laboratoire pierre aigrain
électronique et photonique quantiques

Mesoscopic Quantum Electrodynamics with carbon nanotubes

LPA – Ecole Normale Supérieure – Paris

Experiments:

Laure Bruhat
T. Cubaynes
J.J. Viennot
M.C. Dartiailh
M.M. Desjardins
T. Kontos

Theory:

A. Cottet
B. Douçot

What is mesoscopic QED ?

Mesoscopic quantum electrodynamics

=

Cavity quantum electrodynamics with **mesoscopic circuits**

Here : Quantum dot circuits

Cavity QED

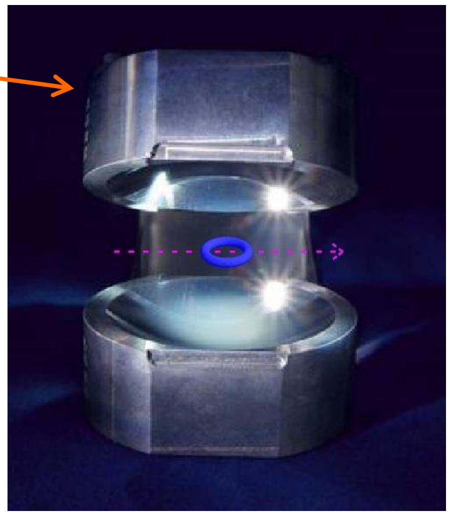
Quantum transport

Cavity Quantum ElectroDynamics (QED): from optical systems to superconducting chips

Atomic Cavity QED

High-quality mirror cavity

Rydberg atom

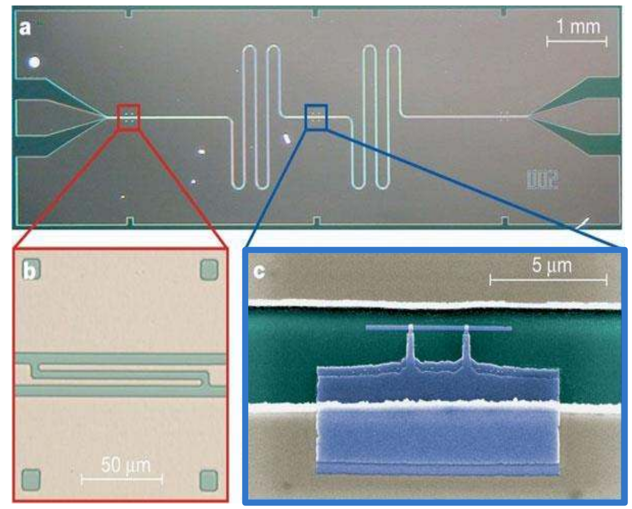


M. Brune et al., PRL 76, 1800 (1996)

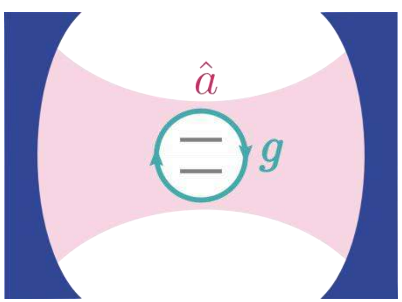
Circuit QED

Coplanar waveguide cavity

Super--conducting qubit



A. Wallraff et, Nature 431, 162 (2004)



Jaynes-Cummings Hamiltonian

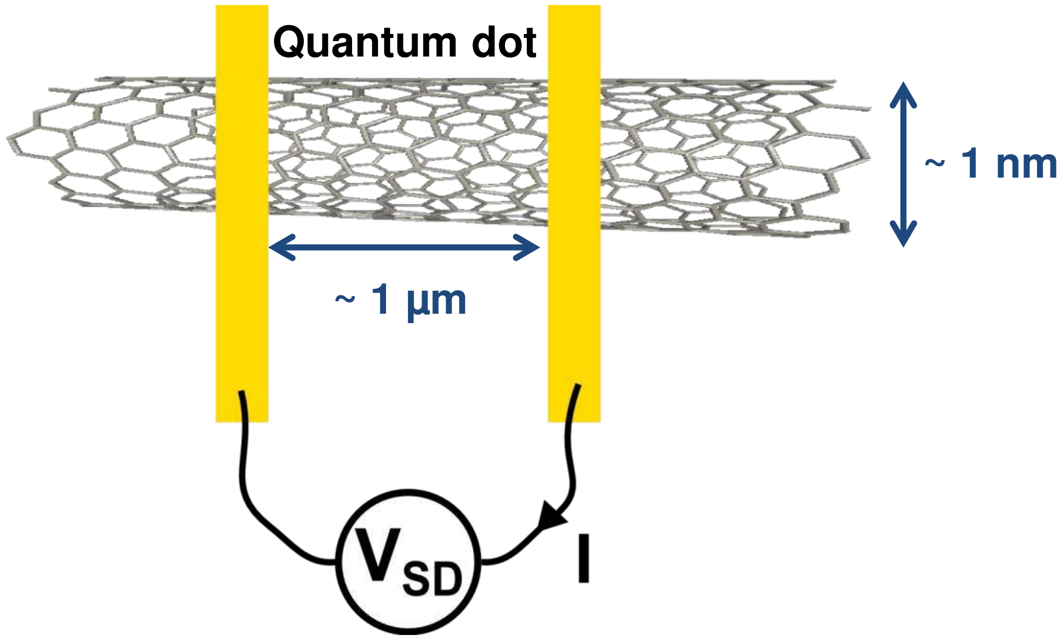
$$\hat{H} = -\frac{\hbar\omega_s}{2}\hat{\sigma}_z + \hbar\omega_{cav}\hat{a}^\dagger\hat{a} + g\hat{\sigma}_x(\hat{a}^\dagger + \hat{a})$$

Two level system

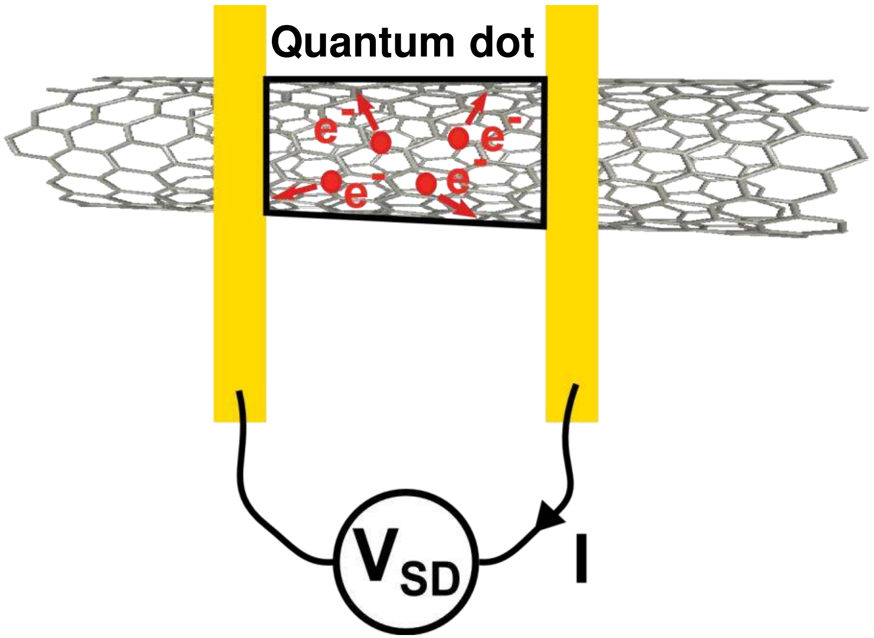
Cavity photons

Transverse coupling

Carbon nanotube quantum dot circuits



Carbon nanotube quantum dot circuits

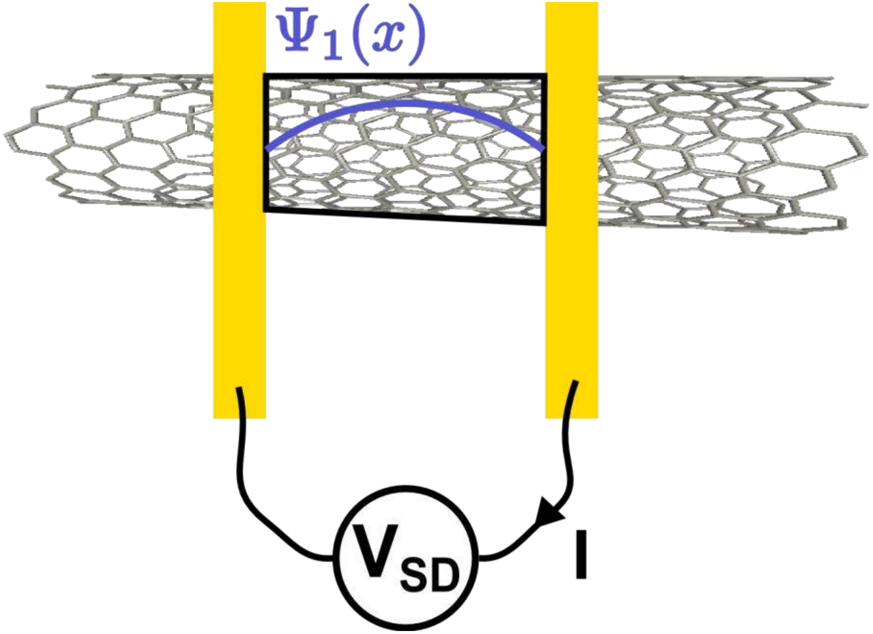


Repulsion between electrons

U : Coulomb energy

Typical range 1-10 meV

Carbon nanotube quantum dot circuits



Repulsion between electrons
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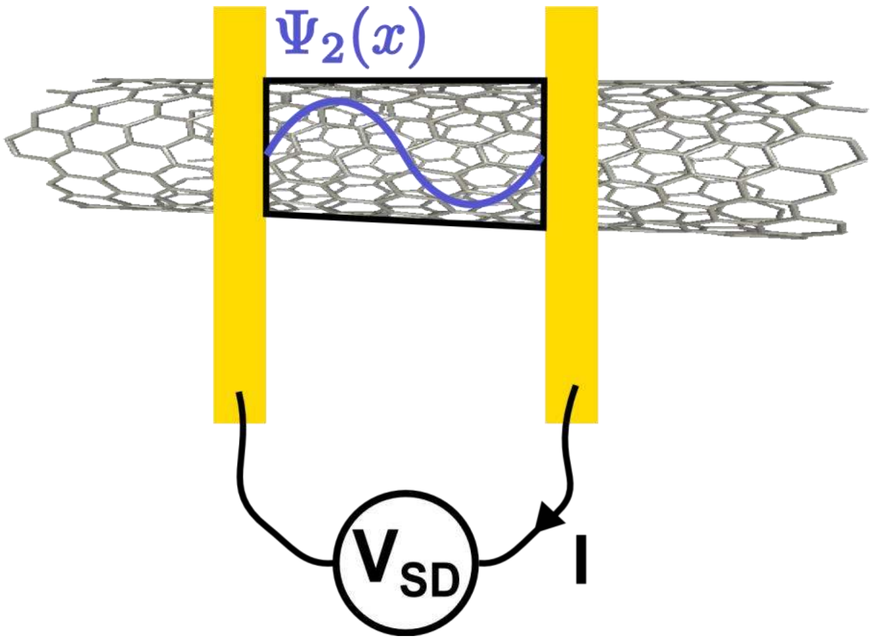
Confinement
ΔE: level spacing
Typically ~ 1 meV

Carbon nanotube quantum dot circuits



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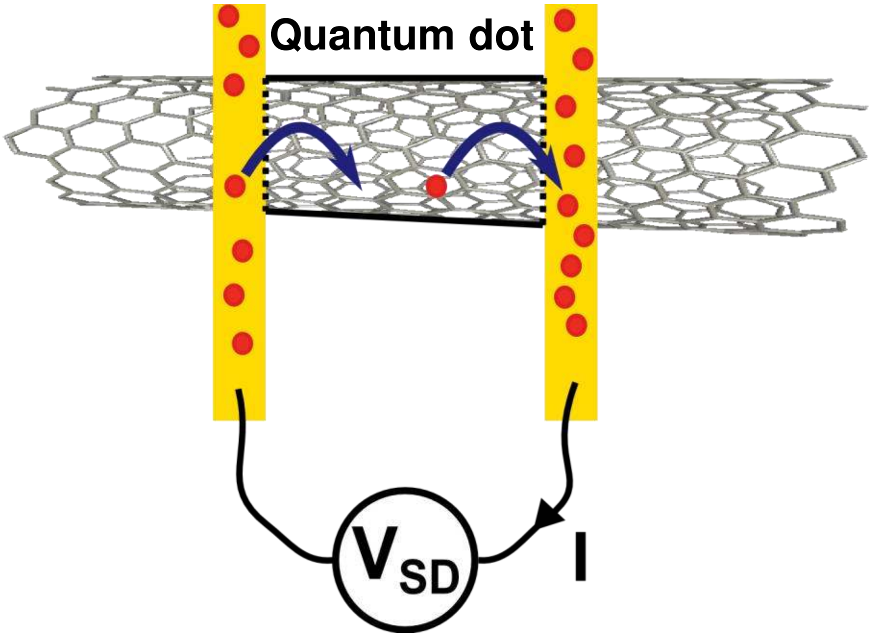

