Application of Wilson's NRG to Majorana-Kondo systems.

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NRG UFU/2019 Advanced Studies School
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Physics @ USP – São Paulo.

Physics Institute-USP

6 departments
~130 active faculty
~250 grad students
~400 undergrad students

IF - USP

S.Paulo-Uberlândia ~600 km

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Outline

- Basics: Majorana bound states in condensed matter systems.
- *Detecting* Majorana states with quantum dots.
- Interacting quantum dots: Wilson's NRG
- Kondo-Majoranana co-existence.
- *Manipulating* Majorana states with (double) quantum dots.

What are Majorana fermions?

Majorana Fermions

Majorana solution: Representarions of Dirac matrices with *only imaginary non-zero elements* while still satisfying

$$\begin{array}{l}\tilde{\gamma}_0^\dagger = \tilde{\gamma}_0 \\ \tilde{\gamma}_i^\dagger = -\tilde{\gamma}_i\end{array} \quad \Longrightarrow \quad [i\tilde{\gamma}^\mu \partial_\mu - m]\,\Psi = 0$$

http://www.giornalettismo.com/archives/255332/il-ritorno-di-ettore-majorana/

Real solutions: $[i\tilde{\gamma}^\mu \partial_\mu - m]\,\gamma = 0$ $\quad \boxed{\gamma = \gamma^\dagger}$

- A Dirac fermion can be "written" in terms of two Majorana fermions

$$\begin{cases} \Psi = \frac{1}{2}(\gamma_1 + i\gamma_2) \\ \Psi^\dagger = \frac{1}{2}(\gamma_1 - i\gamma_2) \end{cases}$$

or

$$\boxed{\gamma_1 = (\Psi^\dagger + \Psi)}$$

E. Majorana, *Nuovo Cimento* **5**, 171 (1937)

Where do we find Majorana fermions?

Majorana quasiparticles in condensed matter systems?

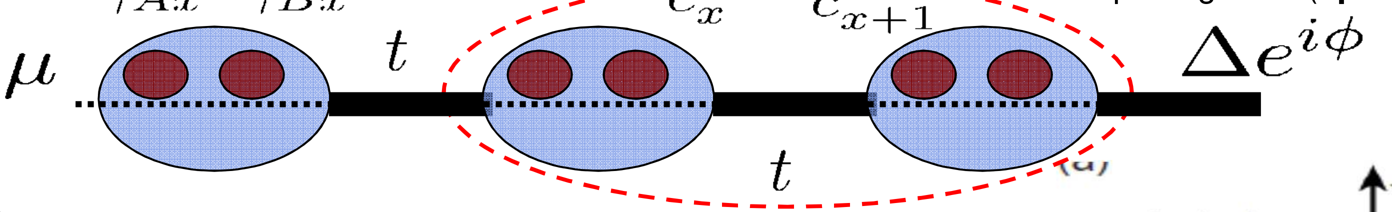
- Fractional Quantum Hall liquids (ν=5/2): "non-Abelian anyons". — Moore and Read, *Nucl. Phys. B* (1991).
- Two-channel Kondo non-Fermi-liquid state. — Emery, Kivelson, *PRB* (1992). Coleman, Ioffe, Tsvelik *PRB* (1995). Maldacena, Ludwig, *Nucl. Phys. B.* (1997). Zhang, Hewson, Bulla, *Solid State Comm.* (1999).
- Interface of topological insulators with BCS superconductors — Fu and Kane, *Phys. Rev. Lett.* (2008).
- Spin-polarized ("spinless") p-wave superconductors. — Read and Green, *Phys. Rev. B* (2000). Kitaev, *Phys. Usp.* (2001).

Motivation: entanglement of particles with non-abelian statistics ("Ising anyons"); topologically protected quantum computation.

1D p-wave superconductor (Kitaev model)

$$H = -\mu \sum_x c_x^\dagger c_x - \frac{1}{2}\sum_x (t c_x^\dagger c_{x+1} + \Delta e^{i\phi} c_x c_{x+1} + h.c.)$$

P-wave pairing term (**spinless** fermions)



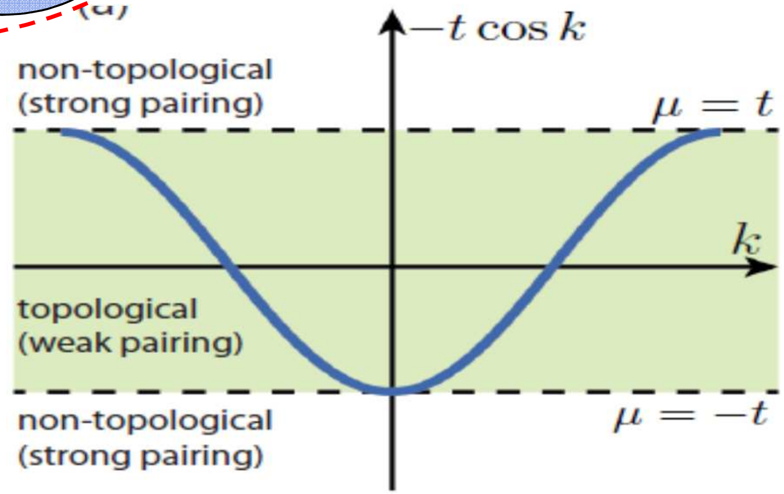
Energy spectrum:

$$E(k) = \pm\sqrt{(t\cos k + \mu)^2 + (\Delta \sin k)^2}$$

$|\mu| > t$ Gapped (E_+-$E_->0$): **trivial**

$\mu = \pm t$ Gappless modes (E=0) : $k = \pm\pi$ or $k = 0$

$|\mu| < t$ Gapped: **topological** ($\Delta \neq 0$)



J. Alicea, *Rep. Prog. Phys.* **75**, 076501 (2012)

Majorana states in the Kitaev model.

Map into a "chain of Majorana modes" using:

$$\begin{cases} c_x = \frac{e^{-i\phi/2}}{2}\left(\gamma_{B,x} + i\gamma_{A,x}\right) \\ c_x^\dagger = \frac{e^{+i\phi/2}}{2}\left(\gamma_{B,x} - i\gamma_{A,x}\right) \end{cases}$$

$$H = -\mu \sum_x c_x^\dagger c_x - \frac{1}{2}\sum_x \left(t c_x^\dagger c_{x+1} + \Delta e^{i\phi} c_x c_{x+1} + h.c.\right)$$

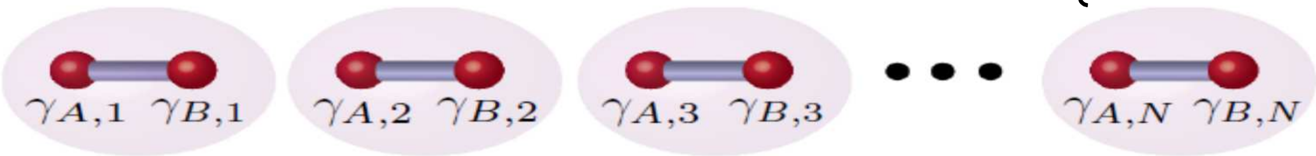
$$\Downarrow$$

$$H = -\frac{\mu}{2}\sum_x^N \left(1 + i\gamma_{B,x}\gamma_{A,x}\right) - \frac{i}{4}\sum_x^{N-1} \left(\Delta + t\right)\gamma_{B,x}\gamma_{A,x+1} + \left(\Delta - t\right)\gamma_{A,x}\gamma_{B,x+1}$$

Majorana states in the Kitaev model.

$$H = -\frac{\mu}{2}\sum_{x}^{N}\left(1 + i\gamma_{B,x}\gamma_{A,x}\right) - \frac{i}{4}\sum_{x}^{N-1}\left(\Delta + t\right)\gamma_{B,x}\gamma_{A,x+1} + \left(\Delta - t\right)\gamma_{A,x}\gamma_{B,x+1}$$

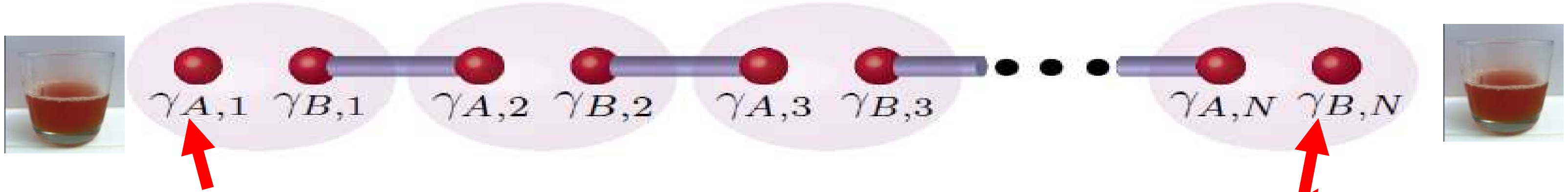
$|\mu| > t$ Gapped: **trivial.** Special case: $\begin{cases} \mu \neq 0 \\ t = \Delta = 0 \end{cases}$



$$E_+ - E_- = 2\mu$$

$|\mu| < t$ Gapped: **topological.** Special case: $\begin{cases} \mu = 0 \\ t = \Delta \neq 0 \end{cases}$

$$E_+ - E_- = 2\Delta$$



Topological regime: Majorana modes (e=μ=0!!!) at the *edges* of the chain!

Can the Kitaev model be realized experimentally?

How to realize a p-wave SC: Quantum wires.

Theory: Lutchyn et al. PRL, **105**, 077001 (2010); Oreg et al. PRL,**105**, 077002 (2010);

- Step 1:

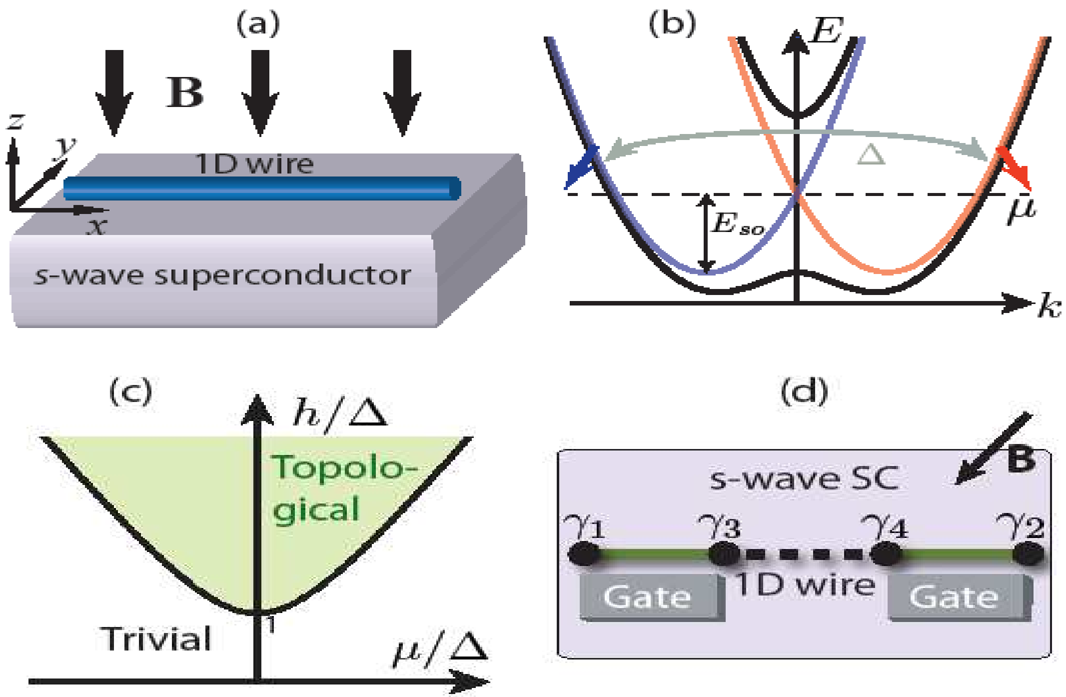
create spinless 1D fermions.

Ingredients: spin-orbit, B field.

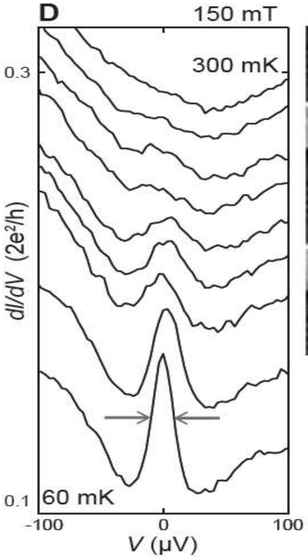
- Step 2:

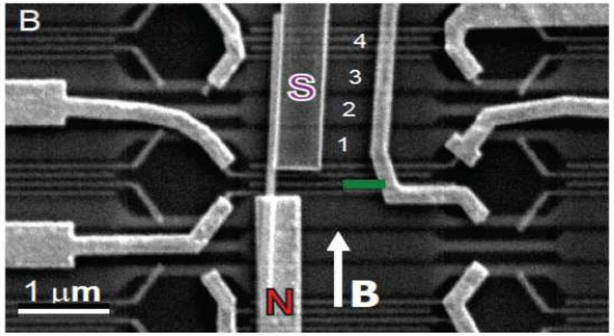
Introduce SC pairing.

Ingredients: proximity with a BCS SC



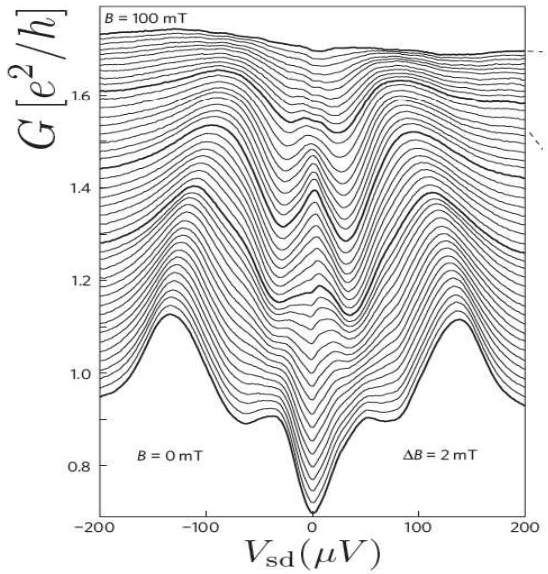
Experiment on InSb nanowires.

