Poznań, 28 June 2011

Interplay between correlations and superconductivity in the electron transport through the quantum dots

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Outline

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★ **Physical setup**

/ metal - QD - superconductor /

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★ **Relevant issues**

/ correlations vs superconductivity /

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- **Experimental realization**
  /enhancement of the Andreev conductance /

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  $\Longrightarrow$ *quantum interference in the multiple QDs*

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⇒ *QD in the multiterminal structures*

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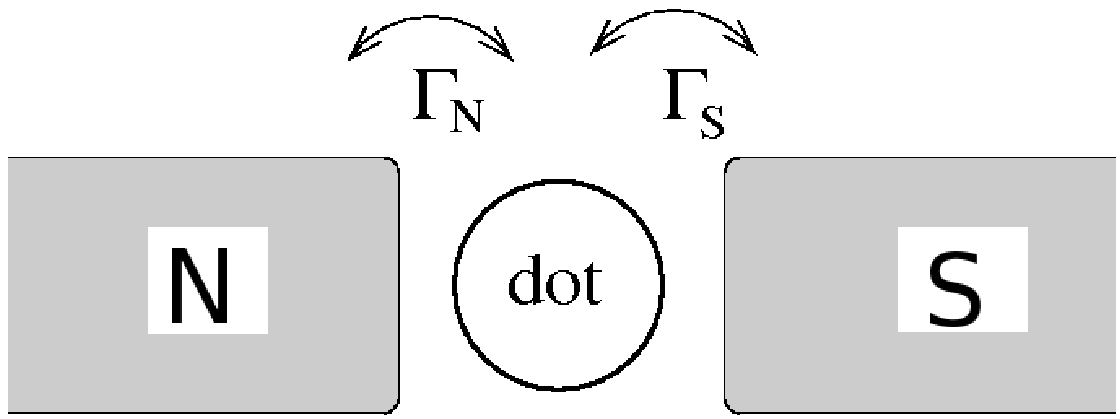

metallic lead QD superconductor

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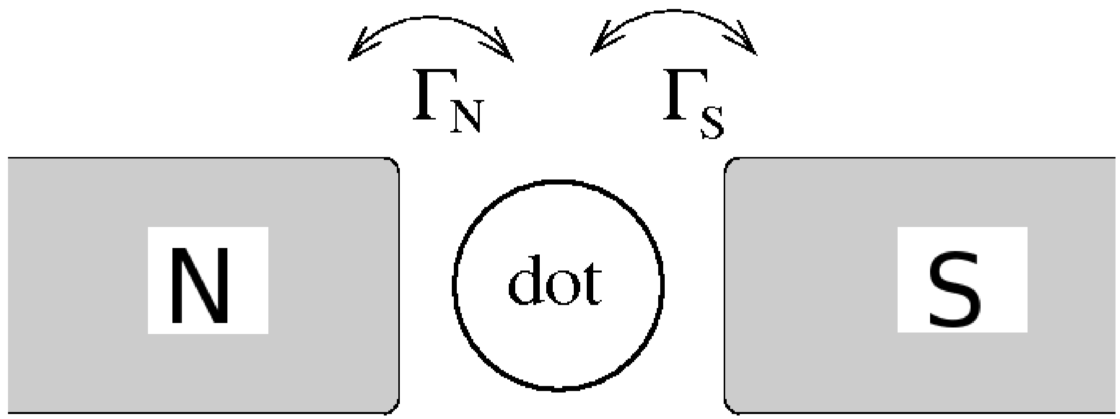

metallic lead

QD

superconductor

This represents a particular version of the SET.

Relevant issues

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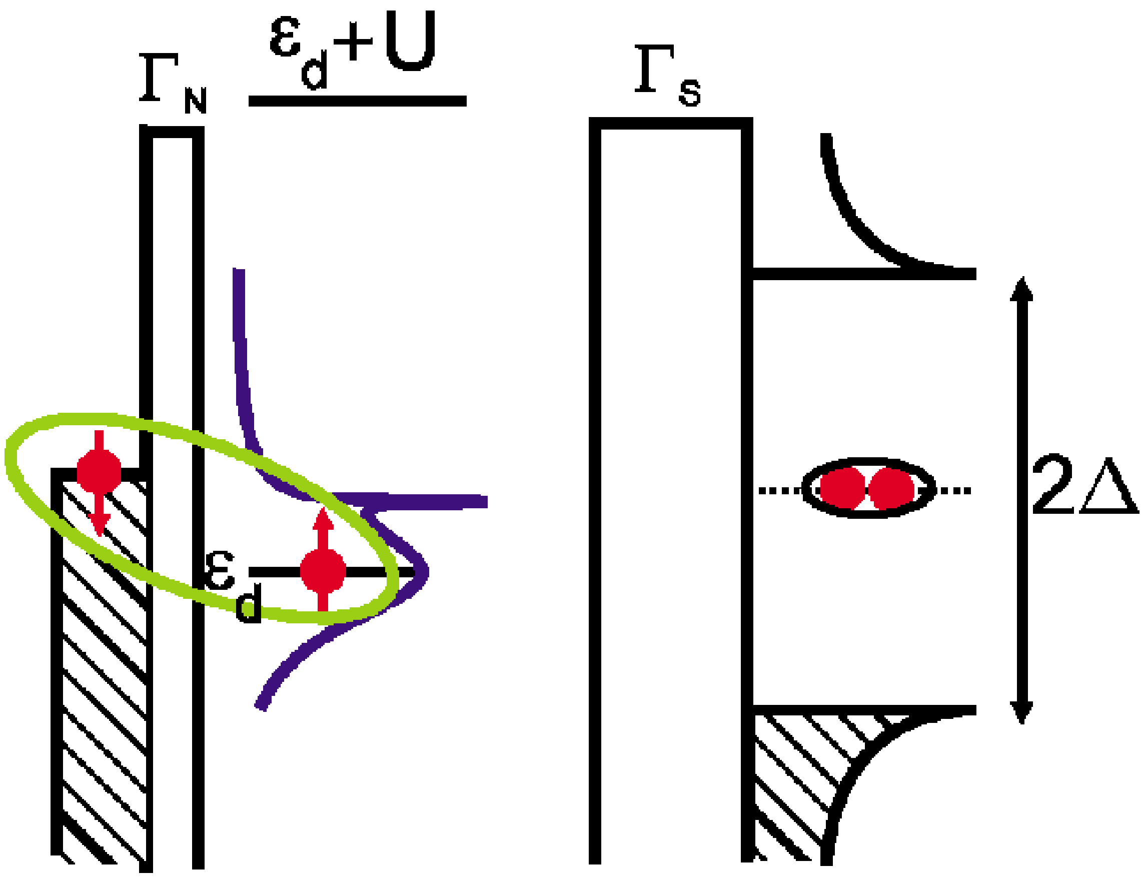

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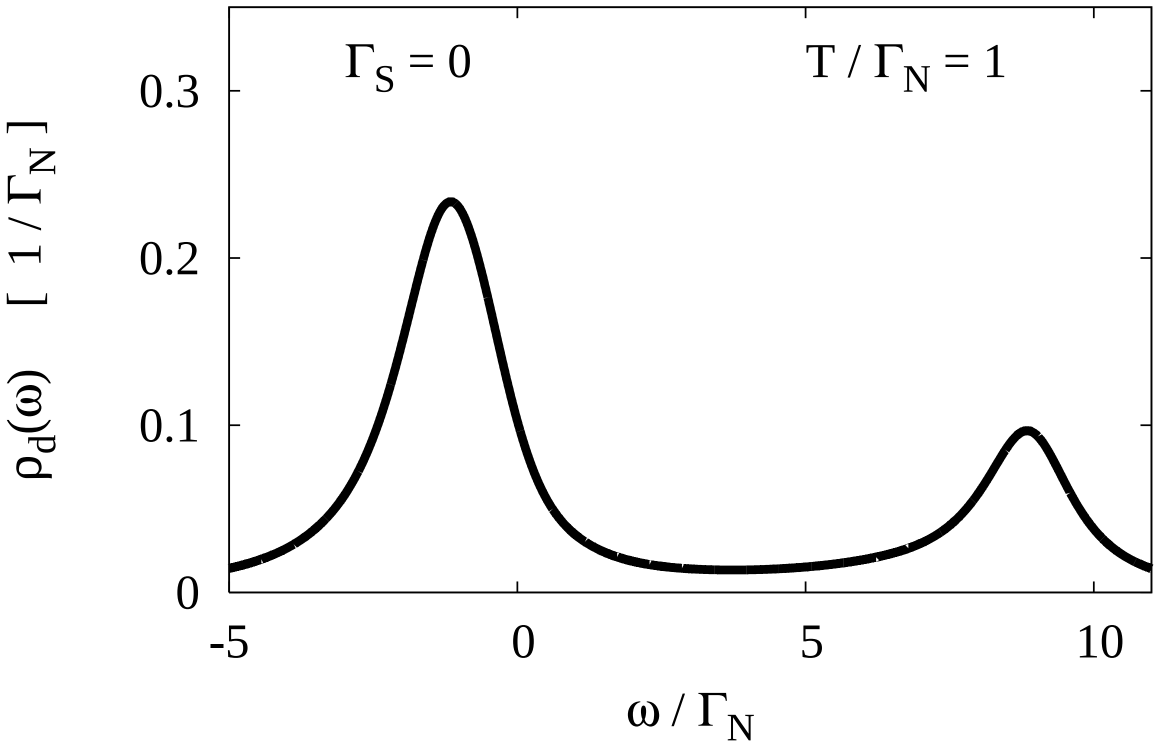

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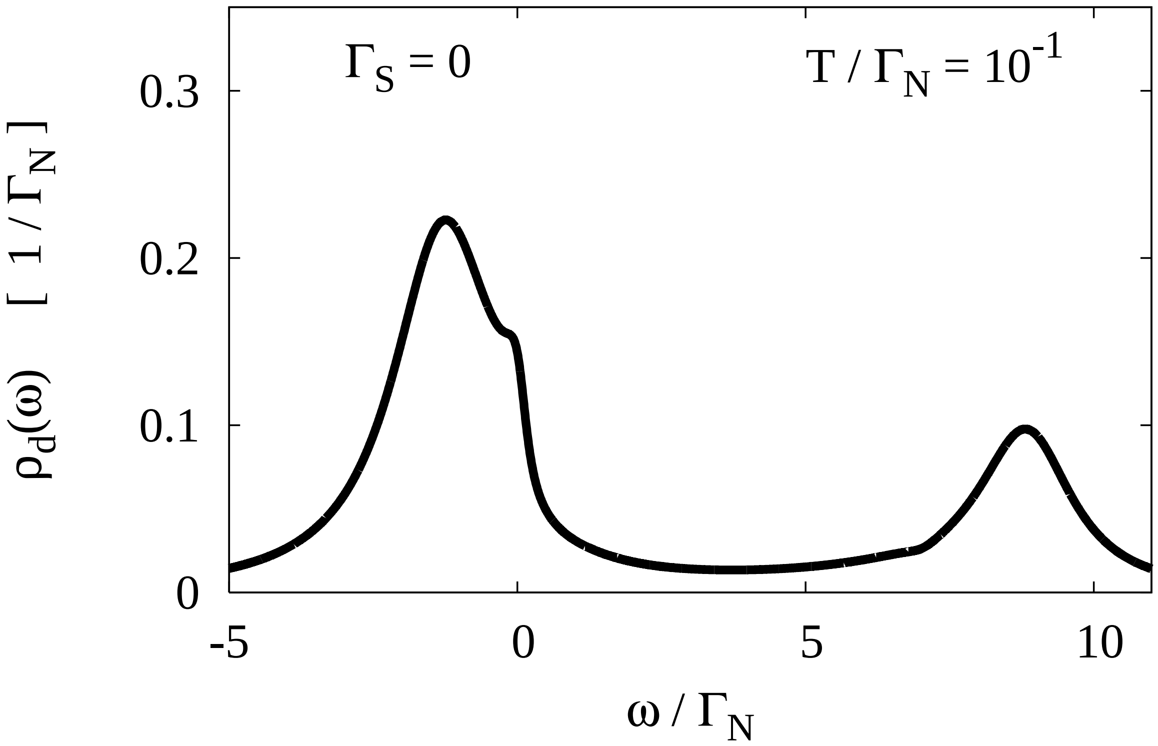

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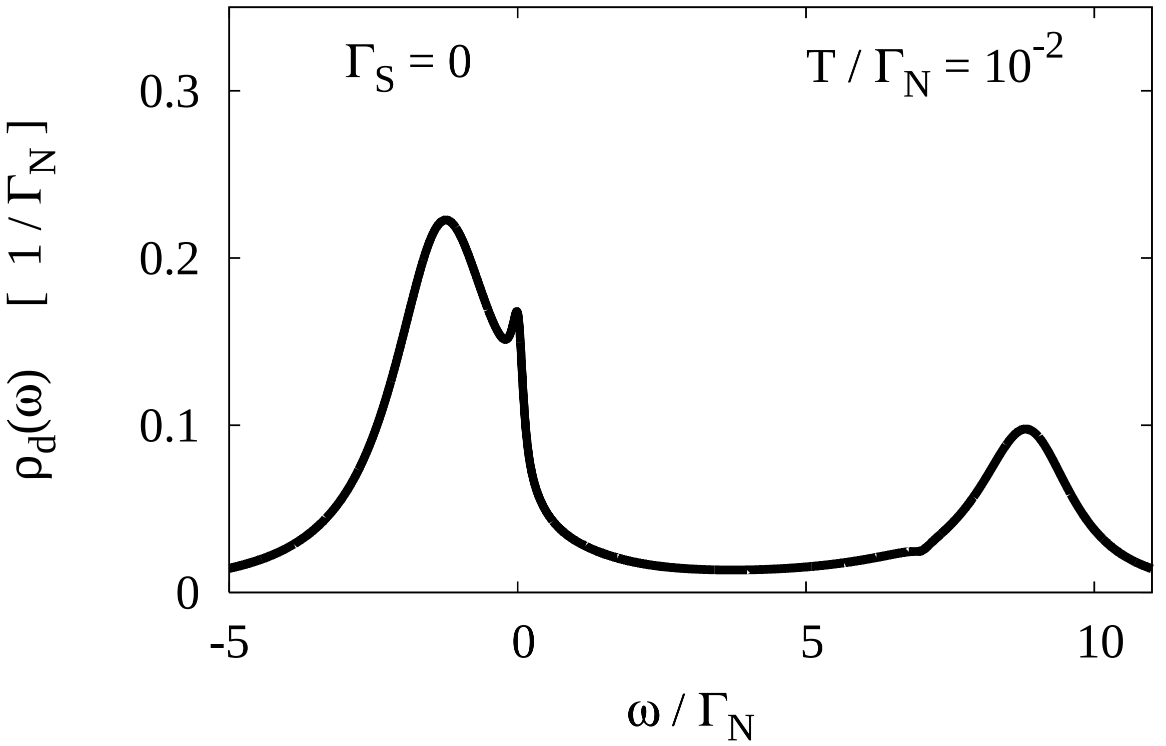

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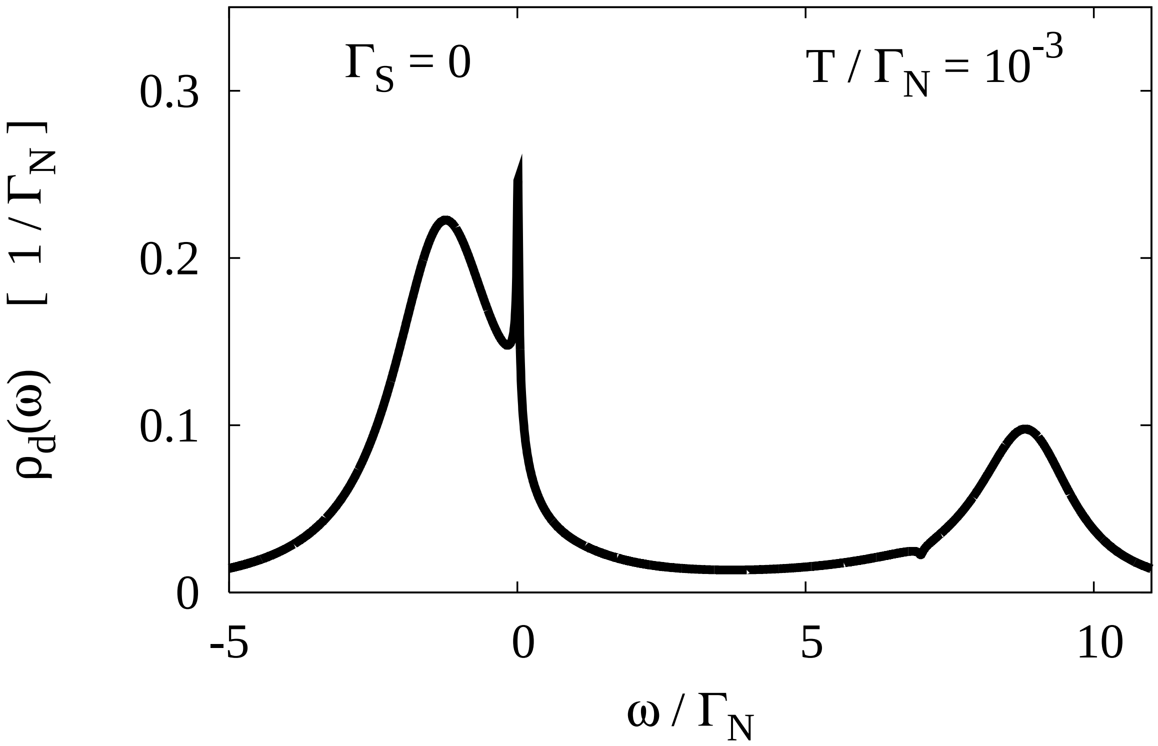

- ★ a broadening of the QD levels and
- ★ appearance of the Kondo resonance at $T \leq T_K$.

Physical aspects : # 2

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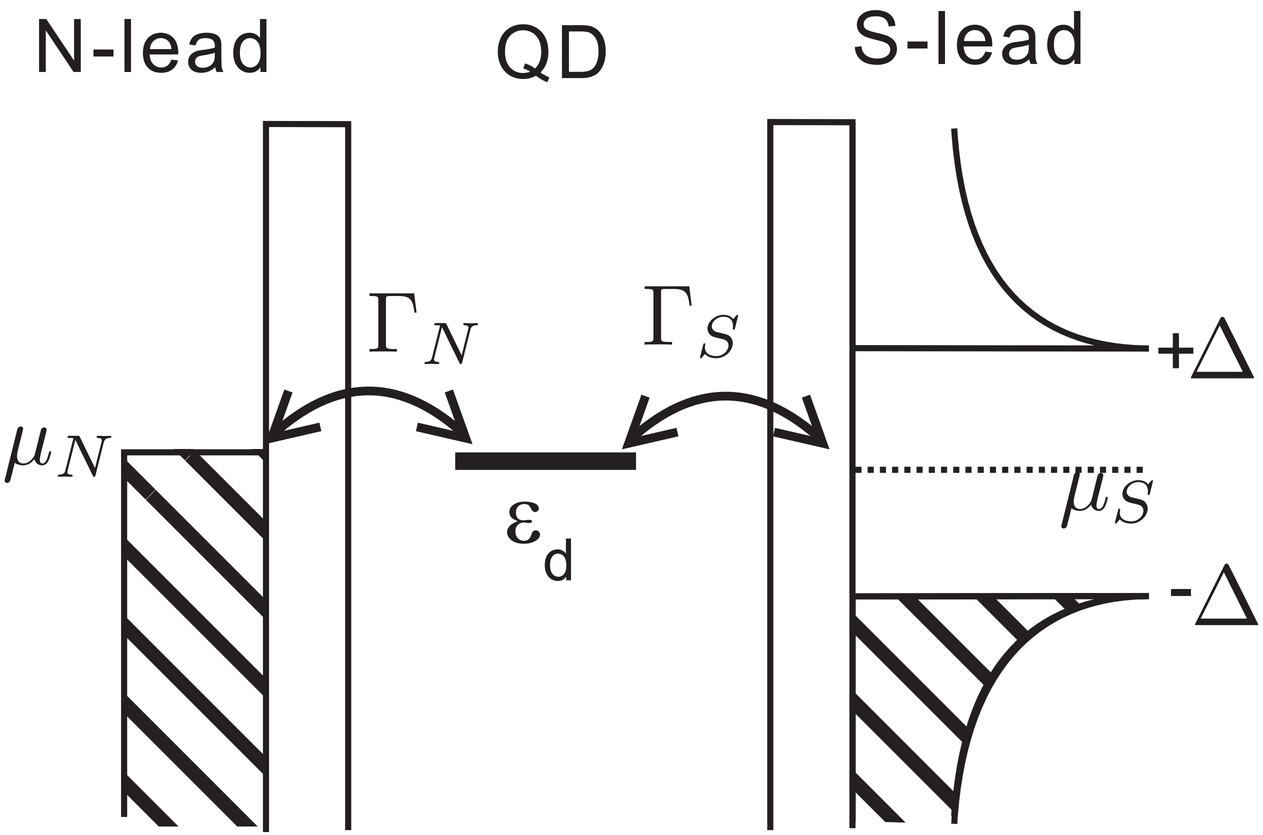
Hybridization of the QD to superconducting lead



Physical aspects : $\#$ 2

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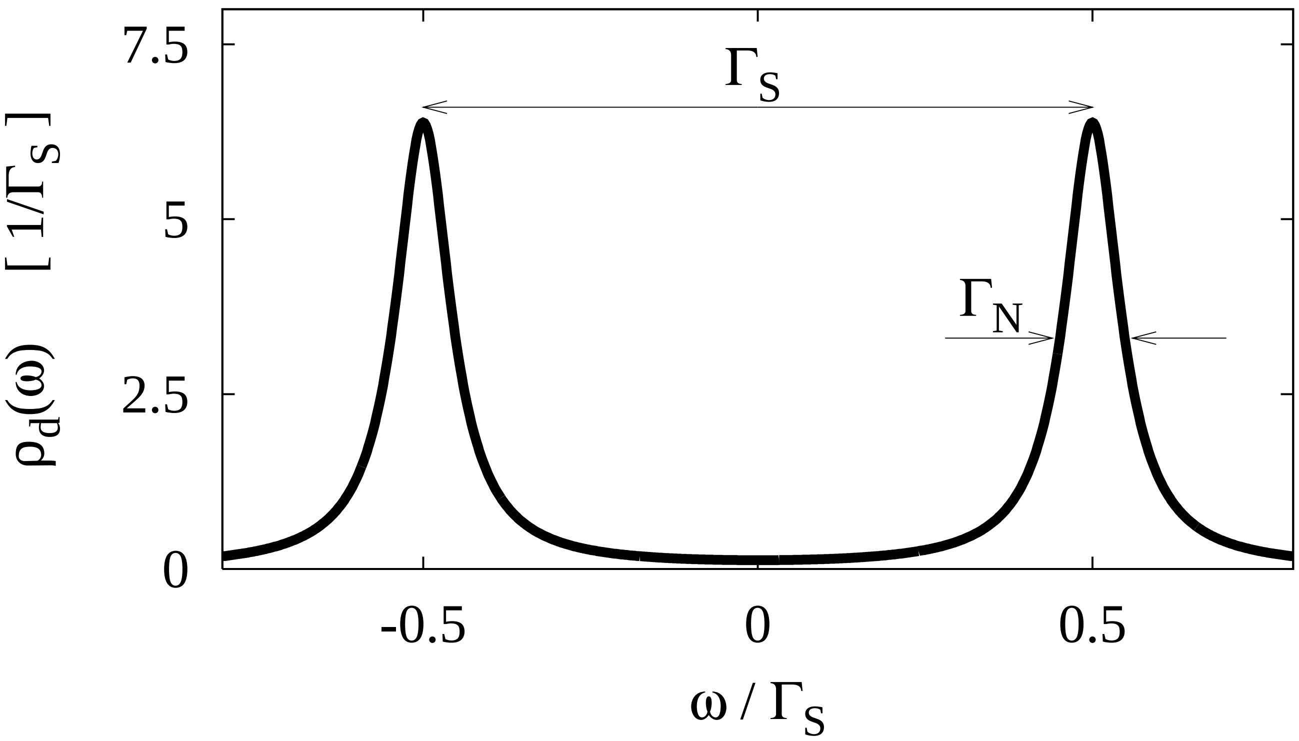

