

# Topological quantum registers

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Ben-Gurion University  
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Dutch-Israeli Quantum Technology & 5G mini-symposium, 1.12.2020



European  
Commission

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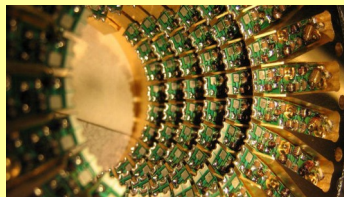
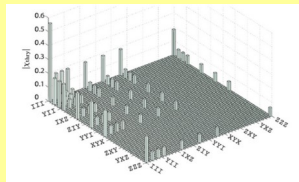
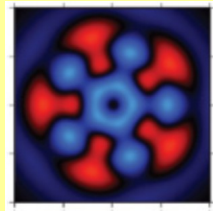
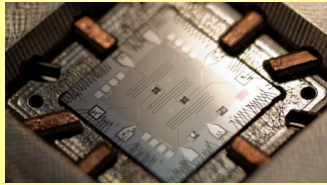
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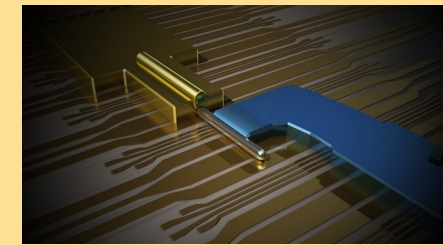
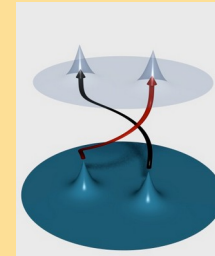
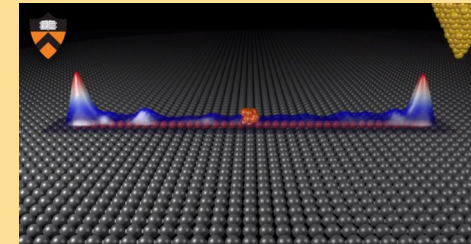
THE ROYAL  
SOCIETY

# Hybrid qubits: a marriage of two paradigms

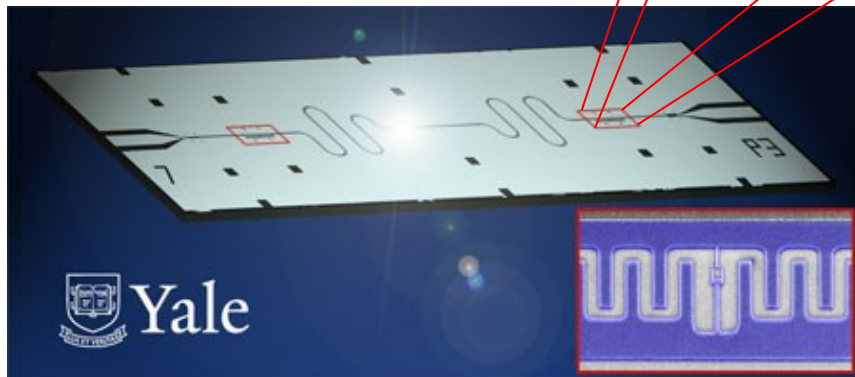
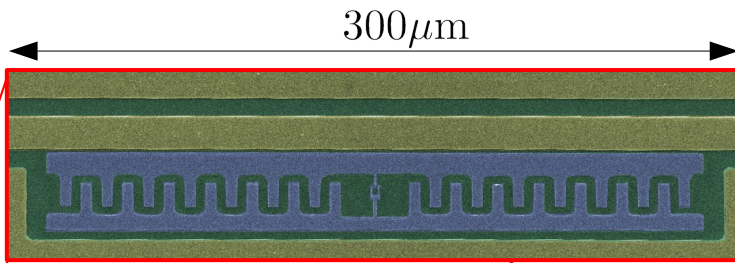
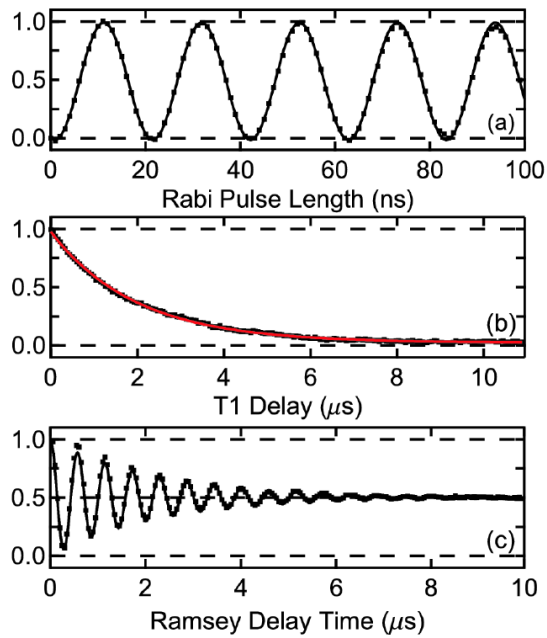
## Superconducting Qubits



