Trogir (Croatia), 18 - Sept - 2015

Superconductivity in nanoscopic systems

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Marie Curie-Skłodowska University,

Lublin, Poland

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

Outline

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⇒ **how can we obtain nano-superconductivity**

/ proximity effect /

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⇒ **how can we obtain nano-superconductivity**

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⇒ **how can we observe nano-superconductivity**

/ spectroscopic signatures /

⇒ **where can we use nano-superconductors**

/ practical aspects /

1. Nano-superconductivity:

$\Rightarrow$ **how to obtain it ?**

Superconducting state – of bulk materials

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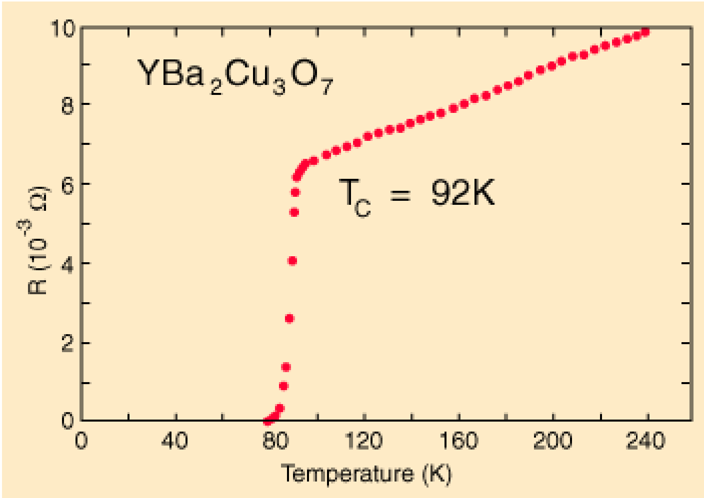
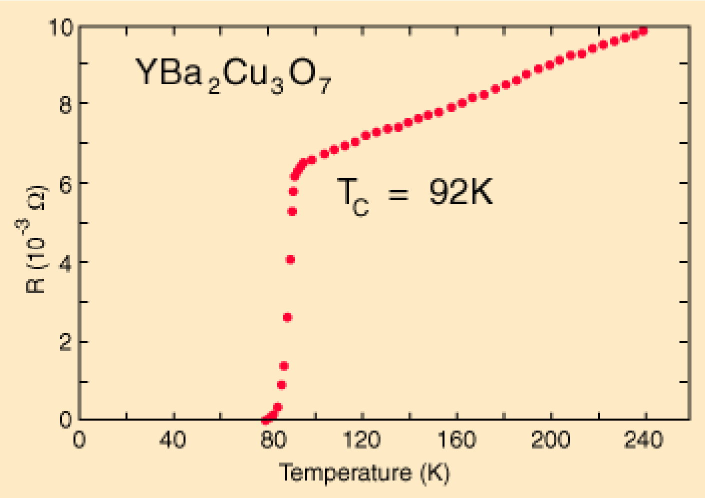
- ideal d.c. conductance

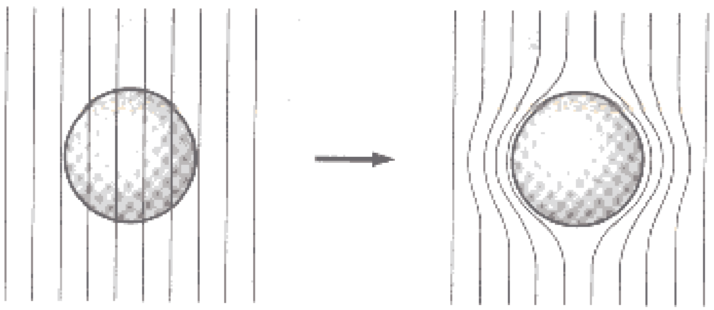


Superconducting state – of bulk materials

★ **ideal d.c. conductance**



★ **ideal diamagnetism** /perfect screening of the d.c. magnetic field/



$T > T_c$ $\qquad$ $T < T_c$

Superconducting state – of bulk materials

⇒ ideal d.c. conductance (vanishing resistance)

⇒ ideal diamagnetism (Meissner effect)

are caused by the superfluid electron pairs

$$n_s(T) \propto 1/\lambda^2$$

that move coherently over macroscopic distances.

Superconducting state – of bulk materials

The pairing mechanisms originate from:

1. **phonon-exchange**

   / classical superconductors, MgB_2, ... /

2. **magnon-exchange**

   / heavy fermion compounds /

3. **strong correlations**

   / spin exchange $\frac{2t_{ij}^2}{U}$ *in the high* T_c *superconductors /*

.. **other exotic processes**

   / ultracold atoms, nuclei, gluon-quark plasma /

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Onset of the fermion pairing often goes hand in hand with appearance of the superconductivity/superfluidity, but it doesn't have to be a rule.

Proximity effect – induced superconductivity

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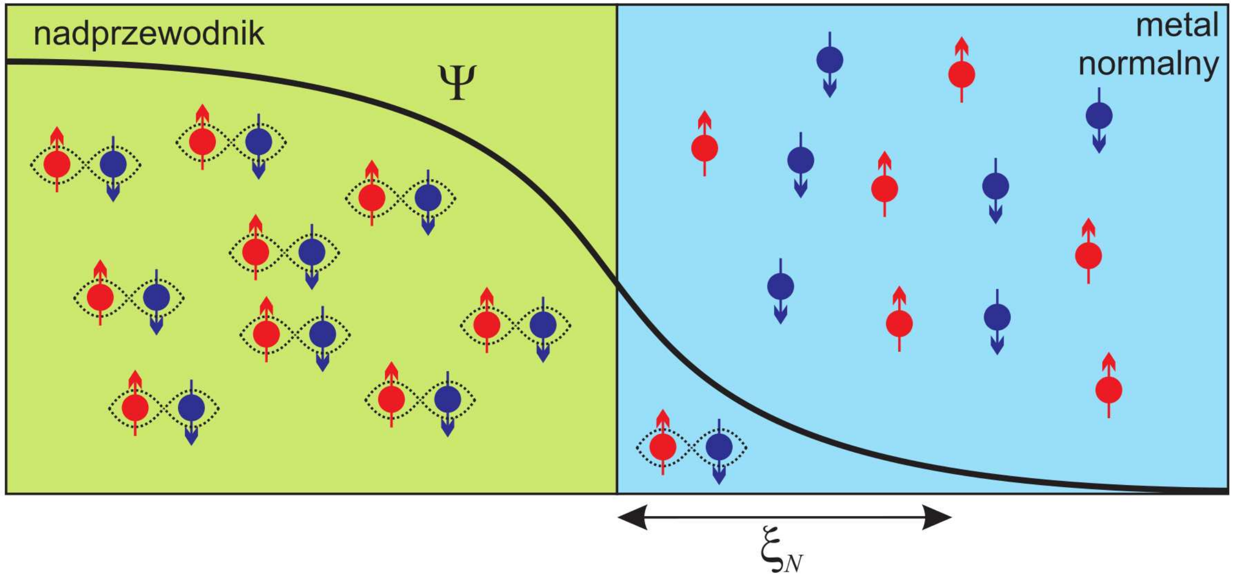
- Any material brought in contact with superconductor



Proximity effect – induced superconductivity

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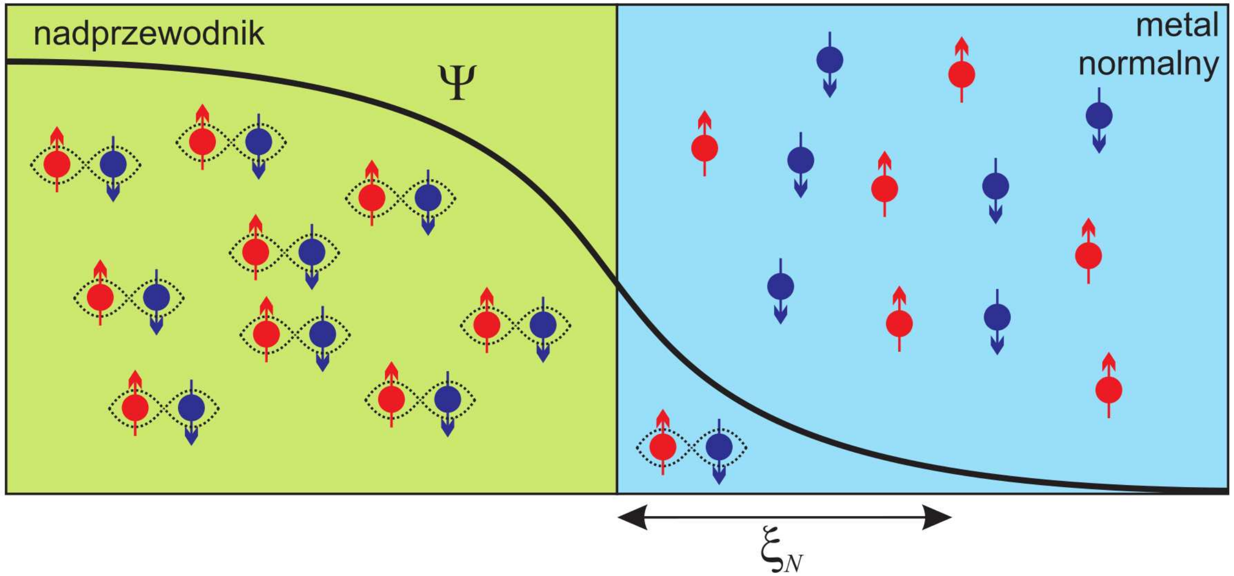

absorbs the paired electrons up to distances $\sim \xi_n$.

Proximity effect – **induced superconductivity**

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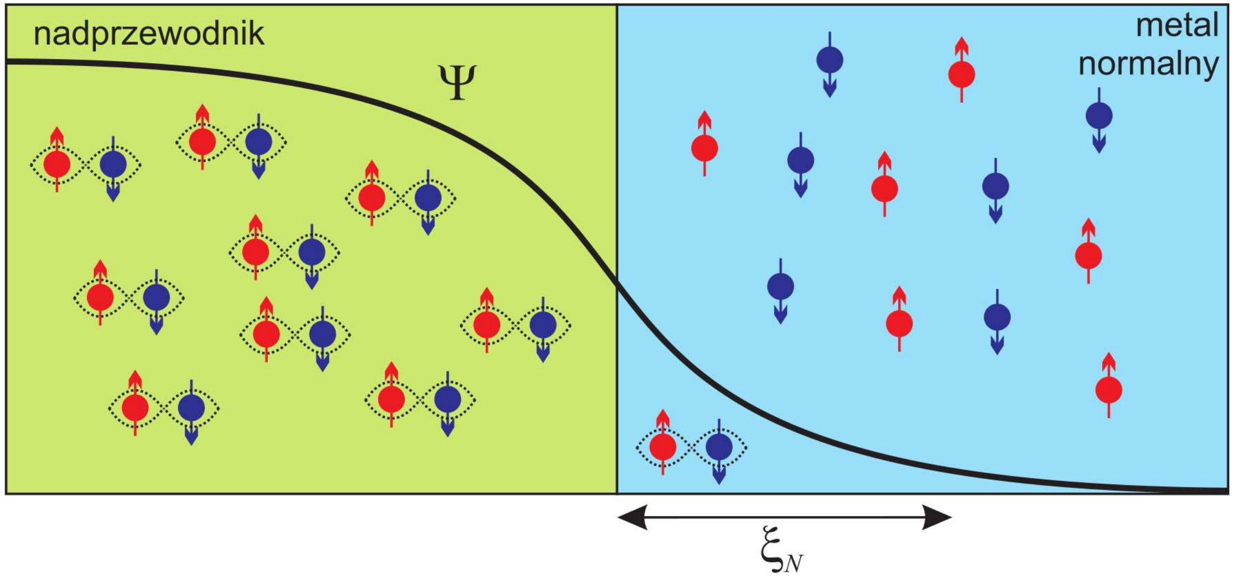

absorbs the paired electrons up to distances $\sim \xi_n$.

★ **Spatial size** L **of nanoscopic objects is** $L \ll \xi_n$ **!**

2. Nano-superconductivity:

$\Rightarrow$ **how can we observe it ?**

Superconductivity in nanosystems – specific issues

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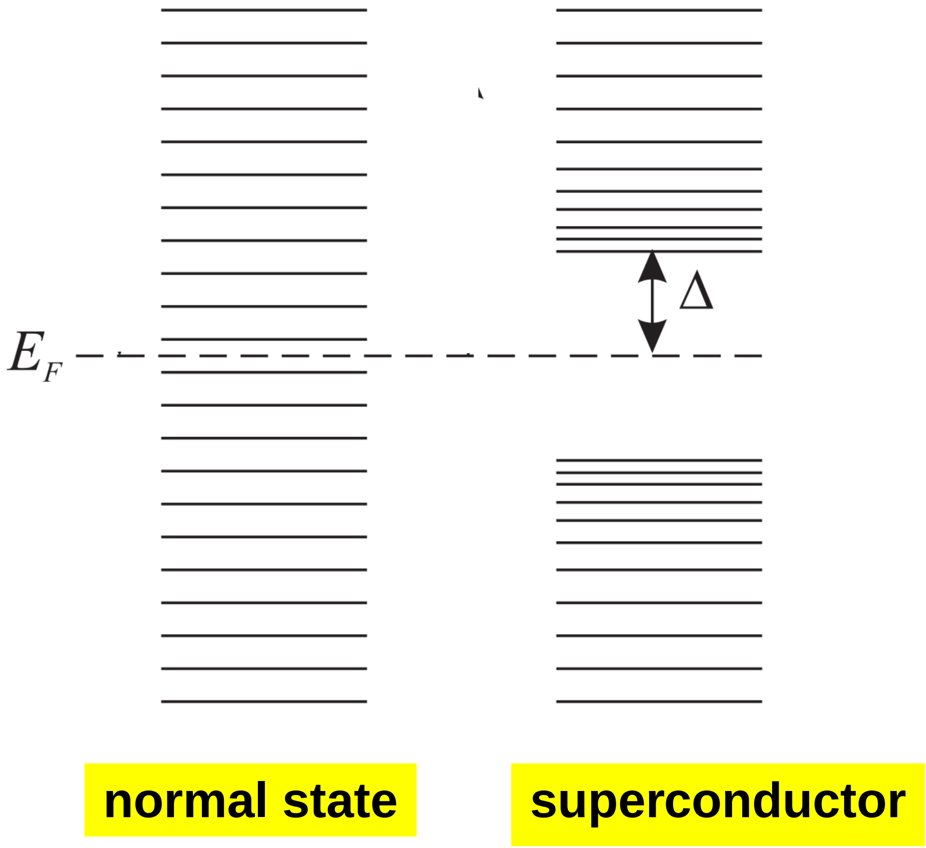
1. Quantum Size Effect ⟶ discrete energy spectrum



Superconductivity in nanosystems – specific issues

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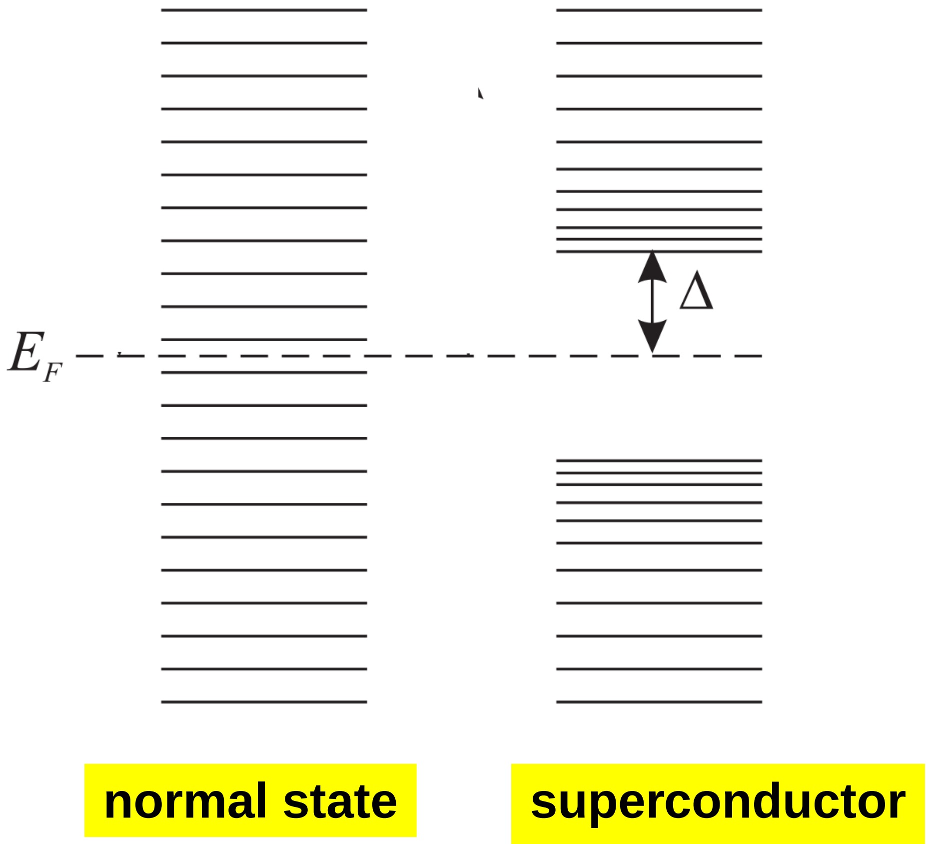

Anderson criterion: superconductivity only for $\Delta > \varepsilon_{i+1} - \varepsilon_i$

Superconductivity in nanosystems – specific issues

2. Coulomb blockade (electron pairing vs repulsion)

The odd / even electron number plays the important and qualitative role !

