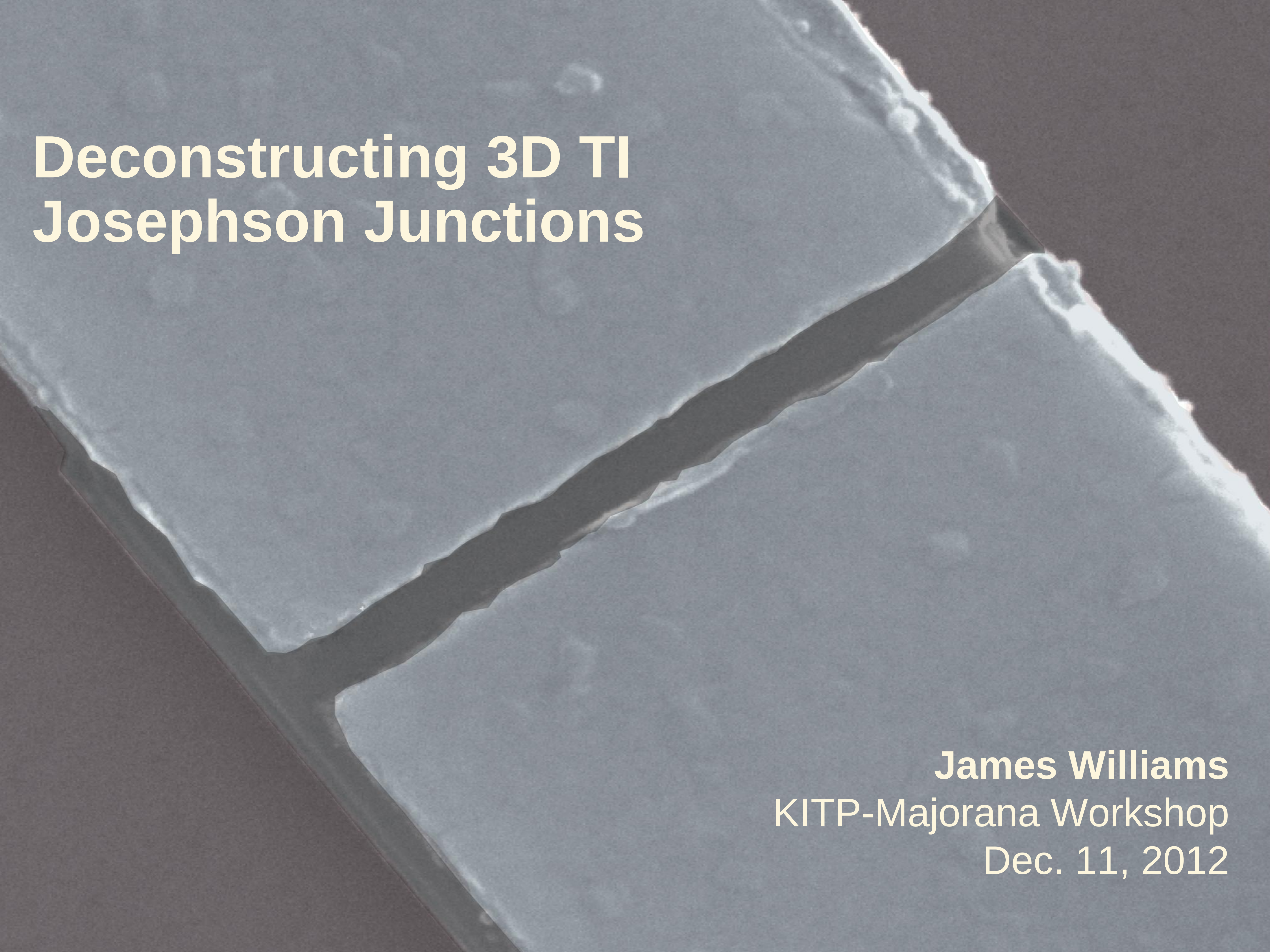
Deconstructing 3D TI Josephson Junctions



James Williams

KITP-Majorana Workshop

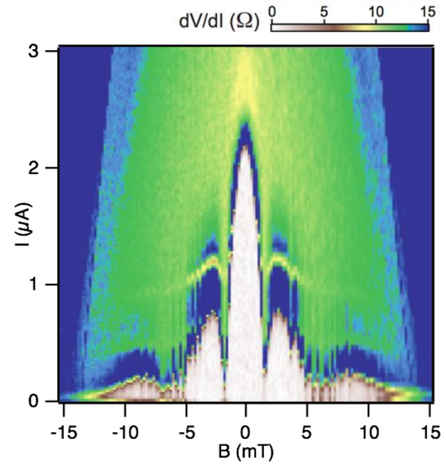
Dec. 11, 2012

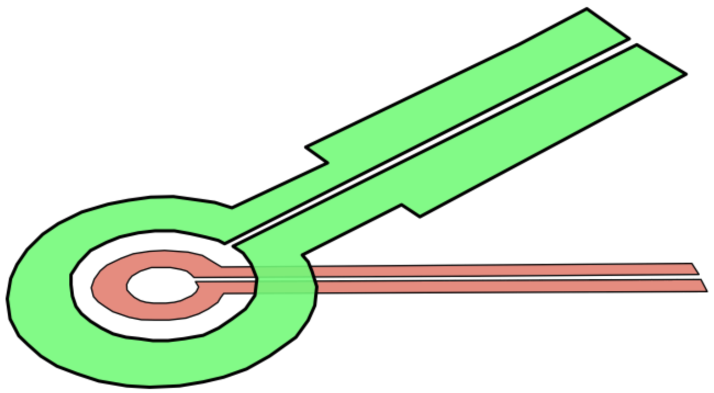
Outline

Motivation and background

Interesting deviations from normal Josephson junction behavior noted in devices made from Bi_2Se_3

Phys. Rev. Lett. **109** 056803 (2012)





Scanning SQUID measurements of JJ Rings

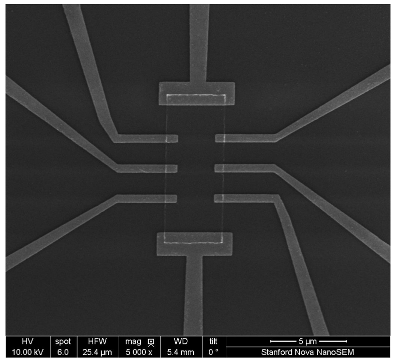
Devices

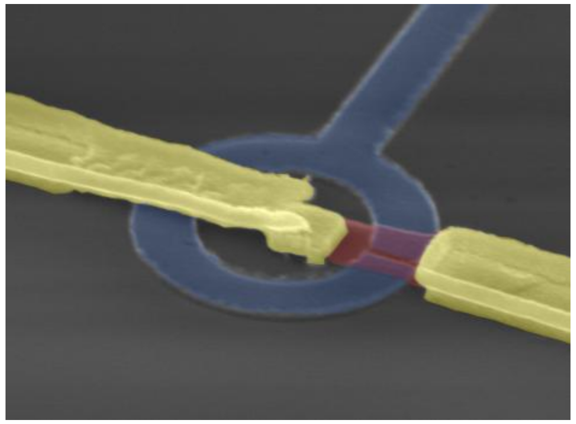
Curious features in the data

Must closely examine the S-TI interface

Highly Tunable TI films grown by MBE

Devices created from thin MBE TI can be routinely tuned through the “Dirac” point





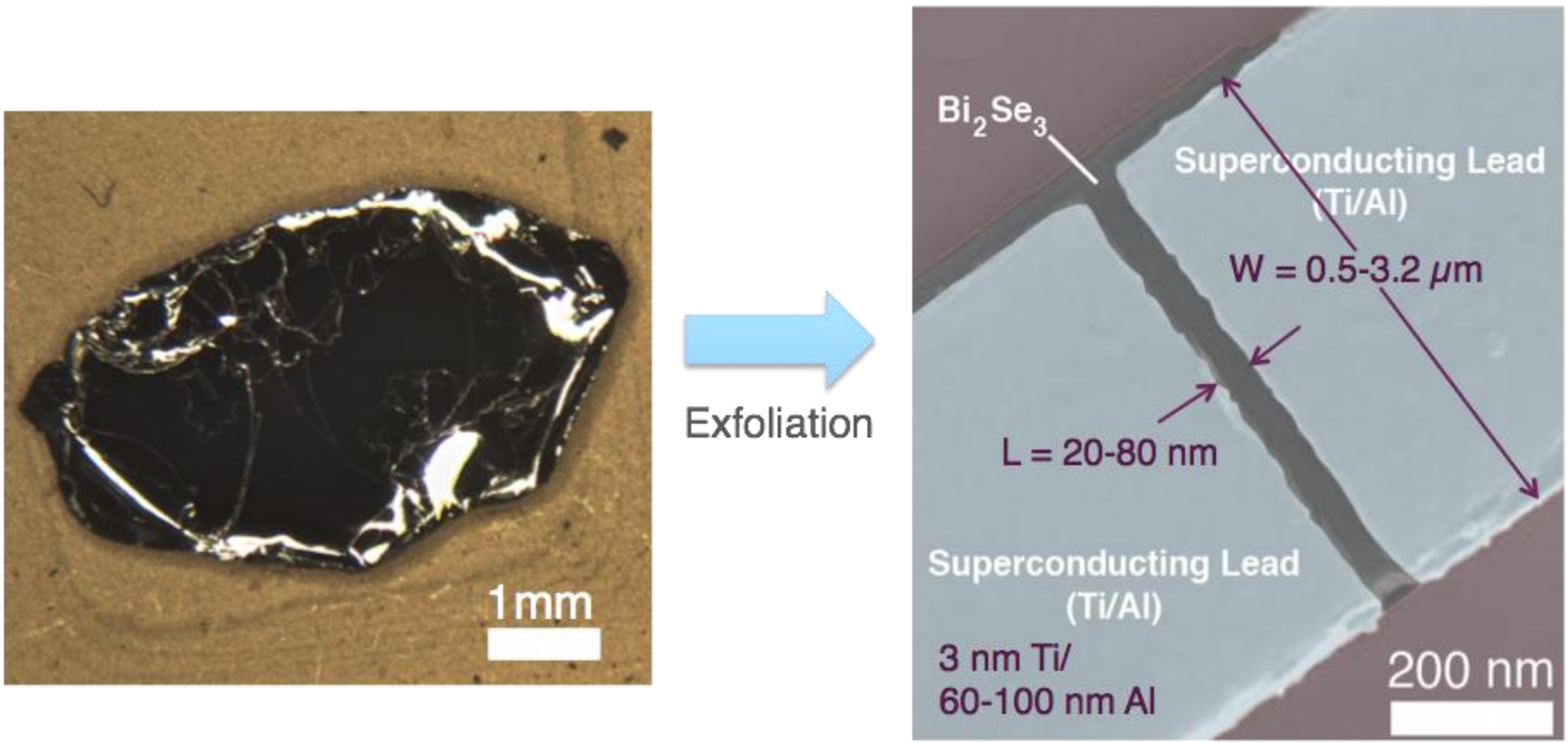
New Measurements

Work by Wieder et al. caused us to look at transport along junction

Unexpected temperature and bias-dependence seen

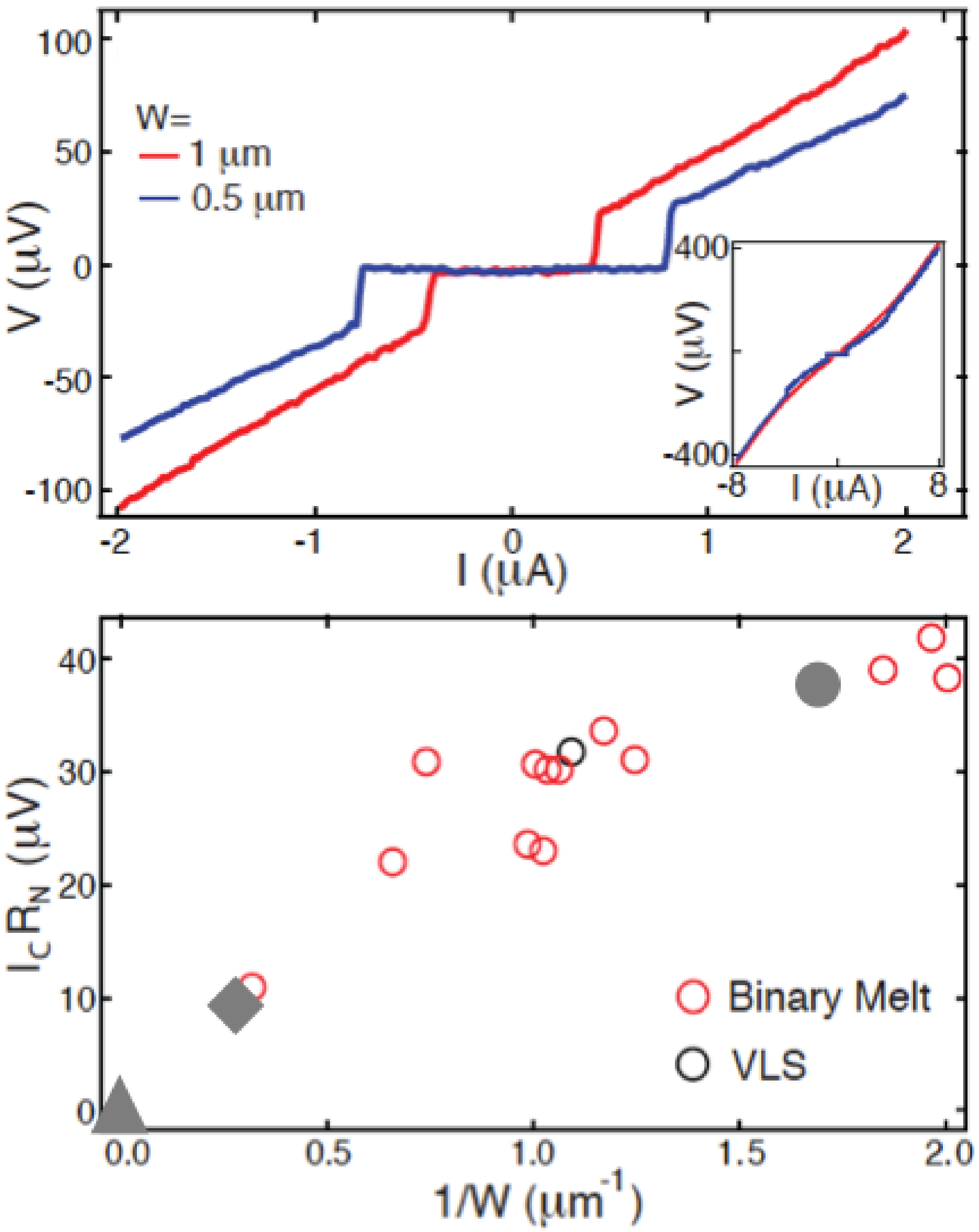
Device fabrication

- Mechanical exfoliation, e-beam lithography.



Geometry dependence of V_C

- $I_C R_N \sim 1/W$ over a wide range of devices.



Red curve: R_N = 51.5 Ω
Blue curve: R_N = 56.1 Ω

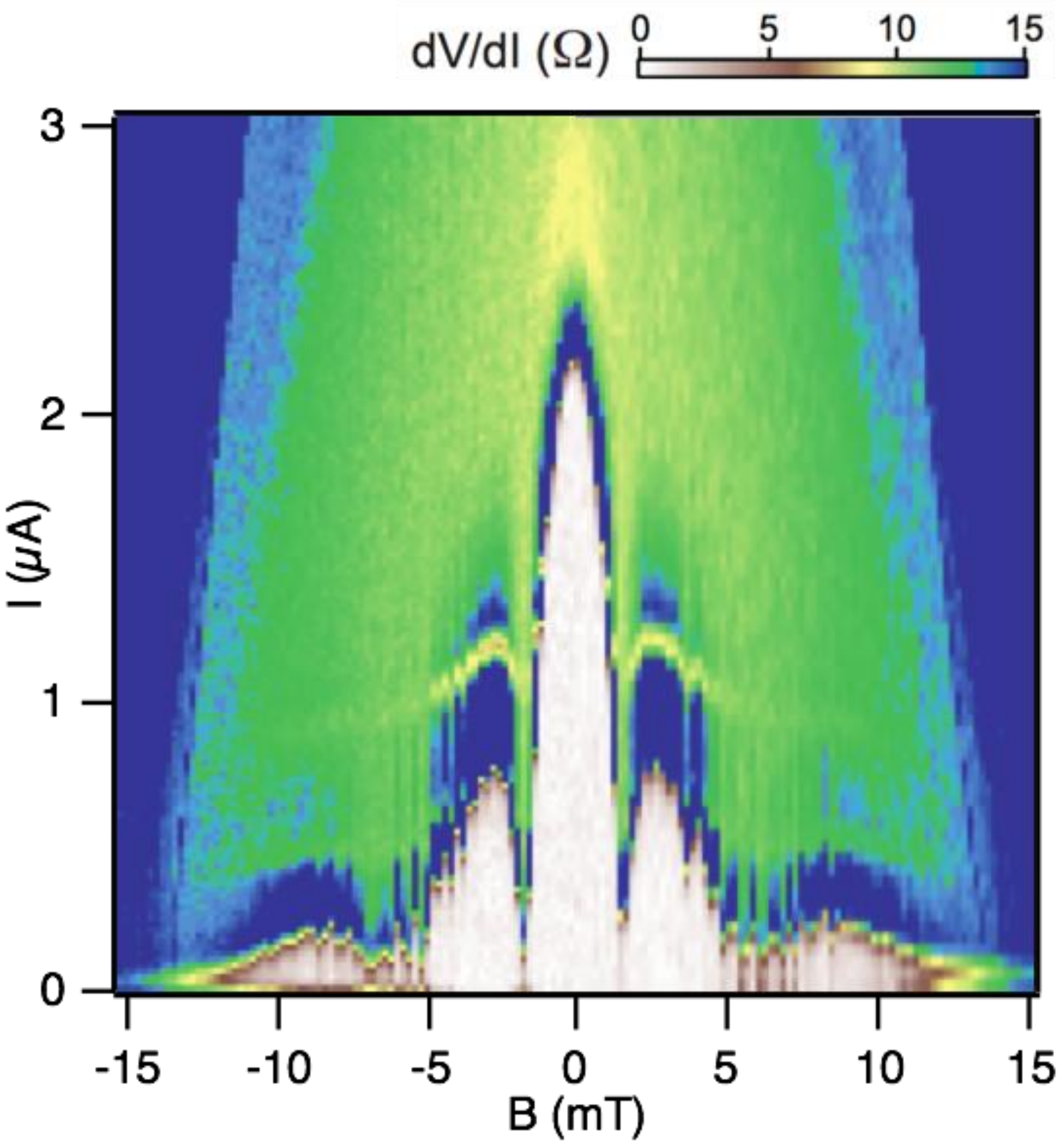
Circle: Zhang *et al.*, PRB, 2011
Bi_2Se_3 nanowires

Diamond: Sacépé *et al.*, Nat Comm, 2012
Exfoliated Bi_2Se_3

Triangle: Wang *et al.*, PRB, 2012
MBE Bi_2Se_3

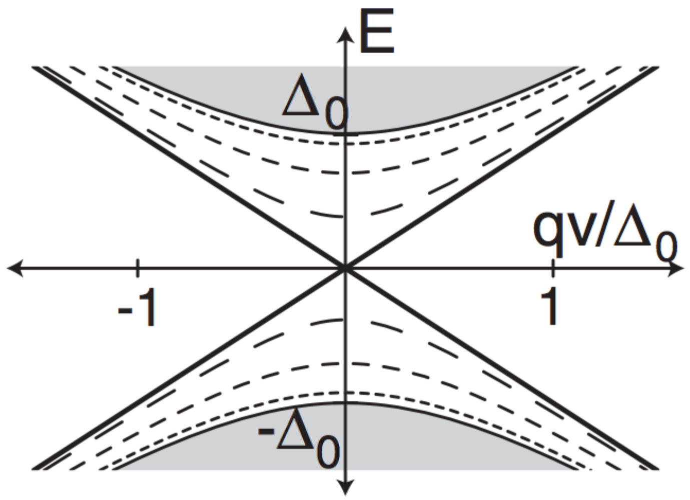
Measured magnetic diffraction pattern

- At first glance appears conventional, but...

