Warszawa, 5 Jan 2018

Majorana quasiparticles: concepts & challenges

Tadeusz Domański (UMCS, Lublin)

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In collaboration with:

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

A. Ptok (IFJ, Kraków)

S. Głodzik & **A. Kobiałka** (UMCS, Lublin)

Outline:

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- **Majorana (quasi)particle** . . . . **/ what is it ? /**

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- **Topological superconductivity:**

$\Rightarrow$ **end/edge quasiparticles** . . . . **/ experimental evidence /**

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- Superconductivity in nanostructures:

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- Topological superconductivity:

⇒ end/edge quasiparticles .... / experimental evidence /

- Major challenges:

⇒ novel materials, nonlocality, realization of quantum computing, ...

1. Majorana fermions: basic notions

Majorana fermions

Majorana fermions

- **P. Dirac (1928)**

$$i\dot{\psi} = (\vec{\alpha}\cdot\vec{p} + \beta m)\,\psi$$

/ relativistic description of fermions /

particles ($E > 0$), anti-particles ($E < 0$)

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Physical implication: particle = antiparticle or creation = annihilation

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- **Does it exist anywhere ?**

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Probably it doesn't !

Hunting for majorana qps – in solids

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- ⋆ So, how about **Majorana quasiparticles** ?

- ⋆ Formaly, any usual fermion can be **majoranized** ...

Majoranization – of ordinary fermions

- Normal fermions (e.g. electrons) obey the anticommutation relations

$$\left\{\hat{c}_i, \hat{c}_j^\dagger\right\} = \delta_{i,j}$$
$$\{\hat{c}_i, \hat{c}_j\} = 0 = \left\{\hat{c}_i^\dagger, \hat{c}_j^\dagger\right\}$$

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- $c_j^{(\dagger)}$ can be recast in terms of Majorana operators

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

'real' and 'imaginary' parts

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- Exotic properties

$$\hat{\gamma}_{i,n}^\dagger = \hat{\gamma}_{i,n}$$
$$\left\{\hat{\gamma}_{i,n}, \hat{\gamma}_{j,m}^\dagger\right\} = \delta_{i,j}\delta_{n,m}$$

creation = annihilation !

fermionic antisymmetry

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- Exotic properties (cd)

$$\hat{\gamma}_{i,n}\,\hat{\gamma}_{i,n} = 1/2$$
$$\hat{\gamma}_{i,n}^\dagger\,\hat{\gamma}_{i,n} = 1/2$$

no Pauli principle !

half ‘occupied’ & half ‘empty’

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$\Rightarrow$ half-empty & half-filled entities

- topologically protected

$\Rightarrow$ immune to decoherence ... yet be cautious about that !

Various candidates – for Majorana quasiparticles

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  Volovik (1999)

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- **magnetic atoms chain on superconducting substrate**

  Choy *et al* (2011); Martin & Morpugo (2012); Nadj-Perge *et al* (2013)

2. Experimental evidence

Experimental evidence – for Majorana quasiparticles

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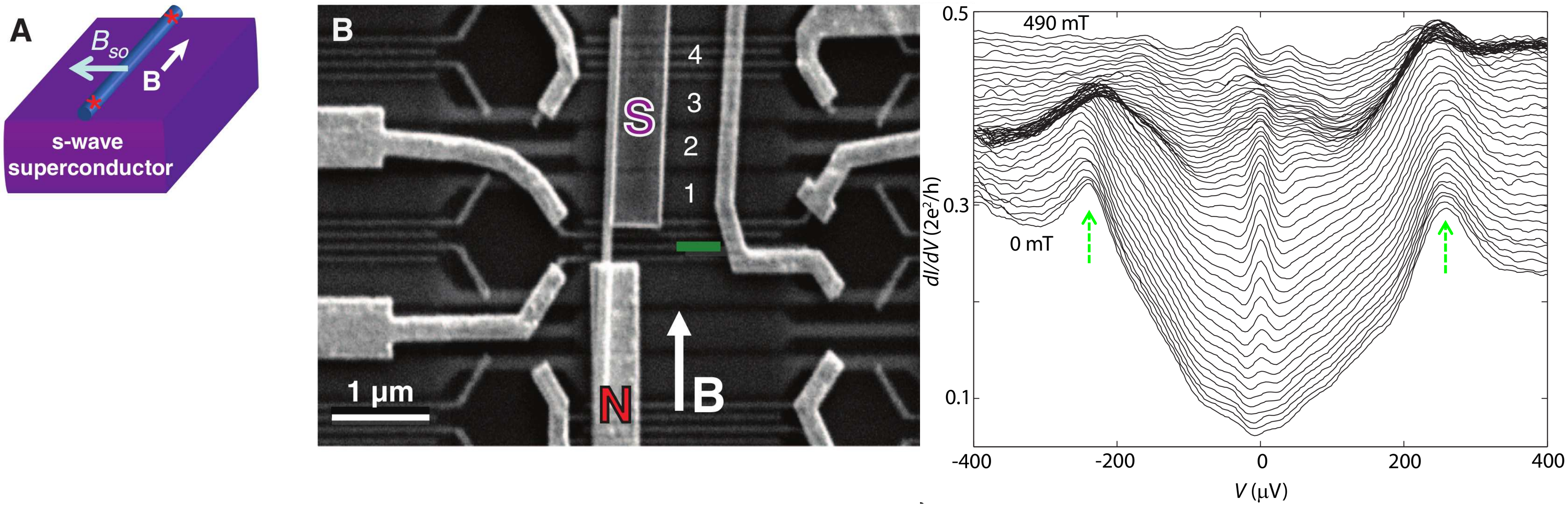
InSb nanowire between a metal (gold) and a superconductor (Nb-Ti-N)



dI/dV measured at 70 mK for varying magnetic field B indicated:

$\Rightarrow$ **a zero-bias enhancement due to Majorana state**

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

/ Kavli Institute of Nanoscience, Delft Univ., Netherlands /

 – for Majorana quasiparticles

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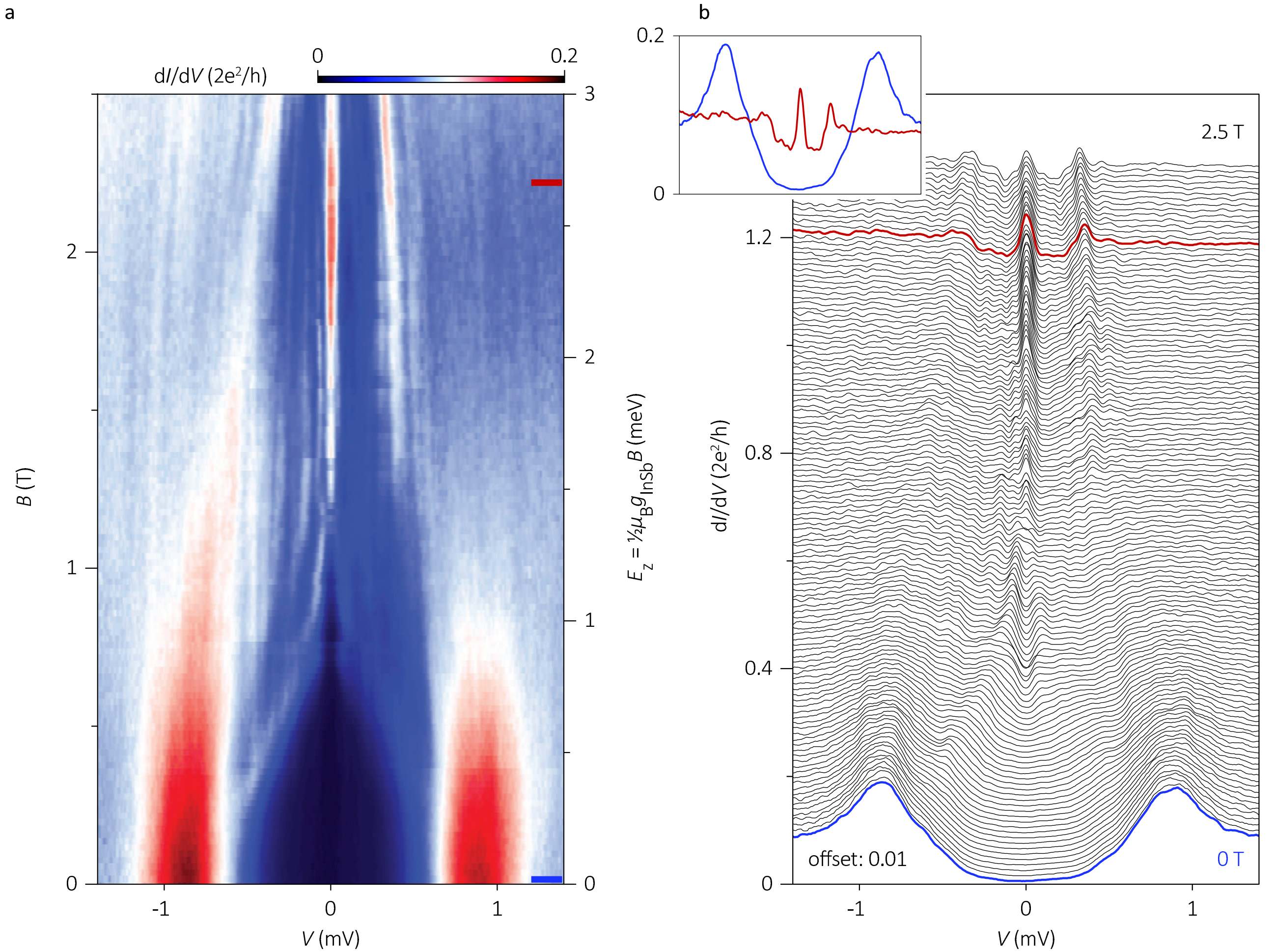
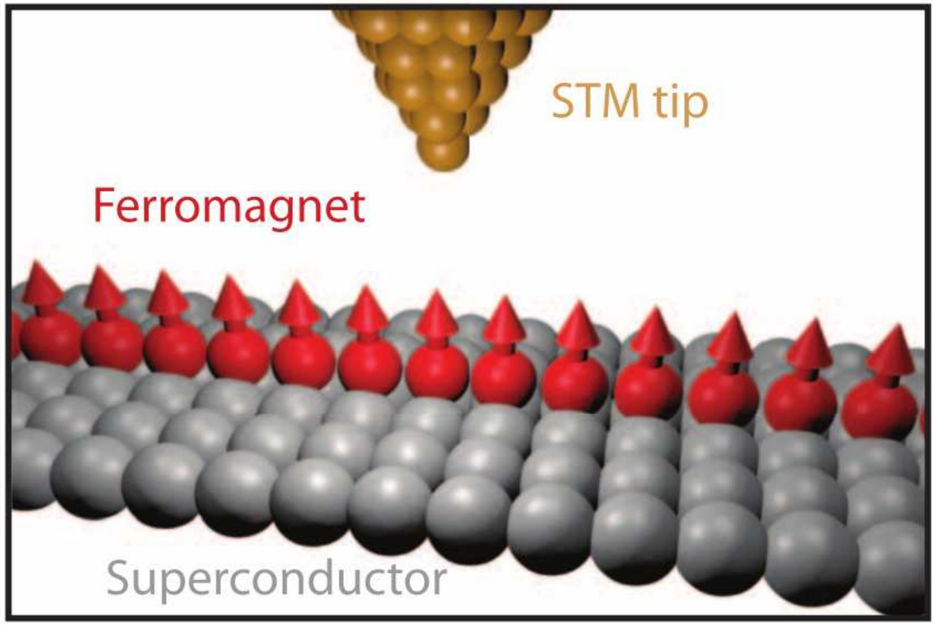


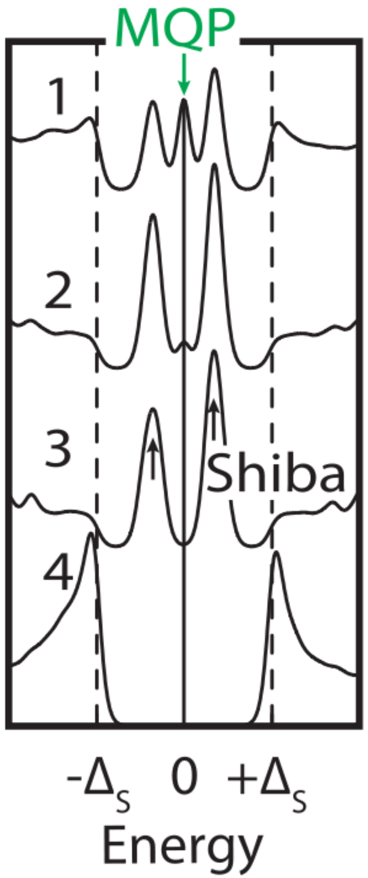
H. Zhang, ..., and L.P. Kouwenhoven, arXiv:1603.04069 (2016).

