Landau-level spectroscopy of helical Dirac fermions in a topological insulator Bi_2Se_3

RIKEN
Tetsuo Hanaguri

RIKEN M. Kawamura

U. Tokyo/RIKEN H. Takagi

Tokyo Inst. Tech. K. Igarashi
T. Sasagawa

Why STM?

Search for unusual electronic states

Breaking down "boring" materials

Detection ↓

- quantum structure
- interface
- impurity
- …

Microscopic properties

Electron Systems

Macroscopic properties

- superconductivity
- magnetism
- …

Emergence ↑

Building up "boring" electrons

Why STM is powerful?

- **Atomic spatial resolution**
  - ~0.1 nm laterally, ~pm vertically
  - local information is available
- **Momentum-space accessible**
  - FT-STS with large field of views
- **Very high energy resolution**
  - as high as ~μeV
- **Workable under extreme/variable environments**
  - high fields, low temperature, UHV…
  - can be used to study phase transitions

Powerful tool to explore the electronic states

Target specifications of spectroscopic STM

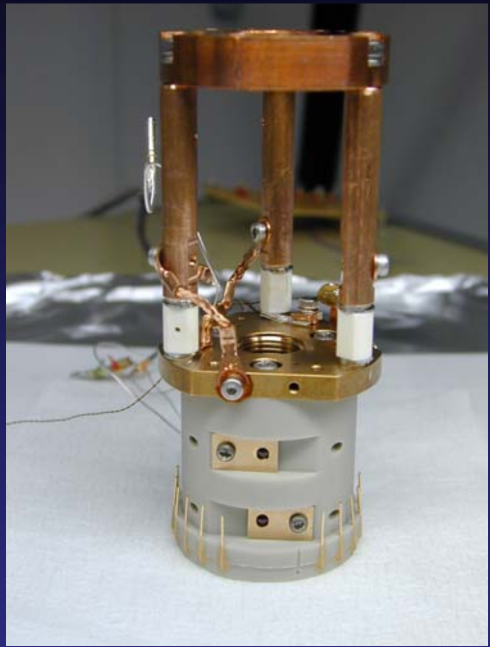
- **Ultra-high vacuum ~10^{-10} Torr**
  - to keep the surface clean for a long time
- **High magnetic field >10 T**
  - to control the spin, orbital and phase
- **Very-low temperature <1 K**
  - to reduce the thermal broadening (1 K ~ 0.1 meV)

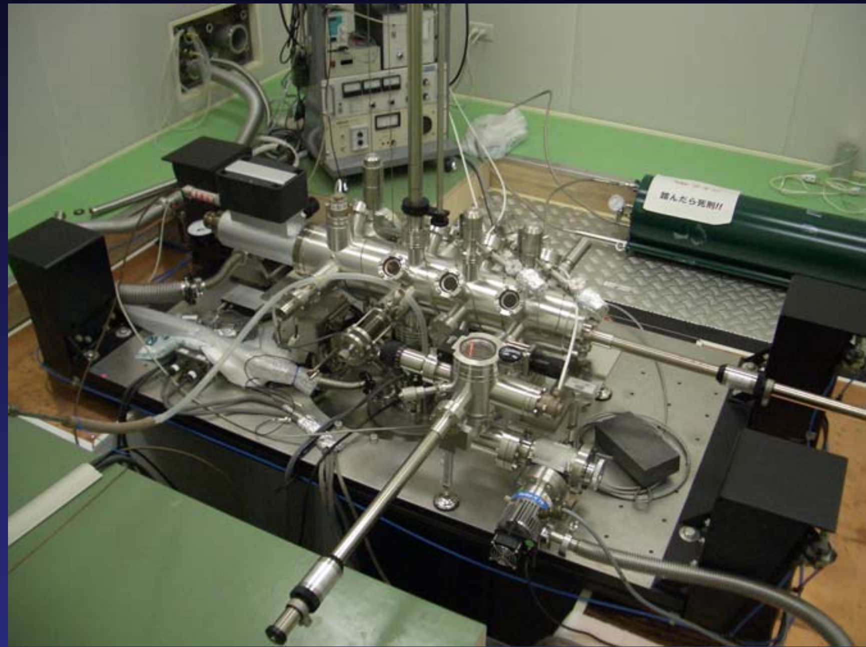
    Mott gap : ~ eV
    SC gap (HTSC) : ~10 meV
    Impurity resonances : ~1 meV
    Zeeman energy : ~ 0.06 meV/T

- **Variable temperature**
- **Long-term stability**
  - 256 × 256 pts, 2 sec/pt, → **36 hours**

RIKEN multi-extreme STM (based on UNISOKU USM-1300)

T. Hanaguri, J. Phys.: Conf. Ser. **51**,514 (2006).



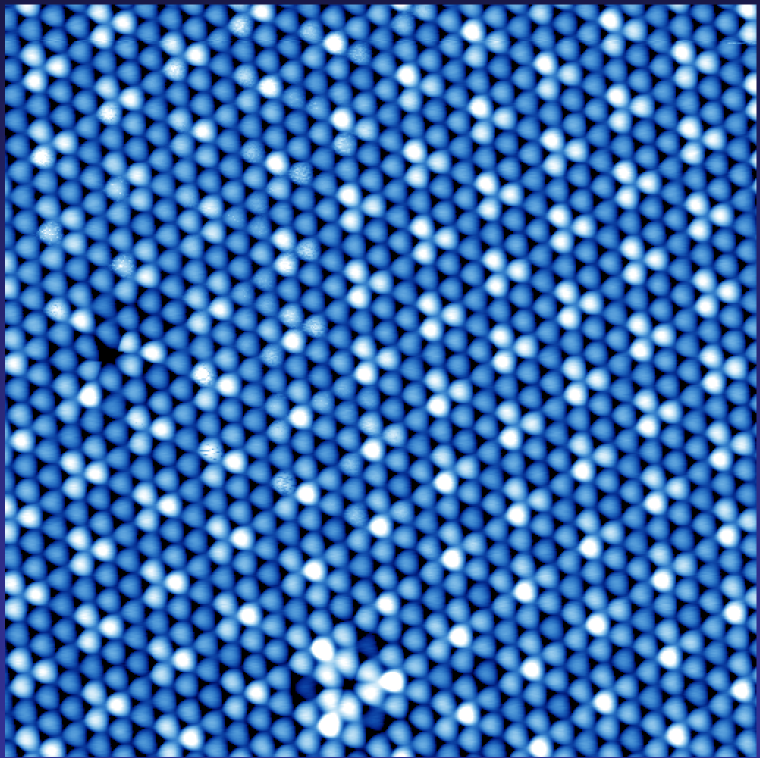


- Very-low and variable temp. (400 mK – 60 K)
- High field (11 T), UHV (~10^{-10} Torr)
- *In-situ* tip/sample exchange (resonant freq. 5.5 kHz)
- Atomically controlled tip sharpening by FIM
- Noise levels (1 kHz BW) < 0.5 pm, 1 pA

