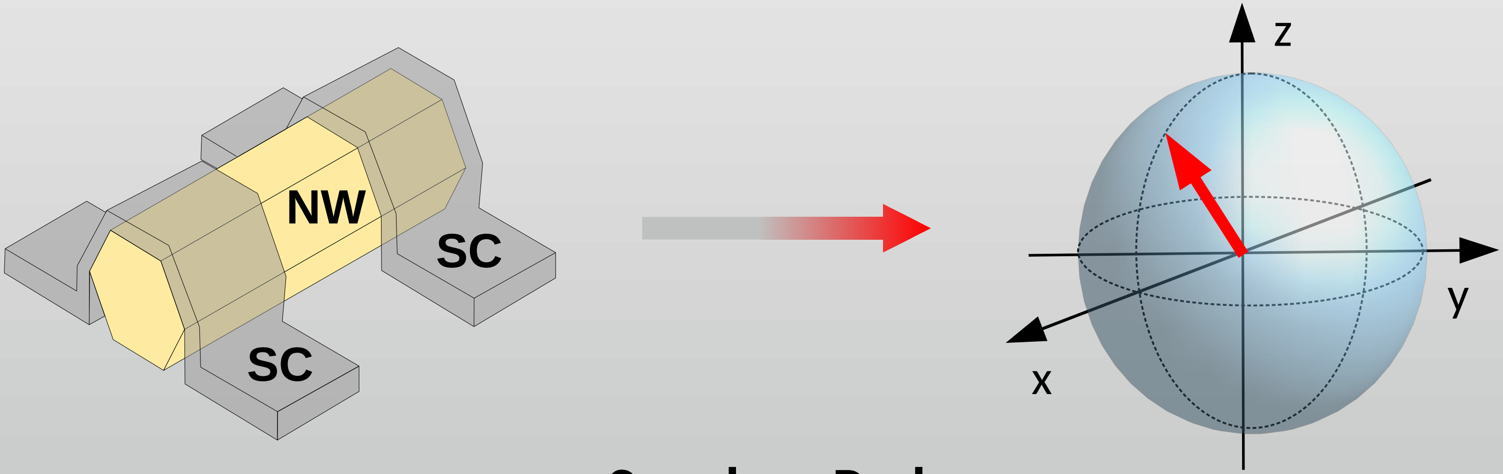
Nanowire-Based Quantum Devices



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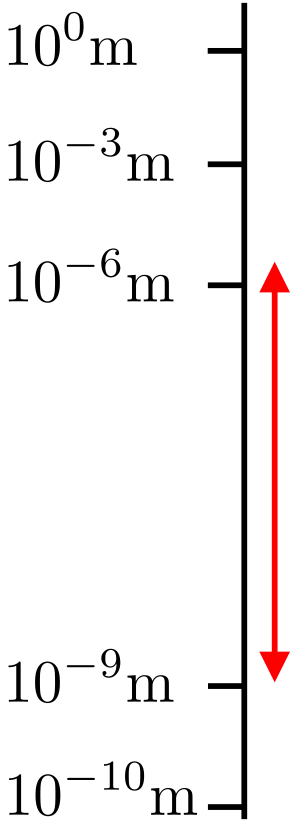
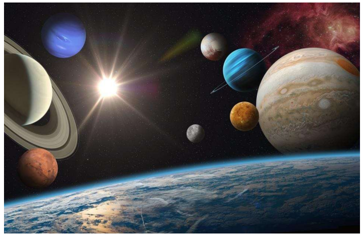
PCS Center for Theoretical Physics of Complex Systems

ibs Institute for Basic Science

Macroscopic quantum mechanics

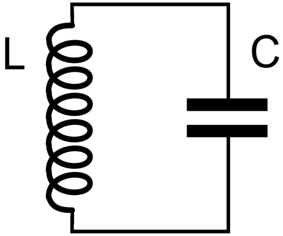


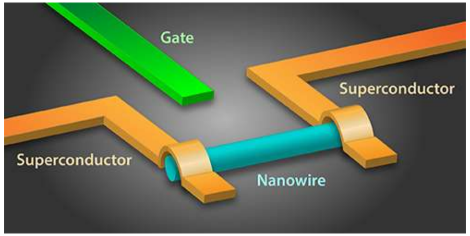
Macroscopic (Classical)



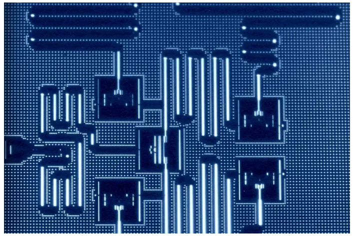
GETTY

Mesoscopic (Artificial atoms, Quantum devices)



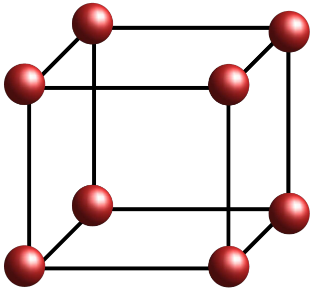


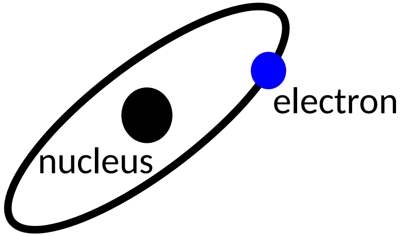
APS/Alan Stonebraker



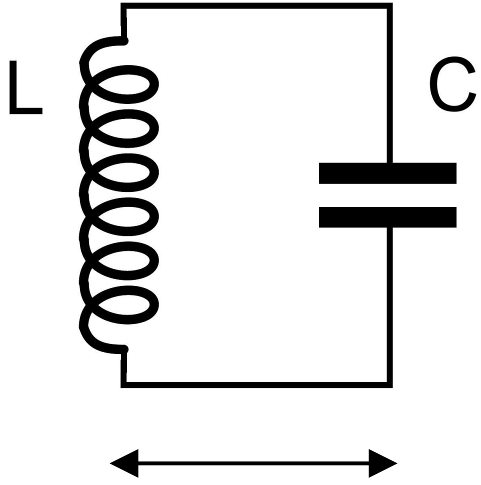
IBM

Microscopic (Quantum)





Quantum LC resonator



$\lesssim 1\text{mm}$

Lumped element

$$\mathrm{L} = 1\ \mathrm{nH}, \quad \mathrm{C} = 10\ \mathrm{pF}$$

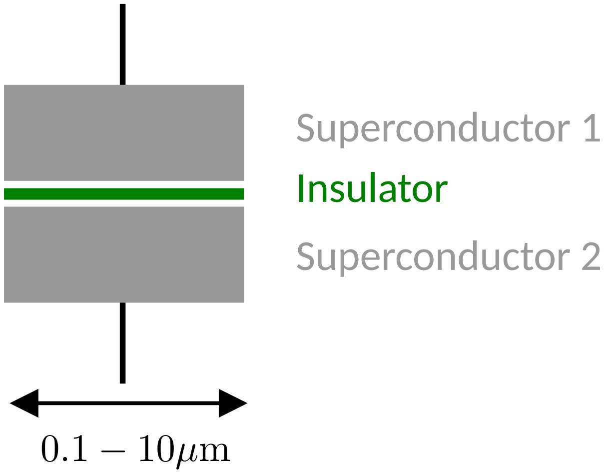
cf. electrical components:

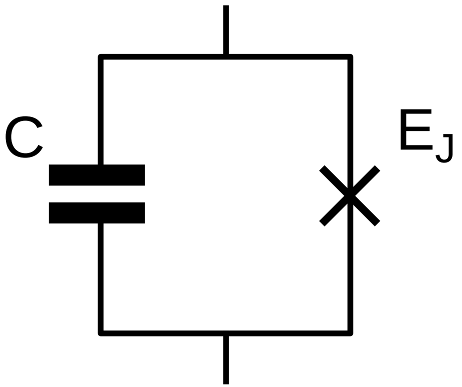
$L_e = 1\mu\mathrm{H} - 1\mathrm{mH},\ C_e = 1\mu\mathrm{F} - 1\mathrm{mF}$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \simeq 1.6\ \mathrm{GHz}$$

Wavelegnth $\lambda \simeq 20$ cm

Josephson tunnel junction

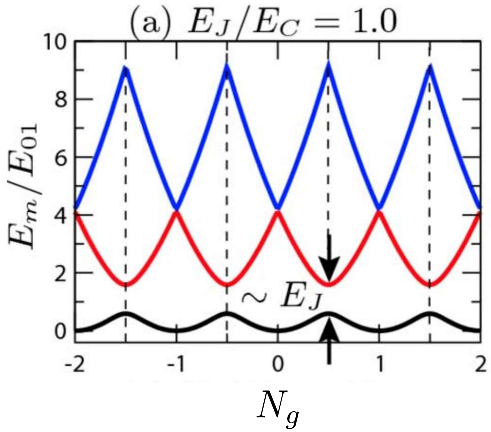




$$H = \sum_N 4E_C(\hat{N} - N_g)^2 - E_J \cos\hat{\varphi}$$

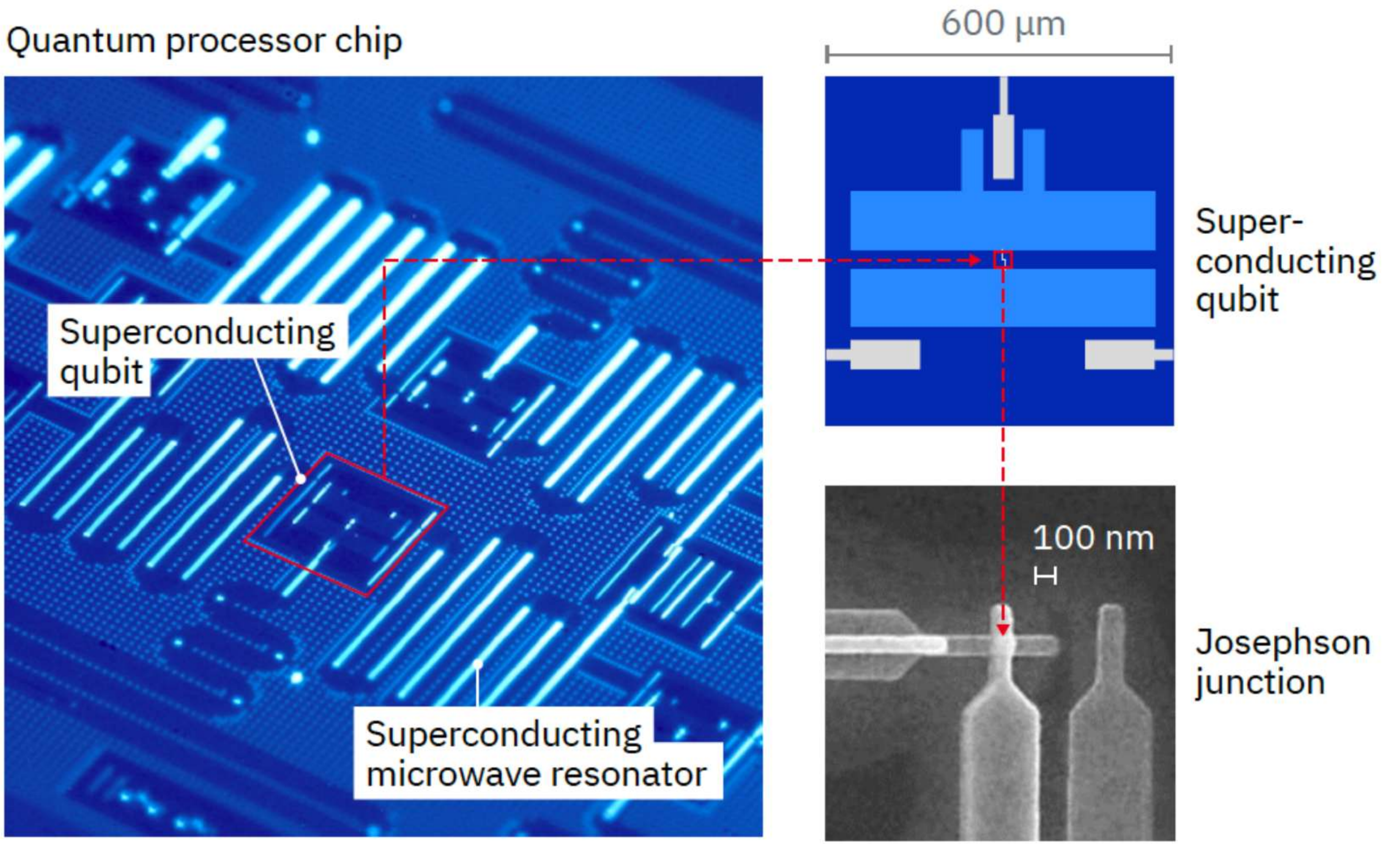
$$= \sum_N 4E_C(\hat{N} - N_g)^2 - \frac{E_J}{2}\left(|N\rangle\langle N+1| + |N+1\rangle\langle N|\right)$$

$$E_C = \frac{e^2}{2C}, \quad E_J = \frac{h}{8e^2} G_t \Delta$$



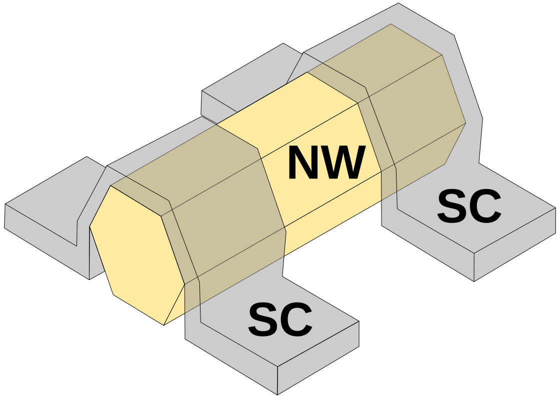
Koch et al., PRA 76, 042319 (2007)
Vool and Devoret, Int. J. Circuit Theory Appl. 45, 897 (2017)

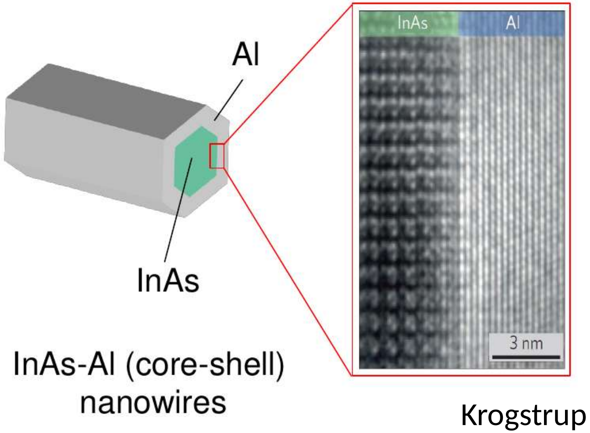
A superconducting quantum processor at IBM

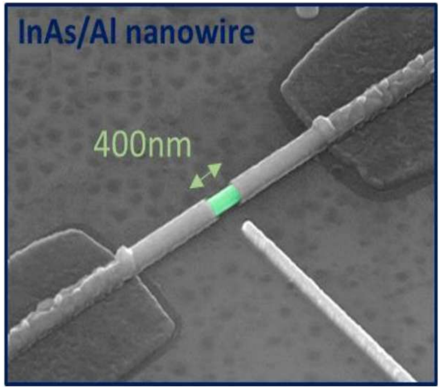


Gil and Green, arXiv:1911.08446 (2019)

Nanowire Josephson junction







Krogstrup et al., Nature Materials 14, 400 (2015)
Goffman et al., New J. Phys. 19, 092002 (2017)

Goal of the research

- **Understanding the physics of Andreev bound states in nanowire Josephson junctions**
- **Maximizing the advantages and strengths of the nanowire-superconductor hybrid systems**

