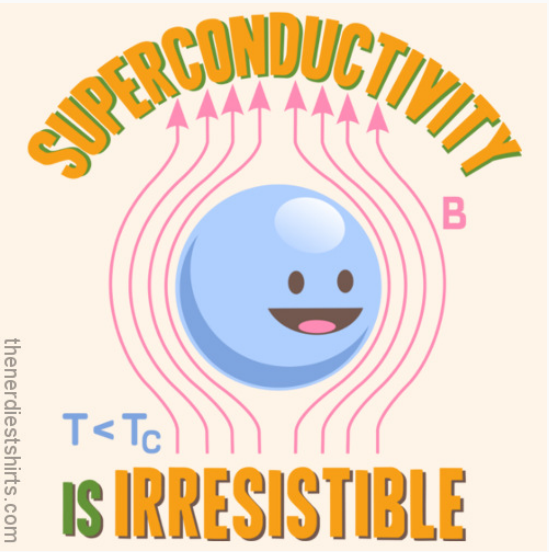
DELOCALISATION OF MAJORANA MODES IN LOW-DIMENSIONAL HYBRIDS

Tadeusz DOMAŃSKI

M. Curie-Skłodowska University, Lublin (Poland)



"New^{3}SC – 12"

Oxford (UK), 31 March - 5 April 2019

OUTLINE

Superconductivity in low dim systems:

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  bound states ..... (Yu-Shiba-Rusinov & Andreev)

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- **dim=1**
  topological phase ..... (Majorana qps)

- **hybrid structures: $1+2$ dim**
  delocalized Majorana qps ..... (itinerant modes?)

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- ⇒ **magnetic atoms ..... (for instance Fe, Co)**
- ⇒ **correlated quantum dots ..... (Anderson-type impurities)**
- ⇒ **molecules ..... (multi-level or vibrating)**
- ⇒ **magnetic islands ..... (Shiba glasses and/or lattices)**
- ⇒ **nanowires ..... (carbon nanotubes, Fe-chains)**
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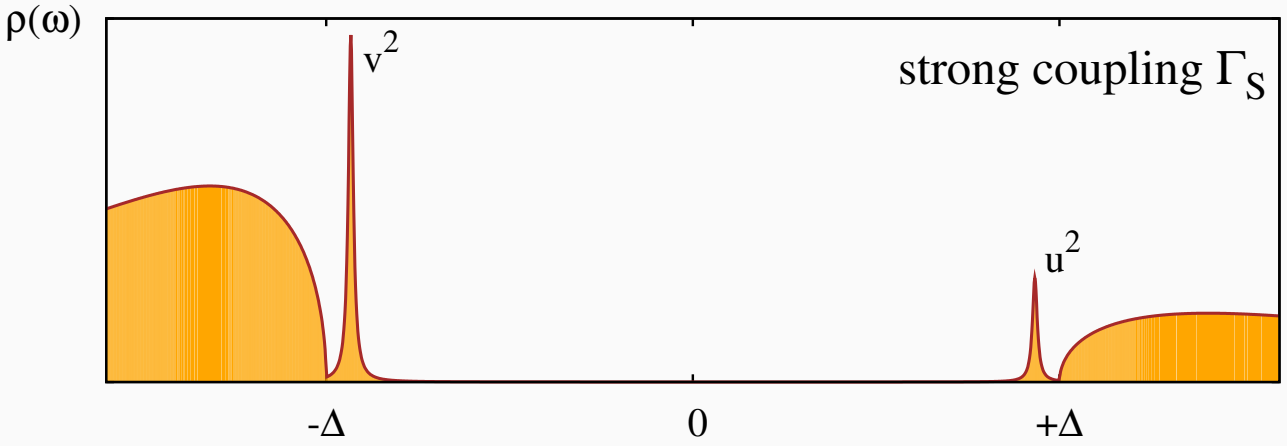
acquire the electron pairing via *proximity effect*.

IN-GAP STATES

Spectrum of an uncorrelated impurity coupled to superconductor:



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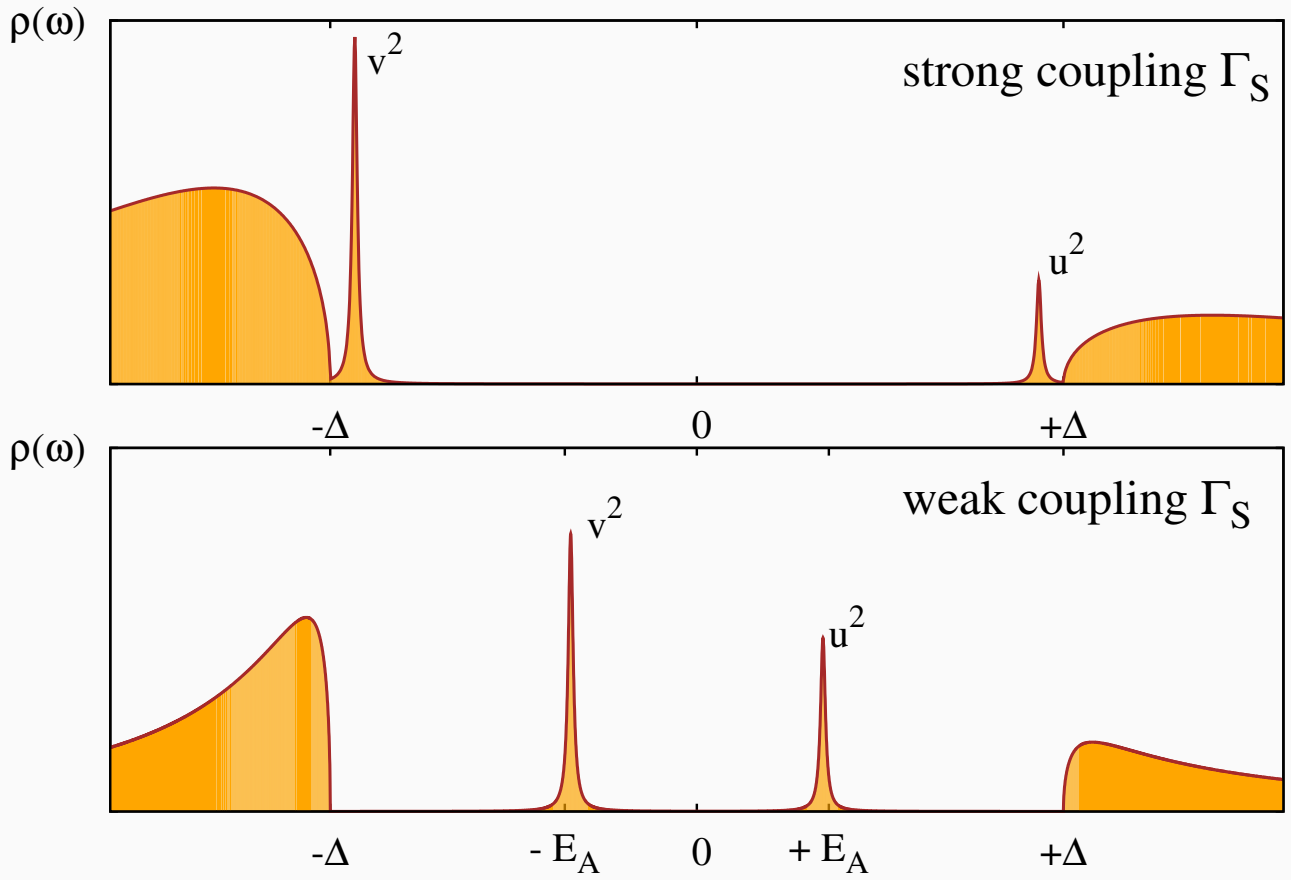

Bound states appearing in the subgap region $E \in \langle -\Delta, \Delta \rangle$

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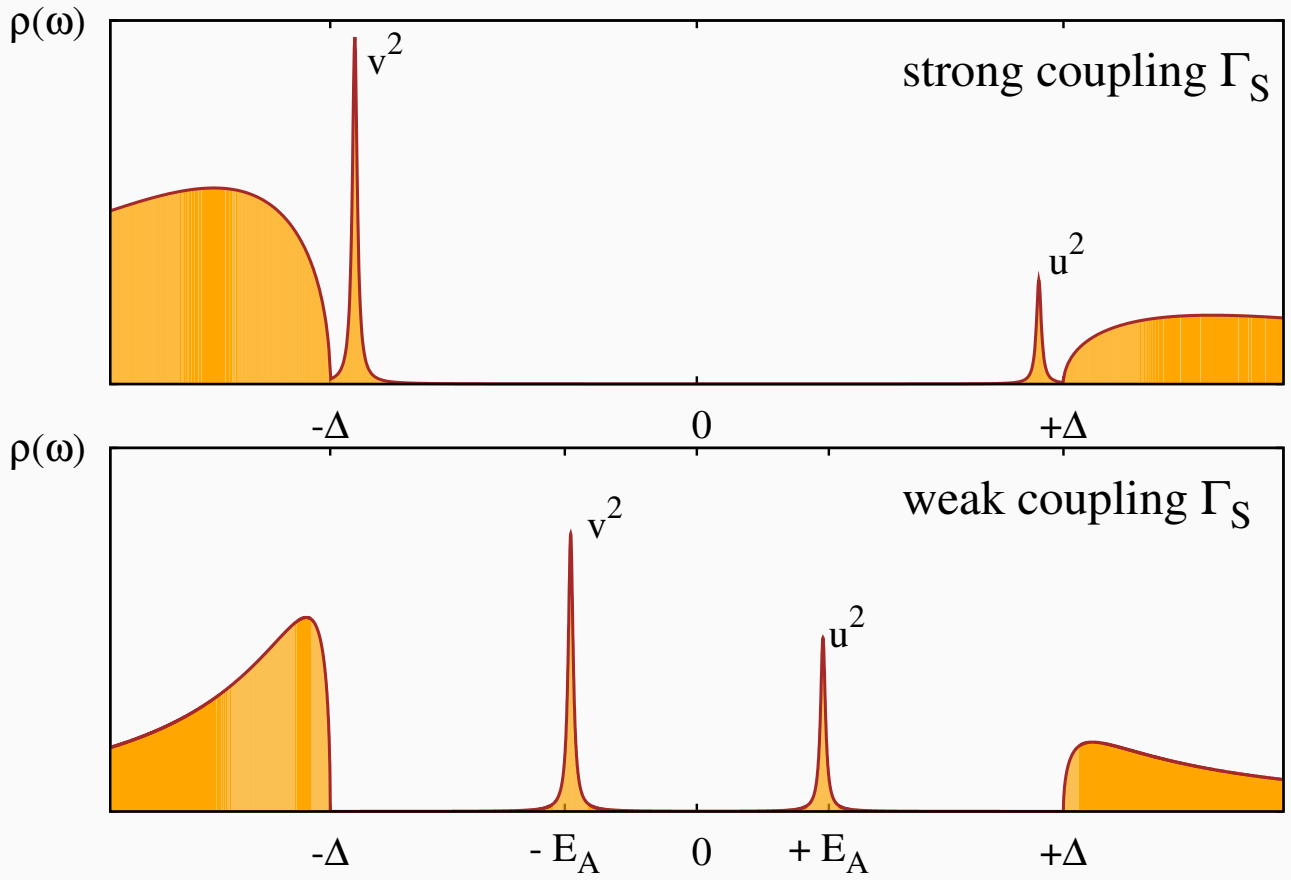
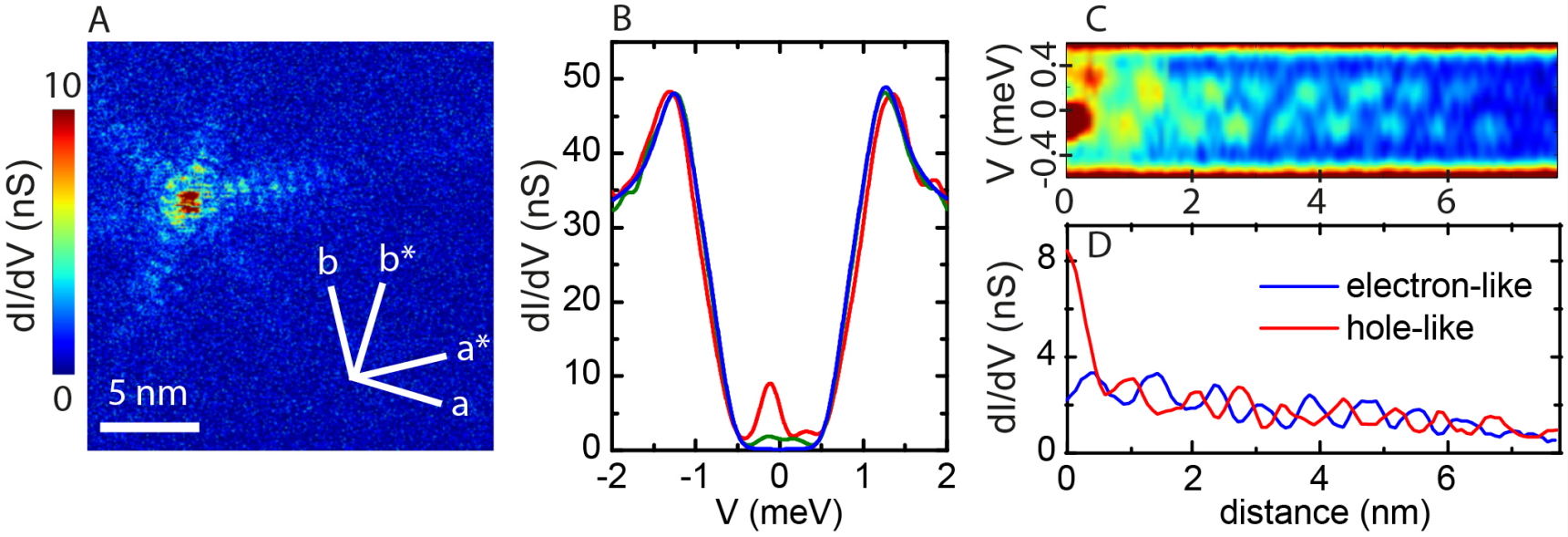


Bound states appearing in the subgap region $E \in \langle -\Delta, \Delta \rangle$ are dubbed Yu-Shiba-Rusinov (or Andreev) quasiparticles.

TOPOGRAPHY AND SPATIAL EXTENT

Empirical data obtained from STM measurements for $NbSe_2$



a) bound states extending to 10 nm

b) alternating particle-hole oscillations

G.C. Menard et al., Nature Phys. 11, 1013 (2015).

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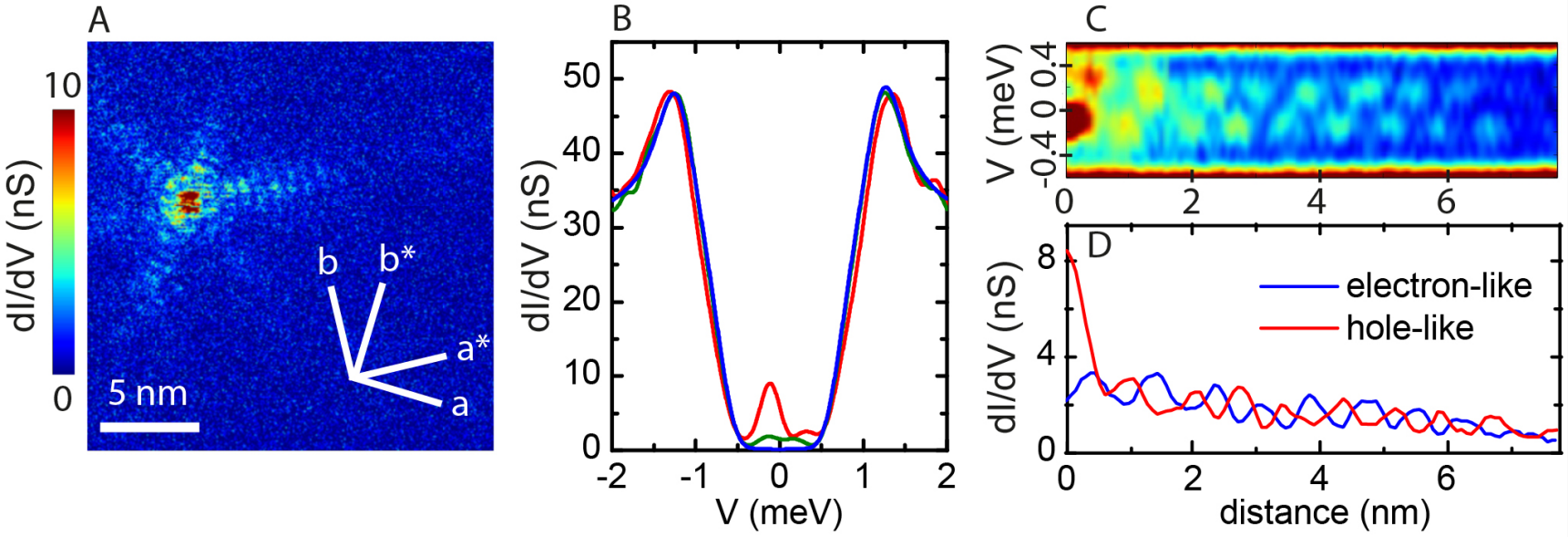

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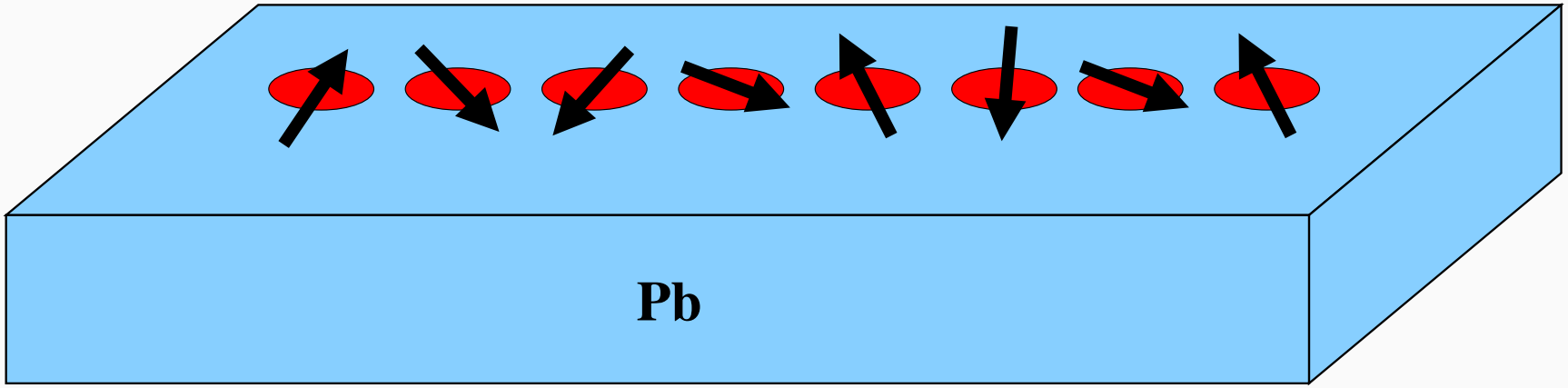
MAGNETIC CHAINS IN SUPERCONDUCTORS

Nanochain of magnetic impurities embedded in superconductor:



T.-P. Choy, J.M. Edge, A.R. Akhmerov, and C.W.J. Beenakker,

Phys. Rev. B 84, 195442 (2011).

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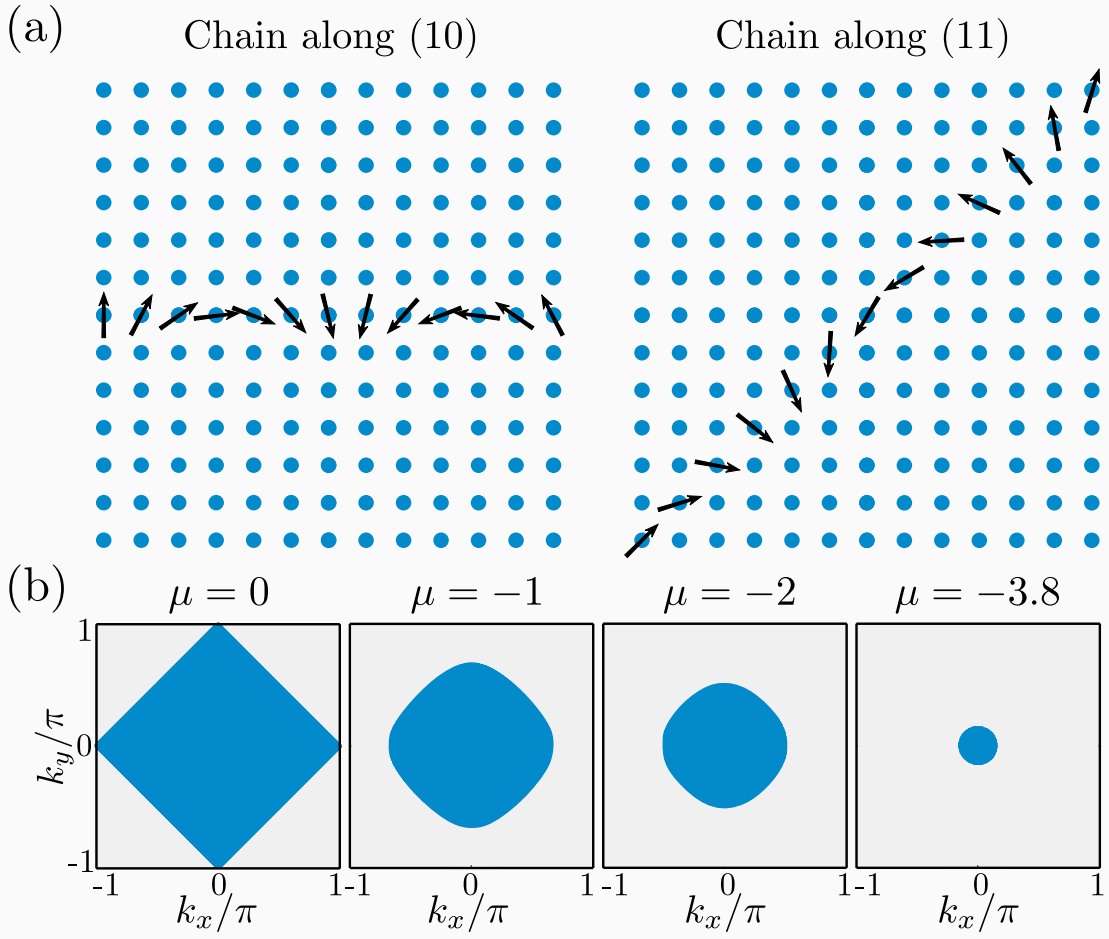

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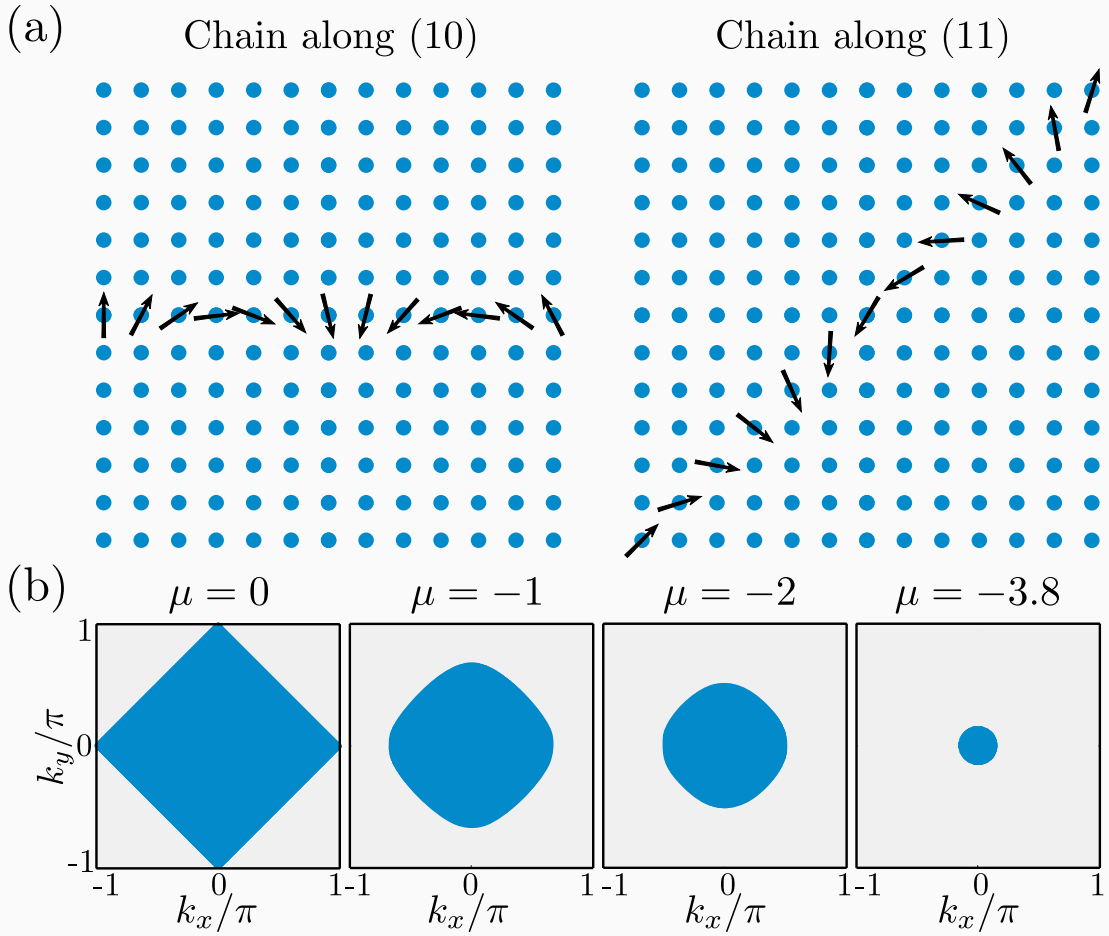

arrange the in-gap bound states into Shiba-band(s).

M.H. Christensen ... J. Paaske, Phys. Rev. B 94, 144509 (2016).

