FROM BOGOLUBOV TO MAJORANA QPS IN TOPOLOGICAL SUPERCONDUCTORS

Tadeusz DOMAŃSKI

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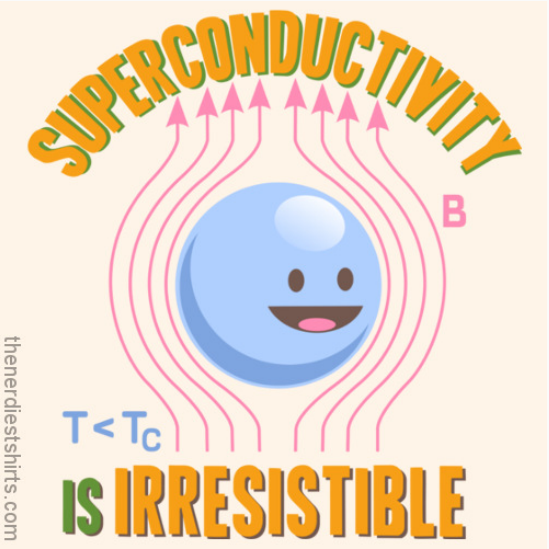

5th Conf. Stat. Phys.: Modern Trends & Applications, Lwów, 3 July 2019

OUTLINE

- **Bogolubov quasiparticles in superconductors**

$\Rightarrow$ **particle vs hole dilemma**

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N. Bogolubov J. Bardeen E. Majorana



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I. **On the theory of superfluidity**

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II. **On a new method in the theory of superconductivity**

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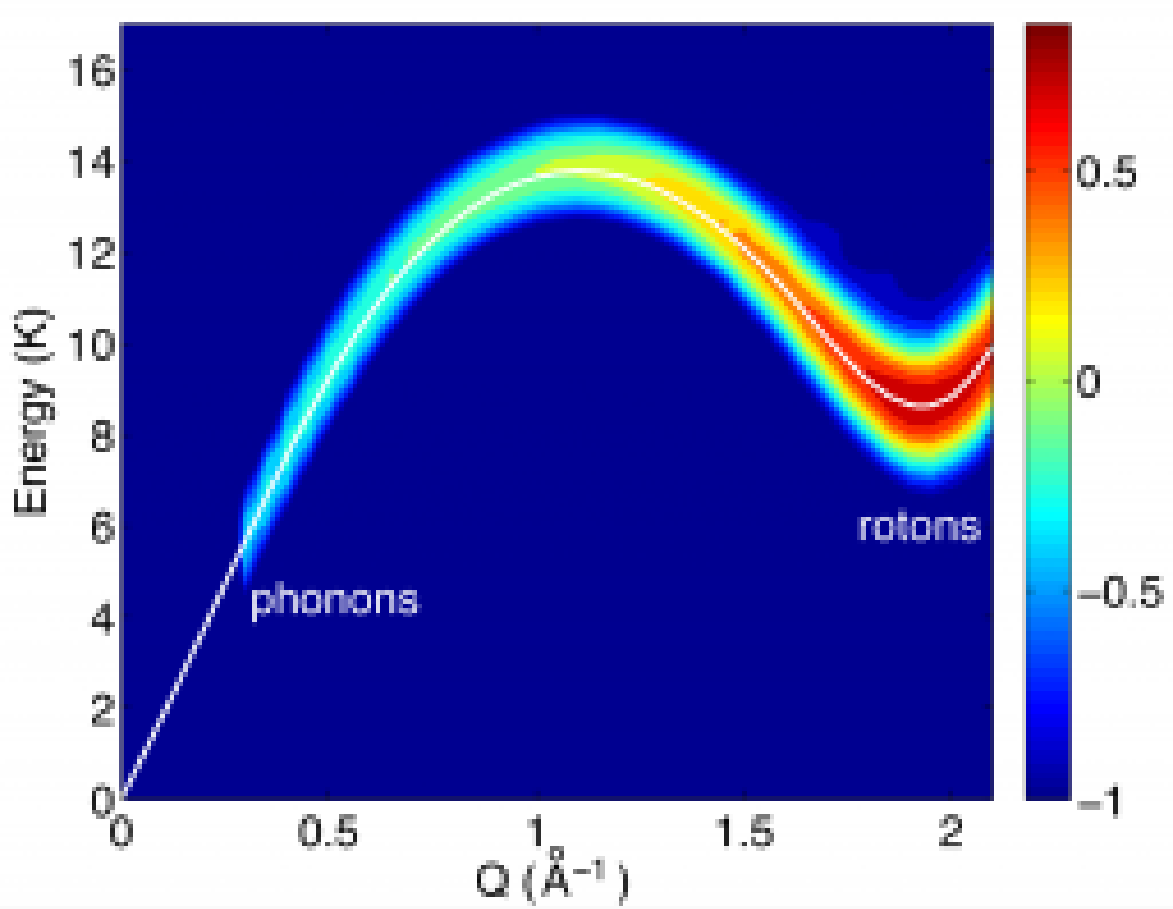

Effective spectrum of the superfluid ^{4}He

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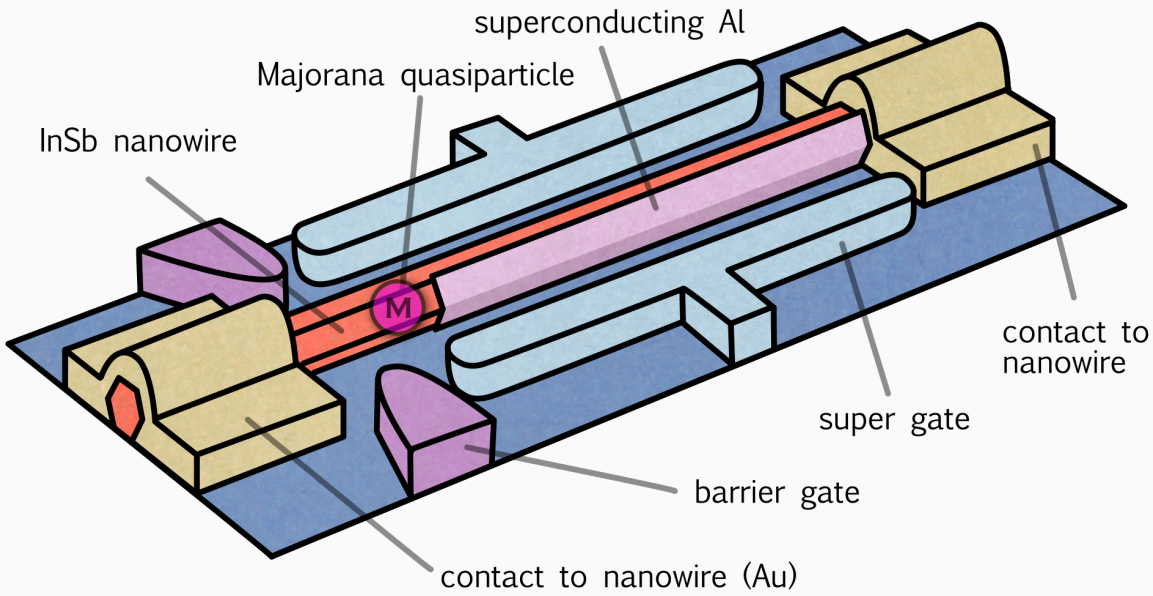
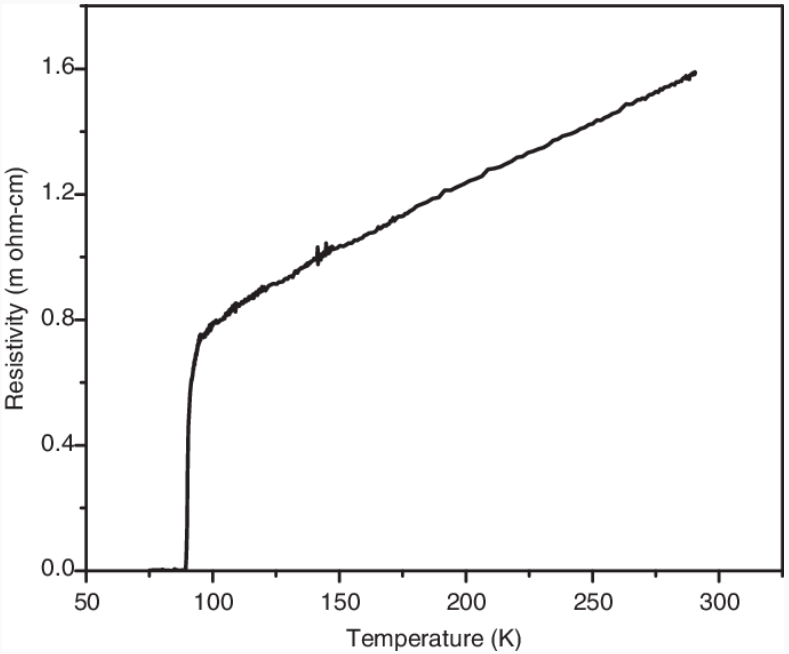


Bulk superconductors

SUPERCONDUCTOR

Perfect conductor



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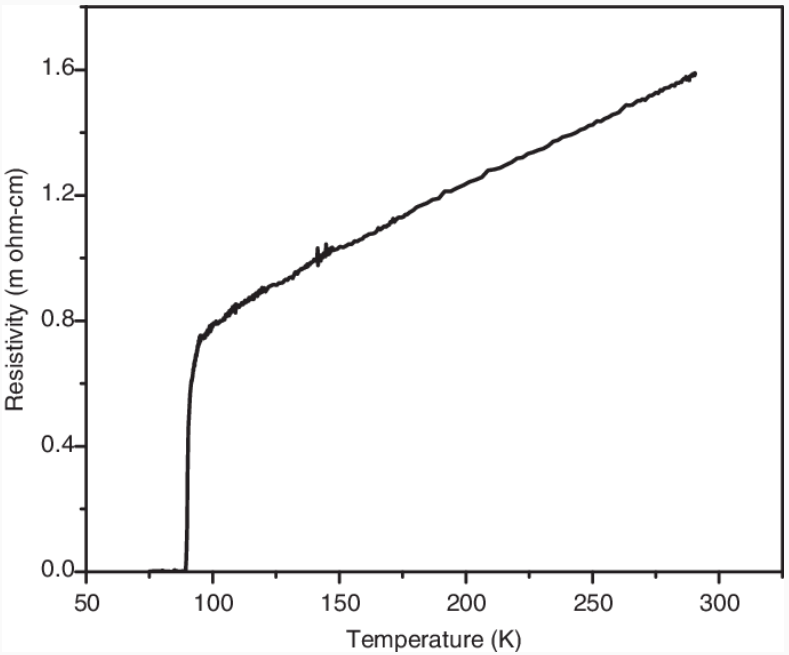

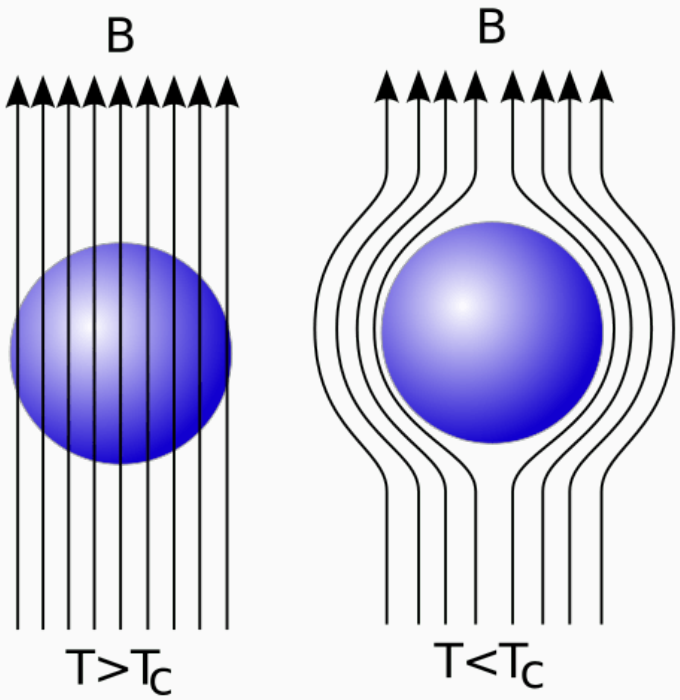

Perfect diamagnet

HALLMARKS OF ELECTRON PAIRING

BCS ground state :

$$|\mathbf{BCS}\rangle = \prod_k \left(u_k + v_k \, \hat{c}^\dagger_{k\uparrow} \, \hat{c}^\dagger_{-k\downarrow} \right) \; |\mathbf{vacuum}\rangle$$

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$$\begin{aligned} \hat{\gamma}_{k\uparrow} &= u_k \hat{c}_{k\uparrow} + v_k \hat{c}^\dagger_{-k\downarrow} \\ \hat{\gamma}^\dagger_{-k\downarrow} &= -v_k \hat{c}_{k\uparrow} + u_k \hat{c}^\dagger_{-k\downarrow} \end{aligned}$$

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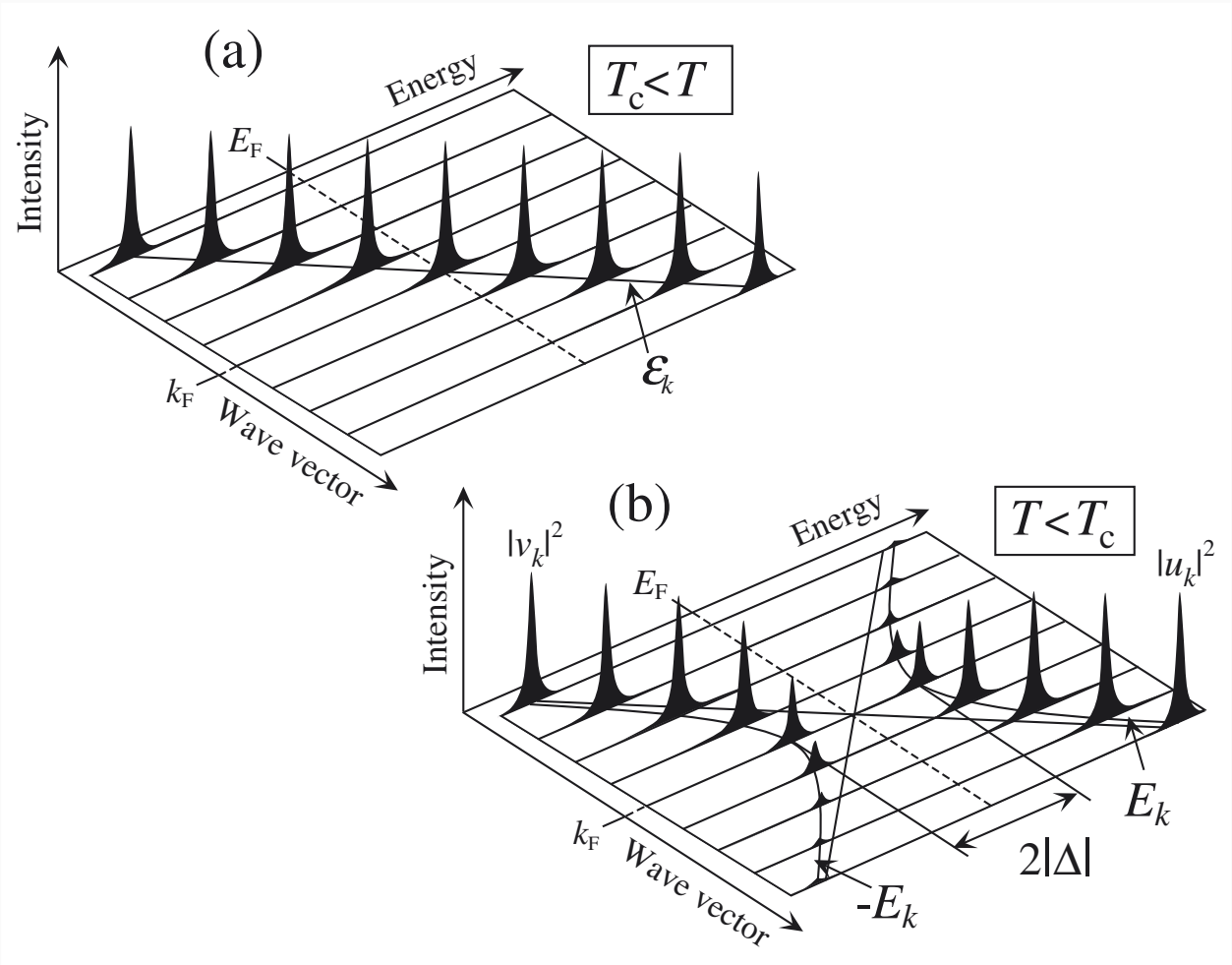
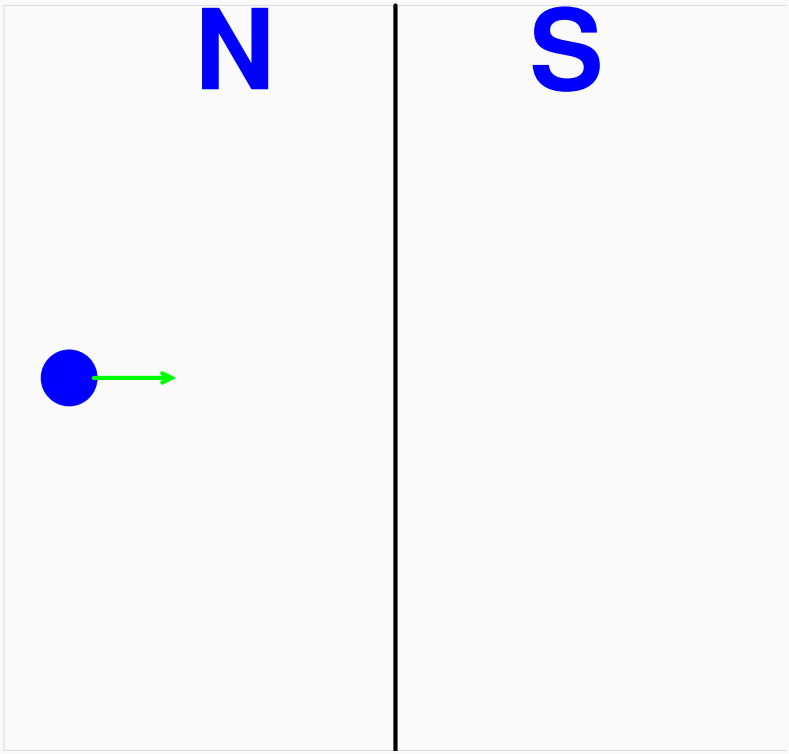
BOGOLIUBOV QUASIPARTICLES

Quasiparticle spectrum of conventional superconductors consists of the Bogoliubov (p/h) branches gaped around E_F



PARTICLE VS HOLE

Let us consider the interface of metal N and superconductor S



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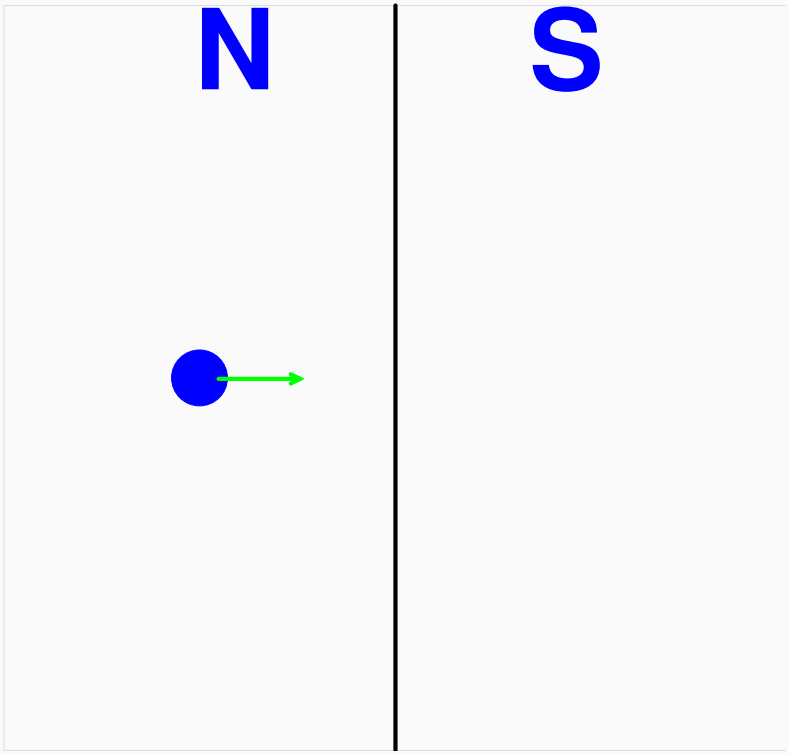

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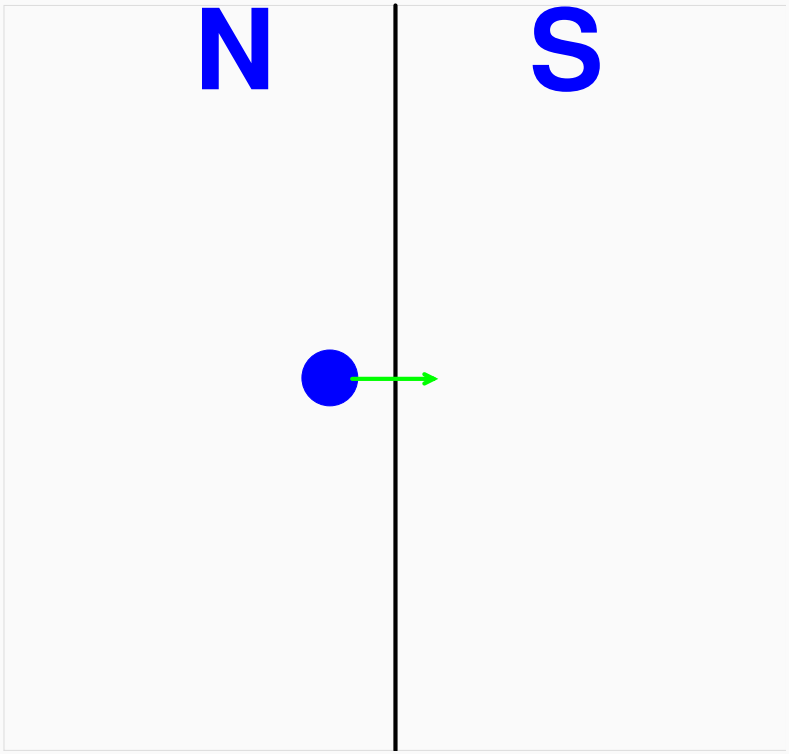

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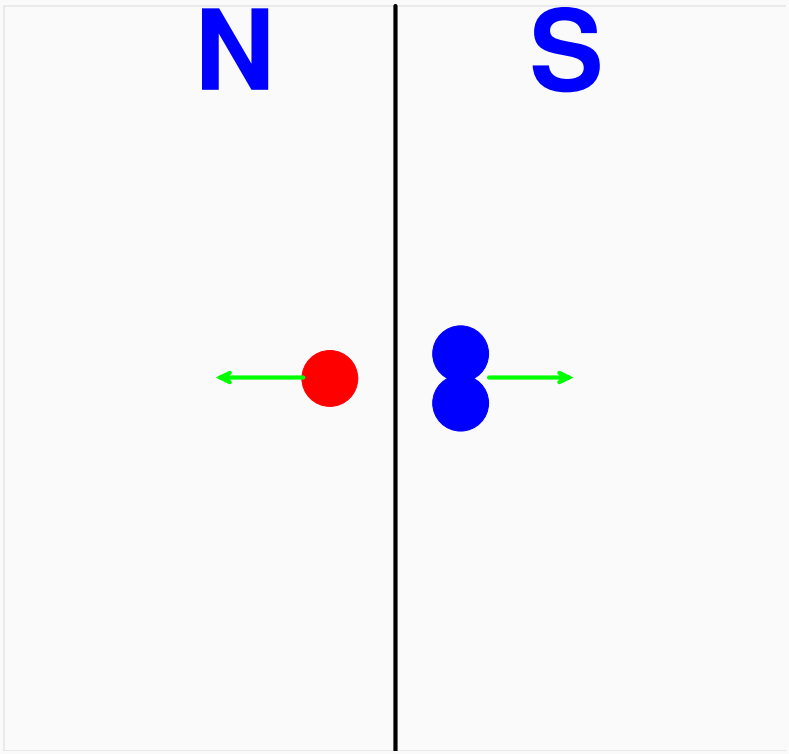

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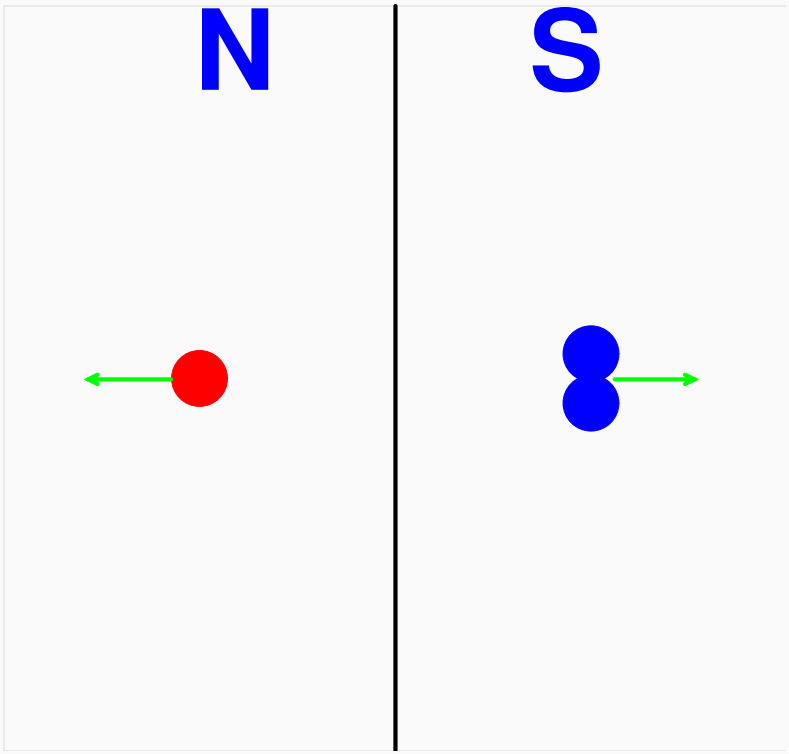

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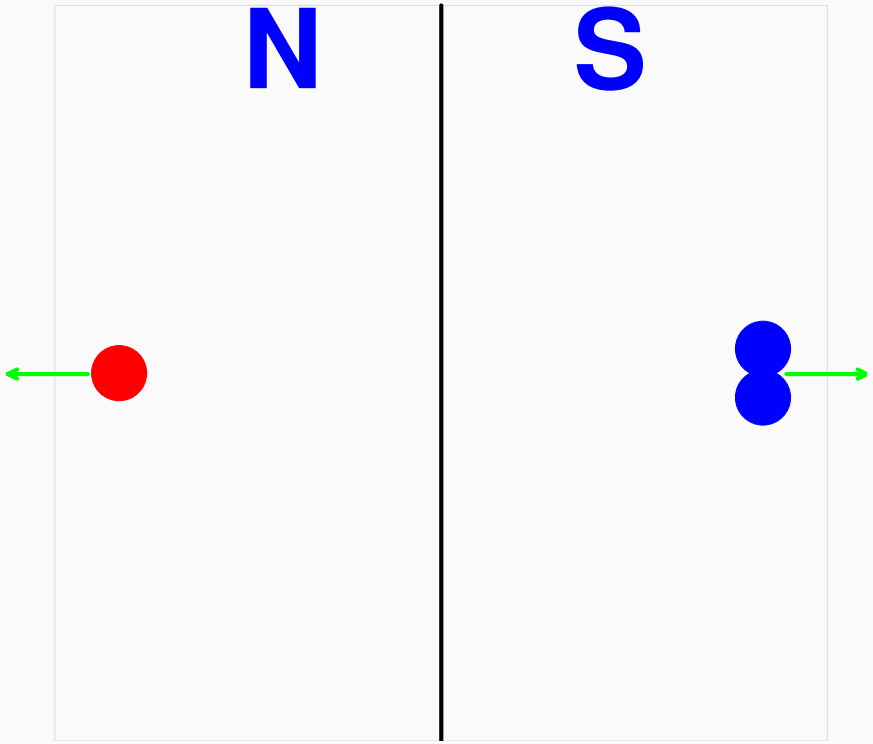

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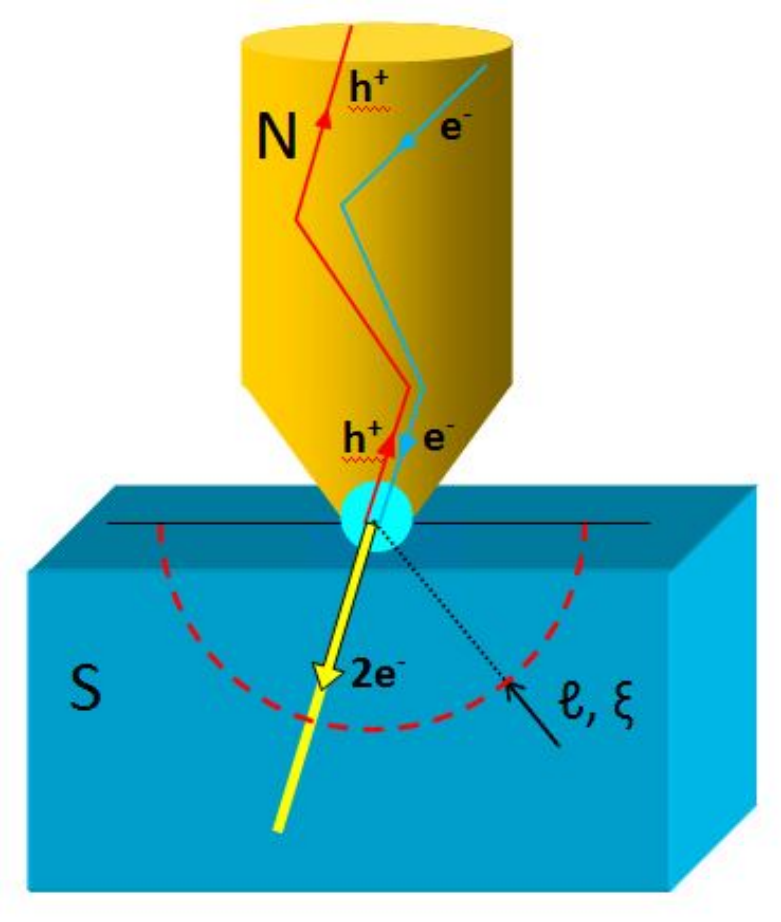

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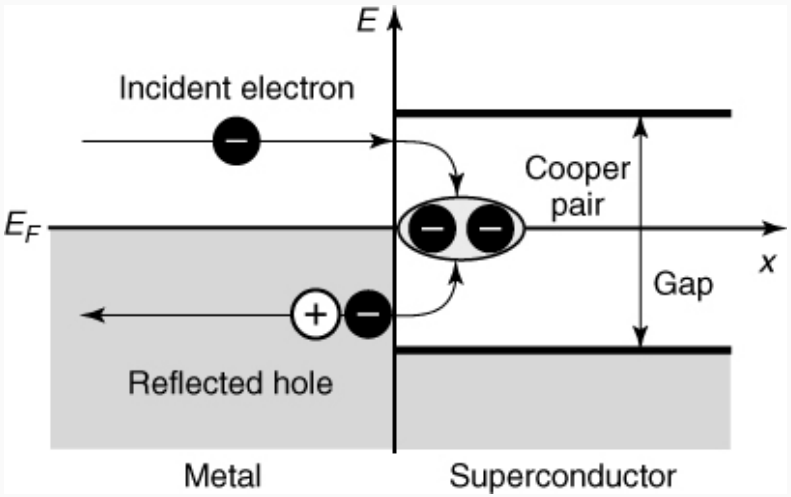

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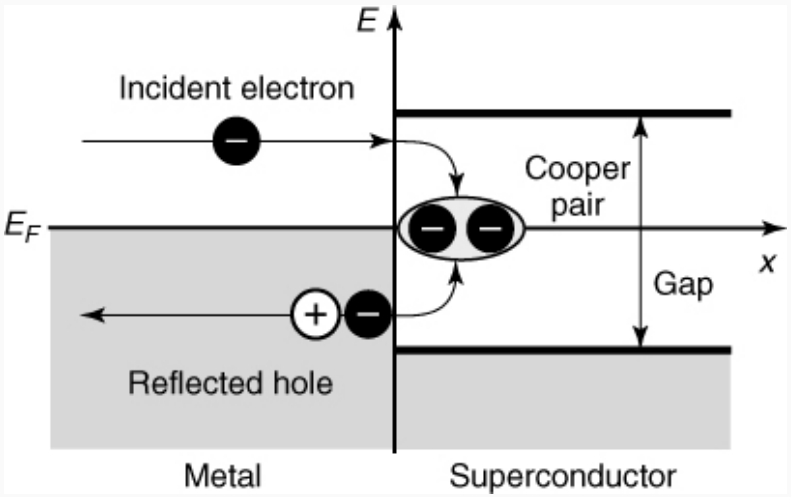

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$\Rightarrow$ **a hole is reflected back (Andreev scattering).**

Topological superconductors

KITAEV CHAIN: PARADIGM FOR MAJORANA QPS

Itinerant 1-dimensional 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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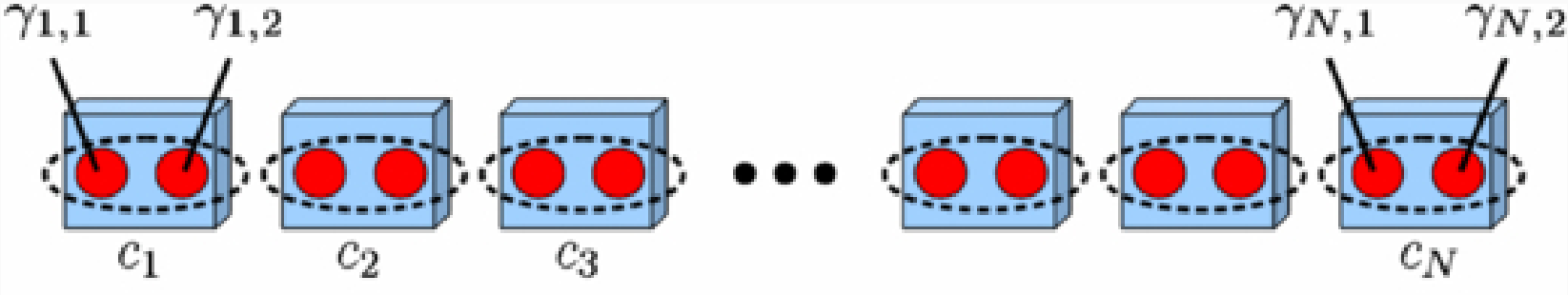

Alexei Y. Kitaev, Phys. Usp. 44, 131 (2001).

