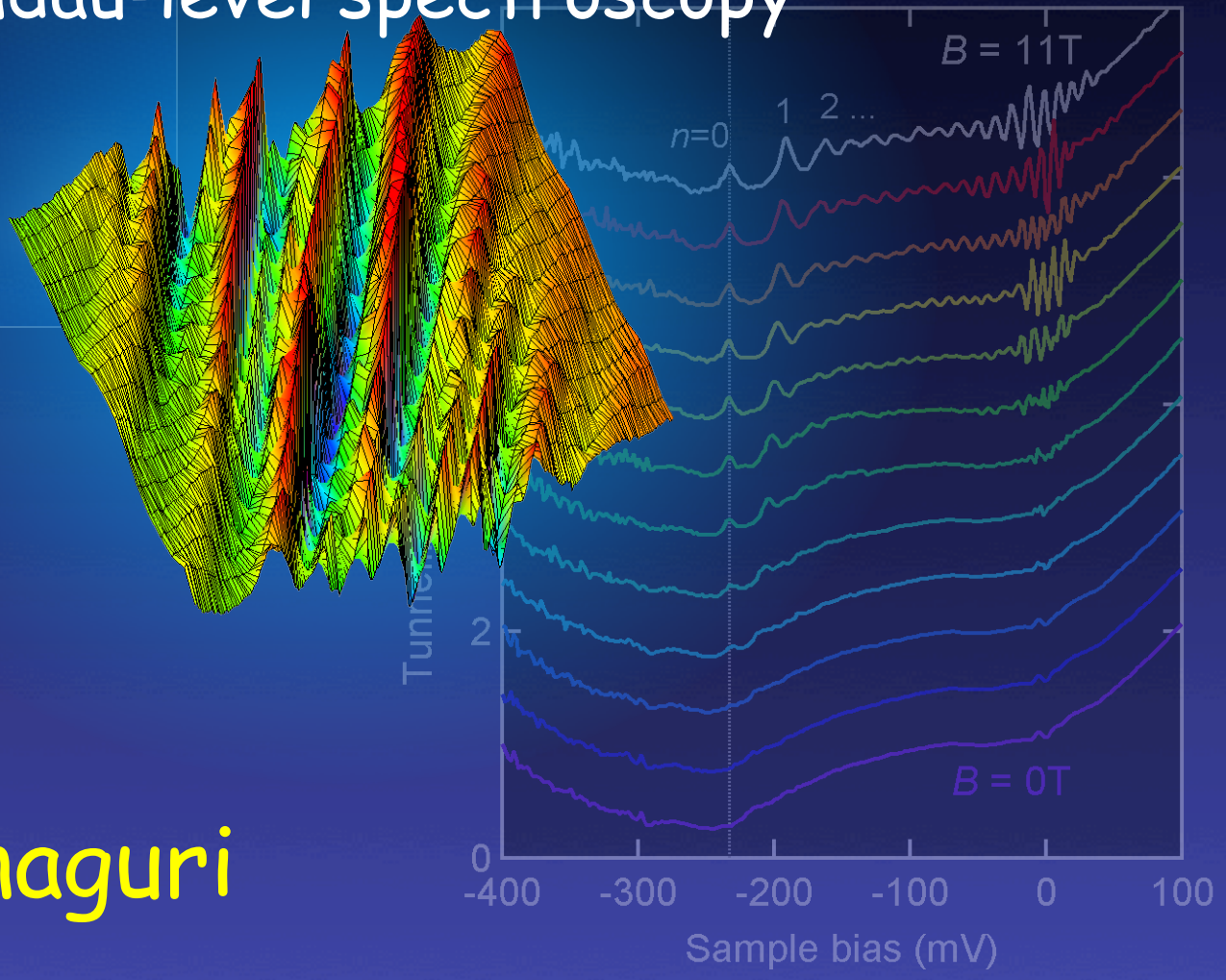
STM/STS studies of a topological insulator

~ Landau-level spectroscopy ~



RIKEN

Tetsuo Hanaguri

Collaborators

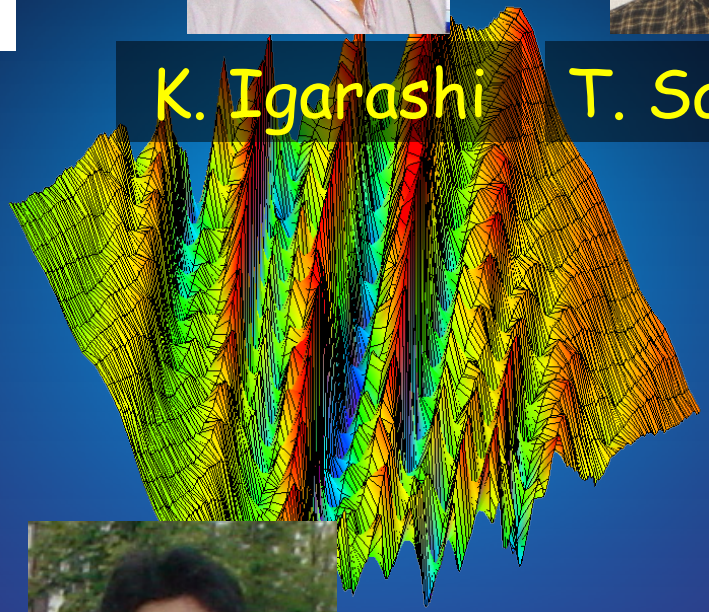




Tokyo Tech.

K. Igarashi

T. Sasagawa





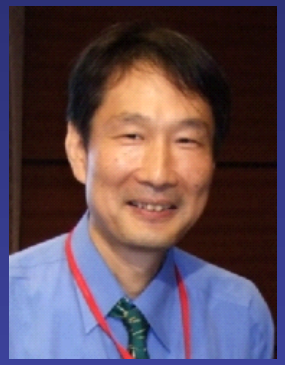


RIKEN

Y. Fu

M. Kawamura

Univ. Tokyo /RIKEN



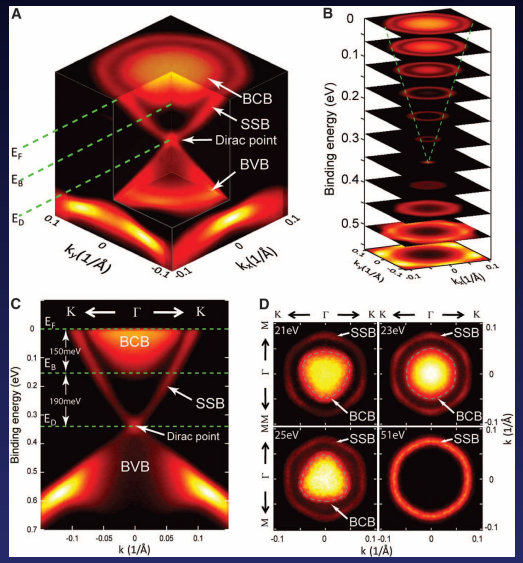
H. Takagi

Outline

- Background
- Why STM/STS?
- Landau-level spectroscopy on Bi_2Se_3
  - Momentum-resolved Landau-level spectroscopy
  - Electronic inhomogeneity near E_F and E_{DP}
- "Memory effect" in Bi_2Te_2Se
- Summary

3D topological insulator ~ARPES studies

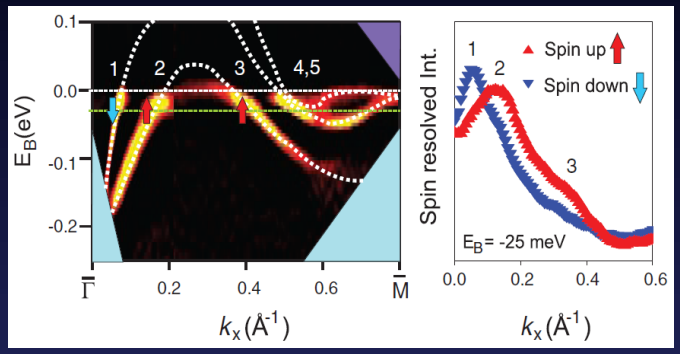
Bi_2Se_3



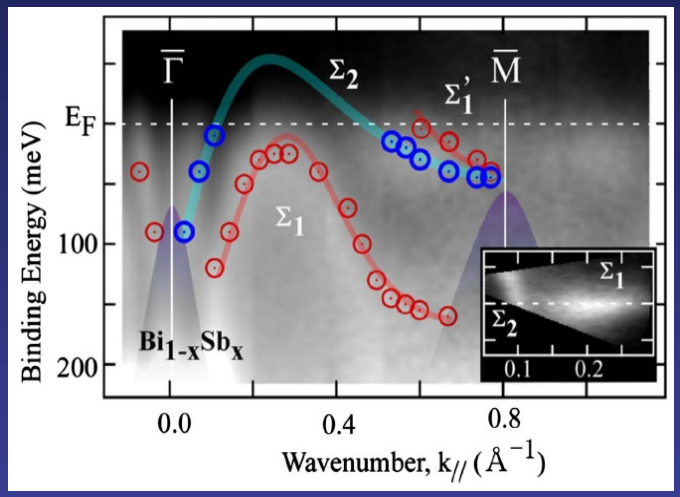
Y. L. Chen *et al.*,
Science **329**, 659 (2010).

SP-ARPES

Bi-Sb

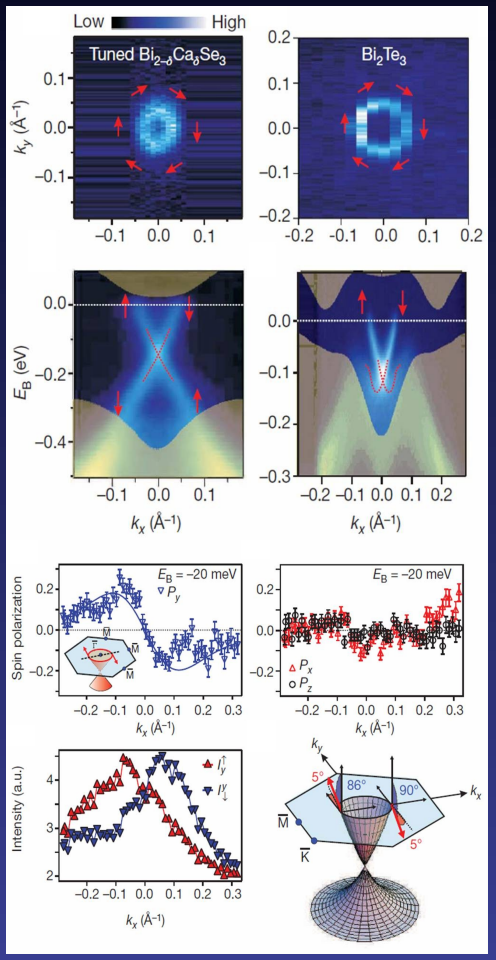


D. Hsieh *et al.*,
Science **323**, 919 (2009).



A. Nishide *et al.*,
PRB **81**, 041309(R)
(2010).

Bi_2Se_3, Bi_2Te_3



D. Hsieh *et al.*,
Nature **460**, 1103 (2009).

Helical Dirac cones at the surface are confirmed experimentally.

There is a helical Dirac cone. No doubt !!

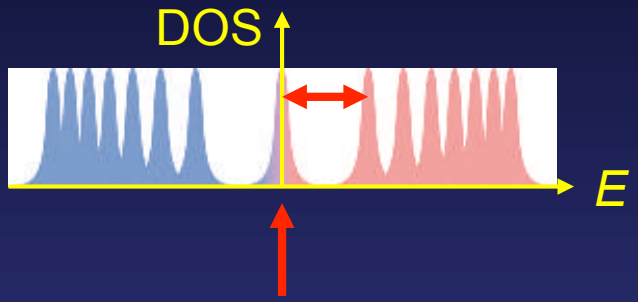


Massless Dirac dispersion ~unusual Landau levels

Lessons from graphene

A. H. Castro Neto *et al.*, Rev. Mod. Phys. **81**, 109 (2009).
A. K. Geim and K. S. Novoselov, Nat. Mat. **6**, 183 (2007).