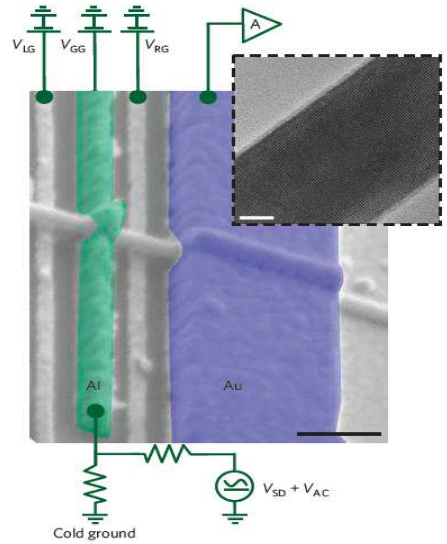




Zero-bia peak in tunneling spectroscopy

Mourik *et al.*, Science **336**, 1003–1007 (2012)
Deng *et al.*, Nano Lett. **12**, 6414 (2012)
Das *et al.*, Nature Phys. **8**, 887 (2012)
Prada et al., Phys. Rev. B **86**, 180503 (2012)
Churchill et al., Phys. Rev. B **87**, 241401 (2013)





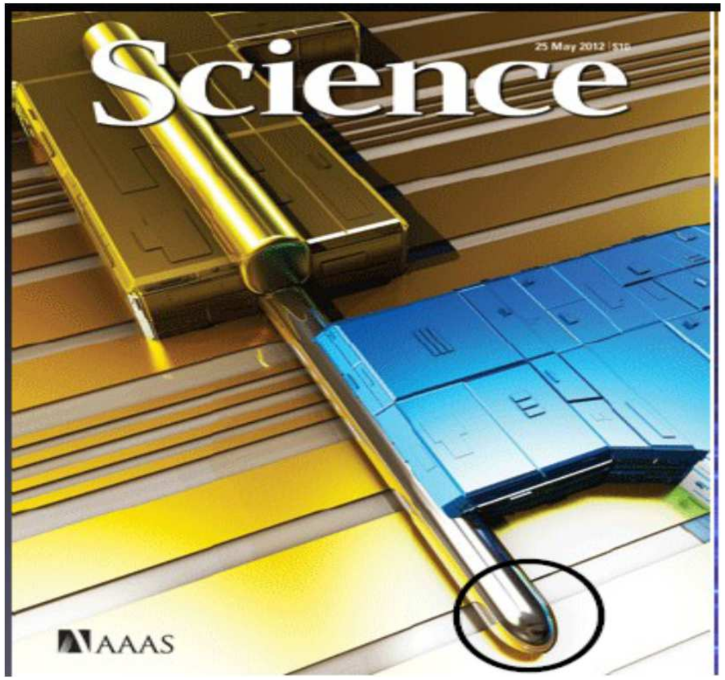
Signatures appear for:

- Large enough magnetic field (topological phase)
- Not too big (that it kills the induced superconductivity)
- Perpendicular to Rashba SO

A success story??

Theory: Lutchyn et al. PRL, **105**, 077001 (2010); Oreg et al. PRL,**105**, 077002 (2010);

Experiment: V. Mourik et al. Science **336** 1003 (2012)



Inside joke:

"Majorana found at the end of a quantum wire"

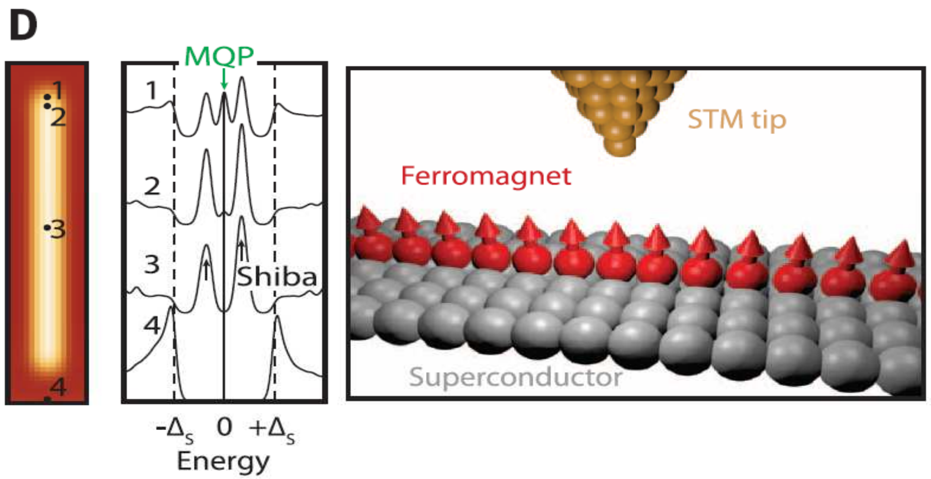
Alternative explanations for the zero-bias peak.

Skepticism:

- Tunneling spectroscopy probes the BULK too
- Possible origins of the zero-bias peak:
  - Localization due to disorder
  - Andreev reflection
  - Kondo effect

Solution*:

Local probing of the wire ends



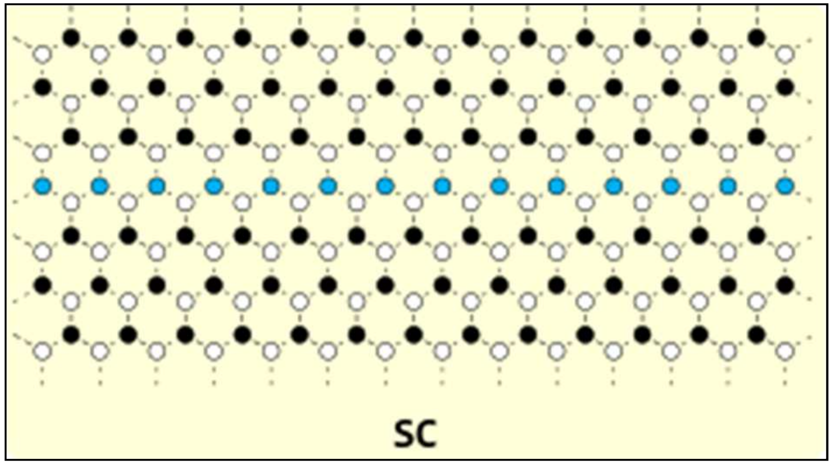
Nadj–Perje *et al.*, Science **346**, 602–607 (2014)

MBSs in magnetic chains on topological insulators

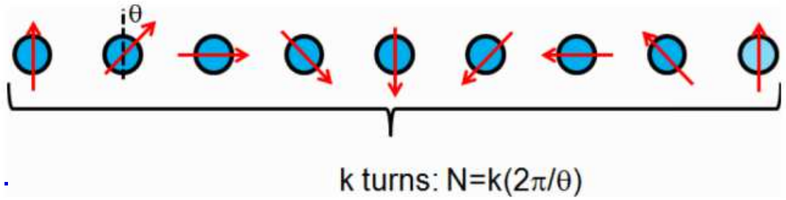
(See poster by Raphael Levy…)

Honeycomb lattices:
Silicene, Stanene…

Kane-Mele-type TIs



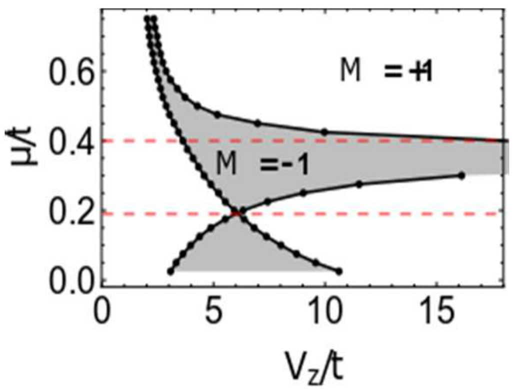
Magnetic chain: spiral angle θ



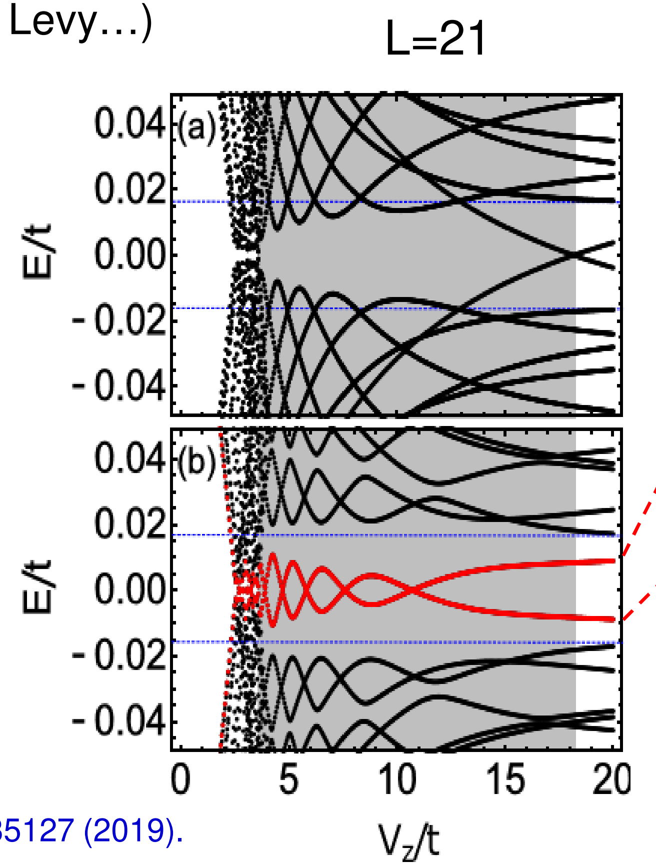
R. Teixeira *et al. Phys Rev B* **99** 035127 (2019).

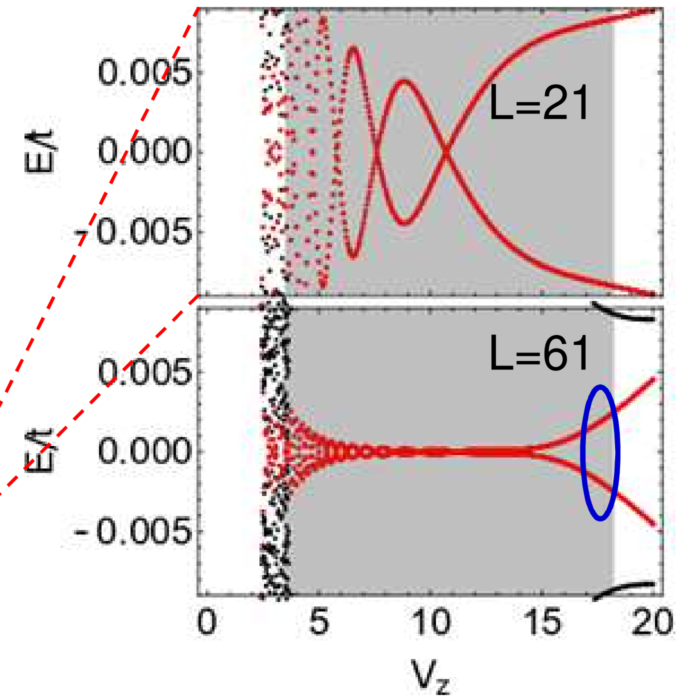
MBSs in magnetic chains on topological insulators

(See poster by Raphael Levy…)



$$\theta = \pi/2$$





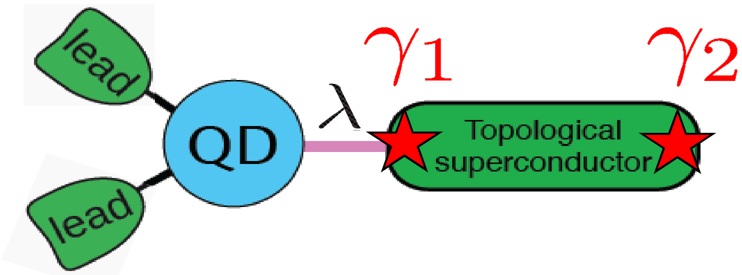
R. Teixeira *et al. Phys Rev B* **99** 035127 (2019).

MBS or ABS?

Detecting MBS with quantum dots.

Better way to measure?

- Quantum dot coupled to metallic leads coupled with at the end of the nanowire.

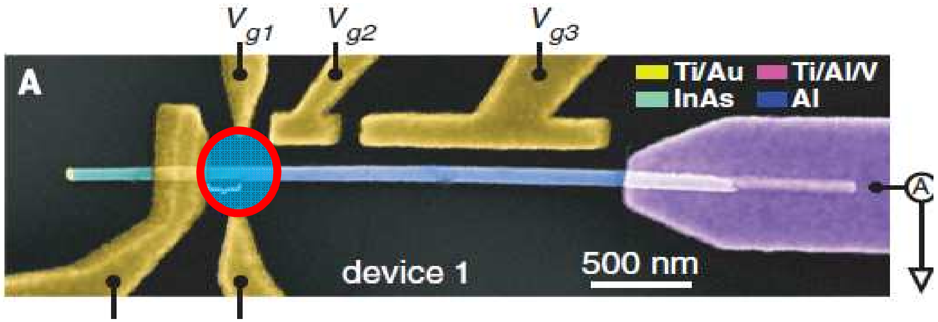


Theory

Liu and Baranger, *Phys Rev B* **84** 201308 (2011).

Vernek et al., *Phys Rev B* **89** 165314 (2014).

Ruiz-Tijerina et al. *Phys Rev B* **91** 115435 (2015).



