

QuMat 2023 Yearly meeting

Lindenberg Cultuurhuis, Nijmegen (Holland), 24 October 2023

# Superconducting Proximity Effect in Topological Insulators

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Topological  
Matter  
Laboratory  
Cologne

# Outline

- Quantum Anomalous Hall insulator (QAHI) & Majorana Fermions
- Crossed Andreev Reflection (CAR) in proximitized QAHI
- Subbands in TI nanowire
- Andreev bound states and CAR in proximitized TI nanowires

## Funding:

DFG Collaborative Research Center



DFG Cluster of Excellence



ERC Advanced Grant  
“MajoranaTopIn”

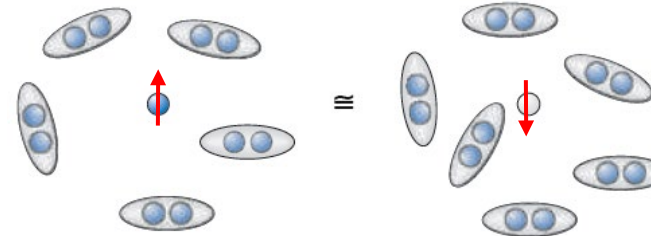


# Topological SC and Majorana Fermions

Majorana Fermion  $\Rightarrow$  Particle is its own antiparticle

Neutrino?

Superconductor (s-wave):



Wilczek (2009)



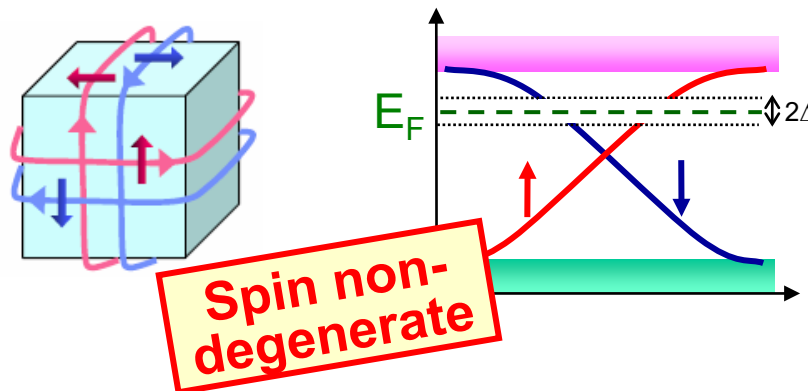
- **Spinless SC** is necessary for realizing Majorana Fermions

$\rightarrow$  Such a SC is **Topological** !

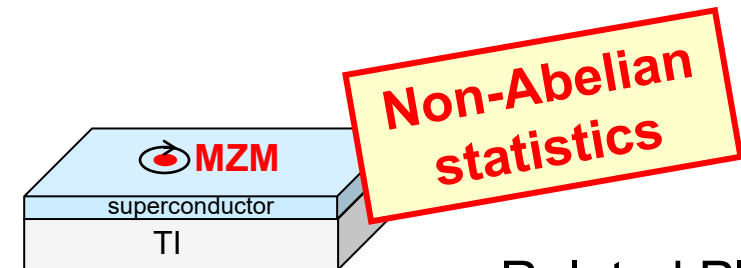
e.g. 2D spinless chiral p-wave SC

Surface State of TIs

Fu & Kane (2008)



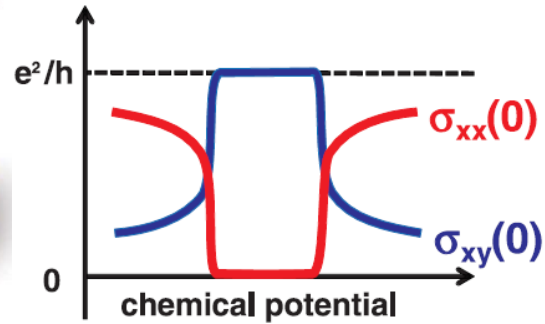
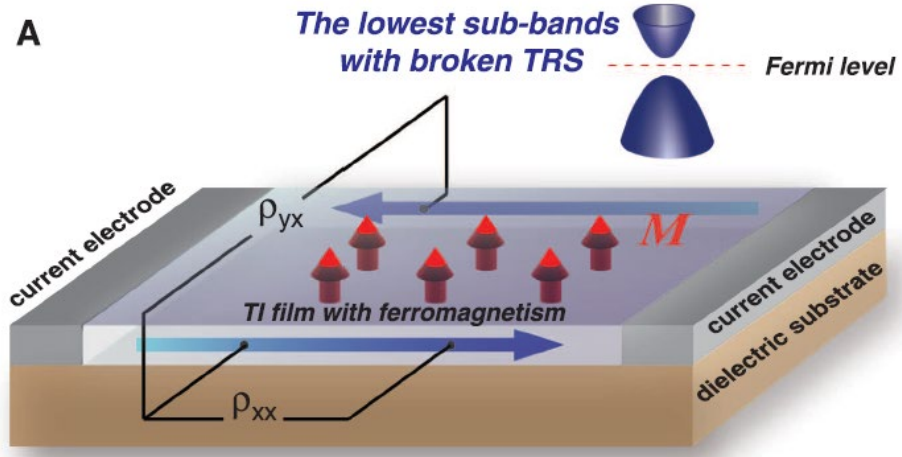
**Spin non-degenerate**



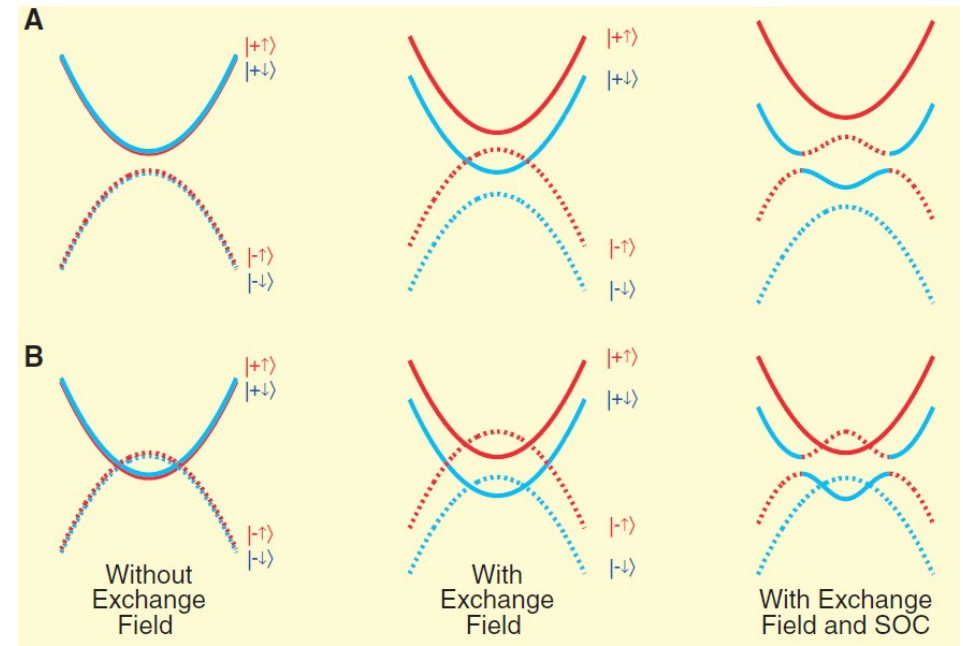
Majorana zero mode in vortices

Related Platform:  
**Quantum anomalous Hall insulator**

# Quantum Anomalous Hall Effect

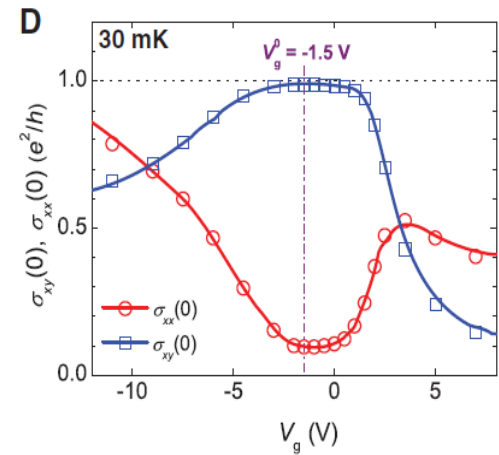
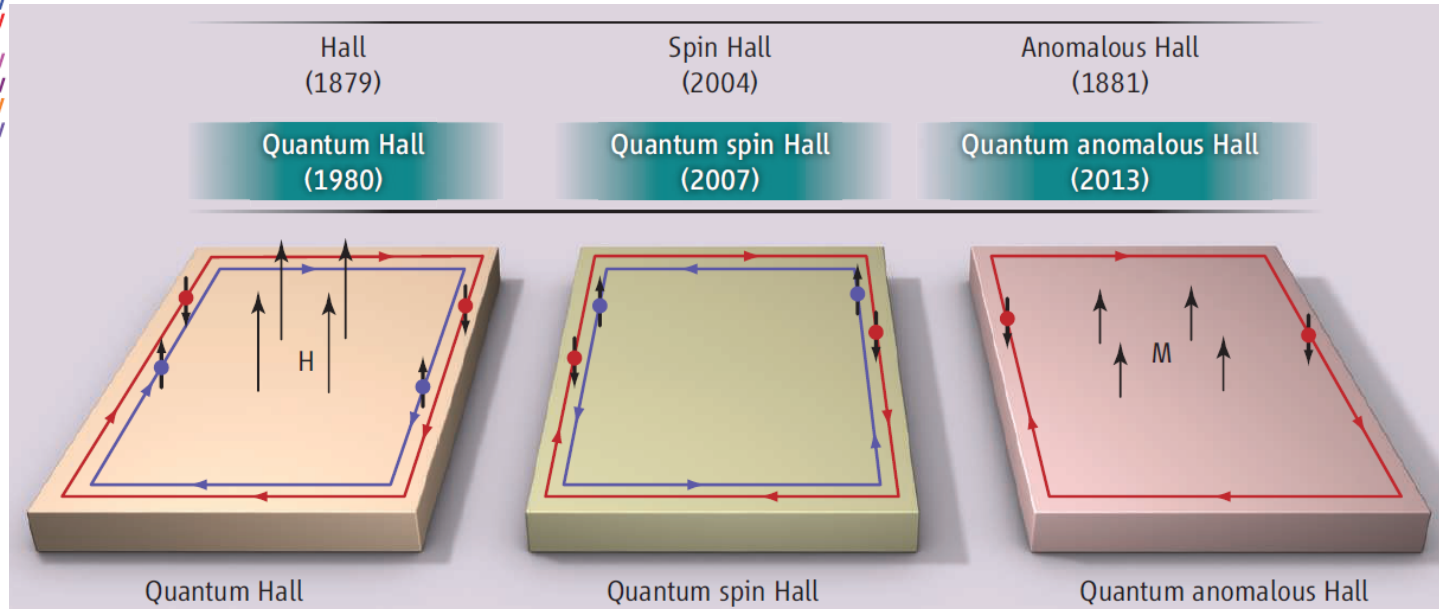


Top and bottom surface states hybridize

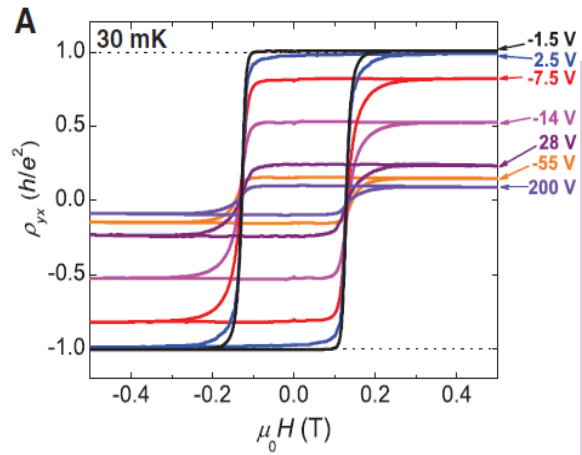


Oh, Science (2013)

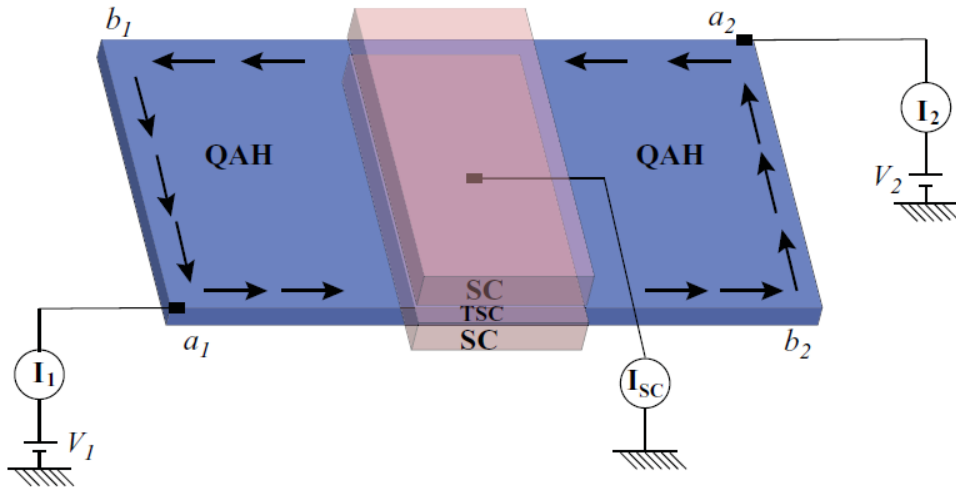
Yu et al., Science (2010)



Chang et al., Science (2013)



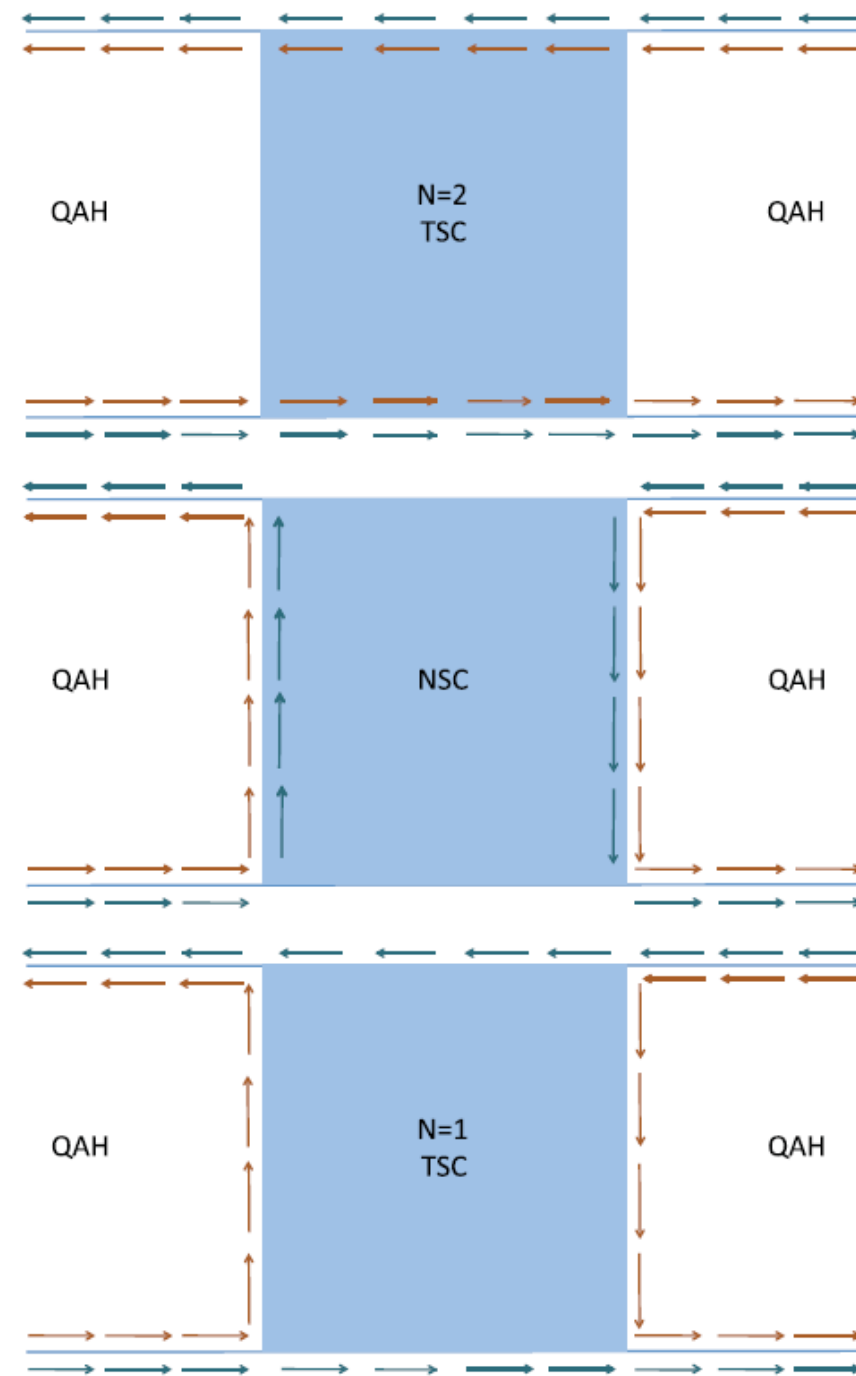
# Proximity Effect in QAHI



$$\begin{aligned}
 m < -\sqrt{|\Delta|^2 + \mu^2} &\Rightarrow \mathcal{N} = 2, \\
 m^2 < |\Delta|^2 + \mu^2 &\Rightarrow \mathcal{N} = 1, \\
 m > \sqrt{|\Delta|^2 + \mu^2} &\Rightarrow \mathcal{N} = 0,
 \end{aligned}$$

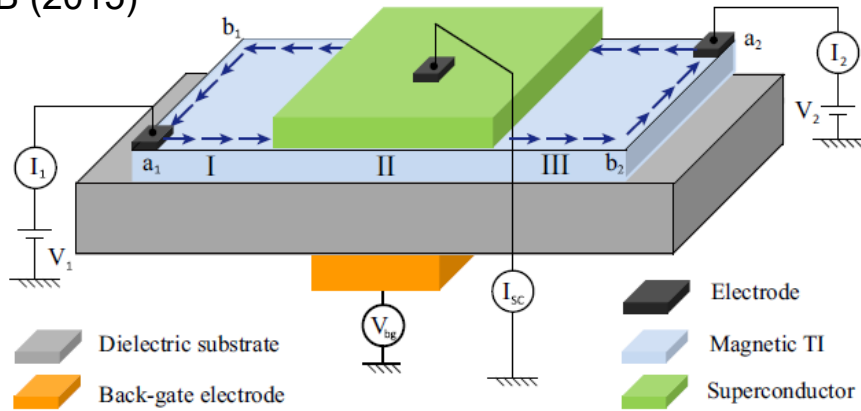
( $m$ : hybridization gap of the surface states)

Chung et al., PRB (2011)



# Proximity Effect in QAHI

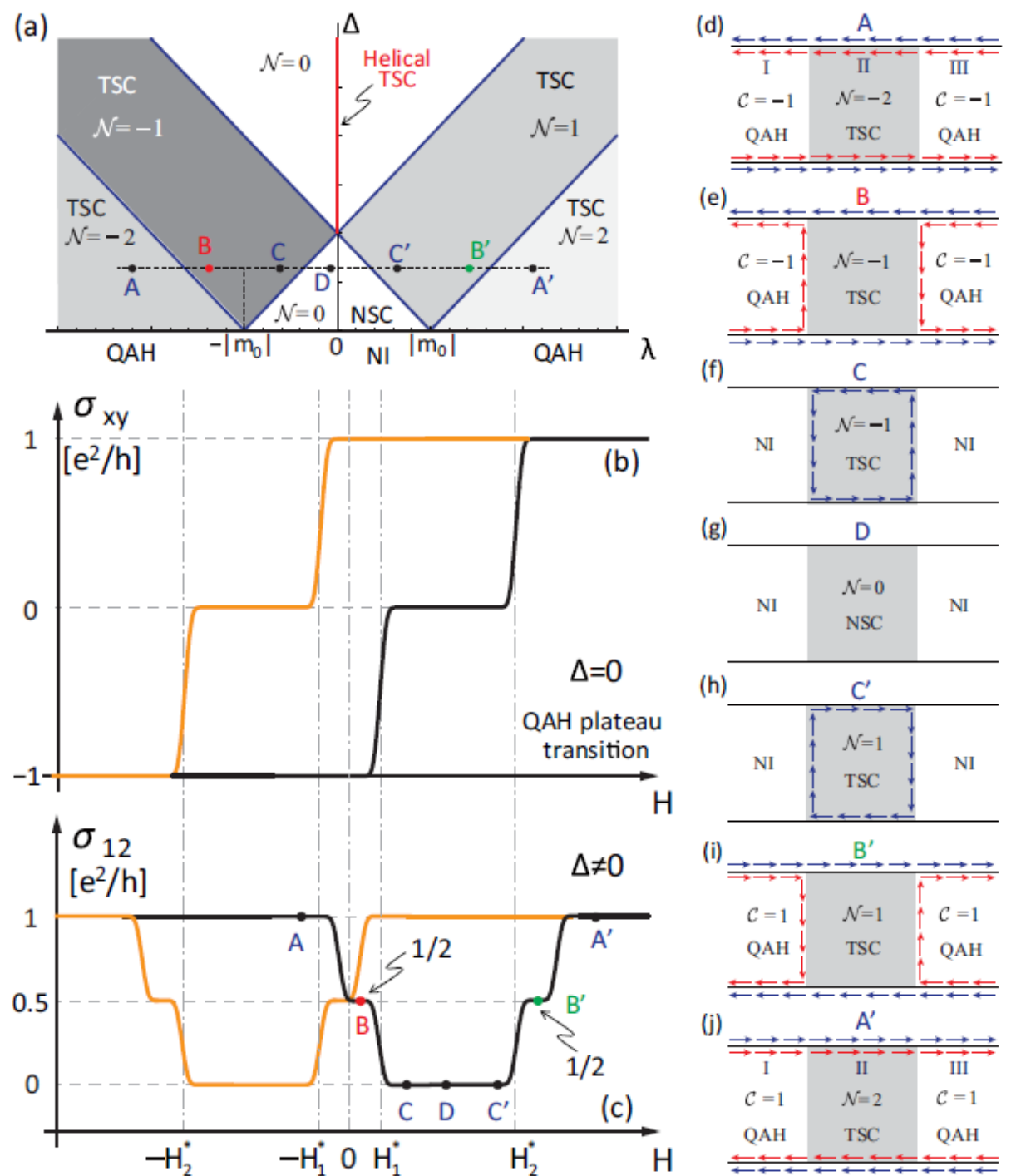
Wang, PRB (2015)



