Nontrivial topological phases in superconducting nanostructures

Tadeusz Domański

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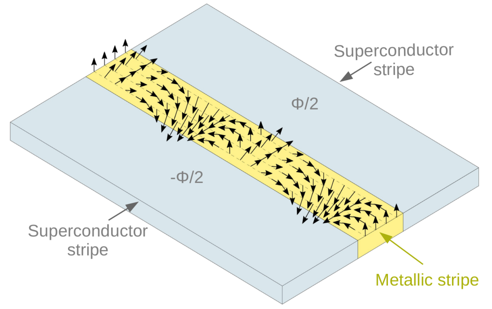


2DTtronics symposium **Poznań, 31 January 2024**

OUTLINE

1. **Topological superconductivity**

   (magnetism vs electron pairing)

2. **Josephson junctions**

   (platform for topological phases)

3. **Dynamical phenomena**

   (in topological nanohybrid structures)

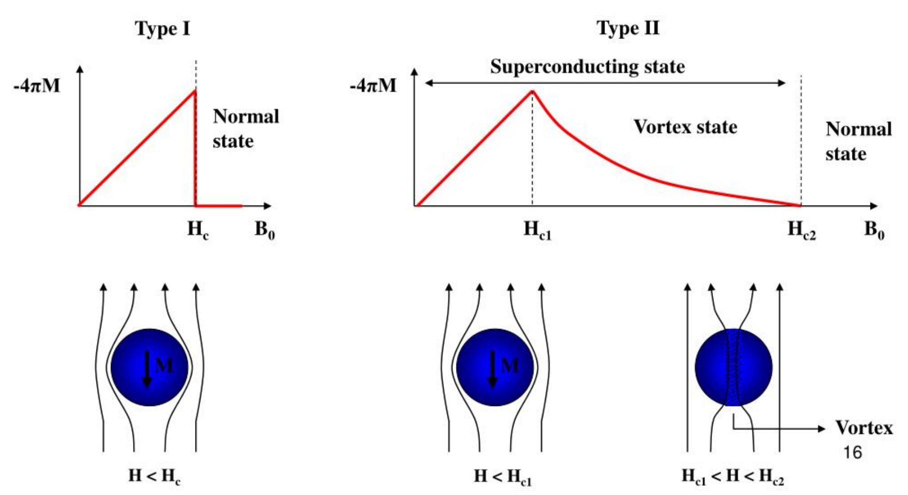
Part 1. Topological superconductivity

(magnetism vs electron pairing)

FRIENDS OR FOES ?

Magnetism vs electron pairing

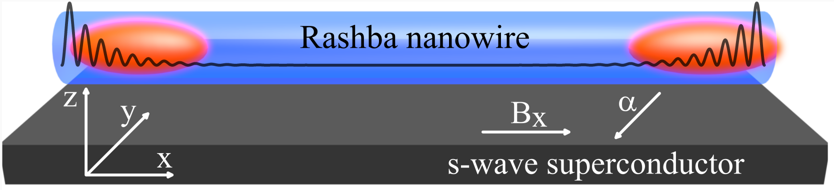
Magnetism vs electron pairing



Magnetic field has destructive influence on superconducting state

PAIRING & MAGNETISM IN NANOWIRES

Spin-orbit (Rashba) interaction in presence of magnetic field applied to semiconducting nanowire proximitized to s-wave superconductor induces the triplet pairing of electrons on the neighboring sites.



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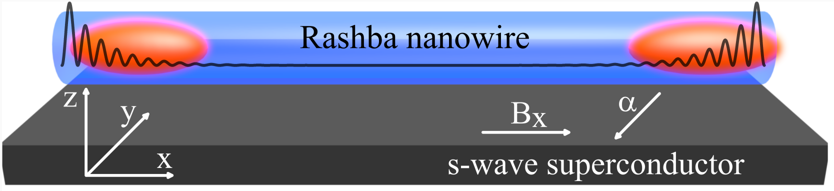
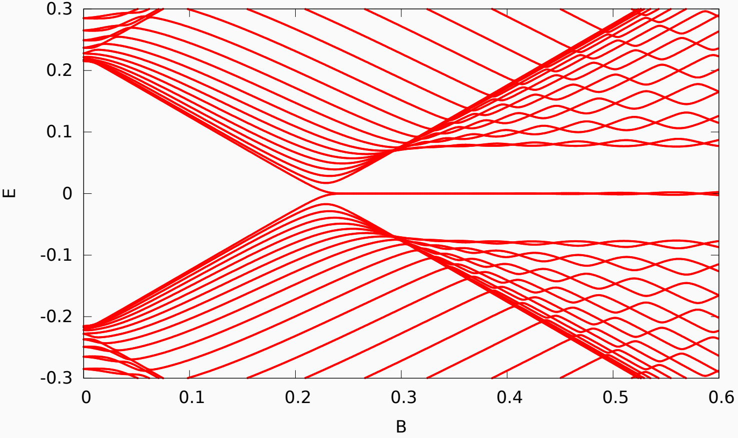


Such intersite triplet pairing of mobile electrons in 1-dimensional chains has been predicted to host the Majorana boundary modes.

Effective quasiparticle states of the Rashba nanowire



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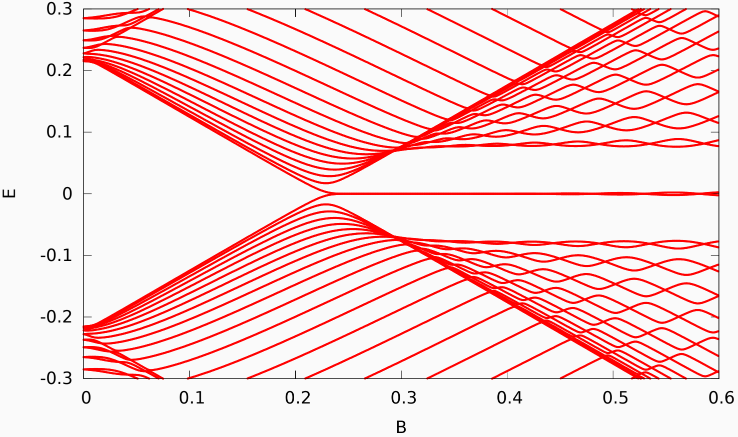
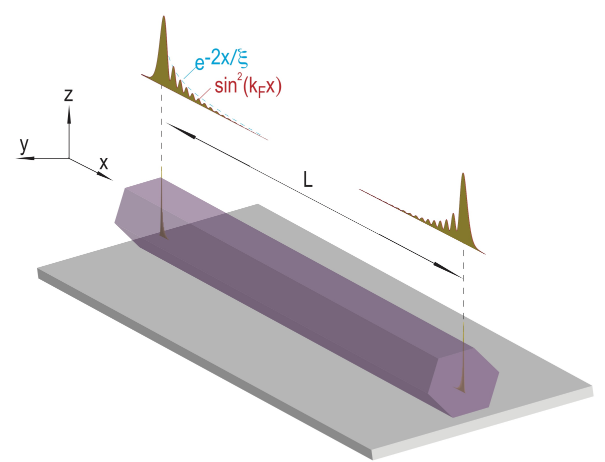


Closing / reopening of a gap $\Longleftrightarrow$ band-invertion of topological insulators

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

SPATIAL PROFILE OF MAJORANA MODES

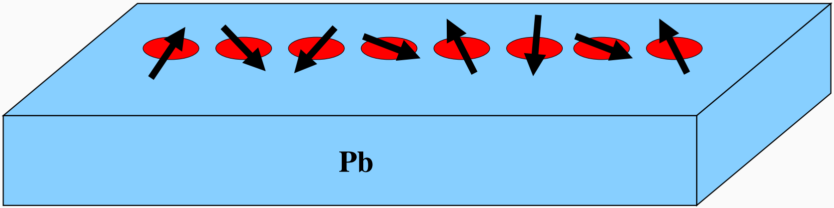
Majorana zero-energy modes are confined on edges (and/or defects)



