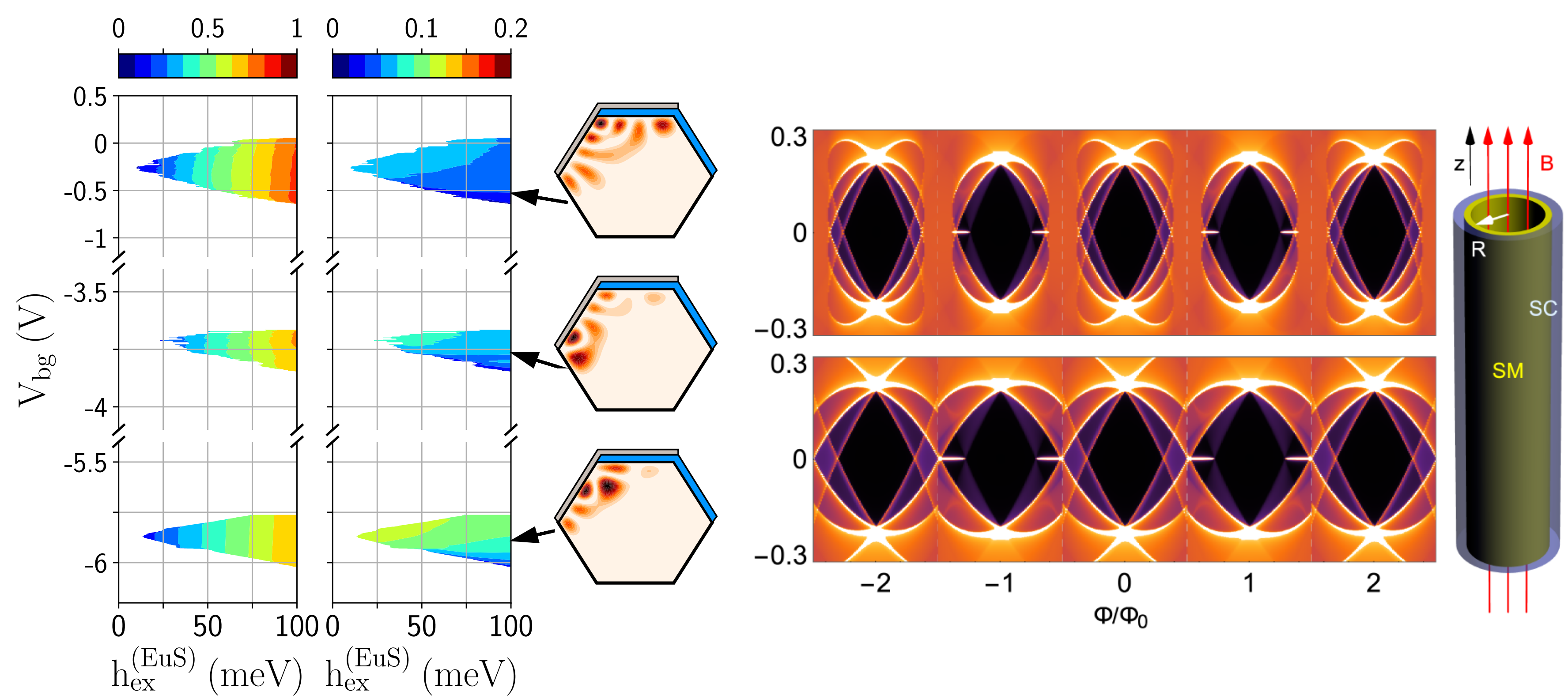
Latest Majorana nanowire designs: ferromagnetic and full-shell hybrid nanowires

Elsa Prada

Instituto de Ciencia de Materiales de Madrid - CSIC



Presentation

Home | My group | Publications | CV | Teaching | Outreach

Elsa Prada's homepage

Instituto de Ciencia de Materiales de Madrid - CSIC

Google scholar

Web of Science ResearcherID:

A-4792-2010

ORCID:

0000-0001-7522-4795

Department: Theory and Simulation of Materials

Group: Theory of Quantum Materials and Solid State Quantum Technologies

INSTITUTO DE CIENCIA DE MATERIALES DE MADRID - CSIC
C/ Sor Juana Inés de la Cruz 3, E-28049 Cantoblanco, Madrid, Spain
Office: 346 — Tel.: (+34) 91 334 9080
Email contact

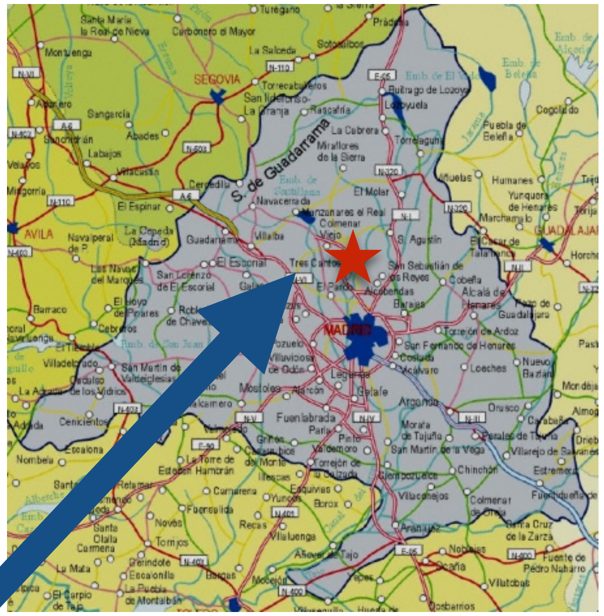
Hi! My name is Elsa Prada and I'm a condensed matter theorist working on systems where quantum phenomena play an important role, such as low dimensional materials and nanostructures. As of July 2020 I belong to the Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC) as a tenured scientist.

Research interests:

Throughout my career my research has dealt with the following topics:

- **Topology in electronic systems**
  - Topological insulators
  - Topological superconductors
  - Majorana zero modes in nanostructures
- **Graphene and other 2D crystals**
  - Monolayers, multilayers, twisted bilayers, superlattices
  - Disorder
  - Magnetotransport, quantum Hall effect

...



icmm CSIC

Consejo Superior de Investigaciones Científicas

https://www.icmm.csic.es/elsaprada/

Majoranas in Madrid: people involved

Pablo San-Jose

Ramón Aguado

icmm

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

UAM
UNIVERSIDAD AUTONOMA DE MADRID

Alfredo Levy Yeyati

PhD Students

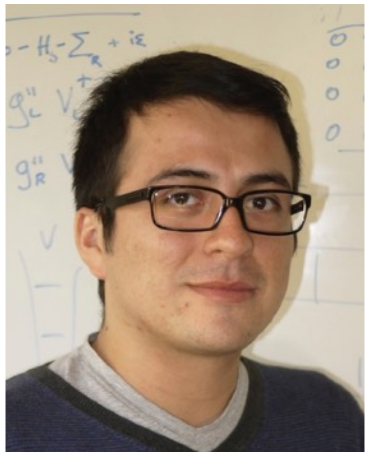
Samuel D. Escribano

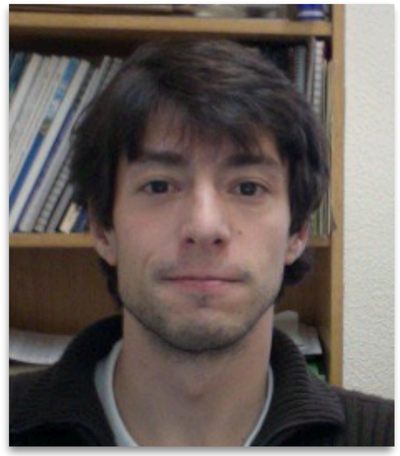
Fernando Peñaranda

Jesús Ávila

Eduardo Lee

Other collaborators in Majoranas


Jorge Cayao


Fernando Domínguez


Annica Black-Schaffer


Jelena Klinovaja


Yuval Oreg


Mintang Deng


Saulius Vaitiekènas


Jesper Nygard


Peter Krogstrup


Charlie Marcus


Marco Valentini


Georgios Katsaros


Sergey Frolov


Attila Geresdi

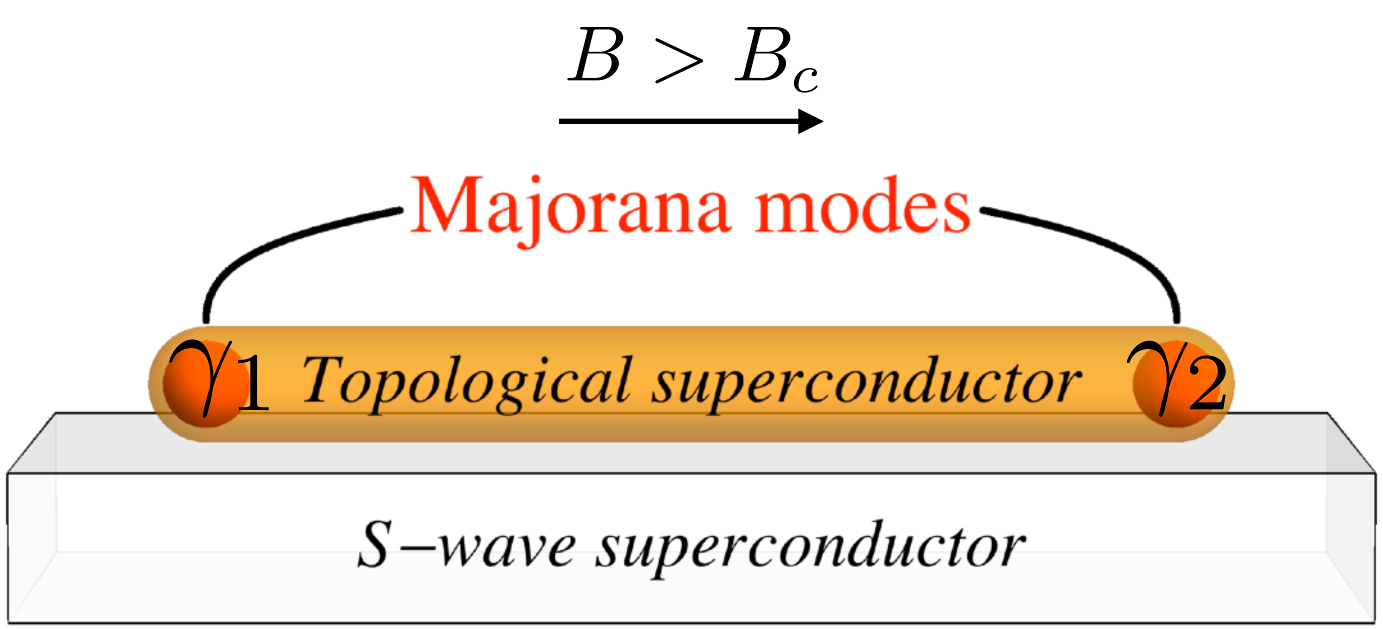

Leo Kouwenhoven

Building a 1D Topological Superconductor

Oreg-Lutchyn proposal ⟶ Majorana Nanowire

1D SM wire with strong Spin Orbit Coupling
+
Zeeman field perpendicular to SO term ⟶ spinless helical liquid
+
proximity to s-wave superconductor

Topological p-wave Superconductor

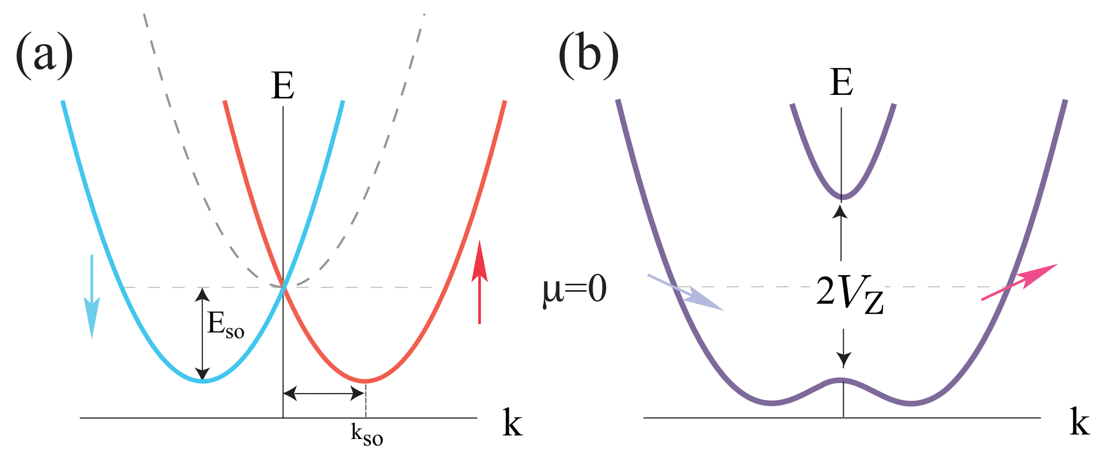


Y. Oreg *et al.* and R. Lutchyn *et al.* *Phys. Rev. Lett.* **105** (2010)

1D (idealised) model for the hybrid wire

$V_Z = g\mu_B B/2$

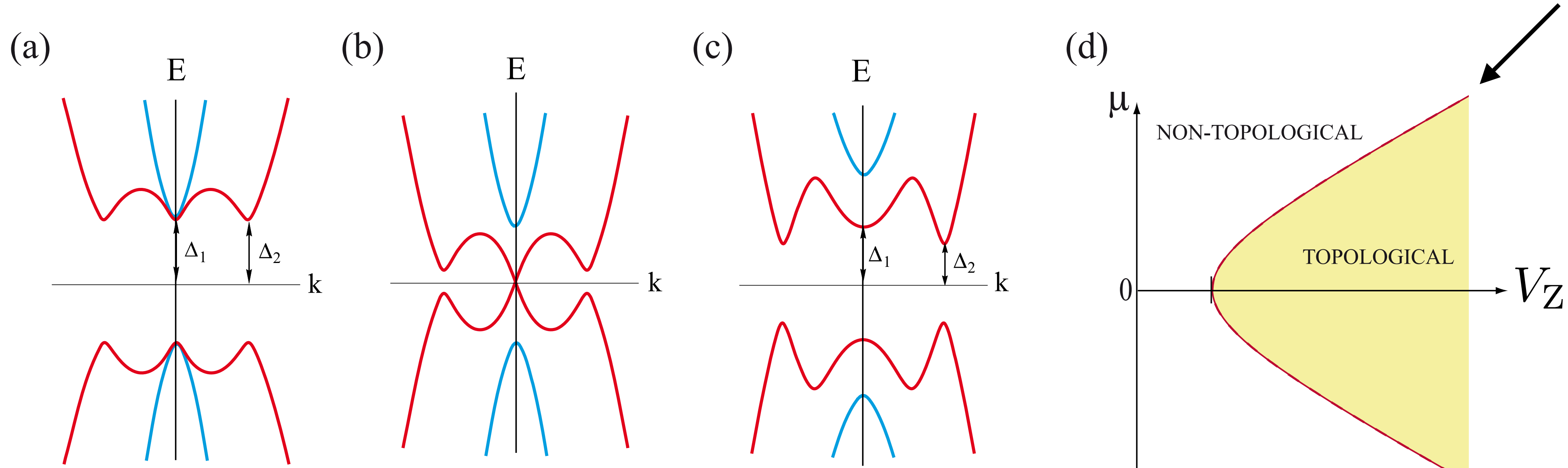
$$H_0 = \int dx\ \psi^\dagger(x)\left[\frac{-\partial_x^2}{2m} - i\alpha_{so}\sigma_y\partial_x + V_Z\sigma_x + U(x) - \mu\right]\psi(x)$$



Helical region

$$H_{pairing} = \int dx\ \psi^\dagger(x) i\Delta(x)\sigma_y\psi^\dagger(x) + \text{h.c}$$

$V_{Z_c} = \sqrt{\Delta^2 + \mu^2}$



Y. Oreg *et al.* and Lutchyn *et al.* *Phys. Rev. Lett.* ***105*** *(2010)* R. Aguado *Rivista del Nuovo Cimento* ***40*** *(2017)*

Nanowires beyond the minimal model

- 3D wires with multiple transverse subbands
- Band bending and inhomogeneous charge density distribution across the wire section
- Effects of electrostatic environment
- Partial proximity effect
- Renormalized g-factors and SO couplings, metallization by the parent SC
- Orbital effects of B
- Smooth density/pairing inhomogeneities along the wire
- Disorder
- QD physics...

