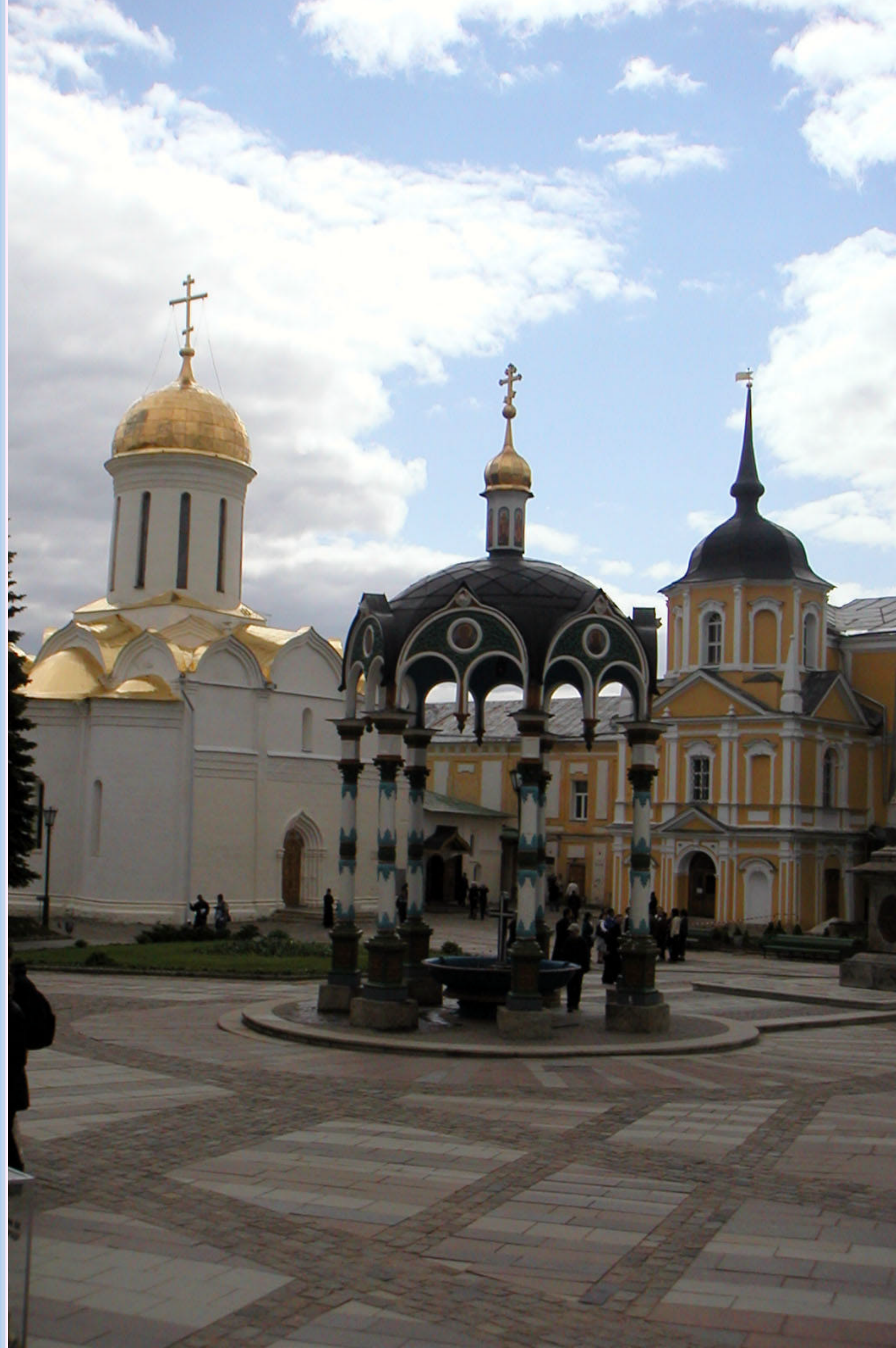
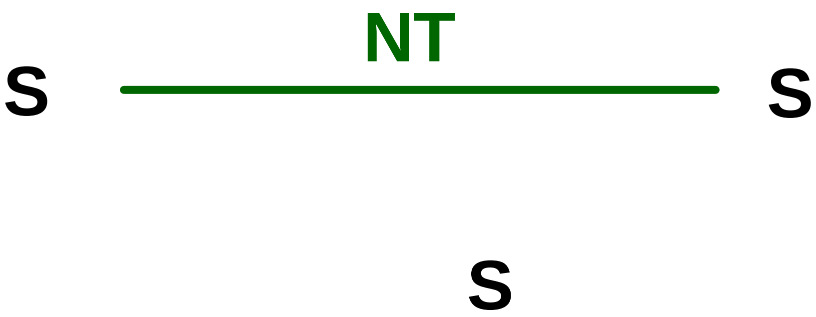



Carbon Nanotube Quantum Dot with Superconducting Leads

Kondo Effect and Andreev Reflection in CNT's

Motivation

Motivation



Orsay group: reported **enhanced** $I_C R_N$ product

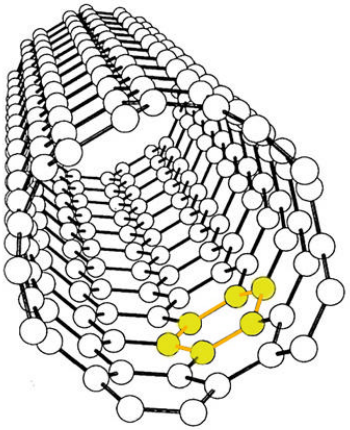
A. Yu. Kasumov et al.

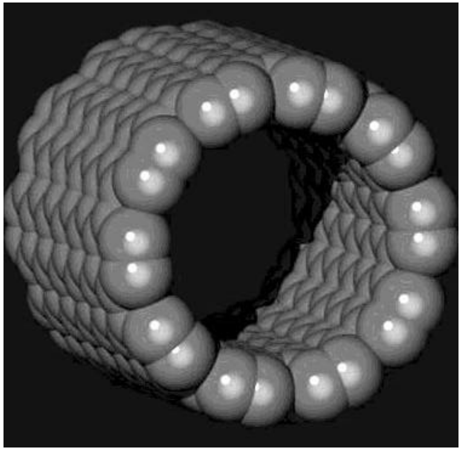
NT **entangler**

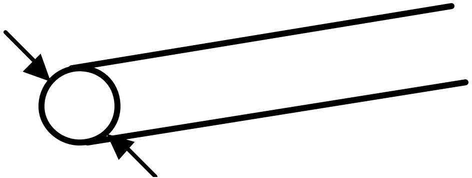
T. Martin ...
M. Fisher ...
D. Loss ...

