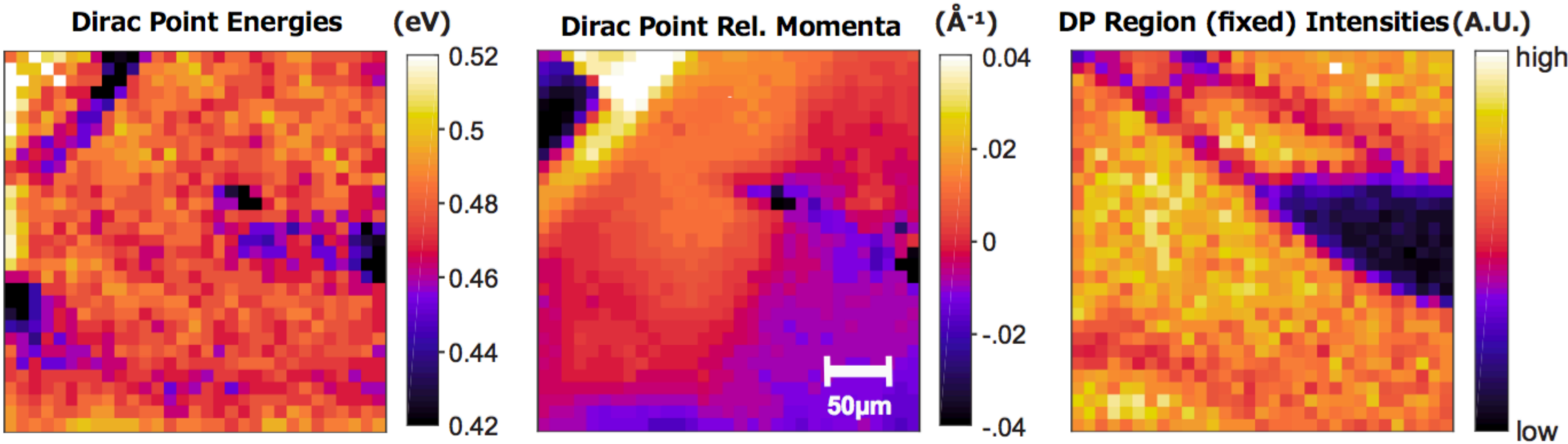
A universal phenomenon?







