Topological superconductivity and boundary modes of magnetic nanostructures

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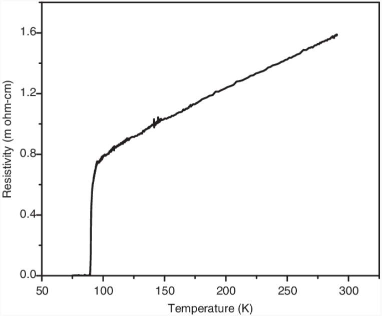
Lublin, Poland

MagTop (Warsaw) **18/Jan/2023**

Magnetism vs superconductivity

BULK SUPERCONDUCTORS

Perfect conductor



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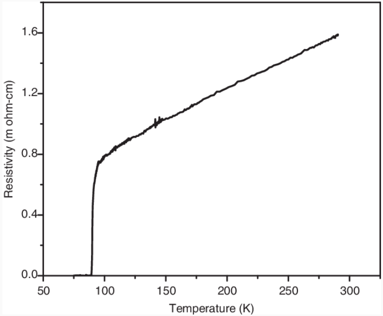

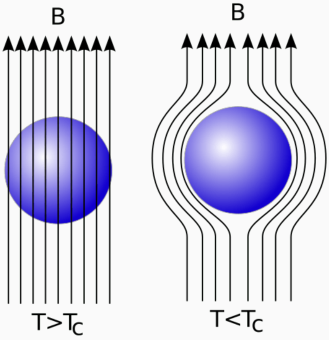

Perfect diamagnet

PAIRING VS MAGNETISM

Are they friends or foes ?

DESTRUCTIVE INFLUENCE OF MAGNETIC FIELD

Magnetism and electron pairing are rather antagonistic ...

DESTRUCTIVE INFLUENCE OF MAGNETIC FIELD

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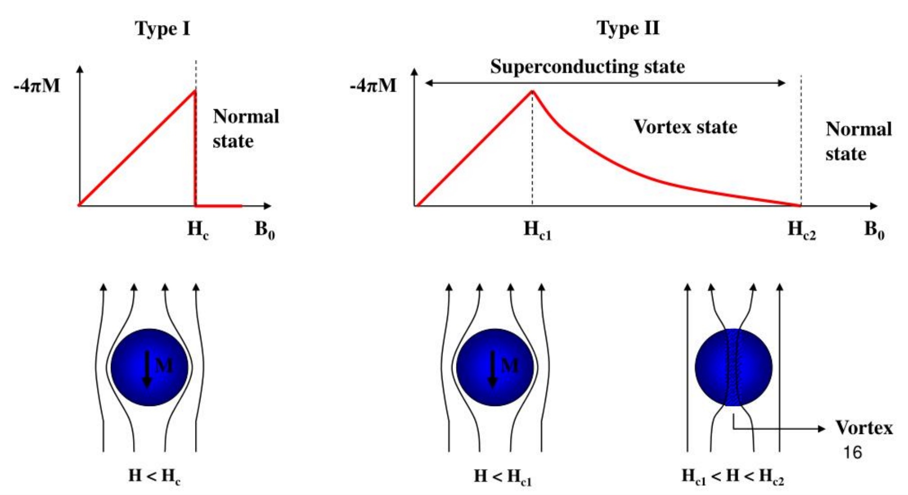
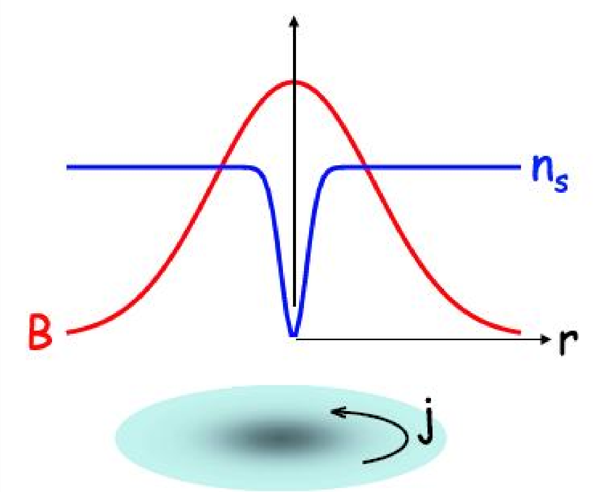


Magnetic field penetrates type-II superconductors (vortex-structure)

VORTEX IN SUPERCONDUCTOR

Single vortex encloses the magnetic field flux $\Phi = \frac{h}{2e}$.



Vortex is a piece of *normal* region inside superconductor.

STATES BOUND TO VORTEX CORE

Volume 9, number 4 PHYSICS LETTERS 1 May 1964

BOUND FERMION STATES ON A VORTEX LINE IN A TYPE II SUPERCONDUCTOR

C. CAROLI, P. G. DE GENNES, J. MATRICON
Service de Physique des Solides, Faculté des Sciences, Orsay (S & O)

Bound-states of the axisymmetric vortex in s-wave superconductors take a form:

$$E_n = \omega_0 \left(n + \frac{1}{2} \right) \qquad n = 0, \pm 1, \pm 2, \dots$$

where

$$\omega_0 \approx \frac{\Delta^2}{E_F}$$

VORTEX IN P-WAVE SUPERCONDUCTOR

JETP LETTERS VOLUME 70, NUMBER 9 10 NOV. 1999

Fermion zero modes on vortices in chiral superconductors

G. E. Volovik

Helsinki University of Technology, Low Temperature Laboratory, FIN-02015 HUT, Finland; Landau Institute of Theoretical Physics, Russian Academy of Sciences, 117334 Moscow, Russia

(Submitted 30 September 1999)
Pis'ma Zh. Éksp. Teor. Fiz. **70**, No. 9, 601–606 (10 November 1999)

Bound-states of the vortex in p-wave (triplet) superconductors are given by:

$$E_n = \omega_0 n \qquad\qquad n = 0, \pm 1, \pm 2, \dots$$

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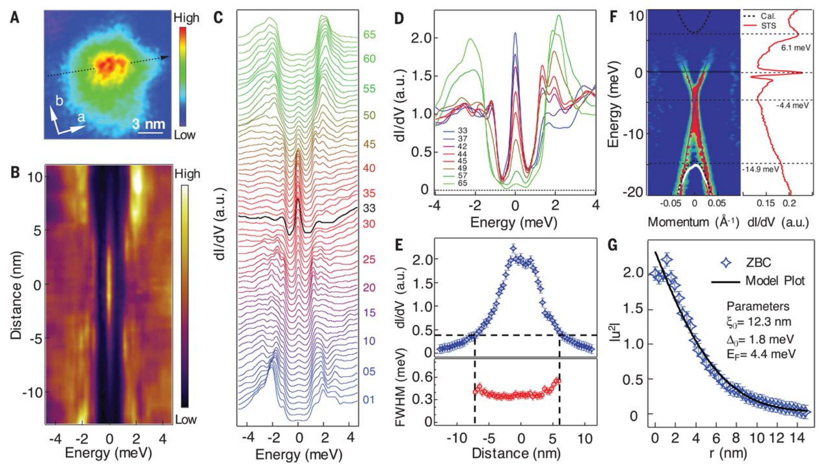
$$E_n = \omega_0 n \qquad n = 0, \pm 1, \pm 2, \ldots$$

implying the bound state at zero-energy !

BOUND STATES IN A VORTEX (EXPERIMENT)

$FeTe_{0.55}Se_{0.45}$ superconductor ($T_c = 14.5$ K, $\Delta = 1.8$ meV, $E_F = 4.4$ meV).

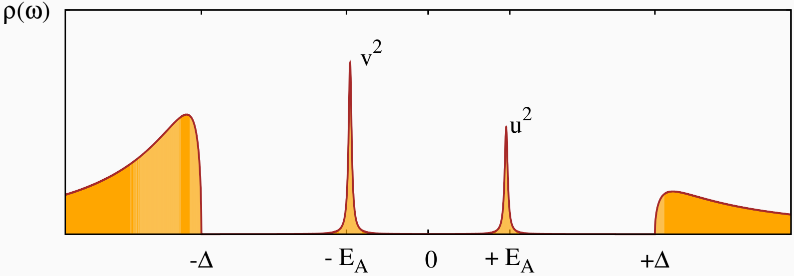


D. Wang et al, Science 362, 333 (2018) /Chinese Academy of Sciences (Beijing)/

Nanoscopic superconductors

SINGLE IMPURITY IN SUPERCONDUCTOR

Typical spectrum of a single impurity in s-wave superconductor:



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

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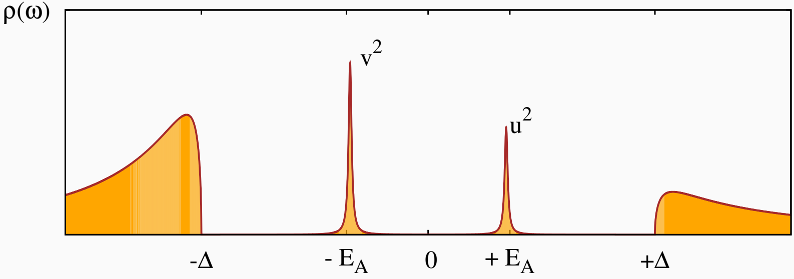
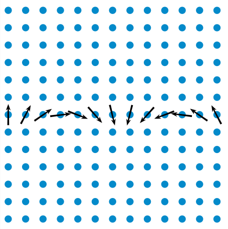


Bound states appearing in the subgap region $E \in \langle -\Delta, \Delta \rangle$

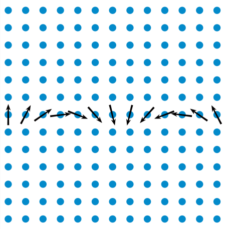
are dubbed Yu-Shiba-Rusinov (or Andreev) quasiparticles.

Magnetic chains

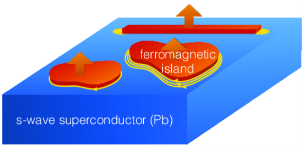


MAGNETIC OBJECTS IN SUPERCONDUCTORS

Magnetic chains



or magnetic islands



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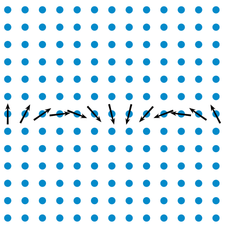

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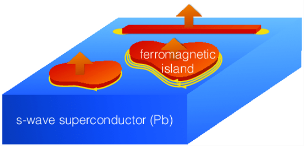
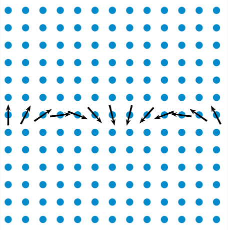


arrange their in-gap bound states in a form of the Shiba-bands.

