# Superconducting Contacts to Topological Insulators

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*Stanford University*
*KITP, December 2011*

# This talk is a snapshot of our understanding back in December

For this slide deck, I’ve only corrected minor typos and names in acknowledgments.

For a more recent and nuanced picture, with added data and analysis, please see:

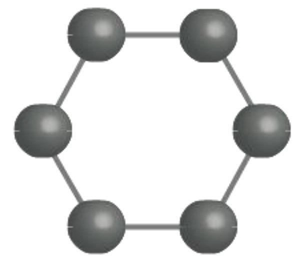
arXiv:1202.2323

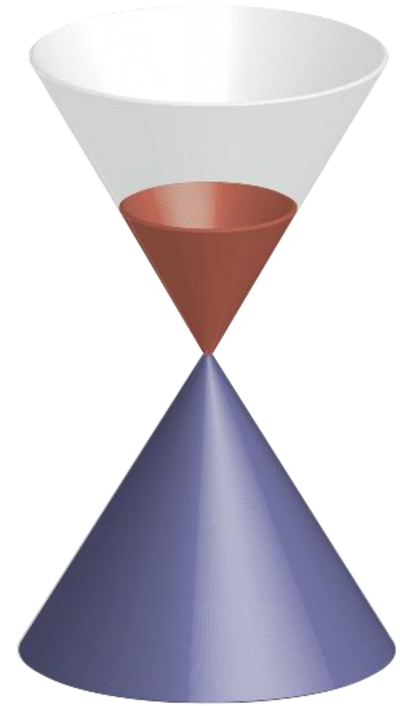
Signatures of Majorana Fermions in Hybrid Superconductor-Topological Insulator Devices

J. R. Williams, A. J. Bestwick, P. Gallagher, Seung Sae Hong, Y. Cui, Andrew S. Bleich, J. G. Analytis, I. R. Fisher, D. Goldhaber-Gordon

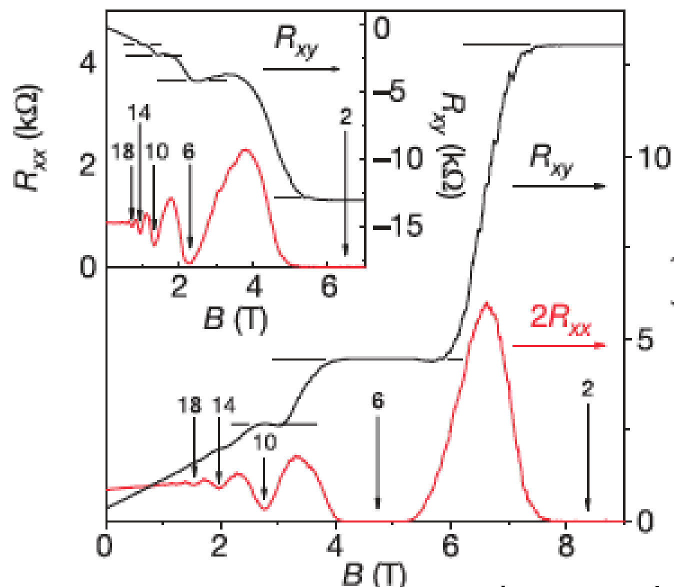
# Novel 2DEGs: **Dirac Particles**

- New class of 2DEGs: Dirac Fermions. [cf. Klein Tunneling in Graphene, PRL **102** 026807 (2009)]
- In graphene, “Dirac” comes from symmetry of crystal structure





- Signatures of Dirac fermions can be seen in transport

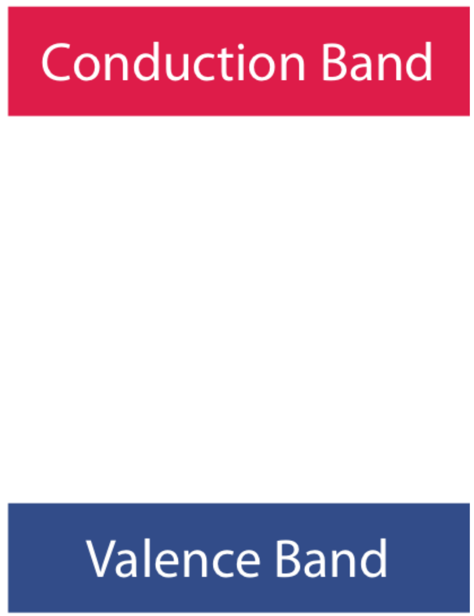



Zhang et al. Nature (2006)

$$E = \hbar c k$$

# Novel 2DEGs: **Dirac Particles** and Spin-Orbit

- New class of Dirac systems: Topological Insulators



# Novel 2DEGs: **Dirac Particles** and Spin-Orbit

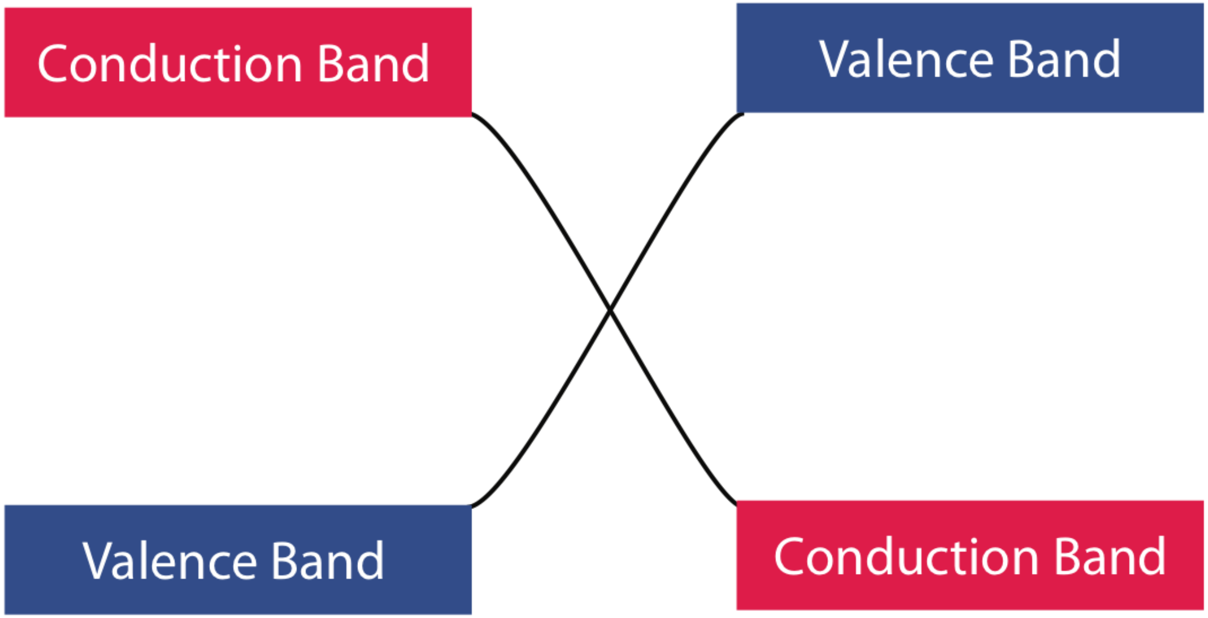
- New class of Dirac systems: Topological Insulators

Topological insulator

# Novel 2DEGs: **Dirac Particles** and Spin-Orbit

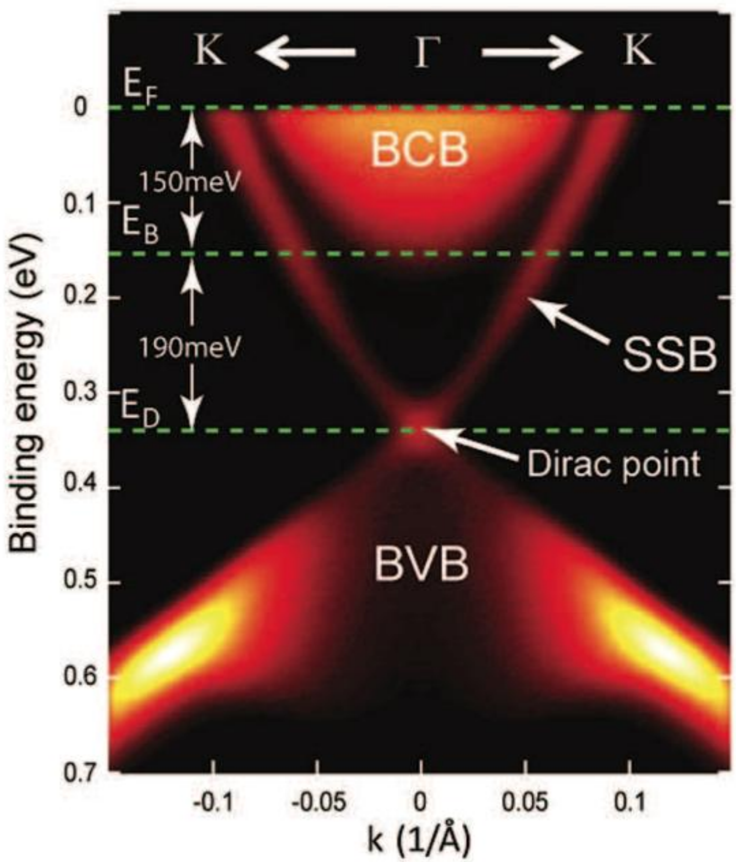
- New class of Dirac systems: Topological Insulators
- Dirac arises from band inversion due to strong spin-orbit coupling
- More exotic particles possible: Majorana fermions, monopoles, etc.

Topological insulator

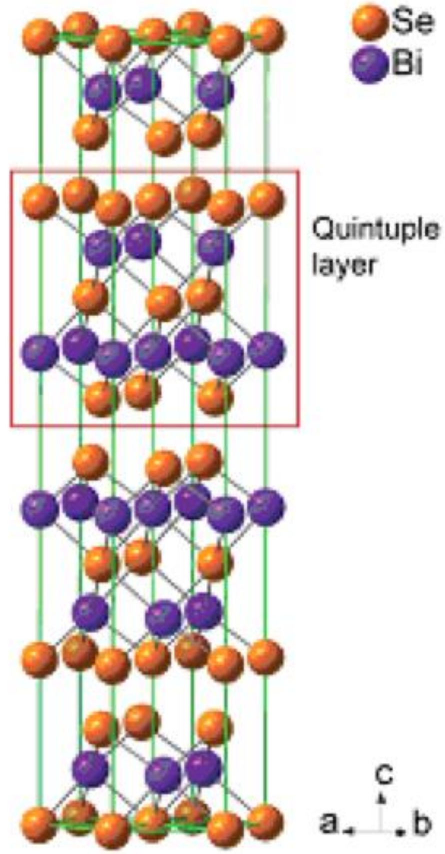


# Novel 2DEG at the surface of a topological insulator: $Bi_2Se_3$

- $Bi_2Se_3$ can be grown as millimeter-scale crystals
- Surface states seen in surface-sensitive probes (ARPES, STM)
- Large gap … but transport still includes bulk
- Layered structure, good for exfoliation




Y.L. Chen *et al.*, Science, 2010




H. Peng *et al.*, Nano Lett., 2009

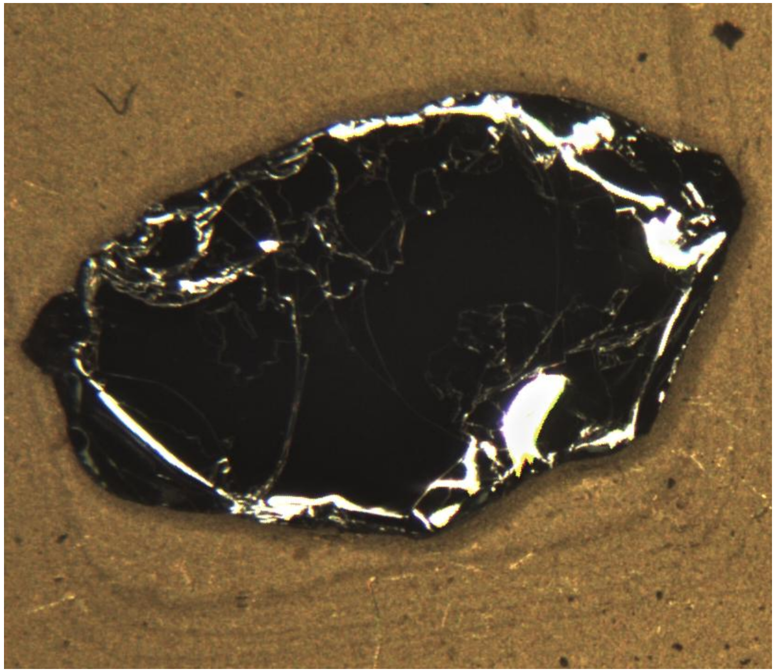
# Outline

- Transport in ‘topologically-insulating’ materials
  - Materials growth and sample preparation
  - Gating: pushing around large charge densities
  - Methods to mitigate doping: materials and encapsulation

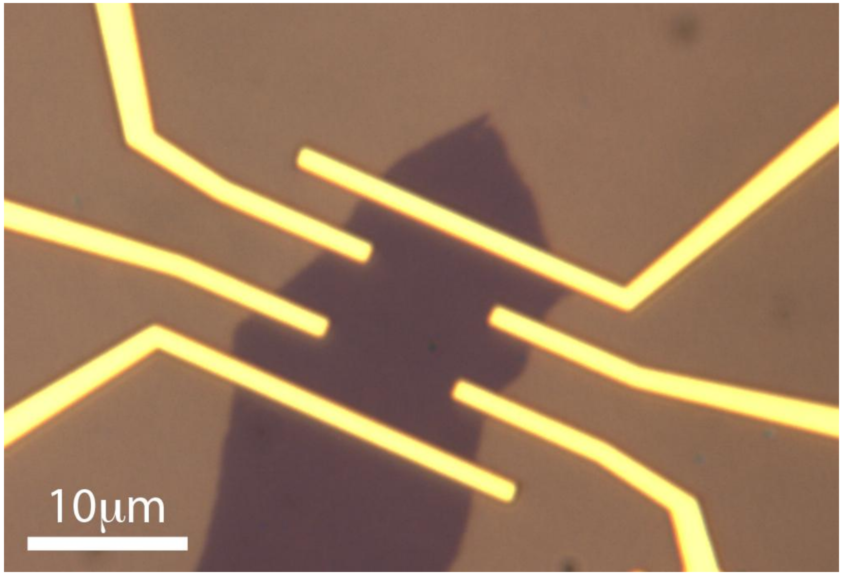
- Proximity-induced superconductivity in $Bi_2Se_3$
  - Sample Fabrication
  - S-TI-S junction dV/dI
  - Geometric dependence of critical current
  - Magnetic field dependence of critical current
  - What’s new and different?

