

Minimal Kitaev chains: toward braiding and fusion

R. Seoane Souto*, A. Tsintzis, M. Pino, K. Flensberg, J. Danon,
M. Leijnse, and R. Aguado

Quantum Matter workshop
May 22nd 2024

*ruben.seoane@csic.es



CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS



Center for
Quantum
Devices

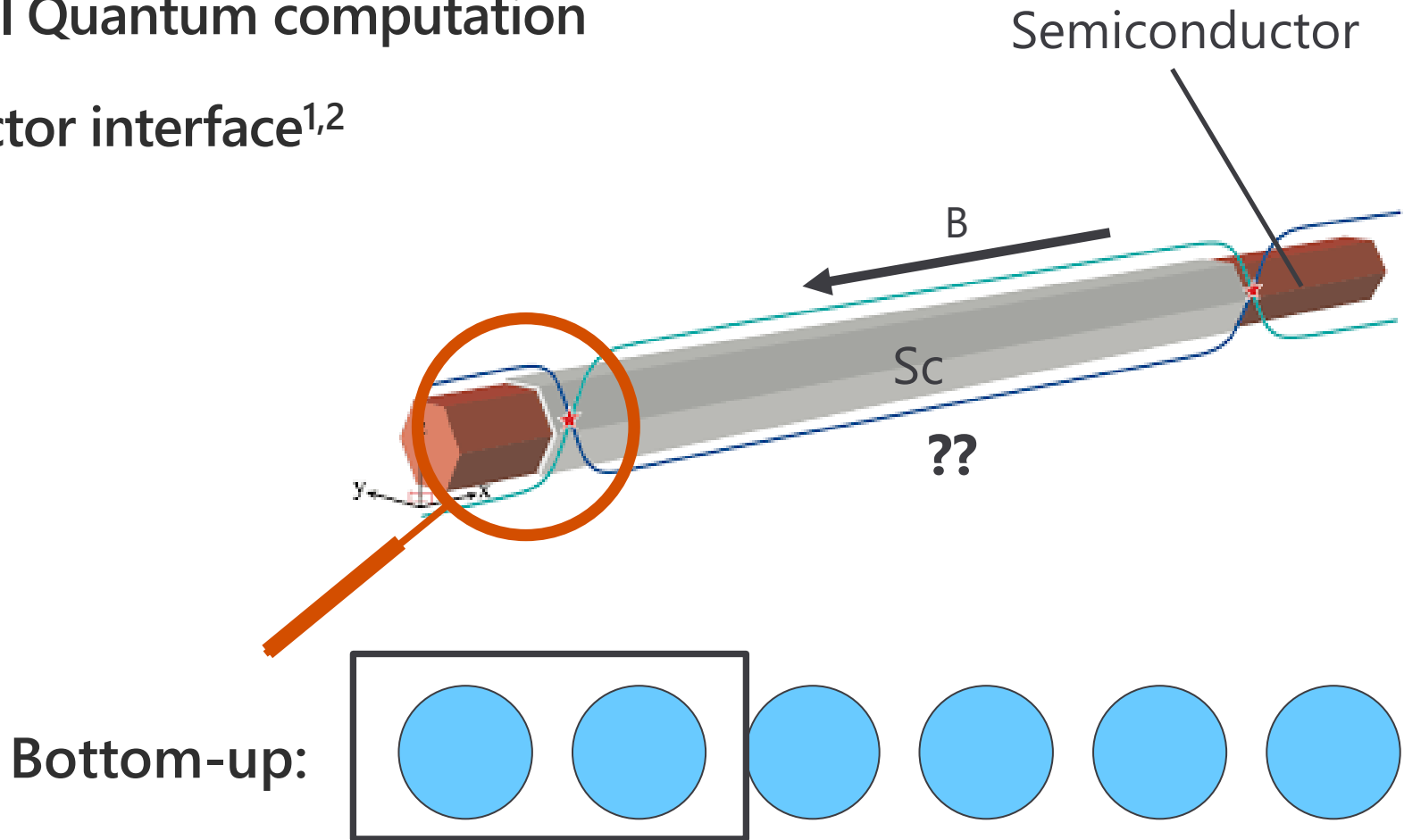
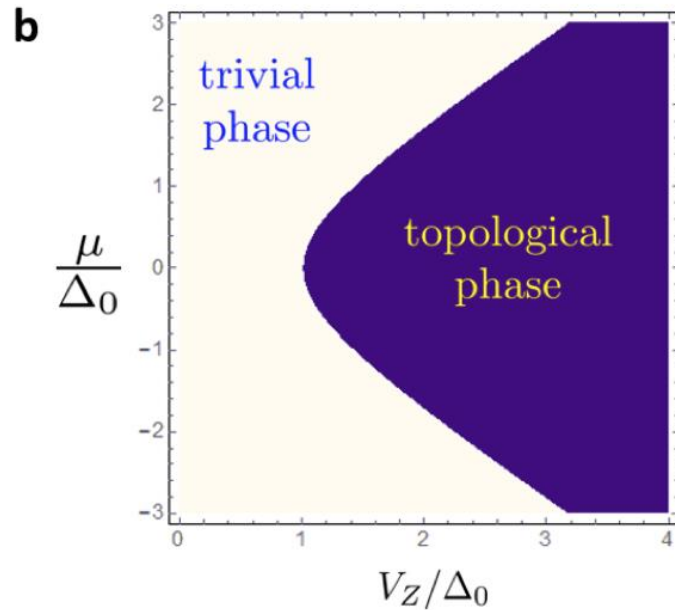


NanoLund
CENTER FOR NANOSCIENCE

Introduction

Majorana states → Topological Quantum computation

Semiconductor-superconductor interface^{1,2}



¹R. Lutchyn et. al. PRL **105**, 077001 (2010)

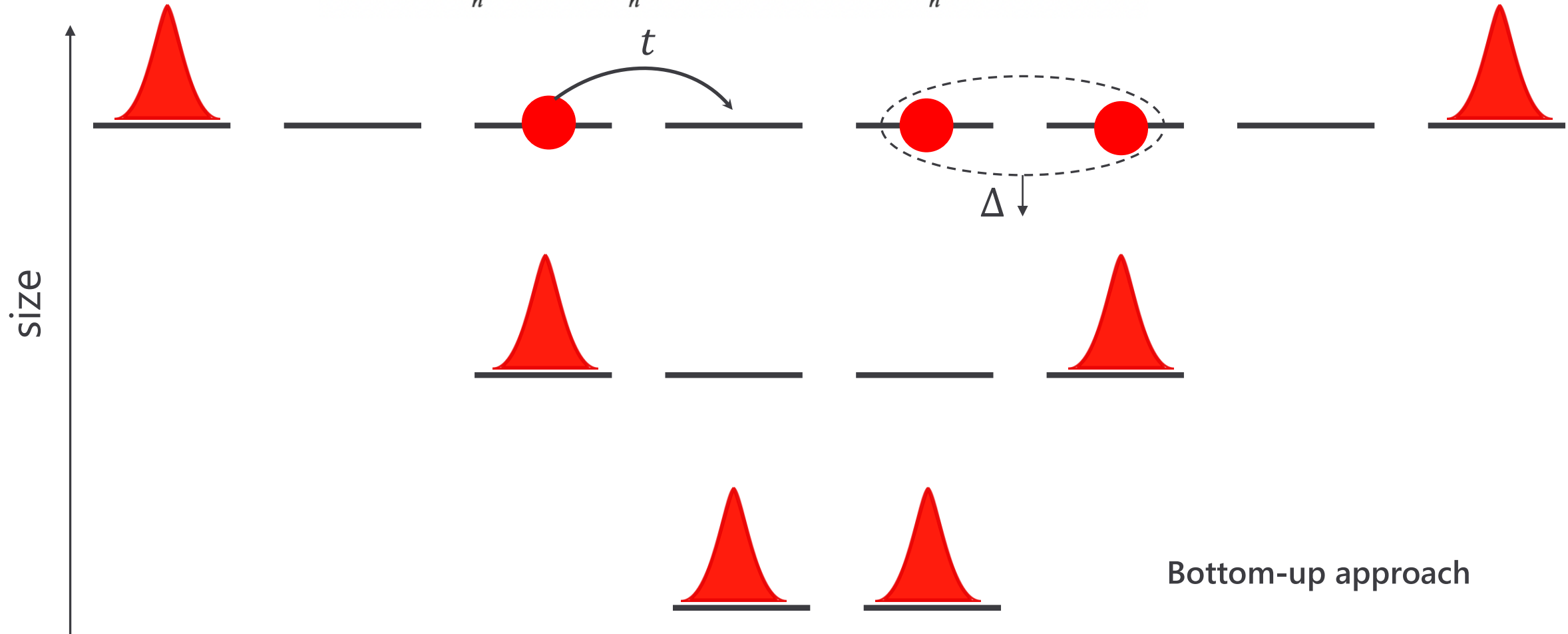
²Y. Oreg et. al. PRL **105**, 177002 (2010)

Topological superconductivity

Kitaev model

$$H = -\mu \sum_n c_n^\dagger c_n - t \sum_n (c_{n+1}^\dagger c_n + \text{h.c.}) + \Delta \sum_n (c_n c_{n+1} + \text{h.c.})$$

$\Delta = t$ and $\mu = 0 \rightarrow$ Majoranas



Bottom-up approach

Fine-tuned Majoranas



Elastic cotunneling t : t_{ECT}

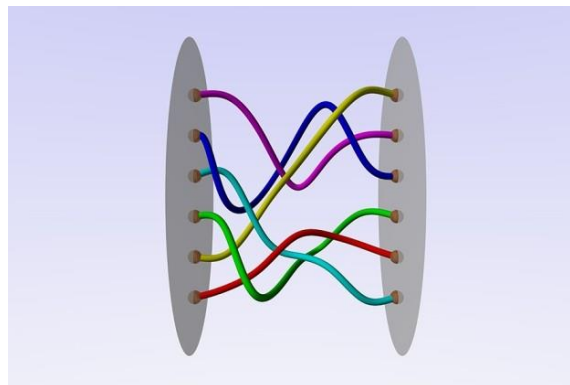
Crossed Andreev reflection Δ : t_{CAR}



=
Majoranas!

No topological protection

All properties from Majoranas

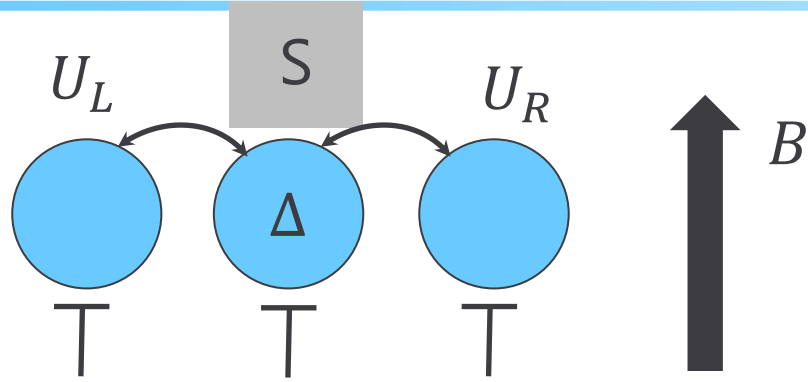


Interactions?

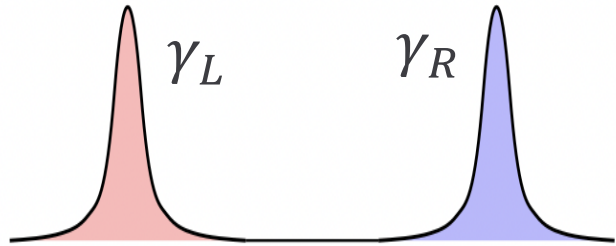
Strong tunnel coupling?

Finite field in the dots?

Fine-tuned Majoranas



High MP



Low MP



$$\begin{aligned}
 H_{QDs} = & \sum_{\sigma,j} \varepsilon_j n_{j\sigma} + \sum_j U_j n_{j\uparrow} n_{j\downarrow} + \sum_j E_{Zj} n_{j\downarrow} \\
 & + \sum_{\sigma,j \neq C} \left[t_j d_{j\sigma}^\dagger d_{C\sigma} + h.c. \right] \\
 & + \sum_{j \neq C} \left[t_j^{SO} d_{j\uparrow}^\dagger d_{C\downarrow} - t_j^{SO} d_{j\downarrow}^\dagger d_{C\uparrow} + h.c. \right] \\
 & + \Delta \left[d_{C\uparrow}^\dagger d_{C\downarrow}^\dagger + h.c. \right].
 \end{aligned}$$

Majorana polarization (MP):

$$M_j = \frac{\sum_{\sigma} (w_{\sigma}^2 - z_{\sigma}^2)}{\sum_{\sigma} (w_{\sigma}^2 + z_{\sigma}^2)},$$