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Coulomb potential U_C is usually much smaller than Δ, therefore its influence can be in practice observed only indirectly, via :

$$|\uparrow\rangle \quad \Longleftrightarrow \quad u\,|0\rangle - v\,|\uparrow\downarrow\rangle$$

(quantum phase transition)

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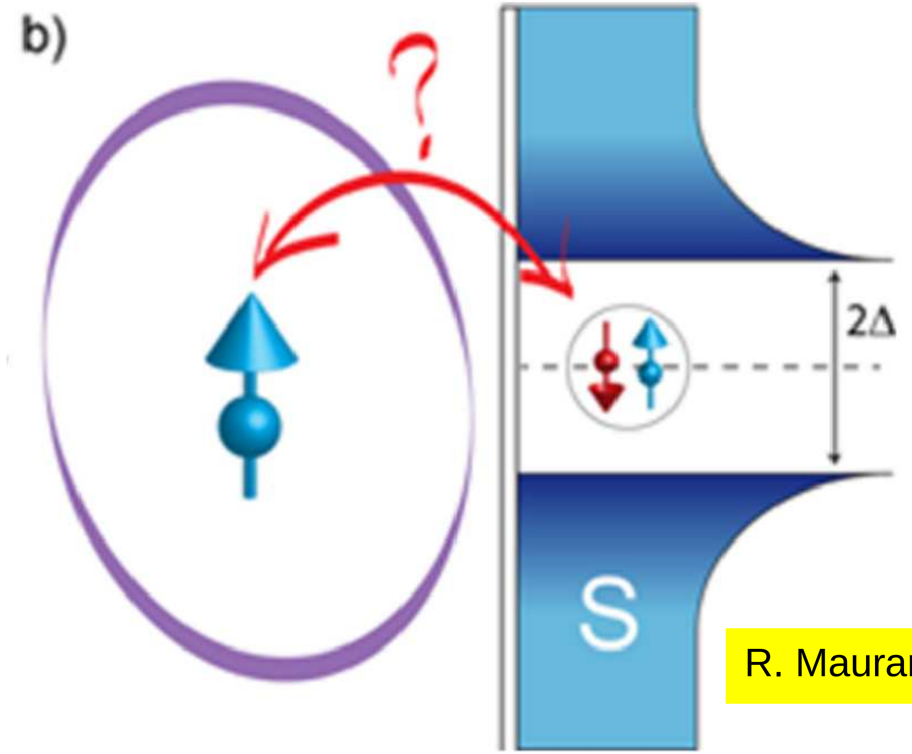
Physical consequences:

$\Rightarrow$ inversion of the Josephson current (in S-QD-S junctions)

$\Rightarrow$ activation/blocking of the Kondo effect (in N-QD-S junctions)

Superconductivity in nanosystems – specific issues

3. Pairing vs Kondo state ('to screen or not to screen')



R. Maurand, Ch. Schönenberger, Physics **6**, 75 (2013).

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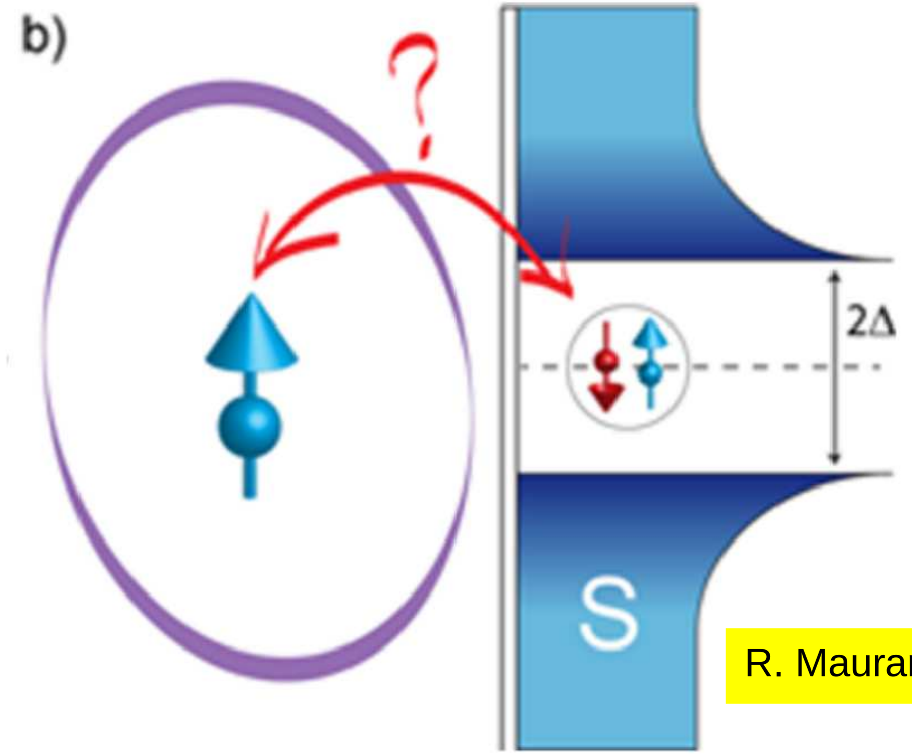

R. Maurand, Ch. Schönenberger, Physics **6**, 75 (2013).

⇒ states near the Fermi level are depleted

⇒ electron pairing vs the Kondo state (nontrivial relation)

Theoretical model – single Anderson impurity

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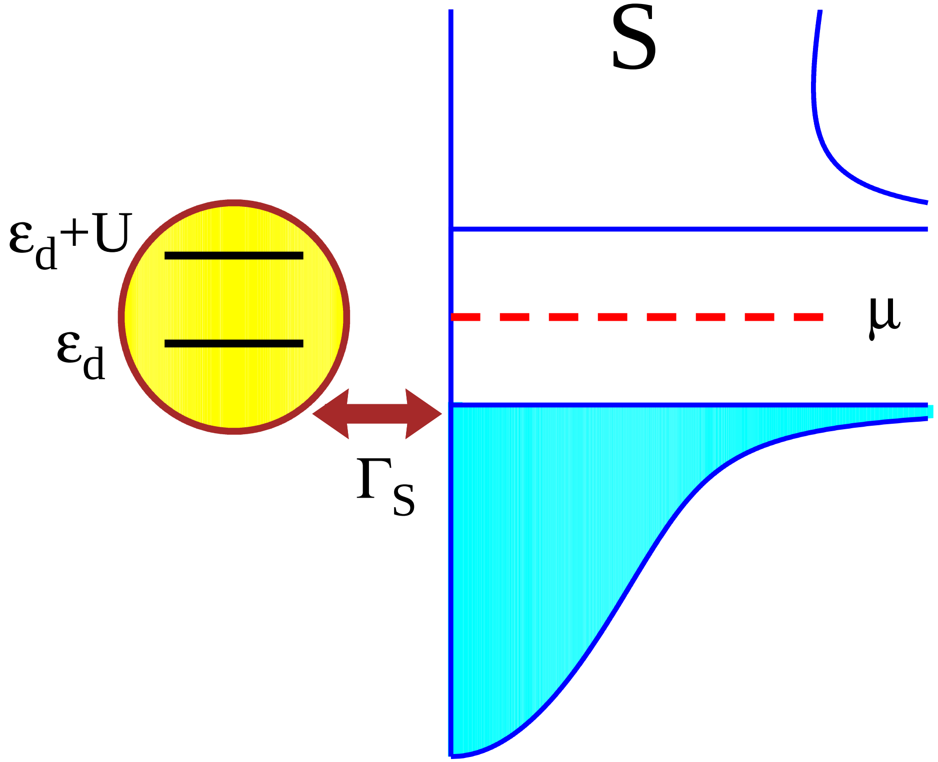
The single quantum impurity (dot) coupled to superconducting reservoir



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

Theoretical model – single Anderson impurity

Hamiltonian

$$\hat{H} = \sum_{\sigma} \epsilon_d \hat{d}^{\dagger}_{\sigma} \hat{d}_{\sigma} + U\, \hat{n}_{d\uparrow}\, \hat{n}_{d\downarrow} + \sum_{\mathbf{k},\sigma} \left(V_{\mathbf{k}}\, \hat{d}^{\dagger}_{\sigma} \hat{c}_{\mathbf{k}\sigma} + V^{*}_{\mathbf{k}}\, \hat{c}^{\dagger}_{\mathbf{k}\sigma} \hat{d}_{\sigma} \right) + \hat{H}_S$$

where

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

describes the BCS-type superconductor.

Microscopic description – exact solution for $U = 0$

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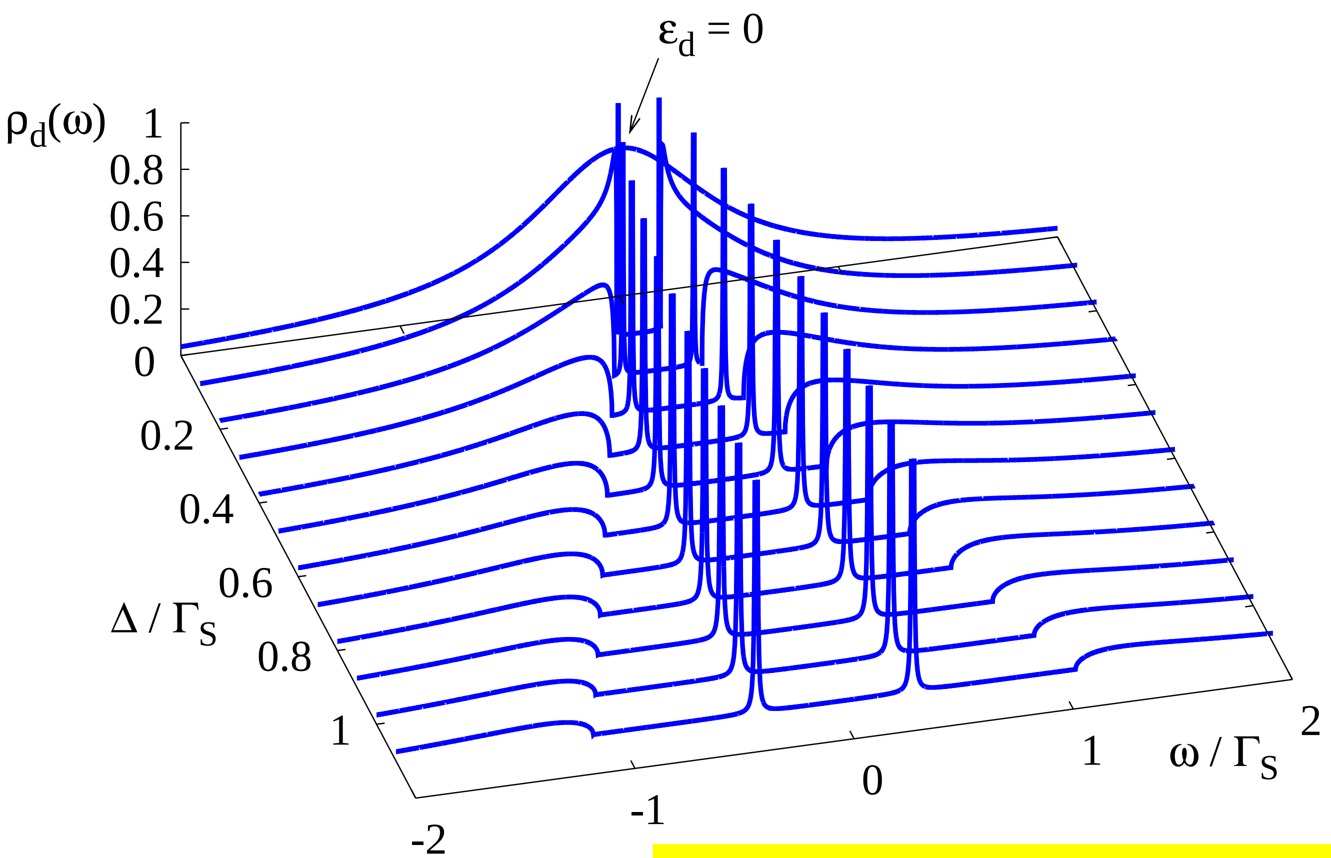


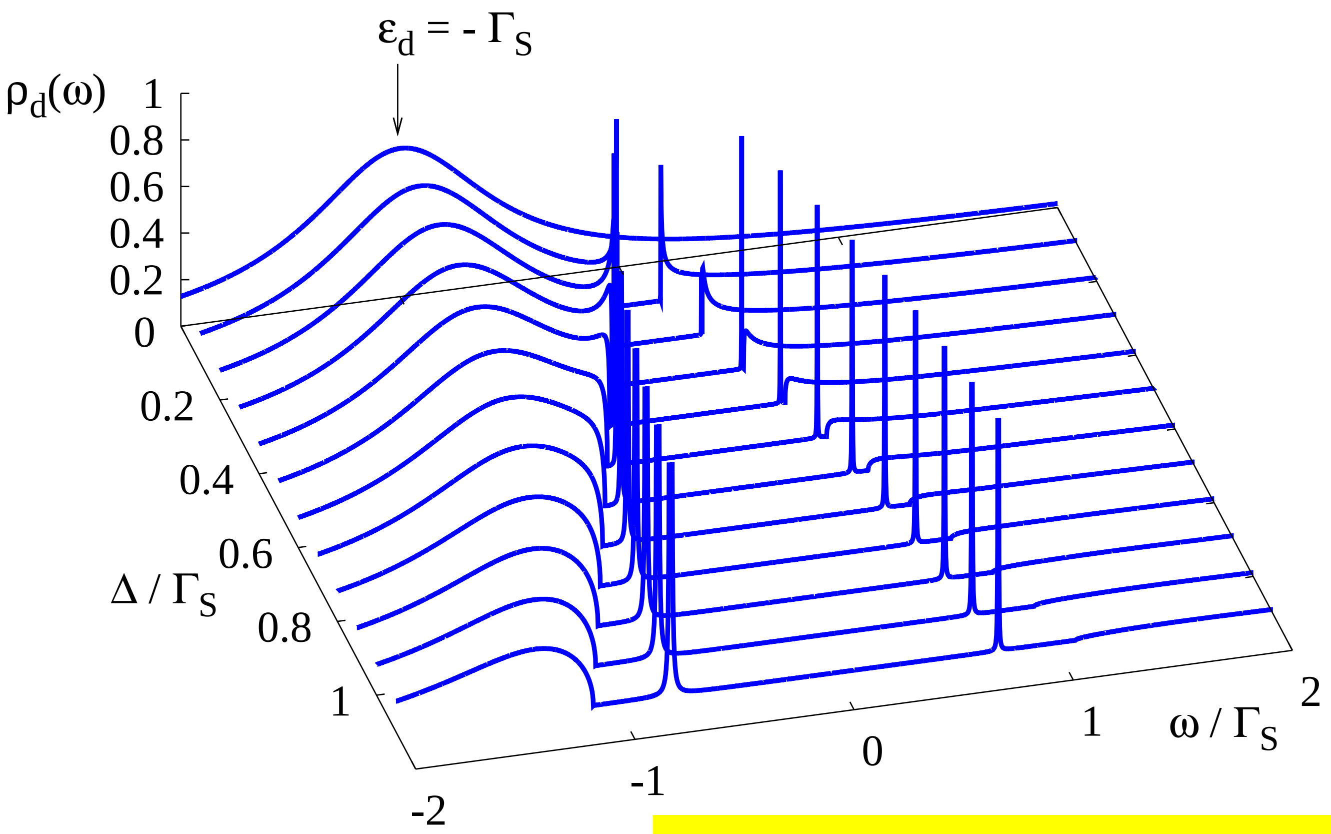
J. Phys.: Condens. Matter **25**, 435305 (2013).

Spectrum consists of:

⇒ **a continuum at energies $-\Delta < \omega < \Delta$**

⇒ **in-gap resonances (Andreev bound states)**

Microscopic description – exact solution for $U = 0$



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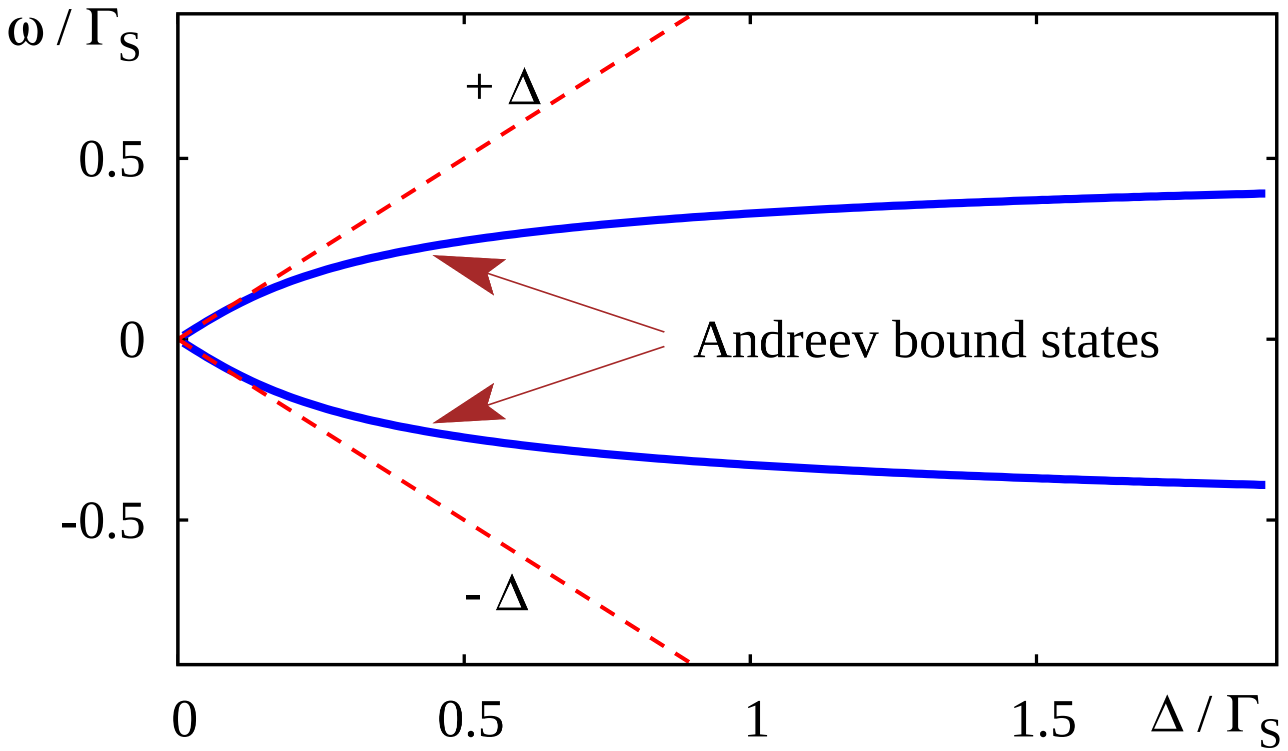
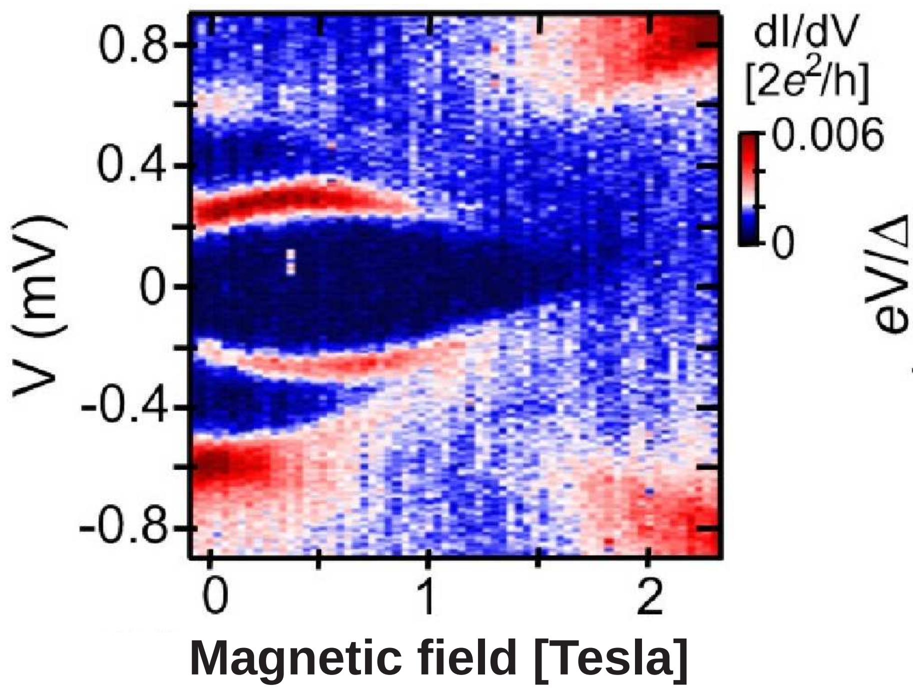
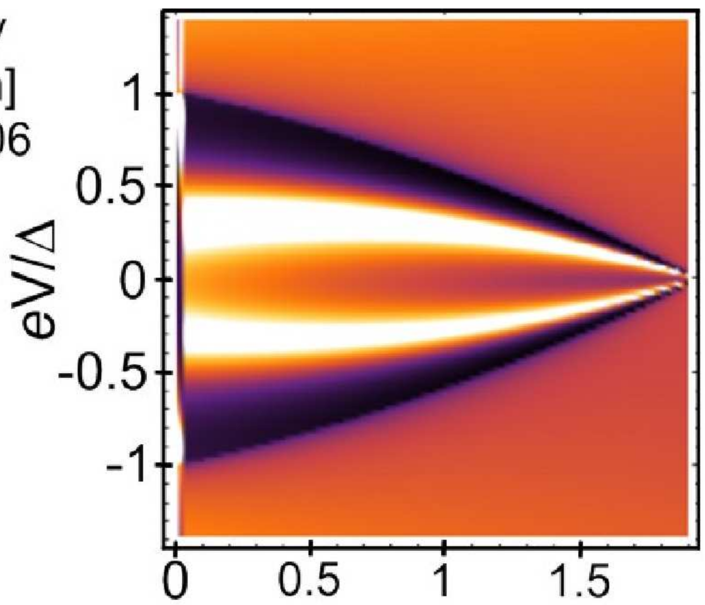