MAGNETIC OBJECTS IN SUPERCONDUCTORS

Magnetic chains



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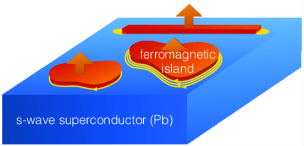


arrange their in-gap bound states in a form of the Shiba-bands.

Specific magnetic textures of chains and islands can guarantee topologically non-trivial phases, hosting the Majorana modes !

A few examples ...

1. Rashba nanowires

TOPOLOGICAL SUPERCONDUCTING NANOWIRE

Spin-orbit (Rashba) interaction in presence of magnetic field applied to semiconducting nanowires proximitized to s-wave superconductor induces the triplet pairing of electrons, hosting Majorana modes.

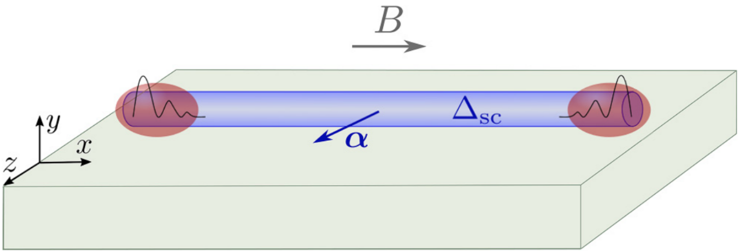
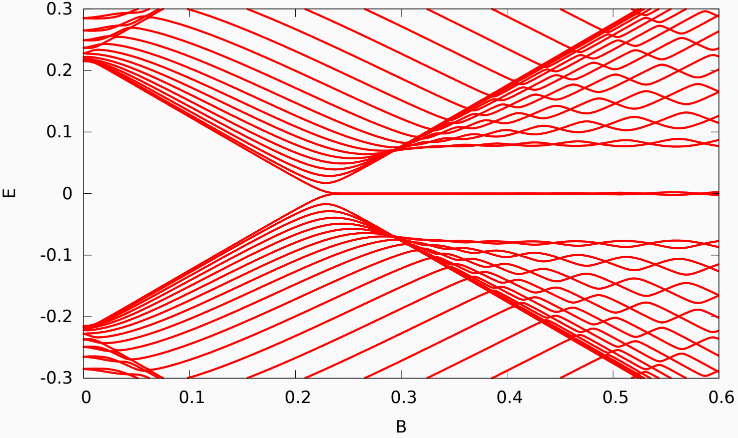


FIG. 1. A nanowire (blue) placed on a superconducting substrate (green). The SOI vector $\boldsymbol{\alpha}$ is taken to lie along the z axis and determines the spin quantization axis. A magnetic field B is applied along the x axis such that it is oriented perpendicularly to the SOI vector. By proximity, the substrate induces a superconducting pairing of strength Δ_{sc} in the nanowire. In the topological phase [see Eq. (41)], MBSs (red) emerge at the wire ends.

Effective quasiparticle states of the Rashba nanowire



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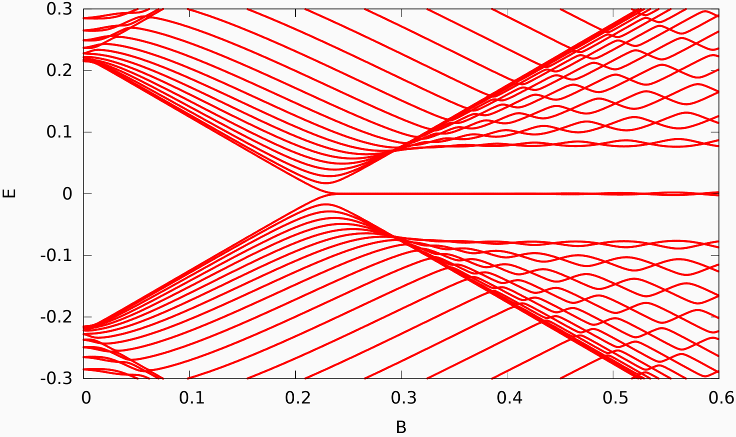
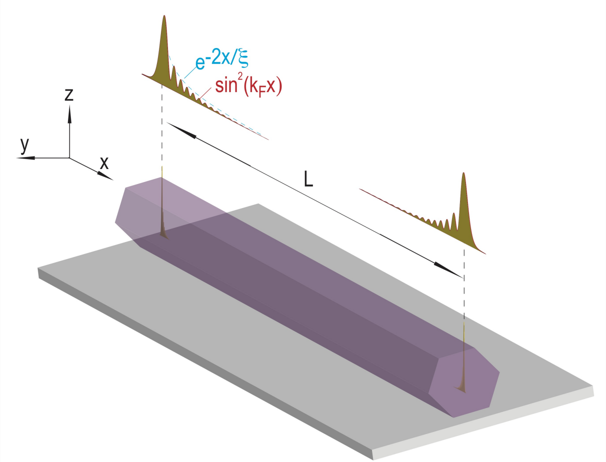


Closing / reopening of a gap $\Longleftrightarrow$ band-invertion of topological insulators

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

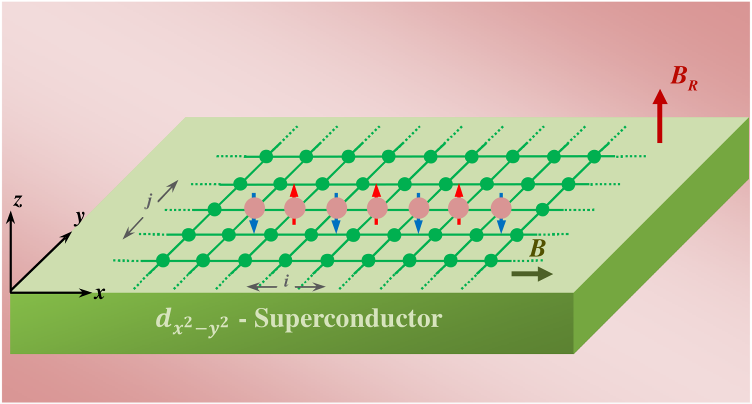
Majorana qps are localized near the edges



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

PROXIMITY TO D-WAVE SUPERCONDUCTOR

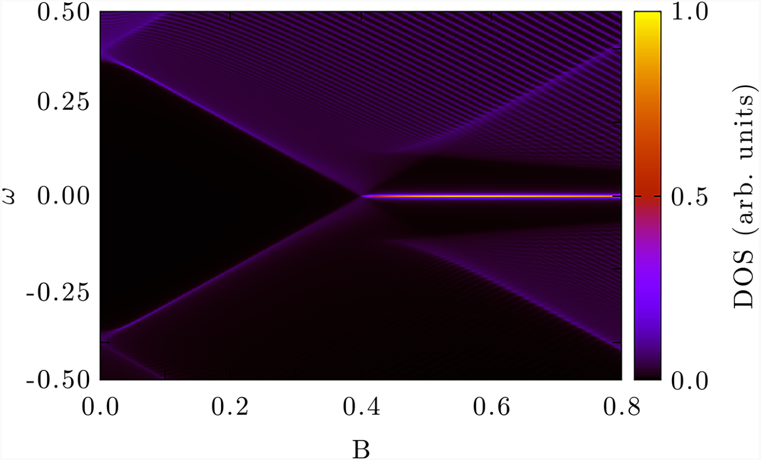
Rashba nanowire deposited along a-axis of high T_c superconductor



T. Domański, S. Vosoughinia, A. Kobiałka, Acta Phys. Polon. A 142, 679 (2022).

PROXIMITY TO D-WAVE SUPERCONDUCTOR

Transition to topological phase:

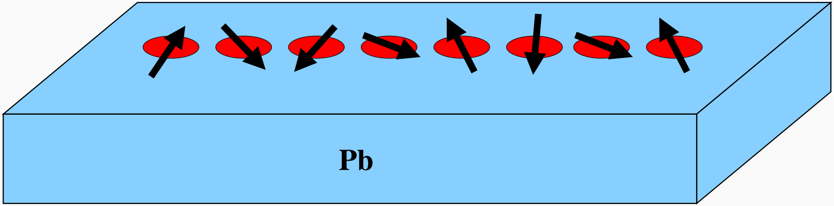


T. Domański, S. Vosoughinia, A. Kobiałka, Acta Phys. Polon. A 142, 679 (2022).

2. Selforganised magnetic chains

MAGNETIC CHAINS ON SUPERCONDUCTORS

Magnetic atoms (like Fe) on a surface of s-wave superconductor (for example Pb) arrange themselves into such spiral order, where topological superconducting phase is selfsustained



MICROSCOPIC MODEL

Itinerant electrons in the chain of magnetic impurities placed on a surface of isotropic superconductor can be described by the Hamiltonian:

$$H = -t\sum_{i,\sigma}\left(\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{i+1,\sigma} + \text{H.c.}\right) - \mu\sum_{i,\sigma}\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{i,\sigma} + J\sum_{i}\vec{S}_i\cdot\hat{\vec{s}}_i + \sum_{i}\left(\Delta\hat{c}^{\dagger}_{i\uparrow}\hat{c}^{\dagger}_{i\downarrow} + \text{H.c.}\right)$$

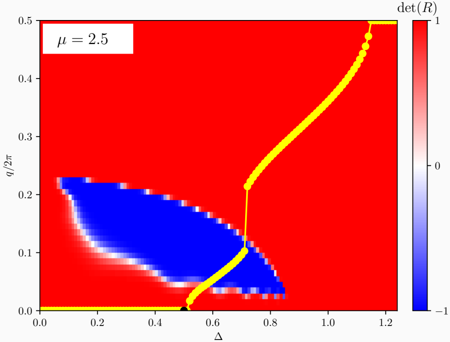
Here $\vec{S}_i$ are the classical magnetic moments and $\hat{\vec{s}}_i = \frac{1}{2}\sum_{\alpha,\beta}\hat{c}^{\dagger}_{i,\alpha}\vec{\sigma}_{\alpha\beta}\hat{c}_{i,\beta}$ denote the spins of mobile electrons