/ Kavli Institute of Nanoscience, Delft Univ., Netherlands /

Experimental evidence – **for Majorana quasiparticles**

A chain of iron atoms deposited on a surface of superconducting lead





STM measurements provided evidence for:

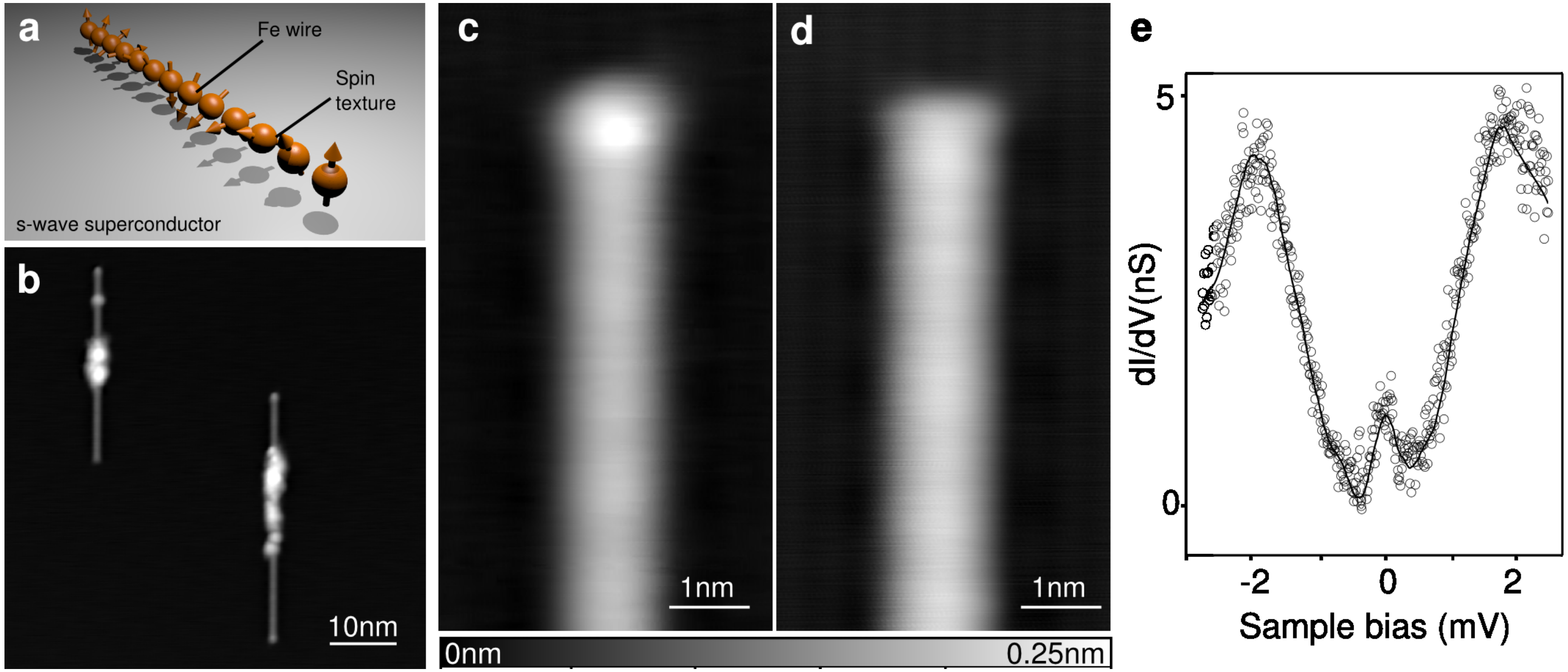
⇒ **Majorana bound states at the edges of a chain.**

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

/ Princeton University, Princeton (NJ), USA /

Experimental evidence – for Majorana quasiparticles

Self-assembled Fe chain on superconducting Pb(110) surface



AFM combined with STM provided evidence for:

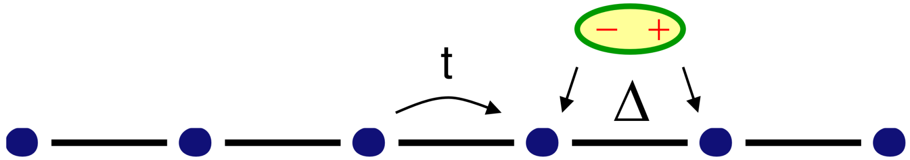
⇒ **Majorana bound states at the edges of a chain.**

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

/ University of Basel, Switzerland /

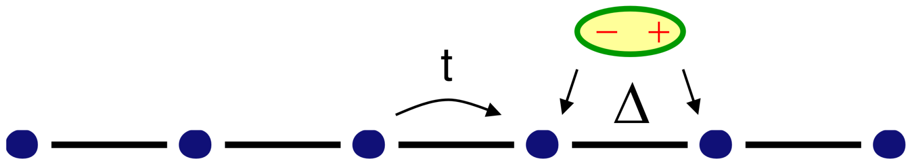
How can we understand this zero-energy state ?

Kitaev chain – a paradigm for Majorana modes



inter-site pairing of equal spin fermions

Kitaev chain – a paradigm for Majorana modes



inter-site pairing of equal spin fermions

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

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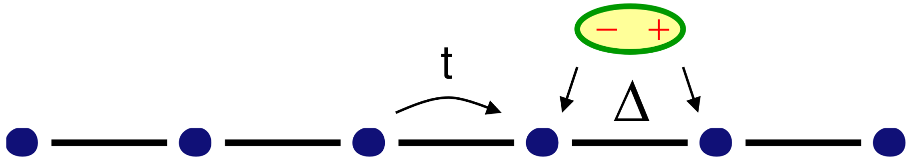

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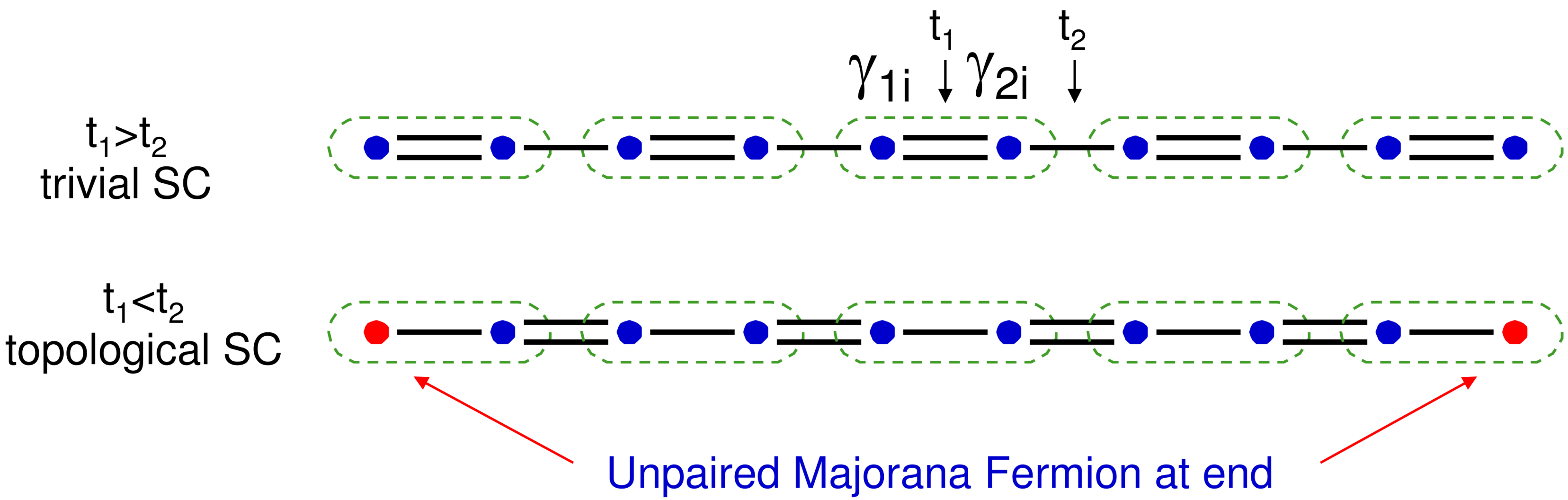
This toy-model can be exactly solved in Majorana basis. For $\Delta = t$ one obtains:



$t_1 \equiv |\mu|$

$t_2 \equiv 2t$

Kitaev toy model

/ Phys. Usp. 44, 131 (2001) /

★ **In the special case $\Delta = t$ and $|\mu| < 2t$**

operators $\hat{\gamma}_{1,1}$ and $\hat{\gamma}_{2,N}$ are decoupled from all the rest. This implies

zero-energy modes appearing at the ends of chain

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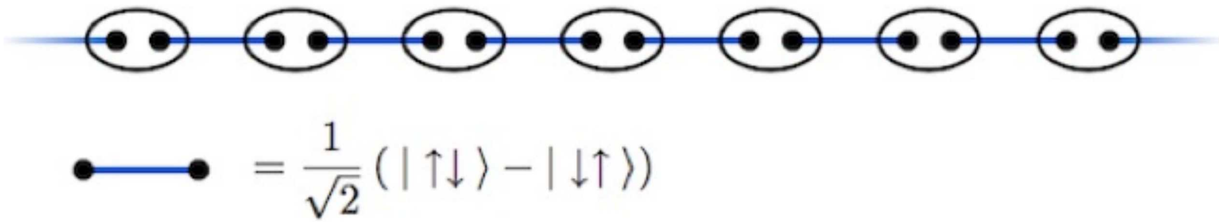
★ **Similar ideas have been considered for 1D Heisenberg chain of 1/2 spins**



$$= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

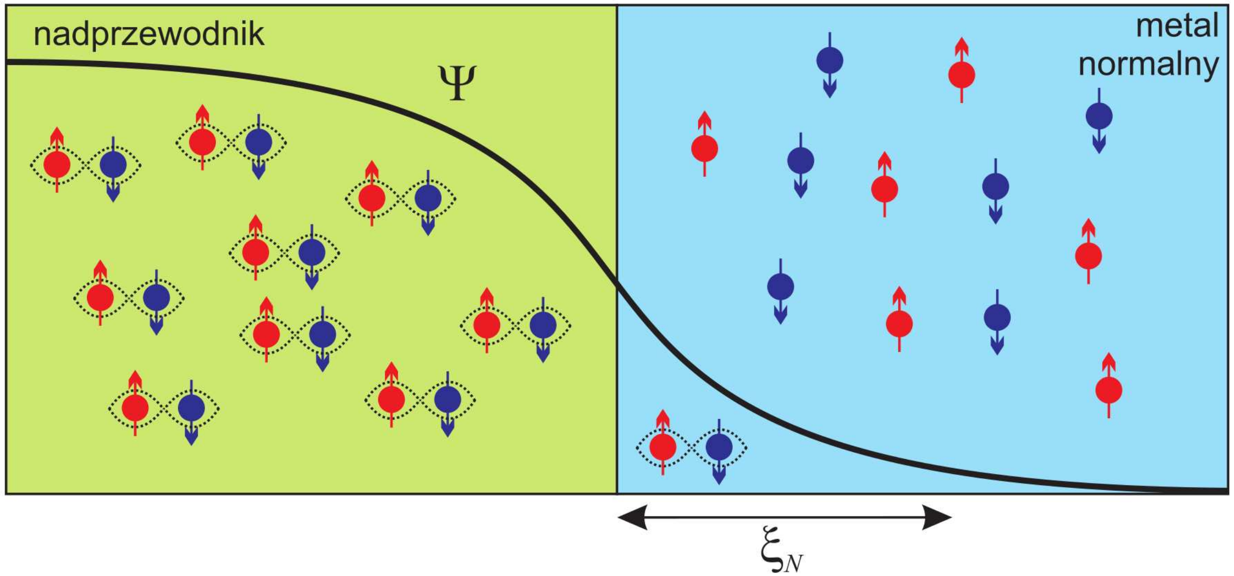
F.D.M. Haldane, Phys. Rev. Lett. 50, 1153 (1983)

Nobel Prize, 2016

3. Superconductivity in nanosystems

Pairing in nanosystems

Any material brought in a contact with some bulk superconductor absorbs the Cooper pairs



Cooper pairs leak into non-superconducting region on a spatial length ξ_N.

