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# Developing Topological Superconductivity Through Hybrid Material Systems

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# Quantum Technology

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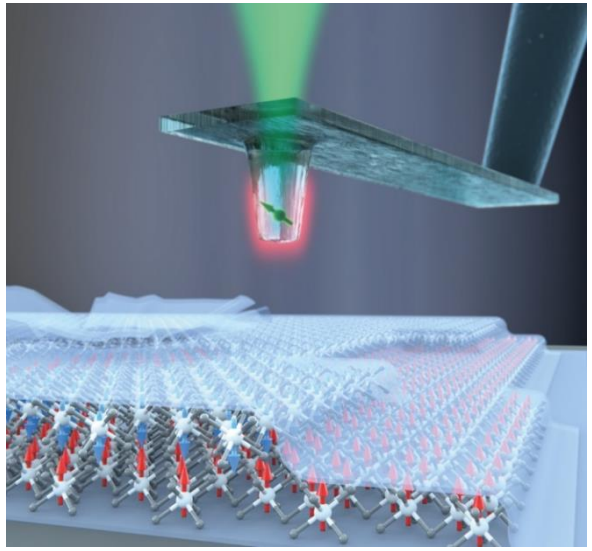
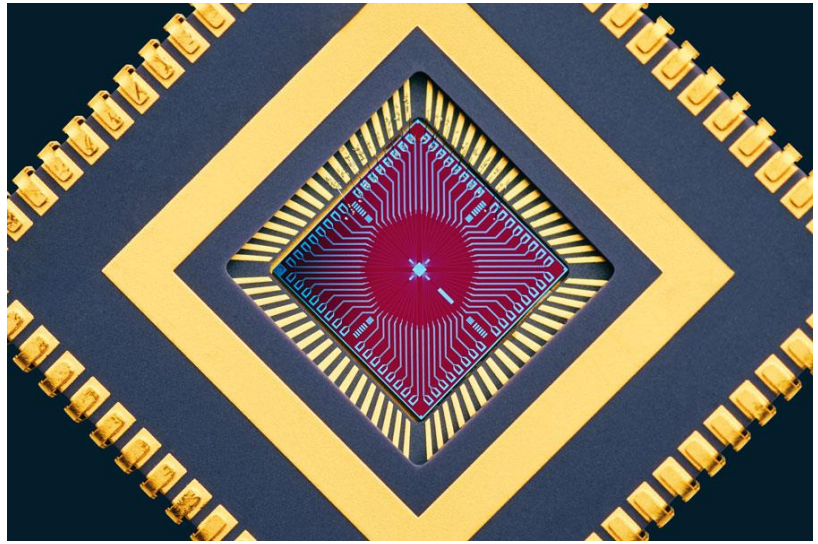
One can use the quantum state to build up more advanced quantum technologies: such as quantum communication, quantum computer, quantum sensing, and detectors

Source: Google quantum



Source: Basel University



Source: JPL

To engineer and understand the quantum device is important to meet our technology needs.

# Qubit research

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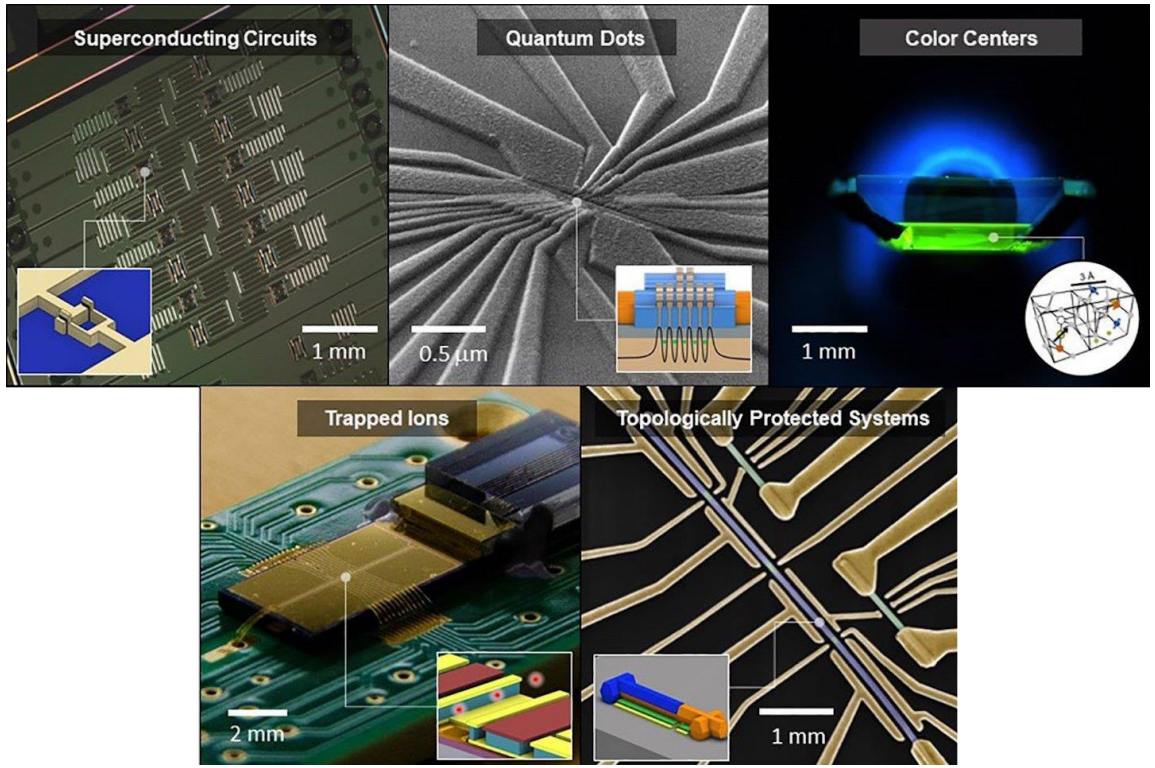
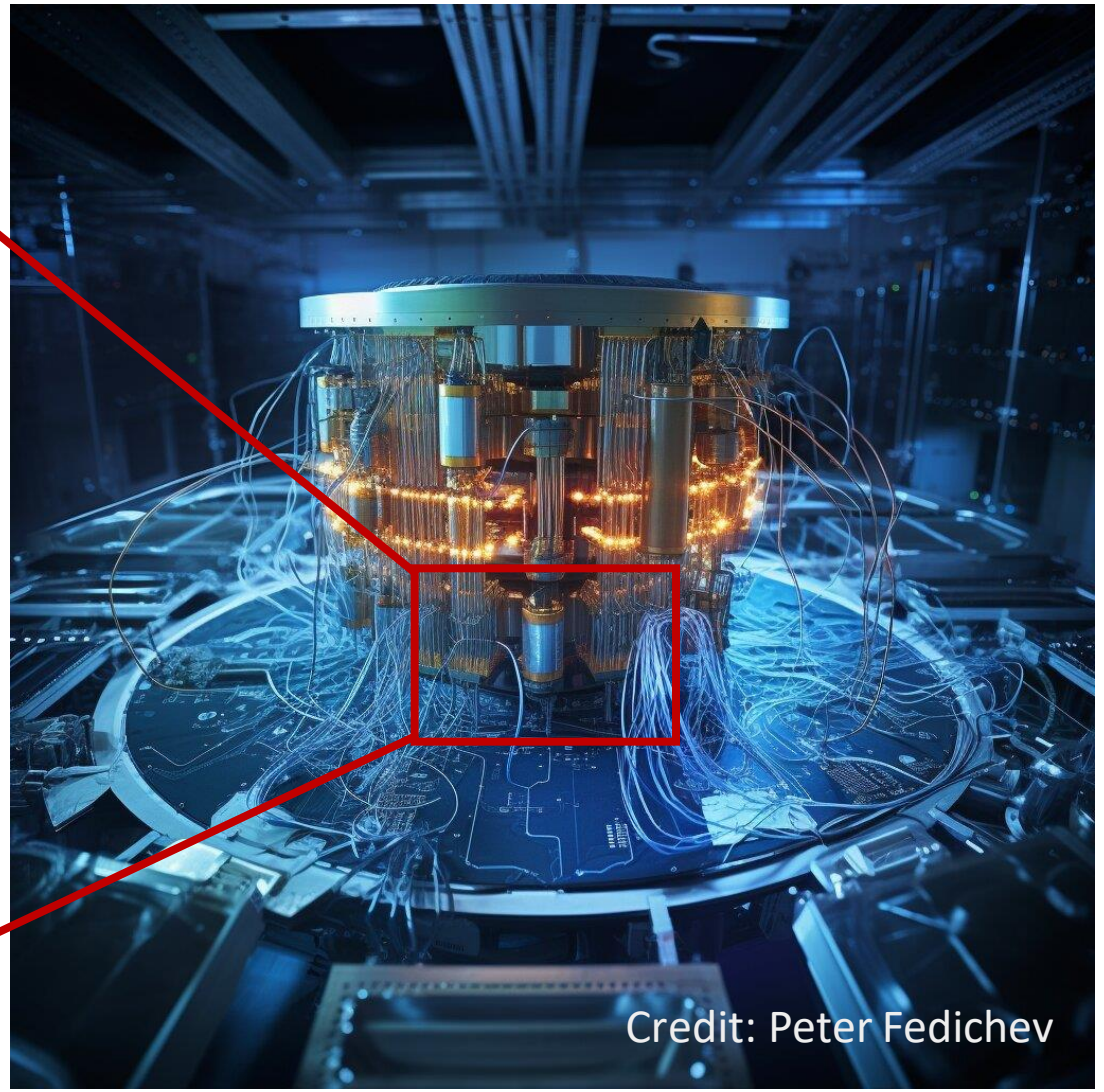
## Develop outstanding qubits



# Qubit research

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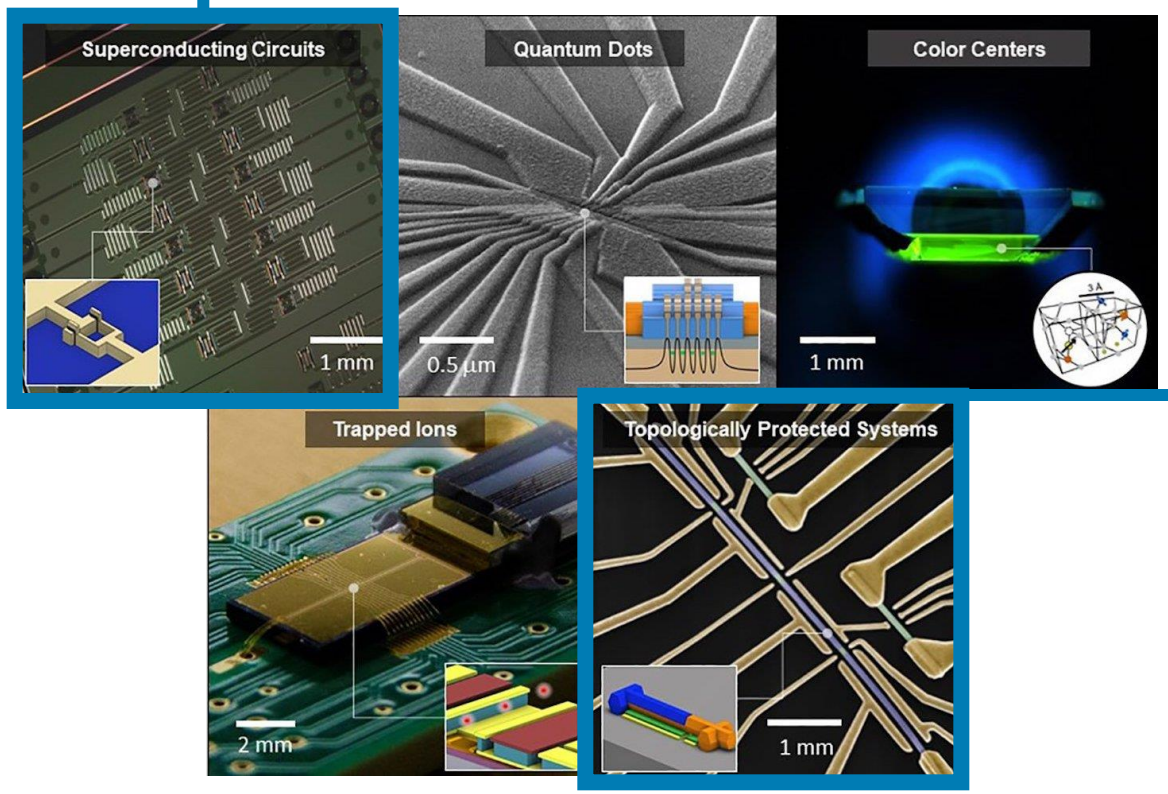
## Develop outstanding qubits




### Optimize qubit & environment

1. Longer coherent time
2. Optimize the readout
3. Better measurement scheme

and more

### Search for a different qubit scheme

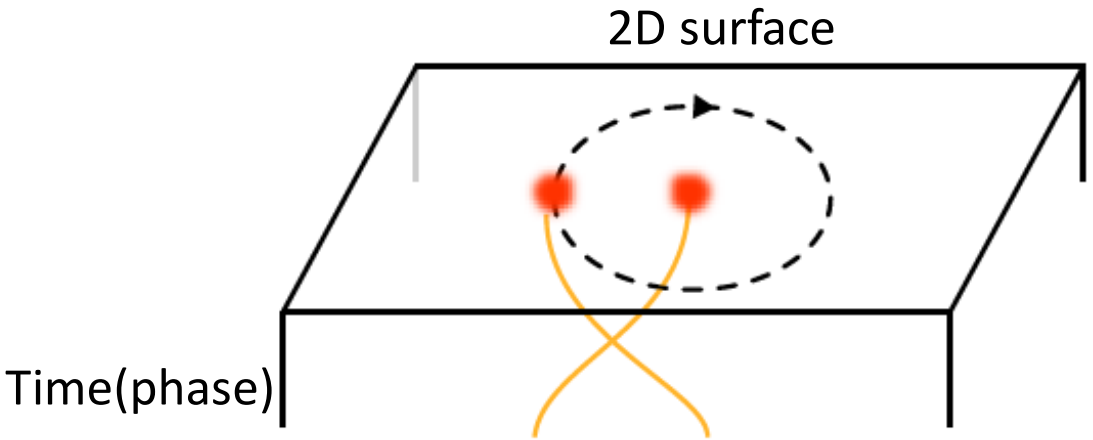
1. Tolerant to noise
2. A different qubit scheme
3. Different choices of materials

