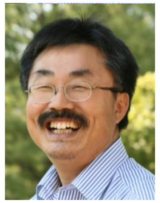
Induced Superconductivity in the Fractional Quantum Hall Edge in Graphene Heterostructures










Onder Gul **Yuval Ronen** **Jonathan Zauberman** **Jing Shi** **Gil-Ho Lee** **Si Young Lee** **Young Hee Lee** T. Taniguchi, K. Watanabe






Sean Hart **Amir Yacoby** **Sagar Bhandari** **Bob Westervelt** **Hassan Shapourian** **Ashvin Vishwanath**

Inducing Superconducting Correlation in Quantum Hall Edge States
G.-H. Lee, K.-F. Huang, D. K. Efetov, D. S. Wei, S. Hart, T. Taniguchi, K. Watanabe, A. Yacoby, P. Kim
Nature Physics 13, 693–698 (2017)

Imaging Andreev Reflection in Graphene
S. Bhandari, G.-H. Lee, K. Watanabe, T. Taniguchi, P. Kim & R. M. Westervelt
Semiconductor Science and Technology 35, 09LT02 (2020)

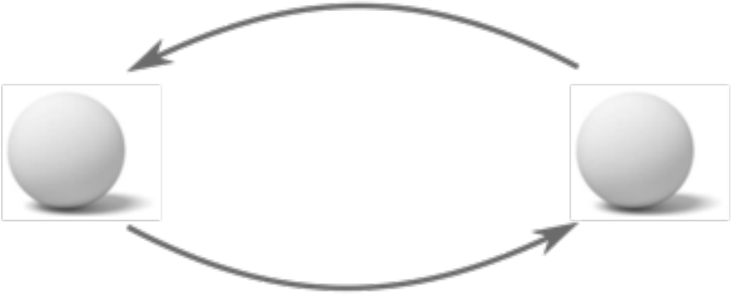
Induced superconductivity in the fractional quantum Hall edge
Ö. Gül, Y. Ronen, S. Y. Lee, H. Shapourian, J. Zauberman, Y. H. Lee, K. Watanabe, T. Taniguchi, A. Vishwanath, A. Yacoby, P. Kim
Phys. Rev. X 12 021057 (2022)

Philip Kim

Physics & Applied Physics, Harvard University

Exchange Statistics of Quasi-particles

Indistinguishable particles



3-Dimension (and higher)

bosons $\psi_{(r_1,r_2)} \rightarrow +\psi_{(r_2,r_1)}$

fermions $\psi_{(r_1,r_2)} \rightarrow -\psi_{(r_2,r_1)}$

2-Dimension is special!

For non-degenerate ground state

$$\psi_{(r_1,r_2)} \rightarrow e^{i\theta} \cdot \psi_{(r_2,r_1)}$$

Anyon quasiparticles

$$\theta = \pm\pi/m$$

$m = 0, 1, 2, 3 \ldots$

If the ground state is degenerated,

$$\vec{\psi}_{(r_1,r_2)} \rightarrow U_{12}\vec{\psi}_{(r_2,r_1)}$$

U_{12} : unitary operator

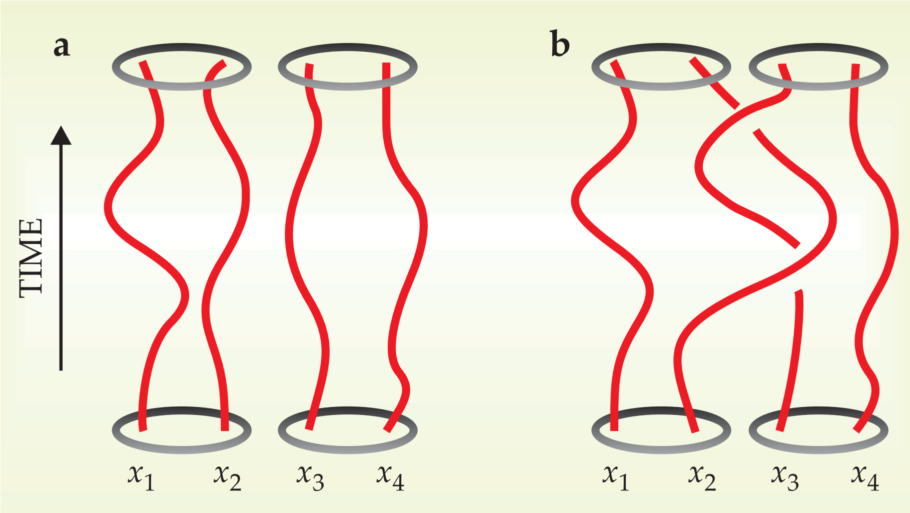
Non-Abelian Anions For Topologically Protected Qubit

Non-abelian anyons

$$\vec{\psi}_{(r_1,r_2)} \rightarrow U_{12}\vec{\psi}_{(r_2,r_1)}$$

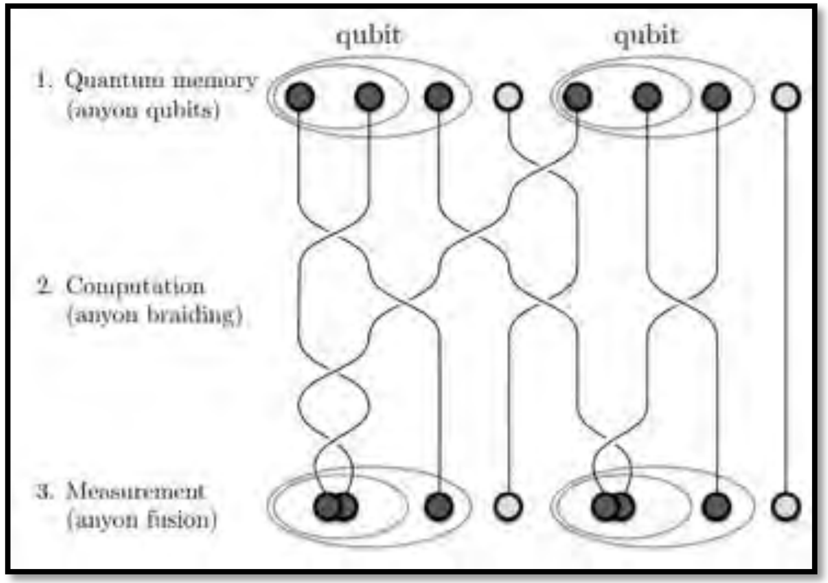
$$U_{12}\, U_{21} \neq U_{21}\, U_{12}$$

By braiding the anyons one can create non-local entangled qubits



Das Sarma, Freedman, Nayak Physics Today (2006)

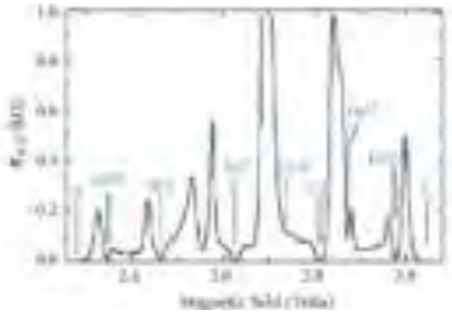
Topologically protected quantum computing with non-abelian anyons



Field and Simula, (2018)

Quantum Material Platforms For Topologically Protected Qubit

5/2 Fractional Quantum Hall State



theory:
Moore, G. & Read, N., Nucl. Phys. B 360, 362 (1991)
Das Sarma, S. et al. PRL 94, 166802 (2005)
Stern, A. & Halperine, B.I., PRL 96, 016802 (2006)
Nayak, C. et al. Rev. Mod. Phys. 80, 1083 (2008)
experiment
Dolev, M. et al. Nature 452, 829 (2008)
Bid, A. et al. Nature 466, 585 (2010)
Mitali B. et al. Nature 559, 205 (2018)
Willett et al PNAS 2009 (Bell Labs)

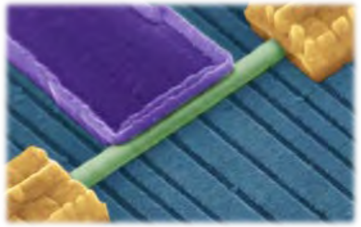
Non-abelian quasiparticles in topological superconductors

Superconductor

+

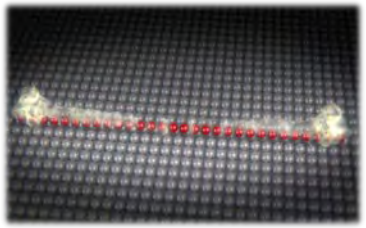
topological insulator

theory: Fu, Kane PRL 2008
experiment:
Hart et al Nature Phys 2014 (Harvard/Würzburg)
Wiedenmann et al Nature Comm 2016 (Würzburg)
Sun et al PRL 2016 (Shanghai)
Li et al Nature Mat 2018 (Twente)



1D semiconductor

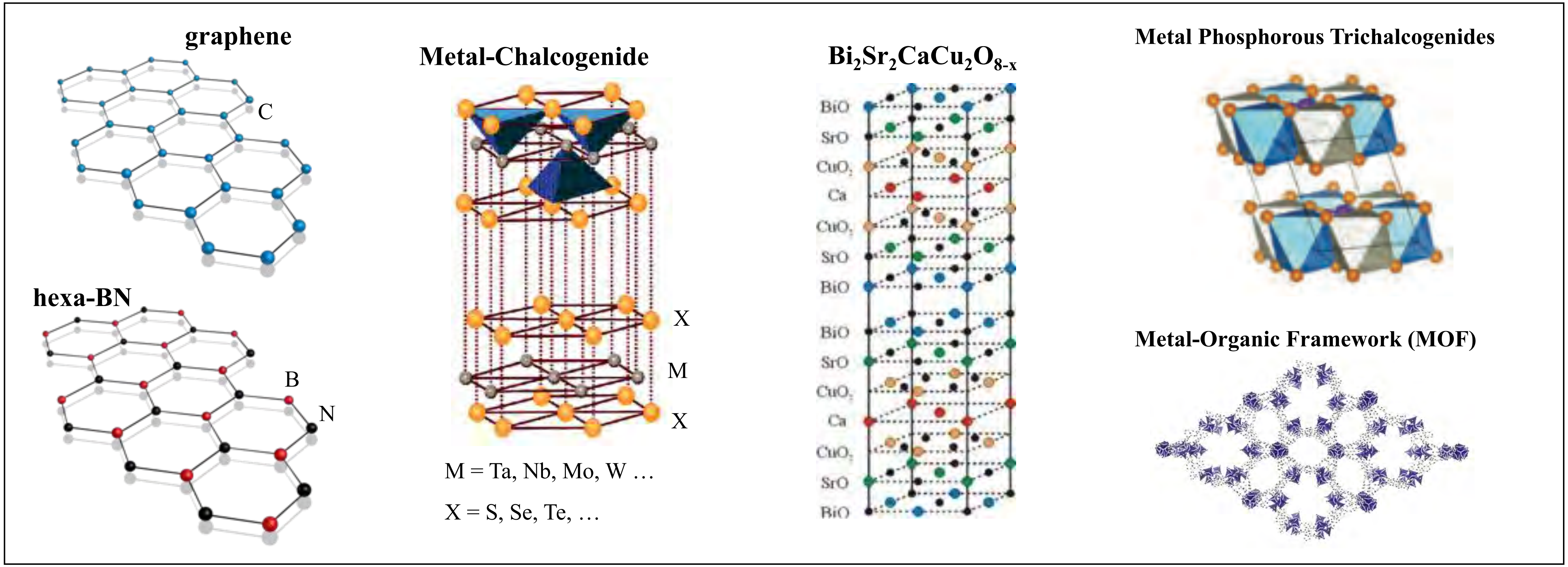
theory: Lutchyn et al PRL 2010; Oreg et al PRL 2010
experiment:
Mourik et al Science 2012 (Delft)
Rokhinson et al Nature Phys 2012 (Purdue)
Das et al Nature Phys 2012 (Weizmann)
Deng et al Nano Lett 2012 (Lund/Beijing)
Albrecht et al Nature 2016 (Copenhagen)



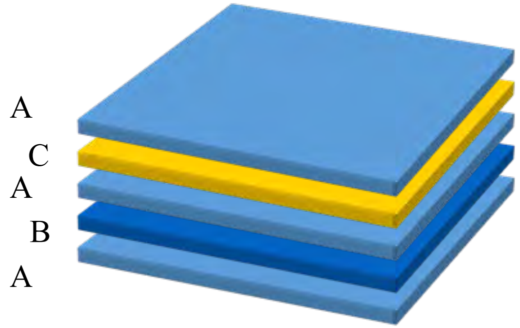
atomic chain

theory: Nadj Perge et al PRB 2013
experiment:
Nadj Perge et al Science 2014 (Princeton)
Pawlak et al npj Quantum Info 2016 (Basel)
Ruby et al PRL 2015 (Berlin)

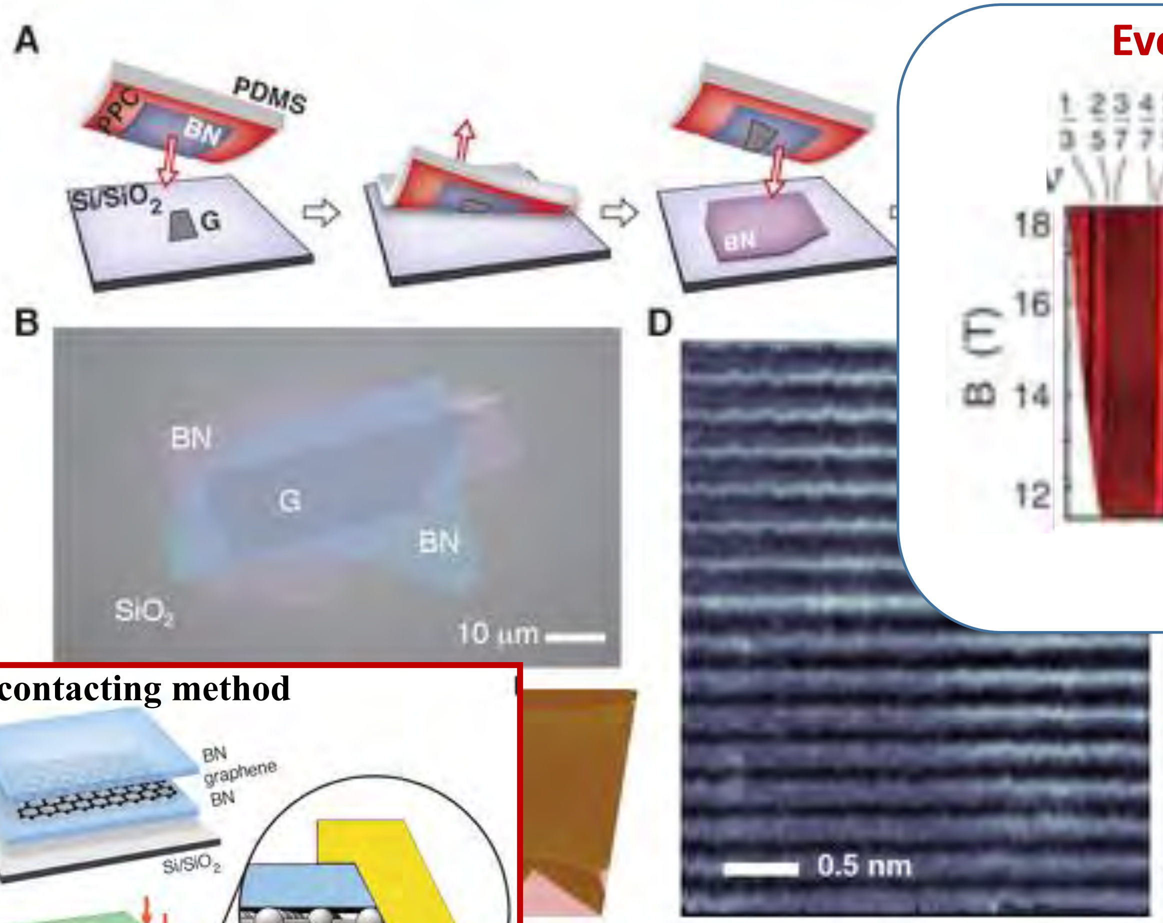
Rise of 2D van der Waals Systems



- Semiconducting materials: WSe_2, $MoSe_2$, MoS_2, …
- Complex-metallic compounds : $TaSe_2$, TaS_2, …
- Magnetic materials: Fe-TaS_2, CrI_3, $CrGeTe_3$,…
- Superconducting: $NbSe_2$, WTe_2, $Bi_2Sr_2CaCu_2O_{8-x}$, ZrNCl,…