Performance tests

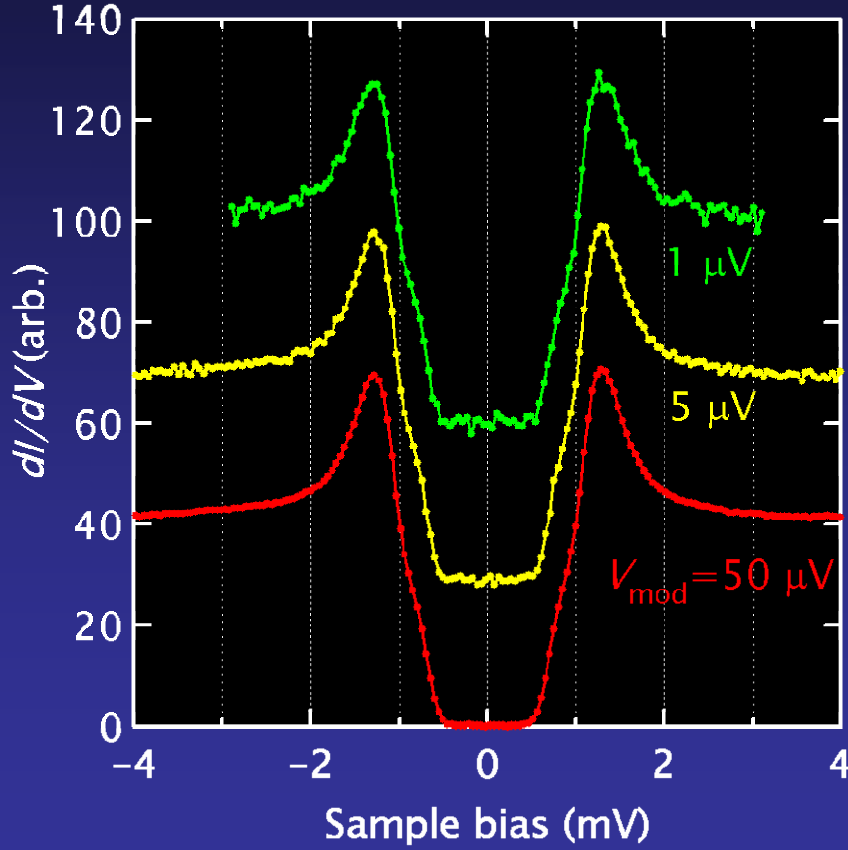
$NbSe_2$ $\quad T_c = 7.1$ K, $T_{CDW} = 29$ K

T ~ 1.5 K



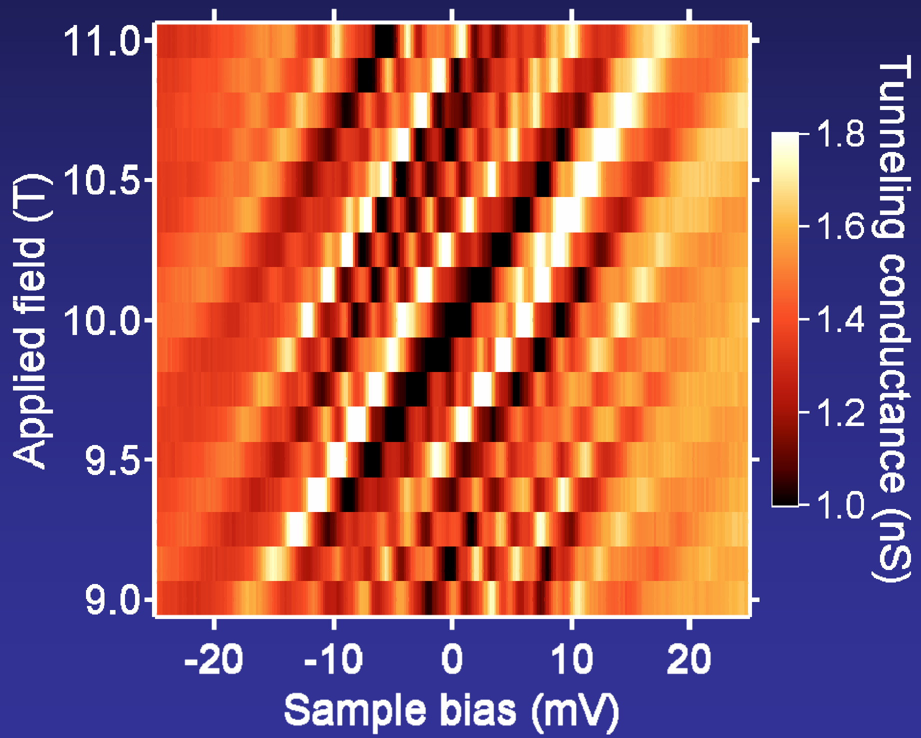
10 nm × 10 nm, +50 mV/0.1 nA

T ~ 400 mK



Energy resolution is thermally limited.

Momentum-resolved Landau level spectroscopy in a topological insulator Bi_2Se_3



Topological insulators

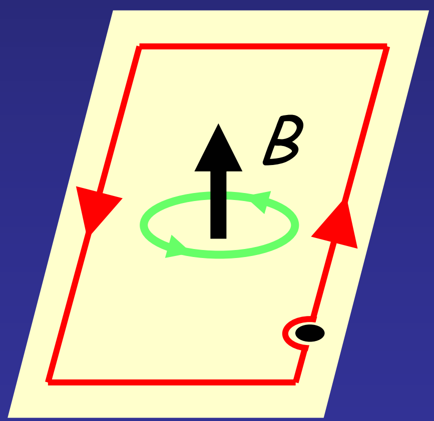
X. -L. Qi and S. -C. Zhang, Physics Today **63**, 33 (2010).
M. Z. Hasan and C. L. Kane, arXiv:1002.3895v1.

(Band) **insulators** with
robust **gapless** edge or surface state

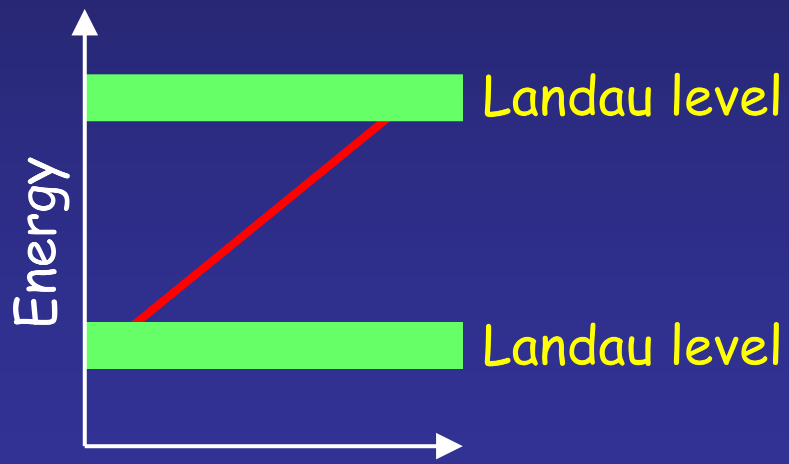
How can they become true?

→ Band structure with specific "topology"

ex. Quantum Hall state



Gapless edge-state



Time-reversal symmetry is broken.

Topological insulators

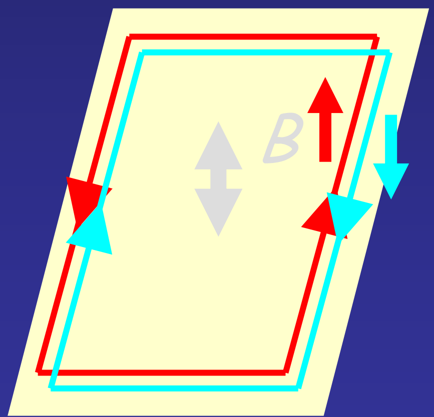
X. -L. Qi and S. -C. Zhang, Physics Today **63**, 33 (2010).
M. Z. Hasan and C. L. Kane, arXiv:1002.3895v1.