and more

# A different rout

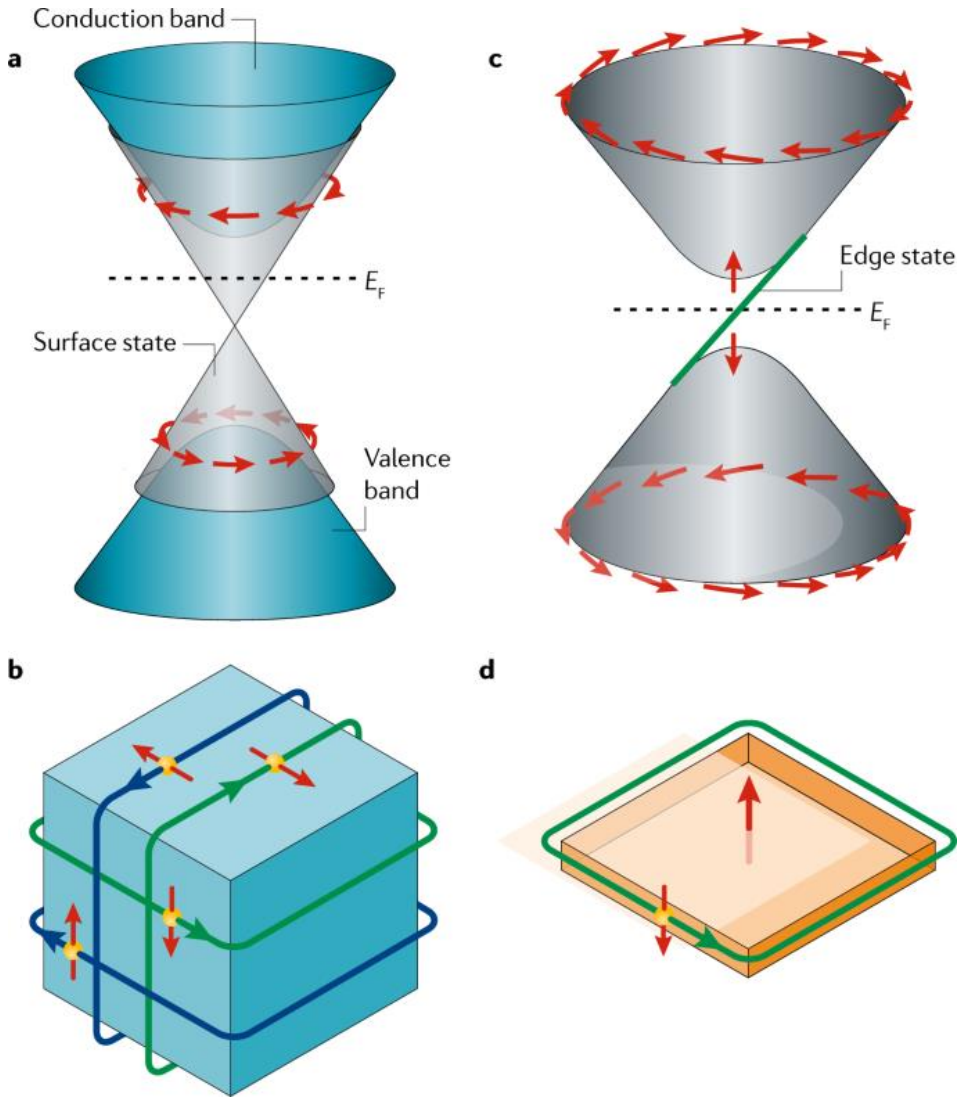


**Using topological phase**




Exchange particle to
register the information

**Information is immune to local perturbation.**

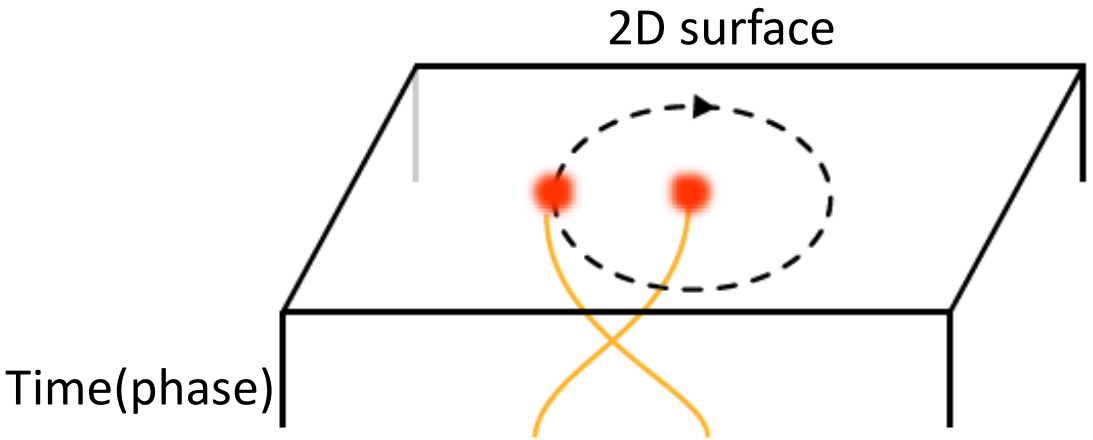



Yoshinori Tokura et al, Nature Review Physics (2019)

# A different rout



## Using topological phase

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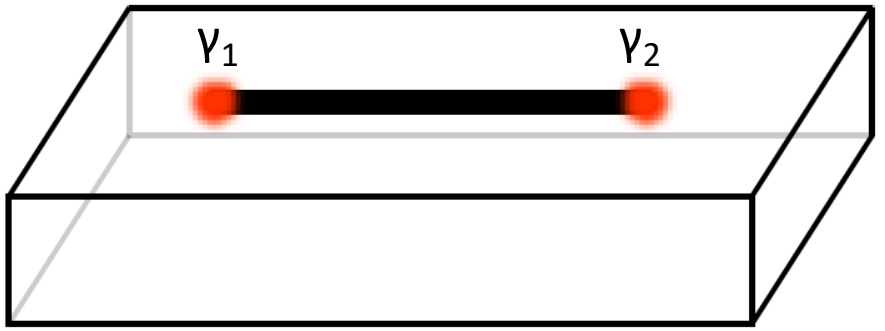


Kitaev 2001

- A pair of zero energy states(MZM)
- Nonlocality
- Topological gap
- Need a p-wave superconductor

**Using hybrid material systems**

# Topological Superconductivity

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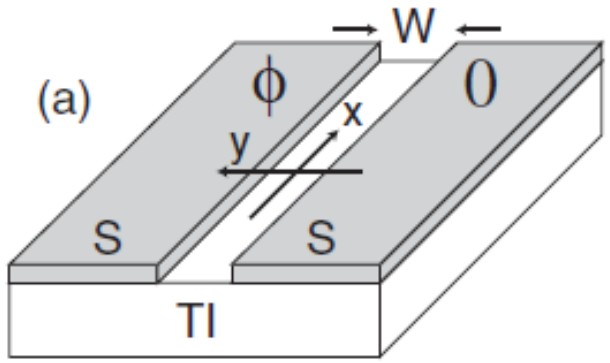
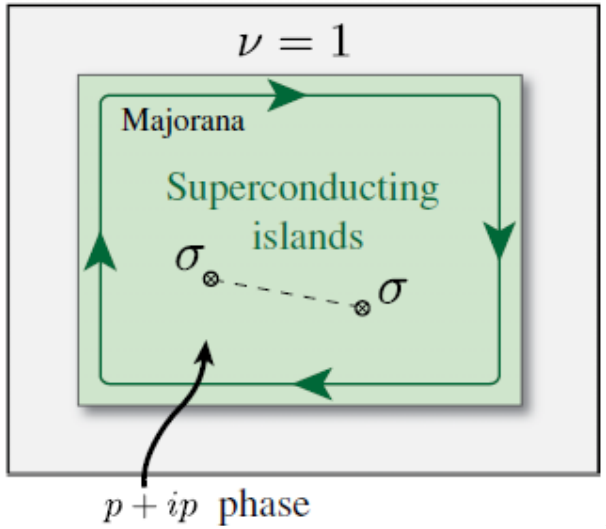
## Realize the topological phase

**SC + TI**



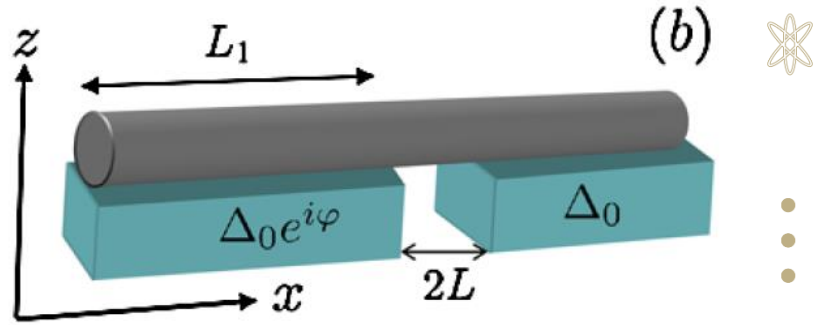

Fu and Kane PRL (2008)

**SC + QH**




Mong et al. PRX (2014)

**SC + SOC semi. + Zeeman**



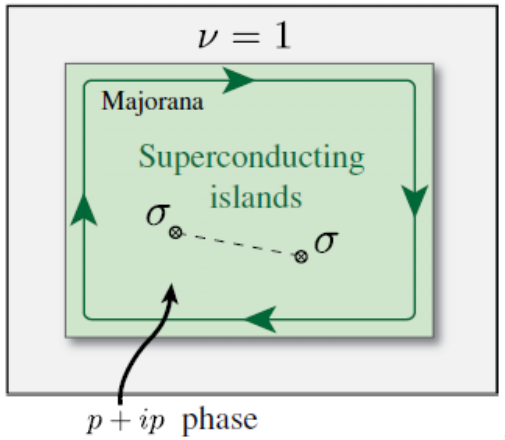

Lutchyn. et al. PRL (2010)
Oreg et al. PRL. (2010)

Using hybrid material systems, it is possible to create MZMs

# Creating Topo-SC

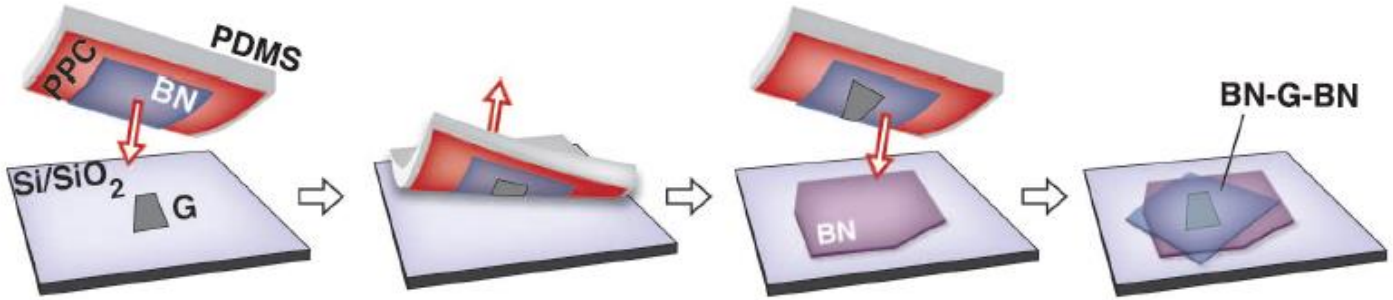


## Quantum Hall effect and superconductivity

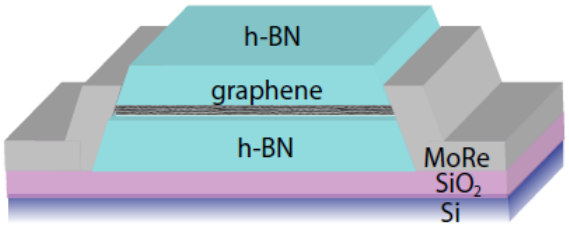



Mong et al. PRX (2014)

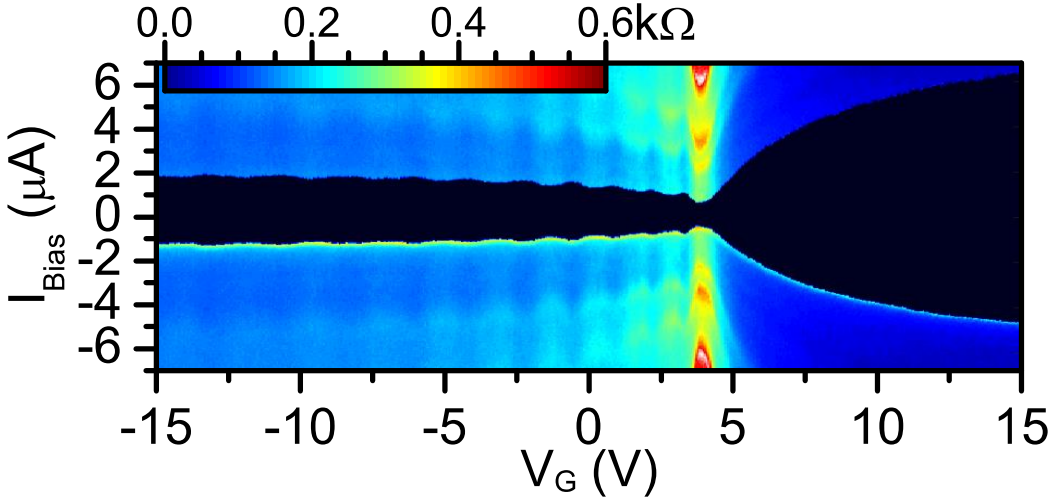
Constructing the Quantum Hall states requires a clean 2D system.




L. Wang et al. Science (2013)




- Use Raman, AFM then lithography to define the junction region.
- Sputter MoRe ($T_c$=10 K and $H_{c2}$≈8T)




Borzenets, Amet, Ke et al. PRL. 2016

# Quantum Hall and superconductivity

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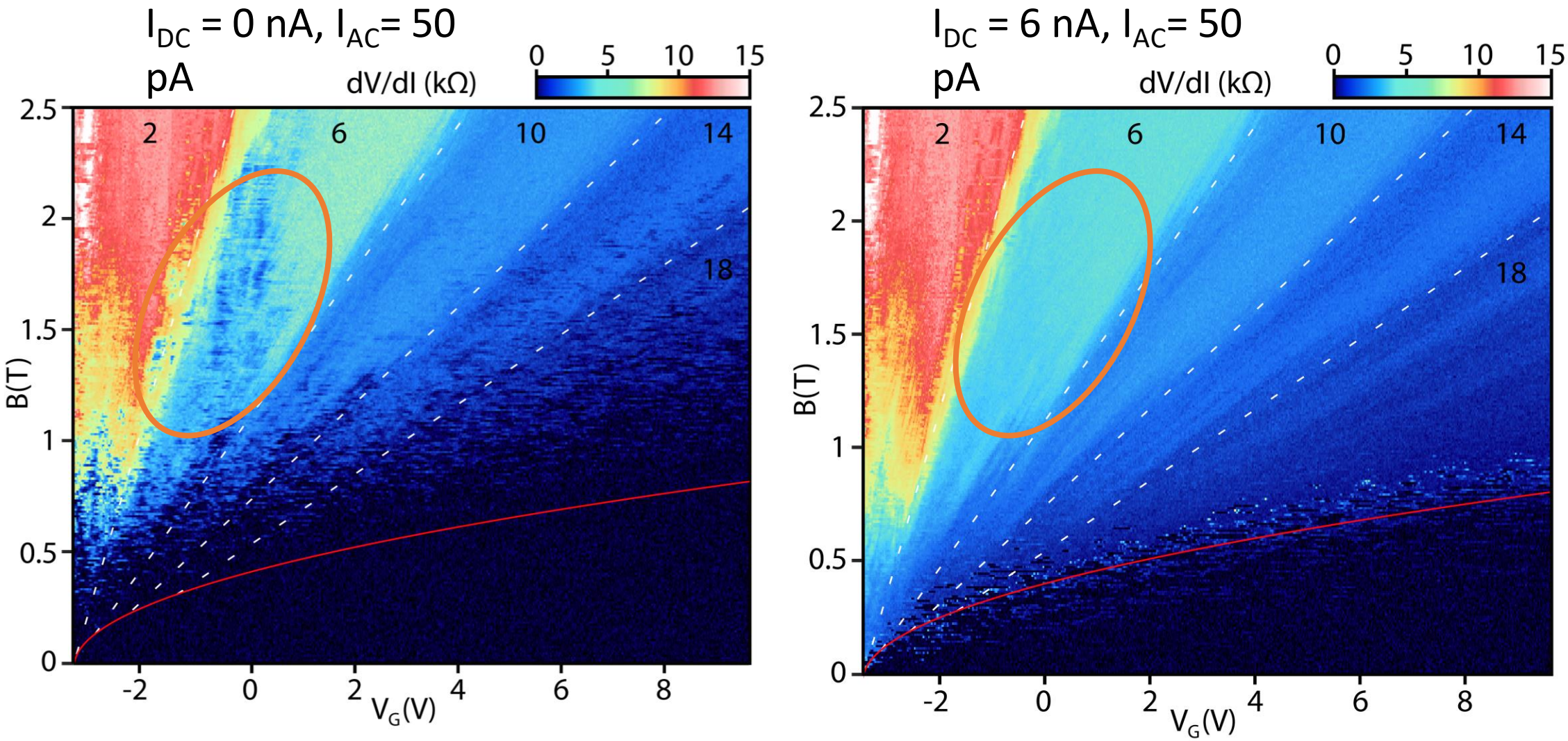

