Phenomenology of Majorana zero modes in full-shell hybrid nanowires

C. Payá[1], S.D. Escribano[2], A. Vezzosi[3], F. Peñaranda[4], R. Aguado[1], P. San-Jose[1], E. Prada[1]

[1]Instituto de Ciencia de Materiales de Madrid (ICMM), CSIC, Spain.
[2]Department of Condensed Matter Physics, Weizmann Institute of Science, Israel.
[3]Dipartamento di Science Fisiche, Informatiche e Matematiche, Università di Modena e Reggio Emilia, Italy
[4]Donostia International Physics Center, Spain.

Introduction and motivation

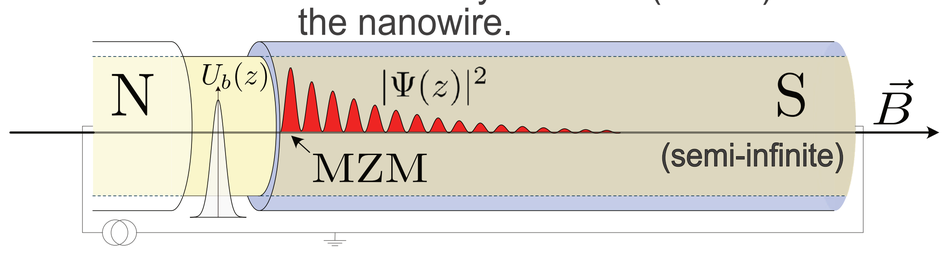
- **Full-shell hybrid nanowires** are a platform for **Majorana zero modes (MZMs)** with several advantages over previous devices.
- There are experimental claims of **MZMs** in this model[1].
- The system presents a **rich phenomenology,** involving subgap states known as Caroli-de Gennes-Matricon analogs (CdGMs)[2].
- **Our goal:** understanding the behavior of the MZMs alongside the CdGMs in several variations of this geometry:
  - **Tubular-core:** the charge is pushed towards the interface due to the **geometry.**
  - **Solid-core:** the charge is pushed towards the interface due to a **dome-like** electrostatic **potential** radial profile.

Device

Ingredients:
- Semiconductor (SM) nanowire with **strong spin-orbit coupling (SOC).**
- Encapsulated by an thin, **s-type** superconductor shell (SC).
- Threaded by a **magnetic flux:** $\Phi = \pi R^2 B$

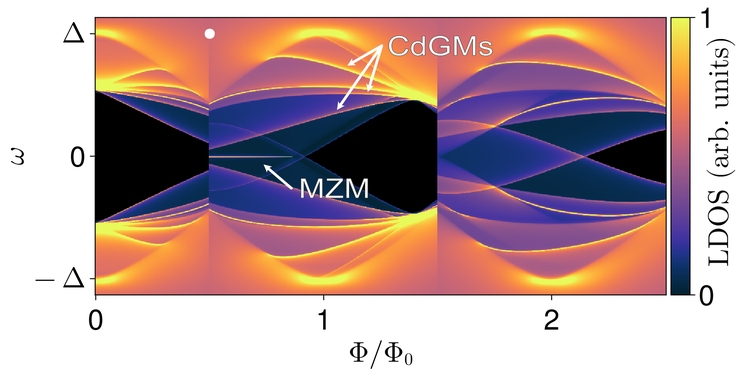
We investigate MZMs: **zero-energy** bound states at the end of a **topological superconductor.**

Our means: local density of states (**LDOS**) at the end of the nanowire.



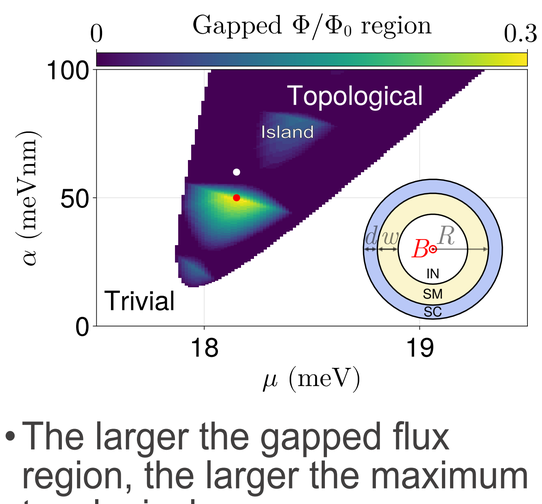
Unprotected Majorana

- CdGM states fill the topological minigap.



- Most common scenario (white dot in PD).
- Topological transition is at **lower flux** than a CdGM zero energy crossing.

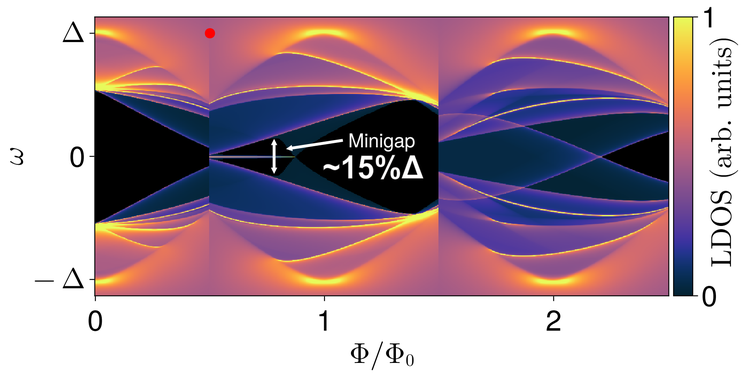
Tubular-core nanowire



- The larger the gapped flux region, the larger the maximum topological gap.

