UAM Poznań, 13-Jan-2017

Majorana quasiparticles in nanoscopic superconductors

Tadeusz Domański

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J. Bardeen

J. Kondo

E. Majorana

Experimental evidence – for Majorana quasiparticles

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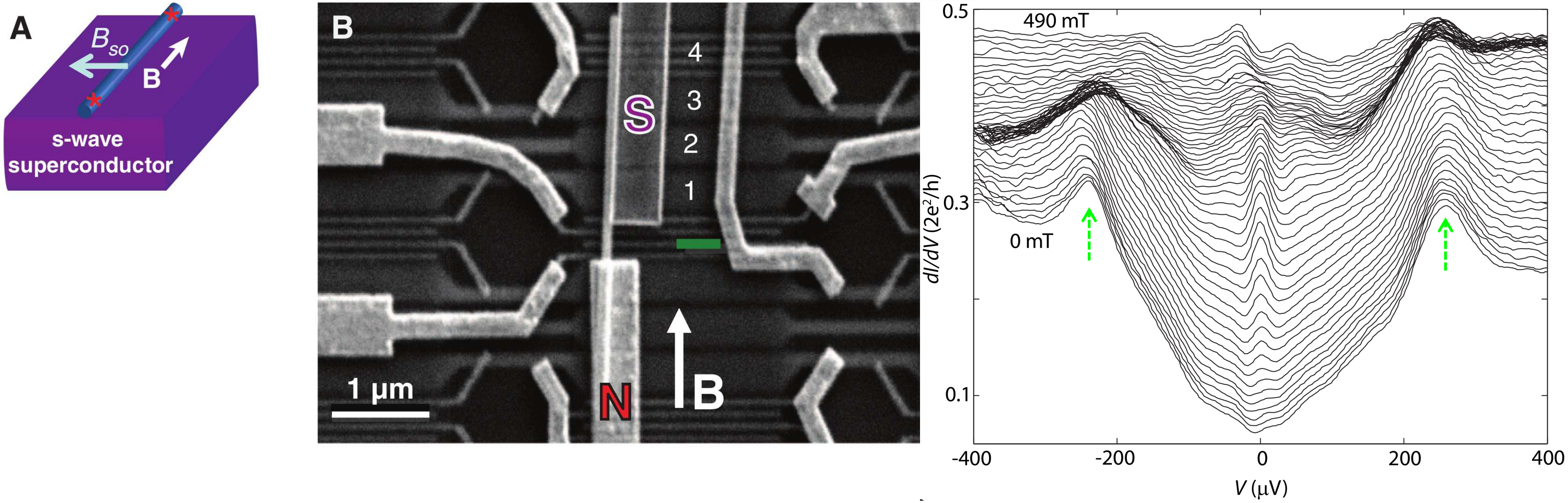
InSb nanowire between a metal (gold) and a superconductor (Nb-Ti-N)



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 /

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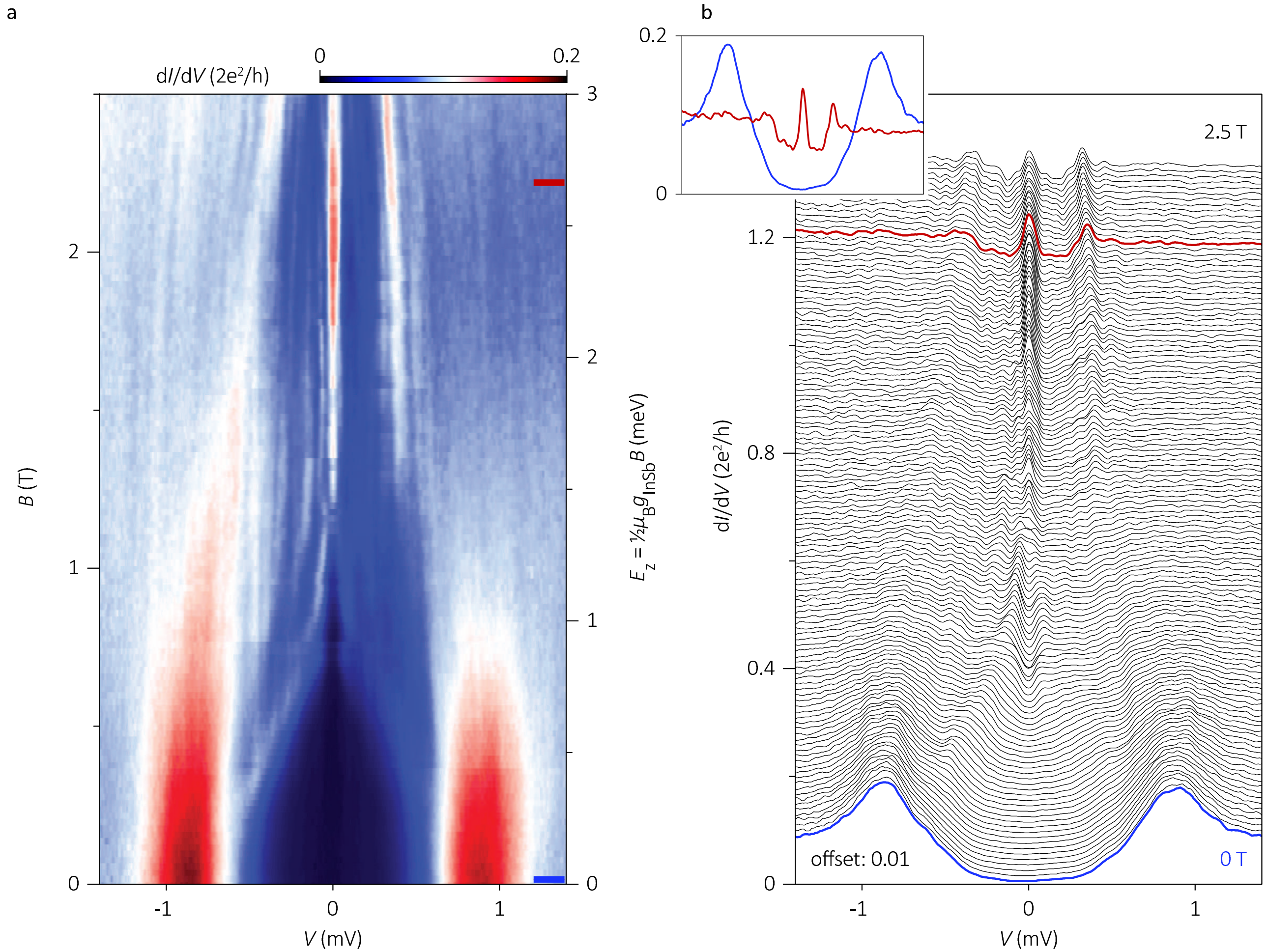

H. Zhang, ..., and L.P. Kouwenhoven, arXiv:1603.04069 (2016).

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

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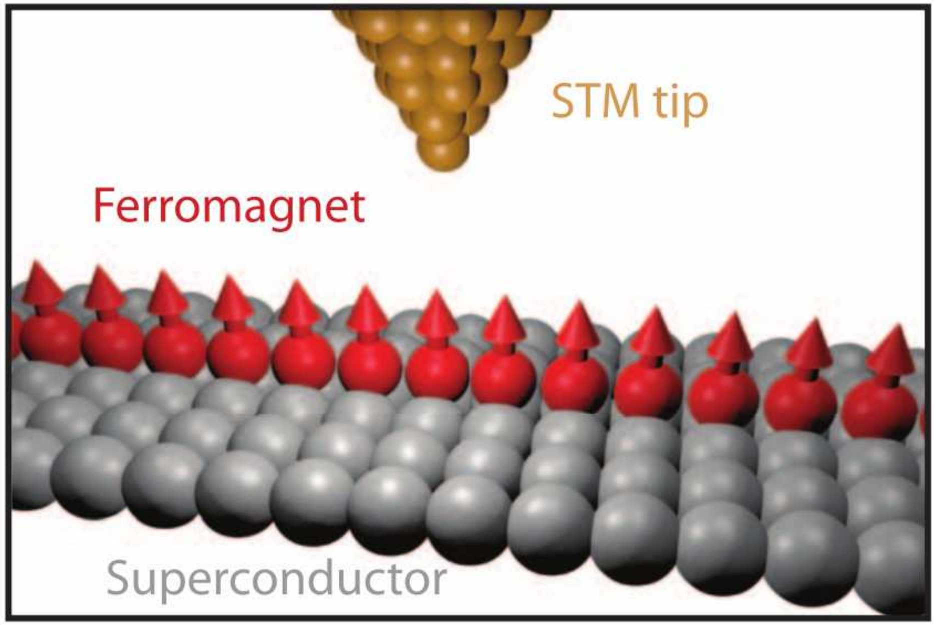
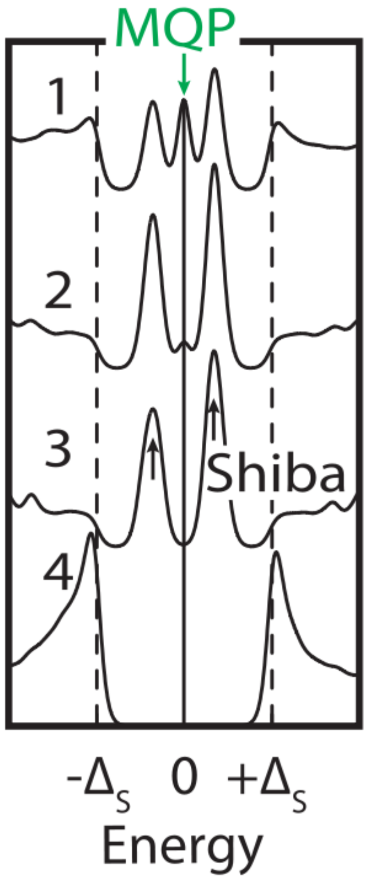
A chain of iron atoms deposited on a surface of superconducting lead





STM measurements provided evidence for:

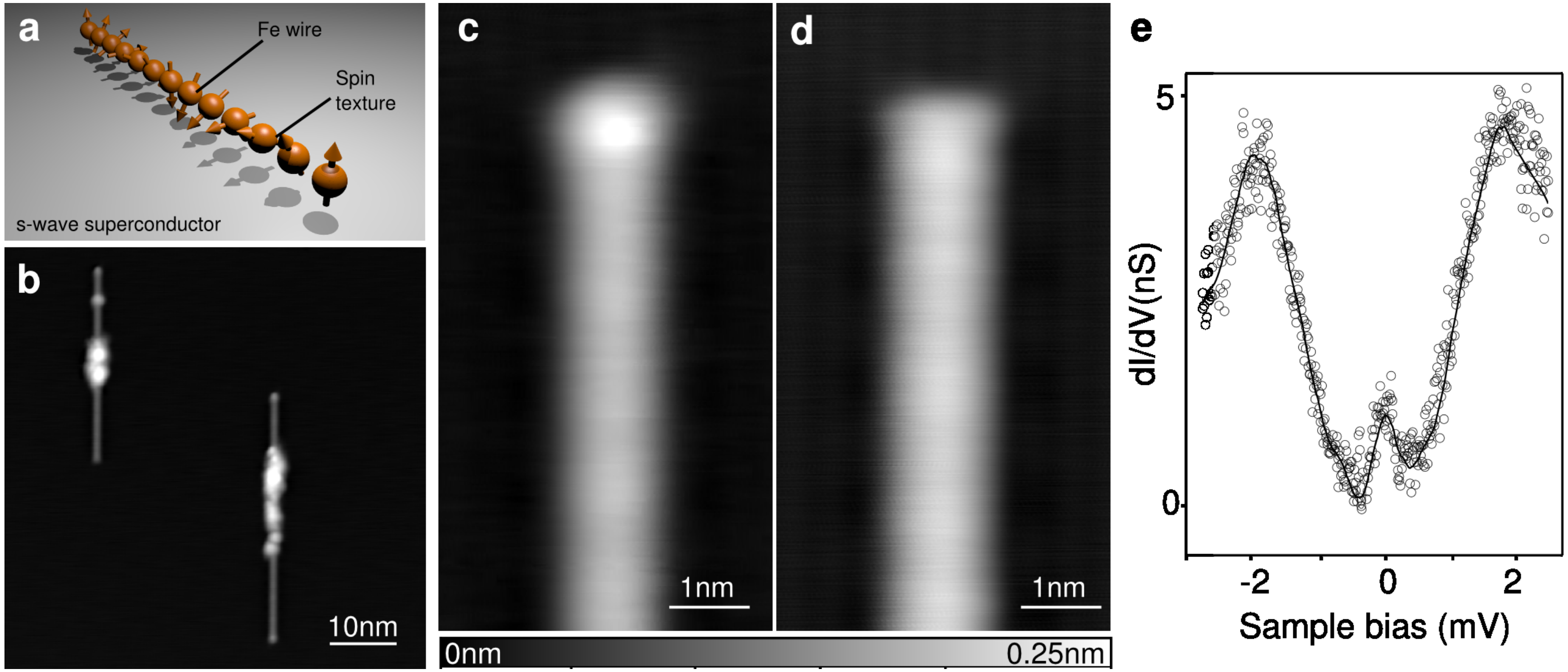
⇒ **Majorana bound states at the edges of a chain.**

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:

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

/ University of Basel, Switzerland /

Outline:

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- **Majorana madness ...**

Basic notions – on Majorana fermions

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- **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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noticed that particular choice of $\vec{\alpha}$ and β yields a real wave-function !

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Physical implication: **particle = antiparticle**

$\Longrightarrow$ **Basic features:** **chargeless**

zero-energy

Searching for majoranas – in particle and nuclear physics

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DOUBLE BETA DECAY

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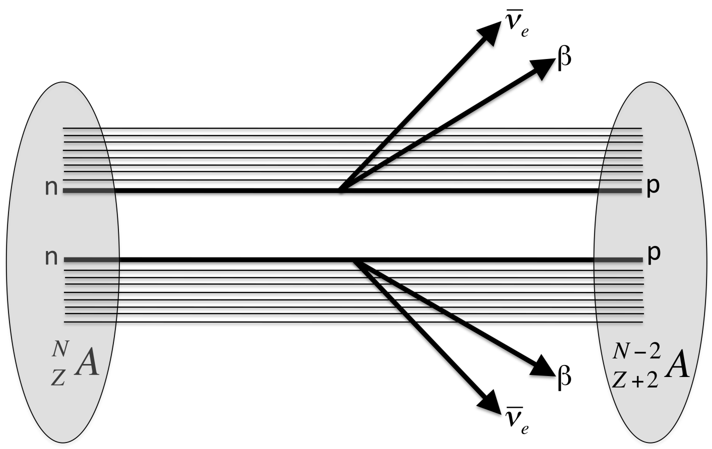
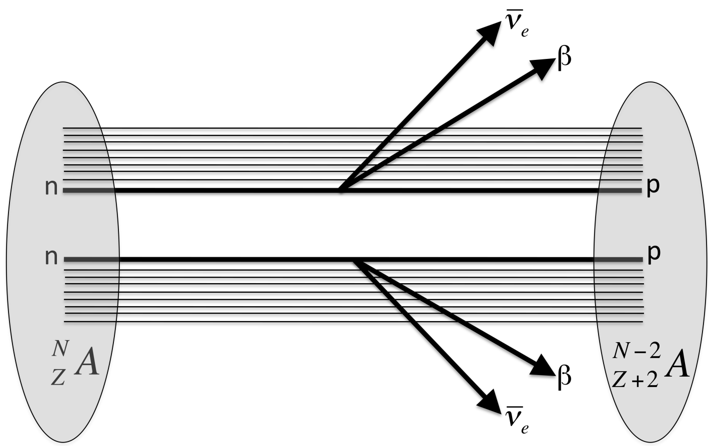


$$^{N}_{Z}A \longrightarrow ^{N-2}_{Z+2}A + 2\beta^- + 2\bar{\nu}_e$$

Searching for majoranas – in particular and nuclear physics

DOUBLE BETA DECAY



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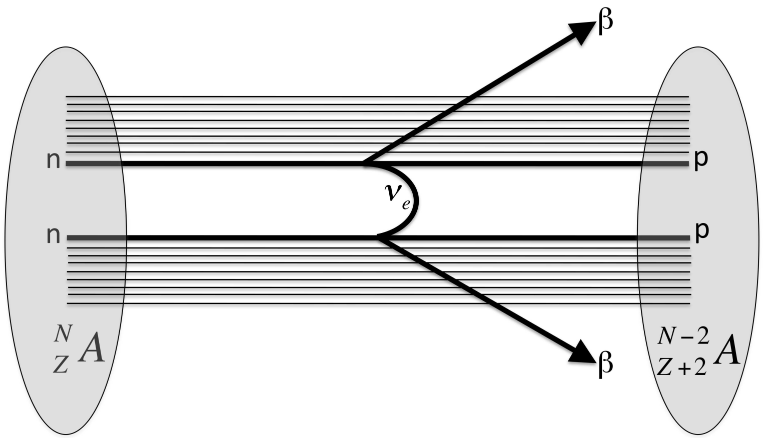

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Neutrinoless decay would imply neutrinos to be majoranas.