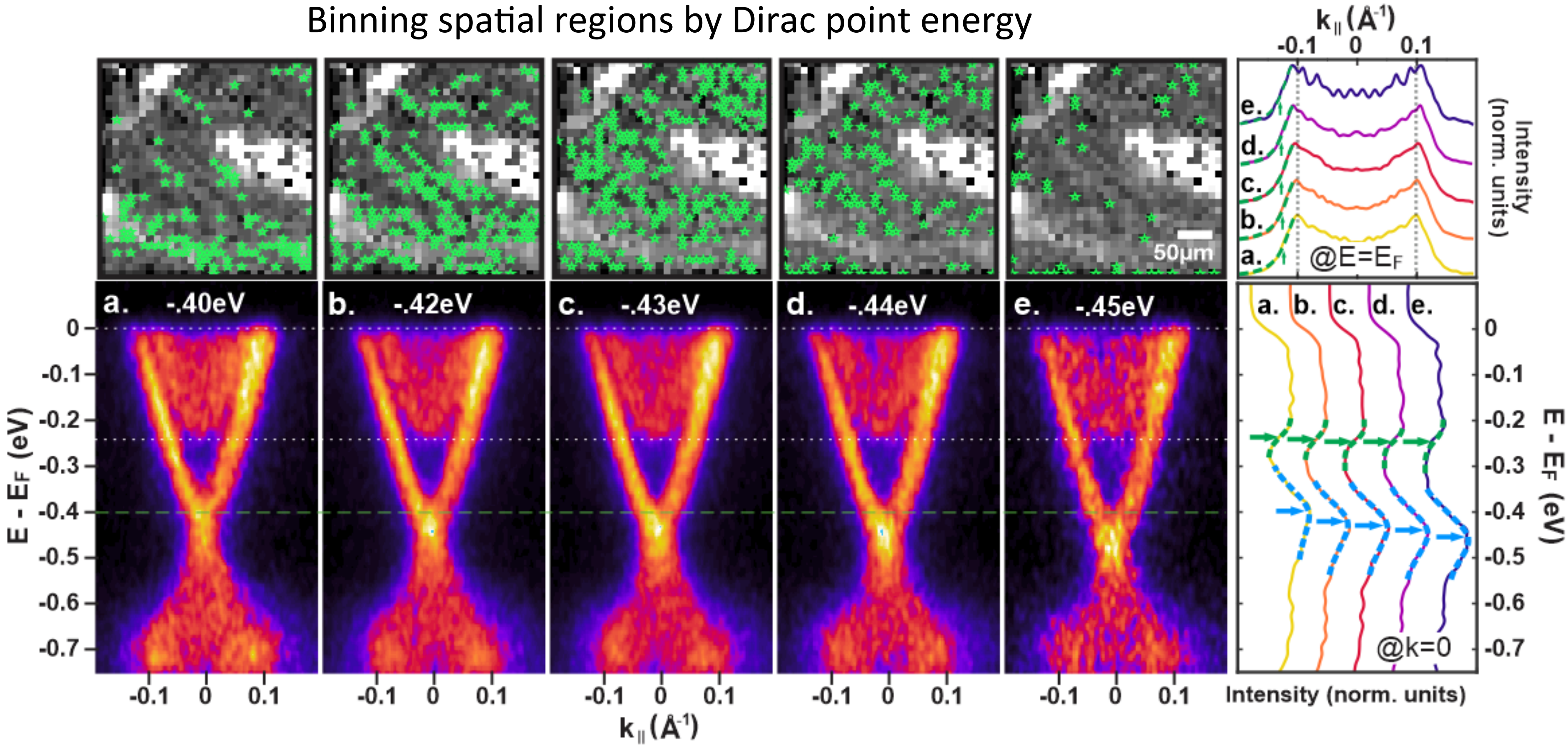
micro-ARPES: a step into the future



30 minute ALS MAESTRO image, April 2017

Anisotropy ~ structural control

Binning spatial regions by Dirac point energy



- What are the causal relationships between different elements of crystallographic and electronic structure?
- Nano-ARPES is also possible! (100 nm beam spot at ALS MAESTRO)

The Quasiparticle is the Device?

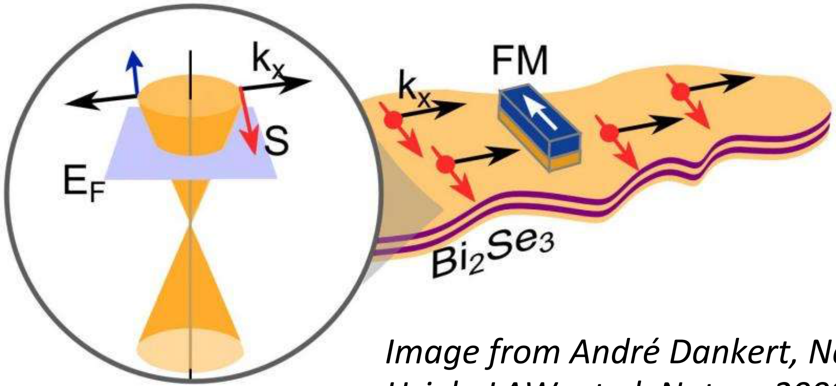
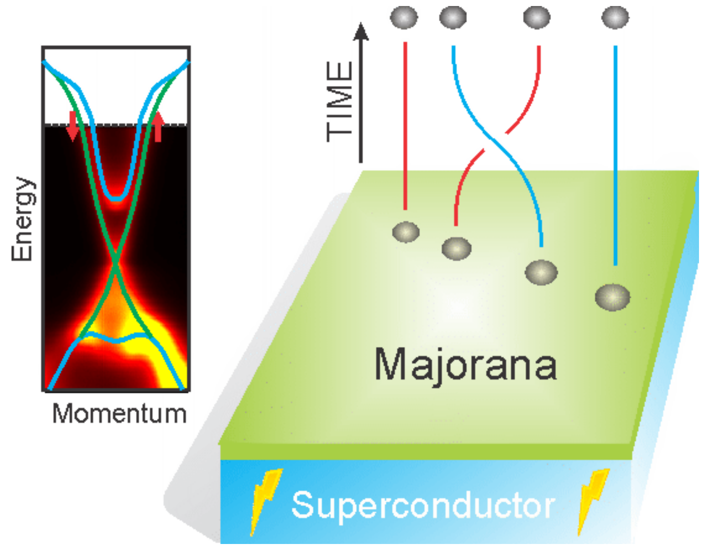
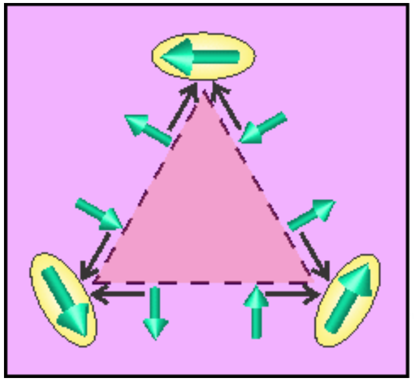