Introduction

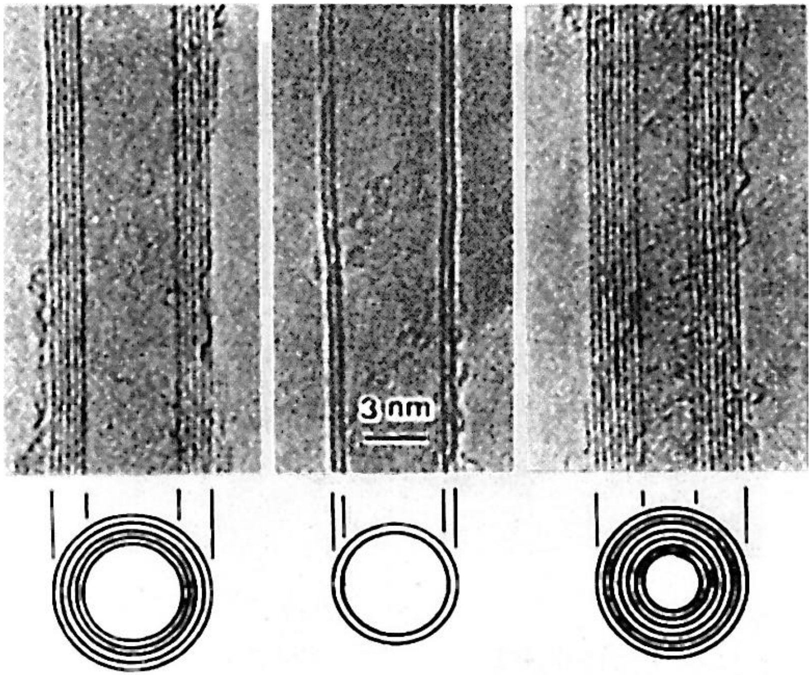
Singlewall ⟷ Multiwall

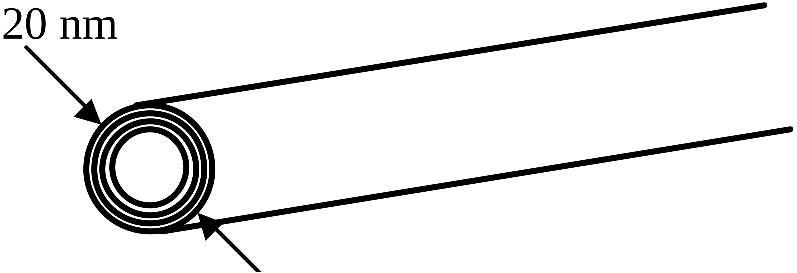




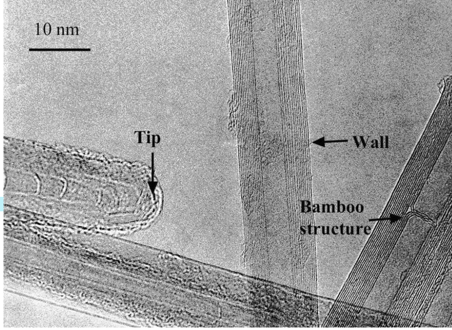


S. Iijima 1991

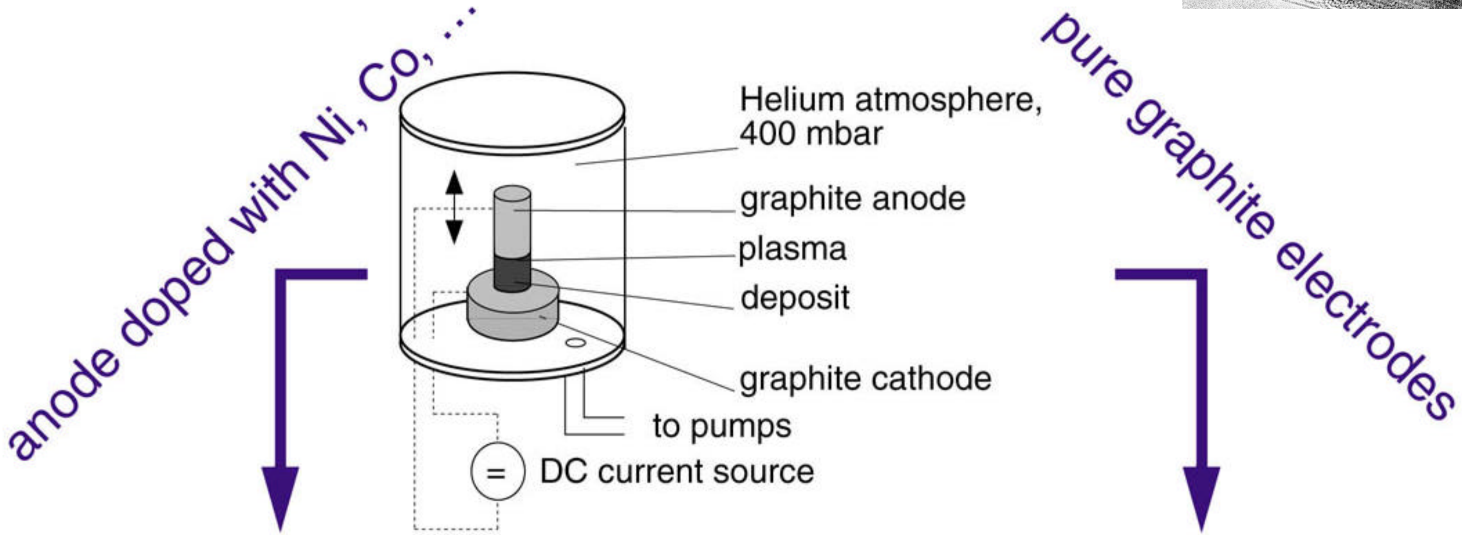




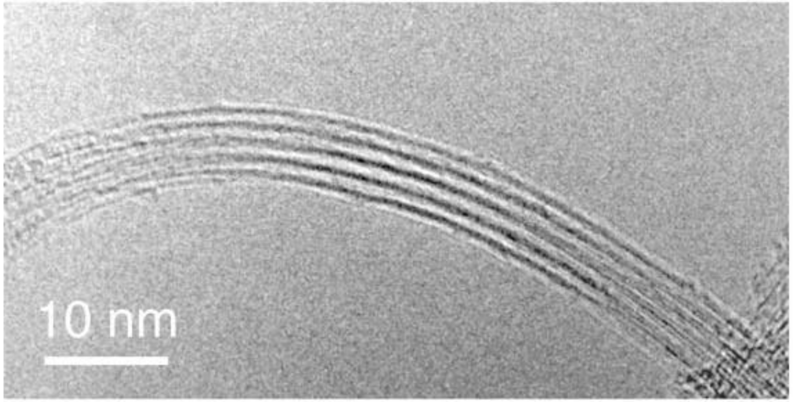
Synthesis: arc discharge



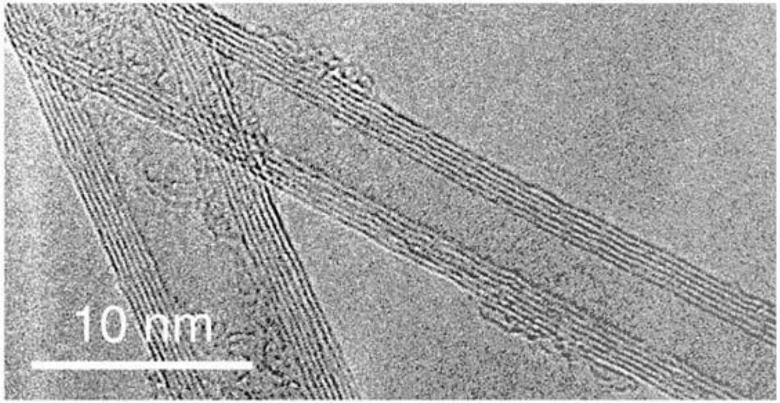
L. Forro et al. EPFL



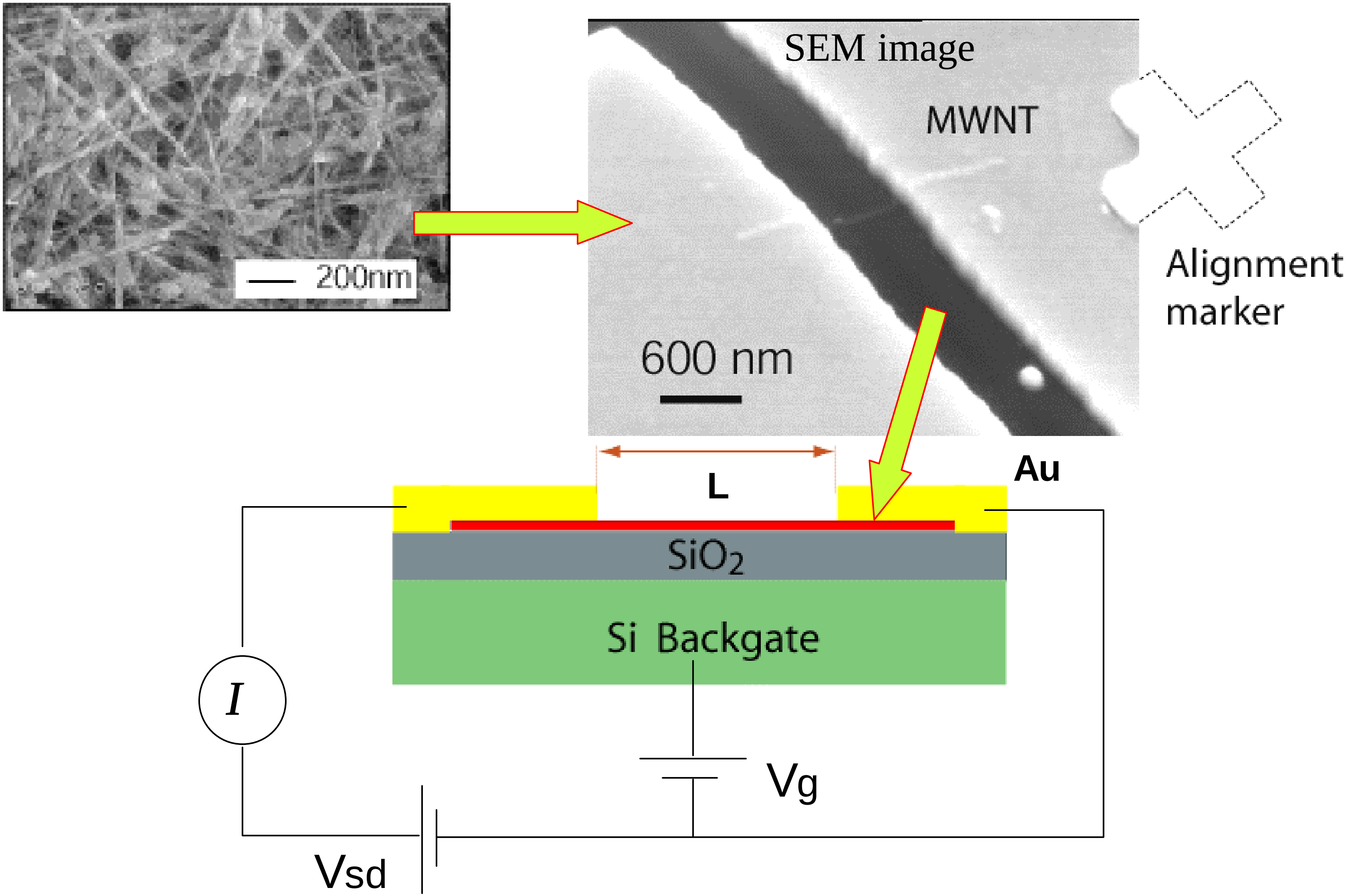
Single wall nanotubes



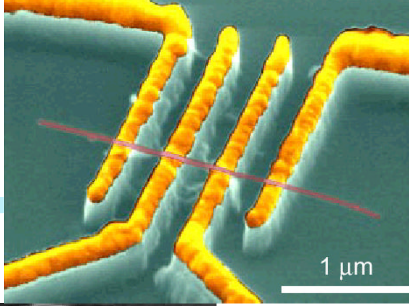
Multiwall nanotubes

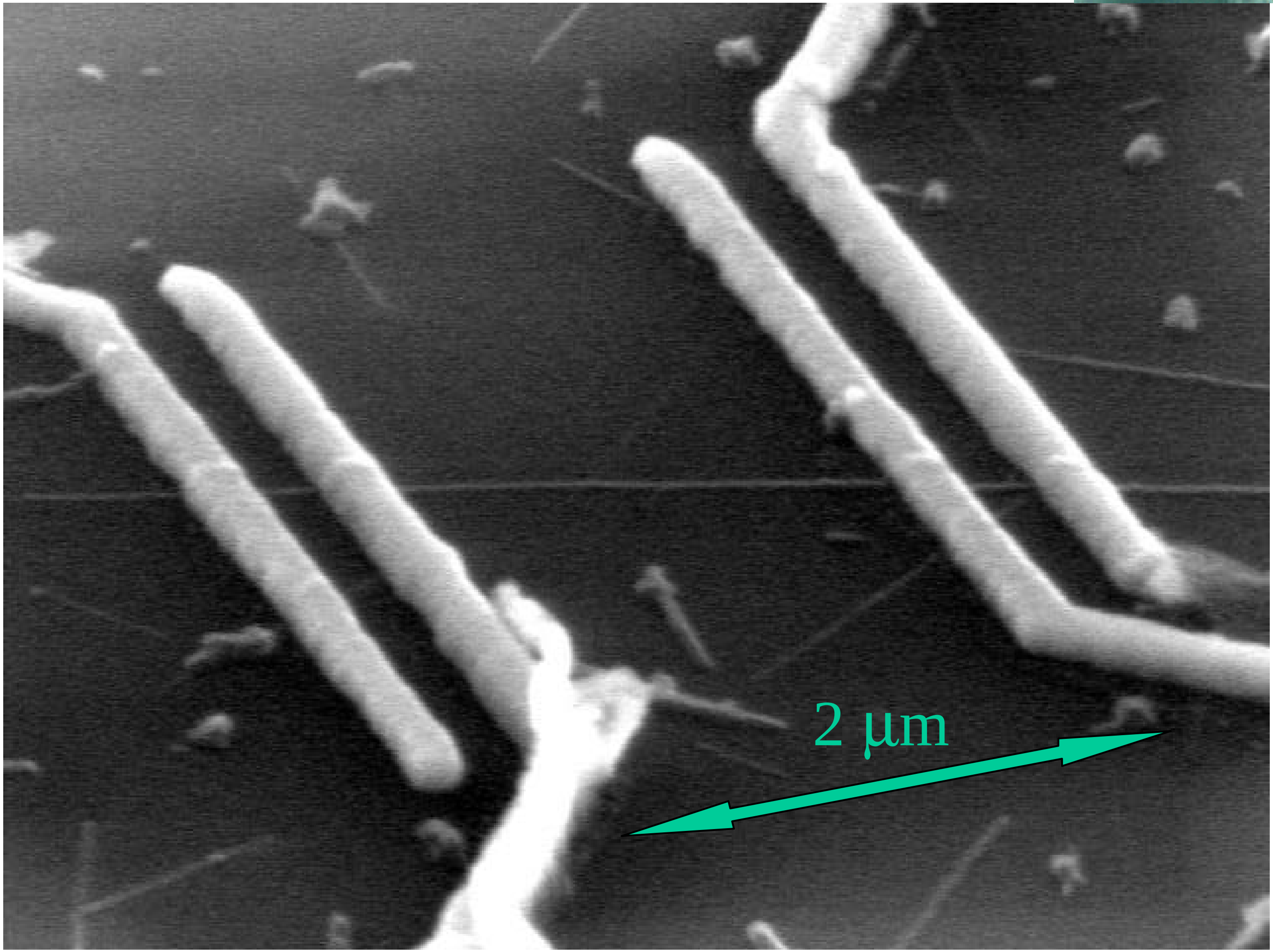


Contacting

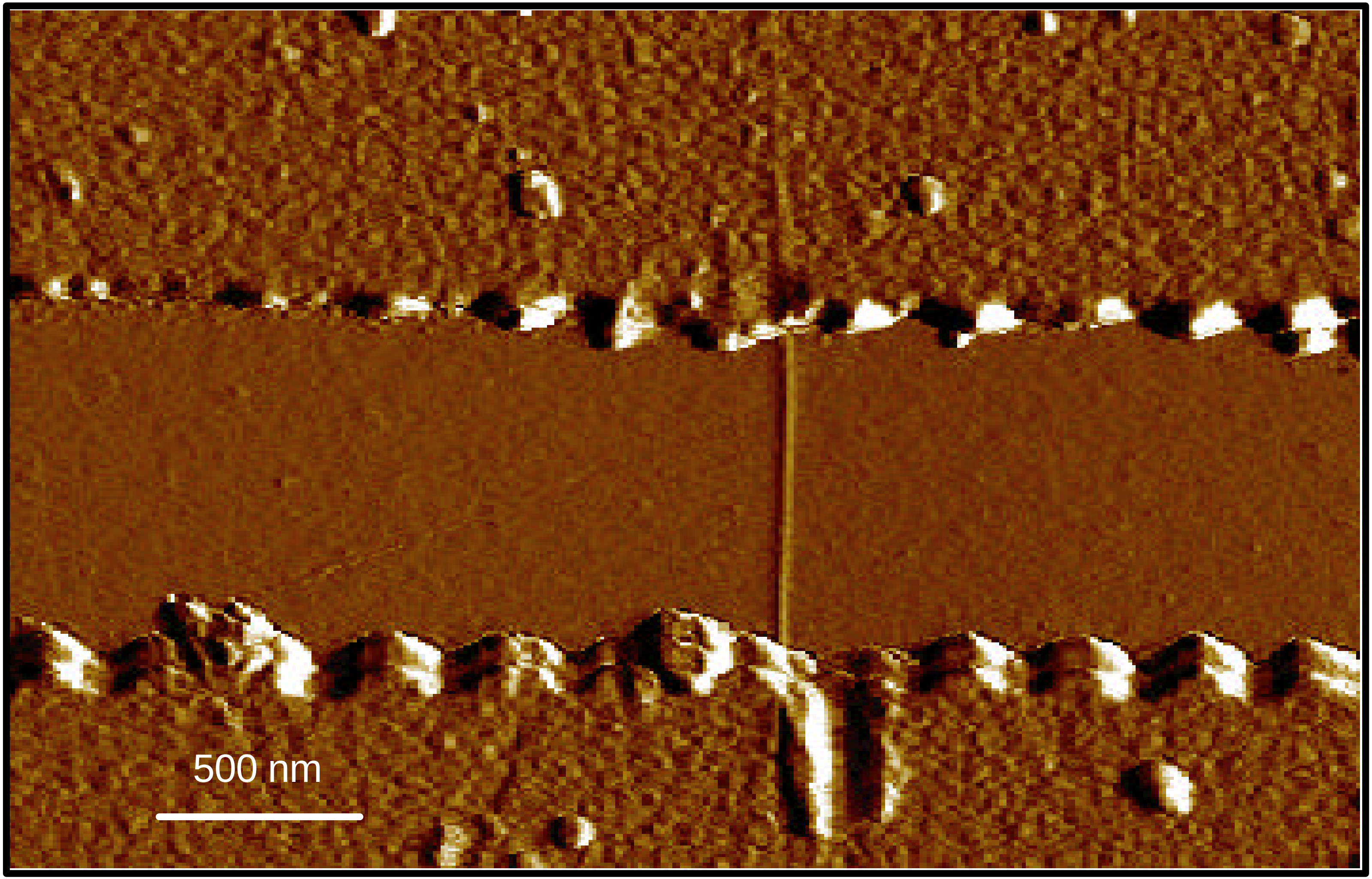

200nm
SEM image
MWNT
Alignment marker
600 nm
L
Au
SiO_2
Si Backgate
I
Vg
Vsd

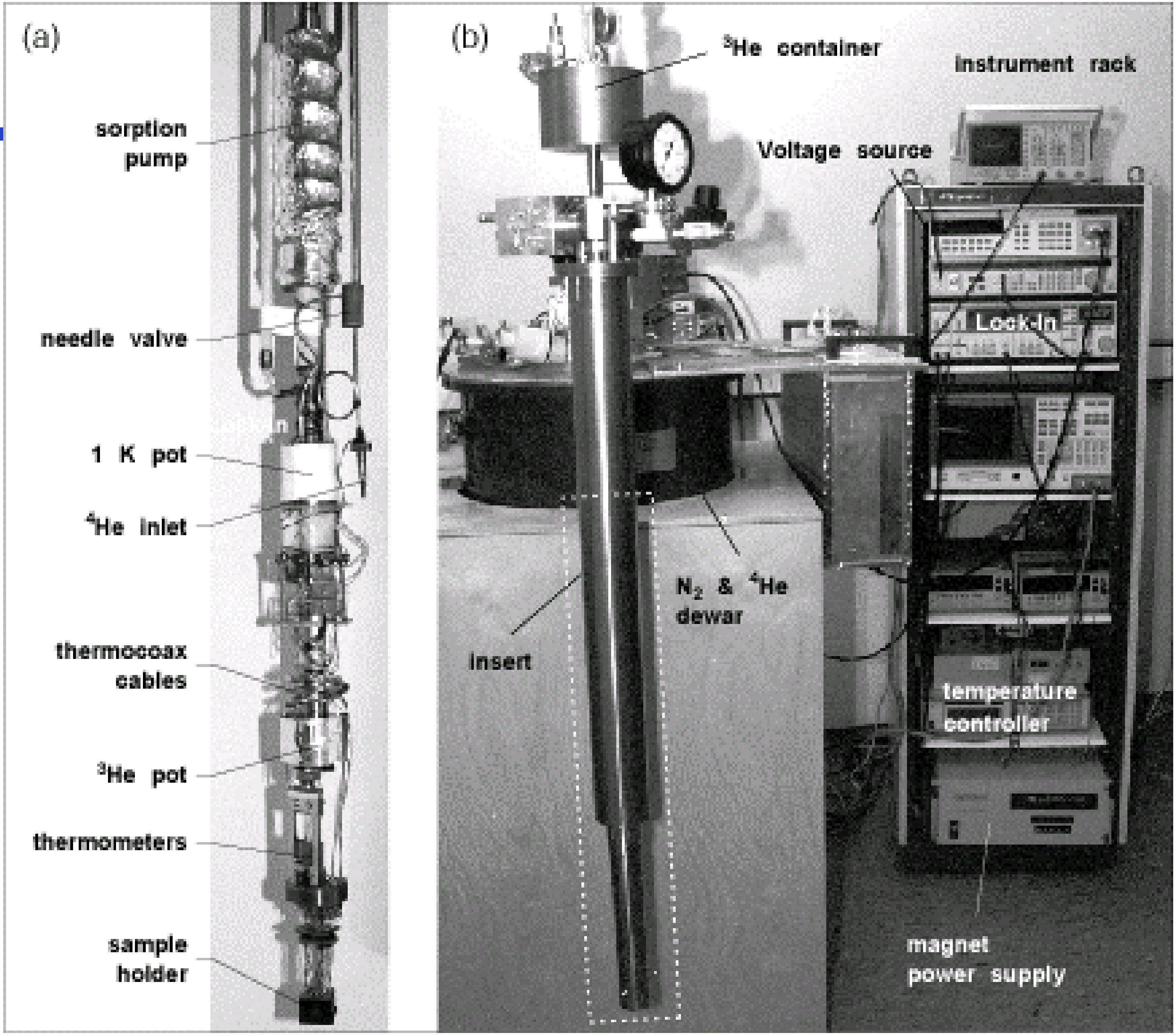
Contacts...





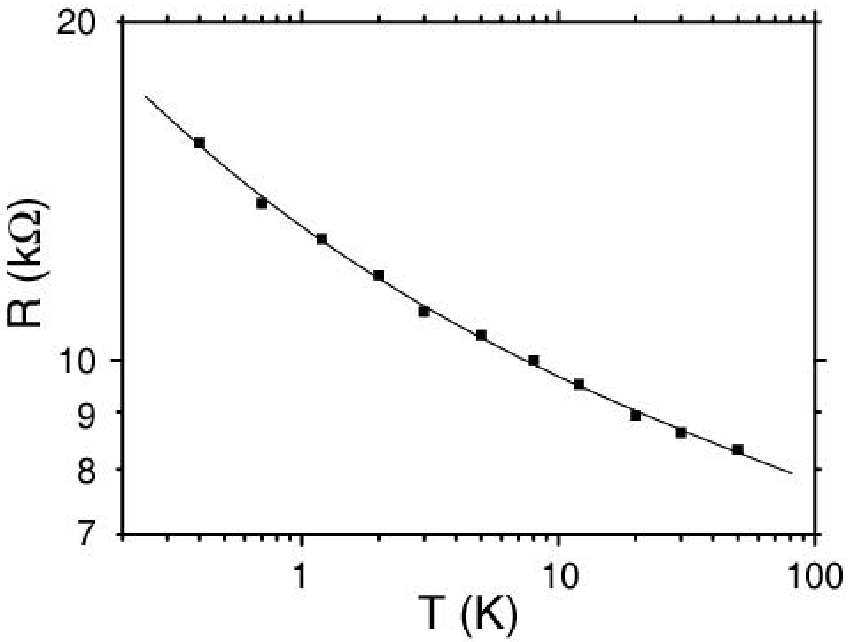
AFM picture

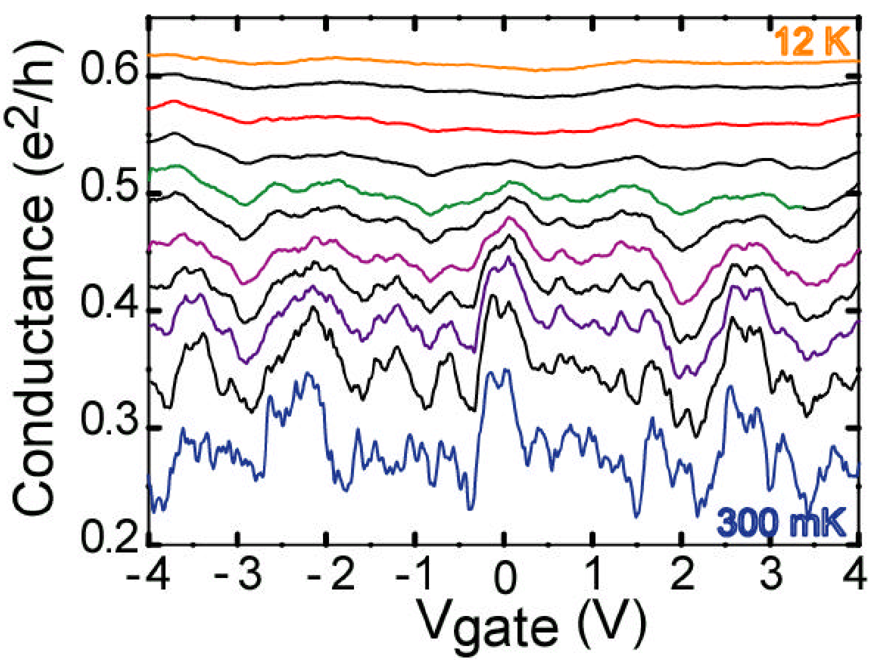



(a)
sorption pump
needle valve
1 K pot
4He inlet
thermocoax cables
3He pot
thermometers
sample holder
(b)
3He container
instrument rack
Voltage source
Lock-In
N2 & 4He dewar
insert
temperature controller
magnet power supply

wire-like behaviour

long tube (7.4 mm)





➔ ZBA

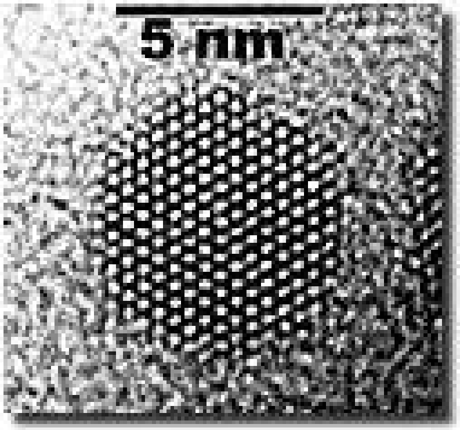
➔ UCF

Quantum Dot Physics

Quantum dots

What are Quantum Dots?