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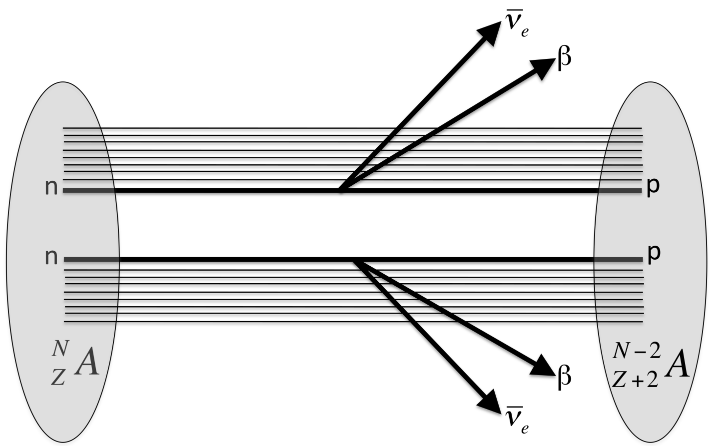

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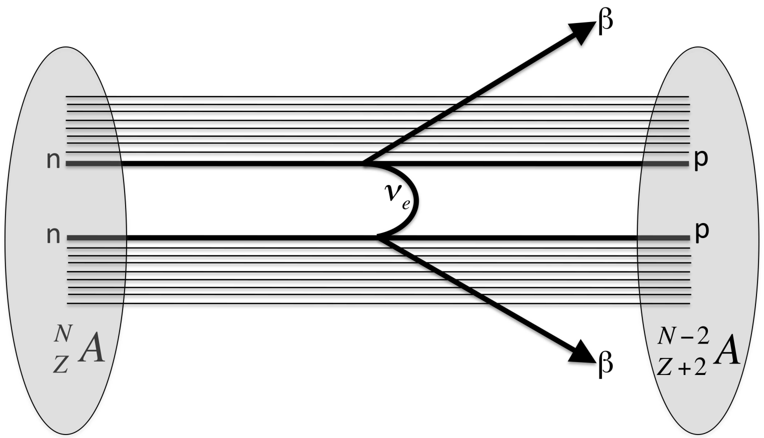

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Neutrinoless decay would imply neutrinos to be majoranas.

This issue is still under dispute.

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- ⋆ So, how about <u>majoranions</u> ?

- ⋆ Formaly, any Dirac fermion can be <u>majoranized</u> ...

Majoranization – of normal fermions

- Dirac 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**

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

’real’ and ’imaginary’ parts

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$\hat{\gamma}_{i,n}$ correspond to <u>neutral</u> objects

- 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

Majoranization – of normal fermions

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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’

Majoranization – does it make sense ?

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- **Majorana-type quasiparticles**

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- resemble the Bogoliubov qps of BCS theory

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- At Fermi level $u_{k_F} = v_{k_F} = 1/\sqrt{2}$, thus

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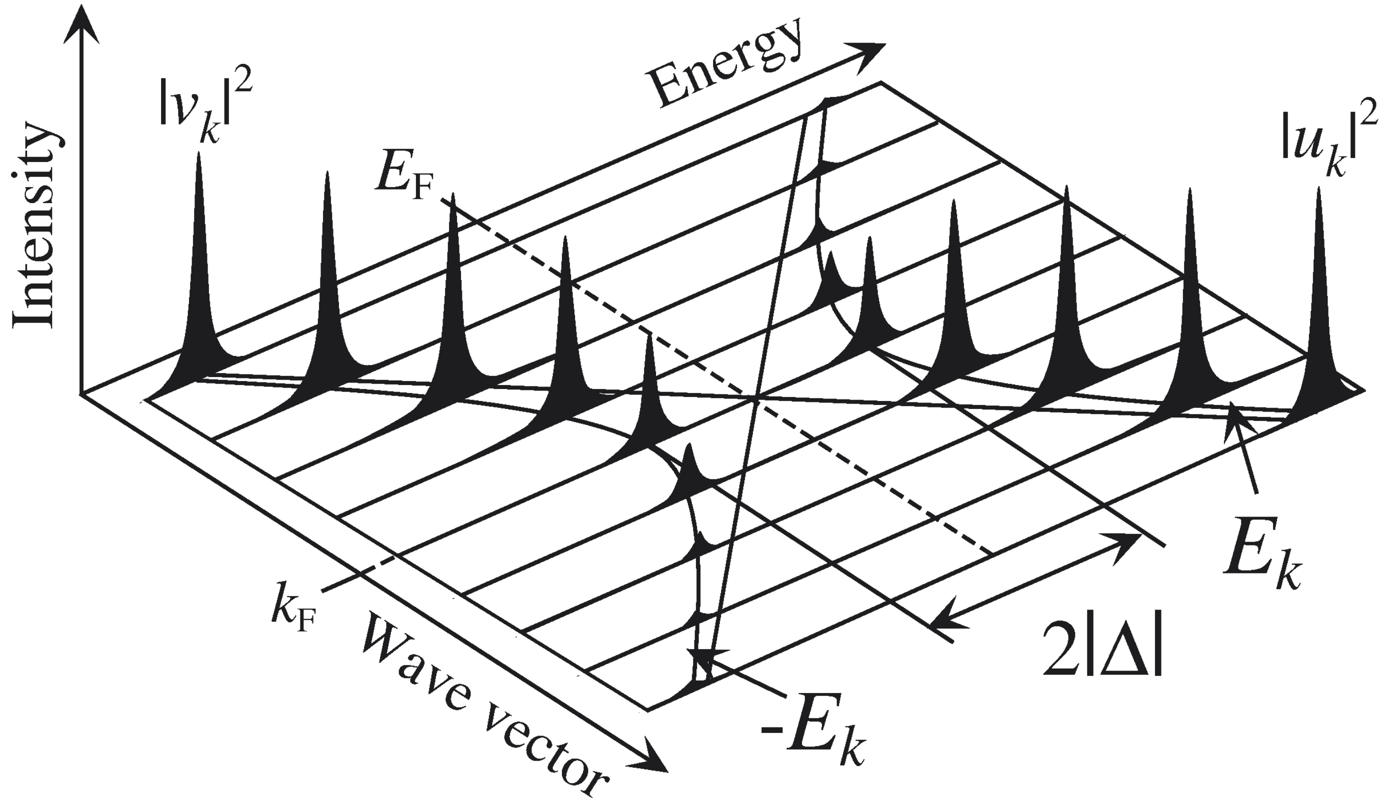
OK, what is their energy ?

Bogoliubov quasiparticles – in superconductors



Bogoliubov qps of s-wave superconductors are gapped $\pm\sqrt{\varepsilon_k^2 + \Delta^2}$.

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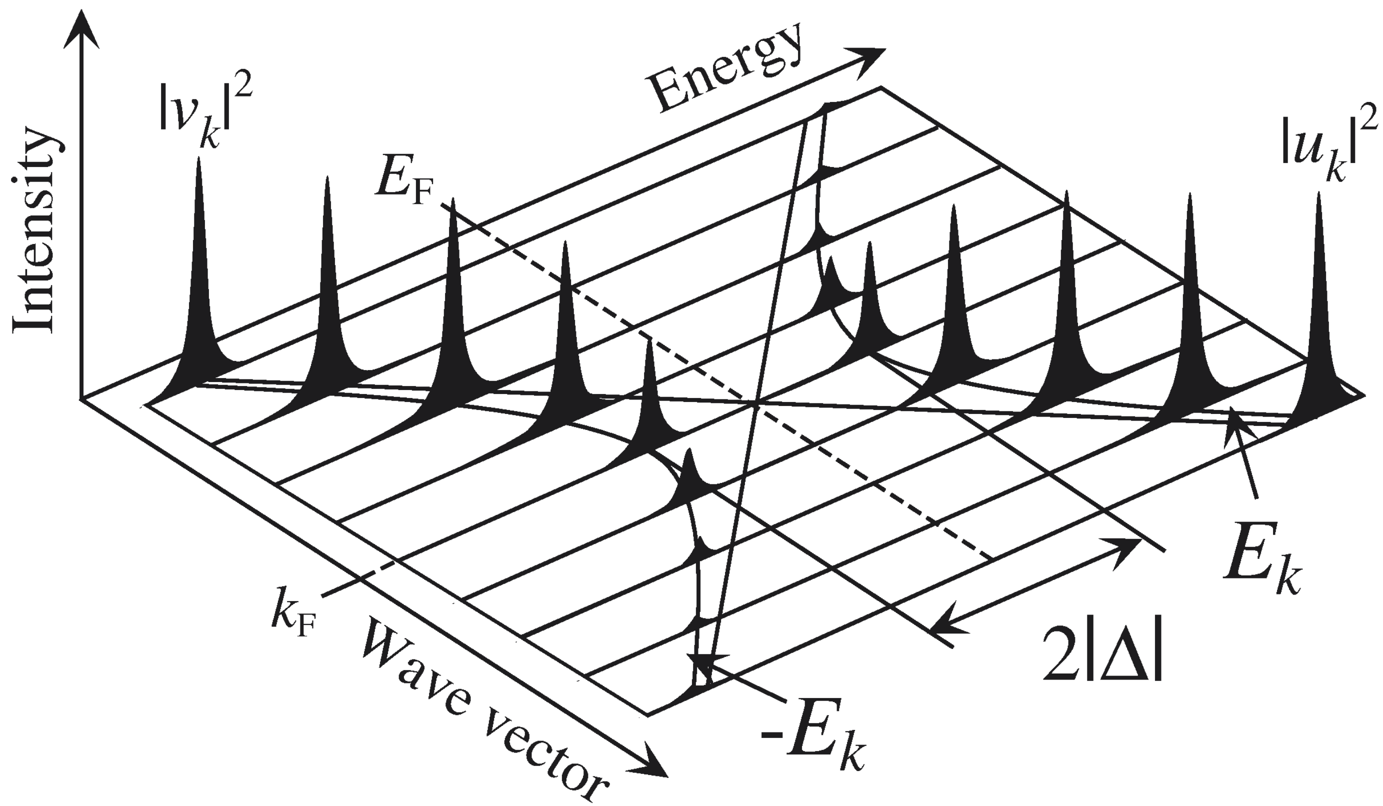

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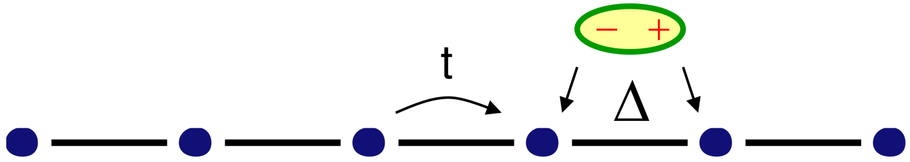
True majoranas have to be the zero energy ($E_k = 0$) quasiparticles !

Kitaev chain – **a paradigm for Majorana modes**



p-wave pairing of spinless 1D fermions

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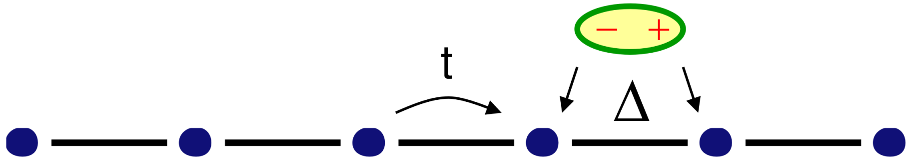

p-wave pairing of spinless 1D fermions

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

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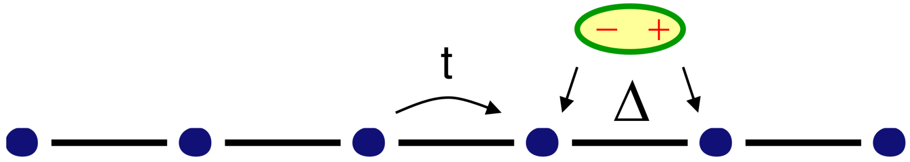

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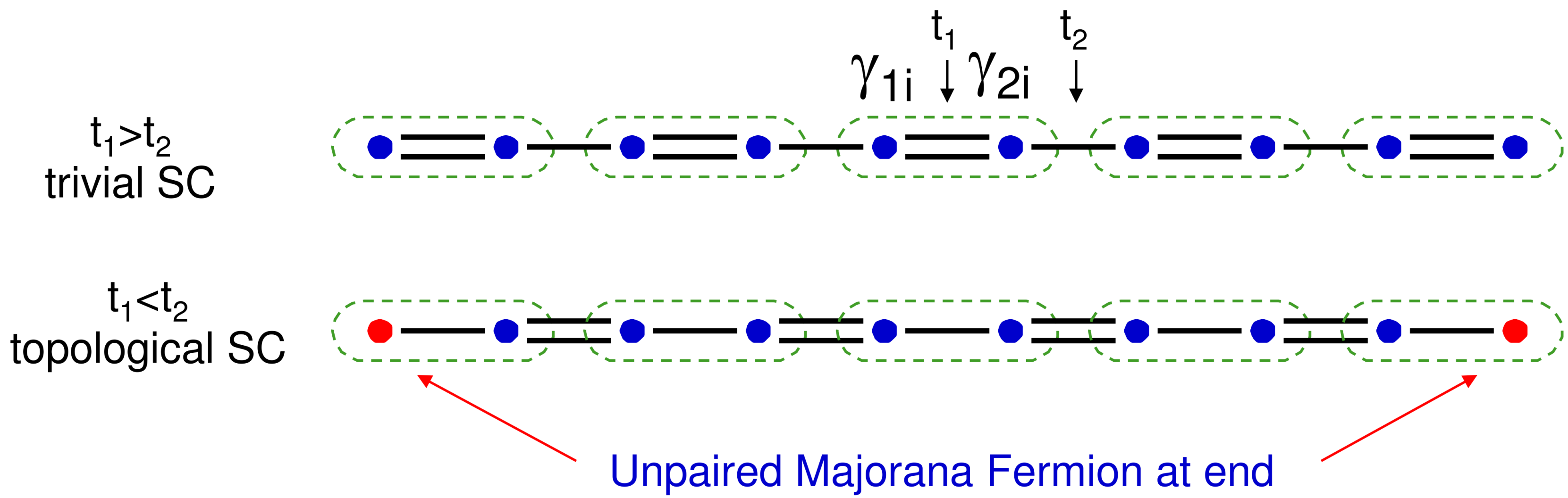
This toy-model can be exactly solved in Majorana basis. For $\Delta = t$ one obtains:



