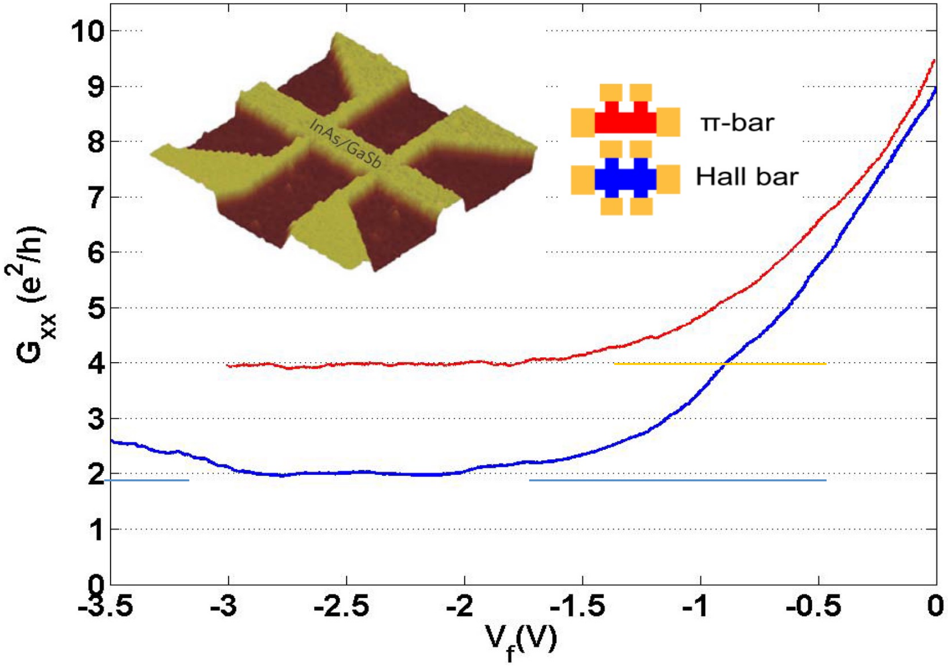
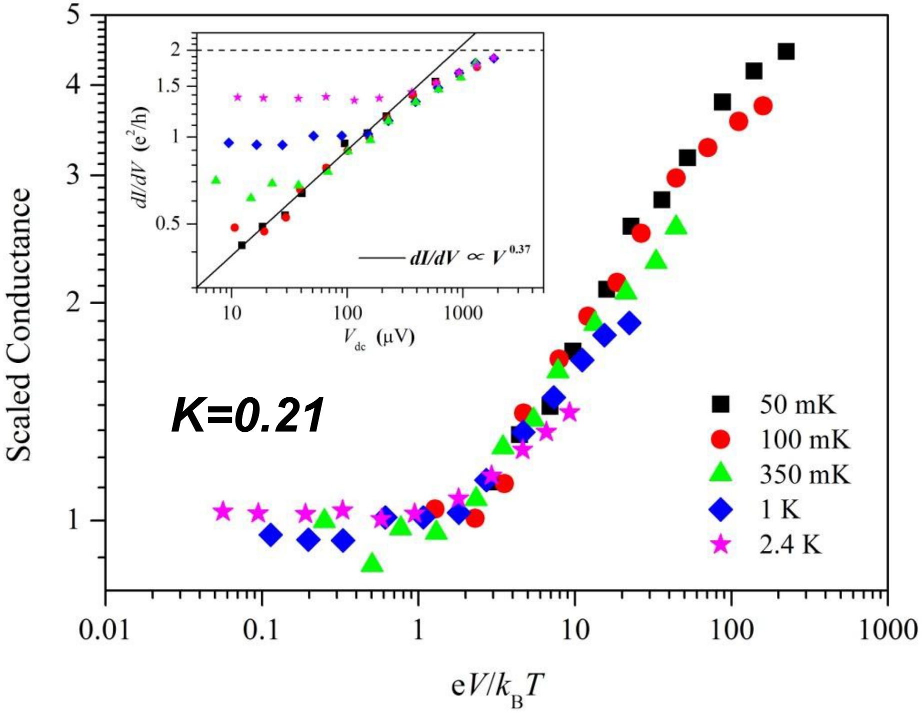
Gate-Controlled Helical Luttinger Liquid In InAs/GaSb Edges

Rui-Rui Du
Rice University/Peking University





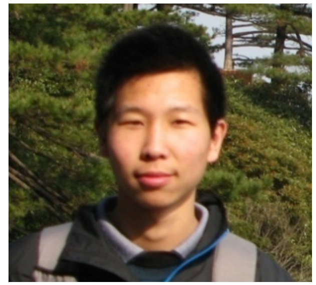
AKNOWLEDGE

Rice

Ivan Knez   Lingjie Du

Peking U

Tingxin Li



Collaborations

Teledyne

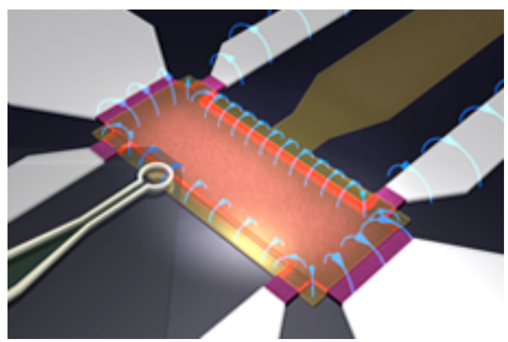
Gerry Sullivan

Stanford

Kathryn Moler

Eric Stanton

MBE



SQUID Imaging

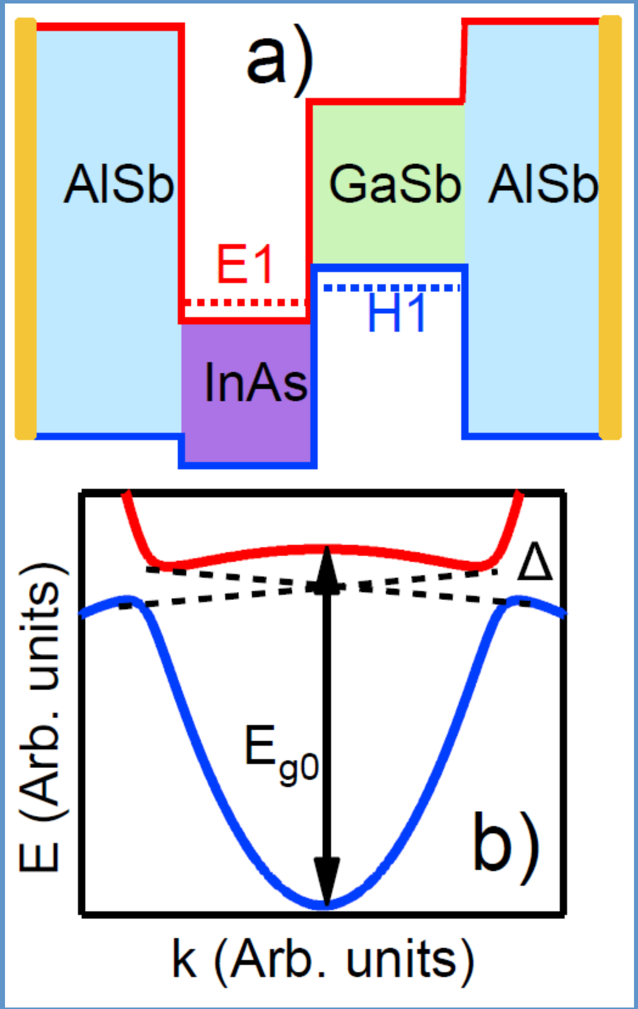
OUTLINE

1. InAs/GaSb: Materials and Devices

2. Quantized and Non-quantized Transport

3. 1D- Helical Luttinger Liquid Transport

4. Outlook: Tuning the Interactions



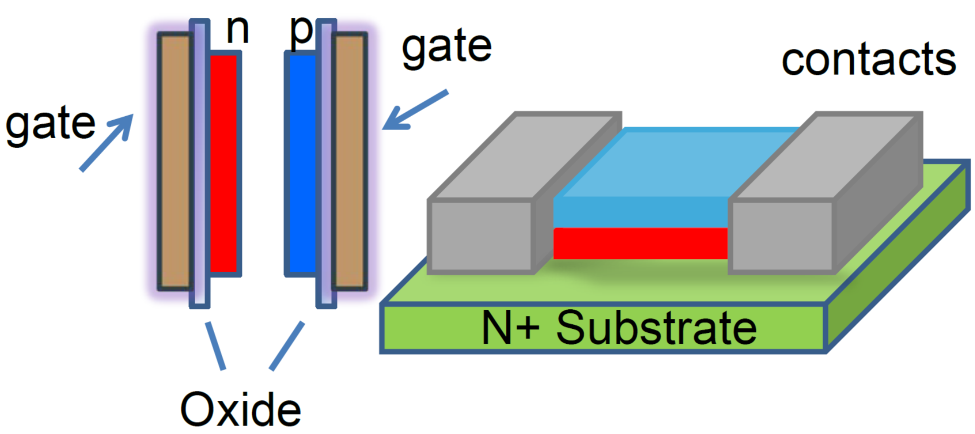
Liu *et al, PRL* **100**, 236601 (2008)

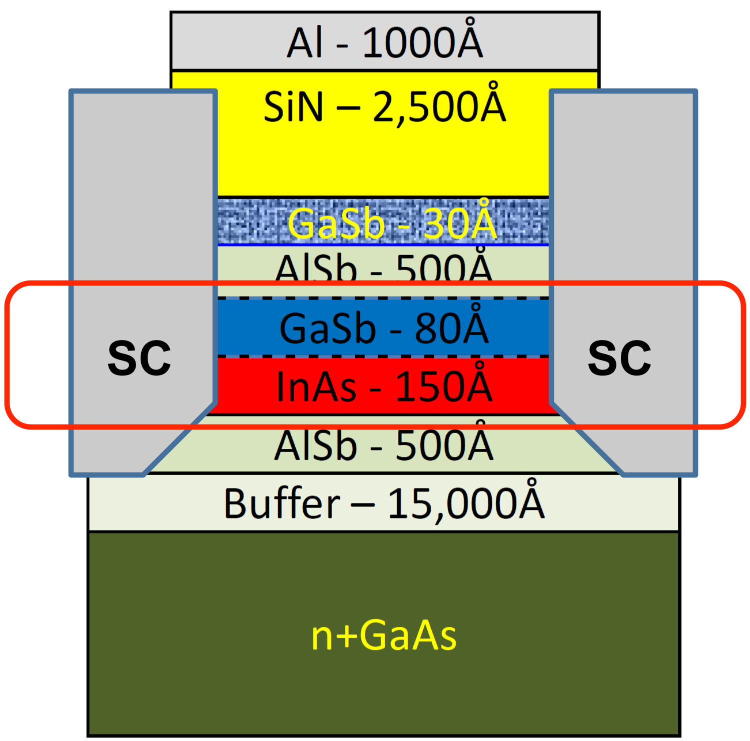
6.1 A Family

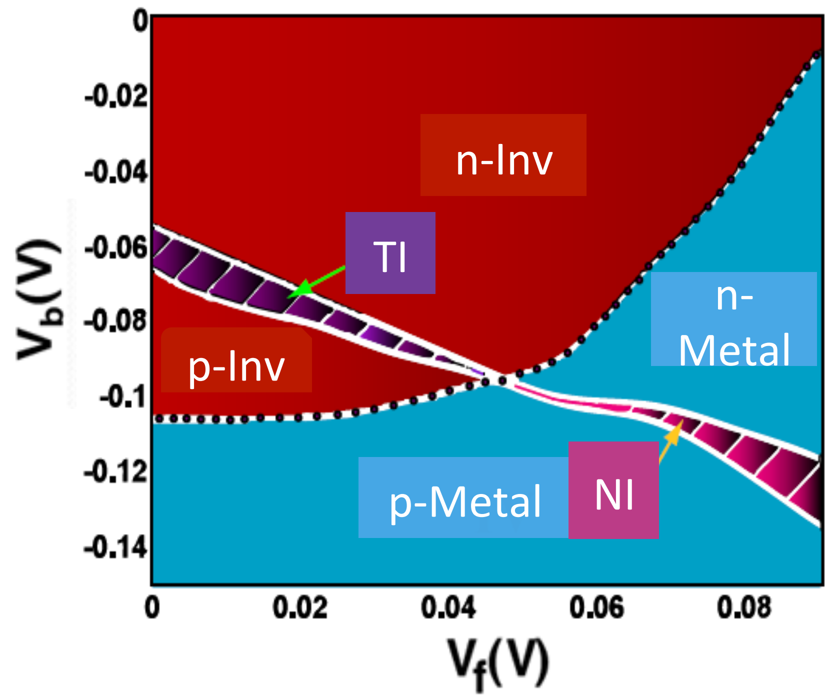
1. **Band parameter**
   ΔE = E1 – H1
   tuned by width, x, gates

2. **ΔE < 0 inverted -0.15 eV to 0**
   Tunneling mix e-h and opens
   a gap at finite *k*-vector

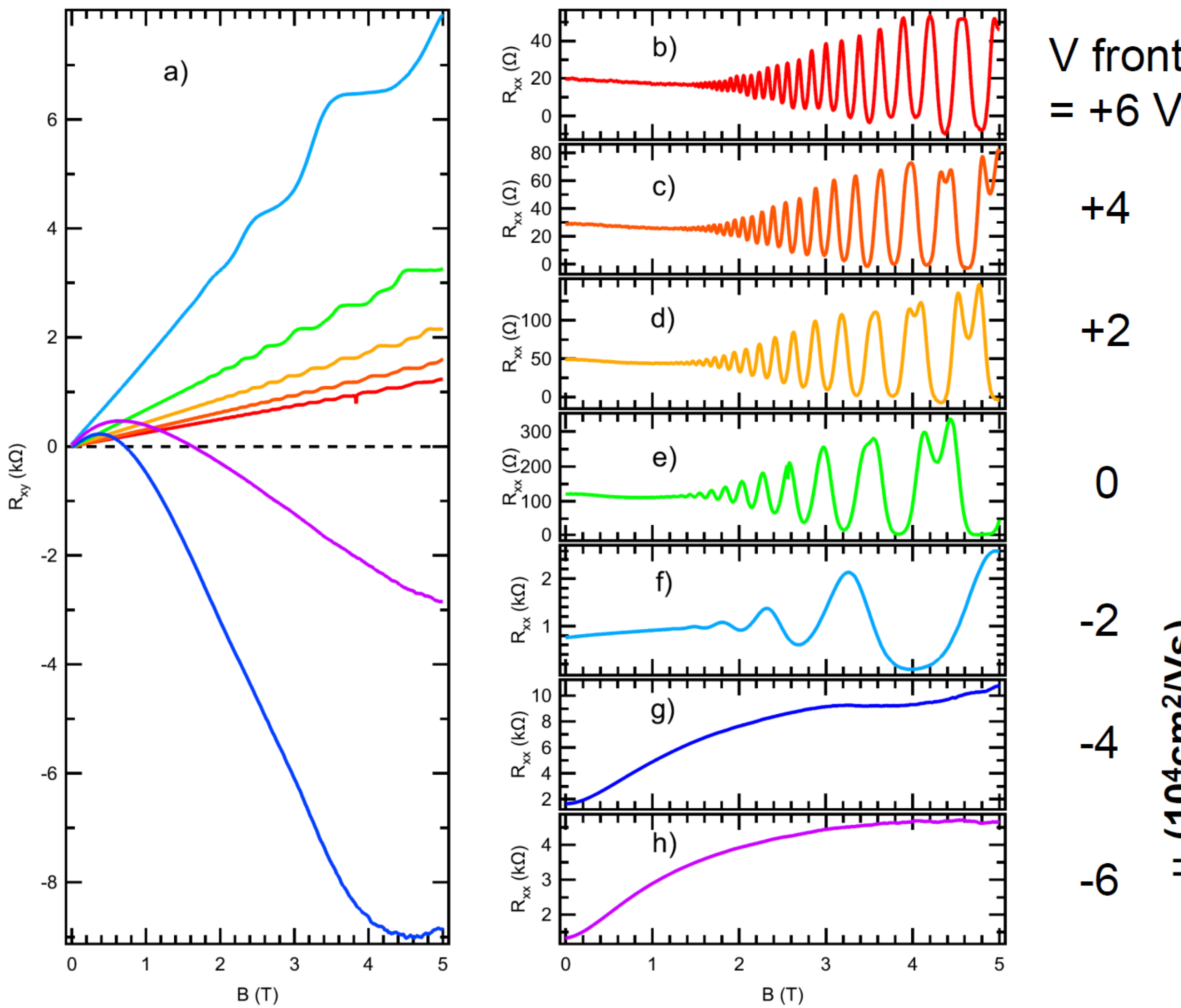
Wafer and Device







General Quality

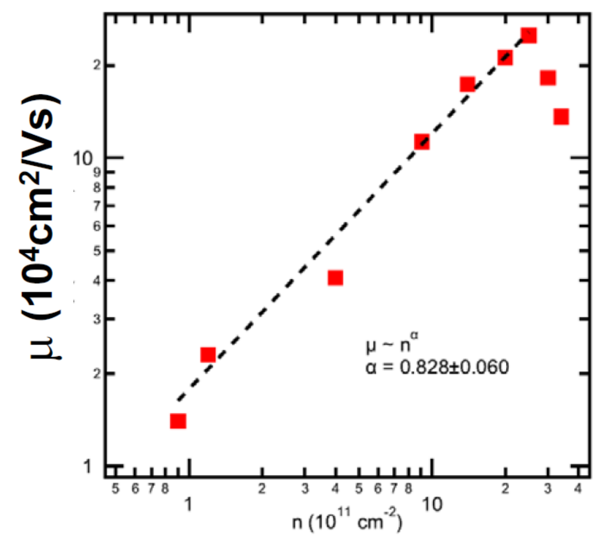


Electron Mobility

~ 2x 10^5 cm^2/Vs

Hole mobility

~ 2 x $10^4 cm^2/Vs$

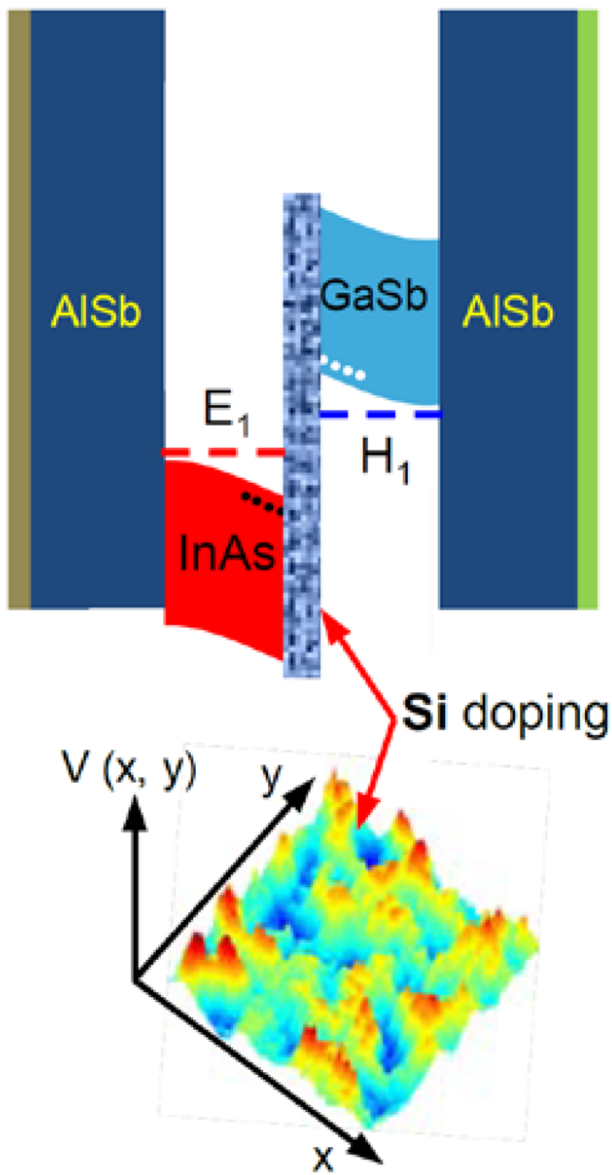


Ivan Knez, Ph. D thesis, Rice University 2011

http://www.ruf.rice.edu/~dulab/index.html

Quantized and Non-quantized Edge Transport

Si-doping at the interface

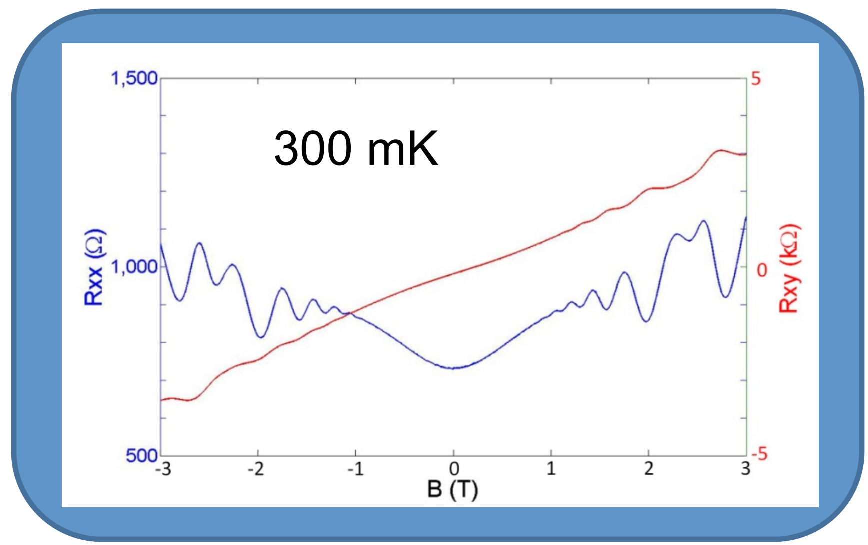


Si: donor in InAs, acceptor in GaSb

*Localize residual *e* and *h*

*Less effective for hybridized *e-h*

* Dipole field opposite to carrier field

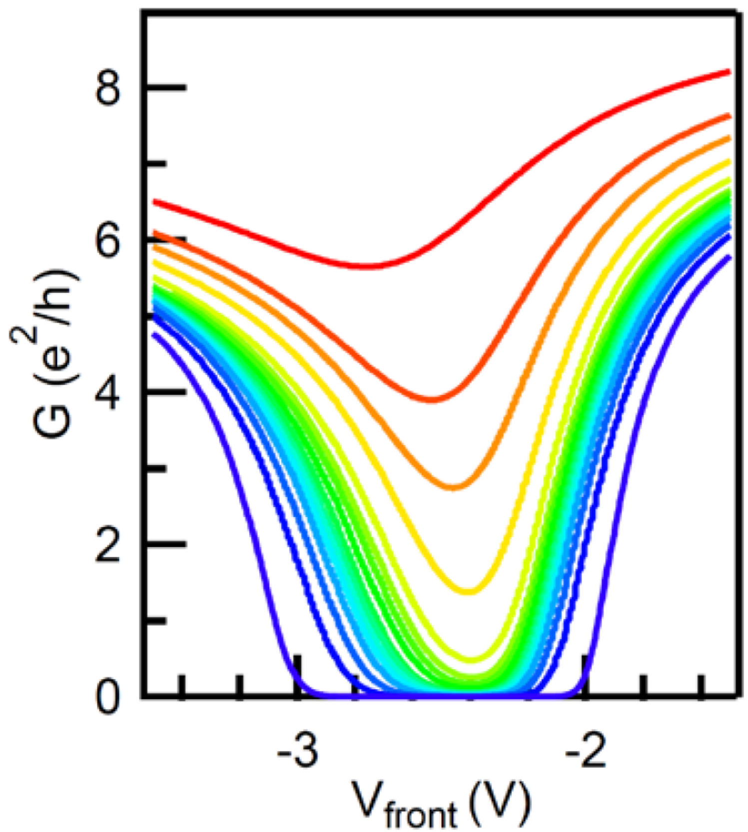


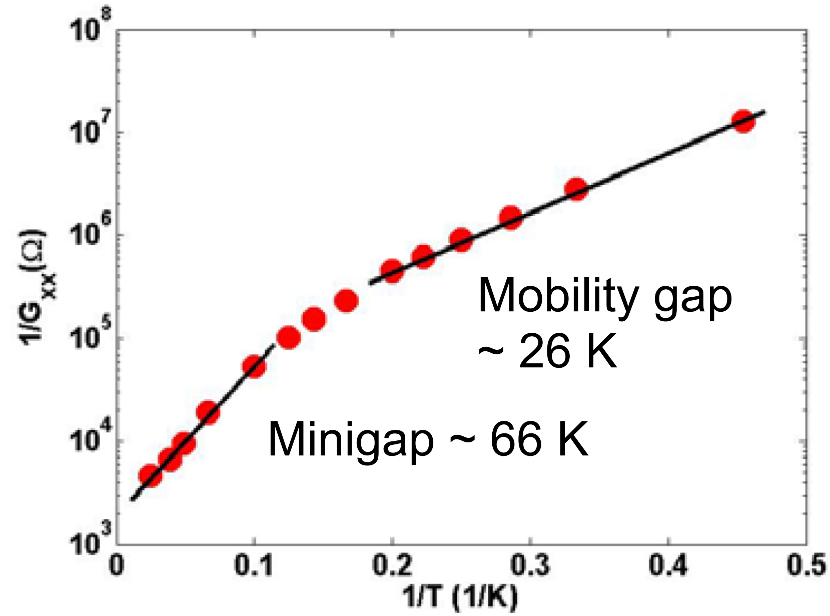
40,000 cm^2/Vs

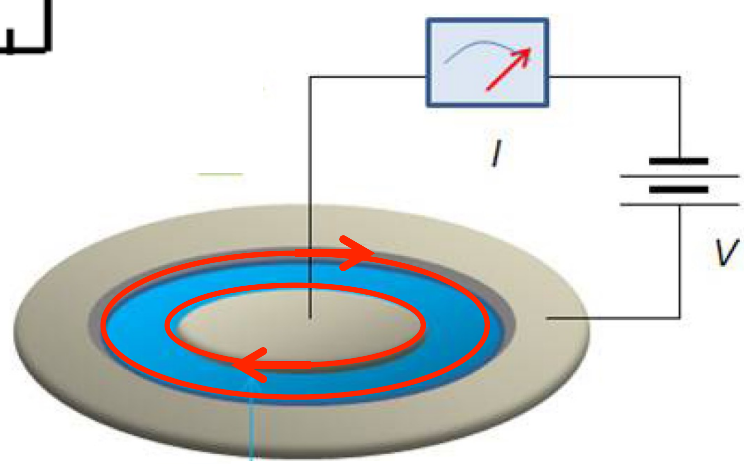
Truly Insulating Bulk

$\rho_{Bulk} > 100\ M\Omega/Sqr$

4 order of mag.