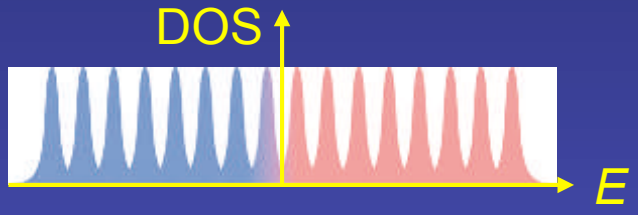
Dirac fermion : $E_n = E_0 + \mathrm{sgn}(n) v \sqrt{2e\hbar|n|B} \propto \sqrt{nB}$



J. W. McClure, PR 104 666 (1956).
Y. Zheng and T. Ando, PRB **65**, 245420 (2002).

- *B* independent LL with $n = 0$
- Large gap between $n = 0$ and 1

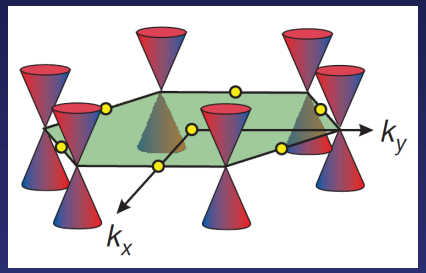
Conventional electron : $E_n = E_0 + \frac{e\hbar B}{m}(n + \frac{1}{2}) \propto nB$



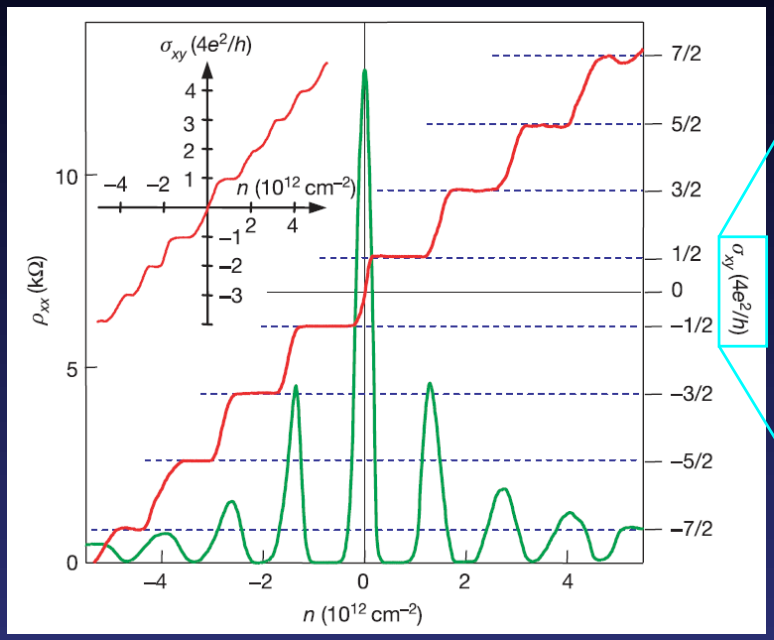
Unusual quantum transport under *B*

Graphene

D. Hsieh *et al.*,
Nature **460**, 1103 (2009).

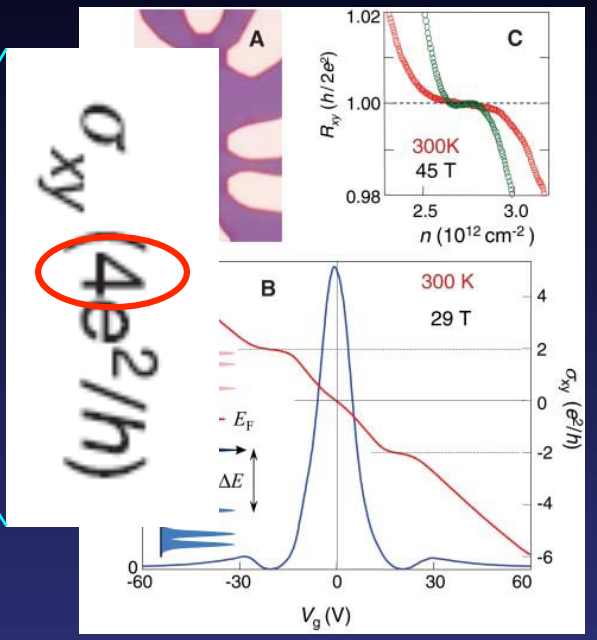


Half-integer QHE



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

QHE at RT



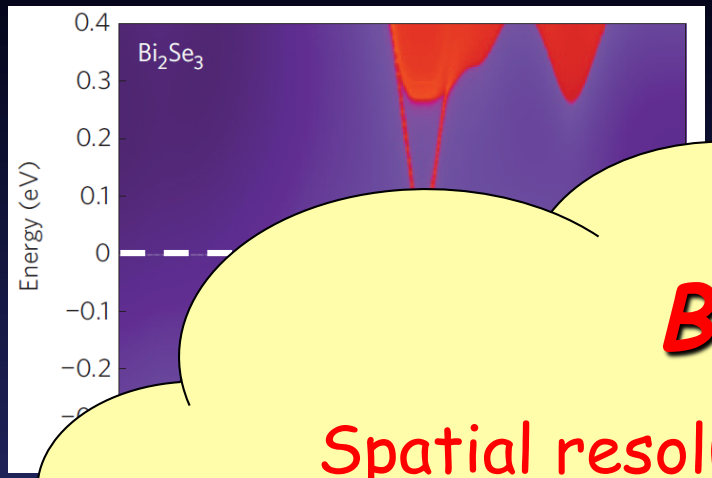
K. S. Novoselov *et al.*,
Science **315**, 1379 (2007).

Topological insulator

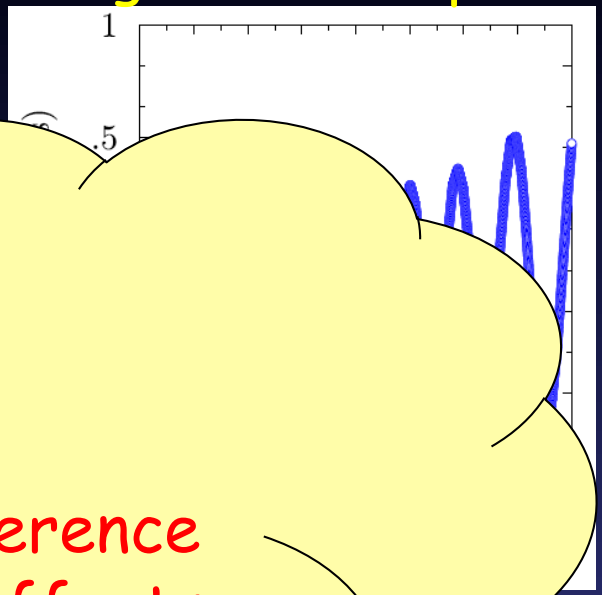
- Dirac fermions at the surface of a **LARGE BULK** material.
- SINGLE Dirac cone may give rise to TRUE half integer QHE.

Unavoidable bulk contribution in Bi_2Se_3...

Band calculation



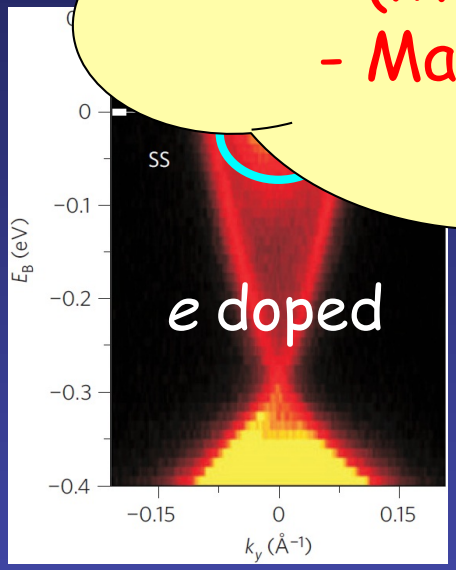
Magneto-transport



Bonus !!

Spatial resolution
- Quasi-particle interference
- (Magnetic) impurity effects
- Many other phenomena...

AR



...es...

Su...nsitive pr... necessary

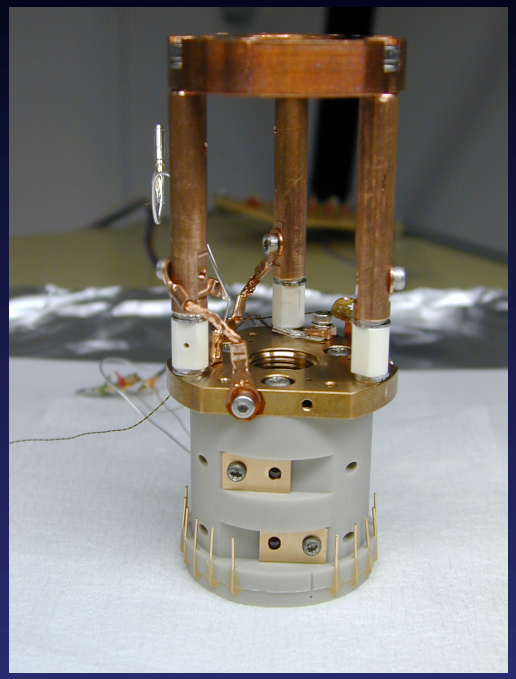
ARPES is not magnetic-f...d compatible.

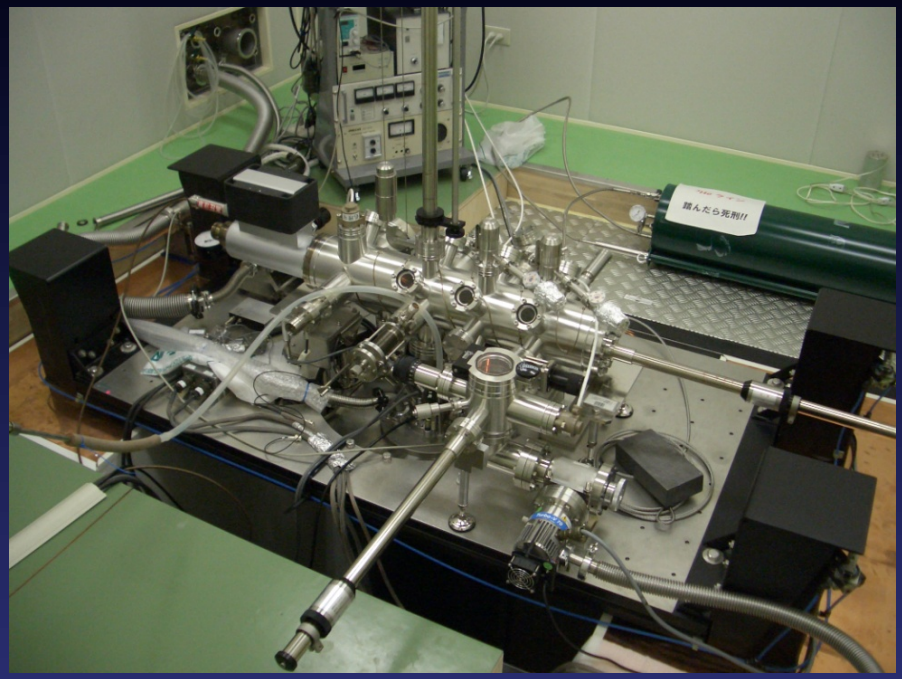
STM !

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

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

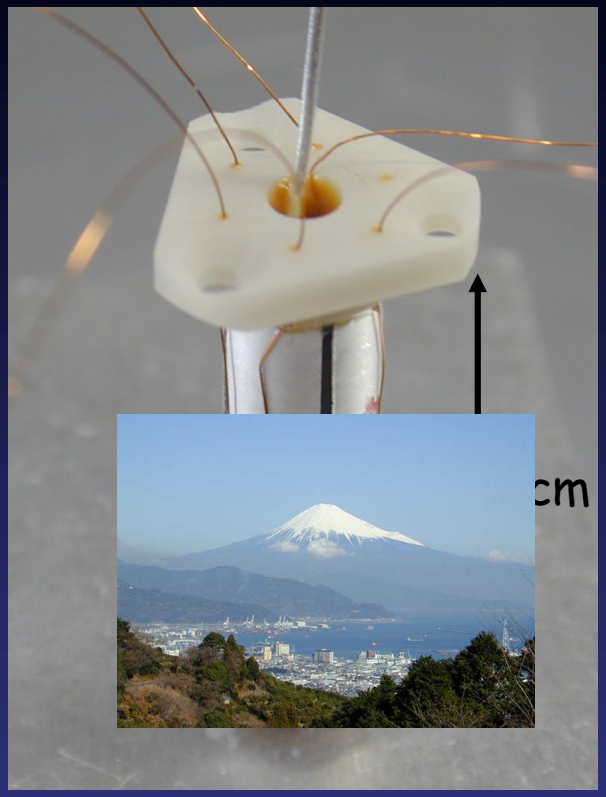
T. Hanaguri, J. Phys.: Conf. Ser. **51**,514 (2006). More info. available on my web page.





- 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)
- Long-term stability at base temp < Å/day
- Noise levels (1 kHz BW) < 0.5 pm, 1 pA

How small the sub-pm noise is?





http://news.xinhuanet.com/ziliao/2002-04/01/content_330553.htm

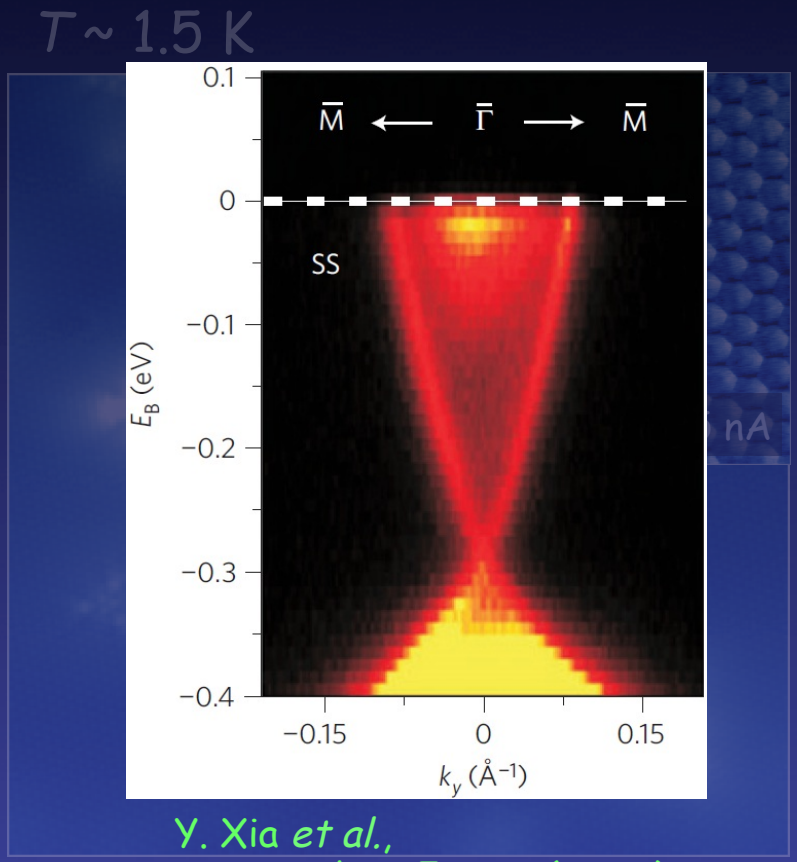
0.5 pm / 2 cm = 0.1 μm / 4000 m

We are manipulating Mt. Fuji with 0.1 μm resolution!