$t_1 \equiv \mu$

$t_2 \equiv 2t$

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, what implies

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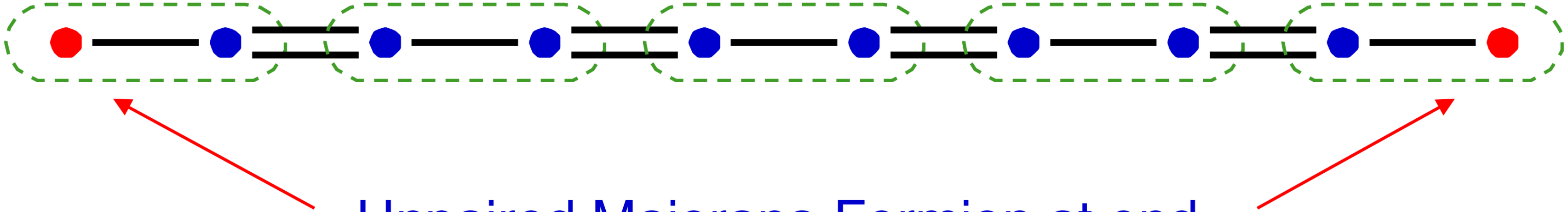

Unpaired Majorana Fermion at end

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

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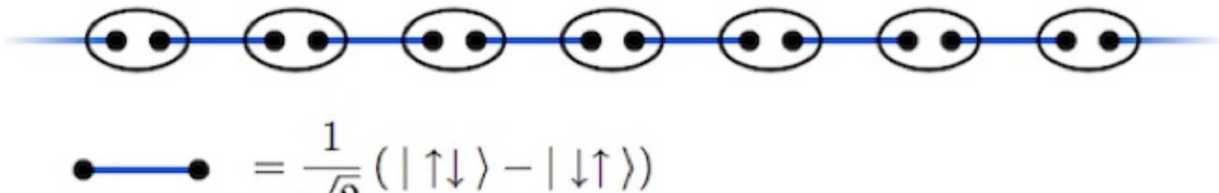
★ **Similar ideas have been considered for 1D Heisenberg chain of 1/2 spins**



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

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

Nobel Prize, 2016

Various scenarios – for Majorana quasiparticles

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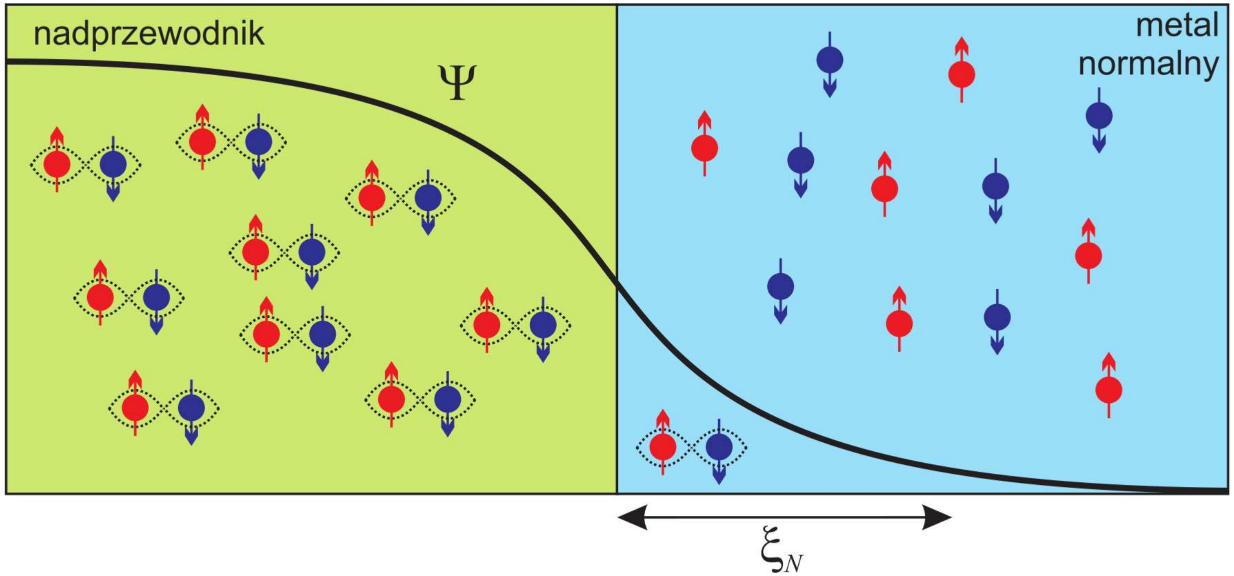
- **magnetic atoms chain on superconducting substrate**

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

2. Electron pairing in nanosystems

Superconductivity in nanosystems

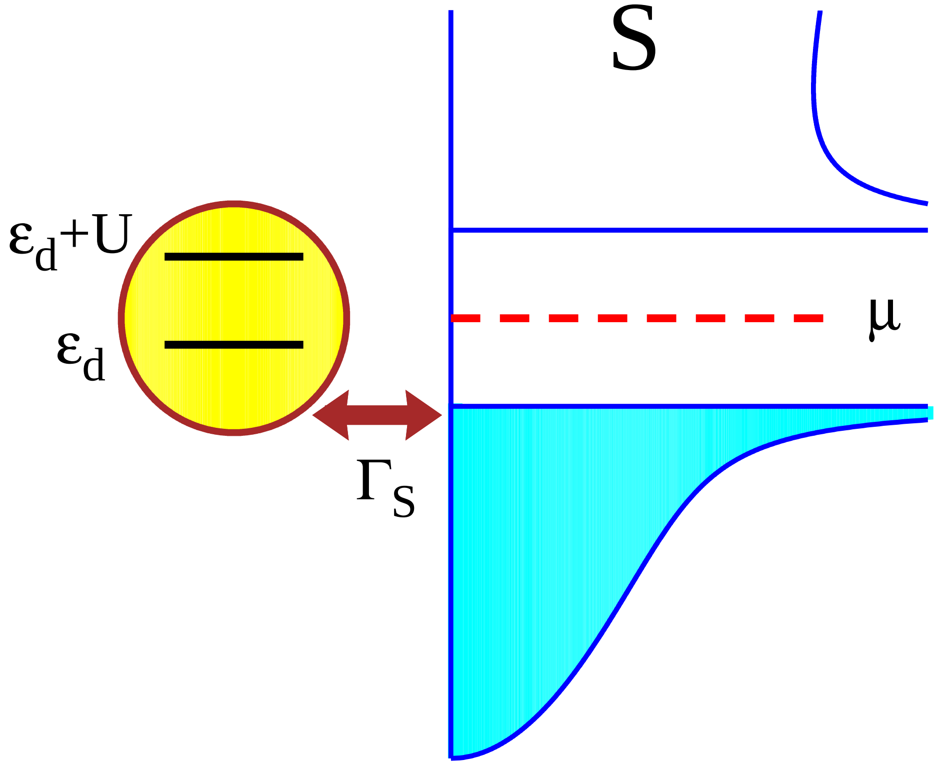
1 Any material brought in contact with a bulk superconductor absorbs the Cooper pairs



Usually the size of quantum dots is smaller than ξ_N

Prototype model – single Anderson impurity

The single quantum impurity (dot) coupled to superconducting reservoir



ε_d – energy level, U – Coulomb potential, Γ_S – hybridization

Microscopic model

Anderson-type Hamiltonian

Quantum impurity (dot)

$$\hat{H}_{QD} = \sum_{\sigma} \epsilon_d \, \hat{d}^\dagger_\sigma \, \hat{d}_\sigma \; + \; U \; \hat{n}_{d\uparrow} \; \hat{n}_{d\downarrow}$$

coupled with a superconductor

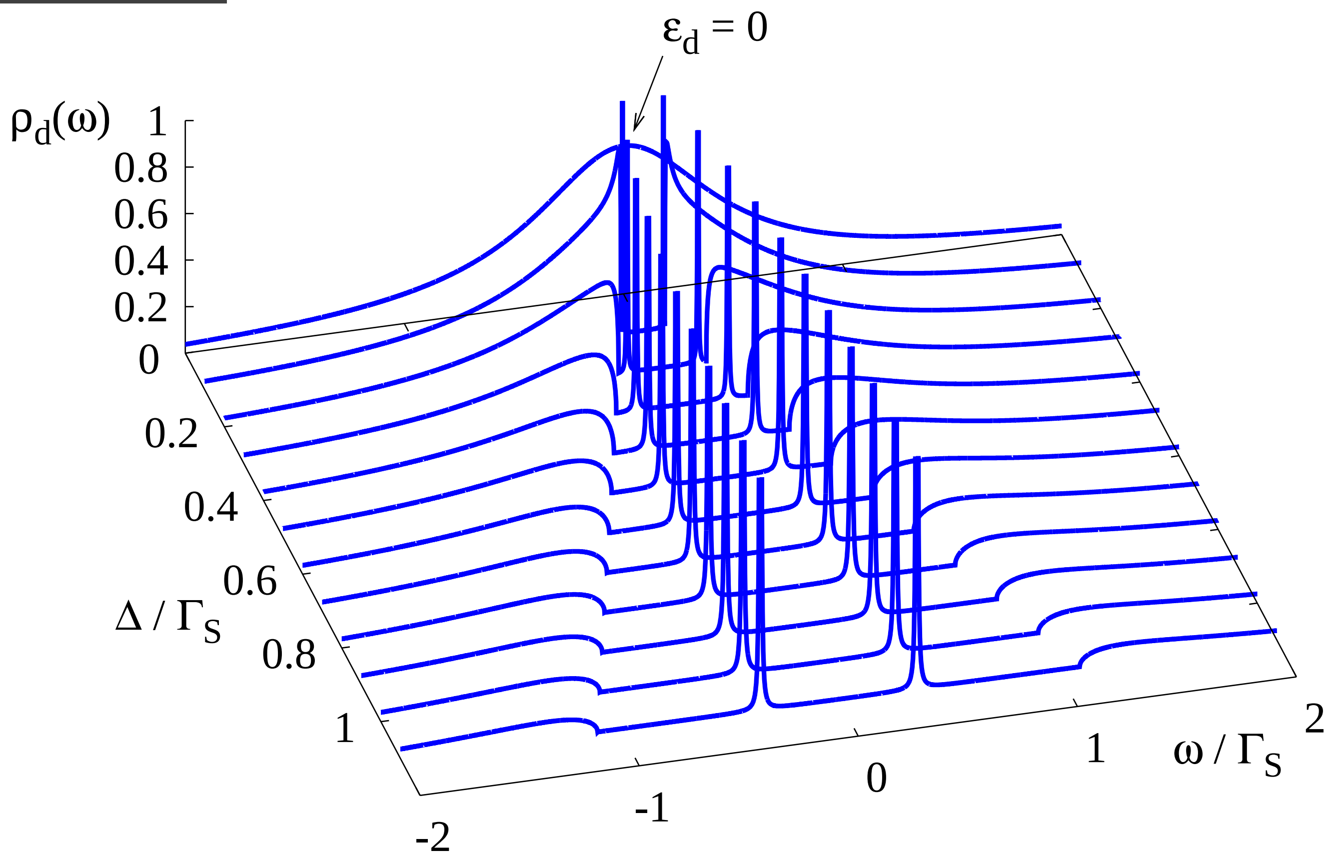
$$\begin{aligned} \hat{H} \;\; &= \;\; \sum_{\sigma} \epsilon_d \hat{d}^\dagger_\sigma \hat{d}_\sigma + U \; \hat{n}_{d\uparrow} \; \hat{n}_{d\downarrow} + \hat{H}_S \\ &+ \;\; \sum_{\mathrm{k},\sigma} \left(V_{\mathrm{k}} \; \hat{d}^\dagger_\sigma \hat{c}_{\mathrm{k}\sigma} + V^*_{\mathrm{k}} \; \hat{c}^\dagger_{\mathrm{k}\sigma} \hat{d}_\sigma \right) \end{aligned}$$

where

$$\hat{H}_S = \sum_{k,\sigma} \left(\varepsilon_k - \mu \right) \hat{c}^\dagger_{k\sigma} \hat{c}_{k\sigma} - \sum_k \left(\Delta \hat{c}^\dagger_{k\uparrow} \; \hat{c}^\dagger_{k\downarrow} + \mathrm{h.c.} \right)$$

Uncorrelated QD

$U_d = 0$ (exactly solvable case)



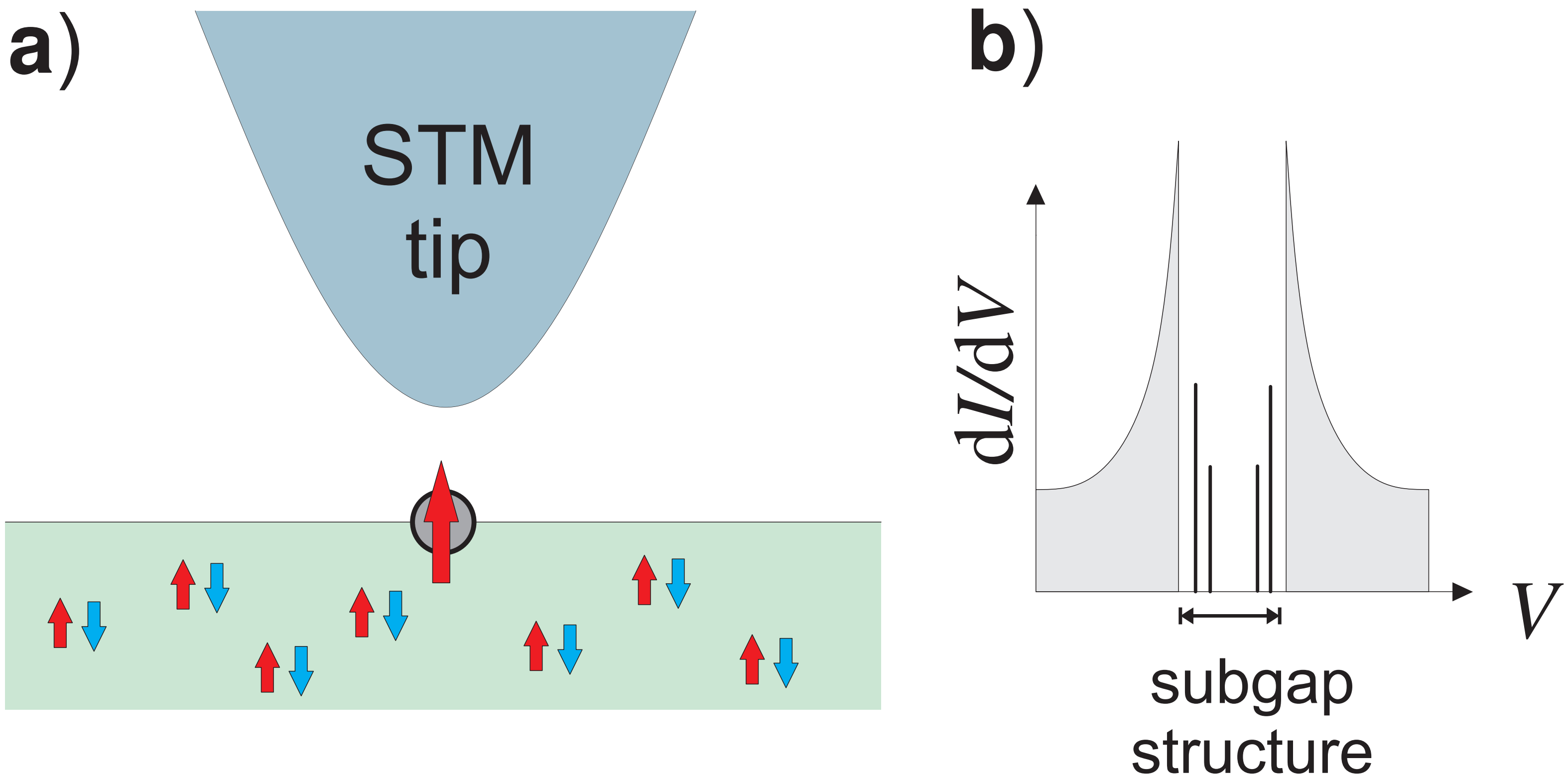
In-gap (Andreev/Shiba) bound states :

⇒ always appear in pairs,

⇒ appear symmetrically at finite energies.