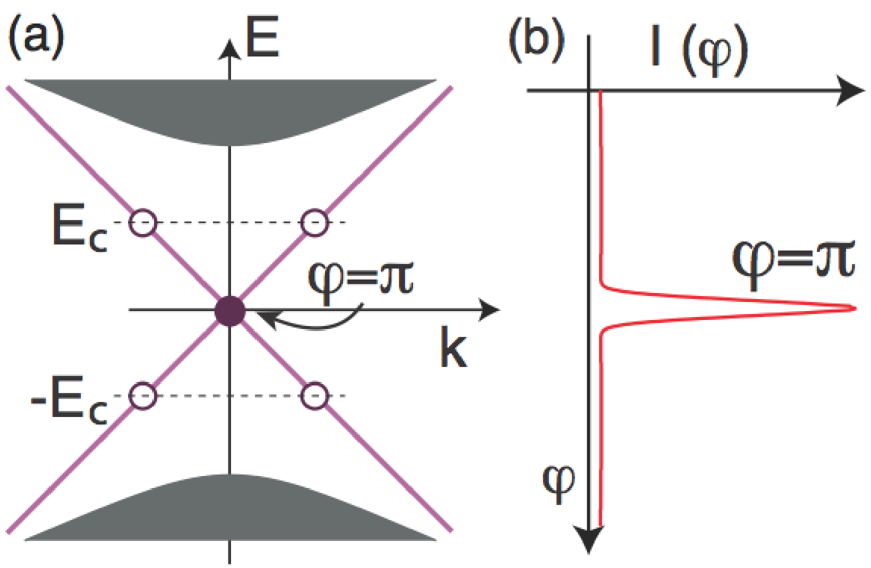


Proposed explanation with Majorana fermions

- Economic, comprehensive, and probably wrong.

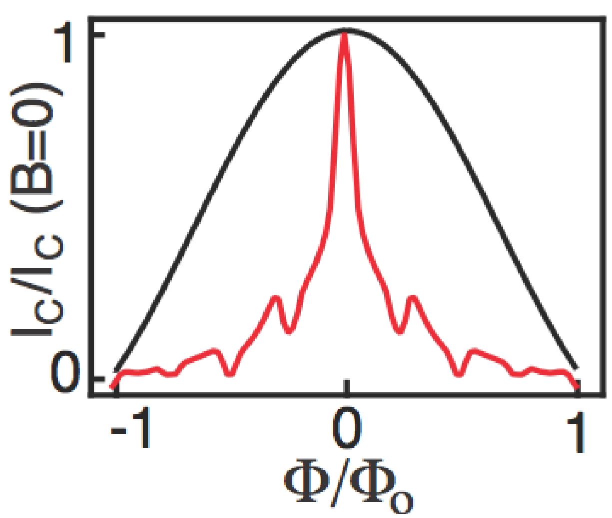


1) Take Fu/Kane picture
When phase difference across junction is π, transverse mode is a Majorana state with zero-energy crossing and linear dispersion. Otherwise, gapped and massive.



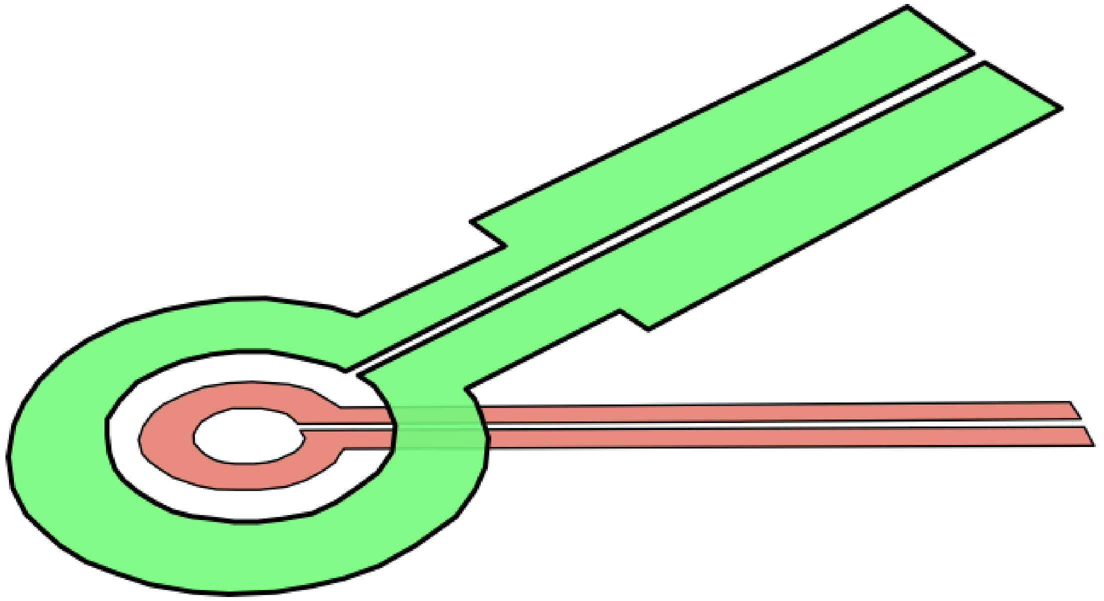
2) Add spatial confinement
Separates topologically-protected neutral state from charged states by confinement energy (~1/*W*).

3) Assume neutral state facilitates supercurrent
Current-phase relation becomes strongly peaked around particular values of phase, rather than sinusoidal.



4) Magnetic diffraction pattern gains sub-Φ_0 features
Depending on choice of CPR, can calculate aperiodic dips below a flux quantum.

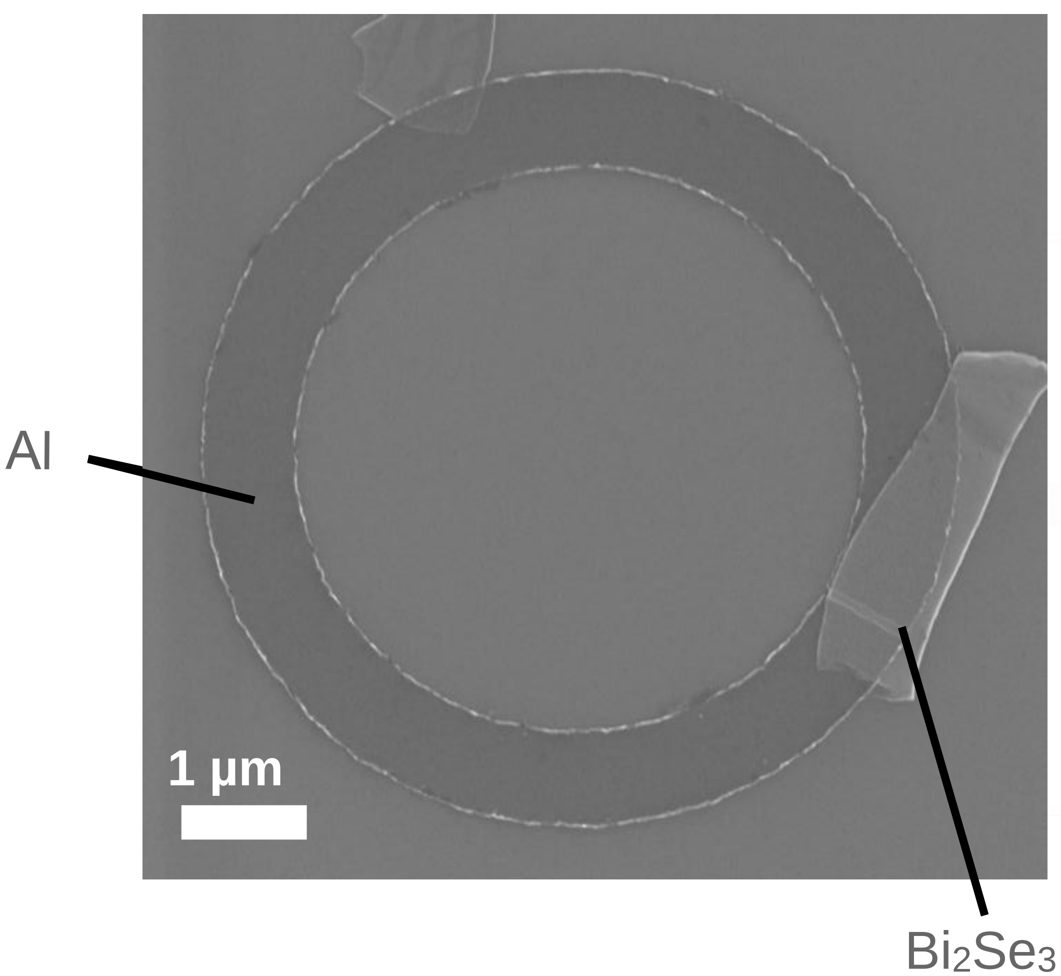
Scanning SQUID Measurements



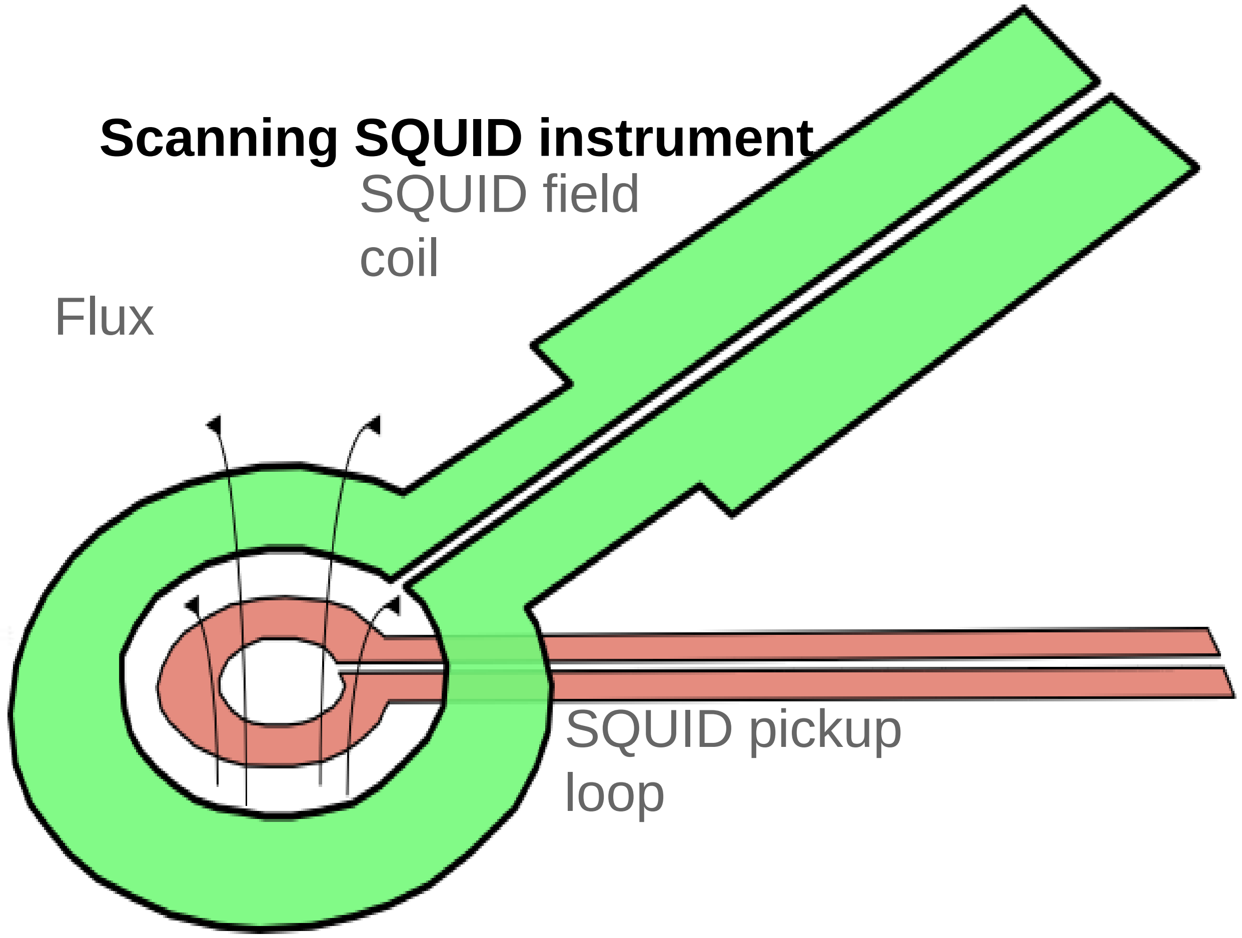
Scanning SQUID measurements

- Local flux detection can directly measure CPR.

Superconductor-TI structures



Scanning SQUID instrument



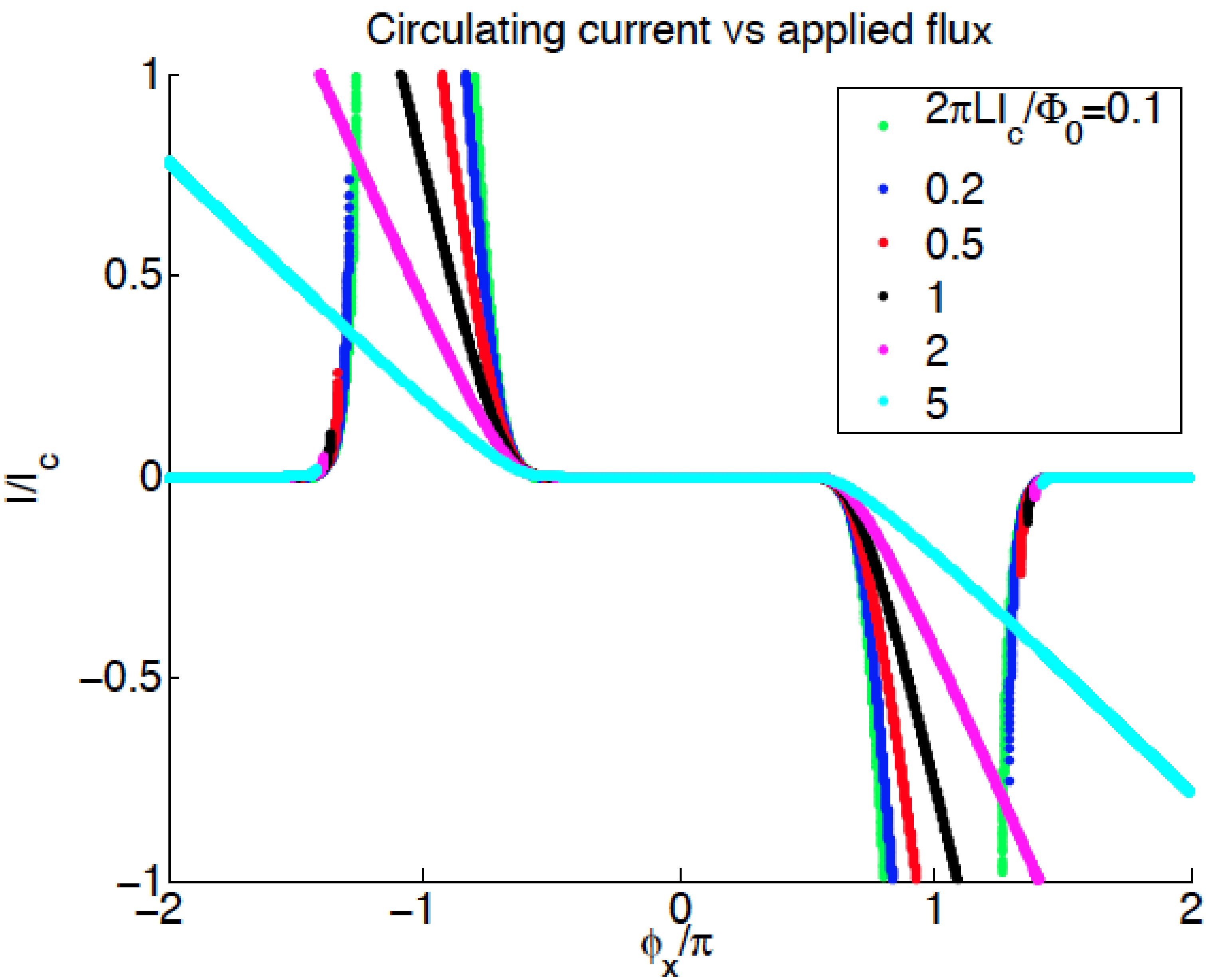
Huber *et al.*, Rev. Sci. Ins., 2008
Koshnik *et al.*, APL, 2008