(Band) **insulators** with robust **gapless** edge or surface state

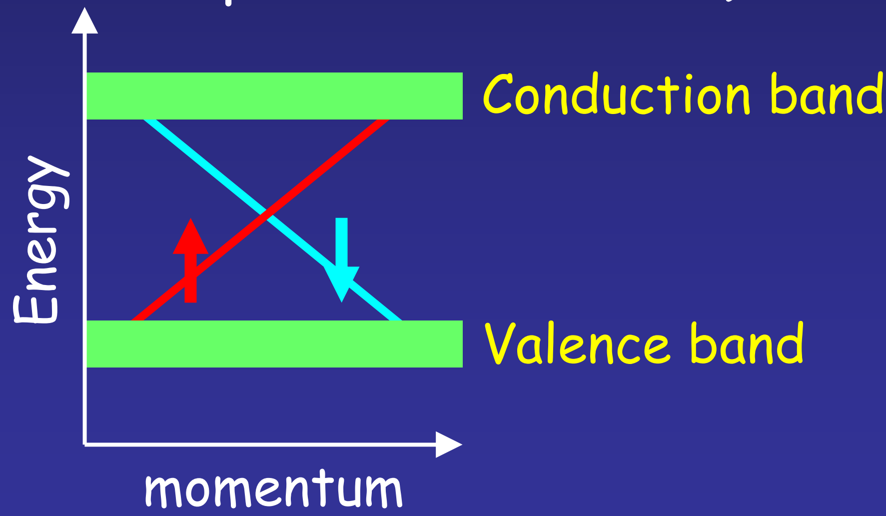
How can they become true?

→ Band structure with specific "topology"

Topological insulator (Quantum Spin Hall insulator)



Gapless edge-state

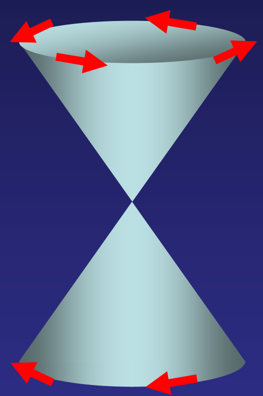


Time-reversal symmetry is preserved.

Dirac cone on the surface

3D topological insulator → Gapless **surface** state

Helical Dirac fermions at the surface



No spin degeneracy ↕ Doubly degenerate

Odd # of cones centered at time-reversal invariant momenta (TRIM) ↕ Always come in pairs

Dirac cones in solid states

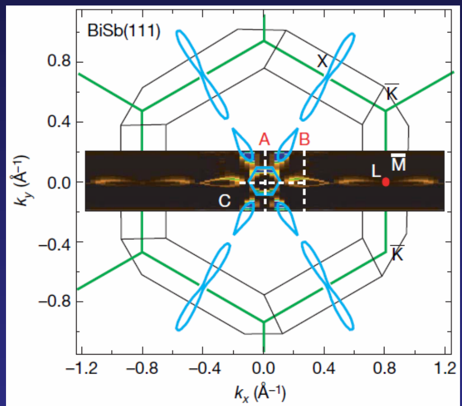
- Graphene A. H. Castro Neto *et al.*, Rev. Mod. Phys. **81**, 109 (2009).
- Organic conductor N. Tajima *et al.*, EPL **80**, 47002 (2007).
- *d*-wave SC A. V. Balatsky, I. Vekhter, and J.-X. Zhu, Rev. Mod. Phys. **78**, 373 (2006).

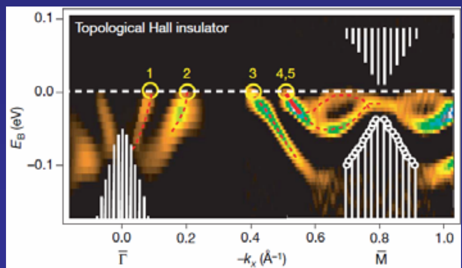
Experimental verifications

- 2D : HgTe quantum well

  B. A. Bernevig, T. L. Hughes, S.-C. Zhang, Science **314**, 1757 (2006).
  M. König *et al.*, Science **318**, 766 (2007).

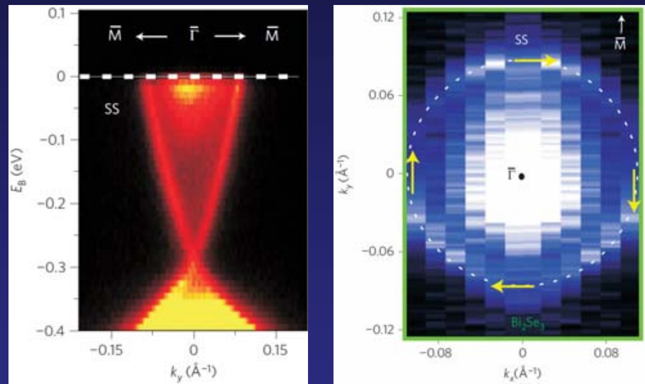
- 3D : Bi-Sb





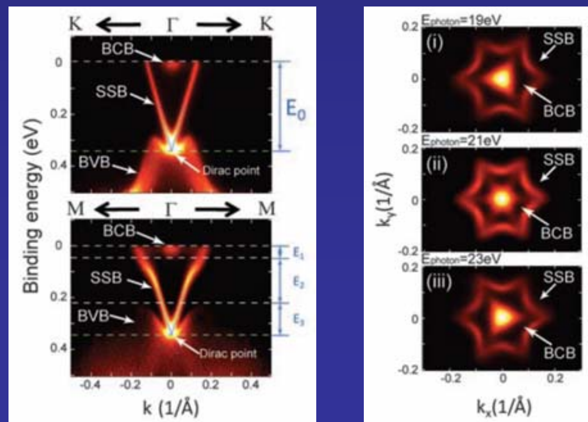
D. Hsieh *et al.*,
Nature **452**, 970 (2008).

Bi_2Se_3 H. Zhang *et al.*, Nature Phys. **5**, 438 (2009).



Y. Xia *et al.*, Nature Phys. **5**, 398 (2009).

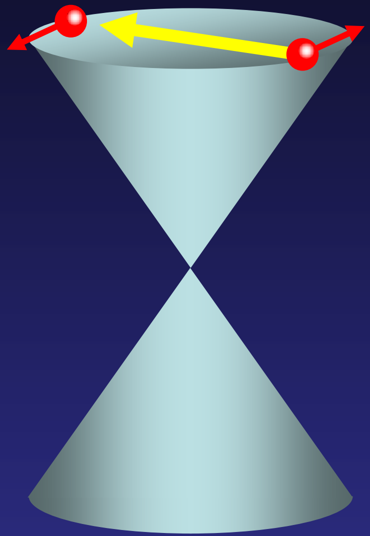
Bi_2Te_3



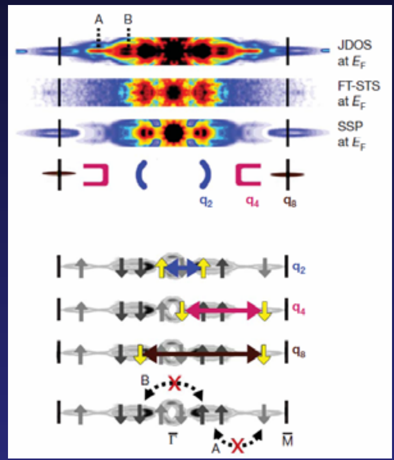
Y. L. Chen, *et al.* Science **325**, 178 (2009).

What unusual things happen?

