Old materials for new tricks: Routes towards Majorana zero-modes in InAs/GaSb system and beyond

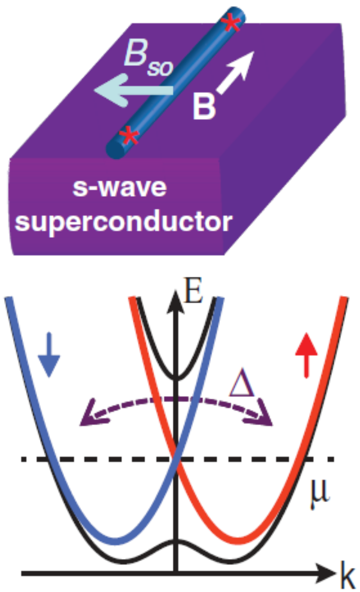
[1]Ivan Knez, [2]Rui-Rui Du, [3]Gerard Sullivan

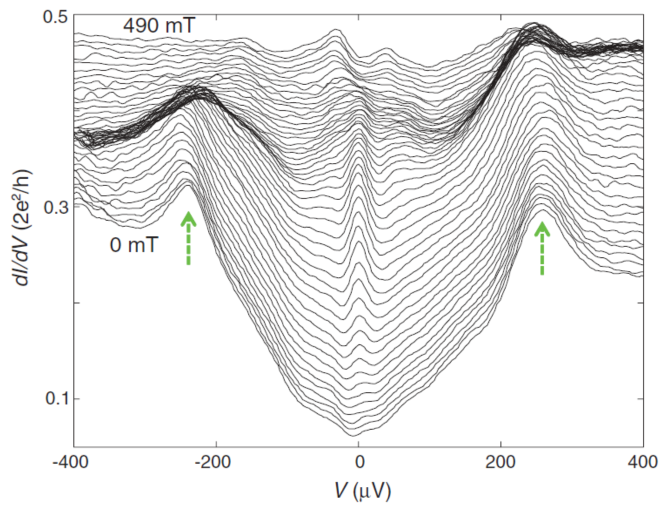
[1] IBM Almaden Research Center

[2] Department of Physics and Astronomy, Rice University

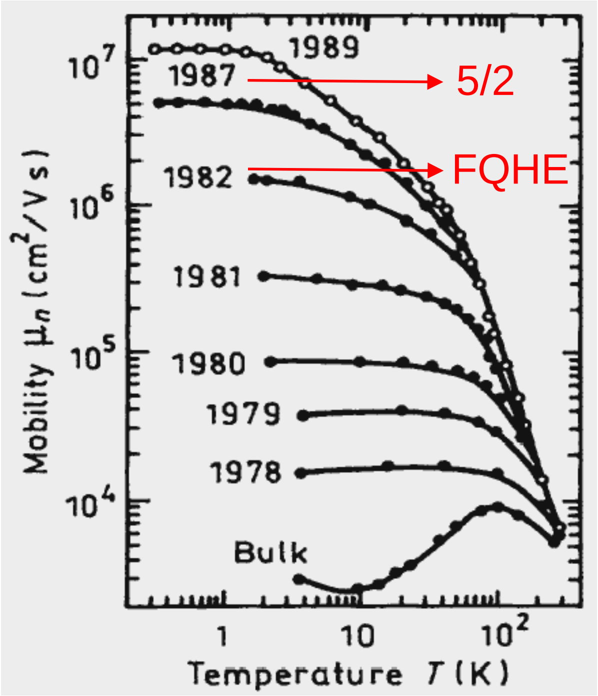
[3] Teledyne Scientific and Imaging

Majoranas or Majorana ghosts?





Van Mourik *et al* Science 2012



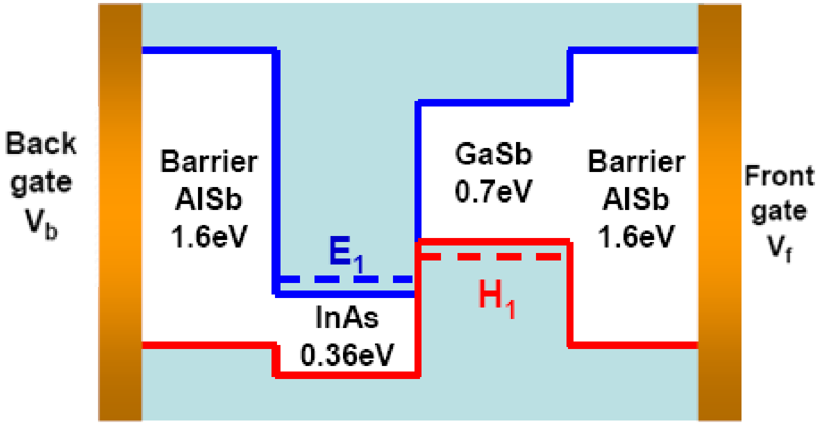
Bell Laboratories

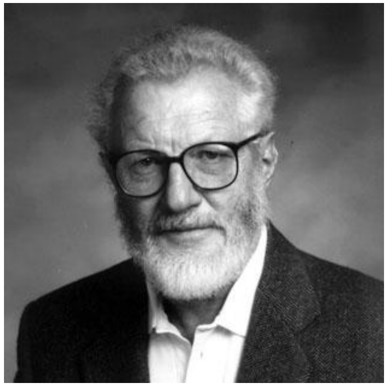
- **Strategies towards more robust Majoranas:**
  - Increase the energy scale
  - Develop systems with in-built protection
- **Advertisment: InAs/GaSb is an excellent system for Majoranas**

Synopsis

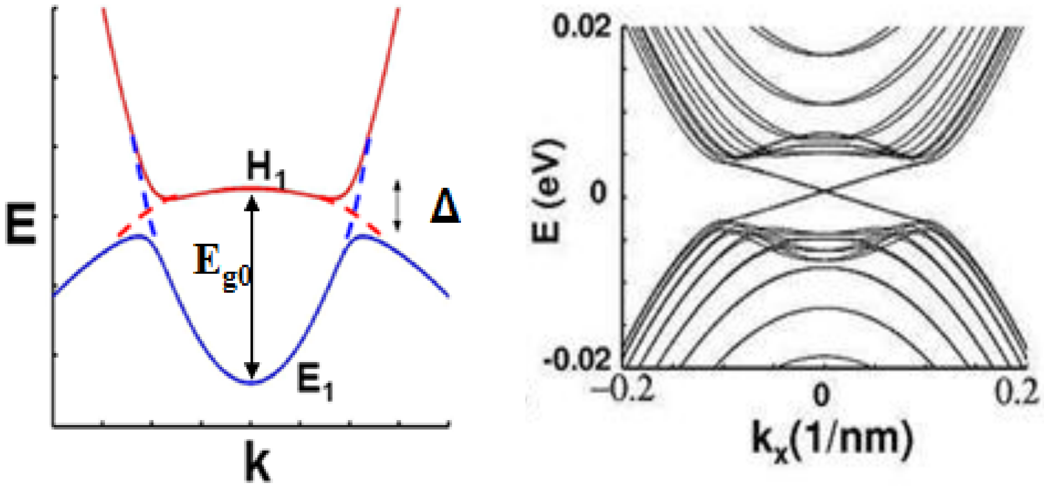
- **InAs/GaSb is a 2D TI showing highly quantized edge transport and insulating bulk**
- **Shows evidence for perfect Andreev reflection**
- **Indicates considerable degree of topological protection**
- **Contains all key ingredients for realizing MBS**
- **It is “user” friendly and commercially available**

