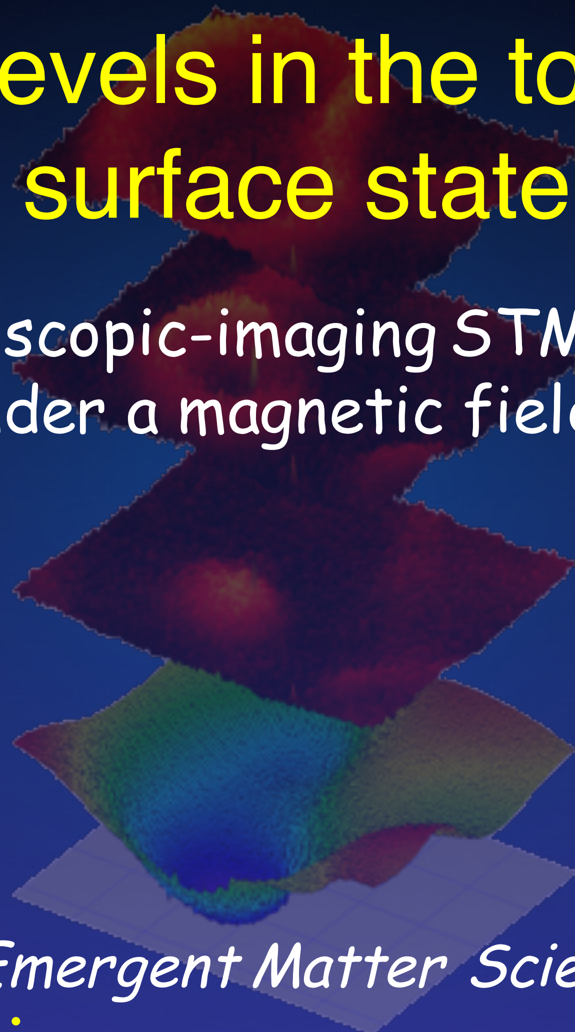
Imaging the wave functions of Dirac–Landau levels in the topological surface state



~ Spectroscopic-imaging STM on Bi_2Se_3 under a magnetic field ~

RIKEN CEMS

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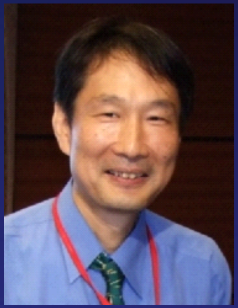
MPI-FKF, Germany



H. Takagi

Y. -S. Fu, M. Kawamura *et al.*, Nature Phys., **10**, 815 (2014).

Topological insulators

X. -L. Qi and S. -C. Zhang, RMP **83**, 1057 (2011).
M. Z. Hasan and C. L. Kane, RMP **82**, 3045 (2010).

(Band) insul

re

Magnetic Field !!

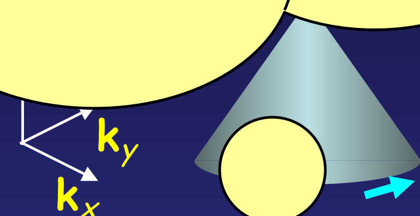
linear d

Massle

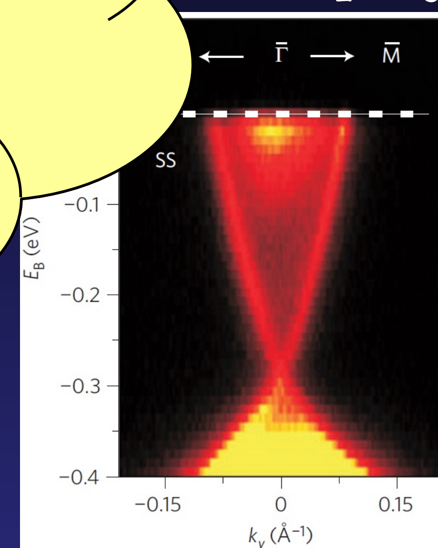
Dirac

spin-orbit interac

Spin-momentum locking



S on Bi_2Se_3



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

Helical Dirac fermions at the surfaces characterize 3D topological insulators.

Dirac Landau levels of topological surface state

- Eigen energies

Conventio… …ons

$E_n = \ldots$ $\sqrt{2e\hbar|n|B}$

Where and how
2-component feature
manifests itself?