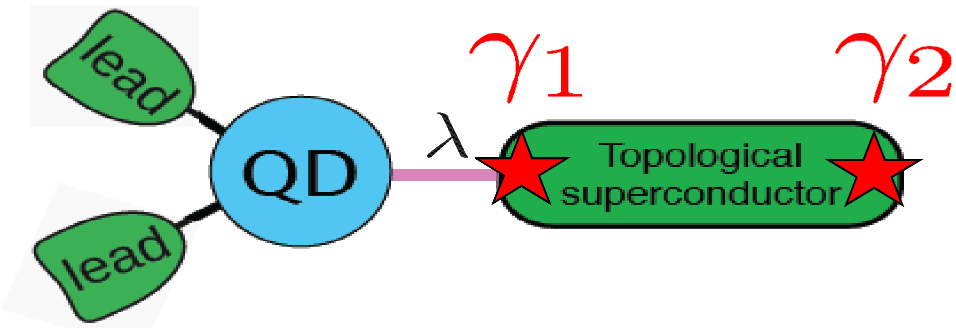
Experiment (Marcus' group)

M.T. Deng et al., *Science* **354** 1557 (2016).

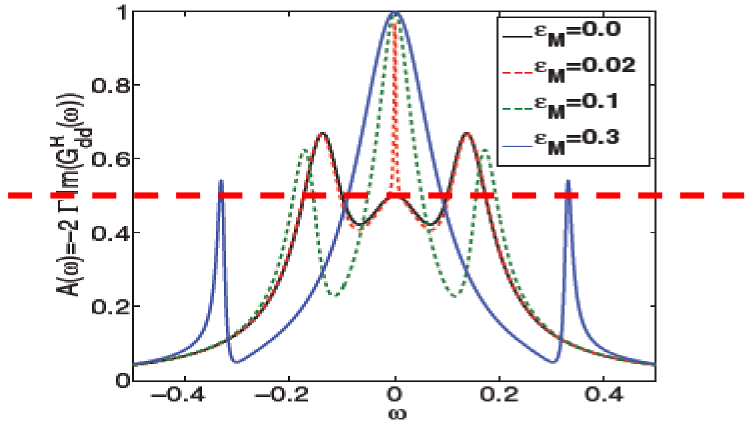
Better way to measure?

Liu and Baranger, *Phys Rev B* **84** 201308 (2011).

Vernek et al., *Phys Rev B* **89** 165314 (2014).



U=0!!!



- Connect a quantum dot + metallic leads at the end of the nanowire.
- Measure conductance through the dot
- 0.5 e^2/h = signature of the Majorana mode for U=0
- What happens for the (common) case of non-zero U???

  Ruiz-Tijerina et al. *Phys Rev B* **91** 115435 (2015).

Majoranas + interaction

- Kondo impurity + Majorana edge states (NRG)

  R. Zitko, *Phys. Rev. B* **83**, 195137 (2011).

  R. Zitko, P. Simon, *Phys. Rev. B* **84**, 195310 (2011).

- Quantum dot + Kitaev (NRG)

  M. Lee, et al., *Phys. Rev. B* **87**, 241402 (2013).

  Chirla et al., *Phys. Rev. B* **90**, 195108 (2014).

  Ruiz-Tijerina et al., *Phys. Rev. B* **91**, 115435 (2015).

- Quantum dot + Kitaev (DMRG)

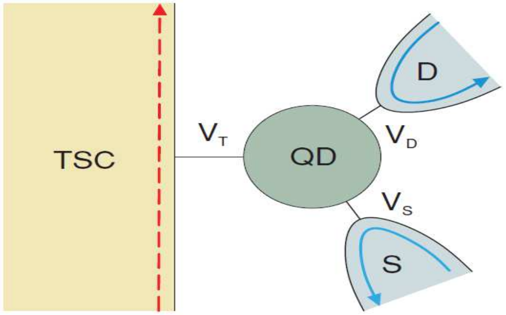
  Korytár and Schmitteckert, *JPCM* **25** 475304 (2014).

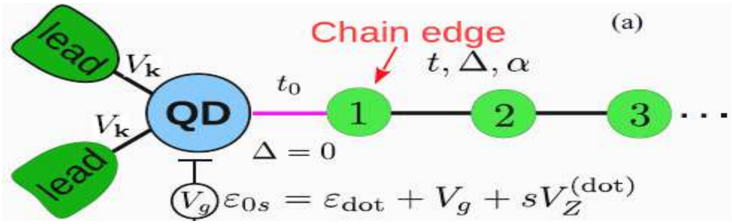
  Cheng et al., *Phys. Rev. X* **4**, 031051 (2014).

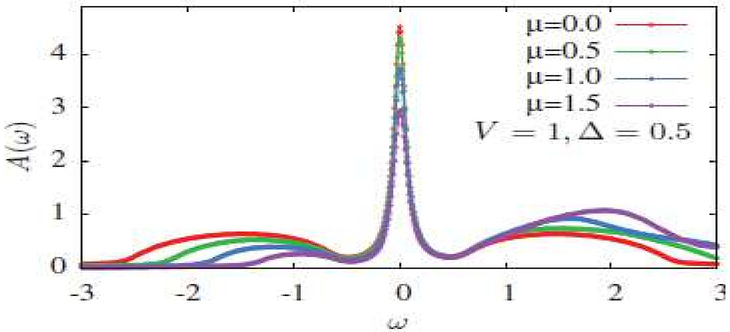
- Interacting Kitaev model (DMRG)

  Stoudenmire et al., *Phys. Rev. B* **84** 014503 (2011).

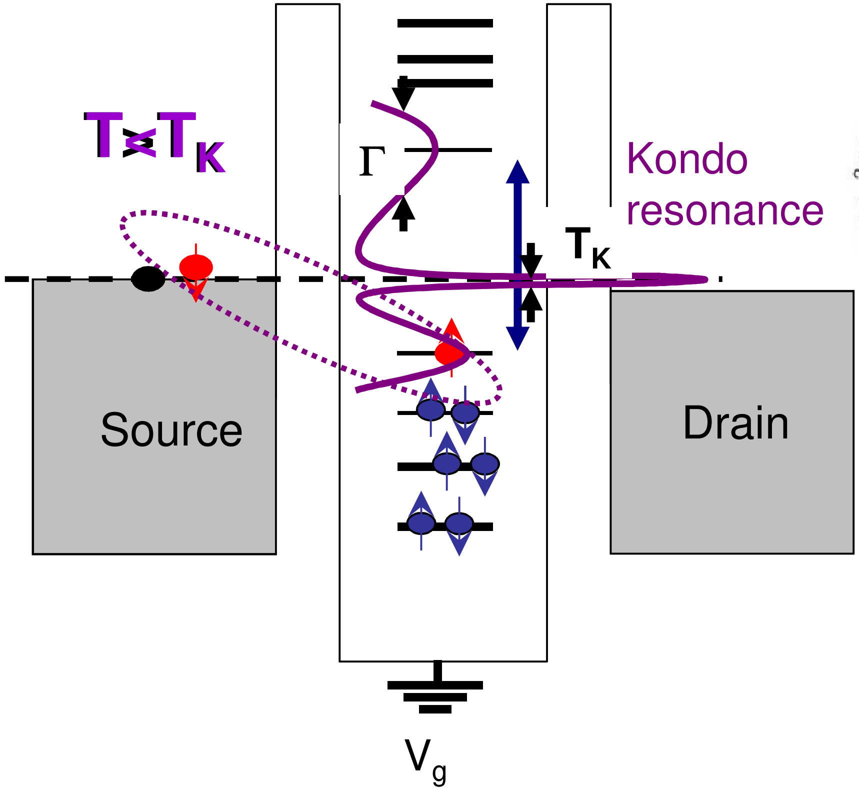
  Thomale et al., *Phys. Rev. B* **88** 161103(R) (2013).

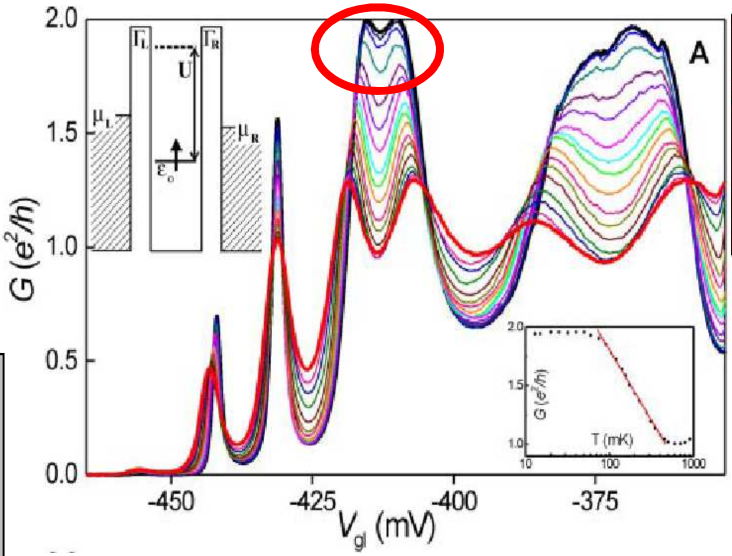


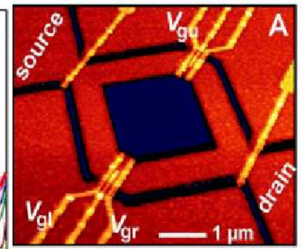




Kondo Effect in Quantum Dots: zero-bias transport.



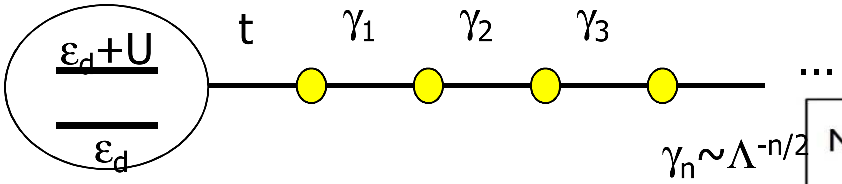




van der Wiel et al., *Science* **289** 2105 (2000).

•$T>T_K$: Coulomb blockade (low G)
•$T<T_K$: Kondo singlet formation
•Kondo resonance at E_F (width T_K).
•New conduction channel at E_F:
Zero-bias enhancement of G ($\rightarrow 2e^2/h$!)

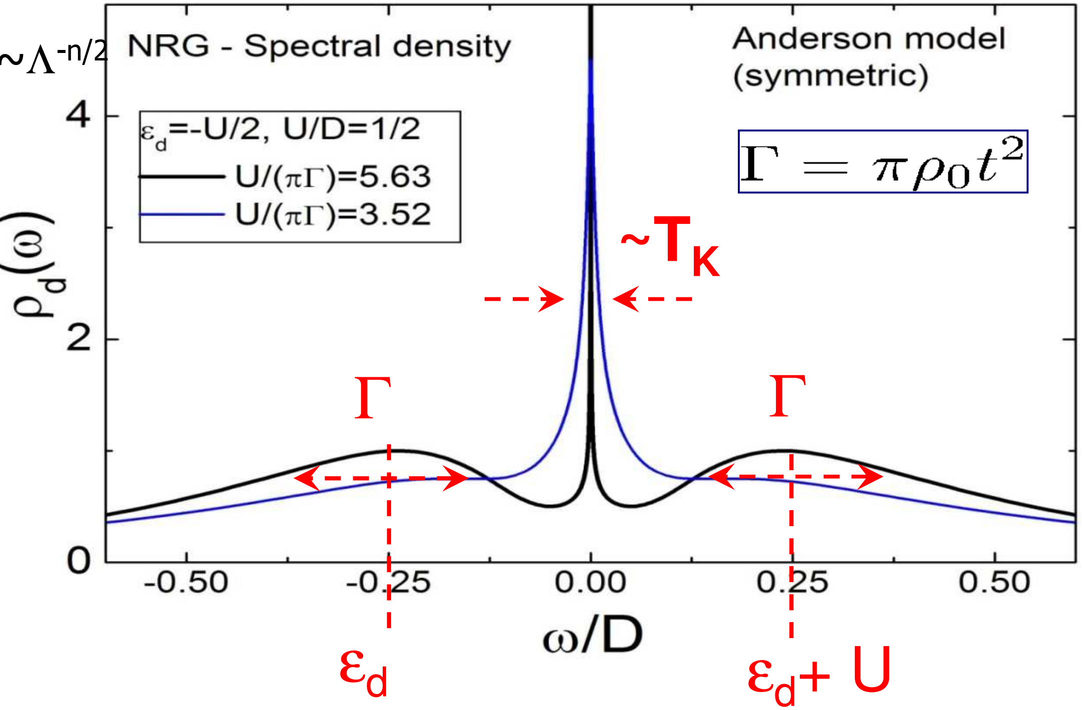
Kondo resonance with Wilson's NRG



- Spectral density:
  - Single-particle peaks at ε_d and ε_d+U.
  - *Many-body* peak at the Fermi energy: ***Kondo resonance*** (width ~T_K).
- NRG: very good resolution at low ω.