# Transport in $Bi_2Se_3$ and $Bi_2Te_2Se$

- Created nanometers-thin $Bi_2Se_3$ samples via mechanical exfoliation of thick Sn-doped $Bi_2Se_3$ crystals
- Pattern electrical leads with e-beam lithography

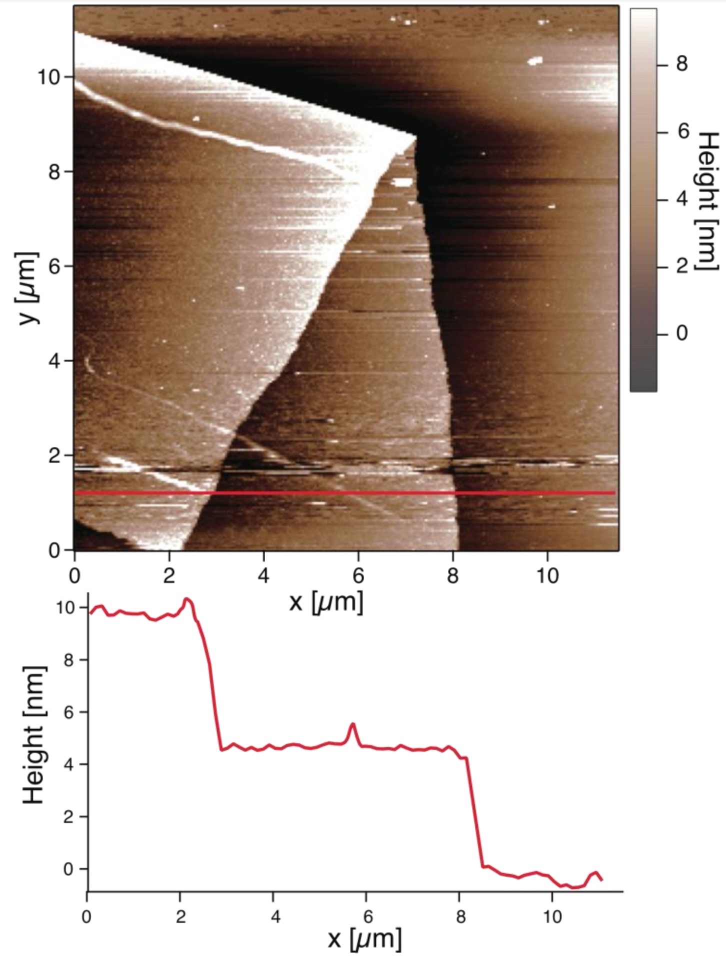


Exfoliation

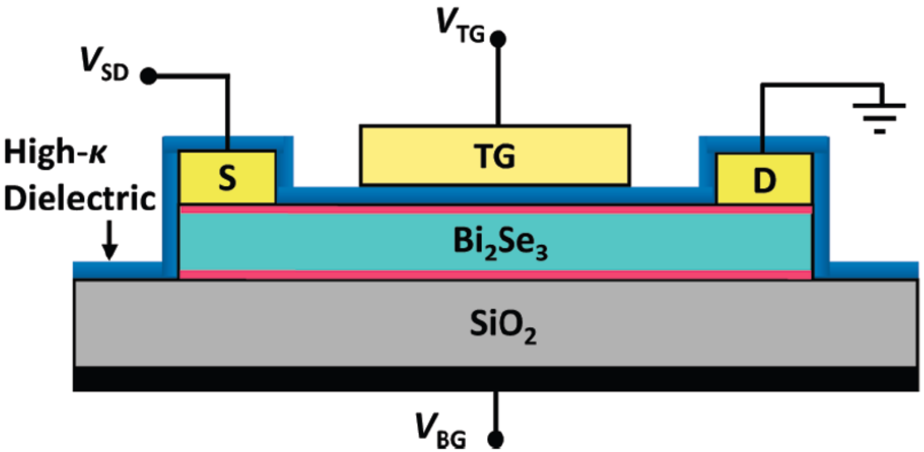


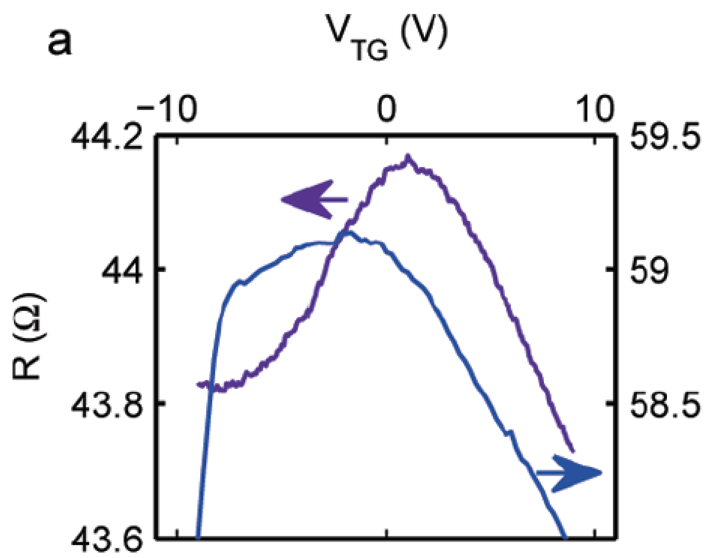
# Atomically-flat exfoliated $Bi_2Se_3$

- AFM shows that flakes are often atomically flat and have lateral dimensions of many microns
- Thickness ranges from ~4nm  to ~500nm

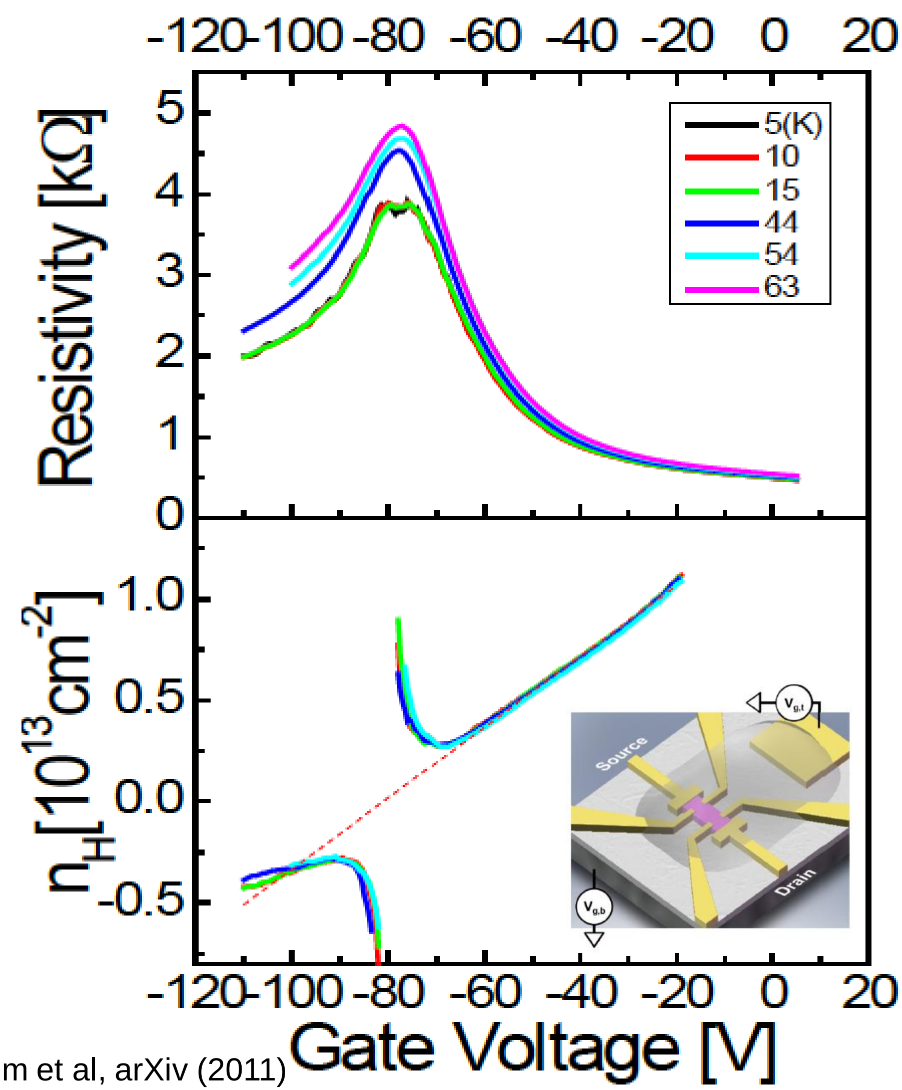


# Getting to the Dirac Point



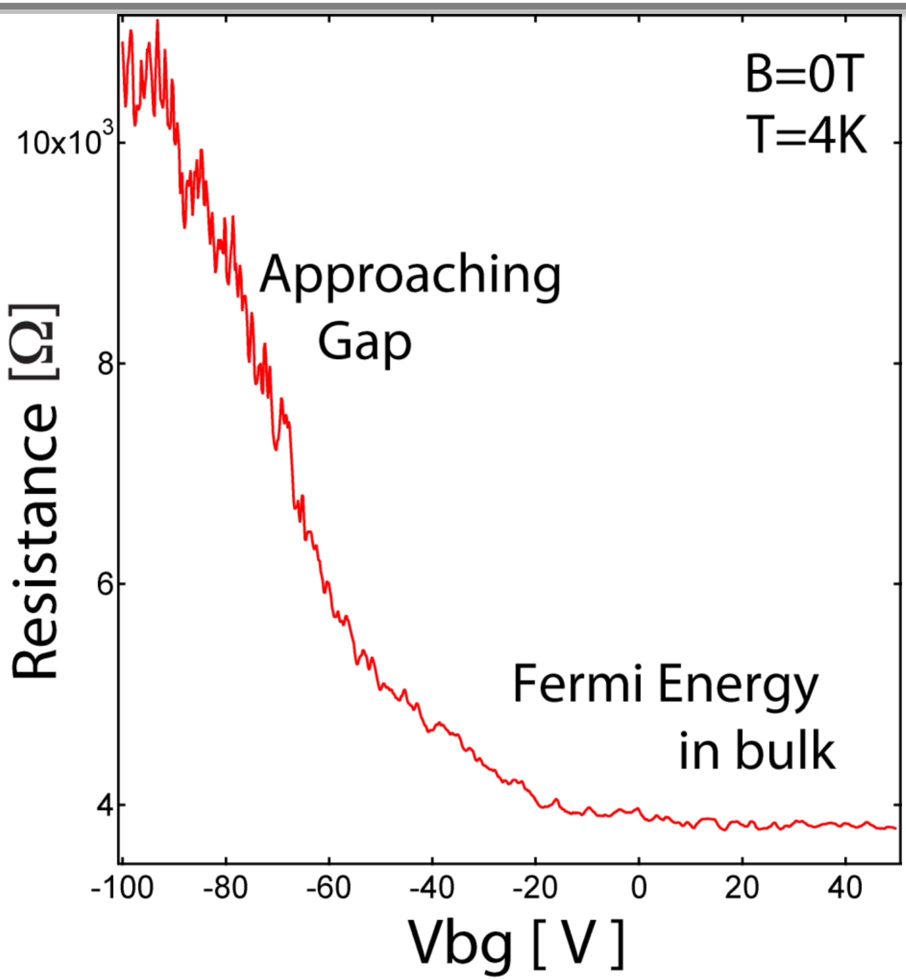




Steinberg et al, Nano Lett (2010)



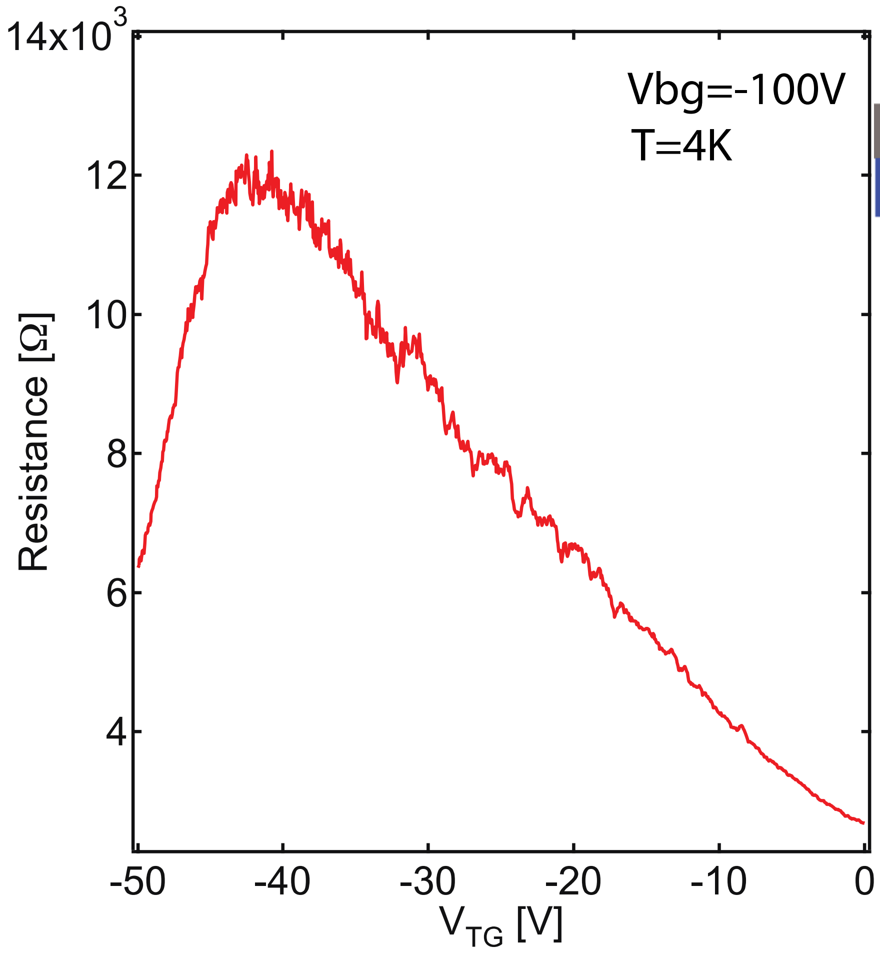

Kim et al, arXiv (2011)

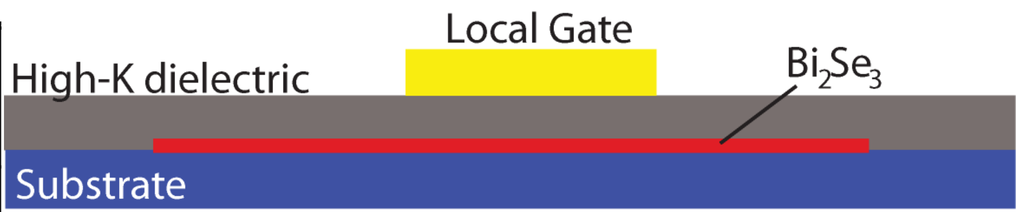
# Our Work on Gating




- Thin samples (5-15 nm) highlight surface transport
- Chemical potential can be tuned via gate electrode
- But chemical potential not in bulk gap before gating