Pick-up Technique and Edge Contacts for Multilayer vdW Stacking



Even denominator FQHE in bilayer graphene

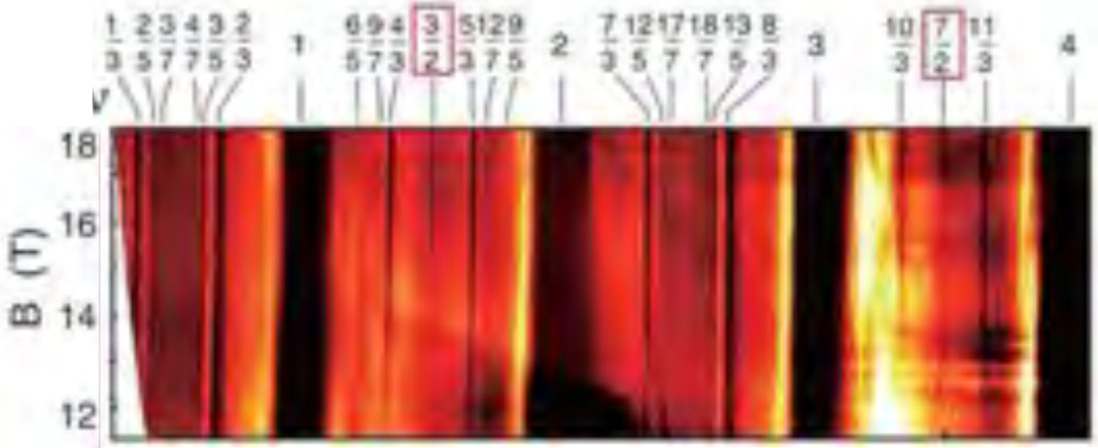
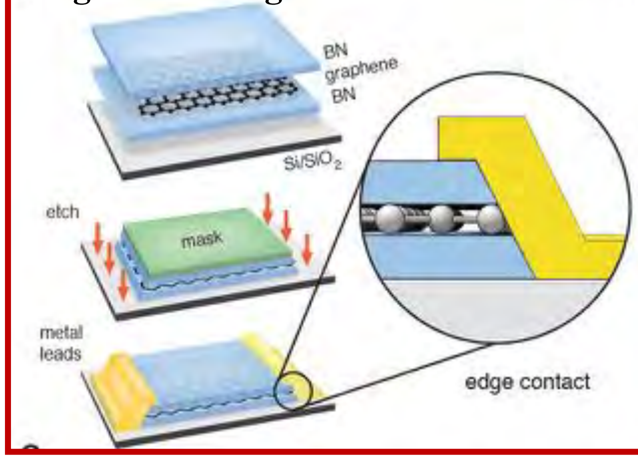


figure from Li et al *Science* (2017), see also Zibrov et al *Nature* (2017)

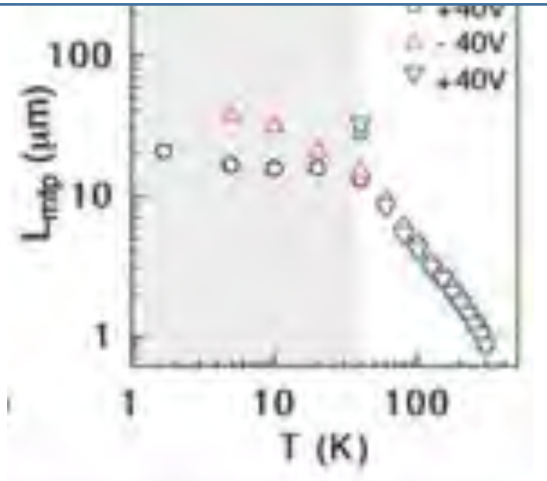
Edge contacting method



Contac Resistance: <100 Ω µm

Mobility > 10^6 $cm^2/Vsec$

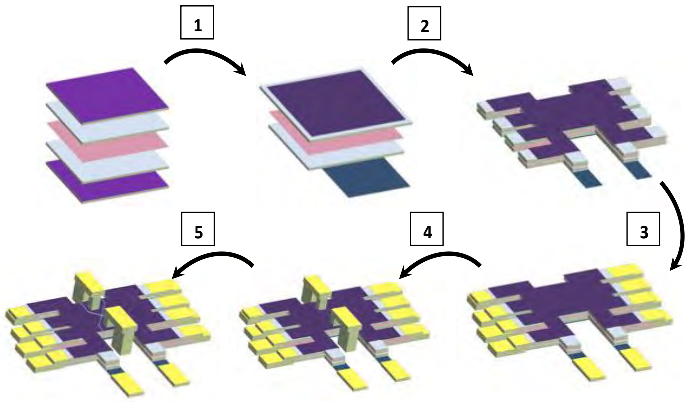
Mean free path > 10 µm

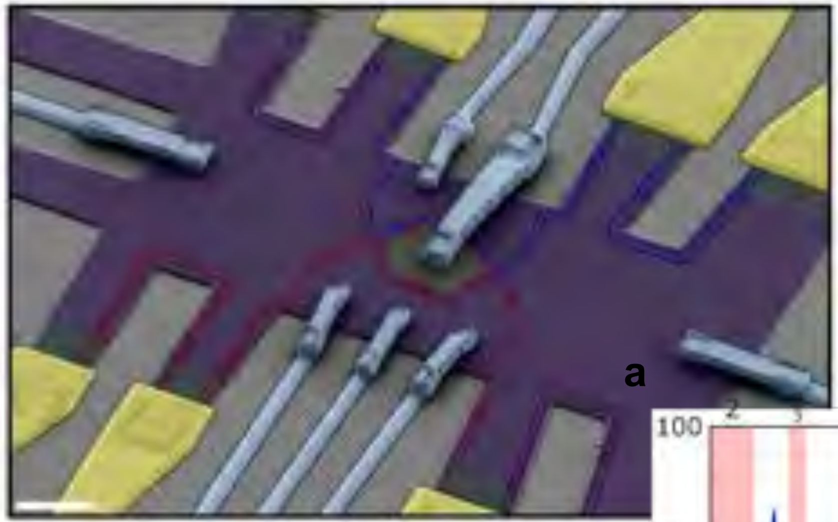


L. Wang *et al*, Science (2013)

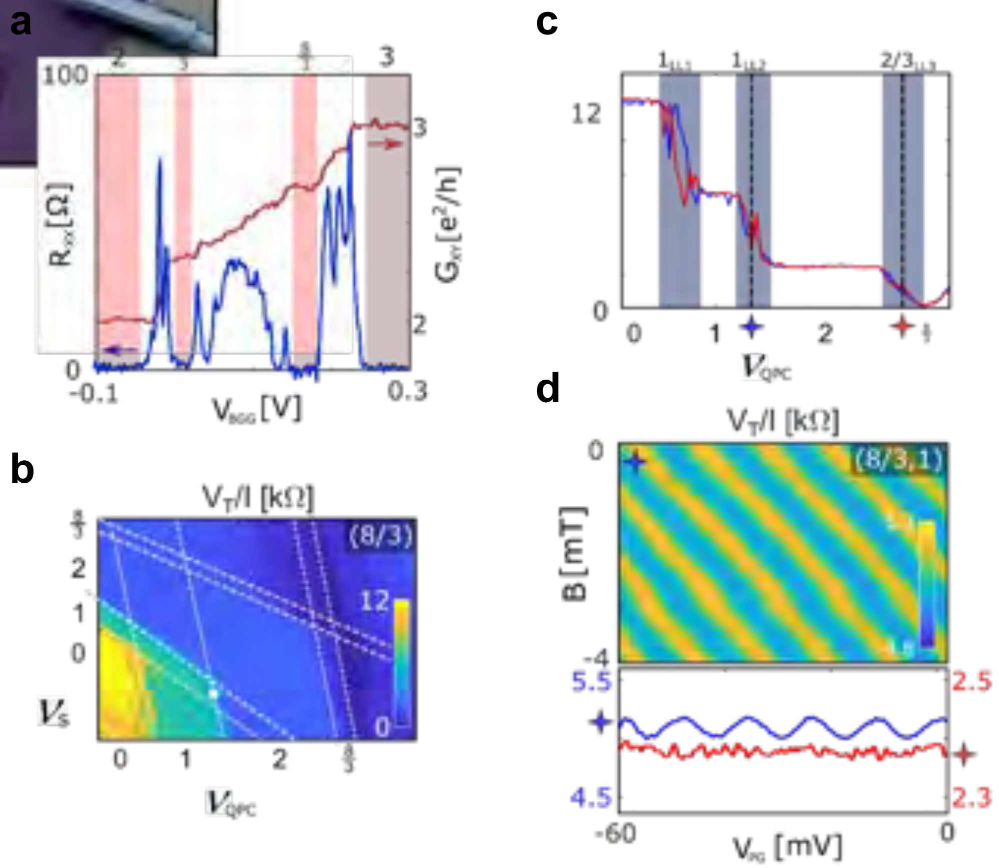
Graphene Based Quantum Electronic Devices

Quantum Interferometers

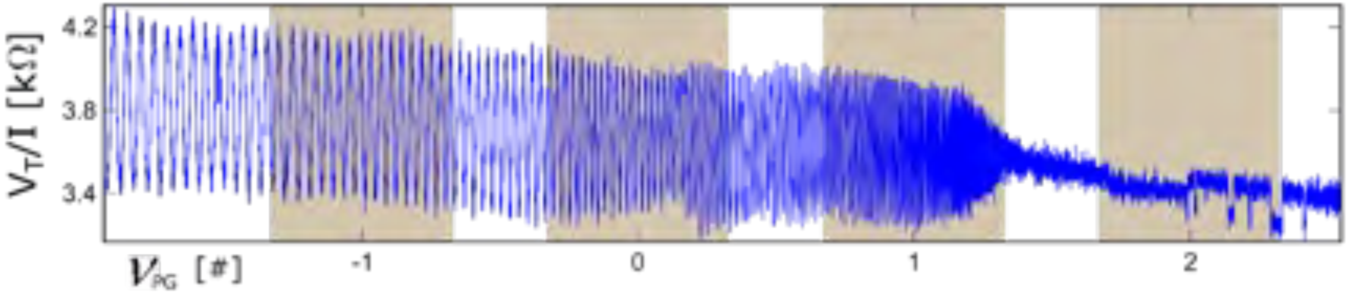




Electron Fabry-Perot Interference in FQH regime



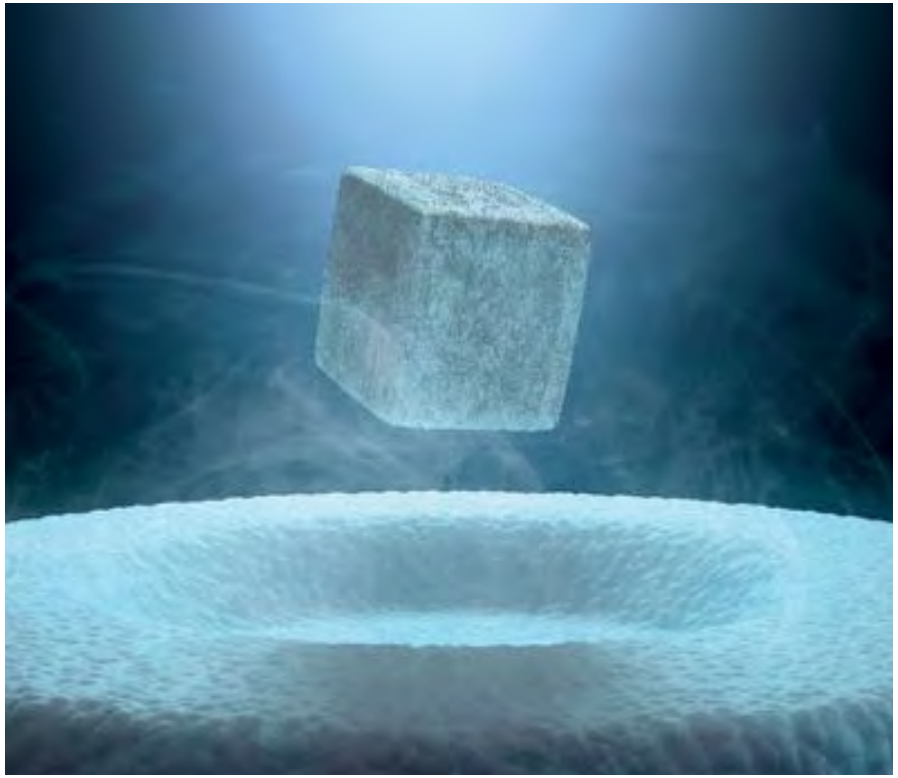
Electron Fabry-Perot Interference



Ronen*, Werkmeister* et al., Nature Nano (2021)

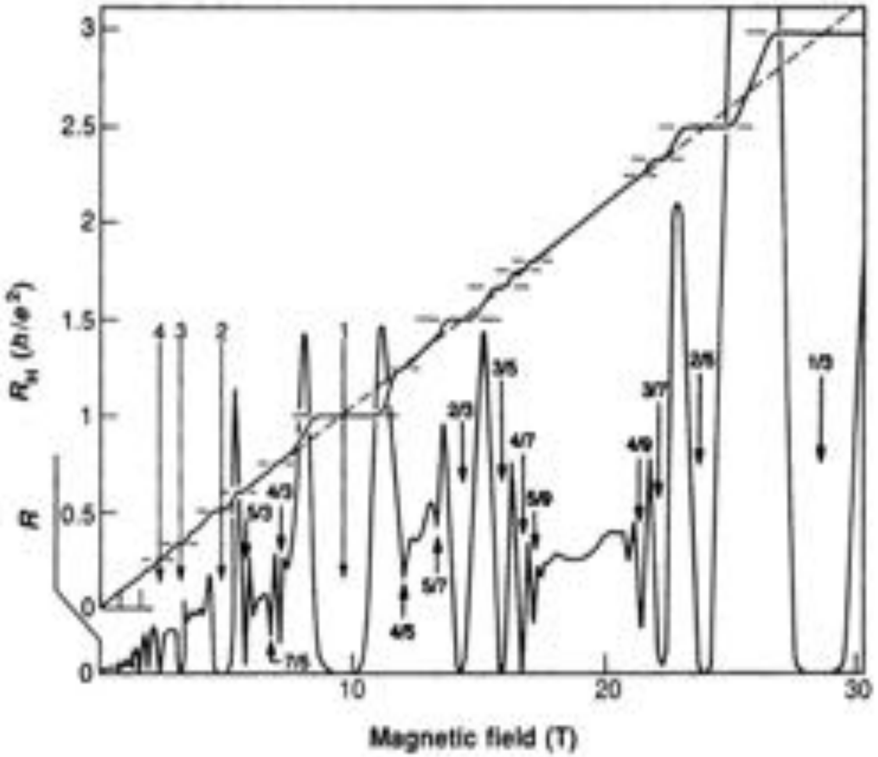
Induced Superconductivity in Fractional Quantum Hall Edge

Superconductivity



+

Fractional quantum Hall

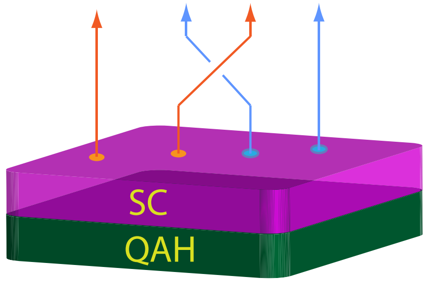


Superconducting Proximity in Quantum Hall State

PHYSICAL REVIEW B **82**, 184516 (2010)

Chiral topological superconductor from the quantum Hall state

Xiao-Liang Qi,[1,2] Taylor L. Hughes,[1,3] and Shou-Cheng Zhang[1]



Proximitized quantum (anomalous) Hall states:
Localized majorana zero mode in the vortex core, and delocalized majorana edge states.