Qualitat… …and B dependence

ex. G…

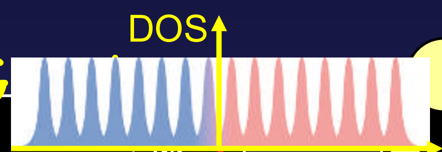
Half-integer
QHE

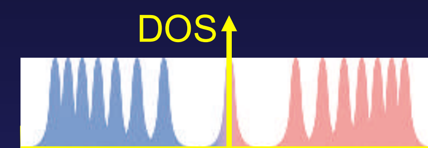
QHE
at RT

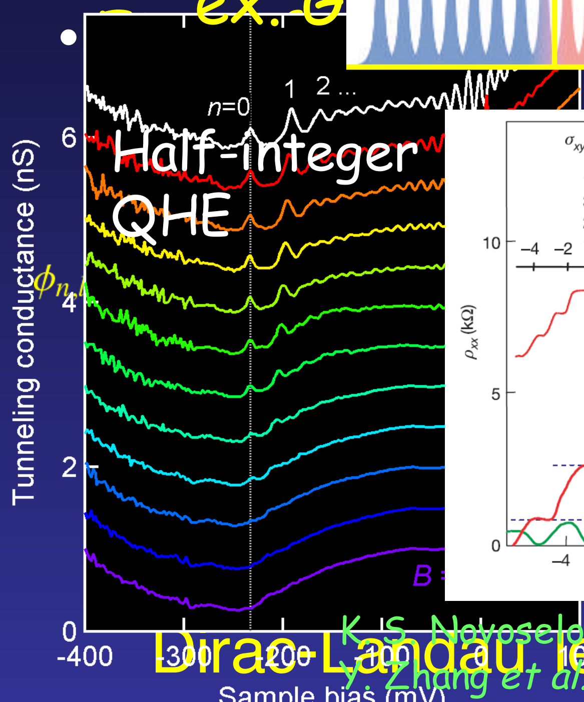
Dirac-Landau scaling

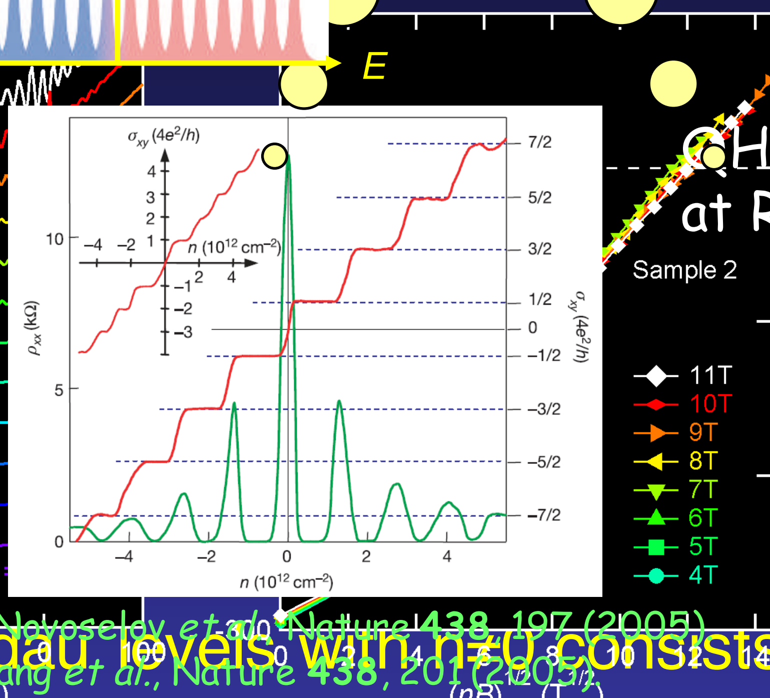
…$_2Se_3$

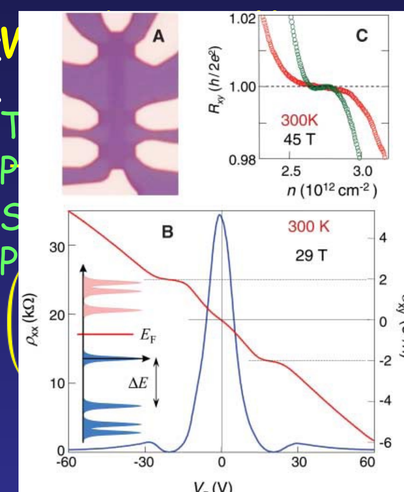
$n \neq 0$











K. S. Novoselov *et al.*, Nature **438**, 197 (2005).
Y. Zhang *et al.*, Nature **438**, 201 (2005).

K. S. Novoselov *et al.*, Science **315**, 1379 (2007).

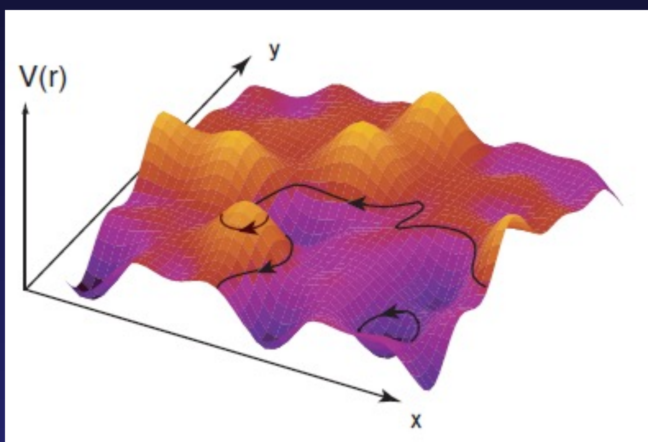
Dirac Landau levels with $n \neq 0$ consists of 2 components

How to image the Landau wave function?

We must localize the Landau orbit in real space…

Introduction of potentia

Localized/extended states



K. Nomura, http://www-lab.imr.tohoku.ac.jp
/~nomura/note_nomura.pdf

$$\Psi_{0,j_z}(r,\theta) = \begin{pmatrix} 0 \\ \phi_{n,l_z}(r,\theta) \end{pmatrix} \quad n = 0$$

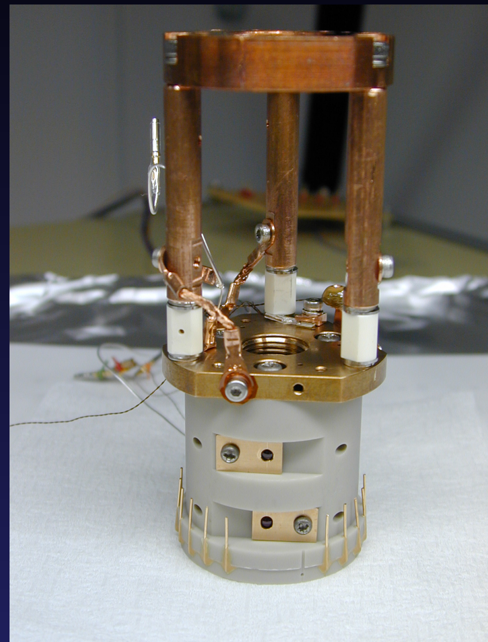
$$\Psi_{n,j_z}(r,\theta) = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathrm{sgn}(l_z)\,\phi_{n-1,l_z}(r,\theta) \\ \phi_{n,l_z}(r,\theta) \end{pmatrix} \quad n \neq 0$$