Energies of the in-gap resonances (Andreev bound states)

J. Phys.: Condens. Matter **25**, 435305 (2013).

Microscopic description – exact solution for $U = 0$





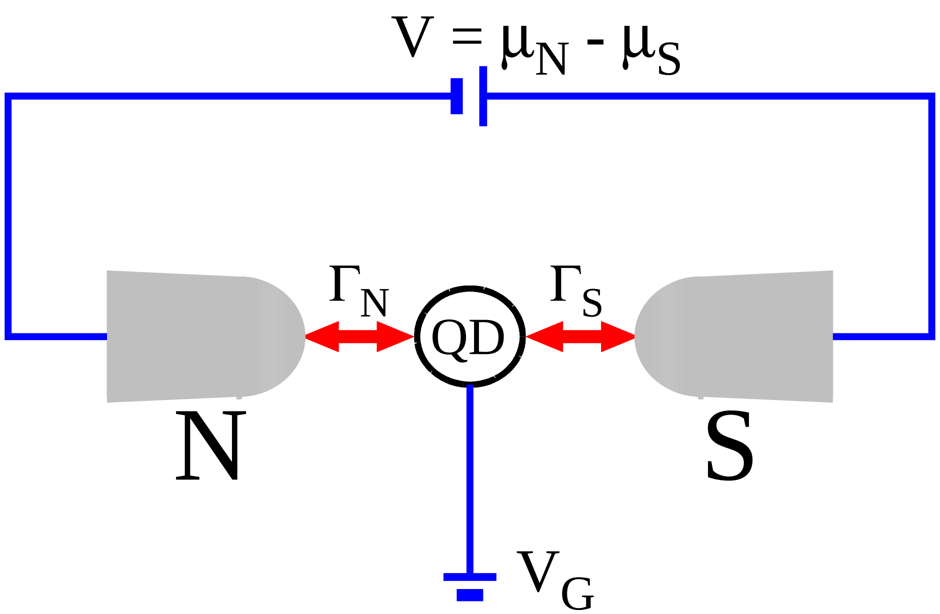
Differential conductance of nanotubes coupled to vanadium (S) and gold (N)

/ external magnetic field changes a magnitude of the pairing gap $\Delta(B)$ /

Eduardo J.H. Lee, ..., S. De Franceschi, Nature Nanotechnology **9**, 79 (2014).

Spectroscopic tools – probing nano-superconductors

To probe the in-gap states one can study the electron transport through a quantum dot (QD) coupled between the normal (N) and superconducting (S) electrodes



metallic lead QD superconductor

This N–QD–S setup has been practically studied in several experiments.

N - QD - S junctions – pairing vs Coulomb repulsion

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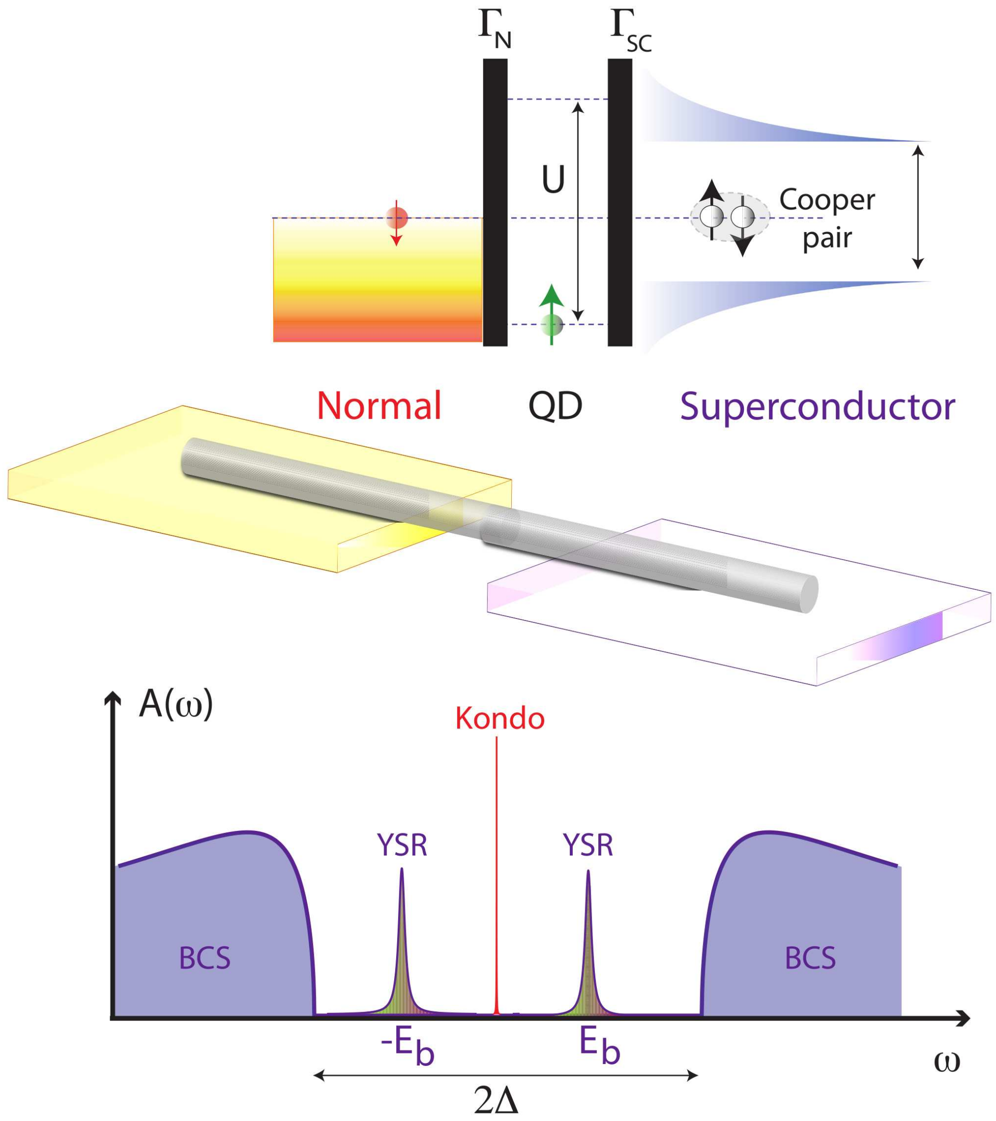

R. Žitko, J.S. Lim, R. López, and R. Aguado, Phys. Rev. B **91**, 045441 (2015).

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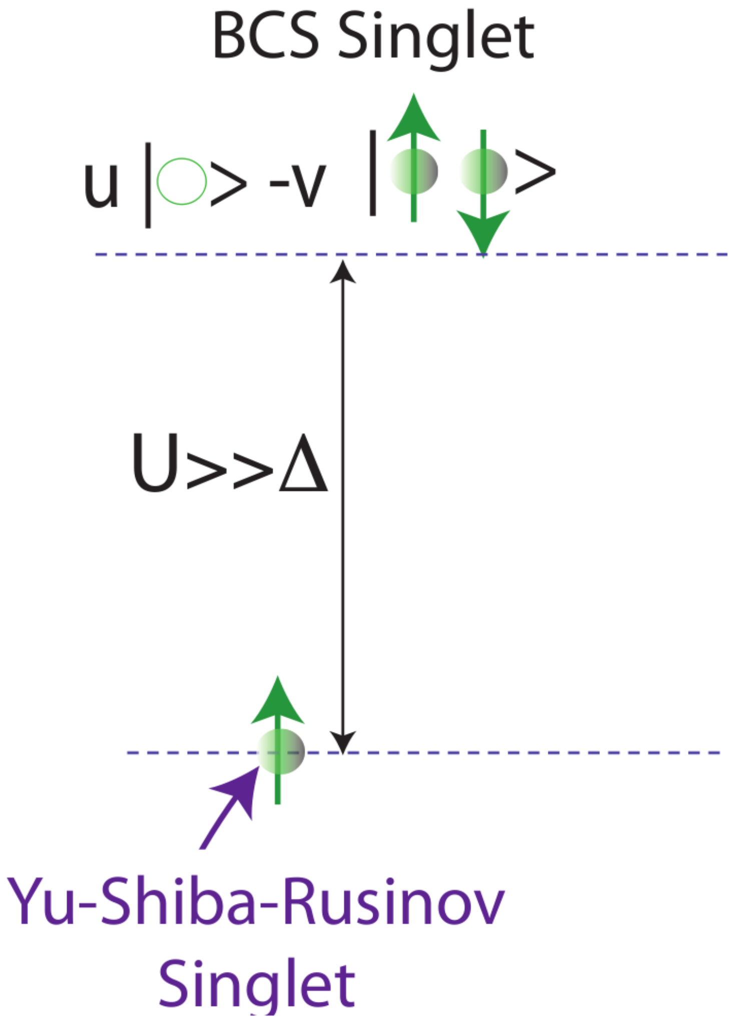

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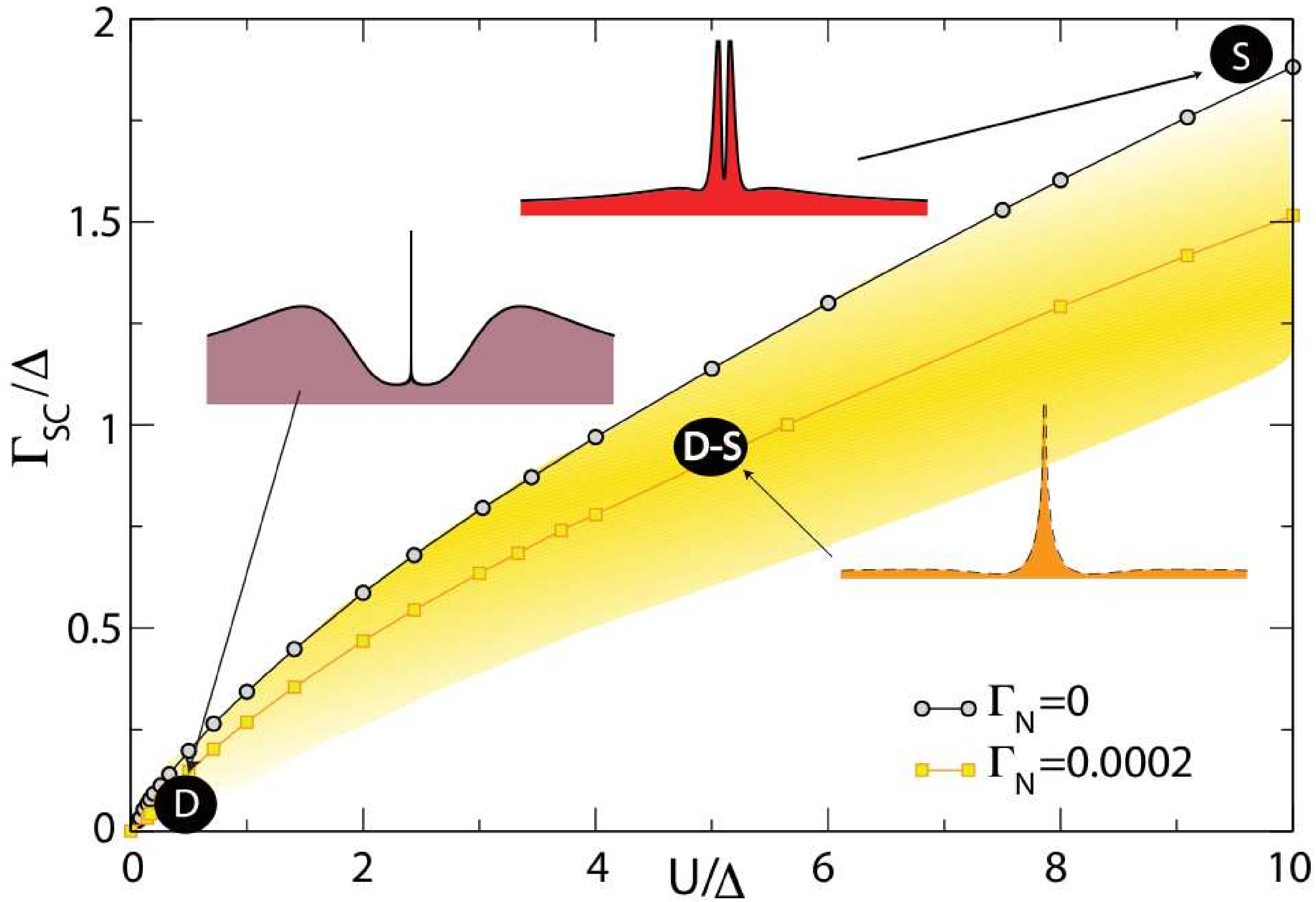

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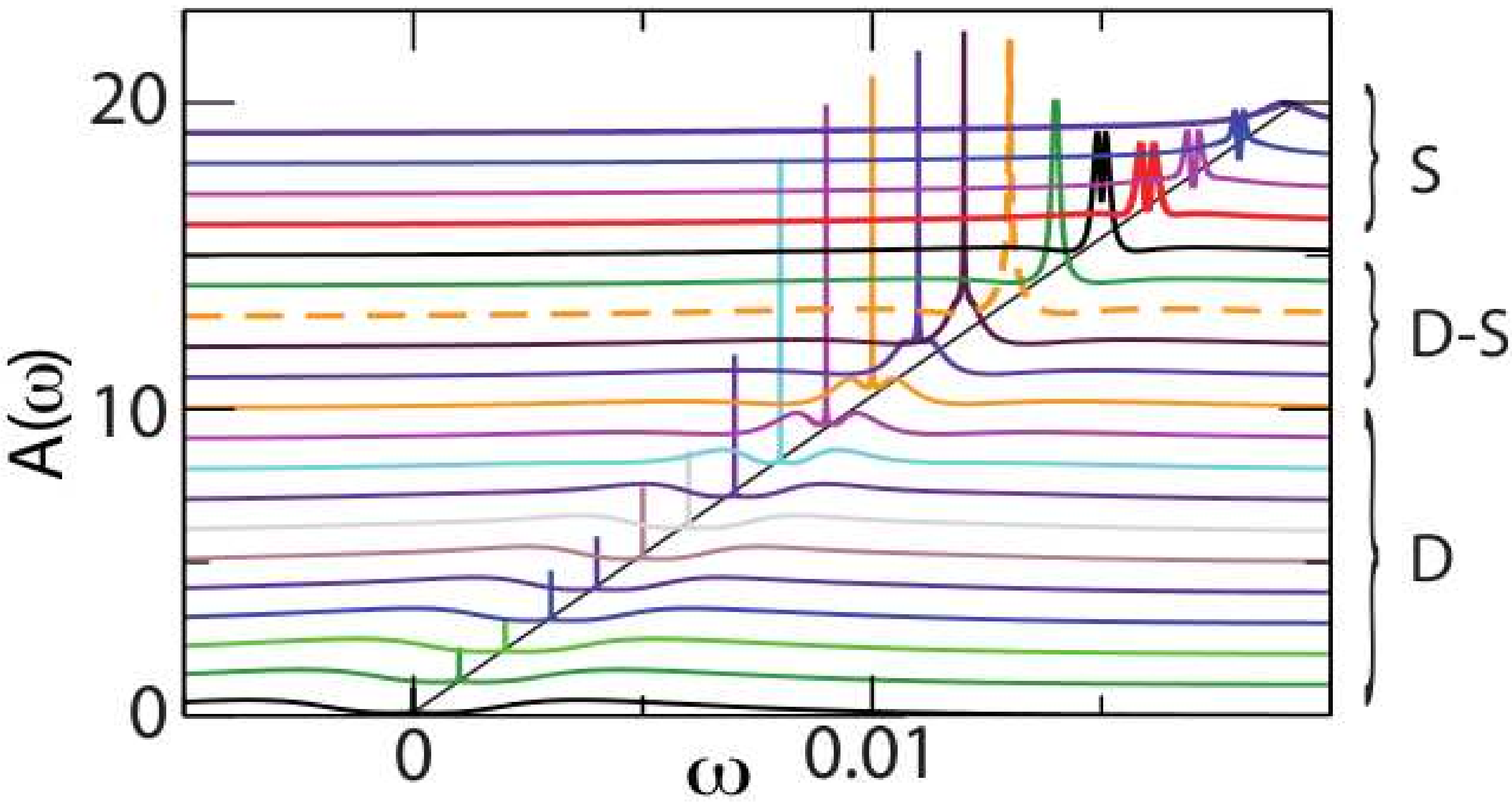

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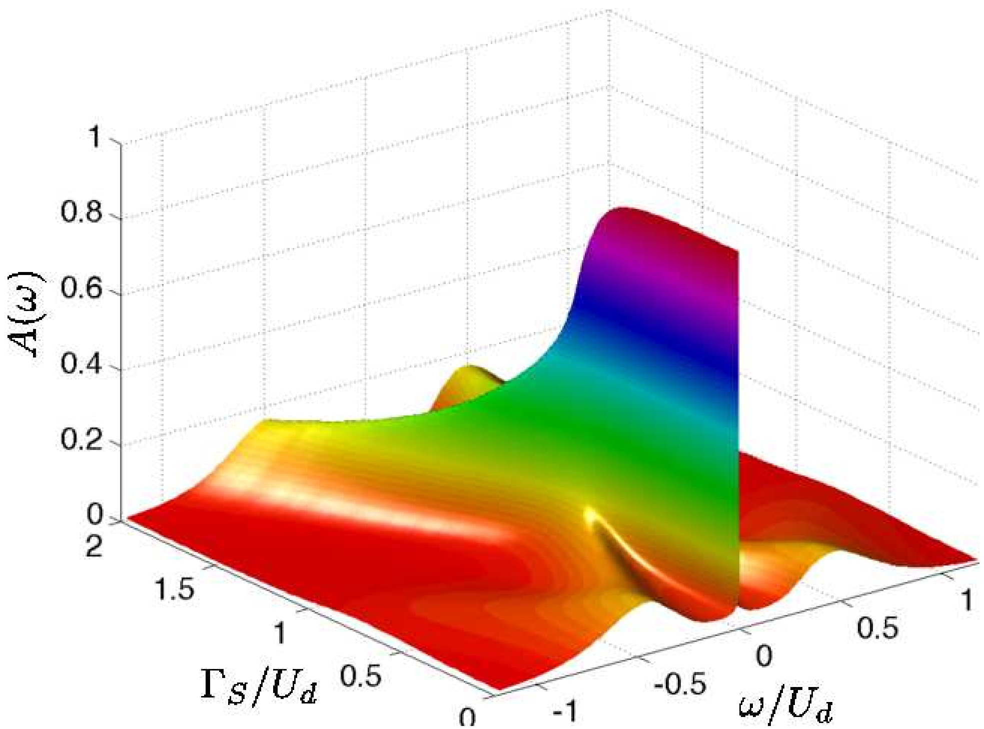