# Double-Gated Devices

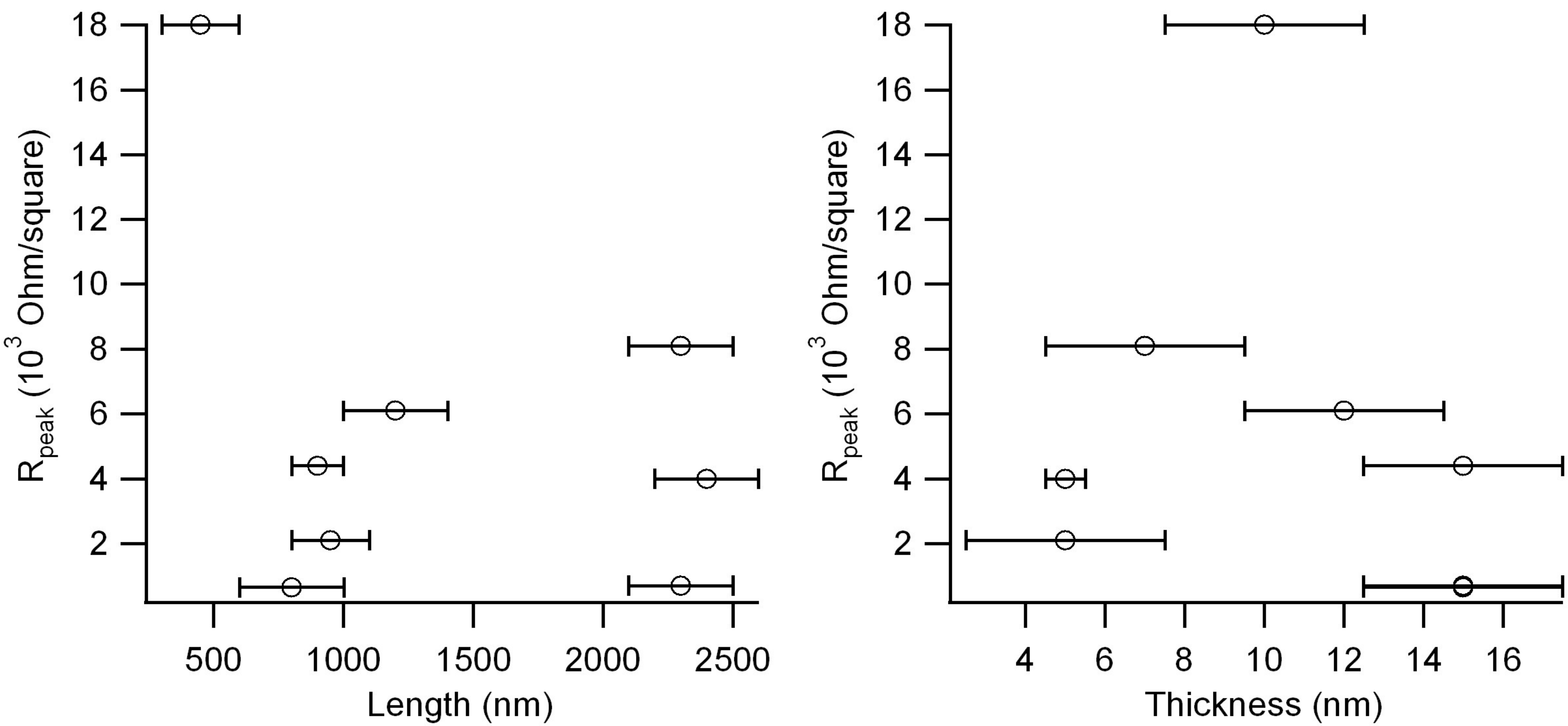


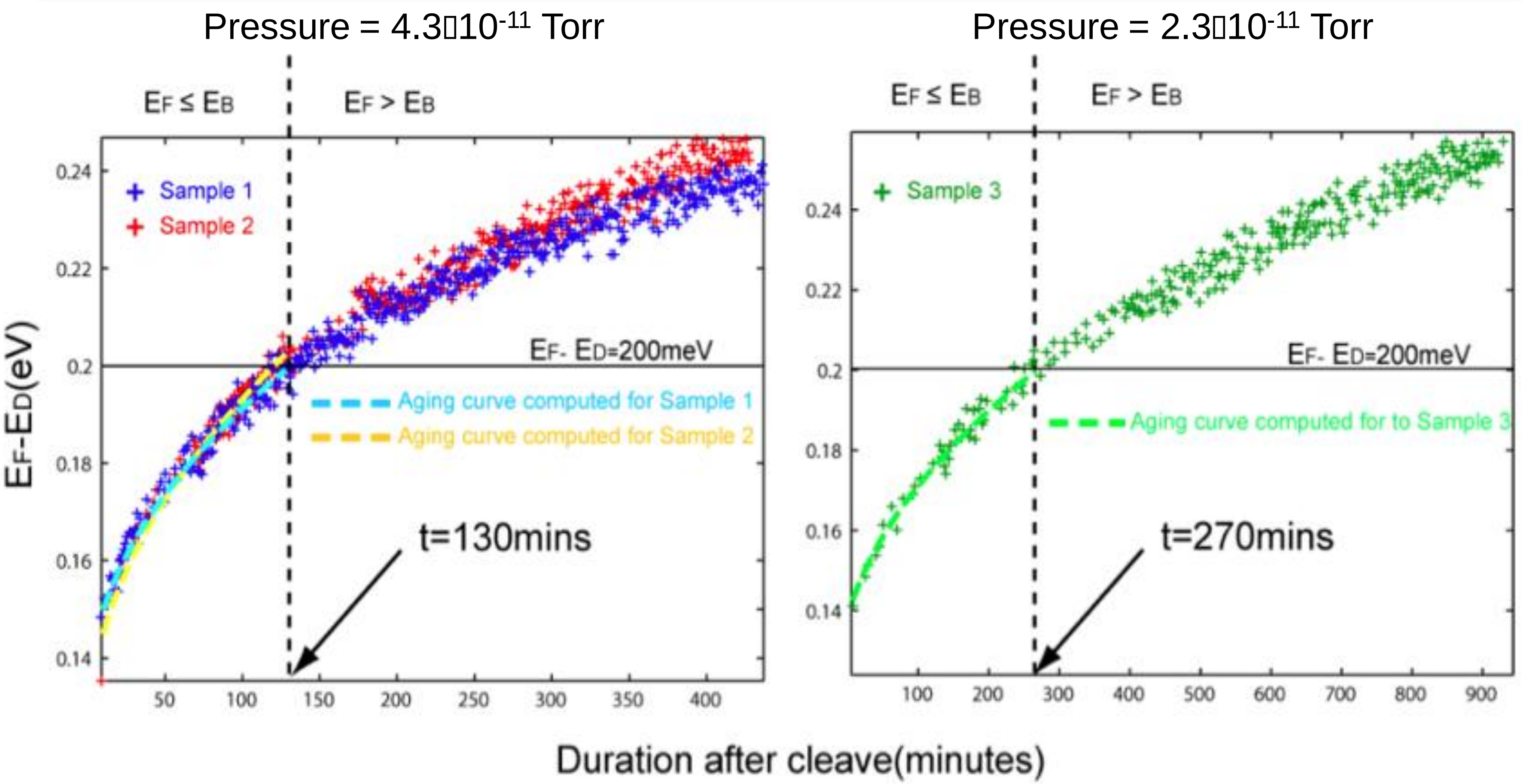

- Can achieve density swings of ~$10^{13}$ cm$^{-2}$.
- Observe peaks in resistance: presumably the peak occurs when the Fermi energy crosses the Dirac point.
- Magnetic field has little effect, likely due to the low mobility (high impurity doping).

# Summary of Devices

- Resistance peak vs. gate voltage in 8 devices of various lateral geometries, aspect ratios and thickness
- Peak resistance independent of device geometry



# A Culprit: Exposure to Air

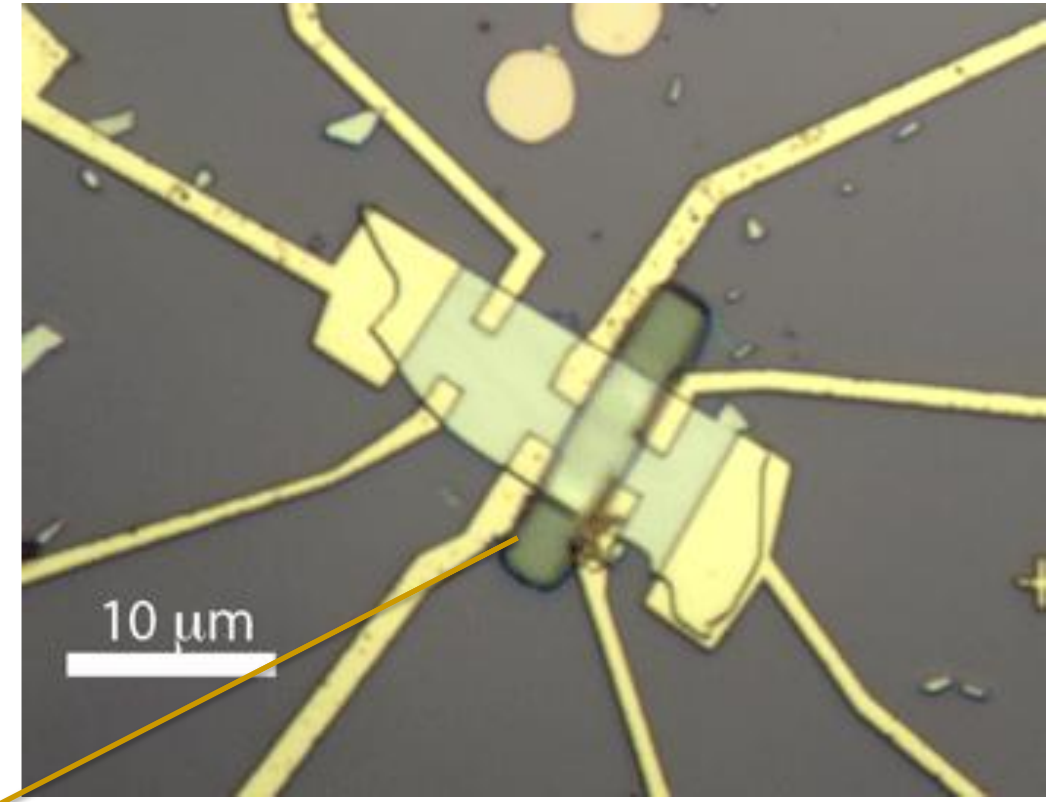



Y.L. Chen *et al*., Science, 2010

See also, D. Kong arXiv (2011)

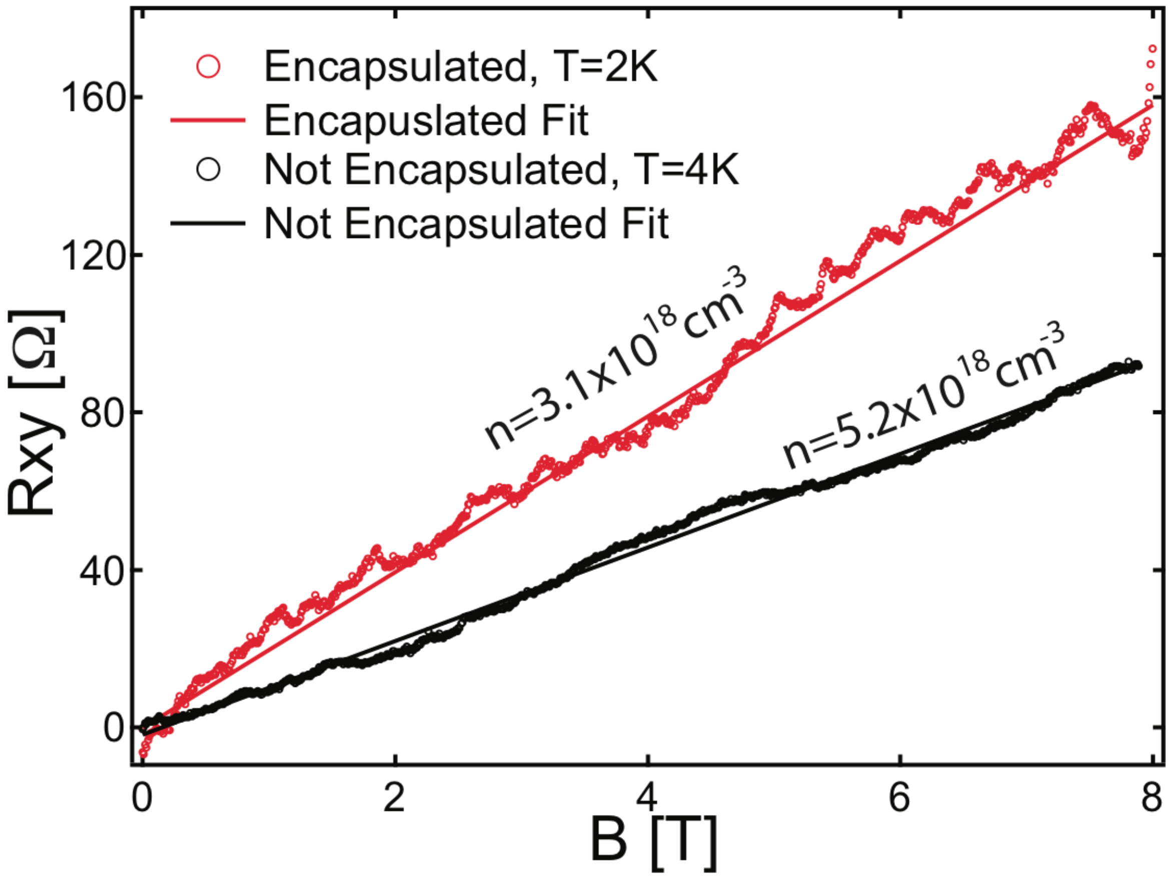
# Device Encapsulation

- Cover device with a hydrophobic material to prevent water doping (surface, electron doping) of the device.
- Devices are exfoliated in a glove box and covered with PDMS.
- E-beam lithography allows for the definition of the covered area.
- Can measure transport in the covered and uncovered areas.



