Detecting and manipulating Majorana bound states with quantum dots.

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Weyl Fermions in Condensed Matter
IIP, July 25, 2019.

Physics @ USP – São Paulo.

Physics Institute-USP

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

IF - USP

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Group members

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Outline

- Basics: Majorana bound states in condensed matter systems.
- *Detecting* Majorana states with quantum dots.
- *Manipulating* Majorana states with (double) quantum dots.
- Majorana zero modes in magnetic chains on topological insulators with superconductivity.
- Gap oscillations: some clues for the behavior found in nanowires.

What are Majorana fermions?

Majorana Fermions

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

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

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

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

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

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

Where do we find Majorana (quasi) particles?

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-FL fixed point.

  Emery, Kivelson, *PRB* (1992).
  Coleman, Ioffe, Tsvelik *PRB* (1995).
  Maldacena, Ludwig, *Nucl. Phys. B.* (1997).
  Bulla, Hewson, Zhang, *PRB* (1997).

- Interface of topological insulators with BCS superconductors

  Fu and Kane, *Phys. Rev. Lett.* (2008).

- Spin-polarized ("spinless") p-wave superconductors.

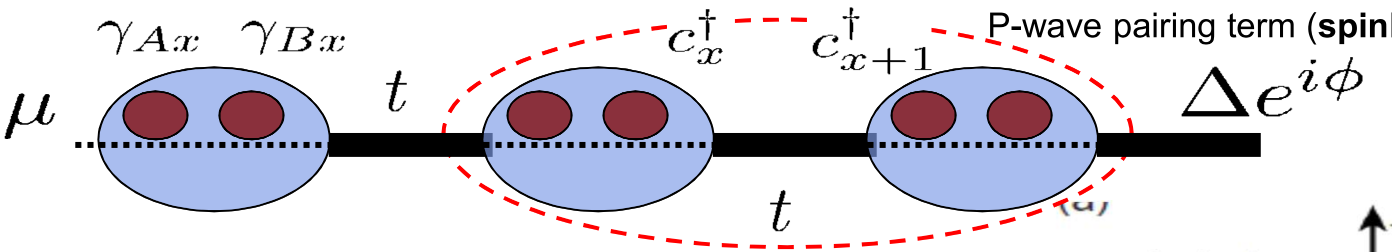
  Read and Green, *Phys. Rev. B* (2000).
  Kitaev, *Phys. Usp.* (2001).

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)



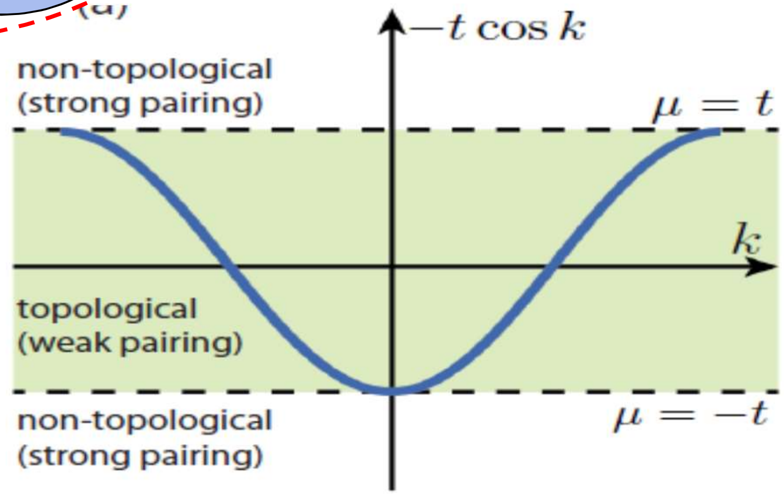
Energy spectrum:

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

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

$\mu = \pm t$ Gapless 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:

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

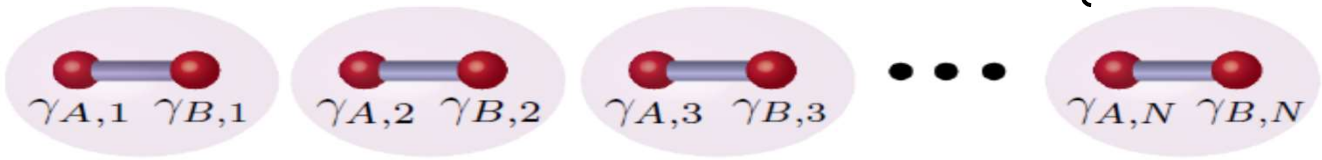
$$H = -\mu \sum_x c_x^\dagger c_x - \frac{1}{2}\sum_x (t c_x^\dagger c_{x+1} + \Delta e^{i\phi} c_x c_{x+1} + h.c.)$$

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

Majorana states in the Kitaev model.

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

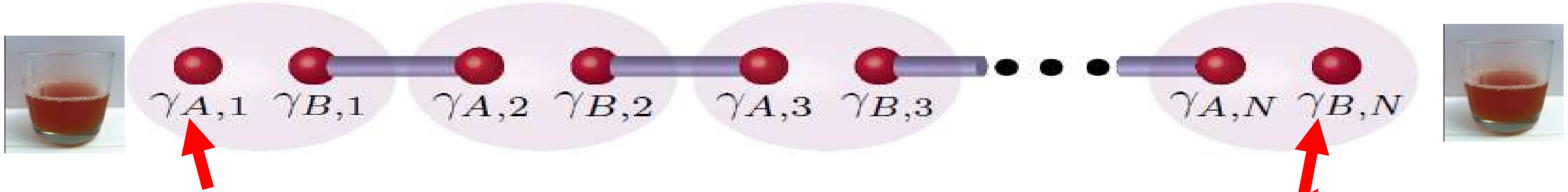
$|\mu| > t$ Gapped: **trivial.** Special case: $\begin{cases}\mu \neq 0 \\ t = \Delta = 0\end{cases}$



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

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

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



Topological regime: Majorana zero 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:

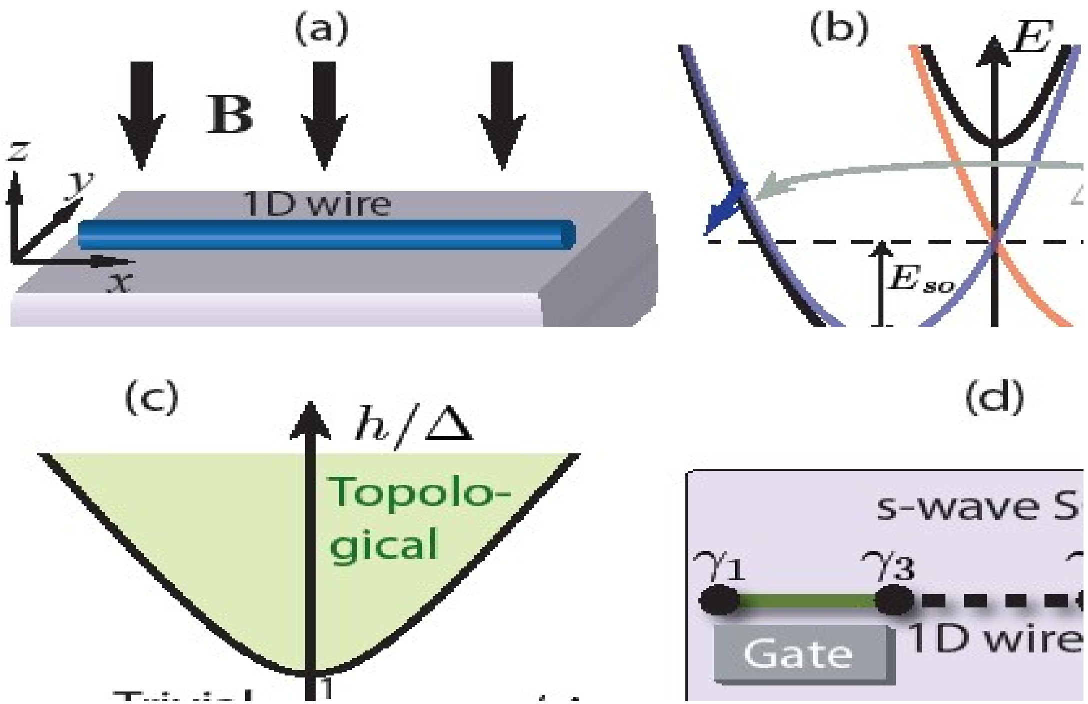
create spinless 1D fermions.

Ingredients: spin-orbit, B field.

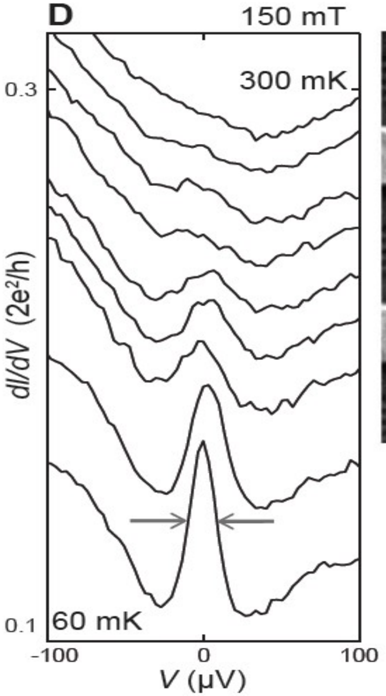
- Step 2:

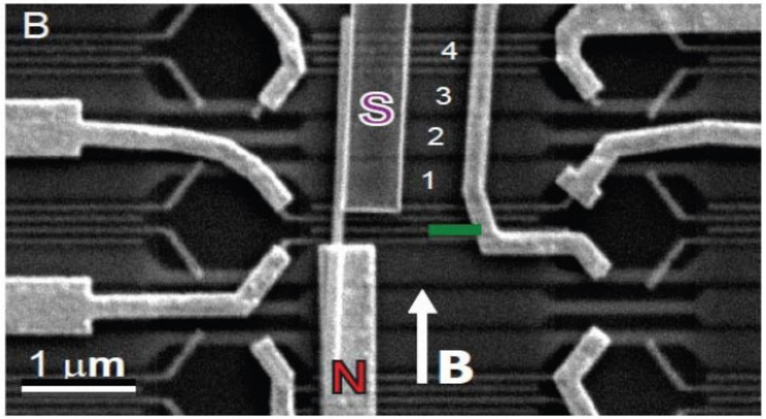
Introduce SC pairing.

Ingredients: proximity with a BCS SC



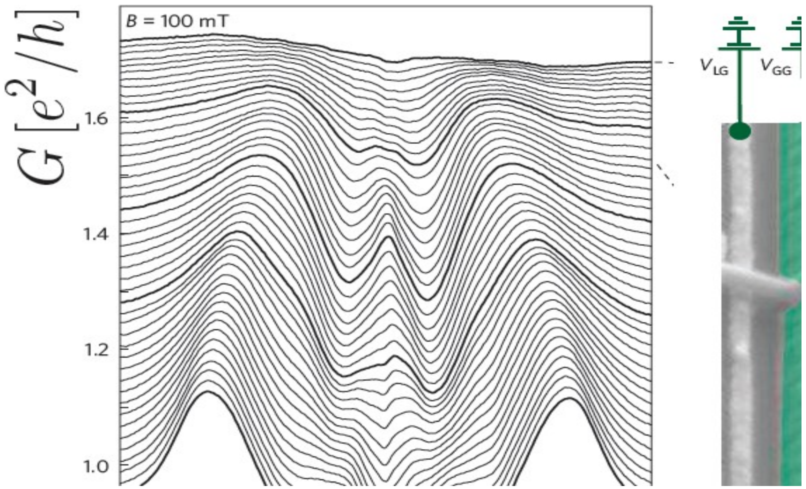
Experiment on InSb nanowires.





Zero-bia peak in tunne

Mourik *et al.*, Science **336**
Deng *et al.*, Nano Lett. 1
Das *et al.*, Nature Phys. 8
Prada et al., Phys. Rev. I
Churchill et al., Phys. Re



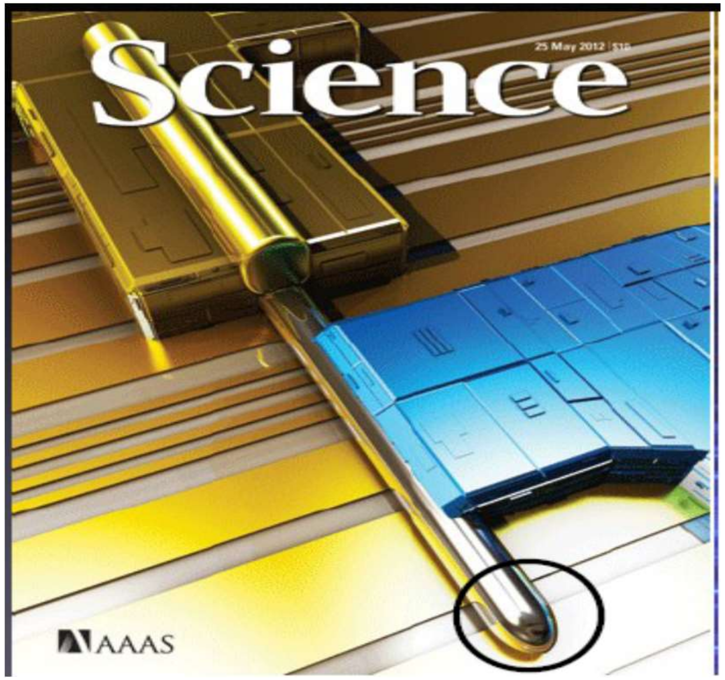
Signatures appear for:

- Large enough magnetic field (topological phase)

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:

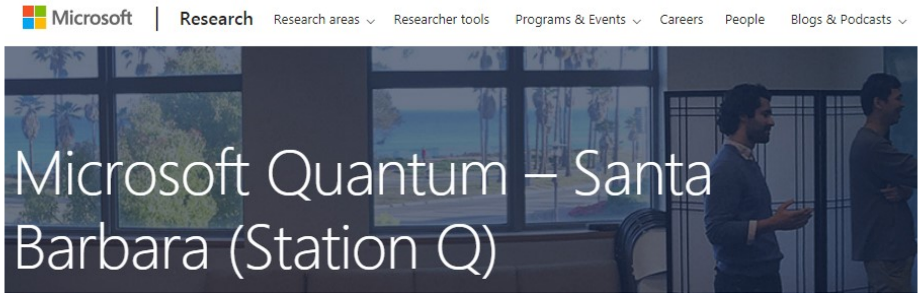
"Majorana found at the end of a quantum wire"

What do we do with them?