Quantum dots are nanometer (10^{-9} meter) scale particles that are neither small
molecules nor bulk solids. Their composition and small size (a few hundred to a few
thous ... s extraordinary optical properties that can be readily
custo ... e or compo ... light,
then ... ut in a diffe
inorg ... henomeno ... e
would ... ching with ... d have
multi ... an be exci ... ion
wave ... ely fit this



TEM by Andreas Kadavanich. Transmission electron microscopy shows the crystalline arrangement of atoms in a 5 nm CdSe Qdot particle.

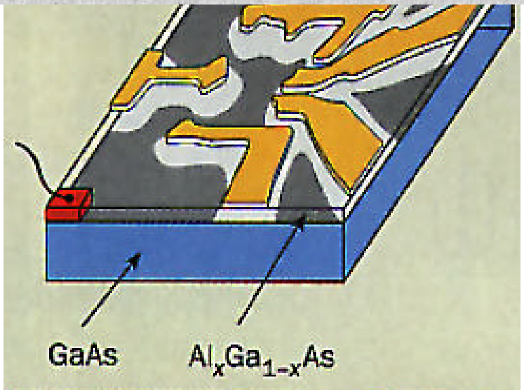
A family of Qdot particles can be made to emit a full spectrum of colors when excited with a single excitation source.

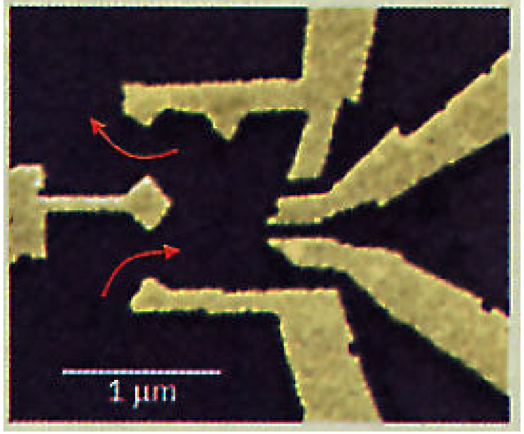
Quan ... rystals) co ... stics,
such ... ntness, off
semic ... ing diodes) ... e
many ... that are fo ... ng
prope ... antum dots ... an be
"tune ... gth by simp ... ind
this ... tum confir ... ed
quantum dots emitting light of different wa... of
semiconductor materials and an array of different sizes, QDC can make quantum dots
with colors that span the spectrum, from ultraviolet to infrared.

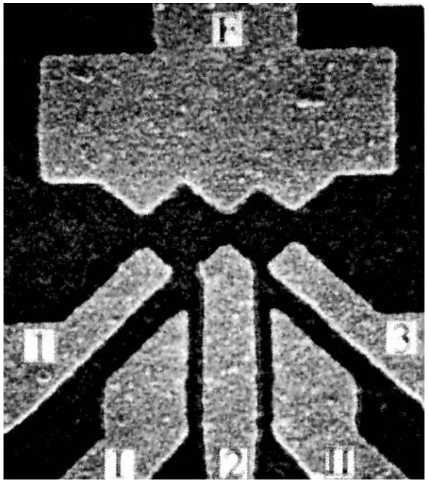
(„conventional“) Quantum dots

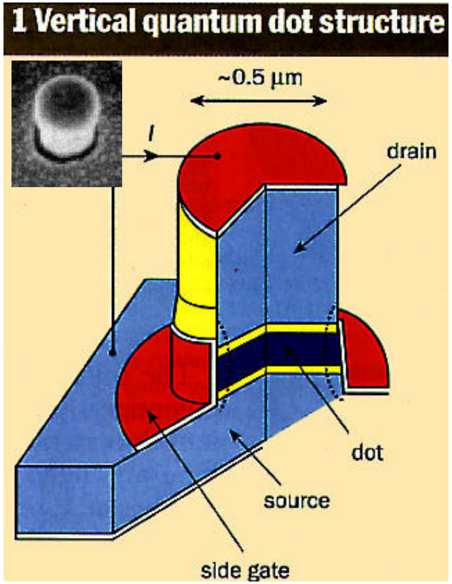
Quantum Dots

Quantum dots are nanometer-scale "boxes" for selectively holding or releasing electrons. Over the past 10 years they have been transformed from laboratory curiosities to the building blocks for a future computer industry.

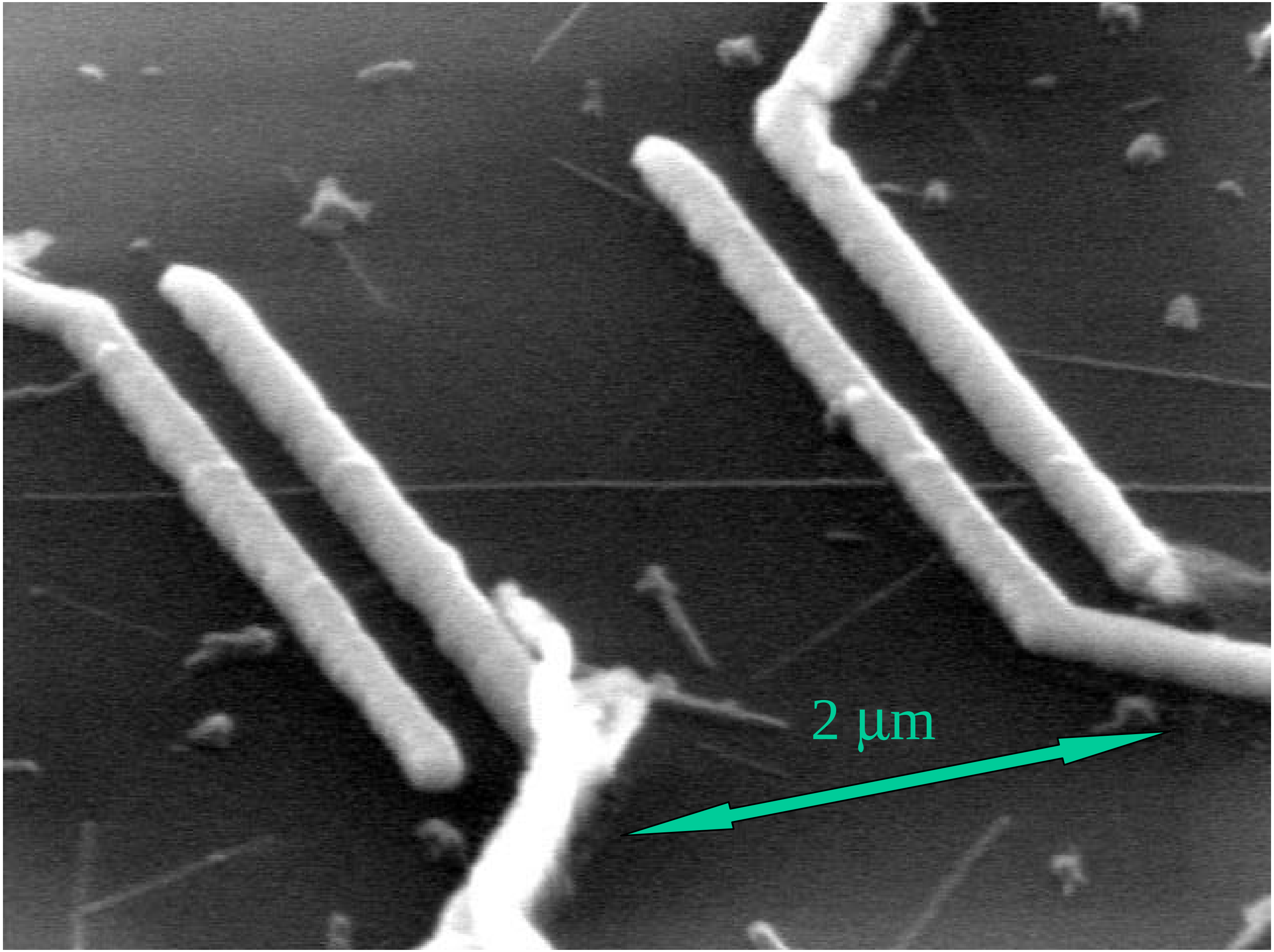








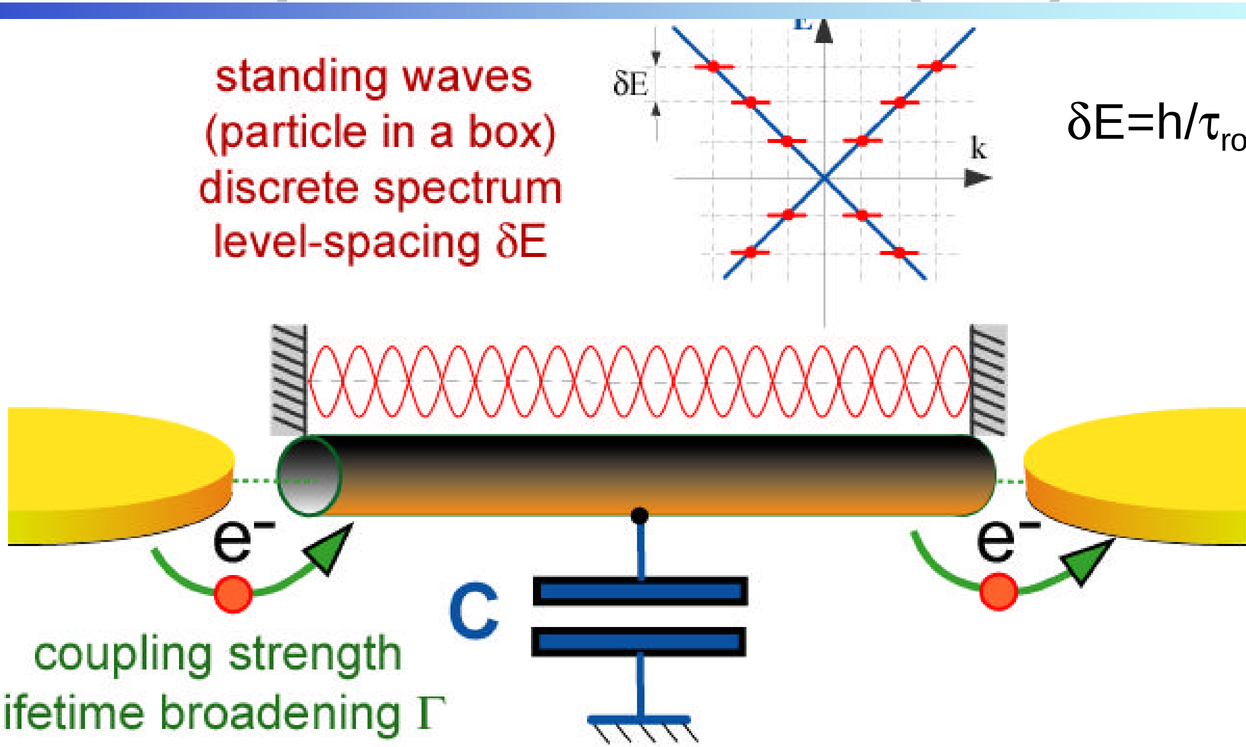
quantum **dot** ?



1d quantum dot (0d)

standing waves
(particle in a box)
discrete spectrum
level-spacing δE

$\delta E = h/\tau_{round\text{-}trip}$



coupling strength
lifetime broadening Γ

$\Gamma < \delta E$ for any quantum dot

Coulomb interaction
single-electron charging energy U

in addition:
eV and kT

if we use superconducting electrodes, there is in addition
a **6th parameter**: Δ

Contacts matter, i.e. G

$U >> \Gamma$ „charge box“ (independent of δE) *metal nano-particle*

$U > \delta E > \Gamma$ „quantized charge box“ *„Tarucha dots“*

$\Gamma > (U, \delta E)$ „weak link“

$\delta E > U > \Gamma$ strongly interacting quantum dot

$\delta E > \Gamma > U$ weakly interacting quantum dot

} *carbon nanotubes*

simplified...