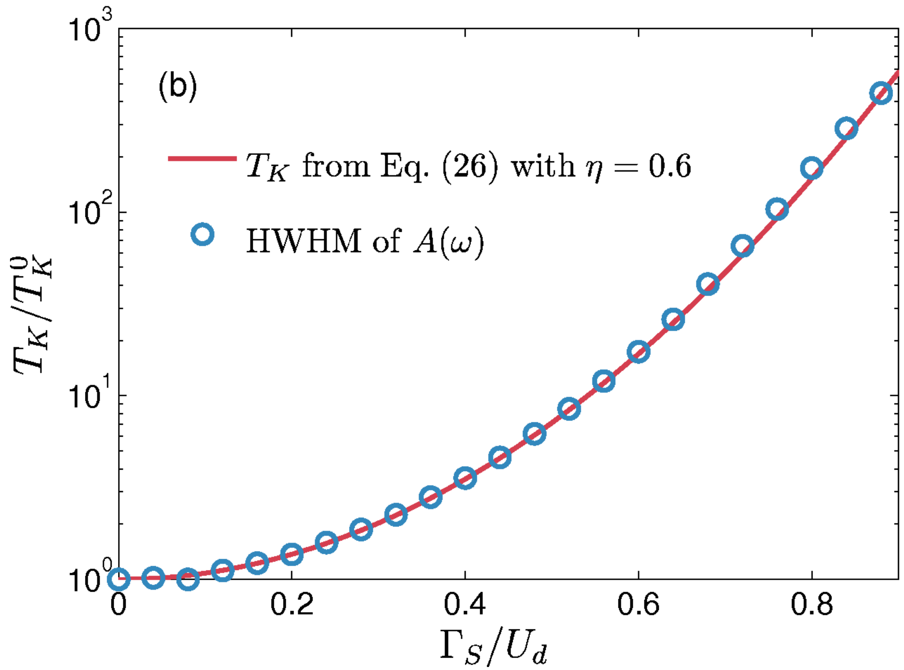

T. Domański, I. Weymann & M. Barańska, arXiv:1507.01851 (2015) preprint.

Our and R. Žitko's studies reveal that: T_K is enhanced by Γ_S

3. Nano-superconductivity:

$\Rightarrow$ **some practical aspects**

Andreev reflections – possible applications

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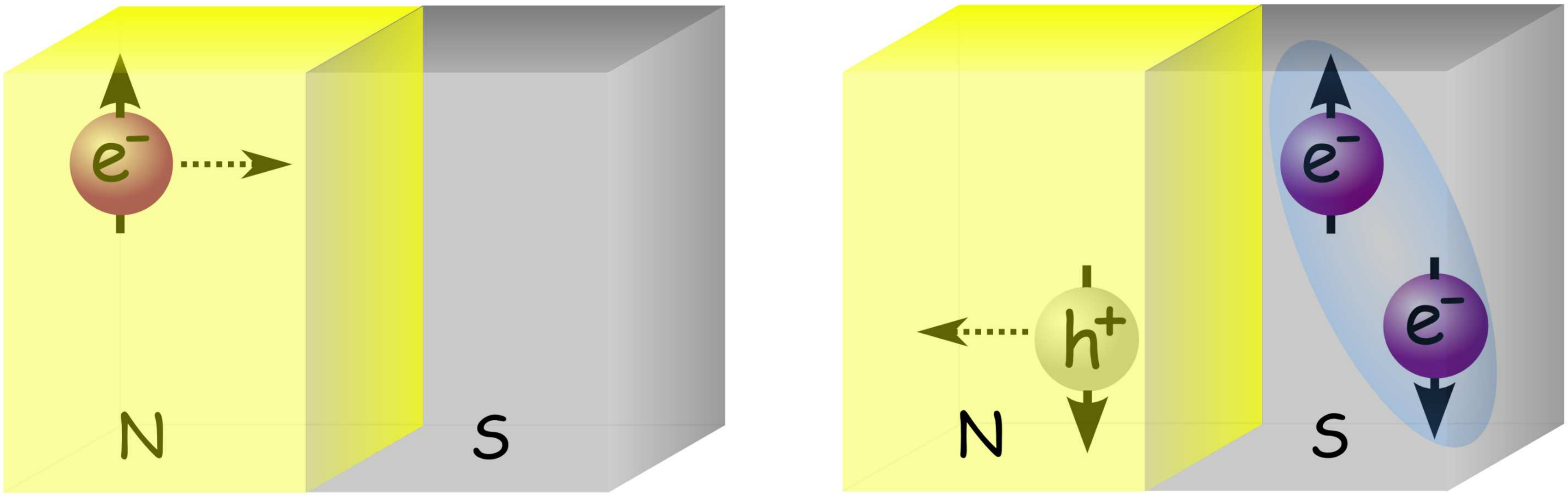
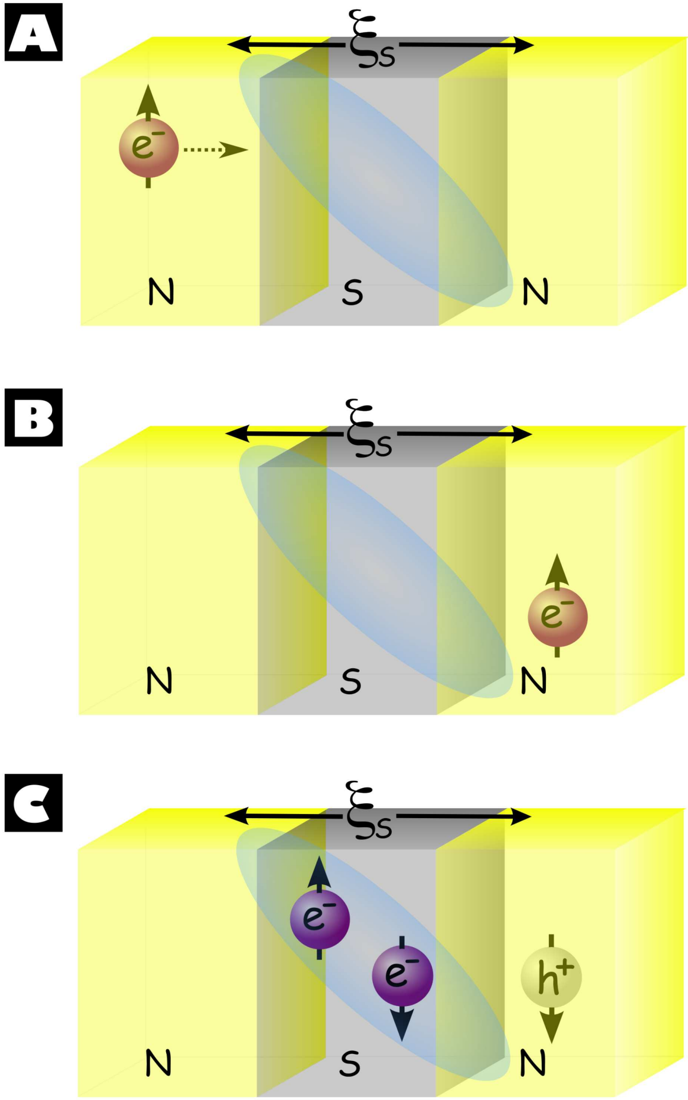


Schematic illustration of the Andreev-type scattering

Andreev reflections – possible applications

Andreev-type scattering can be also considered in more complex junctions

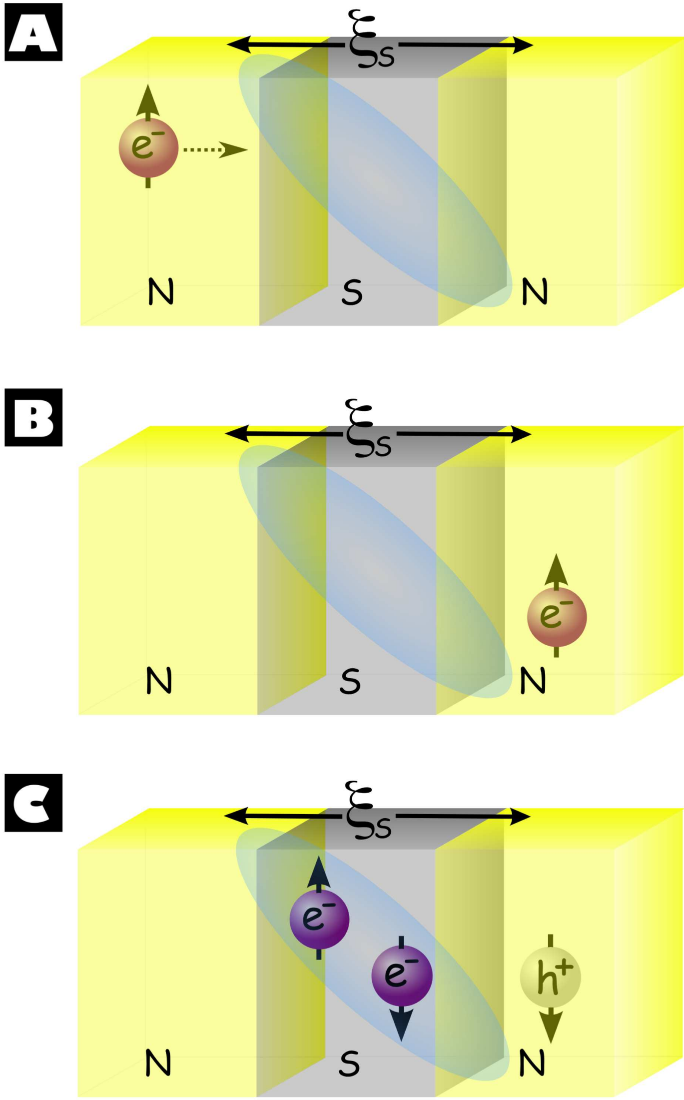


P. Cadden-Zimansky, Ph.D. thesis, Northwestern University (2008).

Andreev reflections – possible applications

Andreev-type scattering can be also considered in more complex junctions

incident electron



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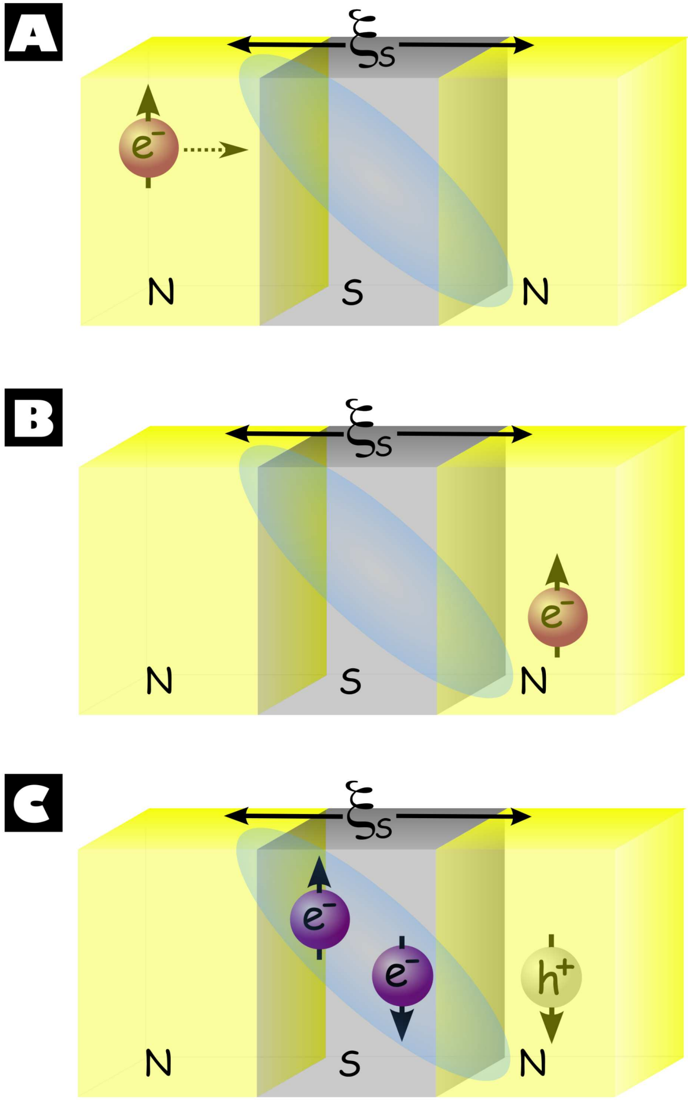

incident electron

elastic tunelling

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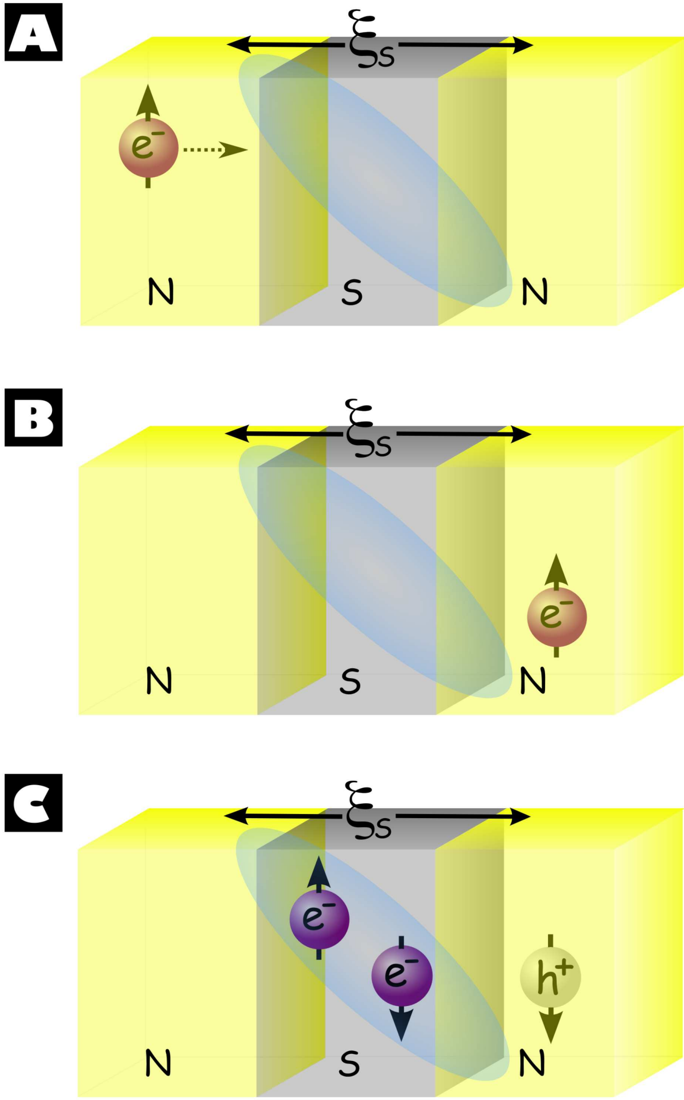

elastic tunelling

crossed Andreev refl.

P. Cadden-Zimansky, Ph.D. thesis, Northwestern University (2008).

Non-local transport – planar junctions

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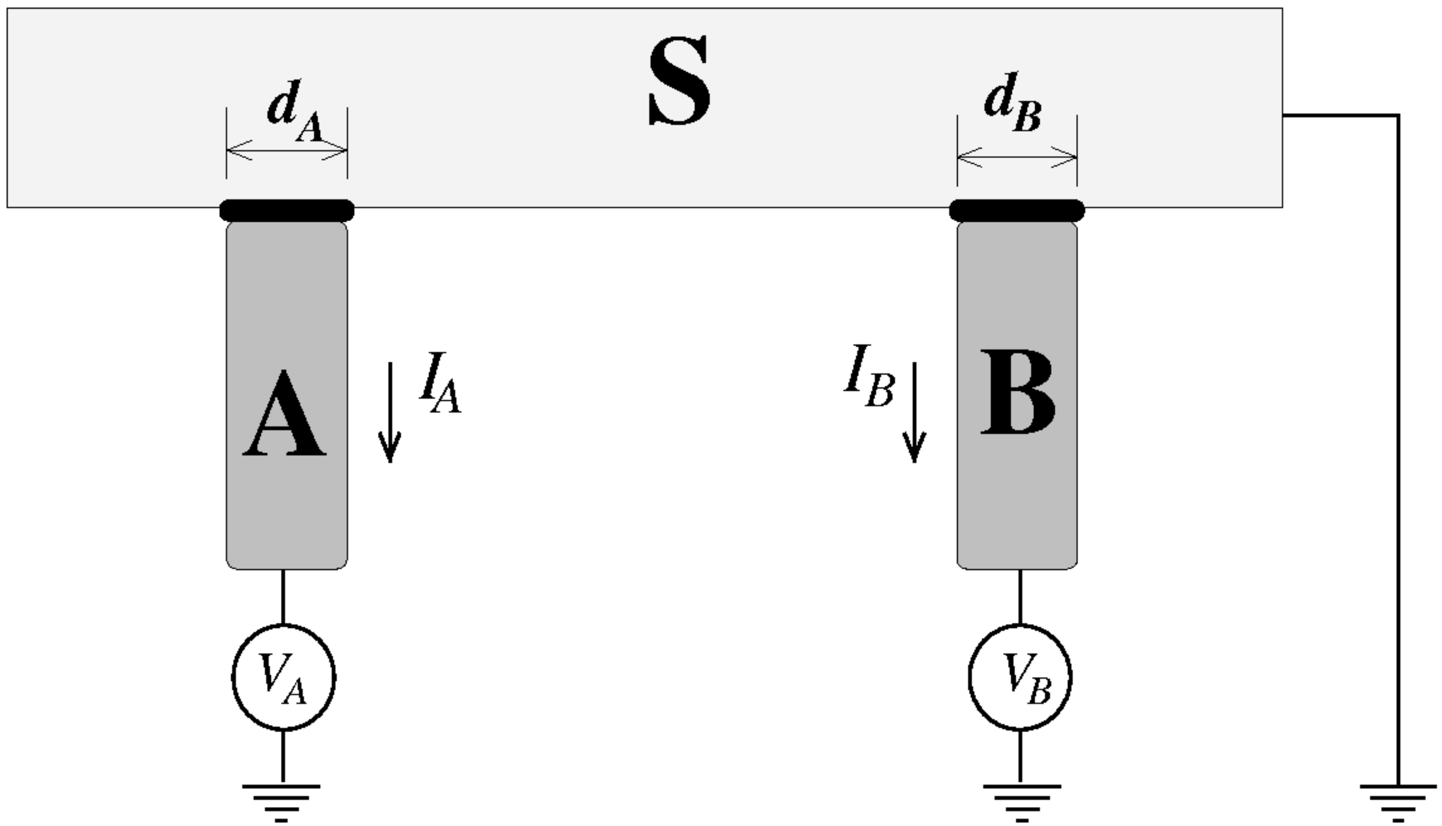
These ET/CAR processes have first considered in the planar junctions