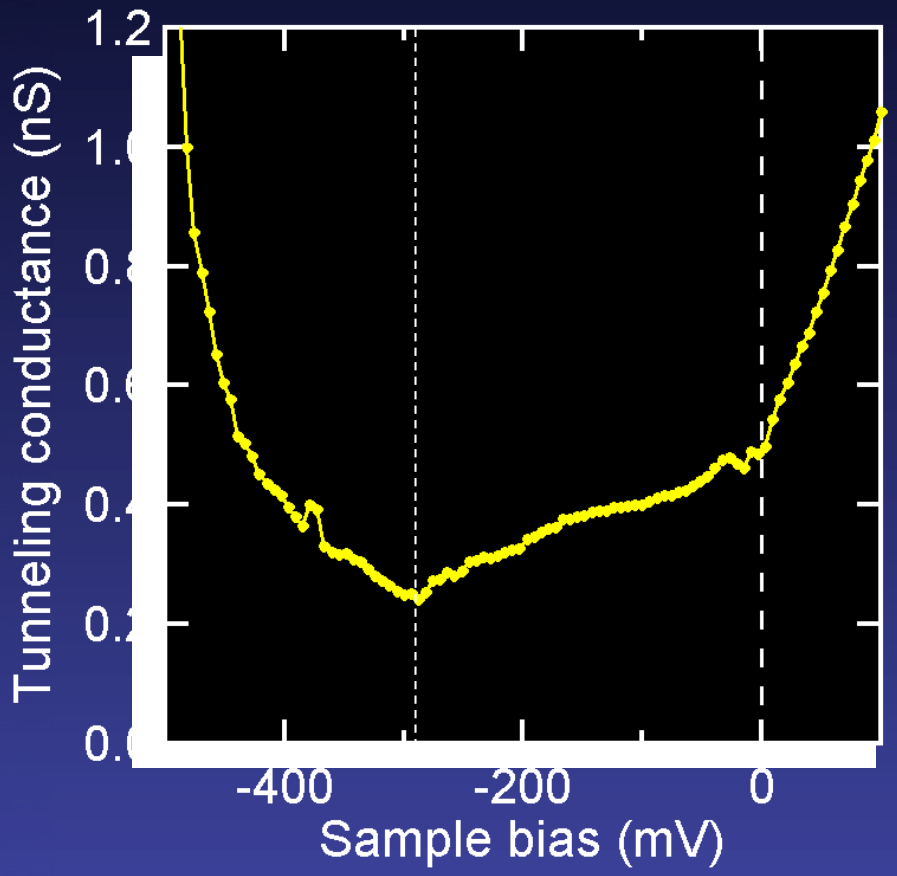
STM/STS on Bi_2Se_3

T. Hanaguri *et al.*, PRB **82**, 081305(R) (2010).

X'tals grown by Igarashi & Sasagawa (TIT)



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

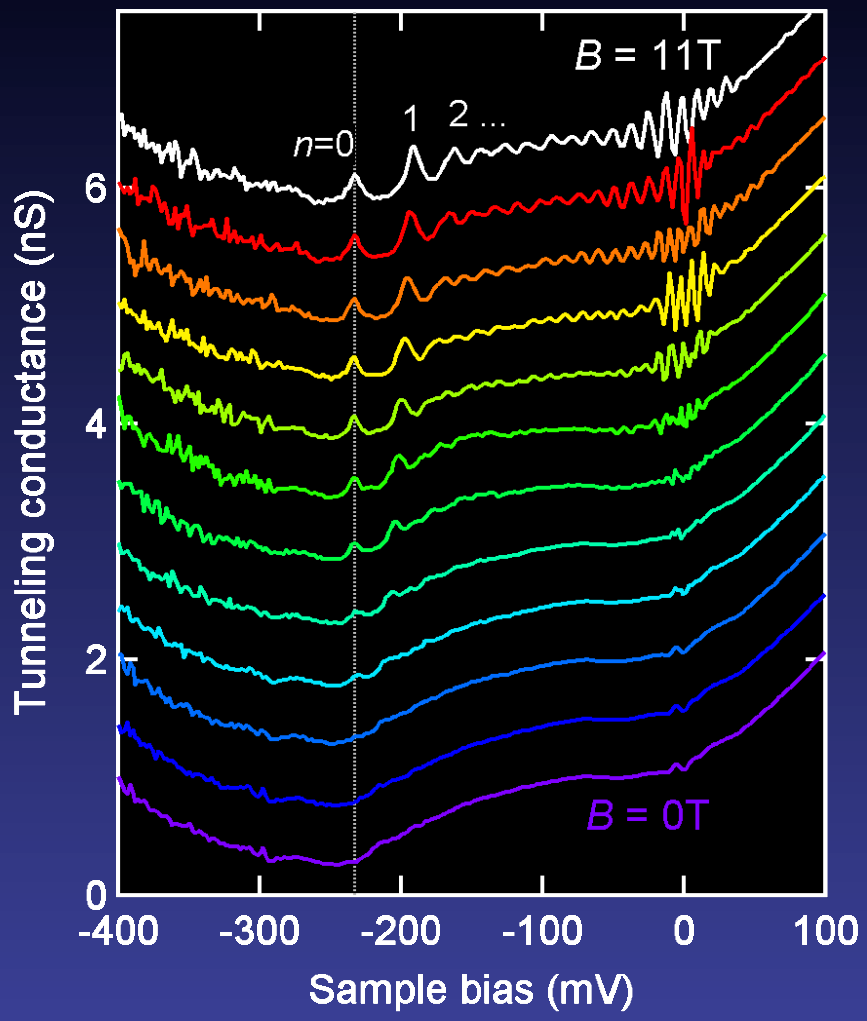


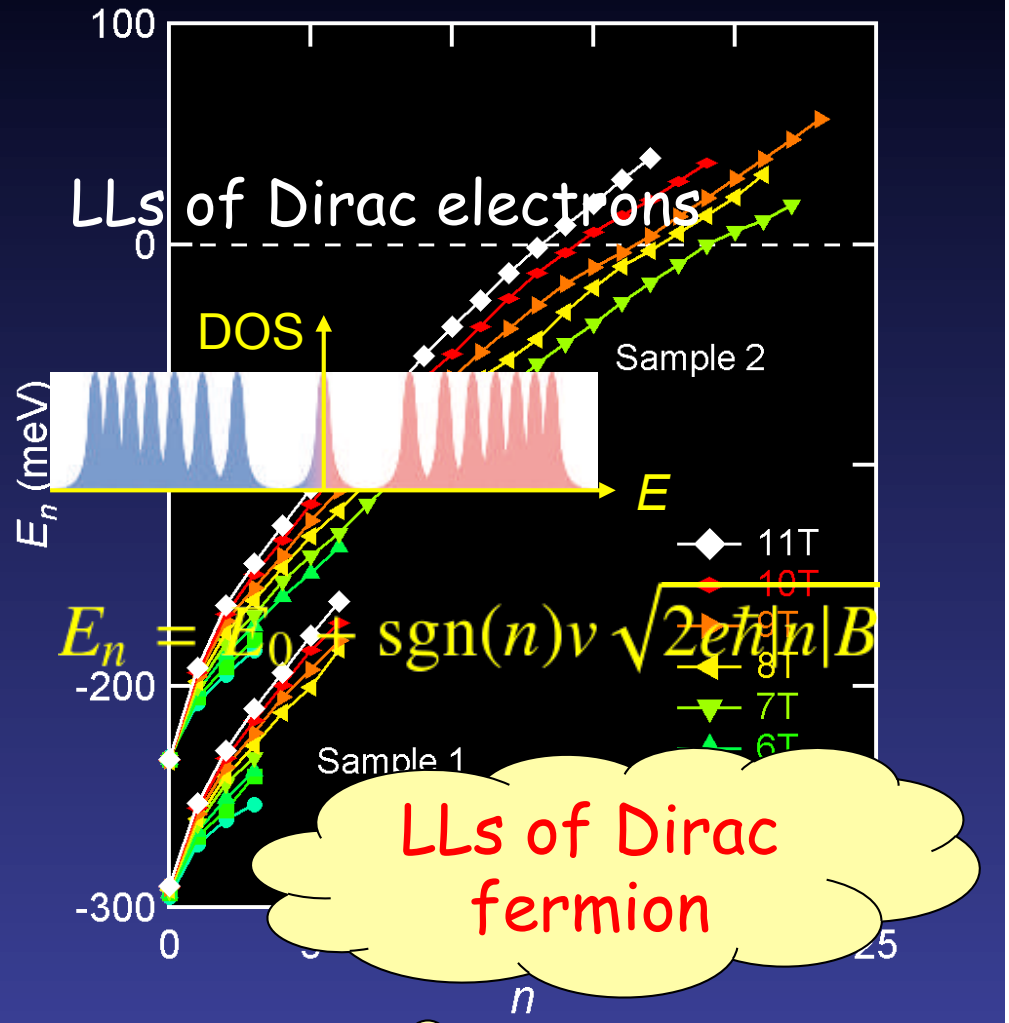
cf. S. Urazhdin *et al.*, Phys. Rev. B **66**, 161306(R) (2002); S. Urazhdin *et al.*, *ibid.* **69**, 085313 (2004).

Landau level spectroscopy in Bi_2Se_3

T. Hanaguri *et al.*, PRB **82**, 081305(R) (2010).
See also P. Cheng *et al.*, PRL **105**, 076801 (2010).

Data taken every 1 T





LLs of Dirac fermion

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

Scaling analysis

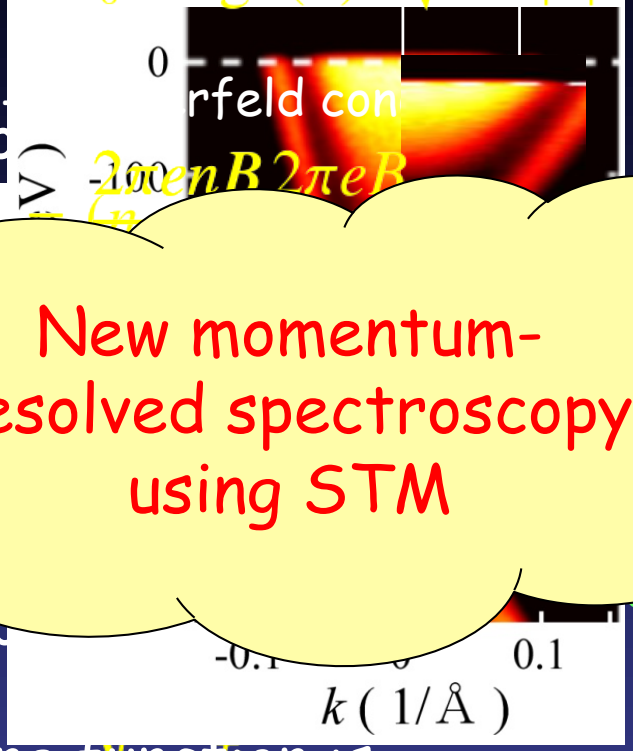
T. Hanaguri *et al.*, PRB **82**, 081305(R) (2010).

Comparison with ARPES

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

Bohr-
Grap
rfeld con

$\frac{2\pi enB}{} \quad \frac{2\pi eB}{}$



New momentum-resolved spectroscopy using STM

k_n

Scaling function is NOT linear in $(nB)^{1/2}$.

Y. L. Chen *et al.*, Science **329**, 659 (2010).

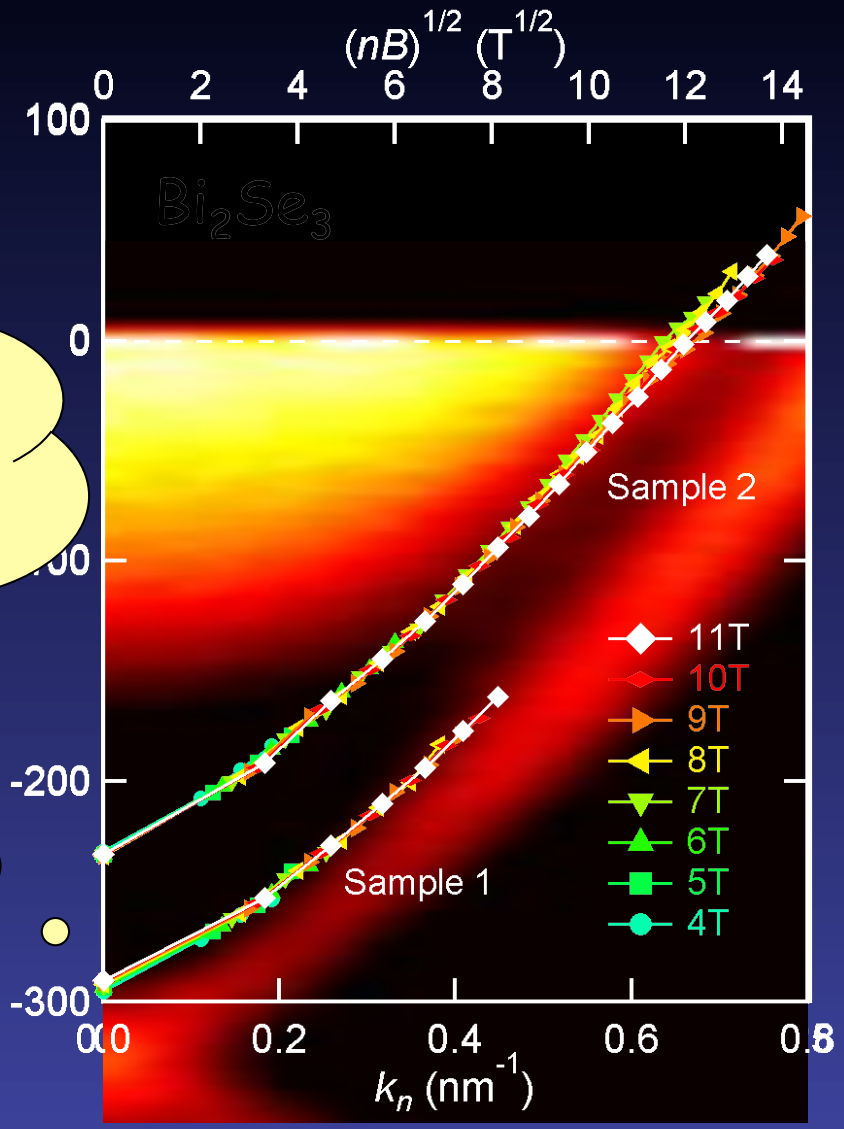


nergy dependent in Bi_2Se_3.