Outline

Part I. Nanowire Josephson junction

Part II. Josephson junction coupled to a microwave

Part III. Overview of recent studies

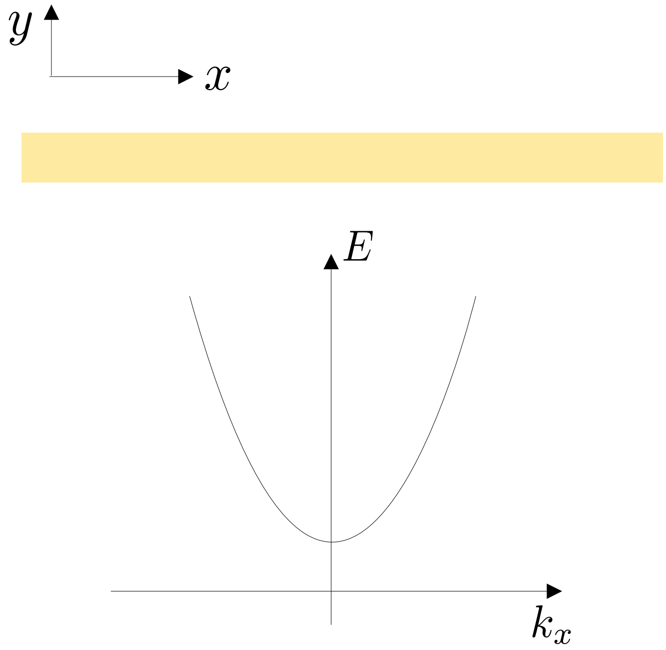
Part I. Nanowire Josephson junction

- Andreev reflections

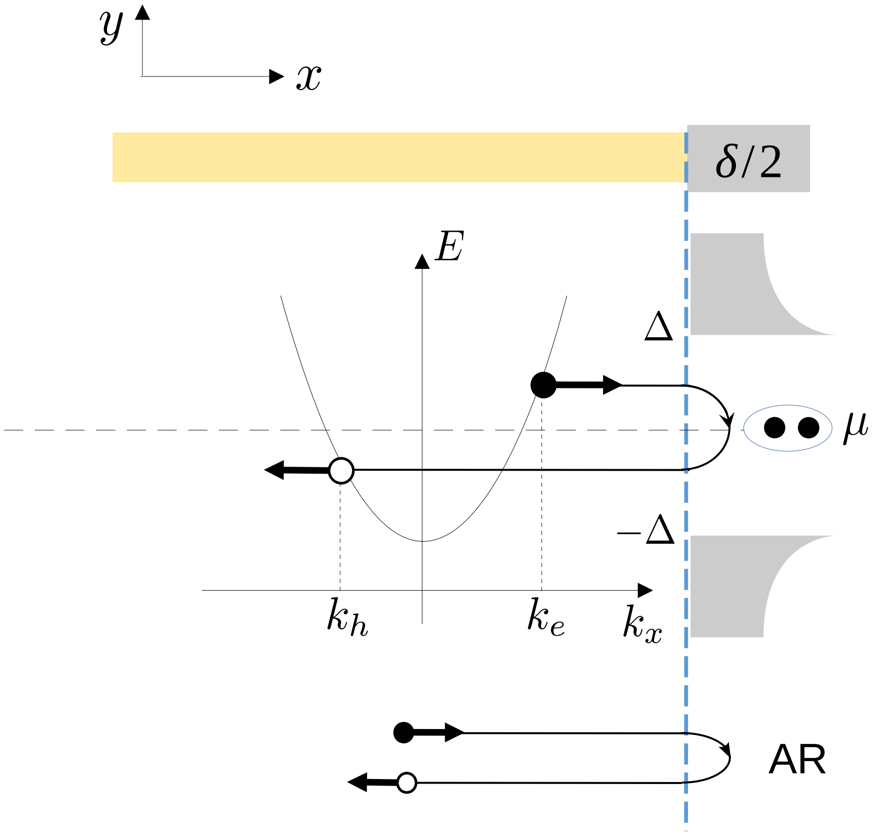
- Andreev bound states

- Effect of scattering and spin-orbit coupling

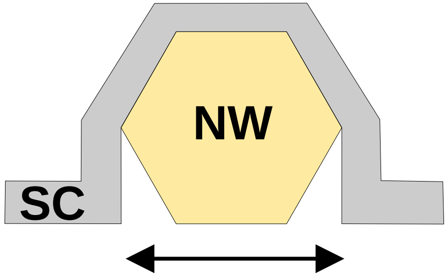
A single band



Andreev reflection



Cross section



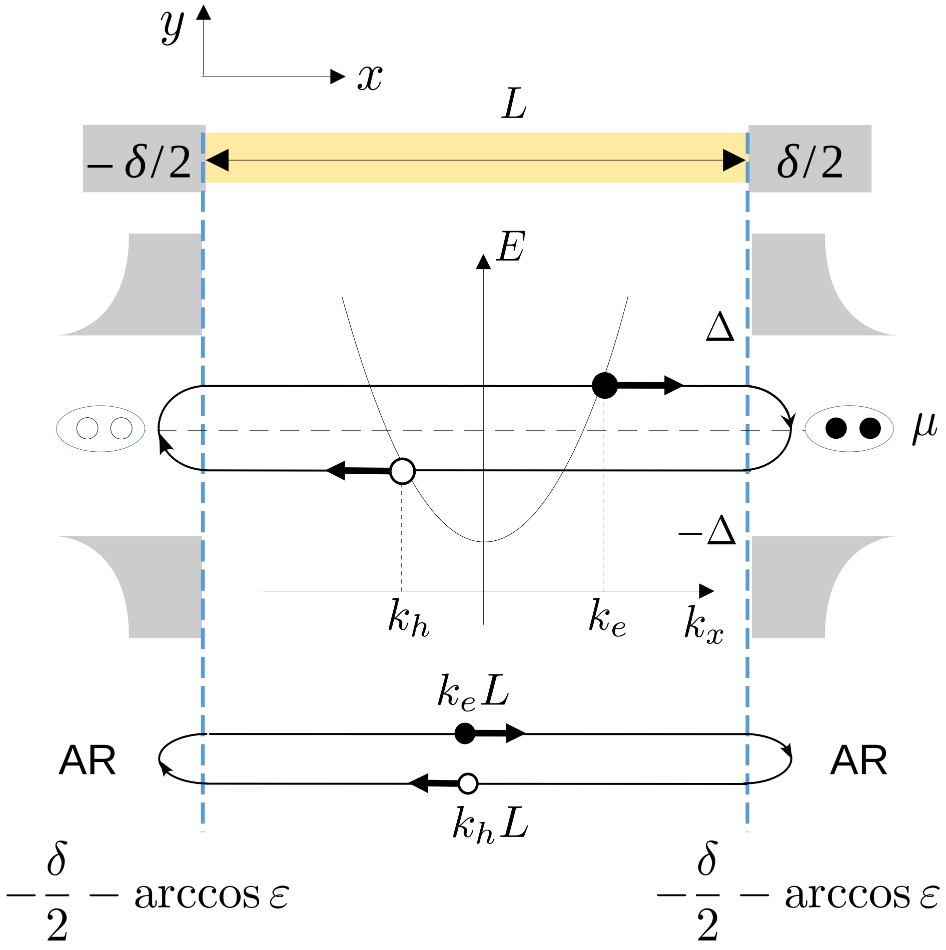
$$d \lesssim \xi = \frac{\hbar v_F}{\Delta}$$

Superconducting proximity effect

Andreev reflection phase: $-\dfrac{\delta}{2} - \arccos \varepsilon$

$$\varepsilon = \frac{E - \mu}{\Delta}$$

Ballistic channel



$$k_e = k_F + \frac{E-\mu}{\hbar v_F}, \quad k_h = -k_F + \frac{E-\mu}{\hbar v_F}$$

Dynamical phase

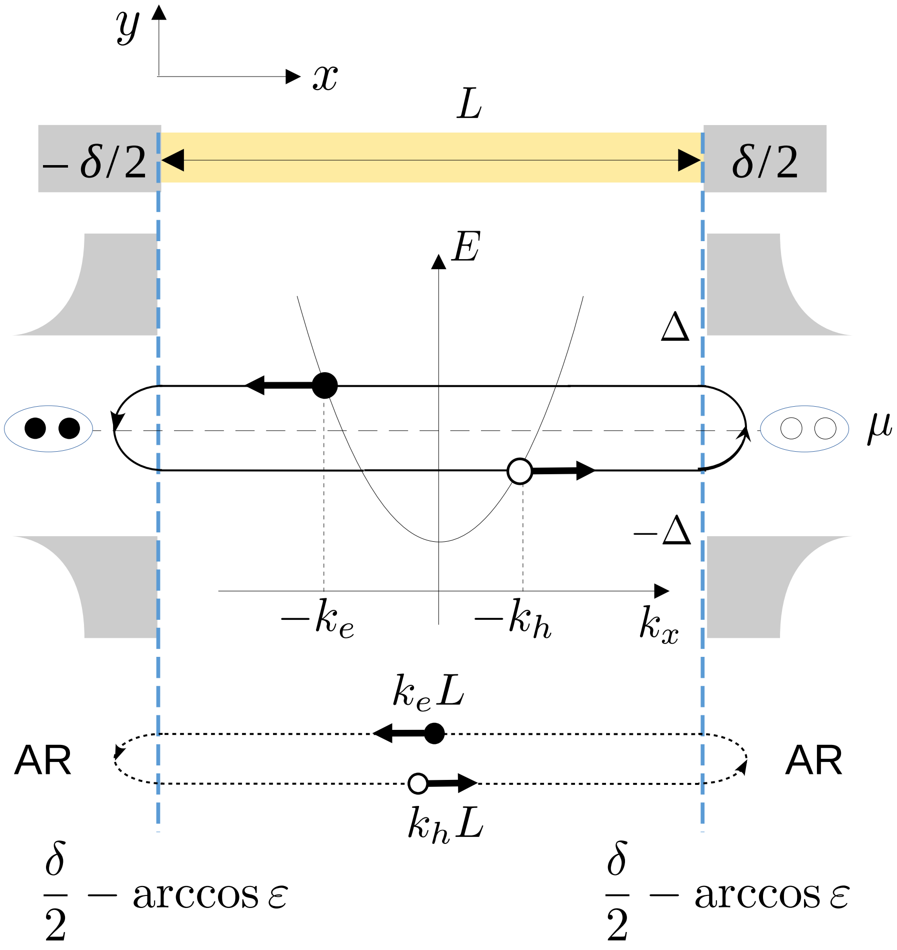
$$k_eL + k_hL = 2\lambda\varepsilon$$

$$\lambda = \frac{L\Delta}{\hbar v_F} = \frac{L}{\xi}$$

Energy quantization condition

$$-\delta - 2\arccos\varepsilon + 2\lambda\varepsilon = 2\pi n$$

Ballistic channel



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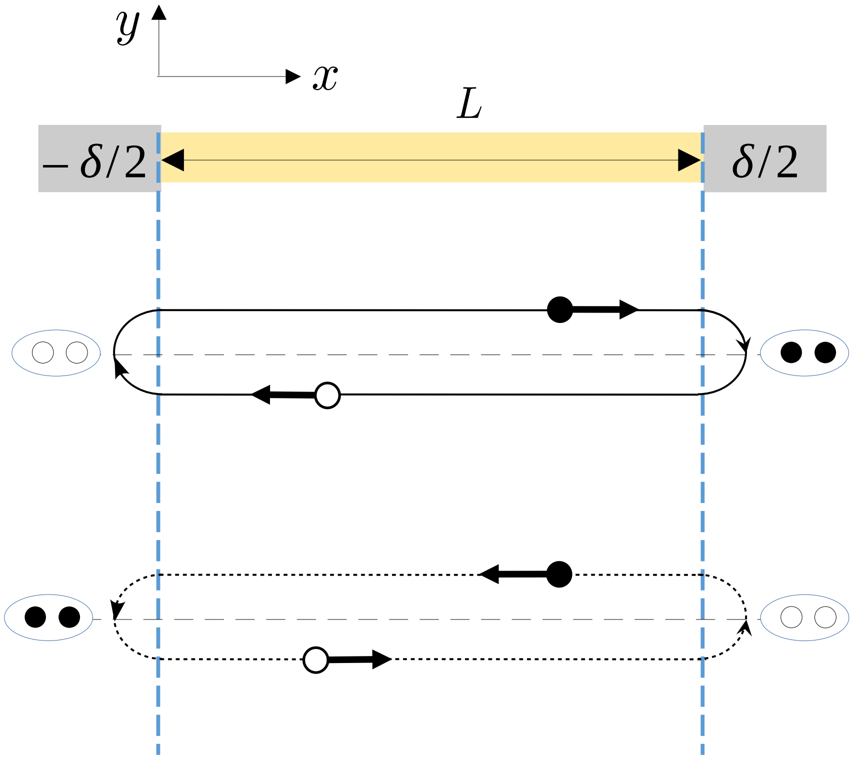
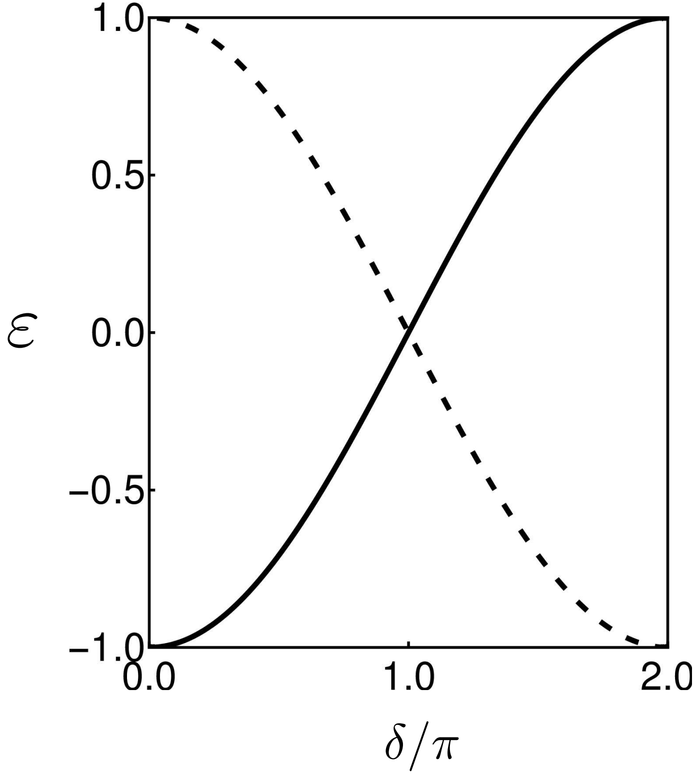
Andreev bound states – ballistic case



$$\mp\delta - 2\arccos\varepsilon + 2\lambda\varepsilon = 2\pi n$$

$$\lambda = L/\xi = 0$$

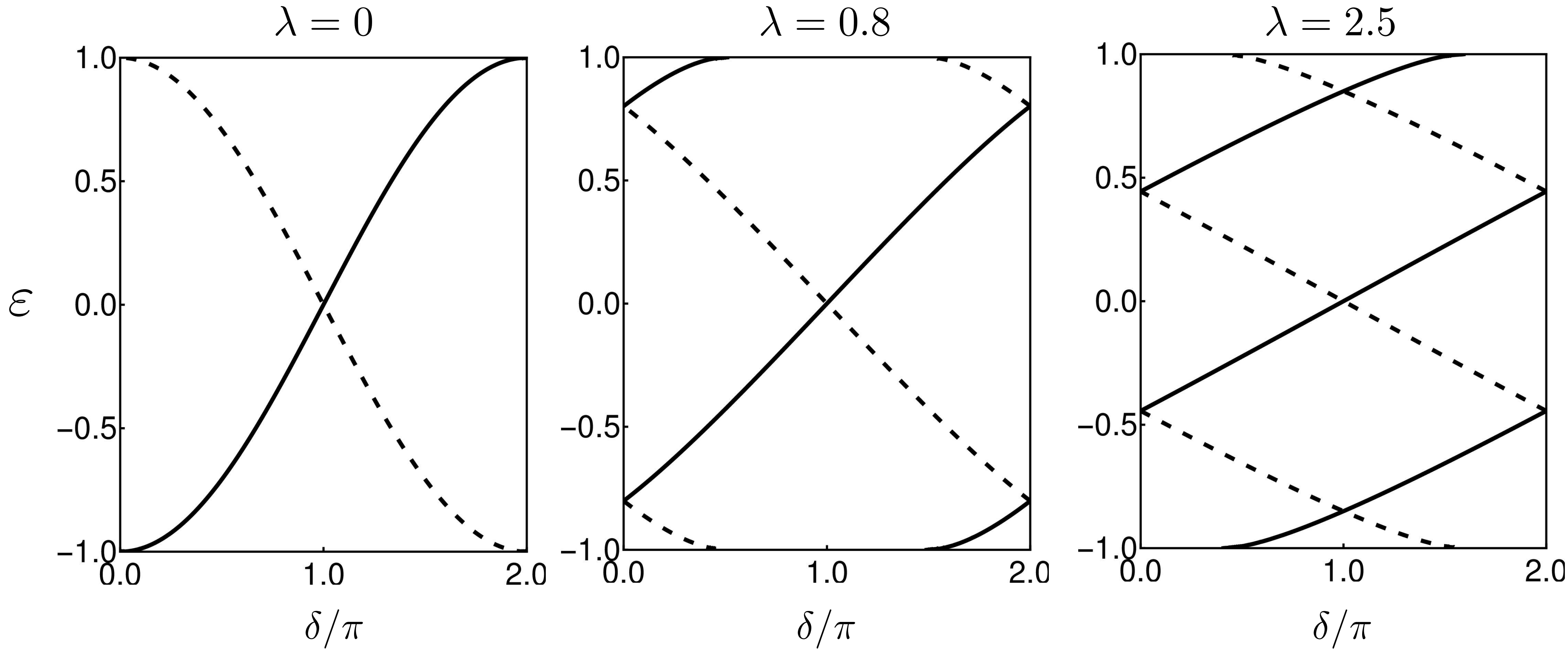


Bagwell, PRB 46, 12573 (1992)
Beenakker and Houten, PRL 66, 3056 (1991)
Kulik, JETP 30, 944 (1970)