First, **ideal** quantum dot has: d**E** ® ¥

„easy“, if $U << \Gamma$ → **resonant tunneling**

„easy“, if $U >> \Gamma$ → **single-electron tunneling**

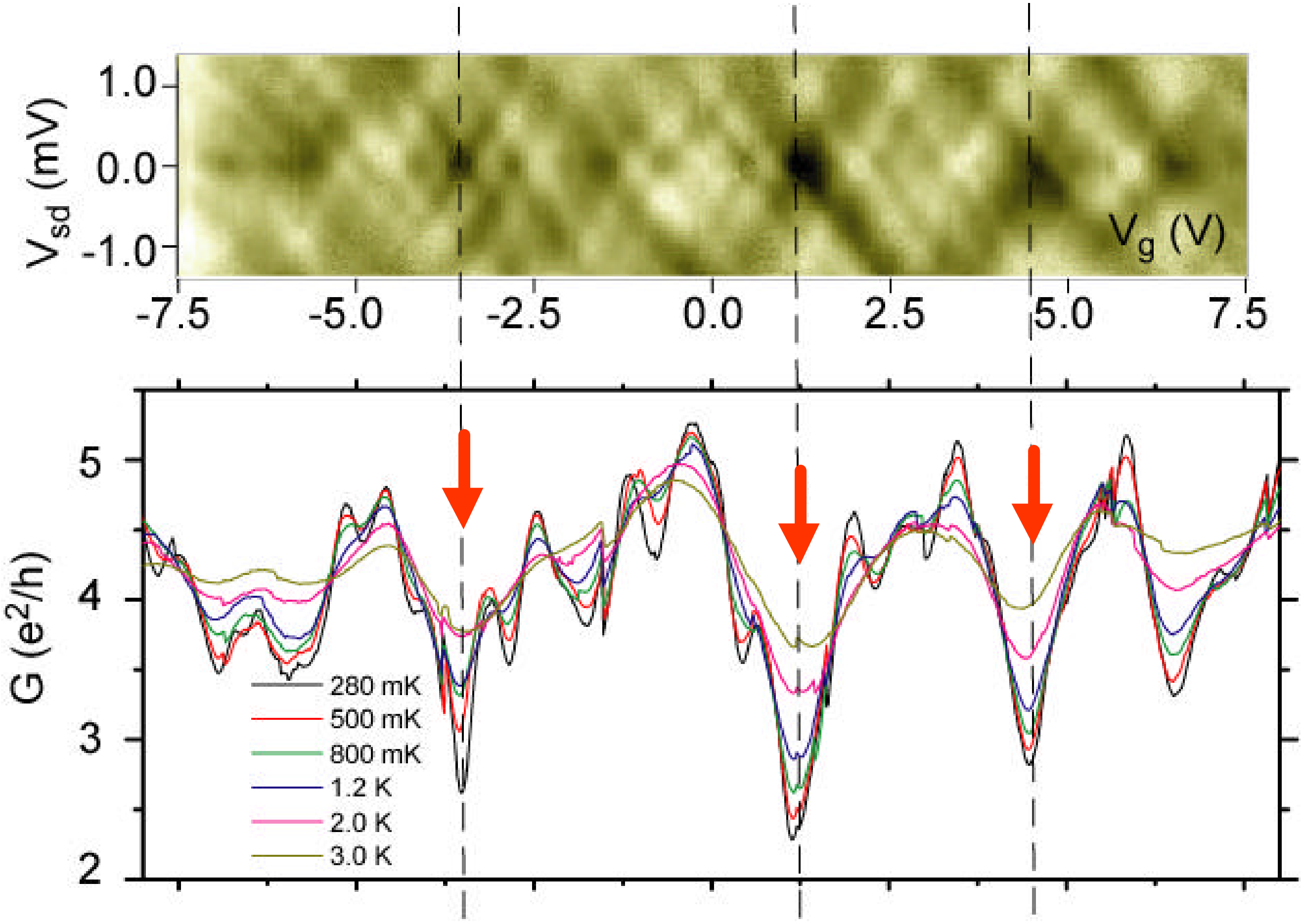
not „easy“, if $U \sim \Gamma$ → **correlated electron transport**

„open" nanotube dot

$G >> U$

normal leads

MWNT open Q-dot (δE~Γ>U)



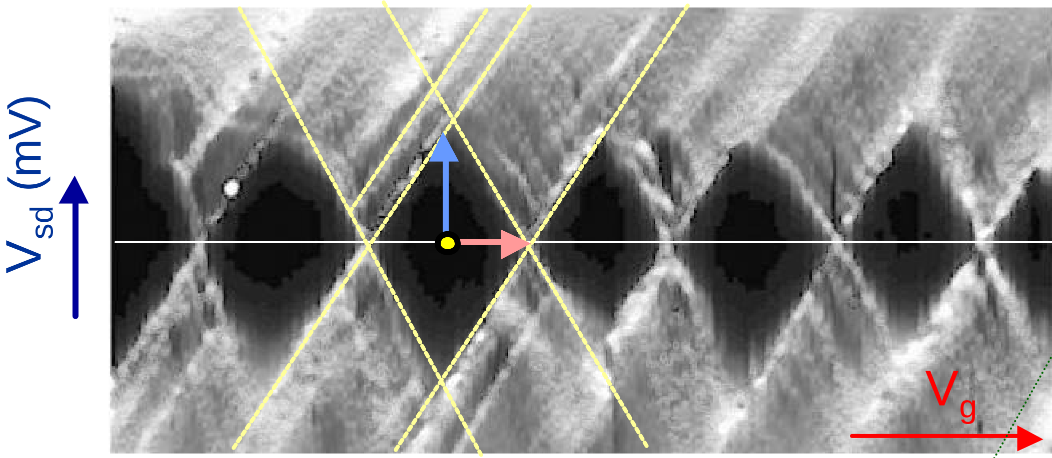
*Buitelaar et al. PRL **88**, 156801 (2002)*
*similar to Fabry-Perot of SWNTs: W. Liang et al., Nature **411**, p 665 (2001)*

„closed“ nanotube dot

G<< U

normal leads

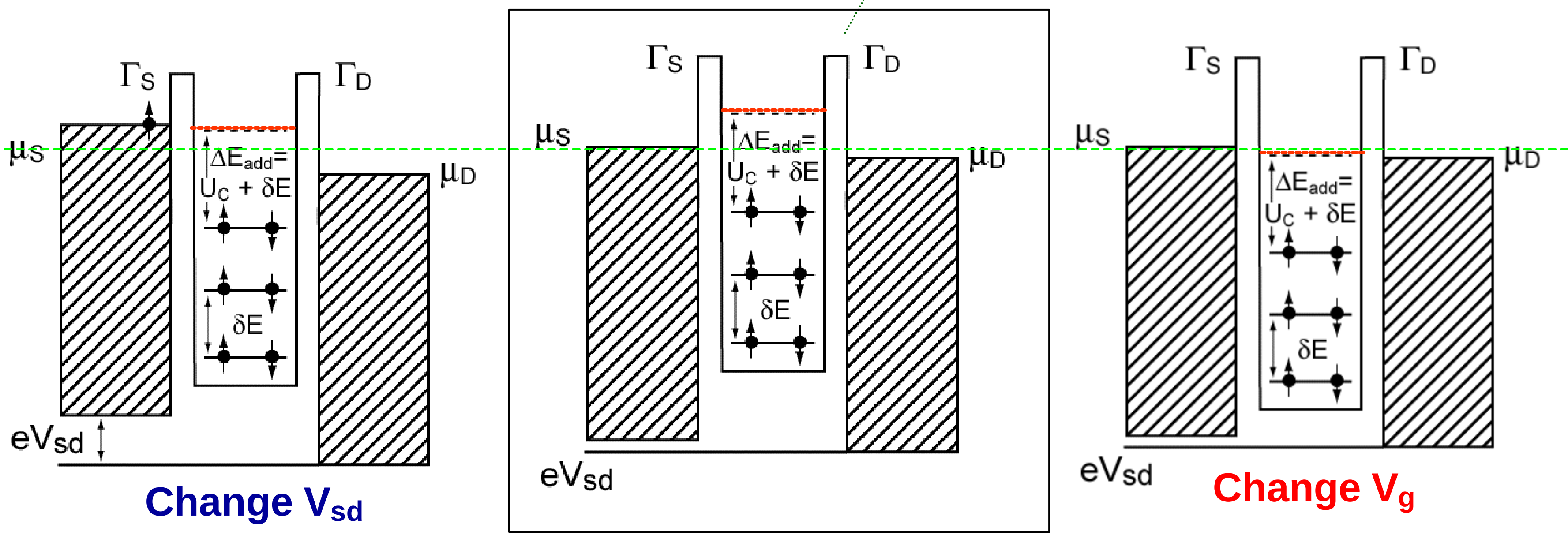
single-electron tunneling

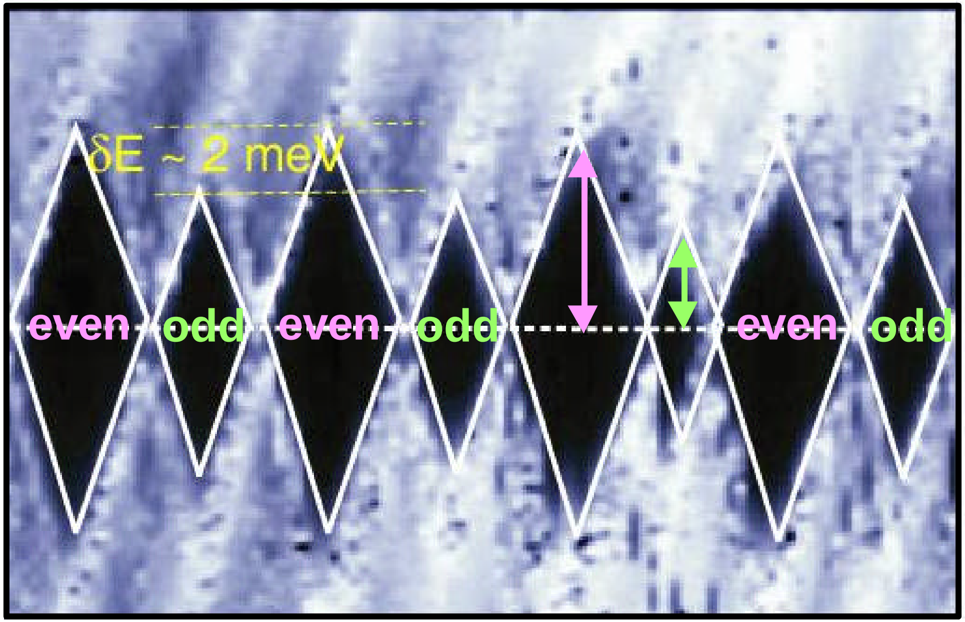


ΔE_{add} addition energy,
i.e. sum of:

single-electron charging energy U_C

level-spacing δE

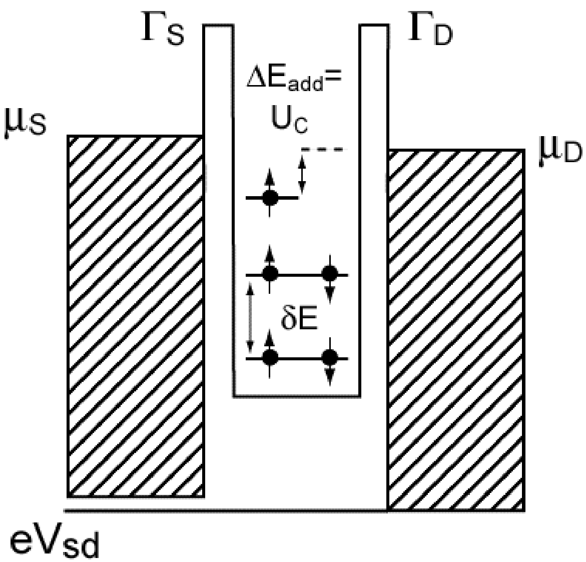




filling of states according to S = **1/2 →0 →1/2** ...

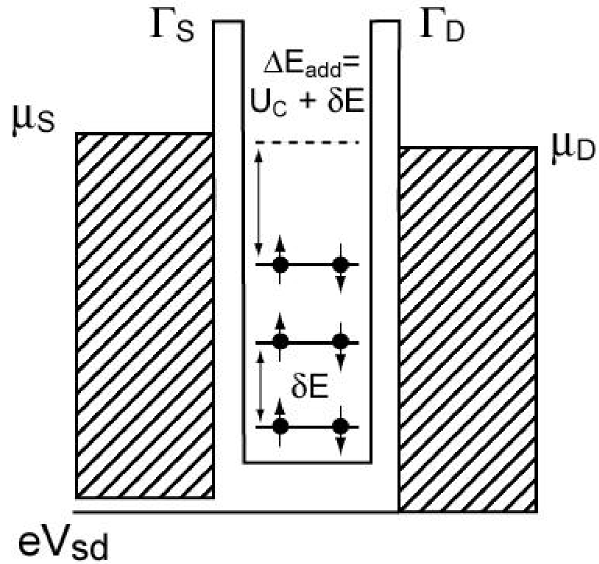
odd number of electrons:

$DE_{\text{add}} = U_C$



even number of electrons:

$DE_{\text{add}} = U_C + dE$



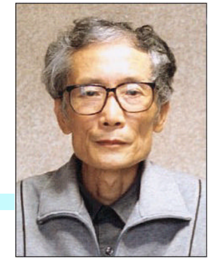
„open" nanotube dot

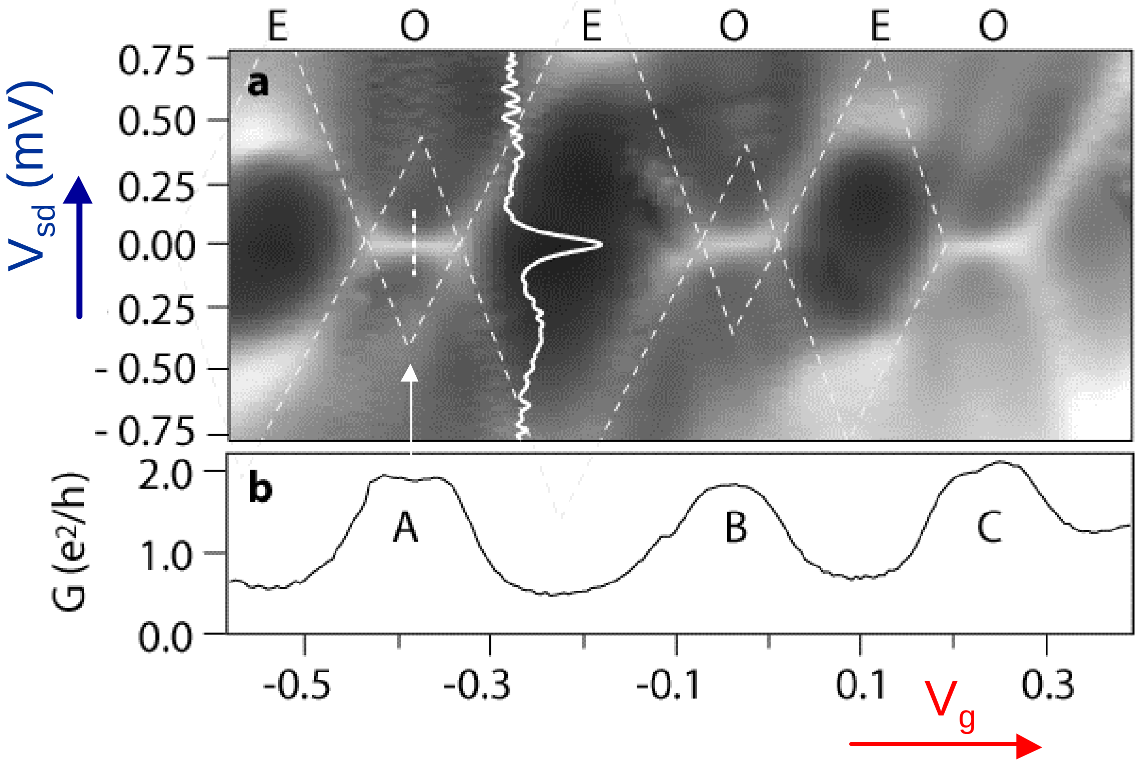
G~ U

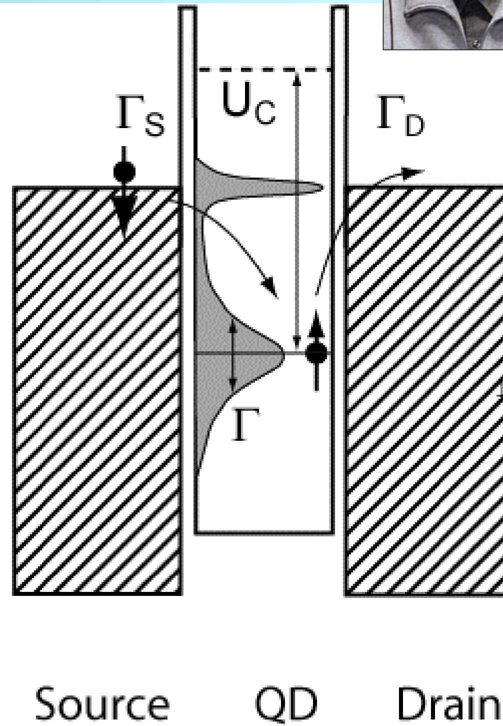
(correlated transport)