Specific example

(bound states at quantum impurities)

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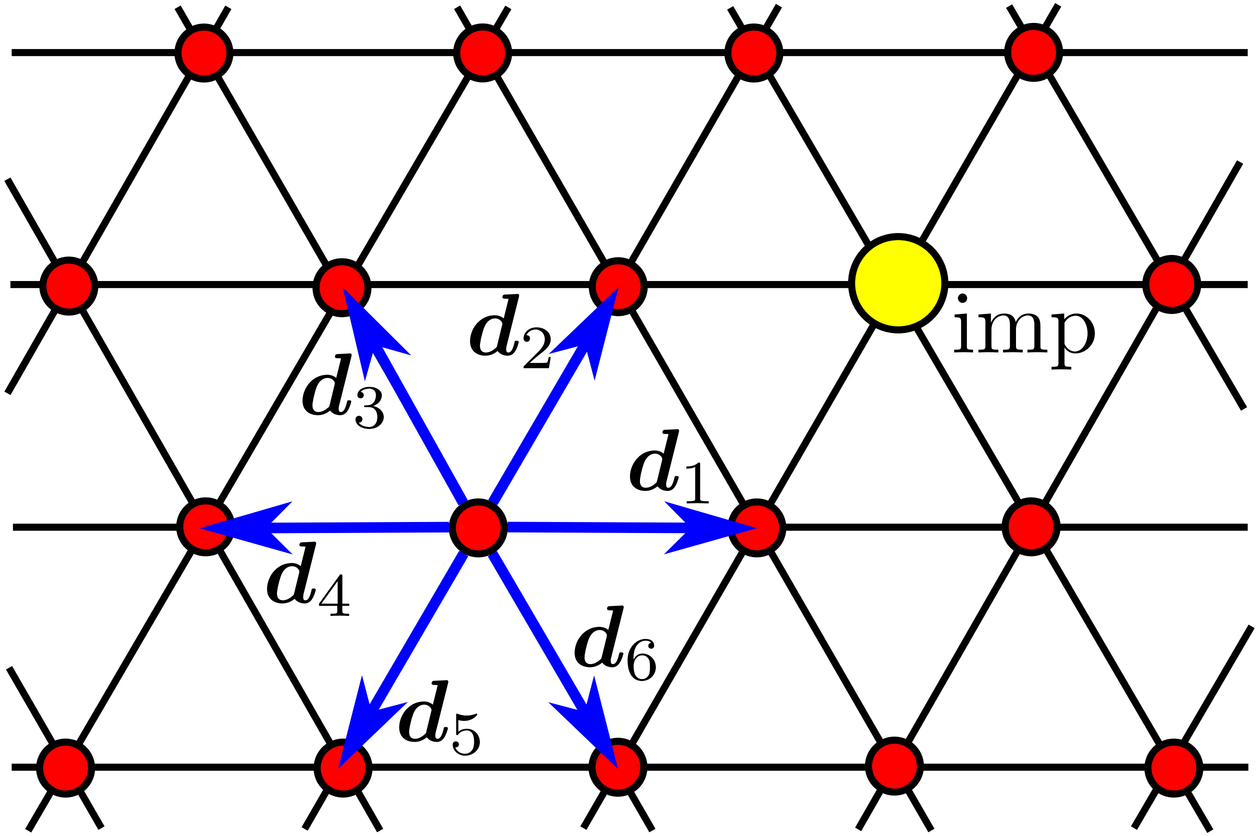
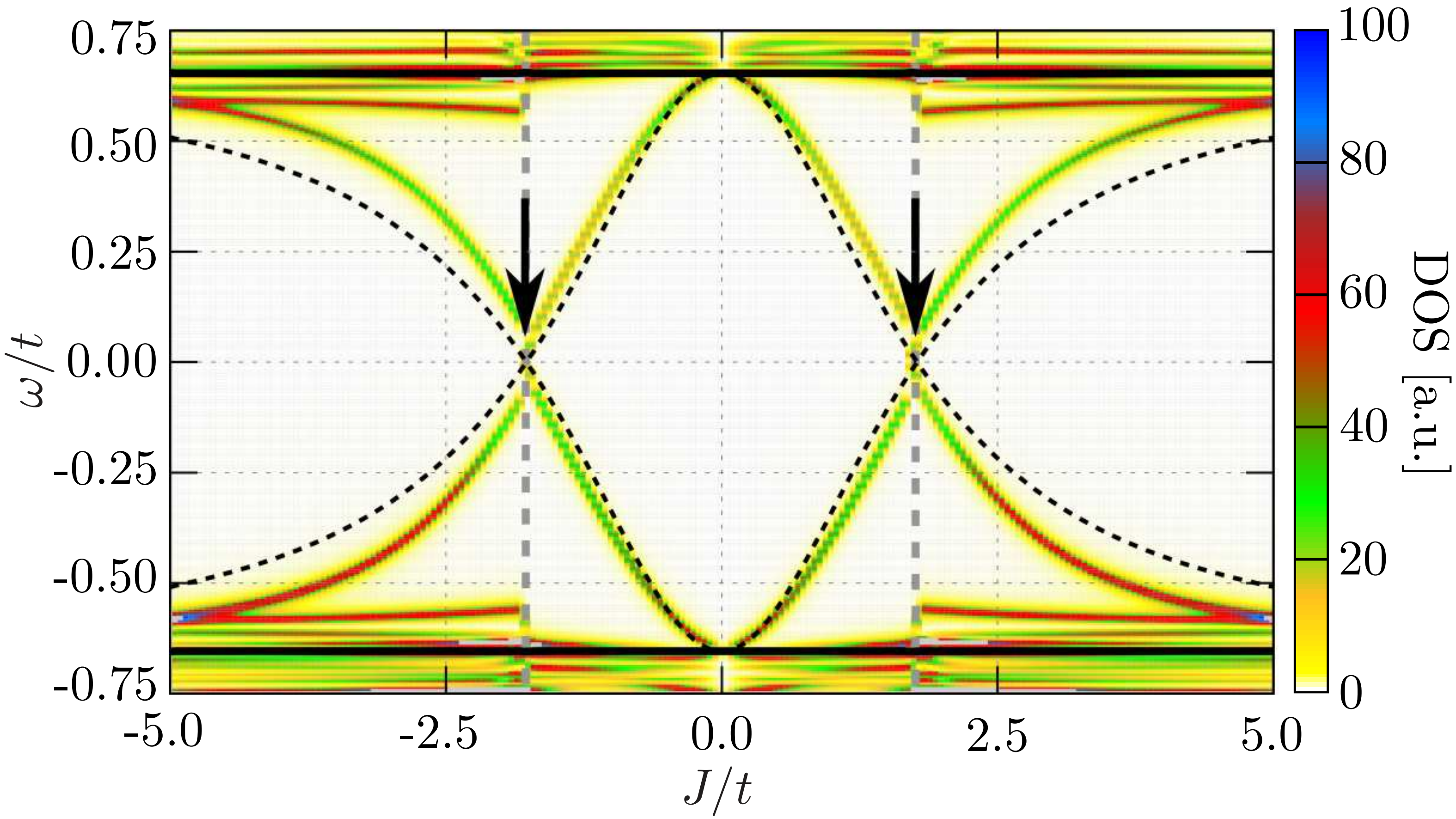


Let's consider a single magnetic impurity in $NbSe_2$ ($T_c \approx 7$ K)

$\Rightarrow$ characterized by a triangular lattice,

$\Rightarrow$ with in-plane spin orbit interactions.

Specific example (bound states at quantum impurities)

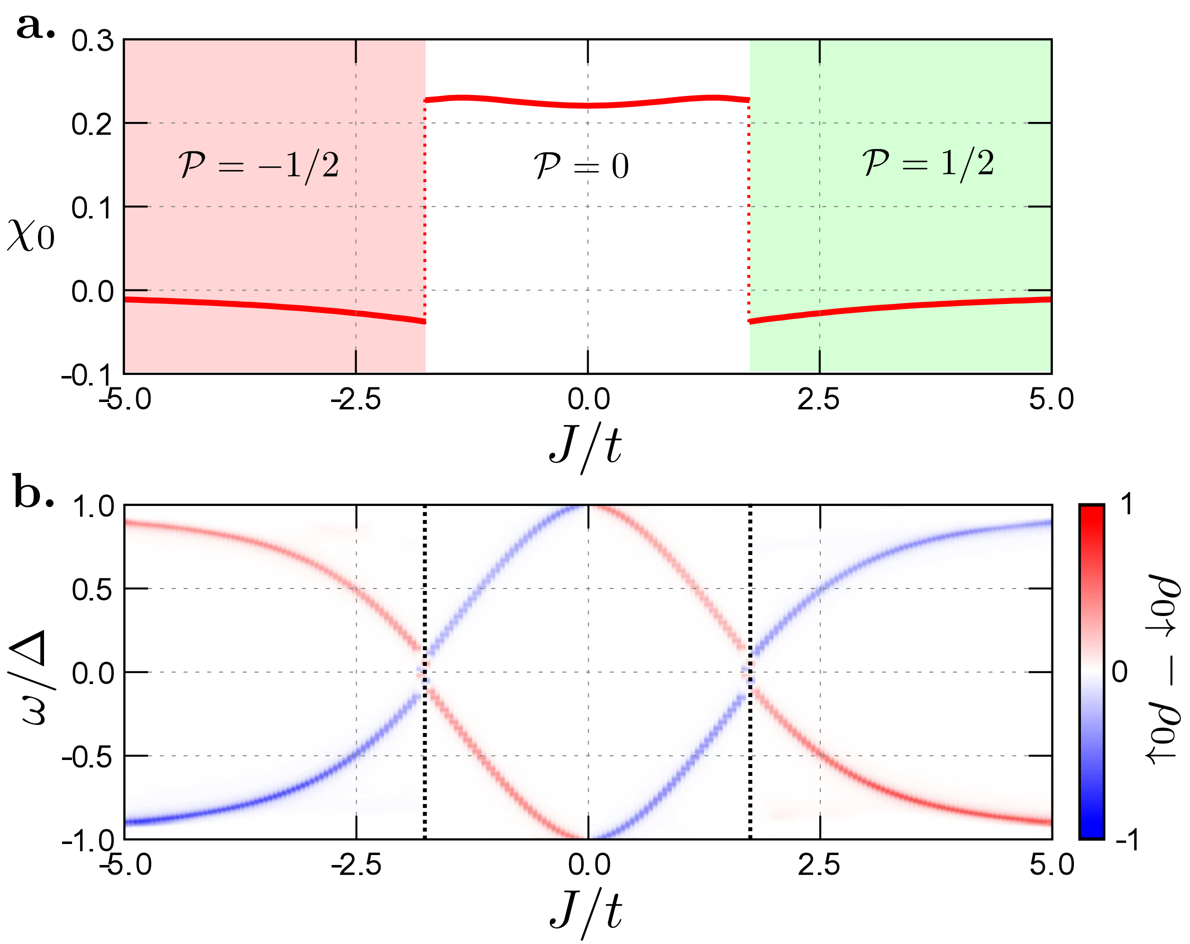


Low energy (subgap) spectrum reveals:

$\Rightarrow$ **two bound (Yu-Shiba-Rusinov) quasiparticle states,**

$\Rightarrow$ **which cross each other at $J_c \approx 2t$.**

Specific example **(bound states at quantum impurities)**

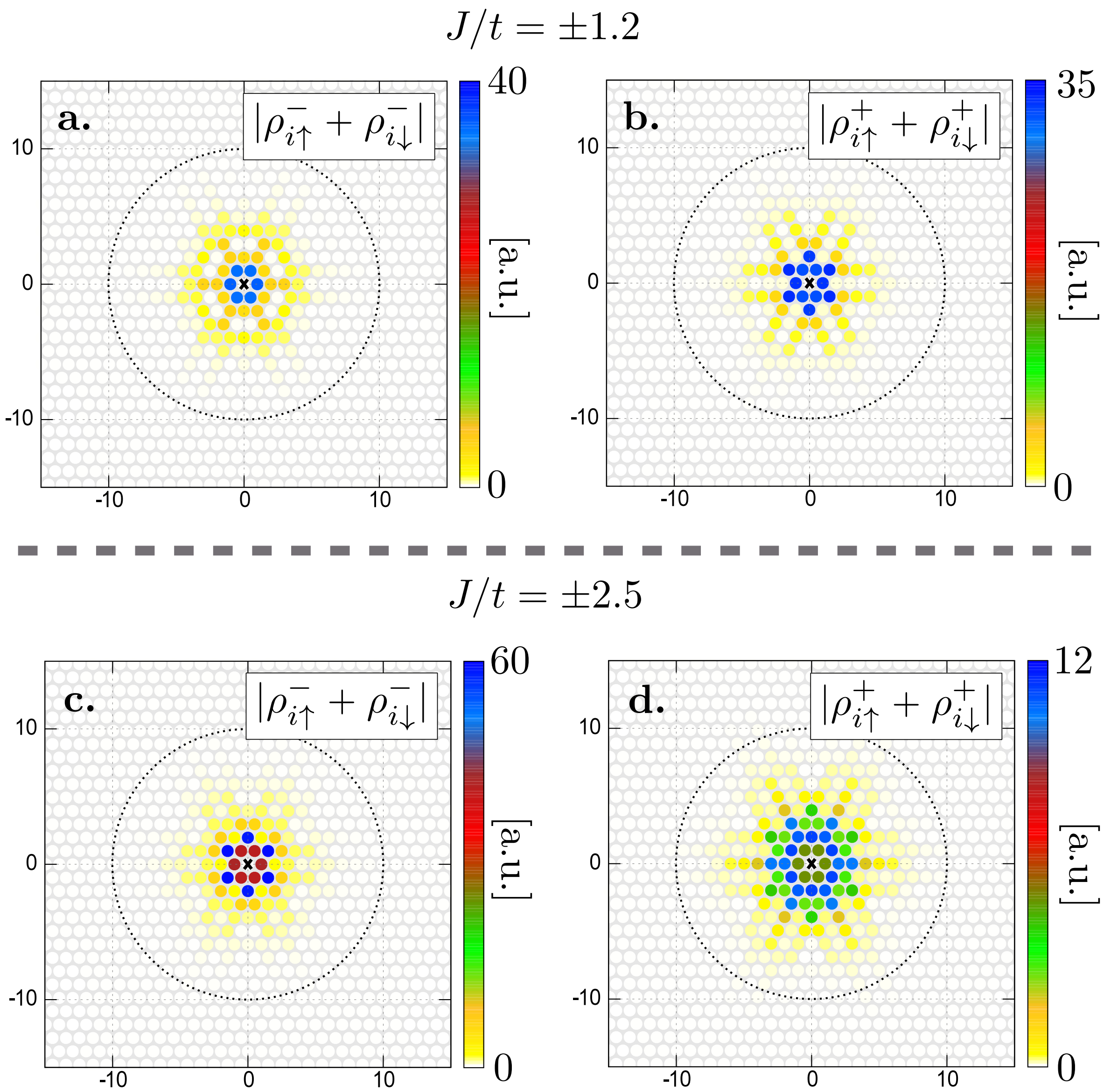


Crossing of the YSR quasiparticles signifies:

$\Rightarrow$ **the quantum phase transition,**

$\Rightarrow$ **reversal of the magnetic polarizations.**

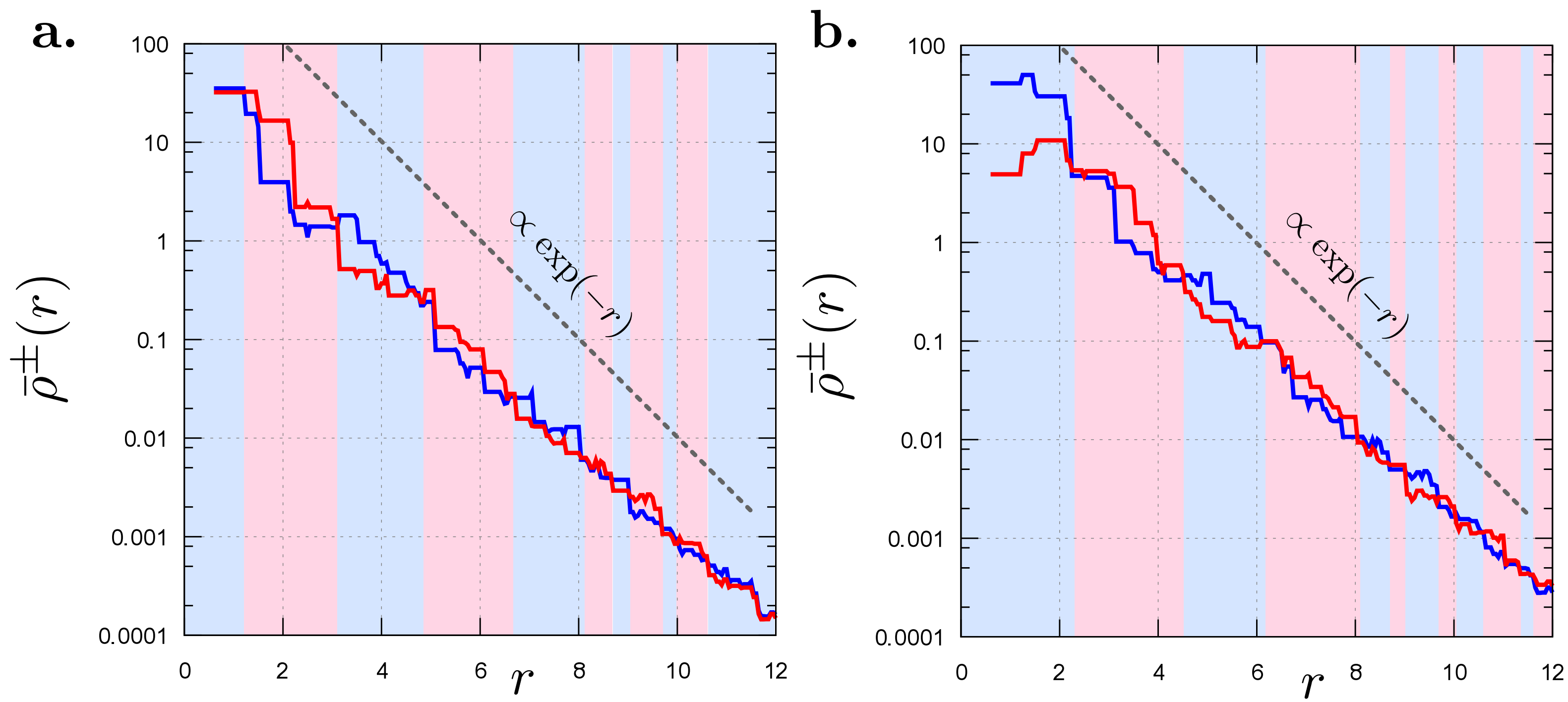
Specific example **(bound states at quantum impurities)**



Characteristic star-shape spatial patters of the YSR quasiparticles.

Specific example

(bound states at quantum impurities)



Particle/hole branches of the YSR quasiparticles:

$\Rightarrow$ **reveal quantum oscillations (shifted in phase by π),**

$\Rightarrow$ **spread onto several lattice constants from magnetic impurity.**

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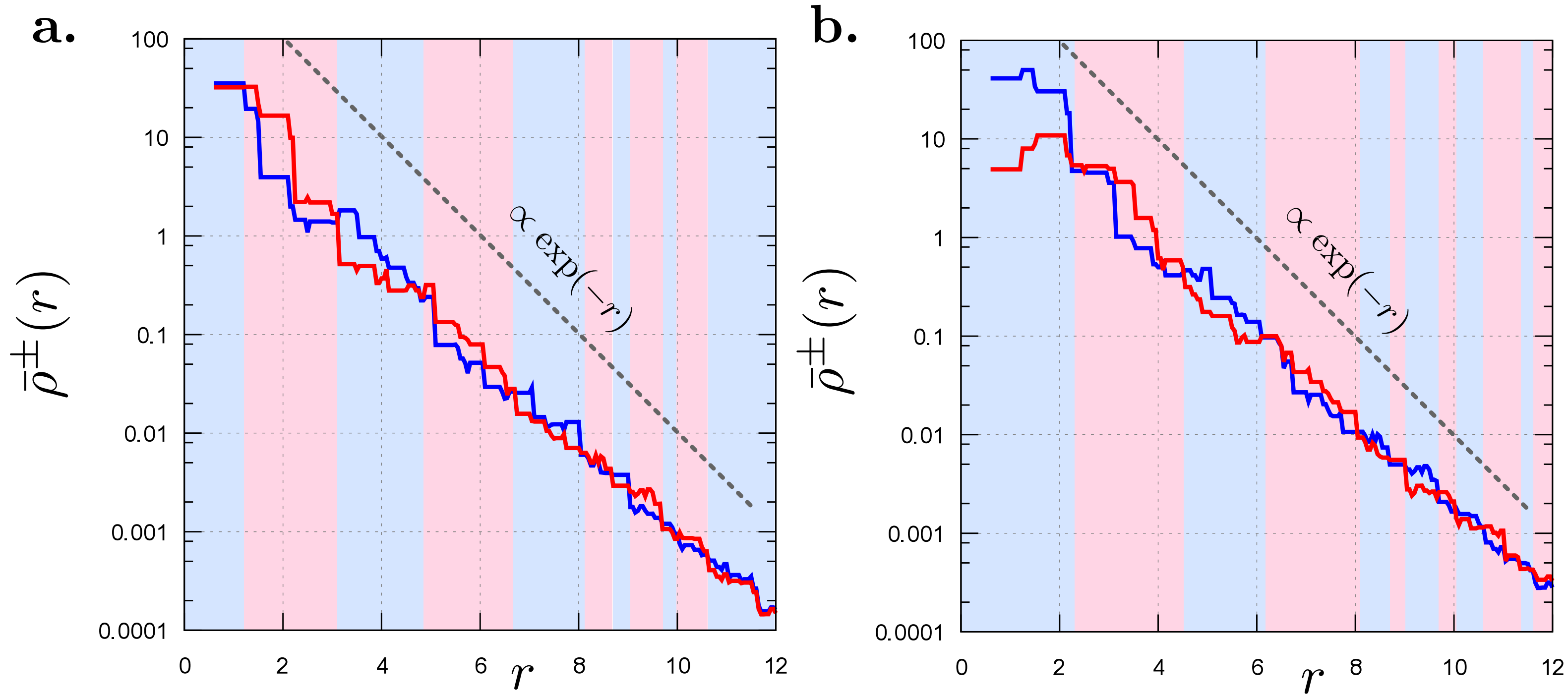
(bound states at quantum impurities)



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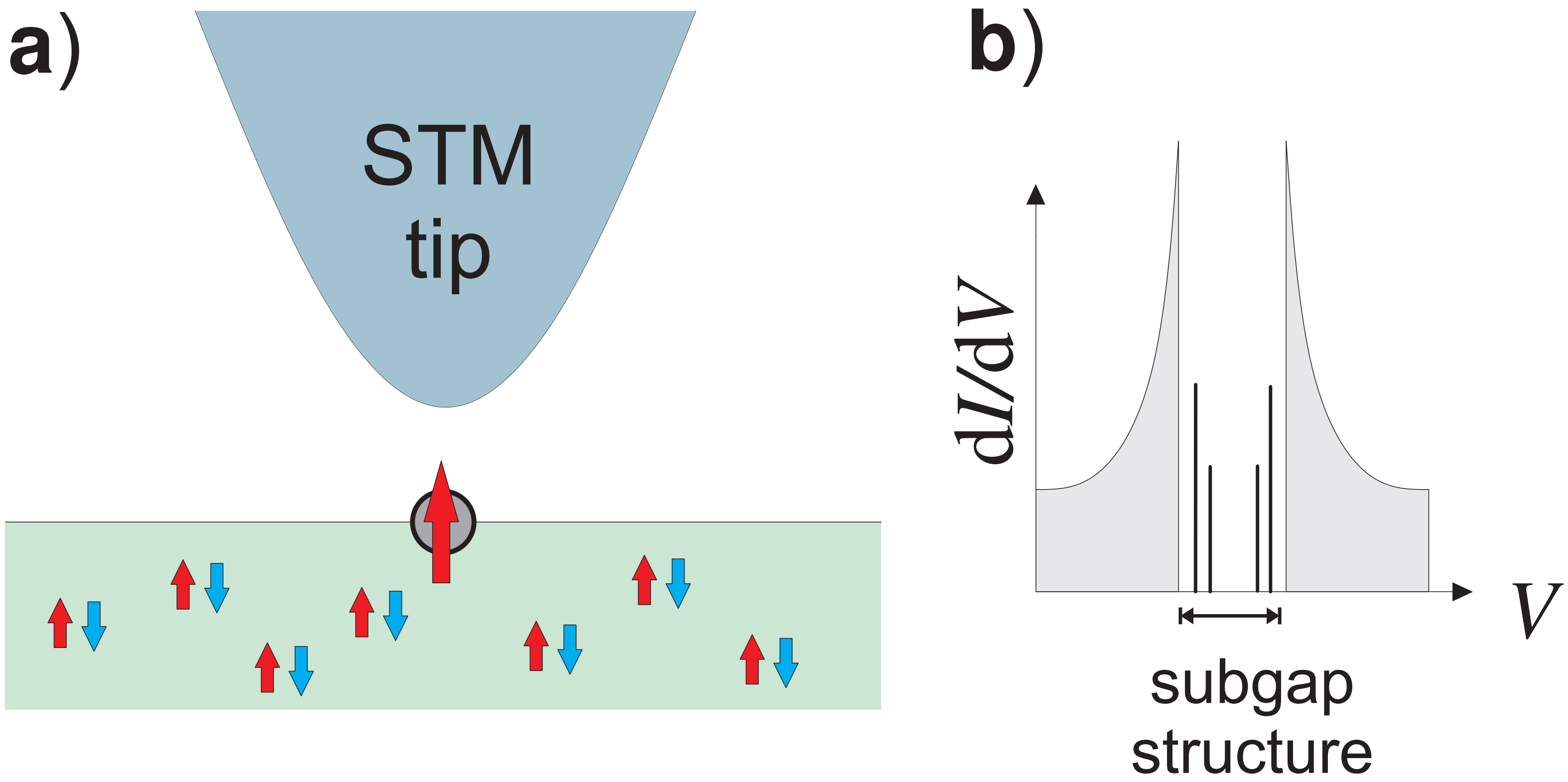
A. Ptok, Sz. Głodzik, & T. Domański, Phys. Rev. B **96**, 184425 (2017).

Subgap states **of multilevel quantum impurities**



a) STM scheme and b) differential conductance for multilevel quantum impurity adsorbed on surface of bulk superconductor.