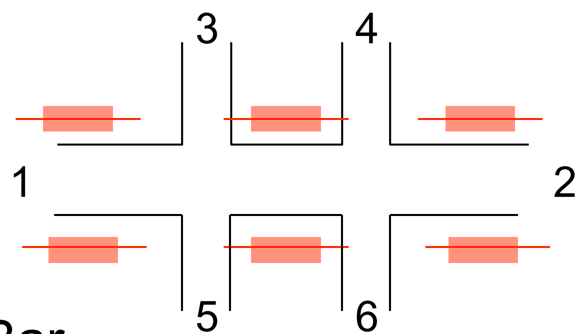




Corbino Disk

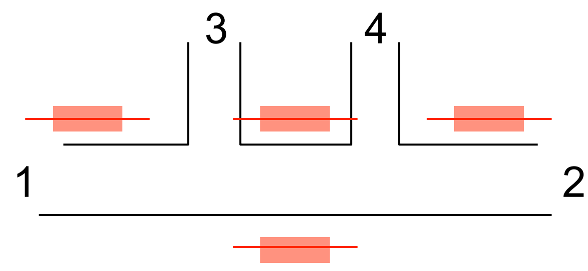
Conductance of Helical Edge Modes: Nonlocal - Transport

- For phase coherent sample Landauer-Buttiker formula gives conductance value



Hall Bar

$$G_{12,34} = \frac{2e^2}{h}$$

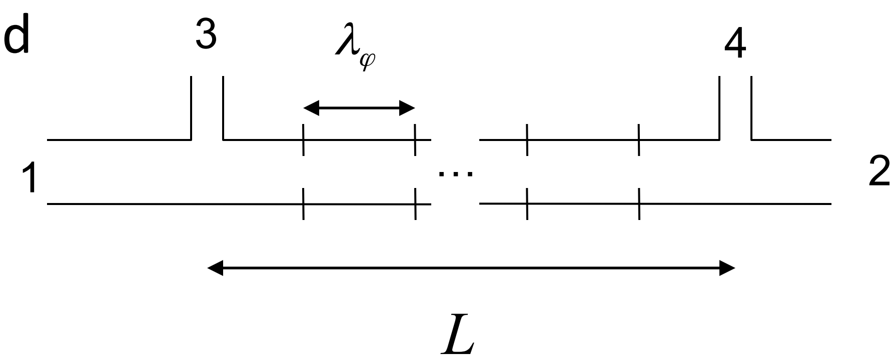


π Bar

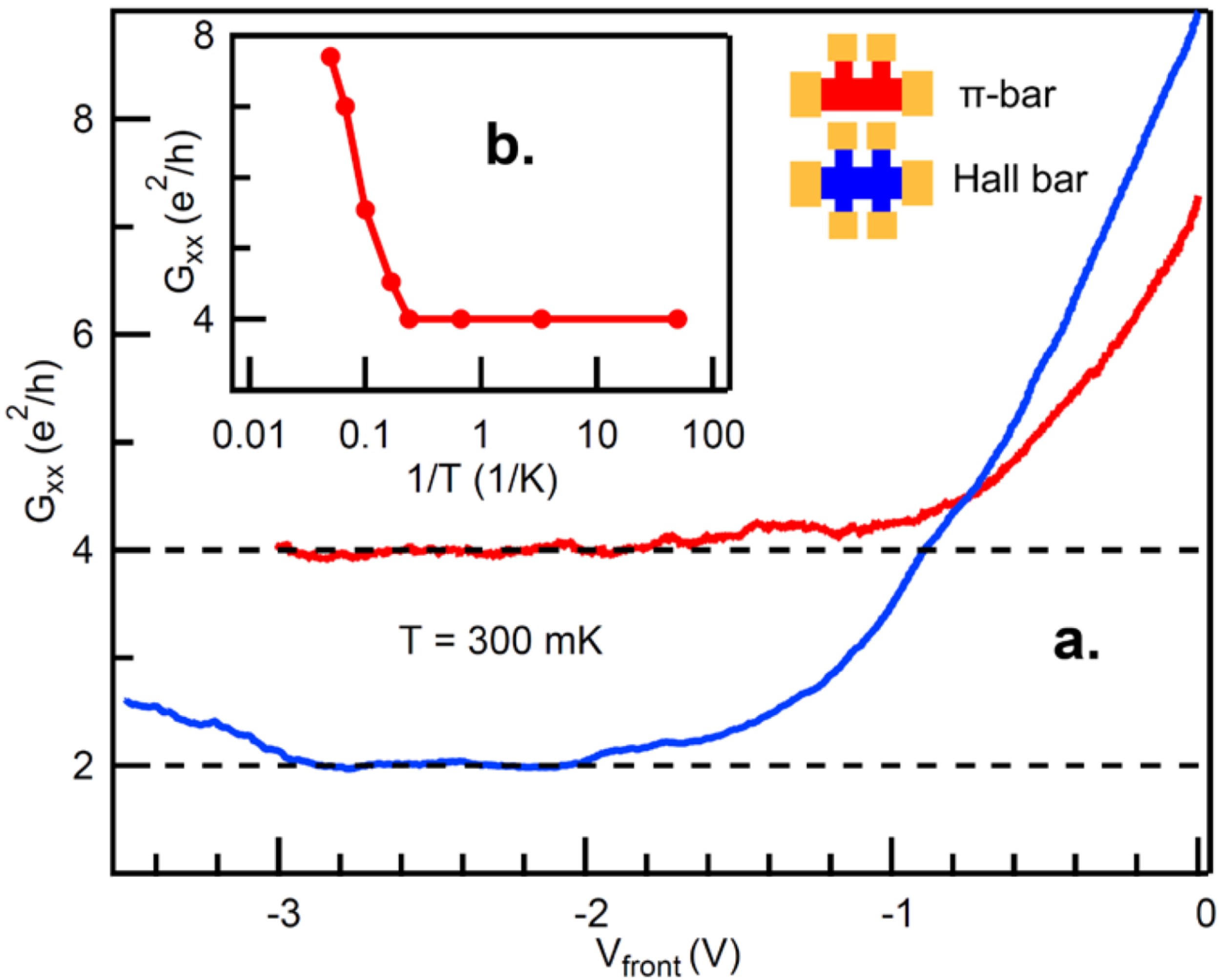
$$G_{12,34} = \frac{4e^2}{h}$$

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

$$G_{12,34} = \frac{2e^2}{h}\left(\frac{\lambda_\varphi}{L} + \left(\frac{\lambda_\varphi}{L}\right)^2\right)$$

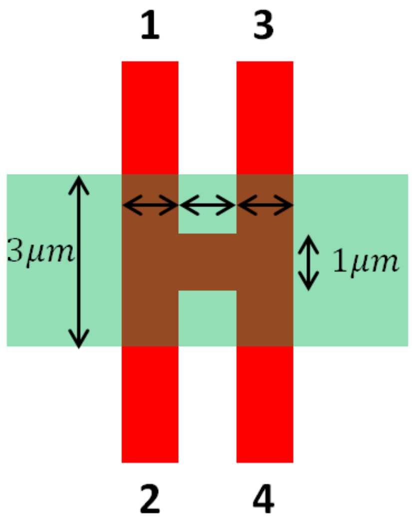


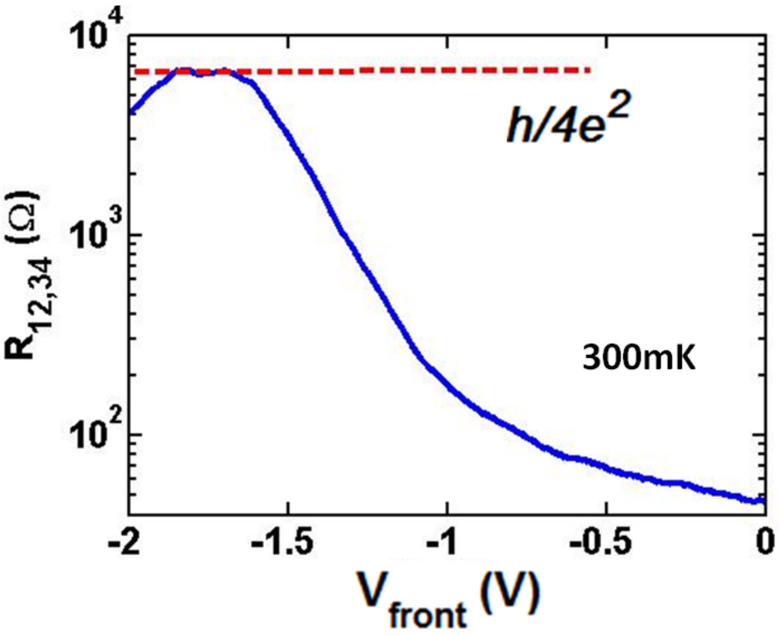
Conductance Plateau up to 4 K



Lingjie Du

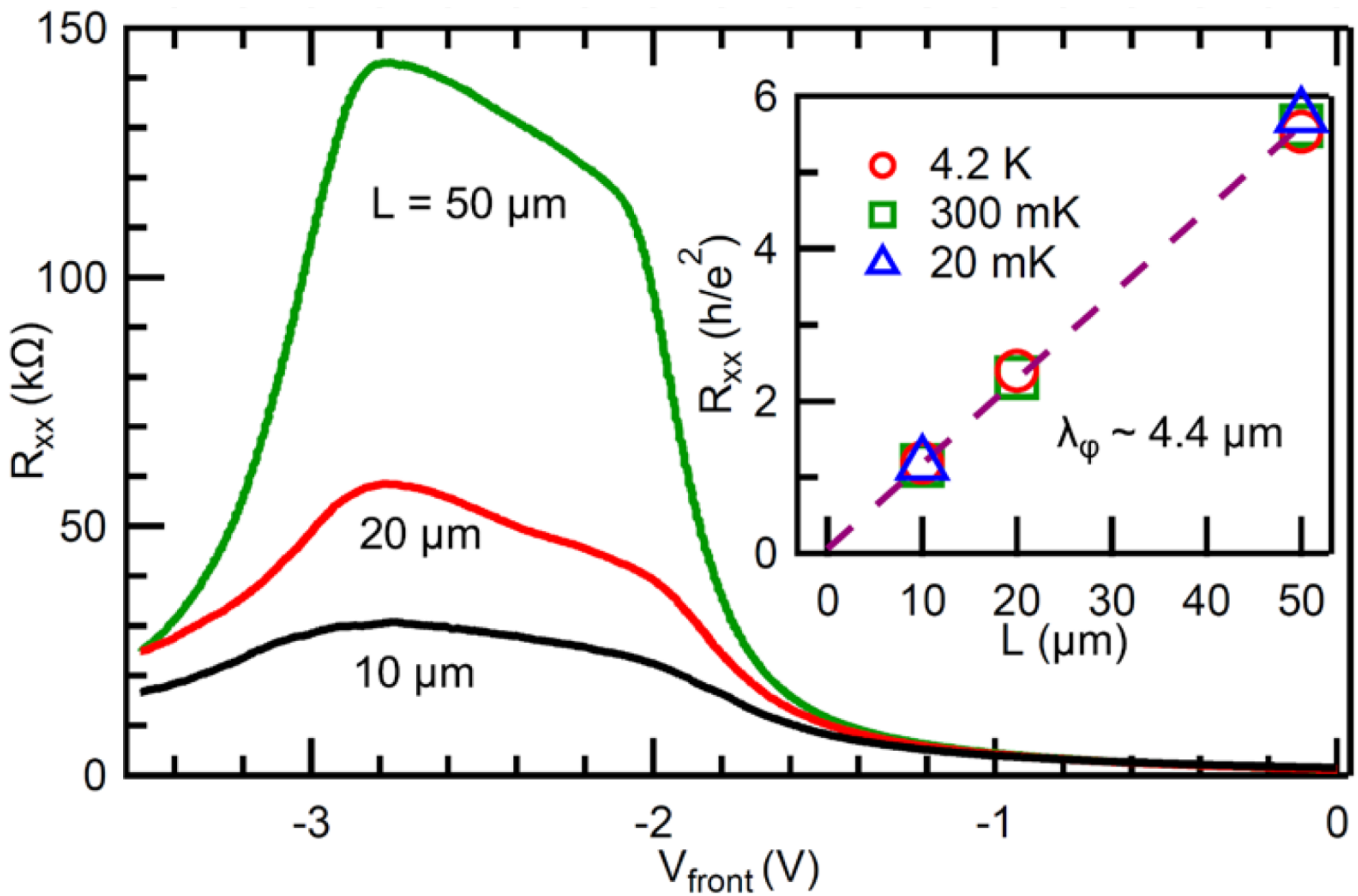
Non-Local Edge Transport: H-Bar





Lingjie Du

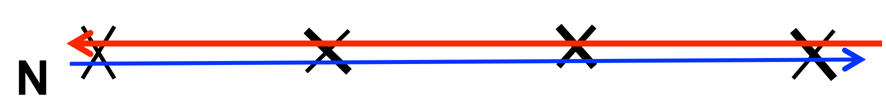
Longer Samples



$$G = \frac{2e^2}{h}\left(\frac{\lambda_\varphi}{L} + \left(\frac{\lambda_\varphi}{L}\right)^2\right)$$

"Mean-Free-Path" λ_ϕ ~ 4 μm

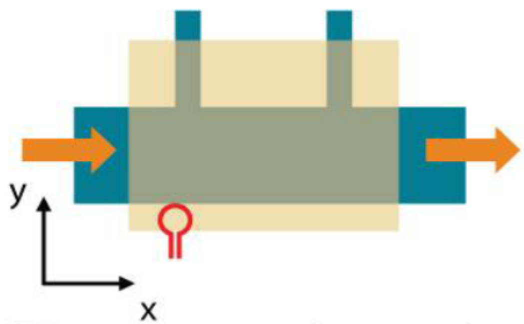
Indep. with T 20 mK 4K

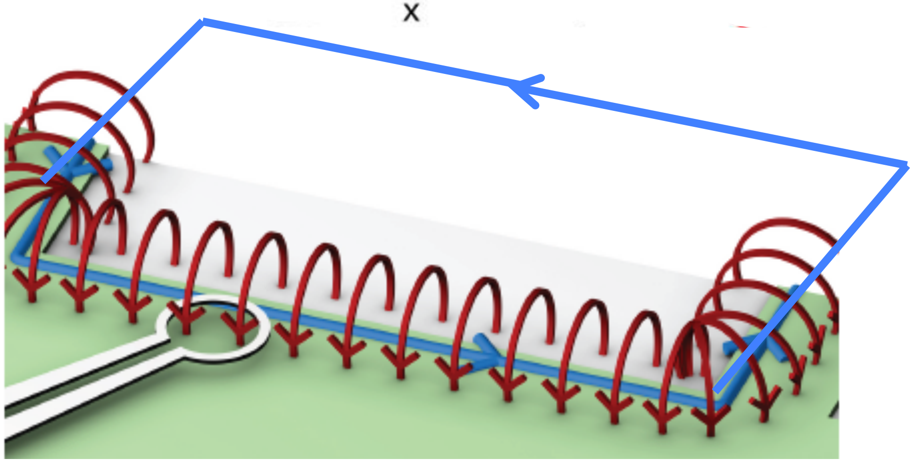


SQUID Imaging of InAs/GaSb Edge Modes

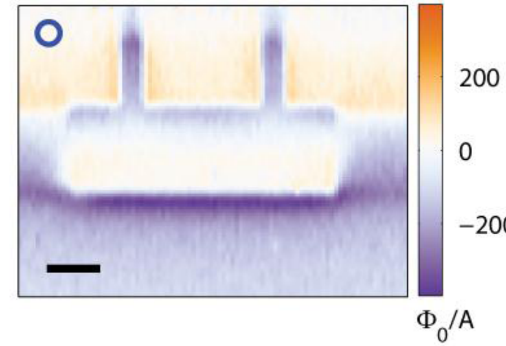
Stanford: Spanton, Moler
Rice: Lingjie Du, RRD
PRL 14

50 μm

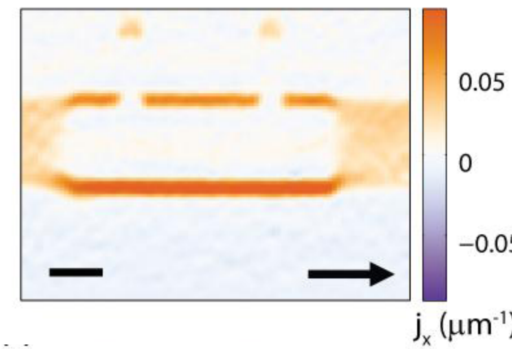




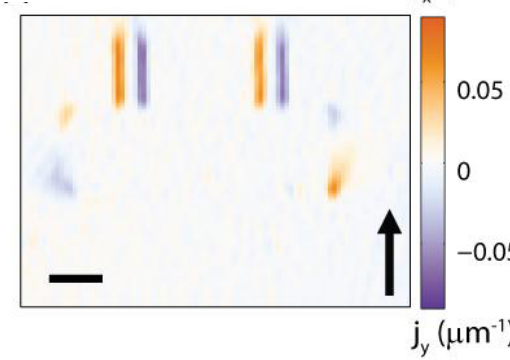
Flux



Current
(Horizontal)

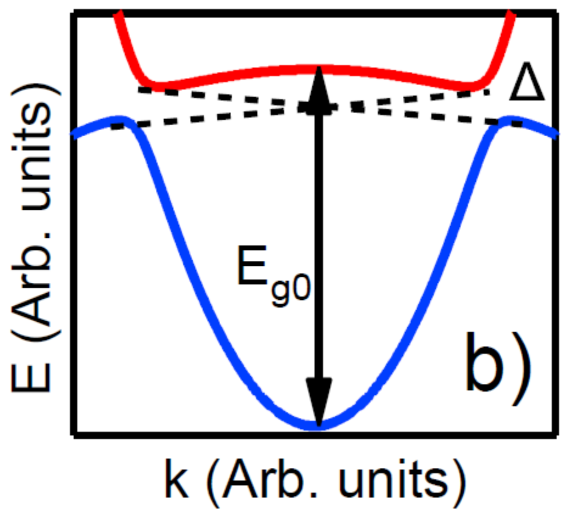


Current
(Vertical)



Properties of InAs/GaSb Edge States

- Quantized plateau for short samples (a few μm)
- Non-quantized conductance for long samples
- Conductance nearly T-independent over large range of T
- Robust under high B



- Low velocity of edge modes

$\upsilon_F \sim 2 \times 10^4 \ m/s$

$k_F \sim 1 \times 10^6/cm$

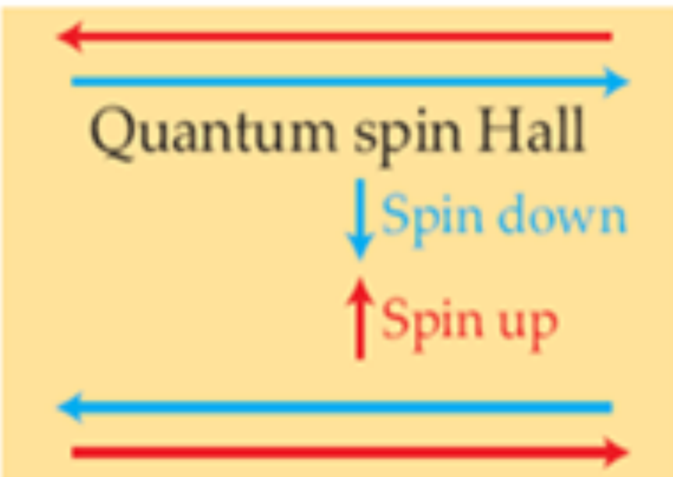
- Extreme. long scattering time

$\tau = \lambda/\upsilon_F = 4\mu m/(2\times10^4 m/s) \sim 200 \ ps$

- Origins of back-scattering?

- Tunable mode dispersion

Interaction Effects in InAs/GaSb Helical Edge States



Non-Interacting Model:

1. TRS protected topological Insulator
2. Spin-momentum locking
3. non-magnet. impurity does not cause backscattering

Non-linear Edge Channel Conduct.

C. L. Kane and M. P. A. Fisher, Transport in a one-dimensional Luttinger liquid, *Phys. Rev. Lett.*. **24**, 1220 (1992); Phys. Rev. B**46**, 15233 (1992)

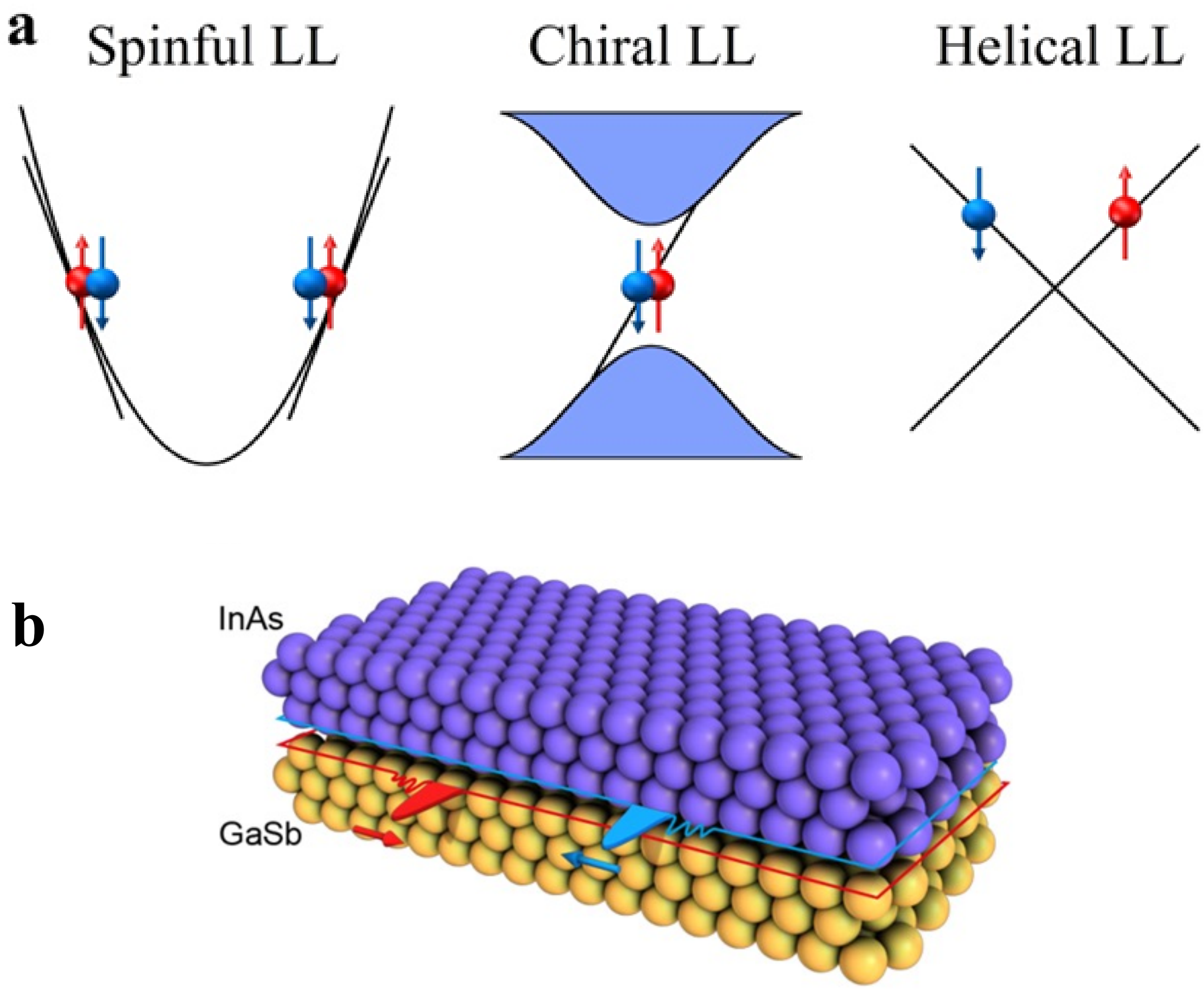
M. P. A. Fisher and L. Glazman, Transport in a one-dimensional Luttinger Liquid.