Competition between:

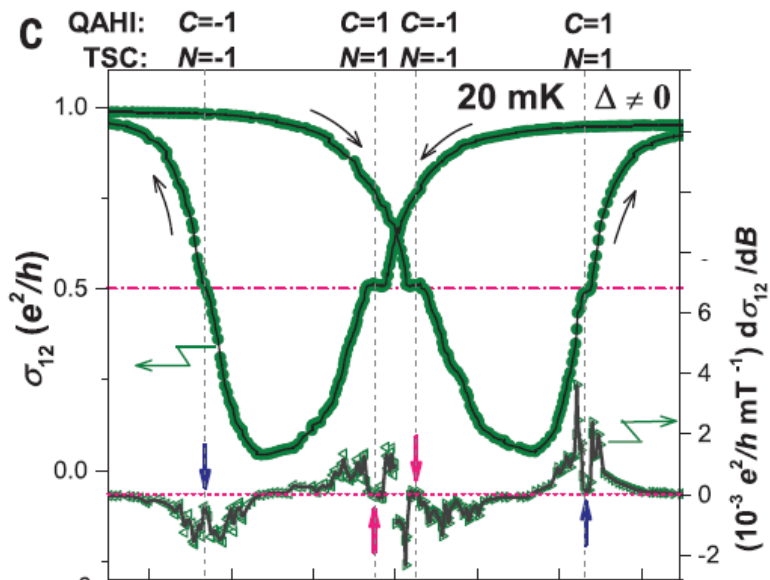
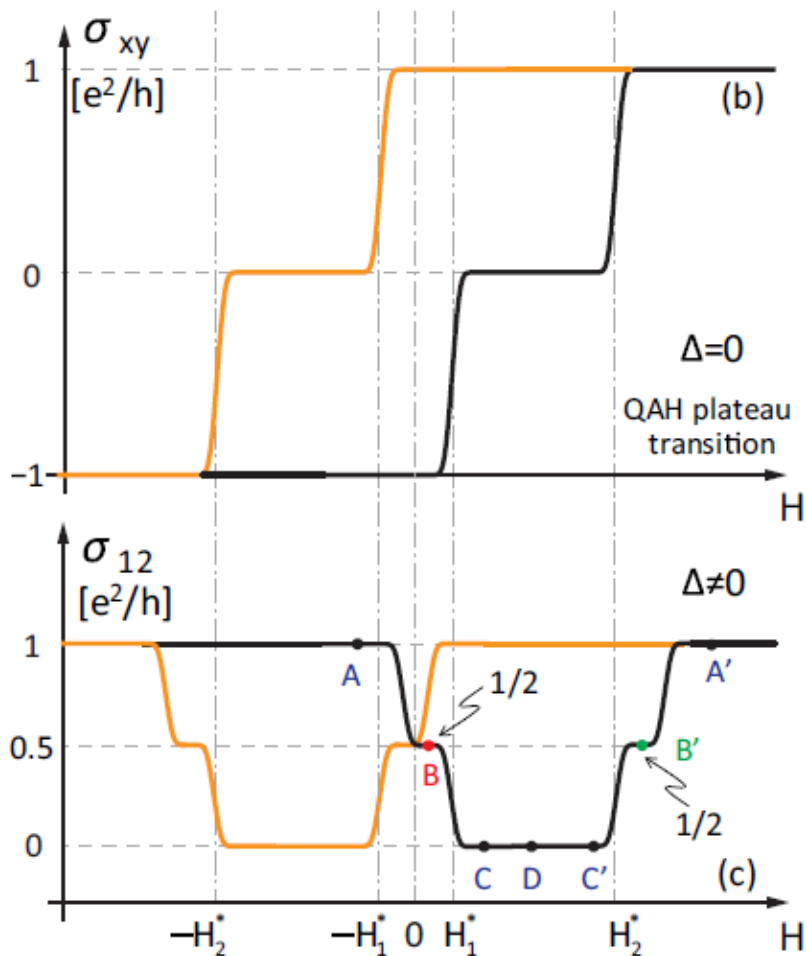
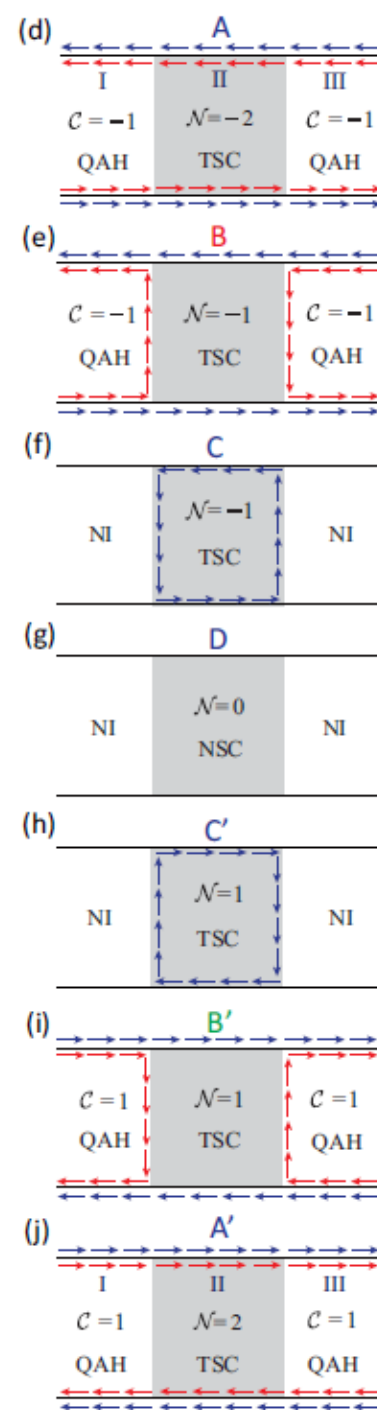
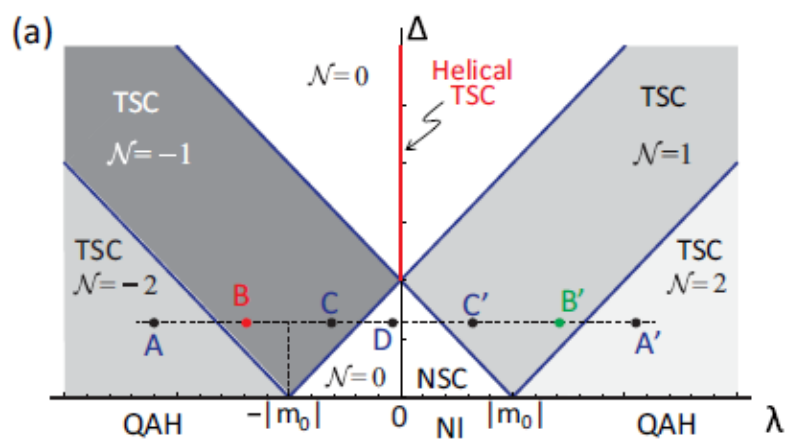
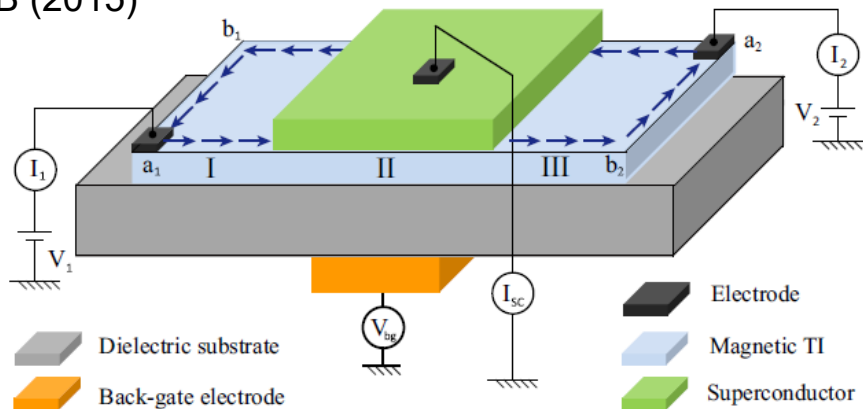
- Hybridization gap
- Magnetic gap
- SC gap

( $\mu = 0$  is assumed here)



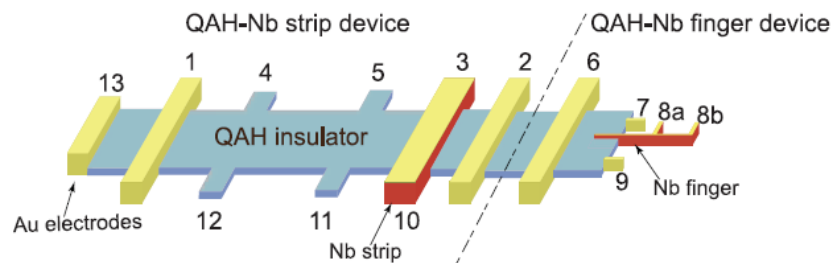
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Wang, PRB (2015)

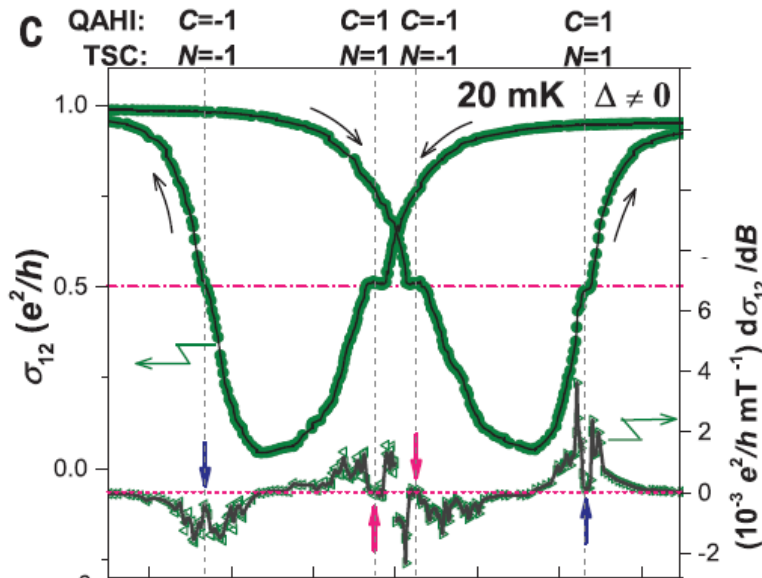
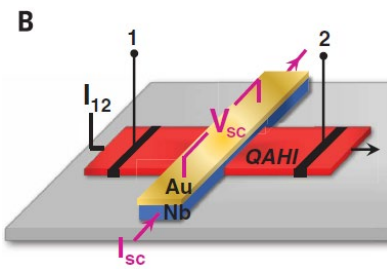
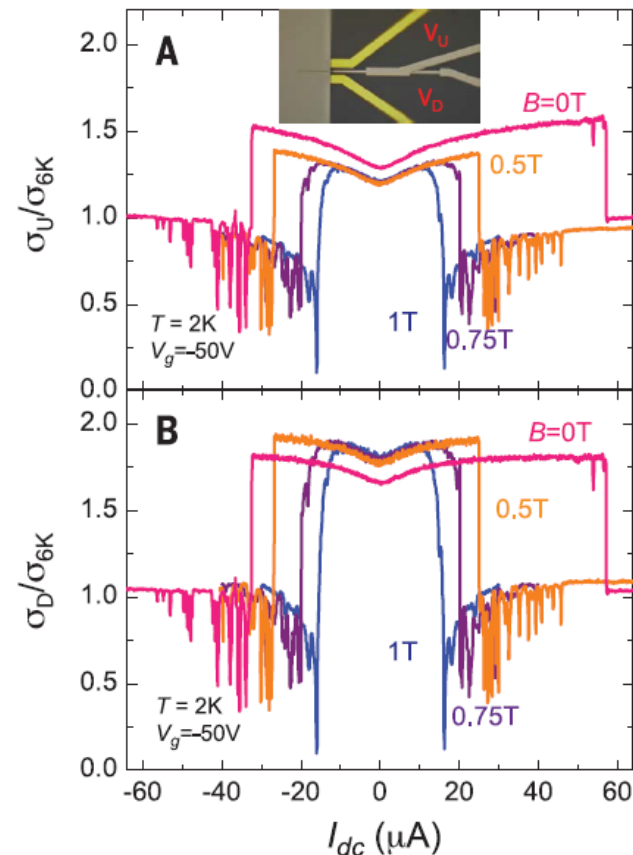
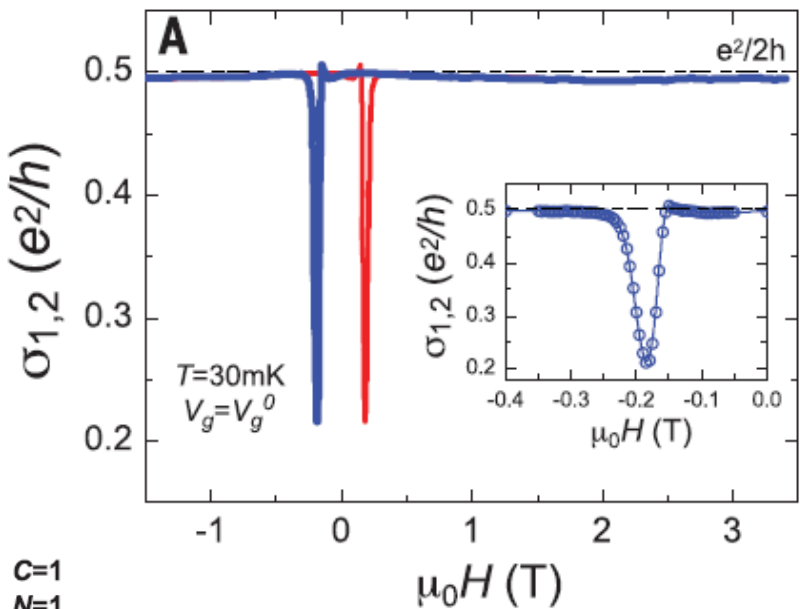


He et al., Science (2017) -- retracted

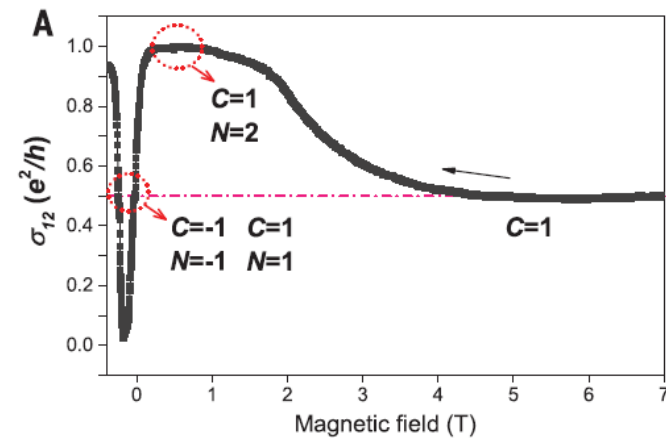
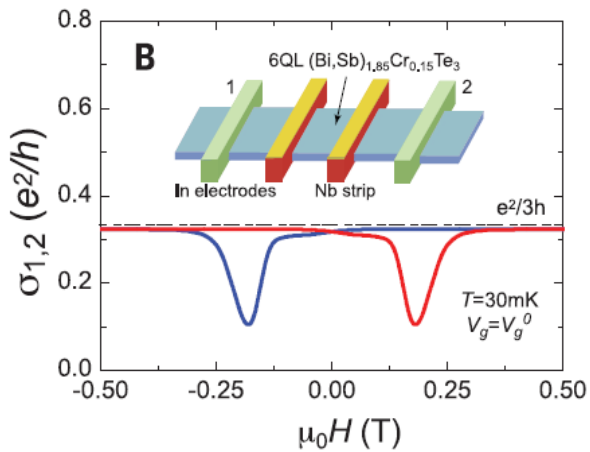
# Proximity Effect in QAHI



Kayalha et al., Science (2020)