R. Žitko, O. Bodensiek, and T. Pruschke, Phys. Rev. B **83**, 054512 (2011).

Andreev vs Majorana states – 'A story of mutation'

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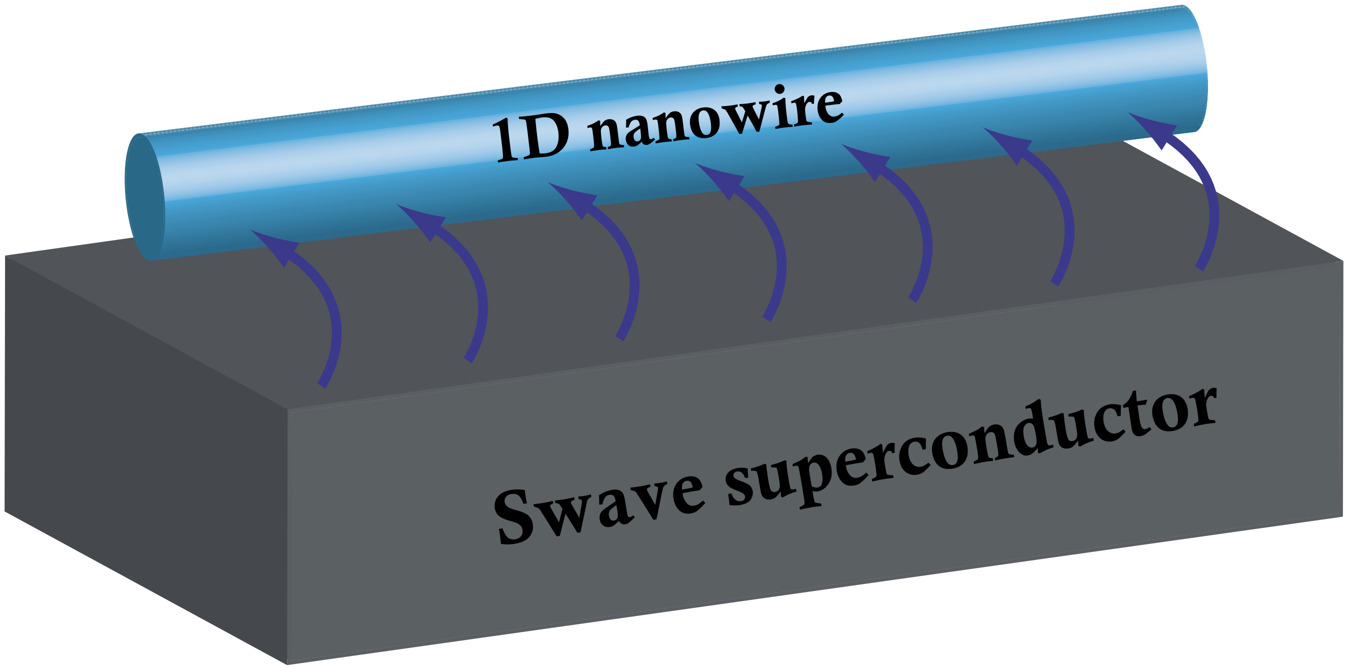
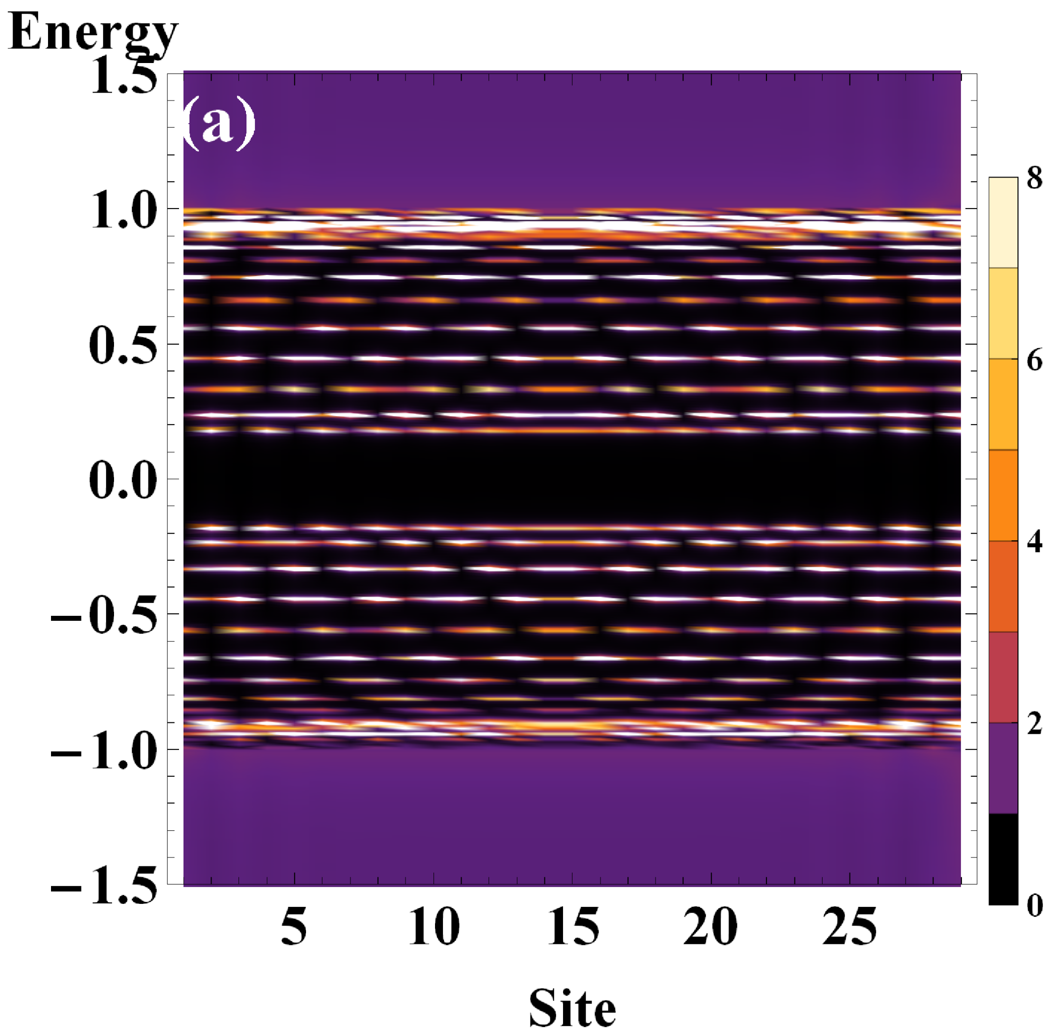
Let us consider:



1D quantum wire deposited on s-wave superconductor

D. Chevallier, P. Simon, and C. Bena, Phys. Rev. B **88***, 165401 (2013).*

Andreev vs Majorana states – 'A story of mutation'



Electronic spectrum comprises a series of Andreev states.

D. Chevallier, P. Simon, and C. Bena, Phys. Rev. B ***88****, 165401 (2013).*

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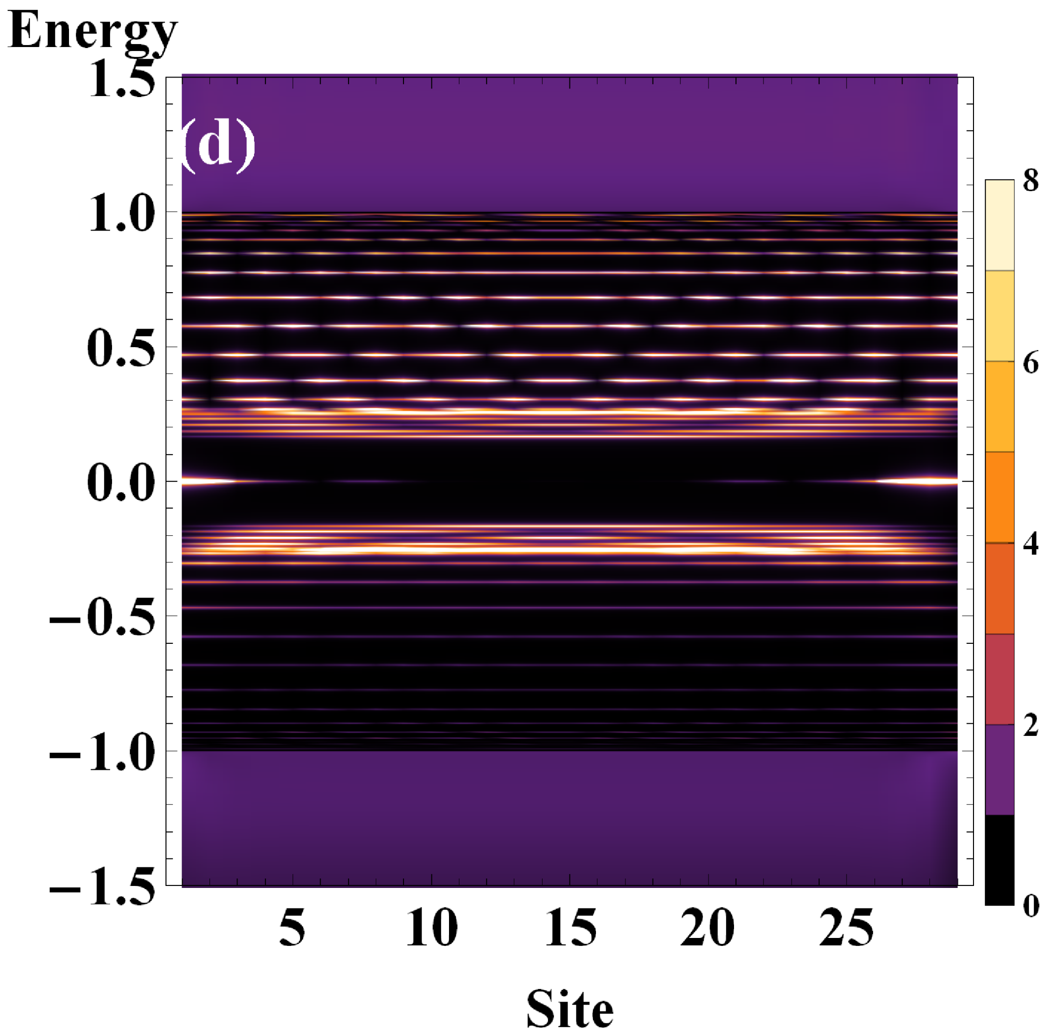
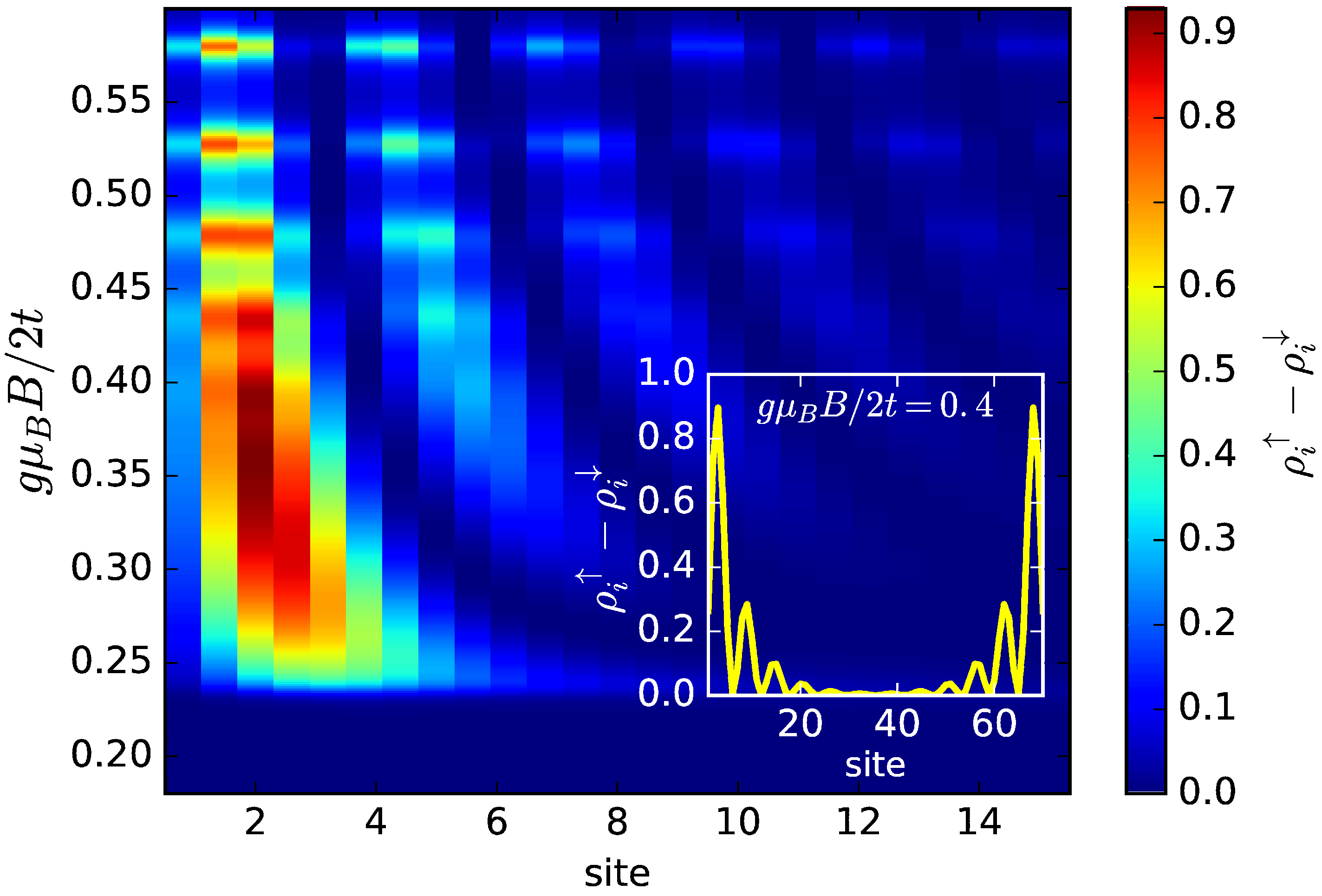


Spin-orbit + Zeeman interactions induce the Majorana edge modes.