KITAEV CHAIN: PARADIGM FOR MAJORANA QPS

Itinerant 1D fermions with intersite (*p-wave*) pairing

$$\hat{H} = t \sum_i \left(\hat{c}_i^\dagger \hat{c}_{i+1} + \text{h.c.} \right) - \mu \sum_i \hat{c}_i^\dagger \hat{c}_i + \Delta \sum_i \left(\hat{c}_i^\dagger \hat{c}_{i+1}^\dagger + \text{h.c.} \right)$$

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This toy-model can be recast in the Majorana basis

$$\begin{aligned} \hat{\gamma}_{j,1} &\equiv \frac{1}{\sqrt{2}} \left(\hat{c}_j + \hat{c}_j^\dagger \right) \\ \hat{\gamma}_{j,2} &\equiv \frac{1}{i\sqrt{2}} \left(\hat{c}_j - \hat{c}_j^\dagger \right) \end{aligned}$$

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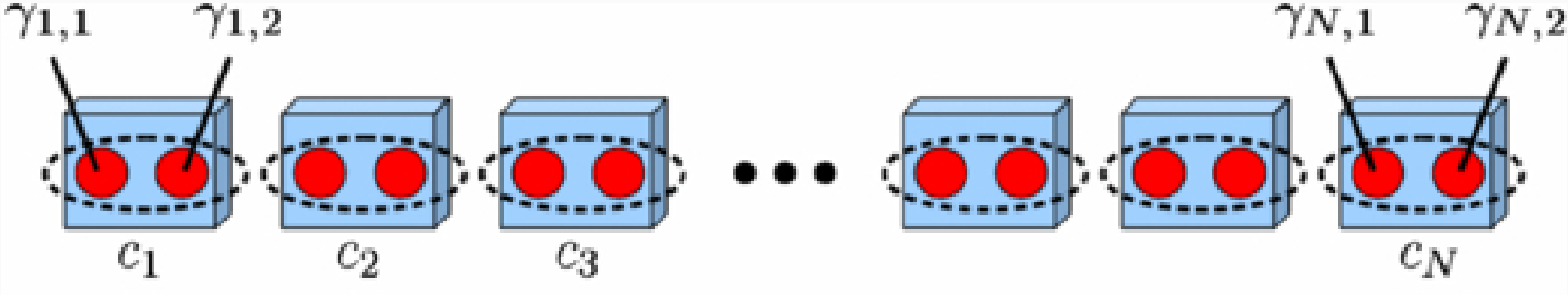
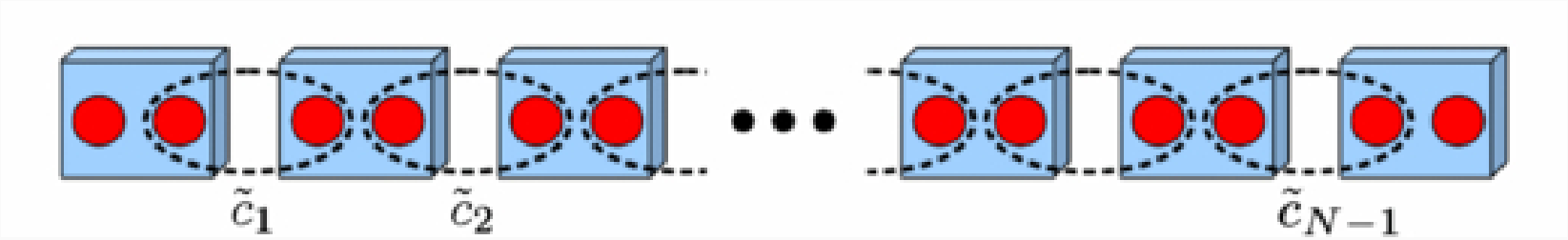


Yu. Kitaev, Phys. Usp. 44, 131 (2001).

KITAEV CHAIN: PARADIGM FOR MAJORANA QPS

In particular, for $\Delta = t$ and when $|\mu|$ is inside the band

two operators $\hat{\gamma}_{1,1}$ and $\hat{\gamma}_{2,N}$ *decouple* from all the rest



inducing the zero-energy modes at the chain edges.

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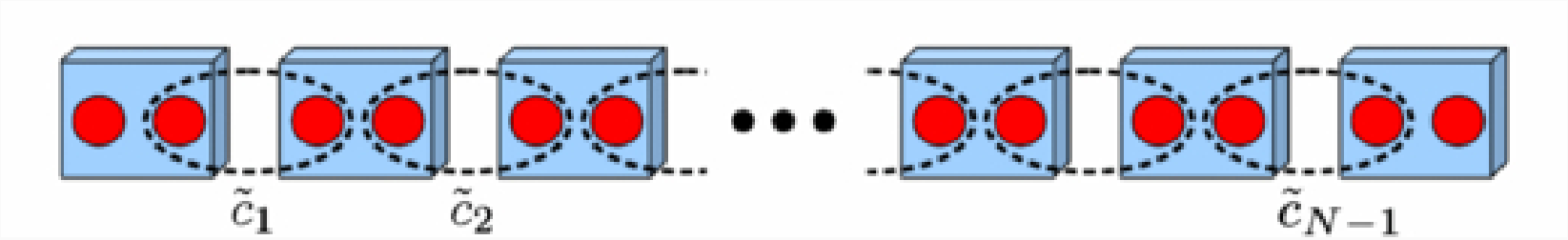


inducing the zero-energy modes at the chain edges.

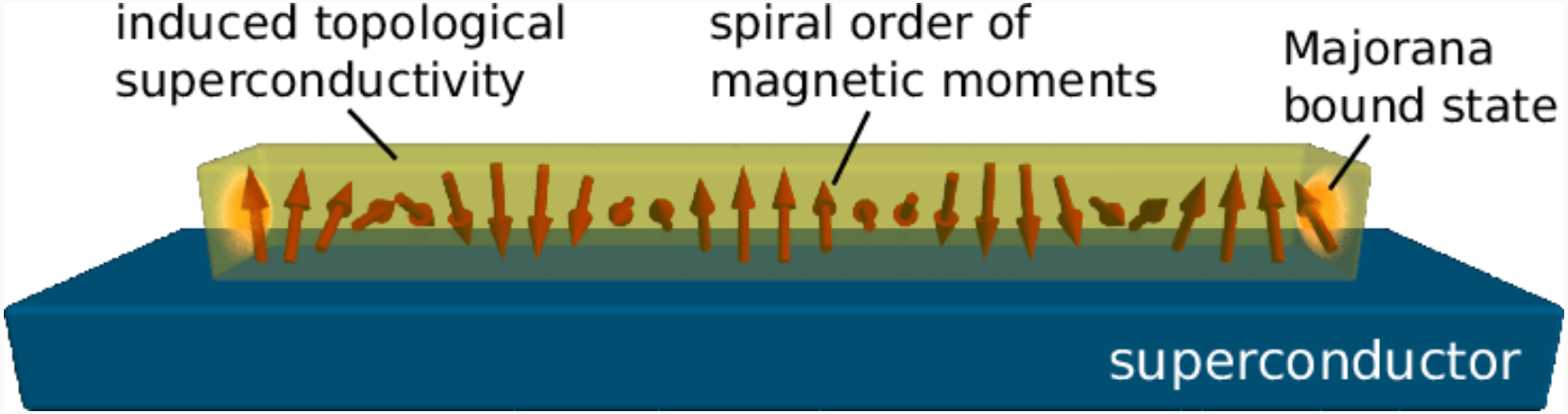
They can be regarded as *fractions* of non-local fermion

$$\hat{c}_{nonlocal} \equiv (\hat{\gamma}_{1,1} + i\hat{\gamma}_{N,2})/\sqrt{2}$$
$$\hat{c}^{\dagger}_{nonlocal} \equiv (\hat{\gamma}_{1,1} - i\hat{\gamma}_{N,2})/\sqrt{2}$$

as manifested by a number of unique phenomena.

MAGNETIC CHAINS IN SUPERCONDUCTORS

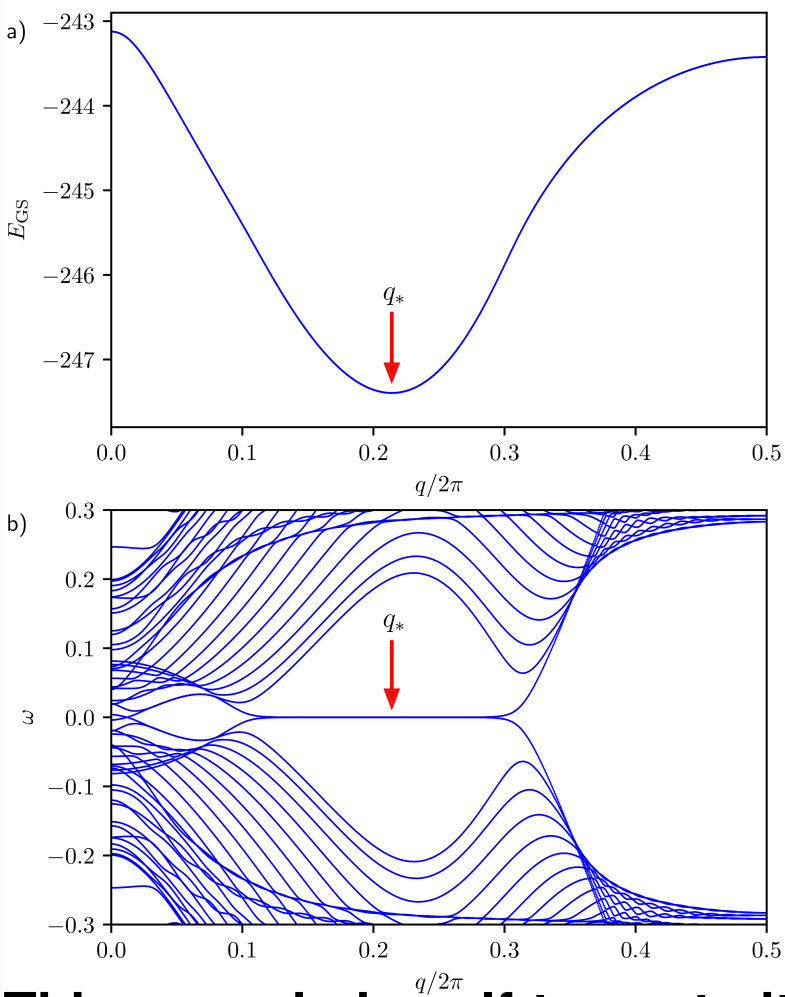
Topological superconductivity can be driven e.g. by the spin-orbit Rashba interaction combined with the external magnetic field.



R. Lutchyn, J. Sau, S. Das Sarma, Phys. Rev. Lett. 105, 077001 (2010).

Y. Oreg, G. Refael, F. von Oppen, Phys. Rev. Lett. 105, 177002 (2010).

MAGNETIC CHAINS IN SUPERCONDUCTORS



Ground state energy vs the pitch vector q

In-gap Shiba states

This nanochain self-tunes to its *topological phase* (topofilia)

A. Gorczyca-Goraj, T. Domański & M.M. Maśka, arXiv:1902.1902.06750.

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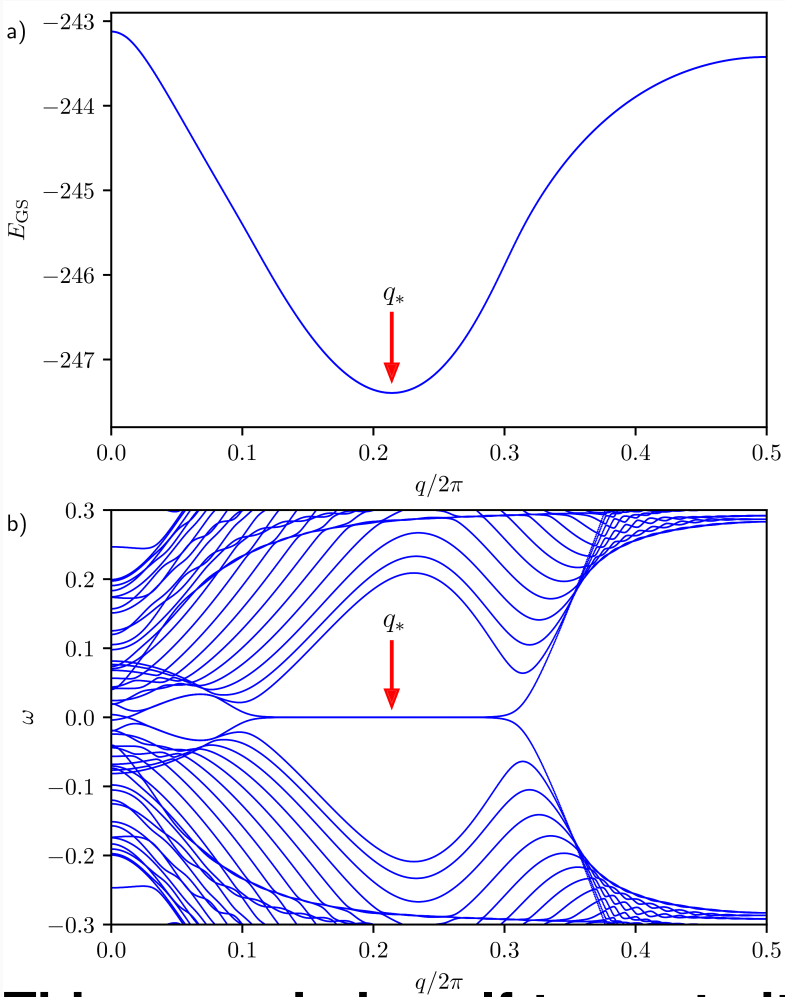

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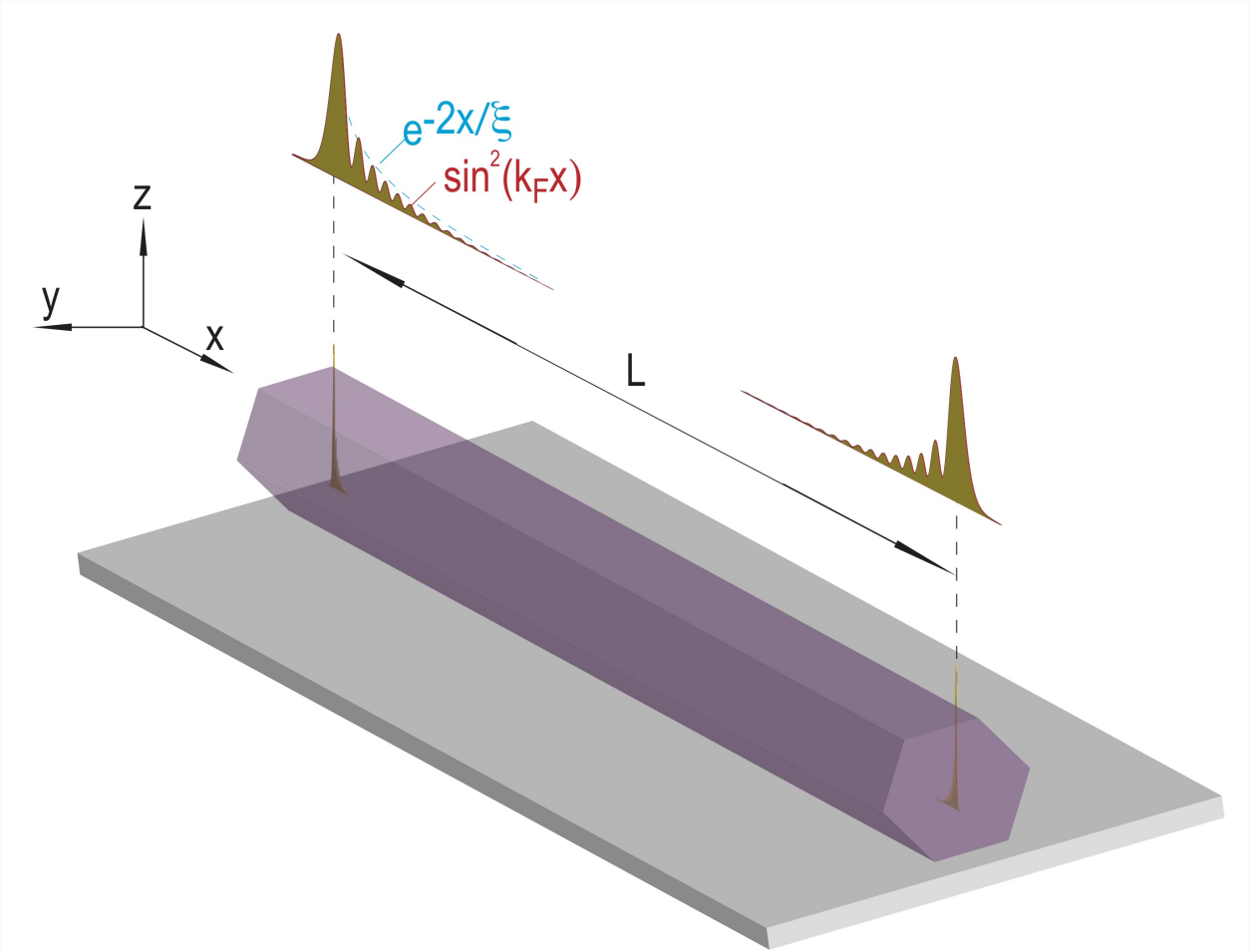
/ details provided in the lecture by Maciek Maśka /

SPATIAL PROFILE OF MAJORANA QPS

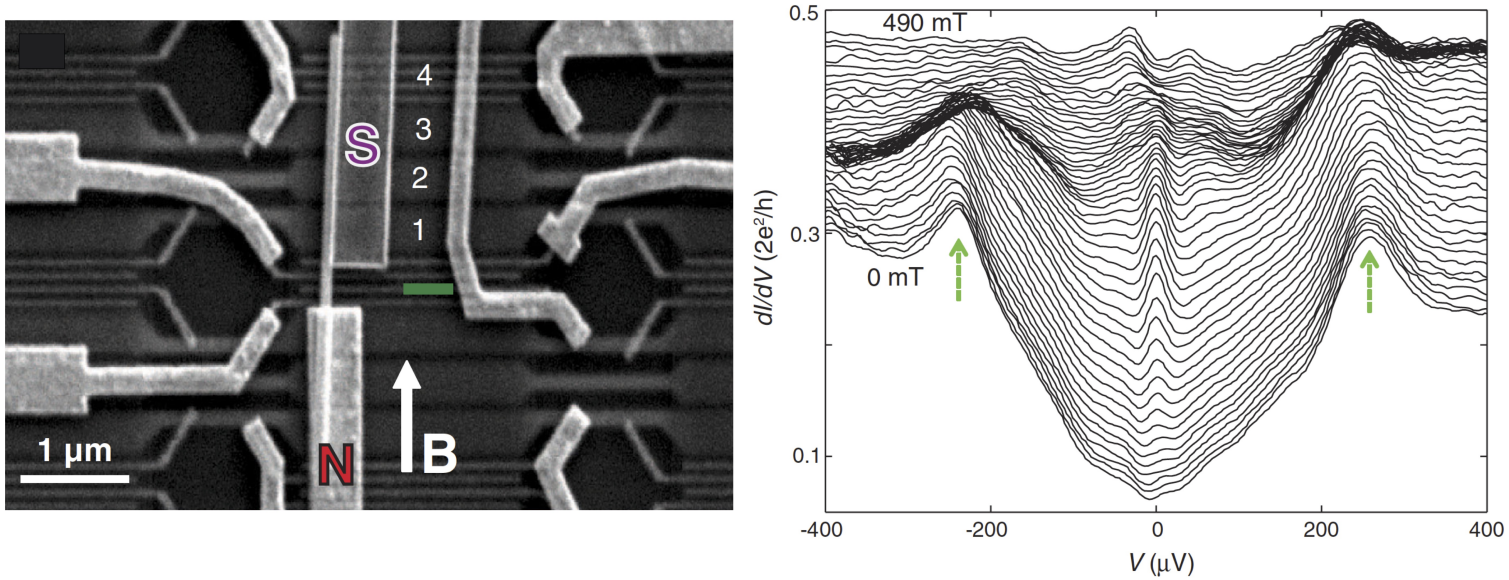
Majorana qps are exponentially localized at the edges



R. Aguado, Riv. Nuovo Cim. 40, 523 (2017).

EMPIRICAL REALIZATION: EXAMPLE # 1

Differential conductance dI/dV obtained for InSb nanowire at 70 mK upon varying a magnetic field.

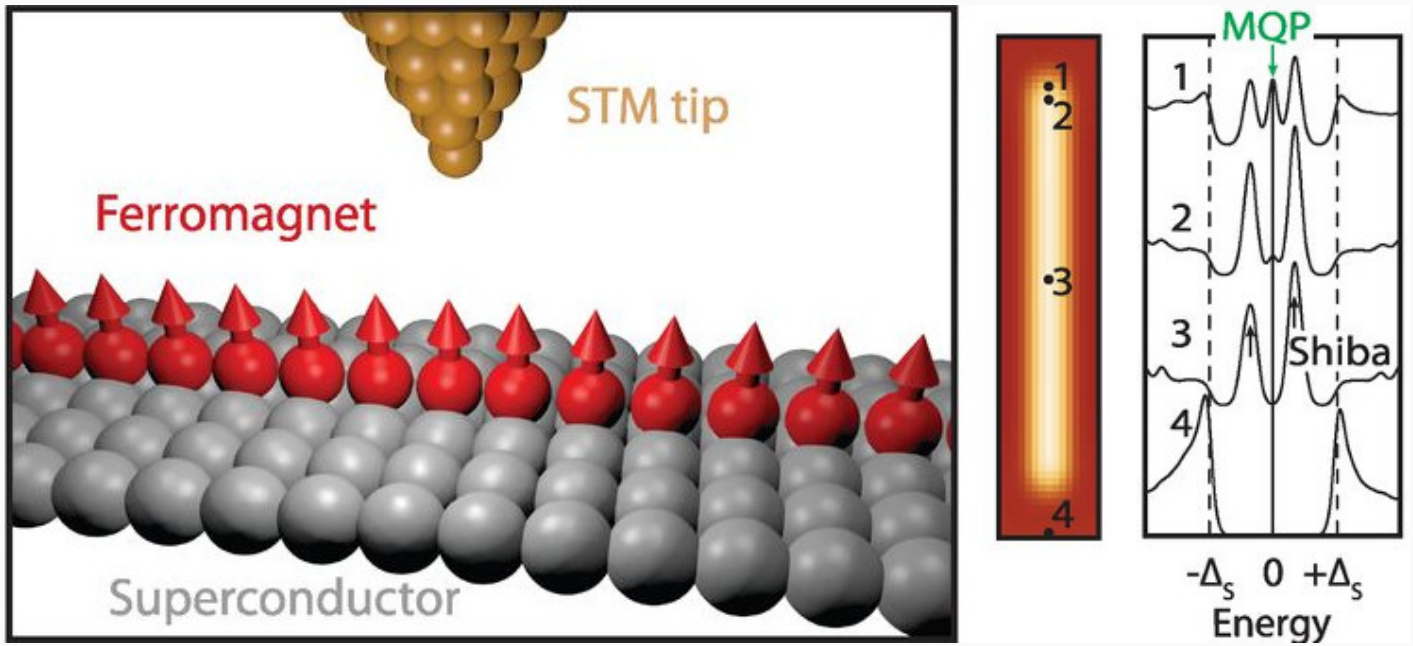


V. Mourik, ..., and L.P. Kouwenhoven, Science **336**, 1003 (2012).

/ Technical Univ. Delft, Netherlands /

EMPIRICAL REALIZATION: EXAMPLE # 2

STM measurements for the nanochain of Fe atoms self-organized on a surface of superconducting Pb.