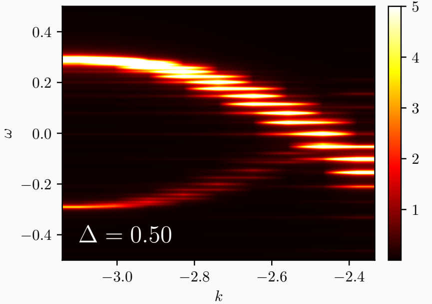
$\Longrightarrow$ **J is the coupling between magnetic atoms and itinerant electrons**

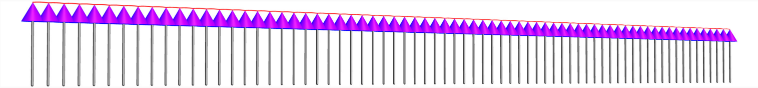
$\Longrightarrow$ **Δ is the proximity induced on-site pairing**

SELFORGANISATION (TOPOFILIA)

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







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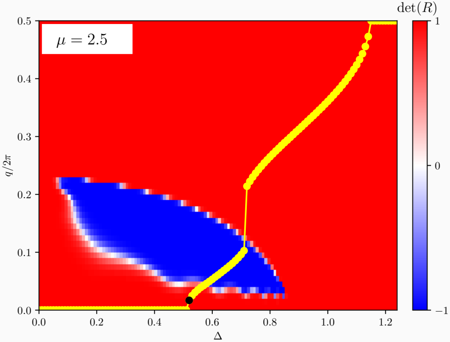

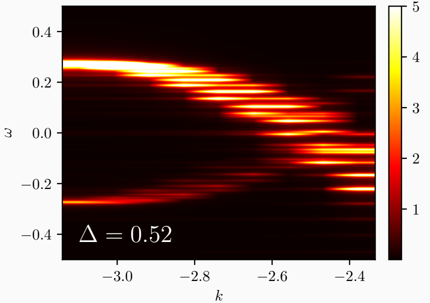

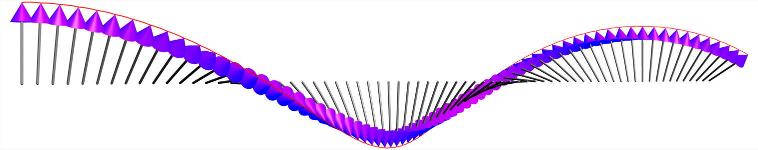

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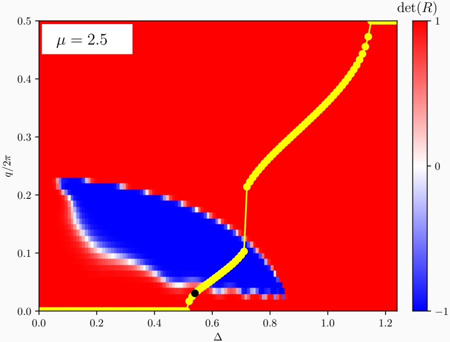

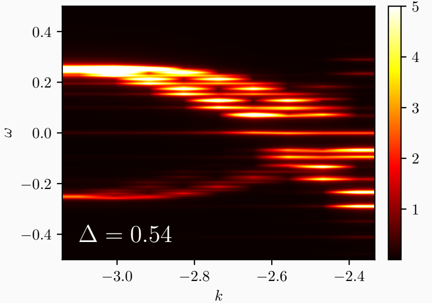

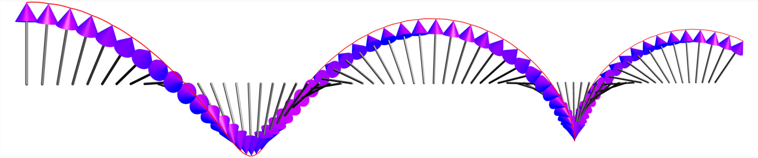

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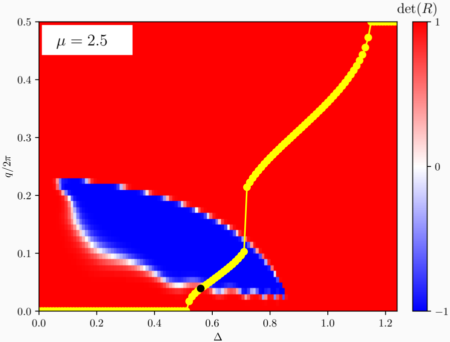

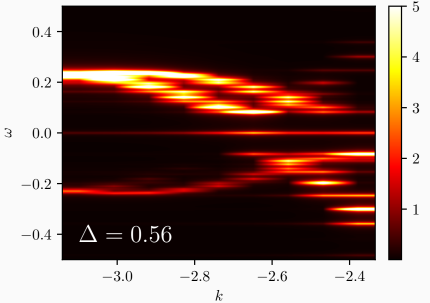

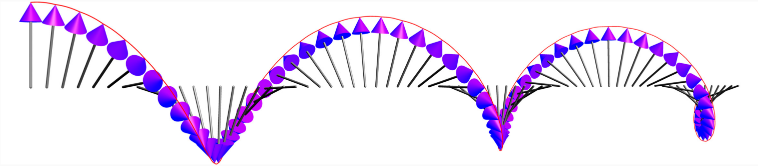

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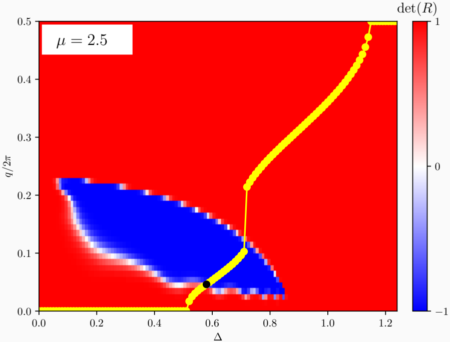

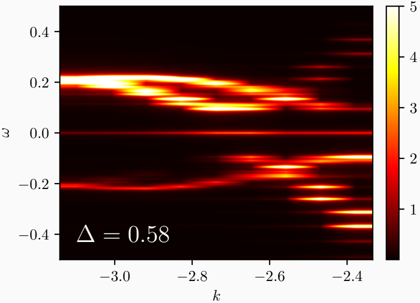

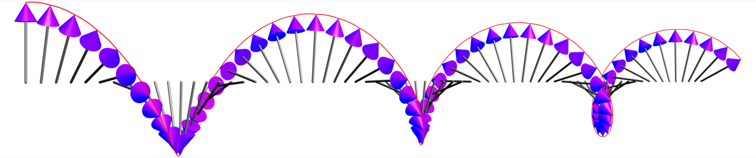

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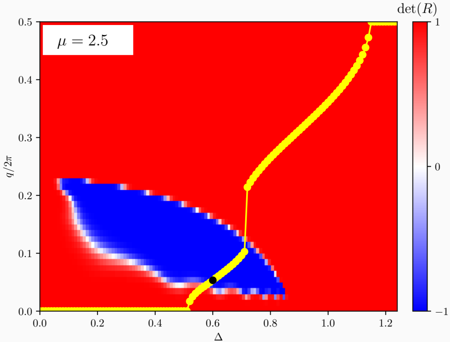

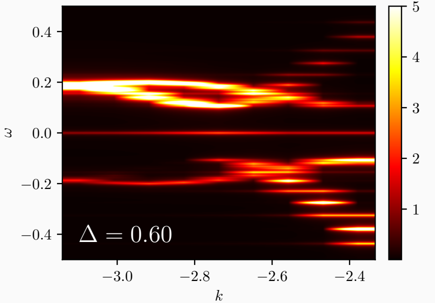

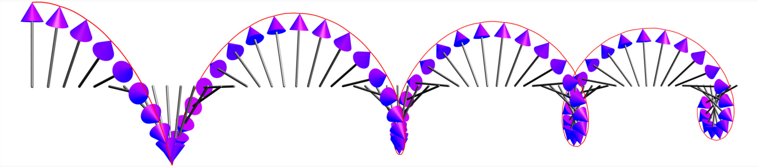

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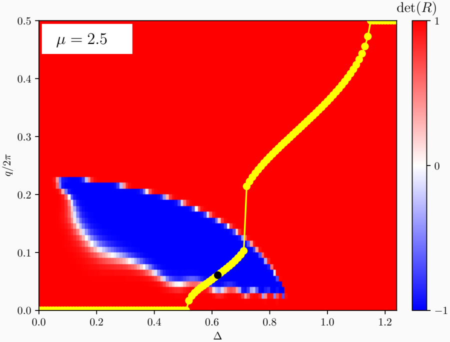

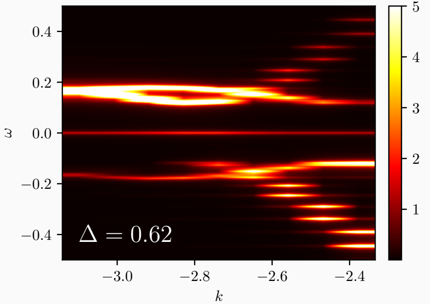

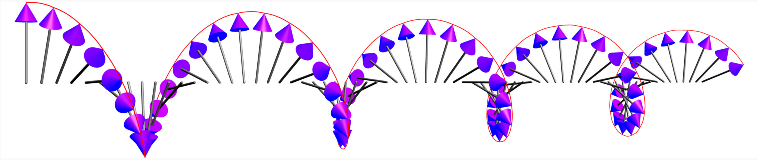

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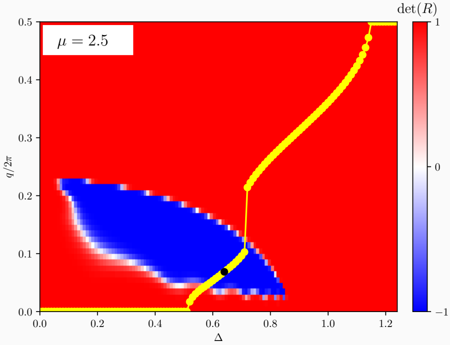