"Topological Quantum Computation"

Microsoft's high-stakes game...

https://www.microsoft.com/en-us/research/lab/quantum/



Michael Freedman
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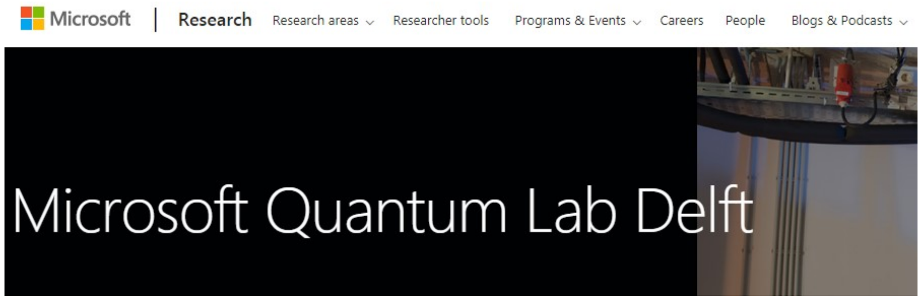
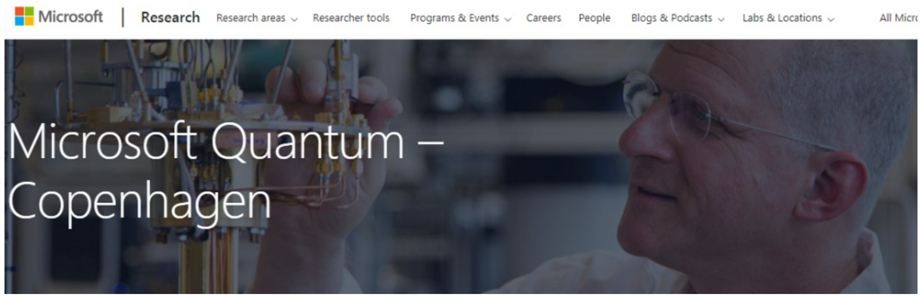


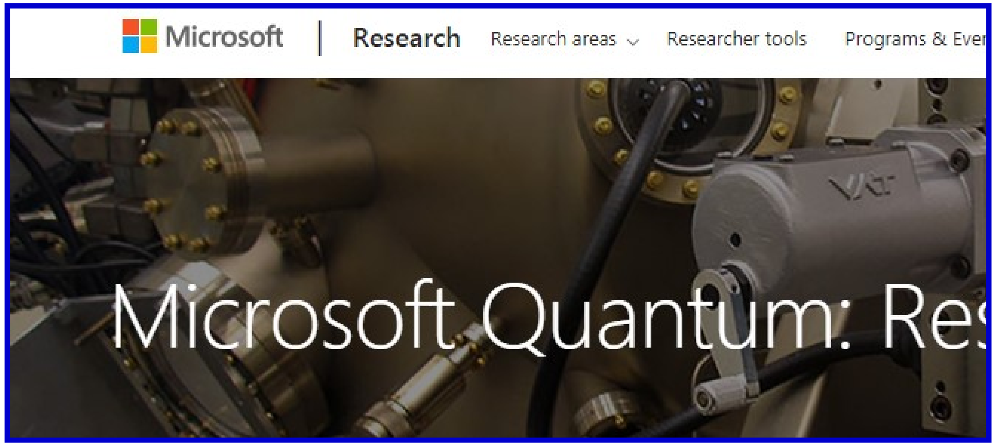
Leo Kouwenhoven
(Delft University)



Charlie Marcus
(Univ. of Copenhaguen – Niels Bohr Inst)

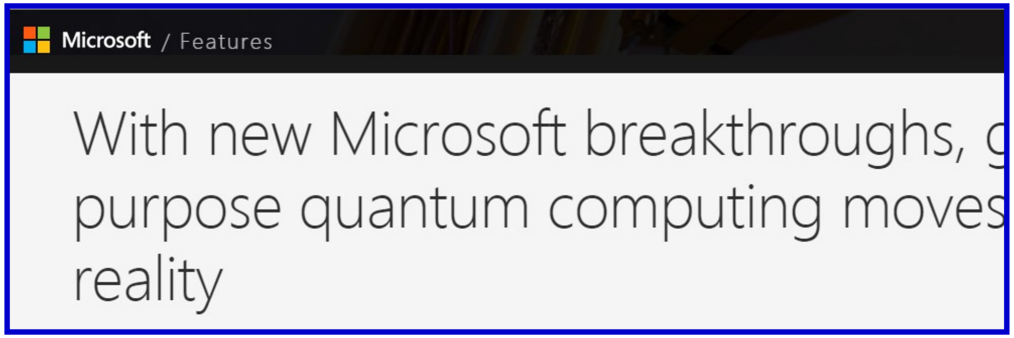
Microsoft's high-stakes game...

https://www.nytimes.com/2016/11/21/technology/microsoft-spends-big-to-build-quantum-computer.html?smid=tw-share



https://www.microsoft.com/en-us/research/lab/quantum/

https://blogs.microsoft.com/ai/microsoft-doubles-quantum-computing-bet/



https://news.microsoft.com/features/new-microsoft-breakthroughs-general-purpose-quantum-computing-moves-closer-reality/

Detecting MBS with quantum dots.

Collaborators
in this work:

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(2013-2016)

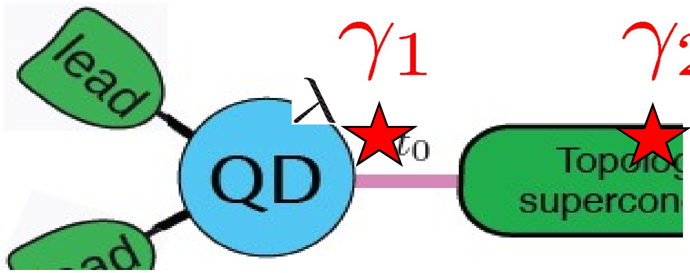
Carlos Egues
IFSC-USP

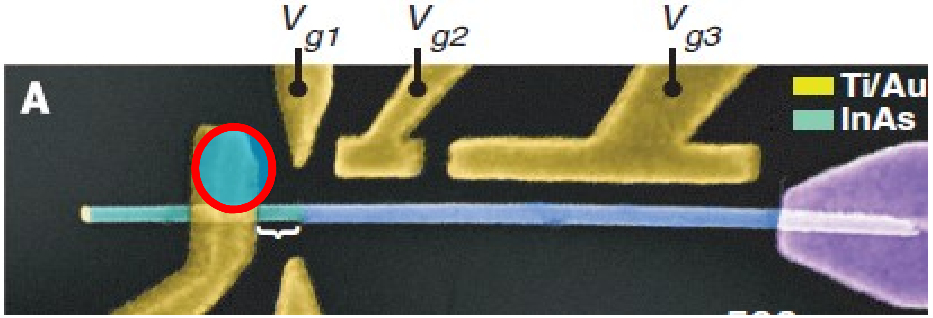
Edson Vernek
UFU

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

How to positively identify an MBS?

- 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).

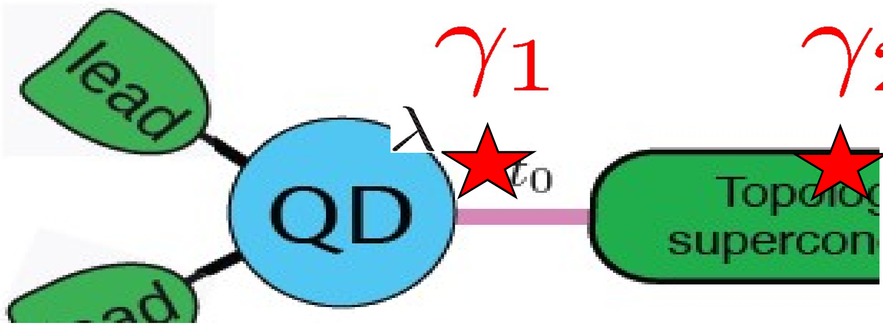
Experiment (Marcus' group)

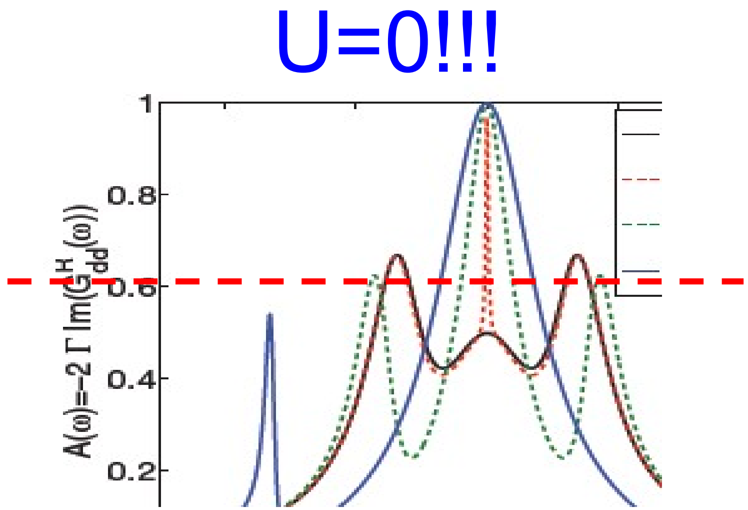
M.T. Deng et al., *Science* **354** 1557 (2016).

How to positively identify an MBS?

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

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





- 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)

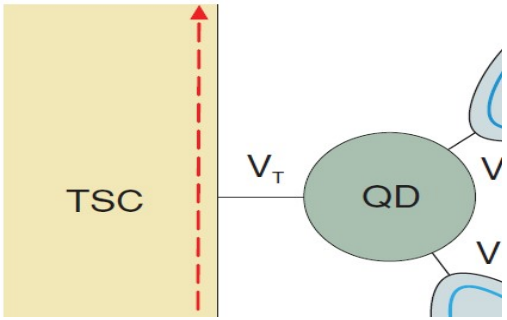
  Korytár and Schmitteckert, *JPCM* **25** 475304 (2014).

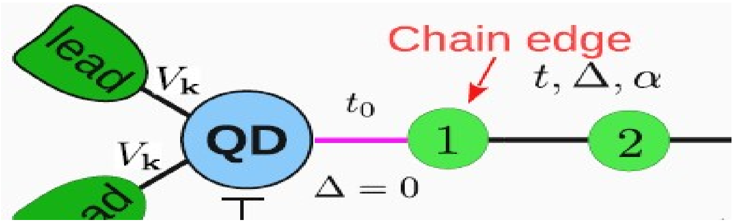
  Cheng et al., *Phys. Rev. X* **4**, 031051 (2014).

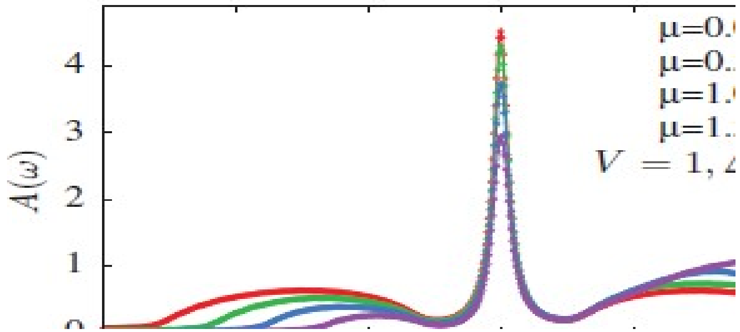
- Interacting Kitaev model (DMRG)

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

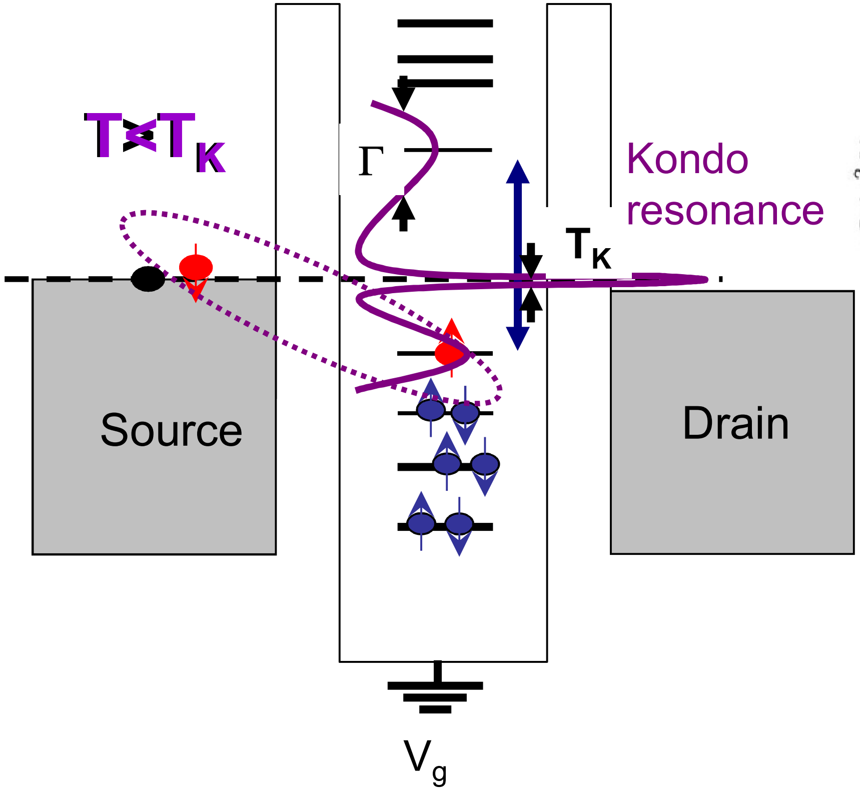
  Thomale et al., *Phys. Rev. B* **88** 161103(R) (2013).

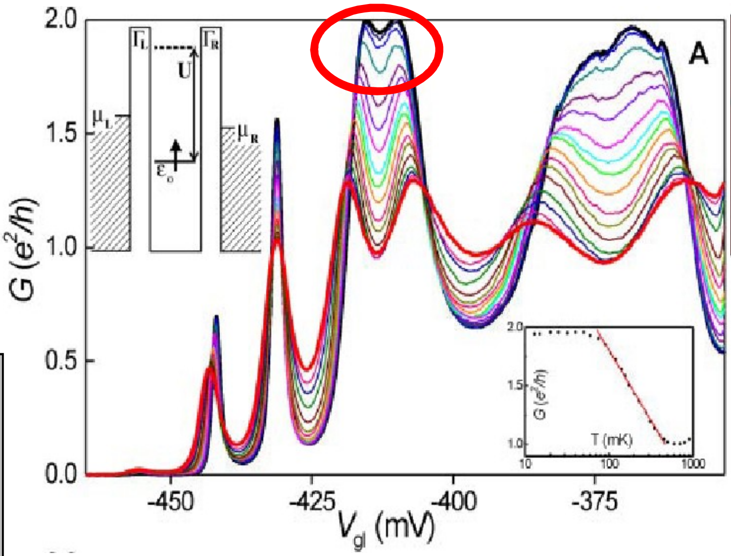


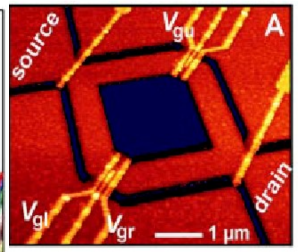




Kondo Effect in Quantum Dots: zero-bias transport.





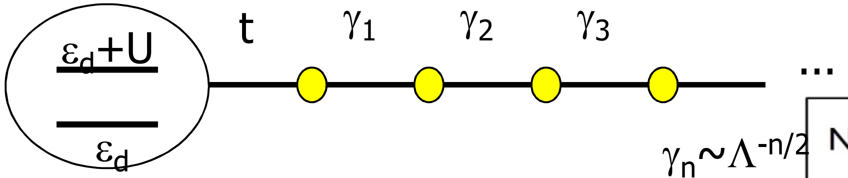


van der Wiel et al., *Science* **289** 2105 (2000).

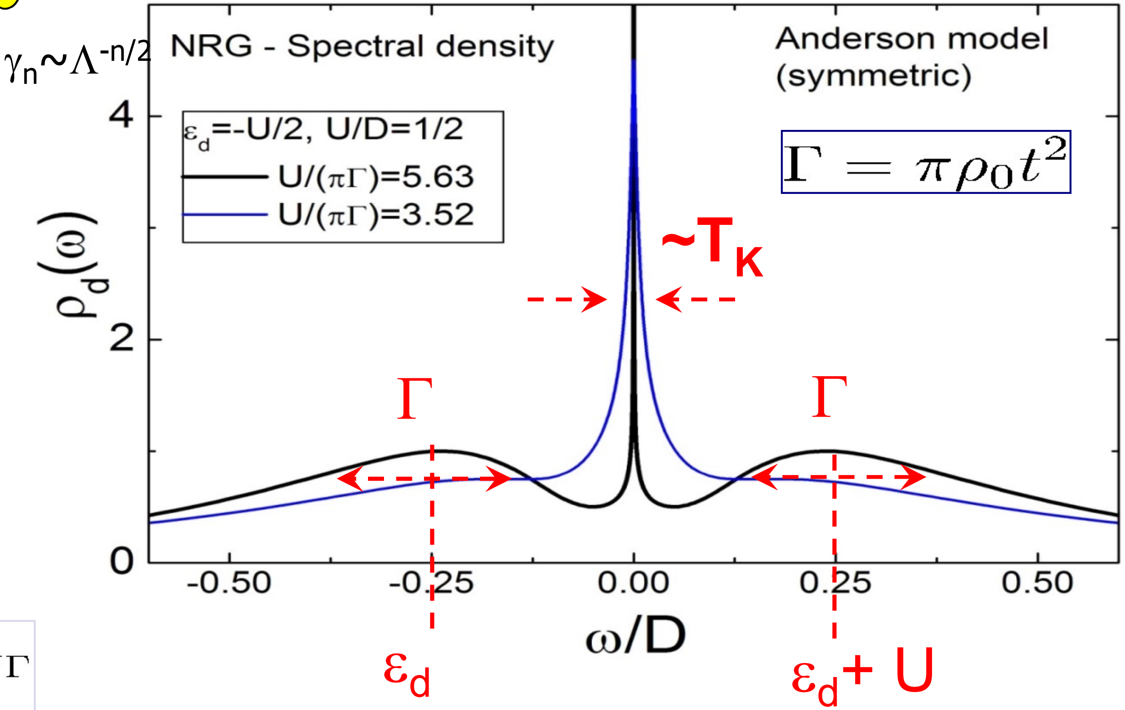
- $T>T_K$: Coulomb blockade (low G)
- $T<T_K$: Kondo singlet formation
- Kondo resonance at E_F (width T_K).
- New conduction channel at E_F:

Zero-bias enhancement of G ($\rightarrow 2e^2/h$!)