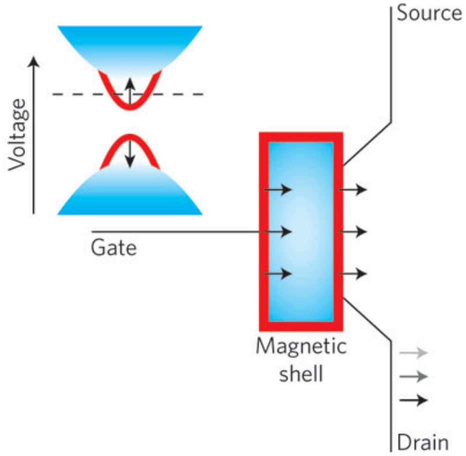
Image from André Dankert, Nano Letters
Hsieh, LAW, et al, Nature 2009 X2
A. R. Mellnik et al, Science 2014
Y. Fan et al, Nature Materials 2014



Fu PRL 2008,
LAW et al, Nat. Phys. 2010



Terrace corner spin moments
Y. Xu, R. Biswas, LAW,
submitted to N. J. Phys. 2018

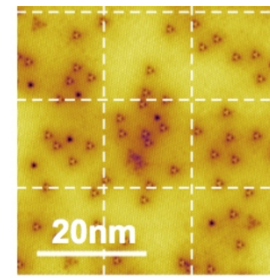


"Topological Transistor,"
LAW Nat. Phys. 2012

Overview

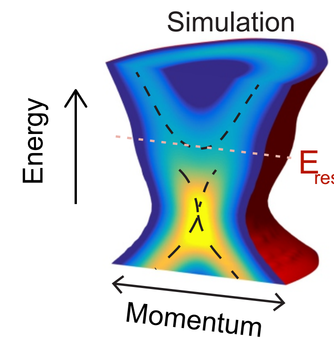
Topological order opens up new realms of possibility, such as

- TO+Gating: "Giant" zig-zag Rashba splitting
- TO+Disorder or Structure: New transport channels!
- TO+superconductivity: Quantum computing
- TO+magnetism: new transistors, 1-way nanowires, and quasiparticles