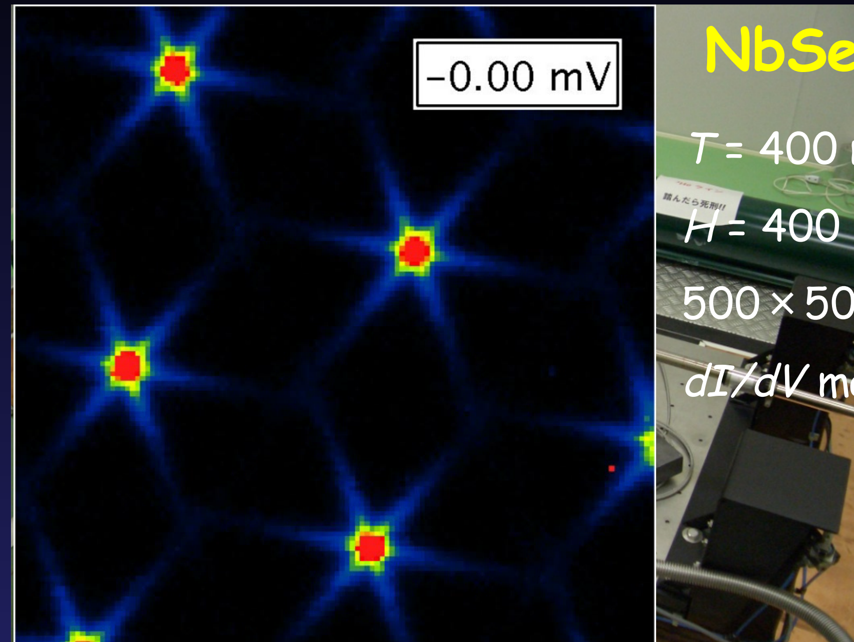
$$\phi_{n,l_z}(r,\theta) = \frac{1}{\sqrt{2\pi} l_B} \sqrt{\frac{N!}{(N+|l_z|)!}} \exp\left(-\frac{1}{4}\left(\frac{r}{l_B}\right)^2 + i l_z \theta\right) \left(\frac{r}{\sqrt{2} l_B}\right)^{|l_z|} L_N^{|l_z|}\left(\frac{r^2}{2 l_B^2}\right)$$

How does Dirac-Landau orbit look like?

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

T. Hanaguri, J. Phys.: Conf. Ser. **51**,514 (2006). More info. available in my web page.

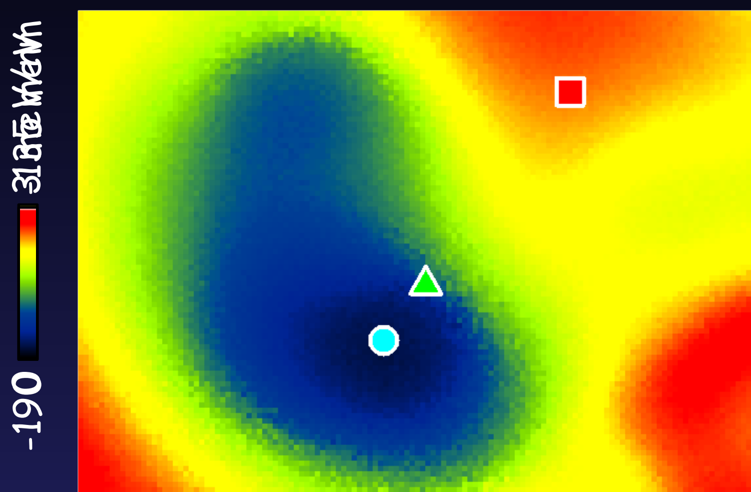


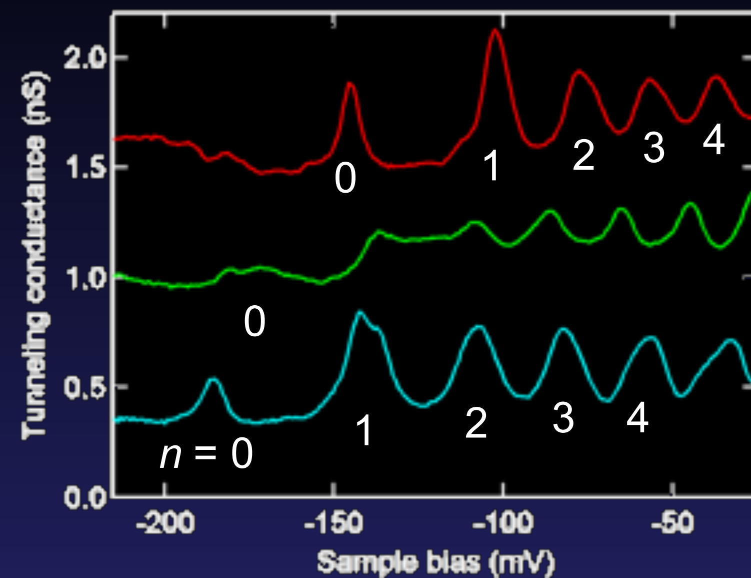


- UHV (~10^{-10} Torr), Very-low temp. (400 mK), High field (12 T)
- In-situ tip cleaning/sharpening by field-ion microscope.
- *In-situ* tip/sample exchange (resonant freq. 5.5 kHz)
- Long-term stability at base temp < Å/day
- Noise levels (1 kHz BW) < 0.5 pm, 1 pA