Kondo resonance with Wilson's NRG



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



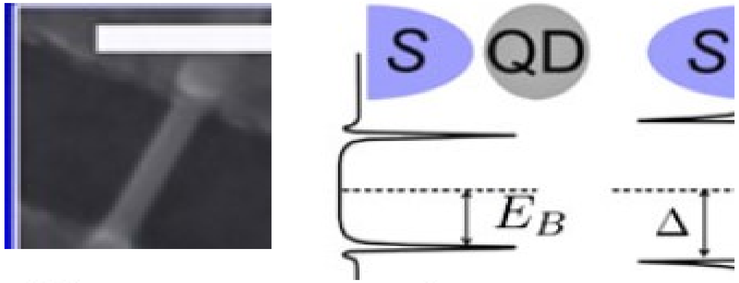
$$\Gamma = \pi \rho_0 t^2$$

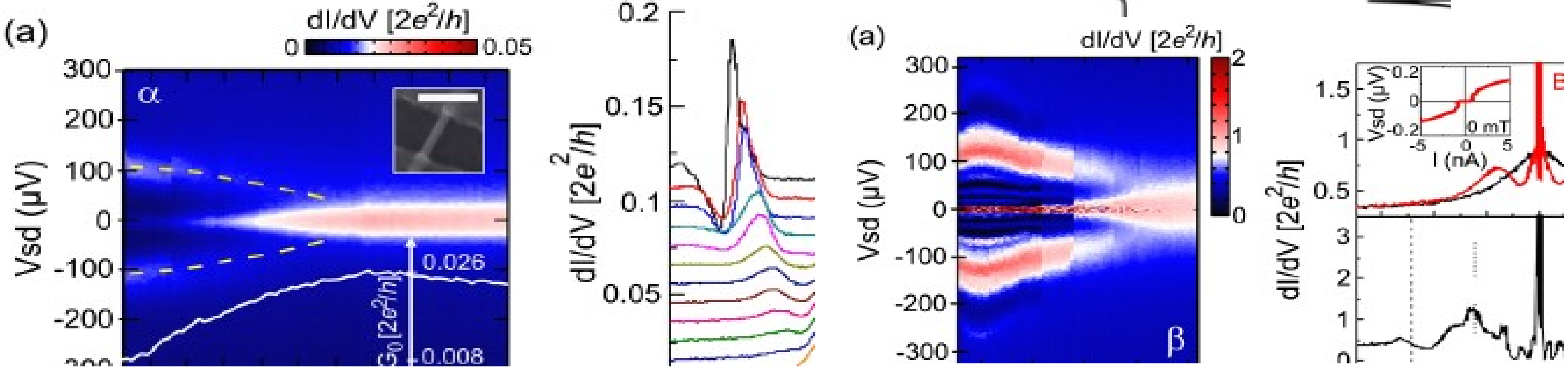
- Spectral density:
  - Single-particle peaks at ε_d and ε_d+U.
  - *Many-body* peak at the Fermi energy: ***Kondo resonance*** (width ~T_K).
- NRG: very good resolution at low ω.

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

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

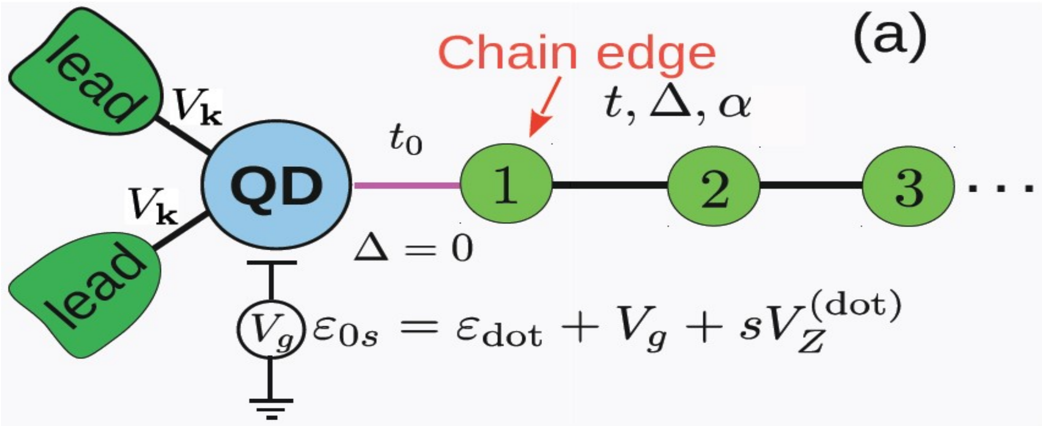
E.J. Lee et al. PRL **109** 186802 (2012)

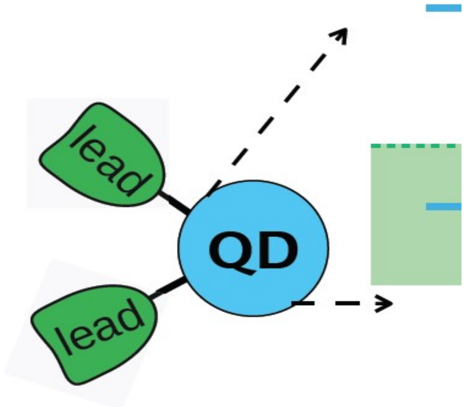




- Quantum dot defined in InAs/InP quantum wires coupled to superconducting leads.
- Kondo-like zero-bias peak emerges at a critical field B_c .

Model: Quantum dot + quantum wire + SC pairing.





Quantum wire:

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

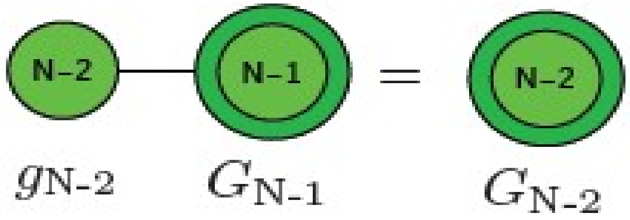
Quantum dot:

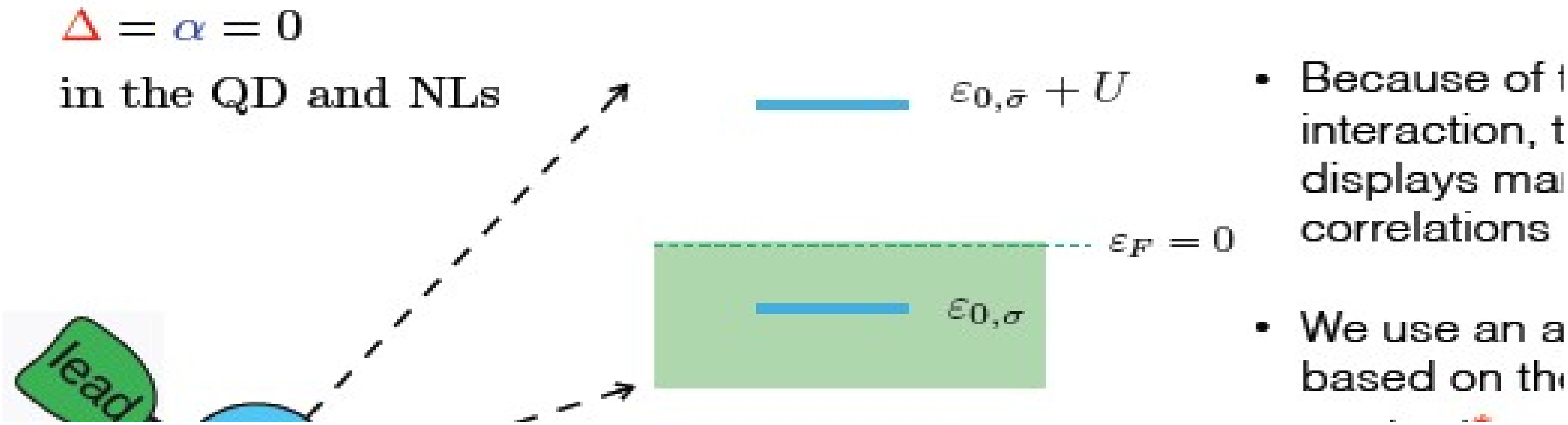
$$H_{\rm dot} = \sum_{s=\uparrow,\downarrow} \varepsilon_{0,s}\, n_{0,s} + U\, n_{0,\uparrow} n_{0,\downarrow}$$