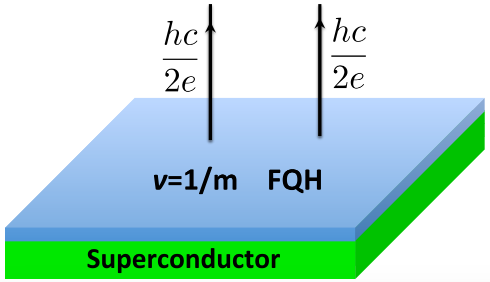
ARTICLE nature COMMUNICATIONS

Received 14 Sep 2012 | Accepted 26 Nov 2012 | Published 8 Jan 2013 DOI: 10.1038/ncomms2340

Exotic non-Abelian anyons from conventional fractional quantum Hall states

David J. Clarke[1,2], Jason Alicea[1,2] & Kirill Shtengel[3,4,5]

(also, Vaezi (2012), Linder *et al* (2012), Cheng *et al*. (2012), Barkershi *et al* (2012))



$$\gamma_1^{2m} = \gamma_2^{2m} = 1 \qquad \gamma_i^{\dagger} = \gamma_i^{2m-1}$$

$$\gamma_1\gamma_2 = e^{i\pi/m}\gamma_2\gamma_1$$

Proximitized Fractional Quantum Hall states:
Localized parafermions in the vortex core, and delocalized parafermionic edge states.

Parafermions for Universal Topological Quantum Computing

PHYSICAL REVIEW X **2**, 041002 (2012)

Fractionalizing Majorana Fermions: Non-Abelian Statistics on the Edges of Abelian Quantum Hall States

Netanel H. Lindner
Institute of Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA
Department of Physics, California Institute of Technology, Pasadena, California 91125, USA

Erez Berg
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Ady Stern
Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel
(Received 1 May 2012; published 11 October 2012)

PHYSICAL REVIEW B **86**, 195126 (2012)

Superconducting proximity effect on the edge of fractional topological insulators

Meng Cheng

PHYSICAL REVIEW B **87**, 035132 (2013)

Fractional topological superconductor with fractionalized Majorana fermions

Abolhassan Vaezi*

PHYSICAL REVIEW X **4**, 011036 (2014)

Universal Topological Quantum Computation from a Superconductor-Abelian Quantum Hall Heterostructure

Roger S. K. Mong,[1] David J. Clarke,[1] Jason Alicea,[1] Netanel H. Lindner,[1,2] Paul Fendley,[3] Chetan Nayak,[3,5] Yuval Oreg,[6] Ady Stern,[6] Erez Berg,[6] Kirill Shtengel,[7,8] and Matthew P. A. Fisher[5]

$\nu = 1/m$ $g > 0$

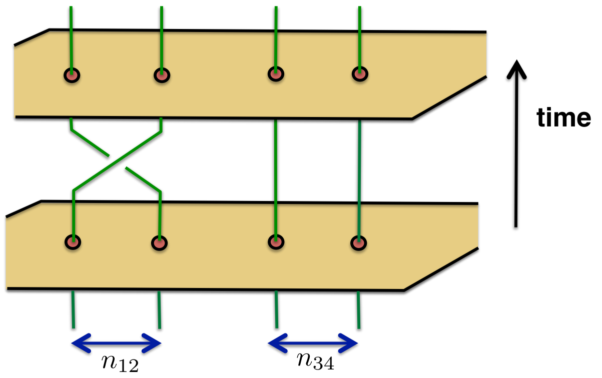
Parafermions

SC Insulator w/SOC SC

$\nu = 1/m$ $g < 0$

Localizing parafermions

Braiding parafermions for quantum gating



$$B_{12}\,|n\rangle = e^{in^2\pi/m}\,|n\rangle$$

Proximitizing Quantum Hall Edge by Superconductors

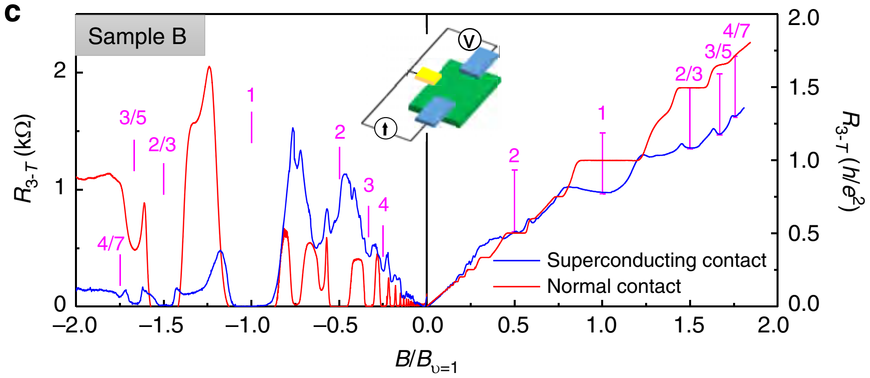
nature COMMUNICATIONS

ARTICLE

Received 3 Dec 2014 | Accepted 5 May 2015 | Published 11 Jun 2015 DOI: 10.1038/ncomms8426 OPEN

Induced superconductivity in high-mobility two-dimensional electron gas in gallium arsenide heterostructures

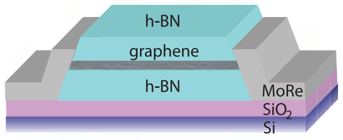
Zhong Wan[1], Aleksandr Kazakov[1], Michael J. Manfra[1,2,3,4], Loren N. Pfeiffer[5], Ken W. West[5] & Leonid P. Rokhinson[1,2,4]

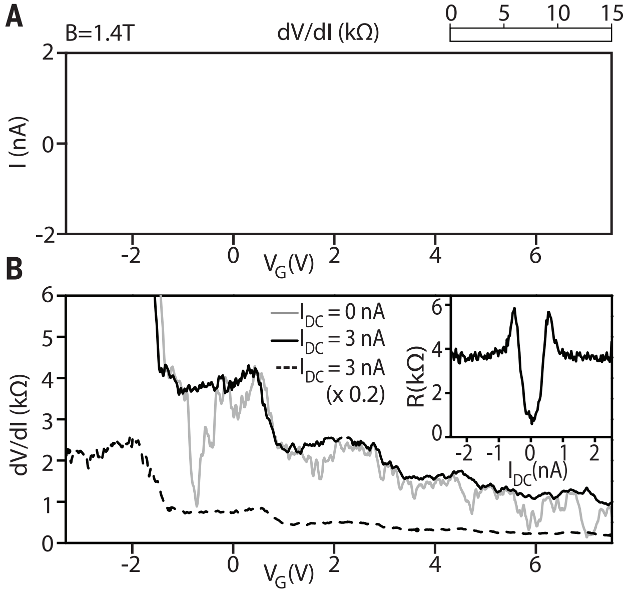


966 20 MAY 2016 • VOL 352 ISSUE 6288 SCIENCE

Supercurrent in the quantum Hall regime

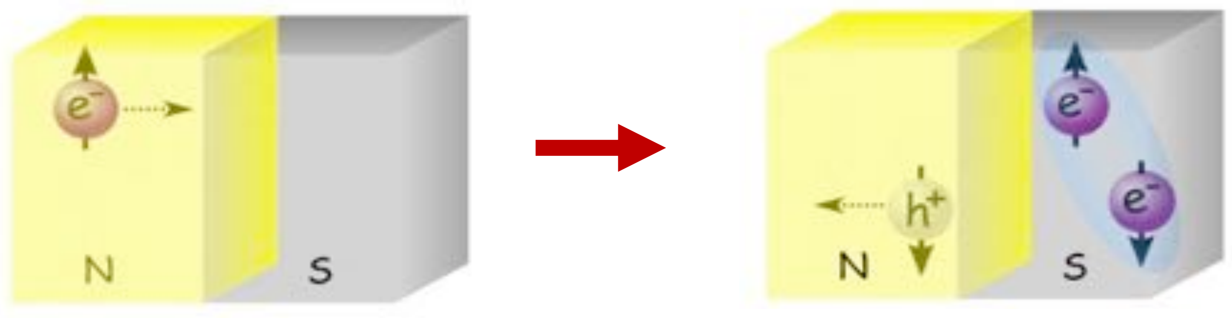
F. Amet,[1,2*†] C. T. Ke,[1†] I. V. Borzenets,[3] J. Wang,[1] K. Watanabe,[4] T. Taniguchi,[4] R. S. Deacon,[5] M. Yamamoto,[3,6] Y. Bomze,[1] S. Tarucha,[3,5] G. Finkelstein[1*]

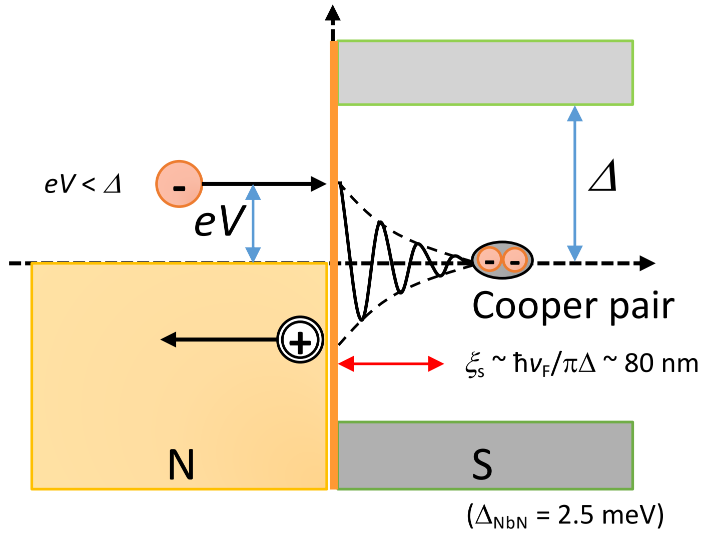




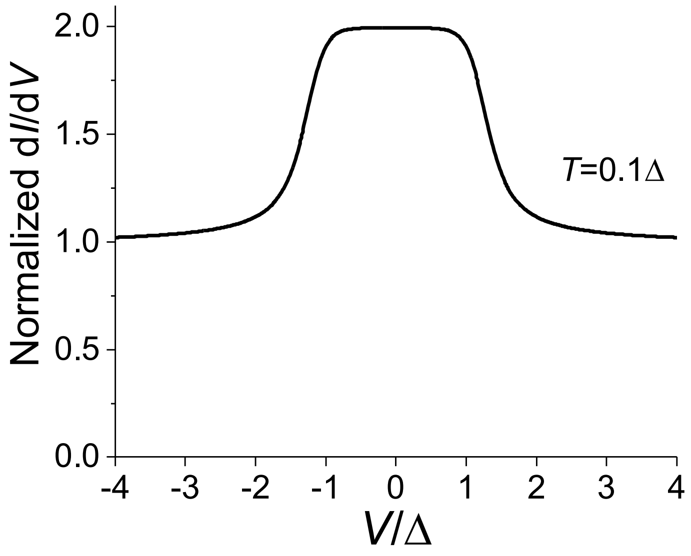
Andreev Reflection

A.F. Andreev, Soviet Physics JETP **19**, 1228 (1964)





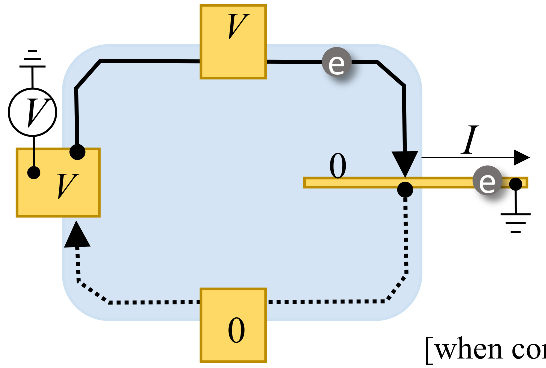
G.E. Blonder, M. Tinkham, and T. M. Klapwijk (1982)



Solving Bogoliubov-de Gennes Equation

Crossed Andreev Reflection in Quantum Hall Edge

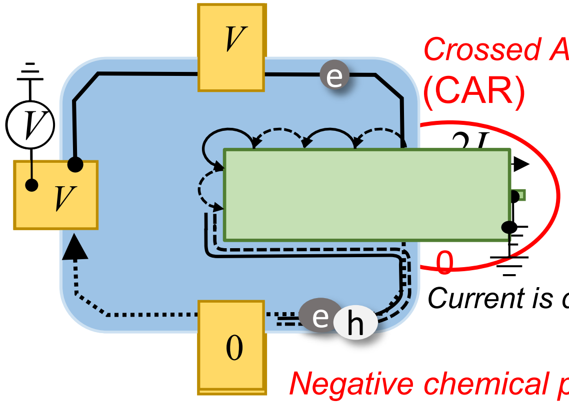
Normal drain electrode



$$R_{xy} = \frac{V-0}{I} = \frac{V}{I} = h/\nu e^2$$

[when contact is perfect.]

Superconducting drain electrode



Crossed Andreev Reflection (CAR)

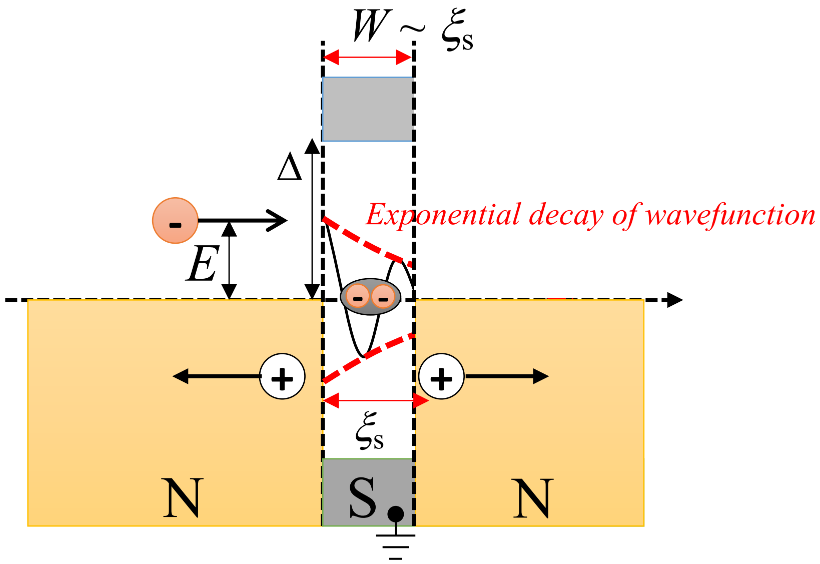
Current is doubled.