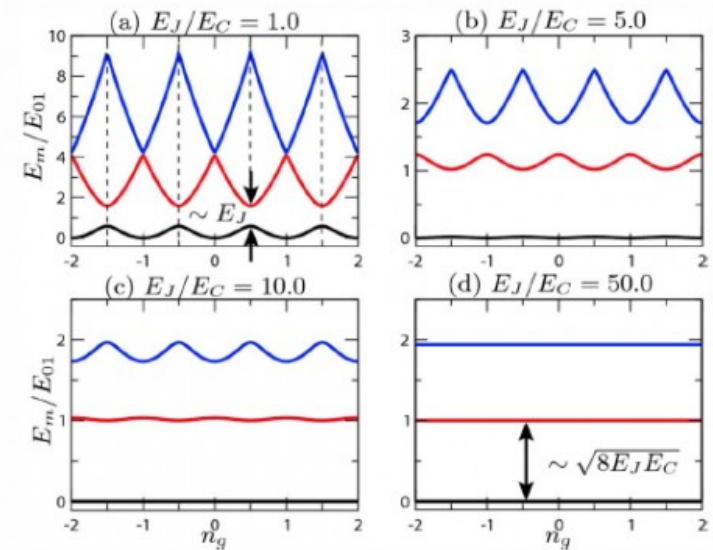
## Topological Superconductors



# The Transmon Qubit



$$E_J \gg E_C$$

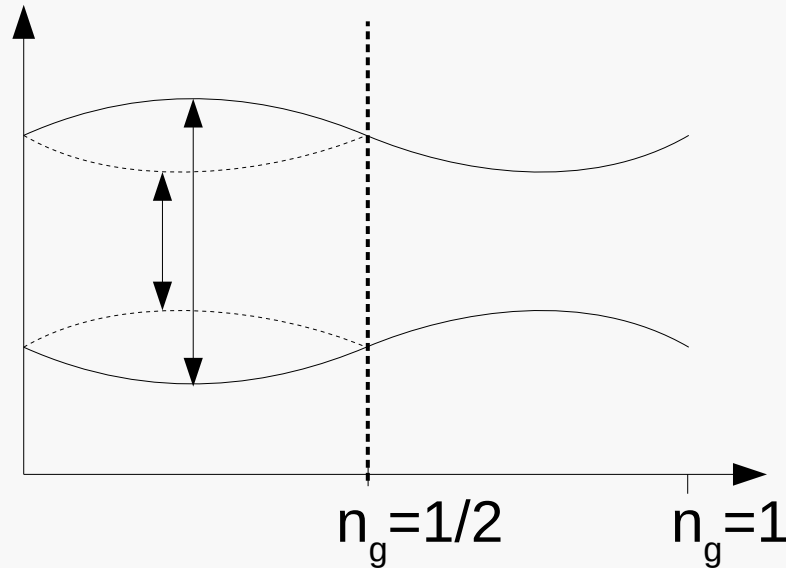


$$H_T = 4E_C(\hat{n} - n_g)^2 - E_J \cos(\varphi)$$

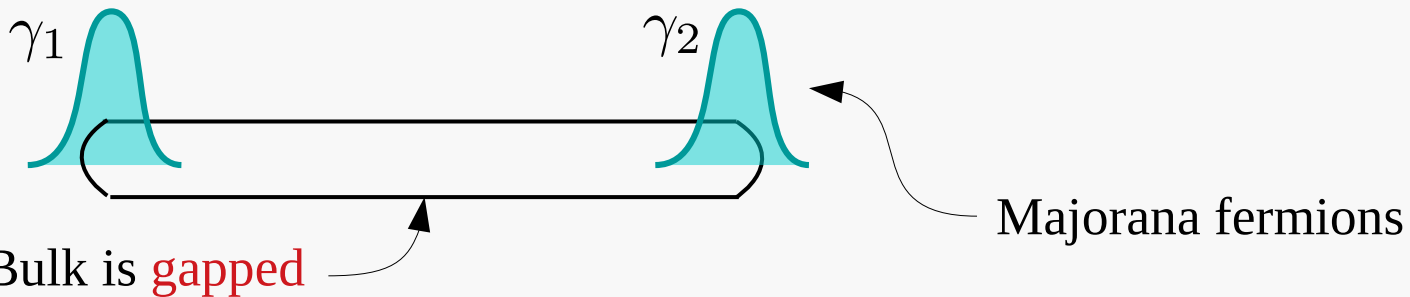


# Transmon: the role of quasi-particles

## Non-coherent quasi-particles



## Coherent quasi-particles



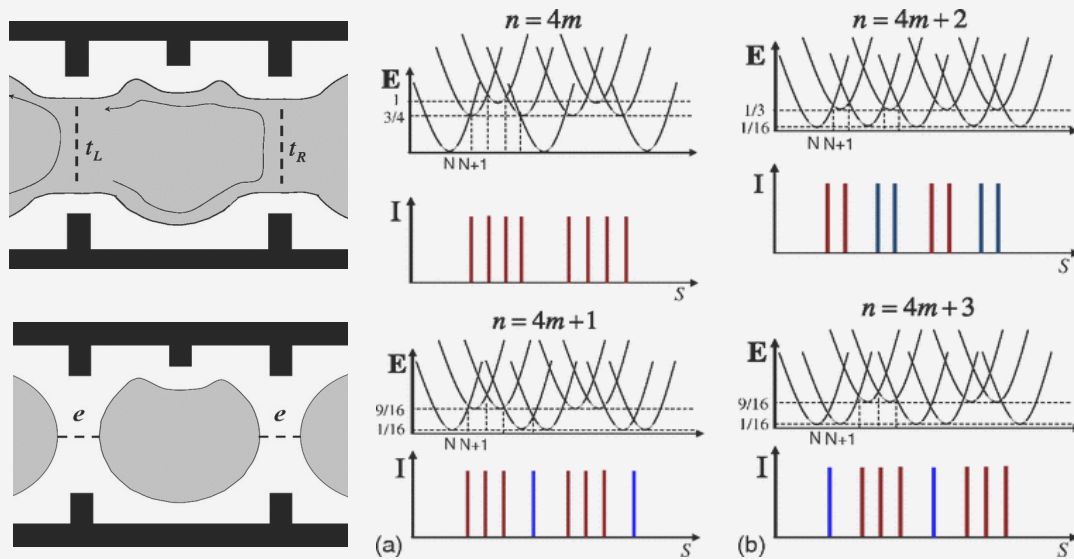
Two Majorana fermions  $\leftrightarrow$  neutral zero energy non-local single fermion level