D. Chevallier, P. Simon, and C. Bena, Phys. Rev. B **88**, *165401 (2013).*

More detailed picture – oscillations & polarization

Spatial profiles of the Majorana qps



T. Domański *et al*, arXiv:1712.03172 (2017).

4. Present challenges (a few examples)

1. Novel structures – for realization of Majorana qps

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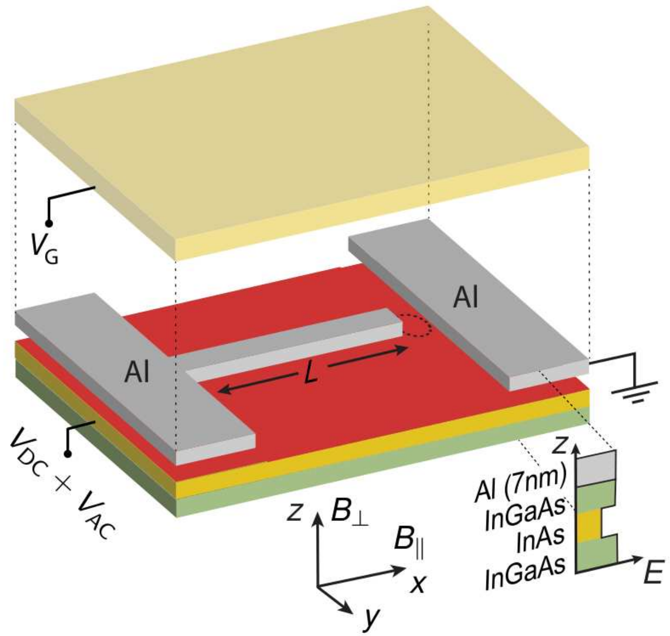
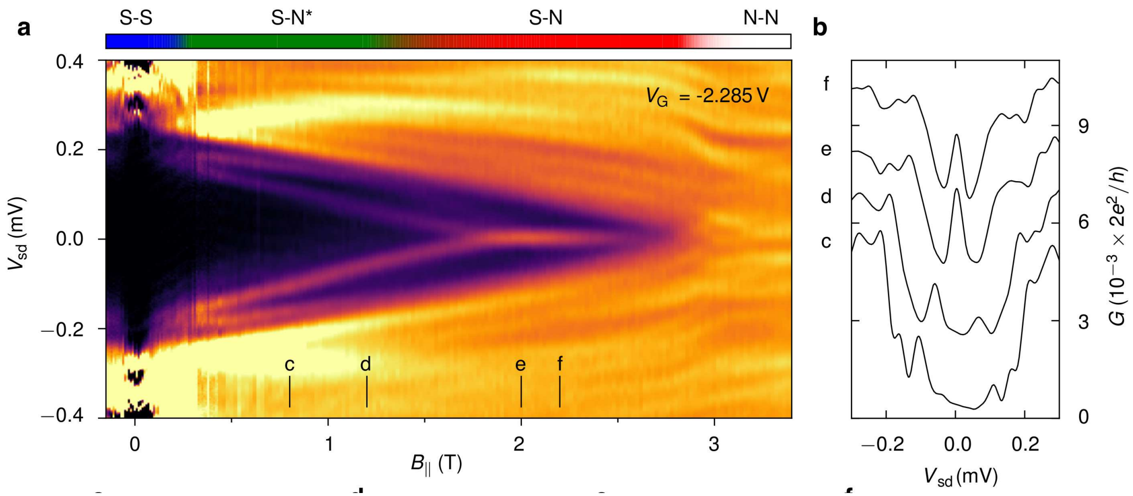
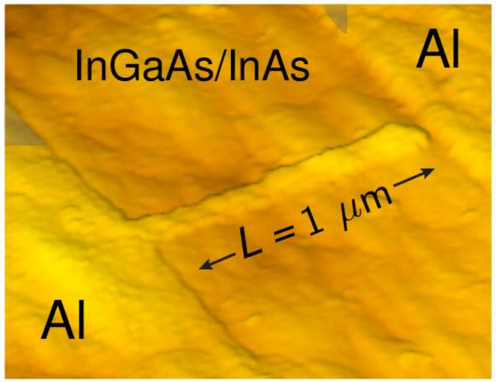
a) wire-like device constructed lithographically





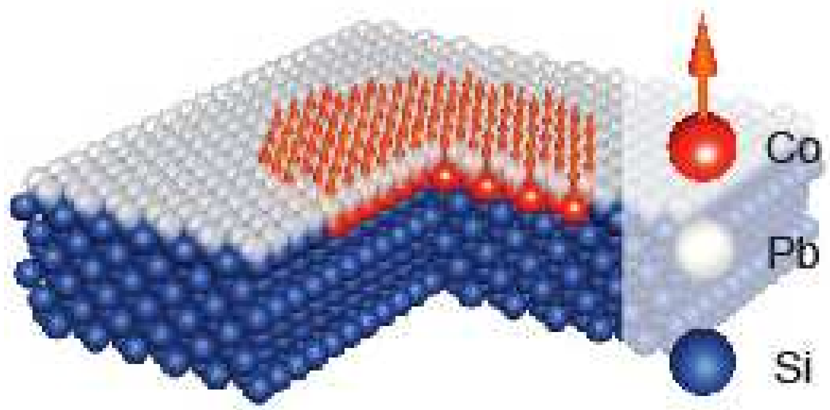


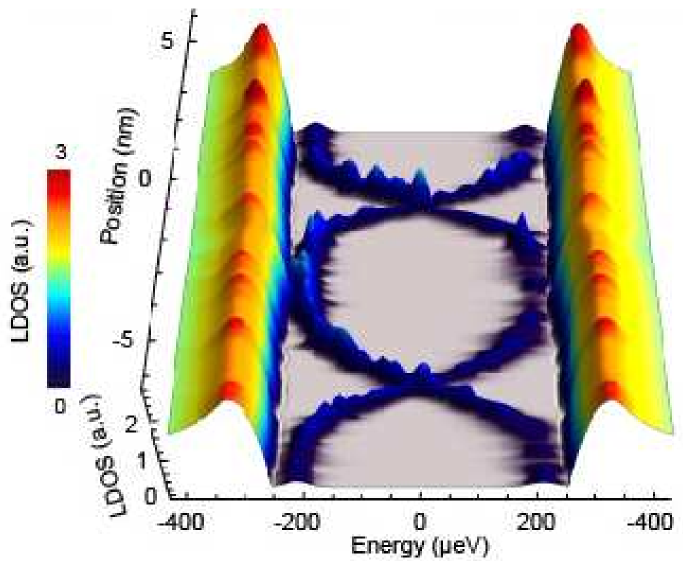
H.J. Suominen *et al*, Phys. Rev. Lett. **119**, 176805 (2017).

/ University of Copenhagen, Denmark /

1. Novel structures – **for realization of Majorana qps**

b) chiral Majorana modes at the edges of magnetic atoms cluster





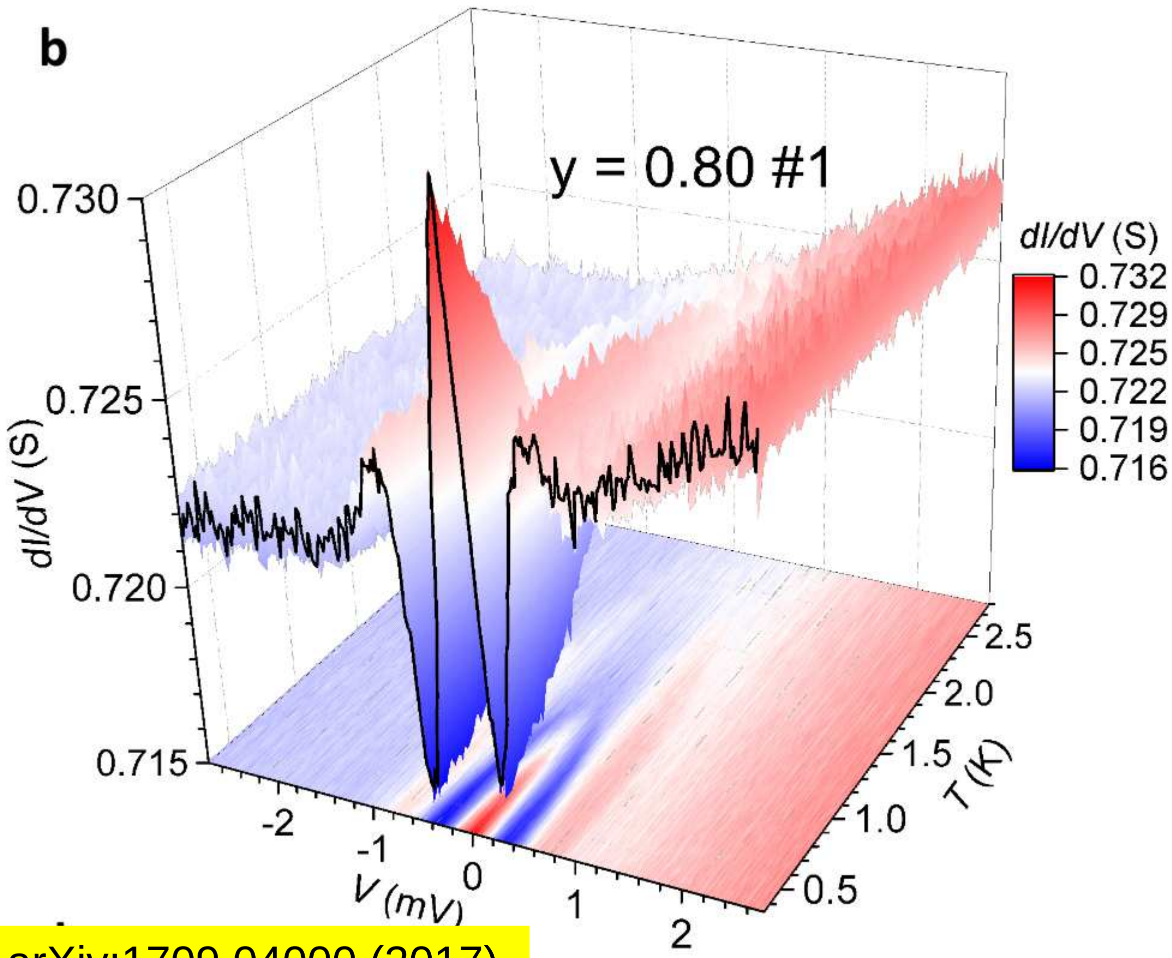
Delocalized (dispersive) modes !

G.C. Ménard *et al*, Nature Comm. **8**, 2040 (2017).

/ Univ. Pierre & Marie Curie, Paris, France /

1. Novel structures – **for realization of Majorana qps**

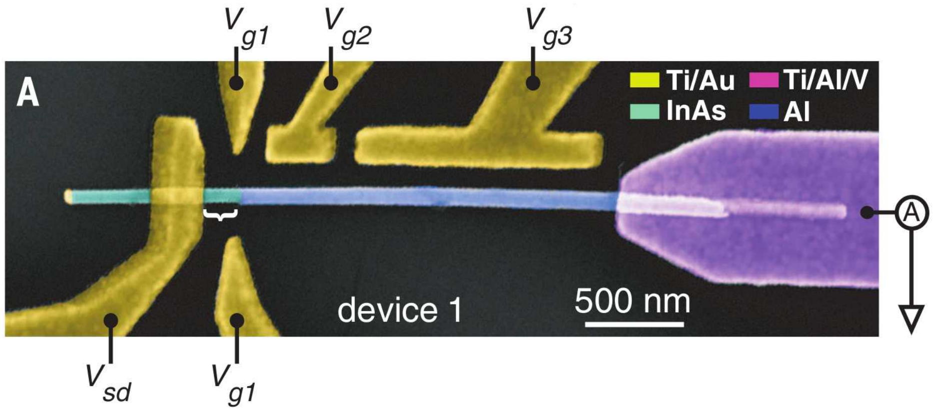
c) zero-energy mode on ferromagnetic topological insulator



G.P. Mazur *et al*, arXiv:1709.04000 (2017).