p-induced band bending

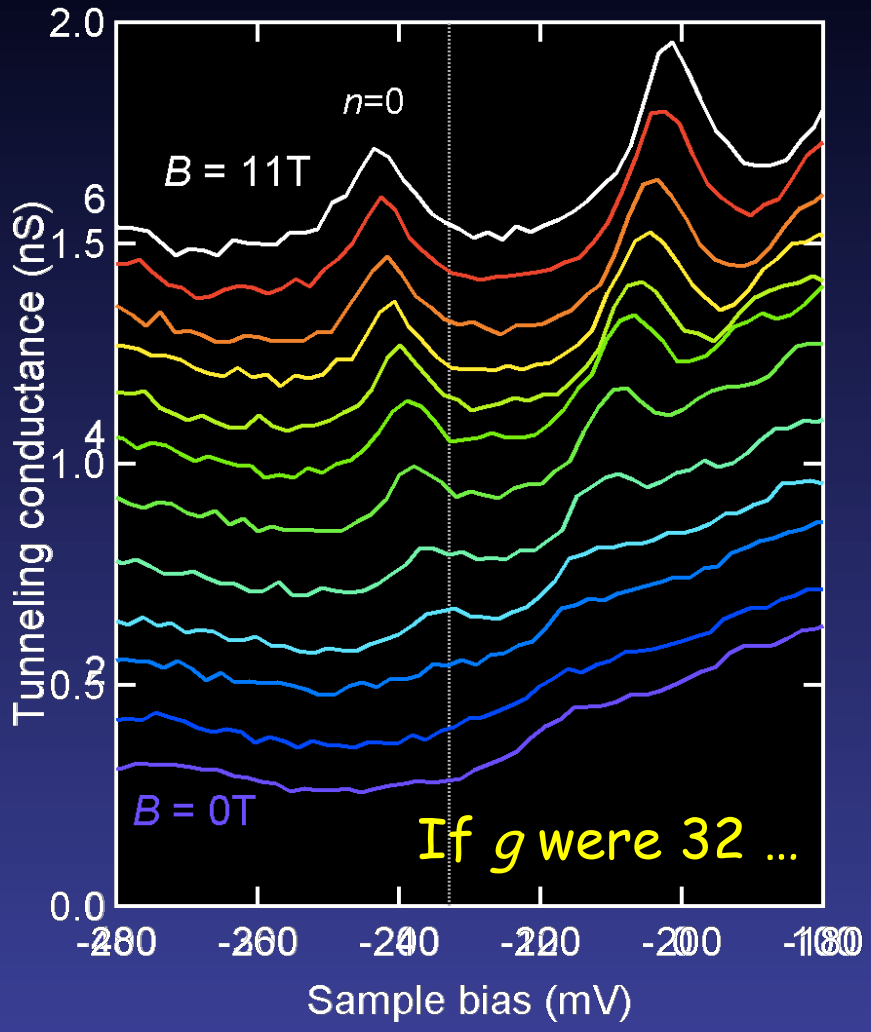
Cheng *et al.*, PRL **105**, 076801 (2010).

M. Kawamura



Other unusual features

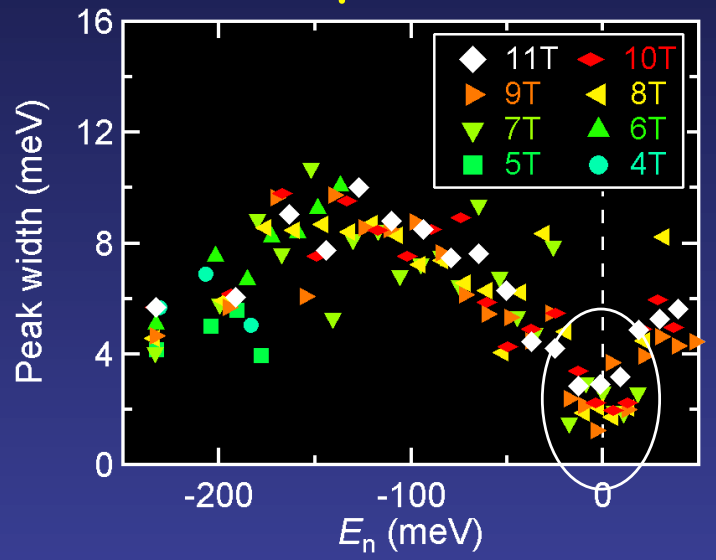
T. Hanaguri *et al.*, PRB **82**, 081305(R) (2010).



- Zeeman effect is small
  - cf. bulk g factor ~ 32

H. Köhler and F. Wüchner, Phys. Status Solidi (b) **67** , 665 (1975).

- Enhaned amplitude near E_F



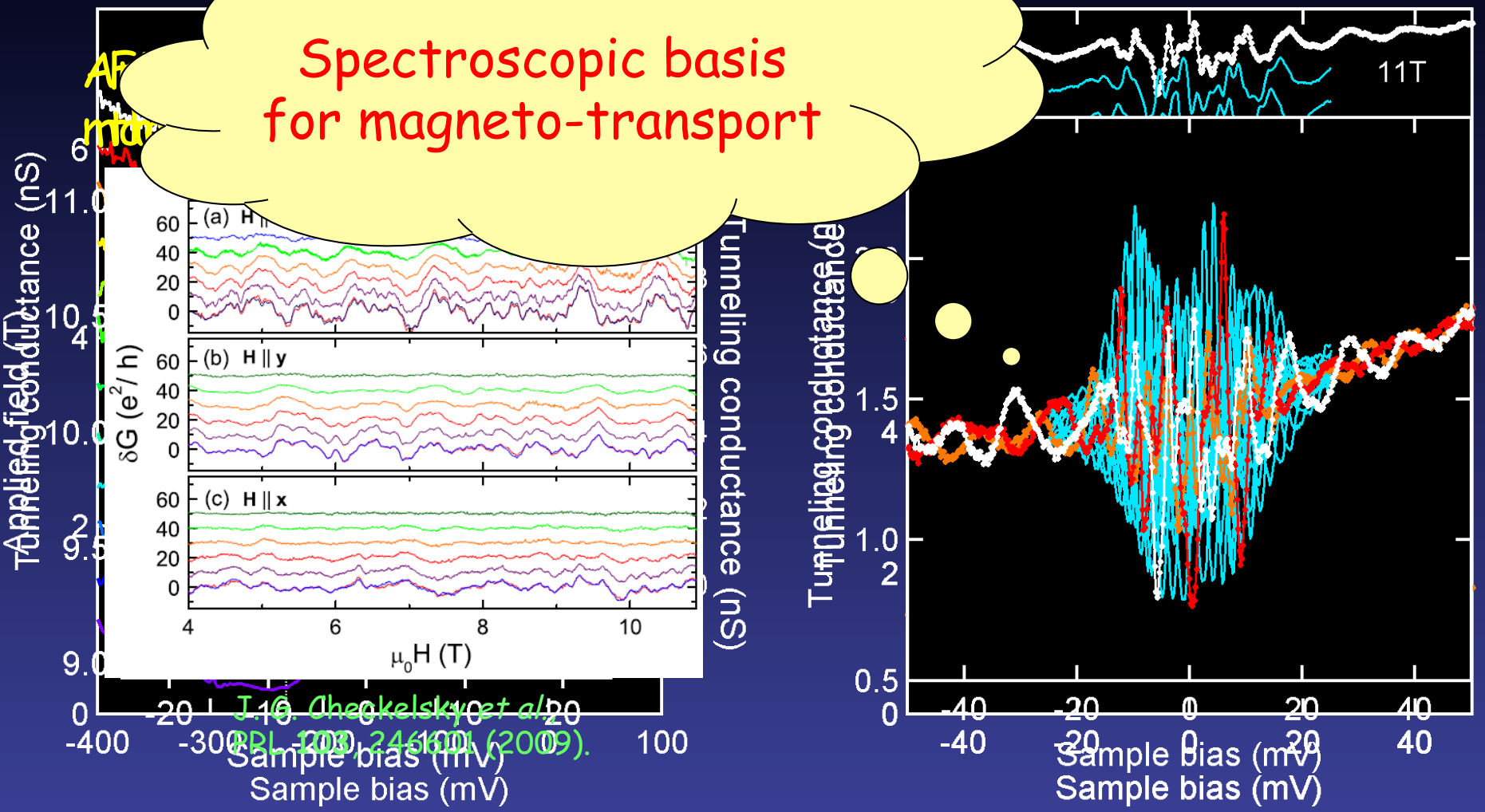
-E-dependent QP lifetime

cf. S. R. Park *et al.*, PRB **81**, 041405(R) (2010).

Anomalous fine features near E_F

T. Hanaguri *et al.*, PRB **82**, 081305(R) (2010).

Spectroscopic basis
for magneto-transport



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

- Fine structures appear near E_F
- Amplitude enhances suddenly $|E| <$ ~15 mV

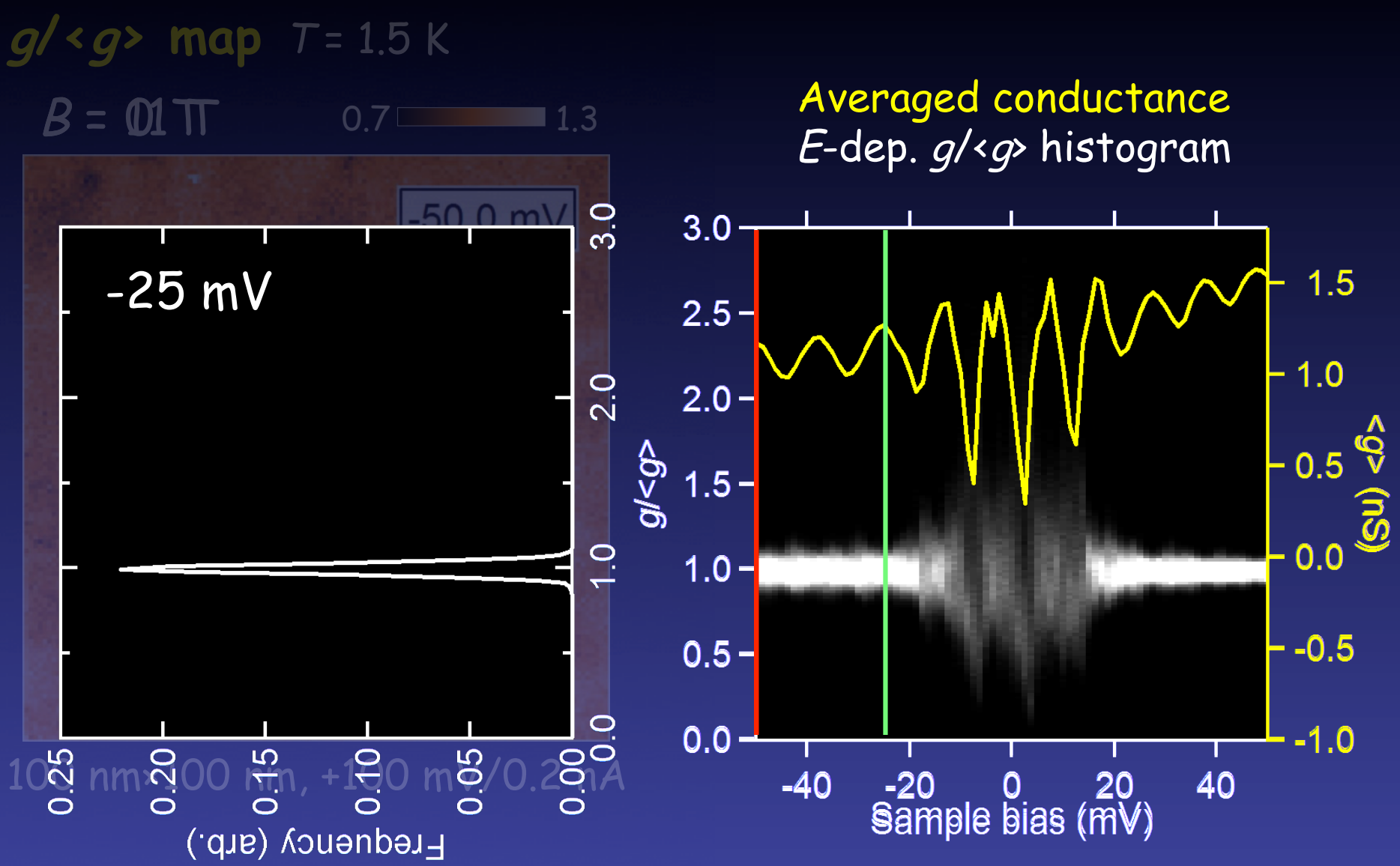
What's next?

Bonus !!