InAs/GaSb System as 2D TI





Prof. Herbert Kroemer



Liu *et al*, *Phys. Rev. Lett.* **100**, 236601 (2008)

- **Broken-gap band alignment**
- **Inverted band structure**
- **TRS**
- **Topologically protected helical edge states**
- **First order elastic back-scattering processes are not allowed**

Helical Edge Modes - Quantized Transport

- For phase coherent systems – ballistic transport:

$$I_p = \sum_q G_{qp} V_p - G_{pq} V_q$$

$$G_{pq} = \frac{e^2}{h} T_{p \leftarrow q} \quad \text{and } T_{p \leftarrow q} = 1$$

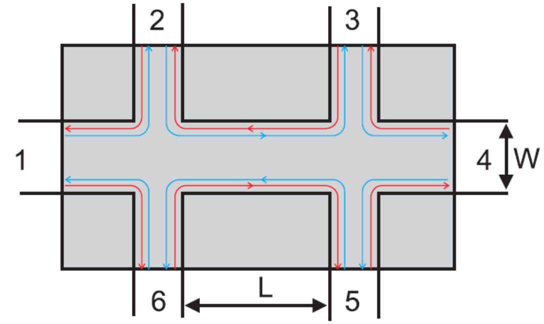
$$G_{14,23} = \frac{2e^2}{h}$$

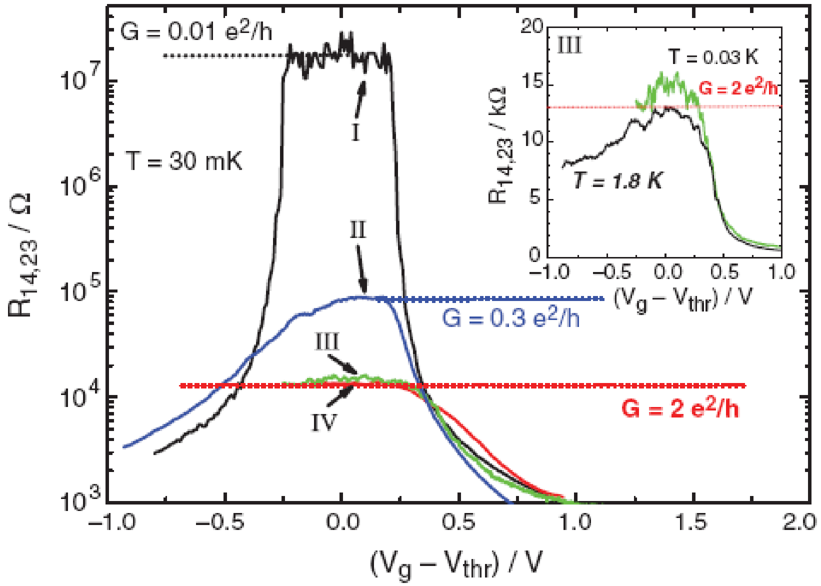
- For macroscopic devices*:*

$$G_{14,23} \cong \frac{L_\phi}{L} \frac{2e^2}{h}$$

- First observed in HgTe/CdTe QWs

Koenig *et al, JPSJ,* **77**,031007,(2008)



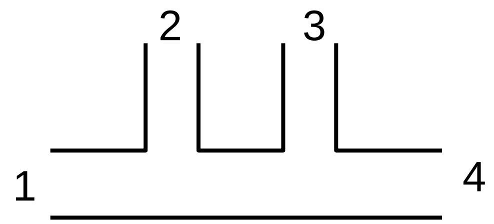


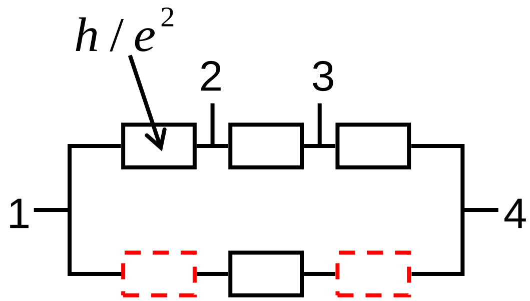
Konig et al, *Science,* **318**, 766 (2007)

Helical edge modes in four probe geometry

- **For phase coherent samples Landauer-Buttiker formula gives conductance value:**

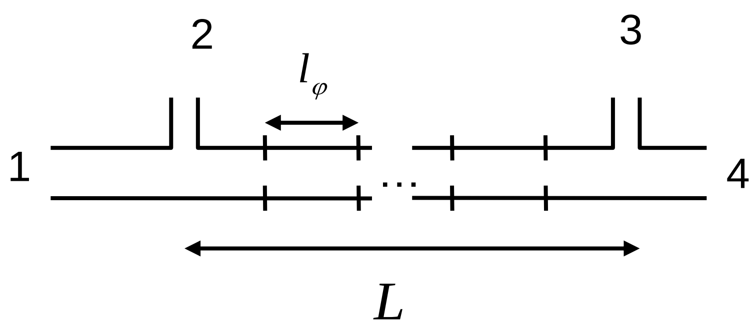
$$G_{14,23} = \frac{4e^2}{h}$$





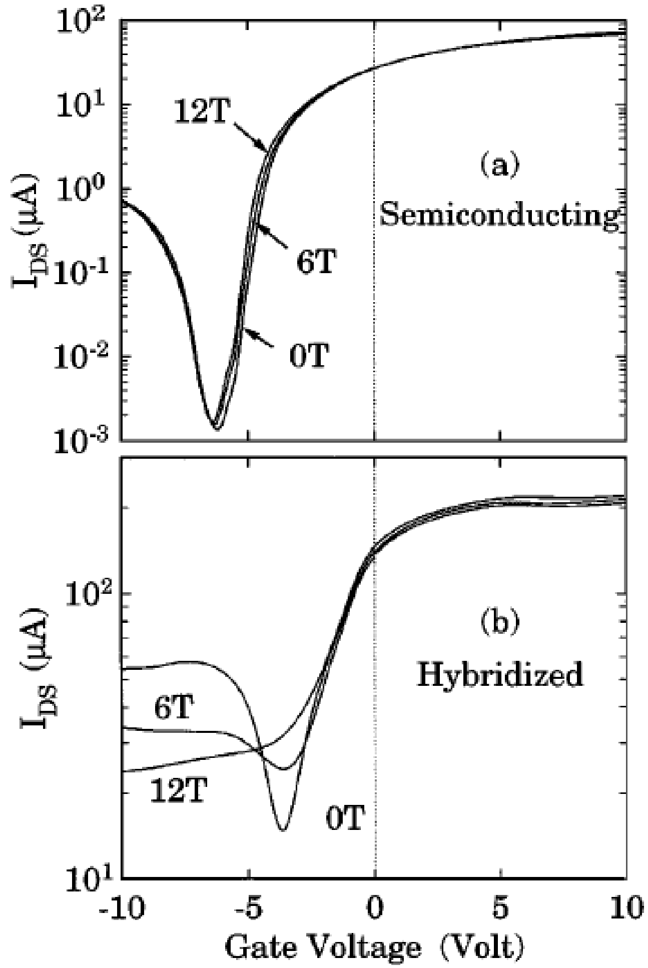
- **Longer samples can be modeled by inserting phase breaking probes and applying LB-formula:**

$$G_{14,23} = \frac{2e^2}{h}\left(\frac{l_\varphi}{L} + \left(\frac{l_\varphi}{L}\right)^2\right)$$