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

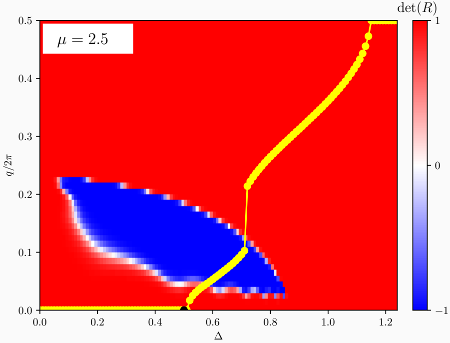
MAGNETIC CHAINS ON SUPERCONDUCTORS

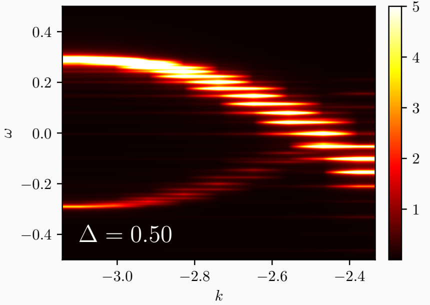
Magnetic atoms (like Fe) on a surface of s-wave superconductor (for example Pb or Al) arrange themselves into the spiral order, promoting the topological superconducting state (topofilia).

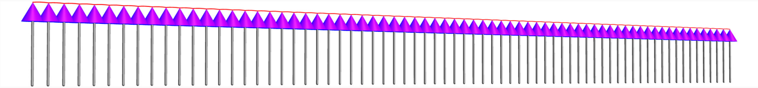


SELFORGANISATION (TOPOFILIA)

A. Gorczyca-Goraj, T. Domański & M.M. Maśka, Phys. Rev. B 99, 235430 (2019).







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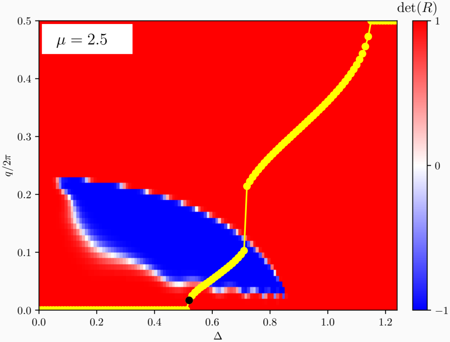

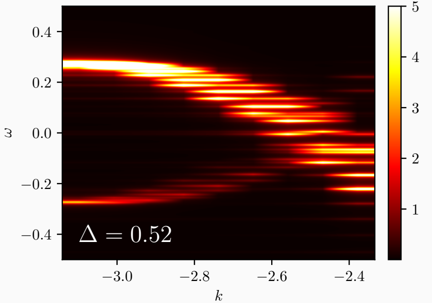

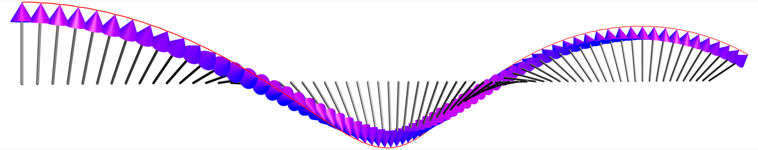

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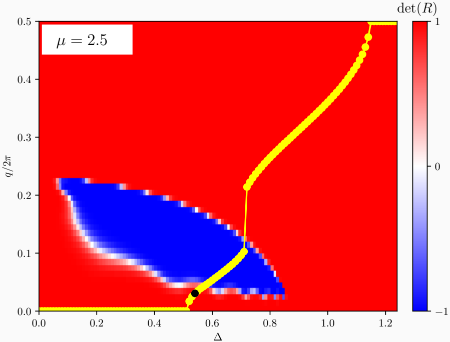

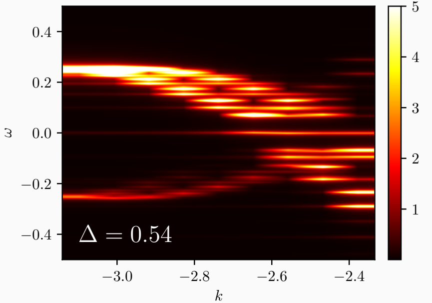

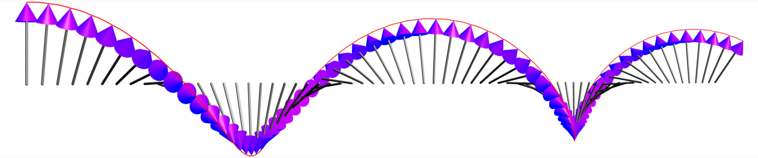

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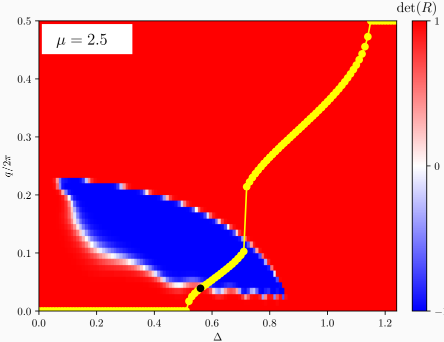

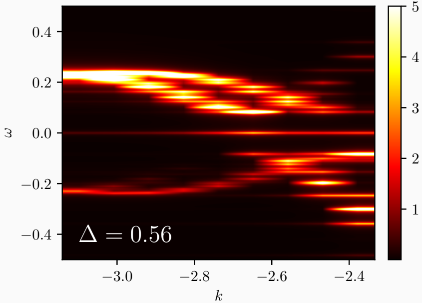

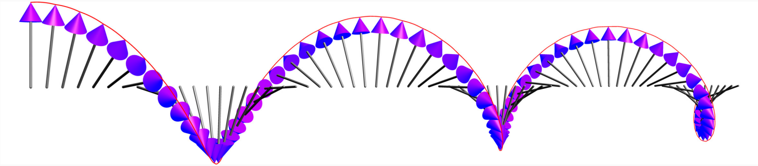

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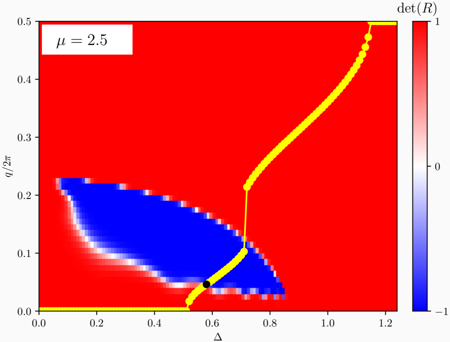

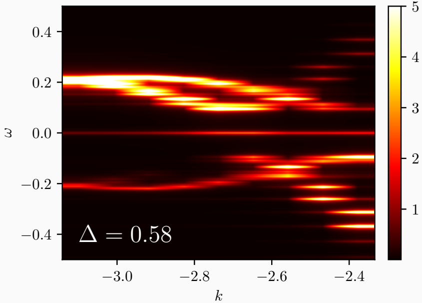

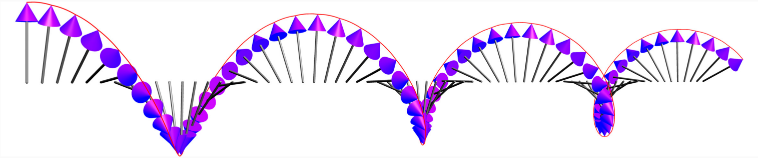

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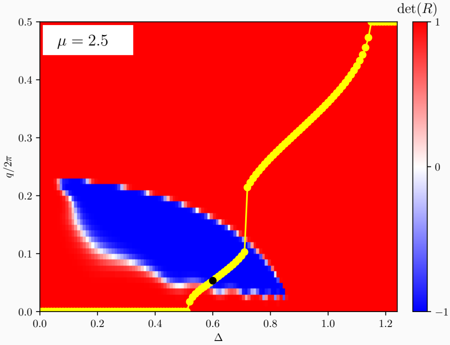