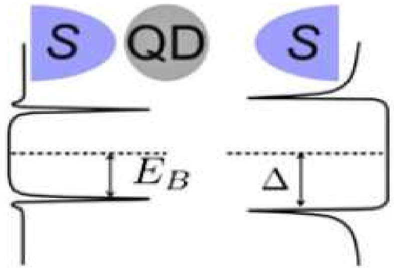
$$T_K \sim \sqrt{\frac{U\Gamma}{2}} e^{-\pi|\epsilon_d+U|\epsilon_d/2U\Gamma}$$

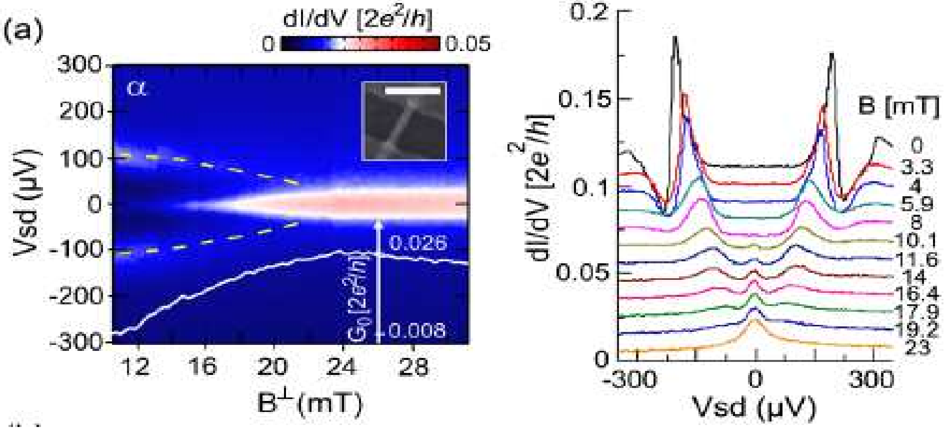
$$\rho_d(\omega) = -\mathrm{Im}\ G_d(\omega)$$

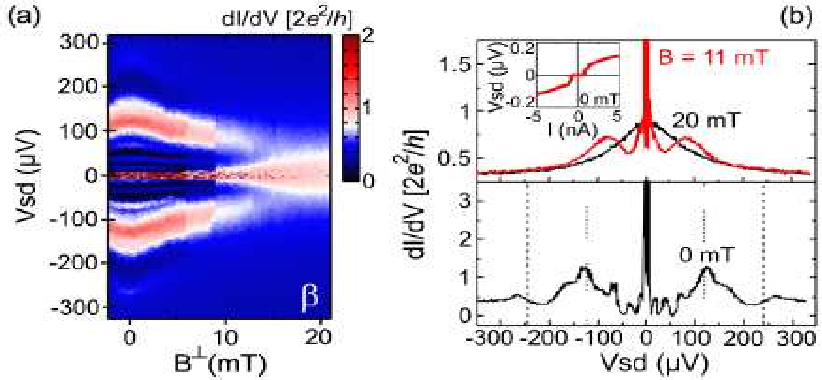


Kondo zero-bias peak in quantum wires coupled to SC leads.

E.J. Lee et al. PRL **109** 186802 (2012)

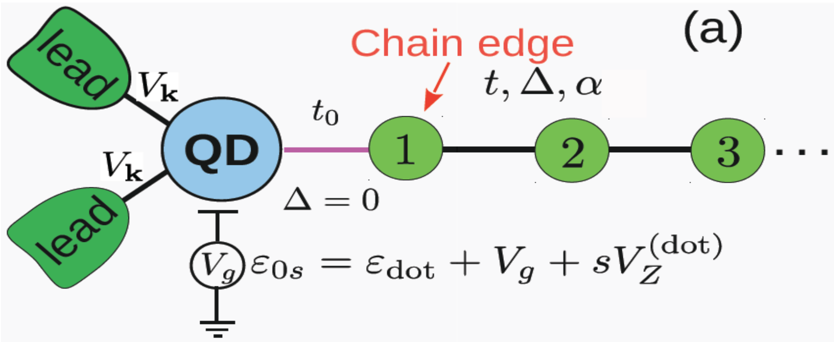


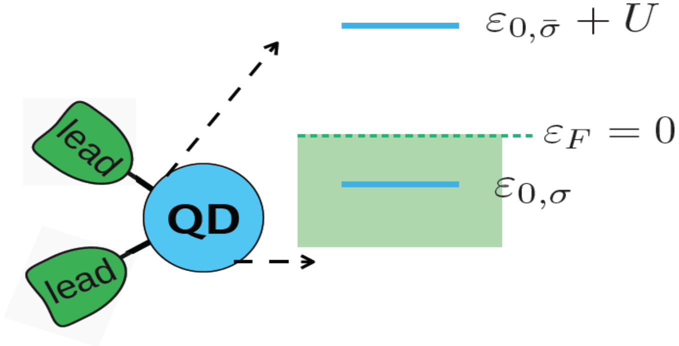




- Quantum dot defined in InAs/InP quantum wires coupled to superconducting leads.
- Kondo-like zero-bias peak emerges at a critical field B_c .

Model: Quantum dot + quantum wire + SC pairing.





Quantum wire:

$$H_{\text{wire}} = H_{\text{TB}}(\mu, t, V_Z) + H_{\text{Rashba}}(\alpha) + H_{\text{SC}}(\Delta)$$

Quantum dot:

$$H_{\text{dot}} = \sum_{s=\uparrow,\downarrow} \varepsilon_{0,s}\, n_{0,s} + U\, n_{0,\uparrow} n_{0,\downarrow}$$

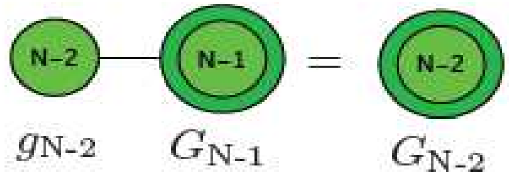
Topological phase for $|V_Z| > \sqrt{\mu^2 + \Delta^2}$

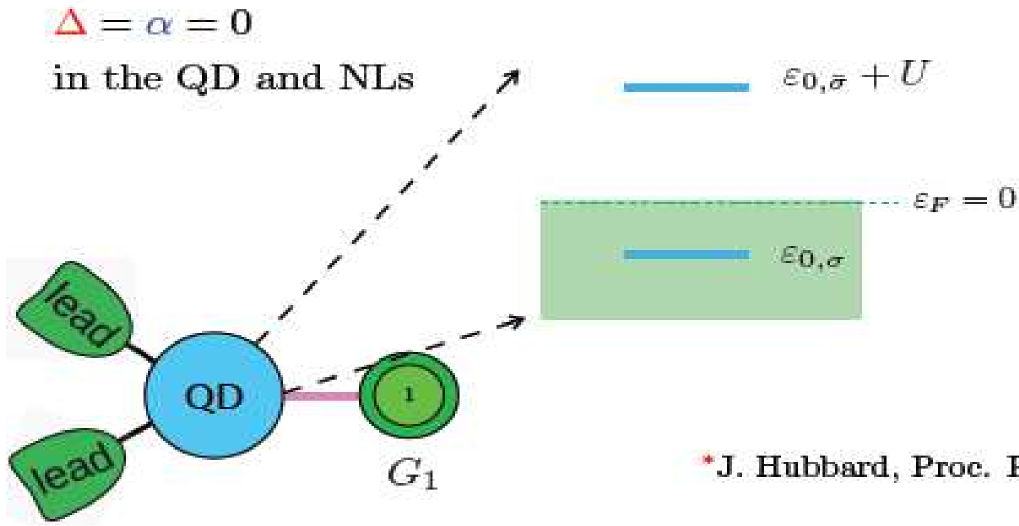
Rainis *et al.*, Phys. Rev. B **87**, 024515 (2013)

QD-wire coupling:

$$H_{\text{dot-wire}} = t_0 \sum_{s=\uparrow,\downarrow} \left[c_{0,s}^\dagger c_{1,s} + c_{1,s}^\dagger c_{0,s} \right]$$

Iterative Green's functions + mean field (Hubbard I).

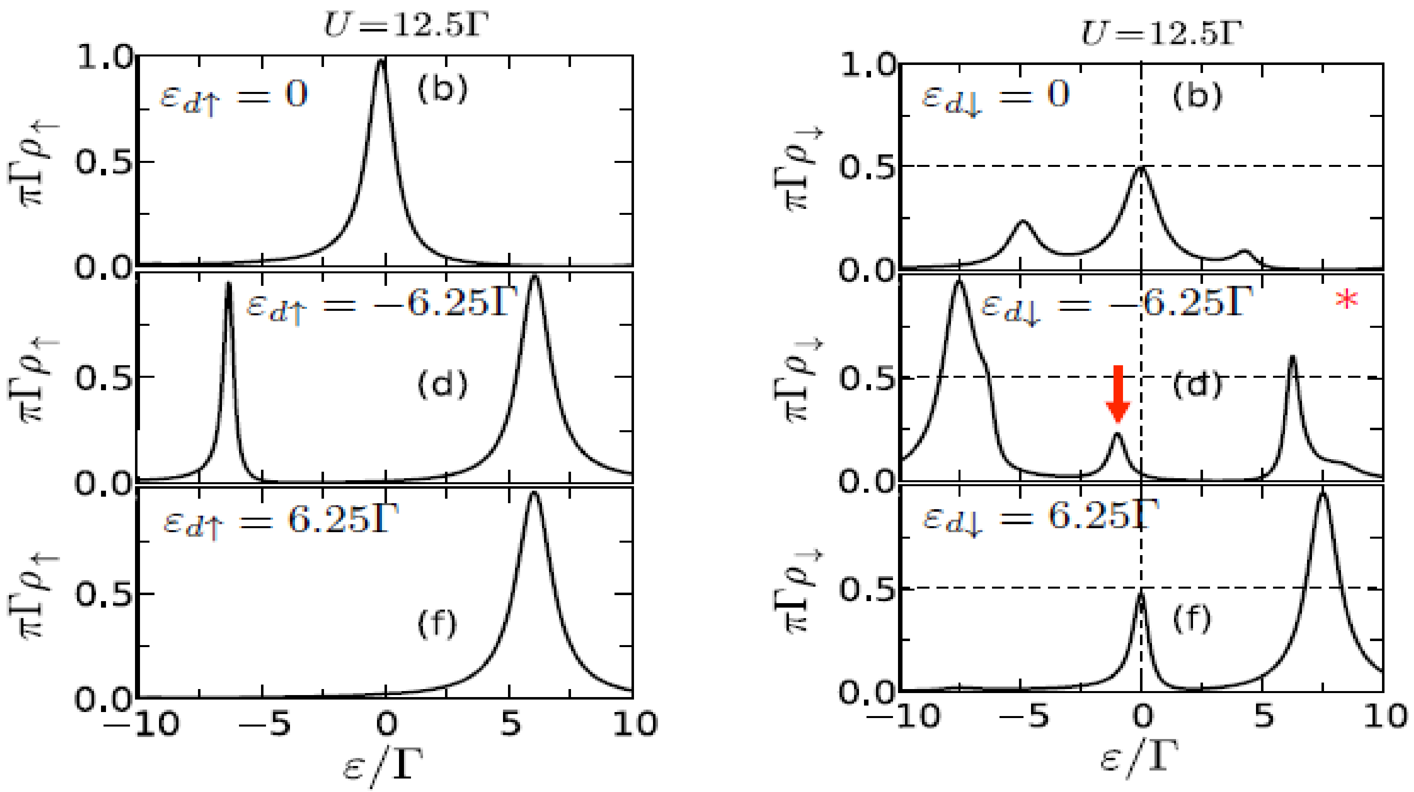




- Because of the Coulomb interaction, the **NL–QD** part displays many–body correlations (Kondo physics).
- We use an approximation based on the *Hubbard I method** to obtain the Green's function.

*J. Hubbard, Proc. Roy. Soc. (London) **A276**, 238 (1963)

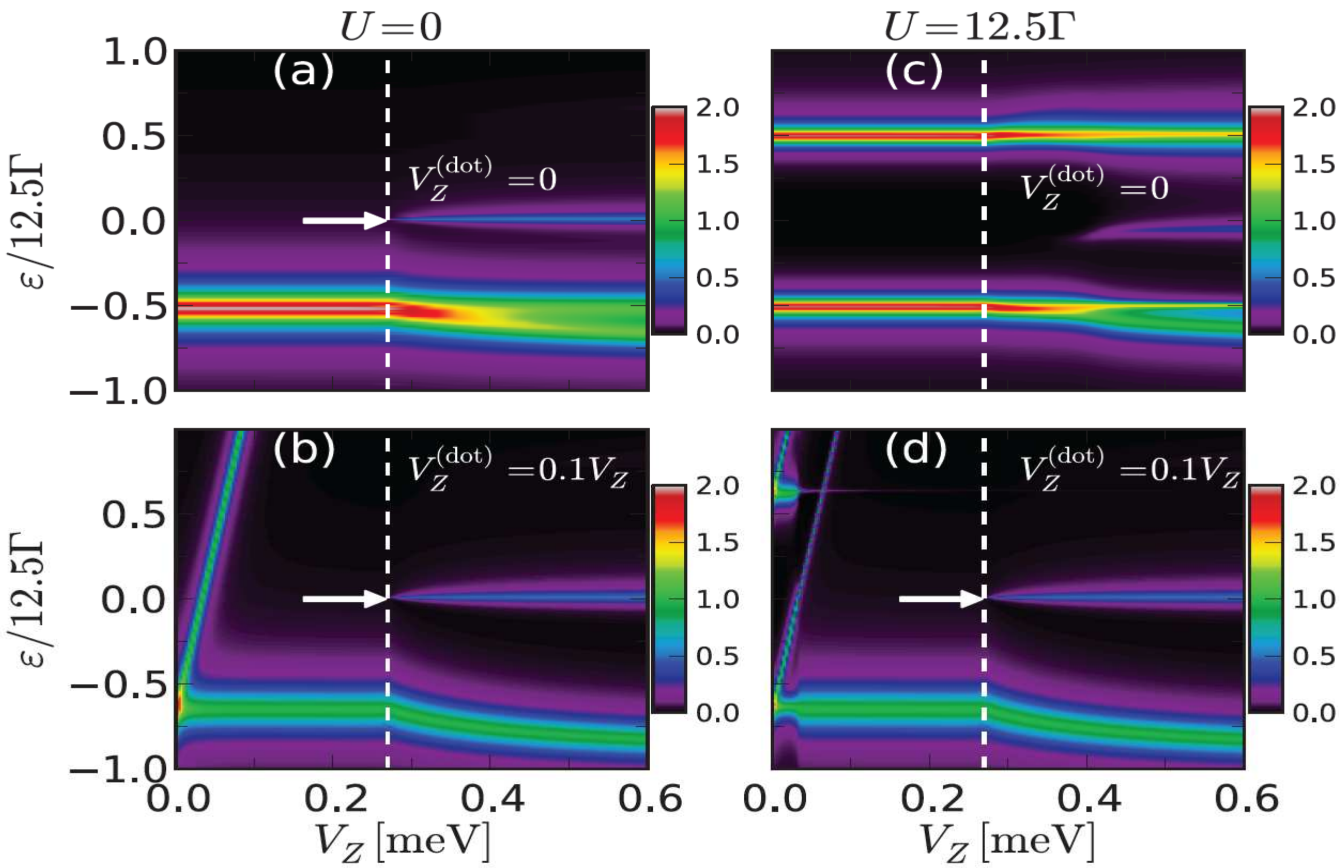
Iterative Green's functions + mean field (Hubbard I).