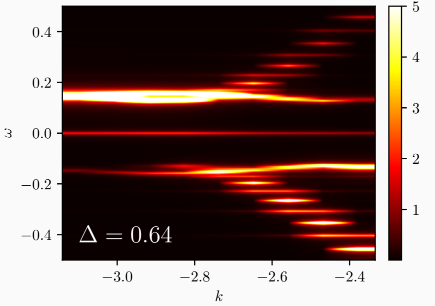

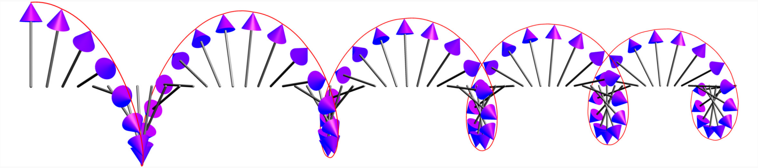

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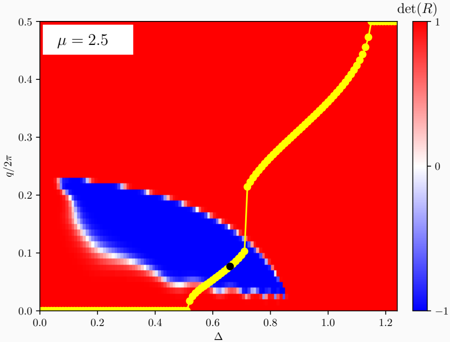

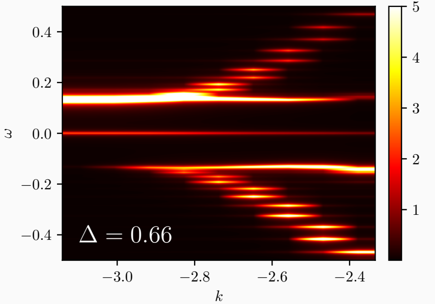

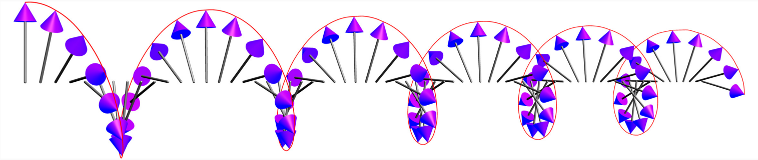

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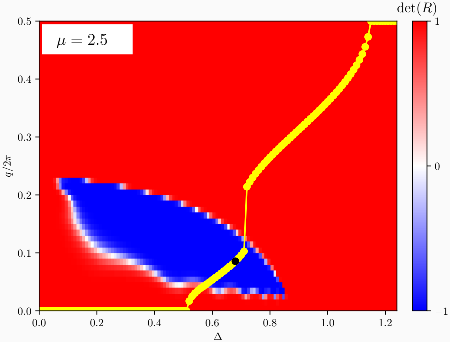

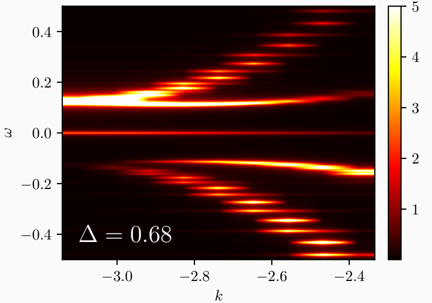

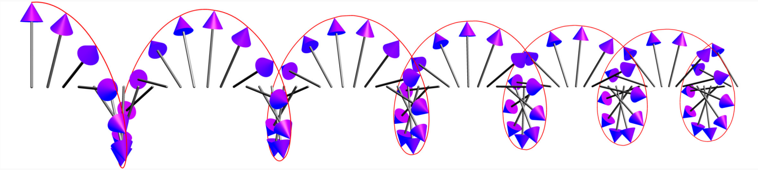

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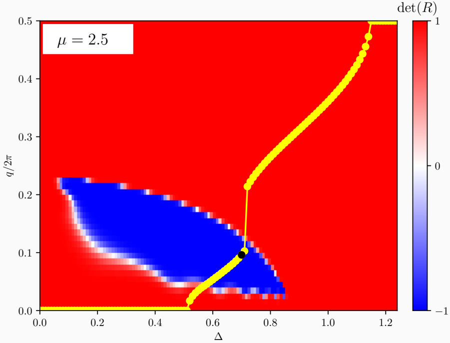
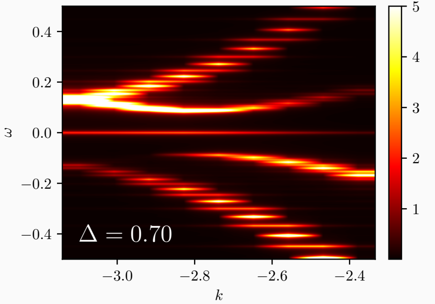
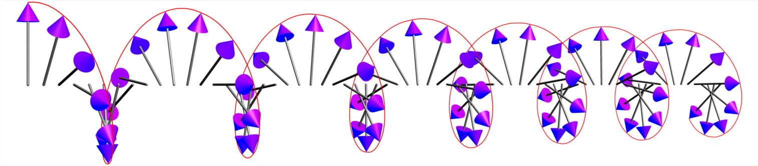
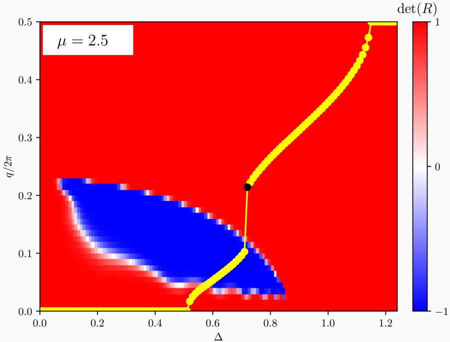


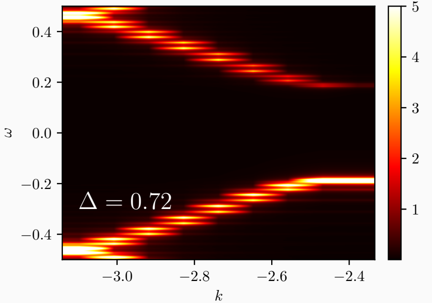


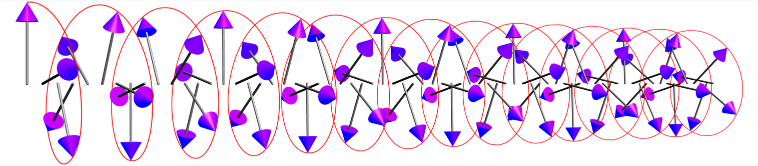


SELFORGANISATION (TOPOFILIA)

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

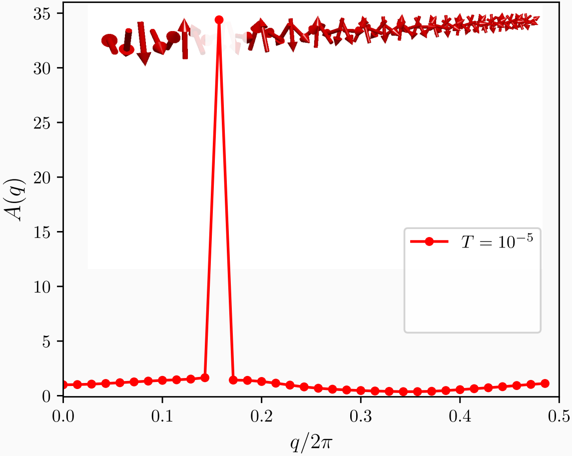






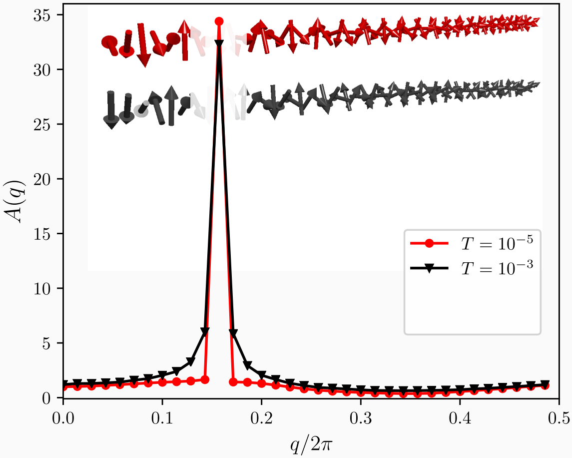
SPIRAL ORDER AT FINITE TEMPERATURES

Structure factor: $A(q) = \frac{1}{L}\sum_{jk} e^{iq(j-k)}\langle \vec{S}_j \cdot \vec{S}_k \rangle$



SPIRAL ORDER AT FINITE TEMPERATURES

Structure factor: $A(q) = \frac{1}{L} \sum_{jk} e^{iq(j-k)} \langle \vec{S}_j \cdot \vec{S}_k \rangle$



SPIRAL ORDER AT FINITE TEMPERATURES

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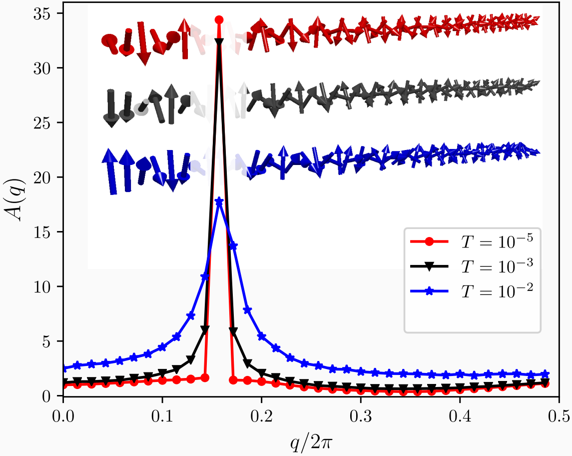