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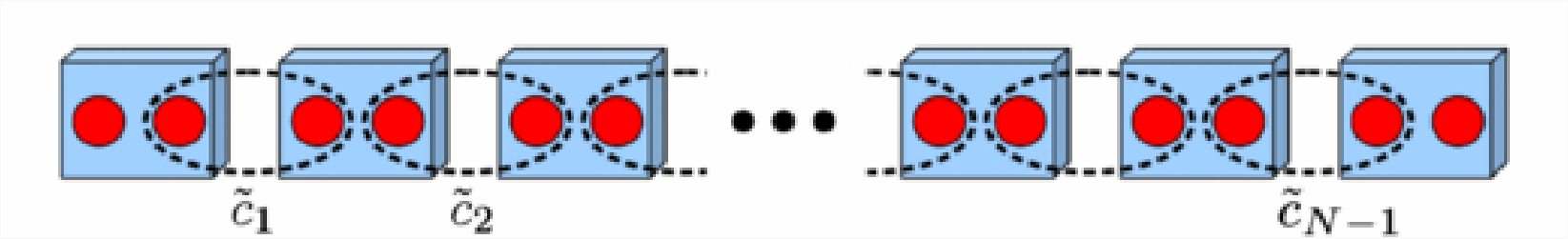

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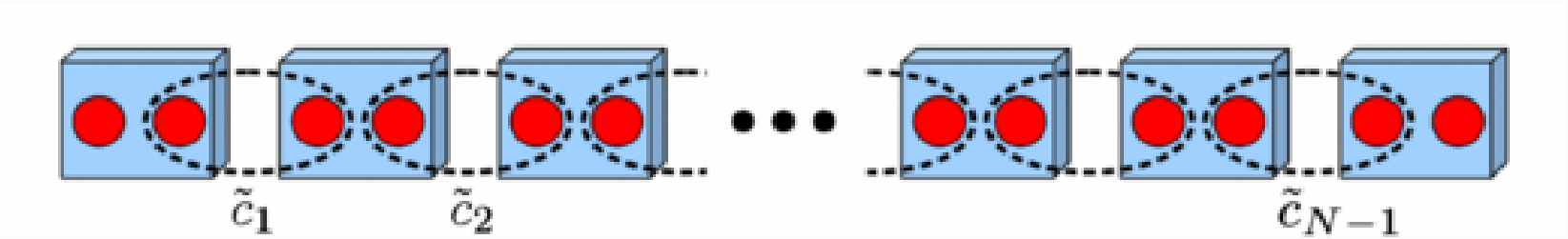

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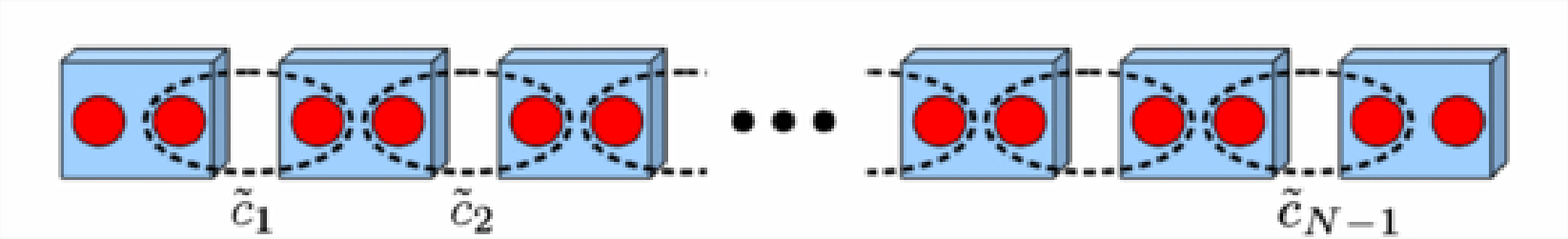

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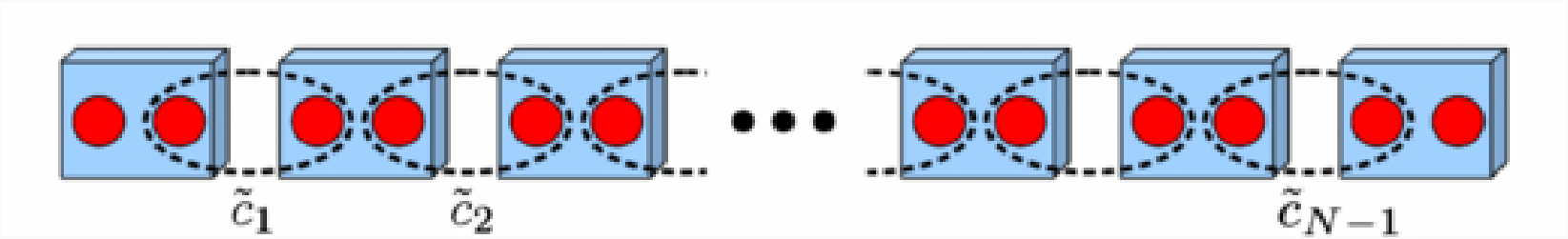

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They manifest themselves by very exotic phenomena !

PROPERTIES OF MAJORANA QPS

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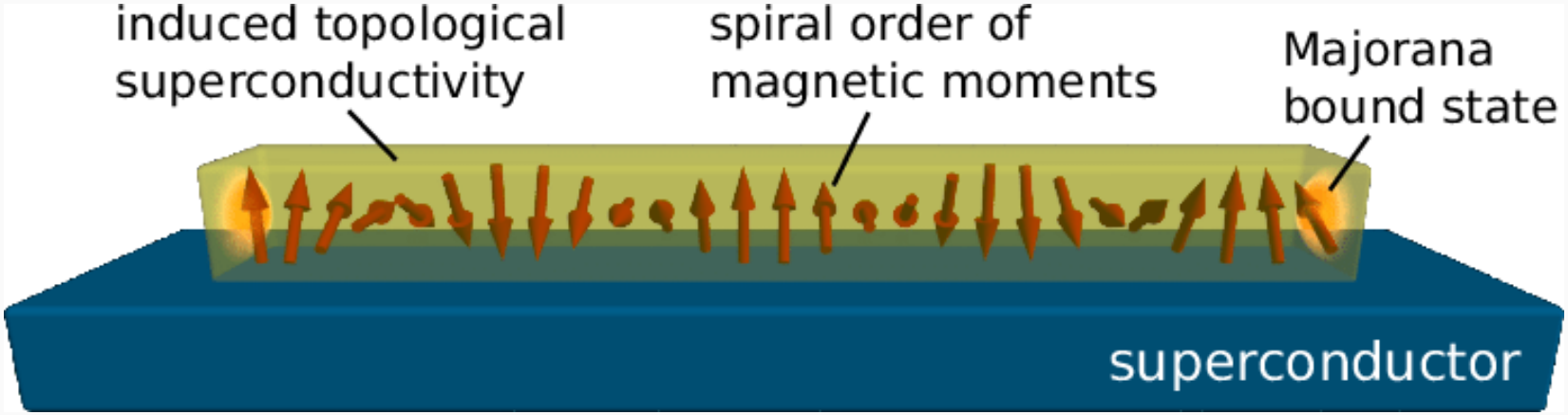
- **topologically protected**

$\Rightarrow$ **immune to dephasing/decoherence**

REALIZATIONS OF KITAEV SCENARIO

Intersite pairing of the same spin electrons can be driven e.g. by the spin-orbit (Rashba) interaction in presence of the external magnetic field, using nanowires proximitized to *s-wave* superconductor.



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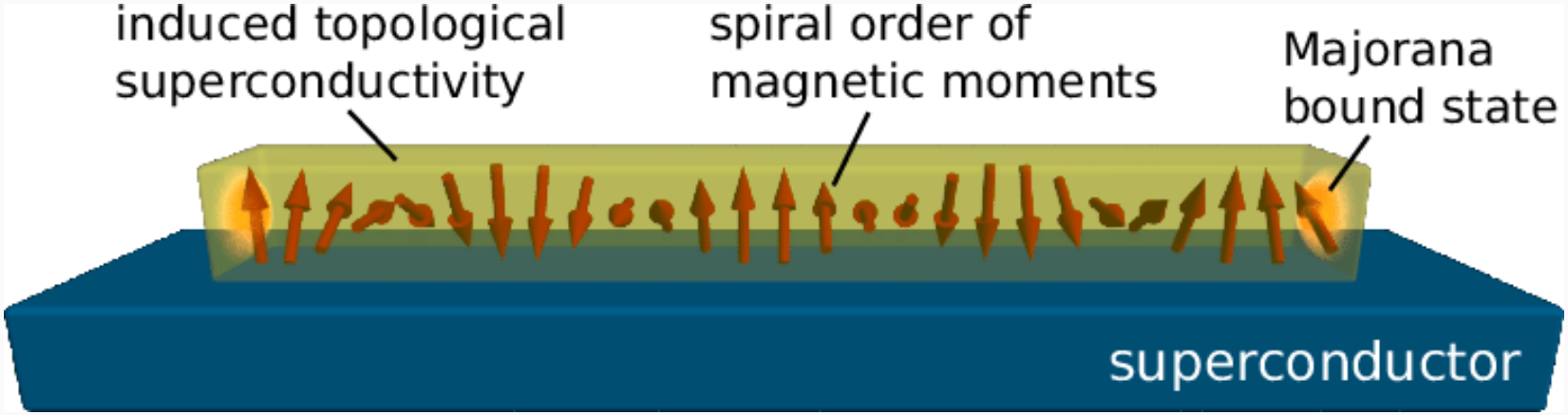

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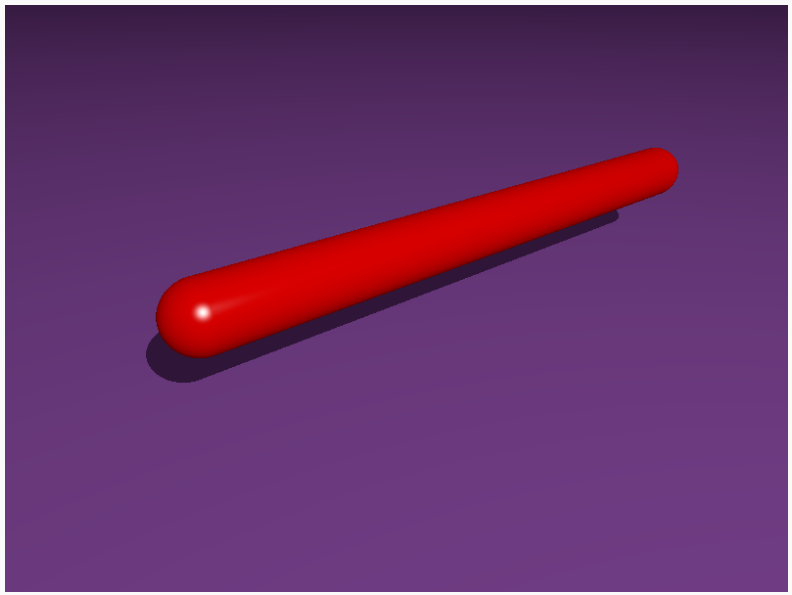
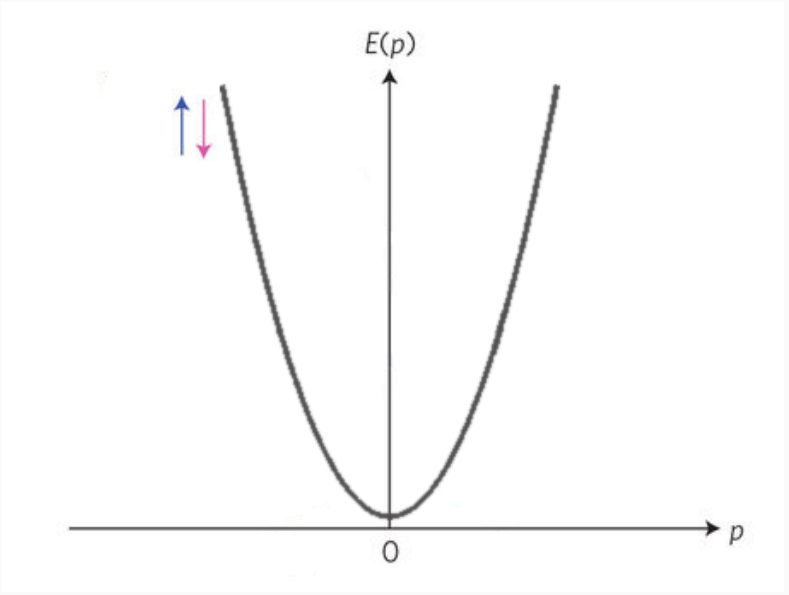
Roman Lutchyn was born in Lviv and received his M.Sc. in Kyiv !

MAJORANA QPS: UNDERLYING MECHANISM

Nanowire





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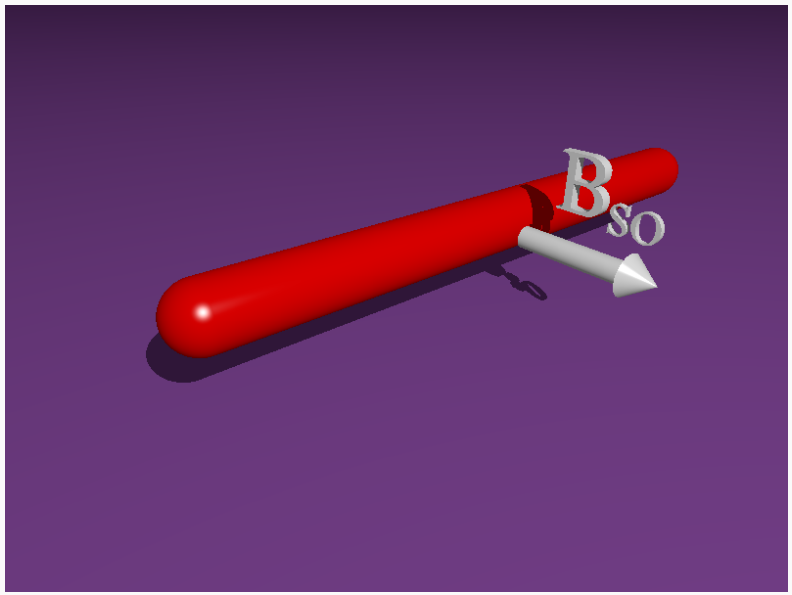
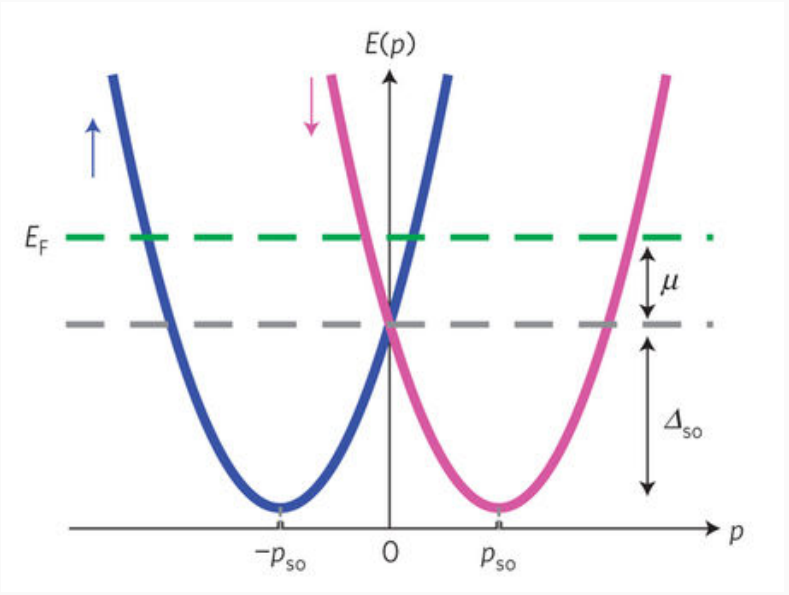
Nanowire + Rashba





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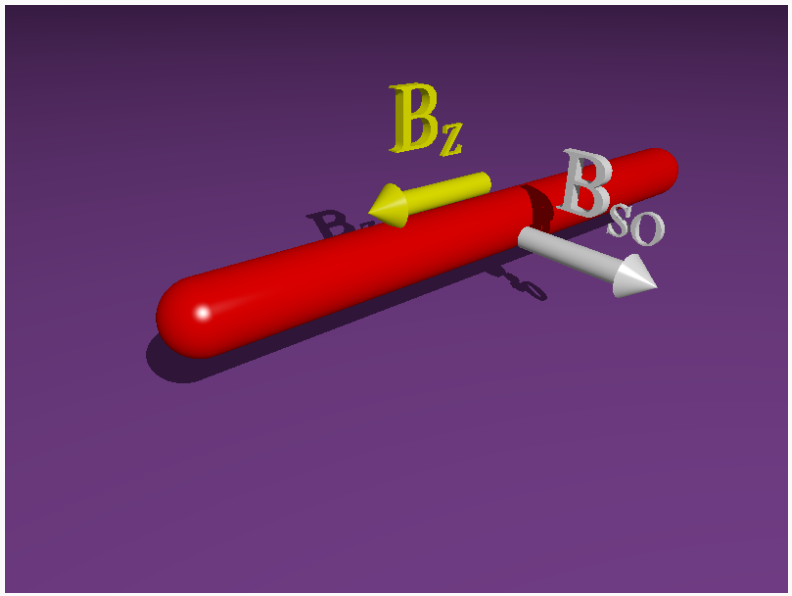

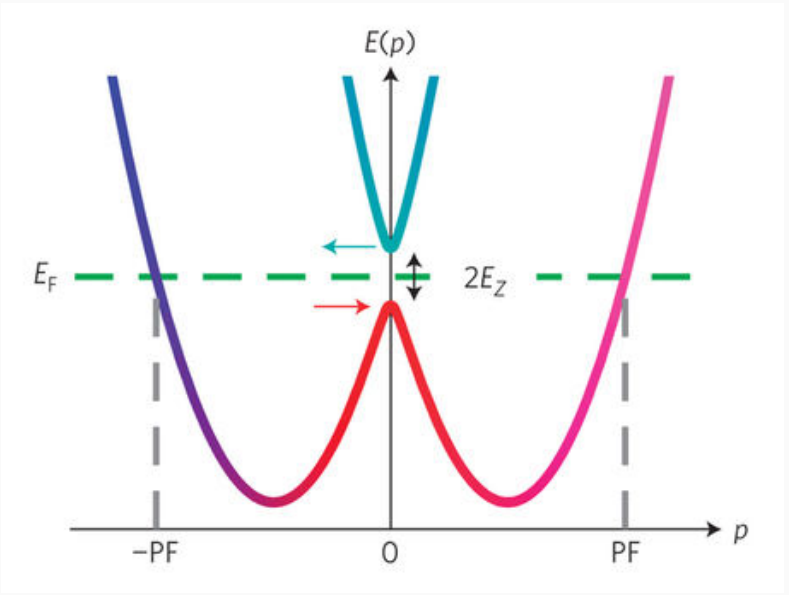

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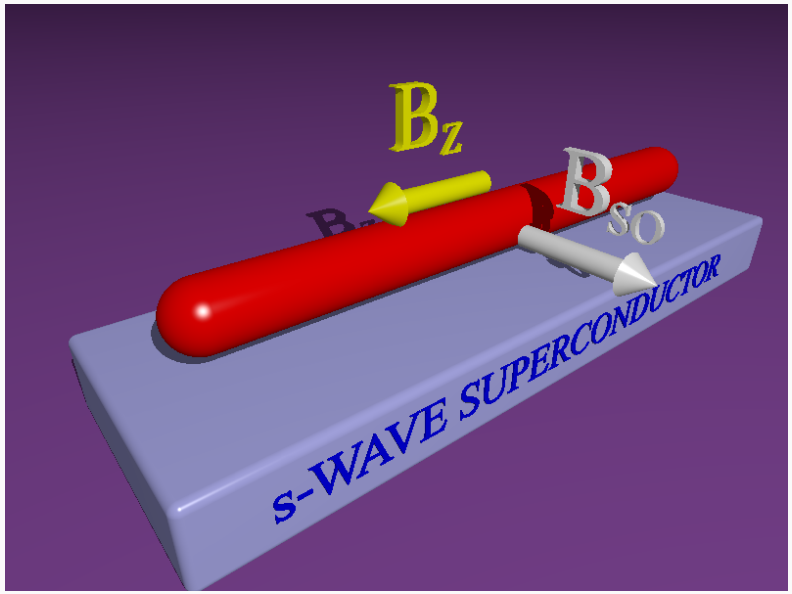

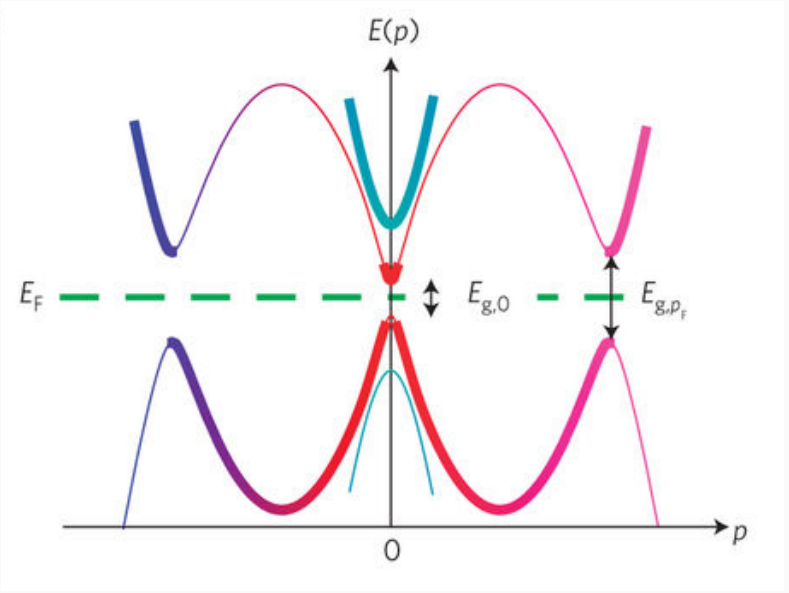

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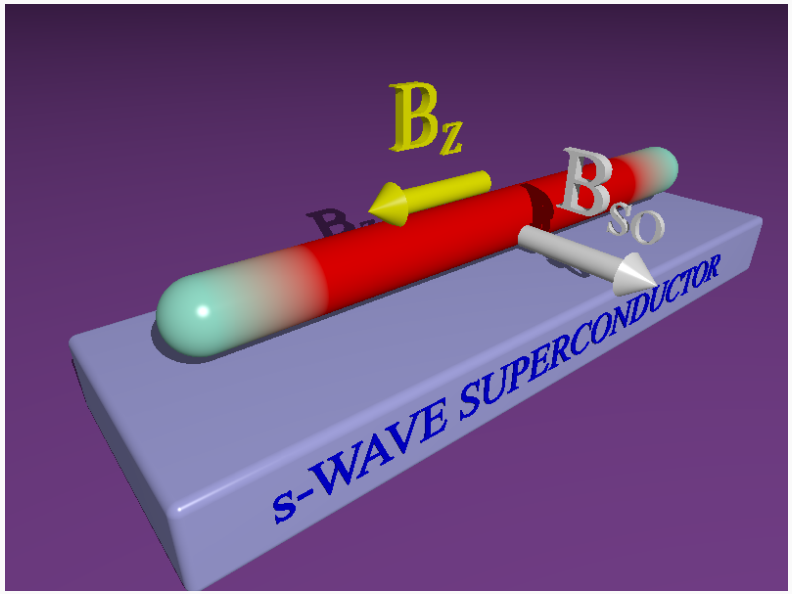
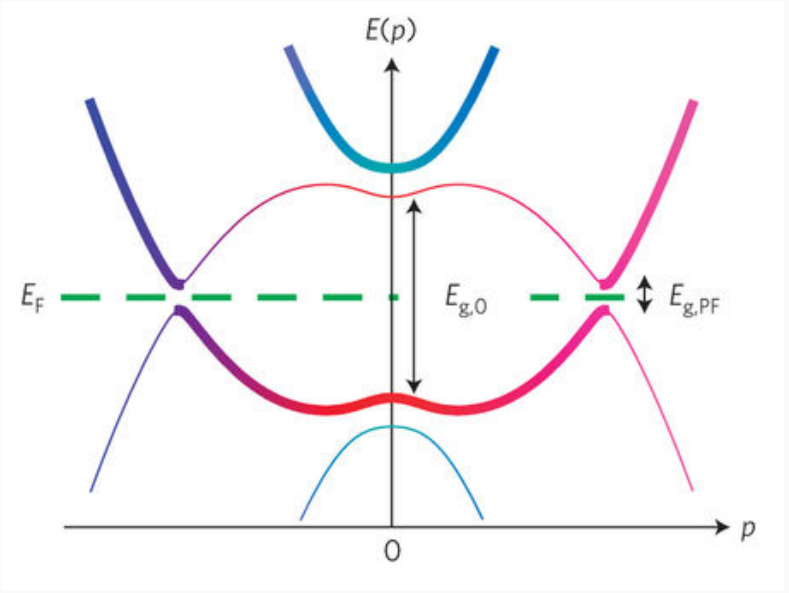
$B < B_{cr} \longrightarrow$ **trivial superconducting phase**