/ PAS & MagTop, Warsaw, Poland /

2. Nonlocality of Majorana qps – / leakage on other objects /

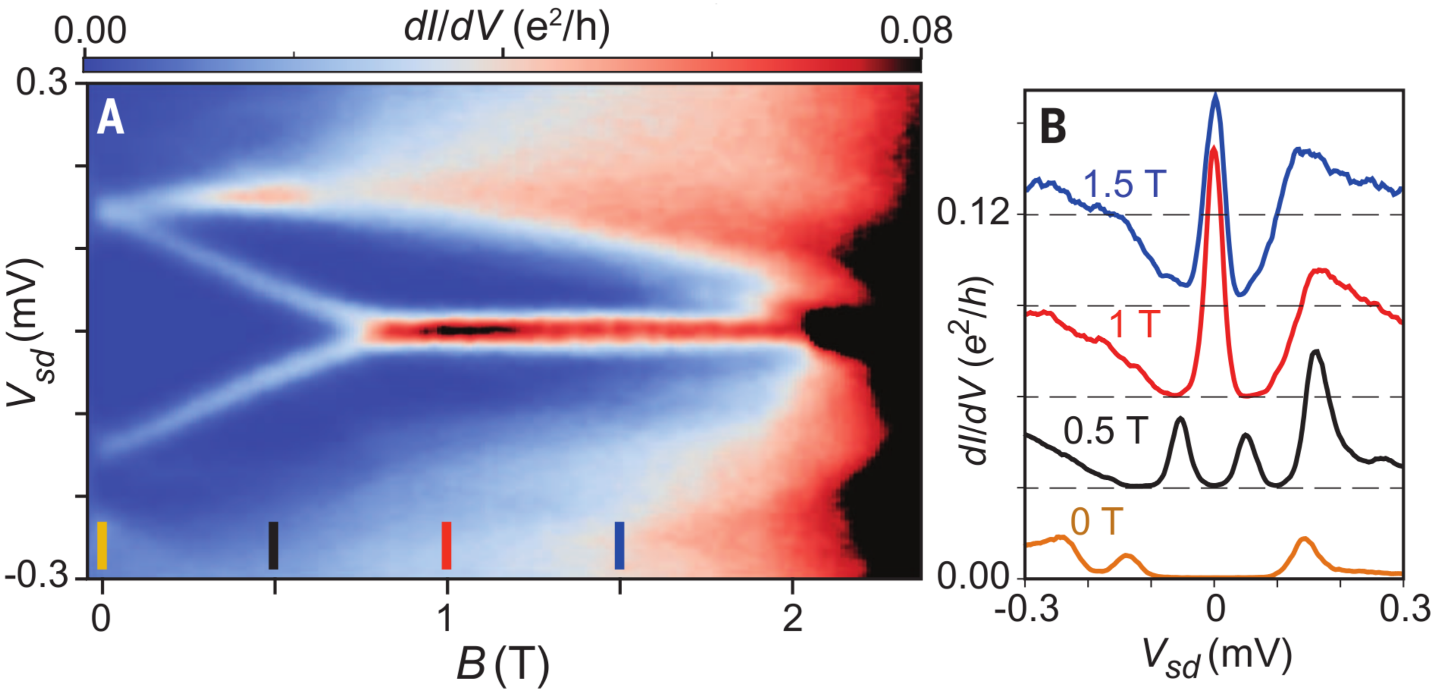


TOPOLOGICAL MATTER

Majorana bound state in a coupled quantum-dot hybrid-nanowire system

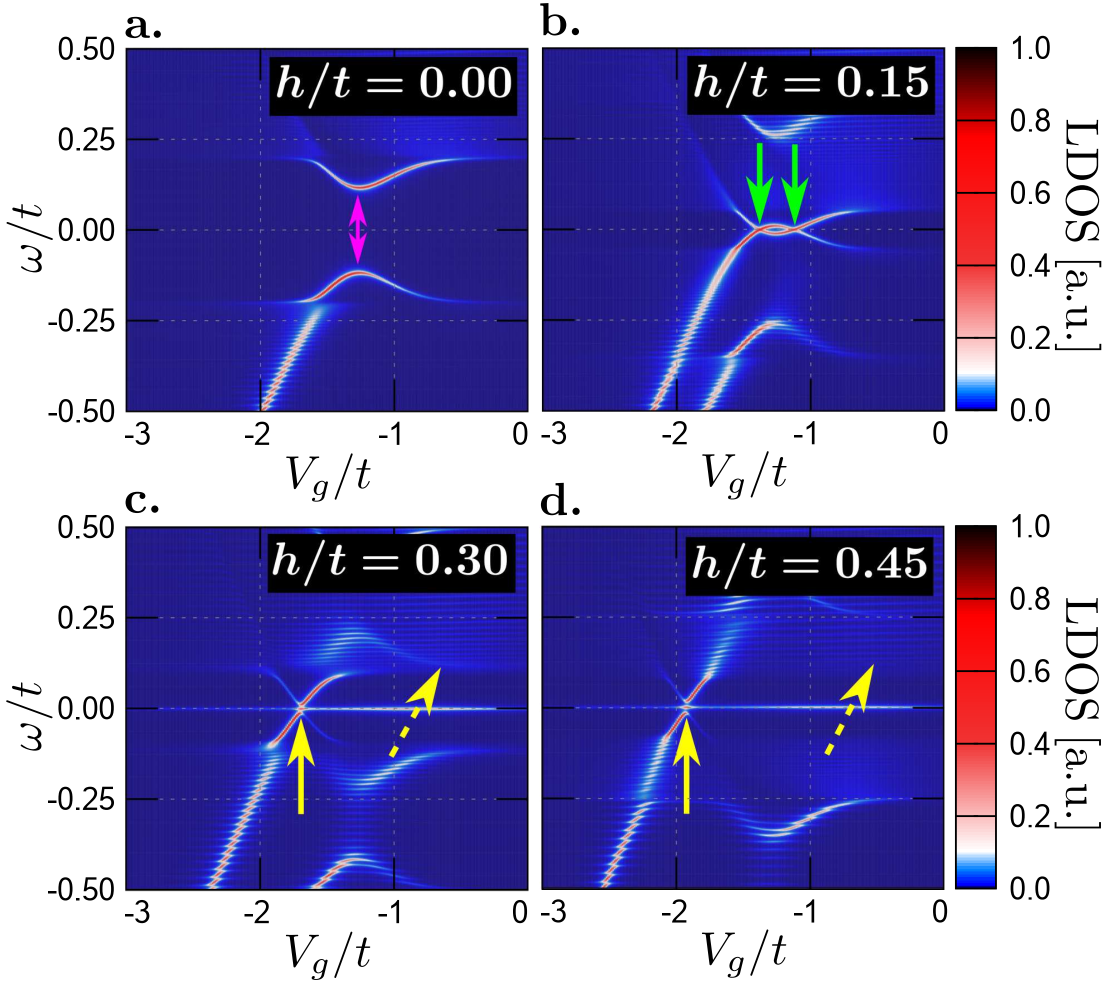
M. T. Deng,[1,2] S. Vaitiekėnas,[1,3] E. B. Hansen,[1] J. Danon,[1,4] M. Leijnse,[1,5] K. Flensberg,[1] J. Nygård,[1] P. Krogstrup,[1] C. M. Marcus[1]*

Science **354**, *1557 (2016).*



Leakage of Majoranas

(on side-attached normal wire)



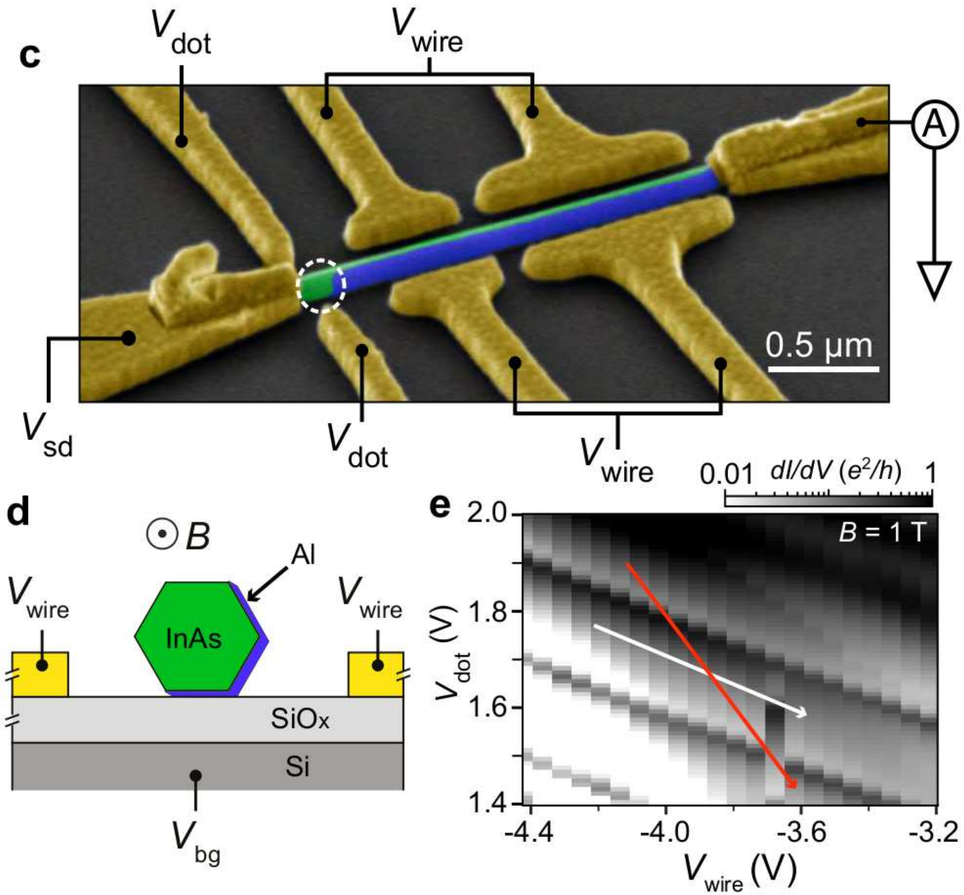
Coalescence of Andreev states to Majorana quasiparticles.

A. Ptok, A. Kobiałka, & T. Domański, Phys. Rev. B **96**, 195430 (2017).

2. Nonlocality of Majorana qps

(recent experimental data)

Non-locality measured via the side-coupled quantum dot



M.T. Deng *et al*, arXiv:1712.03536 (2017).

/ Univ. of Copenhagen, Denmark &

Univ. Autonoma de Madrid, Spain /

2. Nonlocality of Majorana qps

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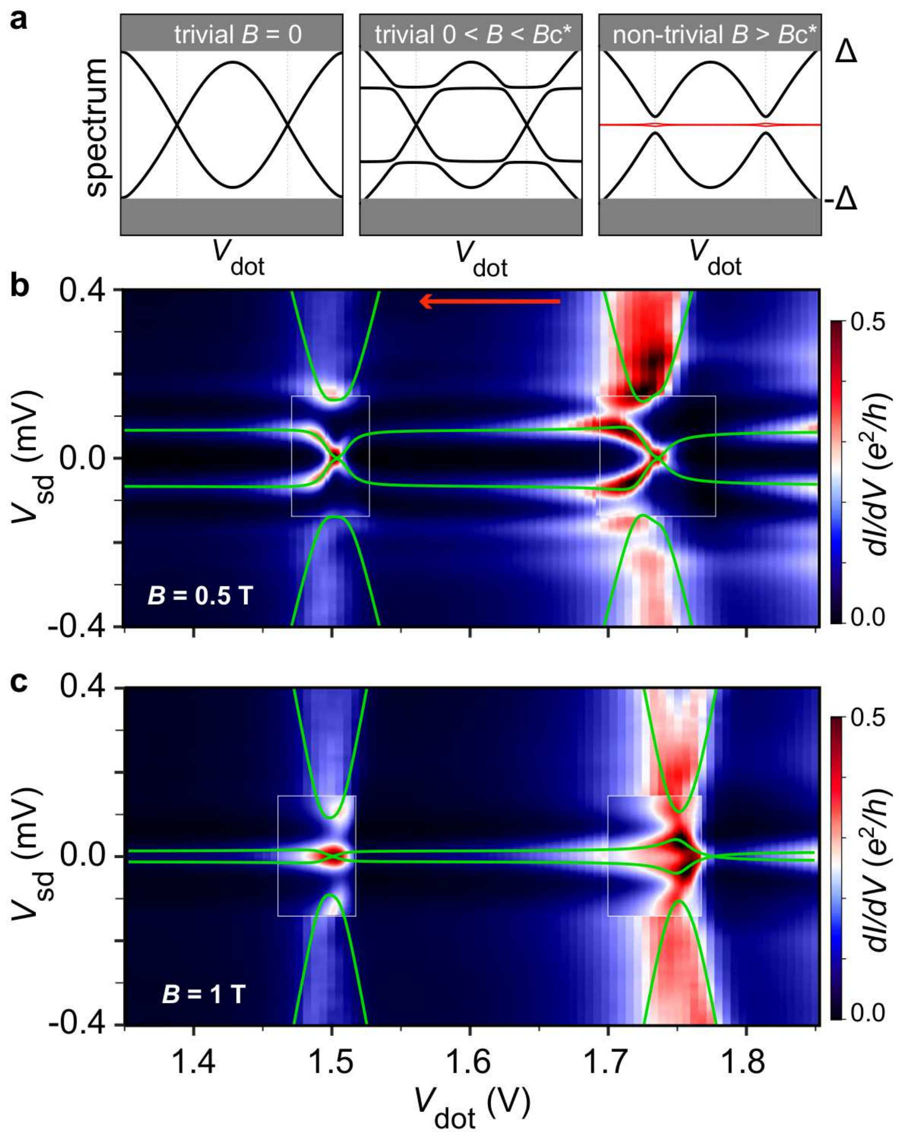
Non-locality probed via the side-coupled quantum dot



M.T. Deng *et al*, arXiv:1712.03536 (2017).