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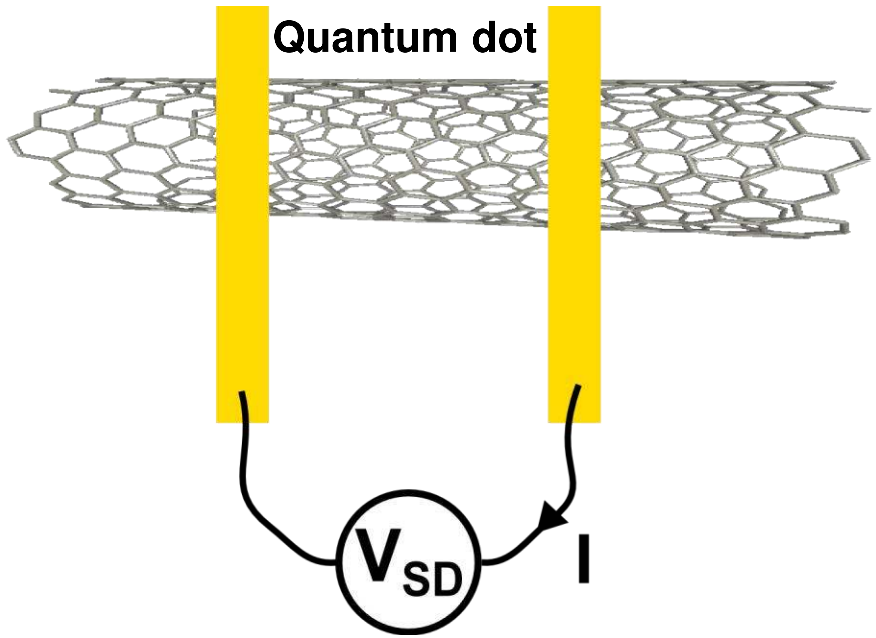
Electron transfer dot-contacts
Γ: tunnelling energy
Typical range μeV-meV

Carbon nanotube quantum dot circuits



3 characteristic energy scales + **thermal energy k_BT**

Room temperature ≈20°C ~ 25 meV

Repulsion between electrons
U : Coulomb energy
Typical range 1-10 meV

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Typically ~ 1 meV

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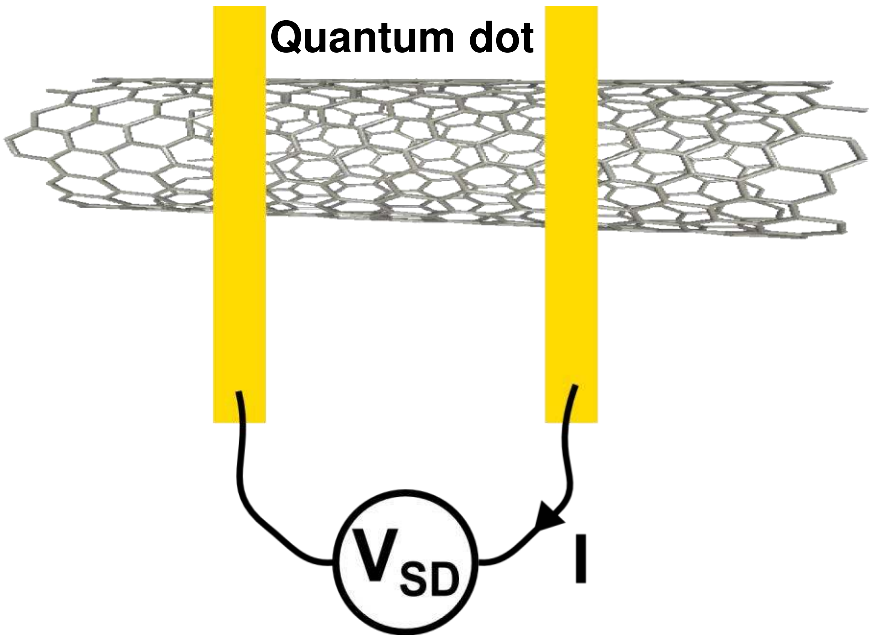

3 characteristic energy scales + **thermal energy k_BT**

50mK≈4 µeV !

Repulsion between electrons
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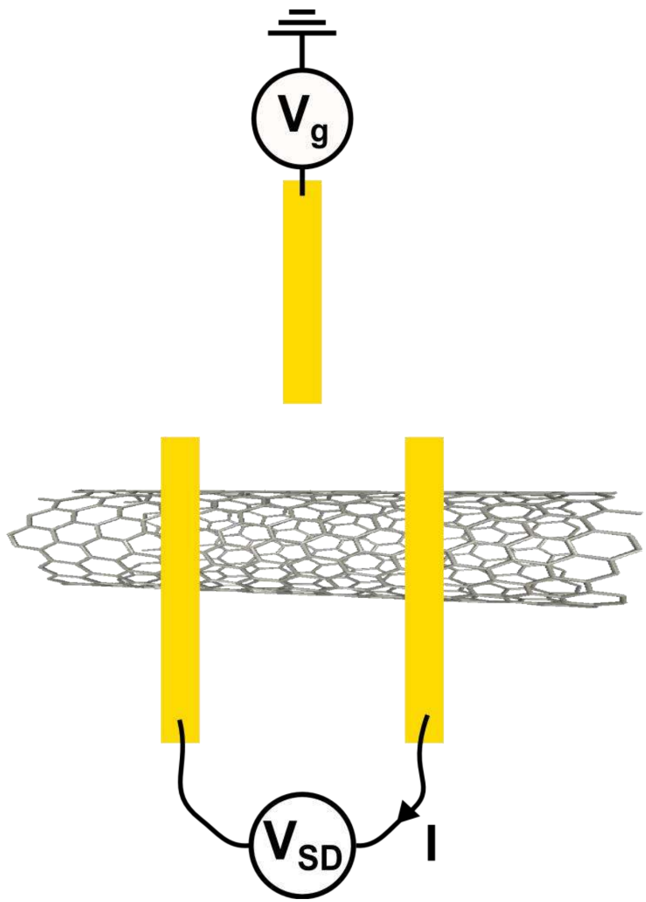
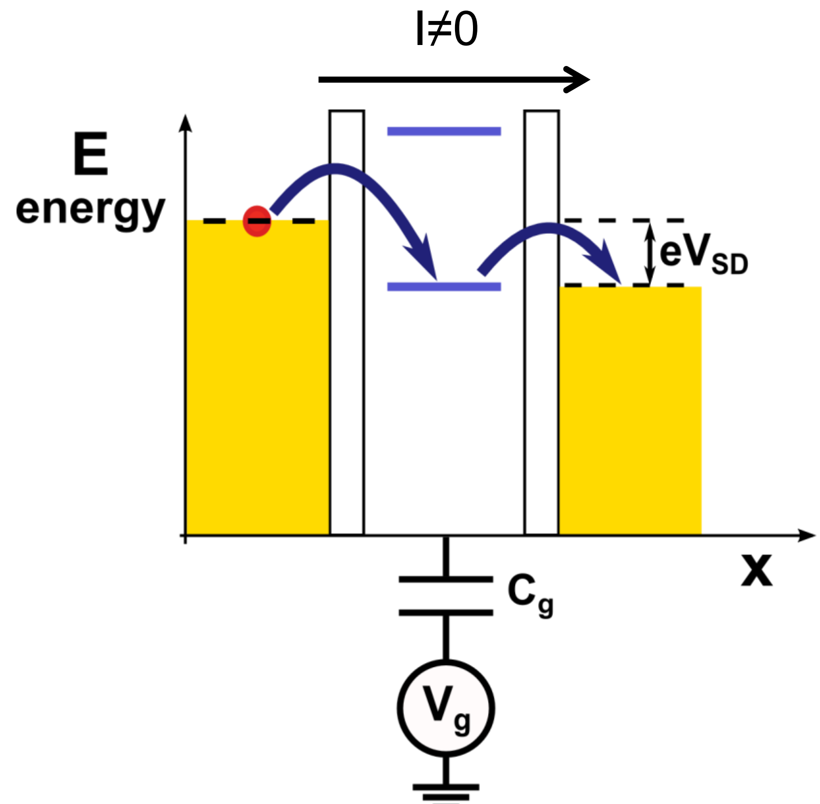
Carbon nanotube quantum dot circuits



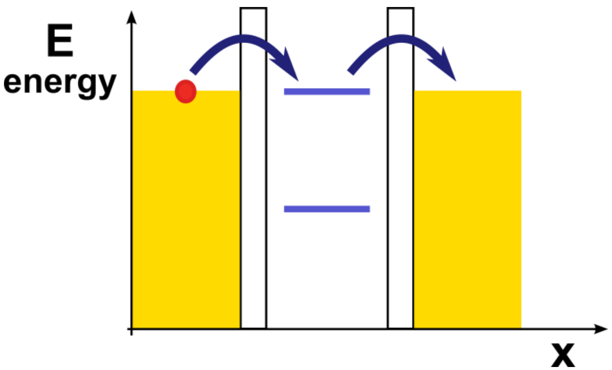
Circuit energy profile



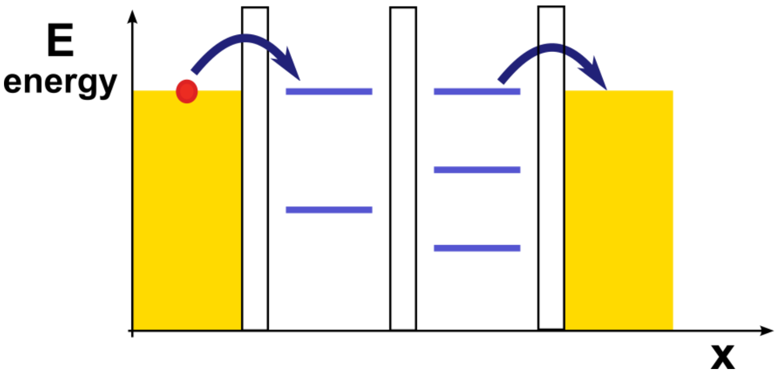
2 electrical knobs : gate voltage V_g and **bias voltage V_{SD}**

From single dot to multiple dot circuits

Nanofabrication allows to complexify the **circuit geometry**.



Single dot



Double dot

Triple dot
Quadruple dot…

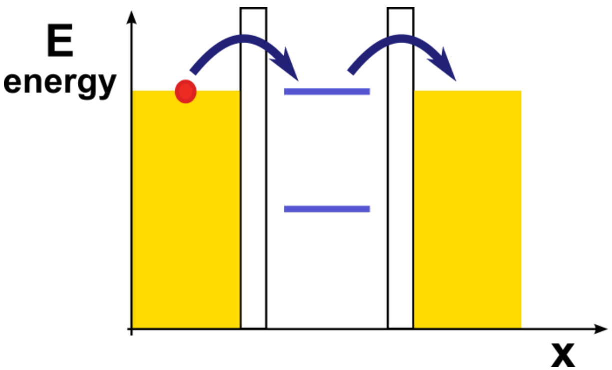
What can we do with these circuits ?