normal leads

rel. open MWNT Q-dot



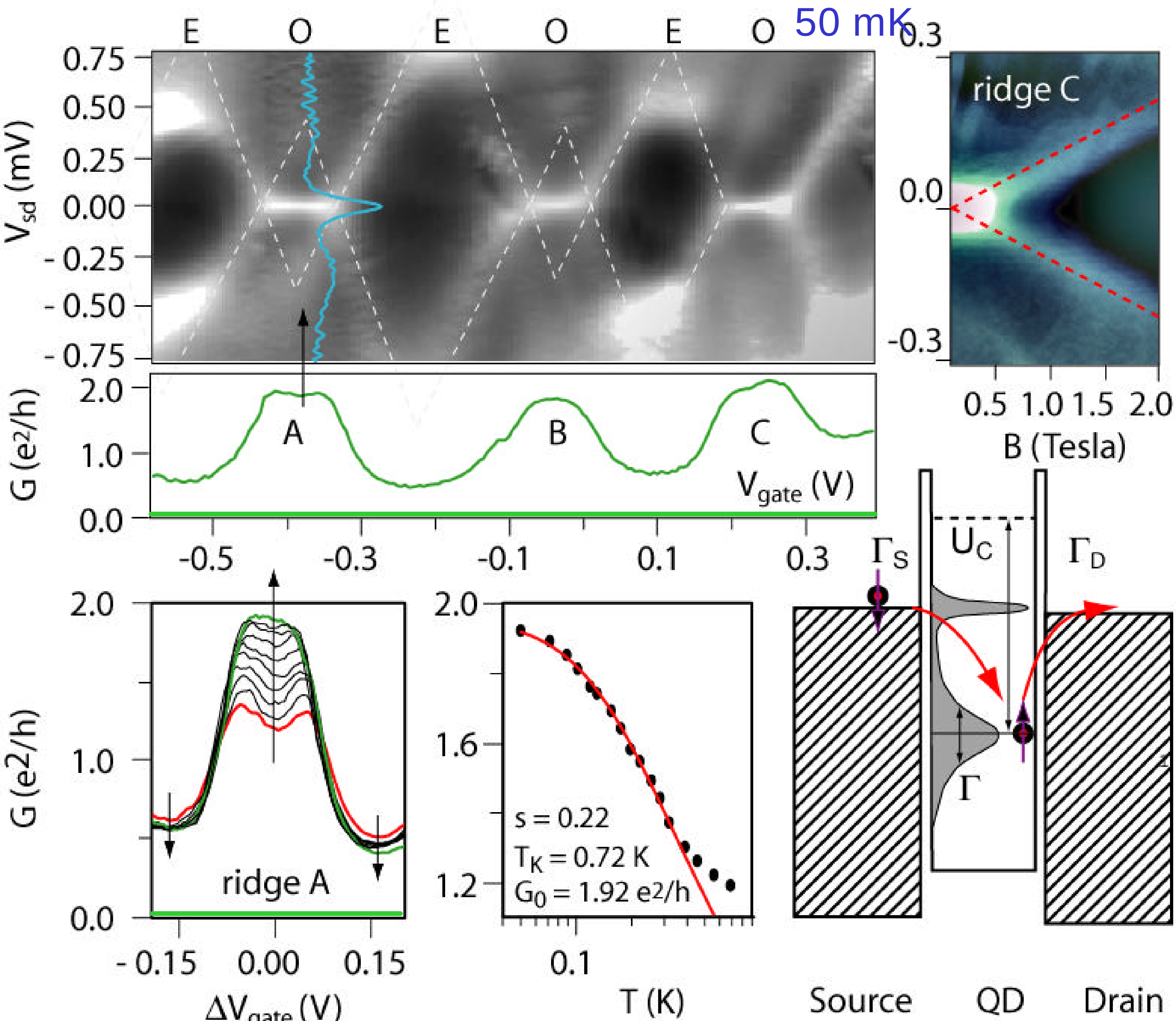




When the number of electrons on the quantum dot is **odd**, spin-flip processes (which screen the spin on the dot) lead to the formation of a narrow resonance in the density-of-states at the Fermi energy of the leads.

This is called the **Kondo effect**

Related work: J.Nygard et al, Nature 408, 342 (2000)



δE ~ 0.6 meV

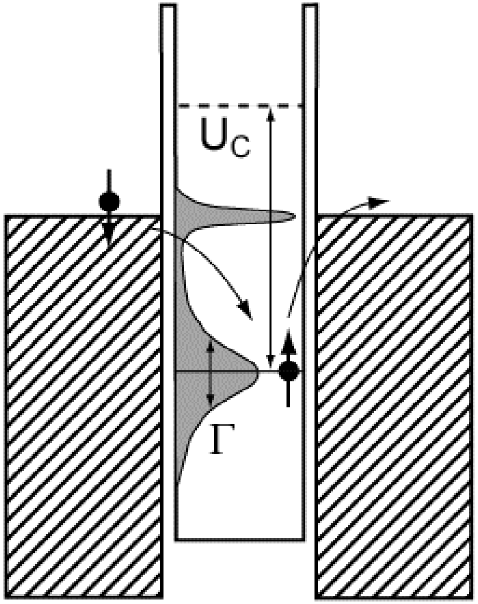
U_C ~ 0.4 meV

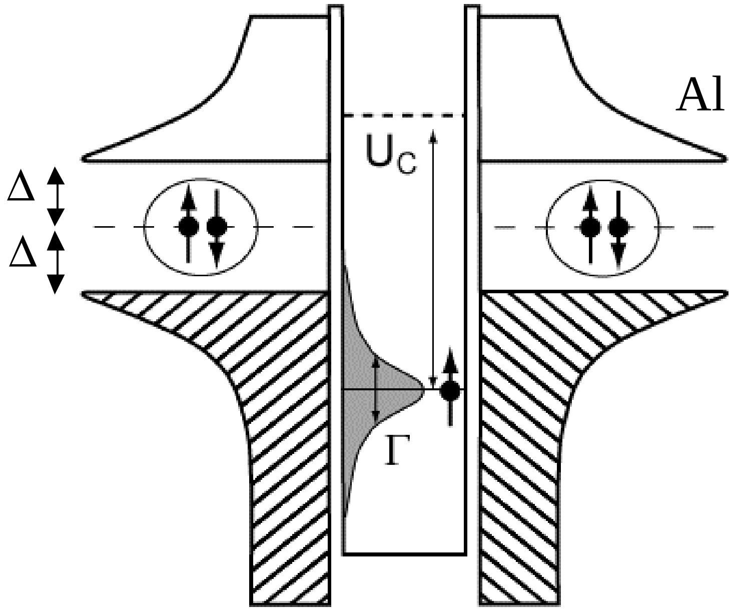
Γ ~ **0.3 meV**

Mark Buitelaar et al. PRL ***89****, 256801 (2002)*

open dot with superconducting leads

Kondo physics + superconductivity



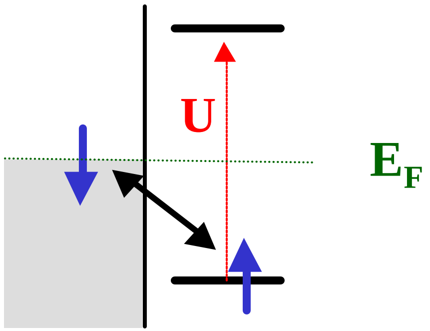


Kondo effect and superconductivity are many-electron effects

- can Kondo and superconductivity coexist or do they exclude each other ?

spin 1/2 Kondo + S-leads

normal case



Kondo effect is the **screening** of the **spin-degree** of the dot spin by exchange with **electrons** from Fermi-reservoirs (the leads)

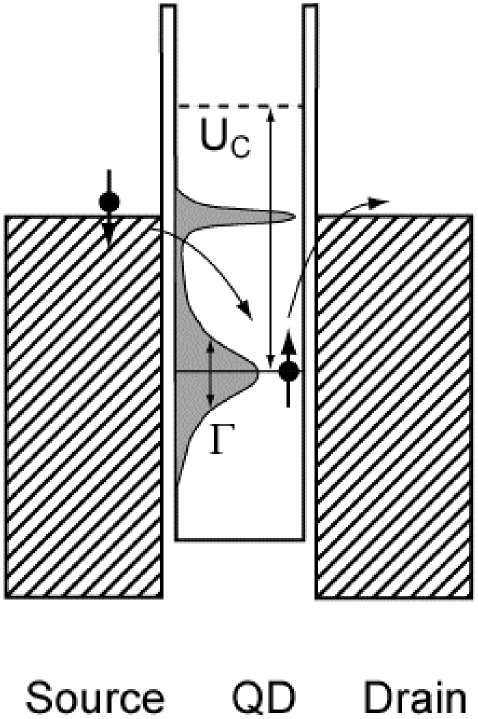
superconducting case

1. a gap opens in the leads

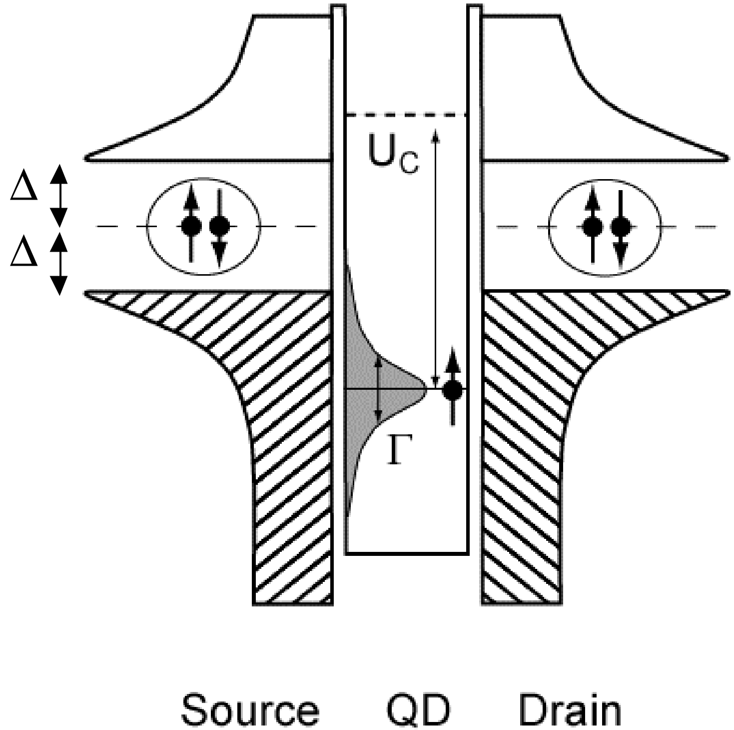
2. Cooper pairs have S=0

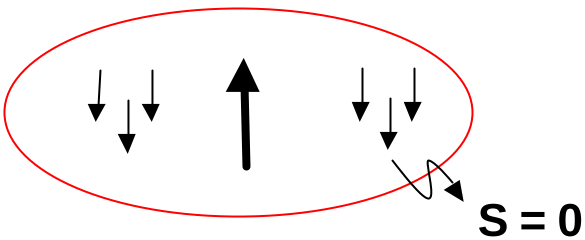
Hence: Kondo effect suppressed, but ....

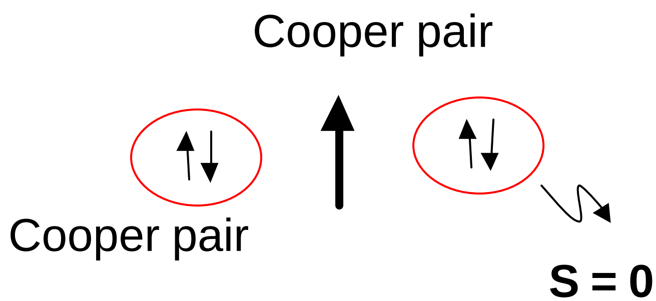
Kondo effect



Superconductivity



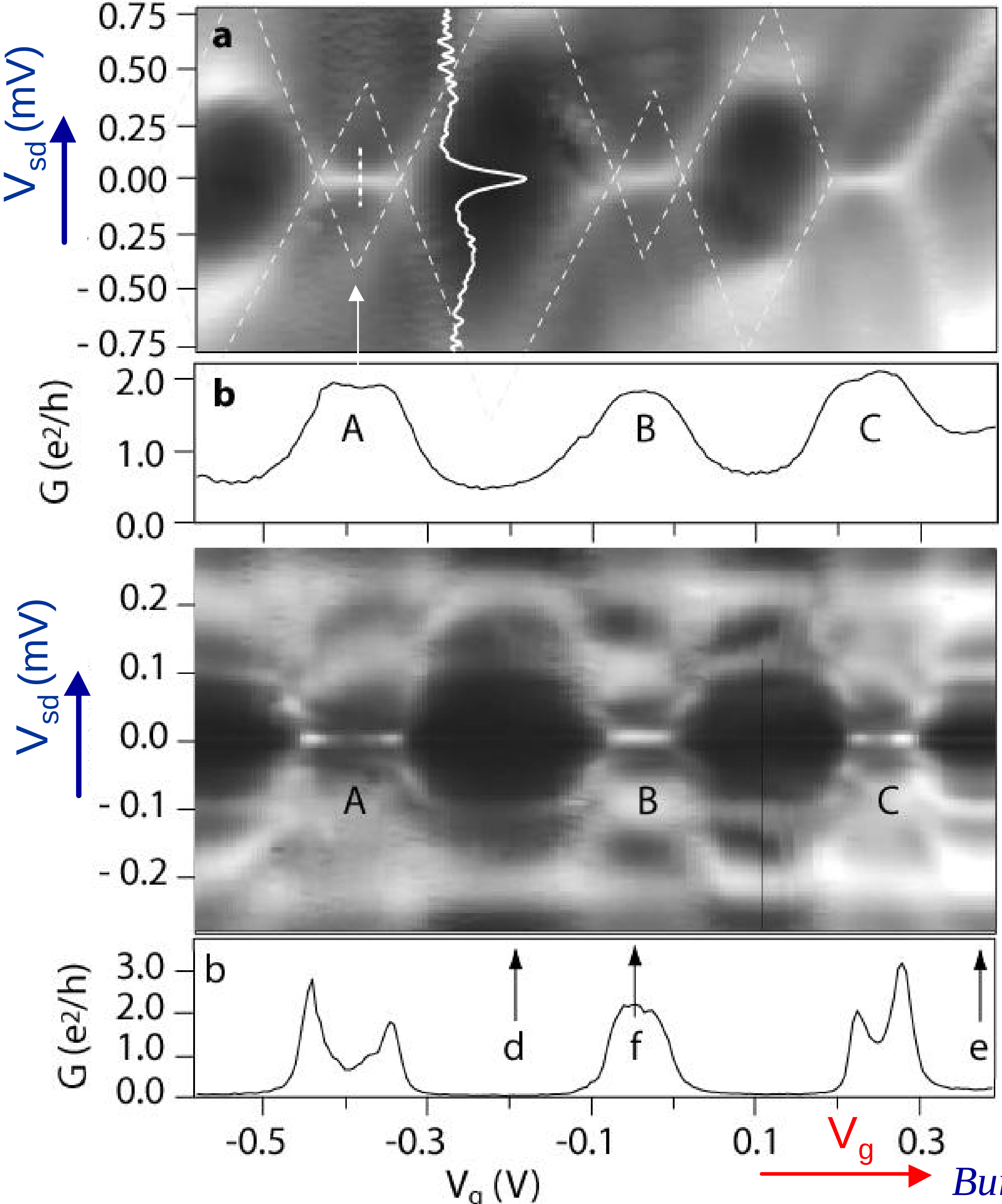




Energy scale : ~ $\mathbf{k_b\ T_K}$

Energy scale : ~ D

A **cross-over** expected at $\mathbf{k_b\ T_K}$ ~ D



Buitelaar et al. PRL 88, 156801 (2002)