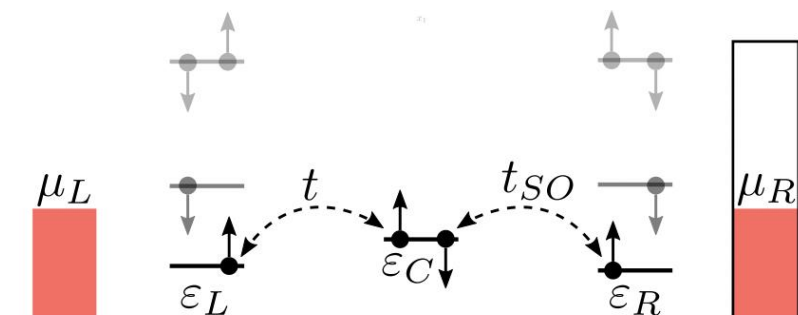
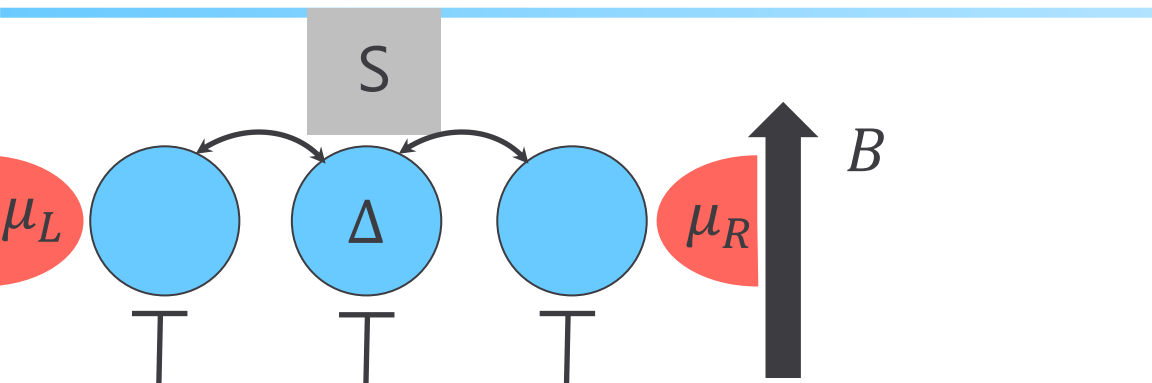
$|MP| \approx 1 \rightarrow$ Good Majorana

$$w_{\sigma} = \langle O | (d_{j\sigma} + d_{j\sigma}^\dagger) | E \rangle,$$

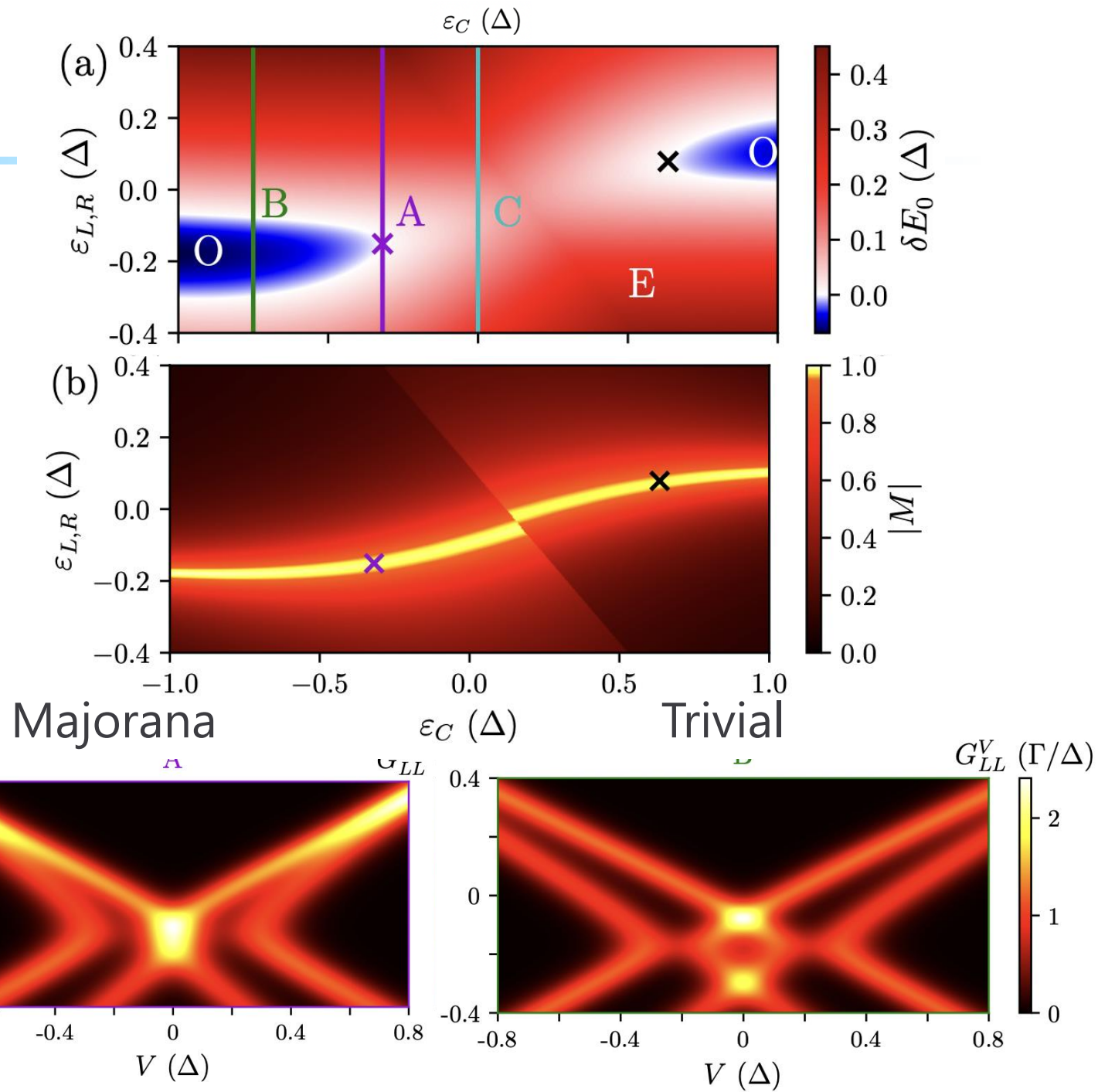
$|MP| < 1 \rightarrow$ Bad Majorana

$$z_{\sigma} = \langle O | (d_{j\sigma} - d_{j\sigma}^\dagger) | E \rangle,$$

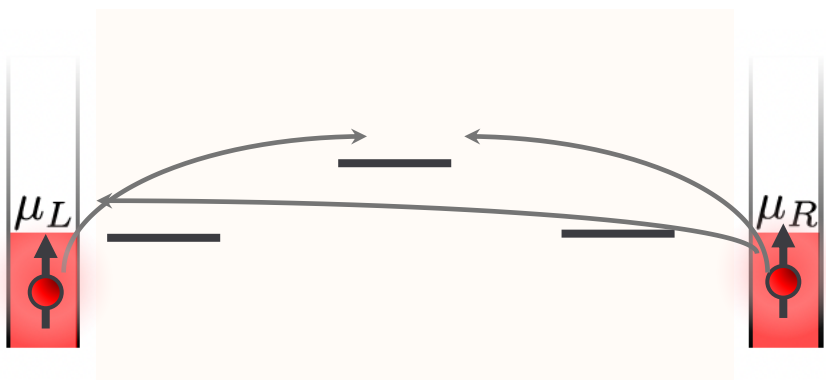
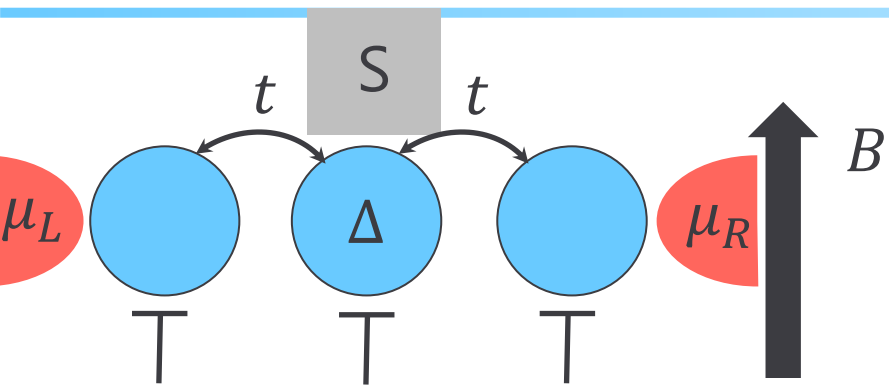
Fine-tuned Majoranas



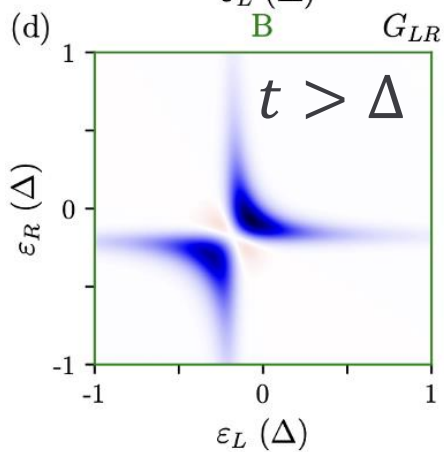
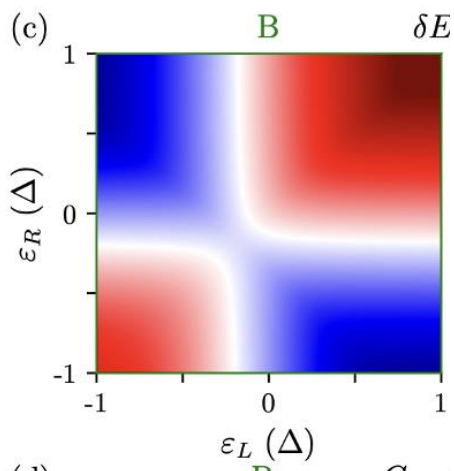
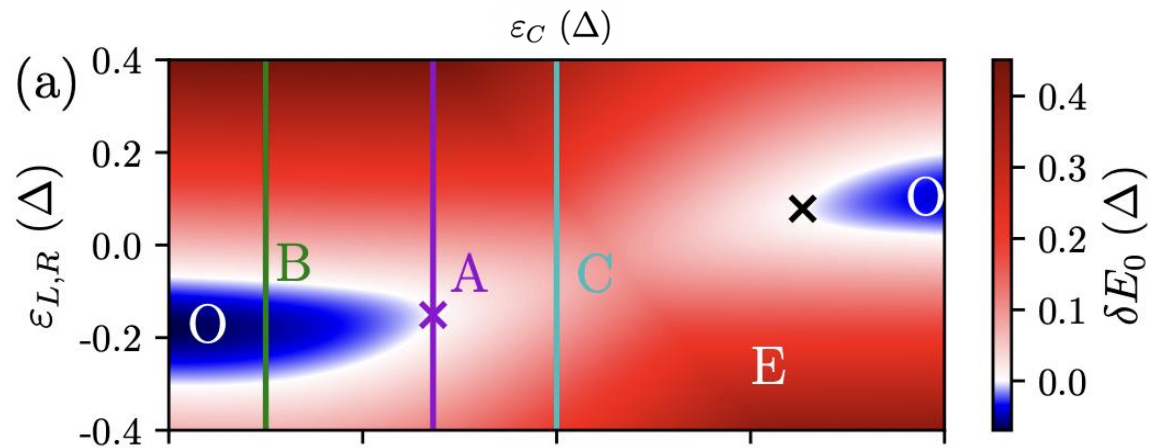
QMEQ: Transport calculations



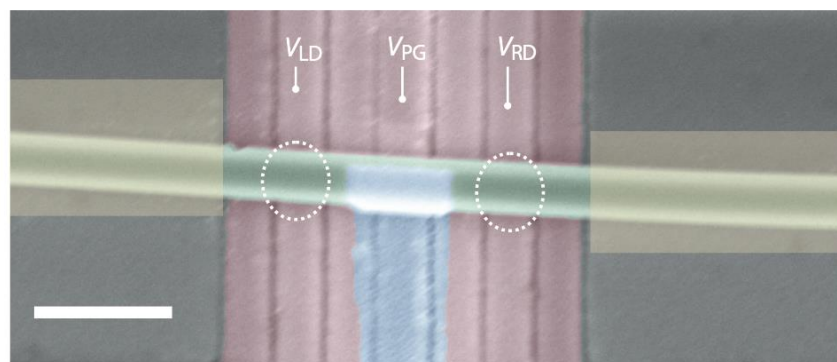
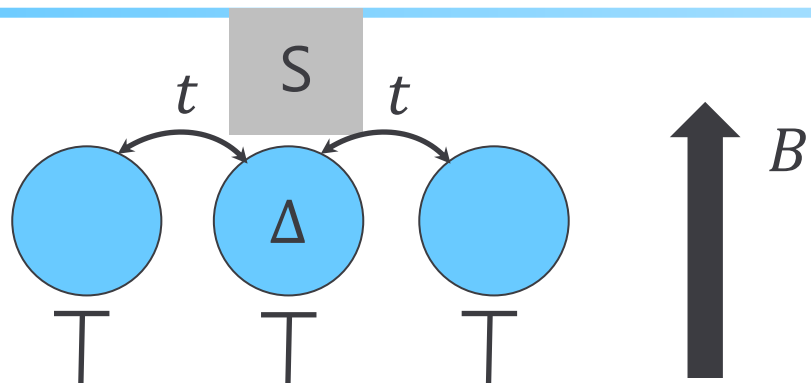
Fine-tuned Majoranas