Andreev energies from short to long junction length

$$\lambda = \frac{L\Delta}{\hbar v_F}$$

$$\mp\delta - 2\arccos\varepsilon + 2\lambda\varepsilon = 2\pi n$$



Andreev energies from short to long junction length

$$\lambda = \frac{L\Delta}{\hbar v_F}$$

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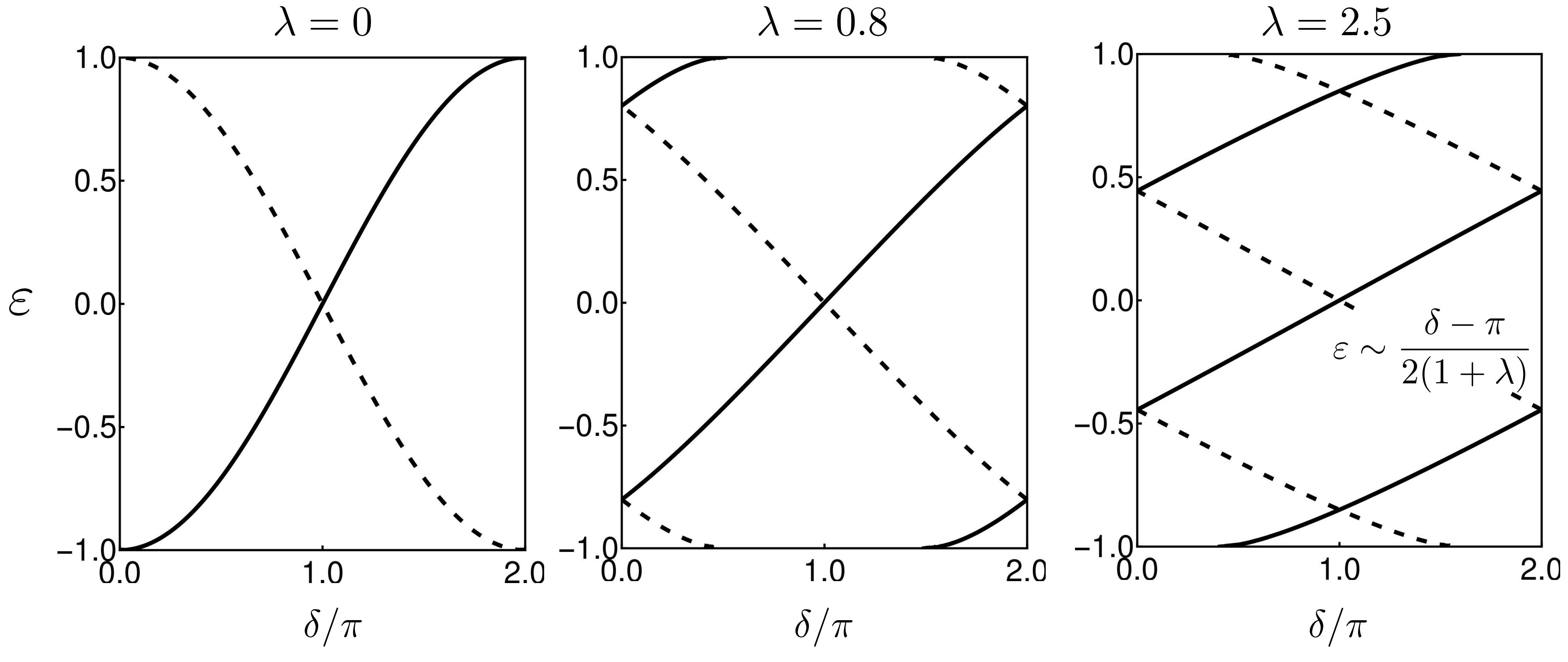
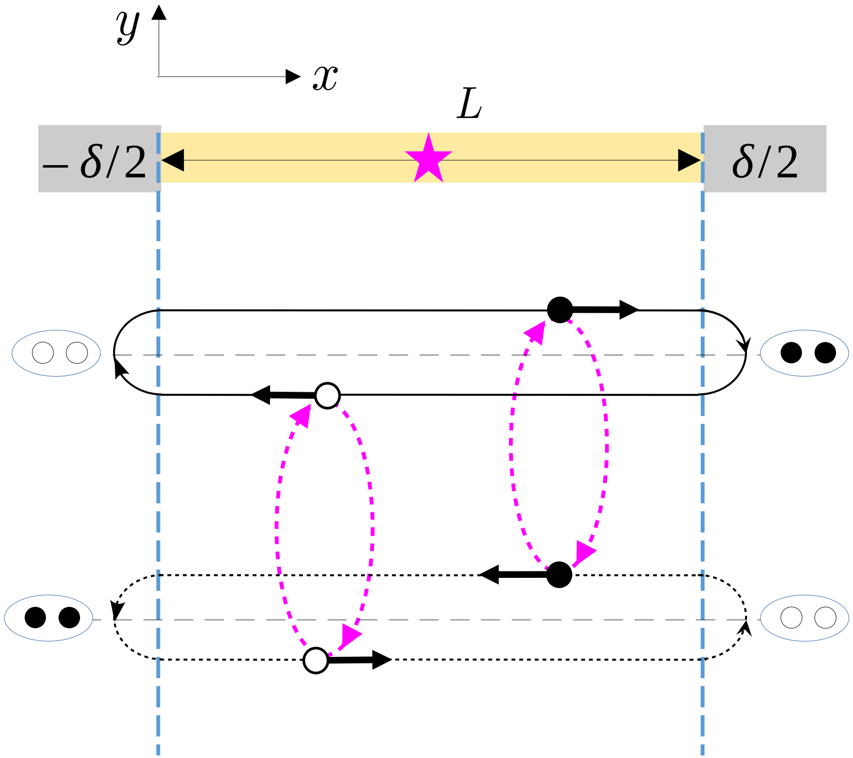
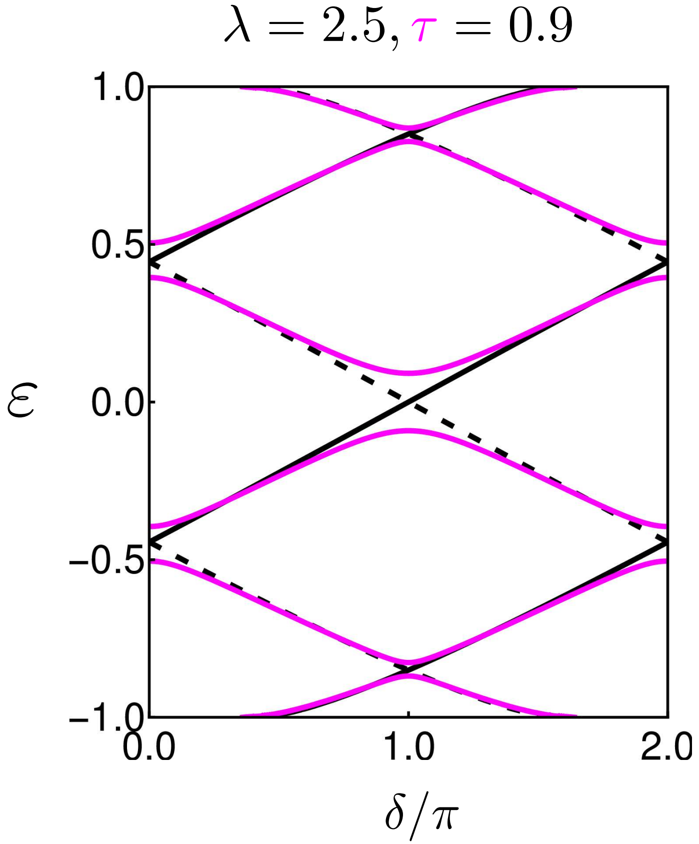


Andreev bound states with scatterer



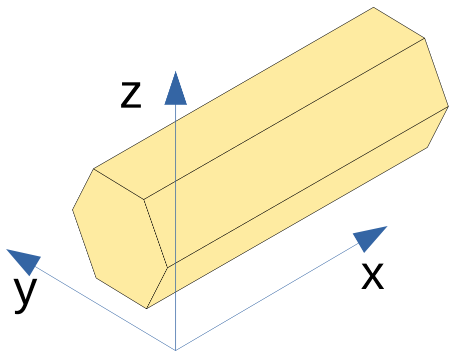
$$\cos\left(2\arccos\varepsilon - 2\lambda\varepsilon\right) = \tau\cos(\delta) + (1-\tau)\cos(2\lambda\epsilon x_r)$$

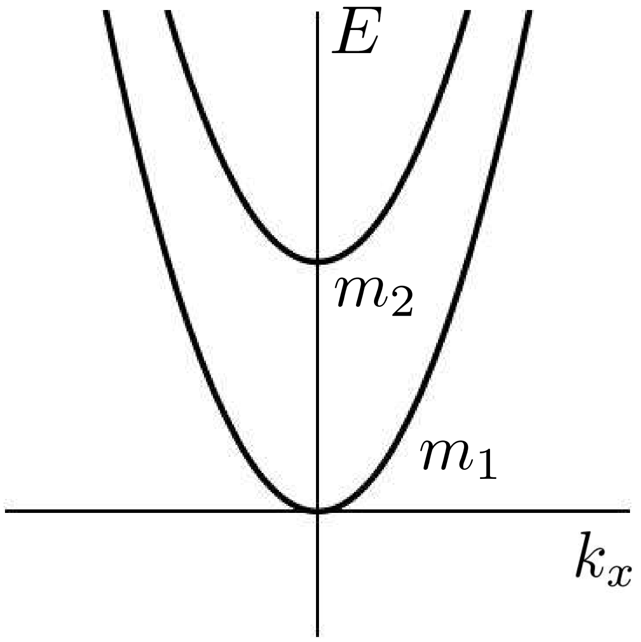


Rashba spin-orbit effect

$$H_{NW} = \underline{\frac{p_x^2}{2m} + \frac{p_y^2 + p_z^2}{2m} + U_c(y,z)} - \alpha p_x \sigma_y + \alpha p_y \sigma_x$$

Nanowire (InAs or InSb)



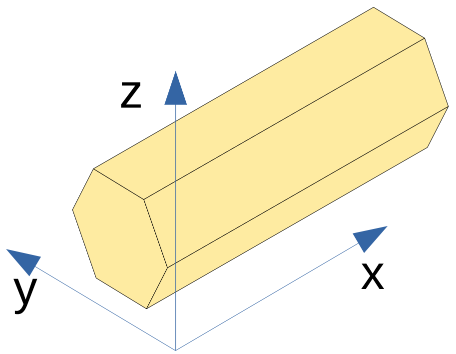


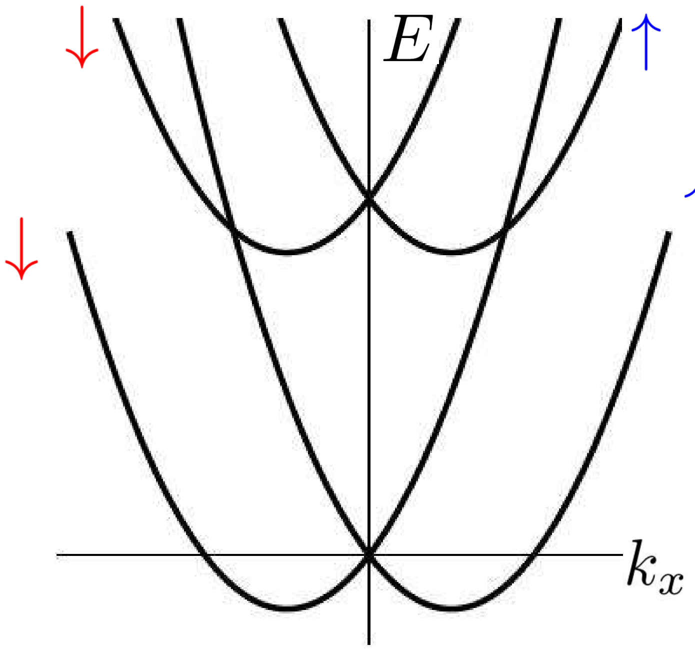
Measurement of the SOC: Fasth et al., PRL 98, 266801 (2007)

Rashba spin-orbit effect

$$H_{NW} = \frac{p_x^2}{2m} + \frac{p_y^2 + p_z^2}{2m} + U_c(y,z) \boxed{- \alpha p_x \sigma_y} + \alpha p_y \sigma_x$$

Nanowire (InAs or InSb)

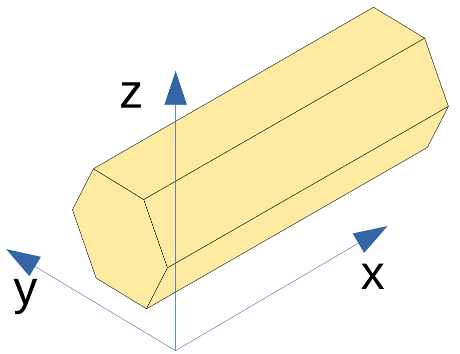


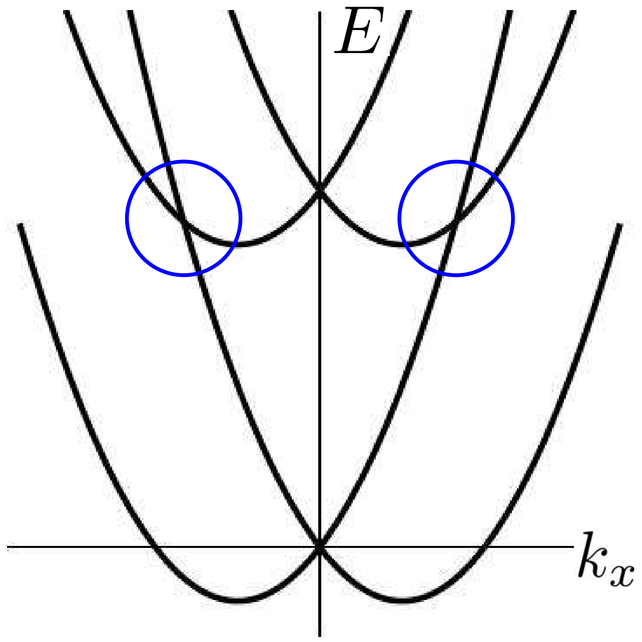


Rashba spin-orbit effect

$$H_{NW} = \frac{p_x^2}{2m} + \frac{p_y^2 + p_z^2}{2m} + U_c(y,z) - \alpha p_x \sigma_y + \boxed{\alpha p_y \sigma_x}$$

Nanowire (InAs or InSb)





Rashba spin-orbit effect

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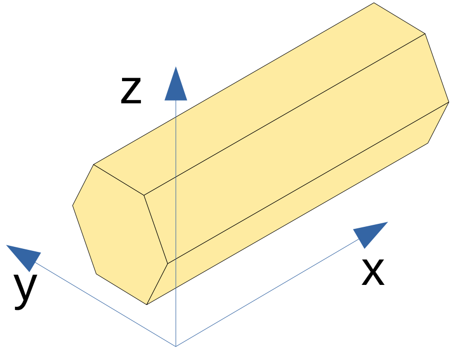
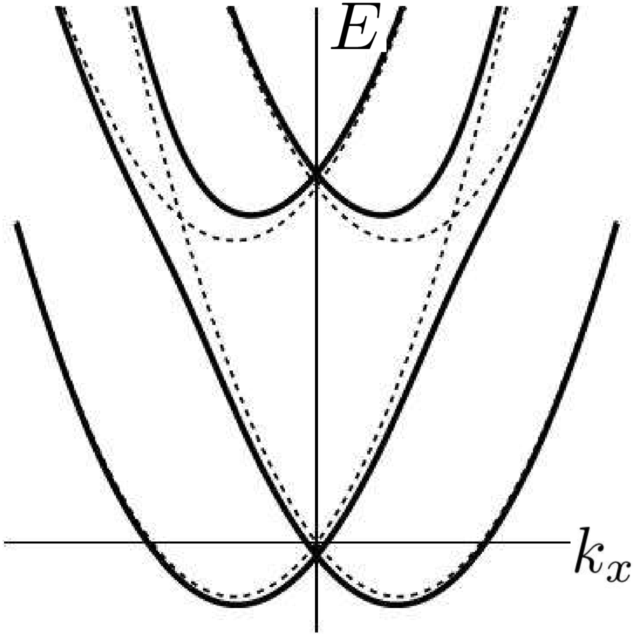
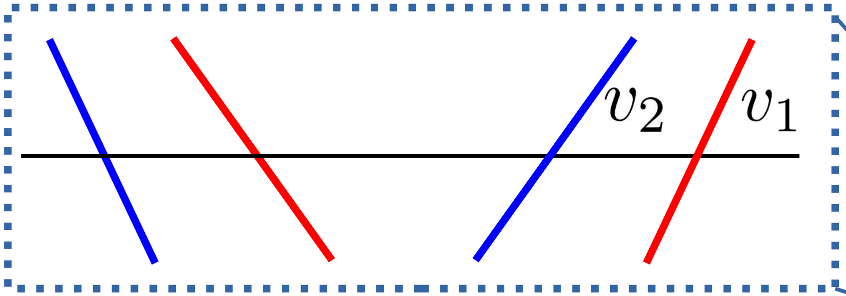
Nanowire (InAs or InSb)