Wu, C., Bernevig B. A. & Zhang S. C. Helical liquid and the edge of quantum spin Hall systems. *Phys. Rev. Lett.* **96**, 106401 (2006).

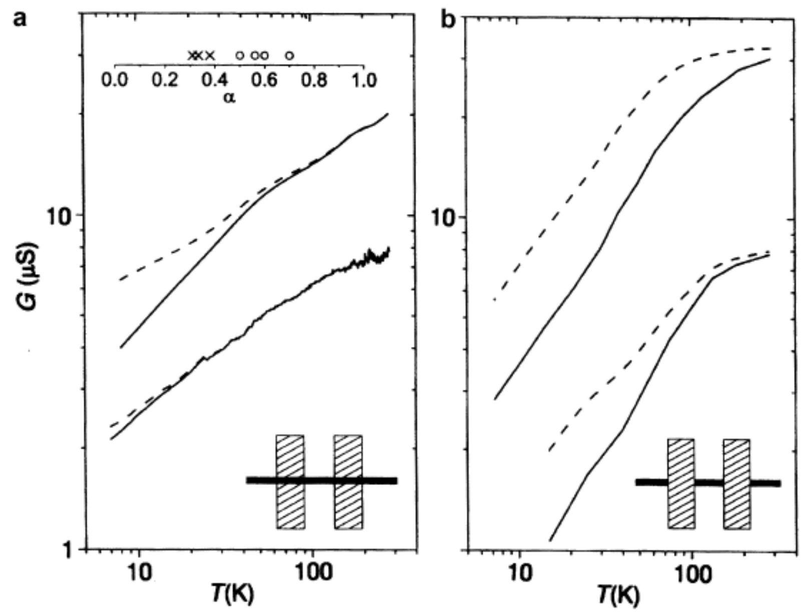
Teo, J. C. Y. & Kane, C. L. Critical behavior of a point contact in a quantum spin Hall insulator. *Phys. Rev. B* **79**, 235321 (2009).

Maciejko, J. *et al*. Kondo effect in the helical edge liquid of the quantum spin Hall state. *Phys. Rev. Lett.* **102**, 256803 (2009).

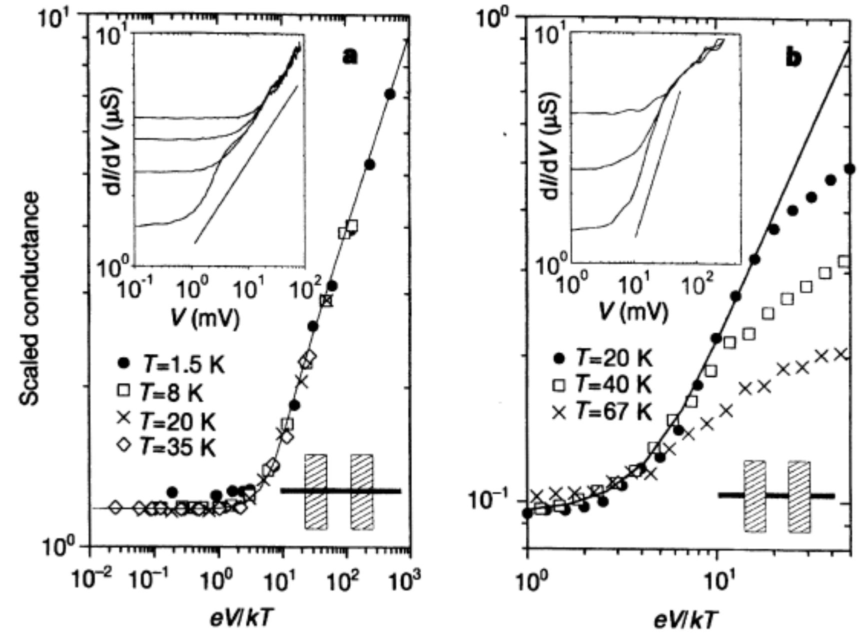
Family of Luttinger Liquids



Carbon Nanotube (Spin-Full LL)



"Bulk Contacted" "End Contacted"

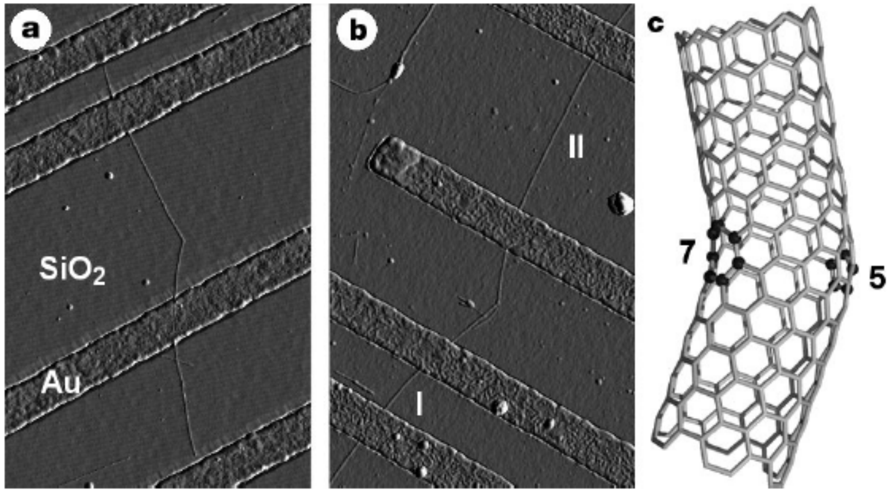


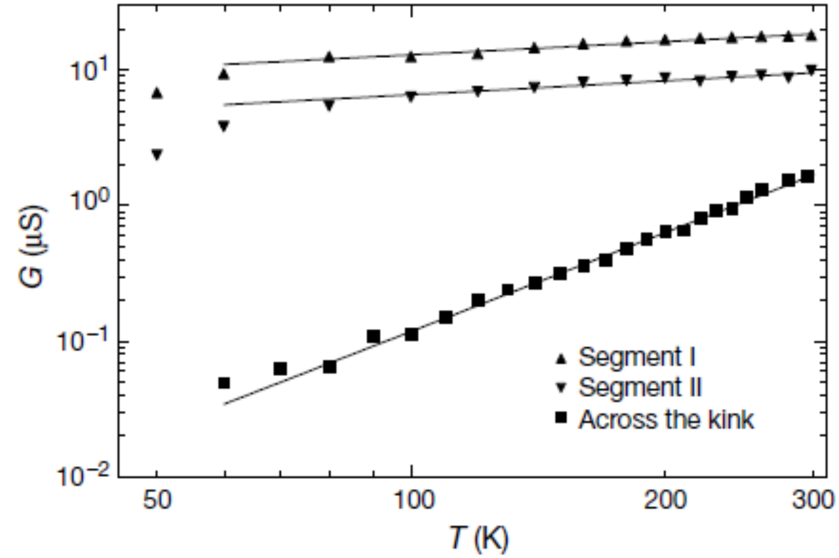
"Bulk Contacted" "End Contacted"

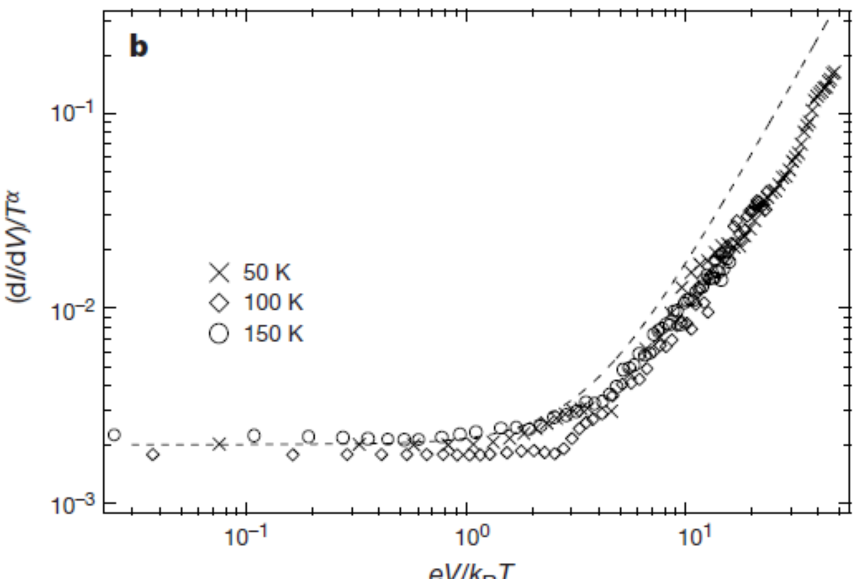
- Metal contacts connect to rope of carbon nanotubes, serve as tunneling probes.
- $G \propto T^{\alpha}$, $dI/dV \propto V^{\alpha}$; $\alpha_{bulk} \sim 0.3$, $\alpha_{end} \sim 0.6$

M. Bockrath *et al.*, *Nature* **397** 598 (1999).

Carbon Nanotube (Spin -Full LL)



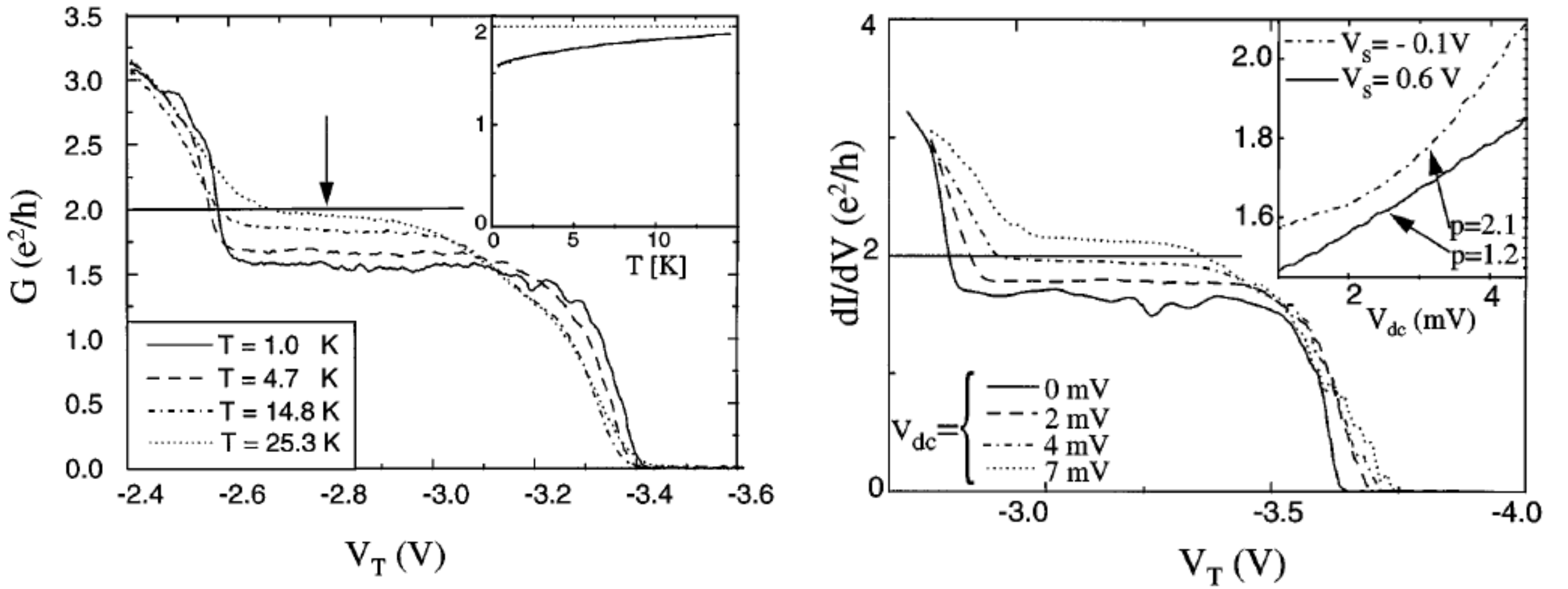




- Transport through Single-wall carbon nanotubes (SWNTs) with a kink.
- $G \propto T^\alpha$, $dI/dV \propto V^\alpha$

Z. Yao *et al.*, *Nature* **402** 273 (1999).

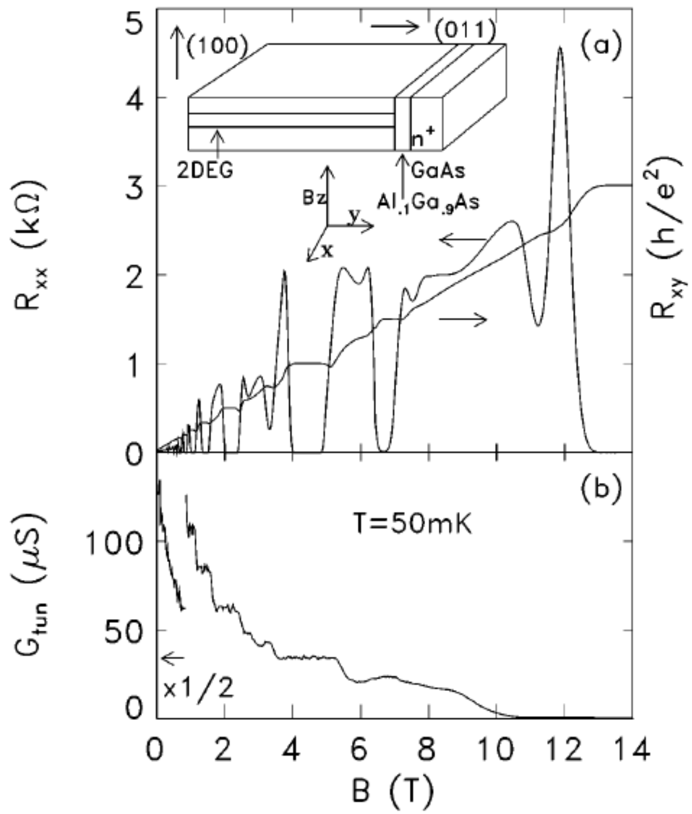
Quantum wires (Spin-Full LL)



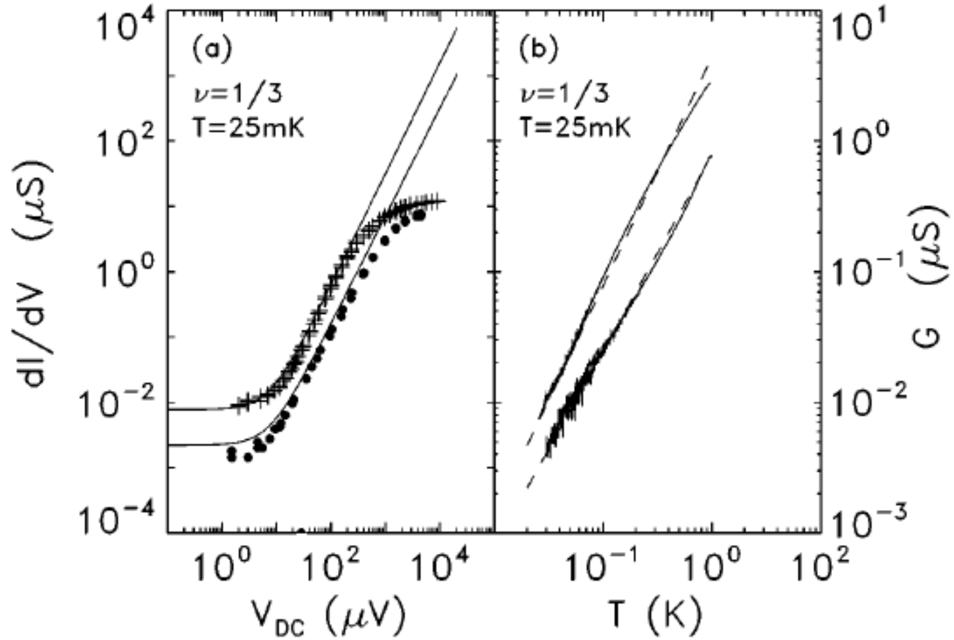
- High-quality quantum wires fabricated in GaAs-AlGaAs by using cleaved edge overgrowth.
- The conductance plateaus deviate from the universal quantized value at low temperature and low bias.
- $\mathrm{d}I/\mathrm{d}V = \mathrm{c} + \mathrm{A}V^{\mathrm{p}}$

A. Yacoby *et al*., *PRL* **77** 4612 (1996).

Fractional Quantum Hall Edge (Chiral LL)



Cleaved-edge overgrowth



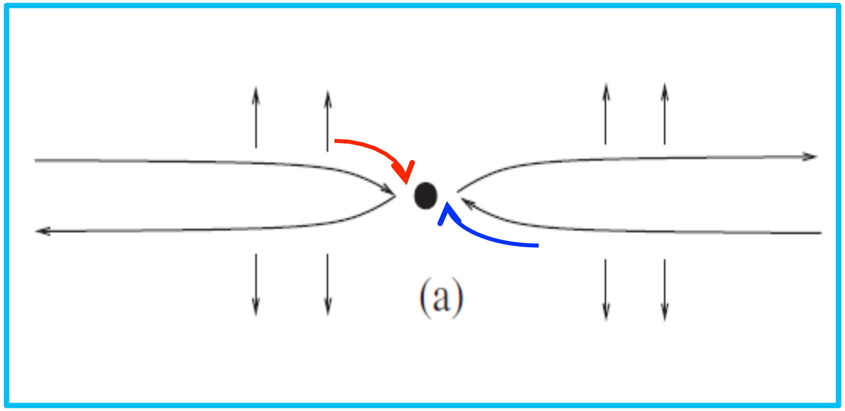
- $\nu = 1/3$ FQH edge
- $dI/dV \propto V^{1.7}$, $G \propto T^{1.75}$

A. M. Chang *et al*., *PRL* **77** 2539 (1996).

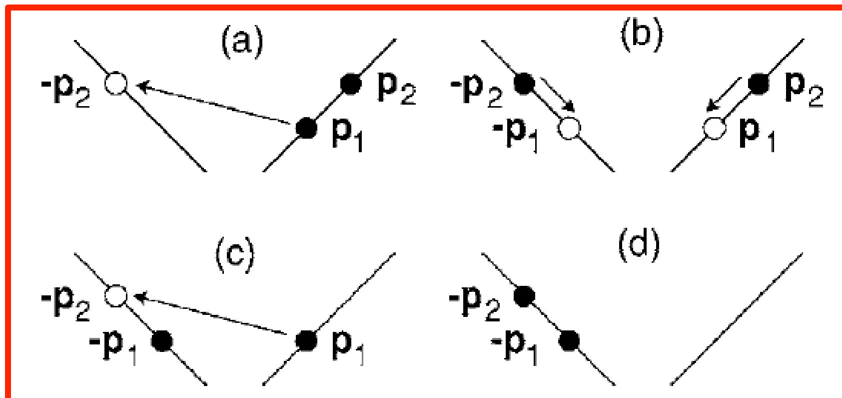
Interacting Model: 1 > K > 1/2; 1/2 > K > 1/4;

Correlated 2-Particle Scattering is Allowed by TRS

C. Wu, B. A. Bernevig, and S. C. Zhang, Phys. Rev. Lett. **96**, 106401 (2006).
C. Xu and J. E. Moore, Phys. Rev. B **73**, 045322 (2006).



PHYSICAL REVIEW B **73**, 045322 (2006)



2 particle correlated Backscattering for k < 1/4

---Breaking into two segments

FIG. 1. An allowed two-particle backscattering process: (a) particle at momentum p_1 scatters to intermediate state $-p_2$; (b) particles at $\pm p_2$ interact and become intermediate states $\pm p_1$; (c) and (d), particle at intermediate state p_1 backscatters to state $-p_2$.

Calculating Luttinger Parameter *K*

PRB **79** 235321 (2009), and *PRL* **102** 256803 (2009):

$$K = \left[1 + \frac{2}{\pi^2} \frac{e^2}{\varepsilon \hbar v_F} \ln\left(\frac{7.1d}{\xi + 0.8w}\right)\right]^{-1/2}$$

Where ε is the bulk dielectric constant,

v_F is Fermi velocity of edge state,

d is the distance from the QW layer to a nearby metallic gate as a screening length for the Coulomb potential,

$\xi = 2\hbar v_F / E_{gap}$ (E_{gap} is the gap of bulk QSHI)

w is the thickness of the QW layer.

HgTe/CdTe Quantum Wells

K = 0.8

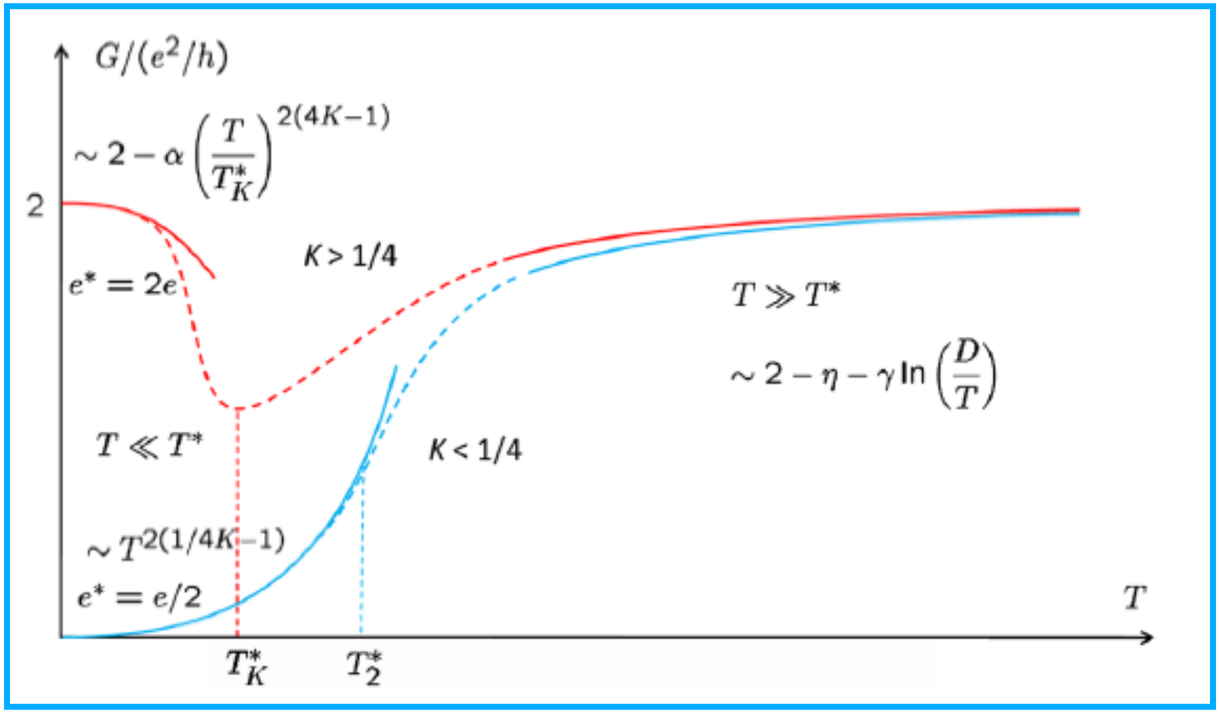
Gated _InAs/GaSb_ Bilayers

K = 0.2 ~ 0.25

Strained _InAs/InGaSb_ QWs

0.5 > K > 0.25

Possible Interacting Effects



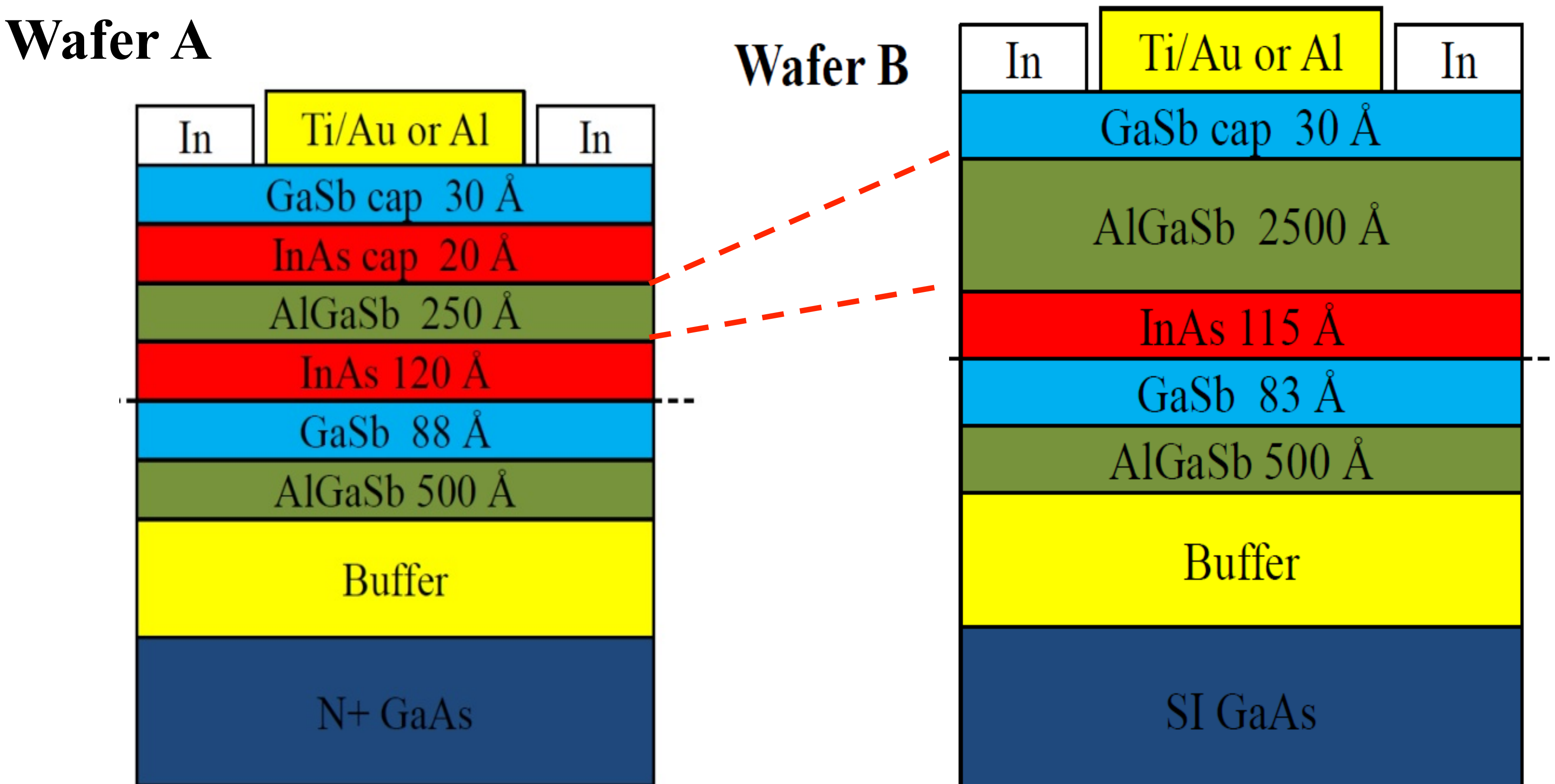
Maciejko et al, PRL 09
Teo and Kane, PRB 09