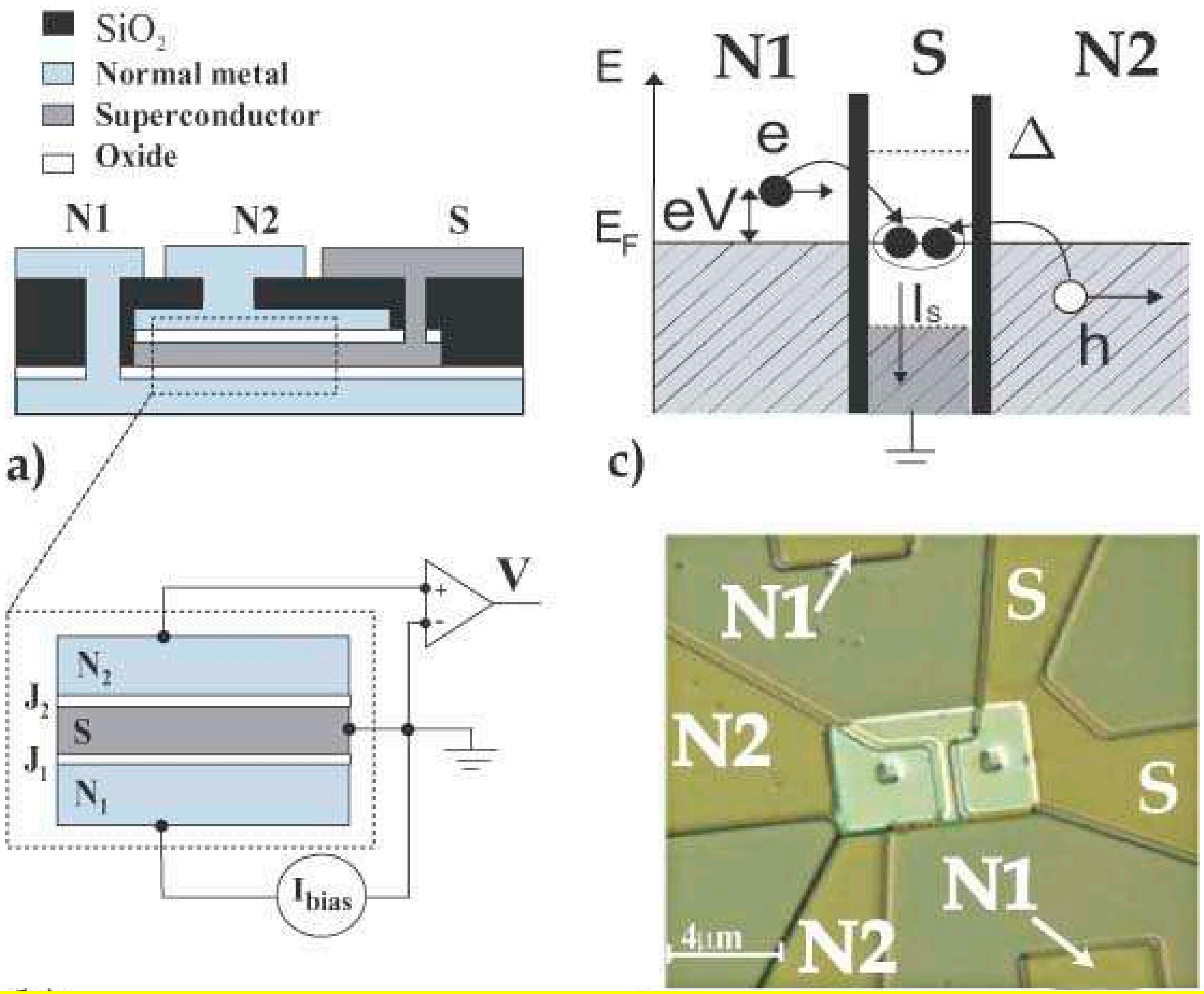


A, B – **normal electrodes,** S – **superconducting material**

G. Falci, D. Feinberg, F. Hekking, Europhys. Lett. **54**, 255 (2001).

Non-local transport – planar junctions

Experimental realization (Delft group)



S. Russo, M. Kroug, T. M. Klapwijk & A.F. Morpurgo, *Phys. Rev. Lett.* **95**, 027002 (2005).

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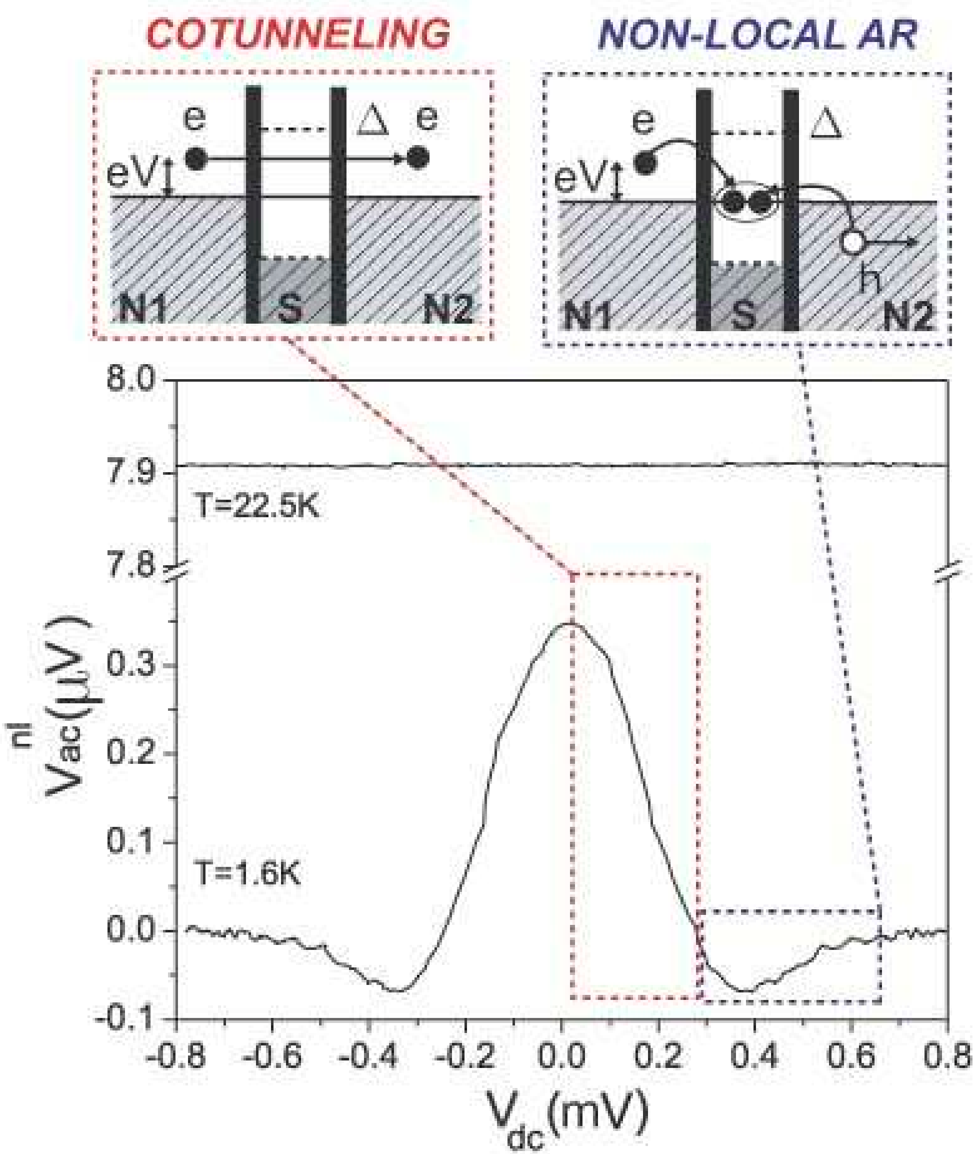

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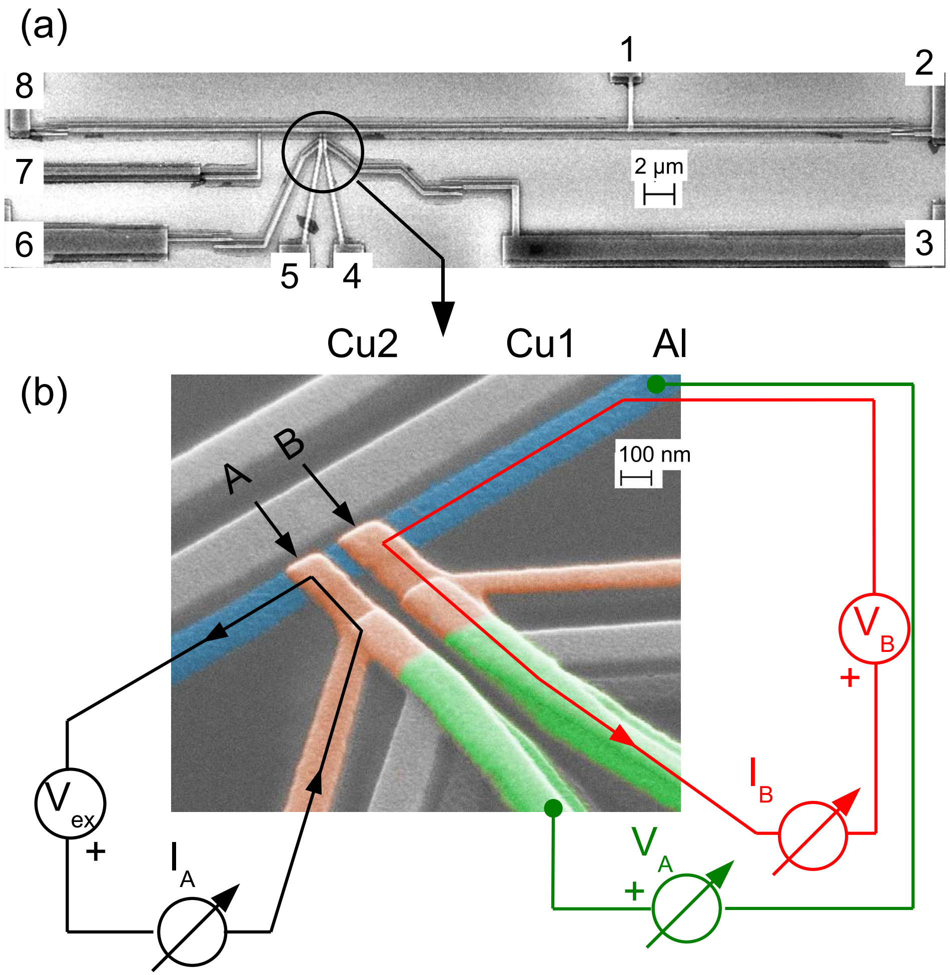
Non-local transport – planar junctions

Experimental realization (Karlsruhe group)



J. Brauer, F. Hübler, M. Smetanin, D. Beckman, D. & H. von Löhneysen, *Phys. Rev. B* **81**, 024515 (2010).

Non-local transport – planar junctions

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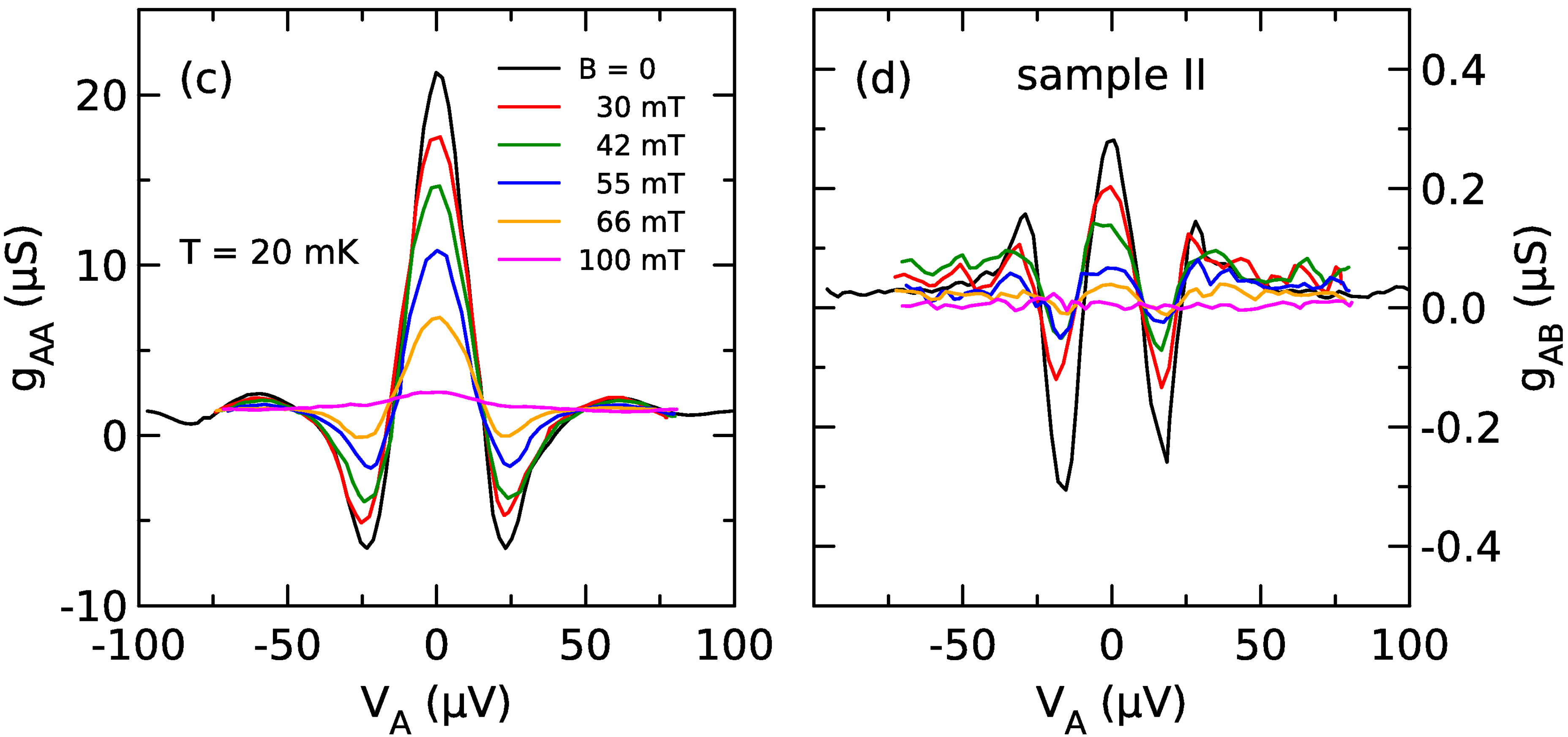

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3-terminal junctions – with quantum dots

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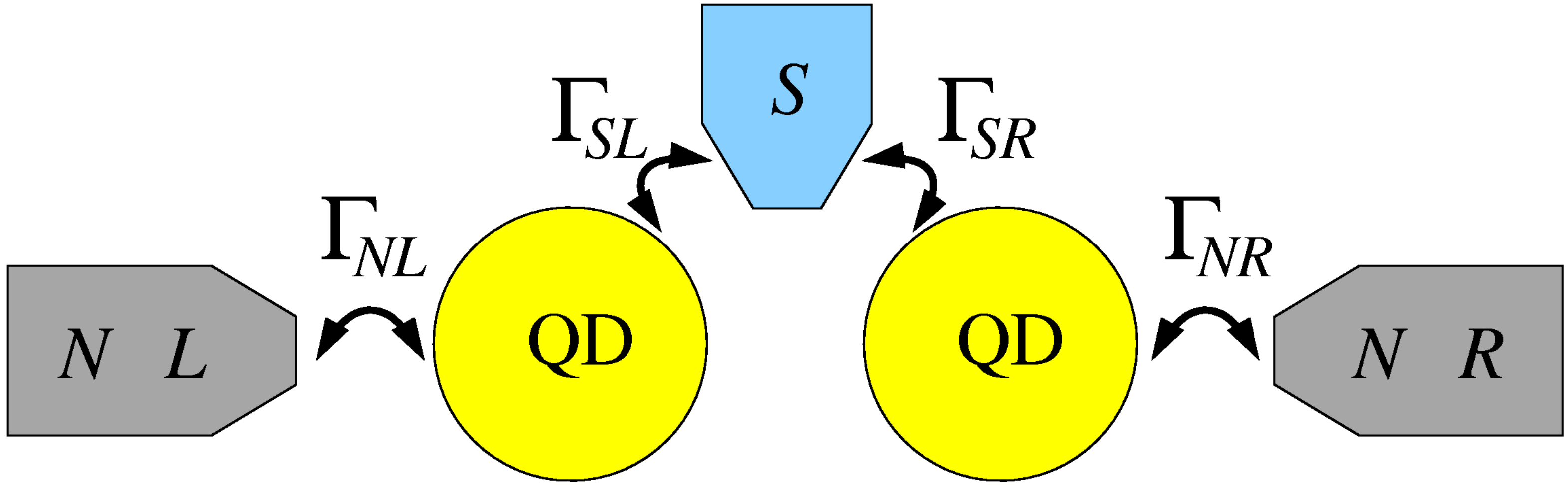


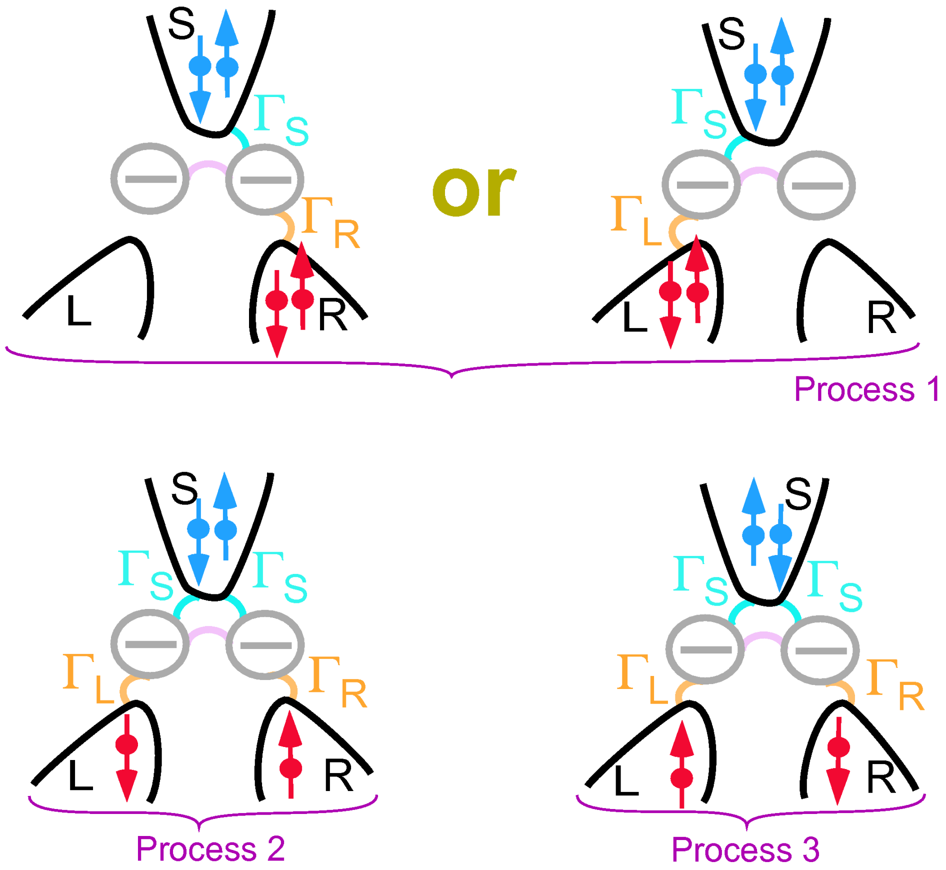
Cooper pairs are split, preserving entanglement of individual electrons.