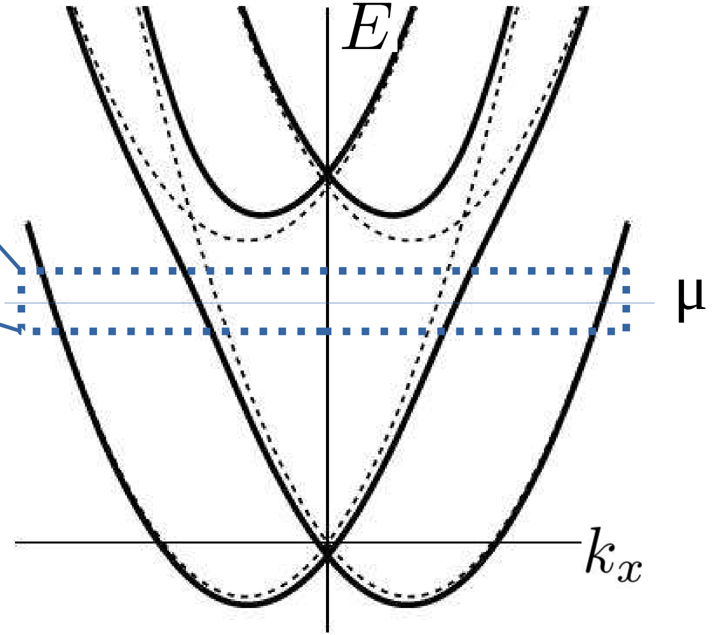




Rashba spin-orbit effect

$$H_{NW} = \frac{p_x^2}{2m} + \frac{p_y^2 + p_z^2}{2m} + U_c(y,z) - \alpha p_x \sigma_y + \alpha p_y \sigma_x$$





Different Fermi velocities $v_1 \neq v_2$

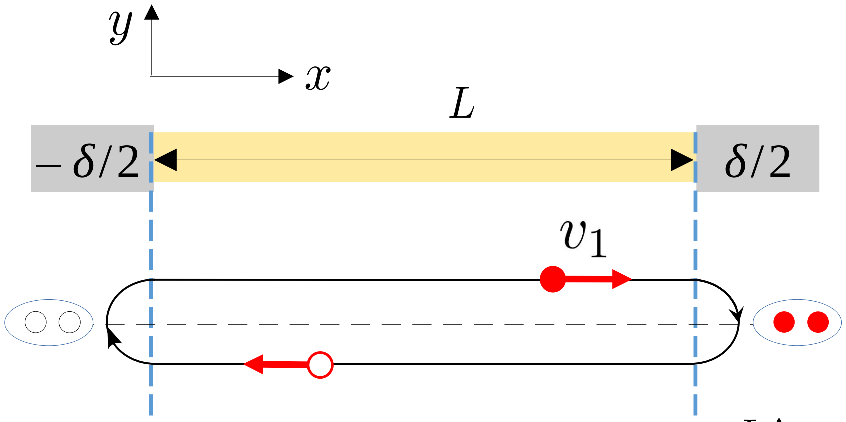
Pseudo-spin

$$|u\rangle = a_u|\uparrow, m_1\rangle + b_u|\downarrow, m_2\rangle$$
$$|d\rangle = a_d|\downarrow, m_1\rangle + b_d|\uparrow, m_2\rangle$$

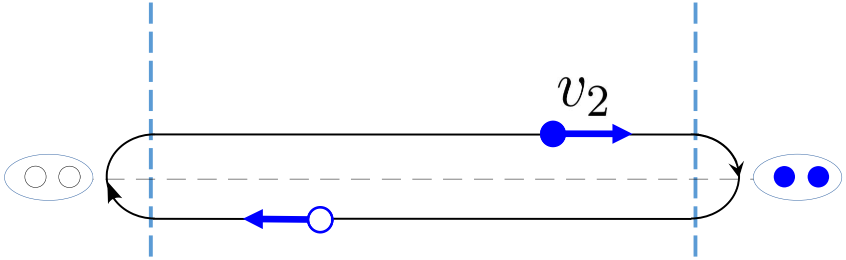
spin: $\uparrow, \downarrow$ transverse modes: m_1, m_2

Moroz and Barnes, PRB 60, 14272 (1999)

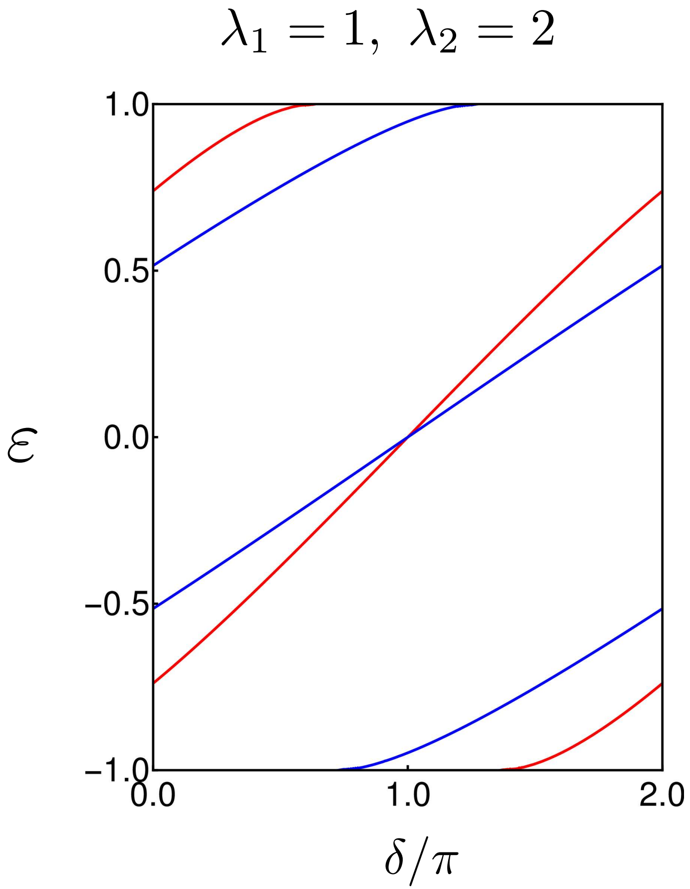
Spin-split Andreev levels – ballistic channel



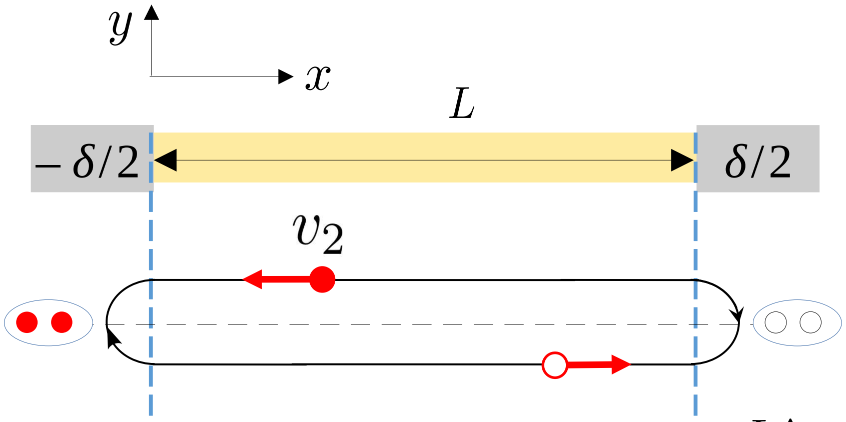
$$-\delta - 2\arccos\varepsilon + 2\lambda_1\varepsilon = 2\pi n_1, \quad \lambda_1 = \frac{L\Delta}{\hbar v_1}$$



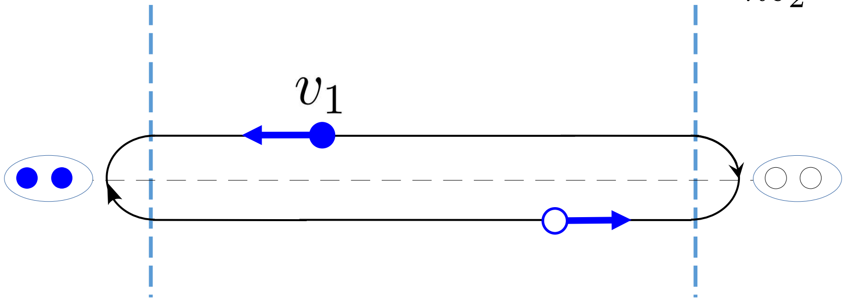
$$-\delta - 2\arccos\varepsilon + 2\lambda_2\varepsilon = 2\pi n_2, \quad \lambda_2 = \frac{L\Delta}{\hbar v_2}$$



Spin-split Andreev levels – ballistic channel



$$\delta - 2\arccos\varepsilon + 2\lambda_2\varepsilon = 2\pi n_1,\quad \lambda_2 = \frac{L\Delta}{\hbar v_2}$$



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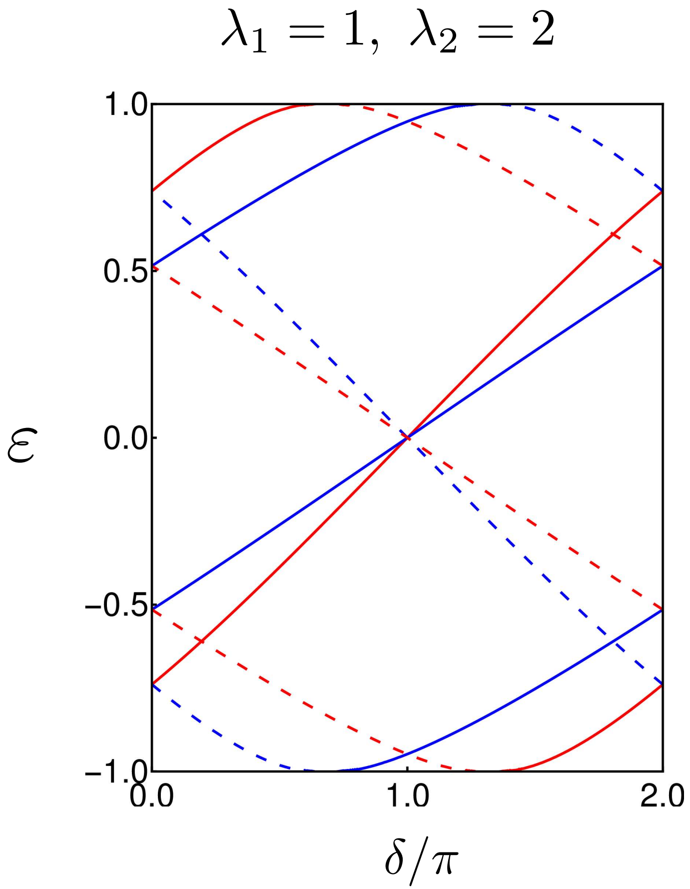
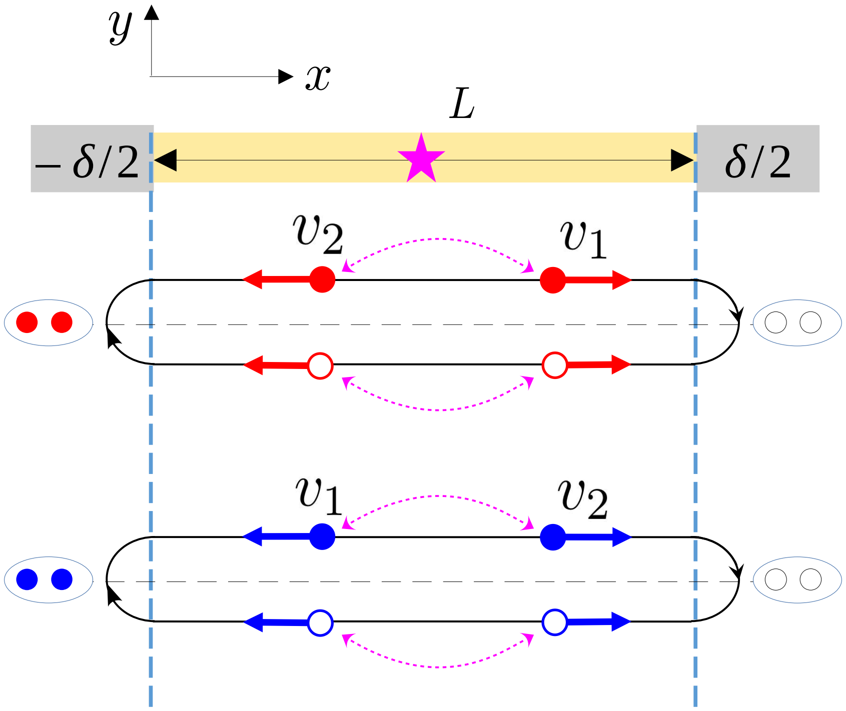
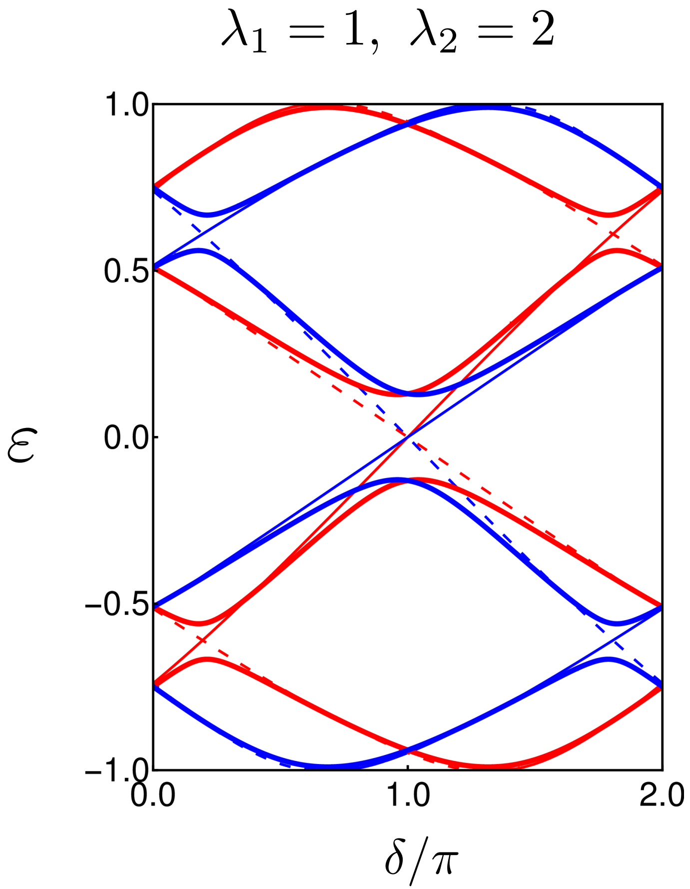


Park and Levy Yeyati, PRB 96, 125416 (2017)
Tosi et al., PRX 9, 011010 (2019)

Spin-split Andreev levels with scatterer





$$\tau\cos\left[(\lambda_1-\lambda_2)\varepsilon\mp\delta\right]+(1-\tau)\cos\left[(\lambda_1+\lambda_2)\varepsilon x_r\right]$$
$$=\cos\left[2\arccos\varepsilon-(\lambda_1+\lambda_2)\varepsilon\right]$$

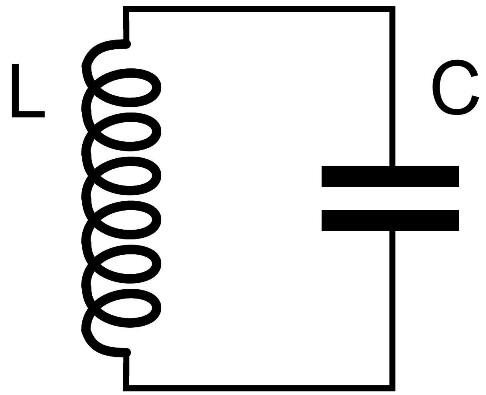
Park and Levy Yeyati, PRB 96, 125416 (2017)
Tosi et al., PRX 9, 011010 (2019)

Part II. Josephson junction coupled to a microwave

- Coherent coupling

- Readout: state-dependent frequency shift

Superconducting LC resonator



$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$H_r = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L}$$
$$= hf_r\left(a^\dagger a + \frac{1}{2}\right)$$