Helical Liquid with strong Coulomb interactions:

1. *Log T-dependence at high T*
2. Insulating phase at low T

Relevant to InAs/GaSb

2 Samples for Ultralow T Measurements

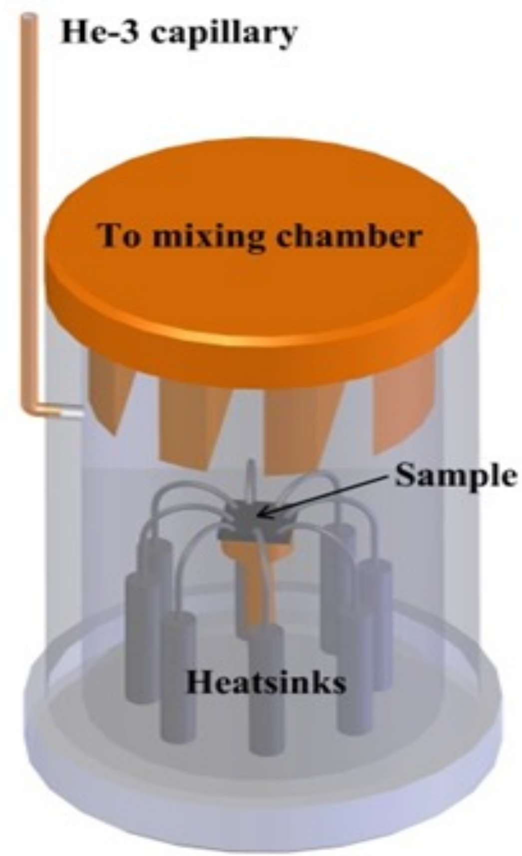


K ~ 0.23

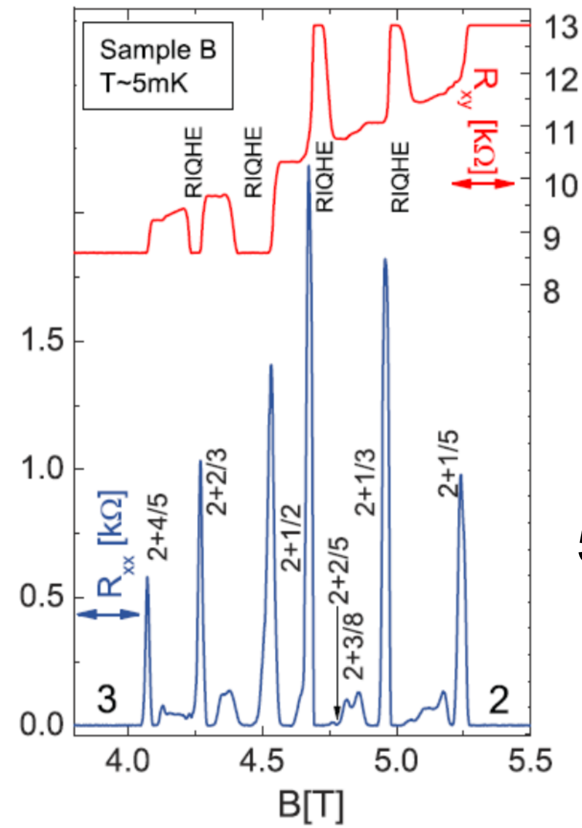
K ~ 0.21

Cooling Electrons

Purdue Group: *Gabor Csathy / Kate Schreiber*
PKU group: *Xi Lin/ Pengjie Wang, Hailong Fu*



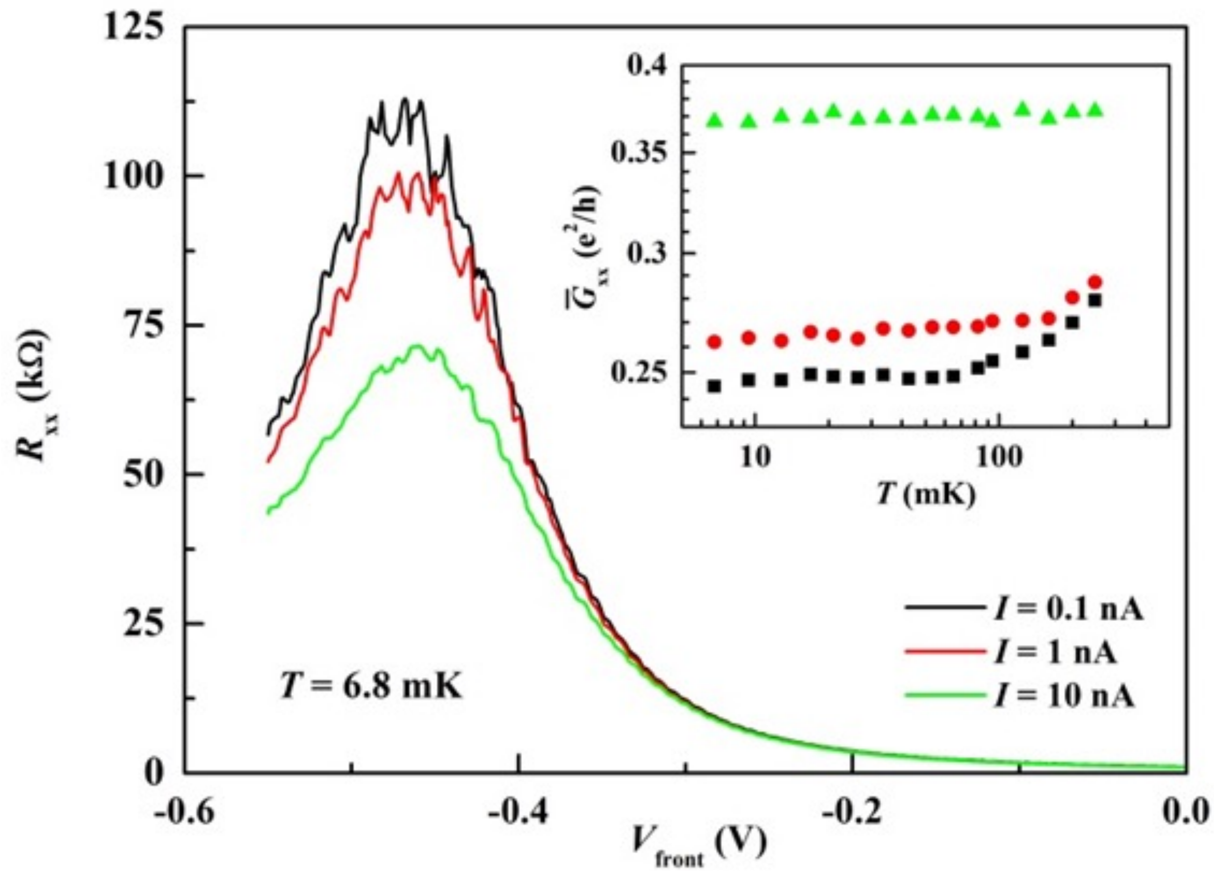
He3 Immersion Cell



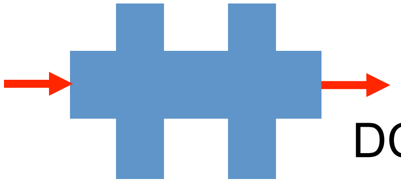
5/2 FQHE

Down to 6.9 mK:

Tingxin Li

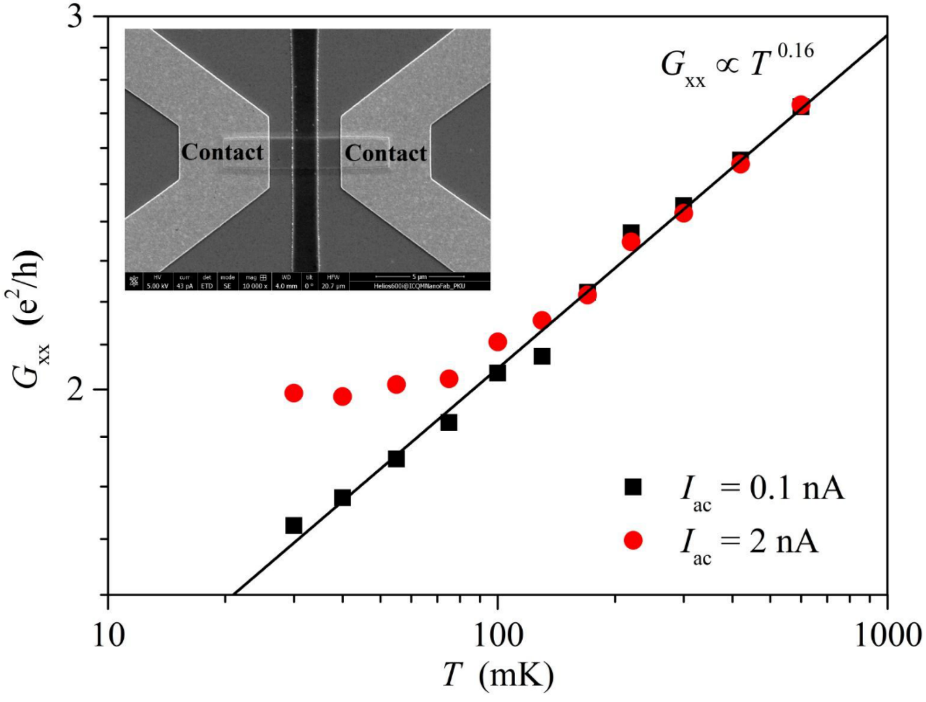


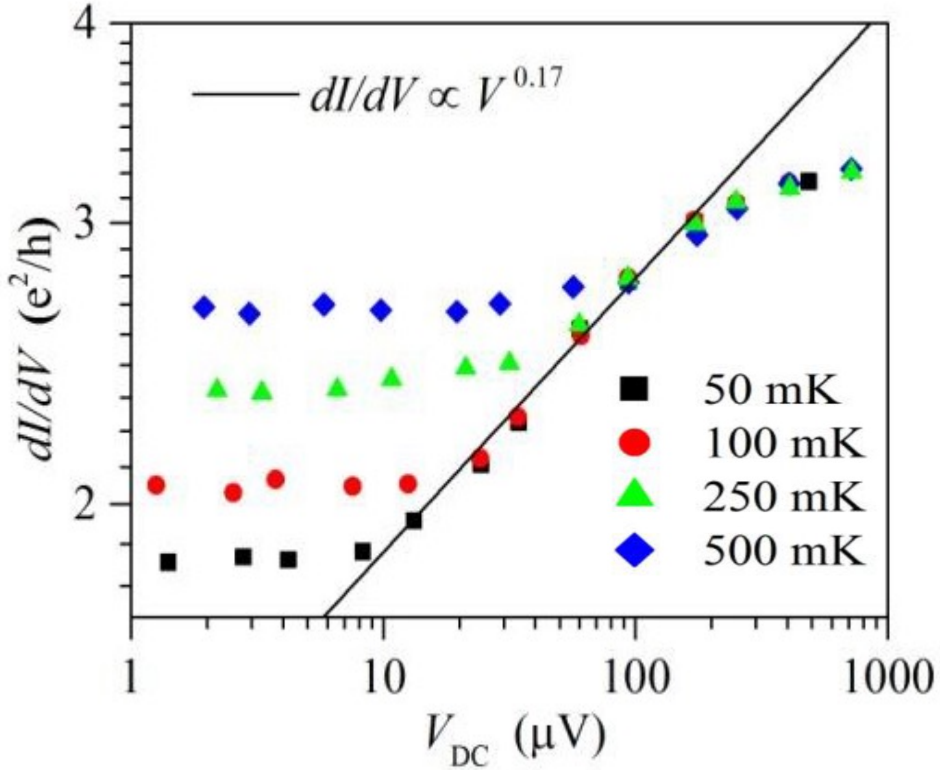
4-terminal Resistance: L= 10um
Strongly nonlinear with bias current



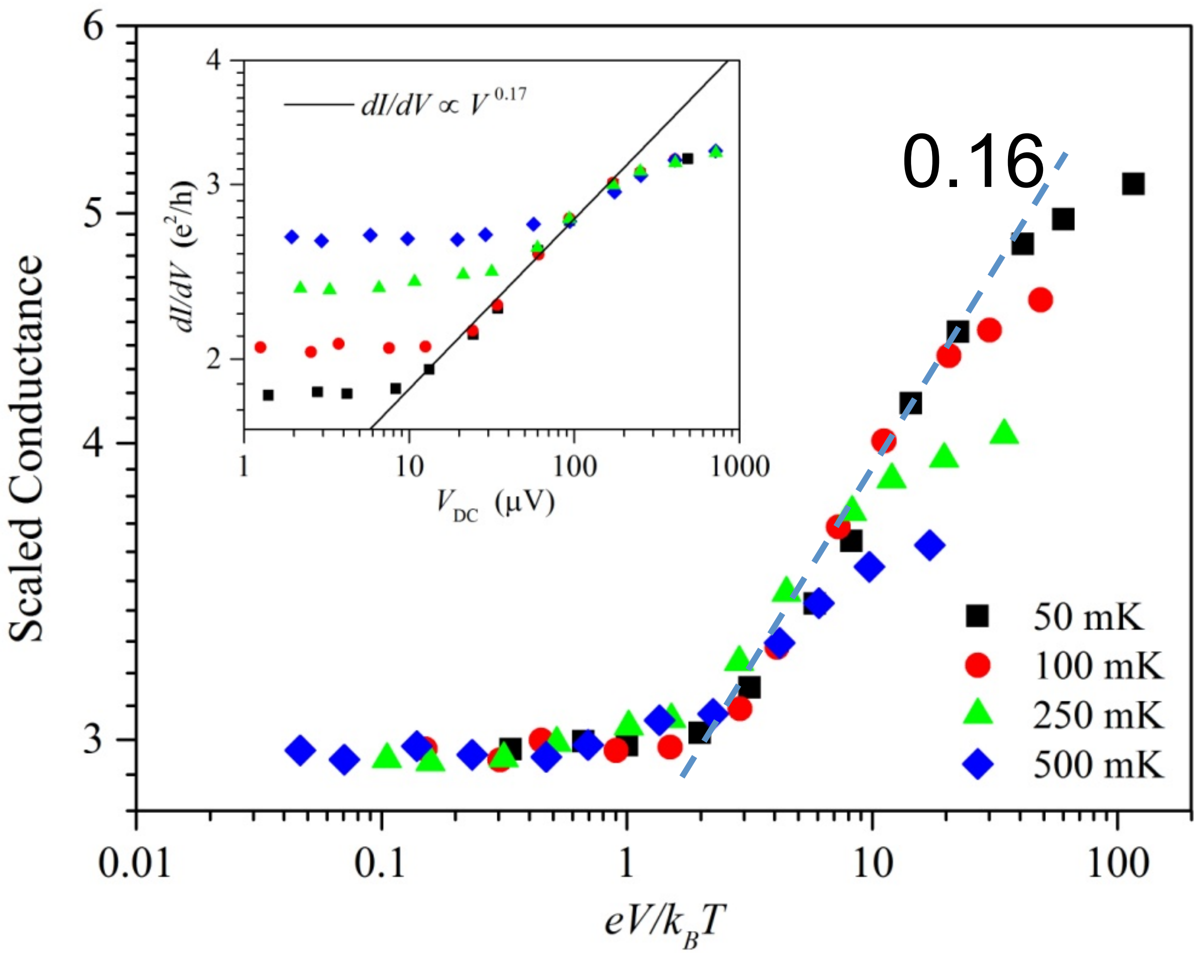
Voltage drops across $eV=R_{xx*}I_{ac}$

Temperature or DC bias -dependent



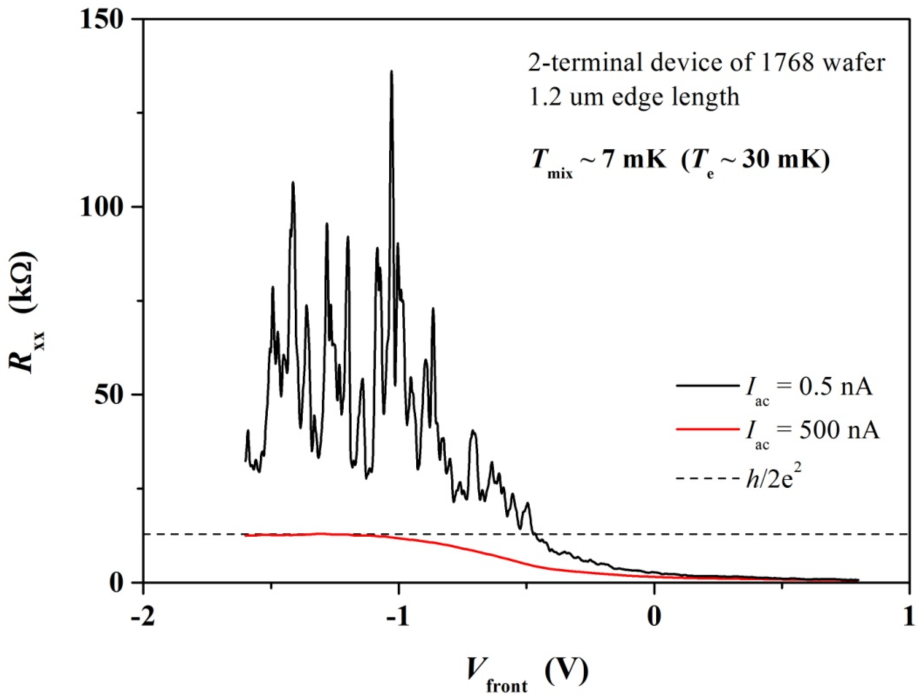


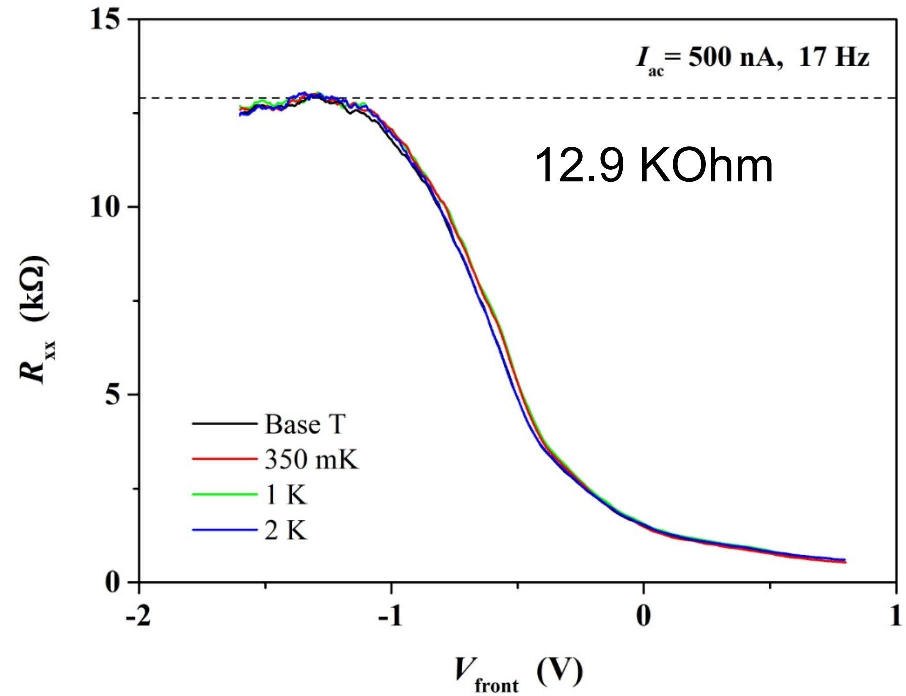
Wafer A Scaling Relation



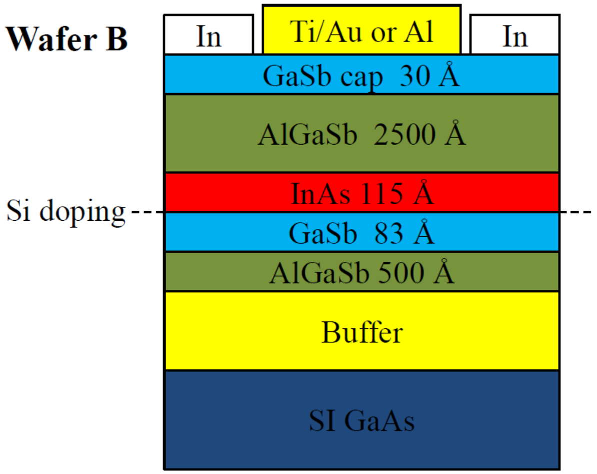
- **Conductance and differential conductance scale as power-laws with temperature and bias voltage, respectively.**