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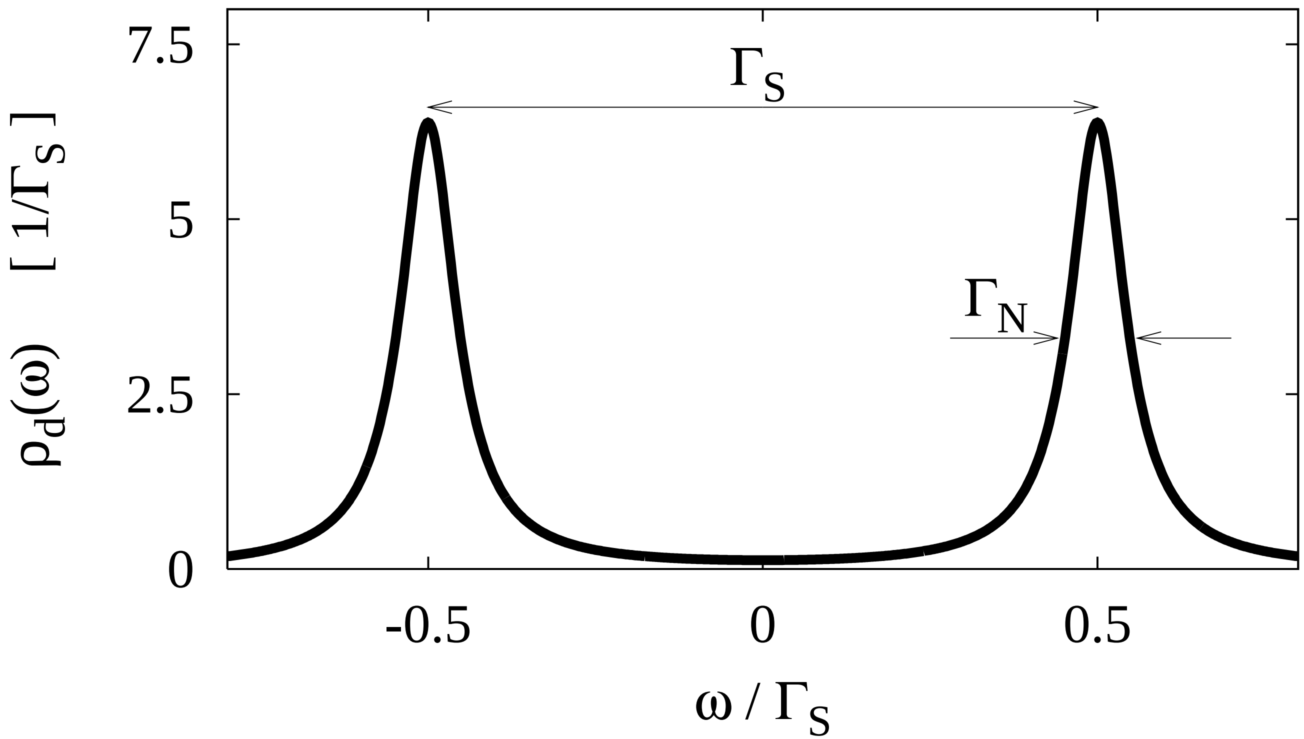

QD spectrum obtained for $\varepsilon_d = 0, \quad U = 0$

Physical aspects :

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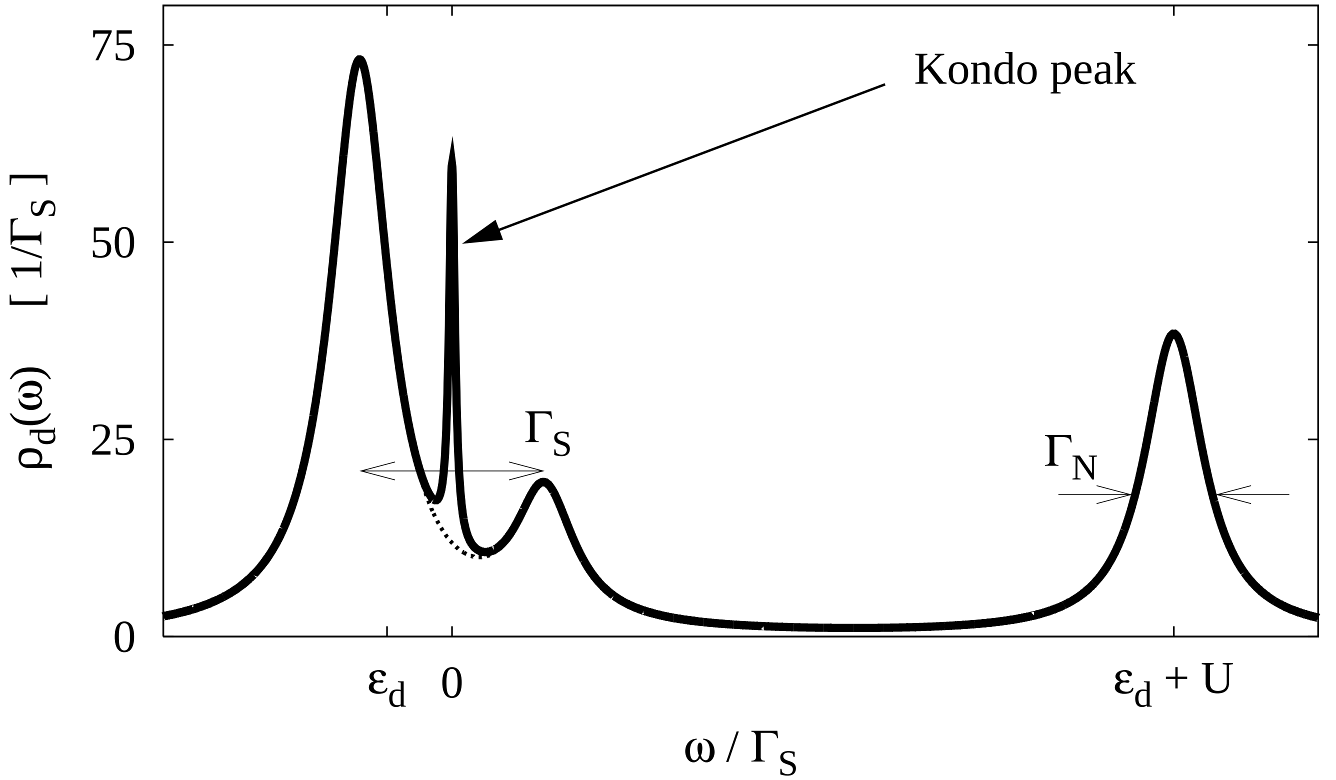
Hybridizations Γ_N and Γ_S lead to a nontrivial



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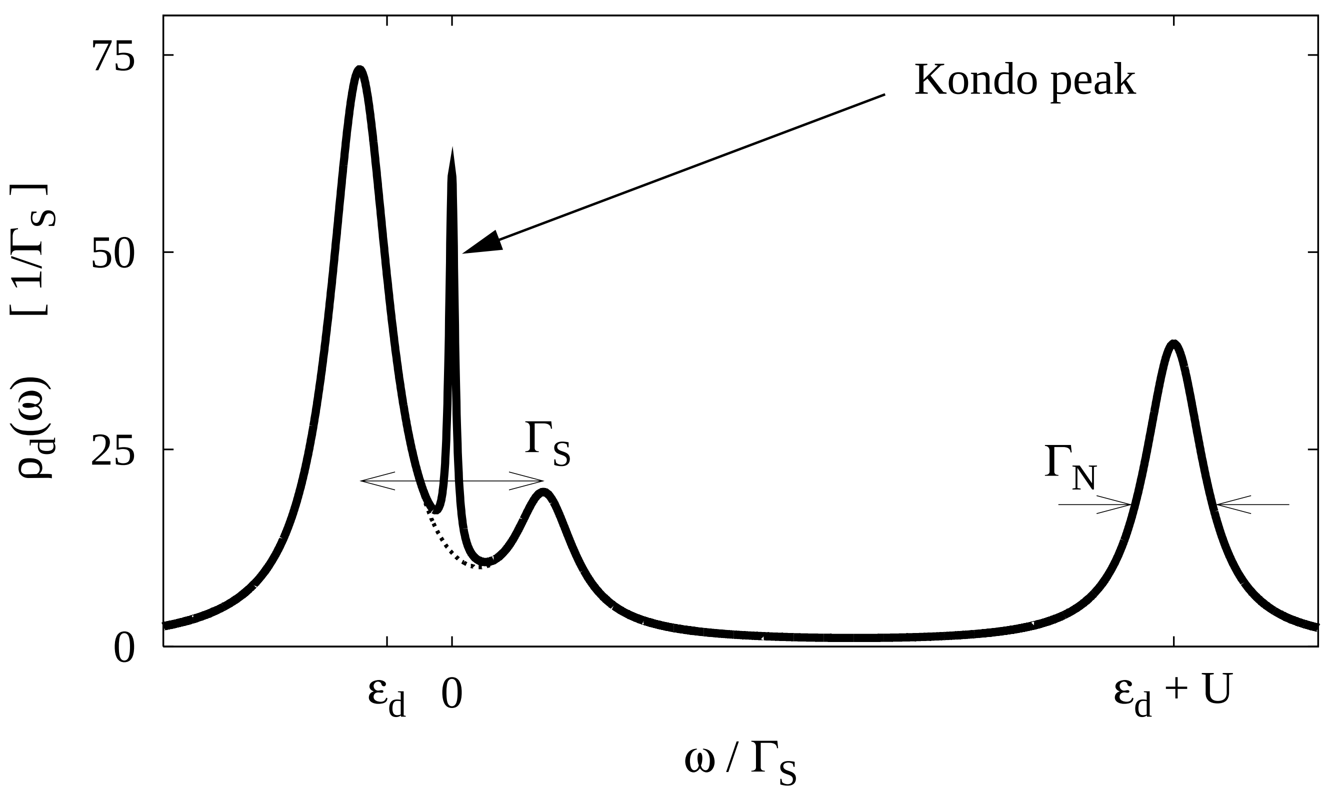

interplay between the superconductivity and Kondo effect

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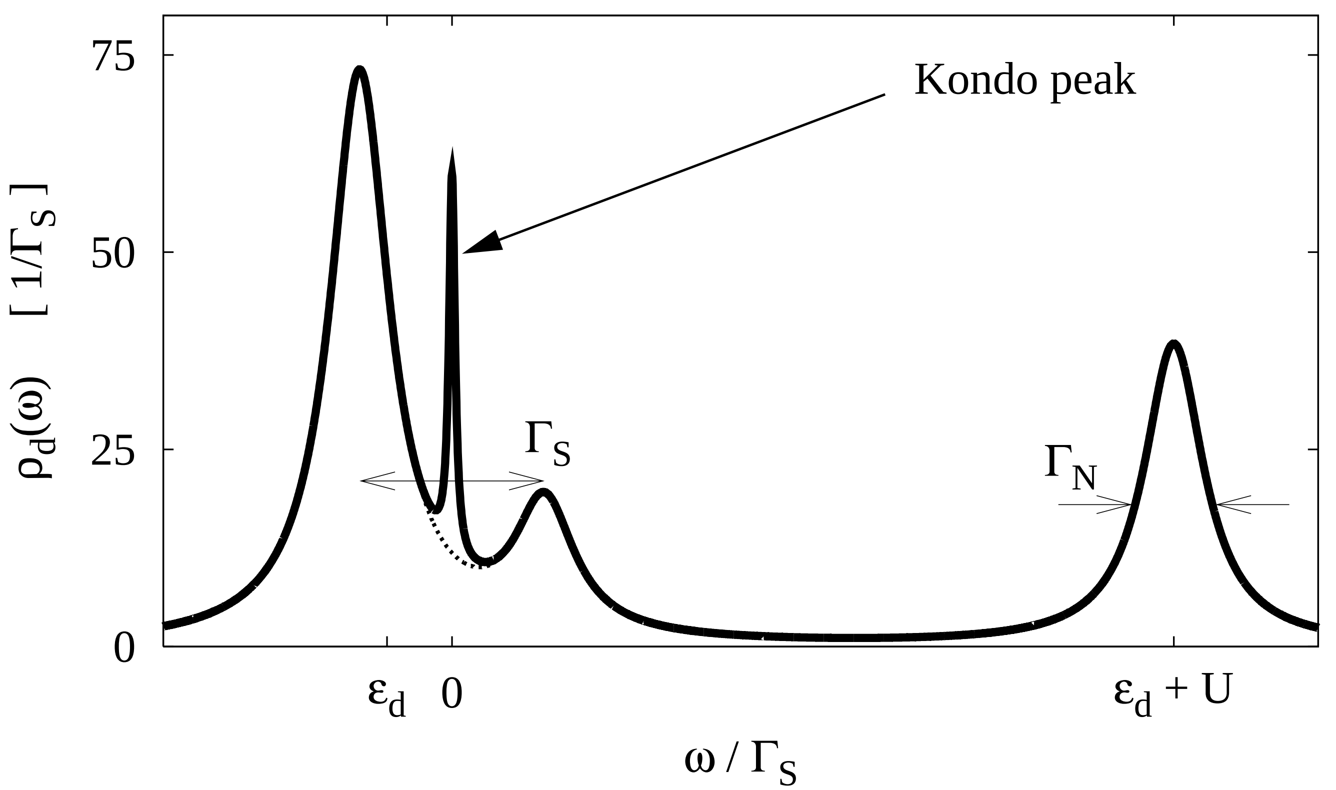

interplay between the superconductivity and Kondo effect

which is a subject of the present study.

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- How do these effects affect the charge current through N-QD-S junction ?

  Any particular features ?

Microscopic model

To account for the interplay between correlations and superconductivity we use

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$$
\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}_N + \hat{H}_S \\
&+ \sum_{\mathbf{k},\sigma} \sum_{\beta=N,S} \left(V_{\mathbf{k}\beta}\ \hat{d}^{\dagger}_{\sigma} \hat{c}_{\mathbf{k}\sigma\beta} + V^{*}_{\mathbf{k}\beta}\ \hat{c}^{\dagger}_{\mathbf{k}\sigma,\beta} \hat{d}_{\sigma} \right)
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where

$$\hat{H}_N = \sum_{k,\sigma} \left(\varepsilon_{k,N} - \mu_N\right) \hat{c}^\dagger_{k\sigma N} \hat{c}_{k\sigma N}$$

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and

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with

$\Sigma^0_d(\omega)$ **the selfenergy for** $U = 0$

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$\Sigma_d^U(\omega)$ correction due to $U \neq 0$.

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For justification see e.g.

Y. Tanaka, N. Kawakami, and A. Oguri, J. Phys. Soc. Jpn. **76**, *074701 (2007).*

Correlated QD – influence of Γ_S/Γ_N ratio

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Spectral function obtained below T_K for $U = 10\Gamma_N$

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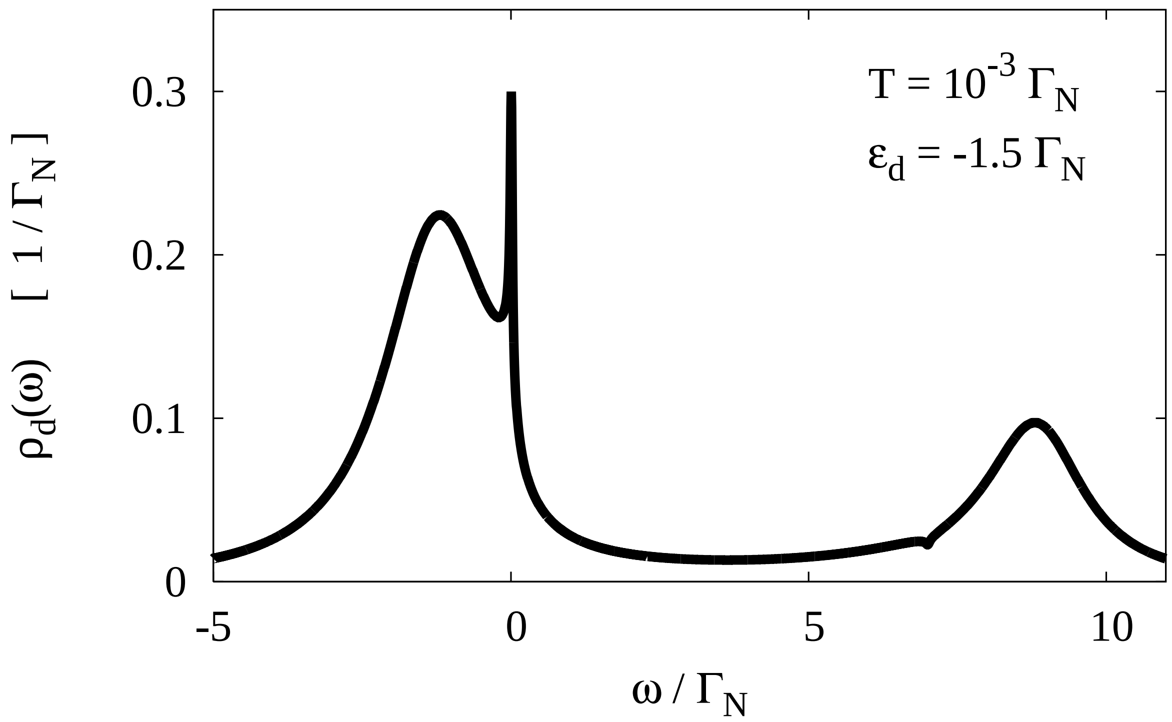

$$\Gamma_S/\Gamma_N = 0$$

Correlated QD – influence of Γ_S/Γ_N ratio

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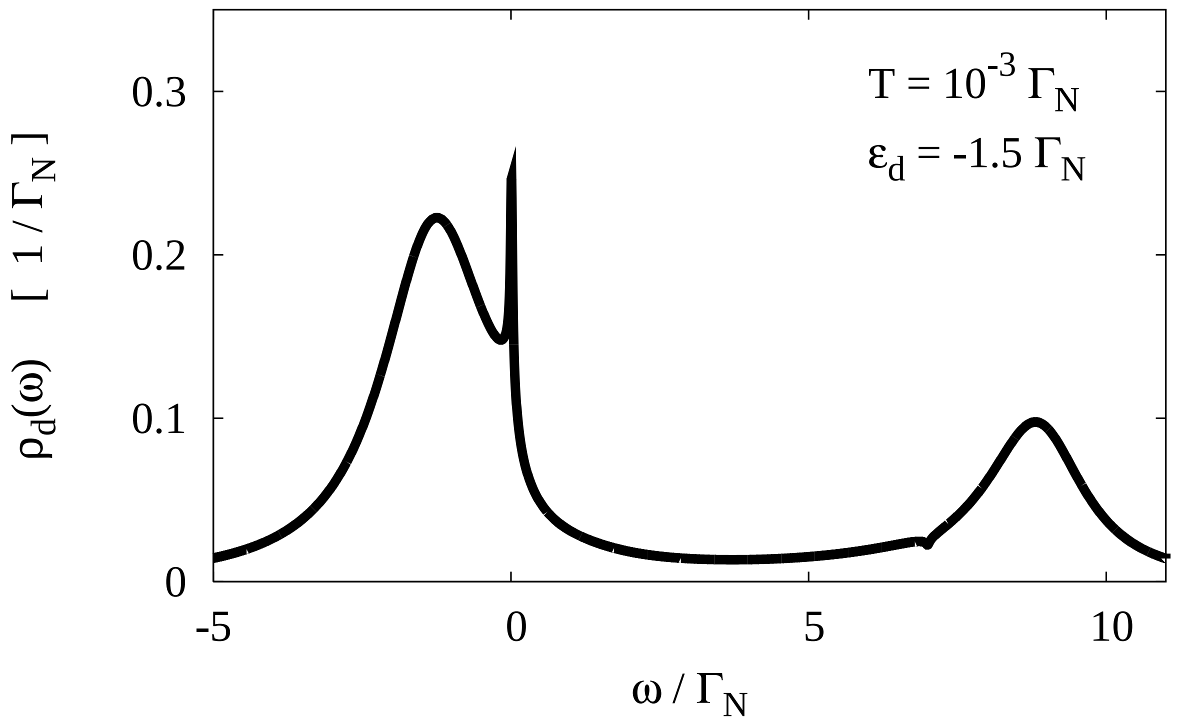

$$\Gamma_S/\Gamma_N = 1$$

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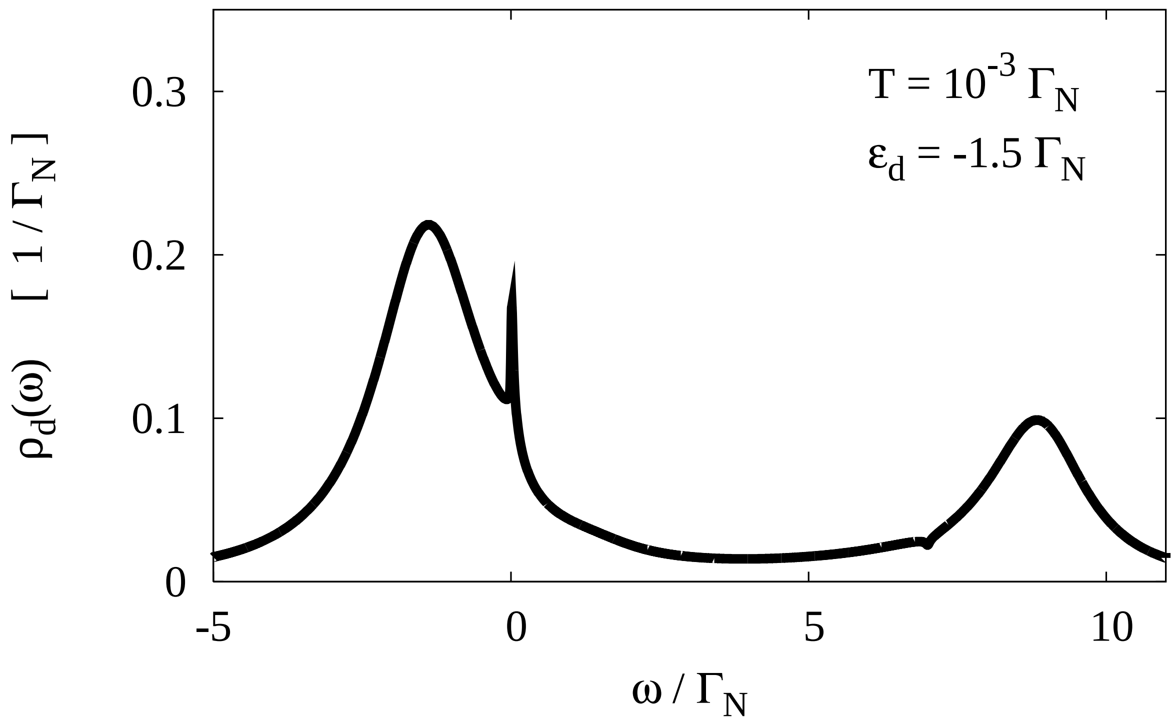