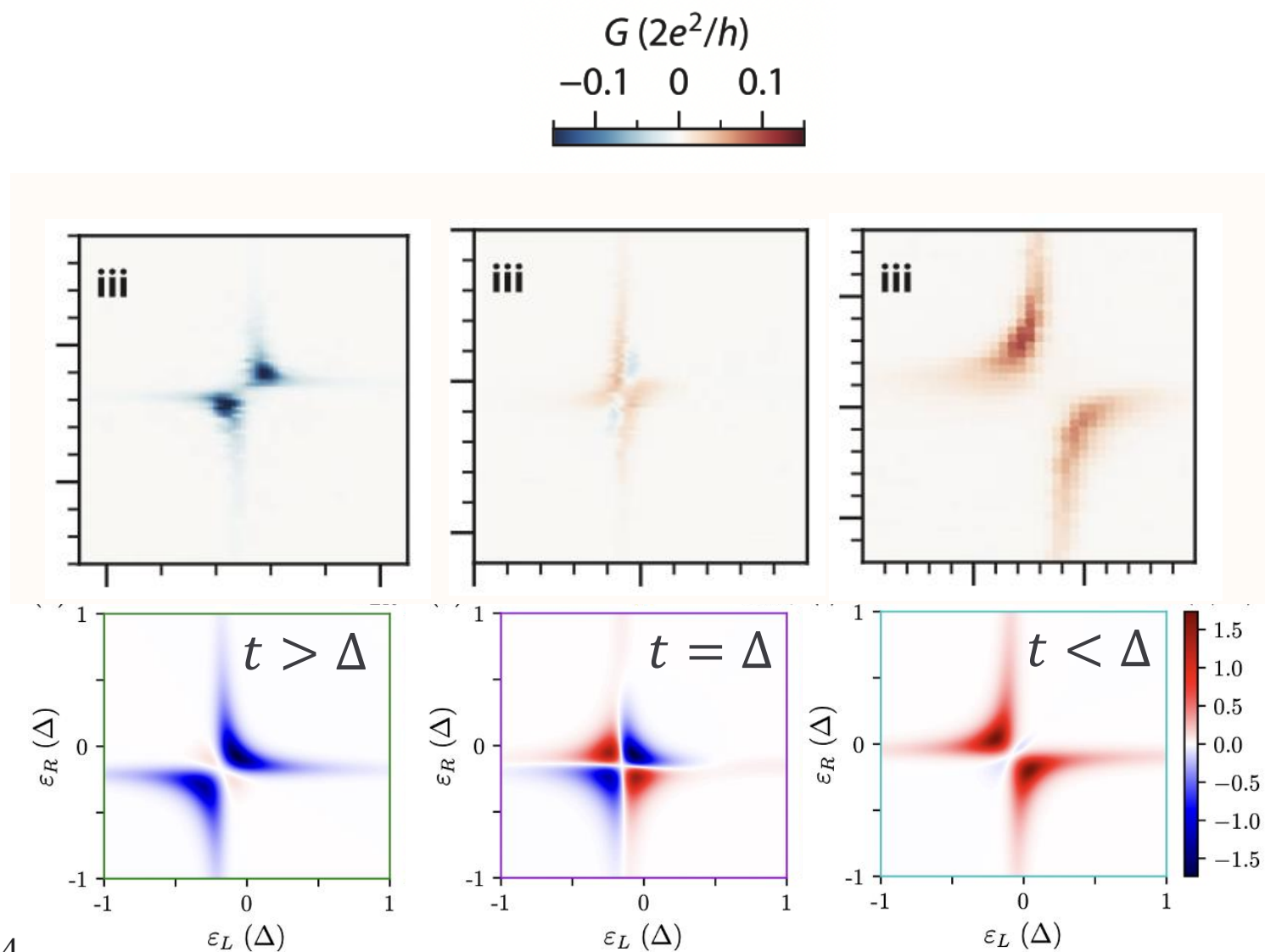
$$G_{LR} = \frac{dI_L}{dV_R}$$



Fine-tuned Majoranas: experiment



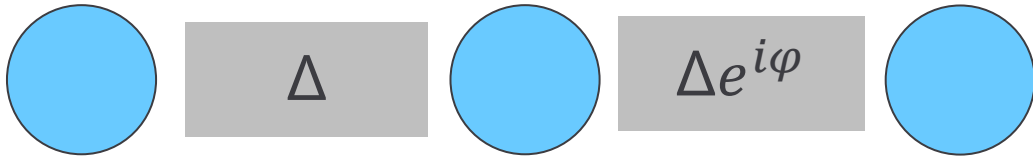
$$G_{LR} = \frac{dI_L}{dV_R}$$



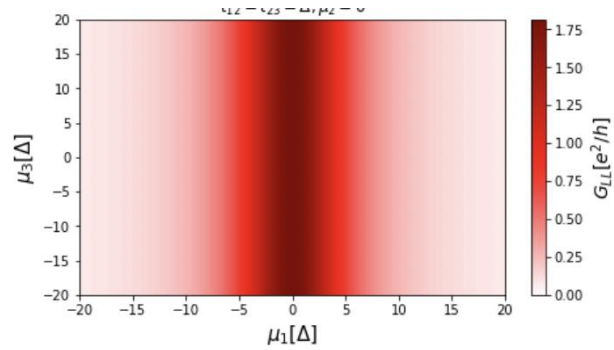
Longer Kitaev chains

Gain protection vs parameters fluctuations

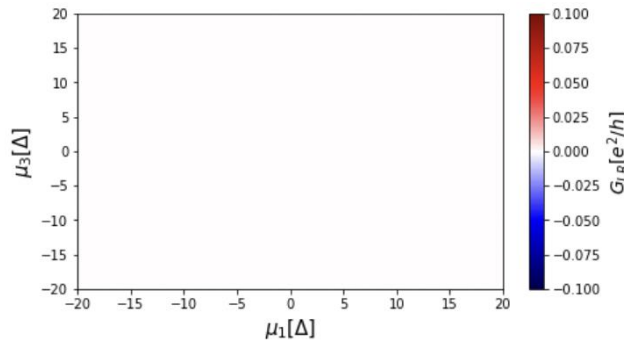
Theory



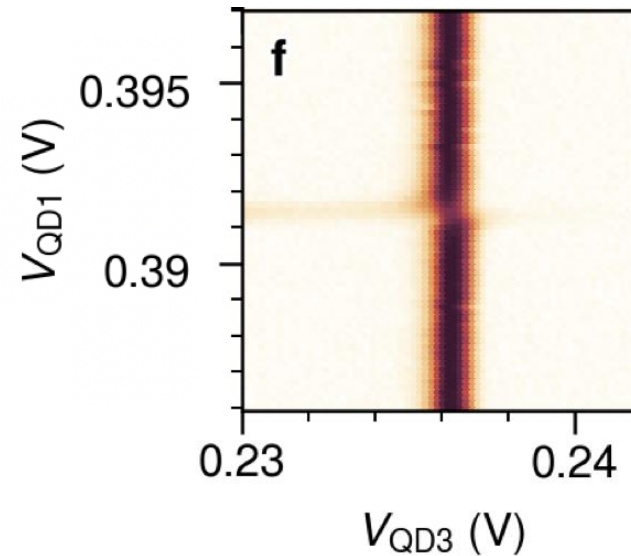
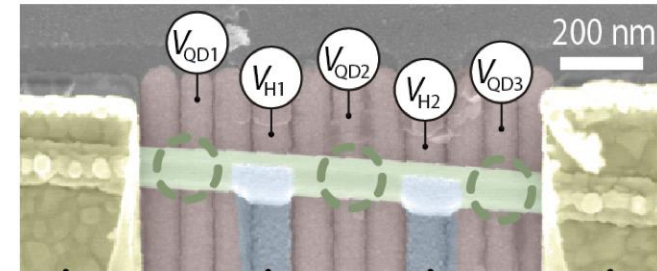
Local conductance



Non-local conductance



Experiment

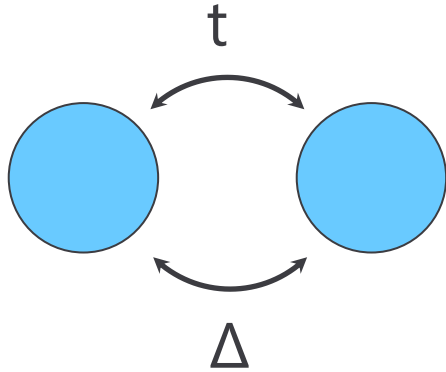


Outlook

- Fine-tuned topology
- **Characterization**
- Quantum coherent experiments
- Conclusions

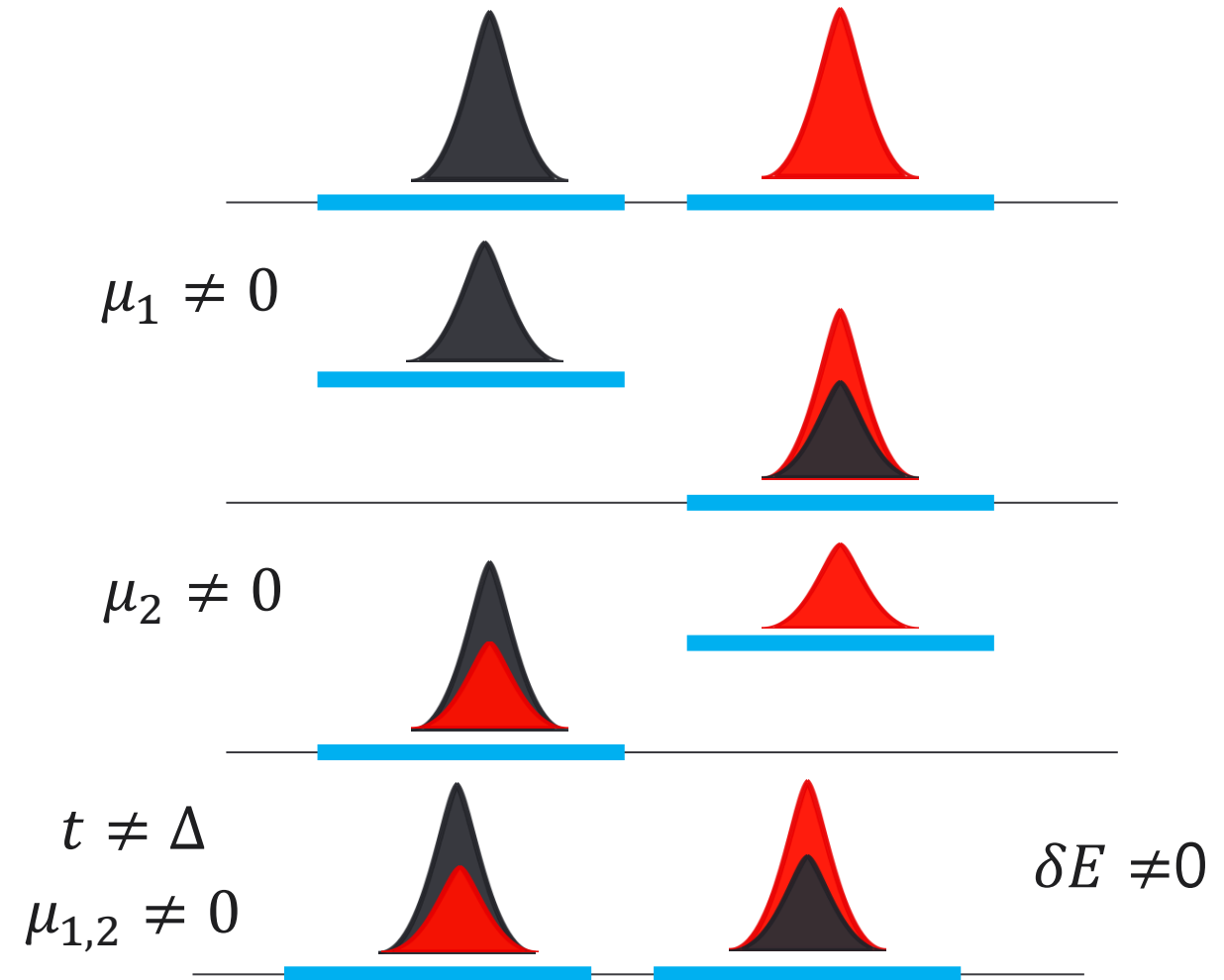
Fine-tuned Majoranas

Simplest model

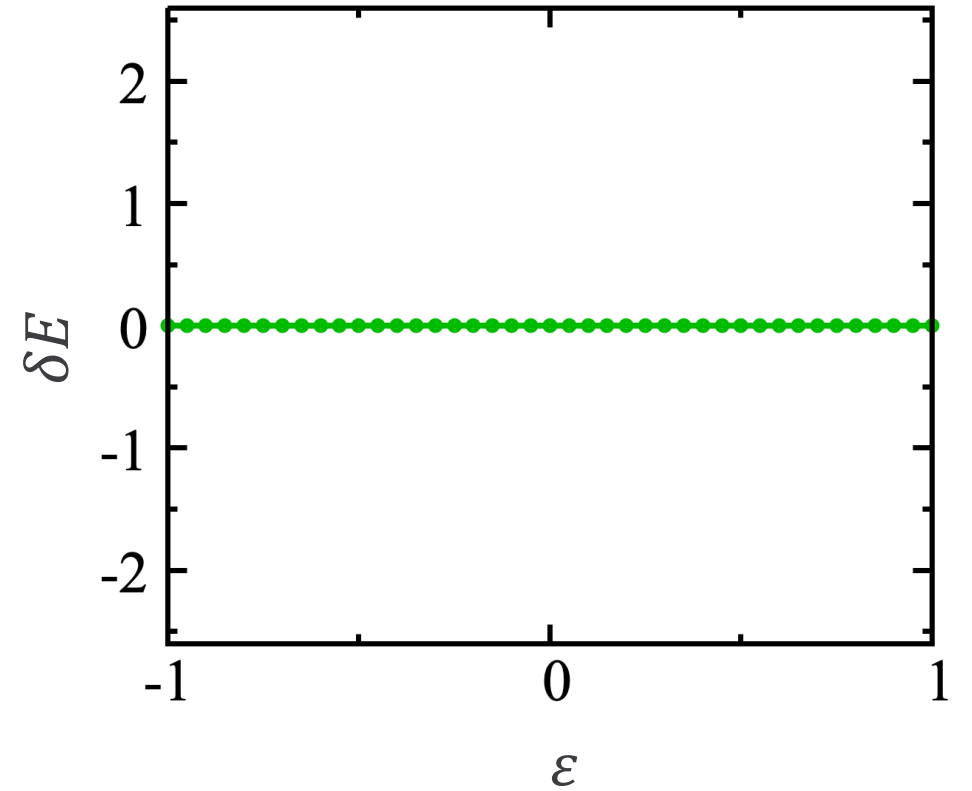
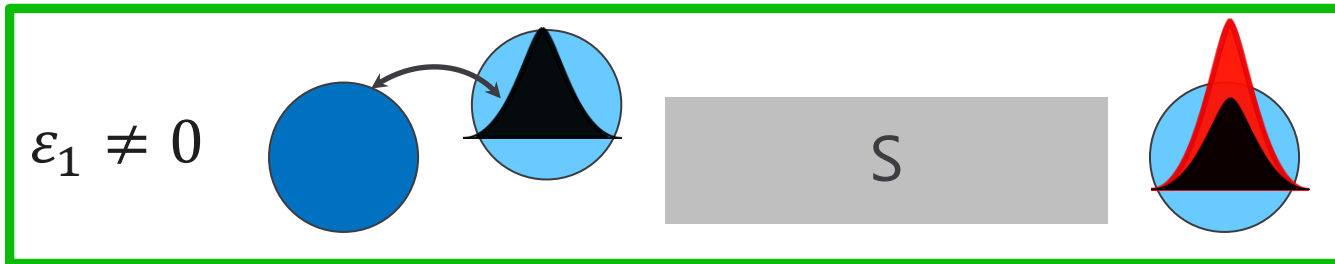
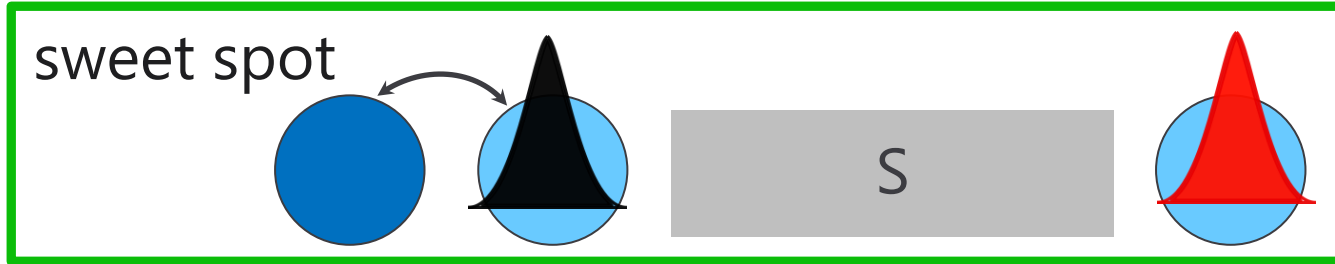


$$H = \sum_{n=1,2} \mu_n d_n^\dagger d_n + t d_1^\dagger d_2 + \Delta d_1^\dagger d_2^\dagger + H.c.$$