Spatial resolution

- Quasi-particle interference
- (Magnetic) impurity effects
- Many other phenomena…

A new energy scale in Bi_2Se_3

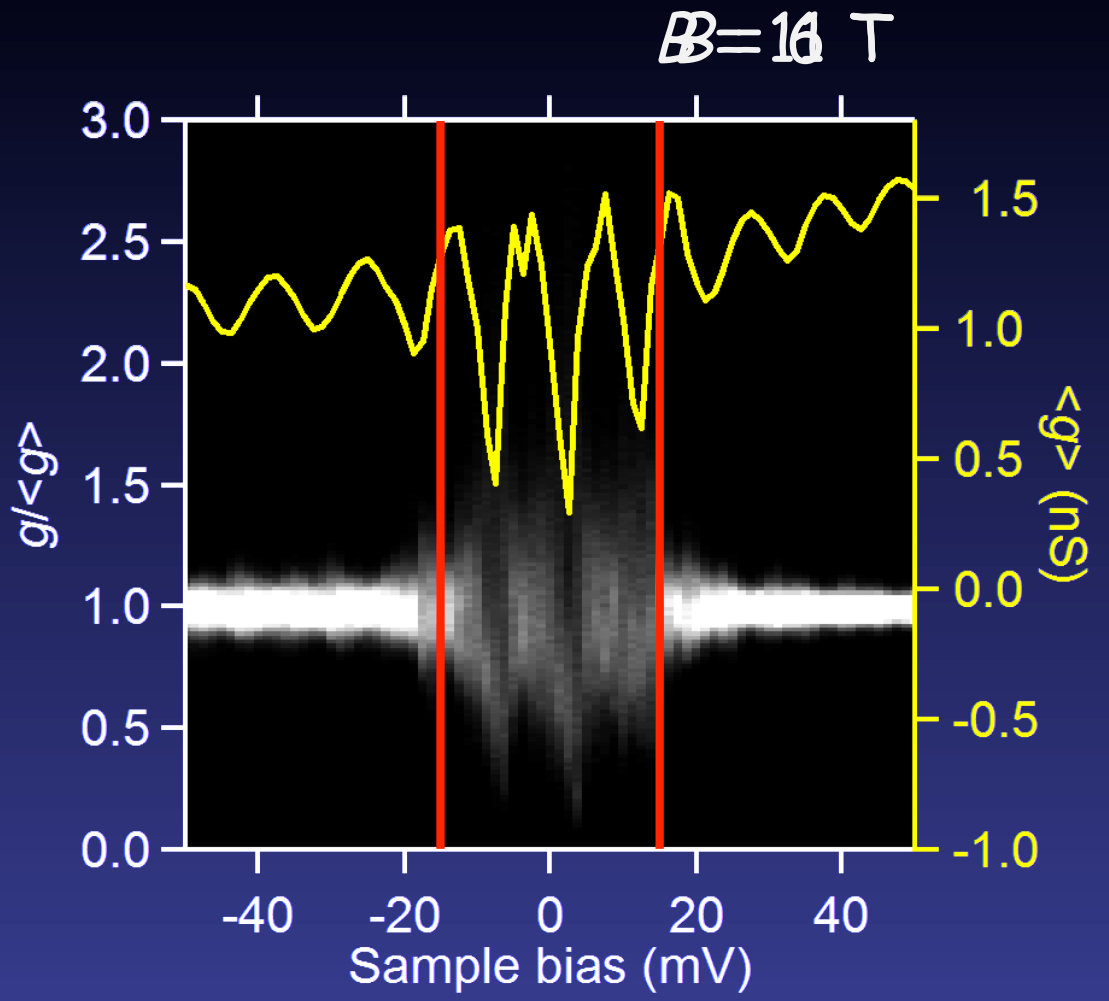


|E| ~ 15 mV is a well defined energy scale !!

What is |E| ~ 15 mV ?

Sample 1
(10^{19}/cm^3)

Sample 2
(10^{20}/cm^3)

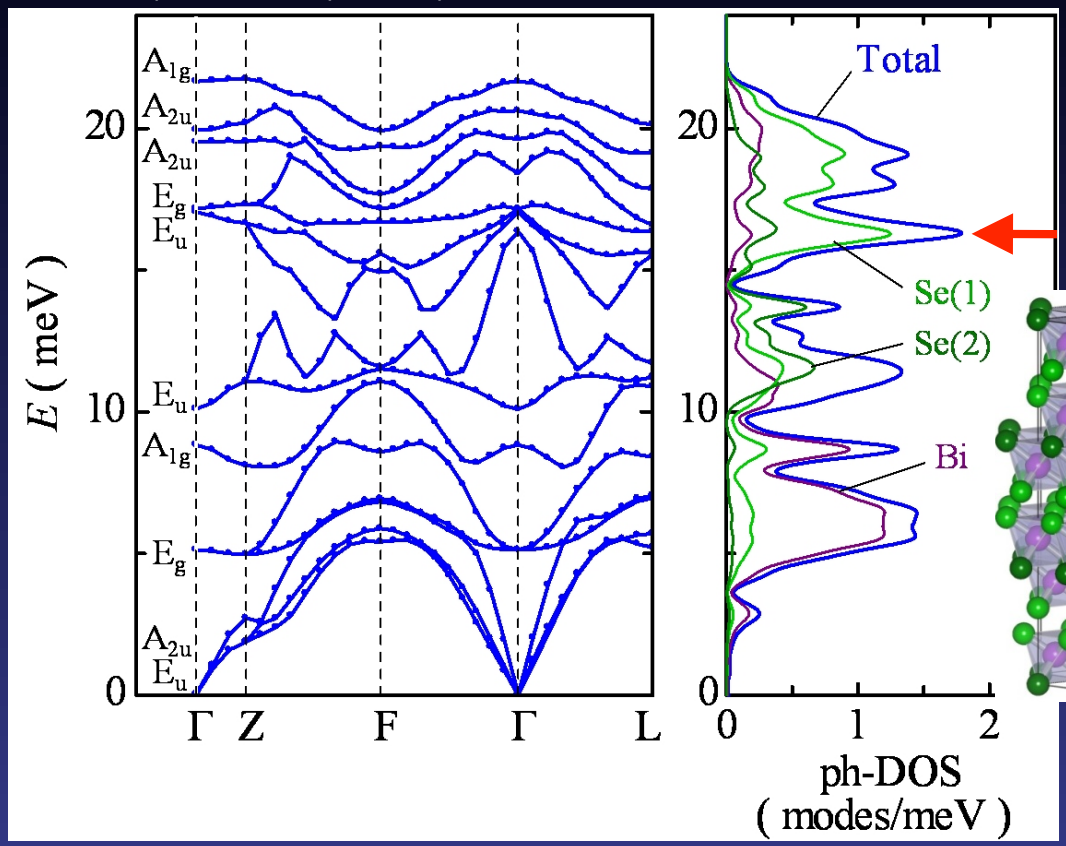


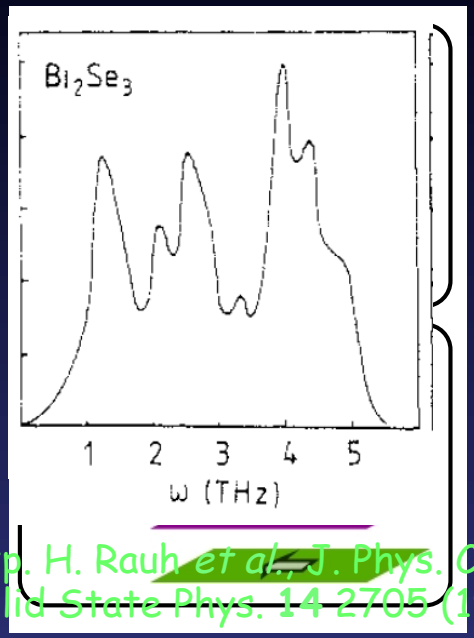
Phonons?

- Symmetric about E_F, corresponding to fine structures
- No field dependence
- No carrier-density dependence

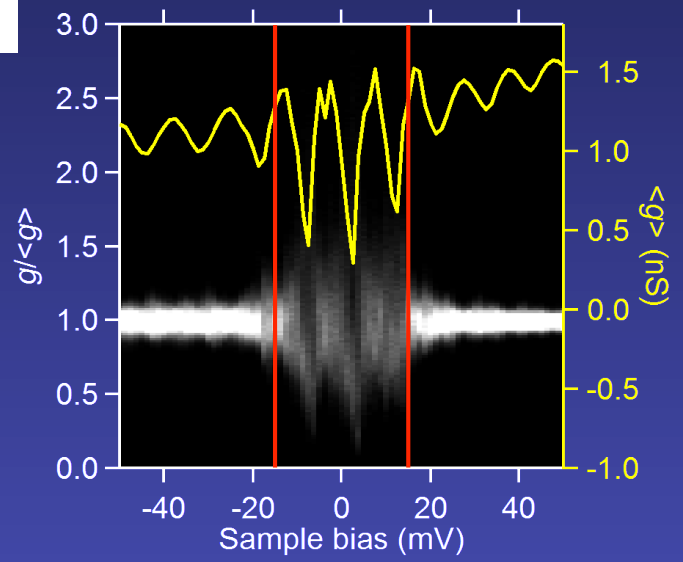
Possible electron-phonon coupling

1st-principle phonon calc. T. Sasagawa





Exp. H. Rauh *et al.*, J. Phys. C: Solid State Phys. 14 2705 (1981).



Inhomogeneity $|E|$ < 15 meV

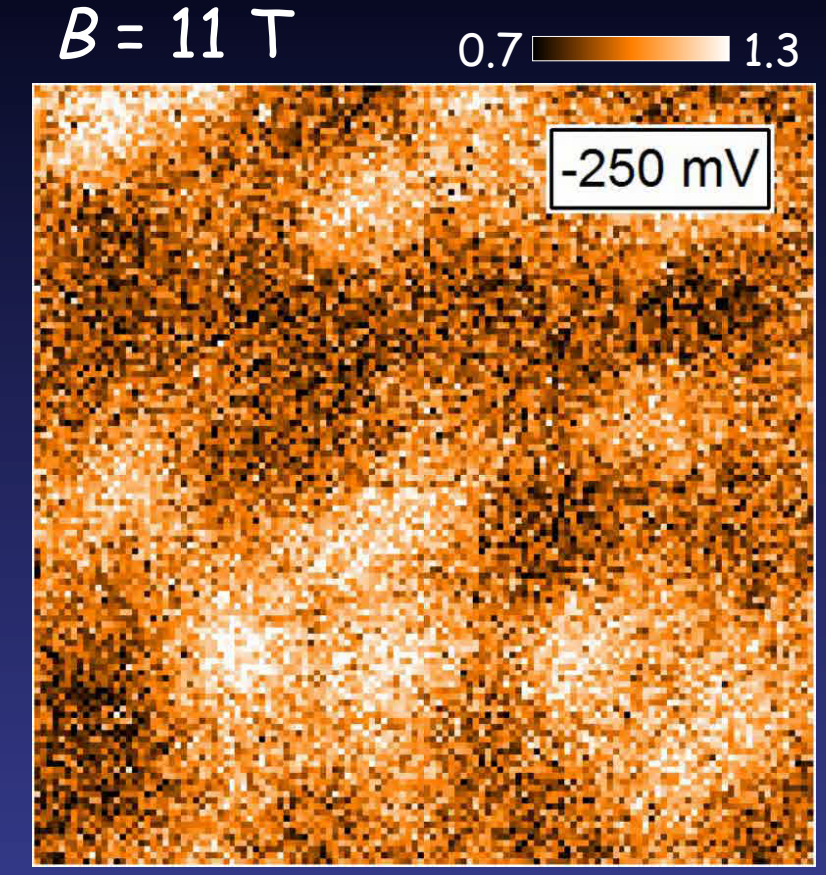
- Landau orbit, Interference

Homogeneity $|E|$ > 15 meV

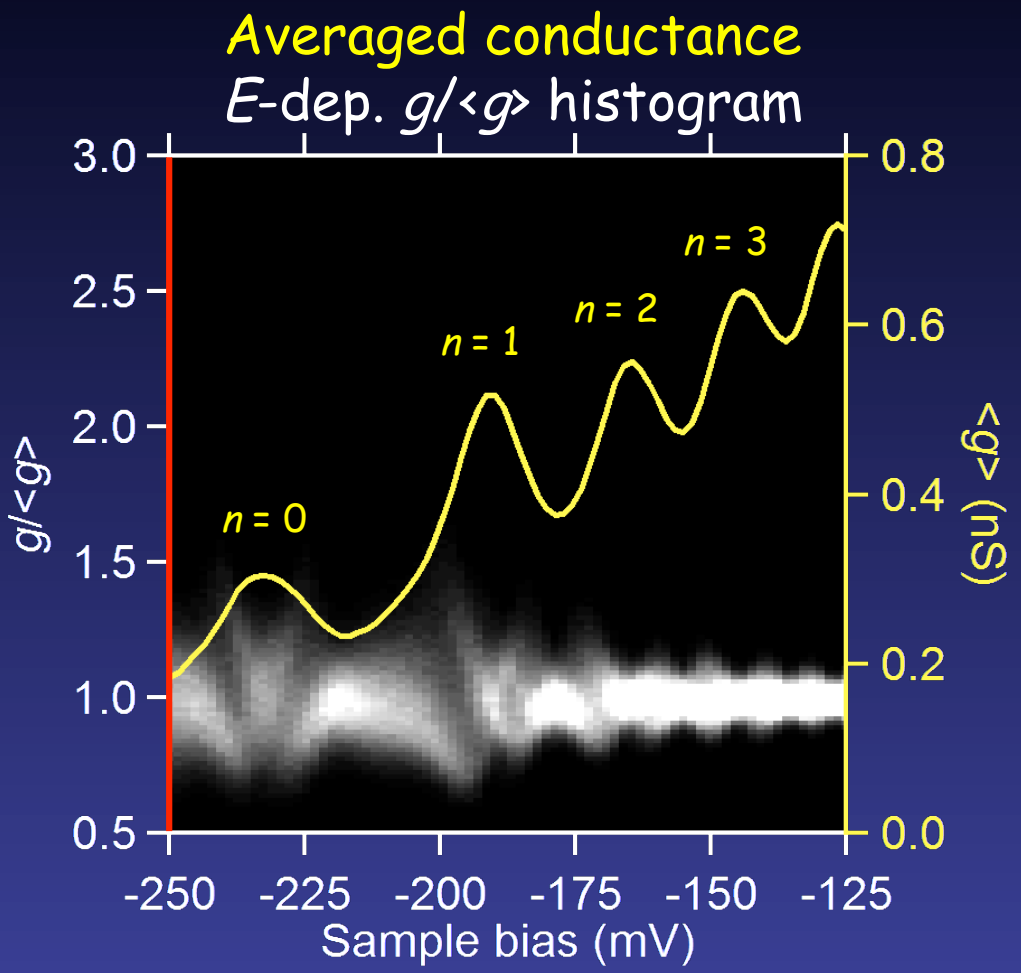
- smearing by exciting phonons

Spatial variations near the Dirac point

$g/\langle g\rangle$ (normalized conductance ∝ LDOS) map T = 1.5 K



100 nm×100 nm, -250 mV/0.2 nA



Evolution of localized/extended states

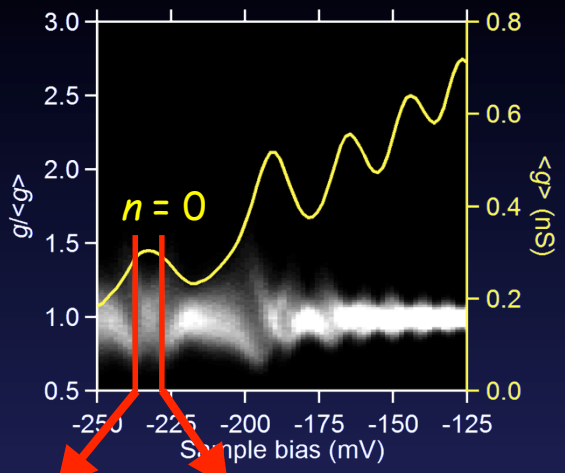
cf. K. Hashimoto *et al.*, PRL **101**, 256802 (2008). *n*-InSb(110)
D. L. Miller et al., Nat. Phys. **6**, 811 (2010). Graphene