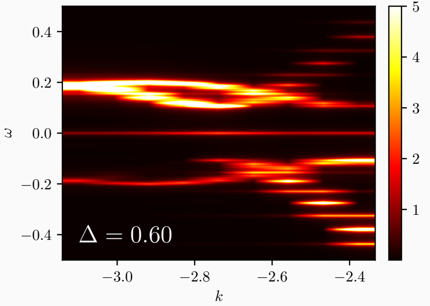

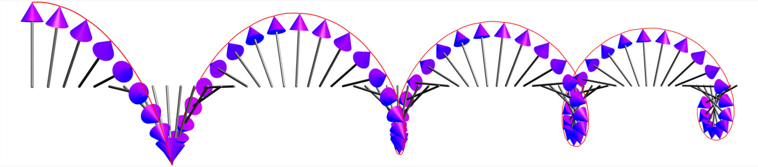

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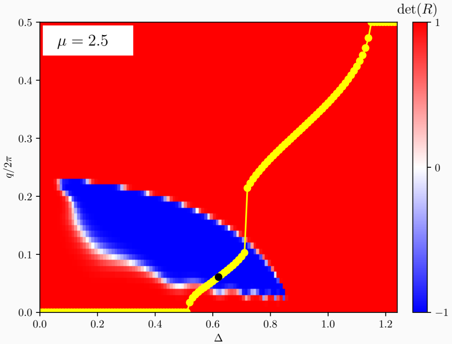

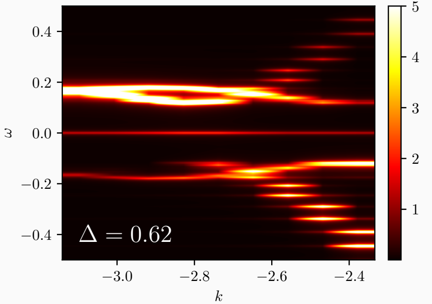

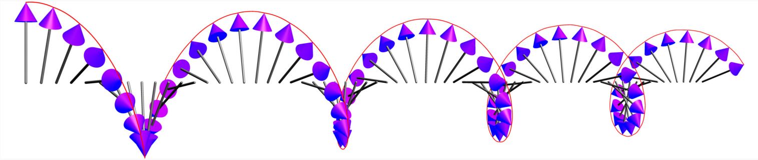

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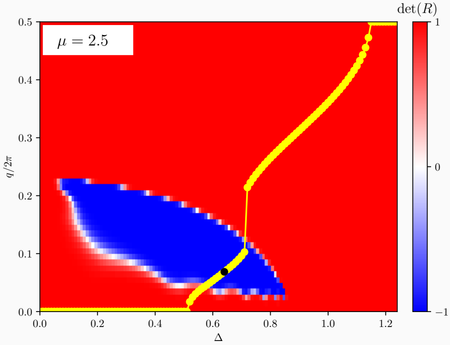

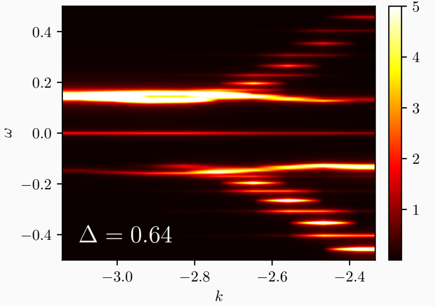

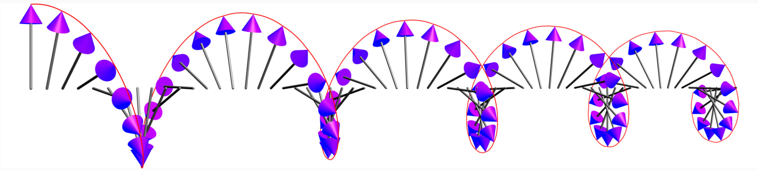

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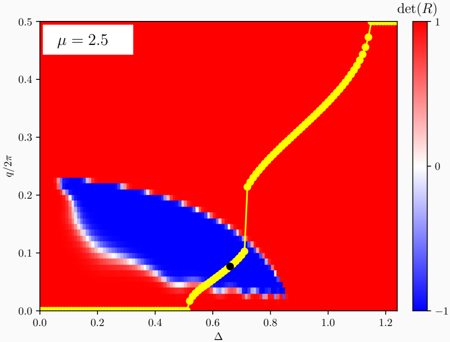

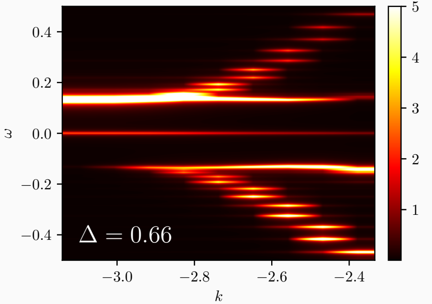

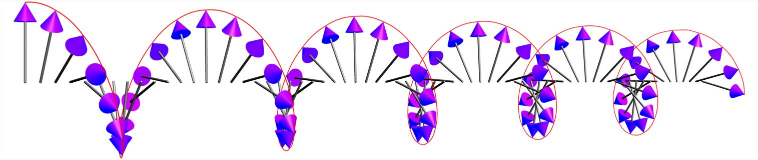

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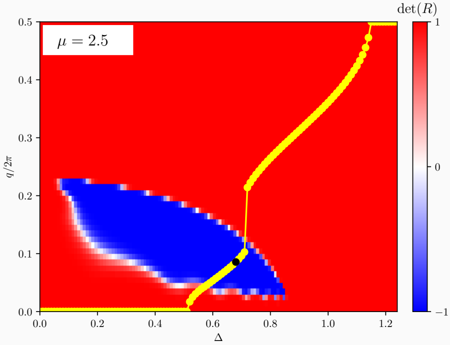

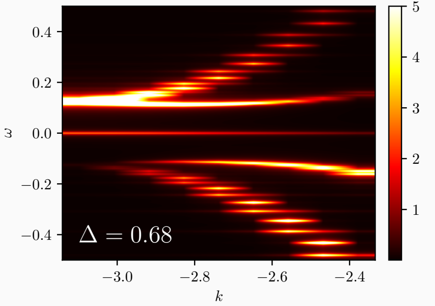

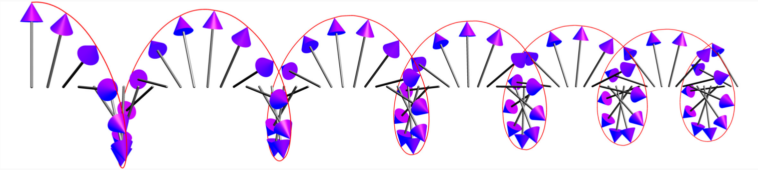

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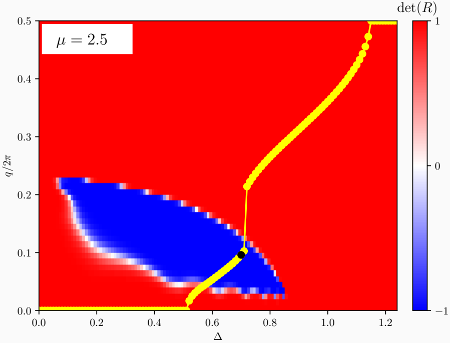