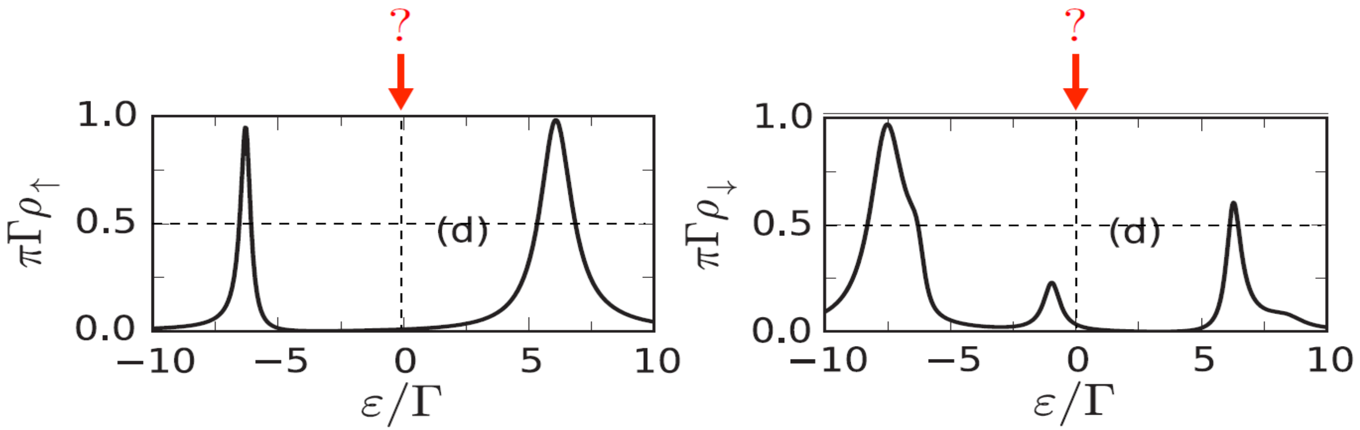
*Particle–hole symmetry

Ruiz-Tijerina, *et al. Phys. Rev. B* **91**, 115435 (2015)

Iterative Green's functions + mean field (Hubbard I).



Shortcomings of the mean-field approximation.

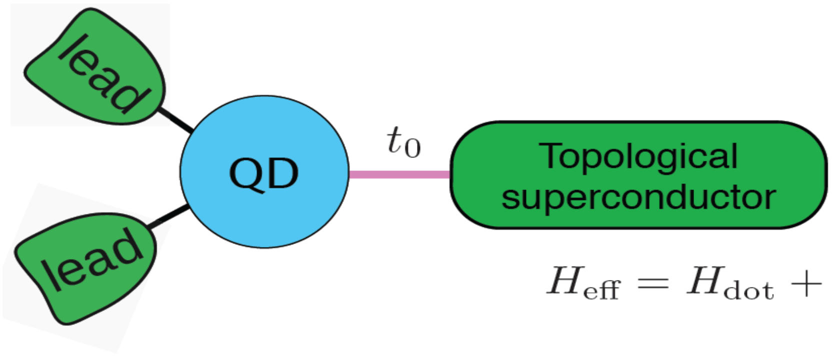


- The Hubbard I approximation captures the Majorana physics outside of the Kondo regime
- It doesn't capture the Kondo correlations
- What if there is a strong Kondo-Majorana interplay?

$*$Particle–hole symmetry

Ruiz-Tijerina, *et al. Phys. Rev. B* **91**, 115435 (2015)

Effective low-energy Anderson model



Lee *et al.*, Phys. Rev. B **87**, 241402 (2013)

- Effective model: MZM couples directly to the QD spin–down ($V_Z > 0$).

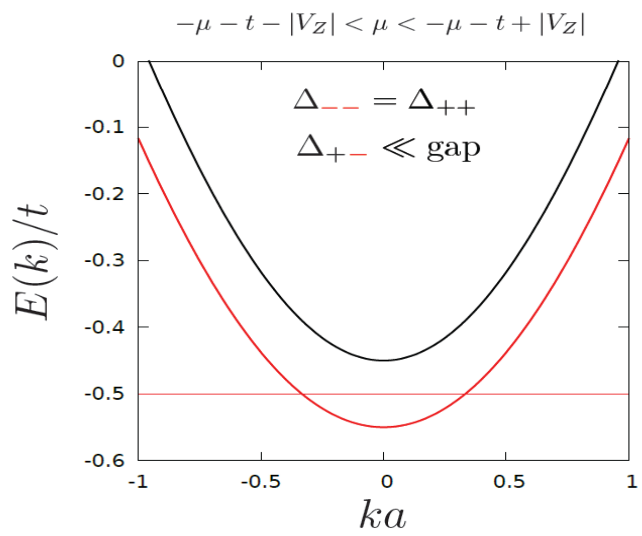
$$H_{\mathrm{eff}} = H_{\mathrm{dot}} + H_{\mathrm{leads}} + H_{\text{dot-leads}} + \lambda\gamma\left(d_\downarrow - d_\downarrow^\dagger\right)$$

$$H_{\mathrm{dot}} = \sum_\sigma \varepsilon_{0\sigma}(\varepsilon_d,\, V_Z^{(\mathrm{dot})})n_{0\sigma} + U\, n_{0\uparrow}n_{0\downarrow}$$

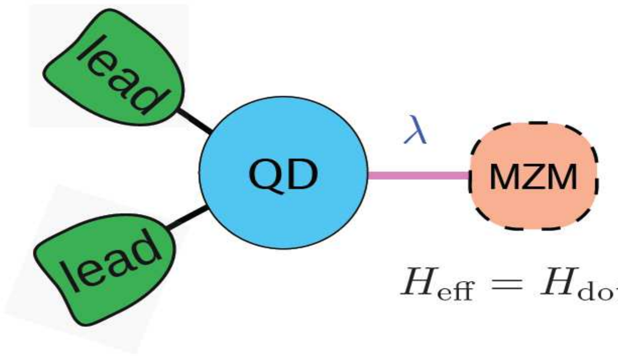
$$H_{\mathrm{leads}} = \sum_{\vec{k}\sigma} \varepsilon_k\, c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma}$$

$$H_{\text{dot-leads}} = \sum_{\vec{k}\sigma} \left[V_{\vec{k}}\, d^\dagger_\sigma c_{\vec{k}\sigma} + \mathrm{H.\ c.}\right]$$

For a positive Zeeman splitting V_Z, the wire couples only to the QD spin-dn.



Effective low-energy Anderson model



Lee *et al.*, Phys. Rev. B **87**, 241402 (2013)

- Effective model: MZM couples directly to the QD spin–down ($V_Z > 0$).

$$H_{\text{eff}} = H_{\text{dot}} + H_{\text{leads}} + H_{\text{dot-leads}} + \lambda\gamma\left(d_\downarrow - d_\downarrow^\dagger\right)$$

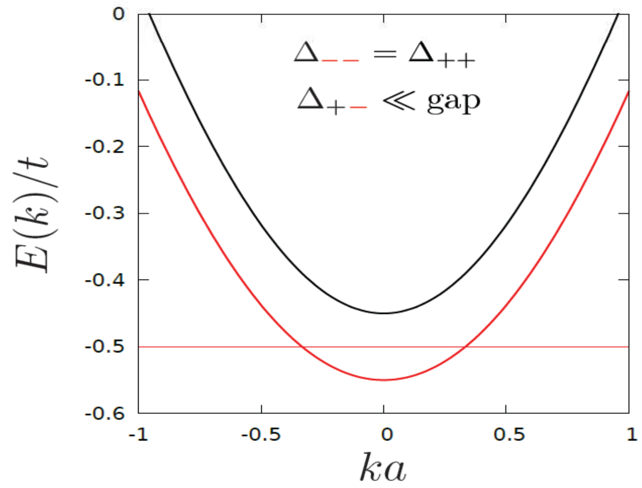
$$H_{\text{dot}} = \sum_\sigma \varepsilon_{0\sigma}(\varepsilon_d,\, V_Z^{(\text{dot})})n_{0\sigma} + U\, n_{0\uparrow}n_{0\downarrow}$$

$$H_{\text{leads}} = \sum_{\vec{k}\sigma} \varepsilon_k\, c_{\vec{k}\sigma}^\dagger c_{\vec{k}\sigma}$$

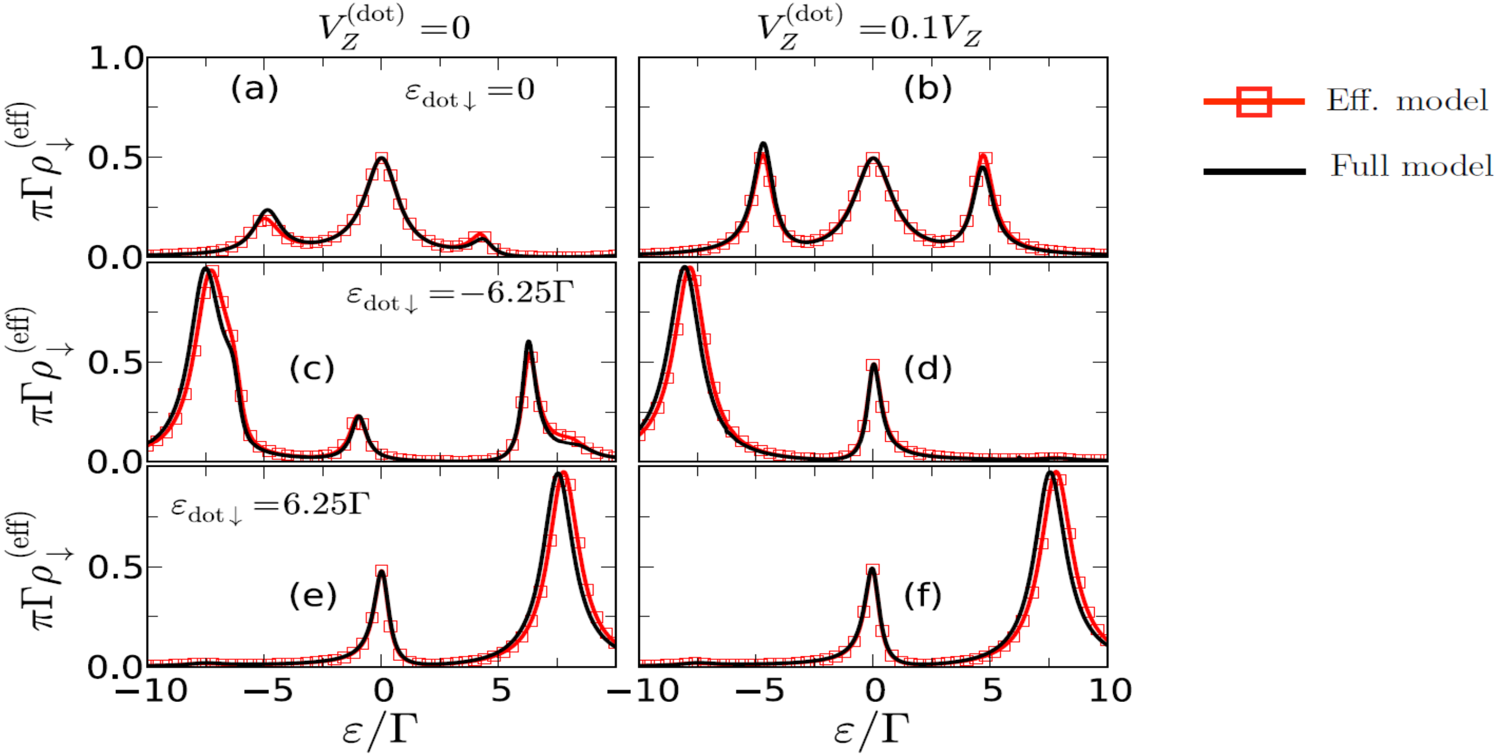
$$H_{\text{dot-leads}} = \sum_{\vec{k}\sigma} [V_{\vec{k}}\, d_\sigma^\dagger c_{\vec{k}\sigma} + \text{H. c.}]$$

For a positive Zeeman splitting V_Z, the wire couples only to the QD spin-dn.

$-\mu - t - |V_Z| < \mu < -\mu - t + |V_Z|$



Effective low-energy Anderson model



With the right choice of λ, we reproduce the numerical results for a given t_0.