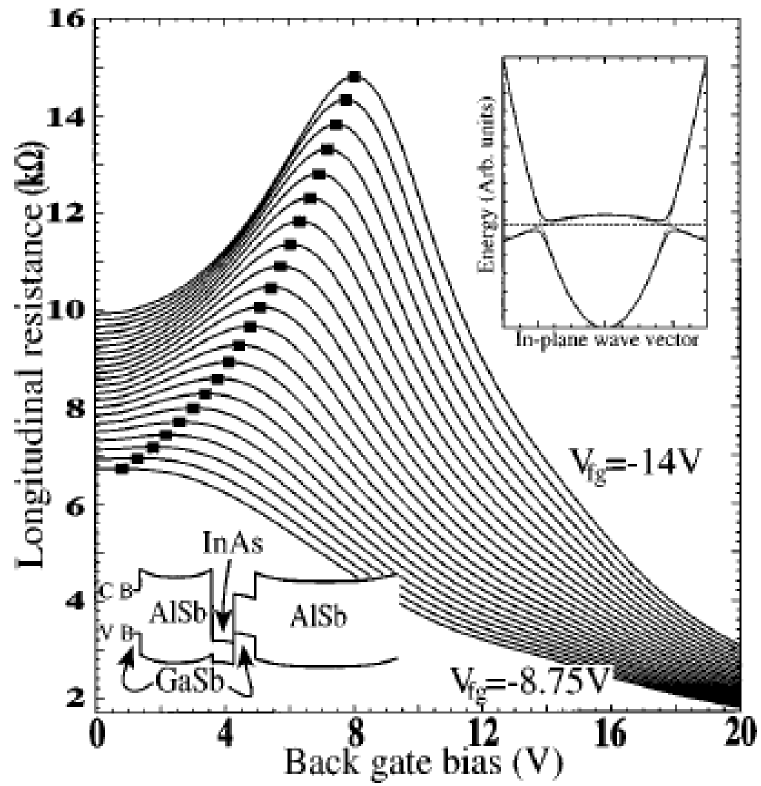


- **In macroscopic limit 2D TIs are poor conductors!**

Early Experimental Work in InAs/GaSb QWs



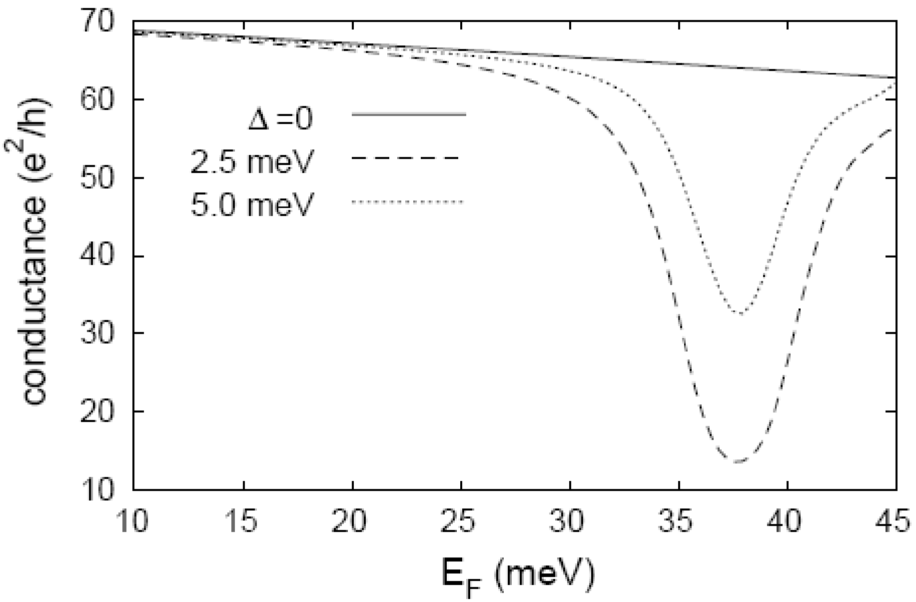
Yang et al., *Phys. Rev. Lett*, **78**, 4613-4616 (1997)



Cooper et al., *Phys. Rev. B*, **57**, 11915-11918 (1998)

Residual bulk conductivity – singular role of disorder

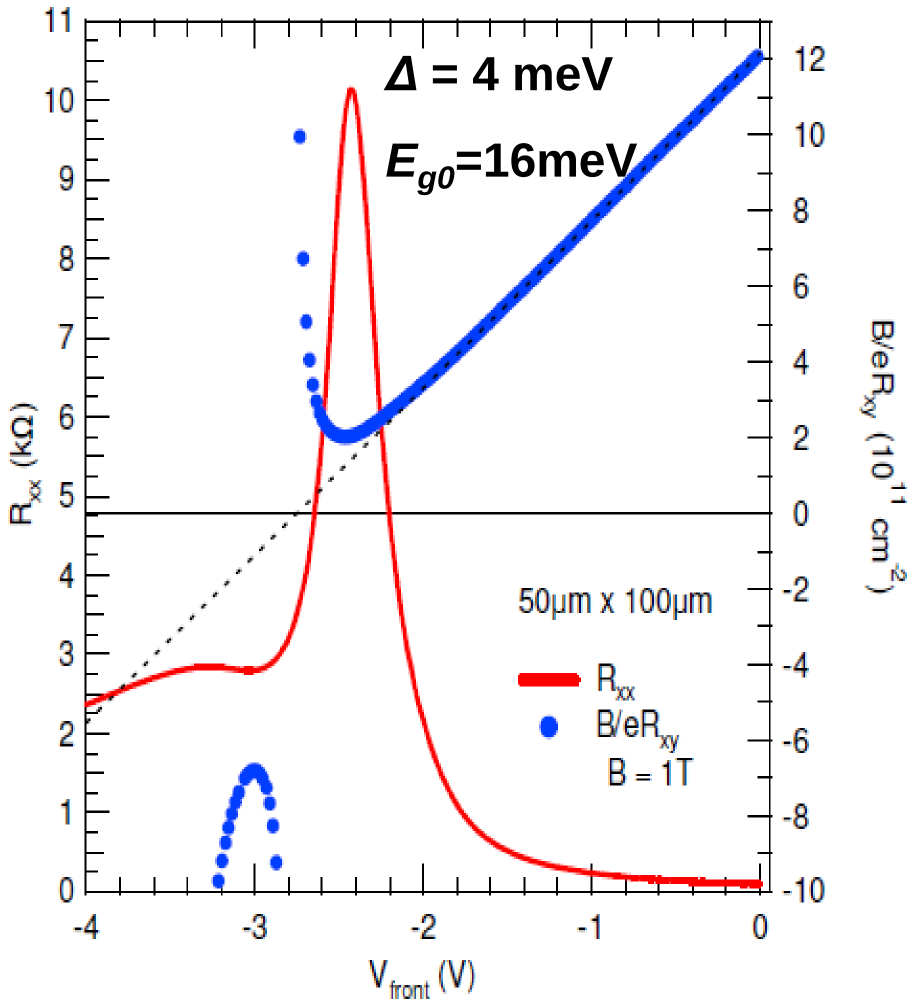
Naveh and Laikthman, *EPL*, **55,**4, (2001)



$$g(T=0) \propto \frac{e^2}{h}\frac{E_{g0}}{\Delta}, \qquad \Gamma << \Delta << E_{g0}$$

- Residual bulk conductivity exists and is driven by disorder (level broadening)
- Not a simple impurity band problem
- Singular effect – non-zero conductivity even in the limit of vanishing level broadening
- Bulk conductivity can be tuned