MAJORANA QPS: UNDERLYING MECHANISM

Nanowire + Rashba + magnetic field + superconductor



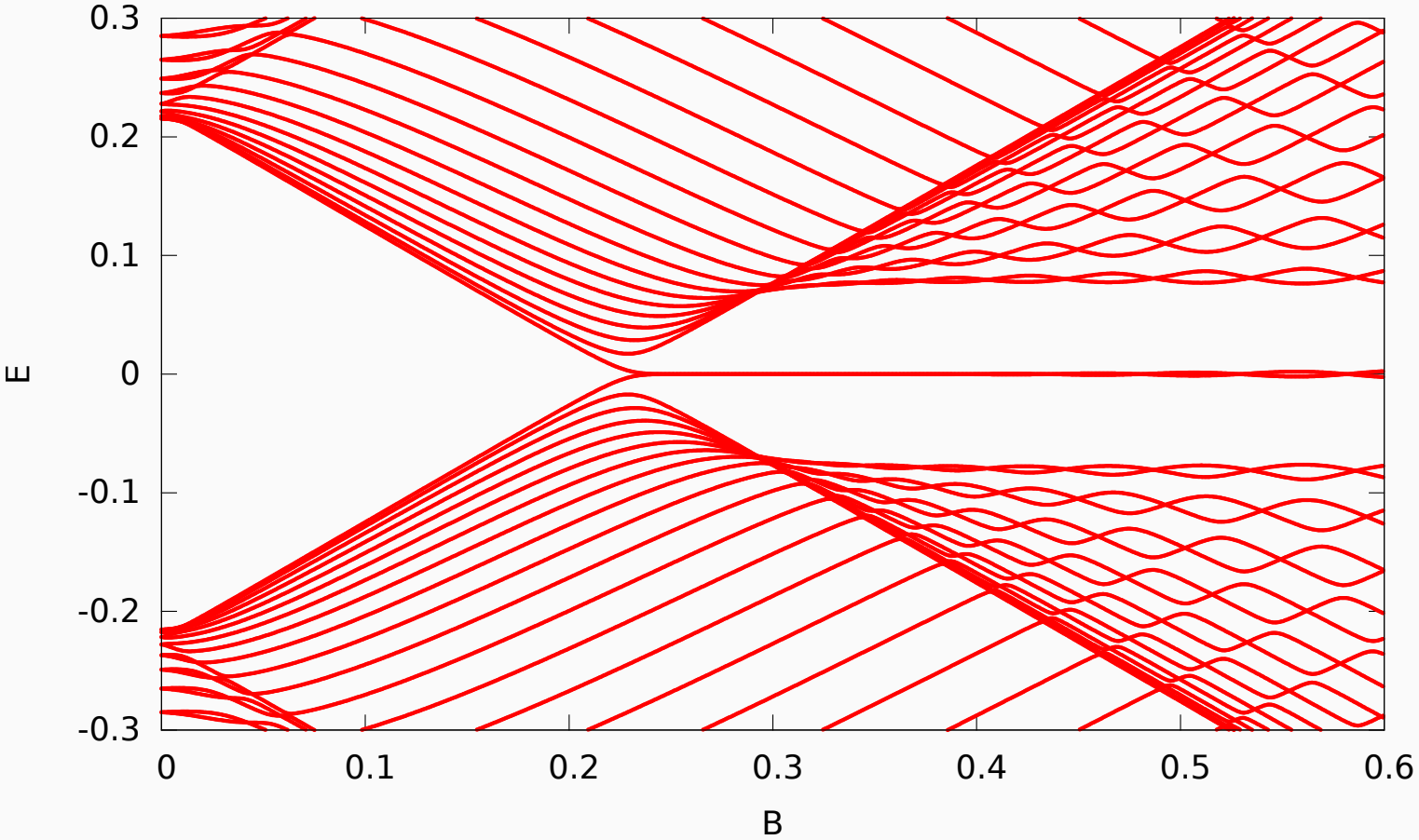


A. Das *et al*, Nature Phys. 8, 887 (2012).

$B > B_{cr} \longrightarrow$ **nontrivial superconducting phase**

TRANSITION FROM TRIVIAL TO TOPOLOGICAL PHASE

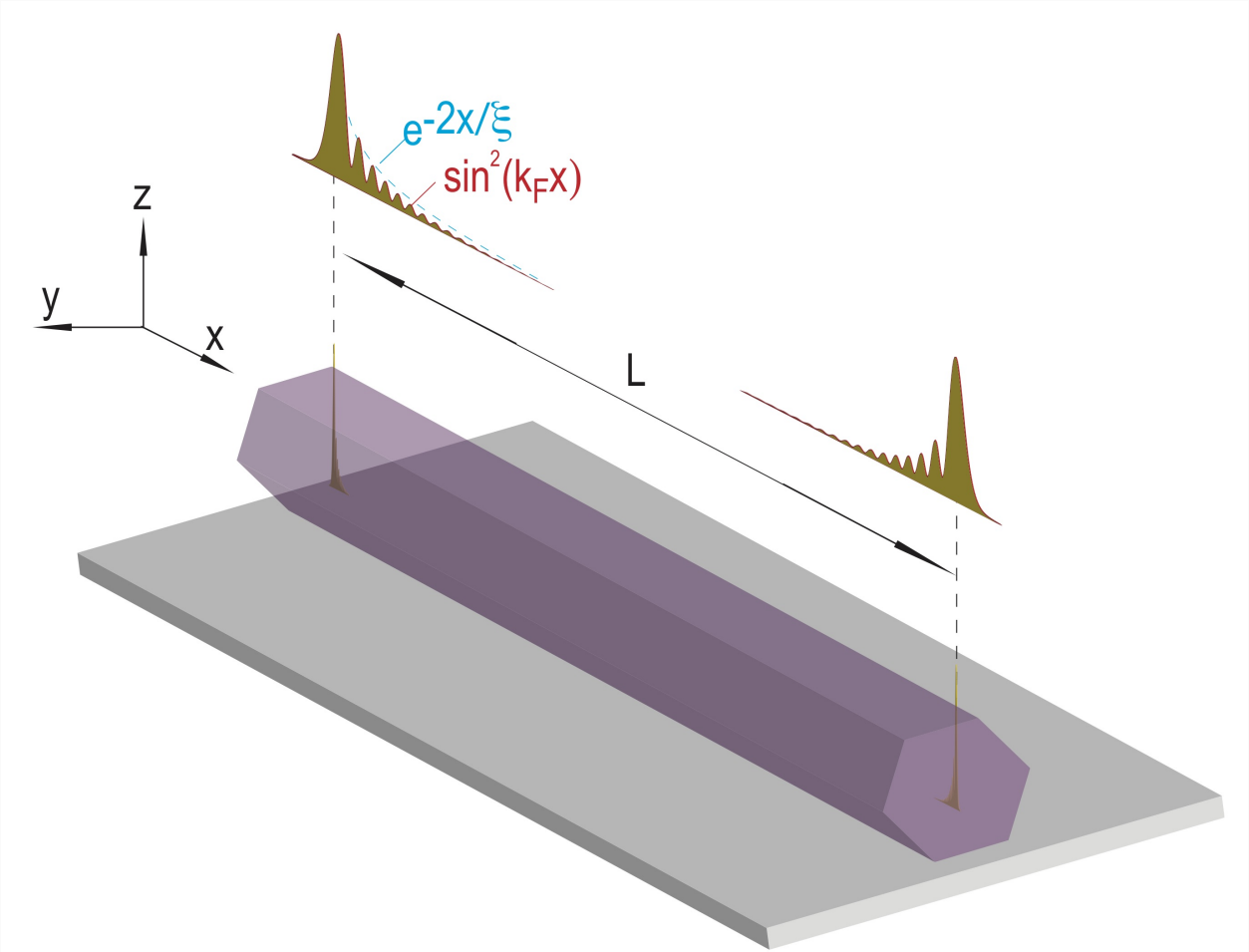
Effective quasiparticle states of the Rashba nanowire



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

SPATIAL PROFILE OF MAJORANA QPS

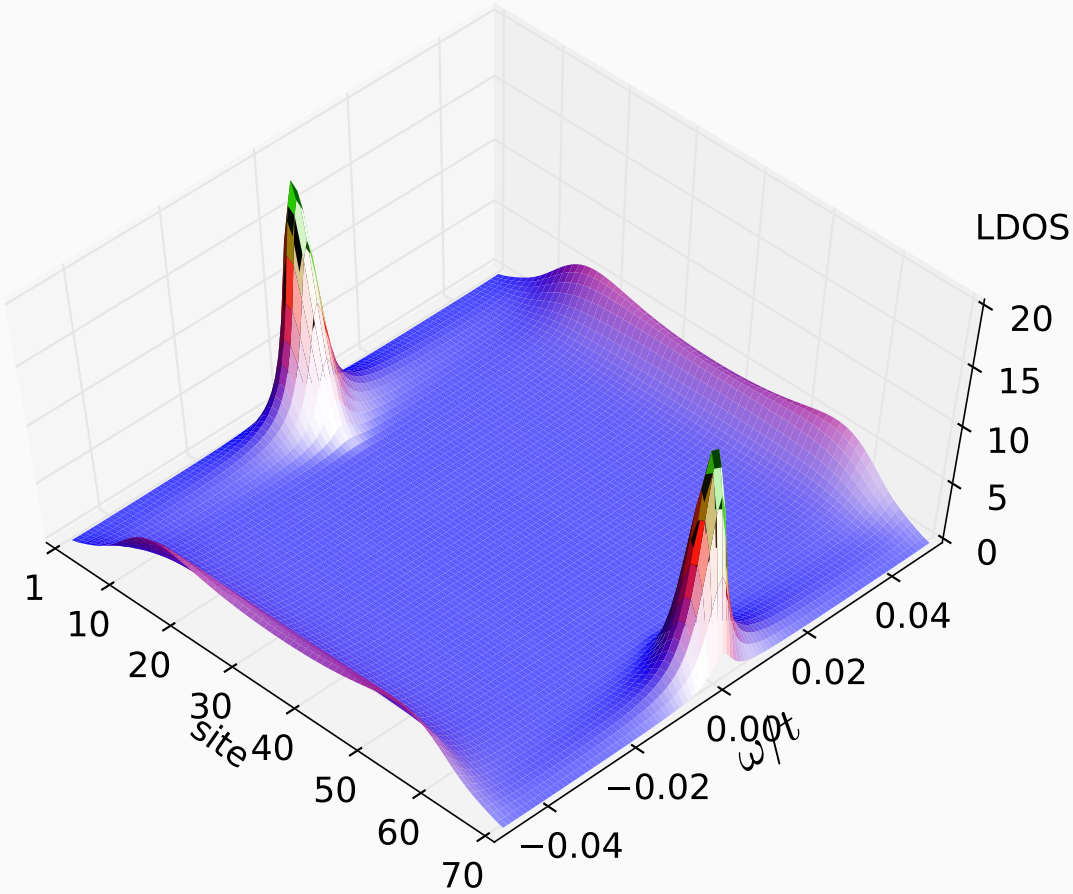
Majorana qps are localized near the edges