$$\Gamma_S/\Gamma_N = 2$$

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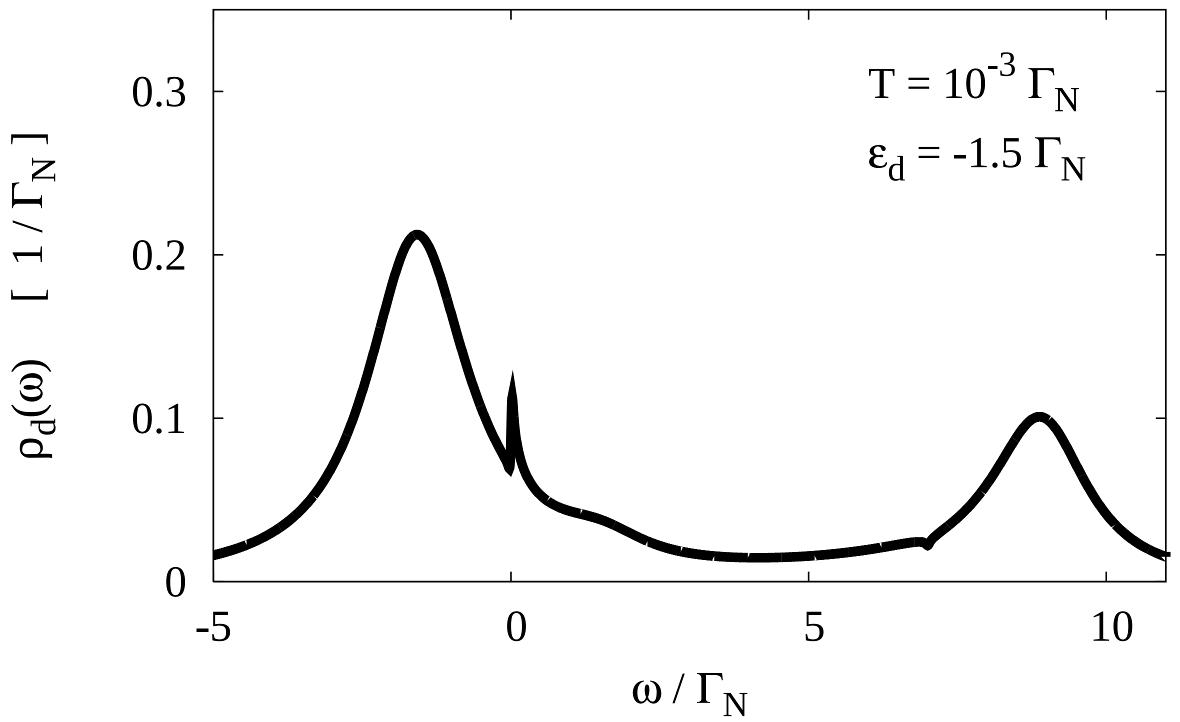
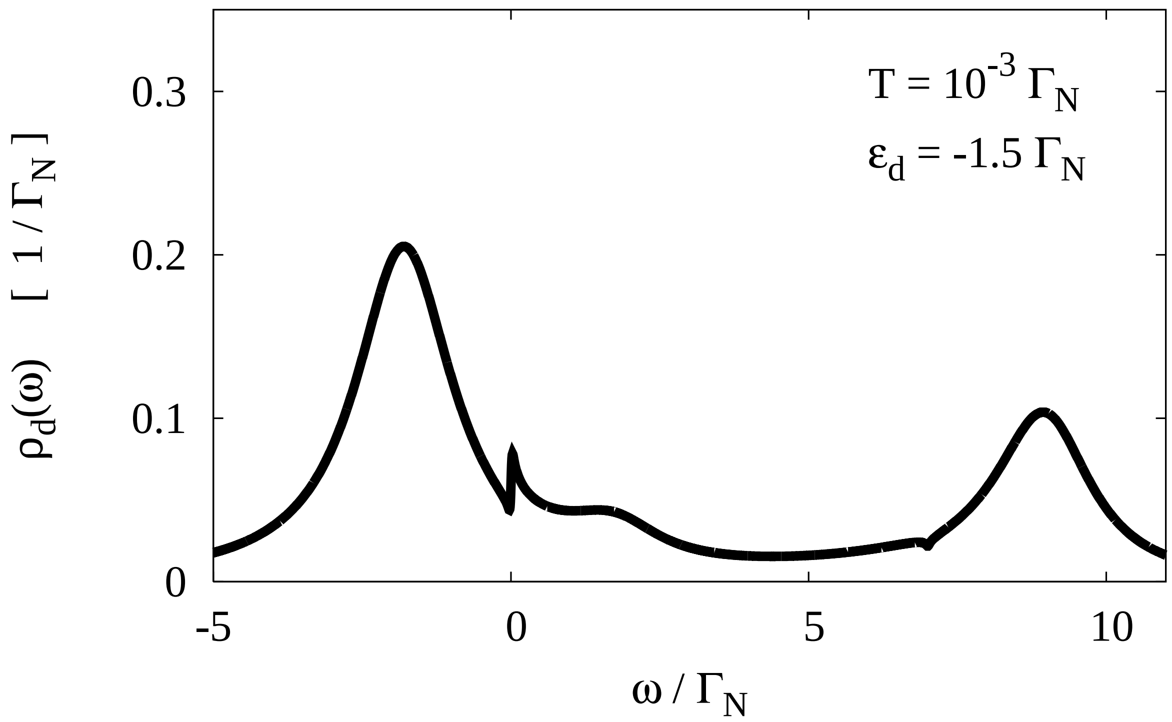


$$\Gamma_S/\Gamma_N = 3$$

Correlated QD – influence of Γ_S/Γ_N ratio

Spectral function obtained below T_K for $U = 10\Gamma_N$



$\Gamma_S/\Gamma_N = 4$

Correlated QD – influence of Γ_S/Γ_N ratio

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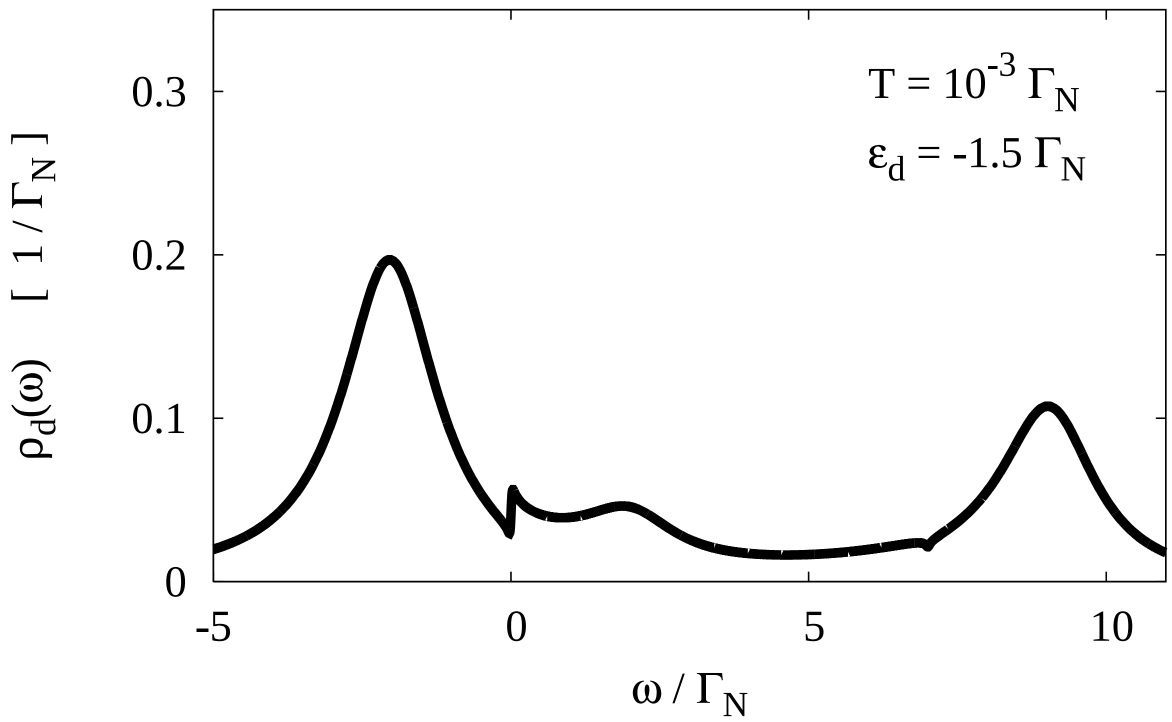

$$\Gamma_S/\Gamma_N = 5$$

Correlated QD – influence of Γ_S/Γ_N ratio

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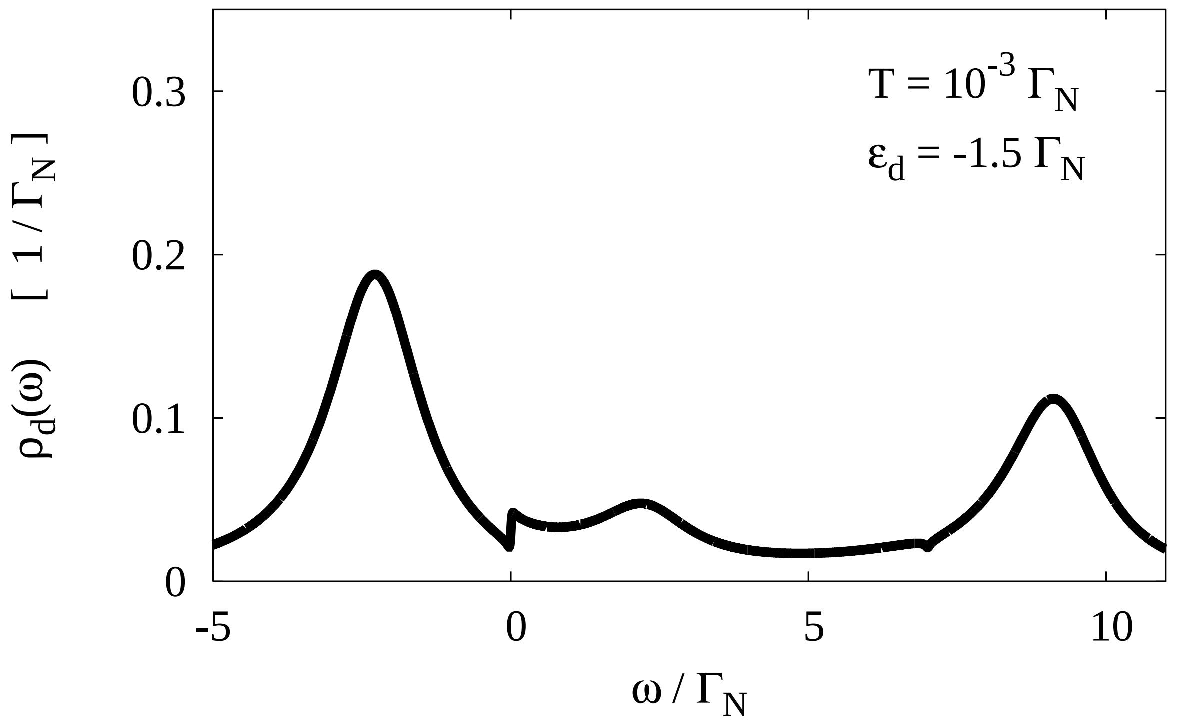

$$\Gamma_S/\Gamma_N = 6$$

Correlated QD – influence of Γ_S/Γ_N ratio

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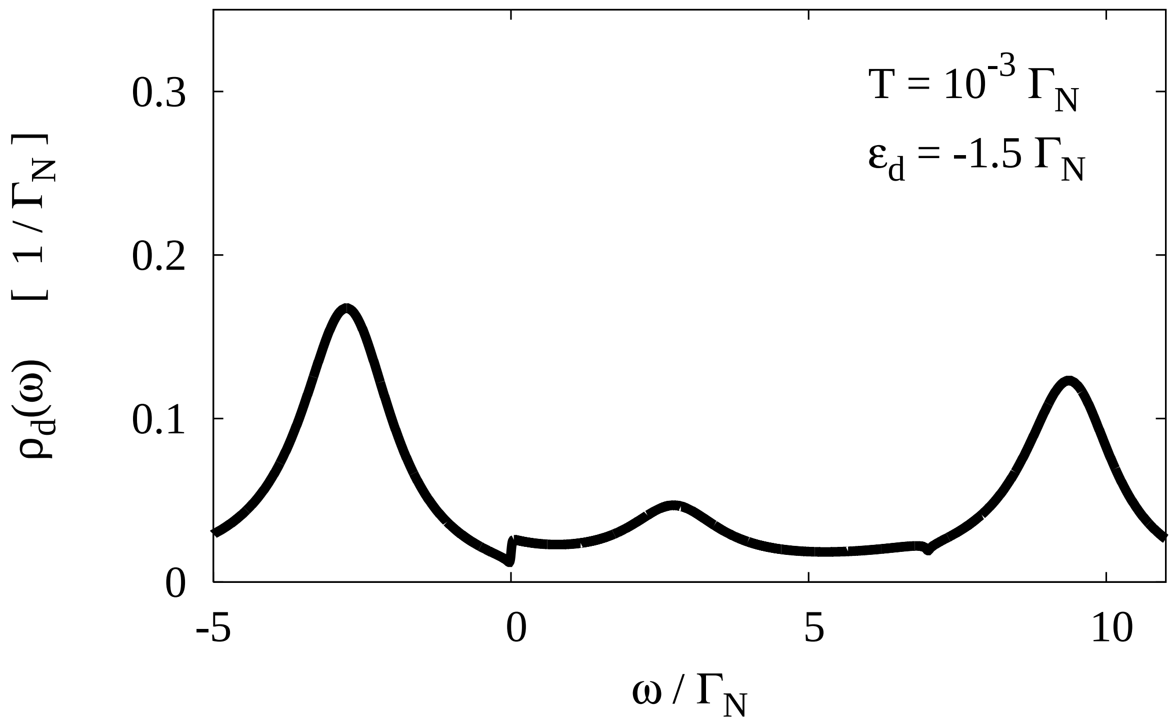

$$\Gamma_S/\Gamma_N = 8$$

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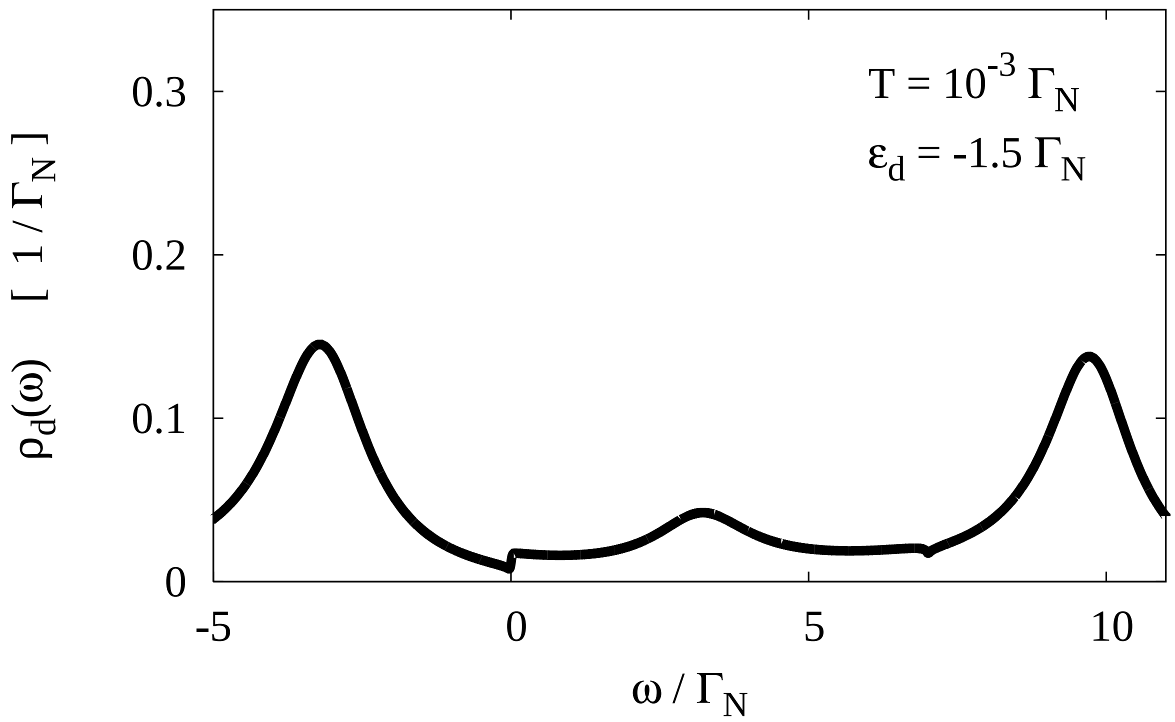
Spectral function obtained below T_K for $U = 10\Gamma_N$



$$\Gamma_S/\Gamma_N = 10$$

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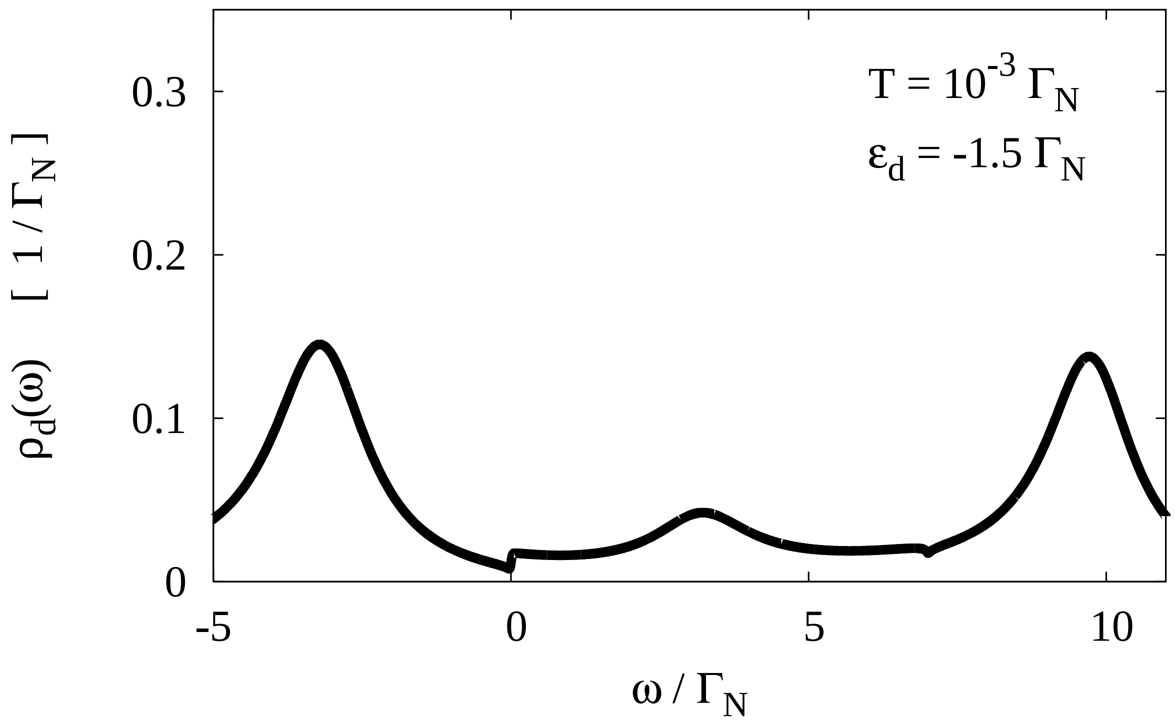

Superconductivity supresses the Kondo resonance

Transport properties

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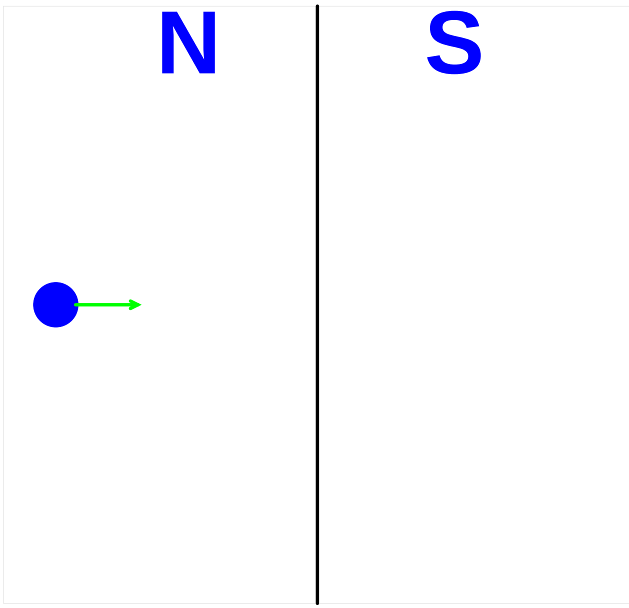

electron

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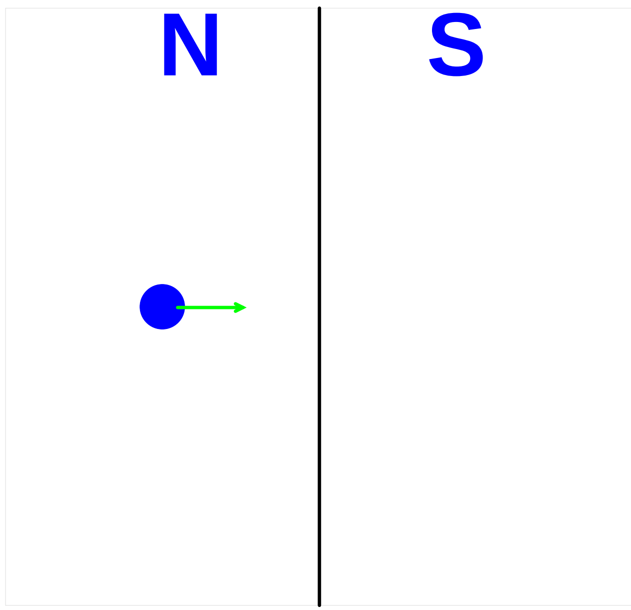

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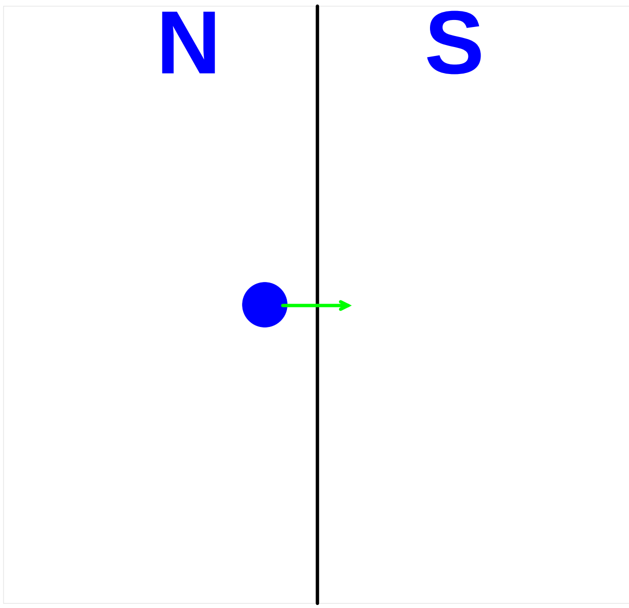

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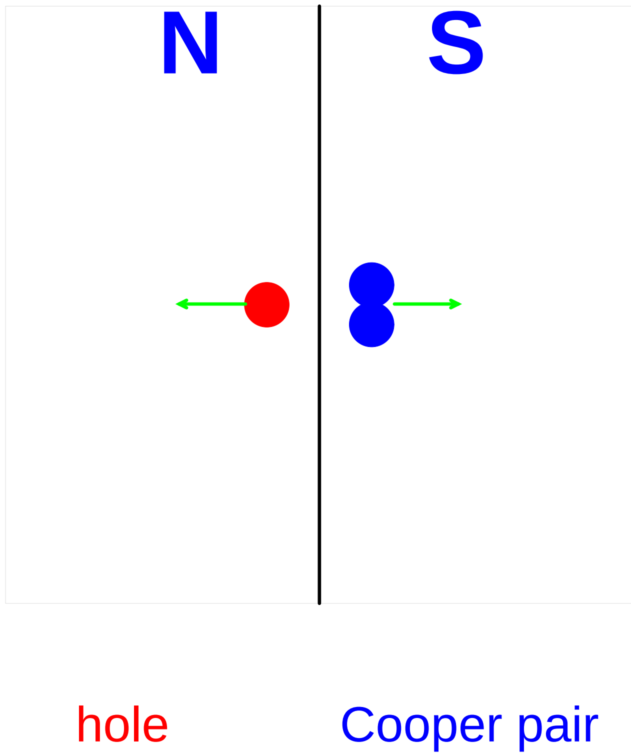

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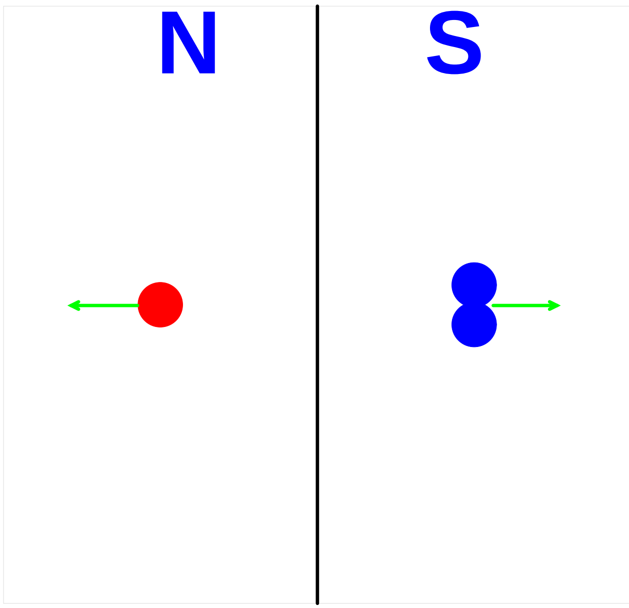

hole Cooper pair

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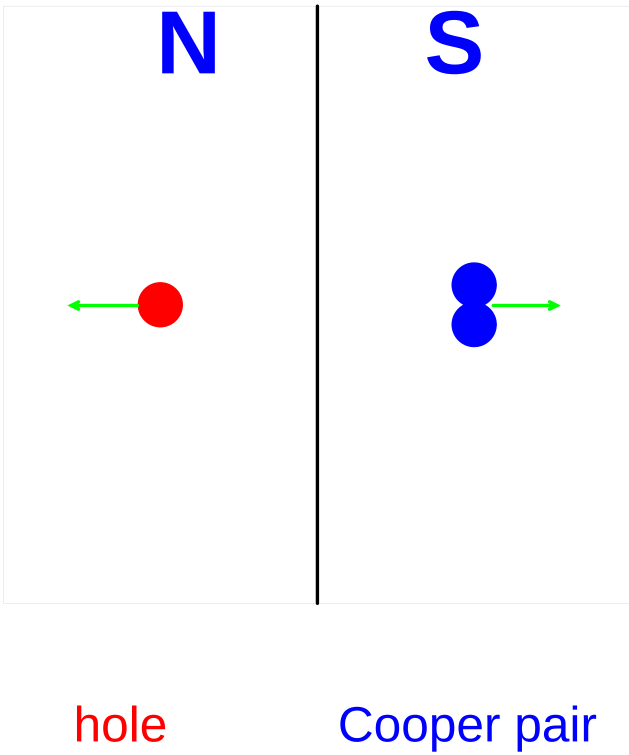

This proccess is called Andreev reflection.