extra degree of freedom ("parity of condensate") = 0,1

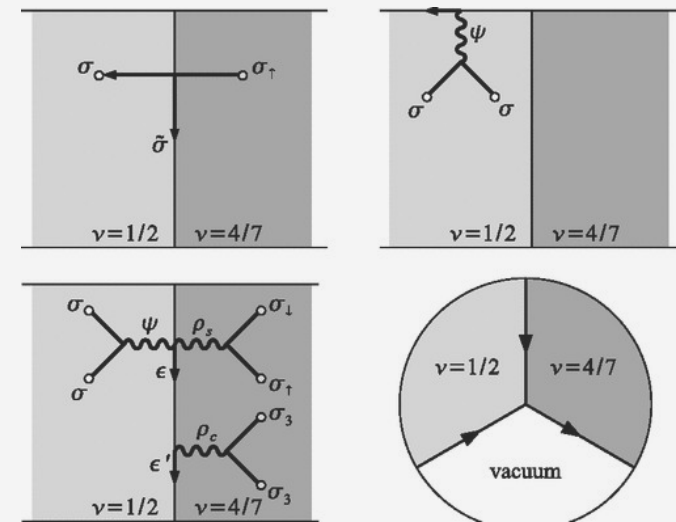


# Origins: the fractional quantum hall effect, filling 5/2

## Experimental signatures of non-Abelian statistics in clustered quantum Hall states



## Non-Abelian Anyons: When Ising Meets Fibonacci



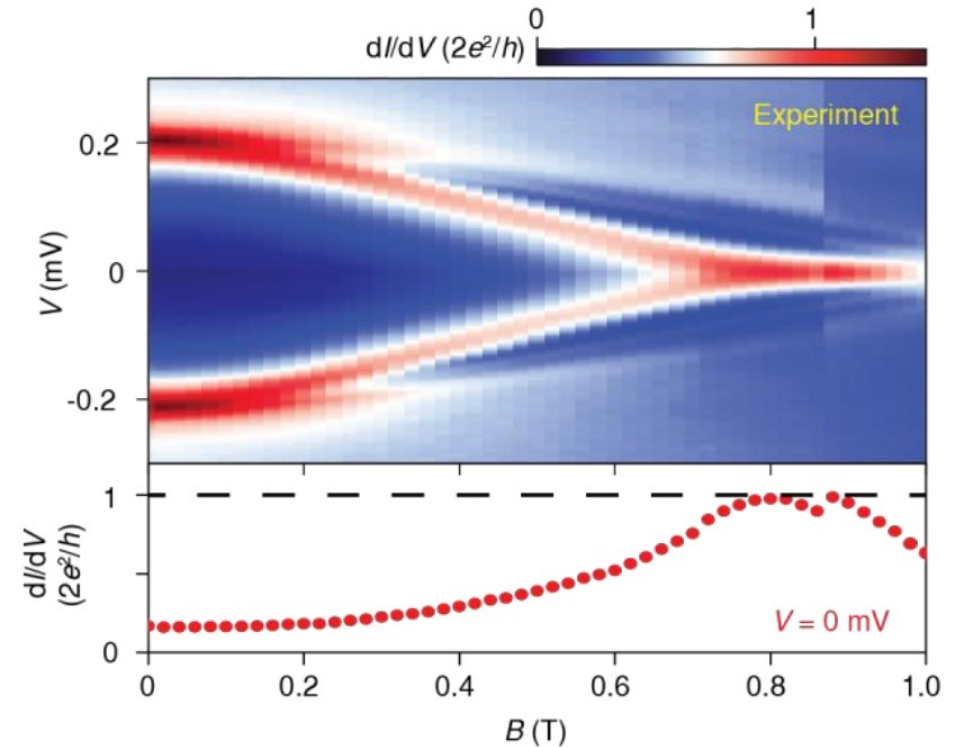
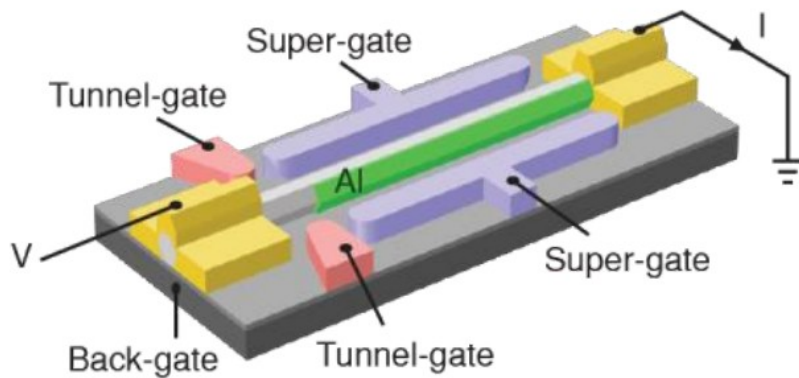
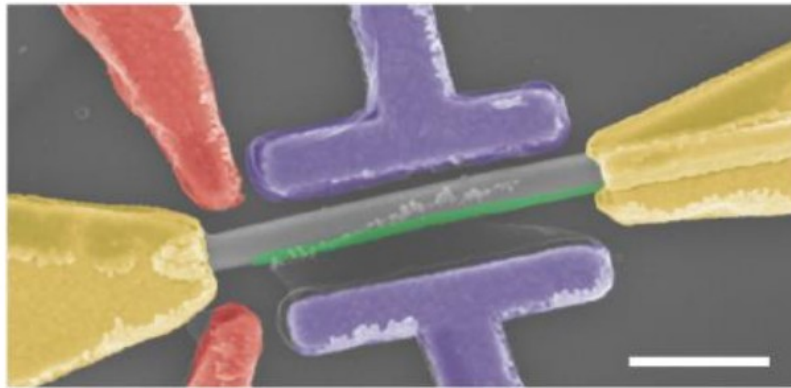
E. Grosfeld and K. Schoutens, PRL **103**, 076803 (2009)

R. Ilan, E. Grosfeld, K. Schoutens, and A. Stern, PRB **79**, 245305 (2009)





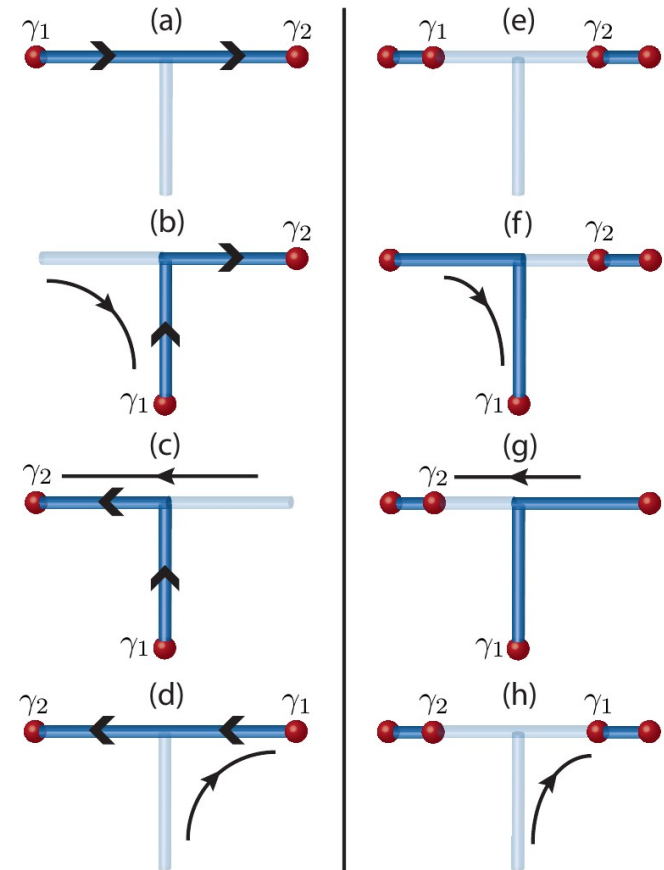
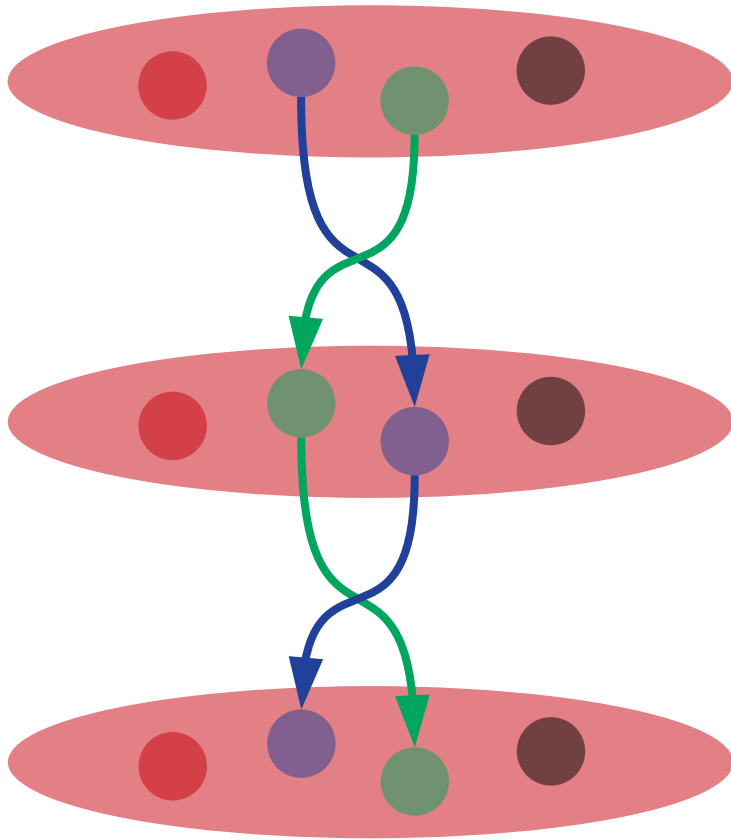
# Majorana fermions – perfect Andreev reflection