N

Kondo ridge **A** : **0.75 K**

Kondo ridge **B** : **1.11 K**

Kondo ridge **C** : **0.96 K**

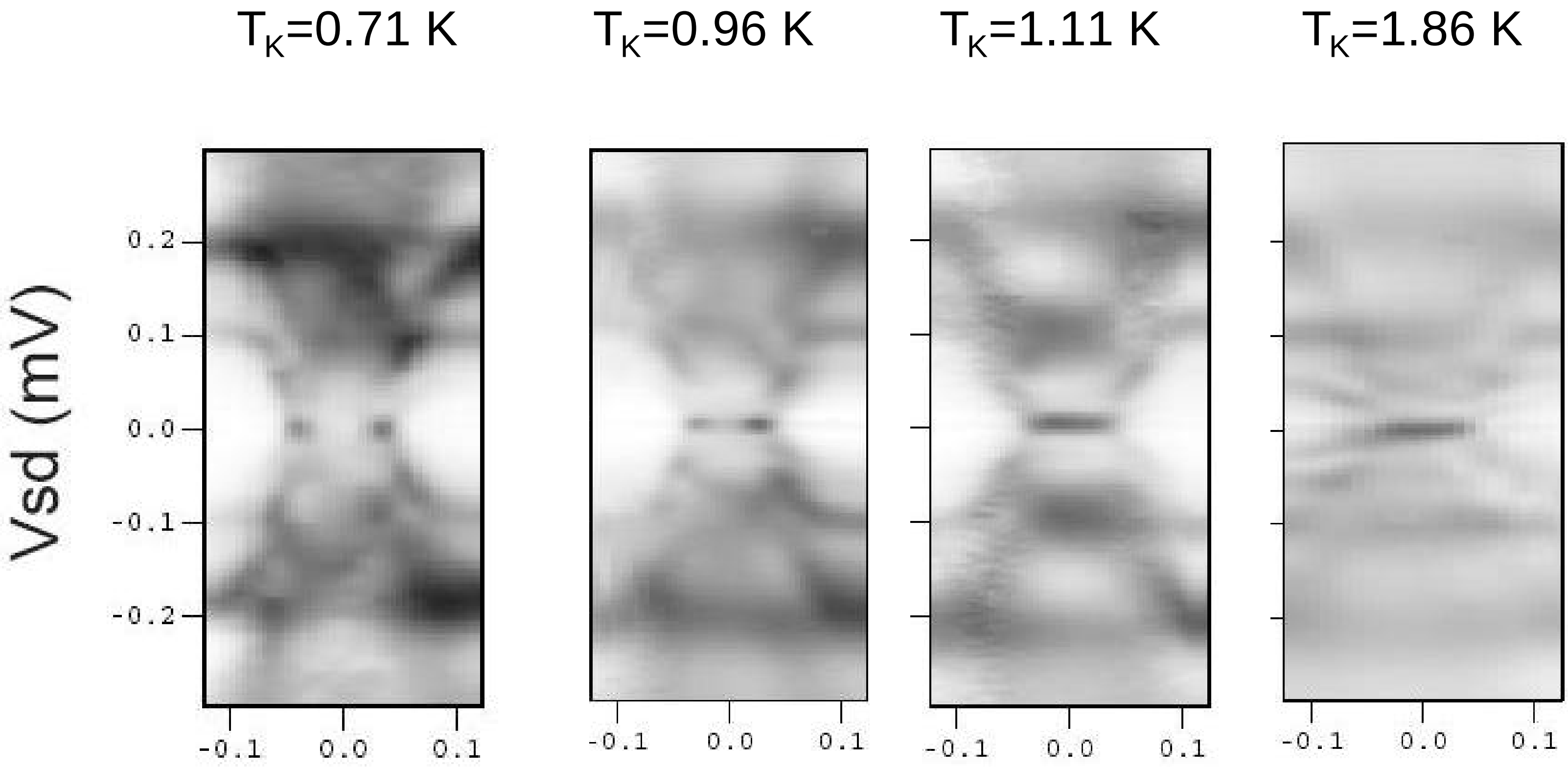
S

A: decreasing conductance

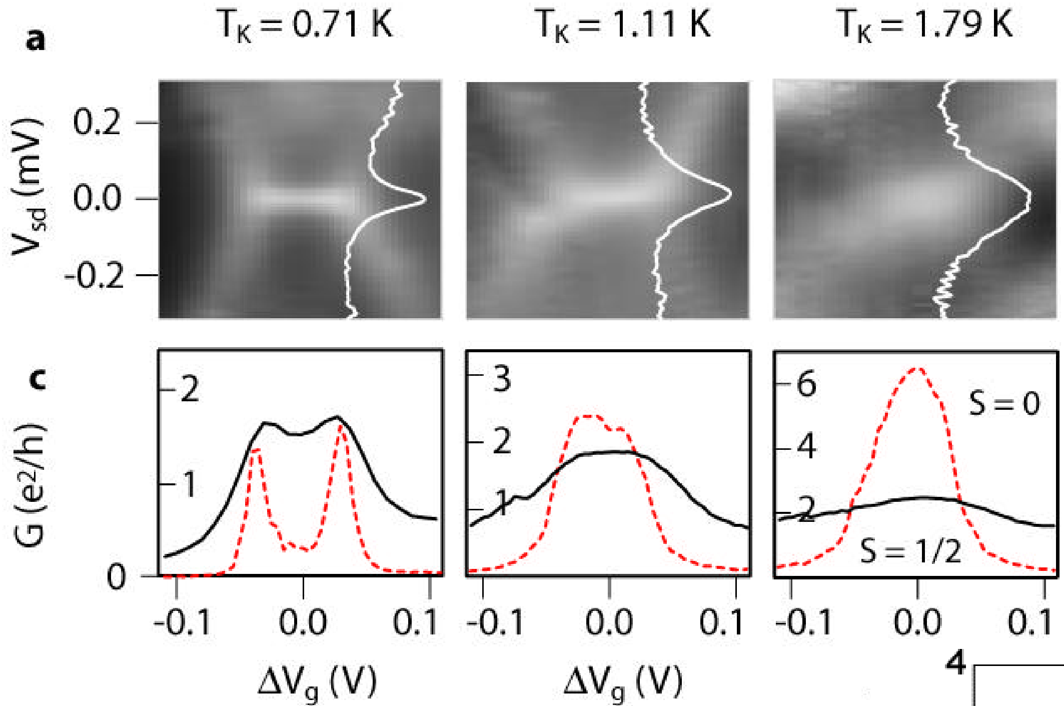
B: increasing conductance

C: decreasing conductance

different Kondo temperature

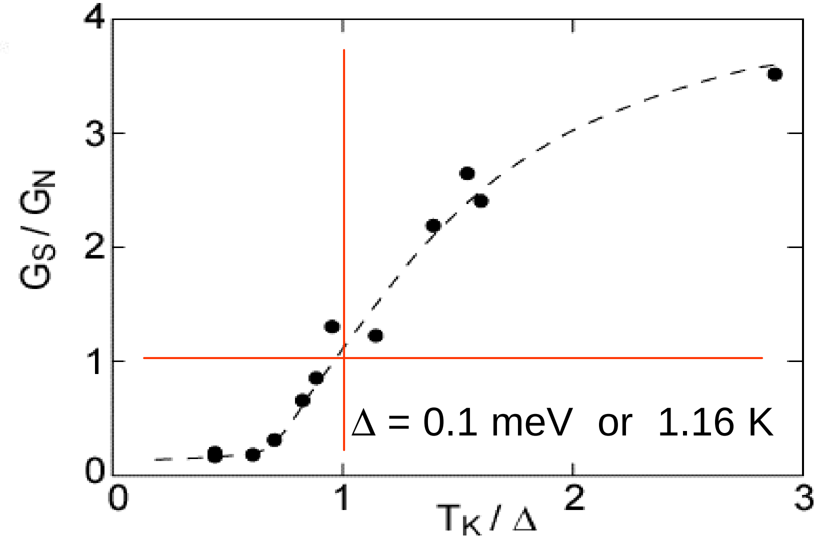


Low T_K → High T_K



normal state

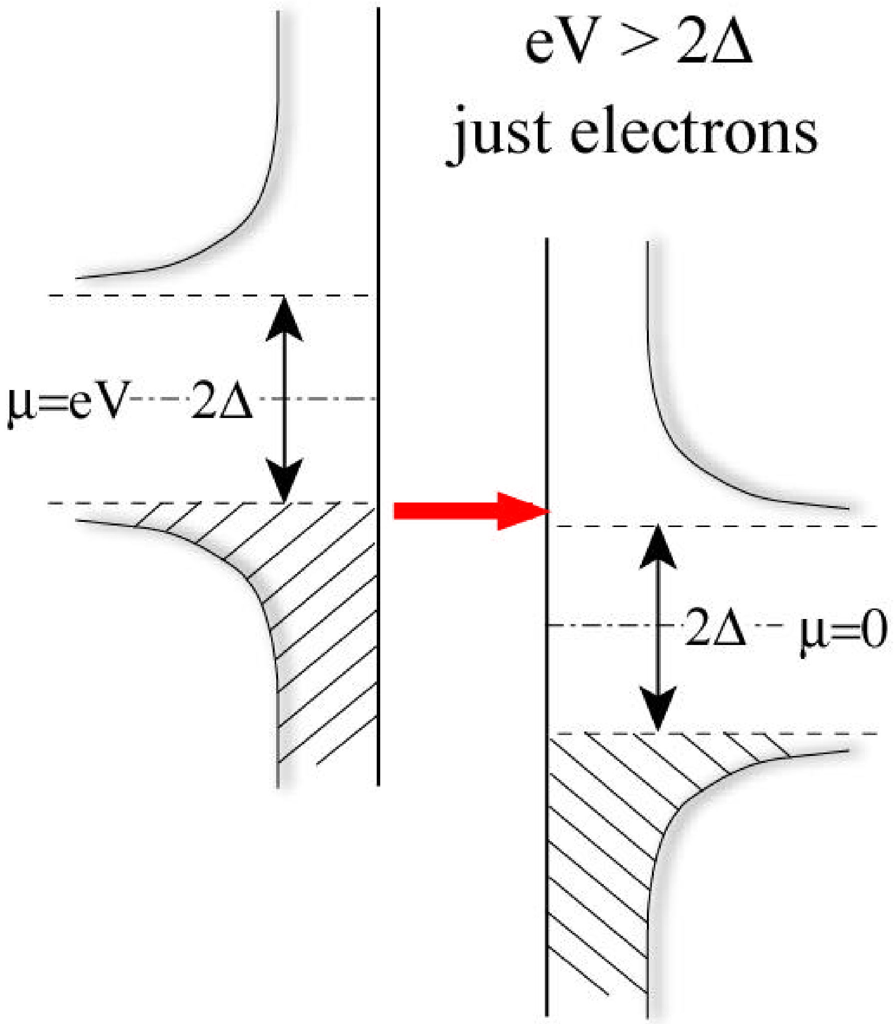
superconducting state



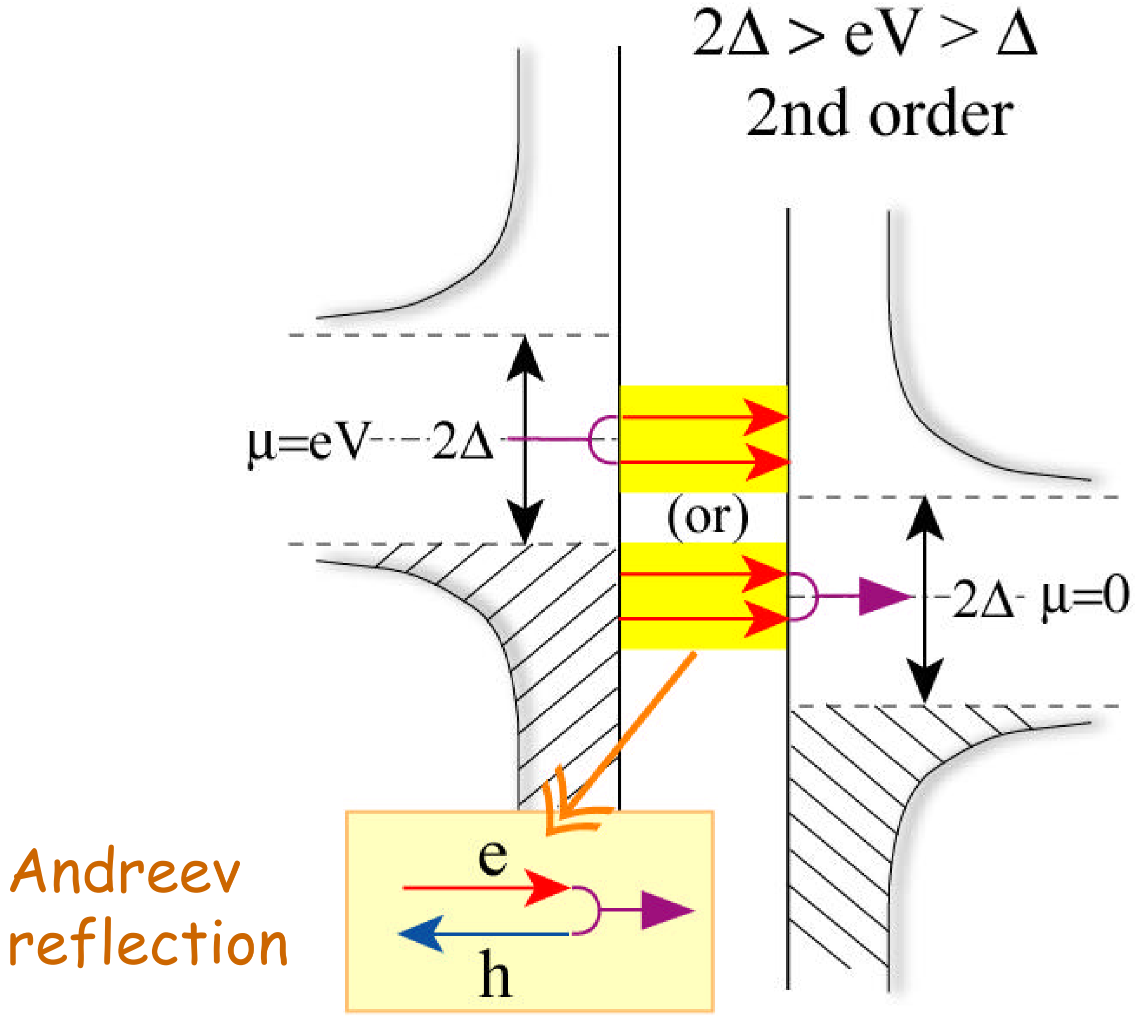
Buitelaar et al. PRL 88, 156801 (2002)

