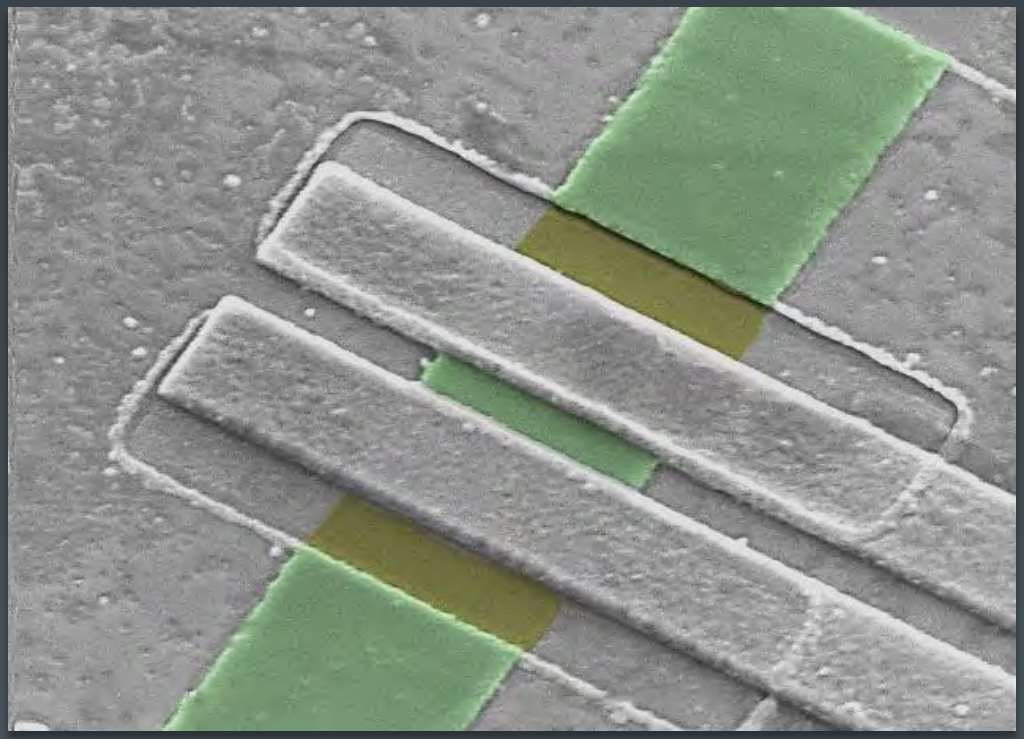
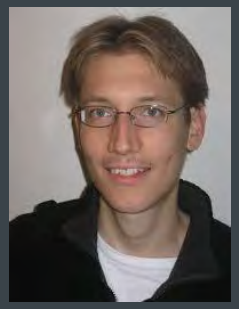
Towards topological superconductivity in 2D TIs

Vlad Pribiag
University of Minnesota



SPICE Workshop, Mainz – August 3, 2015

TU Delft FOM Microsoft KAVLI INSTITUTE of Nanoscience Delft UNIVERSITY OF MINNESOTA Driven to Discover



Arjan Beukman

Fanming Qu

Maja Cassidy

Leo Kouwenhoven

Christophe Charpentier

Werner Wegscheider

Delft
(experiments)

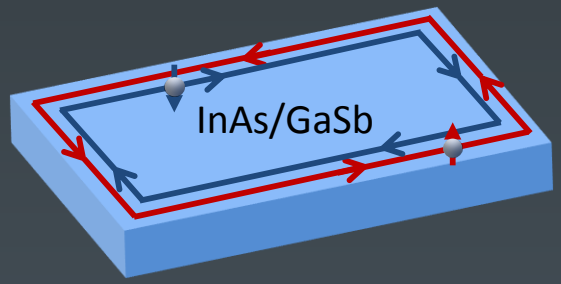
ETH Zürich
(Materials growth)

Overview

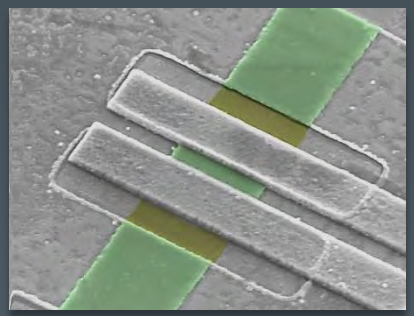
1. Topological Superconductivity and Majoranas

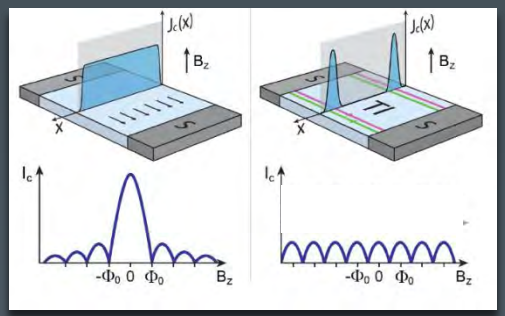
$$\gamma^{\dagger} = \gamma$$

2. 2D TI phase in InAs/GaSb quantum wells



3. Towards topological superconductivity in InAs/GaSb





Topological protection of Majoranas

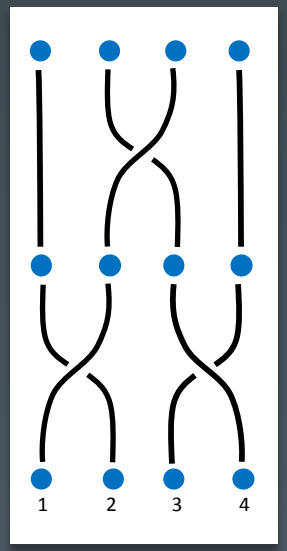
A pair of **spatially-separated** Majoranas forms a **non-local** fermionic state

$$c = \frac{1}{2}(\gamma_1 + i\gamma_2)$$

→ state is **protected against local perturbations**

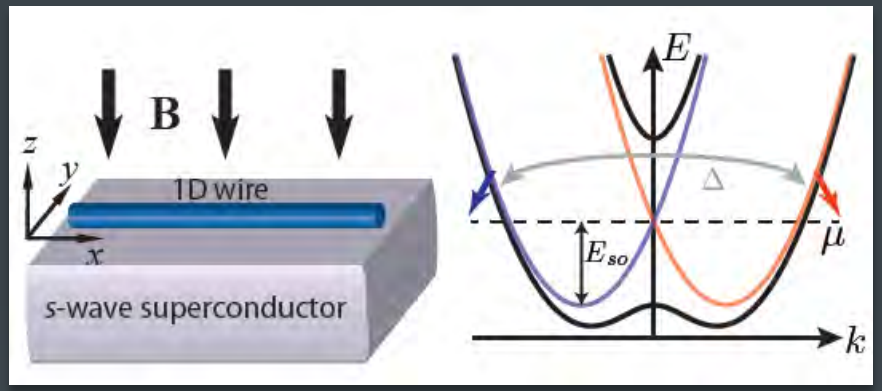
Bound Majorana modes are predicted to be **non-abelian** quasiparticles

→ Majorana exchange follows braiding group
→ **topologically-protected** braiding-based gates



A. Y. Kitaev Phys.-Usp. 44, 131 (2001).
C.Nayak *et al.*, *RMP* **80**,1083 (2008).

Topological superconductivity in helical nanowires



J. Alicea. Rep. Prog. Phys. 75, 076501 (2012).

Ingredients for topological superconductivity:

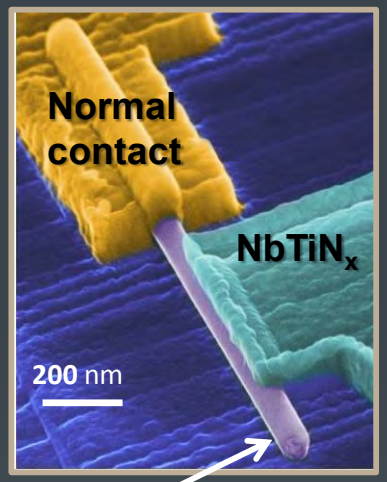
1. material with large SOC
2. s-wave SC
3. B-field

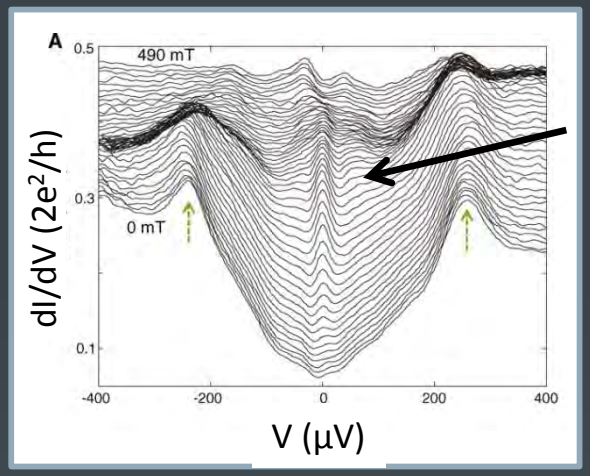
$$E_z > \sqrt{\Delta^2 + \mu^2}$$

J.D. Sau, et al. *PRL* **104**,040502 (2010).
R.M. Lutchyn, et al., *PRL* **105**,077001 (2010).
Y. Oreg, et al. *PRL* **105**,177002 (2010).
V. Mourik et al. Science 336, 1003 (2012).

Experimental signatures of Majorana bound states in nanowires

Kouwenhoven group, *Science* 336, 1003 (2012).



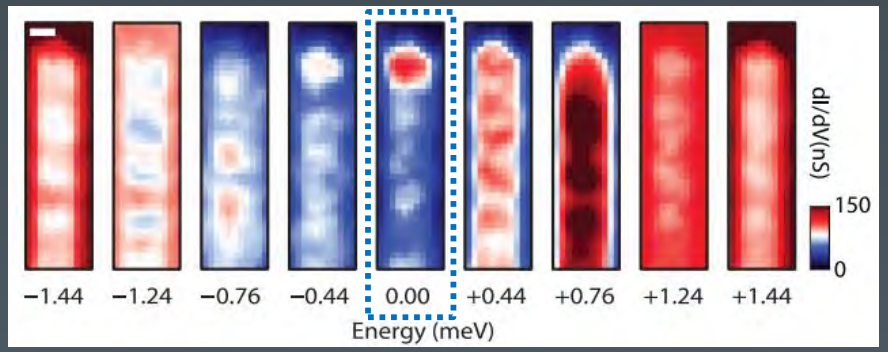


Zero-bias peak is a signature of a localized Majorana mode.

Similar results using InAs nws:

- Das *et al.*, *Nature Phys.* 8, 887 (2012)
- H. O. H. Churchill *et al.*, *PRB* 87, 241401 (2013).

Also, STM DOS spectroscopy of Fe nanowires on Pb substrate:



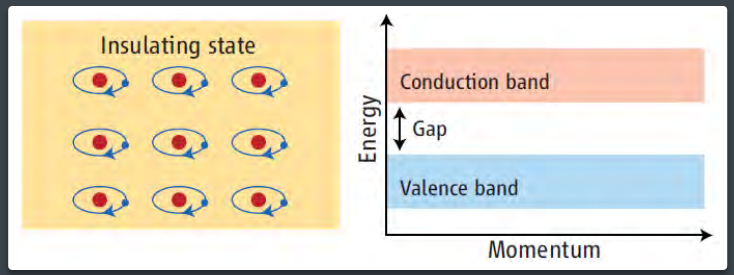
Yazdani group, *Science*, (2014).

Promising complementary approach:

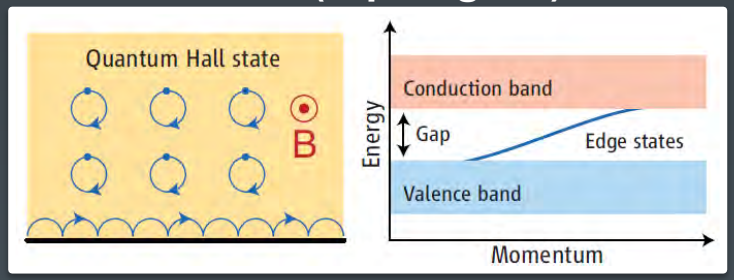
2D topological insulator
+
superconductor

Topological insulators (2D)

Conventional insulator: n = 0

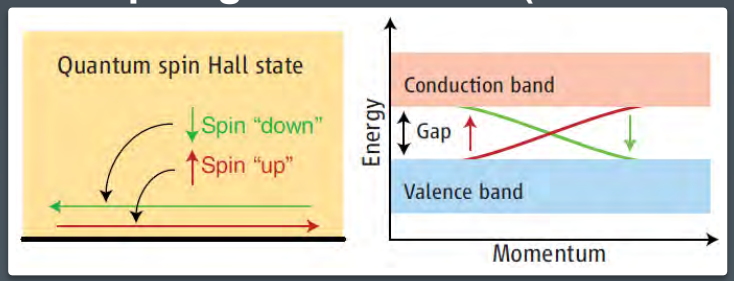


Quantum Hall (topological) insulator:



- Insulating bulk
- **Broken time-reversal symmetry**
- **Chiral** edge modes

2D topological insulator (Quantum Spin Hall insulator)



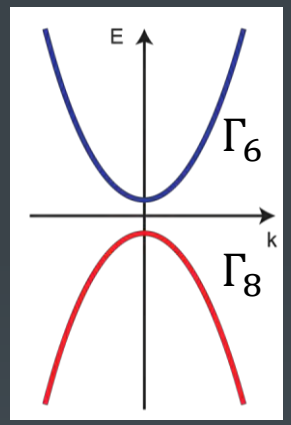
- Insulating bulk
- **Time-reversal symmetric**
- **<u>Helical</u>** edge modes (counter-propagating, spin-polarized)

C. L. Kane and E. J. Mele, *Science* **314** 1692 (2006).
Thouless, Kohmoto, Nightingale and de Nijs, *PRL* **49**, 405 (1982).