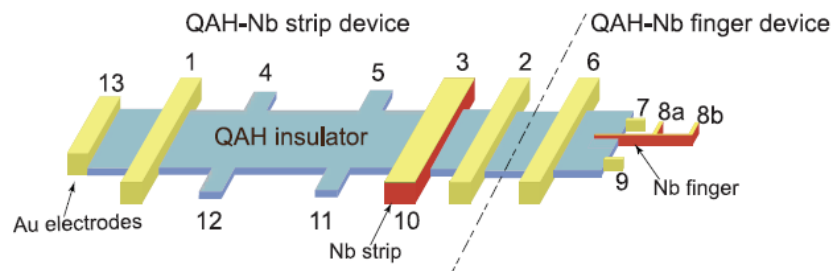
He et al., Science (2017) -- retracted



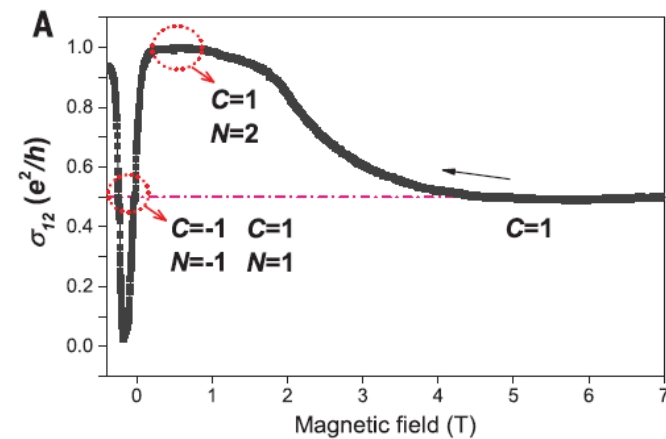
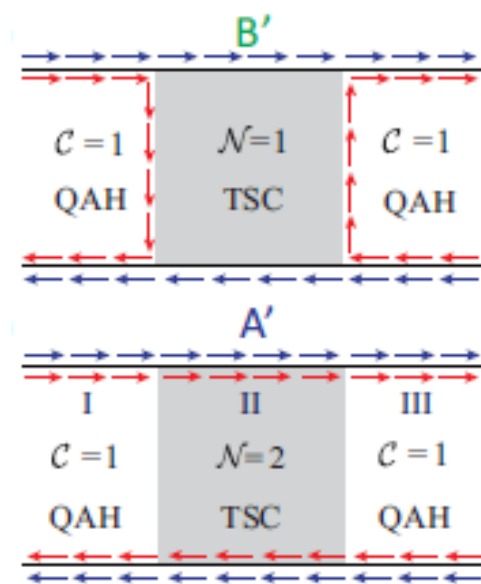
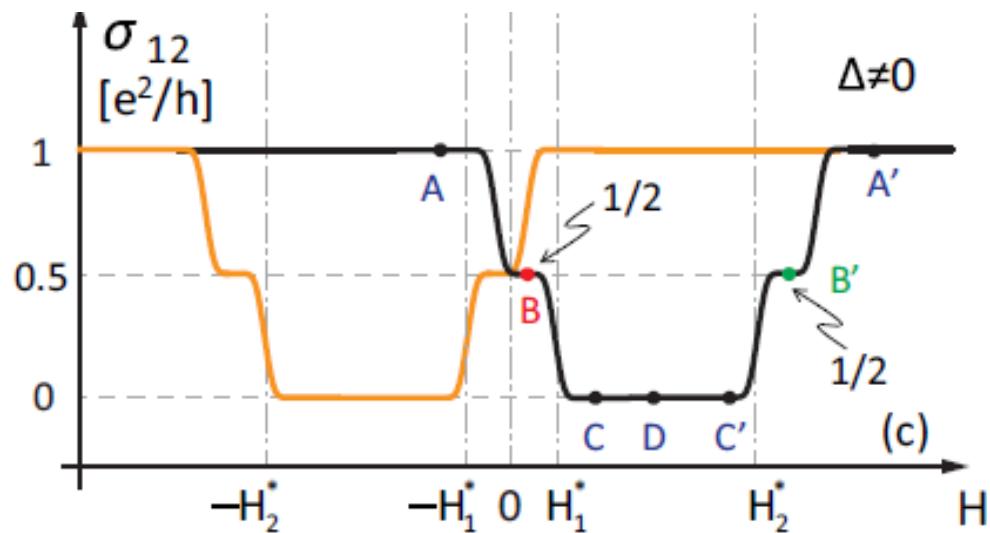
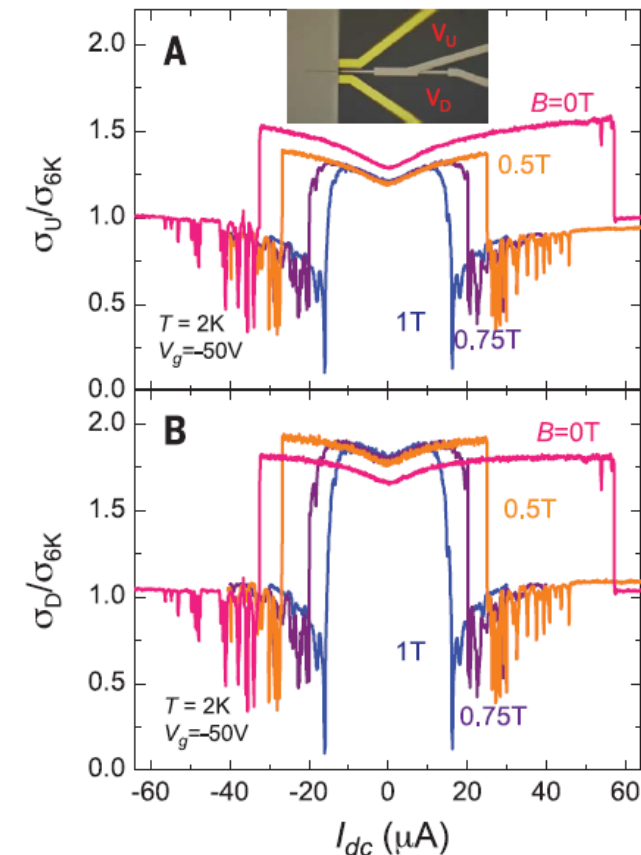
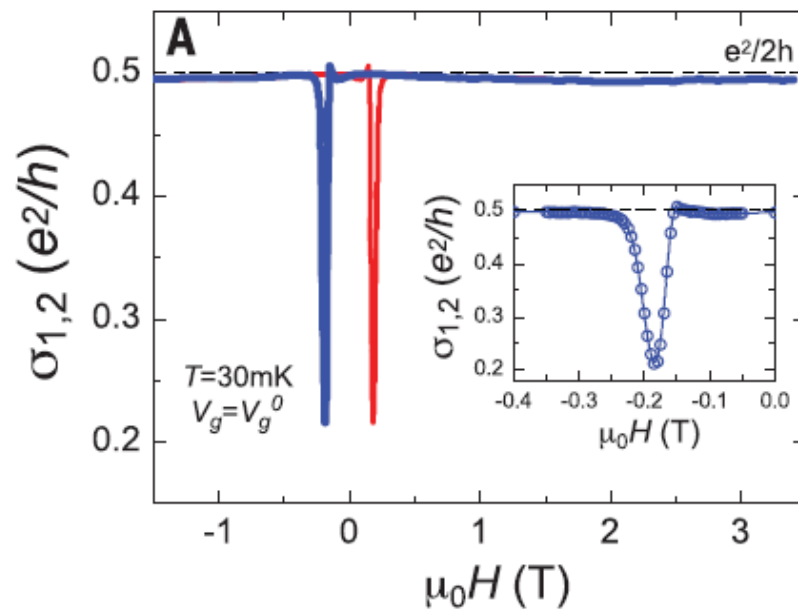
He et al., Science (2017) -- retracted



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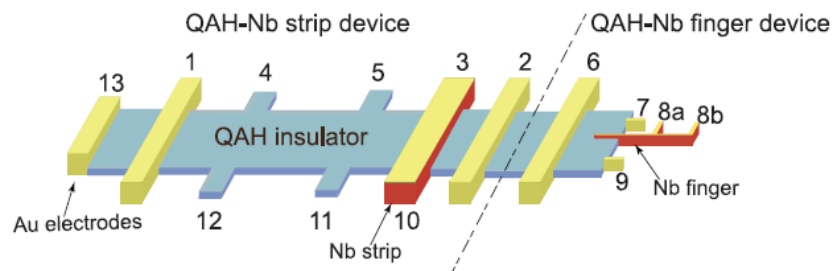


Kayalha et al., Science (2020)

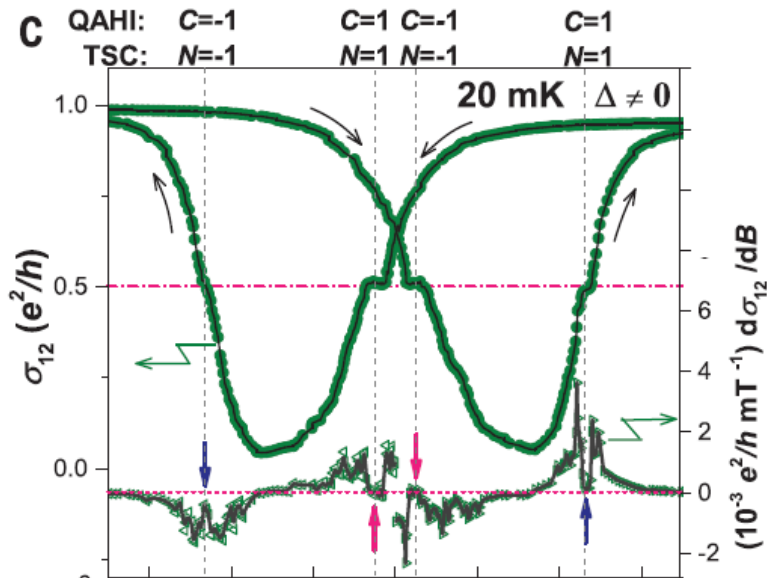
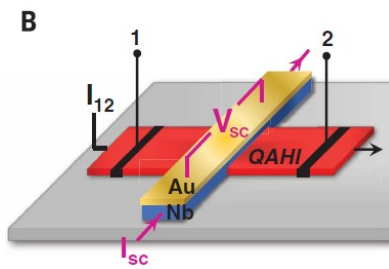
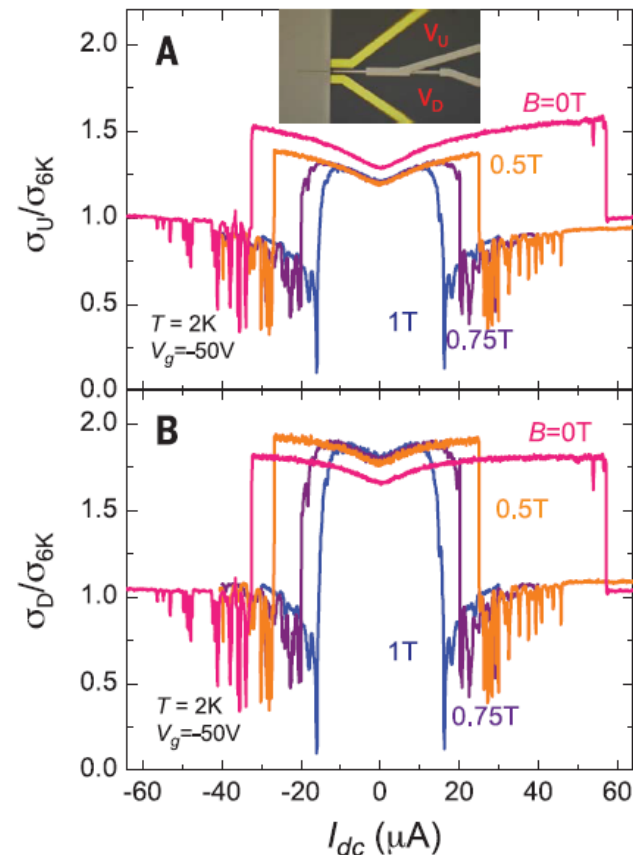
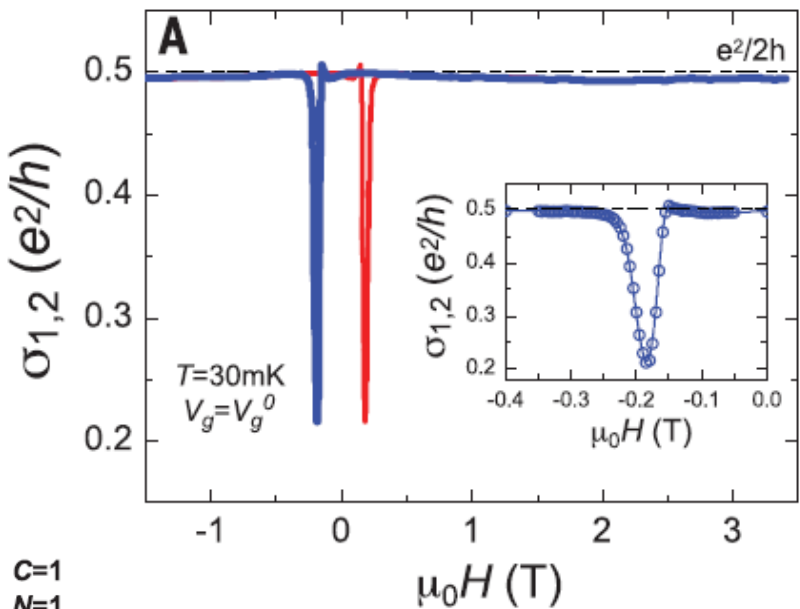


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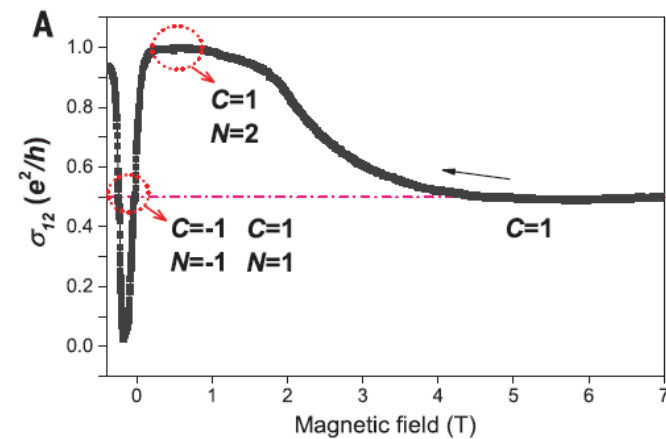
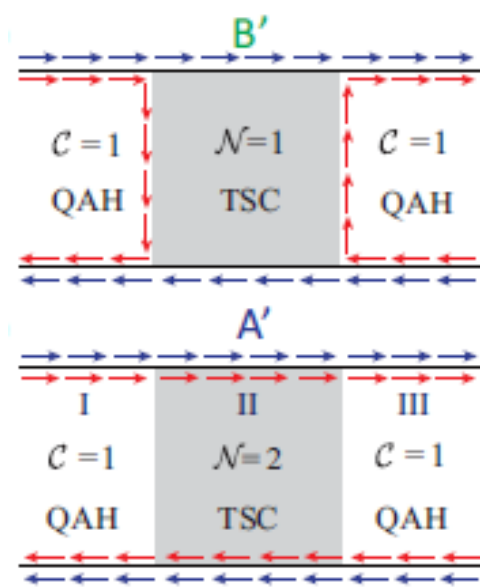
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Kayalha et al., Science (2020)

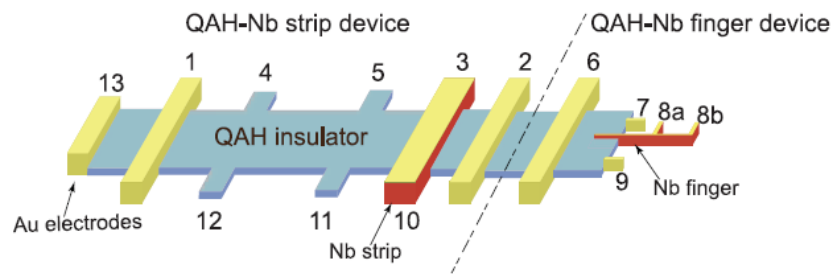


He et al., Science (2017) -- retracted

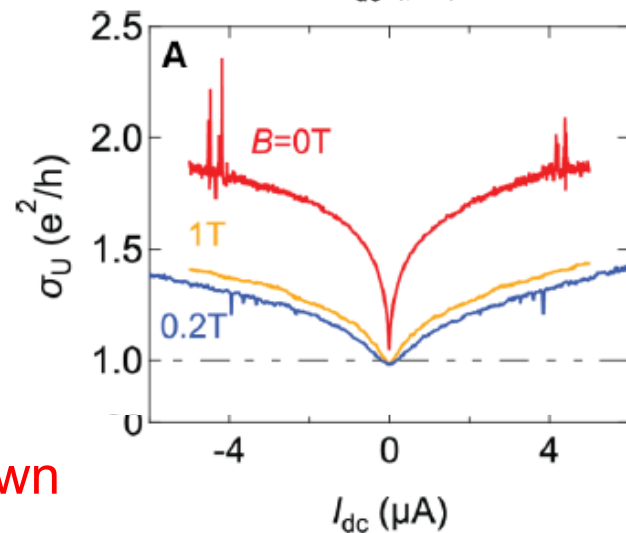
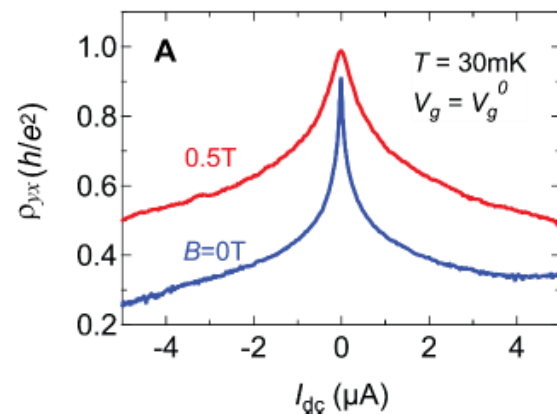
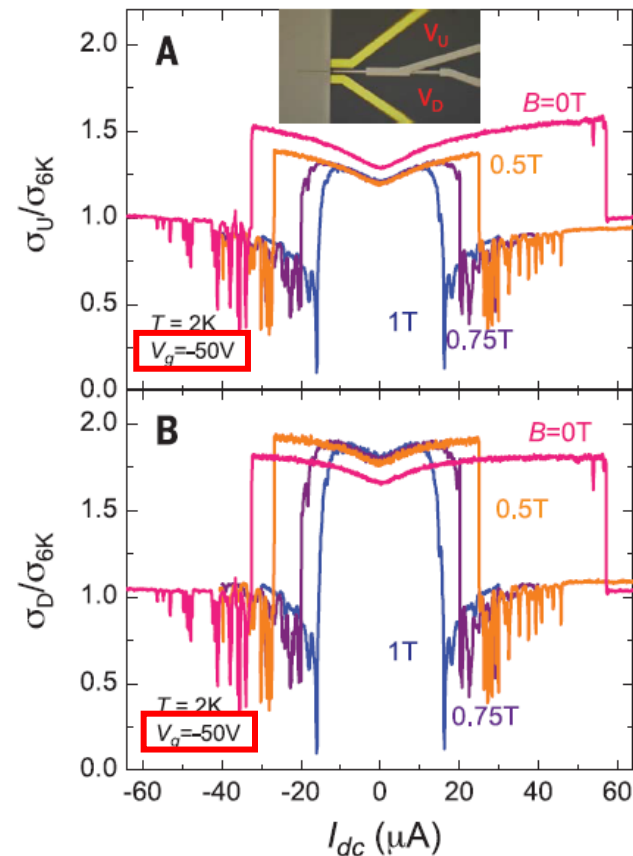
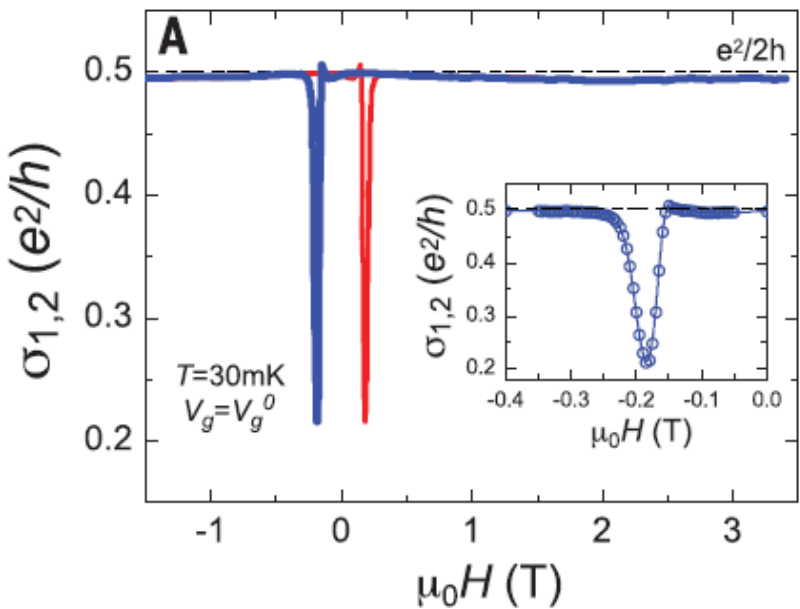


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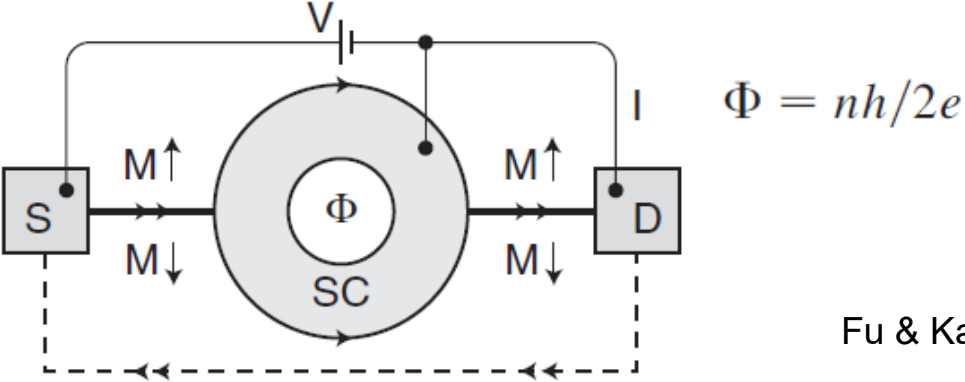
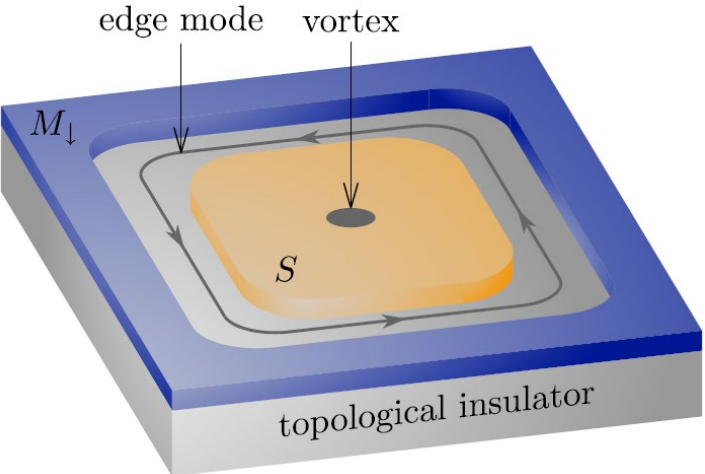


Kayalha et al., Science (2020)