Protected Majorana

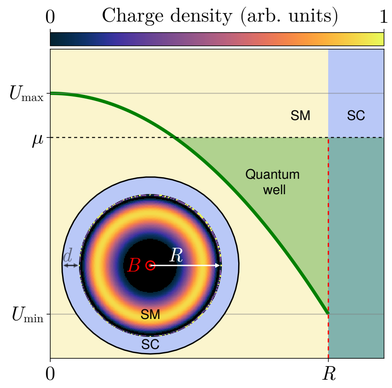
- The Majorana zero energy peak is gapped.

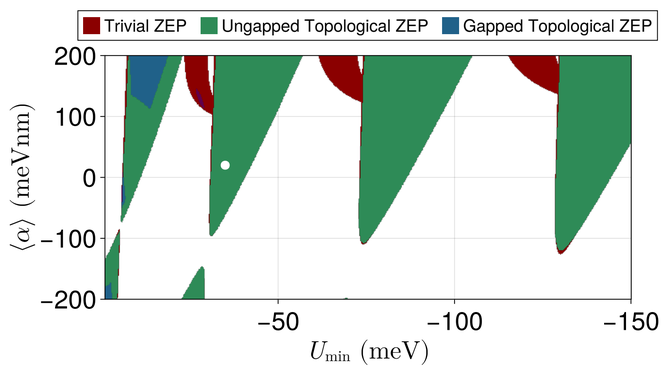


- Inside an ***island*** (red dot in PD).
- Topological transition at **larger flux** than any CdGMs zero energy crossings.

Solid-core nanowire

- Conduction band-bending accumulates **charge at the interface**.

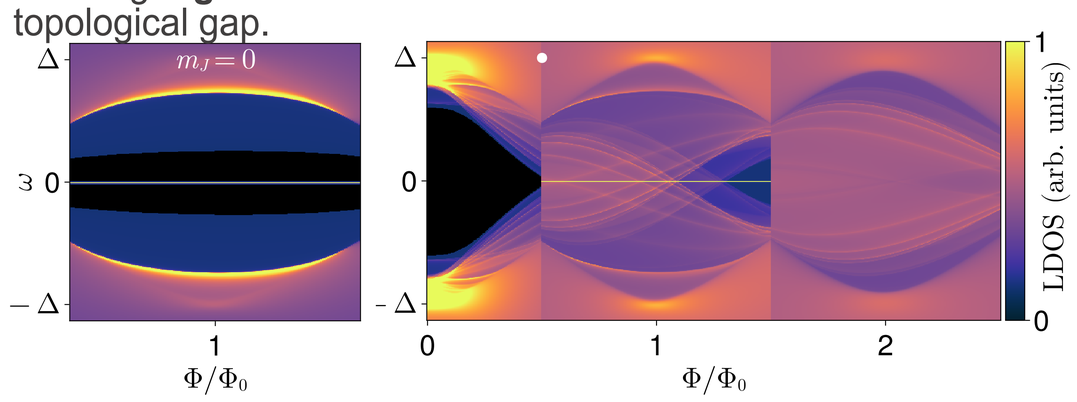




- PD similar to tubular-core, but with one *wedge* per radial mode in the nanowire. Islands **only in the first** radial mode.

Majorana is unprotected for most parameters

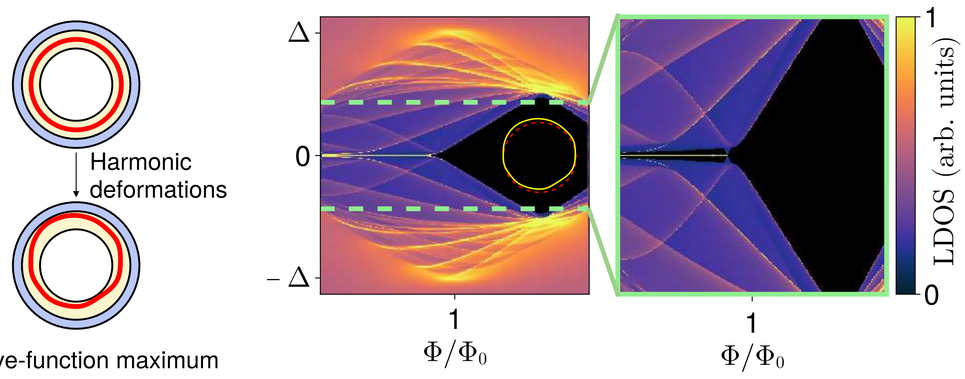
- Allowing **higher radial modes** lets in far **more CdGMs** that fill the topological gap.



- However, the maximum possible topological gap, given by the 0th angular momentum mode own's minigap, is still large.

Angular mode-mixing opens CdGM gaps

- Modeled as deformations of the wave-function radial profile.



- CdGM opening gaps angular momentum numbers must be separated by a harmonic of the deformation.

Conclusions

- **Majorana zero modes coexist with CdGM** analogs that close the topological minigap except for some **parameter *islands.***
- While disorder induced mode-mixing can open gaps, the ones obtained with **tubular-core nanowires are much larger**, making them **a suitable option** for Majoranas in full-shell nanowires.
- The phenomenology of **solid-core** nanowires **depends** on wheter one or more **radial momentum subbands** are occupied. **More than one usually means no** topological minigap.

This, and more, in our paper:

Phys. Rev. B 109, 115428

MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
AGENCIA ESTATAL DE INVESTIGACIÓN

[1]S. Vaitiekénas *et al.*, Science367,eaav3392 (2020). [2]P. San-José *et al.*, Phys. Rev. B 107, 155423 (2023).

carlos.paya@csic.es