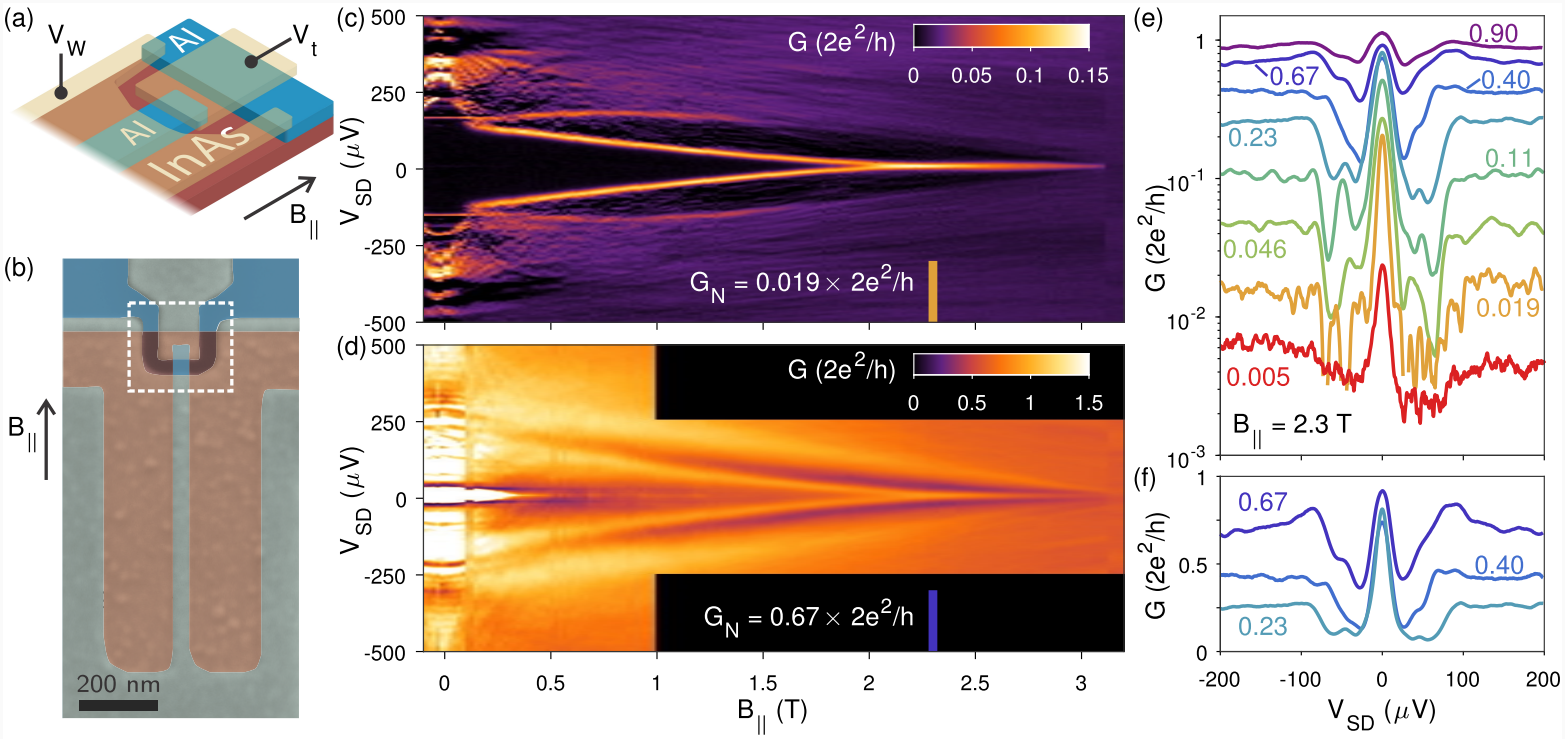


S. Nadj-Perge, ..., and A. Yazdani, Science **346**, 602 (2014).

/ Princeton University, USA /

EMPIRICAL REALIZATION: EXAMPLE # 3

Results for the litographically fabricated Al nanowire

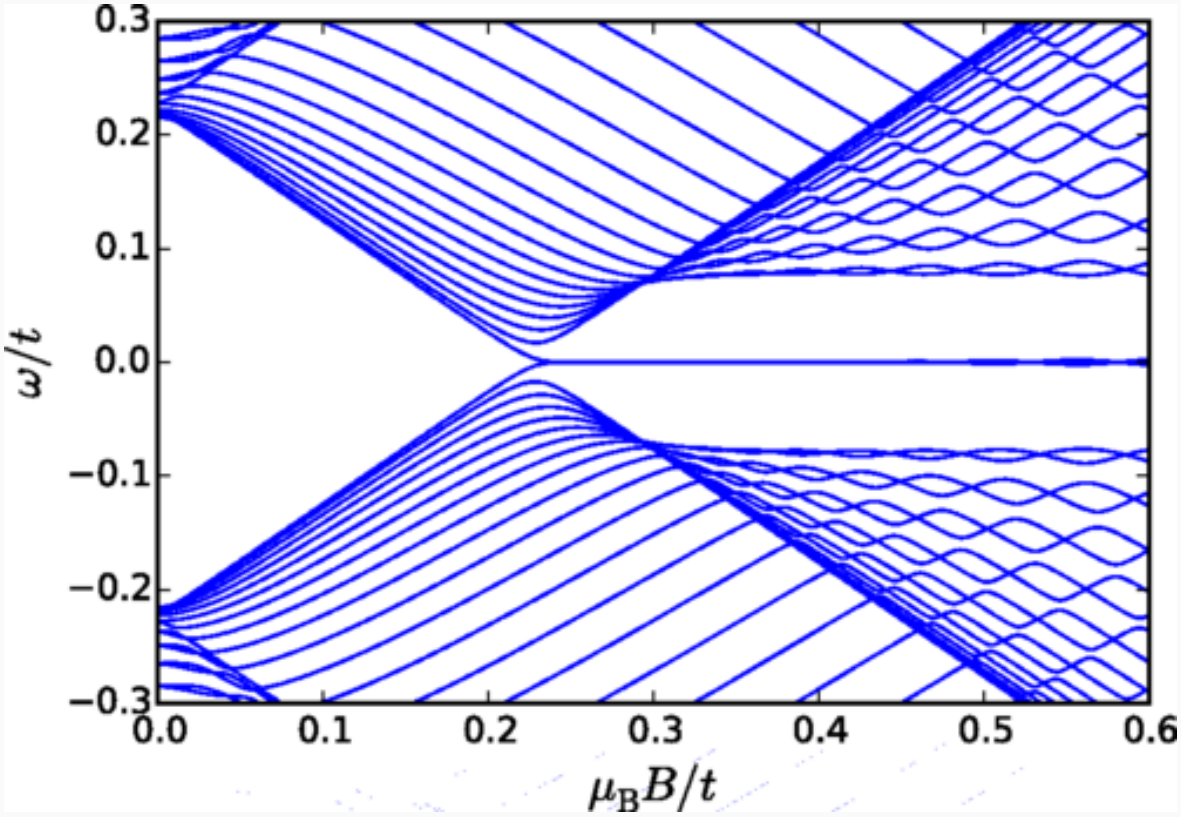


F. Nichele, ..., and Ch. Marcus, Phys. Rev. Lett. **119**, 136803 (2017).

/ Niels Bohr Institute, Copenhagen, Denmark /

TRANSITION FROM TRIVIAL TO TOPOLOGICAL PHASE

A pair of the Shiba (Andreev) states evolve into the Majorana qps

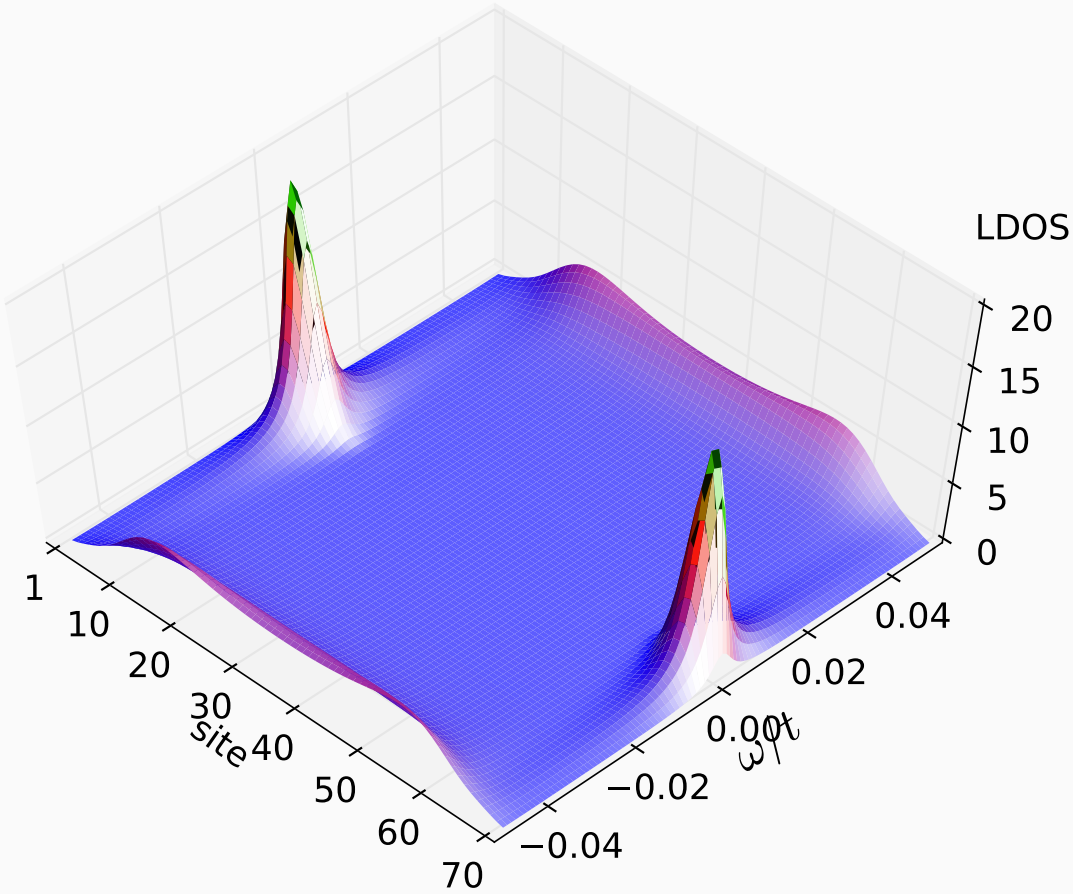


Mutation of the trivial bound states into the nontrivial Majorana modes

M.M. Maśka, A. Gorczyca-Goraj, J. Tworzydło, T. Domański, PRB 95, 045429 (2017).

Low energy quasiparticles of the Rashba nanowire

$t_{35}/t = 1.0$



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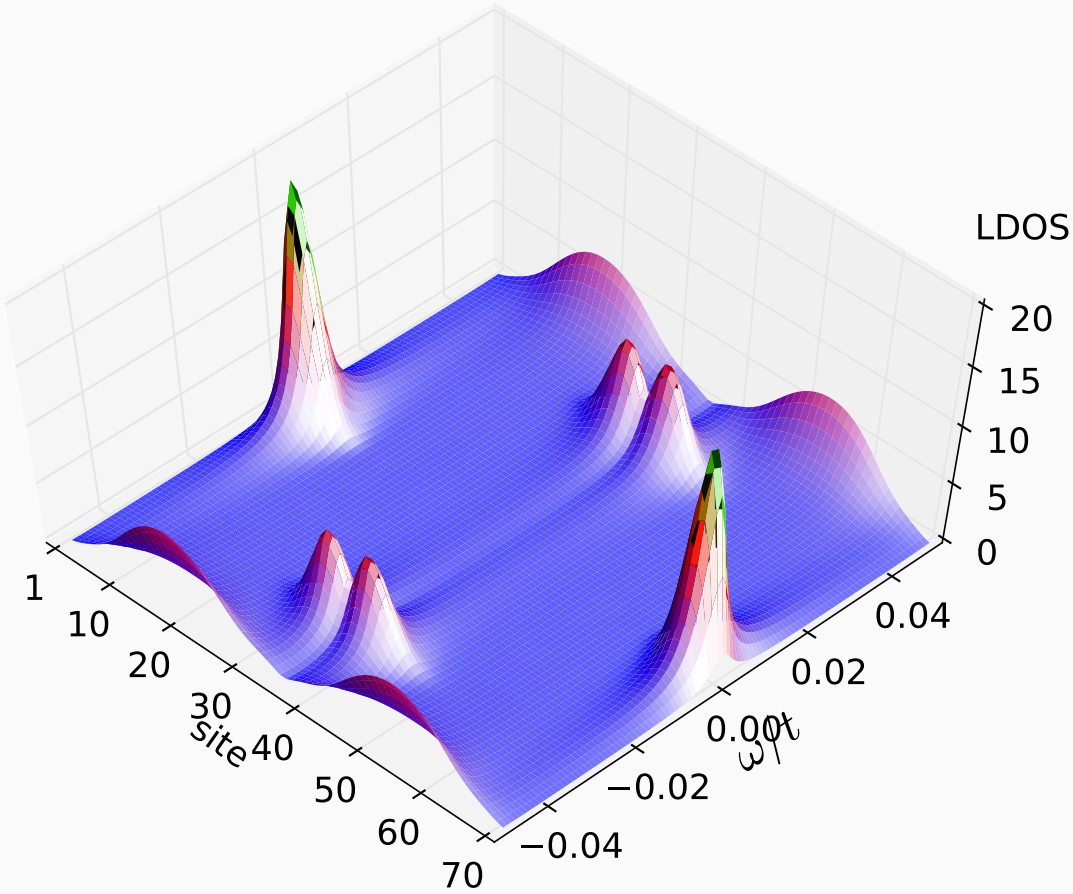
Low energy quasiparticles of the Rashba nanowire

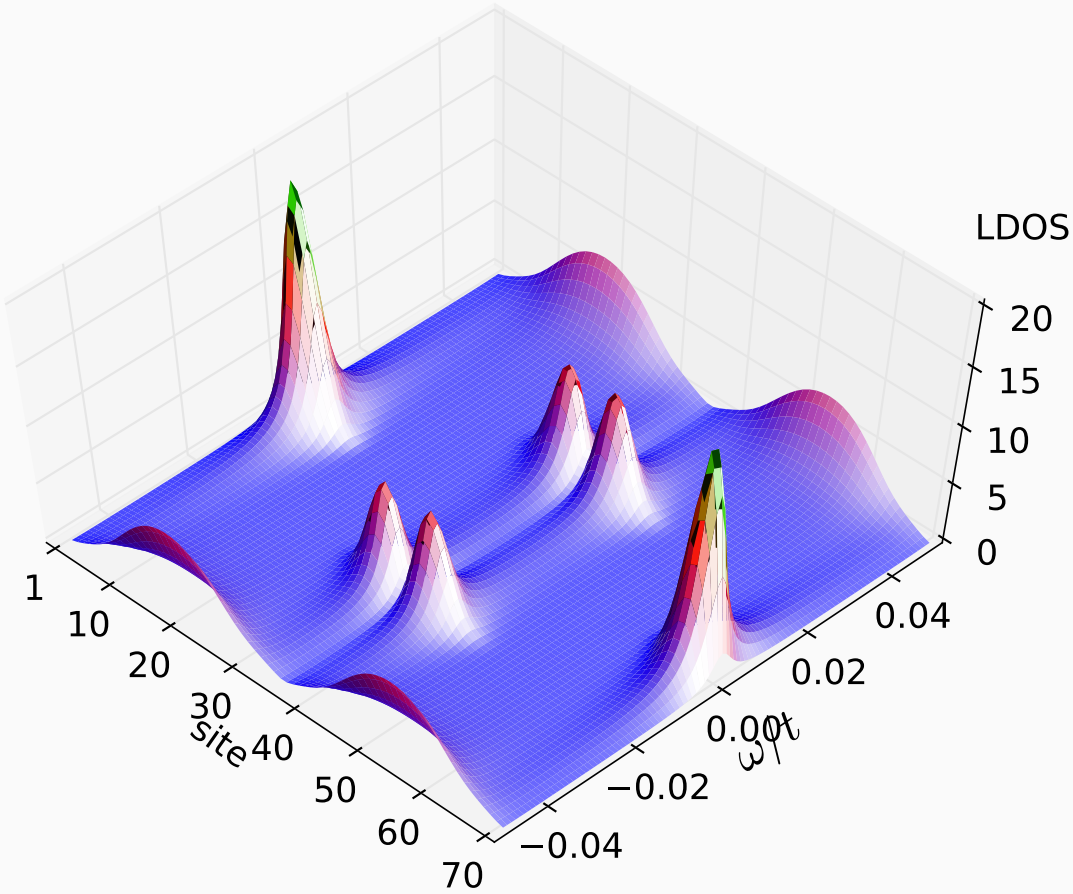
$t_{35}/t = 0.8$



M.M. Maśka, A. Gorczyca-Goraj, J. Tworzydło, T. Domański, PRB 95, 045429 (2017).

Low energy quasiparticles of the Rashba nanowire

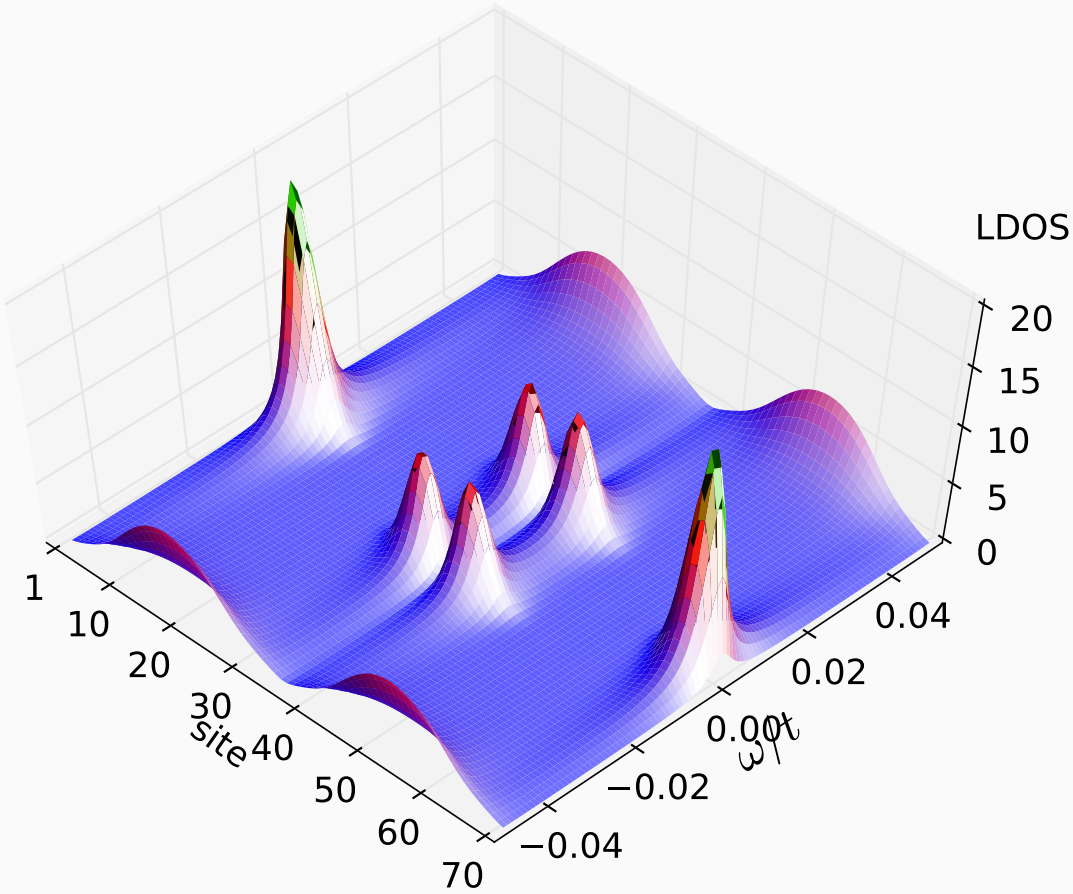
$t_{35}/t = 0.6$



M.M. Maśka, A. Gorczyca-Goraj, J. Tworzydło, T. Domański, PRB 95, 045429 (2017).

Low energy quasiparticles of the Rashba nanowire

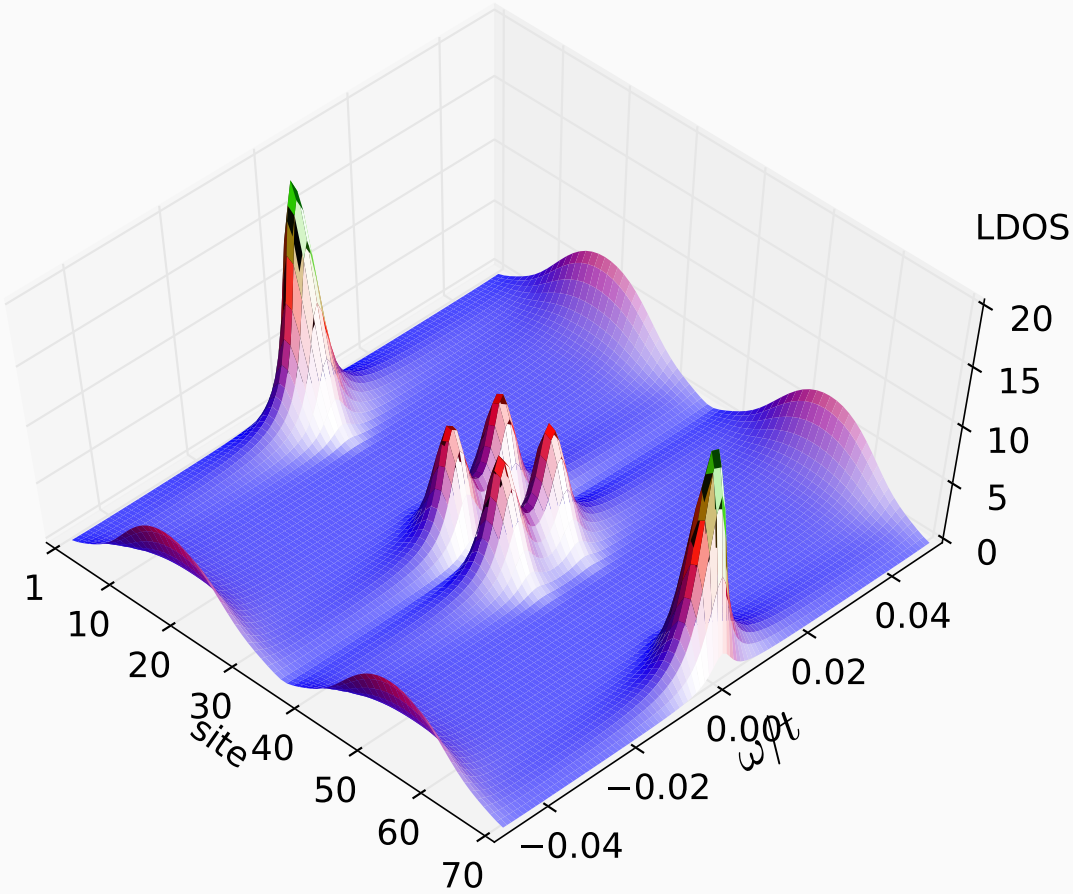
$t_{35}/t = 0.4$



M.M. Maśka, A. Gorczyca-Goraj, J. Tworzydło, T. Domański, PRB 95, 045429 (2017).

Low energy quasiparticles of the Rashba nanowire

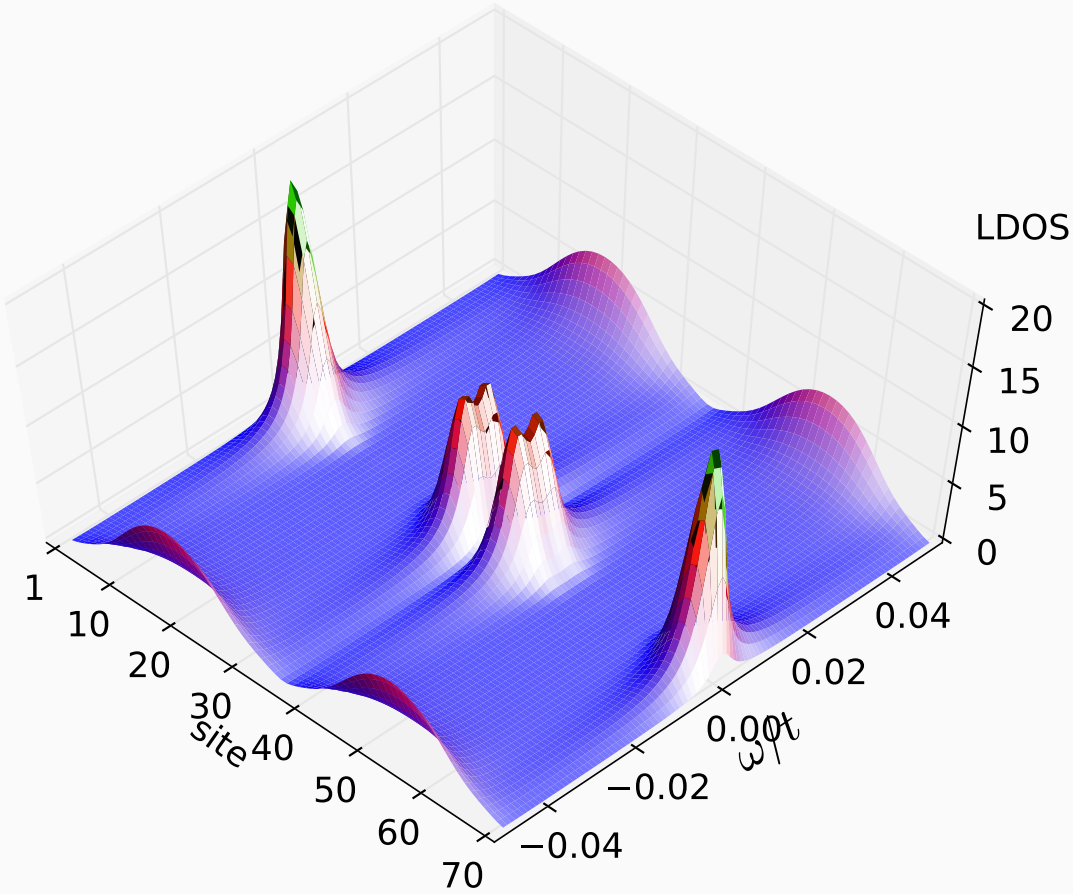
$t_{35}/t = 0.2$



M.M. Maśka, A. Gorczyca-Goraj, J. Tworzydło, T. Domański, PRB 95, 045429 (2017).

Low energy quasiparticles of the Rashba nanowire

$t_{35}/t = 0.1$



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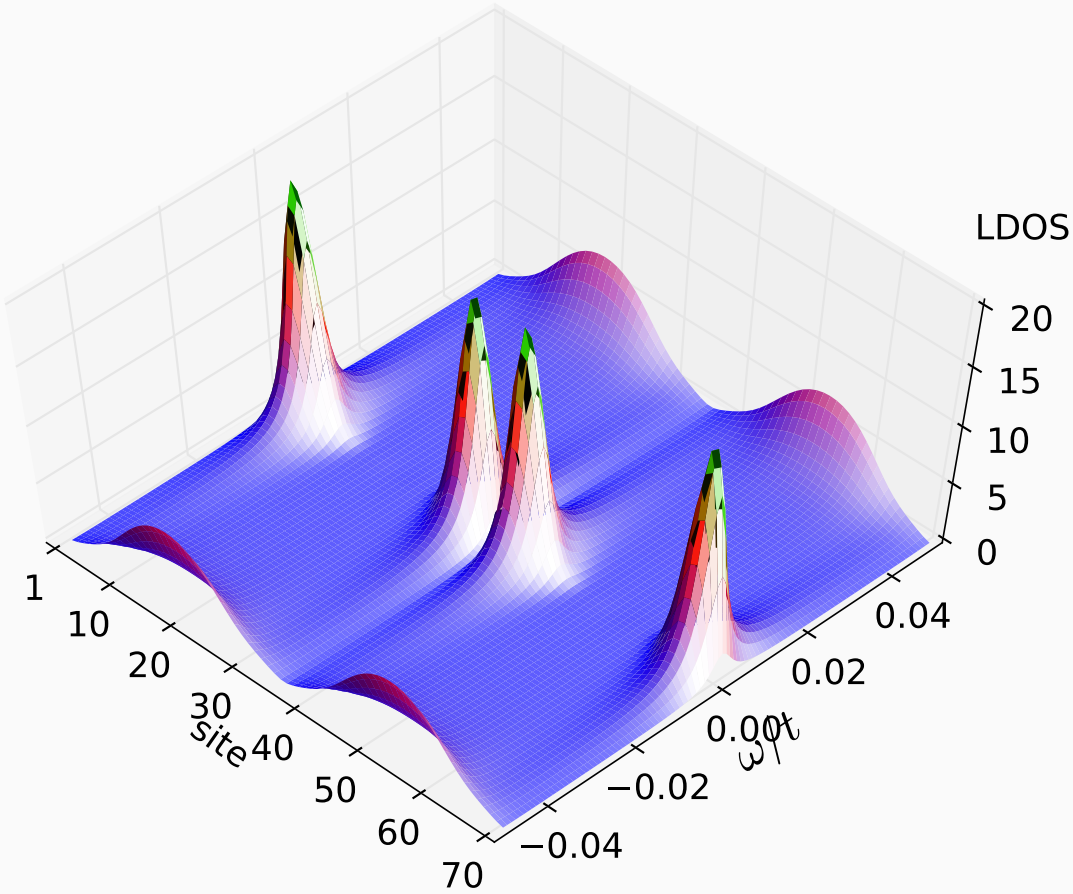
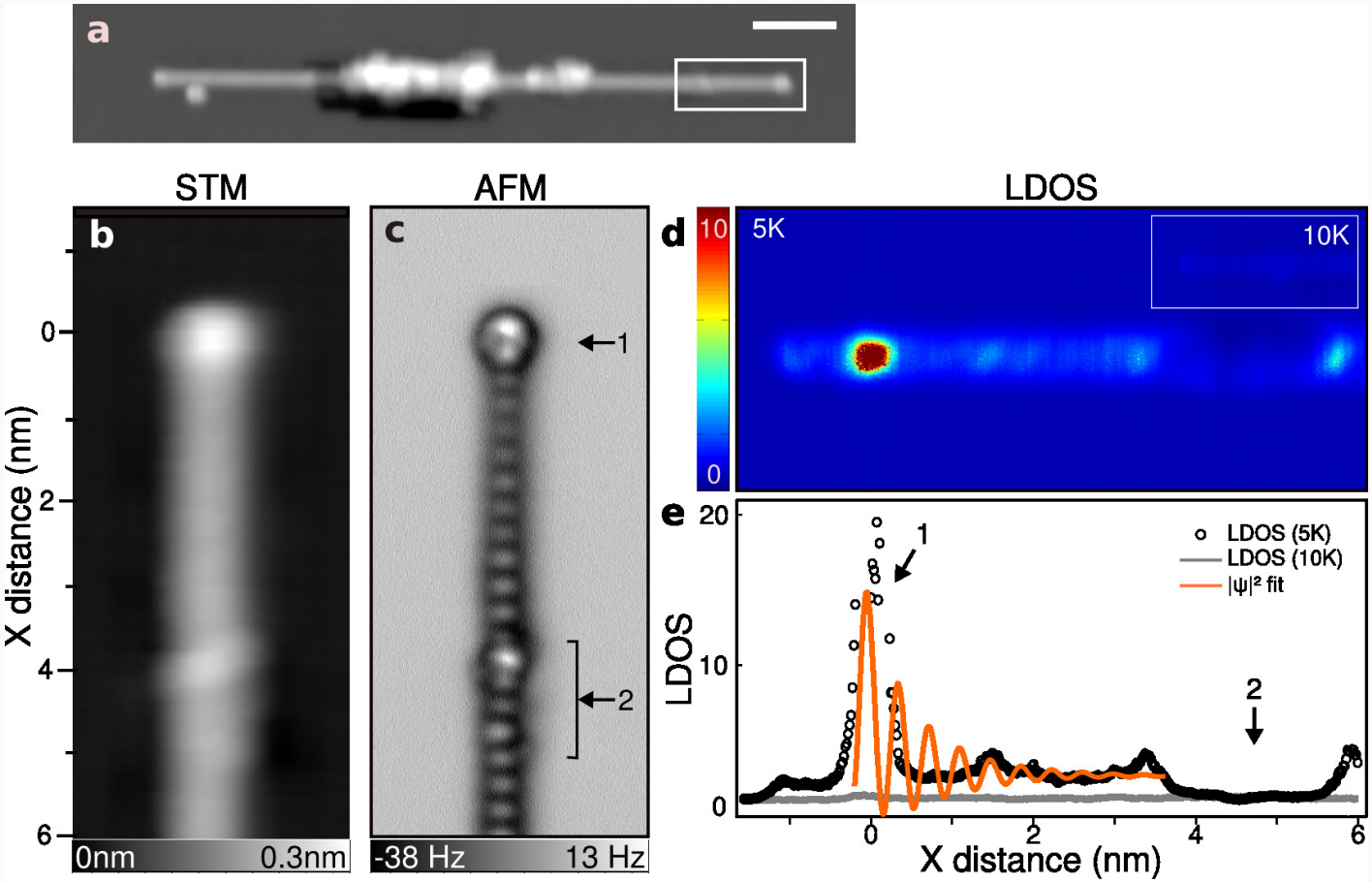


M.M. Maśka, A. Gorczyca-Goraj, J. Tworzydło, T. Domański, PRB 95, 045429 (2017).