Topological phase for |

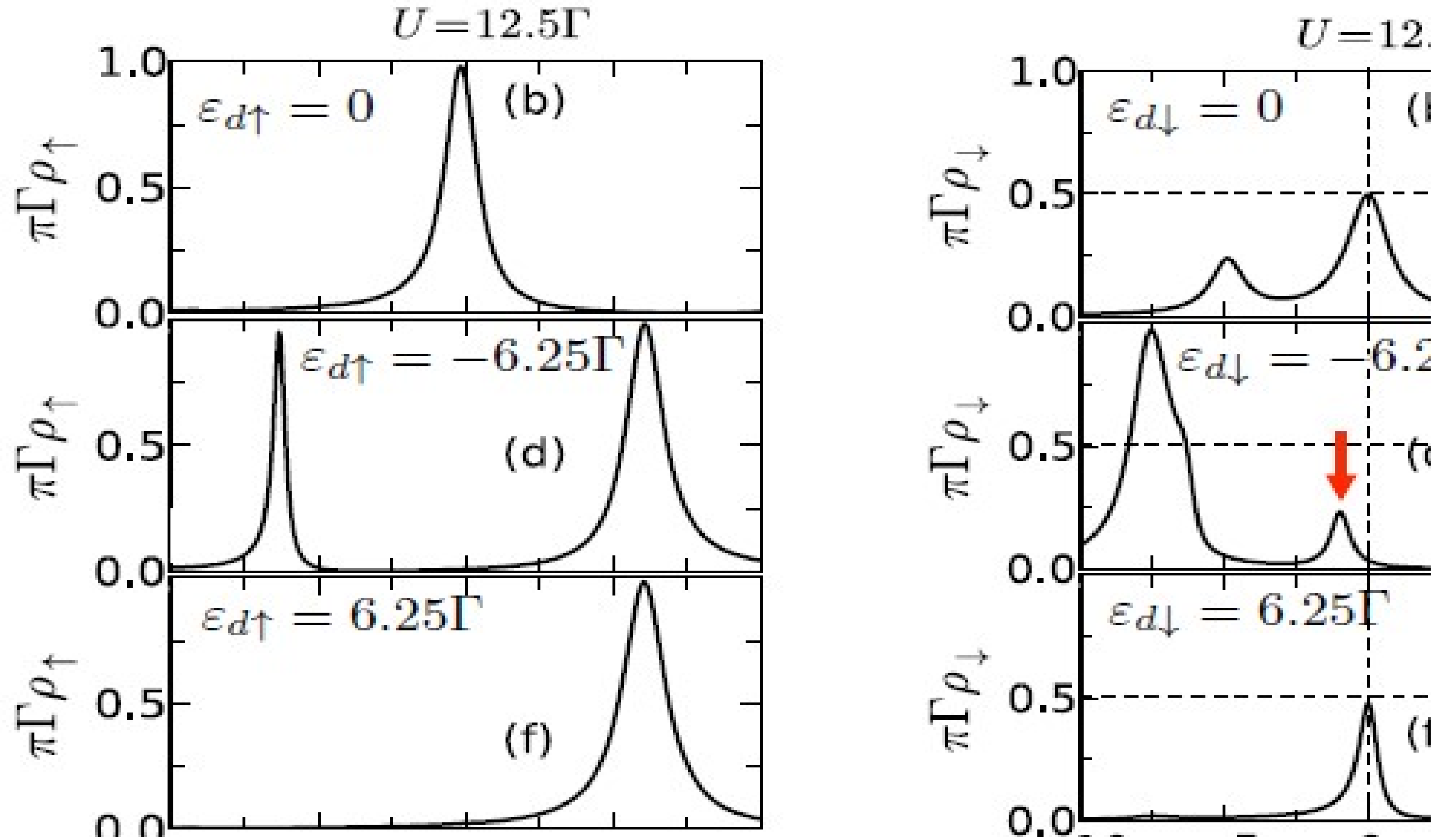
Rainis *et al.*, Phys. Rev

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

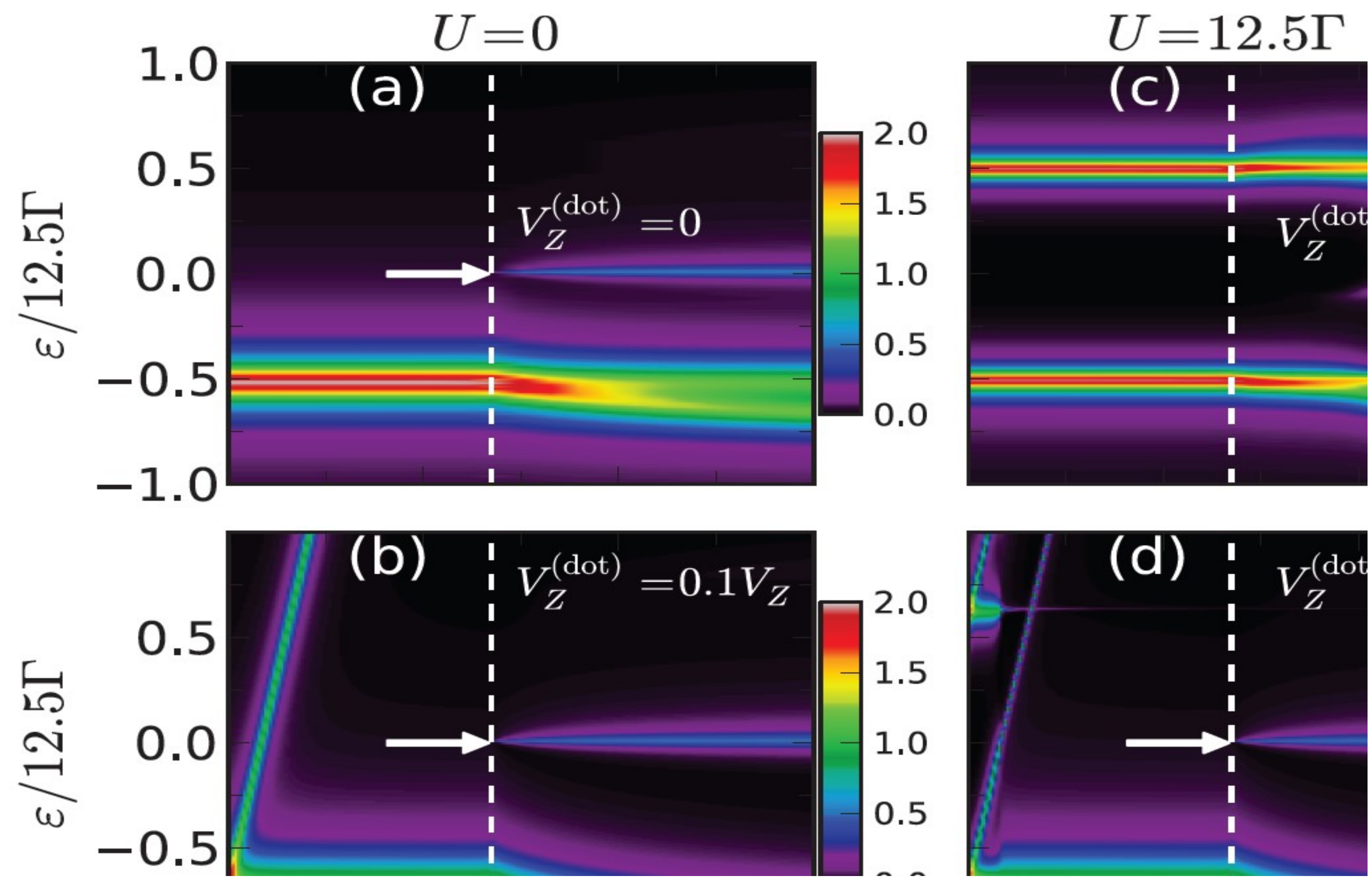




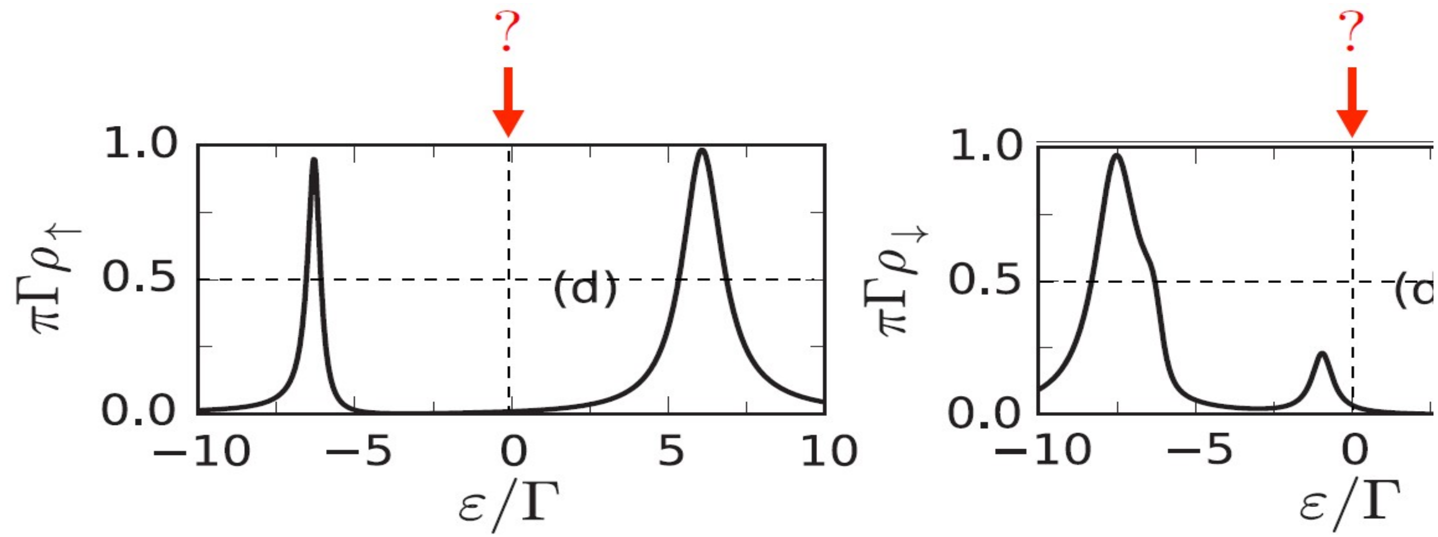
Iterative Green's functions + mean field (Hubbard I).



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

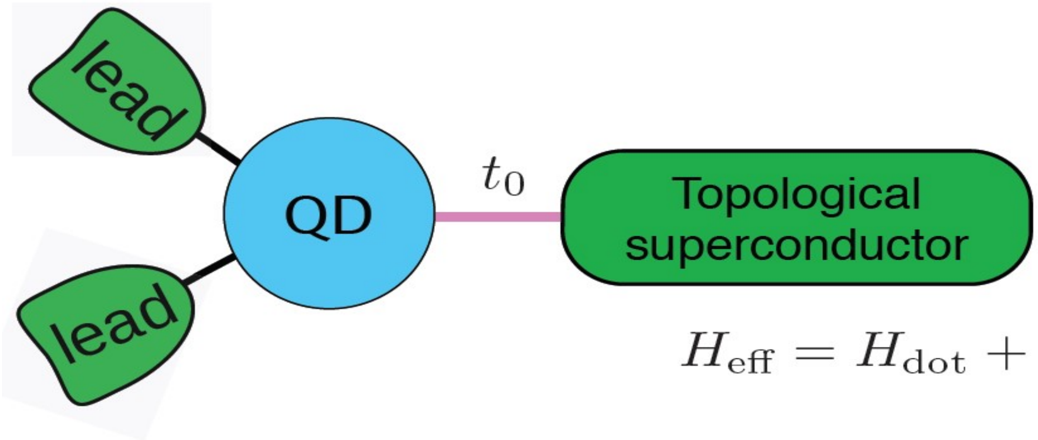


Shortcomings of the mean-field approximation.



- The Hubbard I approximation captures the Majora outside of the Kondo regime
- It doesn't capture the Kondo correlations

Effective low-energy Anderson model



Lee *et al.*, Phys. Rev. E

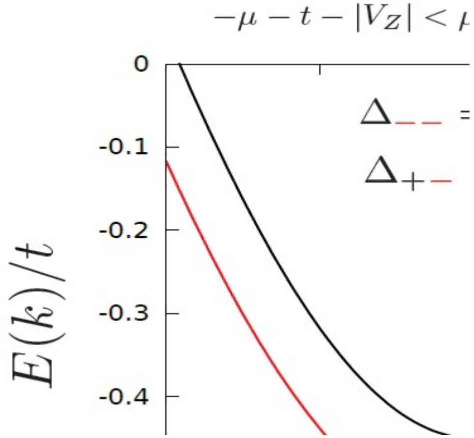
- Effective model: N
directly to the QD
($V_Z > 0$).

$$H_{\rm eff} = H_{\rm dot} + H_{\rm leads} + H_{\text{dot-leads}} +$$

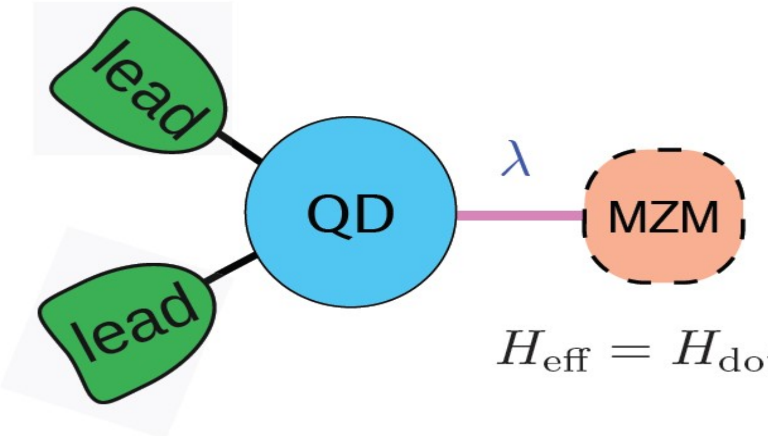
$$H_{\rm dot} = \sum_{\sigma} \varepsilon_{0\sigma}(\varepsilon_d,\, V_Z^{(\rm dot)}) n_{0\sigma} + U\, n_{0\uparrow} n_{0\downarrow}$$

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

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



Effective low-energy Anderson model



Lee *et al.*, Phys. Rev. I

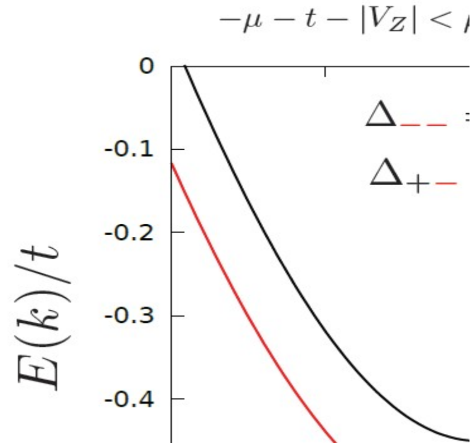
- Effective model: M directly to the QD ($V_Z > 0$).

$$H_{\mathrm{eff}} = H_{\mathrm{dot}} + H_{\mathrm{leads}} + H_{\mathrm{dot\text{-}leads}} +$$

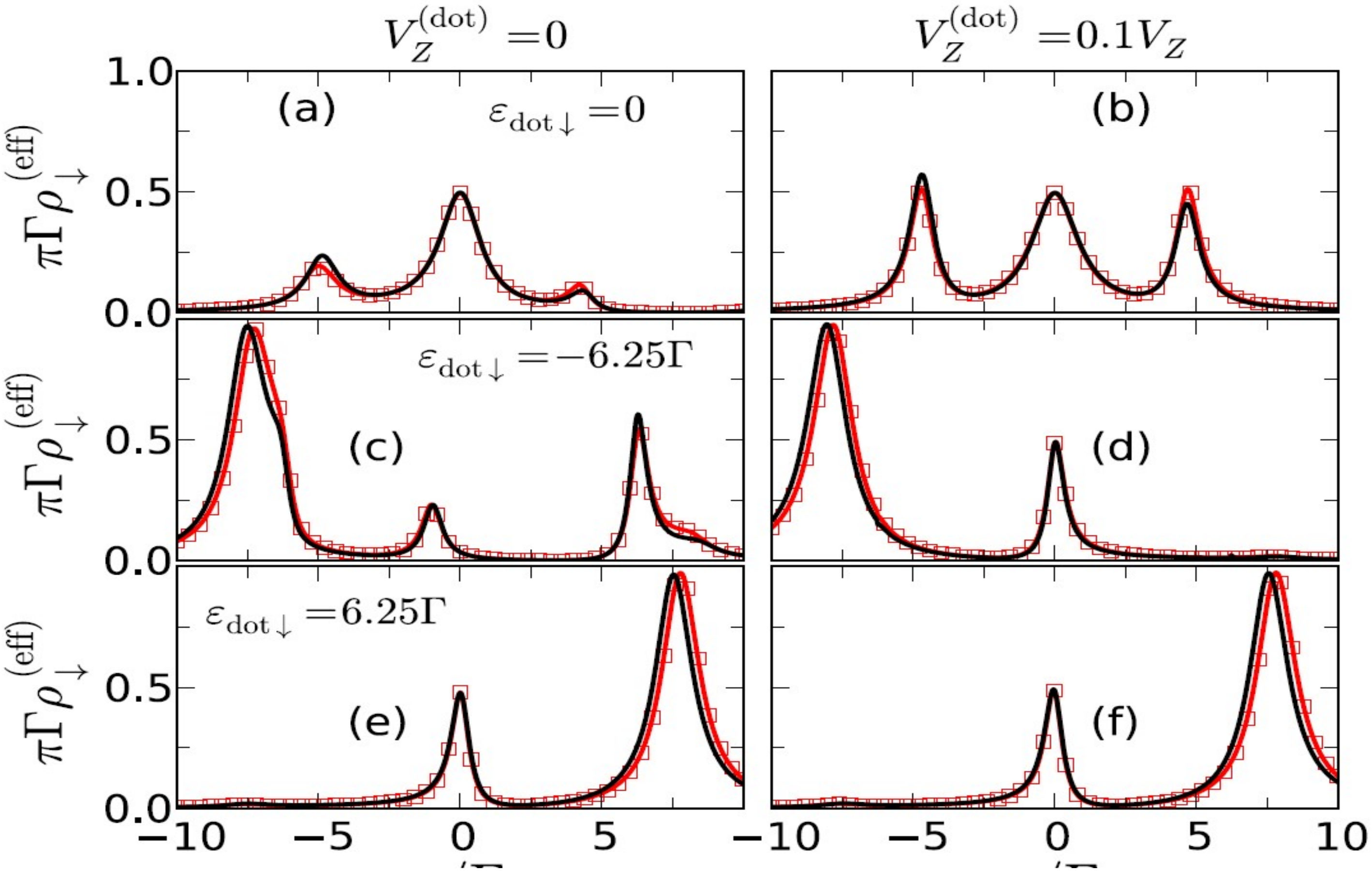
$$H_{\mathrm{dot}} = \sum_{\sigma} \varepsilon_{0\sigma}(\varepsilon_d, V_Z^{(\mathrm{dot})}) n_{0\sigma} + U\, n_{0\uparrow} n_{0\downarrow}$$