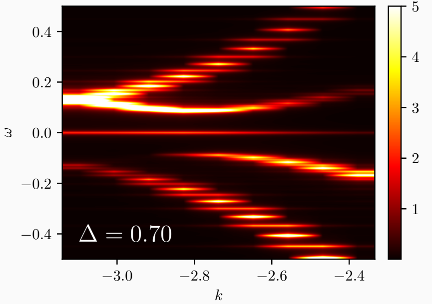

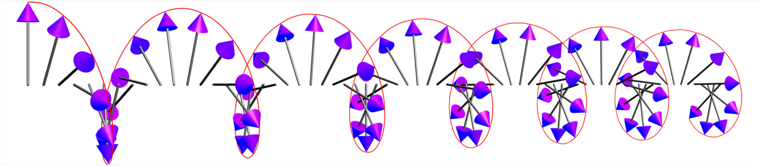

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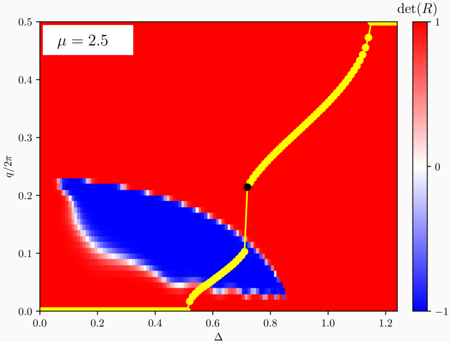
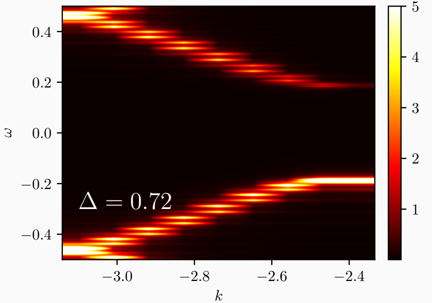
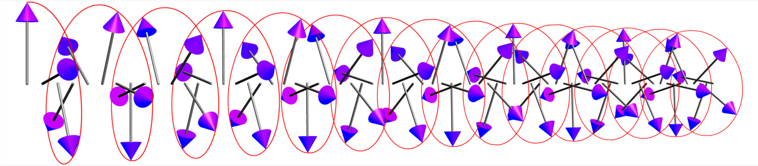






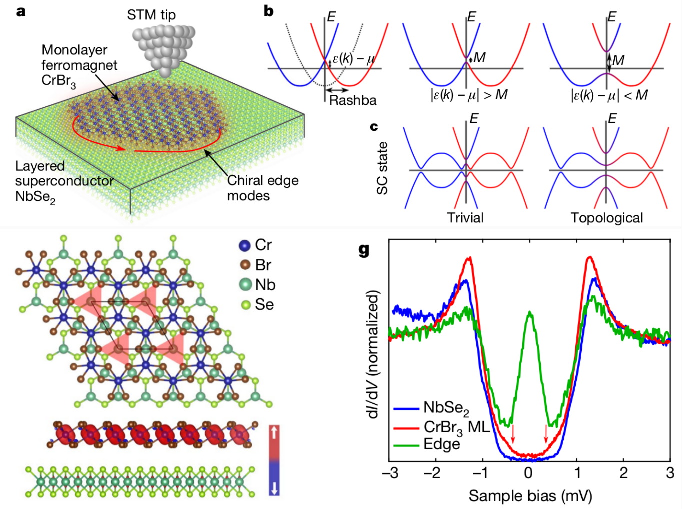
Higher-dimensional textures

Higher-dimensional textures

(platform for chiral Majorana modes)

VAN DER WAALS HETEROSTRUCTURES

Ferromagnetic island $CrBr_3$ deposited on superconducting $NbSe_2$



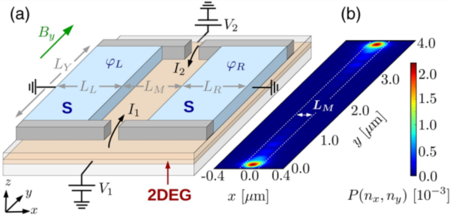
S. Kezilebieke ... Sz. Głodzik ... P. Liljeroth, Nature 424, 588 (2020).

Part 2. Josephson junctions

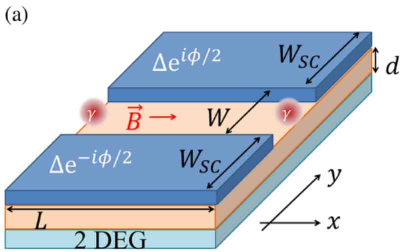
(platform for topological phases)

PLANAR JOSEPHSON JUNCTIONS

Idea: Narrow metallic region with the strong spin-orbit interaction and in presence of magnetic field embedded between external superconductors.



Michael Hell et al., PRL 118, 107701 (2017)



F. Pientka et al., Phys. Rev. X 7,021032 (2017)

PLANAR JOSEPHSON JUNCTIONS

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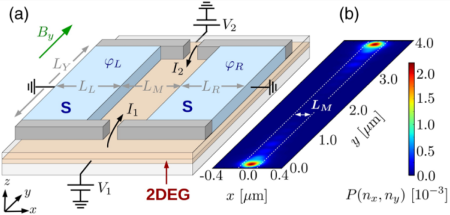
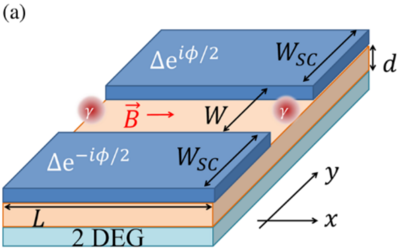


Michael Hell et al., PRL 118, 107701 (2017)



F. Pientka et al., Phys. Rev. X 7,021032 (2017)

Benefit:

Phase-tunable topological superconductivity induced in the metallic stripe.

PLANAR JOSEPHSON JUNCTIONS

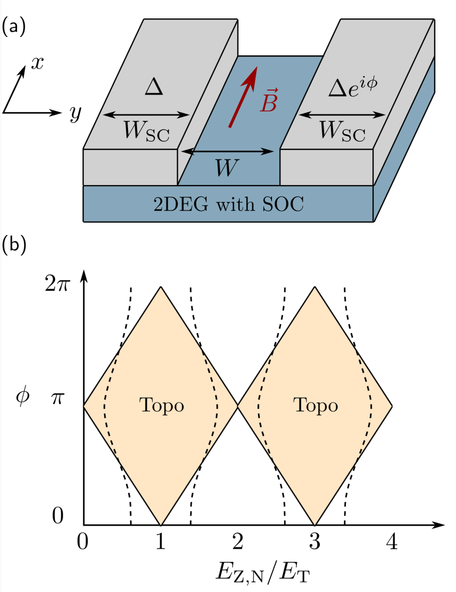
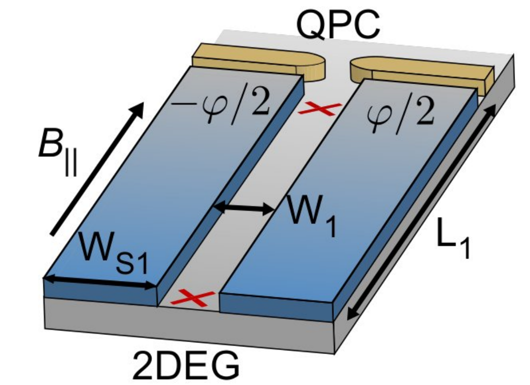


Diagram of topological superconducting state vs
– phase difference ϕ,
– magnetic field E_z.