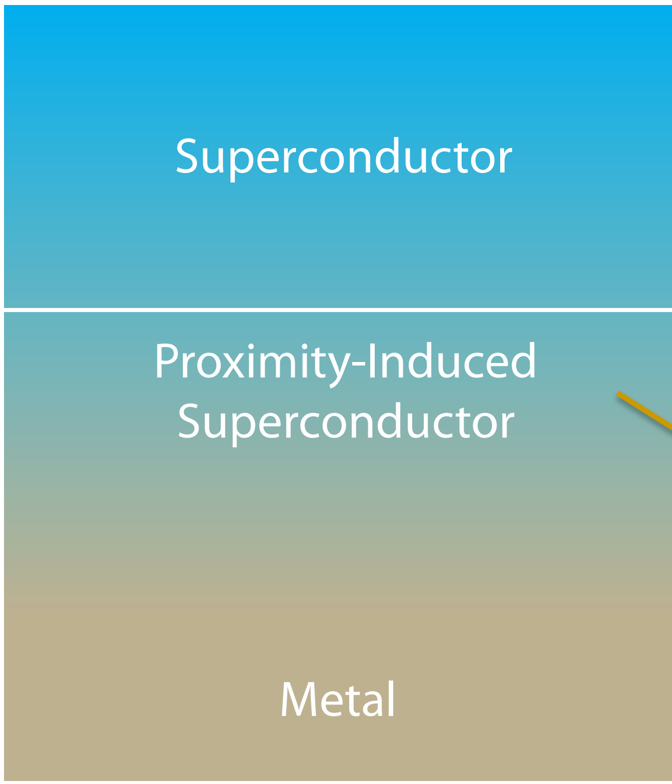

PDMS

# Density modification by encapsulation




- Encapsulation lowers measured density (for a device thickness of 100nm).
- Assuming difference between two regions is entirely in the top ~10 nm, density near surface is reduced by a factor of 10

# Adding interaction between carriers – the proximity effect

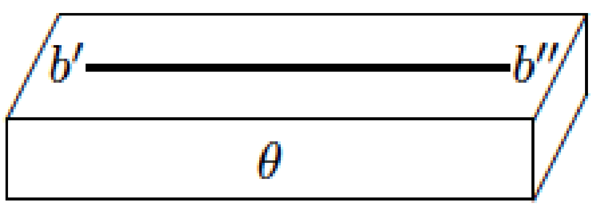


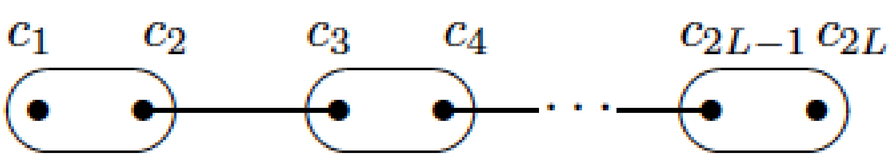

- Can induce extra correlations between electrons by placing a material in proximity to a superconductor
- Resulting system a “hybrid” of the two systems

$$H_{PROX} = K_{METAL} + \Delta_{SUPER} \psi^{+} \psi$$

# Zero Energy Modes in Superconductors

1D quantum wire on a 3D p+ip superconductor

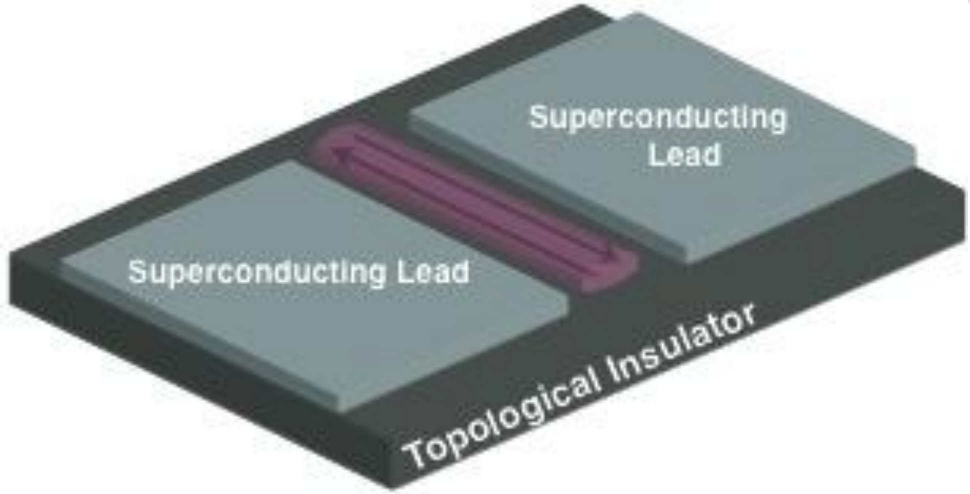


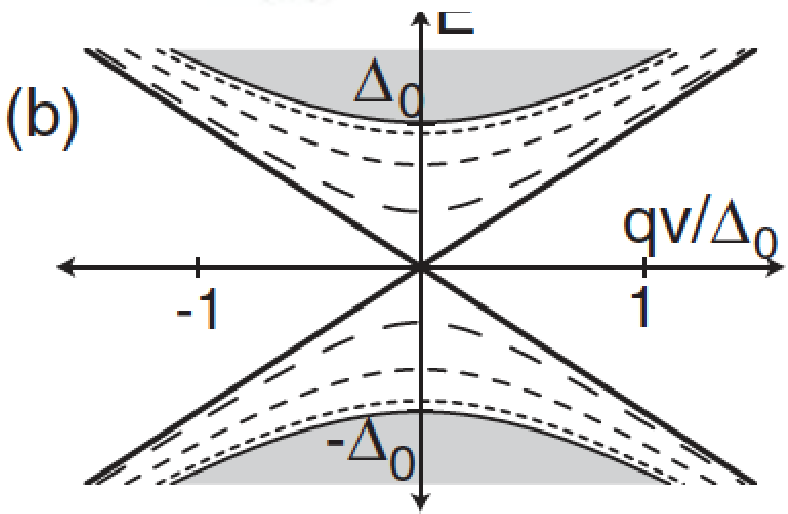




Kitaev, arXiv:condmat/0010440

- Can get situations in superconductors where particle excitations are the same as the antiparticle excitations. But you can’t use just any superconductor
- Kitaev showed that under certain conditions for 1D p+ip superconductors you can have unpaired Majorana fermions at the end of the wire

# Topological Insulators and the Proximity Effect

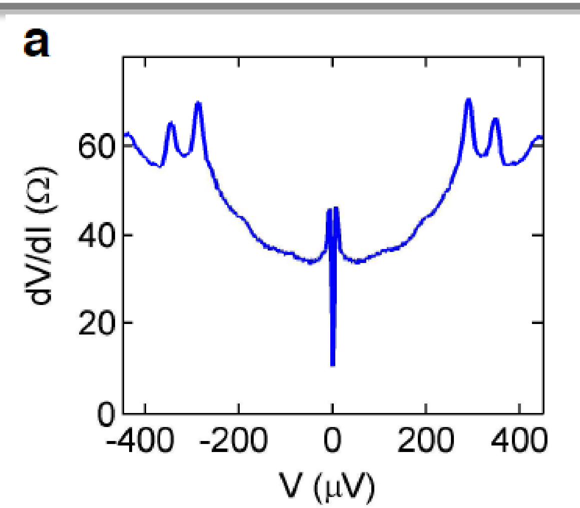


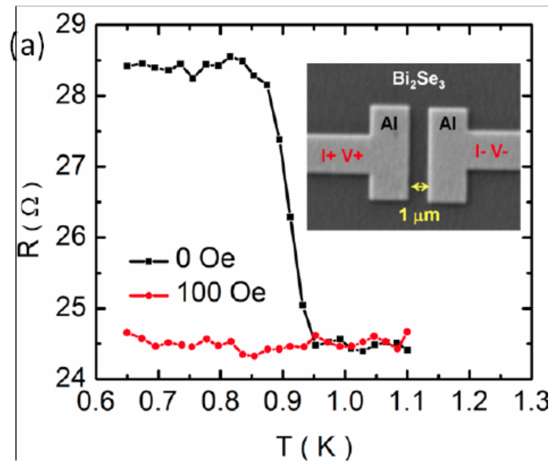

Fu and Kane, PRL, 2008
Titov, Ossipov & Beenakker PRB, 2007

- Topological superconductors (or proximity-induced SC in TI) similar to p+ip superconductors
- 2D: localized Majoranas of the previous case become 1D wire
- 1D wire exists between the superconducting contacts (S)
- Gapless modes for phase difference of π between the leads

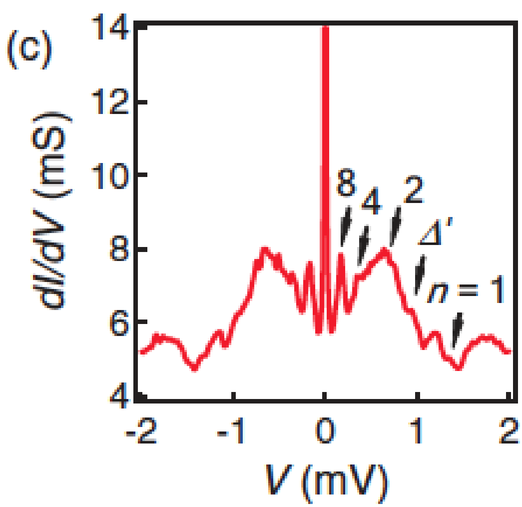
# What's been measured



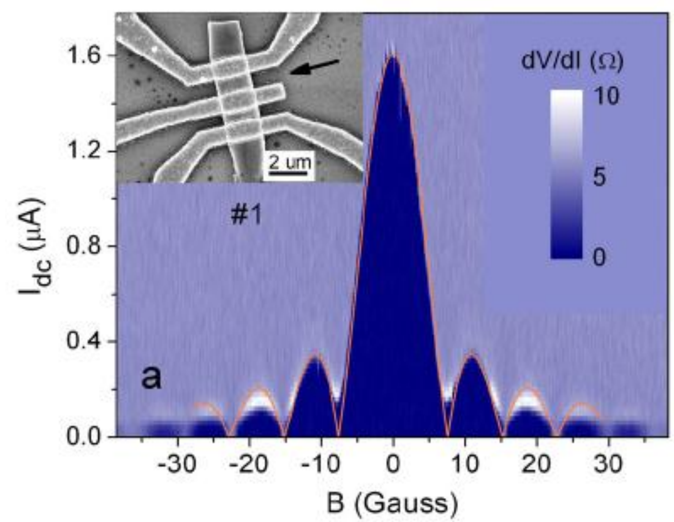

Sacepe et al., arXiv (2011)




Wang et al., arXiv (2011)

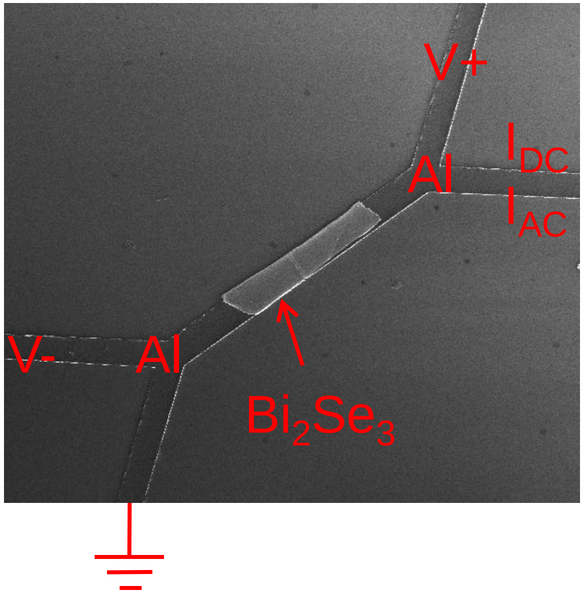



Zhang et al., PRB (2011)

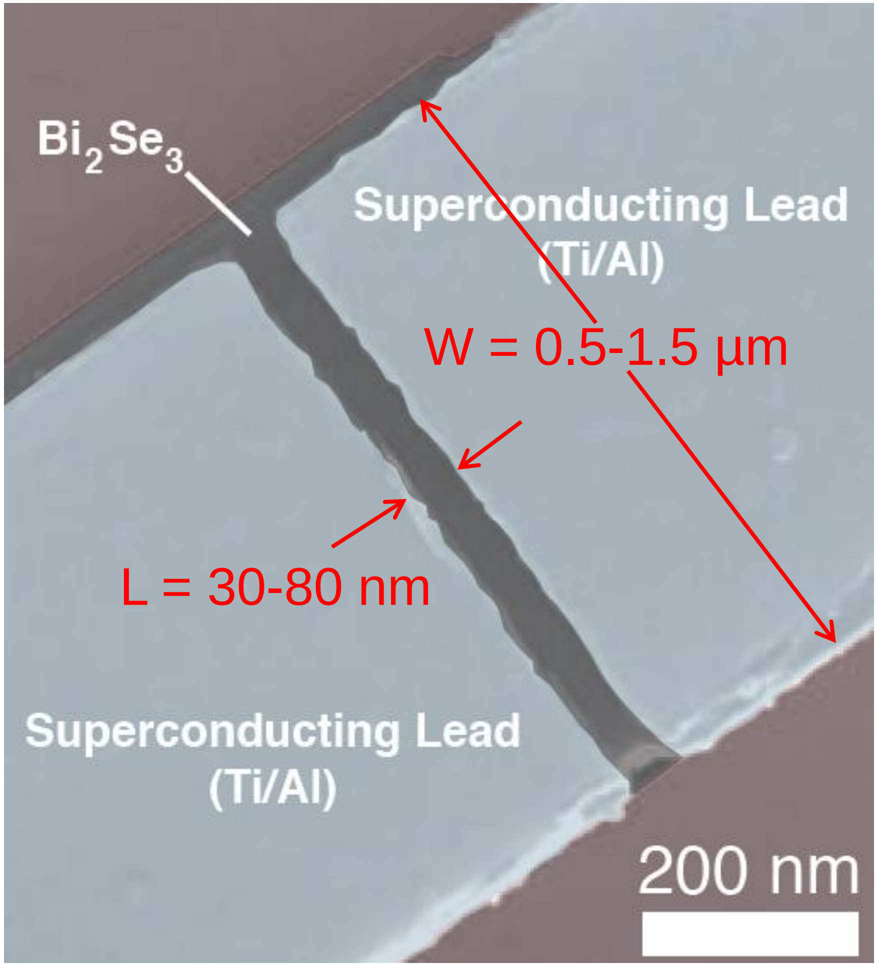



Qu et al., arXiv (2011)