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

Low energy quasiparticles of the Rashba nanowire

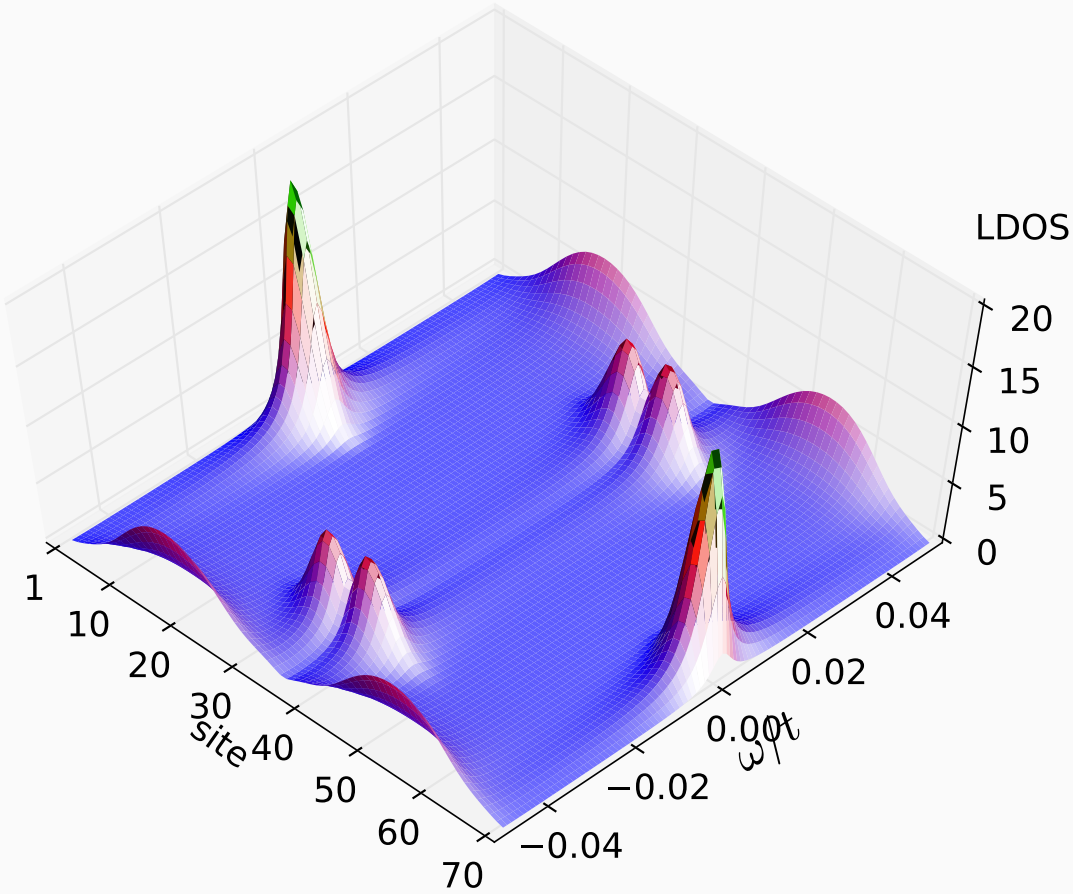
$t_{35}/t = 1.0$



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

Low energy quasiparticles of the Rashba nanowire

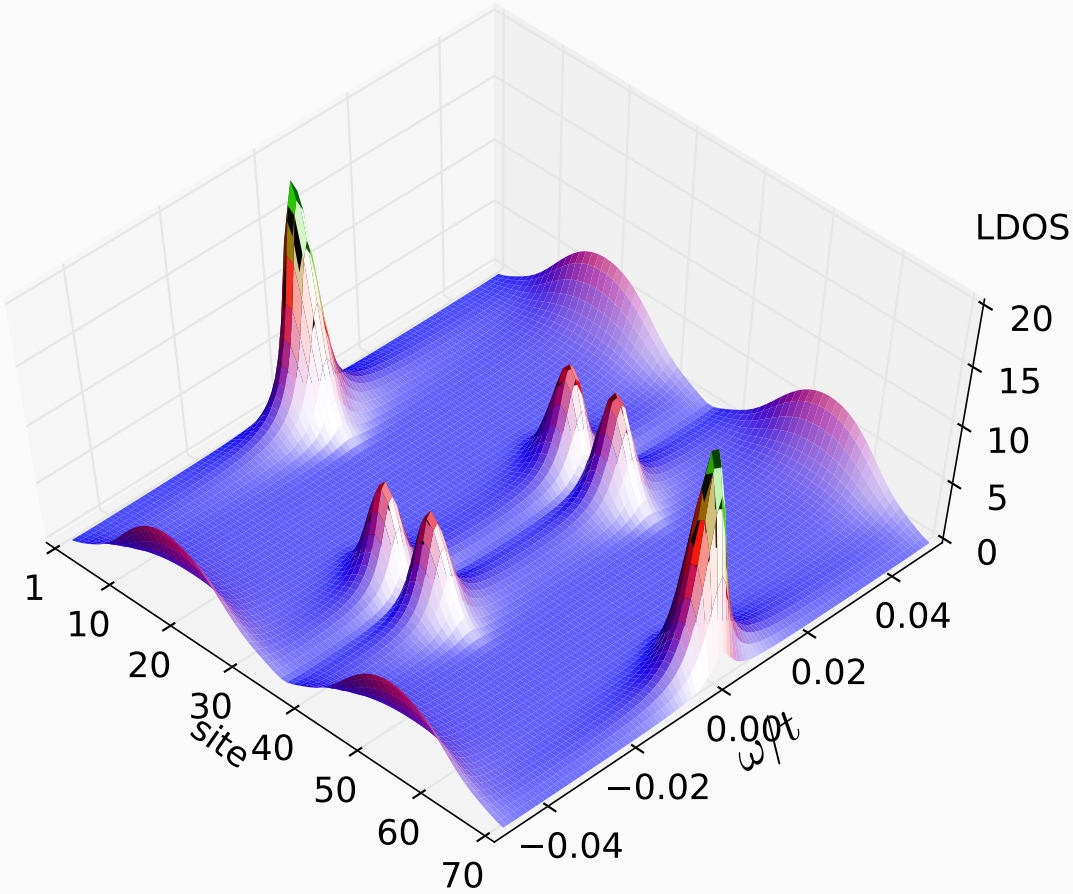
$t_{35}/t = 0.8$



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

Low energy quasiparticles of the Rashba nanowire

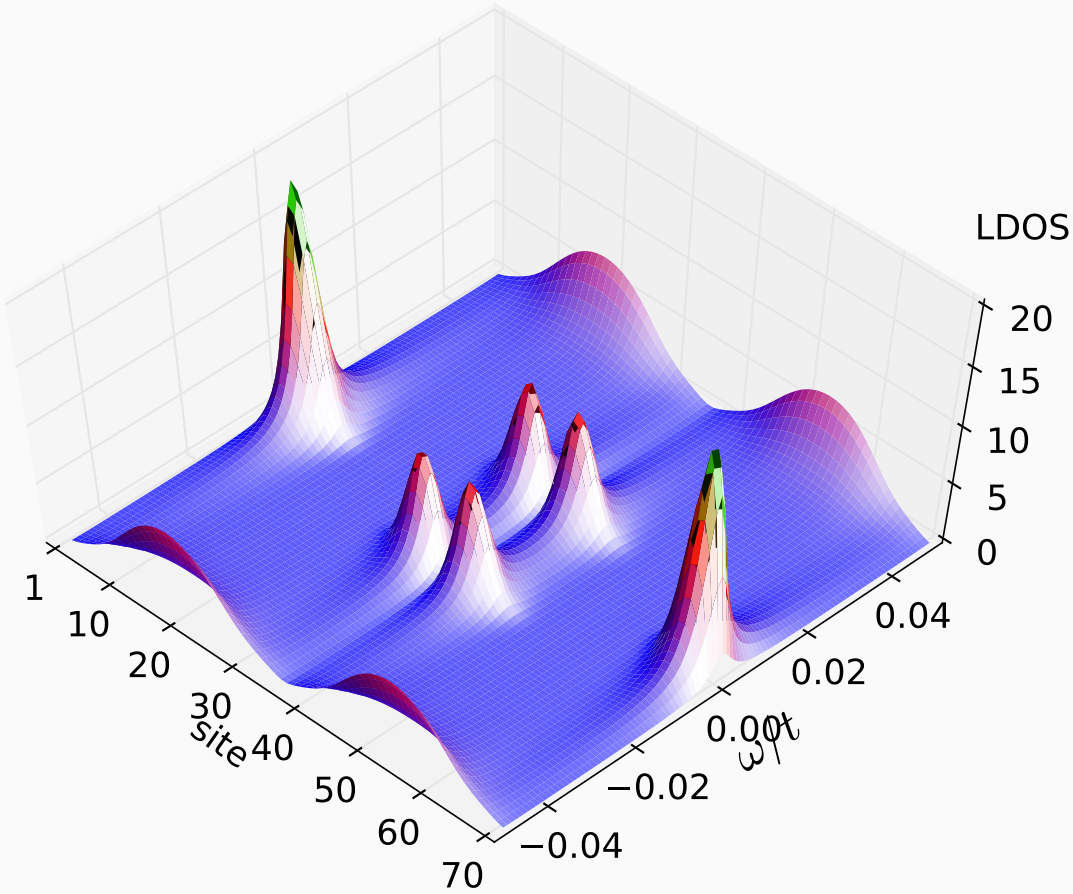
$t_{35}/t = 0.6$



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

Low energy quasiparticles of the Rashba nanowire

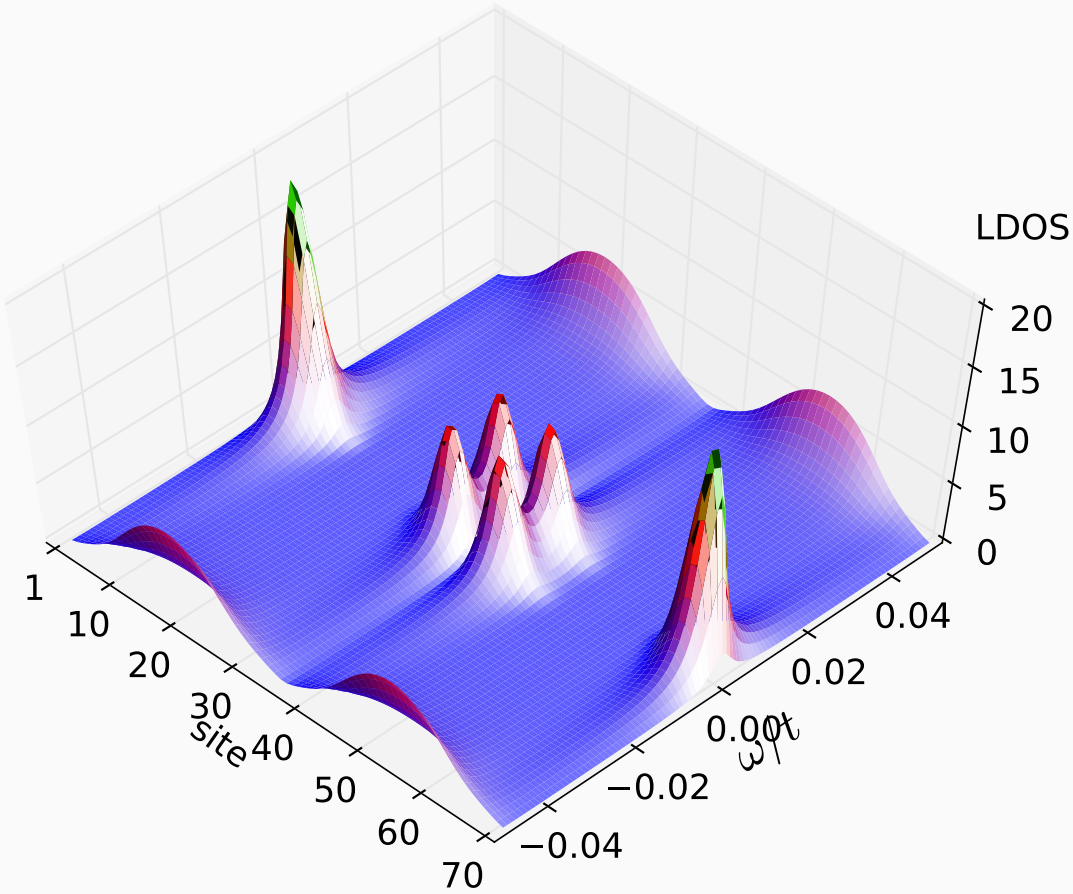
$t_{35}/t = 0.4$



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

Low energy quasiparticles of the Rashba nanowire

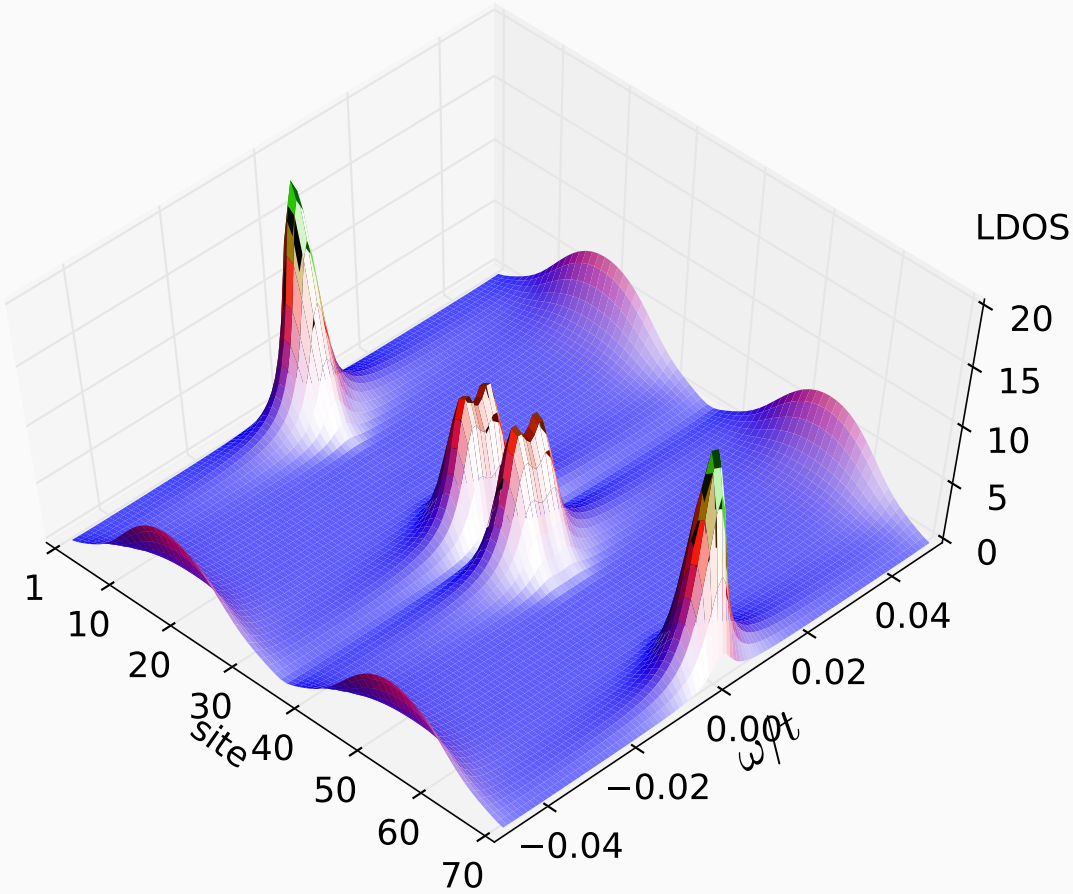
$t_{35}/t = 0.2$



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

Low energy quasiparticles of the Rashba nanowire

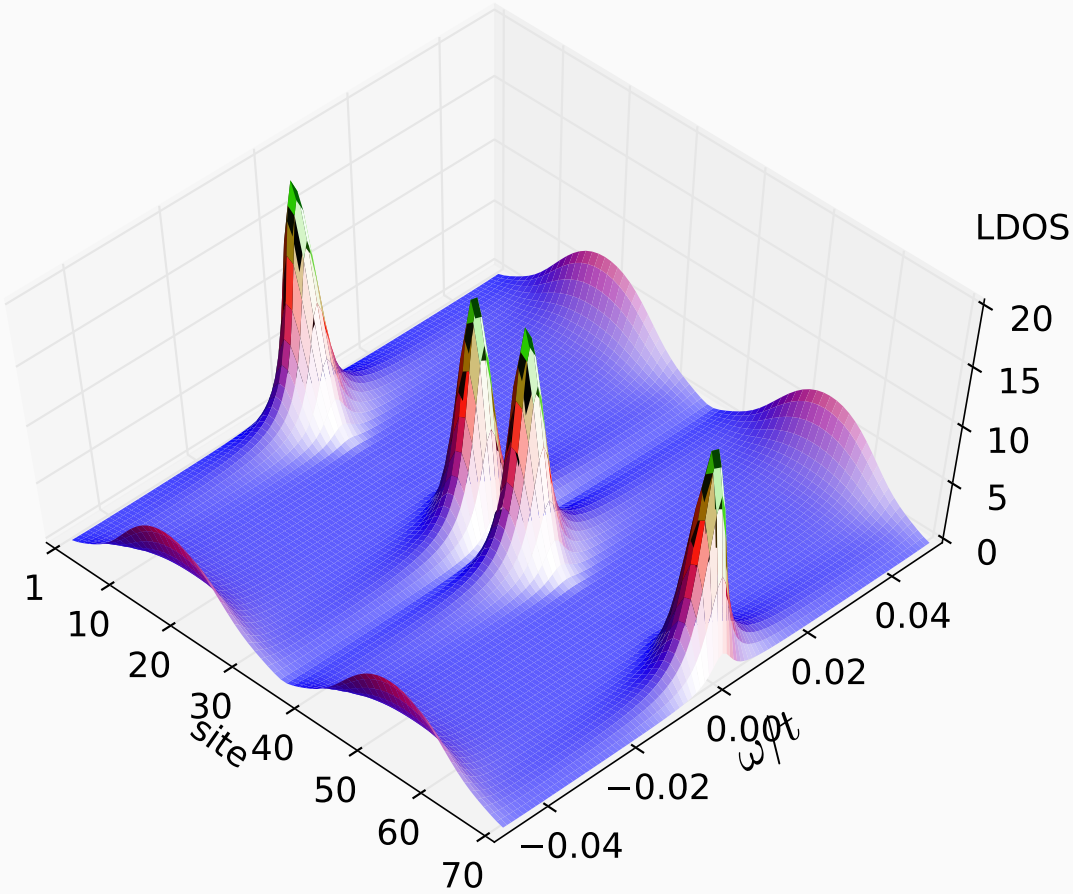
$t_{35}/t = 0.1$



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

Low energy quasiparticles of the Rashba nanowire

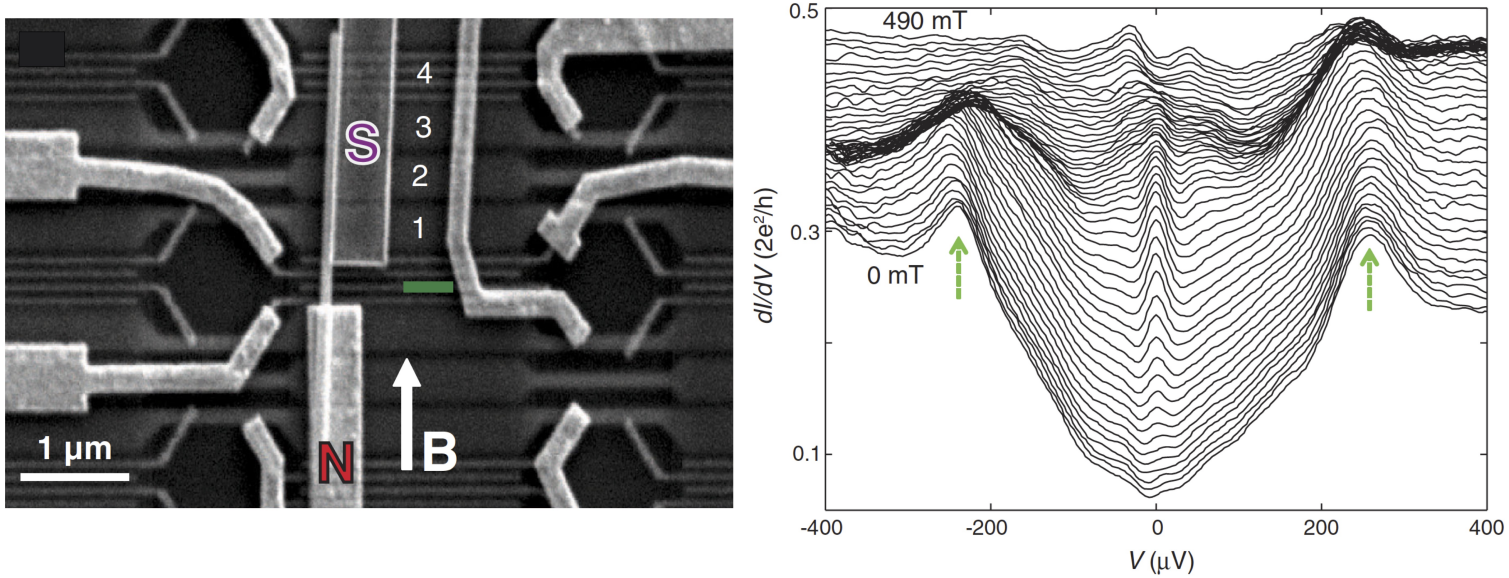
$t_{35}/t = 0.0$



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

EMPIRICAL REALIZATION: EXAMPLE # 1

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

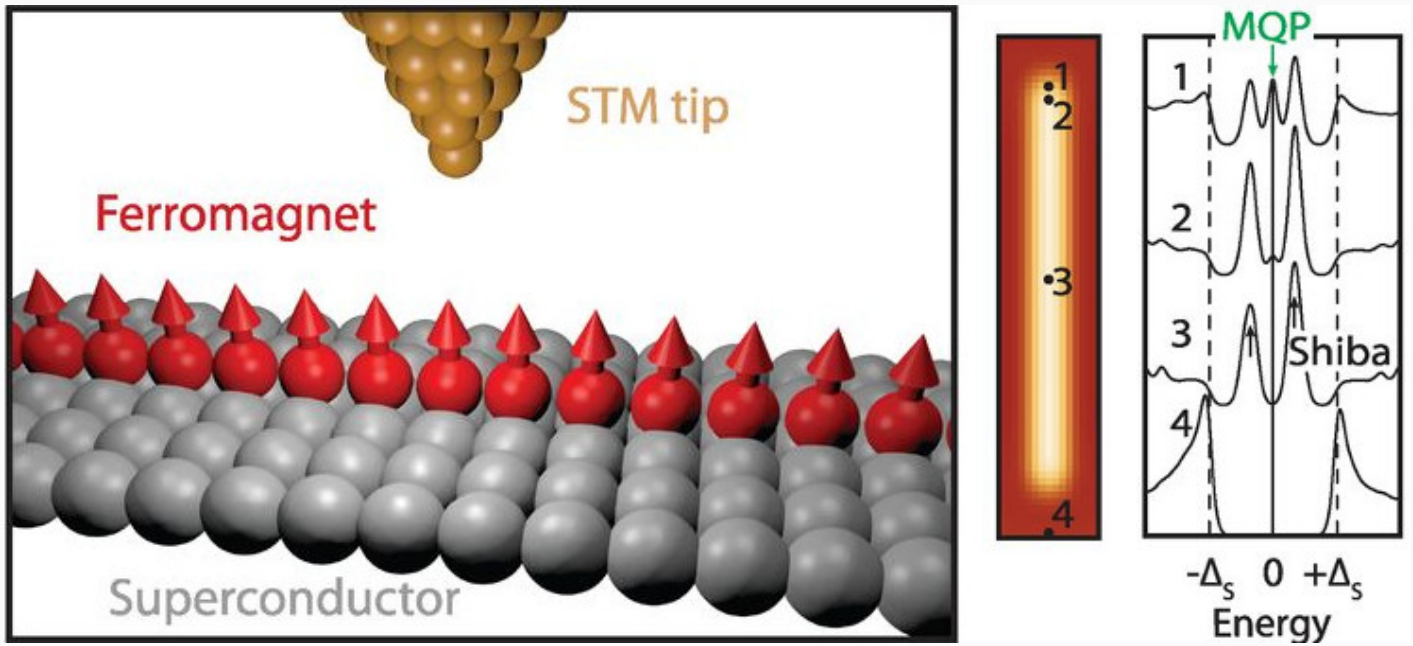


V. Mourik, ..., and L.P. Kouwenhoven, Science **336**, 1003 (2012).

/ Technical Univ. Delft, Netherlands /

EMPIRICAL REALIZATION: EXAMPLE # 2

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

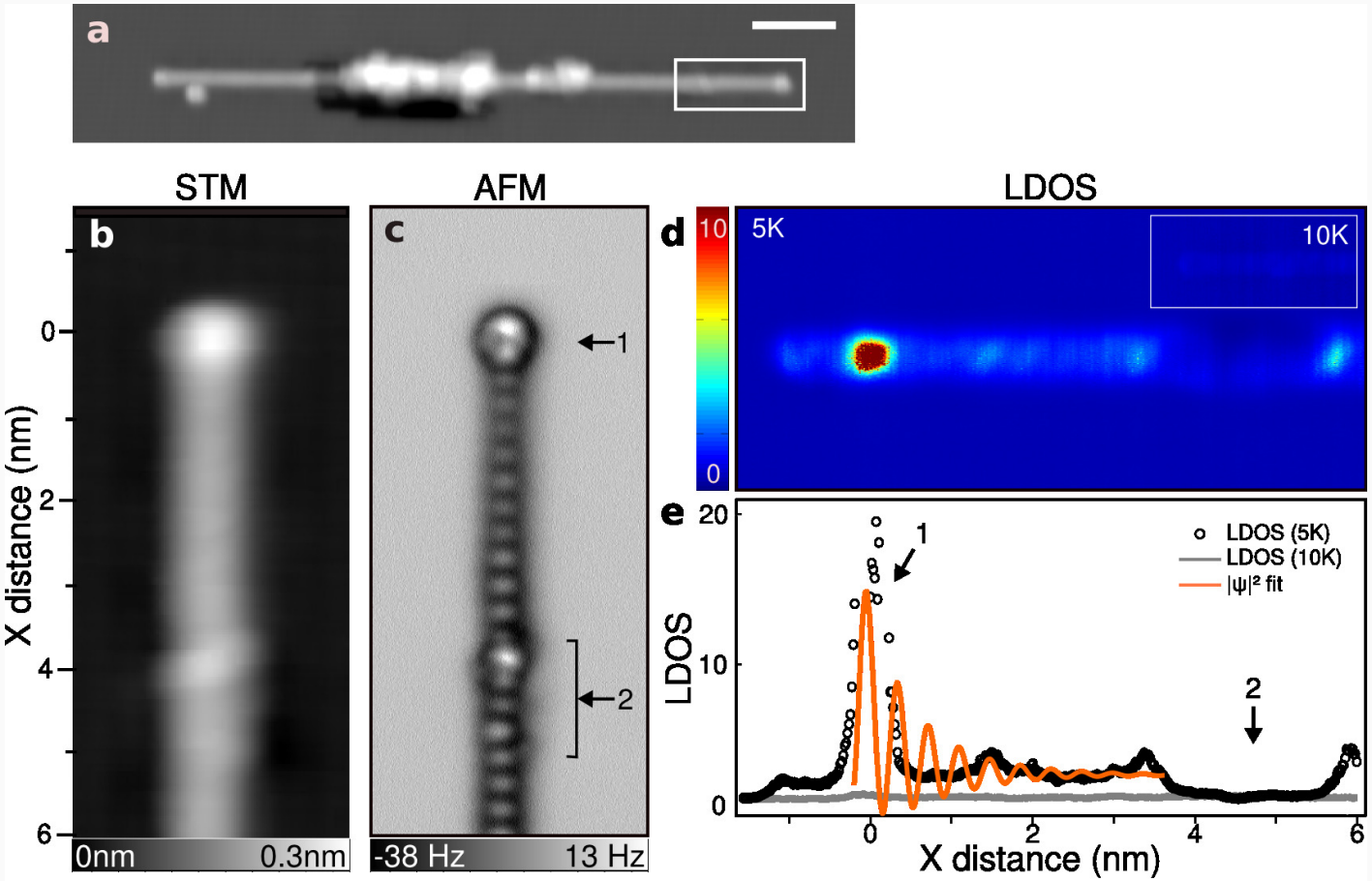


S. Nadj-Perge, ..., and A. Yazdani, Science **346**, 602 (2014).

/ Princeton University, USA /

EMPIRICAL REALIZATION: EXAMPLE # 3

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

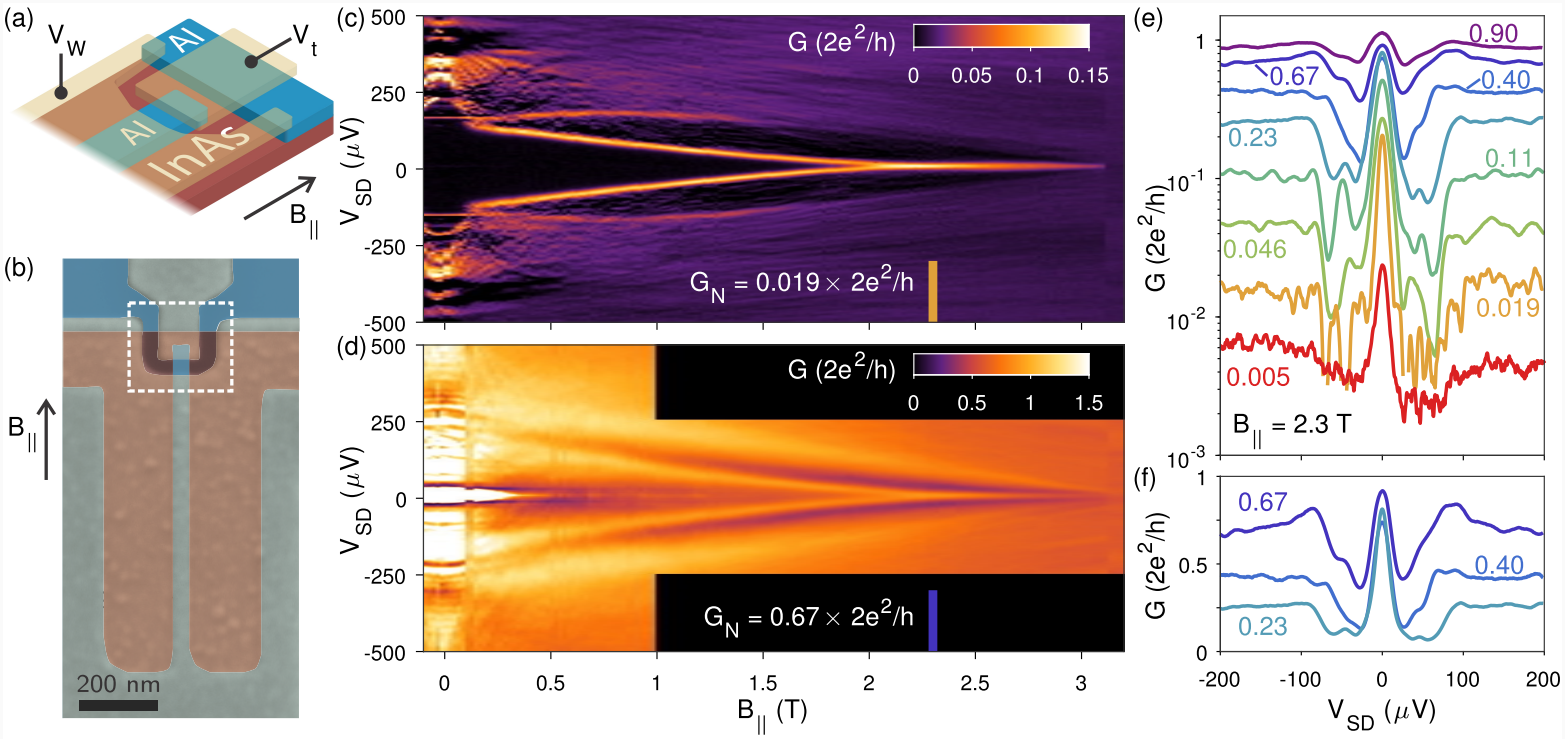


R. Pawlak, M. Kisiel *et al*, npj Quantum Information **2**, 16035 (2016).

/ University of Basel, Switzerland /

EMPIRICAL REALIZATION: EXAMPLE # 4

Results for the litographically fabricated Al nanowire

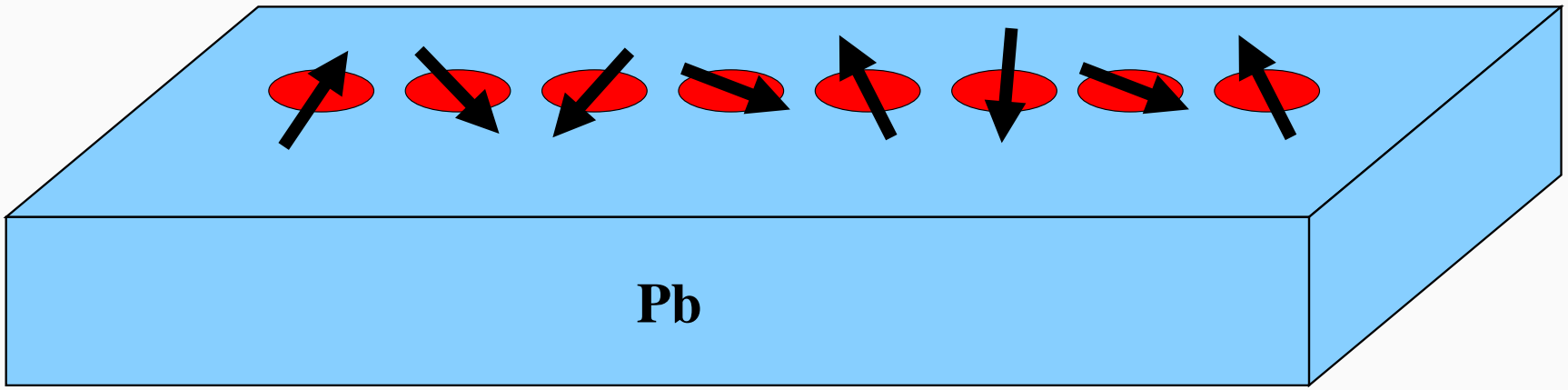


F. Nichele, ..., and Ch. Marcus, Phys. Rev. Lett. **119**, 136803 (2017).

/ Niels Bohr Institute, Copenhagen, Denmark /

MAGNETIC CHAINS IN SUPERCONDUCTORS

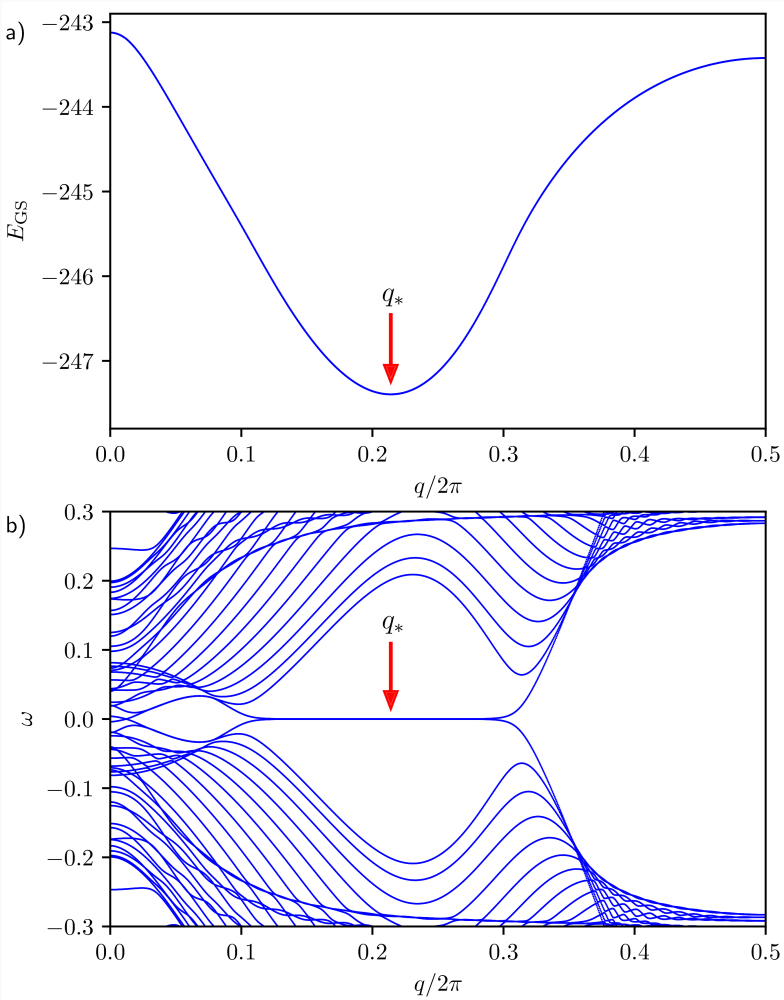
Nanochain of magnetic impurities embedded in superconductor:



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

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

MAGNETIC CHAINS IN SUPERCONDUCTORS



Ground state energy vs the pitch vector q

Quasiparticle energies

This magnetic chain self-tunes to the *topological phase* / topofilia /

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

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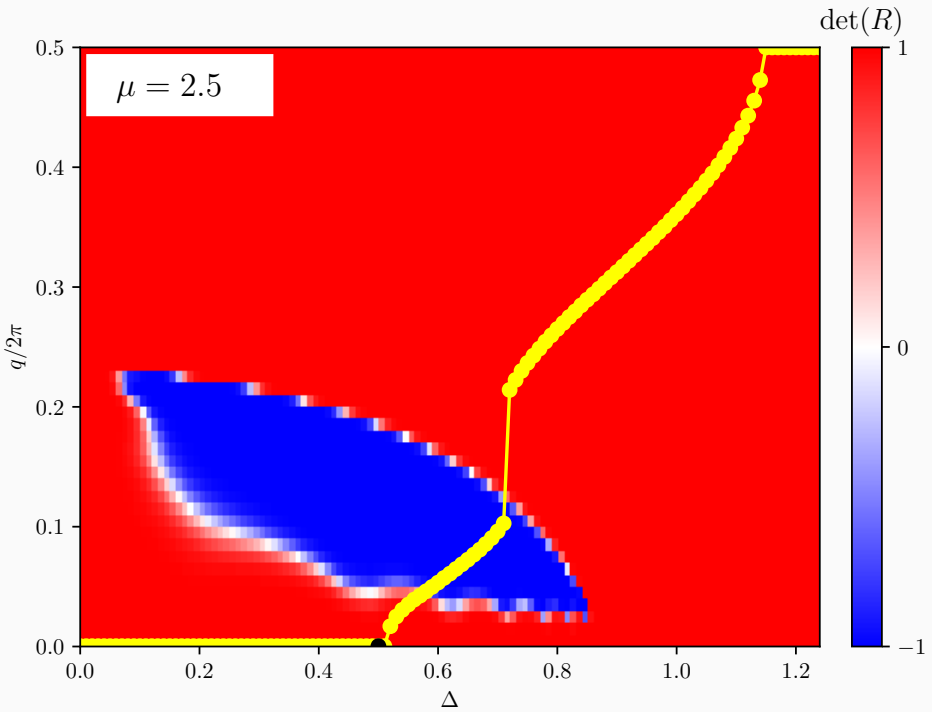
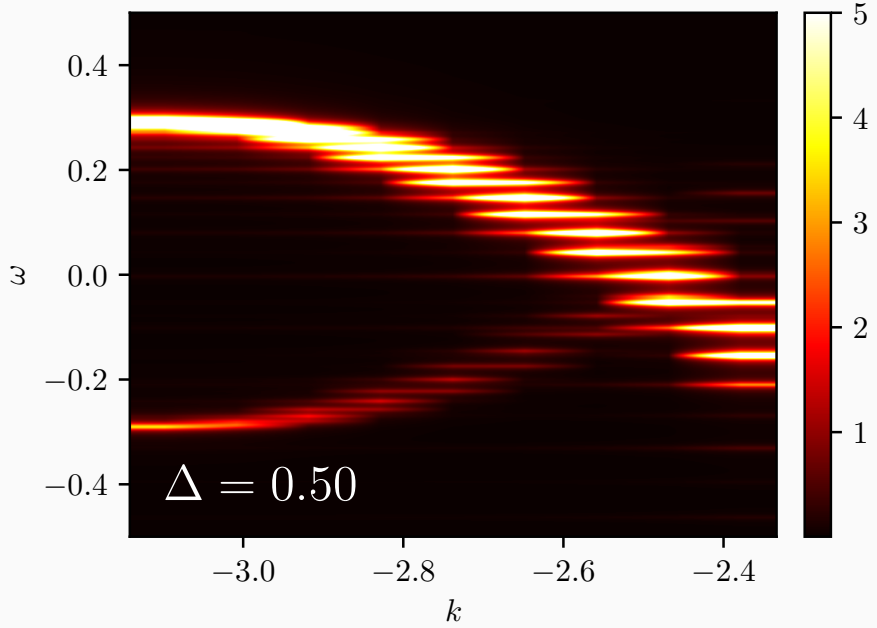
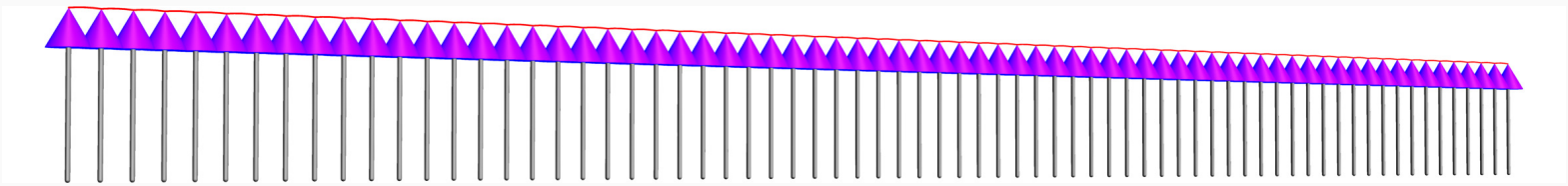
A. Gorczyca-Goraj, T. Domański & M.M. Maśka, Phys. Rev. B 99, 235430 (2019).







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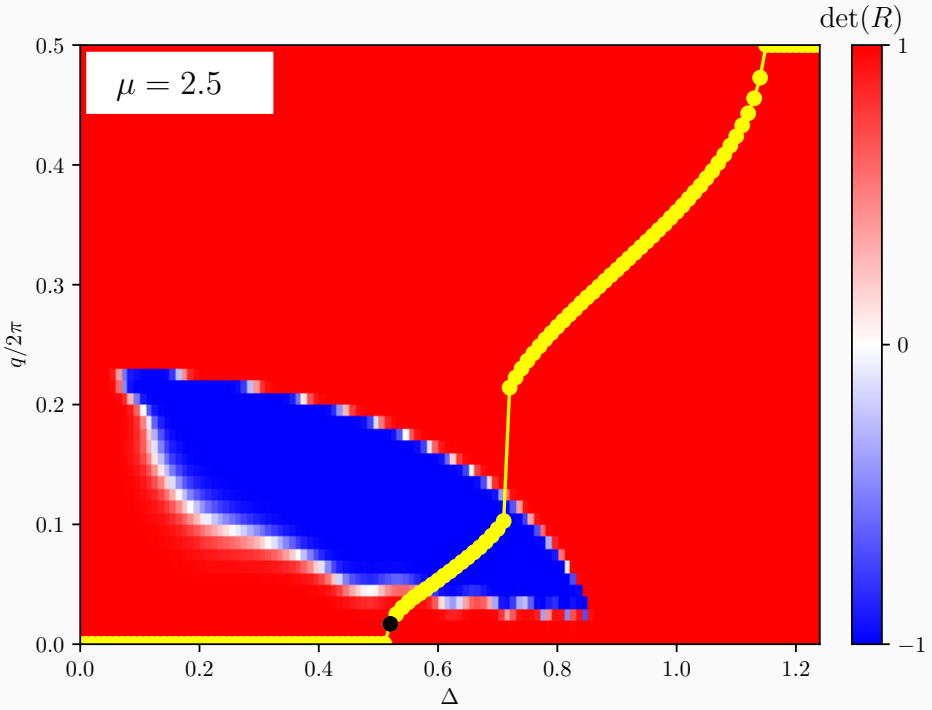
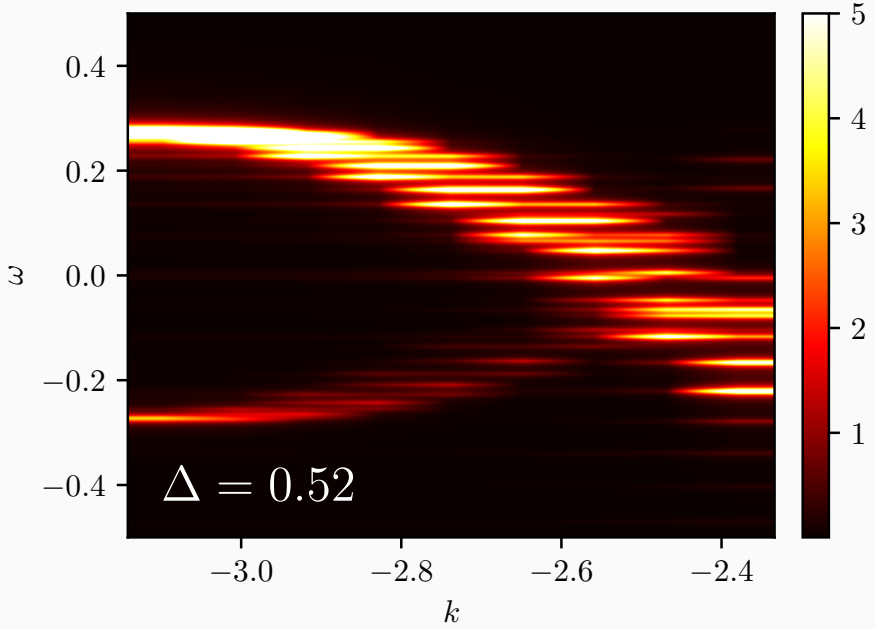
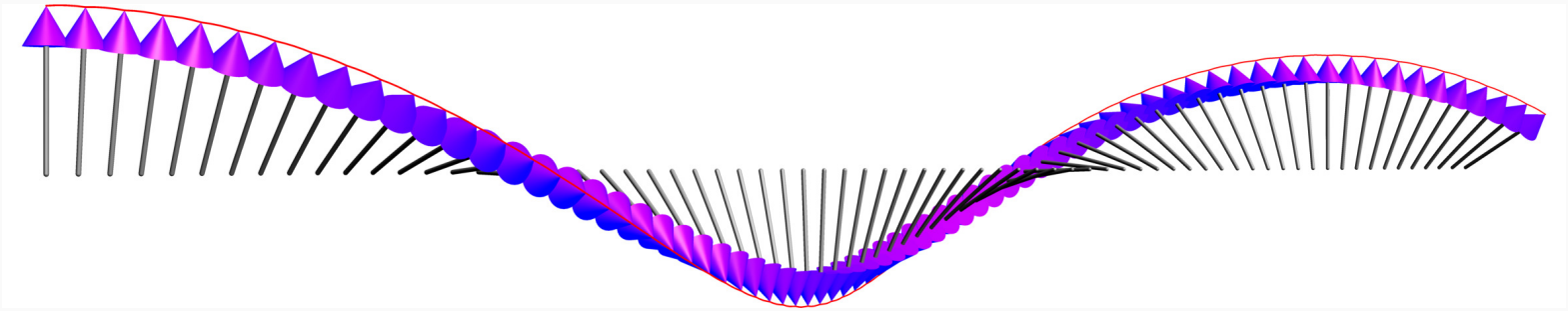
A. Gorczyca-Goraj, T. Domański & M.M. Maśka, Phys. Rev. B 99, 235430 (2019).







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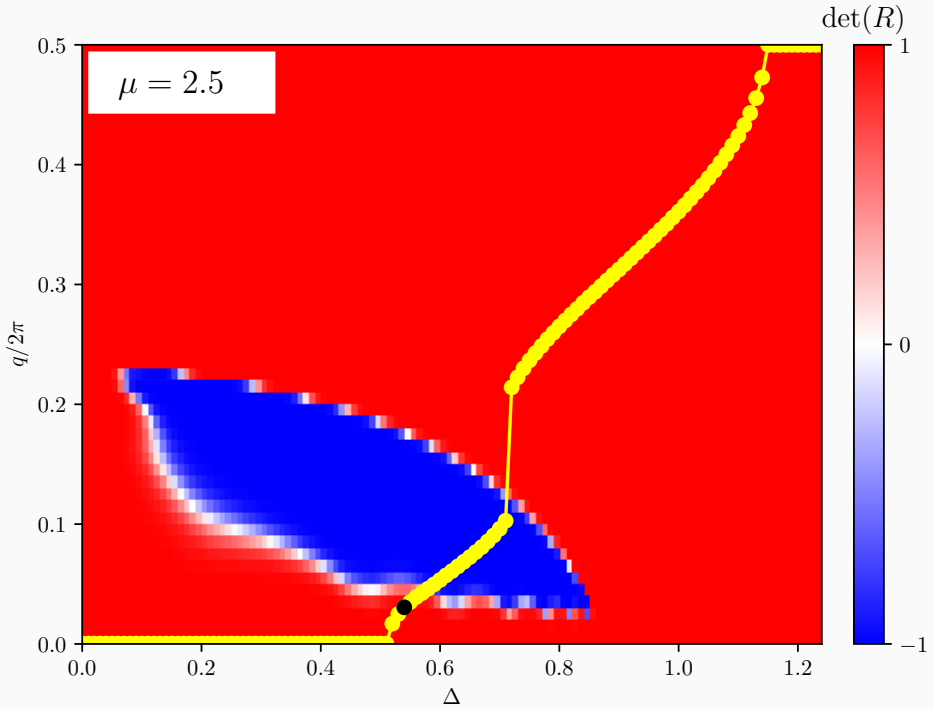
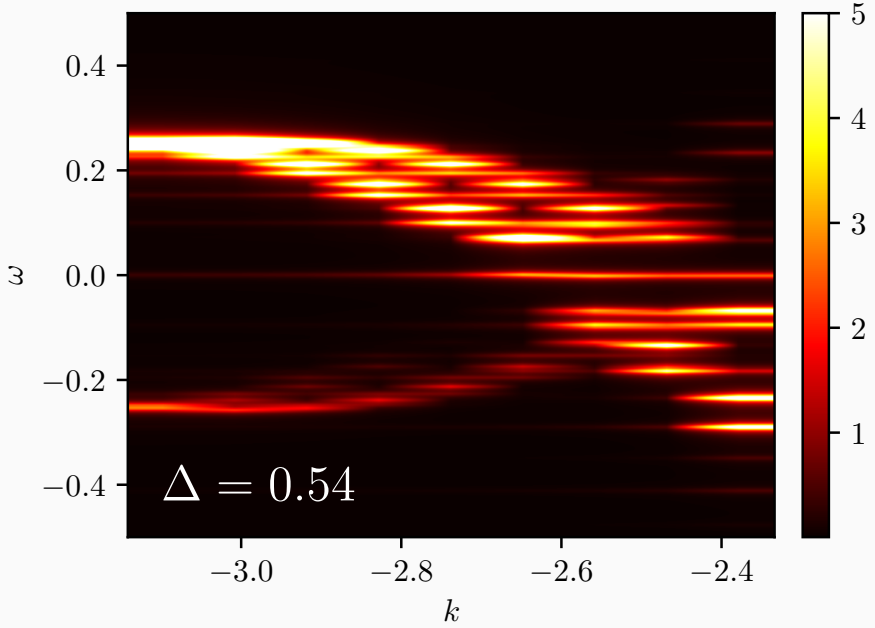
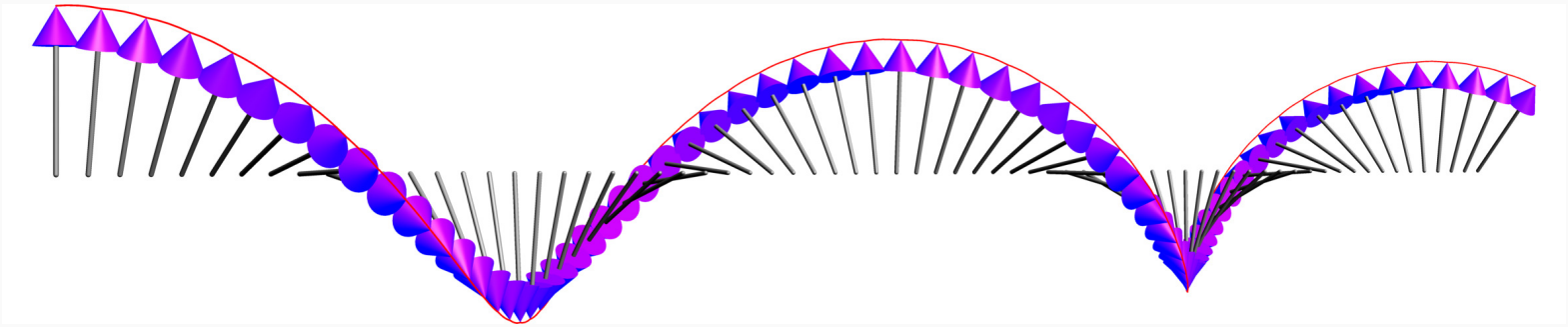
A. Gorczyca-Goraj, T. Domański & M.M. Maśka, Phys. Rev. B 99, 235430 (2019).