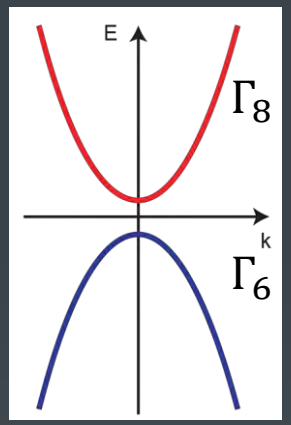
2D topological insulators

Inverted band-structure in the bulk:

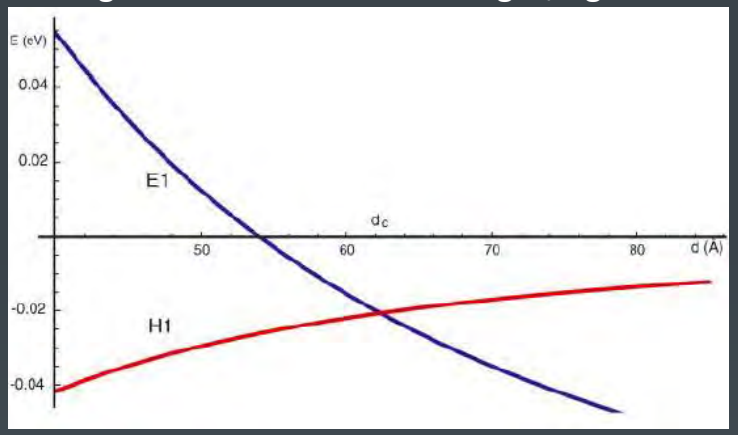
Trivial semiconductor



Topological insulator



Subband alignment vs. thickness for HgTe/HgCdTe QWs



Need opposite band symmetries (e.g. Γ_6 and Γ_8 bands)

BHZ model for 2D TIs (a.k.a. Quantum Spin Hall Insulators):

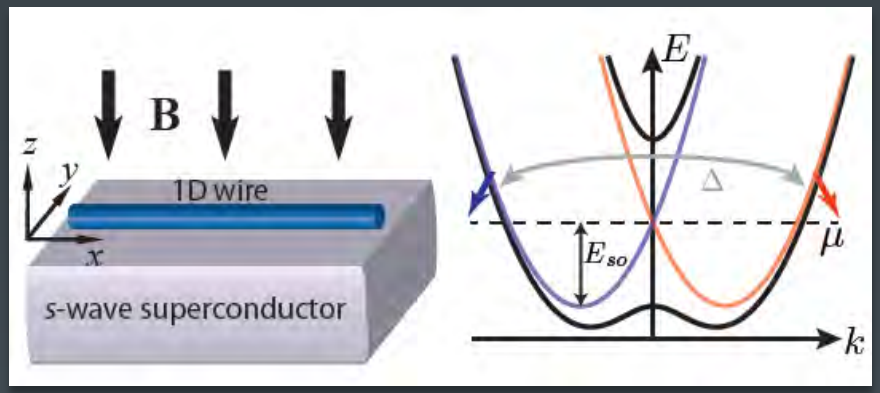
- 4-band Dirac-like effective Hamiltonian, H_{BHZ}, derived from the 6-band Kane model
- E1 and H1 are effective s-like electron and p-like hole subbands in the QW
- At topological phase transition, mass term in H_{BHZ} changes sign

C.L. Kane and E.J. Mele, *PRL* **95** 226801 (2005).
C.L. Kane and E.J. Mele, *PRL* **95** 146802 (2005).
B.A. Barnevig, T.L. Hughes and S.C. Zhang, *Science* **314**, 1757 (2006).

Topological superconductivity in helical 1D systems

Common idea: superconducting coupling between helical modes

Nanowire



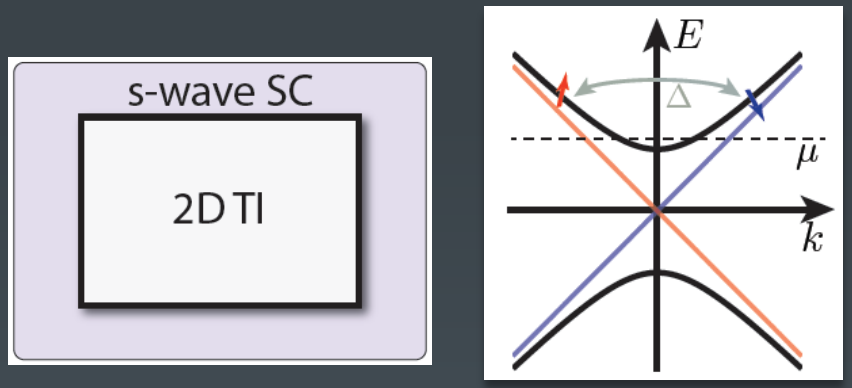
$$E_z > \sqrt{\Delta^2 + \mu^2}$$

Ingredients:

- material with large SOC
- s-wave SC
- B-field

J.D. Sau, et al. *PRL* **104**,040502 (2010).
R.M. Lutchyn, et al., *PRL* **105**,077001 (2010).
Y. Oreg, et al. *PRL* **105**,177002 (2010).
V. Mourik et al. Science 336, 1003 (2012).

2D topological insulator



$$E_z < \sqrt{\Delta^2 + \mu^2}$$

Ingredients:

- topological insulator
- s-wave SC

Helical modes are intrinsic
Induced SC is protected from disorder by TRS

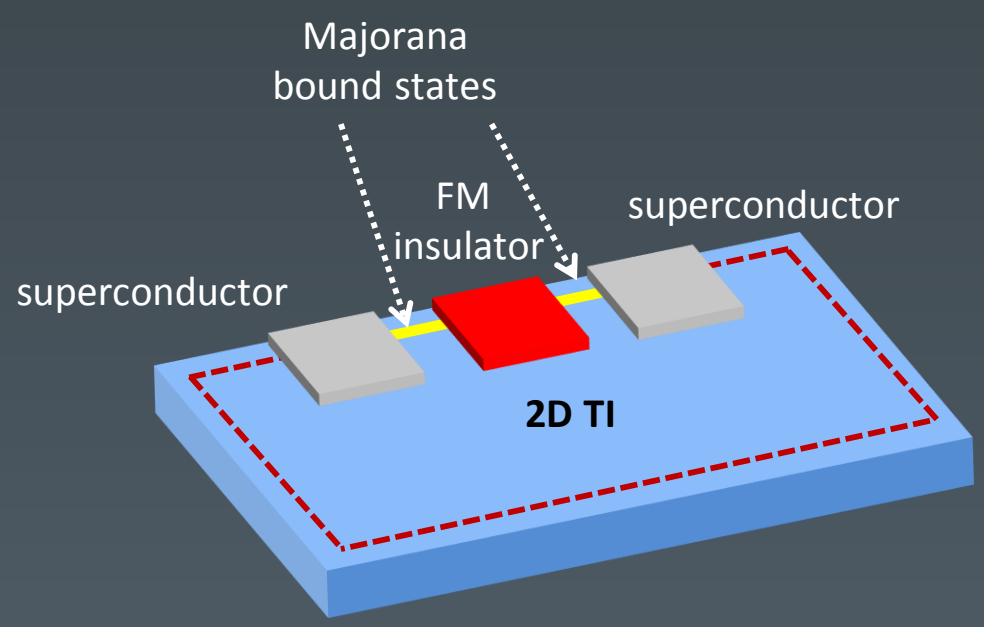
J. Alicea. Rep. Prog. Phys. 75, 076501 (2012).
J. Nilsson *et al.*, *PRB* **101**, 120403 (2008).
L. Fu and C.L. Kane, *PRL* **100**, 096407 (2008).
L. Fu and C.L. Kane, *PRB* **79**, 161408(R) (2009).

Majorana modes in a 2D TI

$$E_z < \sqrt{\Delta^2 + \mu^2}$$

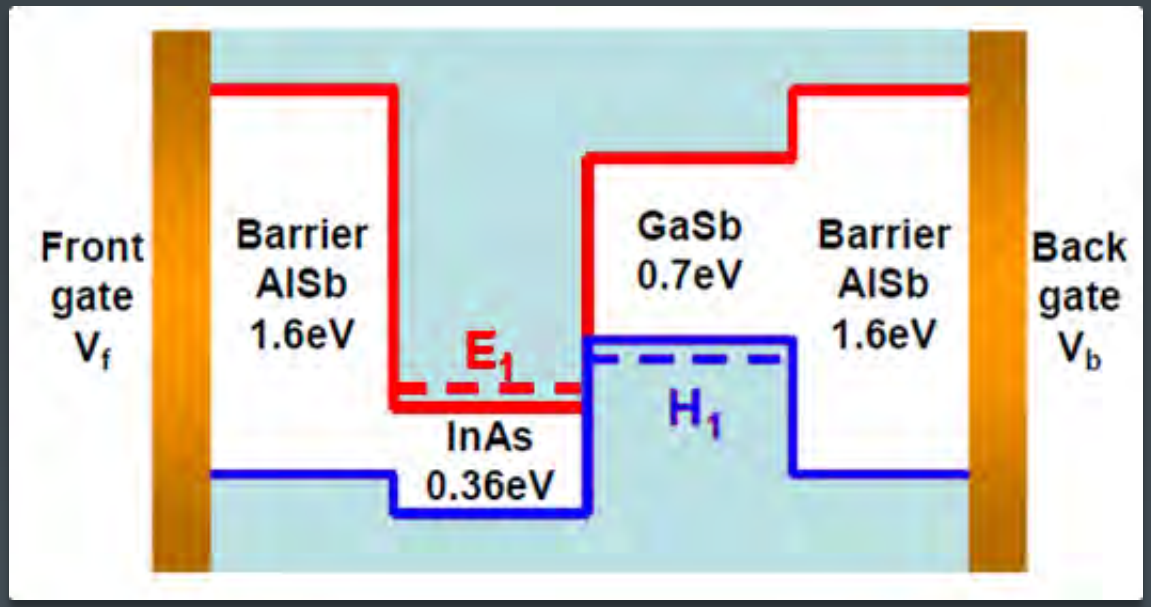
- Superconductivity dominates the gap → 1D topological superconductor at the edge
- Zeeman energy dominates gap → magnetically-gaped edge mode

Majorana bound states are localized at the domain wall:

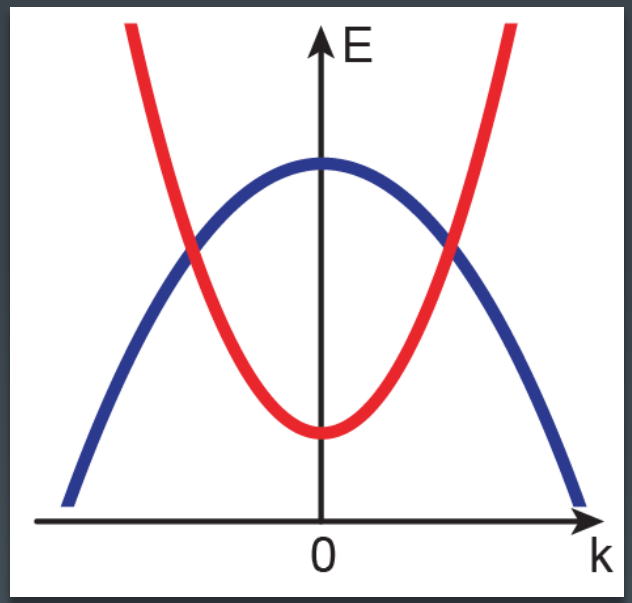


2D TI phase in InAs/GaSb

Origin of subband inversion in InAs/GaSb:



50nm 15nm 8nm 50nm



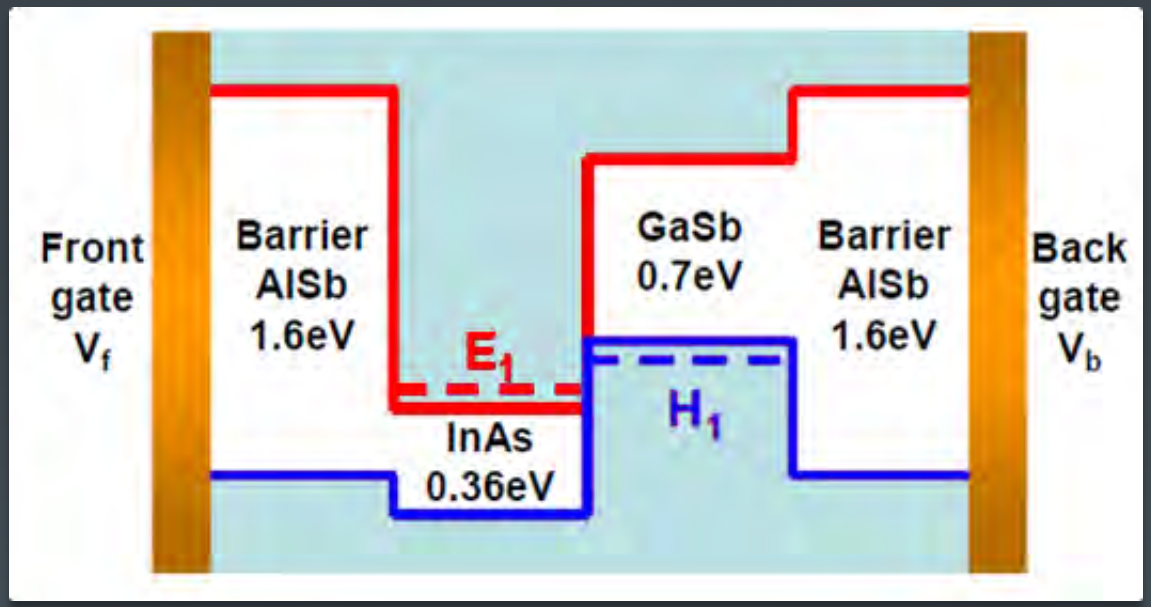
Inverted band-alignment:
requirement for TI phase

Broken-gap band alignment:

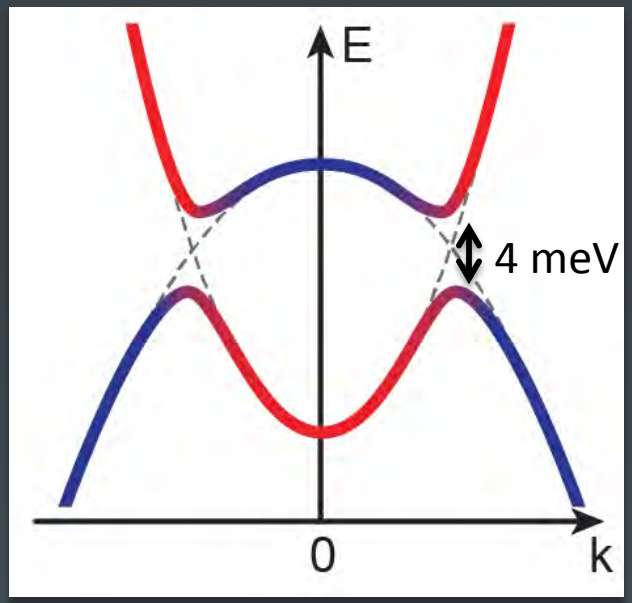
- E1-H1 band offset of ~150 meV

C. Liu et al. PRL, **100**, 236601 (2008).

2D TI phase in InAs/GaSb



50nm 15nm 8nm 50nm



electron-hole coupling → minigap

Broken-gap band alignment:

- E1-H1 band offset of ~150 meV

Evidence of a Hybridization Gap in "Semimetallic" InAs/GaSb Systems
Phys. Rev. Lett. **78**, 4613 – Published 16 June 1997
M. J. Yang, C. H. Yang, B. R. Bennett, and B. V. Shanabrook

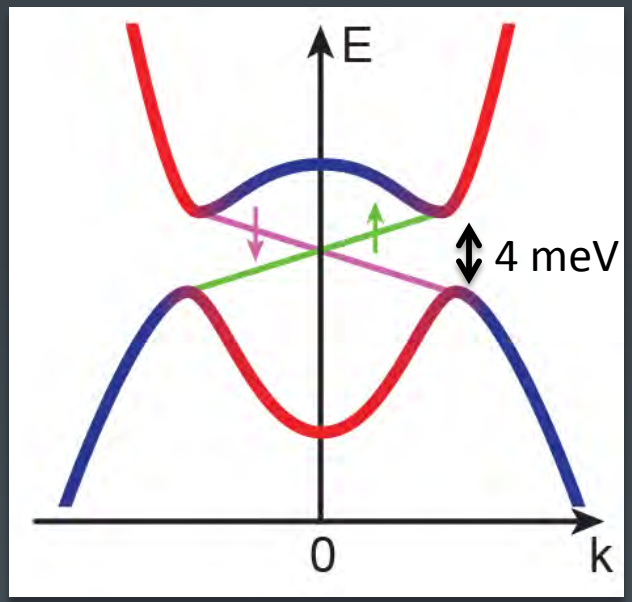
C. Liu et al. PRL, **100**, 236601 (2008).

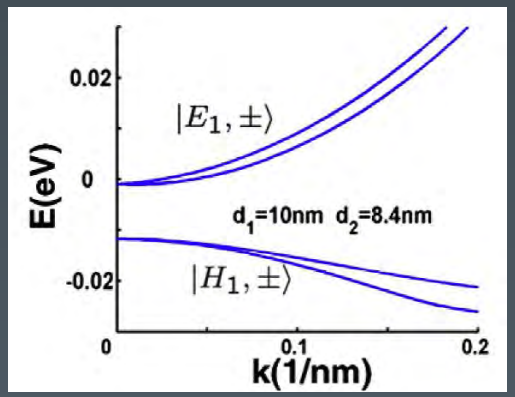
2D TI phase in InAs/GaSb

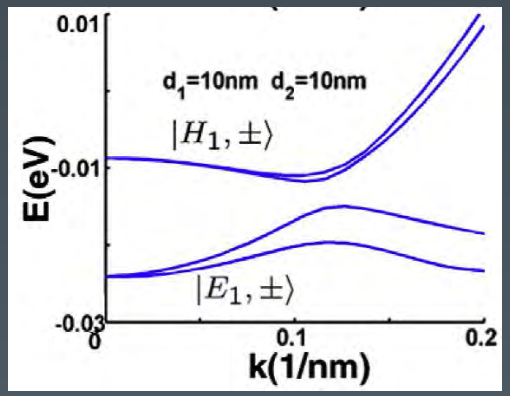
- 2D TI phase arises from a modified BHZ Hamiltonian
- Includes strong Bulk Inversion and Structure Inversion asymmetries:

$$H = H_{BHZ} + H_{BIA} + H_{SIA}$$

- 4-band effective Hamiltonian, H, derived from 8-band Kane model, including the split-off bulk band, Γ_7.
- **Topological phase transition** as function of thicknesses of GaSb (d_1) and InAs (d_2):





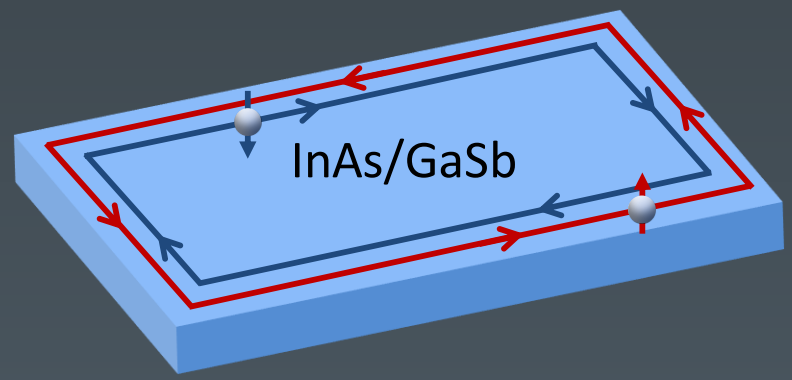


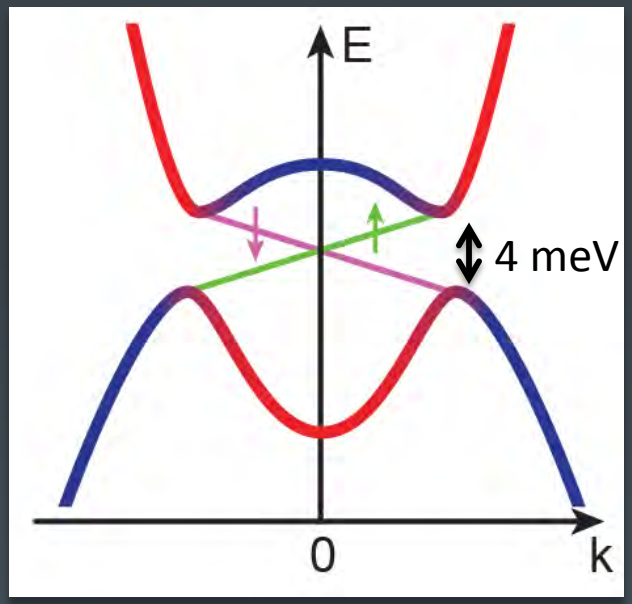
C. Liu et al. PRL **100**, 236601 (2008)

2D TI phase in InAs/GaSb

Characteristics of InAs/GaSb:

- Based on III-V semiconductors
  → advantageous for growth and nanofabrication
- Gate-tunability between topological and trivial phases
- Non-trivial exciton physics
- Possible electron correlation effects



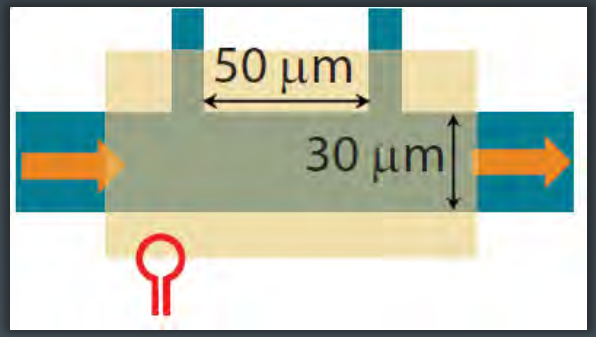


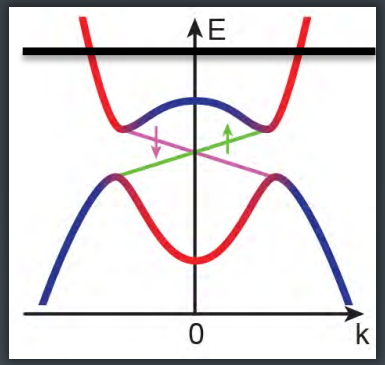
BHZ model → topologically-protected helical edge modes

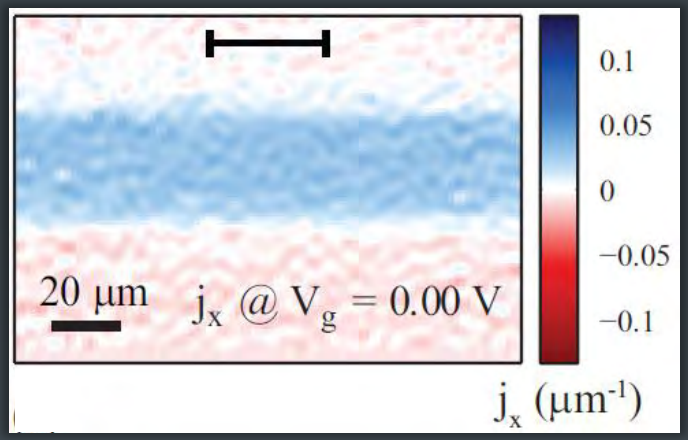
(C. Liu et al. PRL **100**, 236601 (2008))