Study **quantum transport**

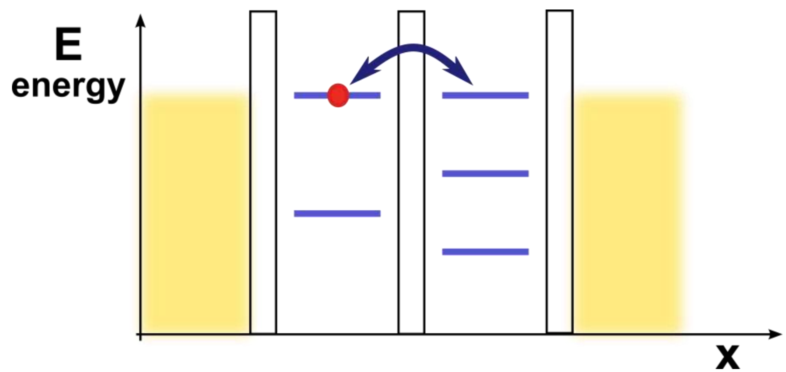
- Involves coupling to **continua of states.**
- Possible **many-body physics**

From single dot to multiple dot circuits

Nanofabrication allows to complexify the **circuit geometry**.



Single dot



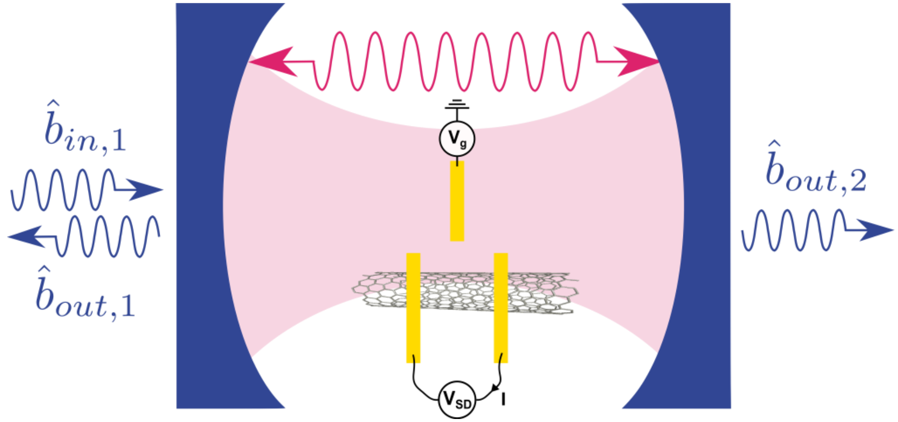
Double dot

Triple dot
Quadruple dot…

Study **quantum transport**
- Involves coupling to **continua of states.**
- Possible **many-body physics**

Study **atomic-like physics**
- Internal dynamics of artificial molecules « isolated » from the contacts
- Possible to make qubits for **quantum information**

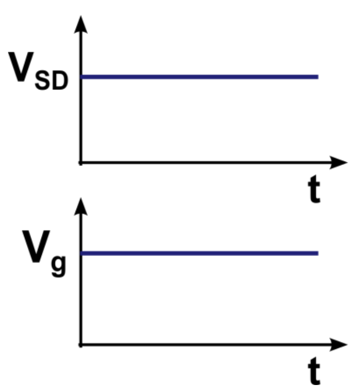
Interests of mesoscopic QED



WHY ???

✓ DC transport

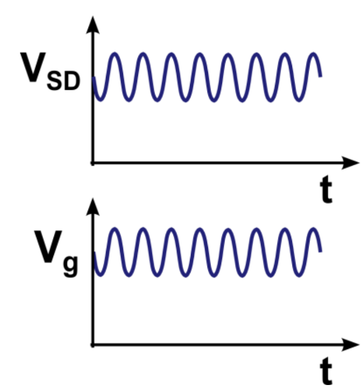
Constant voltages



Many experiments for more than 20 years

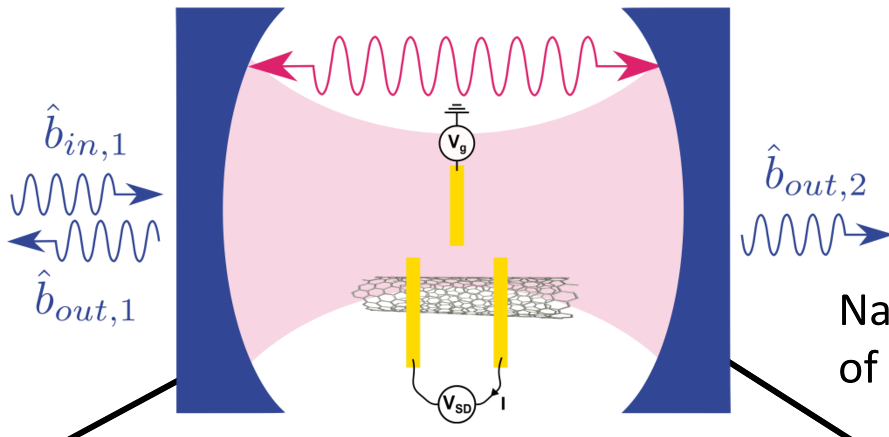
AC transport ?

Time-dependent voltages



Fewer experiments

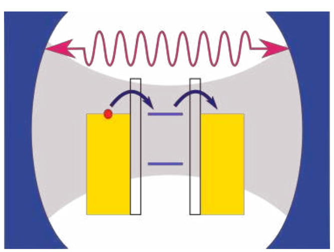
Interests of mesoscopic QED



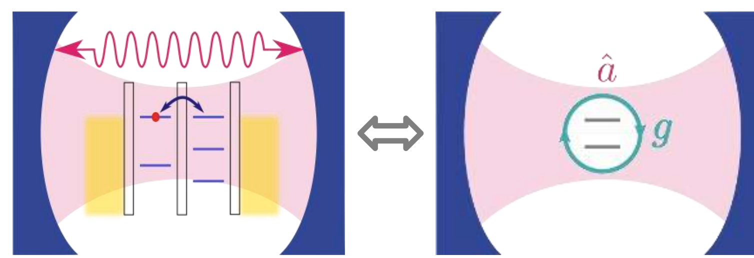
Natural transfer
of cavity QED tools

WHY ???

hf$_c$~ typical energy scale in the circuit



$$hf \sim \Gamma$$



$$hf \sim \hbar\Omega$$

Open quantum dots :

Study quantum transport in a different way ?

Closed quantum dots:

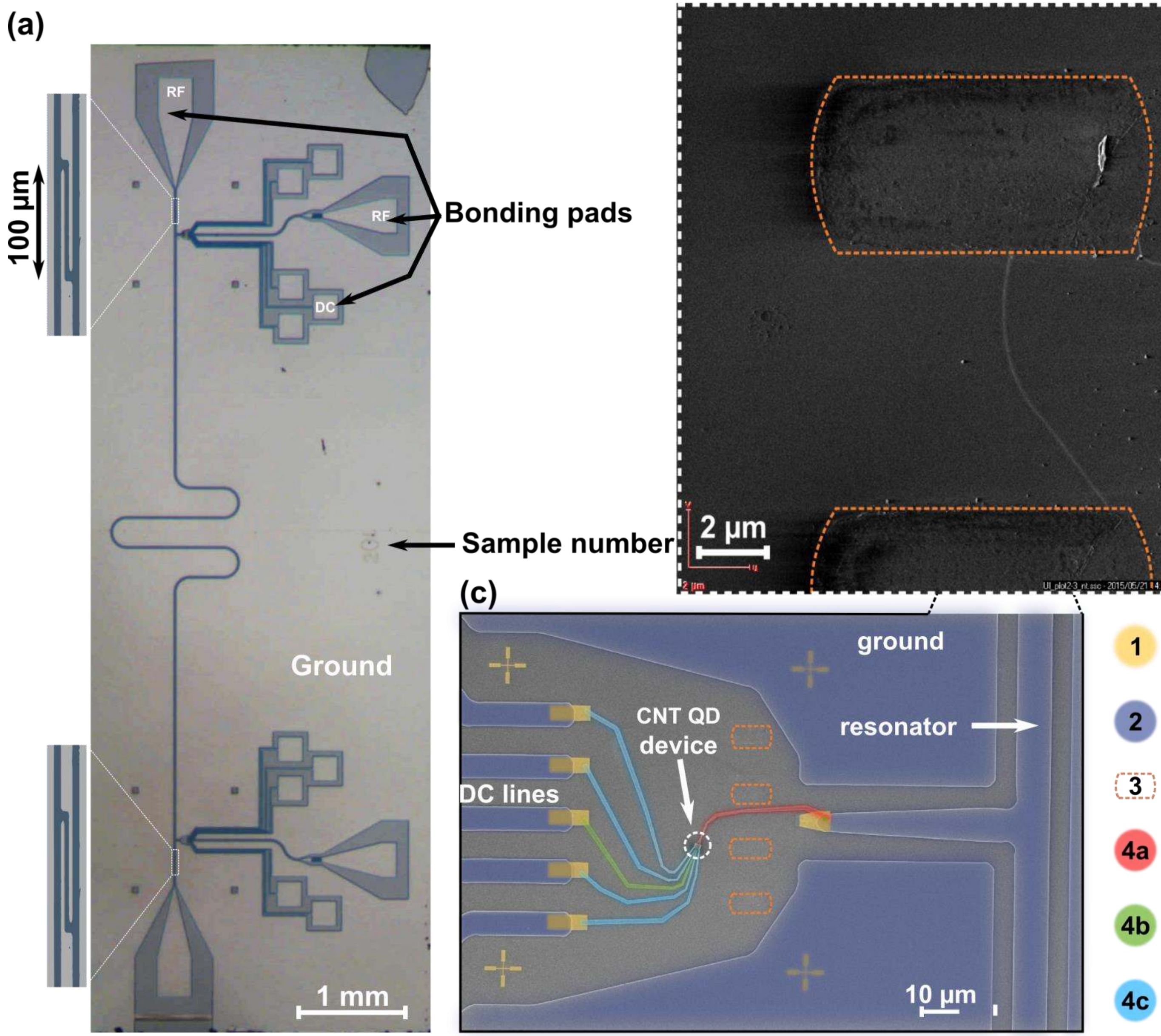
Probe internal quantum states of a mesoscopic circuit ?

See Exp I : S-dot-N in cavity

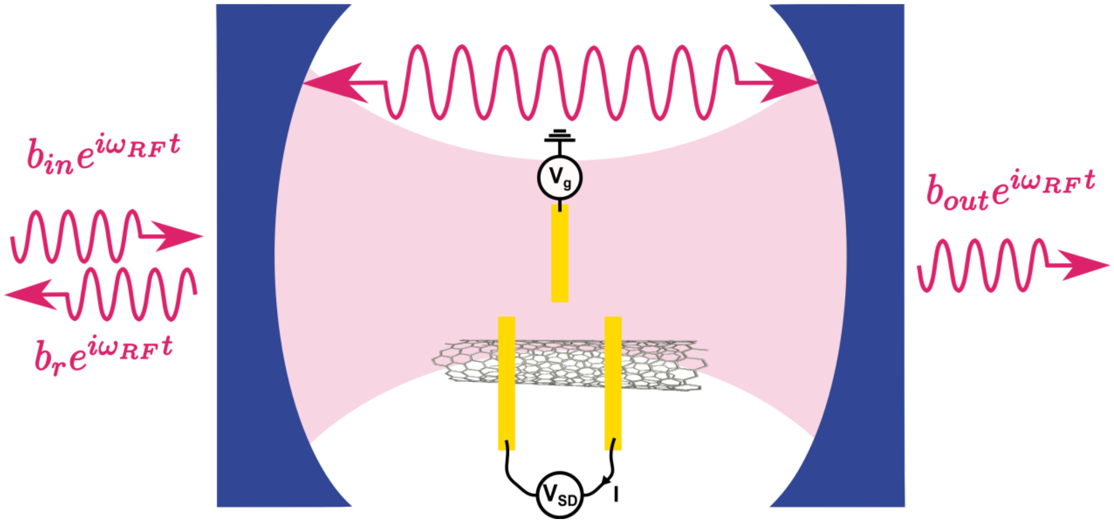
See Exp II : Superconductor-double quantum dot in cavity