# Quantum Hall and superconductivity

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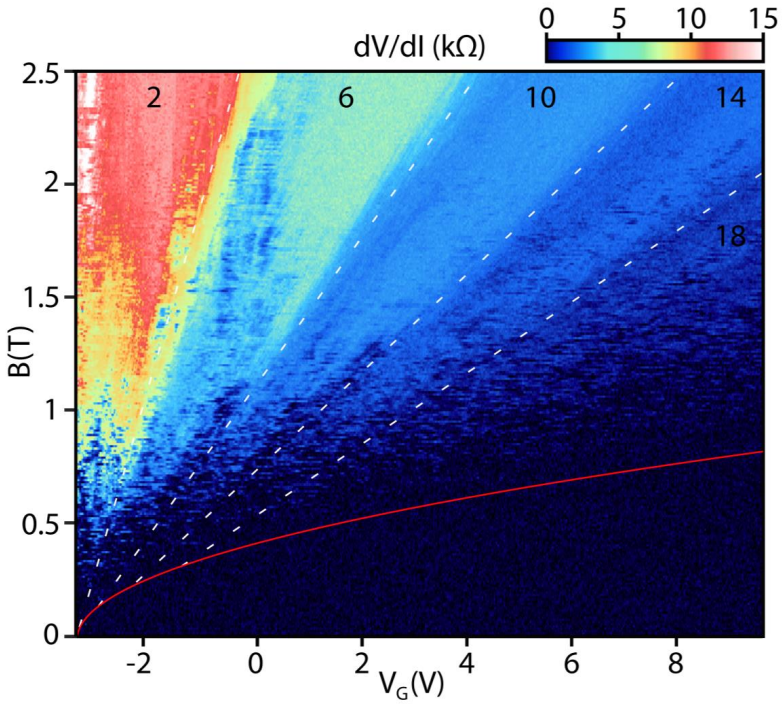
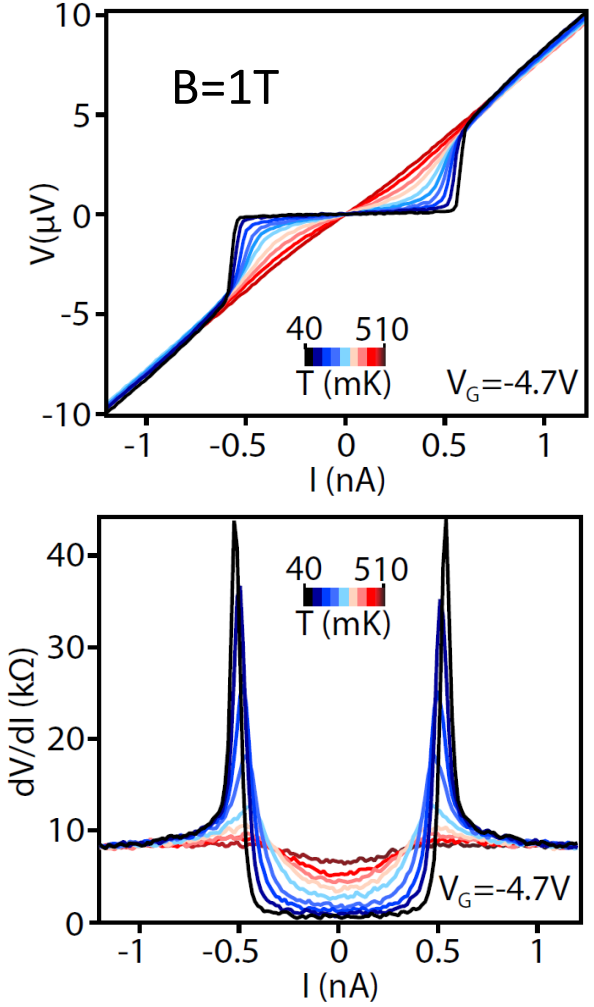
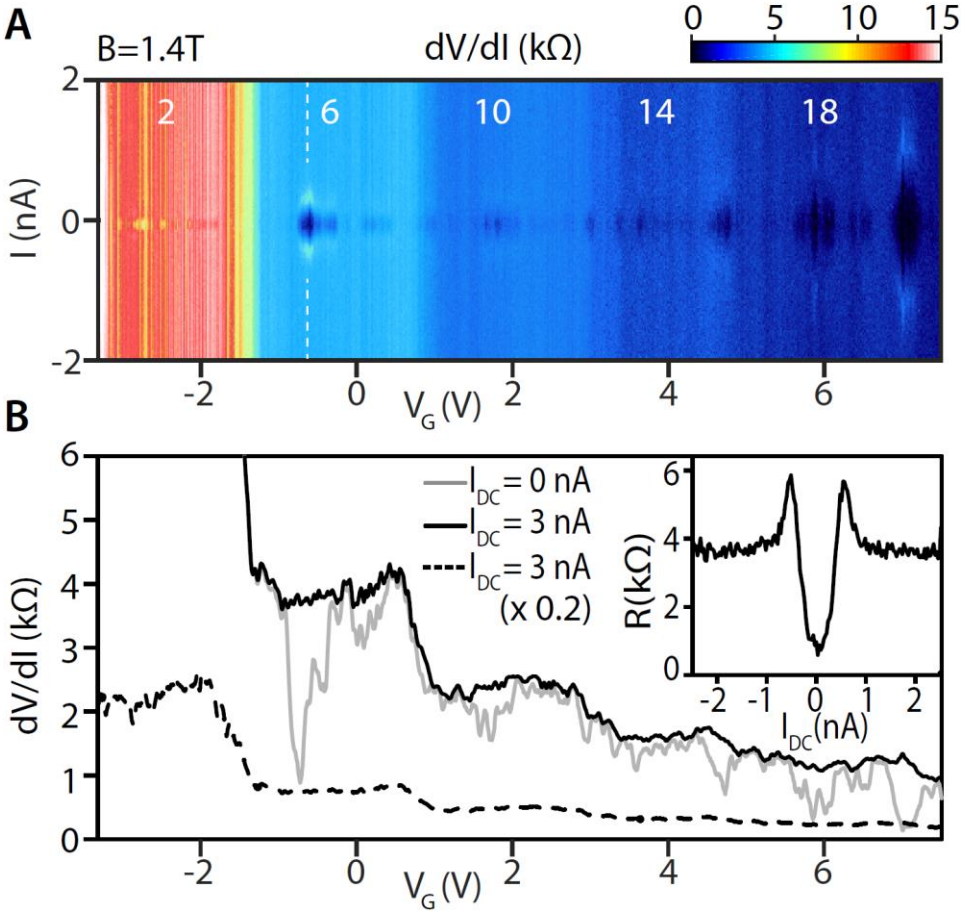
## Quantum Hall effect and superconductivity




**The first observation of SC +QH!**

Amet, Ke et al. Science (2016)

# Semiconductor+SC

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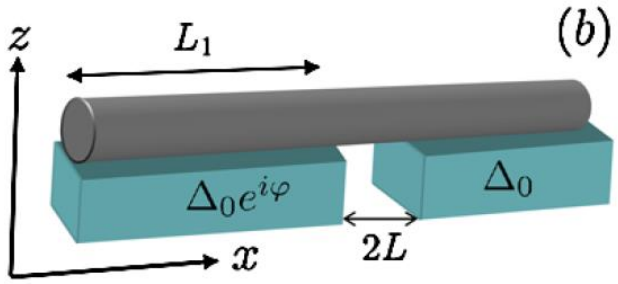
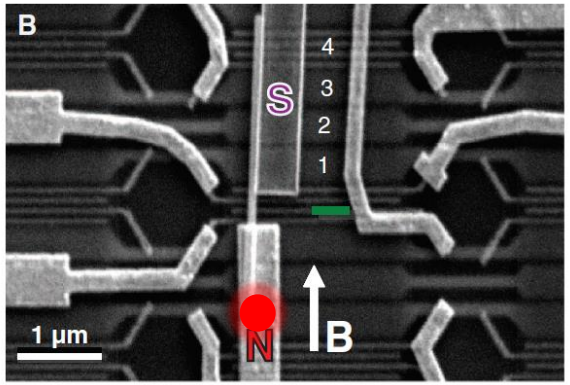


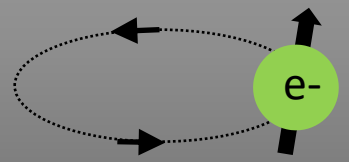

Lutchyn. et al. PRL (2010)
Oreg et al. PRL. (2010)



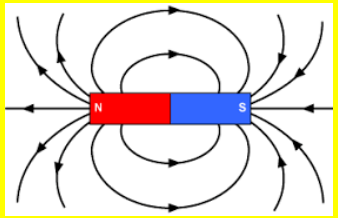

Mourik et al., Science (2012)

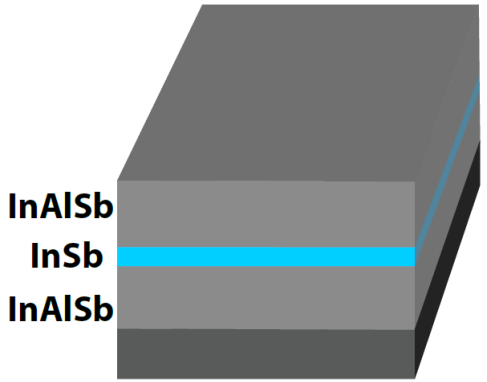
***Superconductivity***

***Spin-orbit coupling***




***Magnetic field***

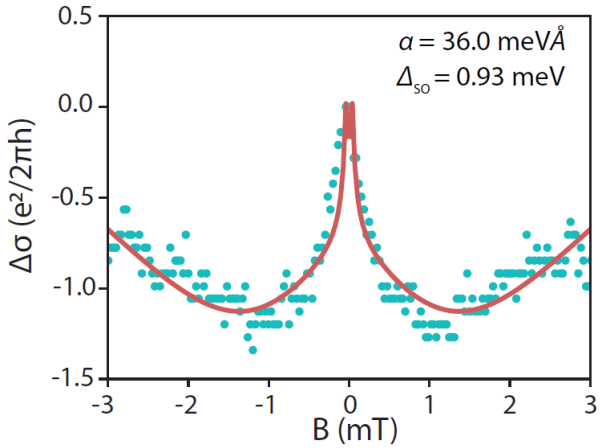



- Good for scalability
- Large g-factor

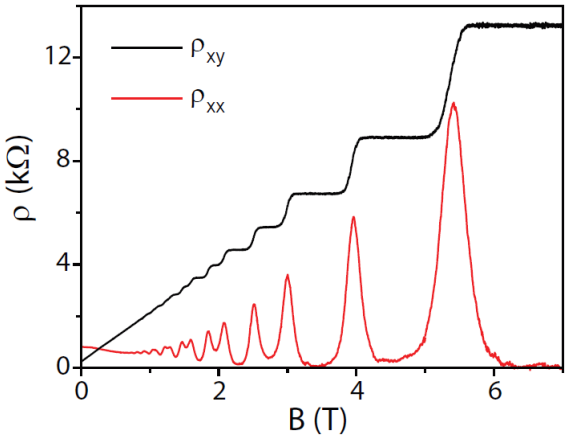
***$g_{//}$-factor ≈ 25***

***Strong spin-orbit interaction (WAL)***




***High mobility***

μ=200,000 cm²/Vs




***Last ingredient : Superconductivity***

# InSb Josephson junction

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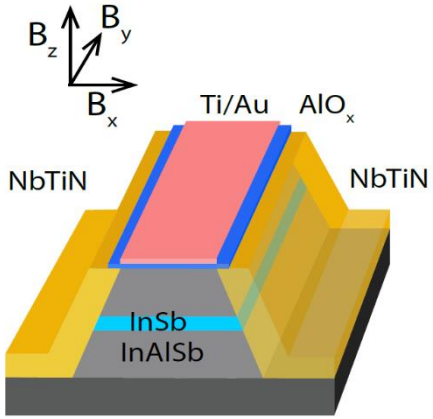
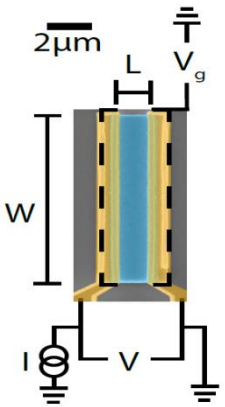
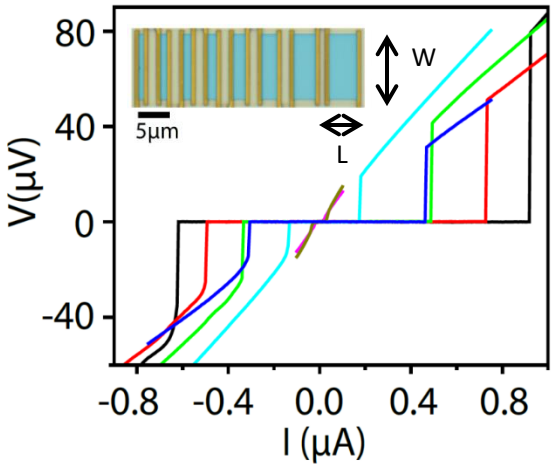
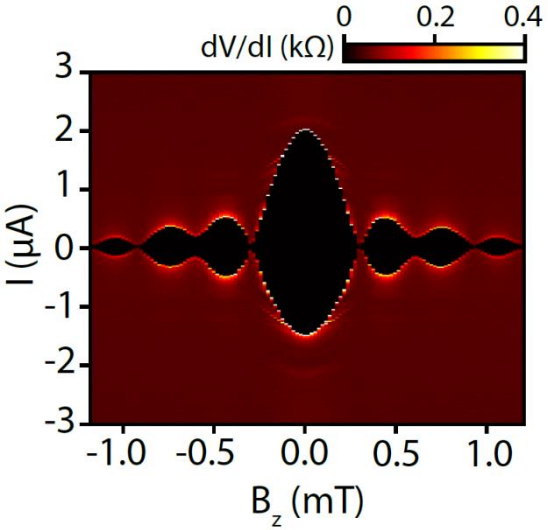
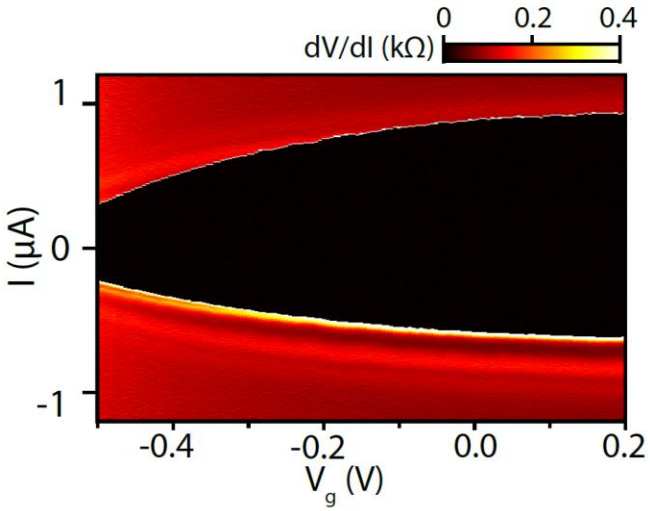
## Realize ballistic superconductivity