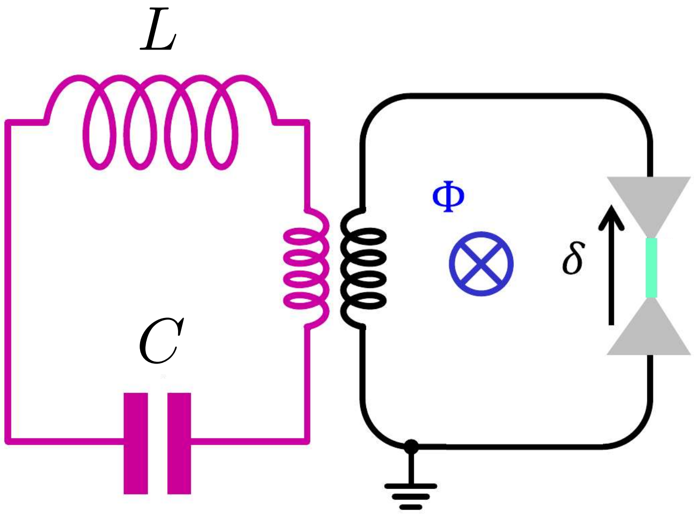
$$\hat{Q} = -i\sqrt{\frac{\hbar}{2}\sqrt{\frac{C}{L}}}(a - a^\dagger), \quad \hat{\Phi} = \sqrt{\frac{\hbar}{2}\sqrt{\frac{L}{C}}}(a + a^\dagger)$$

Quantum fluctuation

$$\left\langle (\Delta Q)^2 \right\rangle \left\langle (\Delta \Phi)^2 \right\rangle \geq \frac{\hbar^2}{4}$$

Vool and Devoret, Int. J. Circuit Theory Appl. 45, 897 (2017)

Resonator-coupled Josephson junction



$$H_J(\delta) \rightarrow H_J(\delta + \hat{\delta}_r)$$

$$\hat{\delta}_r = \delta_{ZP}(a + a^\dagger)$$

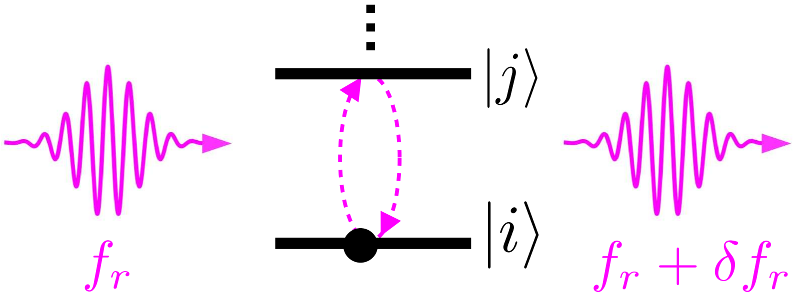
$$H = H_r + H_J(\delta) + \underbrace{\delta_{ZP}\frac{dH_J(\delta)}{d\delta}(a + a^\dagger)}_{\text{First order}} + \underbrace{\frac{\delta_{ZP}^2}{2}\frac{d^2H_J(\delta)}{d\delta^2}(a + a^\dagger)^2}_{\text{Second order}}$$

First order

Second order

Frequency shift of the resonator

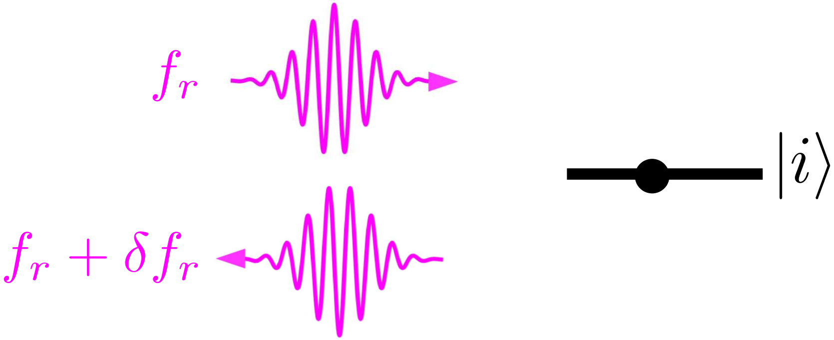
First order coupling contribution



Dominant if $E_j - E_i \sim hf_r$

$$\delta f_r = \delta_{ZP}^2 \frac{\left|\langle i \left| dH_J(\delta)/d\delta \right| j\rangle\right|^2}{E_j - E_i - hf_r}$$

Second order coupling contribution

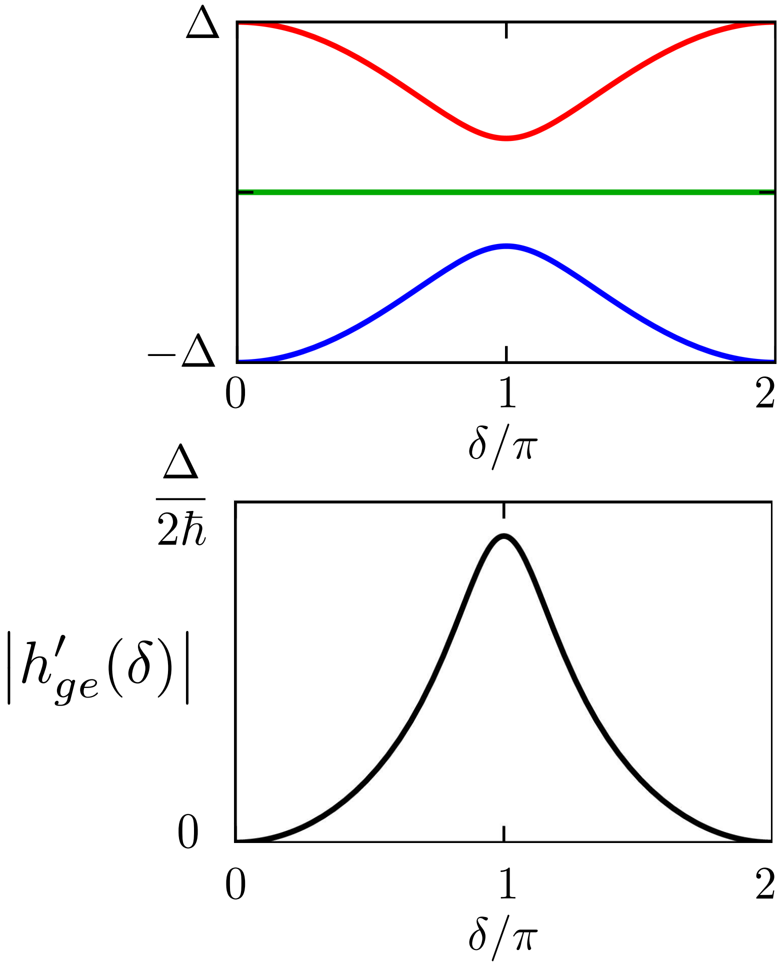


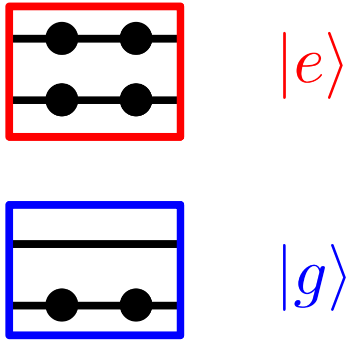
Dominant if $|E_j - E_i| \gg hf_r$

$$\delta f_r = \delta_{ZP}^2 \frac{d^2 E_i(\delta)}{hd\delta^2} = \delta_{ZP}^2 \frac{1}{h} \frac{(h/2e)^2}{L_J}$$

Park et al., PRL 125, 077701 (2020)

State-dependent frequency shift - short Josephson junction



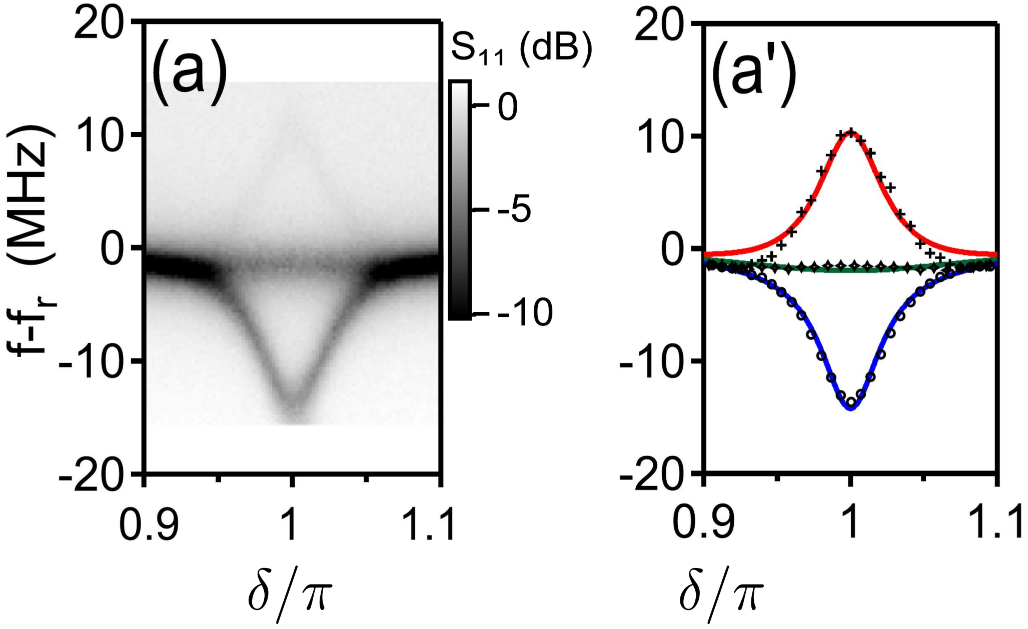


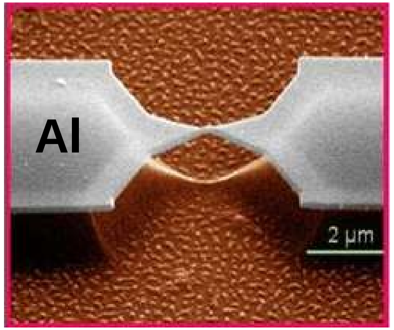
$$h'_{ge}(\delta) = \left\langle g \left| \frac{dH(\delta)}{d\delta} \right| e \right\rangle$$

$$= \frac{\Delta \tau \sqrt{1-\tau} \sin^2(\delta/2)}{2\sqrt{1-\tau \sin^2(\delta/2)}}$$

Park et al., PRL 125, 077701 (2020)

State-dependent frequency shift - short Josephson junction





$$|e\rangle : f - f_r \approx \delta_{ZP}^2 \frac{|h'_{ge}|^2}{E_e - (E_g + hf_r)}$$

$$|g\rangle : f - f_r \approx \delta_{ZP}^2 \frac{|h'_{ge}|^2}{(E_g + hf_r) - E_e}$$

$$f_r = 10.1\text{GHz}$$

Metzger et al., PRR 3, 013036 (2021)

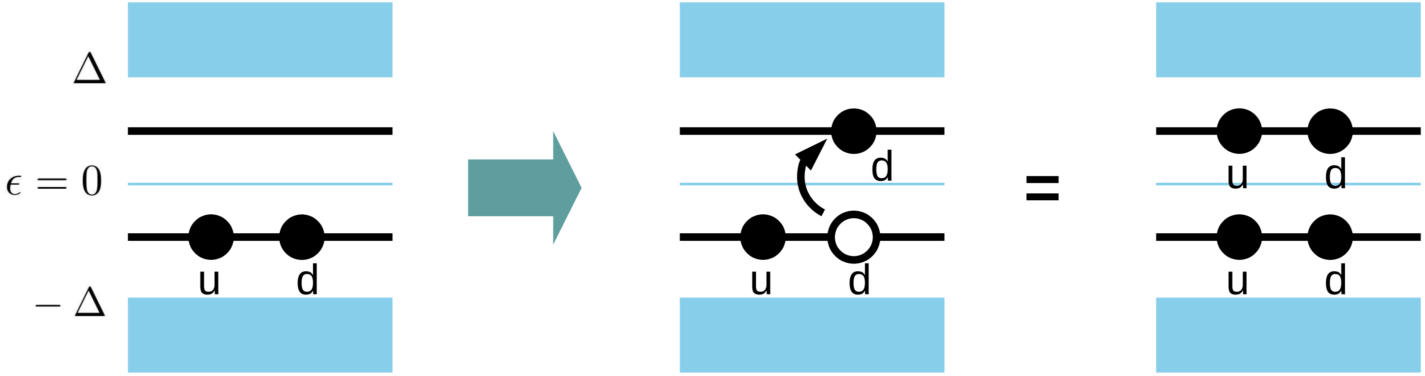
Part III. Overview of recent studies

- Spectroscopic study of spin-split ABSs

- Dynamical parity selection using a microwave

Transitions between Andreev levels by a microwave

Pair transitions : ground state to excited state

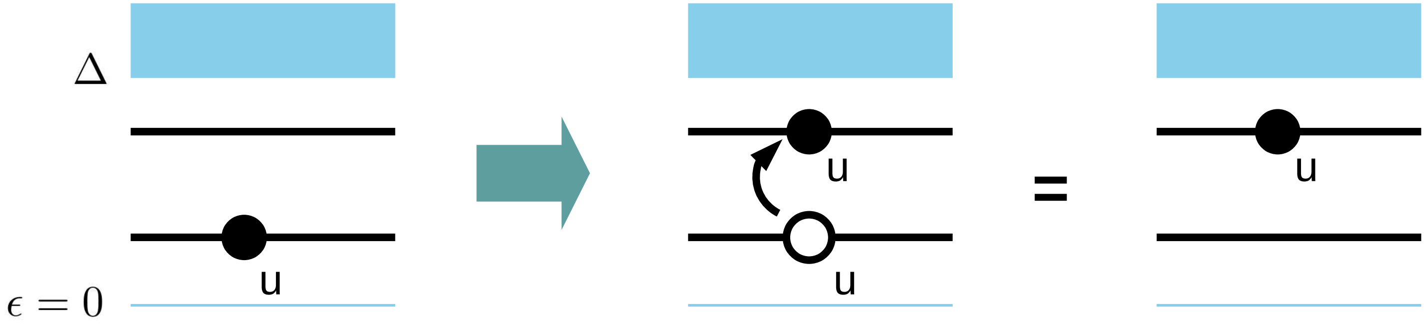


Particle-hole symmetry

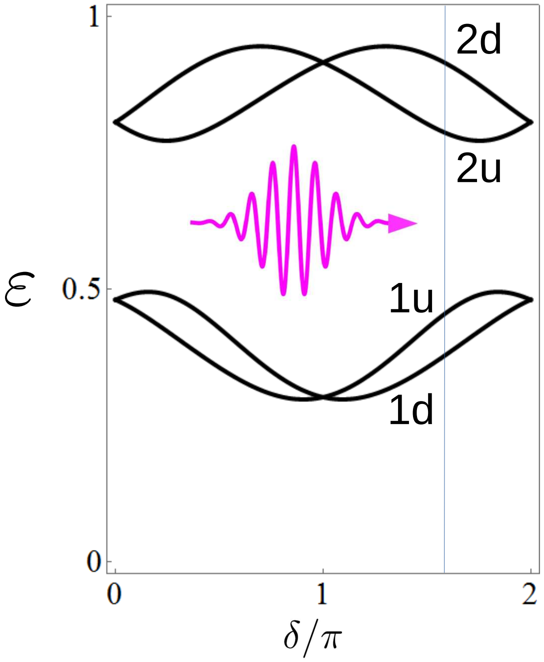
$$\gamma^{\dagger}_{\varepsilon,d}\gamma_{-\varepsilon,d} = \gamma^{\dagger}_{\varepsilon,d}\gamma^{\dagger}_{\varepsilon,u}$$

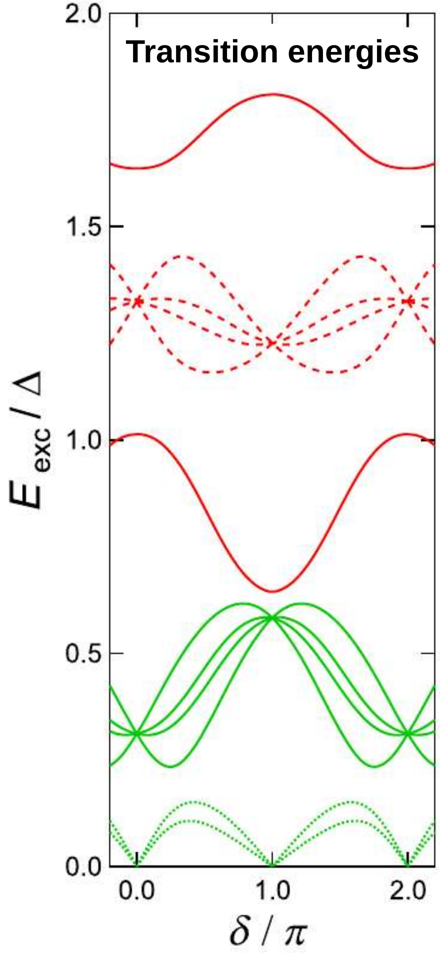
$$\gamma_{-\varepsilon,d} = \gamma^{\dagger}_{\varepsilon,u}$$