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Nat. Rev. Phys. 2, 575 (2020)

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REVIEWS

Check for updates

From Andreev to Majorana bound states in hybrid superconductor–semiconductor nanowires

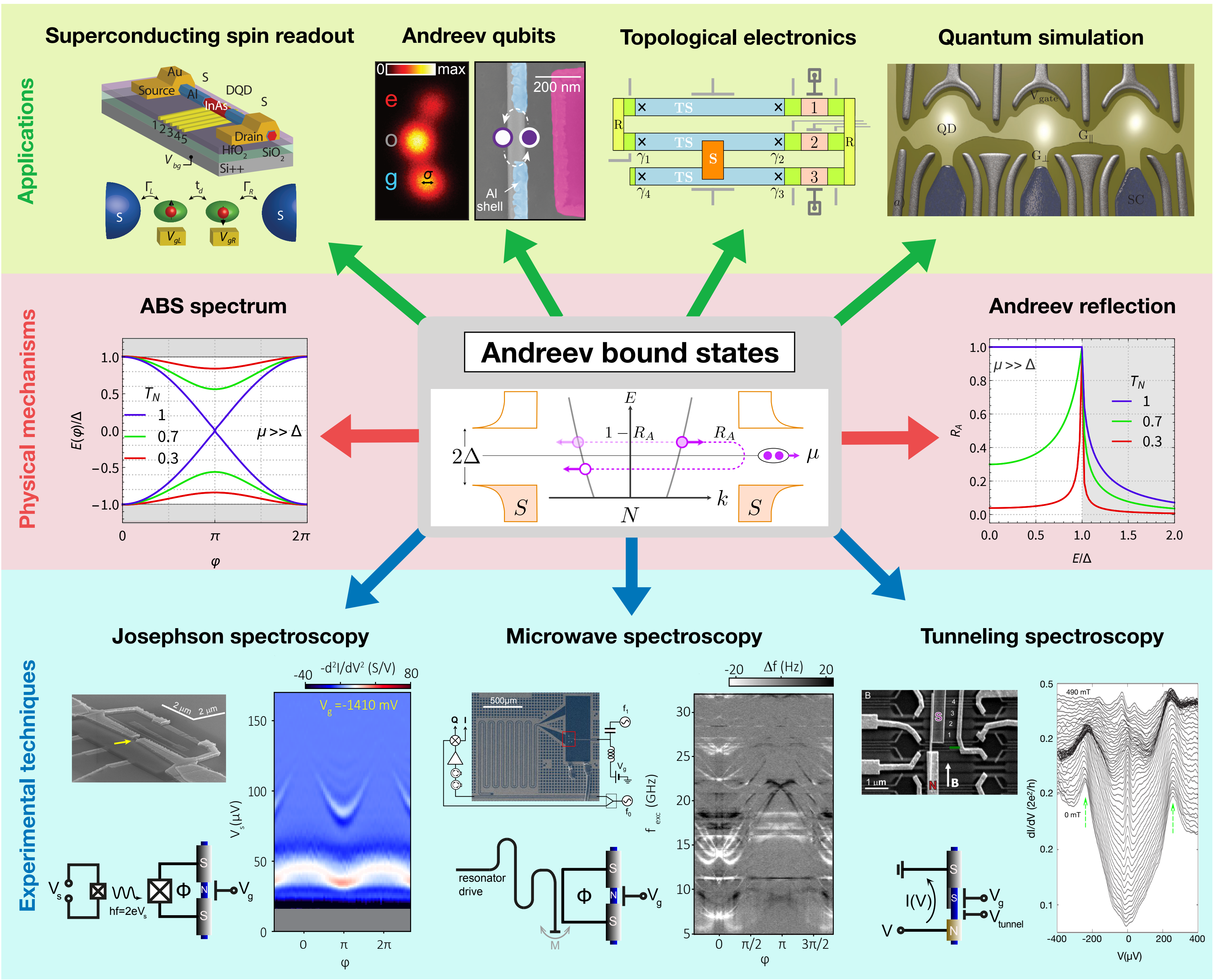
Elsa Prada[1] ✉, Pablo San-Jose[2], Michiel W. A. de Moor[3], Attila Geresdi[3], Eduardo J. H. Lee[1], Jelena Klinovaja[4], Daniel Loss[4], Jesper Nygård[5], Ramón Aguado[2] and Leo P. Kouwenhoven[3,6]

Abstract | Inhomogeneous superconductors can host electronic excitations, known as Andreev bound states (ABSs), below the superconducting energy gap. With the advent of topological superconductivity, a new kind of zero-energy ABS with exotic qualities, known as a Majorana bound state (MBS), has been discovered. A special property of MBS wavefunctions is their non-locality, which, together with non-Abelian braiding, is the key to their promise in topological quantum computation. We focus on hybrid superconductor–semiconductor nanowires as a flexible and promising experimental platform to realize one-dimensional topological superconductivity and MBSs. We review the main properties of ABSs and MBSs, state-of-the-art techniques for their detection and theoretical progress beyond minimal models, including different types of robust zero modes that may emerge without a band-topological transition.

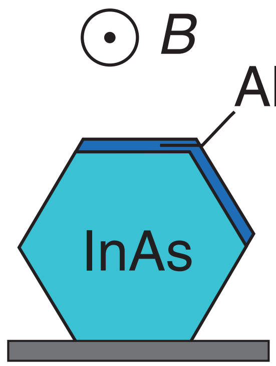
Nat. Rev. Phys. 2, 575 (2020)

From Andreev to Majorana bound states in hybrid superconductor-semiconductor nanowires

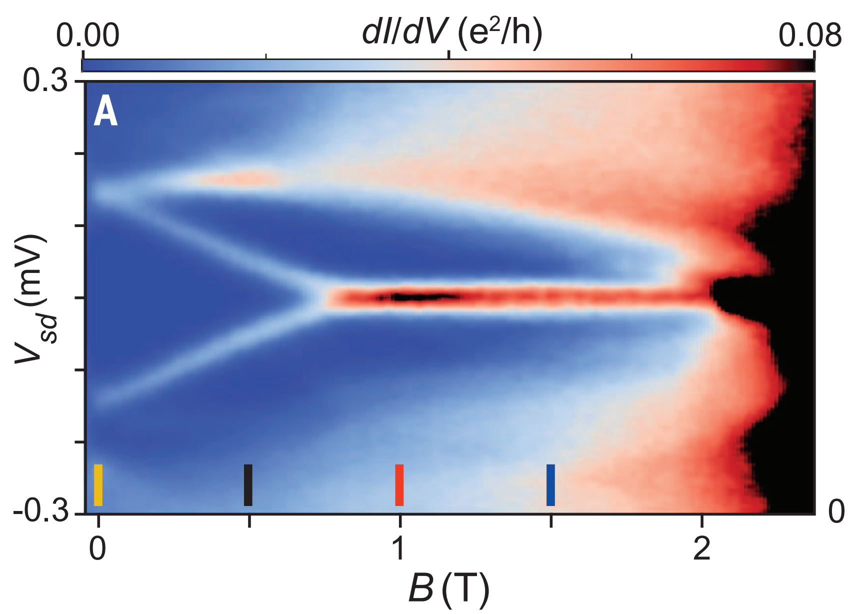
Elsa Prada[1], Pablo San-Jose[2], Michiel W. A. de Moor[3], Attila Geresdi[3], Eduardo J. H. Lee[1], Jelena Klinovaja[4], Daniel Loss[4], Jesper Nygård[5], Ramón Aguado[2], Leo P. Kouwenhoven[3,6]



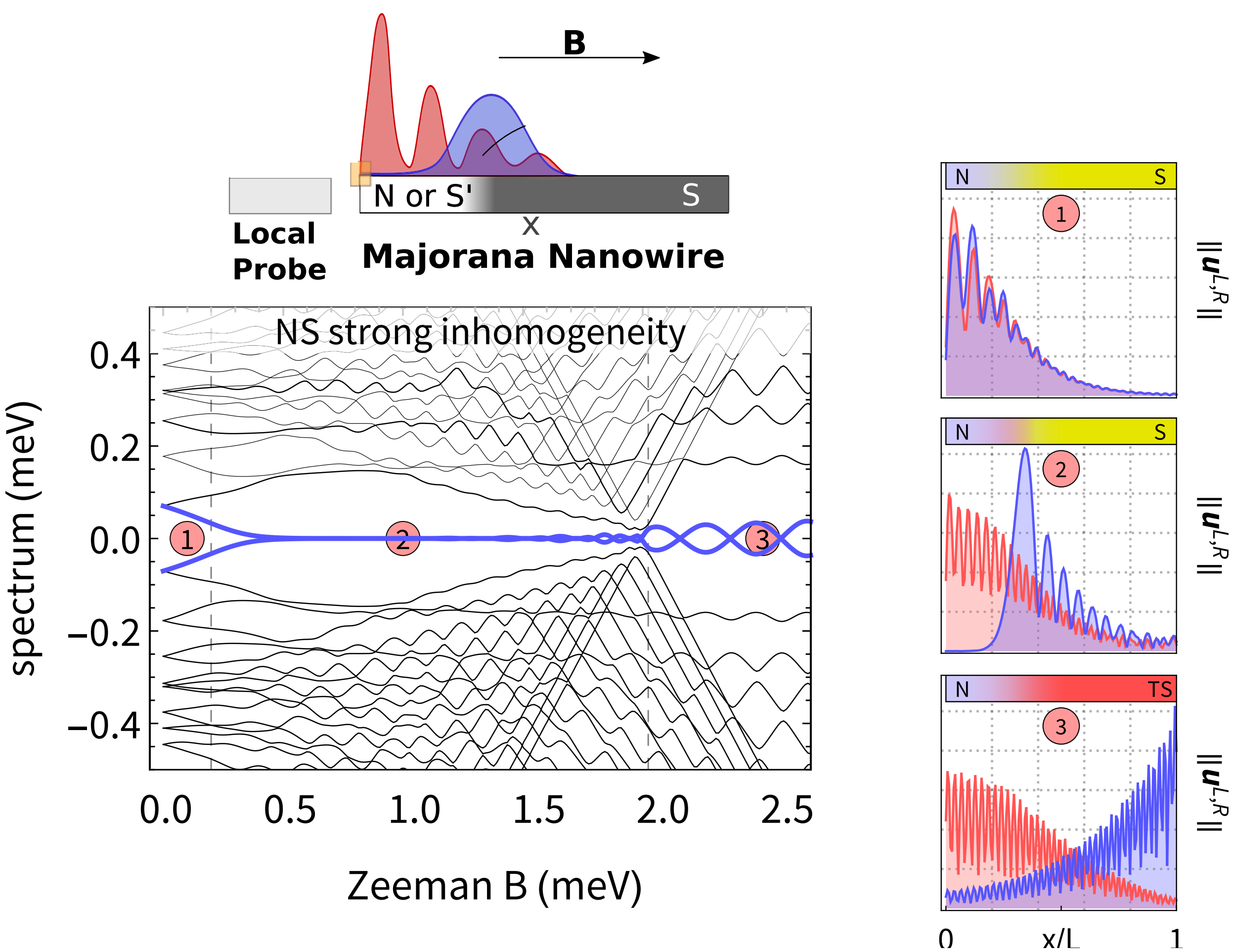
One of the problems of partial-shell nanowires is...



The need to apply **large magnetic fields** to drive the wire into the topological regime



Deng, Vaitiekėnas, Hansen, Danon, Leijnse, Flensberg, Nygård, Krogstrup, and Marcus
Science **354,** 1557 (2016)

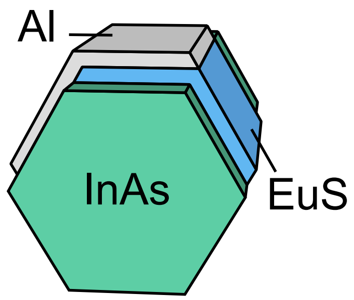


Peñaranda, Aguado, San-Jose and Prada
Phys. Rev. B **98**, 235406 (2018)

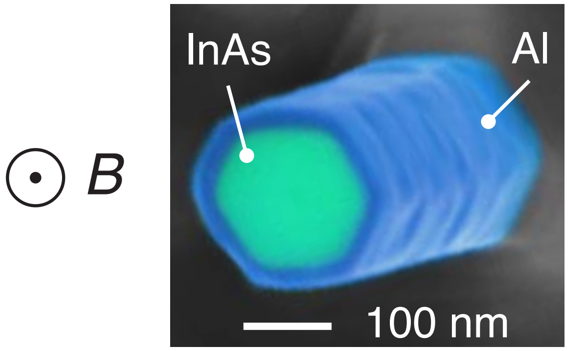
In this talk...

Alternative hybrid nanowire designs

with no or small applied magnetic field



- Ferromagnetic hybrid nanowires



- Full-shell hybrid nanowires

Superconductor-ferromagnet-semiconductor nanowires

nature physics

LETTERS

https://doi.org/10.1038/s41567-020-1017-3

Check for updates

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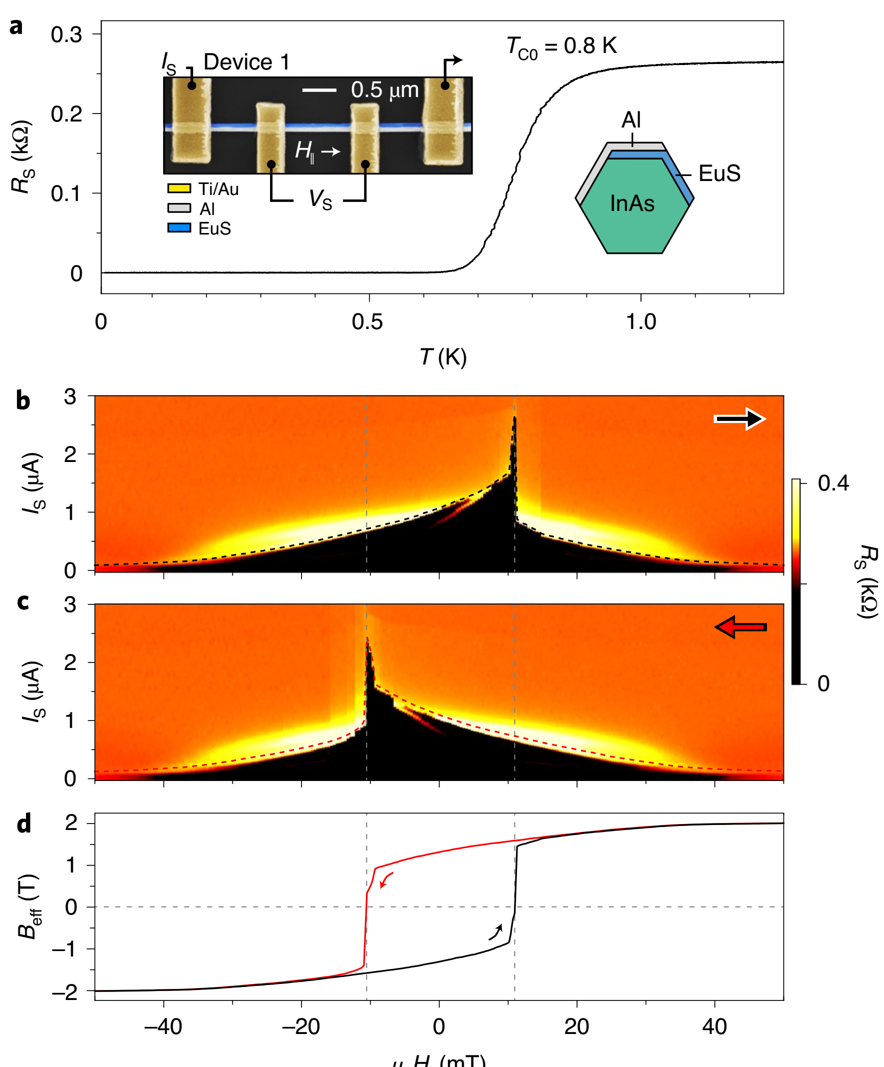
Published online: 07 September 2020

Zero-bias peaks at zero magnetic field in ferromagnetic hybrid nanowires

S. Vaitiekėnas[1,2], Y. Liu[1,3], P. Krogstrup[1,3] and C. M. Marcus[1,2]

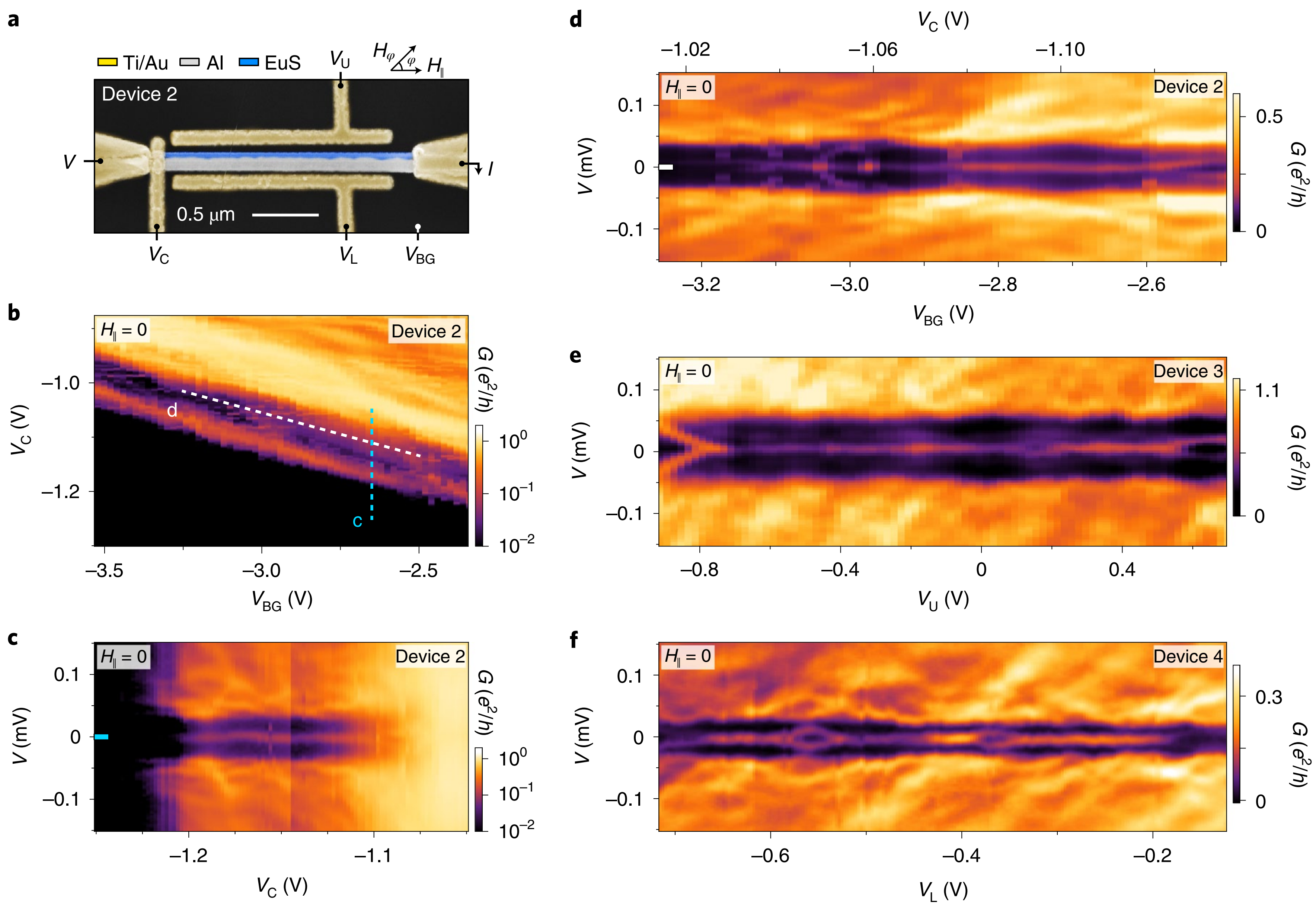
Al/EuS shell characteristics

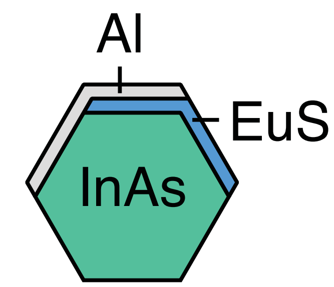


- InAs nanowires grown using molecular beam epitaxy with epitaxial EuS on two facets and Al on two either partly overlapping or adjacent facets.
- Reduced T_C and hysteretic behaviour consistent with an exchange coupling between Al and EuS, which becomes magnetized along the wire axis
- Ferromagnetic exchange coupling results from spin-dependent scattering at the Al-EuS interface
- Effective Zeeman field exceeding 1 T
- Stray magnetic fields are estimated to be smaller than 1 mT

Superconductor-ferromagnet-semiconductor nanowires

Bias spectroscopy at zero magnetic field





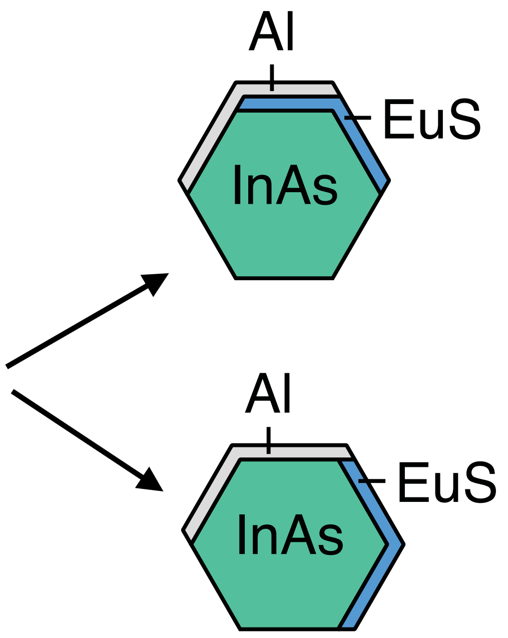
- In overlapping devices, stable zero-bias conductance peaks in bias spectroscopy at zero applied field, "consistent with topological superconductivity".