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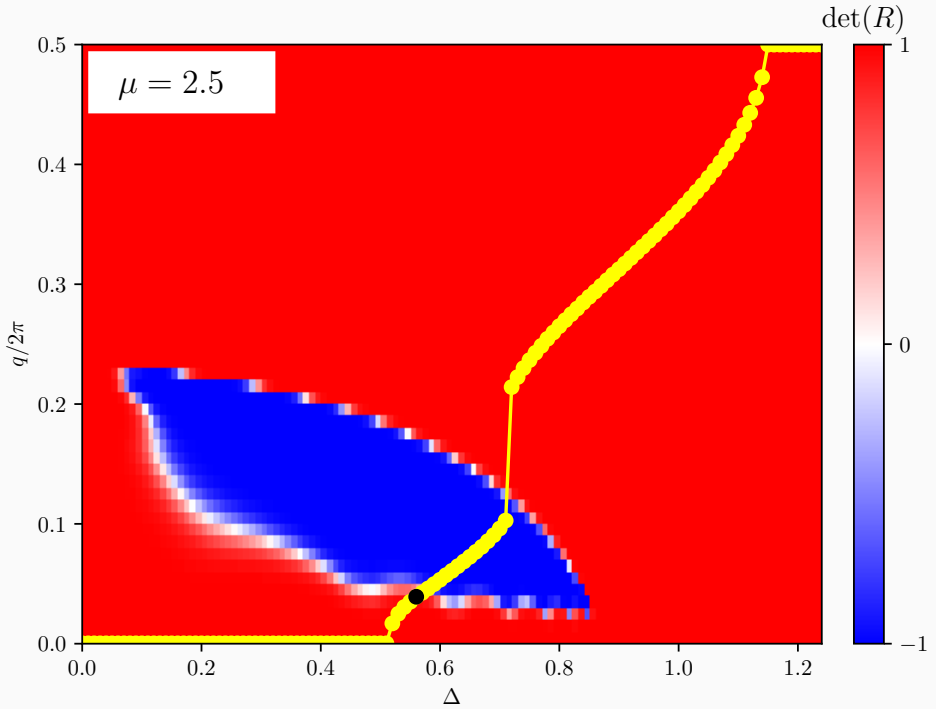

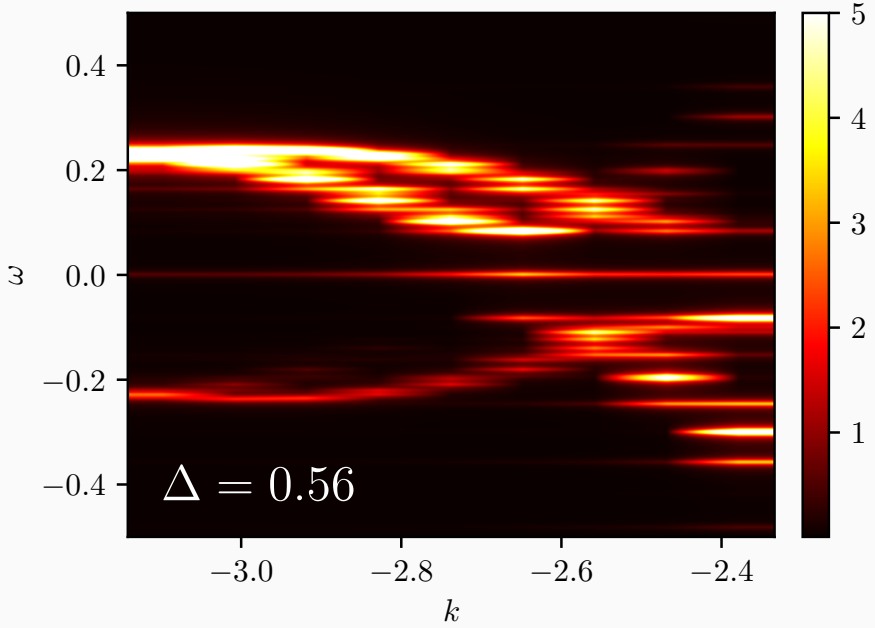

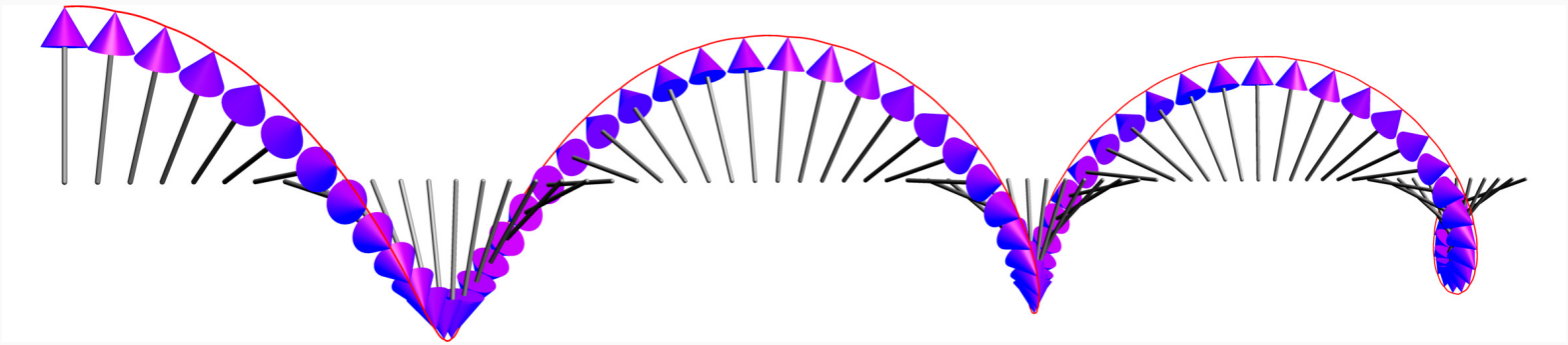

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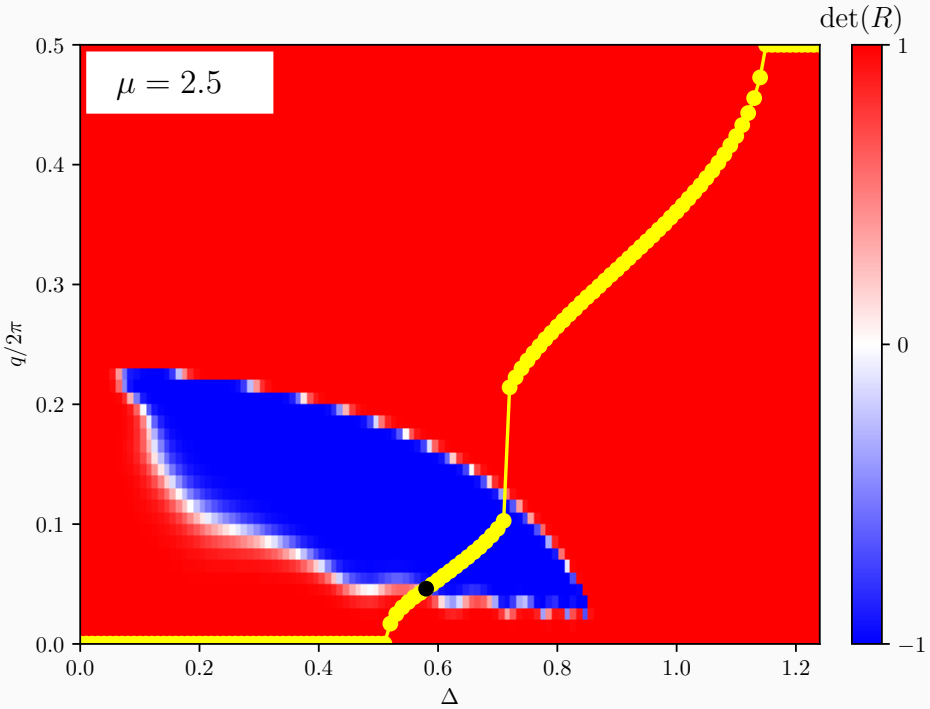
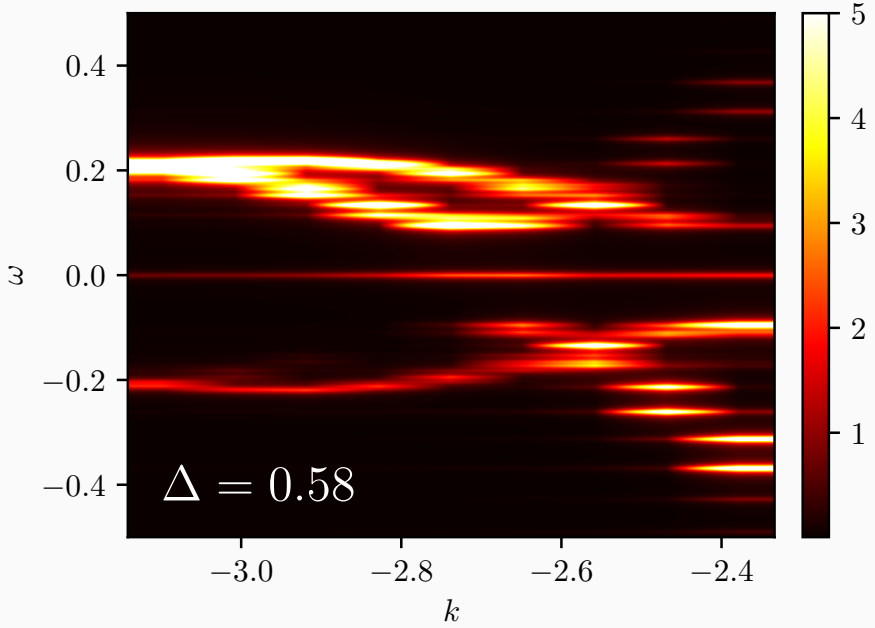
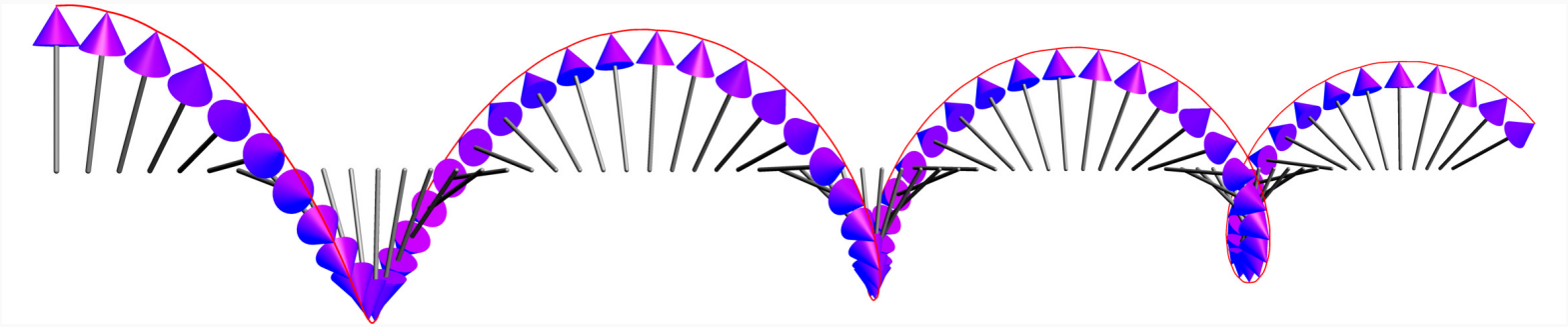
A. Gorczyca-Goraj, T. Domański & M.M. Maśka, Phys. Rev. B 99, 235430 (2019).







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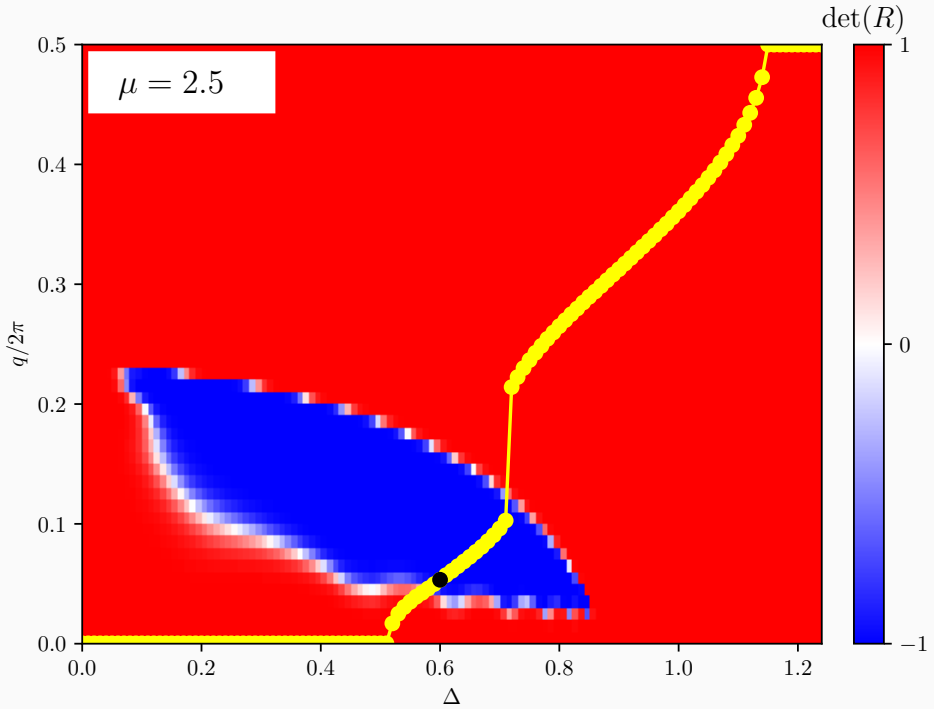
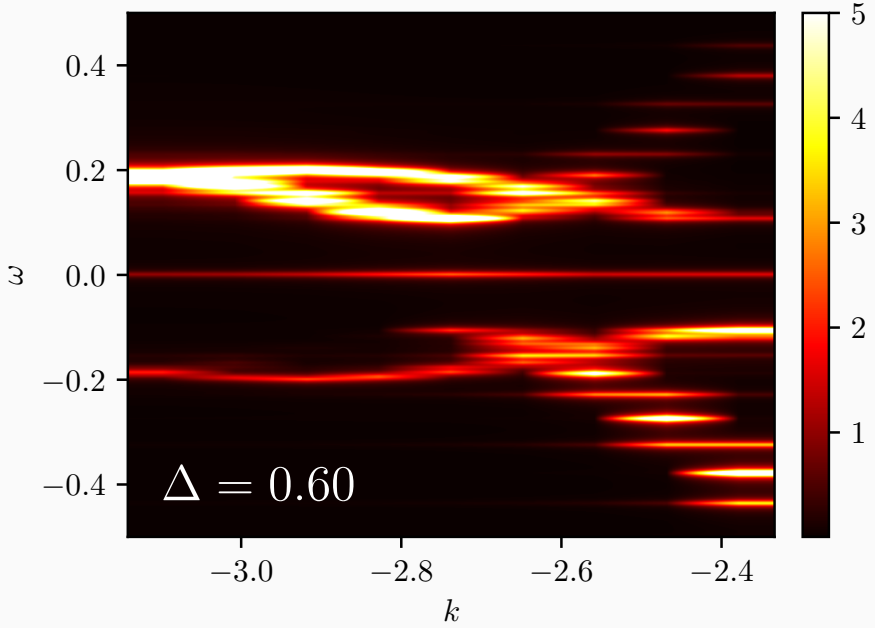
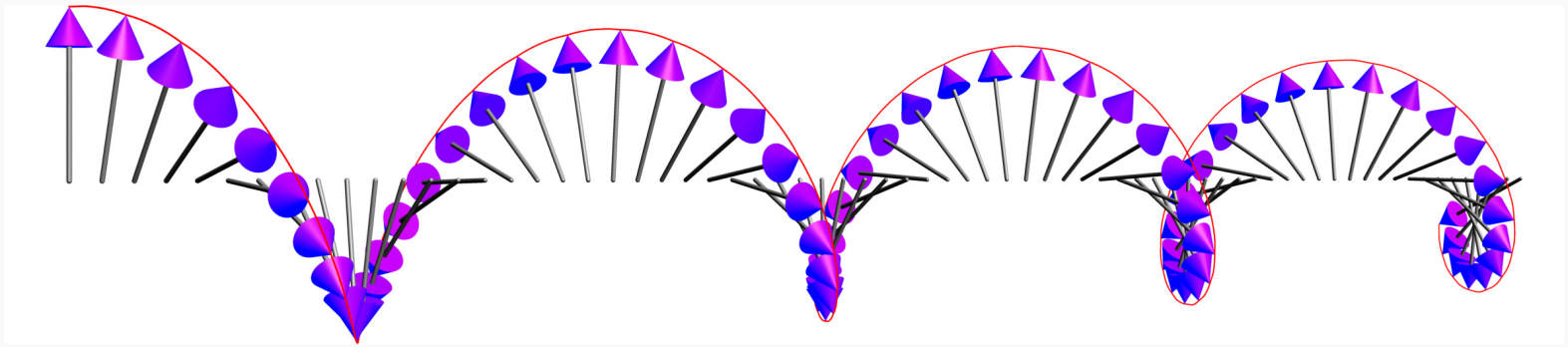
A. Gorczyca-Goraj, T. Domański & M.M. Maśka, Phys. Rev. B 99, 235430 (2019).







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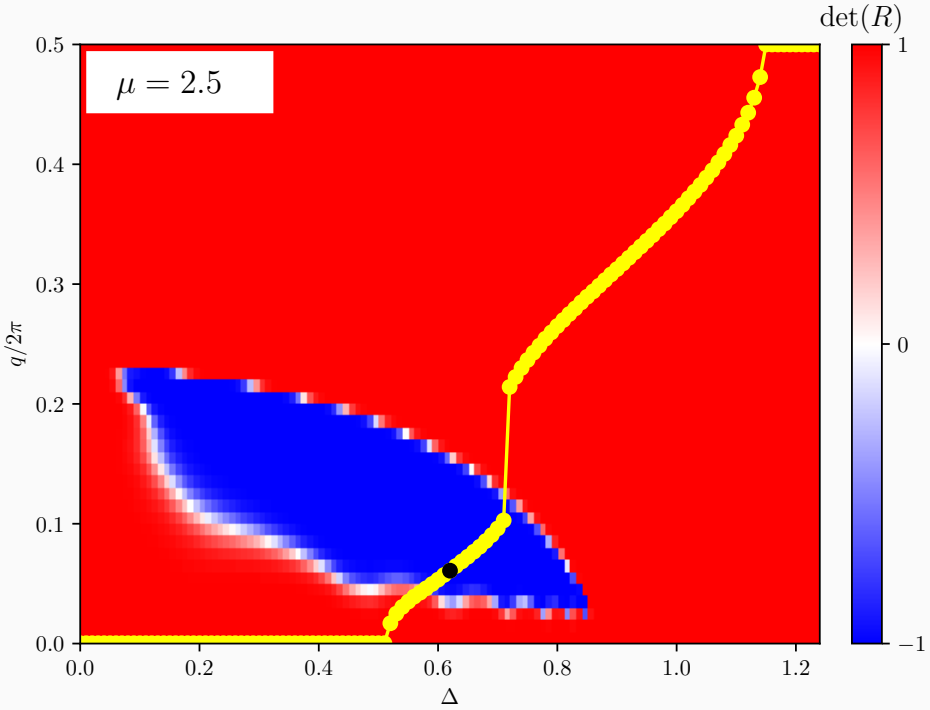

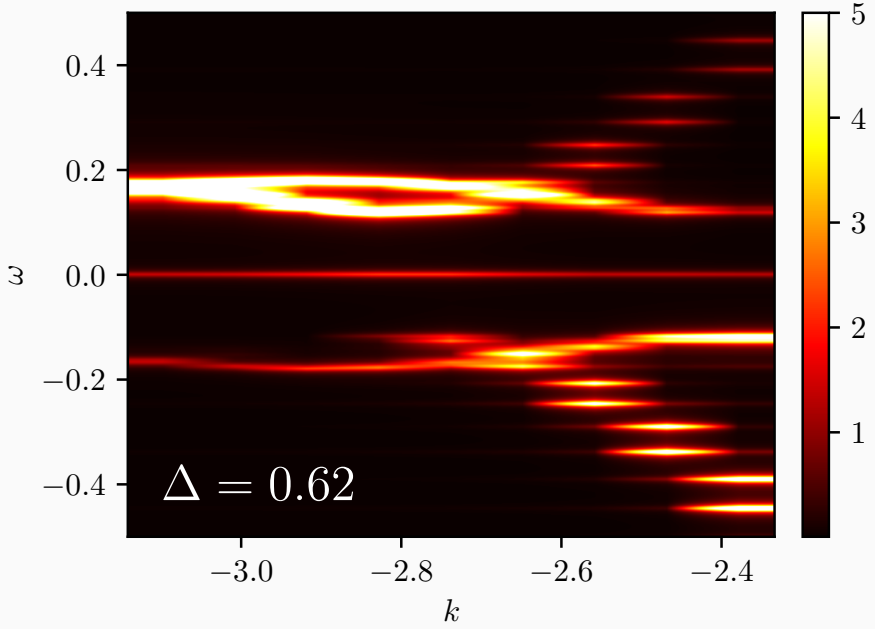

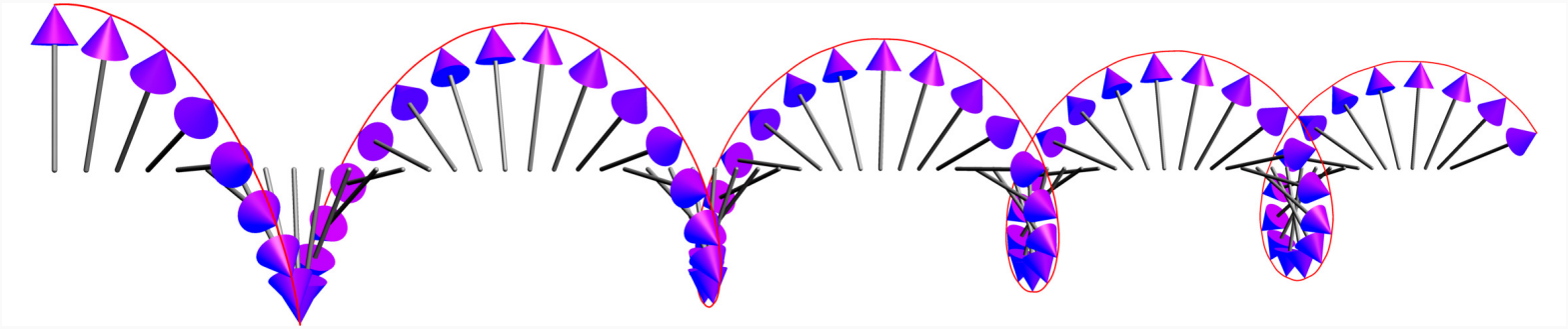

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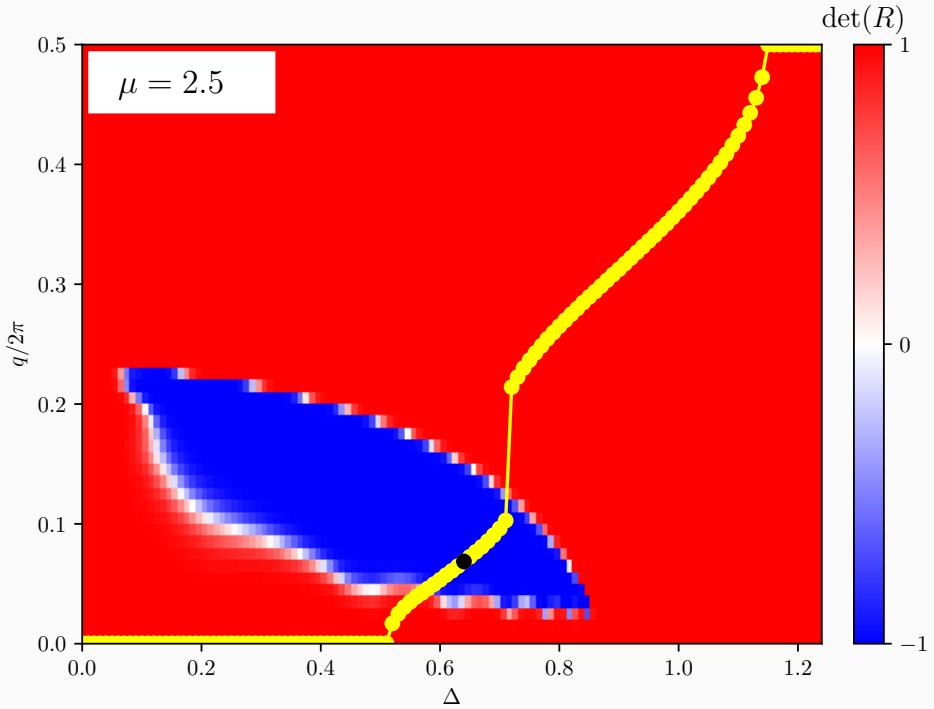

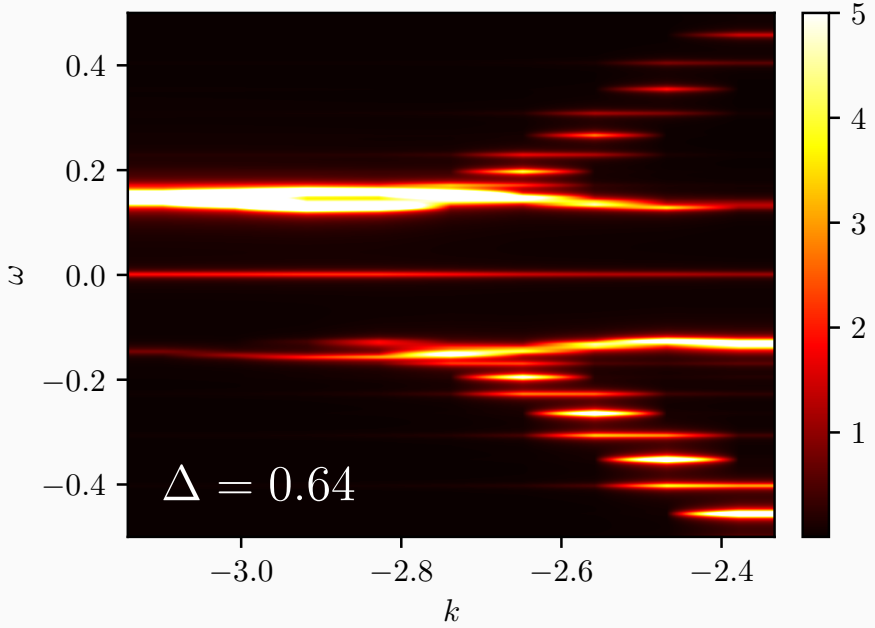

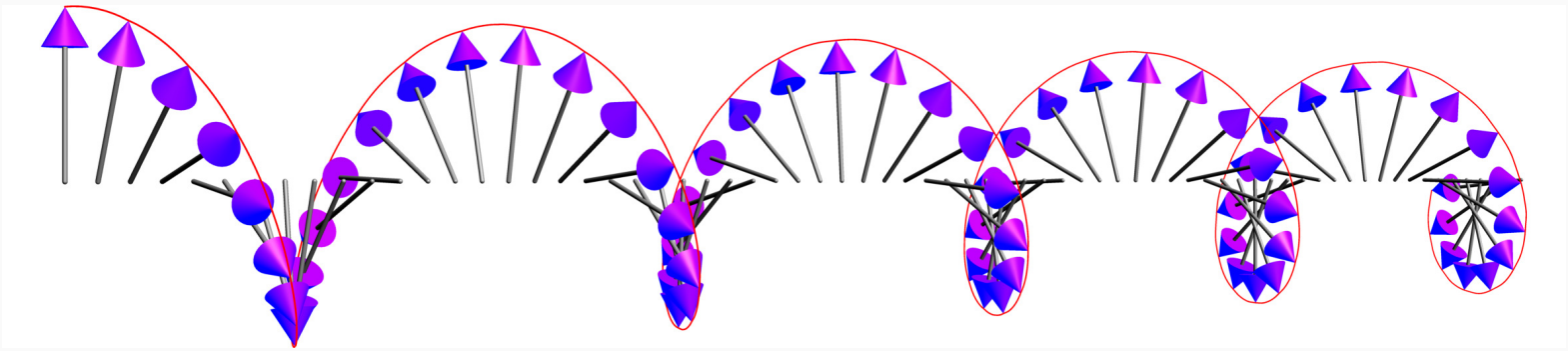

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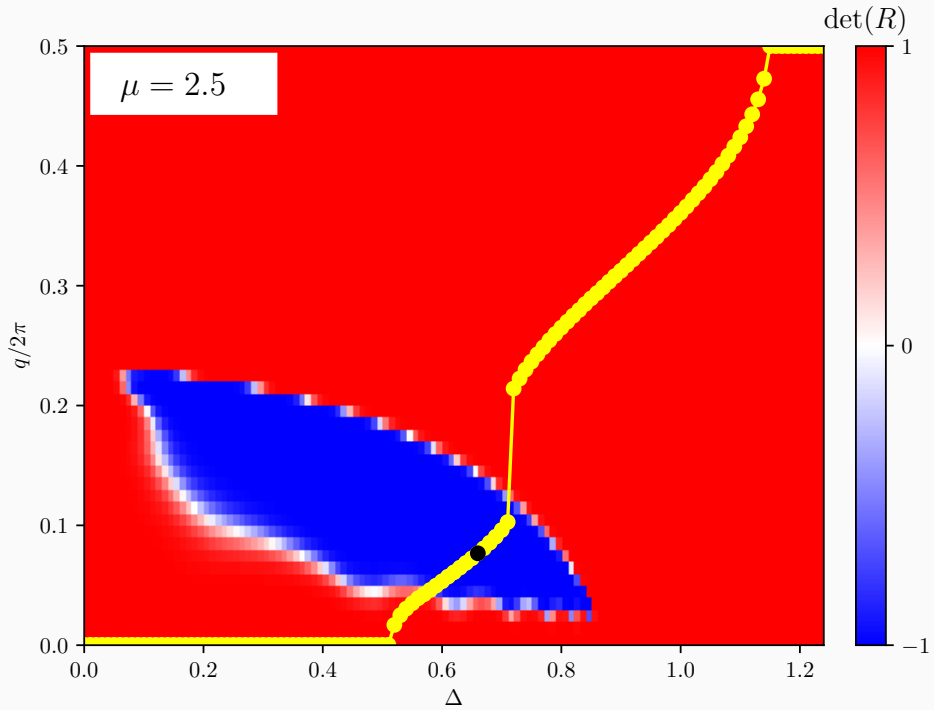

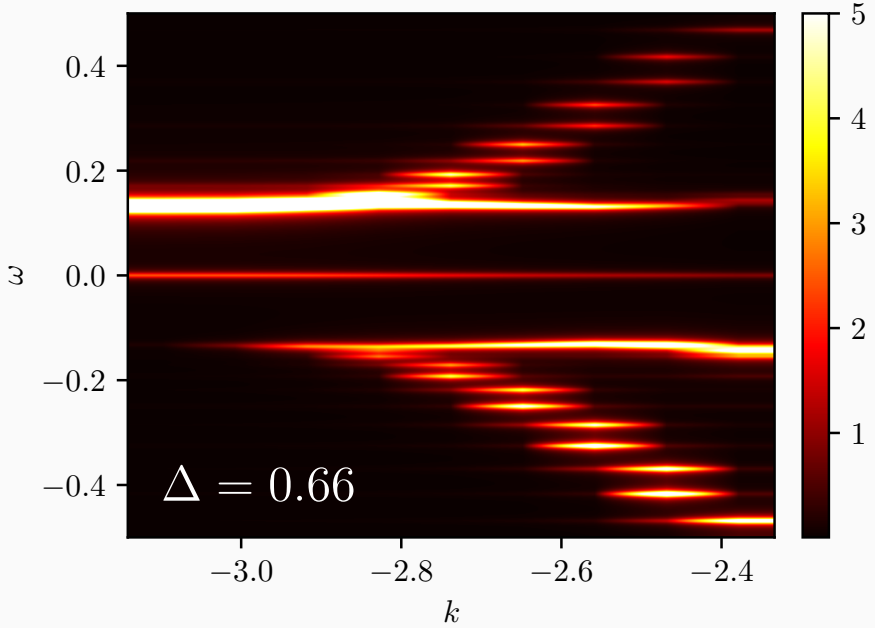

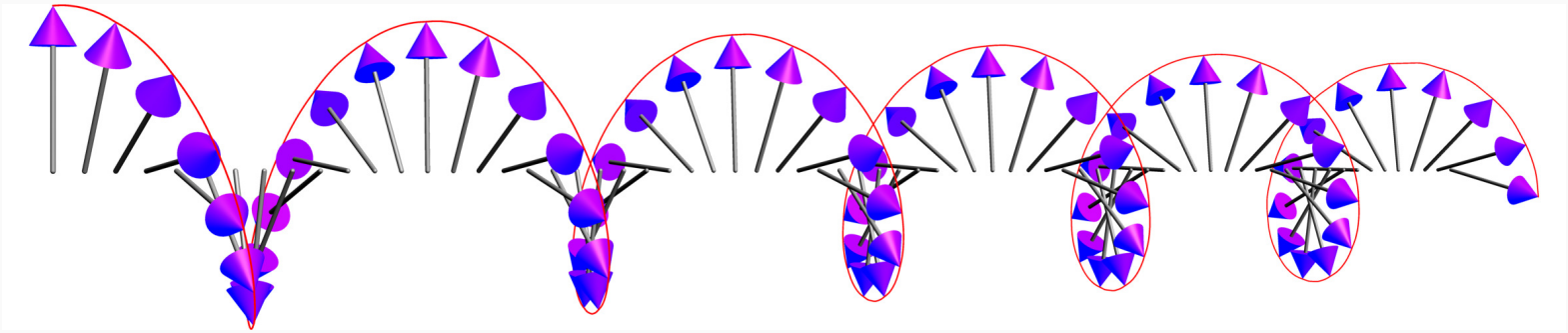

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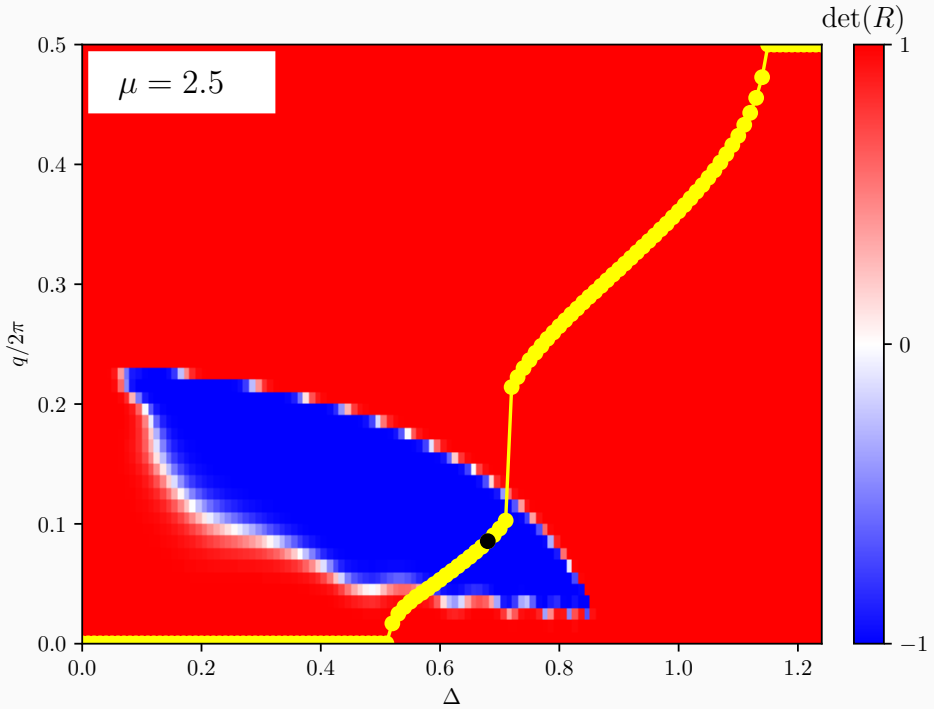