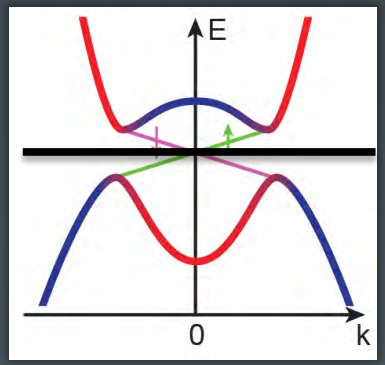
Imaging edge modes of InAs/GaSb

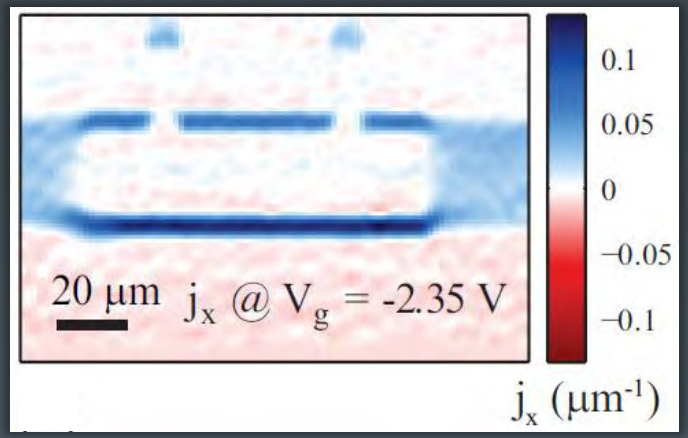
Scanning SQUID imaging:





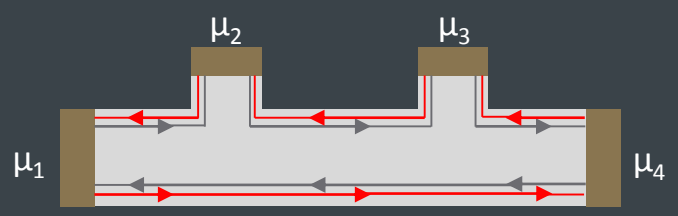




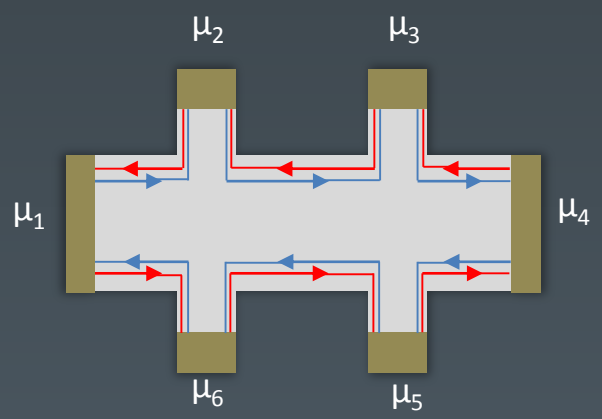


E.M.Spanton *et al., PRL* **113** 026804 (2014).

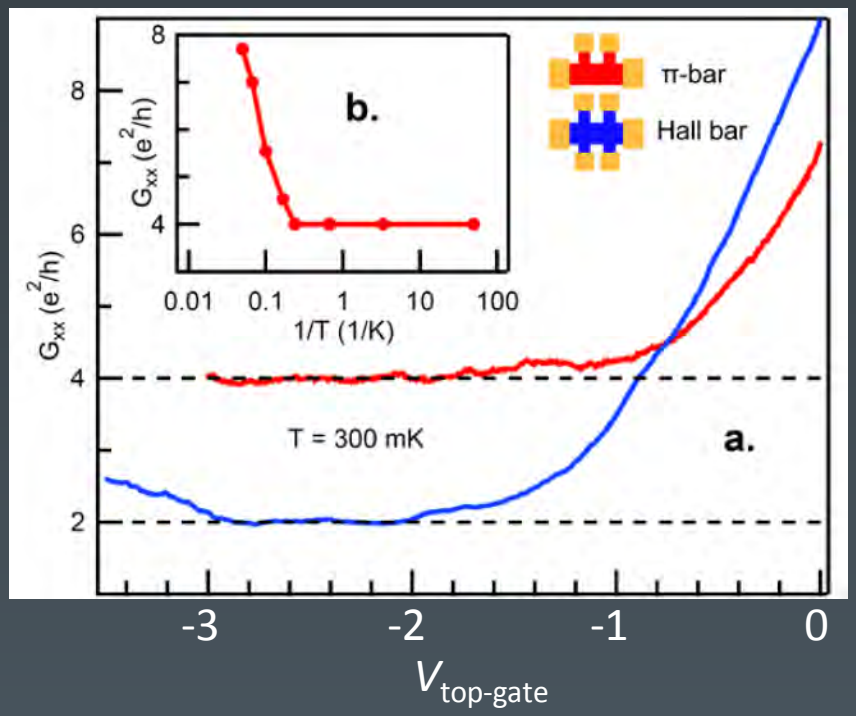
Quantized Conductance in InAs/GaSb



$G_{14,32} = 4e^2/h$

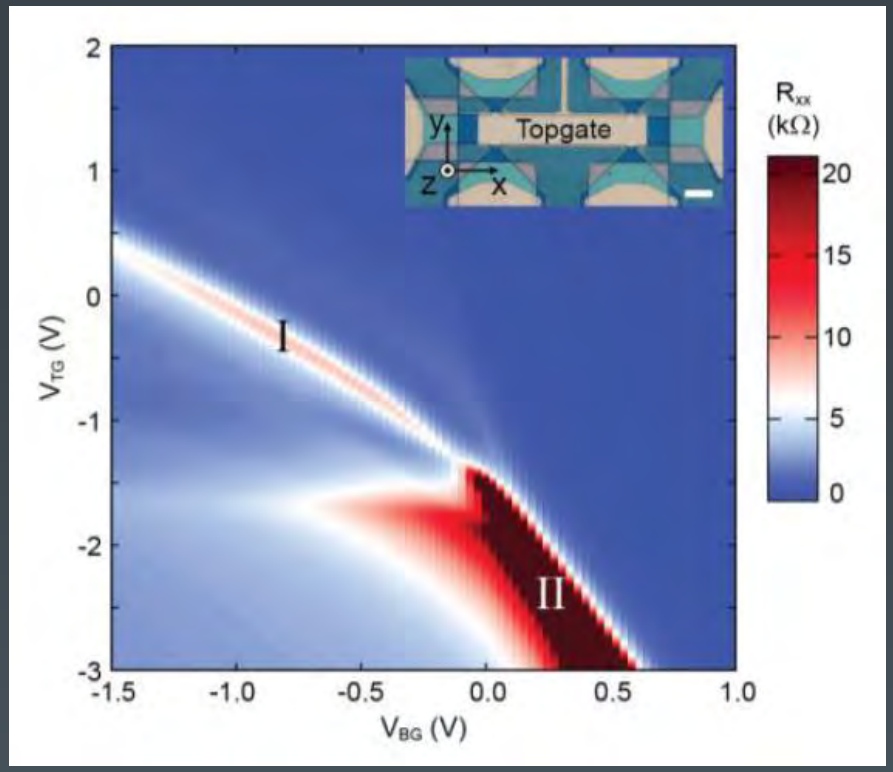


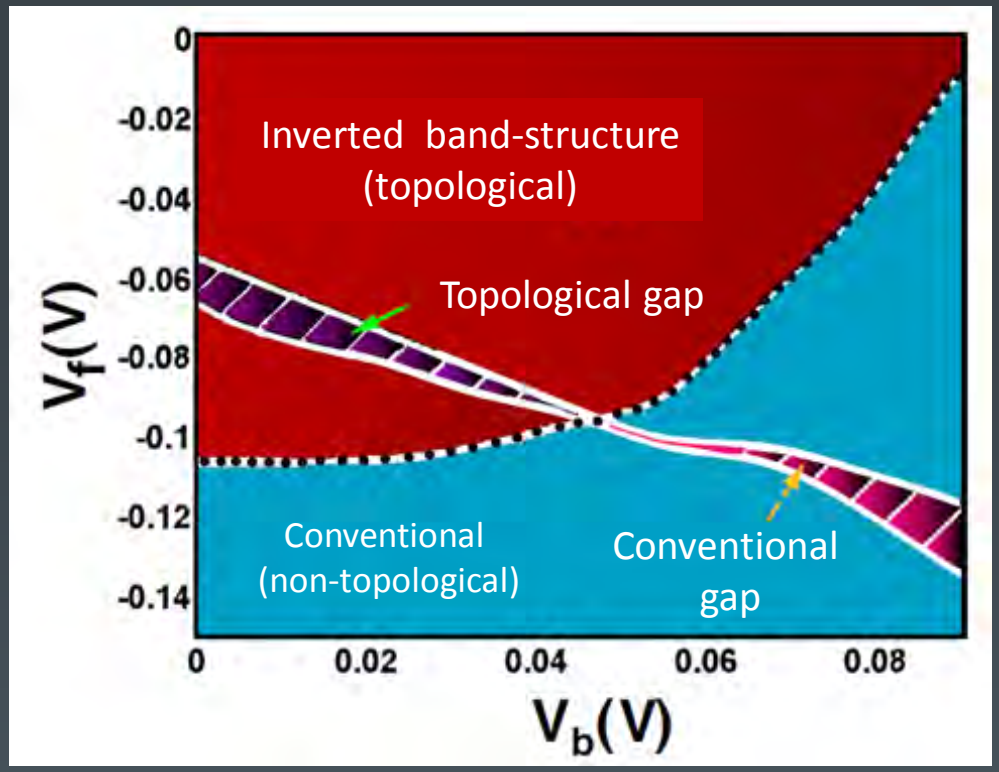
$G_{14,32} = 2e^2/h$



L. Du et al., *PRL* **114**, 096802 (2015).
M. Büttiker, *PRB* **38**, 9375 (1988).

Phase diagram of InAs/GaSb





Experiment: F. M. Qu *et al. PRL* **115**, 036803 (2015)

Theory: C. X. Liu et al. *PRL* **100**, 236601 (2008)

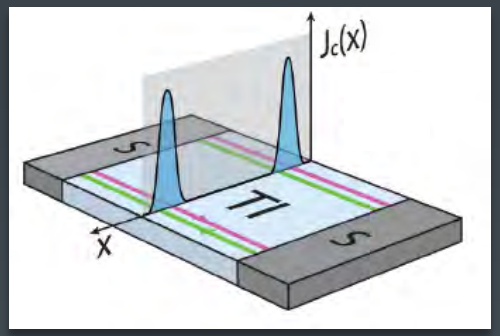
Gate-tunability between topological and trivial phases in InAs/GaSb

Josephson Junctions based on InAs/GaSb

First step towards Majorana physics:

Supercurrent carried by the edge-modes of InAs/GaSb

V.S. Pribiag et *al*., *Nature Nano*. **10**, 593 (2015).



Previous work on hybrid 2D TIs / superconductor devices:

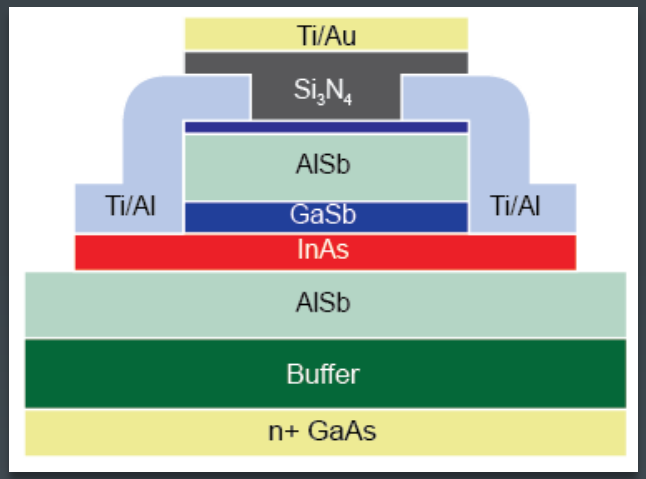
- Andreev reflection in InAs/GaSb

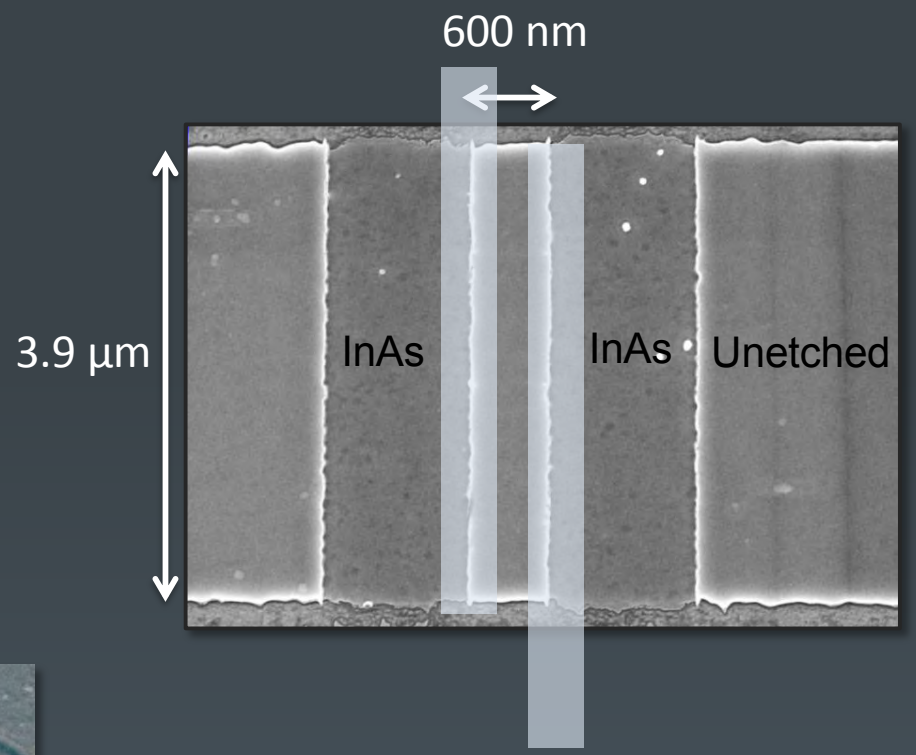
  Knez *et al*. *PRL*, **109**, 186603 (2012).