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

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



Effective low-energy Anderson model



Effective model

$c^\dagger_\alpha$: creates a fermion in state α

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

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

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

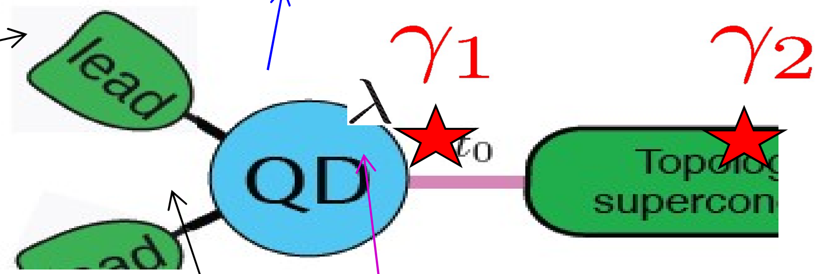
Majorana operators

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

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

Metallic leads

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



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

Coupling to one Majorana

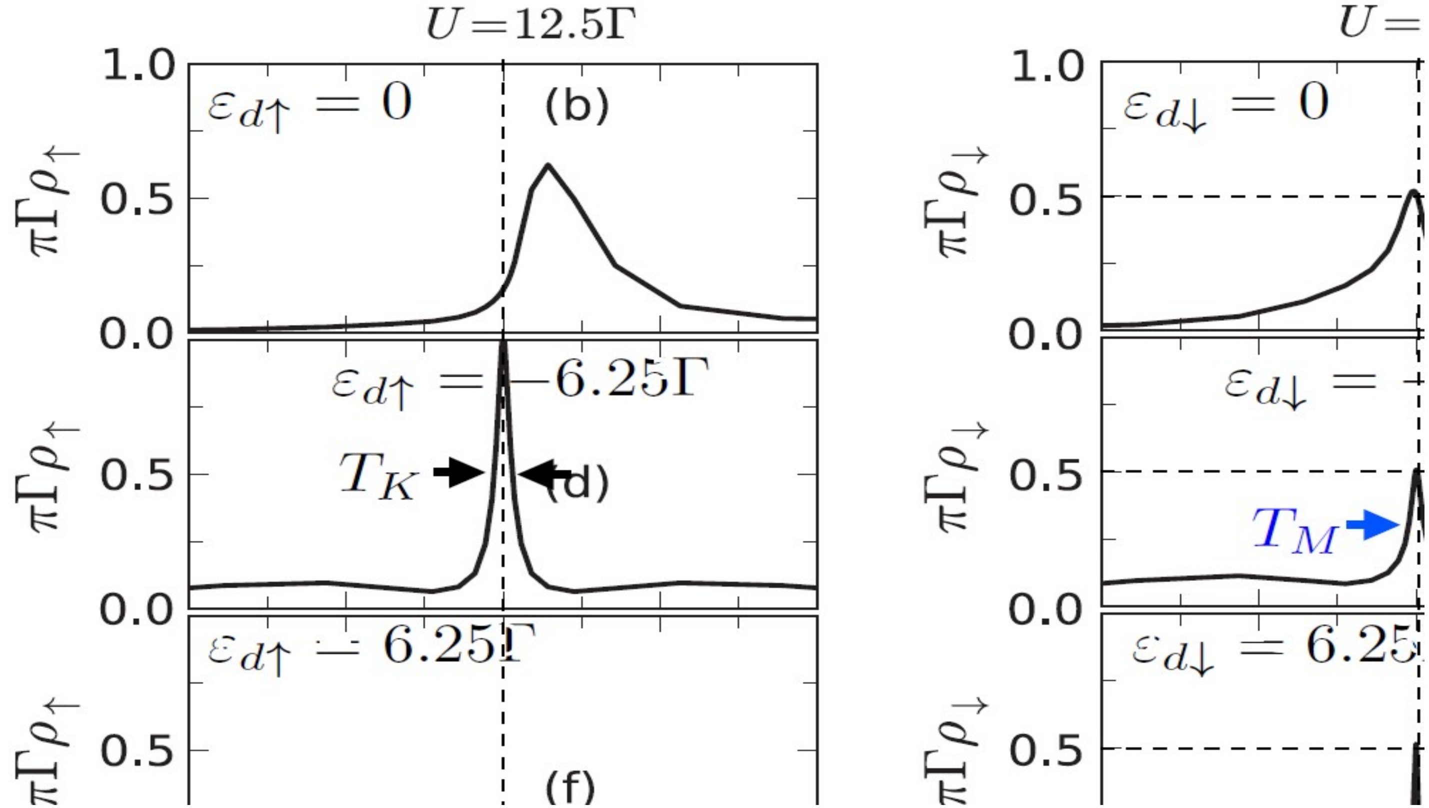
Coupling to the metallic leads

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

NRG: spectral function and conductance

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

Majorana-Kondo co-existence



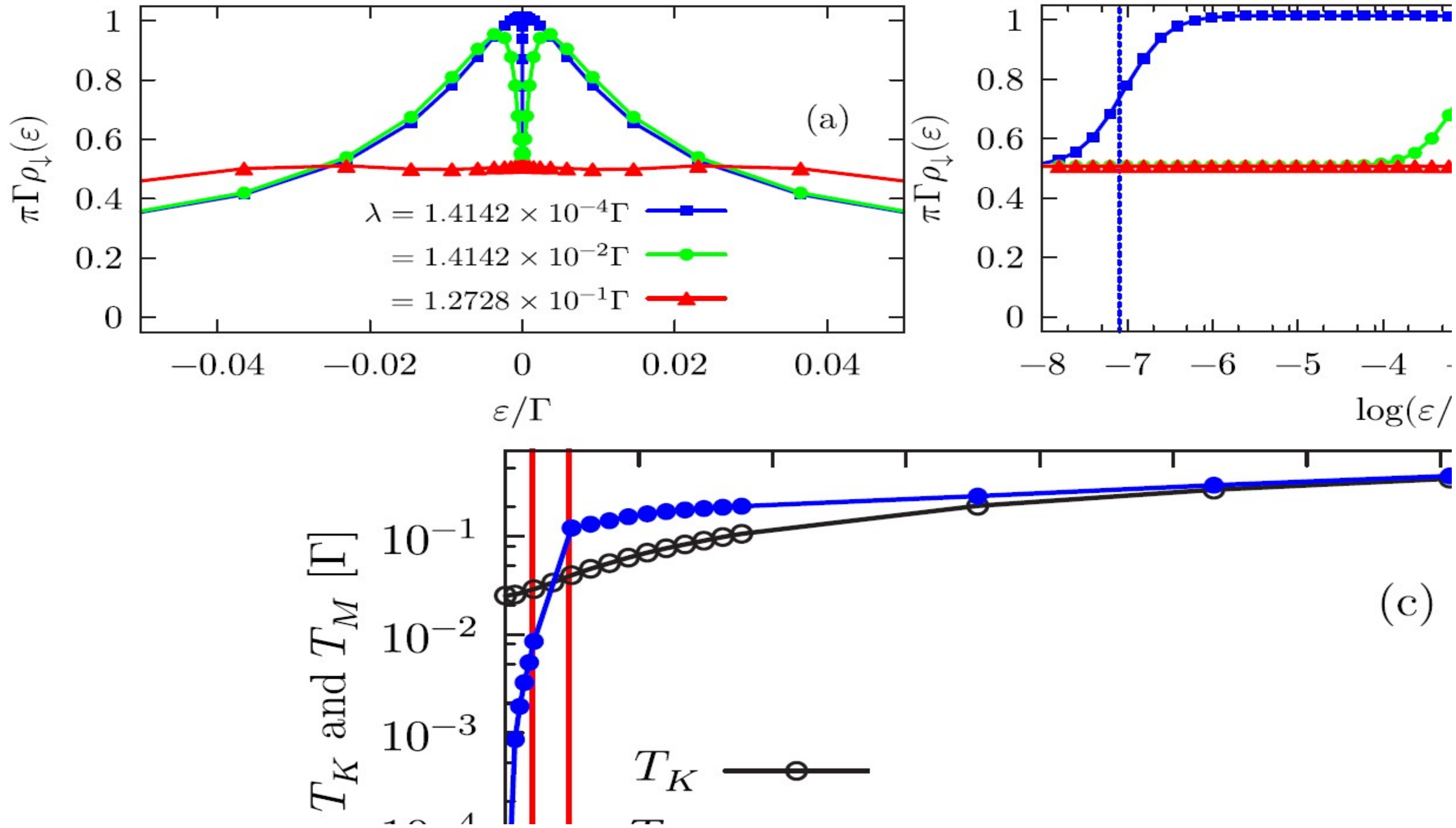
D. A. Ruiz-Tijerina et al. *Phys Rev B* **91** 115435 (2015).

Consistent with:

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

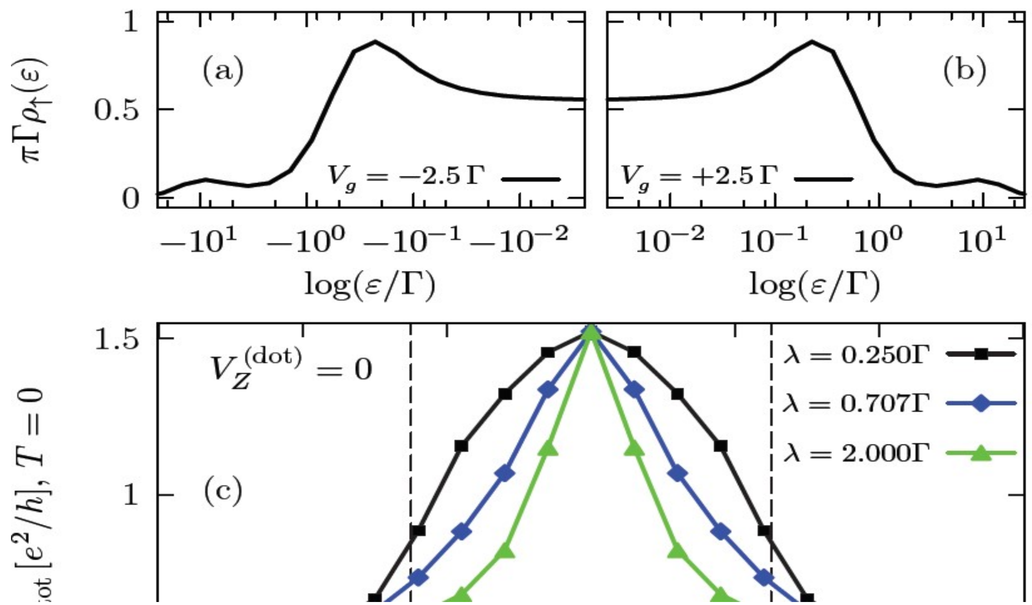
Cheng et al., *Phys. Rev. X* **4**, 031051 (2014).

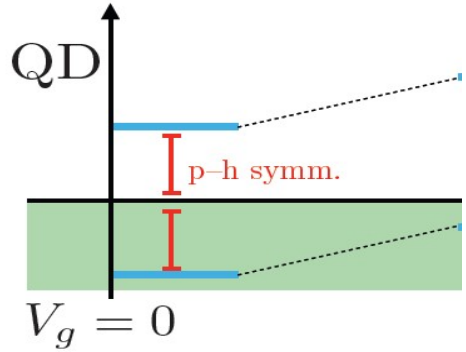
Majorana-Kondo co-existence



Distinguishing Majorana and Kondo signals

QD conductance *vs.* gate voltage (V_g)





Consistent with:

- The Kondo effect
- Majorana contrib

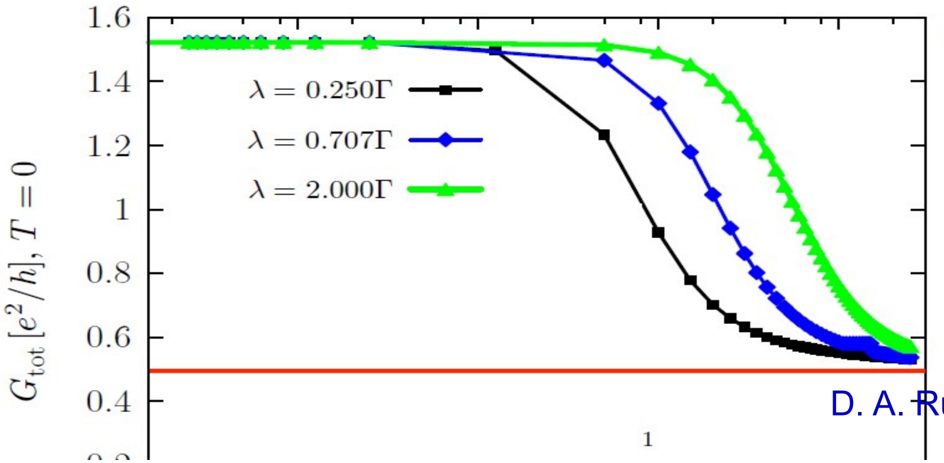
D. A. Ruiz-Tijerina et al. *Phys Rev B* **91** 115435 (2015).

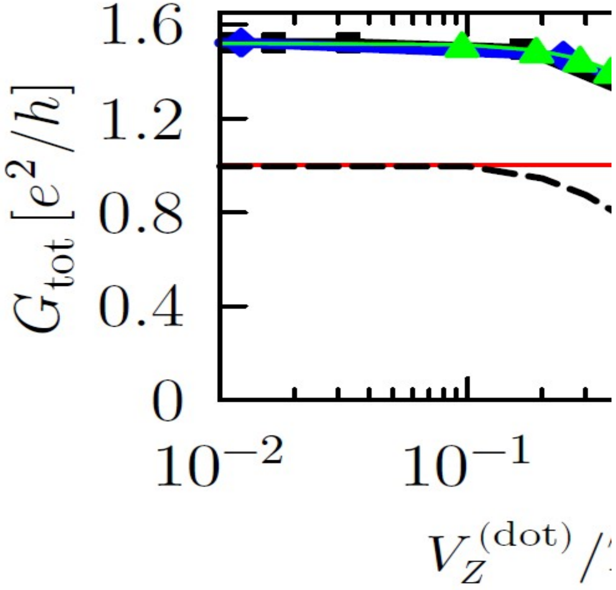
M. Lee, et al., *Phys. Rev. B* **87**, 241402 (2013).

Distinguishing Majorana and Kondo signals

QD Conductance *vs.* magnetic field $V_Z^{(do}$

- The Kondo contribution killed by a magnetic field.
- The Majorana contribution is robust. T_M unchanged.





- Universality

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

Manipulating MBS with quantum dots.

Group members

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Master's

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Master's

Manipulation of MZMs in Double Quantum Dots

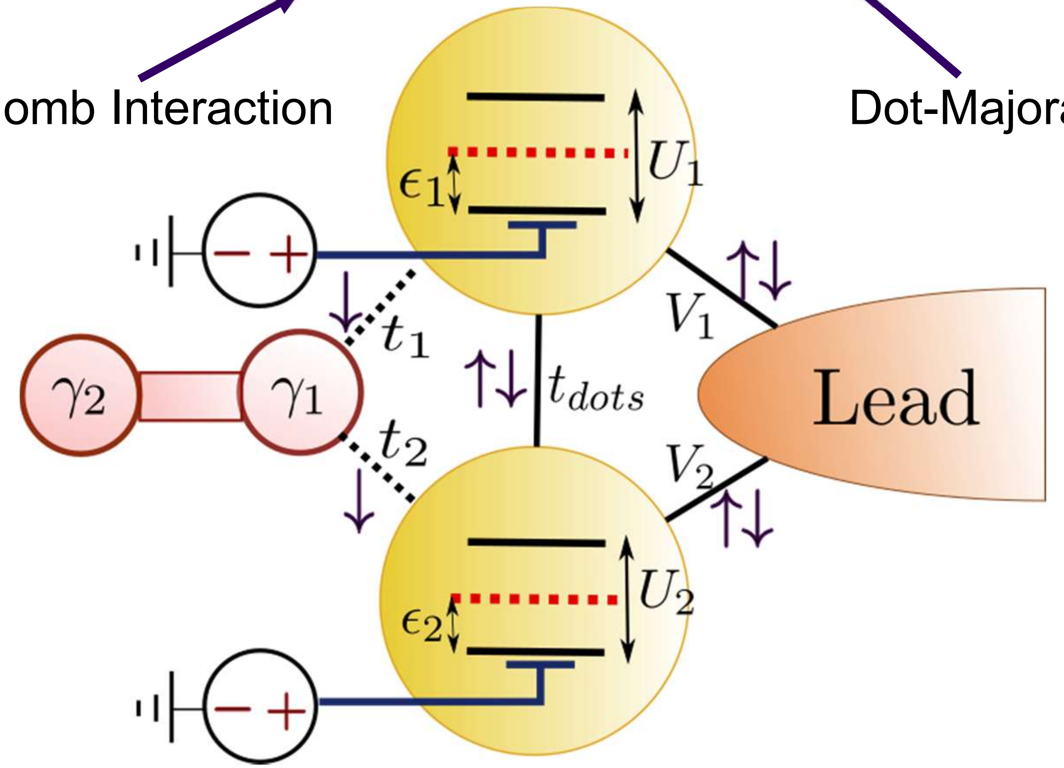
$$H = \sum_{i=1}^{2}\sum_{k,\sigma}\left(\epsilon_i + \frac{U_i}{2}\right) d_{i\sigma}^{\dagger} d_{i\sigma} + \frac{U_i}{2}(d_{i\sigma}^{\dagger} d_{i\sigma} - 1)^2 + t_i \gamma_1 d_{i,\downarrow} + t_i^{*} d_{i,\downarrow}^{\dagger} \gamma_1 + V_i d_{i\sigma}^{\dagger} c_{k\sigma} + V_i^{*} c_{k\sigma}^{\dagger}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