Negative chemical potential

$$R_{xy} = \frac{[V-(-V)]}{2I} = \frac{V}{I} = h/\nu e^2$$

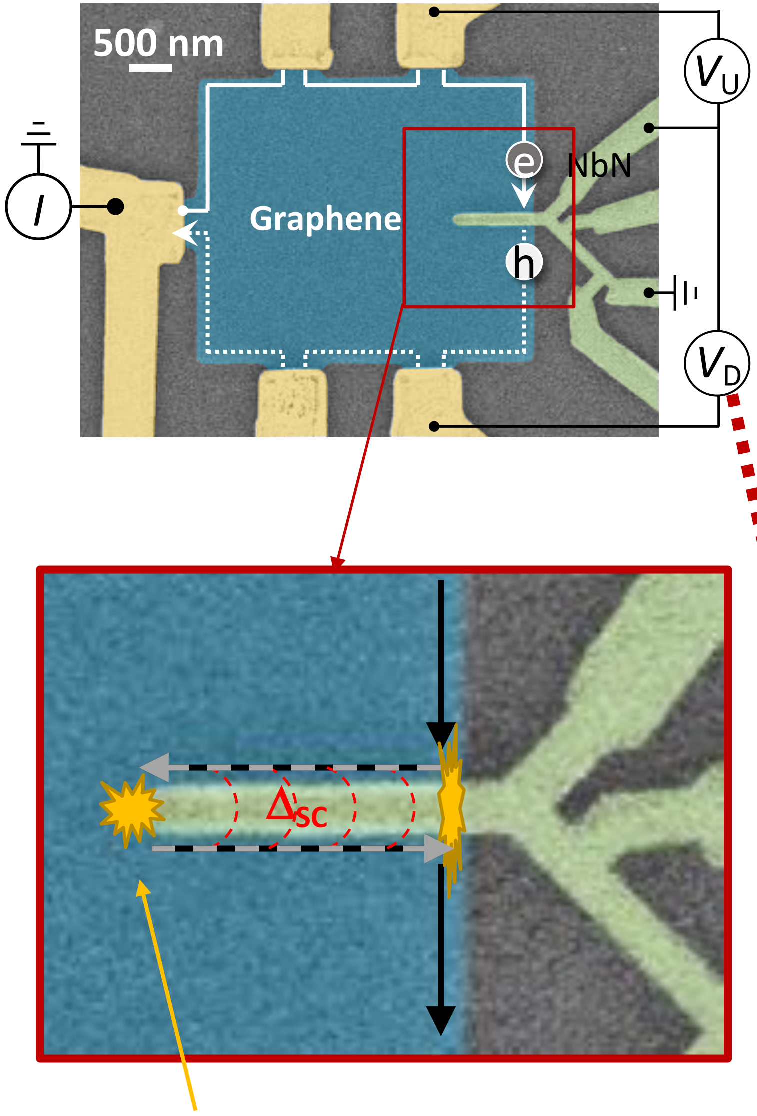
Crossed Andreev reflection (CAR)

= Cooper pair splitting



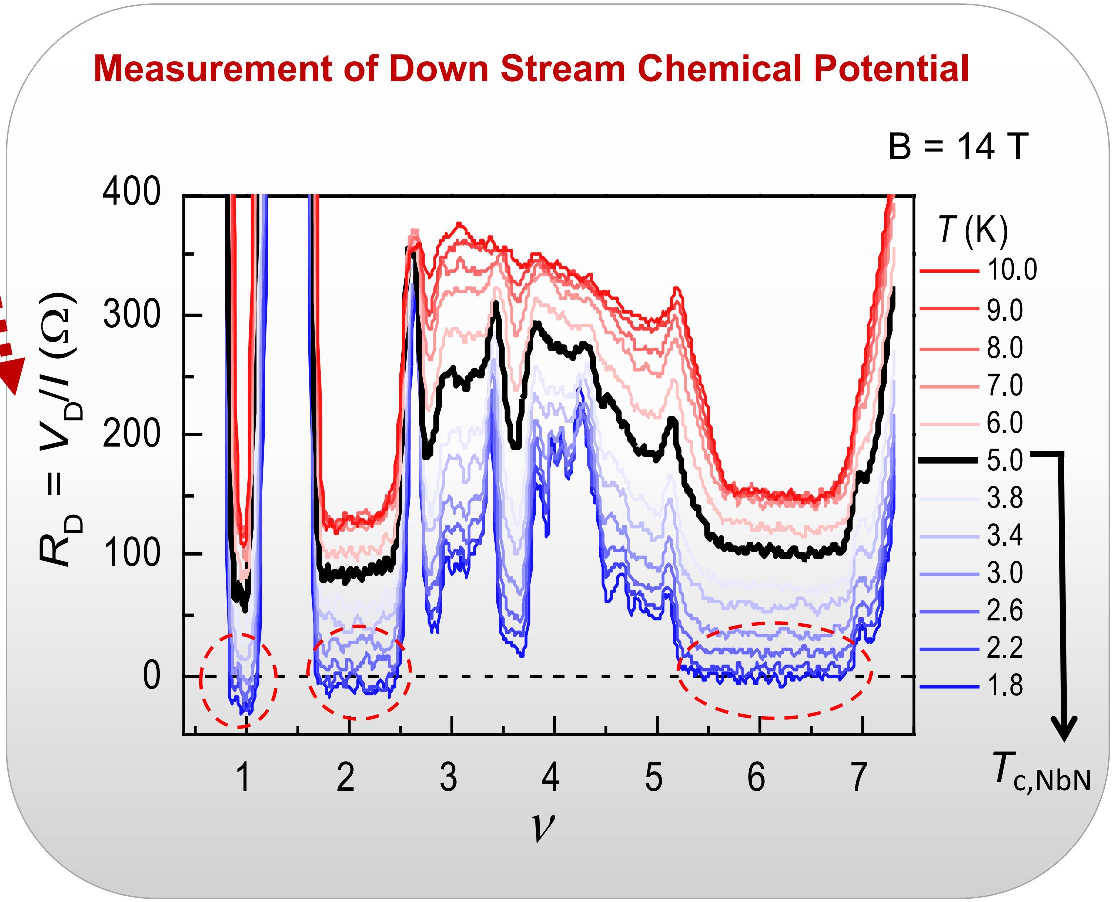
Goal : Measuring negative potential on the downstream edge state

Crossed Andreev Reflection in Graphene Integer Quantum Hall States



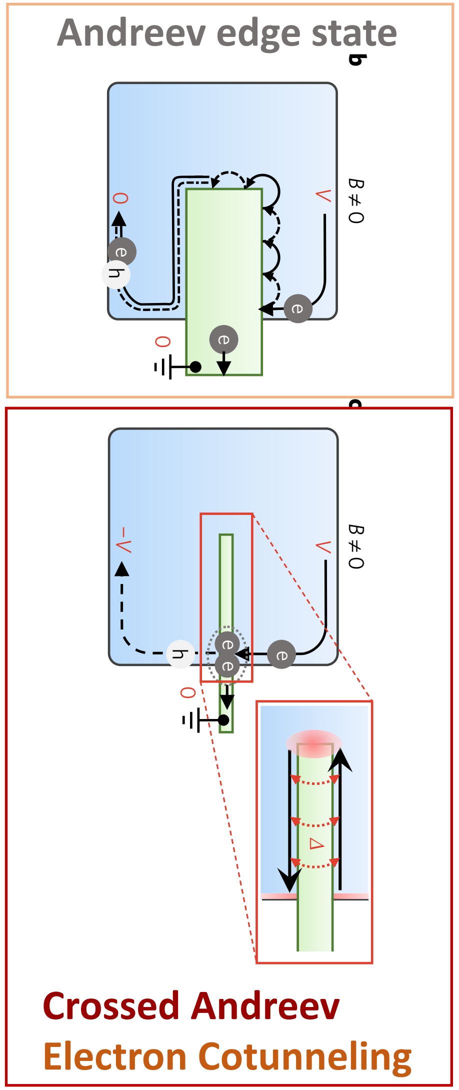
Localized majorana fermions

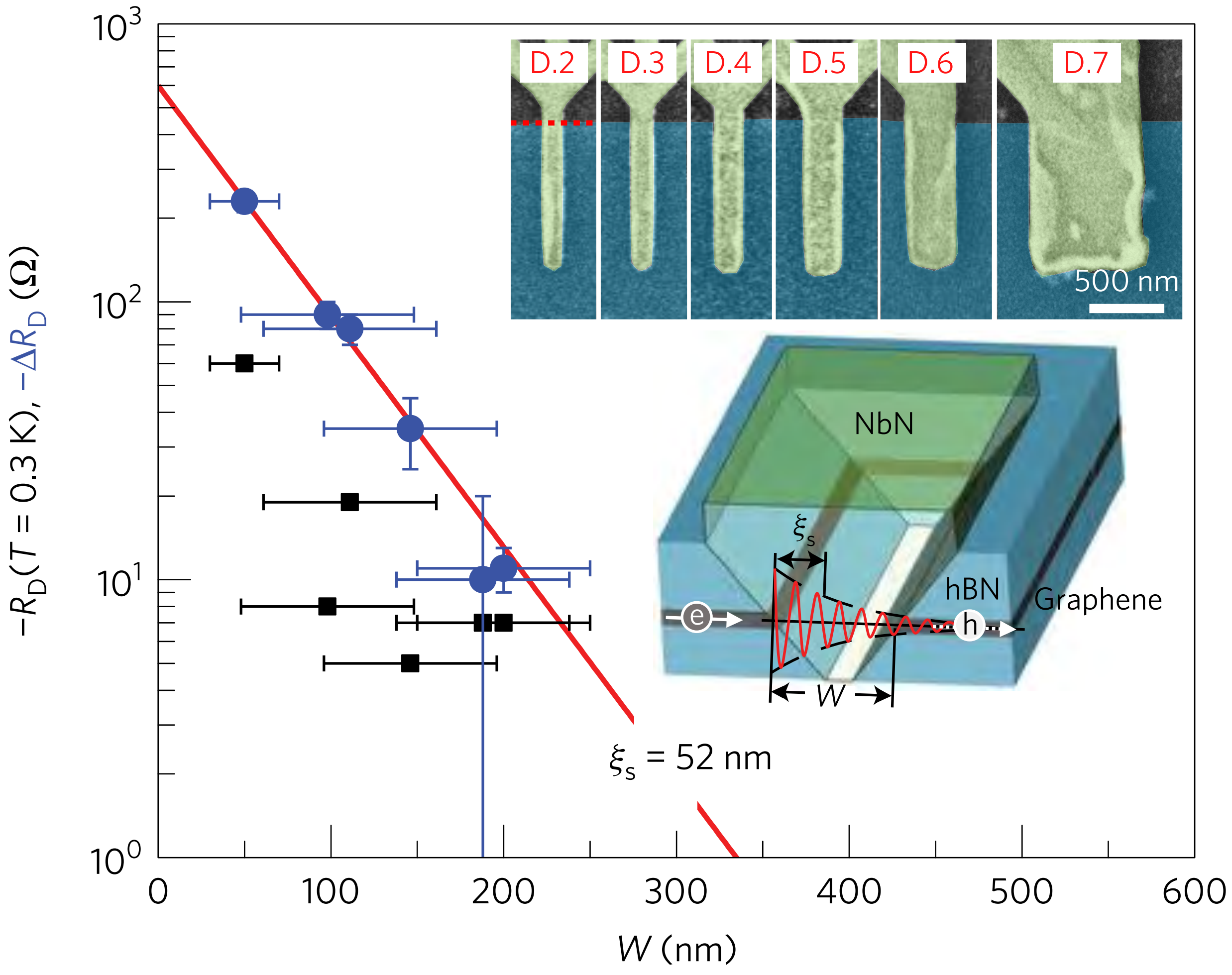
Graphene Hall bar with a superconducting drain contact.
(graphene underneath the contacts are etched away)



G.-H. Lee *et al*. Nature Physics (2017)

Width Dependence of CAR: Superconducting Coherence Length





CAR contribution is dominant for W < 100 nm

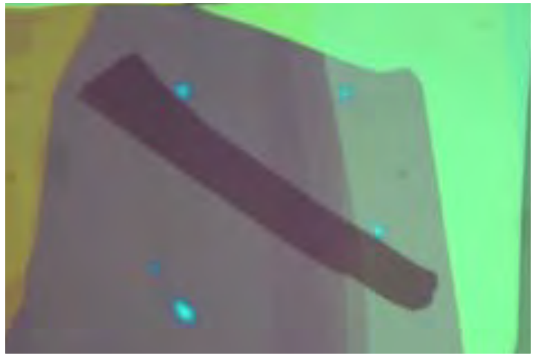
CAR contribution ~ -V exp[-W/ξ_s]

Cotunneling contribution ~ + V exp[-W/ξ_s]

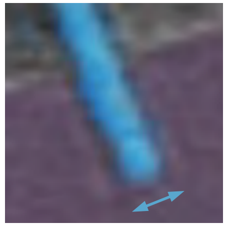
G.-H. Lee *et al*. Nature Physics (2017)