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and can be expressed by the Landauer-type formula

$$J_1(V) = \frac{2e}{h} \int d\omega \, T_1(\omega) \left[f(\omega + eV, T) - f(\omega, T) \right]$$

with the transmitance $T_1(\omega)$ is equal

$$\Gamma_N \Gamma_S \left(\left| G^r_{11}(\omega) \right|^2 + \left| G^r_{12}(\omega) \right|^2 - \frac{2\Delta}{|\omega|} \mathrm{Re} G^r_{11}(\omega) G^r_{12}(\omega) \right)$$

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$$T_A(\omega) = \Gamma_N^2 \, \left| G_{12}(\omega) \right|^2$$

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of the Andreev current J_A appearing at sub-gap voltages !

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Andreev conductance $G_A(V)$ for:

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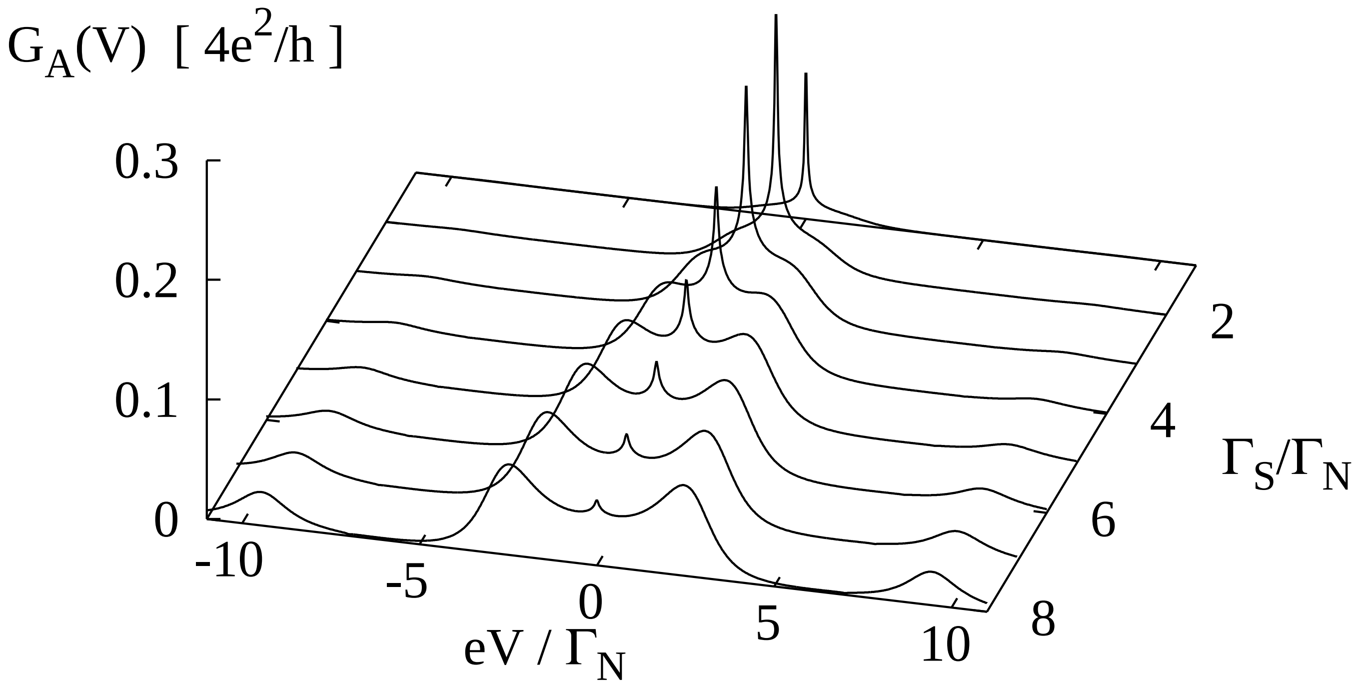

Correlated QD – influence of Γ_S/Γ_N ratio

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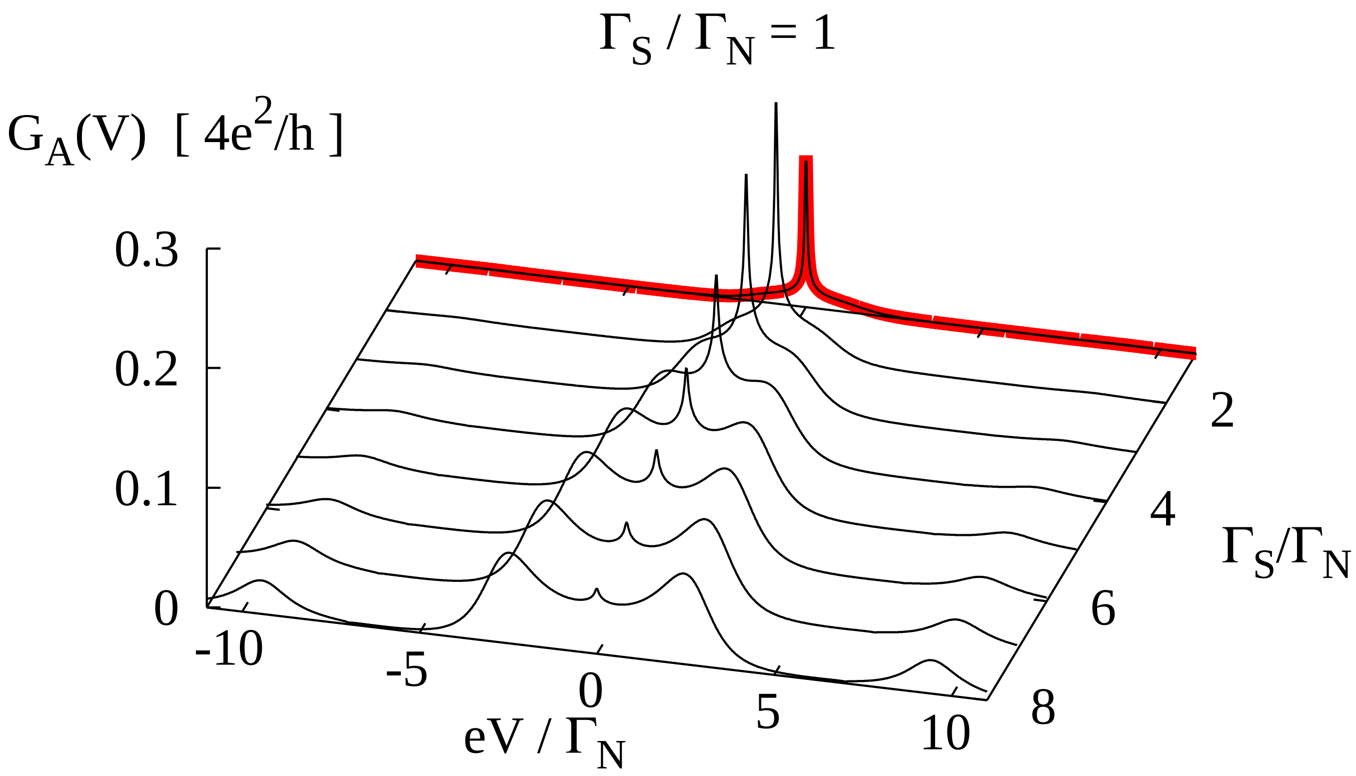

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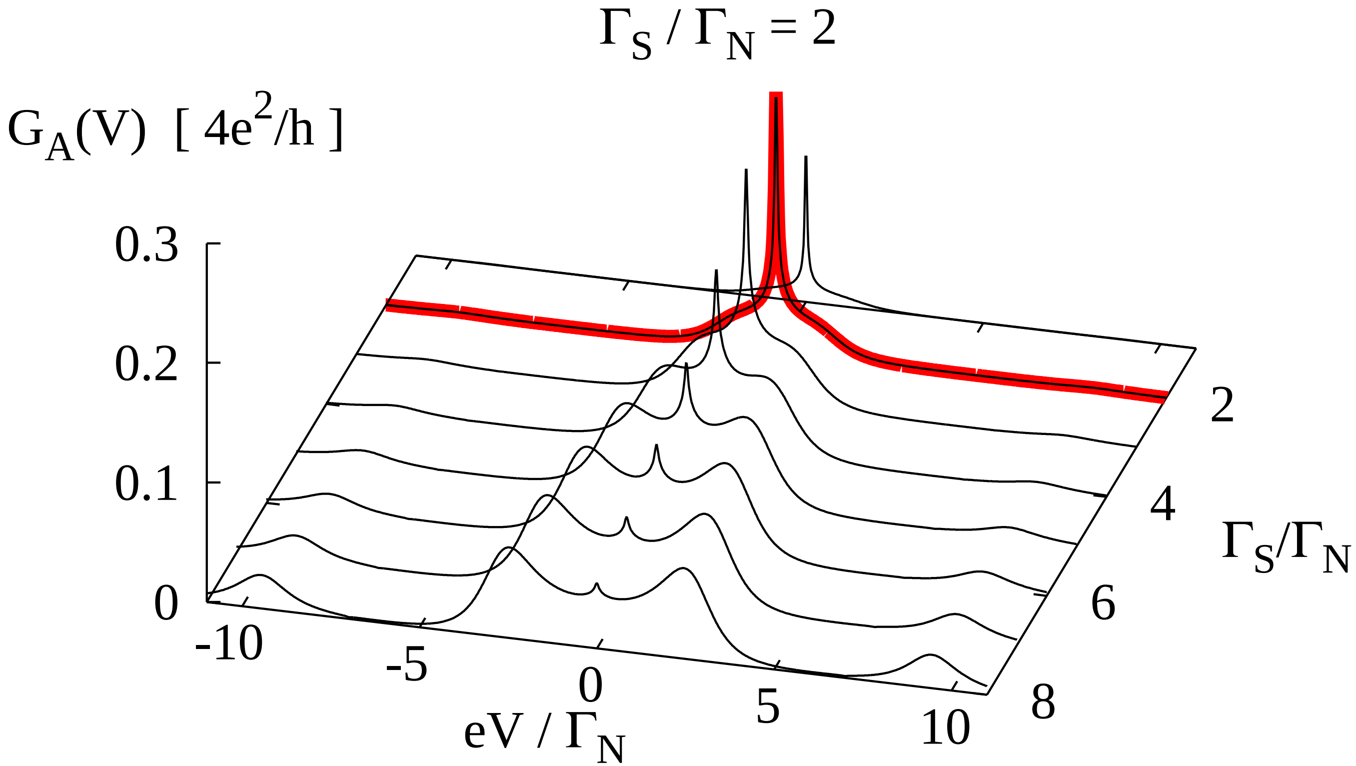

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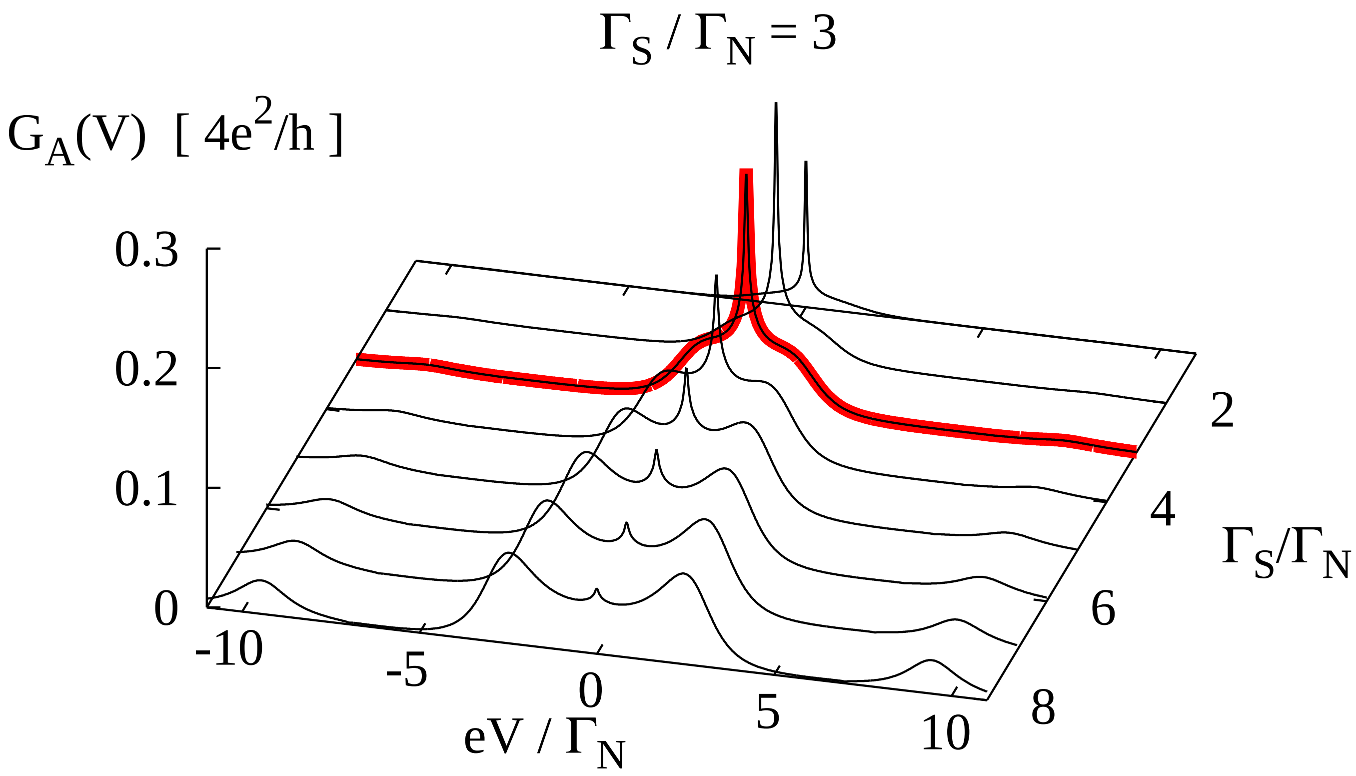

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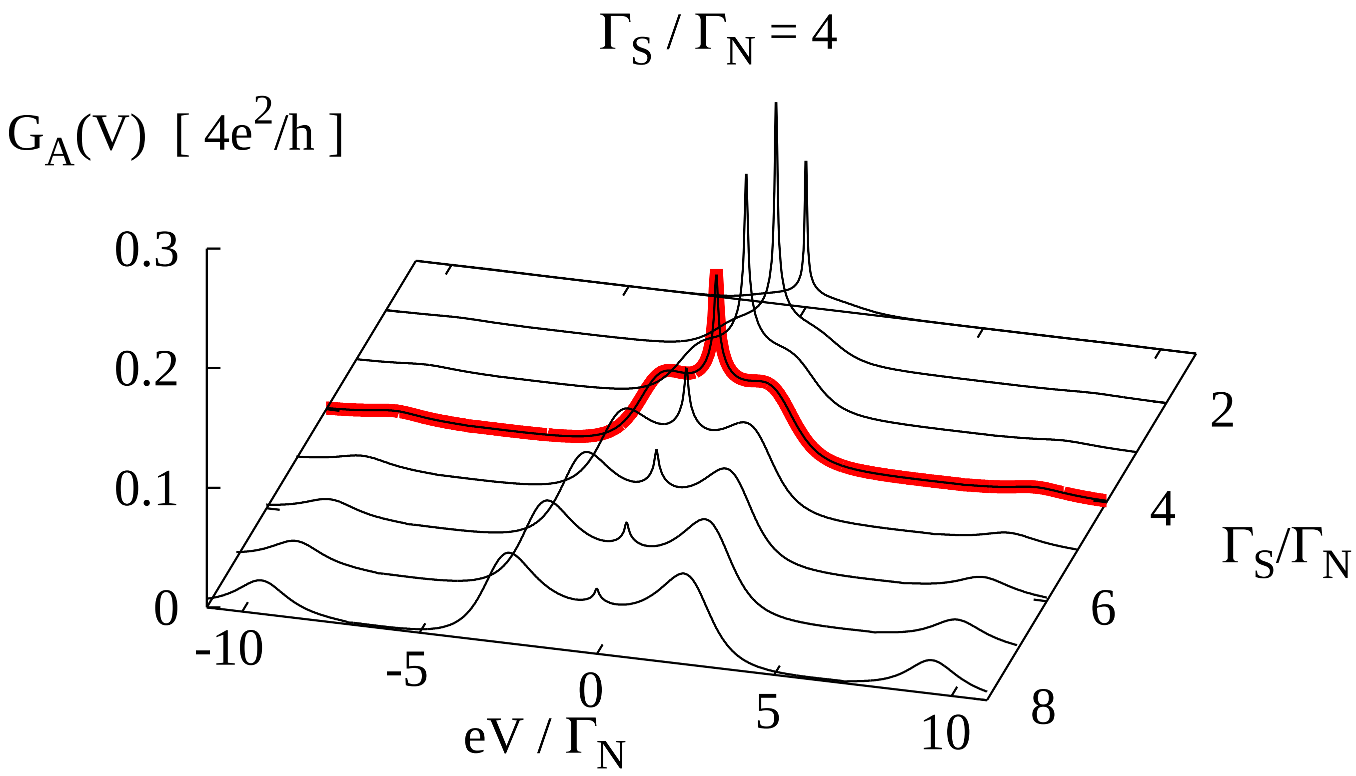

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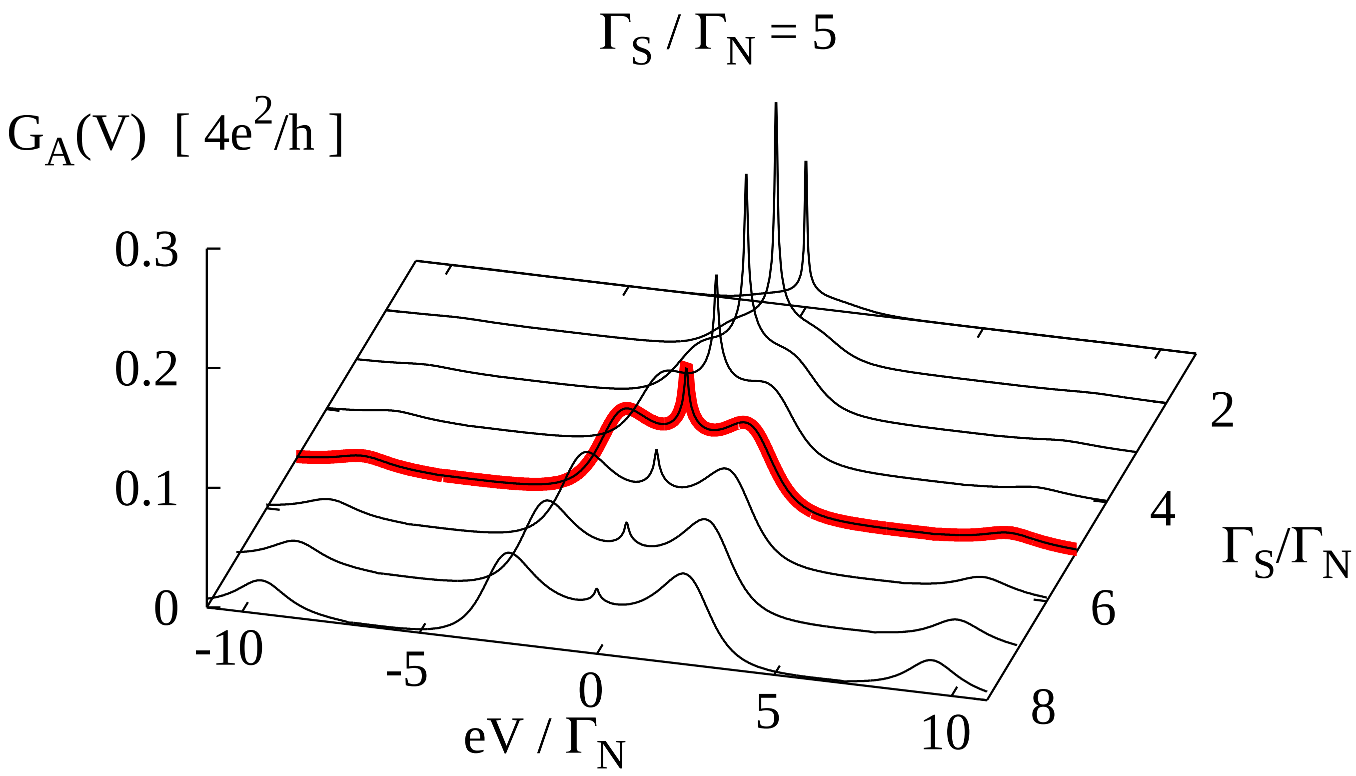