Wafer B, quantized plateaus



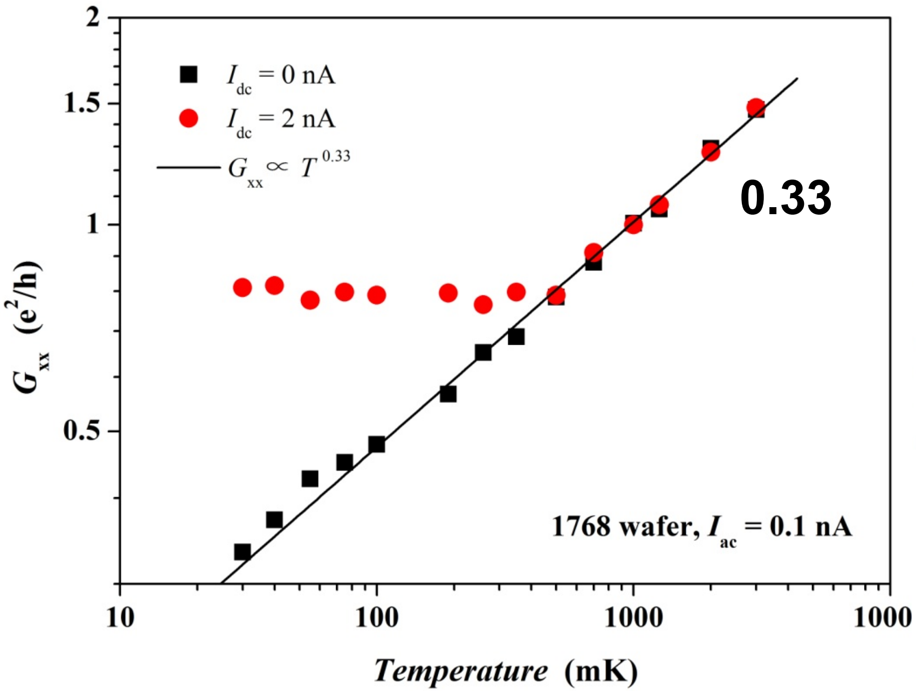


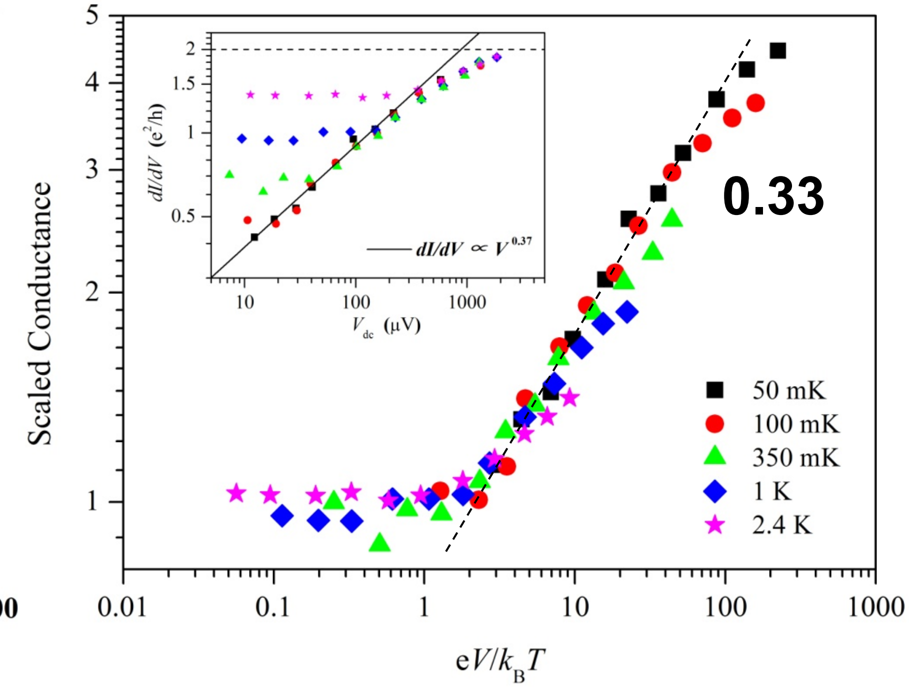
L = 1.2 um, two terminal

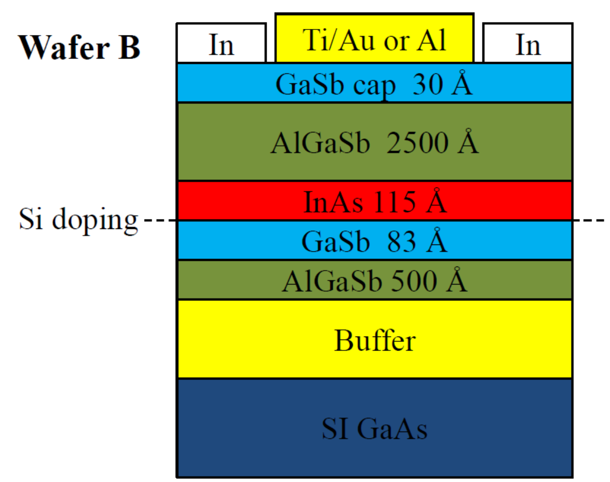


- **There is no change for the quantized plateaus from base temperature to about 3K under large current.**

Wafer B, LL behavior

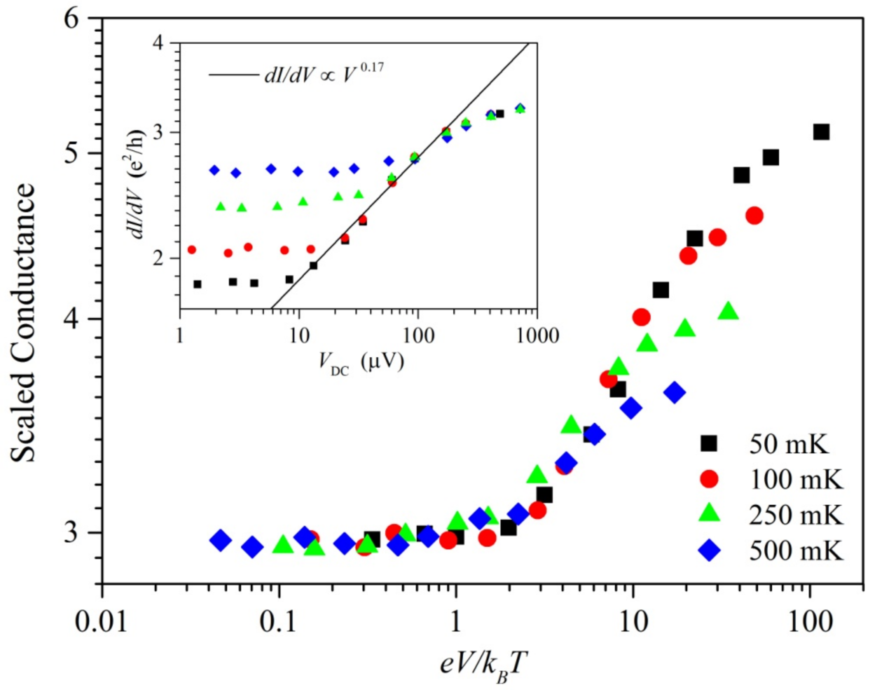


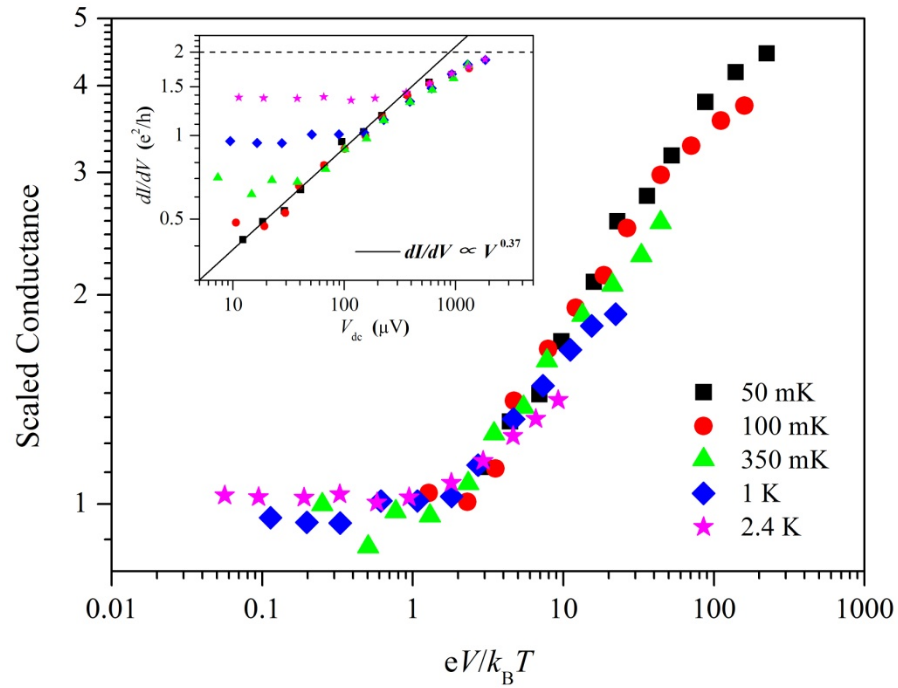




- **Wafer B show stronger power-law behavior than wafer A.**

Comparison of two wafers





Wafer A Power exponent α ~ 0.16,

α = 2(1/4K-1) → K ~ 0.23

Wafer B Power exponent α ~ 0.33,

α = 2(1/4K-1) → K ~ 0.21

- **Both two wafers tend to form a charge insulator at T = 0 and V = 0, consisting with the theoretical predictions for strong interacted helical edge states, i.e. Helical Luttinger-Liquid.**

InAs/GaAs edge transport can be explained based on Luttinger Liquid

Microscopic details to be understood

1) **Short edges** with Fermi liquid leads: Quantized conductivity $2e^2/h$

2) **Long edges** with Fermi liquid leads: reduced cond. from $2e^2/h$

3) **$eV >> k_BT$** Large bias regime: no T- dependence

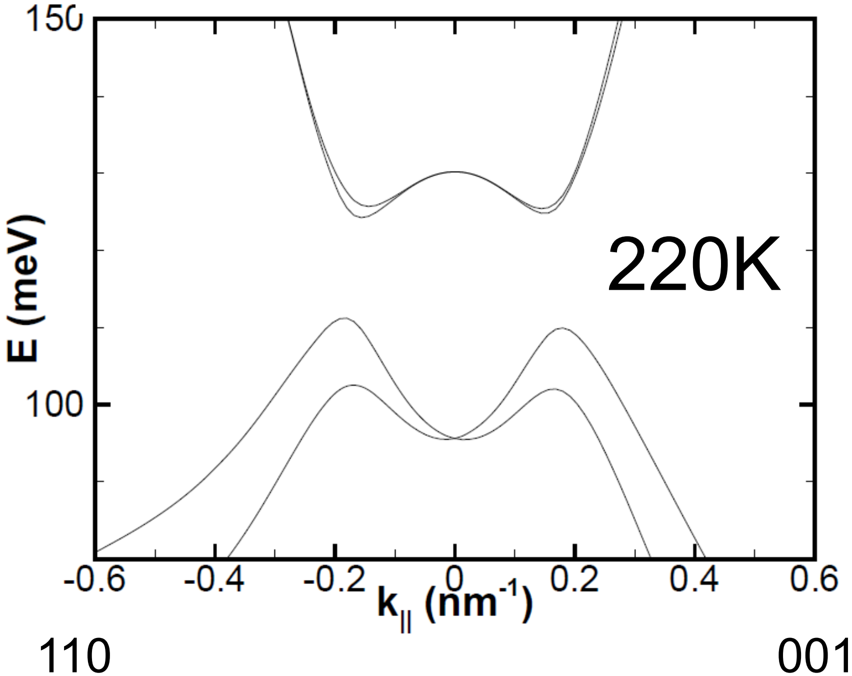
$eV << k_BT$ Small bias regime: no eV –dependence

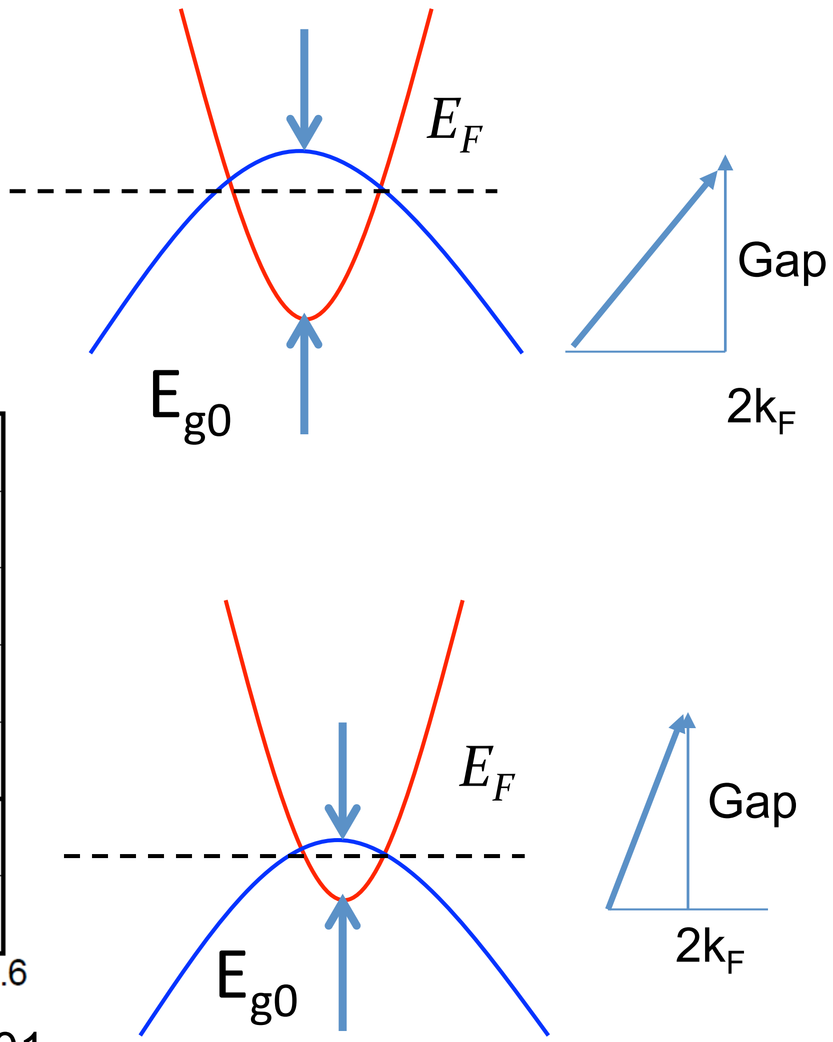
$eV \sim k_BT$ Conductance scaling in eV/K_BT

Outlook:
Tuning the Interactions

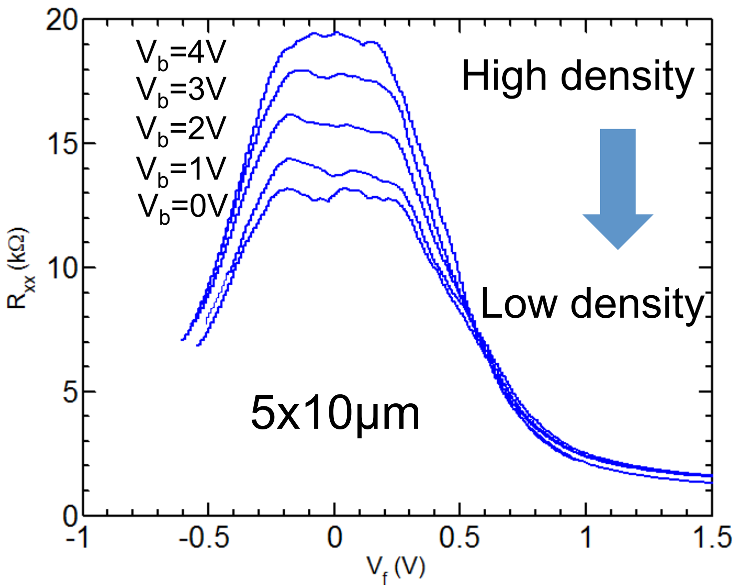
Strain Layer Engineer. + Gating

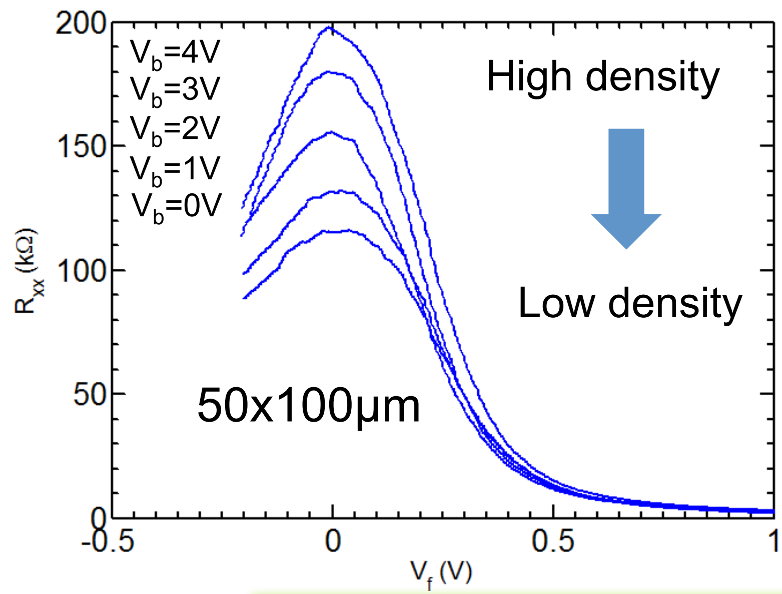
InAs/InGaSb

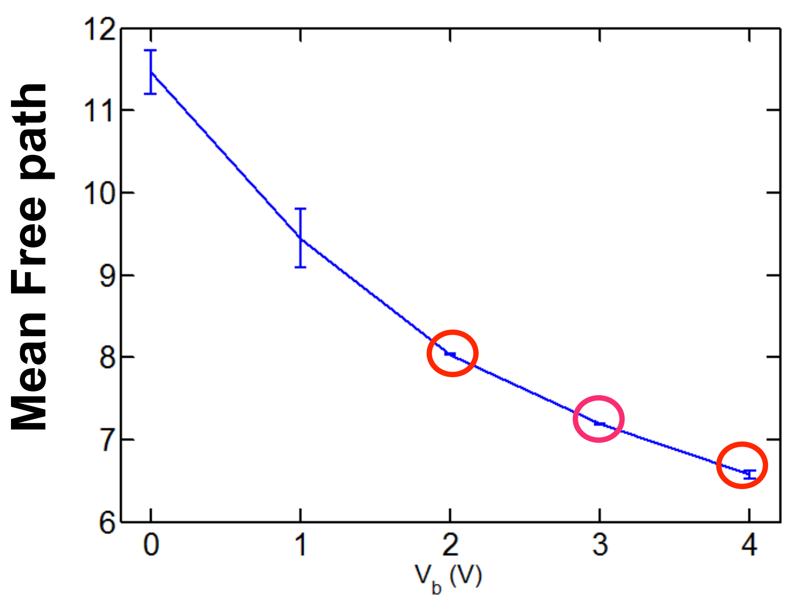


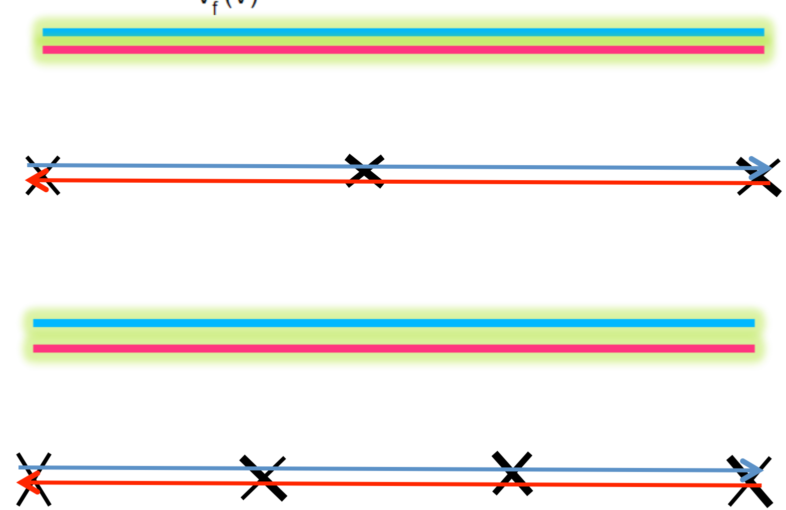


"Mean Free Path" Increases with V_F







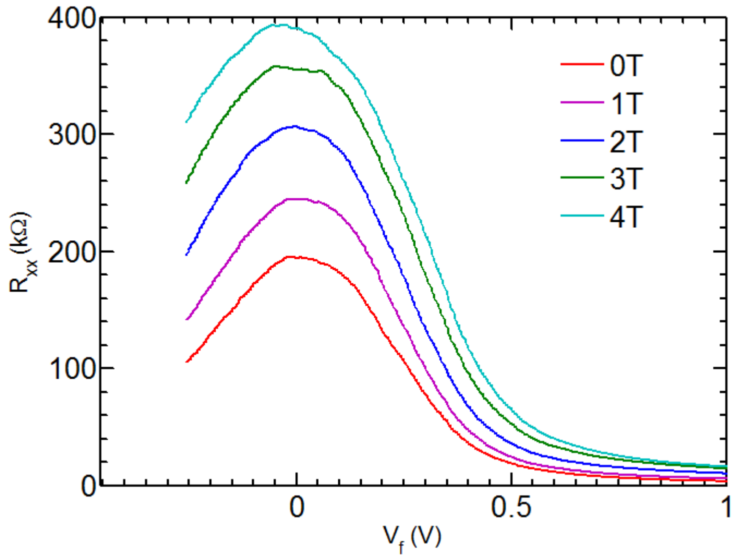


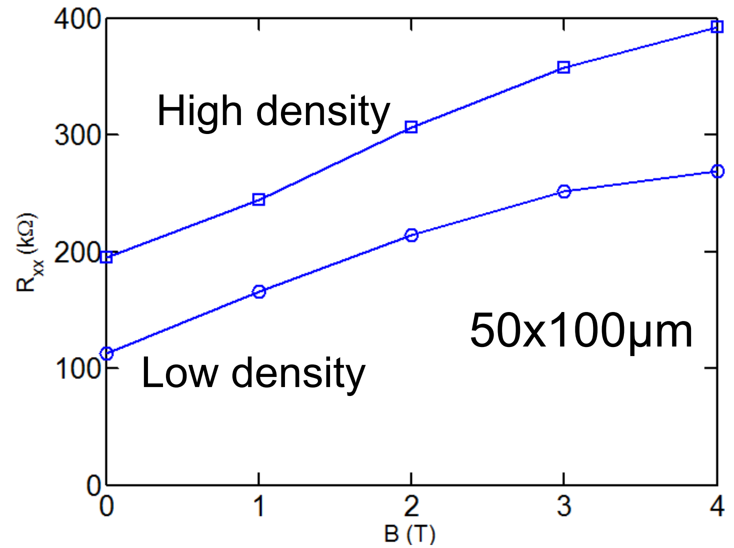
Low density

High density

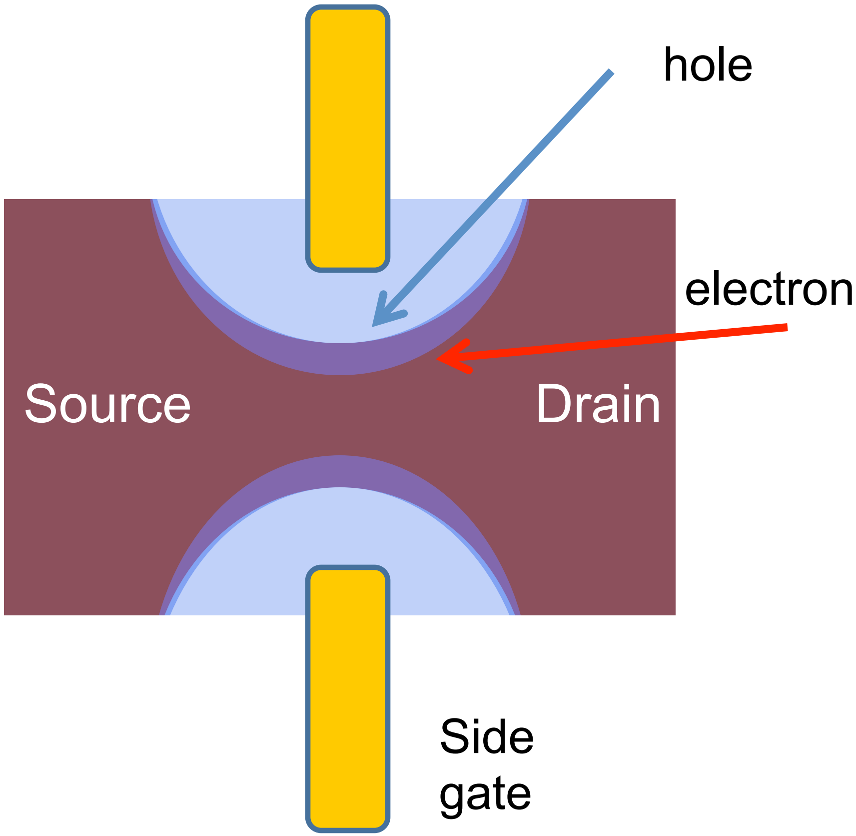
Magnetic Response Depends on V_F

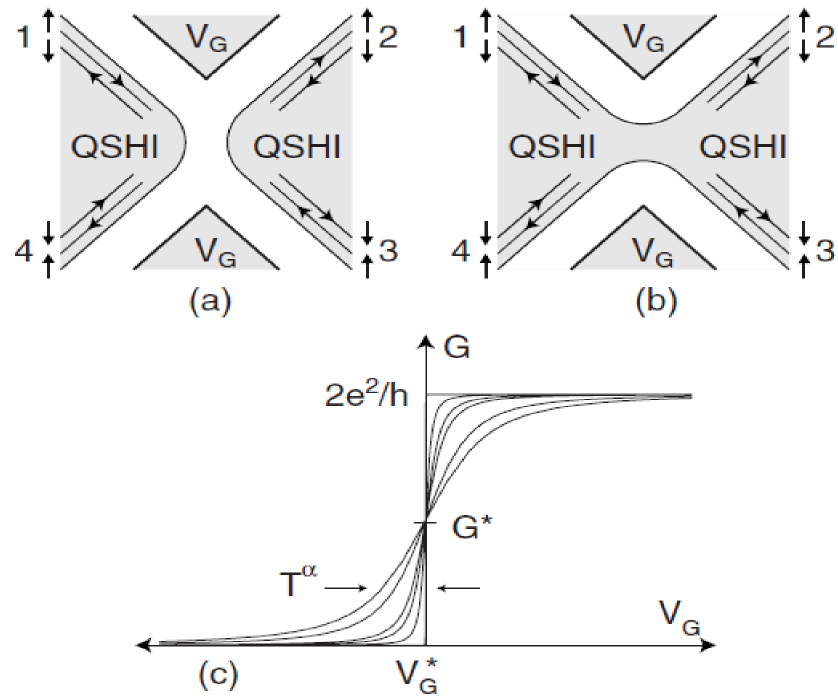
Less Interacting Edge States





Quantum Point Contact



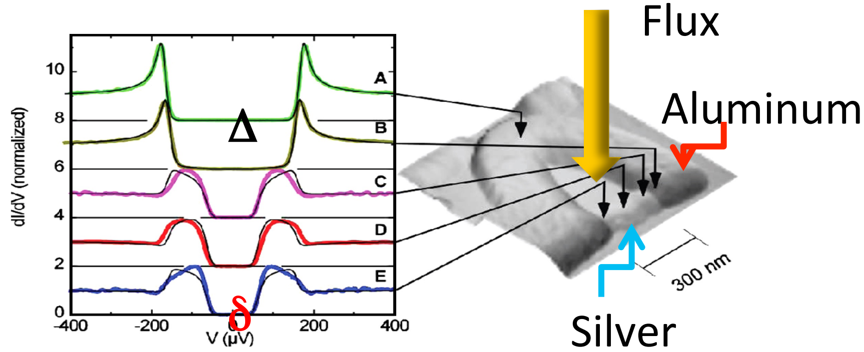


Shot Noise e/2

Quantum Critical Point

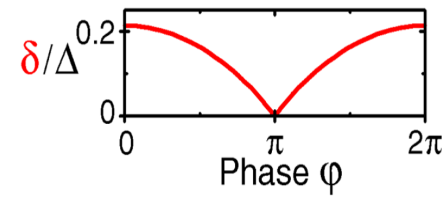
Teo & Kane, 2009

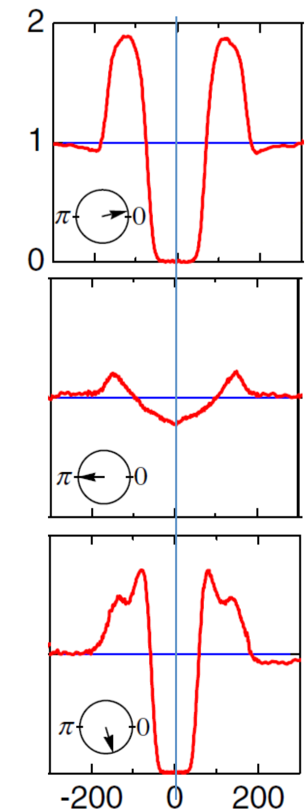
Tunneling Into Phase Controlled Junction