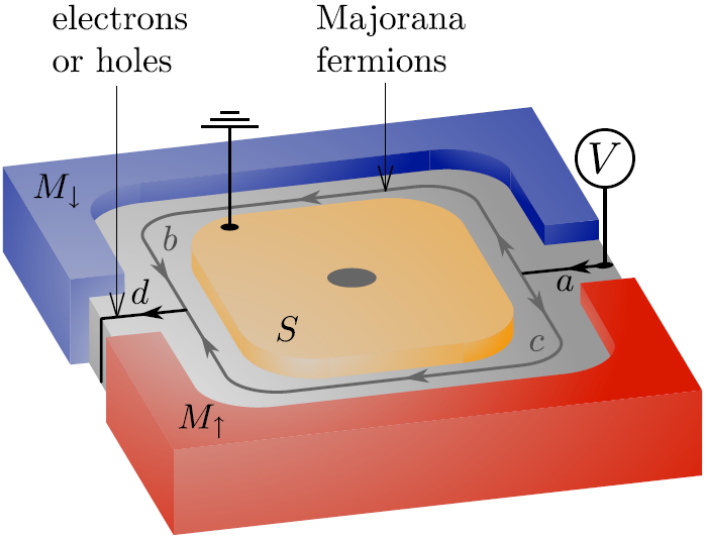
Current-induced breakdown

# Chiral Majorana Fermions in Proximitized 3D Topological Insulator / QAHI

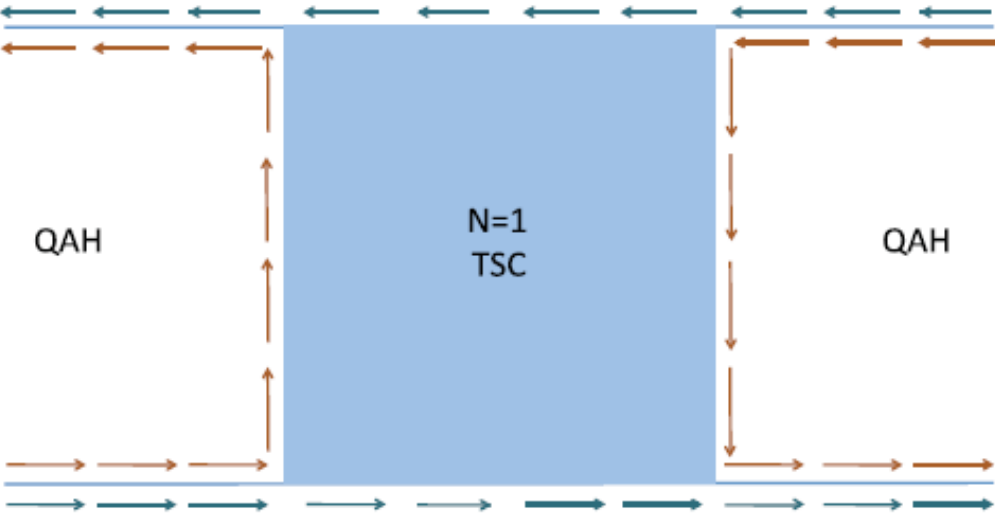


Fu & Kane, PRL (2009)

$$I = (-1)^n \frac{e}{h} \frac{\pi k_B T \sin(eV \delta L / v_M)}{\sinh(\pi k_B T \delta L / v_M)}$$

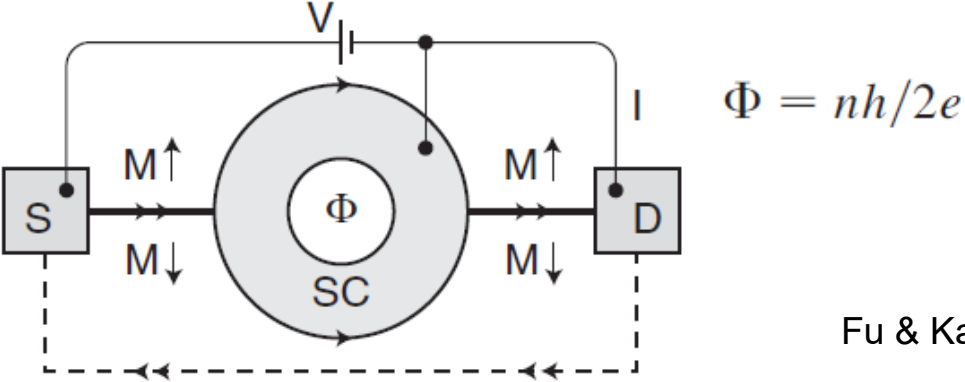
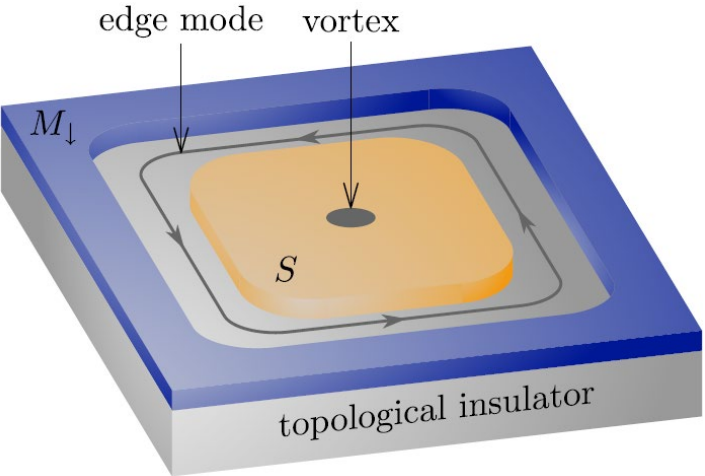


Akhmerov et al., PRL (2009)



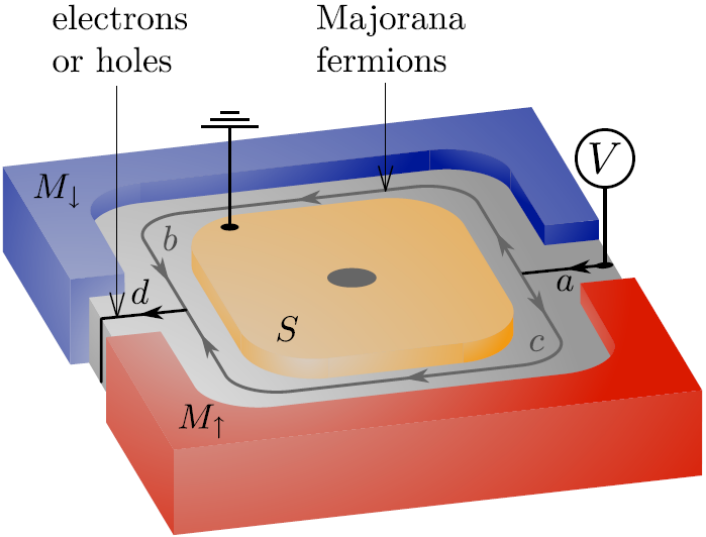
Chung et al., PRB (2011)

# Chiral Majorana Fermions in Proximitized 3D Topological Insulator / QAHI

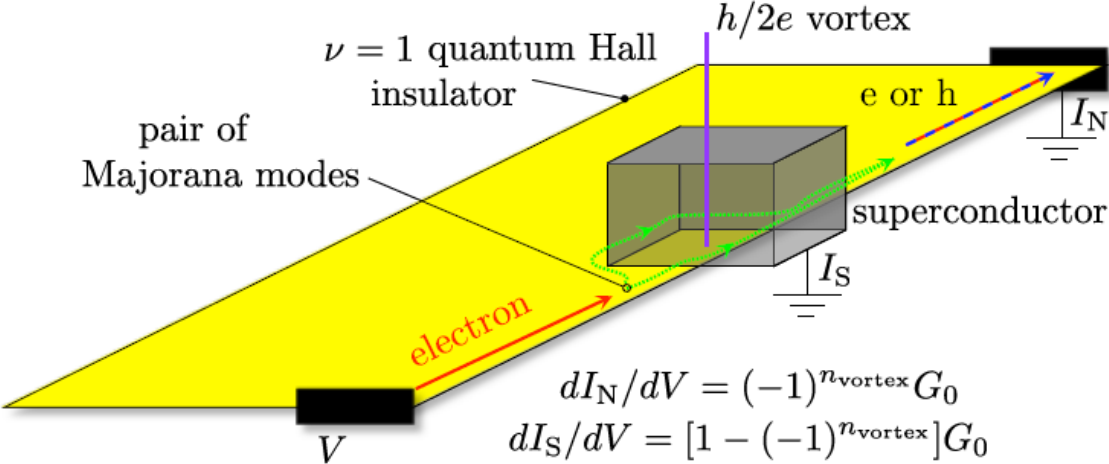


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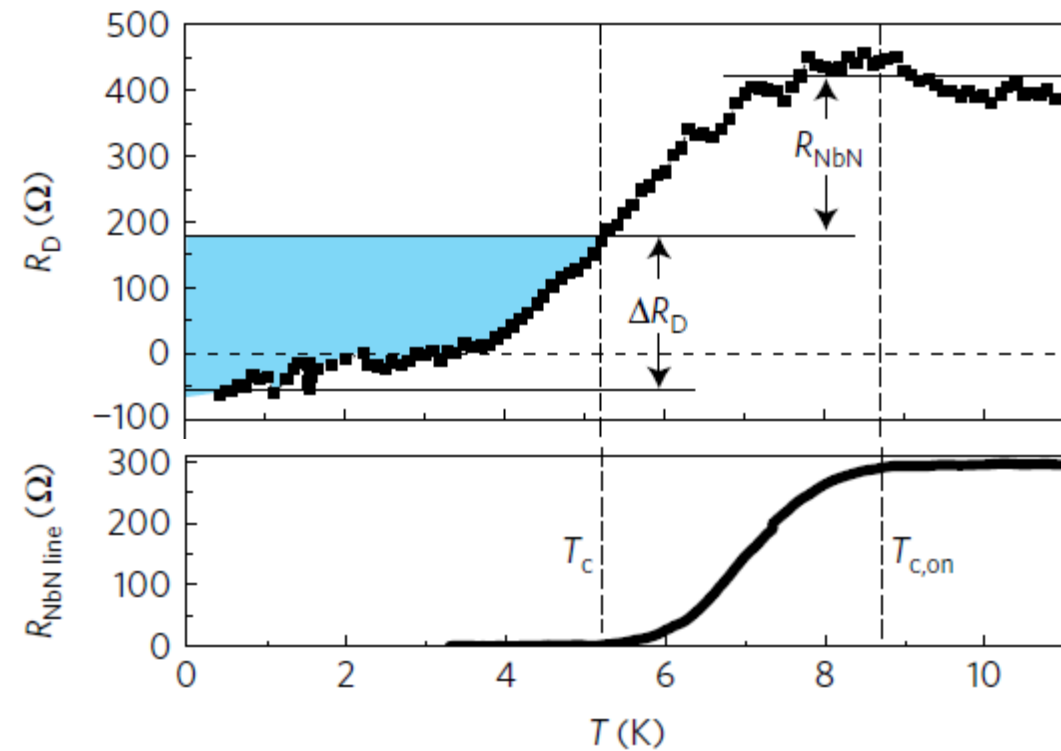
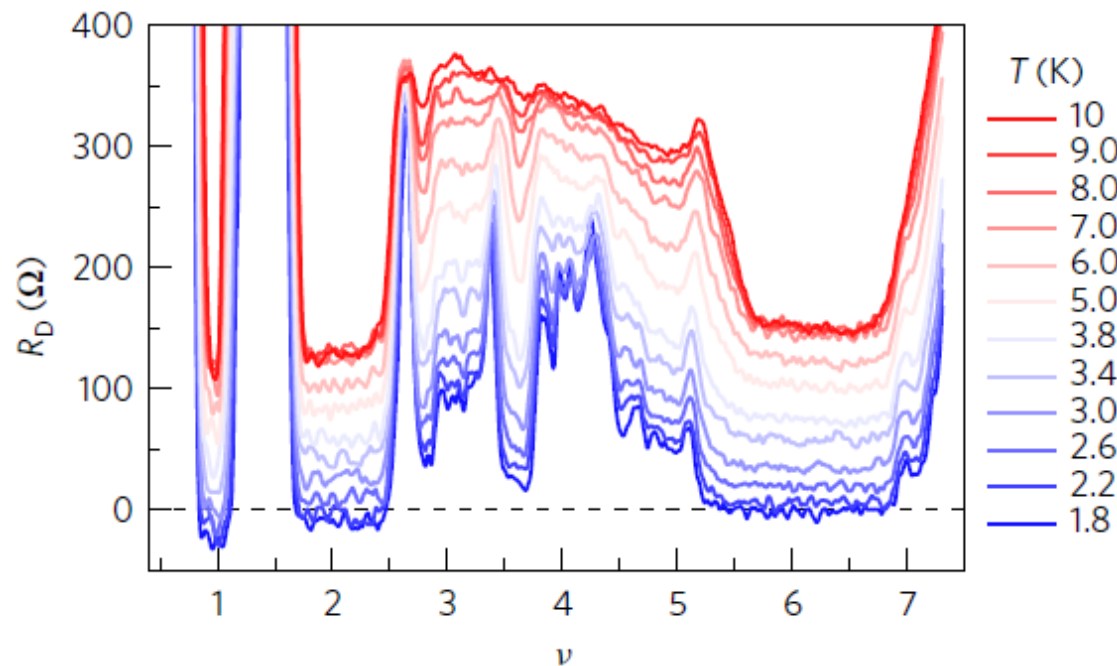
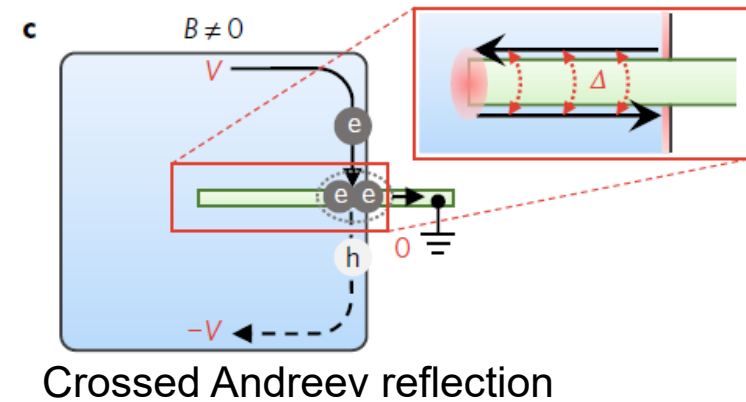
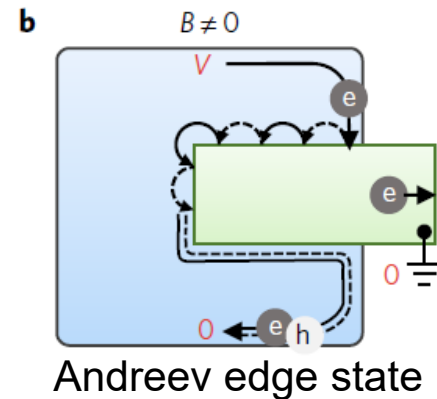
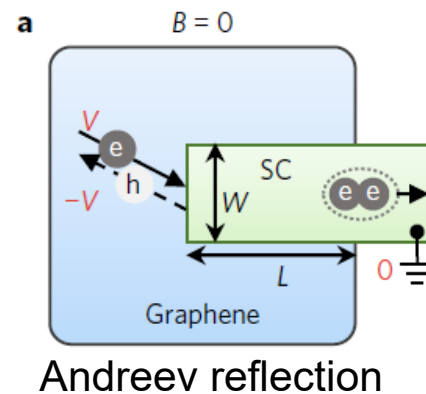
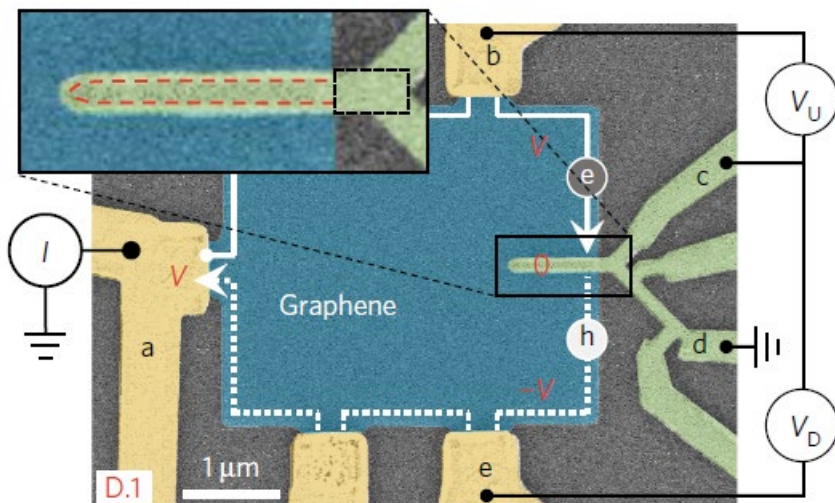
Akhmerov et al., PRL (2009)



Beenakker, condmatjclub (2017)

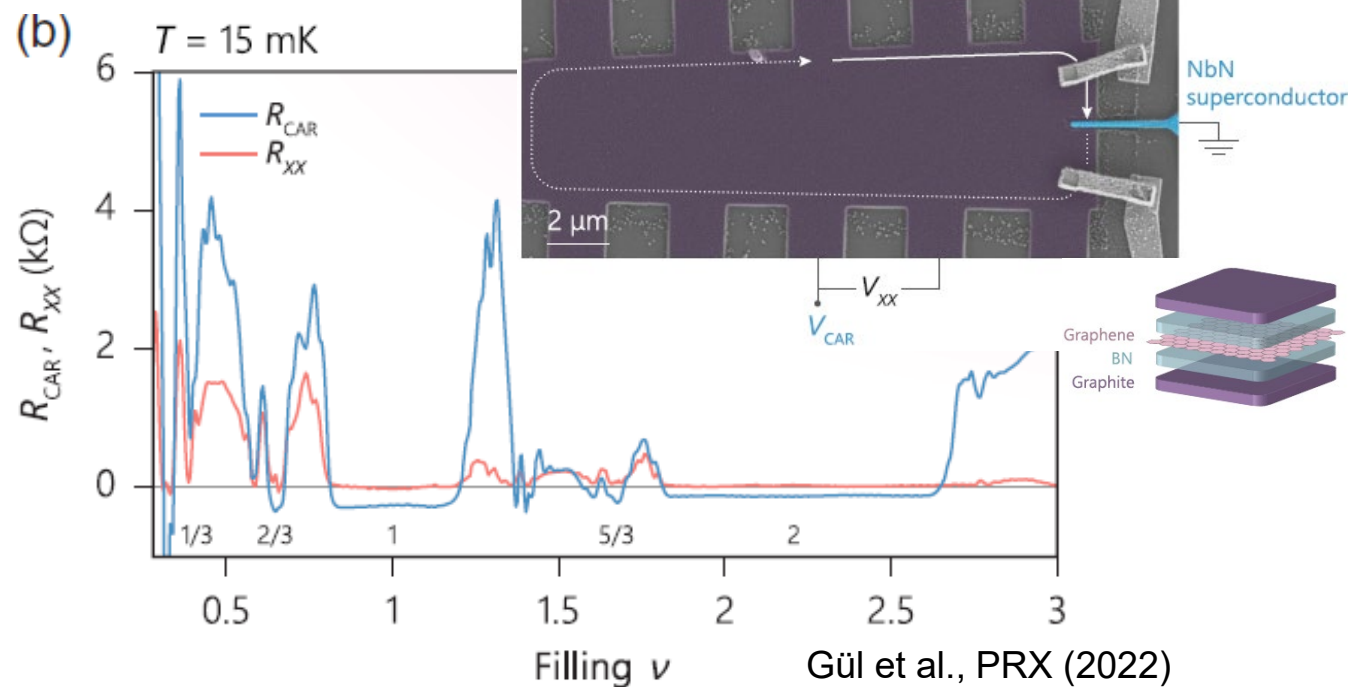
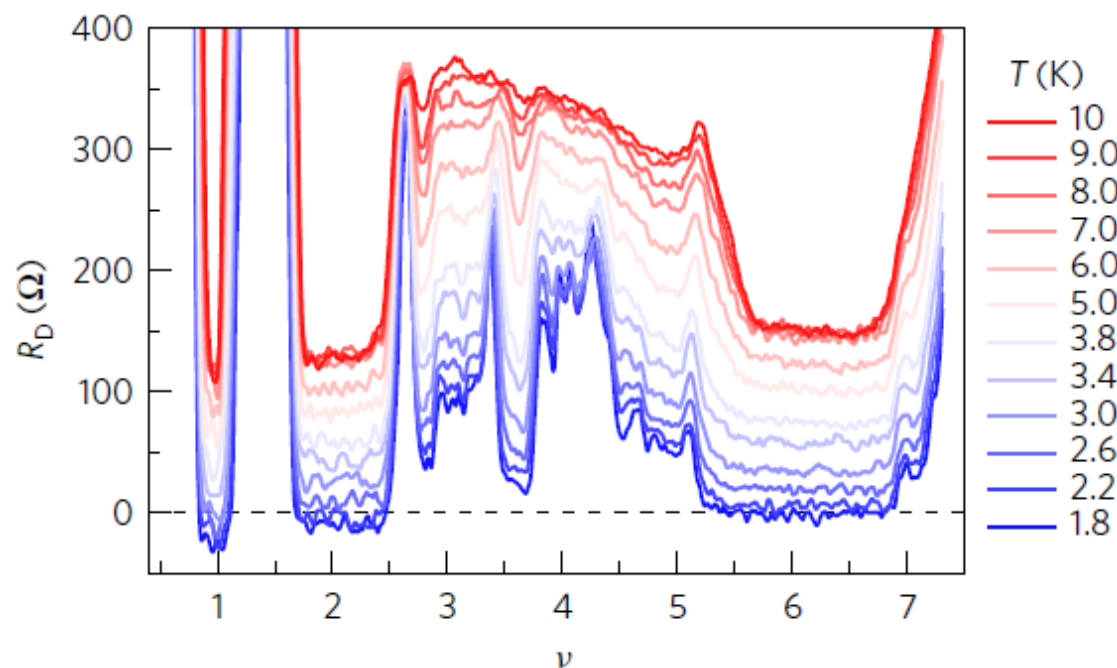
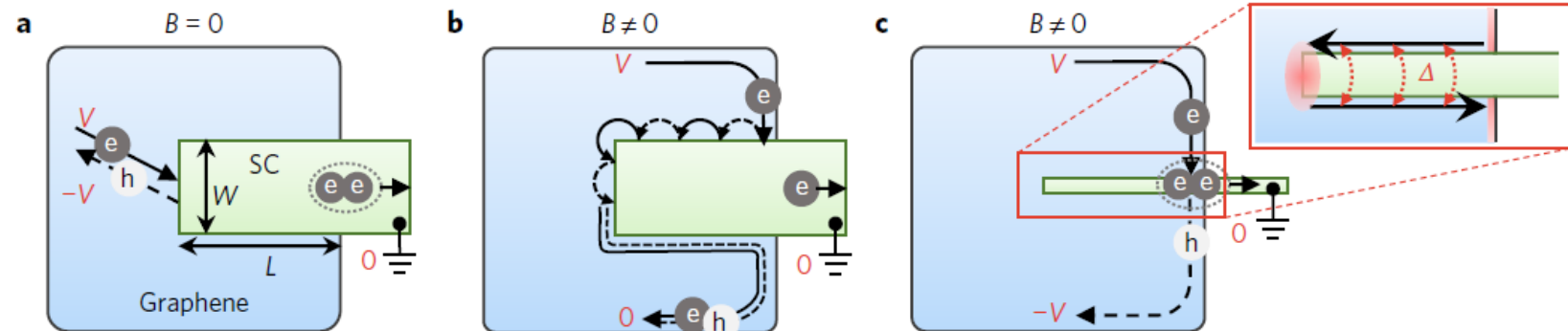
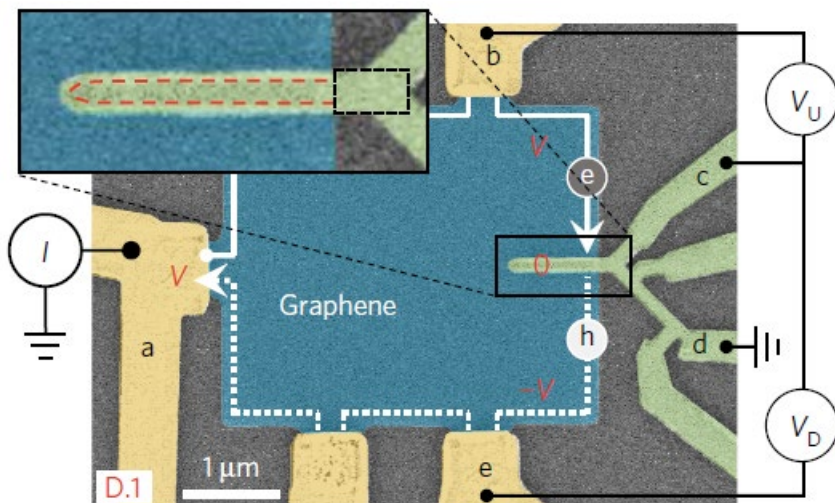
# SC Proximity effect in Quantum Hall Systems