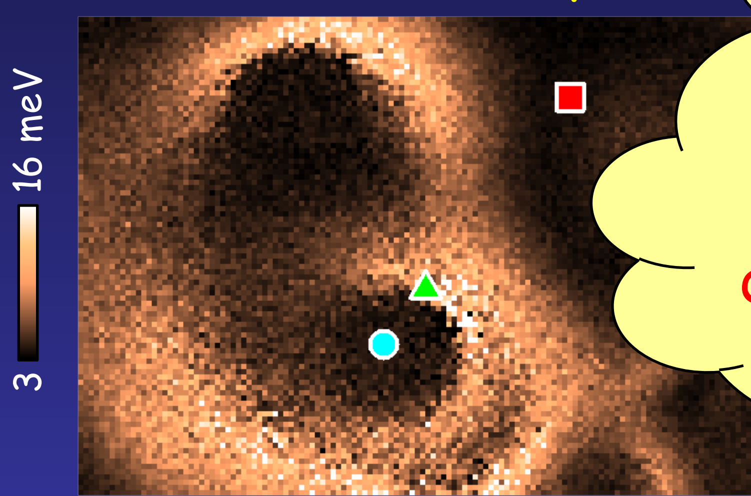
Imaging potential landscape in Bi_2Se_3

E_0 map (potential map) 120 nm × 83 nm





LL_0 Peak width map

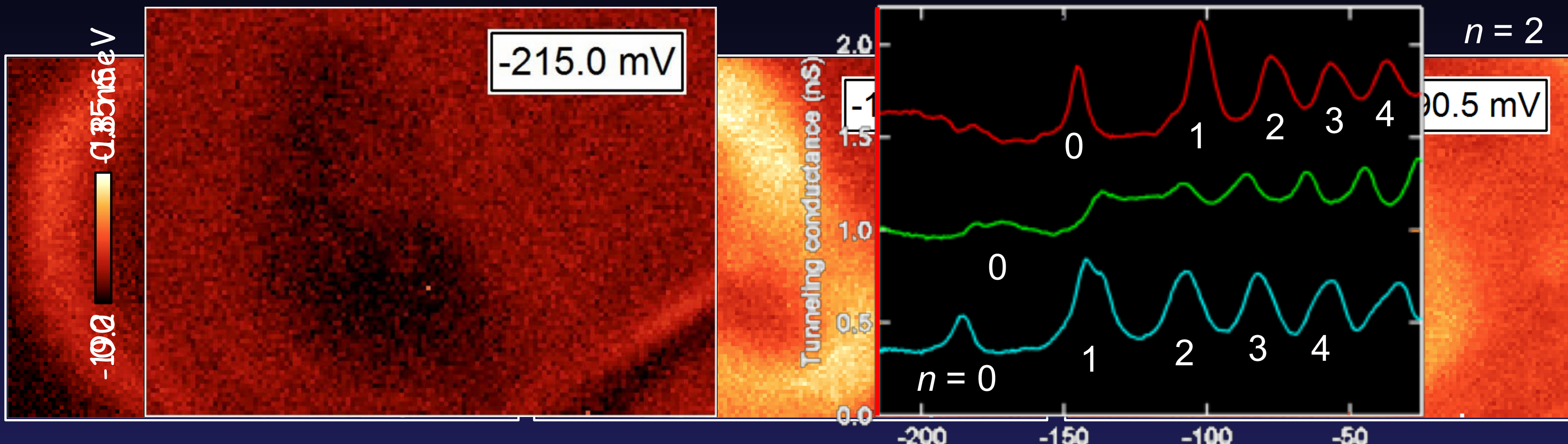


Potential variation lifts the degeneracy of LLs.