Energy level

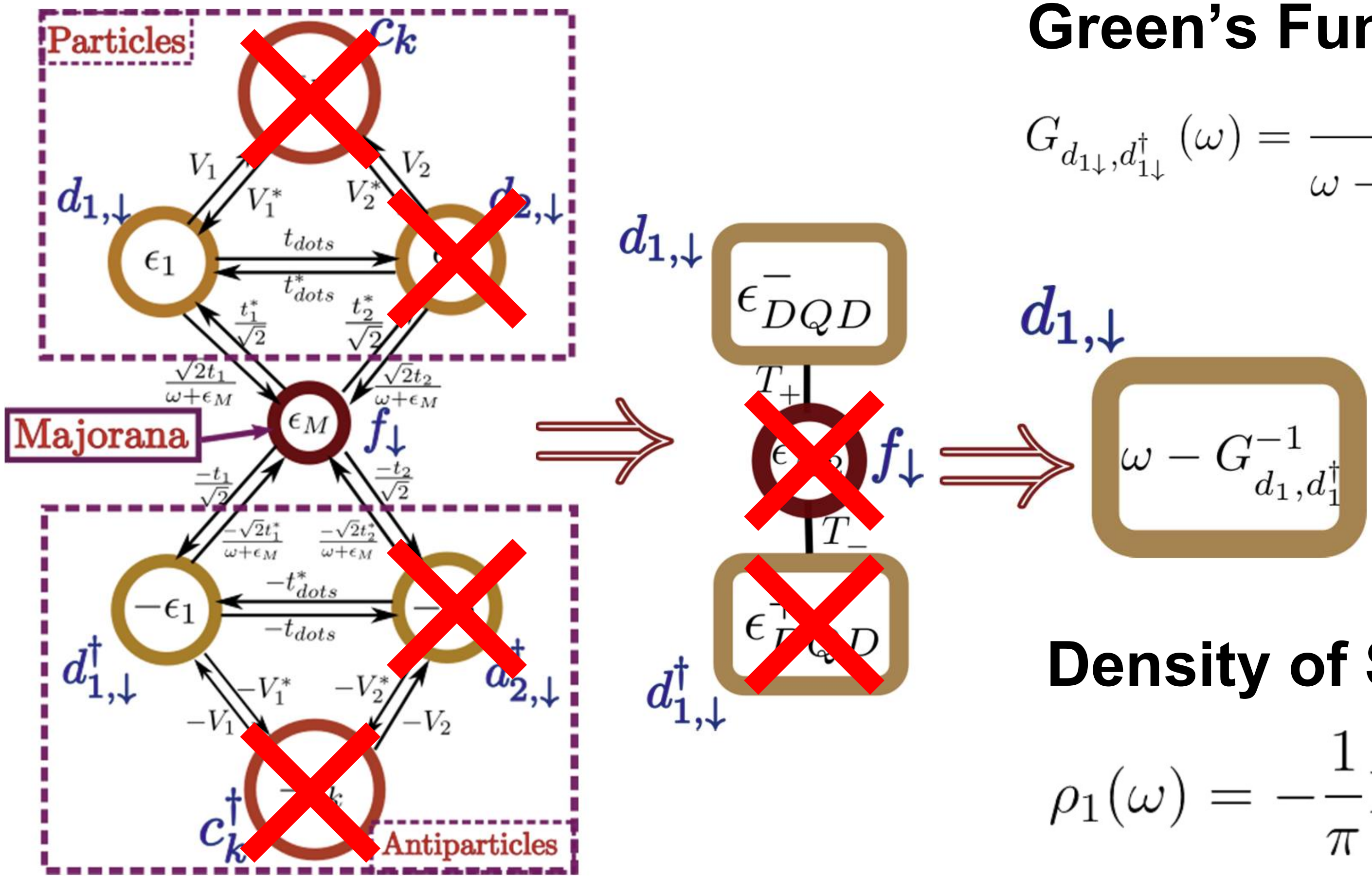
Coulomb Interaction

Dot-Majorana

Dot-Lead



Non-interacting case: spectral densities



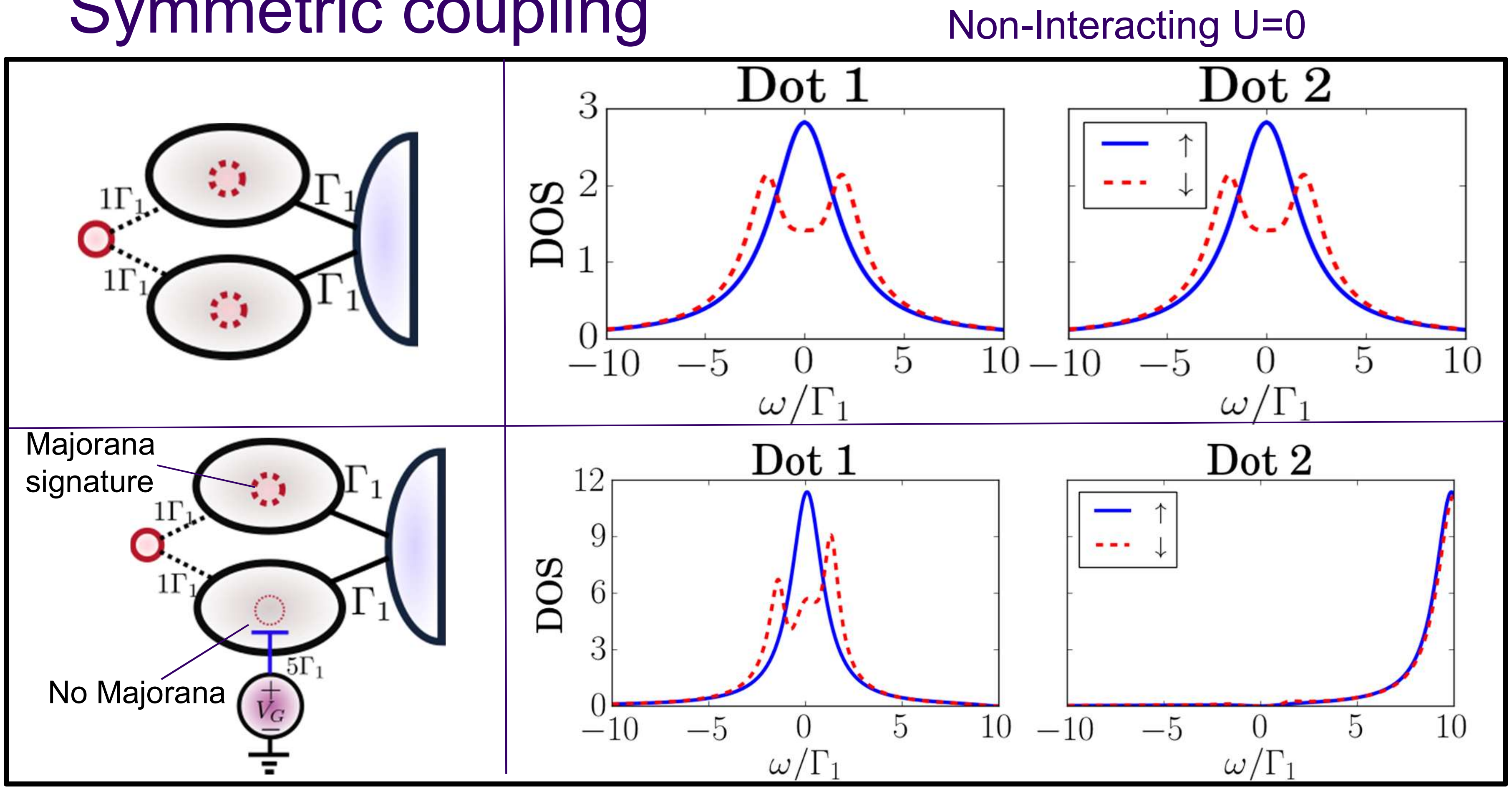
Green's Function

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

Density of States (DOS)

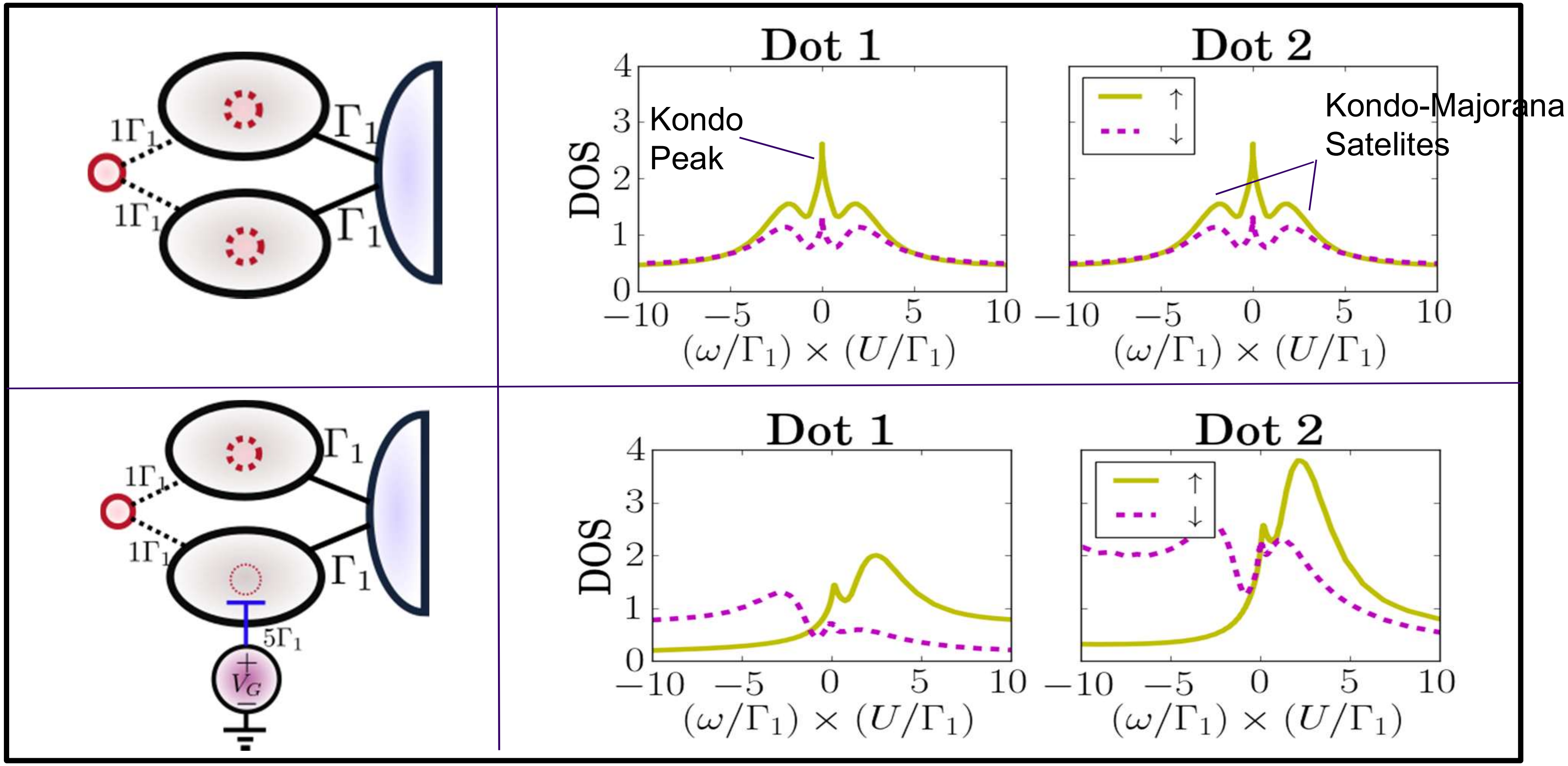
$$\rho_1(\omega) = -\frac{1}{\pi}\mathrm{Im}\Big[G_{d_1,d_1^\dagger}(\omega))\Big] \, .$$

Symmetric coupling



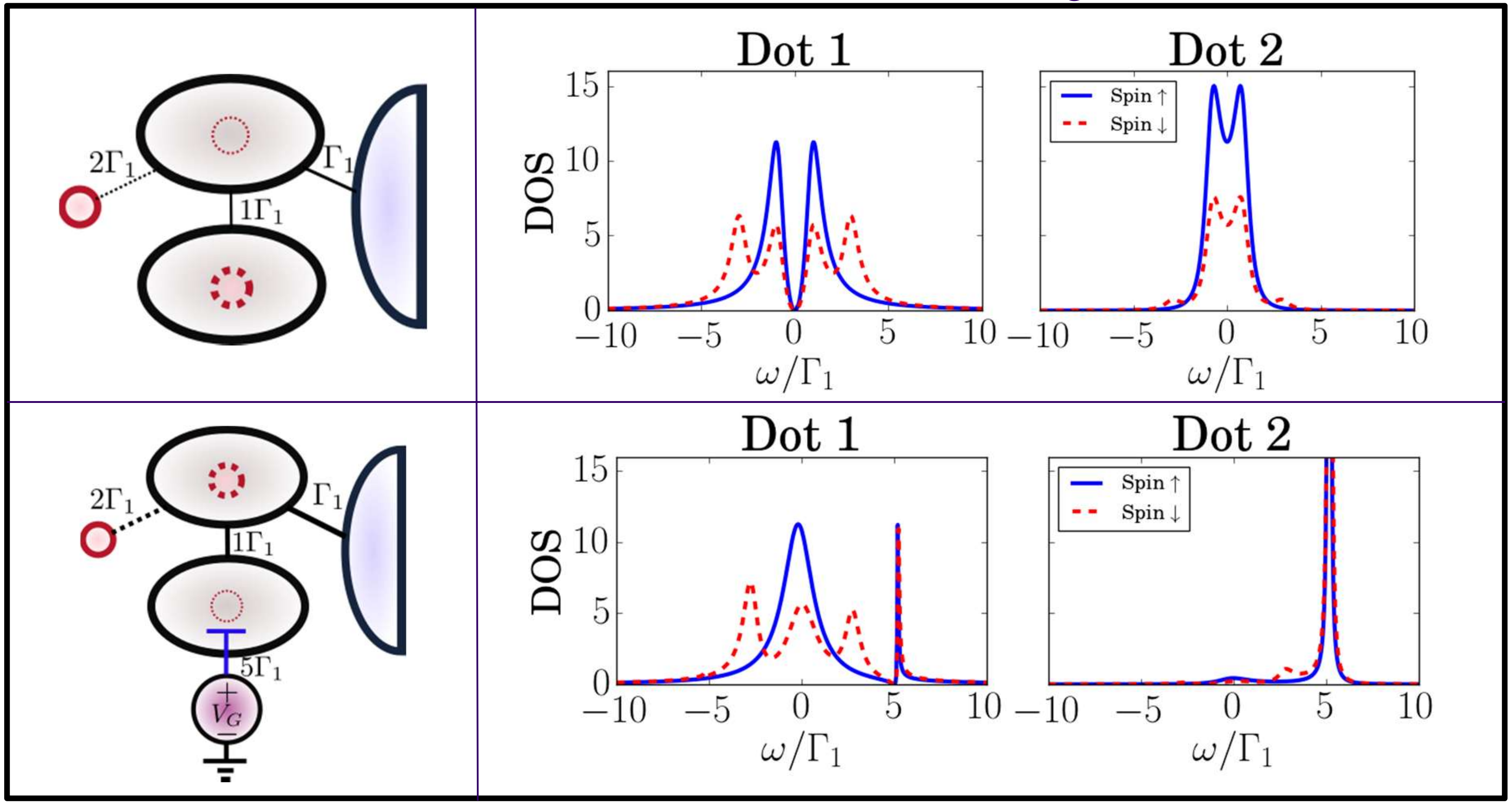
Symmetric coupling

Interacting U>0 (NRG)



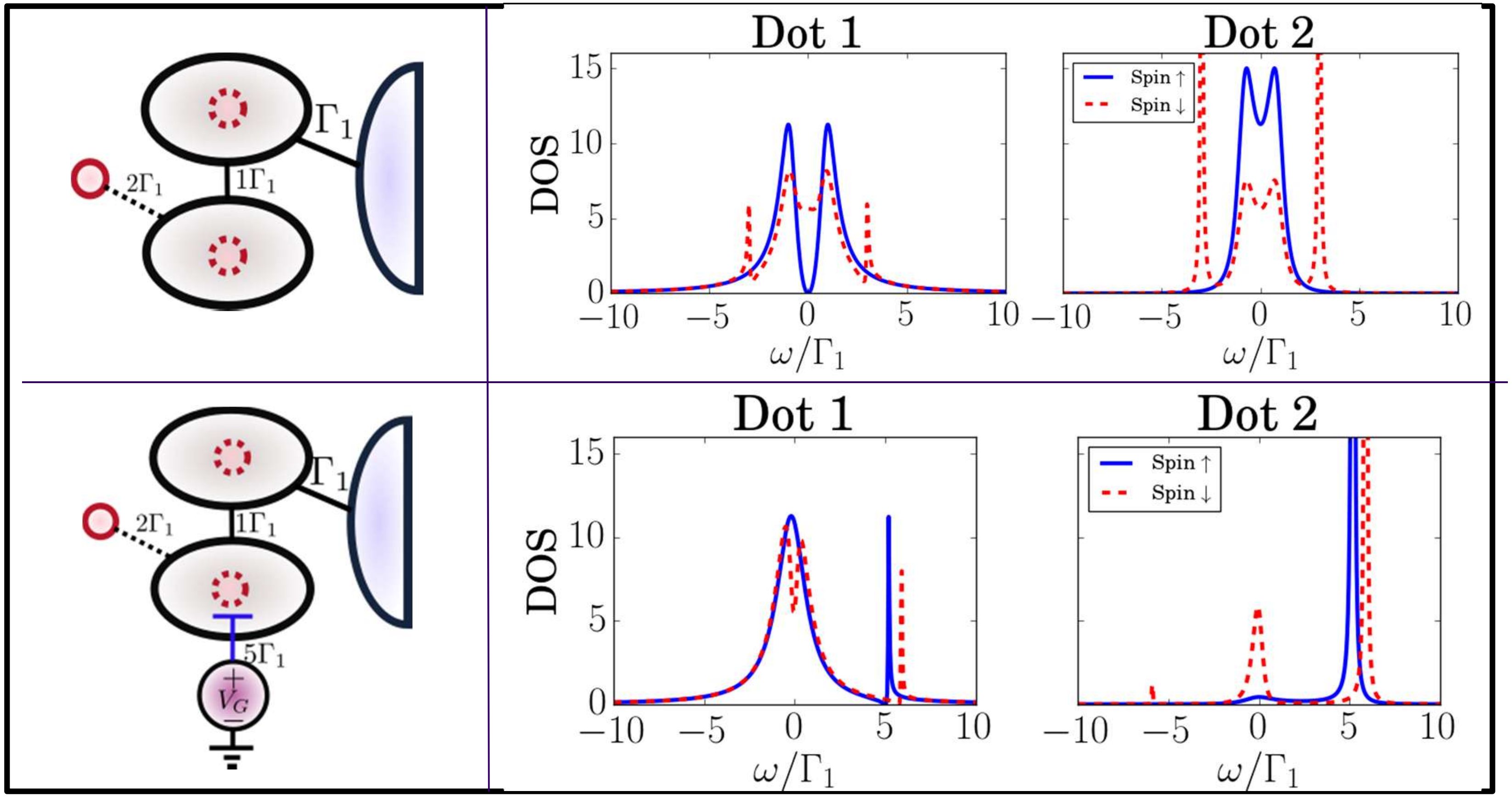
Interference destroying Majorana signature