Toward Fractional Quantum Hall CAR

Graphene Device with superconductor & graphite gates

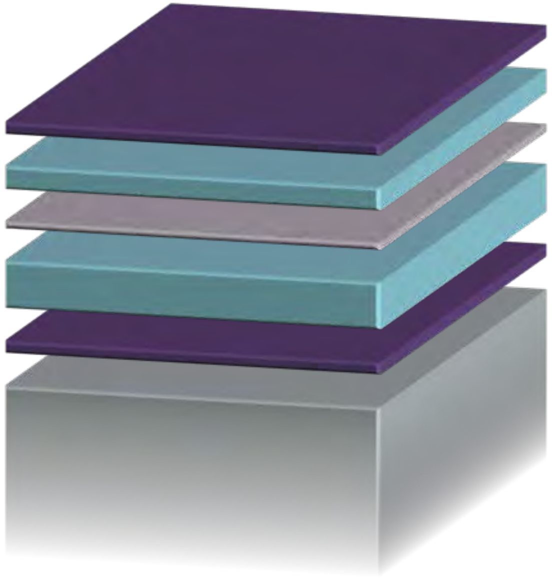


narrow NbN superconductor



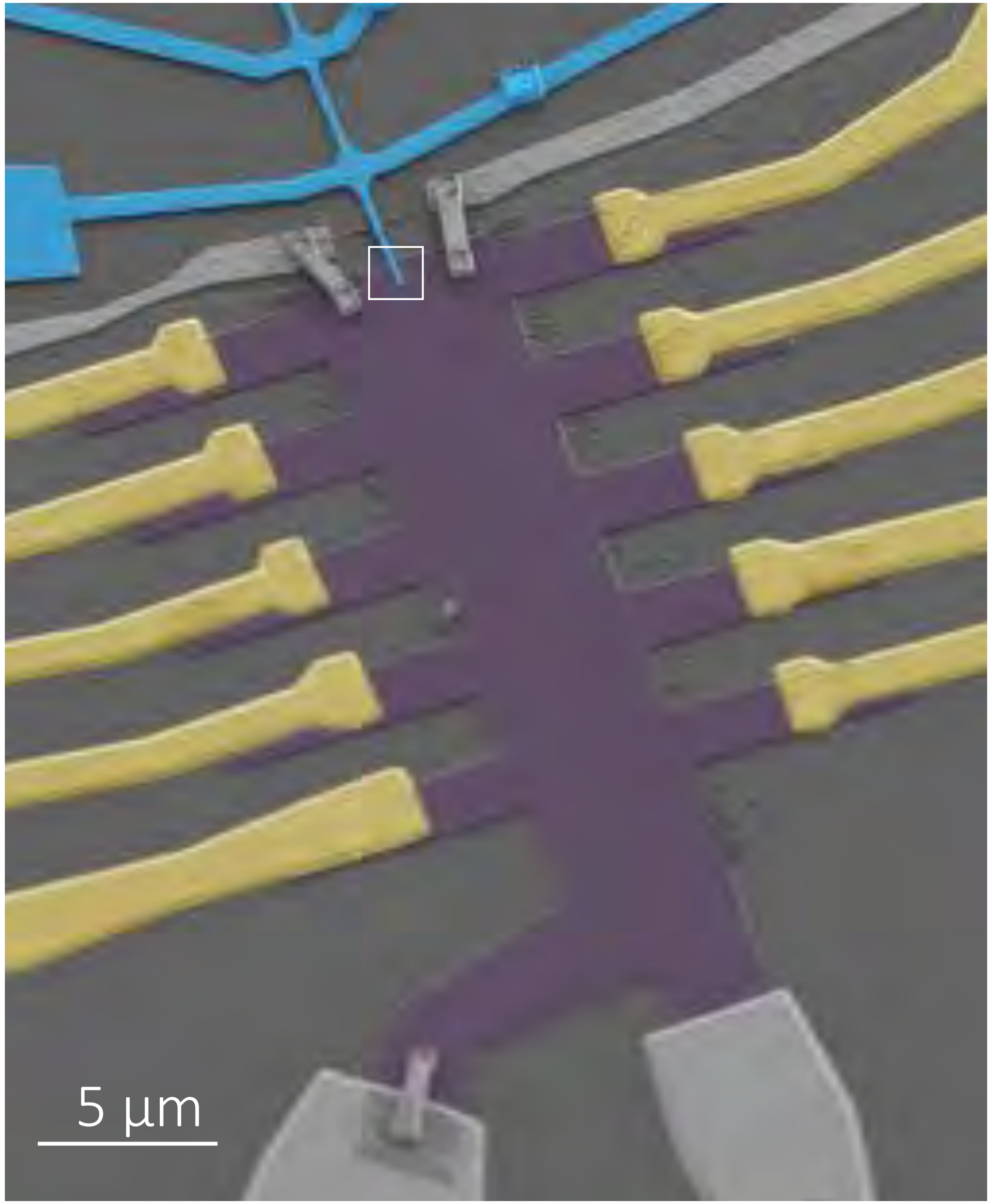
~100 nm

etched under the superconductor



graphene
boron nitride
graphite
SiO_2 substrate

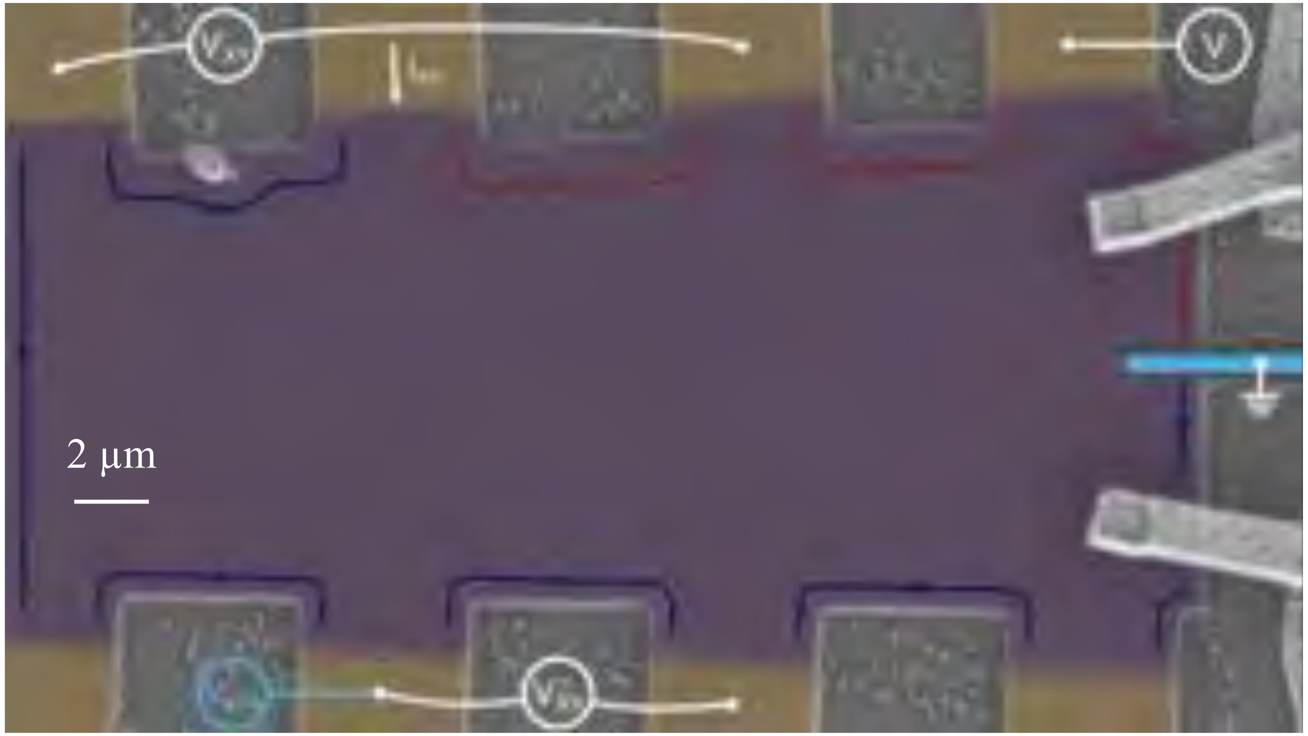
normal leads



Gül, Ronen, *et al.*, arXiv:2009.07836

Cross-Andreev Reflection Probability

Simultaneous Resistance measurement:



In the quantum Hall regime

Longitudinal magneto $R_{xx} = V_{xx} / I \longrightarrow 0$

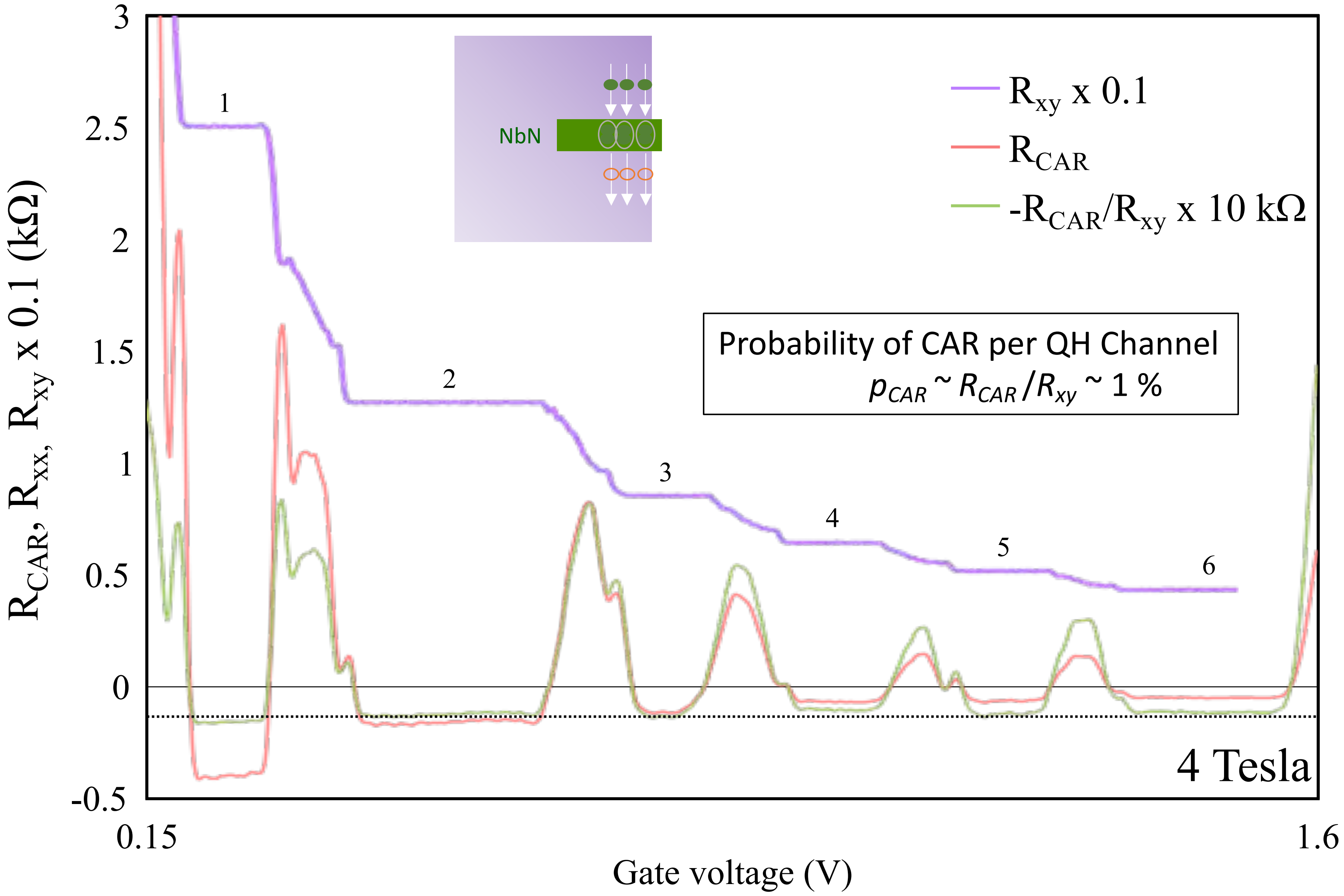
Hall $R_{xy} = V_{xy} / I \longrightarrow h/e^2 \nu$

Cross-Andreev $R_{CAR} = V_{CAR} / I \longrightarrow -R_{xy}/2 < R_{CAR} < 0$

Gül, Ronen, *et al.*, arXiv:2009.07836

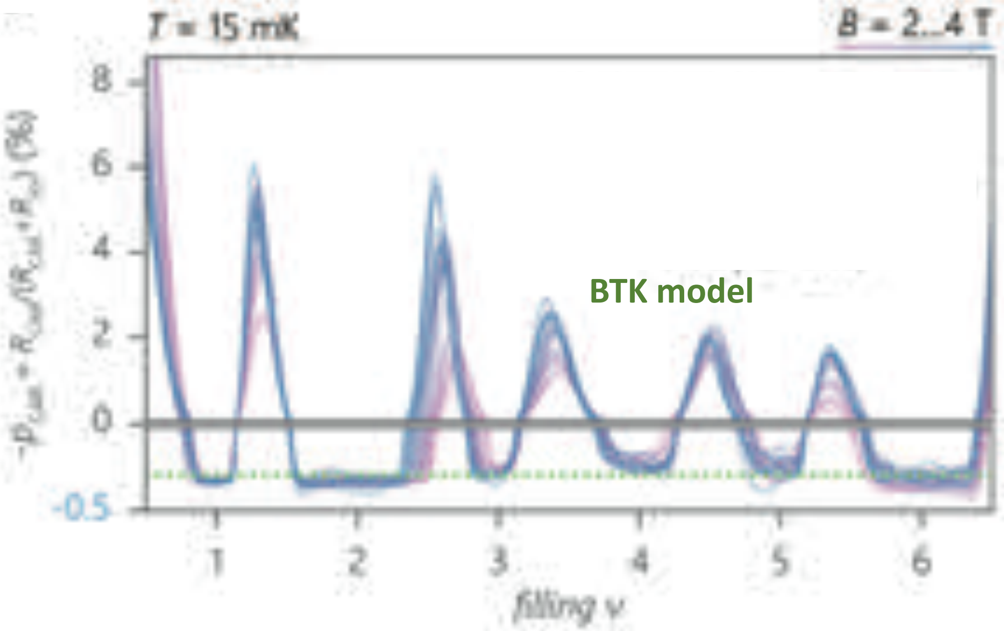
Probability of CAR: $p_{CAR} = -R_{CAR}/(R_{CAR} + R_{xy}) \sim -R_{CAR}/R_{xy}$

Crossed Andreev Reflection Probability



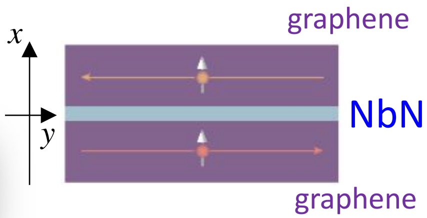
Gül, Ronen, *et al.*, arXiv:2009.07836

p-wave coupled Cross Andreev Edge States



Bogoliubov-de Gennes Equations

$$\hbar v_F \frac{\partial \Psi_y(x)}{\partial y} = i\eta_z\sigma_y[E - h_0(x) - h_{sc}\,\theta(x)]\Psi_y(x).$$



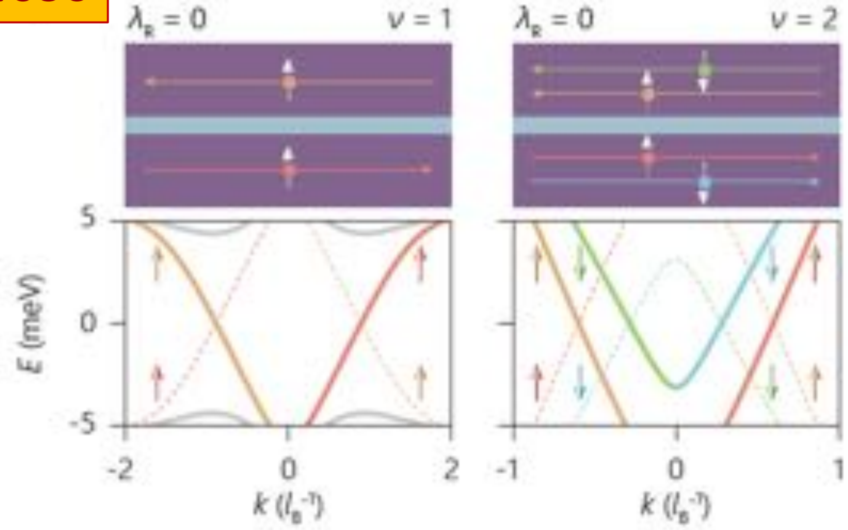
$$h_0(x) = v_F(-i\partial_x)\tau_z\sigma_x + ev_F A_y(x)\sigma_y + \eta_z(m(x)\sigma_z - \mu(x) + g(x)s_z),$$

$$h_{sc} = \Delta_1\eta_y\tau_x s_y + \Delta_2\eta_y s_y + \lambda_{so}\eta_z\tau_z s_z\sigma_z + \lambda_{R,x}\tau_z s_y\sigma_x - \lambda_{R,y}s_x\sigma_y,$$

Spin-orbit coupling in superconductor

Without SOC

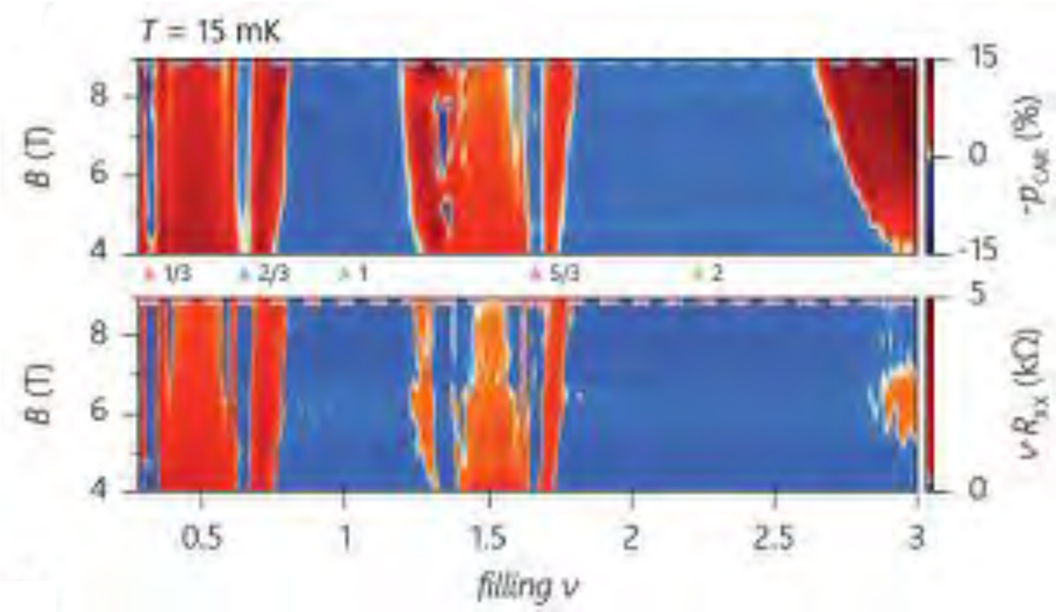
Andreev edge states without CAR

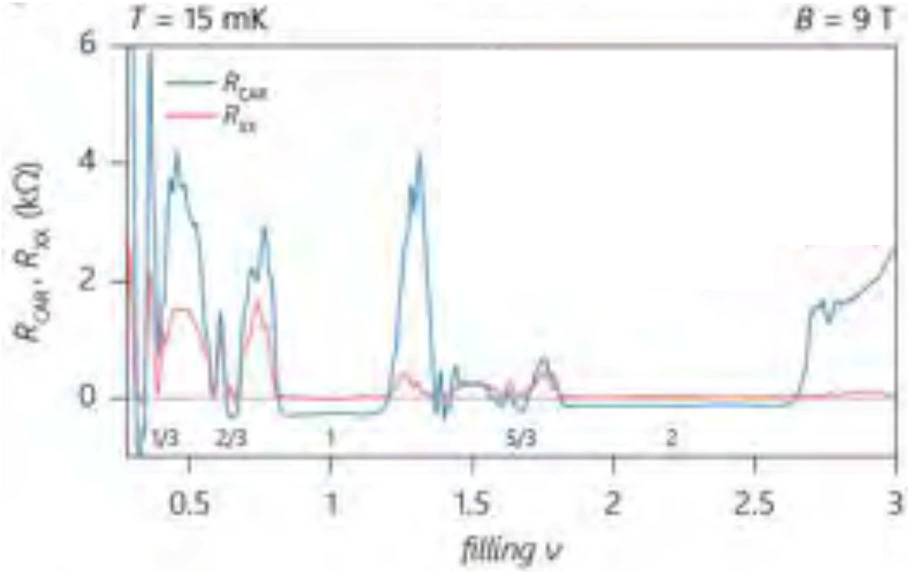


Spin-triplet and p-wave coupling

ν=2 edge states are just two copies of ν=1.