# Superconducting Contacts on Bi2Se3



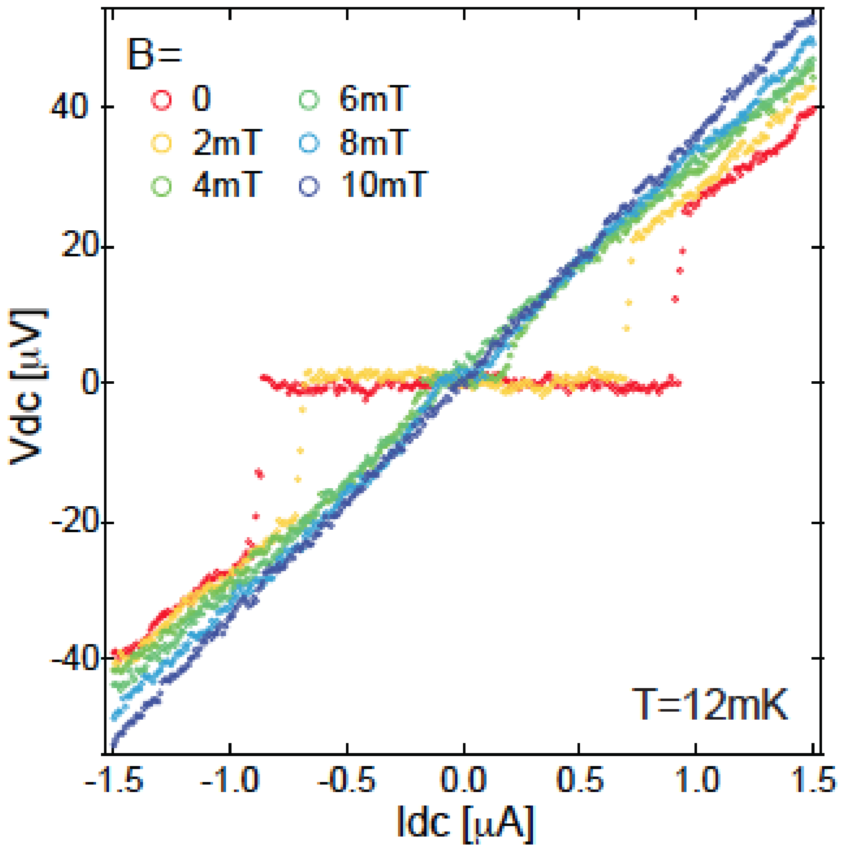

- Exfoliated flakes, thickness ~100nm
- Electrical contacts: Ti/Al 2nm/60nm
- Surface quantum scattering length ~ 200nm*

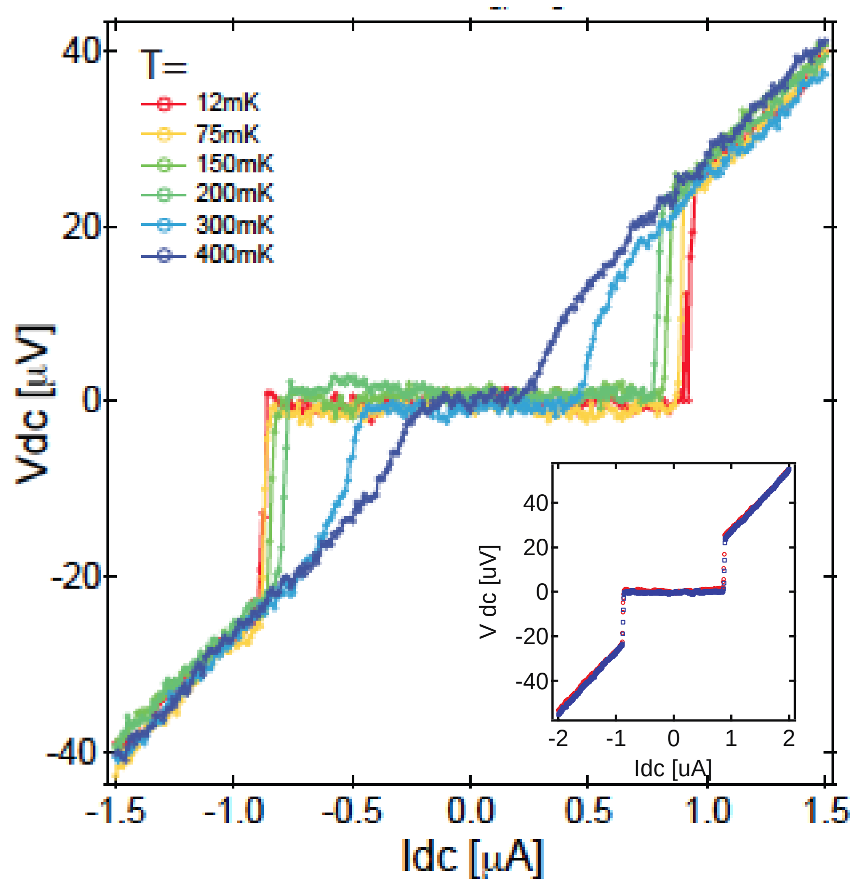



*Qu *et al*., Science, 2010

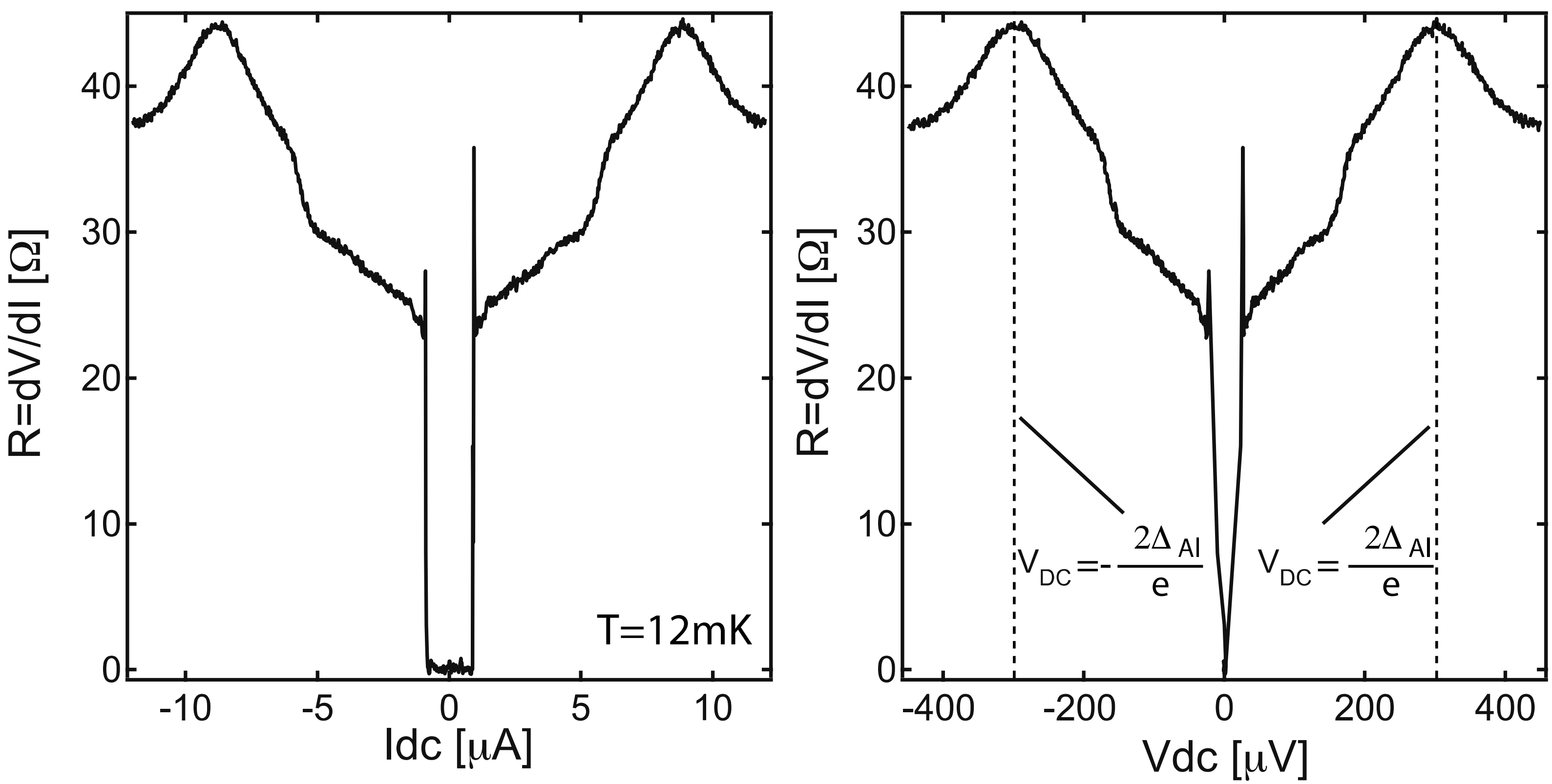
# Supercurrent in $Bi_2Se_3$ Josephson Junction

- Temperature and magnetic field dependence of the DC response of the junction. Note no hysteresis -> over-damped junction



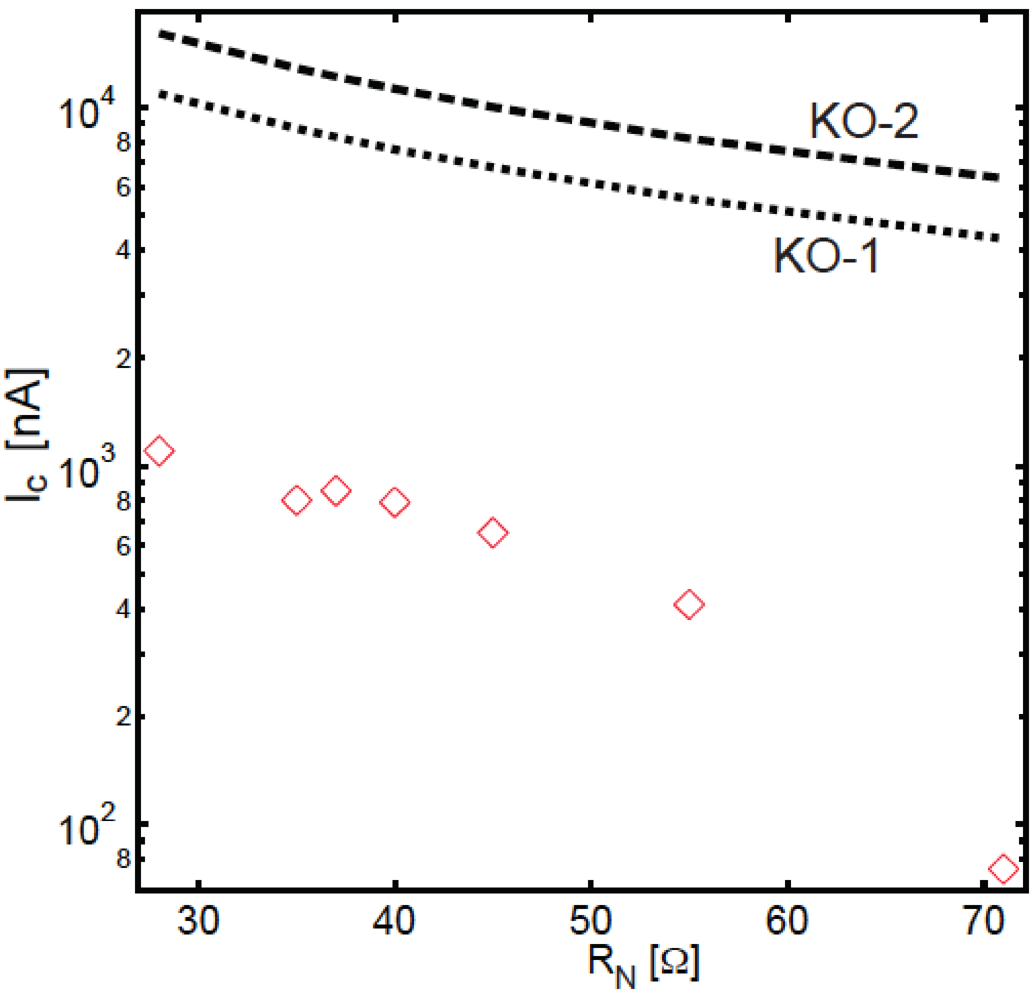
# Supercurrent in $Bi_2Se_3$ Josephson Junction: Differential



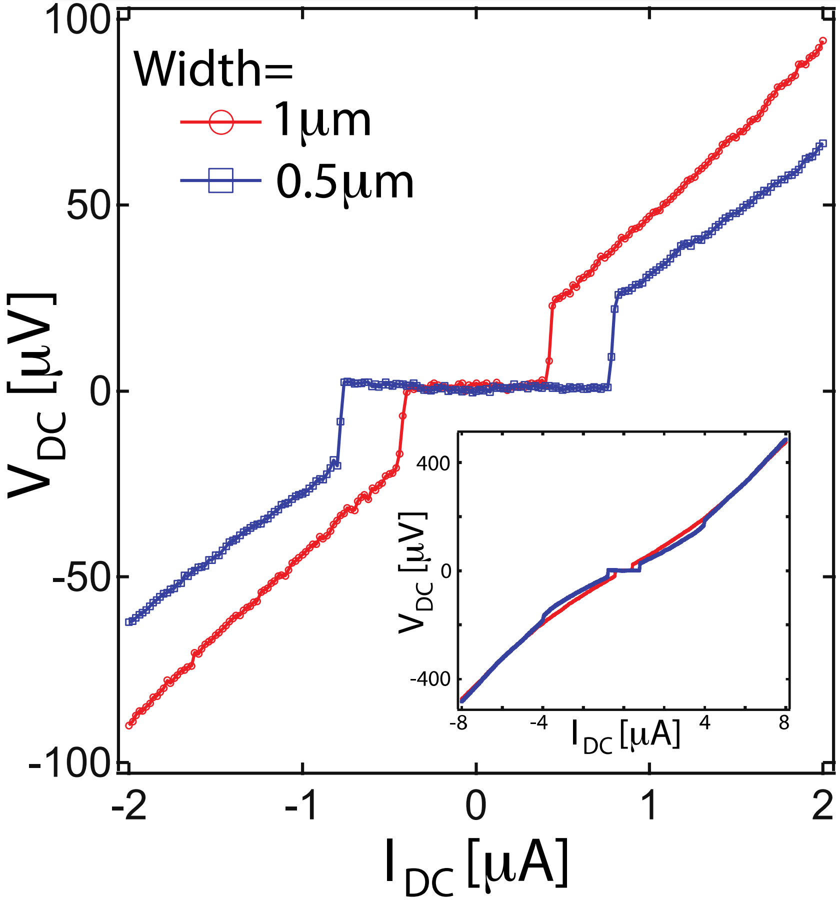

- Left: Current-bias, right: voltage across junction. Features in dV/dI at 2Δ and others below 2Δ.