L. Hofstetter, S. Csonka, J. Nygård, C. Schönenberger, Nature **461***, 960 (2009).*

J. Schindele, A. Baumgartner, C. Schönenberger, Phys. Rev. Lett. **109***, 157002 (2012).*

... and many other groups.

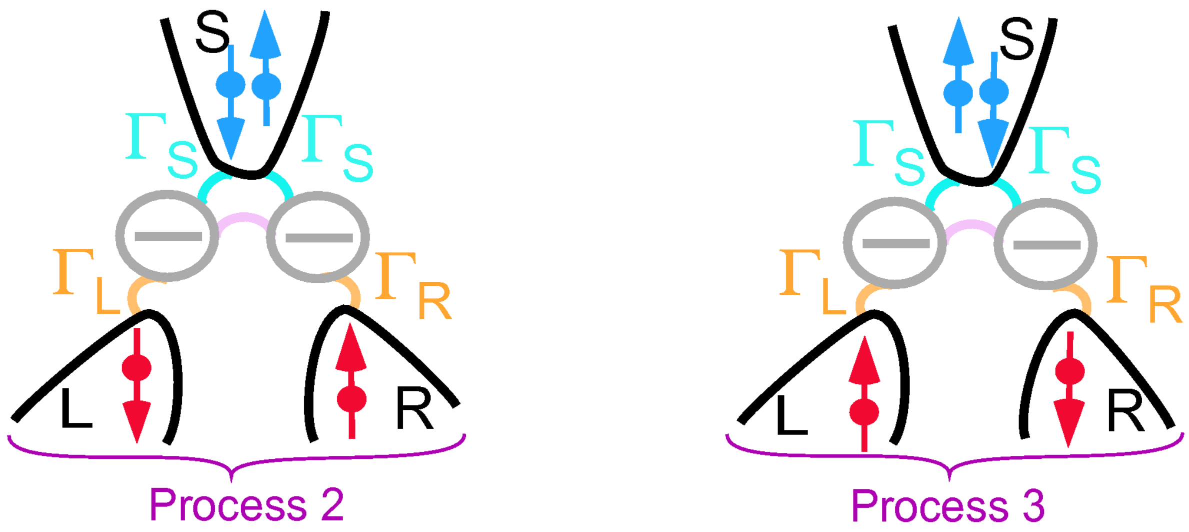
3-terminal junctions – with quantum dots



Possible channels of the Cooper pair splitting

L.G. Herrmann et al, *Phys. Rev. Lett.* **104**, *026801 (2010).*

3-terminal junctions – with quantum dots



These processes are similar to the crossed Andreev scattering and cause the strong non-local transport properties.

Non-local transport – crossed Andreev refelections

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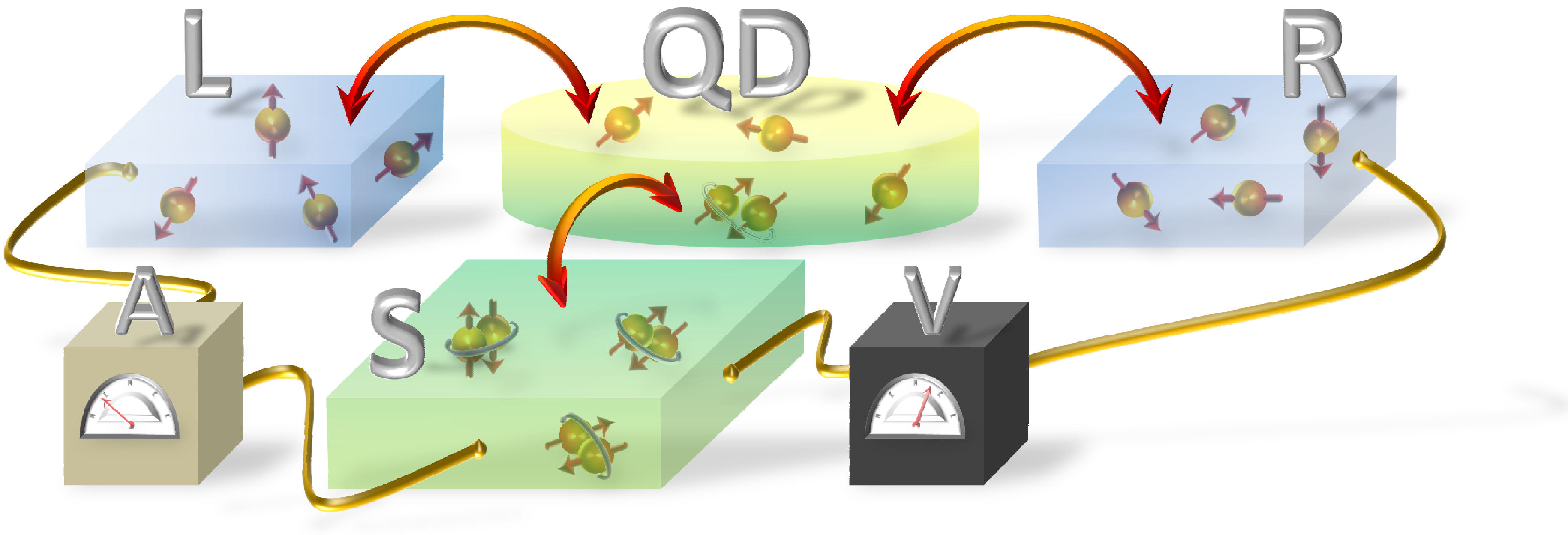
Quantum impurity in the 3-terminal configuration

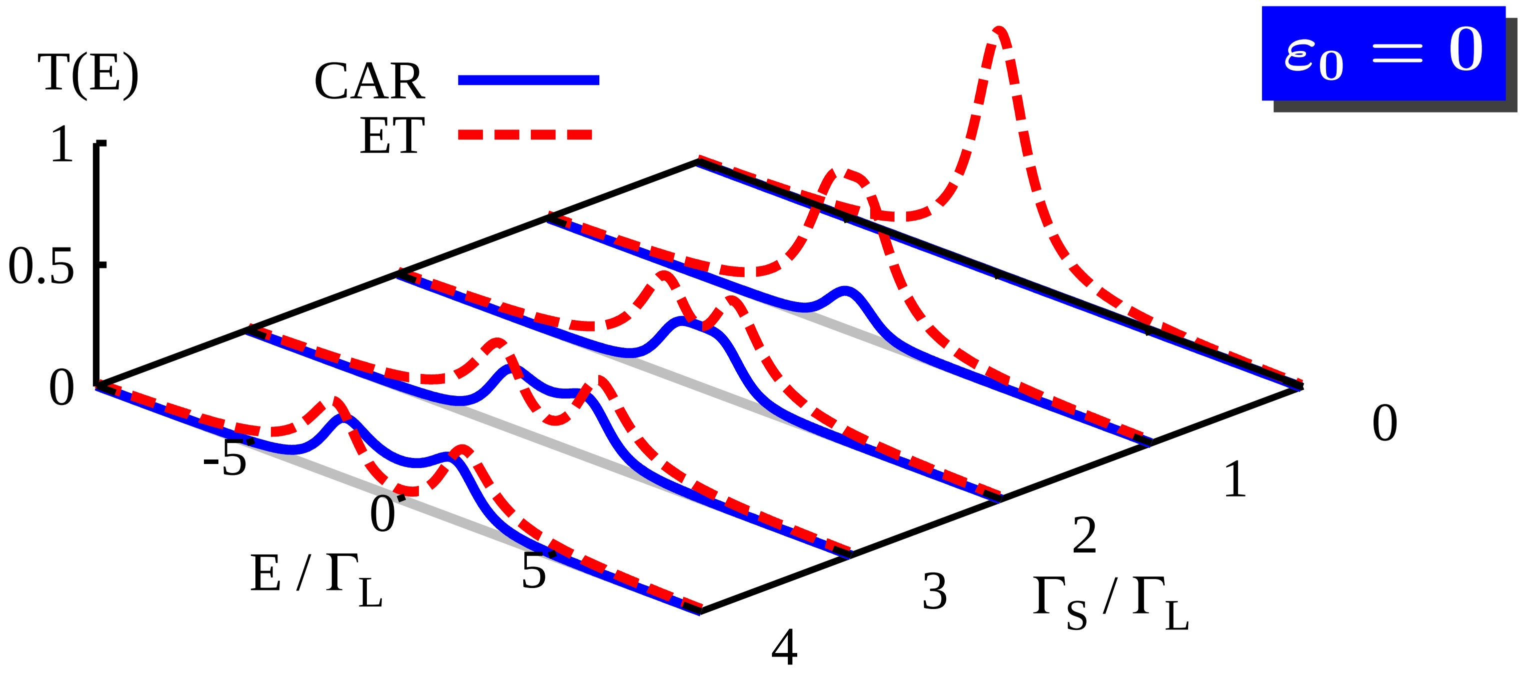


L, R – normal electrodes, S – superconducting reservoir, QD – quantum dot

G. Michałek, T. Domański, B.R. Bułka & K.I. Wysokiński, Scientific Reports **5**, 14572 (2015).

Non-local transport – crossed Andreev refelections

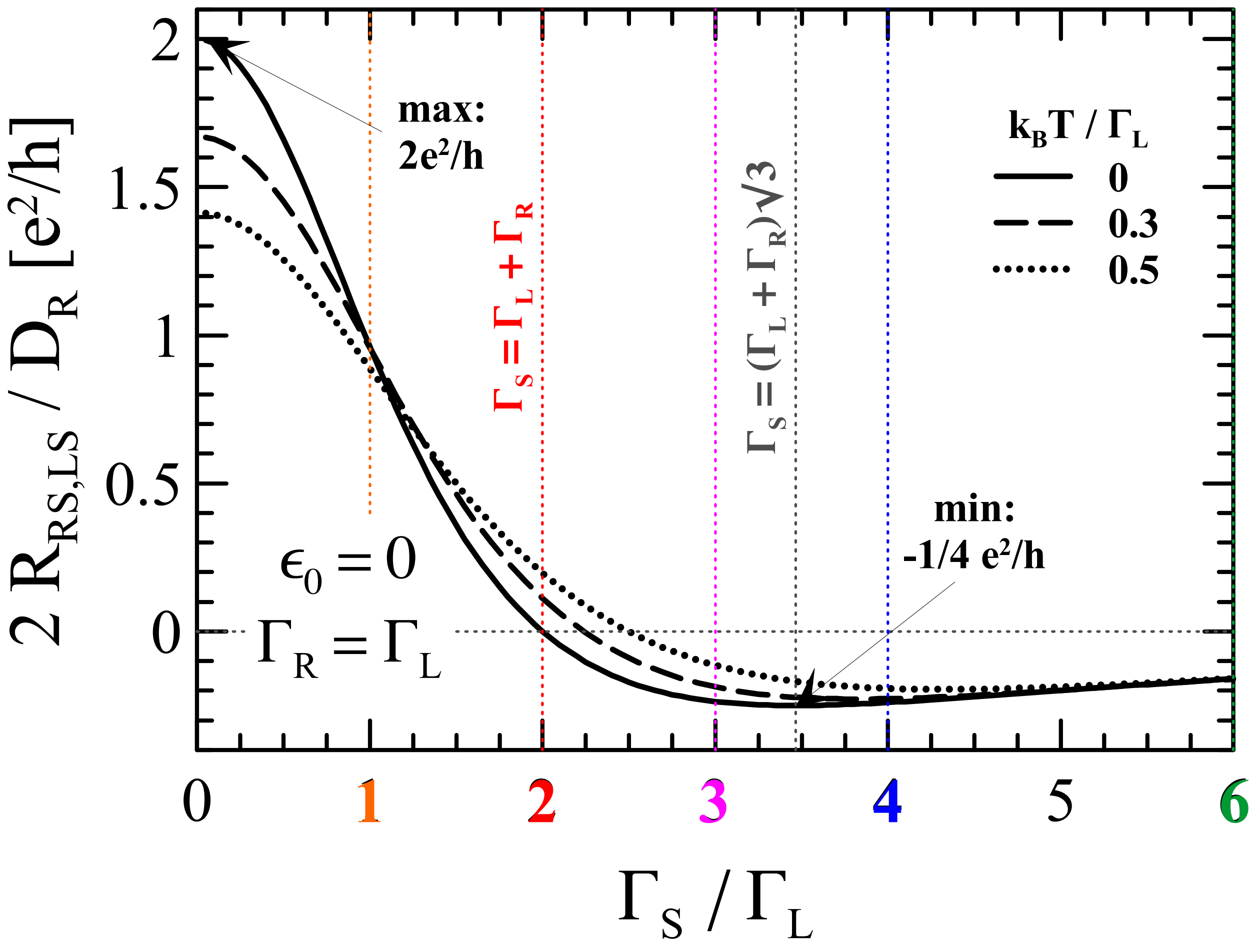
Transmittance of the non-local transport channels



ET – single electron transfer, CAR – crossed Andreev reflection

Non-local transport – crossed Andreev refelections

Non-local resistance in the linear response limit.

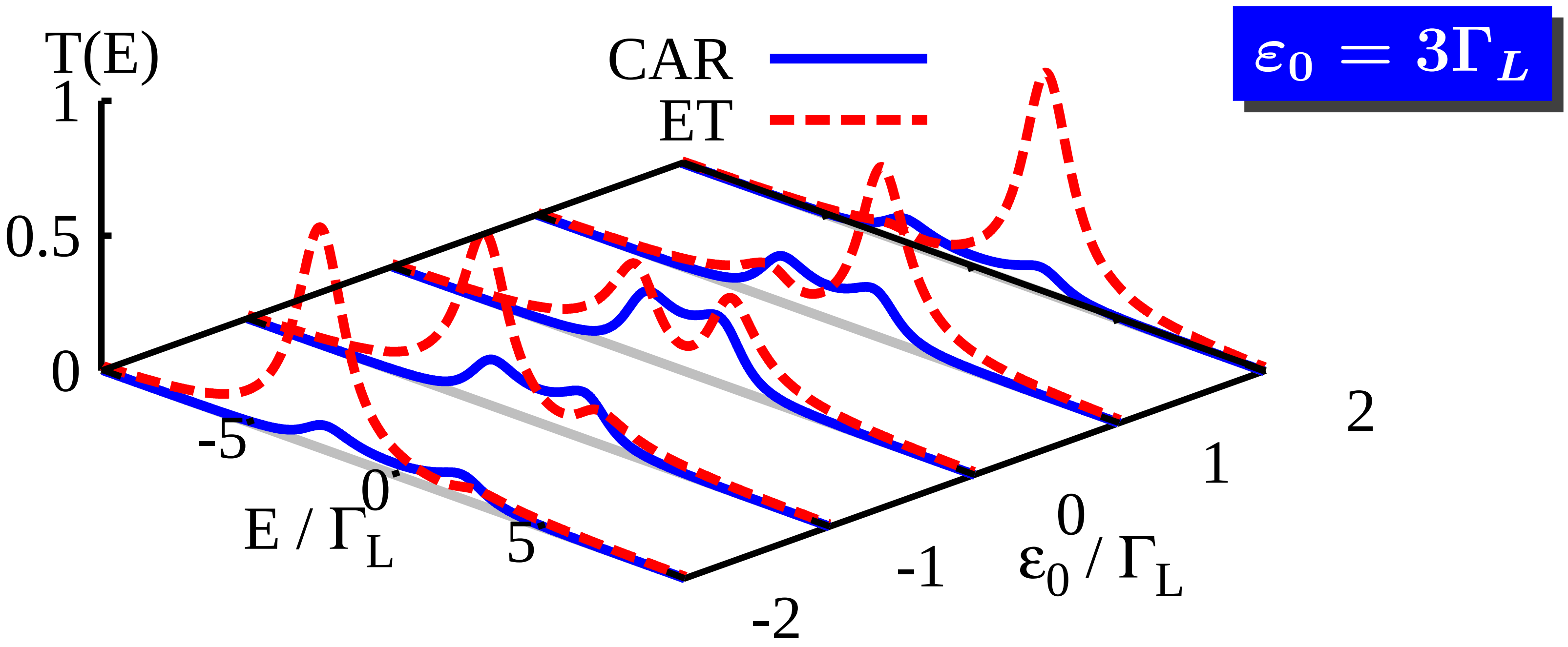


$$R_{RS,LS} \equiv V_{RS}/I_{LS}$$

Negative resistance for strong enough coupling Γ_S !