Current-phase relation

$\Phi_m \sim I_s(\phi)$

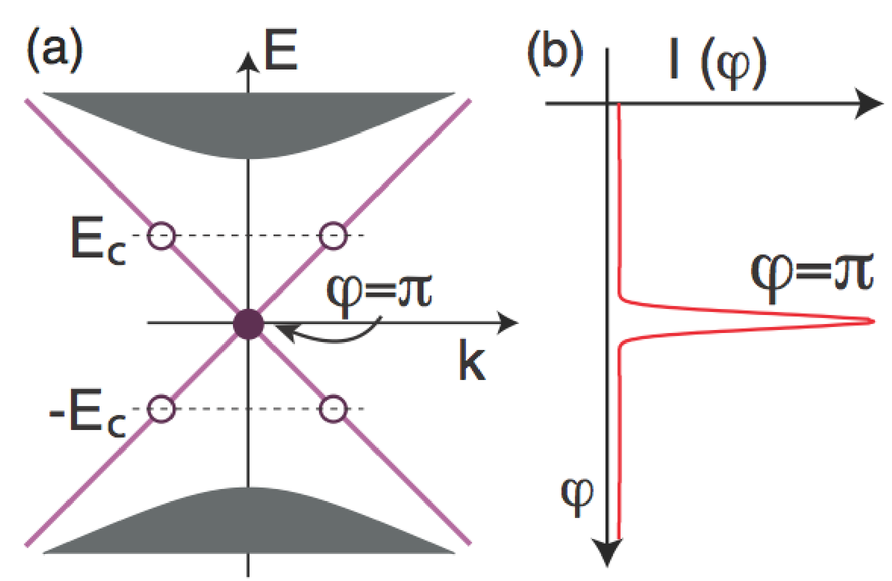
$\phi \sim 2\pi\ \Phi_a/\Phi_0$

Peaked CPR in SQUID measurements



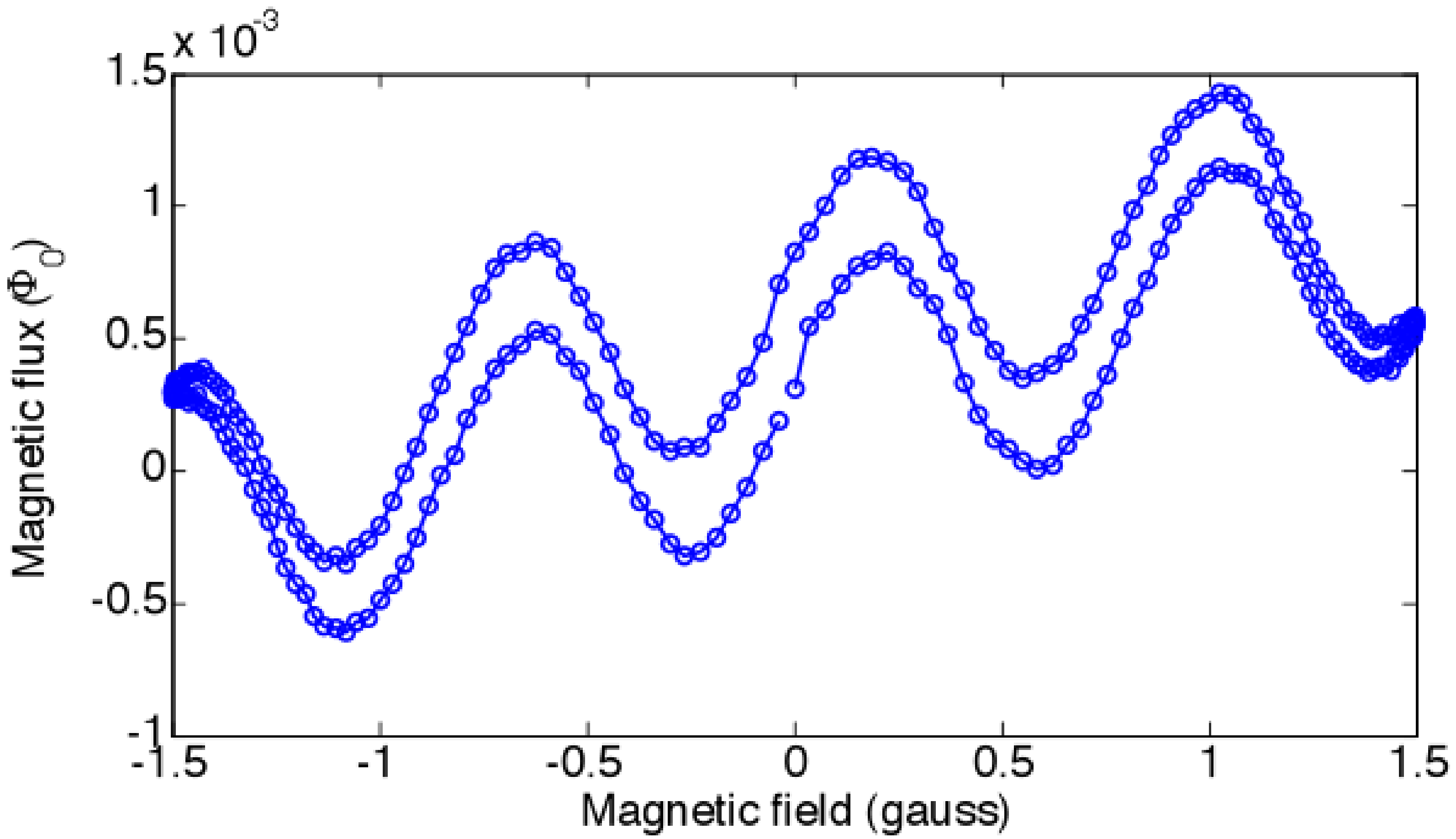
Measuring current phase relations with SQUIDS

A peaked current phase relationship should produced a peaked respond of the SQUID response

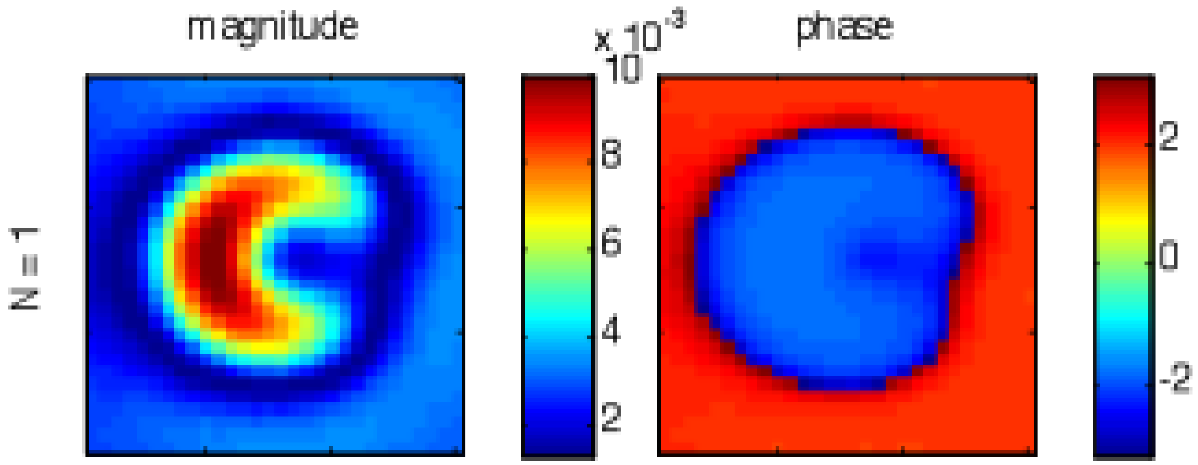


Current-phase relation measurement

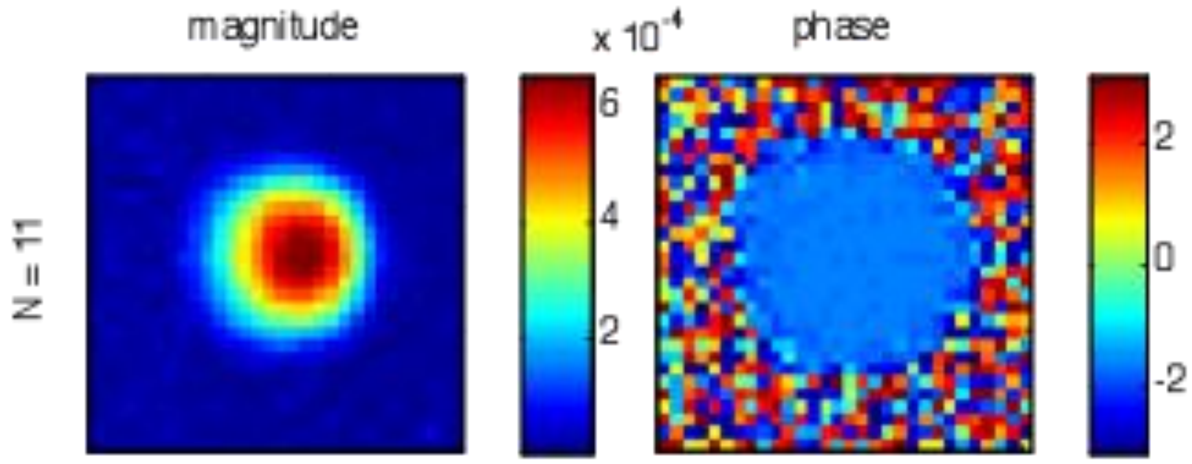
- All indications are of a conventional, sinusoidal CPR.



Low-frequency component (bulk)



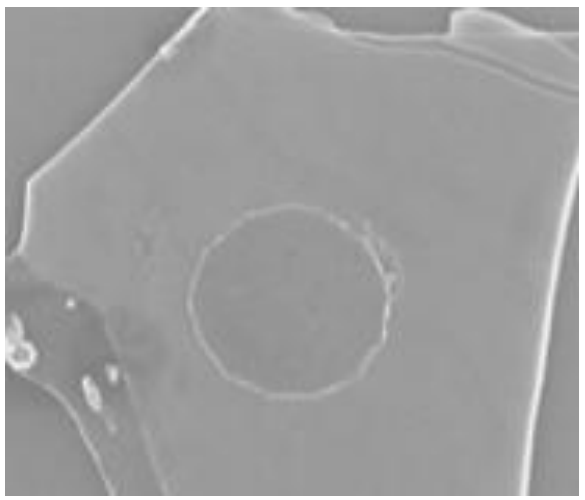
High-frequency component (junction)

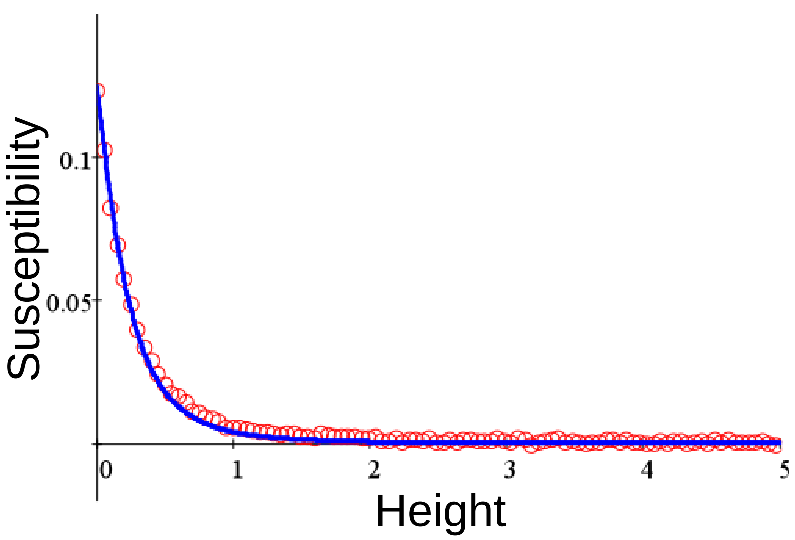


Magnetic penetration depth

- Does proximity to TI dramatically increase penetration?