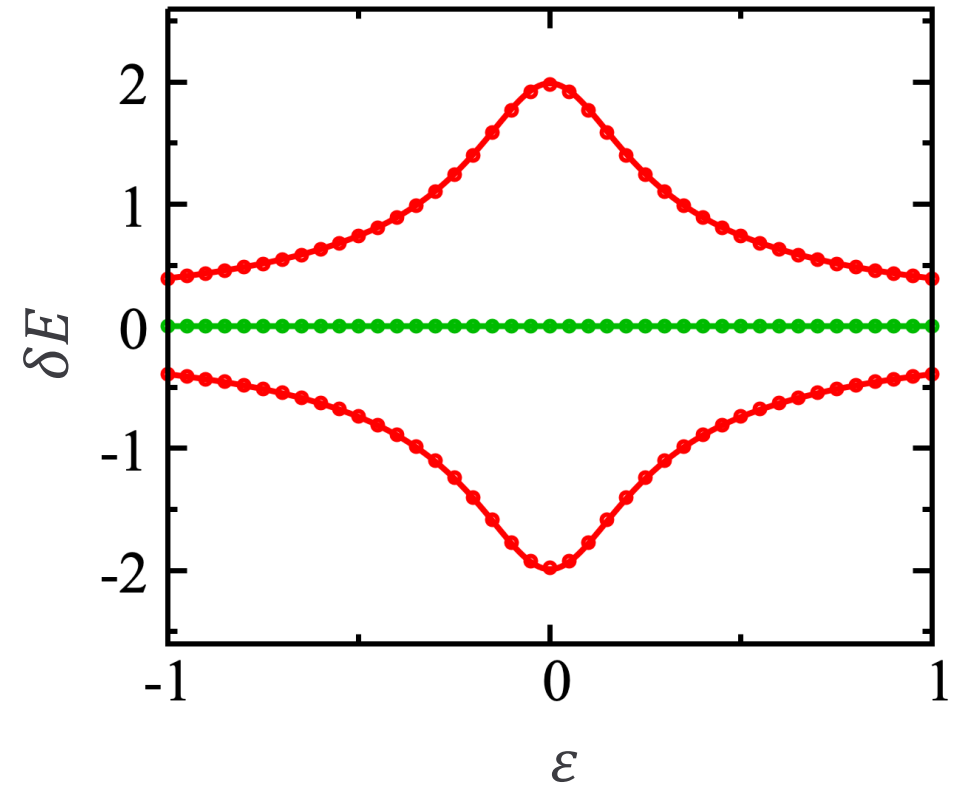
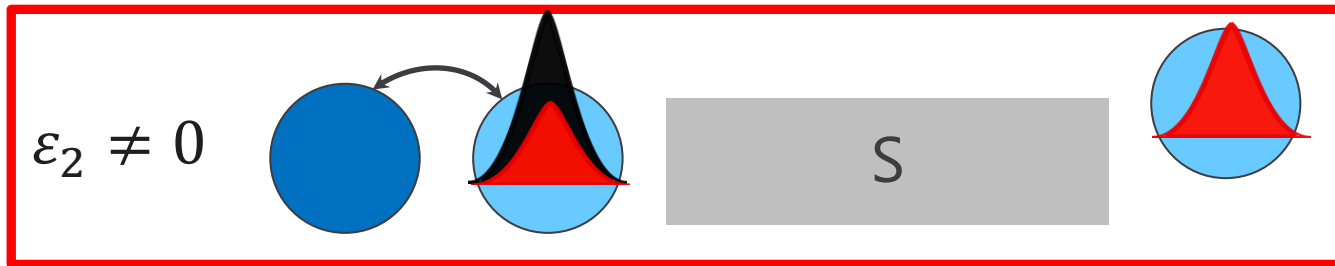
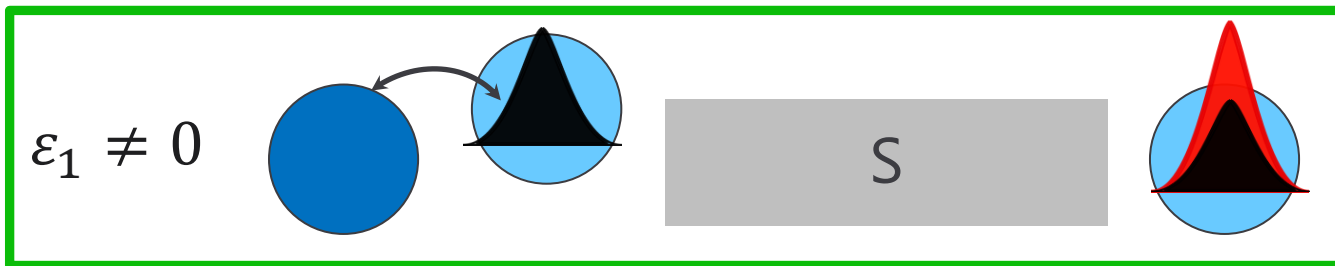
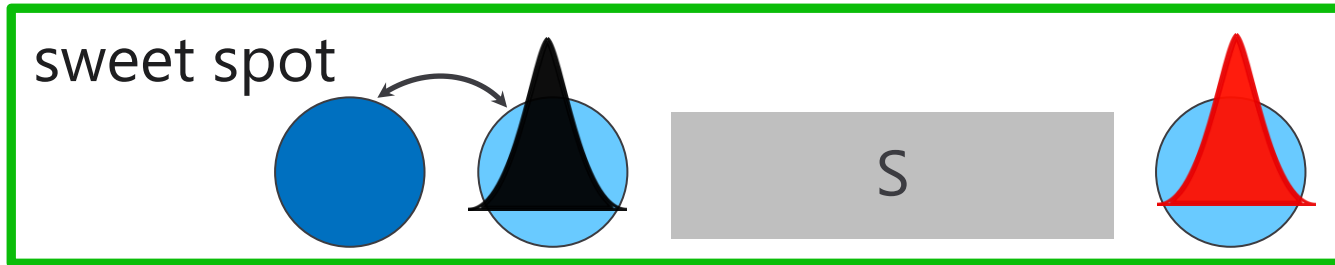
Sweet spot: $t = \Delta, \mu_{1,2} = 0$



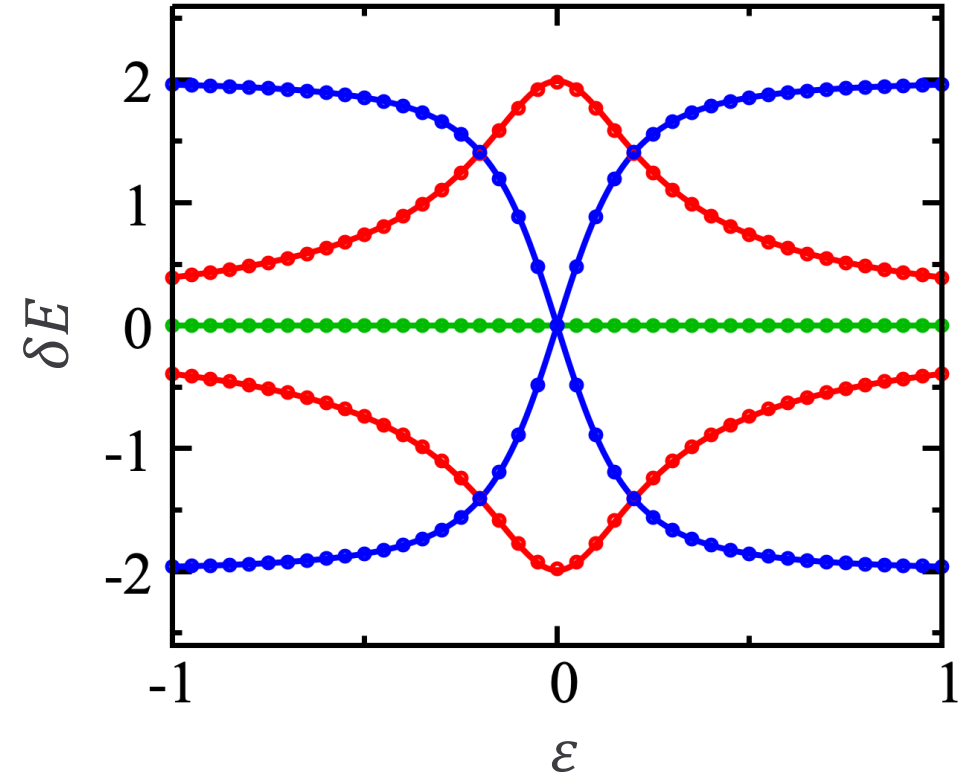
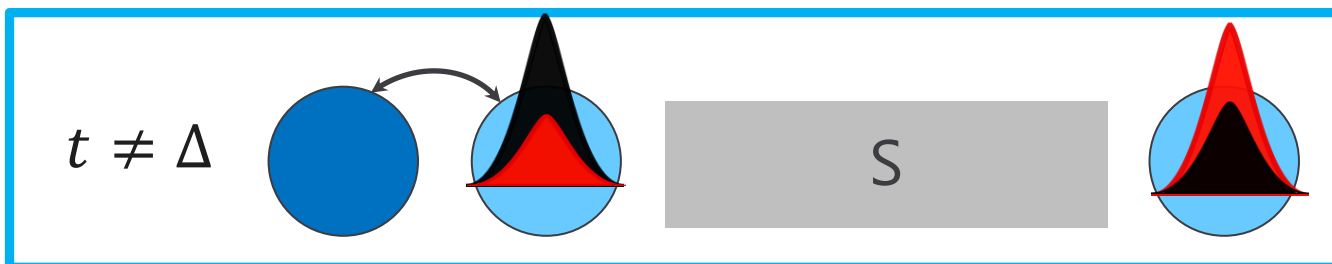
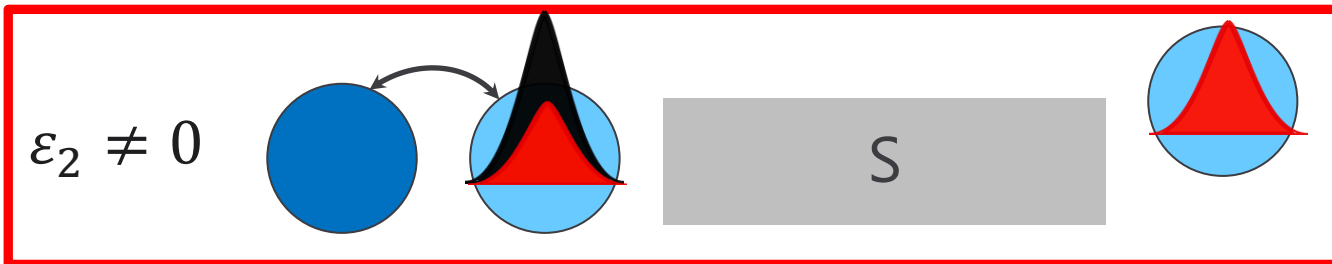
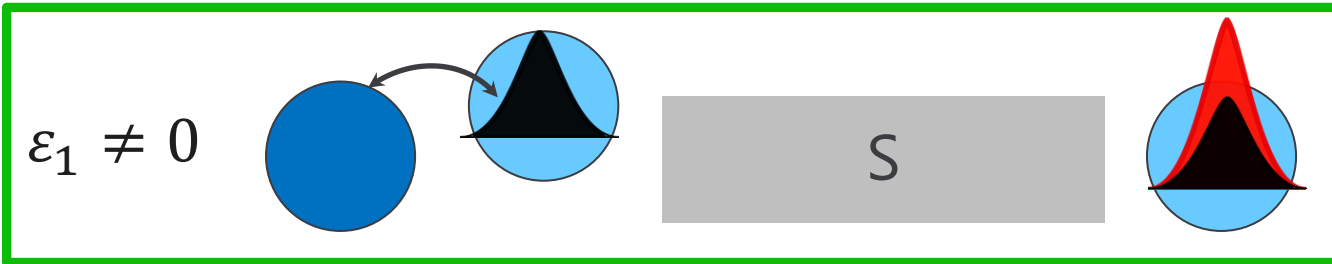
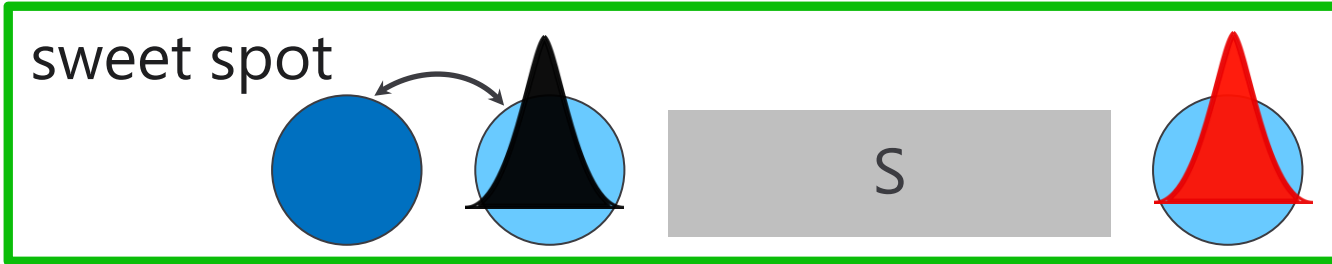
Majorana assessment