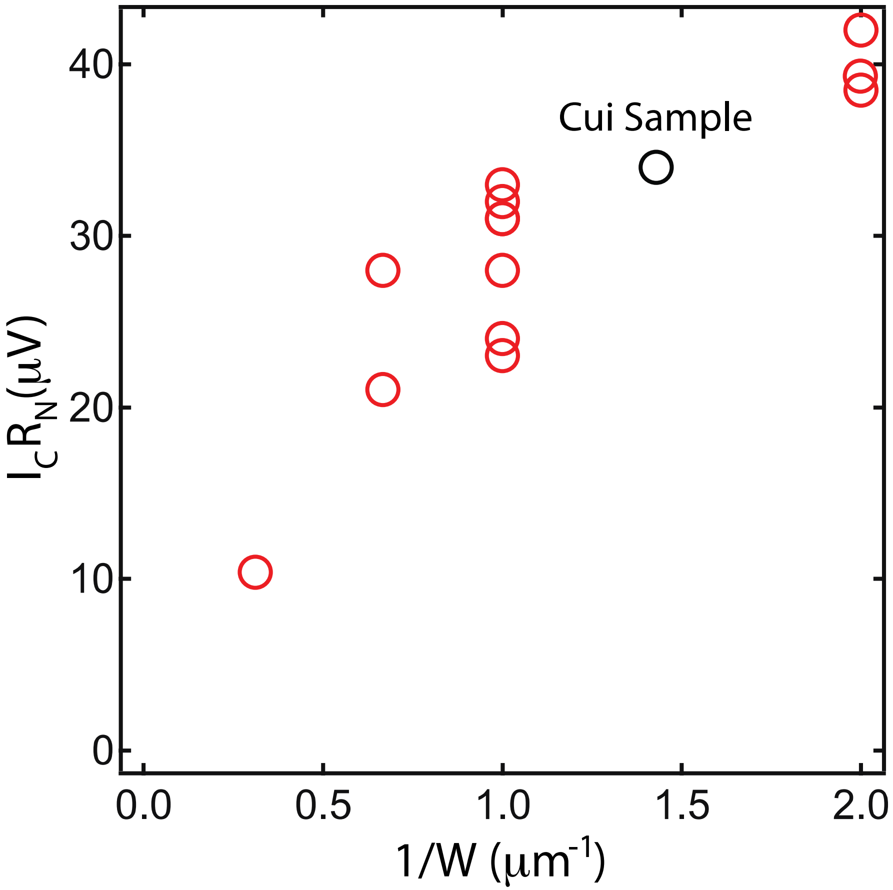
# Critical Currents too low

- Critical currents a factor of ten lower than what is expected from KO theory
- Sources of low critical current (neither apply)
  - Thermal effects – bad filter
  - Junction much longer than the coherence length



# 1/W dependence of $I_C R_N$

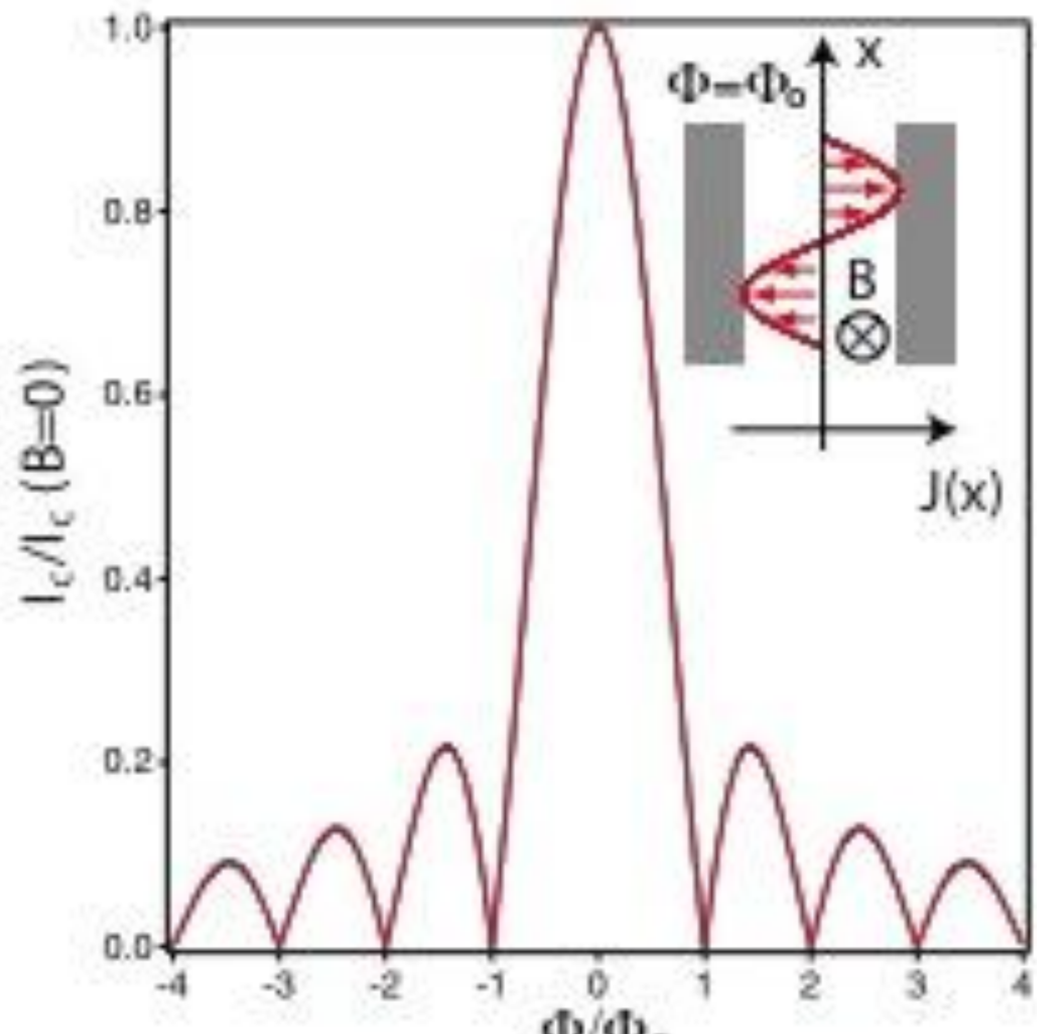


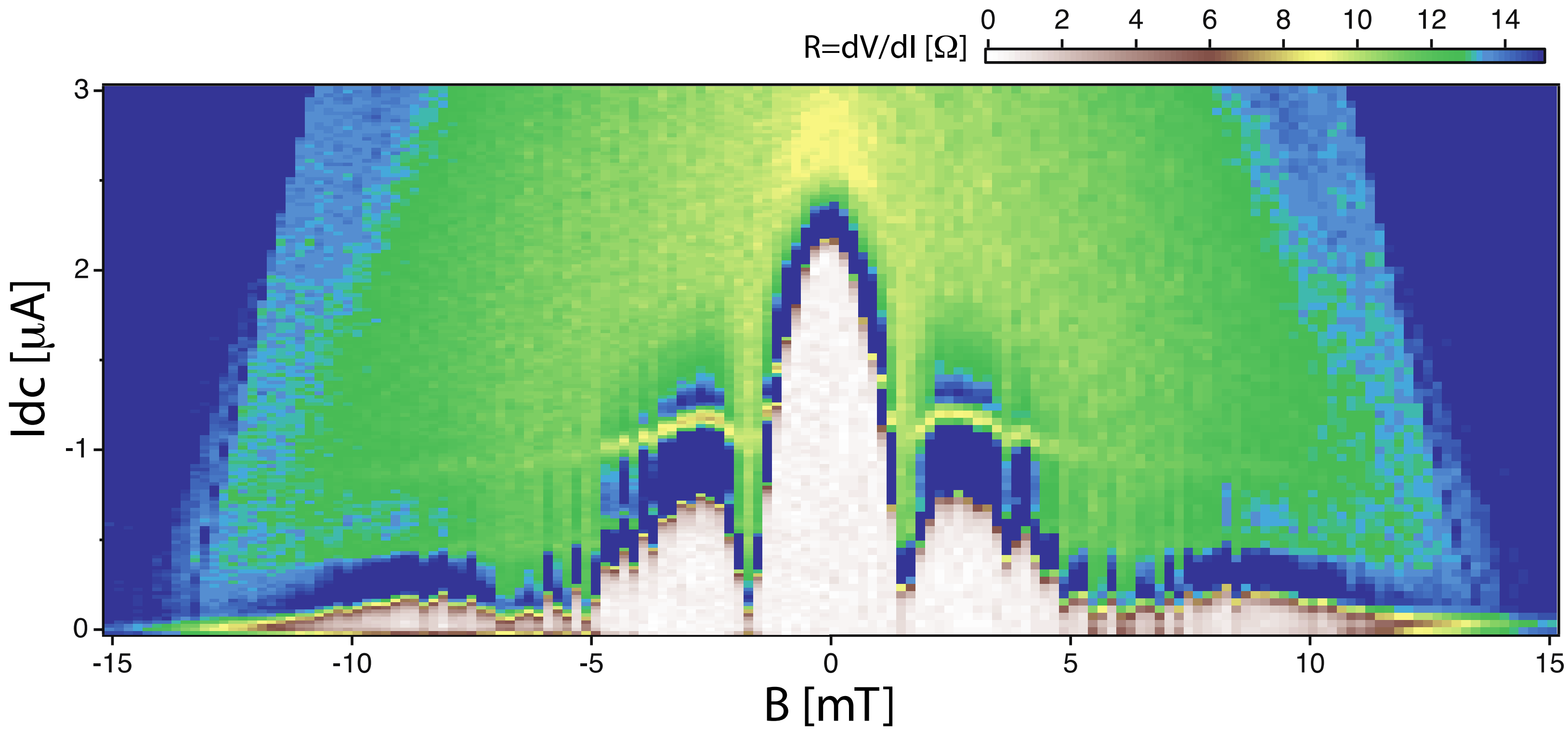

- Left: I-V curves for two devices with similar RN
- Scaling of $I_C R_N$ for all 14 devices we've measured so far.

# Magnetic-field dependence of $I_C$ for standard JJ

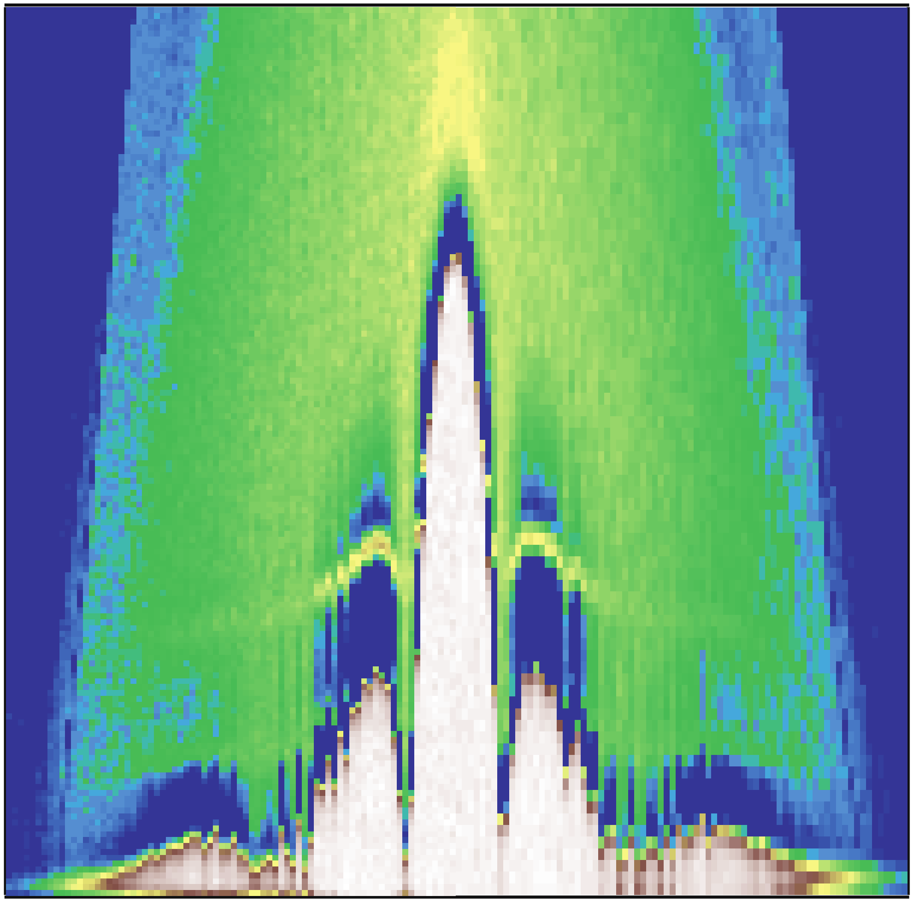
- Fraunhofer pattern expected for measurement of critical current vs. magnetic field
- Magnetic field scale set by device area