- Helical spin structure : Suppressed back scattering

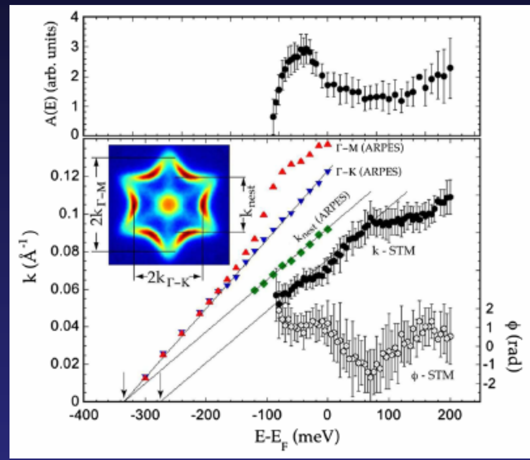


Bi-Sb



P. Roushan *et al.*, Nature **460**, 1106 (2009).

Bi_2Te_3



Z. Alpichshev *et al.*, PRL **104**, 016401 (2010).

- Massless Dirac dispersion: Unusual Landau levels

Conventional electron : $E_n = E_0 + \frac{e\hbar B}{m}\left(n + \frac{1}{2}\right)$

Dirac fermion : $E_n = E_0 + \mathrm{sgn}(n) v \sqrt{2e\hbar |n| B}$

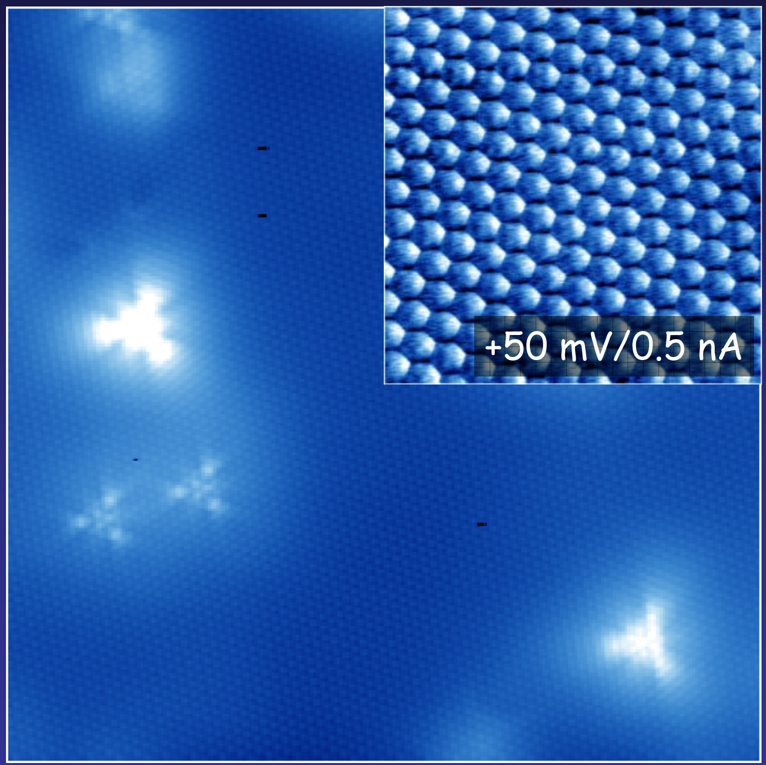
If $n = 0$, LL is B independent.

STM/STS on Bi_2Se_3

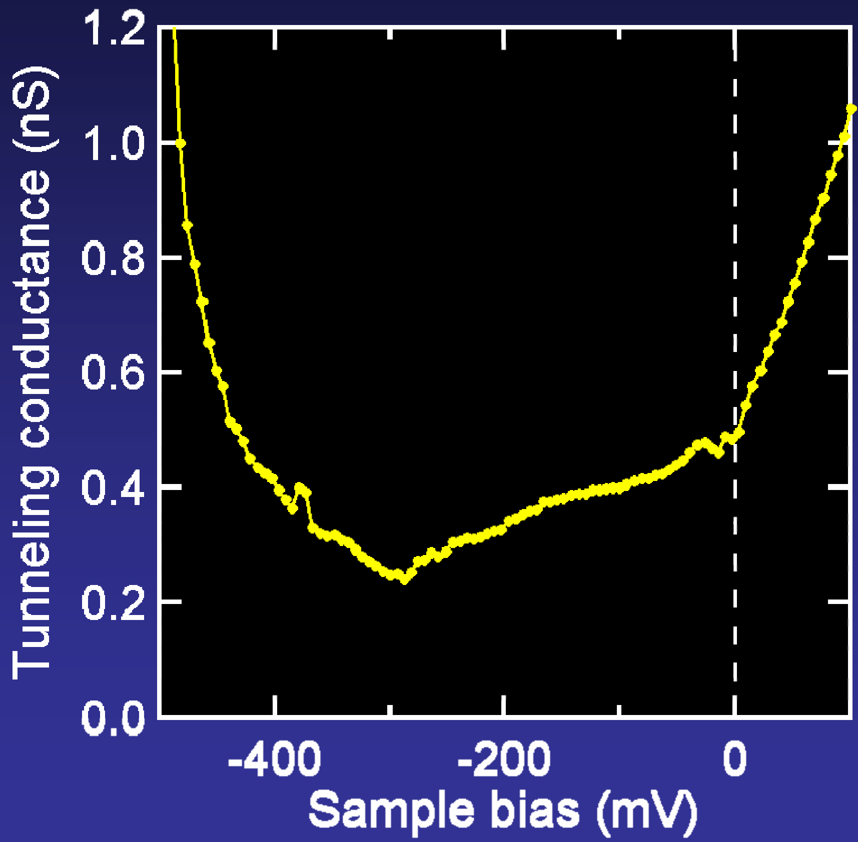
T. Hanaguri *et al.*, arXiv:1003.0100. (PRB-RC *in press.*)

X'tals grown by Igarashi & Sasagawa (TIT)

T ~ 1.5 K



30 nm × 30 nm, -100 mV/0.1 nA



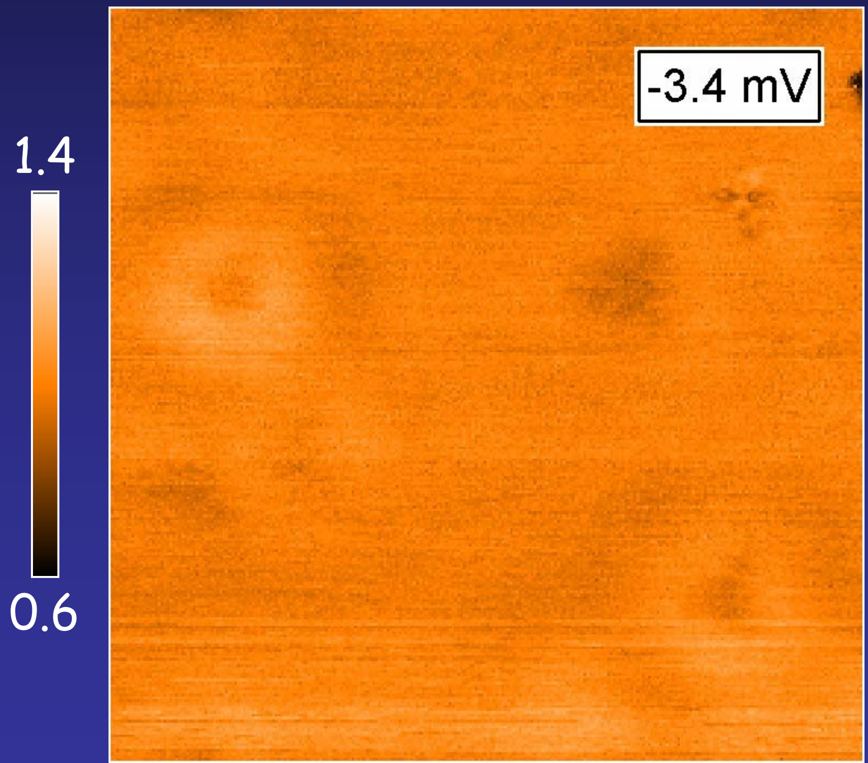
cf. S. Urazhdin *et al.*, Phys. Rev. B **66**, 161306(R) (2002); S. Urazhdin *et al.*, *ibid.* **69**, 085313 (2004).

