Center for Quantum Information Physics

NYU

Measurement in topological superconducting systems

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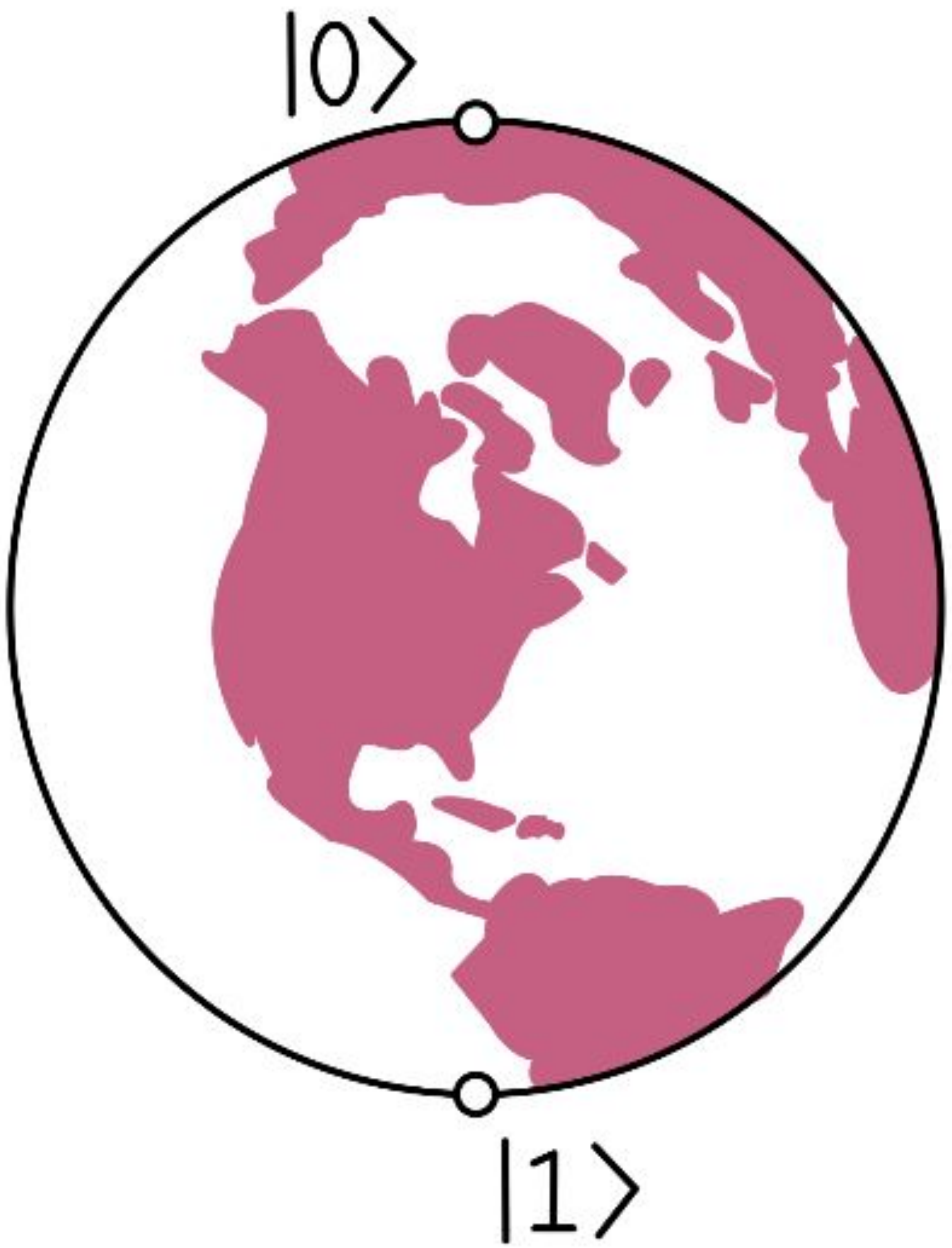
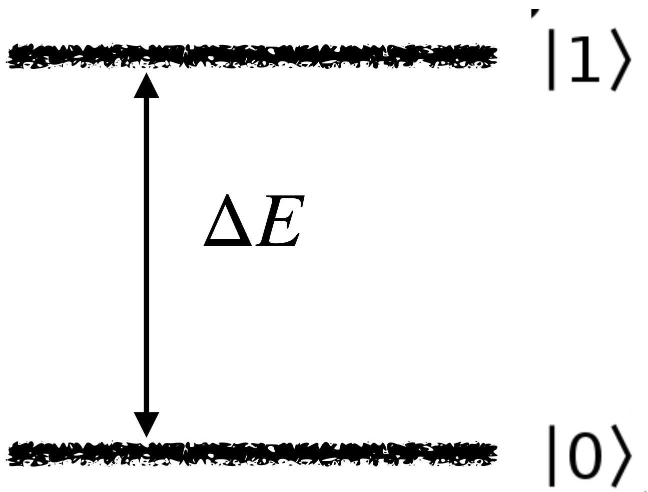
Andrew Higginbotham

Two-level system governed by Schrodinger equation (to become quantum)



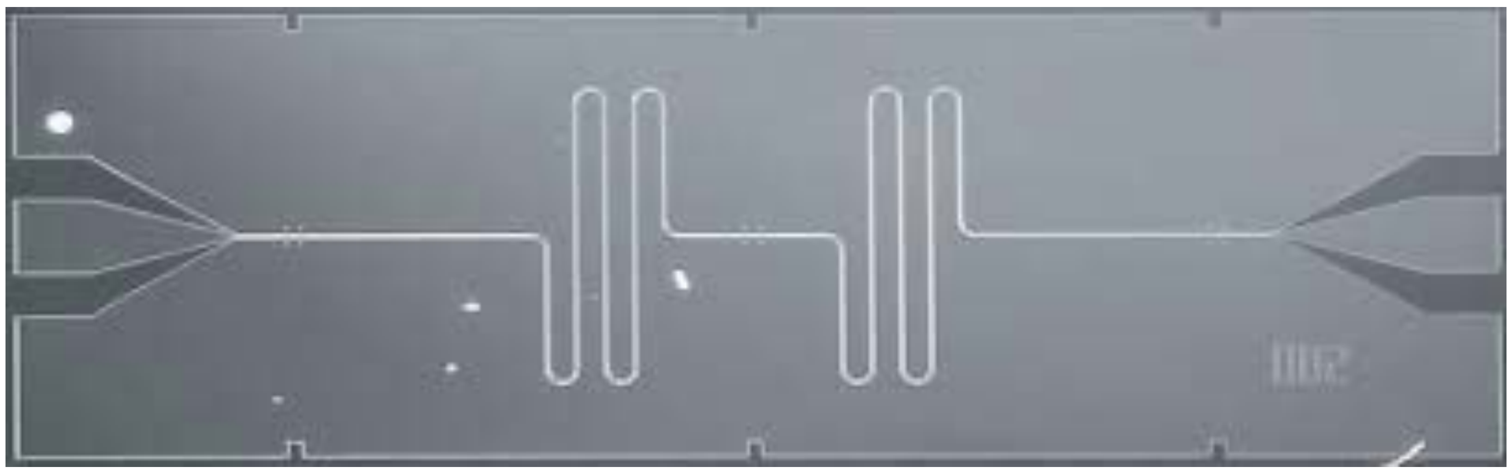


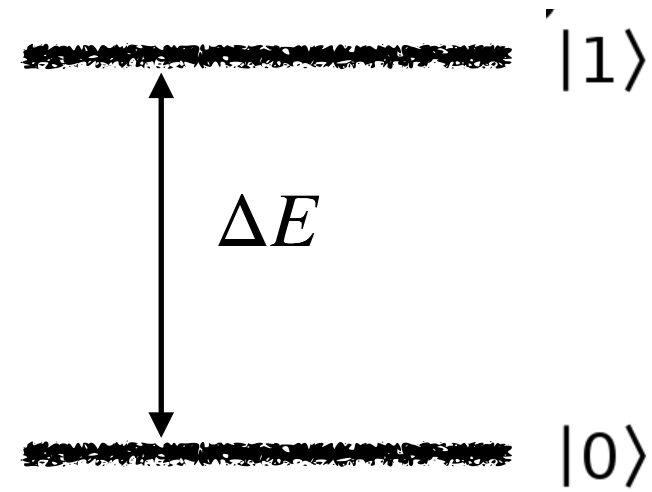
$k_B T \ll \Delta E$ (Thermal)

$\Gamma \ll \Delta E$ (Dissipation)

Qubit can be realized

Two-level system governed by Schrodinger equation (to become quantum)



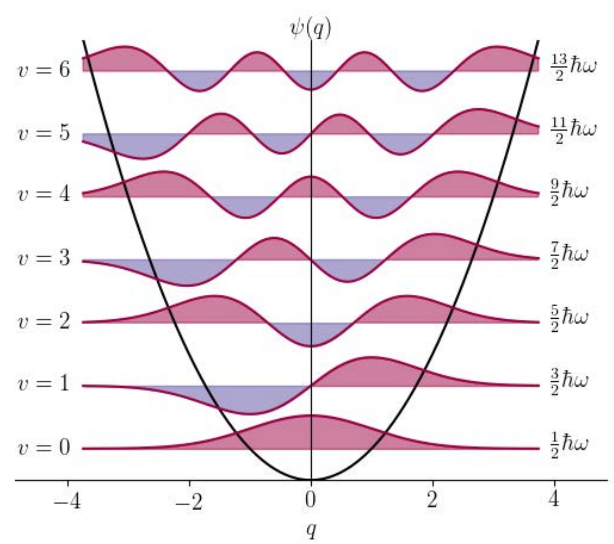


E.g. Superconducting resonator

$$\Delta E \approx 10GHz \approx 500mK$$

$$20mK \ll 500mK$$

$$\Gamma = 0 \ll \Delta E$$

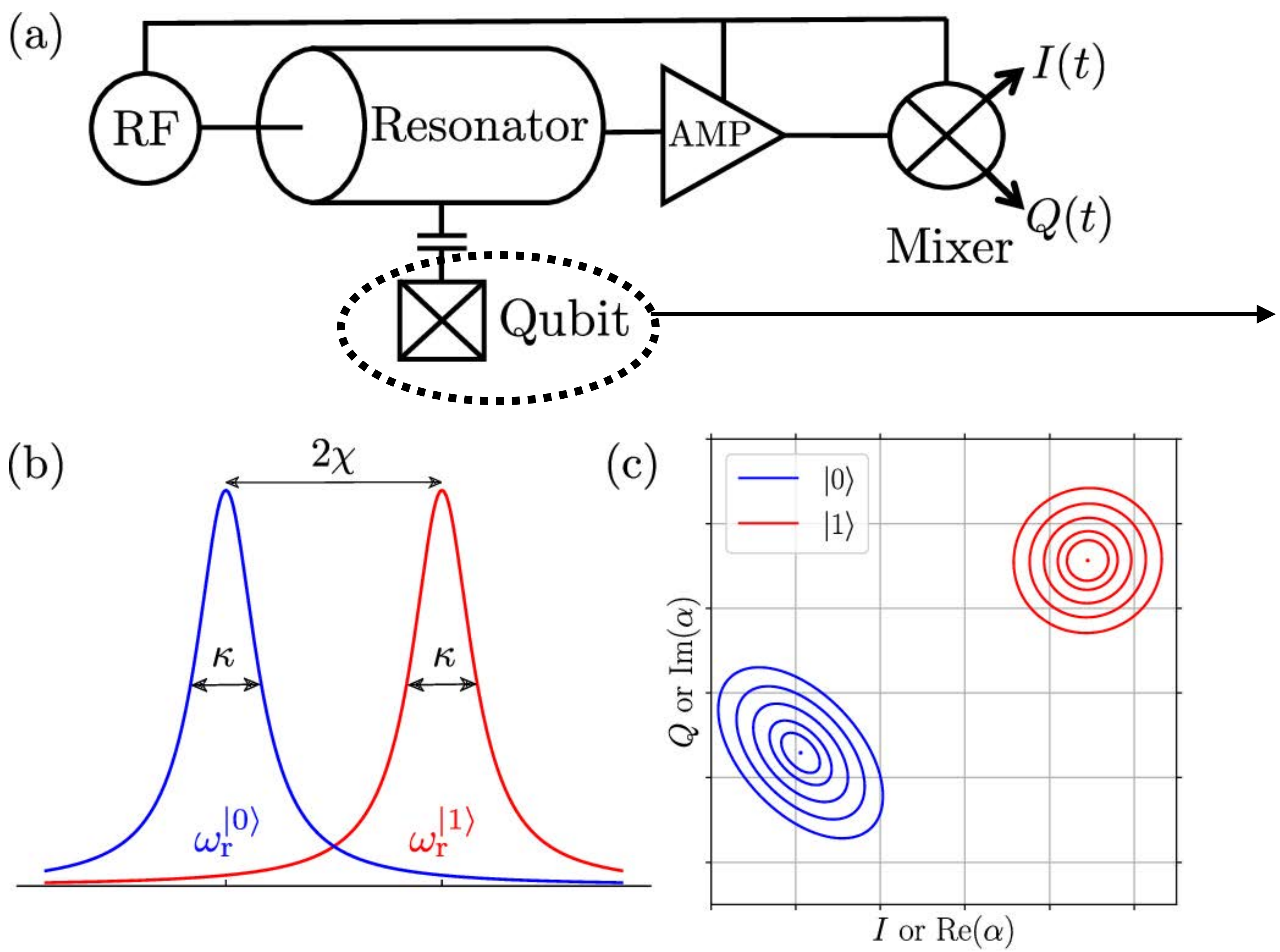


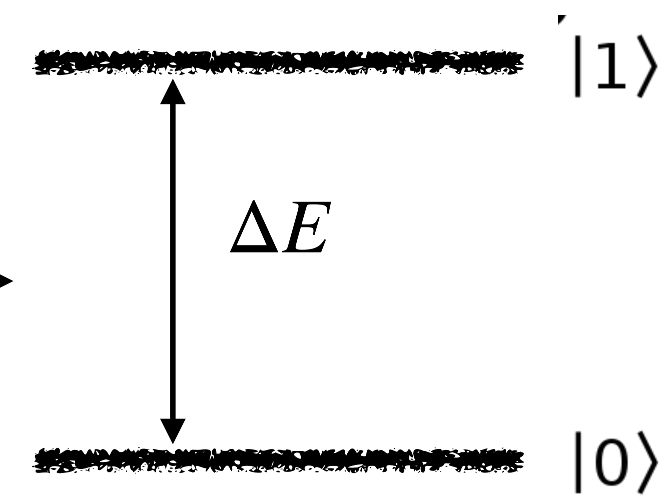
$k_B T \ll \Delta E$ (Thermal)

$\Gamma \ll \Delta E$ (Dissipation)

https://www.semanticscholar.org/paper/Dispersive-Measurement-of-Superconducting-Qubits-Khezri/df60aa53c9908d9f597a69bc873bef3810586e73

Measurement…projection of finding a state in ground state





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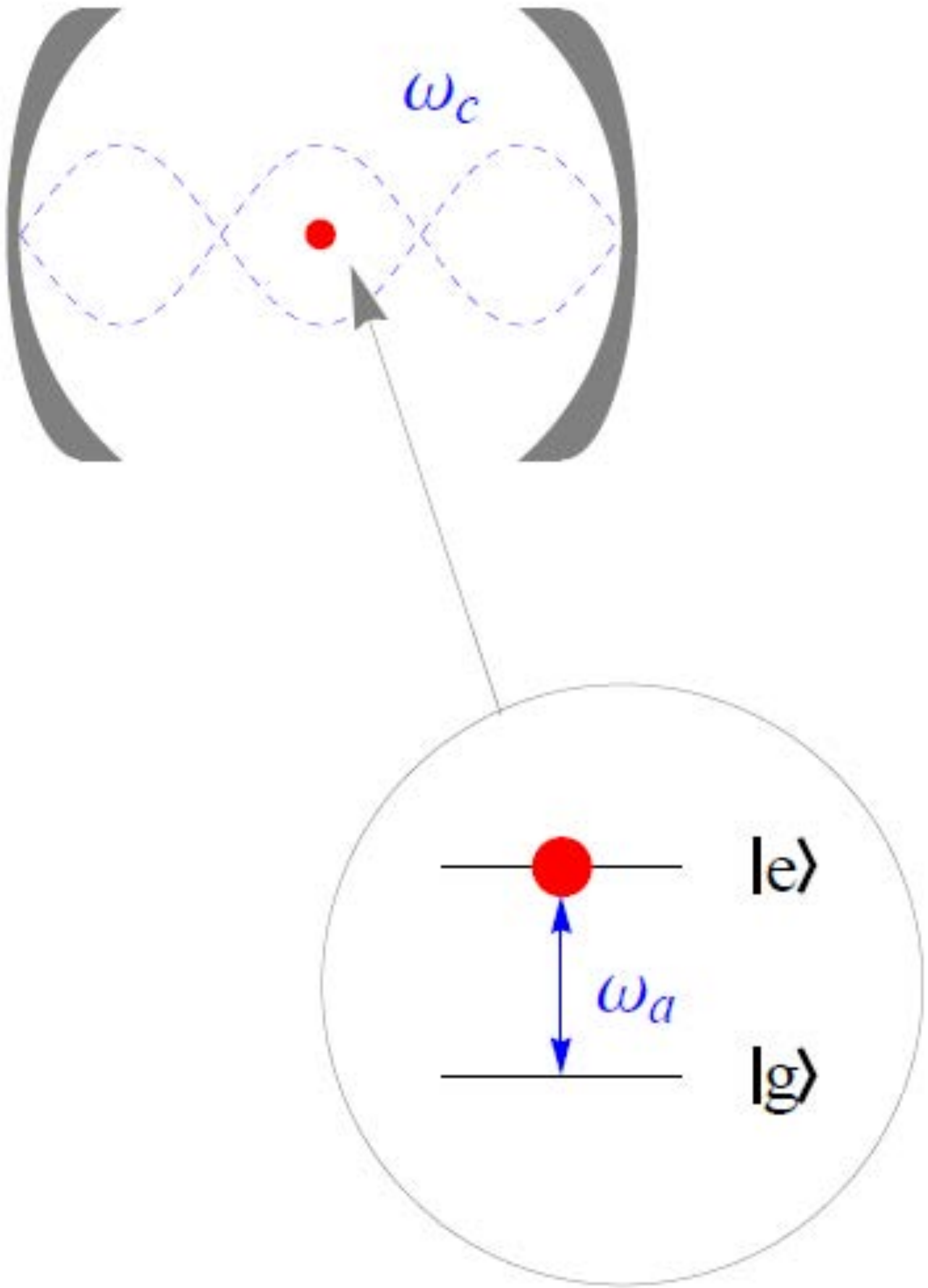
https://www.semanticscholar.org/paper/Dispersive-Measurement-of-Superconducting-Qubits-Khezri/df60aa53c9908d9f597a69bc873bef3810586e73

Hamiltonian: cQED



$$\hat{H} = \hat{H}_{\text{field}} + \hat{H}_{\text{atom}} + \hat{H}_{\text{int}}$$

$$\hat{H}_{\text{field}} = \hbar\omega_c \hat{a}^\dagger \hat{a}$$

$$\hat{H}_{\text{atom}} = \hbar\omega_a \frac{\hat{\sigma}_z}{2}$$

$$\hat{H}_{\text{int}} = \frac{\hbar\Omega}{2}\hat{E}\hat{S}.$$

$$\hat{E} = E_{\text{ZPF}}\left(\hat{a} + \hat{a}^\dagger\right)$$

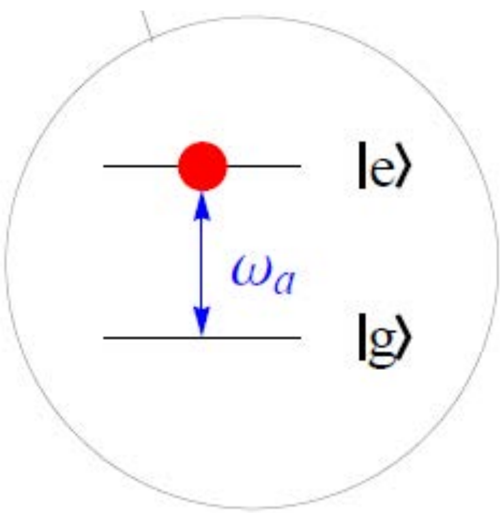
Resonator: Bosonic creation and annihilation operators

$$\hat{S} = \hat{\sigma}_+ + \hat{\sigma}_-$$

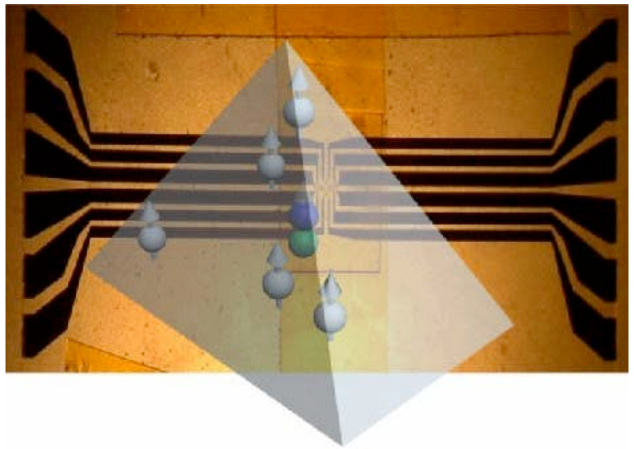
Qubit: Two-level atom is equivalent to a spin-half

Wikipedia cQED

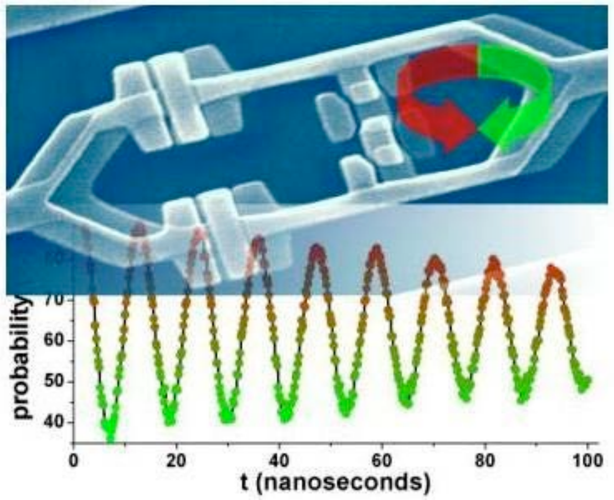
Qubit (First Generation)



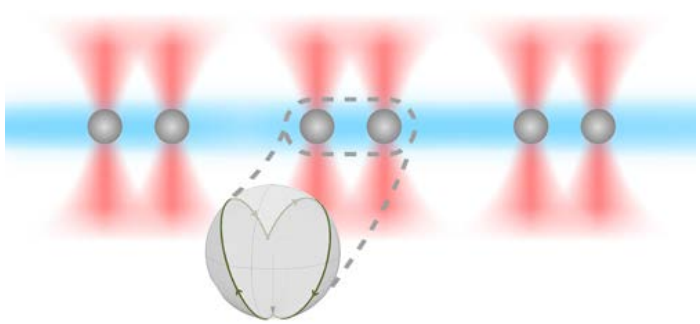
Two level qubits



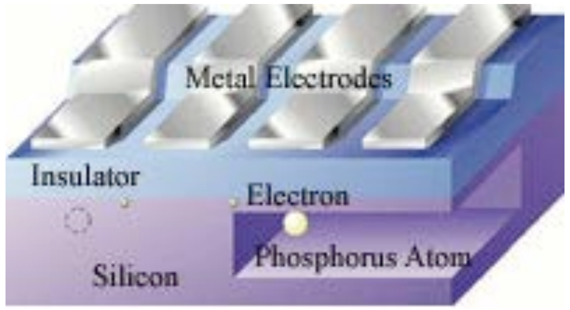
Diamond based



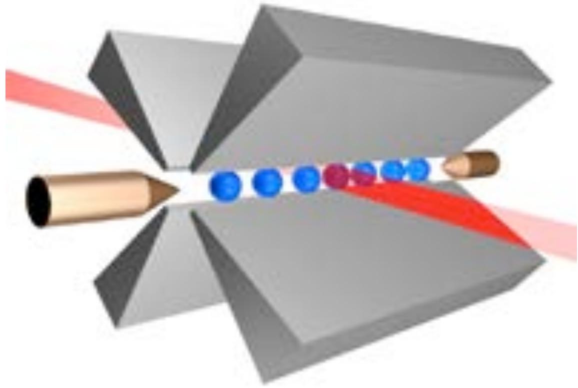
Superconducting



Neutral atoms

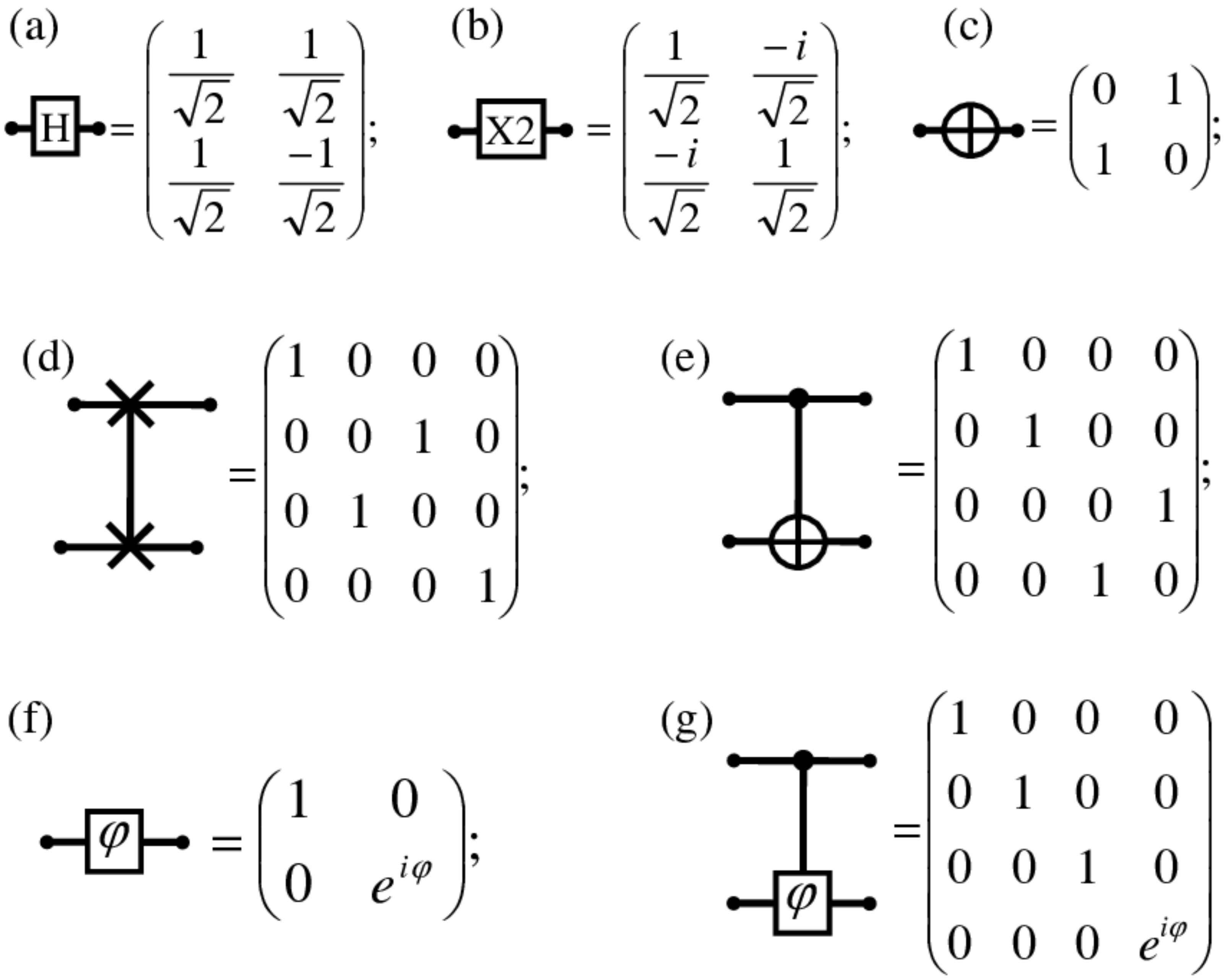


Silicon based



Ion trap

- Systems are evolved by unitary transformations, Measurement are not
    - **Quantum** operations are reversible
    - non-reversible operation is a **Measurement** of a qubit

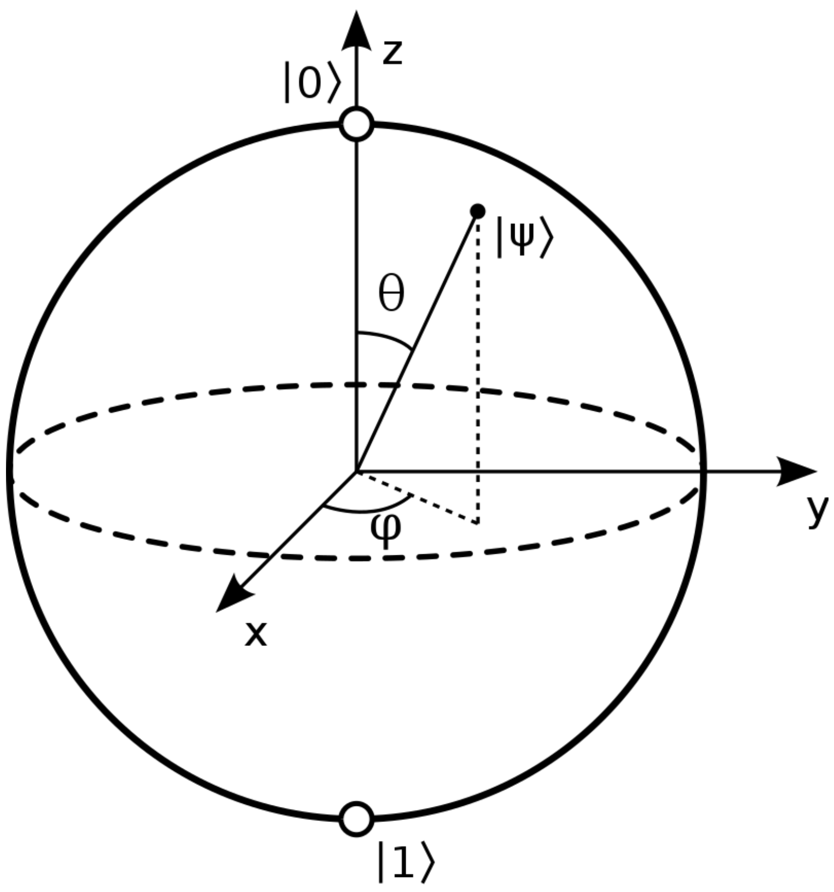


(a) $= \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{pmatrix};$ (b) $= \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{-i}{\sqrt{2}} \\ \frac{-i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix};$ (c) $= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix};$

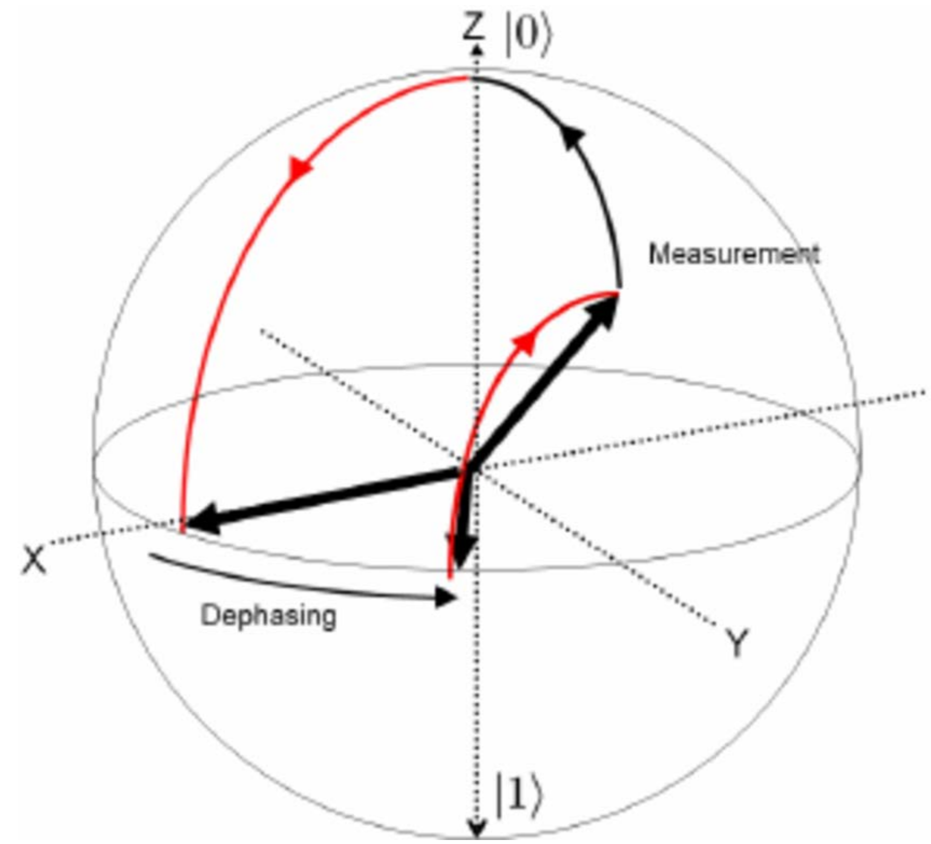
(d) $= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix};$ (e) $= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix};$