Non-local transport – crossed Andreev refelections

Transmittance of the non-local transport channels



ET – single electron transfer, **CAR** – crossed Andreev reflection

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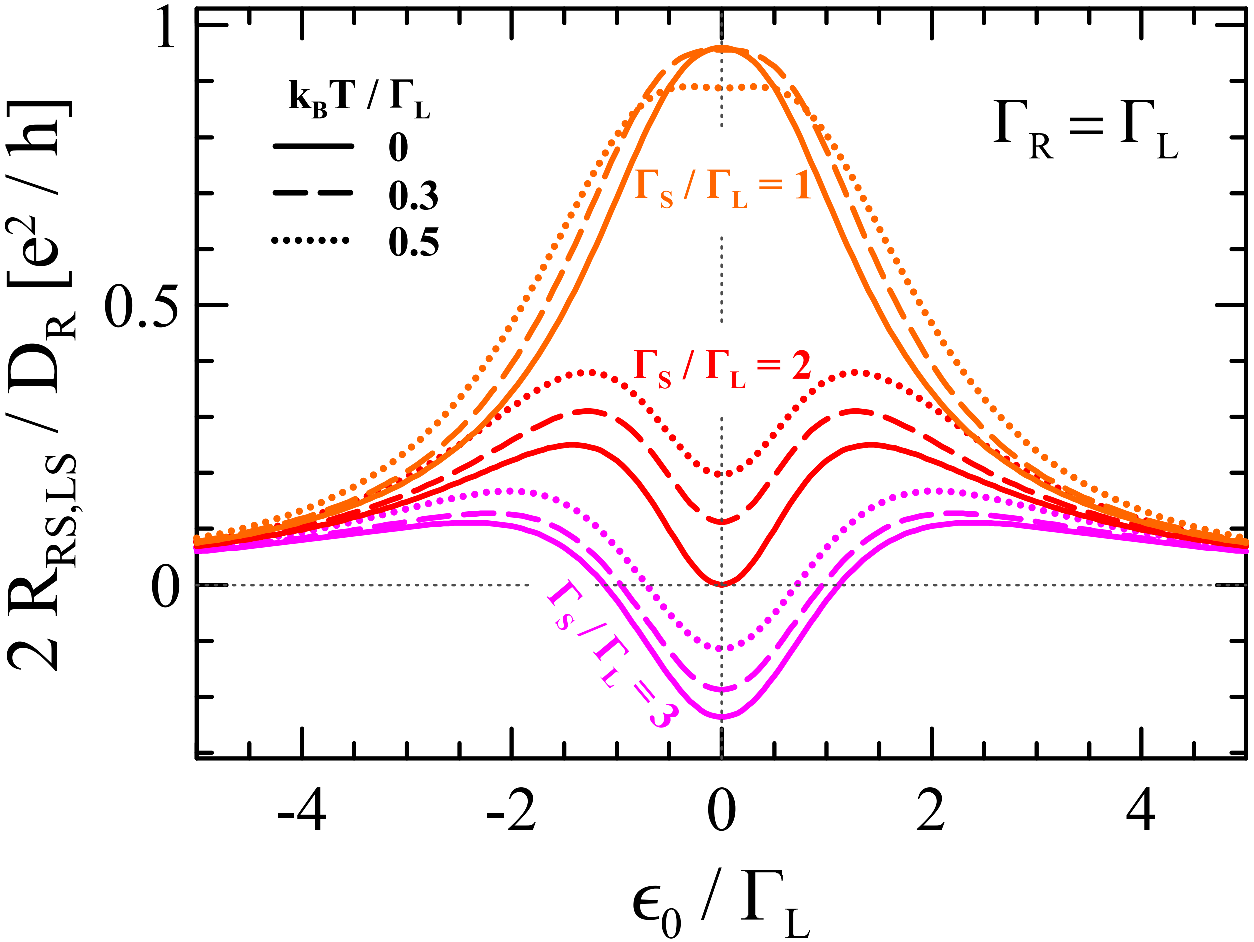
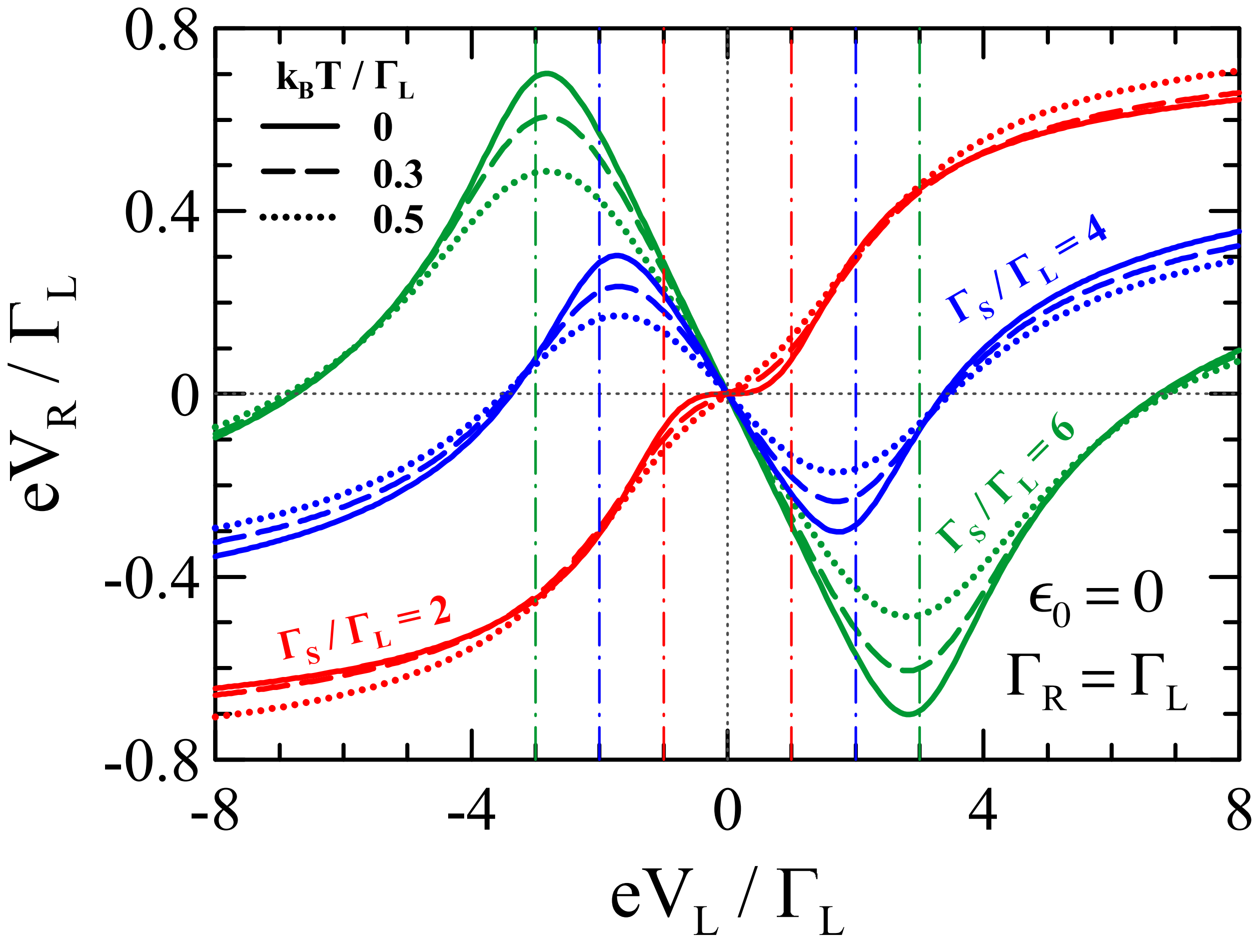


$R_{RS,LS} \equiv V_{RS}/I_{LS}$

Negative resistance for strong enough coupling Γ_S and $\varepsilon_0 \sim 0$!

Non-local transport – crossed Andreev refelections

Beyond the linear response regime.

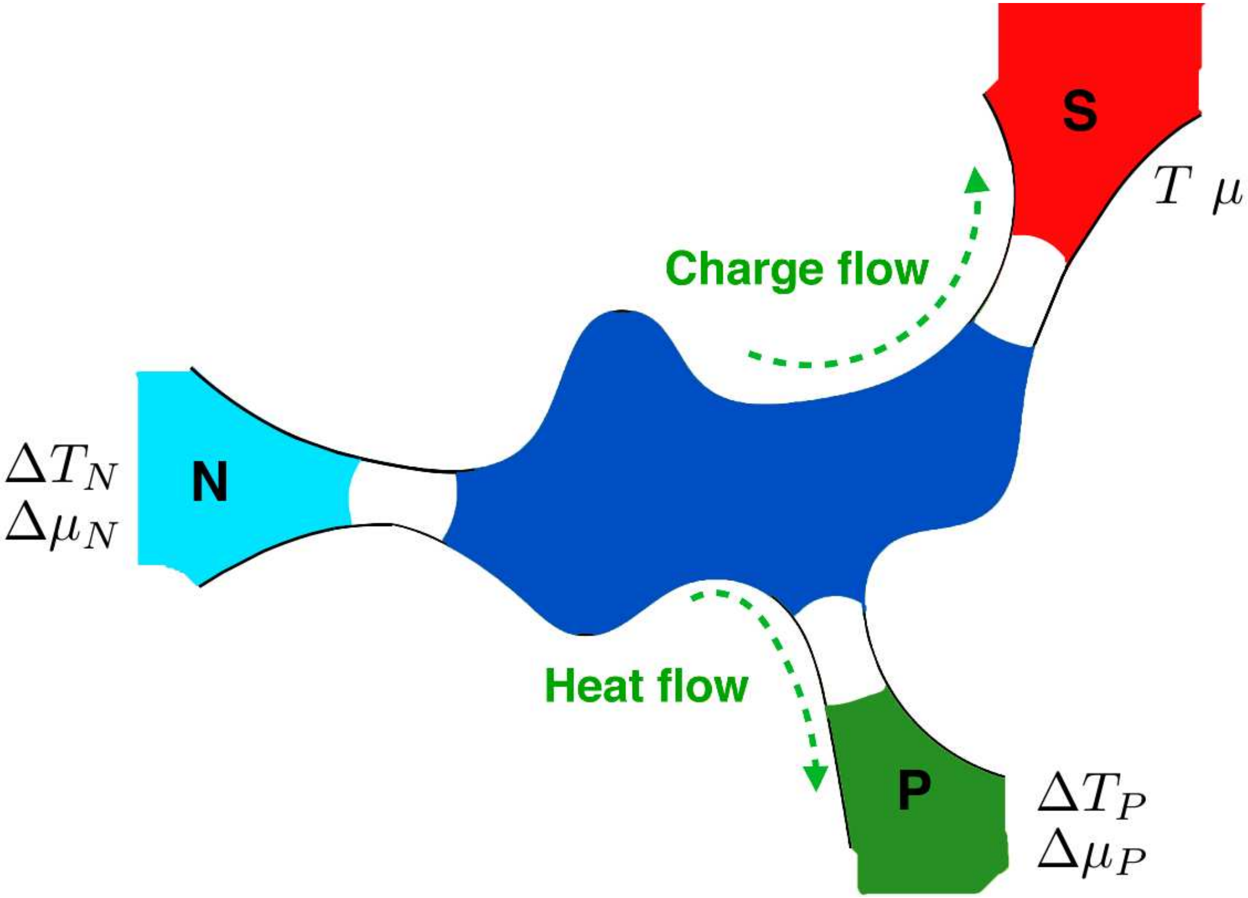


Inverse sign of the non-local voltage for strong enough coupling Γ_S.

Andreev reflections – other perspectives

Andreev reflections – other perspectives

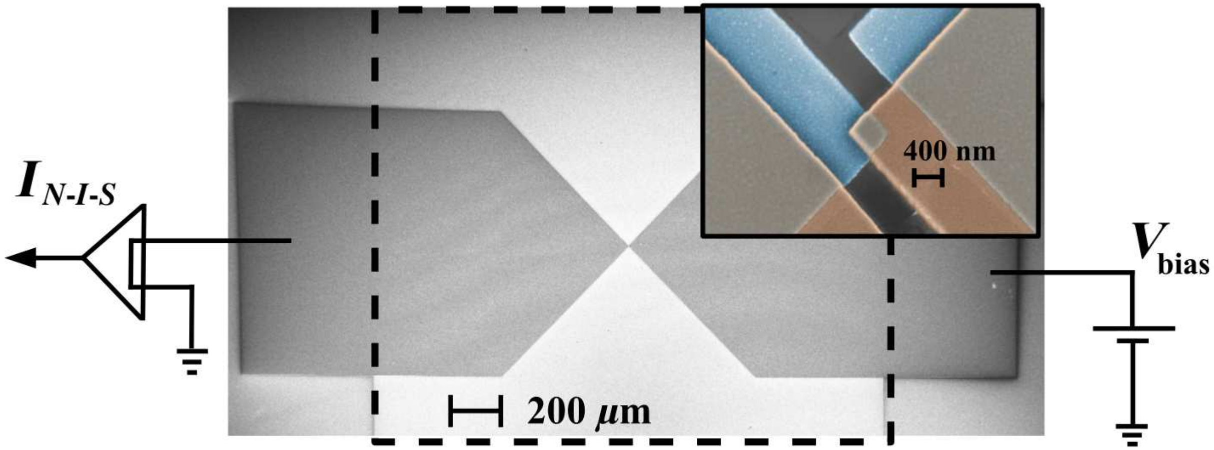
Crossed Andreev reflections enable the separation of charge from heat currents

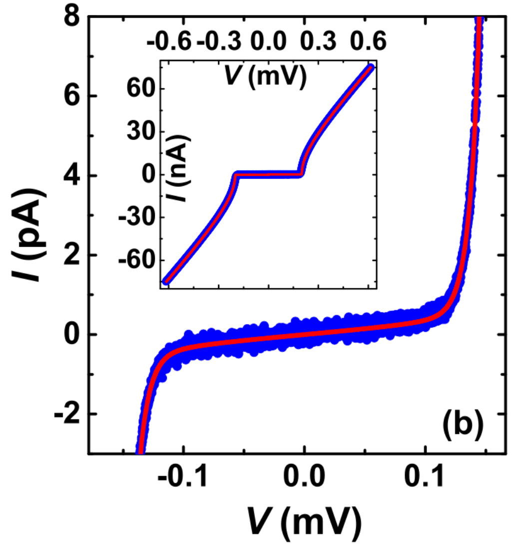


F. Mazza, S. Valentini, R. Bosisio, G. Benenti, V. Giovannetti, R. Fazio and F. Tadddei, Phys. Rev. B **91**, 245435 (2015).

Andreev reflections – other perspectives

On-chip nanoscopic thermometer operating down to 7 mK.





A.V. Feshchenko, L. Casparis, ..., J.P. Pekola & D.M. Zumbühl, Phys. Rev. Appl. **4**, 034001 (2015).

T. Faivre, D.S. Golubev and J.P. Pekola, Appl. Phys. Lett. **106**, 182602 (2015).

Virtues of a device:

⇒ is almost free of any self-heating

⇒ operates at criogenic temperatures

⇒ can thermally-monitor the qubits

Summary

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Nanoscopic superconductors:

Summary

Nanoscopic superconductors:

⇒ **can be induced by the proximity effect**

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$\Longrightarrow$ **can be induced by the proximity effect**

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Nanoscopic superconductors:

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$\Rightarrow$ **realization of exotic quasiparticles (e.g. Majorana-type)**

Summary

Nanoscopic superconductors:

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The anomalous (subgap) tunneling can reveal:

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⇒ separation of the charge from heat currents

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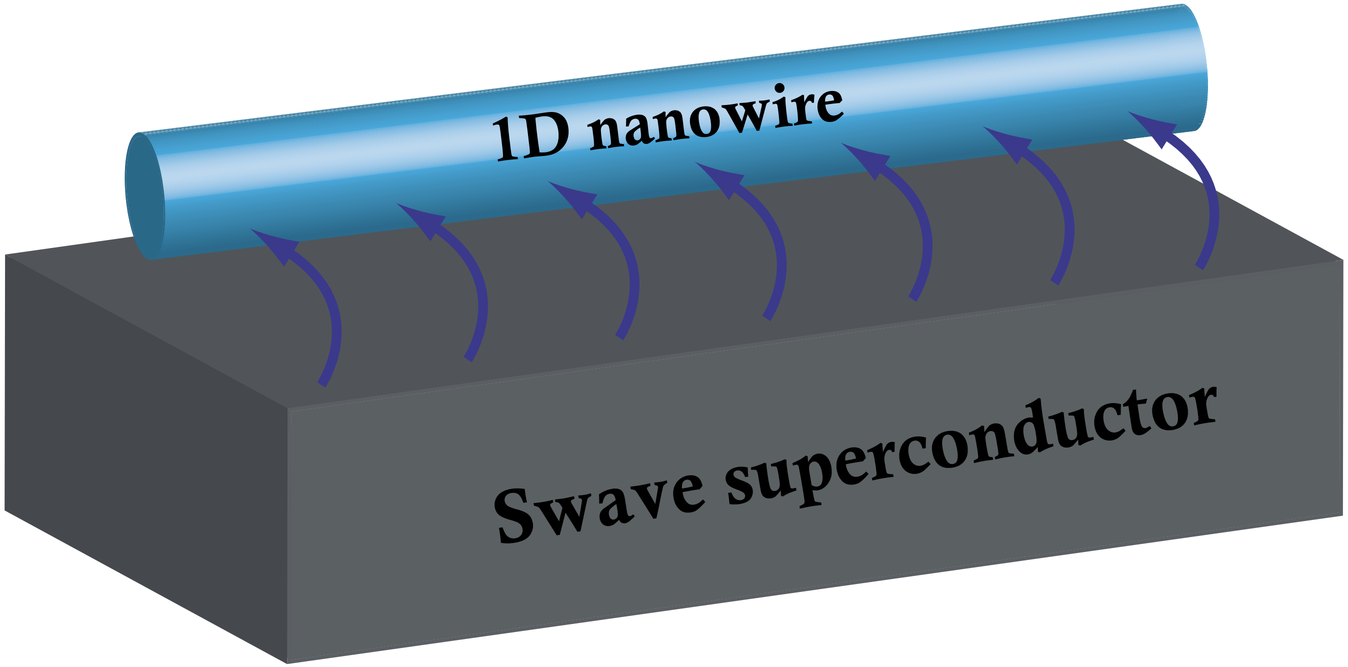
http://kft.umcs.lublin.pl/doman/lectures

Andreev vs Majorana states – a story of mutation

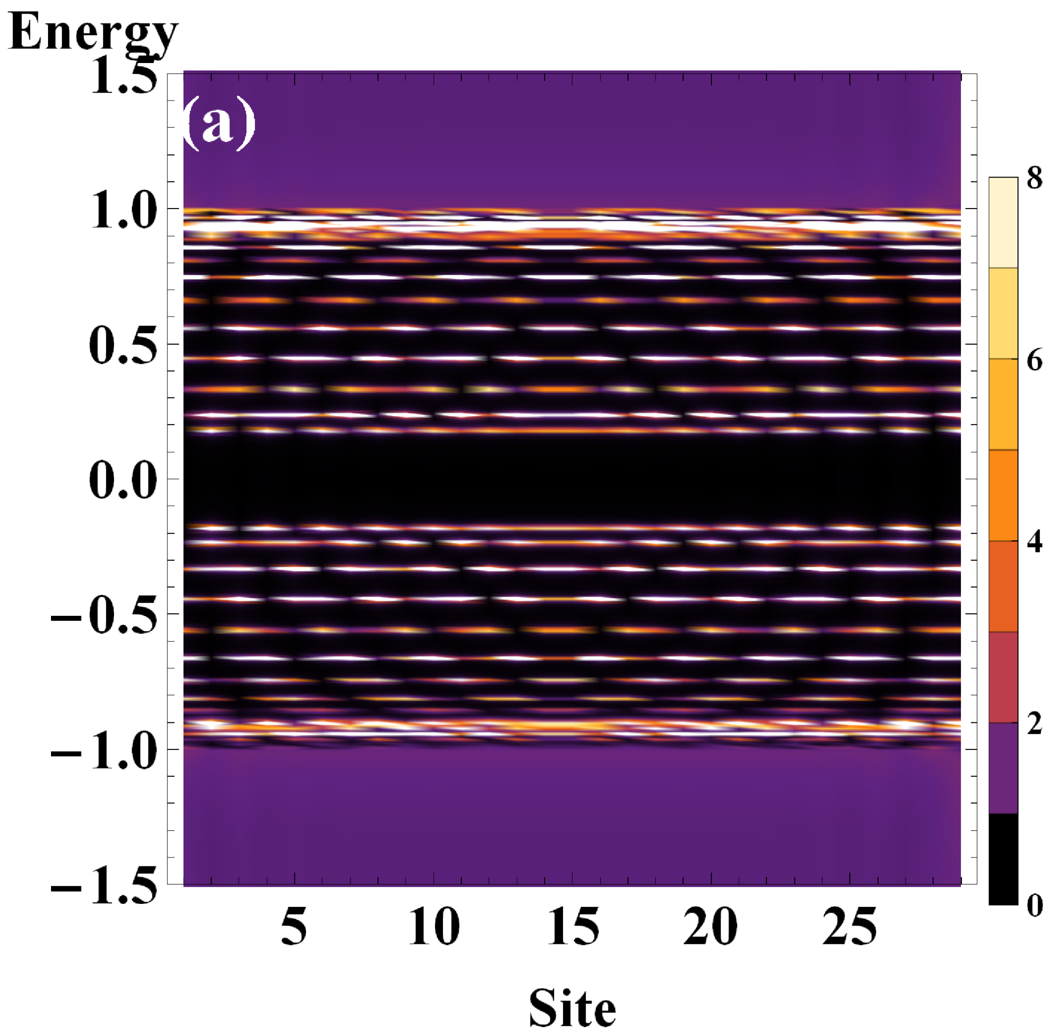
Andreev vs Majorana states – **a story of mutation**