Lee et al., Nat. Phys. (2017)



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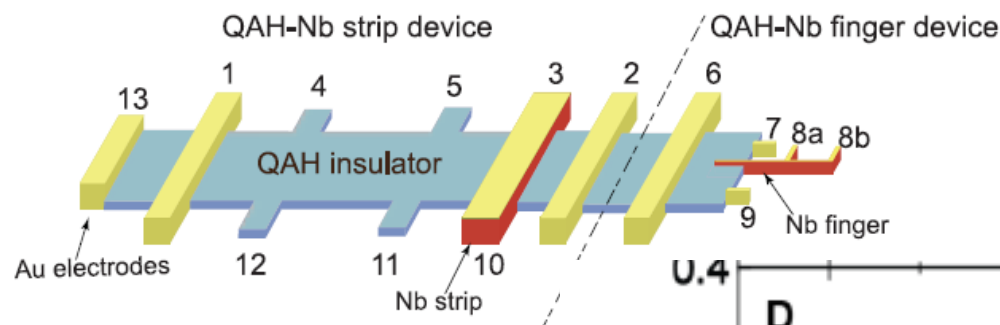
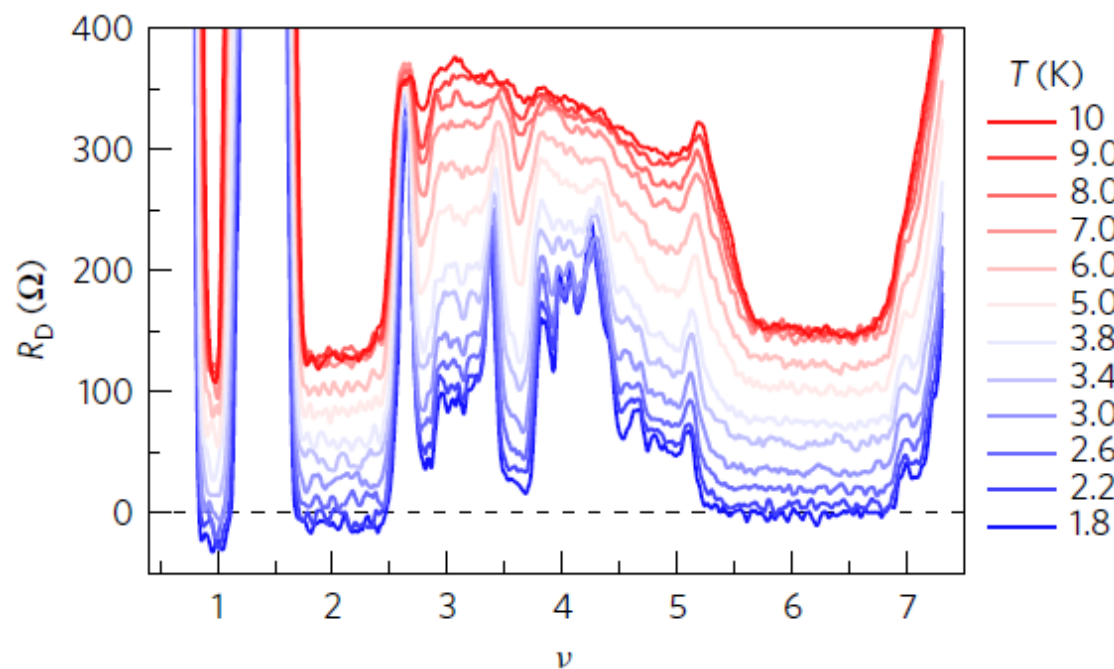
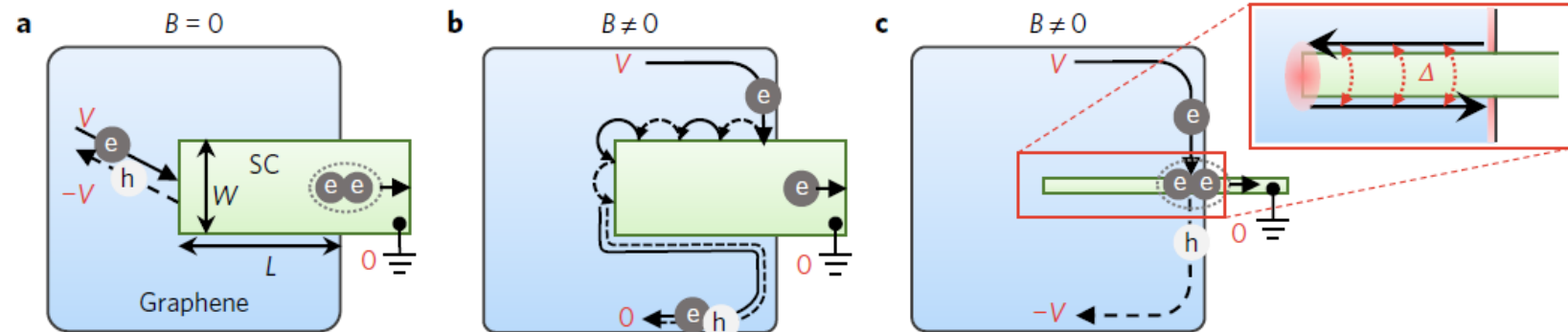
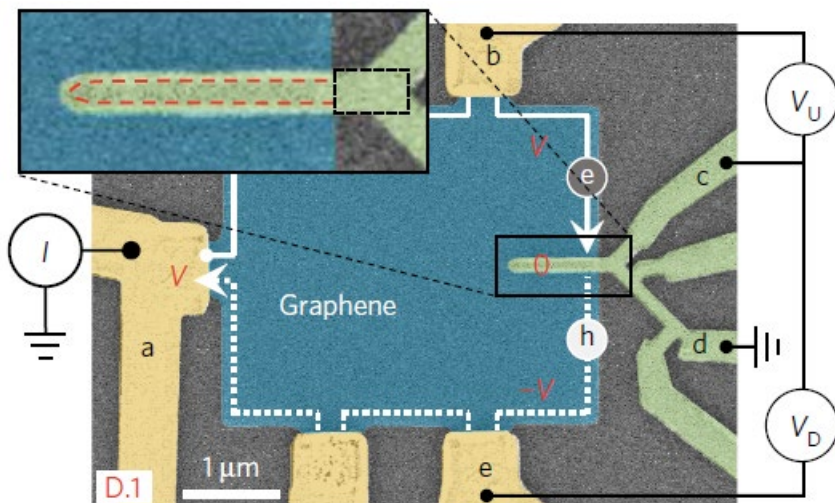
Lee et al., Nat. Phys. (2017)



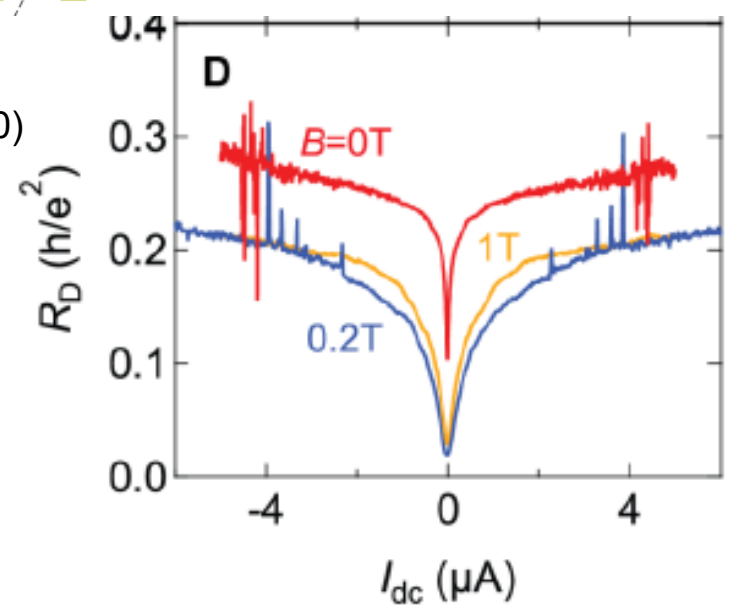
Gül et al., PRX (2022)

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Lee et al., Nat. Phys. (2017)

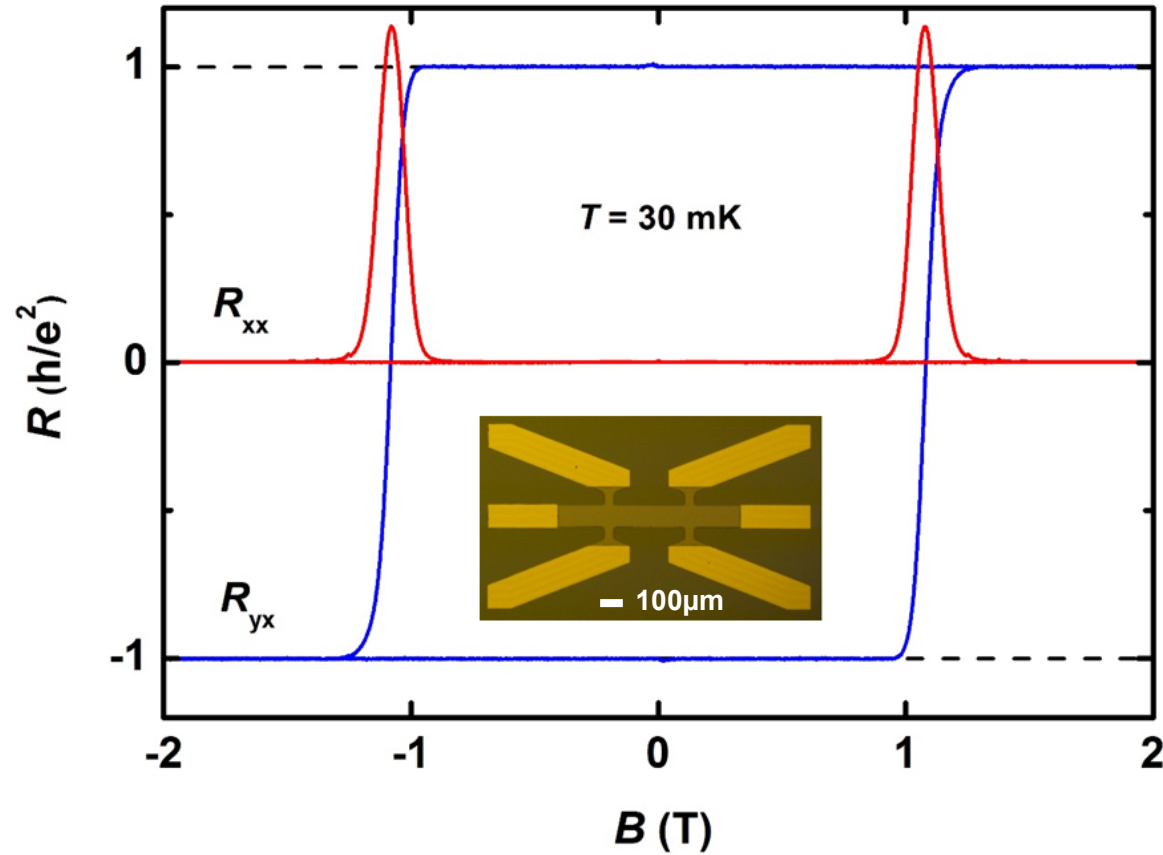
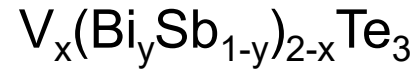


Kayyalha et al., Science (2020)





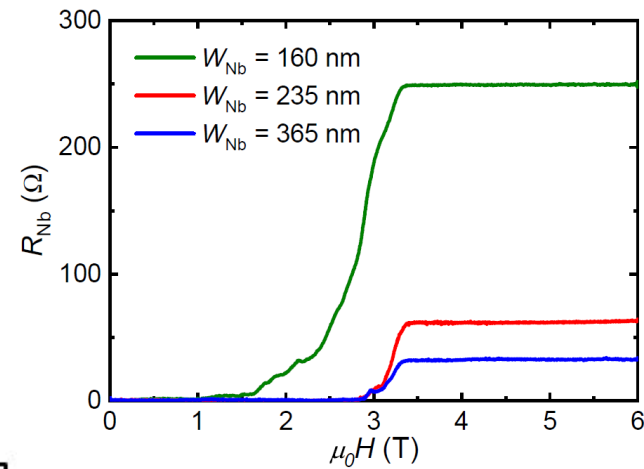
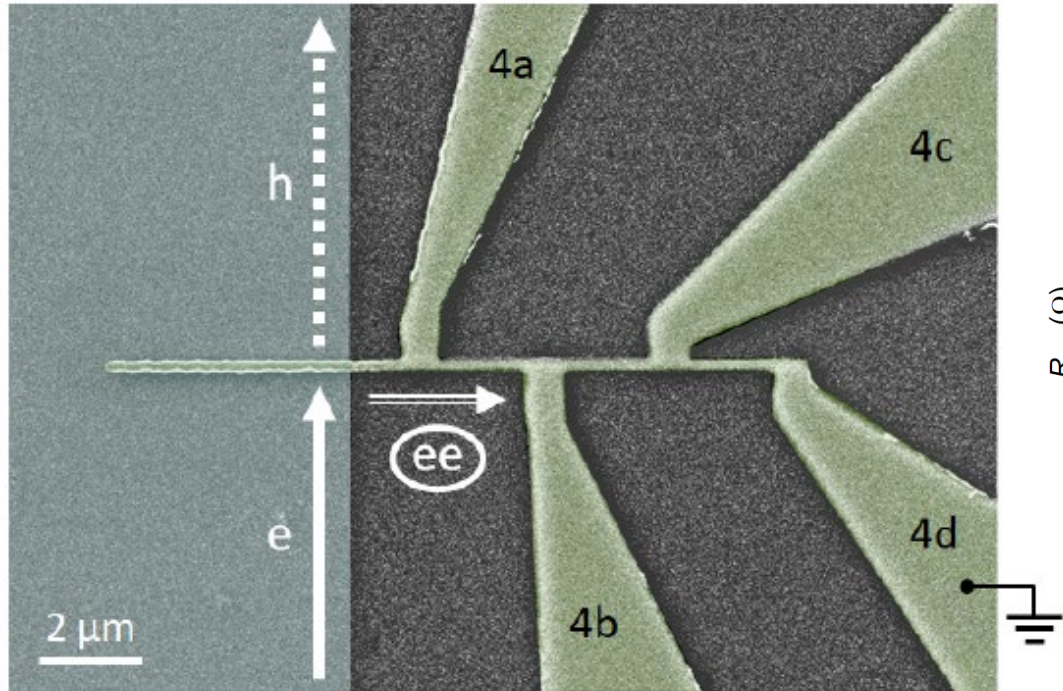
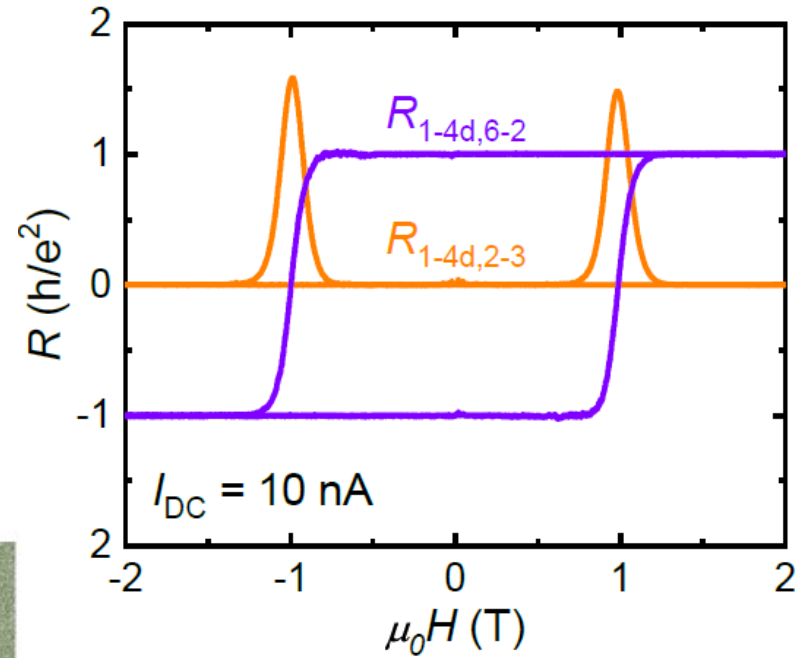
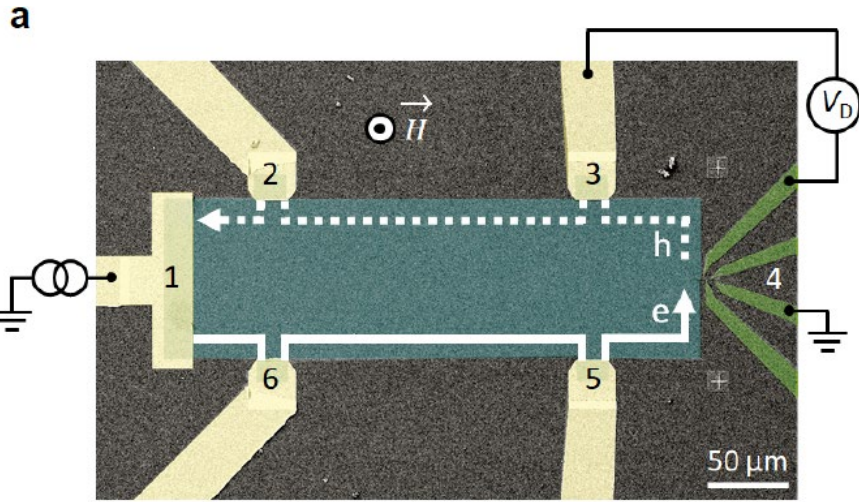
# Quantum Anomalous Hall Effect in Cologne