# Magnetic-field dependence for $Bi_2Se_3$ junctions

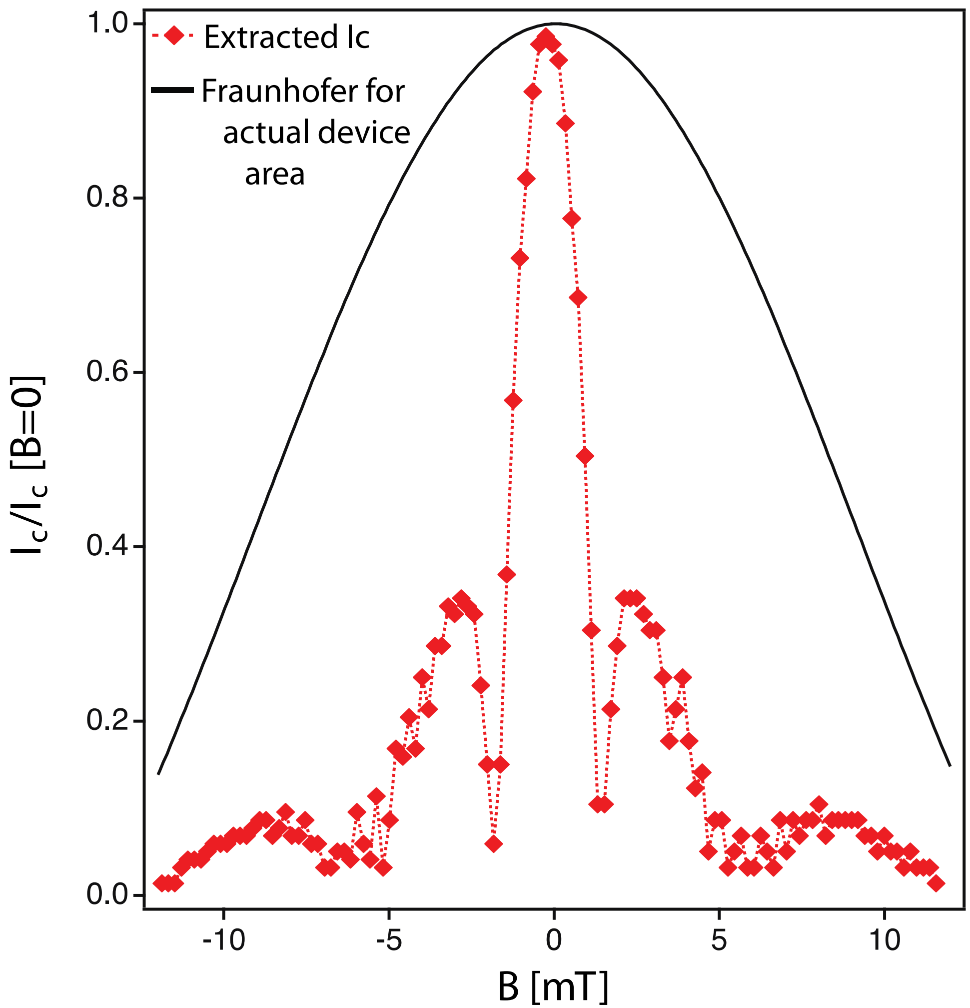


# Magnetic-field dependence for $Bi_2Se_3$ junctions



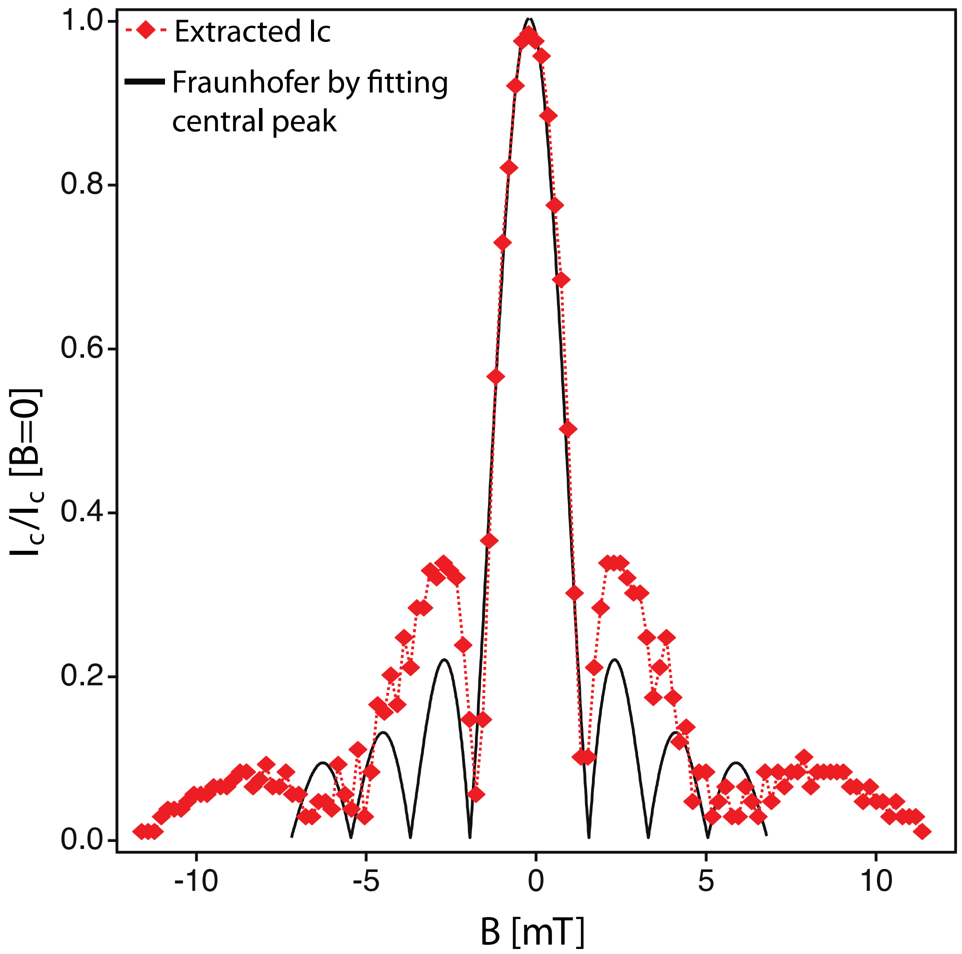
- Three distinct features in this plot
  - Field scale is wrong for the device size
  - Not Fraunhofer
  - Additional features observed that aren't expected

# Magnetic-field dependence: Field scale



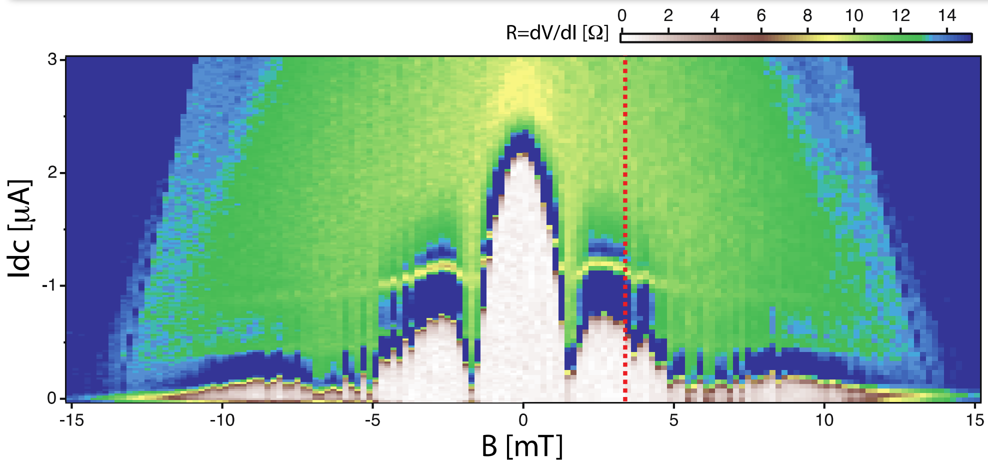

- Black line: Calculated Fraunhofer pattern for device geometry (including penetration depth)
- Scale off for all devices by a factor of ~5.

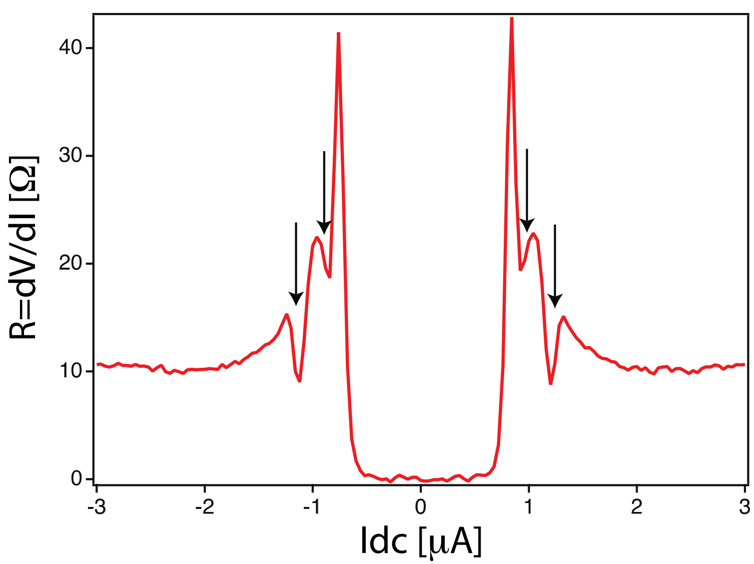
# Magnetic-field dependence: Field scale




- Black line: Calculated Fraunhofer pattern obtained by fitting the central peak
- The spacing of the lobes is 2 times larger than in should be, given the width of the central peak

# Magnetic-field dependence: Additional Features



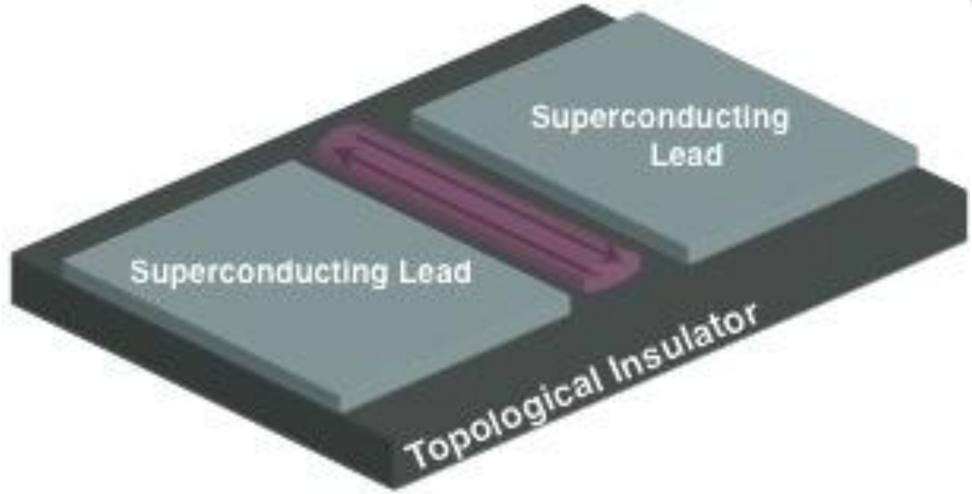



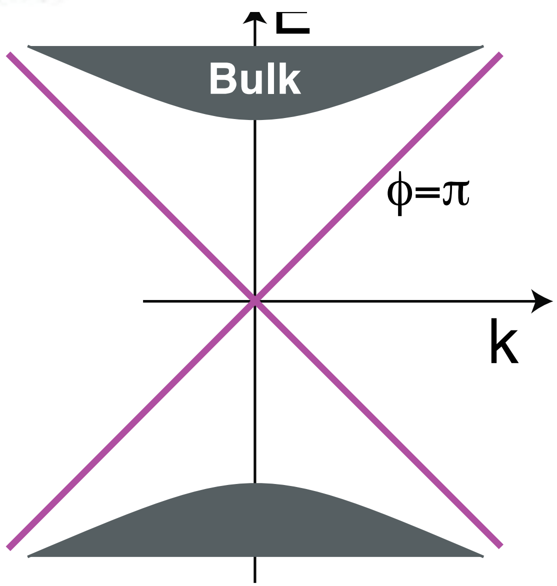

- Above $I_C$, for magnetic fields outside the first lobe, there are two symmetric "shadow" dips that follow the $I_C$ curve
- Shadow effect symmetry about zero DC current

# Key features that we need to understand

- The product $I_C R_N$ is too small, by a factor of about 10
- There is a trend in the product $I_C R_N$; scales as 1/W
- The magnetic field scale and period is inconsistent with typical Josephson Junction behavior

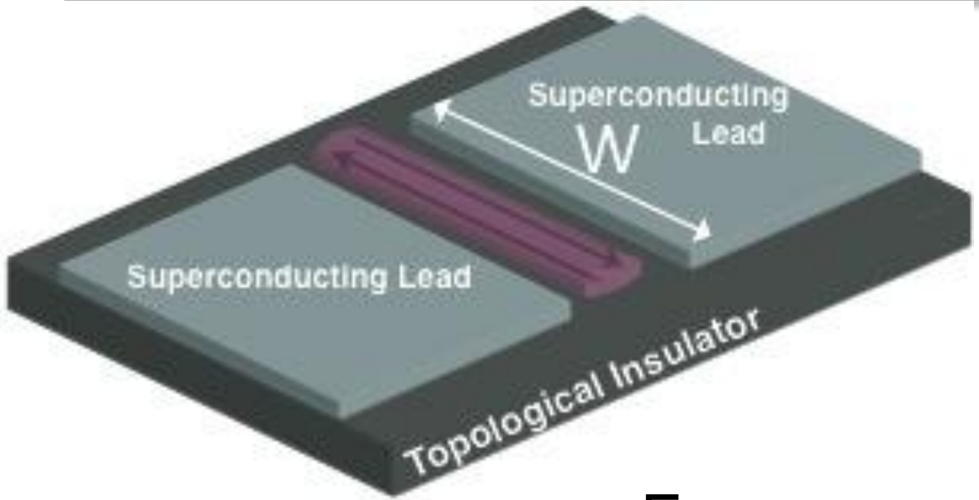
# Returning to Fu/Kane



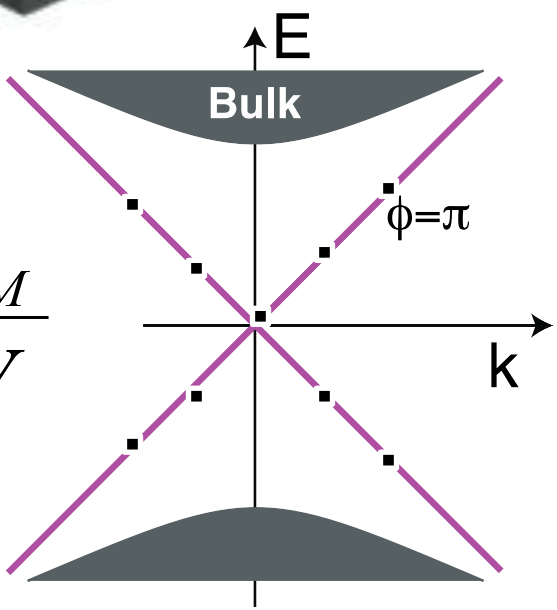




- For a phase difference of π, there is a gapless Majorana mode with zero energy
- This mode is the lowest lying energy state in the junction
- How does it interact with supercurrent?

# Potential Explanation: 1D wire of Majorana fermions

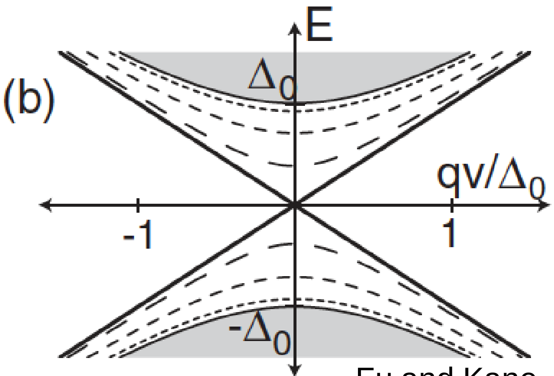


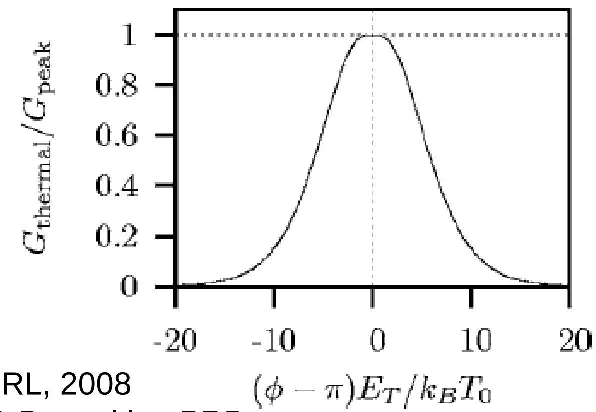

$$E_C = \frac{h v_M}{2W}$$




- For micron sized wire, confinement will occur along the wire
- The confinement will be set by the width of the Josephson Junction
- If the Majorana is dissipative, at energies of $E_C=eV_C$, the device will cease to superconduct
- Explains 1/W dependence
- A fit $V_C=I_C R_N$ to gives a velocity of $10^4$m/s. This is close to the estimate for some but not all predictions for the Majorana velocity