Sample in real life…

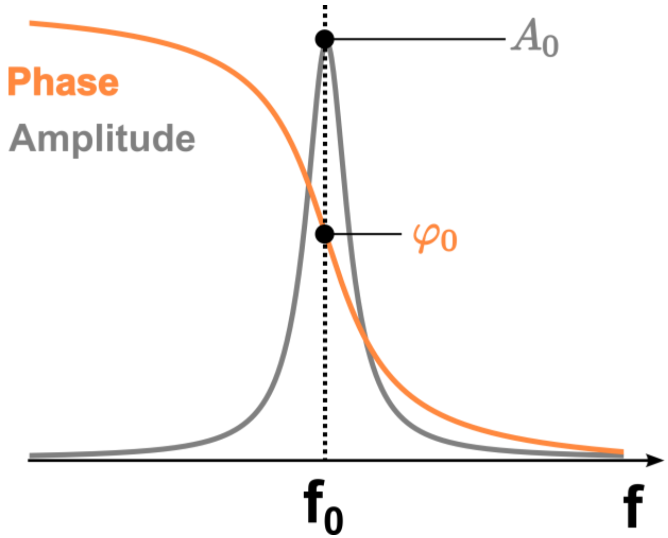
Resonance frequency ~6 GHz



Mesoscopic QED experiments



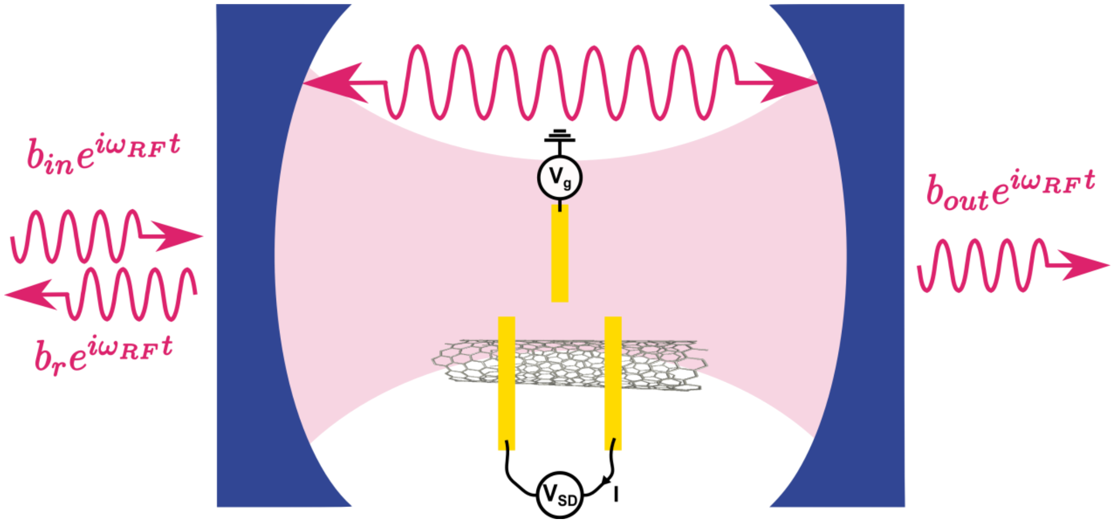
Cavity-current crossed characterisation:
Current I
+
Microwave transmitted signal



$$\frac{b_t}{b_{in}} = A_0 e^{i\varphi_0}$$

Bare cavity resonance :
- Resonance frequency f_0
- Linewidth related to sensitivity

Mesoscopic QED experiments



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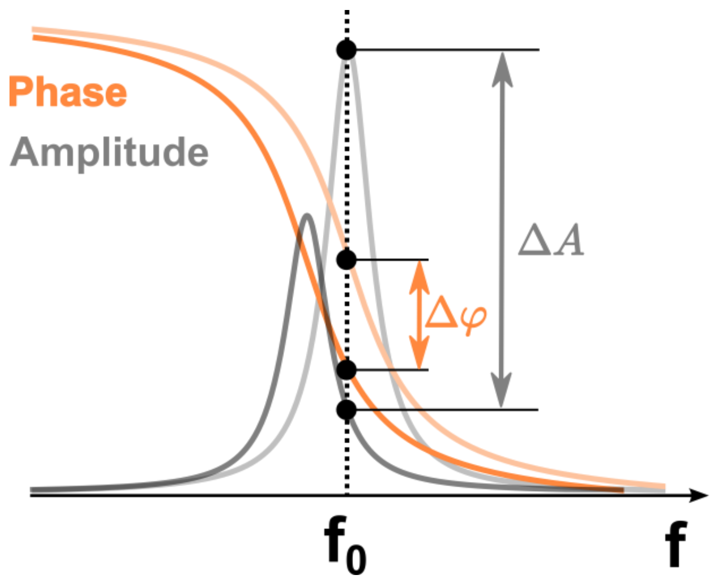
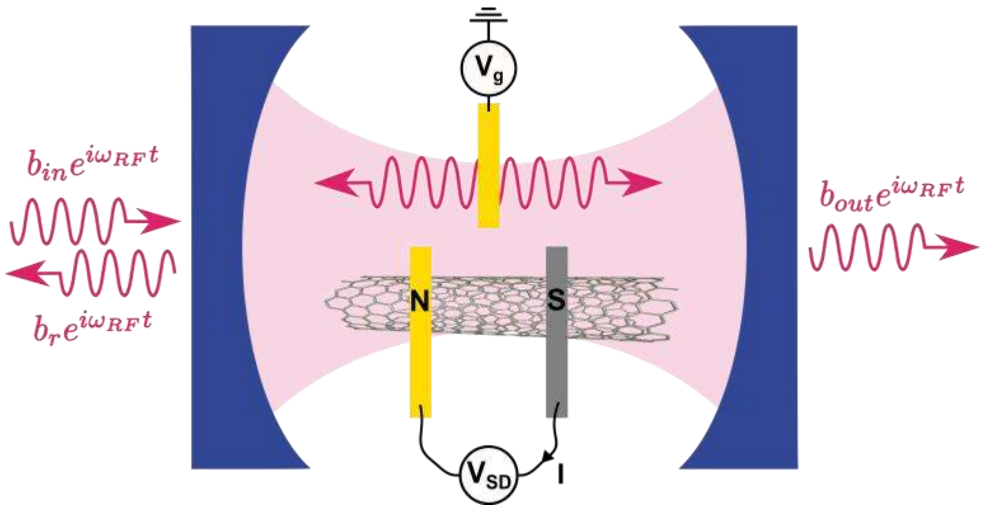


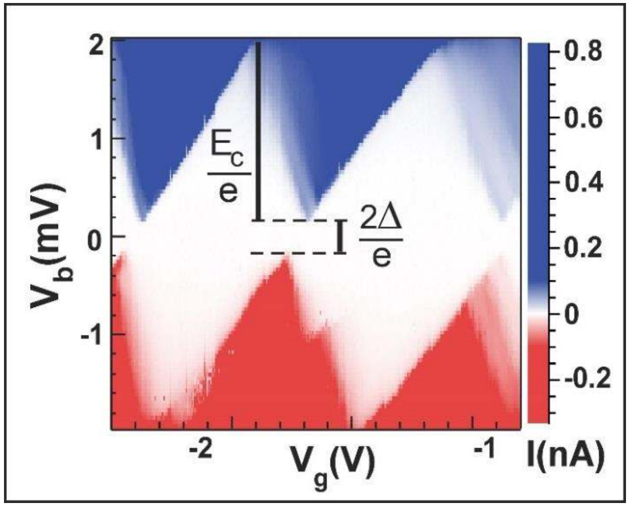
$$\frac{b_t}{b_{in}} = (A_0 + \Delta A)\, e^{i(\varphi_0 + \Delta\varphi)}$$

Usual measurement :

Amplitude and phase shift occasionned by the circuit at the bare cavity frequency f_0

Exp I: Dot contacted to normal (N) and superconducting (S) reservoirs



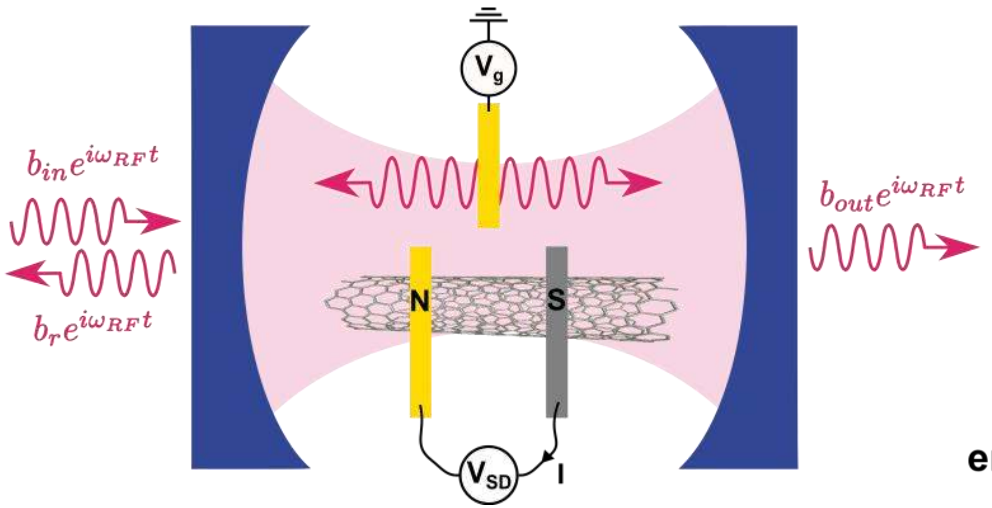


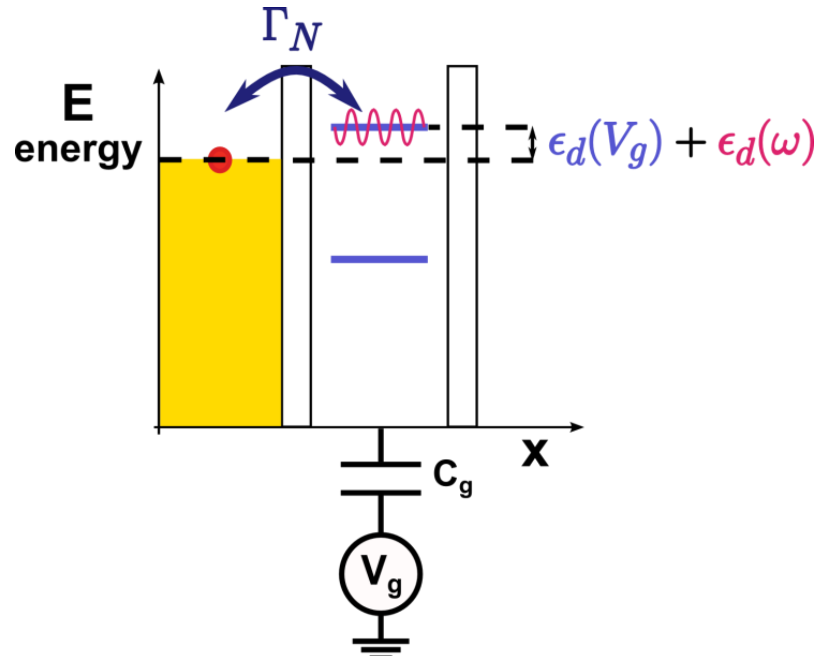
- Coulomb diamonds = **interacting electrons**

- No current in gap = **no Cooper pair transport**

What does this imply ?

Dot contacted to normal (N) and superconducting (S) reservoirs

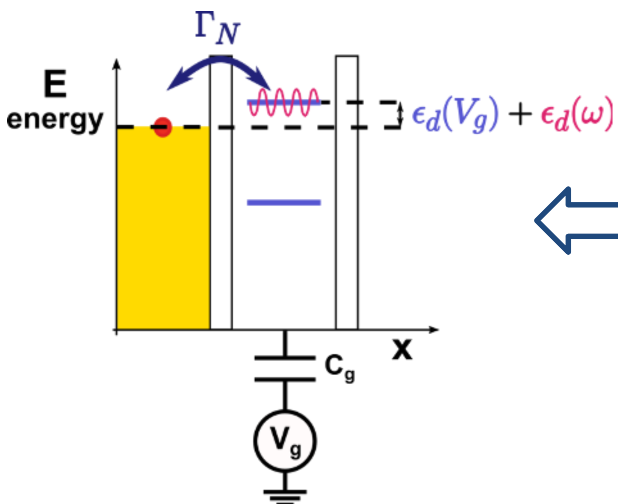


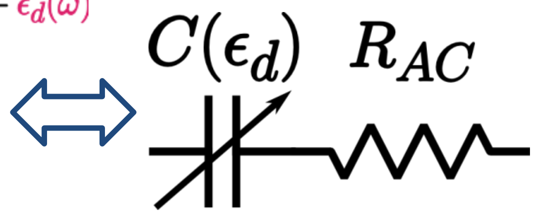


$\Longrightarrow$ **At V_b=0, effective dot/N junction**

Simplest situation to study tunnelling dynamics !