Andreev reflection through a single level

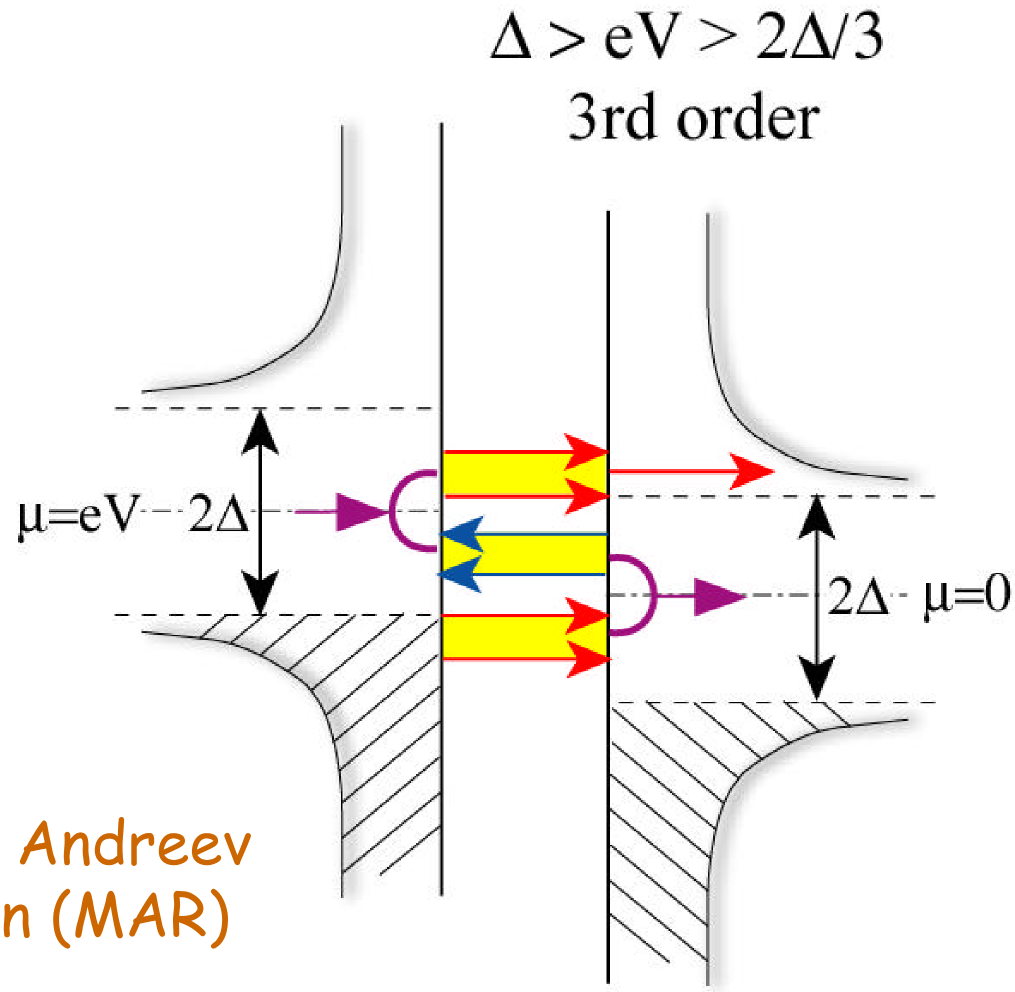
finite bias structure



finite bias structure



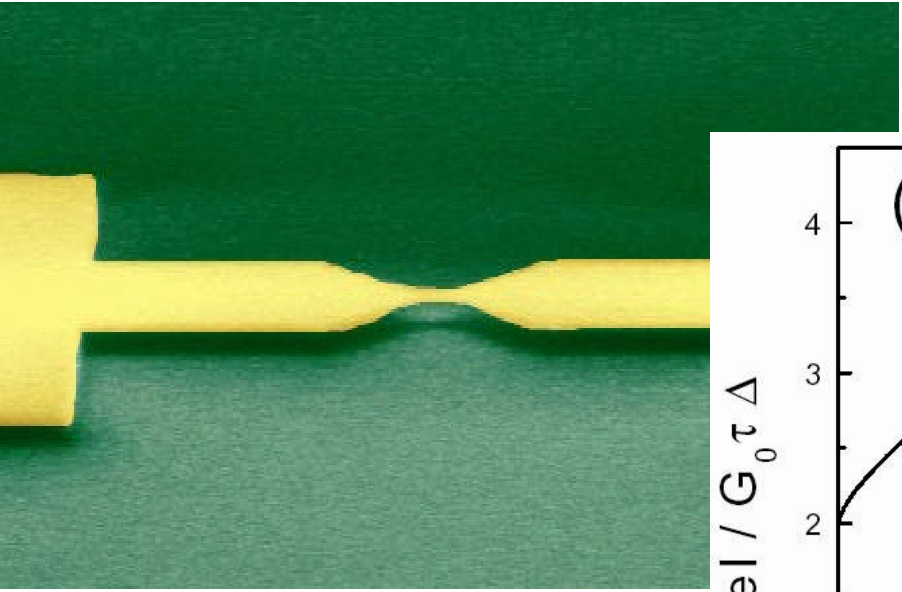
finite bias structure

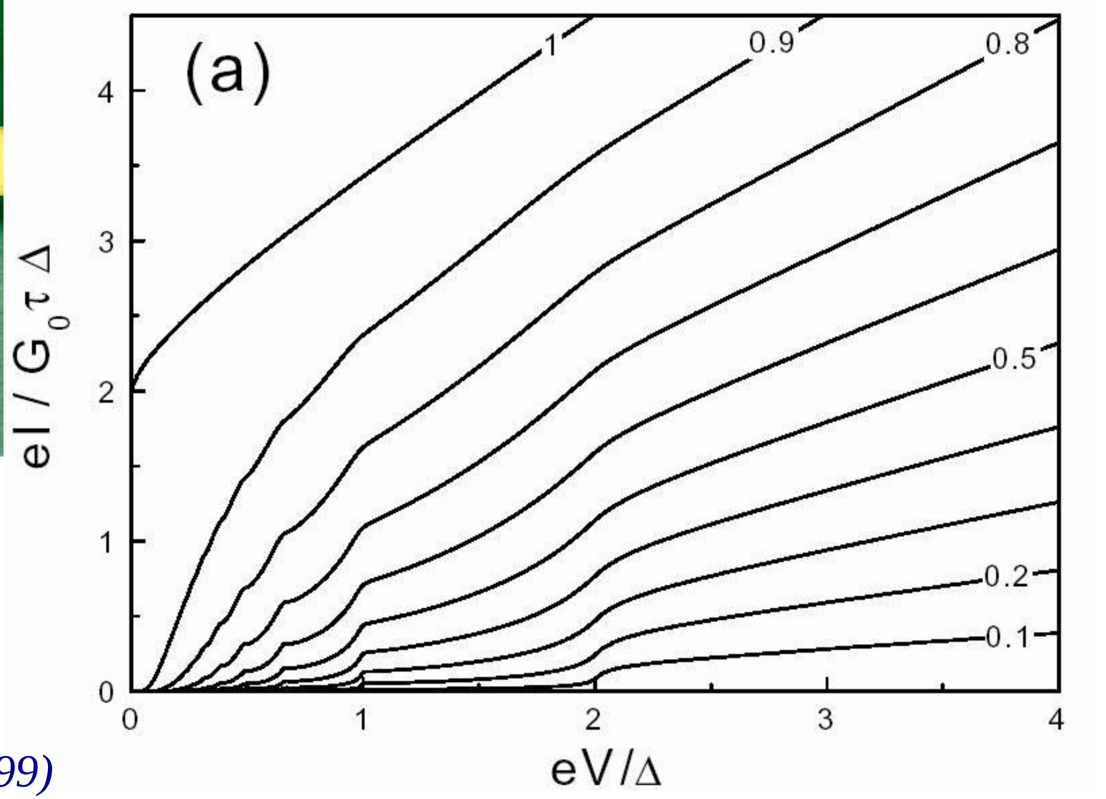


„multiple“ Andreev reflection (MAR)

MAR

- has been explored in **weak links**
- and in **single atom contacts** (break junctions)

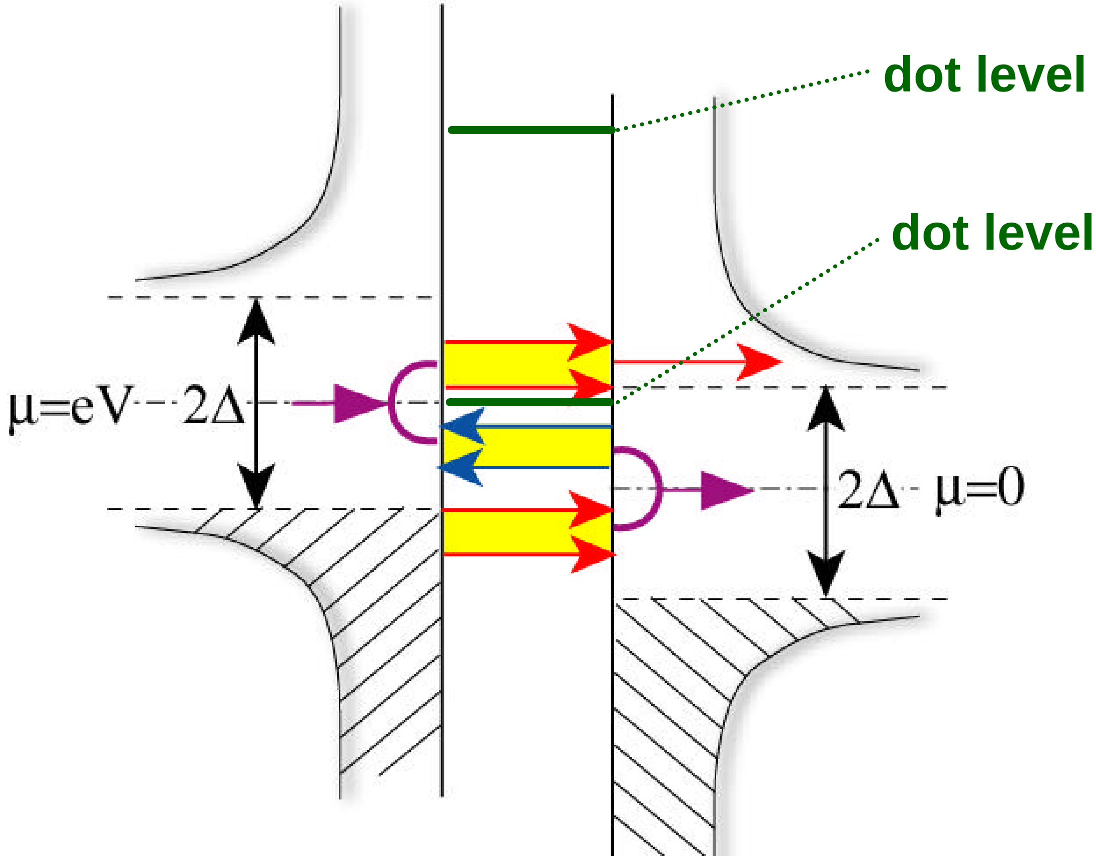




theory: Cuevas et al. PRB 54, 7366 (99)

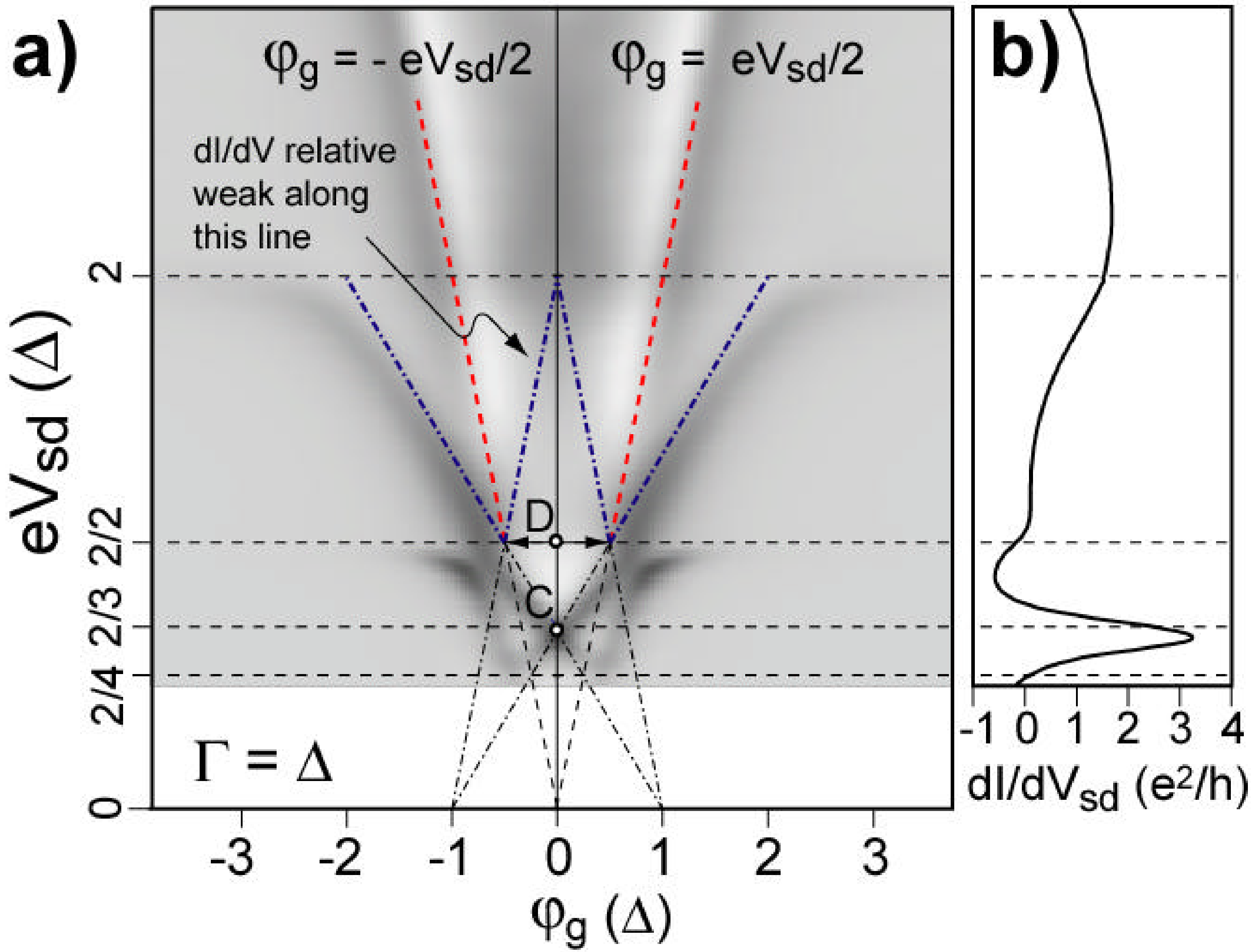
MAR

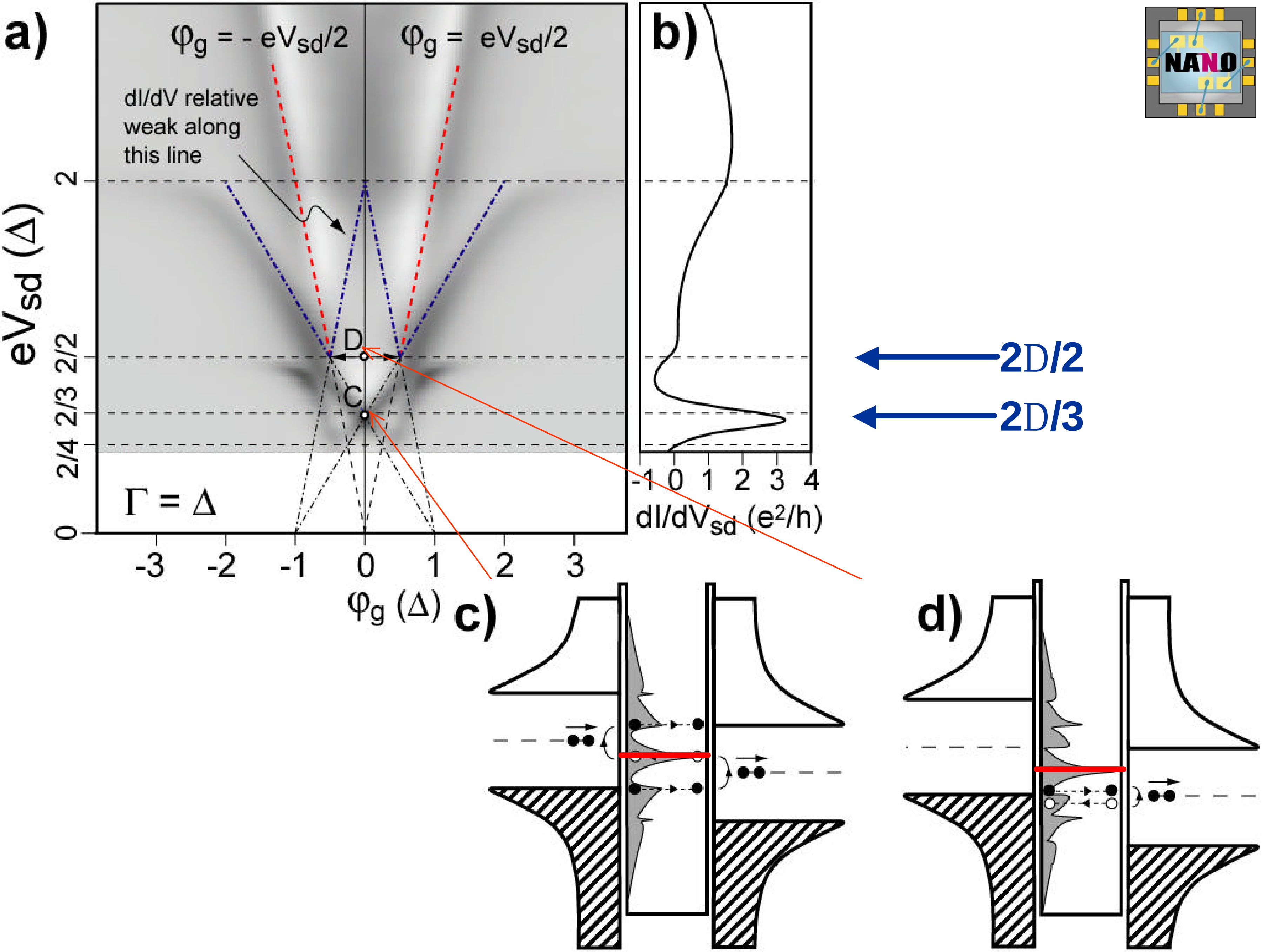
- has been explored in **weak links**
- and in **single atom contacts** (break junctions)
- but **not** in quantum dots