(f) $= \begin{pmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{pmatrix};$ (g) $= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\varphi} \end{pmatrix}$

BIG problem of noise adds to this question of measurement



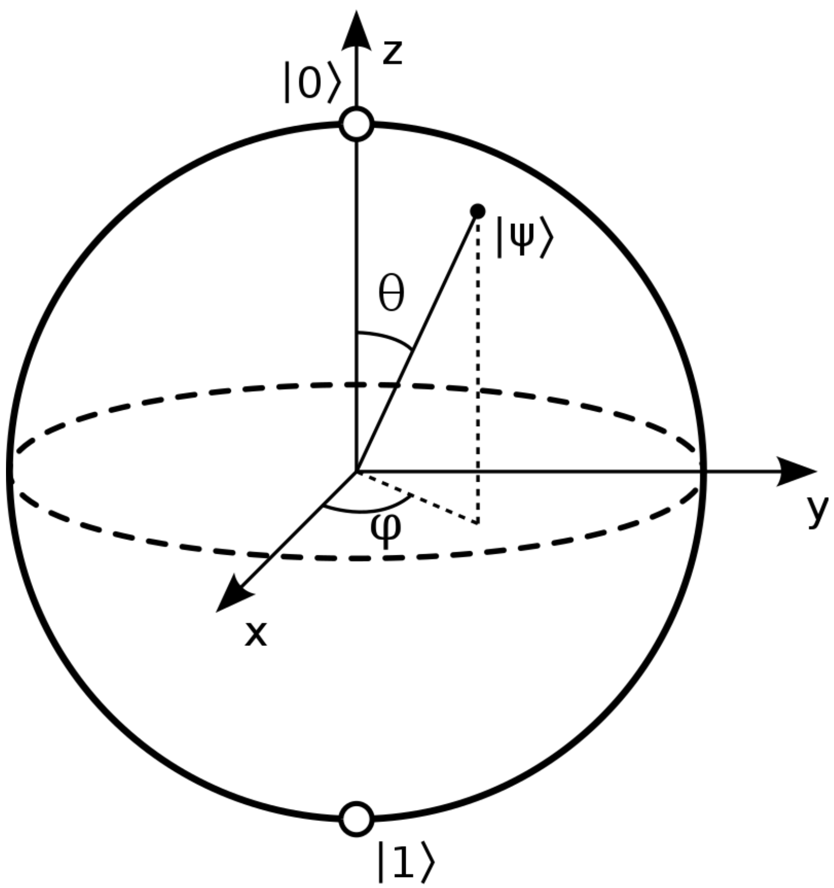
No noise



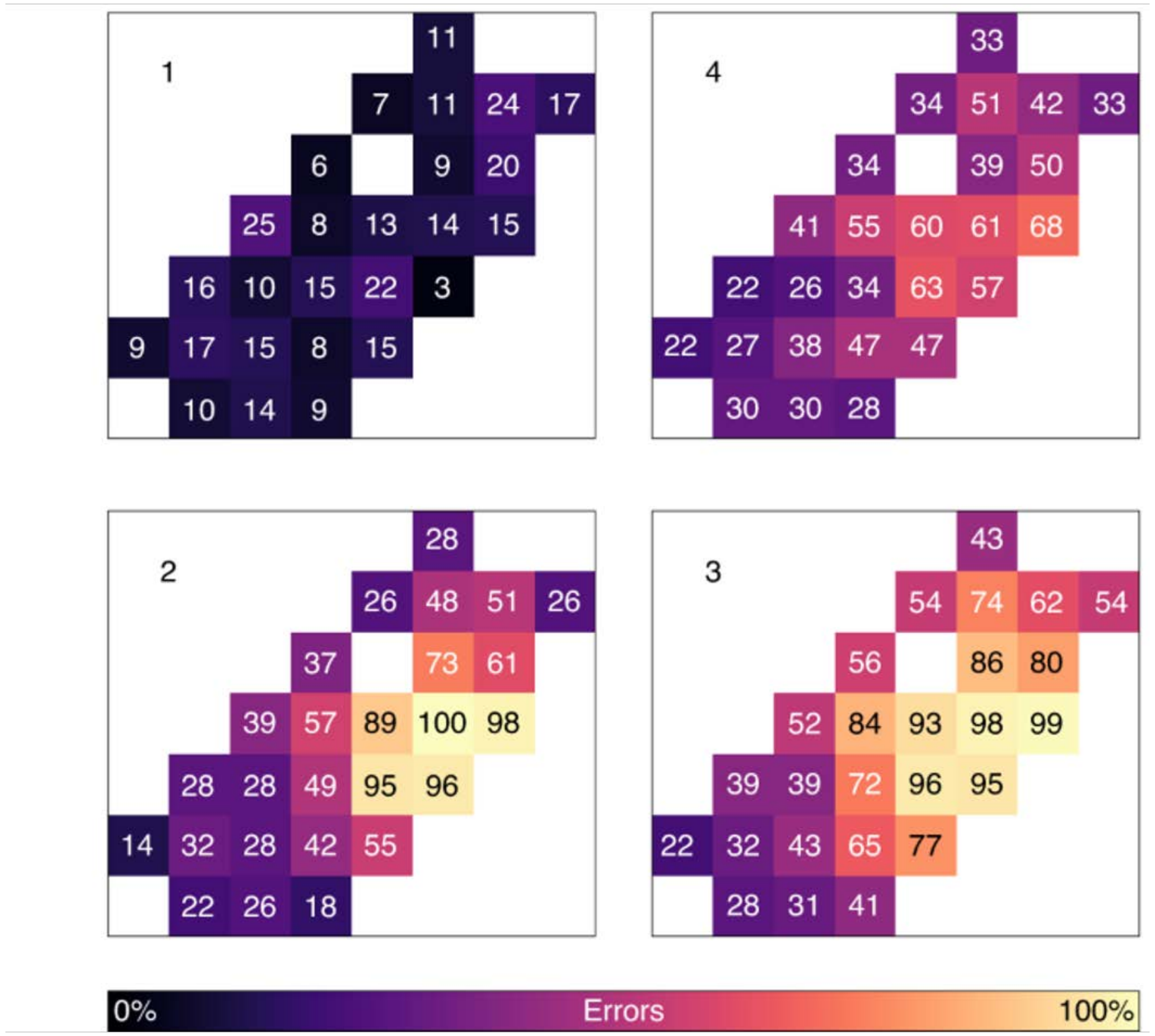
Decoherence

Simple two level systems have no intrinsic protection from relaxation or decoherence

Just gets worse…



No noise

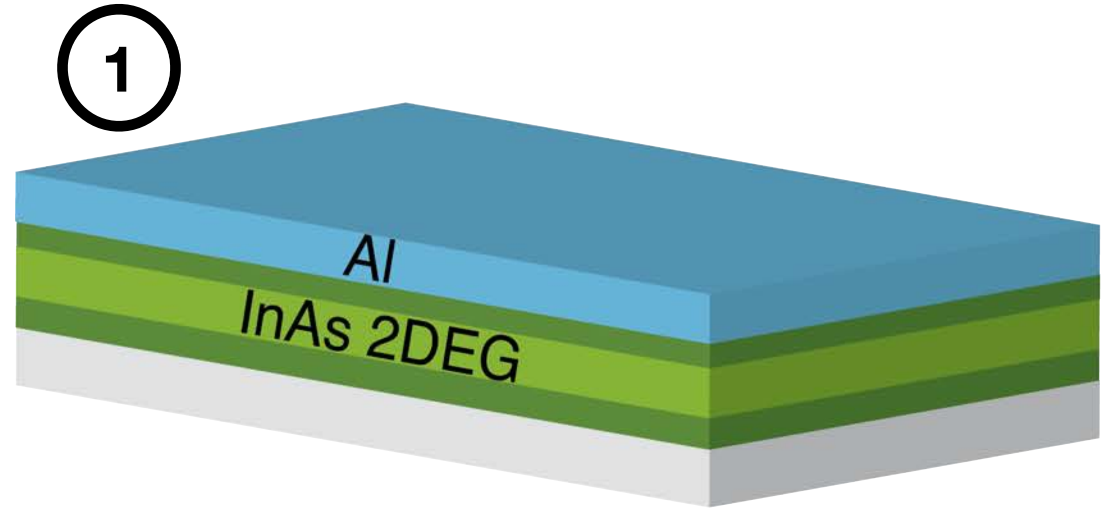


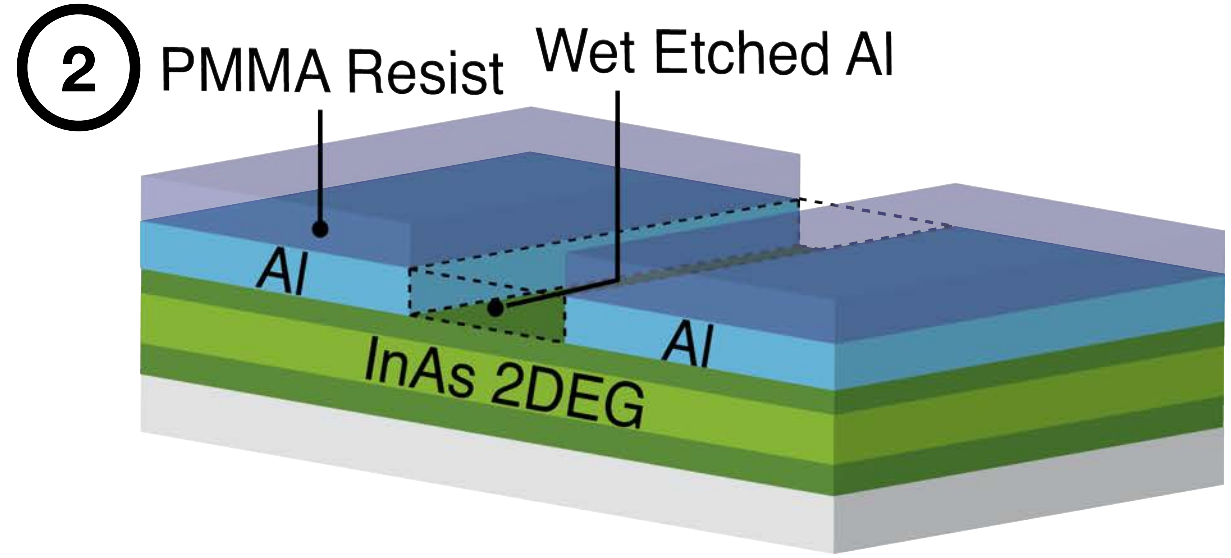
McEwen et al., *Nature Physics*, 18, 107–111 (2022)

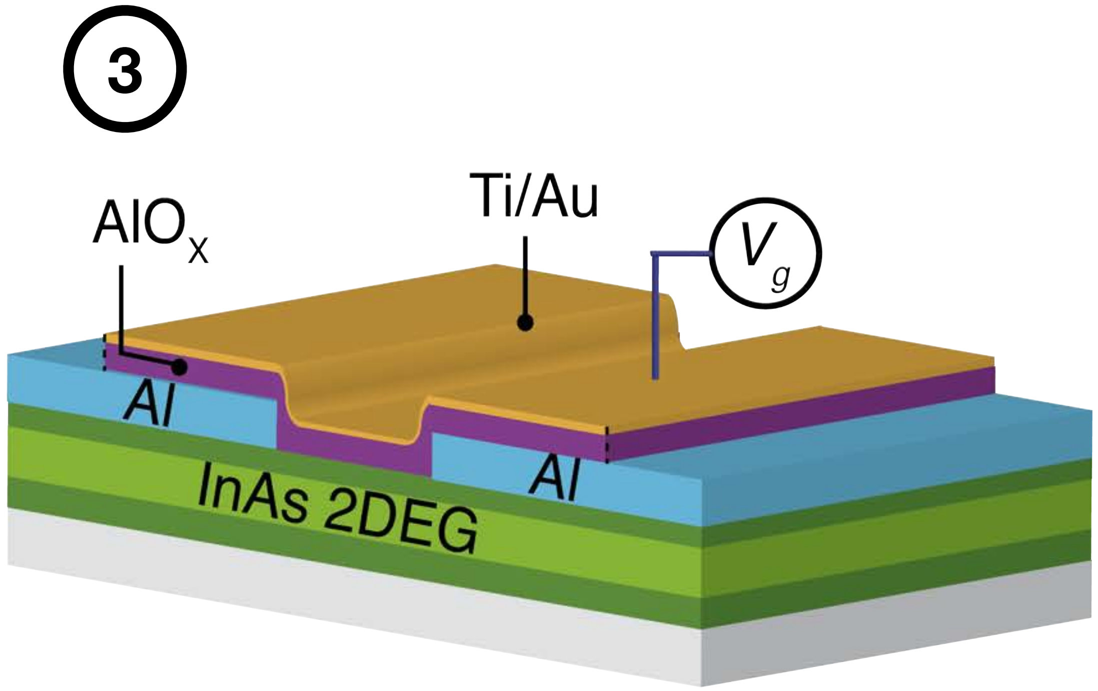
Title: Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits

Simple two level systems have no intrinsic protection from relaxation or decoherence

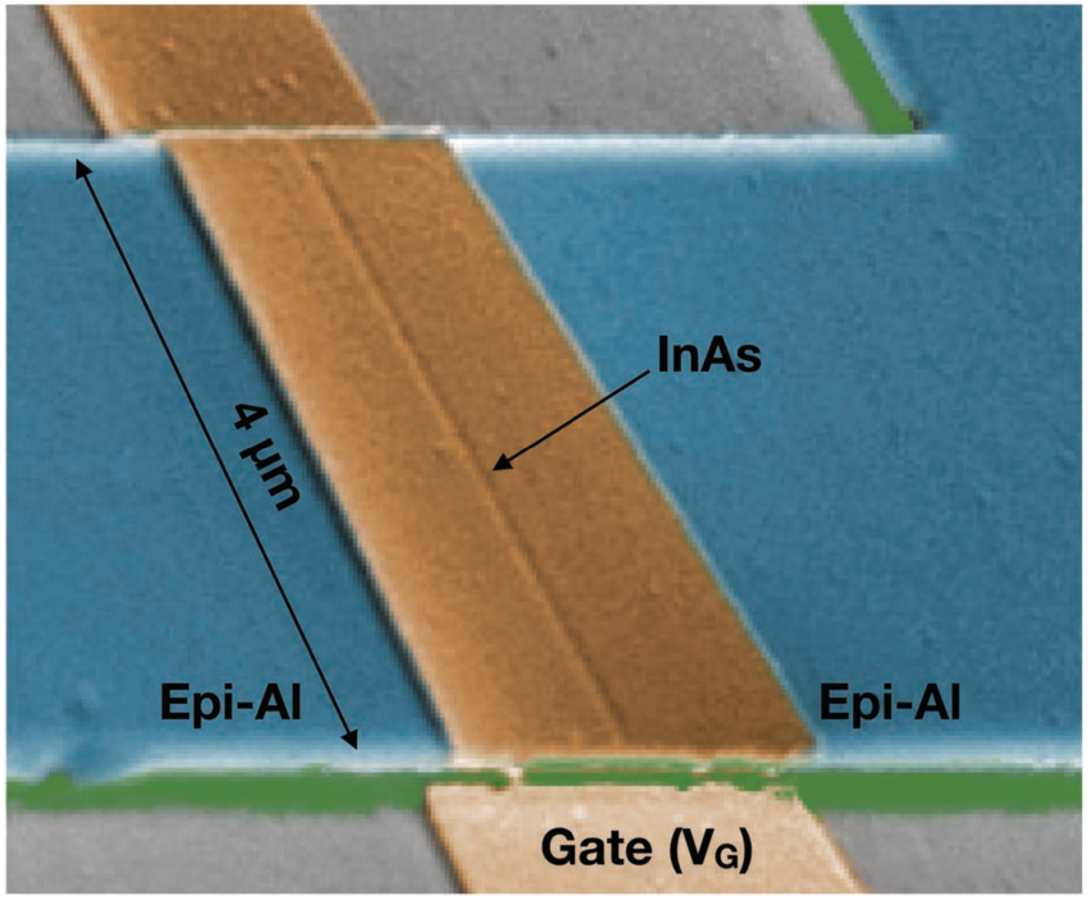
“New" Josephson Junctions





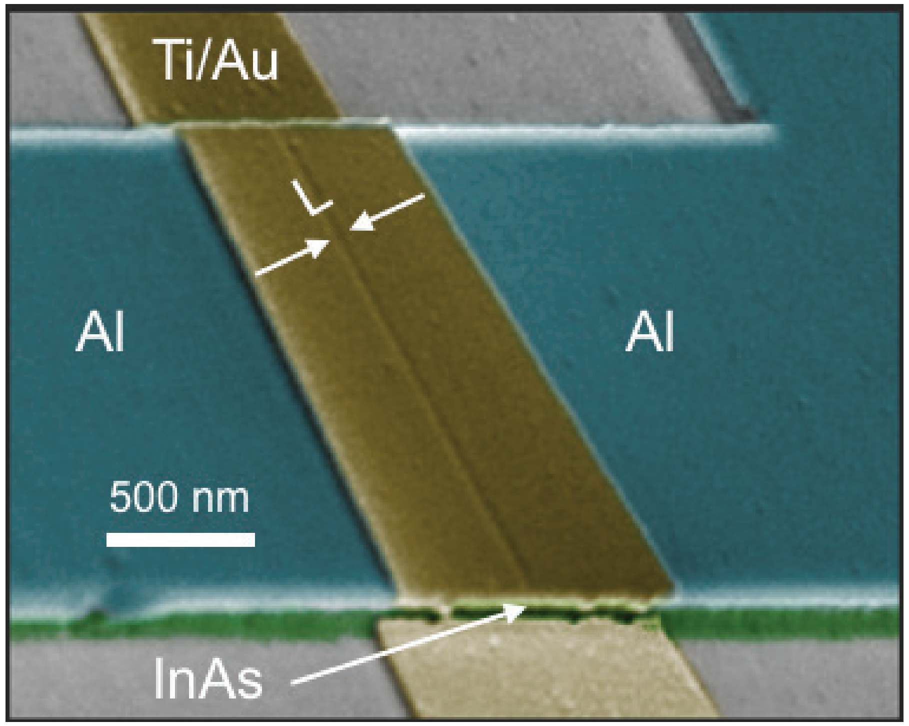


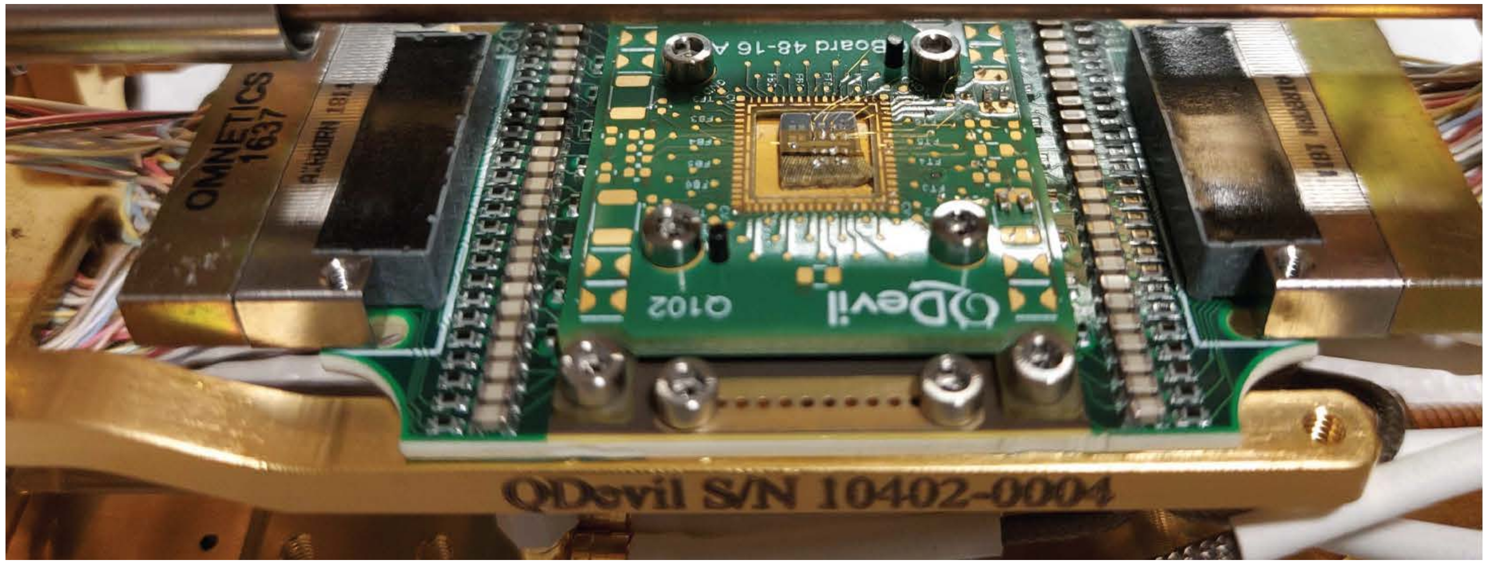
SEM Image (false colored)