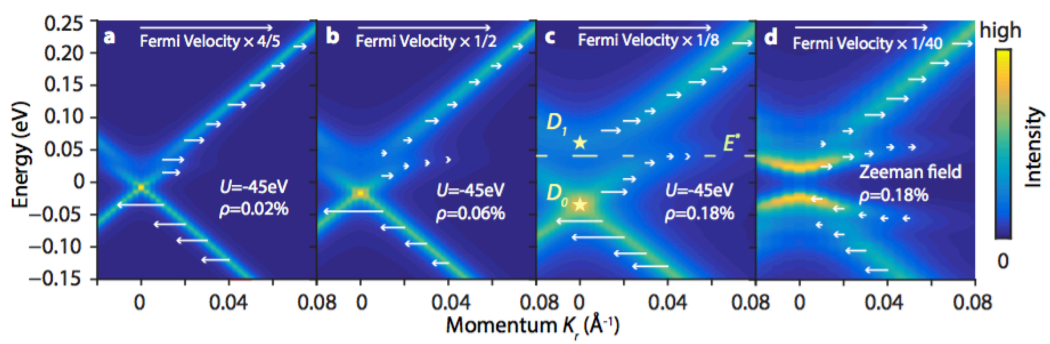
Disorder brings about changes to real space and momentum space

- Particle-like states that profoundly lack translational symmetry
- An emergent band-like feature that supports diffusive transport
- A gap-like feature (without a density of states dip)



Line-like defects act as spin-polarized wires

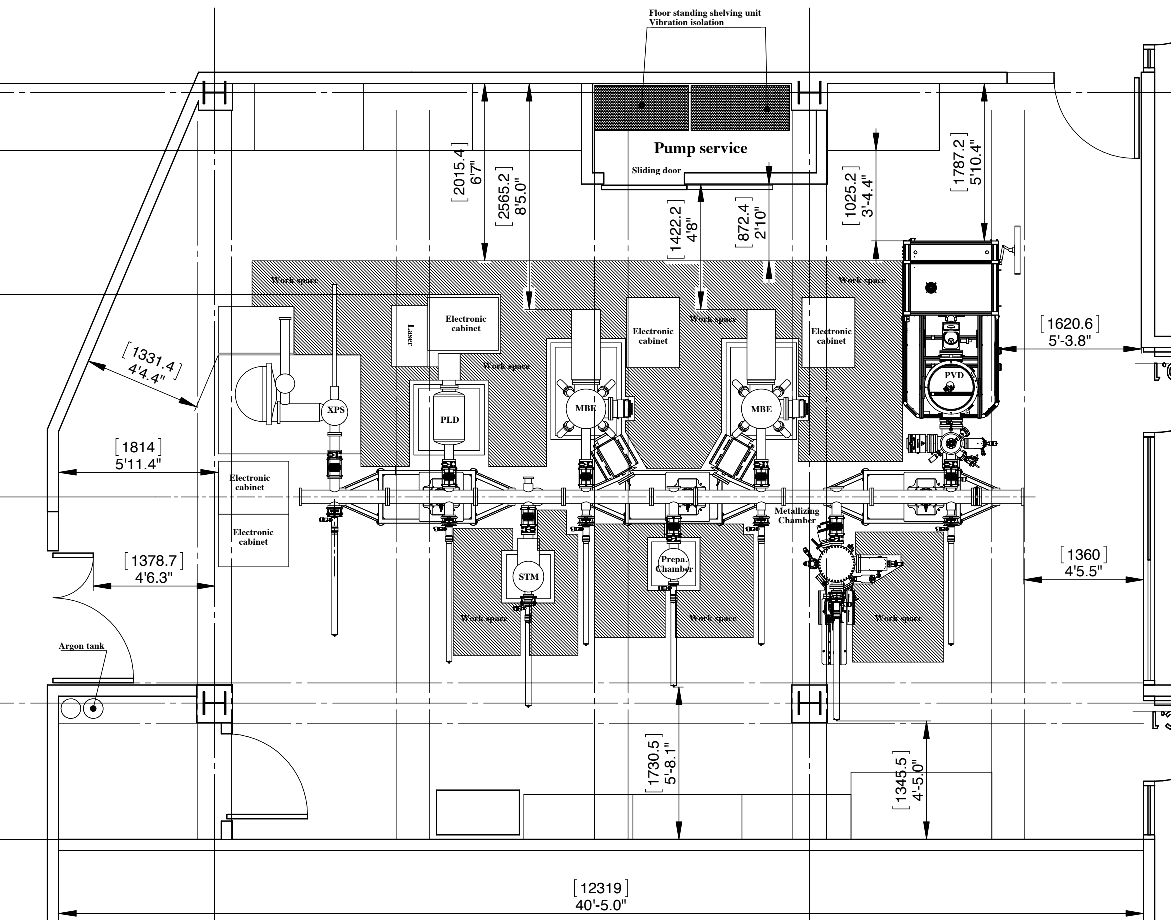
- 1D 'wire' states connect to the 2D Dirac point
- Surface step edges are sufficient to bind these states
- Transport is protected from scattering, similar to spin-Hall edge states