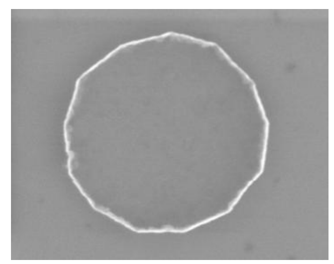
Al dots on Bi_2Se_3

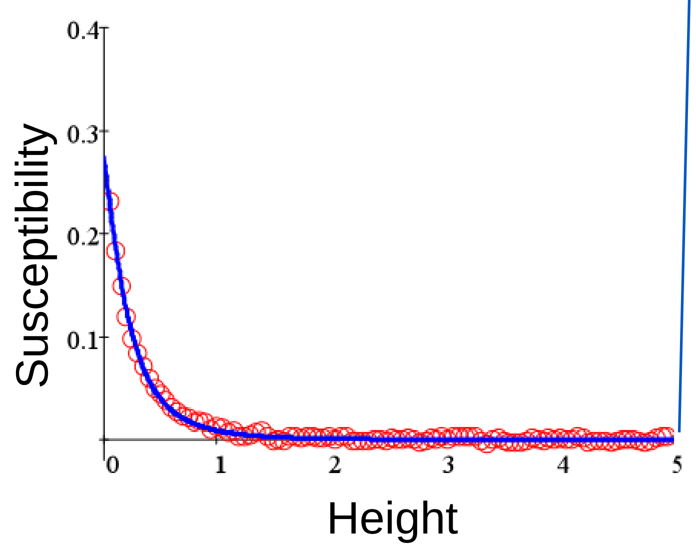




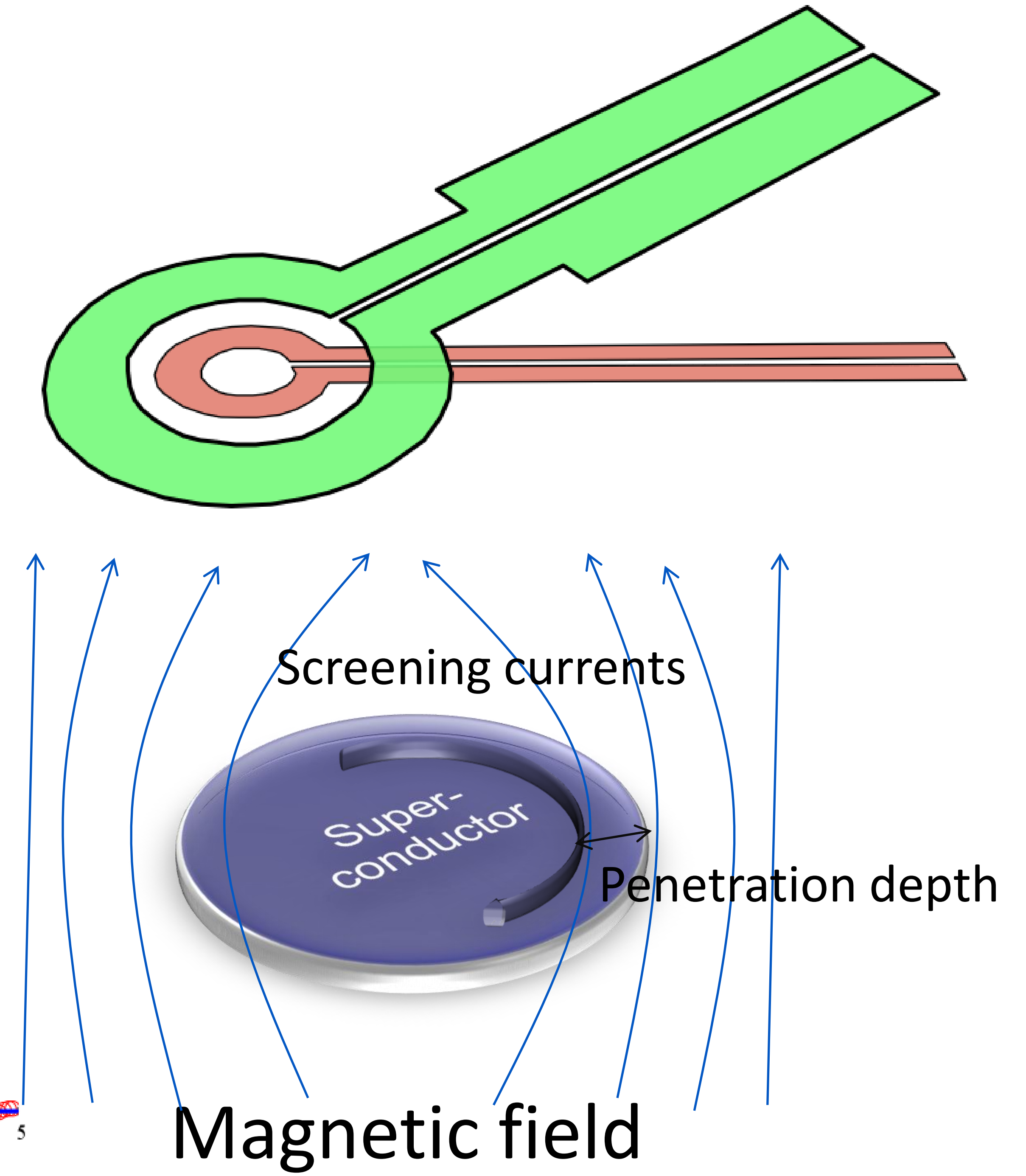
λ ~ 62 nm - 3.2 µm

Al dots on substrate





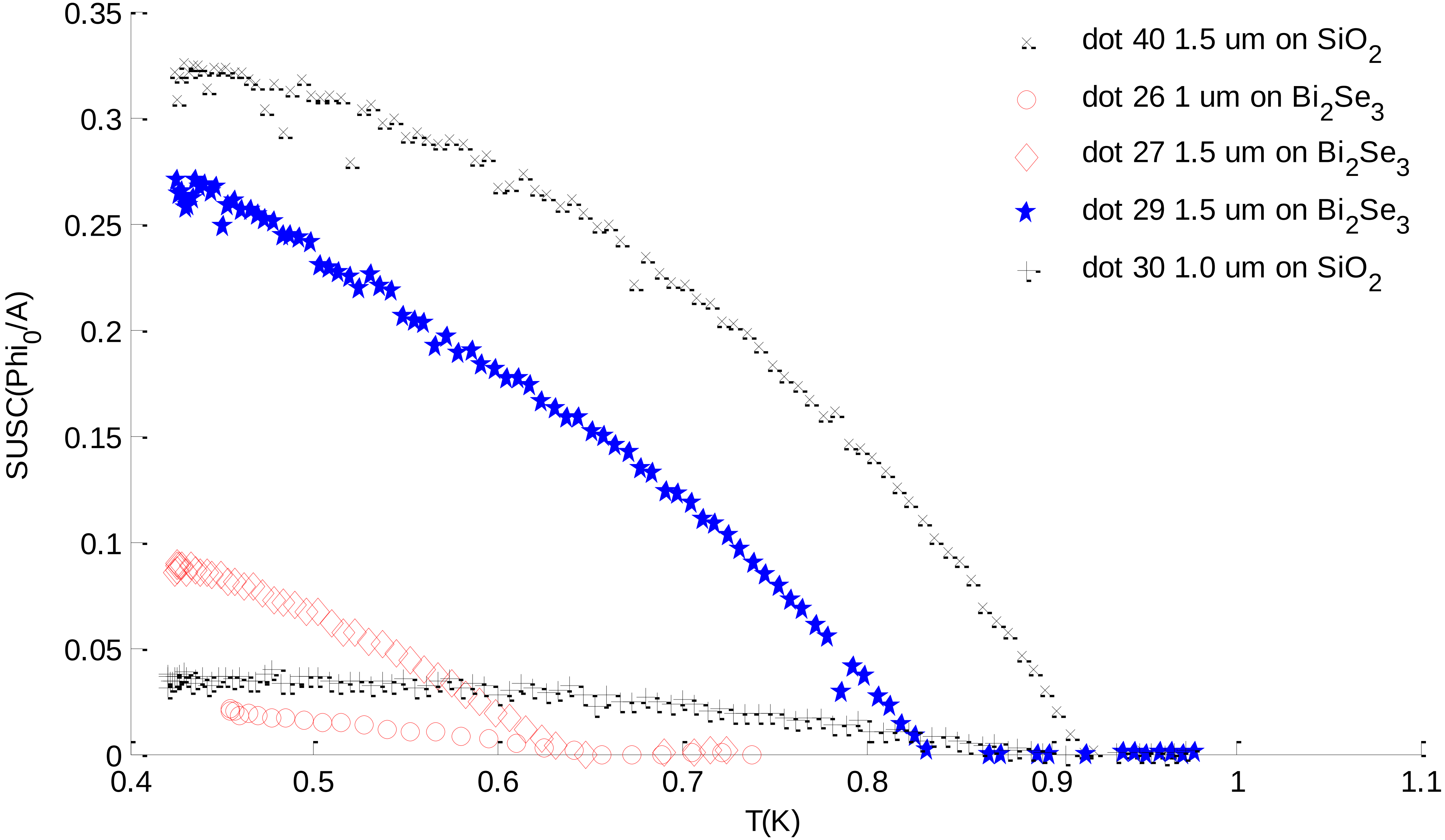
λ ~ 19 nm - 1.4 µm



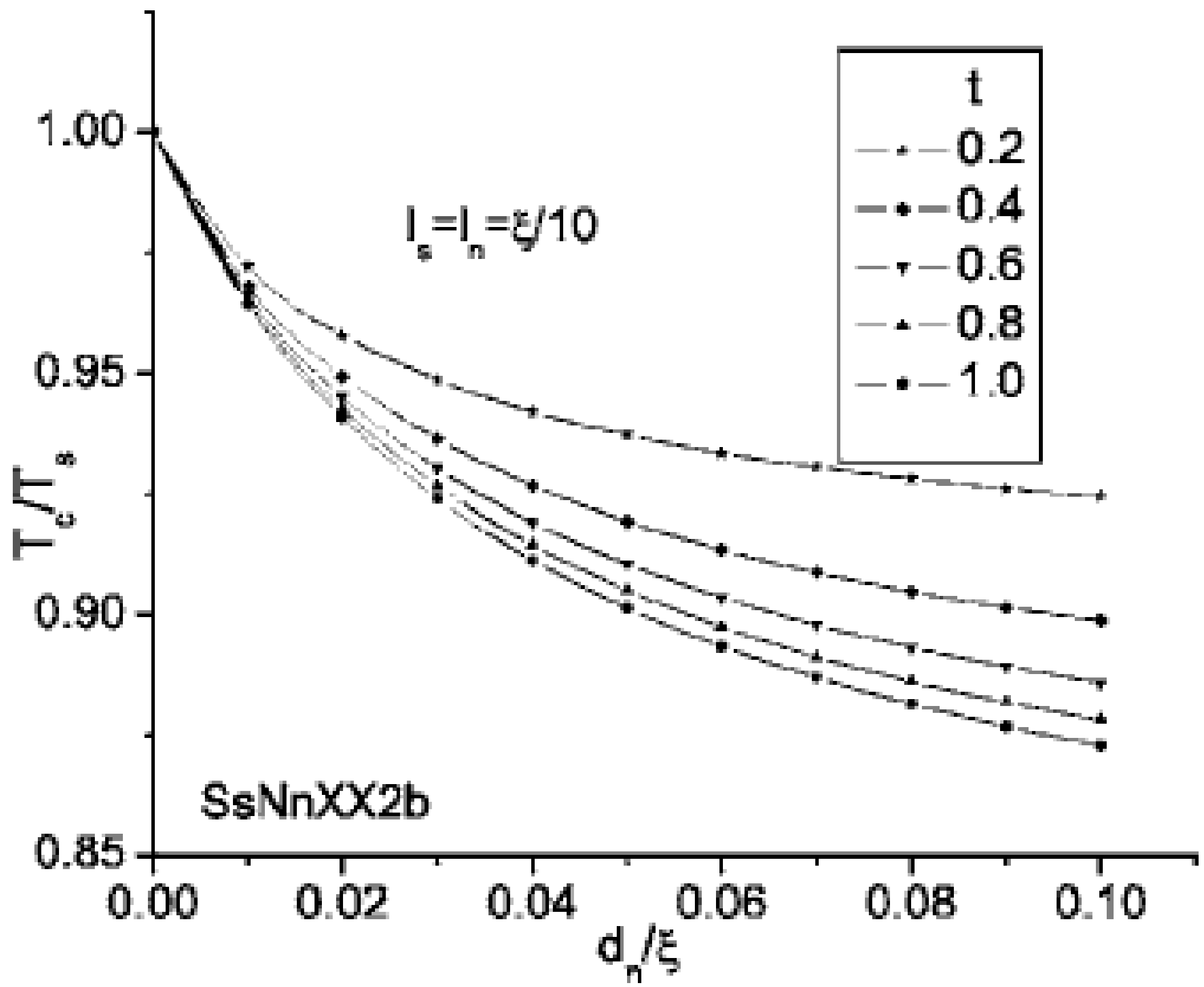
Brandt and Clem PRB 69 184509 (2004)

T_C of Aluminum dots on Bi_2Se_3

- Does proximity to TI decrease the transition temperature?



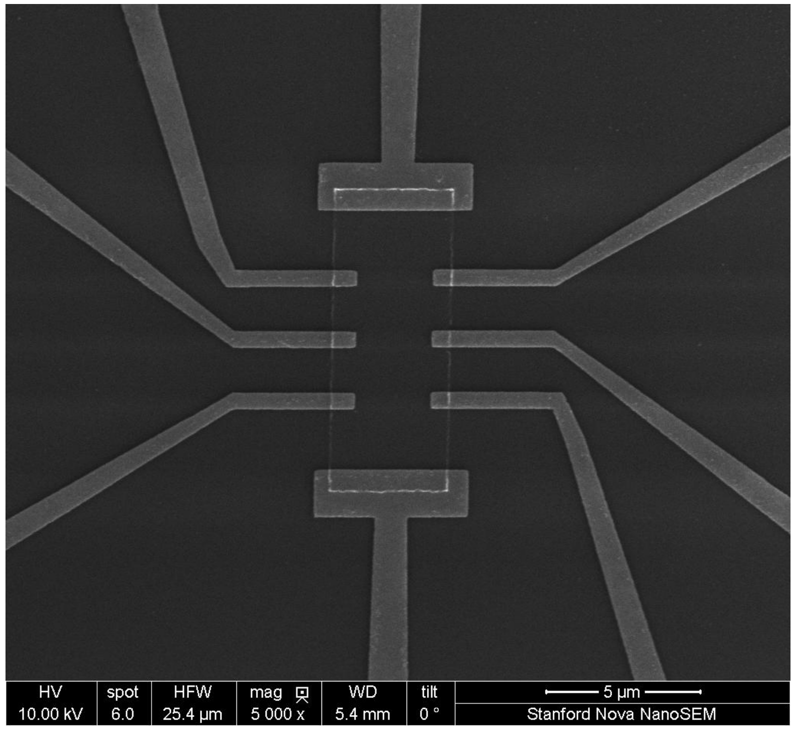
Comparison to metals



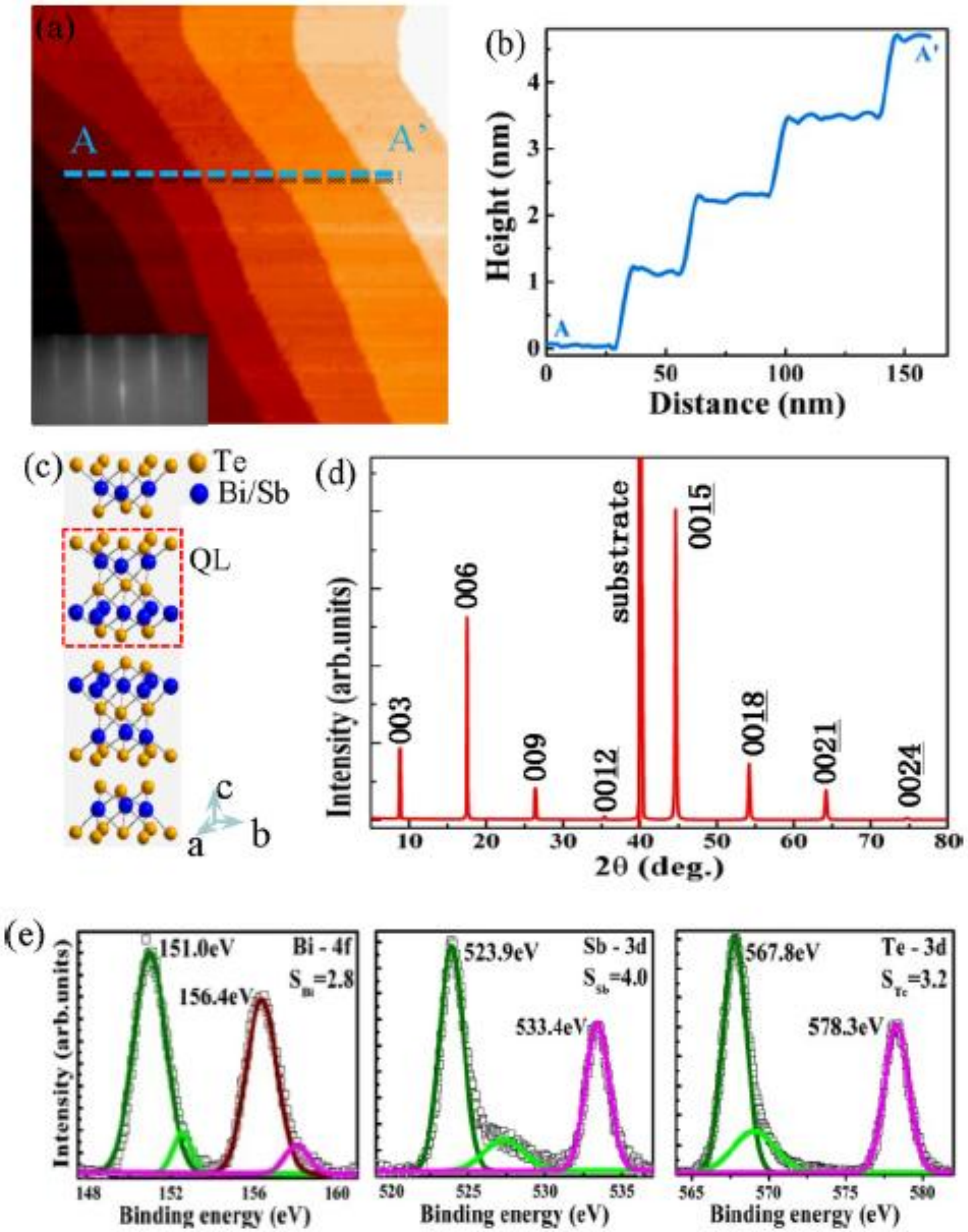
$$S_{sn} = \frac{d_s}{T_{c0}} \left| \frac{dT_c}{dd_n} \right| = \Gamma_{sn} \frac{N_n}{N_s}.$$

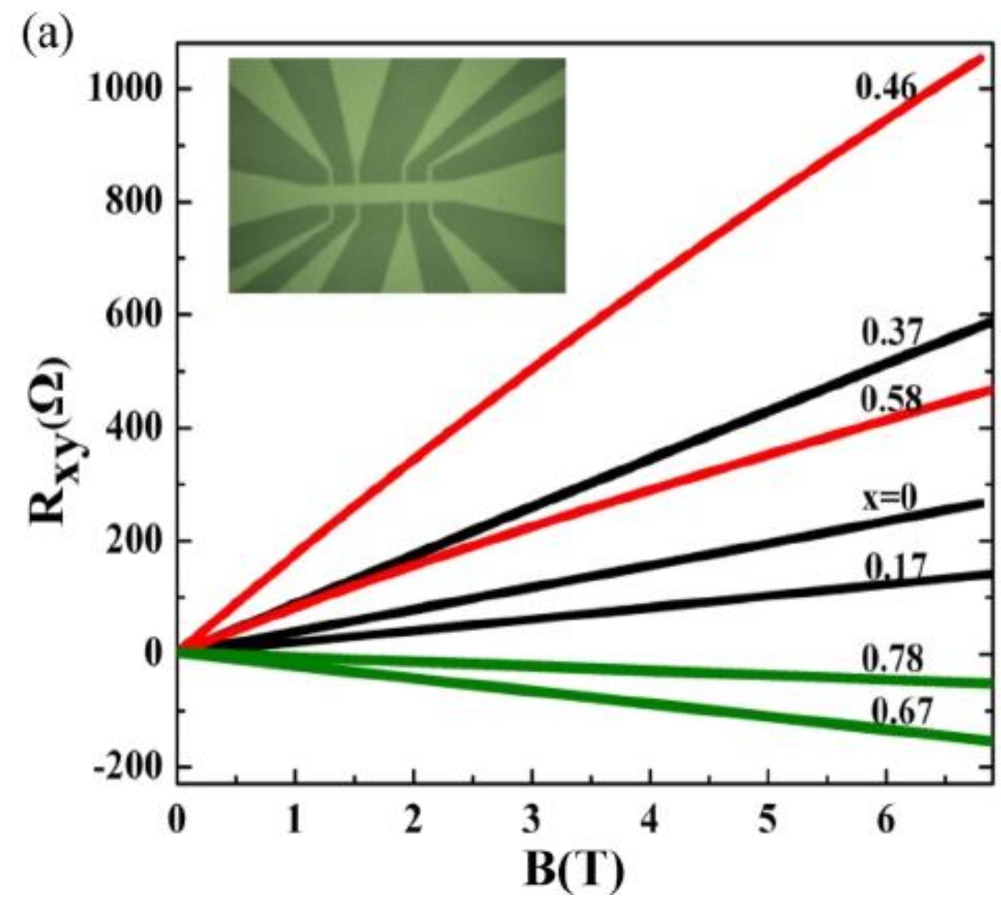
- The proximity effect can account for the reduction of TC, but only if the DOS in the TI is similar to that of a metal
- What effect does strong spin-orbit have on the proximity effect
- Can this help explain the soft gap observed in nanowire experiments