Achieved in 2020 in Cologne

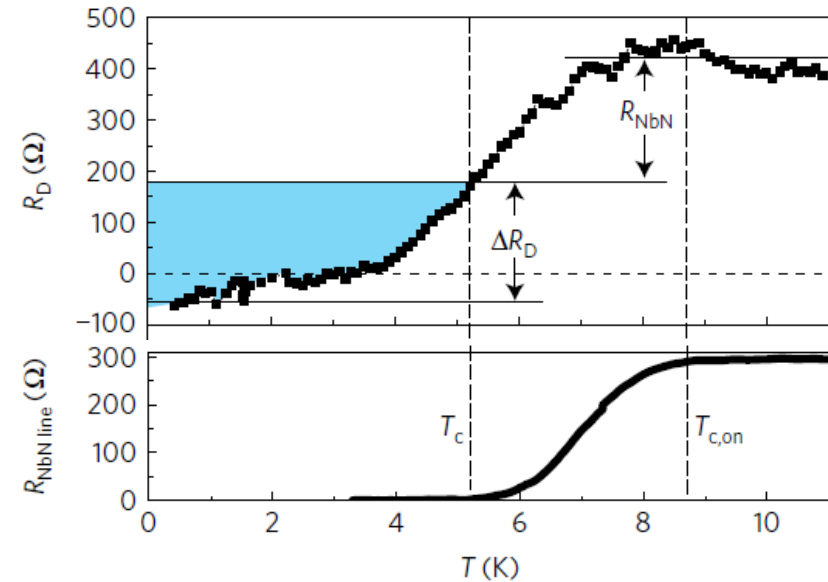
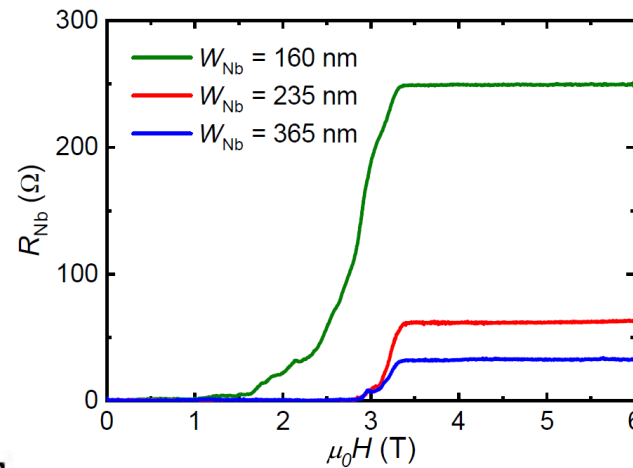
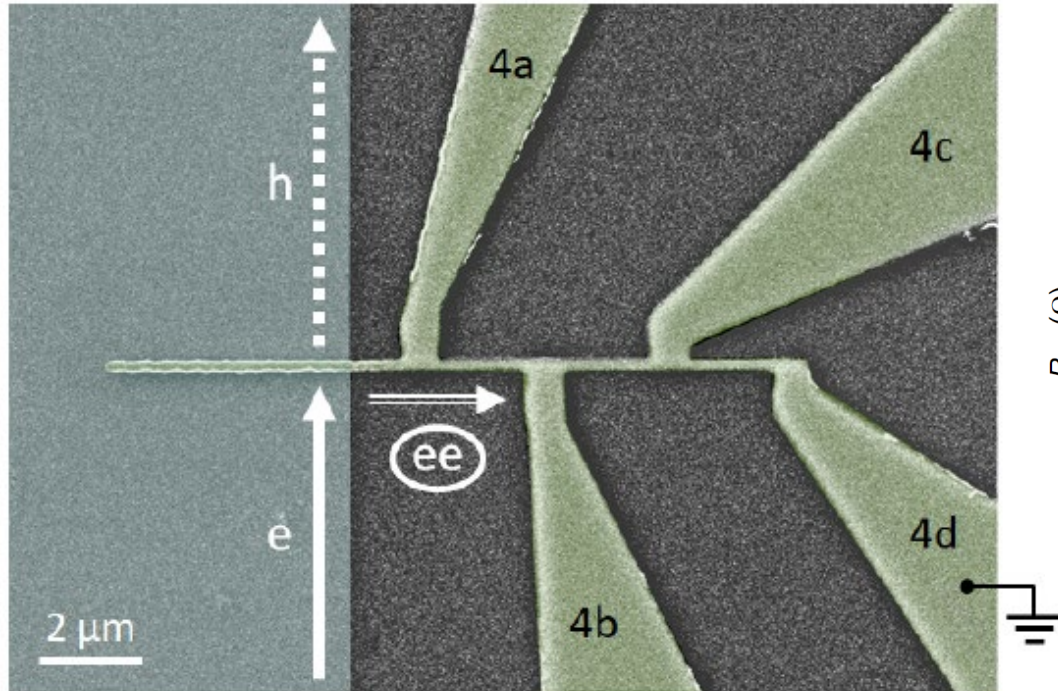
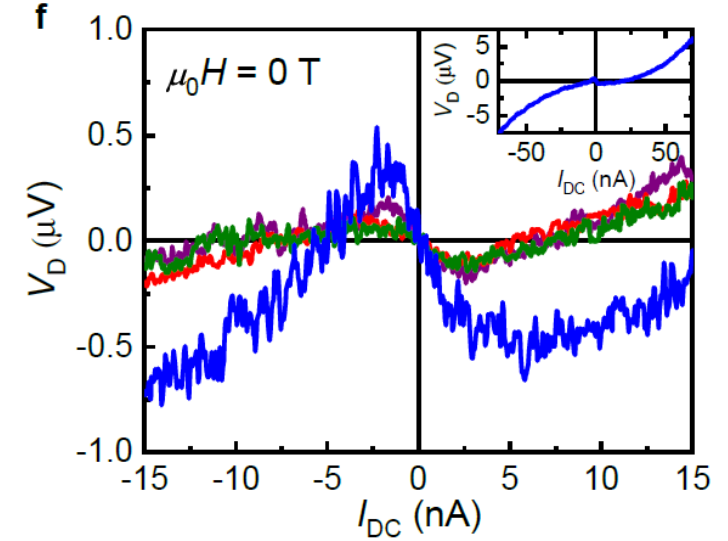
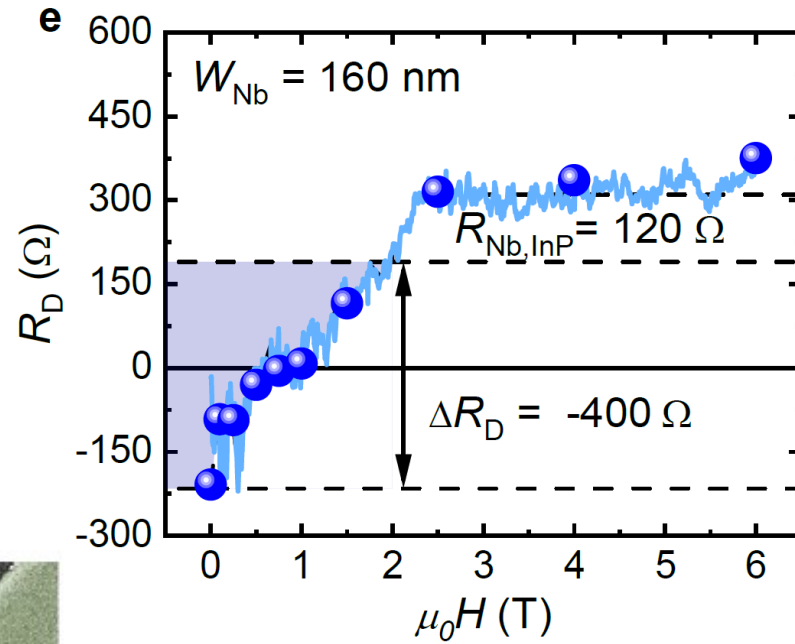
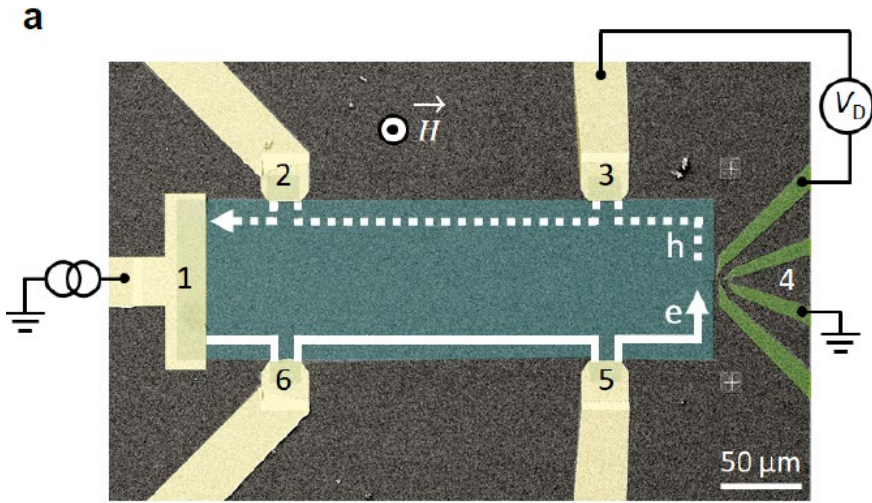
# Proximitizing QAHI and Crossed Andreev Reflection

Uday et al., arXiv:2307.08578



# Proximitizing QAH and Crossed Andreev Reflection

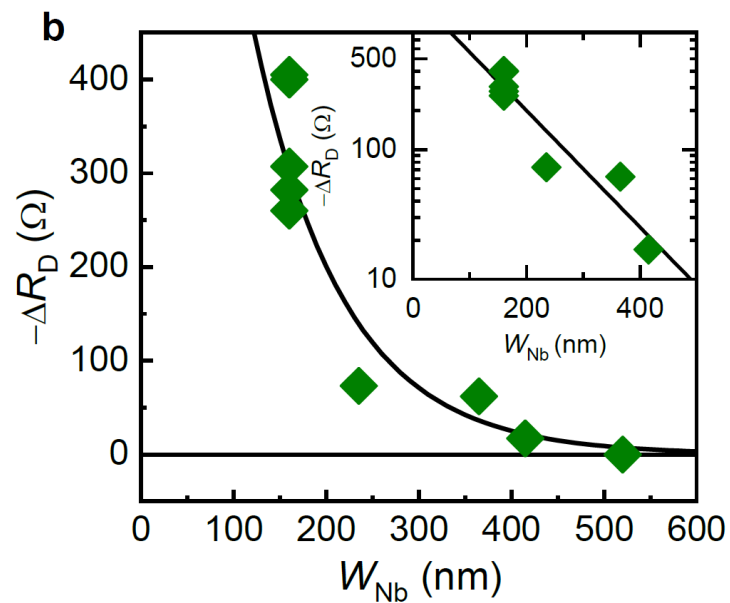
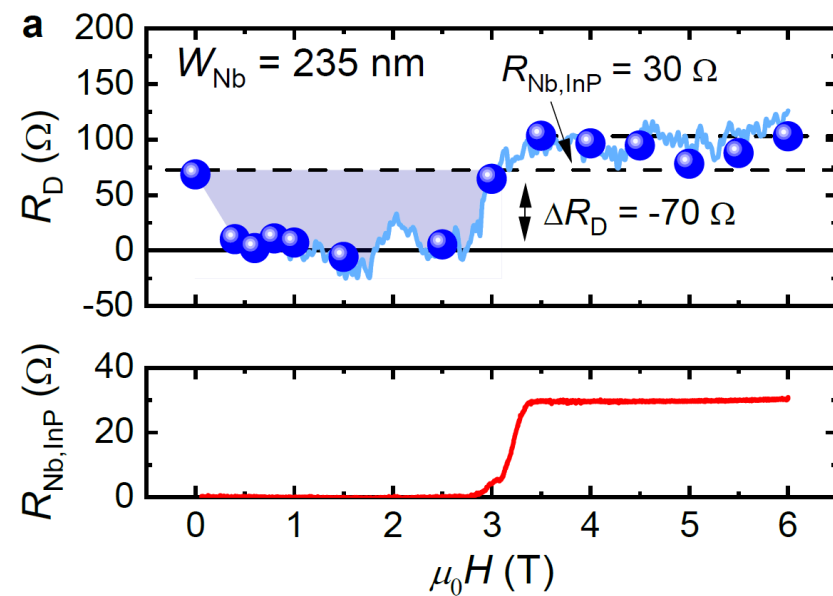
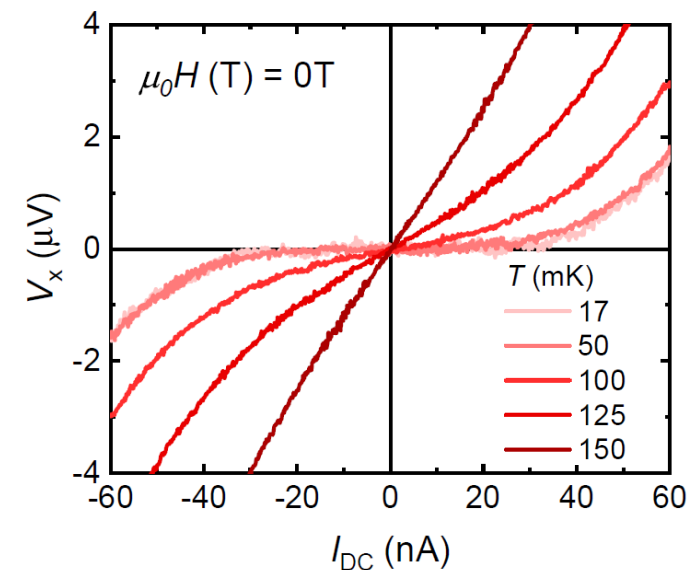
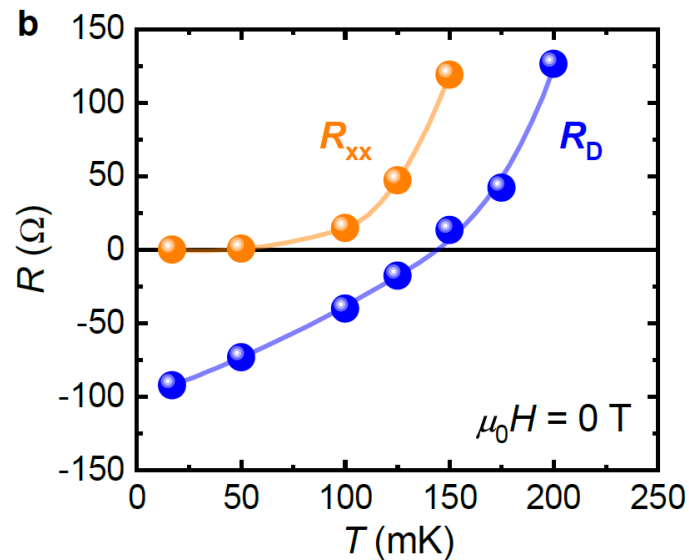
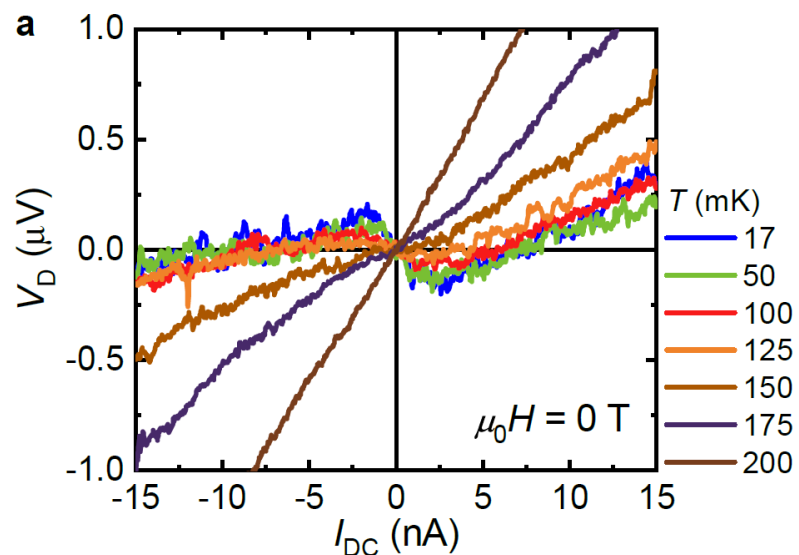
Uday et al., arXiv:2307.08578



Lee et al., Nat. Phys. (2017)

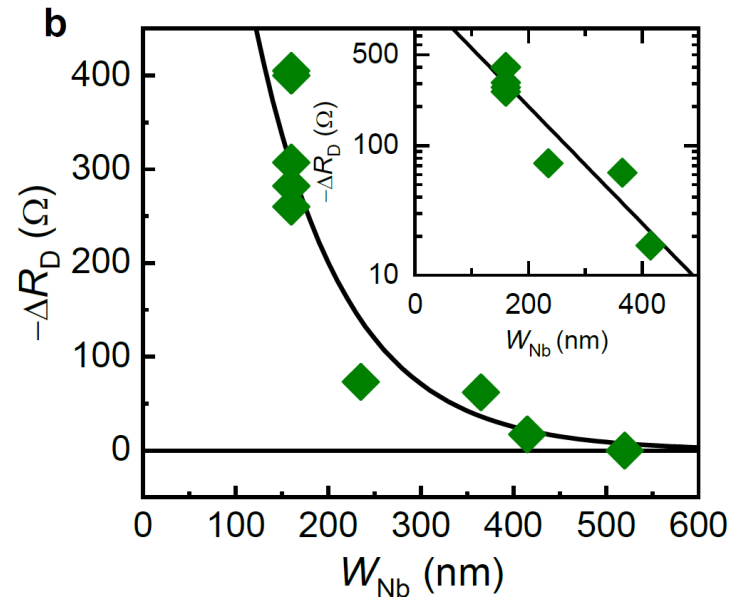
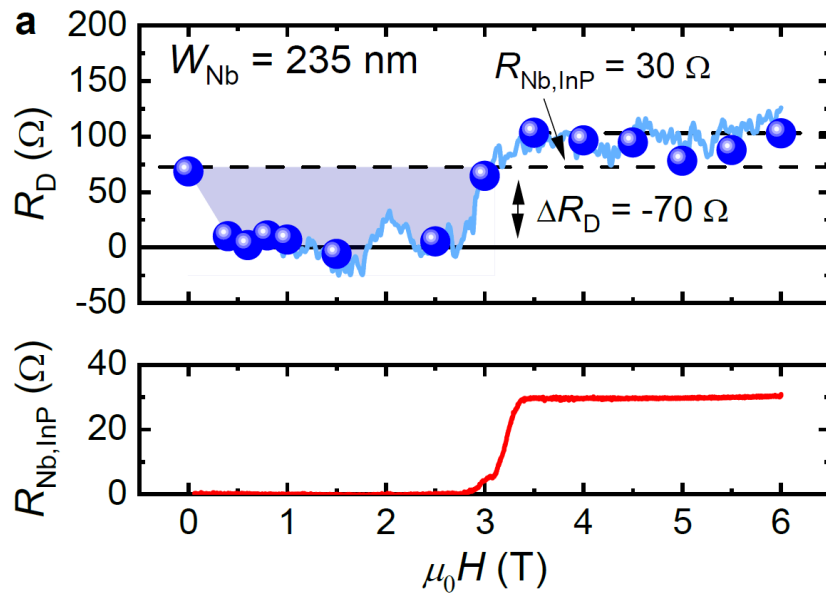
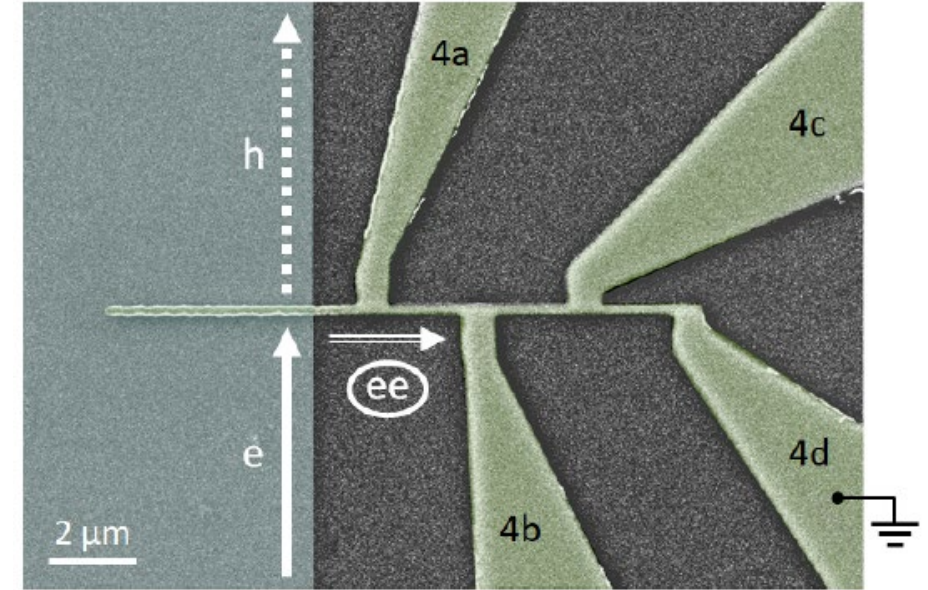
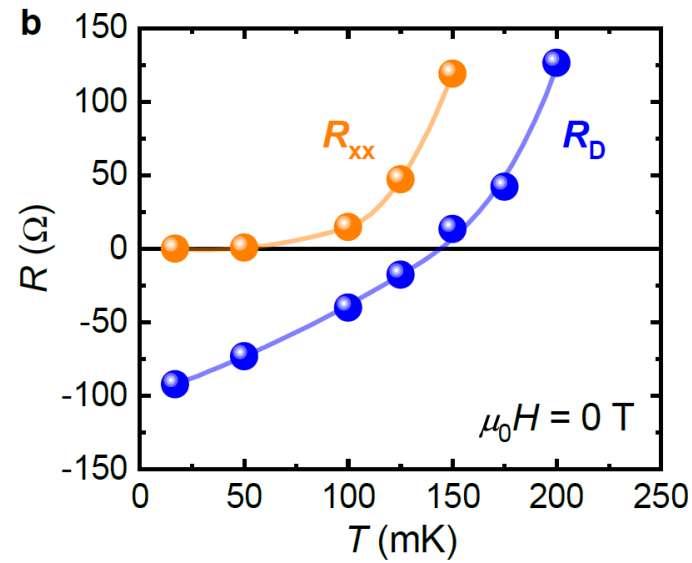
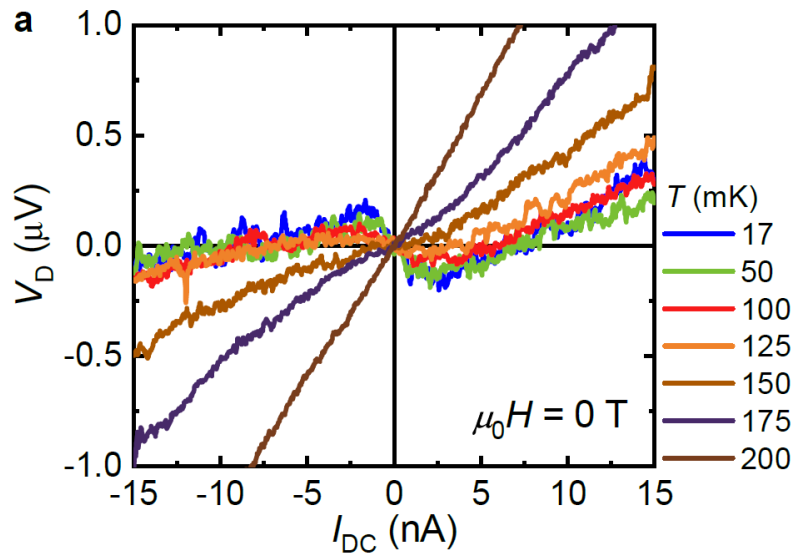
# Proximitizing QAHI and Crossed Andreev Reflection