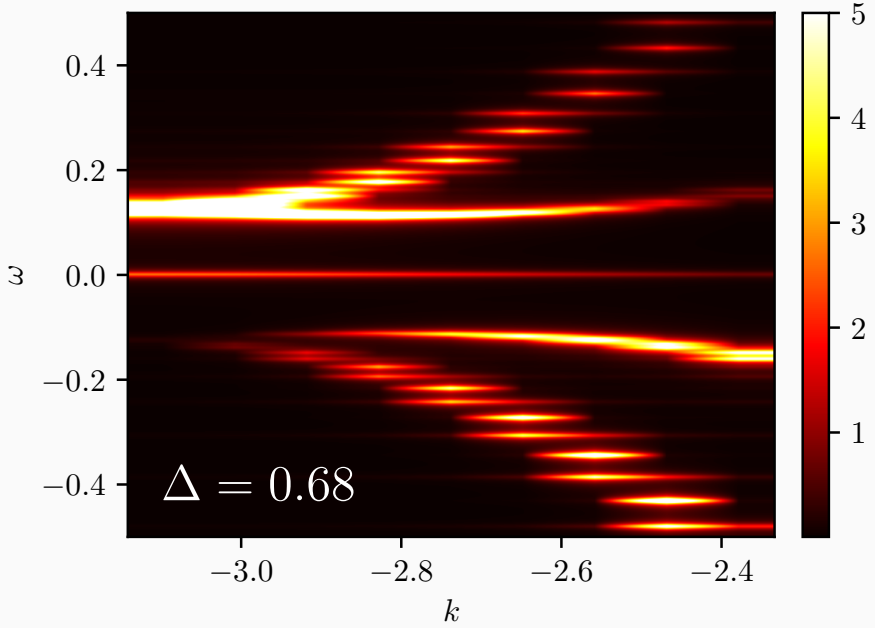

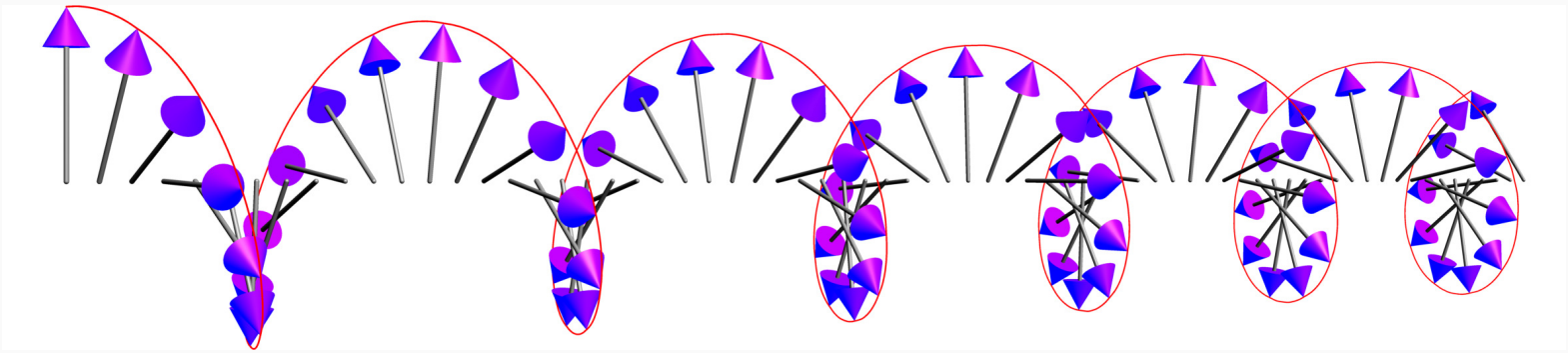

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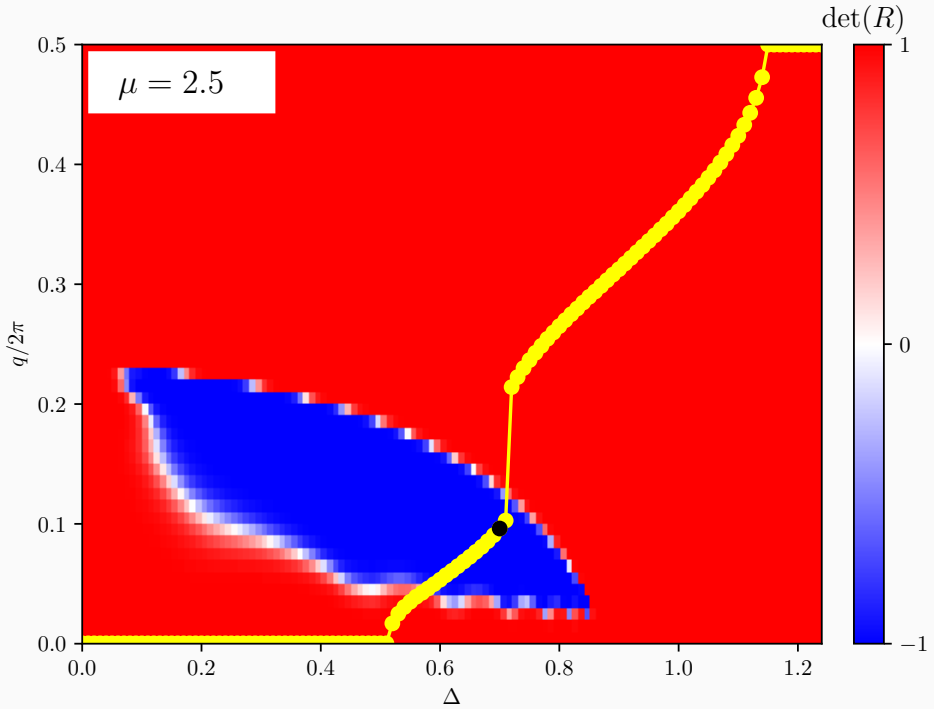
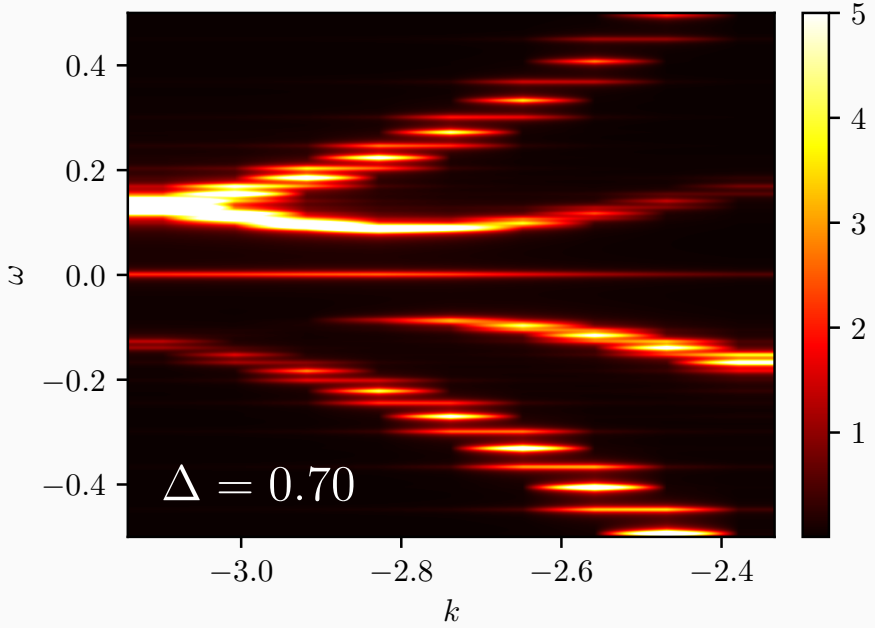
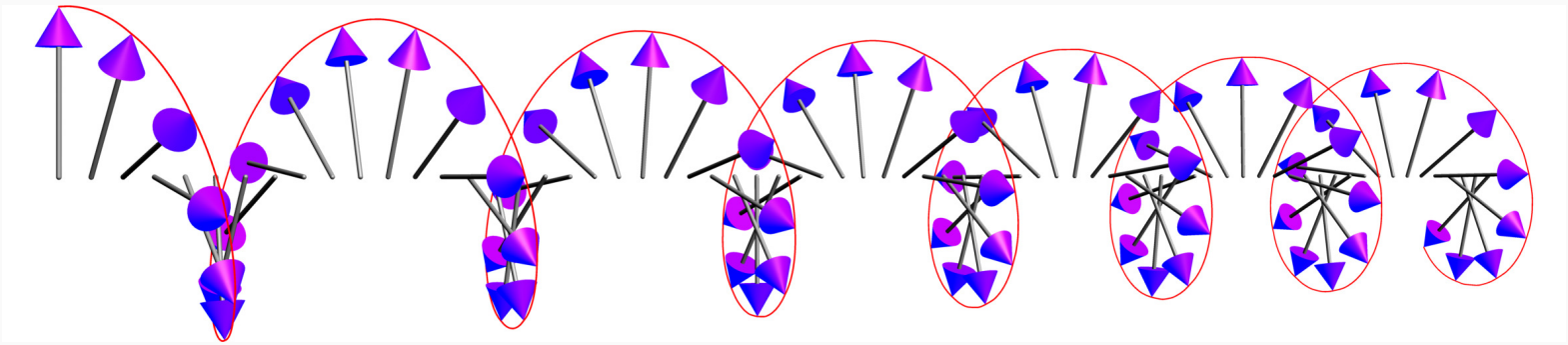
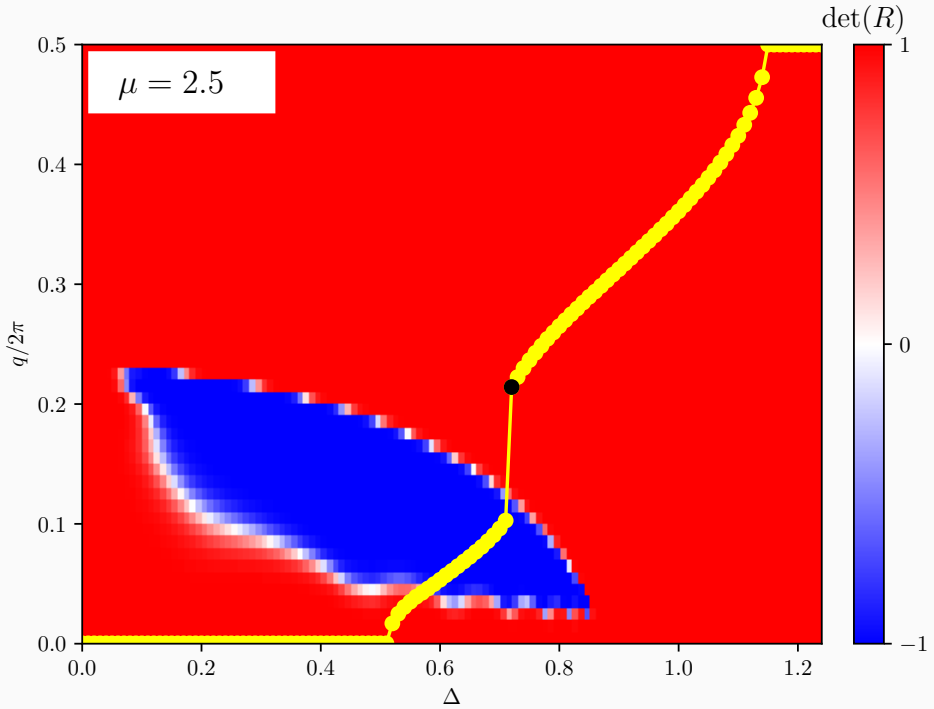


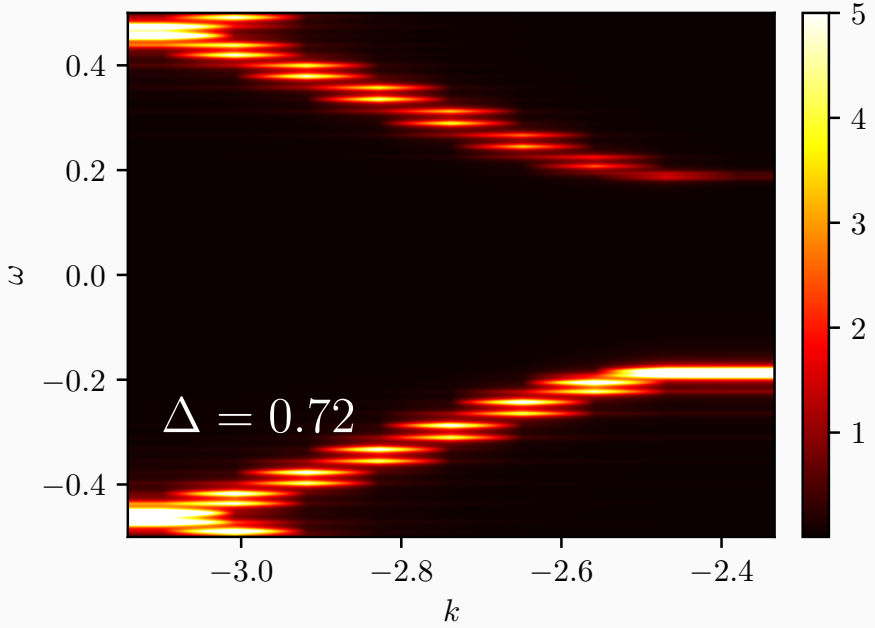


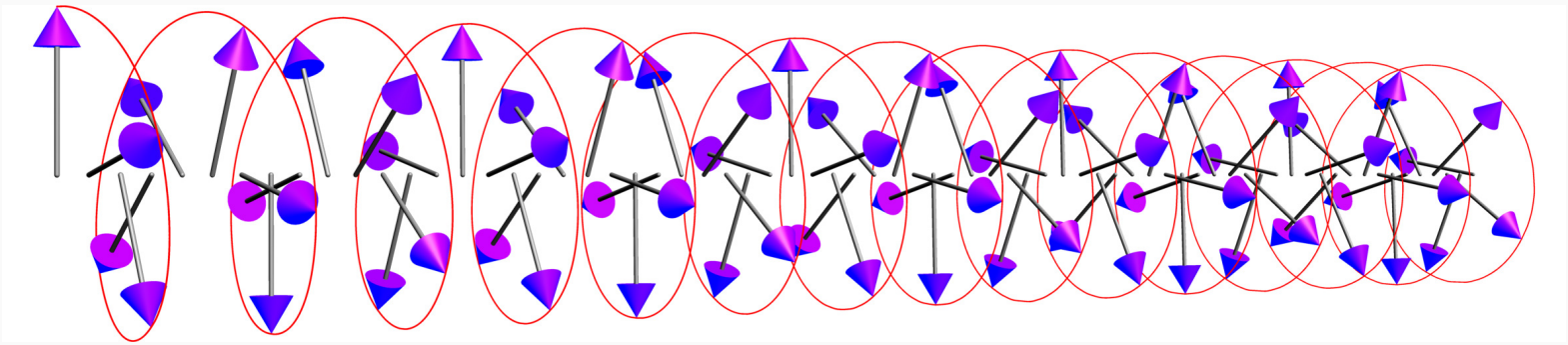


SELFORGANISATION

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

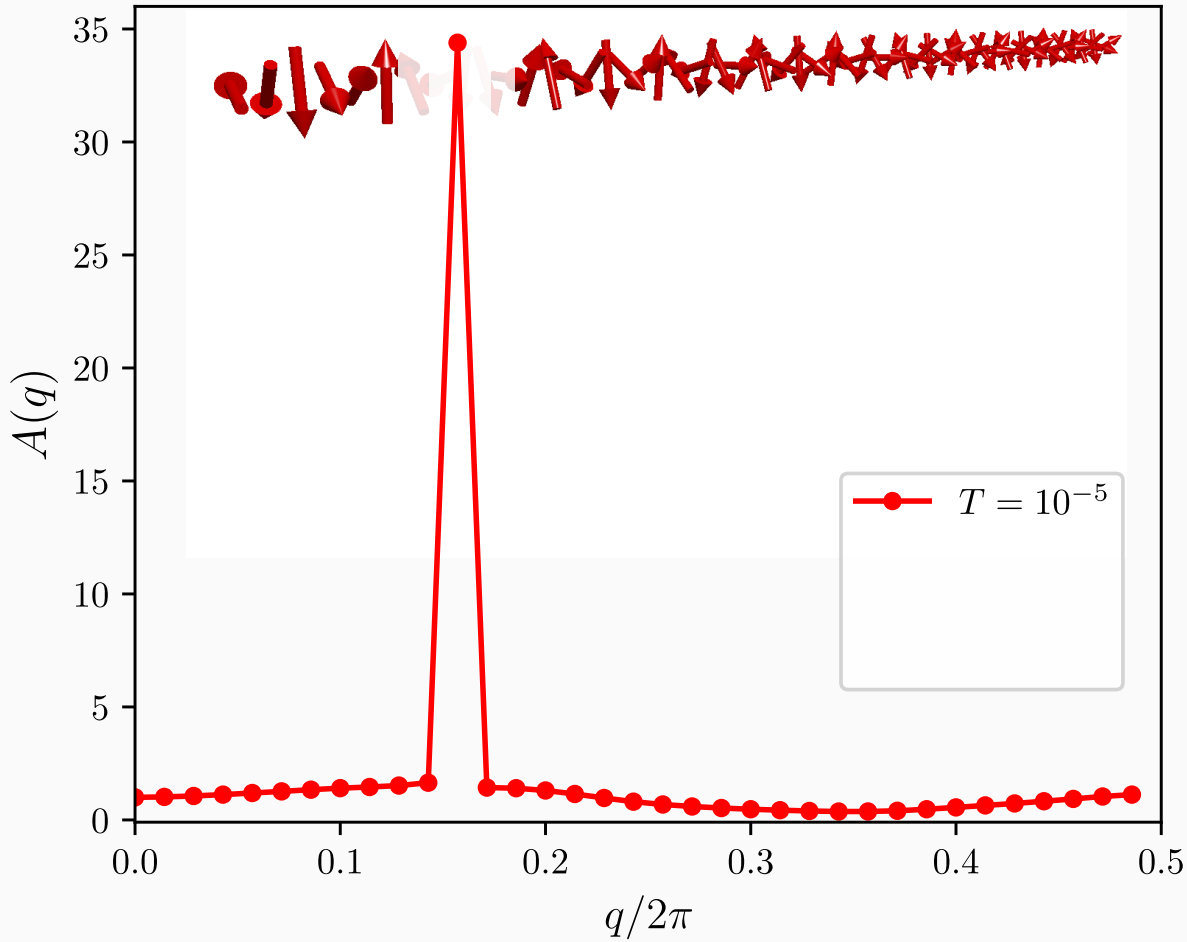






SELFORGANISATION

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



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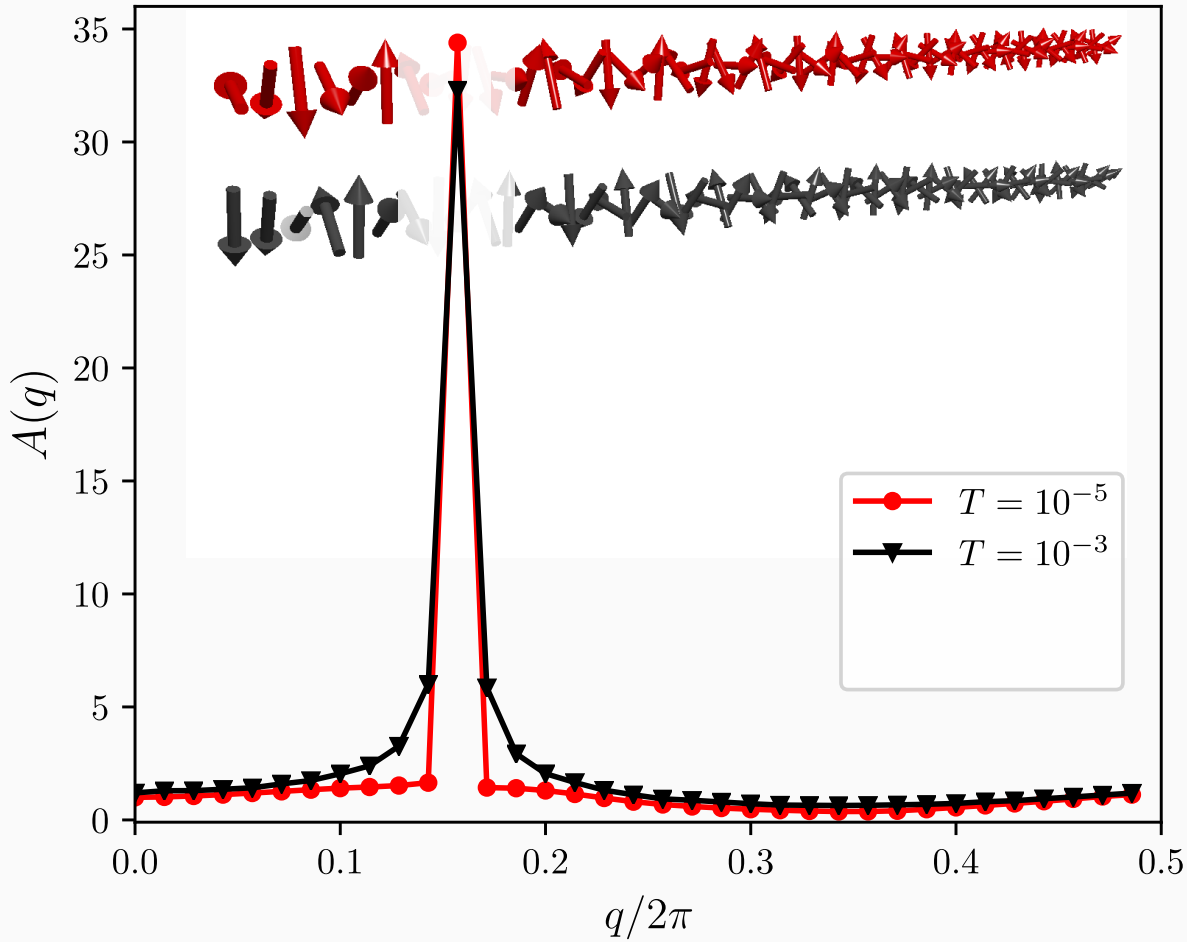

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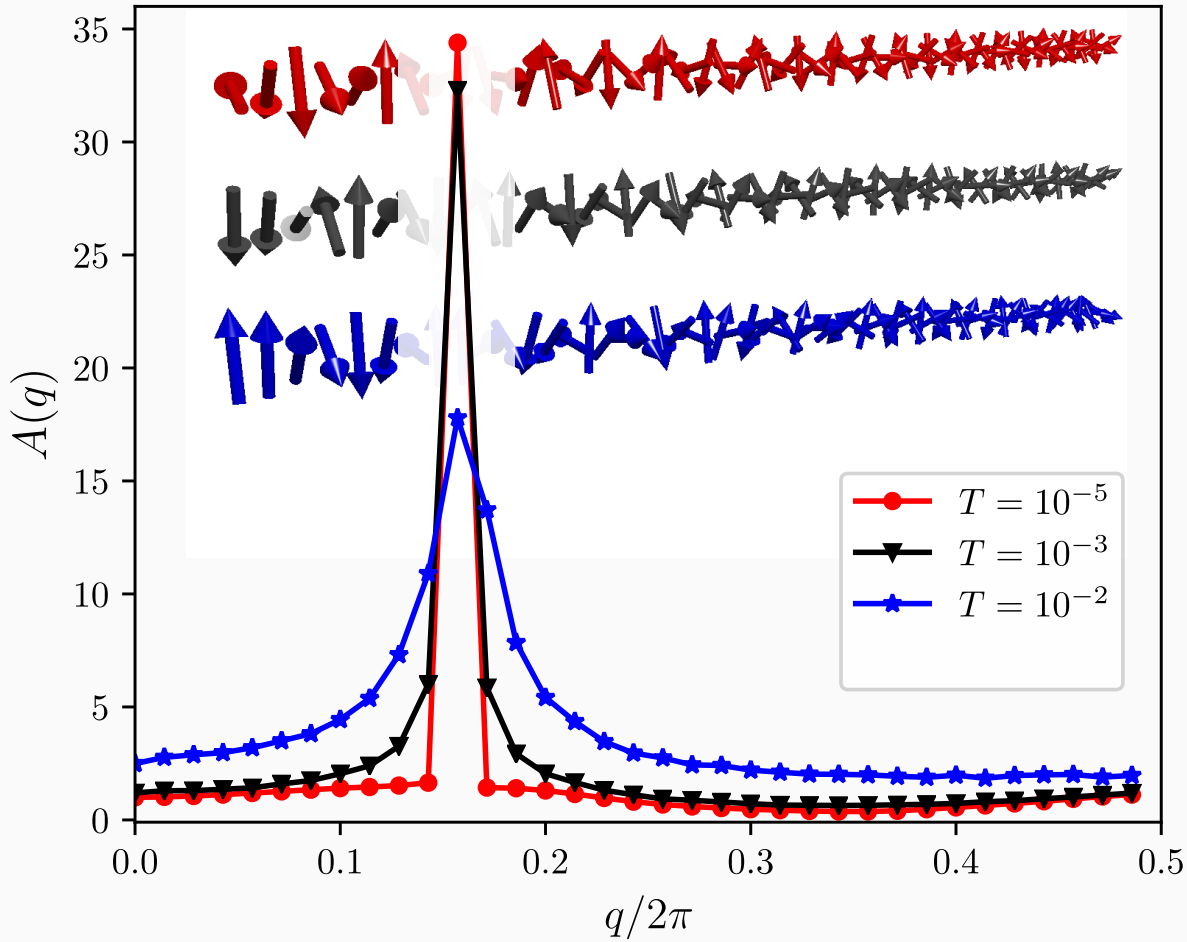