PLANAR JOSEPHSON JUNCTIONS

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



Width:

W_1 **= 80 nm**

Length:

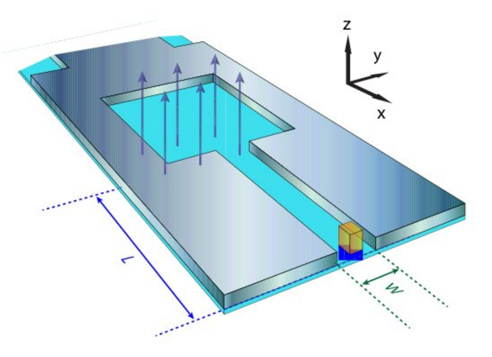
L_1 **= 1.6** μ**m**

A. Fornieri, ..., Ch. Marcus and F. Nichele, Nature 569, 89 (2019).

Niels Bohr Institute (Copenhagen, Denmark)

PLANAR JOSEPHSON JUNCTIONS

Two-dimensional HgTe quantum well coupled to 15 nm thick Al film



Width:

W **= 600 nm**

Length:

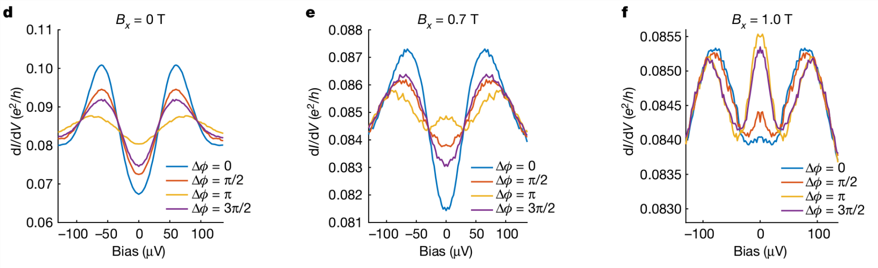
L **= 1.0 μm**

H. Ren, ..., E. Hankiewicz, ... & A. Yacoby, Nature 569, 93 (2019).

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

PLANAR JOSEPHSON JUNCTION: EXPERIMENT

H. Ren, ..., E. Hankiewicz, ... & A. Yacoby, Nature 569, 93 (2019).



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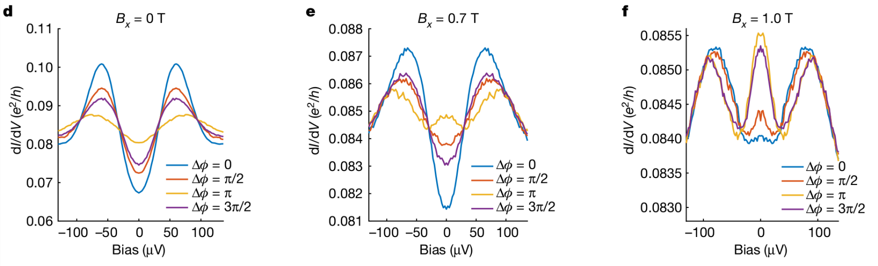
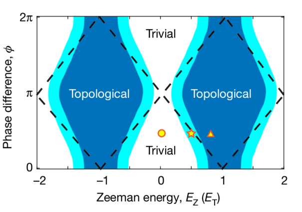


Experimental data obtained for three different magnetic fields indicated by the symbols in phase diagram ⇒.

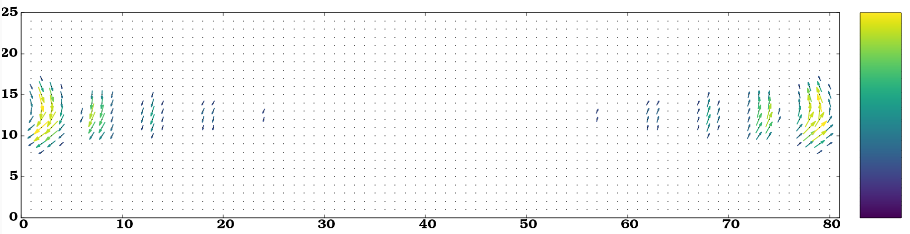


LOCALIZED OR PROPAGATING MODES?

Topography of Majoranas

TOPOGRAPHY OF MAJORANAS

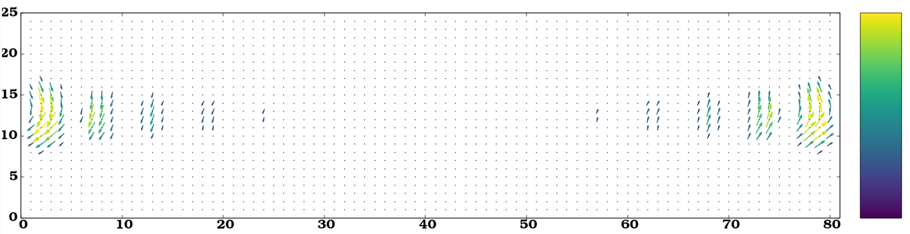
Spatial profile of the zero-energy quasiparticles of a homogeneous metallic strip embedded into the Josephson junction obtained for the phase difference $\phi = \pi$, that is optimal for topological state.



"Majorana polarization vector" $u_{\uparrow,n}v_{\uparrow,n} - u_{\downarrow,n}v_{\downarrow,n}$ obtained for the quasiparticle eigenvalue $E_n = 0$.

TOPOGRAPHY OF MAJORANAS

Spatial profile of the zero-energy quasiparticles of a homogeneous metallic strip embedded into the Josephson junction obtained for the phase difference $\phi = \pi$, that is optimal for topological state.

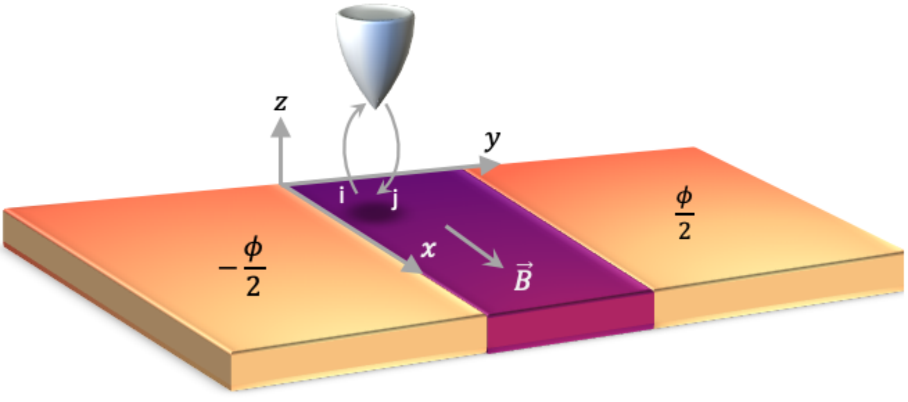


“Majorana polarization vector” $u_{\uparrow,n} v_{\uparrow,n} - u_{\downarrow,n} v_{\downarrow,n}$ obtained for the quasiparticle eigenvalue $E_n = 0$. Magnitude of this quantity can be probed by conductance of the SESAR spectroscopy.

Sz. Głodzik, N. Sedlmayr & T. Domański, PRB 102, 085411 (2020).

TOPOGRAPHY OF MAJORANA MODES

Selective Equal Spin Andreev Reflection (SESAR)

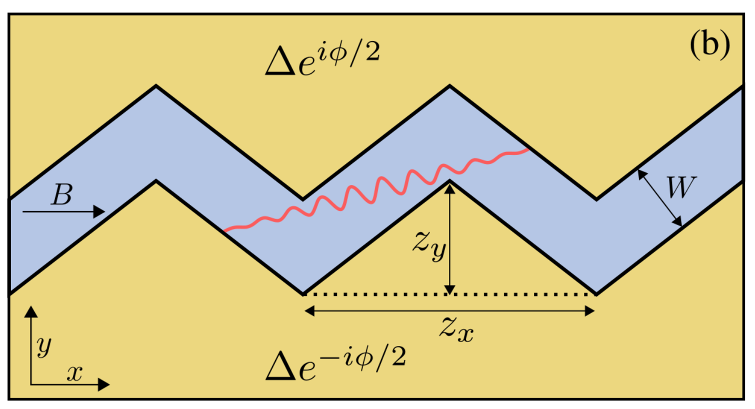


Sz. Głodzik, N. Sedlmayr & T. Domański, PRB 102, 085411 (2020).