AFM & STM data for Fe chain on Pb(110) surface



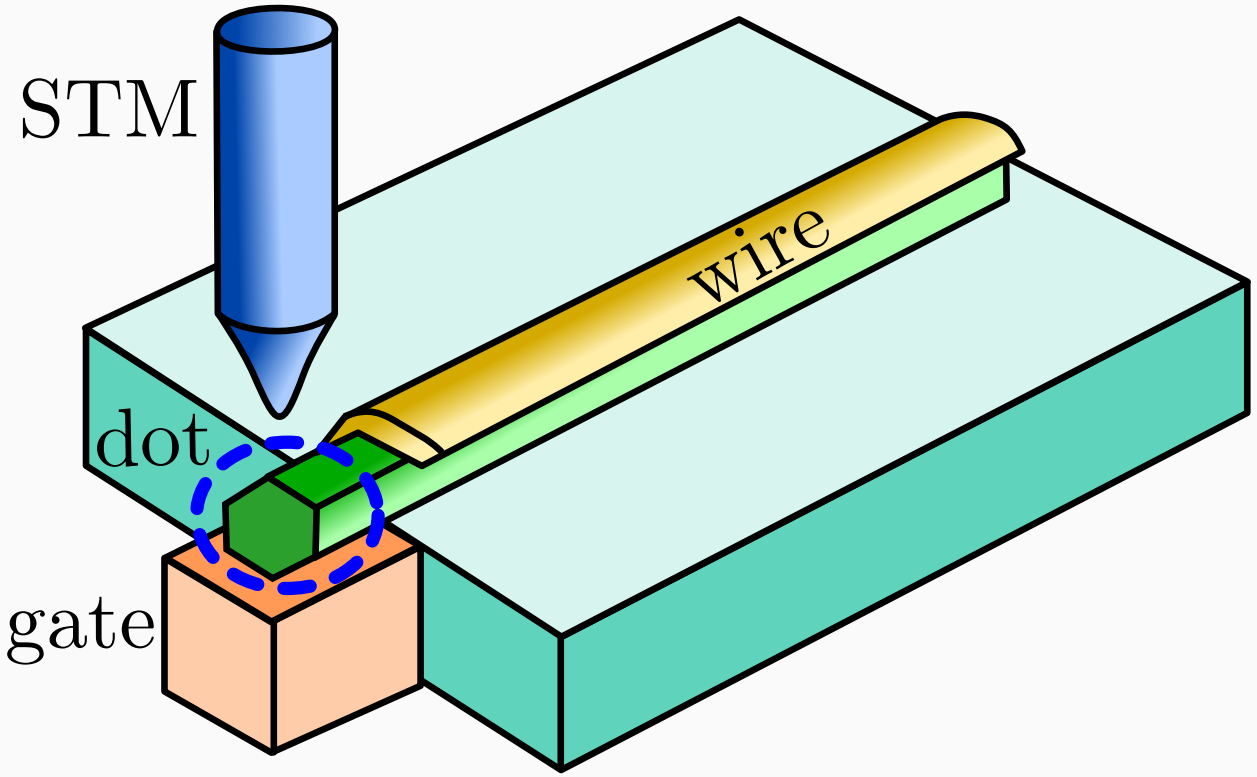
R. Pawlak, M. Kisiel *et al*, npj Quantum Information **2**, 16035 (2016).

/ University of Basel, Switzerland /

Trivial vs Majorana qps

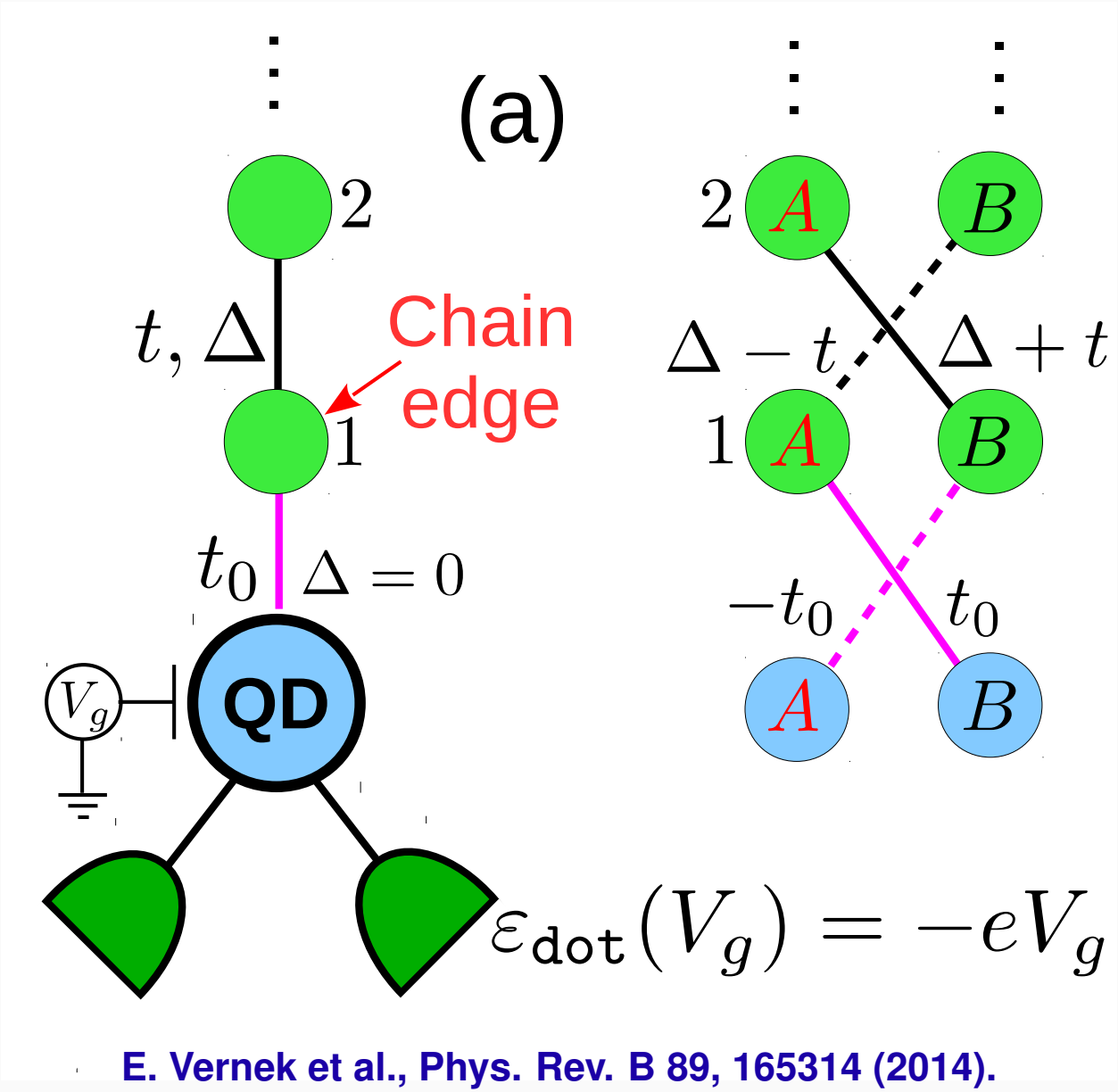
TRIVIAL VS MAJORANA BOUND STATES

Schematics of a quantum dot – nanowire hybrid structure.



A. Ptok, A. Kobiałka & T. Domański, Phys. Rev. 96, 195403 (2017).

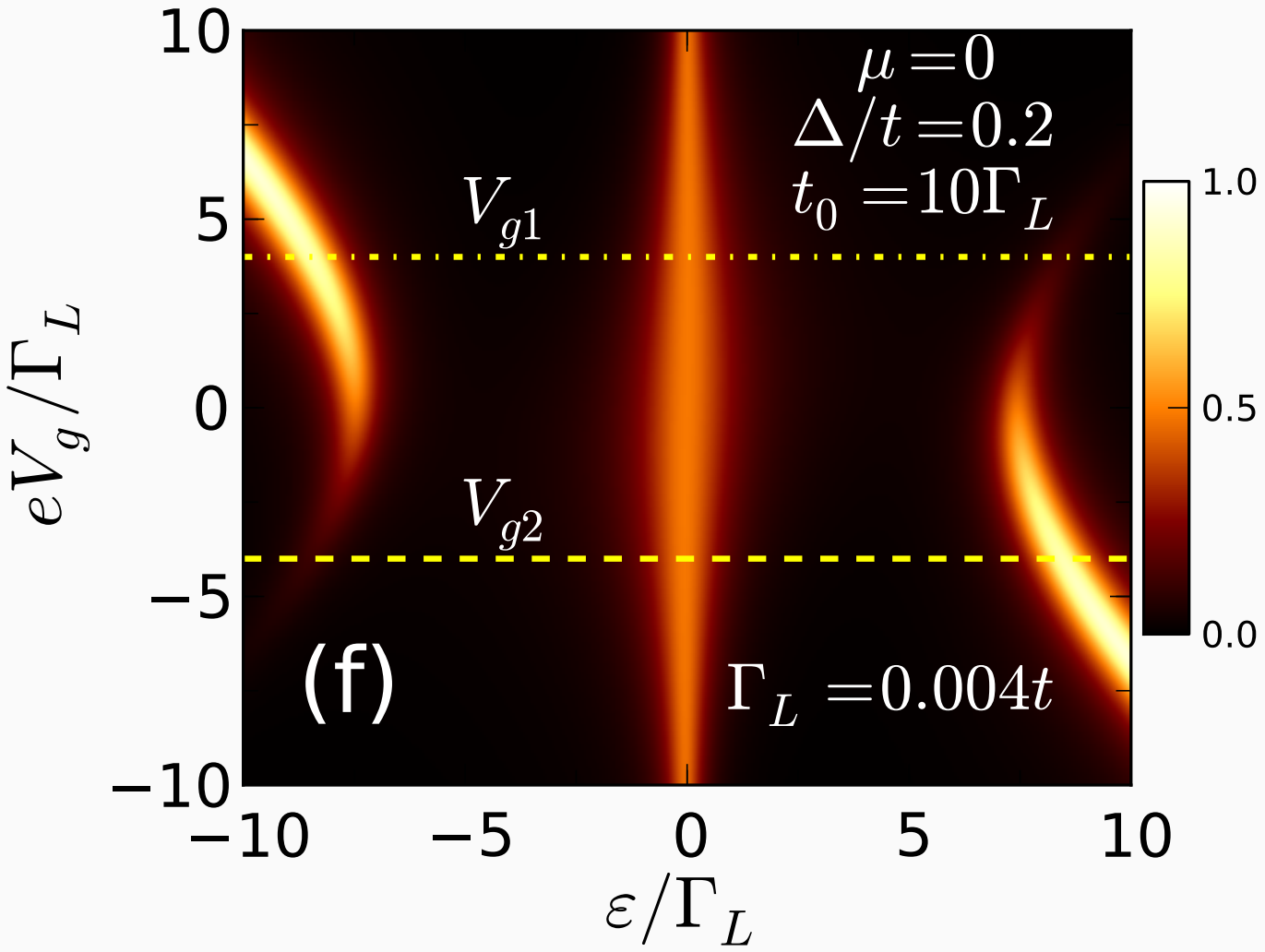
KITAEV CHAIN + NORMAL SITE



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

KITAEV CHAIN + NORMAL SITE

Subtle leakage of a Majorana mode into a quantum dot



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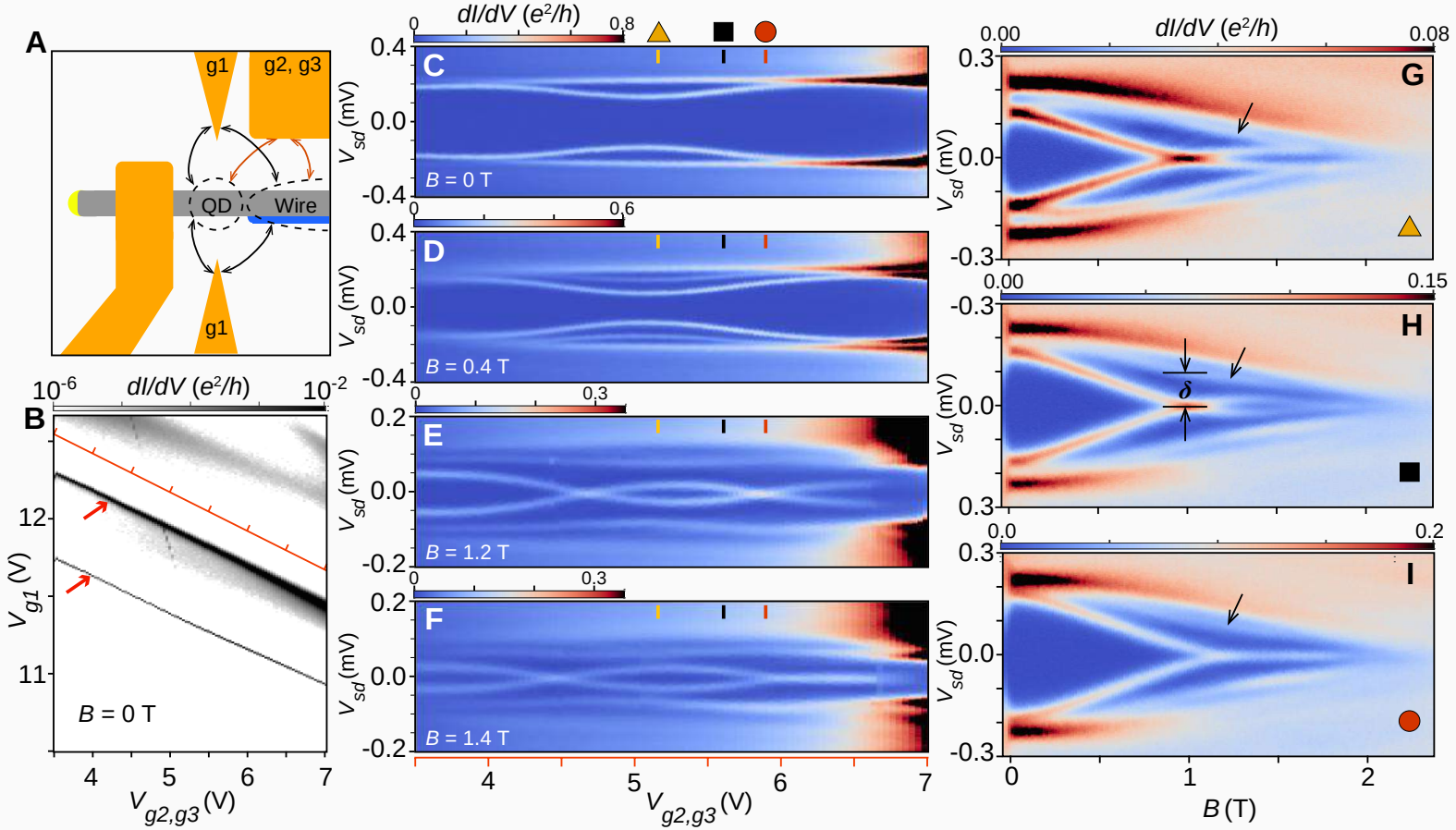
LEAKAGE OF MAJORANAS ON QUANTUM DOT

‘Coalescence’ of the Andreev into Majorana qps

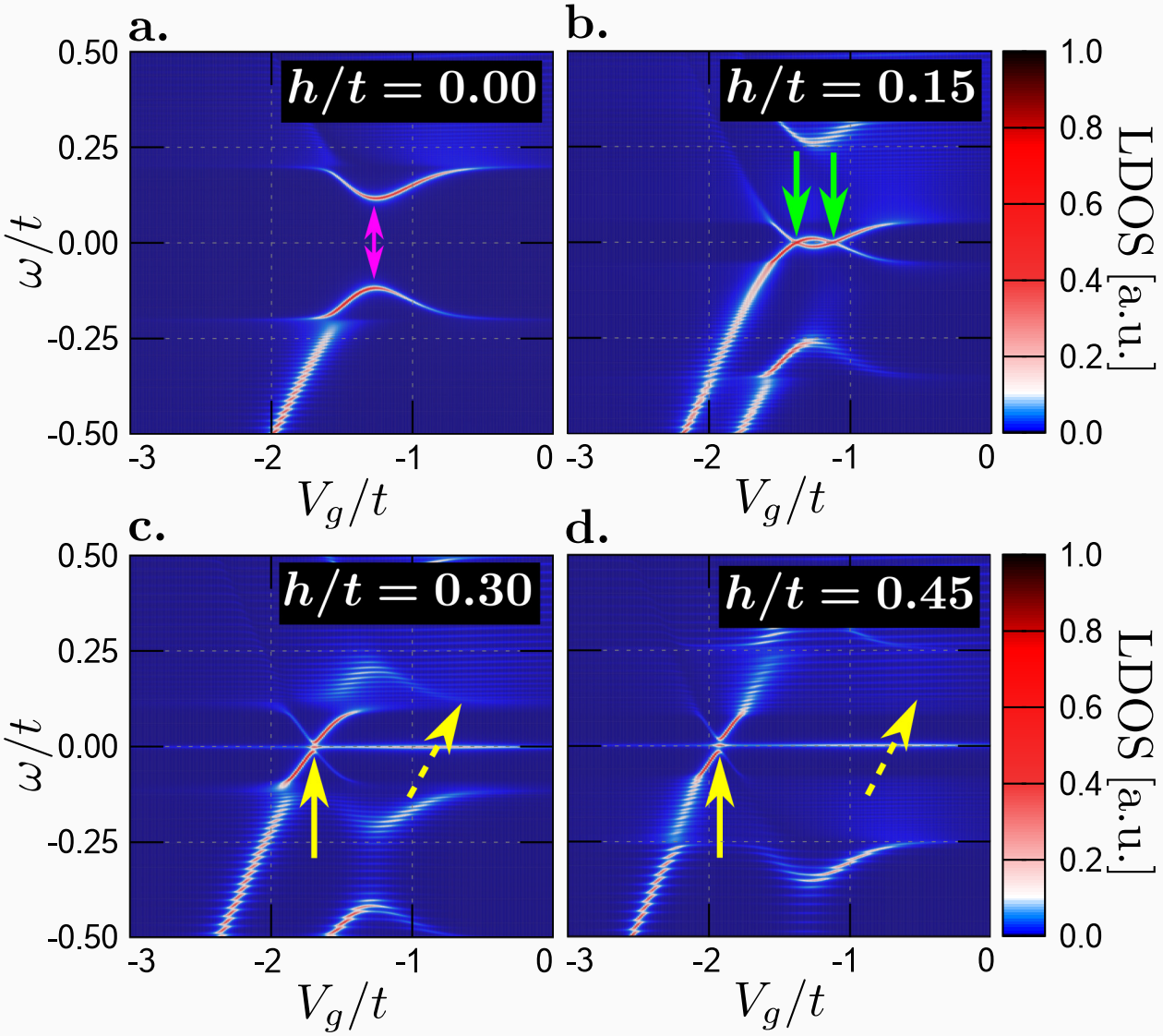


M.T. Deng, ..., and Ch. Marcus, Science 354, 1557 (2016).

/ Niels Bohr Institute, Copenhagen, Denmark /

DISTINGUISHING ANDREEV FROM MAJORANA QPS

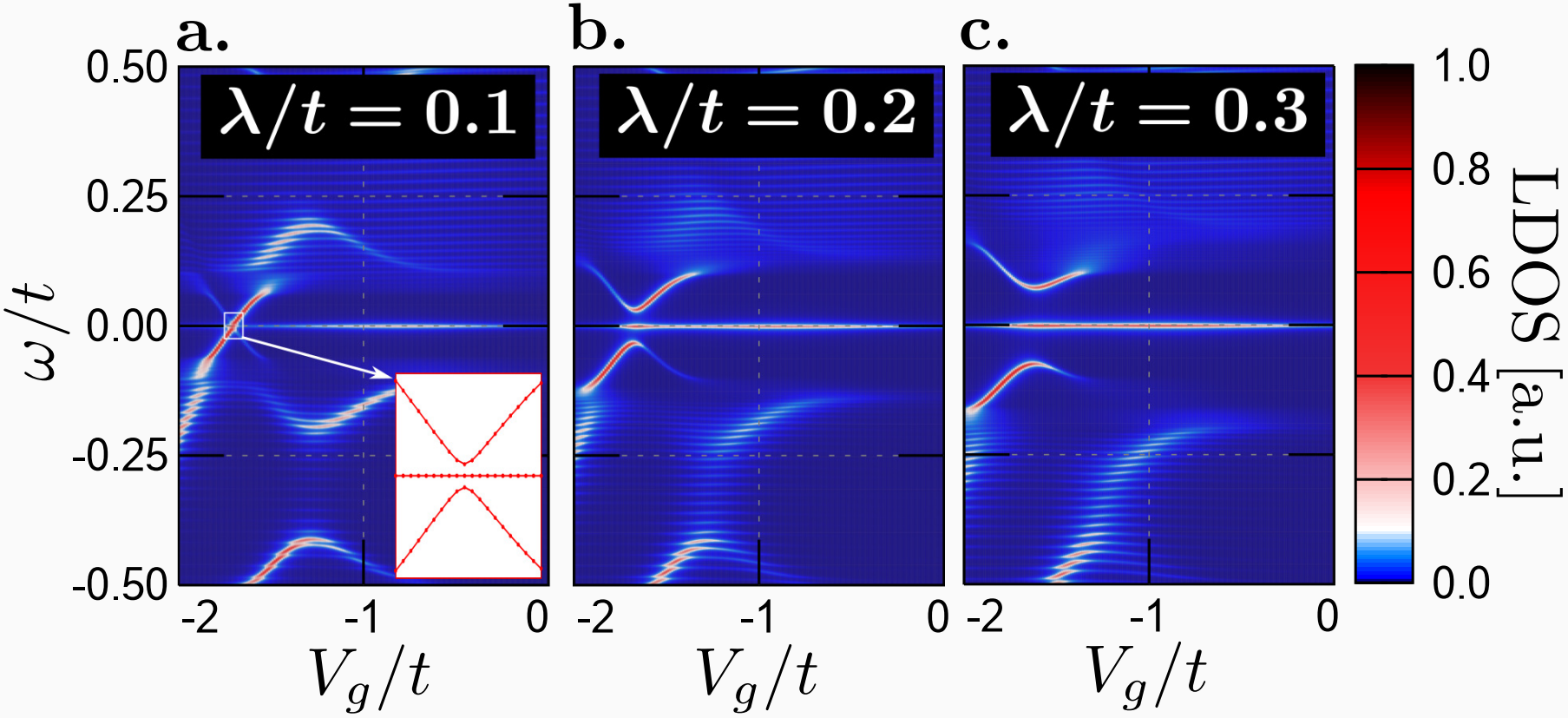
QD spectrum vs gate potential V_g for several magnetic fields h.



A. Ptok, A. Kobiałka & T. Domański, Phys. Rev. 96, 195403 (2017).

DISTINGUISHING ANDREEV FROM MAJORANA QPS

QD spectrum vs gate potential V_g for various spin-orbit couplings λ.