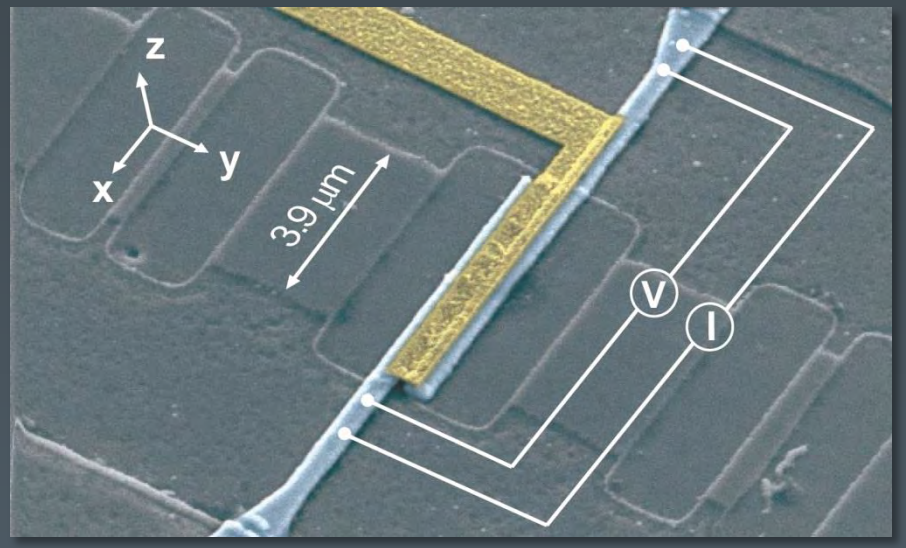
- Induced superconductivity in the edge modes of HgTe/CdTe