Hao Zhang et al, Nature **556**, 74–79 (2018)



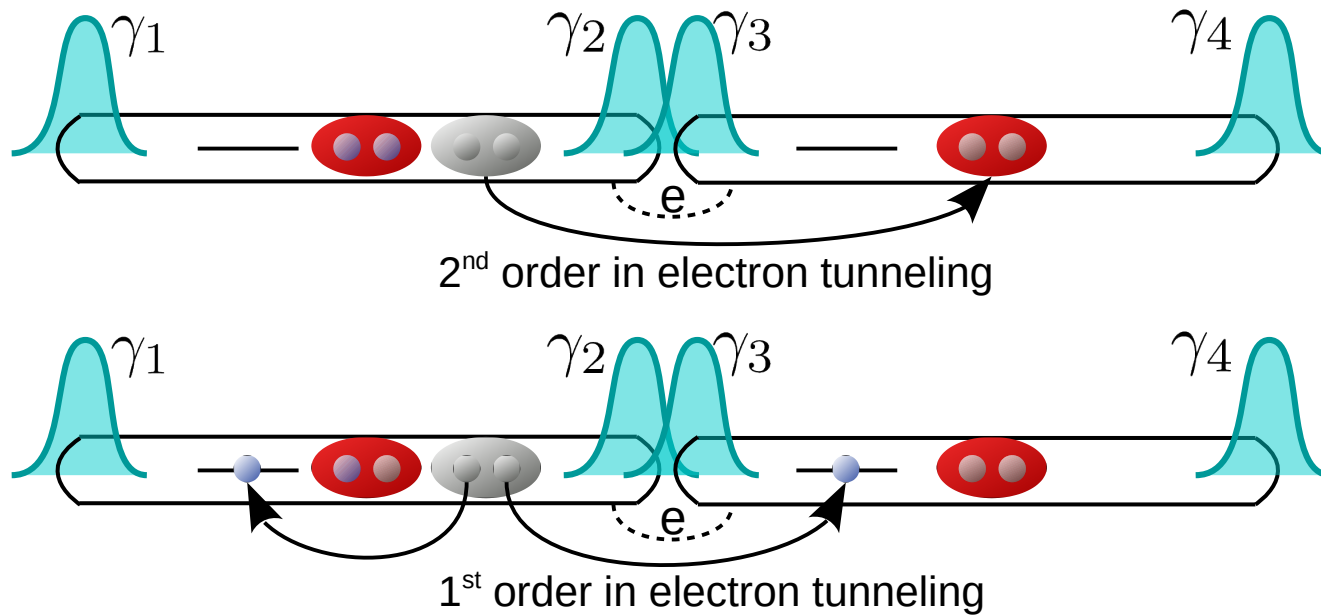
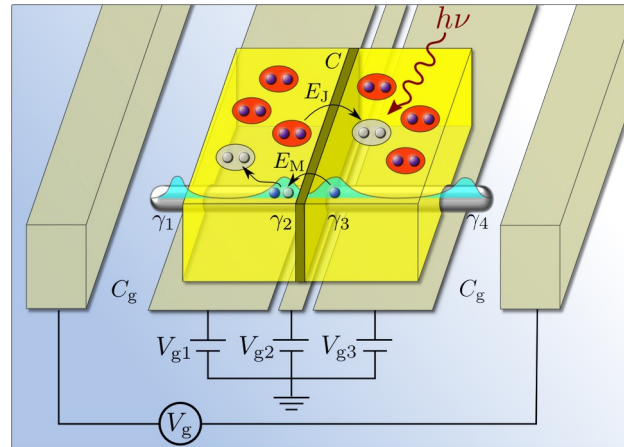
# Topological quantum computation