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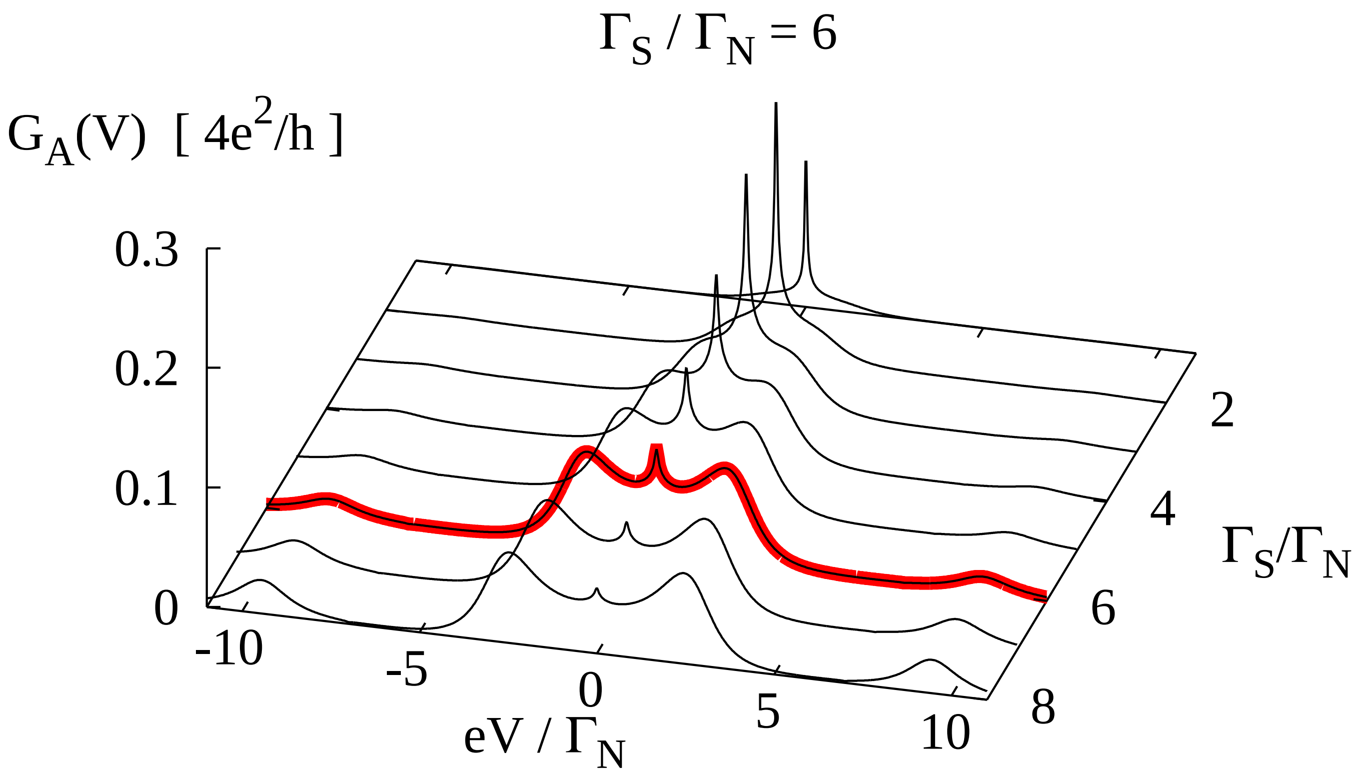

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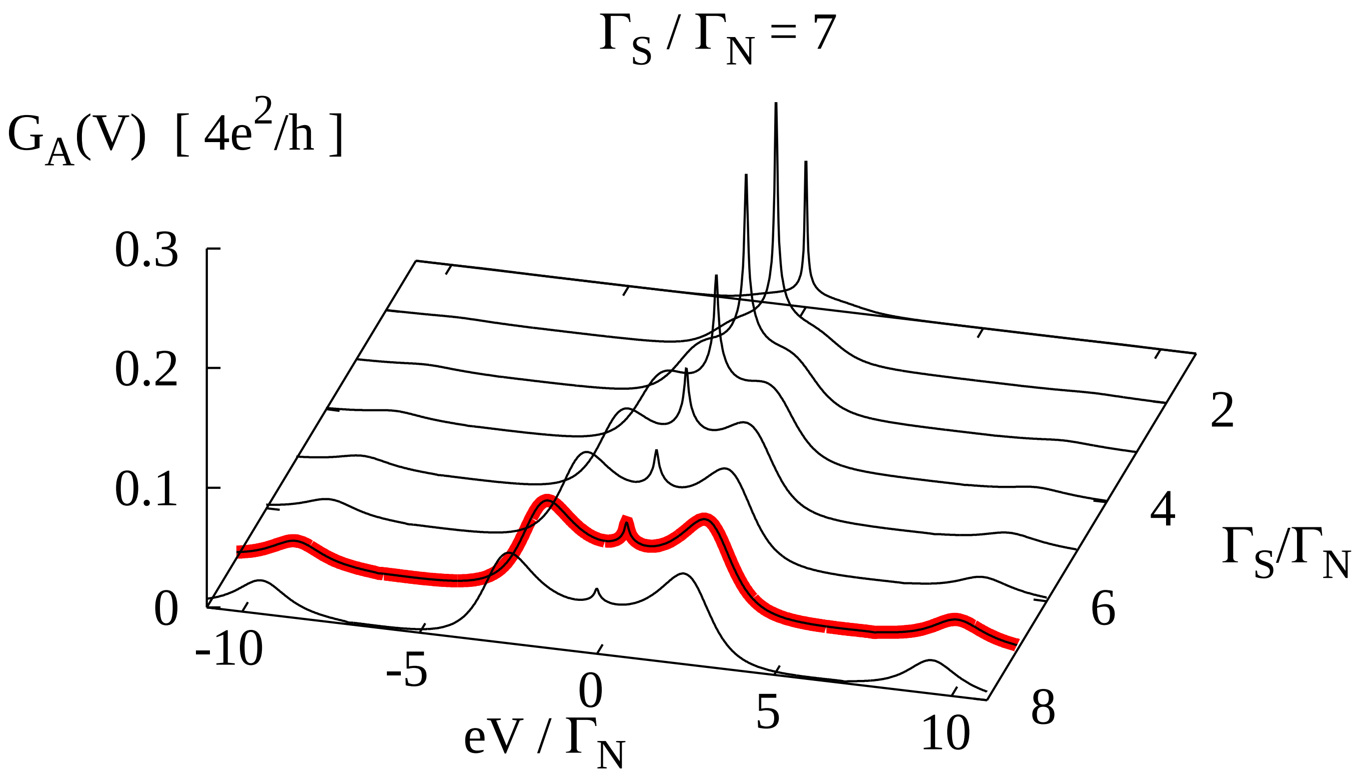

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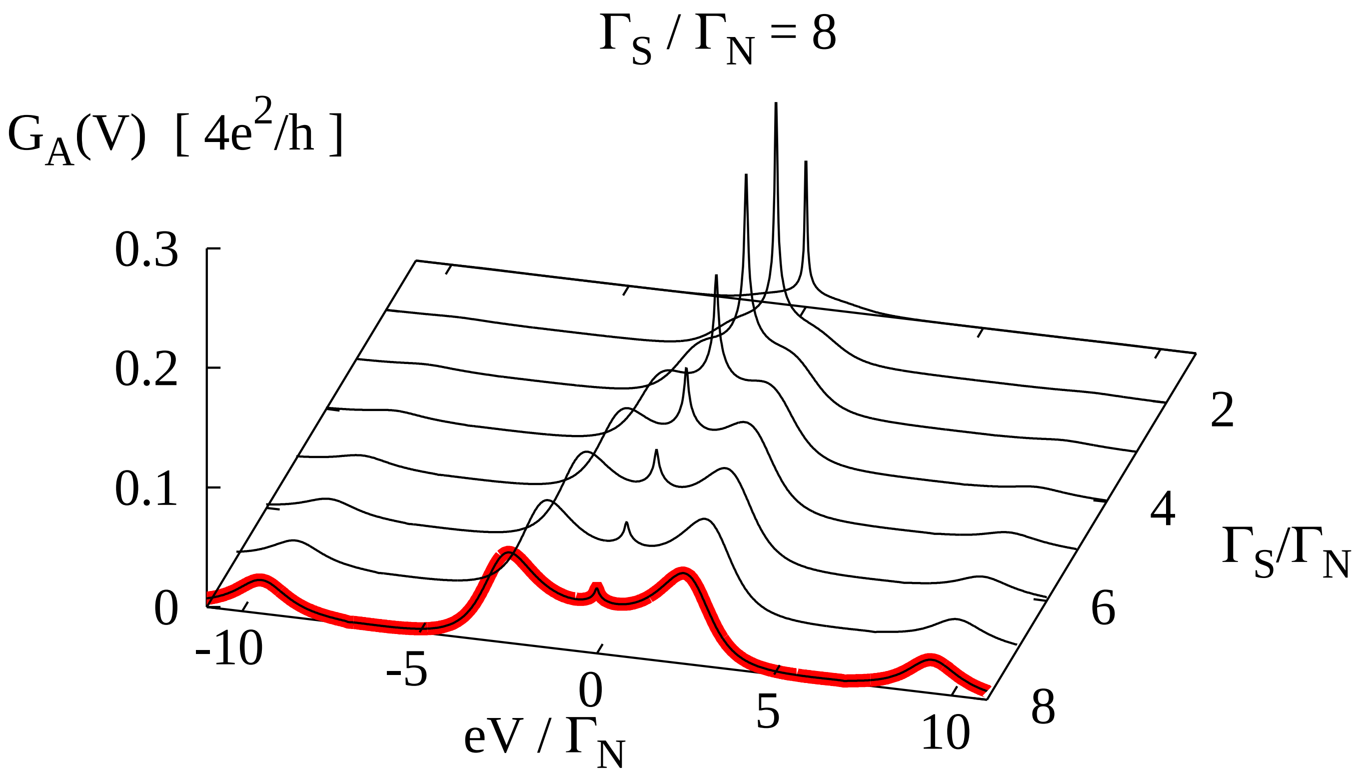

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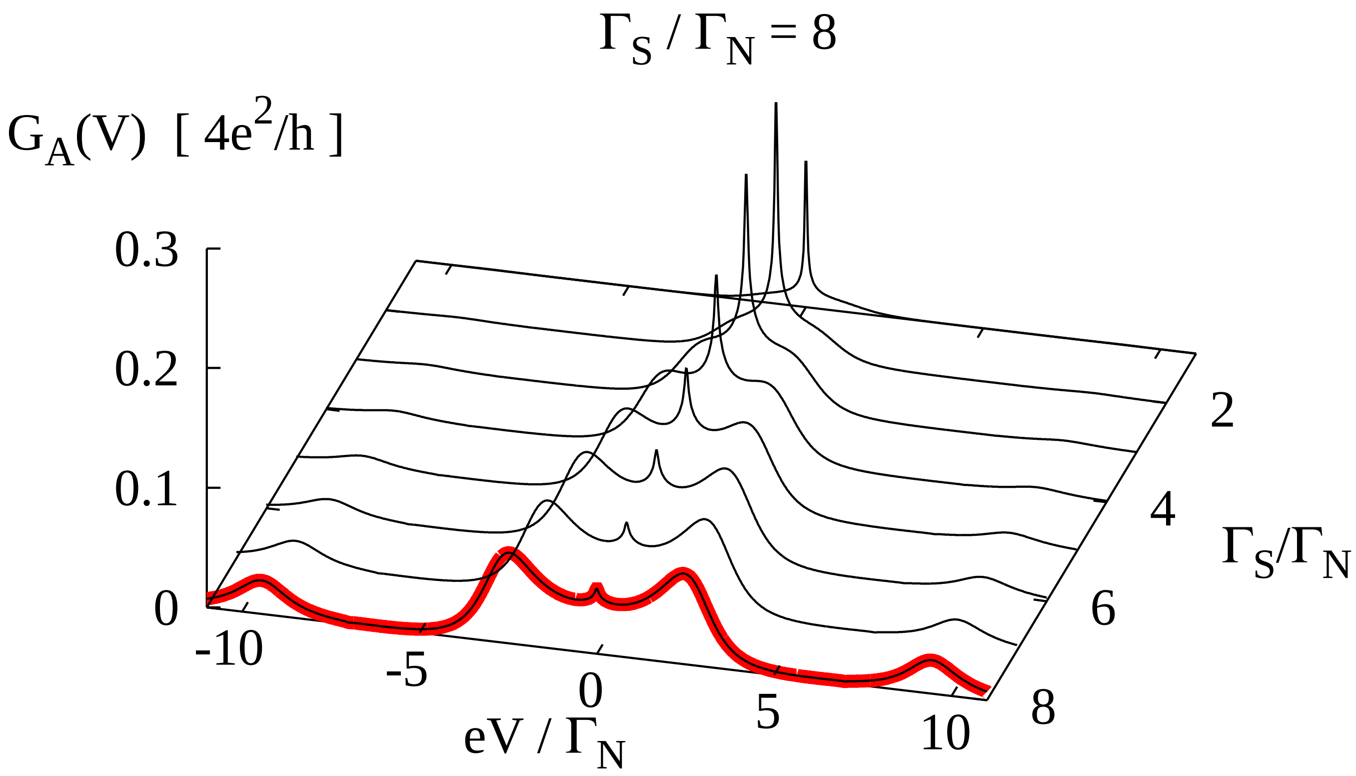


Kondo resonance enhances zero-bias Andreev conductance for $\Gamma_S \sim \Gamma_N$!

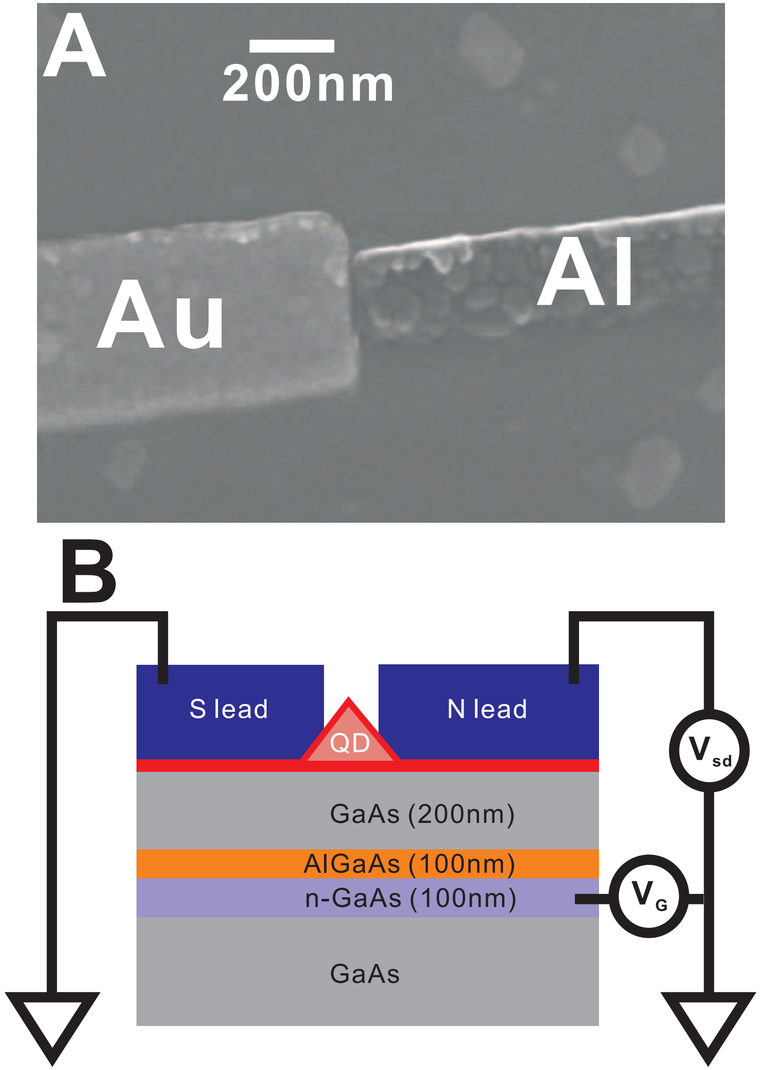
Experimental realization

Experimental setup

/ University of Tokyo /

Experimental setup

/ University of Tokyo /



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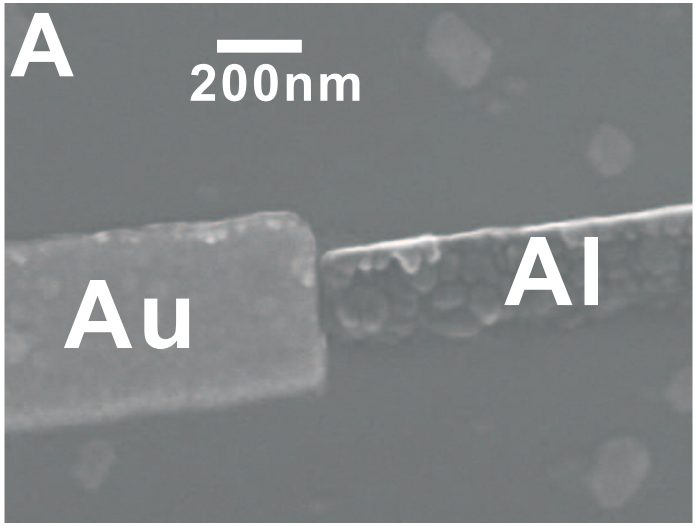
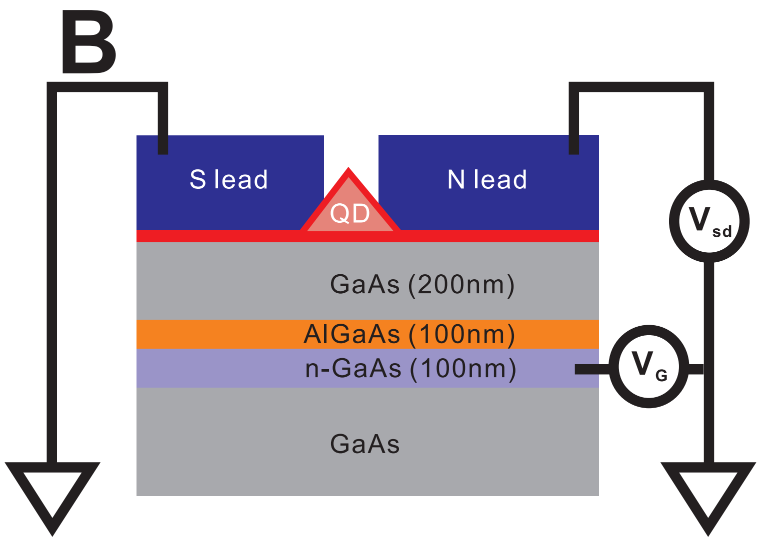




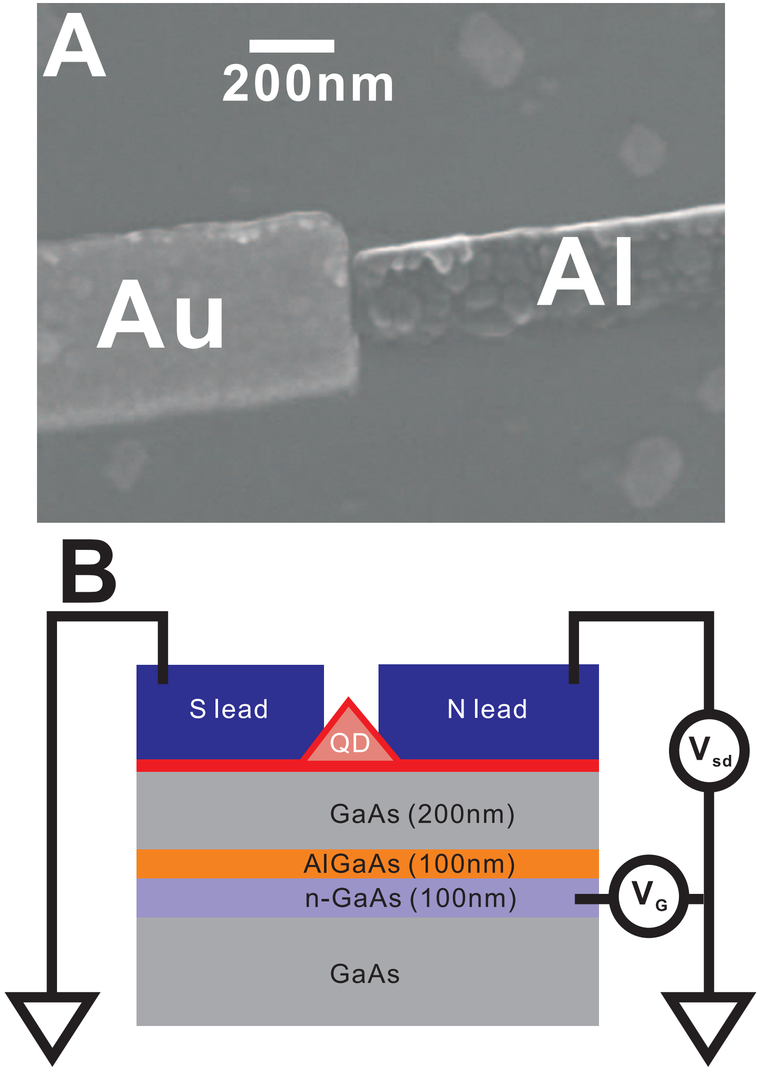
QD : self-assembled InAs

diameter ～ 100 nm

backgate : Si-doped GaAs

Experimental setup

/ University of Tokyo /



$T_K \simeq 1.2\text{K}$

$\Delta \simeq 152\mu\text{eV}$

QD : self-assembled InAs

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R.S. Deacon et al, *Phys. Rev. Lett.* **104**, *076805 (2010).*

Andreev features

/ due to the proximity effect /

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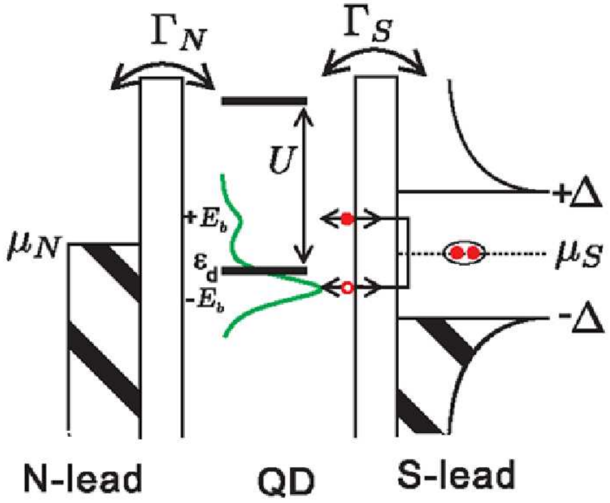