Search for QPI in Bi_2Se_3

T. Hanaguri *et al.*, arXiv:1003.0100. (PRB-RC *in press*.)

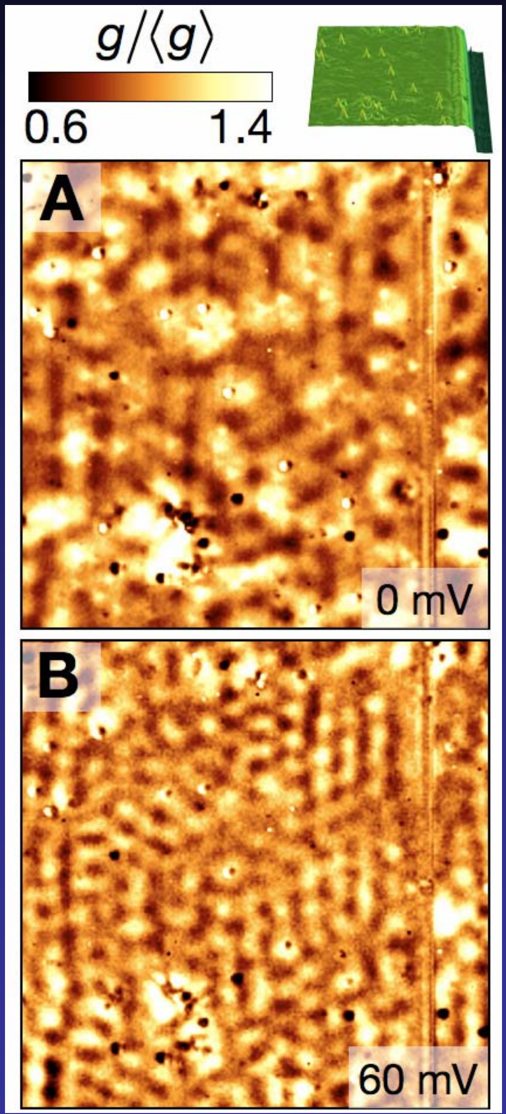
QPI is very weak in single, isotropic and helical Dirac cone.