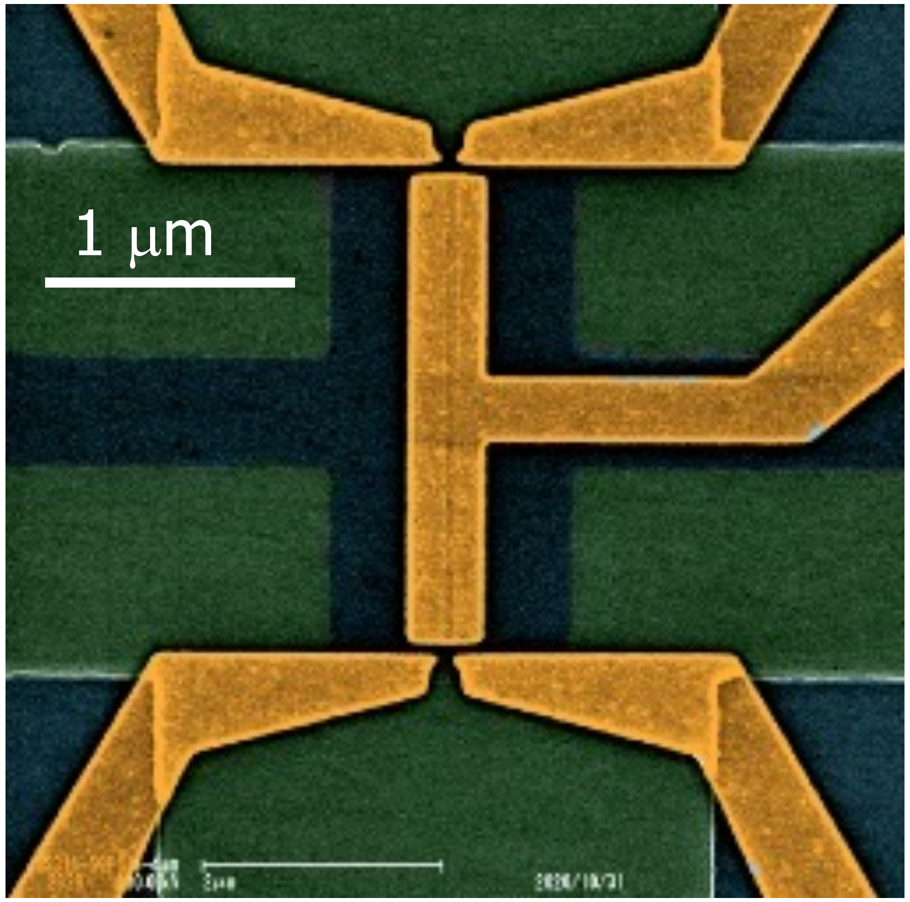


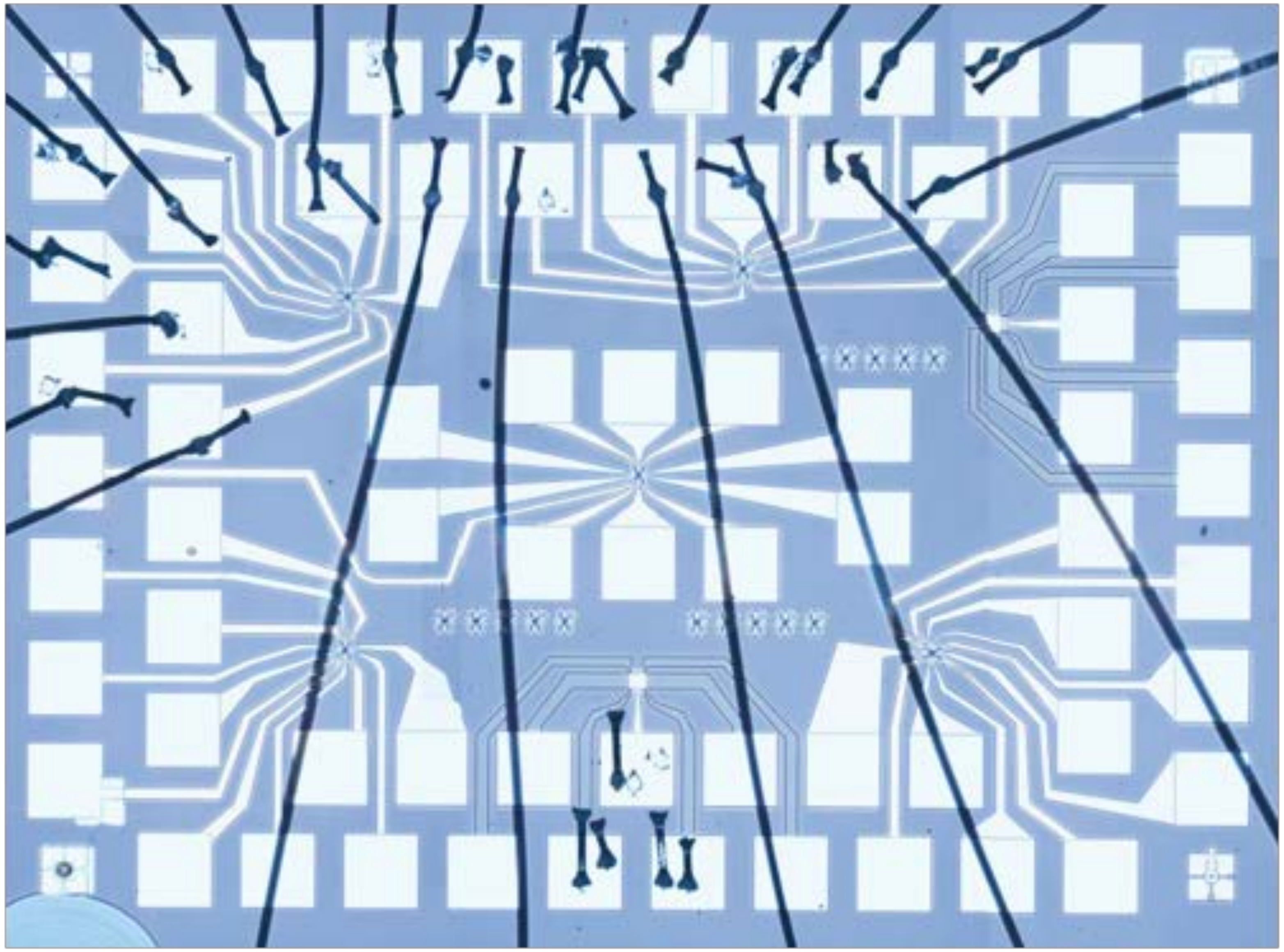
Shabani et al., PRB 2016

Josephson Junction Devices

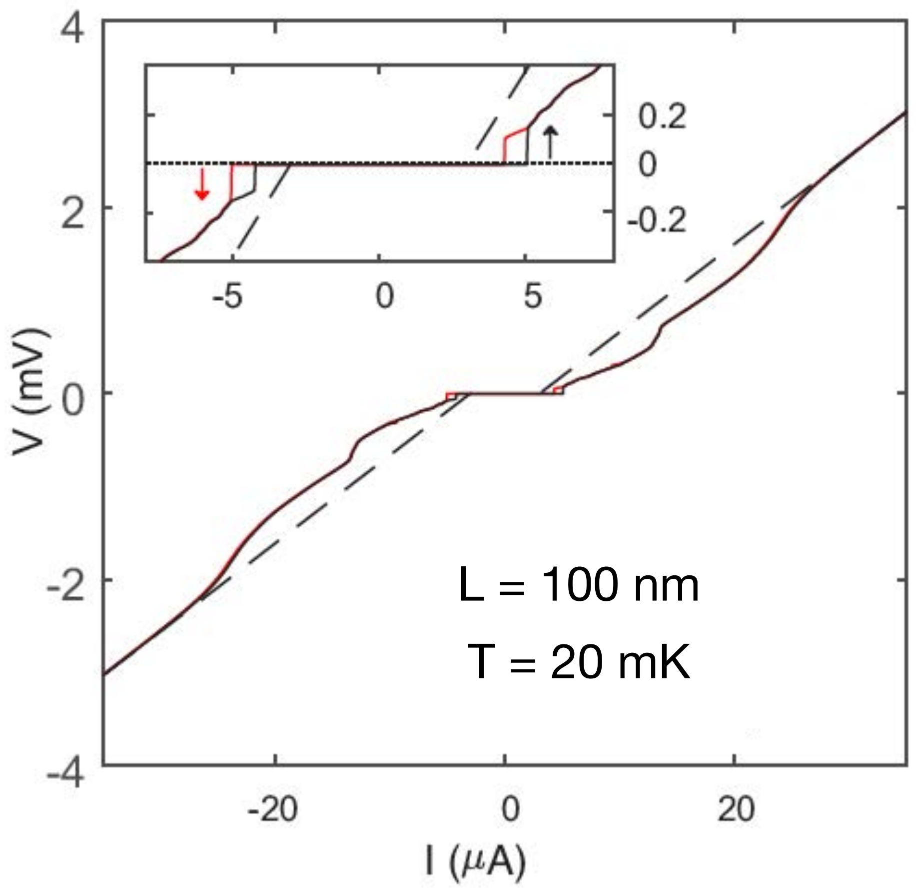


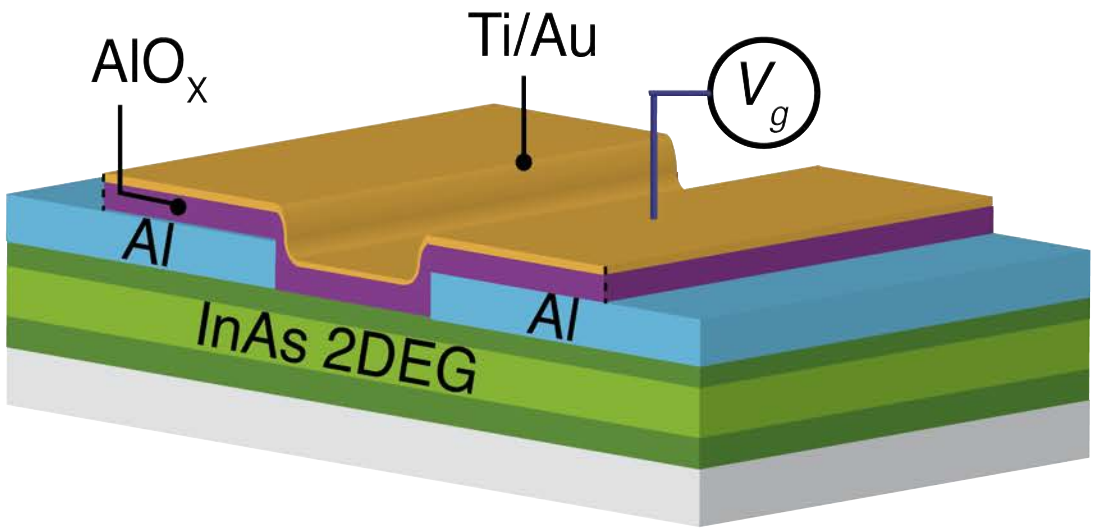


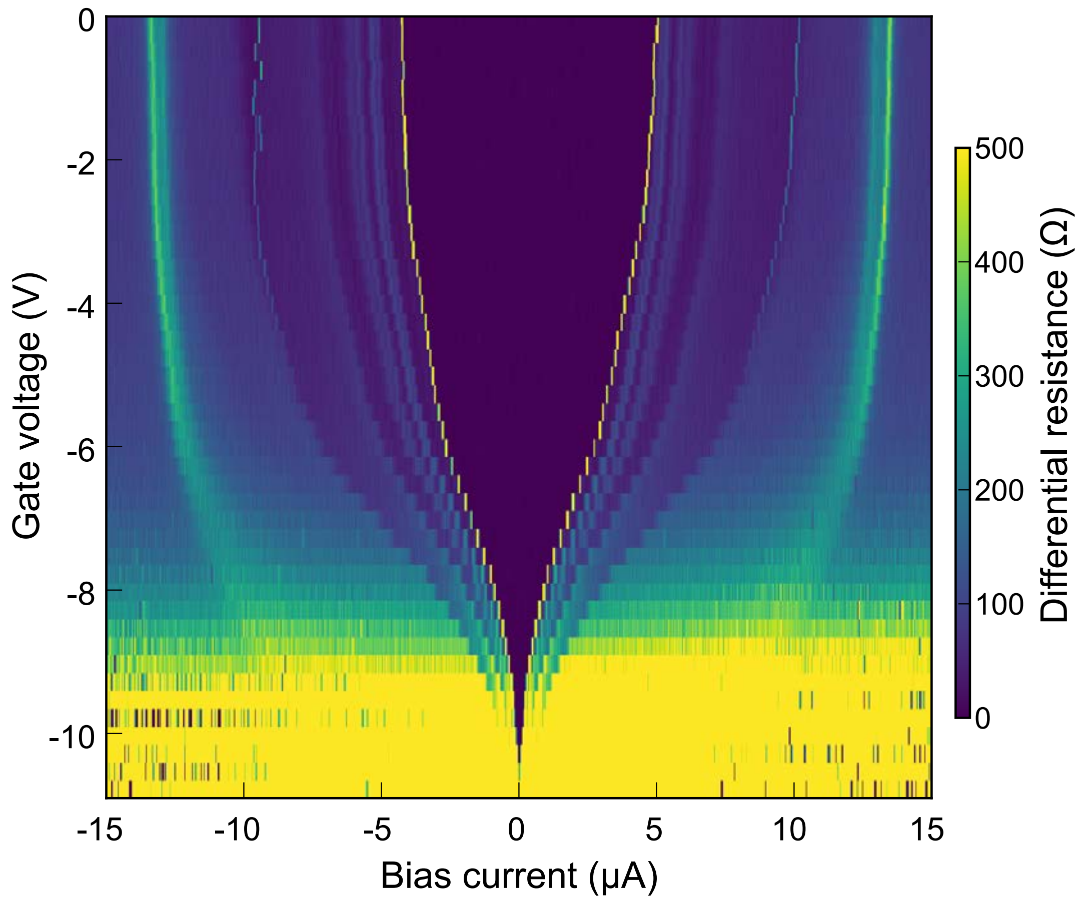




JFET as a new tool for qubits



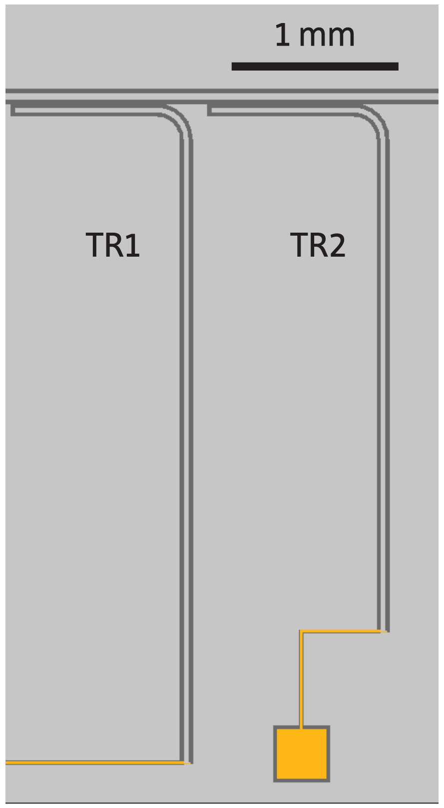


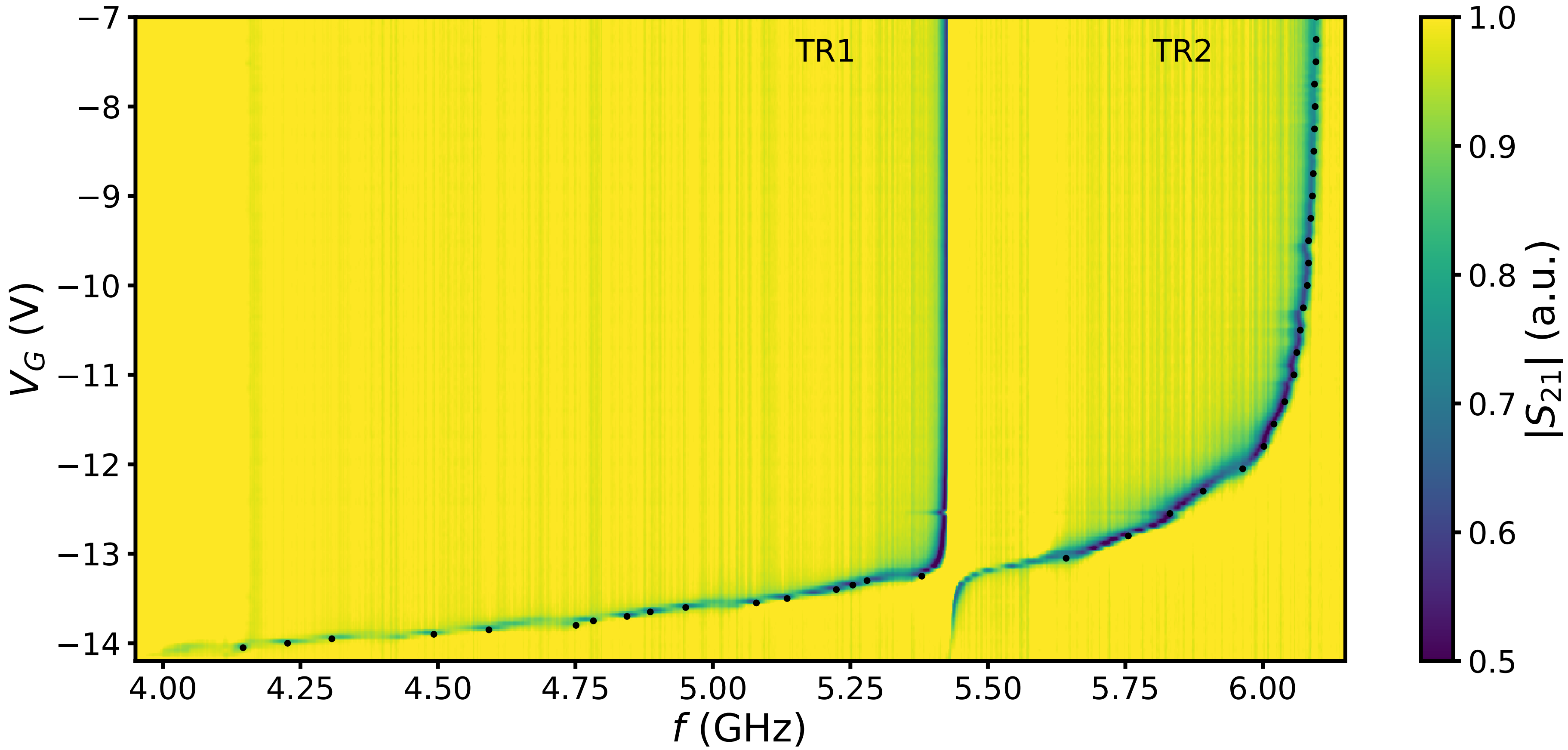


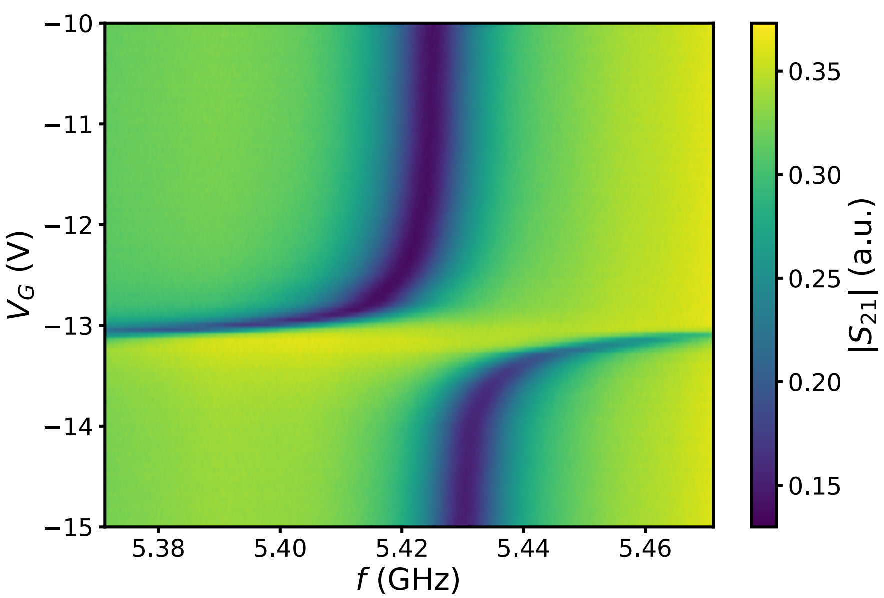
$$\omega \sim \frac{1}{\sqrt{(L_0 + L_J)C_0}}$$

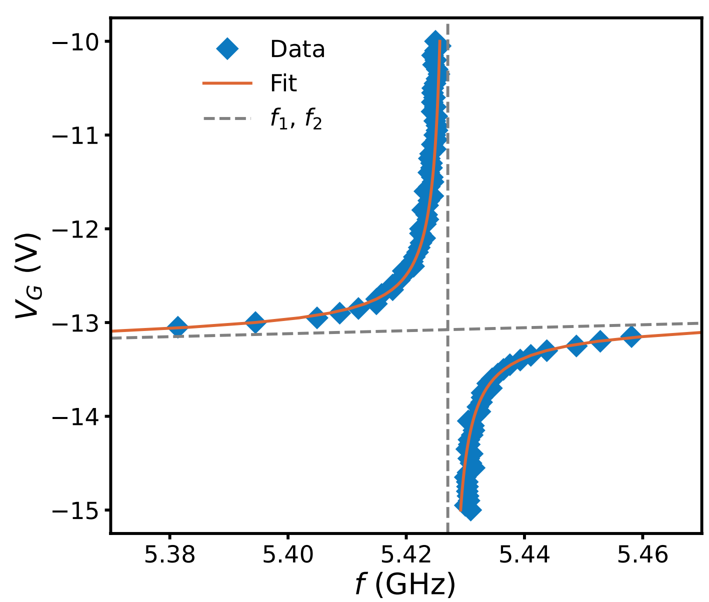
Mayer, W. et al. Appl. Phys. Lett. ***114****, 103104 (2019)*

Tunability of frequency







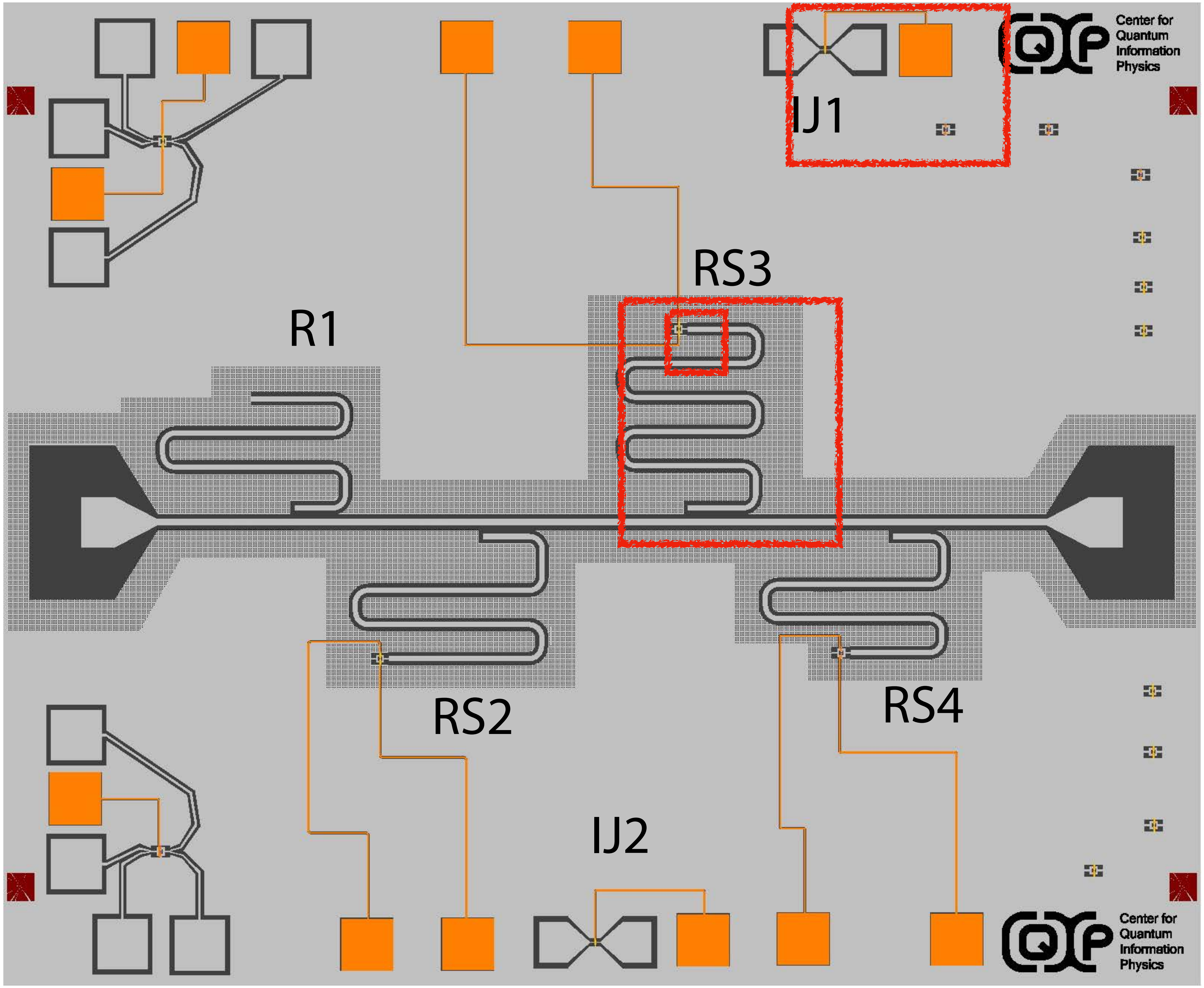


- Fit to two oscillators model with coupling strength g, find a coupling strength of g = 51.203 MHz

$$f_{\pm} = \frac{1}{2}(f_1 + f_2) \pm \sqrt{g^2 + \frac{1}{2}(f_1 - f_2)^2}$$

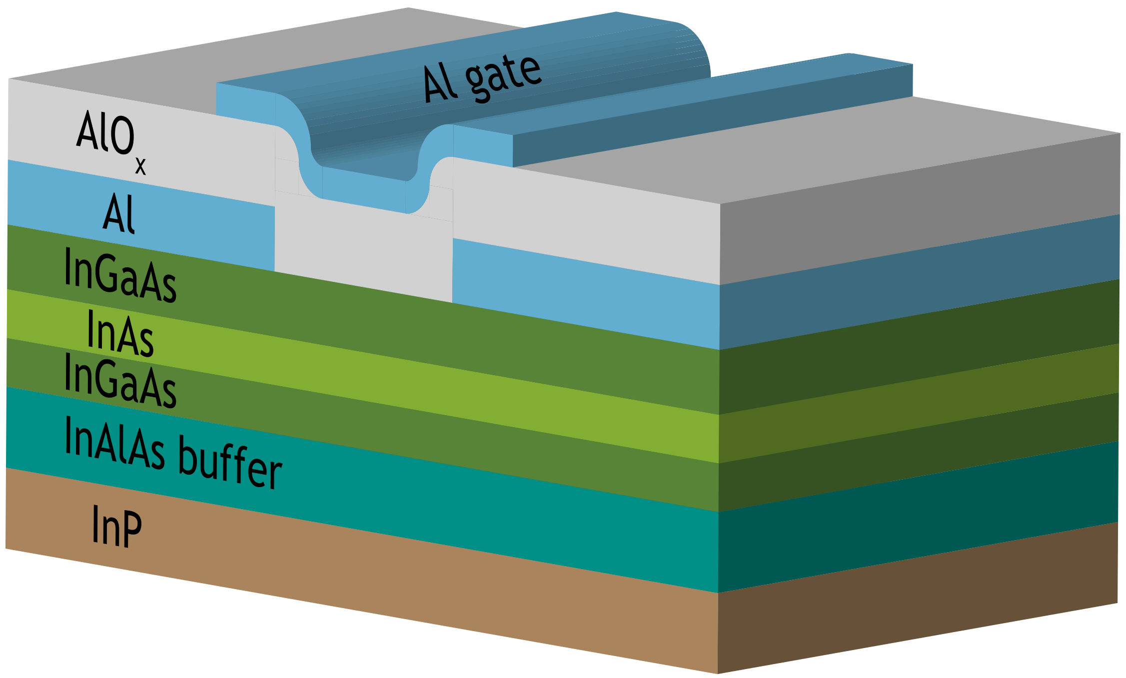
Strickland et al., PR Applied 2023

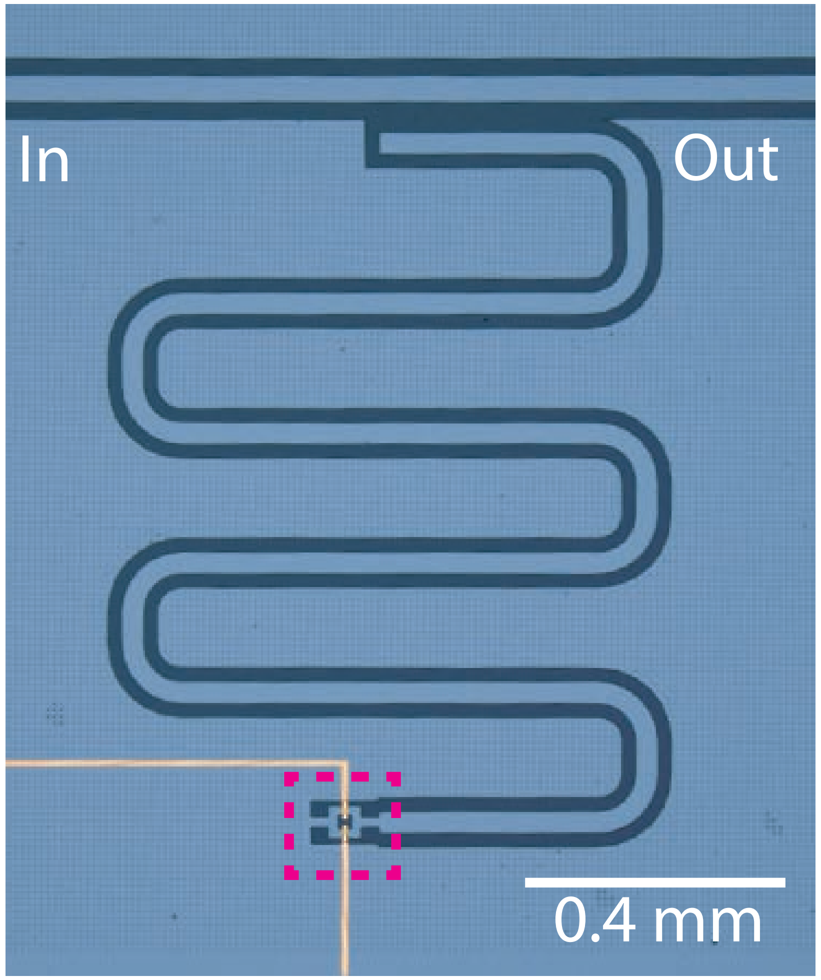
cQED Ideas: spectroscopy - weak measurement



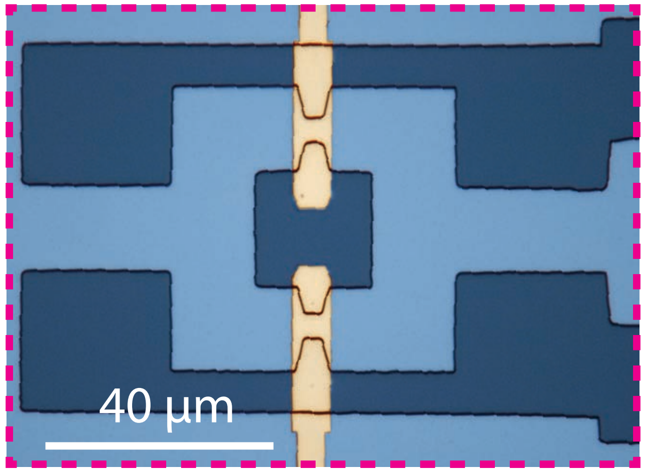
Elfeki et al., arXiv:2303.04784

cQED Ideas: spectroscopy - weak measurement

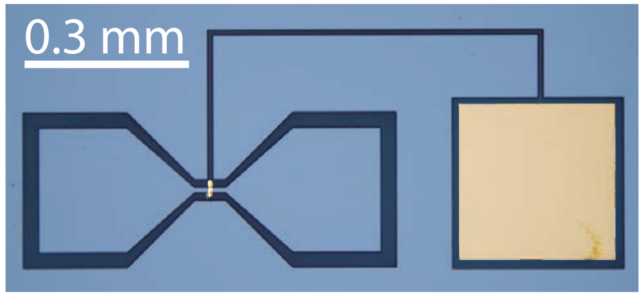




Resonator-SQUID



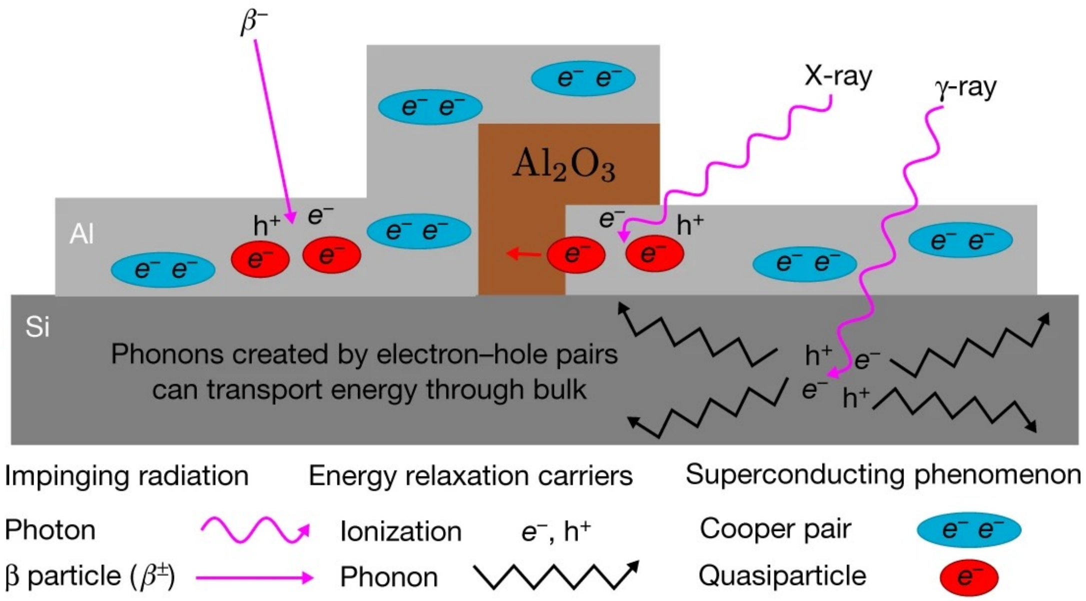
SQUID



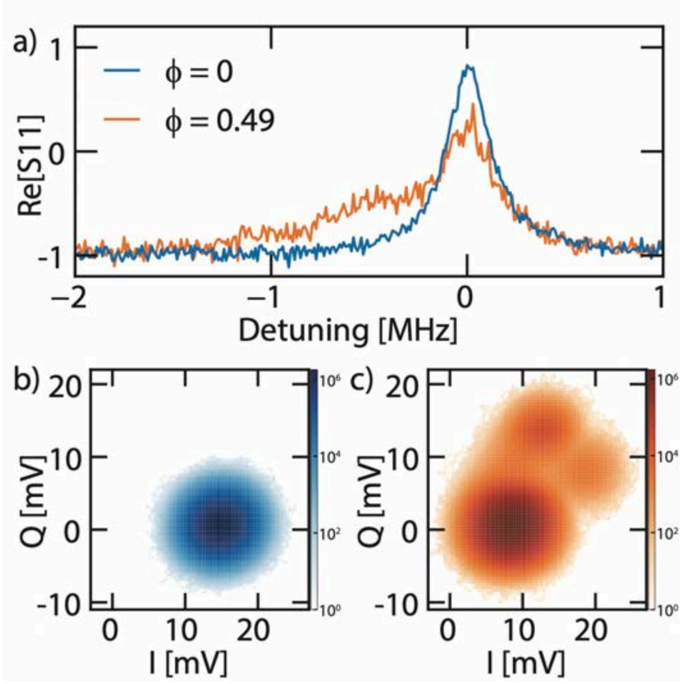
QP injector junction

Control Steps: Quasi Particle Poisoning

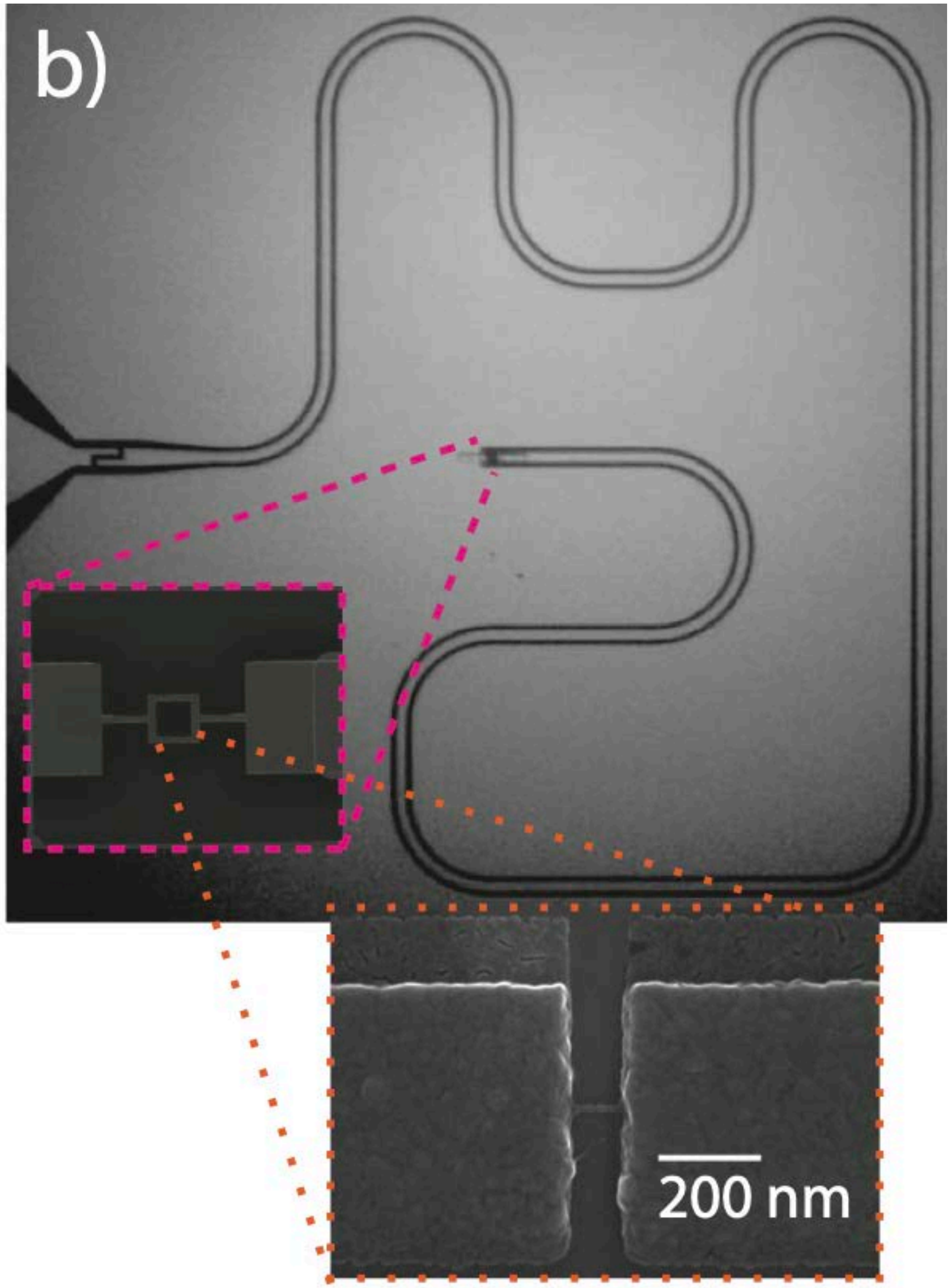
Josephson junction



A. P. Vepsalainen et al., Nature (2020)



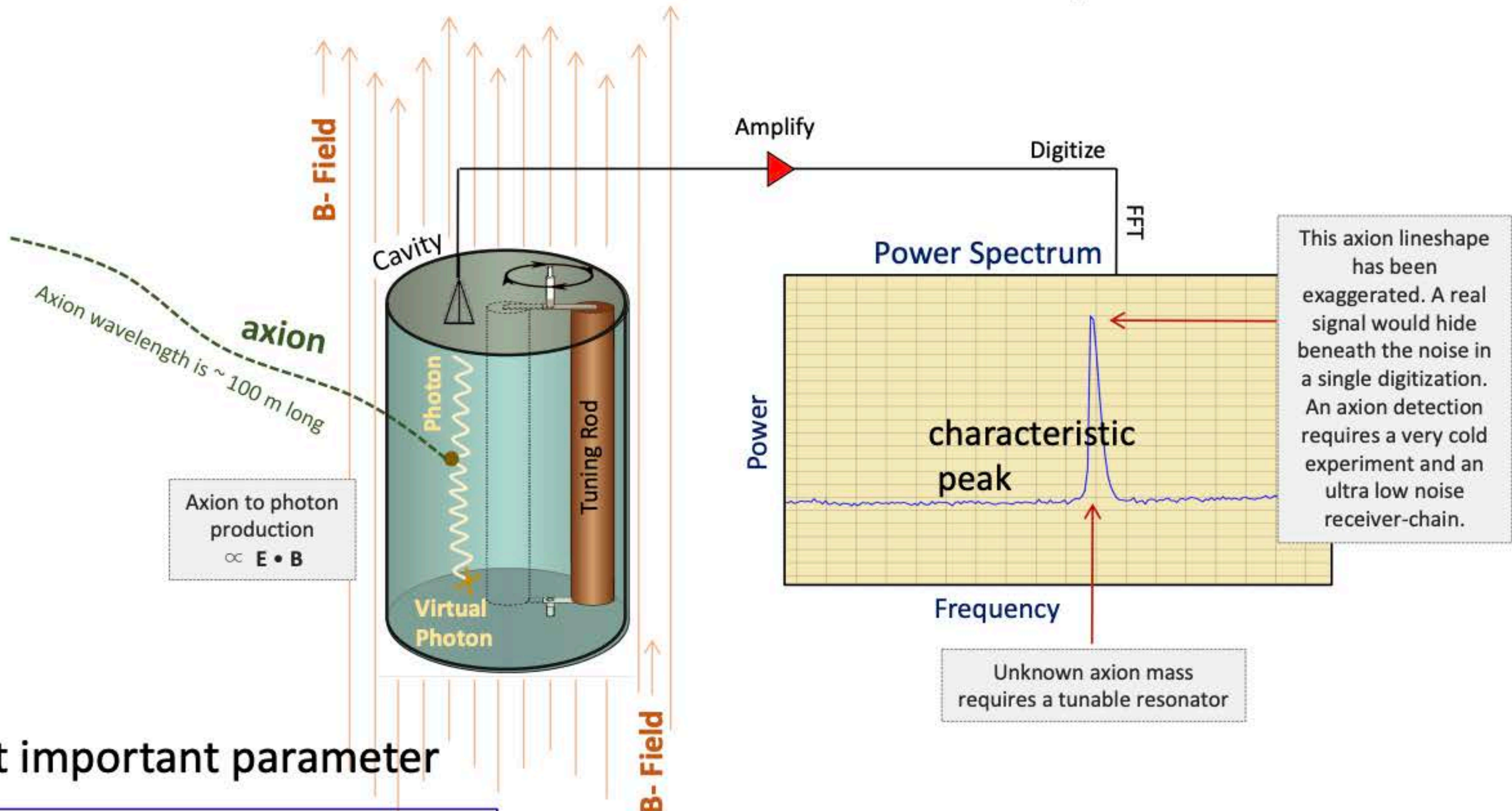
Resonator-SQUID



https://topocondmat.org/w2_majorana/signatures.html
Hays, Springer Theses (2021)
J. Farmer et al., APL (2021)

Axion dark matter radio

The Axion Haloscope

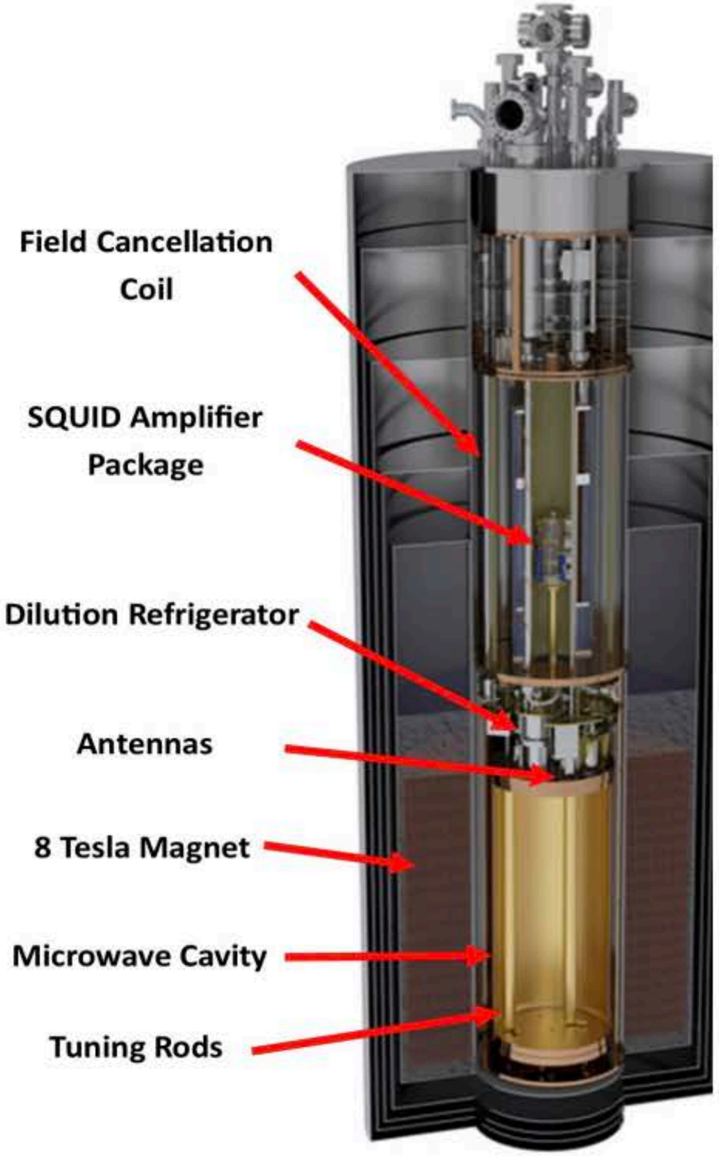


Most important parameter

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

C. Boutan

ADMX detector



Field cancellation coil: cancels the residual magnetic field around the SQUID electronics