Results about AC dynamics of a N/dot junction





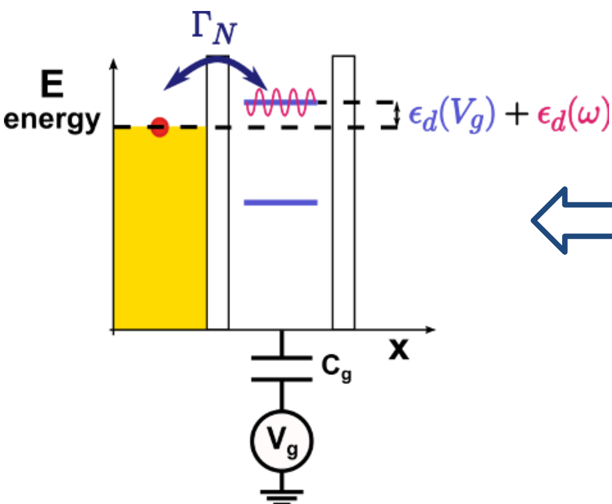
Assuming :

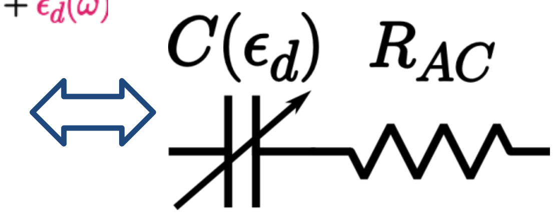
•large tunnel rate **$\Gamma_N >> \omega$**

For **non-interacting** electrons:

Universality of R_{AC}	**Experiment**	**Theory**
$R_{AC}= h/(N*2e^2)$ with N number of channels	*J. Gabelli et al., Science 313, 499 (2006)*	*M. Büttiker et al., Phys. Lett. A 180, 364 (1993)*
R_{AC} independent of dot energy ε_d	?	*M. Büttiker et al., Phys. Lett. A 180, 364 (1993)*

Charge relaxation in the interacting case





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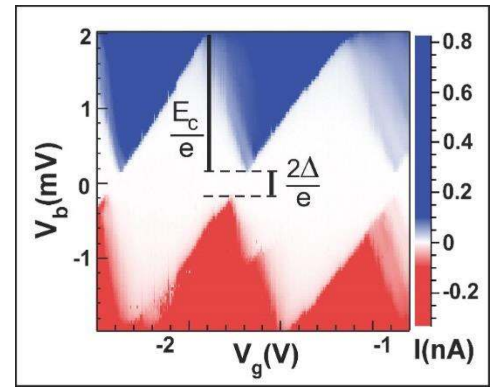


For **interacting** electrons:

Universality of R_{AC}	Experiment	Theory
R_{AC}= h/(N*2e^2) with N number of channels	?	*C. Mora and K. Le Hur, Nat. Phys.* ***6****, 697 (2010).*
R_{AC} independent of dot energy ε_d	?	*C. Mora and K. Le Hur, Nat. Phys.* ***6****, 697 (2010).*

Can we learn something with our setup ?

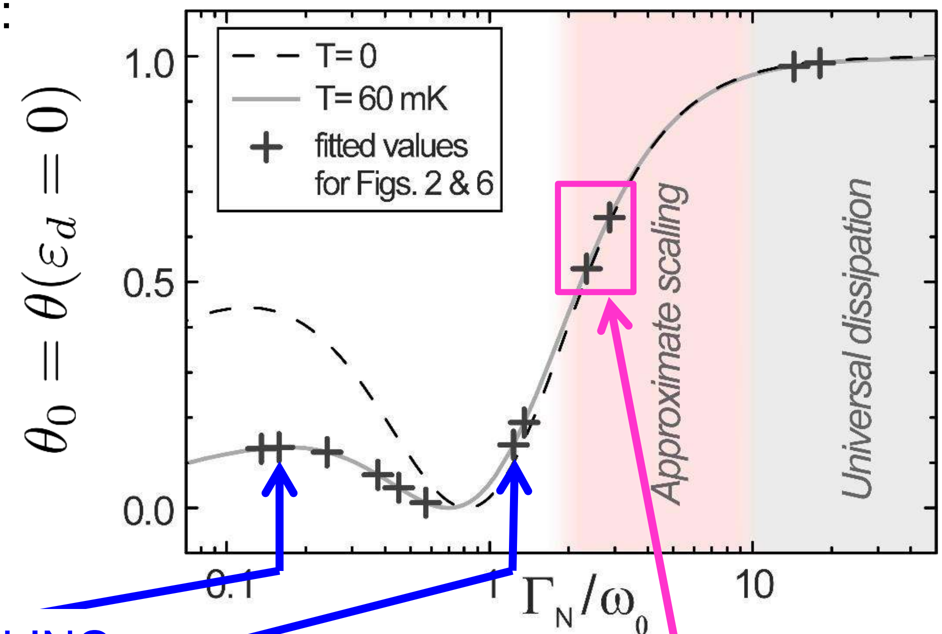
Towards universal charge dissipation

Universality predictions with 2 channels :

$$R_{AC} = \frac{h}{4e^2\theta(\varepsilon_d)}$$

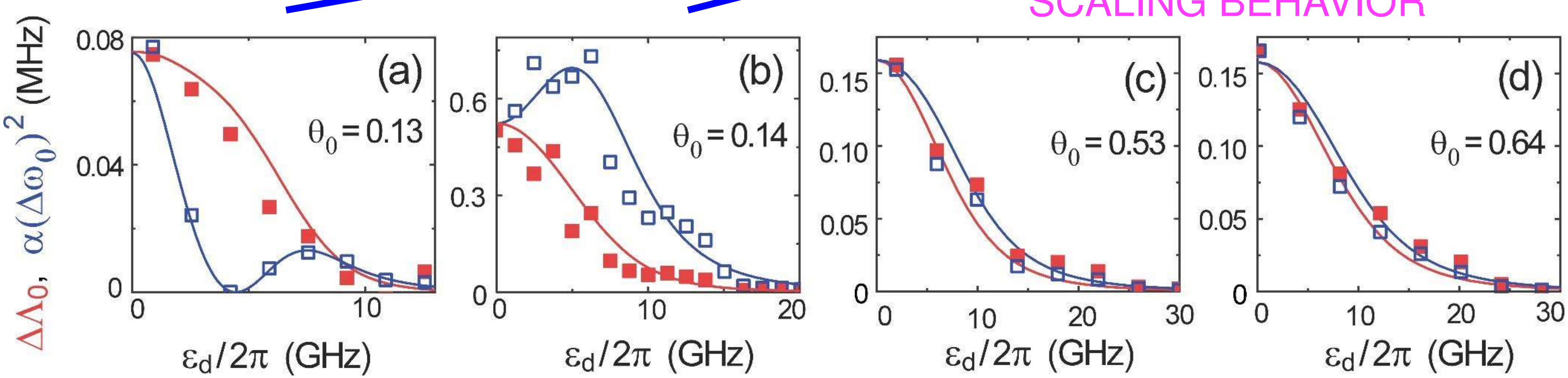
$$\boxed{\lim_{\Gamma_N/\omega_0 \to +\infty} \theta(\varepsilon_d) = 1}$$

$$\boxed{\theta(\varepsilon_d) = \frac{\pi}{2}\frac{\omega_0}{g^2}\frac{(\Delta\omega_0)^2}{\Delta\Lambda_0}}$$



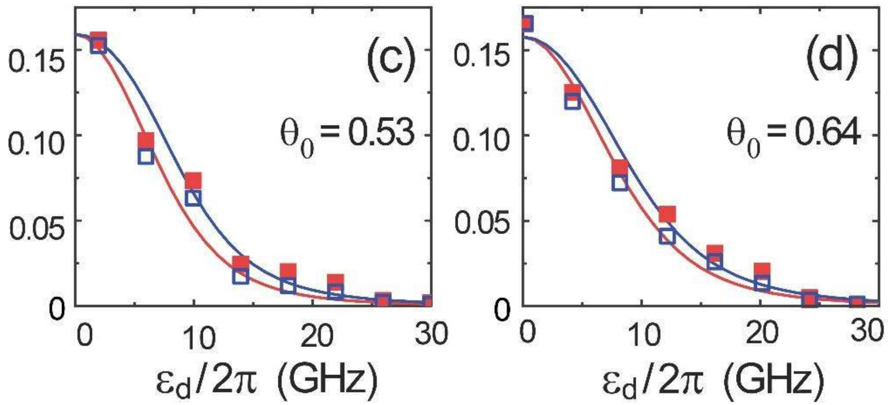
NO-SCALING

SCALING BEHAVIOR



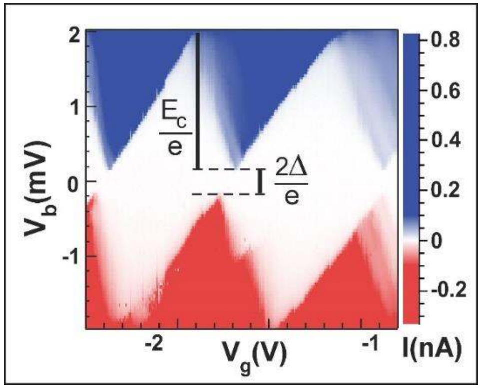
Charge relaxation in the interacting case

SCALING BEHAVIOR



Assuming :

•large tunnel rate $\Gamma_N >> \omega$



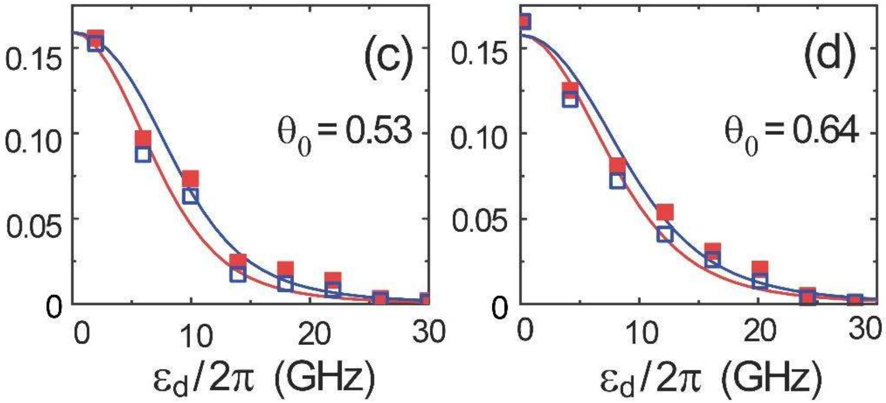
For **interacting** electrons:

Universality of R_{AC}	**Experiment**	**Theory**
$R_{AC}= h/(N*2e^2)$ with N number of channels	?	*M. Filippone, et al., Phys. Rev. Lett. 107, 176601 (2011)*
R_{AC} independent of dot energy ε_d	***LE. Bruhat et al, PRX 2016***	*M. Lee, et al., Phys. Rev. B 83, 201304 (2011)*

We put one piece in the big puzzle of science!

Modelling in terms of charge susceptibility

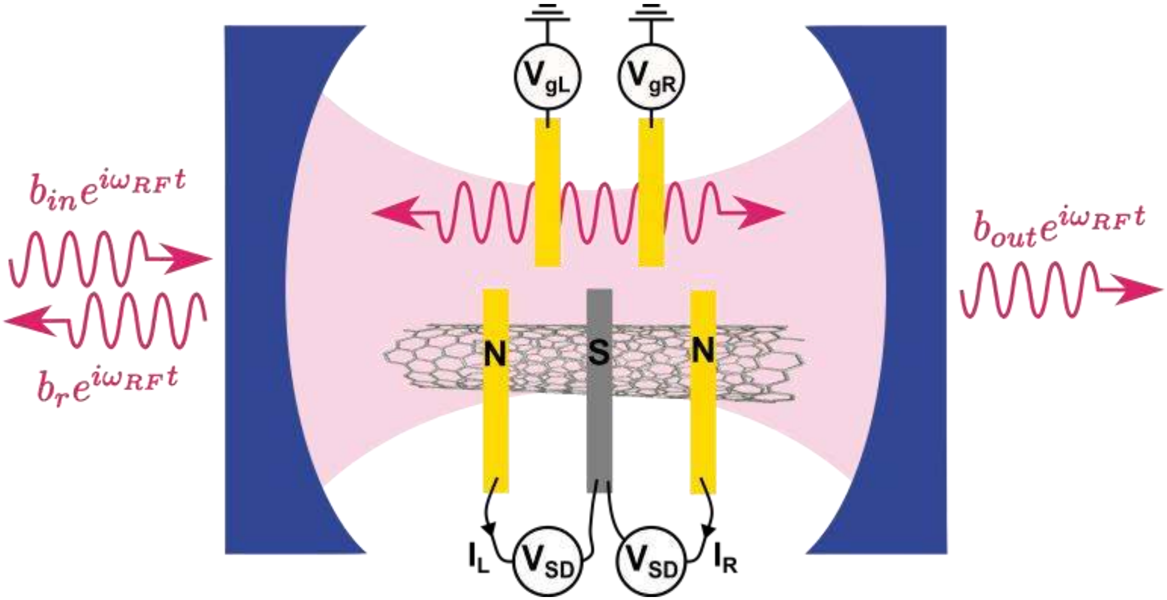
SCALING BEHAVIOR



Good theoretical modelling : first quantitative experimental test of **cavity signals modelling** in terms of **charge susceptibility**

→ opens an avenue because very general method !