Majorana assessment



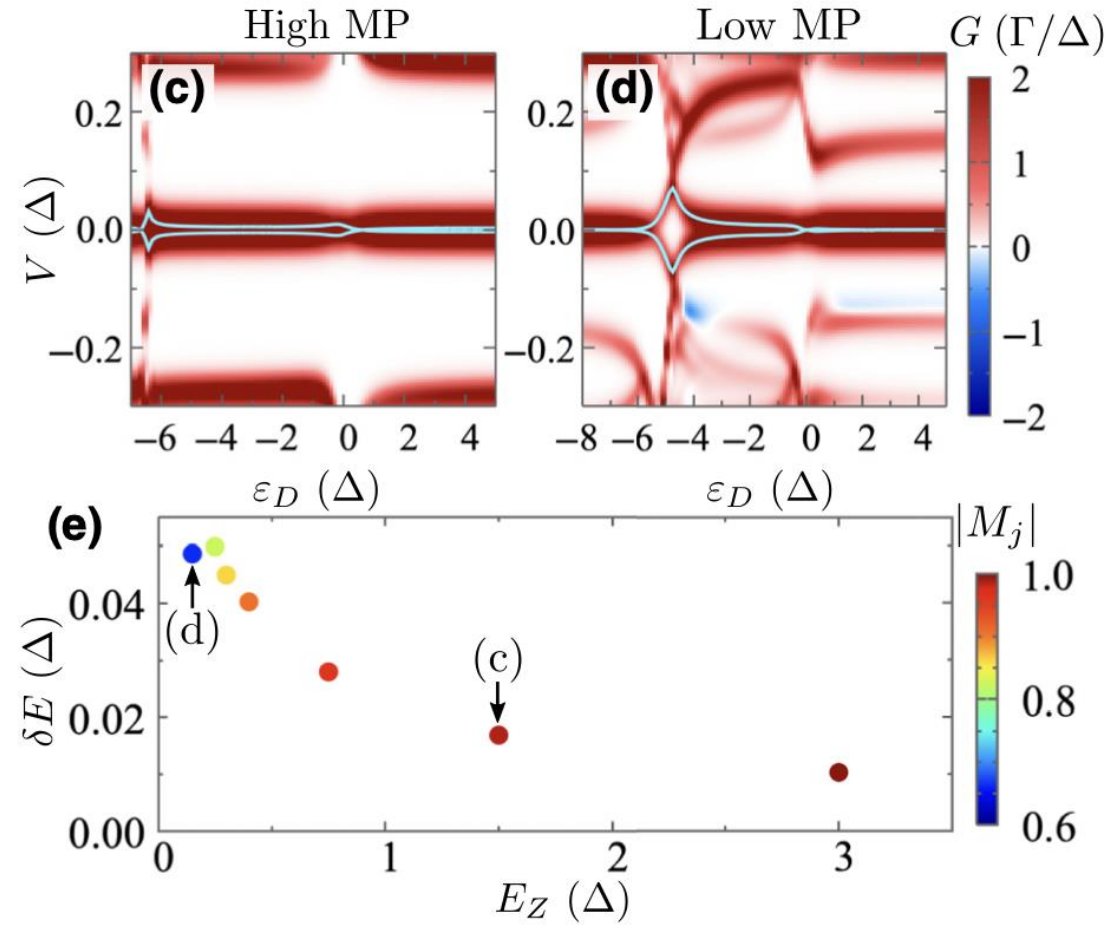
Majorana assessment



Majorana assessment



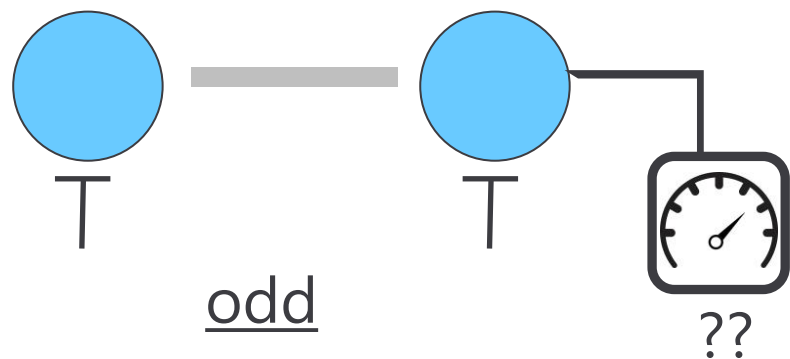
Splitting decreases with increasing MP



Outlook

- Fine-tuned topology
- Characterization
- **Quantum coherent experiments**
- Conclusions

Initialization

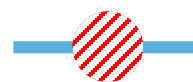


$E=0$

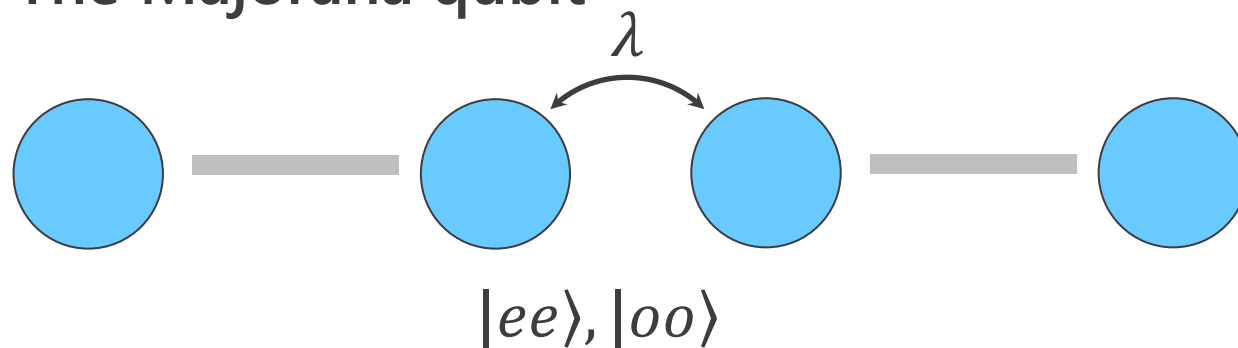


even

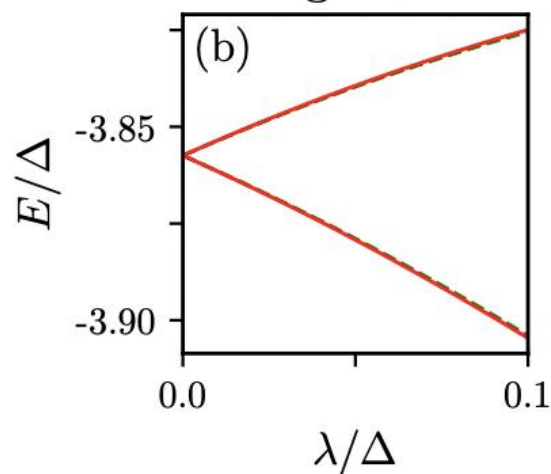
$E=0$



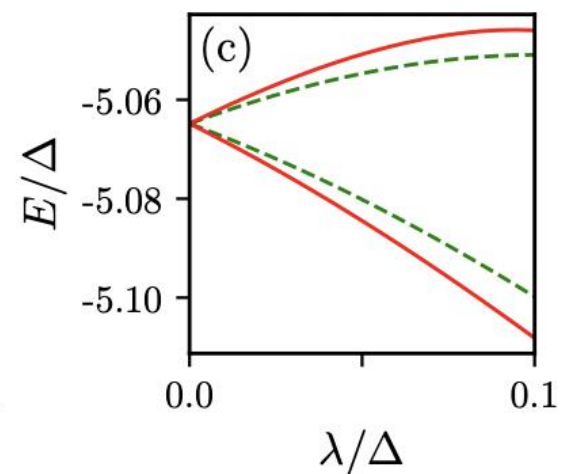
The Majorana qubit



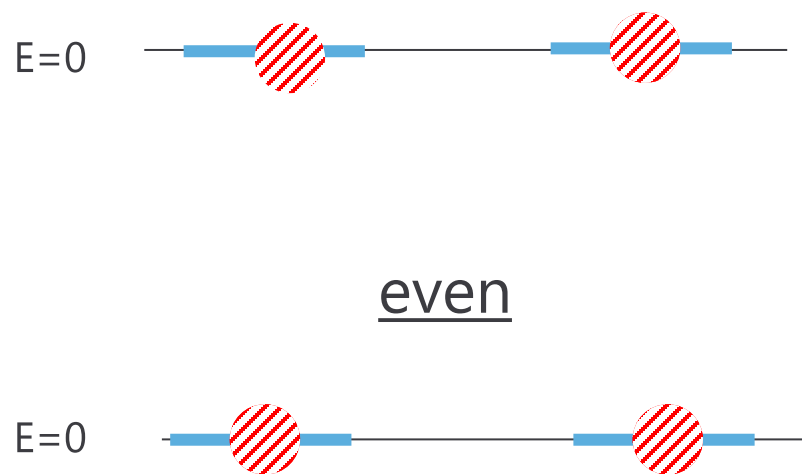
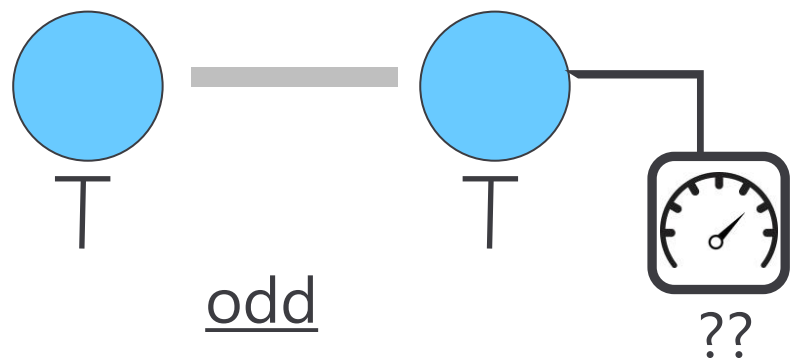
High MP



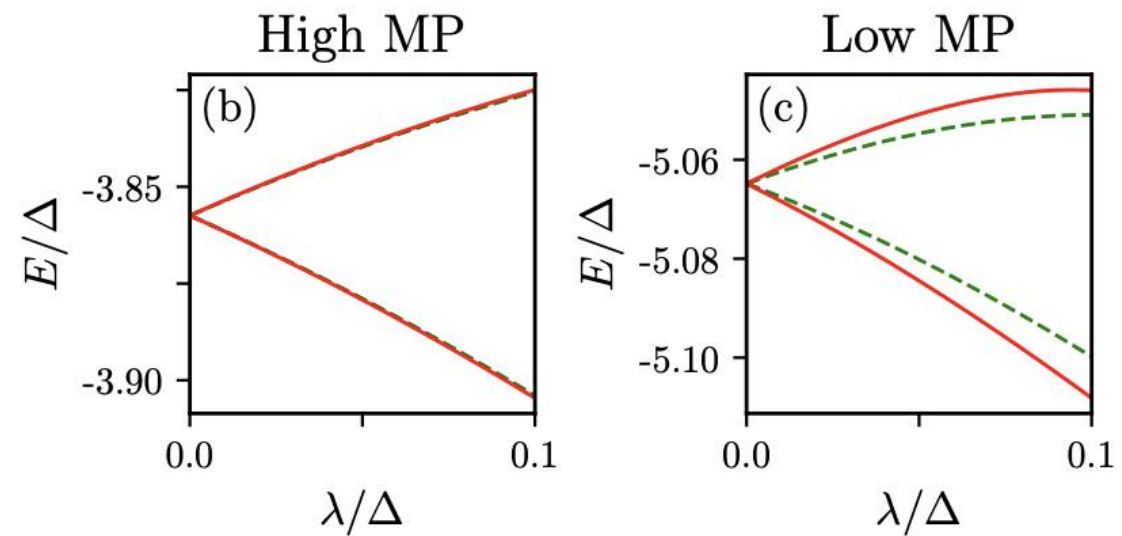
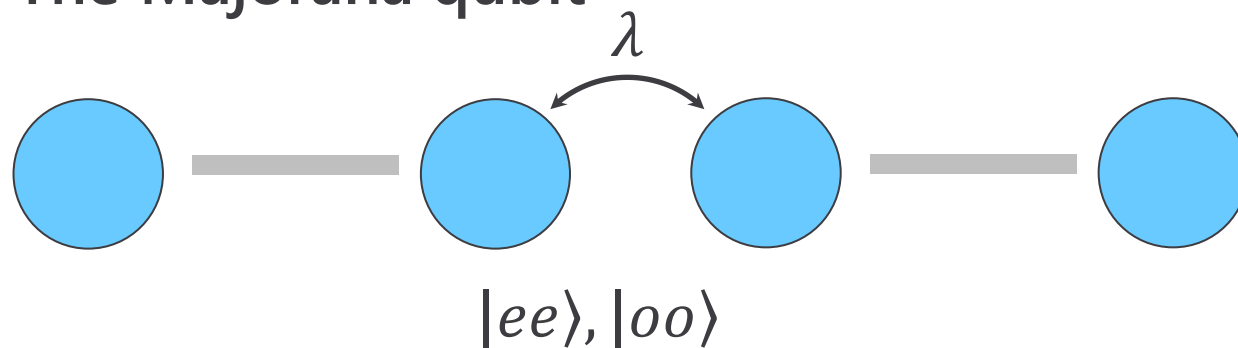
Low MP