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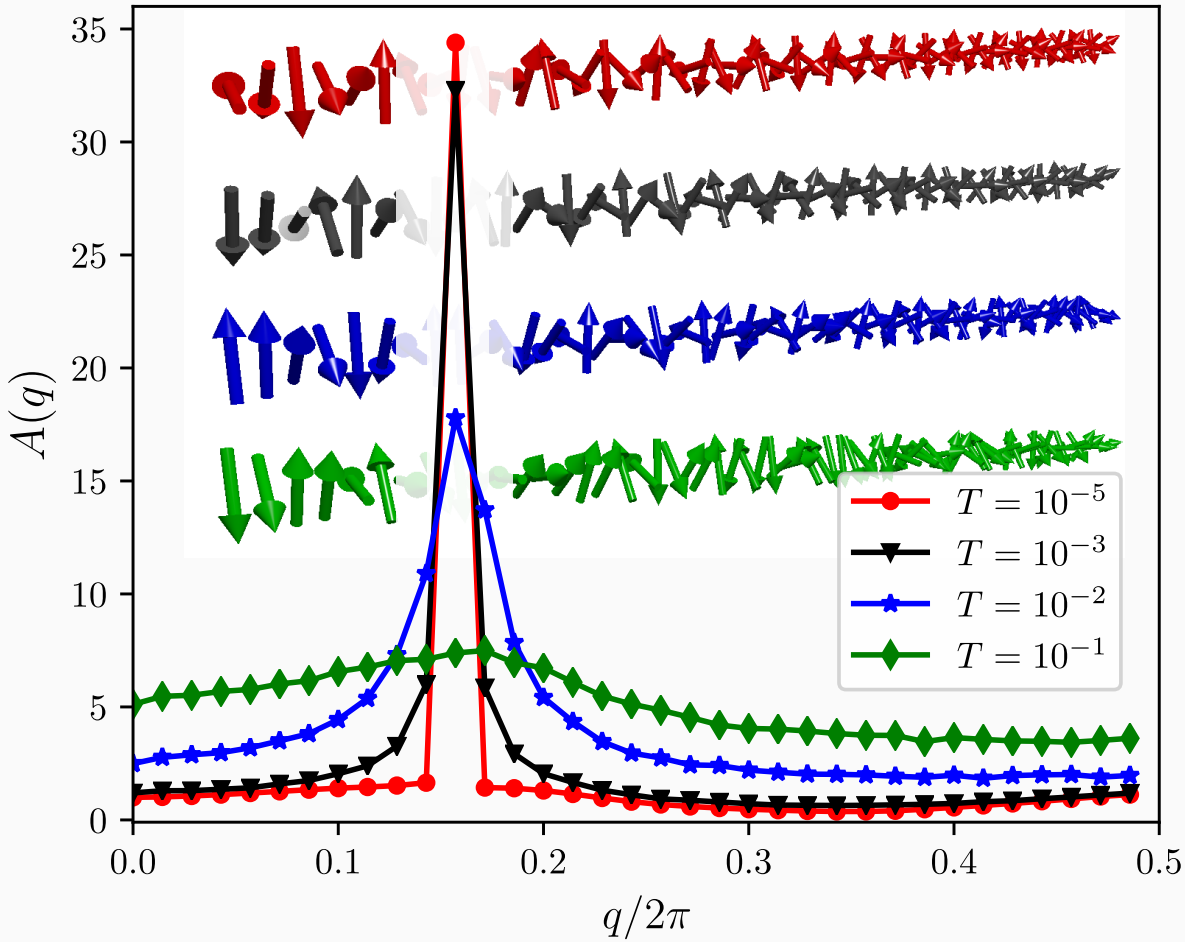
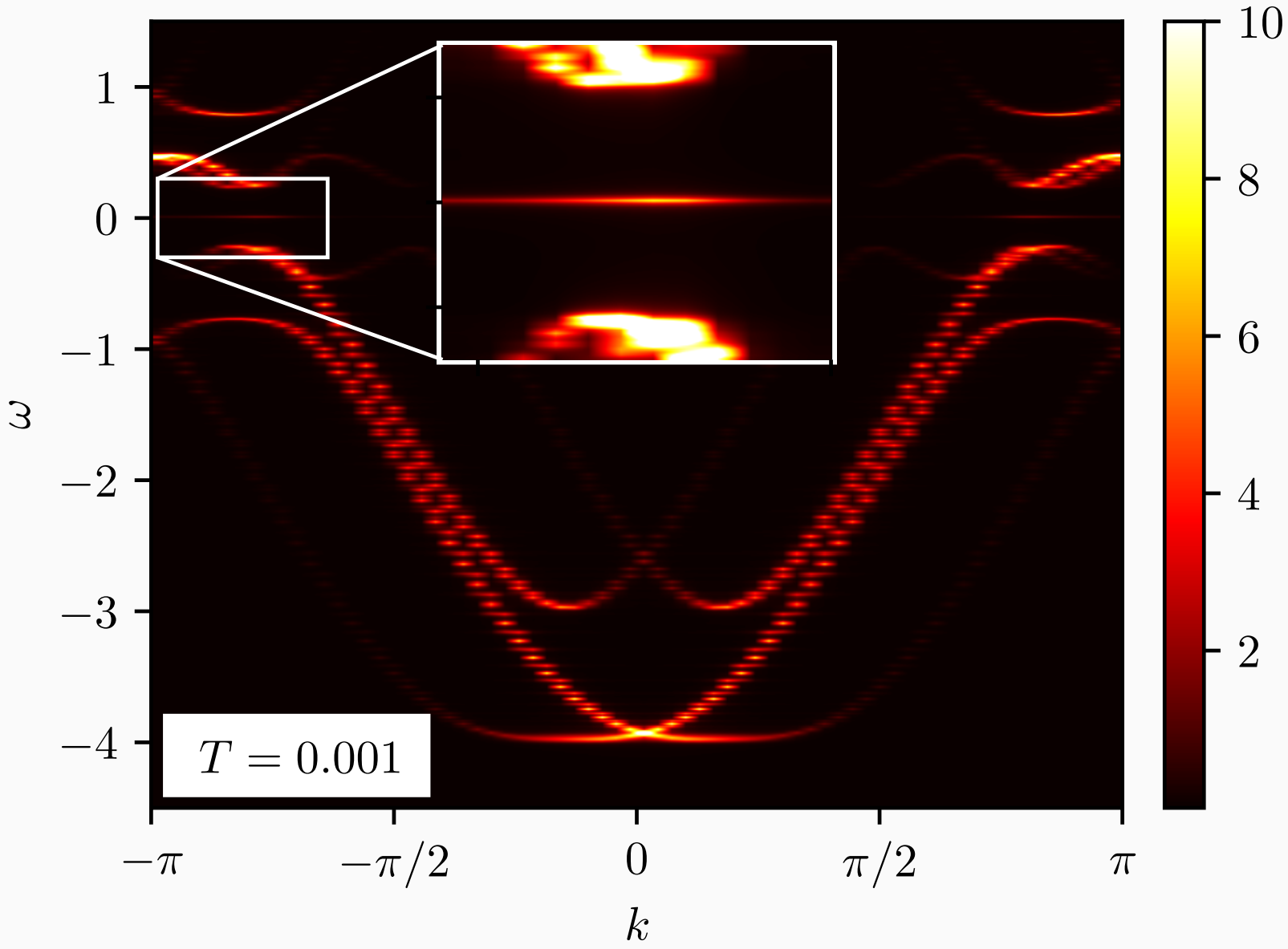
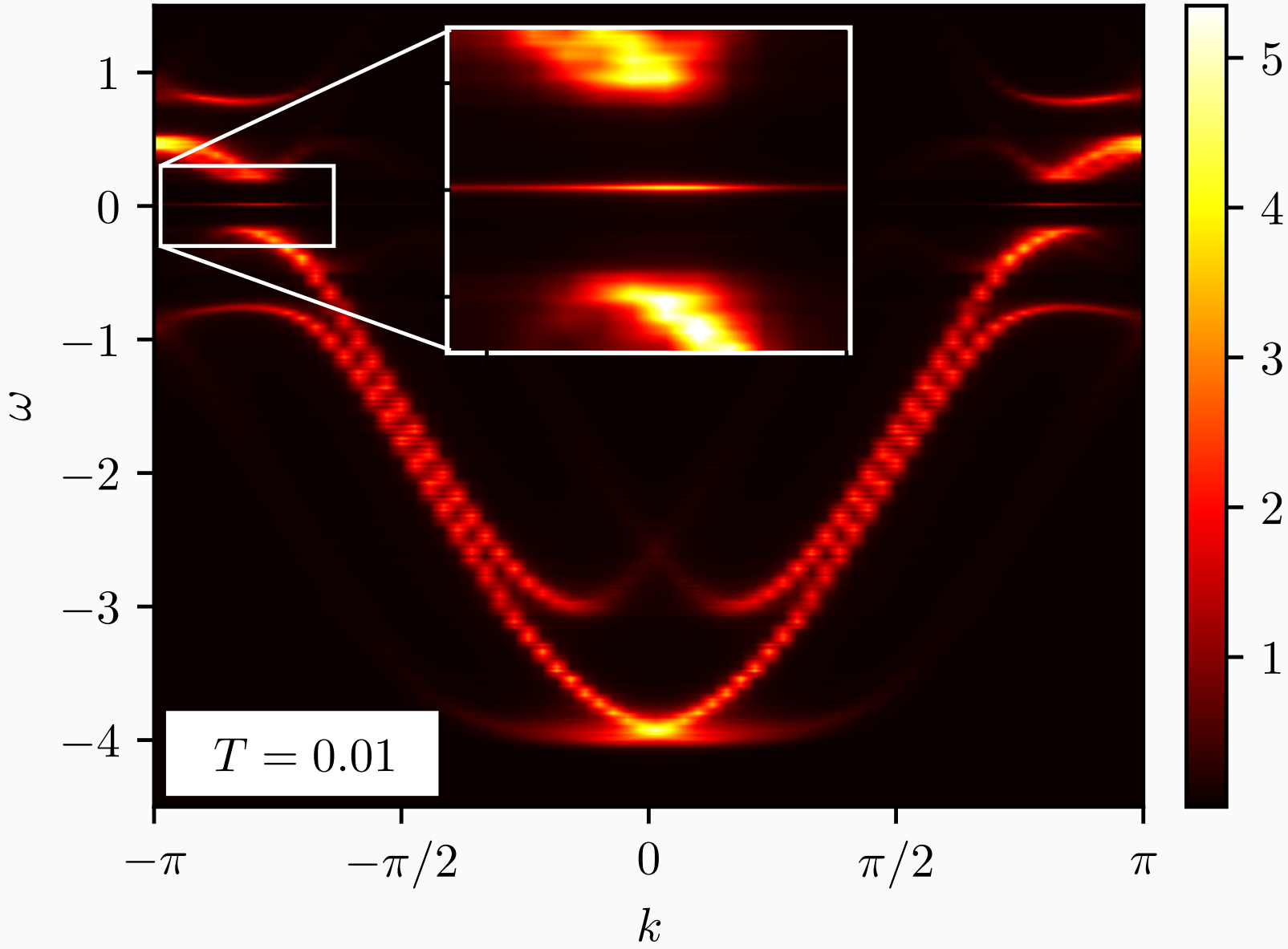


TEMPERATURE EFFECT ON MAJORANA QPS



INFLUENCE OF TEMPERATURE ON MAJORANA QPS



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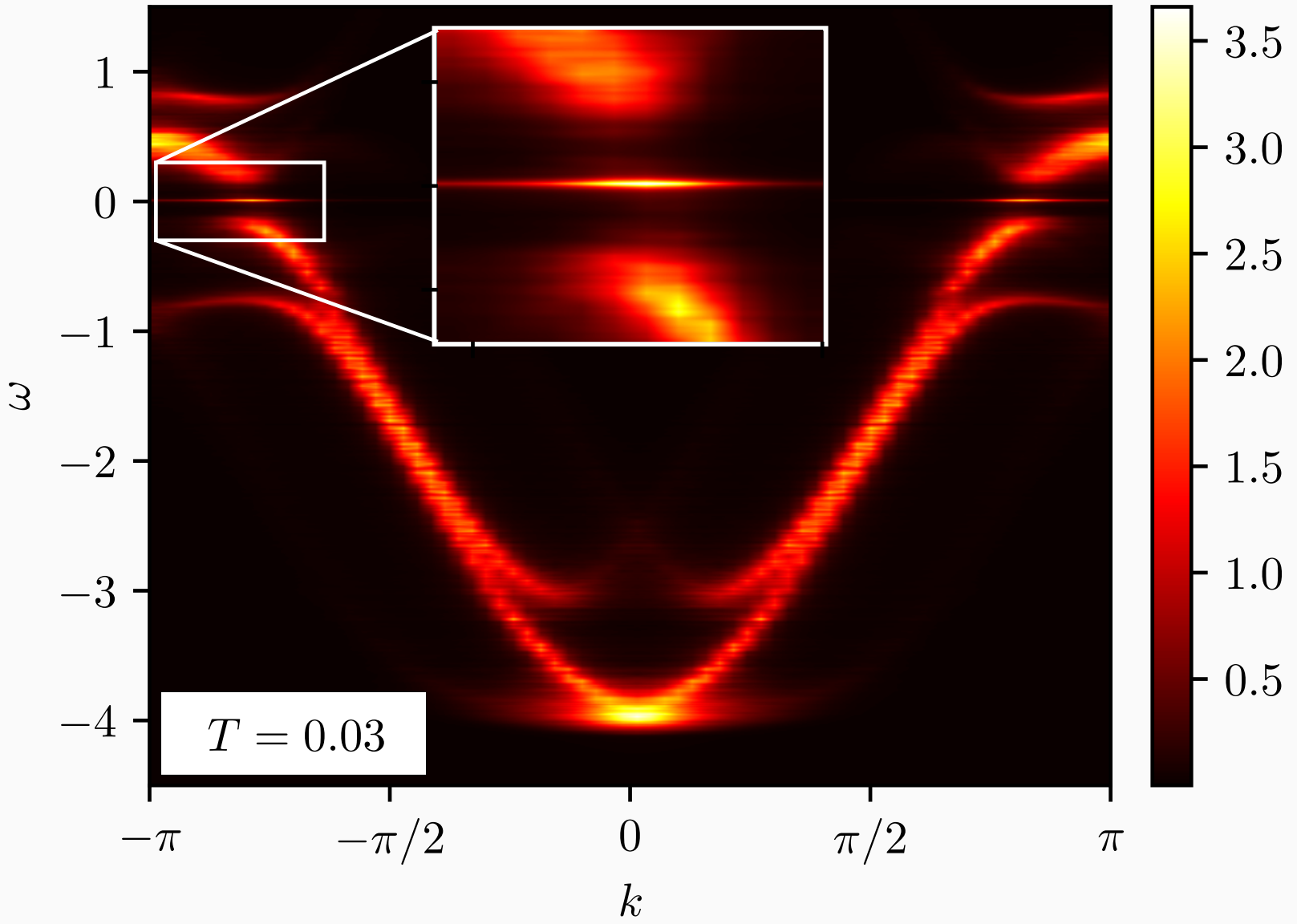

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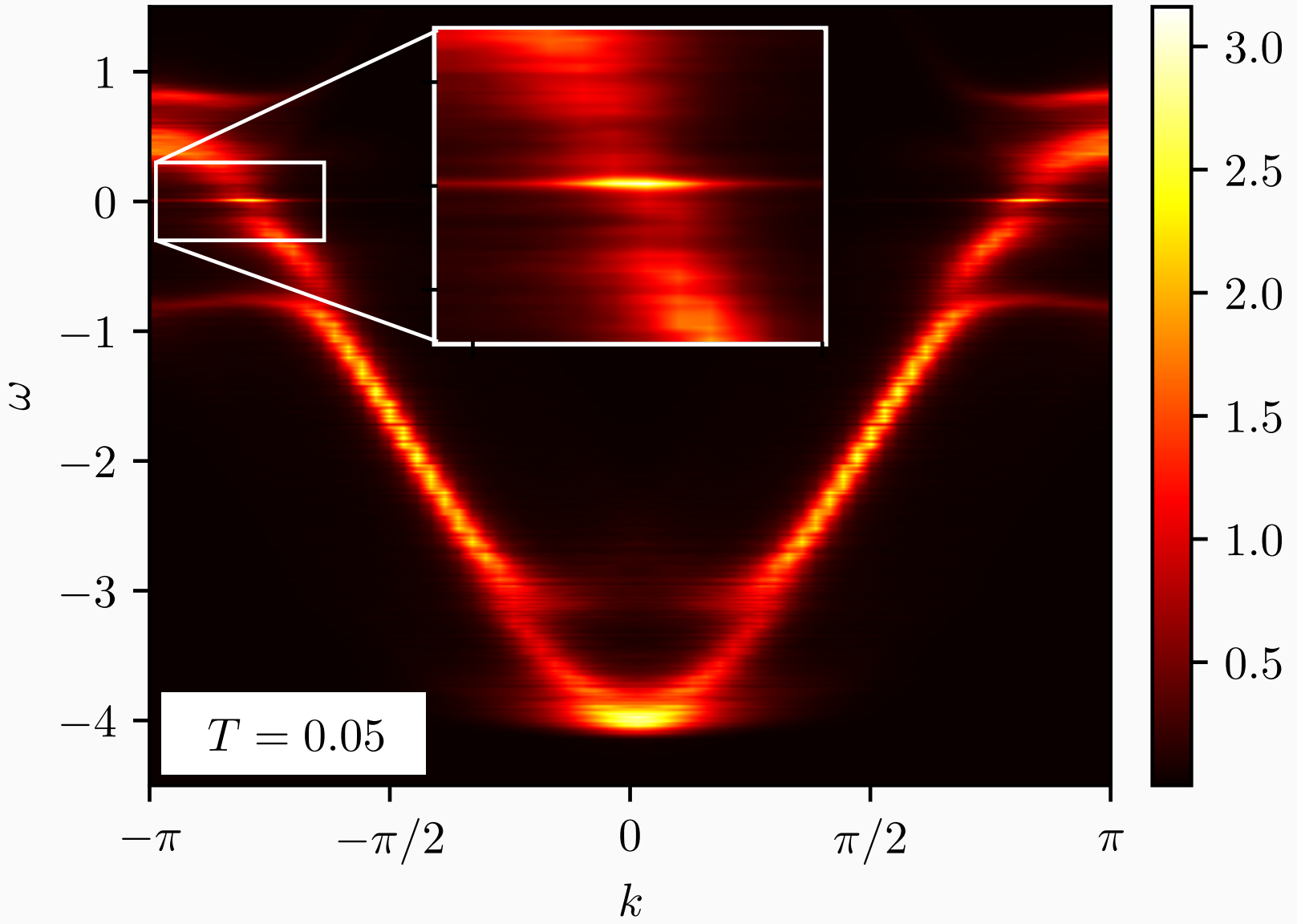

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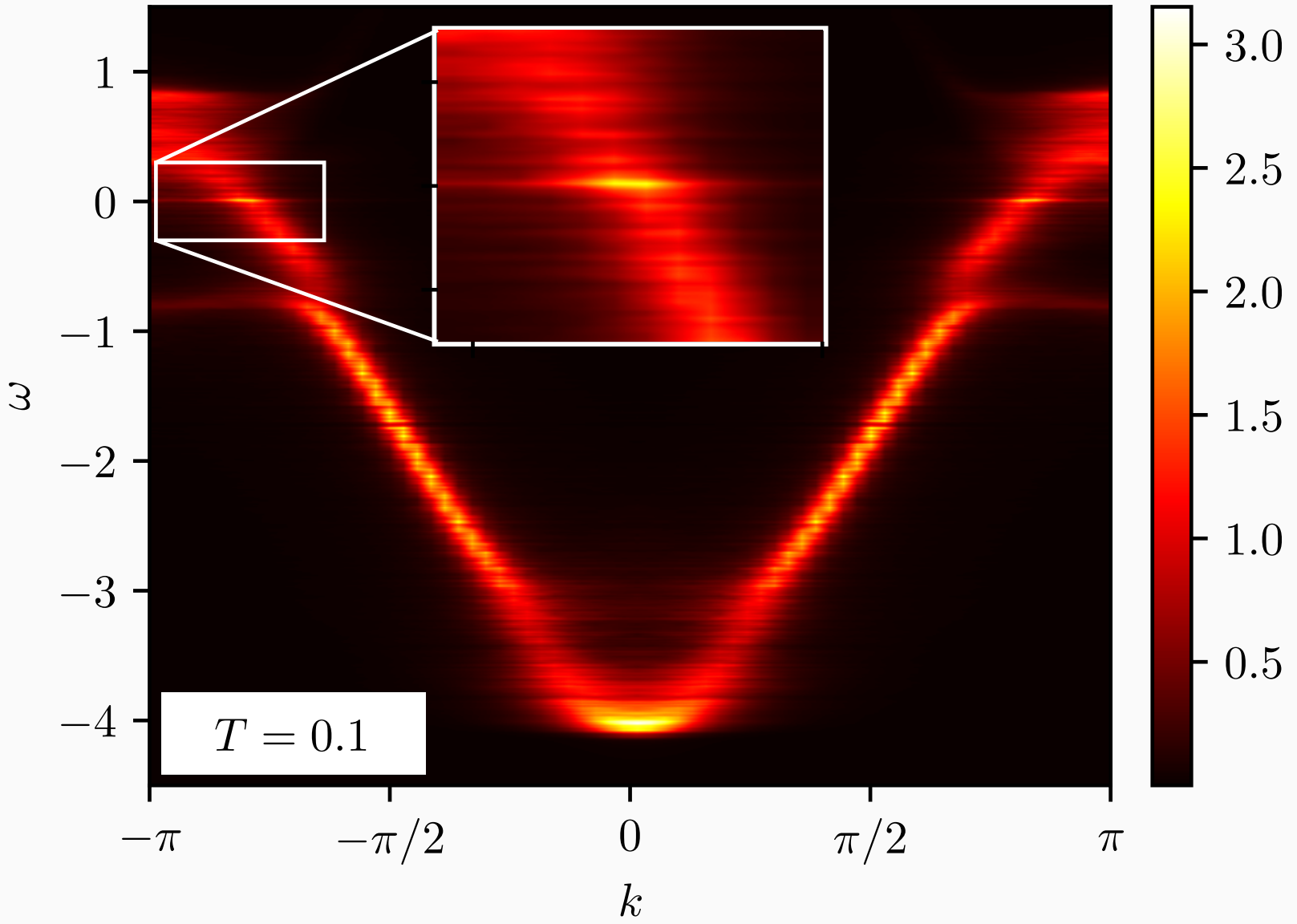

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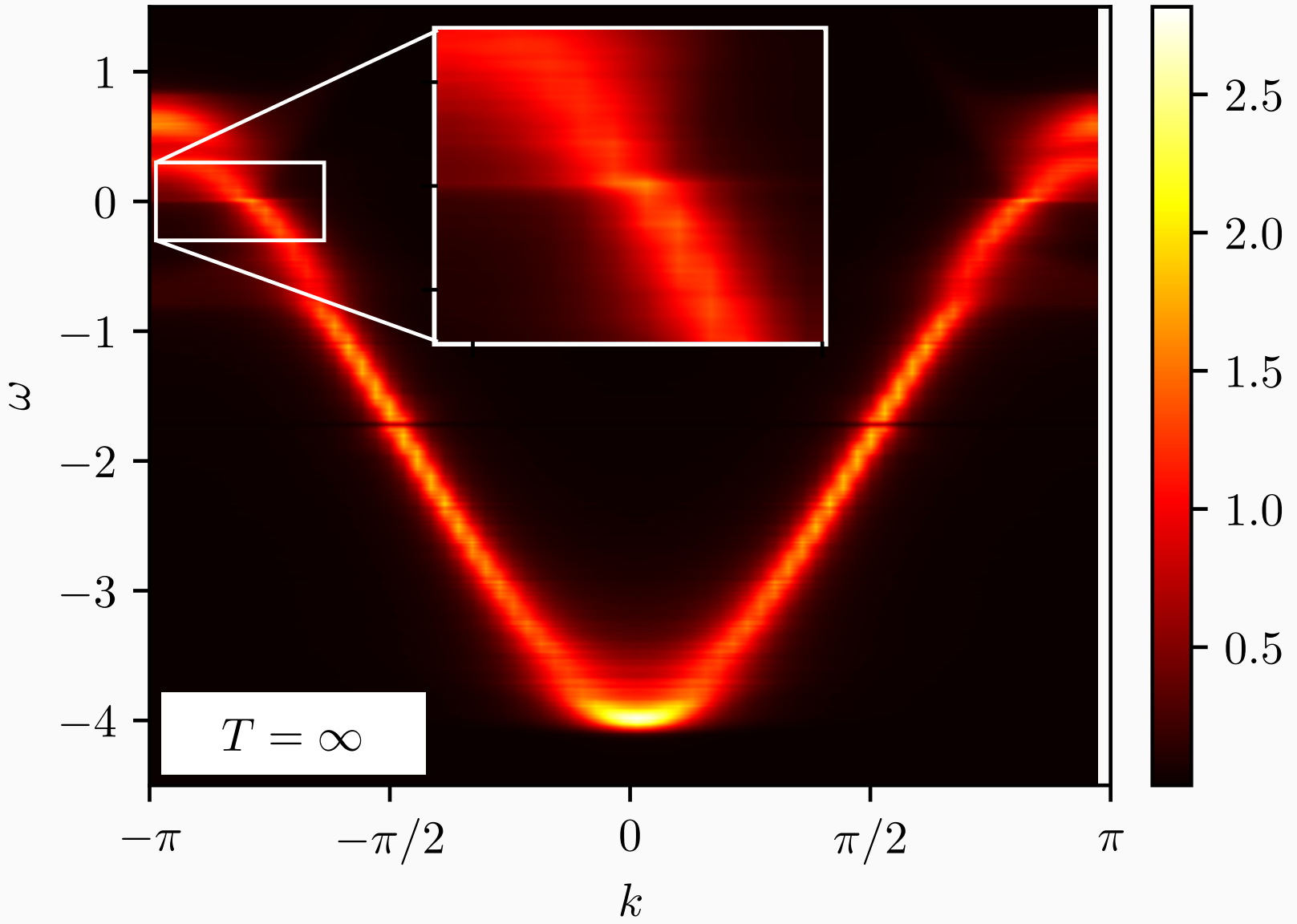

THERMAL EFFECTS: CONCLUSIONS

Thermal effects are responsible for:

$\Rightarrow$ **changeover of topological $\mathbb{Z}_2$ number**

$\Rightarrow$ **scaling of the coherence length $\xi(T) \propto 1/T$**

$\Rightarrow$ **closing of the topological energy gap**

$\Rightarrow$ **overdamping of the Majorana qps**

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$\Longrightarrow$ **overdamping of the Majorana qps**

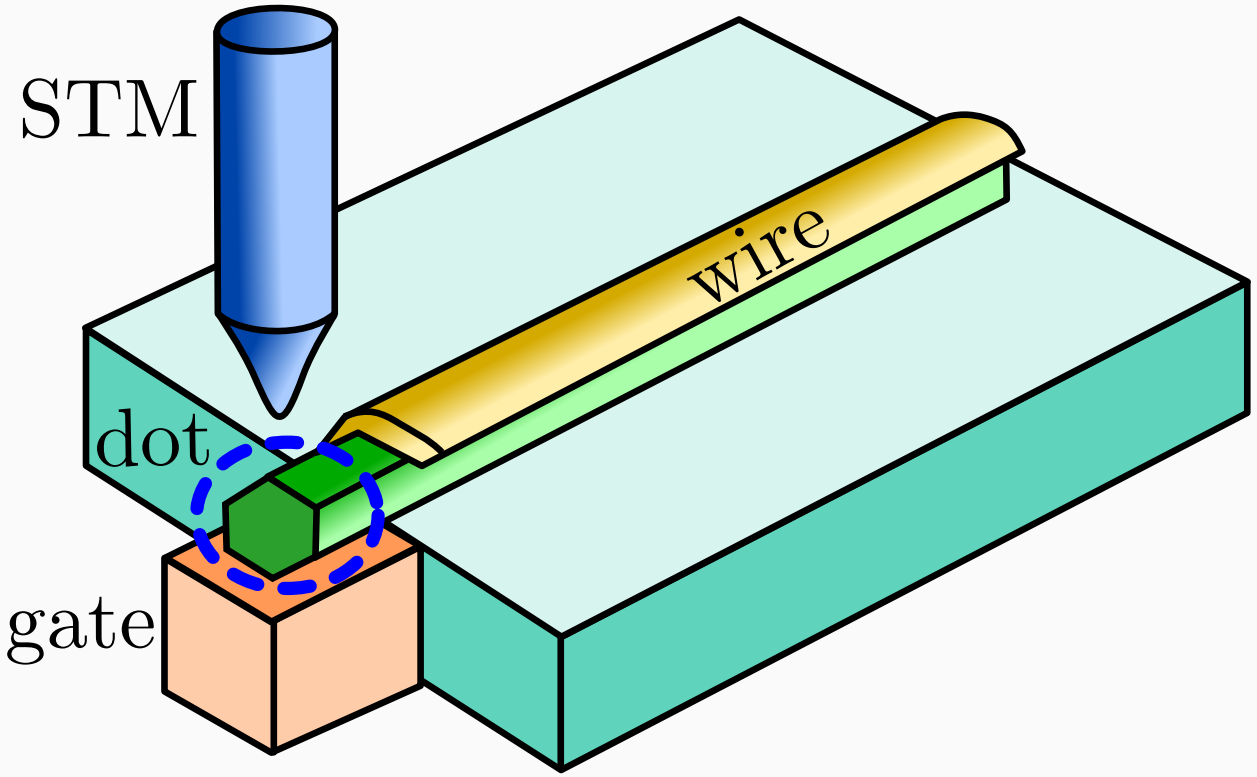
Realistically such critical temperature would be:

$\Longrightarrow$ $T_c \approx$ **5 K**

Ongoing projects & challengies

1. MAJORANA STATES LEAKING TO QUANTUM DOT

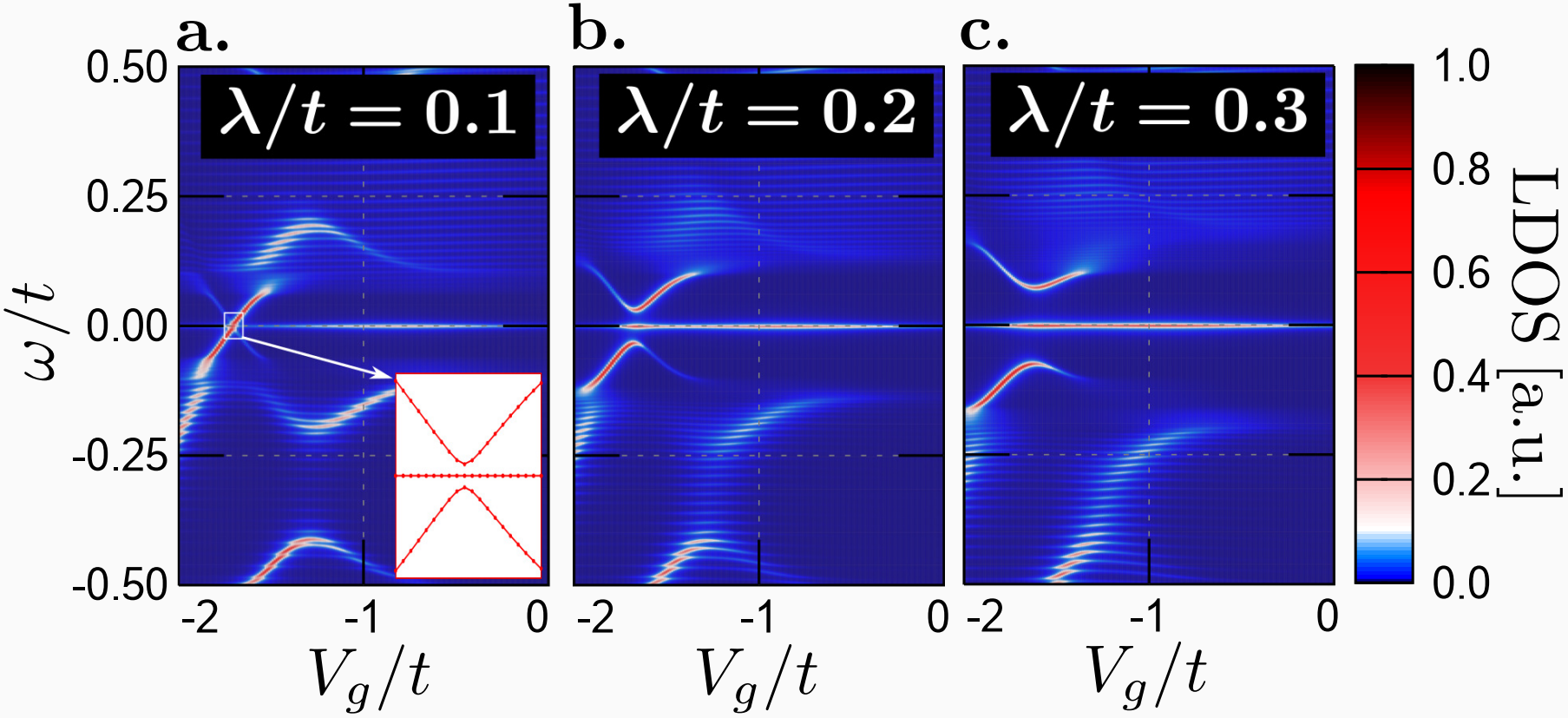
Schematics of a quantum dot – nanowire hybrid structure.



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

1. DISTINGUISHING MAJORANA QPS

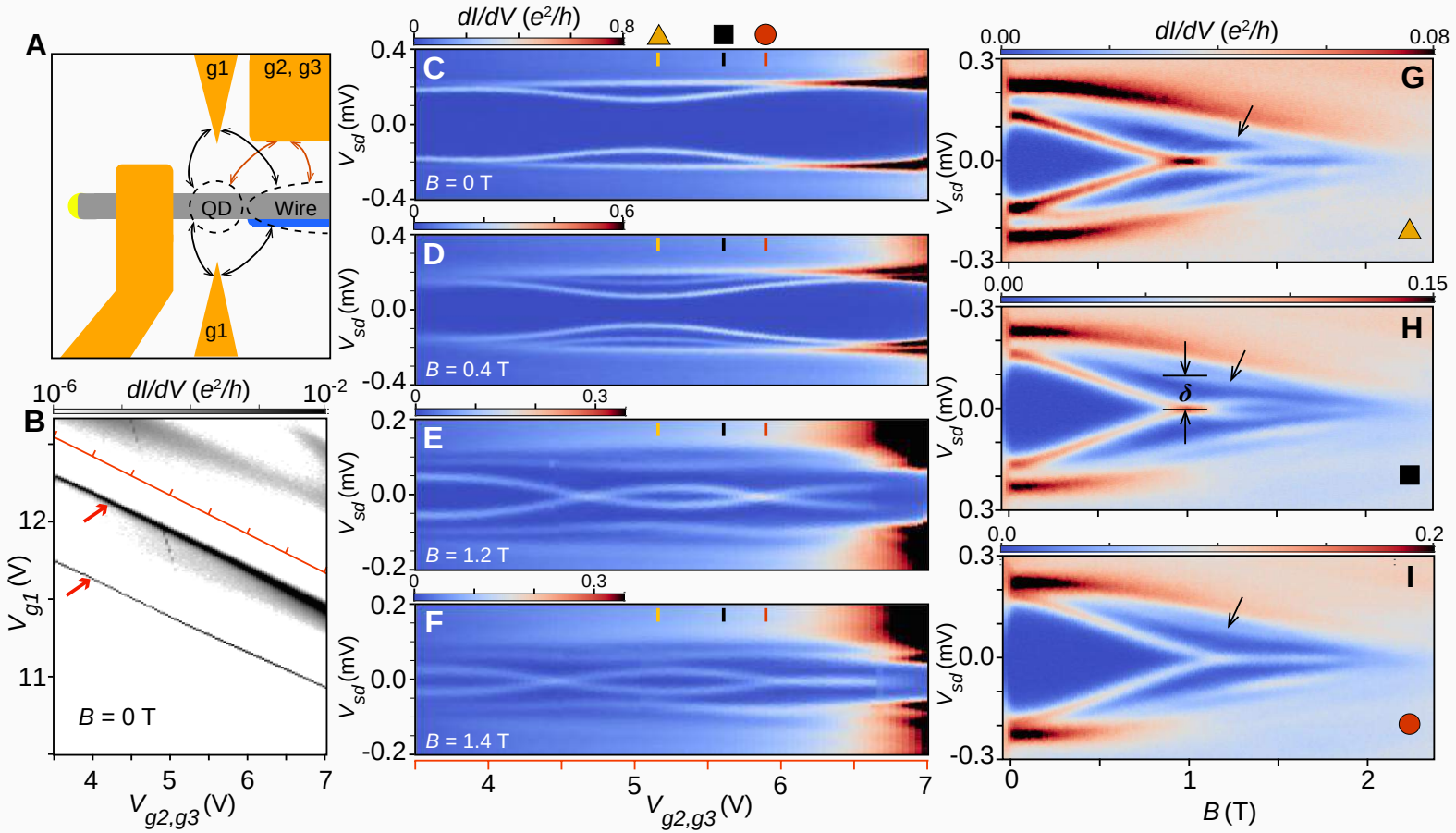
QD spectrum vs gate potential V_g for various spin-orbit couplings λ.



