Majorana zero modes in full-shell hybrid nanowires

Carlos Payá[1], Samuel D. Escribano[2], Ramón Aguado[1], Pablo San-José[1] and Elsa Prada[1]
[1]Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC), Madrid, Spain.
[2]Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, Israel.

CSIC Consejo Superior de Investigaciones Científicas
ICMM Instituto de Ciencia de Materiales de Madrid

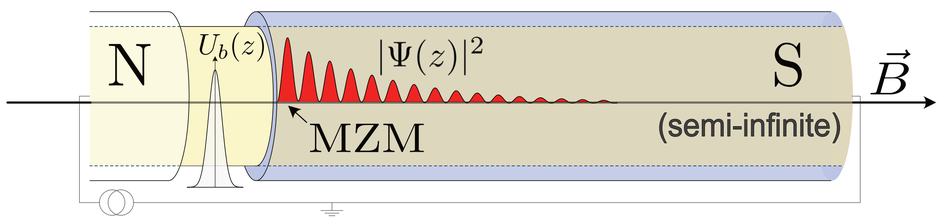
Introduction and motivation

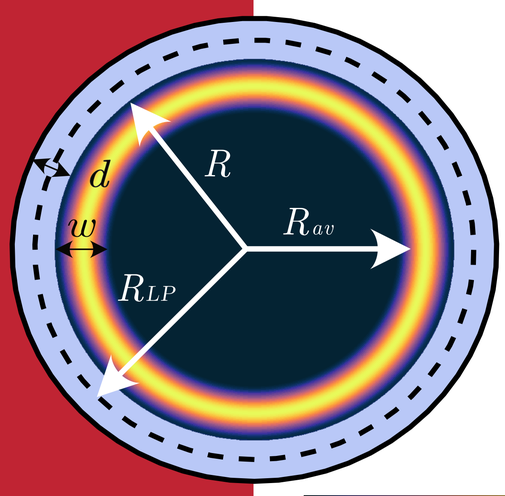
- **Full-shell hybrid nanowires** are a new platform in the search for **Majorana zero modes (MZMs)** with several advantages over previous devices.
- There are experimental claims of **MZMs** in this model[1].
- The system presents a **rich phenomenology**[2].
- **Our goal:** simulate the system's **edge LDOS** to understand the **behavior** of the **MZM** and other **in-gap states** with three levels of complexity:
  - **Hollow-core:** 1D simplistic model, but **intuitive**.
  - **Tubular-core:** 2D and charge **close to the interface.**
  - **Solid-core: full** 2D simulation with a dome-like electrostatic potential radial profile.

Device

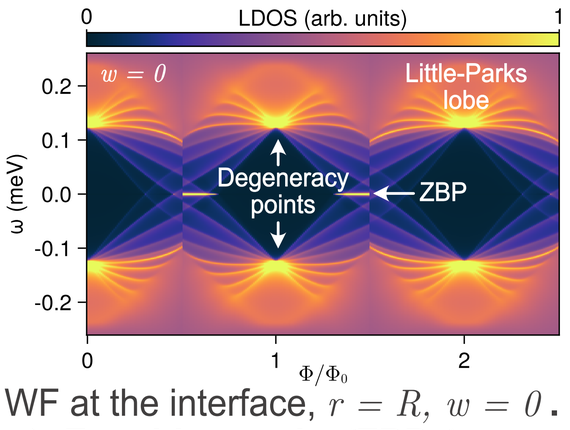
Ingredients
- Semiconductor (SM) nanowire with **strong spin-orbit coupling (SOC).**
- Encapsulated by an thin, **s-type** superconductor shell (SC).
- Threaded by a **magnetic flux:** $\Phi = \pi R^2 B$

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





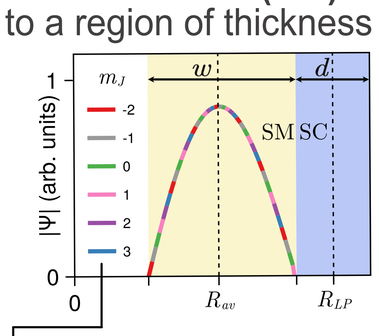
Hollow-core model



WF at the interface, $r = R$, $w = 0$.
- **Zero bias peaks (ZBPs)** indicate a **MZM.** at $n = \lceil \frac{\Phi}{\Phi_0} \rfloor = 1$
- Coexist with CdGM: Caroli-de Gennes-Matricon analog states[2].