Vaitiekėnas et al., Nat. Phys. 17, 43 (2021)

Superconductor-ferromagnet-semiconductor nanowires

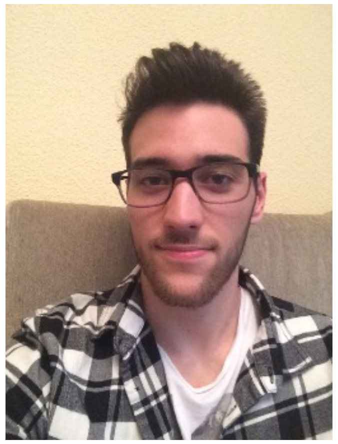
Open questions:

- Is a topological phase possible in actual devices?
  Simplified model in Sau et al., Phys. Rev. Lett. 104, 040502 (2010)
- Why is there a dramatic difference between overlapping and non-overlapping devices? (Only ZBPs in the former).



- What is the exact mechanism of induced magnetization in the InAs wire? (Direct/indirect exchange coupling)

Superconductor-ferromagnet-semiconductor nanowires



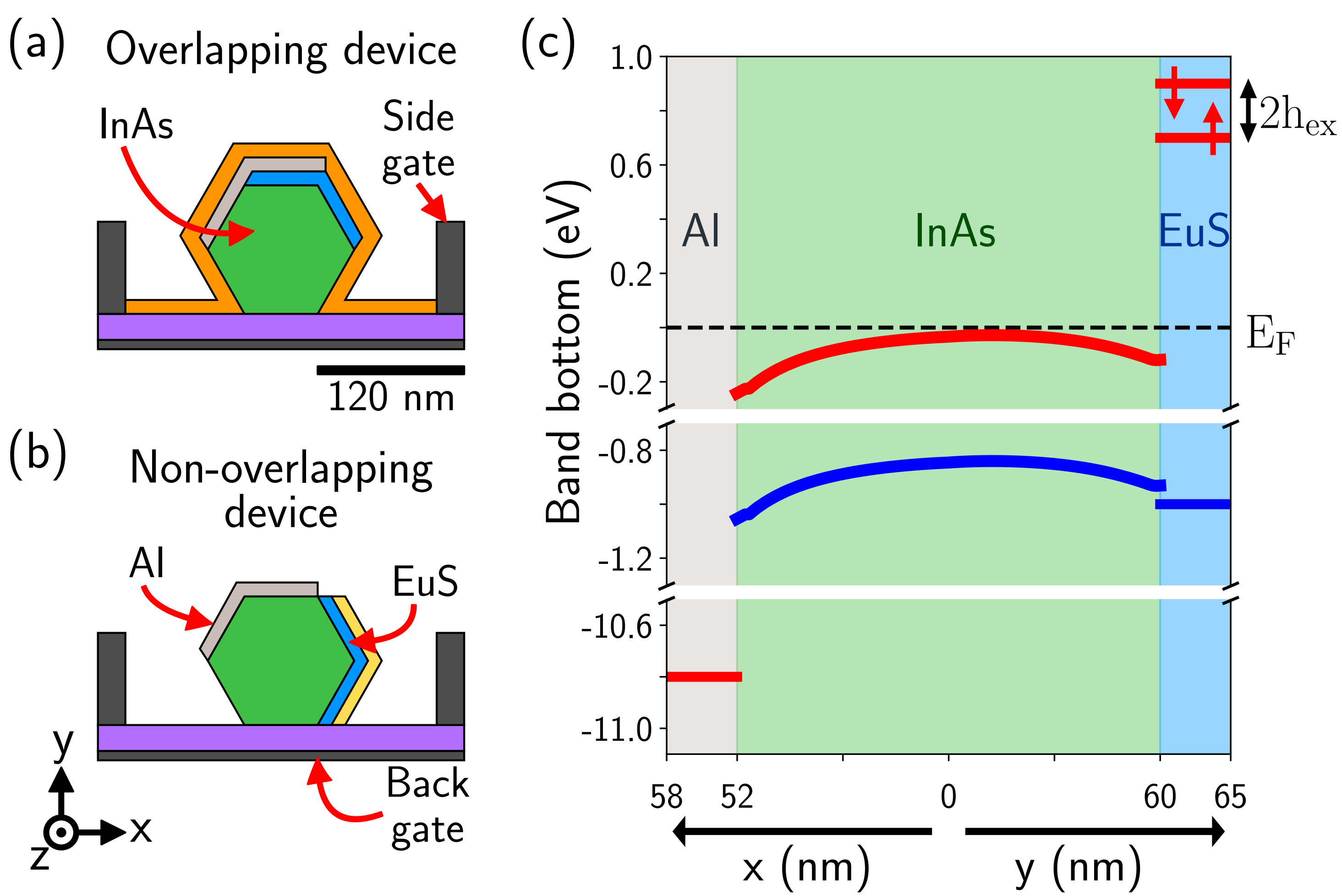
Tunable proximity effects and topological superconductivity in ferromagnetic hybrid nanowires

Samuel D. Escribano,[1] Elsa Prada,[2] Yuval Oreg,[3] and Alfredo Levy Yeyati[1]

[1] *Departamento de Física Teórica de la Materia Condensada C5, Condensed Matter Physics Center (IFIMAC) and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*

[2] *Instituto de Ciencia de Materiales de Madrid (ICMM), Consejo Superior de Investigaciones Científicas (CSIC), E-28049 Madrid, Spain*

[3] *Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, Israel 7610*



- Microscopic numerical simulations of 3D realistic devices.
- Interaction with the electrostatic environment by solving the Schrödinger-Poisson equations self-consistently.
- $h_{ex} \sim \pm 100$meV

Escribano et al., arXiv:2011.06566

Superconductor-ferromagnet-semiconductor nanowires

Continuous full model Hamiltonian:

$$H = \left[\vec{k}\frac{\hbar^2}{2m_{\rm eff}(\vec{r})}\vec{k} - E_{\rm F}(\vec{r}) + e\phi(\vec{r}) + h_{\rm ex}(\vec{r})\sigma_z\right]\tau_z + \frac{1}{2}\left[\vec{\alpha}(\vec{r})\cdot\left(\vec{\sigma}\times\vec{k}\right) + \left(\vec{\sigma}\times\vec{k}\right)\cdot\vec{\alpha}(\vec{r})\right]\tau_z + \Delta(\vec{r})\sigma_y\tau_y$$

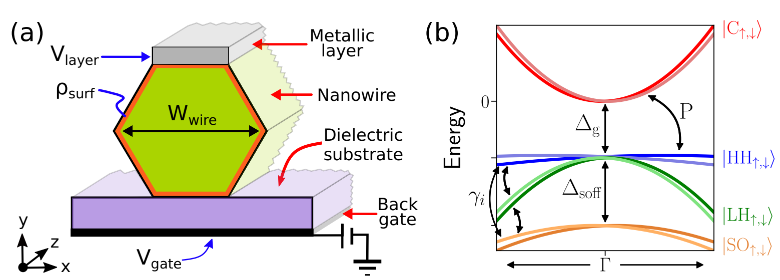
$$\vec{r} = (x, y),\ \vec{k} = (-i\vec{\nabla}_r, k_z)$$

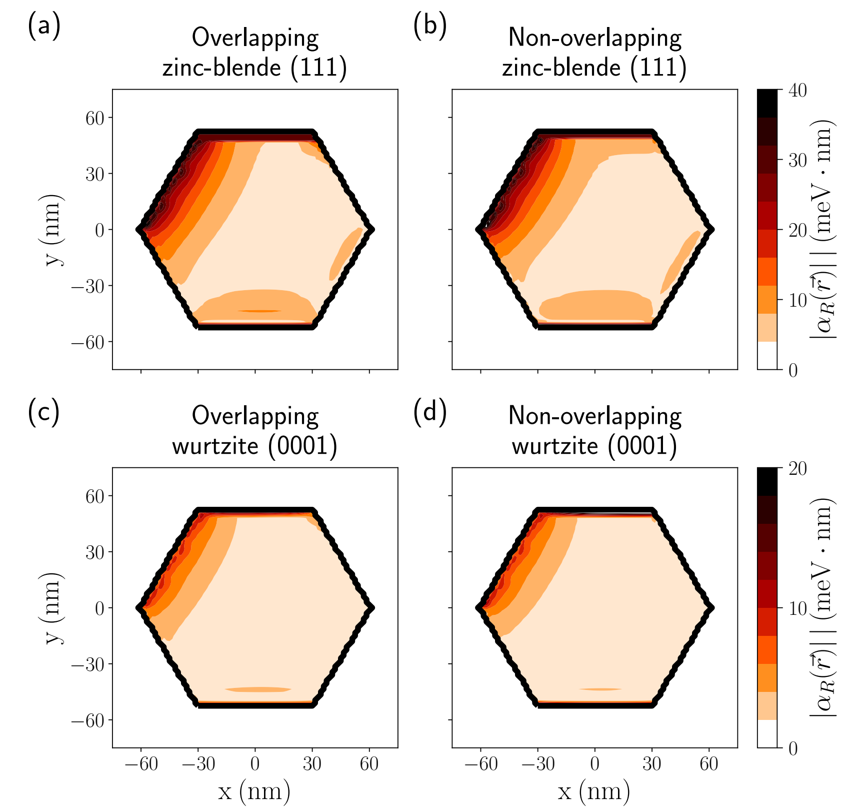
Realistic SOC in nanowires

PHYSICAL REVIEW RESEARCH **2**, 033264 (2020)

Improved effective equation for the Rashba spin-orbit coupling in semiconductor nanowires

Samuel D. Escribano[1,3] Alfredo Levy Yeyati[2,3] and Elsa Prada[1,3,*]



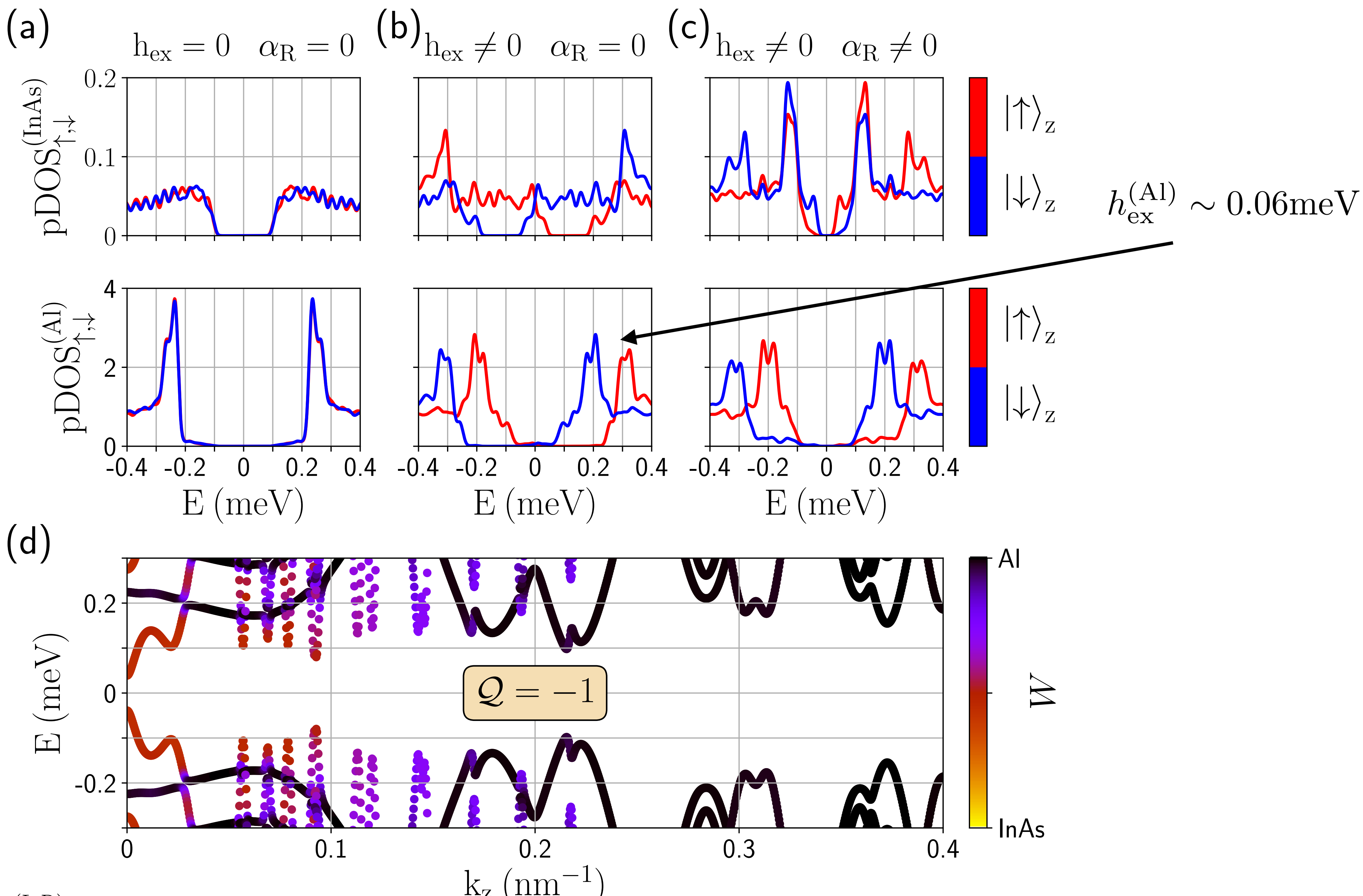


Escribano et al., arXiv:2011.06566

Superconductor-ferromagnet-semiconductor nanowires

Full model results:

Overlapping device

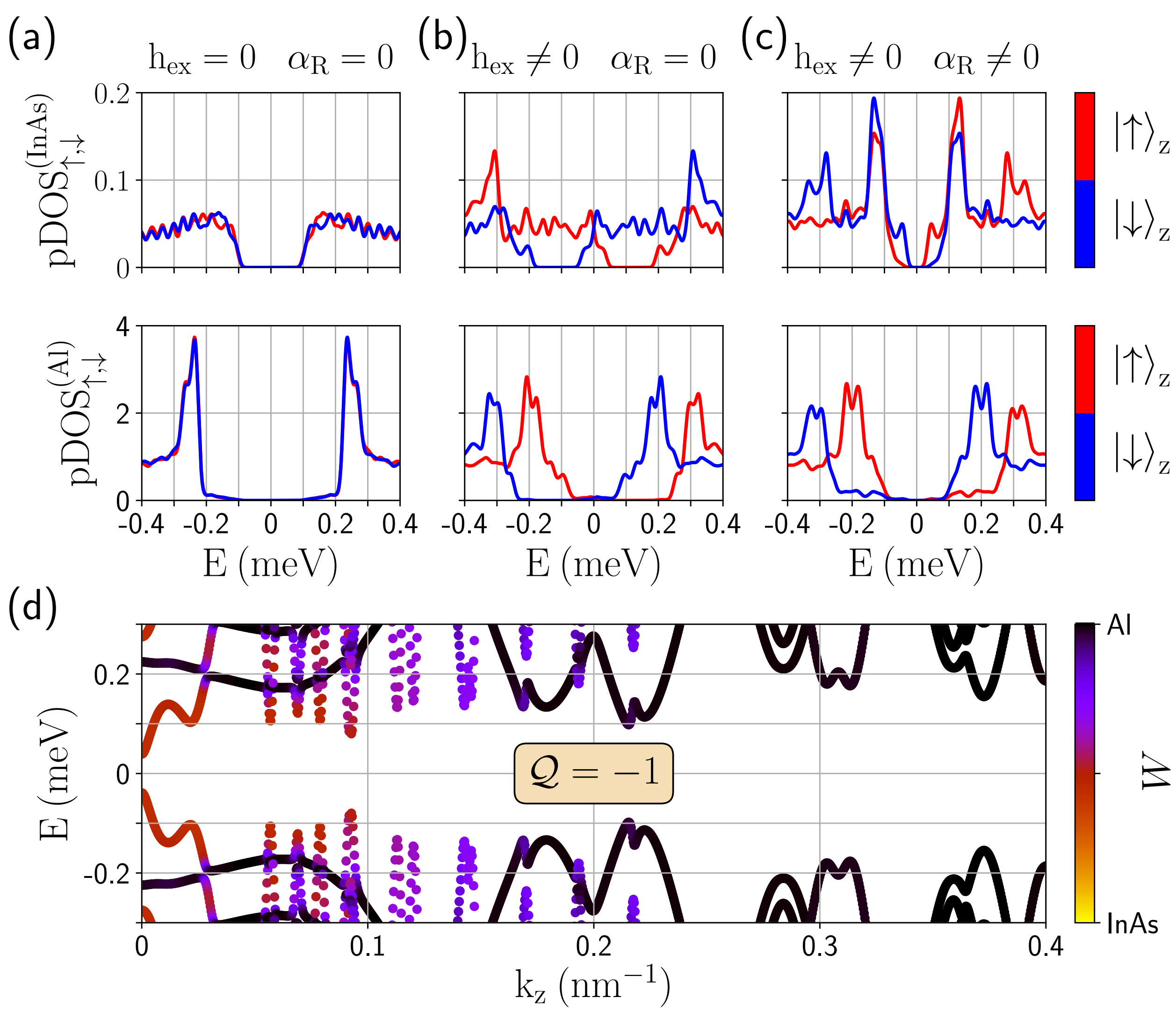


$V_{bg} = -0.95V \qquad V_{sg}^{(L,R)} = 0$

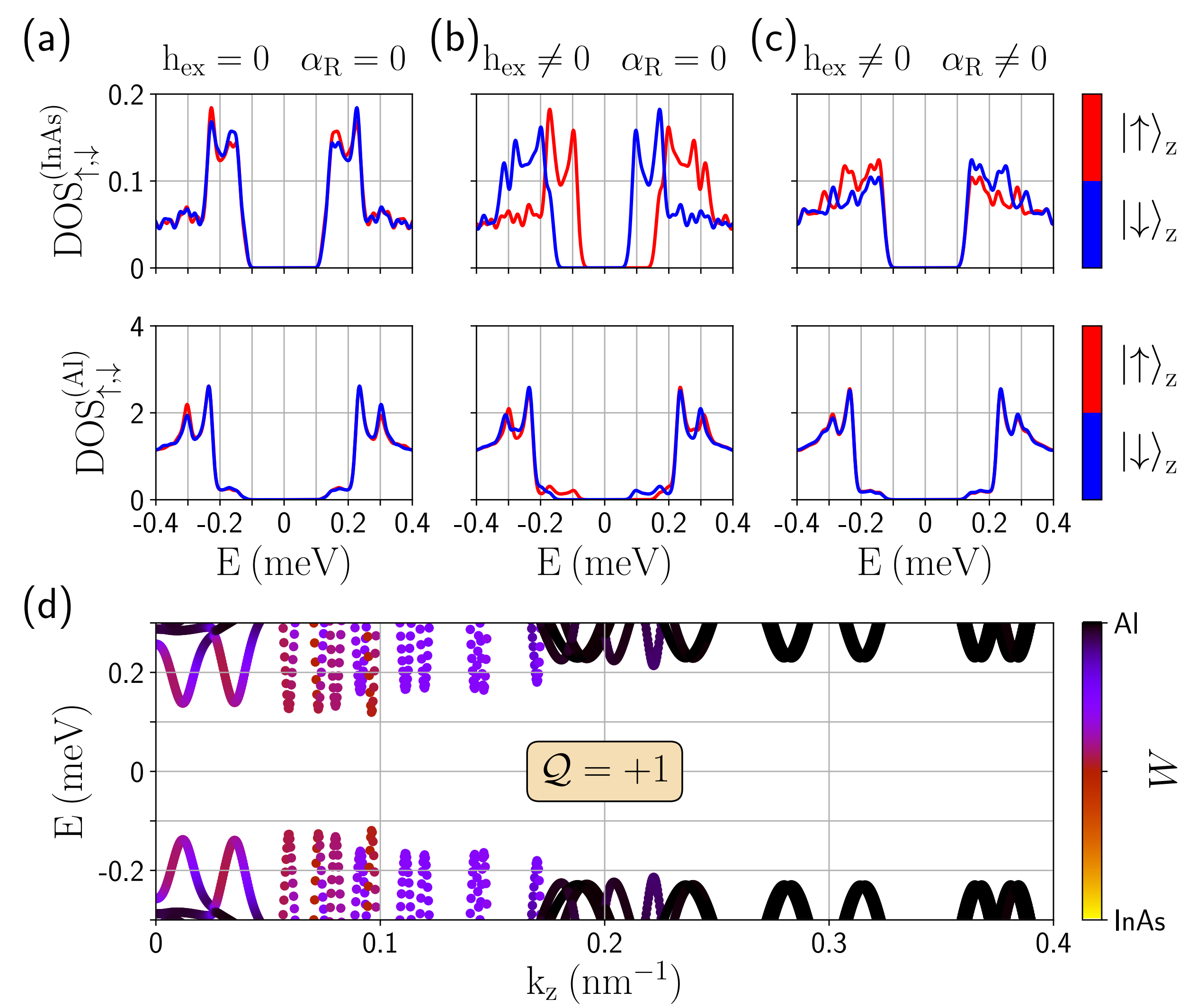
Escribano et al., arXiv:2011.06566

Superconductor-ferromagnet-semiconductor nanowires

Overlapping device



Non-overlapping device

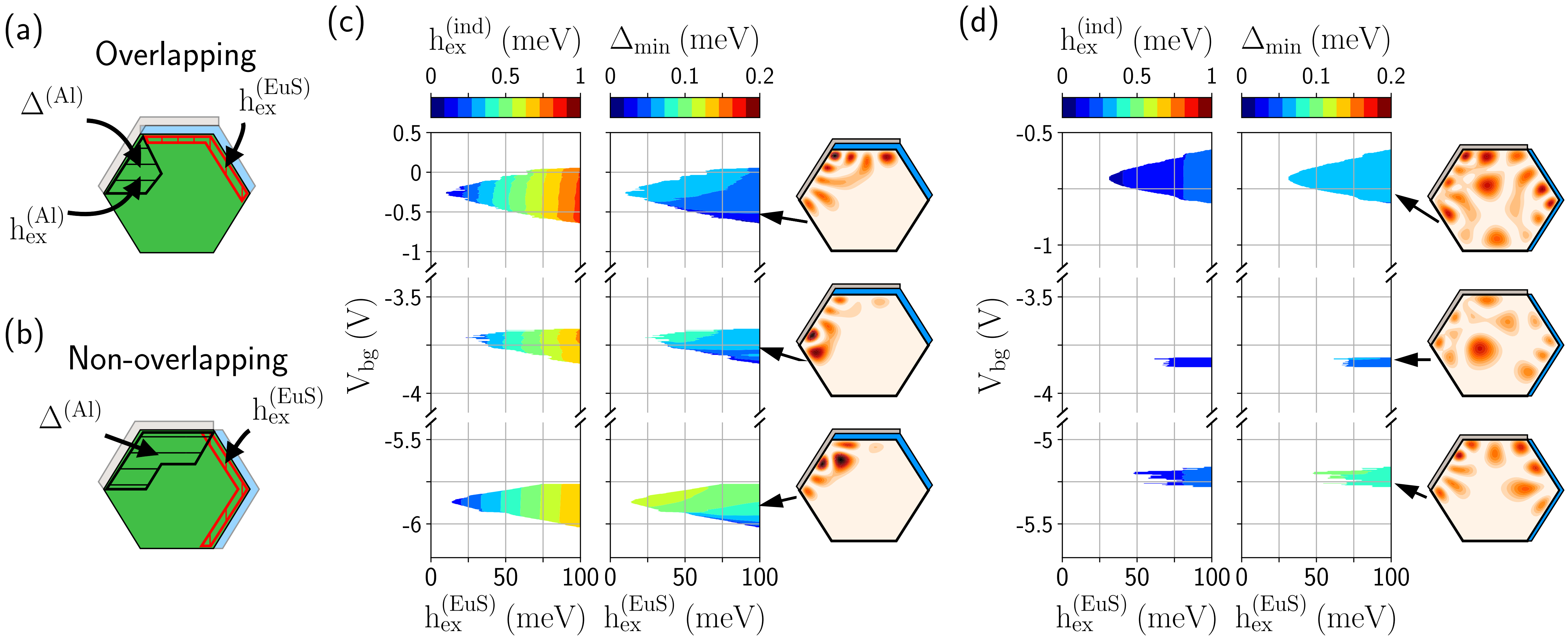


Escribano et al., arXiv:2011.06566

Superconductor-ferromagnet-semiconductor nanowires

Efective model results:

Phase diagrams and wave function distribution



$$\Delta^{(Al)} = 0.23\text{meV}$$
$$h_{ex}^{(EuS)} = 100\text{meV}$$
$$h_{ex}^{(Al)} = 0.06\text{meV}$$

Escribano et al., arXiv:2011.06566

Superconductor-ferromagnet-semiconductor nanowires

Conclusions

- From calculations of the DOS, band structure, topological invariant and the phase diagram, we conclude that the hybrid InAs/Al/EuS nanowires can exhibit topological superconductivity under certain geometrical and gating conditions.
- For a topological phase to exist, the nanowire wavefunction must acquire both superconducting and magnetic correlations such that the induced exchange field exceeds the induced pairing.
- Since the proximity effects occur only in wire cross-section regions close to the Al and EuS layers, the wavefunction needs to be pushed simultaneously close to both materials by means of nearby gates.
- Our numerical simulations demonstrate that this is electrostatically favorable in device geometries where the Al and EuS shells overlap over some wire facet.
- Apart from a direct magnetization from the EuS layer in contact to the wire, there is an indirect one through the Al layer, which favors reaching the topological condition.

Escribano et al., arXiv:2011.06566

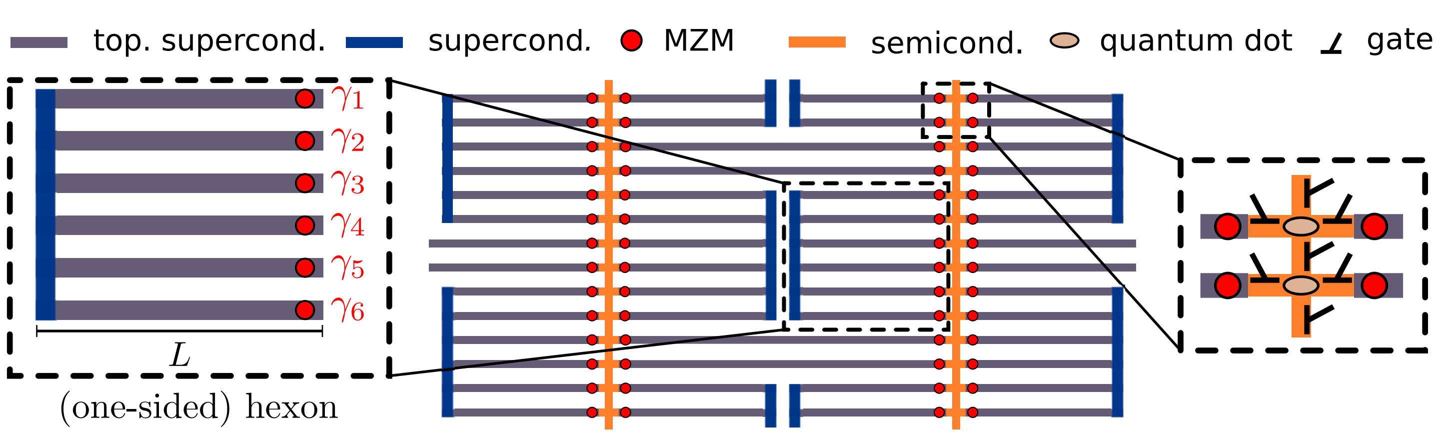
Concurrently...

- 22/Sep/2020: Sam presents our (basically finished) work in the CMD2020GEFES virtual conference: https://youtu.be/vmSYmj_vqk8?t=2669
- 03/Nov/2020: ***Electrostatic effects and topological superconductivity in semiconductor-superconductor-magnetic insulator hybrid wires*** by Benjamin D. Woods and Tudor D. Stanescu
- 12/Nov/2020: ***Microscopic analysis of topological superconductivity in ferromagnetic hybrid nanowires*** by Samuel D. Escribano, Elsa Prada, Yuval Oreg, and Alfredo Levy Yeyati
- 12/Nov/2020: ***Electronic properties of InAs/EuS/Al hybrid nanowires*** by Chun-Xiao Liu, Sergej Schuwalow, Yu Liu, Kostas Vilkelis, A. L. R. Manesco, P. Krogstrup, and Michael Wimmer
- 12/Nov/2020: ***Topological superconductivity in semiconductor-superconductor-magnetic insulator heterostructures*** by A. Maiani, R. Seoane Souto, M. Leijnse, and K. Flensberg
- 12/Nov/2020: ***Topological superconductivity in tripartite superconductor-ferromagnet-semiconductor nanowires*** by Josias Langbehn, Sergio Acero González, Piet W. Brouwer, and Felix von Oppen
- 23/Dec/2020: ***Topological superconductivity in nanowires proximate to a diffusive superconductor-magnetic insulator bilayer*** by Aleksei Khindanov, Jason Alicea, Patrick Lee, William S. Cole, and Andrey E. Antipov

Superconductor-ferromagnet-semiconductor nanowires

Advantages of this new design:

- No need to apply external magnetic field; magnetic fields are detrimental for superconductivity, constrain device materials and operation
- No detrimental orbital effects (just Zeeman-type exchange coupling)
- Facilitates device layout in multiwire setups, e.g. not constrained to parallel wires



Karzig et al., PRB 95, 235305 (2017)

Vaitiekėnas et al., Nat. Phys. 17, 43 (2021)

Superconductor-ferromagnet-semiconductor nanowires

Drawbacks

- Need to grow tripartite wires; only some configurations of the epitaxial layers give topology
- Induced Zeeman field is not tunable (topological phase transition only tunable through gates)
- The ferromagnetic insulator may suffer from magnetic domains
- This hybrid system should display similar problems as conventional partial-shell superconductor-semiconductor wires: inhomogeneous potentials → quasi-Majoranas, disorder, QD formation...