Tunable Transport in MBE-grown $BiSbTi_3$



Growth of TI MBE $(Bi_{1-x}Sb_x)2Te_3$ Films – IOP, Chinese Academy of Science





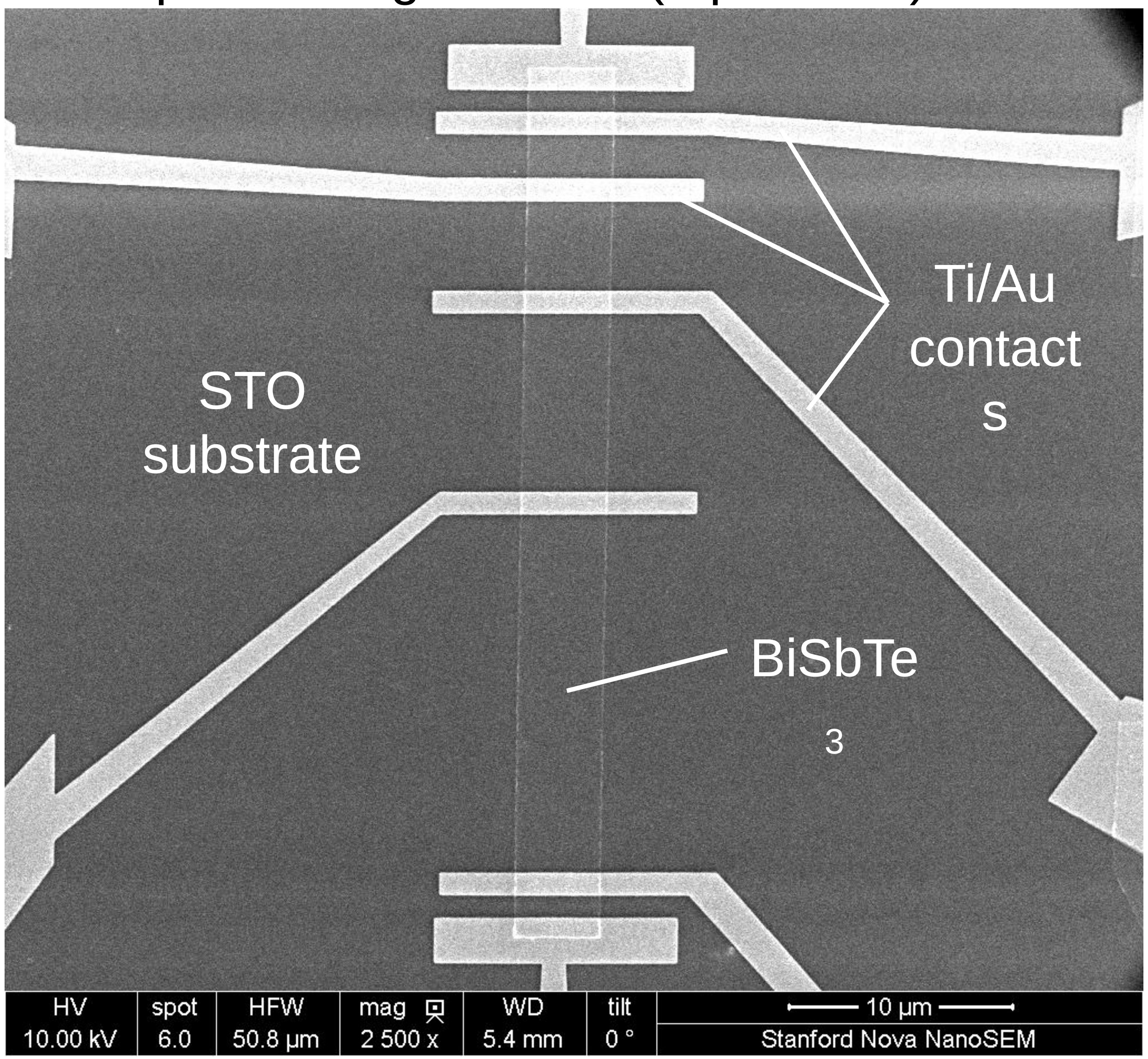
- Our films: x=0.5 and thickness=10nm

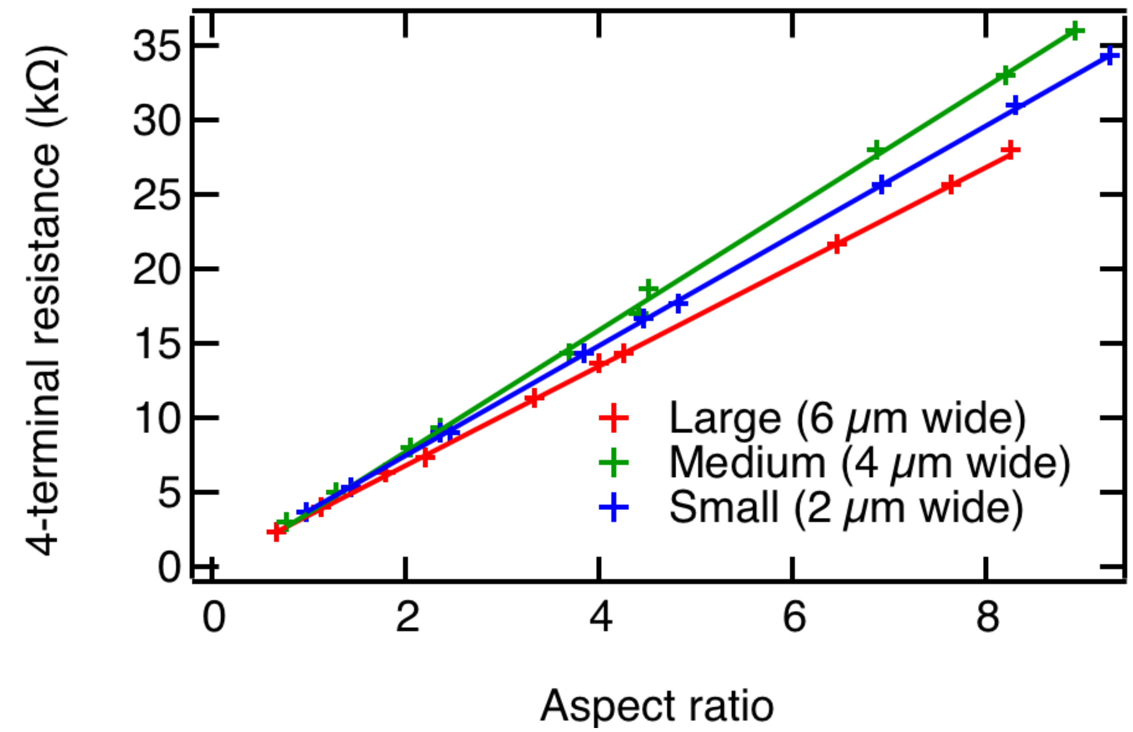
He *et al*., APL **101** 123111 (2012)

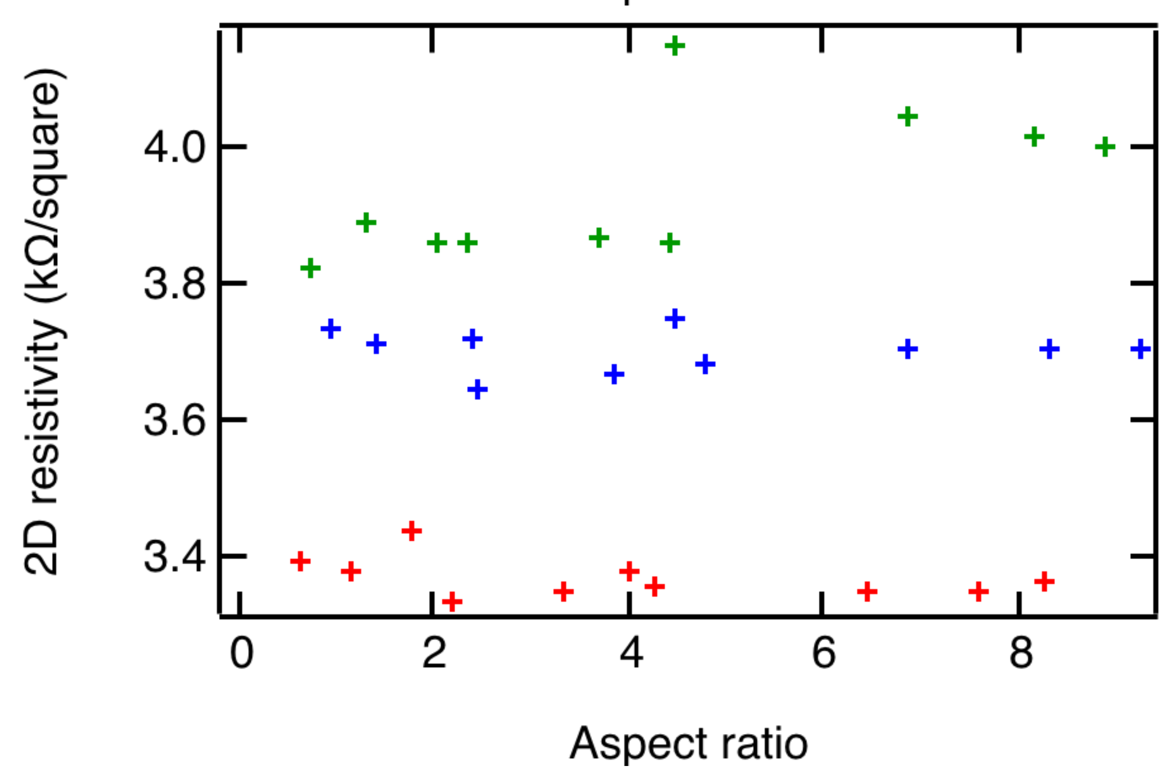
Surface or Edge Conductance?

- Resistance appears to scale with aspect ratio, not length

Example rectangle device (4 μm wide)



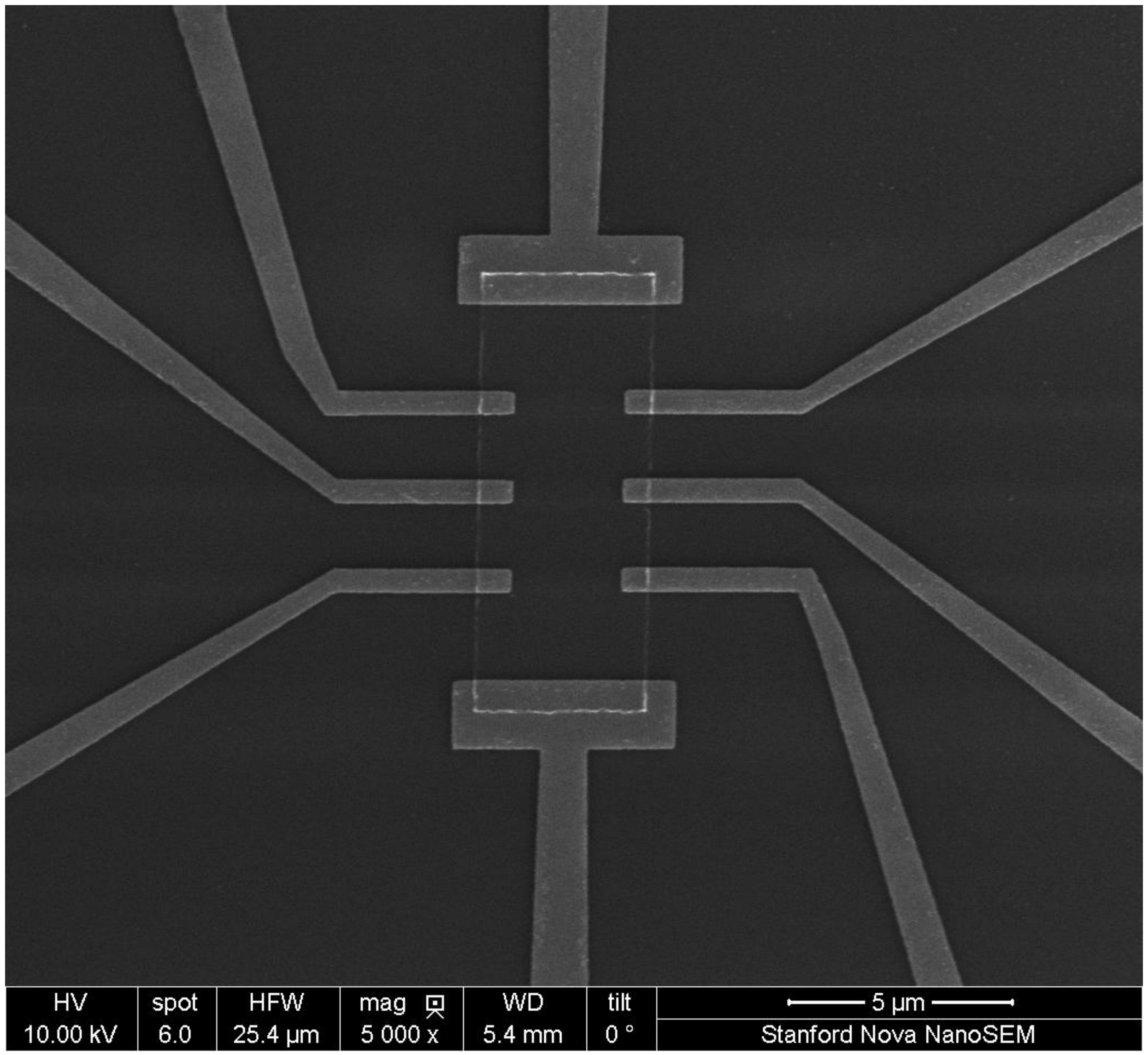


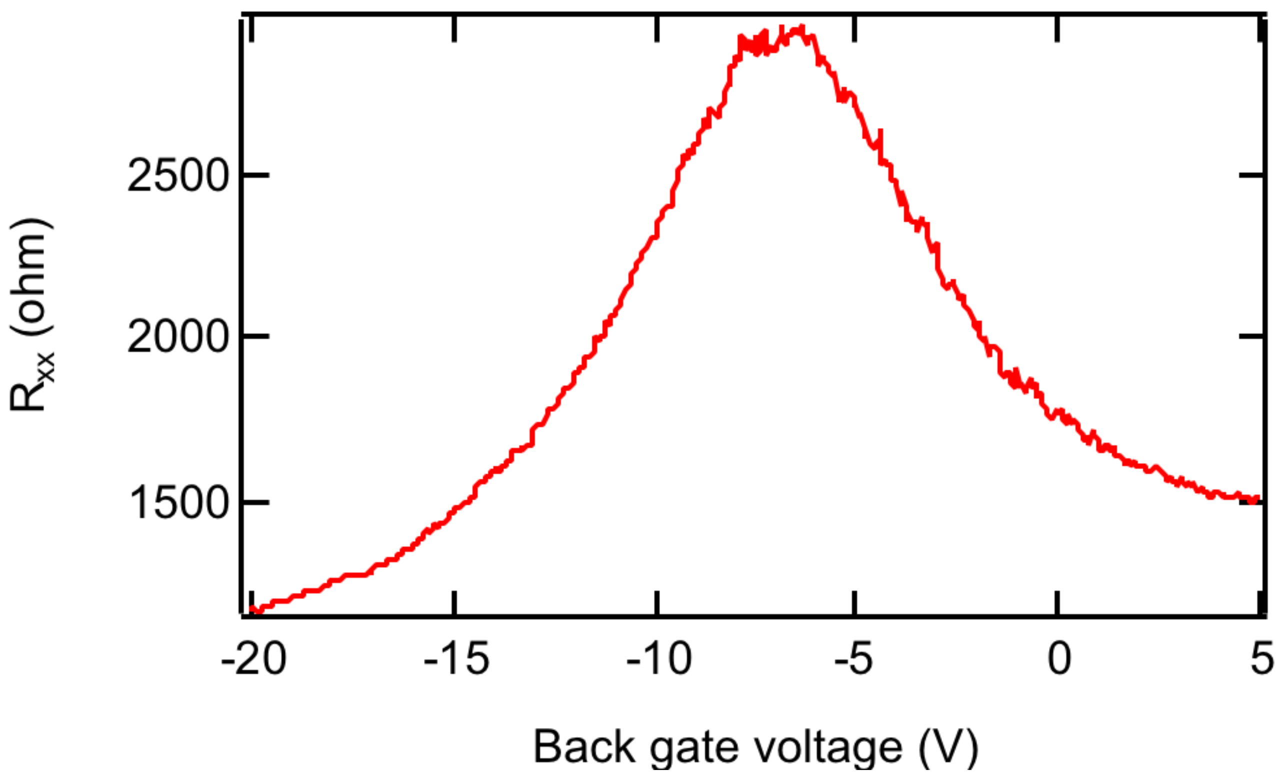


(Typical contact resistance ~ 1-1.5 kΩ)

Hall Bar Device

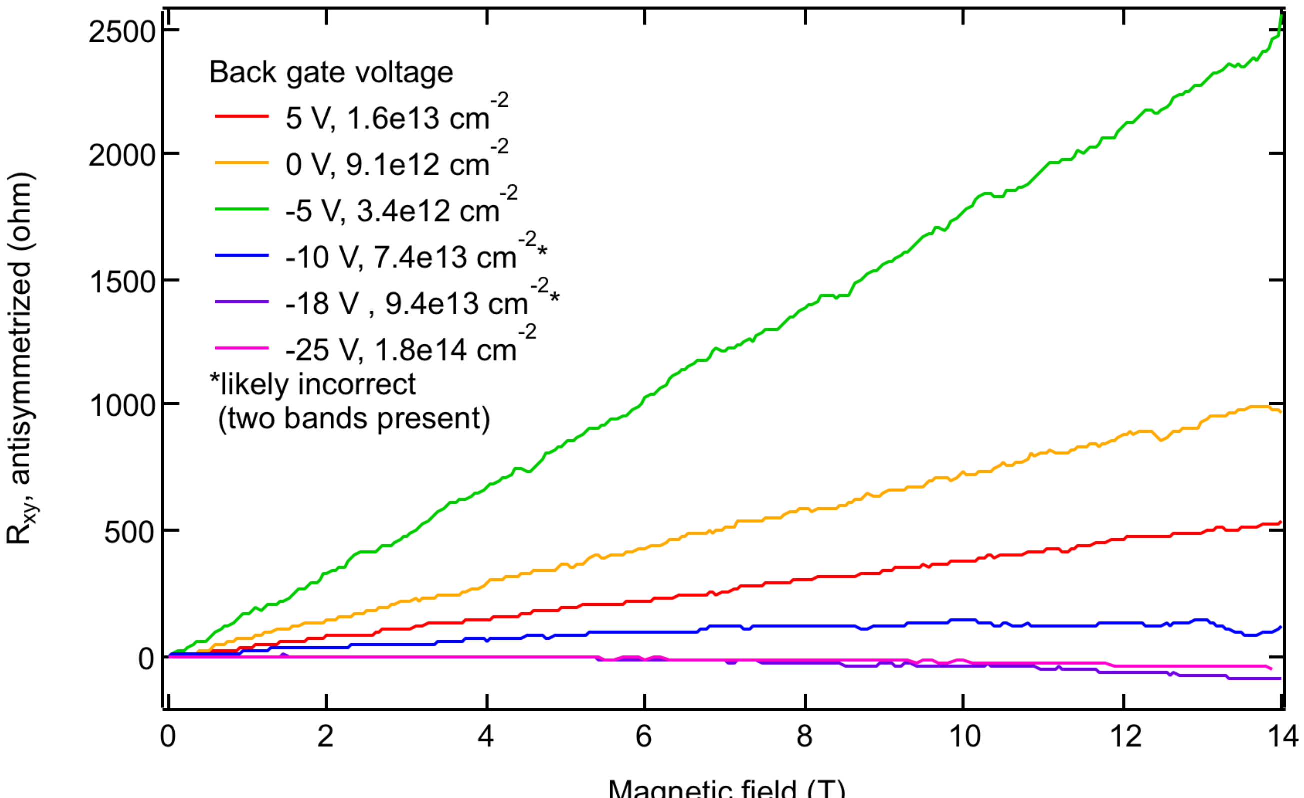
- Conduction tunable with a gate, peaks in R regularly achieved