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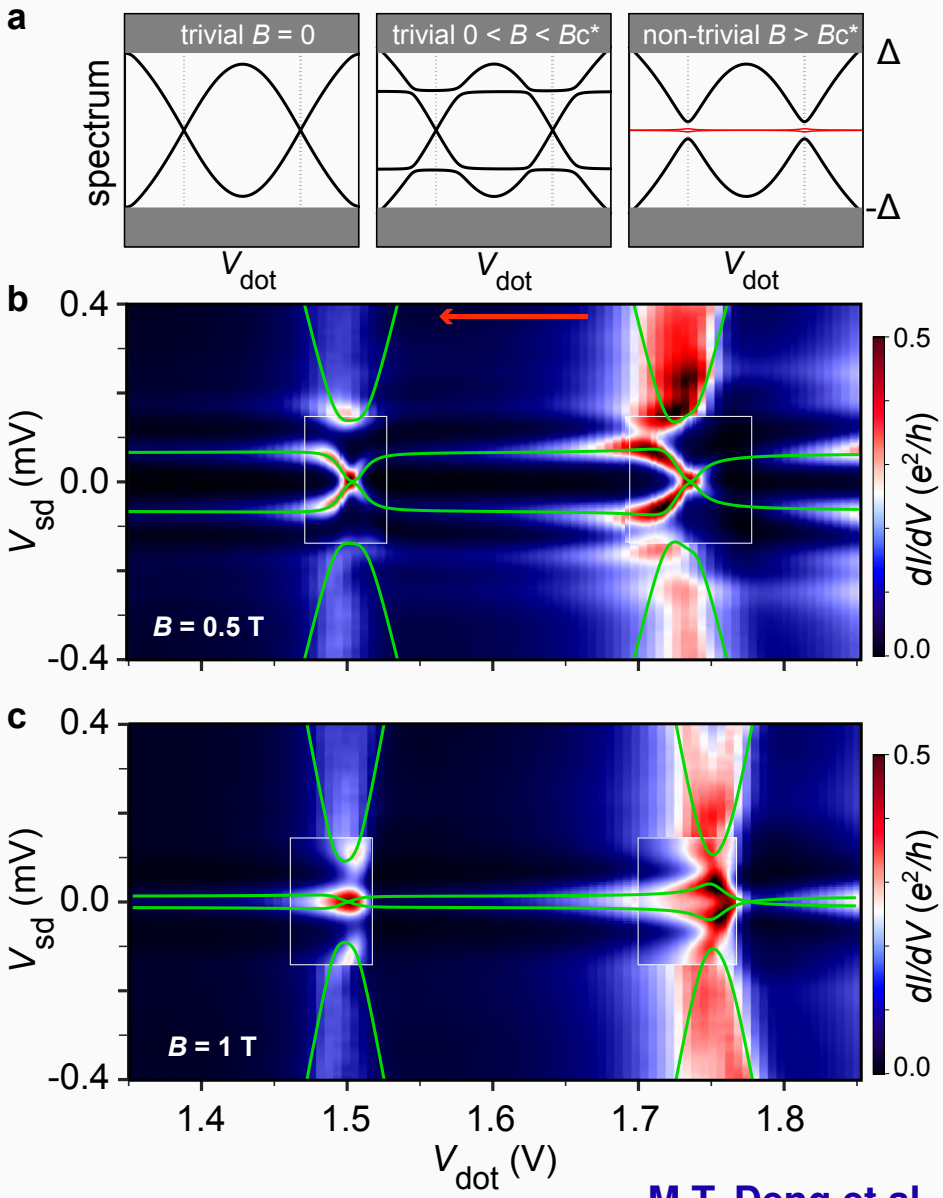
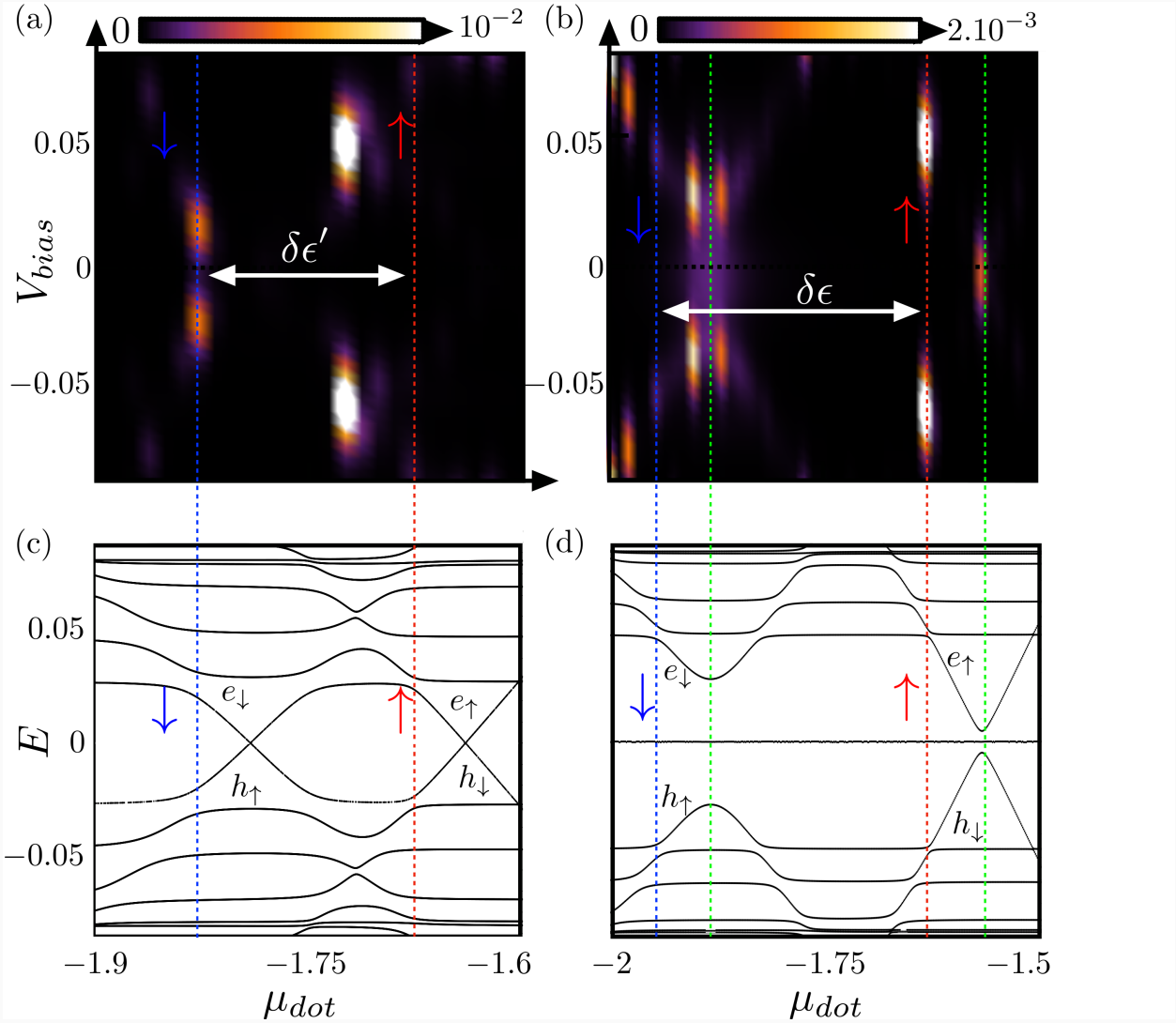
DISTINGUISHING ANDREEV FROM MAJORANA QPS



M.T. Deng et al., Phys. Rev. B 98, 085125 (2018).

DISTINGUISHING ANDREEV FROM MAJORANA QPS



D. Chevallier, ... and J. Klinovaja, Phys. Rev. B 97, 04504 (2018).

ANDREEV VS MAJORANA: CONCLUSIONS

- **Low energy features are very distinct:**

ANDREEV VS MAJORANA: CONCLUSIONS

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ANDREEV VS MAJORANA: CONCLUSIONS

- **Low energy features are very distinct:**

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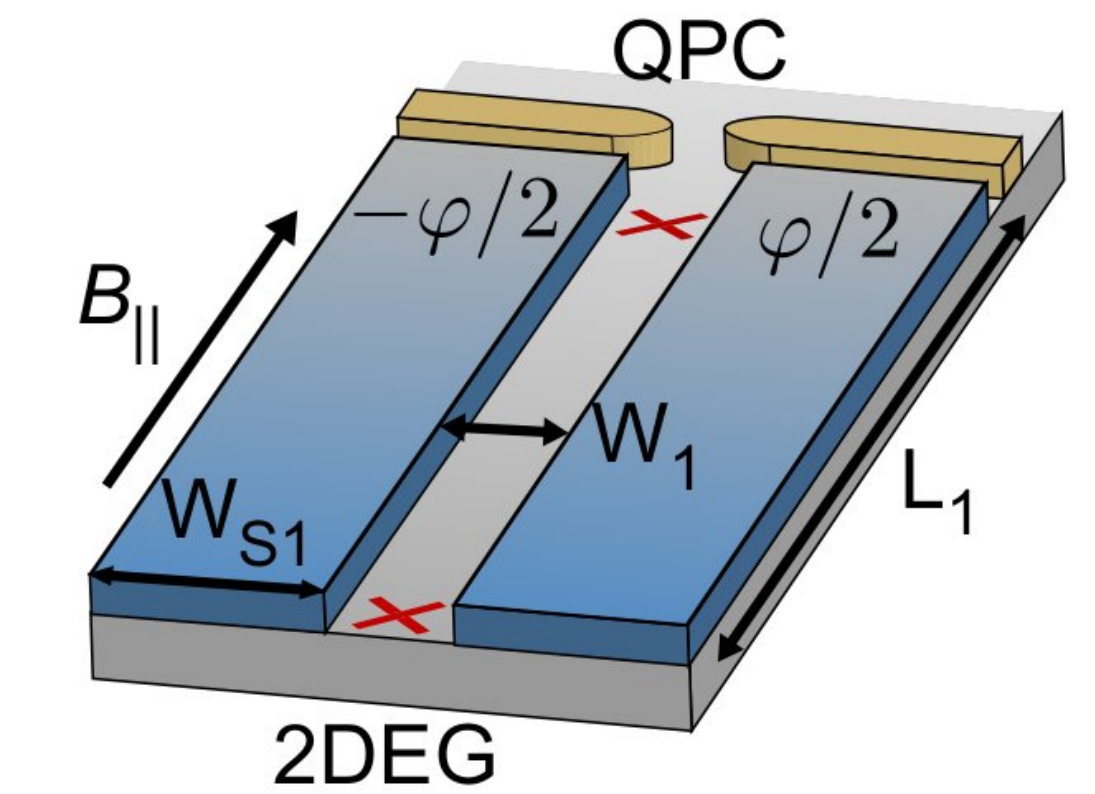
- **Misinterpretation:**

$\Rightarrow$ **coalescence of Andreev into Majorna qps**

Localized Majorana modes in dim=2

PLANAR JOSEPHSON JUNCTIONS

Two-dimensional electron gas of InAs epitaxially covered by a thin Al layer



Width:

W_1 = 80 nm

Length:

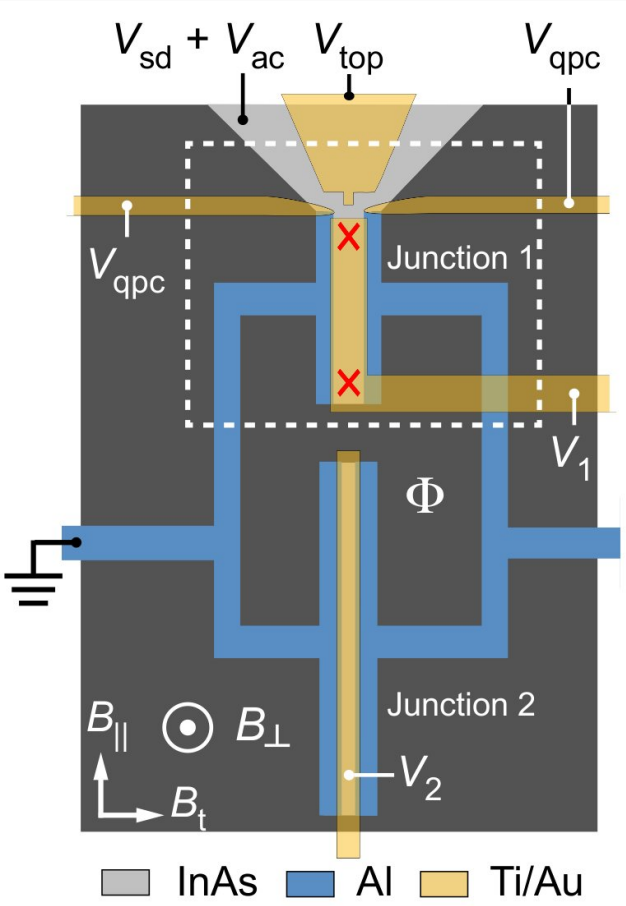
L_1 = 1.6 μm

A. Fornieri, ..., Ch. Marcus and F. Nichele, arXiv:1809.03037 (9 Sept 2018).

/ Niels Bohr Institute (Copenhagen, Denmark) /

PLANAR JOSEPHSON JUNCTIONS

Majorana qps at the ends of 2DEG depend on the phase-difference Φ

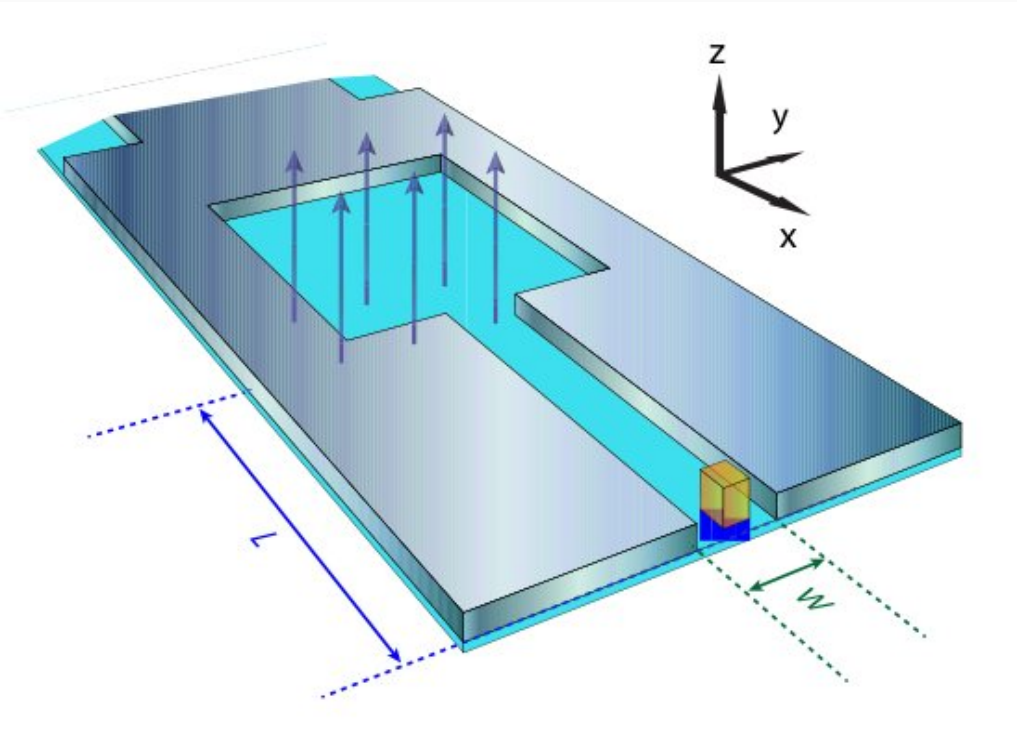


A. Fornieri, ..., Ch. Marcus and F. Nichele, arXiv:1809.03037 (9 Sept 2018).

/ Niels Bohr Institute (Copenhagen, Denmark) /

PLANAR JOSEPHSON JUNCTIONS

Two-dimensional HgTe quantum well coupled to thin Al film

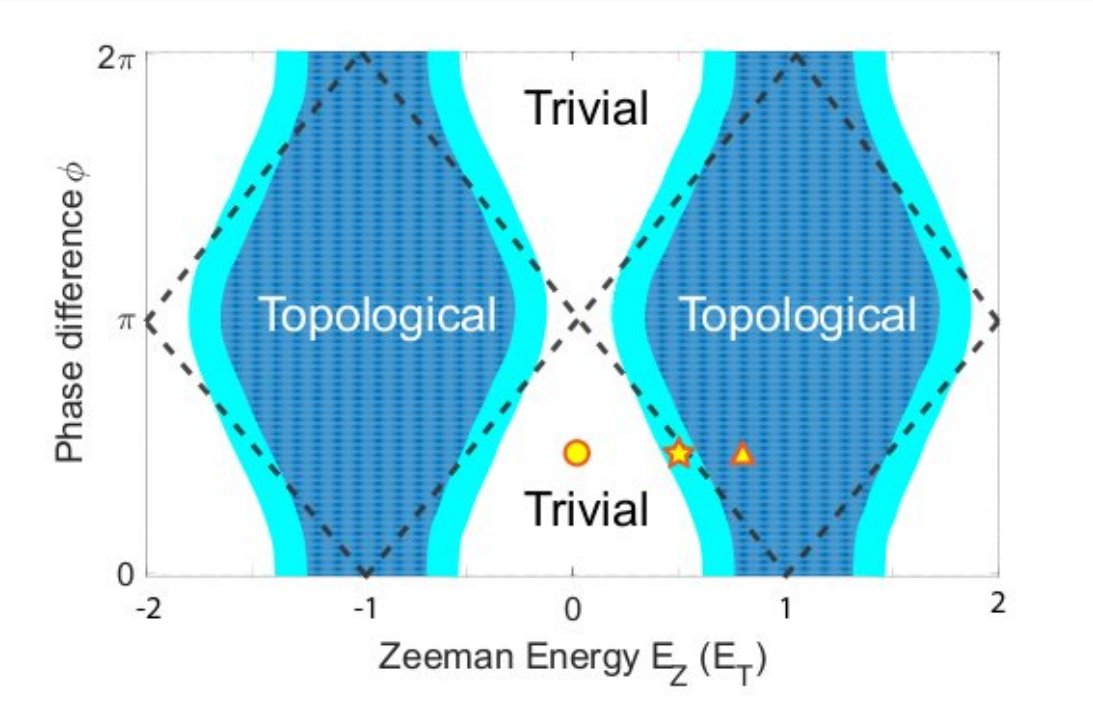


H. Ren, ..., L.W. Molenkamp, B.I. Halperin, A. Yacoby, arXiv:1809.03076 (10 Sept 2018).

/ Würzburg Univ. (Germany) + Harvard Univ. (USA) /

PLANAR JOSEPHSON JUNCTIONS

Tuning between the trivial and topological superconducting state by phase difference ϕ and in-plane magnetic field



H. Ren, ..., L.W. Molenkamp, B.I. Halperin, A. Yacoby, arXiv:1809.03076 (10 Sept 2018).

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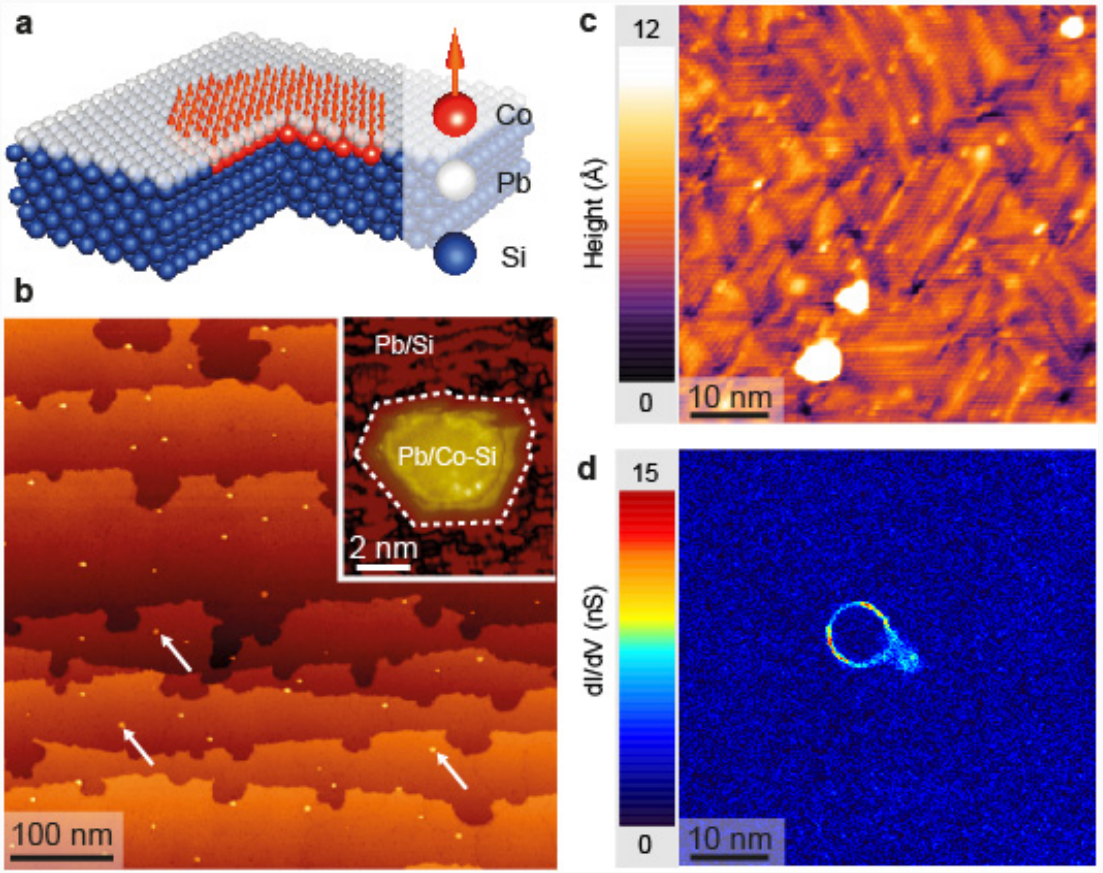
Edge modes in dim=2 systems

TWO-DIMENSIONAL MAGNETIC STRUCTURES

Magnetic island of Co atoms deposited on the superconducting Pb surface



Diameter of island:

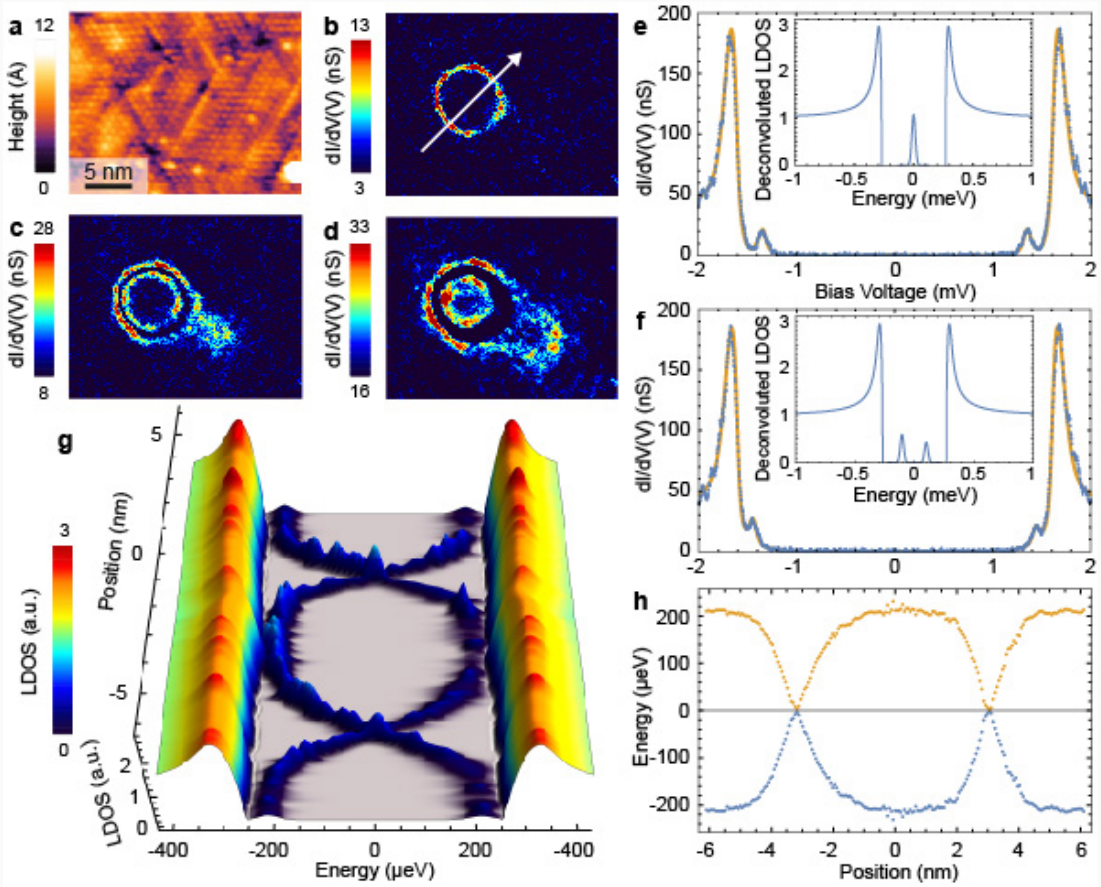
5 – 10 nm

G. Ménard, ..., and P. Simon, Nature Commun. **8**, 2040 (2017).

/ P. & M. Curie University (Paris, France) /

EVIDENCE FOR DELOCALIZED MAJORANA MODES

Majorana modes propagating along magnetic islands

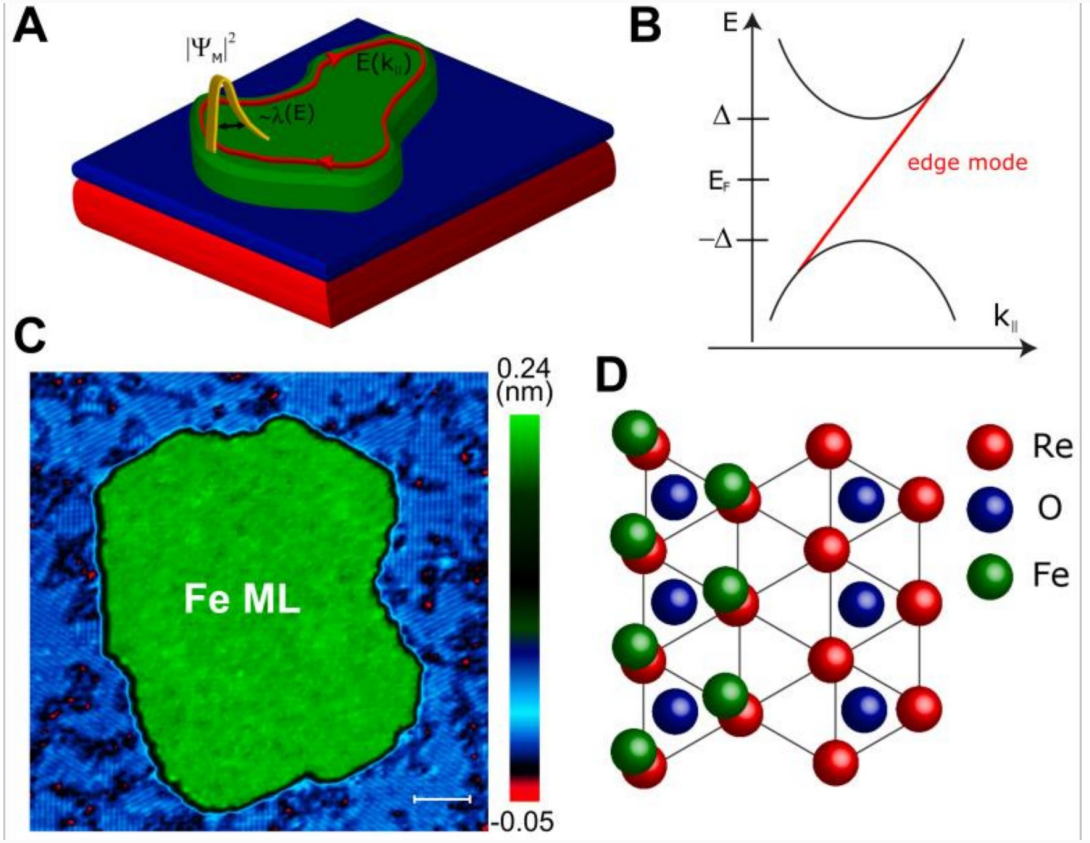


G. Ménard, ..., and P. Simon, Nature Commun. **8**, 2040 (2017).

/ P. & M. Curie University (Paris, France) /

PROPAGATING MAJORANA EDGE MODES

Magnetic island of Fe atoms deposited on the superconducting Re surface



Chern number:

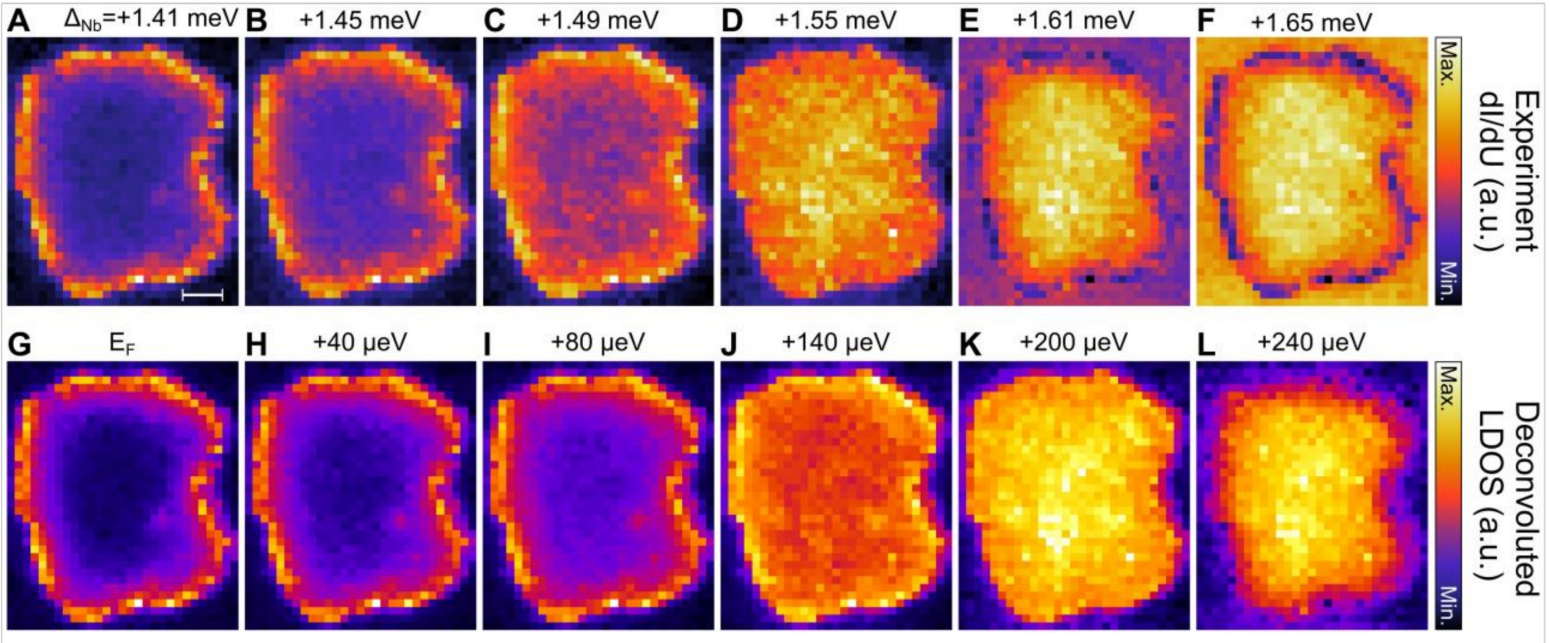
C = 20

A. Palacio-Morales, ..., and R. Wiesendanger, arXiv:1809.04503 (preprint).

/ University of Hamburg (Germany) /

PROPAGATING MAJORANA EDGE MODES

Real space maps of the tunneling conductance (top panel) and deconvoluted DOS (bottom panel) obtained for various energies (as indicated) in the subgap regime ($\Delta = 240 \mu eV$).