Full-shell superconductor-semiconductor nanowires

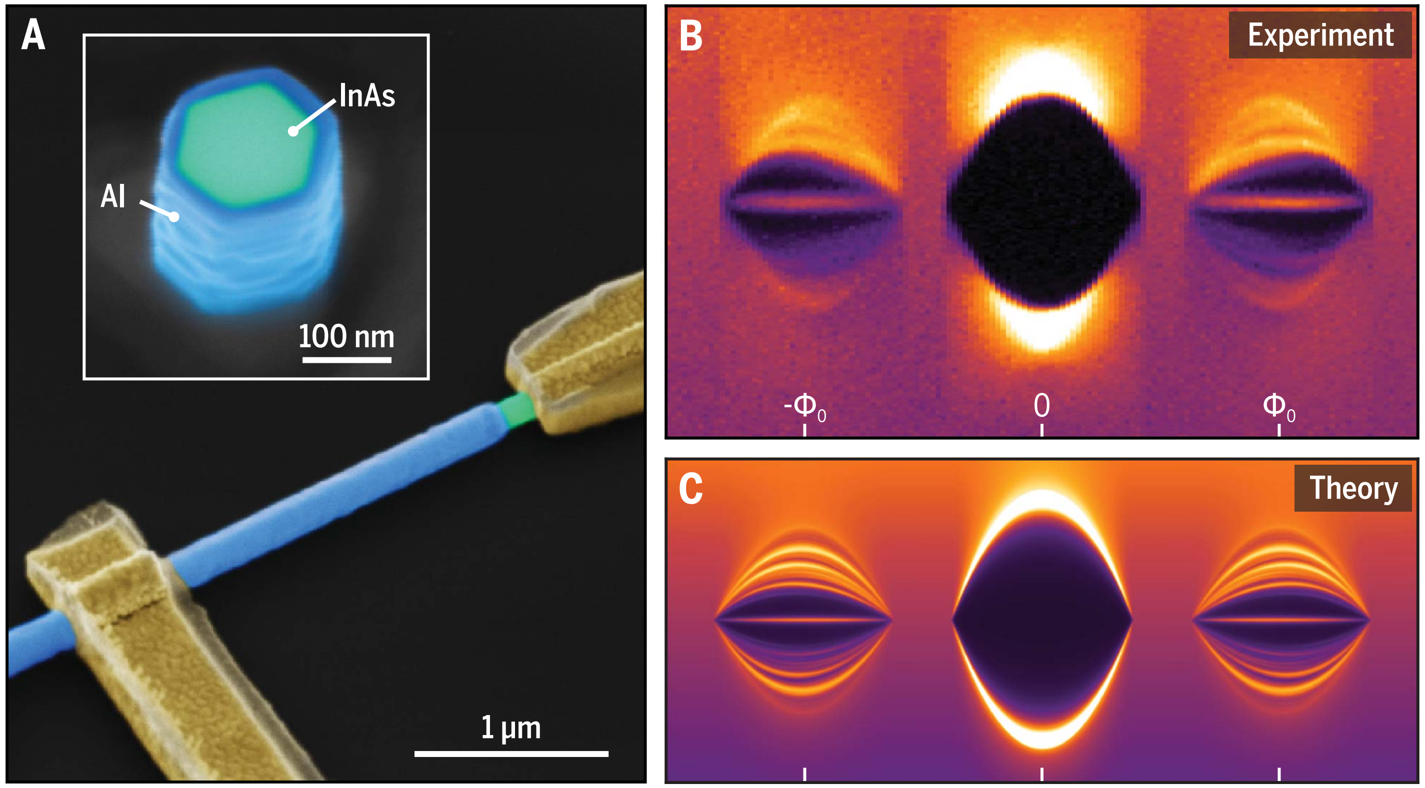
RESEARCH ARTICLE SUMMARY

TOPOLOGICAL MATTER

Vaitiekėnas *et al.*, *Science* **367**, 1442 (2020) 27 March 2020

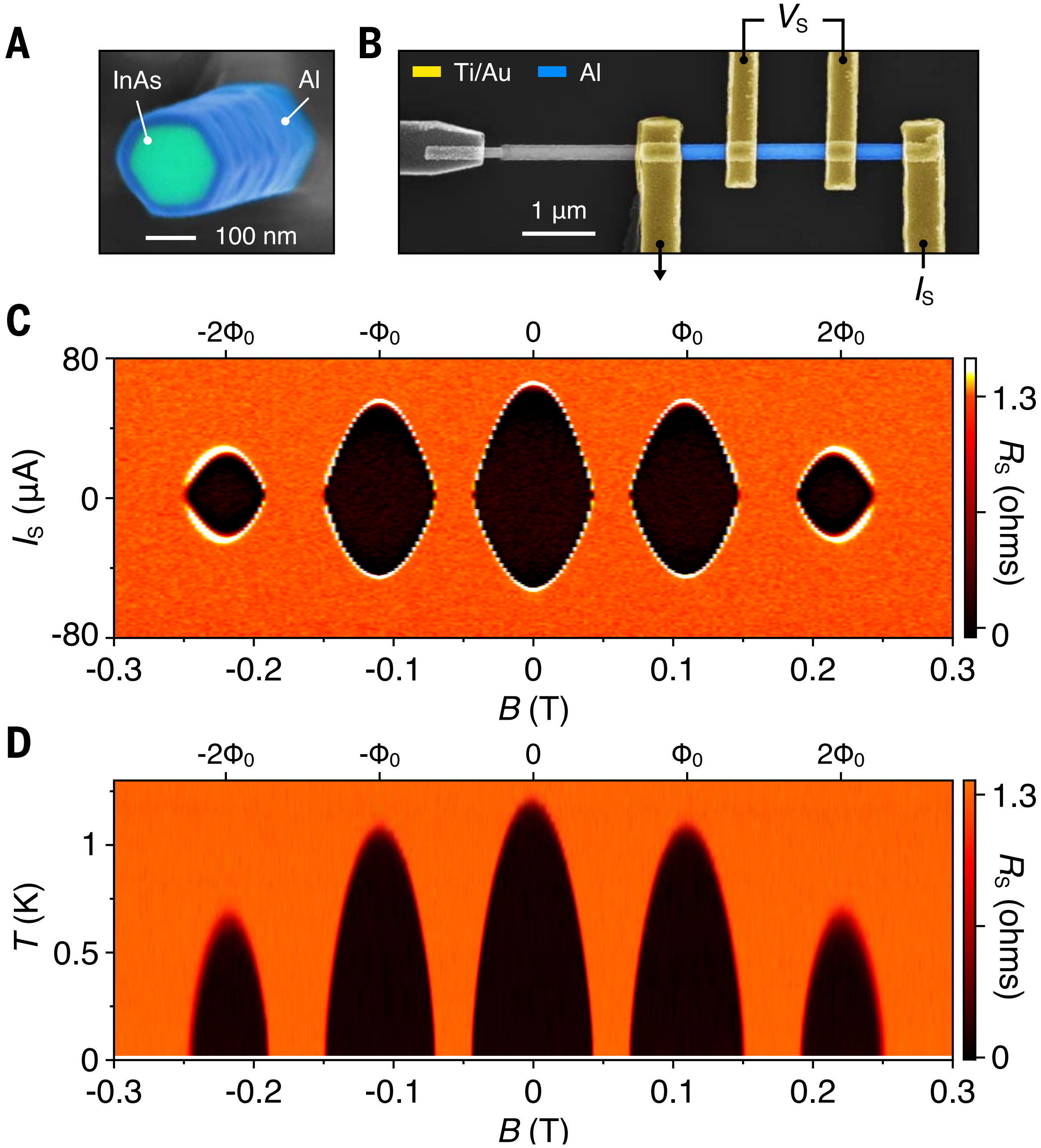
Flux-induced topological superconductivity in full-shell nanowires

S. Vaitiekėnas, G. W. Winkler, B. van Heck, T. Karzig, M.-T. Deng, K. Flensberg, L. I. Glazman, C. Nayak, P. Krogstrup, R. M. Lutchyn*, C. M. Marcus*

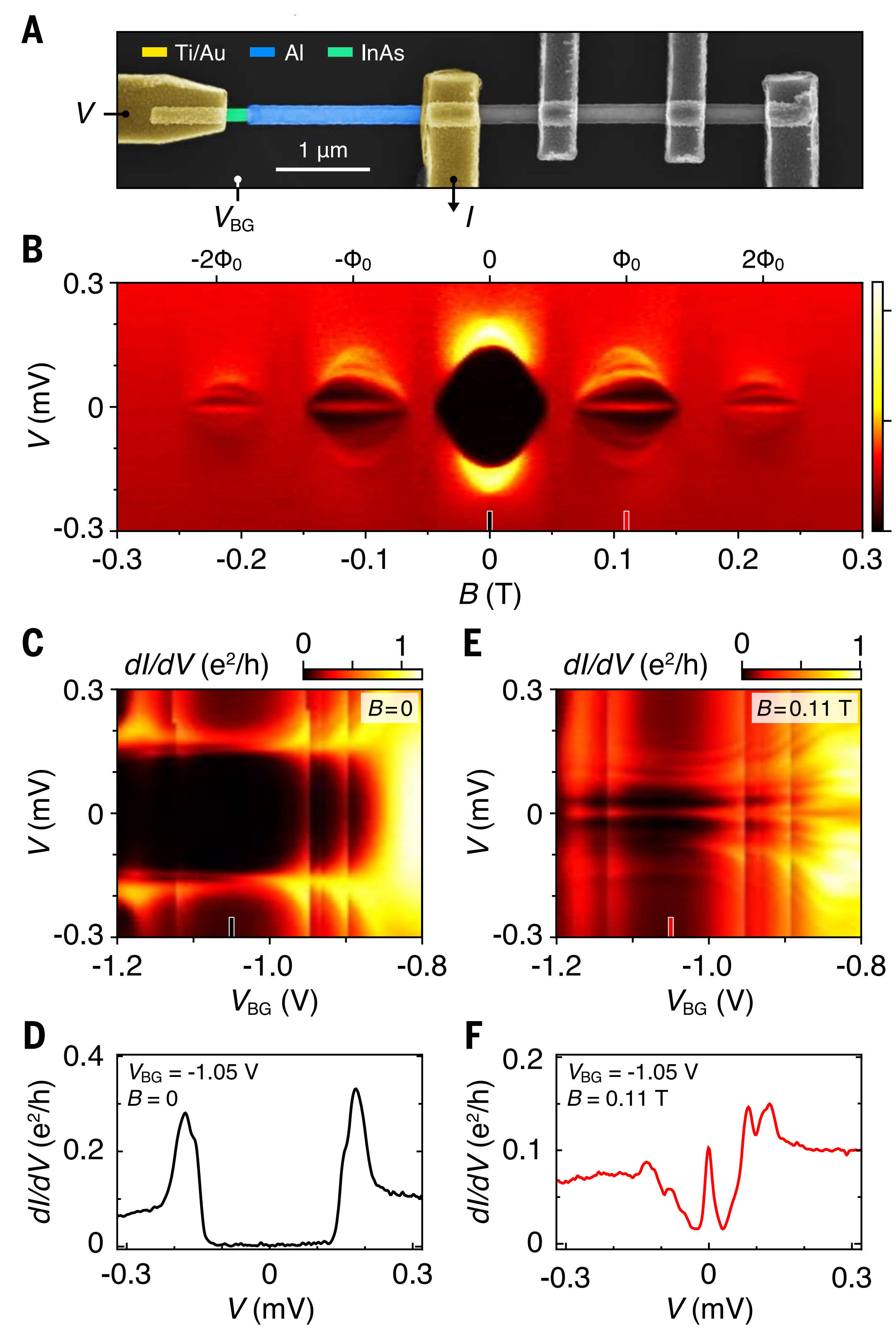


Full-shell superconductor-semiconductor nanowires

Destructive Little-Parks regime



Experimental tunneling spectrum



Vaitiekènas et al., Science 367, 1442 (2020)

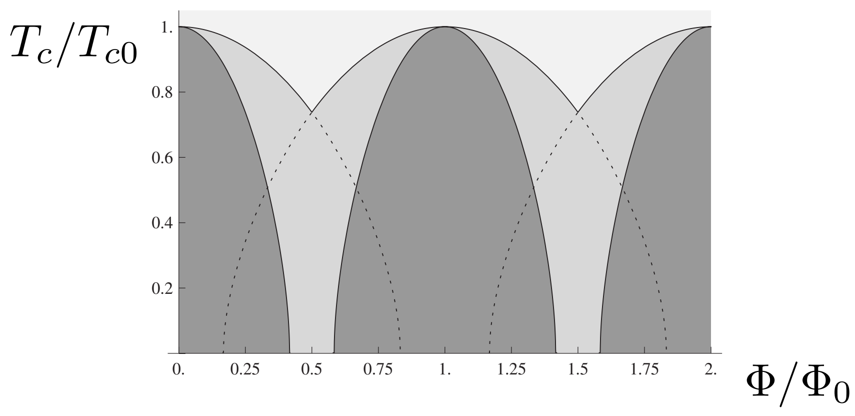
Full-shell superconductor-semiconductor nanowires

The magnetic field induces a **winding** of the superconducting phase of the order parameter:

$$\Delta(\vec{r}) = \Delta(r)e^{-in\varphi}$$

where n = $\lfloor \Phi/\Phi_0 \rceil \in Z$ is the winding number (Φ_0=h/2e) ⟶ **Fluxoid** quantization

The **Little-Parks (LP) effect** arises, whereby the superconducting gap Δ(r) becomes suppressed (even completely in the "destructive" regime) around half-integer flux.



Schwiete, Oreg, PRB 82, 214514 (2010)
Schwiete, Oreg, PRL 103, 037001 (2009)

Weak LP: $R/\xi \gtrsim 1$

Destructive LP: $R/\xi < 0.6$

Full-shell superconductor-semiconductor nanowires

Little-Parks (LP) effect:

G. Schwiete, Y. Oreg, Persistent current in small superconducting rings. *Phys. Rev. Lett.* **103**, 037001 (2009).

$$\ln\left(\frac{T_c(\Phi)}{T_c^0}\right) + \mathcal{D}\left(\frac{1}{2} + \frac{\Lambda_n(\Phi)}{2\pi T_c(\Phi)}\right) - \mathcal{D}\left(\frac{1}{2}\right) = 0$$

$\mathcal{D}$ Digamma function

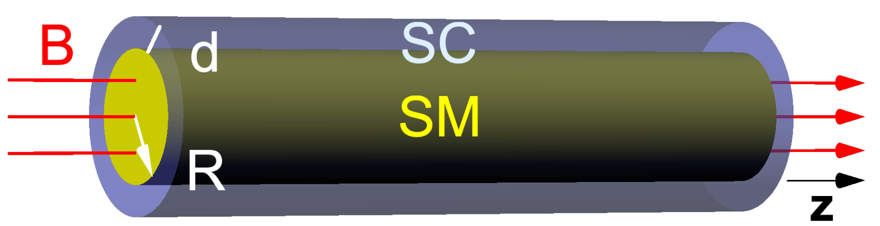
Pair-breaking term derived from the Ginzburg-Landau equations in the presence of impurities

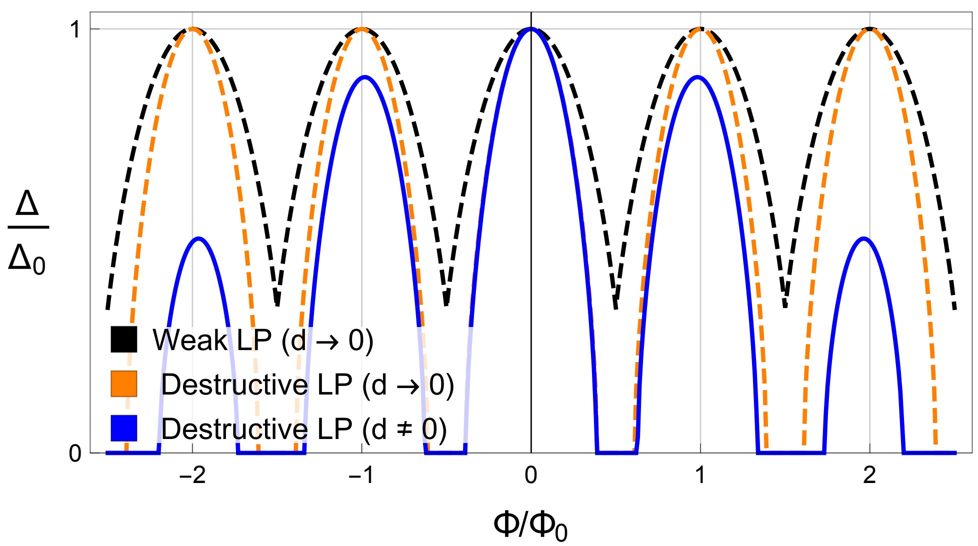
$$\Lambda_n(\Phi) = \frac{T_c^0}{\pi}\frac{\xi^2}{R^2}\left[4\left(n - \frac{\Phi}{\Phi_0}\right)^2 + \frac{d^2}{R^2}\left(\frac{\Phi^2}{\Phi_0^2} + \left(\frac{1}{3} + \frac{d^2}{20R^2}\right)\right)n^2\right]$$

$R/\xi < 0{,}6$

$d \ll R$

$$\frac{|\Delta(\Phi)|}{|\Delta(\Phi = 0)|} = \left(\frac{T_c(\Phi)}{T_c^0}\right)^{3/2}$$





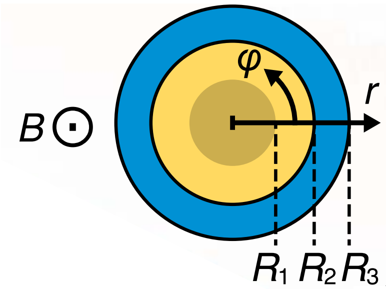
Weak LP: $R/\xi \gtrsim 1$

Destructive LP: $R/\xi < 0.6$

Peñaranda, Aguado, San-Jose and Prada
Phys. Rev. Research **2**, 023171 (2020)

Full-shell superconductor-semiconductor nanowires

3D Hamiltonian in cylindrical coordinates



Effective Hamiltonian for the semiconducting core:

$$H_0 = \frac{(\vec{p} + eA_\varphi \hat{\varphi})^2}{2m^*} - \mu + \alpha \hat{r} \cdot [\vec{\sigma} \times (\vec{p} + eA_\varphi \hat{\varphi})] \qquad A_\varphi = \Phi(r)/2\pi r \qquad \Phi(r) = \pi B r^2$$

$$R_3 - R_2 \ll \lambda_L$$

Bogoliubov–de Gennes (BdG) Hamiltonian for the proximitized nanowire:

$$H_{BdG} = \begin{bmatrix} H_0(\vec{A}) & \Delta(\vec{r}) \\ \Delta^*(\vec{r}) & -\sigma_y H_0(-\vec{A})^* \sigma_y \end{bmatrix}$$

Nambu basis $\Psi = (\psi_\uparrow, \psi_\downarrow, \psi_\downarrow^\dagger, -\psi_\uparrow^\dagger)$

Rotational symmetry of the BdG Hamiltonian: $[J_z, H_{BdG}] = 0$ **m_J: generalized angular quantum number**

Hollow-core toy model $R_1 \approx R_2$

$$\tilde{H}_{m_J} = \left[\frac{p_z^2}{2m^*} - \mu_{m_J}\right]\tau_z + V_Z\sigma_z + A_{m_J} + C_{m_J}\sigma_z\tau_z + \alpha p_z \sigma_y \tau_z + \Delta\tau_x \qquad \Delta \equiv \Delta(R_2)$$

$$V_Z = \phi\left(\frac{1}{4m^* R_2^2} + \frac{\alpha}{2R_2}\right) \qquad \phi = n - \Phi(R_2)/\Phi_0$$