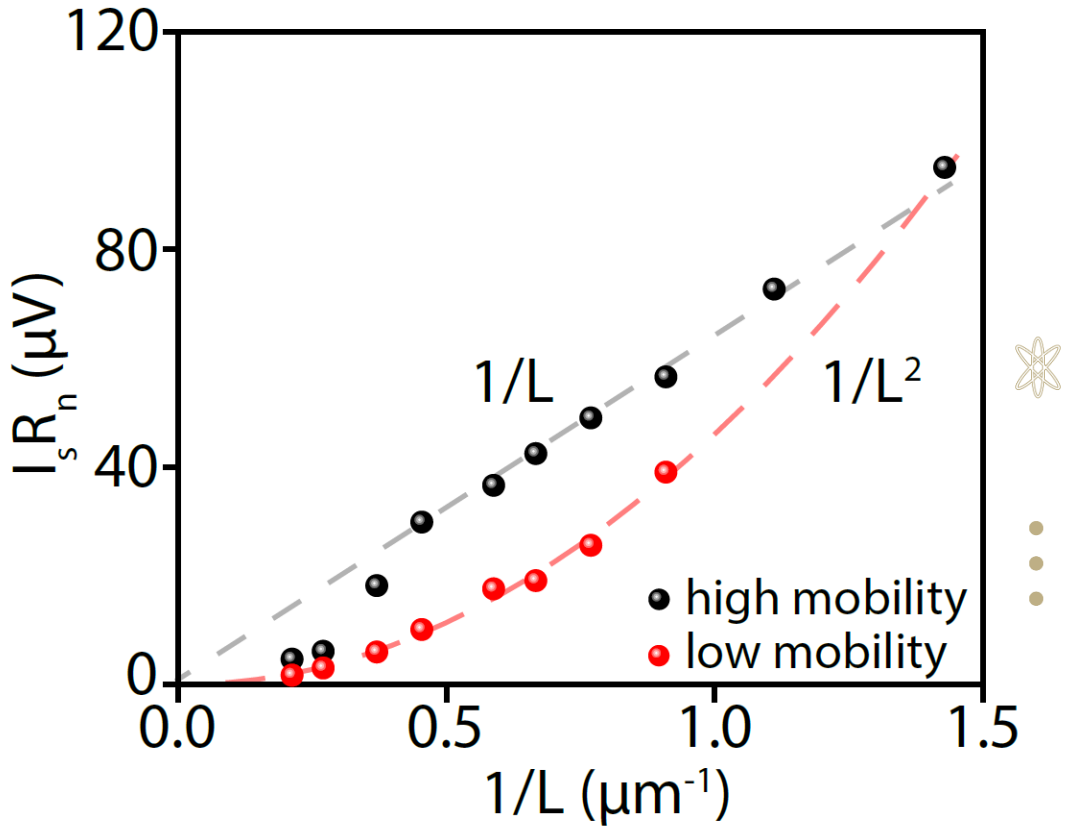




Ke, Moehle et al. Nat. Comm. (2019)

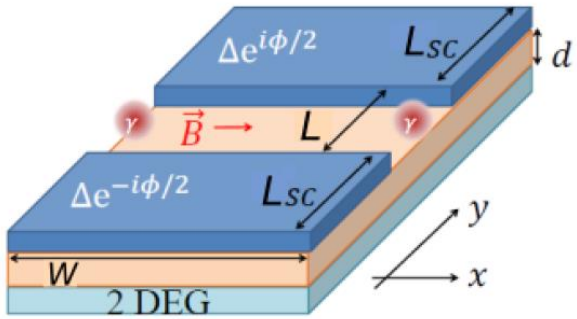


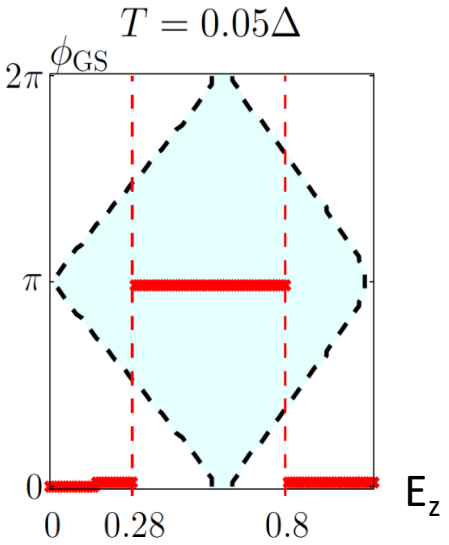

Ballistic : $E_T = \frac{\hbar V_F}{L} \propto I_c R_n$

Diffusive : $E_T = \frac{\hbar D}{L^2} \propto I_c R_n$

# Planar Josephson junction



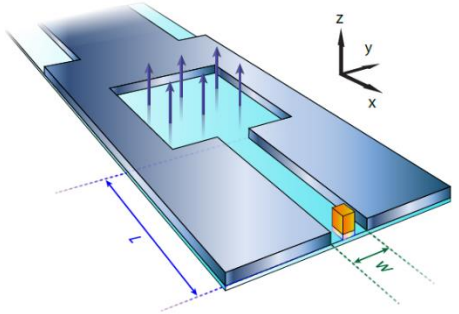


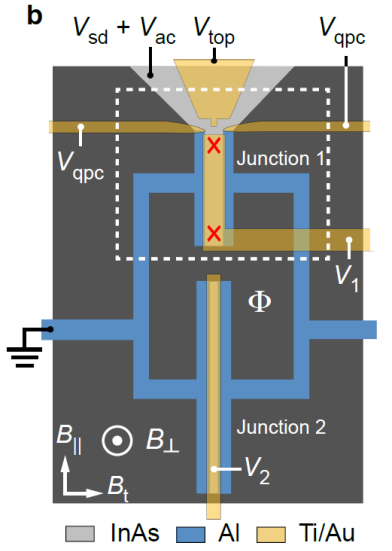




Pientka et al. PRX (2017)
Hell et al. PRL (2017)

- For a π-JJ with strong SO:

1. Lower the required Zeeman field.
2. For 2D system, scalability is possible.
3. Phase control provides additional tuning knob.
4. Large topological phase space for exploring MZM.




Fornieri *et al. Nature* (2019)
Ren *et al. Nature*(2019)

# 0 – π transition

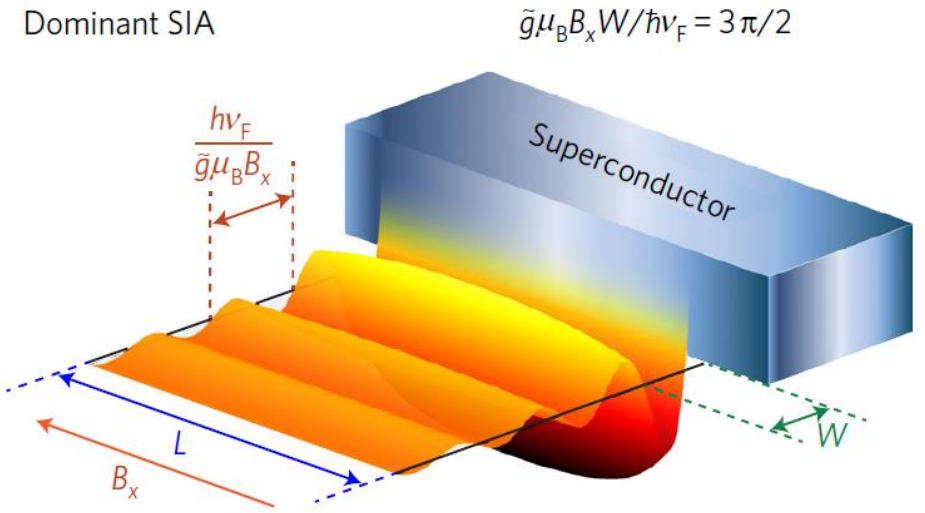


Superconducting order parameter:

$$\Psi(r) \propto \cos(\boldsymbol{\delta k} * \boldsymbol{r})$$

Condition:

$$\delta k * l = (2\mathrm{N} + 1)\pi/2$$




Hart *et al. Nat. Phys.*

$$E_Z = \frac{\pi}{2} E_T \qquad g\mu_B B = \frac{\pi}{2}\frac{\hbar v_F}{L} \qquad B \propto \frac{\sqrt{n}}{g m^* L}$$

Control parameters : $B, L$ and $\sqrt{n}$

# 0 – π transition

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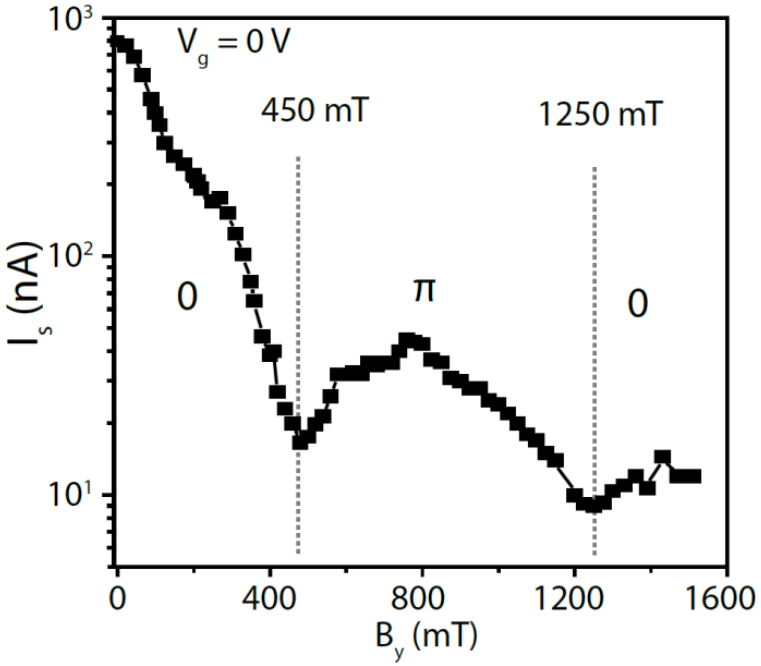
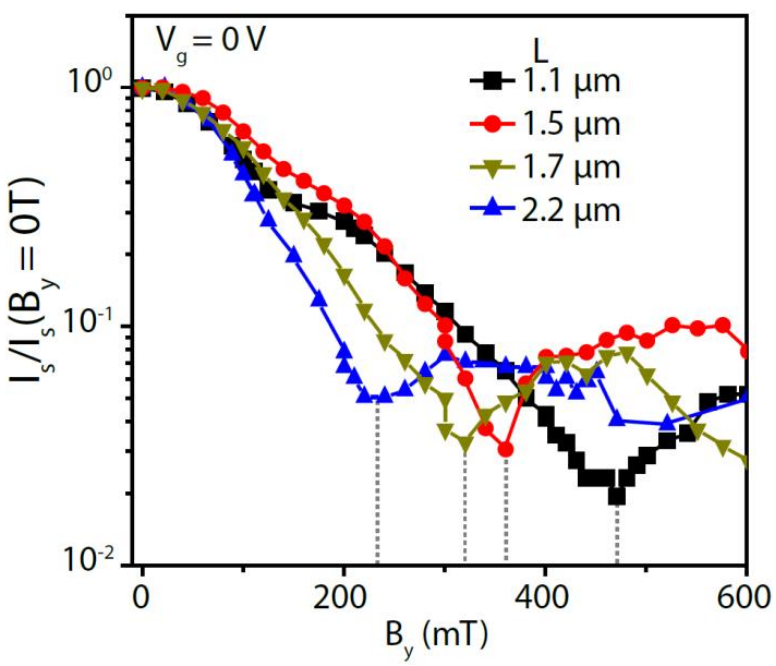
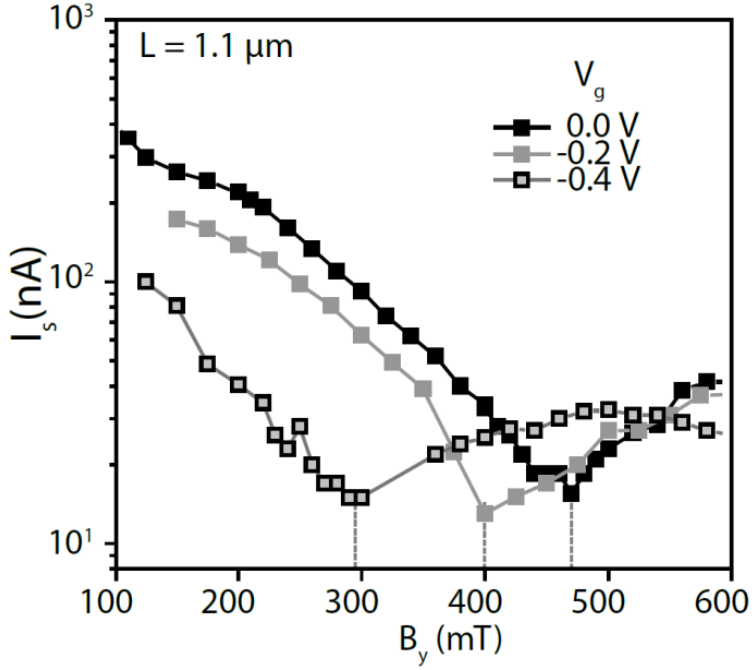
***Zeeman Field***