Uday et al., arXiv:2307.08578



# Proximitizing QAHI and Crossed Andreev Reflection

Uday et al., arXiv:2307.08578



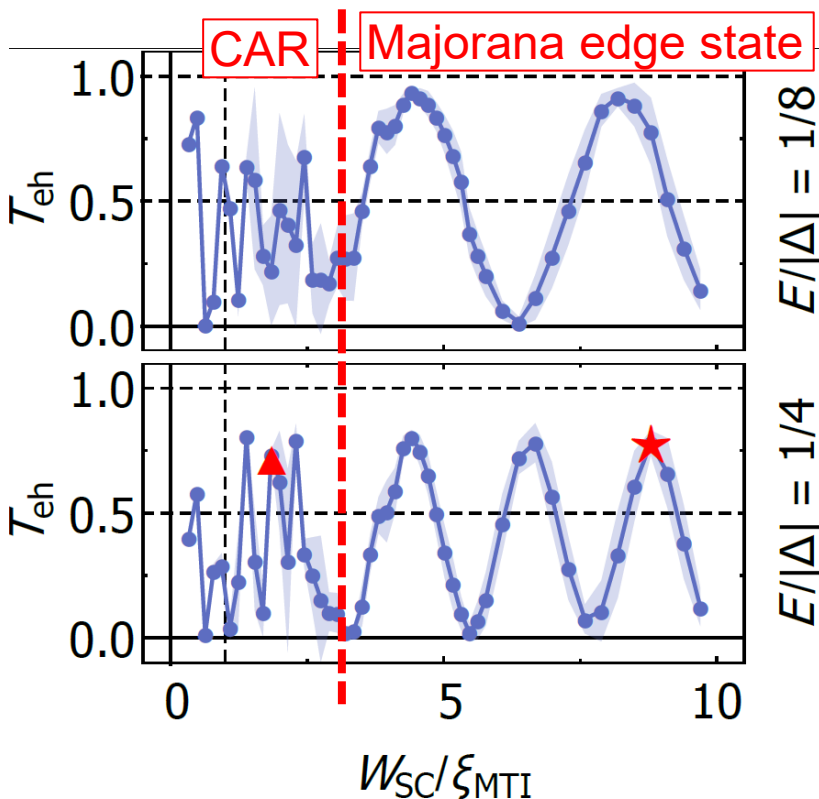
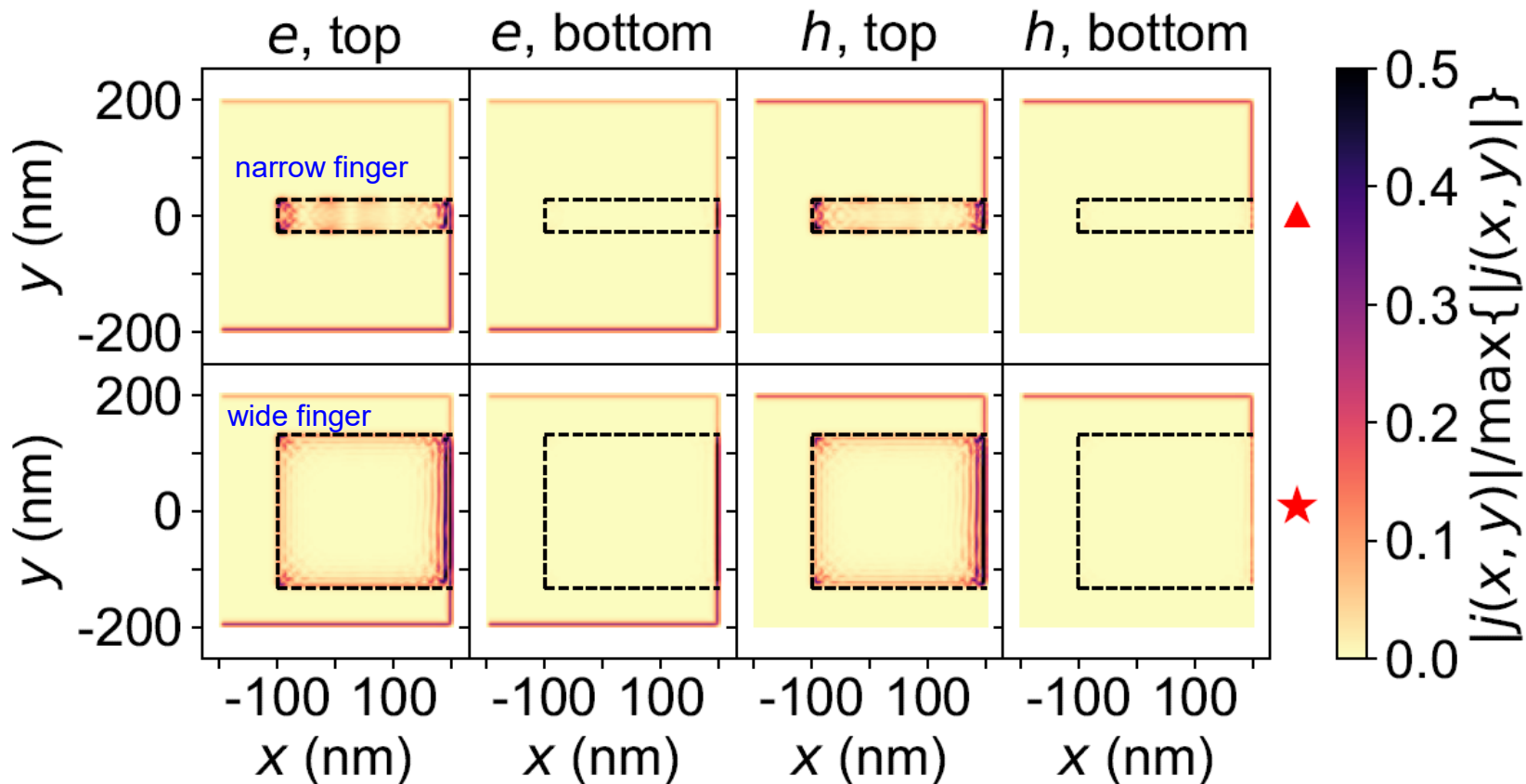
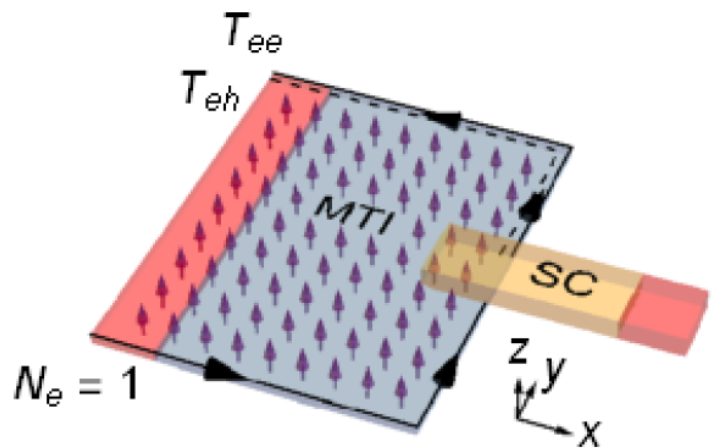
$$\xi_{\text{CAR}} \approx 100 \text{ nm}$$

$$\xi_{\text{Nb}} \approx 30 \text{ nm}$$

CAR is taking place probably through the proximitized surface, not through Nb

# Simulation of the Crossed Andreev Reflection in CAR

Uday et al., arXiv:2307.08578

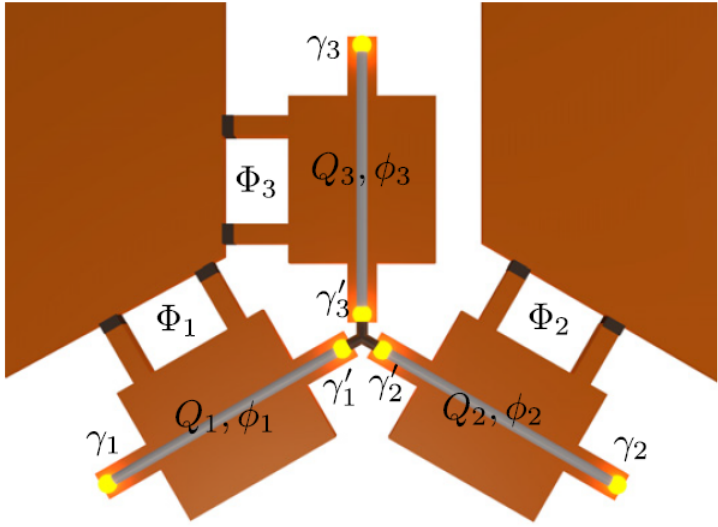
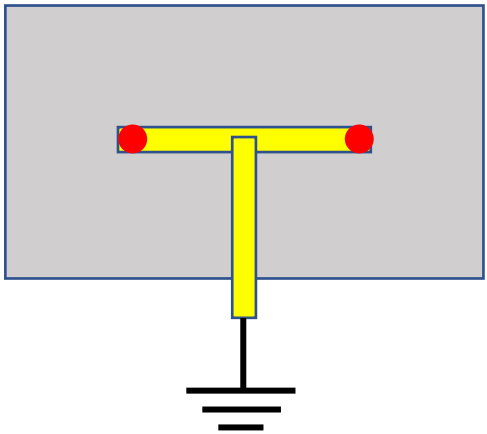
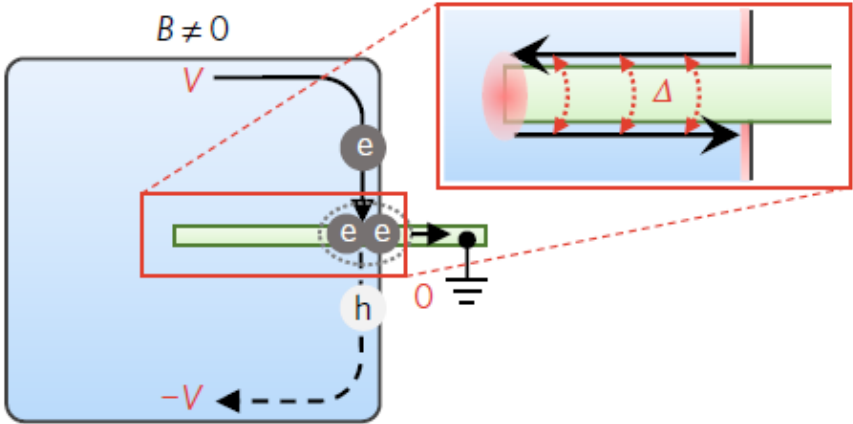


Assumptions:

- Nb contact causes electron doping
- Only the top surface is proximitized

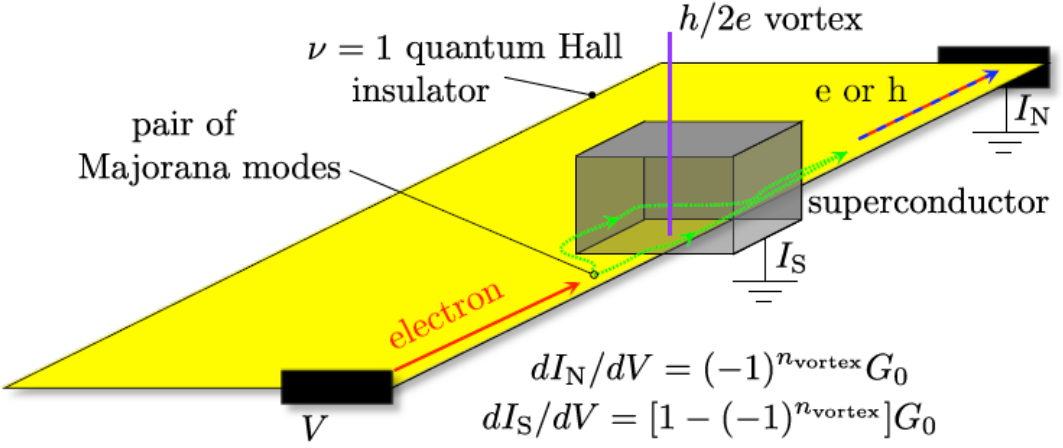
# Future Prospects

CAR process induces pair correlations in the QAH edge

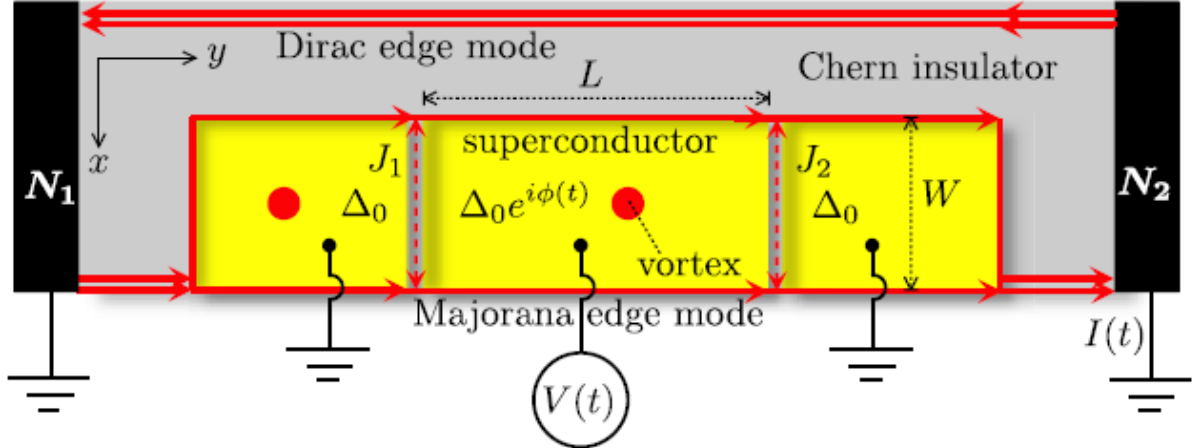


Van Heck et al., NJP (2012)

If the 2D surface of QAHI is indeed proximitized:

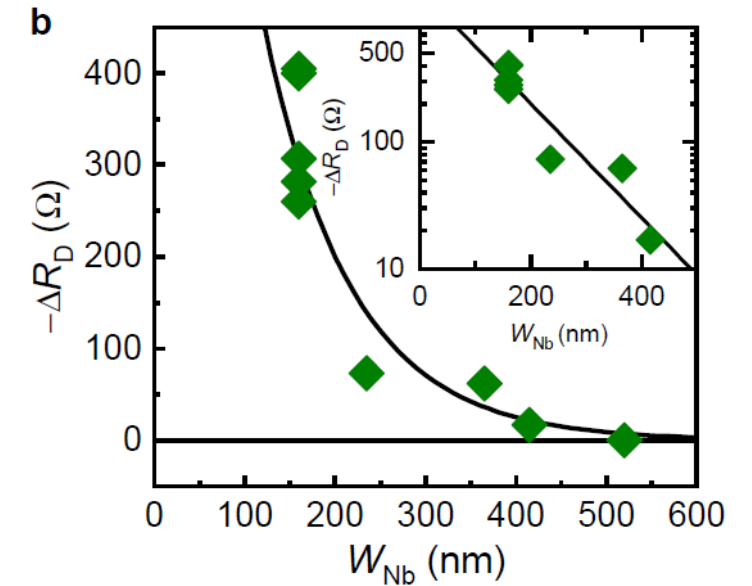
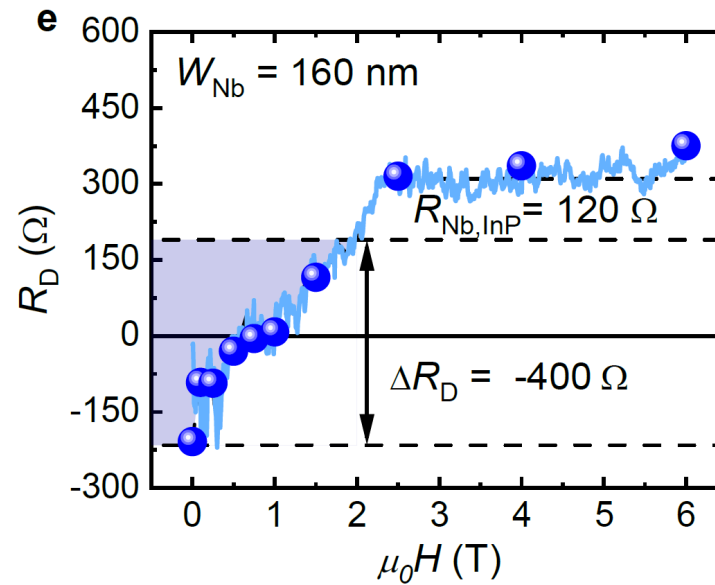
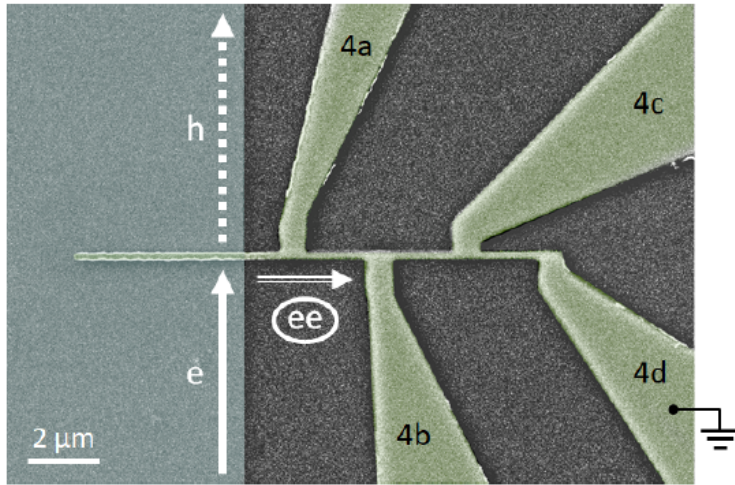


Beenakker, condmatclub (2017)



Beenakker et al. PRL (2019)