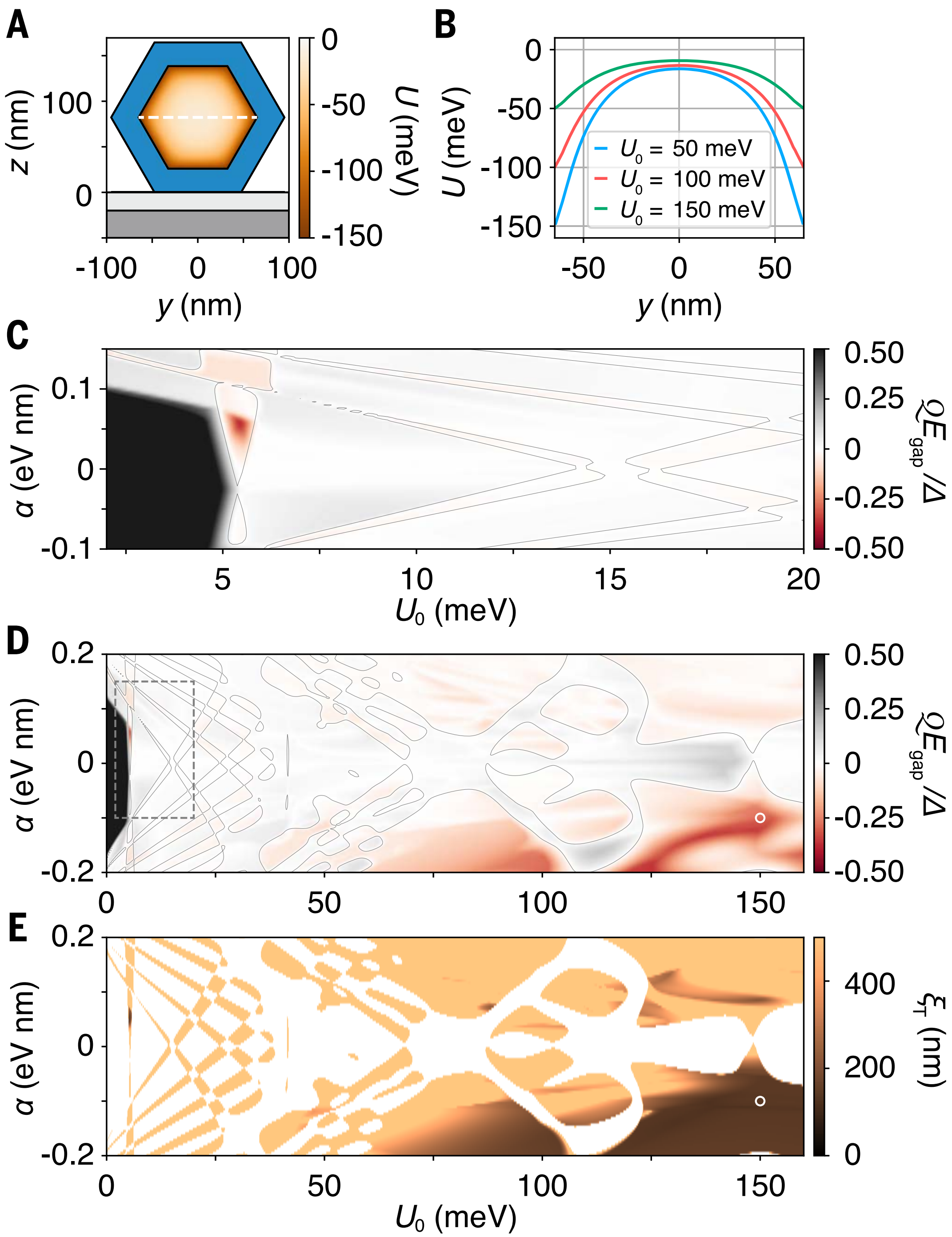
The effective Zeeman term has an orbital origin here and is present even when the g factor in the semiconductor is zero

For m_J =0 in the first lobe (n=1), A_0 and C_0=0, and the Hamiltonian can be **mapped** to the **Oreg-Lutchyn model**

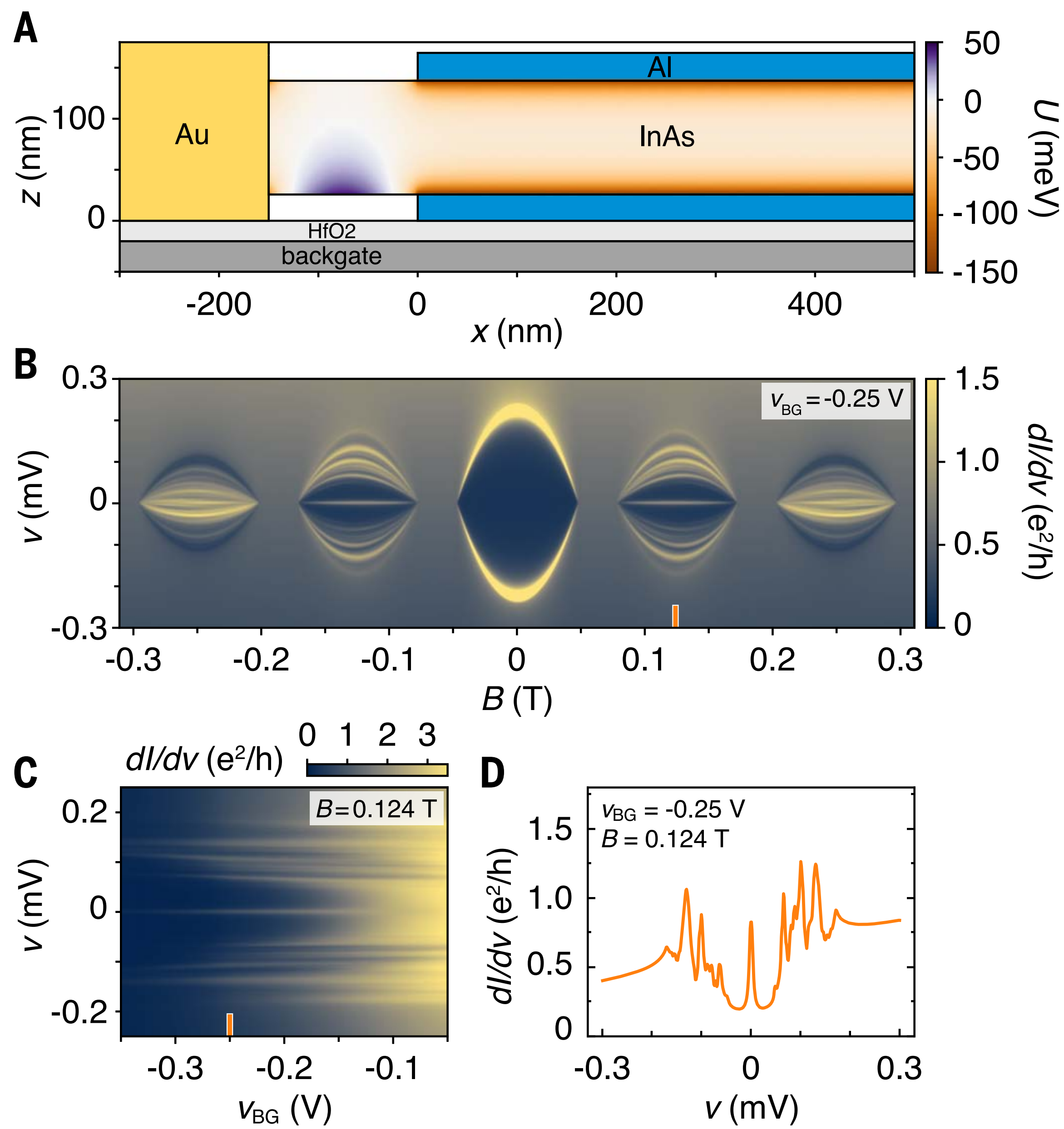
Vaitiekènas et al., Science 367, 1442 (2020)

Full-shell superconductor-semiconductor nanowires

Phase diagram



Simulation of tunneling transport



Vaitiekėnas et al., Science 367, 1442 (2020)

Full-shell superconductor-semiconductor nanowires

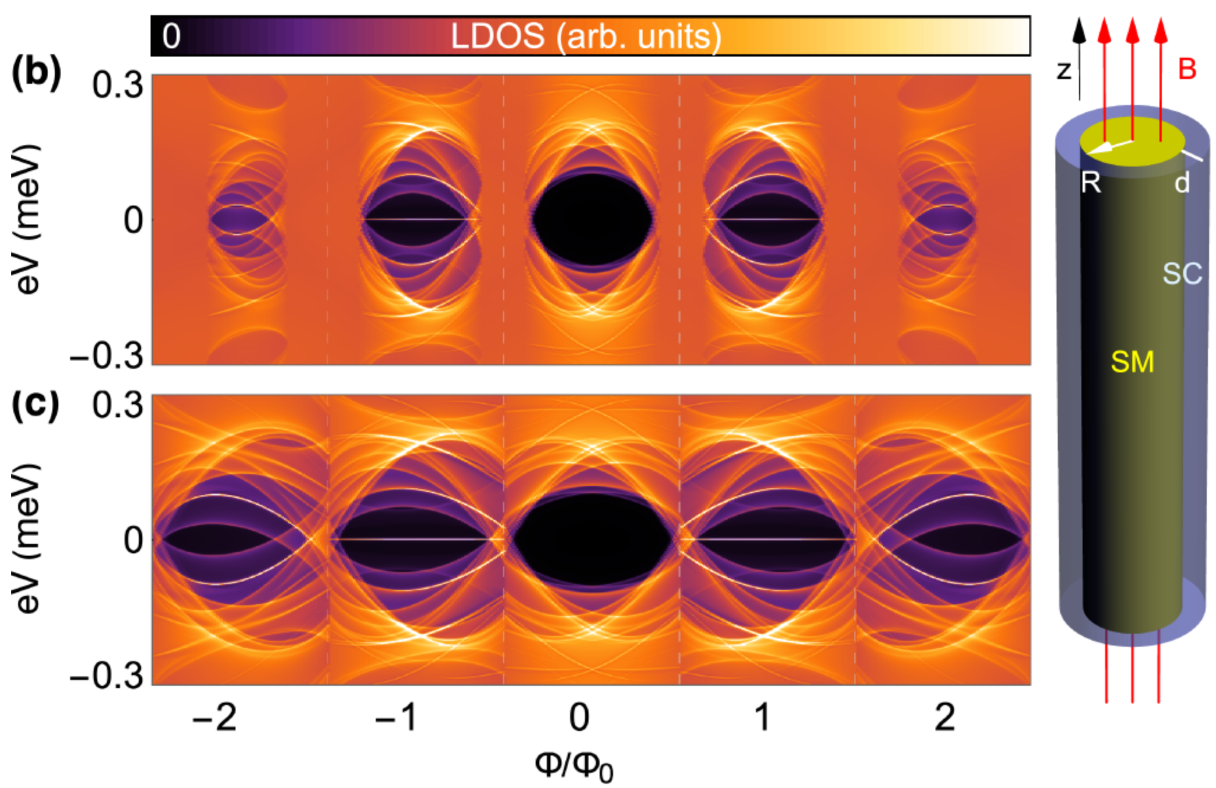
PHYSICAL REVIEW RESEARCH **2**, 023171 (2020)

Even-odd effect and Majorana states in full-shell nanowires

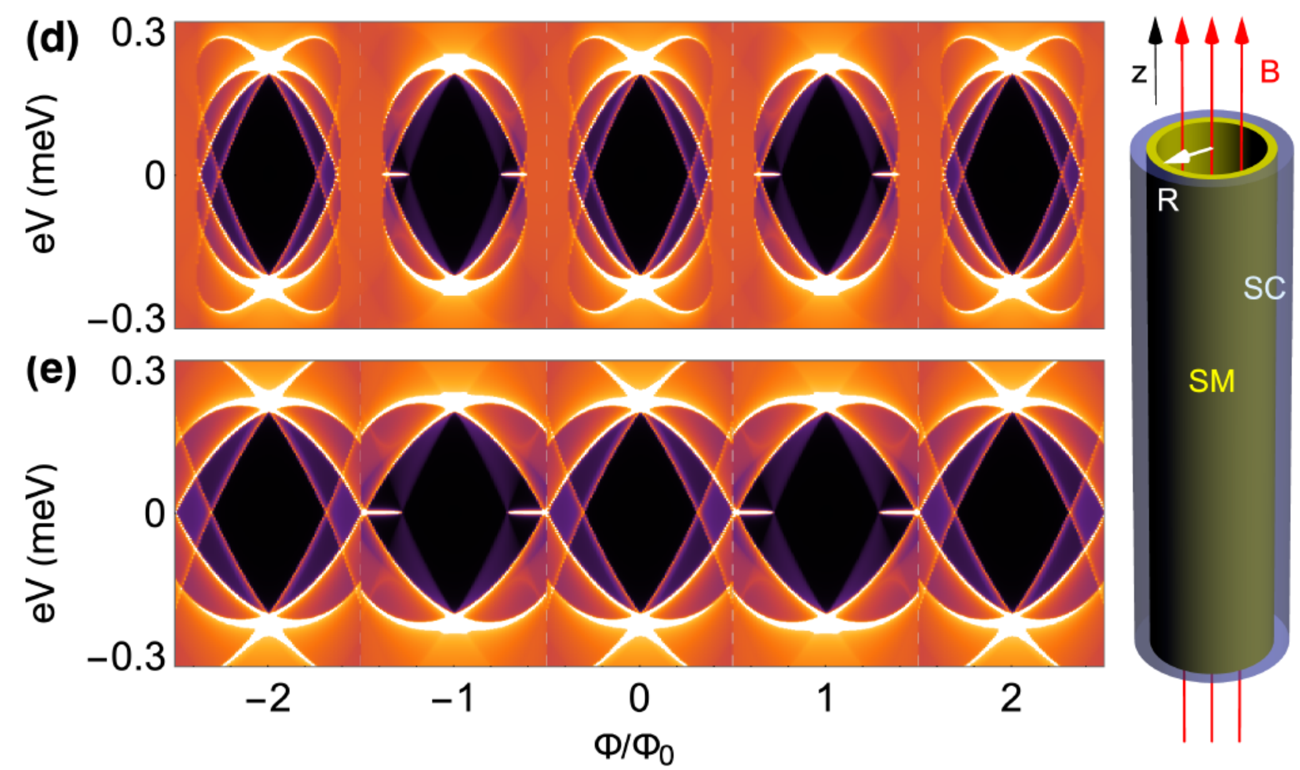
Fernando Peñaranda,[1,2] Ramón Aguado,[1] Pablo San-Jose,[1] and Elsa Prada[2]
[1]*Instituto de Ciencia de Materiales de Madrid (ICMM), Consejo Superior de Investigaciones Científicas (CSIC), and Research Platform on Quantum Technologies (CSIC), Sor Juana Inés de la Cruz 3, 28049 Madrid, Spain*
[2]*Departamento de Física de la Materia Condensada, Condensed Matter Physics Center (IFIMAC) and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*

(Received 16 December 2019; accepted 6 April 2020; published 19 May 2020)

Solid-core wire



Hollow-core wire



$\Delta = 0.2$ meV, $\alpha = 20$ meV nm

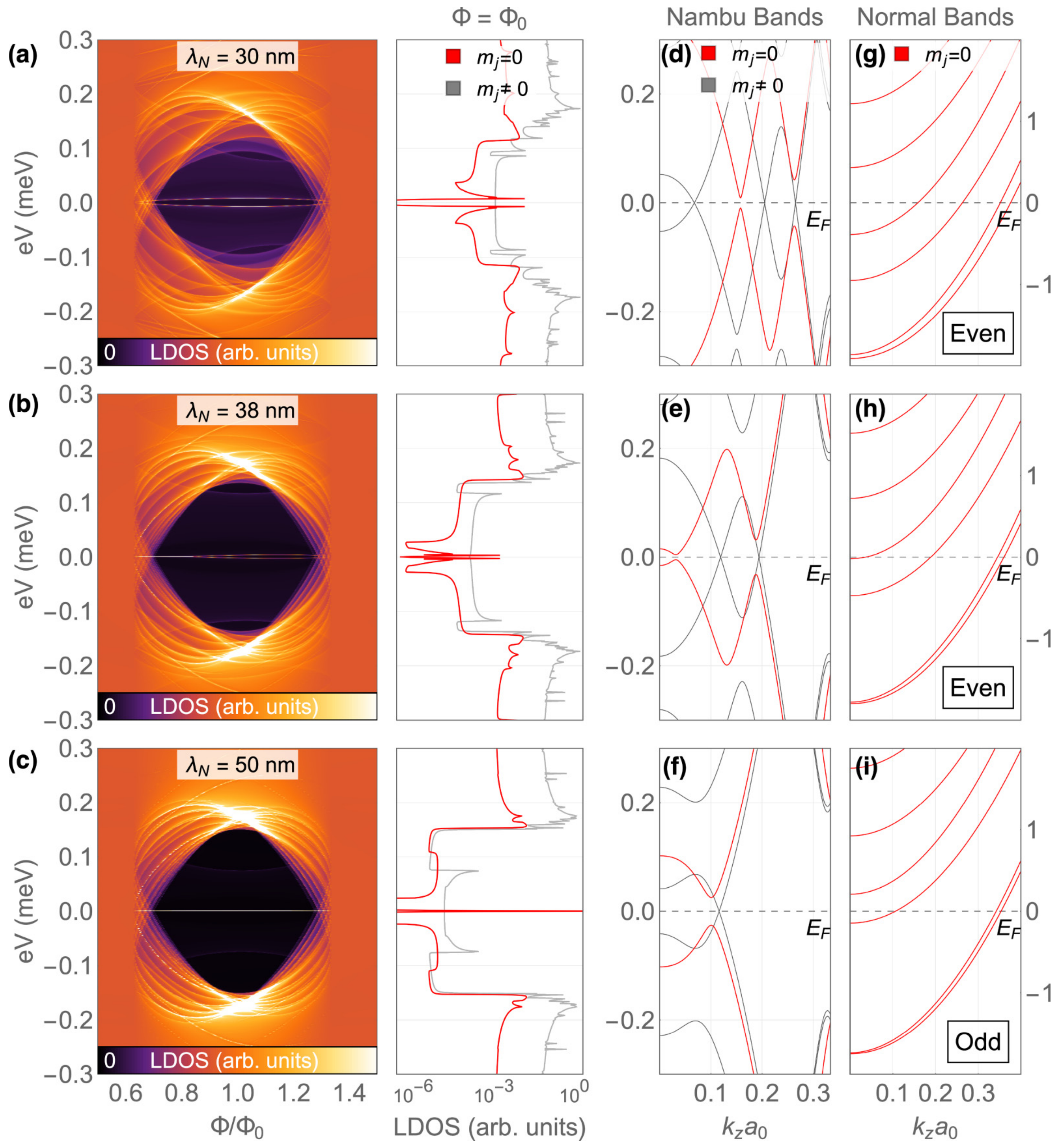
Full-shell superconductor-semiconductor nanowires