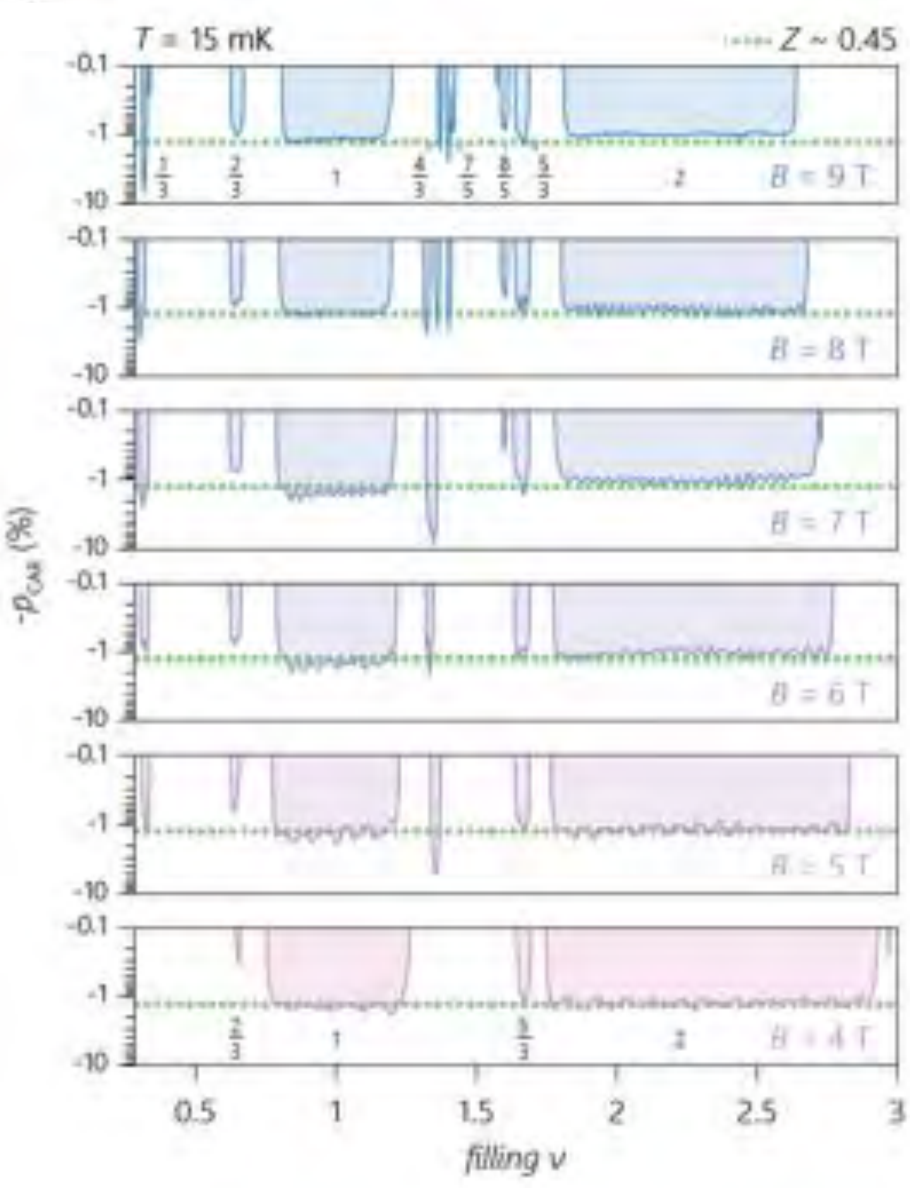
Strong Development of CAR in Fractional Quantum Hall States





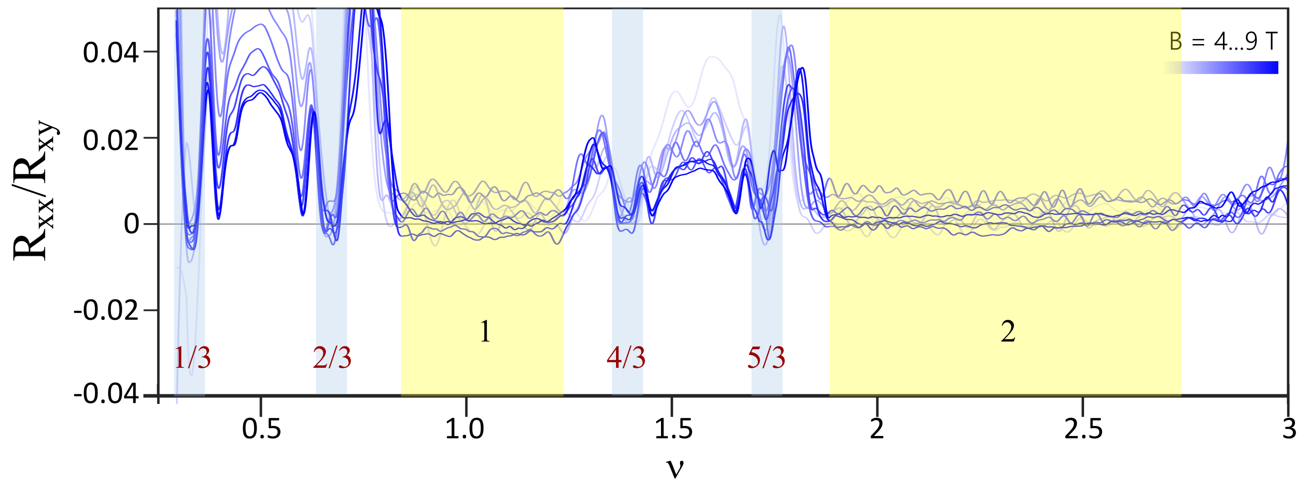
Probability of CAR:

$p_{CAR} = -R_{CAR}/(R_{CAR} + R_{xy})$



Magnetic field

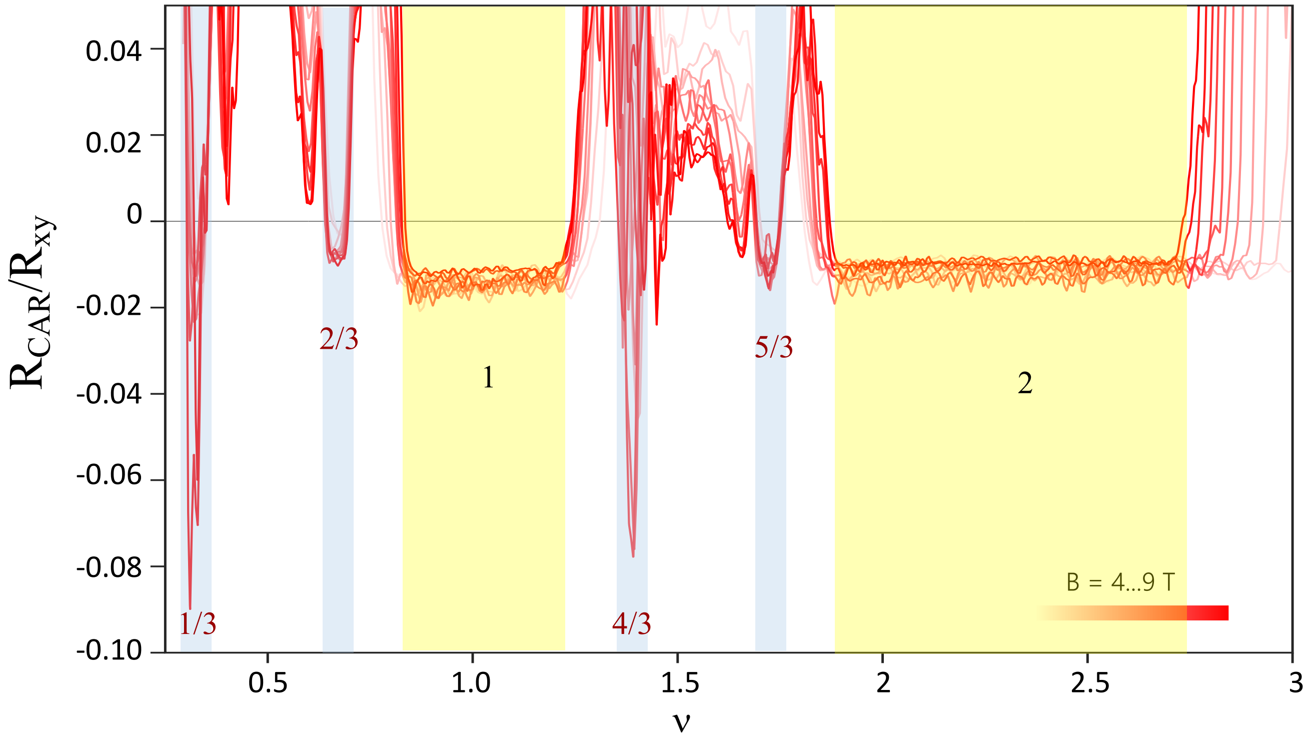
Fractional Crossed Andreev Reflection Probability



4 - 9 Tesla @ 15 mK

$R_{xx}/R_{xy} < 1\ \%$

for both integers and fractions



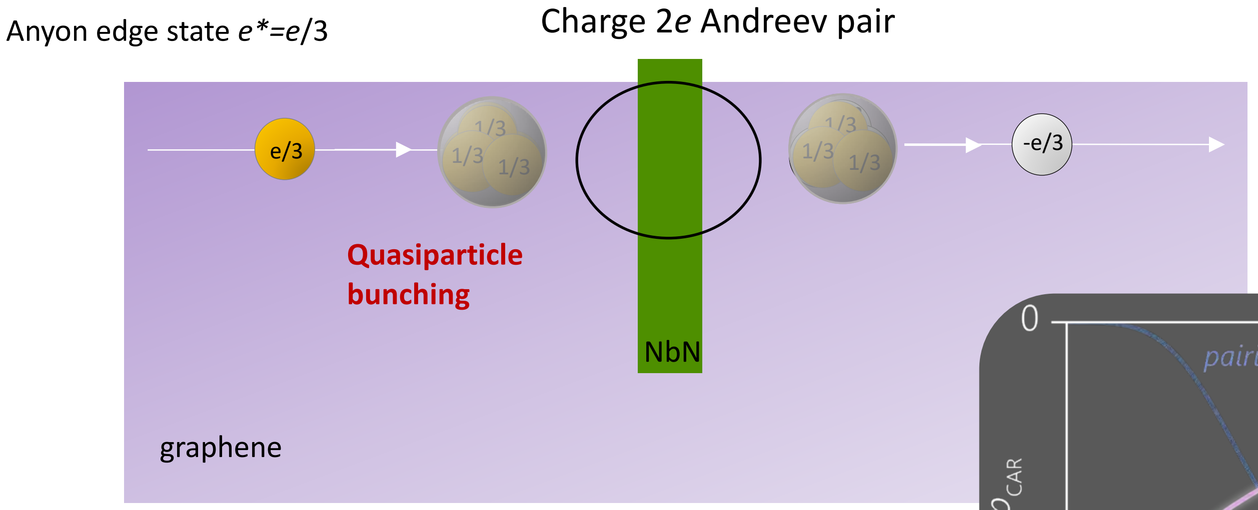
Probability of CAR: $\boldsymbol{R_{CAR}/R_{xy}}$

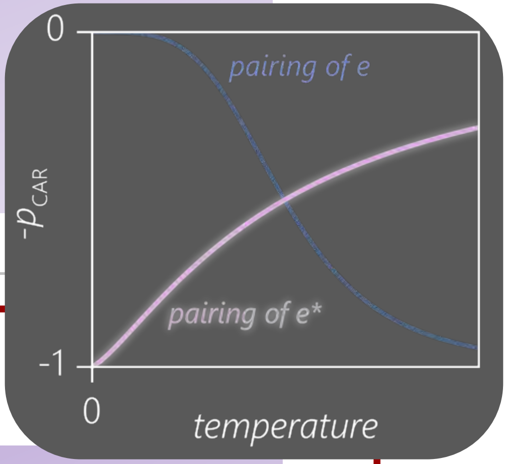
~ 3%: 2/3, 1, 5/3, 2

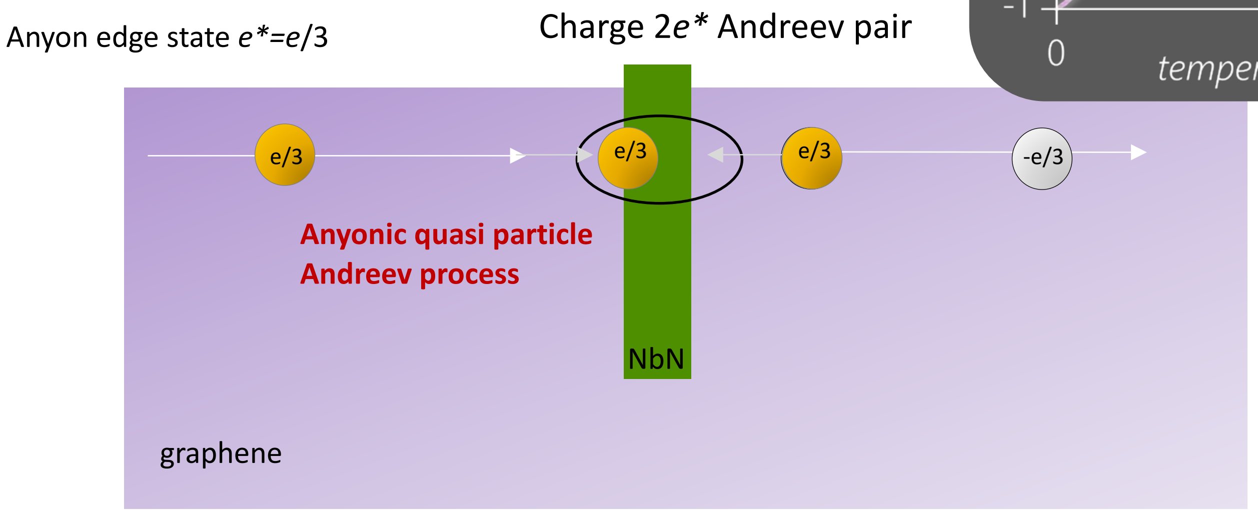
~ 7 %: 4/3

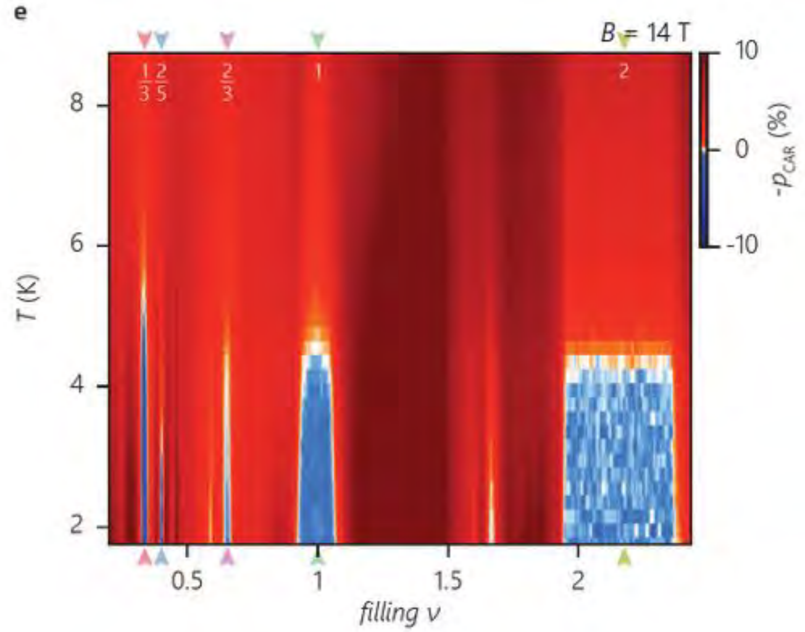
~ 9 %: 1/3

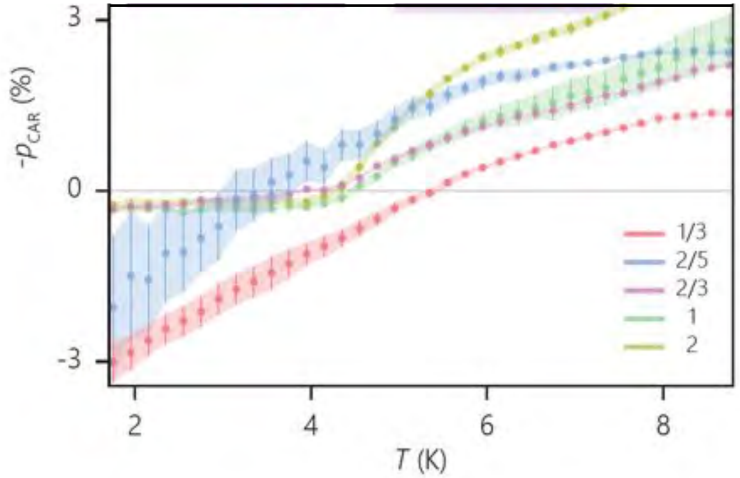
Electron Cooper Pairs versus Quasi Particle Andreev Pairs