***Junction Length***




***Gate control***

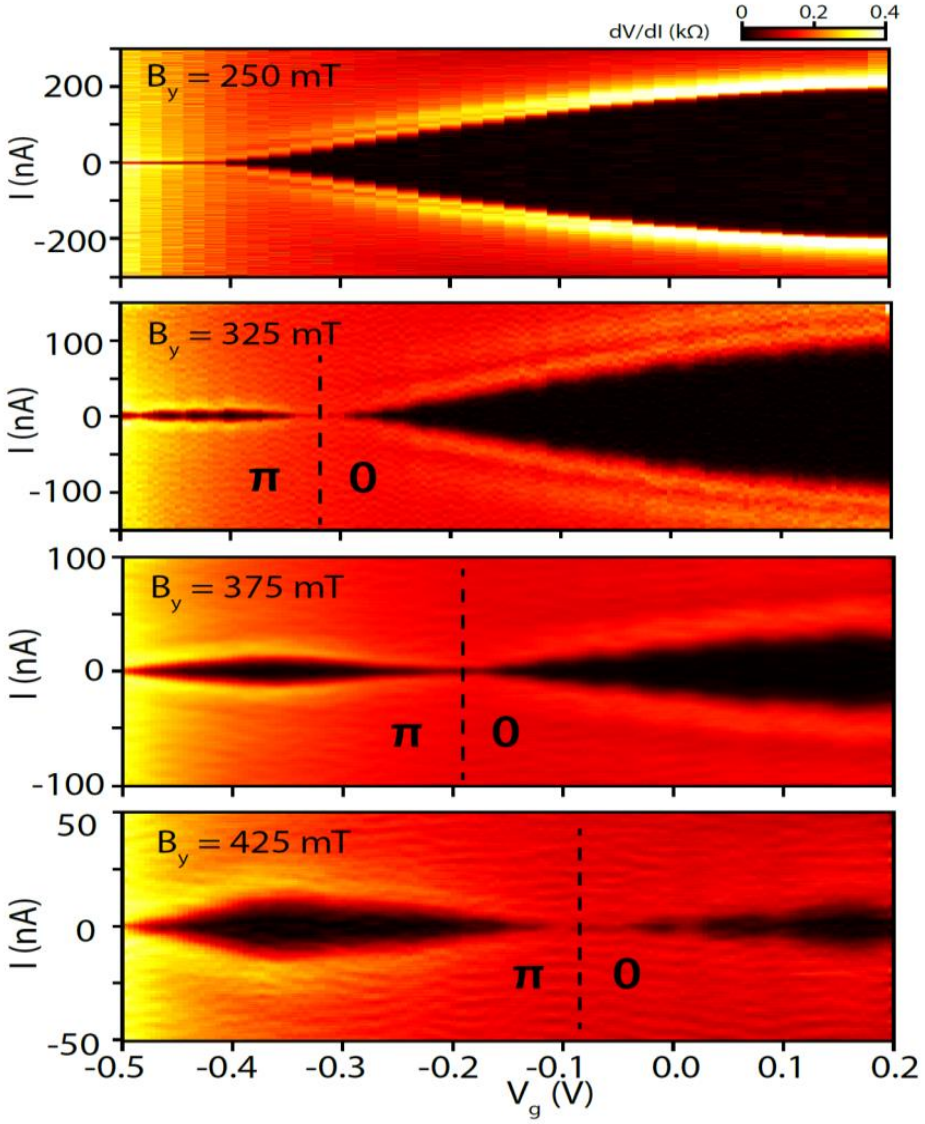


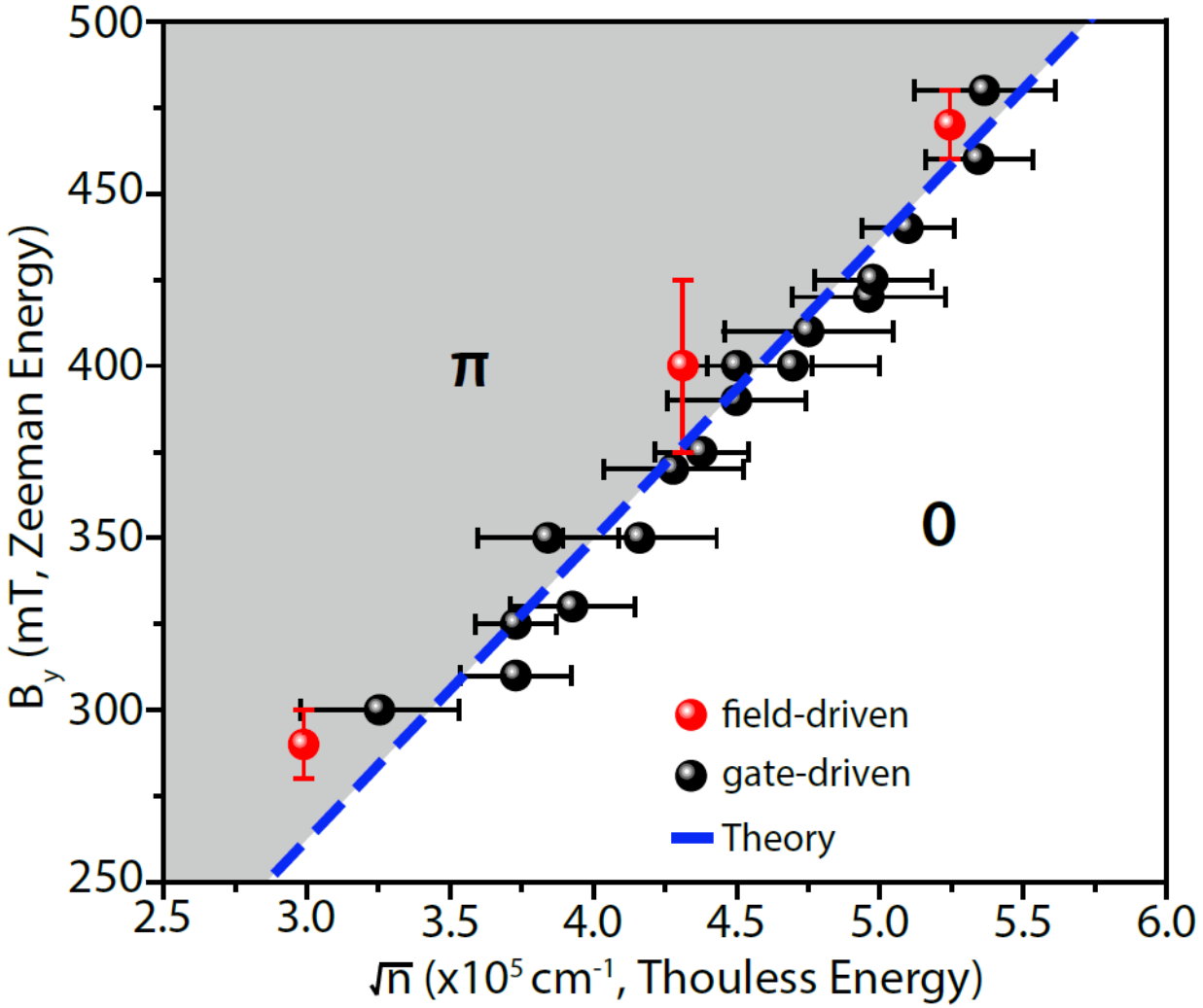

$$B \propto \frac{\sqrt{n}}{gm^*L}$$

Ke, Moehle et al. Nat. Comm. (2019)

# Gate control and Phase diagram





# Andreev spectra

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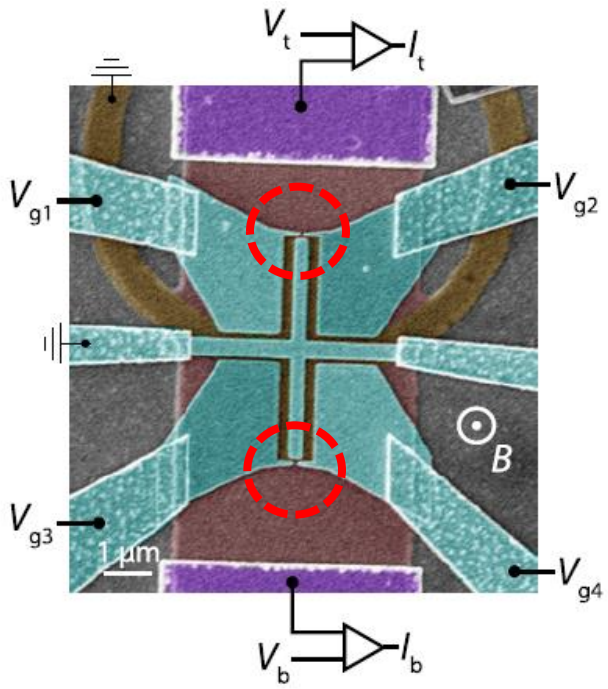
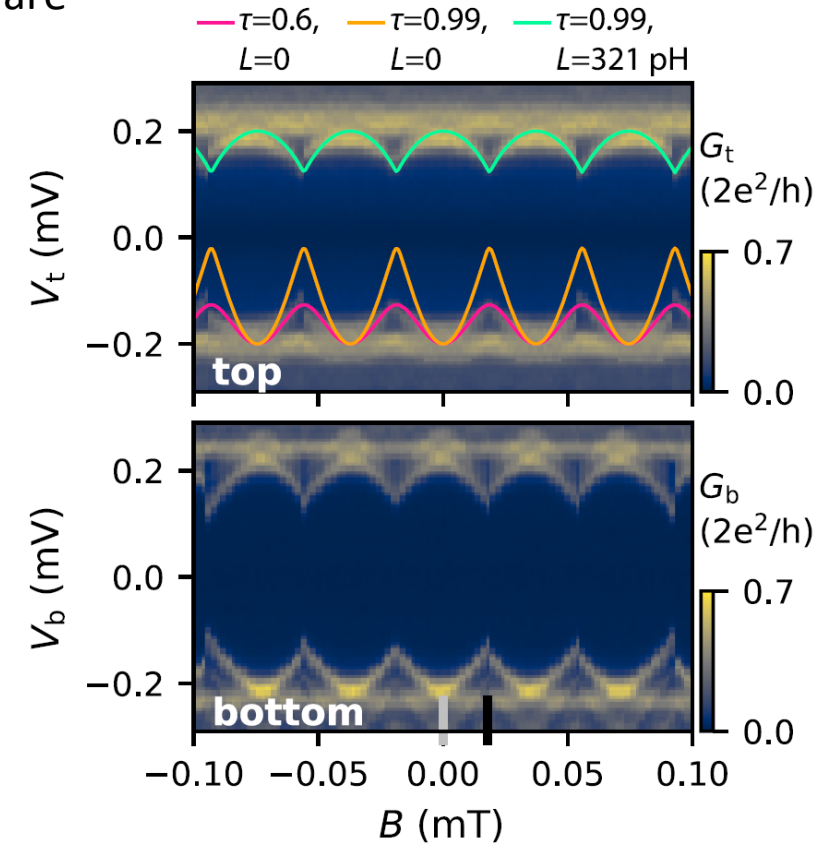
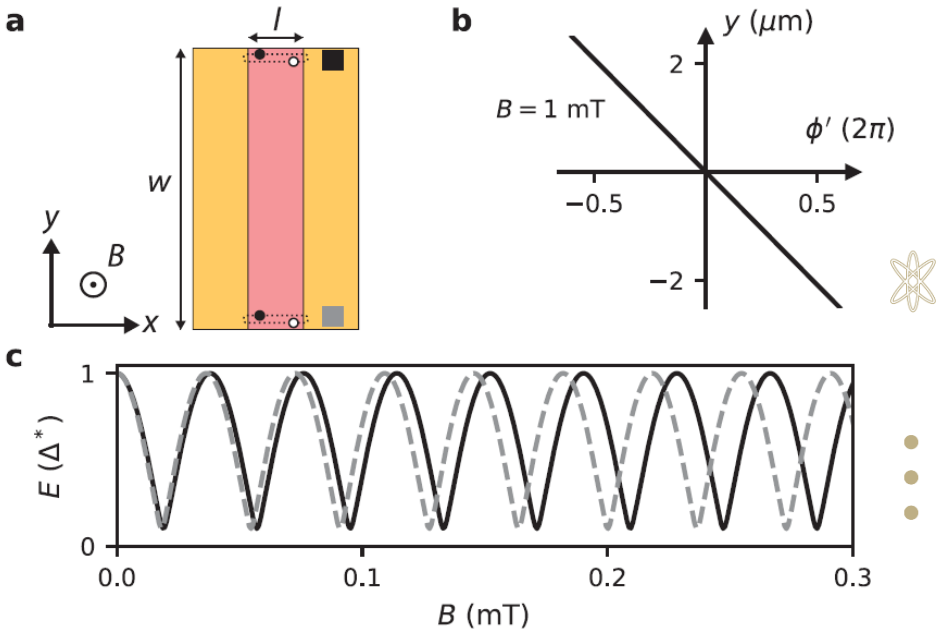
Two sets of gates(QPC, red circle) are made at the edge of the junction.




Allow us to measure two edges simultaneously to probe the DOS of the junction edge.




The inductance of the SQUID can strongly influence the Andreev spectrum in the experiment.




$$\phi' = -2\pi \frac{fBly}{\Phi_0}$$

The influence of the magnetic vector potential on the local Andreev states. The field results in a very different spectrum for the top and bottom ABSs.

Moehle et al. Nano Lett. (2023)

# Andreev spectra: modeling

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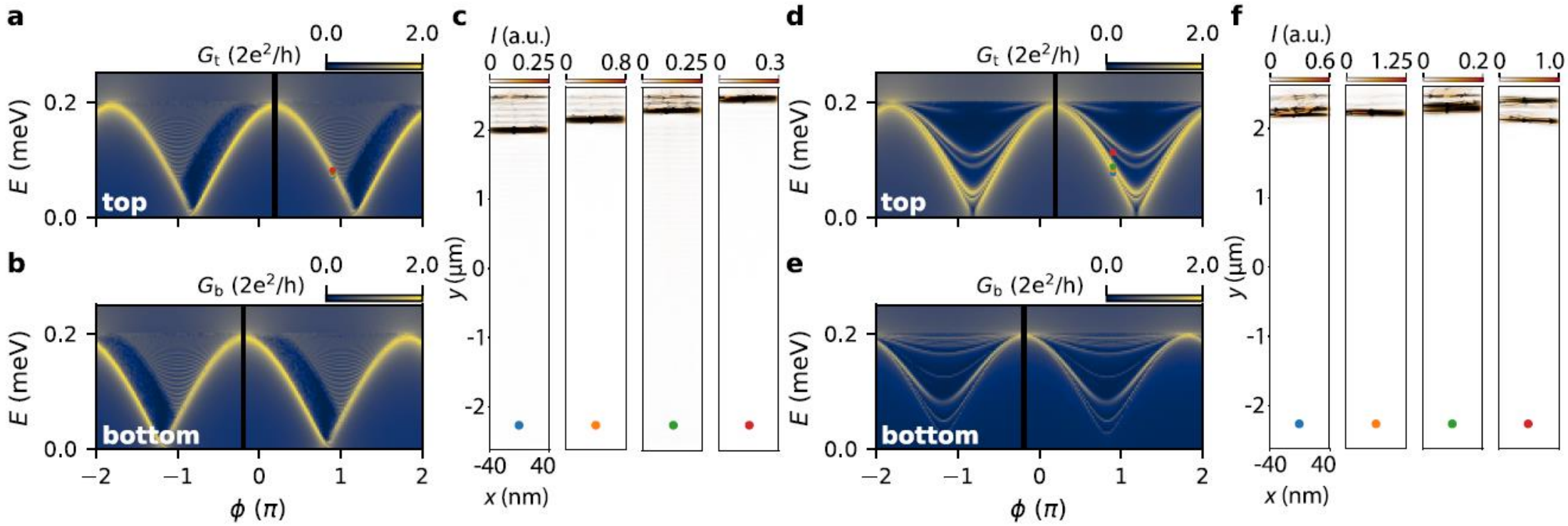
**Numerical simulation of our system:**

Infinite mean free path

finite mean free path (150 nm)



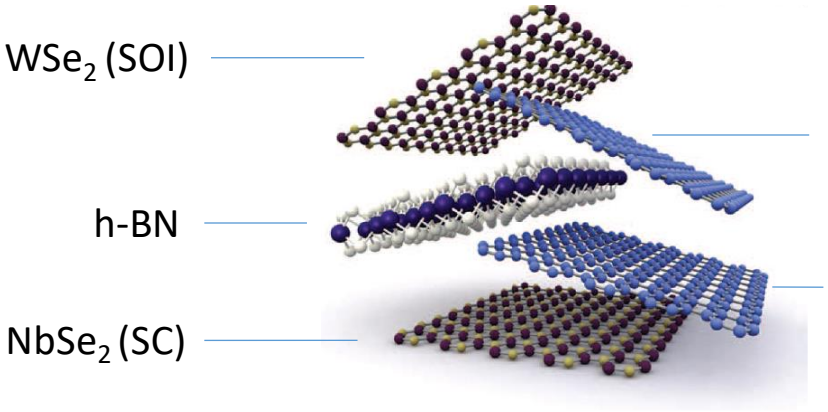

- The phase dependence of the supercurrent position is stronger in the ballistic case.
- More ABS is located at the edge for the disordered case.
- Top and bottom are also different due to disorders.