J. Barański and T. Domański, J. Phys.: Condens. Matter **25**, 435305 (2013).

Subgap states of multilevel quantum impurities



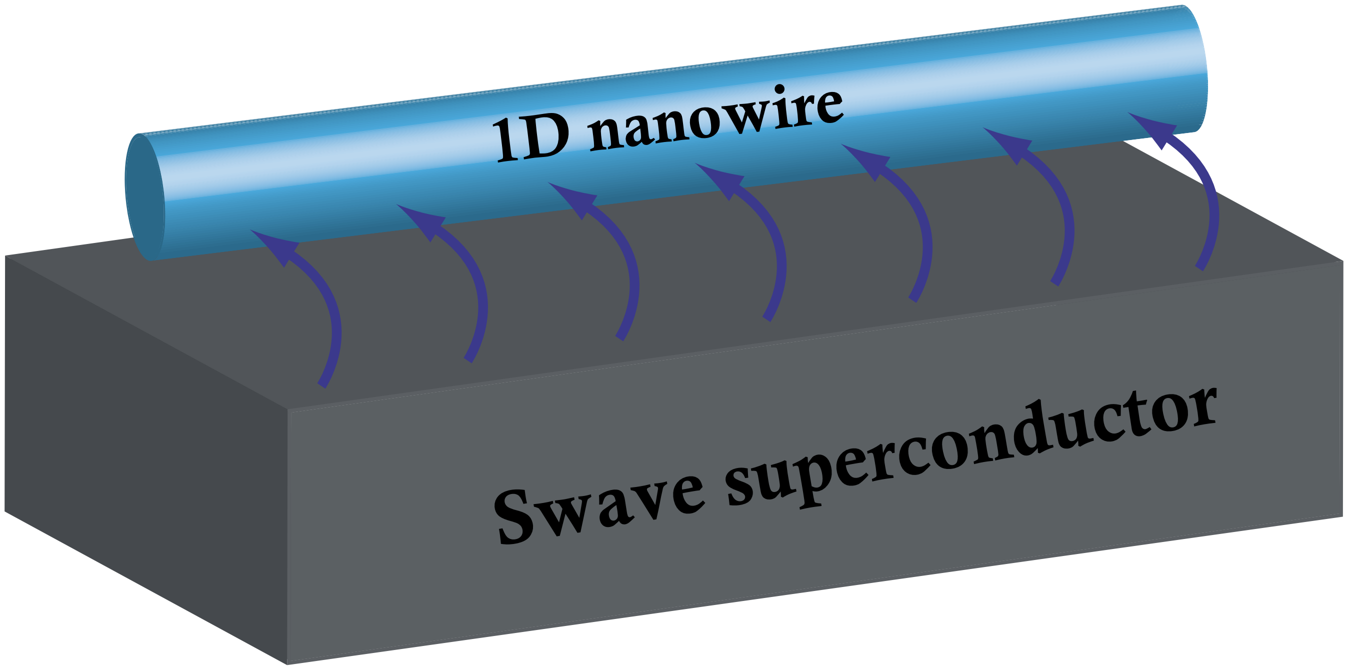
a) STM scheme and b) differential conductance for a multilevel quantum impurity adsorbed on a superconductor surface.

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

Andreev vs Majorana states – a story of mutation

Andreev vs Majorana states – a story of mutation

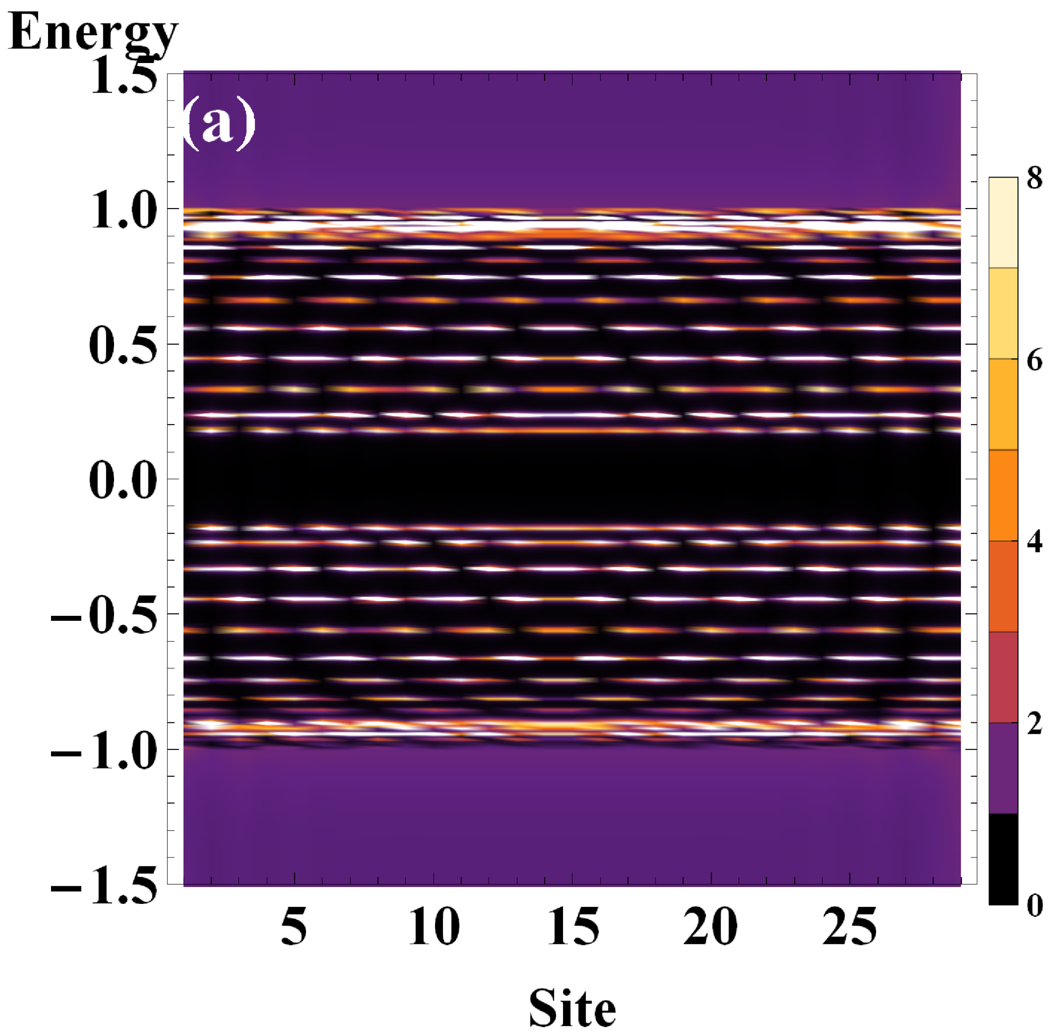
Let us consider:



1D quantum wire deposited on s-wave superconductor

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

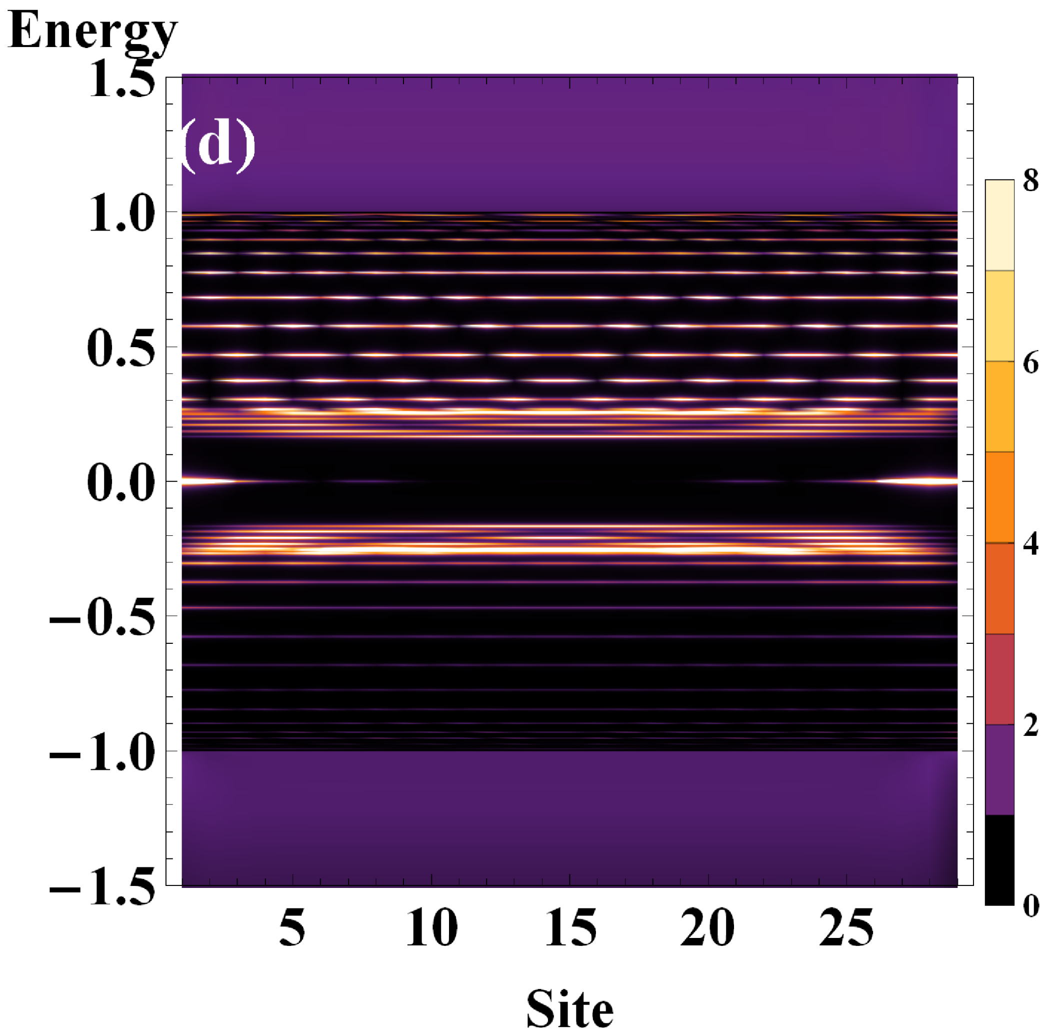
Andreev vs Majorana states – a story of mutation



Spectrum of a quantum wire has a series of Andreev states.

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

Andreev vs Majorana states – a story of mutation



Spin-orbit coupling induces the Majorana-type quasiparticles.

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

Towards more realistic situation

/ Rashba chain + pairing /

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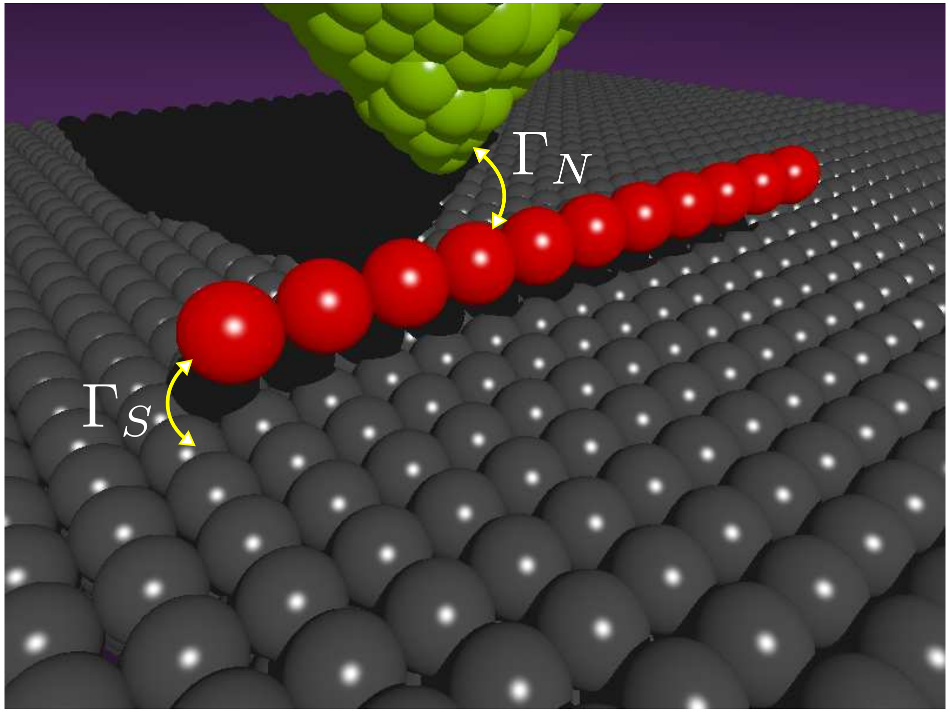
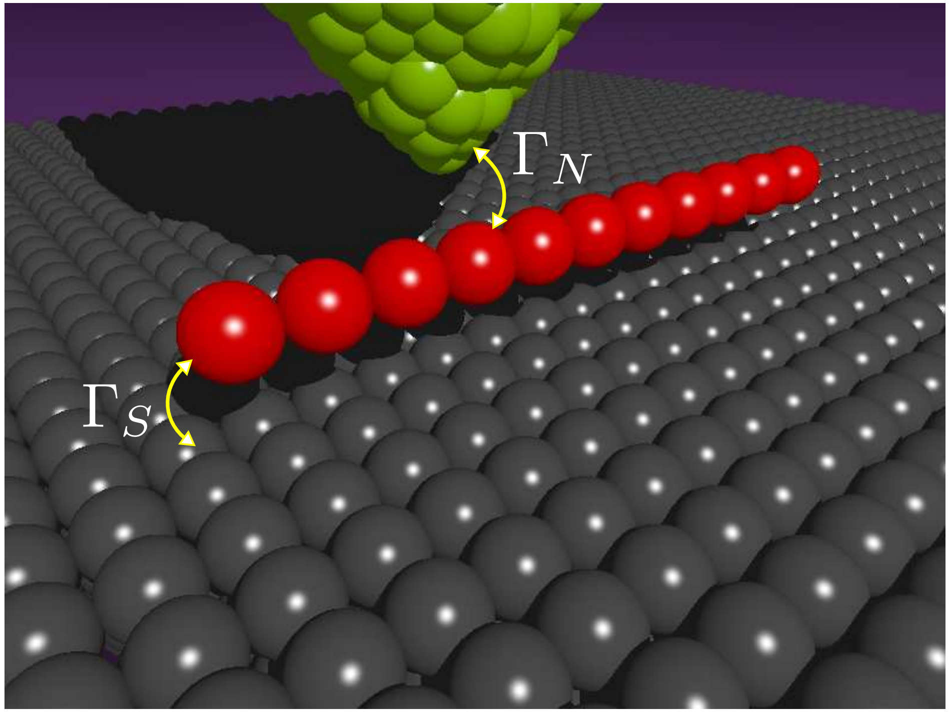