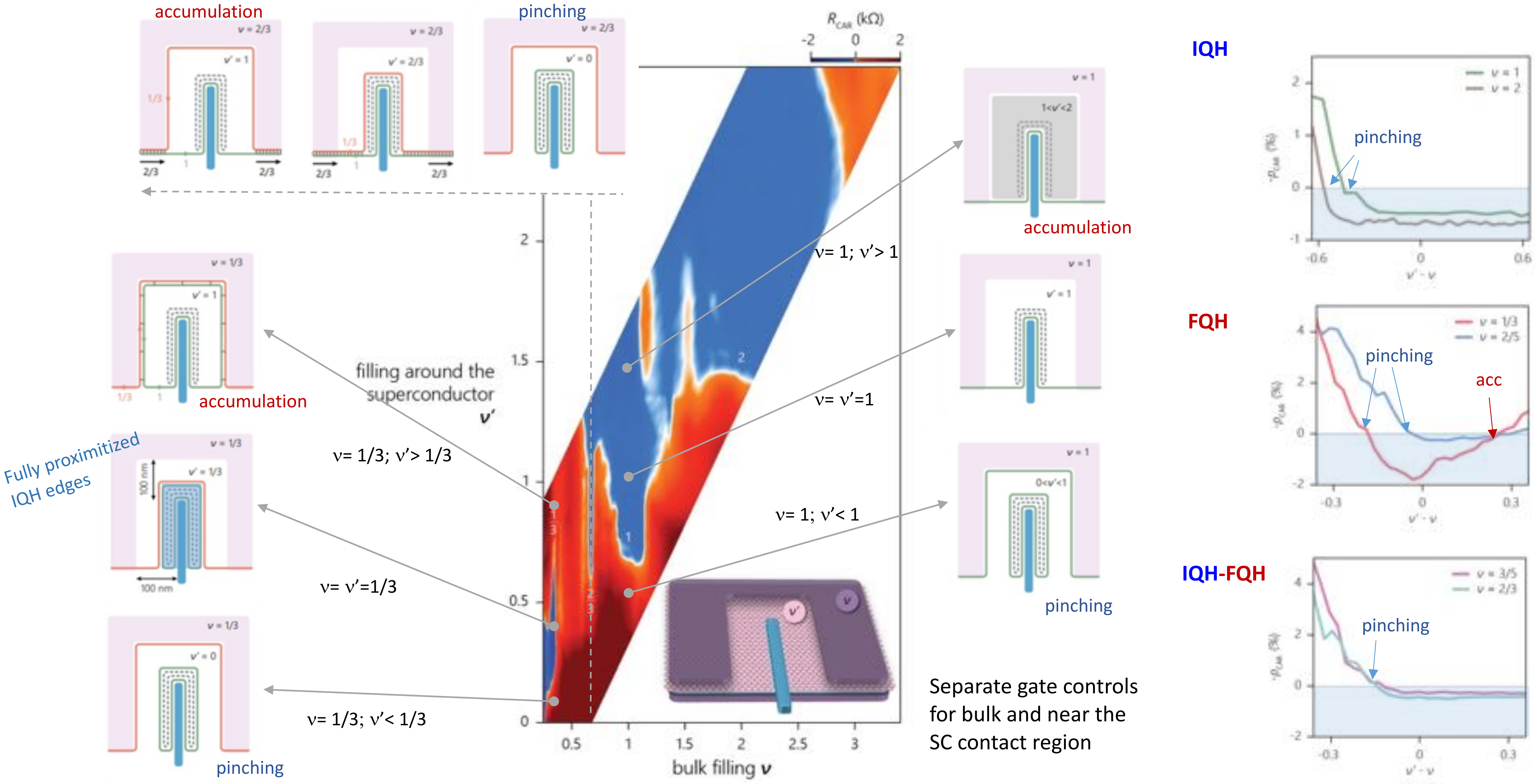






Robust CAR for 1/3 FQHE
at low temperature high magnetic fields!

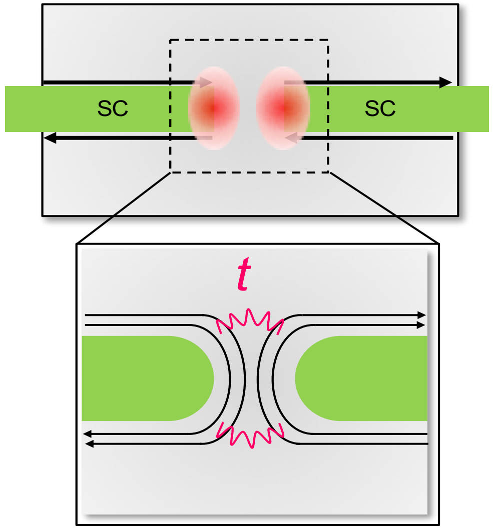
FQH edge–Superconductor Interface: Microscopic Picture

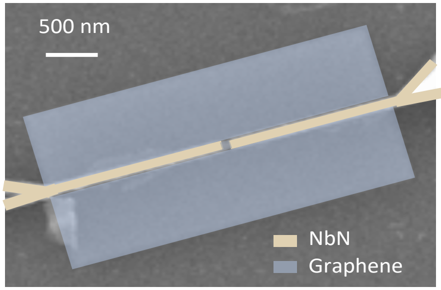


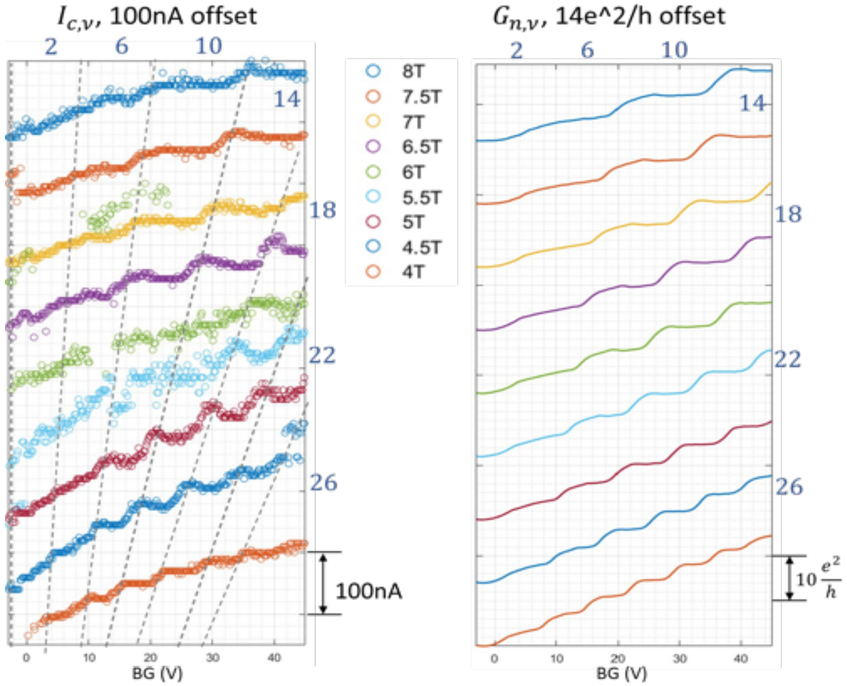
Separate gate controls for bulk and near the SC contact region

What are the next steps?

Parafermion Josephson Junction



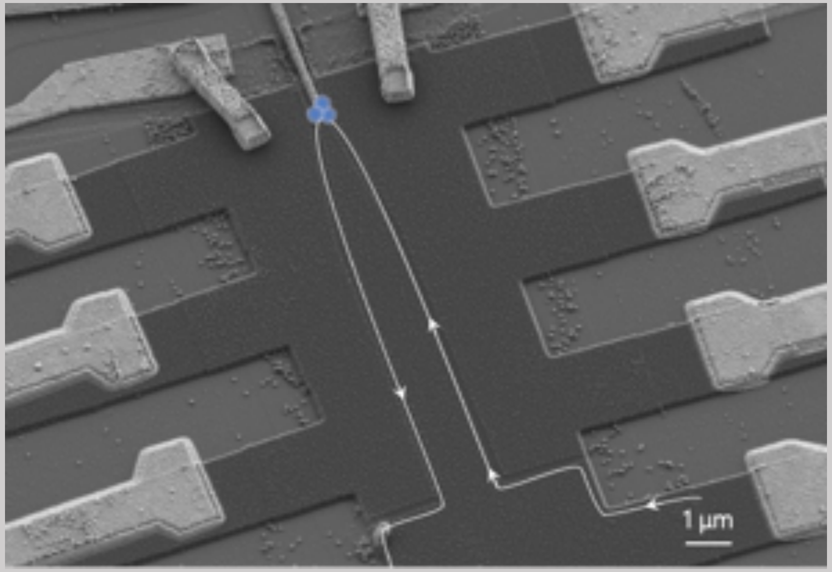




J. Shi *et al*. unpublished

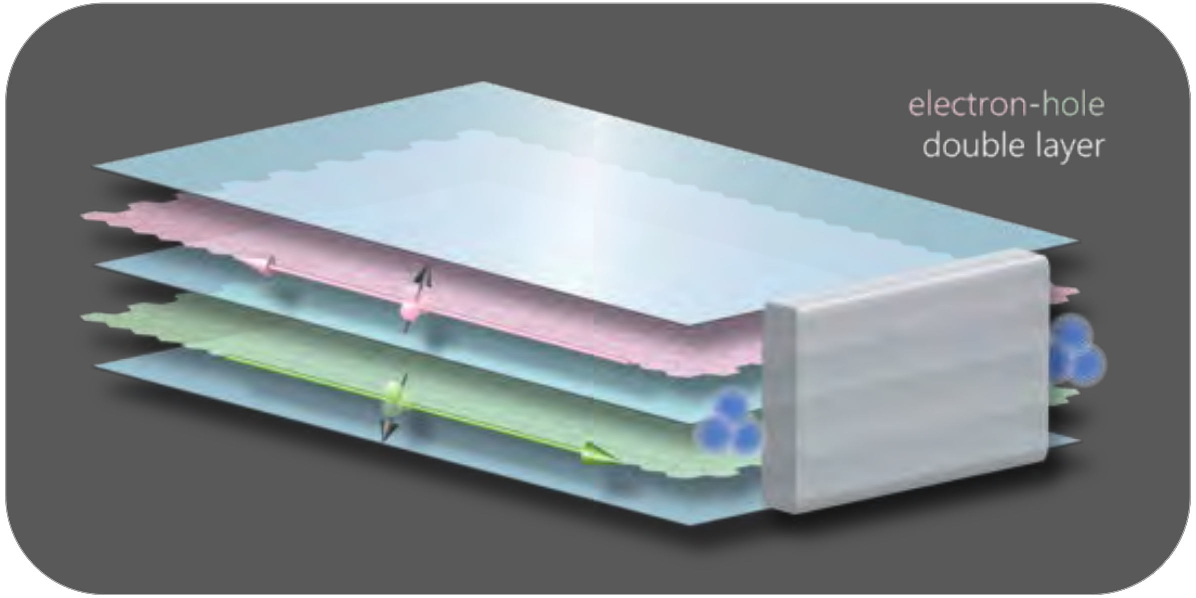
$$\Delta I_c \sim \left(\frac{4e}{h}\right) e\Delta$$

Tunneling into the zero mode



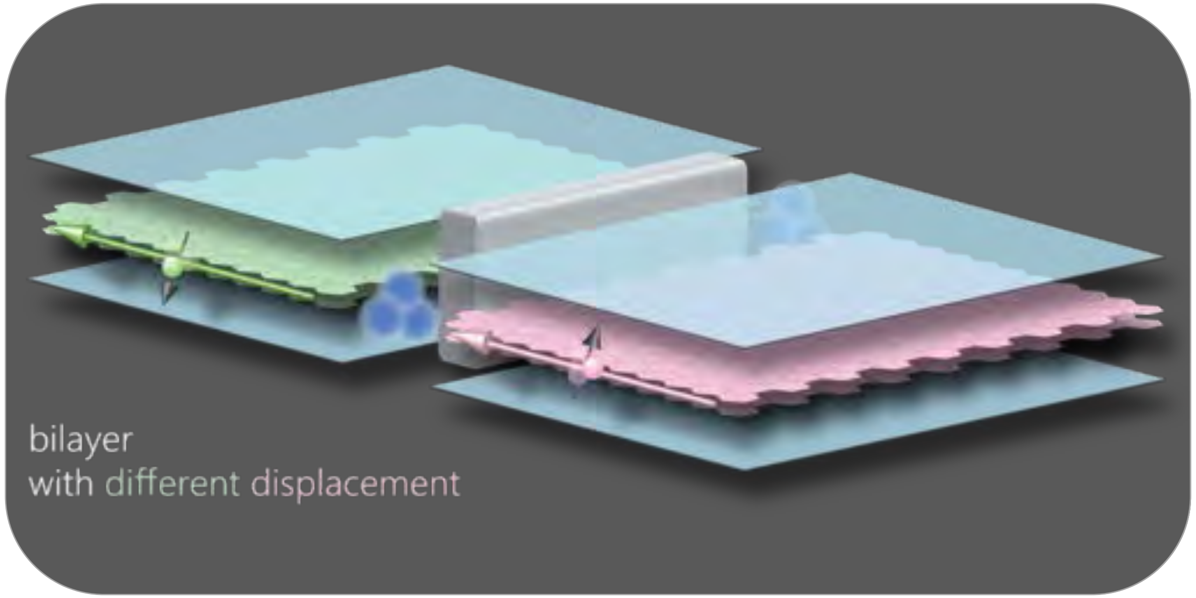
Quantum Hall edge to parafermion zero mode

Outlook



Increasing CAR probability

- *atomically close distance* (~1 nm) *between counterpropagating edges*
- *pairing does not rely on spin-orbit coupling*
- *may allow supercurrent carried by fractional charges*