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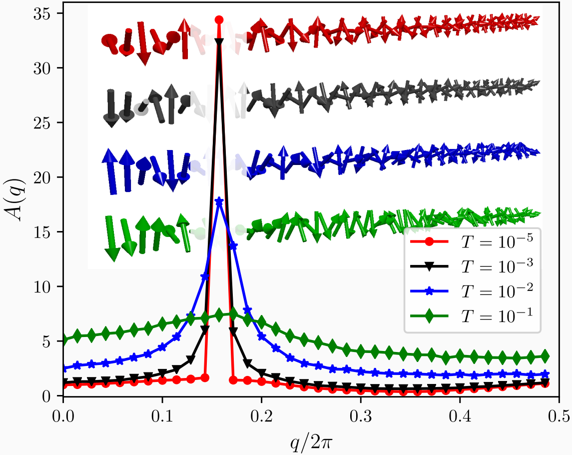
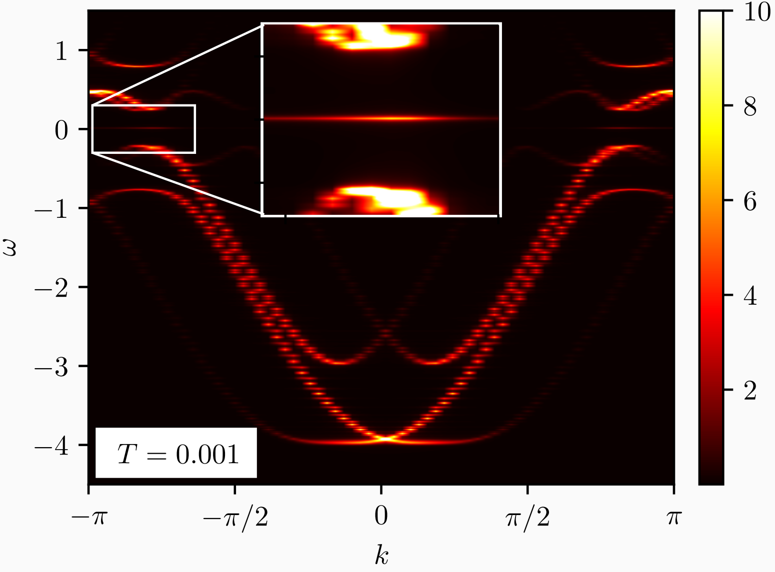
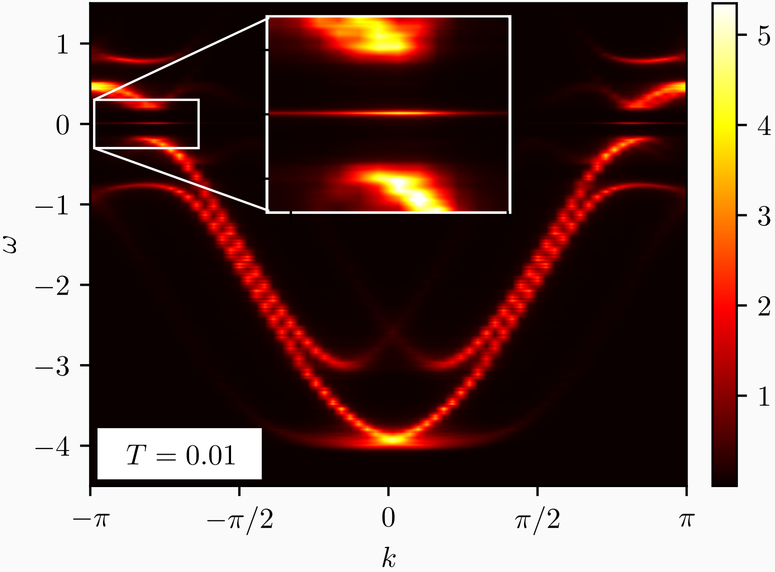


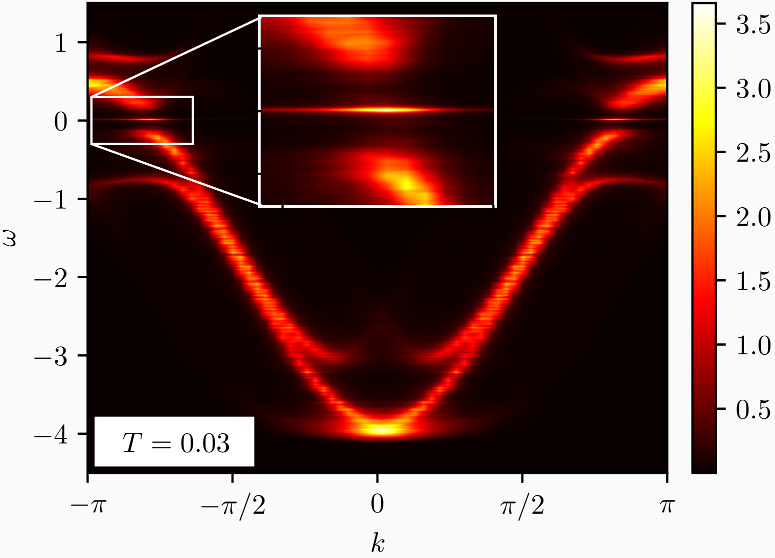
TEMPERATURE EFFECT ON MAJORANA QPS



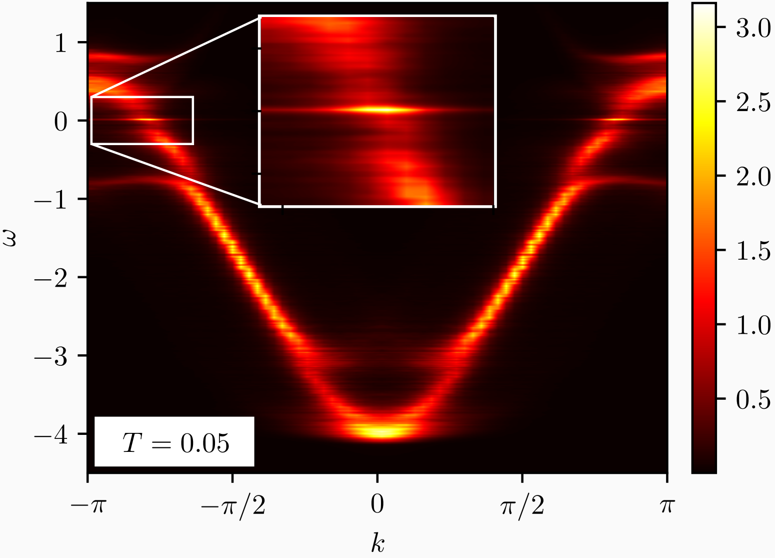
INFLUENCE OF TEMPERATURE ON MAJORANA QPS



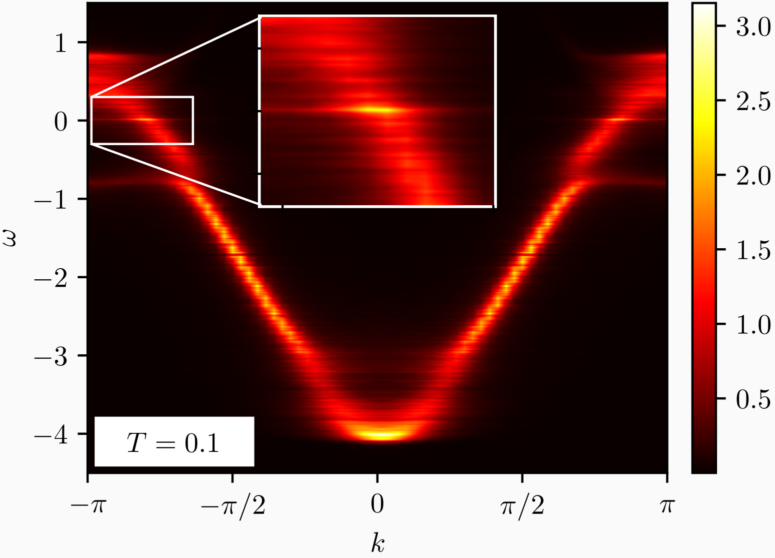
INFLUENCE OF TEMPERATURE ON MAJORANA QPS



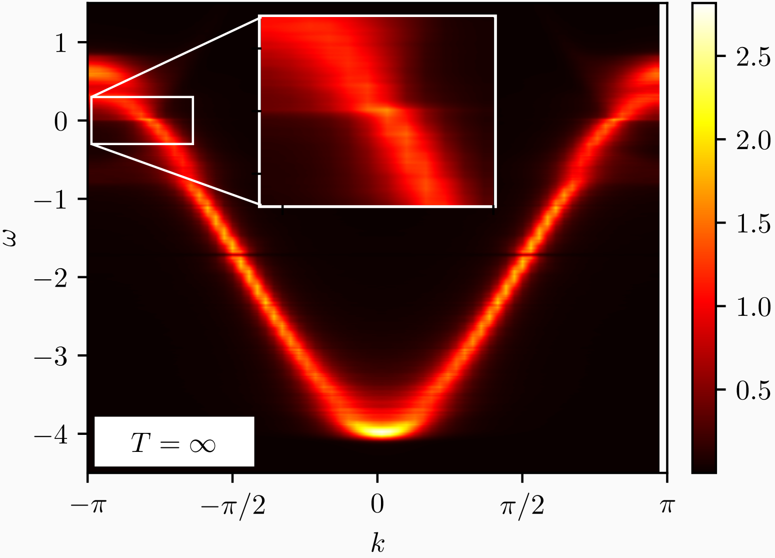
INFLUENCE OF TEMPERATURE ON MAJORANA QPS



INFLUENCE OF TEMPERATURE ON MAJORANA QPS



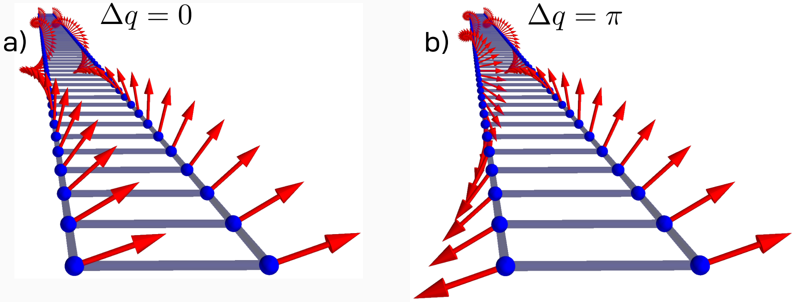
INFLUENCE OF TEMPERATURE ON MAJORANA QPS



3. Magnetic ladders

TOPOLOGICAL MAGNETIC LADDER

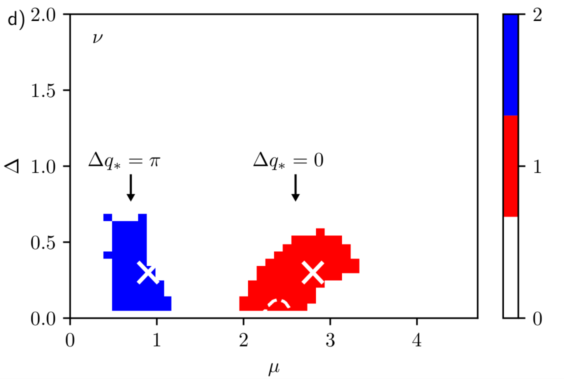
Spiral magnetic order in a ladder deposited on conventinal superconductor.