Scheme of STM configuration

Towards more realistic situation

/ Rashba chain + pairing /



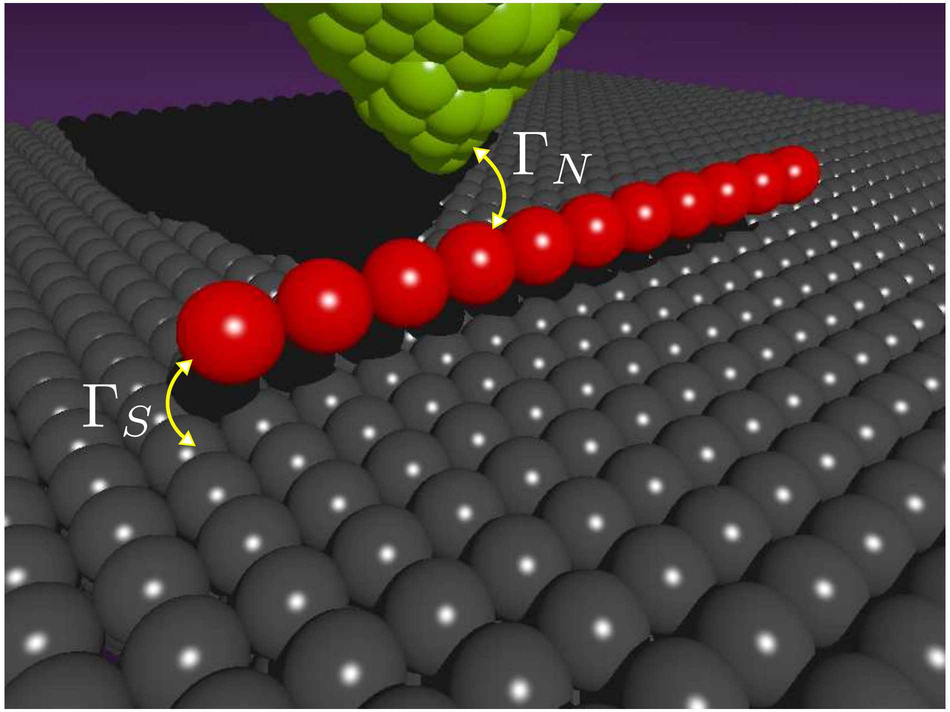
Scheme of STM configuration

$$\hat{H} = \hat{H}_{tip} + \hat{H}_{chain} + \hat{H}_S + \hat{V}_{hybr}$$

We studied this model, focusing on the deep subgap regime $|E| \ll \Delta_{sc}$.

Towards more realistic situation

/ Rashba chain + pairing /



Scheme of STM configuration

where

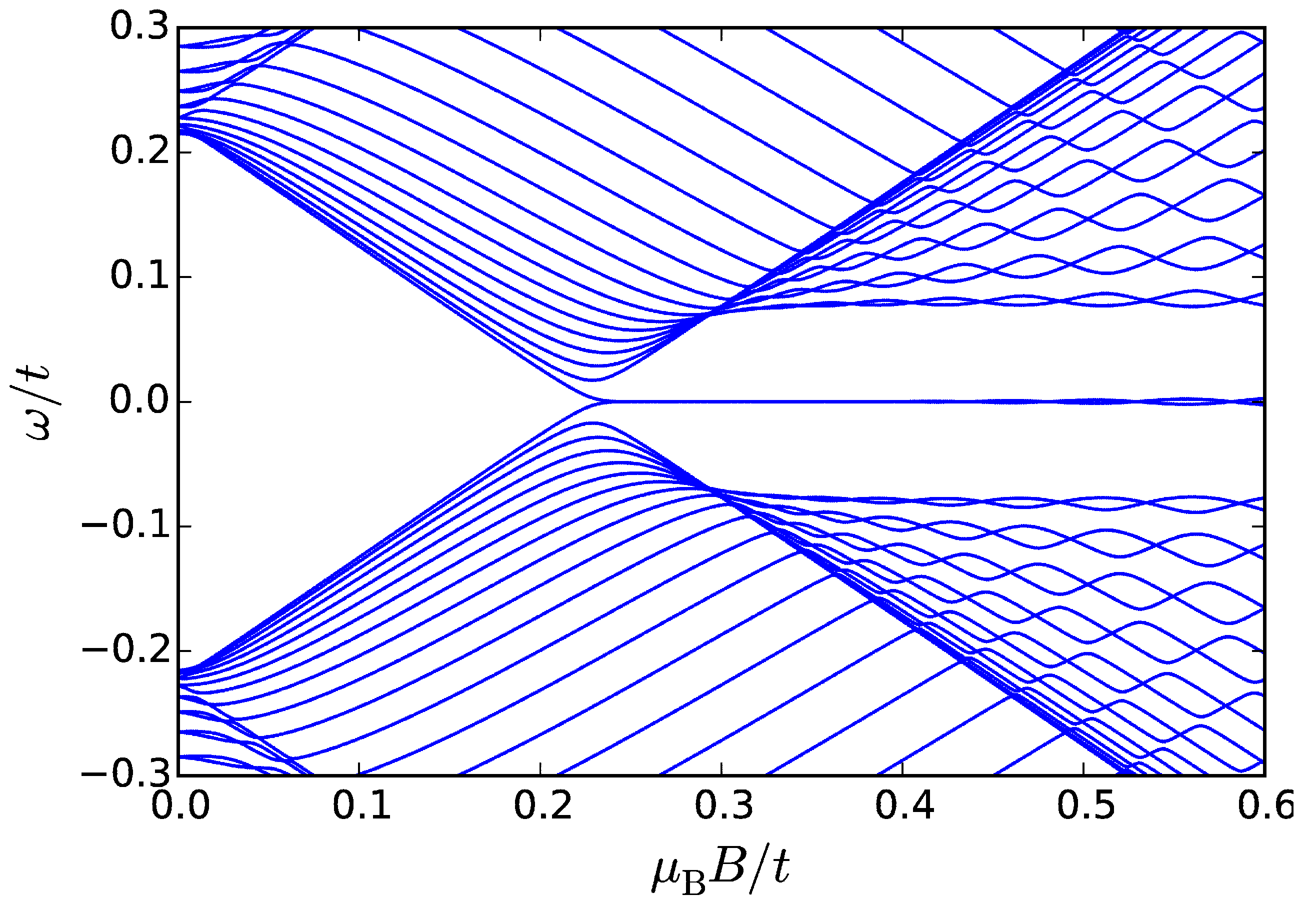
$$\hat{H}_{chain} = \sum_{i,j,\sigma} (t_{ij} - \delta_{ij}\mu) \hat{d}^{\dagger}_{i,\sigma} \hat{d}_{j,\sigma} + \hat{H}_{Rashba} + \hat{H}_{Zeeman}$$

M. Maśka, A. Gorczyca-Goraj, J. Tworzydło and T. Domański, arXiv:1609.00685 (2016).

Majorana states – of the Rashba chain

Majorana states – of the Rashba chain

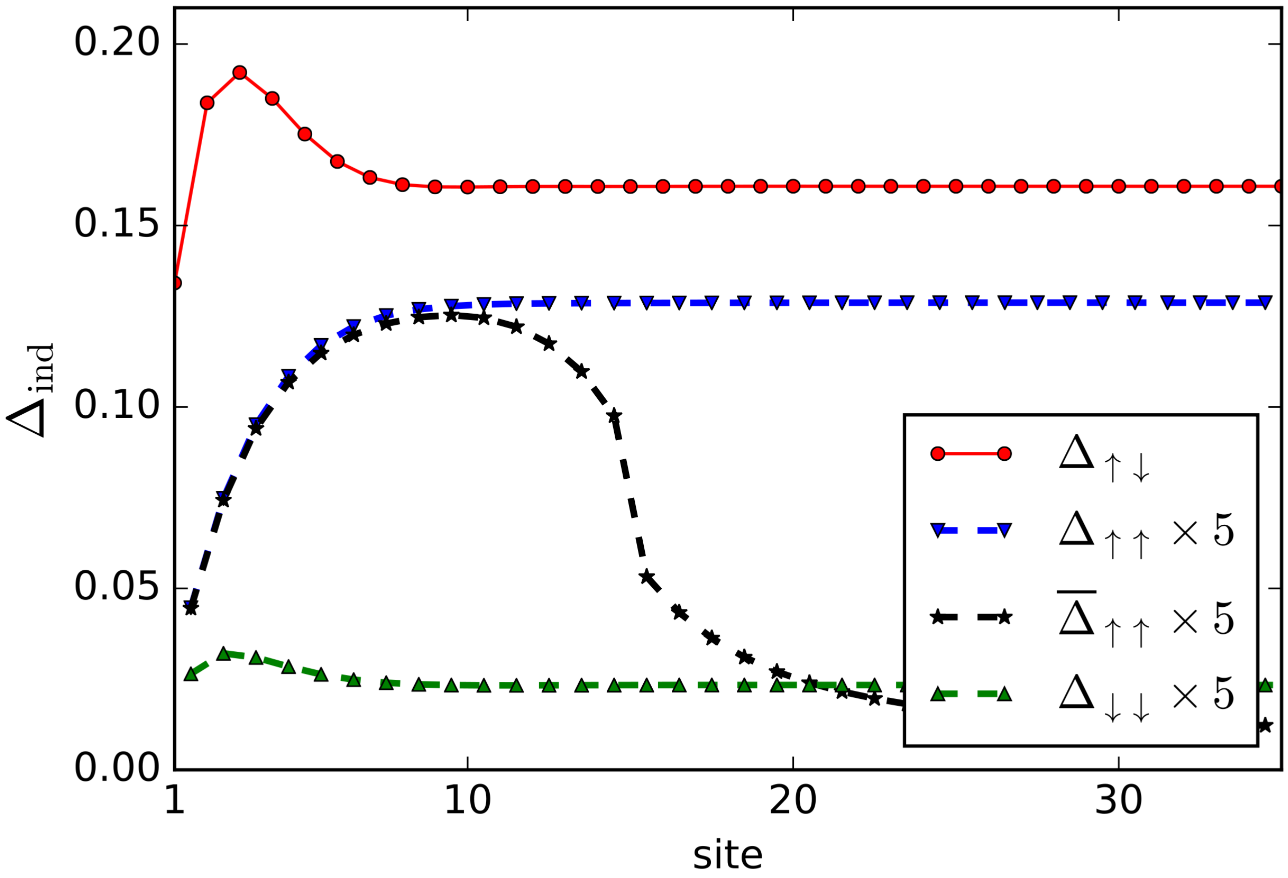
Mutation of Andreev states into zero-energy (Majorana) mode



M. Maśka, A. Gorczyca-Goraj, J. Tworzydło and T. Domański, arXiv:1609.00685 (2016).

Majorana states – of the Rashba chain

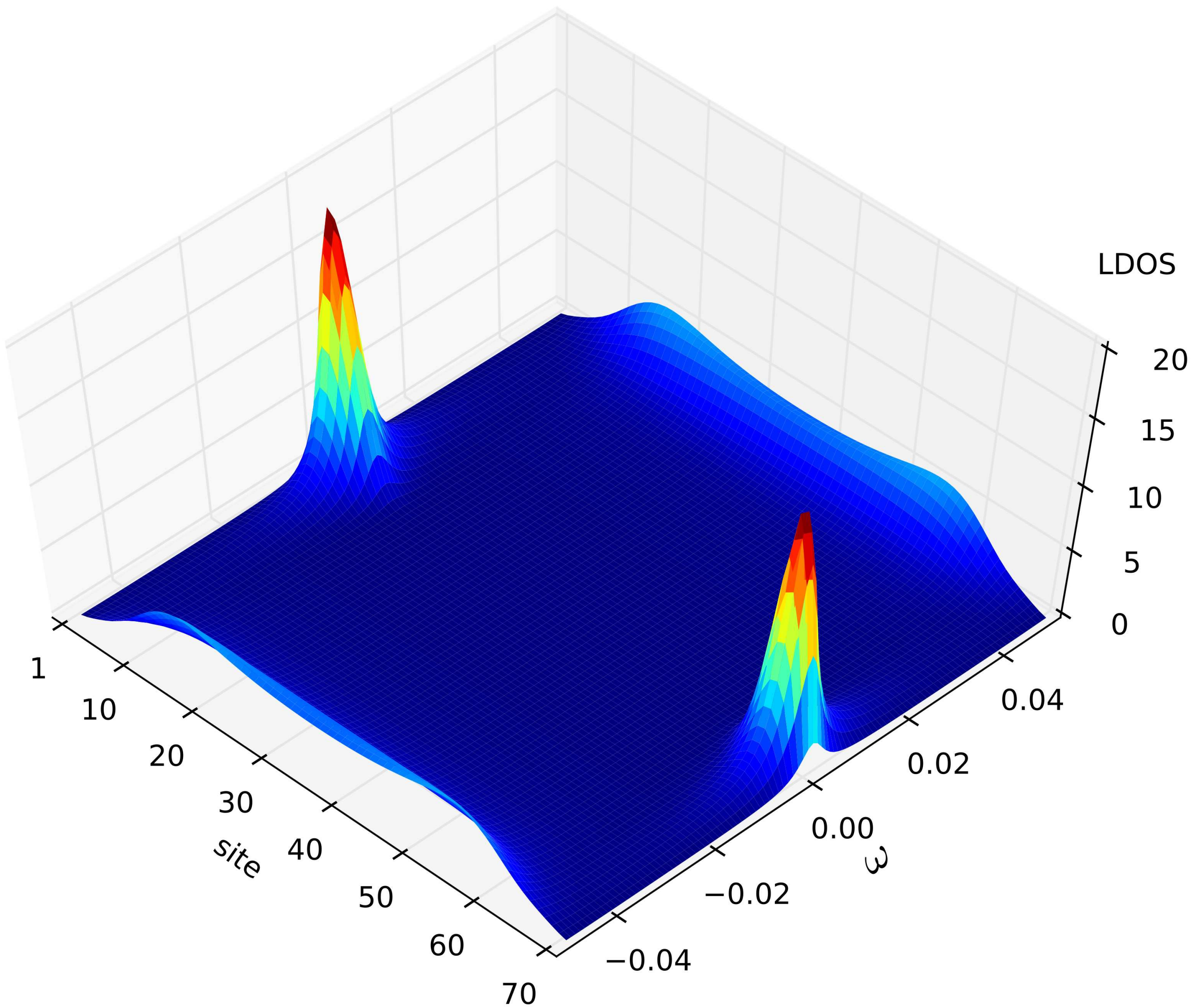
Spatial variation of the induced pairings $\Delta_{\sigma,\sigma'} = \langle \hat{d}_{i,\sigma} \hat{d}_{i+1,\sigma'} \rangle$