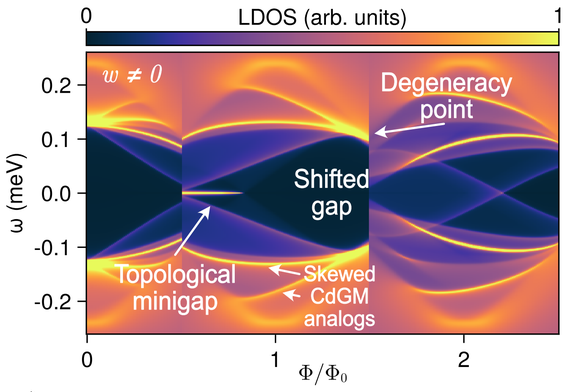
Tubular-core model

Wave-function (WF) confined to a region of thickness w.



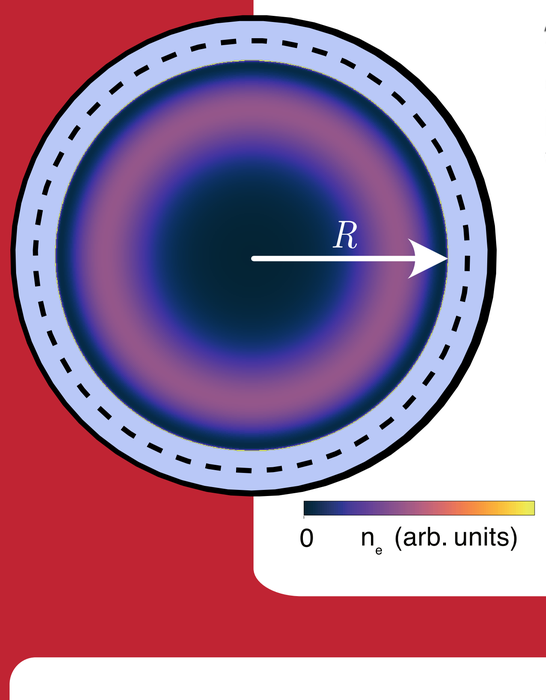
- Generalized angular momentum modes.
  $J_z = -i\partial_\varphi + \frac{1}{2}\sigma_z + \frac{1}{2}n\tau_z$
  (orbital, spin, fluxoid)
- Lowest radial mode.

LDOS at the edge of the nanowire.



- Only left **ZBP** visible with topological minigap.
- **Skewed CdGM analogs.**
- Degeneracy point and gap shift with thickness w towards the right.