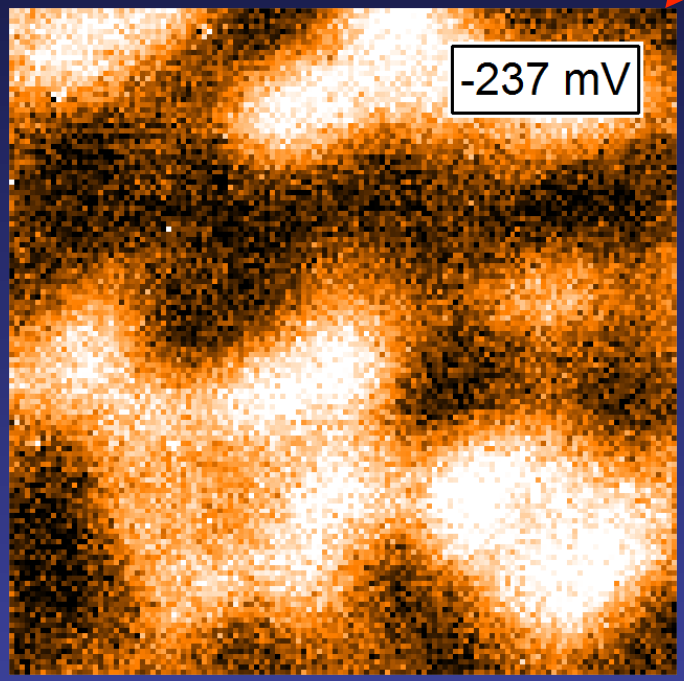
Complementary spatial features below/above E_{DP}

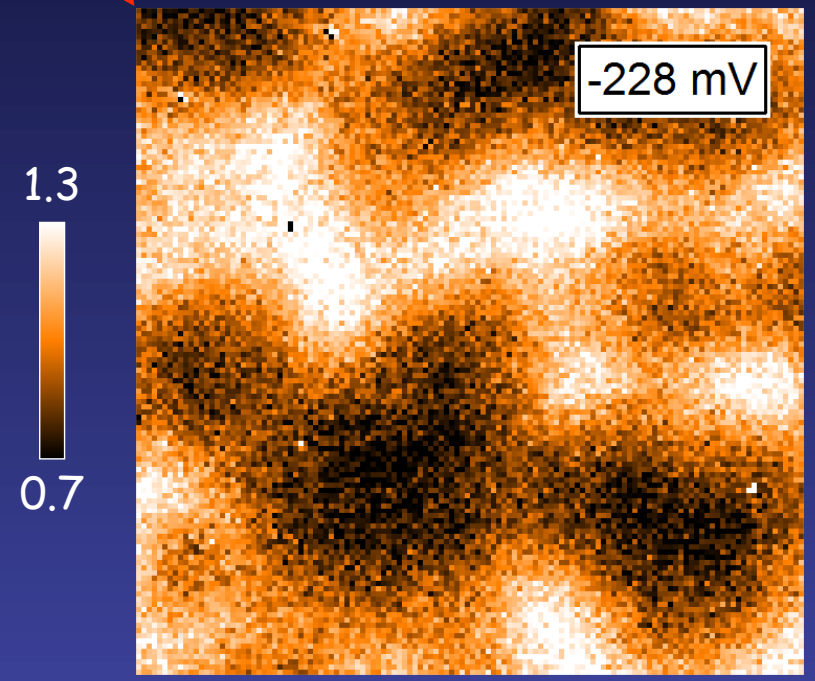
$g/\langle g \rangle$ map T = 1.5 K

B = 11 T

100 nm×100 nm,
-250 mV/0.2 nA







Low/high energy states localize near potential minima/maxima.

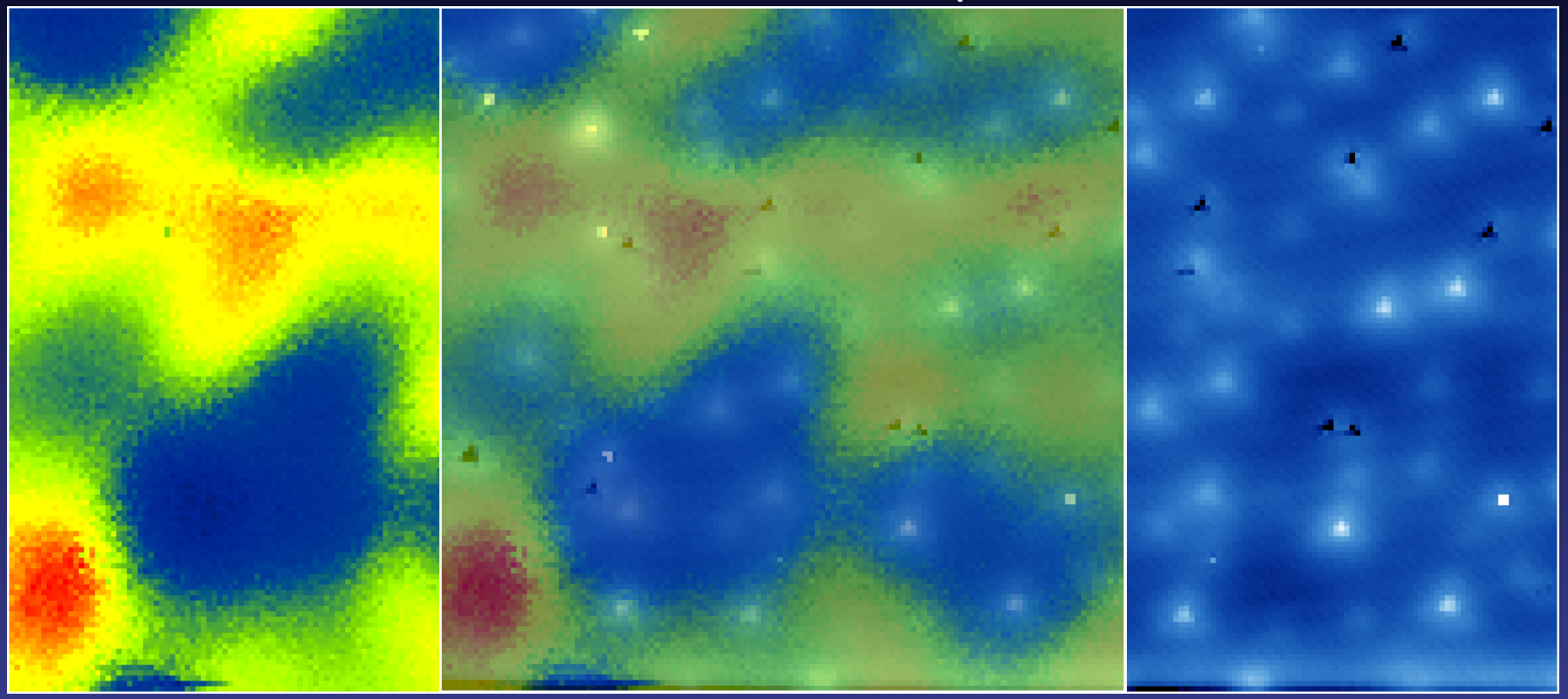
D. L. Miller et al., Nat. Phys. **6**, 811 (2010). Graphene