Moehle et al. Nano Lett. (2023)

# Many possibilities

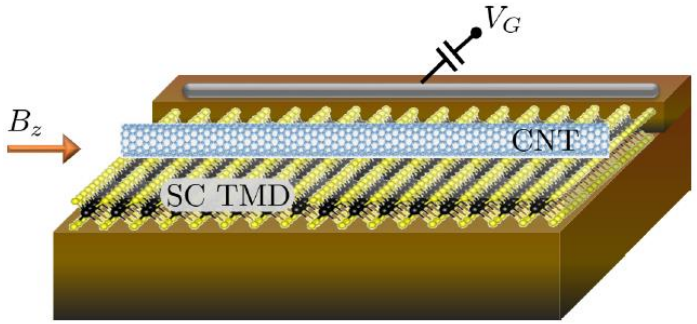


## Using functionality of VdW materials or substrate

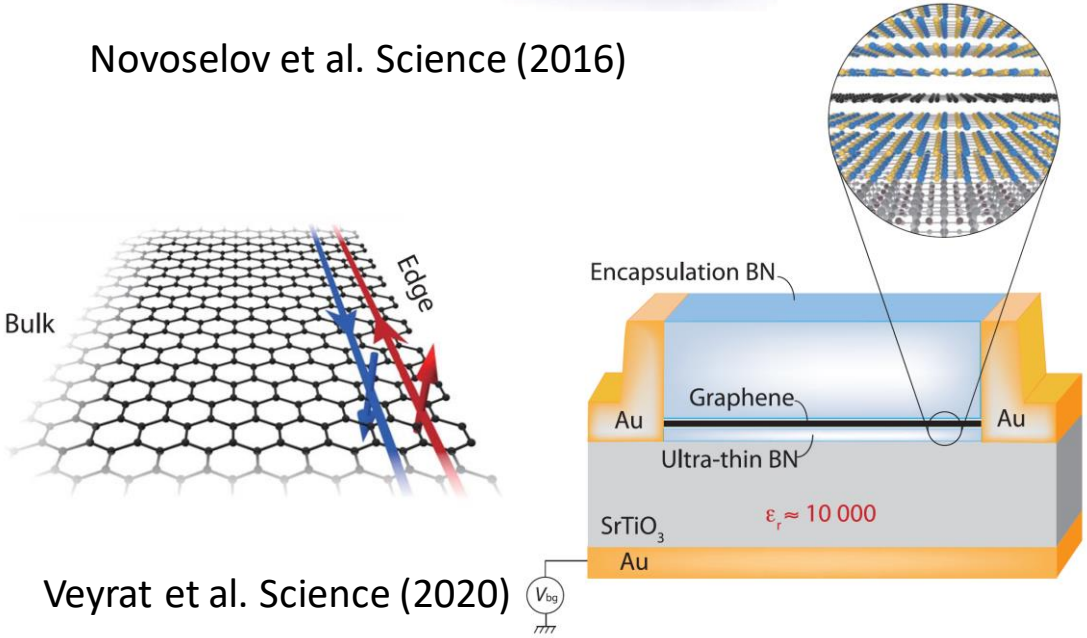



Novoselov et al. Science (2016)

Or (CNT)

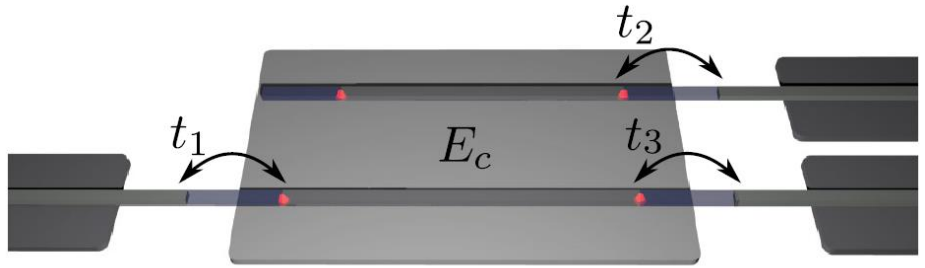



Lesser et al. PRR (2020)




Veyrat et al. Science (2020)

Topological Kondo system




B. Be´ri and N. R. Cooper PRL (2012)

# Preliminary results

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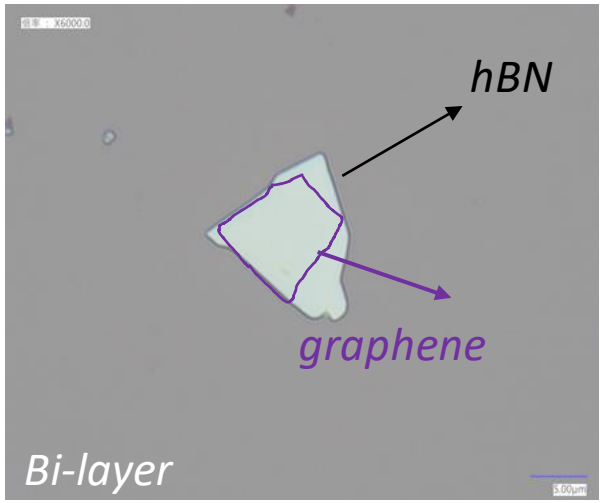
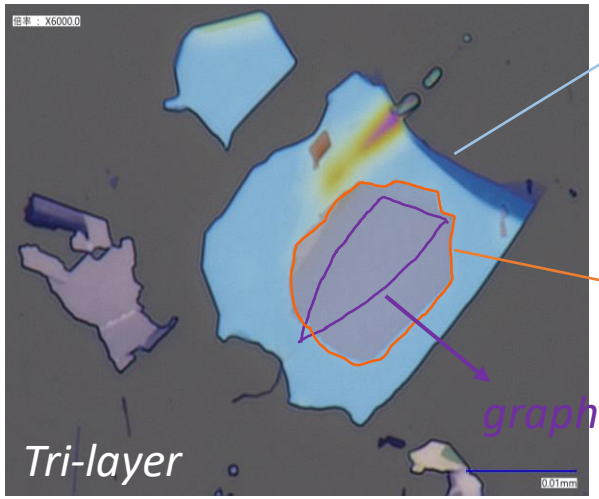
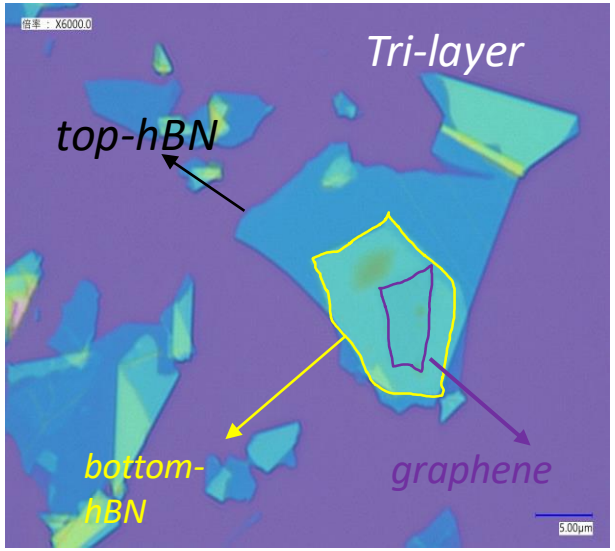
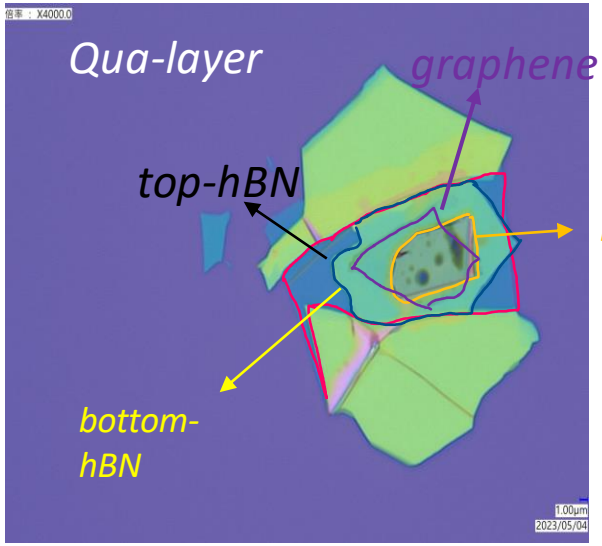
## Induce SO in graphene

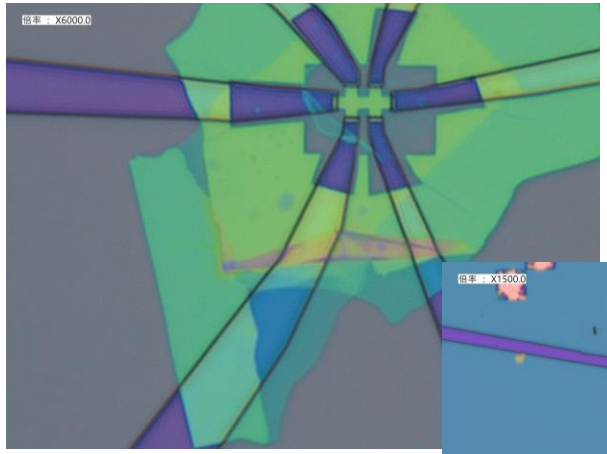


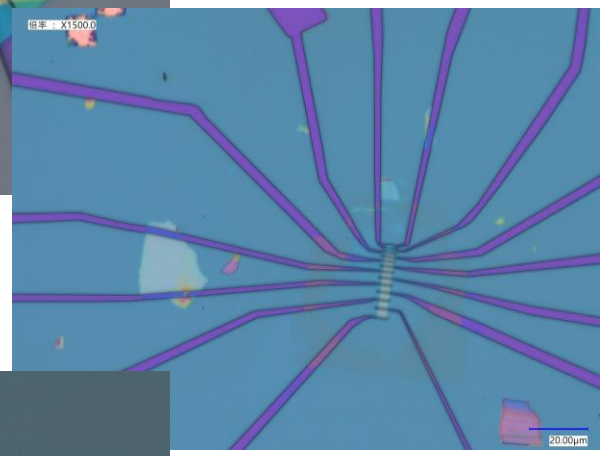



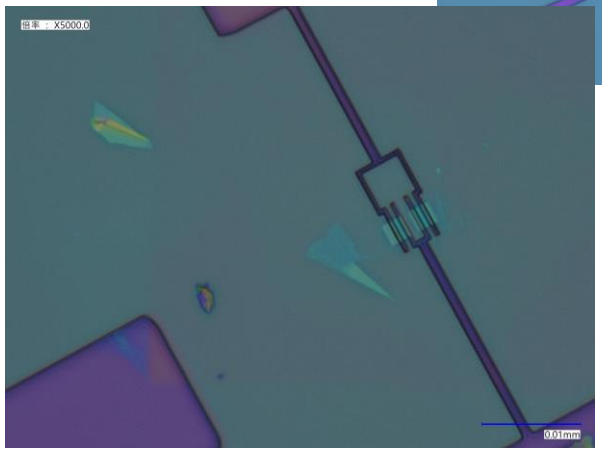

Hall Bar



Multiple junctions



SQUID



# Preliminary results

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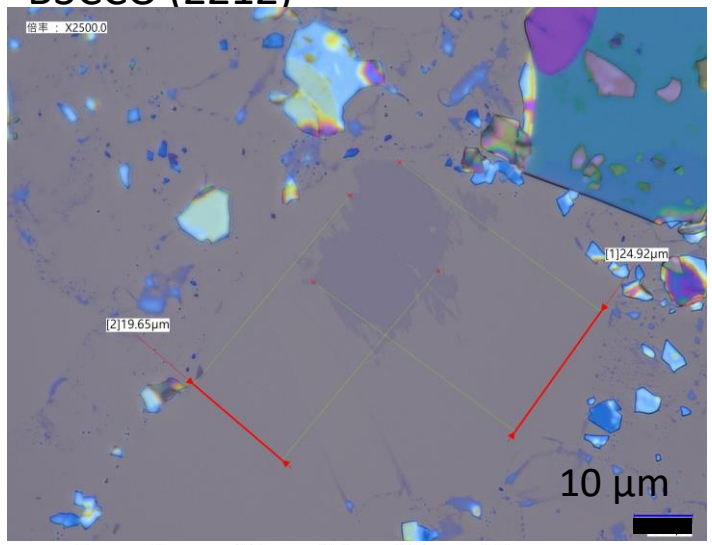
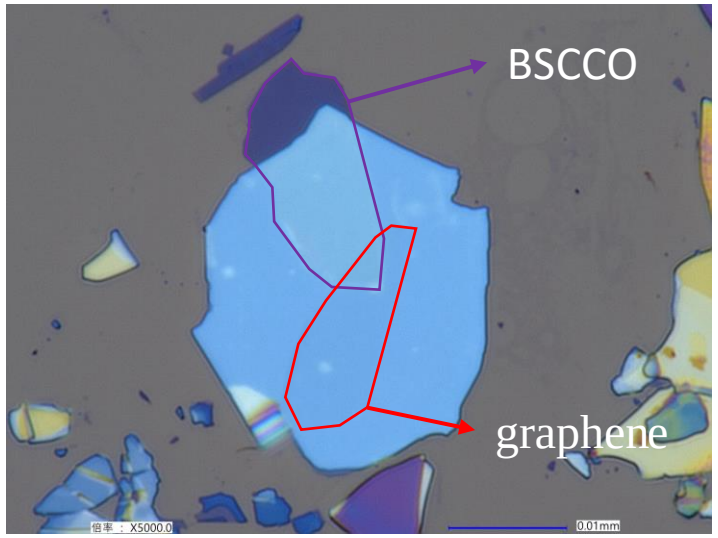
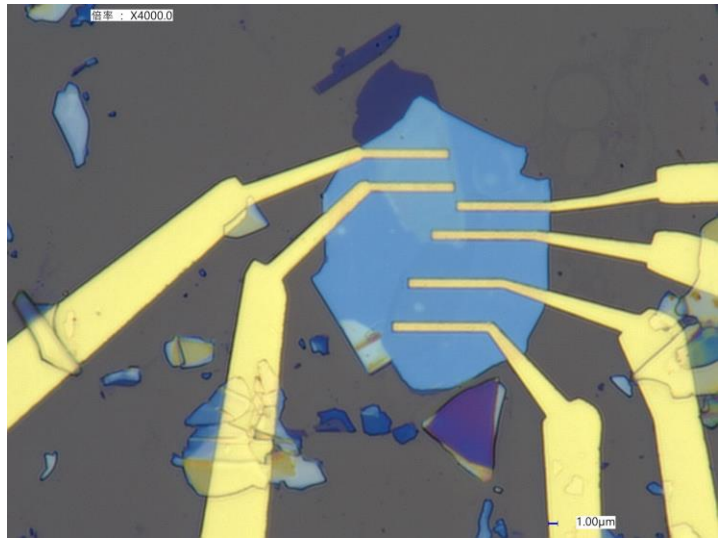
**Probing high Tc layered superconductors**