Superconducting QUantum Interference Device (SQUID) amplifiers: amplifies the signal while being quantum noise limited

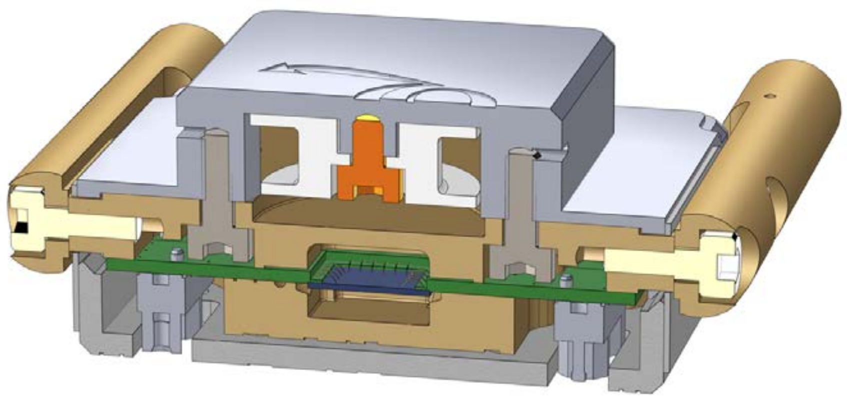
Dilution refrigerator: cools the insert to ~ 90mK

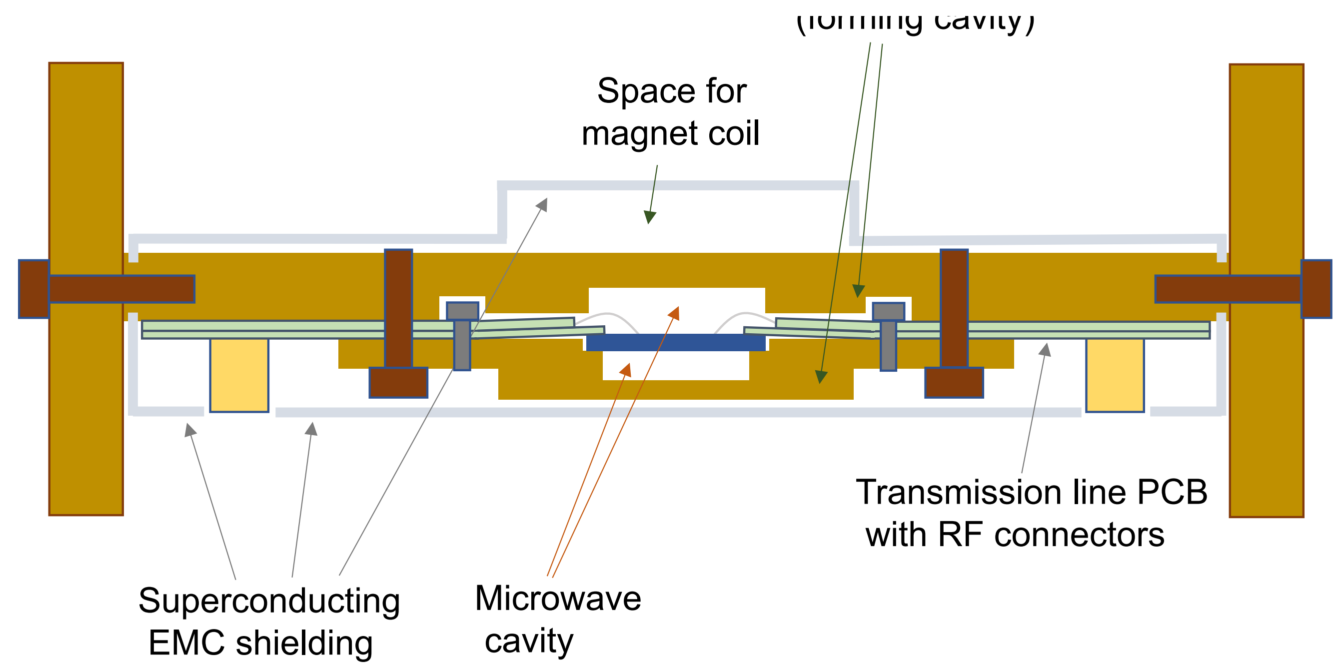
Antennas: pick up signal

Magnet: facilitates the axion conversion to photons, 8T

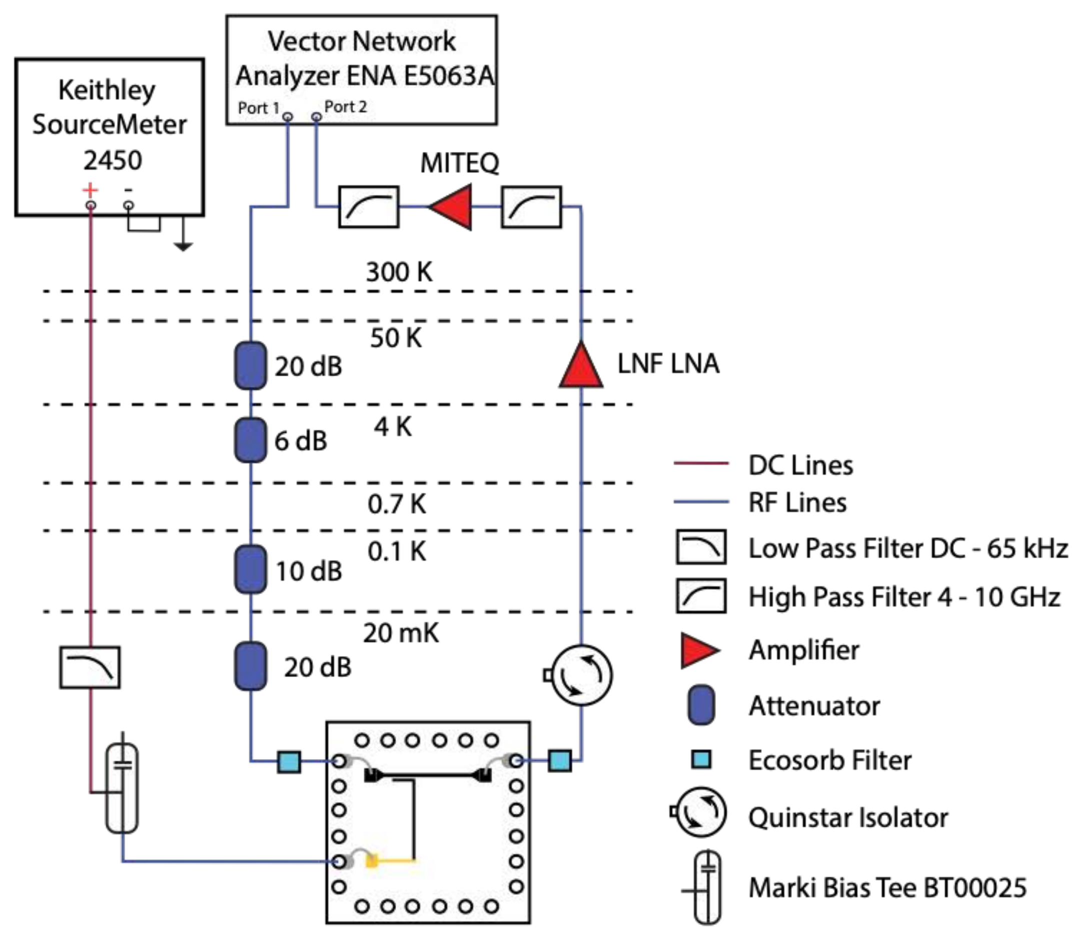
Microwave Cavity: converts axions into photons, tunable

Control Steps: Quasi Particle Poisoning





6-3-1 T Vector Dilution Fridge with qubit setup

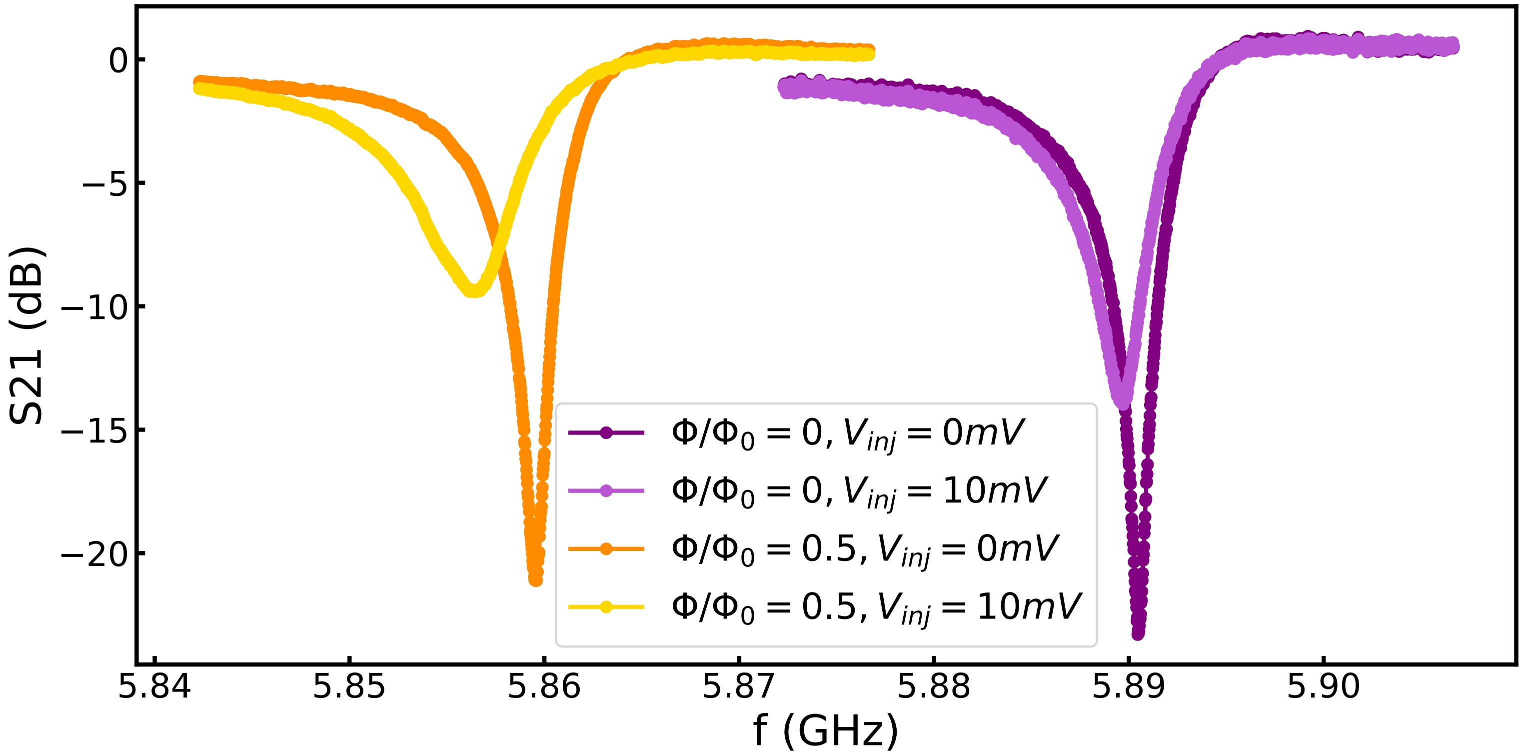


Control Steps: Quasi Particle Poisoning

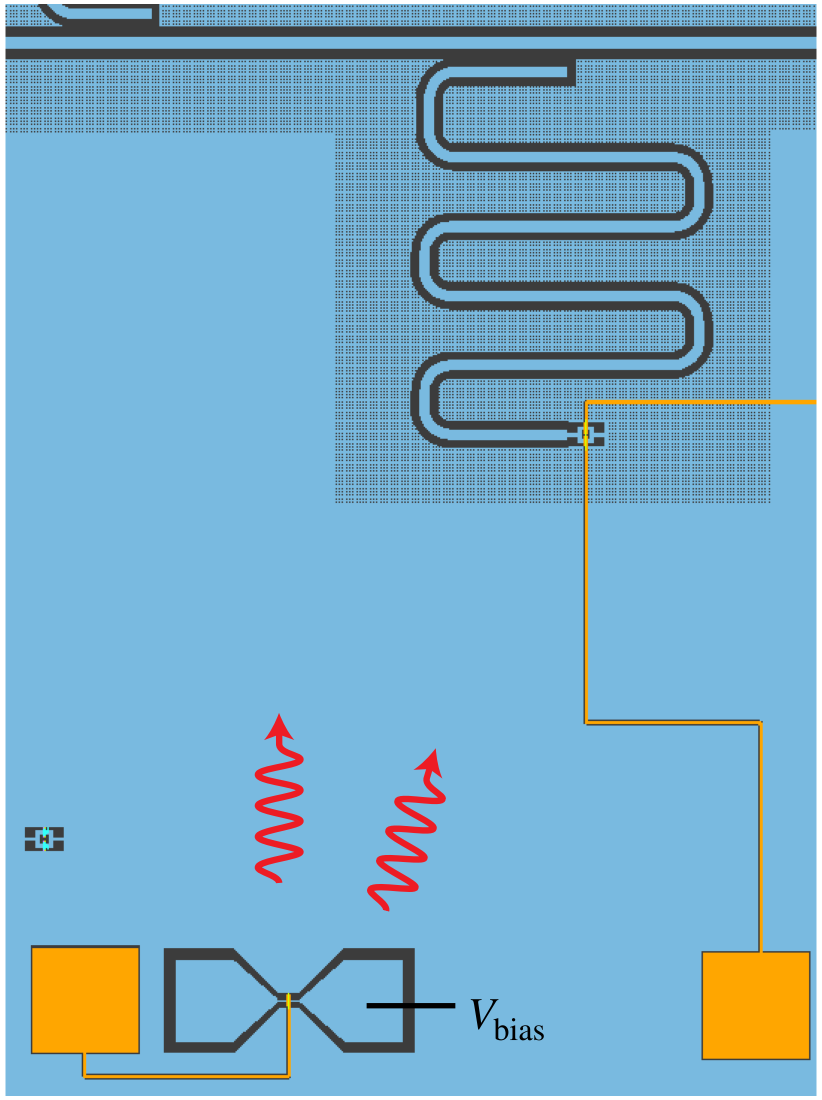
- Deepest trap ($\tau = 1$) at $\phi = 0.5$:

$$\Delta_A = \Delta - \Delta\sqrt{1 - \tau sin^2(\phi/2)} = 15.6 \text{ GHz}$$

- Applied clearing tone frequency = 18GHz



Resonator-SQUID

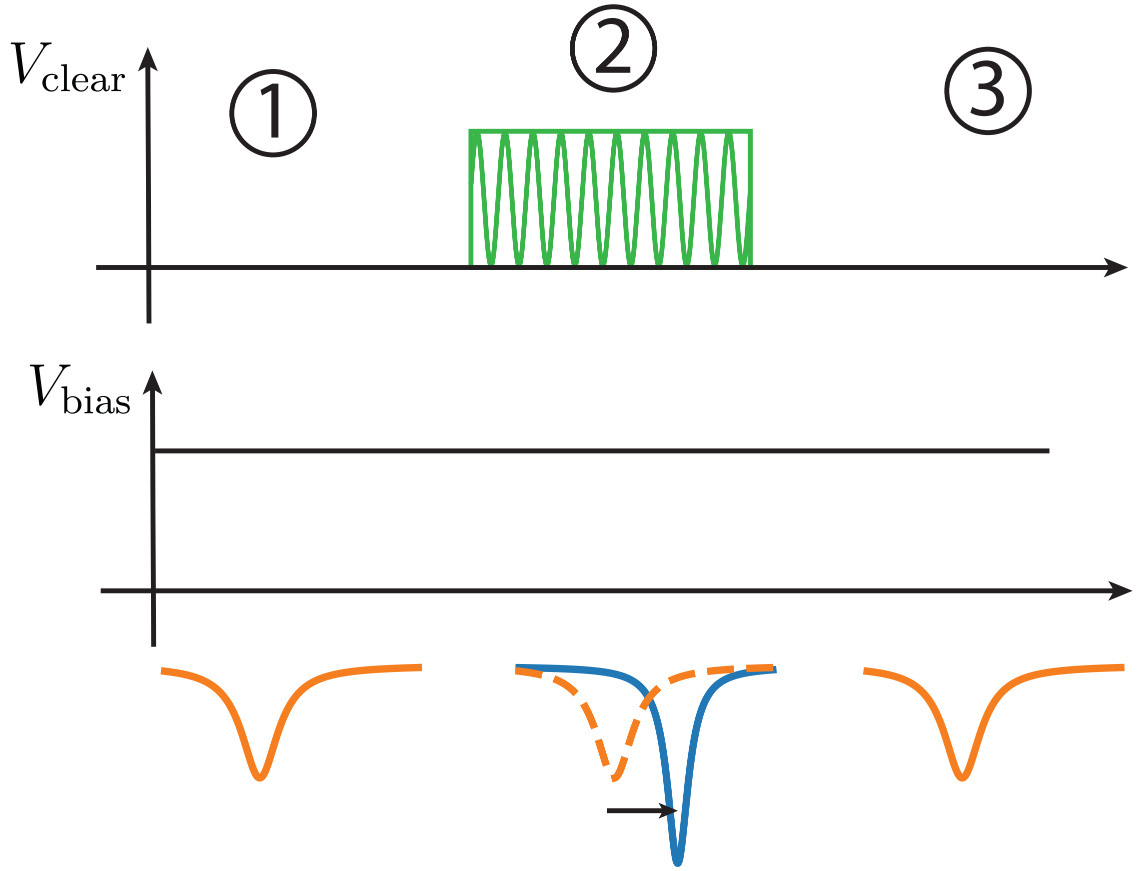


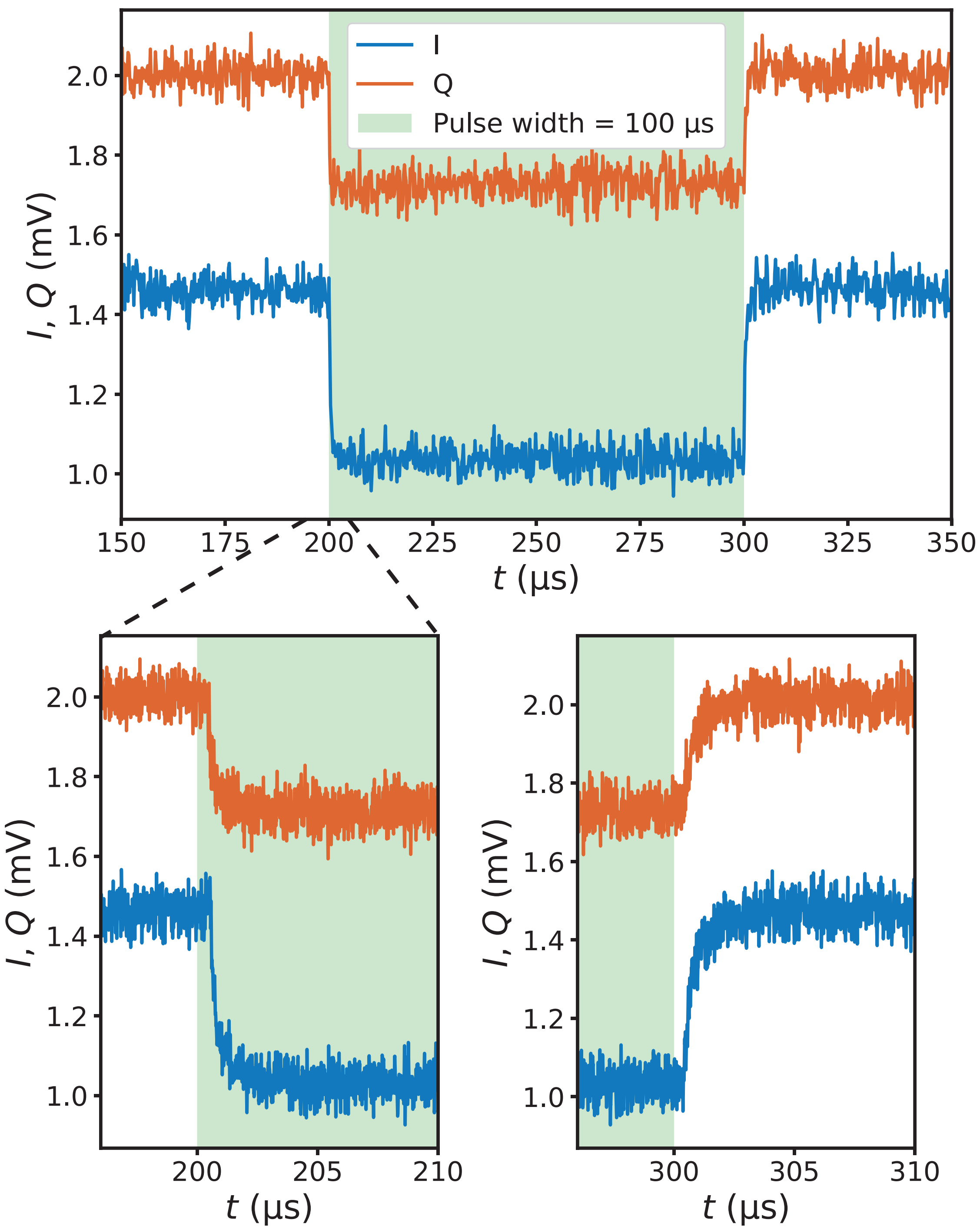
Topological gap (~ns) << Majorana qubit clock time << QPP time

Elfeki et al., arXiv:2303.04784

Control Steps: Quasi Particle Poisoning

Applied clearing tone frequency = 18GHz



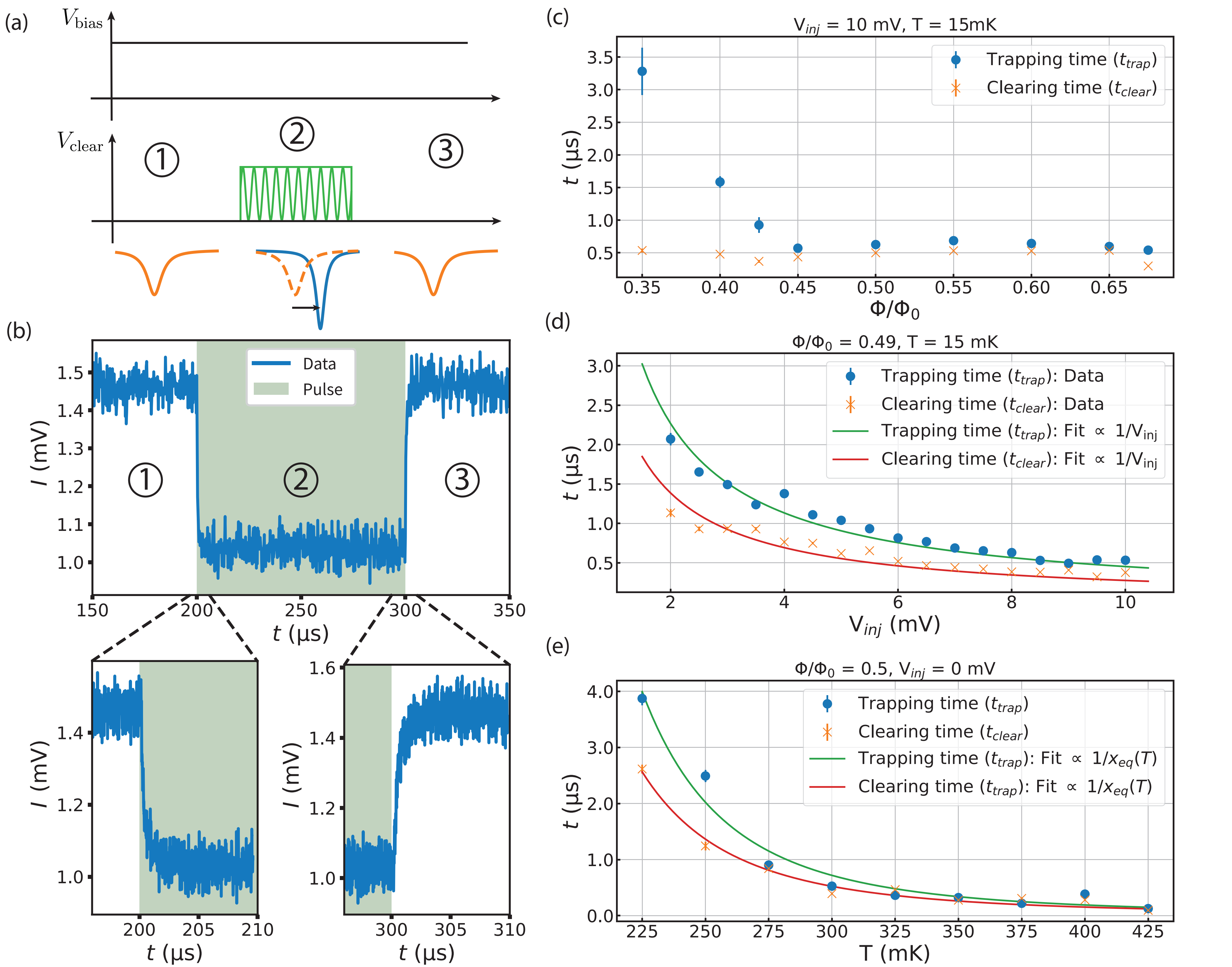


Clearing time: time it takes for QPs to clear out of the Andreev trap after pulse starts

Trapping time: time it takes QPs to fall into Andreev trap after pulse ends

Elfeki et al., arXiv:2303.04784

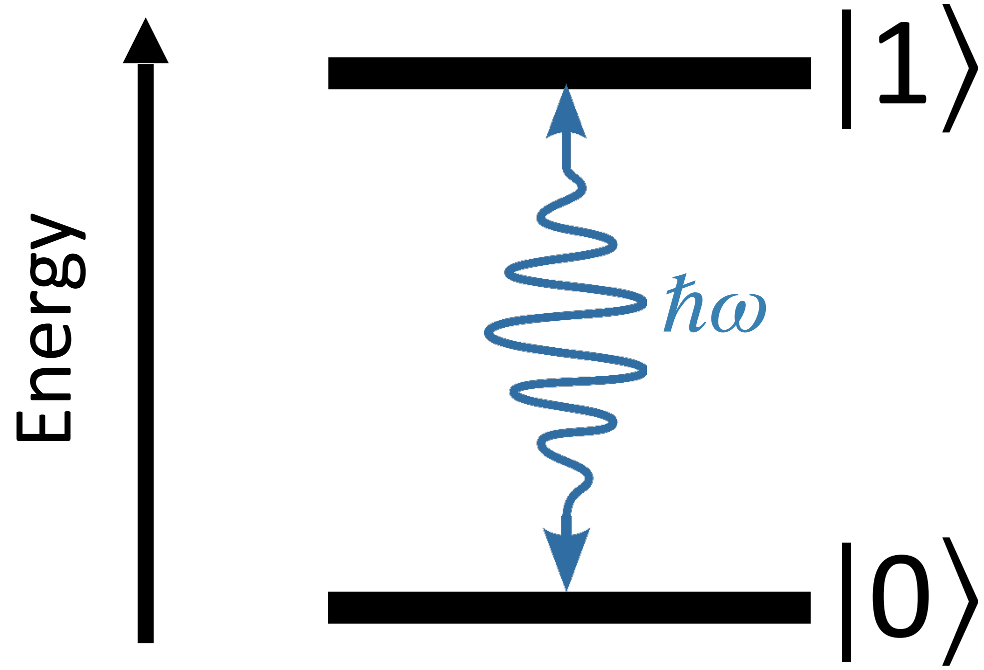
Control Steps: Quasi Particle Poisoning



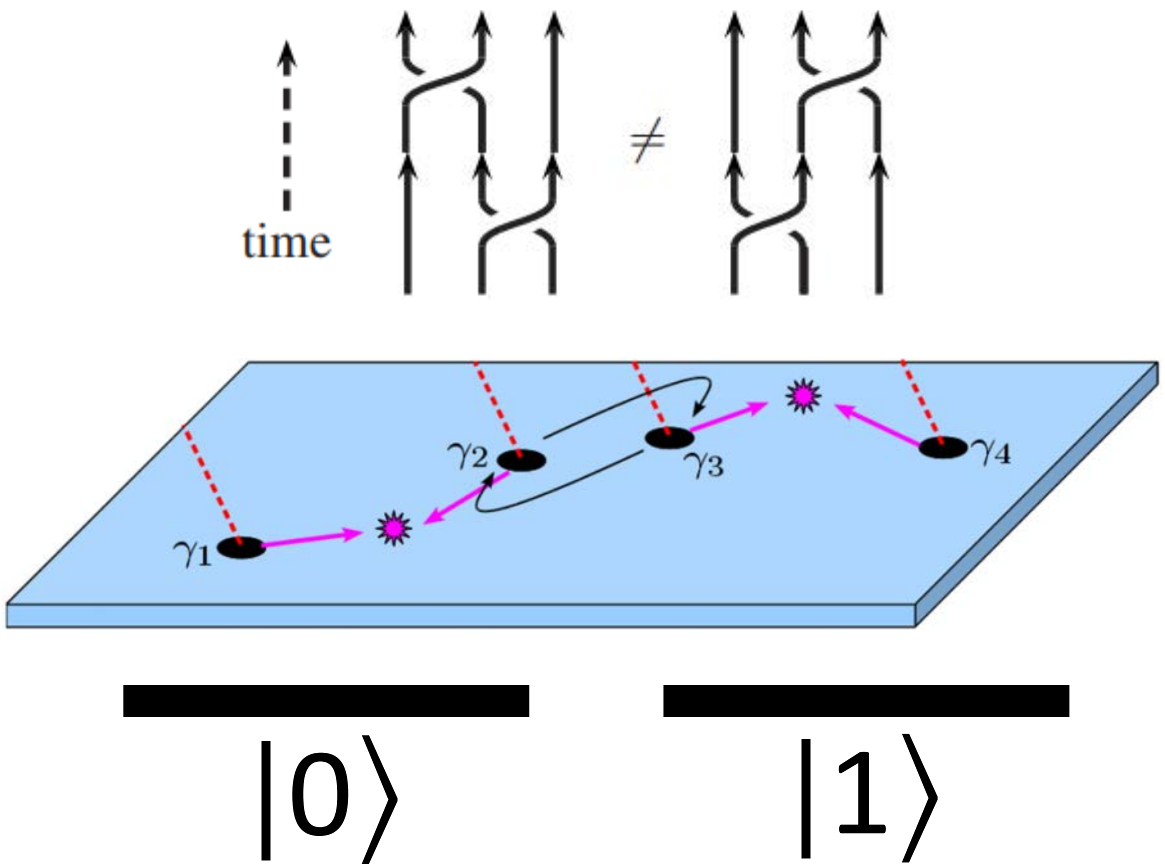
Elfeki et al., arXiv:2303.04784

Different Qubits: Topological Superconducting Systems

“Traditional”



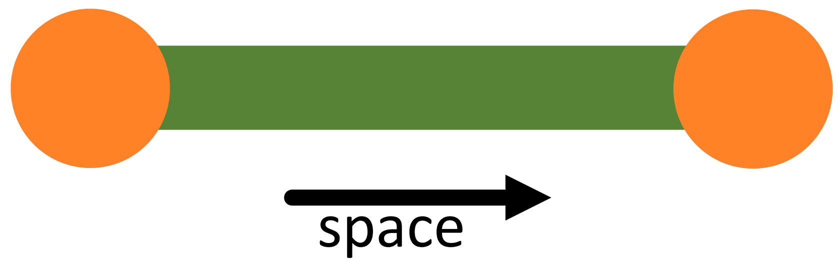
Topological

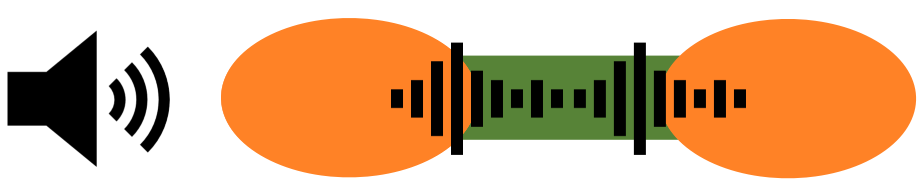


Nayak et al., Rev. Mod. Phys. **80** (2008)
Leijnse & Flensberg, Semicond. Sci. Technol. **27** (2012)