Y. -S. Fu

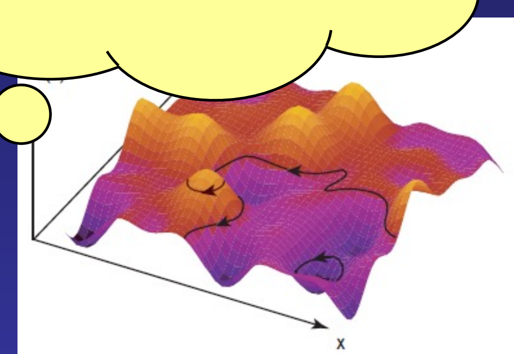
Imaging Landau orbits

120 nm × 83 nm

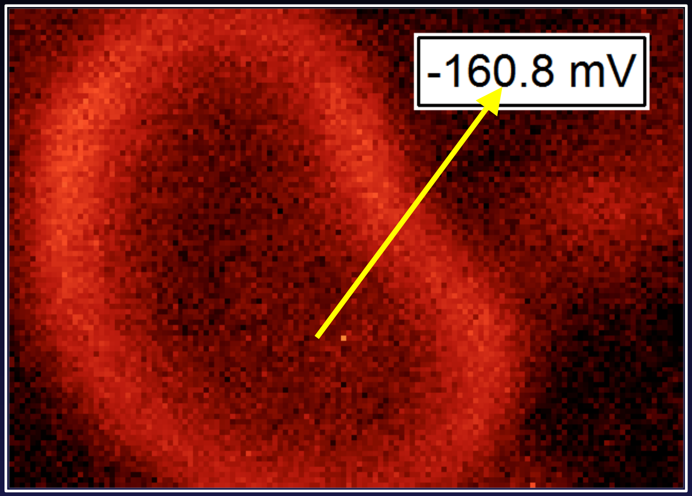


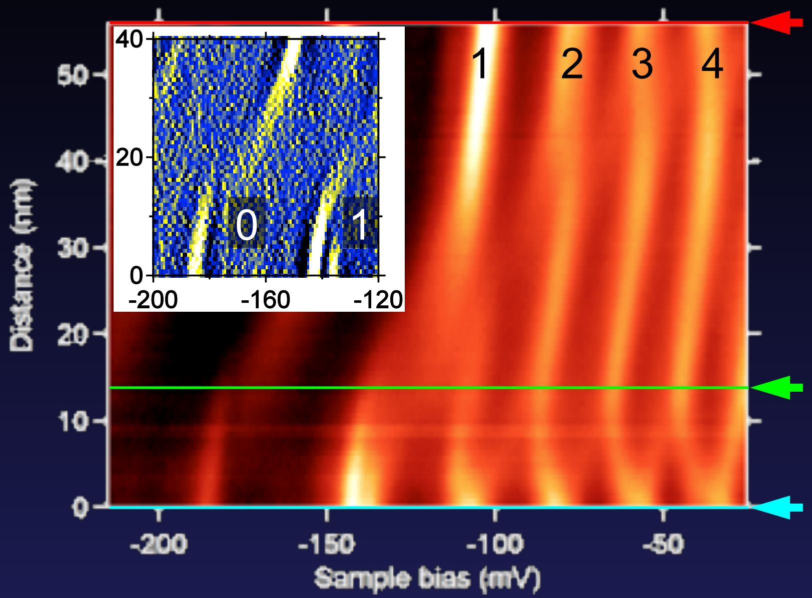
- Apparent ring structure
  - Cyclotron orbit drifting alon
- Concentric ring at higher *n*
  - *n*-dependent internal structure

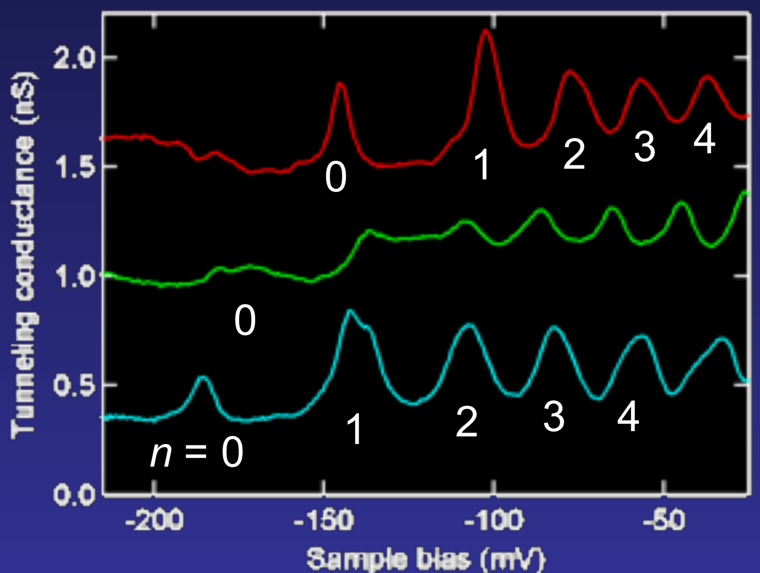
Dirac nature encoded?