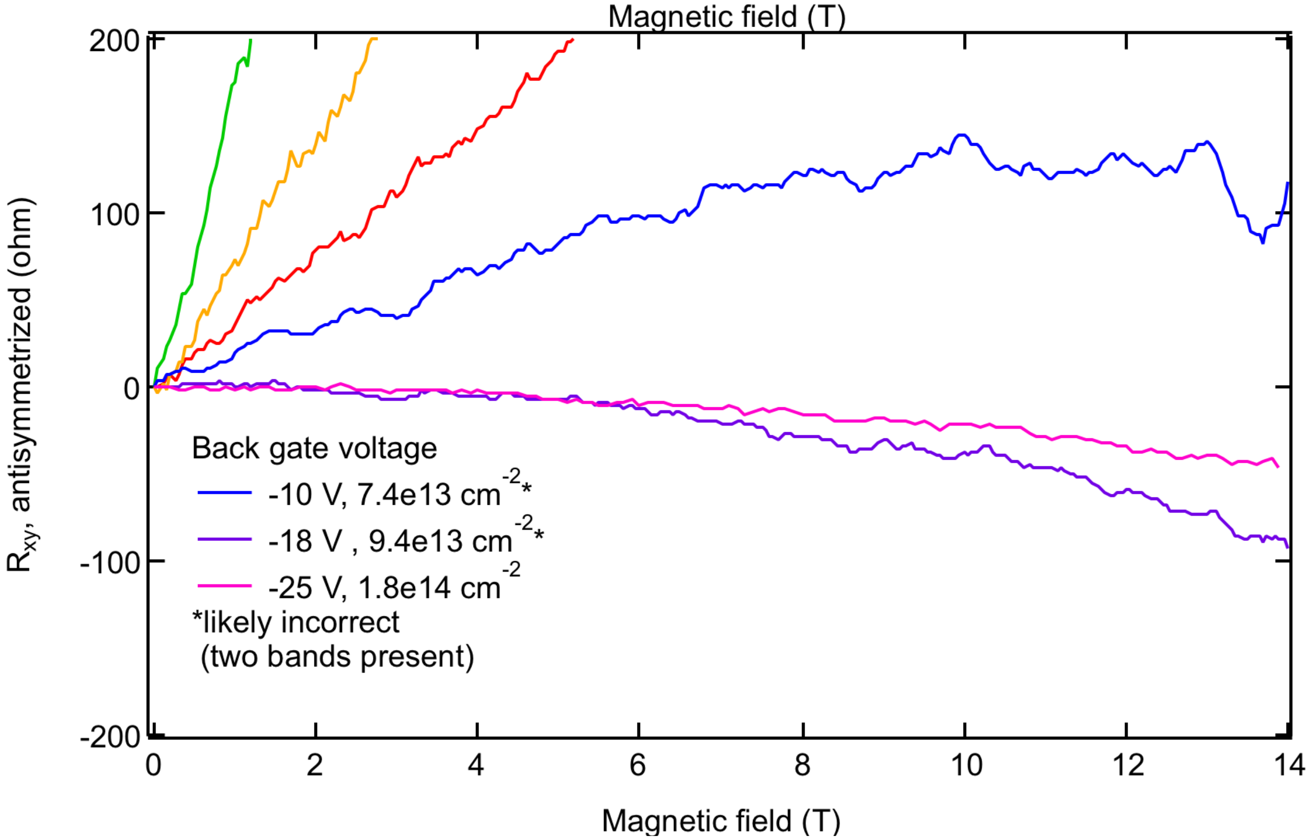


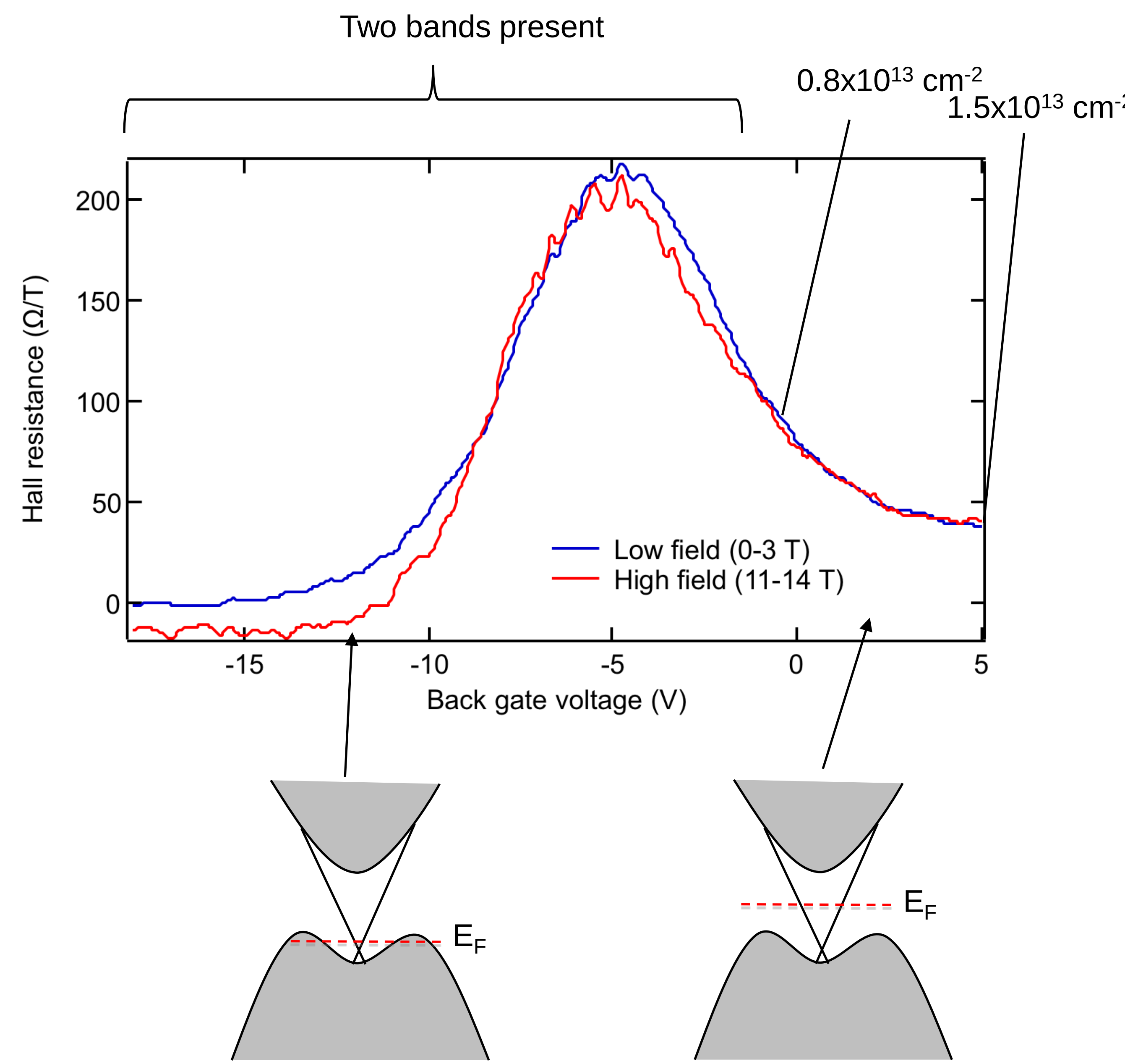


Hall Resistance

- Ambipolar transport achieve at negative backgate voltages

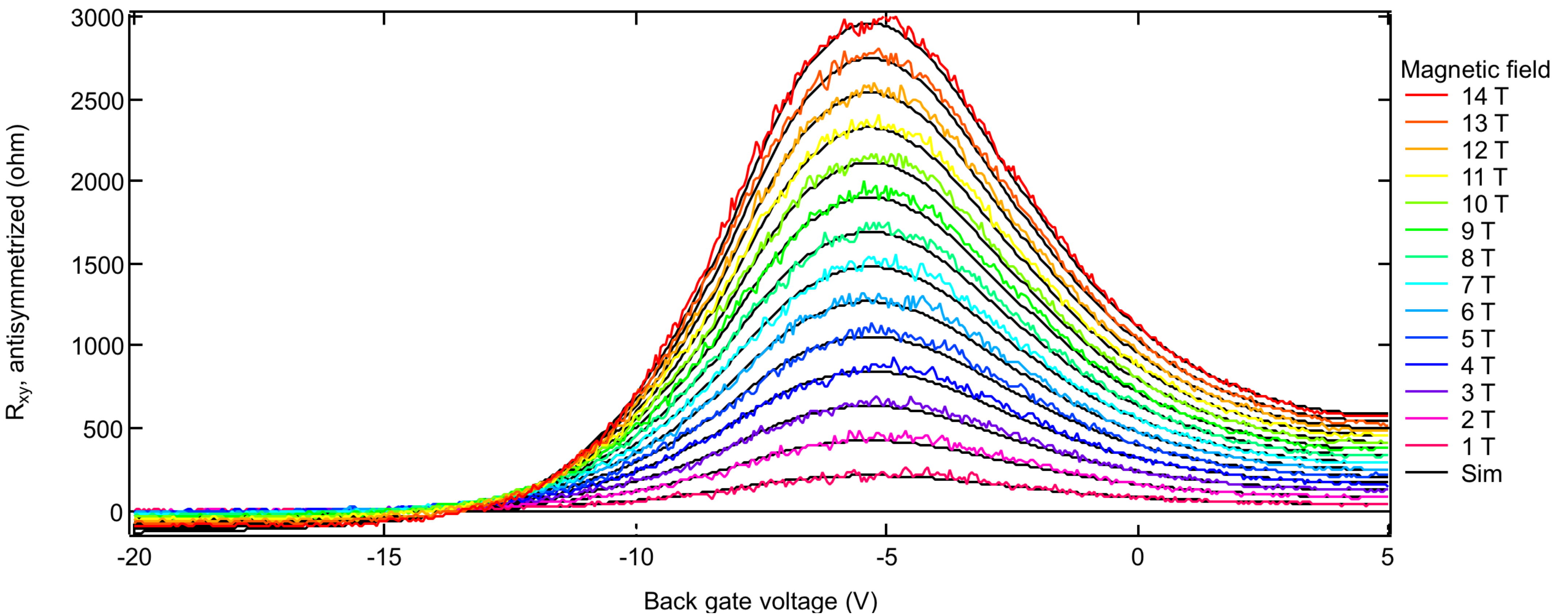


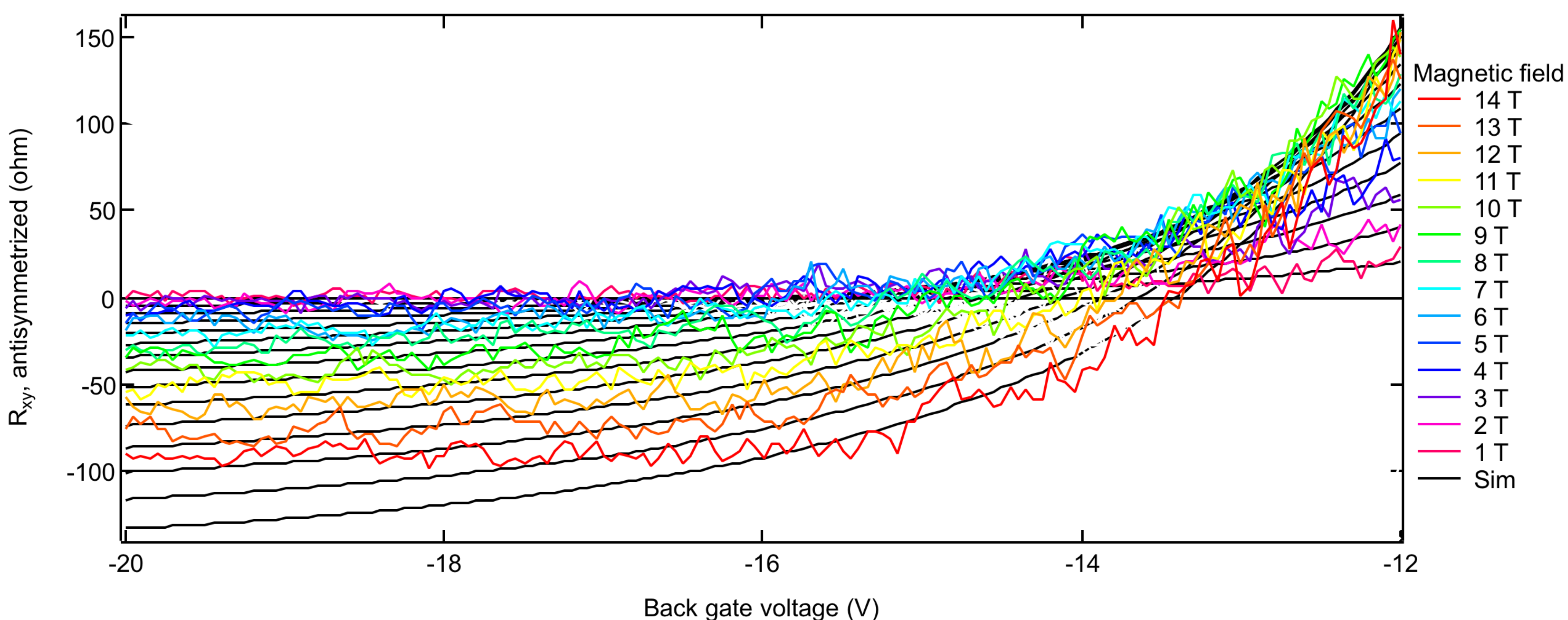




Simulation vs. Hall Data

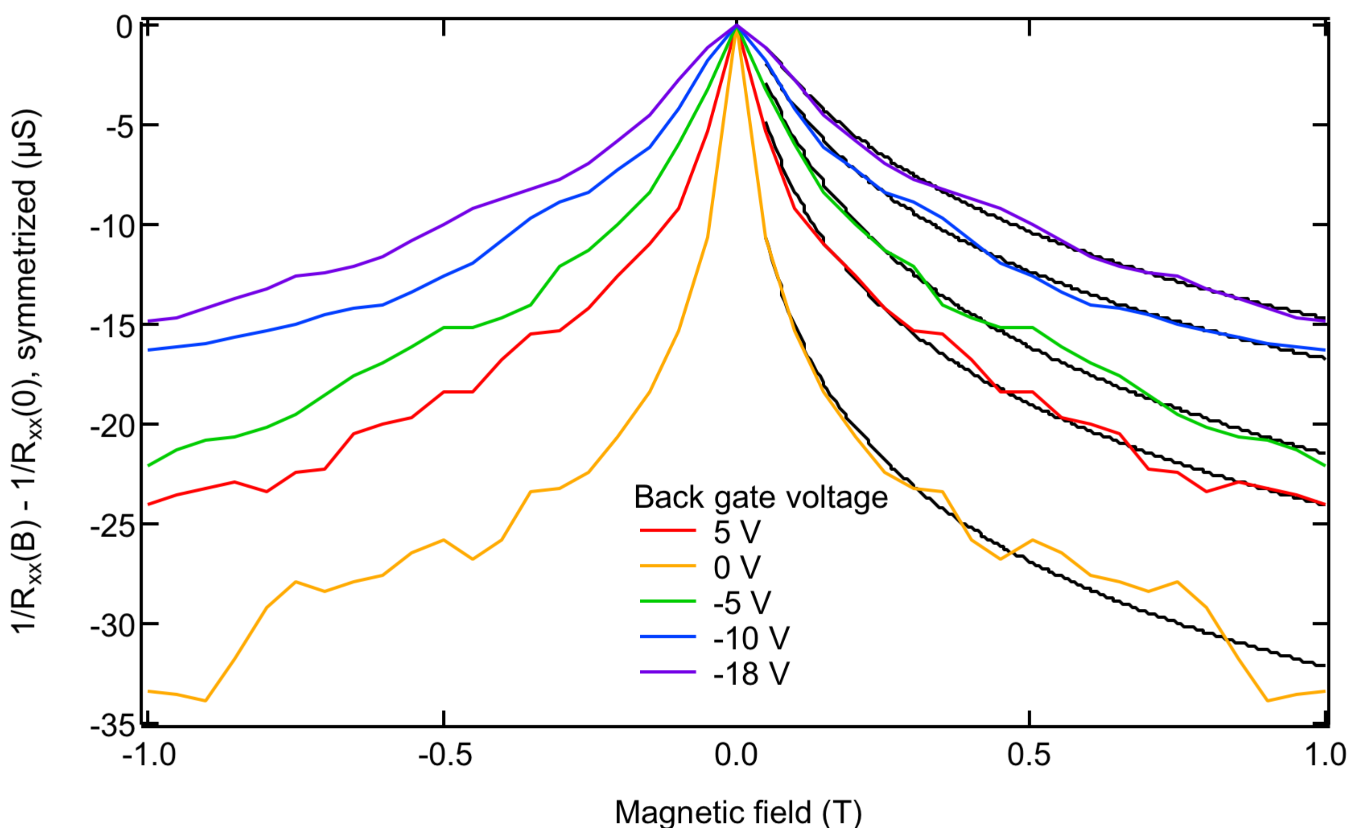
- Fits very good, until more negative gate voltages

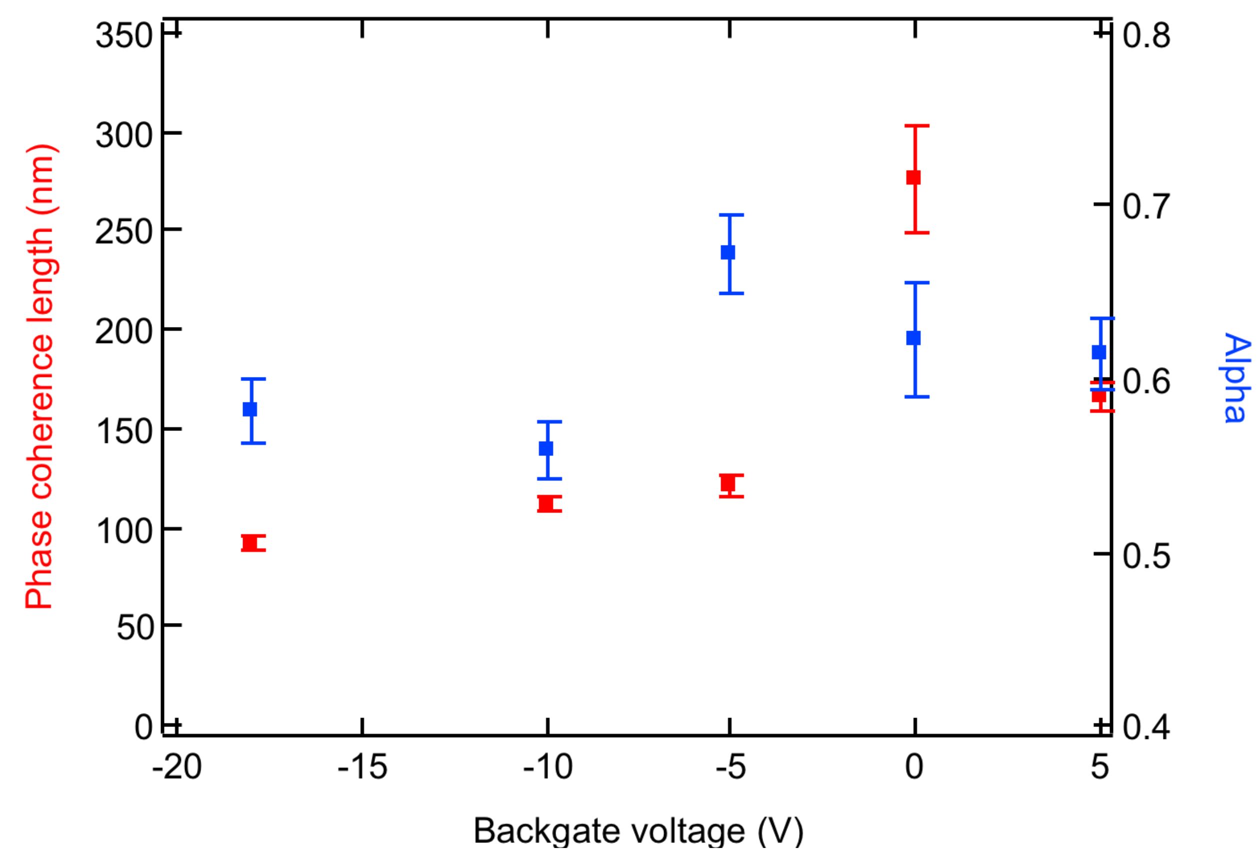




Weak anti-localization

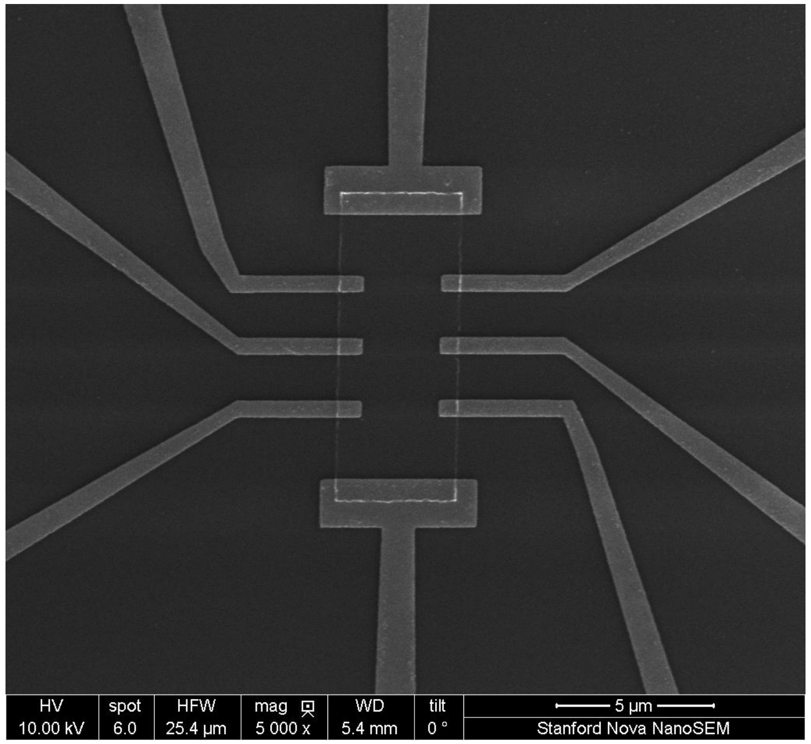
- Fits to HLN, extraction of spin-orbit strength and phase-coherence length