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

1. EXPERIMENTAL EVIDENCE

‘Coalescence’ of the Andreev into Majorana qps

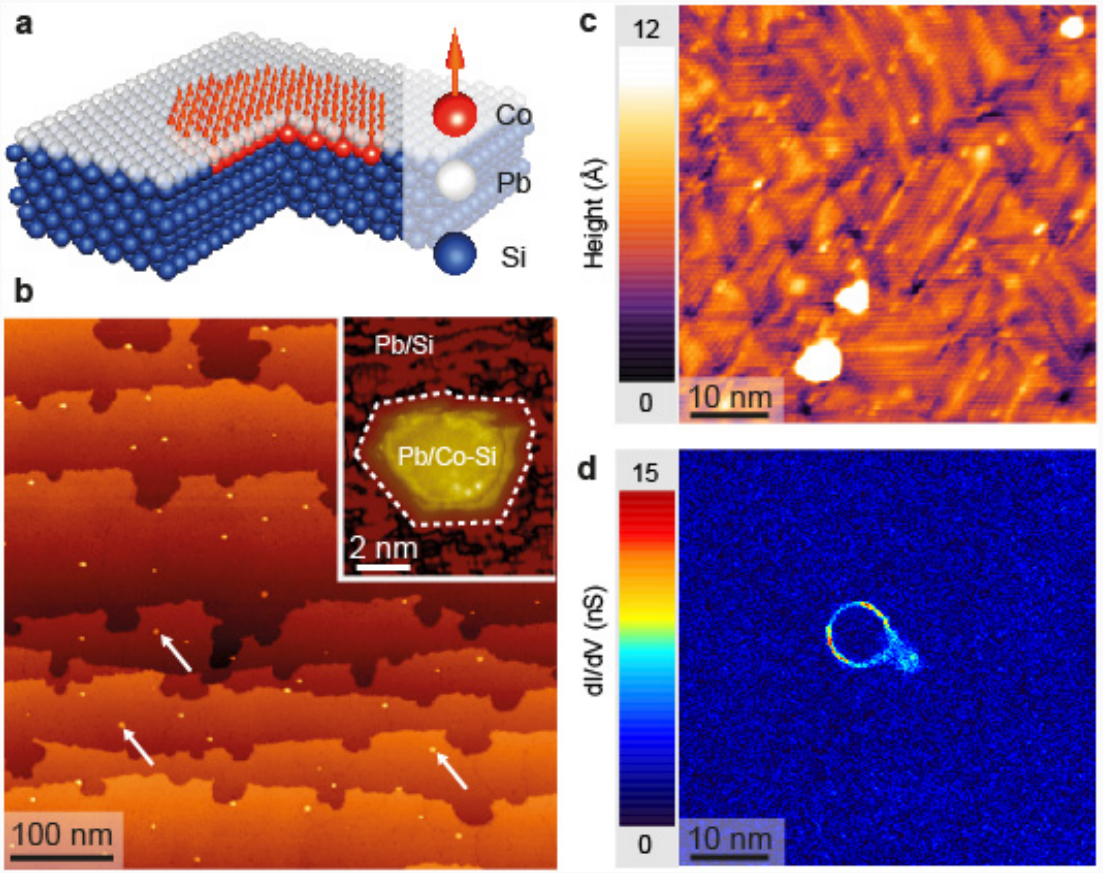


M.T. Deng, ..., and Ch. Marcus, Science 354, 1557 (2016).

/ Niels Bohr Institute, Copenhagen, Denmark /

2. TWO-DIMENSIONAL MAGNETIC STRUCTURES

Magnetic island of Co atoms deposited on the superconducting Pb surface



Diameter of island:

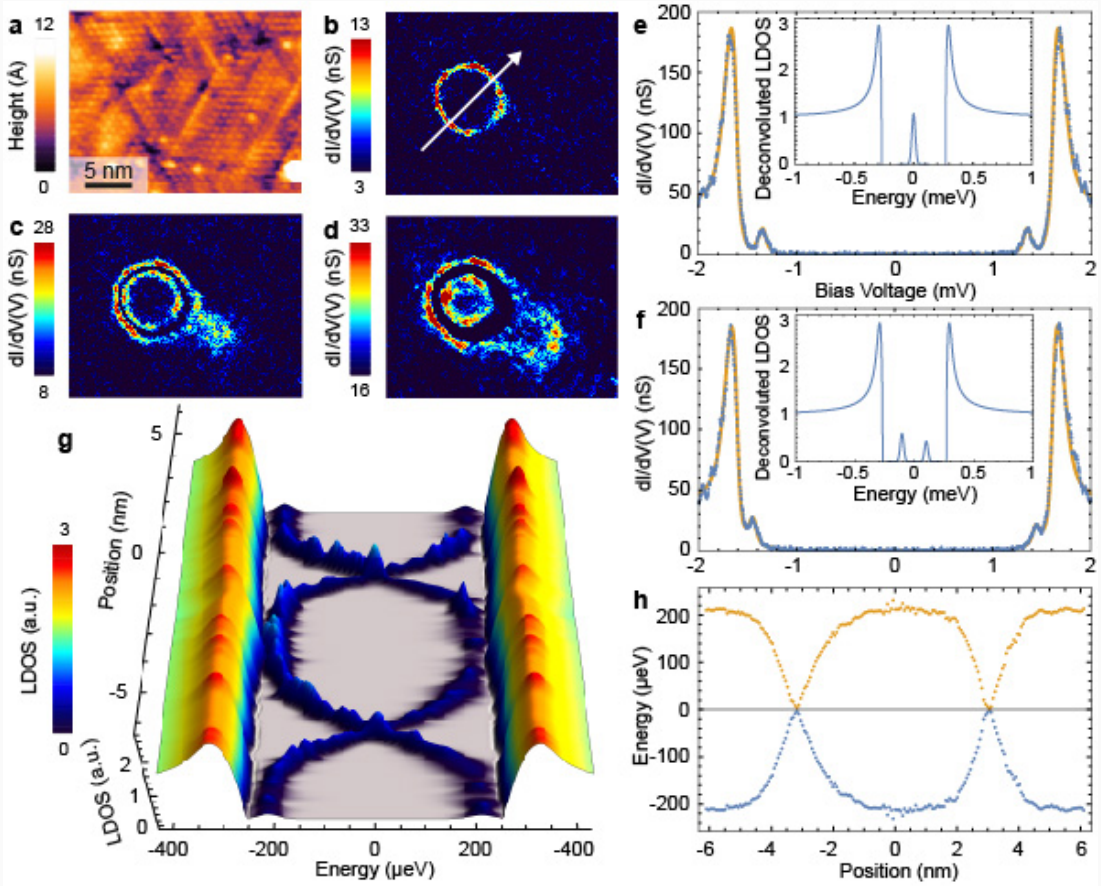
5 – 10 nm

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

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

2. EVIDENCE FOR DELOCALIZED MAJORANA MODES

Majorana modes propagating along magnetic islands

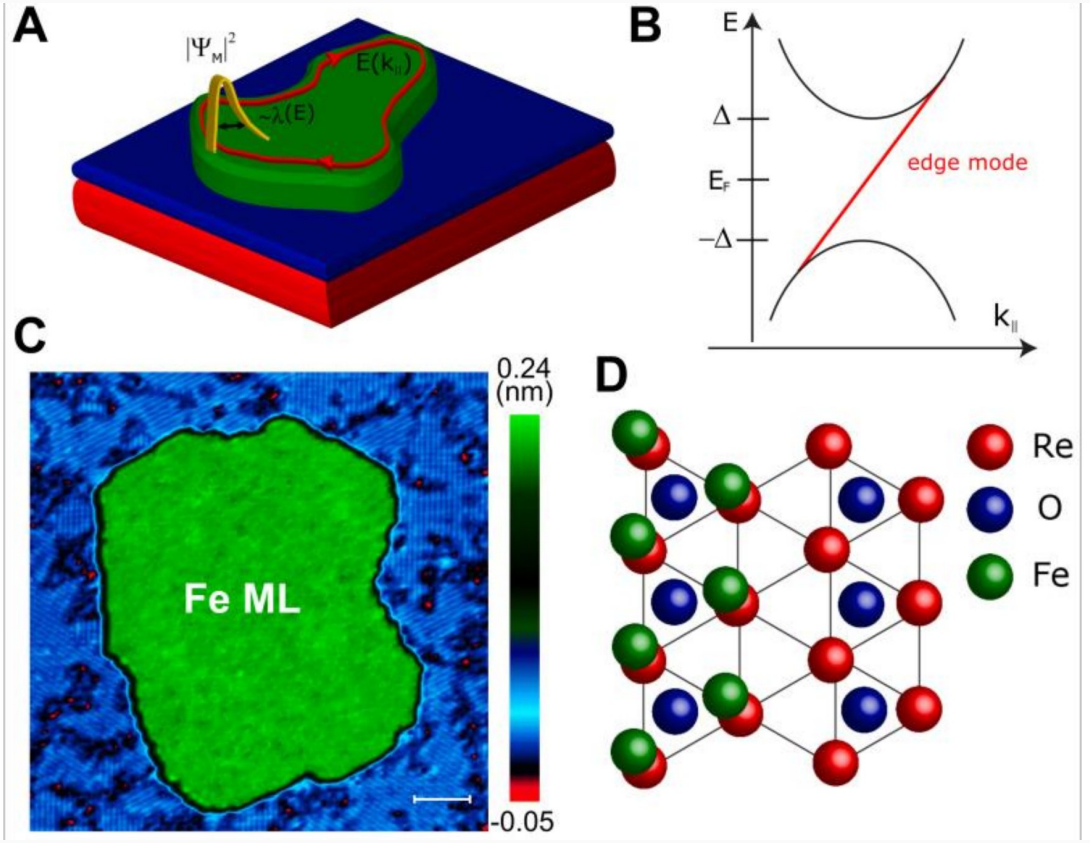


G. Ménard, ..., and P. Simon, Nature Commun. **8**, 2040 (2017).

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

2. PROPAGATING MAJORANA EDGE MODES

Magnetic island of Fe atoms deposited on the superconducting Re surface



Chern number:

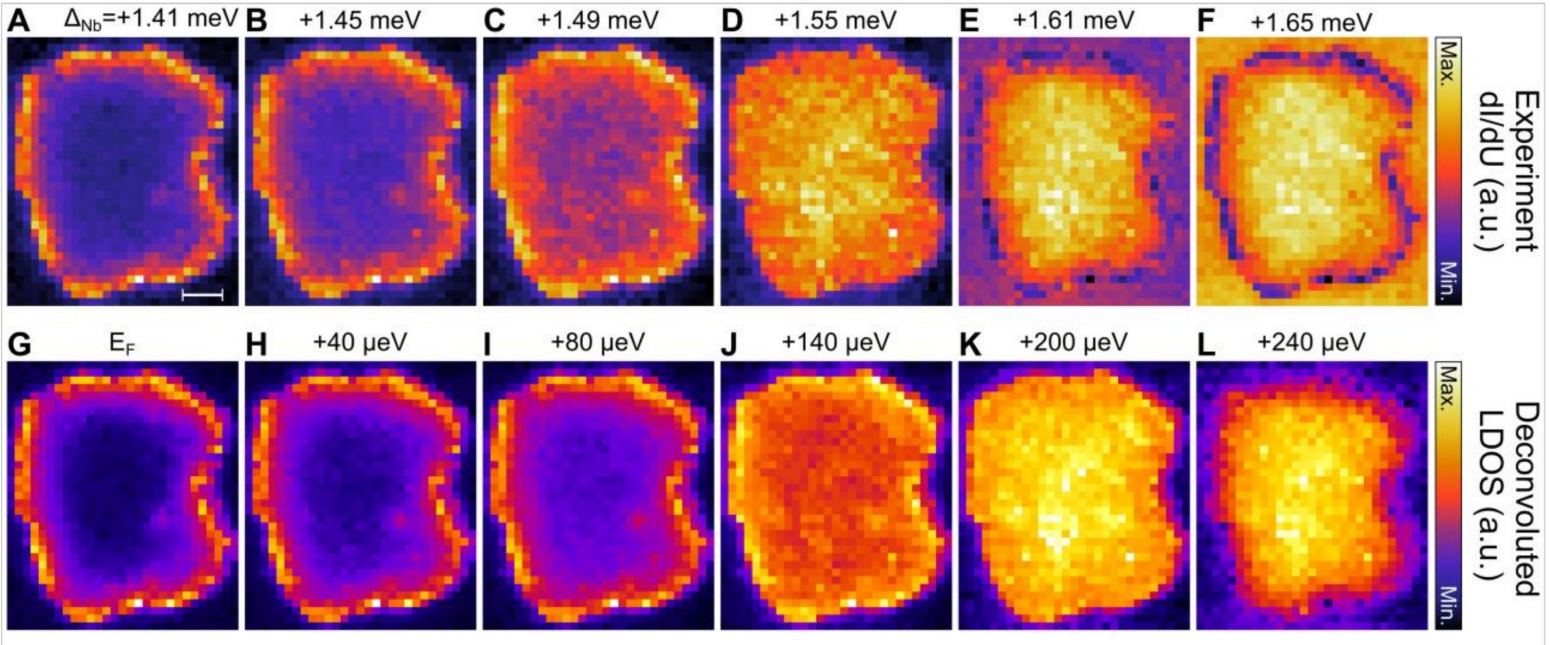
C = 20

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

/ University of Hamburg (Germany) /

2. 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 ($\Delta = 240 \mu eV$).

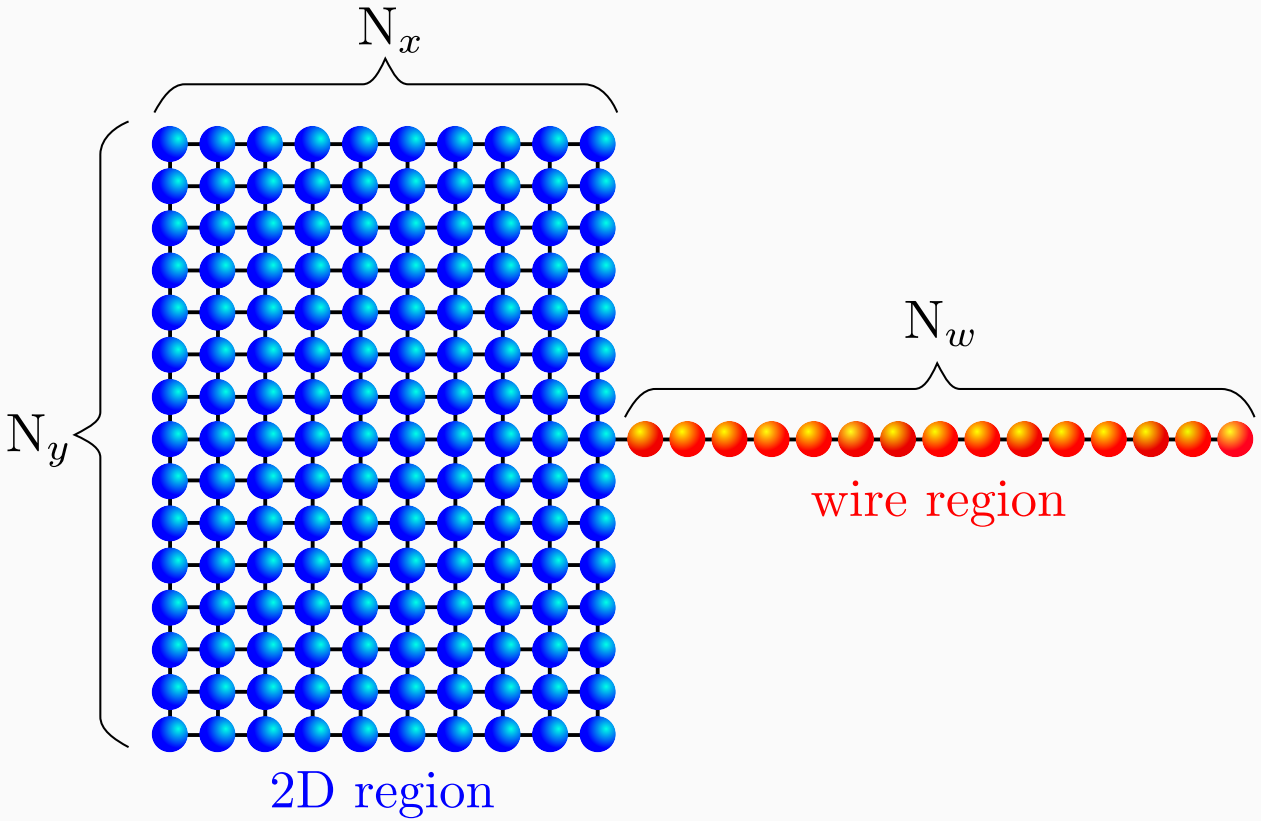


A. Palacio-Morales, ..., and R. Wiesendanger, arXiv:1809.04503 (preprint).

/ University of Hamburg (Germany) /

3. MIXED-DIMENSIONALITY STRUCTURES

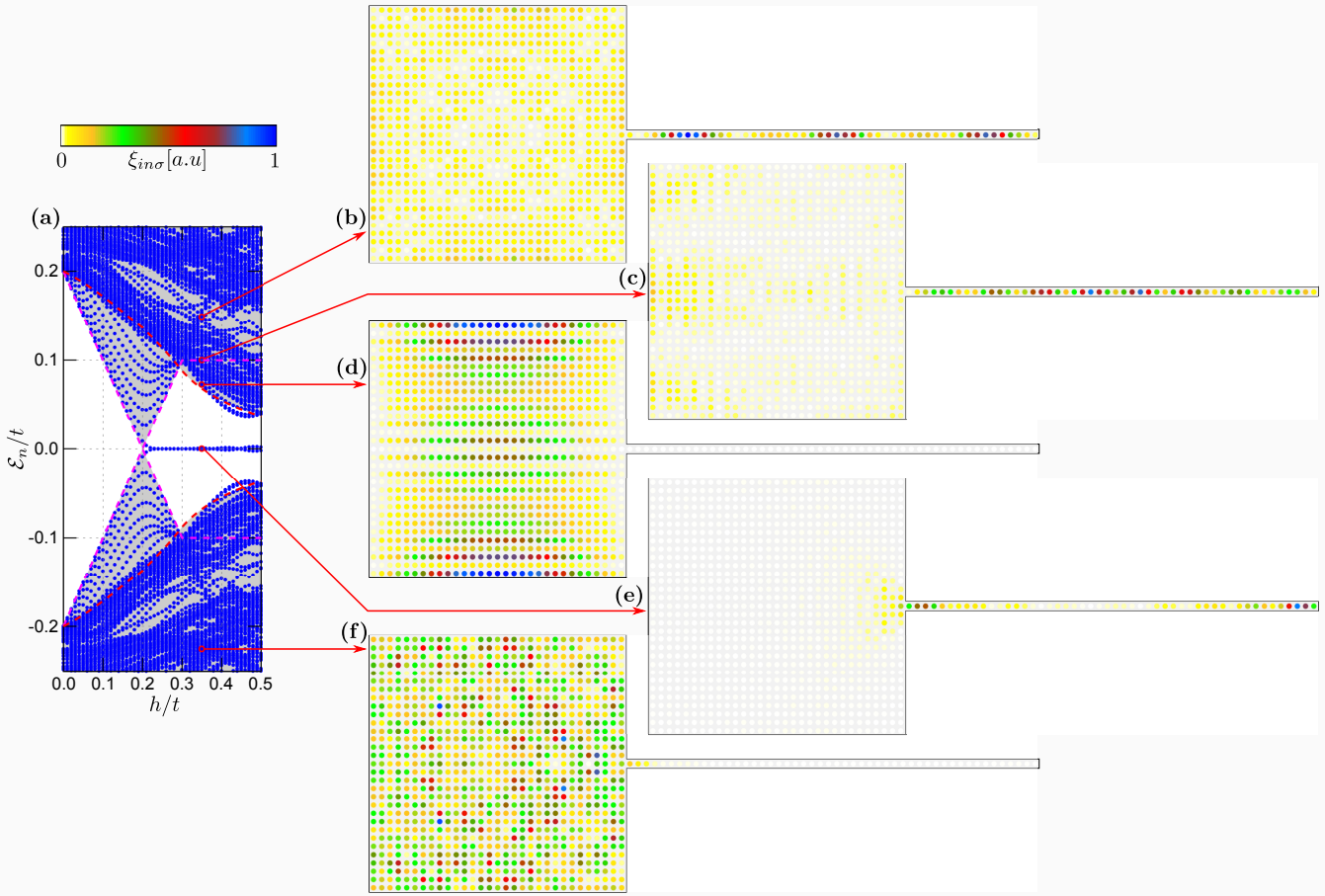
Our project: **Majorana qps of the 1D–2D hybrid structure**



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

3. 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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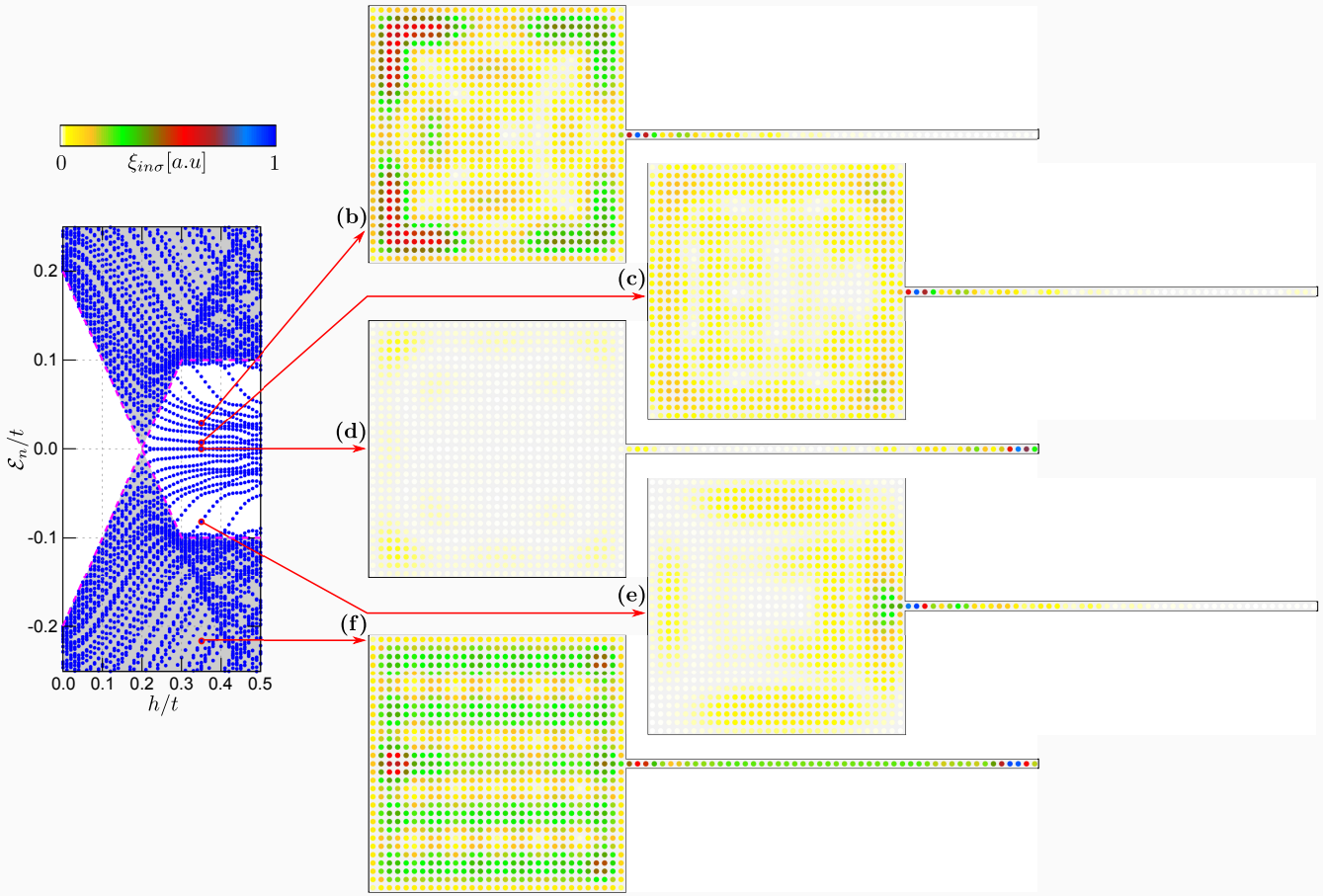
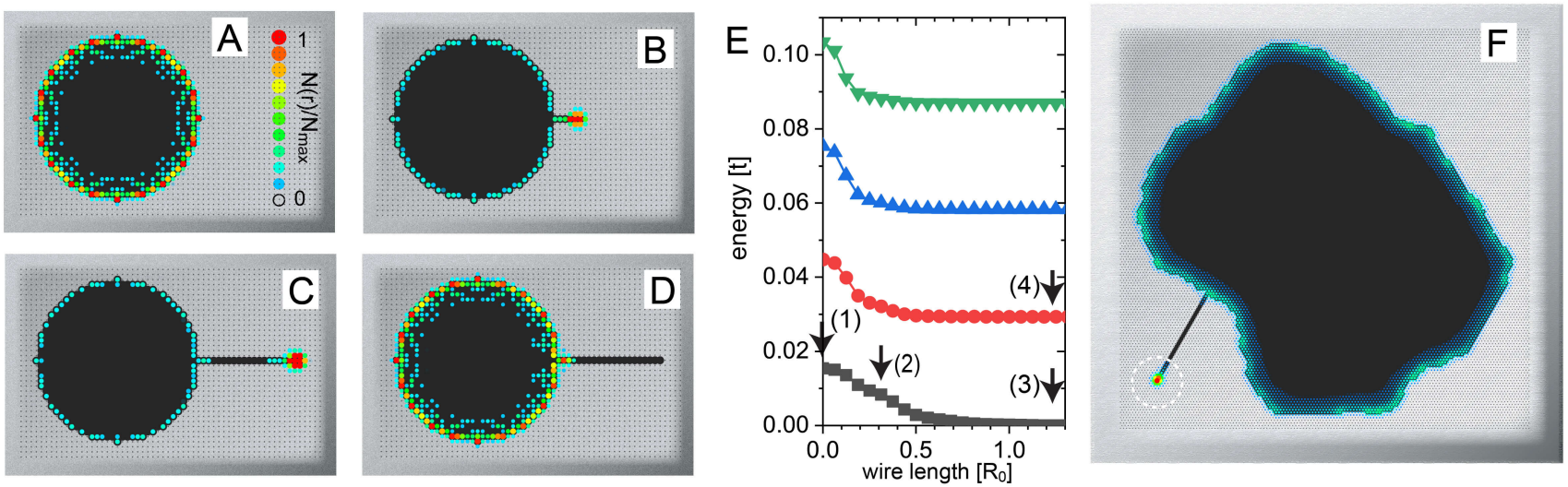


Both regions are assumed to be in topological sc phase.

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

3. ISLAND + NONOWIRE

Itinerant Majorana mode leaking into side-attached nanowire.

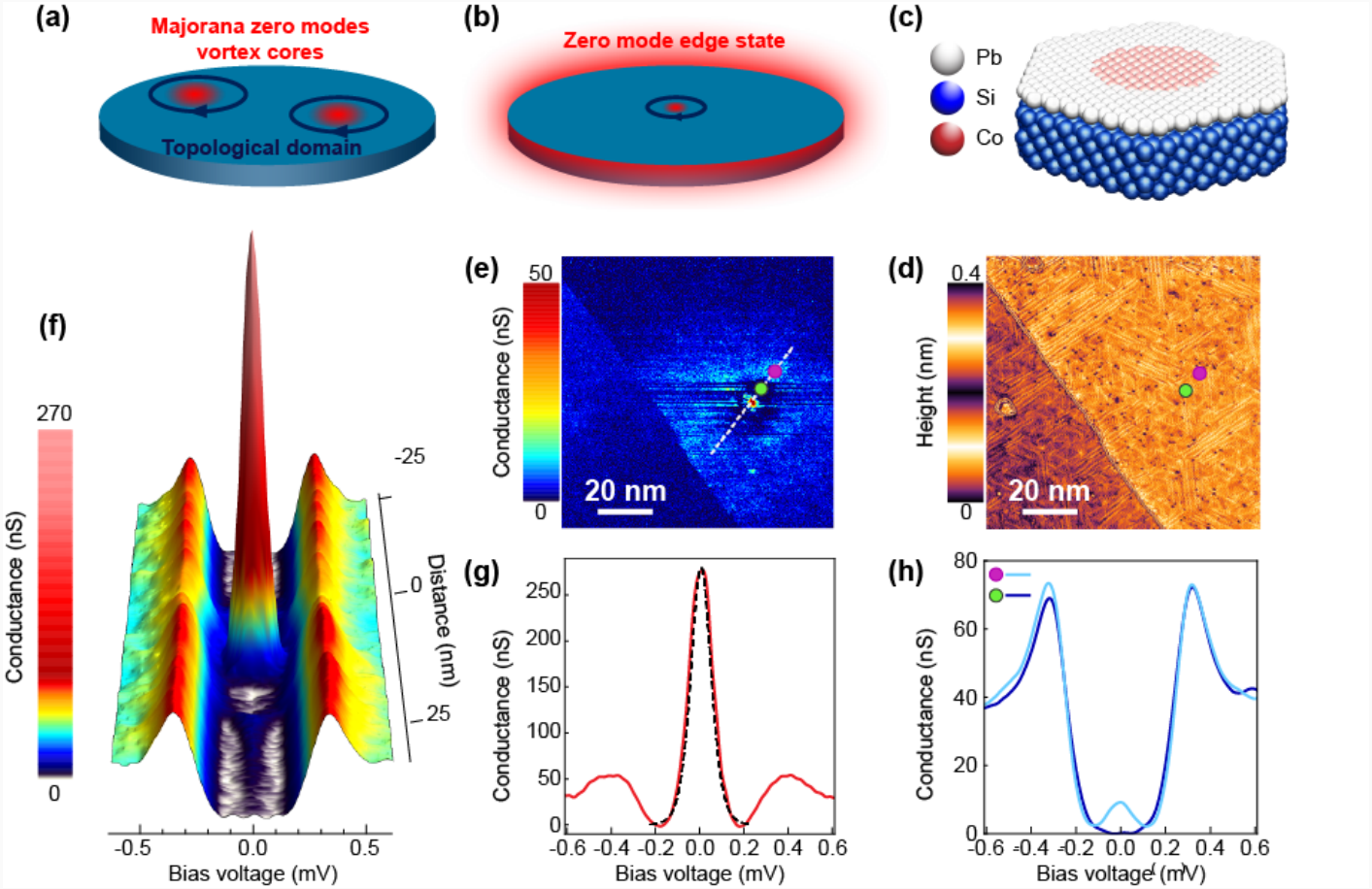


E. Mascot, S. Cocklin, S. Rachel, and D.K. Morr, arXiv:1811.06664

Univ. of Illinois at Chicago (USA)

3. 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)

PERSPECTIVES

- **novel devices** — Majorana spintronics
  - ⇒ **e.g. fractional SQUID**
- **stable quantum bits** — immune to decoherence
- **quantum computing** — non-Abelian braiding
- **Q-stations:** — IBM initiative
  - ⇒ **USA (California & Washington)**
  - ⇒ **Netherland (Delft)**
  - ⇒ **Denmark (Kopenhaga)**
  - ⇒ **Australia (Sydney)**

ACKNOWLEDGEMENTS

- **Majorana quasiparticles**

⇒ **M. Maśka & A. Gorczyca-Goraj (Katowice),**

⇒ **A. Kobiałka (Lublin),**

⇒ **A. Ptok (Kraków),**

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⇒ **Sz. Głodzik (Lublin),**

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