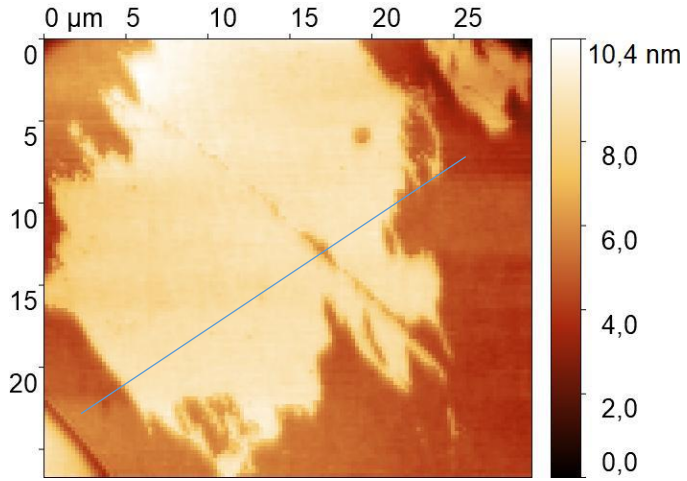
hBN/graphene/BSCCO
Contact metal: Ag/Au

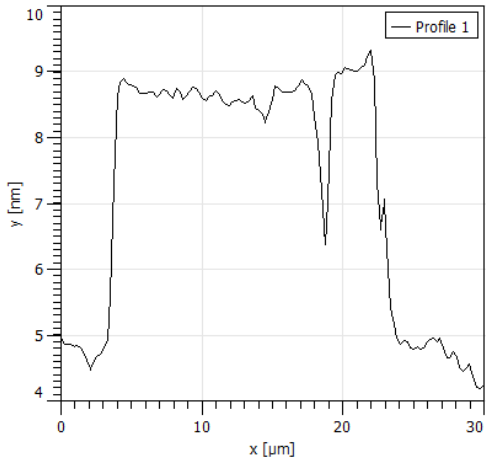
BSCCO (2212)



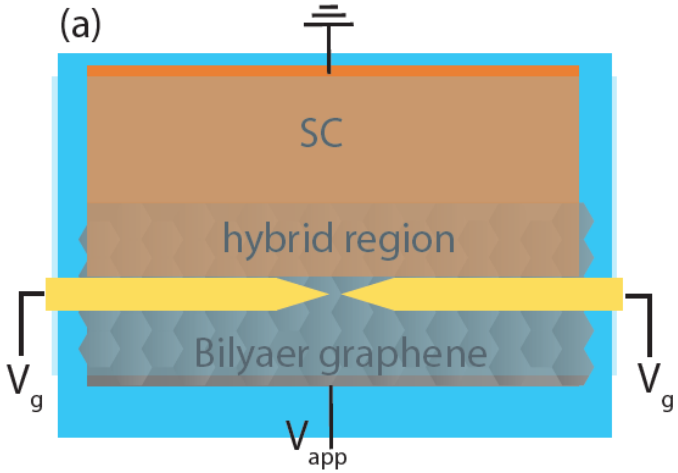






Probing hybrid system
with advanced devices



# Preliminary results

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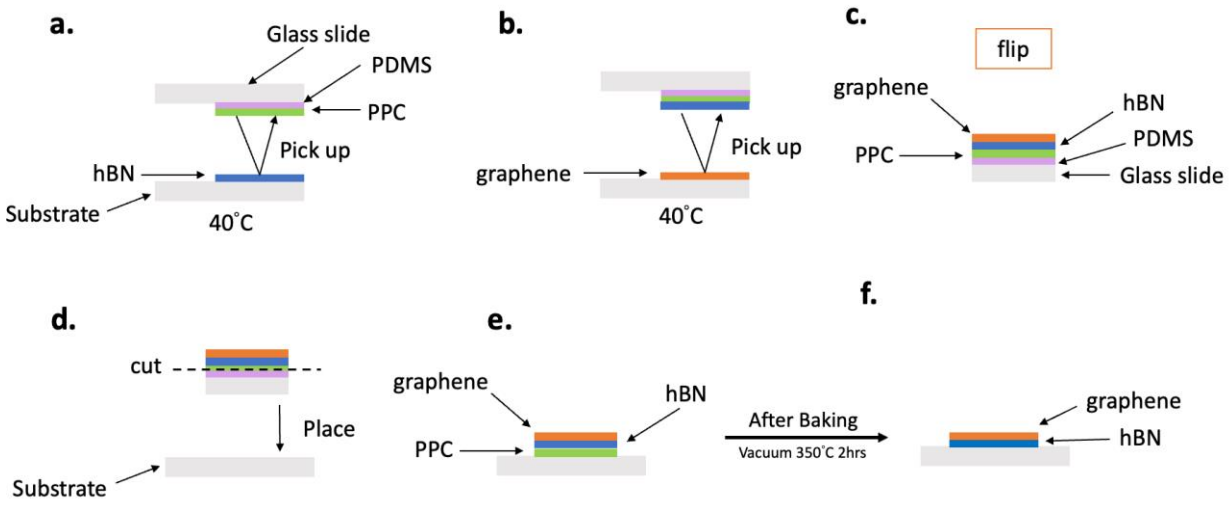
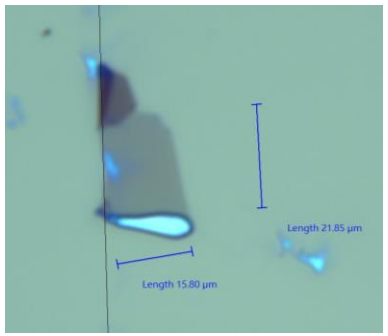
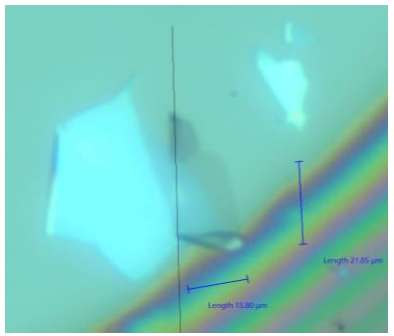
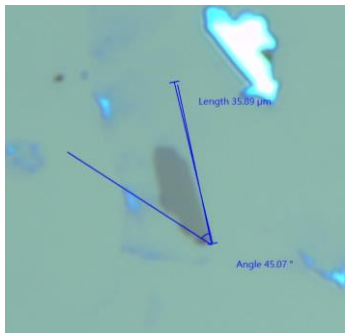
## More degree of freedom

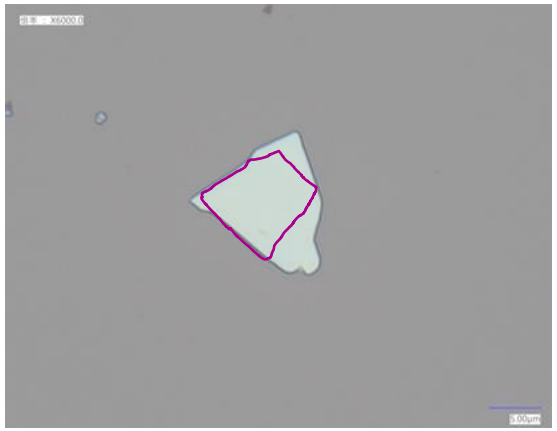
*Flip Process Diagram*

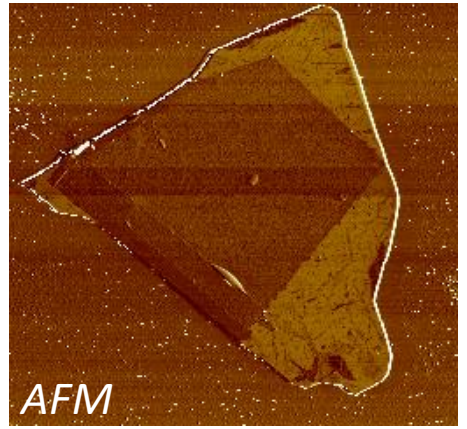


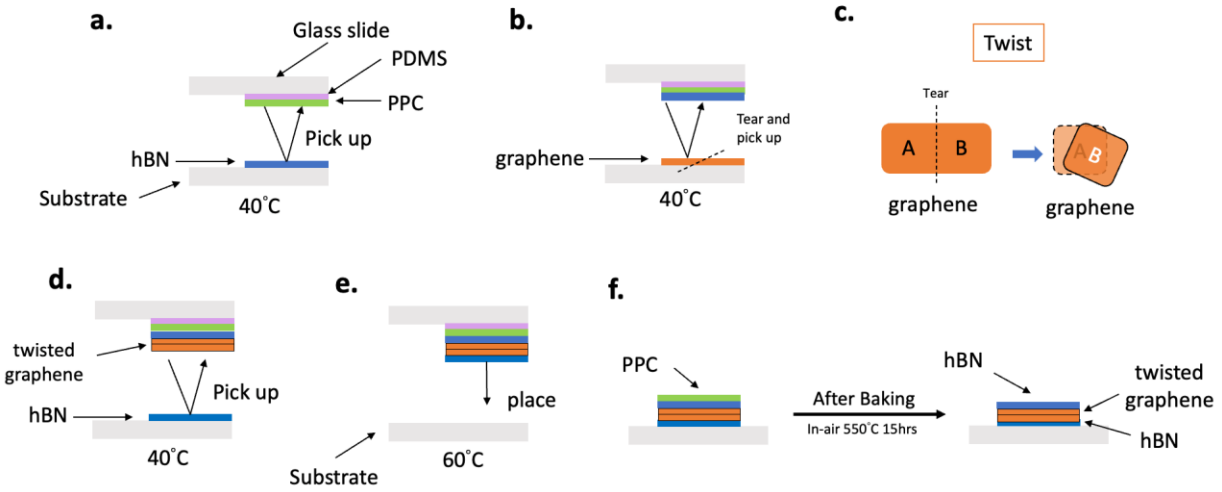









*Twist Process Diagram*



# Extend study on materials

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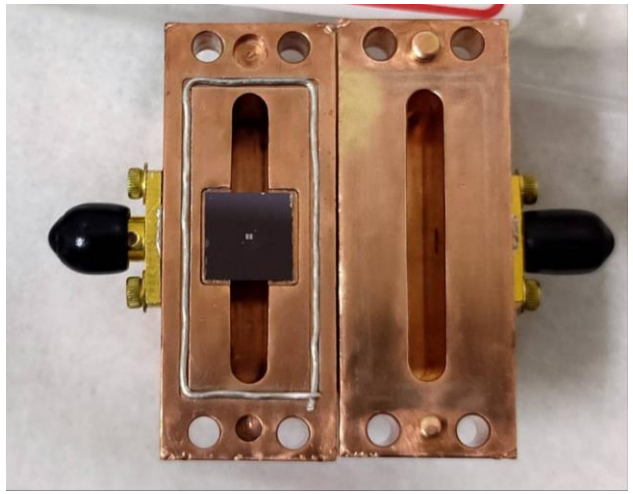
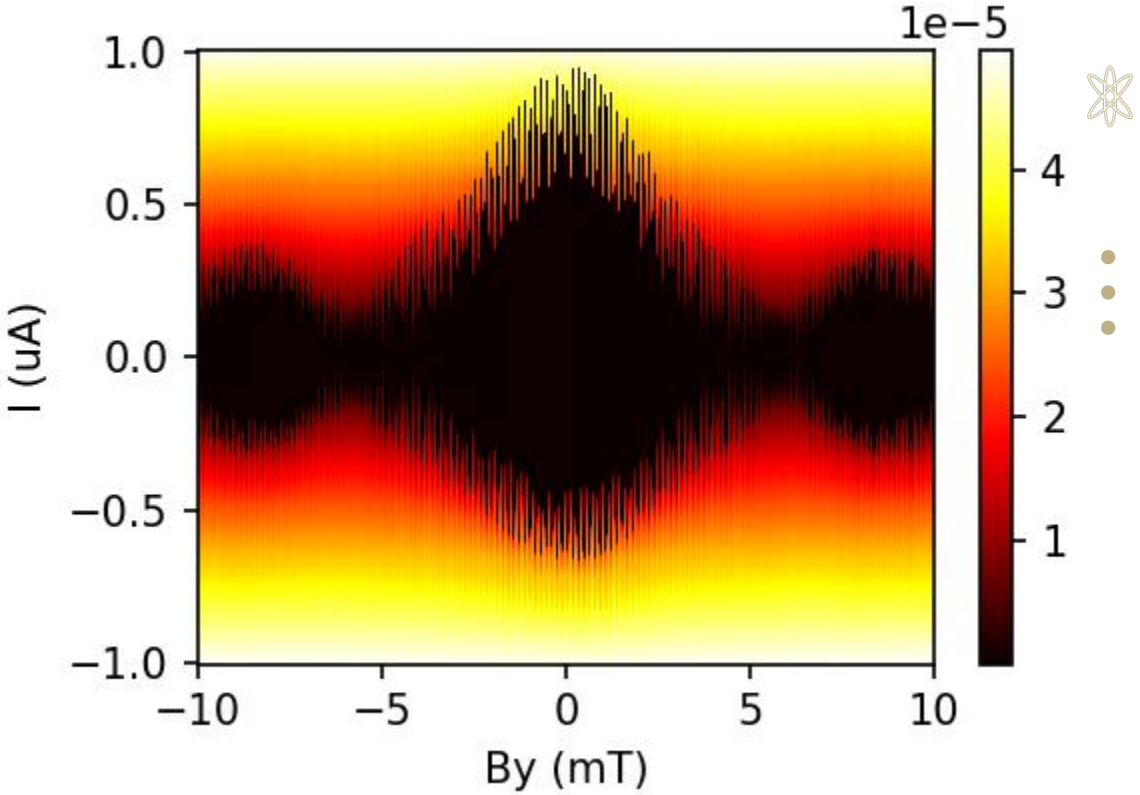
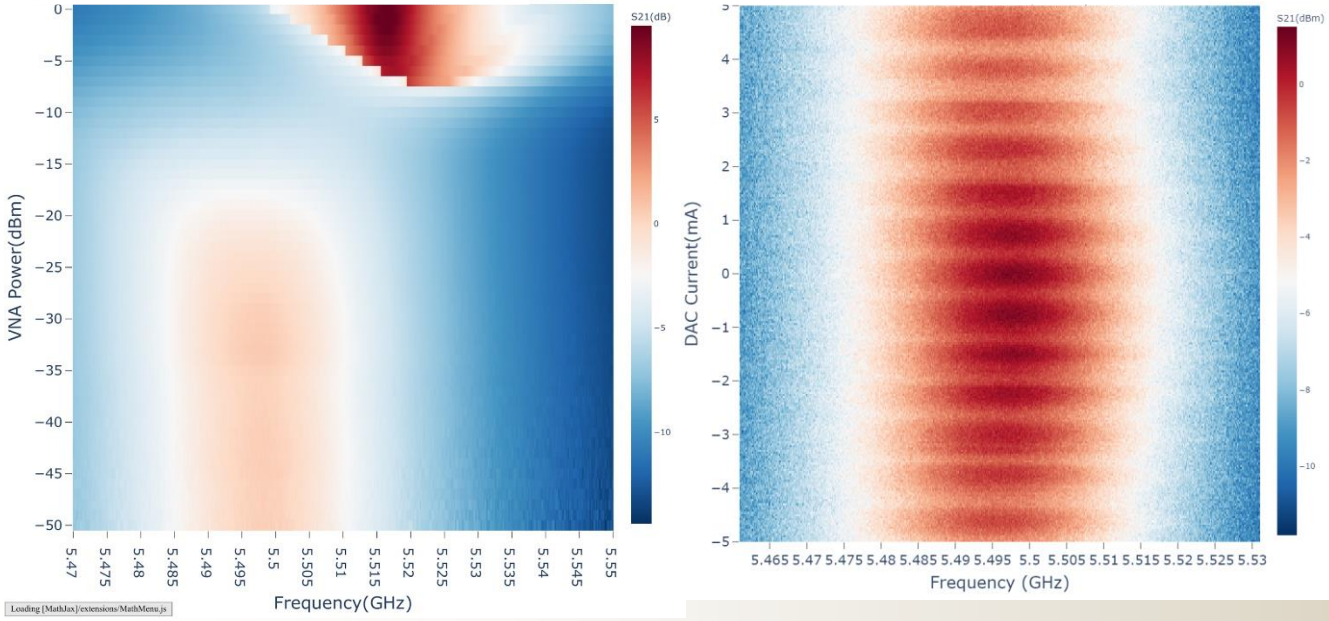
## 3D cavity on 2D materials