Effective model

$c_\alpha^\dagger$: creates a fermion in state α

$\hat{n}_\alpha \equiv c_\alpha^\dagger c_\alpha$: number operator (=0,1)

$$c^\dagger_{E=0} = (\gamma_1 - i\gamma_2)$$ zero energy mode

$$\gamma_{1(2)} = \gamma^\dagger_{1(2)}$$

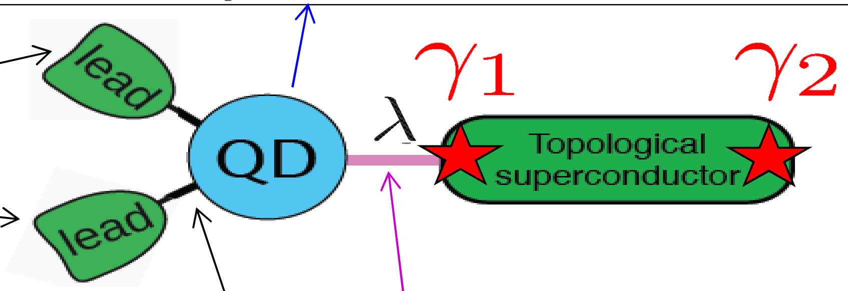
Majorana operators

Quantum dot (V_Z: Zeeman ; U: e-e interaction)

$$H_{\text{dot}} = \sum_\sigma (\varepsilon_d + \sigma . V_Z)\,\hat{n}_{d\sigma} + U\,\hat{n}_{d\uparrow}\hat{n}_{d\downarrow}$$

Metallic leads

$$H_{\text{leads}} = \sum_{\mathbf{k},\sigma} \varepsilon_{\mathbf{k}\ell\sigma}\hat{n}_{\mathbf{k}\ell\sigma}$$



Coupling to the metallic leads

$$H_{\text{dot-leads}} = \sum_{\mathbf{k}} V_{\mathbf{k}} c^\dagger_{d\sigma} c_{\mathbf{k}\sigma} + \text{H.c.}$$

$$H_{\text{dot}-\gamma} = \lambda\left(c_{d\downarrow} - c^\dagger_{d\downarrow}\right)\gamma_1 + \text{H.c.}$$

Coupling to one Majorana

NRG: spectral function and conductance

D. A. Ruiz-Tijerina et al. *Phys Rev B* **91** 115435 (2015).

NRG formulation: quantum numbers

$$\gamma_{1(2)} = \gamma^{\dagger}_{1(2)}$$ Majorana operators

$$f^{\dagger}_{\downarrow} = (\gamma_1 - i\gamma_2)$$ Fermion operators

$$\gamma_1 = \frac{1}{2}\left(f^{\dagger}_{\downarrow} + f_{\downarrow}\right) \Rightarrow$$

$$\boxed{H_{\text{dot}-\gamma} = \frac{\lambda}{2}\left(c^{\dagger}_{d\downarrow} f_{\downarrow} + c^{\dagger}_{d\downarrow} f^{\dagger}_{\downarrow}\right) + \text{H.c.}}$$

$\boxed{N_{\uparrow} = n_{d\uparrow}}$ **OK!**

$N_{\downarrow} = n_{d\downarrow} + n_{f\downarrow}$ **not a good QN!**

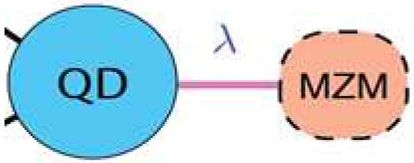
$$\boxed{\langle \downarrow_f \downarrow_d | c^{\dagger}_{d\downarrow} f^{\dagger}_{\downarrow} | 0_d 0_f \rangle \neq 0}$$

However: $\boxed{P_{\downarrow} = (-1)^{N_{\downarrow}}}$ **OK!**

Build blocks such as: $[N_{\uparrow} = 0, P_{\downarrow} = +1] \begin{cases} |0_d 0_f\rangle \\ |\downarrow_d \downarrow_f\rangle \end{cases}$ etc,

See also: M. Lee, et al., *Phys. Rev. B* **87**, 241402 (2013).

NRG formulation: quantum numbers



H_{-1} : block-diagonal:

$$N_{\uparrow} = n_{d\uparrow} \qquad P_{\downarrow} = (-1)^{N_{\downarrow}}$$

$$[N_{\uparrow}=0, P_{\downarrow}=-1] \left\{ \begin{array}{l} |0_d \downarrow_f\rangle \\ |\downarrow_d 0_f\rangle \end{array} \right.$$

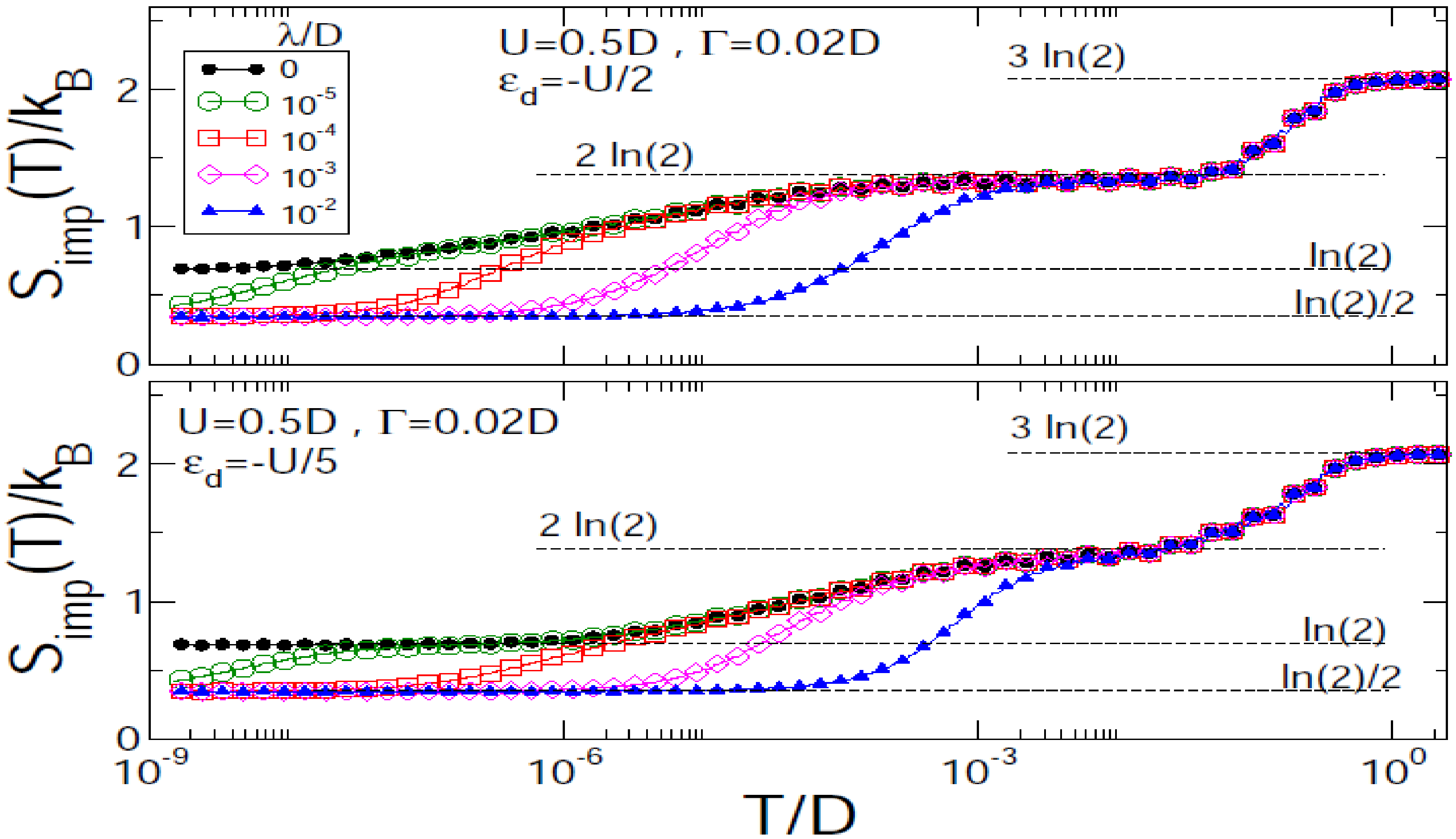
$$[N_{\uparrow}=0, P_{\downarrow}=+1] \left\{ \begin{array}{l} |0_d 0_f\rangle \\ |\downarrow_d \downarrow_f\rangle \end{array} \right.$$

$$[N_{\uparrow}=1, P_{\downarrow}=-1] \left\{ \begin{array}{l} |\uparrow_d \downarrow_f\rangle \\ |(\uparrow\downarrow)_d 0_f\rangle \end{array} \right.$$

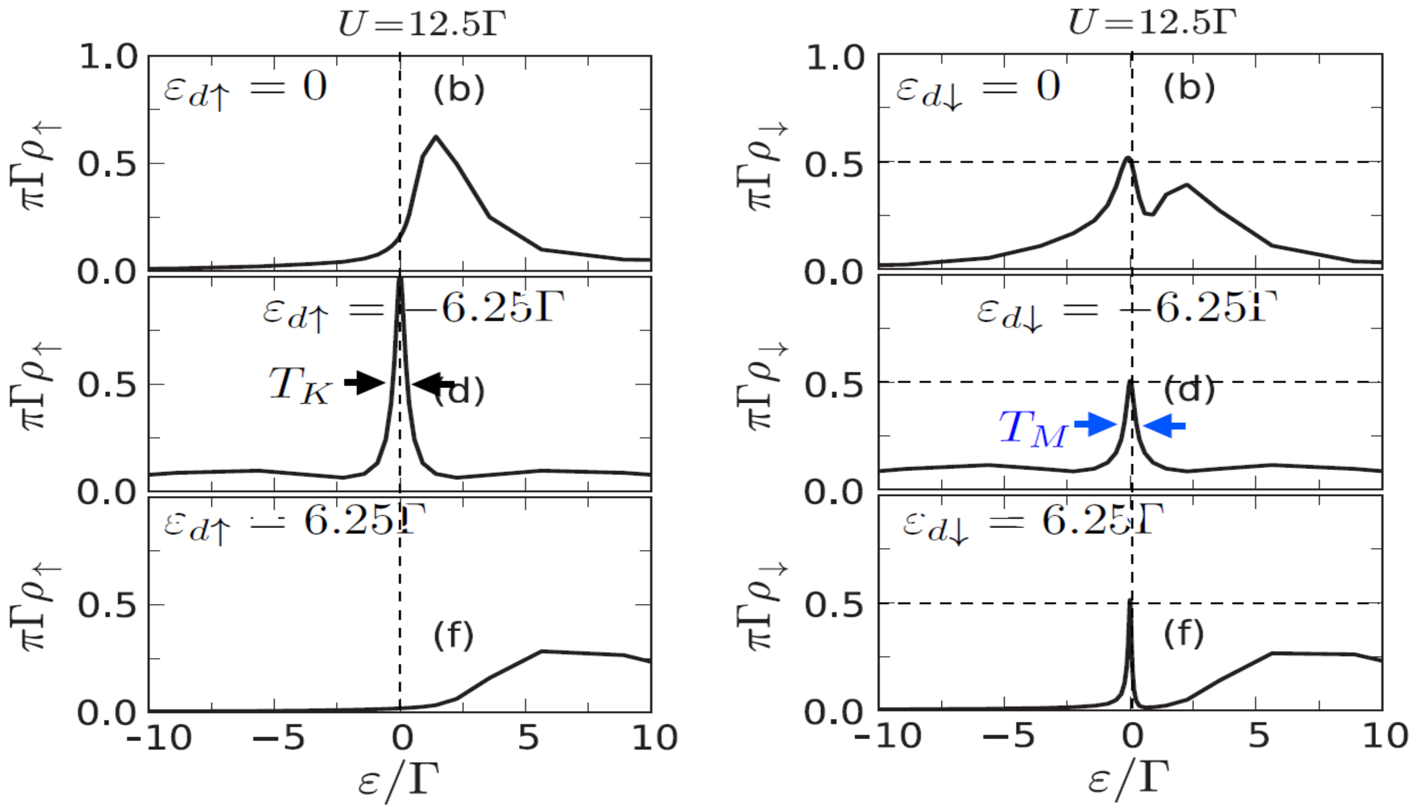
$$[N_{\uparrow}=1, P_{\downarrow}=+1] \left\{ \begin{array}{l} |\uparrow_d 0_f\rangle \\ |(\uparrow\downarrow)_d \downarrow_f\rangle \end{array} \right.$$

H_{-1} matrix	$n_\uparrow=0$ $P_\downarrow=-1$		$n_\uparrow=0$ $P_\downarrow=1$		$n_\uparrow=1$ $P_\downarrow=-1$		$n_\uparrow=1$ $P_\downarrow=1$	
$\|0\rangle_d \times \|\downarrow\rangle_f$	$U/2+\varepsilon_m$	$\bar{t}_-^*$						
$\|\downarrow\rangle_d \times \|0\rangle_f$	$\bar{t}_-$	$\varepsilon_d+U/2-h-\varepsilon_m$						
$\|0\rangle_d \times \|0\rangle_f$			$U/2-\varepsilon_m$	$\bar{t}_+^*$				
$\|\downarrow\rangle_d \times \|\downarrow\rangle_f$			$\bar{t}_+$	$\varepsilon_d+U/2-h+\varepsilon_m$				
$\|\uparrow\rangle_d \times \|\downarrow\rangle_f$					$\varepsilon_d+U/2+h+\varepsilon_m$	$-\bar{t}_-^*$		
$\|\uparrow\downarrow\rangle_d \times \|0\rangle_f$					$-\bar{t}_-$	$2\varepsilon_d+3U/2-\varepsilon_m$		
$\|\uparrow\rangle_d \times \|0\rangle_f$							$\varepsilon_d+U/2+h-\varepsilon_m$	$-\bar{t}_+^*$
$\|\uparrow\downarrow\rangle_d \times \|\downarrow\rangle_f$							$-\bar{t}_+$	$2\varepsilon_d+3U/2+\varepsilon_m$

NFL behavior: $\ln(2)^{1/2}$ residual entropy



Majorana-Kondo co-existence



D. A. Ruiz-Tijerina et al. *Phys Rev B* **91** 115435 (2015).

Consistent with: M. Lee, et al., *Phys. Rev. B* **87**, 241402 (2013).
Cheng et al., *Phys. Rev. X* **4**, 031051 (2014).

Manipulating MBS with quantum dots.