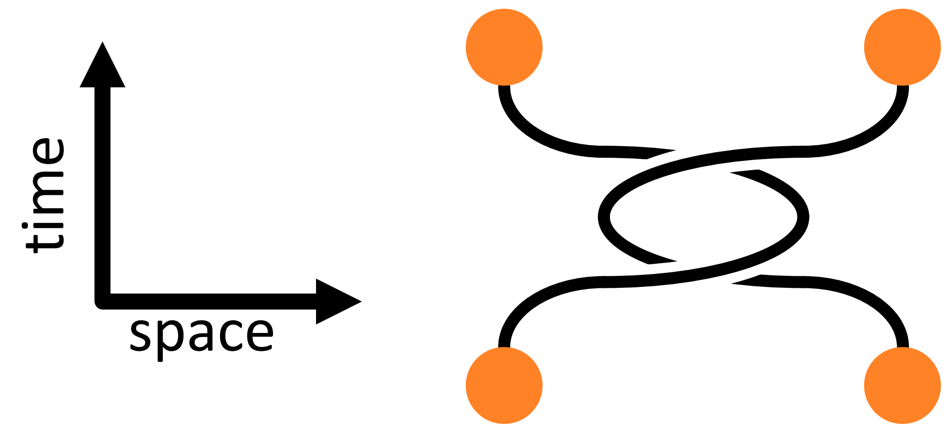
Different Noise: Topological Superconducting Systems

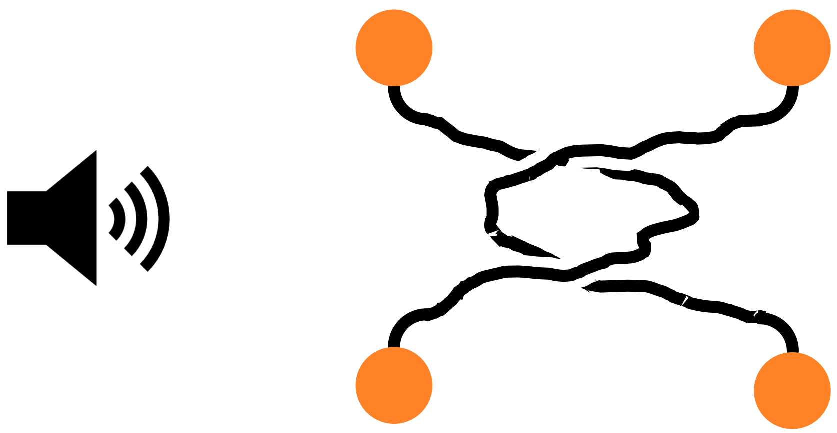
Protected Encoding





Protected Manipulation



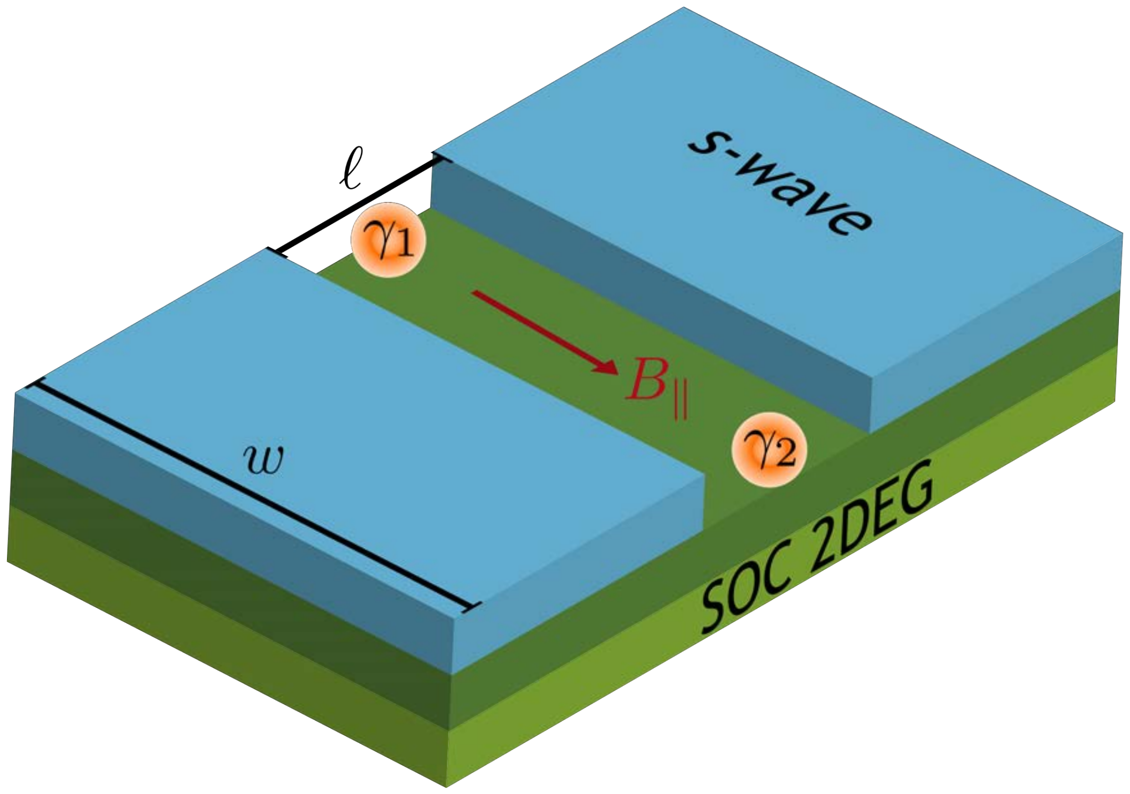


Topological Superconductivity in JJ

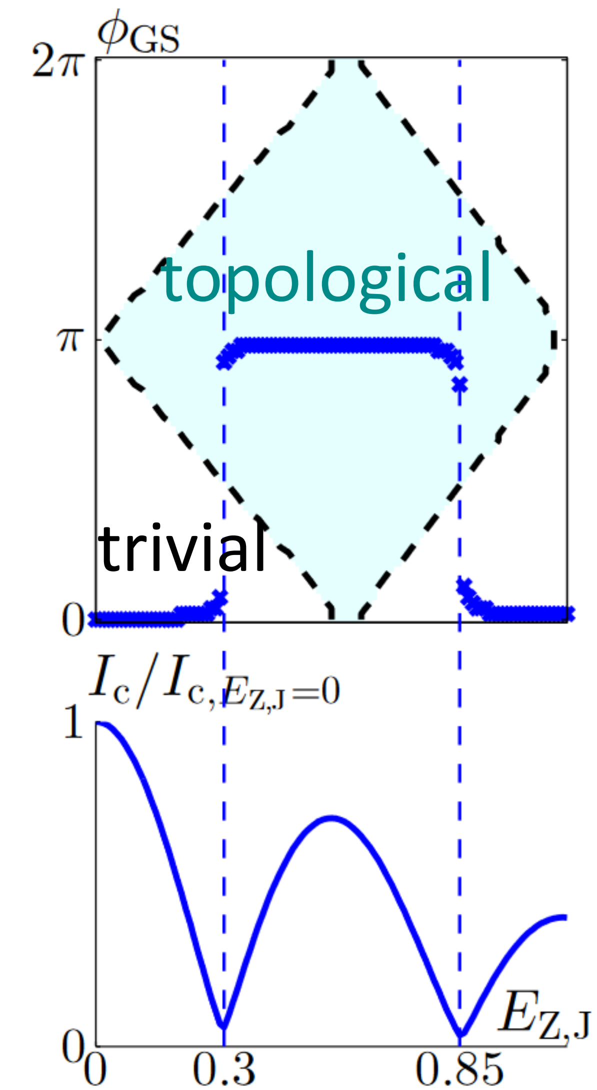
spin-orbit coupling — Zeeman effect — superconductivity

$$H = \left[\frac{\boldsymbol{p}^2}{2m^*} - \mu + \frac{\alpha}{\hbar}\left(p_y\sigma_x - p_x\sigma_y\right)\right]\tau_z - \frac{g^*\mu_B}{2}\boldsymbol{B}\cdot\boldsymbol{\sigma} + \Delta e^{i\varphi/2}\tau_+ + \Delta^* e^{-i\varphi/2}\tau_-$$

chemical potential — phase



$$E_{SO} \gg E_Z > \sqrt{\Delta^2 + \mu^2}$$



Dartiailh et al. Phys. Rev. Lett. **126**, 036802 (2021)
Mayer et al. Appl. Phys. Lett. **114**, 103104 (2019)

Pientka et al. Phys. Rev. X **7**, 021032 (2017)
Hell et al. Phys. Rev. Lett. **118**, 107701 (2017)

Center for Quantum Information Physics

Topological Superconductivity in JJ

NYU

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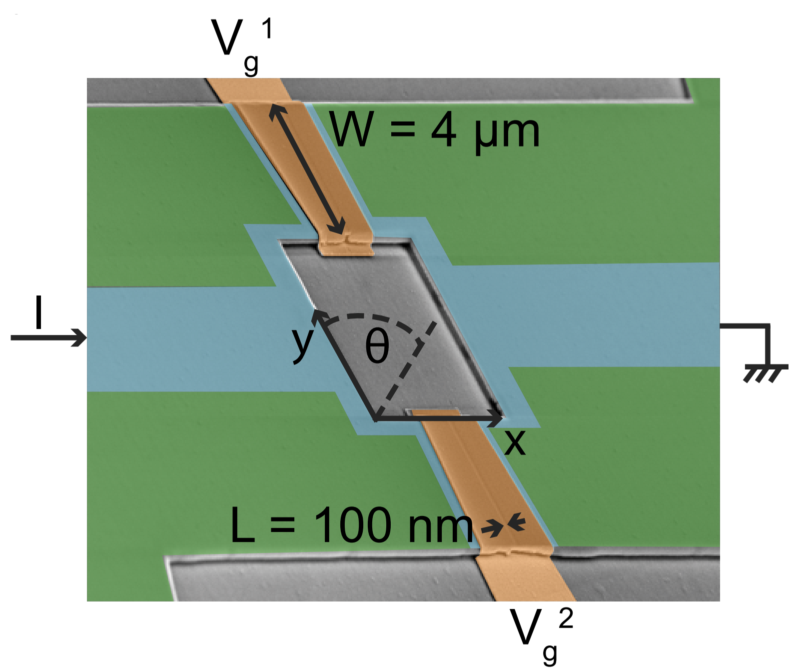
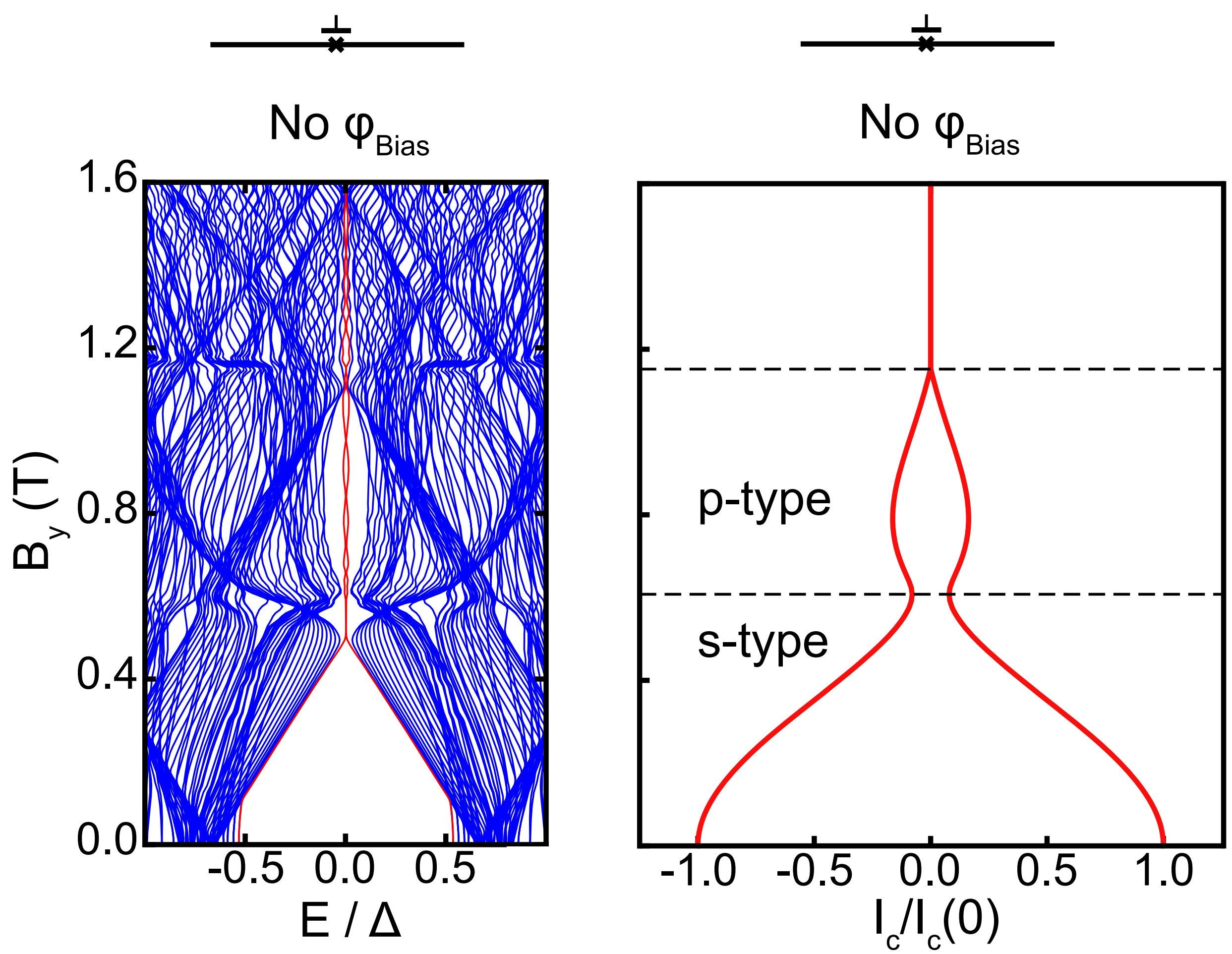
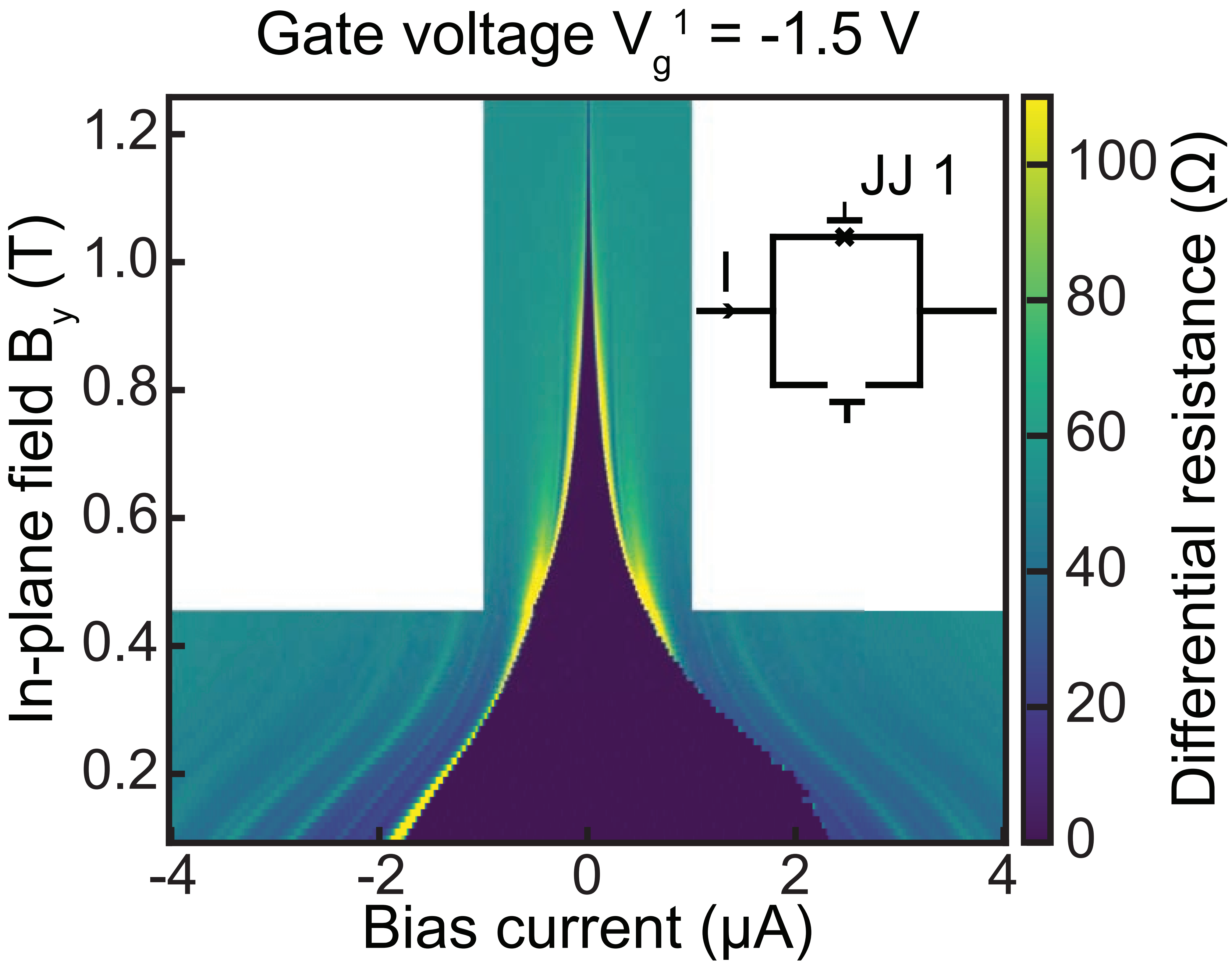




Simulations by Igor Zutic and Alex Matos-Abiague

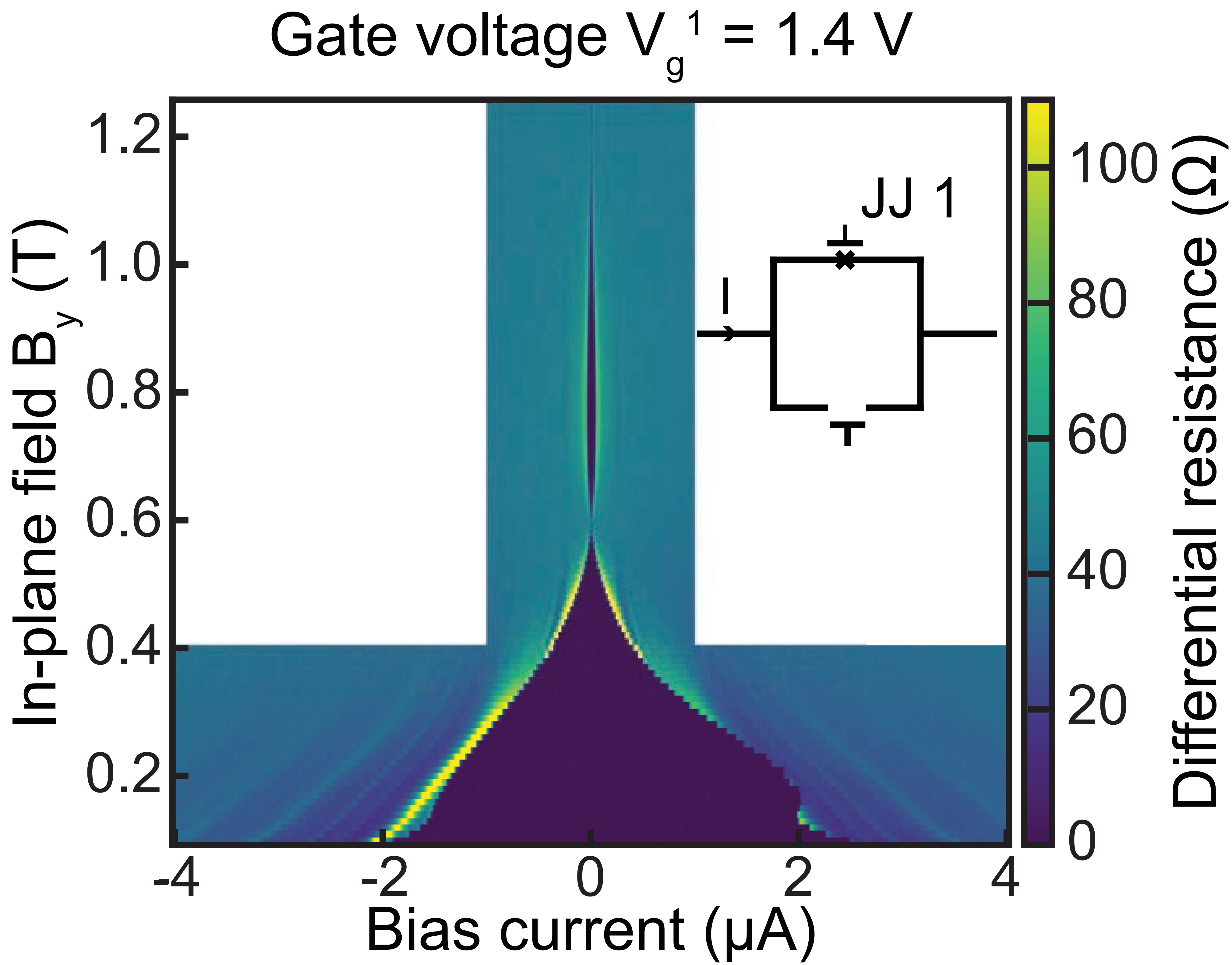
Hell et al., PRL *(2017).*
Pientka et al., PRX *(2017).*
Tkachov, PRB (2019)
Scharf et al., PRB (2019)
Setiawan, et al., PRB (2019)
Ren et al., Nature 2019
Fornieri et al., Nature 2019
Tong et al., PRL (2020)
Pakizer et al., PRR (2021)
Dartiailh et al., PRL (2021)

Experiment: Topological Josephson Junctions



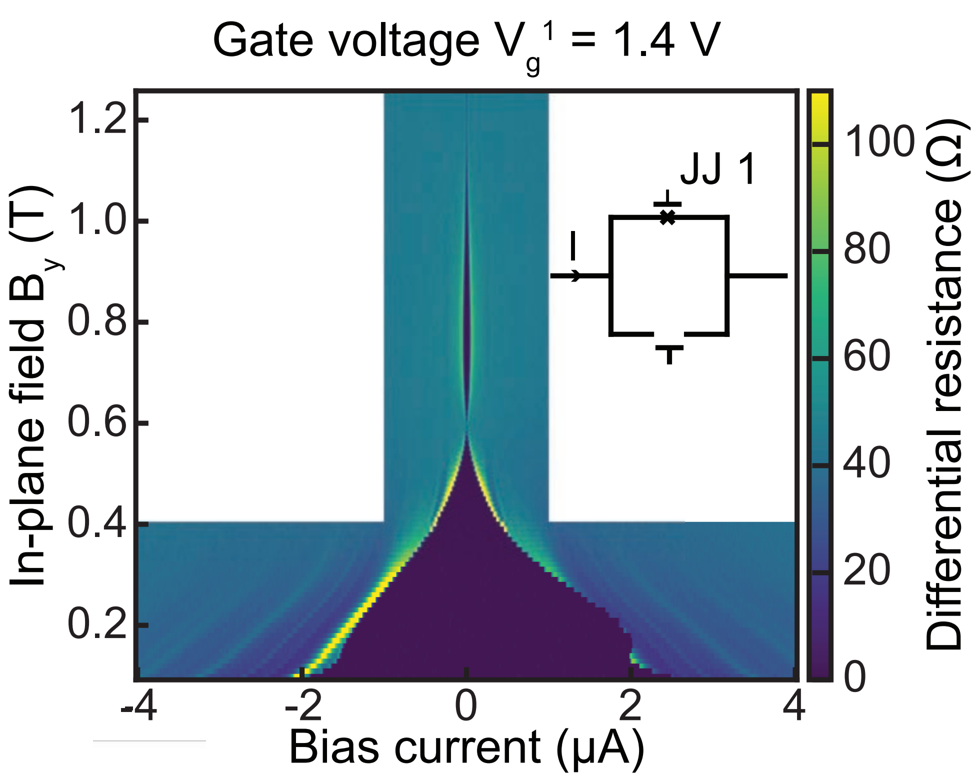
Dartiailh et al., PRL (2021)

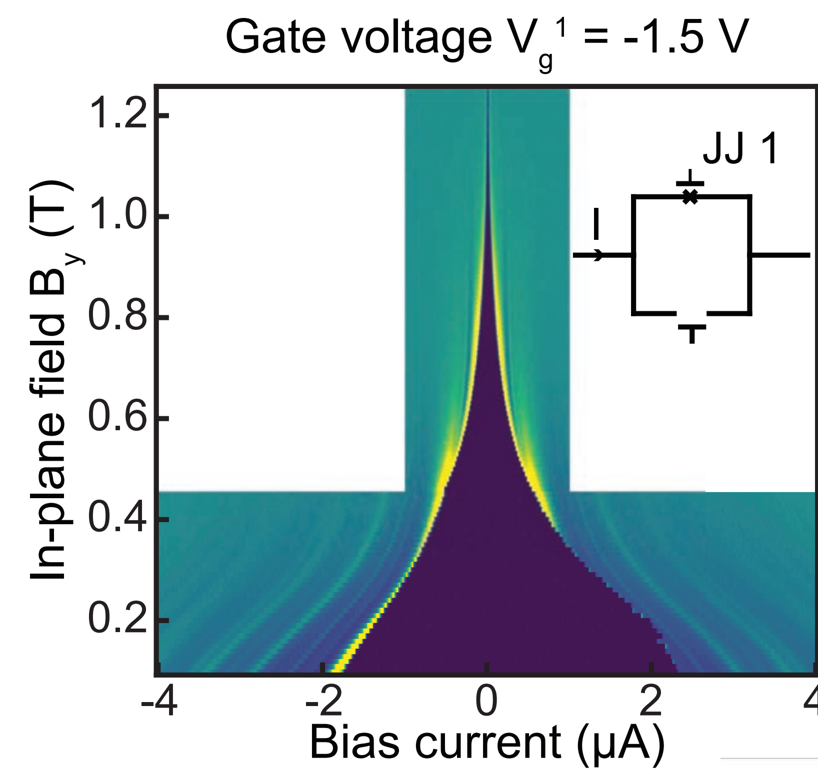
Experiment: Topological Josephson Junctions

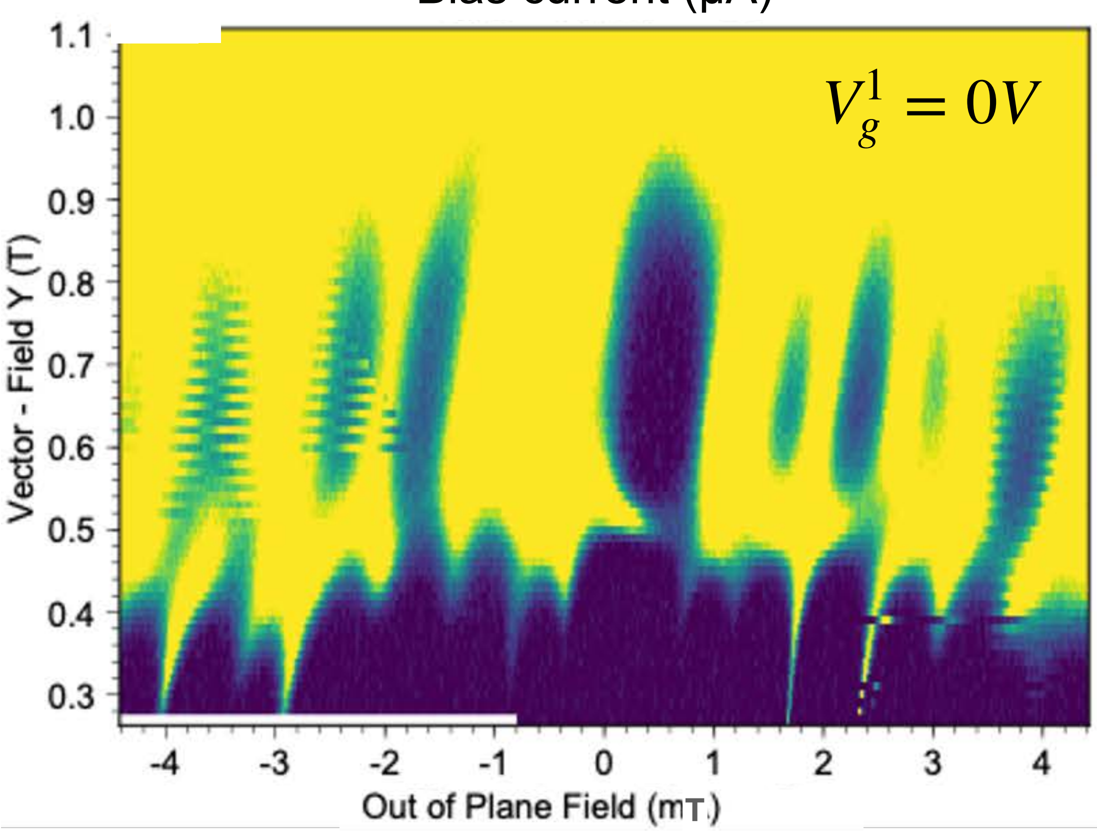


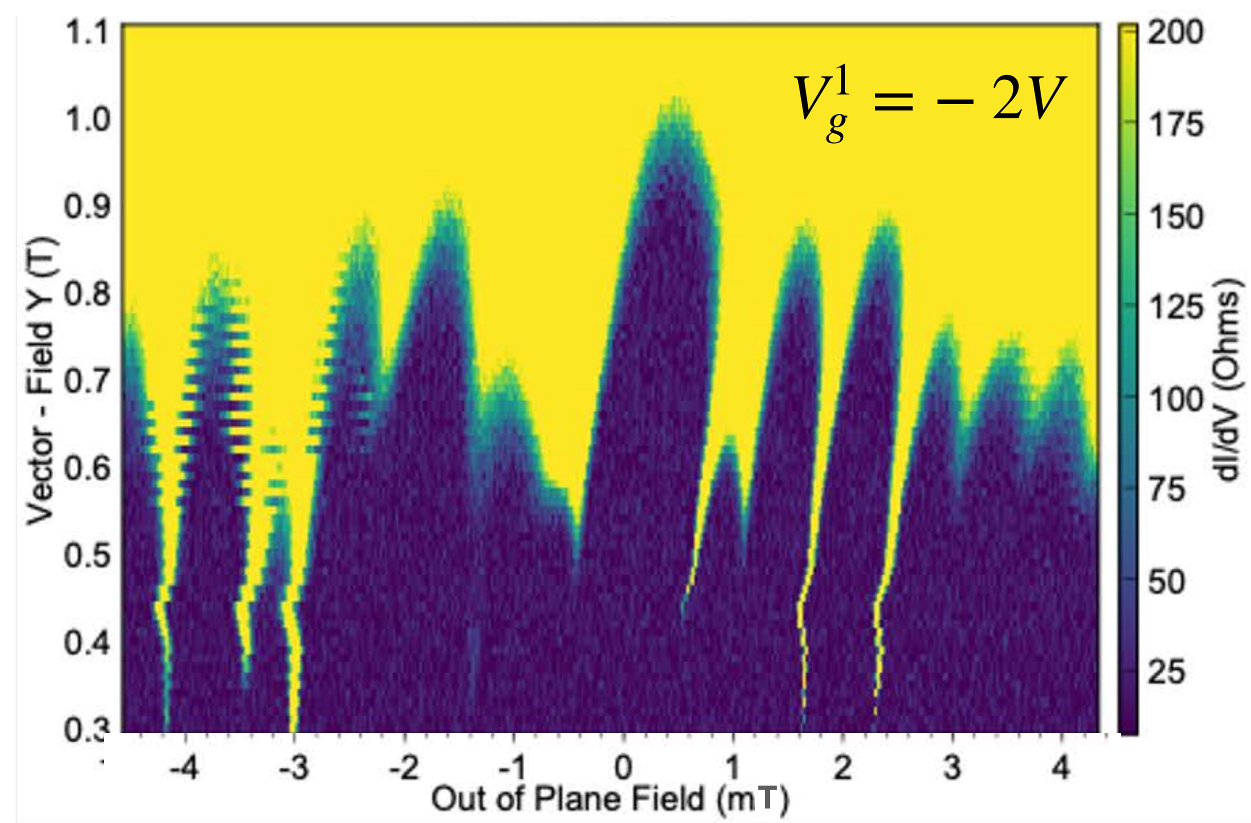
Dartiailh et al., PRL (2021)