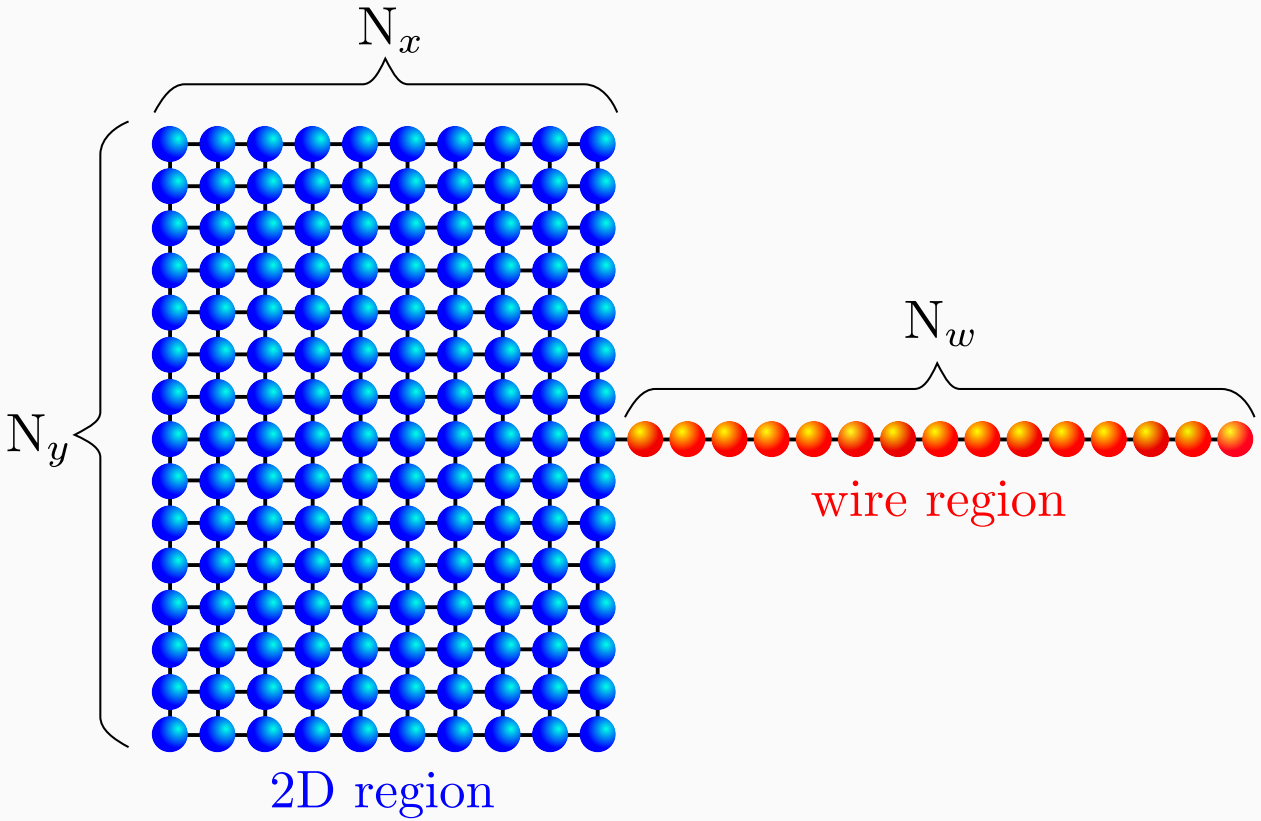
A. Palacio-Morales, ..., and R. Wiesendanger, arXiv:1809.04503 (preprint).

/ University of Hamburg (Germany) /

Mixed – dimensionality structures

CAN MAJORANA QPS BE DECONFINED ?

Our project: **Majorana qps of the 1D–2D hybrid structure**



A. Kobiałka, T. Domański & A. Ptok, arXiv:1808.05281

TOPOLOGICAL INVARIANTS

Constituents of this hybrid-system belong to different homotopy groups:

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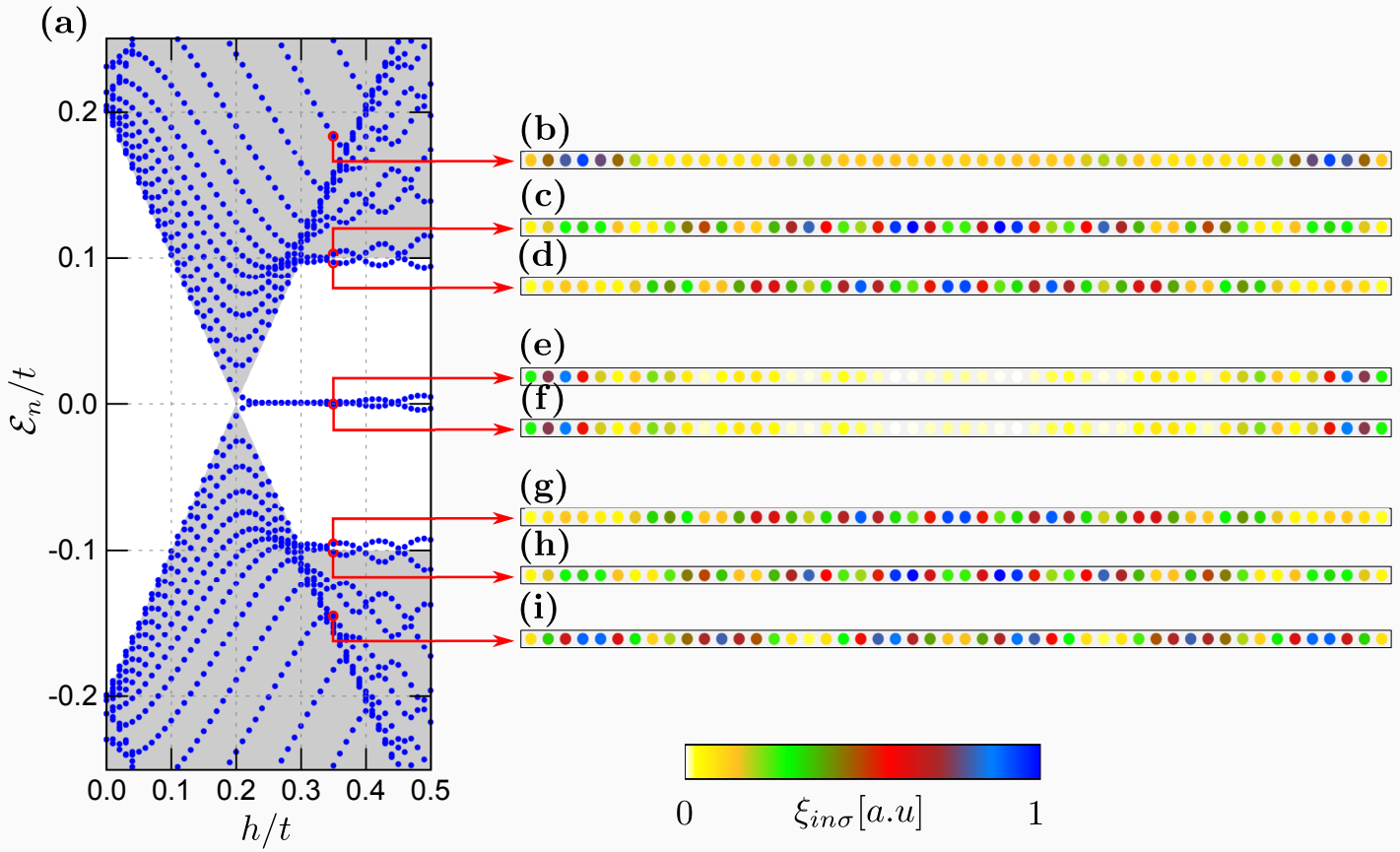
which can be characterized by the Chern number, that is equivalent to the Thouless–Kohmoto–Nightingale–den Nijs number.

For details, concerning the topological criteria see e.g.

- **A. Kitaev, AIP Conf. Proc. 1134, 22 (2009);**
- **M.Z. Hasan & C.L. Kane, Rev. Mod. Phys. 82, 3045 (2010);**
- **X.-L. Qi & S.-C. Zhang, Rev. Mod. Phys. 83, 1057 (2011).**

TRIVIAL VS MAJORANA MODES

Spatial distribution of quasiparticles in the nanowire



/ topological phase /

A. Kobiałka, T. Domański & A. Ptok, arXiv:1808.05281

TRIVIAL VS MAJORANA MODES

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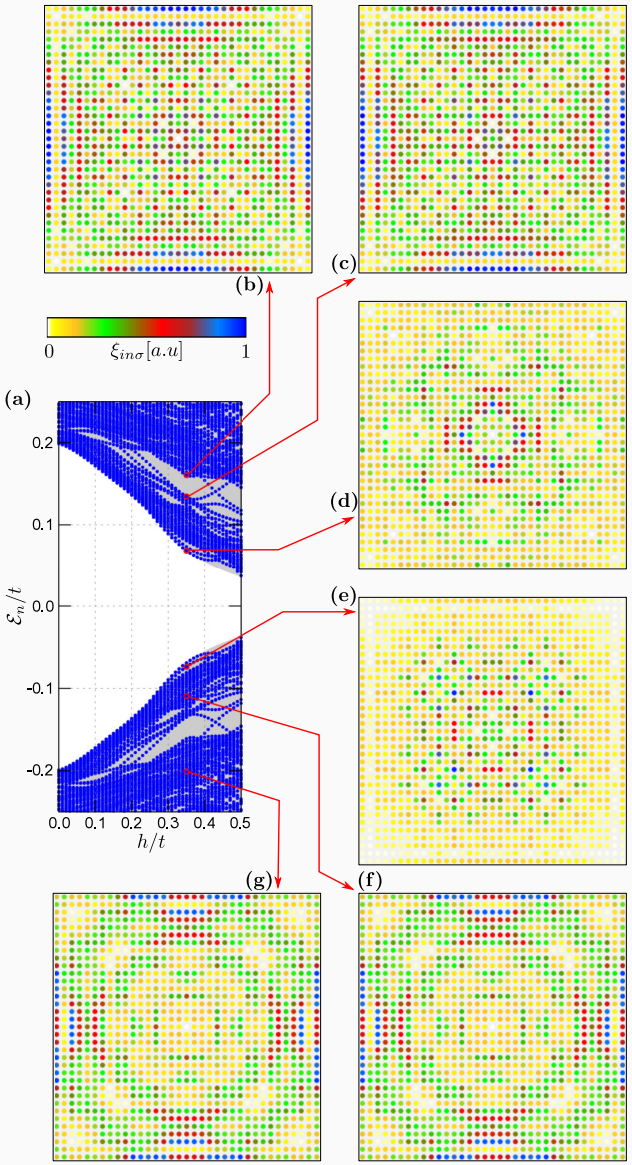

nontopological phase

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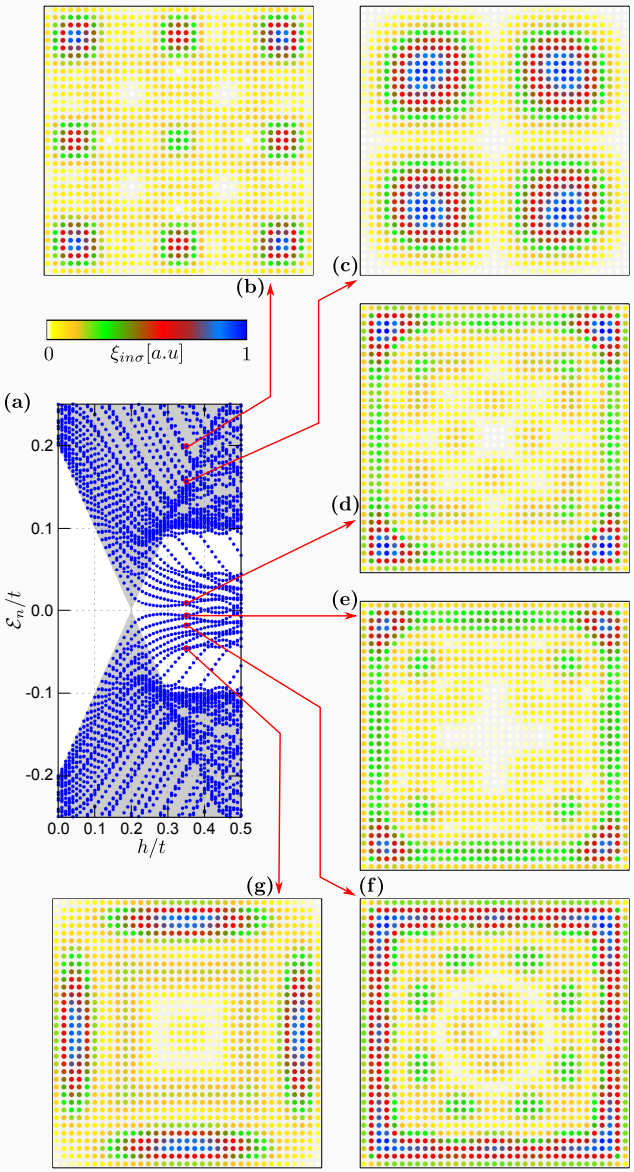
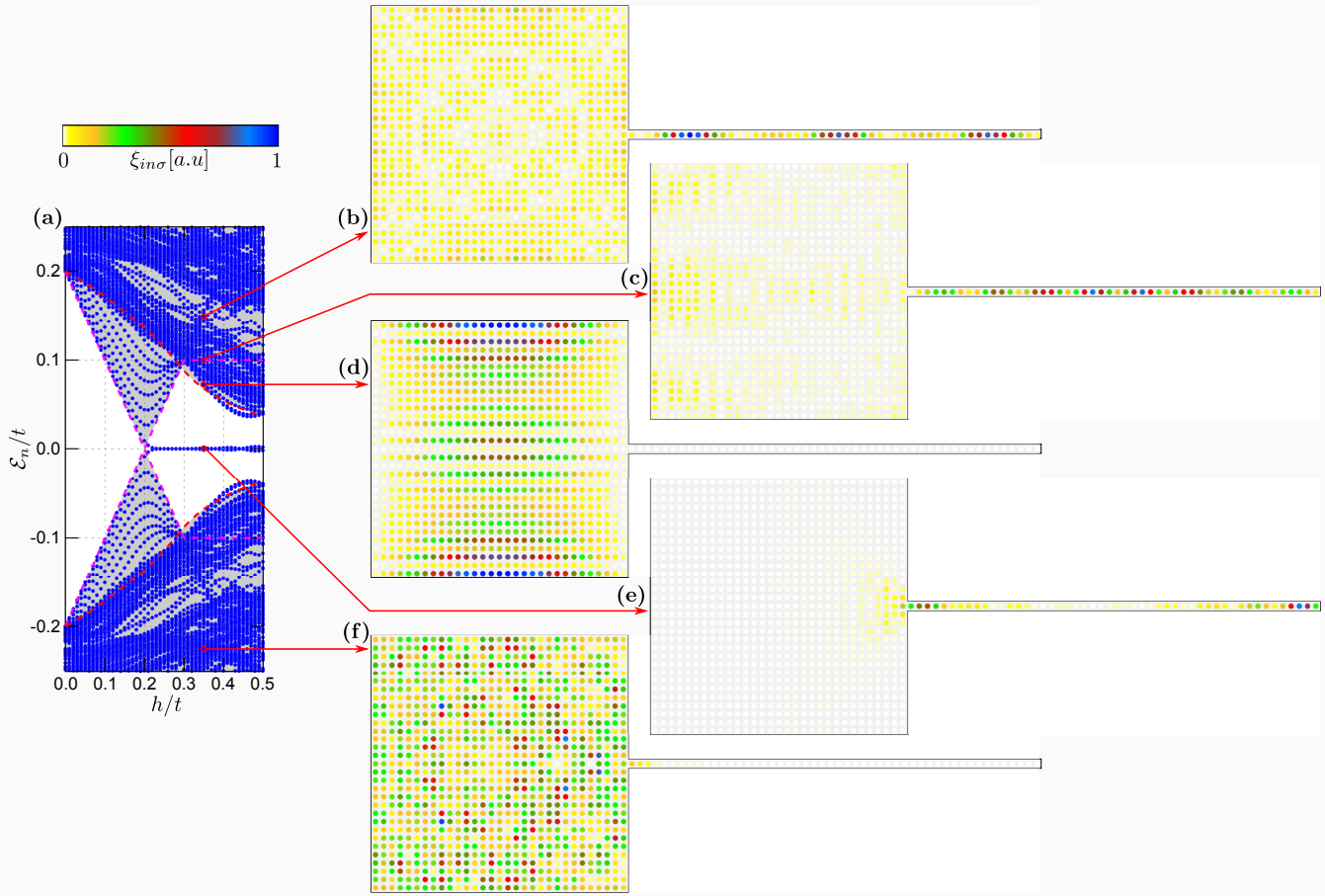


topological phase

TRIVIAL VS MAJORANA MODES

Majorana/Andreev quasiparticles of a wire-plaquette hybrid



plaquette: nontopological ***nanowire: topological***

A. Kobiałka, T. Domański & A. Ptok, arXiv:1808.05281

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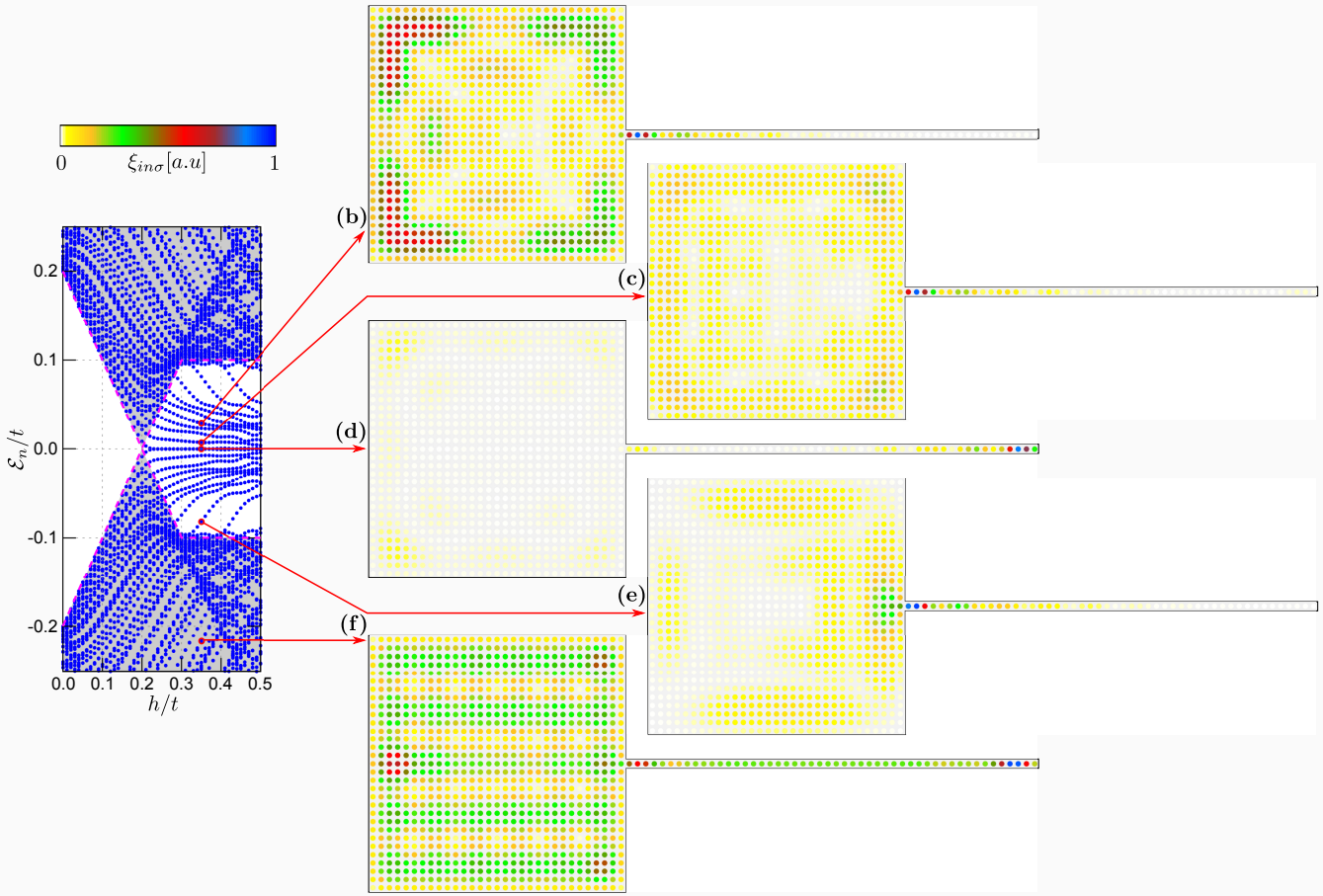

Both regions are assumed to be in topological sc phase.