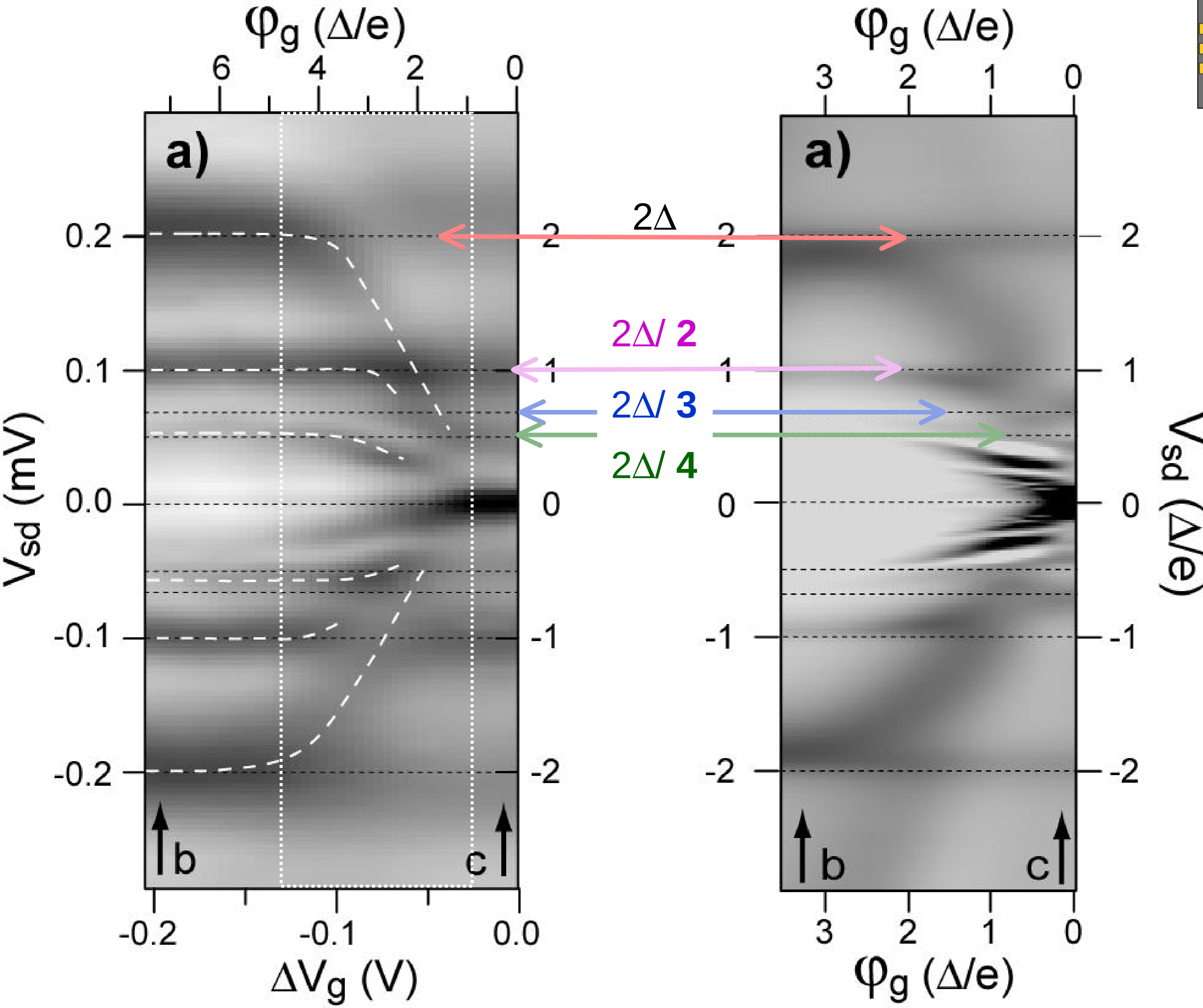


→ G ~ D
(Γ~3Δ)

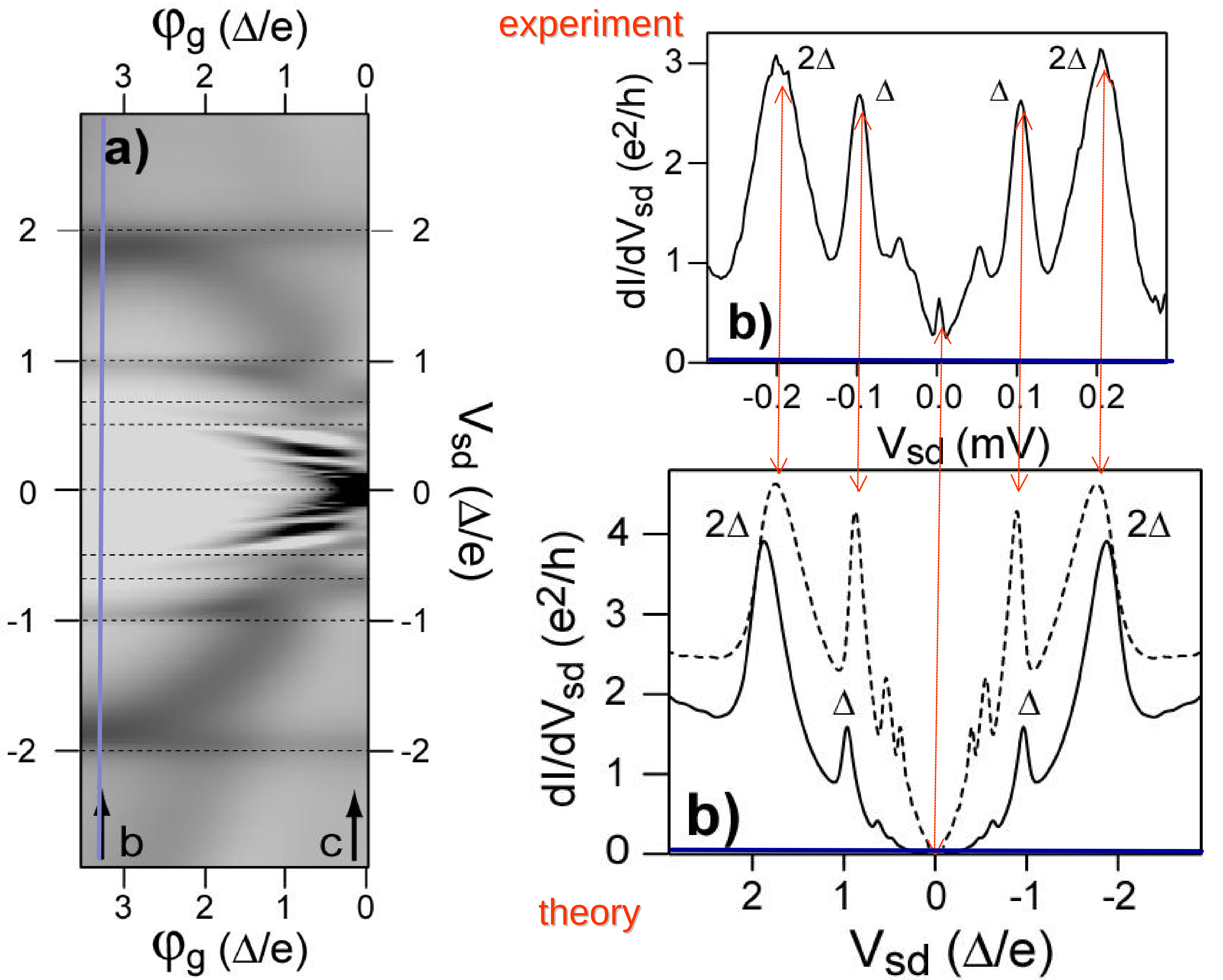
theory (non-interacting)

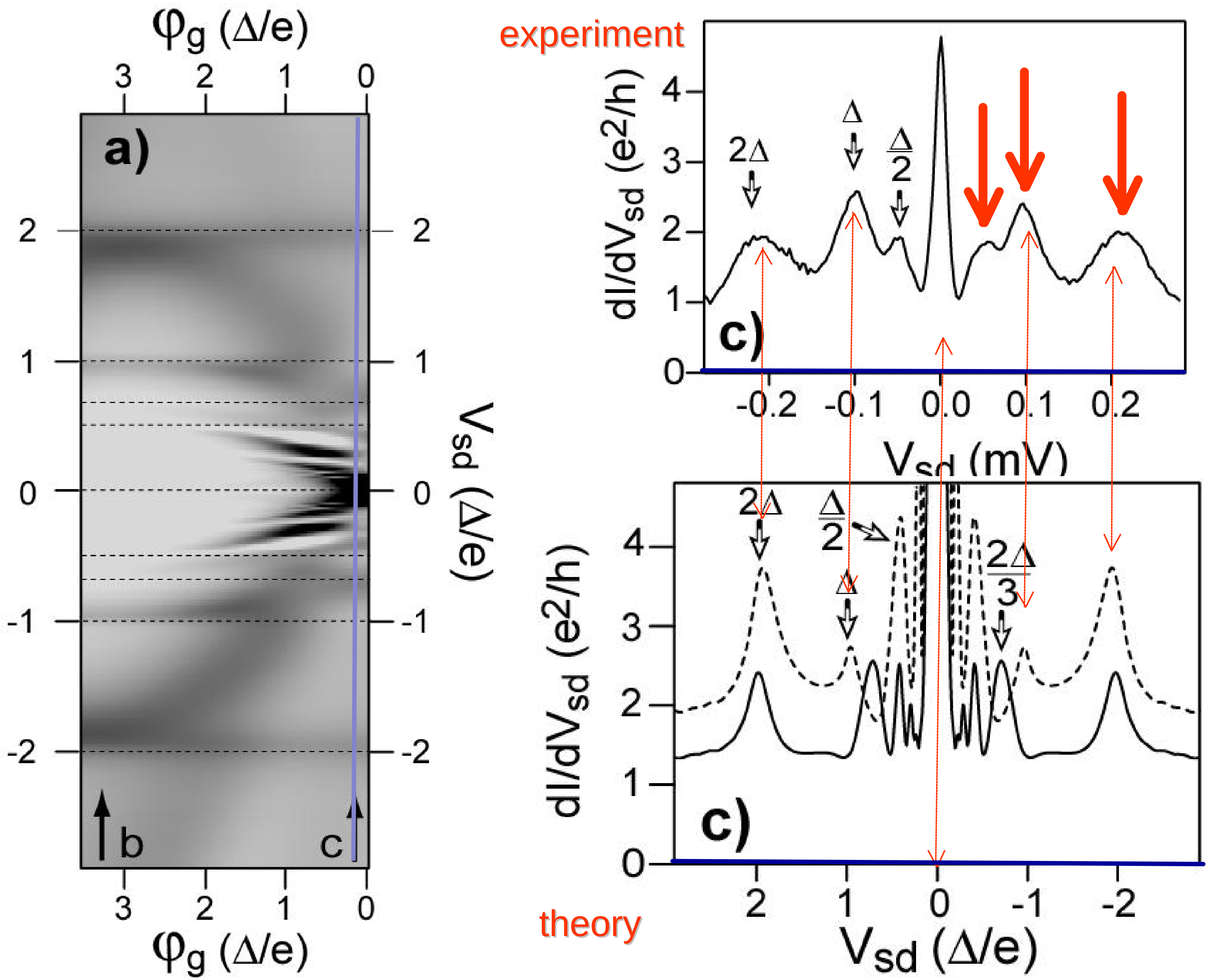



a)
φg = - eVsd/2
φg = eVsd/2
dI/dV relative weak along this line
D
C
Γ = Δ
eVsd (Δ)
2
2/2
2/3
2/4
0
-3 -2 -1 0 1 2 3
φg (Δ)
b)
-1 0 1 2 3 4
dI/dVsd (e2/h)
2D/2
2D/3
c)
d)
NANO



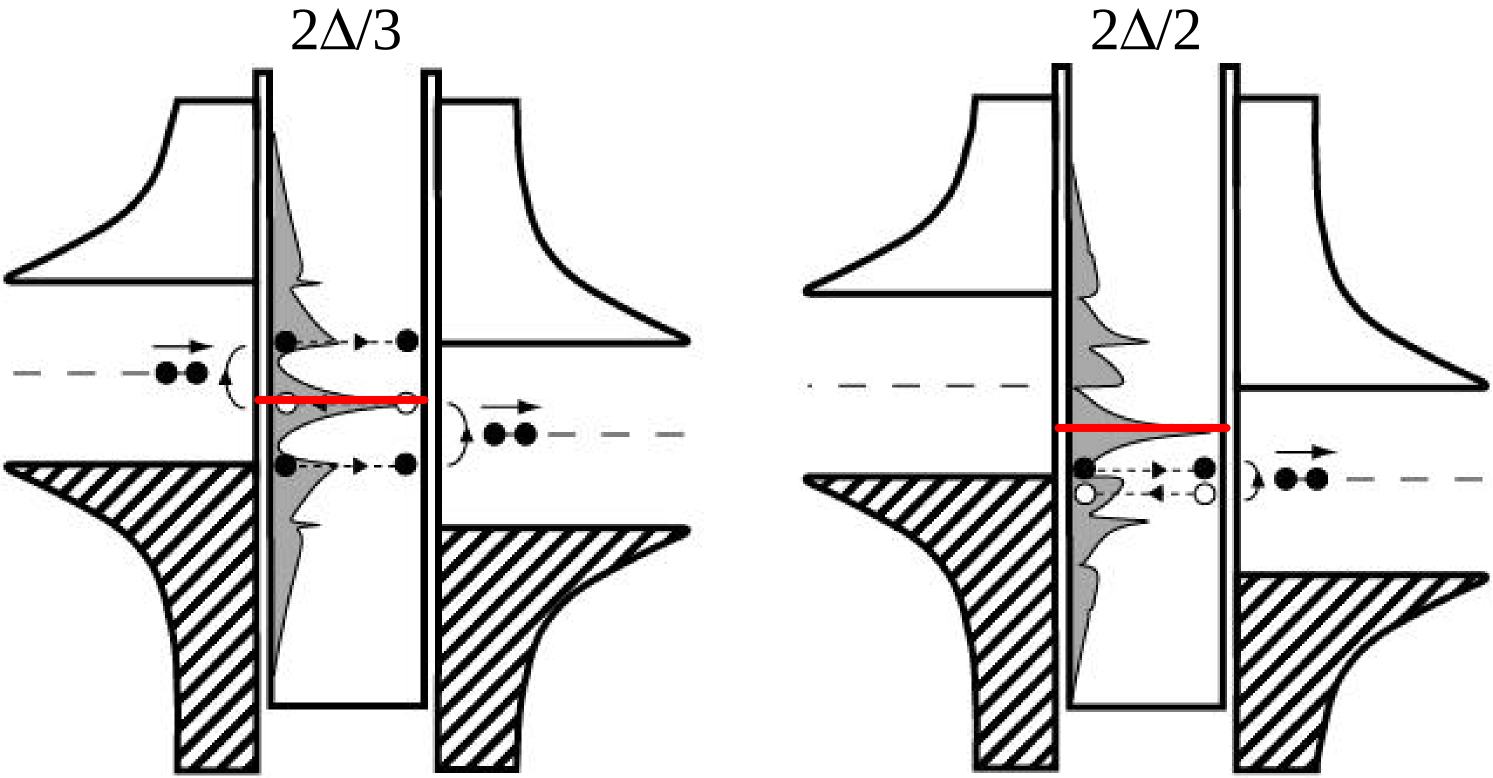
φg (Δ/e)
6
4
2
0
a)
0.2
0.1
0.0
-0.1
-0.2
Vsd (mV)
b
c
-0.2
-0.1
0.0
ΔVg (V)
2Δ
2Δ/ 2
2Δ/ 3
2Δ/ 4
φg (Δ/e)
3
2
1
0
a)
Vsd (Δ/e)
-1
-2
b
c
φg (Δ/e)


experiment
theory
a)
b)
b)
φg (Δ/e)
φg (Δ/e)
Vsd (Δ/e)
dI/dVsd (e2/h)
dI/dVsd (e2/h)
Vsd (mV)
Vsd (Δ/e)
2Δ
Δ
Δ
2Δ
2Δ
Δ
Δ
2Δ
b
c



experiment
theory
a)
b
c
c)
c)
φg (Δ/e)
Vsd (Δ/e)
Vsd (mV)
dI/dVsd (e2/h)
2Δ
Δ
Δ/2
2Δ/3

explanation ?



- BCD-DOS modified
- Kondo

Conclusions

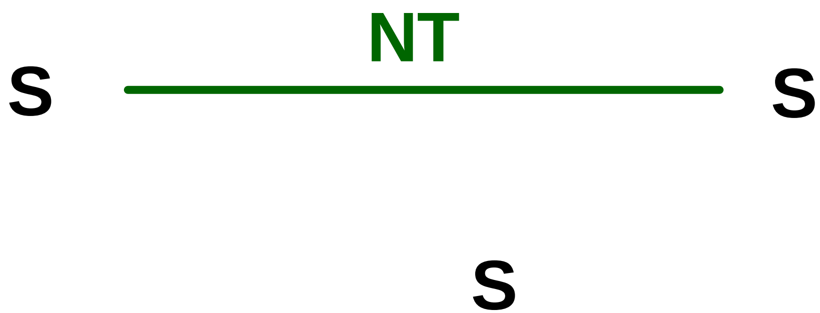
nanotubes serve as a **model system**
to study physics

- Kondo physics (co-tunneling)
- Interplay between Kondo physics & superconductivity
- (superconducting) correlations through a single level

www.unibas.ch/phys-meso group Web-page

www.nccr-nano.org NCCR on Nanoscience

Outlook



Orsay group: reported **enhanced** $I_C R_N$ product

A. Yu. Kasumov et al.

NT **entangler**

T. Martin ...
M. Fisher ...
D. Loss ...

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