Non-Interacting

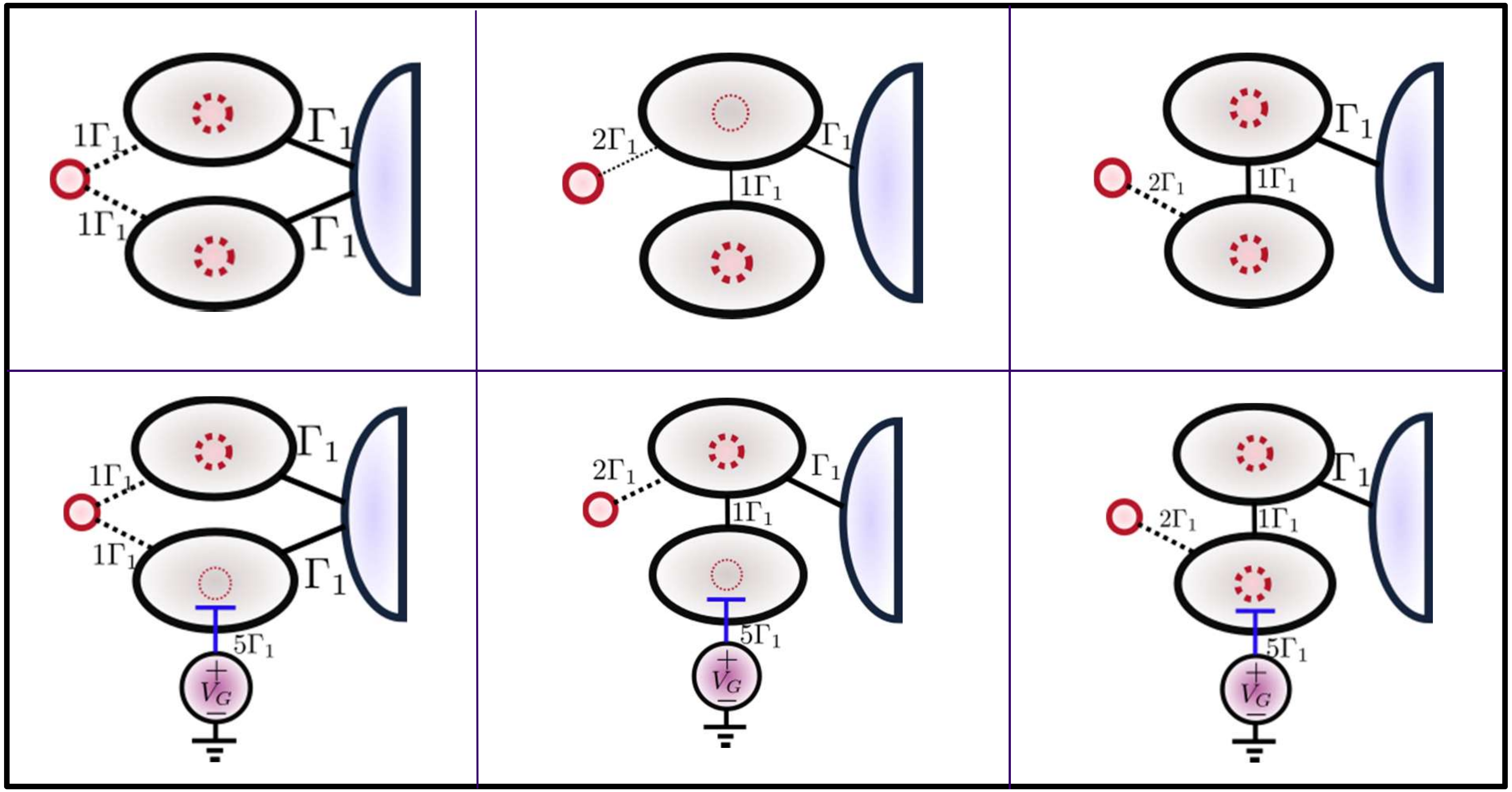


Indirect Majorana Coupling

Non-Interacting



Manipulating with couplings/gate voltages.



MBS in magnetic chains:
Gap oscillations

Group members

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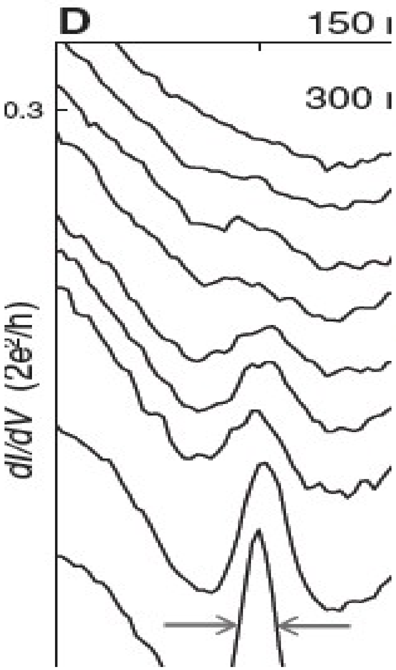
Master's

Alternative explanations for the zero-bias peak.



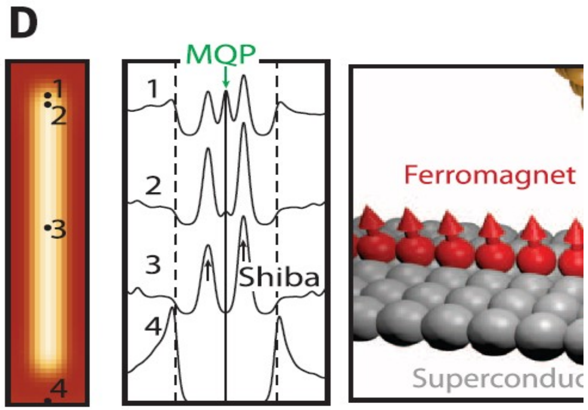
V. Mourik et al. Science **336** 1003 (2012)

Skepticism:

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

Solution*:

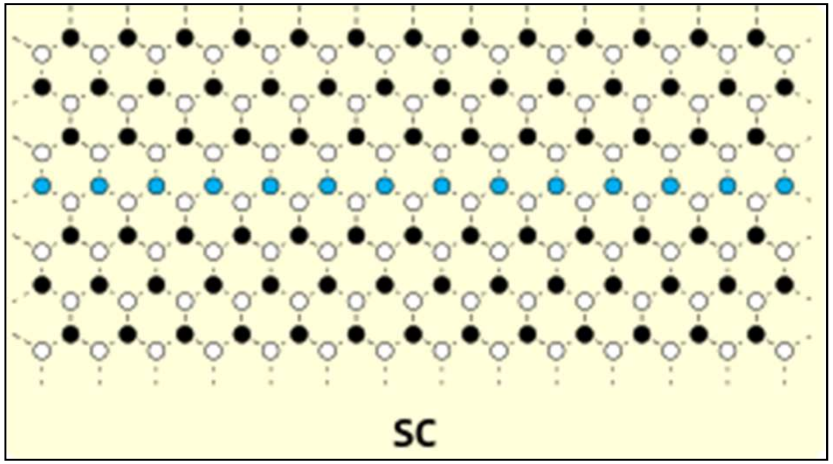
Local probing of the wire e



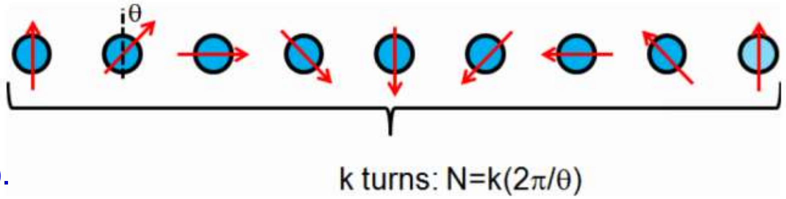
MBSs in magnetic chains on topological insulators

Honeycomb lattices:
Silicene, Stanene…

Kane-Mele-type TIs



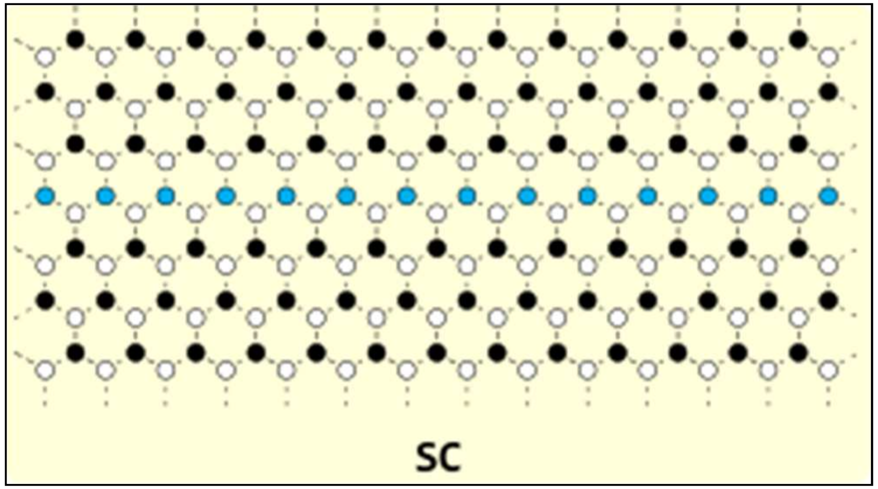
Magnetic chain: spiral angle θ



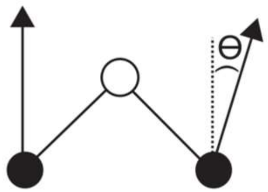
R. Teixeira *et al. Phys Rev B* **99** 035127 (2019).

Majorana gap oscillations - model

Honeycomb lattices: Silicene, Stanene…



Magnetic chain: spiral angle θ



Hamiltonian:

$$\mathcal{H} = \mathcal{H}_{\rm KM} + \mathcal{H}_{\rm SC} + \mathcal{H}_{\rm imp}$$

Kane-Mele model:

$$\mathcal{H}_{\rm KM} = t \sum_{\langle i,j \rangle} c^\dagger_{i,\sigma} c_{j,\sigma} + i \frac{\lambda_{SO}}{3\sqrt{3}} \sum_{\langle\langle i,j \rangle\rangle} \nu_{ij} c^\dagger_{i,\sigma} (s_z)_{\sigma\sigma'} c_{j,\sigma'} - \mu \sum_i c^\dagger_{i,\sigma} c_{i,\sigma}$$

Induced SC:

$$\mathcal{H}_{\rm SC} = -U_{\rm sc} \sum_i c^\dagger_{i,\uparrow} c_{i,\uparrow} c^\dagger_{i,\downarrow} c_{i,\downarrow}$$

Magnetic Impurities (xy-plane):

$$\mathcal{H}_{\rm imp} = \sum_{i \in \mathcal{I}} V_z c^\dagger_{i,\sigma} (\hat{n}_i \cdot \vec{s})_{\sigma\sigma'} c_{i,\sigma'}$$

Majorana gap oscillation - model

Self-consistency SC

$$\mathcal{H}_{\rm SC} = \sum_i \Delta c_{i,\uparrow} c_{i,\downarrow} + \text{H.c.} \rightarrow \Delta = -U \left\langle c_{i,\uparrow} c_{i,\downarrow} \right\rangle$$

Initial guess Δ^0

↓

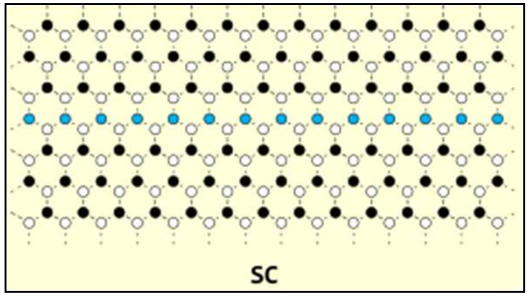
Eigenvectors of $\mathcal{H}$

↓

New Δ^i

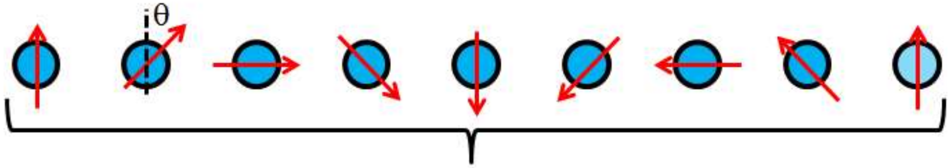
↓ $|\Delta^i - \Delta^{i-1}| < e$

Δ



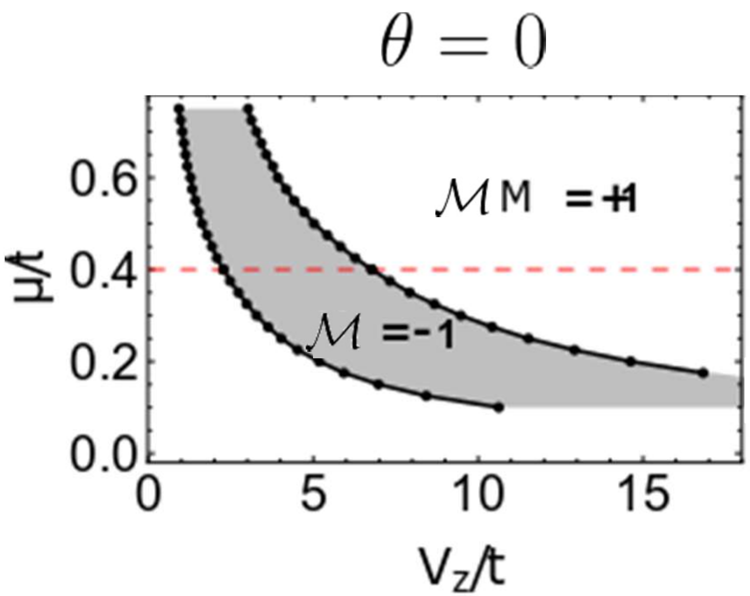
Majorana Number $\mathcal{M}$

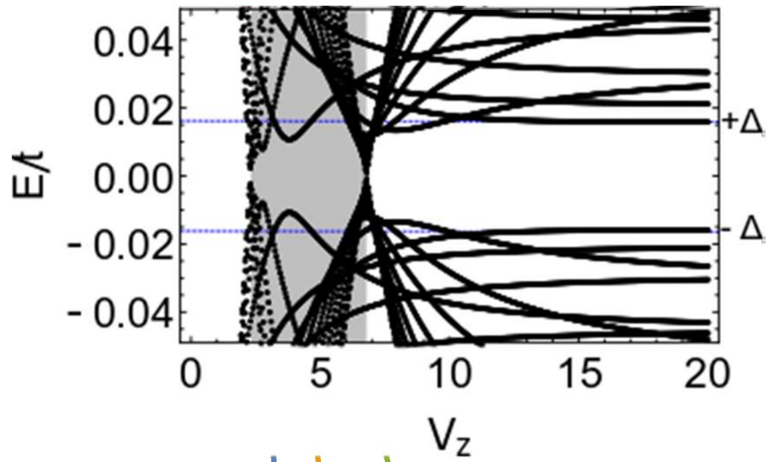
$$\mathcal{M}(\mathcal{H}) = \frac{\text{Sgn}\ [\text{Pf}\ (\mathcal{H}(N_1 + N_2))]}{\text{Sgn}\ [\text{Pf}\ (\mathcal{H}(N_1))]\ \text{Sgn}\ [\text{Pf}\ (\mathcal{H}(N_2))]}$$