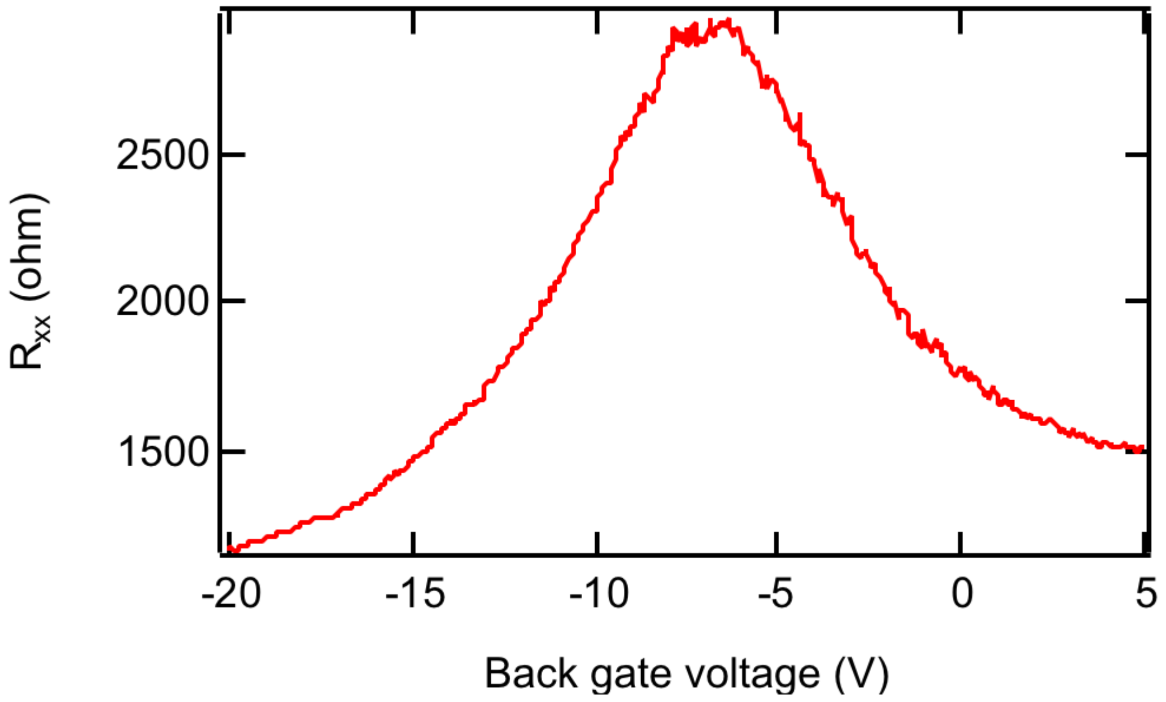




$$\Delta\sigma \approx \alpha \frac{e^2}{2\pi^2\hbar}\left(ln\left(\frac{B_\phi}{B}\right) - \psi\left(\frac{1}{2} + \frac{B_\phi}{B}\right)\right)$$

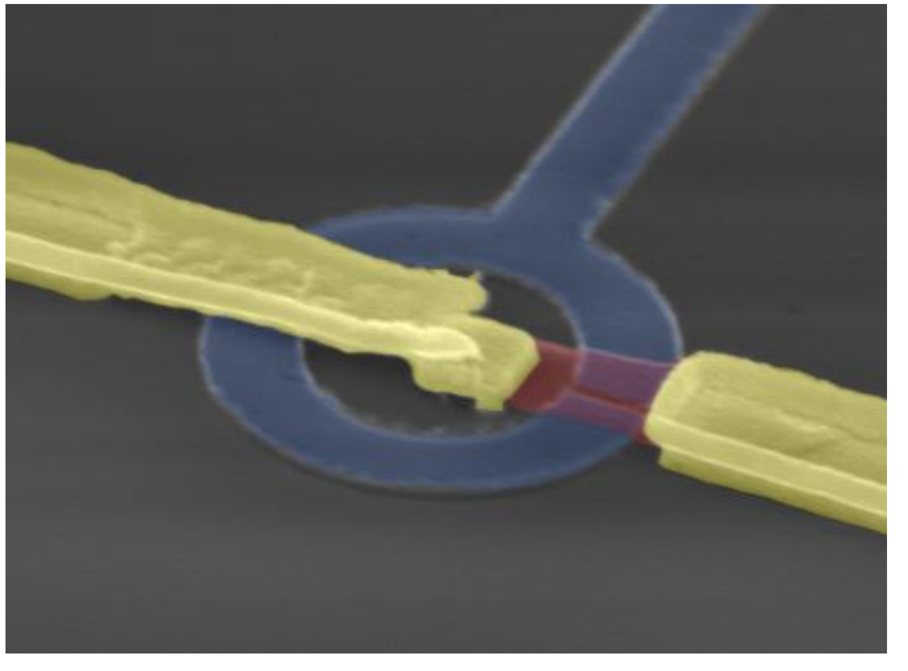
Transport in MBE-grown TI films





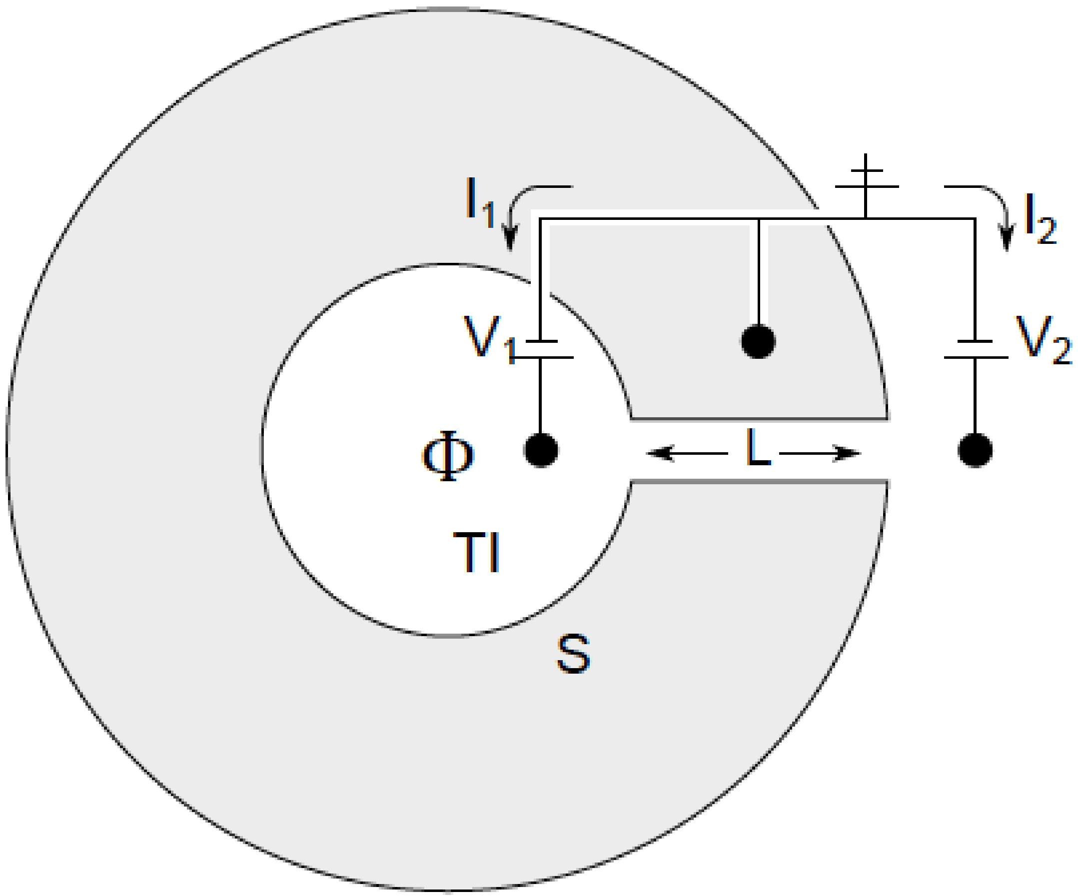
- Can tune through the ambipolar ("Dirac") point in this material and can do it routinely
- Can understand the shape of the Hall resistance and use it to get both electron and hole densities/mobilities
- Mobility current low (500 cm^2/Vs). Growers have improved the surface morphology and have succeeded in capping the surface