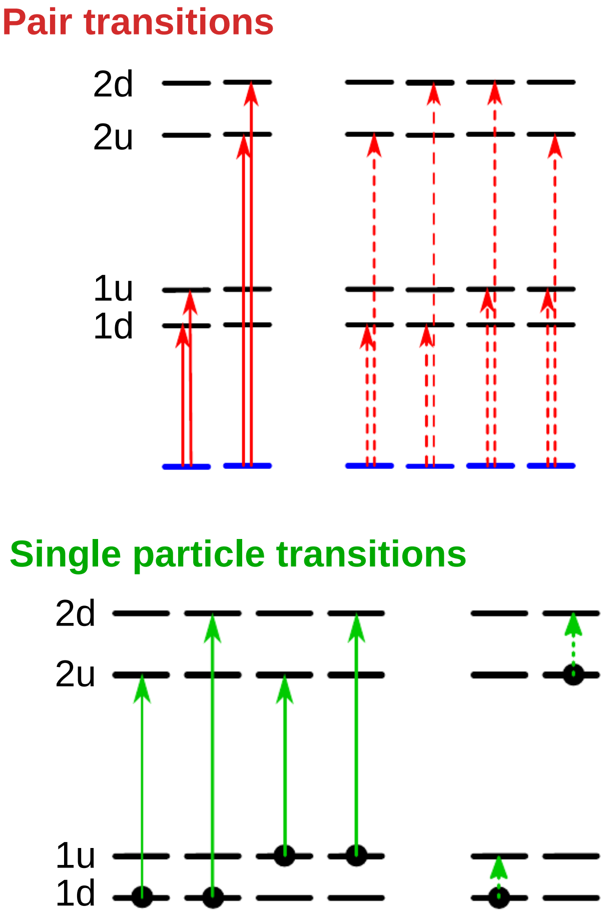
Single quasiparticle transitions



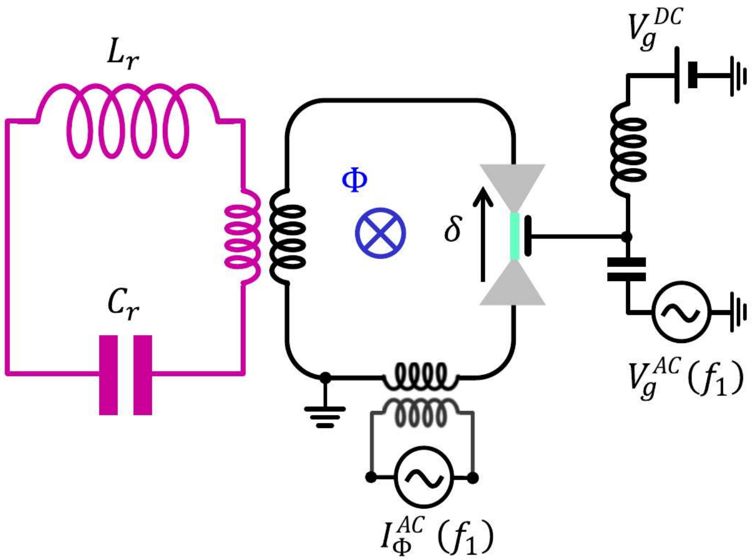
Transitions between spin-split Andreev levels by a microwave

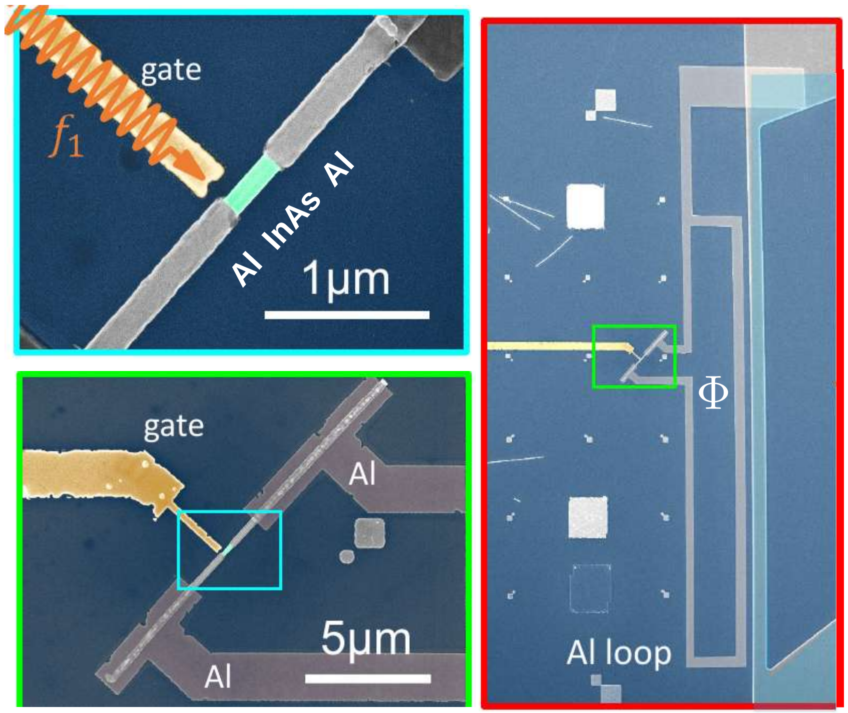






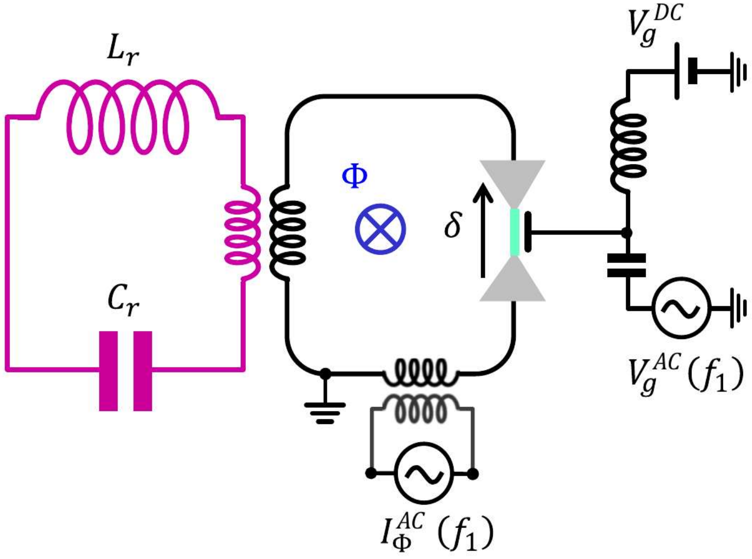
Experimental setup – Quantronics group at CEA Saclay

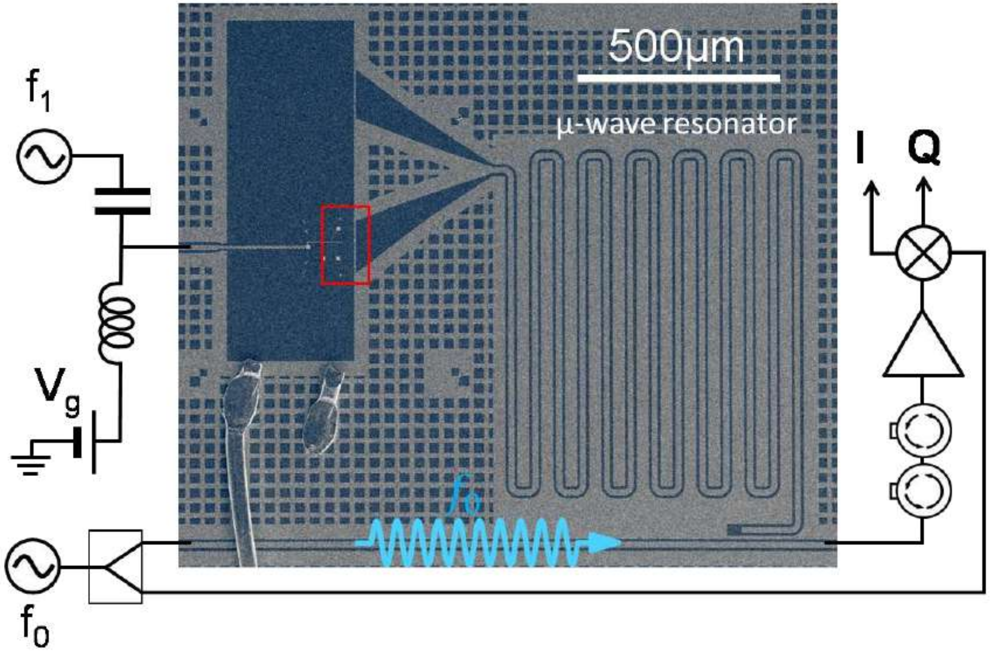




Tosi et al., PRX 9, 011010 (2019)
Metzger et al., PRR 3, 013036 (2021)

Experimental setup – Quantronics group at CEA Saclay

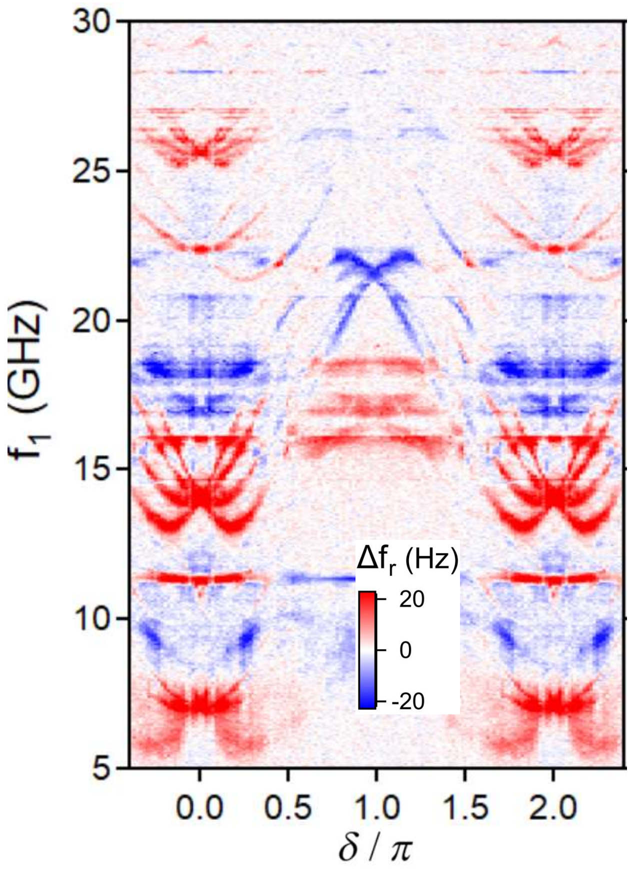


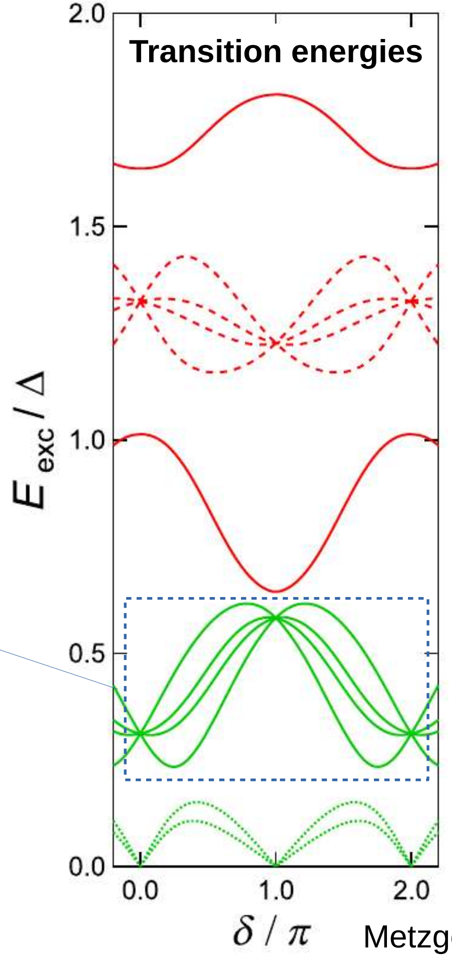


Tosi et al., PRX 9, 011010 (2019)
Metzger et al., PRR 3, 013036 (2021)

Two-tone spectroscopy

$V_g = 0.5V, \quad f_r = 3.26\,\mathrm{GHz}$

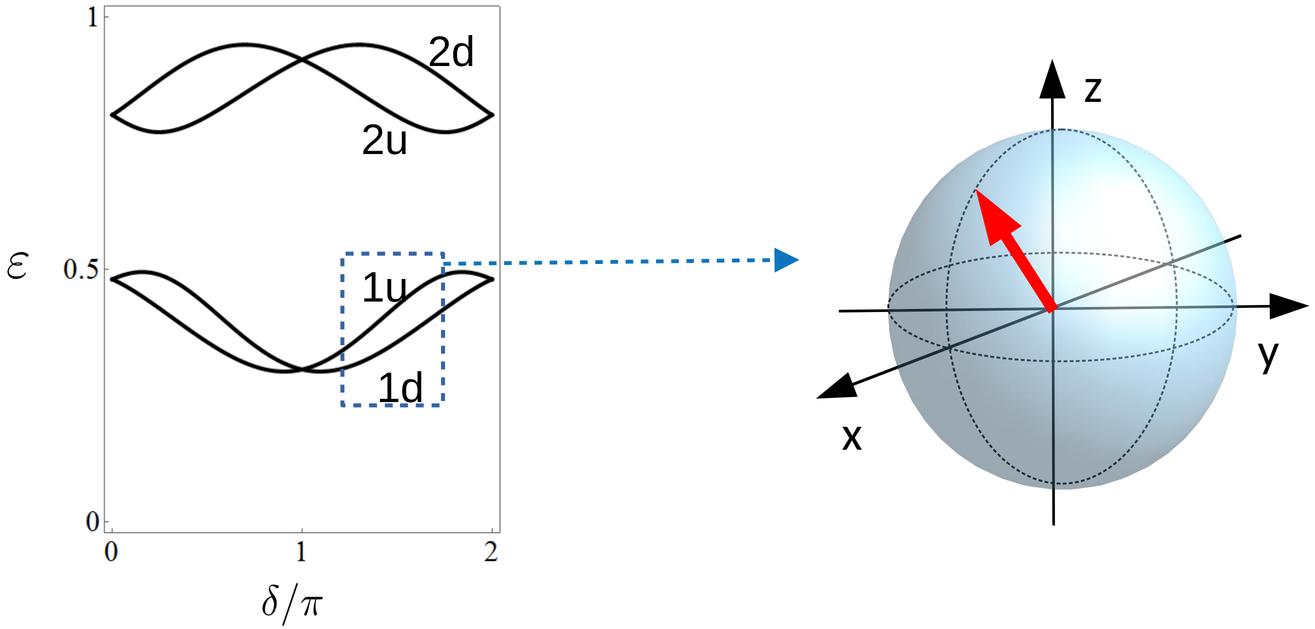




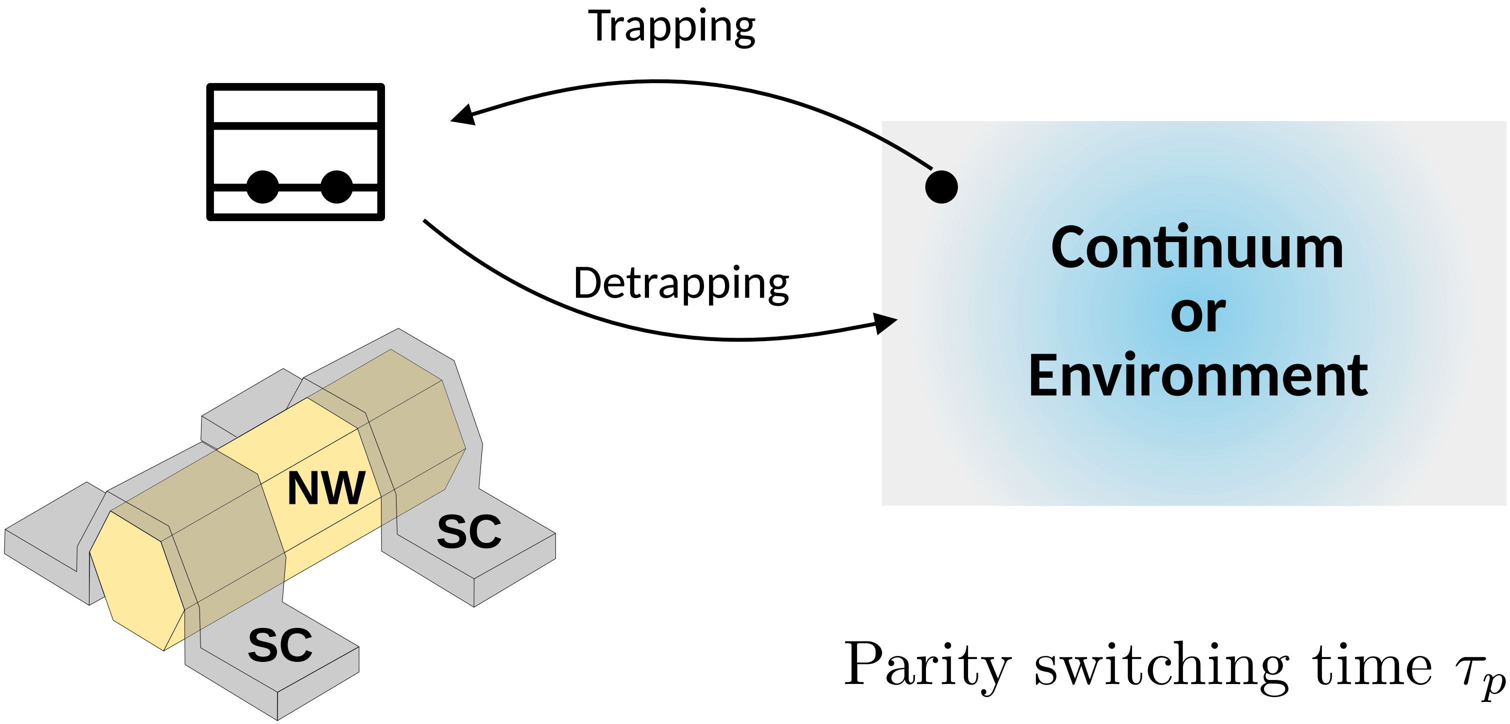
Metzger et al., PRR 3, 013036 (2021)