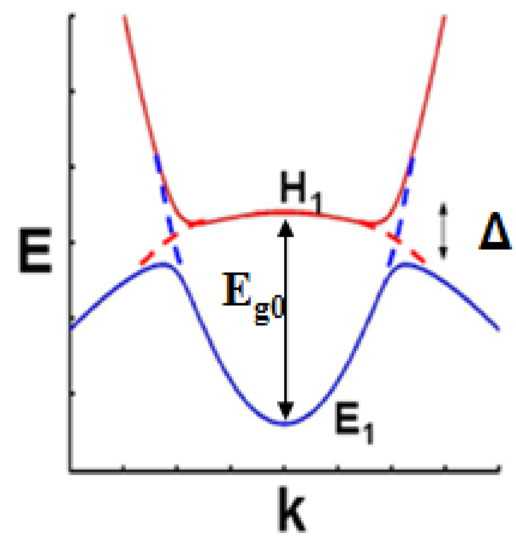
Transport in macroscopic devices



Knez *et al*, *Phys. Rev. Lett.* **107**, 136603 (2011)

InAs/GaSb QW 12.5nm/5nm

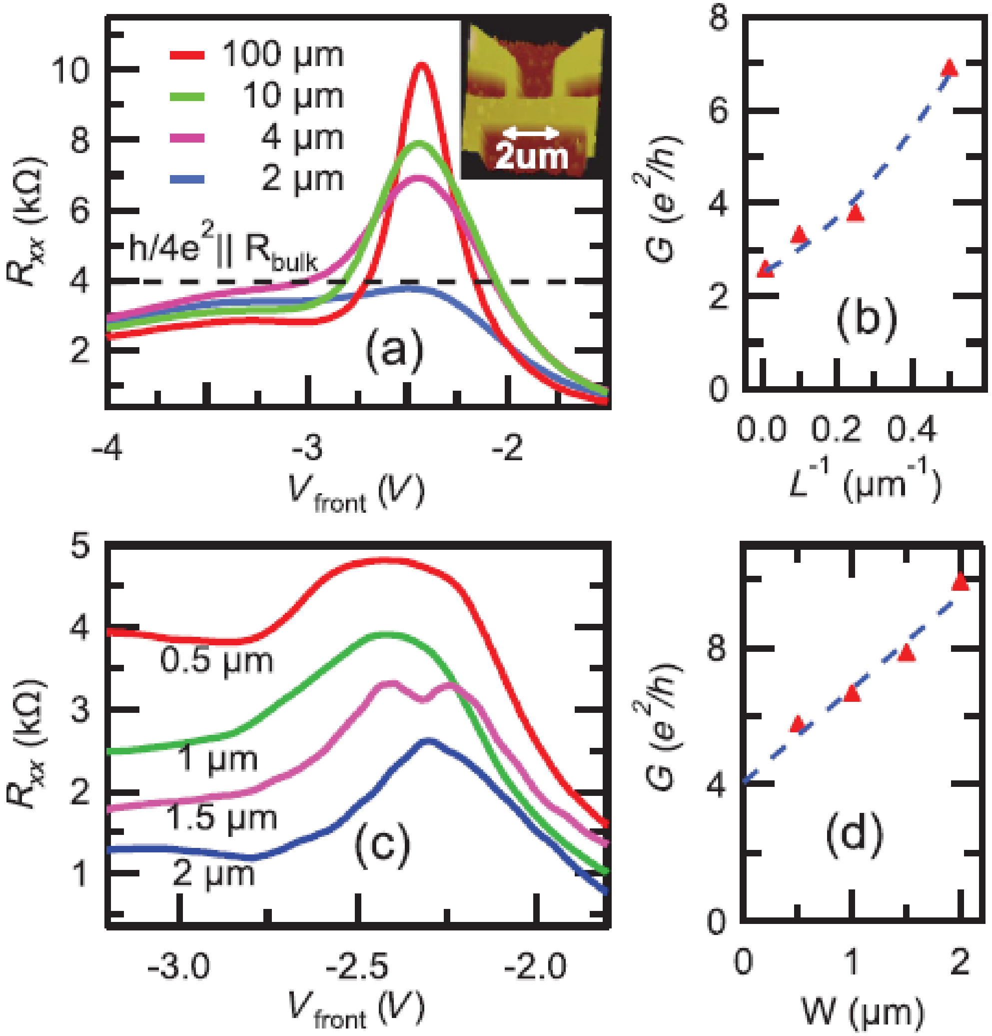
E_1-H_1≈-18meV



$$g_{bulk}^{th.} \approx \frac{e^2}{h}\frac{E_{g0}}{\Delta} = \frac{4e^2}{h}$$

$$g_{bulk}^{\exp} = 5.05\,\frac{e^2}{h}$$

Scaling evidence for helical edge channels



$$\frac{L}{W} = 2$$

$$G_{14,23} \cong G_{bulk} + \frac{2e^2}{h}\left(\frac{l_\varphi}{L} + \left(\frac{l_\varphi}{L}\right)^2\right)$$

$$G_{bulk} = (2.5 \pm 0.3)\frac{e^2}{h}$$

$$l_\varphi = (2.1 \pm 0.3)\mu m$$

$$L = 2\,\mu m$$

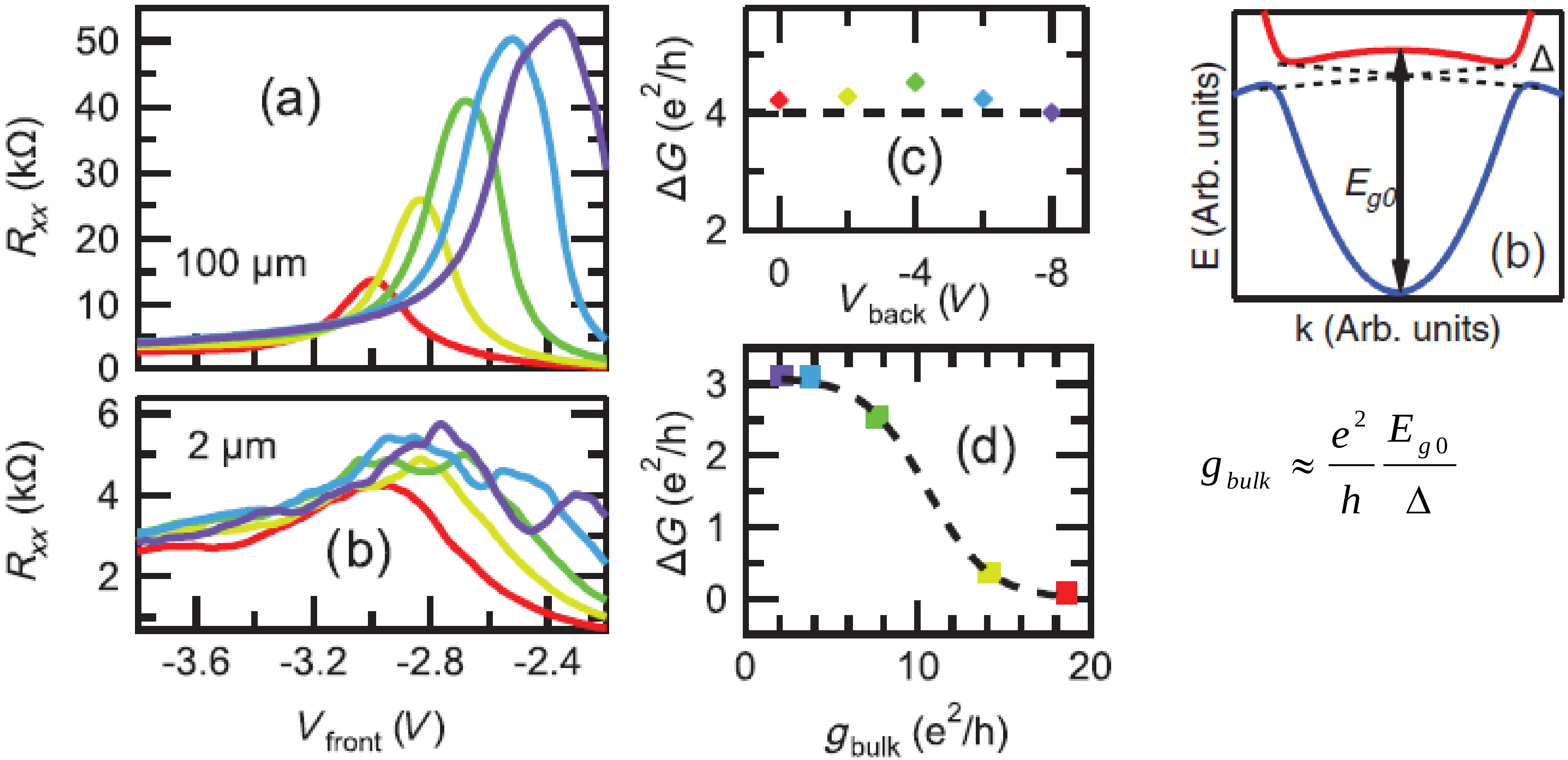
$$G_{14,23} = G_{edge} + \frac{g_{bulk}}{L}\cdot W$$