  S. Hart, H. Ren *et al.*, *Nat.Phys.* **10**, 638 (2014).

S-InAs/GaSb-S junctios

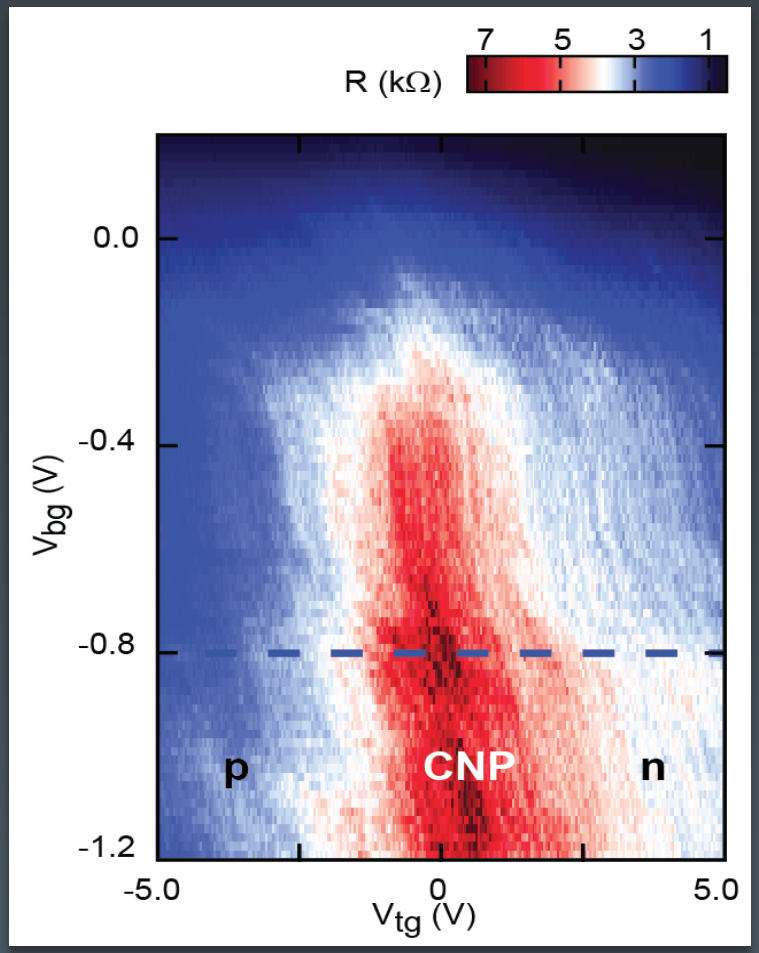


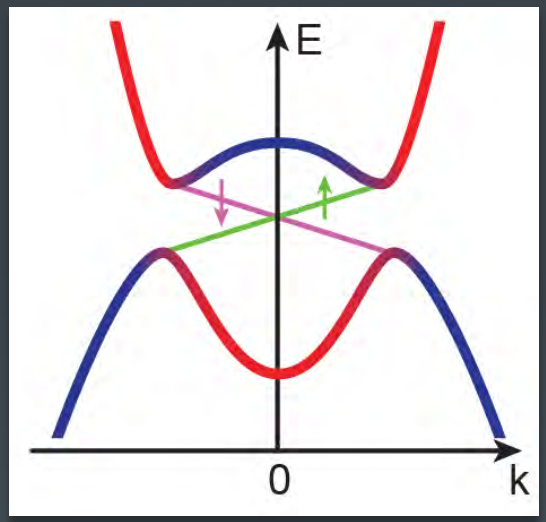


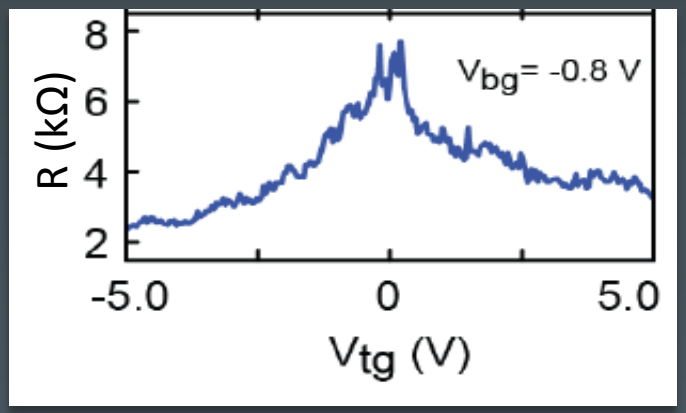


Gate-tunable Josephson junctions based on the 2D TI InAs/GaSb

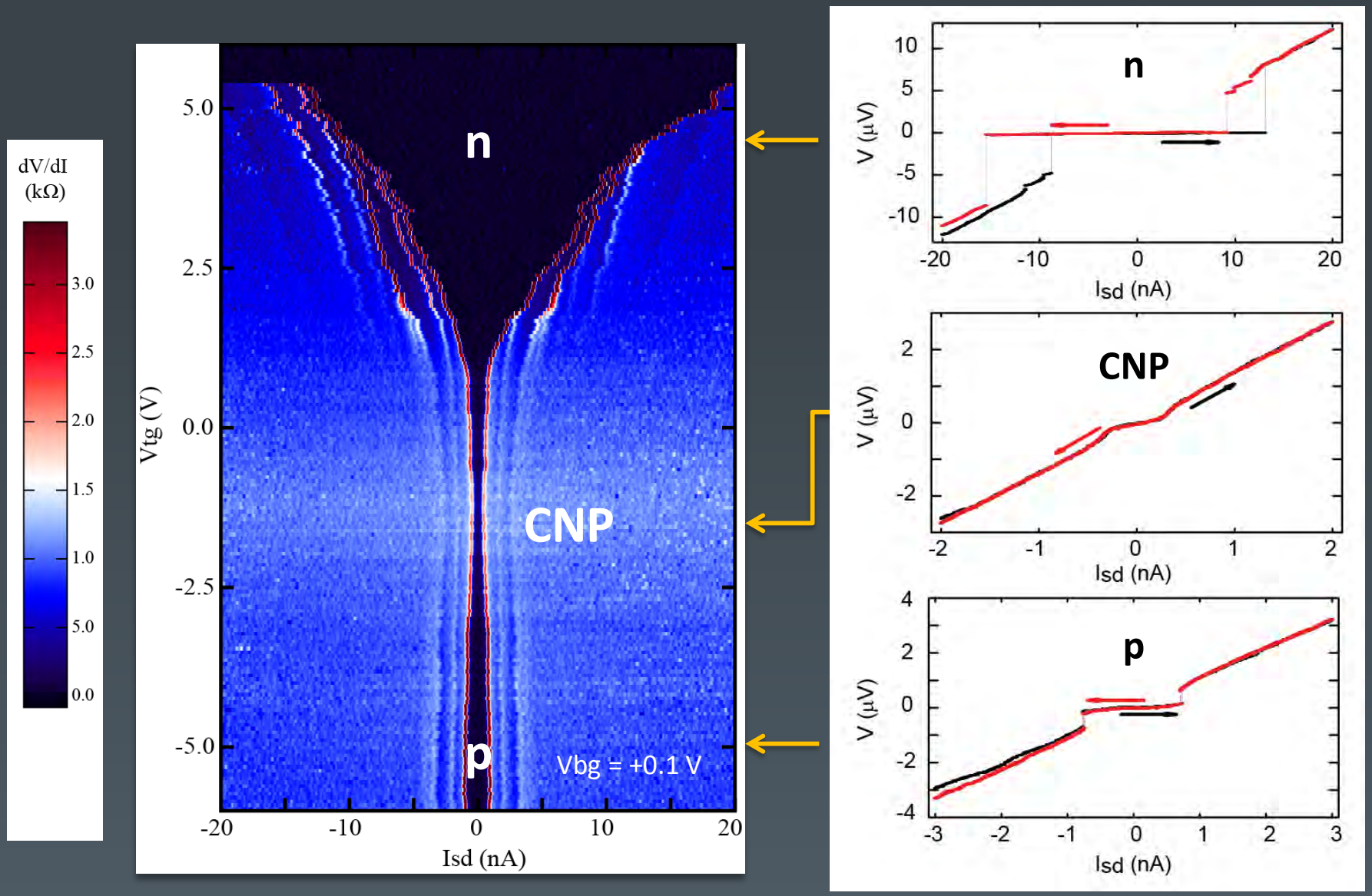
Normal state: B_z=0.1T



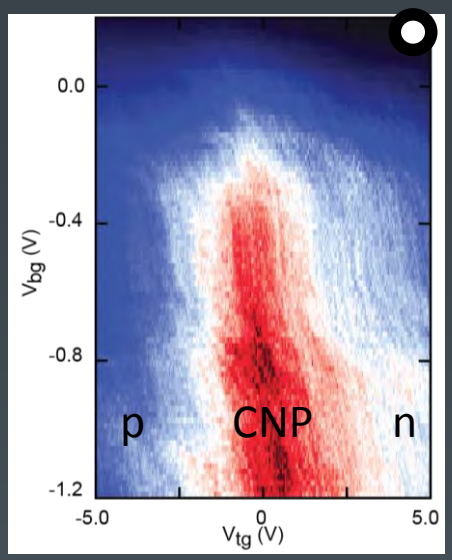


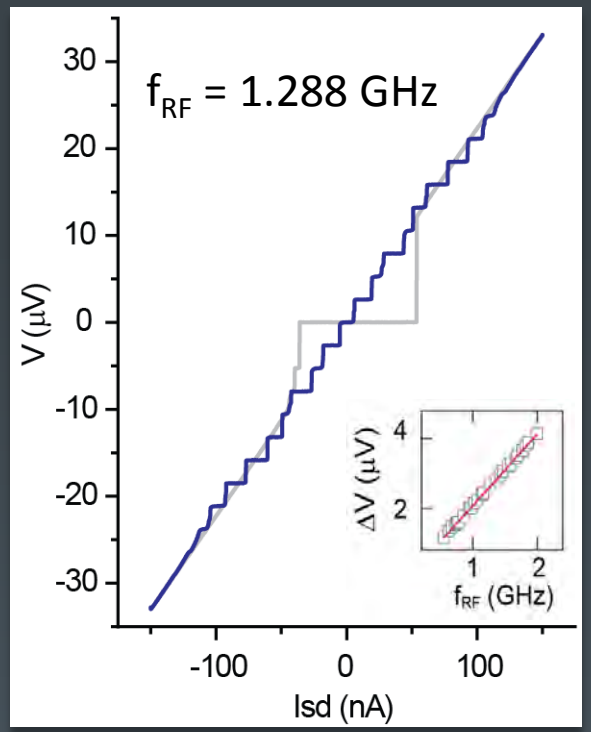


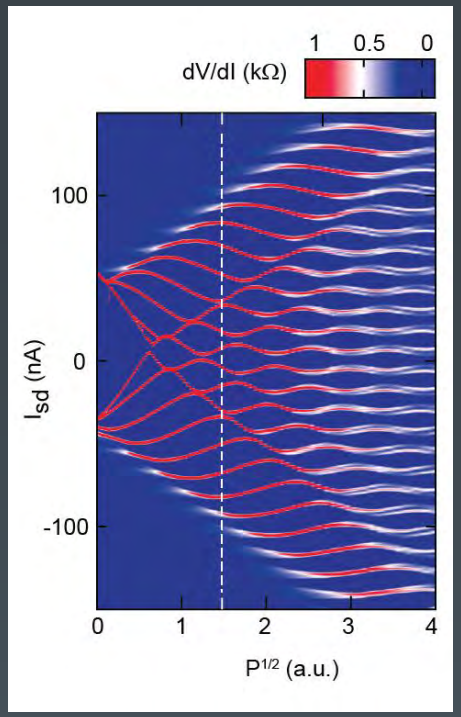
DC Josephson effect



AC Josephson effect



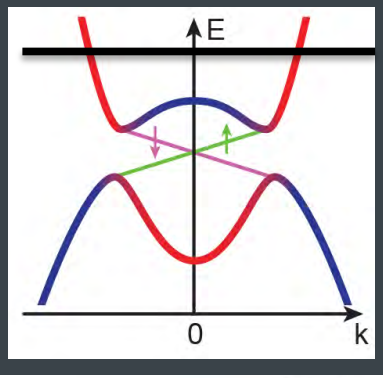


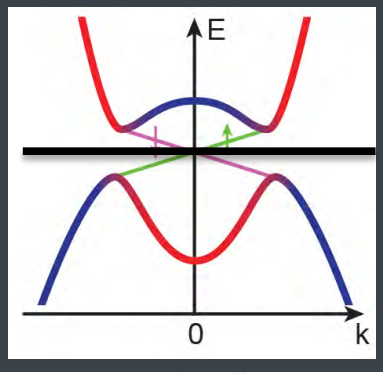


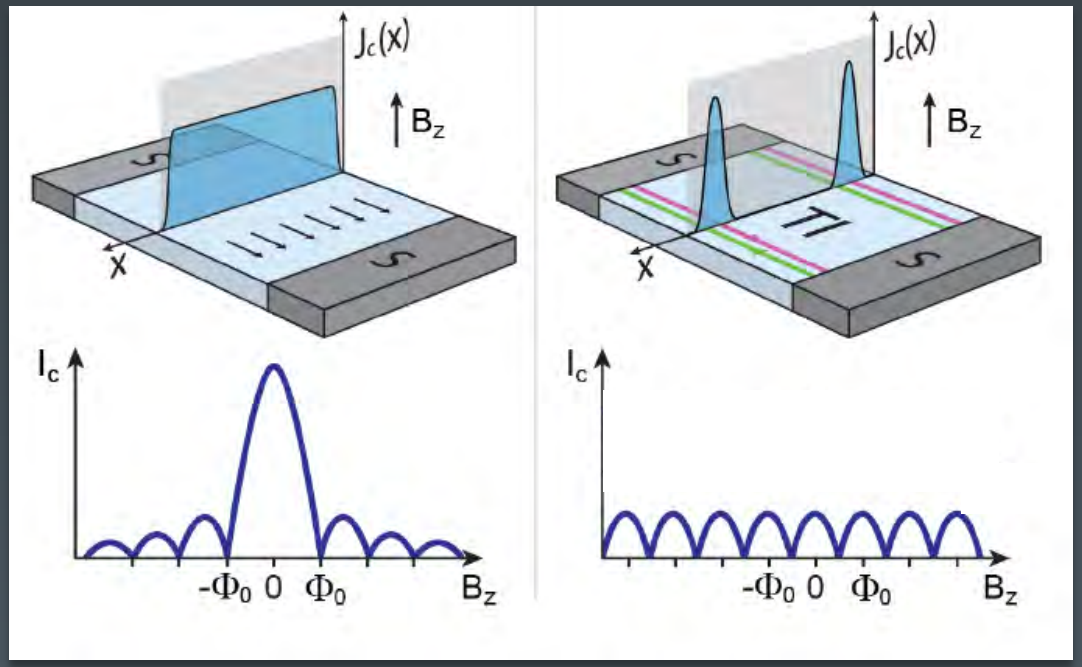
Shapiro steps: $V = n \cdot \frac{h f_{RF}}{2e}$

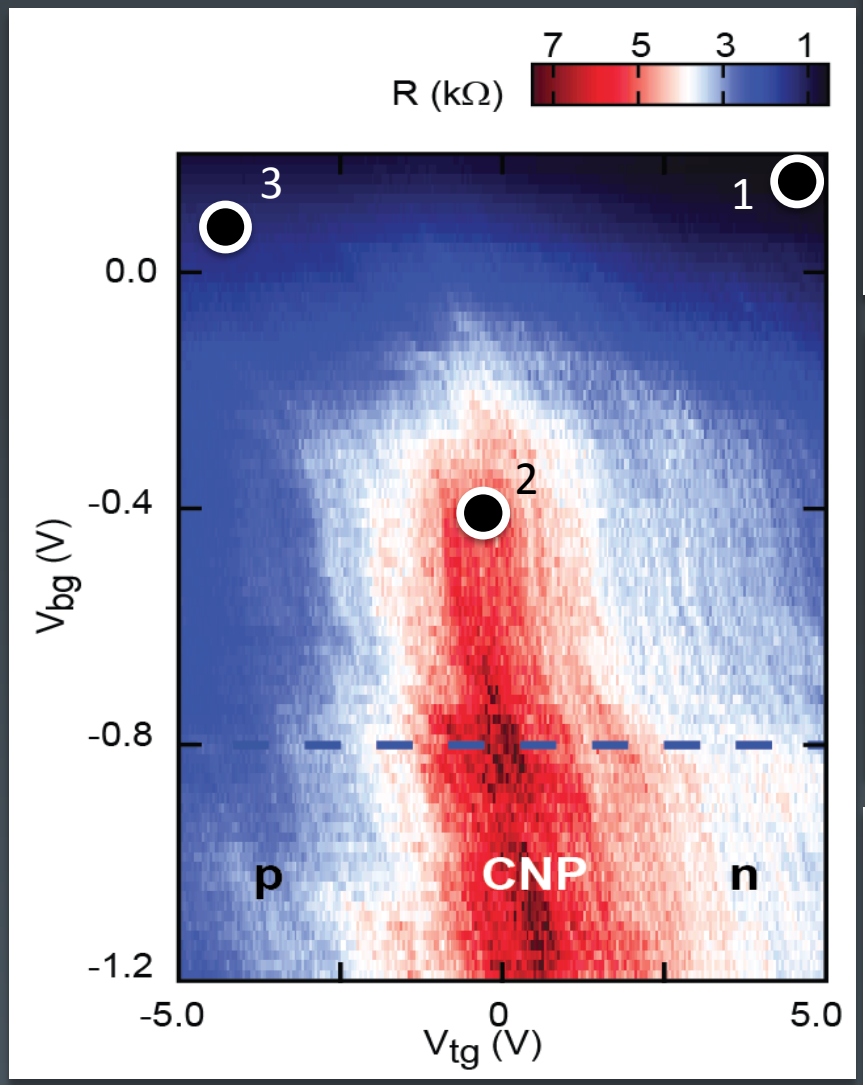
$n = 0, \pm 1, \pm 2, \ldots$

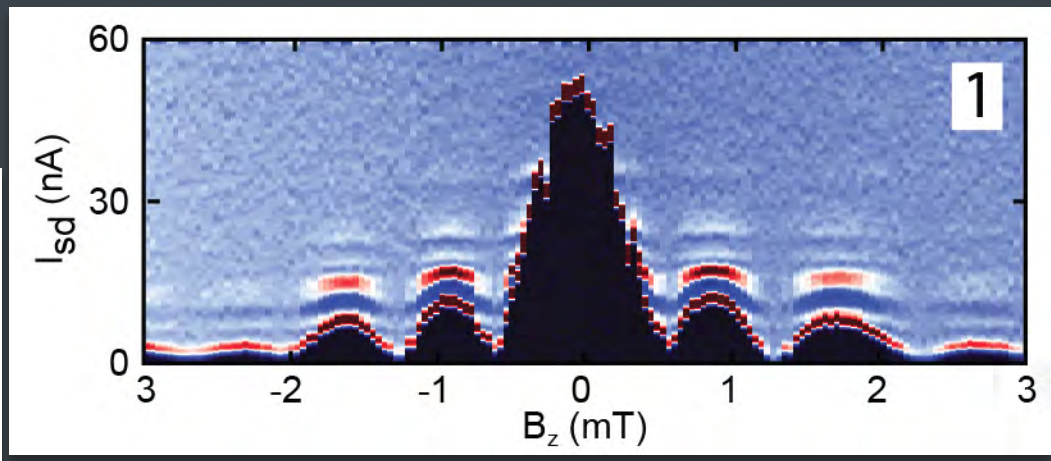
Superconducting quantum interference

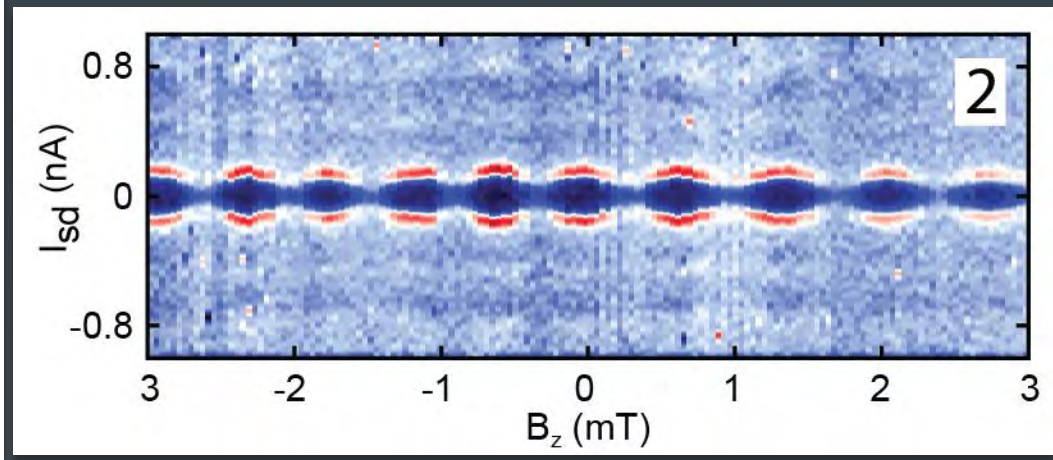


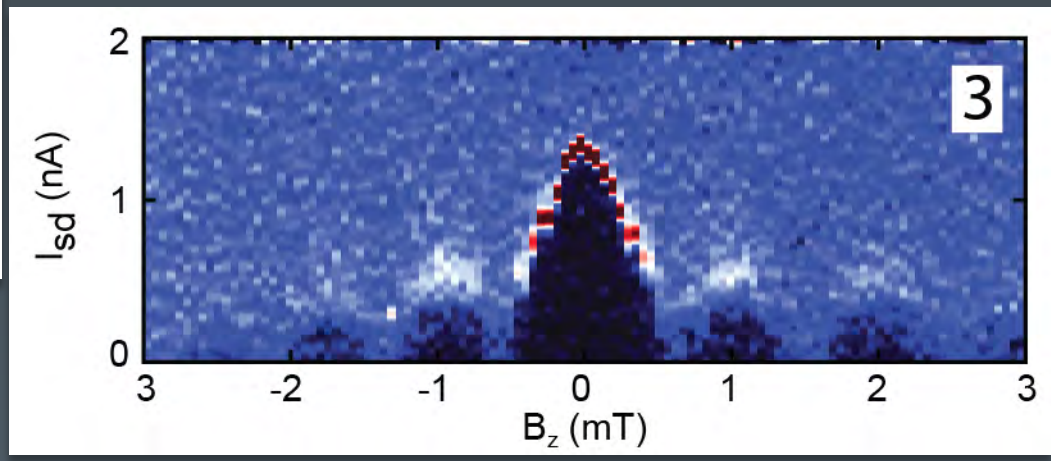












V.S. Pribiag et *al*., *Nature Nano*. **10**, 593 (2015)