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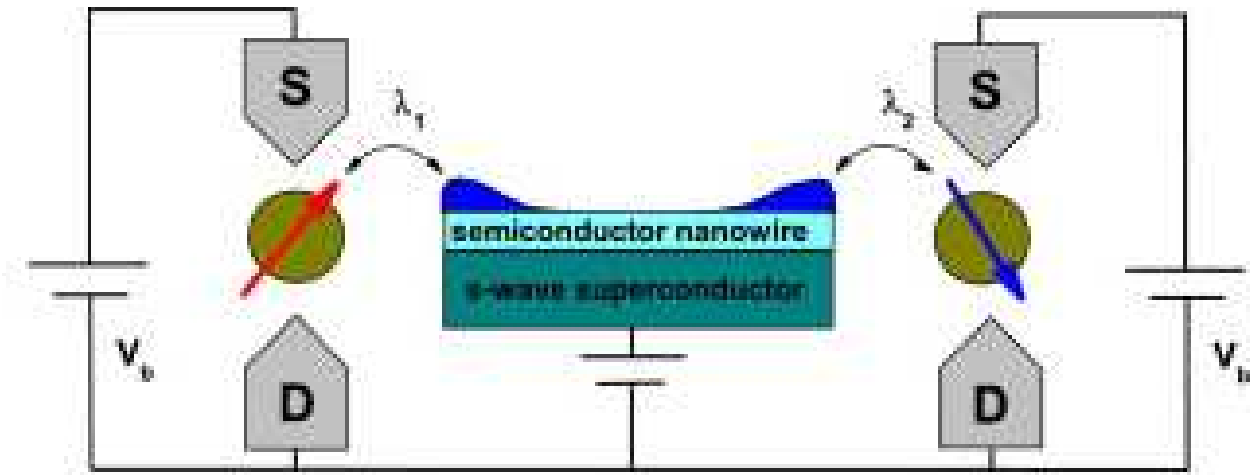
(further ideas)

Entangled pair of the Majorana quasiparticles can lead to further non-local effects, signified e.g. by interference ...



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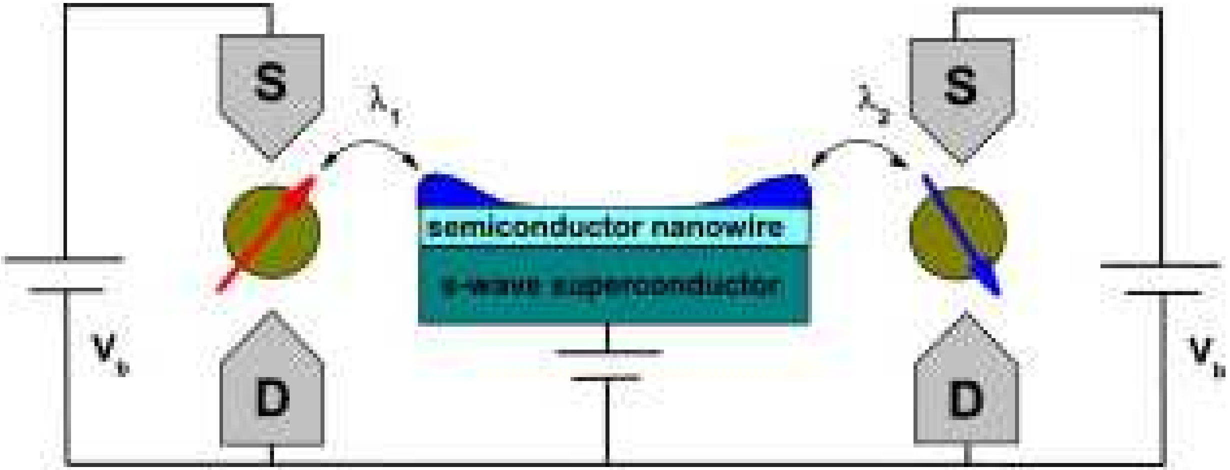
Entangled pair of the Majorana quasiparticles can lead to further non-local effects, signified e.g. by interference or charge teleportation.



PRL **104,** 056402 (2010) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2010

Electron Teleportation via Majorana Bound States in a Mesoscopic Superconductor

Liang Fu

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 23 October 2009; published 2 February 2010)

3. Practical use – Majorana qubits & quantum computing

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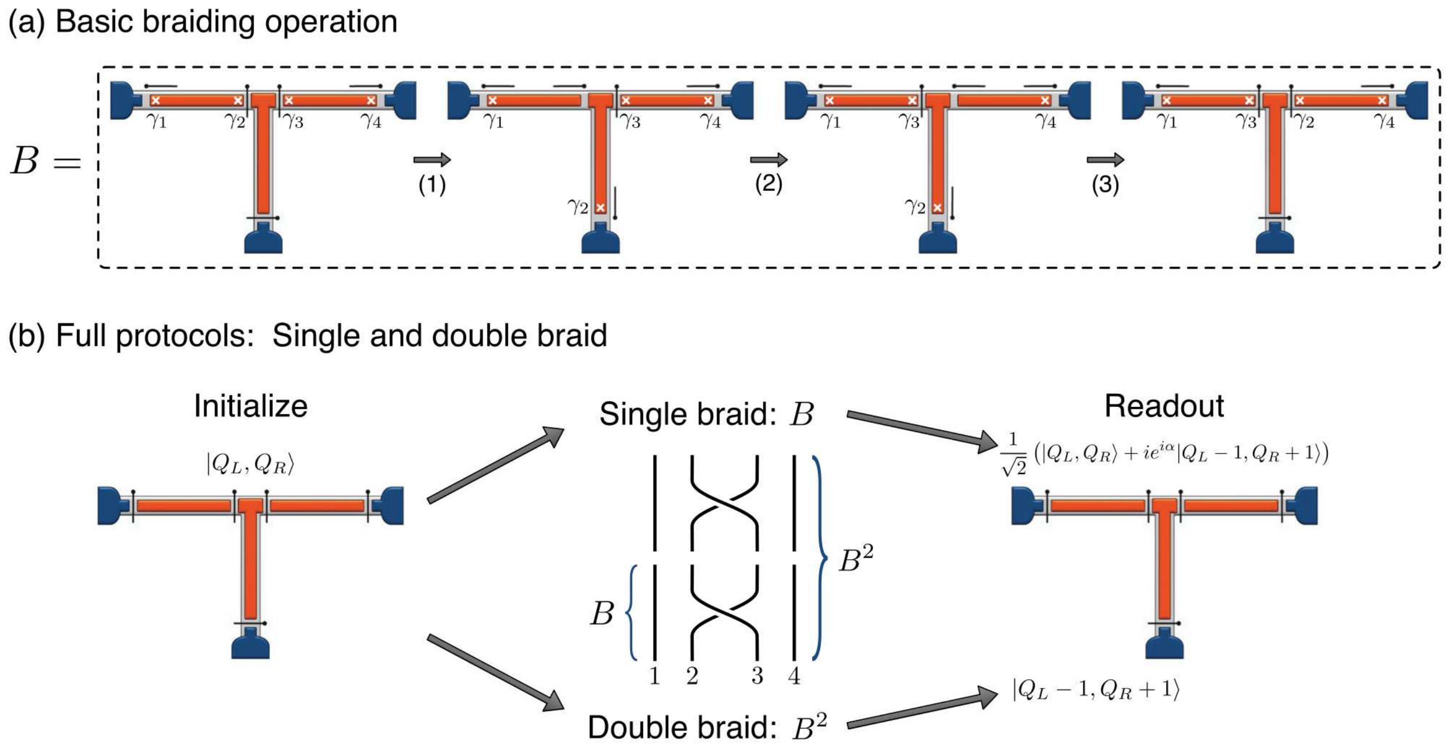
Many proposals for qubits based on Majorana qps & their braiding



PHYSICAL REVIEW X **6,** 031016 (2016)

Milestones Toward Majorana-Based Quantum Computing

David Aasen,[1] Michael Hell,[2,3] Ryan V. Mishmash,[1,4] Andrew Higginbotham,[5,3] Jeroen Danon,[3,6] Martin Leijnse,[2,3] Thomas S. Jespersen,[3] Joshua A. Folk,[3,7,8] Charles M. Marcus,[3] Karsten Flensberg,[3] and Jason Alicea[1,4]

3. Practical use – **Majorana qubits & quantum computing**

Some recent theoretical ideas for quantum operations

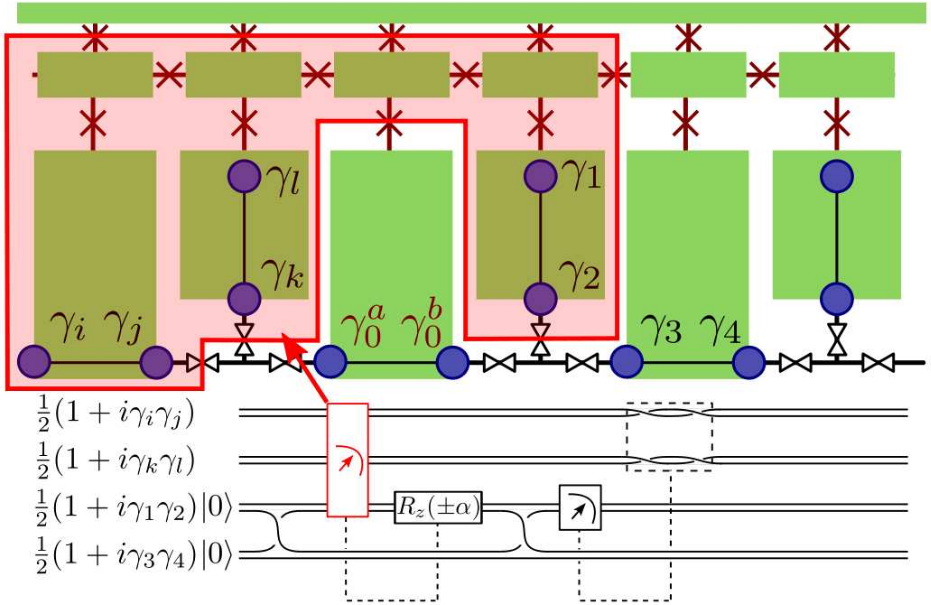


FIG. 1. Top: a $1D$ implementation of a Majorana circuit. Majoranas (blue dots) occur at either the edge of a nanowire (black line) or as it crosses the boundary of a superconductor (light green). Josephson junctions (red crossed lines) connect superconducting islands to a common base, allowing for parallel joint parity measurements. Fully-tunable T-junctions

/ Delft University, Netherlands /

T.E. O'Brien, P. Rożek, A.R. Akhmerov, arXiv:1712.02353 (2017).

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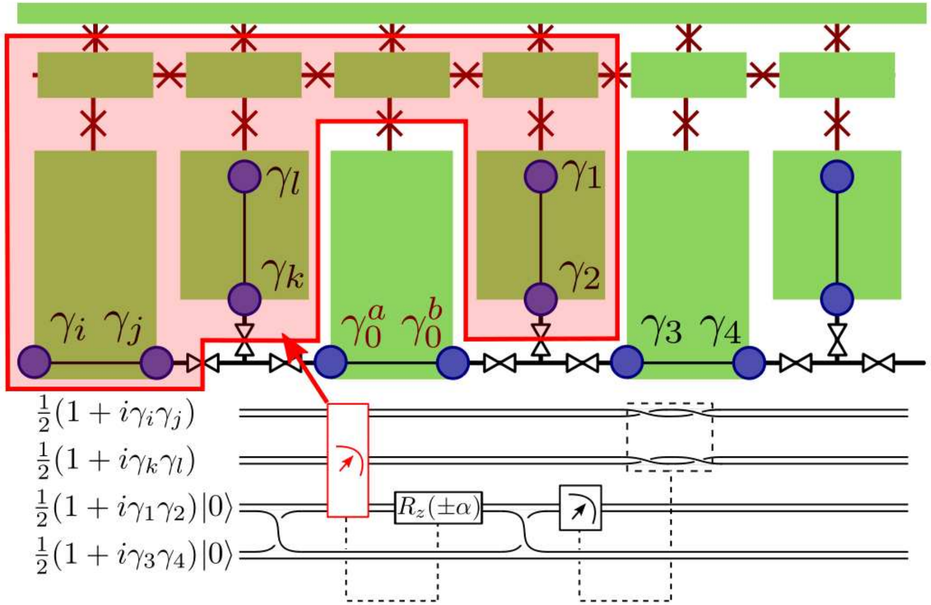

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However any experimental realization is missing !

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⇒ immune to decoherence/disorder ... talk by Maciek Maśka !

Summary on Majorana qps: – possible applications

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- **novel SQUID devices**

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