M.M. Maśka, N. Sedlmayr, A. Kobiałka, T. Domański, Phys. Rev. B 103, 235419 (2021).

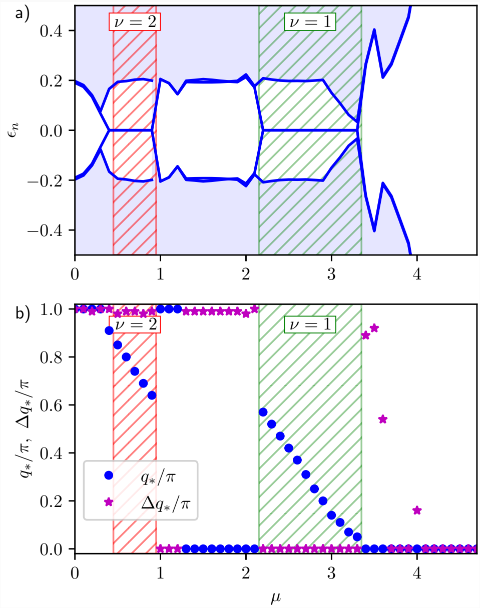
TOPOLOGICAL PHASES

For thermodynamic limit ($N \to \infty$) we have computed the topological invariant $\mathbb{Z}$ of this system, belonging to AIII class.



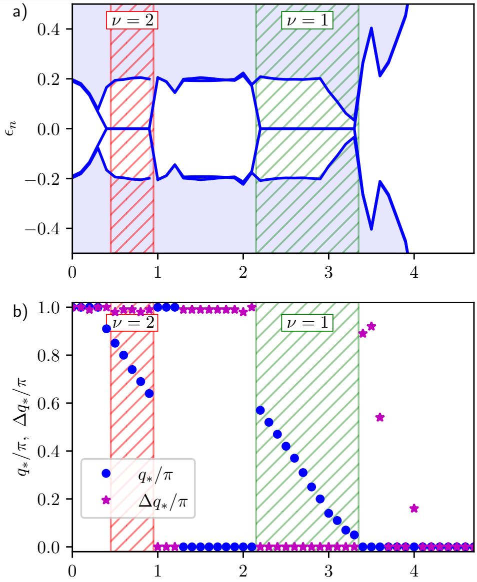
Regions of the topological superconducting phase coincide either with the antiparallel or parallel spiral arrangements of the magnetic ladder.

UNCONVENTIONAL TOPOLOGICAL TRANSITIONS



Variation of eigenenergies ε_n against μ for $\Delta = 0.3$

Variation of $q_\star$ and $\Delta q_\star$

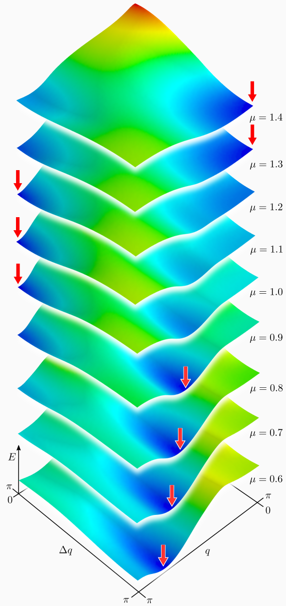


Variation of eigenenergies ε_n against μ for $\Delta = 0.3$

Variation of $q_\star$ and $\Delta q_\star$

Discontinuous transitions to/from topological phase without gap closing!

DISCONTINUOUS TRANSITIONS



Total energy as function of q and Δq obtained for $\Delta = 0.3t$ and several μ.

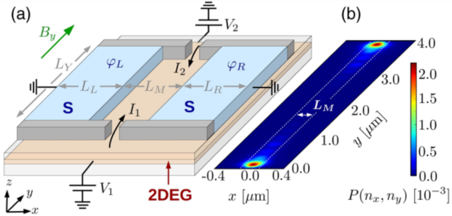
Red arrows indicate the minimum energy.

Majorana modes in Josephson junctions

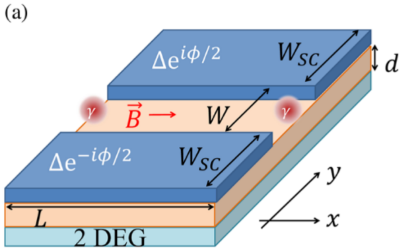
Theoretical concept (2017)

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)

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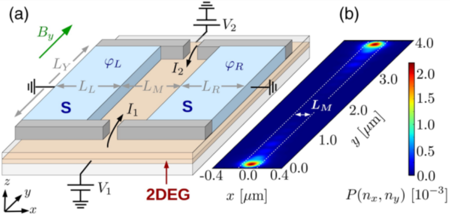
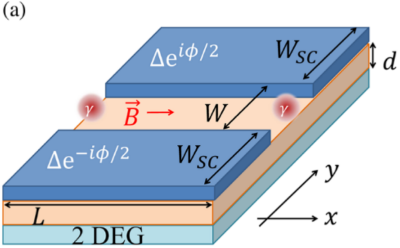


Michael Hell et al., PRL 118, 107701 (2017)



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

Benefit:

Phase-tunable topological superconductivity induced in the metallic stripe.

PLANAR JOSEPHSON JUNCTIONS

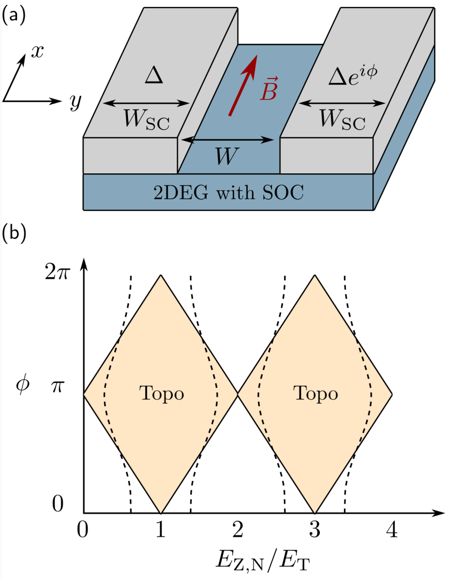
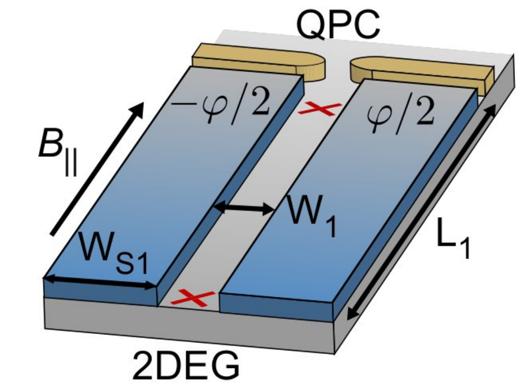


Diagram of the topological superconducting state with respect to: phase difference ϕ and in-plane magnetic field E_z.

Experimental realization (2019)

PLANAR JOSEPHSON JUNCTIONS

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



Width:

W_1 = 80 nm

Length:

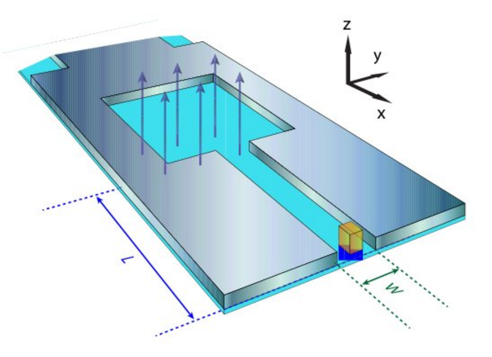
L_1 = 1.6 μm

A. Fornieri, ..., Ch. Marcus and F. Nichele, 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

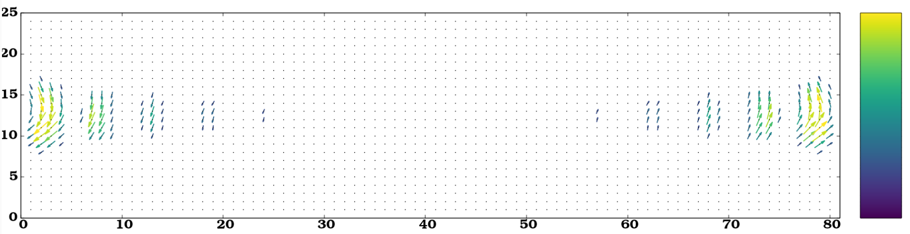
H. Ren, ..., L.W. Molenkamp, B.I. Halperin & A. Yacoby, Nature 569, 93 (2019).

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

Topography of Majorana modes

TOPOGRAPHY OF MAJORANA MODES

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



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

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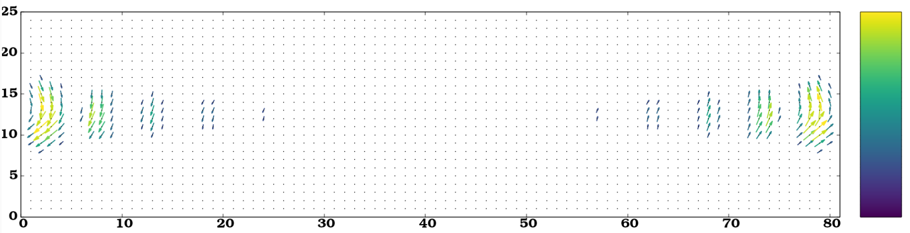
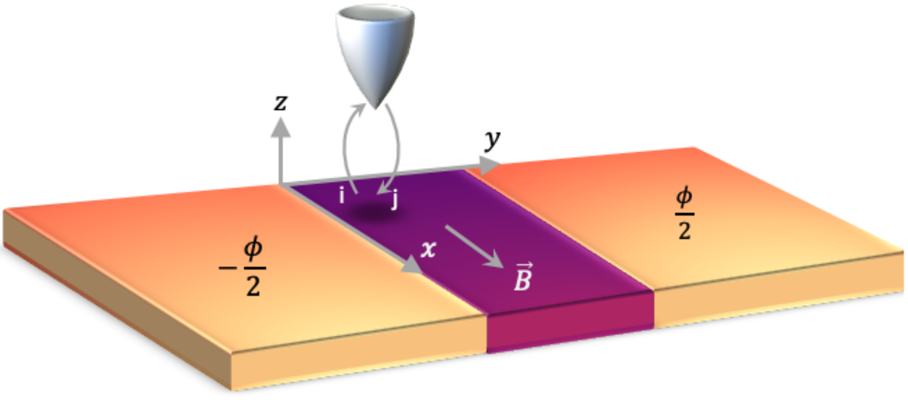