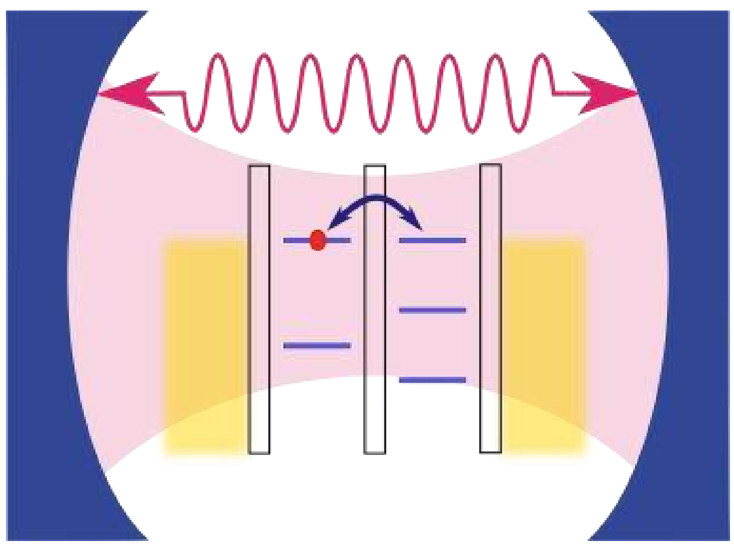
We developped the tools to put MORE PIECES in the big puzzle of science!



NEW!

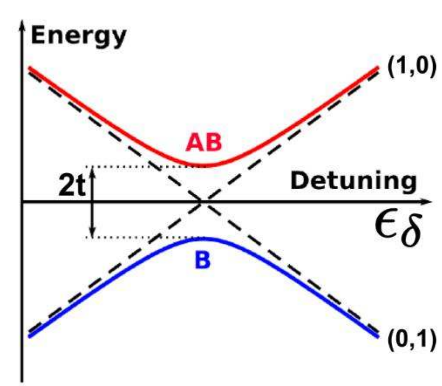
First time such a circuit was placed in a cavity!

Atomic-like device probed by a cavity



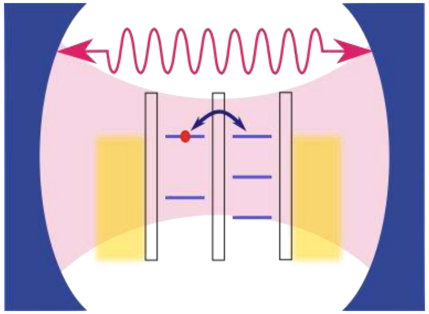
THE CLASSIC!

Most reproduced experiment in mesoscopic QED!



The double dot charge qubit

Use the cavity as a spectroscopic probe



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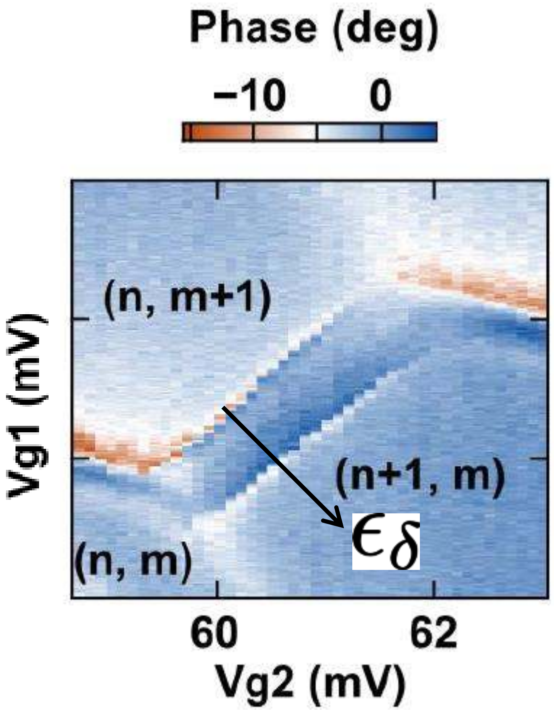
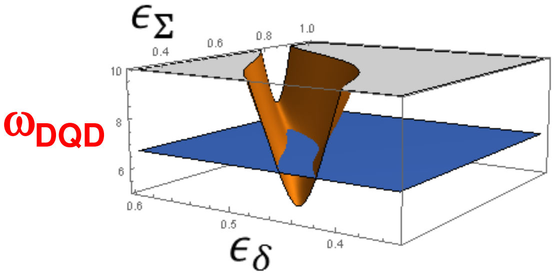


Sign change in phase
=
Resonant condition

$$hf = \hbar\Omega$$

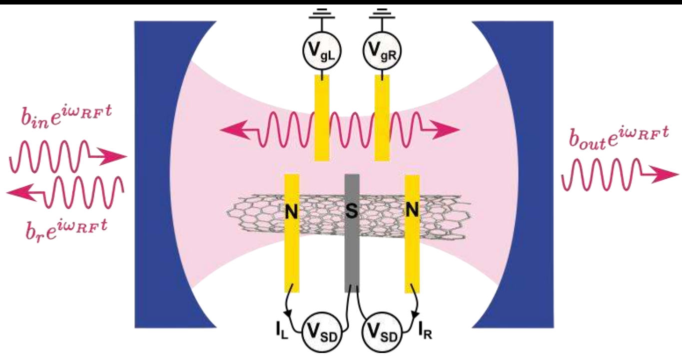


Double dot charge qubit:

$$\Omega(\varepsilon_\delta)$$

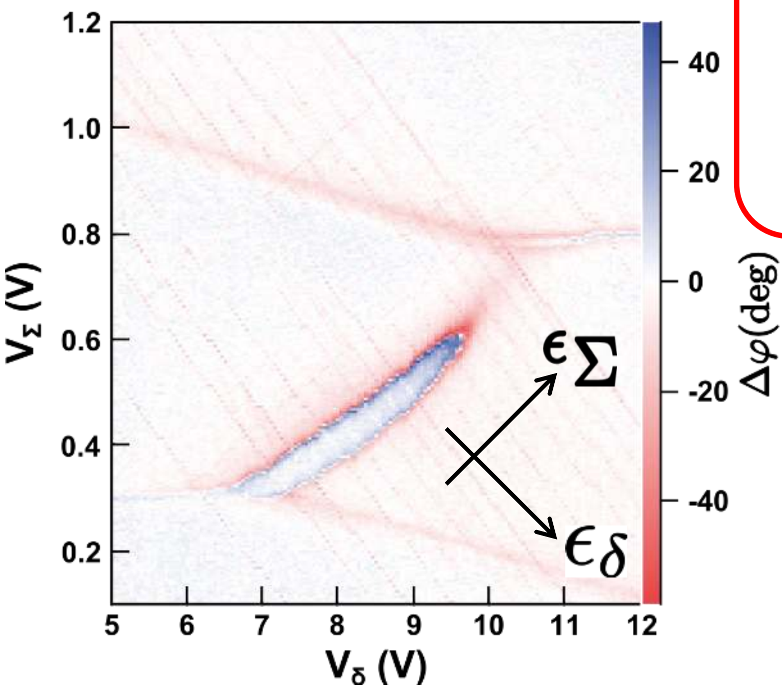
J.J. Viennot et al., Science 349, 408, (2015)

Use the cavity as a spectroscopic probe



NEW!

First time such a shape is observed!



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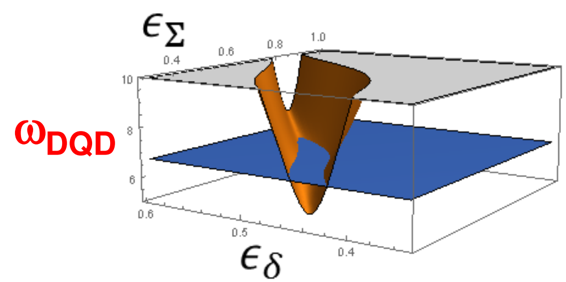


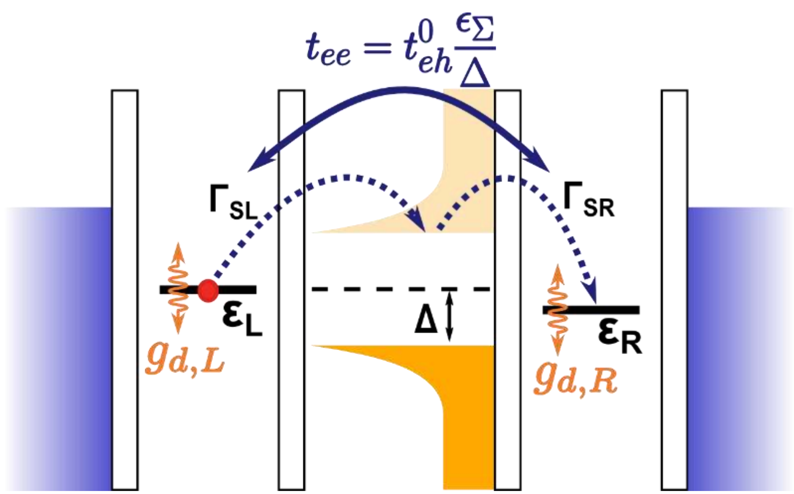
Superconductor-double quantum dot:

$$\Omega(\varepsilon_\delta, \varepsilon$$

Sign of the modification of the spectrum by the superconductor ?

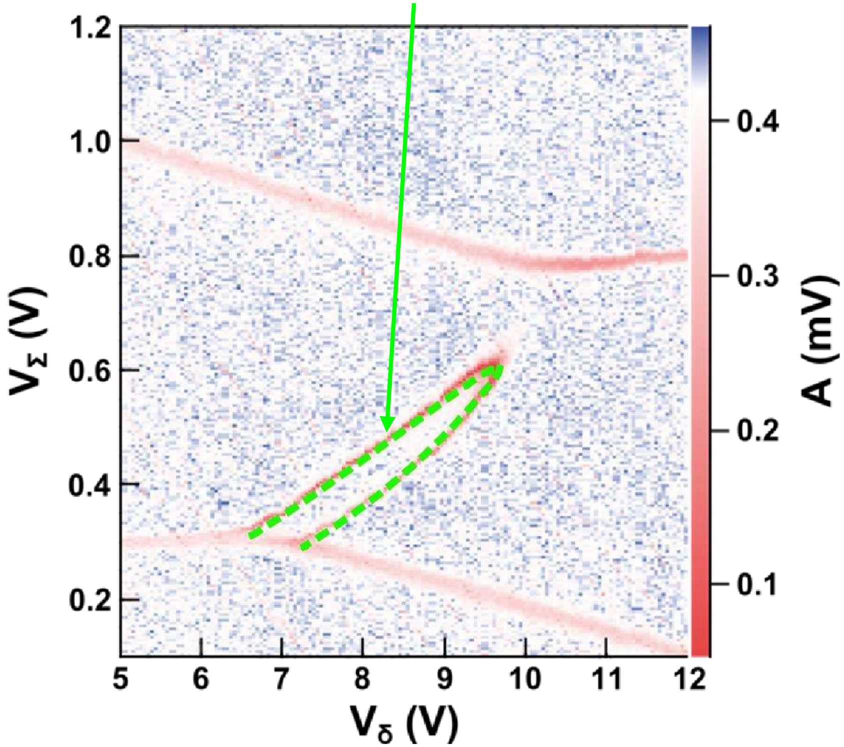
Charge qubit dressed by the superconductor