Fraunhofer pattern vs in-plane field

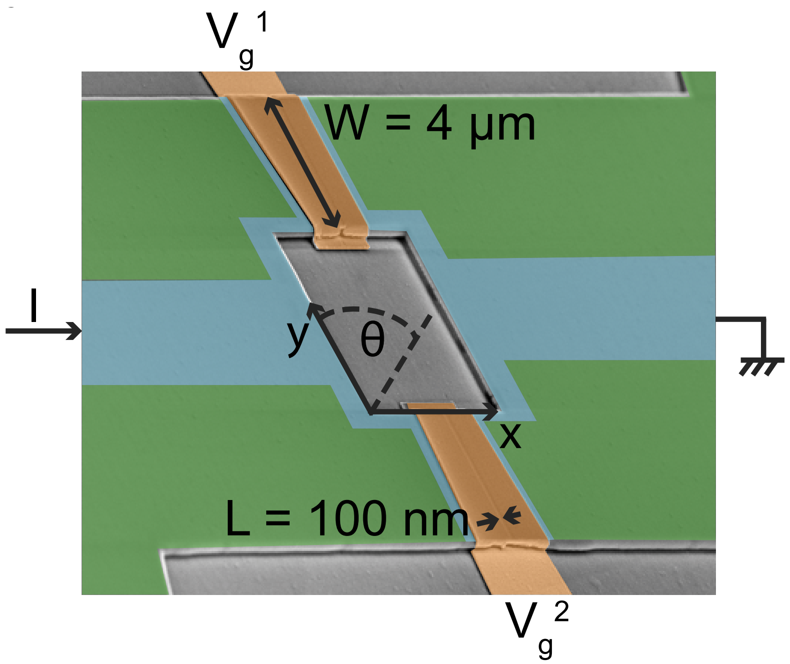




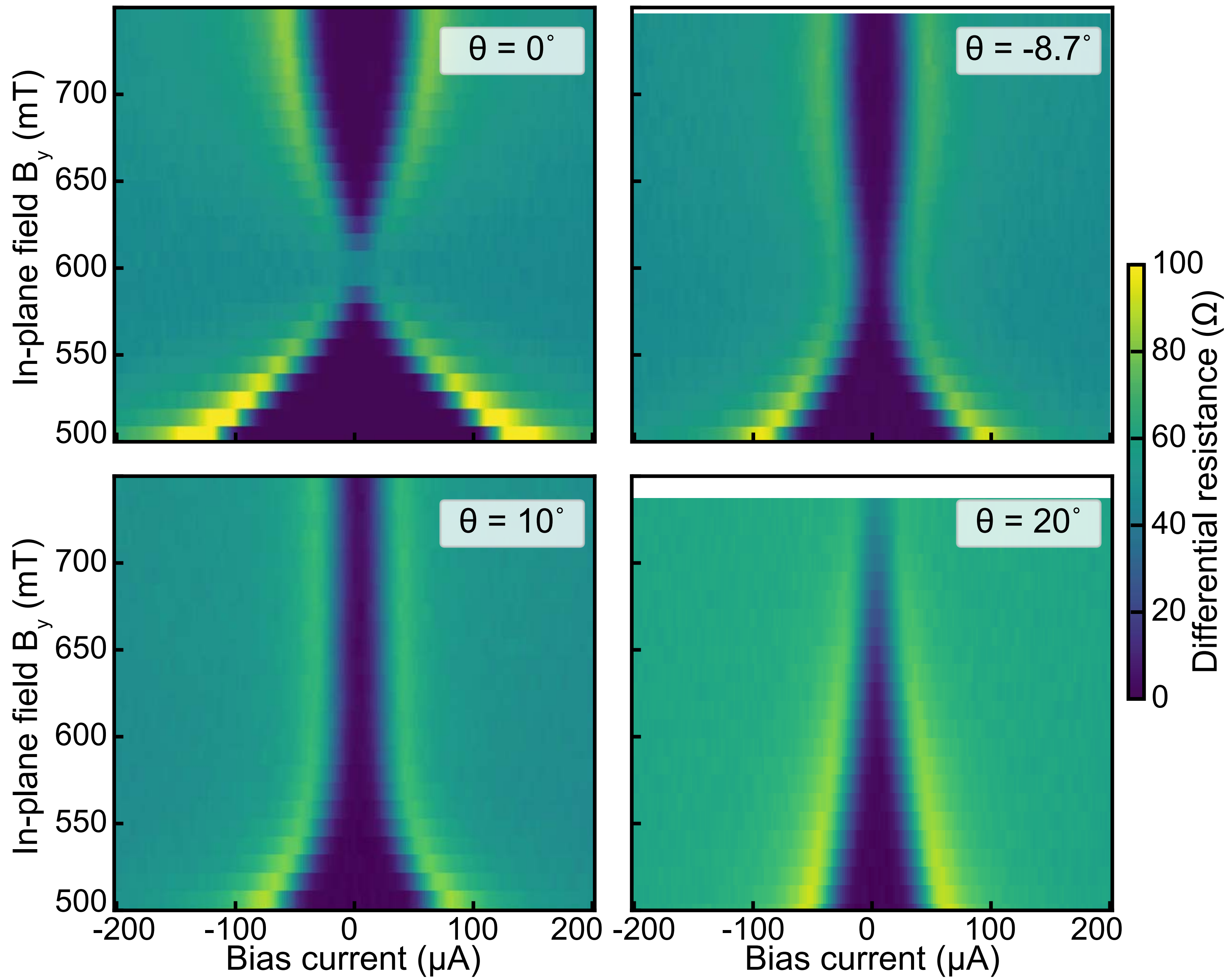




Dependence of magnetic field angle



$$H \approx \frac{\alpha}{\hbar}(p_x \sigma_y)$$

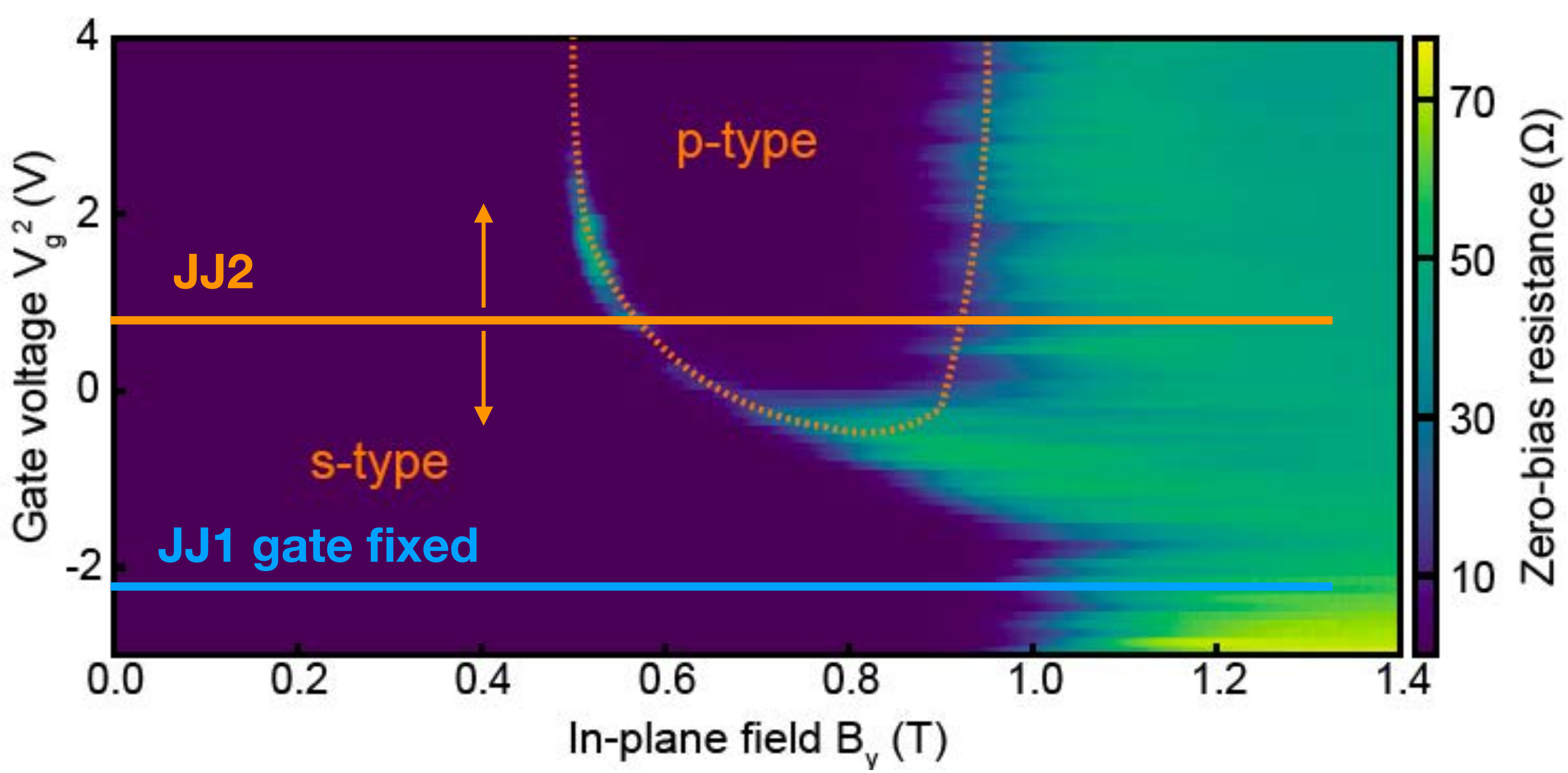


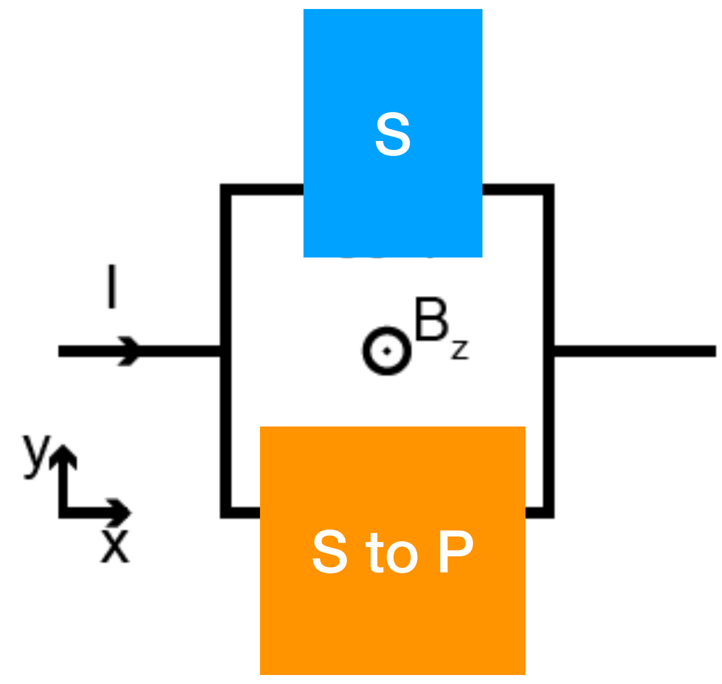
- Supercurrent is in x-direction

- Rashba SOC couples B to momentum *only if* B is oriented in y direction

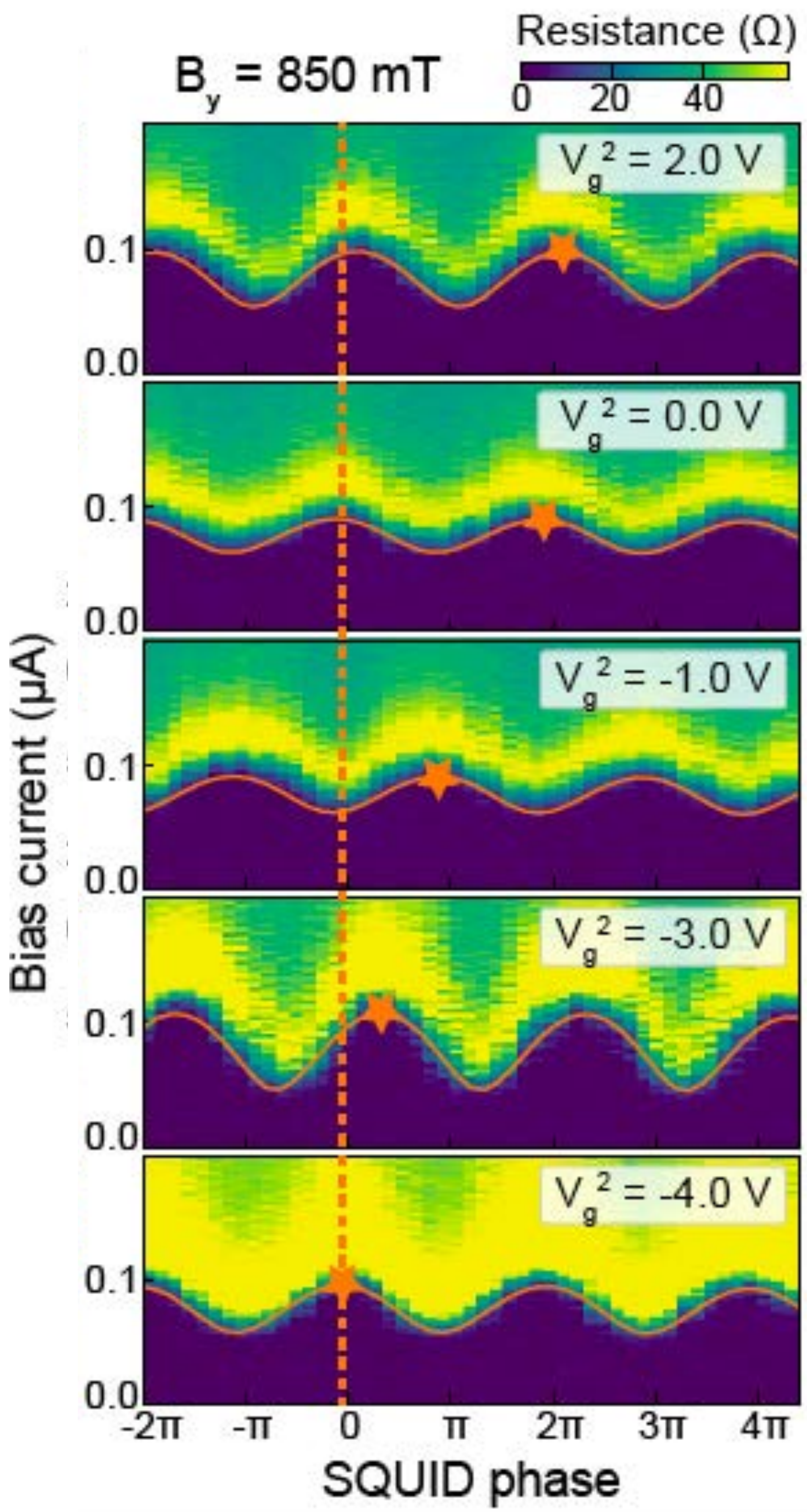
Dartiailh et al., PRL (2021)

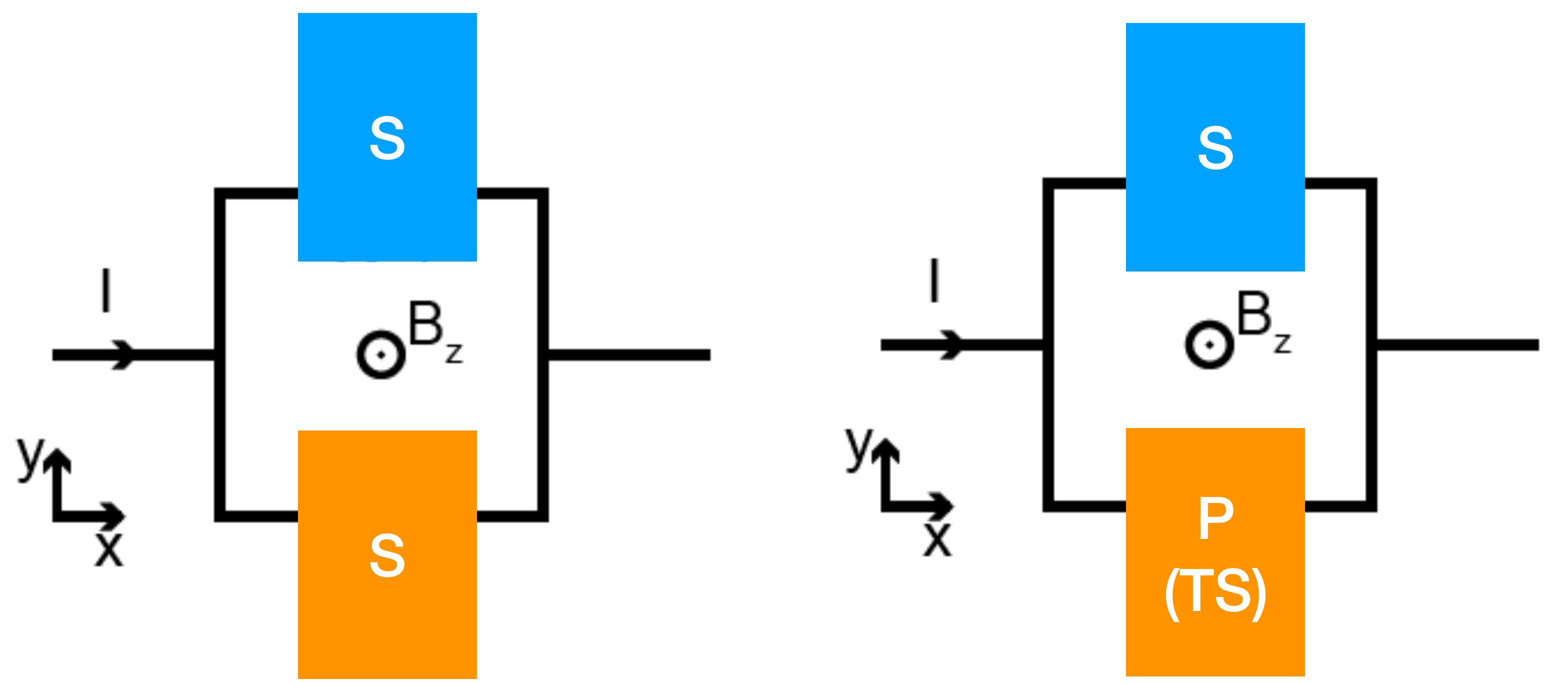
Setting up phase measurement reference

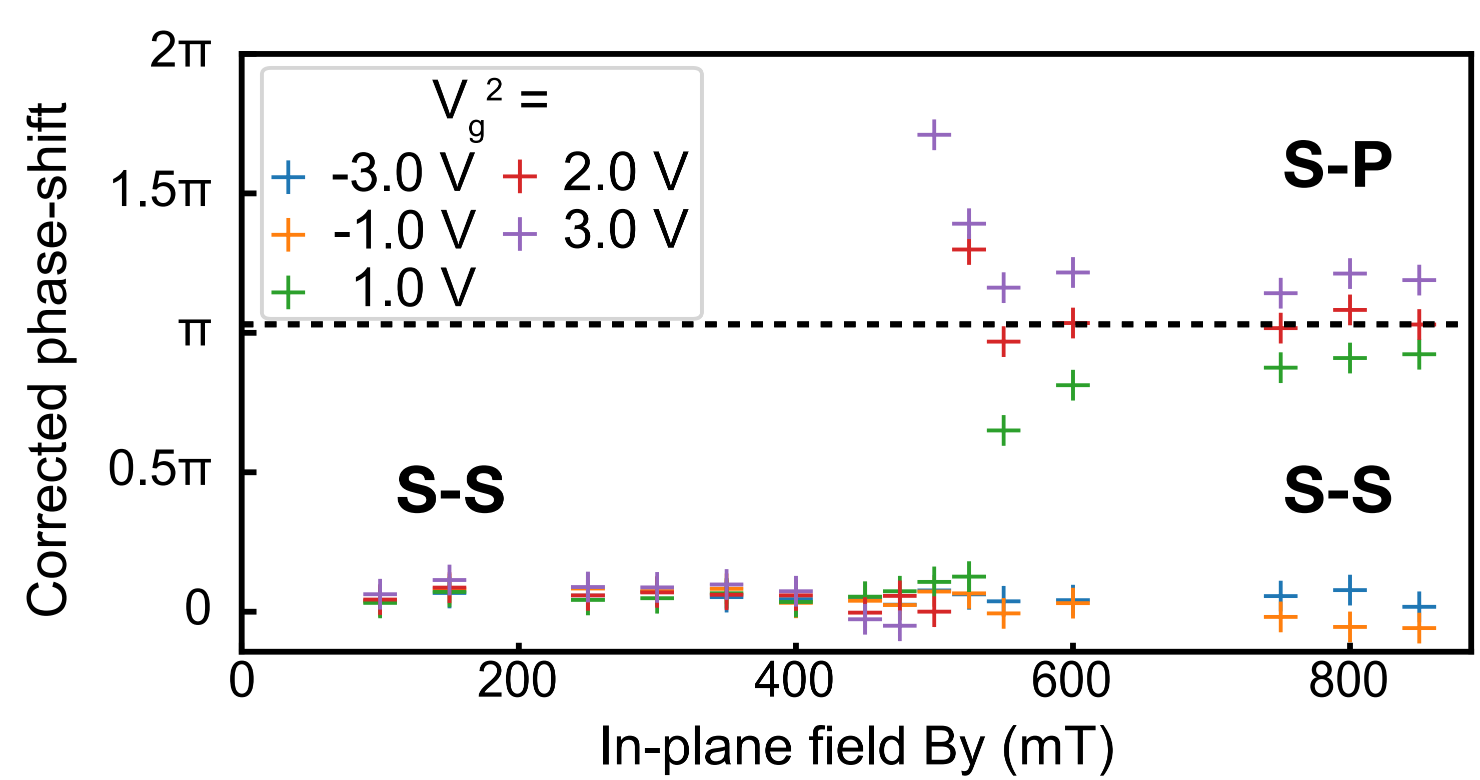




Topological Superconductivity in JJ



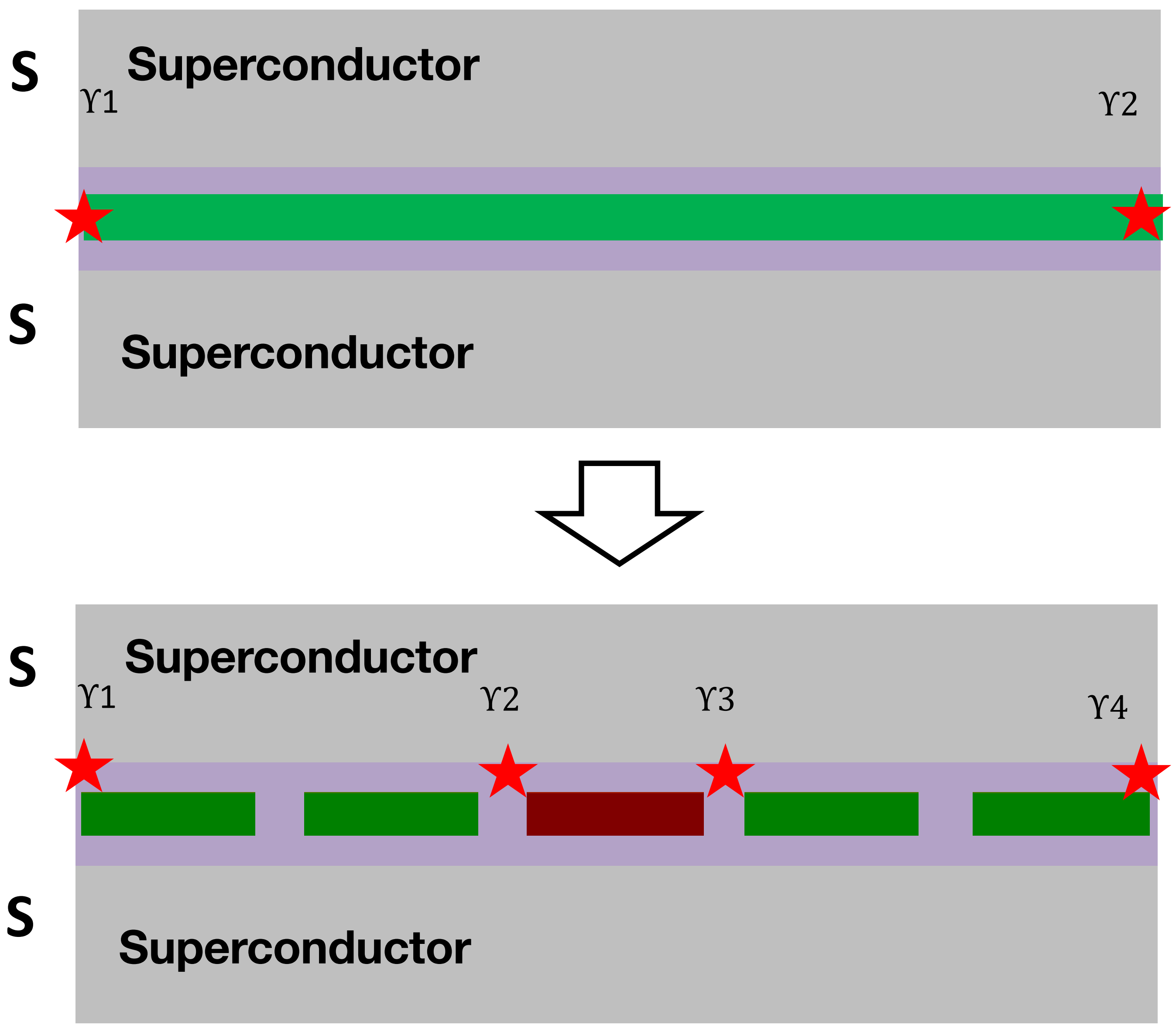


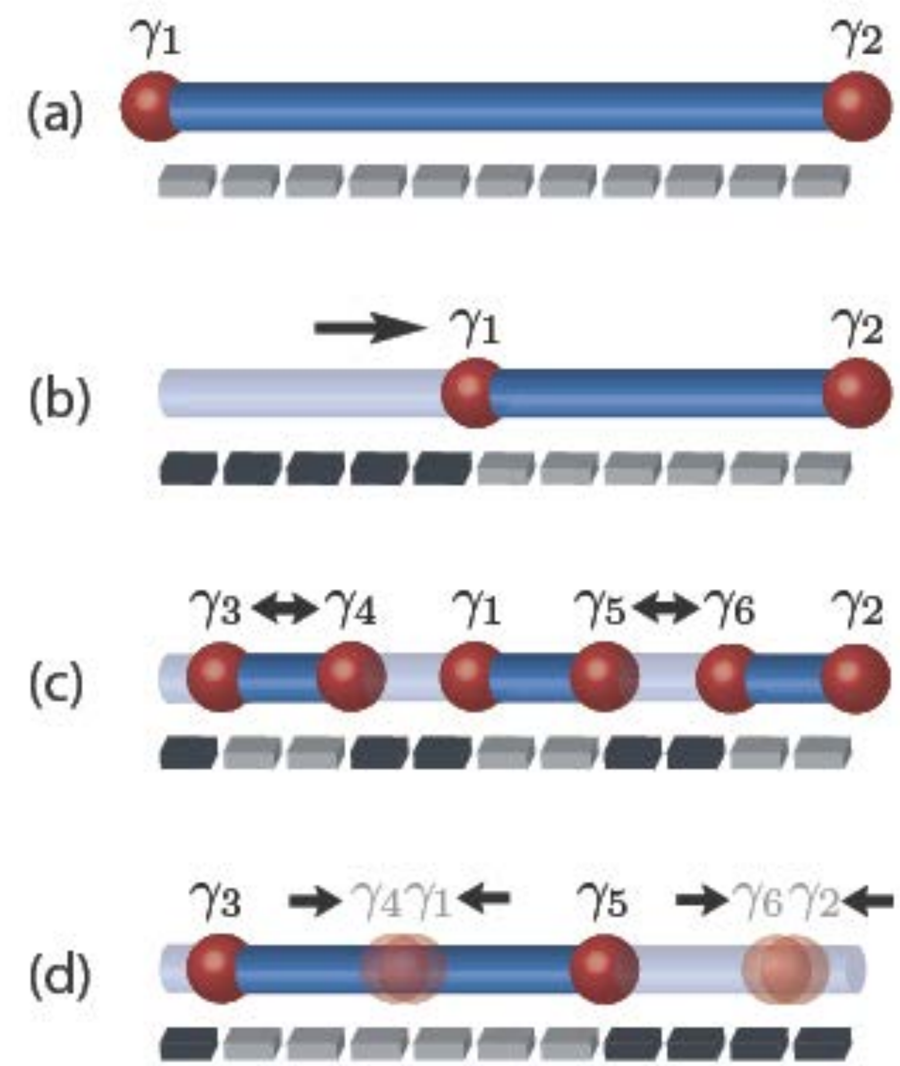


Dartiailh et al., PRL (2021)

Outlook for Fusion Experiments

We showed single-gate JJs can make a phase transition. If this transition is topological then:



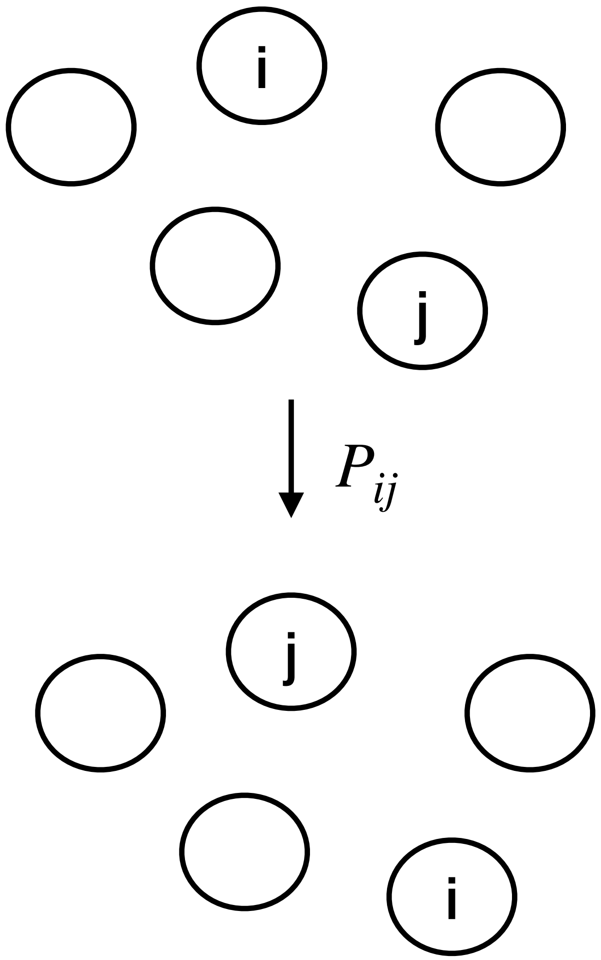


Alicea et al., Nature Physics, 7, 412 (2011)
Bauer et al., SciPost Phys. 5, 004 (2018)

Going back to foundations

$$P_{ij}\Psi(\vec{x}_1 \ldots \vec{x}_i \ldots \vec{x}_j \ldots \vec{x}_N) = e^{i\theta_{ij}}\Psi(\vec{x}_1 \ldots \vec{x}_j \ldots \vec{x}_i \ldots \vec{x}_N)$$

The particles are **identical** since an overall phase is not observable.



But changing back amounts to nothing!

$$P_{ij}^2\Psi(\vec{x}_1 \ldots \vec{x}_i \ldots \vec{x}_j \ldots \vec{x}_N) = \Psi(\vec{x}_1 \ldots \vec{x}_i \ldots \vec{x}_j \ldots \vec{x}_N)$$

$$P_{ij}^2 = 1 \quad \Rightarrow \quad e^{i\theta} = \pm 1$$

So there are only two alternatives:

$$P_{ij} = 1 \quad ; \quad \theta_{ij} = 0$$ Boson

$$P_{ij} = -1 \quad ; \quad \theta_{ij} = \pi$$ Fermion

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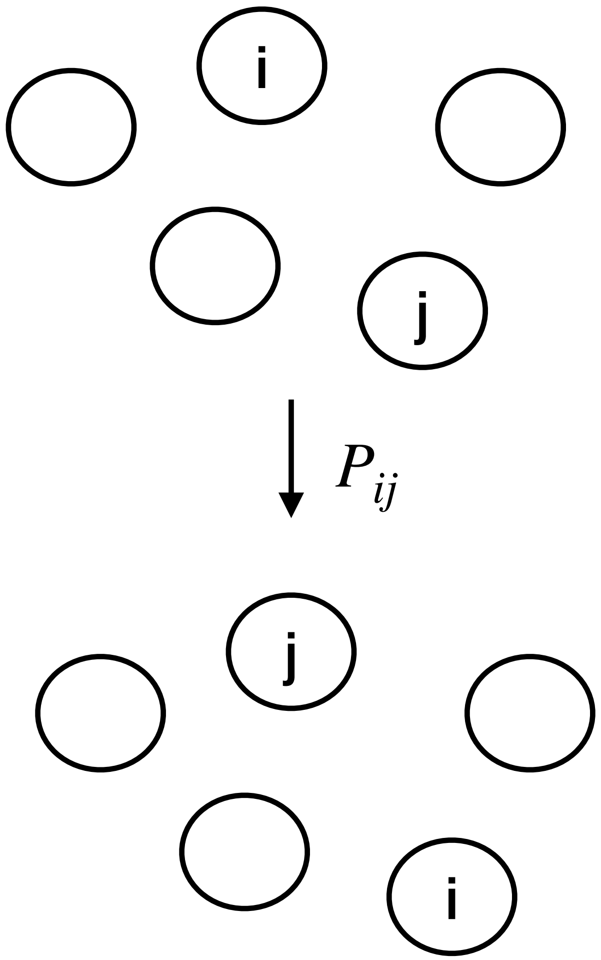

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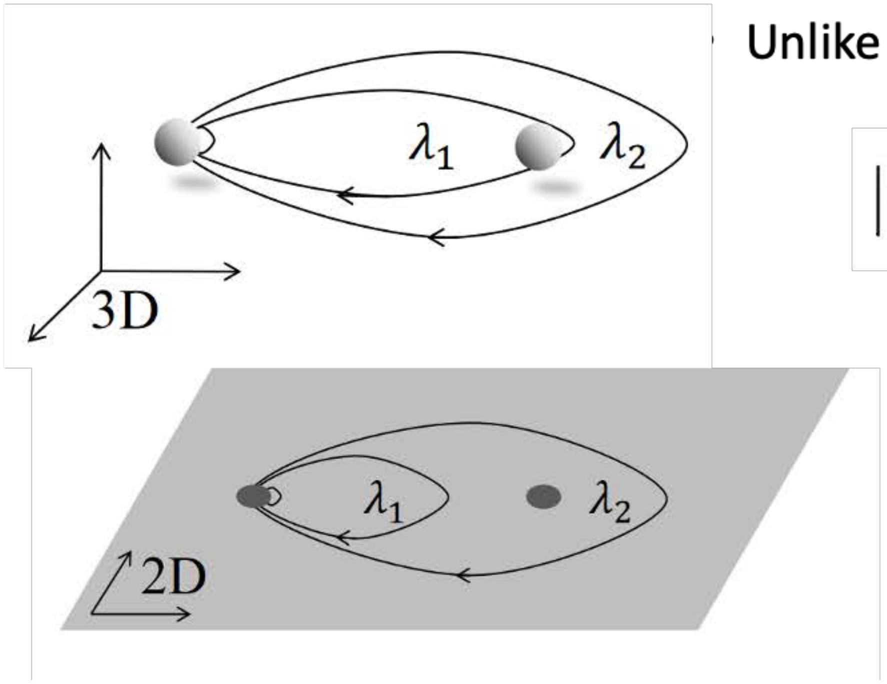
- A quasiparticle emergent in 2-D quantum systems with **topological** nature.
- Unlike **fermions** and **bosons**, under particle exchange they obey statistics as:

$$|\psi_1\psi_2\rangle = e^{i\theta}\,|\psi_2\psi_1\rangle$$

where $e^{i\theta}$ can be **any** value between -1 and +1.