Means to localize Majoranas

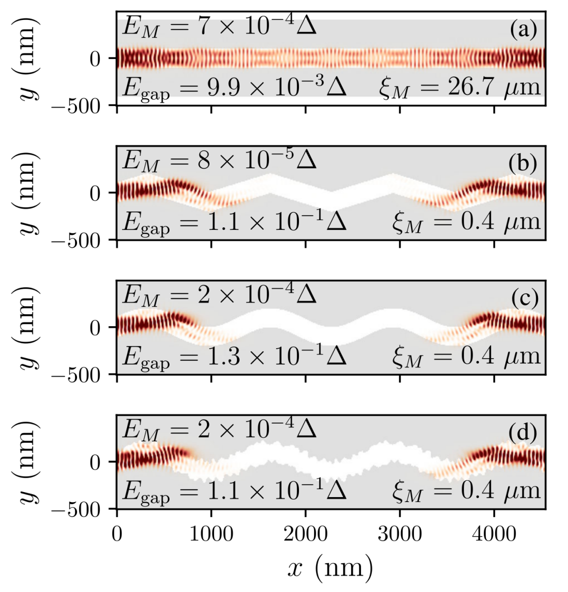
I. DESHAPED JOSEPHSON JUNCTION

To reduce spatial extent of the Majorana modes and increase the topological gap one can use zigzag-shape metallic stripe.



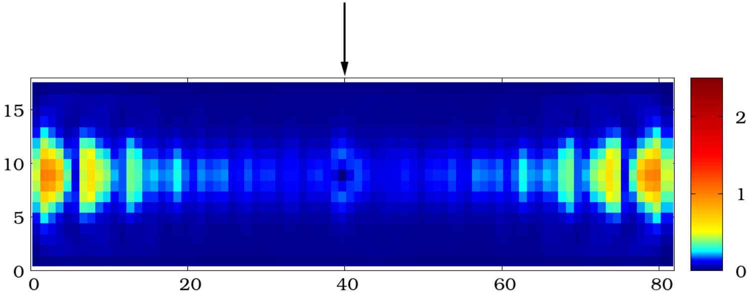
T. Laeven, B. Nijholt, M. Wimmer & A.R. Akhmerov, PRL <u>102</u>, 086802 (2020).

I. DESHAPED JOSEPHSON JUNCTION



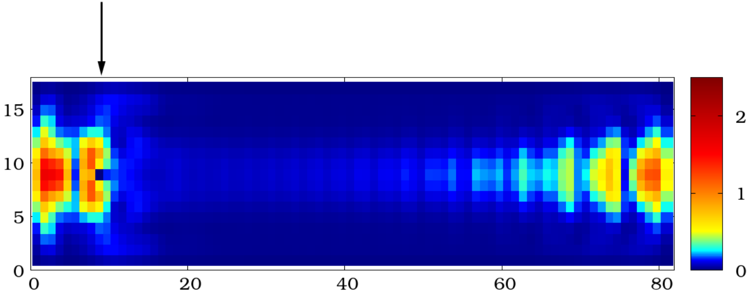
T. Laeven, B. Nijholt, M. Wimmer & A.R. Akhmerov, PRL 102, 086802 (2020).

Spatial profile of the Majorana modes in presence of the strong electrostatic defect placed in the center.



Sz. Głodzik, N. Sedlmayr & T. Domański, PRB 102, 085411 (2020).

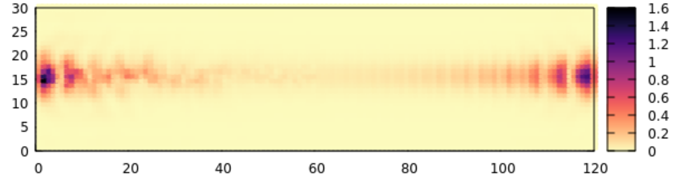
Spatial profile of the Majorana modes in presence of the strong electrostatic defect placed near the edge.



Sz. Głodzik, N. Sedlmayr & T. Domański, PRB 102, 085411 (2020).

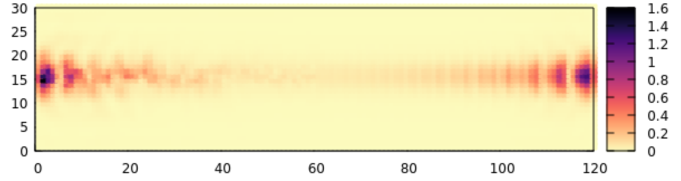
III. RANDOM DISORDER

The left-hand-side part of the metallic stripe is randomly disordered

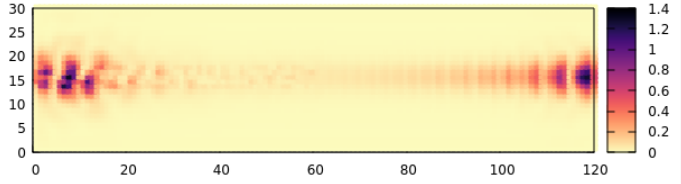


weak disorder

The left-hand-side part of the metallic stripe is randomly disordered



weak disorder



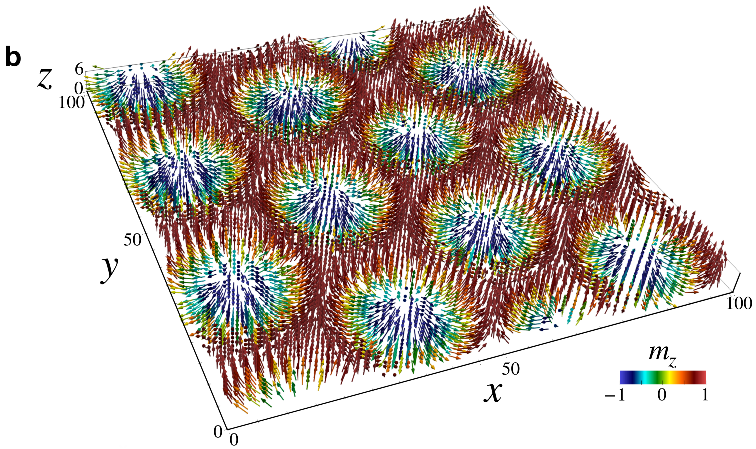
moderate disorder

Sz. Głodzik, N. Sedlmayr & T. Domański, PRB 102, 085411 (2020).

Theoretical proposals

SKYRMIONS UNDER JOSEPHSON JUNCTION

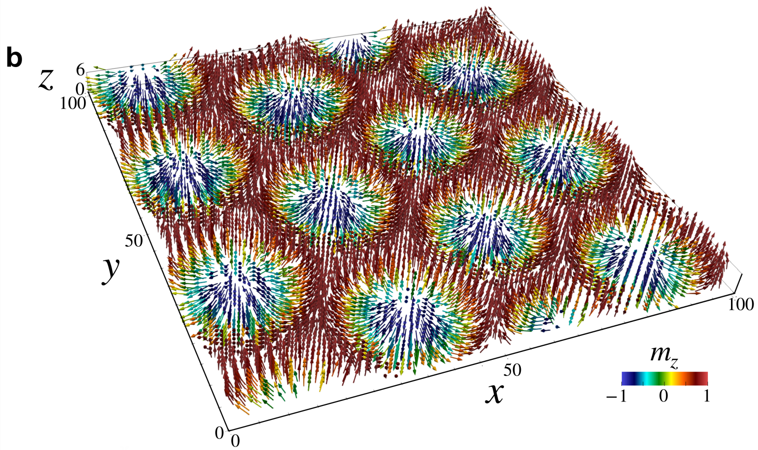
N. Mohanta, S. Okamoto & E. Dagotto, Communications Physics 4, 163 (2021).