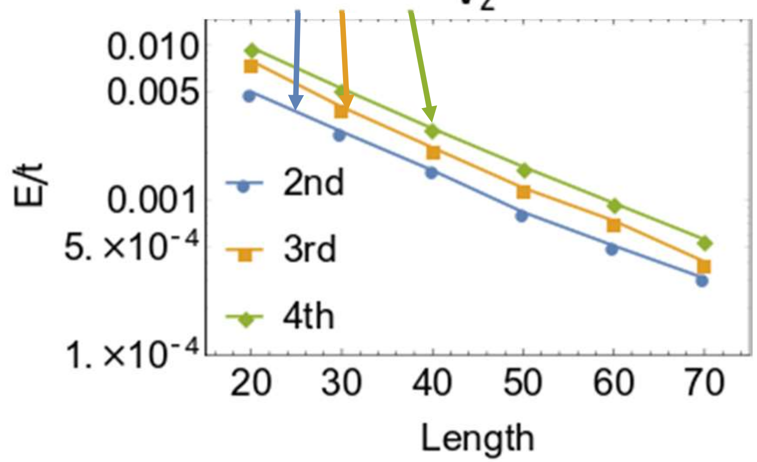


k turns: N=k(2π/θ)

Majorana gap oscillation – Exponential Protection

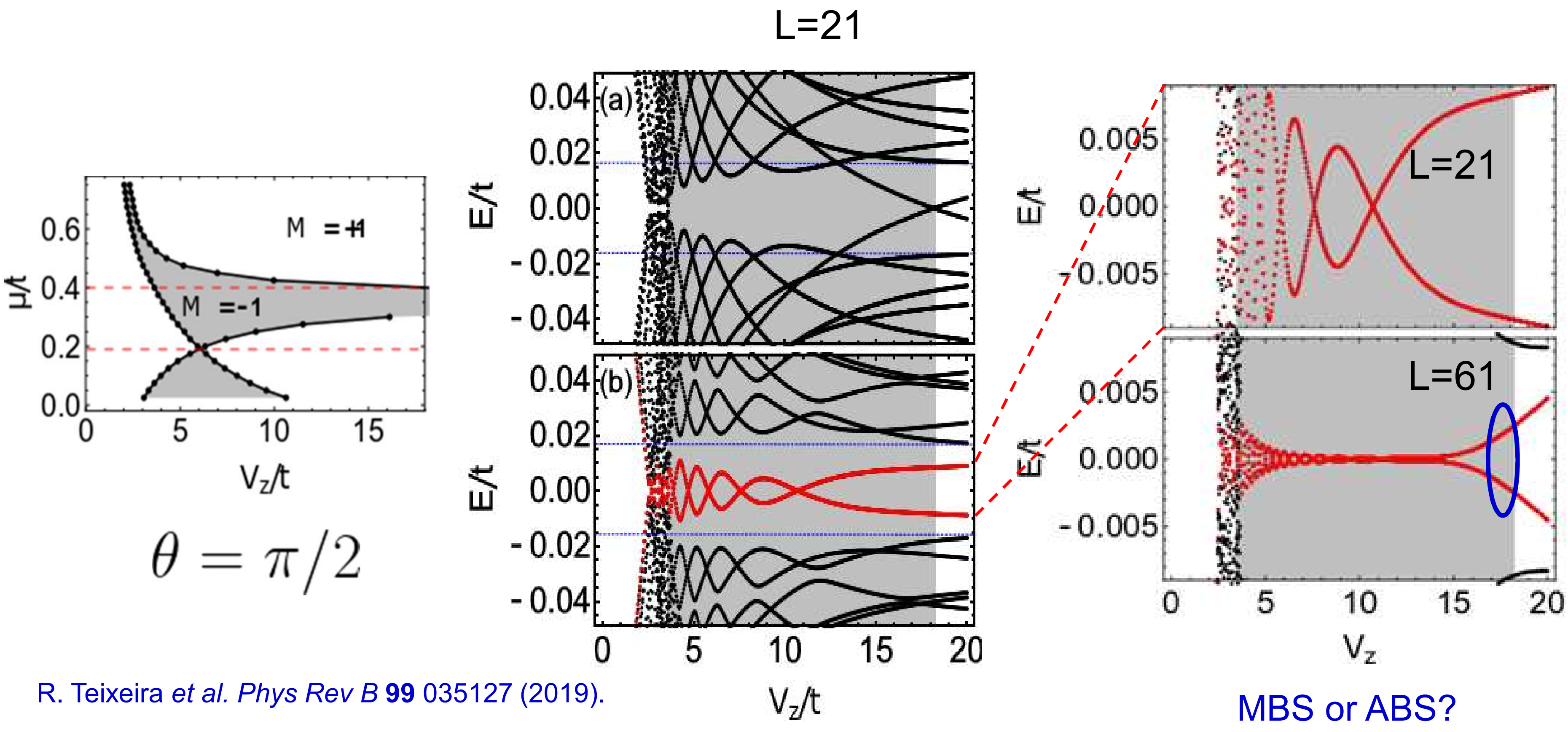






R. Teixeira *et al. Phys Rev B* **99** 035127 (2019).

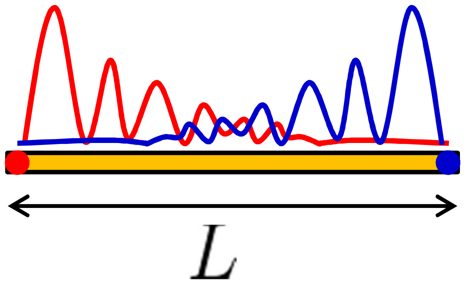
MBSs in magnetic chains on topological insulators



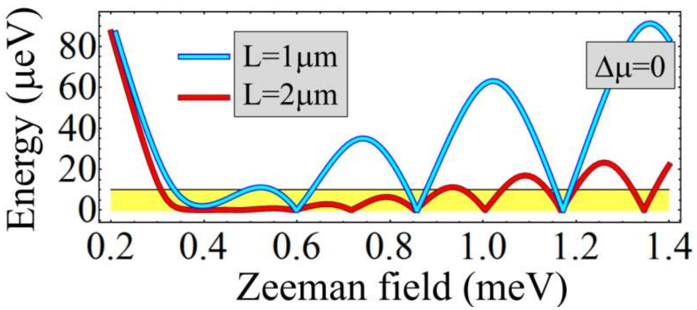
R. Teixeira *et al. Phys Rev B* **99** 035127 (2019).

Majorana splitting: energy oscillations (nanowire)

Finite size effect: Smoking gun?

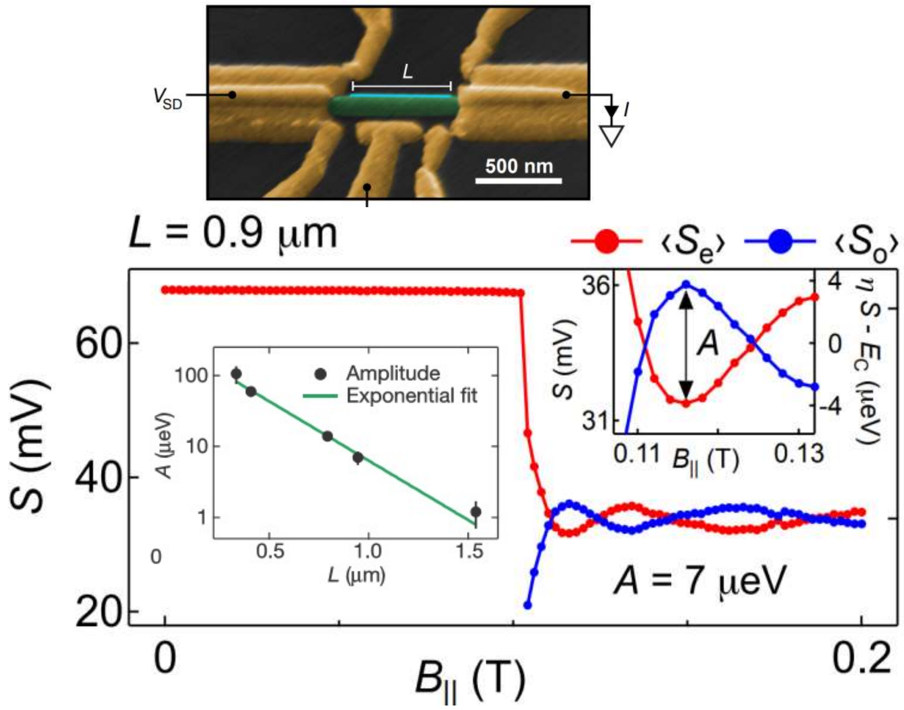


$$\Delta\epsilon(V_z) \sim k_F e^{-2L/\xi} \cos(k_F L)$$



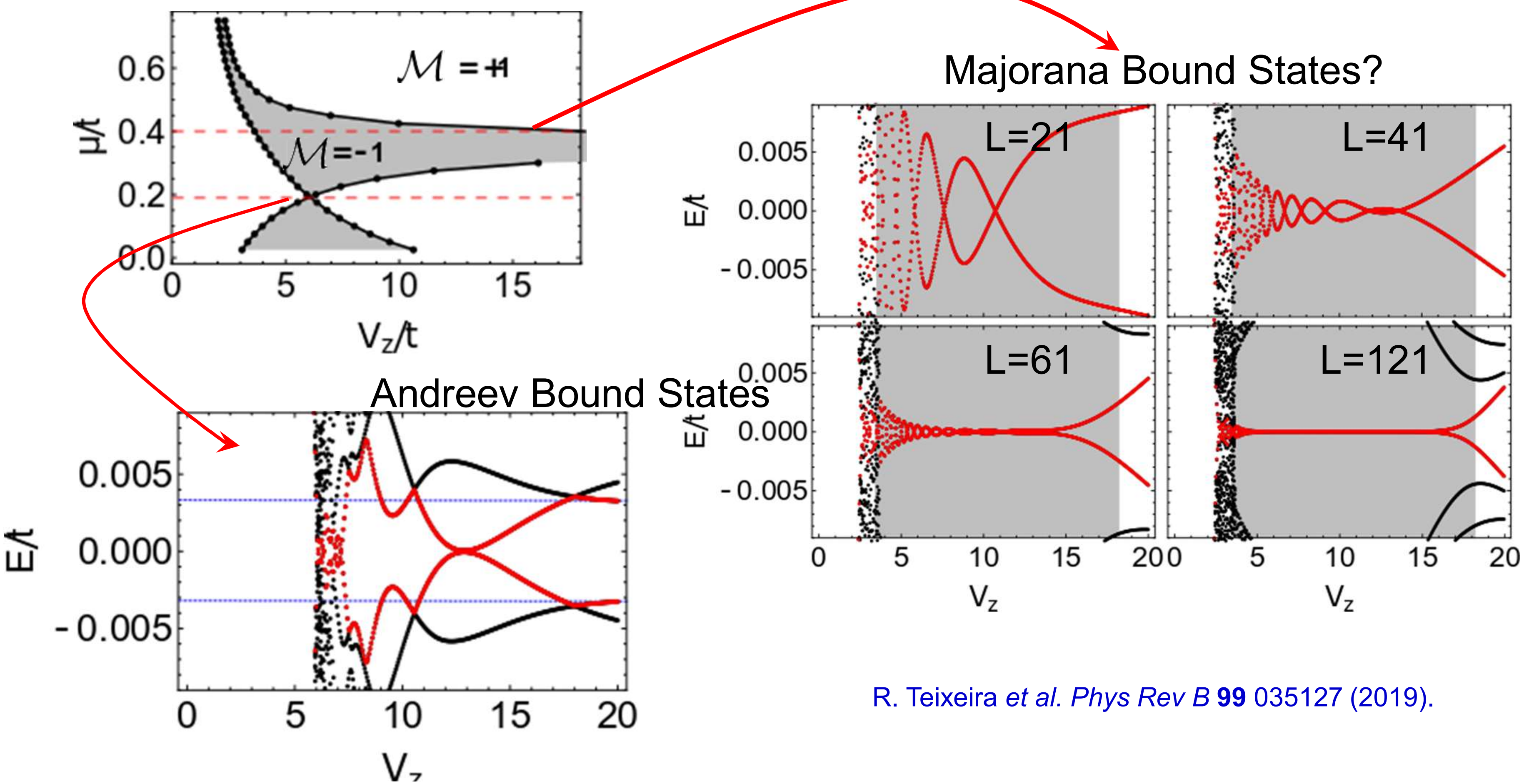
Das Sarma et al, *Phys, Rev. B.* **86** 220506 (2012)

Experiments – different behavior



Albrecht et al, *Nature.* **531** 206-209 (2016)

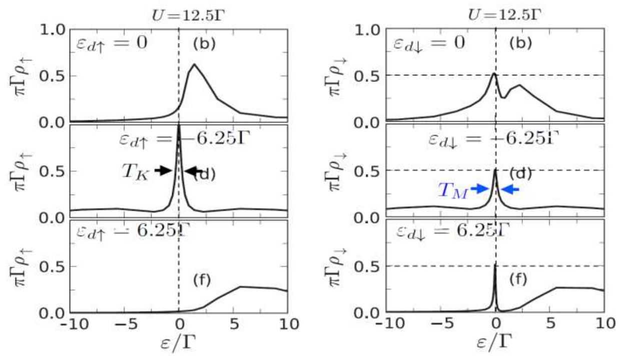
Majorana gap oscillation $\theta = \pi/2$

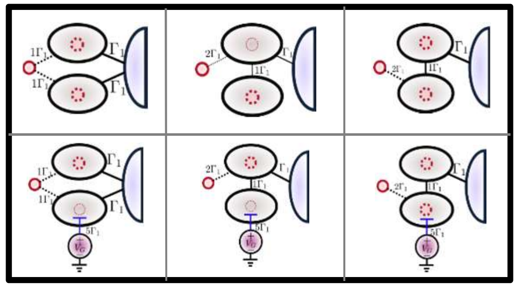


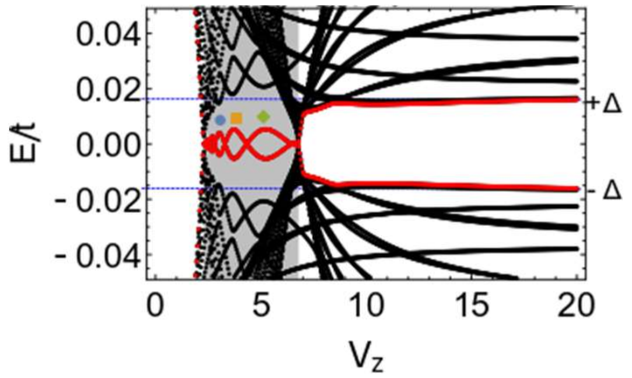
R. Teixeira *et al. Phys Rev B* **99** 035127 (2019).

Summary

- *Coexistence of MZM and Kondo states in interacting quantum dots*
- Detecting MZMs using quantum dots: signature in the spin-resolved density of states $\rightarrow$ large ($e^2/2$) reduction in the conductance.
- Manipulating MZMs using double quantum dots using only gate voltages and couplings.
- Splitting gap oscillations are non-universal.
- Rich topological phase diagrams in magnetic chains on hexagonal lattices: perspectives for MZMs in other systems.

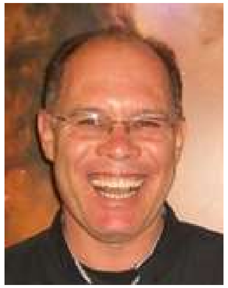






Collaborators in these works

David Ruiz-Tijerina



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Support: *FAPESP (2016/18495-4); CNPq (308351/2017-7 and 449148/2014-9); CAPES, FAPEMIG, USP-PRP Q-Nano.*