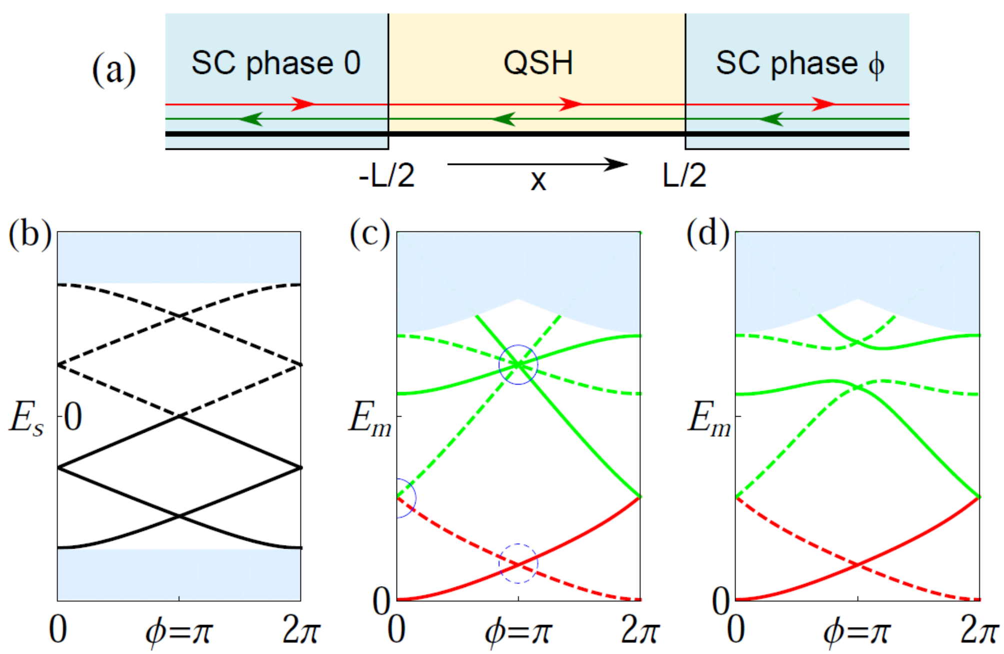


H. le Sueur et al, PRL 08

Phase Control







8-Pi *Josephson Effect due to Interaction*

Zhang & Kane PRL 13

SUMMARY

1) Robust Quantum Spin Hall Effect

2) InAs/GaSb Helical Edge: clean and highly-tunable 1D system

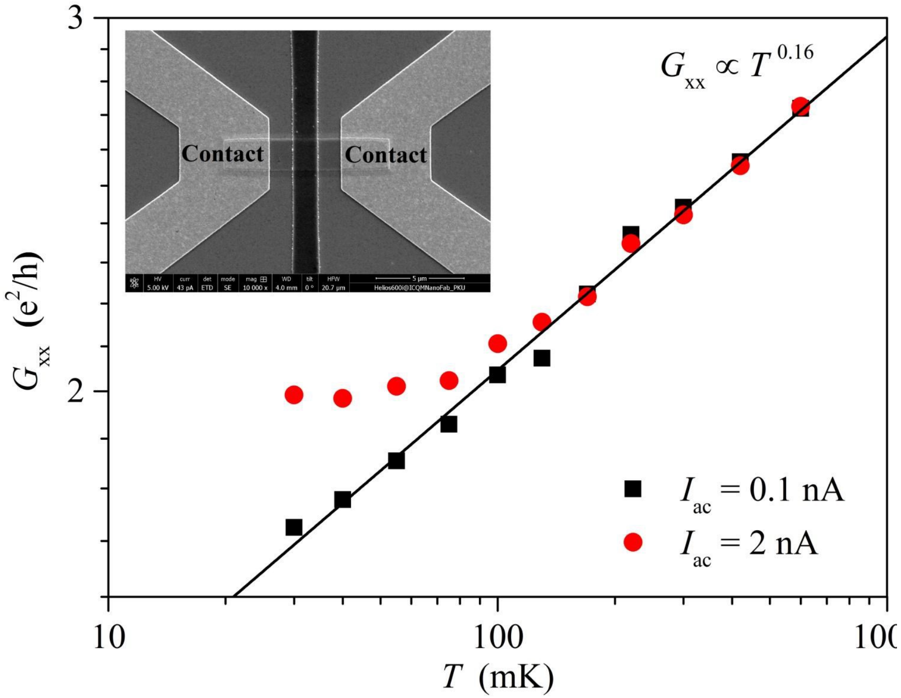
3) Strong Evidences for Helical Luttinger Liquid

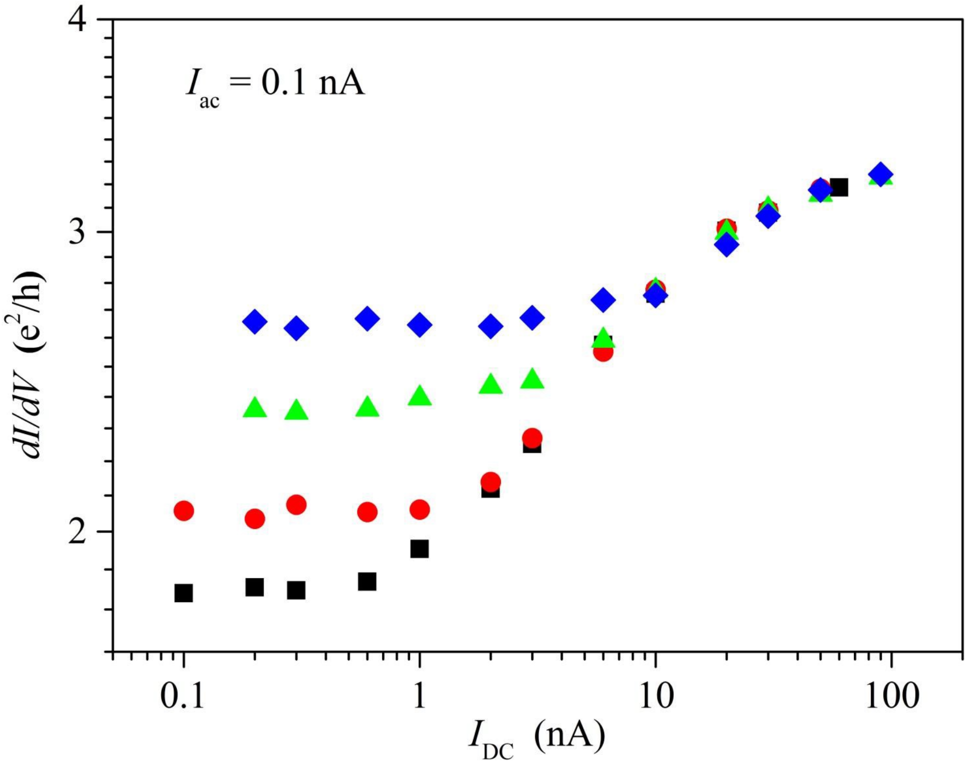
   Microscopic details to be understood

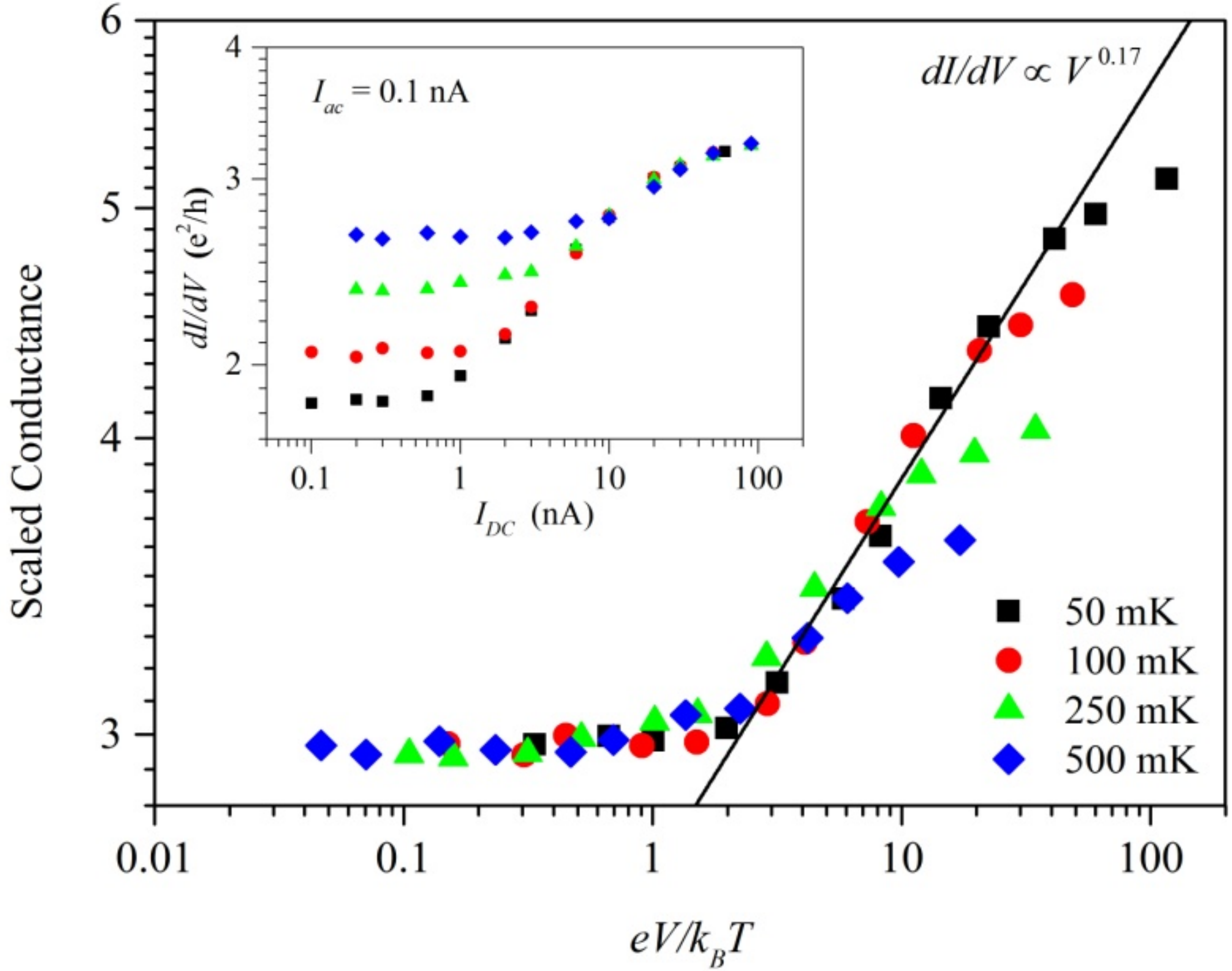
   New opportunities to study 1D correlation effects and related fractional charge and fractional Josephson effect

THANKS

Temperature-dependent in small-bias regime

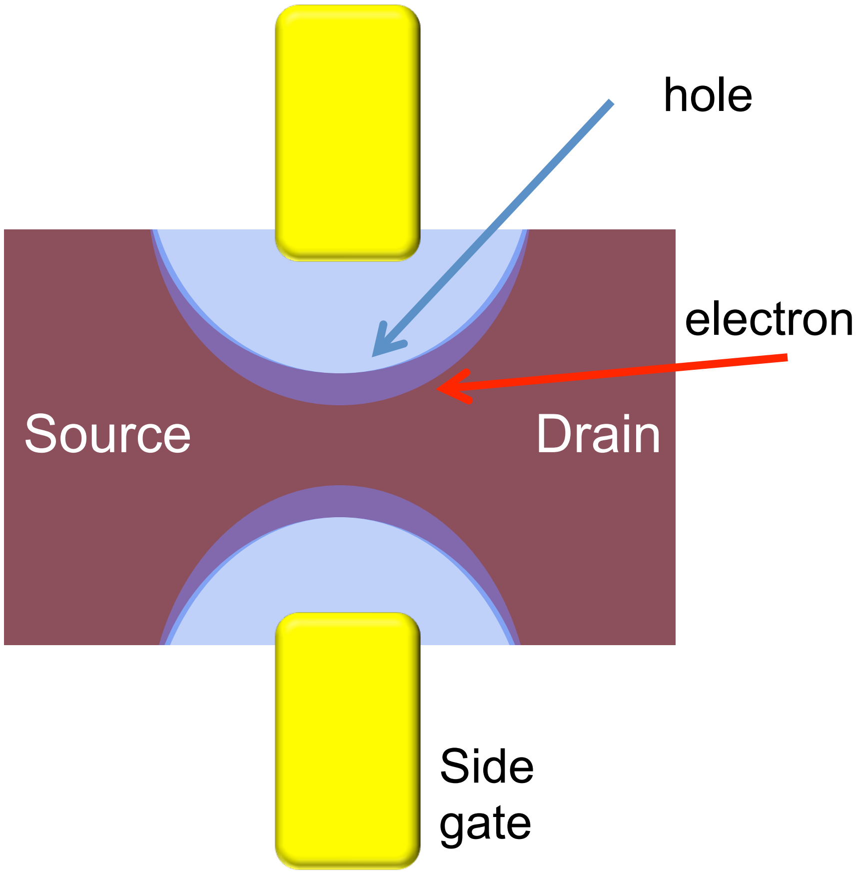


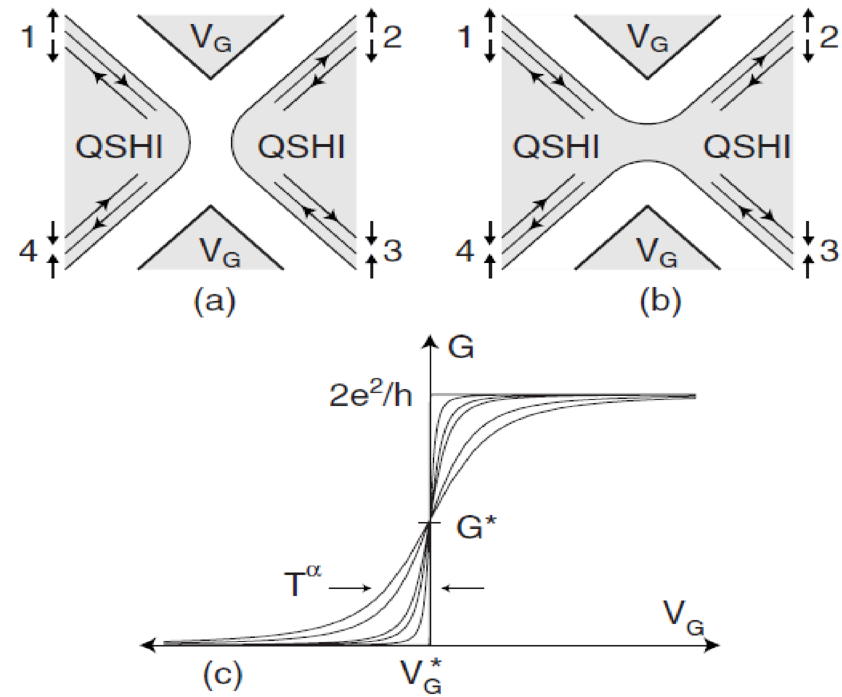




6
5
4
3
Scaled Conductance
0.01
0.1
1
10
100
eV/k_BT
$dI/dV \propto V^{0.17}$
50 mK
100 mK
250 mK
500 mK
I_{ac} = 0.1 nA
dI/dV (e^2/h)
I_{DC} (nA)

Quantum Point Contact

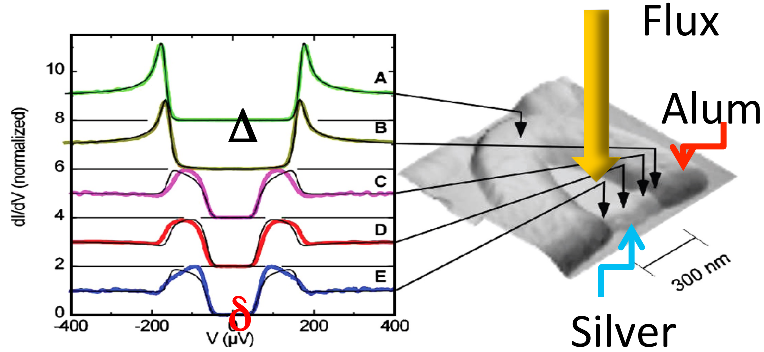




Shot Noise e/2

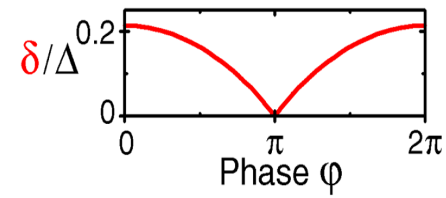
Quantum Critical Point

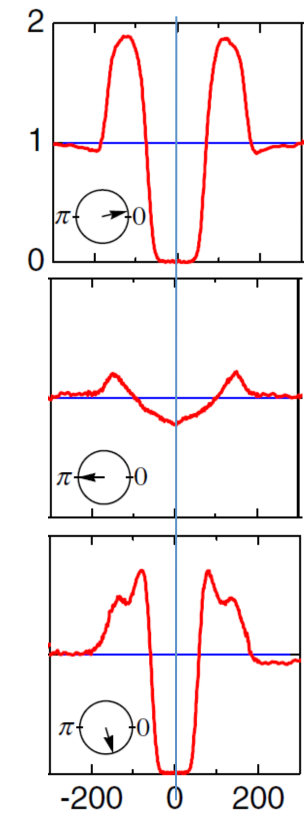
Tunneling Into Phase Controlled Junction

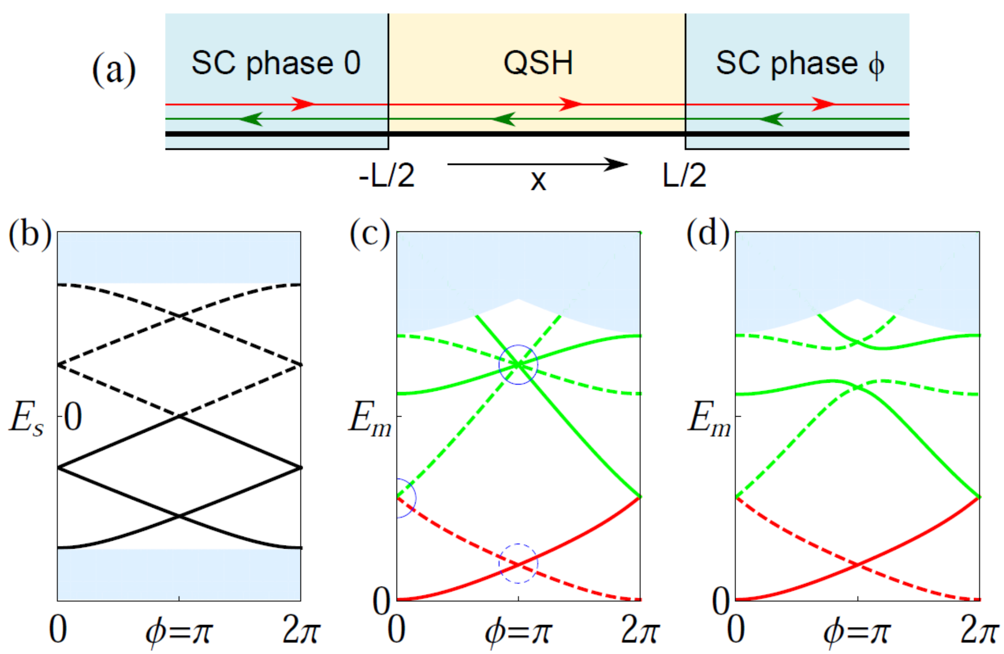


H. le Sueur et al, PRL 08

Phase Control







8-Pi
Josephson Effect due to Interaction

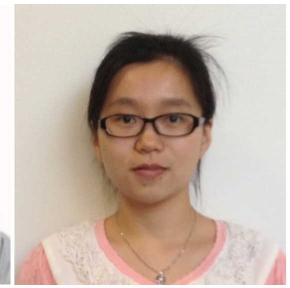
Zhang & Kane PRL 13

AKNOWLEDGE

Rice

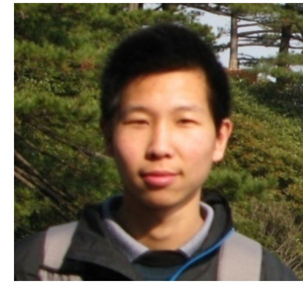
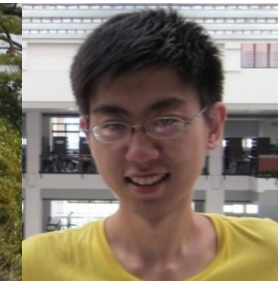
Ivan Knez Lingjie Du Ruiyuan Liu Jie Zhang



Peking U

Tingxin Li Xiaoyang Mu

Collaborations

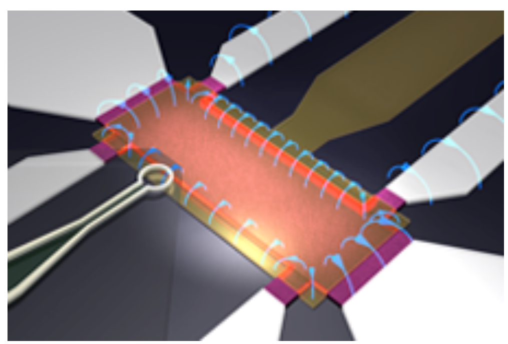
Teledyne

Gerry Sullivan

MBE

Stanford

Kathryn Moler
Eric Stanton



SQUID Imaging

Theory:

Carol Beenakker
Kai Chang
Matt Foster
Liang Fu
Dmitry Pikulin
Shoucheng Zhang
……

Among many others

SUMMARY

1) Robust Quantum Spin Hall Effect

2) InAs/GaSb Helical Edge: clean and highly-tunable 1D system

3) Strong Evidences for Helical Luttinger Liquid

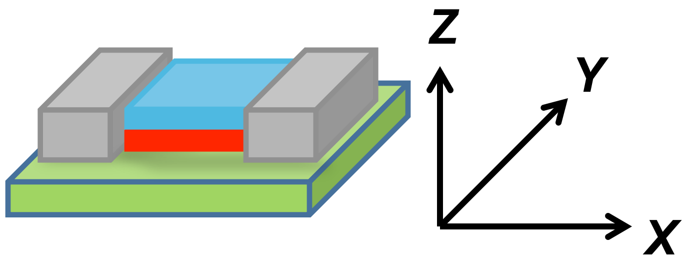
   must understood before engineering Majorana bound states