Collaborate with NSYSU



DC measurement at IOP, AS



# Other research directions

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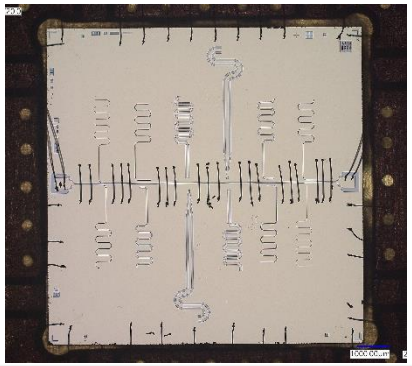
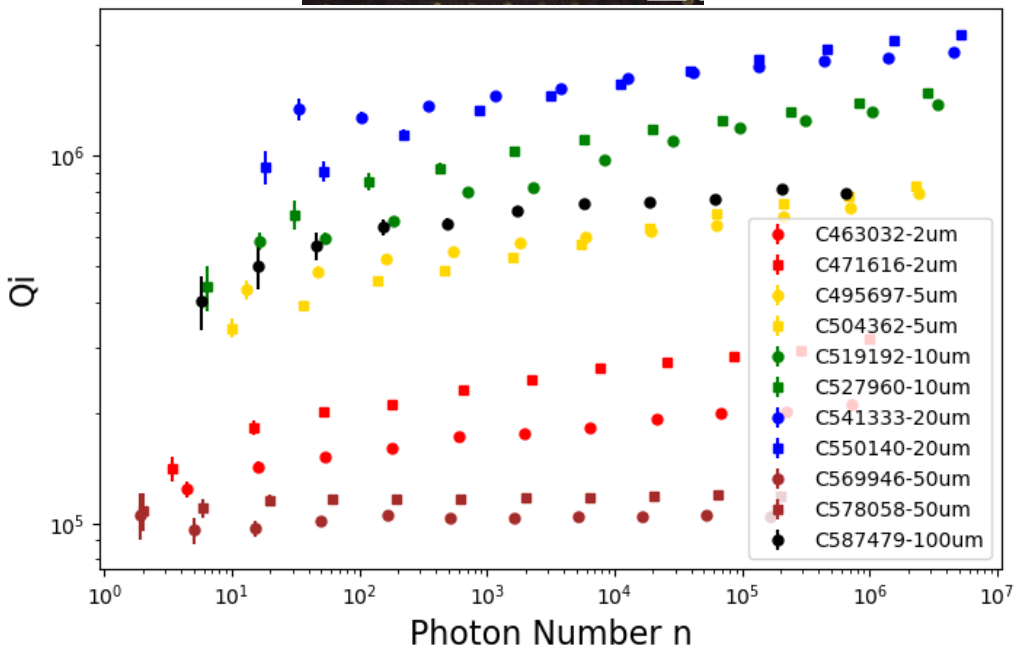
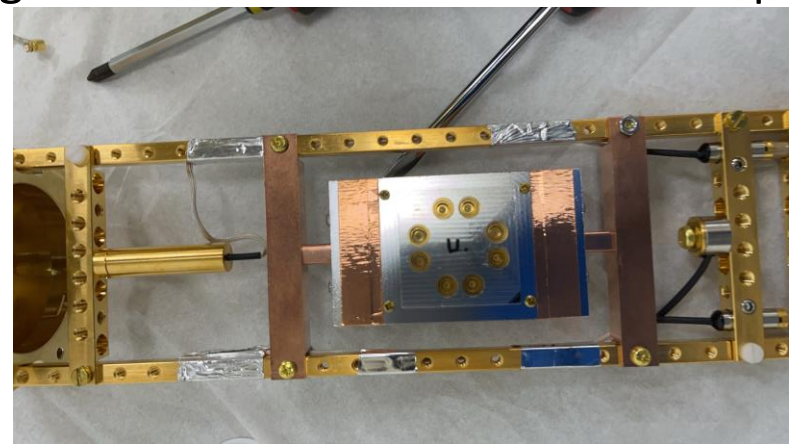
## Better superconducting qubit

Improve the resonator quality

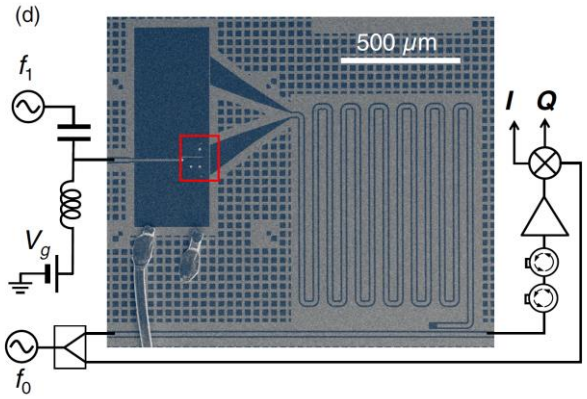


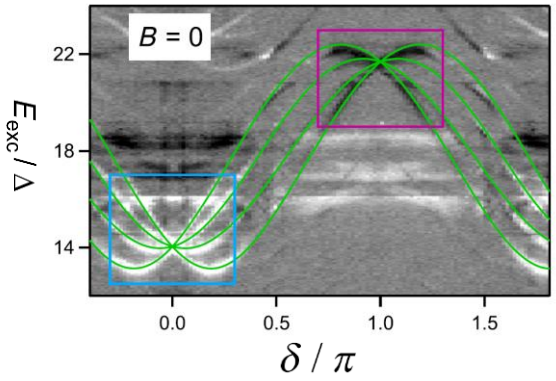



Higher coherence time with a better package



## Probing the unique states via cQED/STM



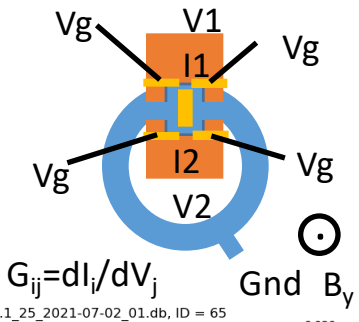




Tosi et al. PRX (2019)

# In summary

- Many interesting materials can be explored
- We aim to explore and develop a better qubit for future quantum computers.
- To explore different physics, our measurement setup aims to cover Hz to GHz regions.
- Understanding the intrinsic properties of hybrid materials is important to

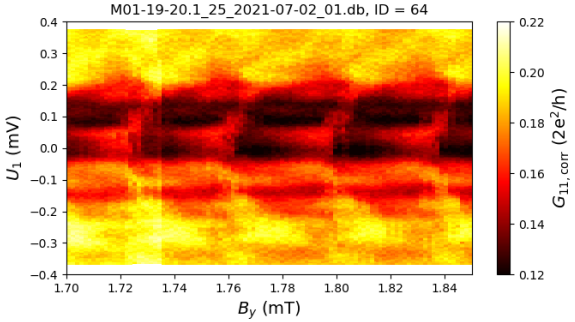
# More directions

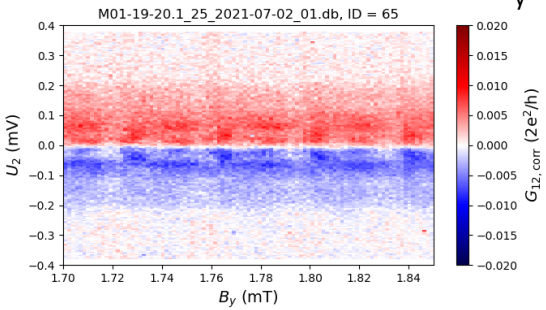


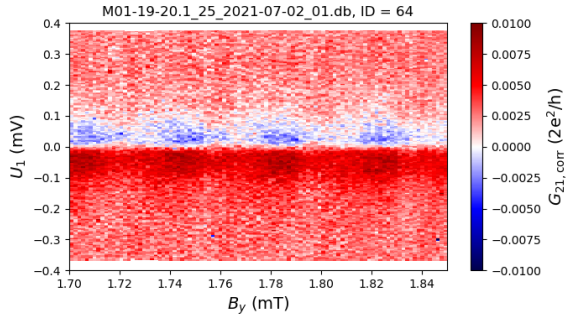

$G_{ij}=dI_i/dV_j$

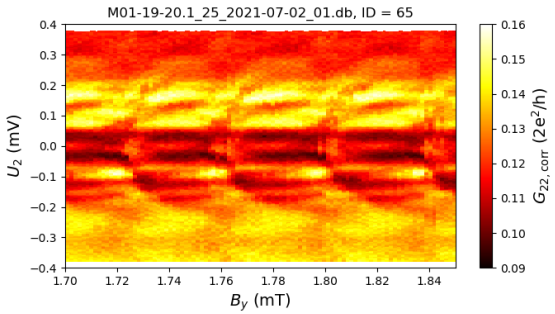
## Nonlocal measurement

Bz=475 mT

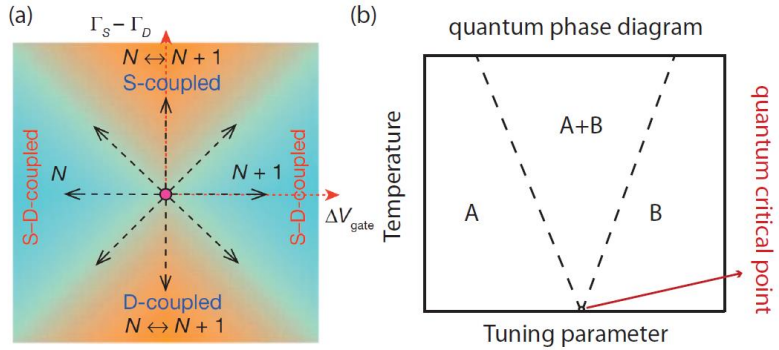



## Quantum phase transition



# Collaborations

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TU Delft

QuTech

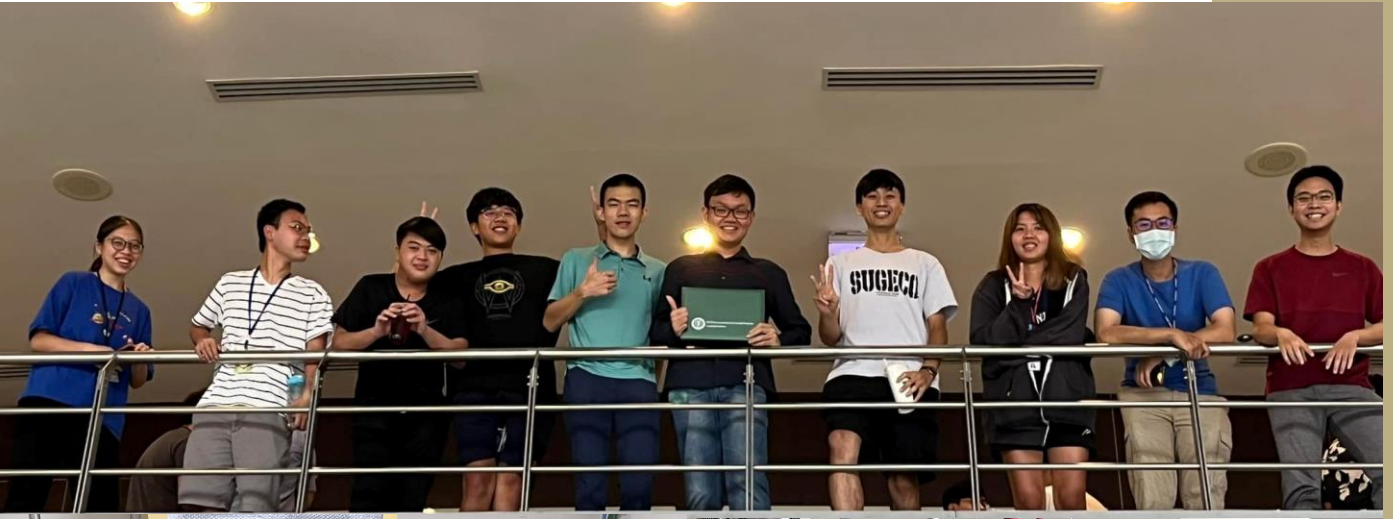
Duke UNIVERSITY

國立陽明交通大學
NATIONAL YANG MING CHIAO TUNG UNIVERSITY

國立臺灣大學
National Taiwan University

工業技術研究院
Industrial Technology Research Institute

NATIONAL SUN YAT-SEN UNIVERSITY





Website

Thank you
Any questions?