Complex "Majorana polarization" $u_{\uparrow,n}v_{\uparrow,n} - u_{\downarrow,n}v_{\downarrow,n}$ obtained for eigenvalue $E_n = 0$. Magnitude of this quantity is measurable by the conductance of SESAR spectroscopy. For details see:

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

TOPOGRAPHY OF MAJORANA MODES

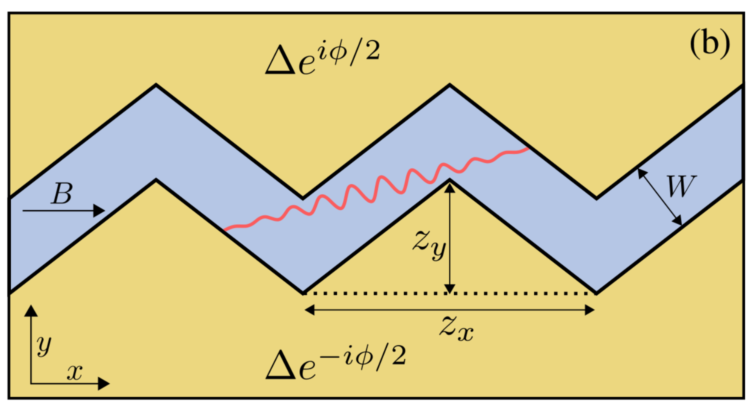
Selective Equal Spin Andreev Reflection (SESAR) spectroscopy:



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

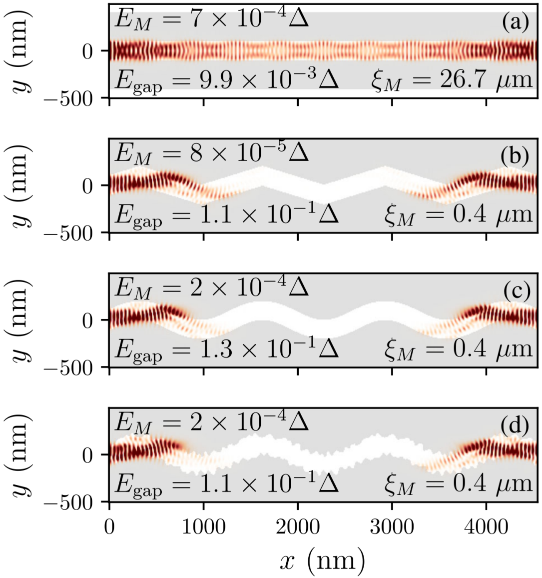
Means to localize Majoranas

In order to reduce the spatial extent of the Majorana modes one can use zigzag-shape metallic stripe.



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

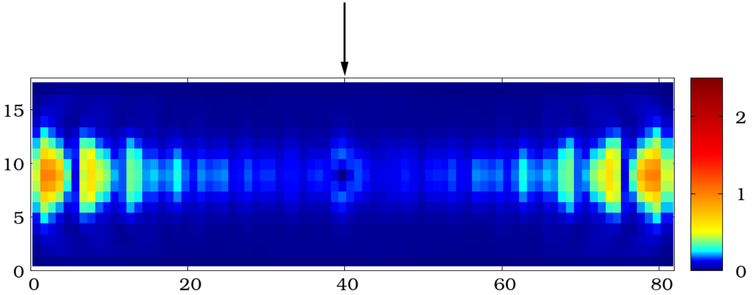
I. DESHAPED JOSEPHSON JUNCTION



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

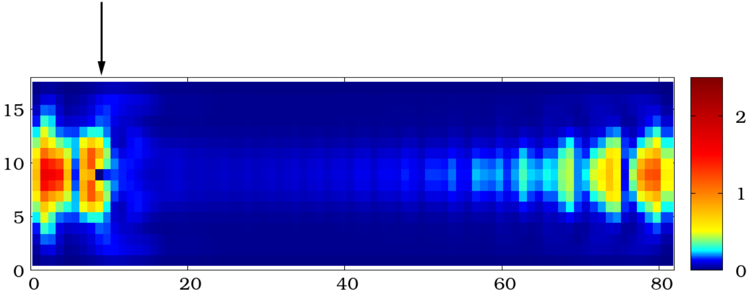
II. LOCAL DEFECT IN JOSEPHSON JUNCTION

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).

"Benefits of Weak Disorder in dim=1 Topological Superconductors"

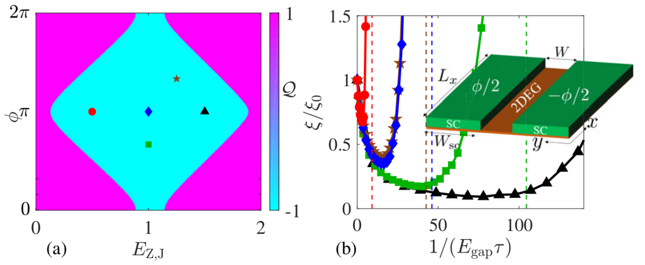
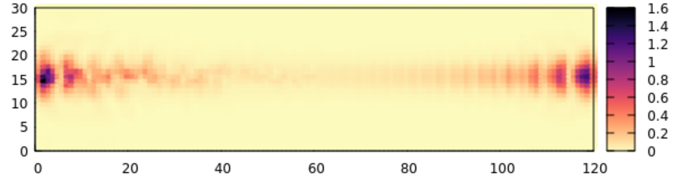


FIG. 1. (a) Phase diagram of the planar Josephson junction Eq. (1) in the clean limit. In the topological phase ($\mathcal{Q} = -1$), the system supports zero-energy MBSs at each end of the junction. (b) The Majorana localization length ξ versus the disorder-induced inverse mean free time τ^{-1} for different points inside the topological phase [see markers in (a)].

A. Haim & A. Stern, Phys. Rev. Lett. 122, 126801 (2019).

III. RANDOM DISORDER

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



weak disorder

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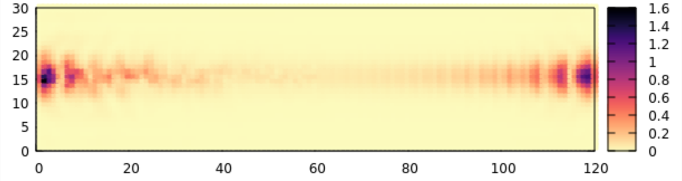
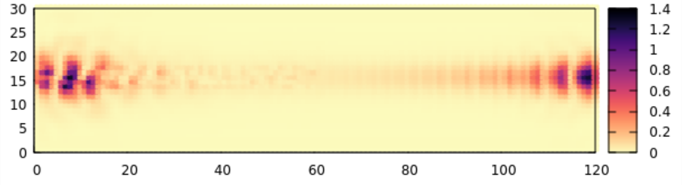


weak disorder



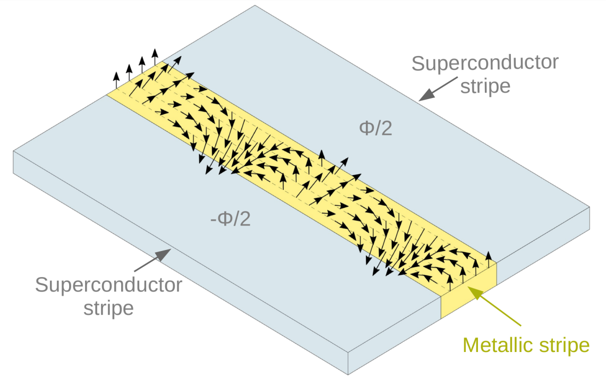
moderate disorder

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

Selforganized magnetic stripes

PLANAR MAGNETIC JOSEPHSON JUNCTION

A small metallic piece with the classical magnetic moments placed between two external superconductors, differing in phase Φ.



M. Dziurawiec, M. Strzałka, M.M. Maśka – work in progress

(Technical University in Wrocław)

PLANAR MAGNETIC JOSEPHSON JUNCTION

Preliminary results: **numerical calculations reveal that magnetic moments arrange themselves in such textures, which sustain the topological superconducting state of the metallic stripe.**

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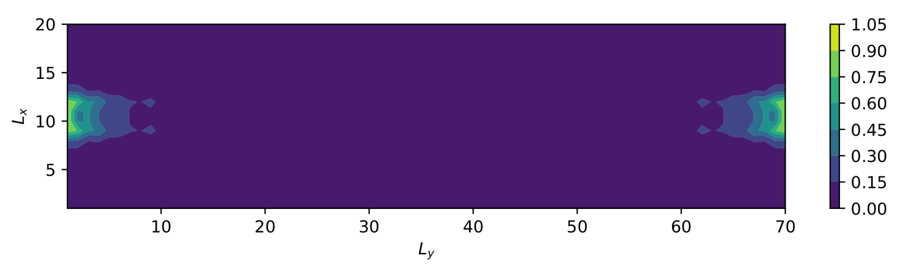


Spatial profile of Majorana modes obtained for phase difference $\Phi = \pi$.