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Manipulation of Majorana fermions in Double Quantum Dots

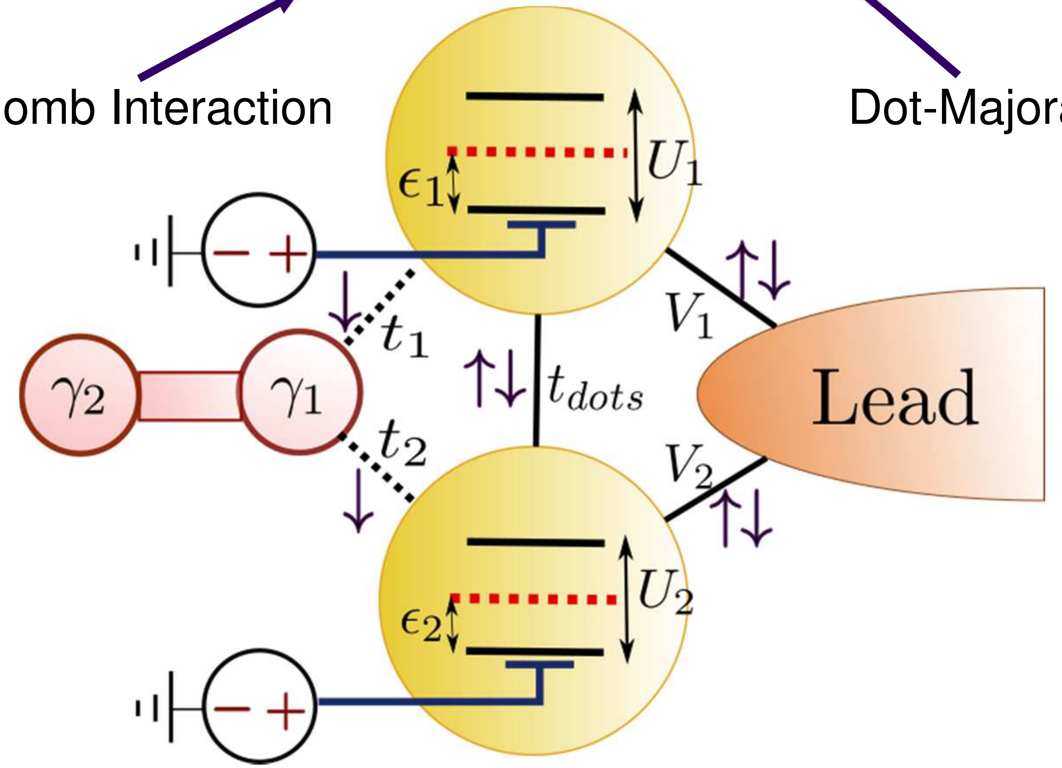
$$H = \sum_{i=1}^{2} \sum_{k,\sigma} \left(\epsilon_i + \frac{U_i}{2} \right) d_{i\sigma}^{\dagger} d_{i\sigma} + \frac{U_i}{2} (d_{i\sigma}^{\dagger} d_{i\sigma} - 1)^2 + t_i \gamma_1 d_{i,\downarrow} + t_i^* d_{i,\downarrow}^{\dagger} \gamma_1 + V_i d_{i\sigma}^{\dagger} c_{k\sigma} + V_i^* c_{k\sigma}^{\dagger} d_{i\sigma} .$$

Energy level

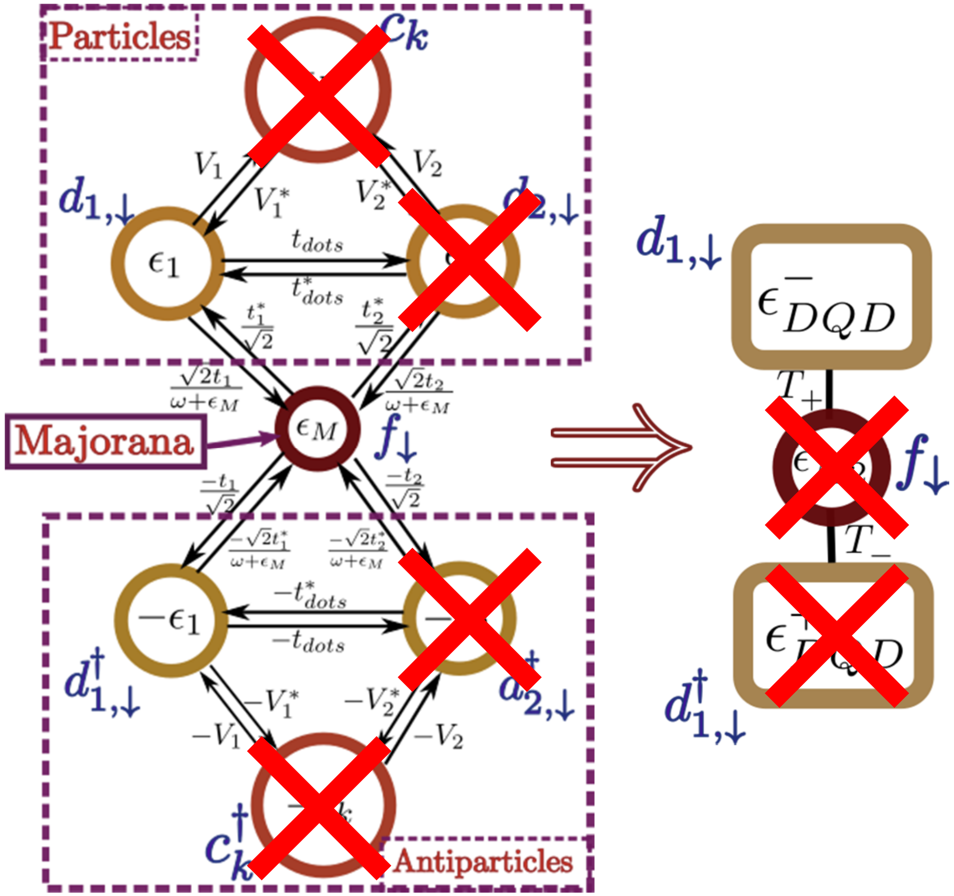
Coulomb Interaction

Dot-Majorana

Dot-Lead

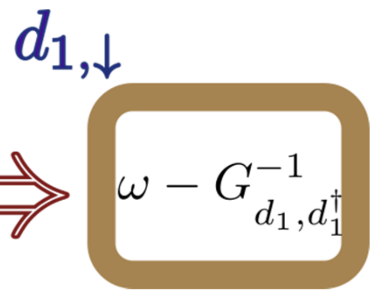


Non-interacting case: spectral densities



Green's Function

$$G_{d_{1\downarrow},d^\dagger_{1\downarrow}}(\omega) = \frac{1}{\omega - \epsilon^+_{DQD} + \frac{\|T_+\|^2}{\omega - \epsilon_{M2} - \frac{\|T_-\|^2}{\epsilon^-_{DQD}}}}$$

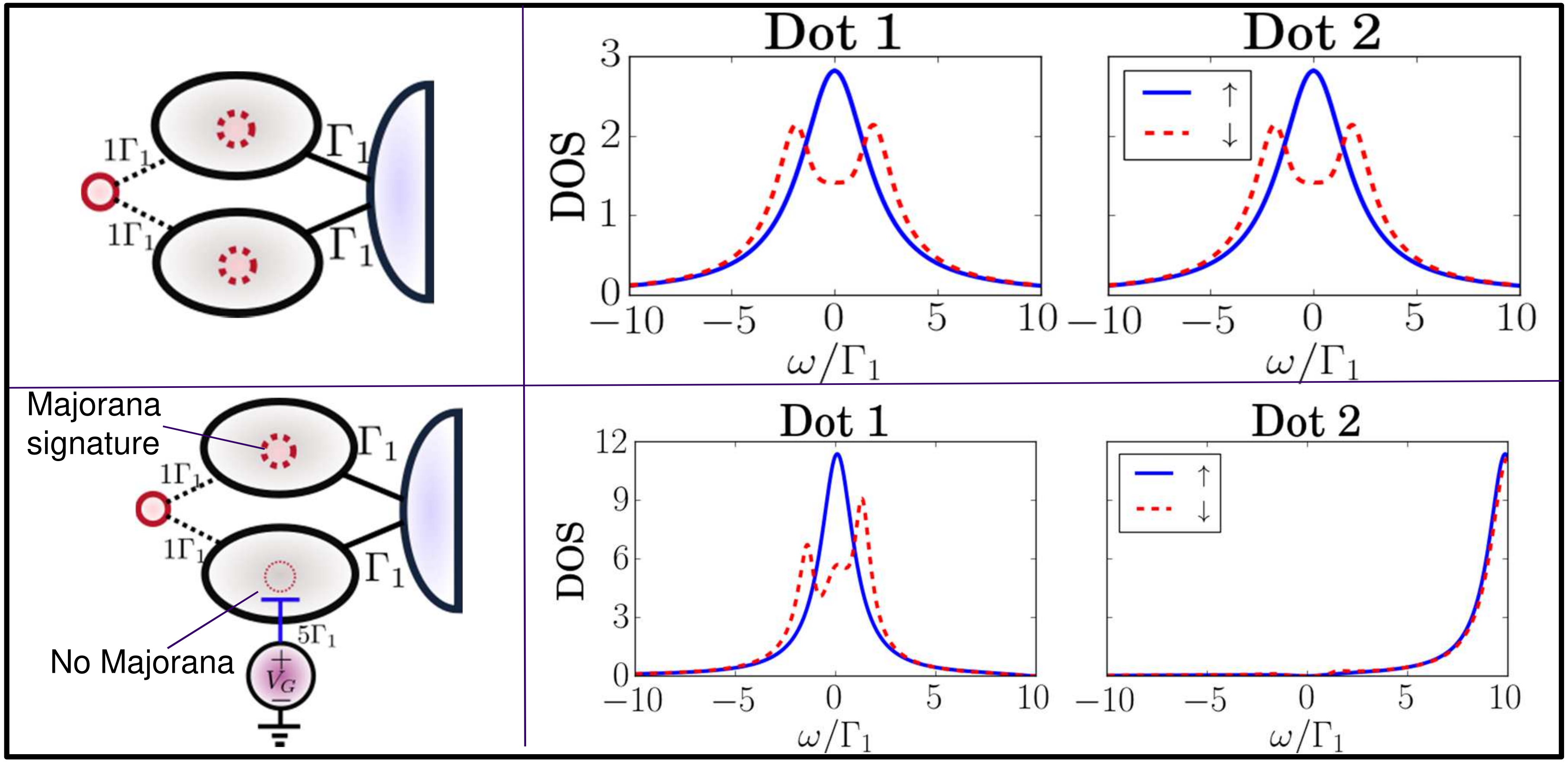


Density of States (DOS)

$$\rho_1(\omega) = -\frac{1}{\pi}\mathrm{Im}\left[G_{d_1,d_1^\dagger}(\omega))\right].$$