J. Alicea et al, Nature Physics 7, 412–417 (2011)



# The Majorana-Transmon

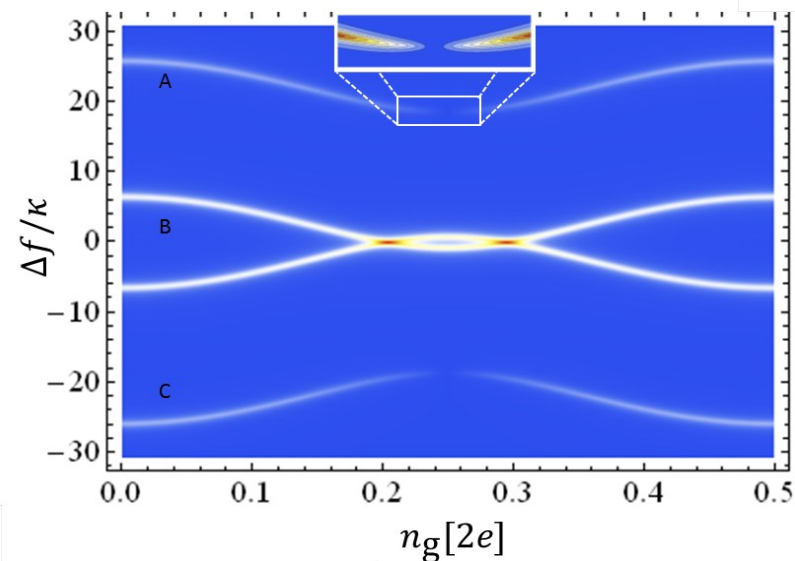
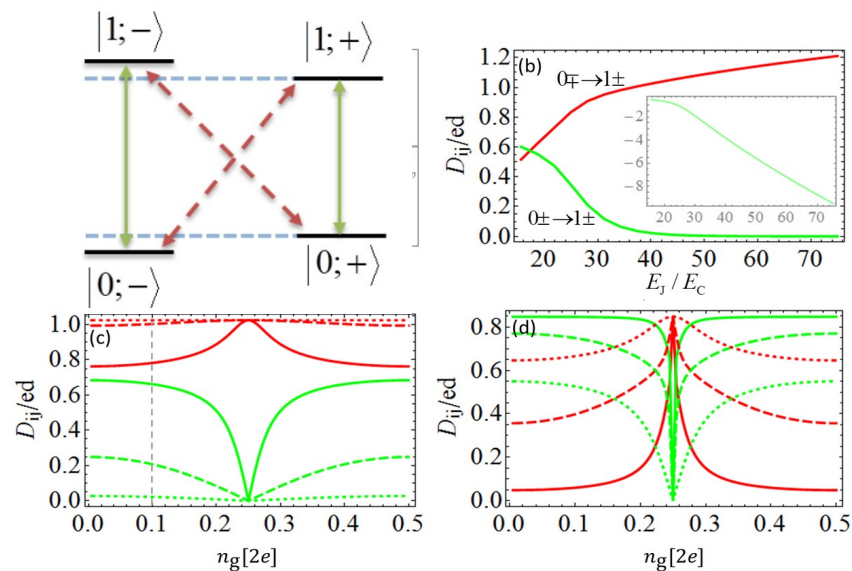
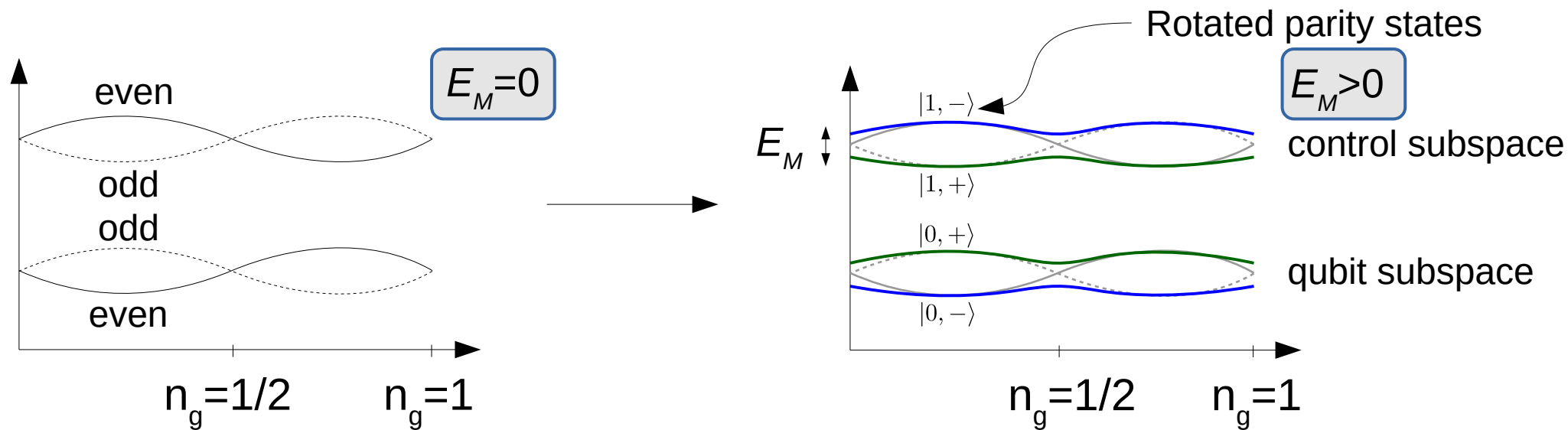


E. Ginossar and E. Grosfeld, Nature Communications 5, 4772 (2014)

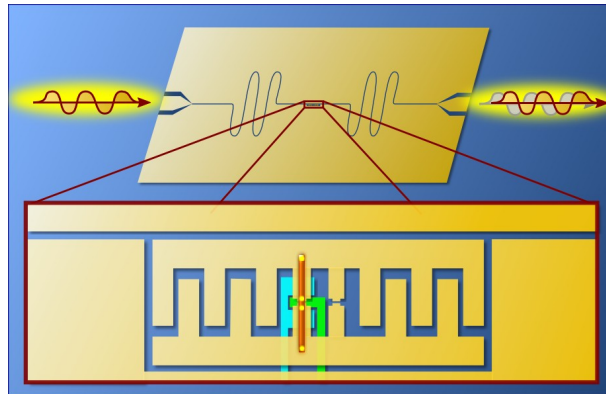




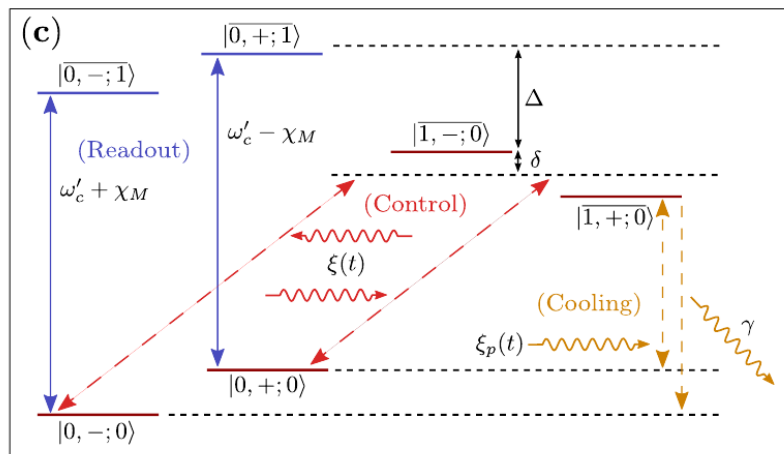
# Double-Lambda system



# Majorana circuit-QED (McQED)



$$H_{\text{eff}} = \left( \frac{\omega_c}{2} - \frac{\Delta}{2} - E_M \tau_z \right) \sigma_z + \frac{I + \sigma_z}{2} (-\chi_T + \chi_M \tau_z) + a^\dagger a (\omega_c - \chi_T \sigma_z) + \chi_M a^\dagger a \sigma_z \tau_z$$



A term that mixes the photon,  
the transmon and the parity!