# Summary 1



- Successful proximitization of the QAH edge state with a Nb finger electrode
- Crossed Andreev Reflection is observed, giving evidence for induced pair correlations in the QAH edge state
- CAR is taking place probably through the proximitized surface, not through Nb



# Collaborators

## QAH Edge

### Cologne: Ando Lab

Alexey Taskin

Oliver Breunig

Junya Feng

Jakob Schluck

Jens Brede

Christian Dickel

Yongjian Wang

Matthias Rößler

Gertjan Lippertz

Anjana Uday

Mahasweta Bagchi

Jonas Krause

Elmore Vaal

Linh Dang

Luc Janssen

Roozbeh Ravari

Ella Nikodem

Cornelius Dietrich

(Past members)

Subhamoy Ghatak

Lionel Andersen

Andrea Bliesener

Richard Bounds

Dingxun Fan

Mengmeng Bai

Felix Munning

Poojitha Umesh



### Basel

Henry F. Legg

Jelena Klinovaja

Daniel Loss

### Cologne: Theory

Achim Rosch

Thomas Bömerich

Jinhong Park

Alexander Altland

### Twente

Alexander Golubov

### Moscow

Igor Soloviev

Mikhail Kupriyanov

### KU Leuven

Lino M. C. Pereira

### Jülich

Detlev Grützmacher

Thomas Schäpers

Gergor Mussler

Peter Schüffelgen

Kristof Moors

Joachim Mayer

Martina Luysberg

Xiankui Wei

Stefan Tautz

Stefan Blügel

### Aachen

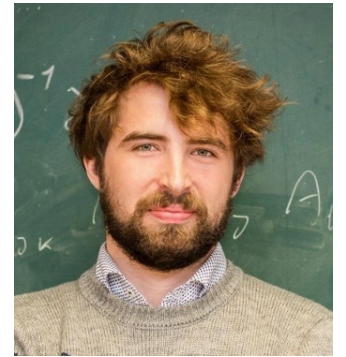
Fabian Hassler

### Düsseldorf

Reinhold Egger

### Paul-Scherrer Inst.

Aline Ramires



Henry F. Legg



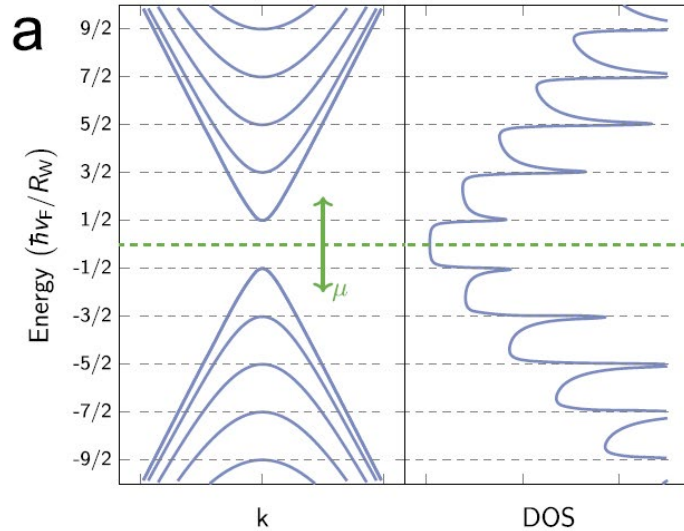
Kristof Moors



Lino M.C. Pereira

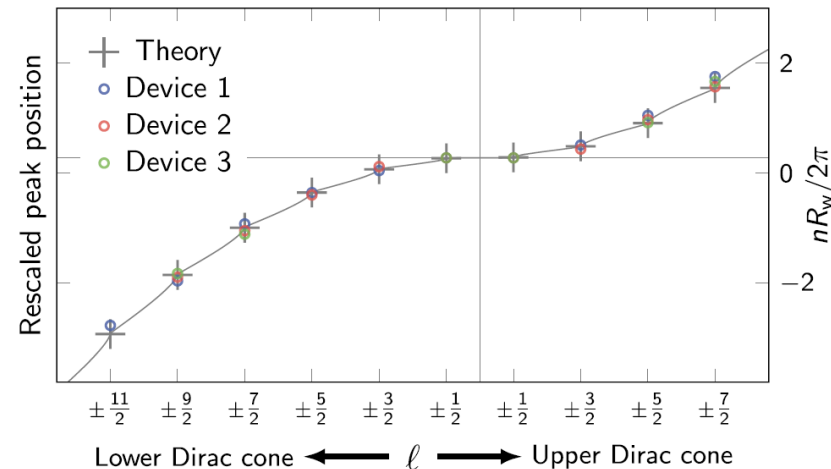
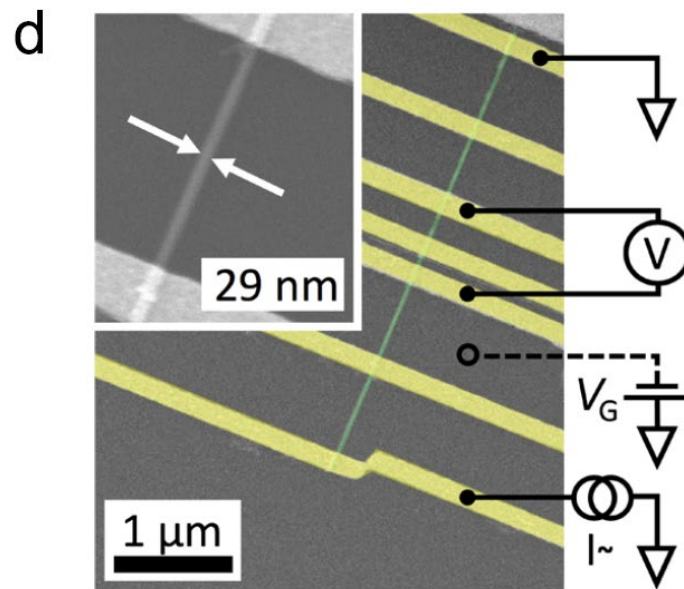
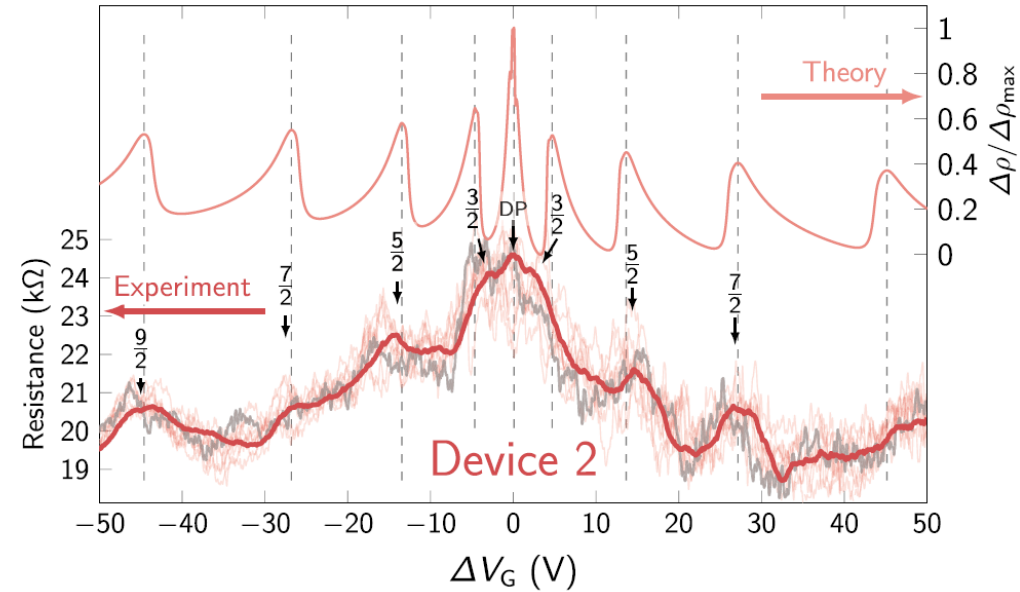
# Topological Insulator Nanowires

# Subbands in 3D Topological Insulator Nanowire



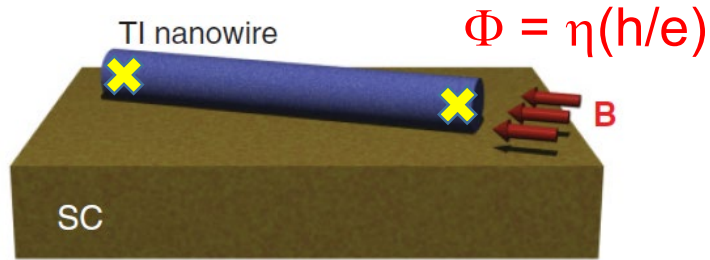
$$E_\ell(k) = \pm \hbar v_F \sqrt{k^2 + \left( \frac{\ell - (\Phi / \Phi_0)}{R} \right)^2}$$

$\ell$  is half-integer due to the Berry phase



Münning *et al.*,  
 Nat. Commun. (2021)

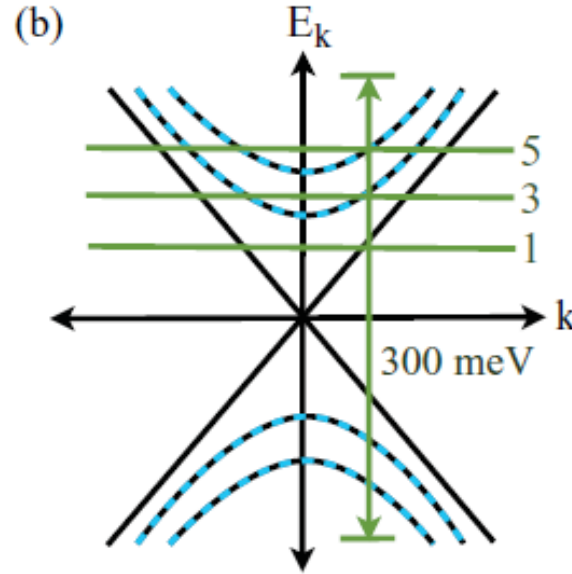
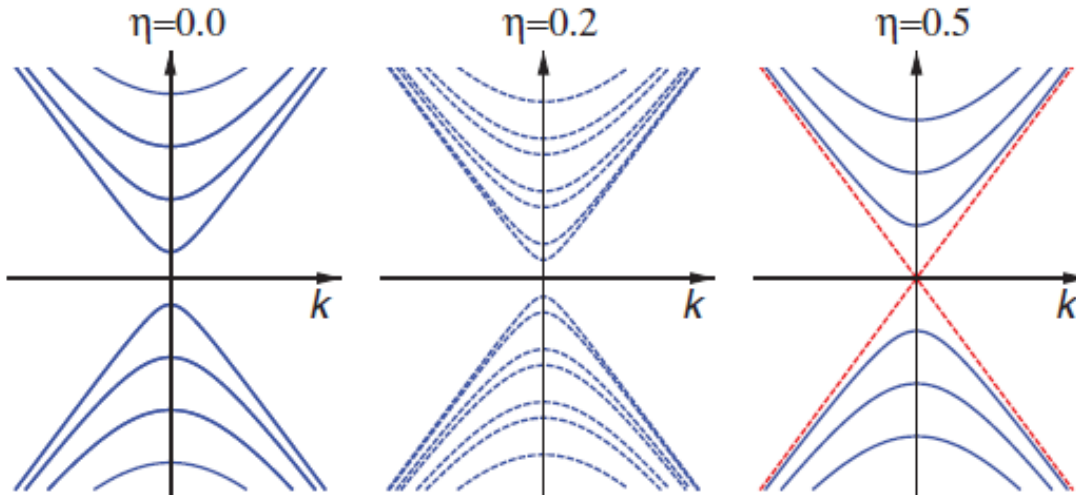
# Majorana Zero Modes in TI Nanowires with $\Phi_0/2$ flux



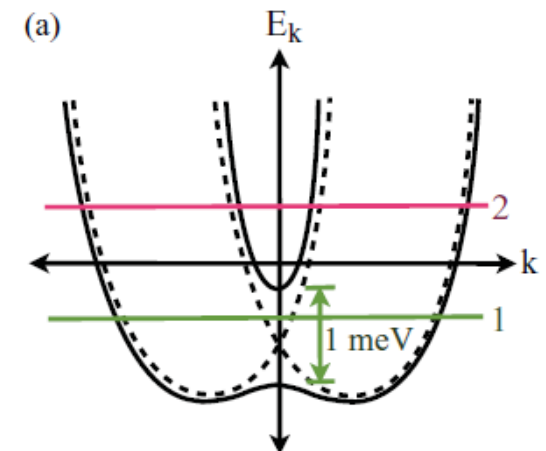
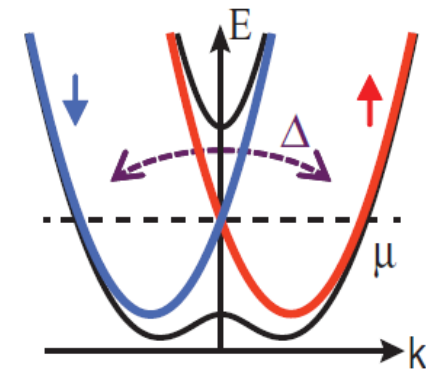
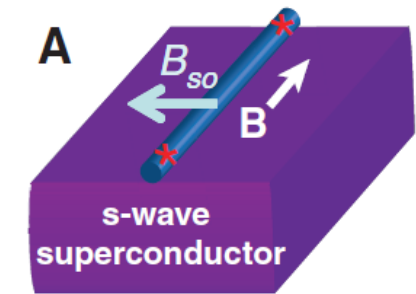
Cook & Franz, PRB (2011)

$$E_\ell(k) = \pm \hbar v_F \sqrt{k^2 + \left( \frac{\ell - (\Phi/\Phi_0)}{R} \right)^2}$$

$\ell$  is half-integer due to the Berry phase

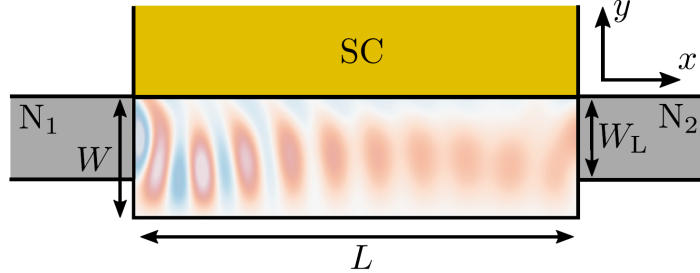
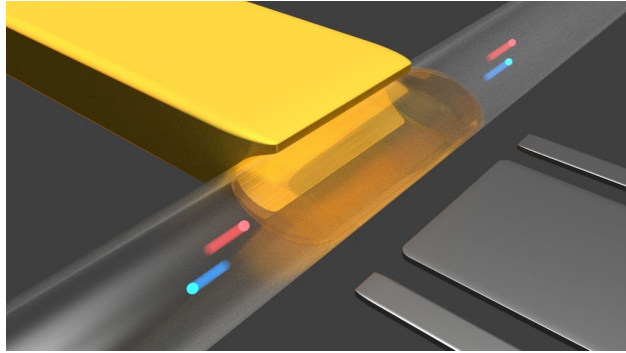


InAs nanowire on SC

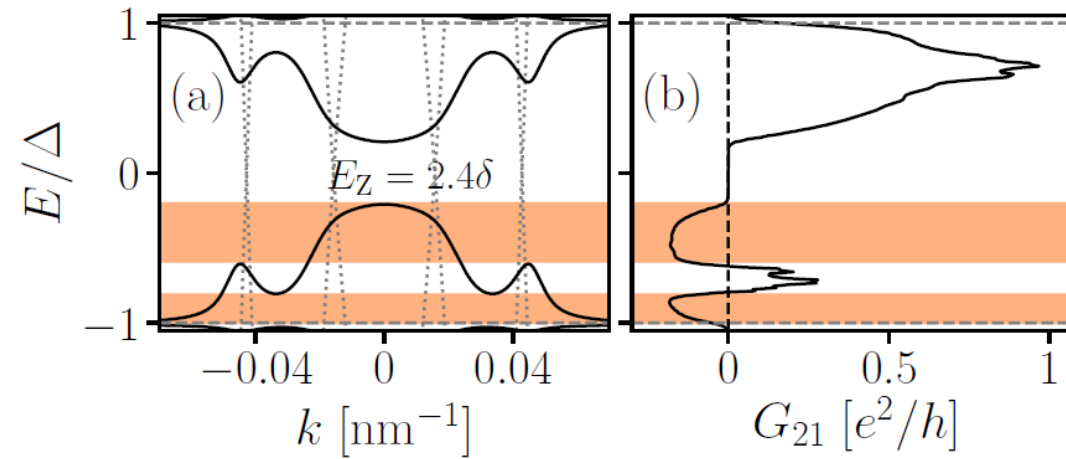
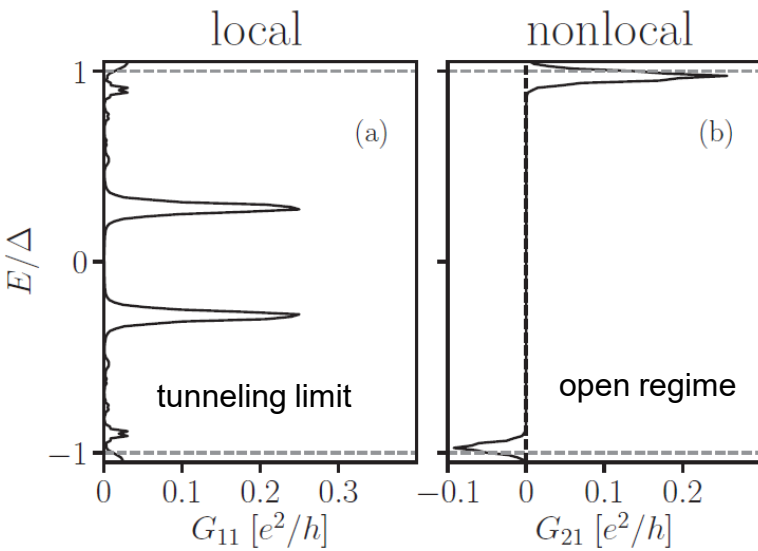
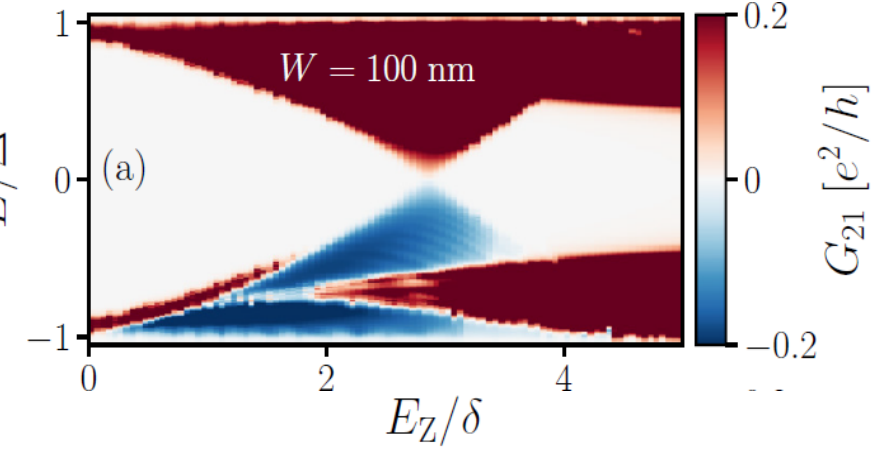
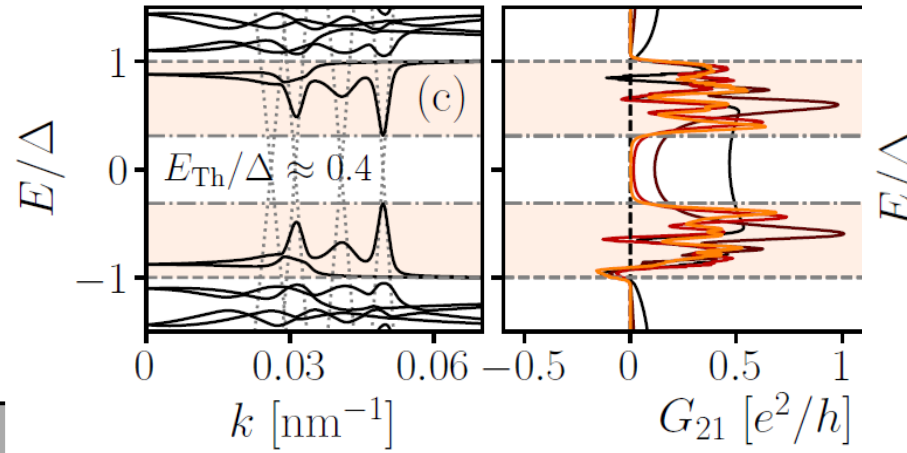


# Nonlocal Conductance in Proximitized Nanowires

Rosdahl *et al.*, PRB (2018)



—  $L = \xi/2$  —  $L = \xi$  —  $L = 2\xi$  —  $L = 3\xi$



Crossed Andreev reflection

(slides removed since the data are unpublished)