Towards the Next Generation of Quantum Materials

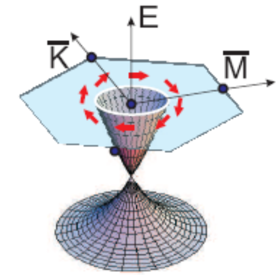
Unique heterostructure synthesis capabilities

- MBE, PLD and PVD *in situ* growth systems
- Single atom Se_1 and O_1 sources
- Low temperature MBE
- PVD/PLD high pressure RHEED



Powerful single-electron analysis

- Small-spot ARPES (<2meV resolution!)
- STM/AFM imaging
- XPS and real-time Auger



PIs:

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Paul Chaikin

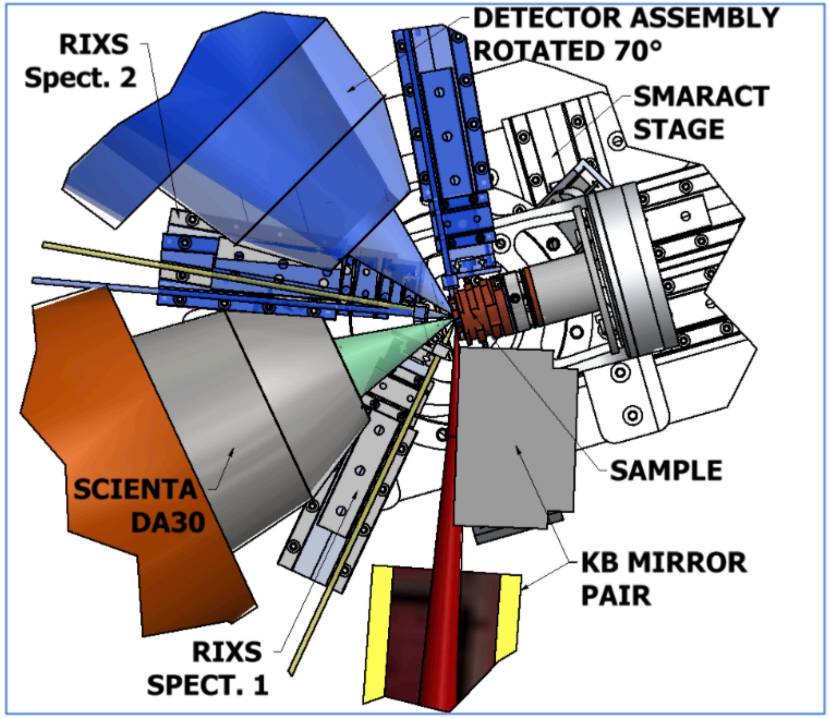
CQP Center for Quantum Phenomena

Gordon and Betty MOORE FOUNDATION

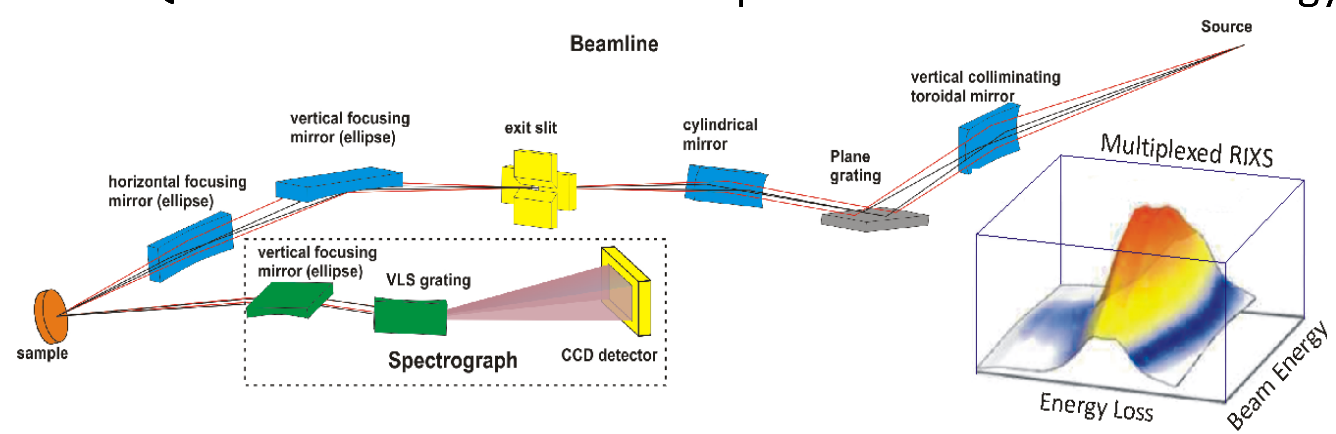
NSF

…and New Dimensions of Spectroscopic Study