K. Yavilberg, E. Ginossar and E. Grosfeld, Phys. Rev. B 92, 075143 (2015)

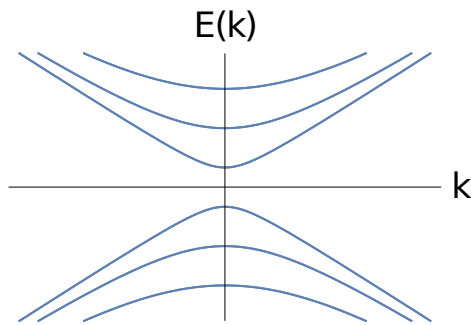


# Realization: topological insulator weak link

- 3D Topological Insulator nano-wire ( $\text{Bi}_2\text{Se}_3$ ,  $\text{Bi}_2\text{Te}_3$ )

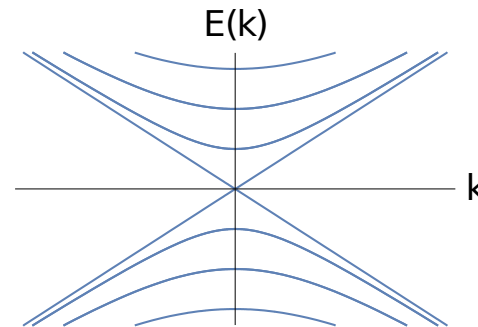
$$H_{\text{surface}} = iv\partial_z\sigma_y - \frac{v}{R} \left( i\partial_\theta + \frac{\Phi}{\Phi_0} \right) \sigma_z$$

Half-integer angular momentum  $\left( -i\partial_\theta \rightarrow \pm\frac{1}{2}, \pm\frac{3}{2}, \dots \right)$



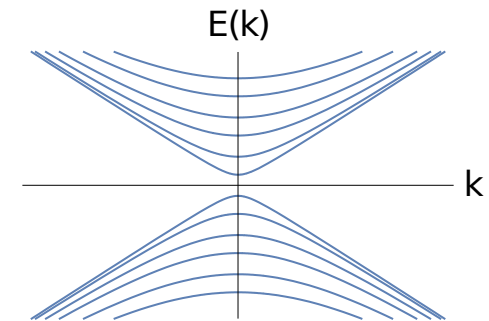
$$\Phi = 0$$

Doubly degenerate spectrum



$$\Phi = \Phi_0/2$$

Dirac cone



$$\Phi = \Phi_0/2 - BR/v$$

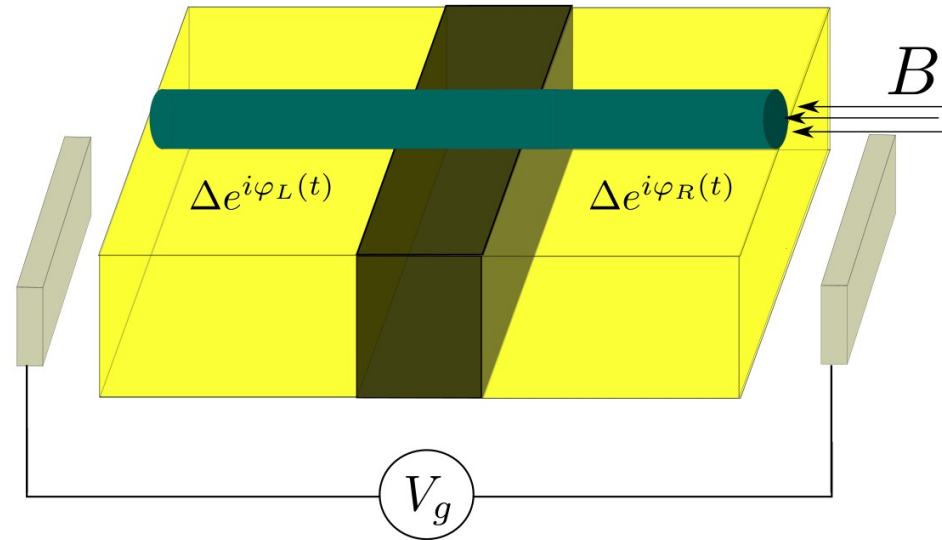
General Case

$$\mu = 0 \Rightarrow \boxed{H_{1\text{DTI}} = iv\partial_z\sigma_y + B\sigma_z}$$

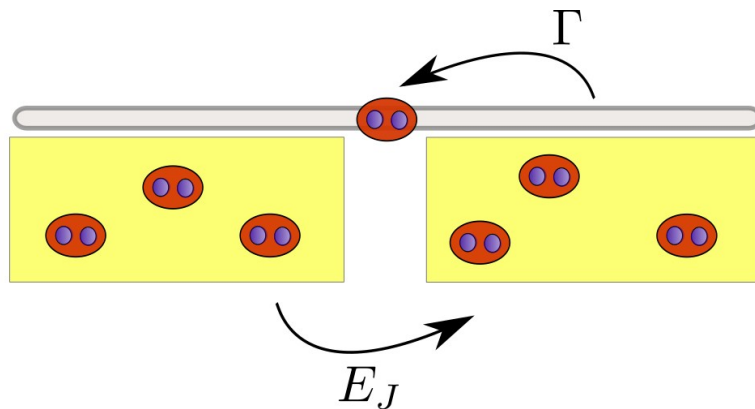
B - "Magnetic Gap"