Role of Cooper pair assisted interdot tunneling



Γ_{SL}=800MHz, Γ_{SR}=400MHz
2t=6.3 GHz, t^0_{eh}=400MHz

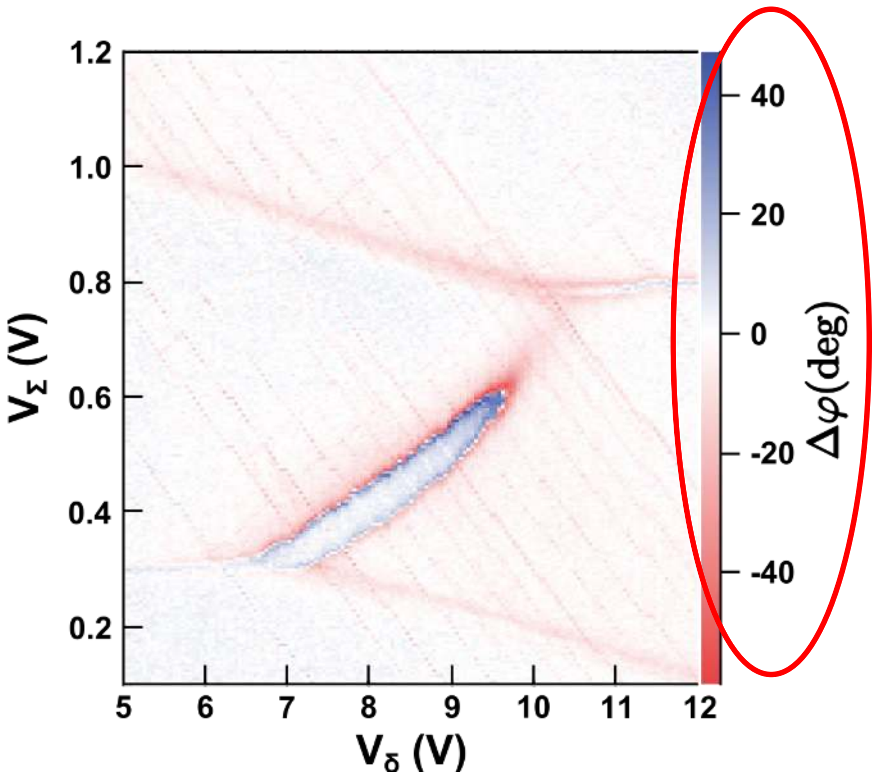
$$\sqrt{(\epsilon_\delta{}^2 + 4t^2)Z(\epsilon_\Sigma,\epsilon_\delta)^2 + 4t_{ee}^{ind}(\epsilon_\Sigma,\epsilon_\delta)^2}$$

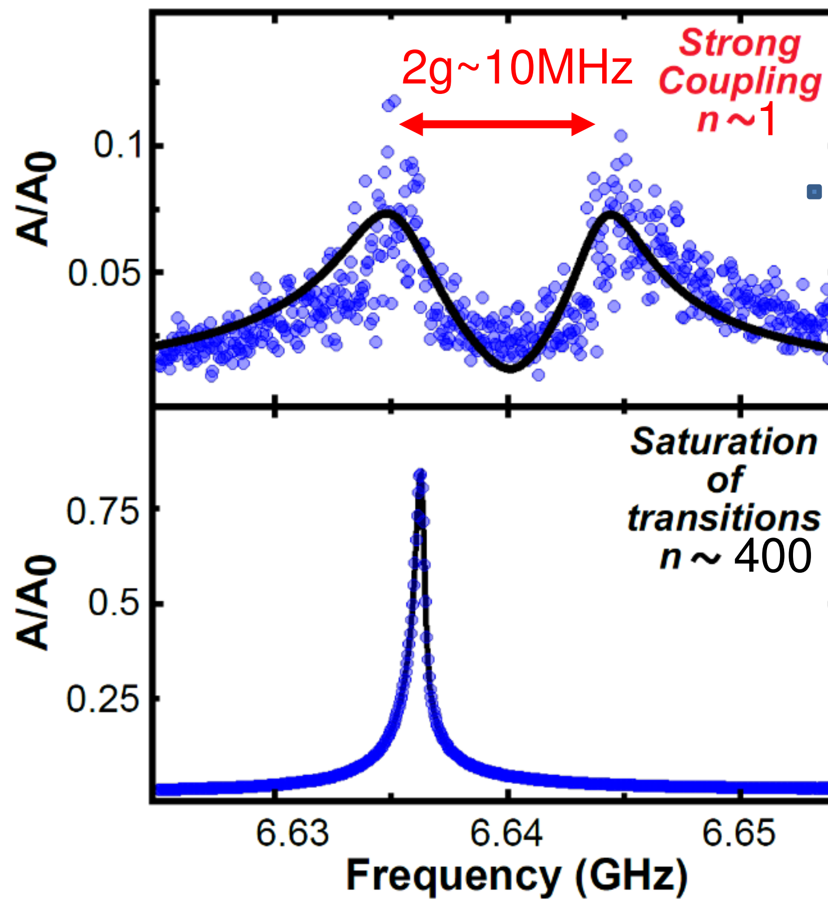


Quantitative agreement with S-induced low energy spectrum.

Observed resonance interpreted as the **transition between (0,1) and (1,0) states « dressed » by the superconductor (odd eigenstates).**

Last big surprise: Vacuum Rabi splitting!

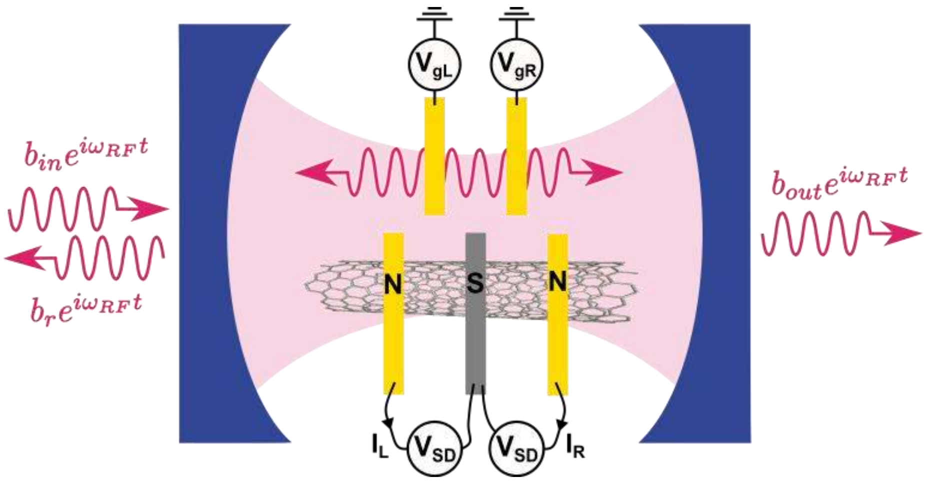




Largest Vacuum Rabi splitting about 10 MHz ~ 3 line widths

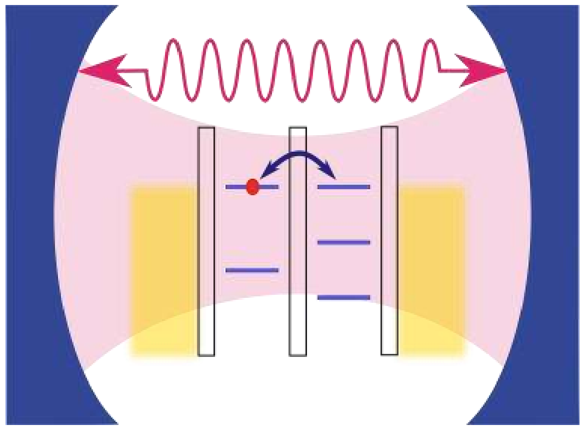
Observation of strong coupling in mesoscopic QED

Simultaneous observed by 3 groups



NEW!

- Observed with the first sample!
  Bruhat et al., arXiv 2016
  PRB 2018
- Built-in key features to reach the **strong coupling regime**!



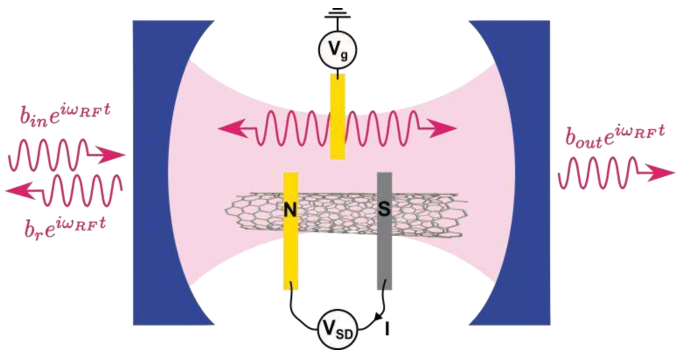
THE CLASSIC!

- Achieved in standard double quantum dots after years of effort.

Mi et al., Science 2017
Stockklauser et al., PRX 2017

Mesoscopic QED is interesting!

I. **Normal/dot/superconductor circuit in cavity**

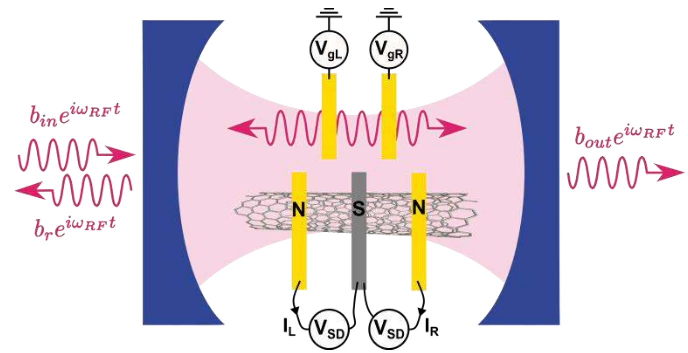


Open quantum dots :

Study quantum transport in a different way

- **Kondo** resonance ***MM Desjardins et al Nature 2017***
- **Majorana fermions**

II. **Superconductor-double quantum dot in cavity**



Closed quantum dots:

Probe/manipulate internal quantum states of a mesoscopic circuit

- Applications in **quantum information processing**

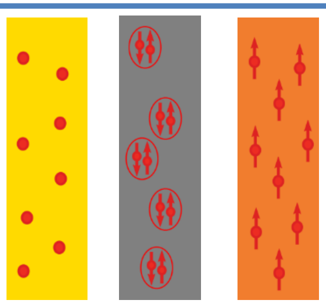
Rich possibilities offered by the combination of different metallic electrodes

see review by A. Cottet et al, *J. Phys. Condens. Matter* ***29***, *(2017).*

Normal (N)

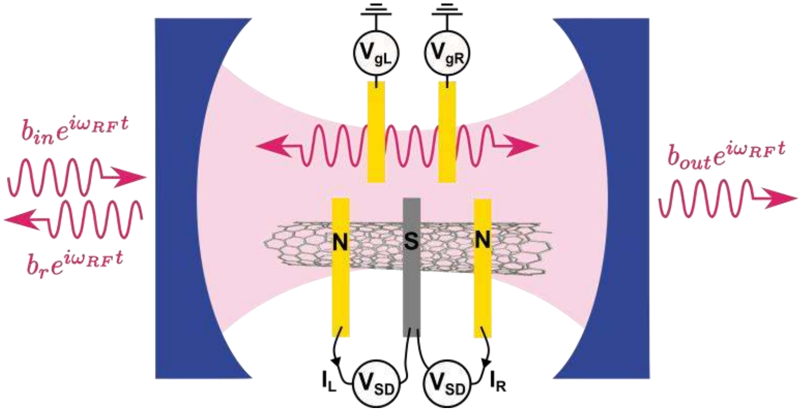
Superconducting (S)

Ferromagnetic (F)



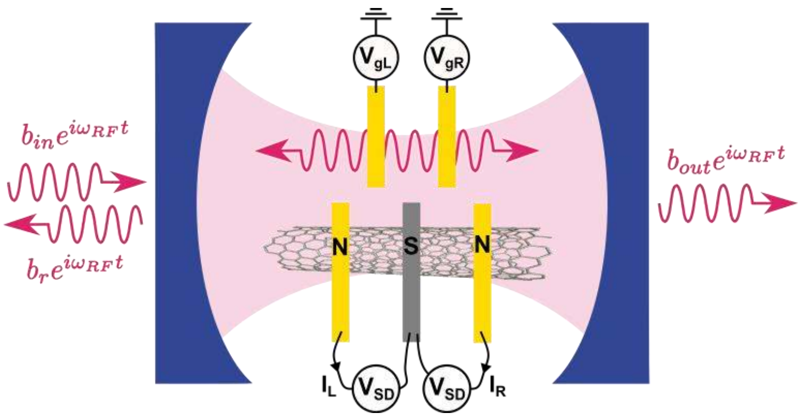
Was this all planned?