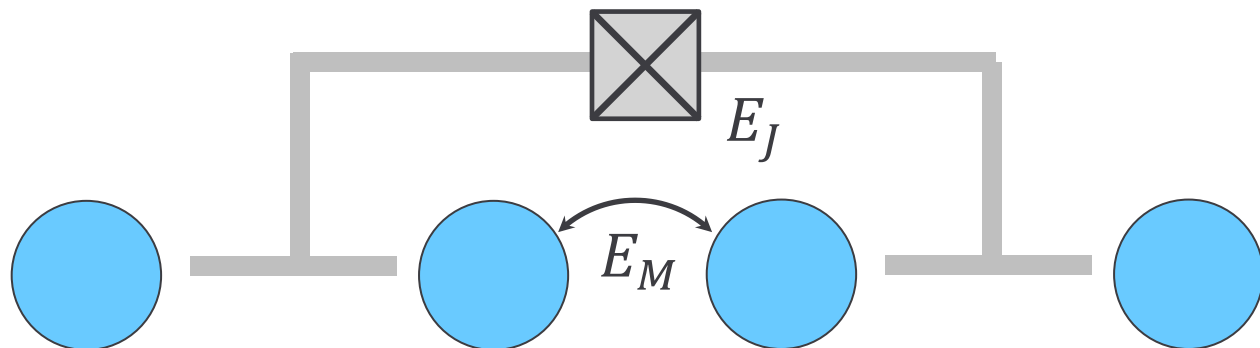
Initialization



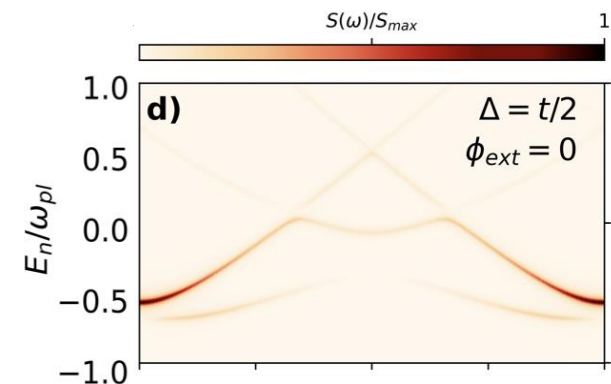
The Majorana qubit



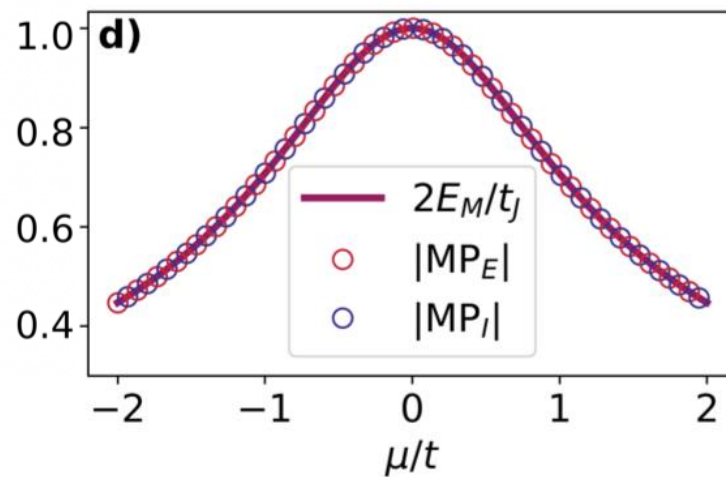
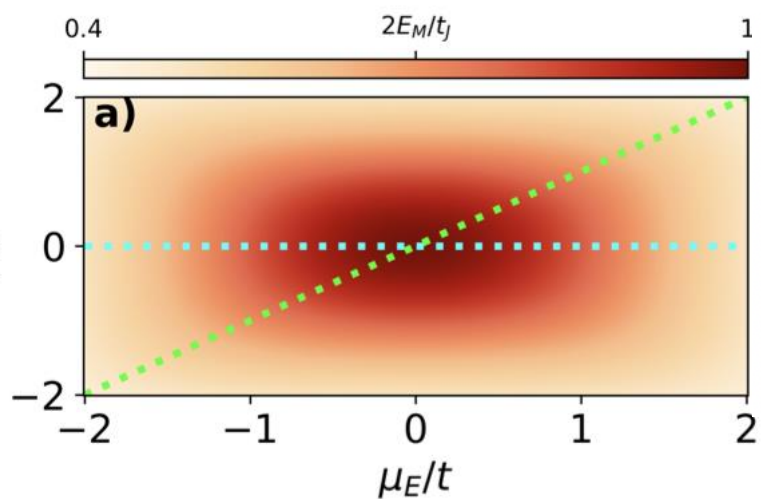
Initialization



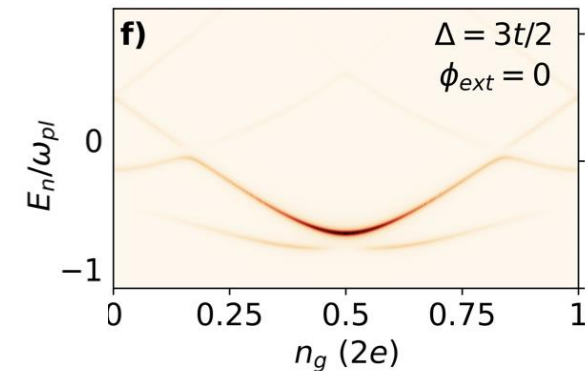
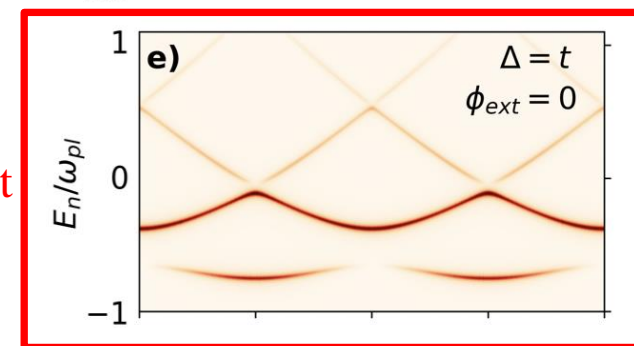
Modified transmon spectrum



Measuring MP using microwave

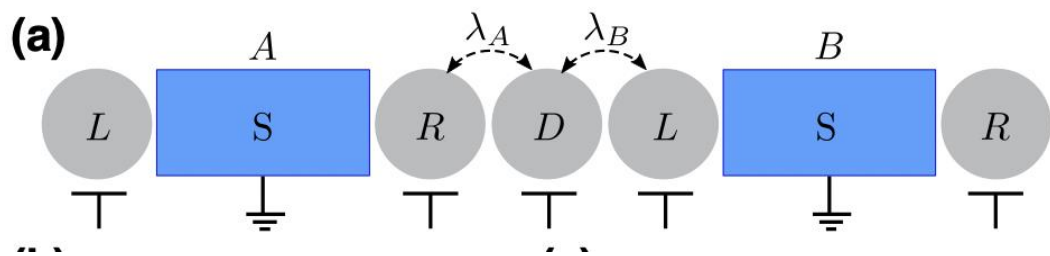


Sweet spot

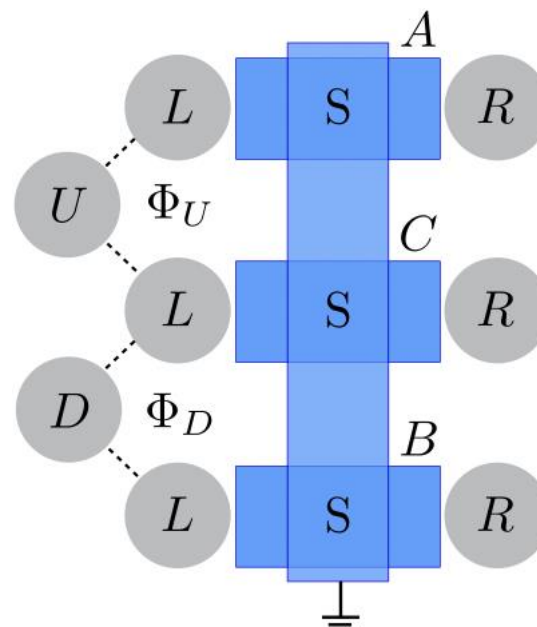


Braiding

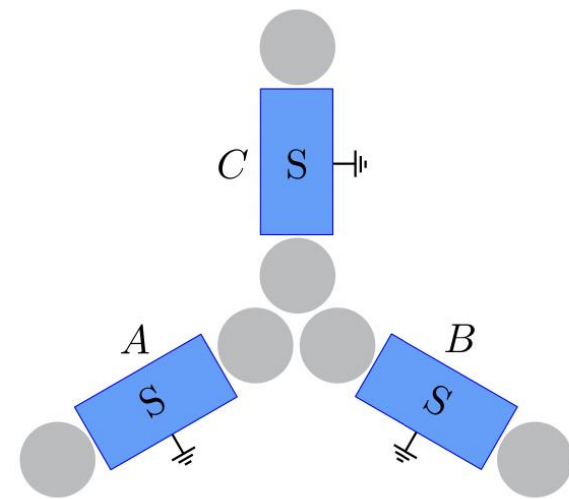
Charge-transfer braid



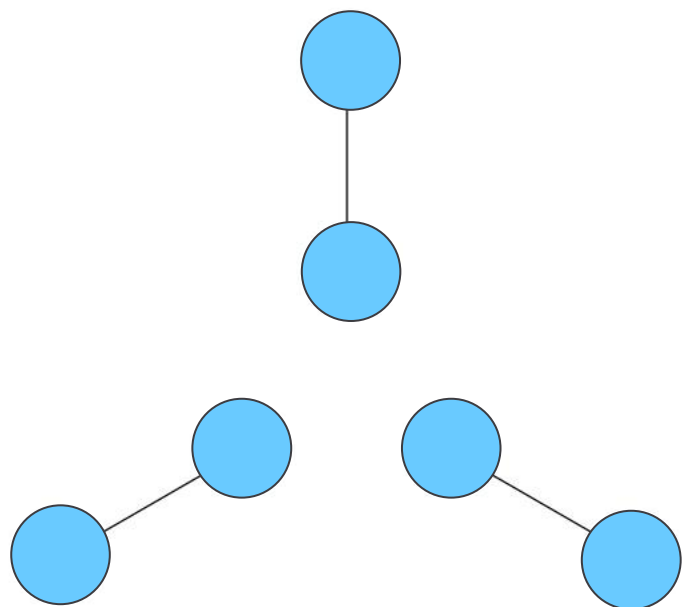
Measurement-base braid



Star braid



Braiding

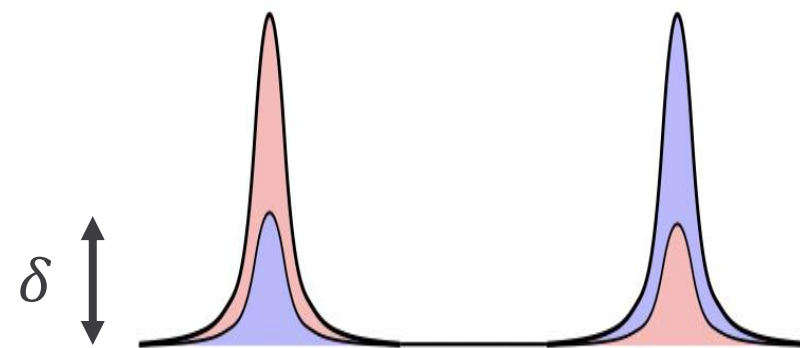


$$H = \sum_{\nu} H_{\nu} + H_T,$$

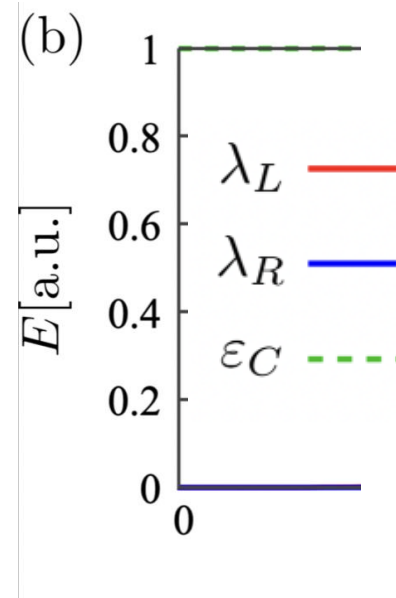
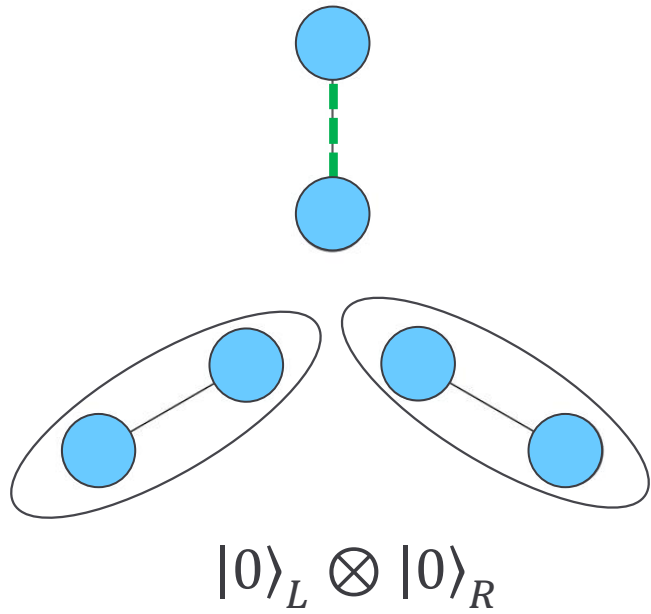
$$H_{\nu} = \epsilon_{\nu} c_{\nu}^{\dagger} c_{\nu}$$

$$H_T = i \sum_{\mu\nu} \frac{t_{\mu\nu}}{2} (\gamma_{\nu} - i\delta\tilde{\gamma}_{\nu})(\gamma_{\mu} - i\delta\tilde{\gamma}_{\mu}) + H.c.$$