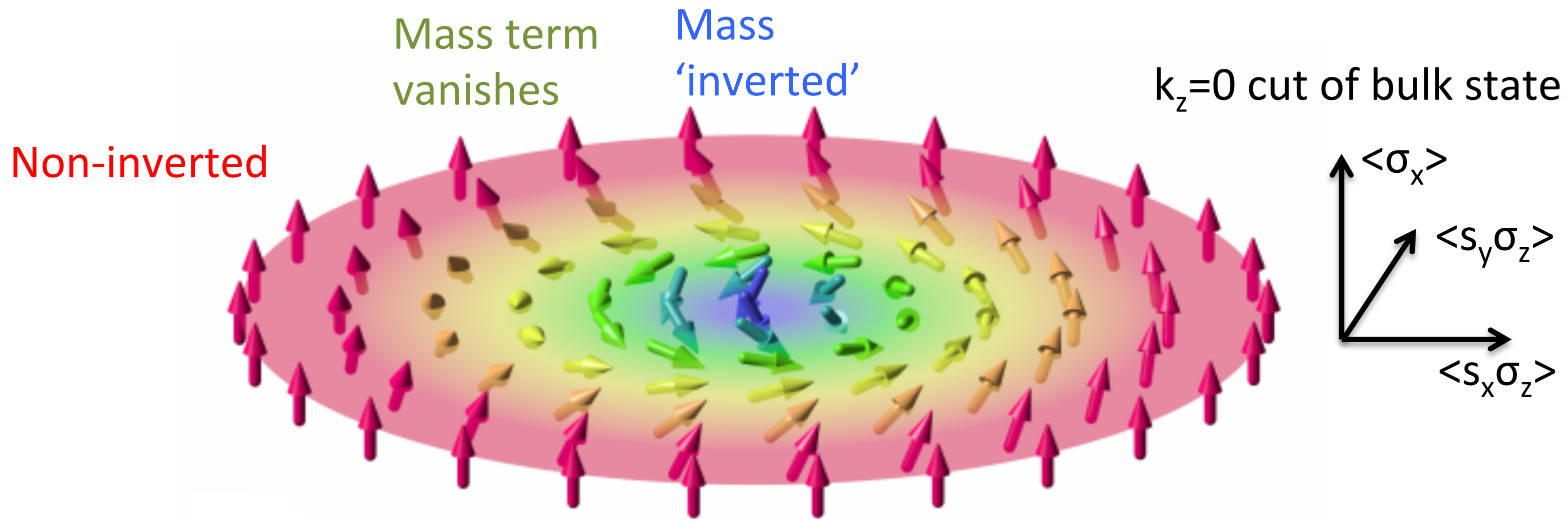
The **ARI beamline** design proposed for NSLS-II offers 100nm resolution *from mirror optics* for **ARPES** and **RIXS**



The ALS **QERLIN RIXS beamline** will map an extra dimension of energy



The simplest TI bulk picture:



k_z=0 momentum plane Γ-matrix expectation values

Near the BZ center:

$$H_0(\mathbf{k}) = m\sigma_x + v(k_x\sigma_z s_y - k_y\sigma_z s_x) + v_z k_z \sigma_y$$

orbital x (mass) spinful orbital z orbital y (this term is debated)

At larger momenta, the mass (parity) term flips sign. The spinful orbital term turns spin chirality into a good quantum number.