Skyrmions can be driven by combining:

SKYRMIONS UNDER JOSEPHSON JUNCTION

N. Mohanta, S. Okamoto & E. Dagotto, Communications Physics 4, 163 (2021).

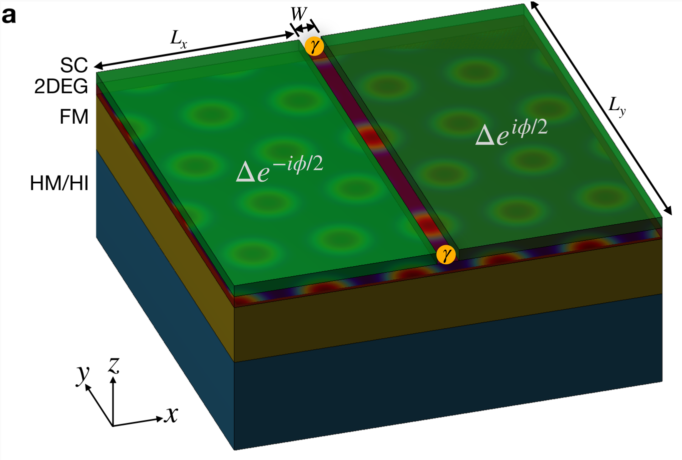


Skyrmions can be driven by combining: ★ **ferromagnetic exchange**

★ **Dzialoshinskii-Moriya interaction** ★ **external magnetic field**

SKYRMIONS UNDER JOSEPHSON JUNCTION

Josephson junction deposited on top of a skyrmion crystal.

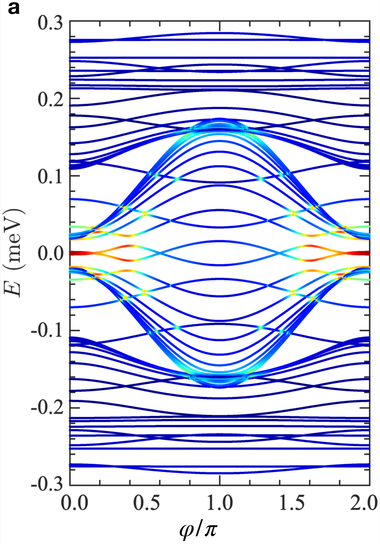


N. Mohanta, S. Okamoto & E. Dagotto, Communications Physics 4, 163 (2021).

FM - ferromagnetic layer **HM/HI - heavy metal or heavy insulator**

SKYRMIONS UNDER JOSEPHSON JUNCTION

Phase difference has detrimental effect on the Majorana modes

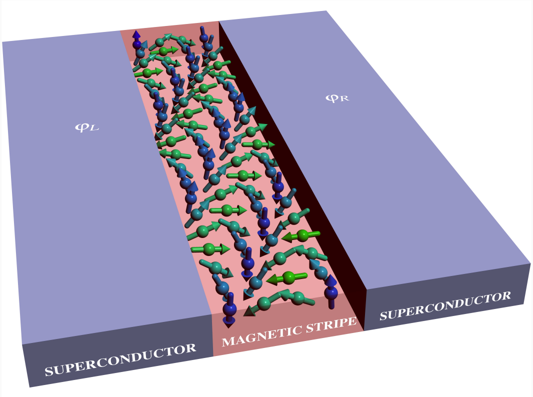


N. Mohanta, S. Okamoto & E. Dagotto, Communications Physics 4, 163 (2021).

What about self-organization ?

SELFORGANIZED MAGNETIC STRIPE

Narrow metallic stripe with the classical magnetic moments placed between two s-wave superconductors, differing in phase $\phi_L \neq \phi_R$.

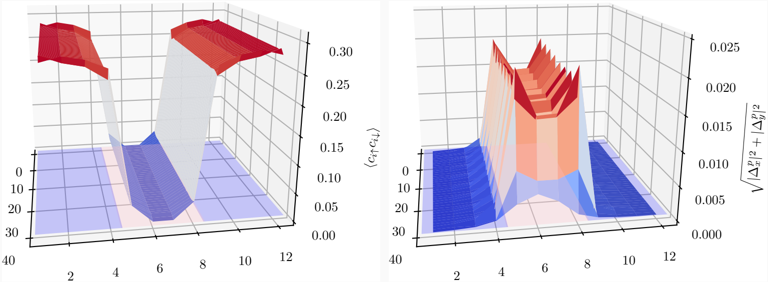


M.M. Maśka, M. Dziurawiec & N. Sedlmayr, T.D. – work in progress

/ Technical University (Wrocław) & UMCS (Lublin) cooperation/

SELFORGANIZED MAGNETIC STRIPE

Proximity-induced s-wave (left) and p-wave (right) pairings.

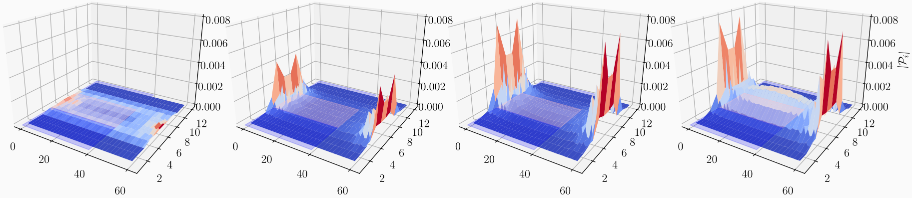


Width: left-side superconductor (sites 1-4),
metallic magnetic stripe (sites 5-8),
right-side superconductor (sites 9-12),

Length: 40 sites.

SELFORGANIZED MAGNETIC STRIPE

Topography of the Majorana quasiparticles obtained for the coplanar moments and for various Josephson phase differences $\phi_R - \phi_L$.



$\phi_R - \phi_L = 0.6\pi$ $\phi_R - \phi_L = 0.4\pi$ $\phi_R - \phi_L = 0.2\pi$ $\phi_R - \phi_L = 0.0$

Phasal dependence of the Majorana boundary modes

/ preliminary results obtained for the coplanar magnetic moments /

SELFORGANIZED MAGNETIC STRIPE

In analogy to the skyrmion based Josephson junction, we observe that the optimal condition for the topological phase occurs at $\phi_L - \phi_R = 0$.

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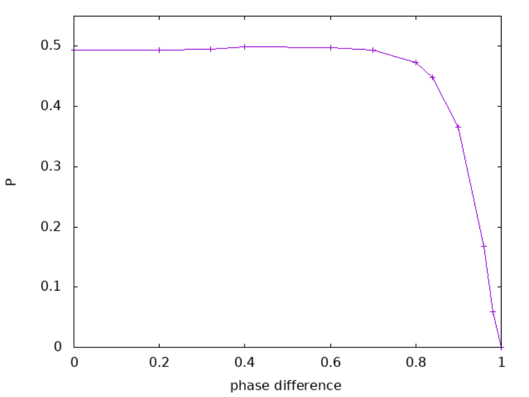

Total spectral weight of Majorana modes vs phase difference.

M.M. Maśka, M. Dziurawiec, N. Sedlmayr & T.D. – work in progress

SELFORGANIZED MAGNETIC STRIPE

Some ideas for the braiding protocols using the phase difference.

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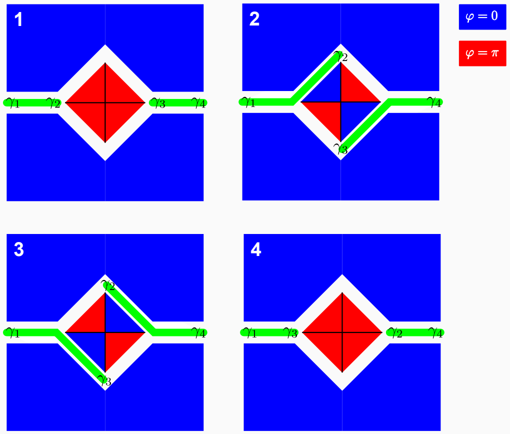


Phase difference is used for moving the Majorana modes.