Even-odd effect in full-shell wires

First lobe

$$\lambda_{N,S} = \frac{\hbar}{2m^* \mu_{N,S}}$$

m_j: generalized angular quantum number



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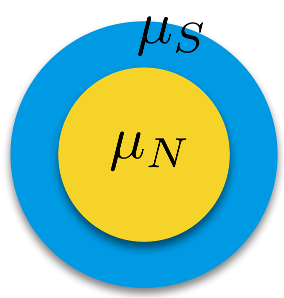
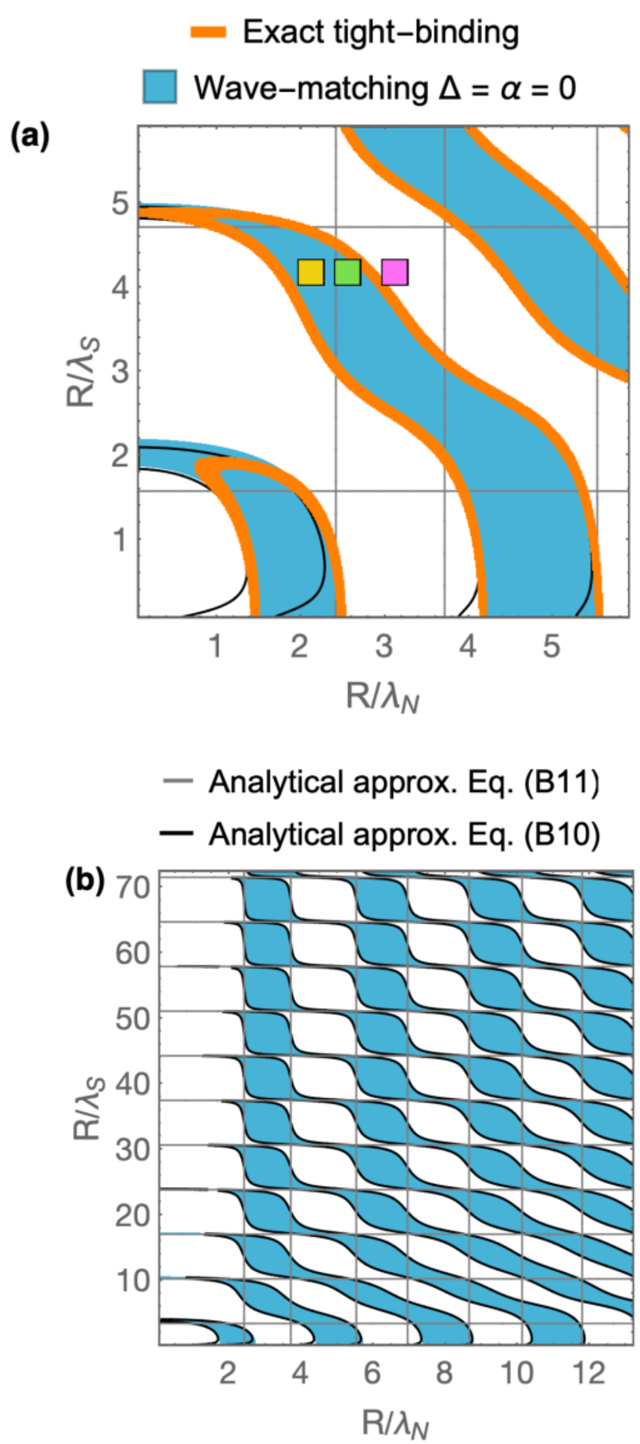
Full-shell superconductor-semiconductor nanowires

$\Phi/\Phi_0 = 1$

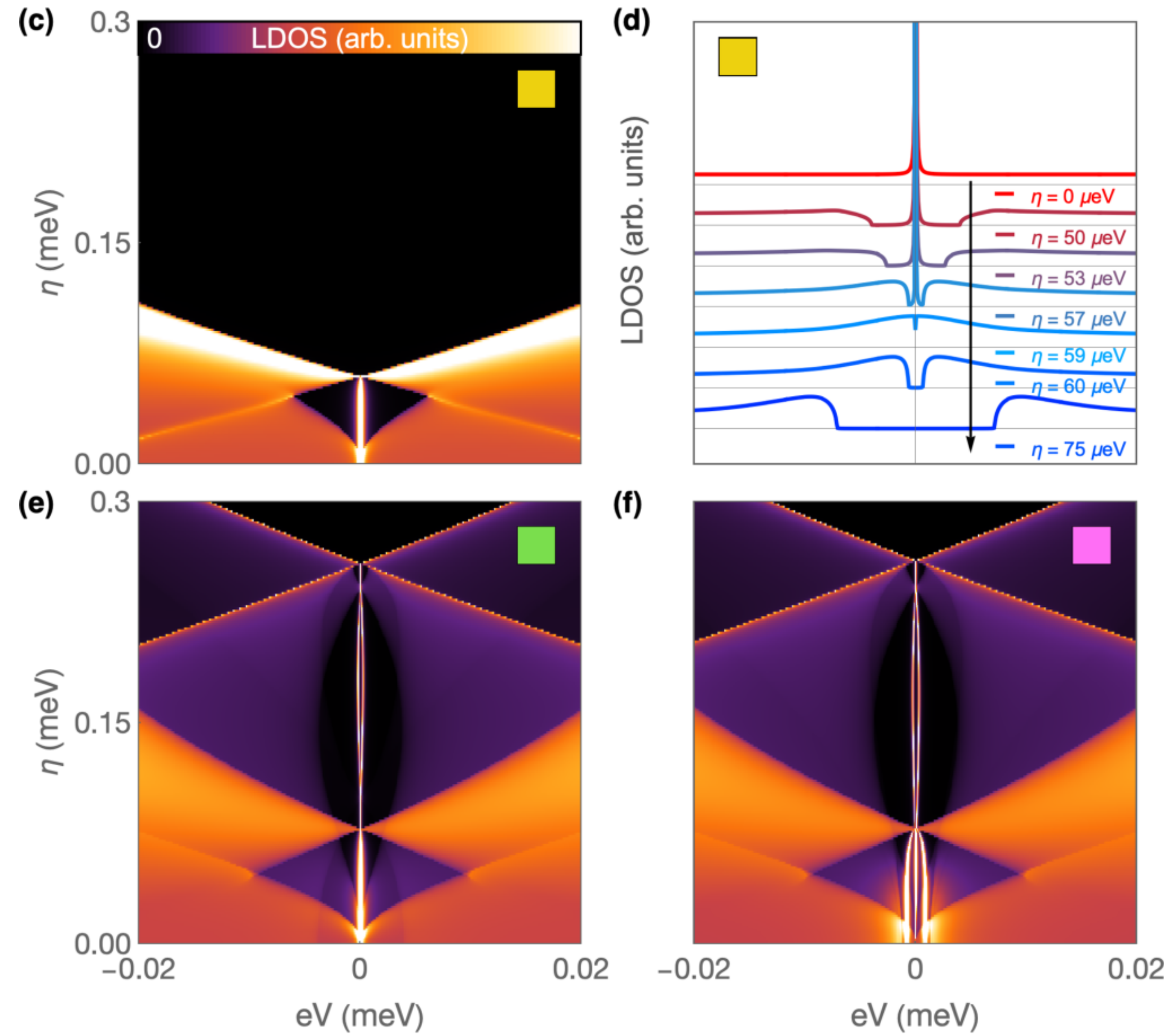


$$\lambda_{N,S} = \frac{\hbar}{2m^* \mu_{N,S}}$$

Phase diagram



Effective model for subband mixing



$$\eta = \langle \phi_{\pm 1} | \hat{V}_\eta | \phi_0 \rangle \qquad m_j = 0, \pm 1$$

Peñaranda et al., Phys. Rev. Research 2, 023171 (2020)

Full-shell superconductor-semiconductor nanowires

Conclusions

- We have established the minimal ingredients necessary to model and explain the subgap tunneling dI/dV phenomenology of full-shell superconductor-semiconductor nanowires of recent experiments.
- The hollow-core version never shows ZBAs throughout a full LP lobe. It is necessary to consider solid-core nanowires with a nonzero charge density throughout the full nanowire section to obtain ZBAs similar to the experiment.
- ZBAs emerge for odd normal-state occupation of the radial $m_j = 0$ subbands. We have mapped analytically and numerically this even-odd effect in the emergence of ZBAs at odd LP lobes throughout the full phase diagram of the system's model, and established the connection between the ZBAs to topologically unprotected $m_j = 0$ Majorana zero modes.
- ZBAs should be a common occurrence in these devices, occupying roughly half of their microscopic parameter space.
- The effect of angular subband mixing on the Majoranas is quite complex, ranging from topological minigap opening to mode splitting or broadening, but always ends up by destroying the Majorana states at sufficiently strong mixing.

Full-shell superconductor-semiconductor nanowires

Advantages of this new design:

- The core of the wire is shielded from unwanted effects of the environment and surface disorder
- Needs smaller applied magnetic fields for topological transition (good to preserve the superconducting state of the parent SC)
- No need for large g-factor semiconducting wires
- Majorana bound states are predicted to appear at very specific regions of parameter space, particularly at the odd LP lobes (this might be useful to distinguish them from other unwanted trivial states)

Vaitiekènas et al., Science 367, 1442 (2020)

Full-shell superconductor-semiconductor nanowires

Drawbacks

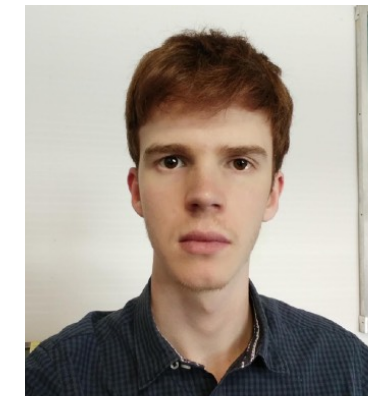
- Chemical potential of the wire is not tunable through direct gating
- SO coupling is not tunable through gates
- Higher angular momentum subbands are in principle not gapped — Majorana bound state coexists with a finite background conductance
- This hybrid system could display some of the problems as conventional partial-shell superconductor-semiconductor wires: inhomogeneous potentials (not inside the wire, but at the ends?) $\longrightarrow$ quasi-Majoranas, disorder, QD formation...

Full-shell superconductor-semiconductor nanowires

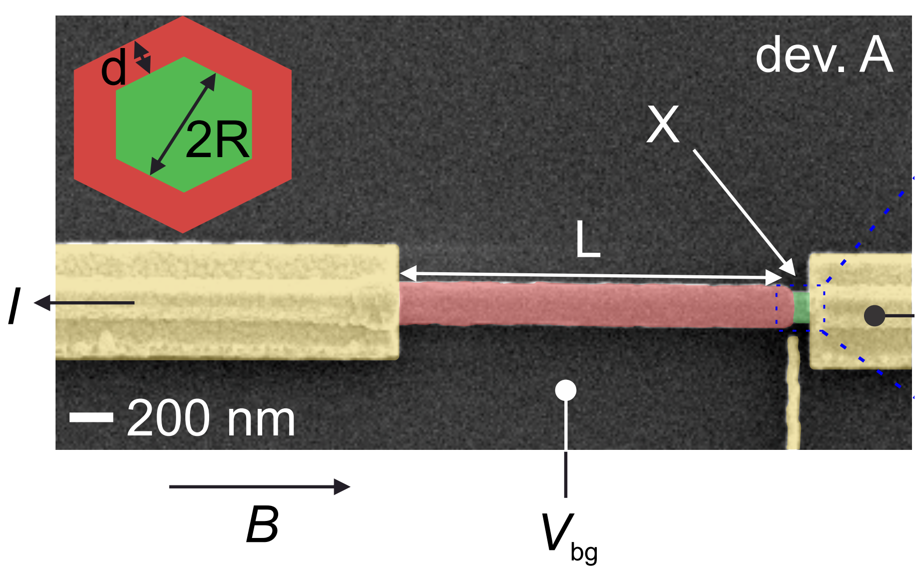
arXiv:2008.02348v2

Non-topological zero bias peaks in full-shell nanowires induced by flux tunable Andreev states

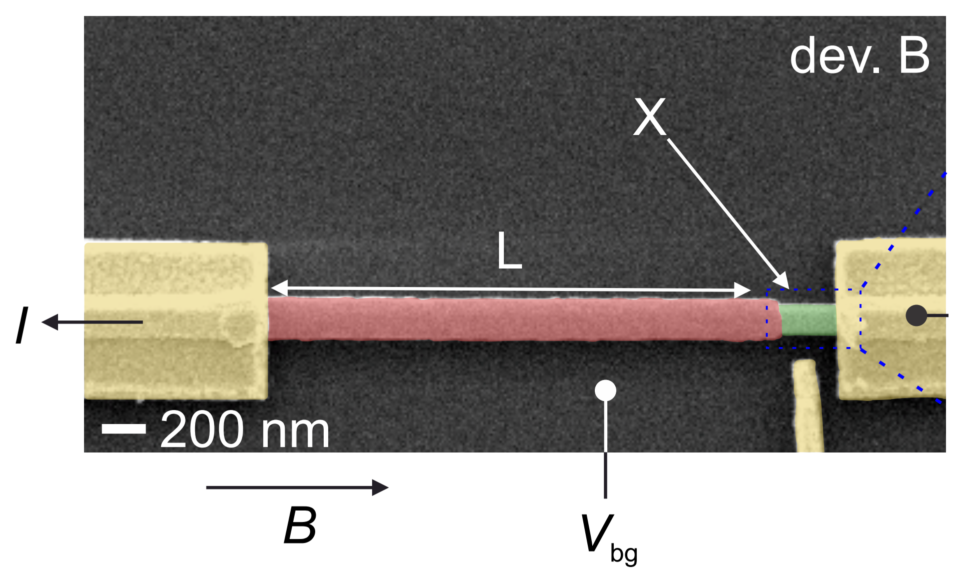
Marco Valentini[1*], Fernando Peñaranda[2], Andrea Hofmann[1], Matthias Brauns[1], Robert Hauschild[1], Peter Krogstrup[3], Pablo San-Jose[2], Elsa Prada[2,4], Ramón Aguado[2*], Georgios Katsaros[1*]
[1] *Institute of Science and Technology Austria, Am Campus 1, 3400 Klosterneuburg, Austria.*
[2] *Instituto de Ciencia de Materiales de Madrid (ICMM), Consejo Superior de Investigaciones Científicas (CSIC), Sor Juana Inés de la Cruz 3, 28049 Madrid, Spain. Research Platform on Quantum Technologies (CSIC).*
[3] *Microsoft Quantum Materials Lab and Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Kanalvej 7, 2800 Kongens Lyngby, Denmark.*
[4] *Departamento de Física de la Materia Condensada, Condensed Matter Physics Center (IFIMAC) and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
(Dated: October 12, 2020)