Imaging potential landscape

Energy of $n = 0$ state $T = 1.5$ K, 100 nm×100 nm

$B = 11$ T

Cross Correlation

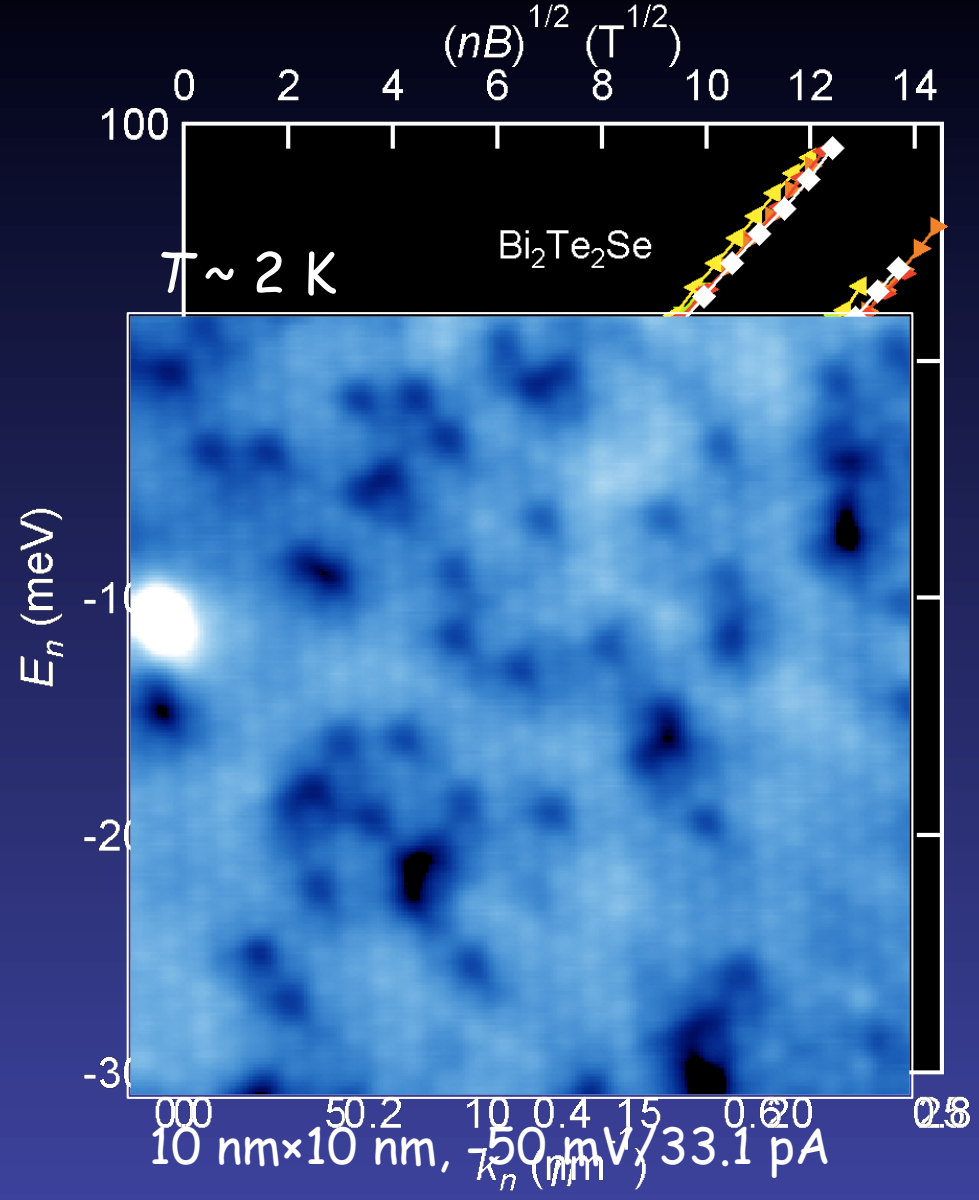


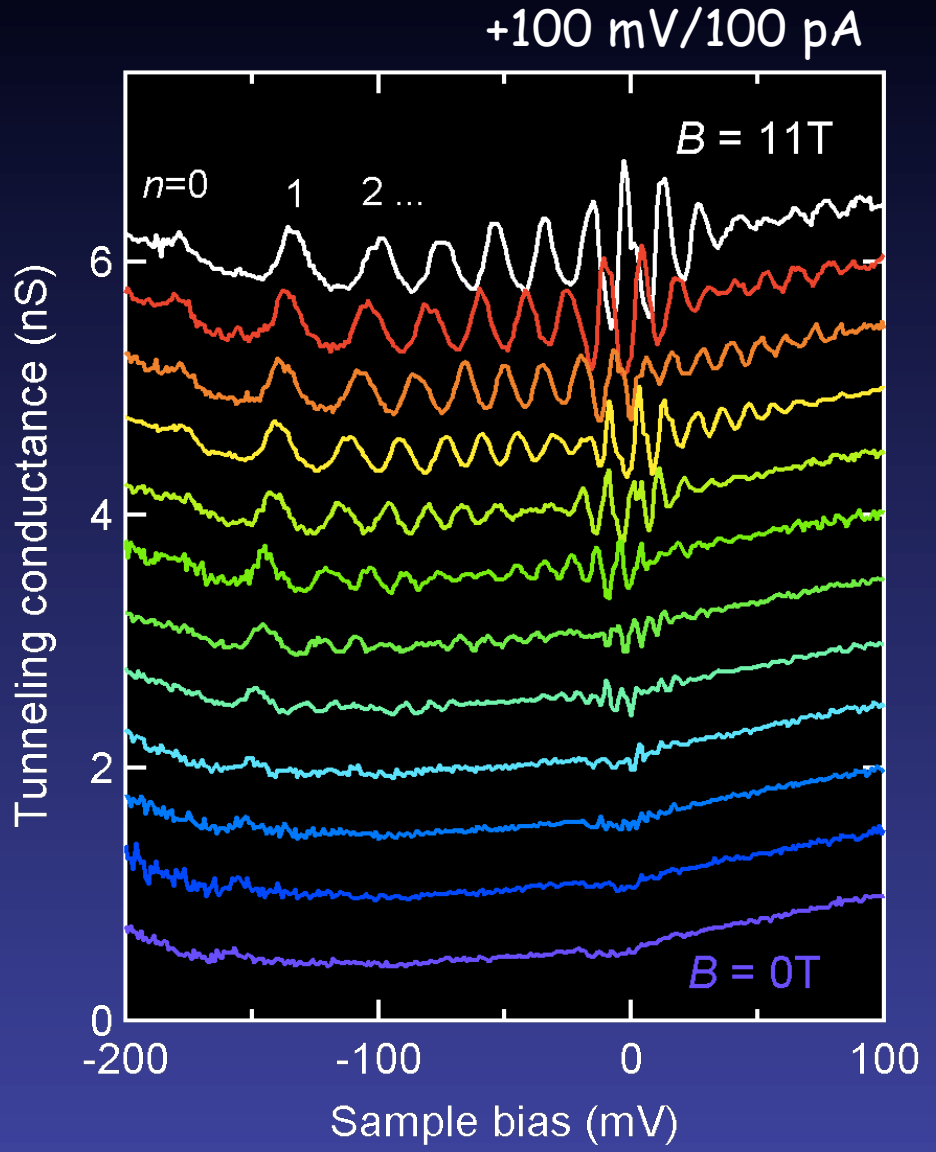
-245mV -220mV

-0.15 0.15

Se vacancies lower E_{DP} ⟶ Electron dopants

Landau levels in Bi_2Te_2Se



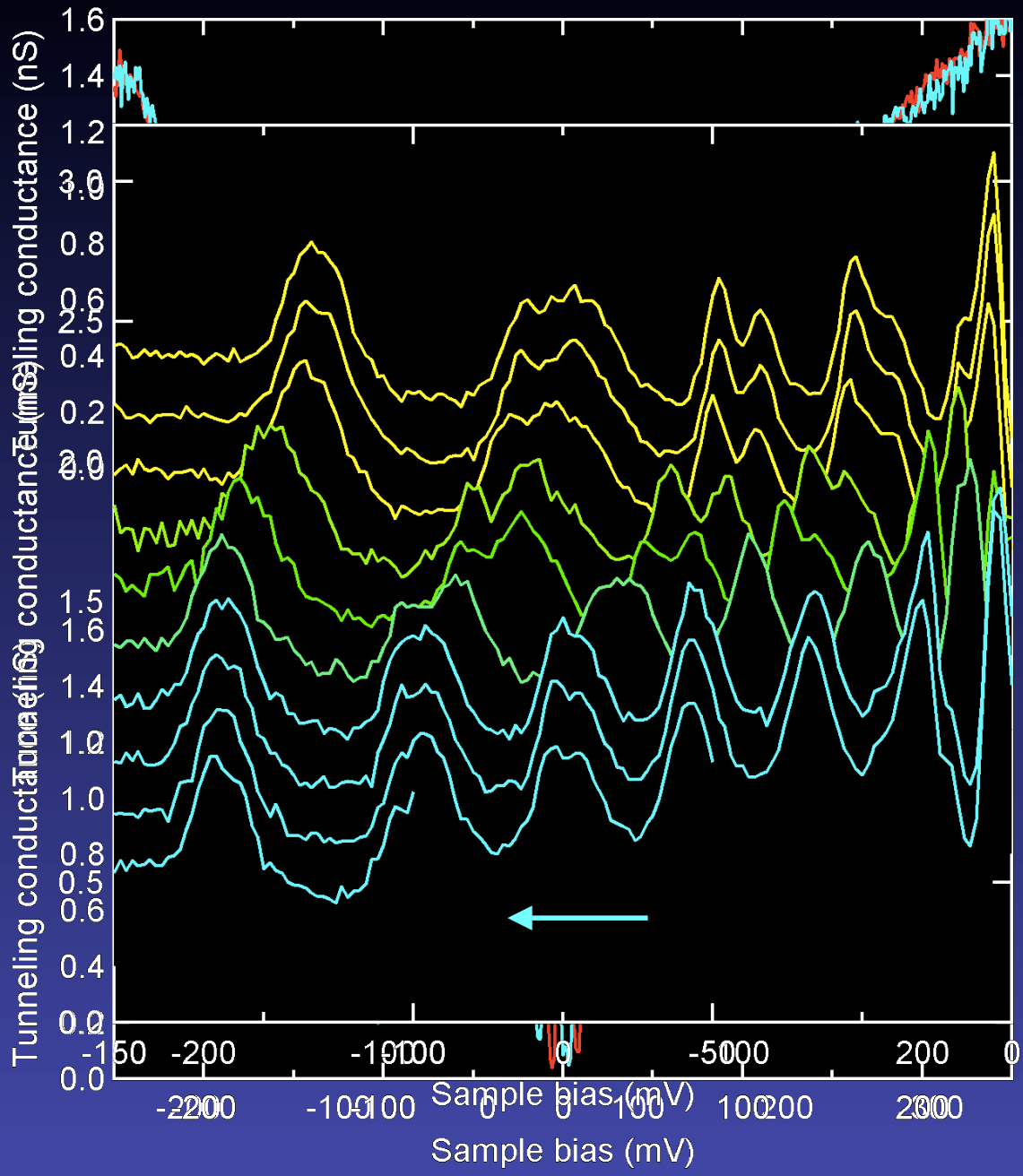


Similar E-k dispersion between Bi_2Se_3 and Bi_2Te_2Se

Anomalous hysteresis in the spectra

$T \sim 2$ K
$H = 11$ T

$V_s = -50$ mV
$I_t = 33.1$ pA



Hysteresis in the spectra appears

$V_{max} < 60$meV
: No shift
No hysteresis

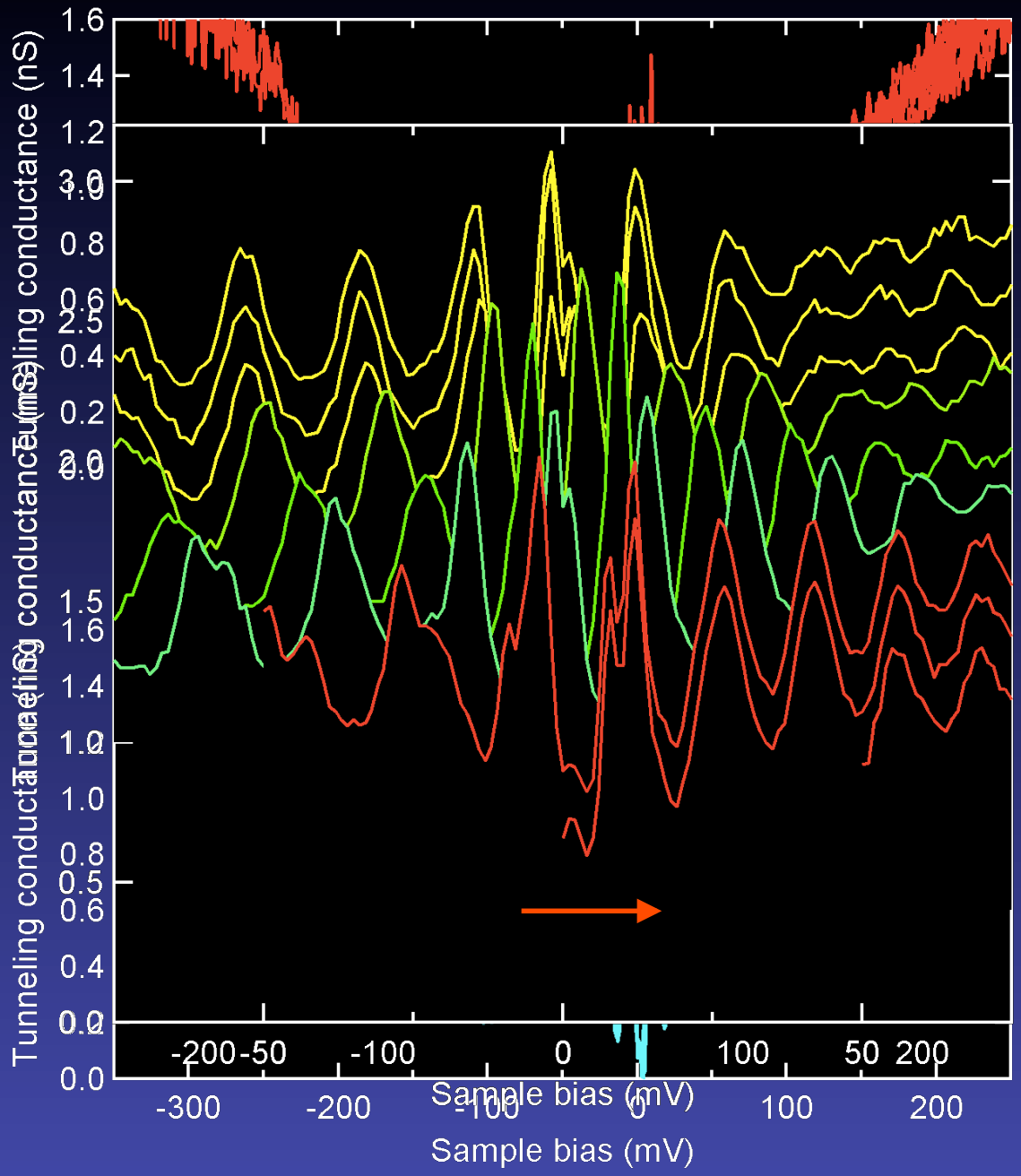
Hysteresis disappears

$V_{max} > 60$meV

Reversing the polarity

$T \sim 2$ K
$H = 11$ T

$V_s = -50$ mV
$I_t = 33.1$ pA



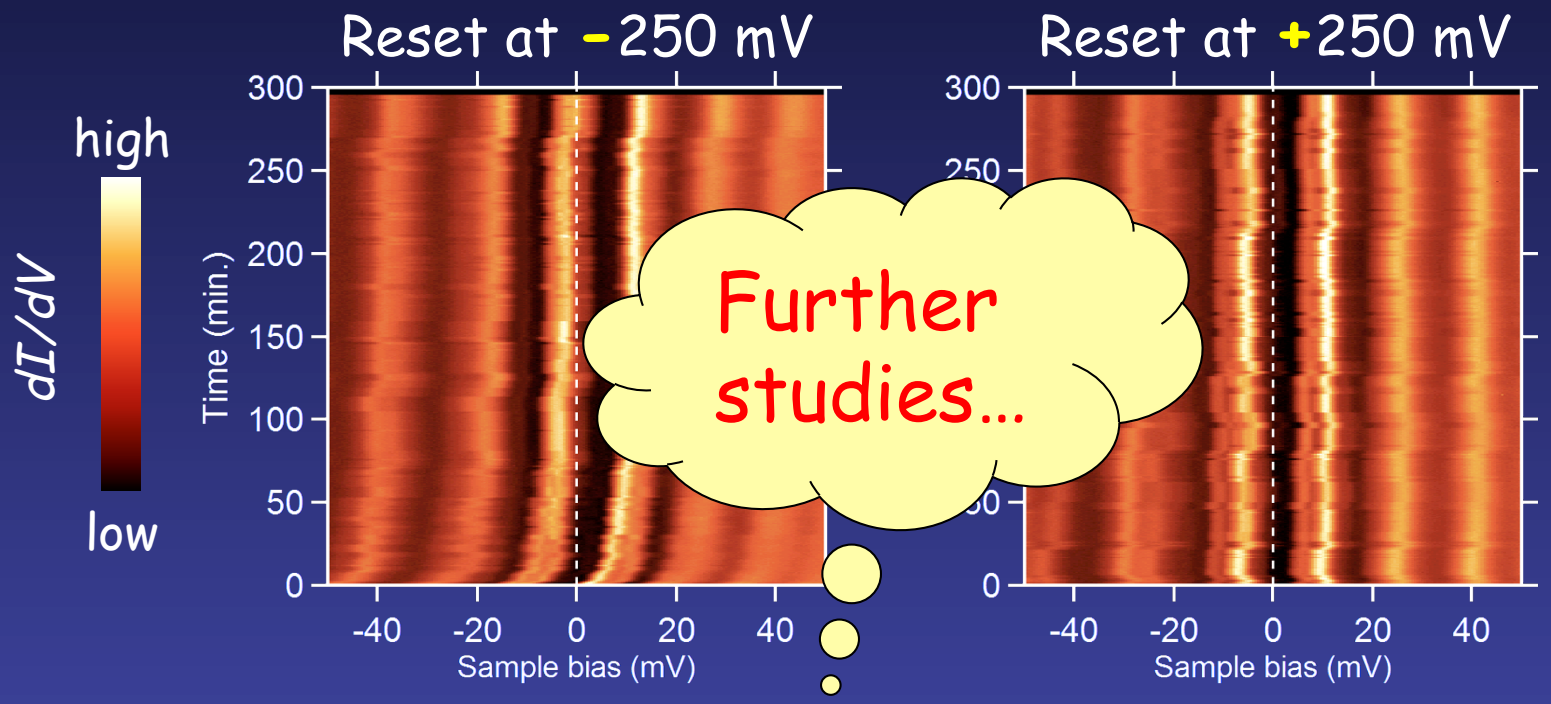
Forward branches do not coincide.