Anyons



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where $e^{i\theta}$ can be **any** value between -1 and +1.

- For **non-Abelian** anyons,

  $e^{i\theta}$ → rotation matrix U(θ)

  → can be used to create universal gates

Example:

The Fibonacci model contains **two particle types**: the vacuum with charge 0 and denoted by **0**, and the non-trivial anyon with charge 1 and denoted by τ. Explicitly, the fusion rules are:

$$\tau \otimes \tau = \mathbf{0} \oplus \tau \qquad \mathbf{0} \otimes \mathbf{0} = \mathbf{0} \qquad \tau \otimes \mathbf{0} = \tau \qquad \mathbf{0} \otimes \tau = \tau$$

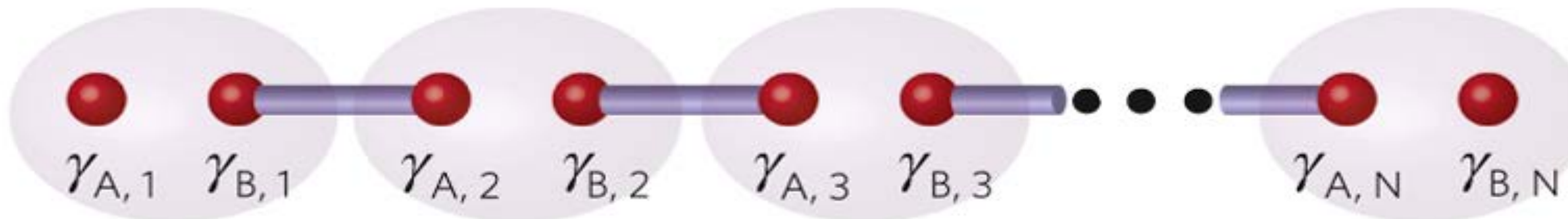
where $\otimes$ denotes the fusion (merging) of two particles and denotes $\oplus$ multiple possible outcomes.

Kitaev - Majorana fermions

- Majorana fermion (1940s): fermion that is its own antiparticle (maybe Neutrino?)

$$\gamma^{\dagger} = \gamma$$

Alexei Kitaev, 2000, 2001

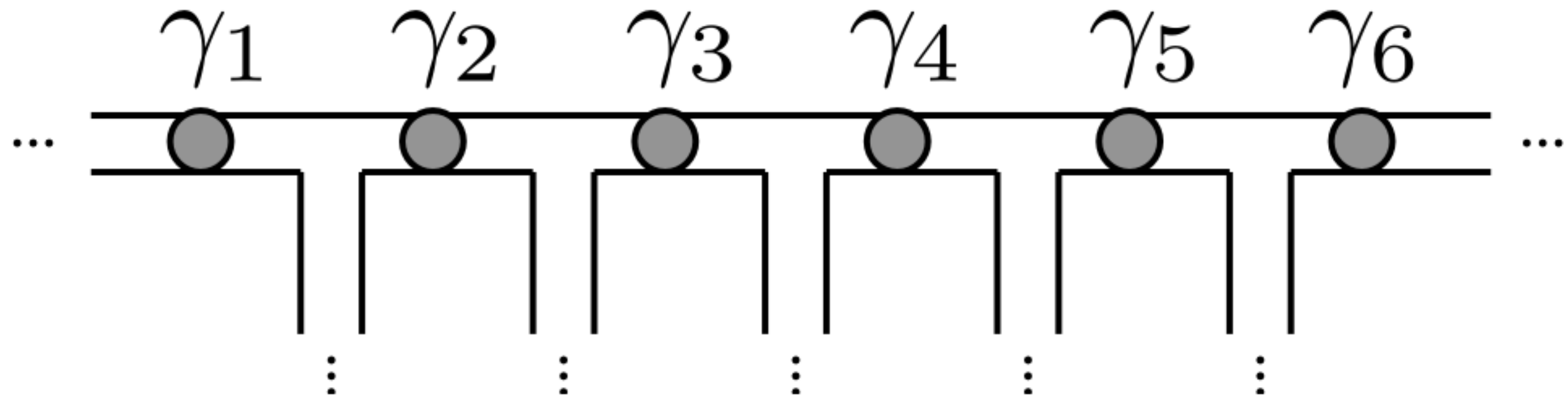


1D toy model

$$H_K = \sum_i \left(-\epsilon c_i^{\dagger} c_i - \frac{J}{2}(c_{i+1} - c_{i+1}^{\dagger})(c_i + c_i^{\dagger}) \right) = \sum_i \left(-\epsilon c_i^{\dagger} c_i - \frac{J}{2}(c_{i+1}^{\dagger} c_i + c_i^{\dagger} c_i) + \frac{\Delta}{2}(c_{i+1} c_i + c_i^{\dagger} c_{i+1}^{\dagger}) \right)$$

Kitaev predicted that a 1D chain under appropriate conditions can host delocalized Majorana modes

Majorana fermion chain



2N

(N pairs)

- The only thing that distinguishes the Majorana zero modes is their position in the network.
- They have no other “flavour” that would allow us to characterize them. They are identical to each other, just like all electrons are identical to each other.
- If we exchanged two Majoranas in space, the system after the exchange would look exactly the same as it looked before the exchange.

$$\gamma_i^\dagger = \gamma_i$$

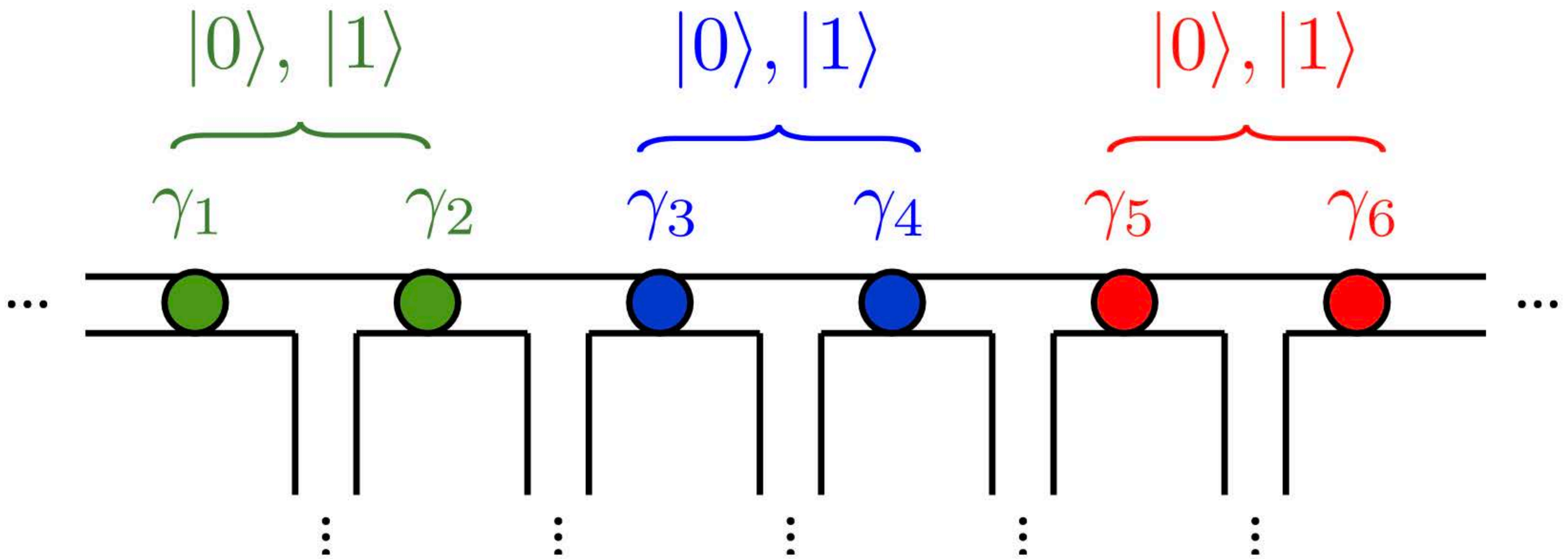
= Degenerate zero energy-state manifold

By construction, we can pair the Majoranas and form fermionic modes

$$c_n^\dagger = \frac{1}{2}(\gamma_{2n-1} + i\gamma_{2n}),$$
$$c_n = \frac{1}{2}(\gamma_{2n-1} - i\gamma_{2n}), \qquad n=1,\ldots,N$$

We have now a set of N fermionic modes with corresponding creation and annihilation operators. Every mode can be empty or it can be occupied by a fermion, giving us two possible degenerate quantum state:

$|0\rangle$ $|1\rangle$ for each pair of Majoranas



- 8 possible states, corresponding to all the possible combinations of the occupation numbers of the 3 fermionic modes

2^N possible quantum states for N pairs of Majoranas

$|s_1\rangle$ if the fermionic mode is not occupied = 0 If occupied = 1

$$|s_1, s_2, \ldots, s_N\rangle$$

- These states are a *complete basis* for the Hilbert space of the set of Majorana modes
- These basis states are all eigenstates of the operators

$$P_n = 1 - 2c_n^\dagger c_n = i\gamma_{2n-1}\gamma_{2n}$$

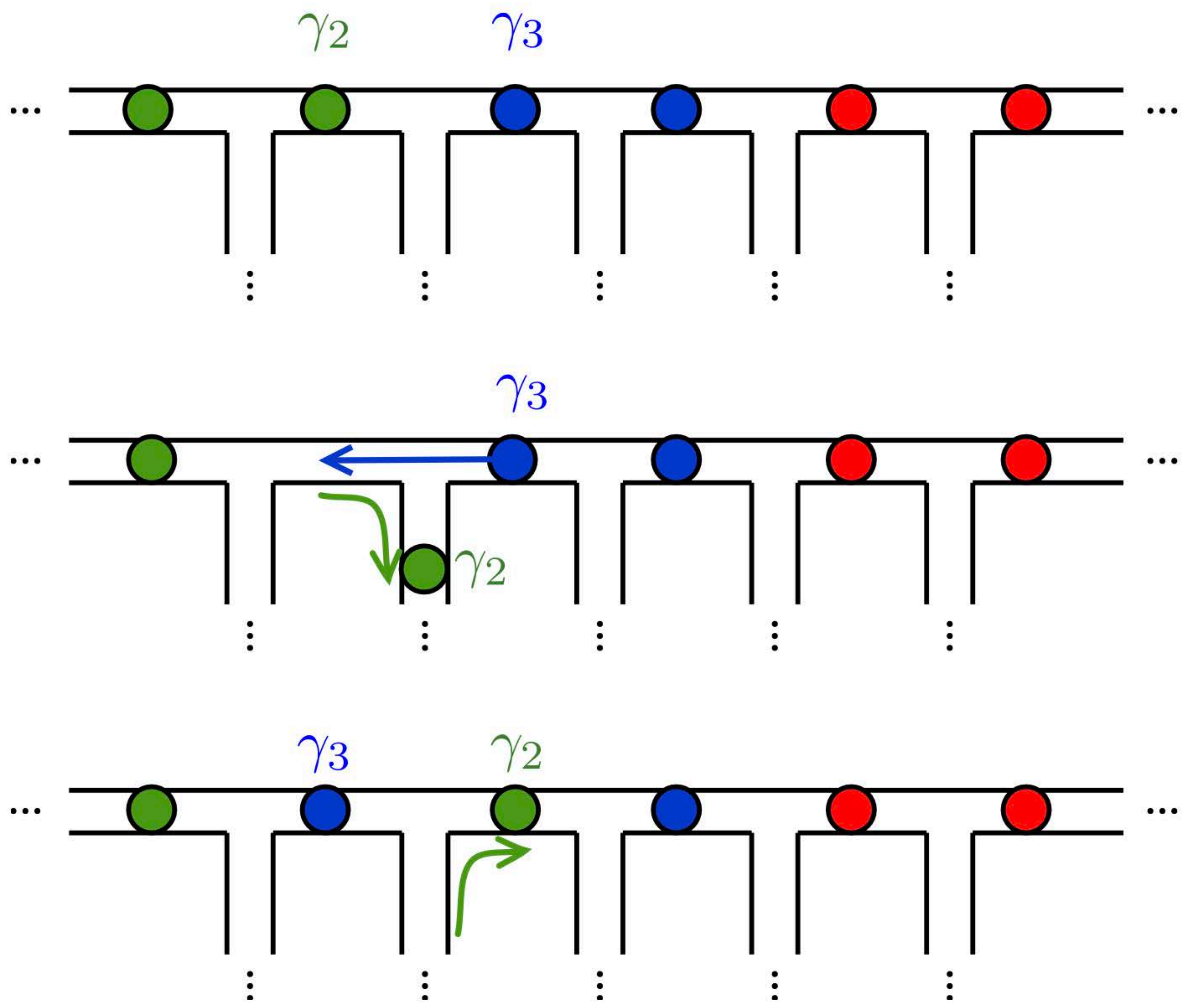
Fermion parity operator

for the pair of Majoranas 2n-1 and 2n

$$|\Psi\rangle = \sum_{s_n=0,1} \alpha_{s_1 s_2 \ldots s_N} |s_1, s_2, \ldots, s_N\rangle$$

Non-Abelian Majorana Zero Modes

We, experimentalist, are not only like to build such a network, but also to move the position of the domain walls and swap the positions of two Majoranas, for instance by performing the following trajectory:



Non-Abelian Majorana Zero Modes

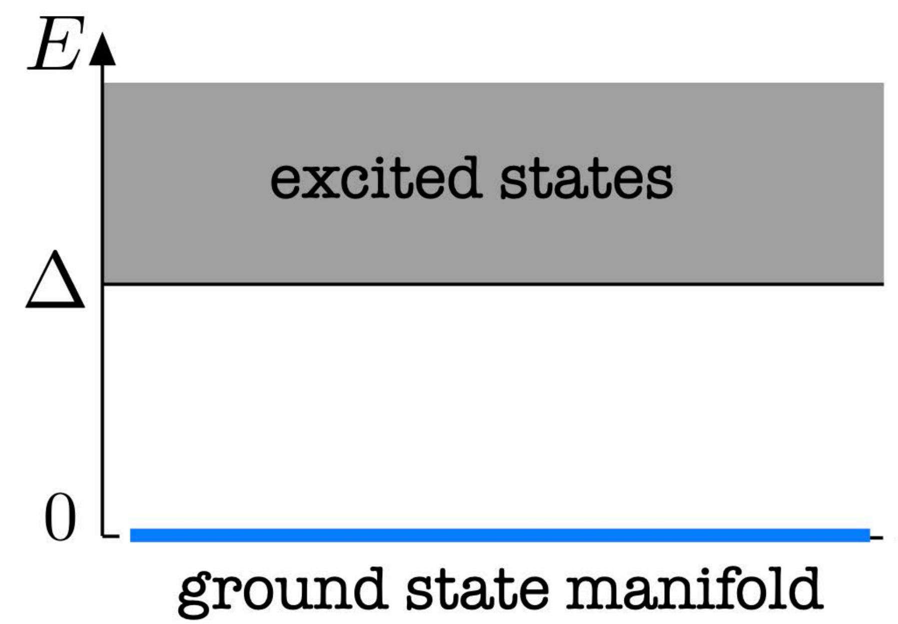
Adiabatic: During moving we never leave the ground state manifold with 2^N states

$$|\Psi\rangle \rightarrow U|\Psi\rangle$$

$2^N \times 2^N$ unitary matrix

- The adiabatic exchange of two Majoranas does not change the parity of the number of electrons in the system

$$[U, P_{\text{tot}}] = 0$$



U: the exponential of i times a Hermitian operator is a unitary operator

$$U \equiv \exp(\beta\gamma_n\gamma_m) = \cos(\beta) + \gamma_n\gamma_m \sin(\beta)$$

$$\beta = \pm\pi/4$$

$$U = \exp\left(\pm\frac{\pi}{4}\gamma_n\gamma_m\right) = \frac{1}{\sqrt{2}}(1 \pm \gamma_n\gamma_m)$$

Consider **four Majoranas:**

$$|00\rangle, |11\rangle, |01\rangle, |10\rangle$$

$$c_1^\dagger = \frac{1}{2}(\gamma_1 + i\gamma_2)$$

First digit is the occupation number of the fermionic mode

$$c_2^\dagger = \frac{1}{2}(\gamma_3 + i\gamma_4)$$

Second digit is the occupation number of the fermionic mode

$$U_{12} = \exp\left(\frac{\pi}{4}\gamma_1\gamma_2\right) \equiv \begin{pmatrix} e^{-i\pi/4} & 0 & 0 & 0 \\ 0 & e^{i\pi/4} & 0 & 0 \\ 0 & 0 & e^{-i\pi/4} & 0 \\ 0 & 0 & 0 & e^{i\pi/4} \end{pmatrix},$$

$$U_{23} = \exp\left(\frac{\pi}{4}\gamma_2\gamma_3\right) \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -i & 0 & 0 \\ -i & 1 & 0 & 0 \\ 0 & 0 & 1 & -i \\ 0 & 0 & -i & 1 \end{pmatrix}$$

Non-Abelian Majorana Zero Modes

- These matrices indeed act in a very non-trivial way on the wave function:

Initial state $|00\rangle$

If we exchange Majoranas 2 and 3

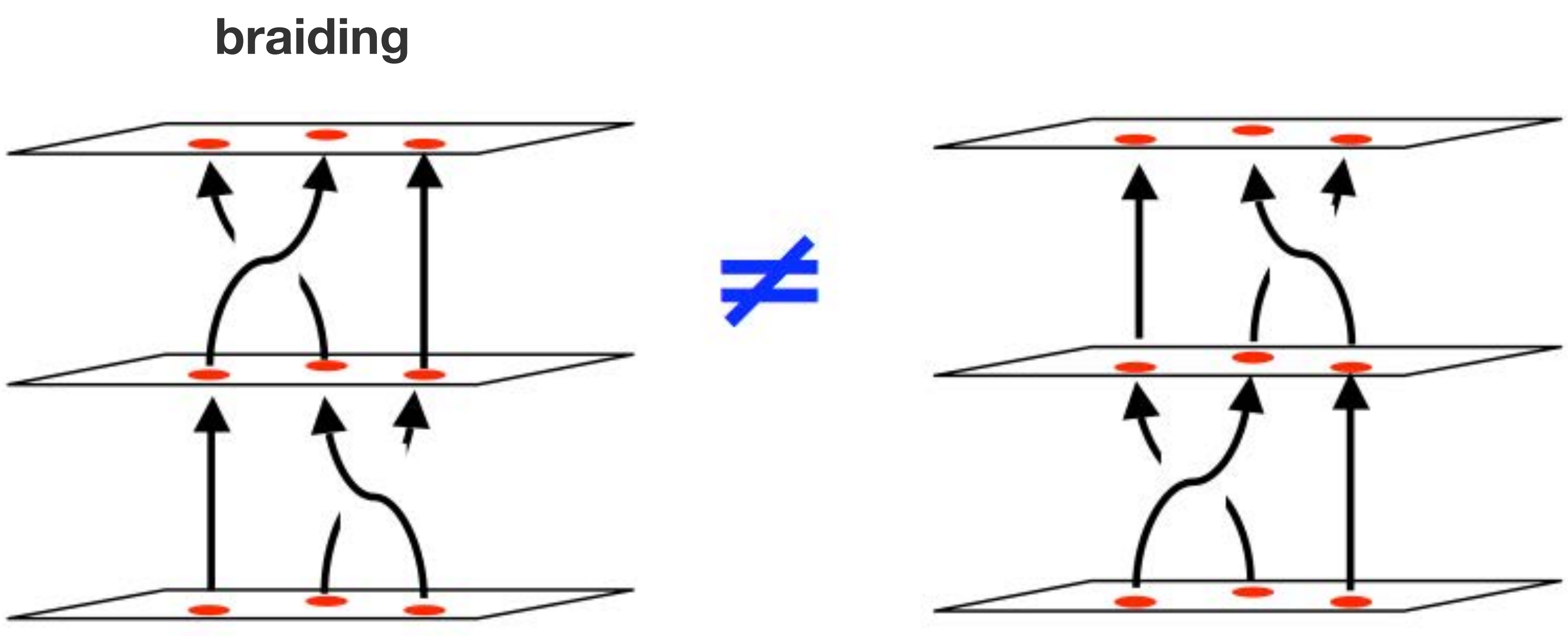
$$|00\rangle \rightarrow U_{23}\,|00\rangle = \frac{1}{\sqrt{2}}(|00\rangle - i\,|11\rangle)$$

which is a superposition of states!

Exchange two Majoranas on the wavefunction amounts to much more than just an overall phase, as it happens for bosons and fermions.

- Let's try sequence of two exchanges which basically means multiplying the corresponding U:

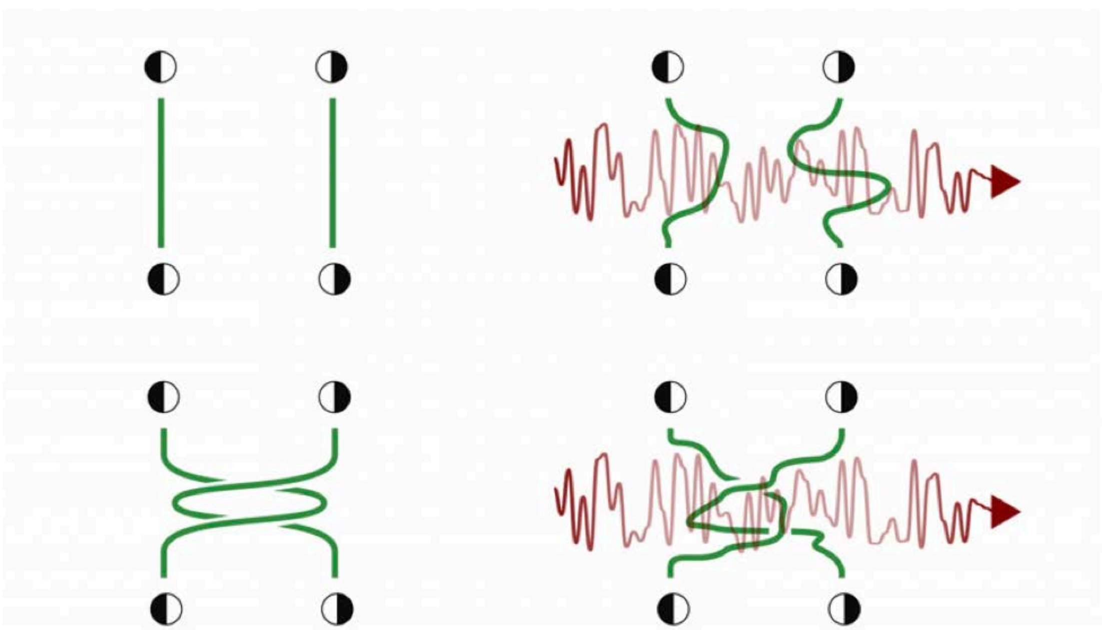
$$U_{23}U_{12} \neq U_{12}U_{23}$$

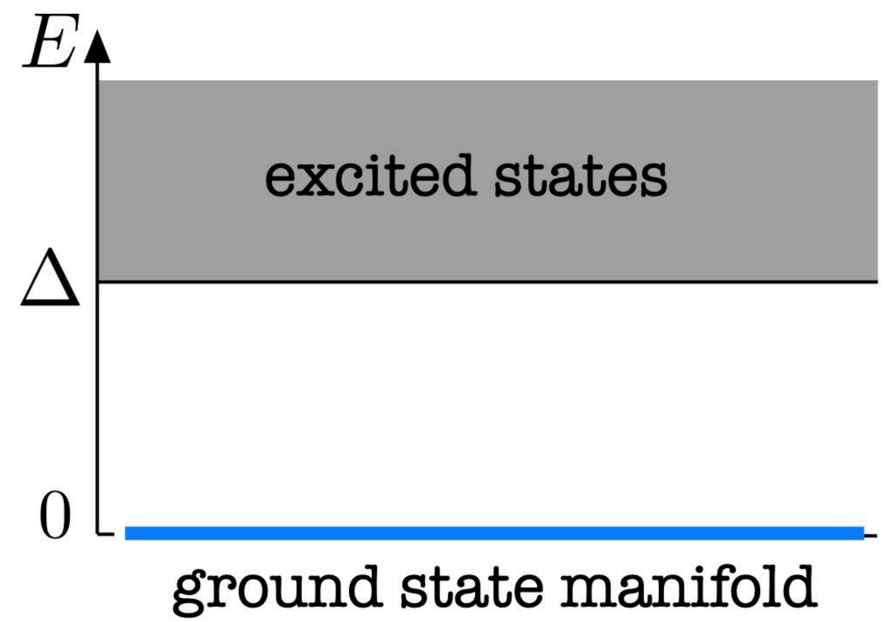


2d (space) + 1 (time)

System as a whole is a quantum memory

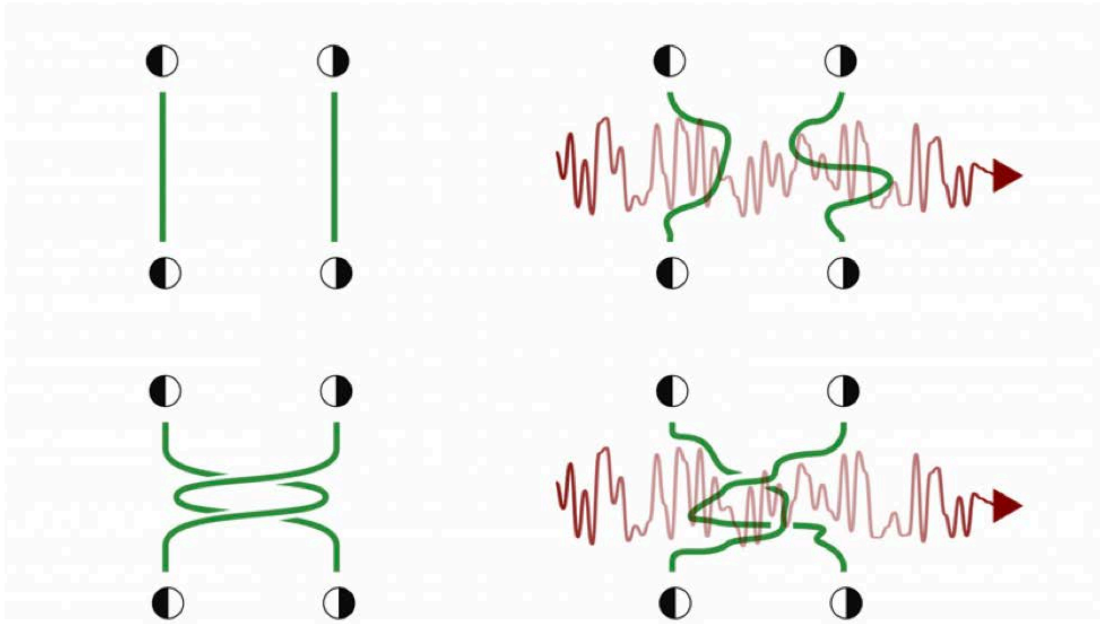
- You could say this is another way to obtain a given unitary operator acting on the wave function. In principle both the state of the register and the algorithms are ***topologically protected***.





- **The state of the register is encoded in the fermion parity degrees of freedom, which are shared *non-locally* by the Majoranas.** This means that no local perturbation can change the state of the register and cause *decoherence* of the quantum state.
- The environment cannot access the information stored in the Majoranas, as long as they are kept far away from each other. The only exception is a change in fermion parity.

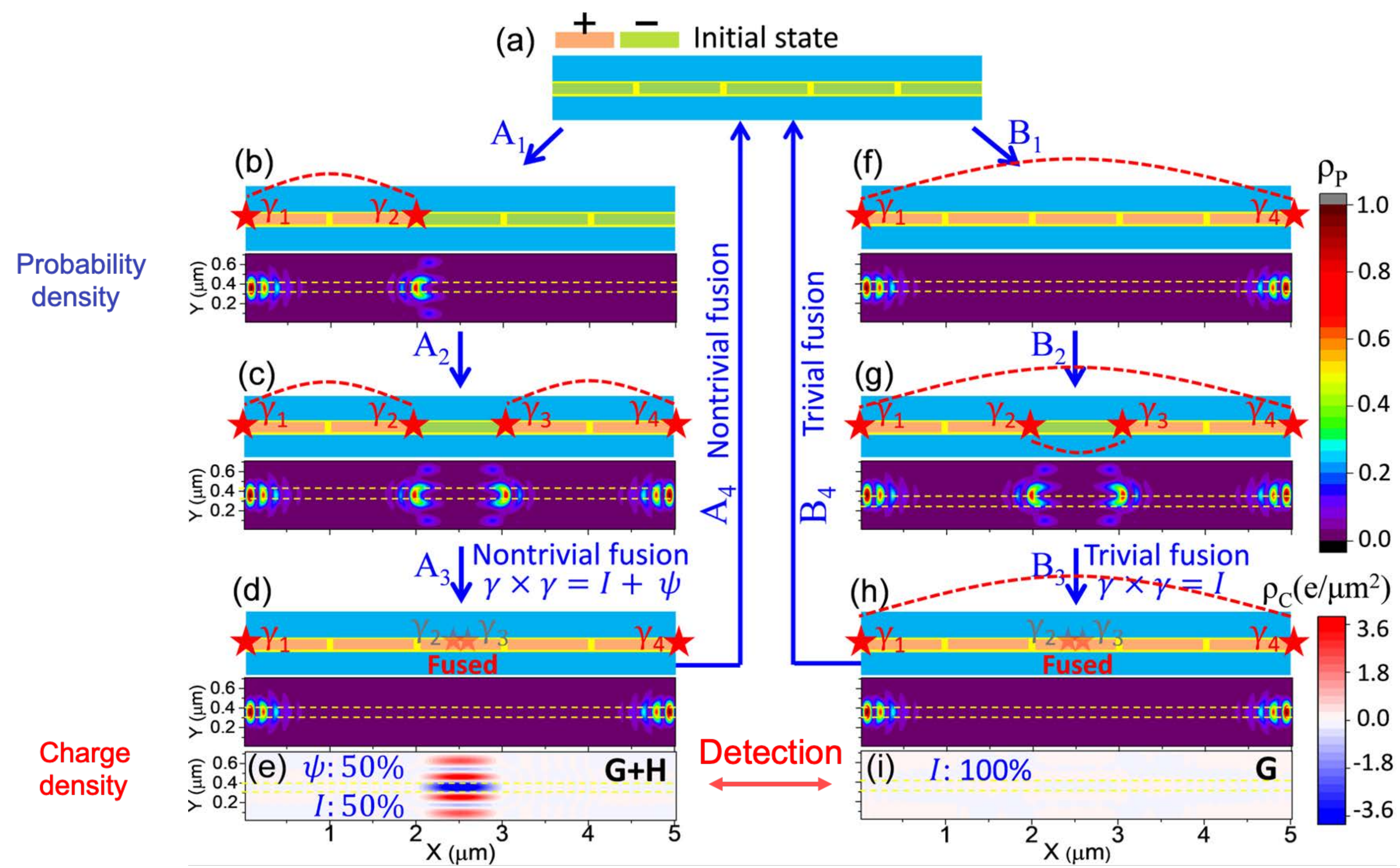
How about “Measurement”?