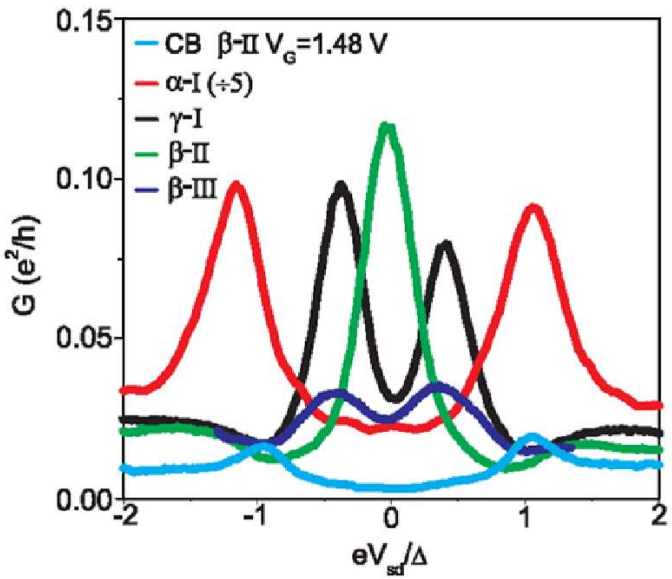

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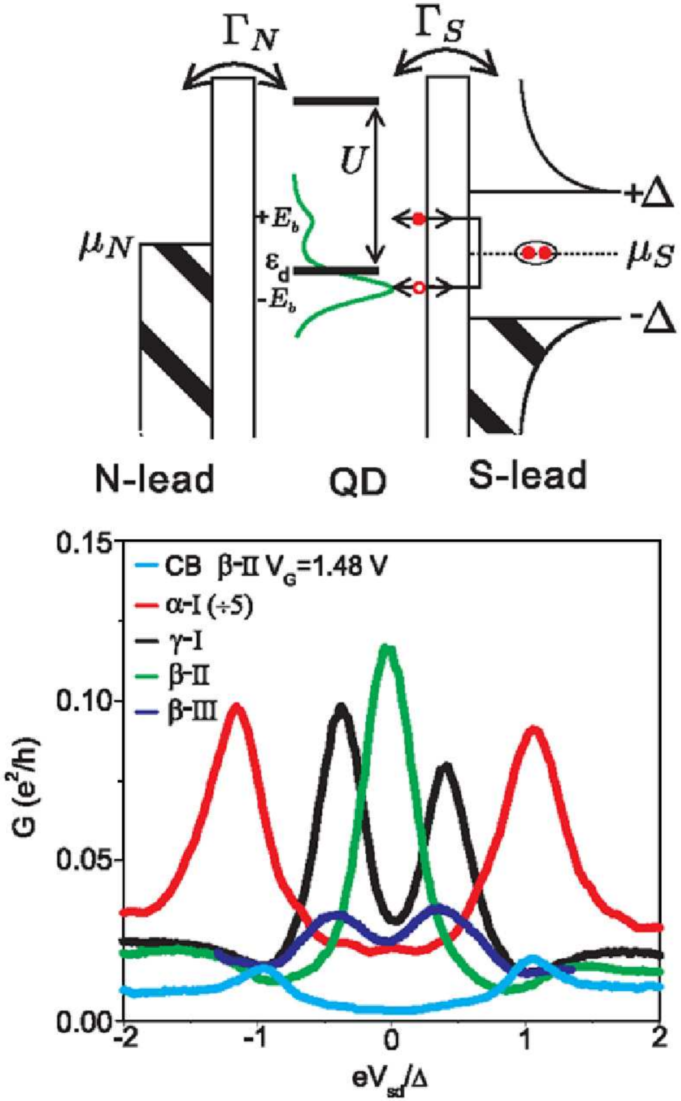

$$\varepsilon_d \sim \mu_{N,S}$$

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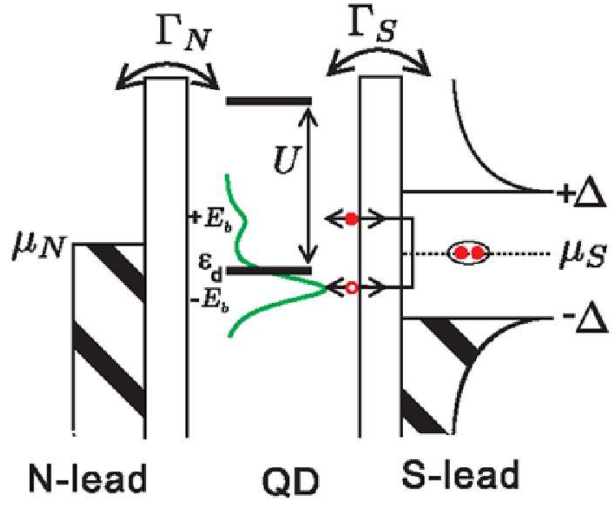

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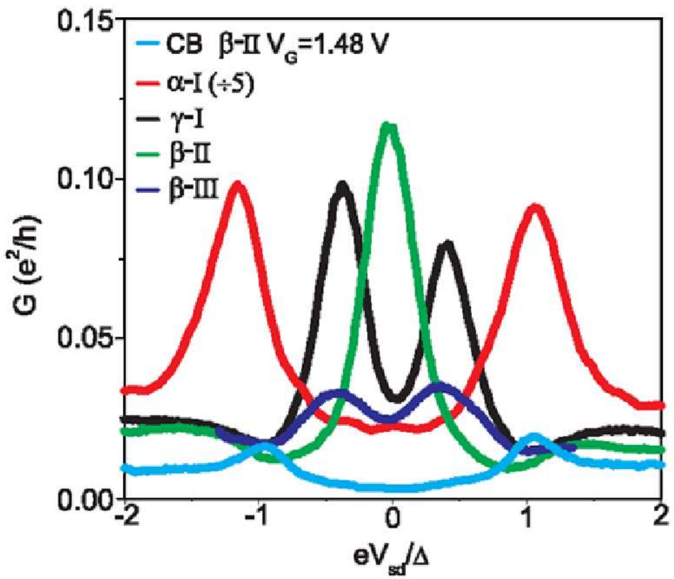

Sample α-I

$$\Gamma_N \sim 12\ \Gamma_S$$

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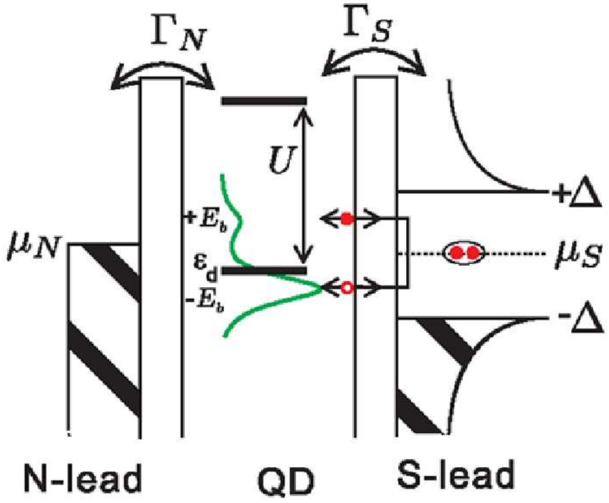

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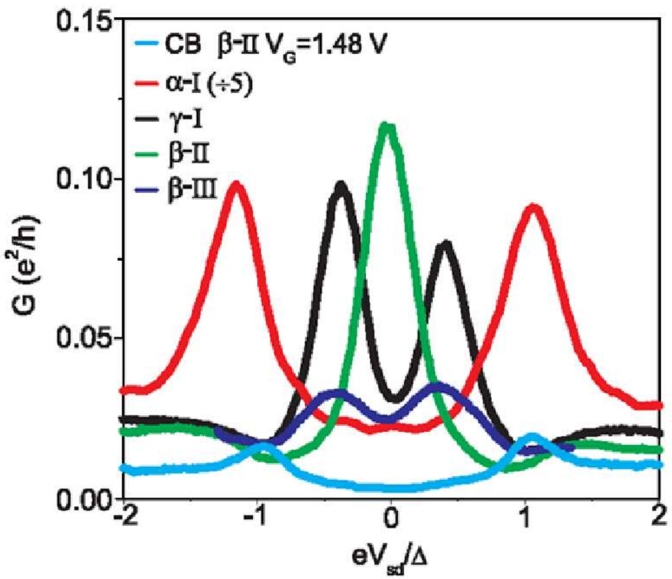

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Samples γ-I, β-III

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Andreev features / due to the proximity effect /

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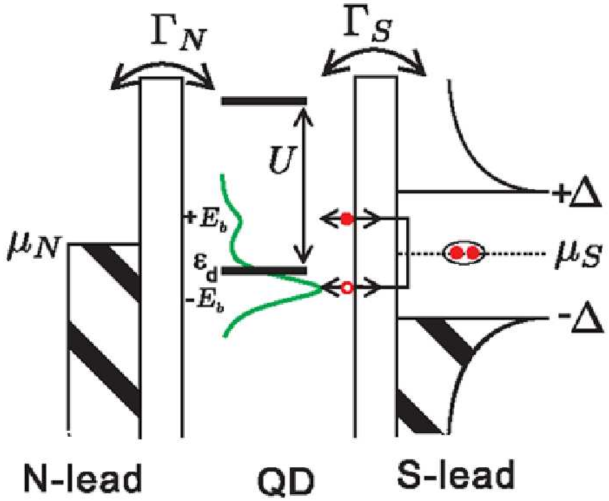

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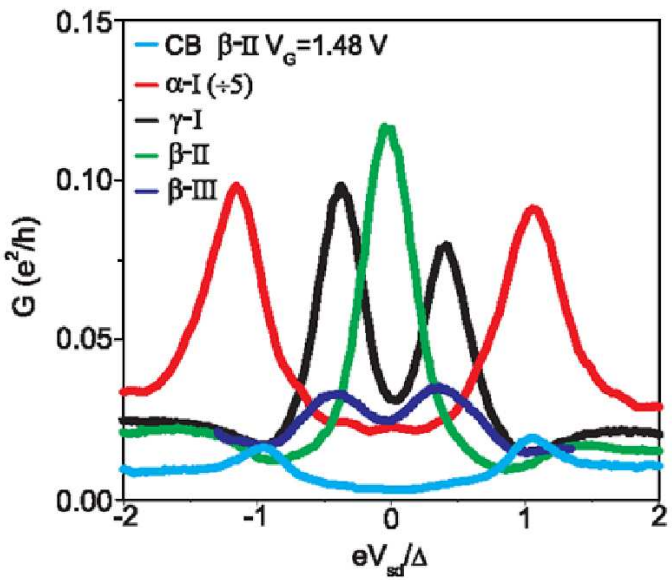

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"We attribute the subgap peaks to resonant Andreev transport ... through electron-hole mixing of the QD energy level."

Interplay with the Kondo effect

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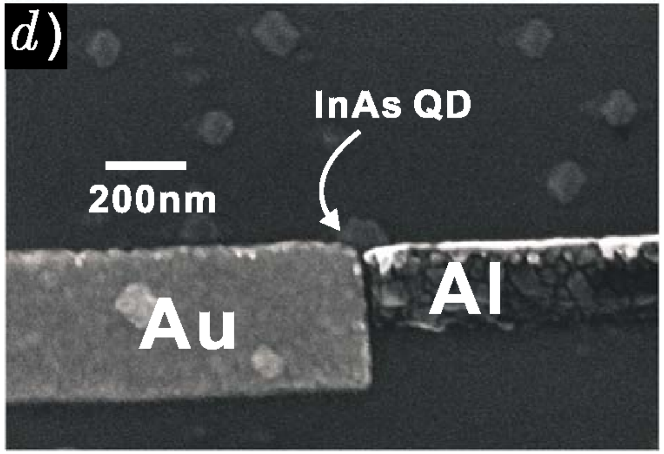

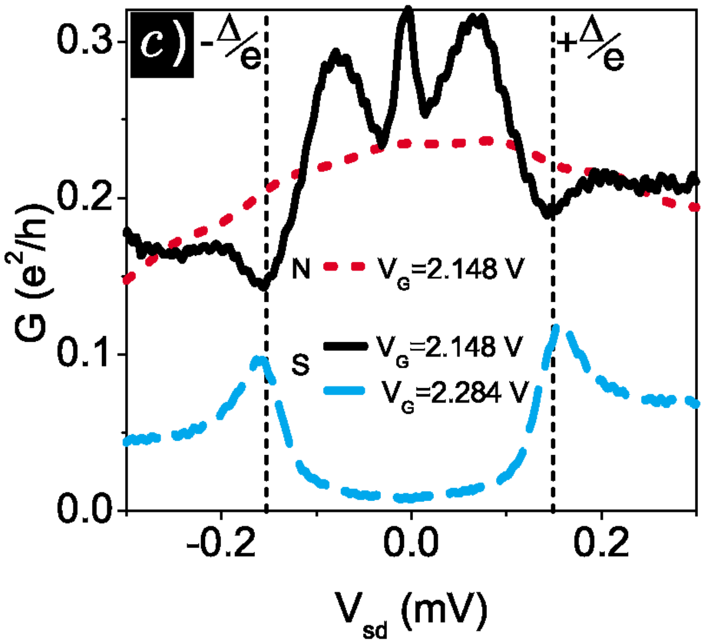

R.S. Deacon et al, *Phys. Rev. B* **81**, *121308(R) (2010).*

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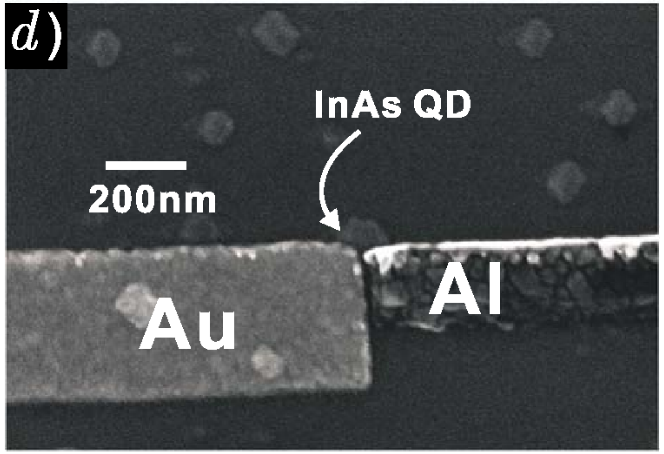
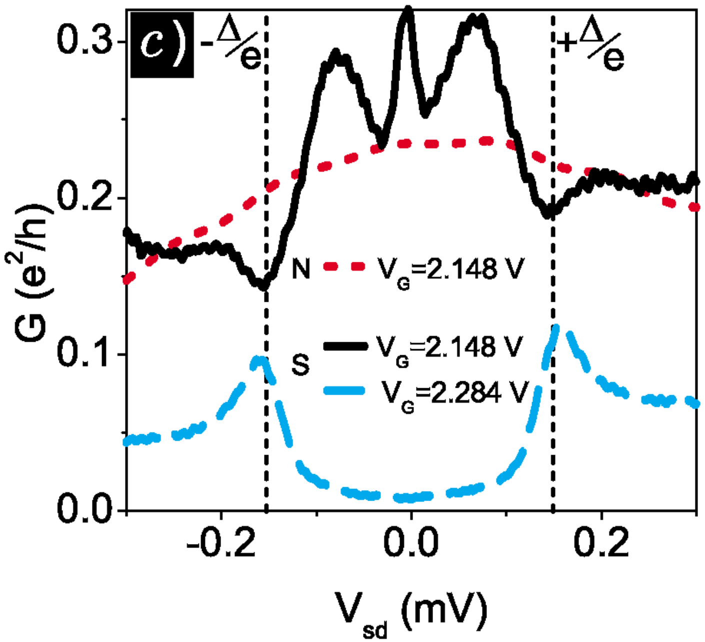


"The zero-bias conductance peak is consistent with Andreev transport enhanced by the Kondo singlet state"



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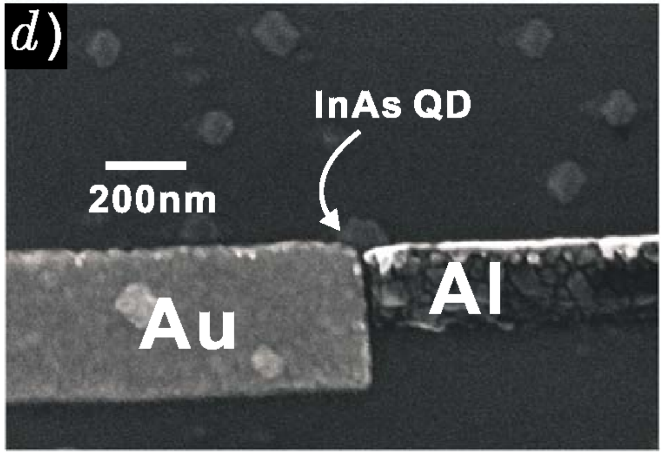

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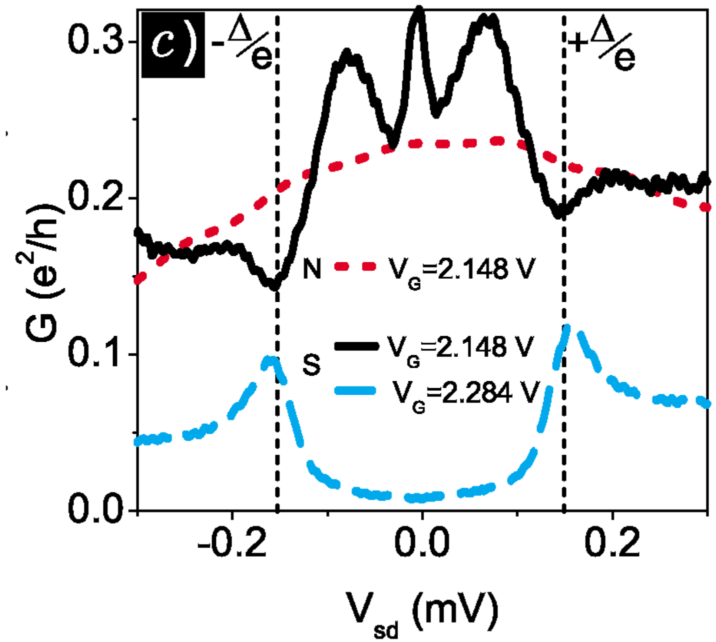

"We note that the feature exhibits excellent qualitative agreement with a recent theoretical treatment by Domanski et al"

R.S. Deacon et al, *Phys. Rev. B* **81**, *121308(R) (2010).*

Further outlook

Double QD – between a metal and superconductor

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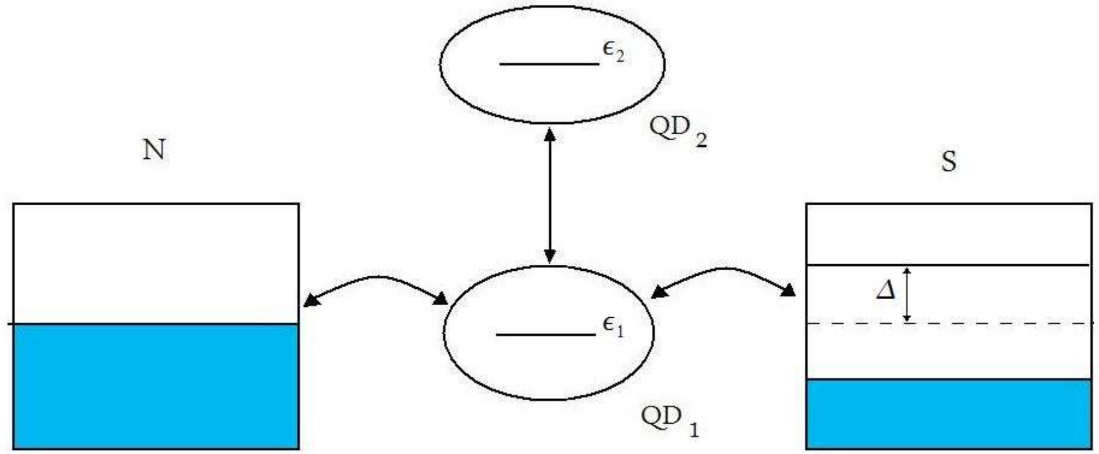

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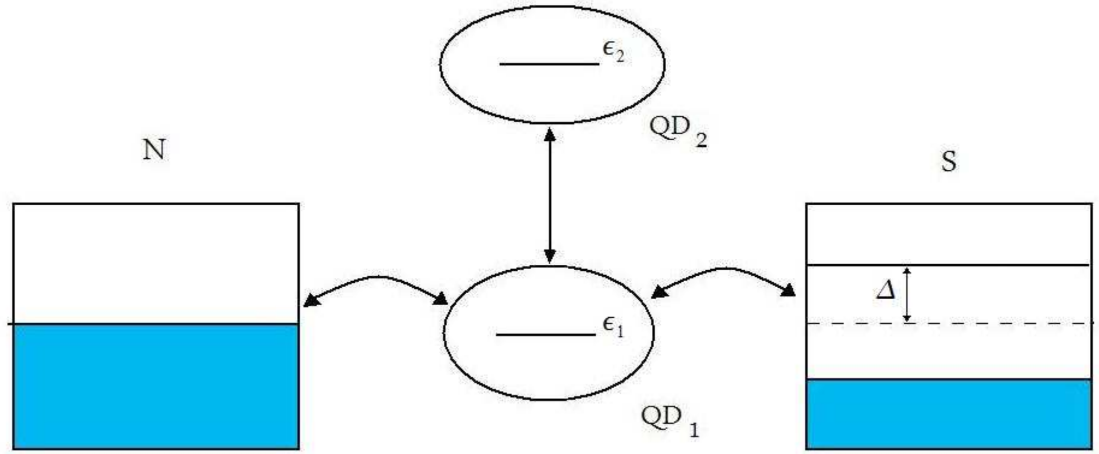

Side-coupled QD (T-shape configuration)

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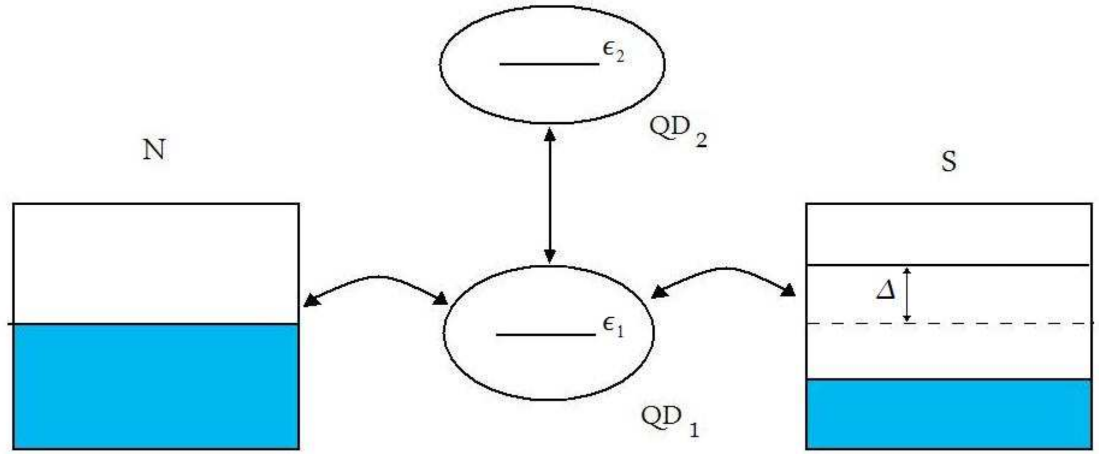
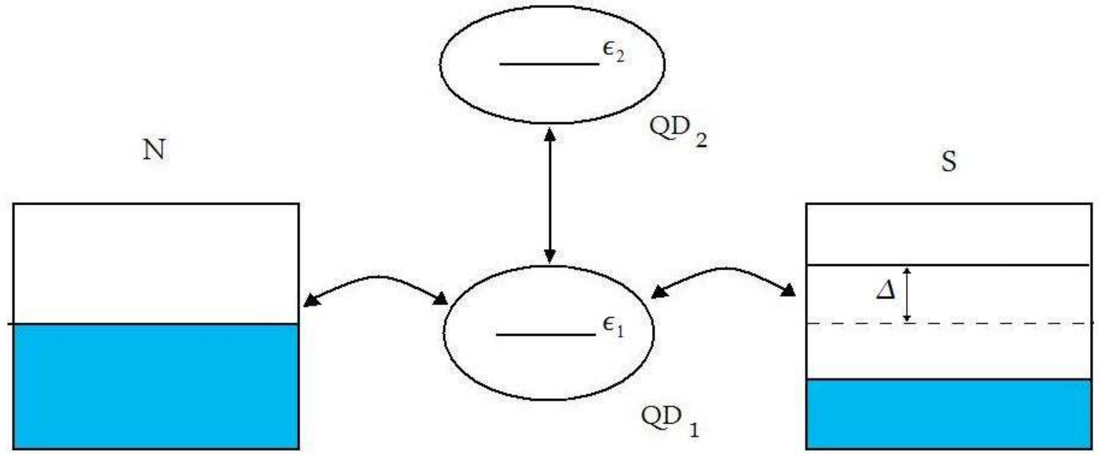


Side-coupled QD (T-shape configuration)

Relevant issues:

Double QD – between a metal and superconductor



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$\Rightarrow$ induced on-dot pairing . . . . (due to Γ_S)