A. Kobiałka, T. Domański & A. Ptok, arXiv:1808.05281

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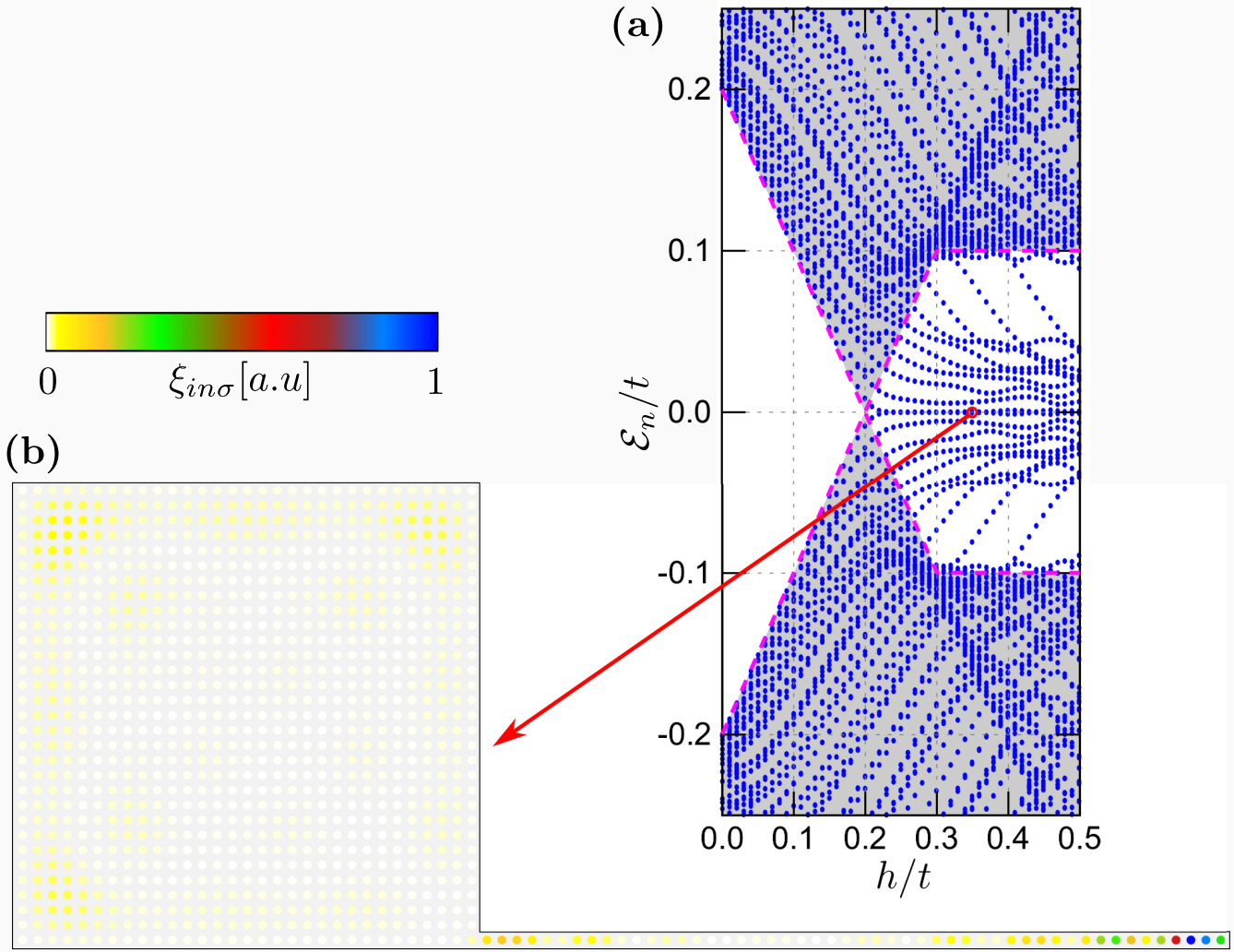

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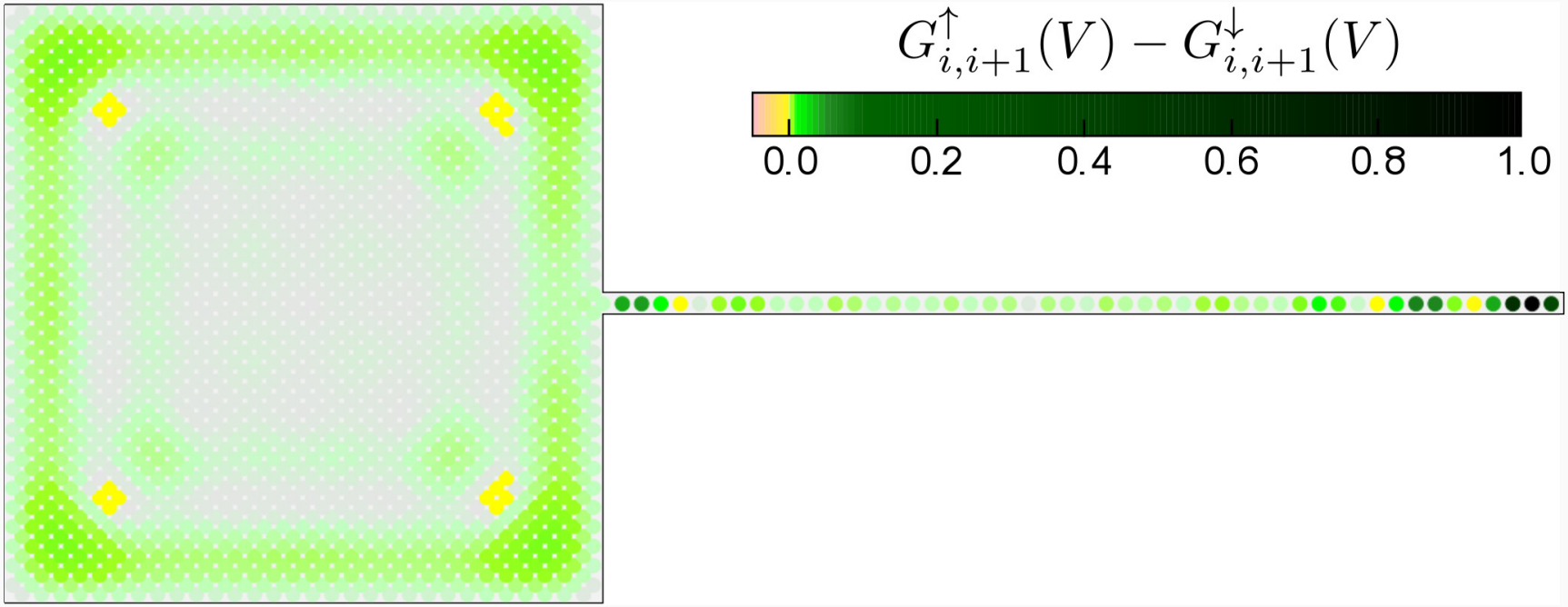
HOW TO DETECT (DE)LOCALIZED MAJORANA QPS

Maps of the SESAR tunneling conductance at zero-bias.



SESAR = Selective Equal Spin Andreev Reflection

A. Kobiałka, T. Domański & A. Ptok, arXiv:1808.05281

DIMENSIONAL HYBRID: CONCLUSION

Plaquette-nanowire hybrid structures enables:

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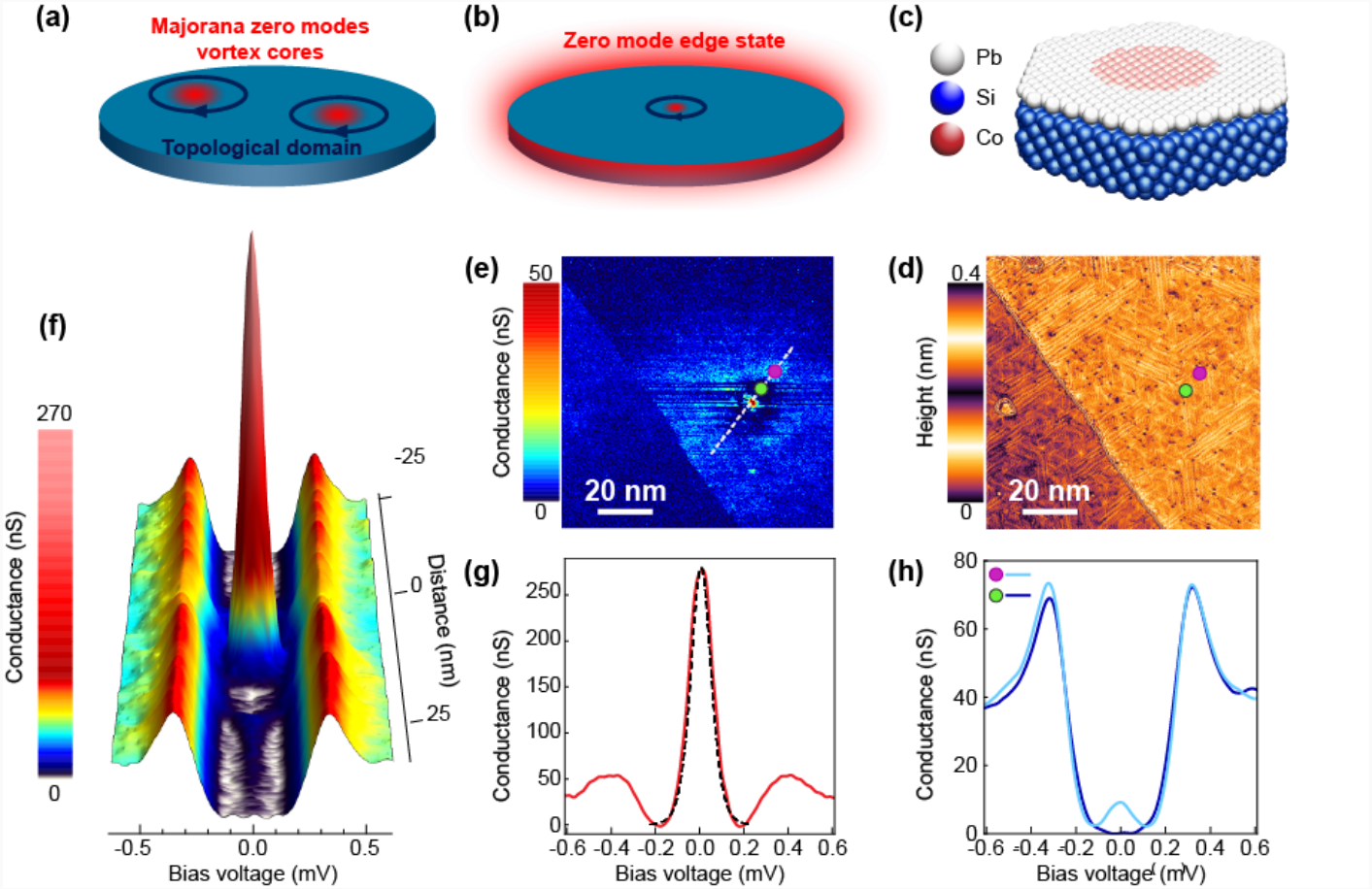
Is this edge mode itinerant ?

Further outlook

SIMILAR IDEAS: DEFECTS IN MAGNETIC ISLAND

Localized Majorana at point-like defect, coexisting with itinerant Majorana edge mode (observed in Co-Si island on disordered Pb)

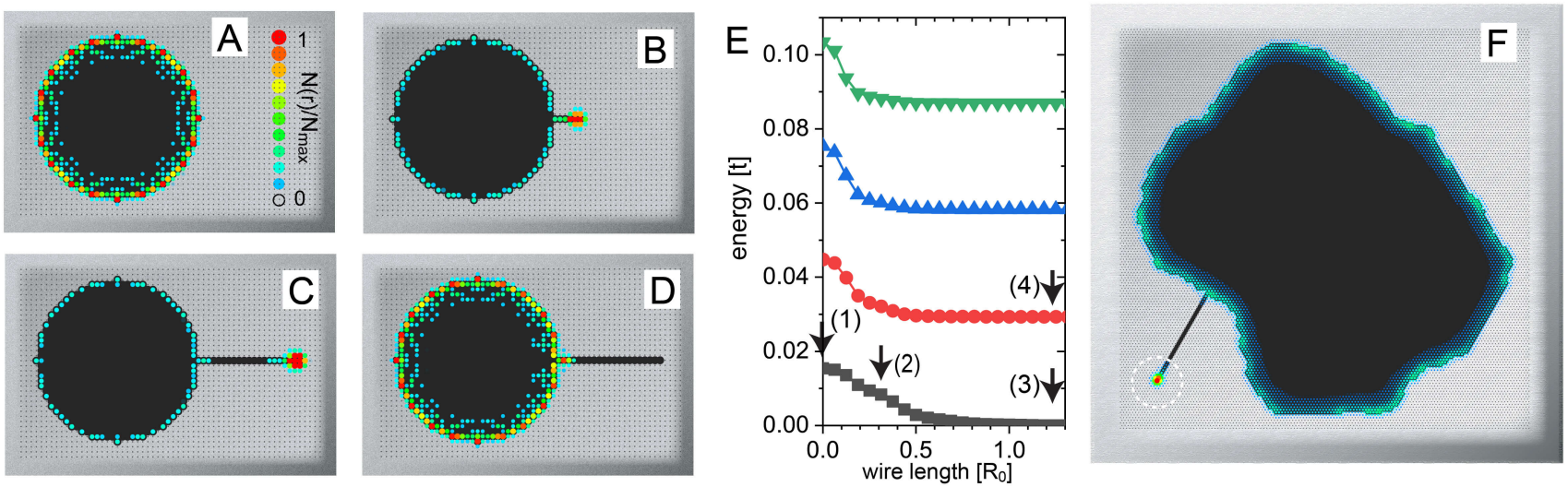


G.C. Ménard, ..., P. Simon and T. Cren, arXiv:1810.09541

Paris (France)

SIMILAR IDEAS: ISLAND + NONOWIRE

Itinerant Majorana mode leaking into side-attached nanowire.



E. Mascot, S. Cocklin, S. Rachel, and D.K. Morr, arXiv:1811.06664

Univ. of Illinois at Chicago (USA)

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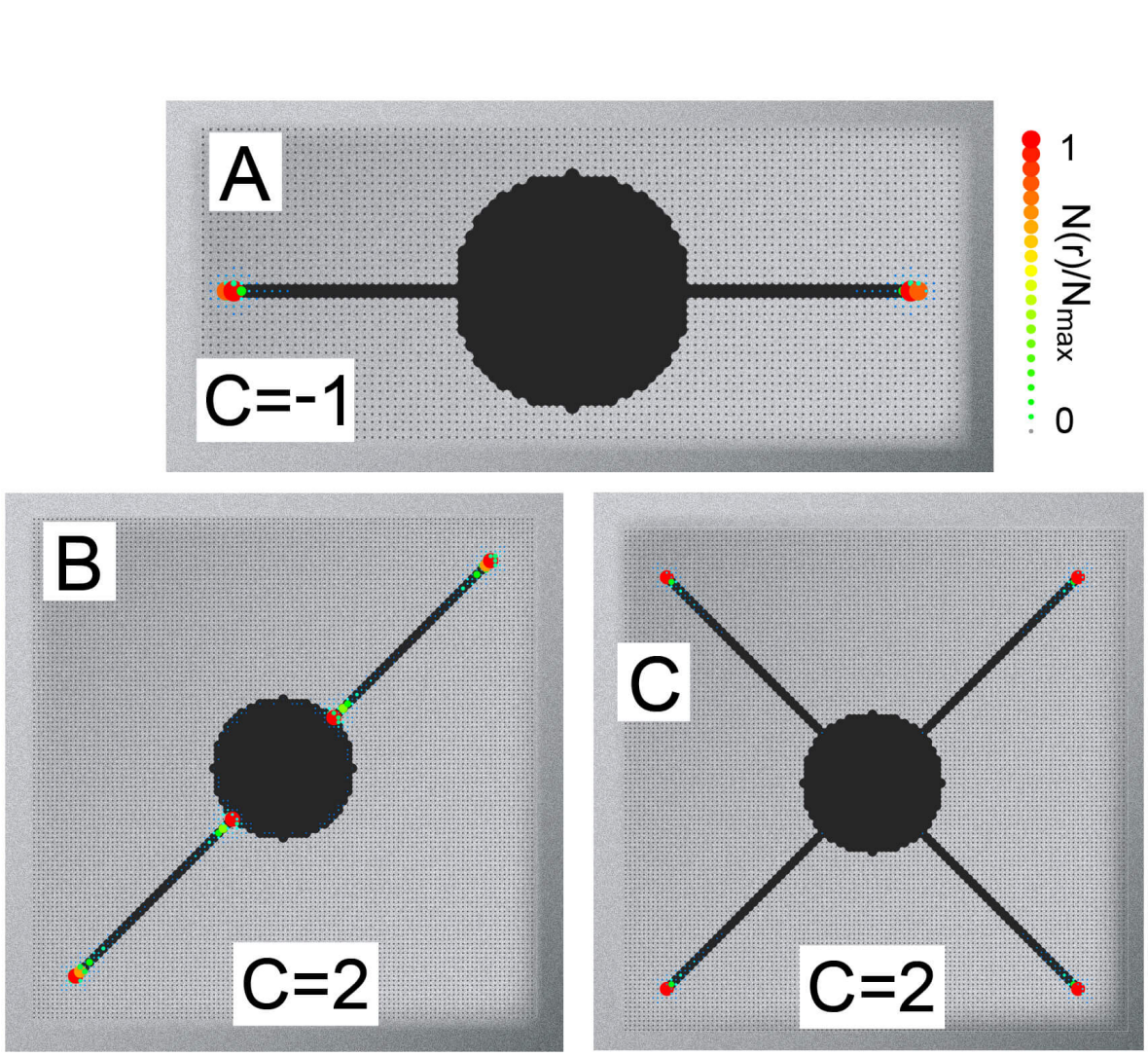
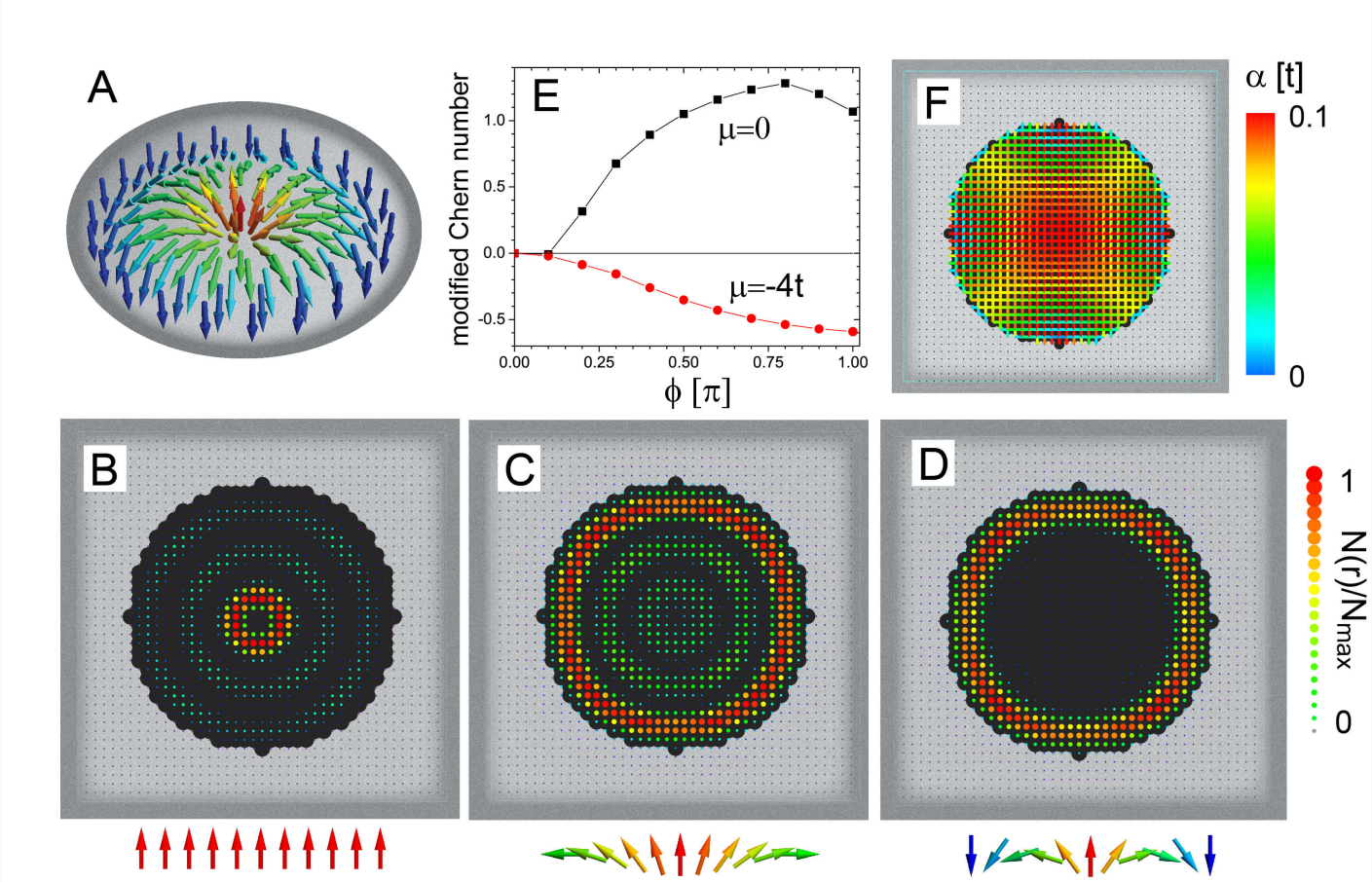
Majorana modes leaking to the side-attached nanowires.



PERSPECTIVES: SKYRMIONS IN SUPERCONDUCTORS

Creation of topological phase through skyrmions.



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Magneto - superconducting hybrid (MSH) structures enable:

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Would it help to realise braiding of Majorana qps ?

ACKNOWLEDGEMENTS

- **Majorana quasiparticles**

  ⇒ **M. Maśka & A. Gorczyca-Goraj (Katowice),**
  ⇒ **A. Kobiałka (Lublin), A. Ptok (Kraków),**
  ⇒ **J. Tworzydło (Warsaw), N. Sedlmayr (Rzeszów).**

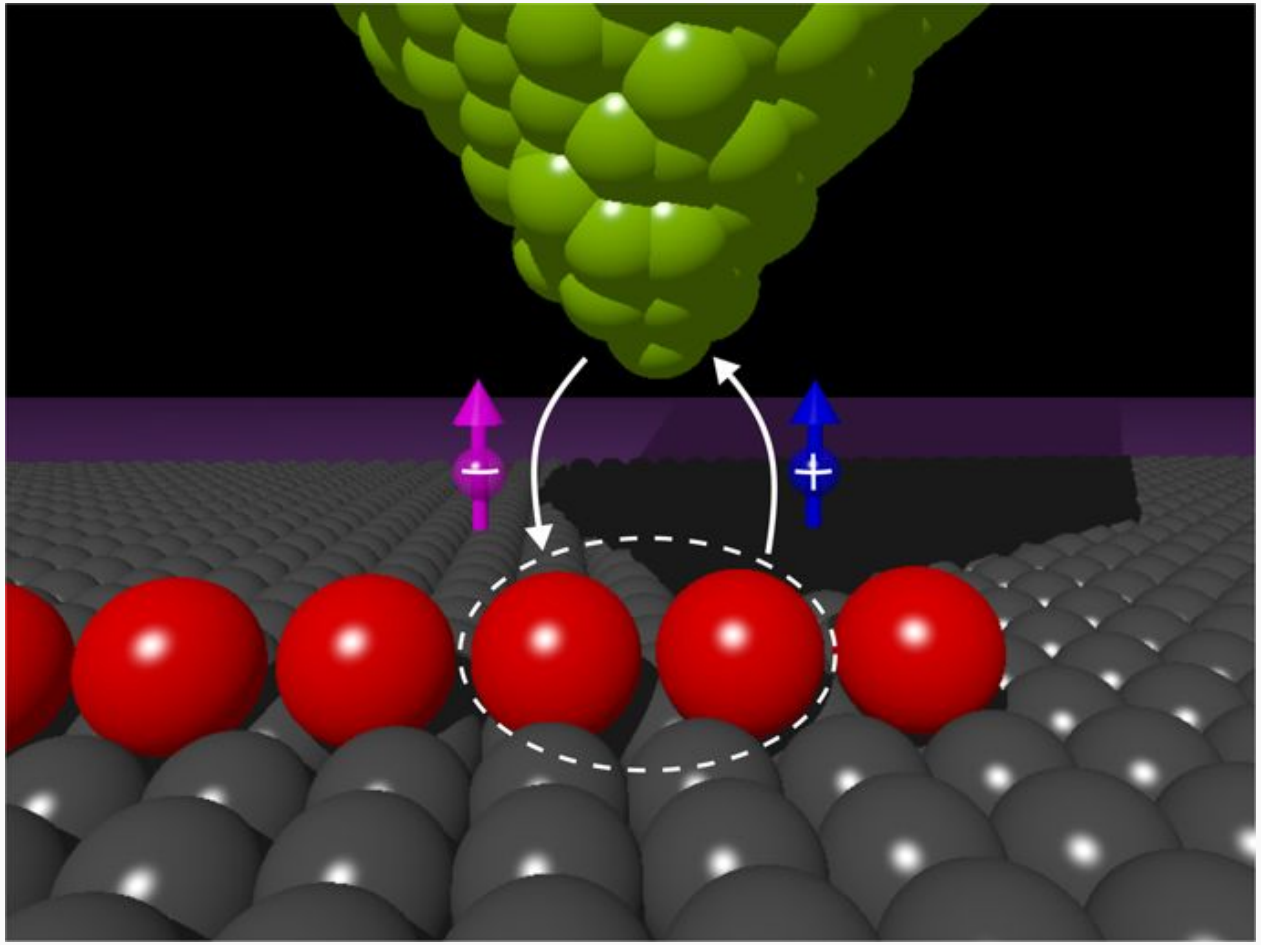
- **Shiba states/bands in topological phases**

  ⇒ **Sz. Głodzik (Lublin)**

- **Majorana vs Kondo**

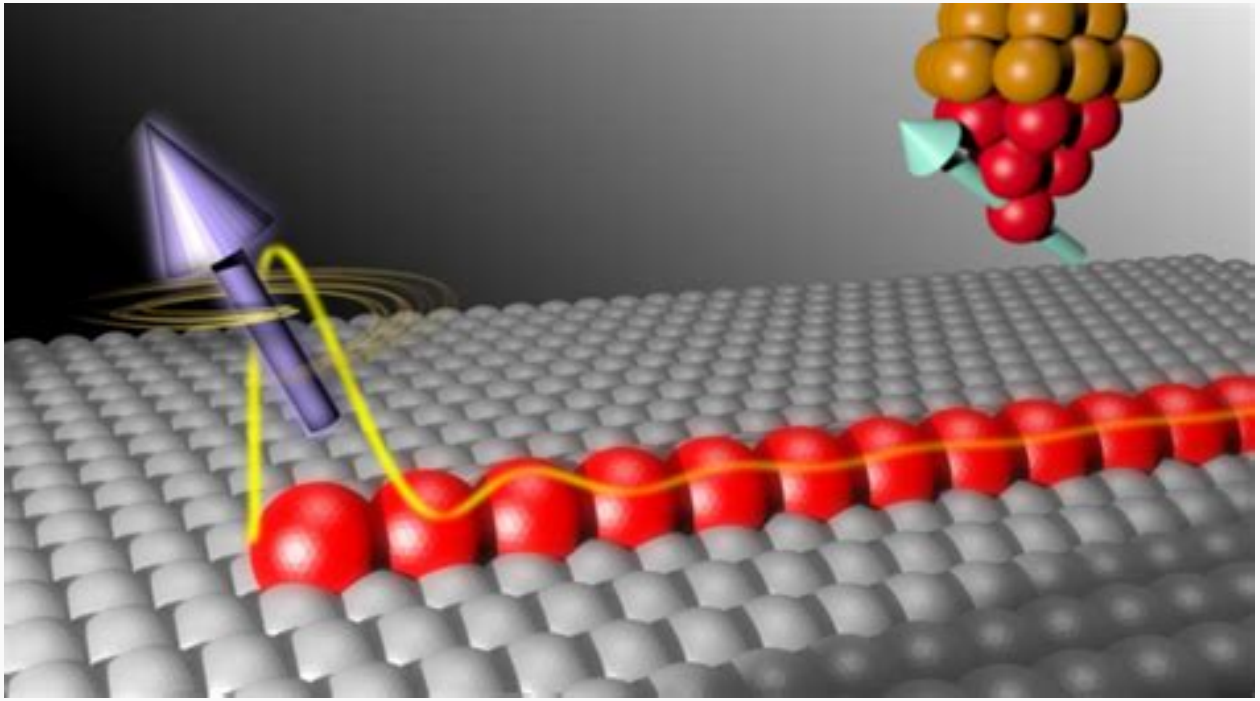
  ⇒ **I. Weymann (Poznań), G. Górski (Rzeszów),**
  ⇒ **T. Novotný, M. Žonda & V. Janiš (Prague).**

Microscopic idea of the SESAR mechanism



M. Maśka and T. Domański, Scientific Reports **7**, 16193 (2017).

STM-type measurements for probing the Majorana qps



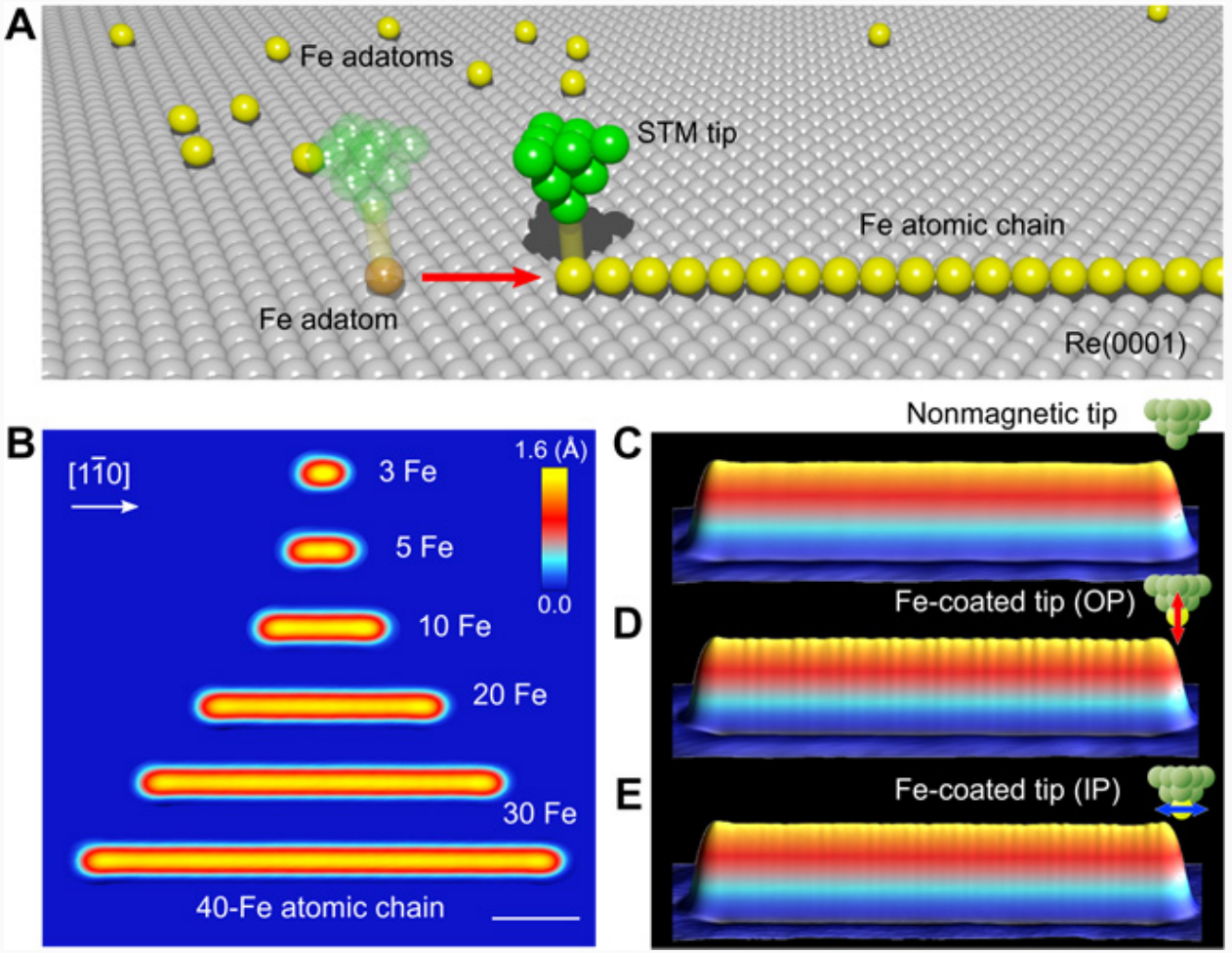
S. Jeon, ... and A. Yazdani, Science **358**, 772 (2017).