Extracting the spatial distribution

measurement

extract spatial distribution

$$I_c(B_z) \equiv \max[I_s(B_z)] = \left| \int_{-\infty}^{\infty} J_c(x) e^{ikx} dx \right|$$

$k = 2\pi L B_z / \Phi_0$

L is the effective junction length

Dynes and Fulton (*PRB* 1971) → estimate the complex phase:

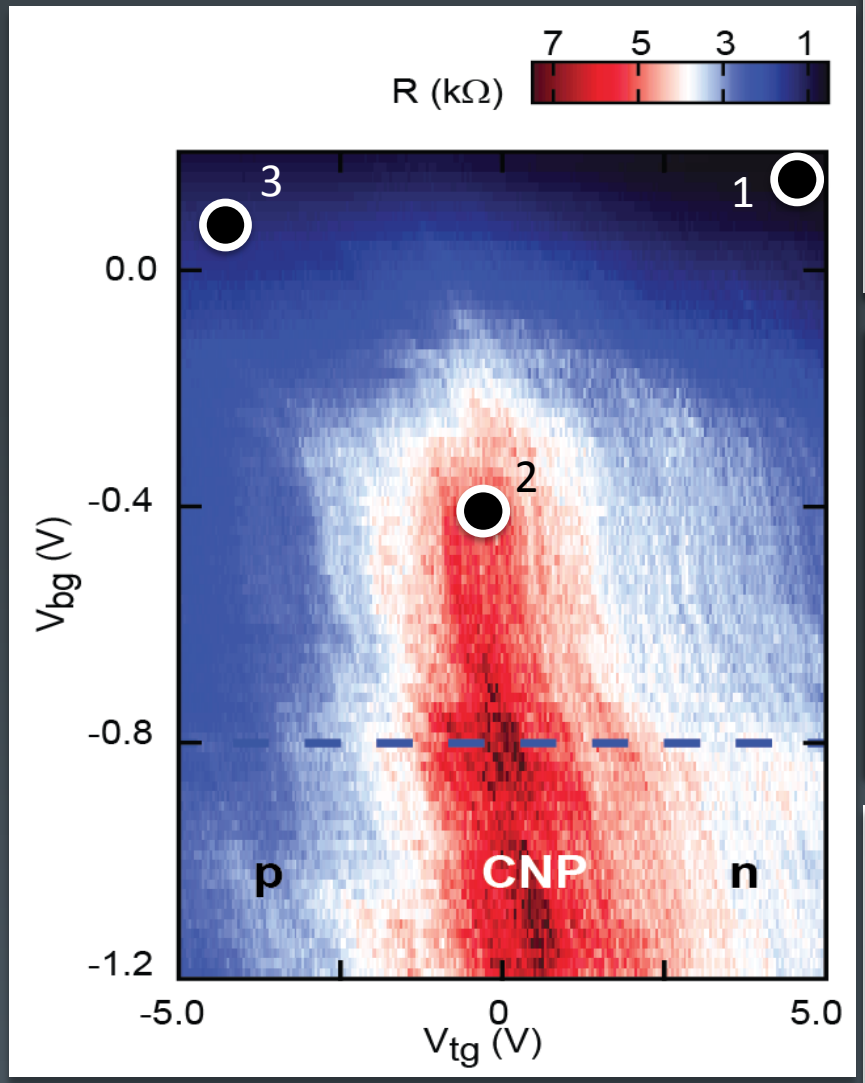
- $J_c(x) = J_{even}(x) + J_{odd}(x)$
- If $J_c(x) \approx J_{even}(x)$, can interpolate near the nodes to estimate $J_{odd}(x)$

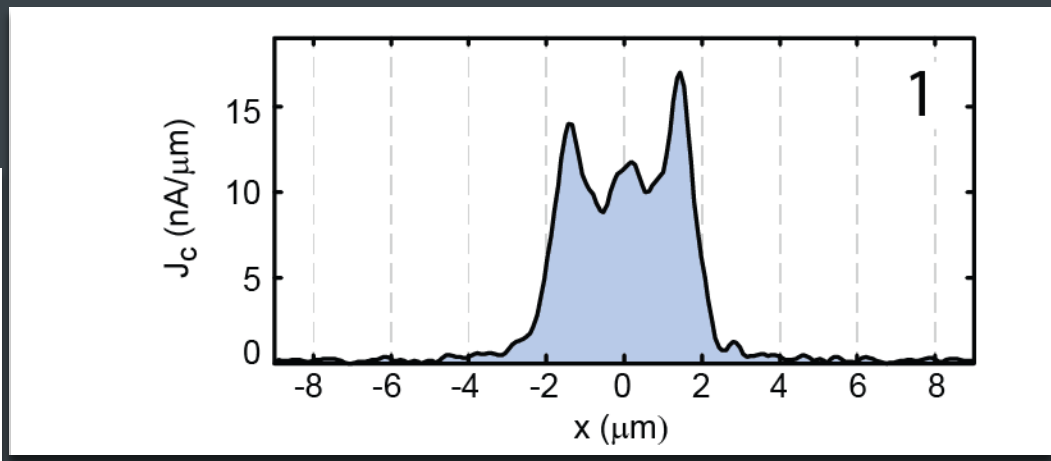
A more general treatment gives good agreement with the Dynes&Fulton method:

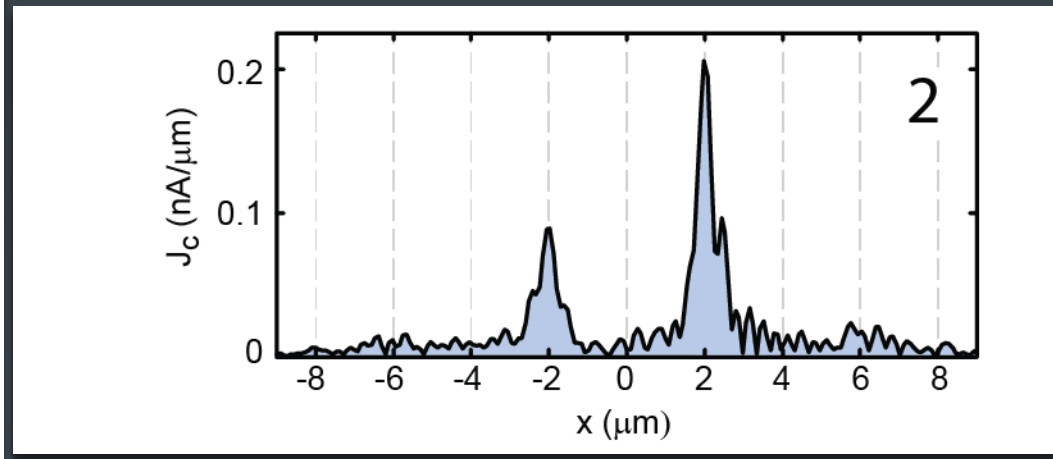
Proximity-induced superconductivity and Josephson critical current in quantum spin Hall systems

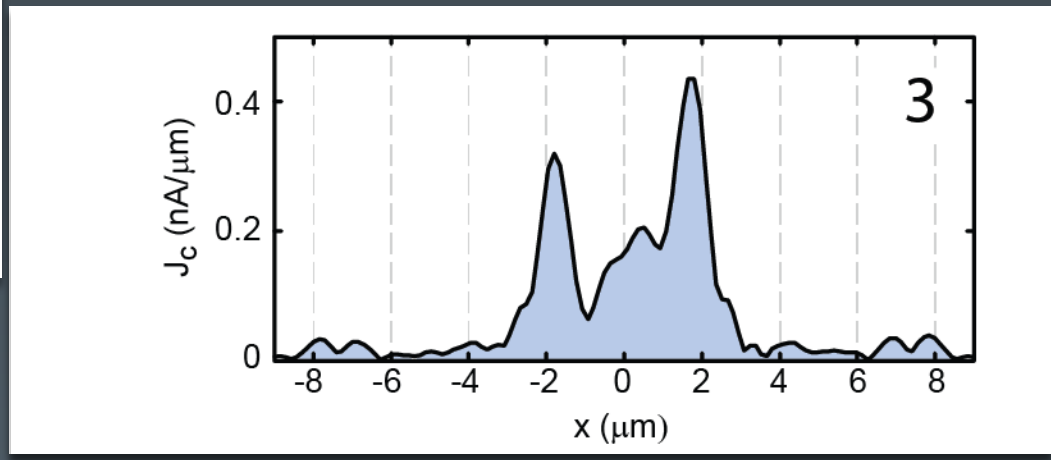
Phys. Rev. B **90**, 224517 – Published 18 December 2014

Hoi-Yin Hui, Alejandro M. Lobos, Jay D. Sau, and S. Das Sarma

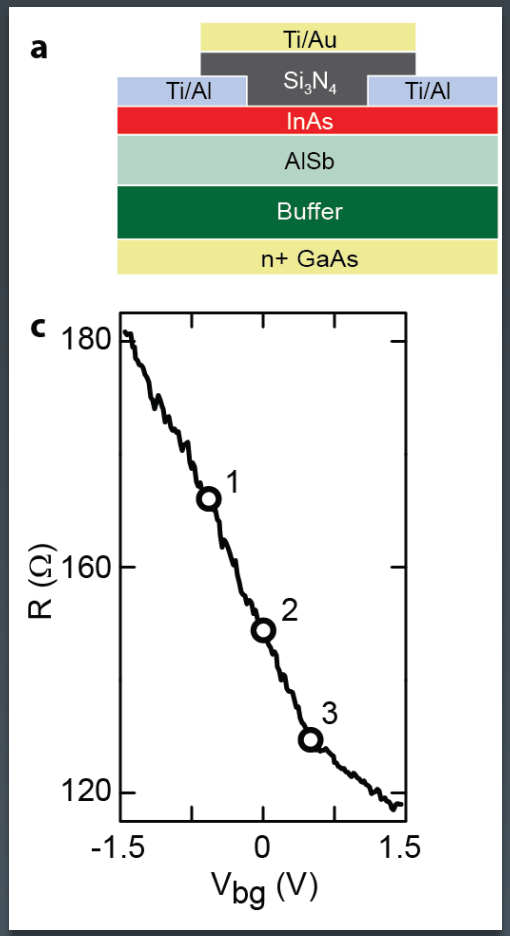

R (kΩ)
7
5
3
1
3
1
2
0.0
-0.4
-0.8
-1.2
V_{bg} (V)
p
CNP
n
-5.0
0
5.0
V_{tg} (V)