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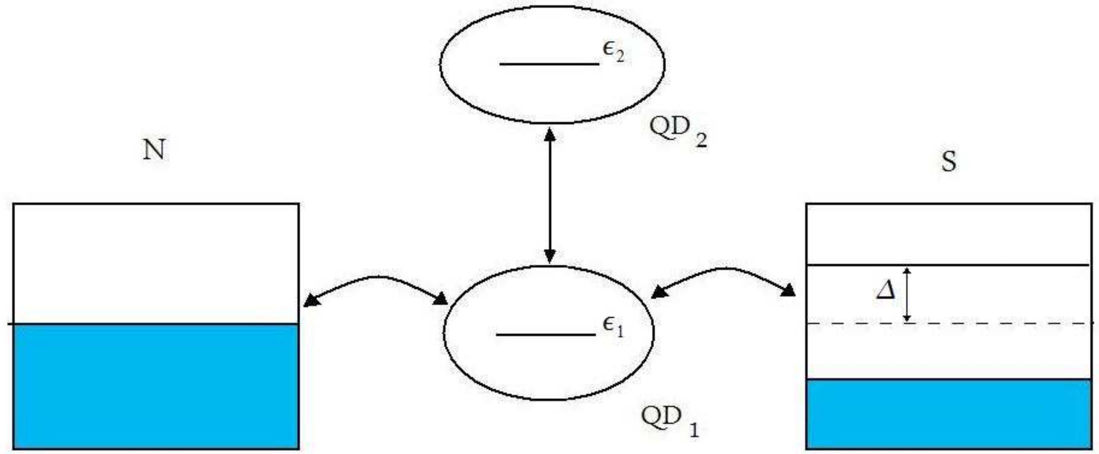

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⇒ Coulomb blockade & Kondo effect .... (due to U)

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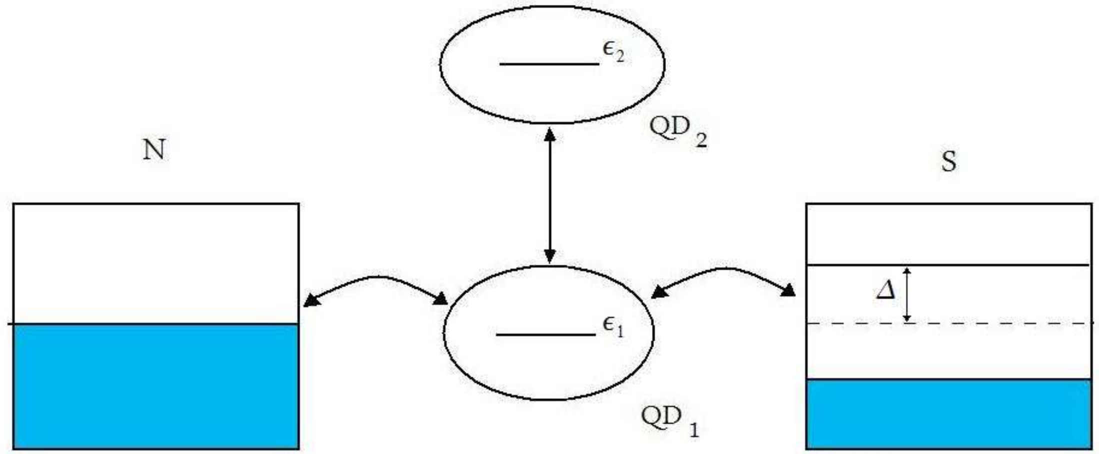

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Quantum interference – effect of t

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Spectral function obtained at QD_1 for $\varepsilon_1 = 0$

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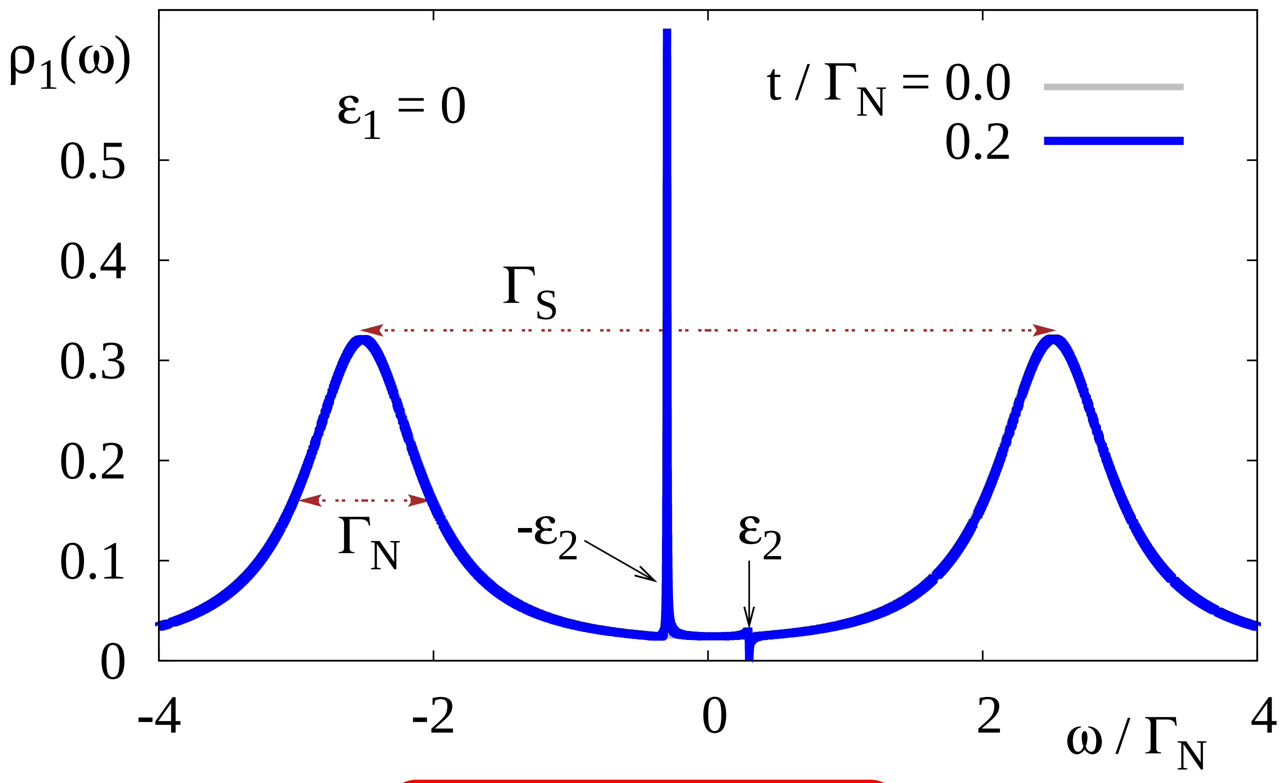

$t/\Gamma_N = 0.2$

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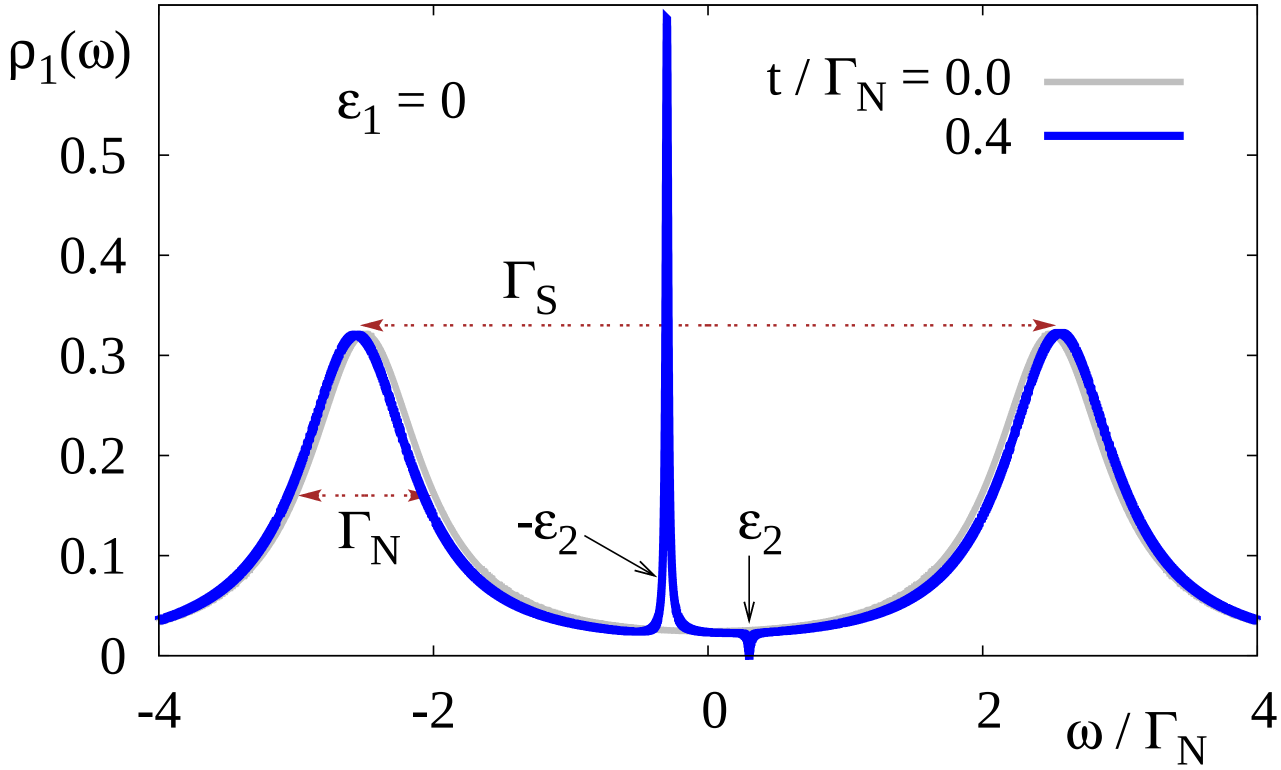

$t/\Gamma_N = 0.4$

Quantum interference – effect of t

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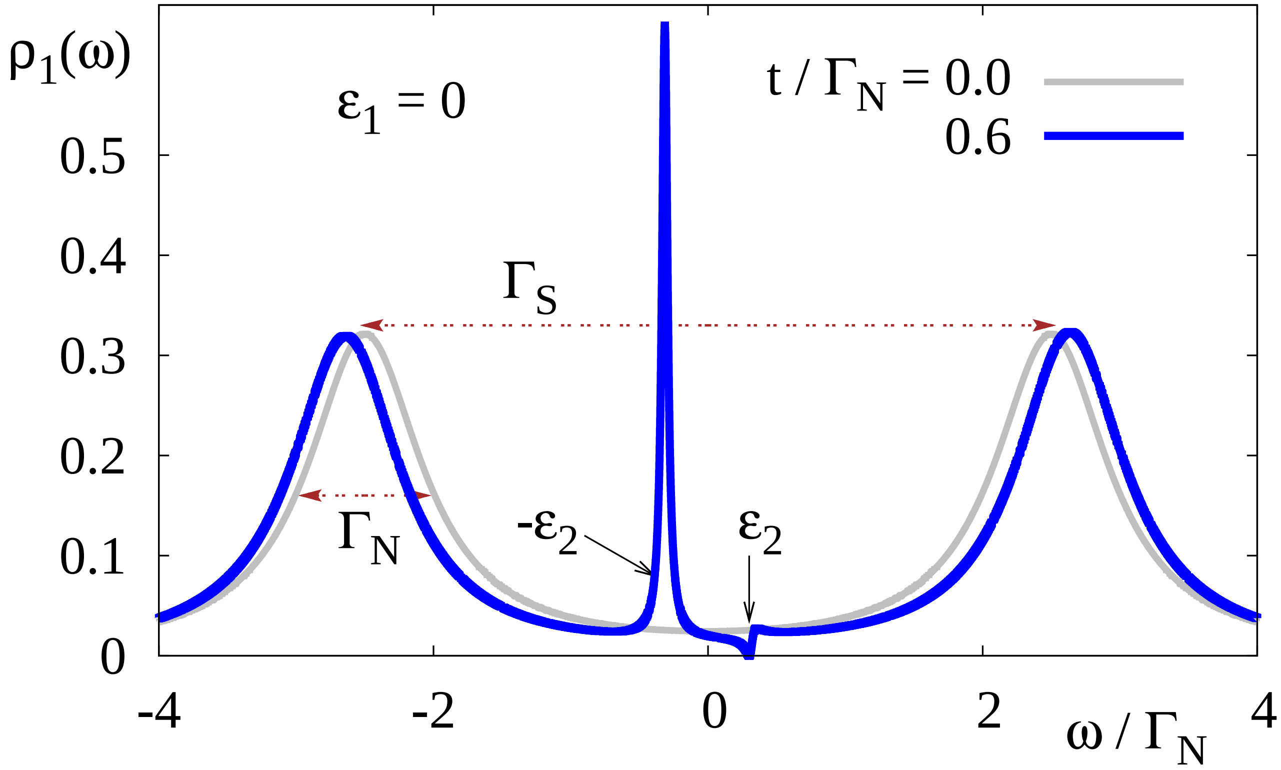
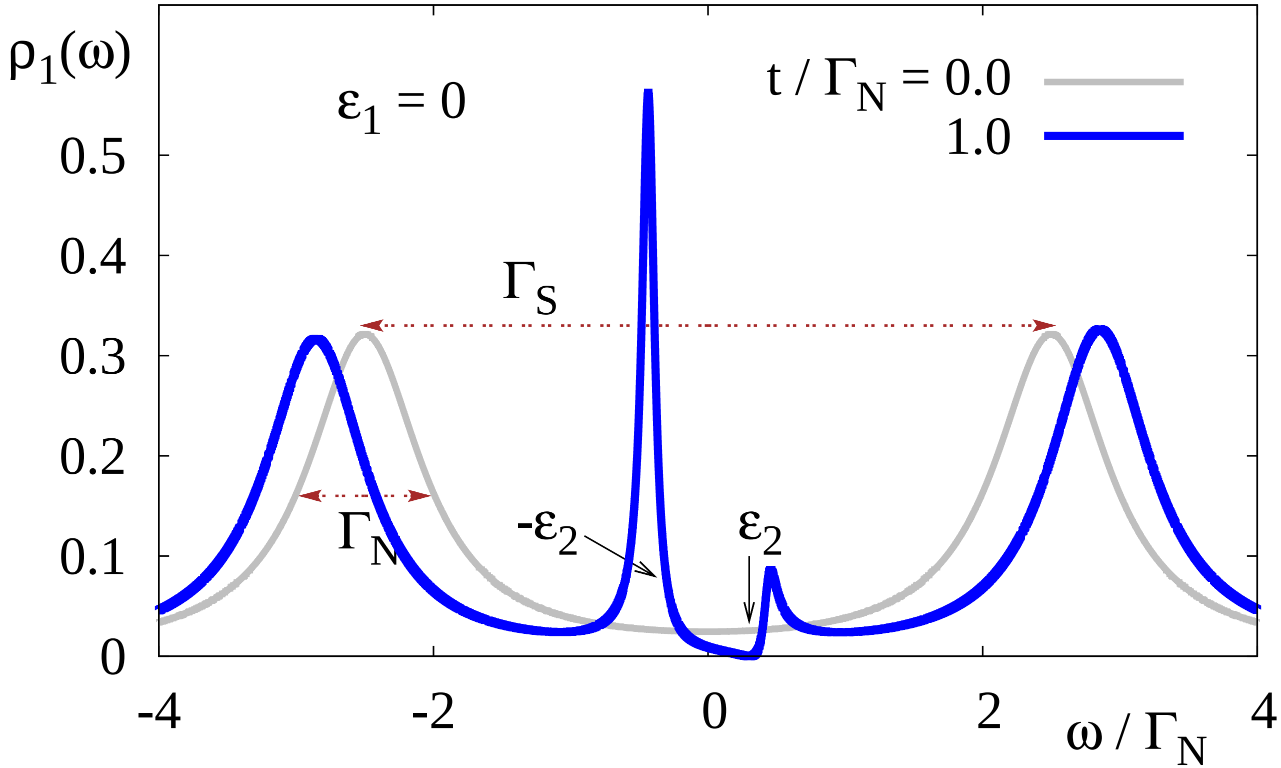


$t/\Gamma_N = 0.6$

Quantum interference – effect of t

Spectral function obtained at QD_1 for $\varepsilon_1 = 0$



$t/\Gamma_N = 1.0$

Fano-type resonance in Andreev conductance

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Differential conductance of the Andreev current

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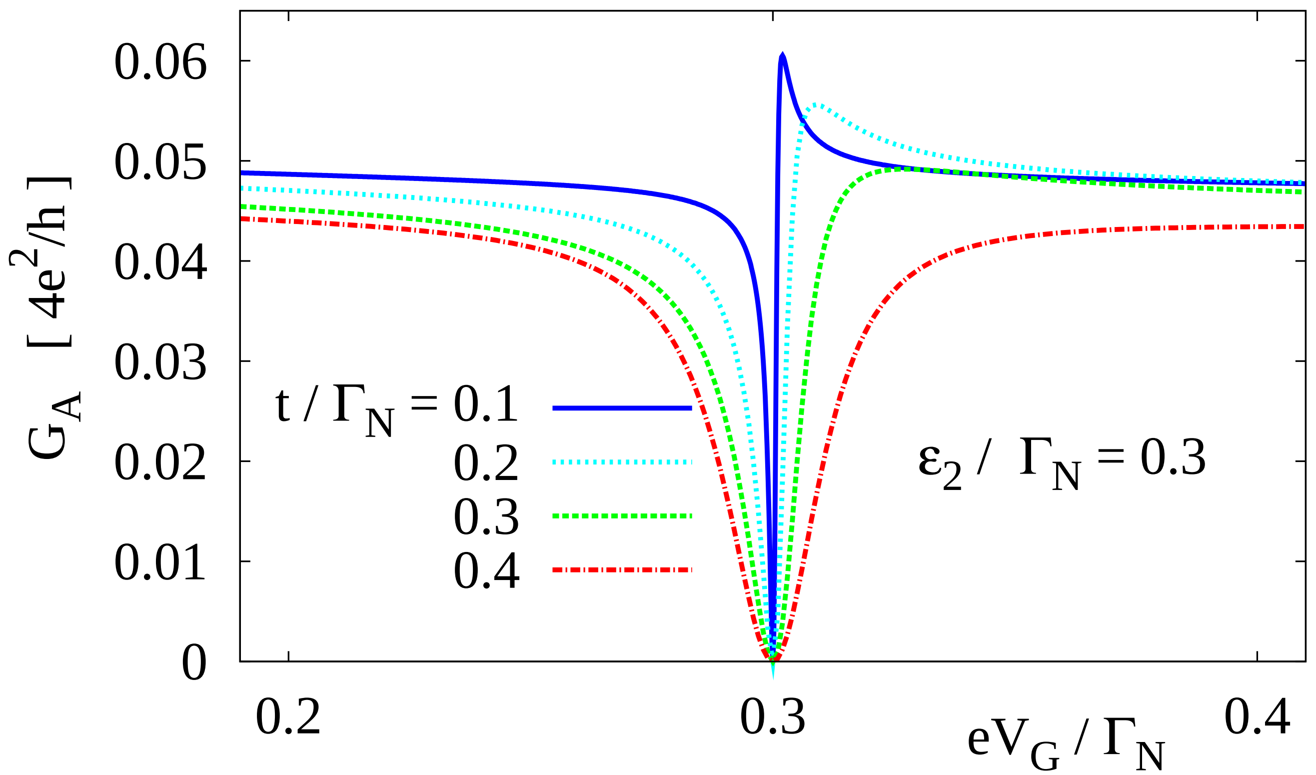

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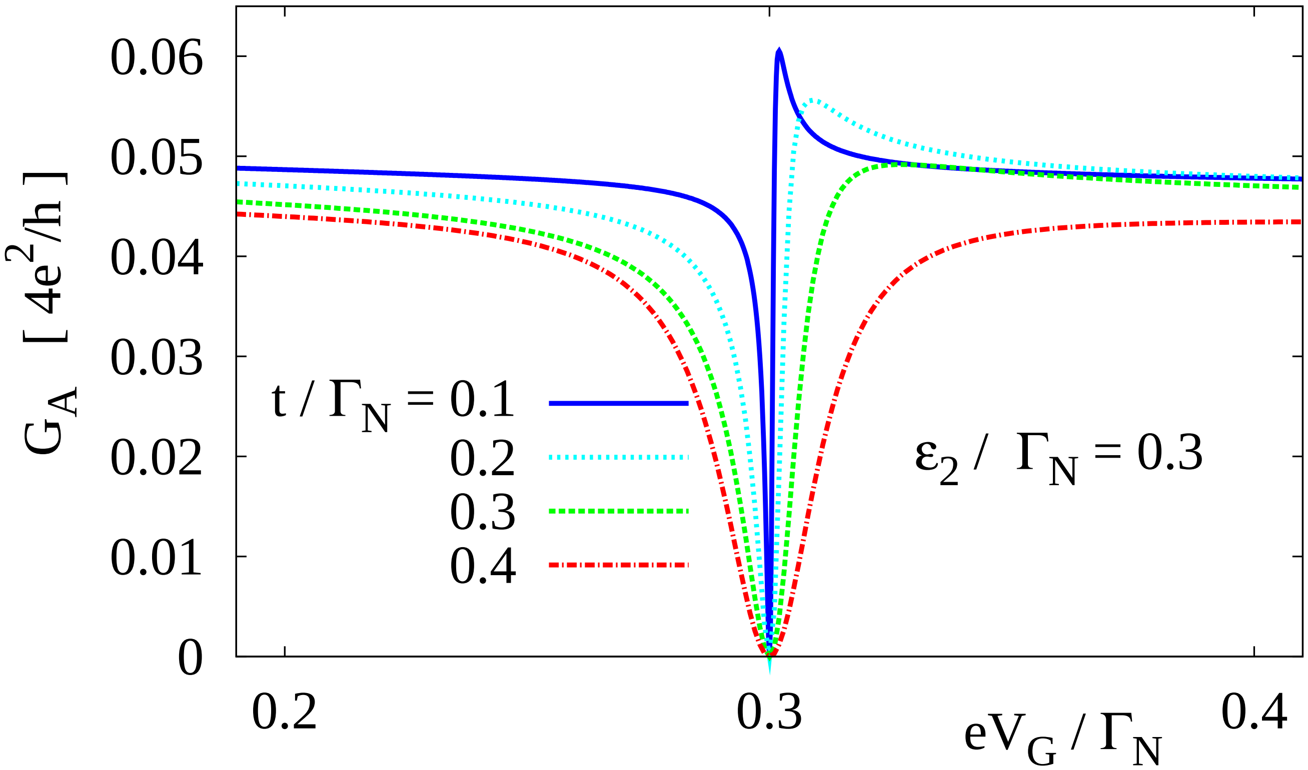

The gate-voltage dependence of G_A obtained for $U = 0$

J. Barański and T. Domański, (2011) submitted.

Fano vs Kondo – competition

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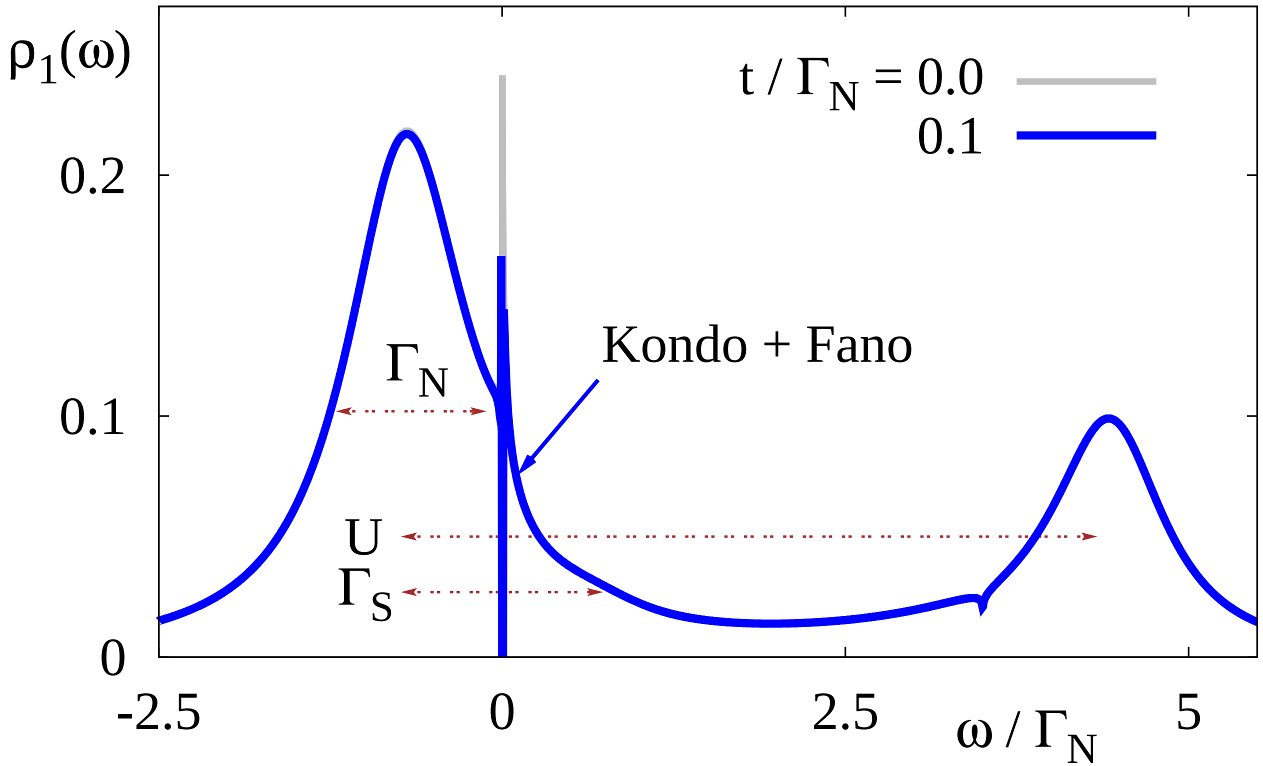