M. Maśka, A. Gorczyca-Goraj, J. Tworzydło and T. Domański, arXiv:1609.00685 (2016).

Majorana states – **of the Rashba chain**

Spectrum with the edge Majorana quasiparticles



Breaking the Rashba chain

by a reduced hopping at site $i = N/2$

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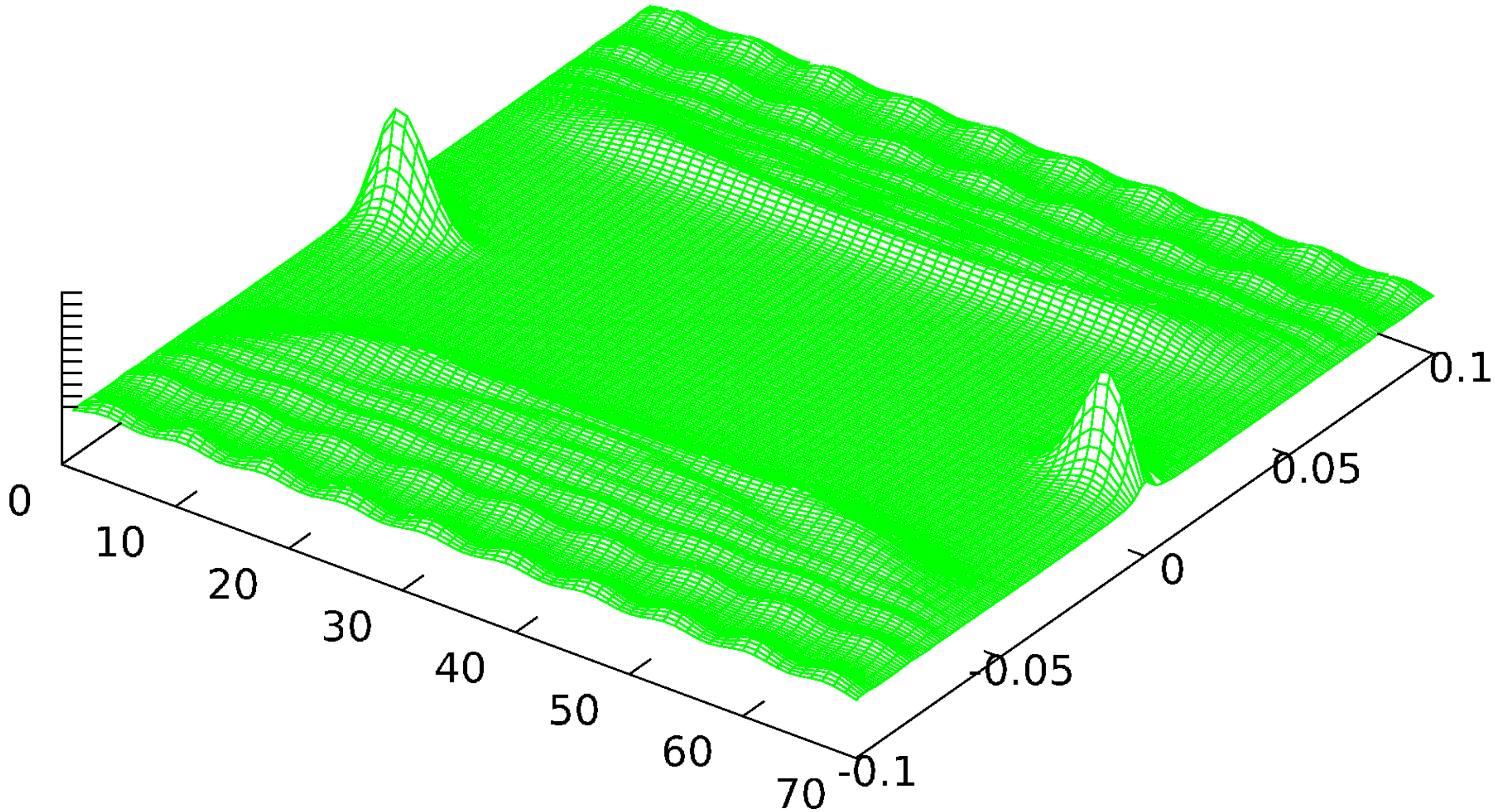
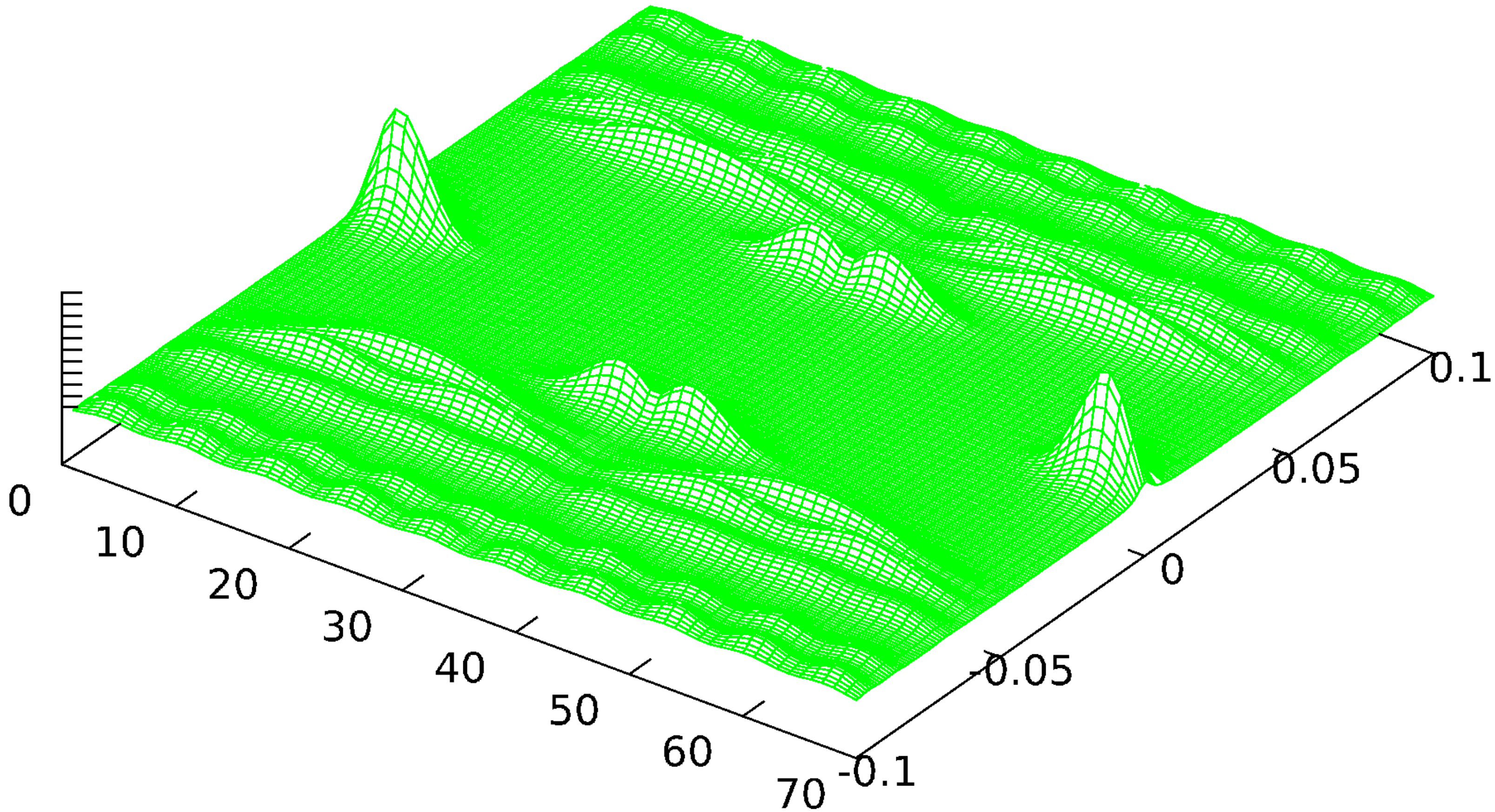
by a reduced hopping at site $i = N/2$