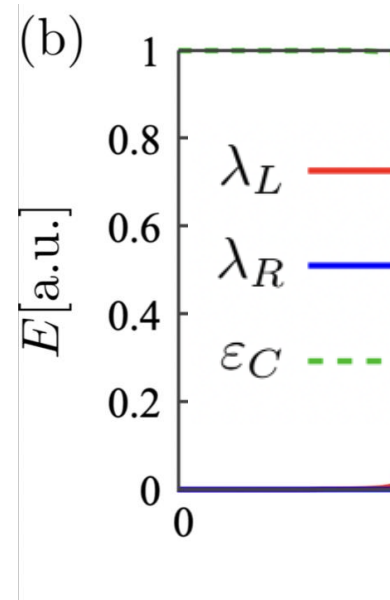
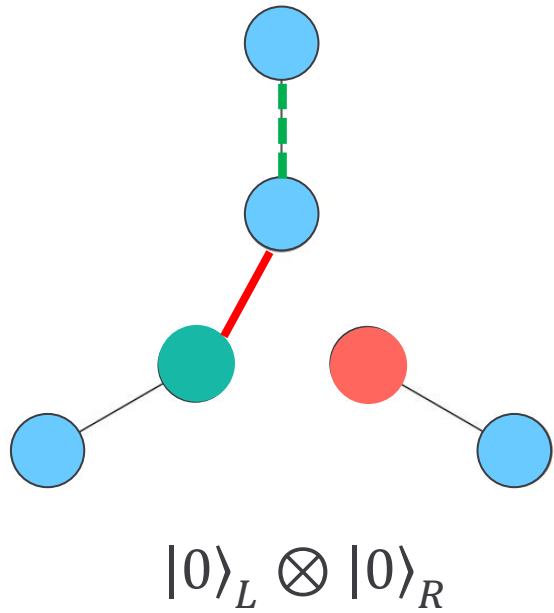
$$H_T = i \sum_{\mu\nu} t_{\mu\nu} (\gamma_{\nu}\gamma_{\mu} + \delta^2\tilde{\gamma}_{\nu}\tilde{\gamma}_{\mu})$$



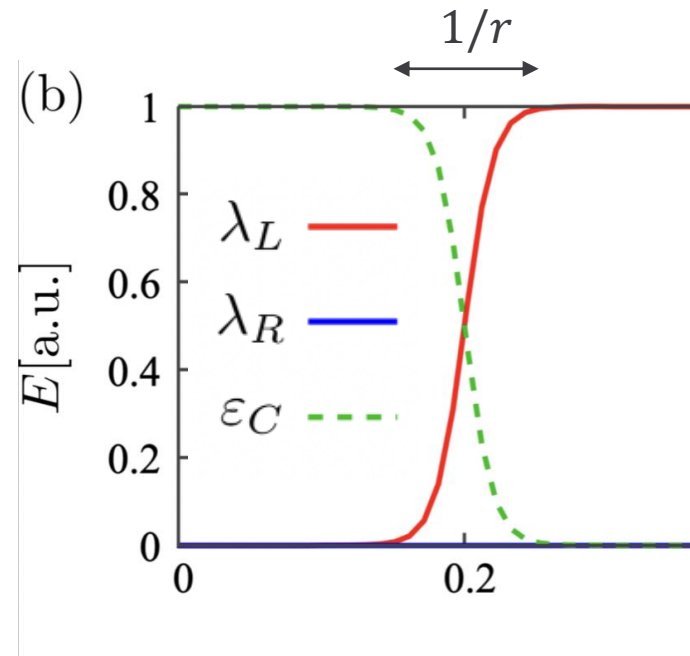
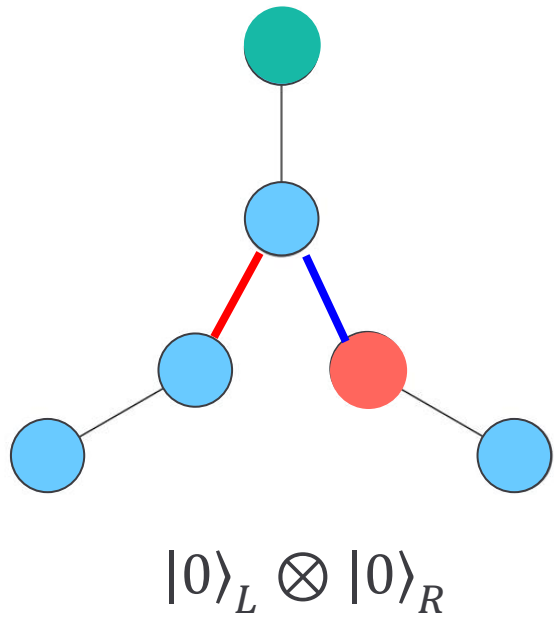
The protocol: initialization



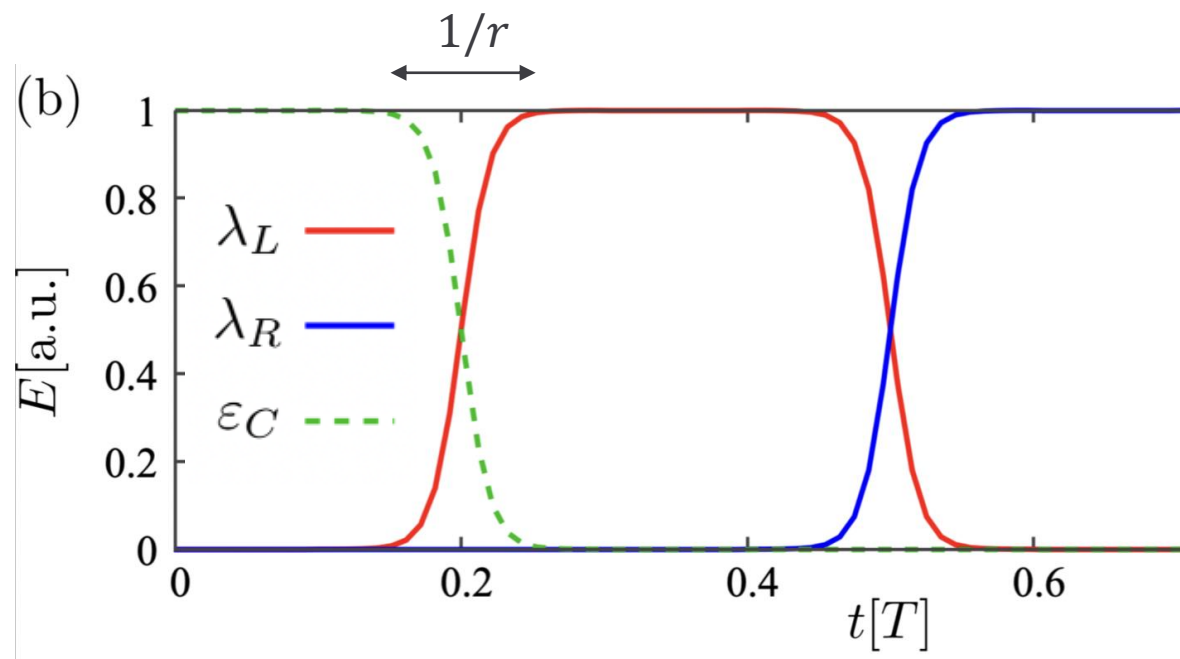
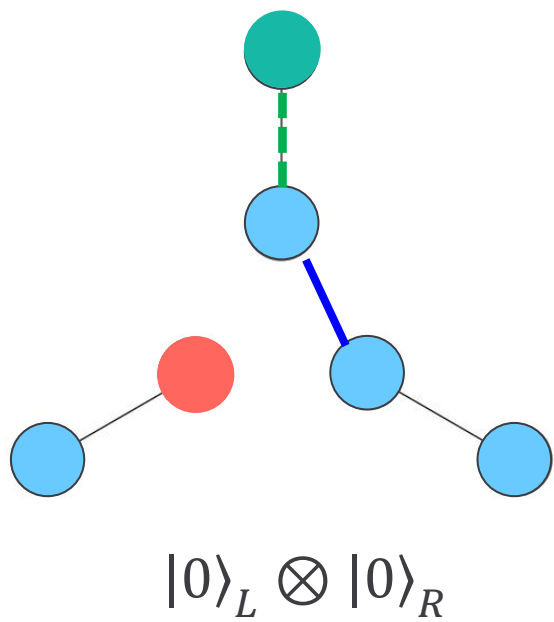
The protocol: exchange