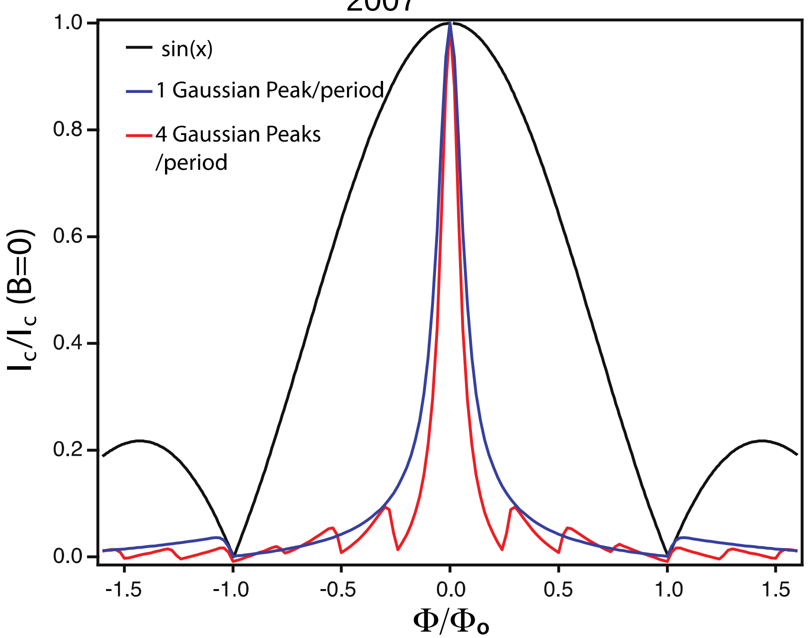
# Narrowing of the field dependence

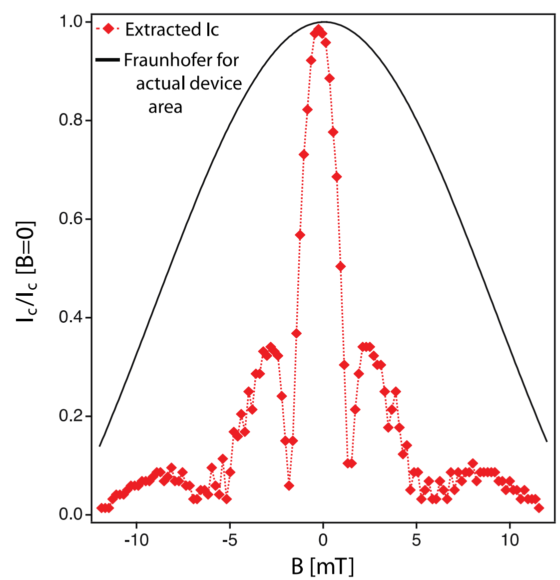



Fu and Kane, PRL, 2008
Titov, Ossipov & Beenakker PRB, 2007

- A peaked current vs. phi can give a narrowing of the magnetic field dependence



# Conclusions

- Have shown gateability of topological insulator materials
- From these measurements, we've seen that the surface can contribute significantly to transport
- We have made measurements on superconducting devices in the quasiballistic regime
- Junctions of Bi2Se3 show many departures from conventional junction
- These departures were explain in terms of gapped 1D Majorana wire in the junction

# Acknowledgments

**Measurements**

- James Williams
- Andrew Bestwick
- Patrick Gallagher

**Growth**

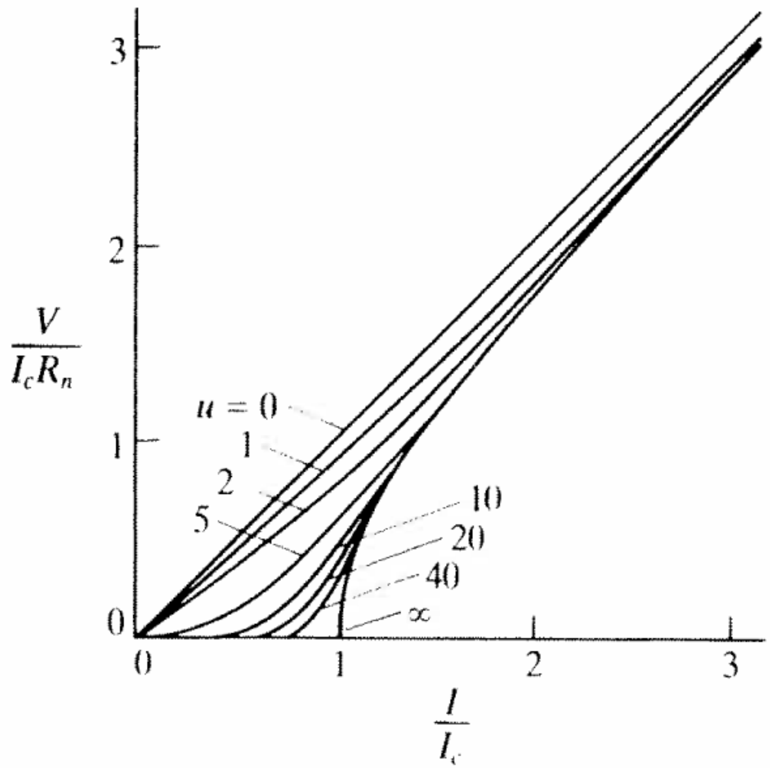
- James Analytis
- Andrew Bleich
- Ian Fisher
- Seung Sae Hong
- Yi Cui

**Useful Conversations**

- Jed Johnson
- John Clarke
- Mac Beasley
- Xiaoliang Qi

# Thermal Noise Effects

## Over-Damped Juncitons: Ambegaokar-Halperin



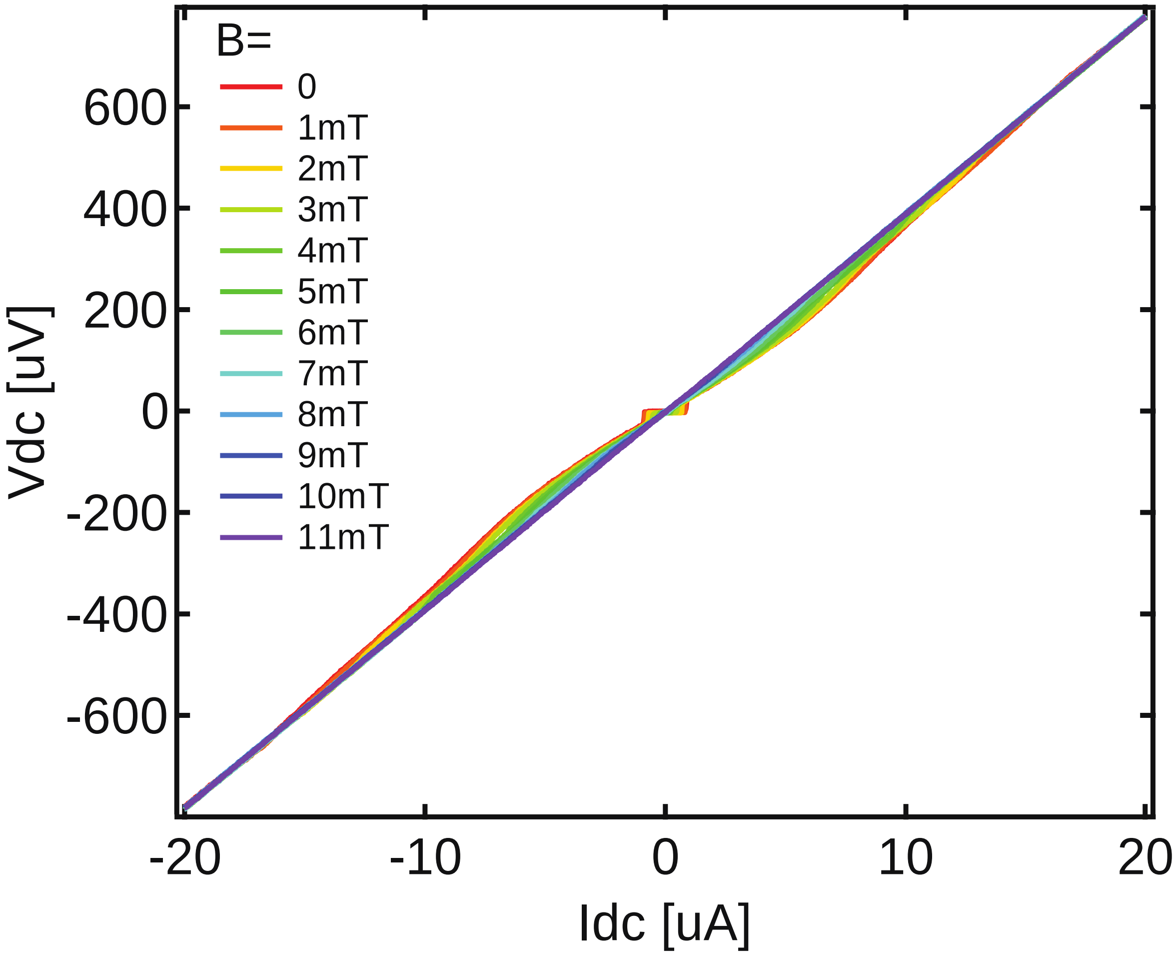

## Under-Damped Juncitons: Fulton-Dunkleberger

$$\langle I_C \rangle = I_{c0}\left\{1 - \left[\frac{E_{therm}}{2E_J}\ln\left(\frac{\omega_p \Delta t}{2\pi}\right)\right]^{2/3}\right\}$$

- Can calculate the amount of thermal fluctuations needed to reduce $I_C$ by 90%, and you get a thermal radiation of 3.8K

# DC (higher current) vs field

- I-V curves for different magnetic fields lie on top of each other above 2Δ, ~300uV.



# KO-2 Theory

- Solutions to Eilenberger equations equations for ballistic structures (Likharev RMP 51, 101 (1979). T=0, peak in phase at π.

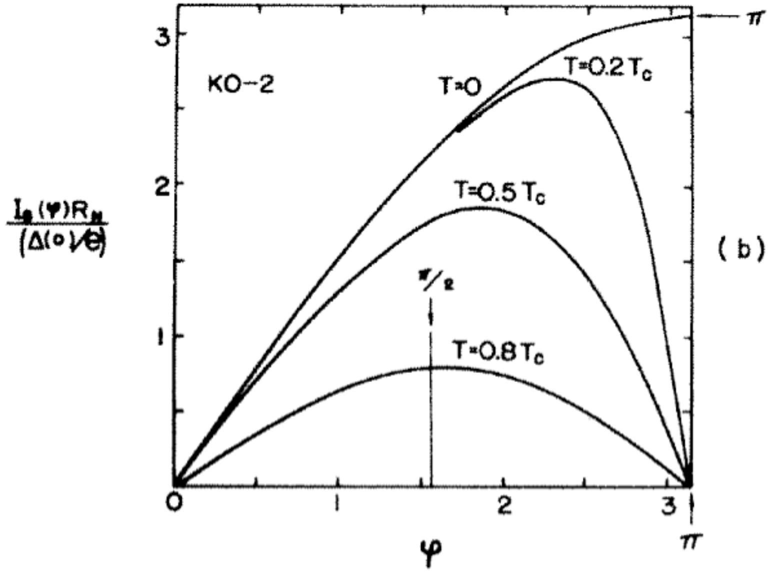
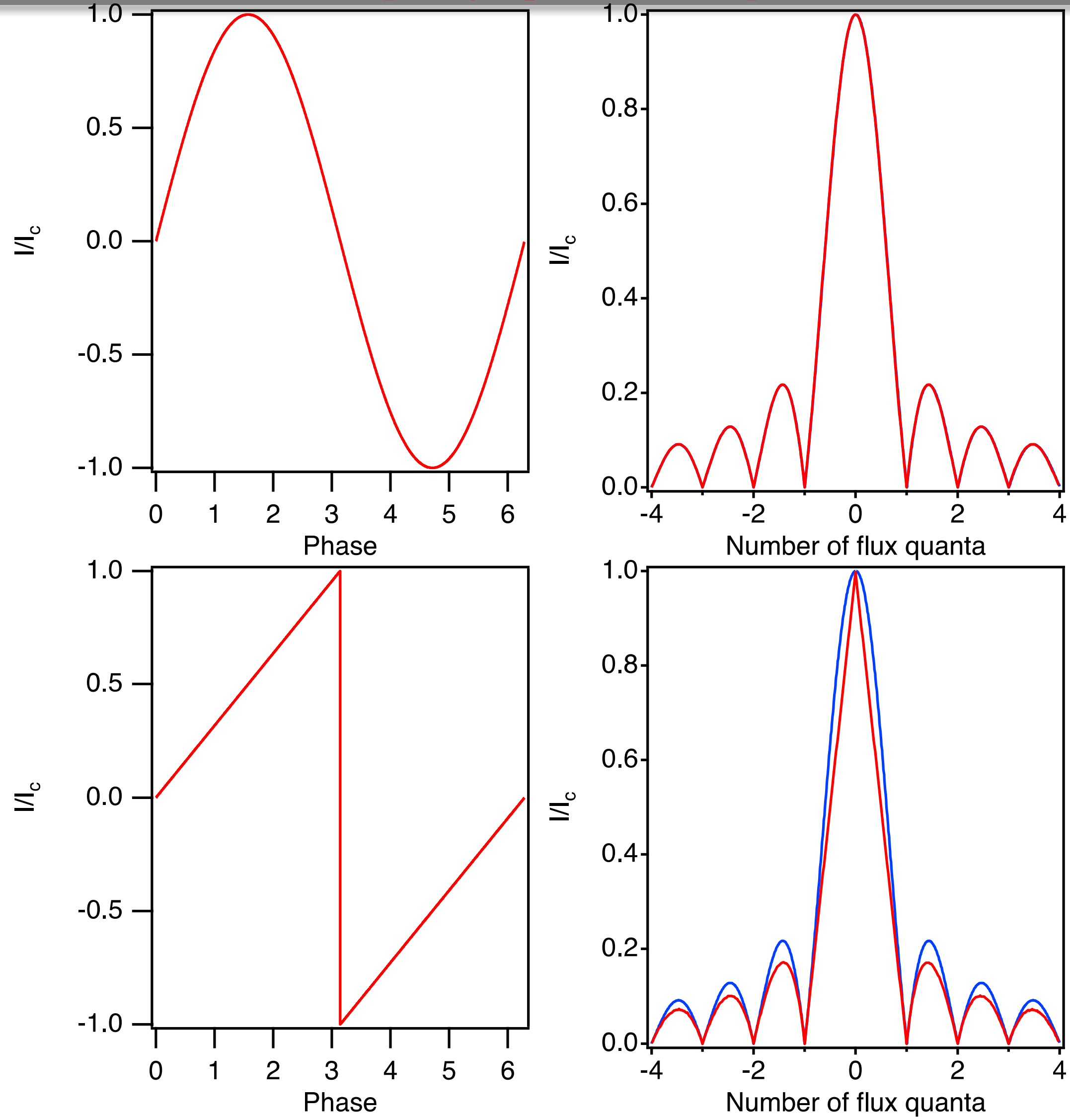



FIG. 10. The KO-2 theory for clean small weak links ($L_{eff} << l, \xi_0$). (a) Two types of electron trajectories in the weak link region: (1) "incoming" part of through trajectory; (2) "outgoing" part of this trajectory; (3) and (4) nonthrough trajectories. (b) Current-phase relationship for different temperatures. Temperature dependence of critical current is shown in Fig. 6.

$$I_C R_N = \frac{\pi\Delta}{e}\sin\left(\varphi/2\right)\tanh\frac{\Delta\cos\left(\varphi/2\right)}{2k_B T}$$

# Current-Phase and Ic vs B (Typical)



# Current-Phase and Ic vs B (Peaked)