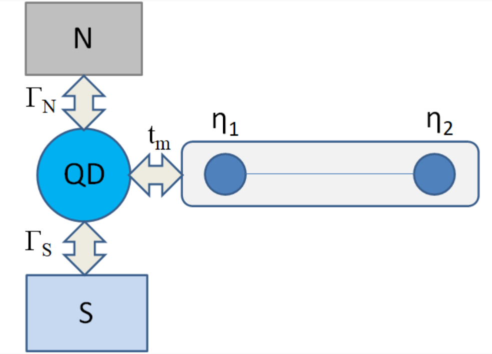
M.M. Maśka, M. Dziurawiec, N. Sedlmayr & T.D. – work in progress

Part 3. Dynamical phenomena

(in topological nanohybrides)

DYNAMICAL MAJORANA-LEAKAGE

Hybrid structure: quantum dot coupled to topological nanowire



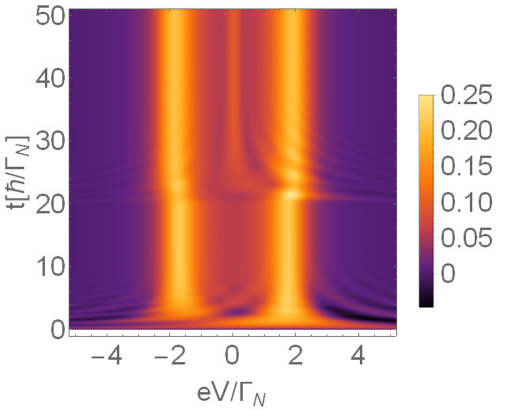
Question:

How much time does it take for the Majorana mode to leak on QD ?

J. Barański, M. Barańska, T. Zienkiewicz, R. Taranko, T.Domański, PRB 103, 235416 (2021).

DYNAMICAL MAJORANA-LEAKAGE

Time-dependent conductance of the biased N-QD-S junction

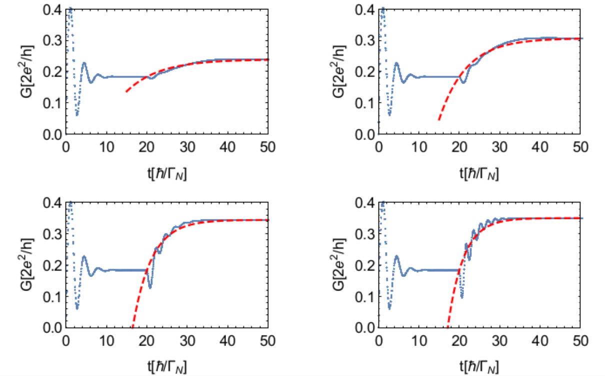


QD is coupled to the topological nanowire at $t = 10$.

Transient effects: Gradual development of the trivial (Andreev) and topological (Majorana) zero-energy bound states in QD.

DYNAMICAL MAJORANA-LEAKAGE

Time-dependent zero-bias conductance

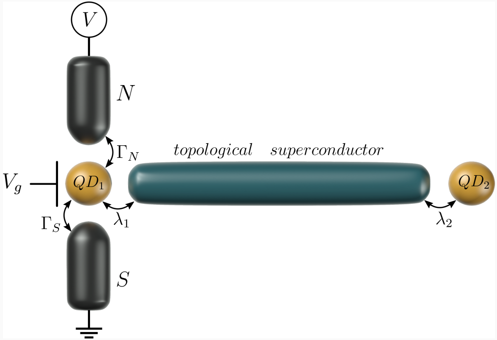


For realistic parameters of the hybrid structure the Majorana zero-bias feature establishes in about nanoseconds.

J. Barański, M. Barańska, T. Zienkiewicz, R. Taranko, T.Domański, PRB 103, 235416 (2021).

NONLOCAL CROSS-CORRELATIONS

Two quantum dots side-attached to the topological nanowire

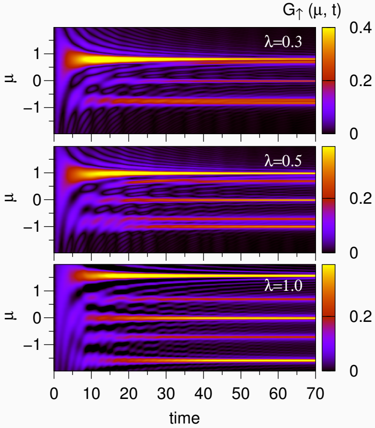


Question: Can any nonlocal cross-correlations be transmitted between QD_1 and QD_2 via the Majorana boundary modes ?

R. Taranko, K. Wrześniewski, I. Weymann, T. Domański, arXiv:2312.04488 (2023).

NONLOCAL CROSS-CORRELATIONS

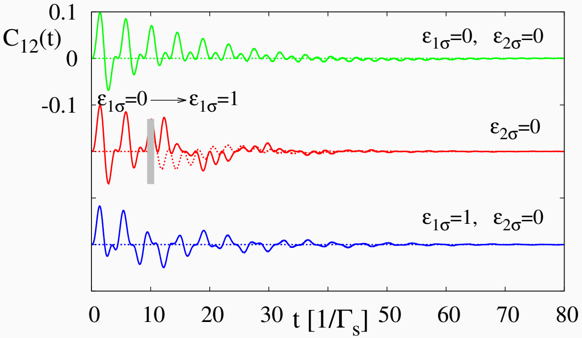
Time-dependent conductance of the biased N-QD$_1$-S junction



Transient effects: **Gradual development of the trivial (Andreev) and topological (Majorana) bound states in QD$_1$.**

NONLOCAL CROSS-CORRELATIONS

Time-dependent interdot electron pairing $C_{12}(t) = \left\langle \hat{d}_{1\downarrow} \hat{d}_{2\uparrow} \right\rangle$

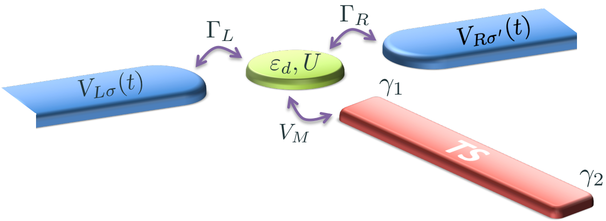


The nonlocal electron pairing persists only over a short transient time-scale. It could be detected by crossed Andreev refelections.

R. Taranko, K. Wrześniewski, I. Weymann, T. Domański, arXiv:2312.04488 (2023).

MAJORANA SIGNATURES IN AC-CONDUCTANCE

Quantum dot coupled to the topological nanowire under ac-voltage



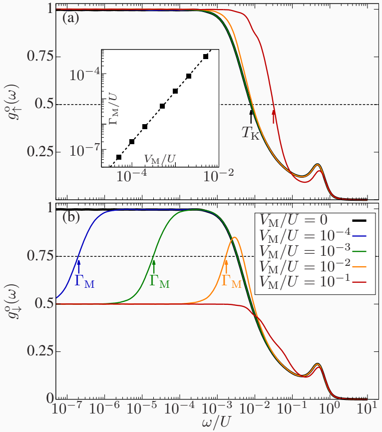
Question:

Can we resolve Majorana and Kondo states in ac-response ?

K.P. Wójcik, T. Domański, I. Weymann, arXiv:2311.03605 [submitted to PRB].

NONLOCAL CROSS-CORRELATIONS

The frequency dependent conductance of *ac*-driven L-QD-R junction



Spin-resolved conductances: **Signatures of the Coulomb peak and the Kondo effect can be clearly observed at finite-frequencies.**

SUMMARY

Nanoscopic superconducting structures can be a platform for realization of the bound states:

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Both types are promising candidates for stable qubits and/or future quantum computations

SUMMARY

Nanoscopic superconducting structures can be a platform for realization of the bound states:

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Both types are promising candidates for stable qubits and/or future quantum computations

http://kft.umcs.lublin.pl/doman/lectures