g(**r**,*E*)/<*g*(**r**,*E*)>   *T* ~ 1.5 K



30 nm × 30 nm, +100 mV/0.1 nA

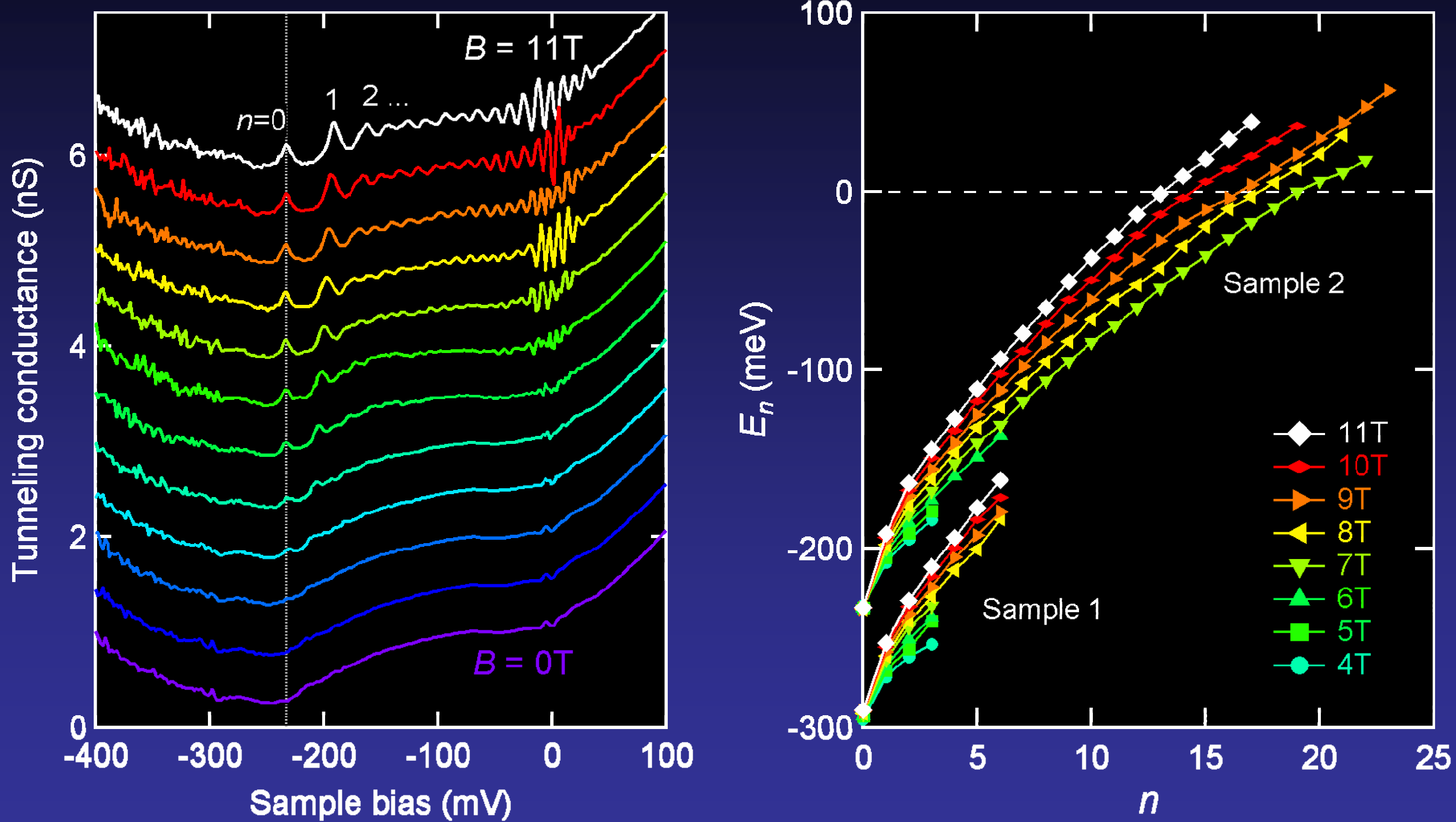
Sb



K. K. Gomes *et al.*, arXiv:0909.0921.

Landau level spectroscopy in Bi_2Se_3

T. Hanaguri *et al.*, arXiv:1003.0100. (PRB-RC *in press.*)
See also, P. Cheng *et al.*, arXiv:1001.3220.



- Field-independent Landau level with $n = 0$
- E_n is sub-linear in n

Scaling analysis

T. Hanaguri *et al.*, arXiv:1003.0100. (PRB-RC *in press*.)

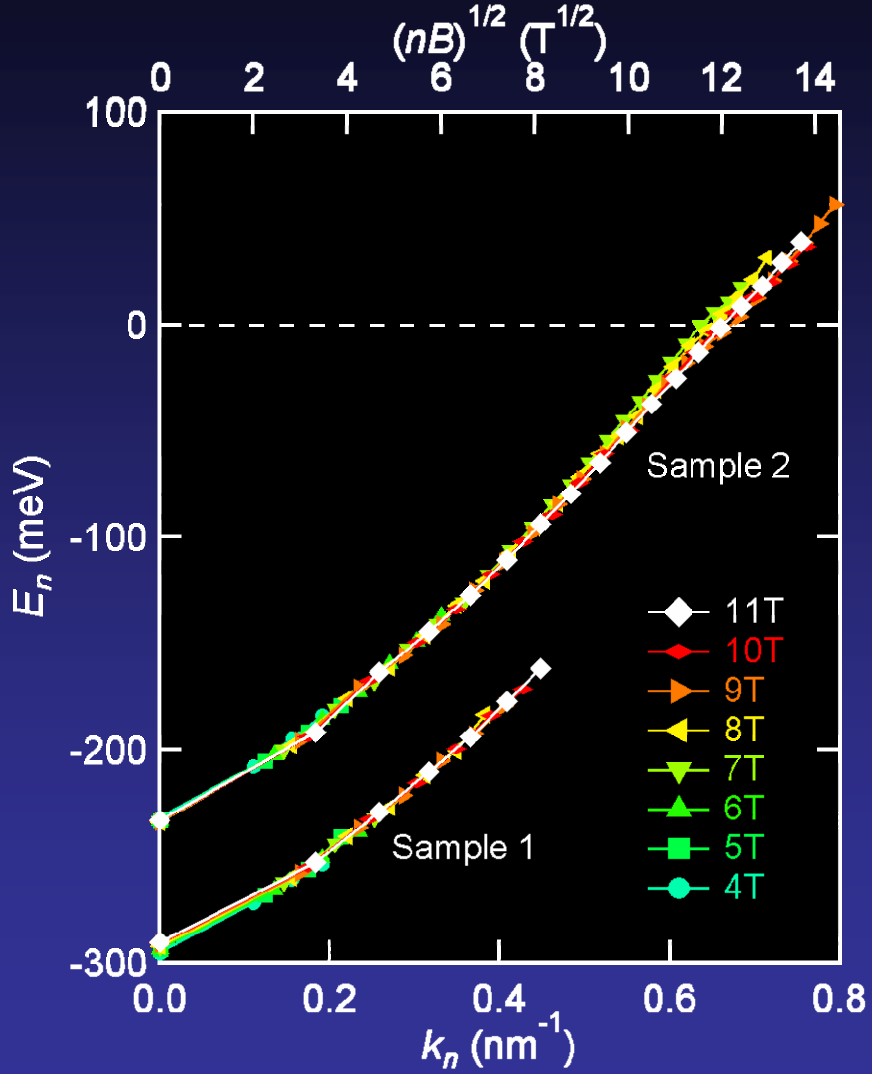
$$E_n = E_0 + \mathrm{sgn}(n) v \sqrt{2e\hbar|n|B}$$

Bohr-Sommerfeld condition

$$S_n = (n+\gamma)\frac{2\pi eB}{\hbar} \approx \pi k_n^2$$

$\gamma = 0$ for Dirac fermion

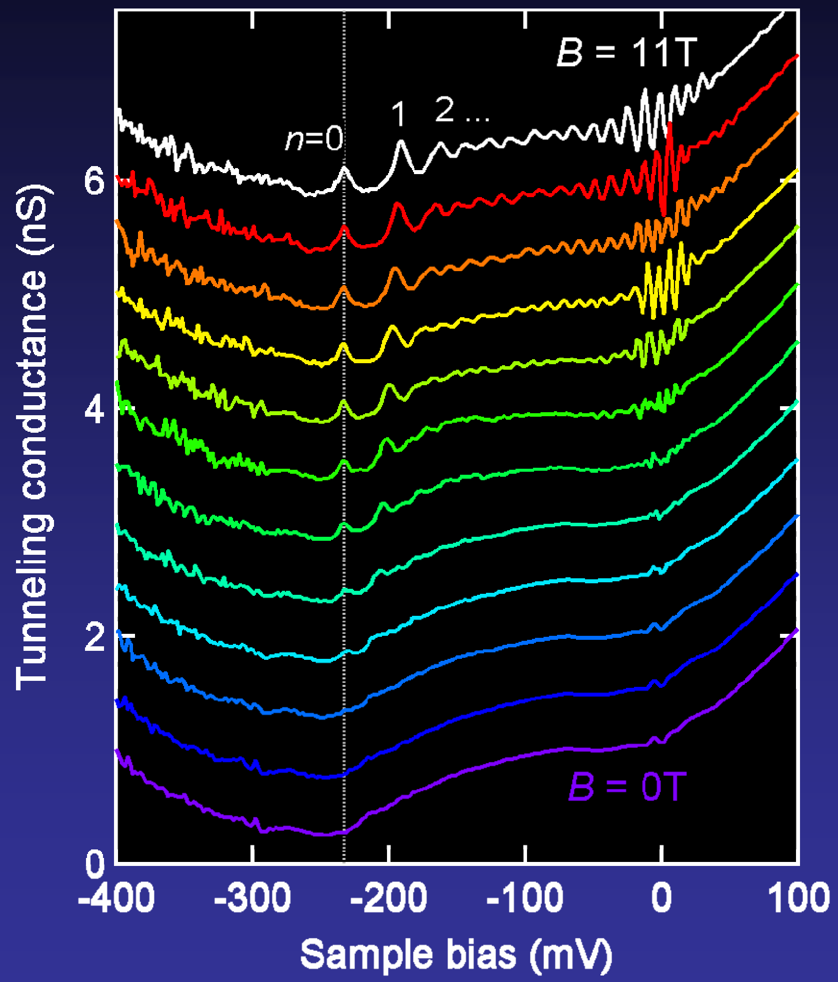
$$k_n = \sqrt{\frac{2e|n|B}{\hbar}}$$



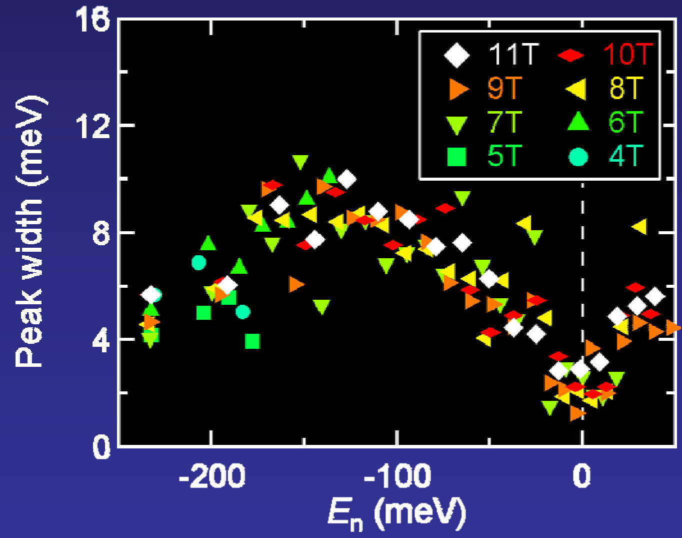
New momentum-resolved spectroscopy using STM