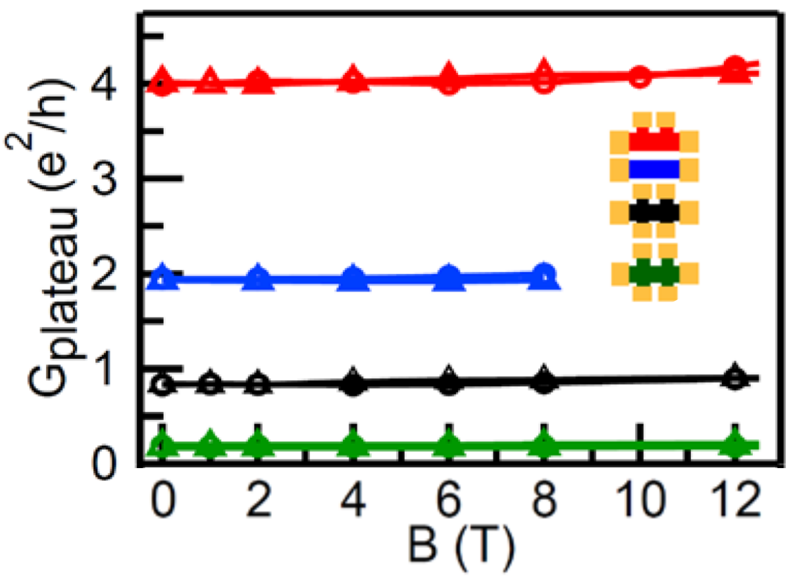
   New opportunities to study 1D correlation effects and related fractional charge and fractional Josephson effect

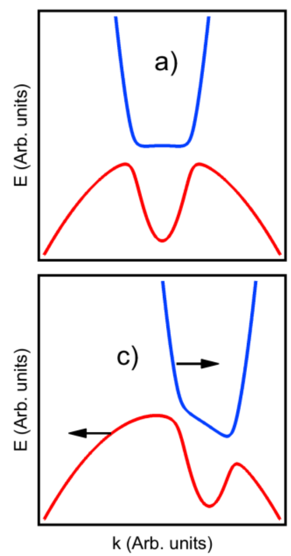
THANKS

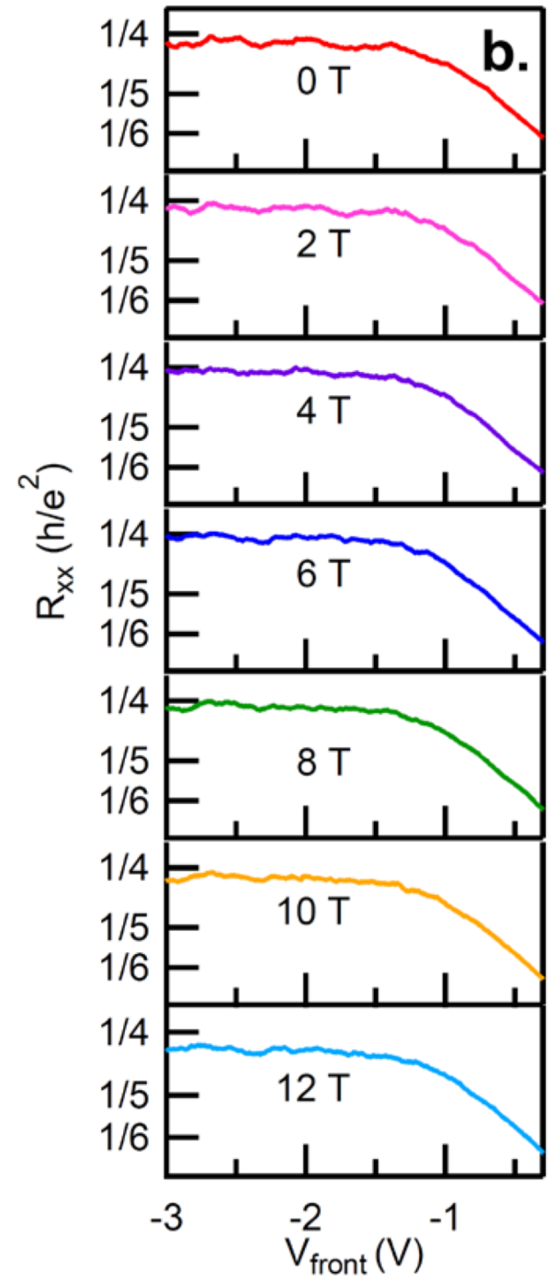
THANKS

In-Plane Magnetic Fields



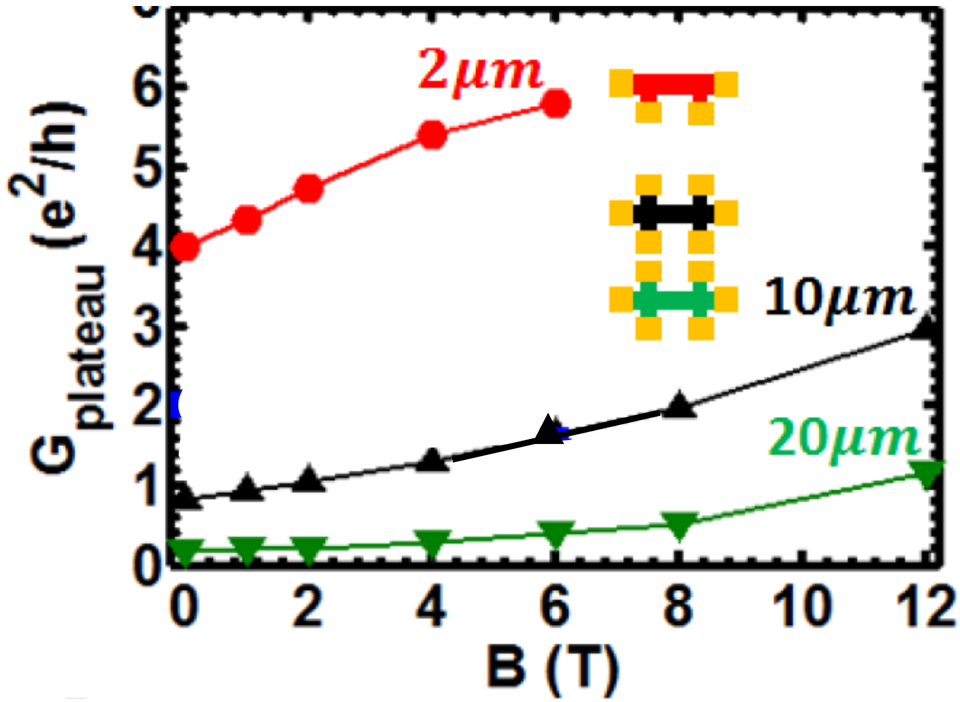


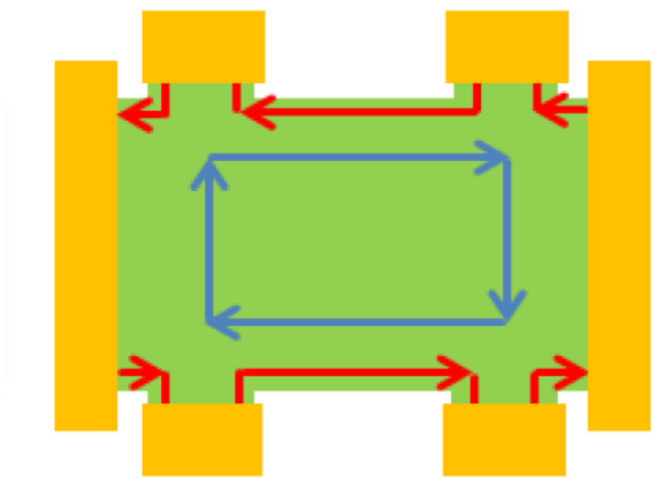




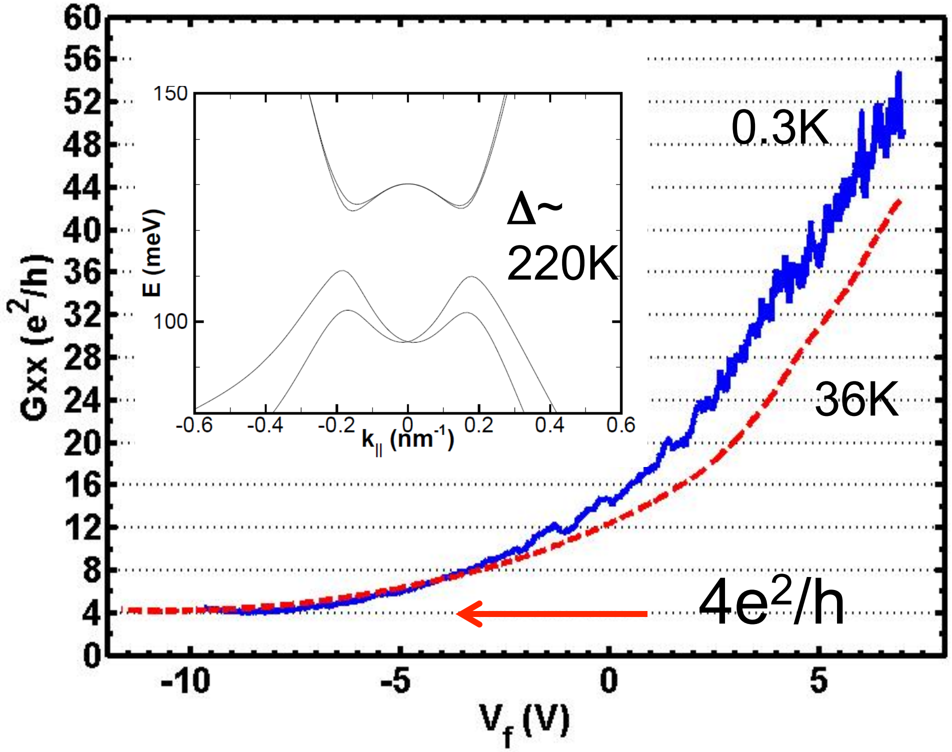
Small g* ~ 0.5 PRB**83**, 155412 (2011)

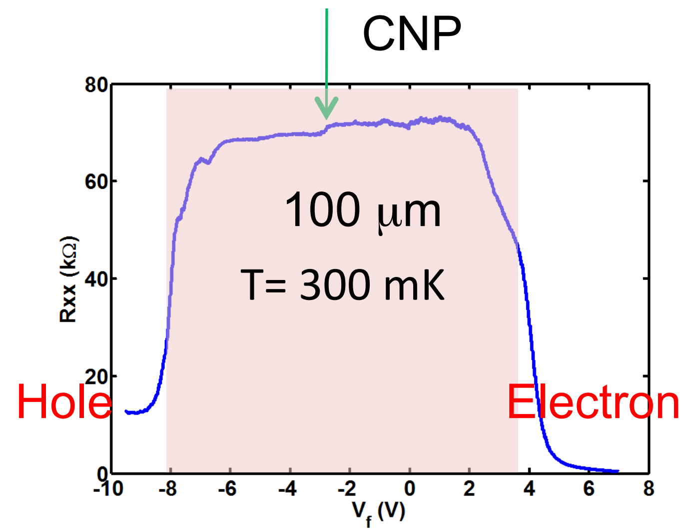
Perpendicular Magnetic Field

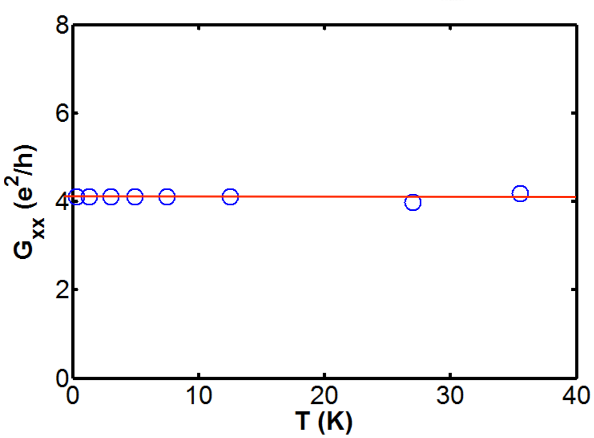




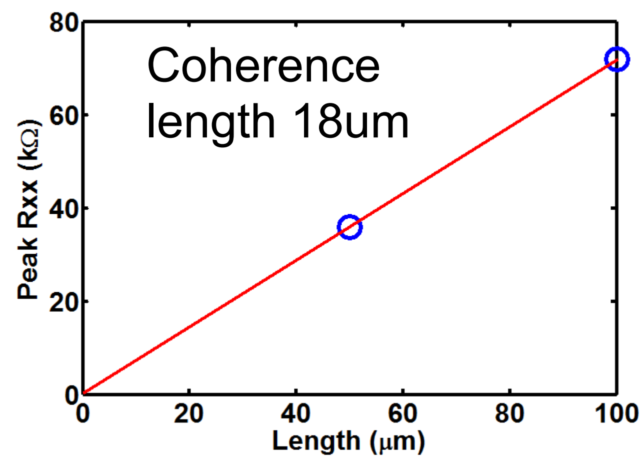
New Wafer (Strained QW) Preliminary Data







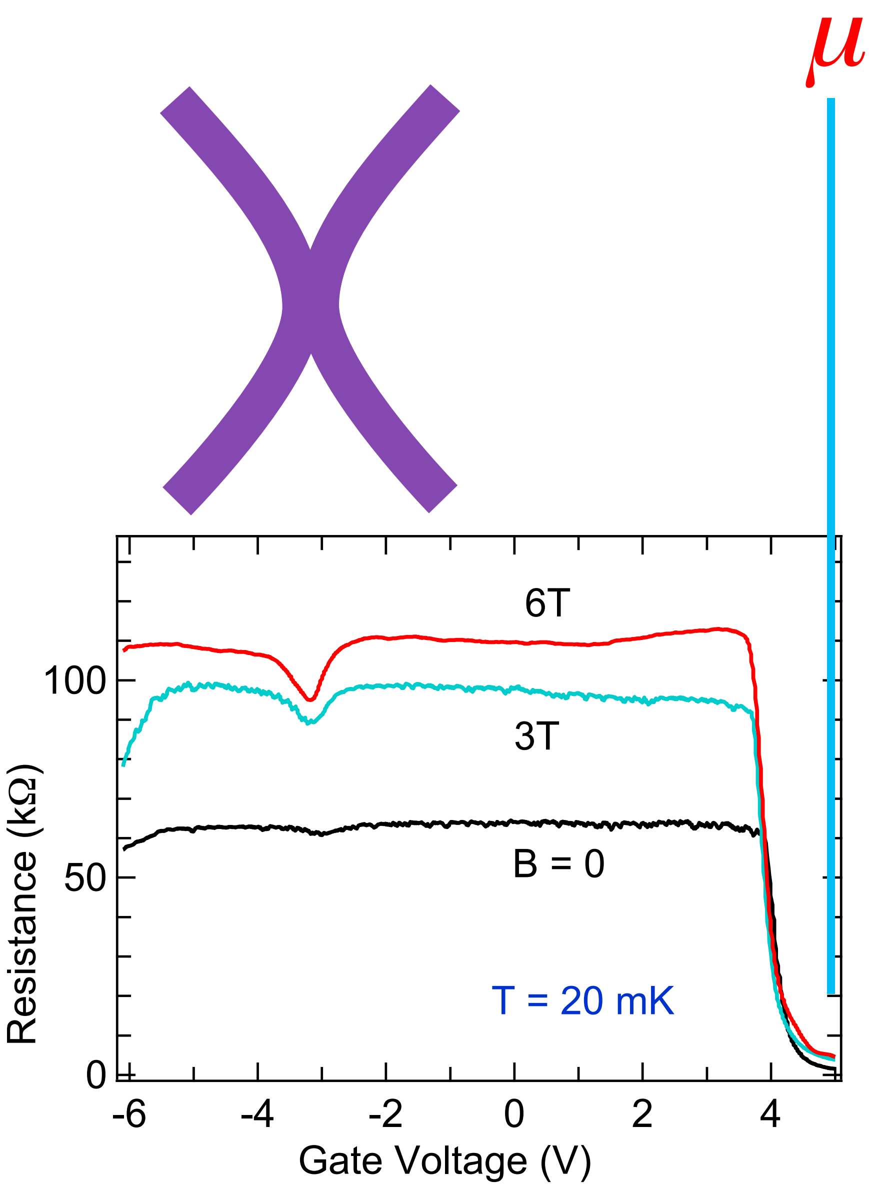
$4e^2/h$



Quantization of edge in small sample up to 36K

$\tau = 18\mu m \;/1\text{x}10^5\; m/s \sim 180\; ps$

Opening of Edge Gap by Perpendicular B



Strained QW of 100 um length

•B = 0: Weak resistance dip already at Dirac point

•Dip deepens with B

•Gap not fully open

Γ **~ 1K**

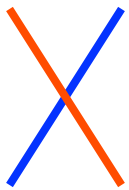
Tunneling DOS: STM

InAs/GaSb Majorana Platform

Inverted
+SO

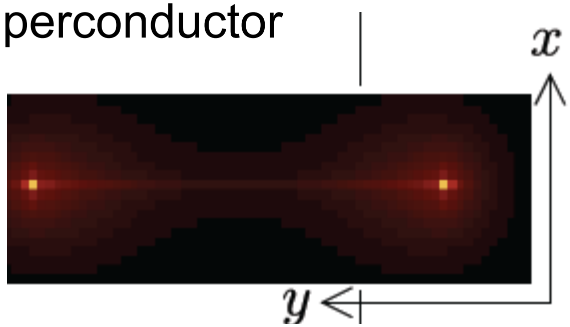
Strong
Tunneling

1- D
Dirac Fermions

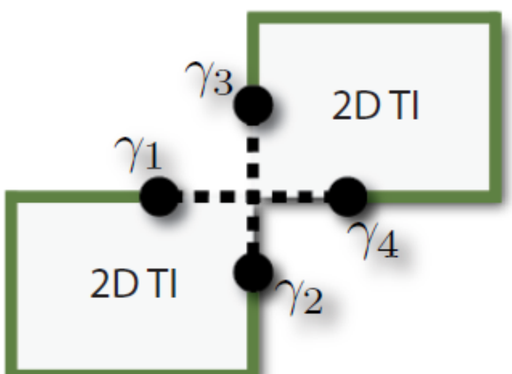


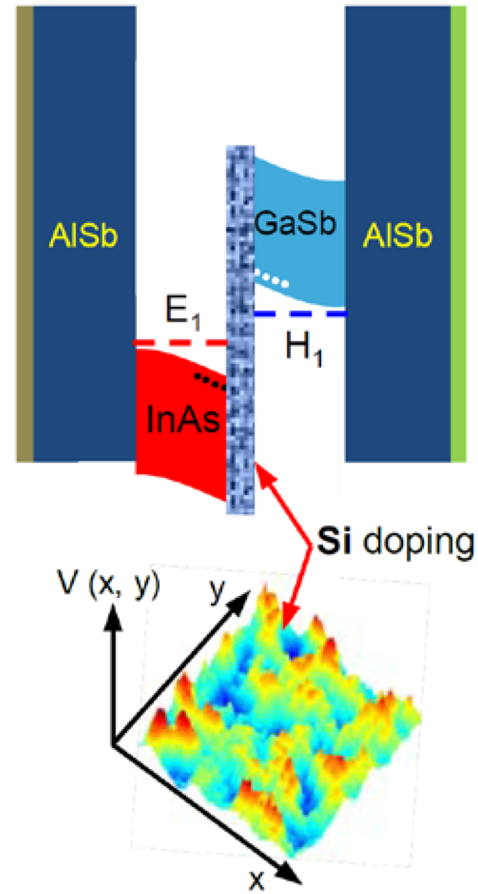
+ ***S***-Superconductor

Majorana
Bound States

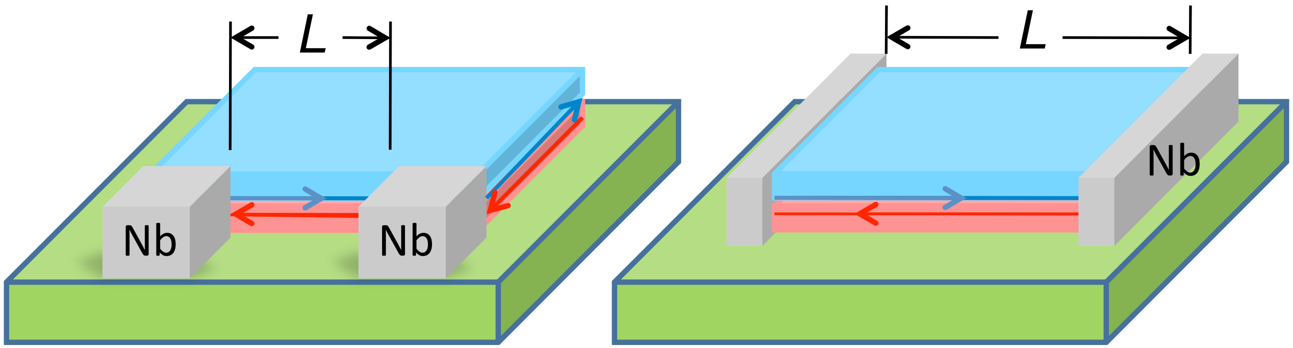


Braiding





General Design



Josephson Junction

SDUID

L = 0.1~ 1μm

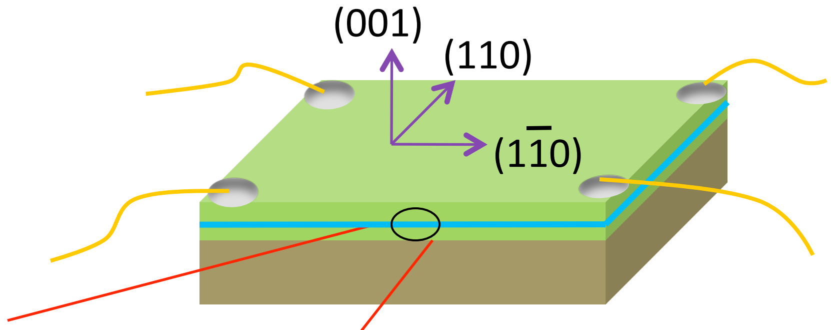
Direct Writing on Cleaved Edge

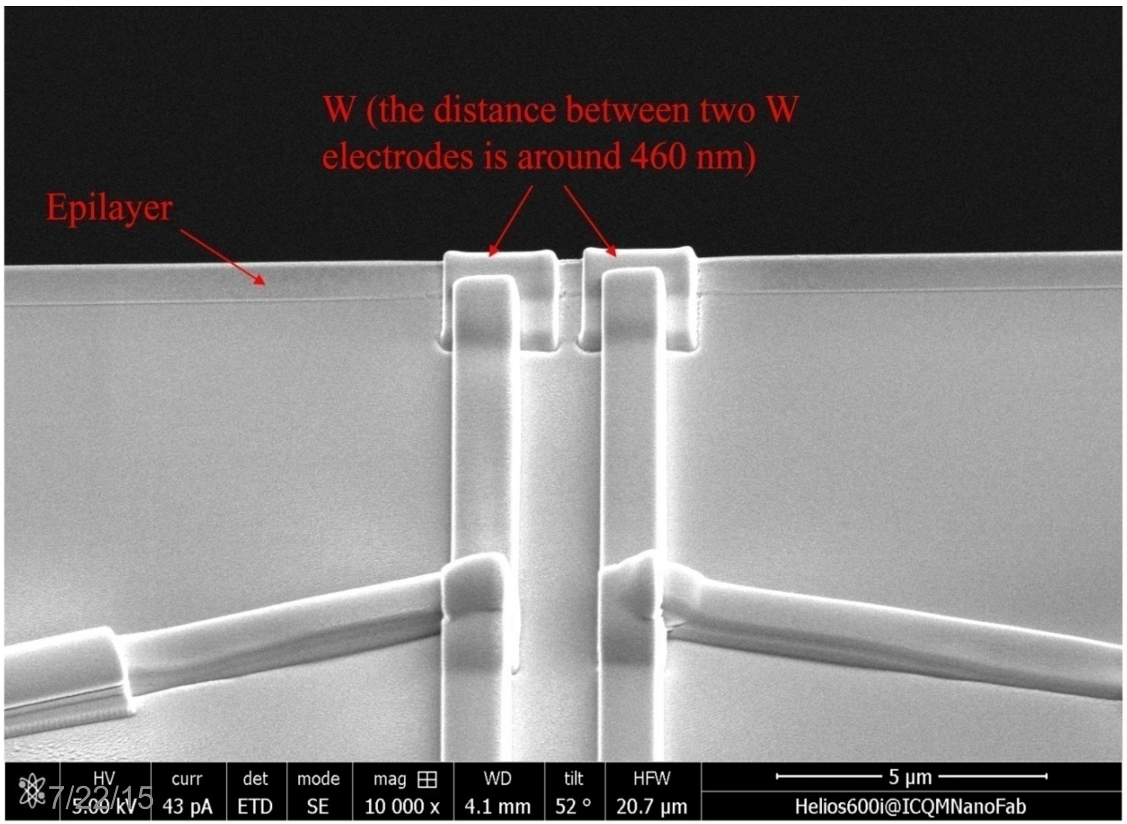
FIB-induced deposition of superconducting nanowires

W(40%):C(40%):Ga(20%)

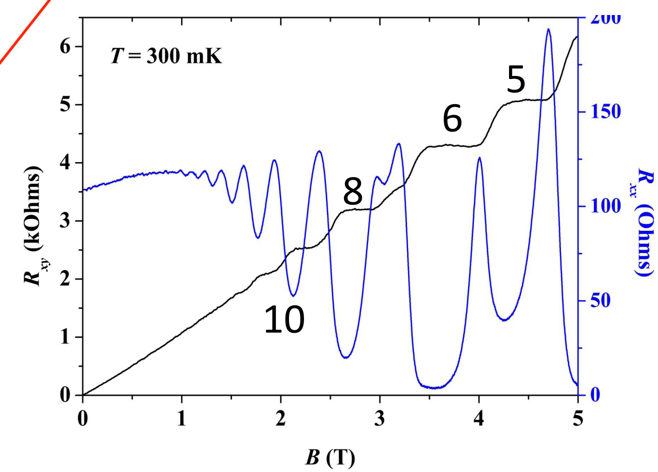
Tc =5.2K, Hc=9.5T

Sadki, Ooi, and Hirata, Appl. Phys. Lett. 85, 6206(2004)