TO DO

- On-demand control of Andreev spin qubit
- Is a competitive qubit ? - coherence time



Fermion parity fluctuation



Parity switching time τ_p

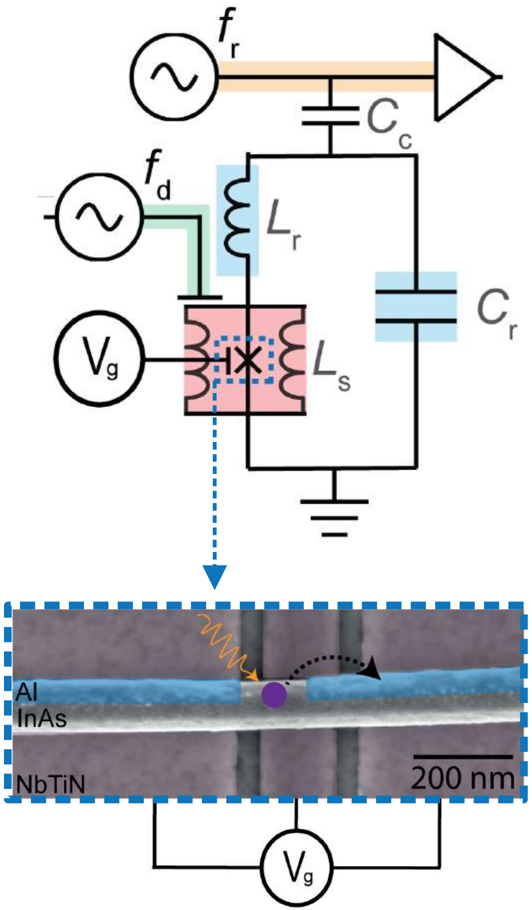
arXiv:2112.01936v1 3 Dec 2021

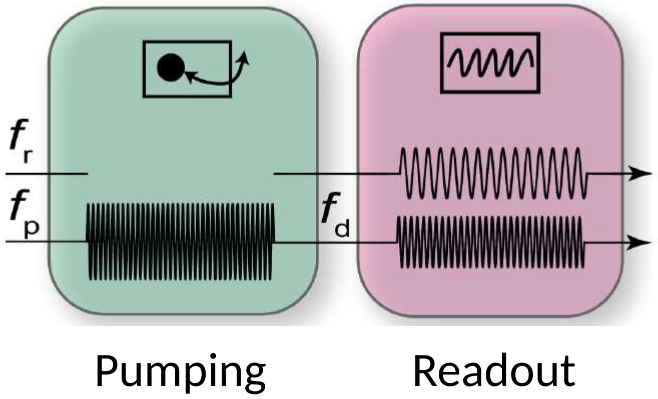
Dynamical polarization of the fermion parity in a nanowire Josephson junction

J. J. Wesdorp[1], L. Grünhaupt[1], A. Vaartjes[1], M. Pita-Vidal[1], A. Bargerbos[1],
L. J. Splitthoff[1], P. Krogstrup[3], B. van Heck[2], and G. de Lange[2]
[1] *QuTech and Kavli Institute of Nanoscience, Delft University of Technology, 2628 CJ, Delft, The Netherlands*
[2] *Microsoft Quantum Lab Delft, 2628 CJ, Delft, The Netherlands*
[3] *Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen and Microsoft Quantum Materials Lab Copenhagen, Denmark*
(Dated: December 6, 2021)

" … the fermion parity of the junction can be even or odd. … Here, we show that we can polarize the fermion parity dynamically using microwave pulses … "

Experimental setup





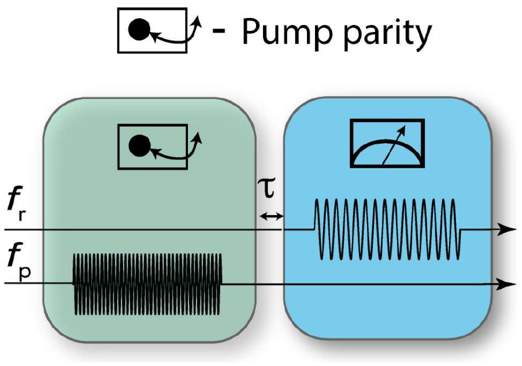
f_r : probe frequency

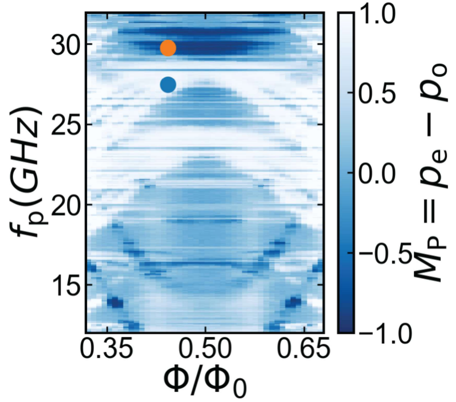
f_p : pumping pulse frequency

f_d : driving frequency

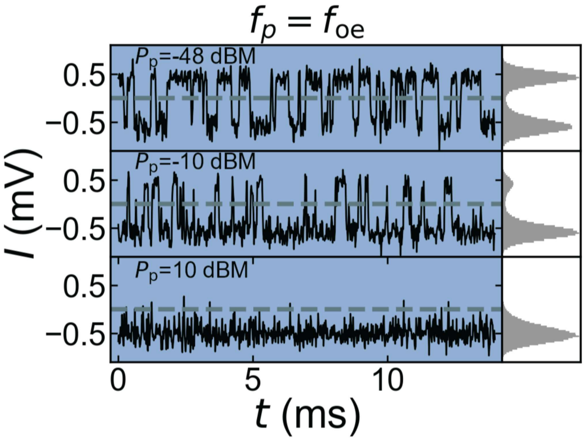
Wesdorp et al., arXiv:2112.01936(2021)

Fermion parity polarization

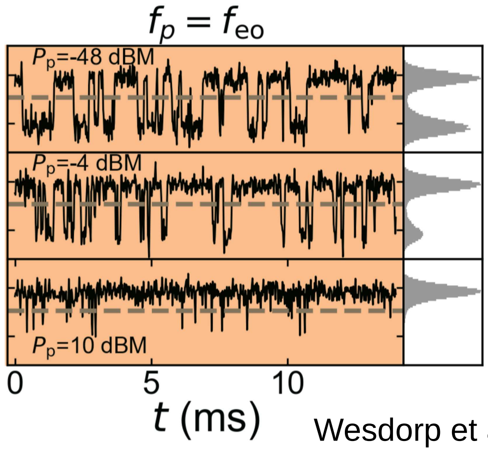




Odd pumping → even parity polarization

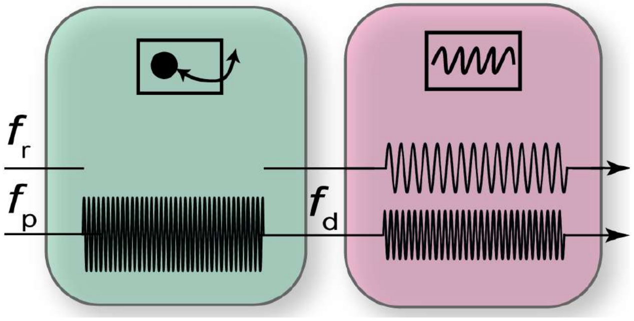


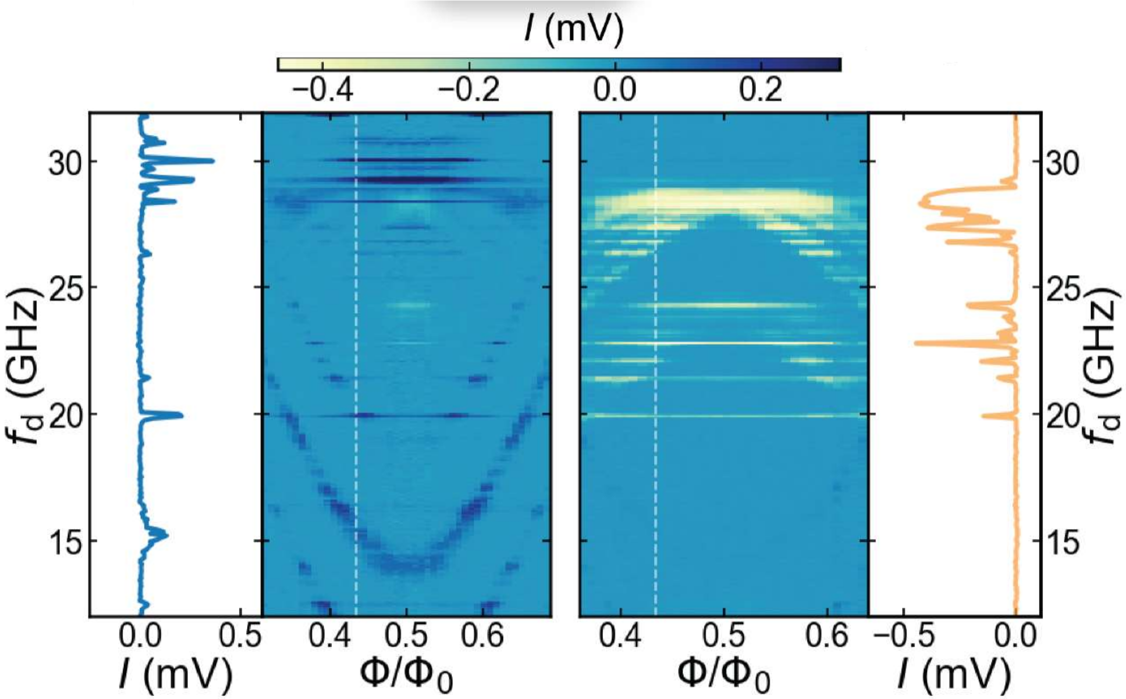
Even pumping → odd parity polarization



Wesdorp et al., arXiv:2112.01936(2021)

Experimental observation





Wesdorp et al., arXiv:2112.01936(2021)

arXiv:2207.05782v1 12 Jul 2022

Dynamical parity selection in superconducting weak links

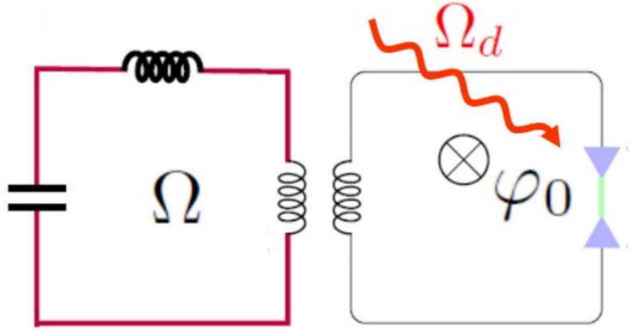
Nico Ackermann,[1] Alex Zazunov,[2] Sunghun Park,[1] Reinhold Egger,[2] and Alfredo Levy Yeyati[1]

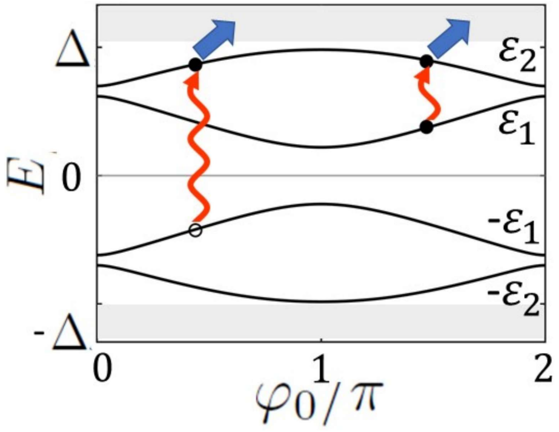
[1] *Departamento de Física Teórica de la Materia Condensada, Condensed Matter Physics Center (IFIMAC) and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, 28049 Madrid, Spain*

[2] *Institut für Theoretische Physik, Heinrich-Heine-Universität, D-40225 Düsseldorf, Germany*

“ … dynamical polarization in a given parity sector is achievable by applying a microwave pulse matching a transition in the opposite parity sector. … ”

What we solve





Finite length nanowire Josephson junction

Lindblad equation

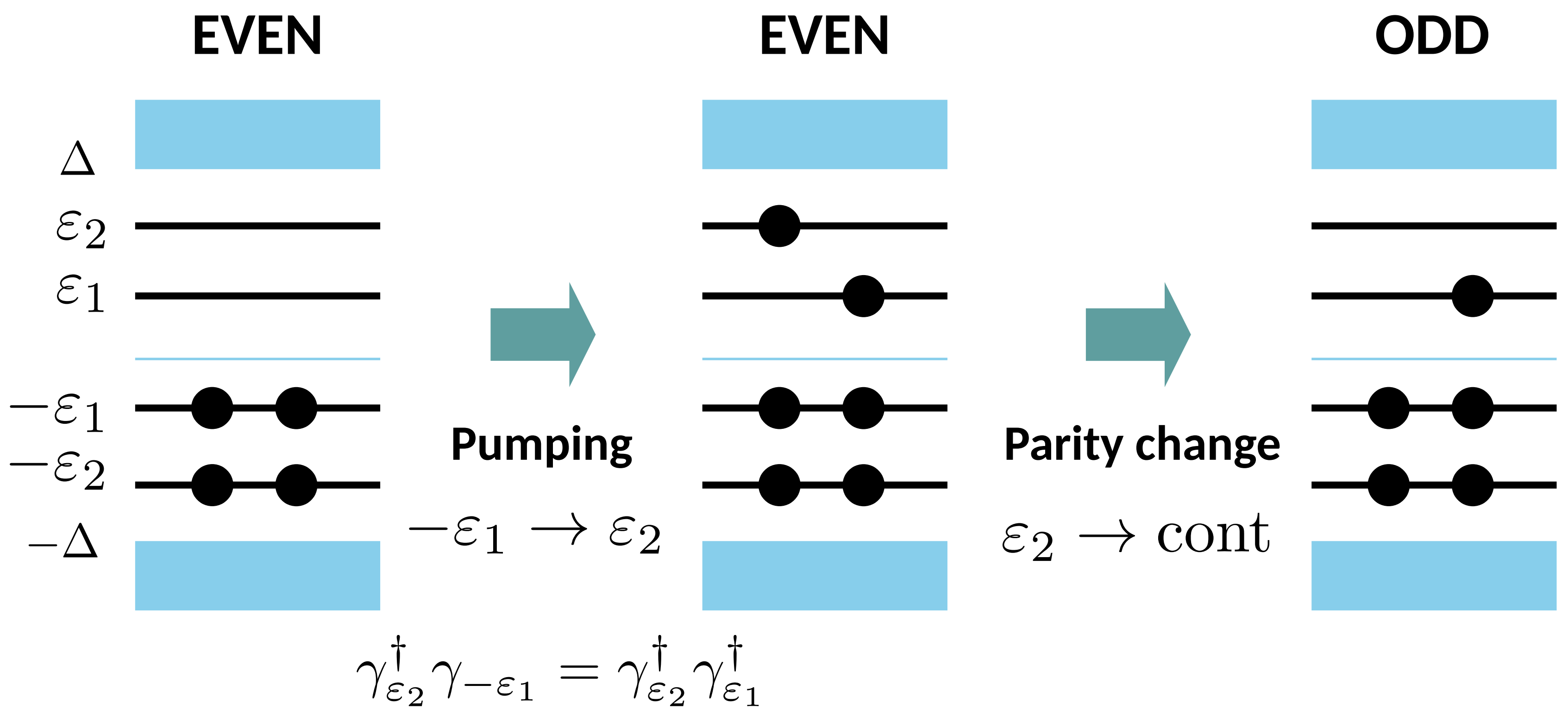
$$\dot{\rho} = -i\,[H_J, \rho] + \sum_{\nu \neq \nu'} \Gamma_{\nu\nu'} \mathcal{L}(Q_{\nu' nu})\rho$$

$$\Gamma_{\nu\nu'} = 2\pi\,|I_{\nu'\nu}|^2\, J(\omega_{\nu\nu'})\,[n_B(\omega_{\nu\nu'}) + 1]$$

$$\mathcal{L}(Q_{\nu'\nu})\rho = Q_{\nu'\nu}\rho Q^\dagger_{\nu'\nu} - \frac{1}{2}\left\{Q^\dagger_{\nu'\nu} Q_{\nu'\nu}, \rho\right\}$$