$$g_{bulk} = (5.4 \pm 1.0)\frac{e^2}{h}$$

$$G_{edge} = (4.1 \pm 0.7)\frac{e^2}{h}$$

Knez *et al*, *Phys. Rev. Lett.* **107**, 136603 (2011)

Tuning the band-structure

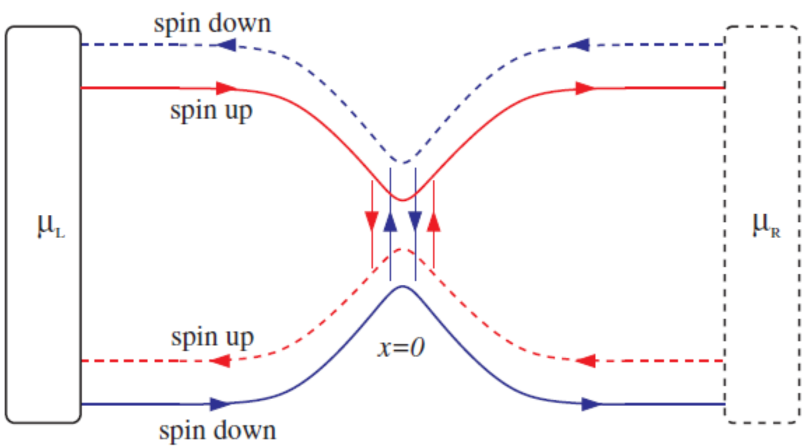


$$g_{bulk} \approx \frac{e^2}{h}\frac{E_{g0}}{\Delta}$$

Resilience of edge channels to bulk conduction for $g_{bulk} \leq 10 \cdot e^2/h$

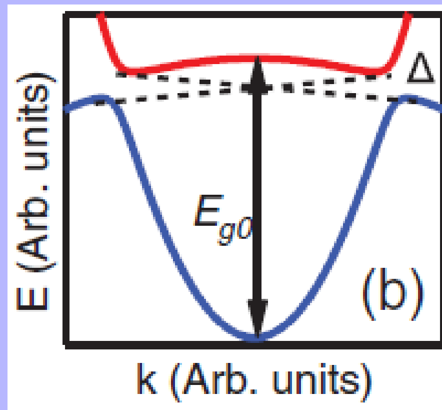
Decoupling of edge to bulk in transport

Ström and Johannesson, *Phys. Rev. Lett.* **102**, 096806 (2009)
Väyrynen and T. Ojanen, *Phys. Rev. Lett.* **106**, 076803 (2011)



$$G = G_{edge} - 2G_{tunneling}(T, \theta)$$

For conductive bulk, edge contribution to transport is expected to diminish.

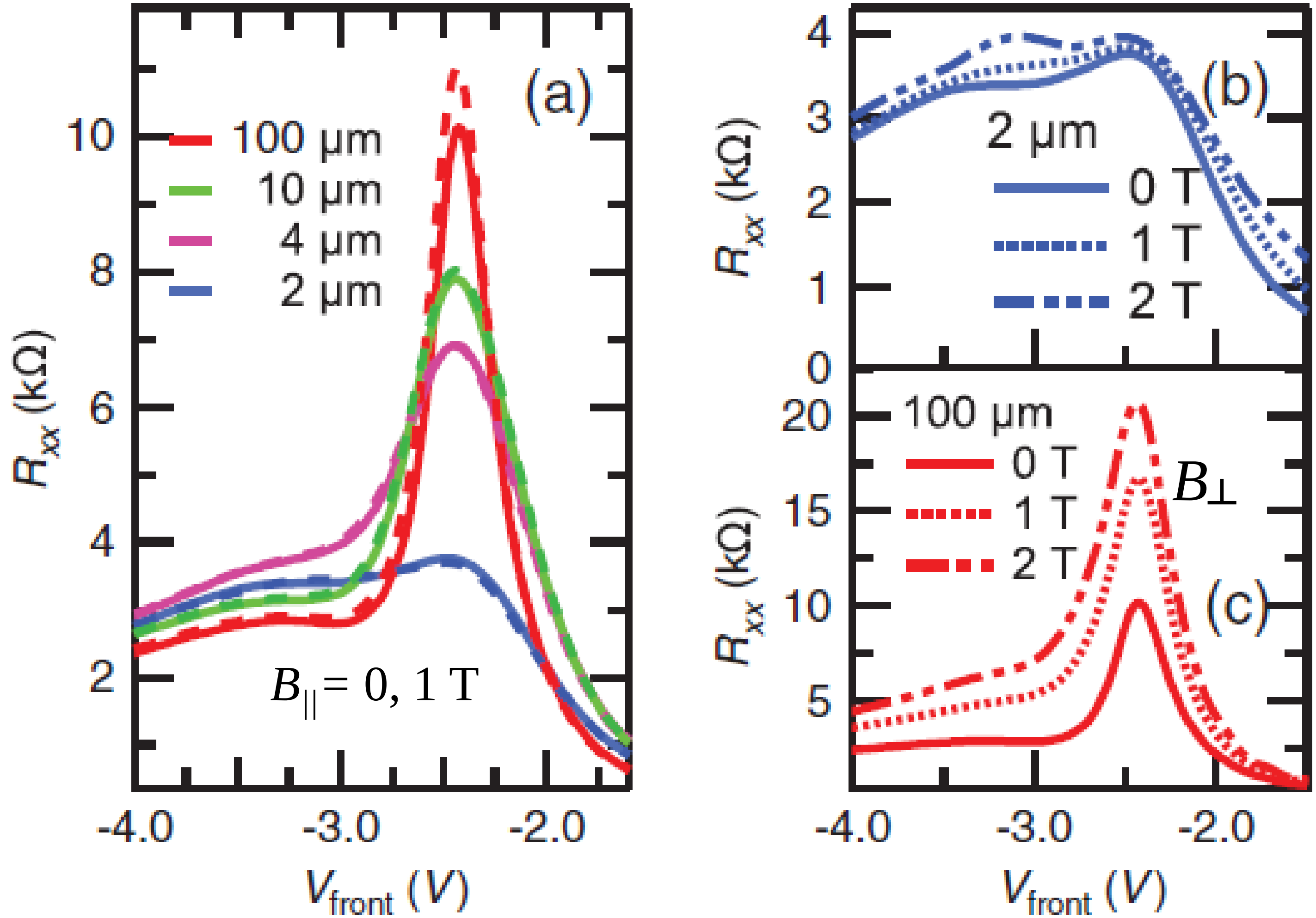


$$v_{edge} \approx 3 \cdot 10^4 \text{ m/s}$$

$$v_{bulk} \approx 5 \cdot 10^5 \text{ m/s}$$

Edge channels decouple due to large Fermi velocity mismatch.