INPUT: **YES!**



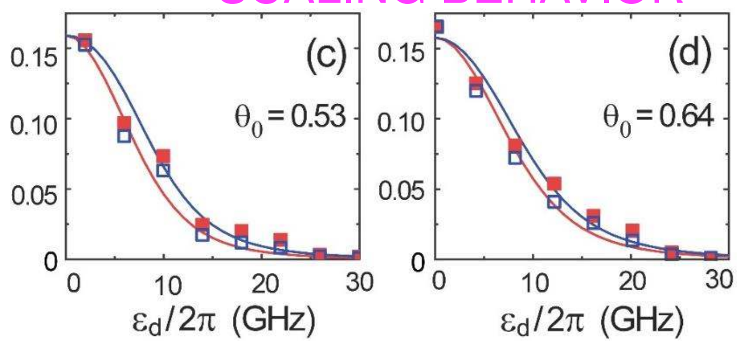
Was this all planned?

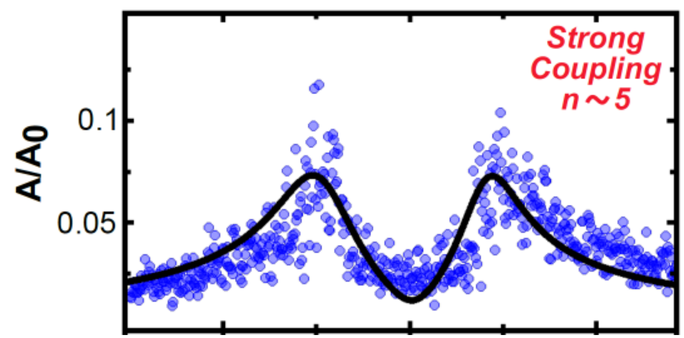
INPUT: **YES!**



OUTPUT: **NO!**

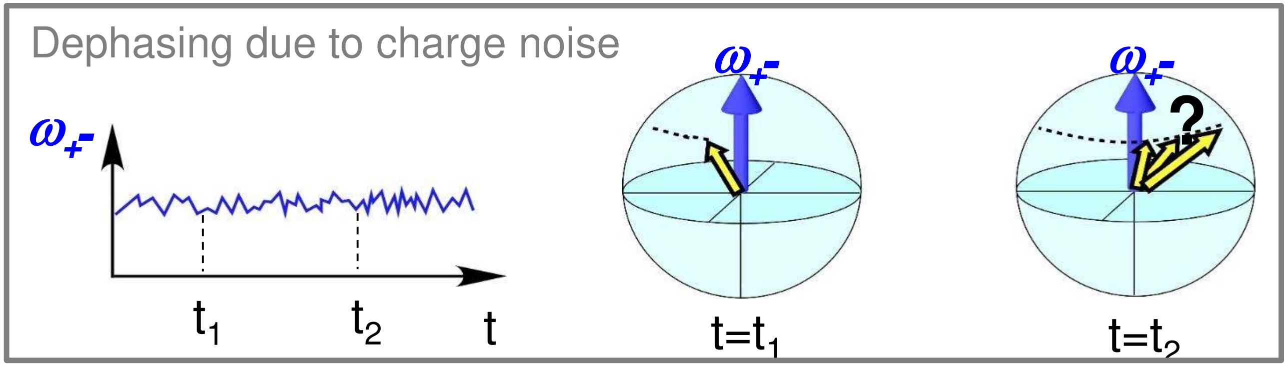
SCALING BEHAVIOR





I wish you many good surprises in your research!
Be receptive!

Stategies to reach the strong coupling regime



$$g_\perp \ll \Gamma_s$$

How do we get $g_\perp \gg \Gamma_s$ **?**

Increase $g_\perp$ **Decrease** Γ_s

$$\Gamma_s \sim \frac{1}{\pi}\frac{\partial^2 \omega_{+-}}{\partial \varepsilon^2} E_c^2 (\delta n)^2$$

Stockklauser et al., PRX 2017
Zurich, GaAs 2DEG
$g_\perp / \Gamma_s = 1.27$

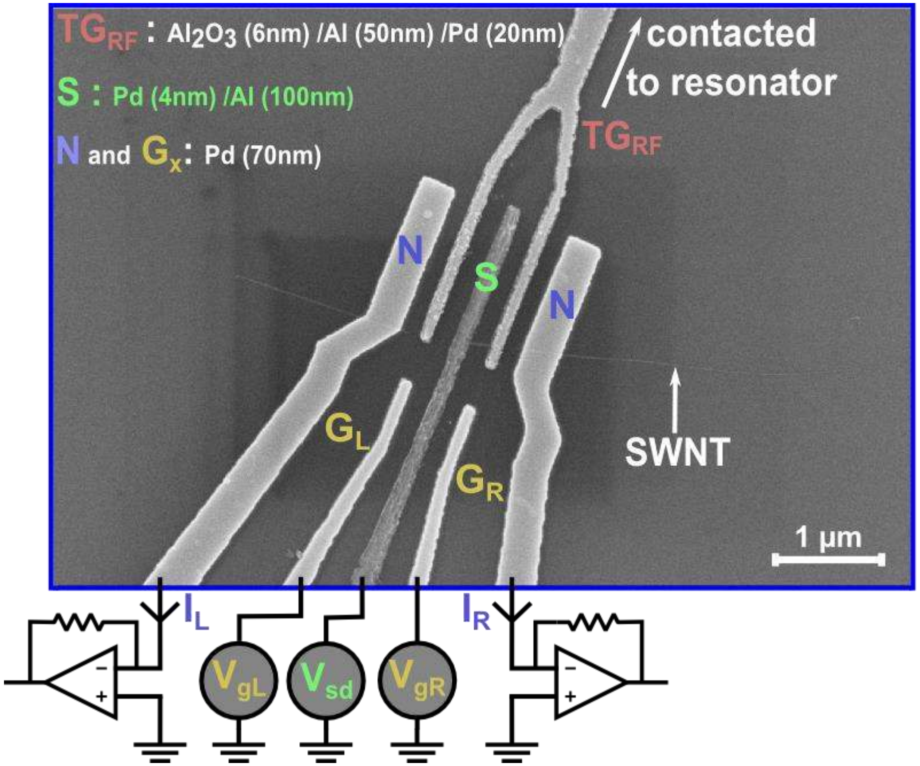
decrease E_c

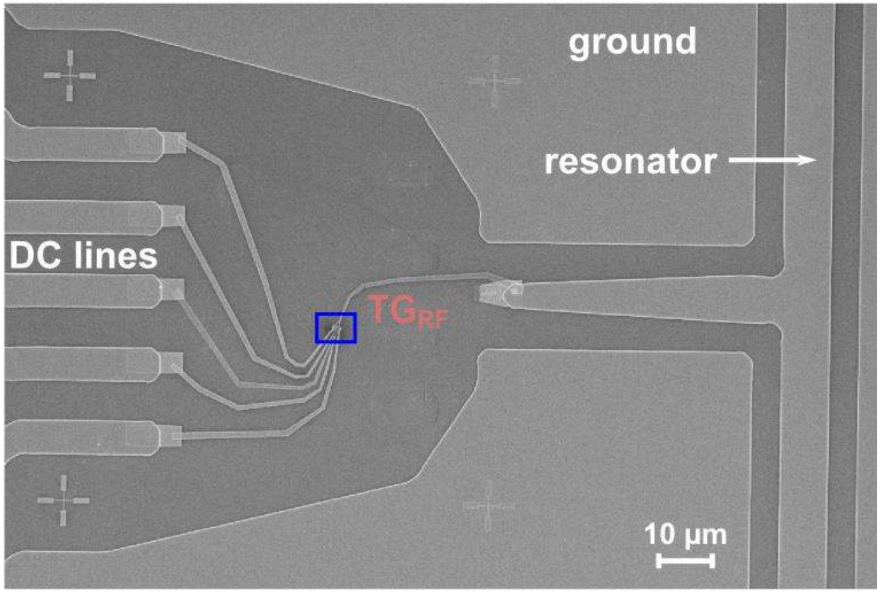
Bruhat et al., arXiv 2016
Paris, carbon nanotube
$\tilde{g}_\perp / \Gamma_s = 2.5$

decrease charge noise

Mi et al., Science 2017
Princeton, Si 2DEG
$g_\perp / \Gamma_s = 2.57$

Key ingredient 1: decrease Ec





Key features

- Double dot with a central superconducting contact
- **Fork top gate** to resonator

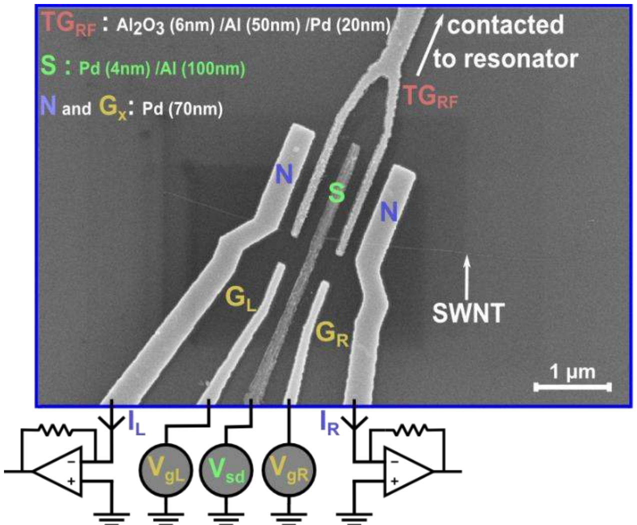
$$E_c = \frac{e^2}{2C_{dot}}$$

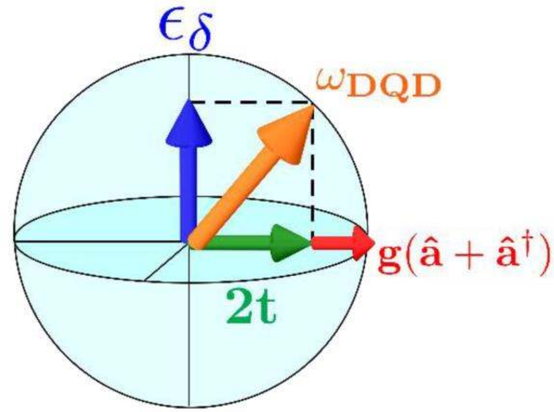
For Ec ≈ 10 meV, Γ_2 ≈ 550MHz

See JJ Viennot et al, PRB 89, 165404 (2014)

Here Ec ≈ 1 meV, Γ_2 ≈ 5MHz

Key ingredient 2: coupling via interdot hopping





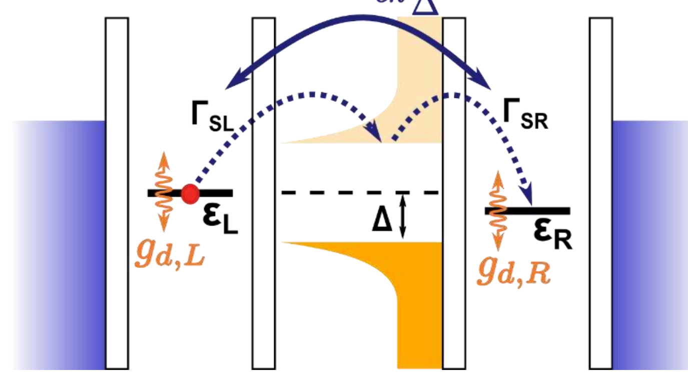
Key features

- Double dot with a central **superconducting contact**

$$\tilde{t} = t + \underbrace{t_{ee}^{ind}}_{\propto \frac{\epsilon_\Sigma}{\Delta}}$$

intrinsic

$$t_{ee} = t_{eh}^0 \frac{\epsilon_\Sigma}{\Delta}$$



Renormalization of L/R hoping from elastic cotunnelling through superconductor

- **Fork** top gate to resonator

$$\epsilon_\Sigma = \epsilon_L + \epsilon_R \propto \alpha V_{gL} + \beta V_{gR} + V_{ac}(a + a^\dagger)$$

large transverse coupling via **symmetric coupling to em field**