/ Princeton University, USA /

Kondo vs Majorana

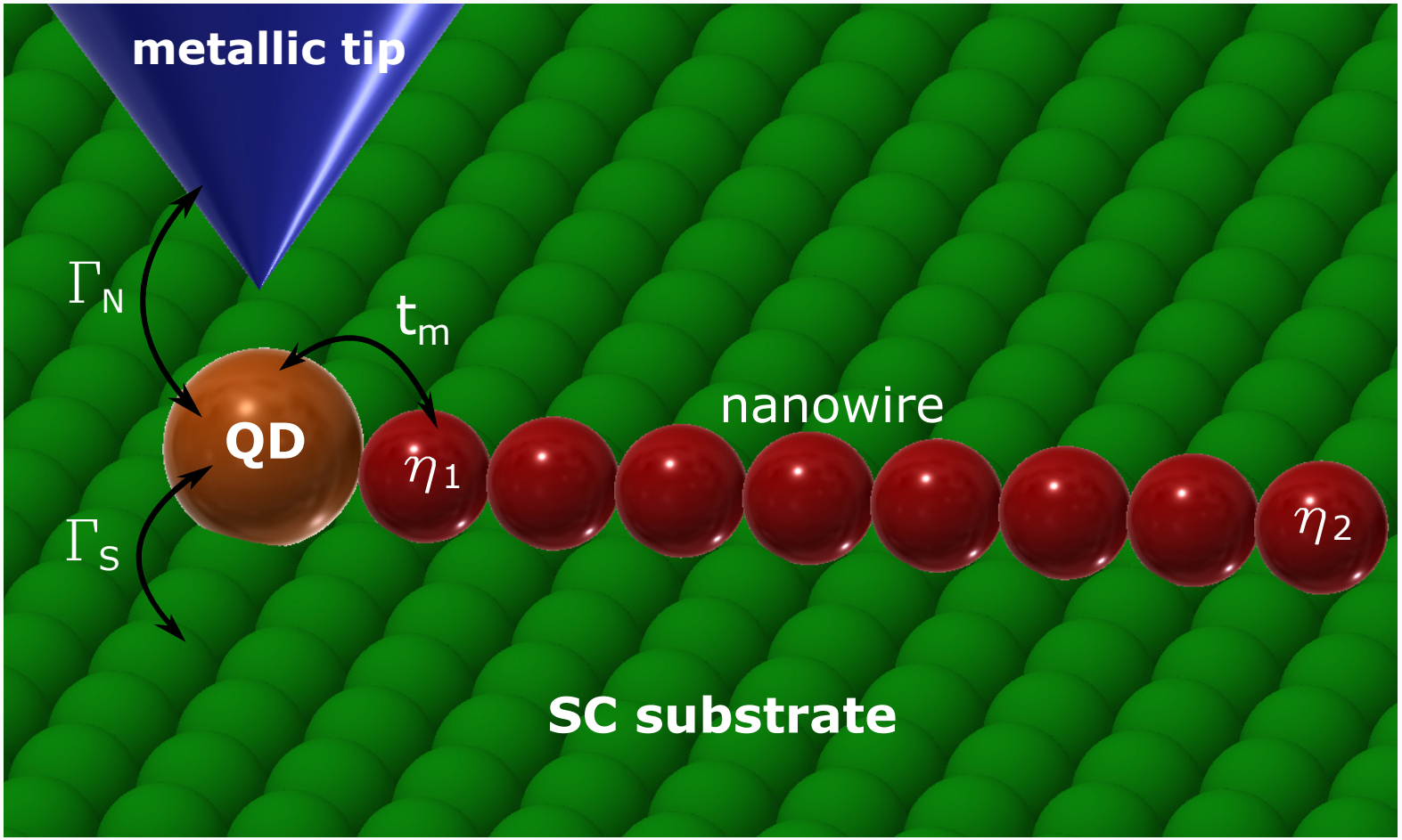
POSSIBLE EXPERIMENTAL REALISATION

Deposition of individual atoms on superconducting surface



H. Kim, ..., and R. Wiesendanger, Science Adv. 4, eaar5251 (2018).

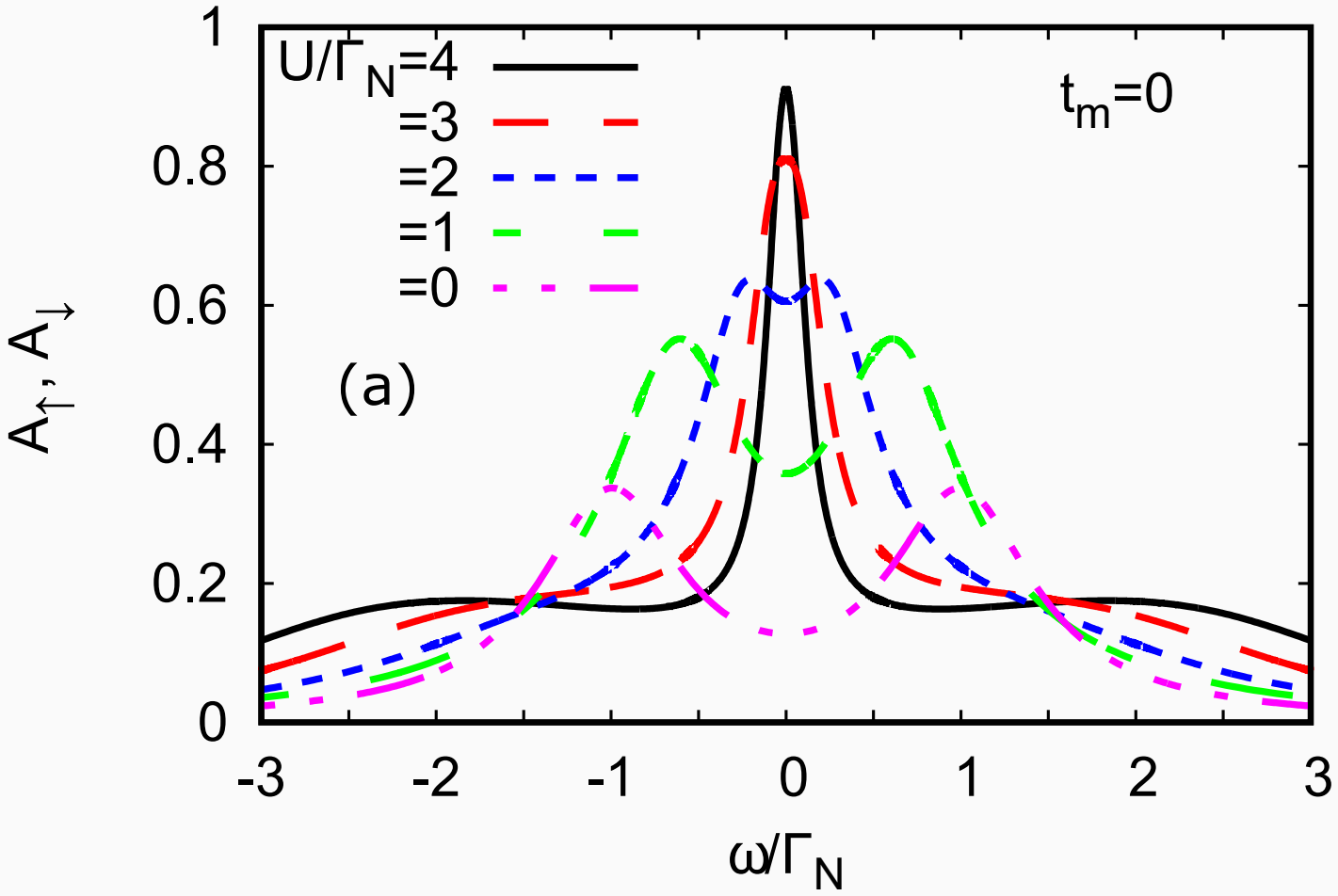
STM-type setup for probing the Kondo – Majorana – pairing effects.



G. Górski, ... and T. Domański, Scientific Reports 8, 15717 (2018).

SUBGAP KONDO PHYSICS

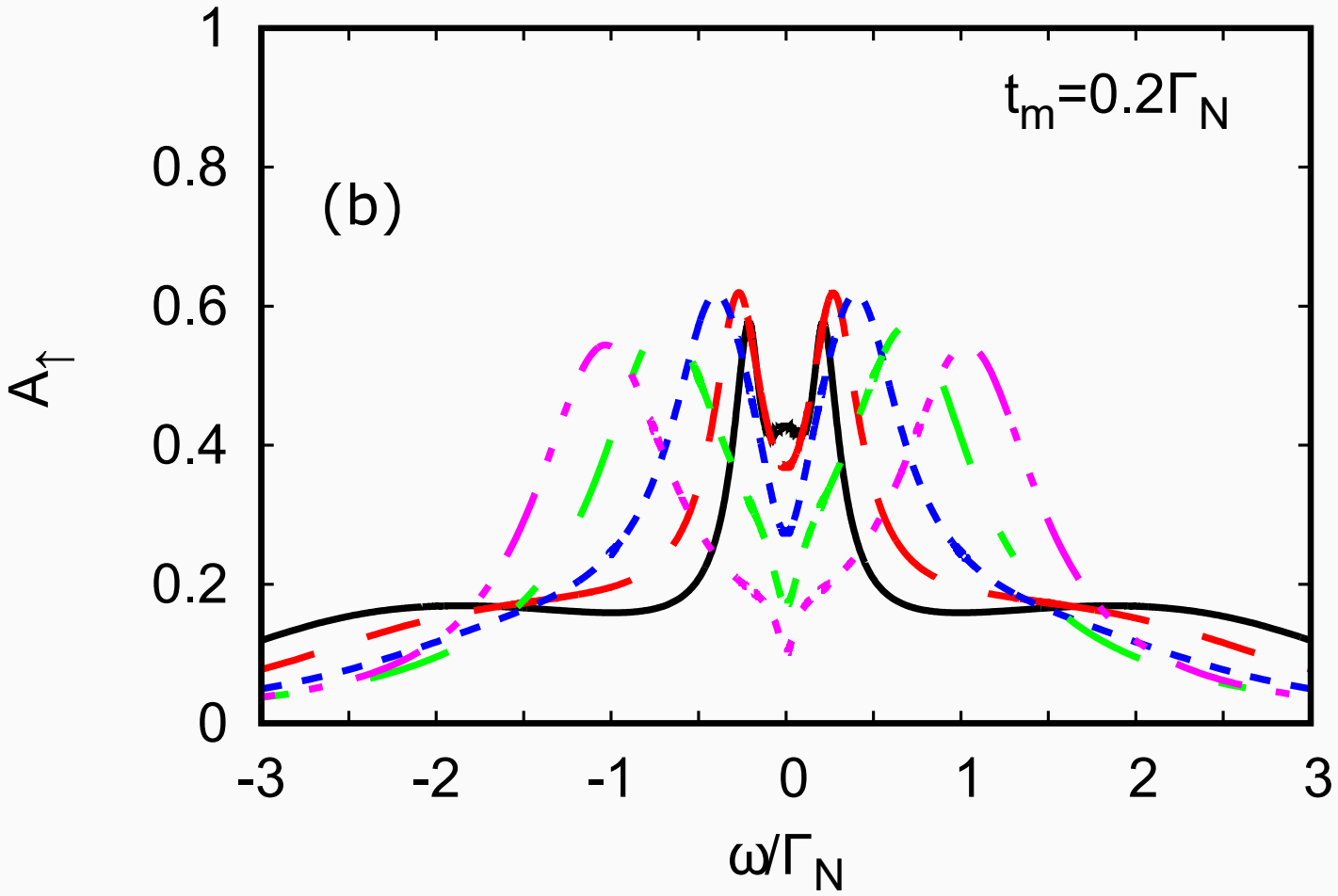
Spectrum of a quantum dot in absence of the Majoranas.



Results obtained for $t_m = 0$

G. Górski, ... and T. Domański, Scientific Reports 8, 15717 (2018).

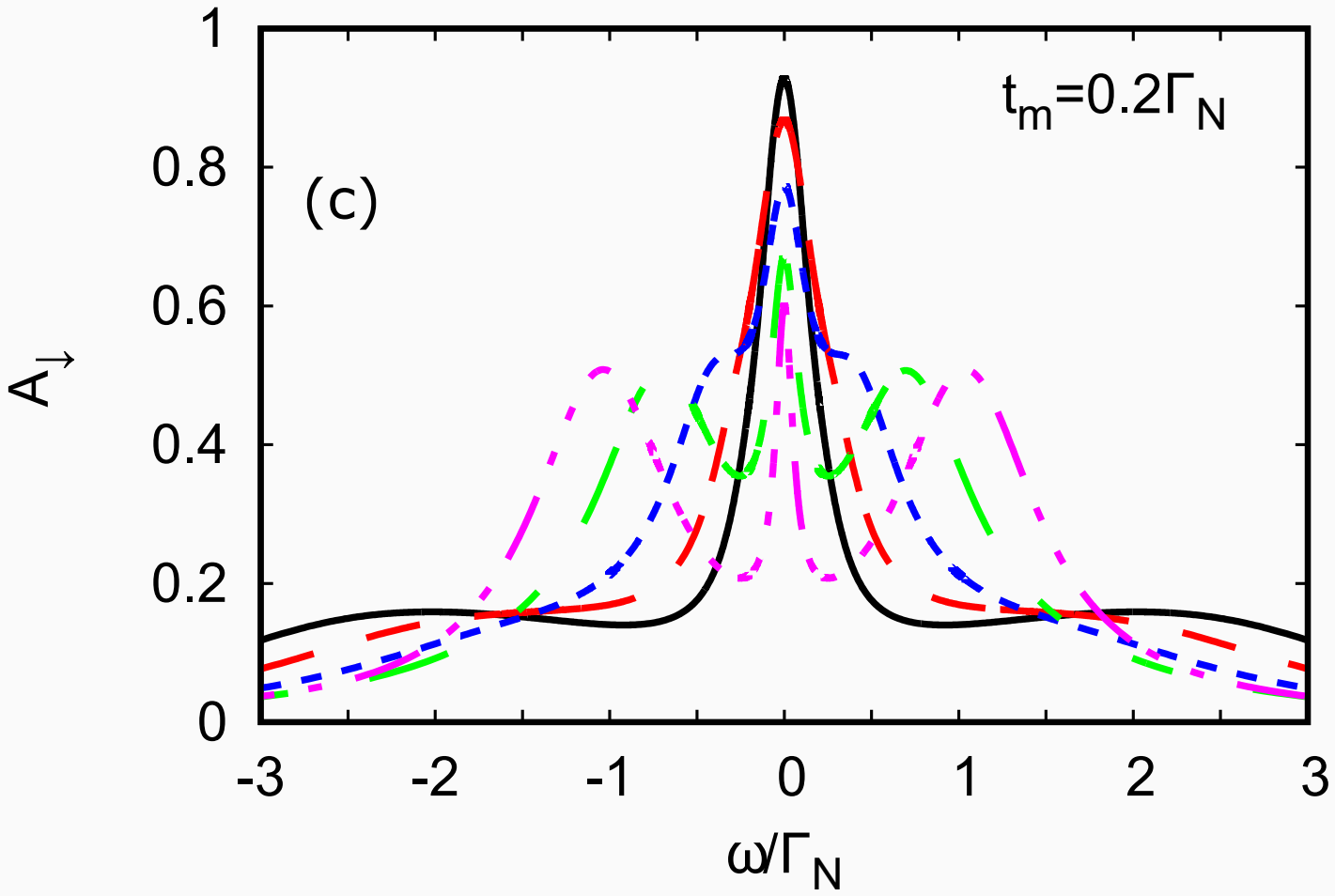
Spectrum of a quantum dot in its Kondo regime.



Results obtained for ↑ spin, assuming $t_m = 0.2\Gamma_N$

G. Górski, ... and T. Domański, Scientific Reports 8, 15717 (2018).

Spectrum of the correlated QD in its Kondo regime.



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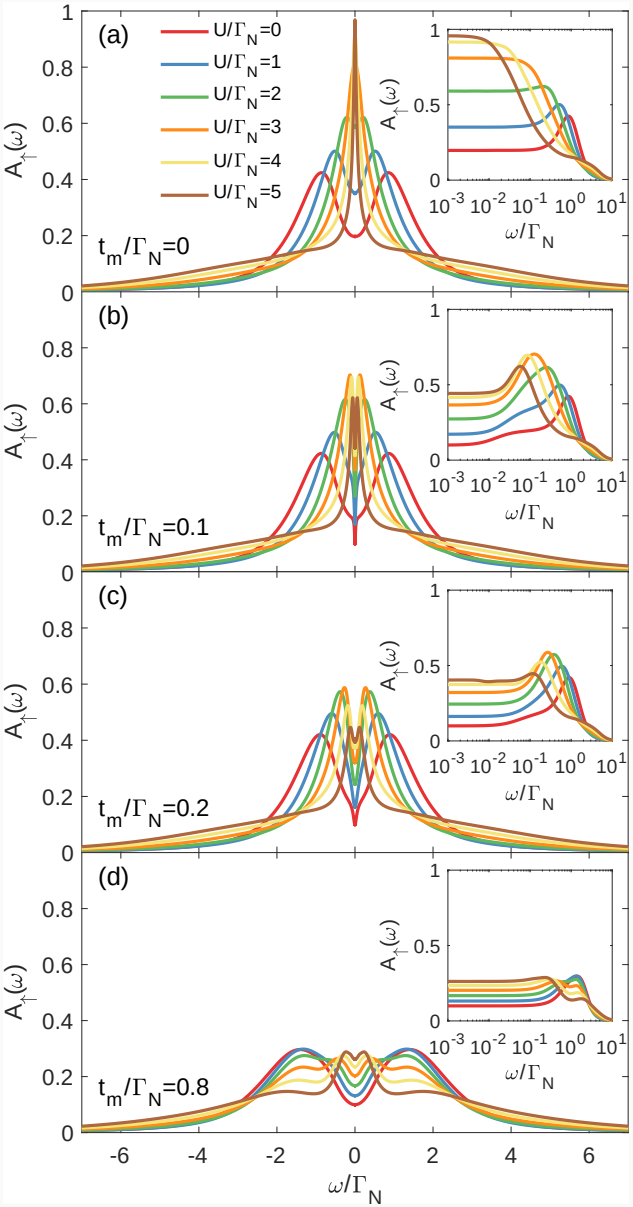
SPIN-RESOLVED NRG DATA



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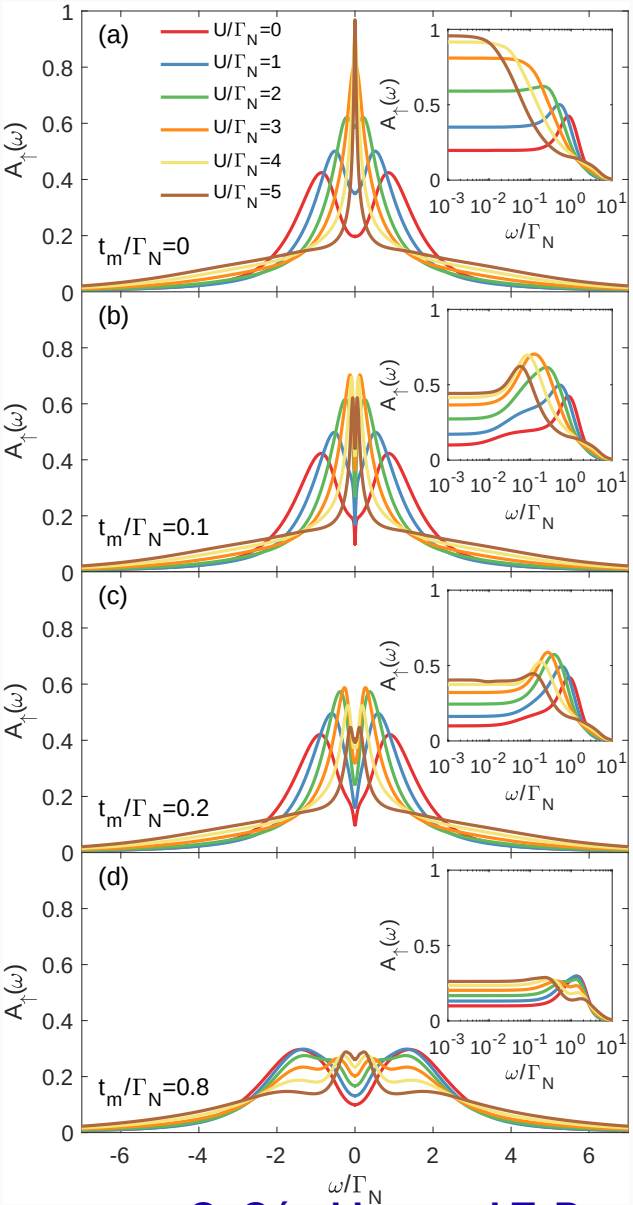

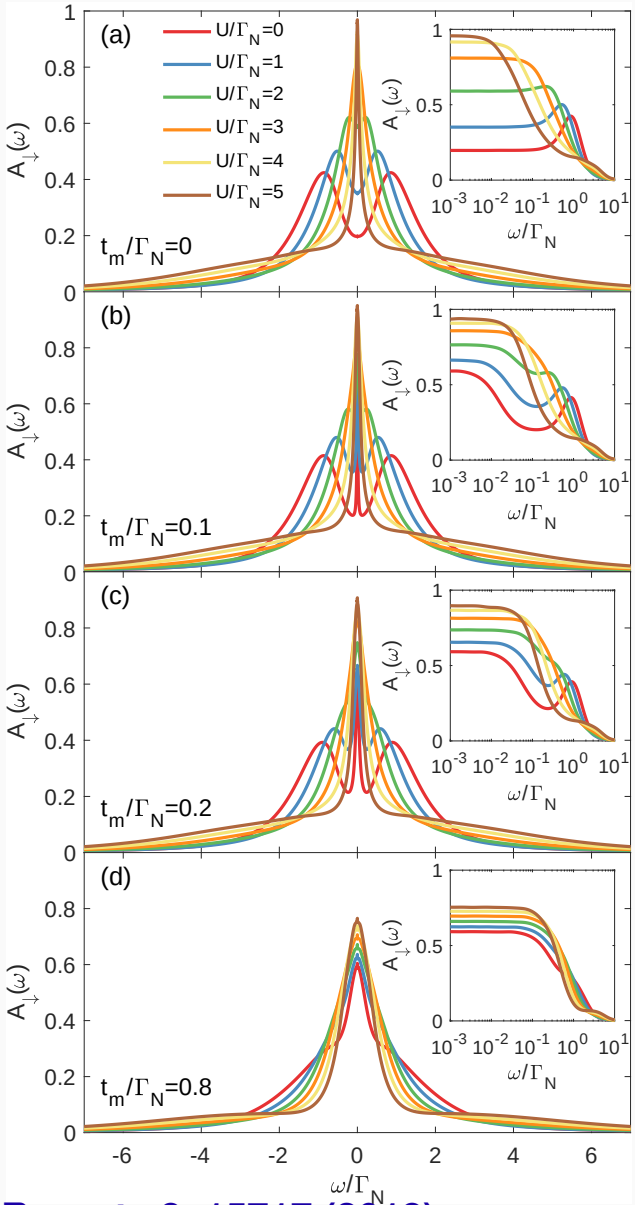

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- **empirical observability via:**

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