Linecut ~ energy dependence

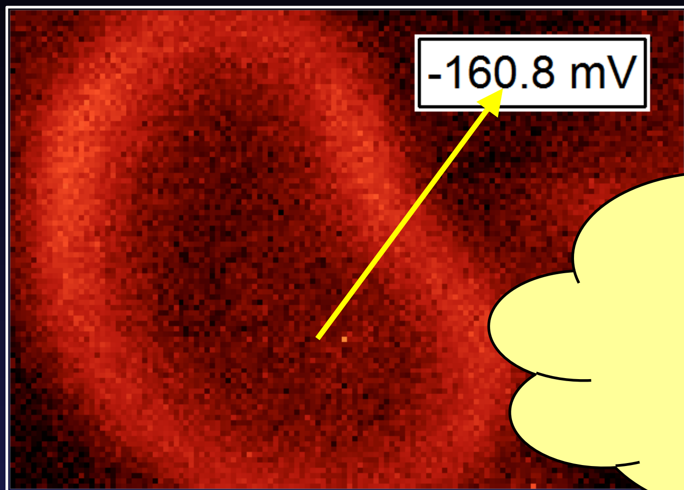


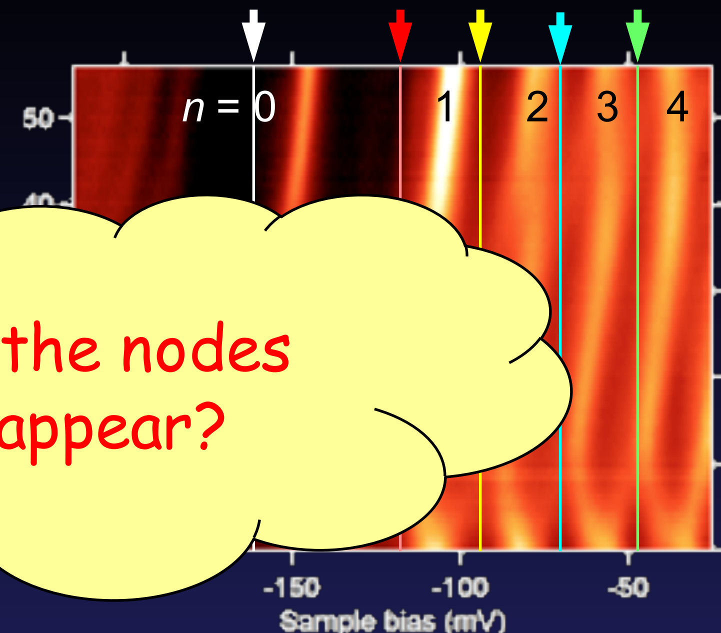




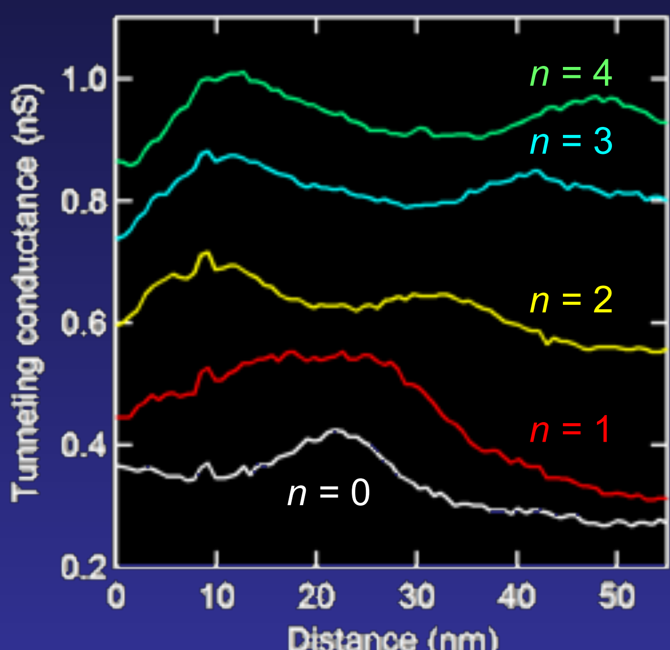
- LLs in a potential form Landau sub-bands.
- LL_0 and LL_1 split into sub-levels.
- LL_1 splits even at the bottom of the potential.
- Apparent two branches for higher LLs.

Linecut ~ position dependence





Why the nodes disappear?

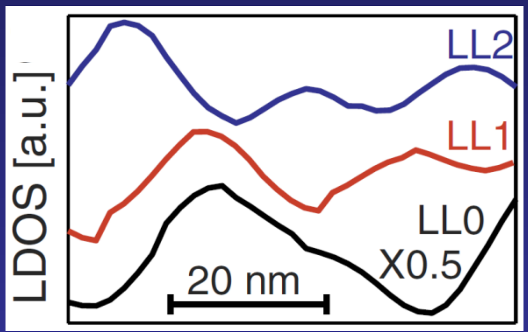


LDOS distribution exhibits only two peaks for ALL of the $n \neq 0$ states.

cf. InSb(110)

n nodes for LL_n

K. Hashimoto, *et al.*, PRL **109**, 116805 (2012).



Model calculation

Dirac Hamiltonian with a potential

M. Kawamura

$$H = H_0 + V(r)\sigma_0$$

$$H_0 = v\begin{pmatrix} 0 & \pi_y + i\pi_x \\ \pi_y - i\pi_x & 0 \end{pmatrix} \qquad \vec{\pi} = \vec{p} - e\vec{A}$$

$$V(r) = \frac{V_0 d}{\sqrt{r^2 + d^2}}$$

Charged defect beneath the surface (circular symmetric)

Good quantum number :

z component of total angular momentum $j_z = l_z - \frac{1}{2}$

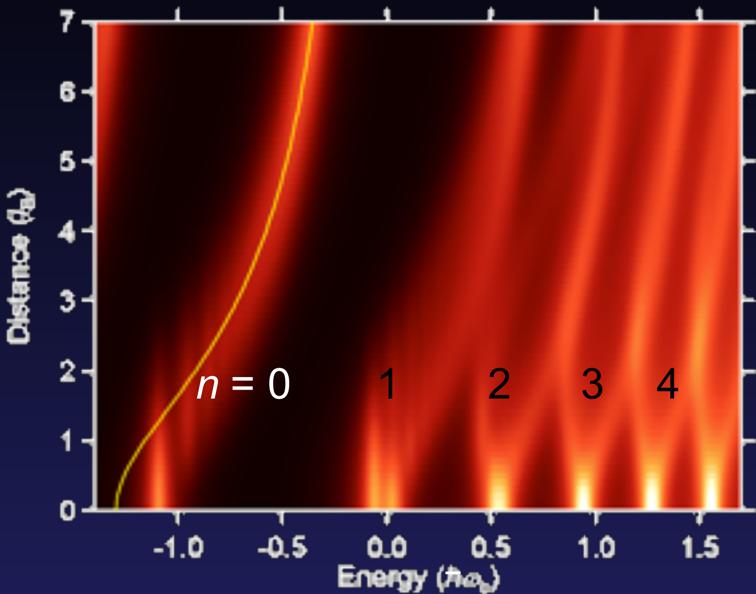
Eigen energies : E_{n,j_z}

LDOS : $LDOS(E, r) = \sum_{n,j_z} \frac{\Gamma}{\left(E - E_{n,j_z}\right)^2 + \Gamma^2} |\Psi_{n,j_z}(r)|^2$

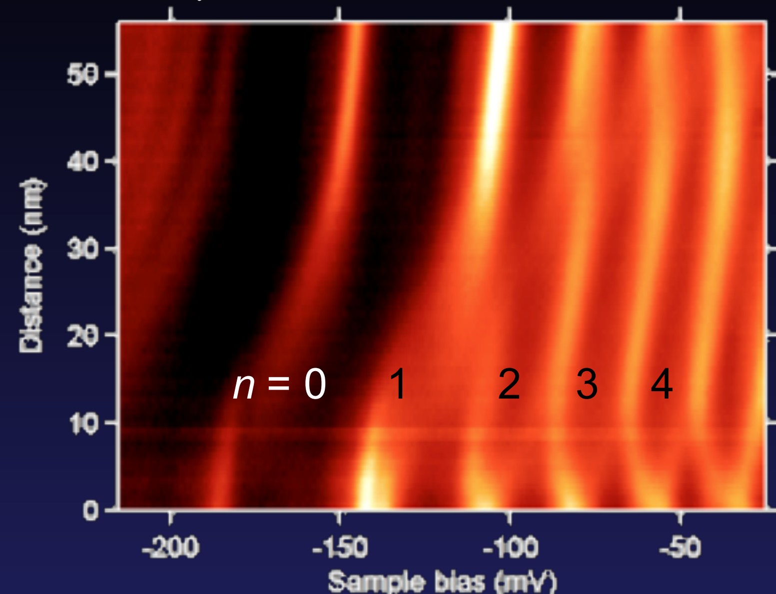
obtained by diagonalizing the block Hamiltonians

Model calculation captures observations

Calculation



Experiment



M. Kawamura

Y. -S. Fu

$\Psi_{0,j_z}(r,\theta$ … $(r,\theta)\Big)$ $n =$ … $,\theta) = \Big(\pm\text{sgn}$ … $\theta)\Big)$ $n \neq 0$

- LLs in … form Landau sub-ba…
- LL_0 and … into sub-levels. … at the …
- … the bottom of the potential.
- Apparent two branches for higher LLs.