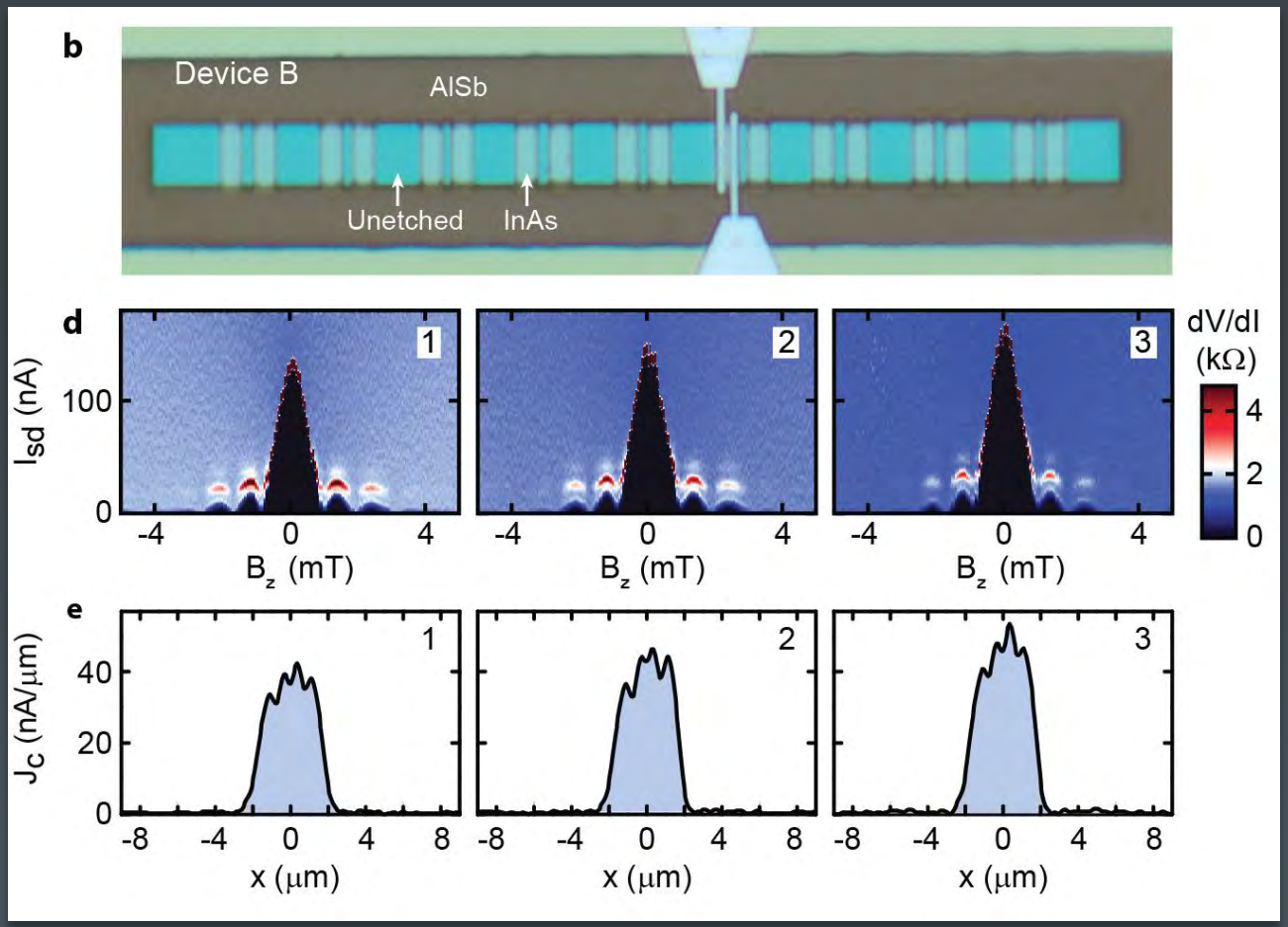

1
15
10
5
0
J_c (nA/μm)
-8
-6
-4
-2
0
2
4
6
8
x (μm)


2
0.2
0.1
0
J_c (nA/μm)
-8
-6
-4
-2
0
2
4
6
8
x (μm)


3
0.4
0.2
0
J_c (nA/μm)
-8
-6
-4
-2
0
2
4
6
8
x (μm)

InAs control device

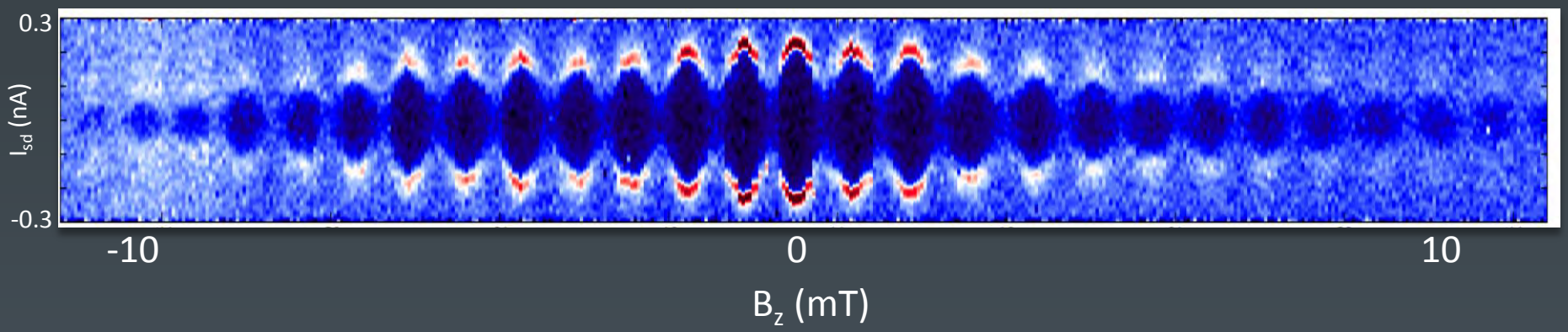


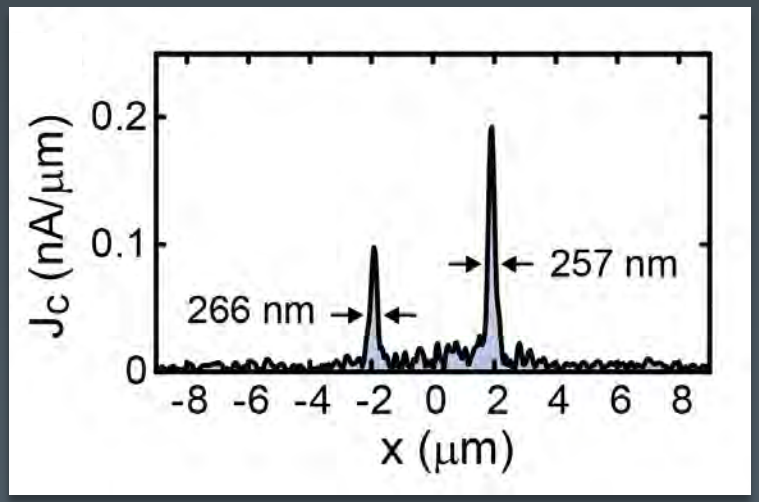


InAs-only → bulk supercurrent

Edge-mode width

Fourier limited: $\Delta x \sim W\Phi_0/\Delta\Phi$

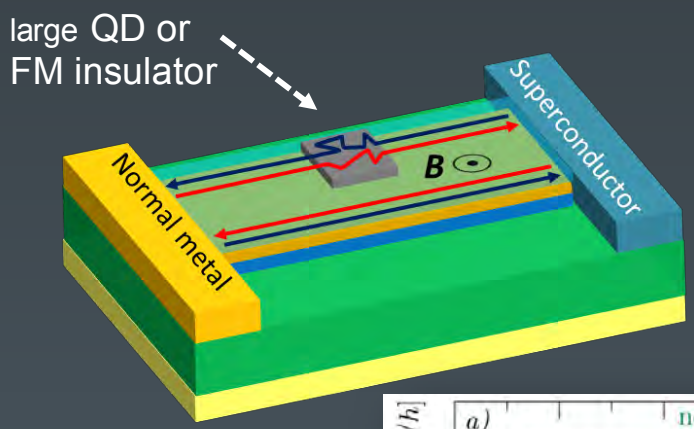


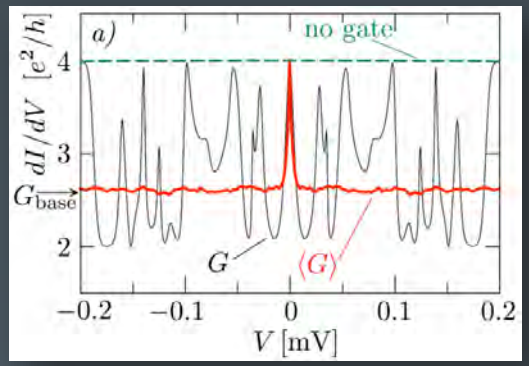


TS and Majorana detection in a 2D TI

Conductance measurements:

- Experimental Signature: ZBCP in the gate-averaged conductance
- insensitive to quasiparticle poisoning





Proposal by S. Mi et al., *PRB* **87** 241405(R) (2013).

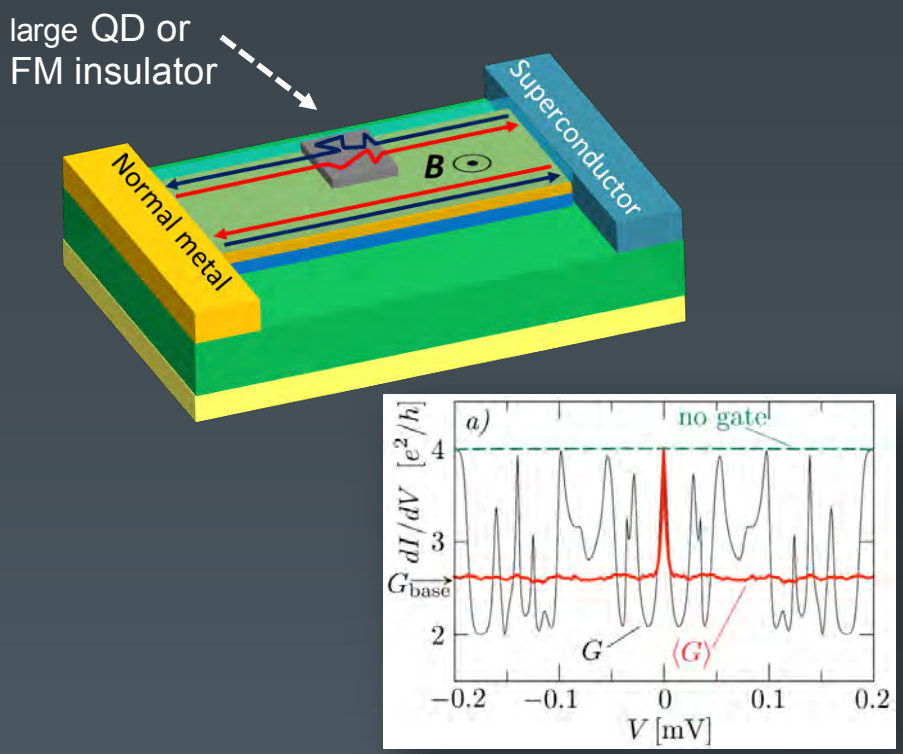
TS and Majorana detection in a 2D TI

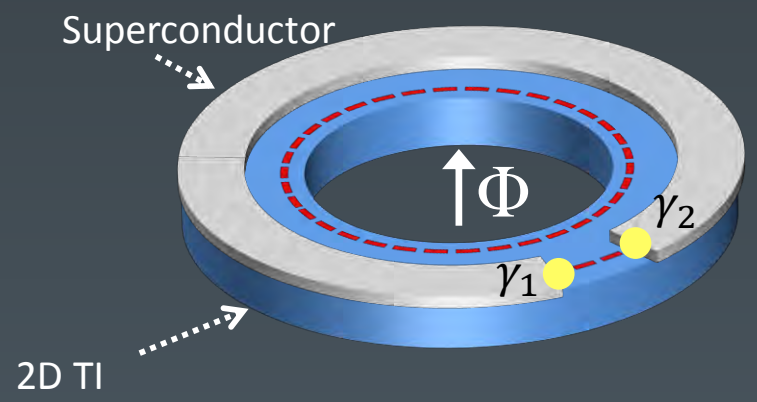
Conductance measurements:

- Experimental Signature: ZBCP in the gate-averaged conductance
- insensitive to quasiparticle poisoning

Current-phase relation:

- Majoranas γ_1 and γ_2 → single-electron can be transported across Josephson junction
- Doubling of current-phase (flux) period: $\frac{h}{2e} \rightarrow \frac{h}{e}$





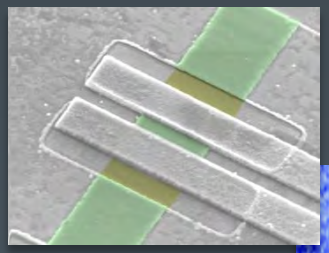
Proposal: S. Mi et al., *PRB* **87** 241405(R) (2013).

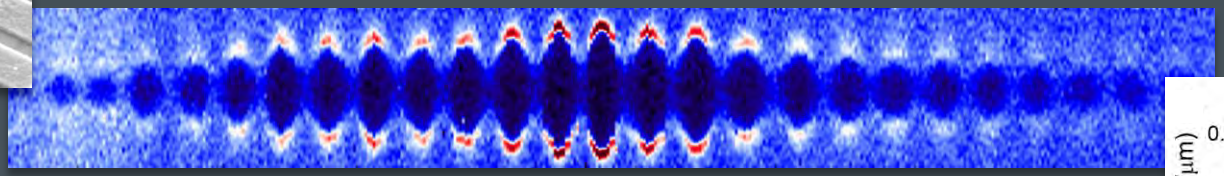
Proposal: L. Fu and C.L. Kane, *PRB* **79**, 161408(R) (2009).

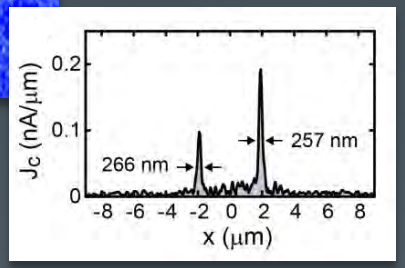
Summary

- Demonstrated edge-mode supercurrent in InAs/GaSb
- Next: Detection of Majoranas and TS in InAs/GaSb

Thank you!







V.S.Pribiag et *al.*, *Nature Nano.* 10, 593 (2015)