One way is to measure exchange properties like fusion:

- need configuration, fast but adiabatic

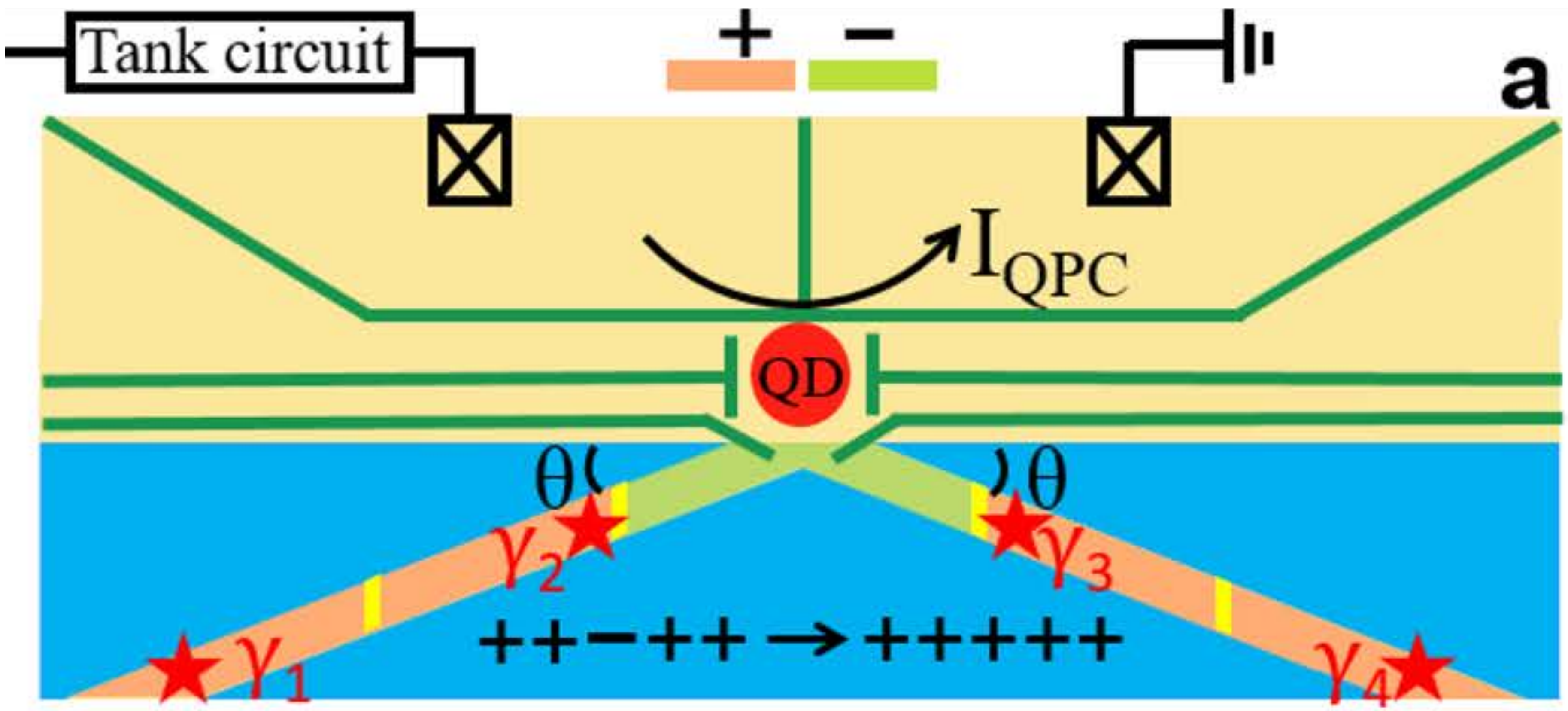
Topological: Fusion experiment from theory perspective

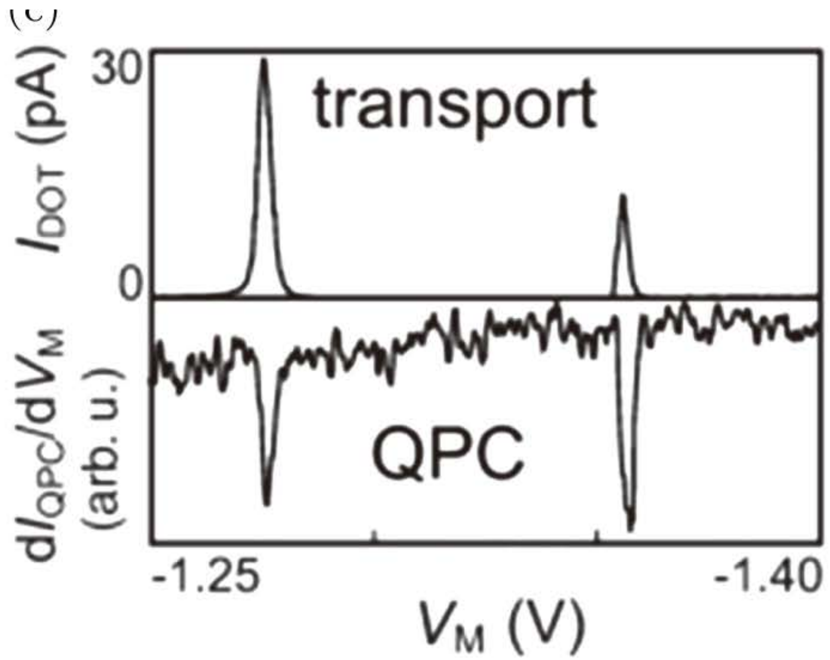


Measurement is equivalent to sending "charge"

T. Zhou, M. C. Dartiailh, K. Sardashti, J. E. Han, A. Matos-Abiague, J. Shabani, I. Zutic, arXiv:2101.09272

Charge sensing measurement

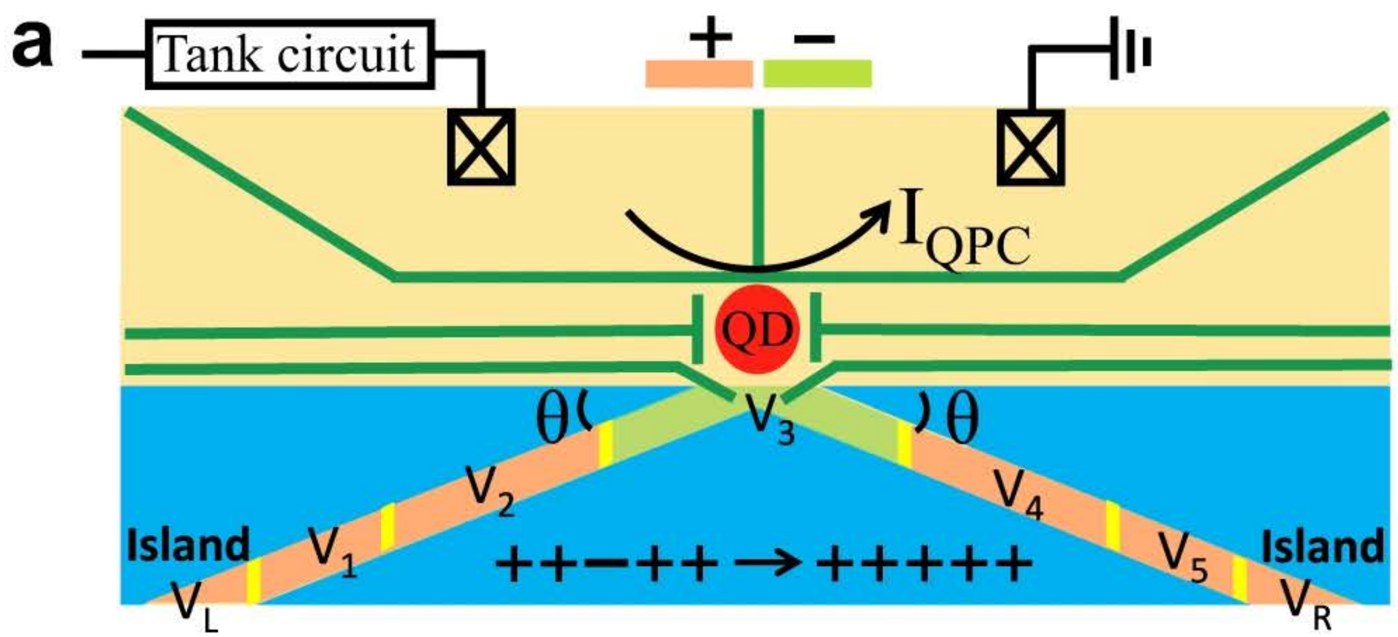


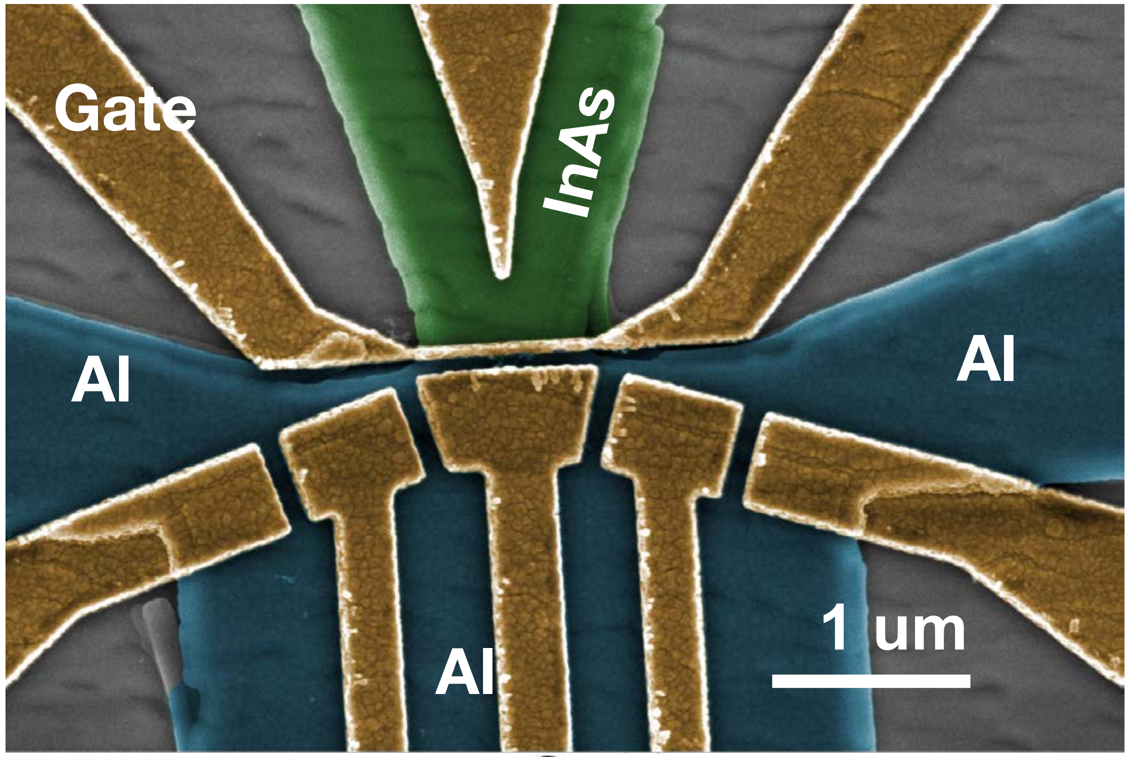


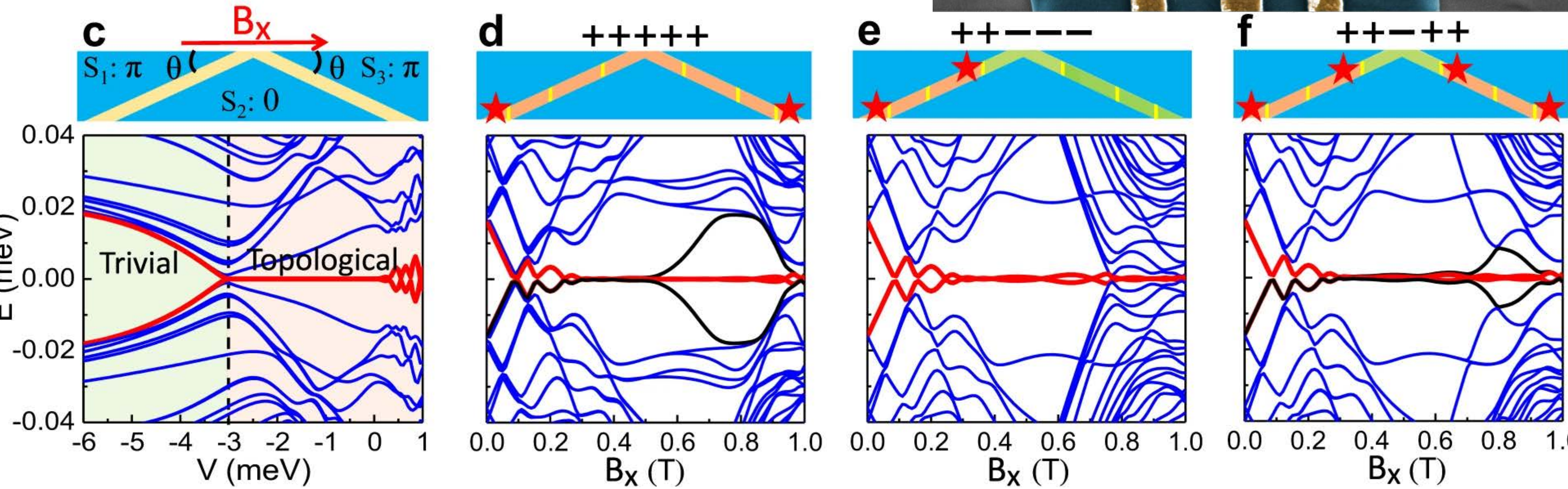
$$\gamma \times \gamma = I + \psi$$ Non- Trivial fusion rule

$$\gamma \times \gamma = I$$ Trivial fusion rule

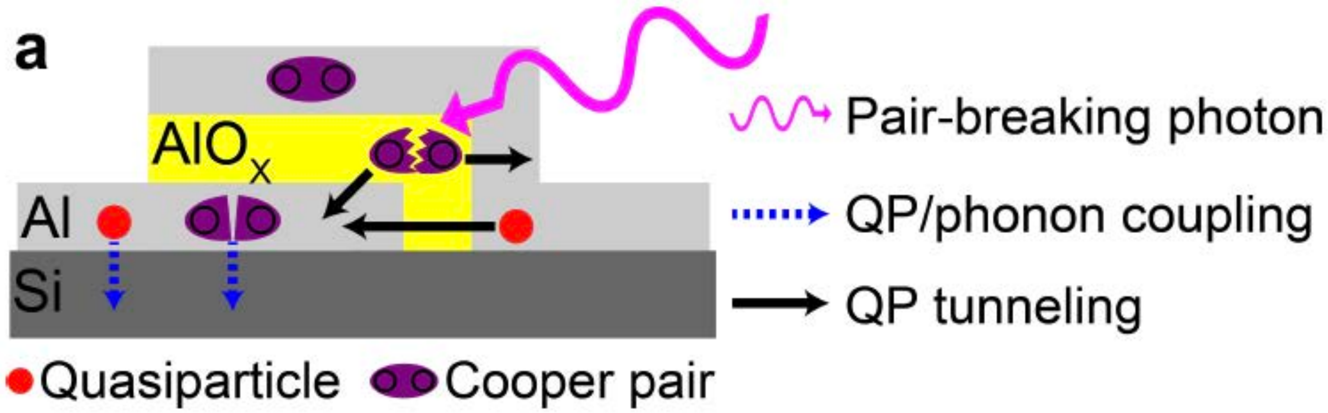
One possible experimental approach: mini gate

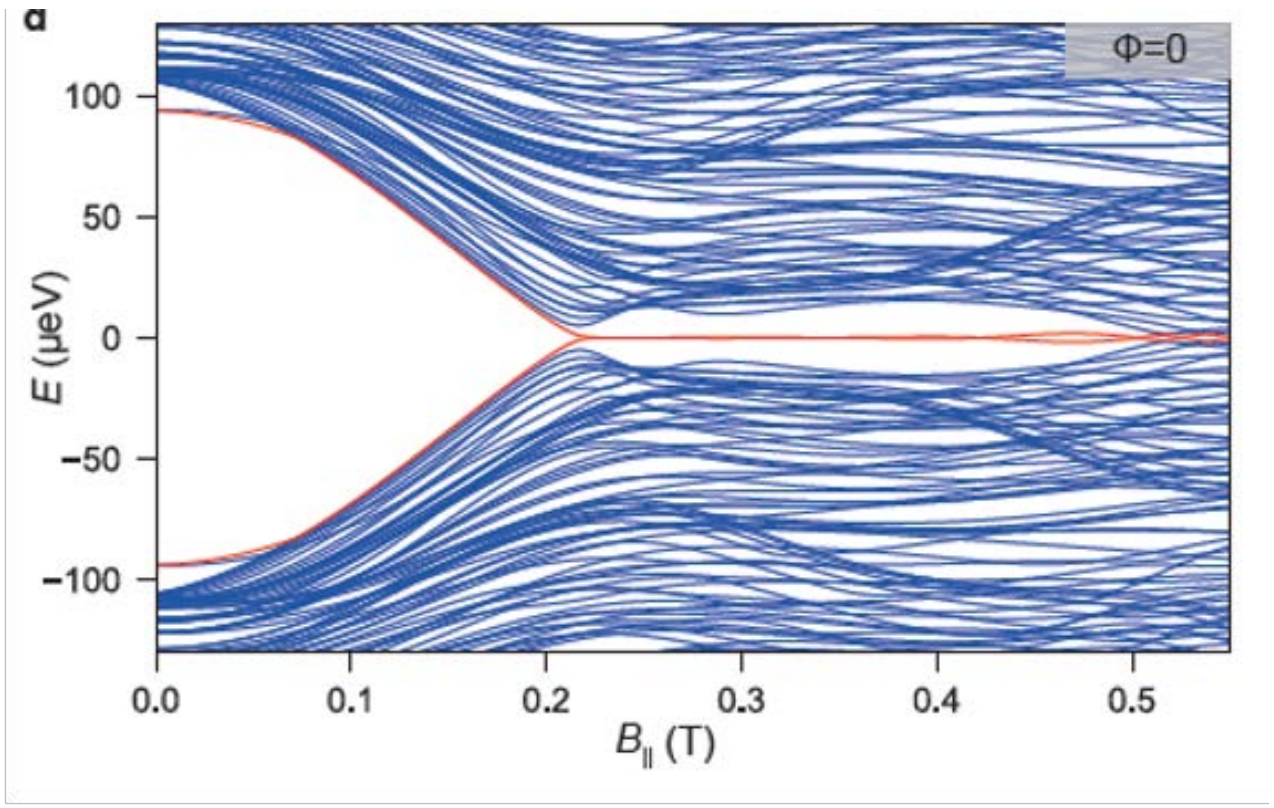






Quasi Particle Poisoning (unpublished)





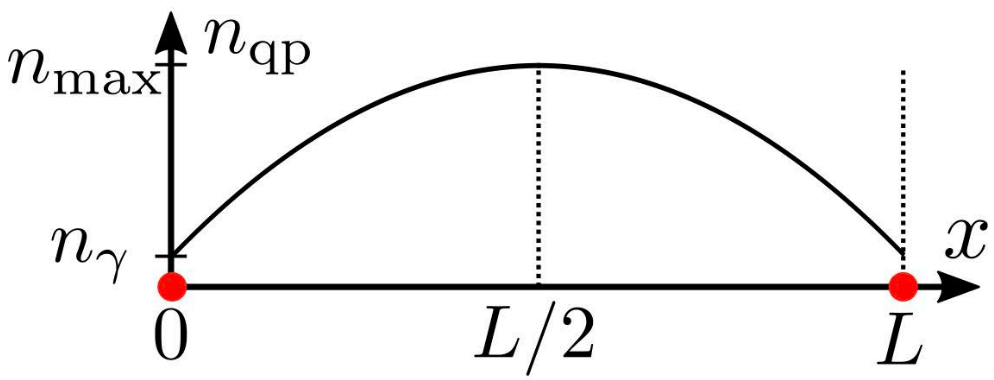
Quasi Particle Poisoning

↓

Parity change

↓

Upper time scale of Majorana qubits



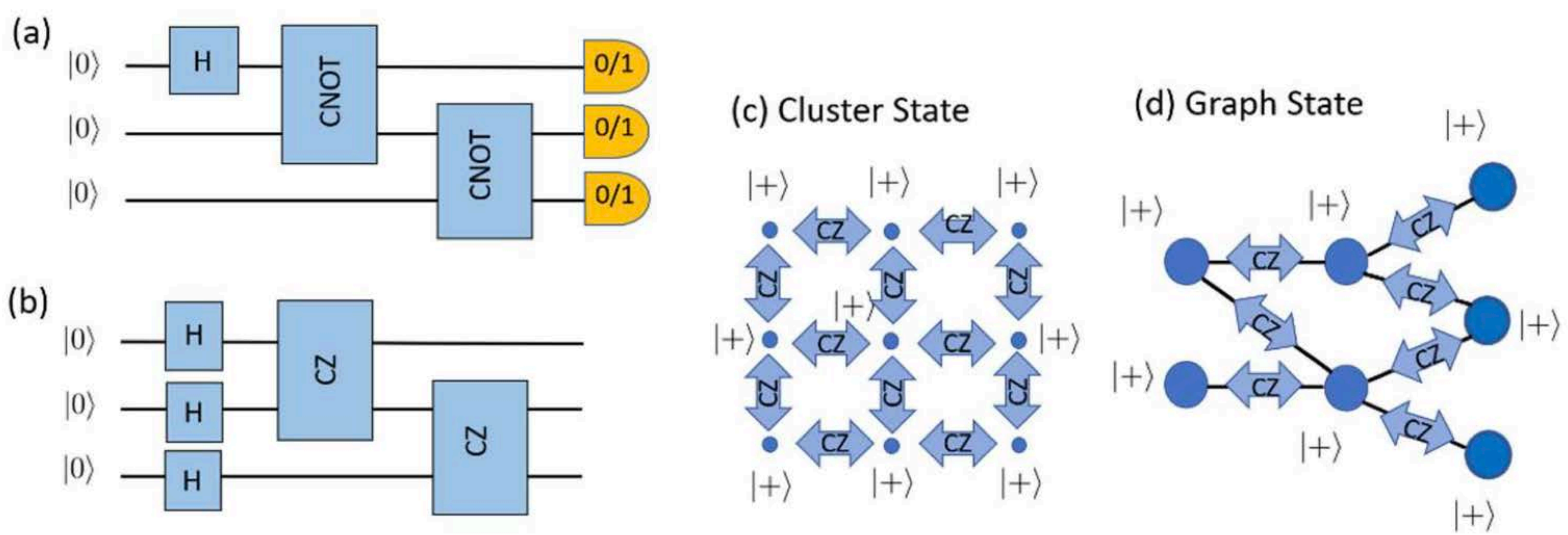
Topological gap (~ns) << Majorana qubit clock time << QPP time

“Measurement based QC”

- Entangled is used as a resource

- Local measurements on qubits are used to drive the computation
  (one-way quantum computer of Raussendorf and Briegel, who introduced the so- called cluster)

- The randomness in the measurement outcomes can be dealt with by adapting future measurement axes so that computation is deterministic



In photonics you can have "Measurement based QC"

- Entanglement is used as a resource
- Local measurements on qubits are used to drive the computation (one-way quantum computer of Raussendorf and Briegel, who introduced the so- called cluster)
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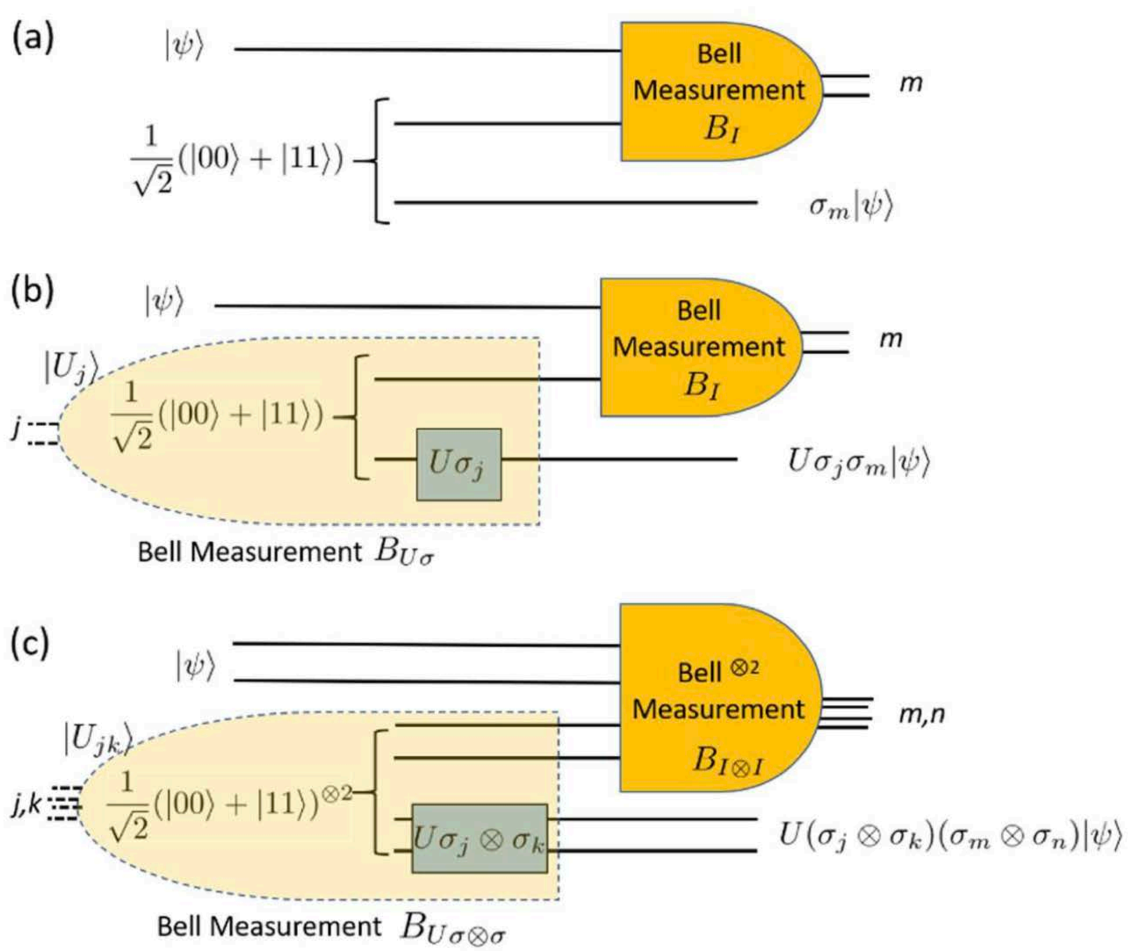

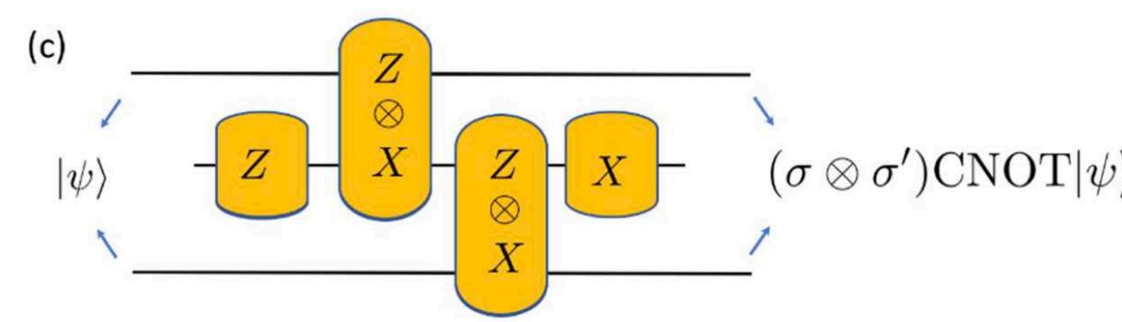

State transfer- based two-qubit CNOT gate

Further possibility is “Measurement based TQC”

Measurement-Only Topological Quantum Computation

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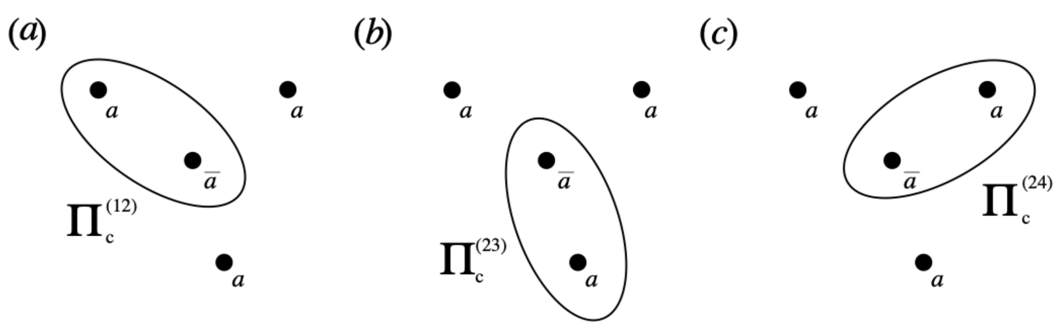
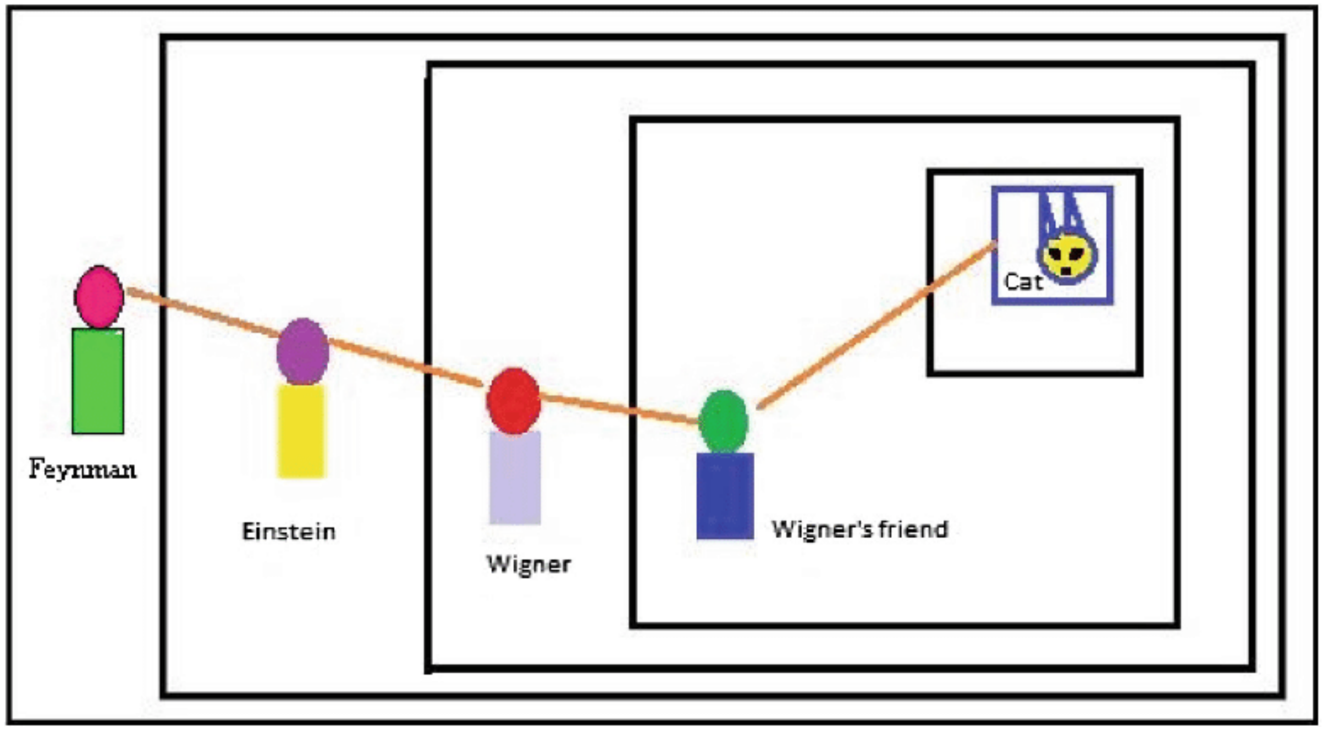
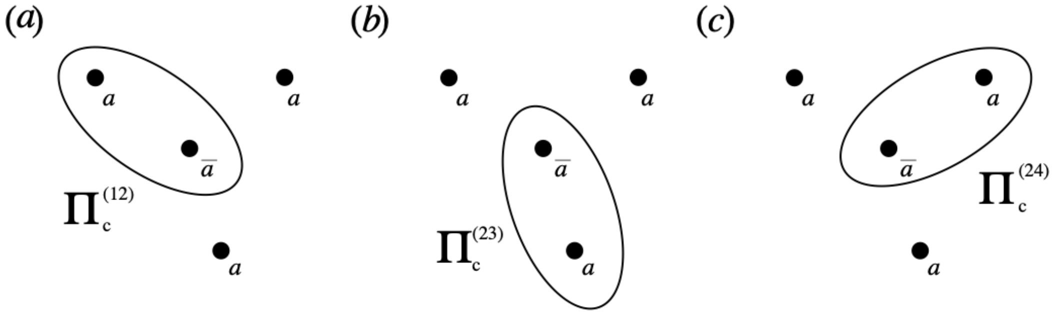


$$\gamma \times \gamma = I + \psi$$

Starting from a maximally entangled anyon pair
+
forced measurements
=
Entanglement resource is fully replenished and returned to its original location
=
Measurement-generated braiding transformations to be employed repeatedly, without exhausting the resources

Possibilities for Measurement in topological superconducting systems





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