$-60\text{meV} < V_{min}$
: No shift
No hysteresis

Backward branches are all same.

Memory effect

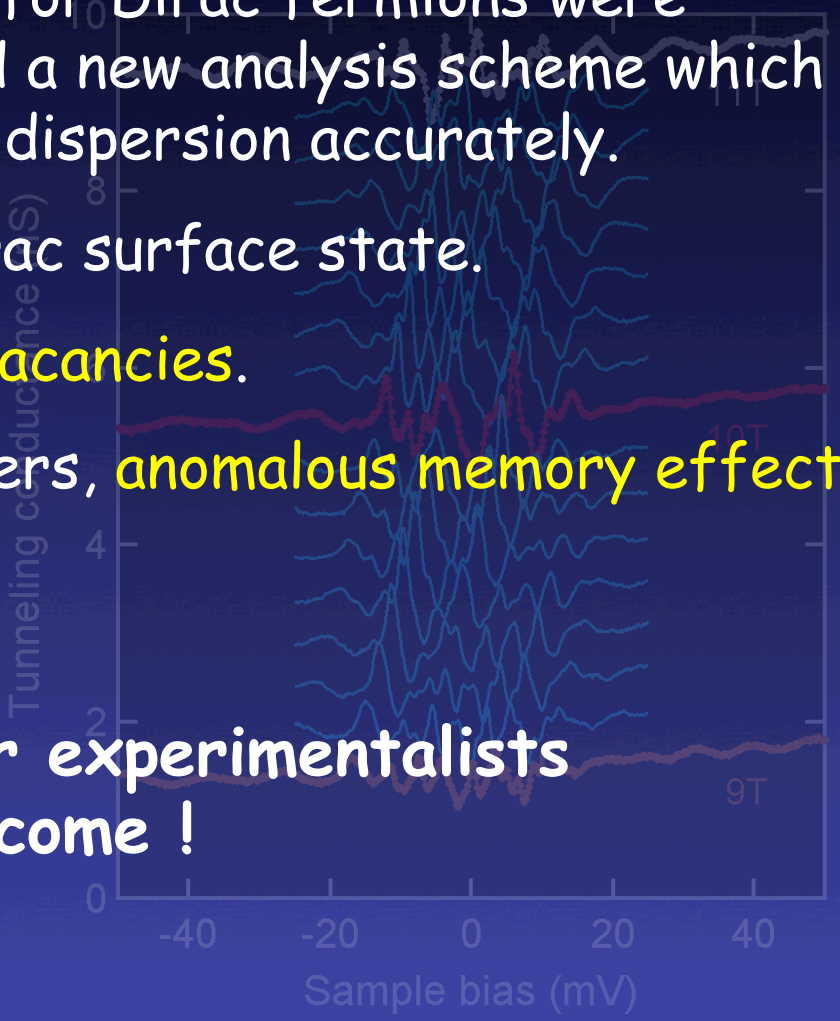
- Reset bias voltage ±220 mV
- Critical bias voltage ±60 mV
- The state reset at positive bias voltage is more robust than that reset at negative bias voltage.



- Tip-induced charging/band bending?
- Dirac surface state plays a role?

Summary

- Dirac fermions at the surface of topological insulators Bi_2Se_3 Bi_2Te_2Se have been studied using STM/STS in a magnetic field.
- Unusual Landau levels expected for Dirac fermions were identified clearly. We developed a new analysis scheme which enables us to determine the QP dispersion accurately.
- Phonons may couple with the Dirac surface state.
- Dirac point correlates with Se vacancies.
- In Bi_2Te_2Se with less bulk carriers, anomalous memory effect has found.



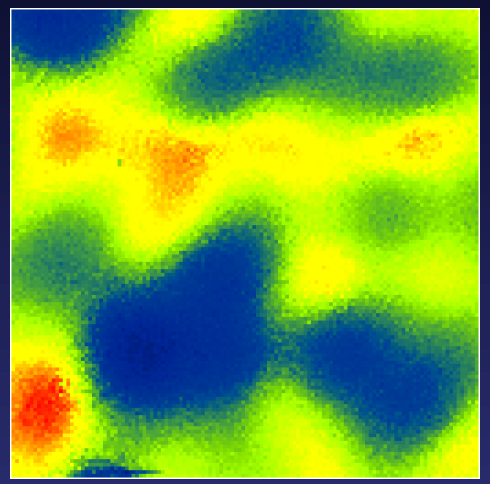
Any suggestions for experimentalists are welcome !

Fin

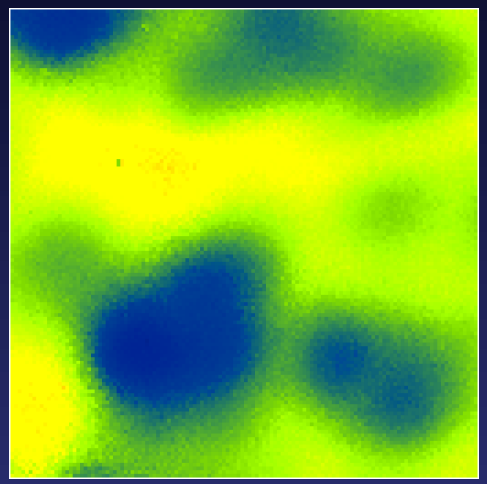
Imaging Landau levels

E_{av} ± 12.5 mV

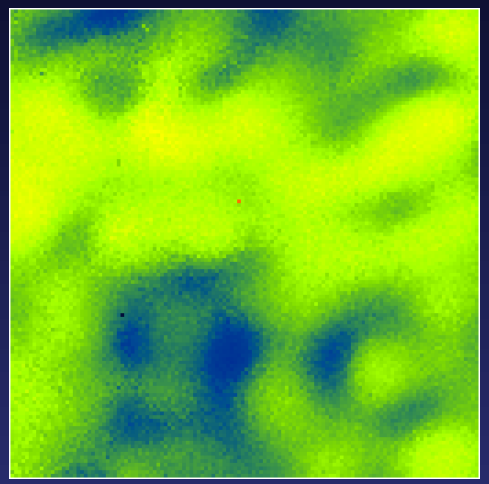
$n = 0$



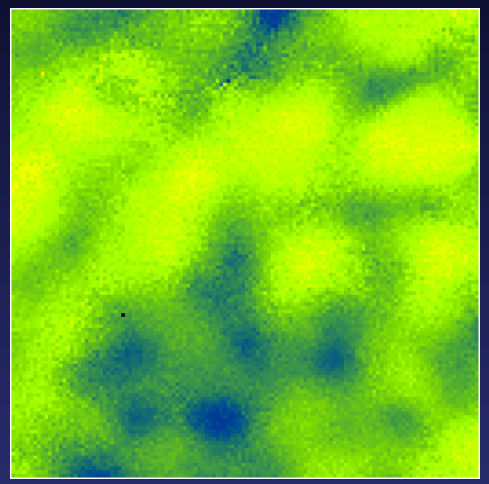
$n = 1$



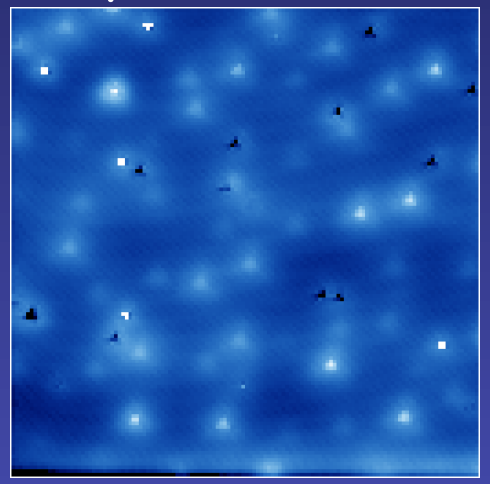
$n = 2$



$n = 3$

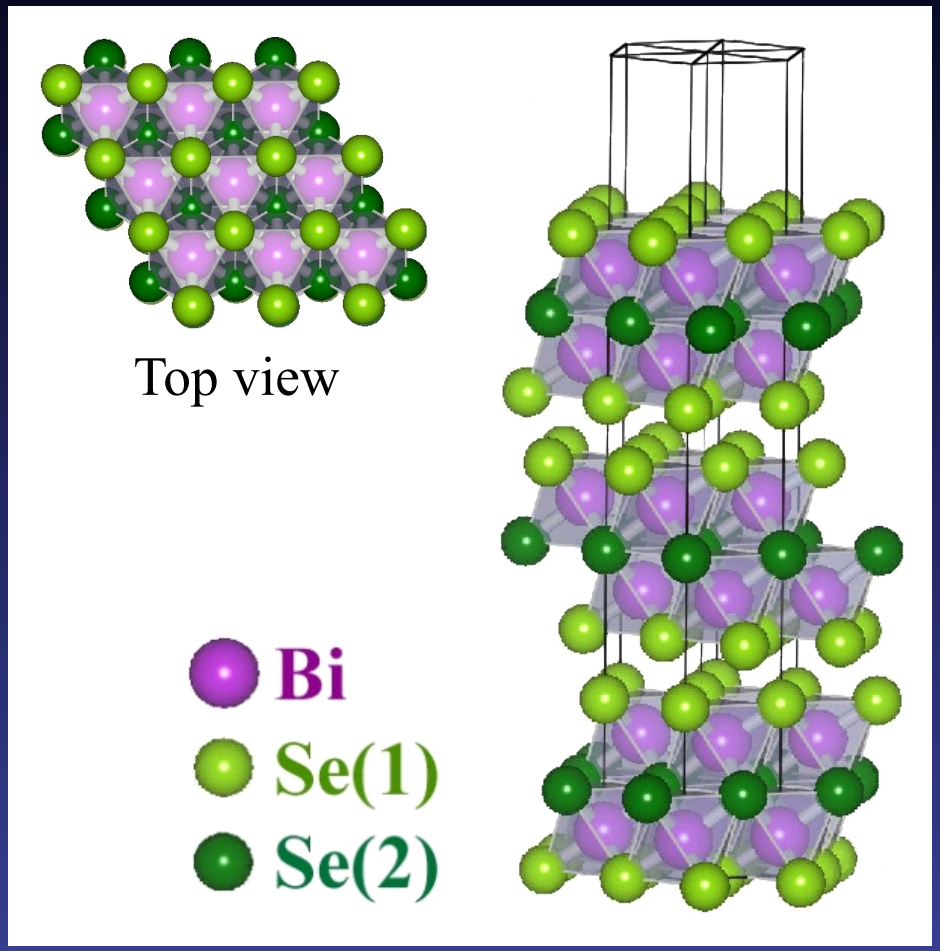


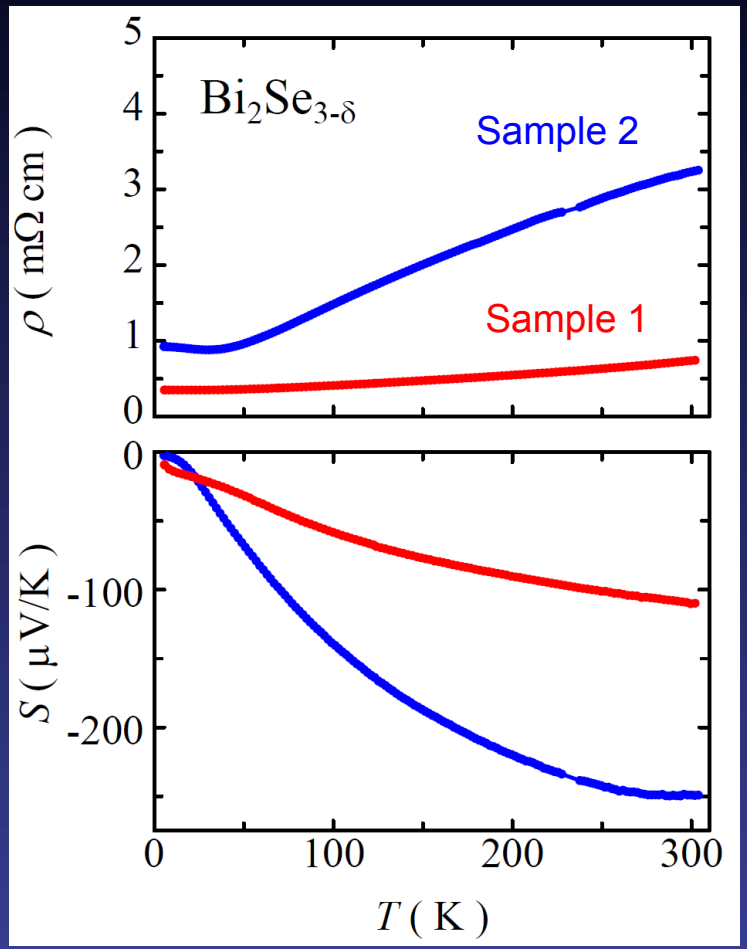
Topo.



Bi_2Se_3

X'tals grown by Igarashi & Sasagawa (TIT)





(Bulk) electron density ~ 10^{20}/cm^3 (Sample 1)

10^{18} ~ 10^{19}/cm^3 (Sample 2)