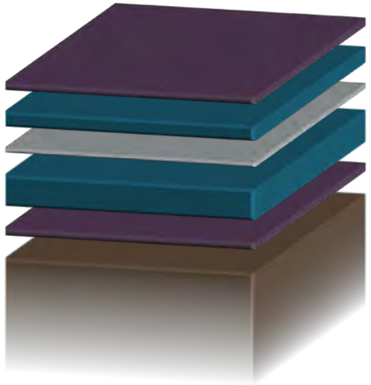


Electric field-control of fractional ground states

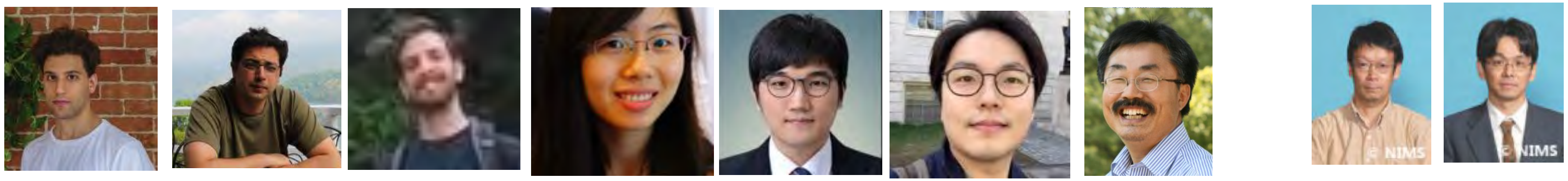
Ideas from Onder Gul *et al*

Summary

- CAR of IQH/FQH is observed in graphene
- Neither valley nor spin are conserved in CAR for IQHE with CAR probability is estimated to be ~ 3 %
- Strong CAR for some FQH edge with up to 10% CAR probability



Acknowledgment

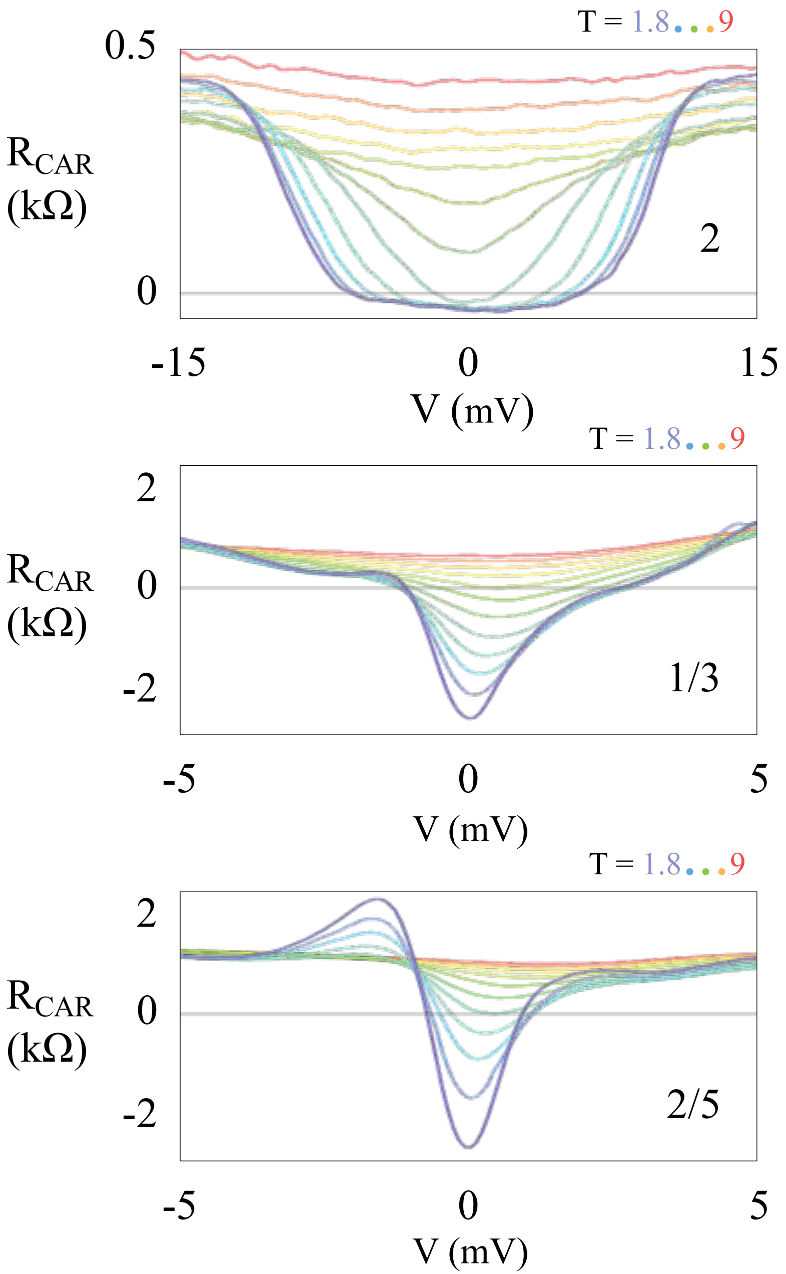


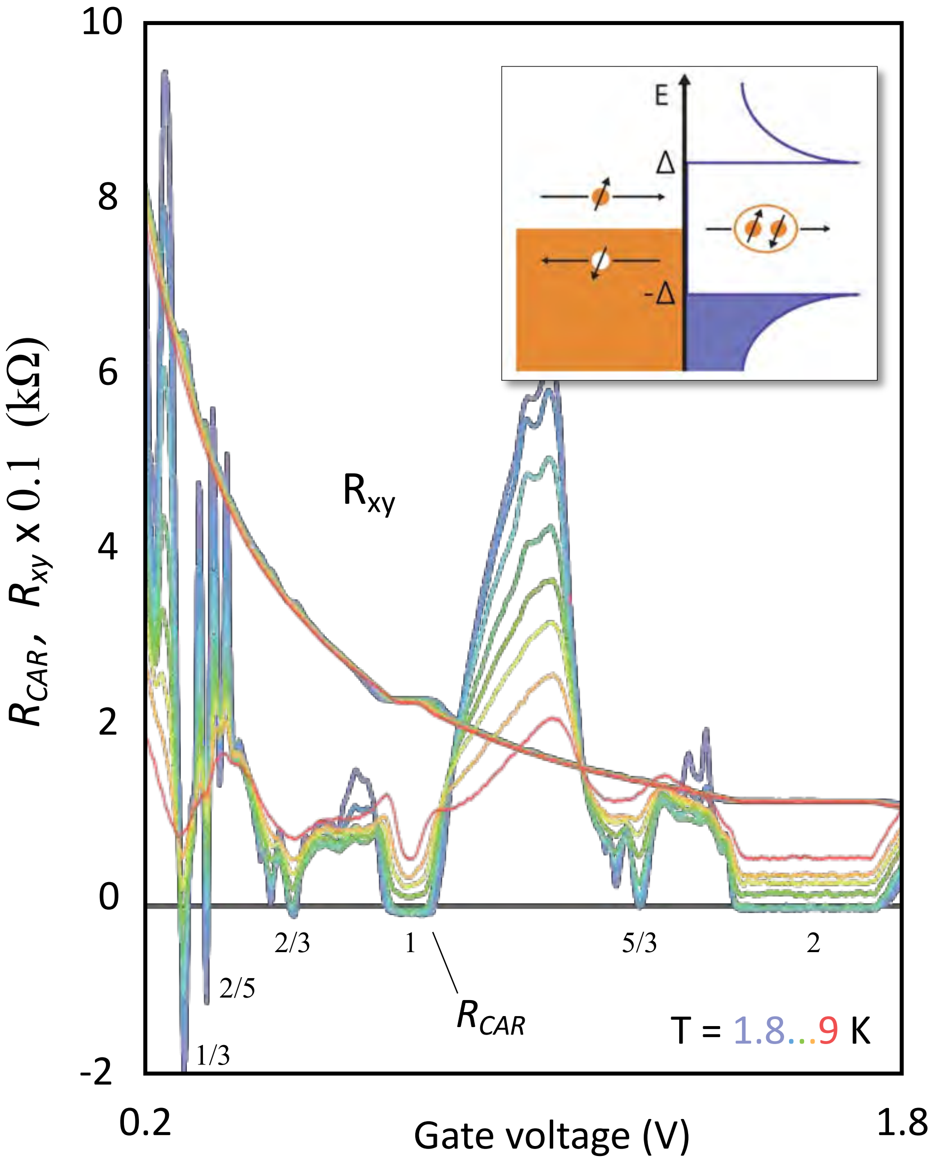
Onder Gul, Yuval Ronen, Jonathan Zauberman, Jing Shi, Gil-Ho Lee, Si Young Lee, Young Hee Lee, T. Taniguchi, K. Watanabe

Sean Hart, Amir Yacoby, Sagar Bhandari, Bob Westervelt, Hassan Shapourian, Ashvin Vishwanath

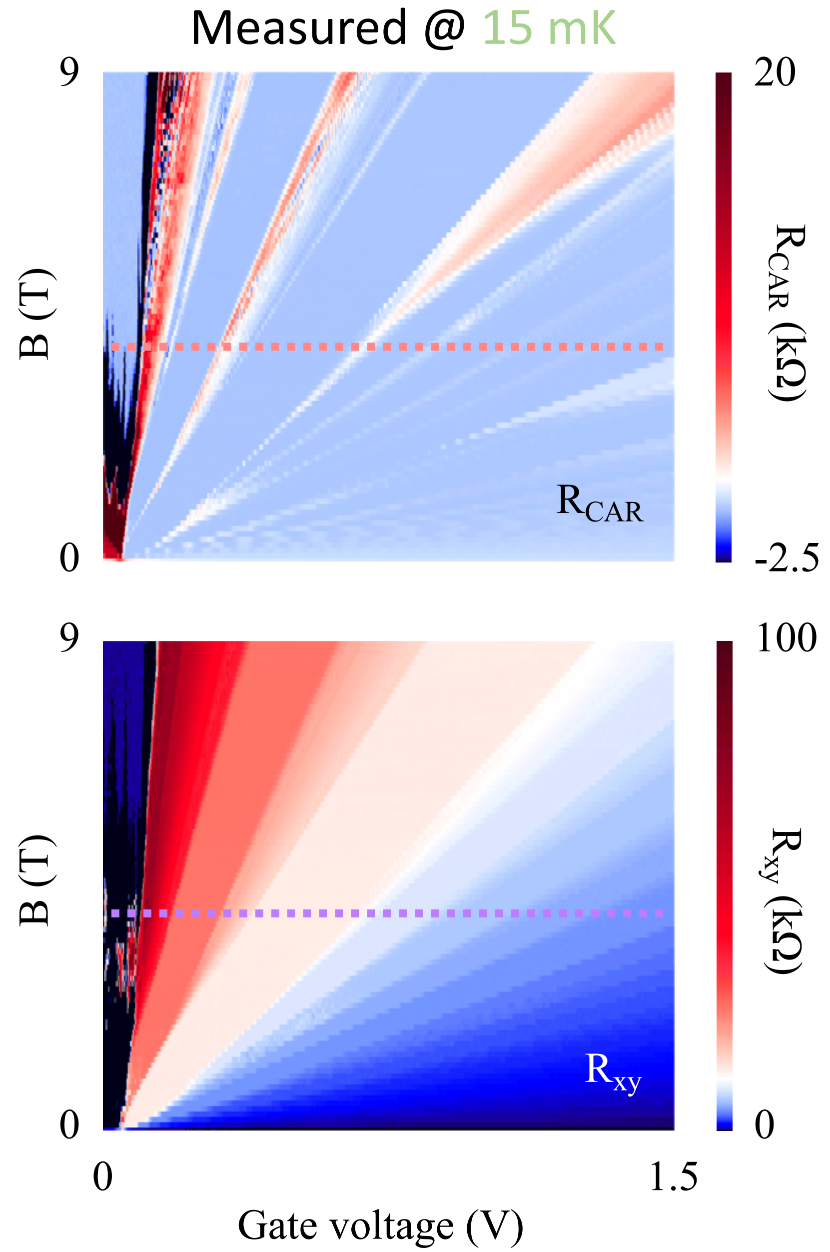
Office of Naval Research

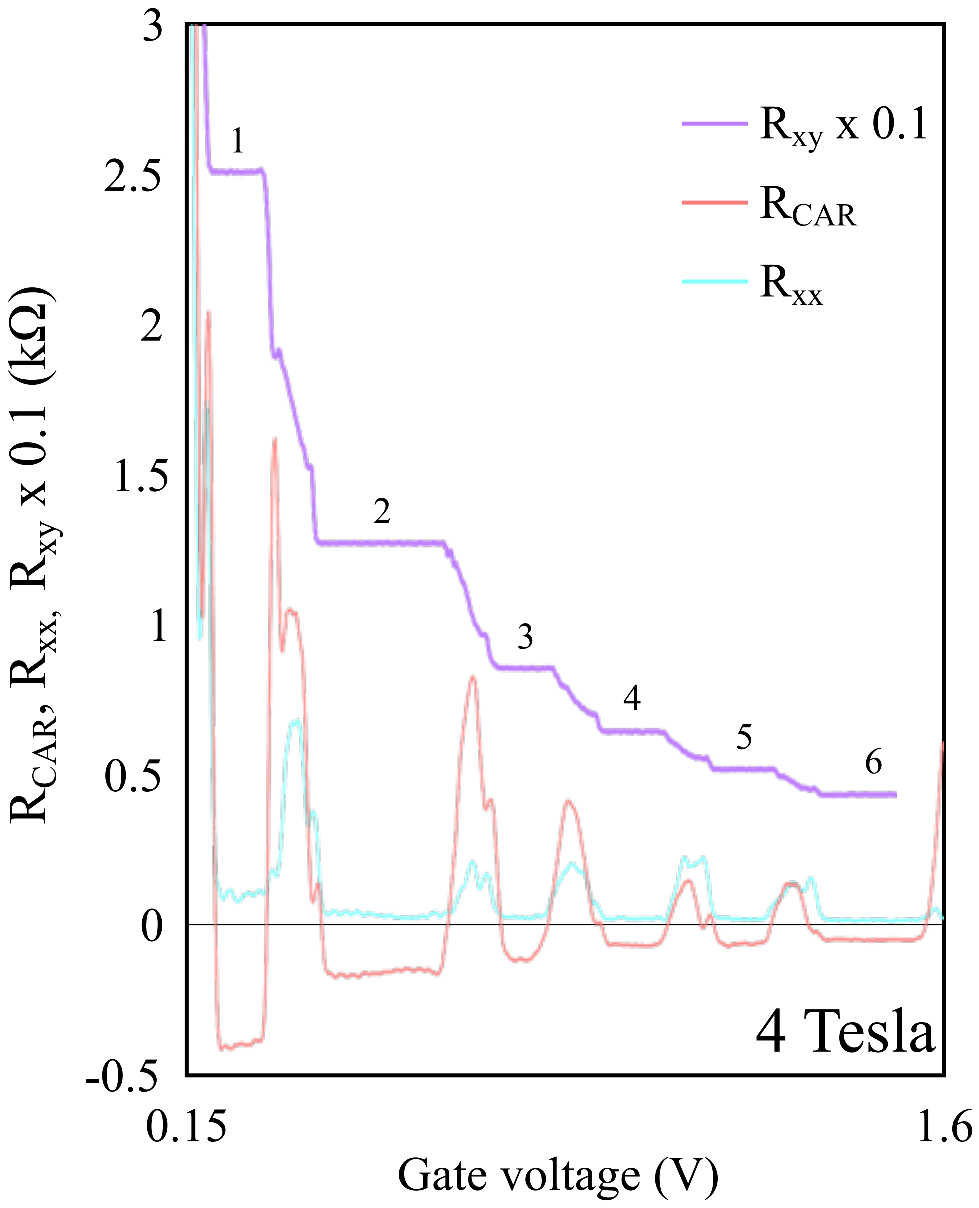
Crossed Andreev Reflection for IQH/FQH: Bias Dependence





Crossed Andreev Reflection for IQH at Low Magnetic Fields





Crossed Andreev Reflection for IQH/FQH: Temperature Dependence