Other unusual features

T. Hanaguri *et al.*, arXiv:1003.0100. (PRB-RC *in press*.)



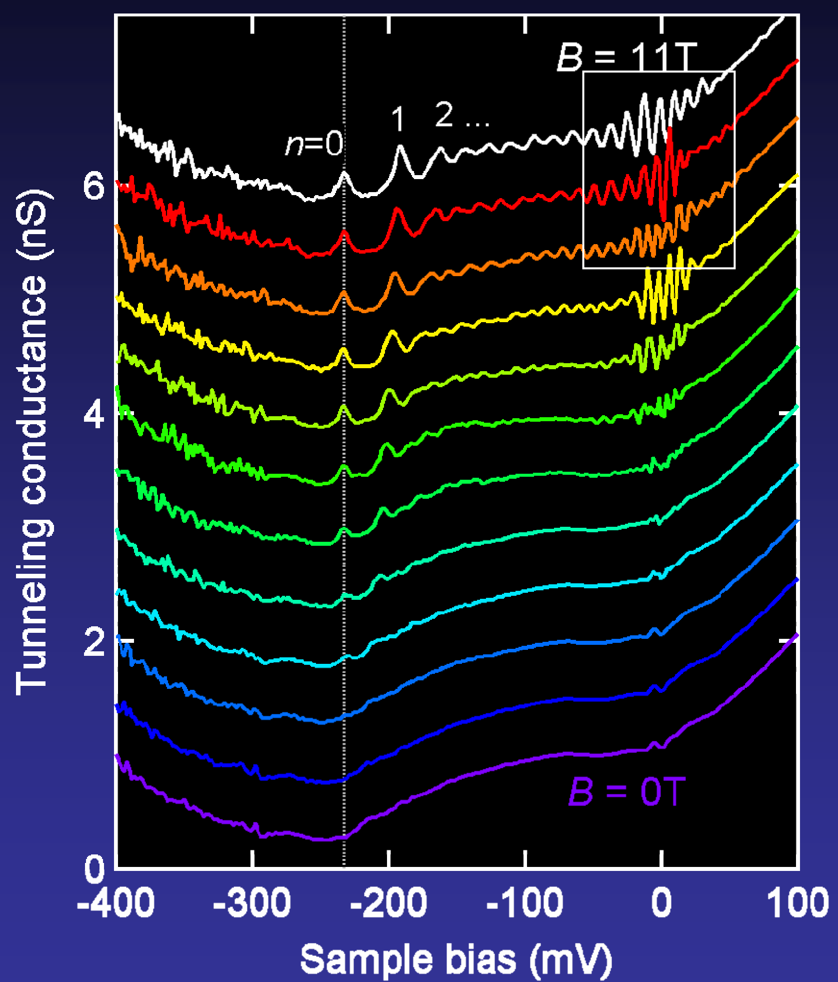
- Missing $n < 0$ LLs
  - coupling with bulk band?
- Enhanced amplitude near E_F