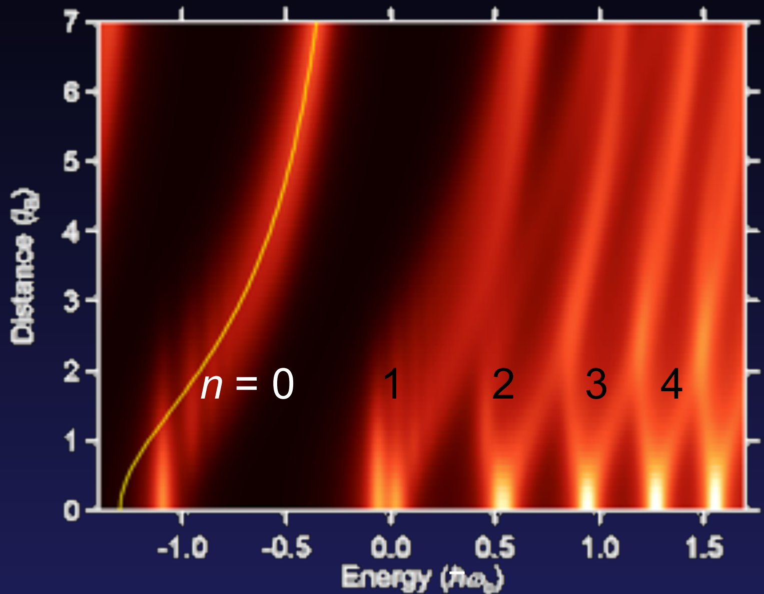
ex. n = 1

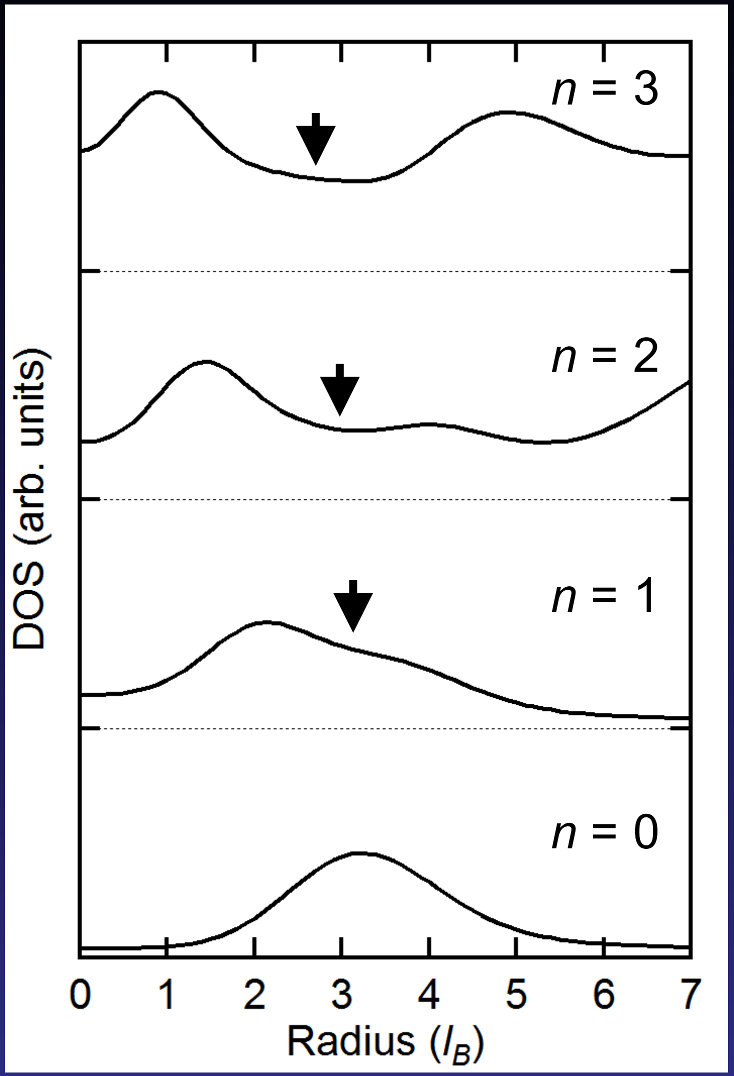
$\Psi_{1,+1/2} = \begin{pmatrix} \phi_{1,0} \\ \phi_{1,1} \end{pmatrix}$

$\Psi_{1,-1/2} = \begin{pmatrix} \phi_{0,-1} \\ \phi_{1,0} \end{pmatrix}$

Two components kill the nodes in DOS

Calculation

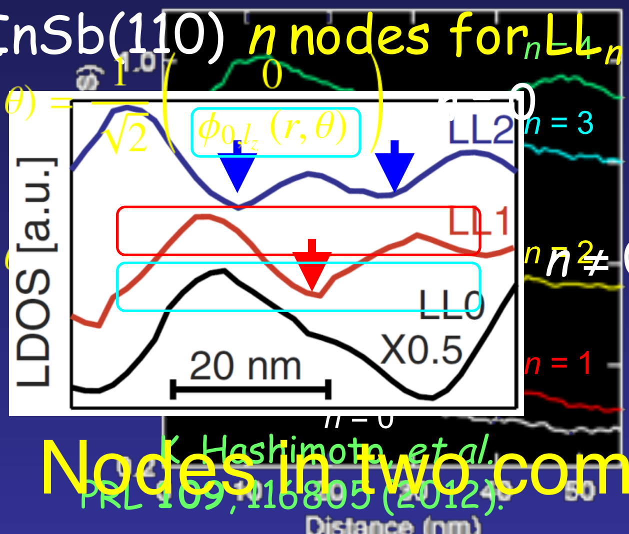




Exp. InSb(110) n nodes for LL$_n$

$$\Psi_{0,j_z}(r,\theta) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \phi_{0,l_z}(r,\theta) \end{pmatrix} \quad n = 0$$