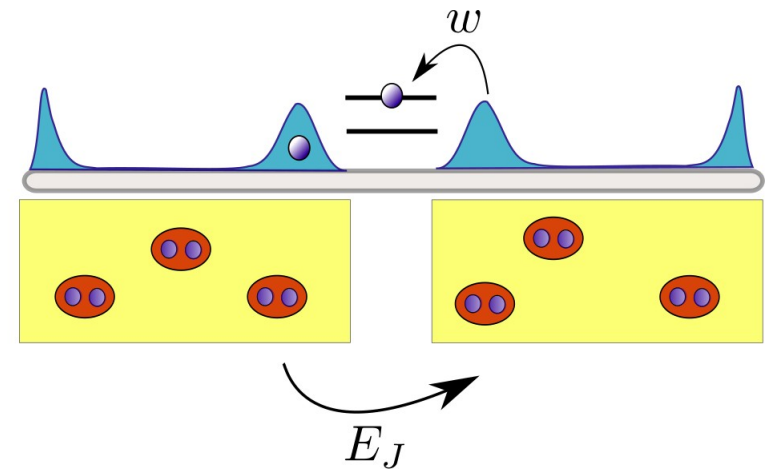
# Mesoscopic TI Josephson Junction



Two fermion process



Single fermion process

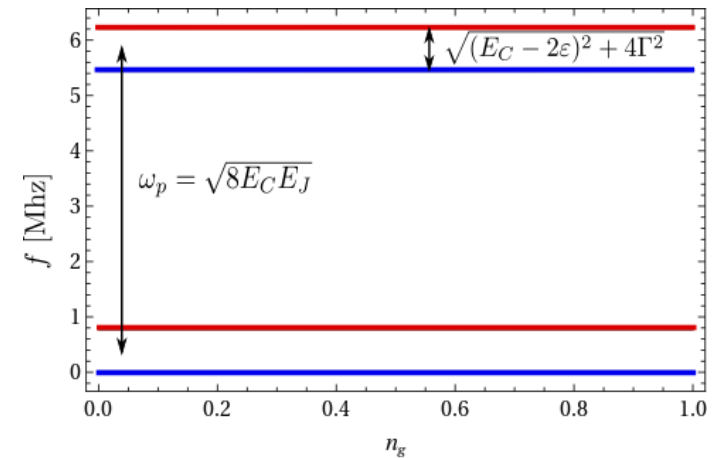
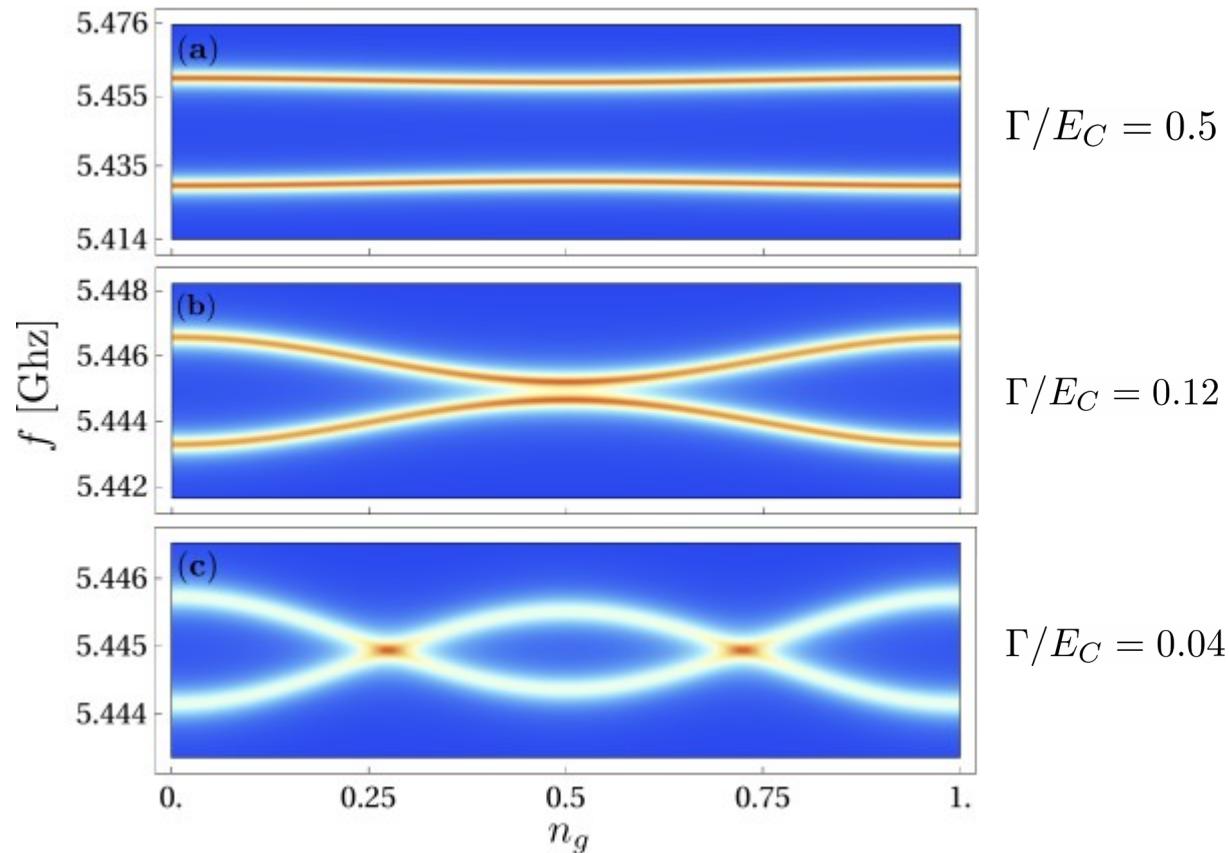


# Andreev Bound States

- $\mathbf{B} = \mathbf{0}$ : No Majorana fermions

$$H = \begin{pmatrix} H_J[N = 0] & \Gamma \cos(\varphi/2) \\ \Gamma \cos(\varphi/2) & H_J[N = -1] + 2\varepsilon \end{pmatrix}$$