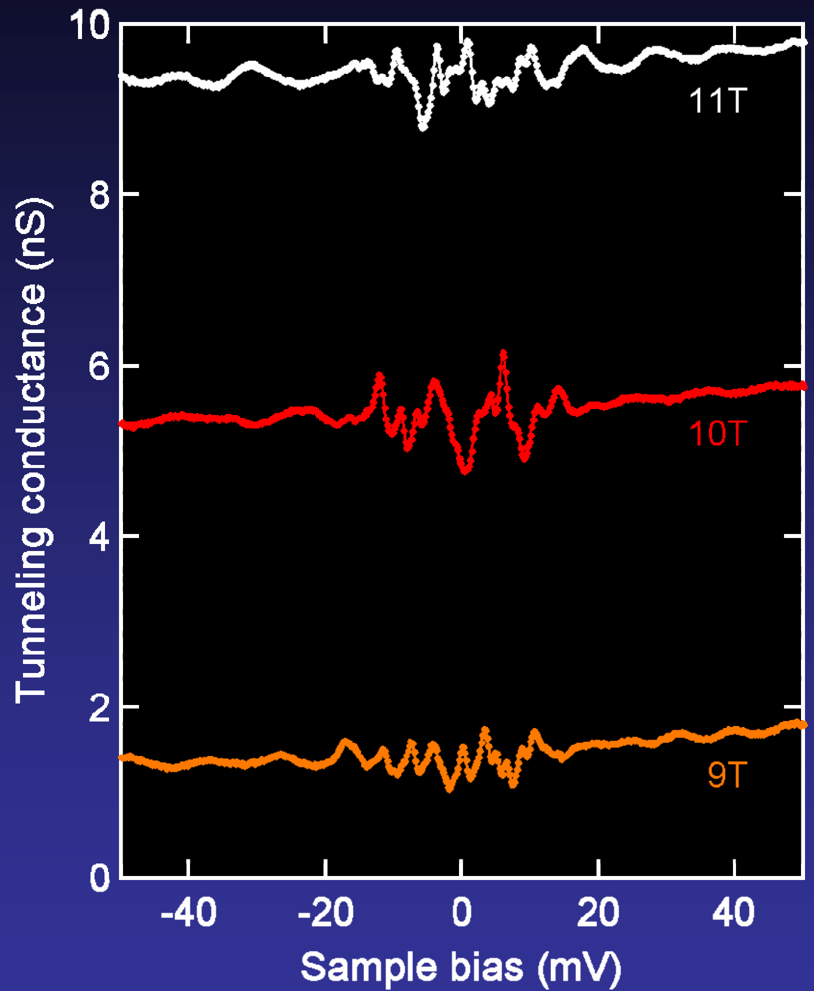


- *E*-dependent QP lifetime

Anomalous fine features near E_F

T. Hanaguri *et al.*, arXiv:1003.0100. (PRB-RC *in press*.)

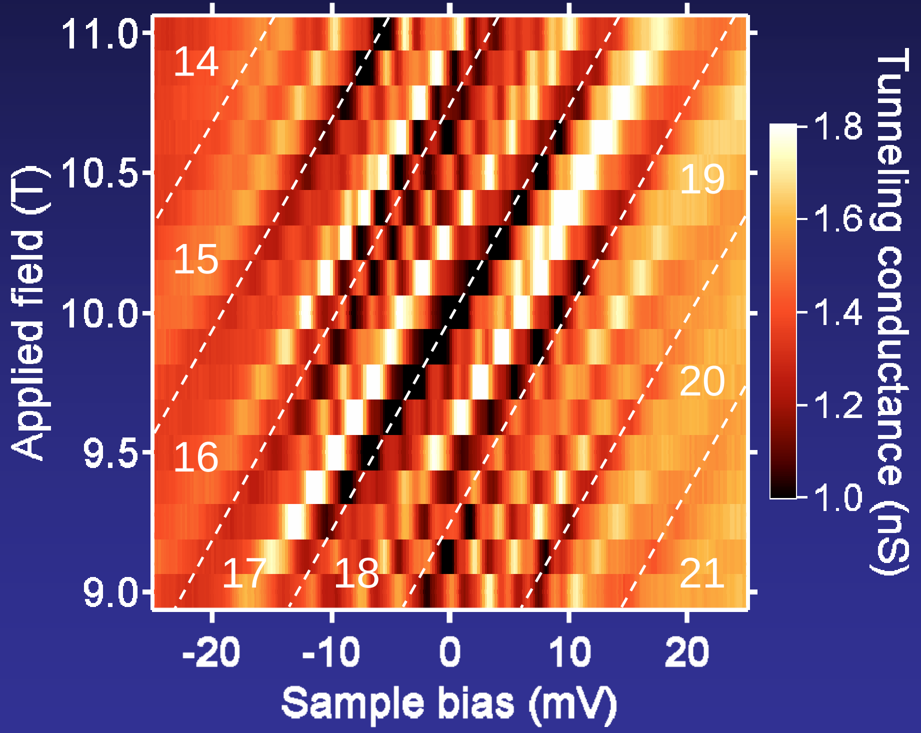


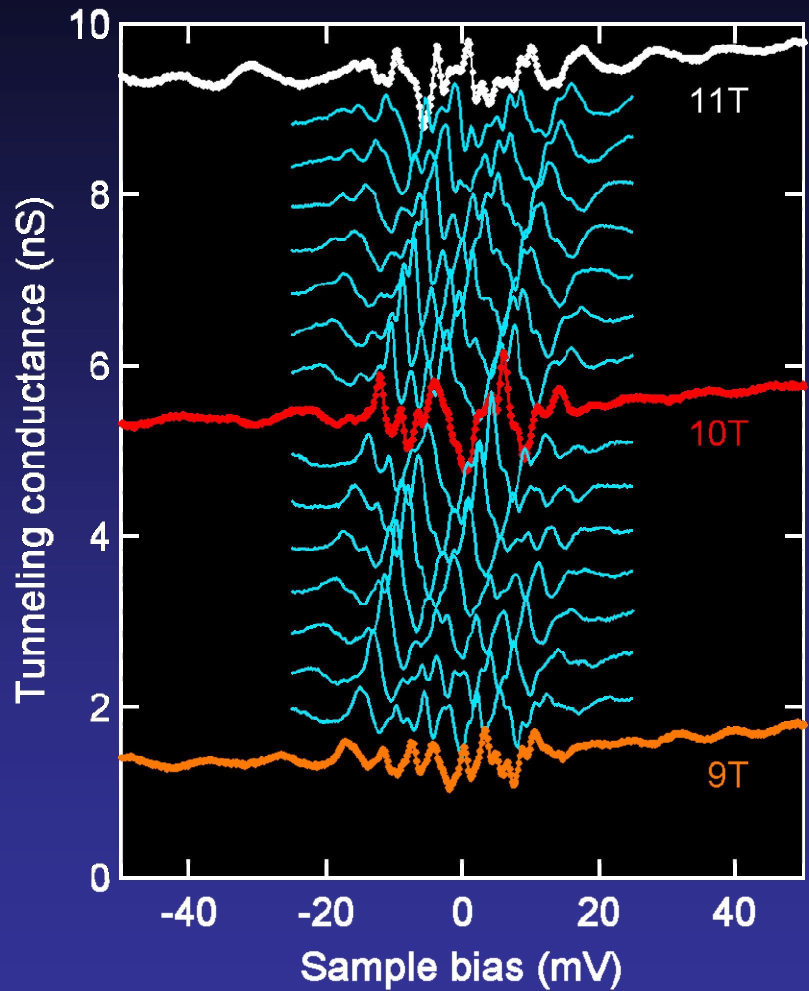


- Fine structures appear near E_F

Anomalous fine features near E_F

T. Hanaguri *et al.*, arXiv:1003.0100. (PRB-RC *in press.*)

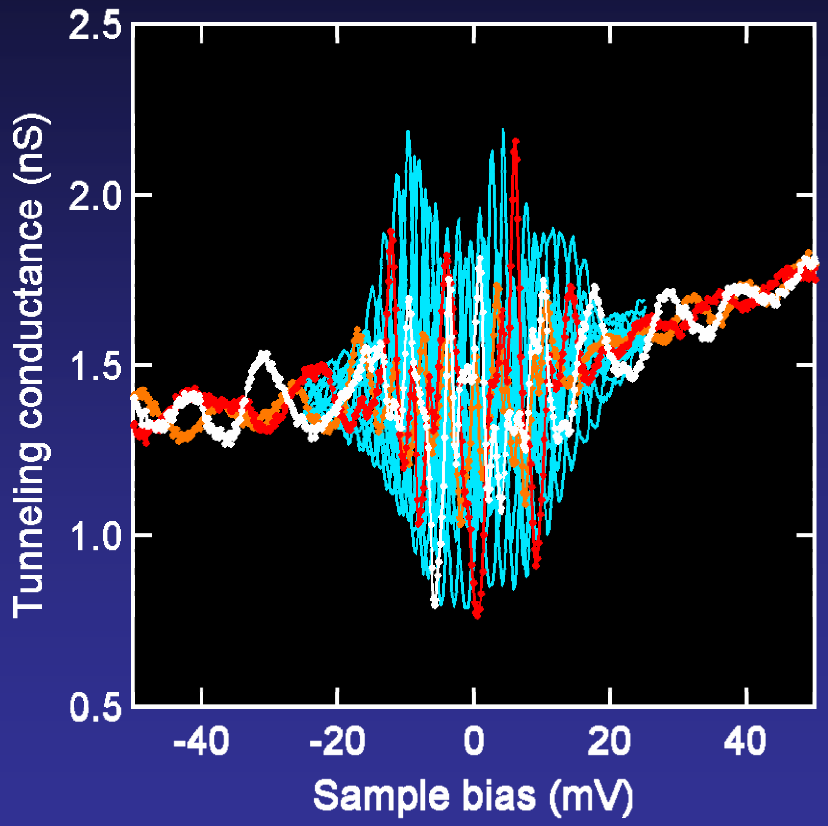




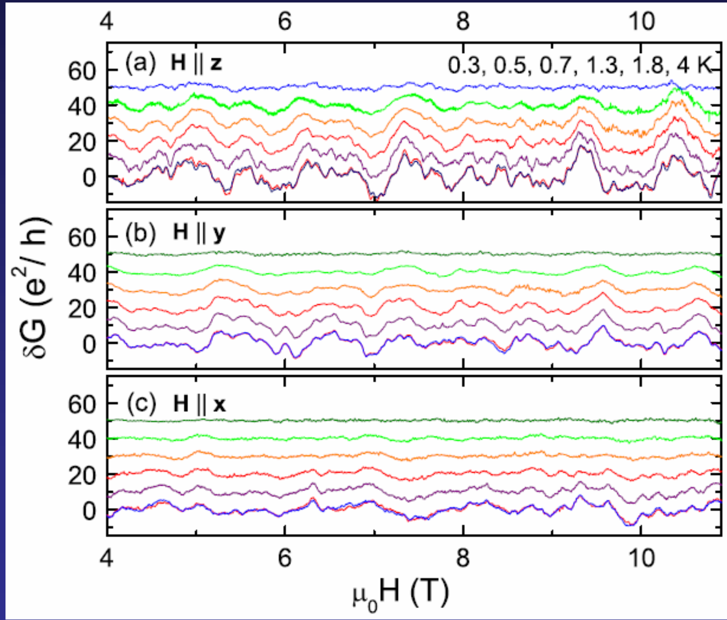
- Fine structures shift in the same manner as LLs

Anomalous fine features near E_F

T. Hanaguri *et al.*, arXiv:1003.0100. (PRB-RC *in press*.)



Anomalously large amplitude magneto-fingerprint effect



J. G. Checkelsky *et al.*, PRL **103**, 246601 (2009).

- Amplitude enhances suddenly $|E| < \sim 20$ mV

Summary

- Stable STM which can be operated under combined extreme conditions has been successfully installed.
- Helical Dirac fermions at the surface of a topological insulator Bi_2Se_3 has been studied using STM/STS in a magnetic field.
- Landau levels were identified clearly. We developed a new analysis scheme which enables us to determine the band dispersion accurately.
- Anomalous fine structures were found near E_F.

Spectroscopic basis for understanding magneto-transport and other properties of topological insulators

Issues

- Magnetic impurity
- How to reduce carriers?