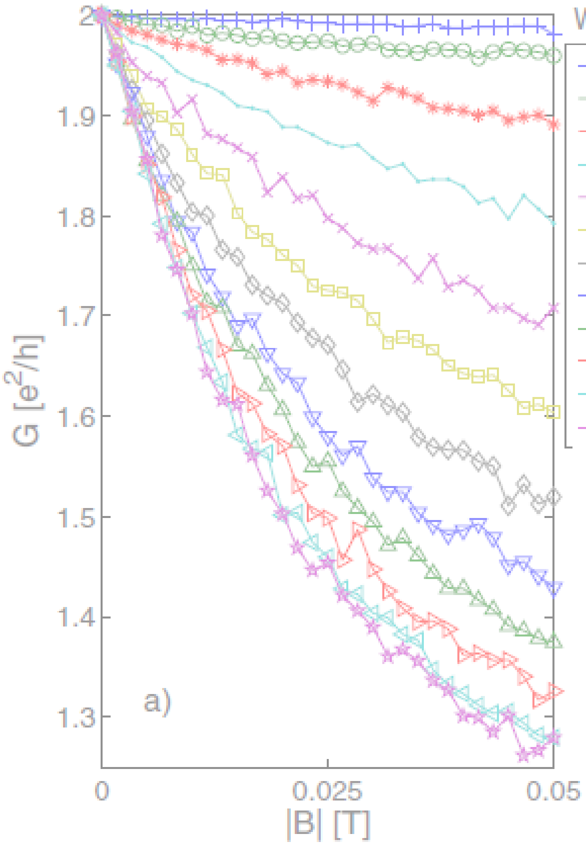
Magnetic field “in”-dependence

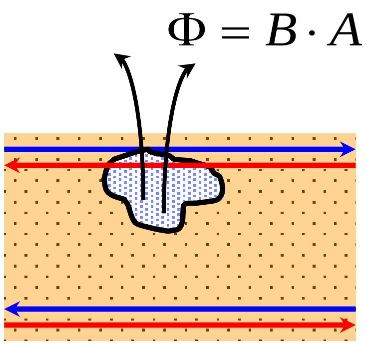


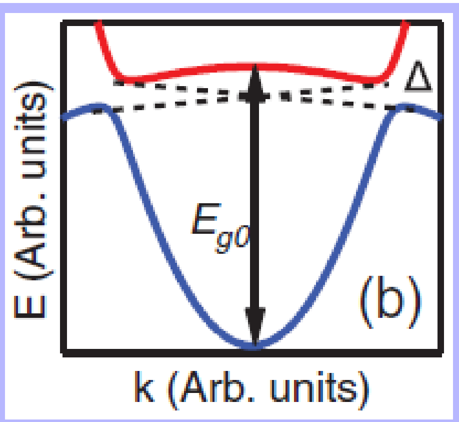
Knez *et al*, *Phys. Rev. Lett.* **107**, 136603 (2011)

Understanding magnetic field "in"-dependence

Maciejko *et al*, *Phys. Rev. B*, **83**, 155310 (2010)







$$v_{edge} \approx 3 \cdot 10^{4} \text{ m/s}$$

$$v_{bulk} \approx 5 \cdot 10^{5} \text{ m/s}$$

- Surprisingly, bulk states are necessary for edge conduction decay in magnetic field!
- Bulk/edge velocity mismatch reduces this possibility in InAs/GaSb

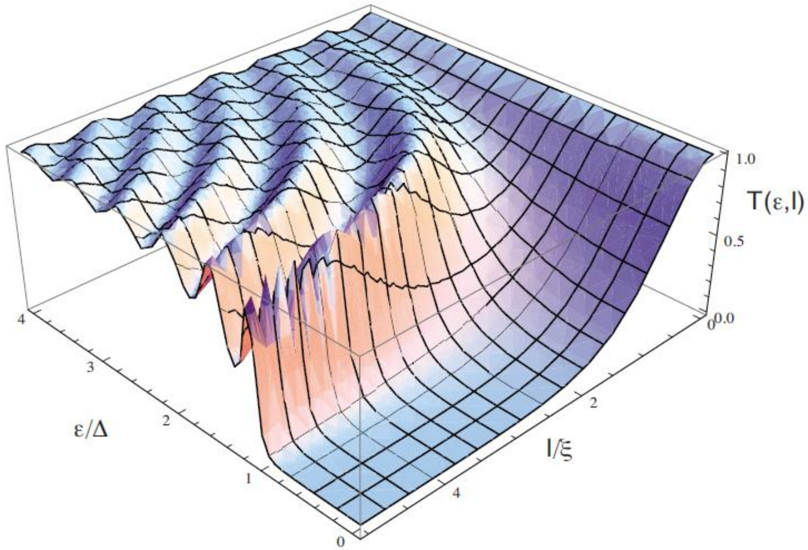
Probing QSH State via Andreev Reflection

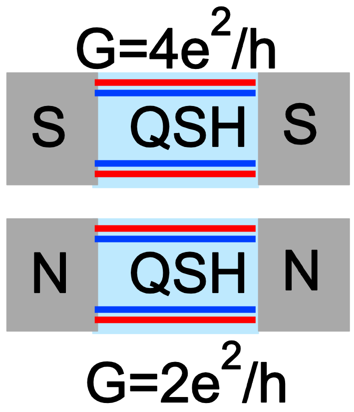
- Proposed by Adrouger *et al*
- At typical S-N interface both normal reflections and Andreev reflections are possible
- At S-QSH interface backscattering is prohibited and normal reflection is excluded

For QSH edges:

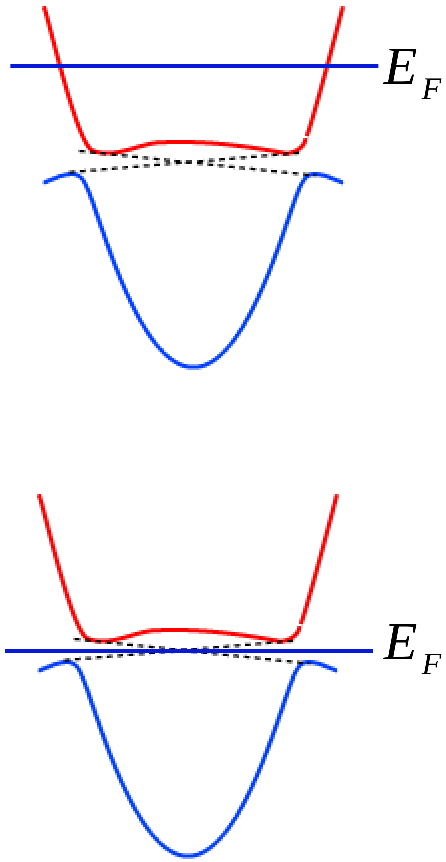
$$I \approx 2\frac{e^2}{h}\cdot[1+A-B]\cdot V$$