$t/\Gamma_N = 0.1$

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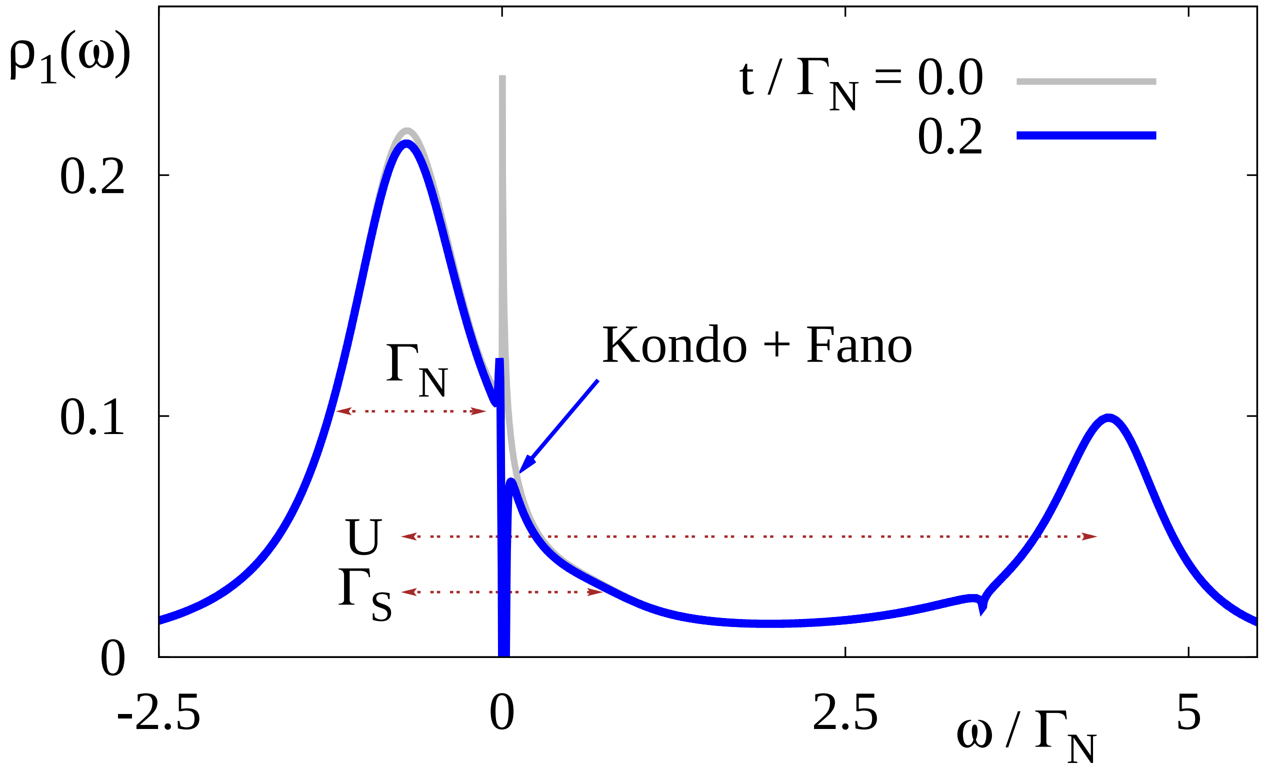

$t/\Gamma_N = 0.2$

Fano vs Kondo – competition

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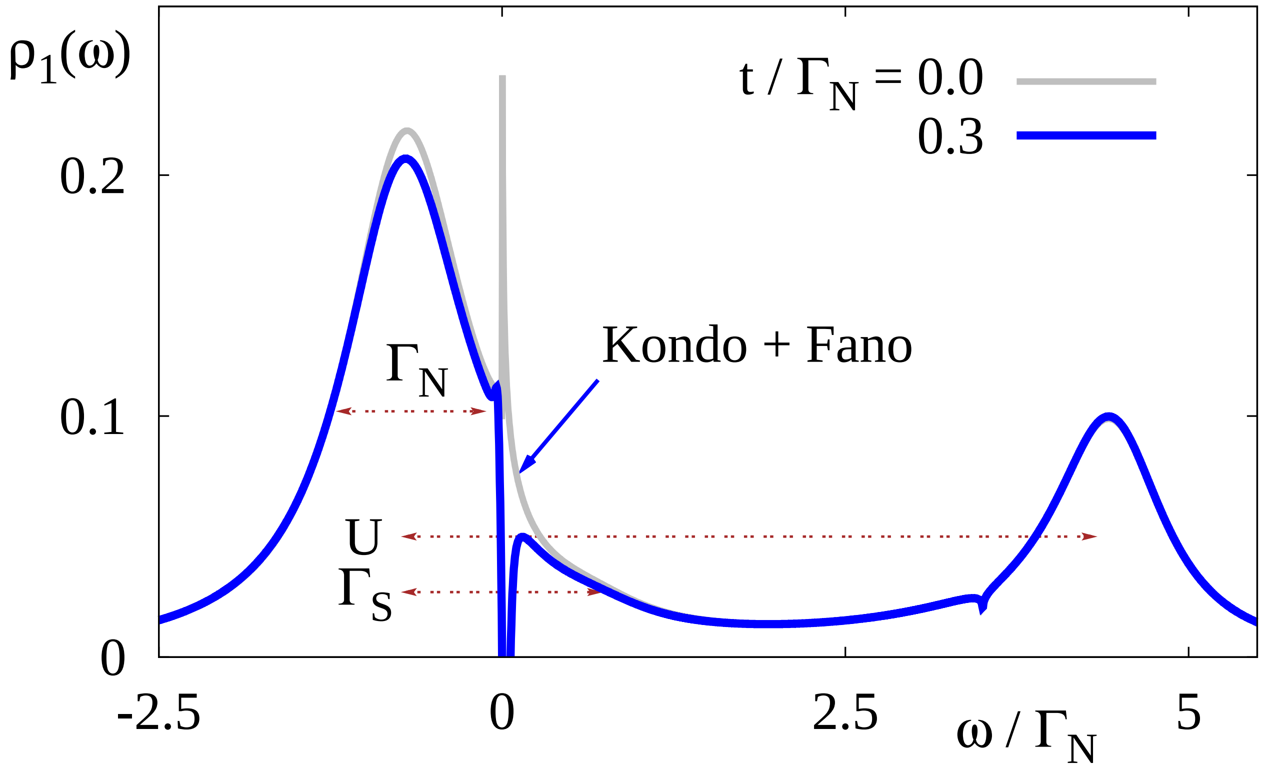

$t/\Gamma_N = 0.3$

Double QD – singlet states

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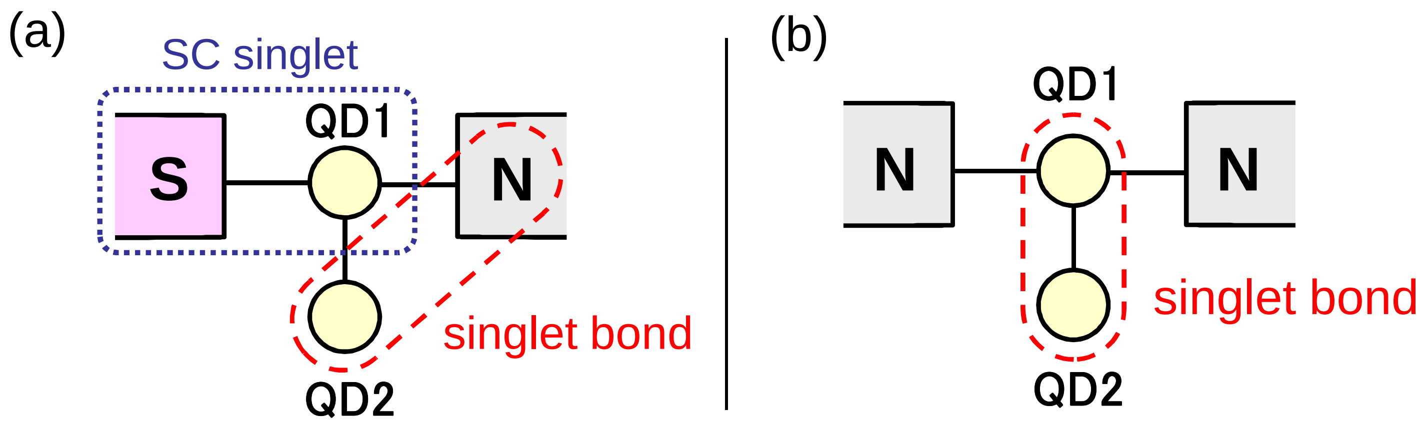

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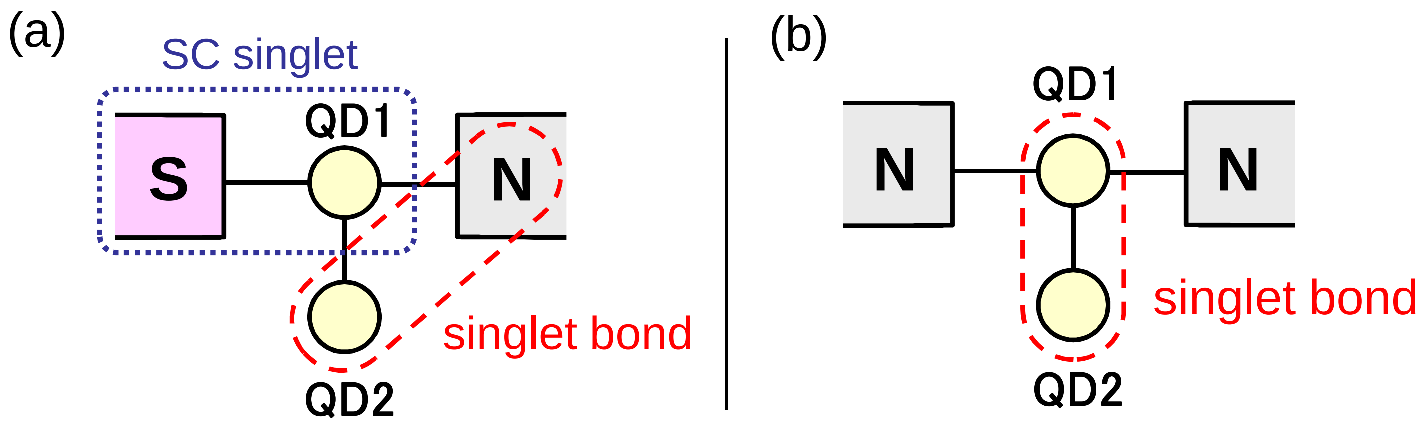

Various kinds of possible singlet states

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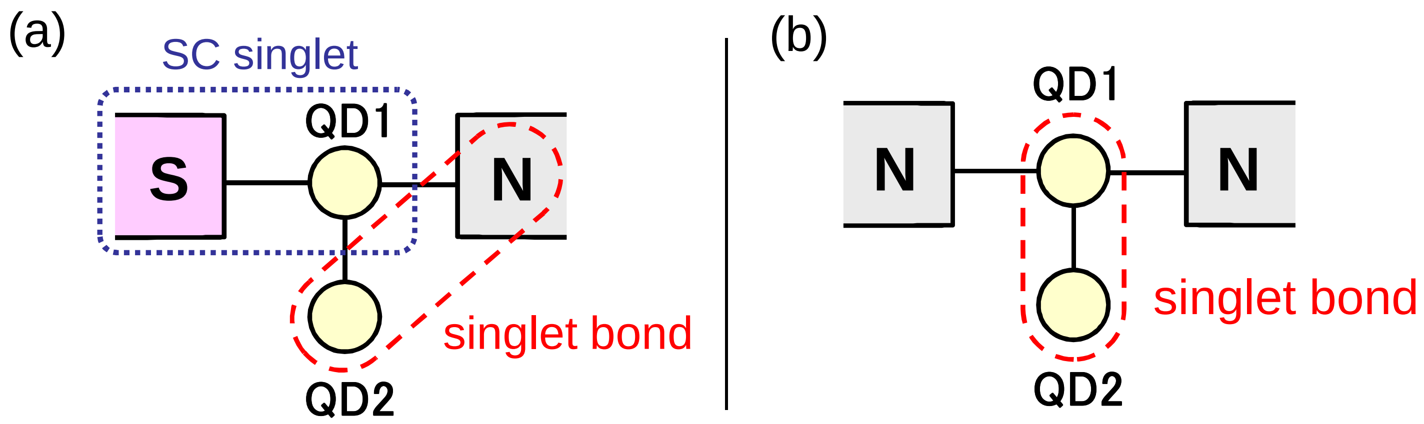

Various kinds of possible singlet states

Y. Tanaka, N. Kawakami, and A. Oguri, Phys. Rev. B ***82****, 094514 (2008).*

Double-QD coupled to three electrodes

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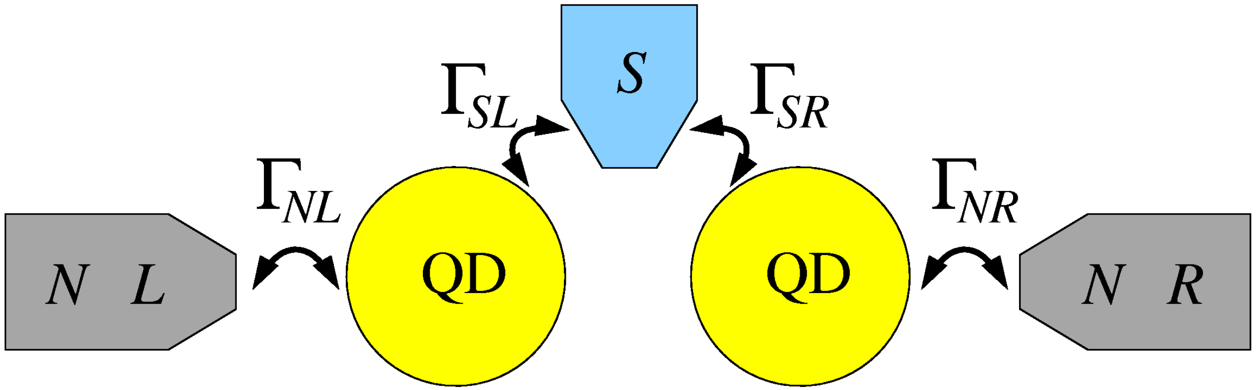
Double-QD acts as a Cooper-pair splitter.



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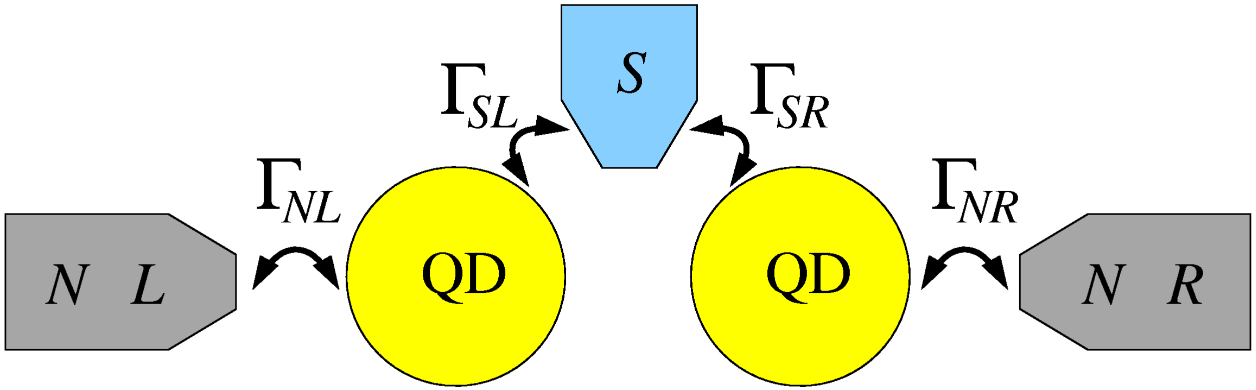

J. Eldridge, M.G. Pala, M. Governale, J. König, Phys. Rev. B **82**, *184507 (2010)*

QD spin-valve

– using a superconducting lead

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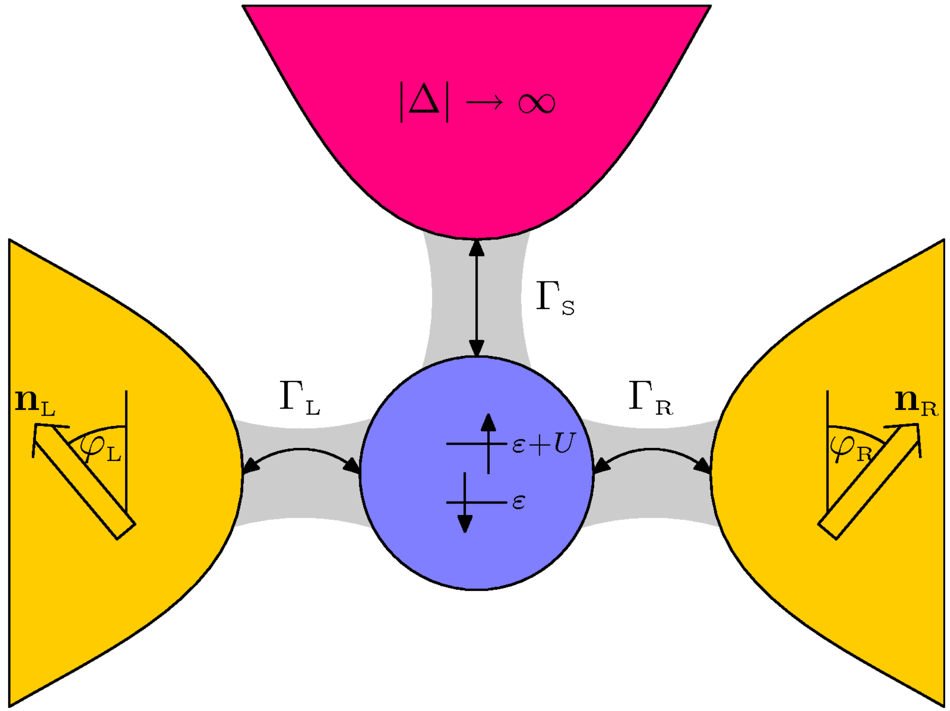

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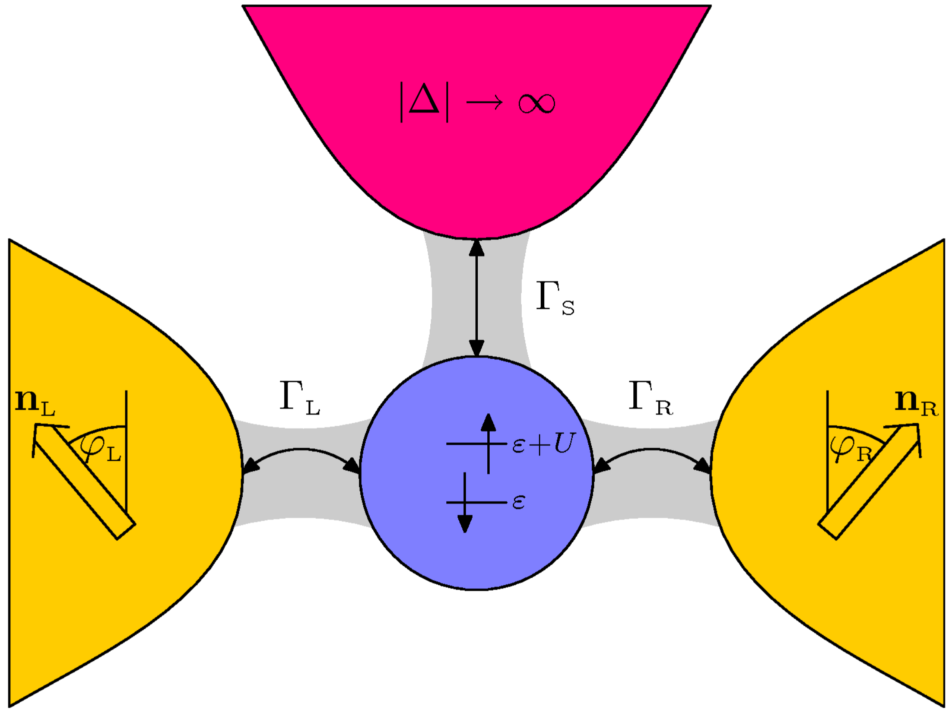
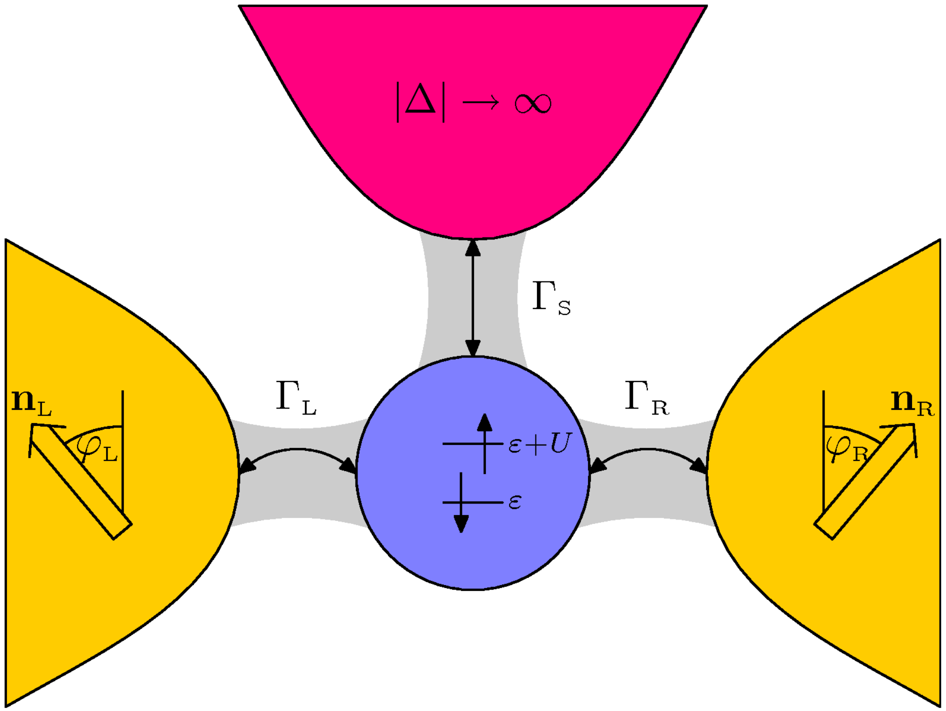


Spintronic transport via the Andreev reflections

QD spin-valve – using a superconducting lead



Spintronic transport via the Andreev reflections

B. Sothmann, D. Futterer, M. Governale, J. König, Phys. Rev. B **82**, *094514 (2010).*

Summary

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