$X \lesssim 100\text{nm}$



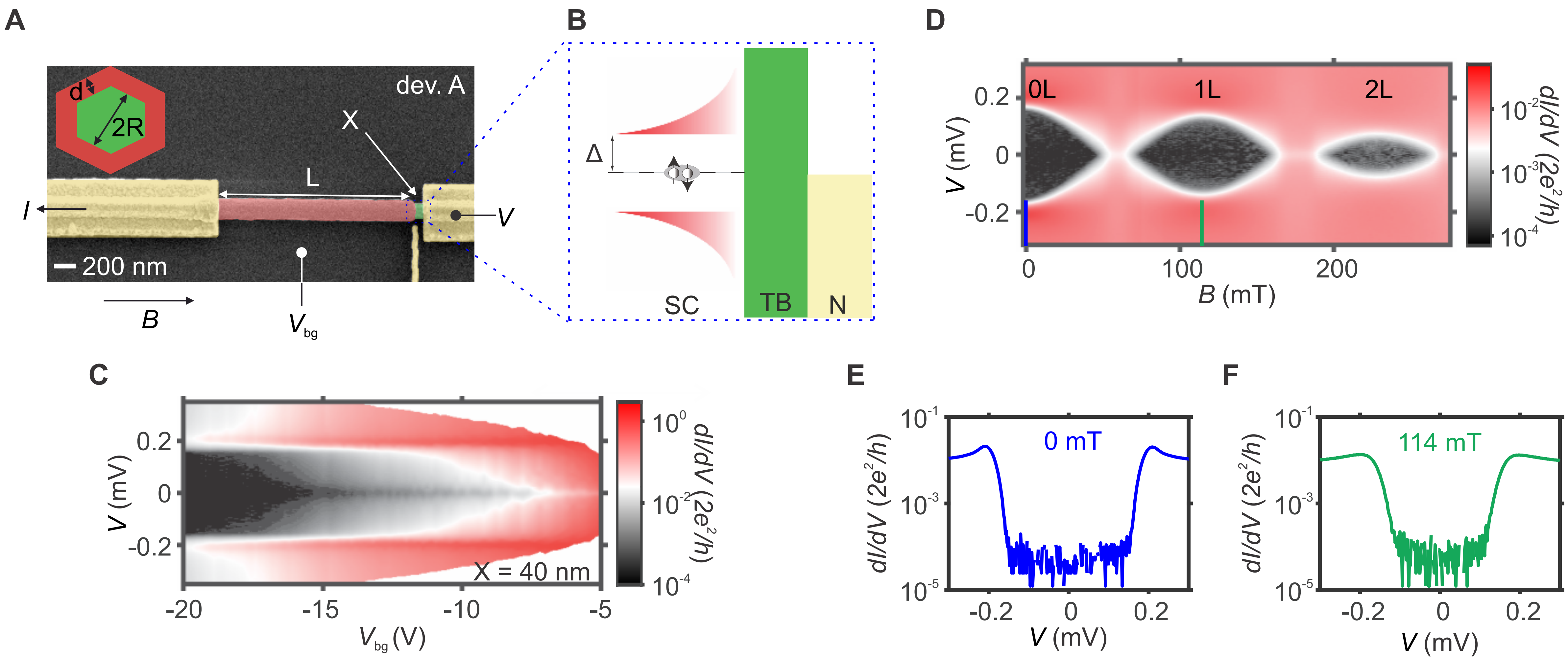
$X \gtrsim 150\text{nm}$



Valentini et al., arXiv:2008.02348

Full-shell superconductor-semiconductor nanowires

Tunneling spectroscopy of a short-junction device $X \approx 40\text{nm}$

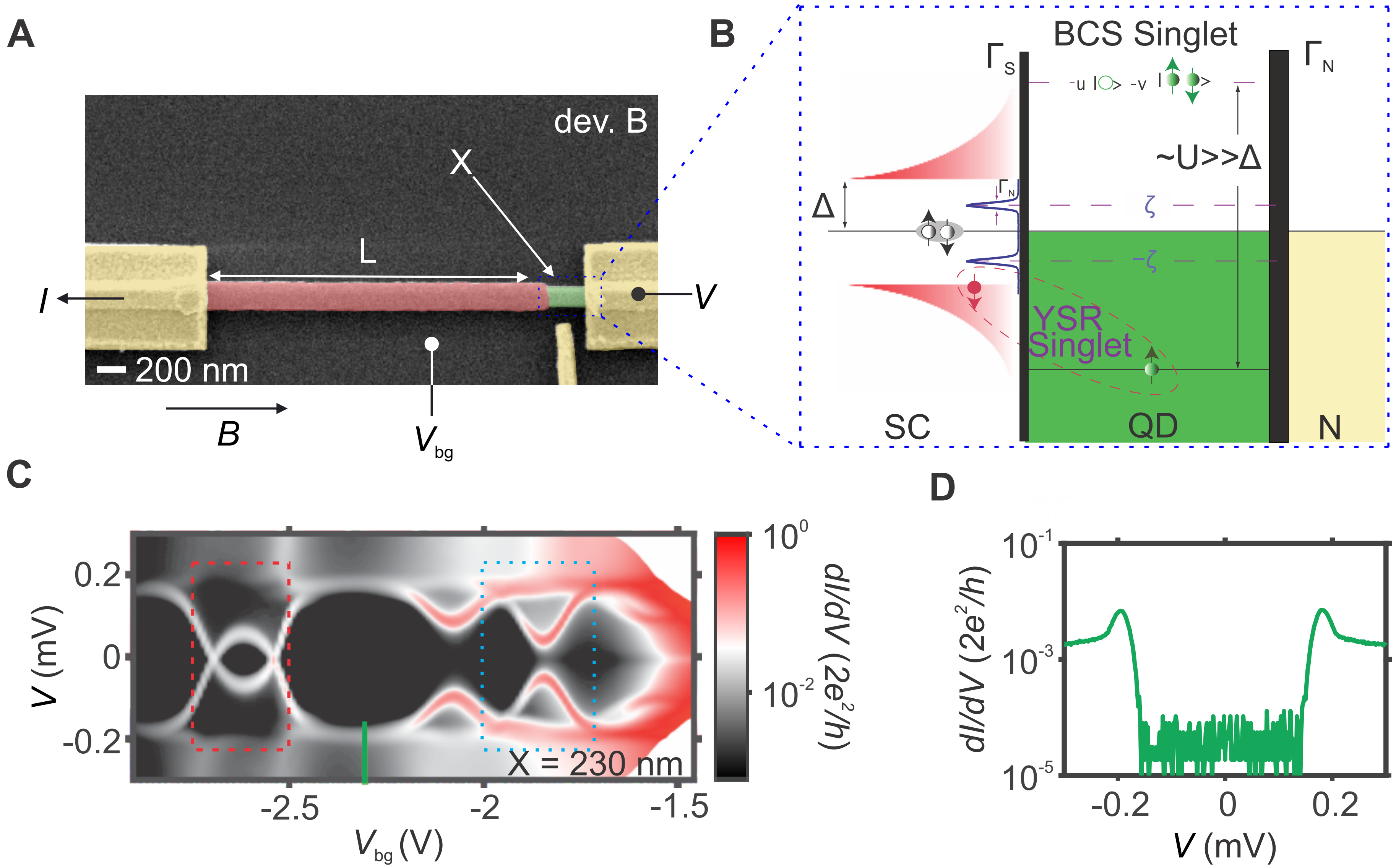


$R \approx 55\text{nm}$ $d \approx 30\text{nm}$ $\xi \approx 160\text{nm}$

Valentini et al., arXiv:2008.02348

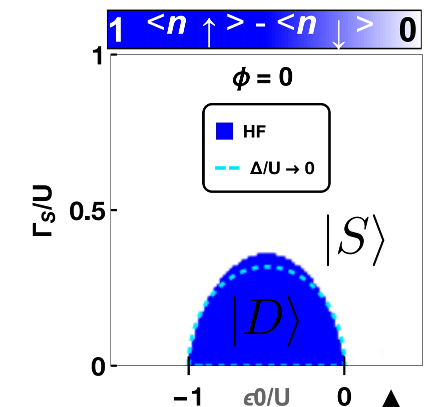
Full-shell superconductor-semiconductor nanowires

Tunneling spectroscopy of a of a long-junction device $X \approx 230\mathrm{nm}$



$U \approx 2.5\mathrm{meV}$

$\Delta \approx 0.18\mathrm{meV}$

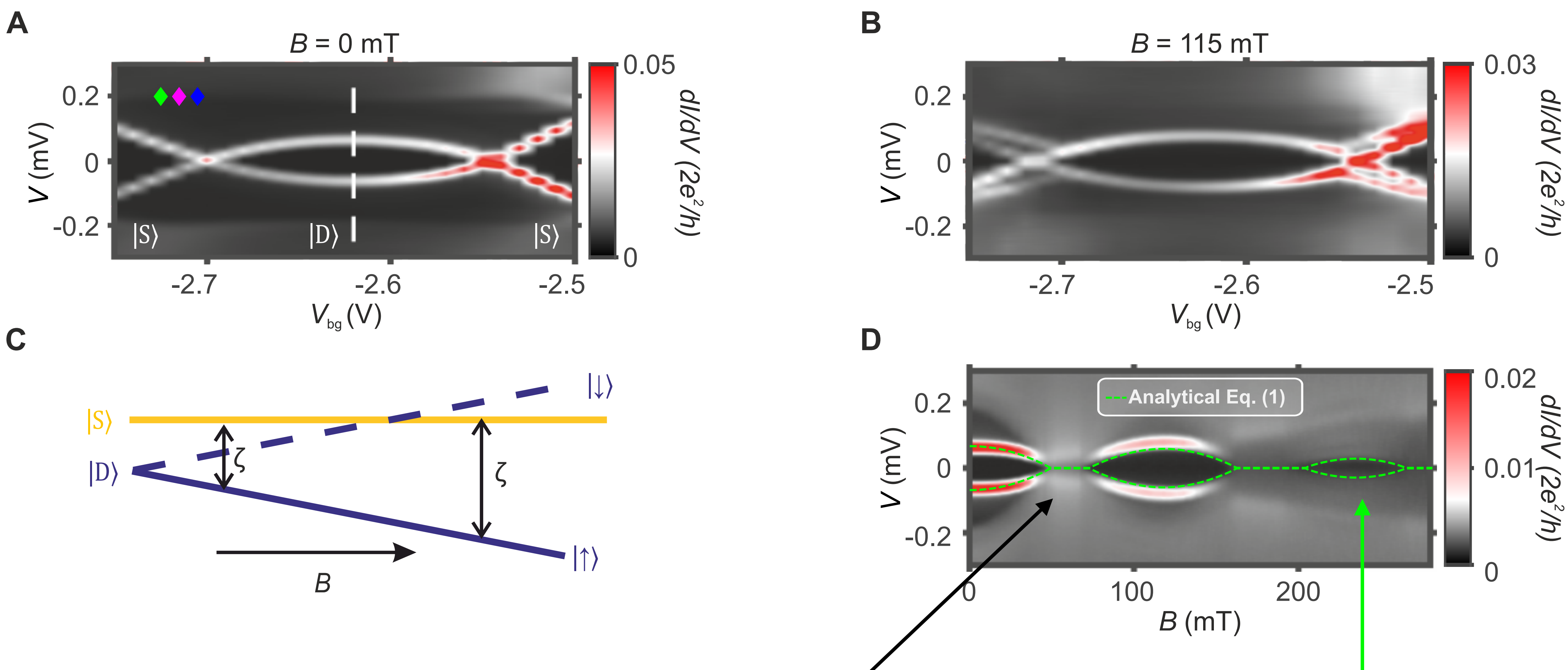


Phase diagram of the dot-level spin-polarized occupations

Theoretical modeling: → **Superconducting single-impurity Anderson model**: Coulomb blockaded QD coupled to a SC lead

Full-shell superconductor-semiconductor nanowires

Andreev bound states in the Little-Parks regime with a doublet ground state



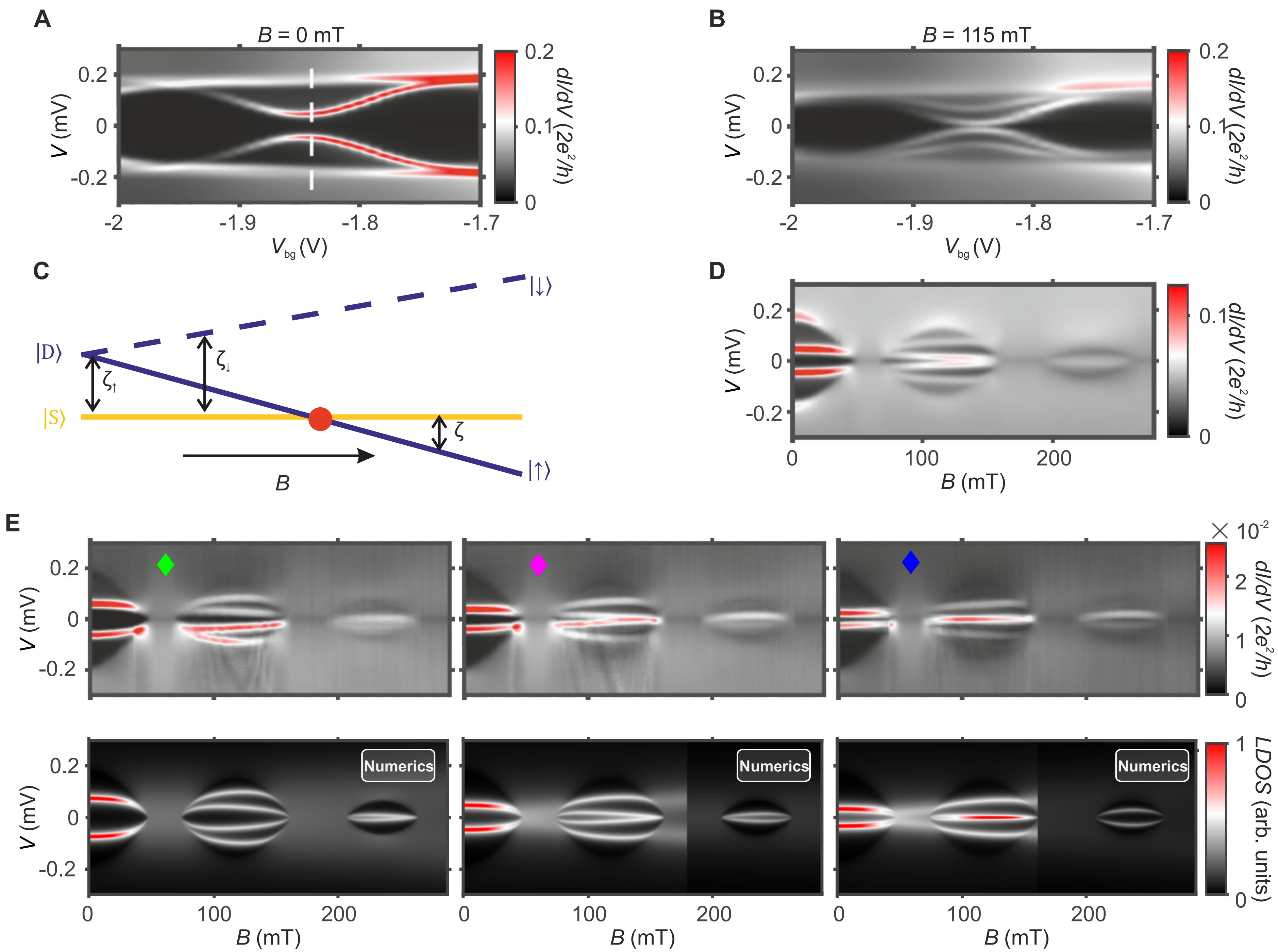
YSR singlets become Kondo singlets in the destructive LP regions

Analytical level position showing that these ABSs are of the YSR type

Valentini et al., arXiv:2008.02348

Full-shell superconductor-semiconductor nanowires

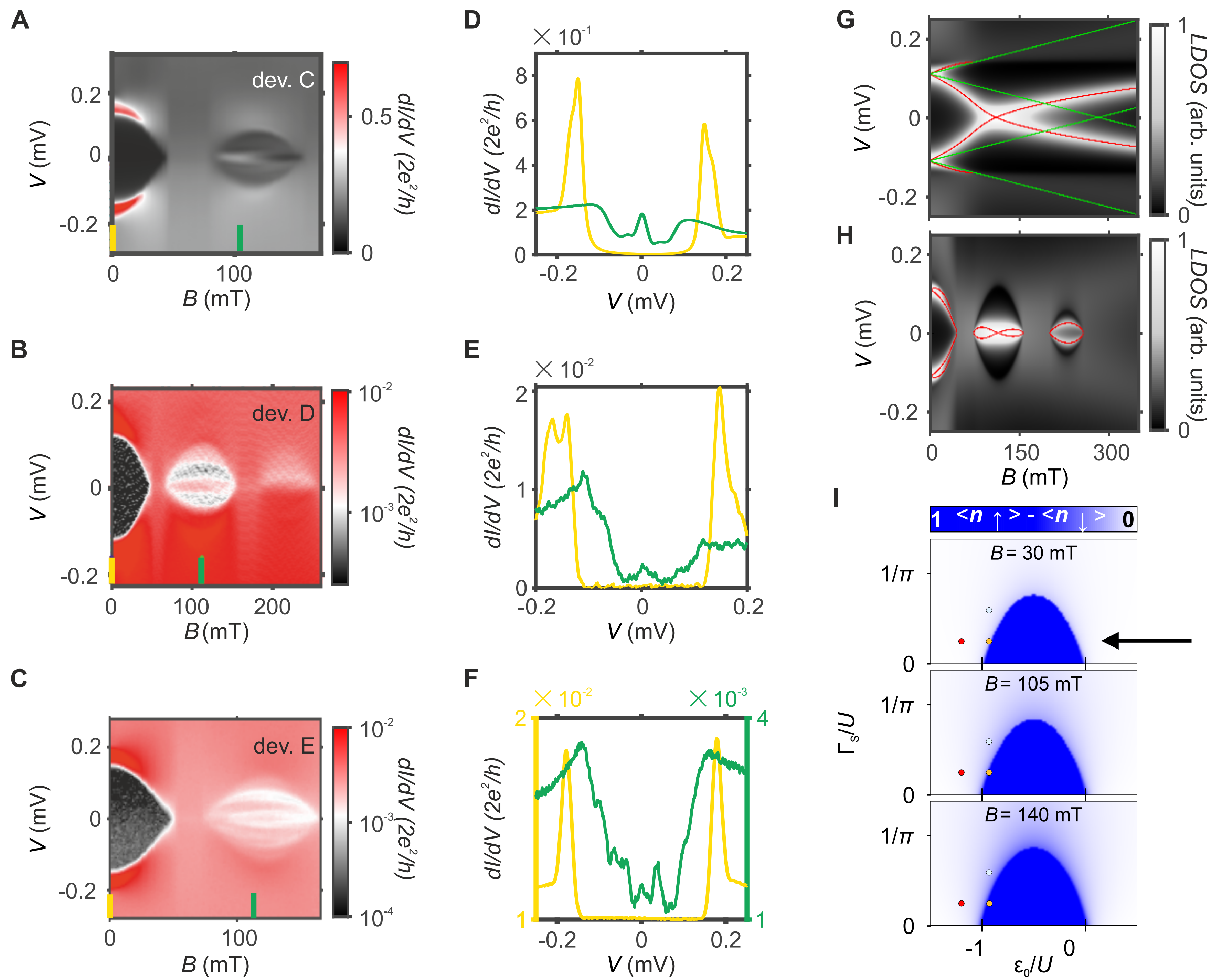
Andreev bound states in the Little-Parks regime with a singlet ground state



Valentini et al., arXiv:2008.02348

Full-shell superconductor-semiconductor nanowires

ZBPs arising from ABSs "hidden" in the superconducting gap edge



$\Delta = \mathrm{cnst.}$

Δ is LP modulated

Phase diagram of the dot-level spin-polarized occupations

Valentini et al., arXiv:2008.02348

Full-shell superconductor-semiconductor nanowires

Conclusions

- Tunneling spectroscopy measurements on hybrid full-shell InAs/Al NWs have shown that, for short junction devices with X≲100nm, no ABSs or other subgap states are observed.
- For long junctions, a rich spectral structure arises in the LP lobes and destructive regimes.
- When the GS is odd, we demonstrate that the subgap excitations of the system are YSR singlets. In the metallic state within the destructive LP regions, these YSR singlets fully develop a Kondo effect, confirming our interpretation in terms of QDs.
- When the GS is a singlet, the flux may induce a QPT to a spin-polarized odd GS. This zero-energy fermionic parity crossing leads to a ZBP. Depending on different gate conditions, this ZBP can persist for an extended magnetic field range in the first LP lobe around $\Phi \sim \Phi_0$.
- When the ABS energy at zero magnetic field is close to the superconducting gap, such robust ZBPs could be mistaken with topological Majorana zero modes.

Thanks for your attention!

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