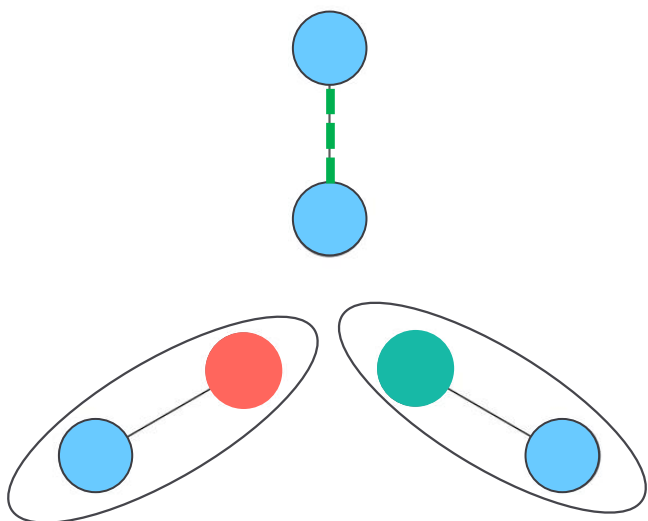
The protocol: exchange



The protocol: exchange



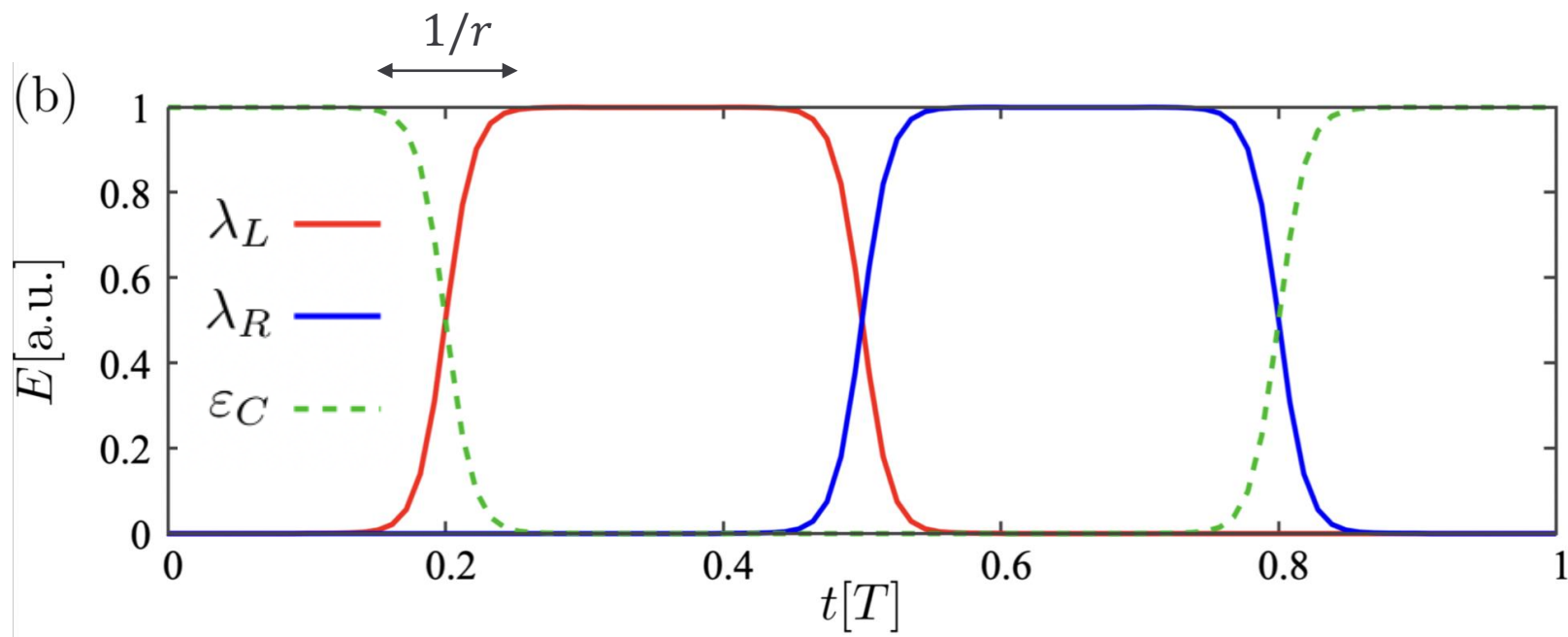
The protocol: Readout



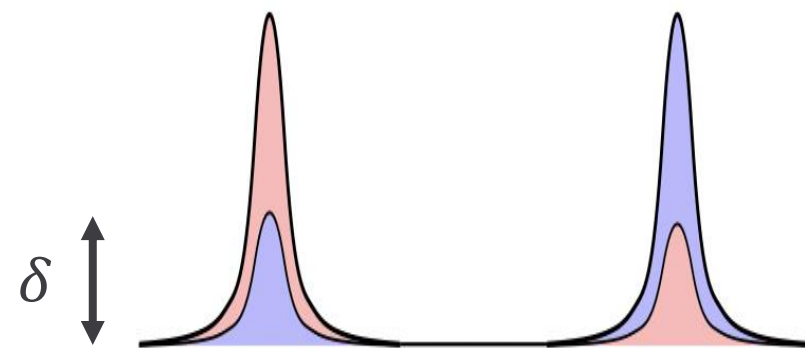
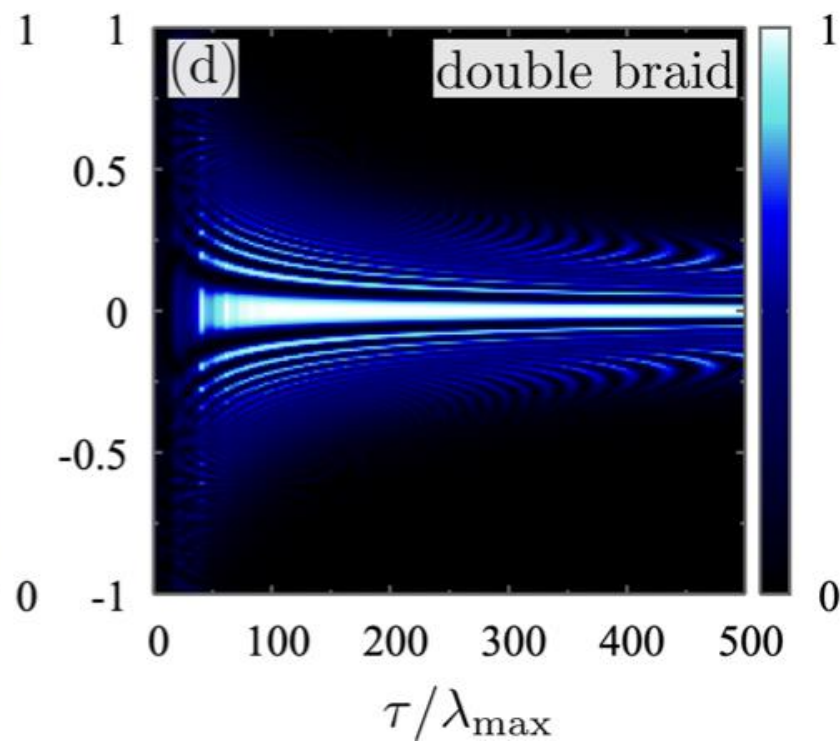
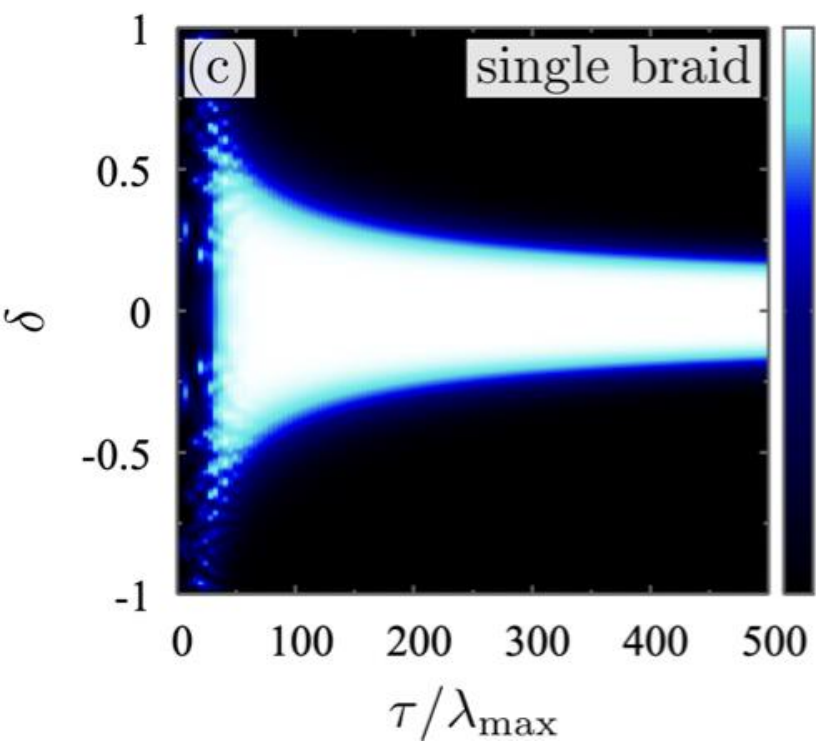
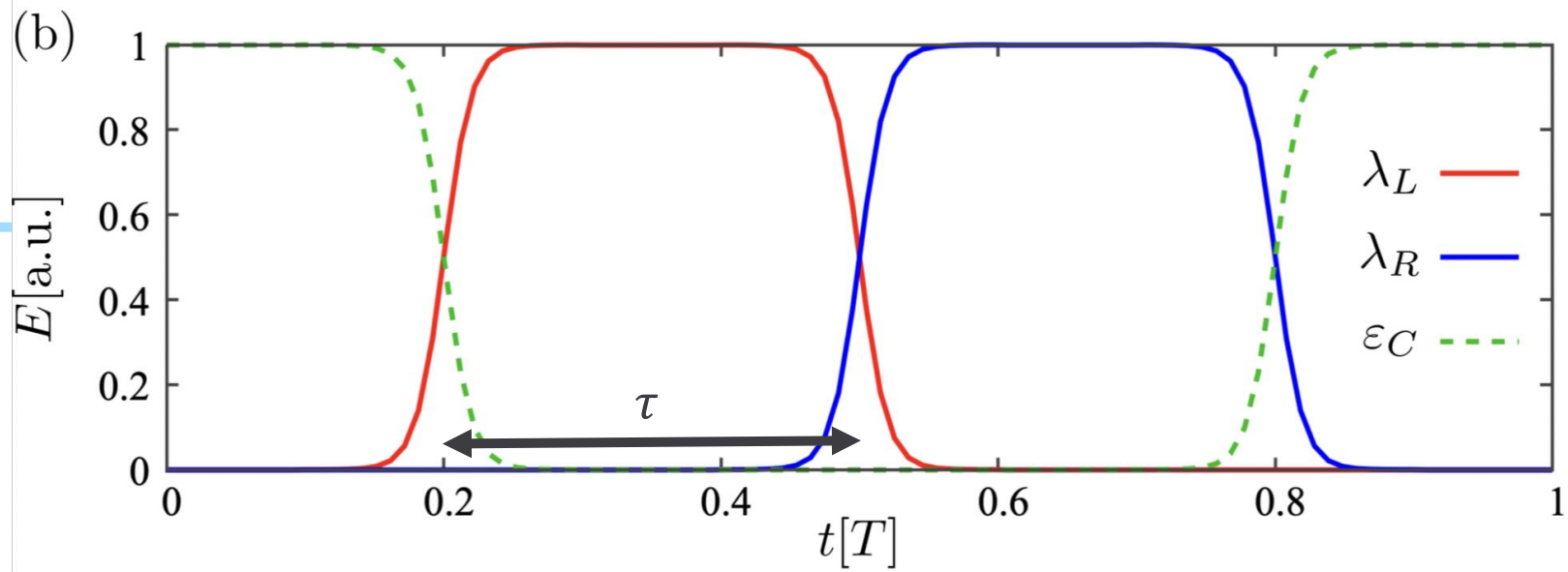
$$|0\rangle_L \otimes |0\rangle_R$$



$$\frac{1}{\sqrt{2}} (|0\rangle_L \otimes |0\rangle_R + |1\rangle_L \otimes |1\rangle_R)$$



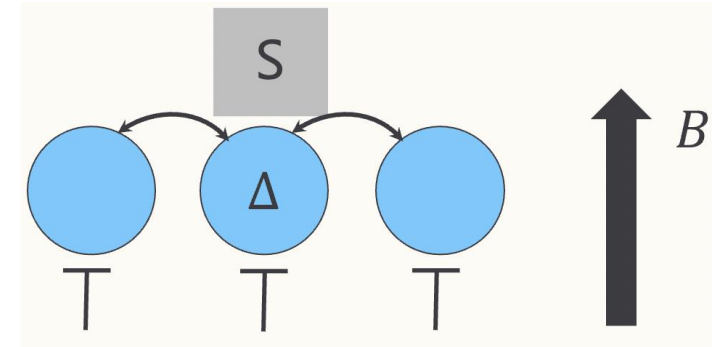
Results



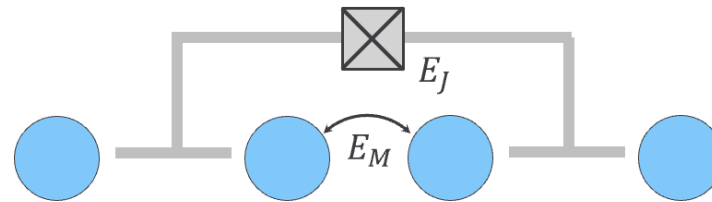
Summary

ruben.seoane@csic.es

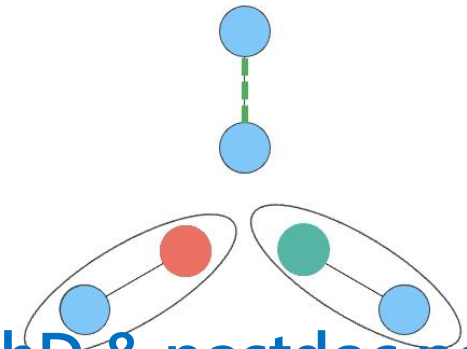
- **Fine-tuned Majoranas** PRB 106, L201404 (22')



- **Kitaev qubits** PRB 109, 075101 (24')



- **Braiding** PRX Quantum 5, 010323



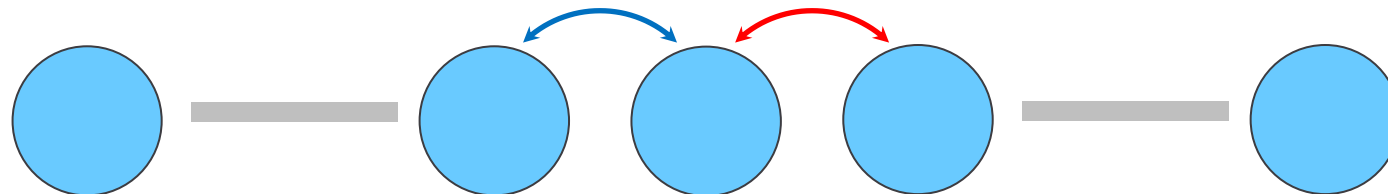
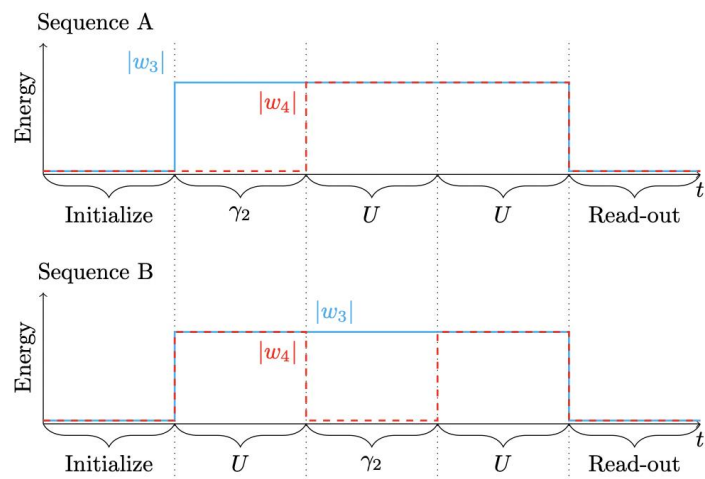
Open PhD & postdoc positions

Thank You!!!

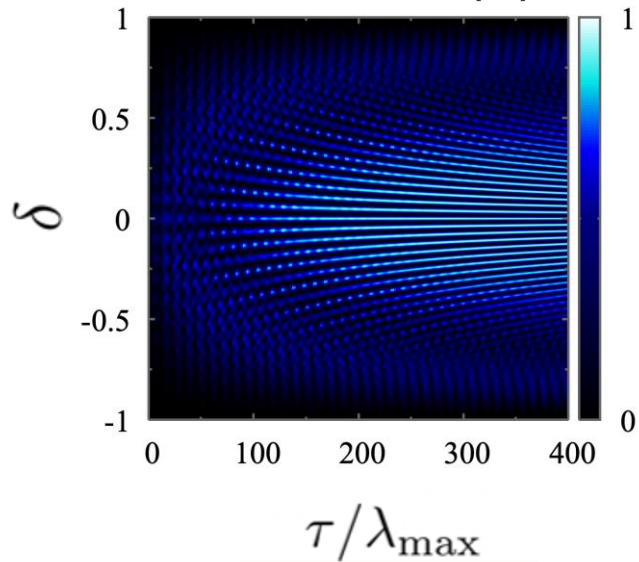


Charge-transfer braid

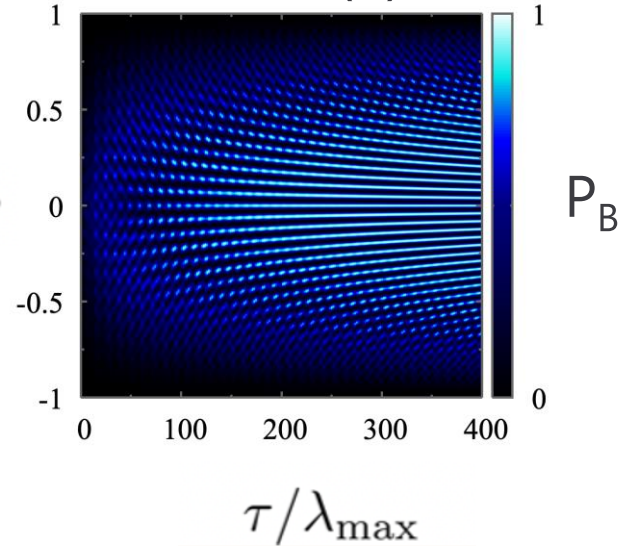
Protocol description: PRB **105**, 045425 (2022)



Reference (A)



Braid (B)



Visibility (A^*B)