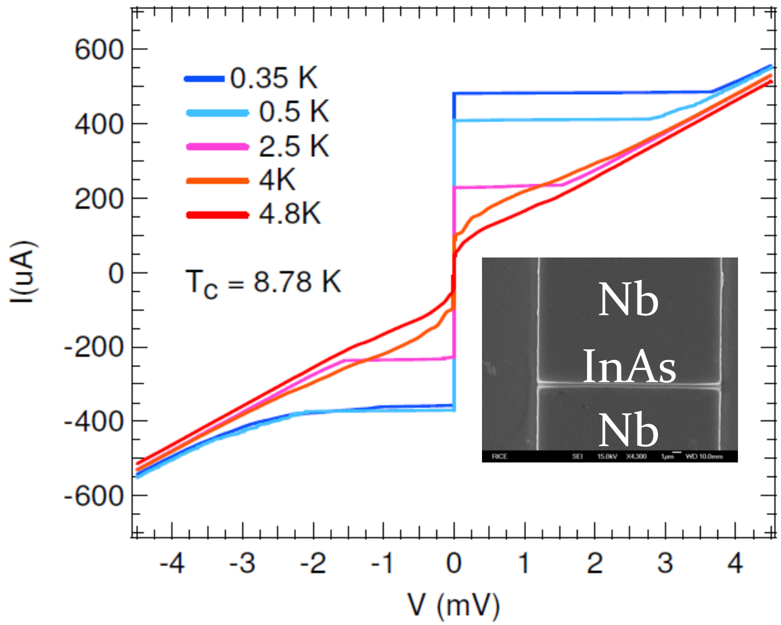
15nm *InAs* QW

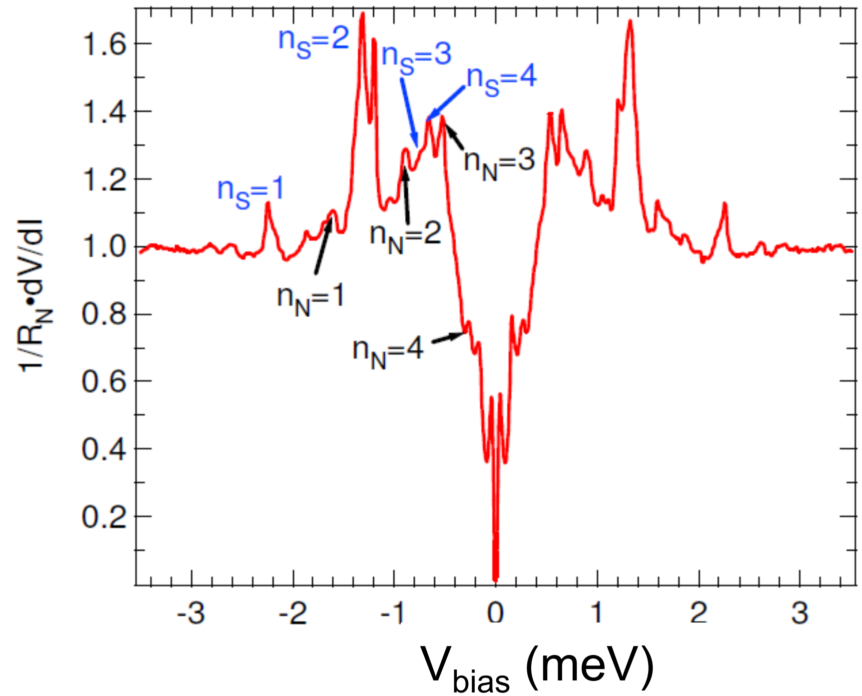


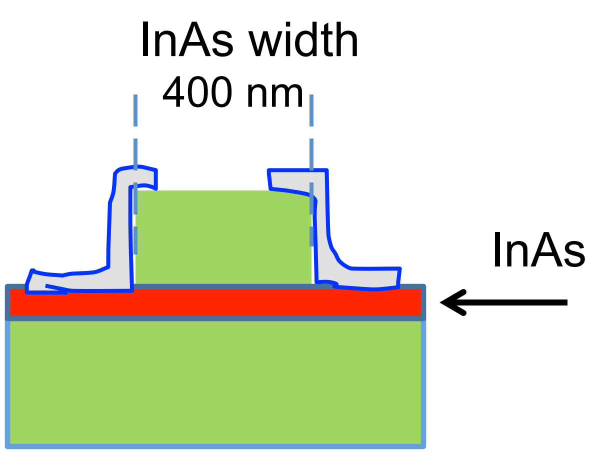
Proximity effect
IQHE edge state

InAs is SC-Friendly: *Standard Nb-InAs-Nb*

Knez, Du, Sullivan 09







Multiple Adreev Reflection:

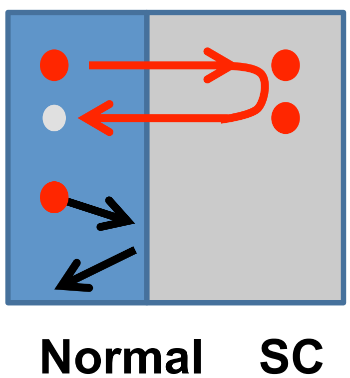
3 sets of peaks: Δ_N, Δ_S, $\Delta_N+\Delta_S$

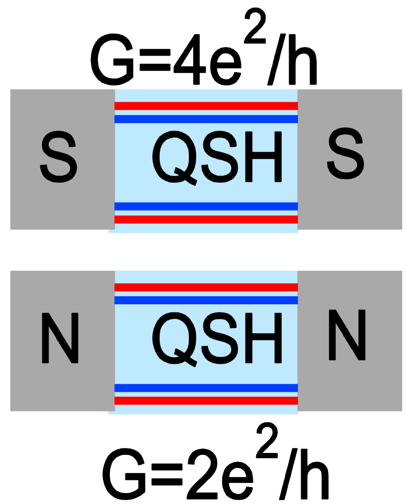
$$V_{SGS} = \frac{2\cdot\Delta_S}{n\cdot e}, \frac{2\cdot\Delta_N}{n\cdot e}, \frac{2\cdot(\Delta_S \pm \Delta_N)}{n\cdot e}$$

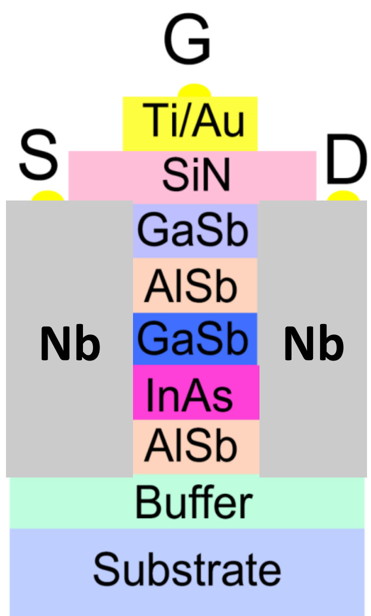
$\Delta_N/\Delta_S \sim 0.67$

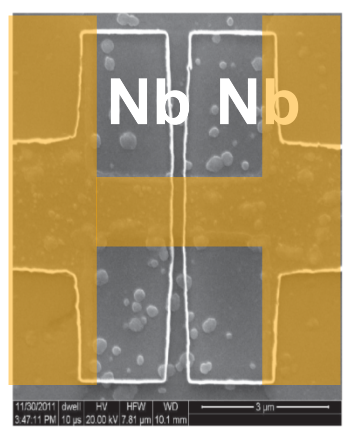
$\Delta_S=1.31 meV$; $\Delta_N = 0.87$ meV

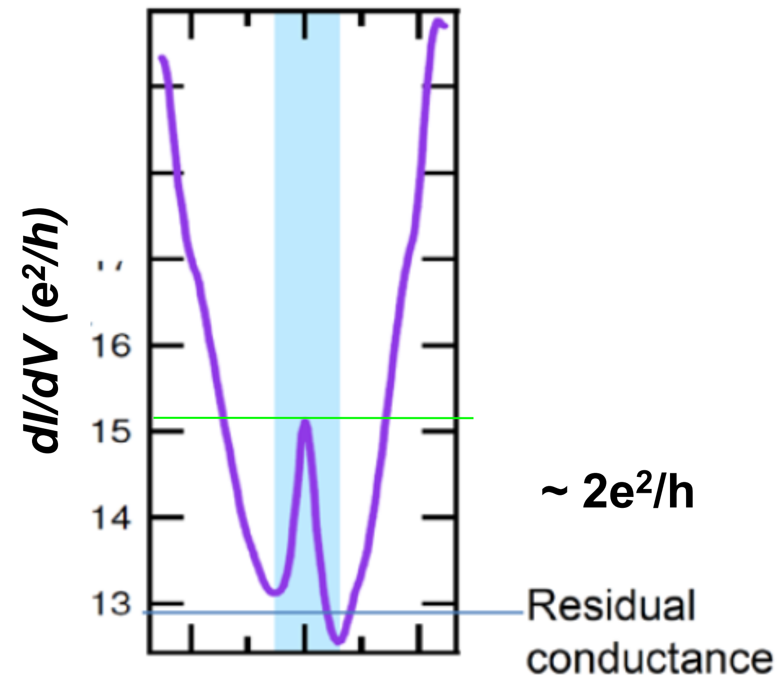
Andreev Reflection of Nb-(InAs/GaSb)-Nb Junction











Knez, PRL 12

(early sample)

Goal: Creating MBS on the Edge

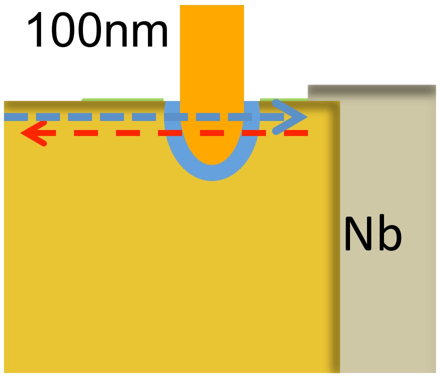
Main challenges:

1. Supercurrent -- small ν_F

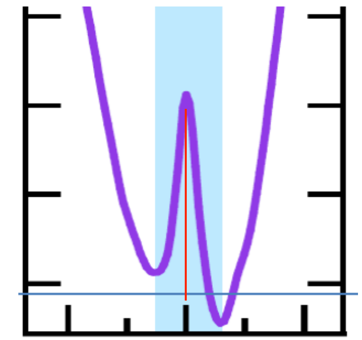
2. Soft induced-SC gap -- interface roughness etc

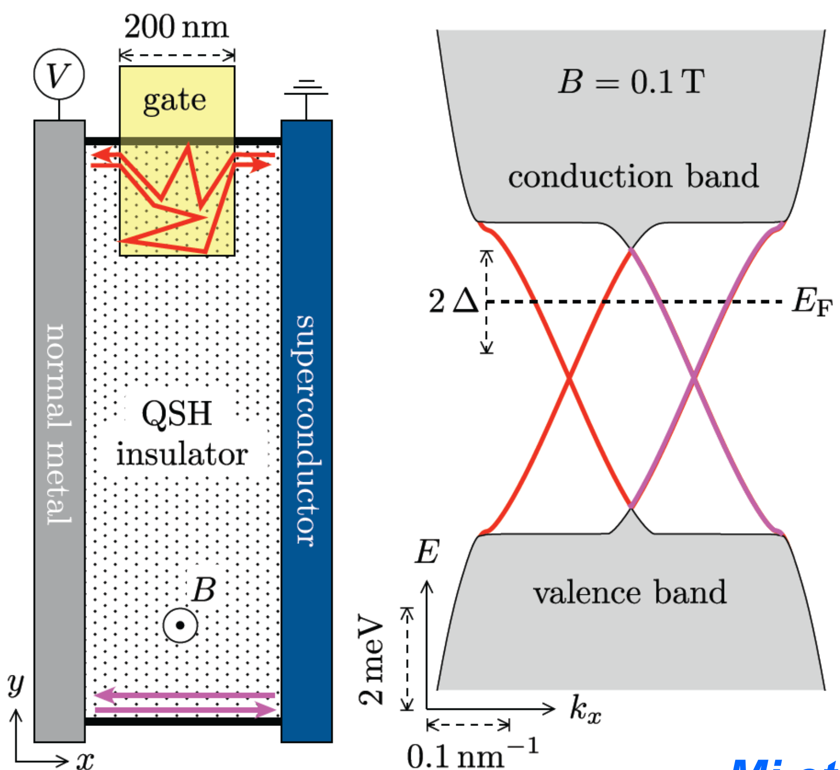
2. Terminating edge --

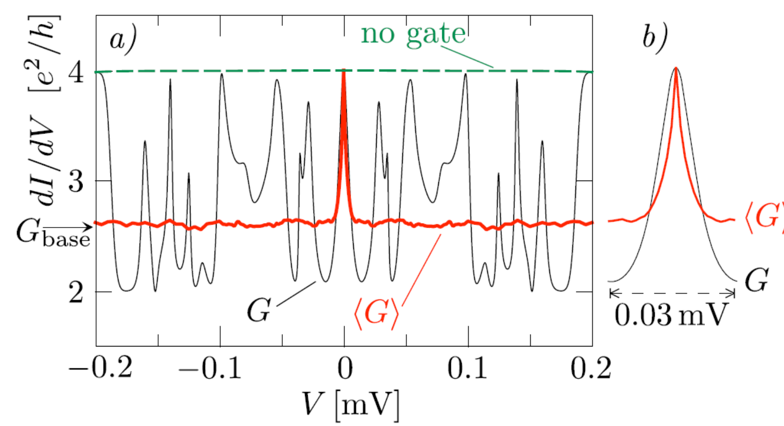
On-Going Experiment towards Isolation

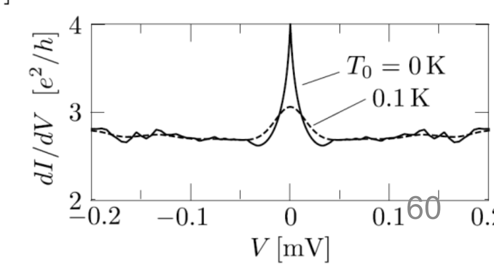


1. MF delocalize
2. Trapping MF by metallic dot + B
3. Backscattering confines MF
4. Zero modes stands out in disorder average



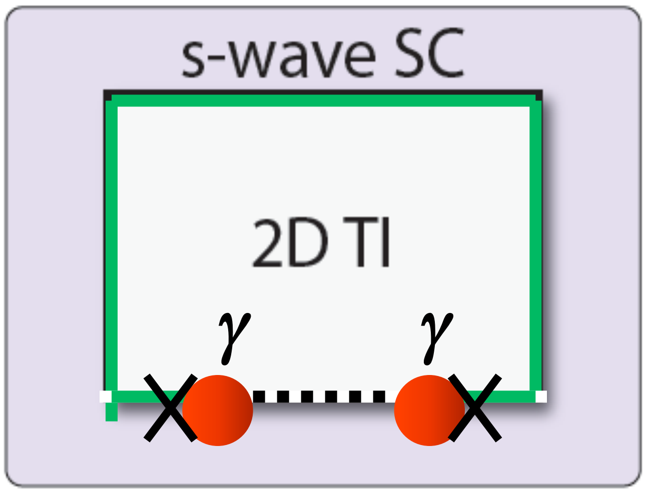


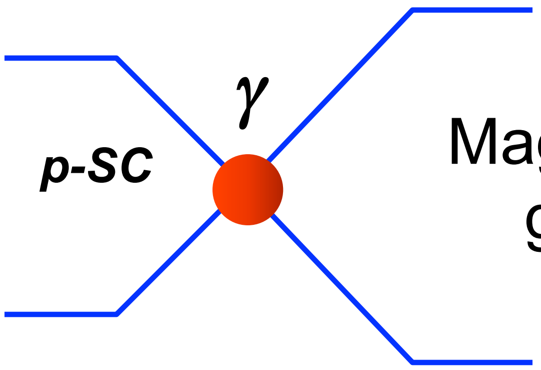




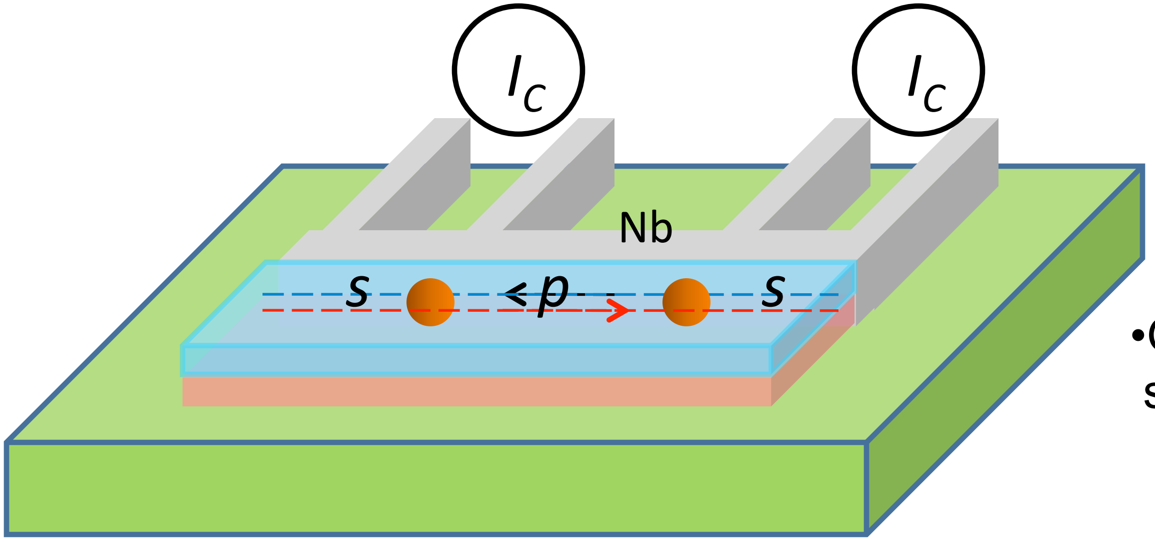
Mi et al, PRB 13

Magnetic Impurity and Supercurrent Isolation



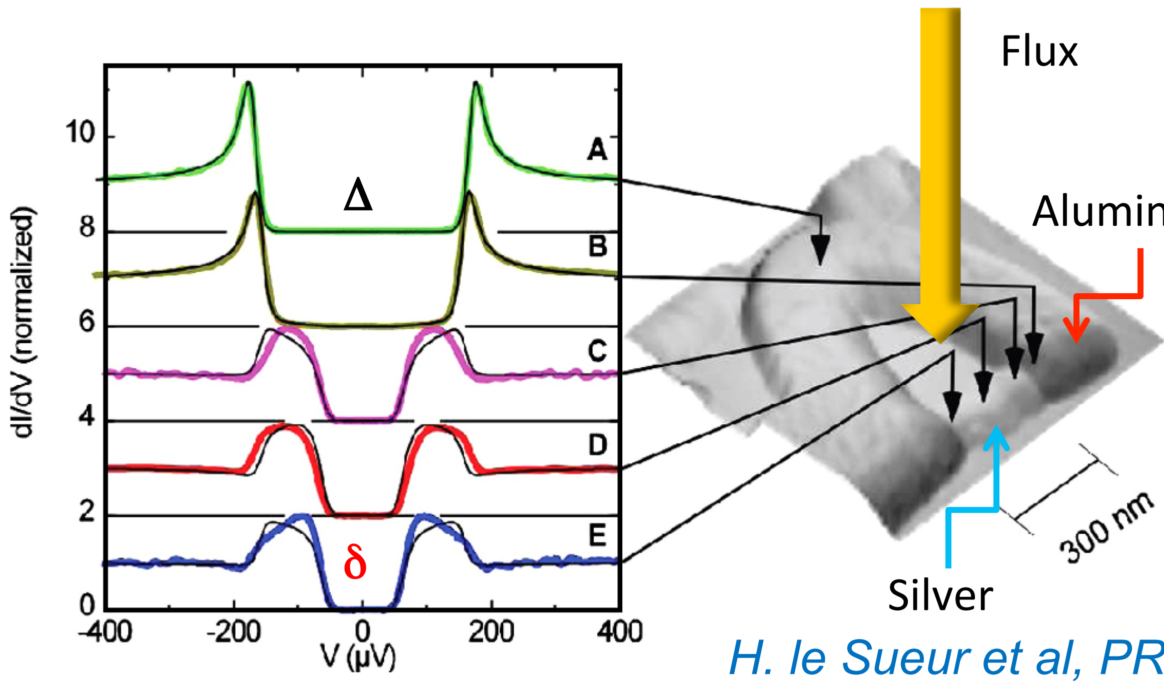


Cobalt, YIG



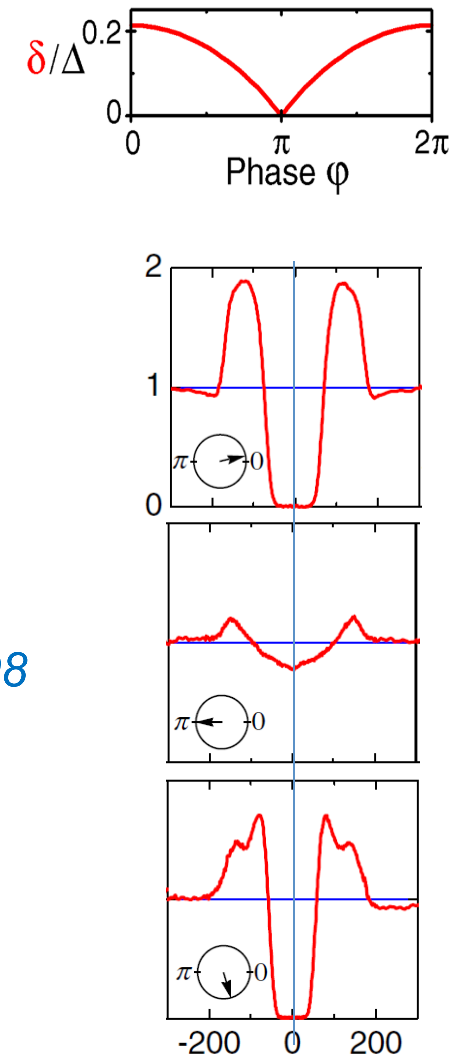
- Gap out topological wire by supercurrent gradient

Tunneling Into Phase Controlled Junction



H. le Sueur et al, PRL 08

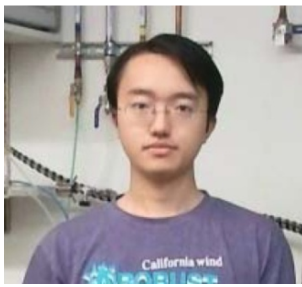
Phase Control

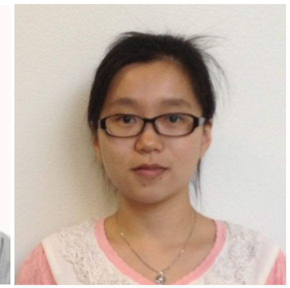


AKNOWLEDGE

Rice

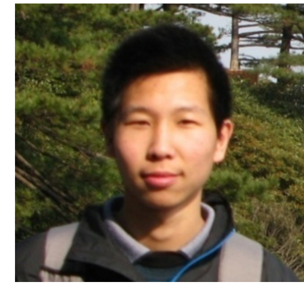
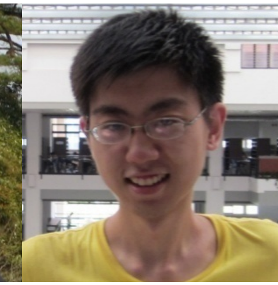
Ivan Knez Lingjie Du Ruiyuan Liu Jie Zhang



Peking U

Tingxin Li Xiaoyang Mu

Collaborations

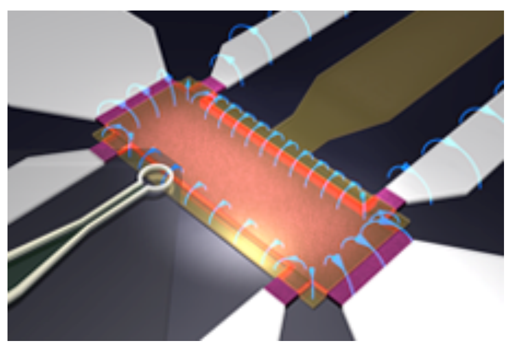
Teledyne

Gerry Sullivan

MBE

Stanford

Kathryn Moler
Eric Stanton



SQUID Imaging

Theory:

Carol Beenakker
Kai Chang
Matt Foster
Liang Fu
Dmitry Pikulin
Shoucheng Zhang
……

Among many others

SUMMARY

1) Robust Quantum Spin Hall Effect:
current technology 77K

2) InAs/GaSb Helical Edge: clean and highly-tunable
1D system limited only by intrinsic factors

3) InAs/GaSb Edge + Superconductor:
a realistic route towards Majorana bound State

THANKS