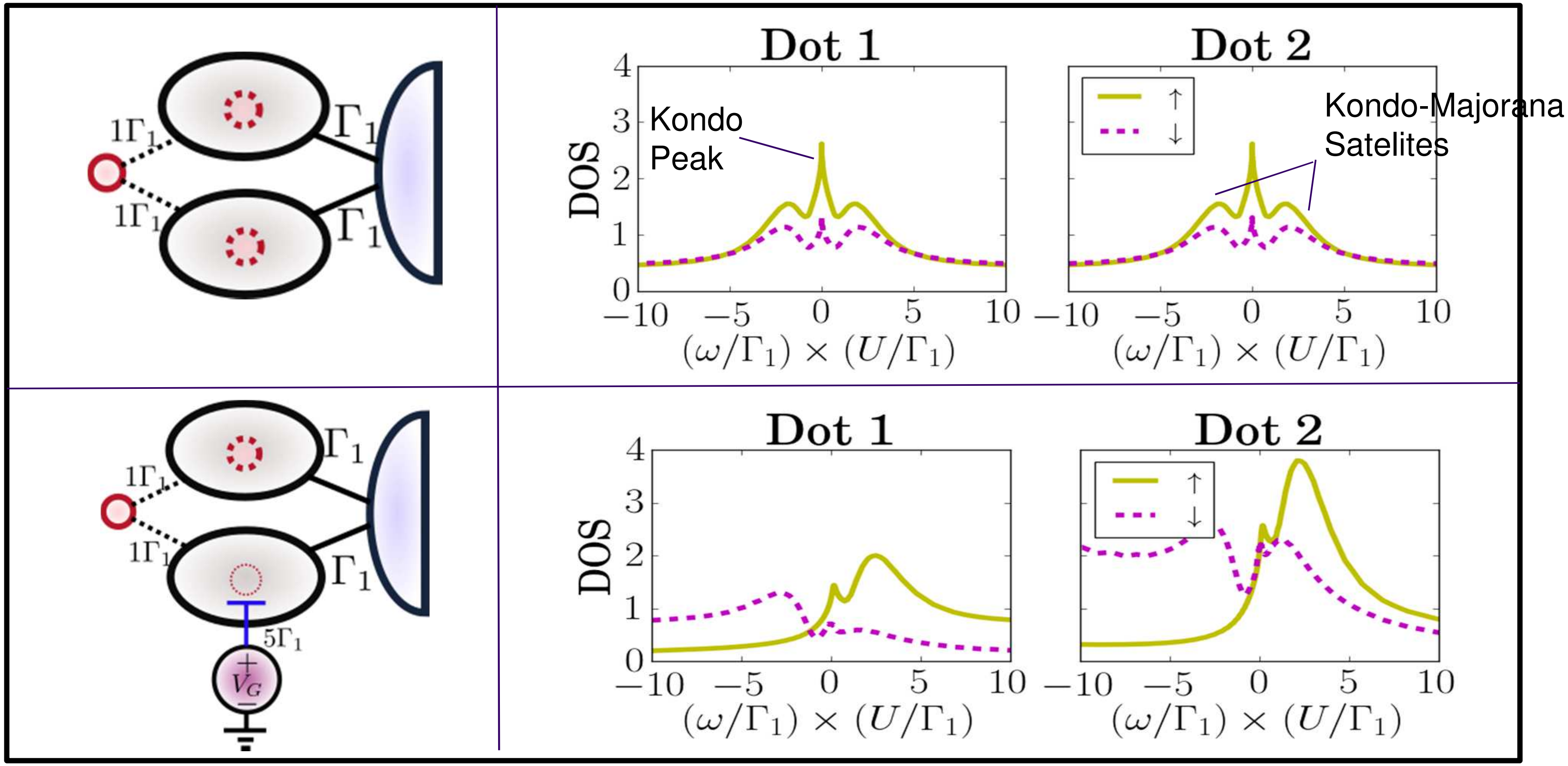
Symmetric coupling

Non-Interacting U=0

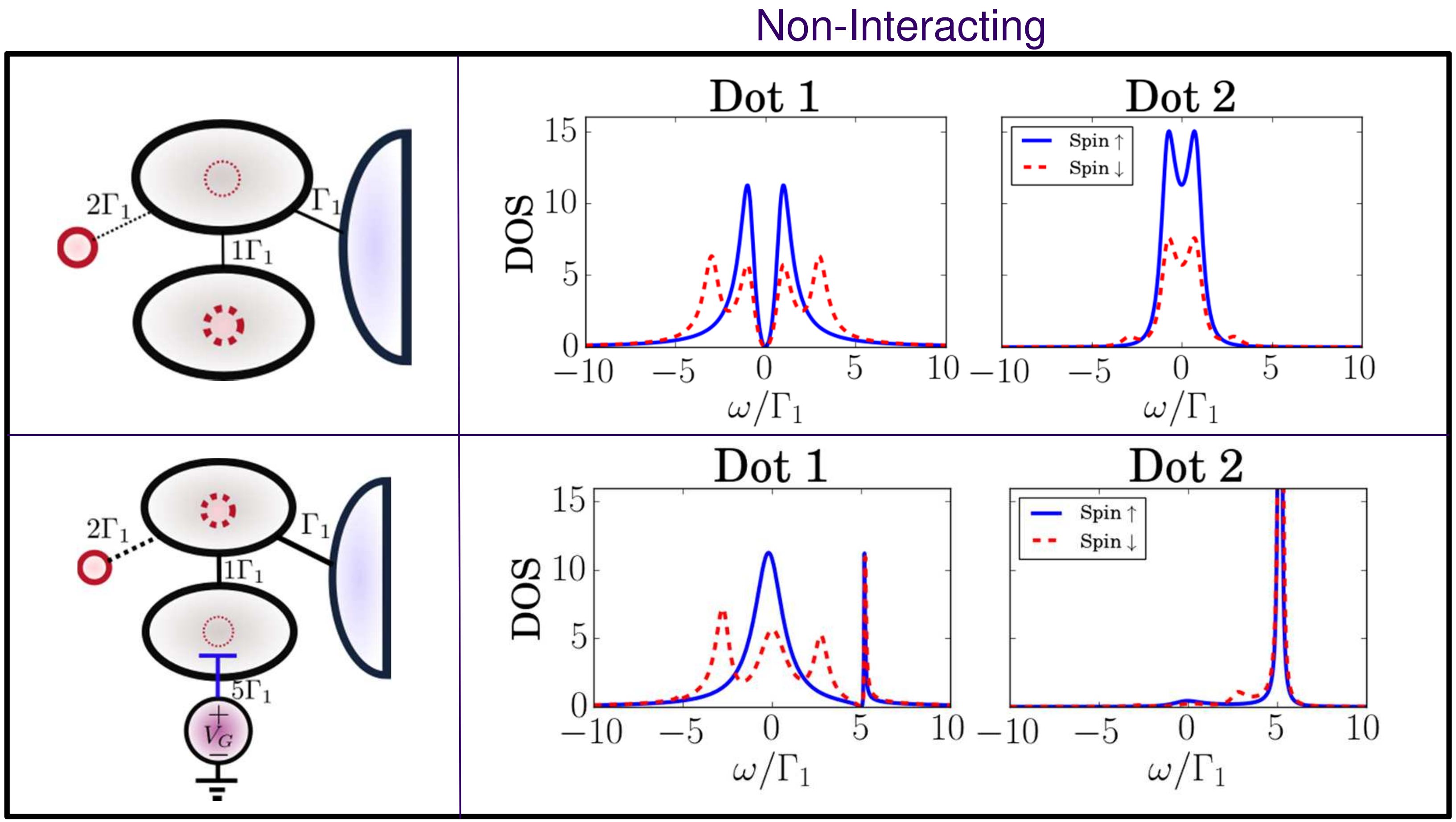


Symmetric coupling

Interacting U>0 (NRG)

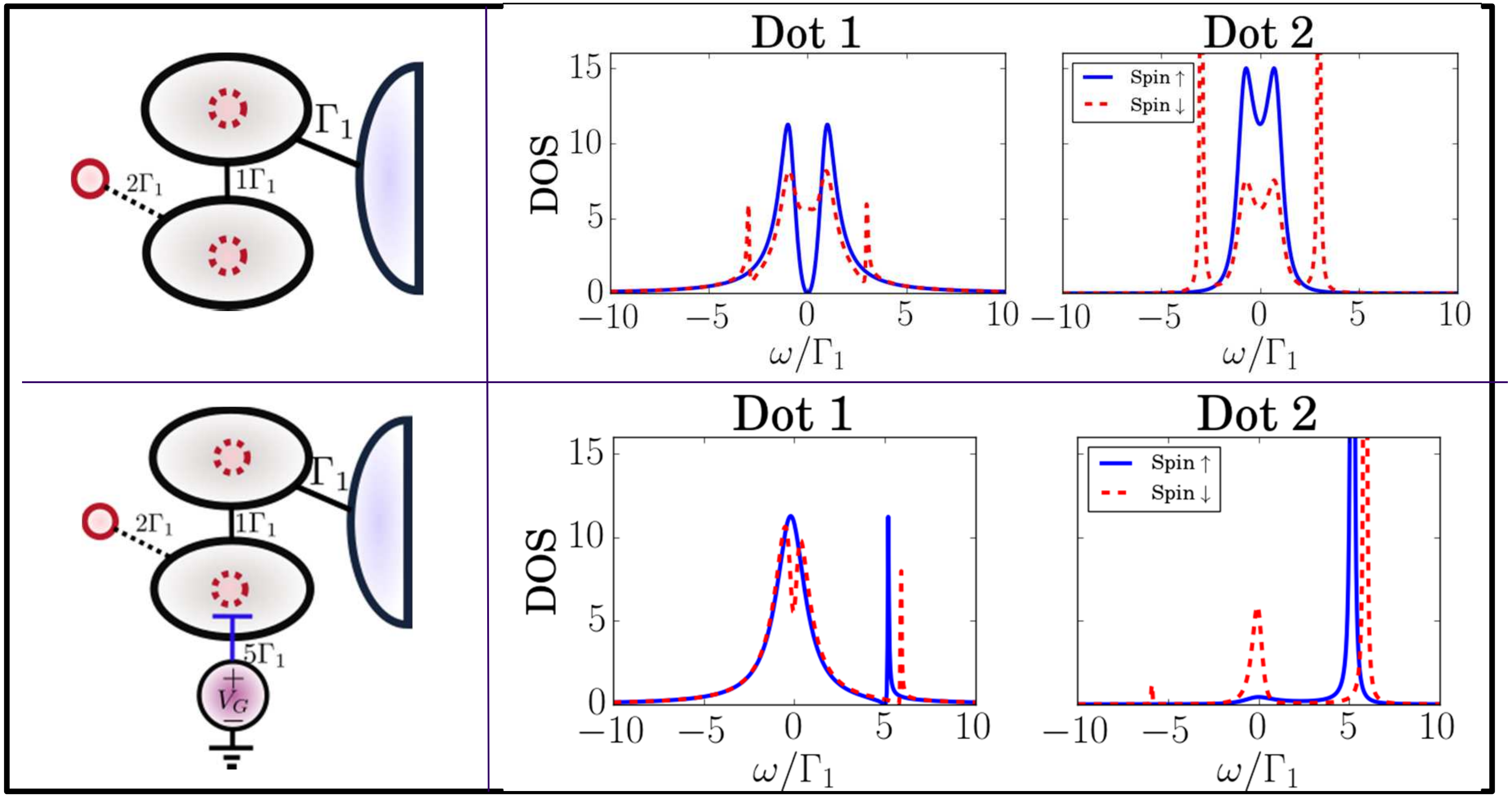


Interference destroying Majorana signature

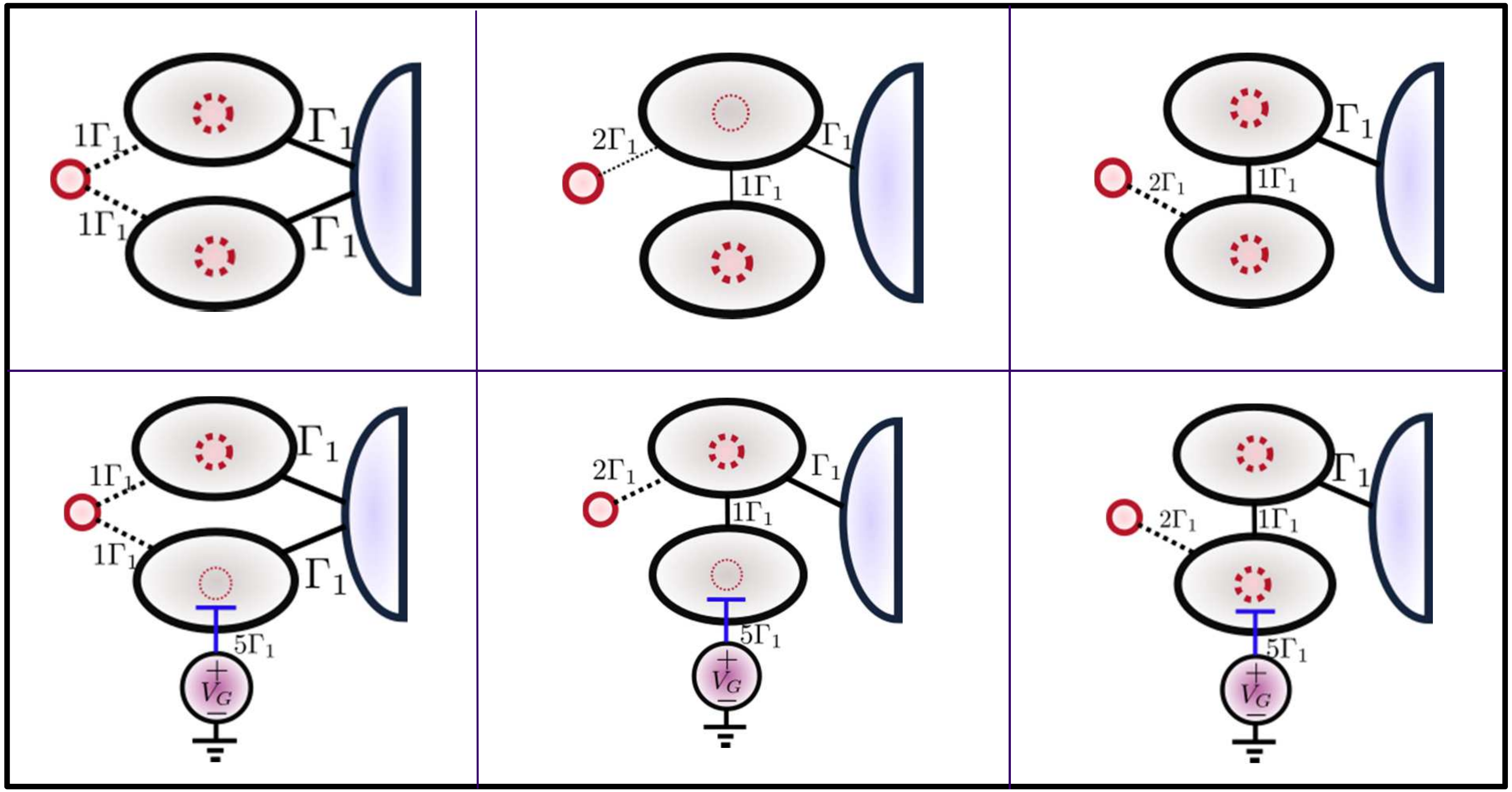


Indirect Majorana Coupling

Non-Interacting

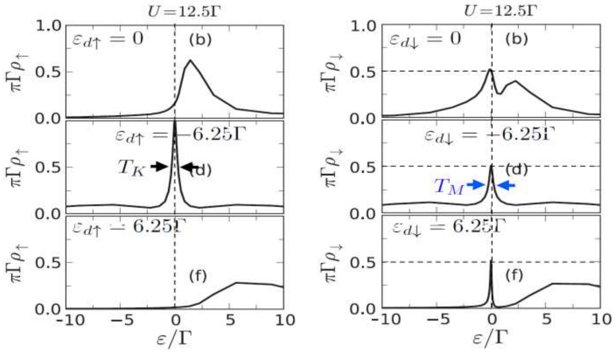


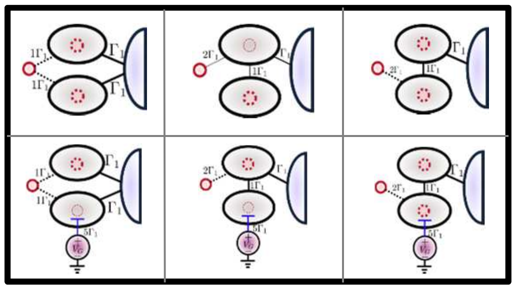
Manipulating with couplings/gate voltages.



Summary

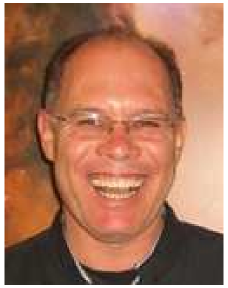
- *Coexistence of MZM and Kondo states in interacting quantum dots*
- Detecting MZMs using quantum dots: signature in the spin-resolved densitity of states $\rightarrow$ large ($e^2/2$) reduction in the conductance.
- Manipulating MZMs using double quantum dots using only gate voltages and couplings.





Collaborators in these works

David Ruiz-Tijerina



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FAPESP CNPq CAPES PRP USP IF - USP