- Dipole Transitions  $\langle i | \hat{n} | j \rangle$



$$\omega_p \simeq 5.7 \text{ GHz}$$

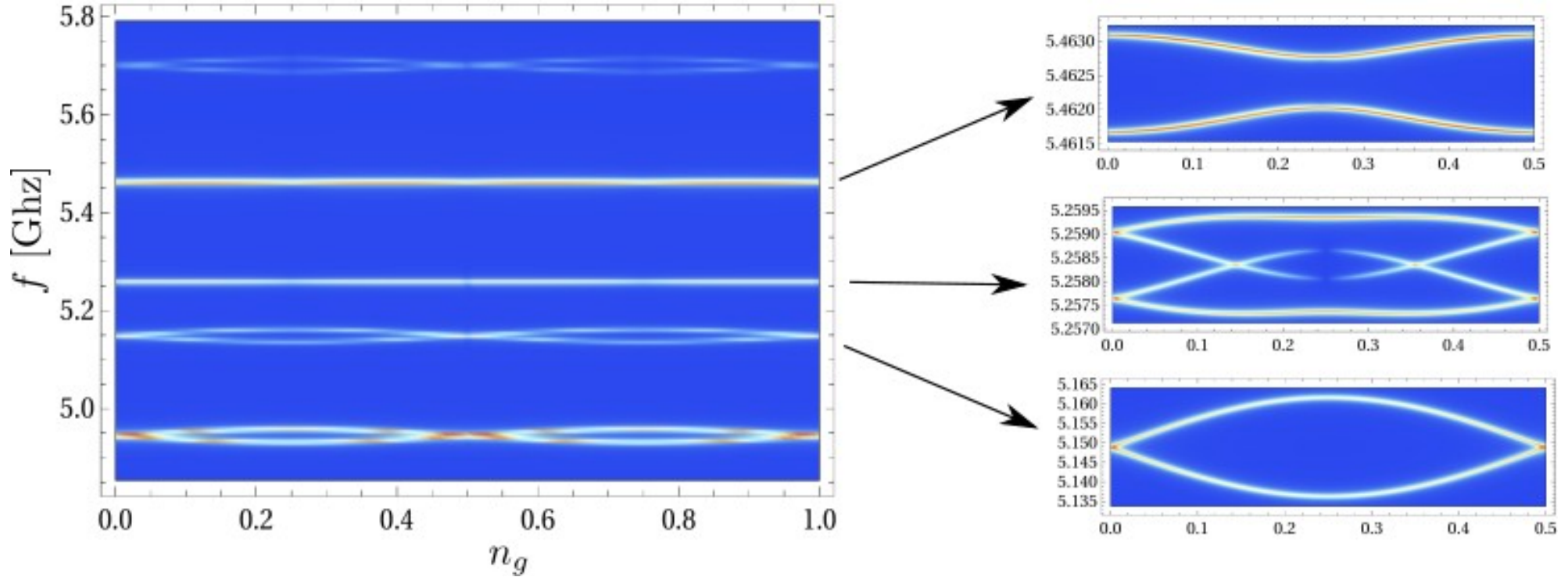
$$\varepsilon/E_C = -1.2$$



# B-dominated Spectrum

- Andreev vs. Majorana assisted charge transfer

$$\omega_p \simeq 5.7 \text{ GHz}, \Gamma/E_C = 0.01, \varepsilon/E_C = -1.2, B/E_C = 12$$



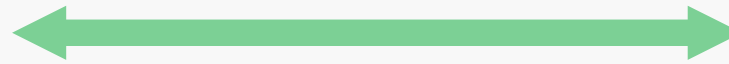
K. Yavilberg, E. Ginossar and E. Grosfeld, Phys. Rev. B **100**, 241408(R), 2019





# SC circuits as simulators for topological matter

Kitaev chain



XY spin chain

*non-local JW transformation*

$$H_{XY} = \sum_i (t + \Delta) \sigma_i^x \sigma_{i+1}^x + (t - \Delta) \sigma_i^y \sigma_{i+1}^y - \mu \sum_i \sigma_z^i$$

Lieb et al, 1961

**Local** perturbations in the *spin language* ↔  
**non-local** perturbations in the *fermionic language*

→ may lead to decoherence!

A. Callison, E. Grosfeld and E. Ginossar, Phys. Rev. B **96**, 085121

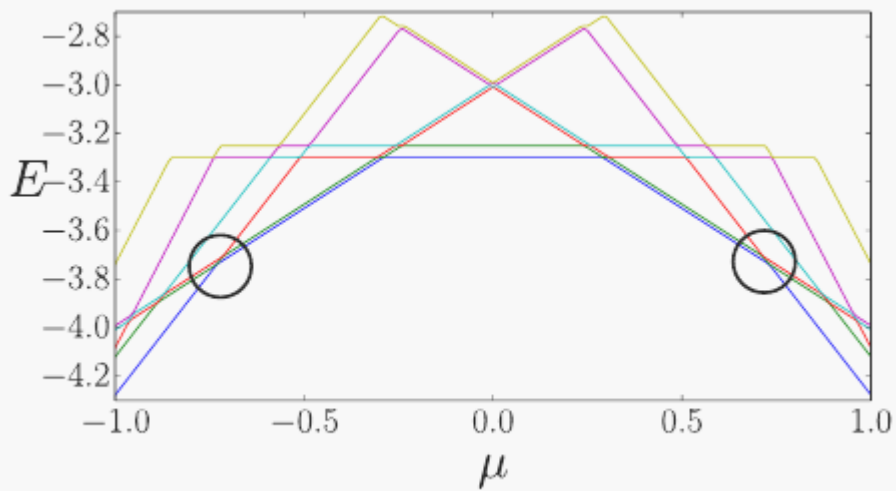


# SC circuits as simulators for topological matter

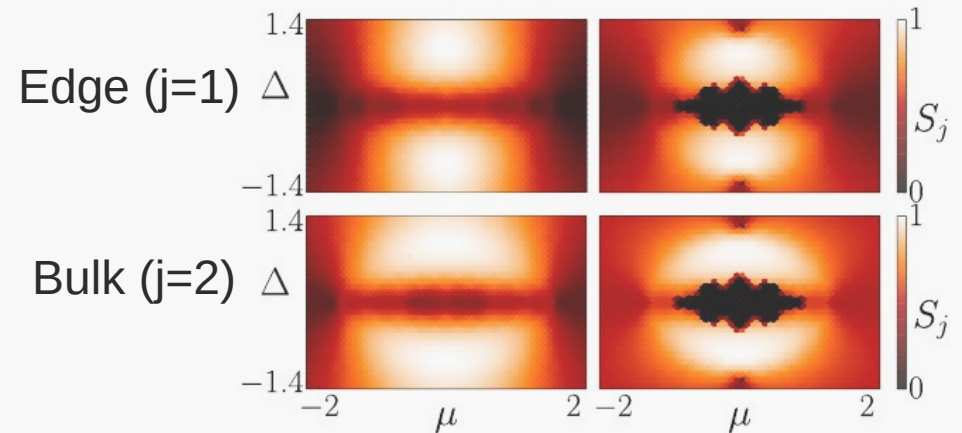
All qubits interact with cavity mode

$$H = \epsilon_i \sigma_z^i + \omega_c a^\dagger a + g \sum_i \sigma_x^i (a + a^\dagger) + \xi(t)(a + a^\dagger)$$

$$H = H_{XY} + H_{FF} \quad H_{FF} = \lambda_{FF} \sum_{ij} (\sigma_i^+ \sigma_j^- + \sigma_i^- \sigma_j^+)$$



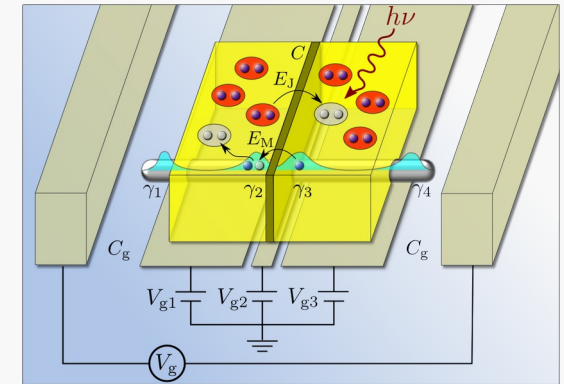
without long-range    with long-range



# Summary

## The Majorana–Transmon qubit

- Proposed & analyzed hybrid device combining topological superconductors in superconducting cQED devices
  - Remains highly coherent due to an almost exact decoupling from cavity
  - Can be initialized, controlled and manipulated via side-band transitions satisfying selection rules
  - Can be used to detect Majorana fermions



## cQED as simulator for topological states

- Generating a protected qubit from a small array of interacting qubits