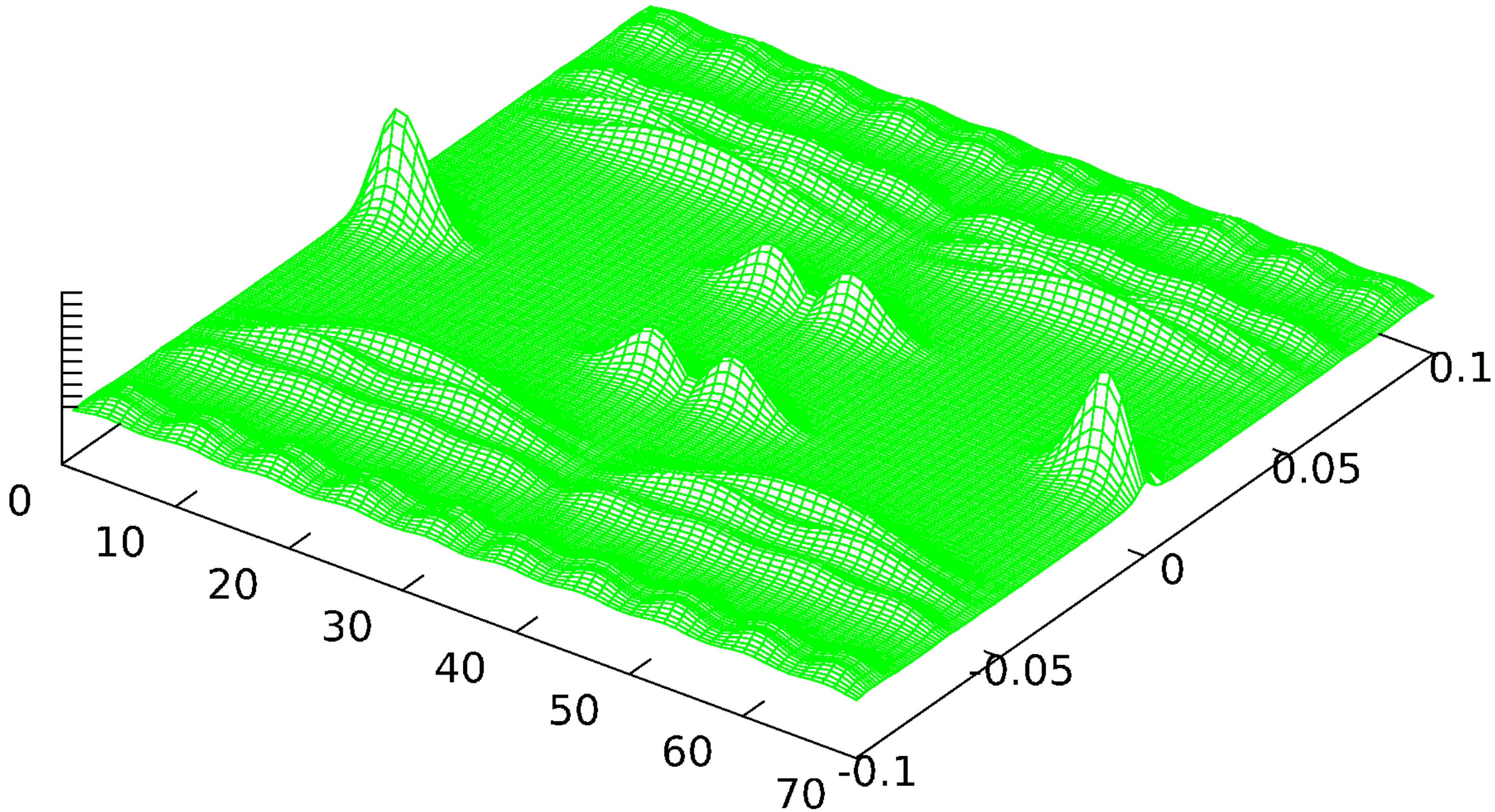
$t_i/t = 1$

Breaking the Rashba chain by a reduced hopping at site $i = N/2$



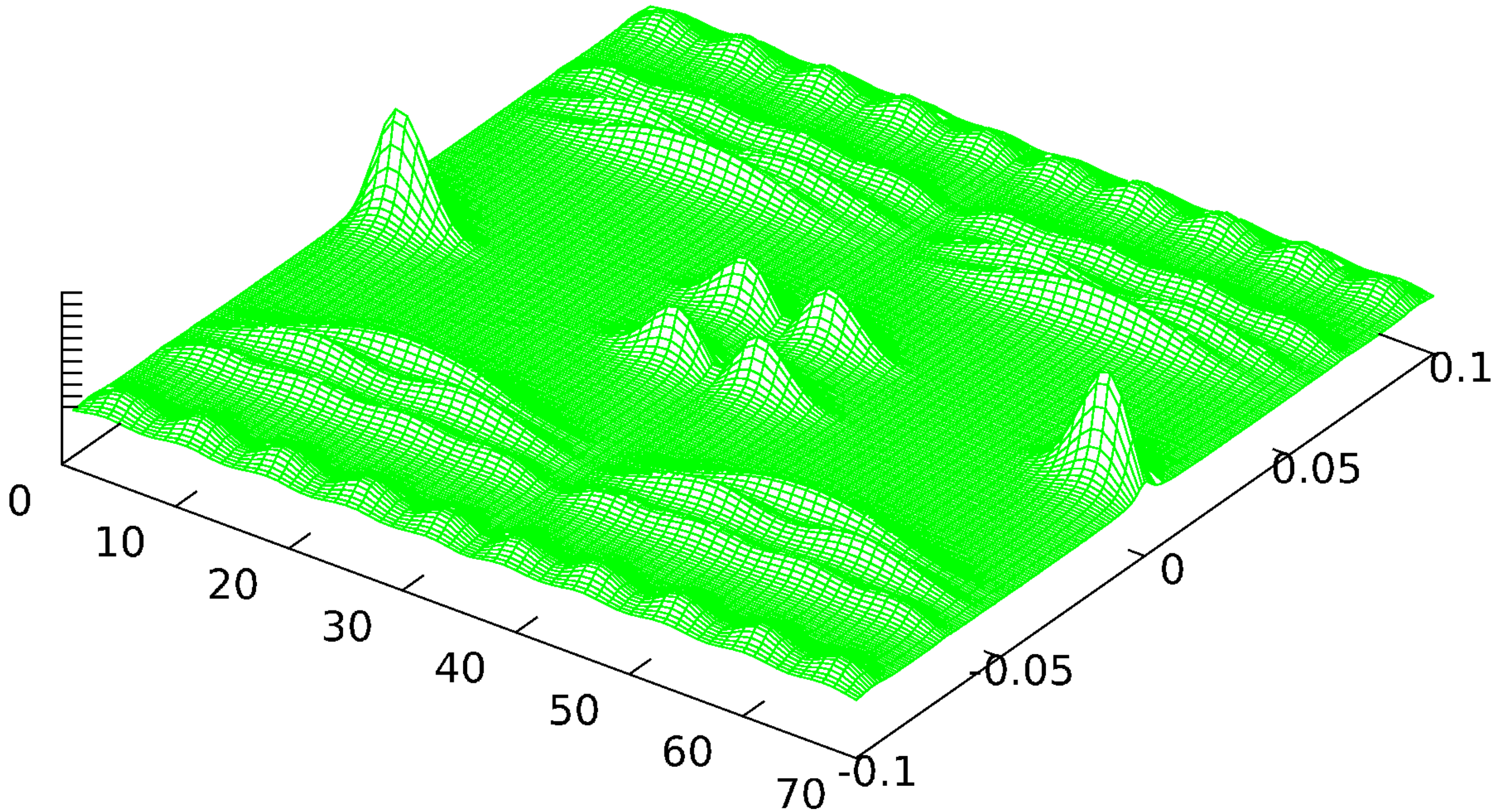
$t_i/t = 0.8$

Breaking the Rashba chain by a reduced hopping at site $i = N/2$



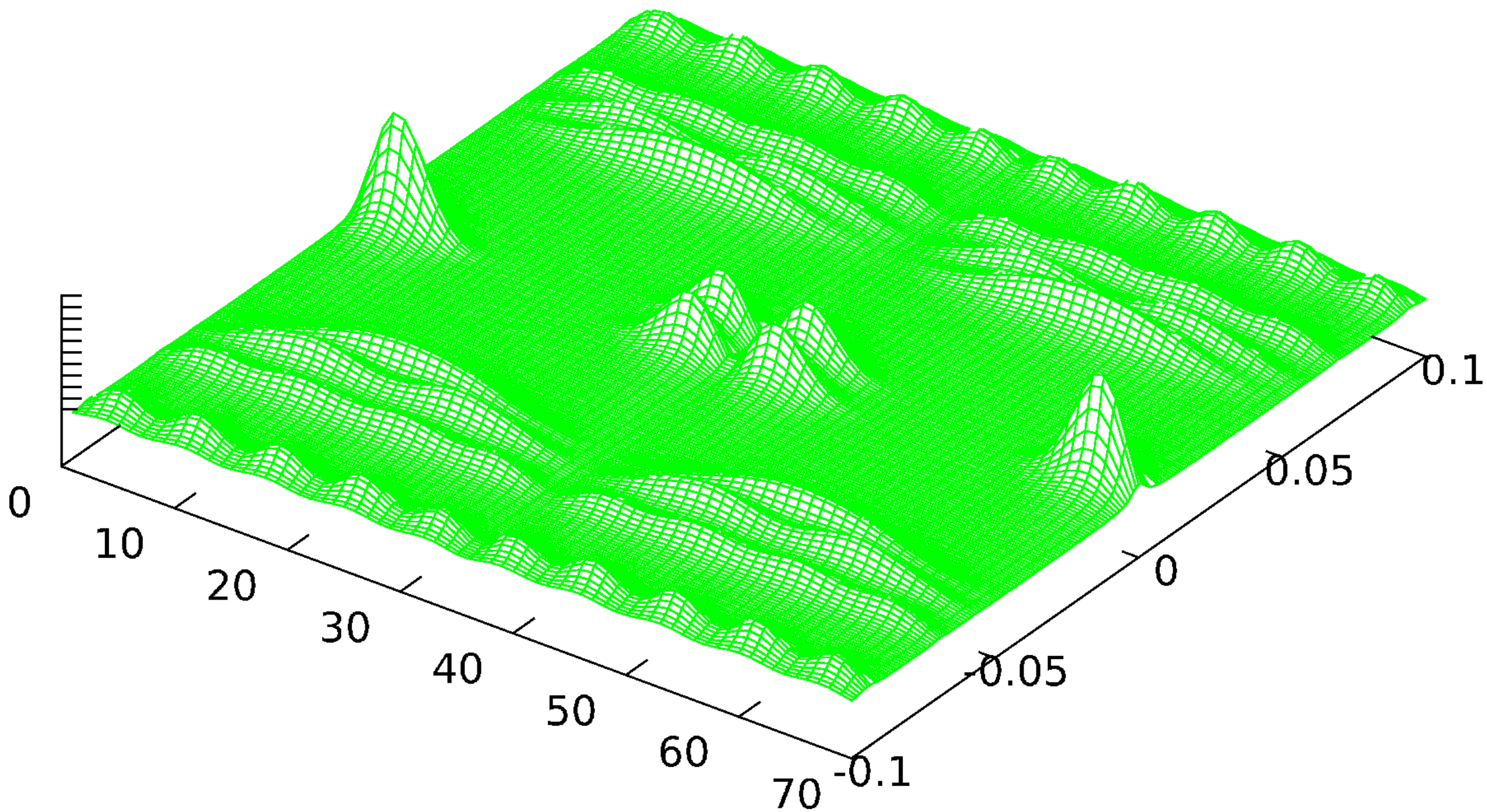
$t_i/t = 0.6$

Breaking the Rashba chain by a reduced hopping at site $i = N/2$



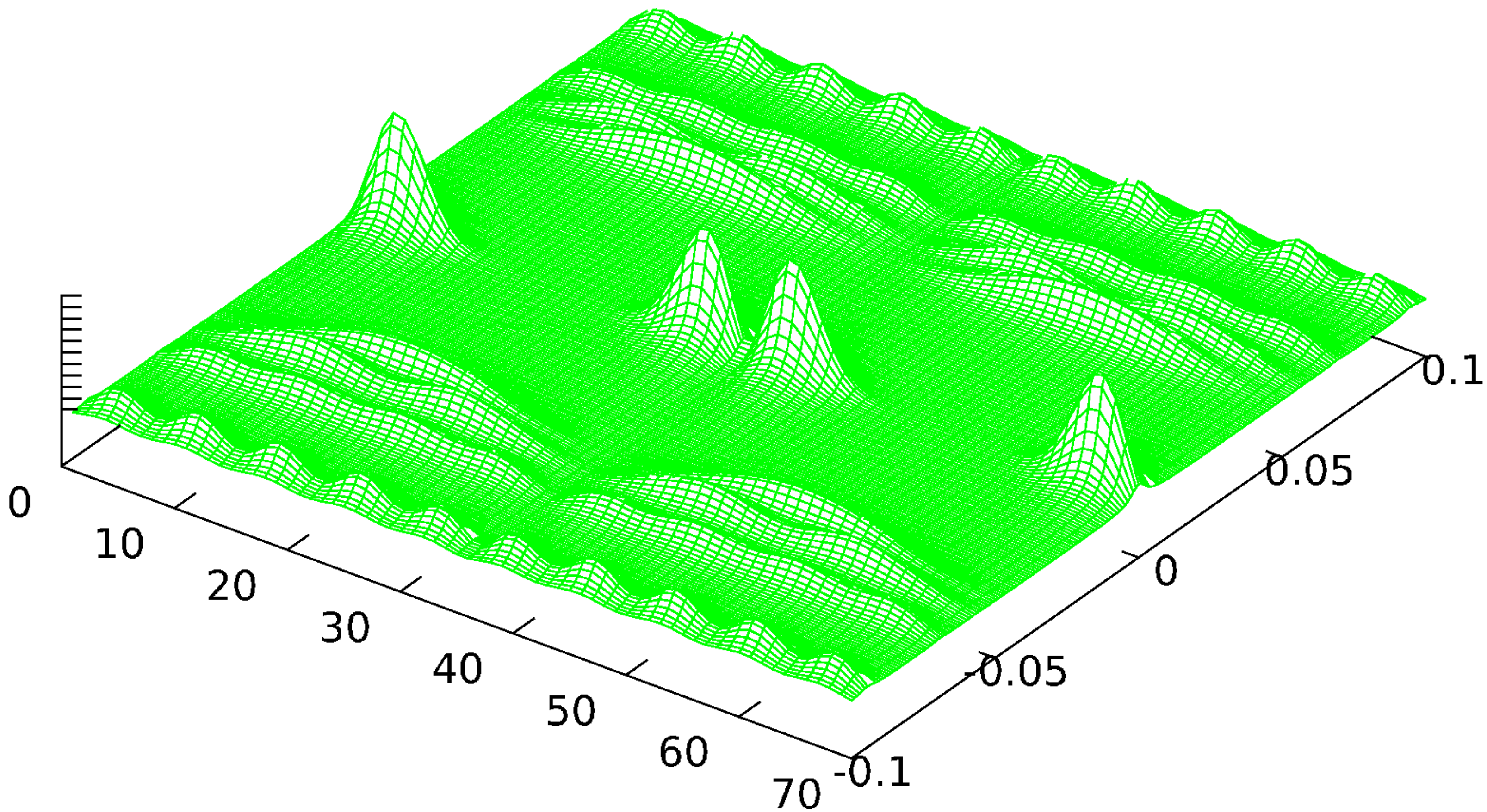
$t_i/t = 0.4$

Breaking the Rashba chain by a reduced hopping at site $i = N/2$



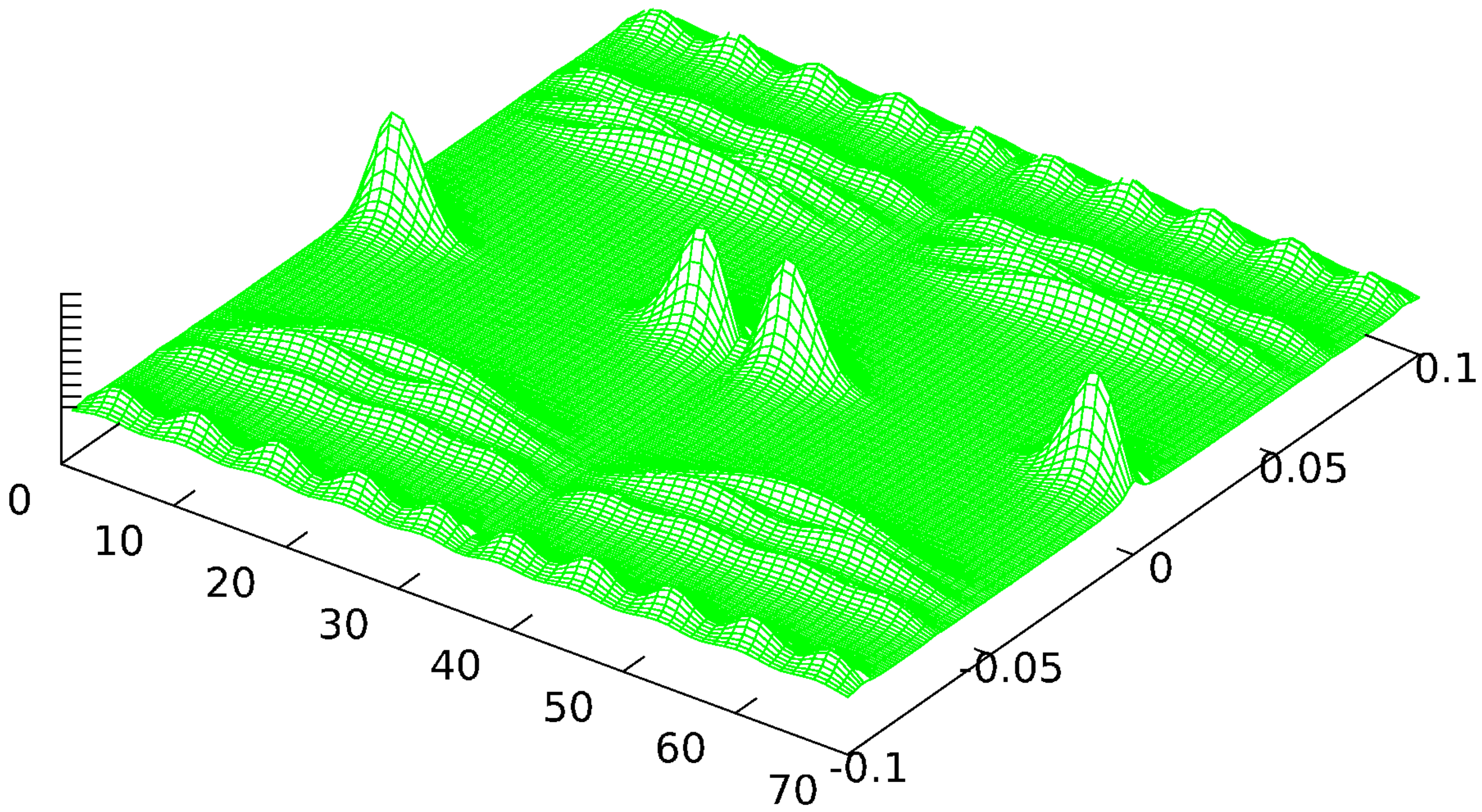
$t_i/t = 0.2$

Breaking the Rashba chain by a reduced hopping at site $i = N/2$



$t_i/t = 0$

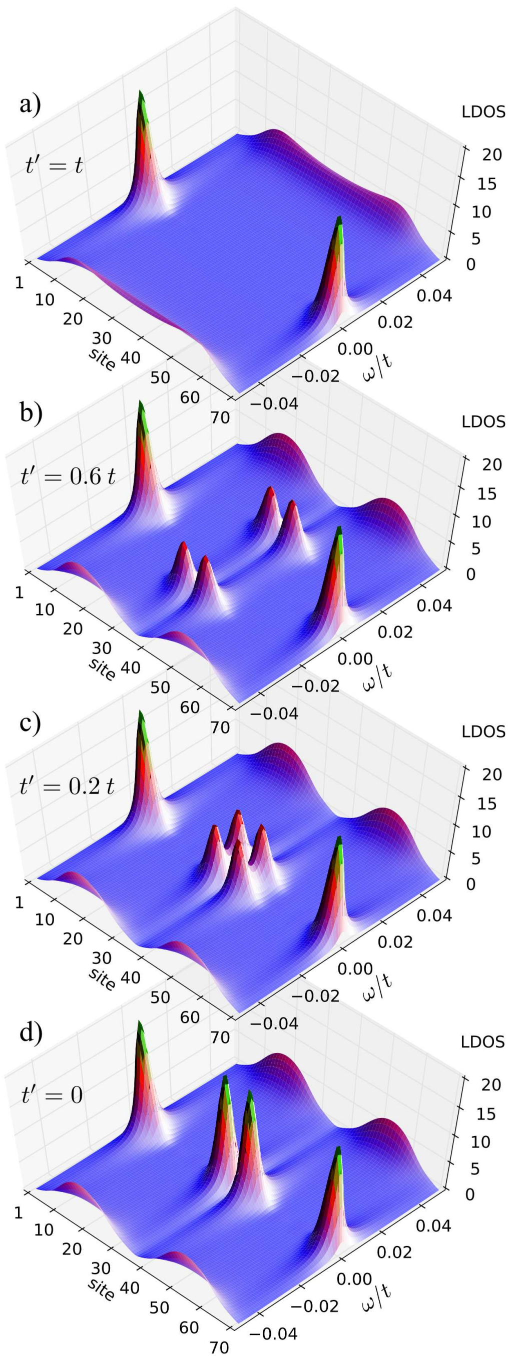
Breaking the Rashba chain by a reduced hopping at site $i = N/2$



Number of Majorana quasiparticles doubled !