Quantum wire deposited on s-wave superconductor

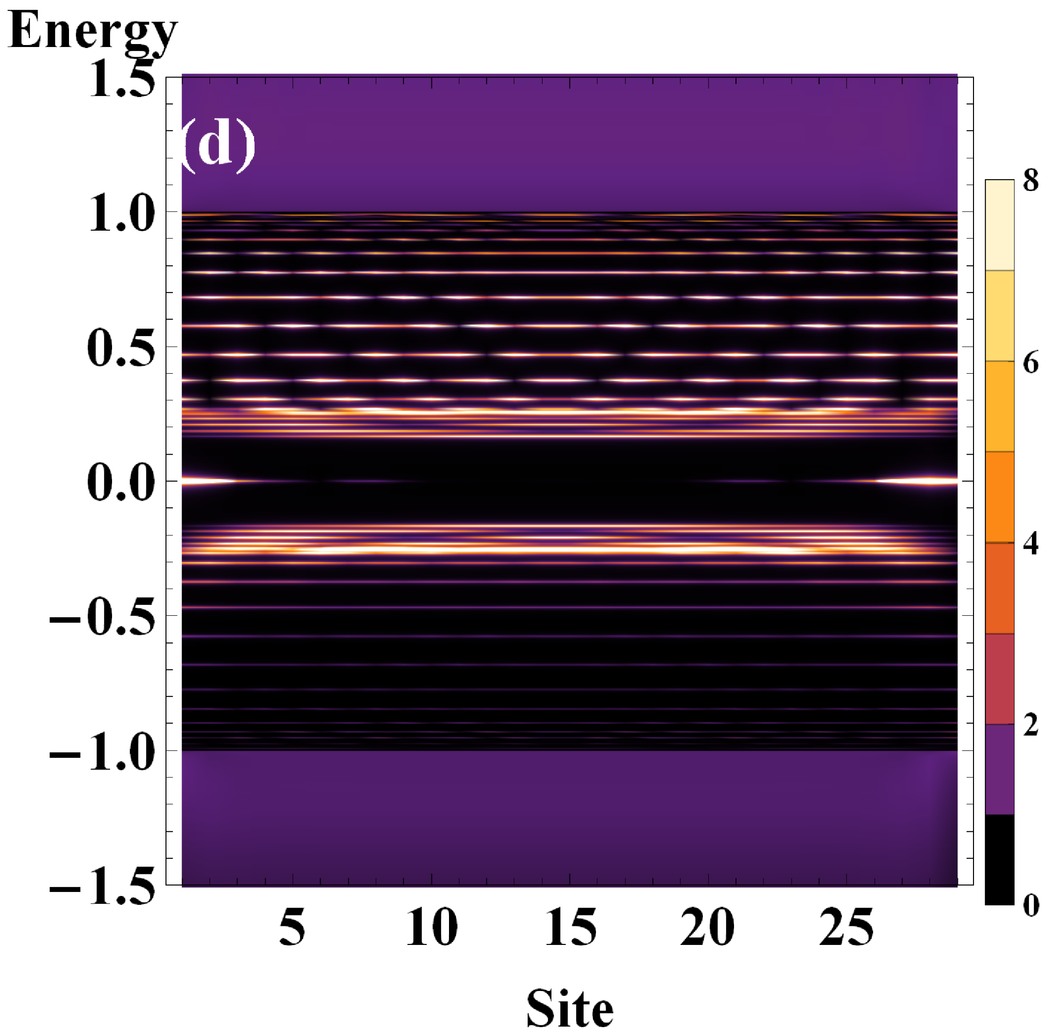
D. Chevallier, P. Simon, and C. Bena, Phys. Rev. B **88**, *165401 (2013).*

Andreev vs Majorana states – a story of mutation



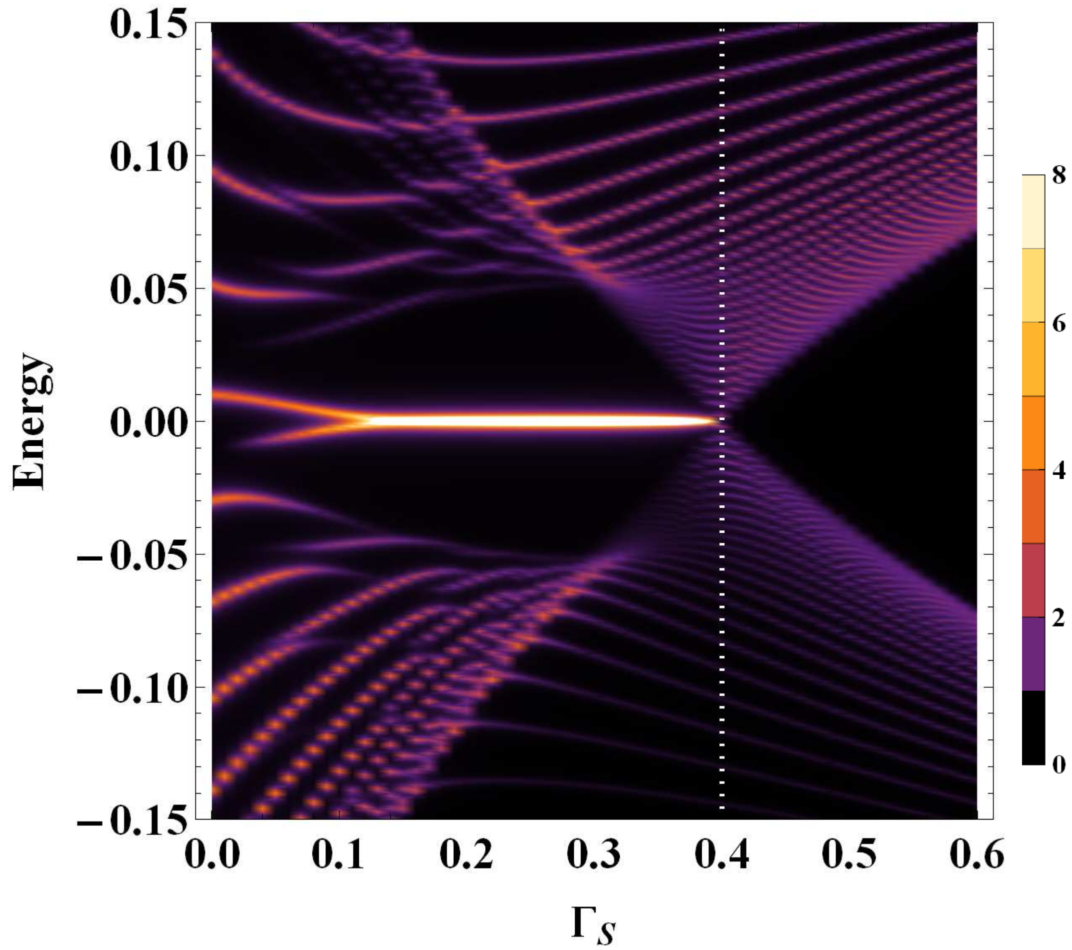
Spectrum of a quantum wire has a series of Andreev states.

Andreev vs Majorana states – a story of mutation



Spin-orbit coupling can induce the Majorana-type quasiparticles.

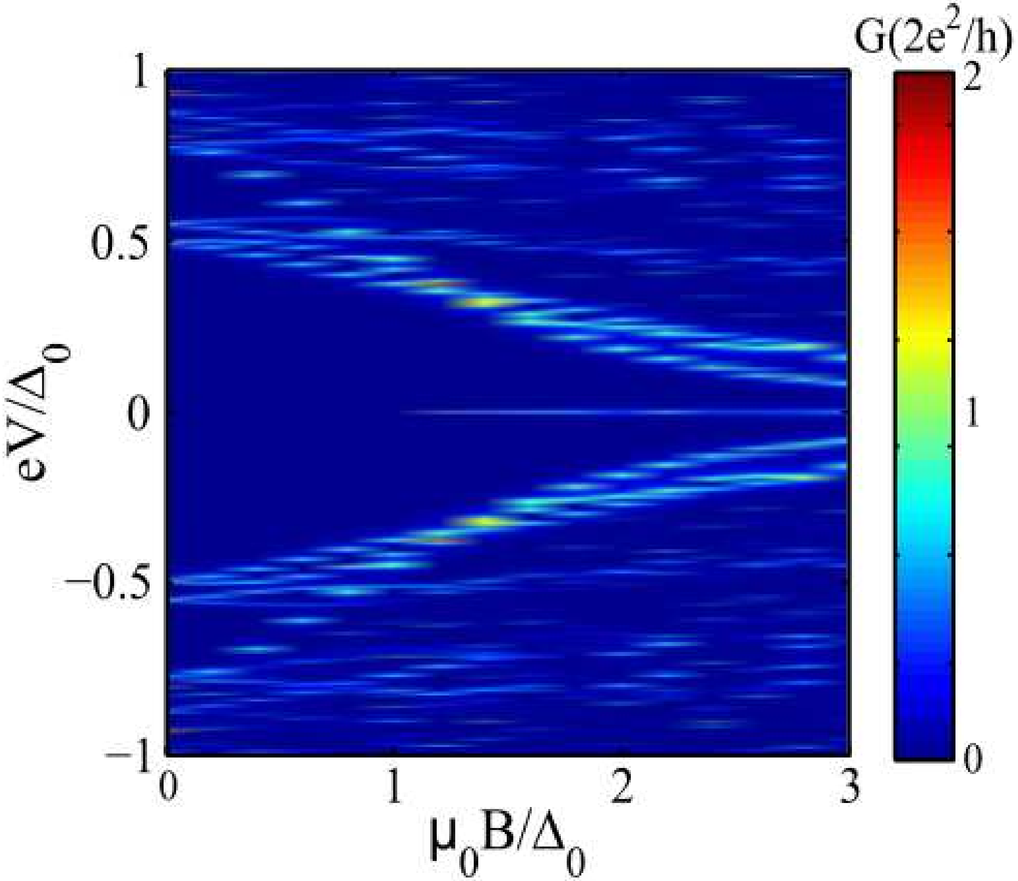
Andreev vs Majorana states – a story of mutation



Majorana quasiparticles appear at the edges of a quantum wire.

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

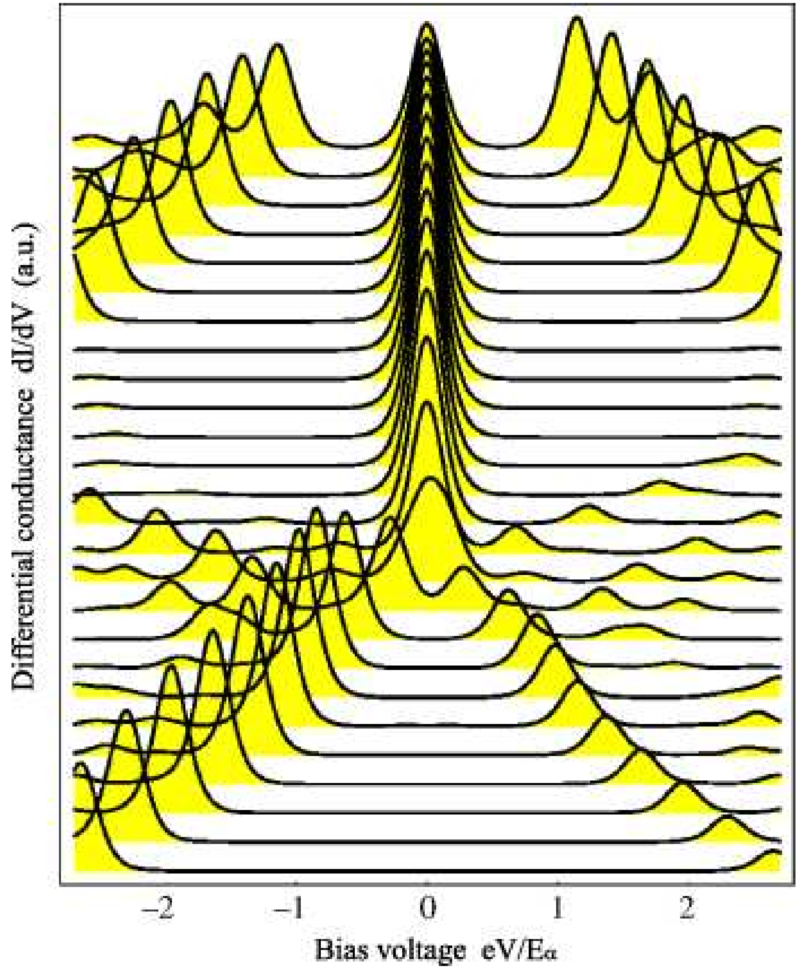
Andreev vs Majorana states – a story of mutation



Quasiparticles at the edge of a quantum wire for varying magnetic field.

J. Liu, A.C. Potter, K.T. Law, and P.A. Lee, Phys. Rev. Lett. **109**, *267002 (2012).*

Andreev vs Majorana states – **a story of mutation**



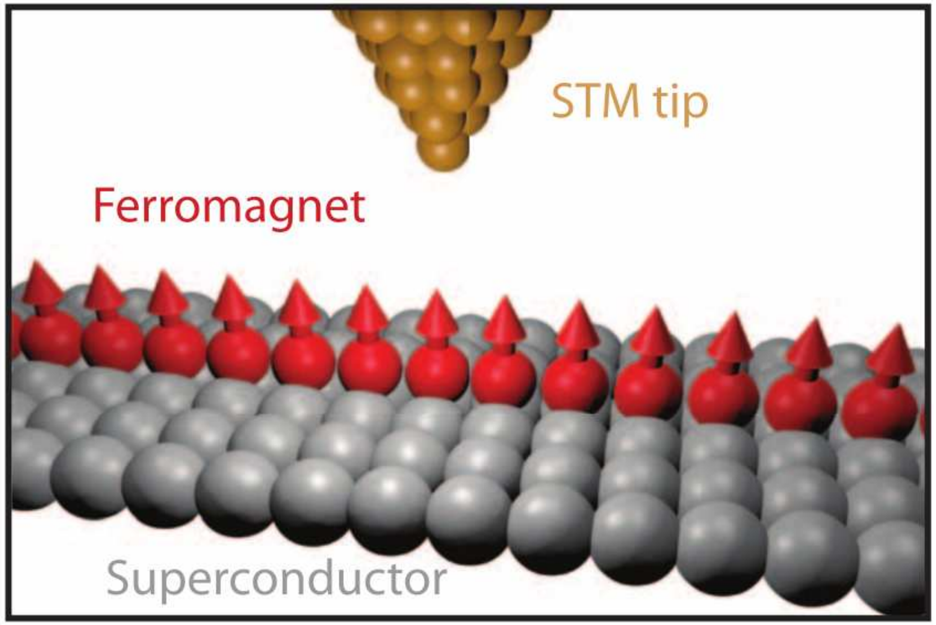
Quasiparticles at the edge of a quantum wire for varying magnetic field.

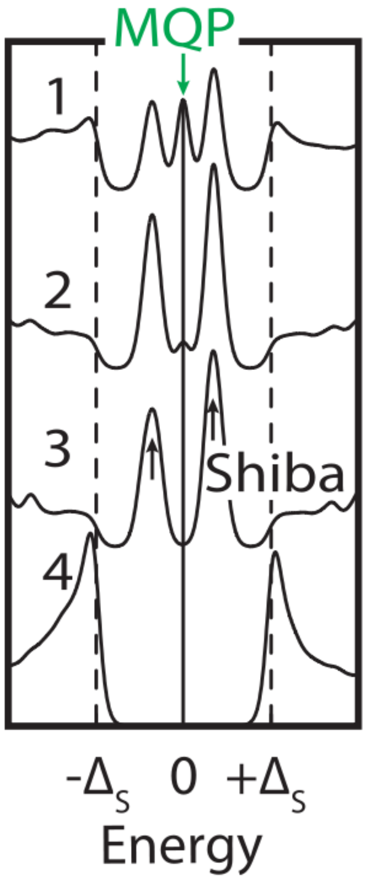
T.D. Stanescu, R.M. Lutchyn, and S. Das Sarma, Phys. Rev. B **84**, *144522 (2011).*

Experimental results – for Majorana quasiparticles

Experimental results – for Majorana quasiparticles

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





STM measurements provided evidence for:

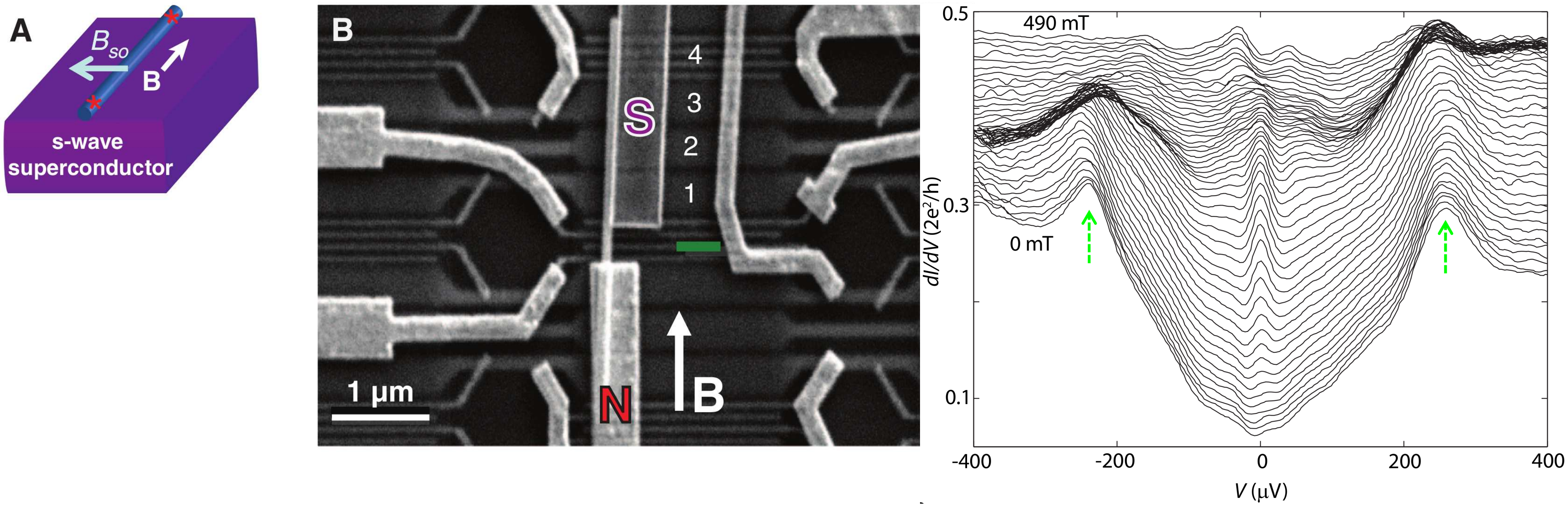
⇒ **Majorana bound states at the edges of a chain.**

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

/ Princeton University, Princeton (NJ), USA /

Experimental results – **for Majorana quasiparticles**

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 /