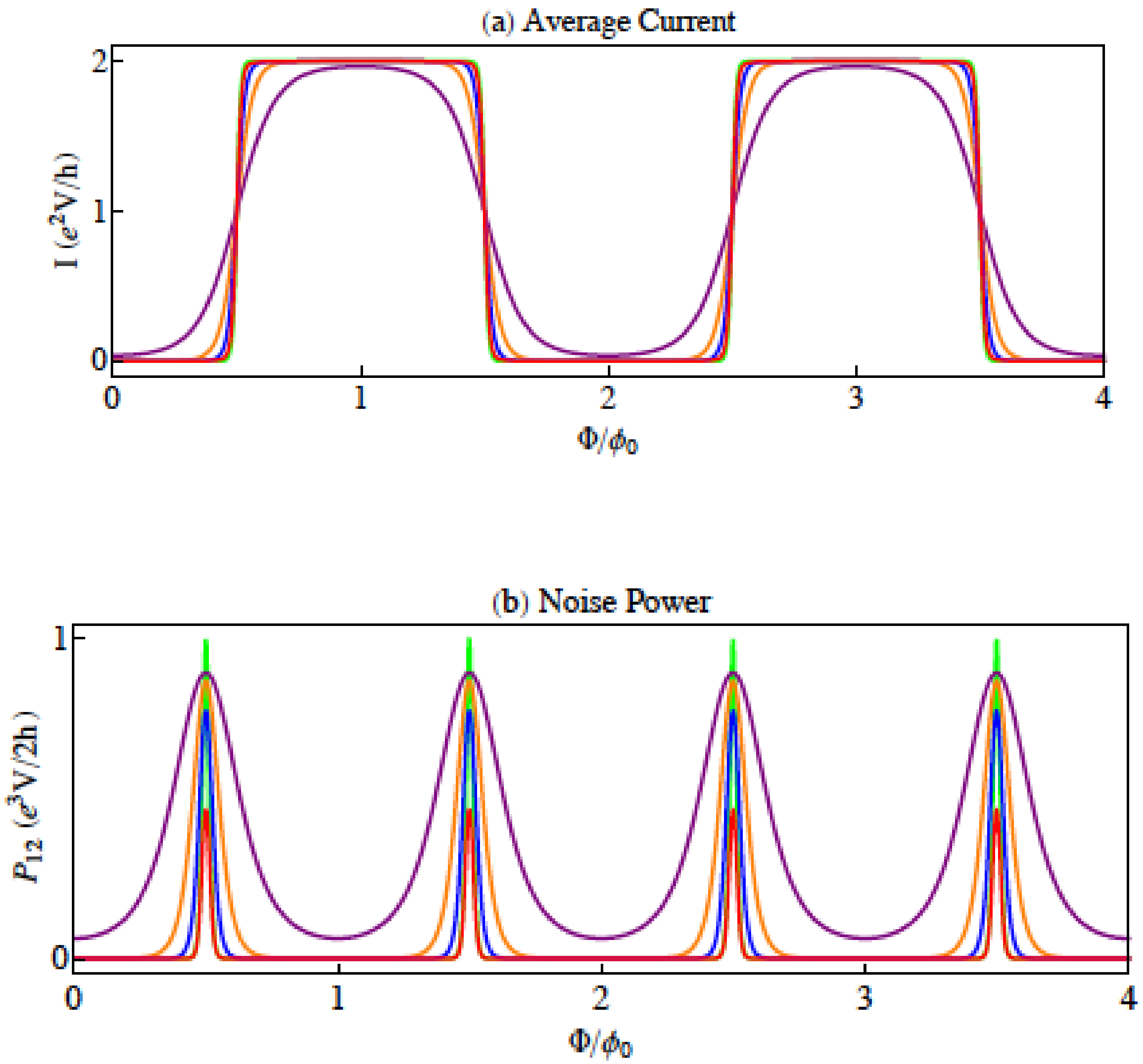
New Measurements

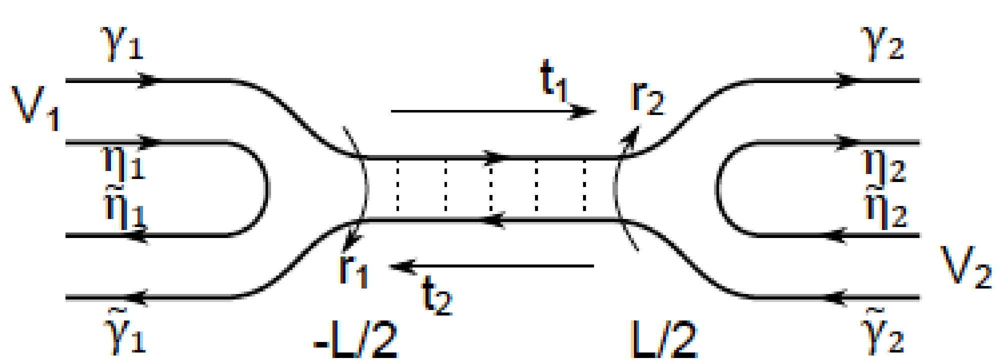


Measuring Transport Along Junctions

- Work from Wieder, Zhang and Kane – coming soon

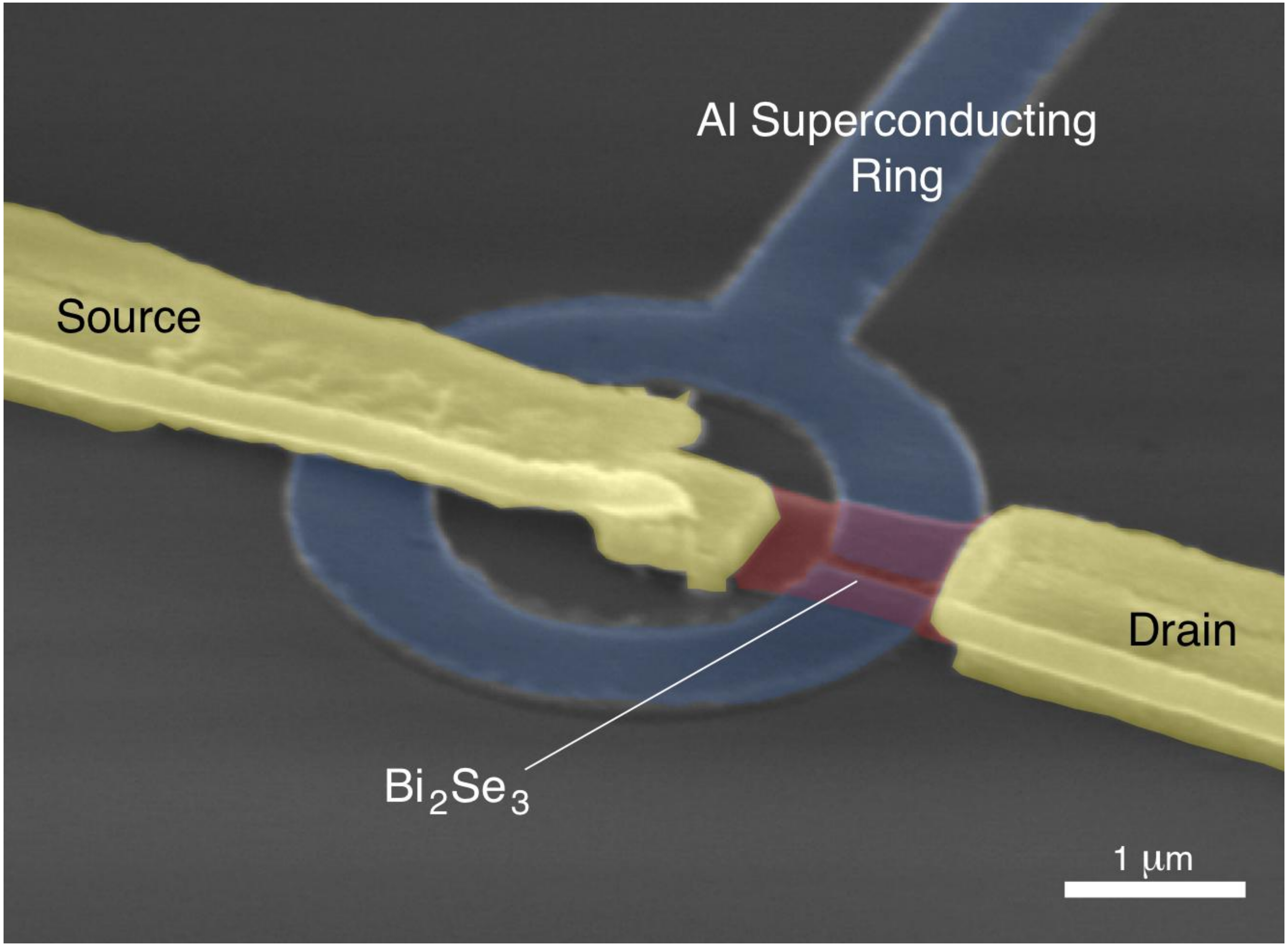






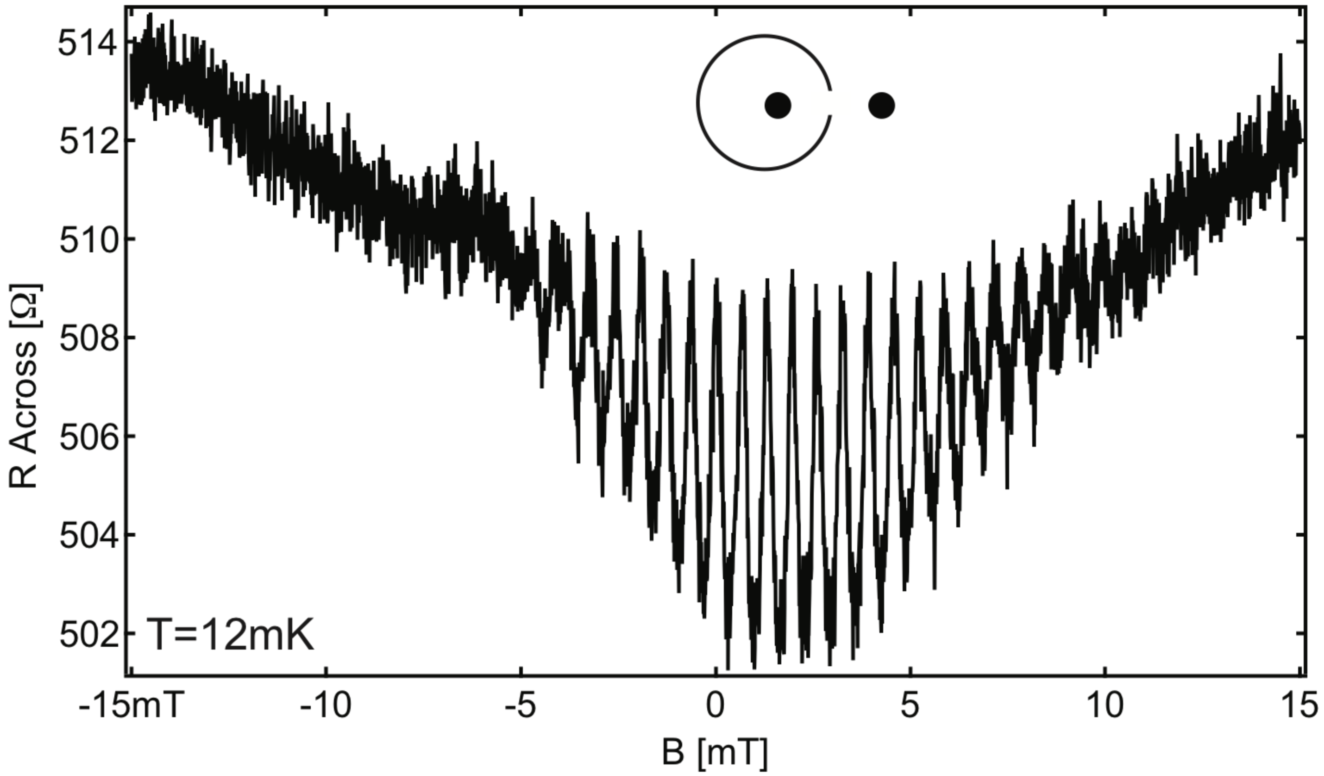
Creating the device

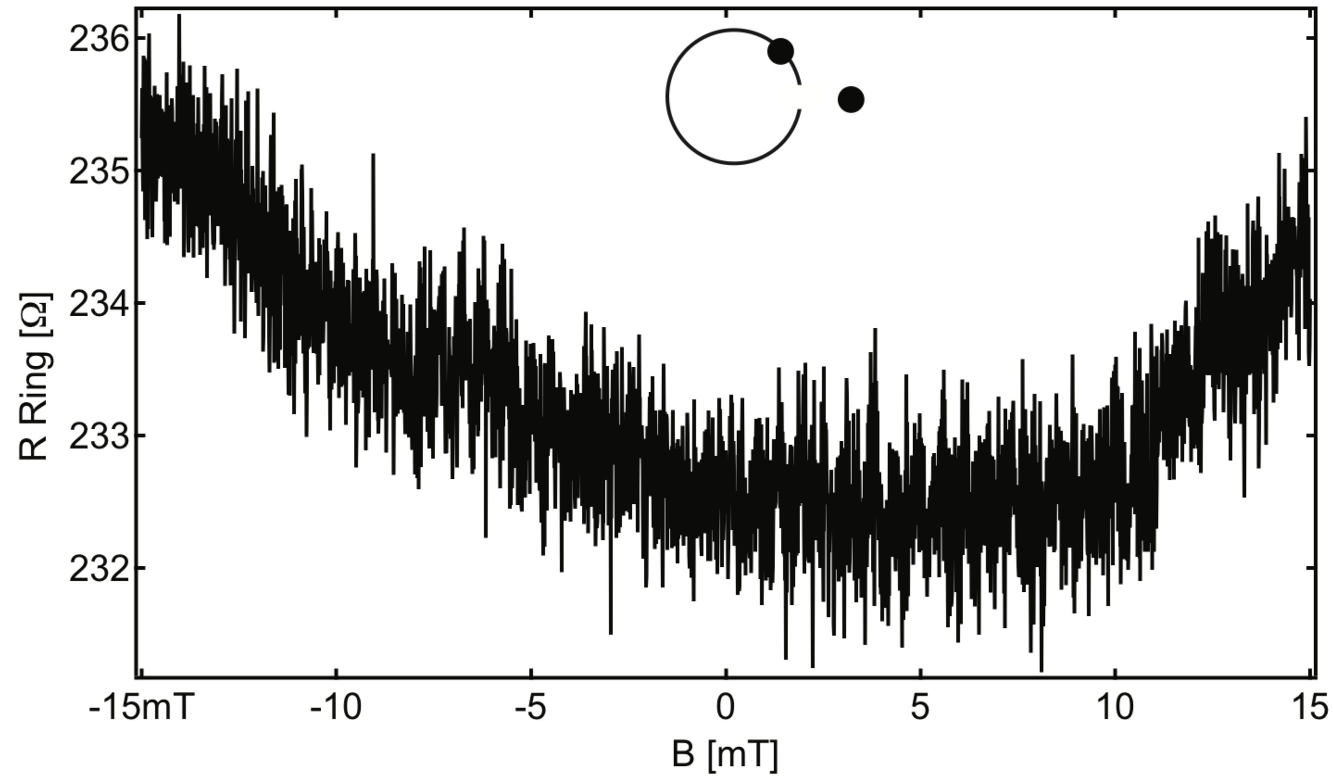
- Set the phase with magnetic field, measure resistance between source and drain, and between ring and drain

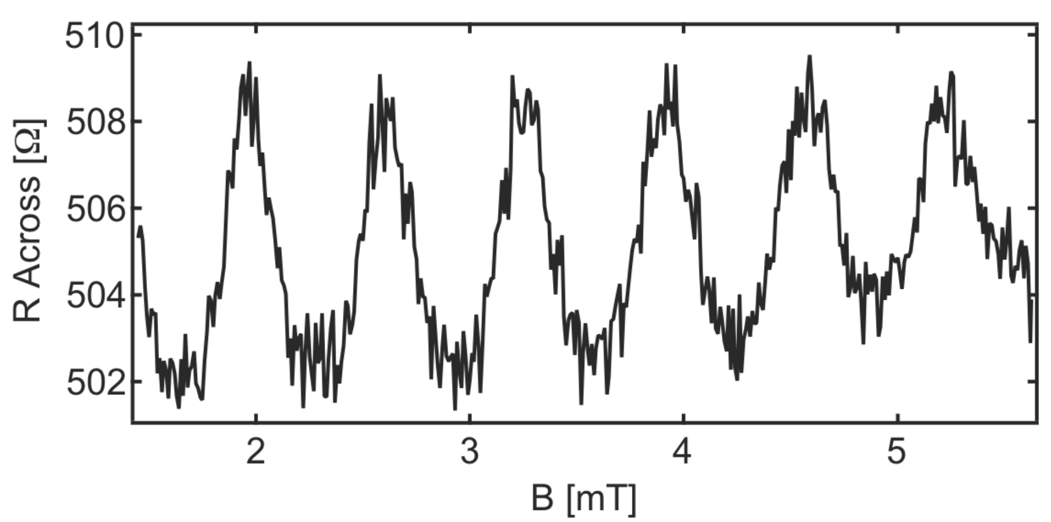


Measuring Transport Along Junctions

- At base, oscillations seen in the resistance across the junction







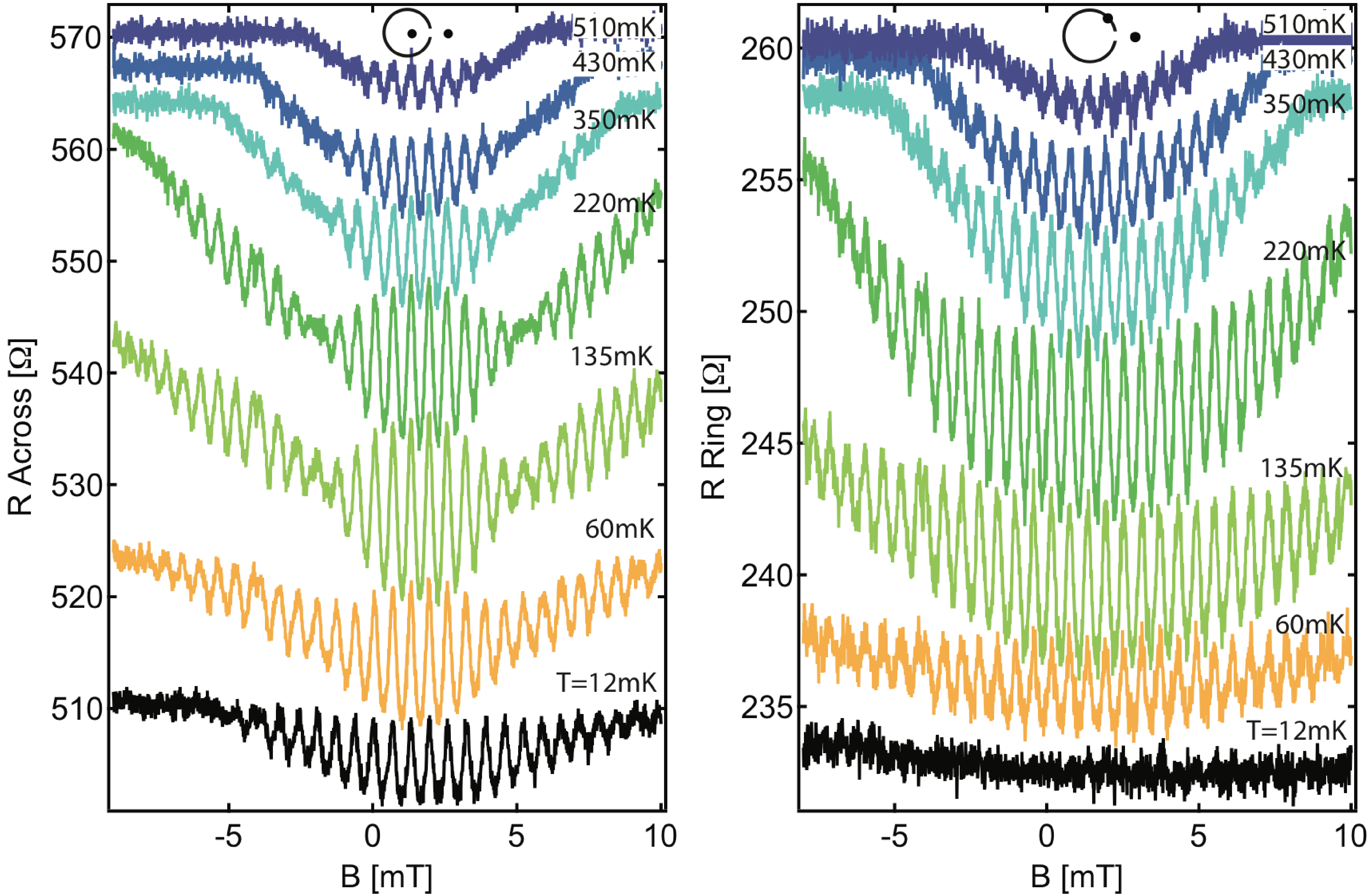
Ring inner radius of 0.8 microns and outer radius of 1.3 microns

Expected period for h/e is 2mT and for h/2e, 1mT (for inner radius)

Measured period is 0.6mT

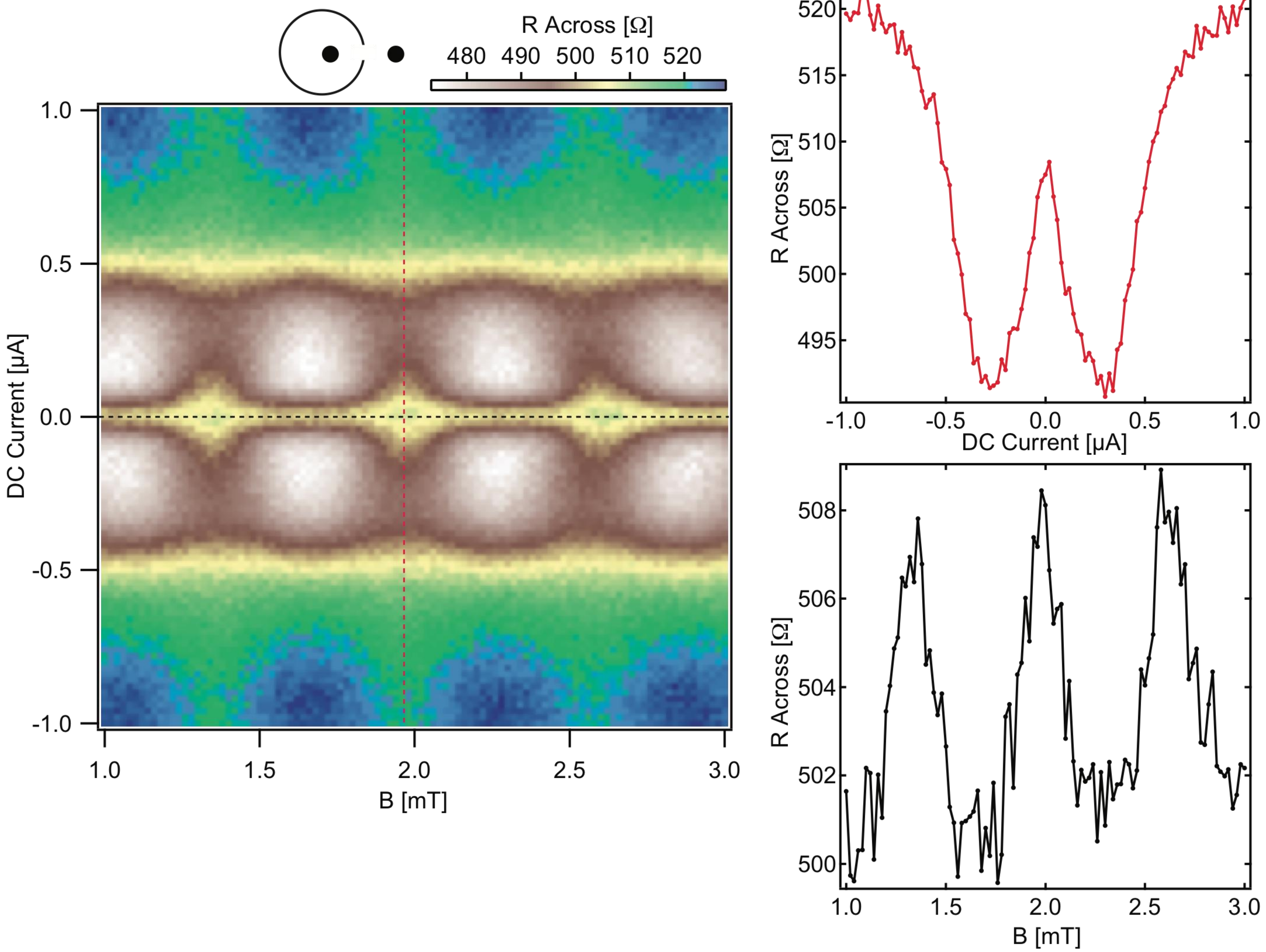
Temperature Dependence of Oscillations

- An unexpected, non-monotonic behavior observed



Bias Dependence of Resistance

- The minimum in resistance is not a zero applied bias



Summary

- Measured superconducting rings (with Bi_2Se_3 JJs) and dots. Rings showed the CPR is likely conventional. Dots shows we should look further into the effect of strong spin-orbit material on conventional superconductors
  - *What does this say about the S-strong-spin-orbit interface?*
- Made progress on transport in MBE TI films. Can now routinely tune through the Dirac point
  - *What can tuning get you in 3D TI Josephson junctions?*
- Measure conduction along phase controlled junctions and saw unexpected behavior in the temperature and bias-dependence of the measured resistance
  - *What are the prospects for measuring this effect and why would we observe this temepraturе dependence?*

Acknowledgements

- This work relies on a tremendous community of researchers:

Fab & measurement

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Patrick Gallagher
David Goldhaber-Gordon

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Ilya Sochnikov
Tom Lippman
John Kirtley
Kathryn Moler

Materials growth

Bulk Crystals
James Analytis
Andrew Bleich
Ian Fisher

Nanowires
Seung Sae Hong
Yi Cui

MBE
Xiaoyue He
Yongqin Li
Kehui Wu

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Mac Beasley
Xiaoliang Qi
Jens Bardarson
Joel Moore