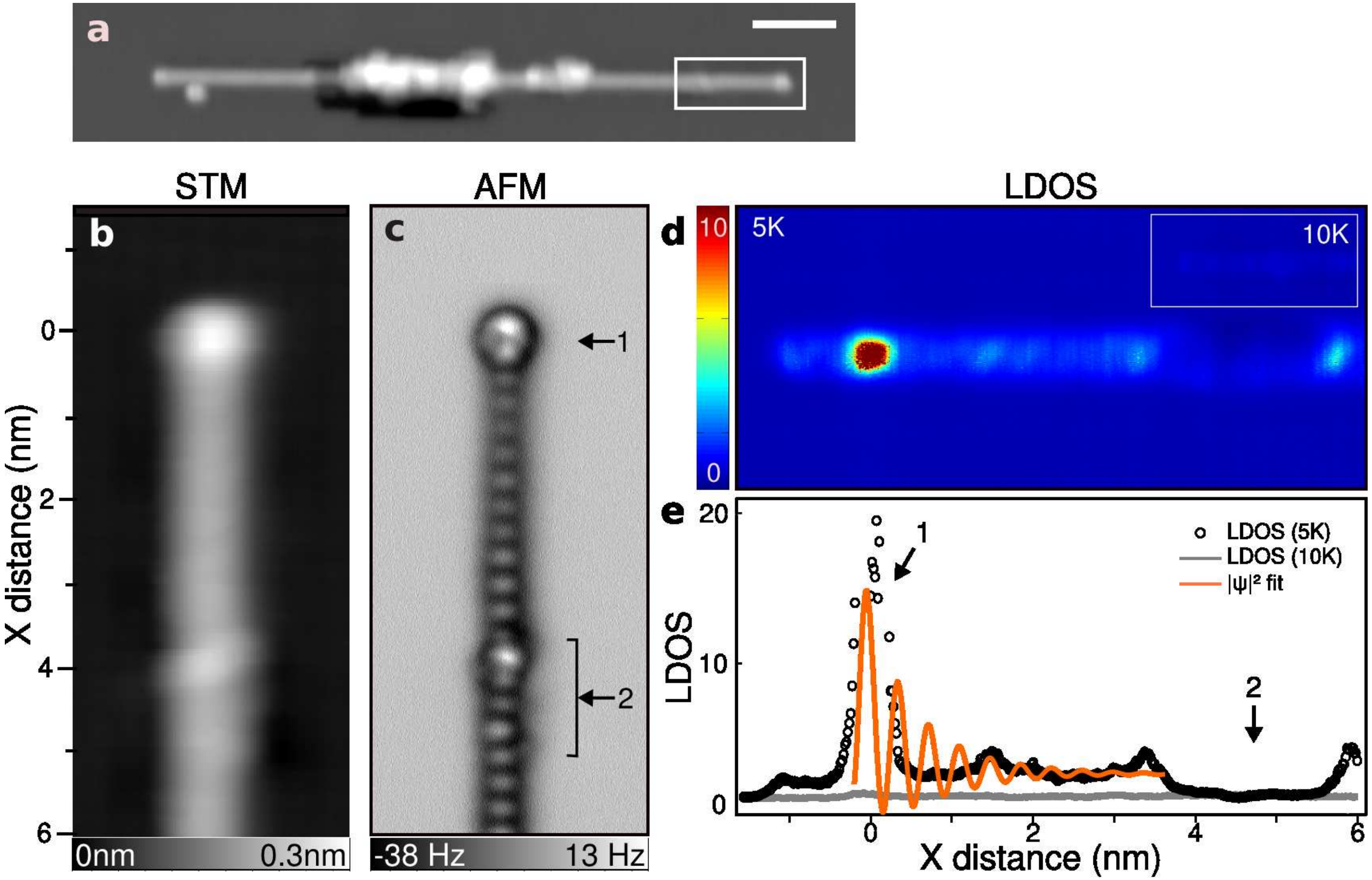
Fussion/splitting of Majorana states

Partitioning
the Rashba chain
into two pieces
via reduced hopping
t_j at site $j = N/2$



M. Maśka et al, arXiv:1609.00685 (2016).

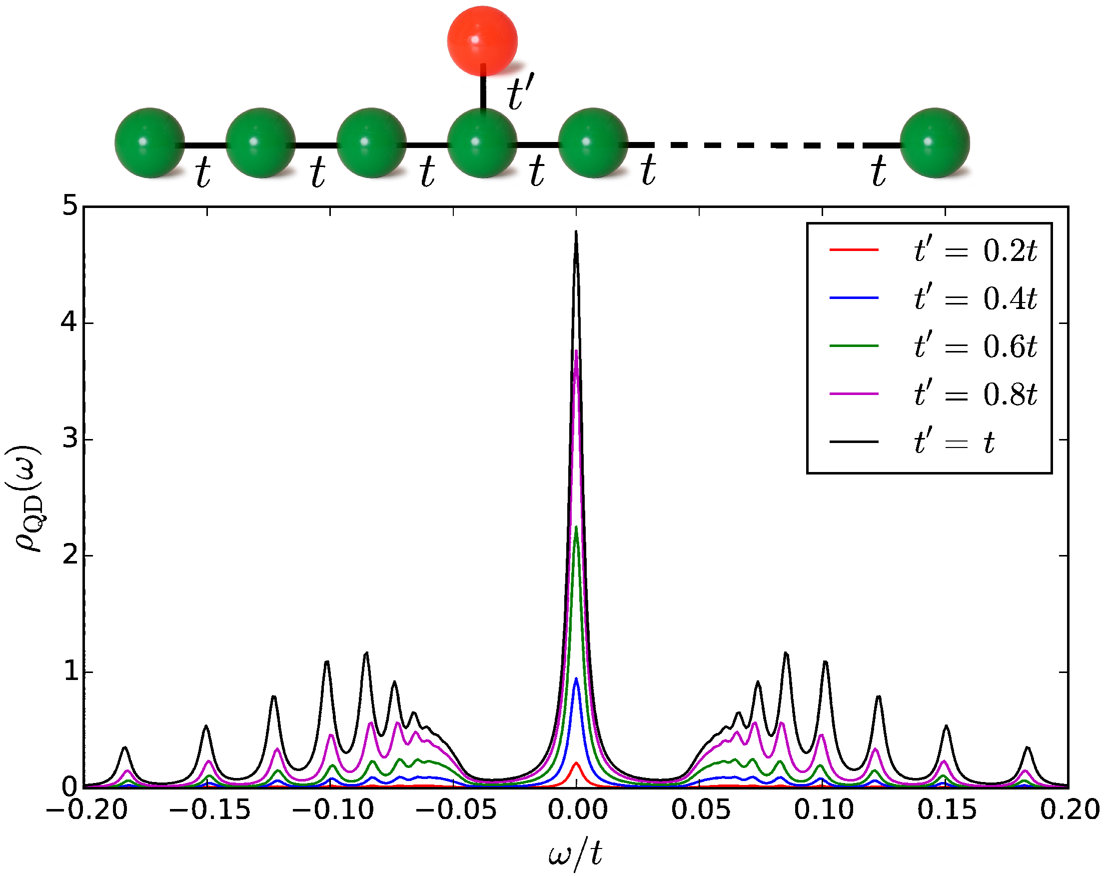
Majoranas at quantum defects – experimental relevance



R. Pawlak, **M. Kisiel**, ..., and E. Meyer, npj Quantum Information **2**, 16035 (2016).

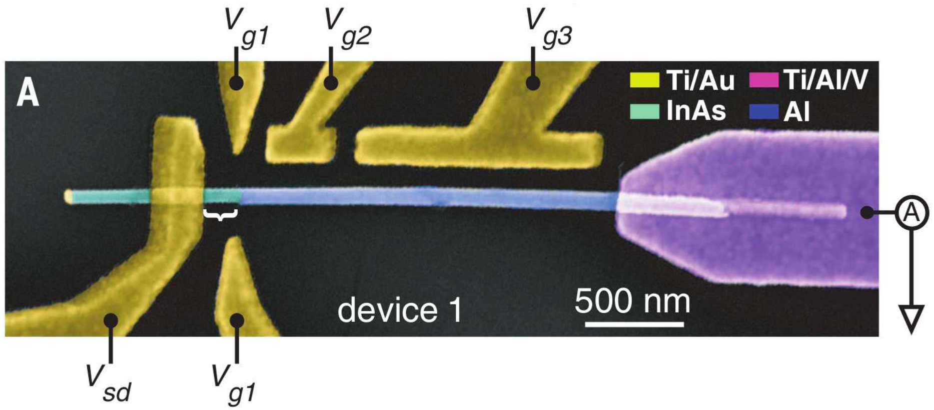
Majorana states – proximity effect

Majorana state can 'leak' into a normal quantum impurity



M. Maśka, A. Gorczyca-Goraj, J. Tworzydło and T. Domański, arXiv:1609.00685 (2016).

Proximity effect – experimental realization (27 Dec 2016)

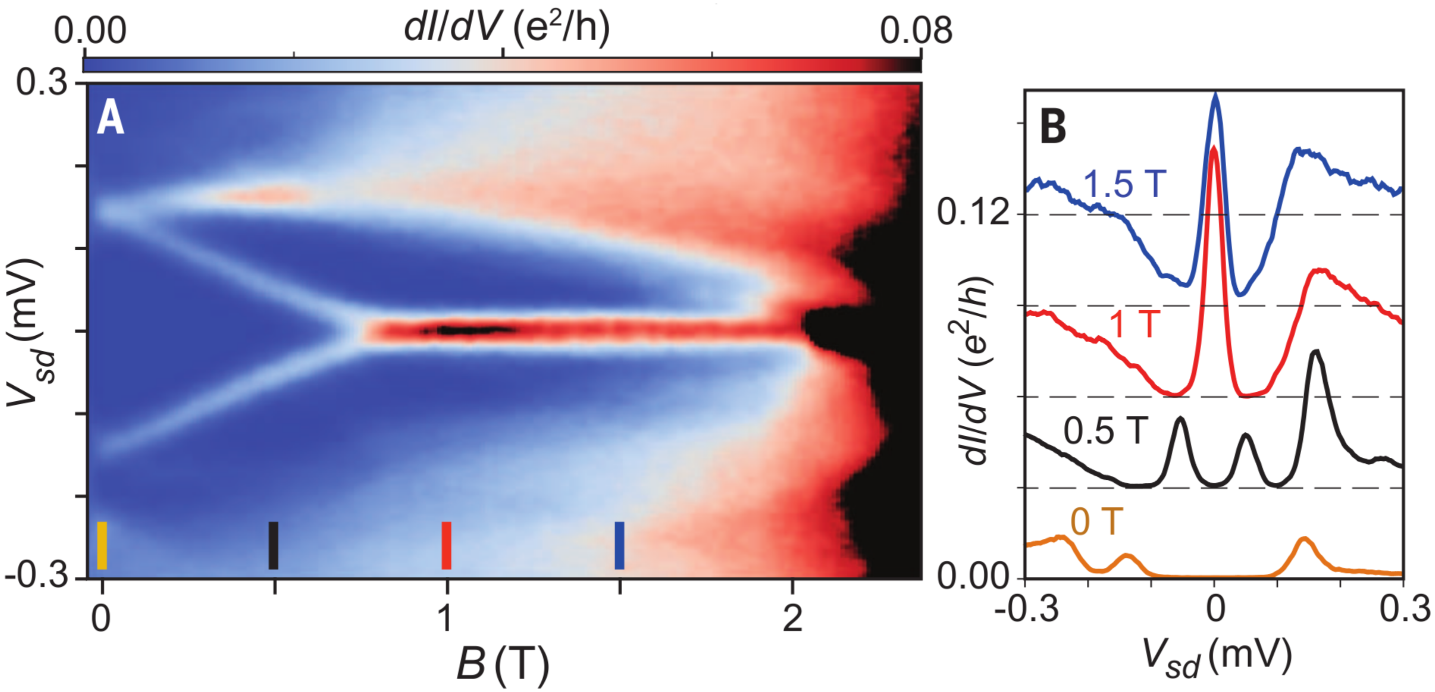


TOPOLOGICAL MATTER

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

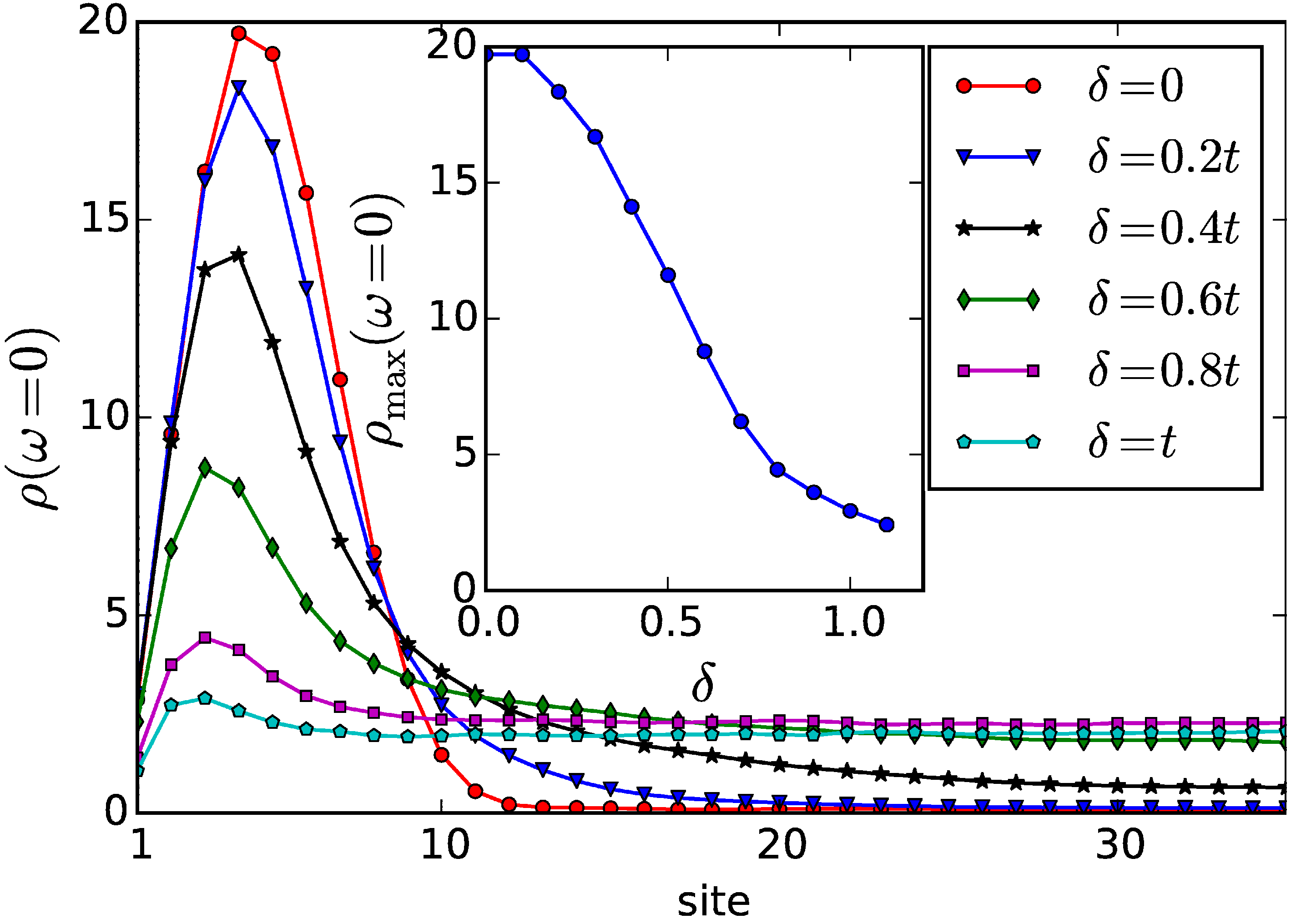
M. T. Deng,[1,2] S. Vaitiekėnas,[1,3] E. B. Hansen,[1] J. Danon,[1,4] M. Leijnse,[1,5] K. Flensberg,[1] J. Nygård,[1] P. Krogstrup,[1] C. M. Marcus[1]*

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



Majorana states – effect of disorder

Majorana quasiparticles are not truly immune to disorder !



M. Maśka, A. Gorczyca-Goraj, J. Tworzydło and T. Domański, arXiv:1609.00685 (2016).

Conclusions

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Majorana quasiparticles:

$\Longrightarrow$ **evolve out of the Andreev/Shiba states**

$\Longrightarrow$ **are non-local (fractional) entities**

$\Longrightarrow$ **can ’leak’ into normal quantum impurities**

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