Alternatively: $H_0 = m\Gamma_0 + v(k_x\Gamma_1 + k_y\Gamma_2) + v_z k_z \Gamma_3$

Where could you find this kind of basis/model?
*Leading answers come from **Haldane, Kane & Mele**, **S-C Zhang**, **R. Cava** and **M. Z. Hasan/H. Lin**)*

Liang Fu and Erez Berg
Phys. Rev. Lett. **105**, 097001 – Published 23 August 2010

NATURE PHYSICS | NEWS AND VIEWS

Device Physics: Topological transistor

L. Andrew Wray

Nature Physics 8, 705–706 (2012) | doi:10.1038/nphys2410
Published online 19 August 2012

NATURE PHYSICS | RESEARCH HIGHLIGHTS

Topological transistor

Luke Fleet

Nature Physics 11, 5 (2015) | doi:10.1038/nphys3217
Published online 23 December 2014

PRL 112, 226801 (2014) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2014

Enhanced Thermoelectric Performance and Anomalous Seebeck Effects in Topological Insulators

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(Received 5 February 2014; published 2 June 2014)

SCIENTIFIC REPORTS

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Quantum strain sensor with a topological insulator HgTe quantum dot

SUBJECT AREAS:
QUANTUM DOTS
SENSORS AND BIOSENSORS
TOPOLOGICAL INSULATORS

Marek Korkusinski & Pawel Hawrylak

Quantum Theory Group, Security and Disruptive Technologies Portfolio, Emerging Technologies Division, National Research Council, Ottawa, Canada K1A 0R6.

ACS APPLIED MATERIALS & INTERFACES Letter
www.acsami.org

High-Performance Bi_2Te_3-Based Topological Insulator Film Magnetic Field Detector

H. B. Zhang,...
[†]State Key Laboratory of Optoelectronic Materials and Technologies, Institute of Optoelectronic and Functional Composite Materials, Nanotechnology Research Center, School of Physics & Engineering, Sun Yat-sen University, Guangzhou, Guangdong 510275, P. R. China
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Applied Physics Express 4 (2011) 094201
DOI: 10.1143/APEX.4.094201

Topological Insulator Cell for Memory and Magnetic Sensor Applications

Takashi Fujita[1], Mansoor Bin Abdul Jalil..., and Seng Ghee Tan...
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Figure 1: Ultrafast photodetector based on topological insulators.

From
Ultrafast helicity control of surface currents in topological insulators with near-unity fidelity

Christoph Kastl, Christoph Karnetzky, Helmut Karl & Alexander W. Holleitner
Nature Communications 6, Article number: 6617 | doi:10.1038/ncomms7617

PHYSICAL REVIEW B 82, 245107 (2010)

Topological insulators for high-performance terahertz to infrared applications

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(Received 16 July 2010; published 8 December 2010)

Topological insulators in the Bi_2Se_3 family have an energy gap in the bulk and a gapless surface state consisting of a single Dirac cone. Low-frequency optical absorption due to the surface state is universally determined by the fine-structure constant. When the thickness of these three-dimensional topological insulators is reduced, they become quasi-two-dimensional insulators with enhanced absorbance. The two-dimensional

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Cite this: *J. Mater. Chem. C*, 2015, 3, 9154

Optoelectronic characteristics of a near infrared light photodetector based on a topological insulator Sb_2Te_3 film

Kun Zheng, ... Tong-Qiang Yu,[a] Rui Lu,[a] Huai-Li Qiu,[b] Zhong-Jun Li[b] and J. C. Andrew Huang*[bc]