M. Dziurawiec, M. Strzałka, M.M. Maśka – work in progress

(Technical University in Wrocław)

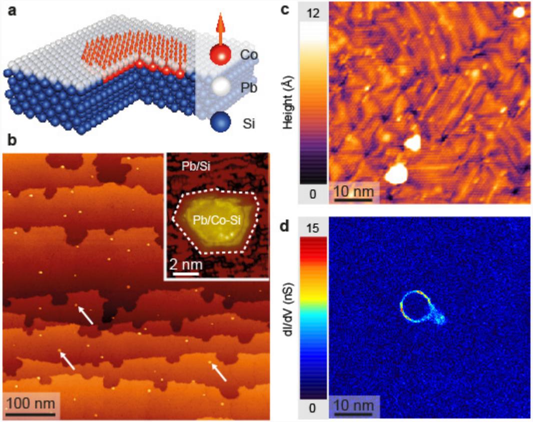
Higher-dimensional topological textures

Higher-dimensional topological textures

(platform for chiral Majorana modes)

TWO-DIMENSIONAL MAGNETIC STRUCTURES

Magnetic island of Co atoms deposited on the superconducting Pb surface



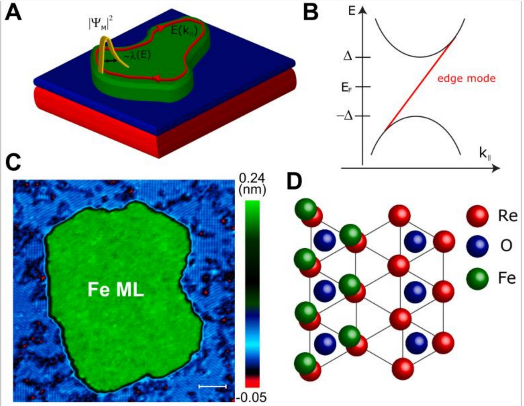
Diameter of island:

5 – 10 nm

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

Pierre & Marie Curie University (Paris, France)

Magnetic island of Fe atoms deposited on the superconducting Re surface



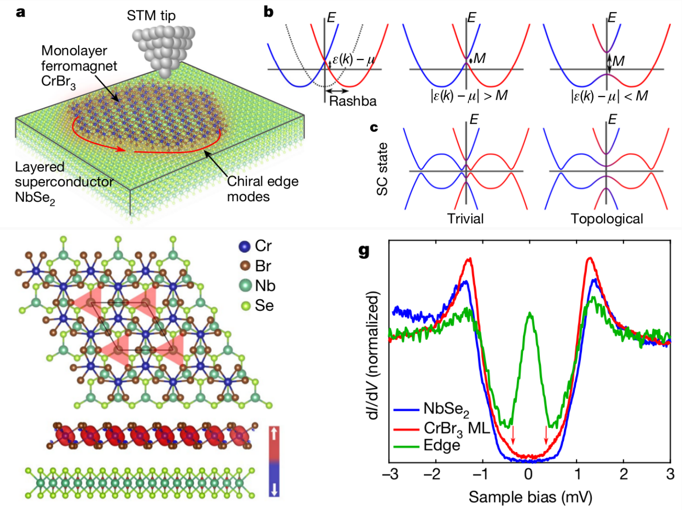
Chern number

C = 20

A. Palacio-Morales, ... & R. Wiesendanger, Science Adv. 5, eaav6600 (2019).

University of Hamburg (Germany)

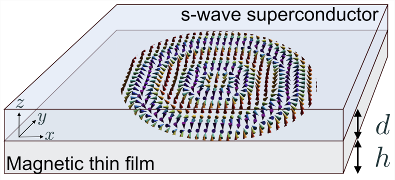
Ferromagnetic island $CrBr_3$ deposited on superconducting $NbSe_2$



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

MAGNETIC SKYRMION-TYPE TEXTURES

Scenario for topological superconductivity induced in 2D magnetic thin film hosting a skyrmion deposited on conventional s-wave superconductor



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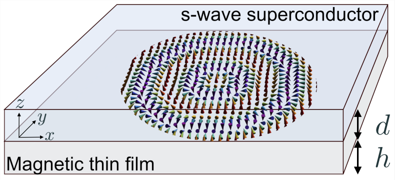

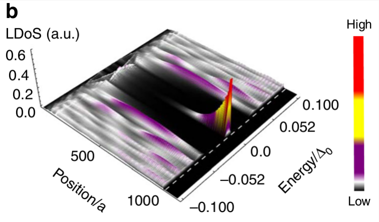

M. Garnier, A. Mesaros, P. Simon, Comm. Phys. 2, 126 (2019).

CONCLUSIONS

Synergy of magnetism and superconductivity in nanoscopic systems:

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$\Longrightarrow$ **allows for their constructive relationship**

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$\Longrightarrow$ **inducing the topological states of matter**

CONCLUSIONS

Synergy of magnetism and superconductivity in nanoscopic systems:

$\Rightarrow$ **allows for their constructive relationship**

$\Rightarrow$ **inducing the topological states of matter**

$\Rightarrow$ **hosting the Majorana boundary modes**

ACKNOWLEDGEMENTS

⇒ **Maciek Maśka & coworkers**

(Technical University, Wrocław)

⇒ **Nick Sedlmayr**

(M. Curie-Skłodowska University, Lublin)

⇒ **Aksel Kobiałka**

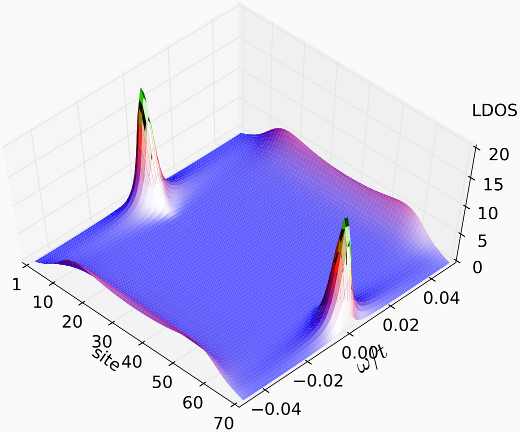
(University of Basel, Switzerland)

⇒ **Szczepan Głodzik**

(University of Ljubljana, Slovenia)

Low energy quasiparticles of the Rashba nanowire

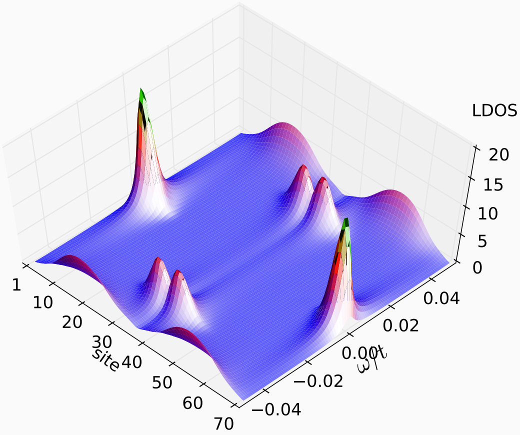
$t_{35}/t = 1.0$



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

Low energy quasiparticles of the Rashba nanowire

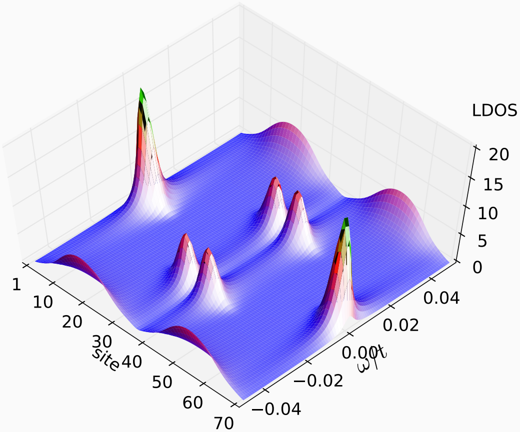
$t_{35}/t = 0.8$



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

Low energy quasiparticles of the Rashba nanowire

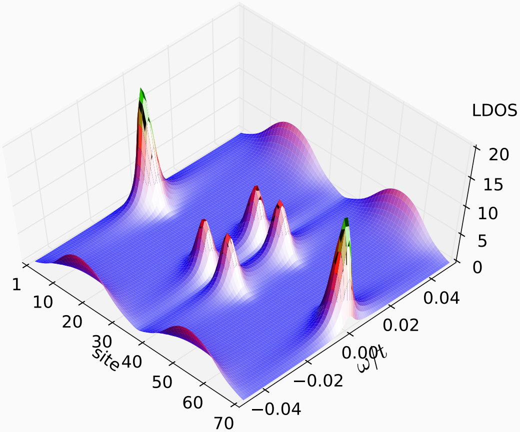
$t_{35}/t = 0.6$



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

Low energy quasiparticles of the Rashba nanowire

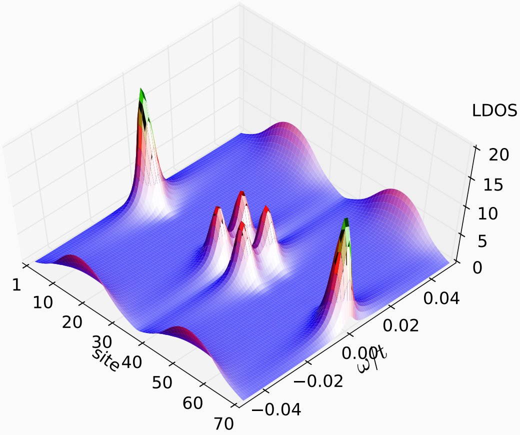
$t_{35}/t = 0.4$



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

Low energy quasiparticles of the Rashba nanowire

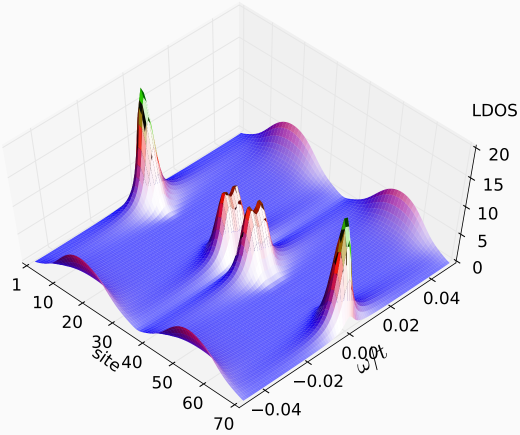
$t_{35}/t = 0.2$



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

Low energy quasiparticles of the Rashba nanowire

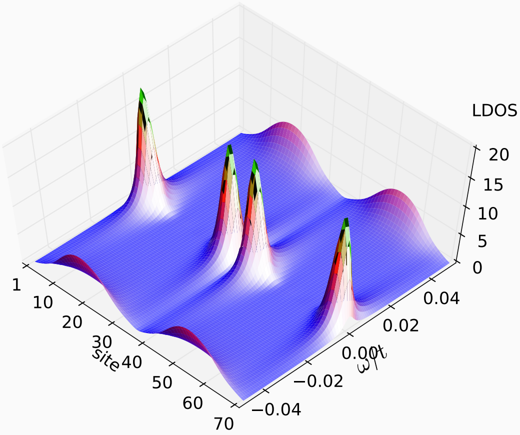
$t_{35}/t = 0.1$



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

Low energy quasiparticles of the Rashba nanowire

$t_{35}/t = 0.0$



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