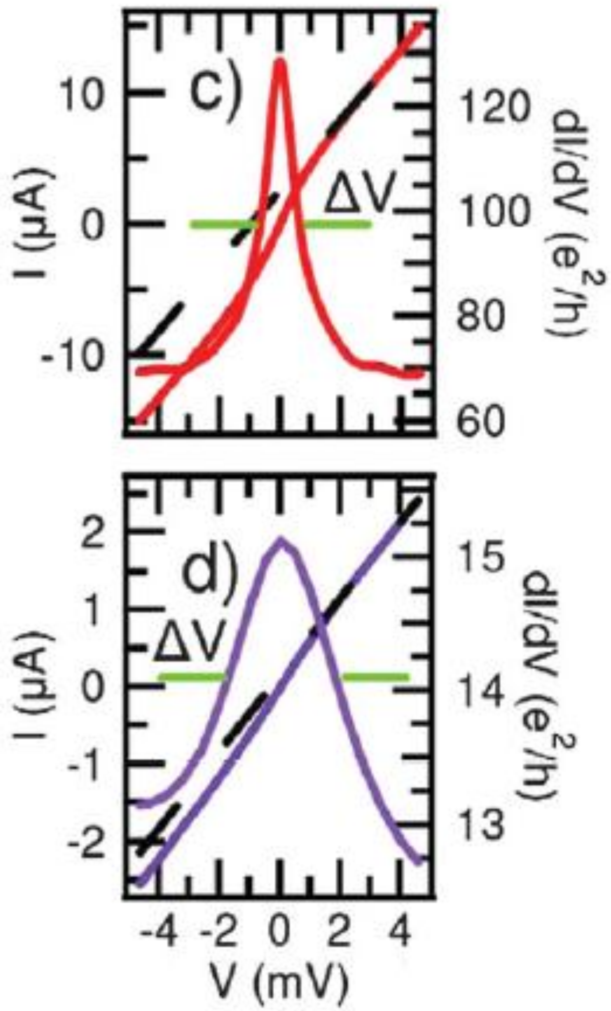
$$A(V) = \begin{cases} 1 & V < \frac{\Delta}{e} \\ \left(\frac{\Delta}{eV}\right)^2 & V >> \frac{\Delta}{e} \end{cases}$$



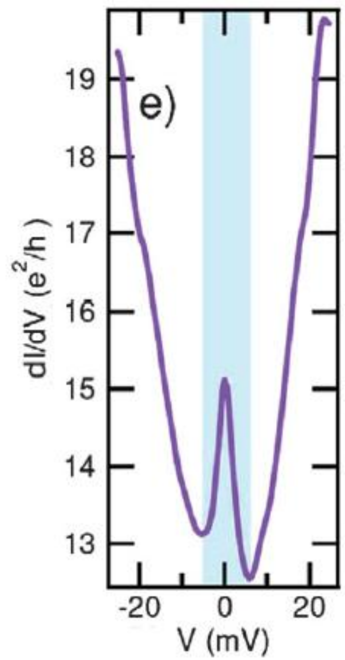


Andreev reflection in and outside of mini-gap





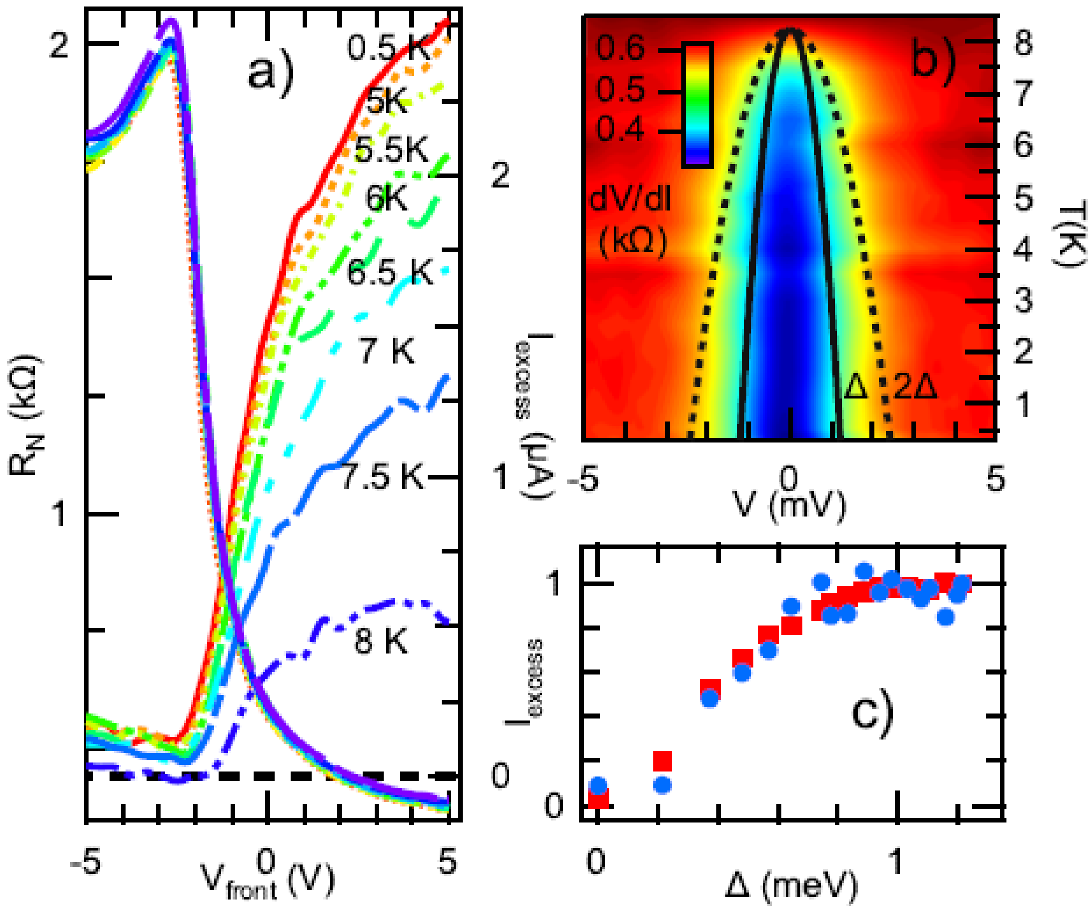
- Interface transparency of 70% in electron regime
- Broad peak of ~$2e^2/h$ in the mini-gap regime



Knez *et al*, *Phys. Rev. Lett.* **109**, 186603 (2012)