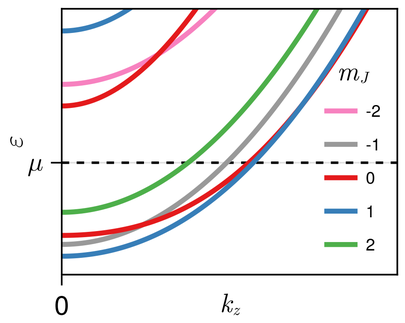
Solid Core model



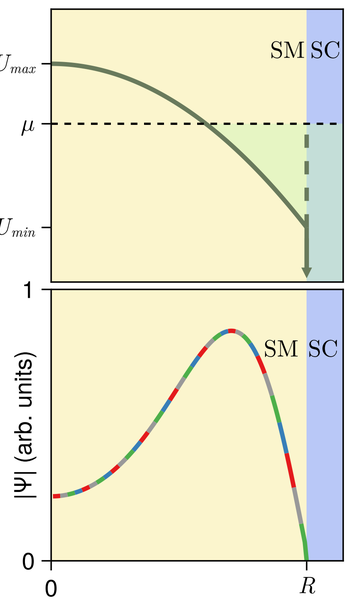
$m_J = 0$ in first radial mode

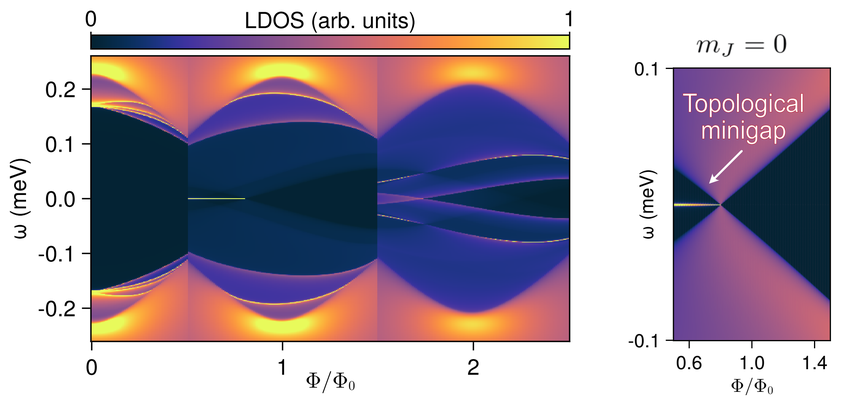
Conduction band bends towards the interface.

WF spreads through all the SM section.



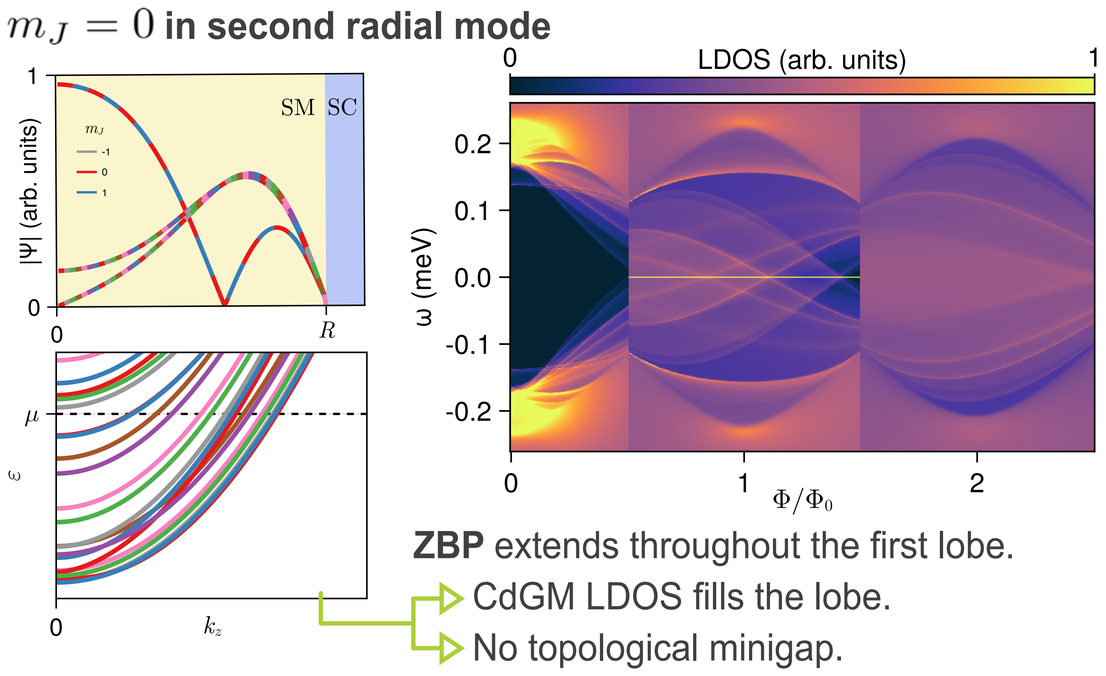
Only the first radial mode is populated





Same qualitative features as tubular-core model.
- But no true minigap.
- First Little-Parks lobe is filled by CdGM with $m_J \neq 0$.

$m_J = 0$ in second radial mode



ZBP extends throughout the first lobe.
- CdGM LDOS fills the lobe.
- No topological minigap.

Conclusions

- **MZM** at hybrid nanowire's end ⇒ **ZBP** in LDOS odd Little-Parks **lobes**.
- **In general, ZBP coexist with other sub-gap states** called **CdGM analogs.**
- In the **tubular-core** nanowire, there can be true **topologically protected MZMs** (eg. minigap $\lessapprox$ 40μeV for InAs/Al)**.**
- In the **solid-core** nanowire, there is typically **no topological minigap** (only for fine-tuned paramaters with negative SOC, the minigap is $\lessapprox$ 30μeV for InAs/Al).

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

carlos.paya@csic.es