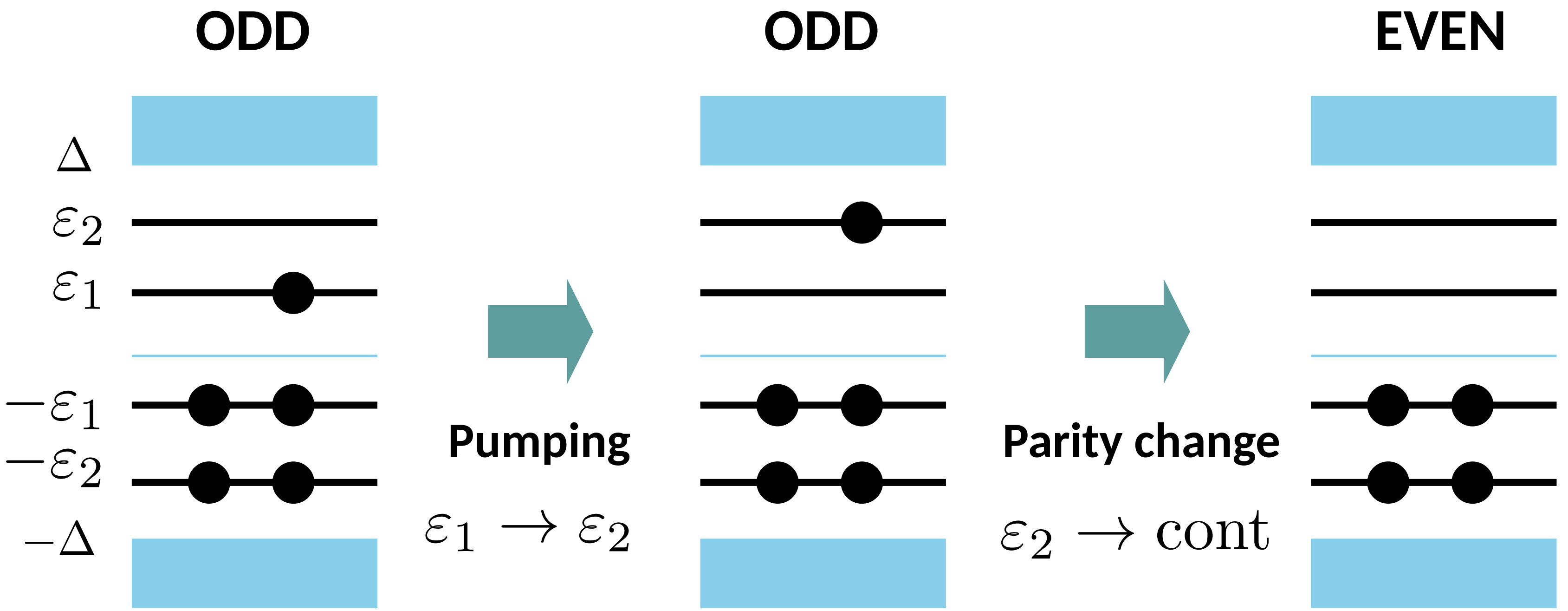
Ackermann et al., arXiv:2207.05782

Main mechanism – Odd polarization



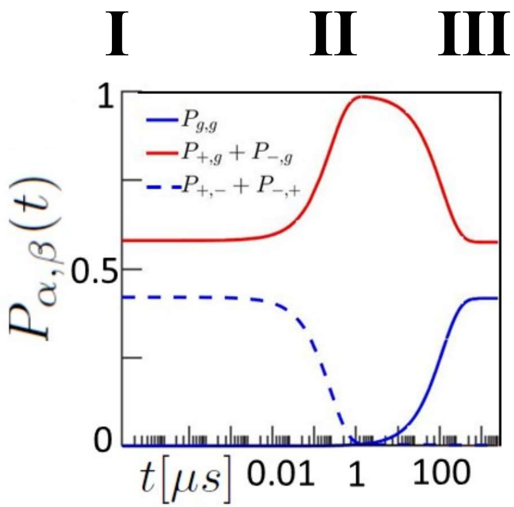
Mixed pair transition ⟶ Odd parity polarization

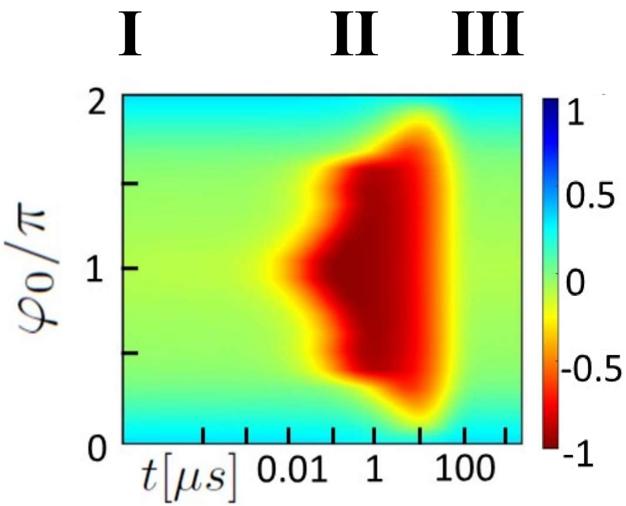
Main mechanism – Even polarization



Single quasiparitcle transition ⟶ Even parity polarization

Theory results – Odd polarization



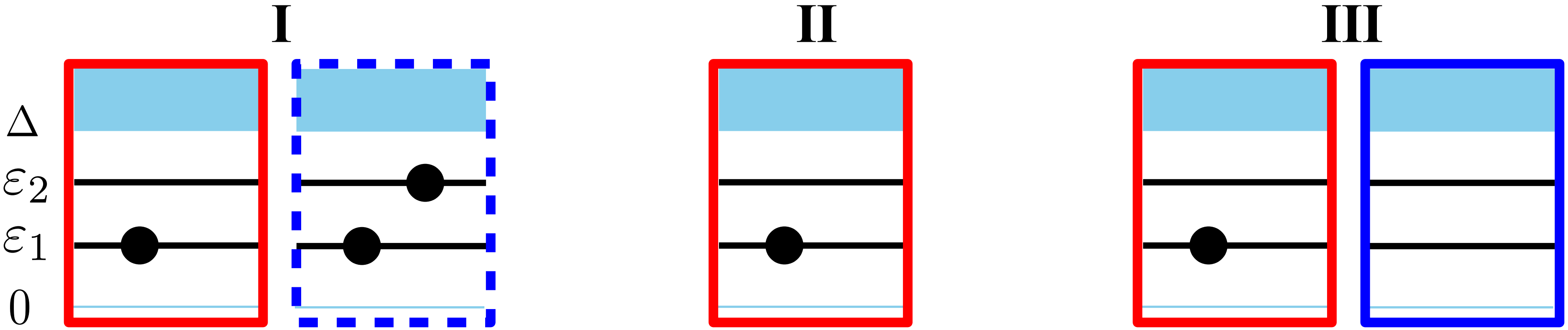


I: P(t=0)

II: Transient period

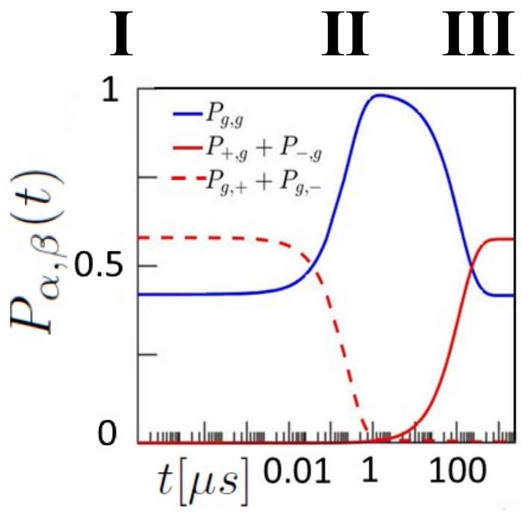
III: Stationary period

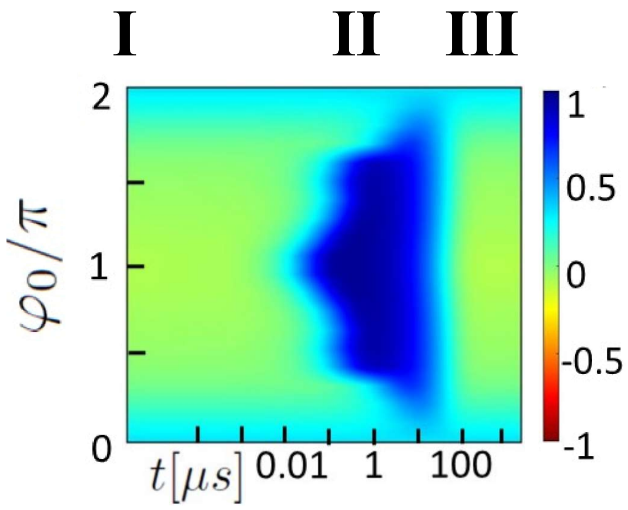
$$\Delta P(t) = P_{\text{even}}(t) - P_{\text{odd}}(t)$$



Ackermann et al., arXiv:2207.05782

Theory results – even polarization





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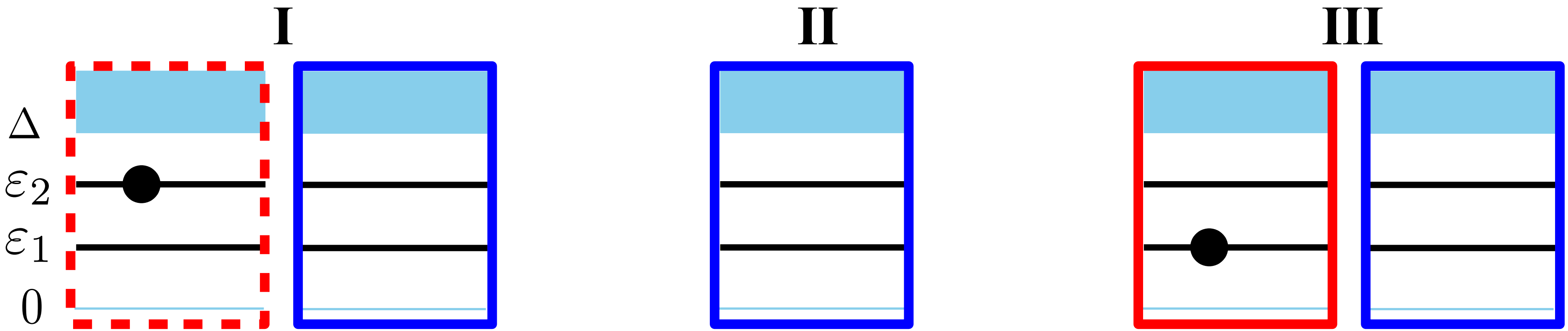
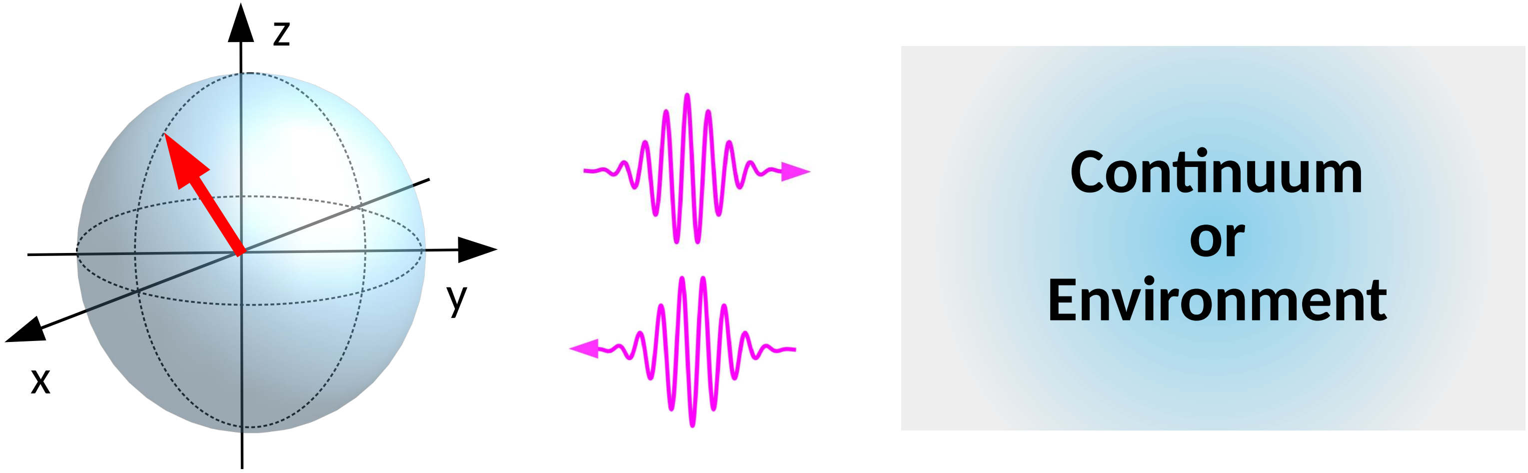


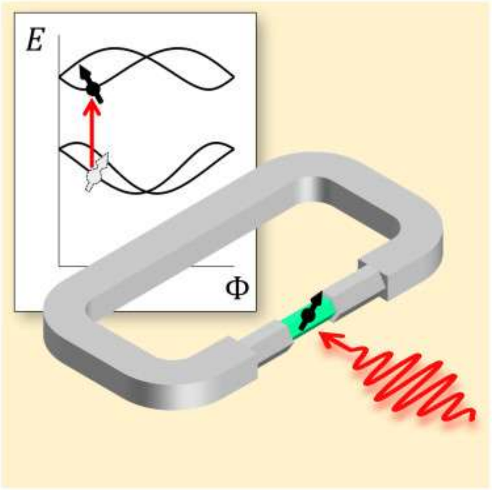
Ackermann et al., arXiv:2207.05782

TO DO

- Theoretical study of the spin-orbit effect
- How to use a bath (environment & continuum) for qubit control



Summary

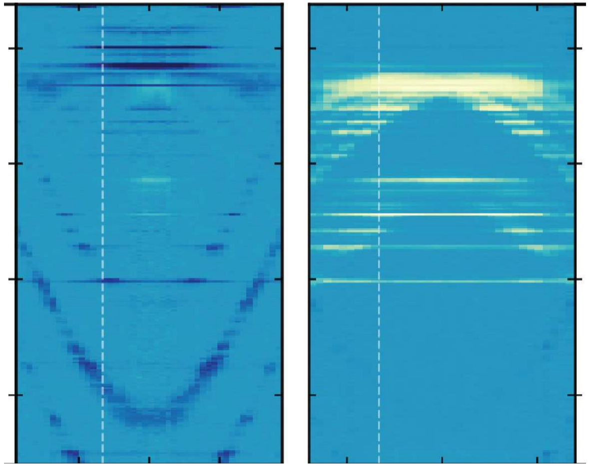


- Nanowire Josephson junction

  - Spin-orbit coupling and multichannel structure
  - Spin-split Andreev levels at zero magnetic field

- Research towards real device applications

  - Coherent manipulation by a microwave
  - Dynamical control of fermion parity



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Leandro Tosi, Andrea Reynoso (Bariloche, Argentina)

Cyril Metzger (Boulder, USA)

Alex Zazunov, Reinhold Egger (Dusseldorf, Germany)