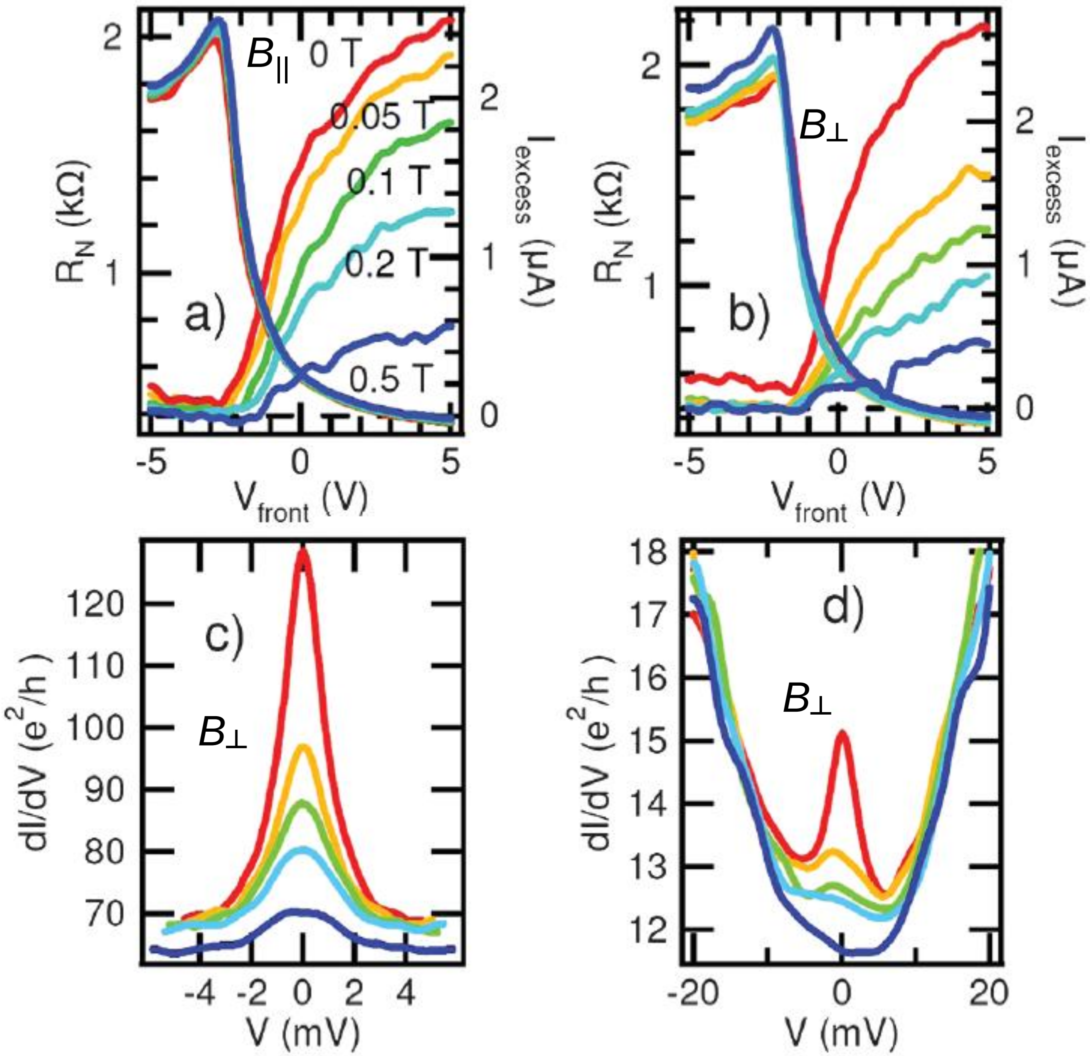
Temperature dependence

Knez *et al*, *Phys. Rev. Lett.* **109**, 186603 (2012)



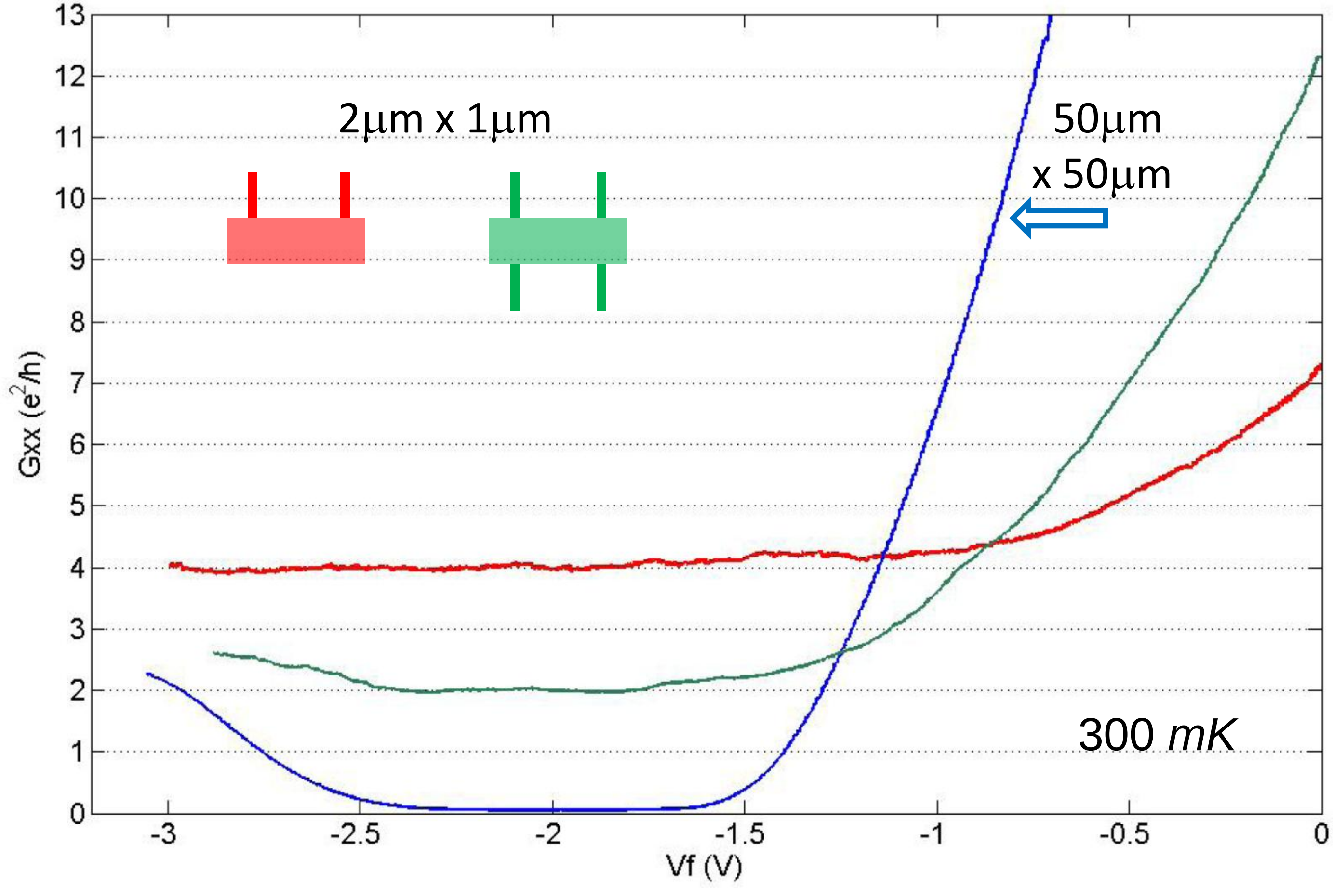
Excess currents in and above the gap show equal suppression with temperature.

Magnetic field dependence



Knez *et al*, *Phys. Rev. Lett.* **109**, 186603 (2012)

News Flash: Conductance Quantization in InAs/GaSb



Raw data:

Lingjie Du, Ivan Knez, Rui-Rui Du, Gerry Sullivan

Conclusions

- **InAs/GaSb shows highly quantized edge transport in the topologically insulating regime**
- **Bulk transport can be completely suppressed by clever structure engineering**
- **Shows evidence for perfect Andreev reflection and topological protection from backscattering of the edge channels**
- **Topological protection, high transparency of superconducting contacts, tuning capability, and commercial availability, make InAs/GaSb “the” system of choice for realizing Majorana bound states**
- **Experiments are underway at Rice, IBM, Stanford, UC Riverside, Peking and elsewhere**
- **We truly hope that this system will exit realms of a single lab and will significantly contribute to further experimental and theoretical exploration of TI physics in its purest form**