$\Psi_{n,j_z}(r,$ … $n \neq 0$



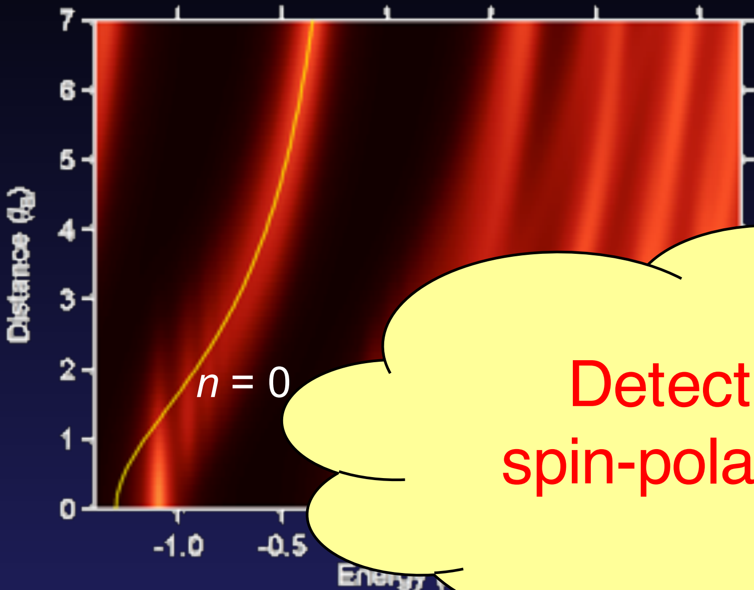
K. Hashimoto, *et al.* PRL 109, 116805 (2012).

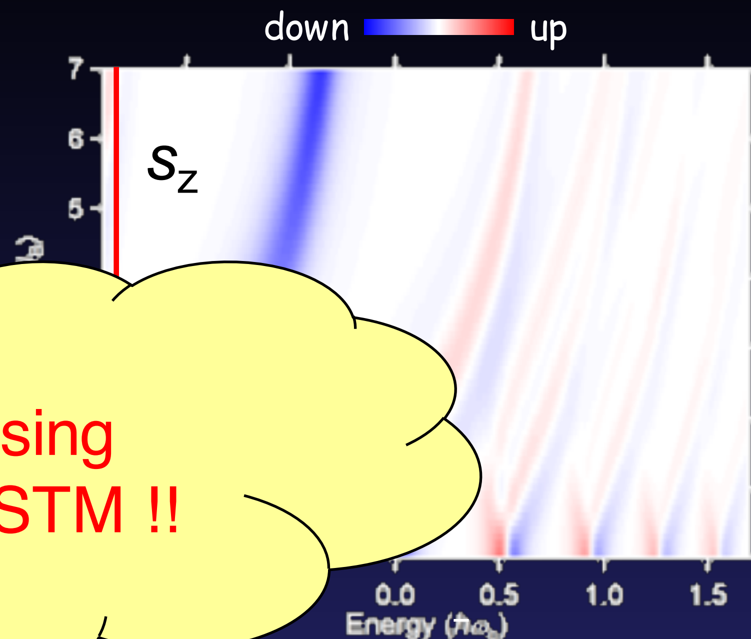
Nodes in two components counteract.

Two peaks, only one minimum for all n > 0

Non-trivial spin-magnetization texture

Calculation

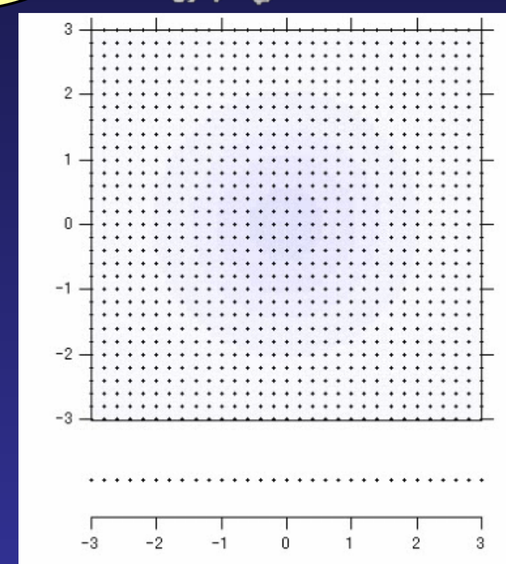




Detectable using spin-polarized STM !!

Spin-magnetization density

$$\langle s_i \rangle = \left\langle \Psi_{n,j_z} \left| \frac{\hbar}{2}\sigma_i \right| \Psi_{n,j_z} \right\rangle \ , \quad i = x, y, z$$



E-dependent cycloidal-helix texture associated with the potential variation!!

Summary

- Dirac Landau levels under potential variation have been studied in a topological insulator Bi_2Se_3 by STM/STS.
- Signatures of two-component wave function manifest themselves in the splitting of $n = 1$ Landau level at the potential minimum and the absence of nodal structure in the density-of-state distribution.
- Model calculation suggests that spin-orbit coupled nature brings about energy-dependent spin texture in a potential, which may be detected by spin-polarized STM and will provide a novel way to manipulate spins.

- Zeeman effect
- Spin-polarized STM
- Quantum anomalous Hall state

For details, see Y. –S. Fu, M. Kawamura *et al.*, Nature Phys., **10**, 815 (2014).