laboratoire pierre aigrain
électronique et photonique quantiques

Cavity quantum electrodynamics with carbon nanotubes : from atomic-like systems to condensed matter



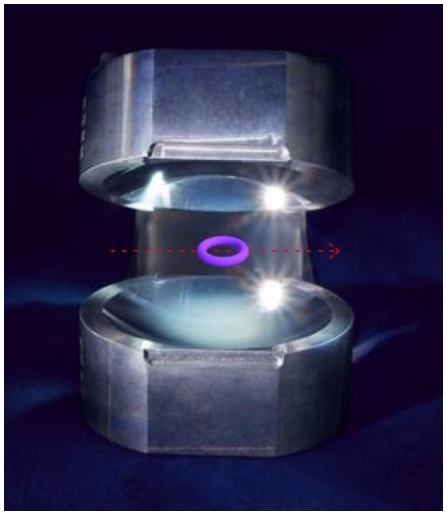
T. Kontos
LPA, ENS Paris

Exp : L.E. Bruhat, M.M. Desjardins, M.C. Dartiailh, T.E. Cubaynes, J.J. Viennot,, M.R. Delbecq
Theory : A. Cottet, M.-S. Choi, M. Lee, B. Douçot

Acknowledgements: Quantronics group, J.M. Raimond, M. Devoret, B. Huard, L. Bretheau, E. Flurin, P. Senellart, L. Lanco, M. Rosticher, J. Palomo, L. Glazman, A. Clerk, H. Baranger.

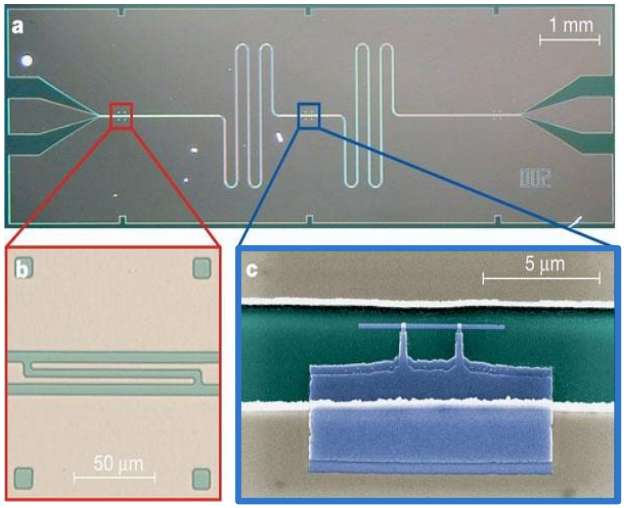
Cavity Quantum ElectroDynamics : from optical systems to superconducting chips

Atomic Cavity QED



M. Brune et al., Phys. Rev. Lett. 76, 1800 (1996)

Circuit QED



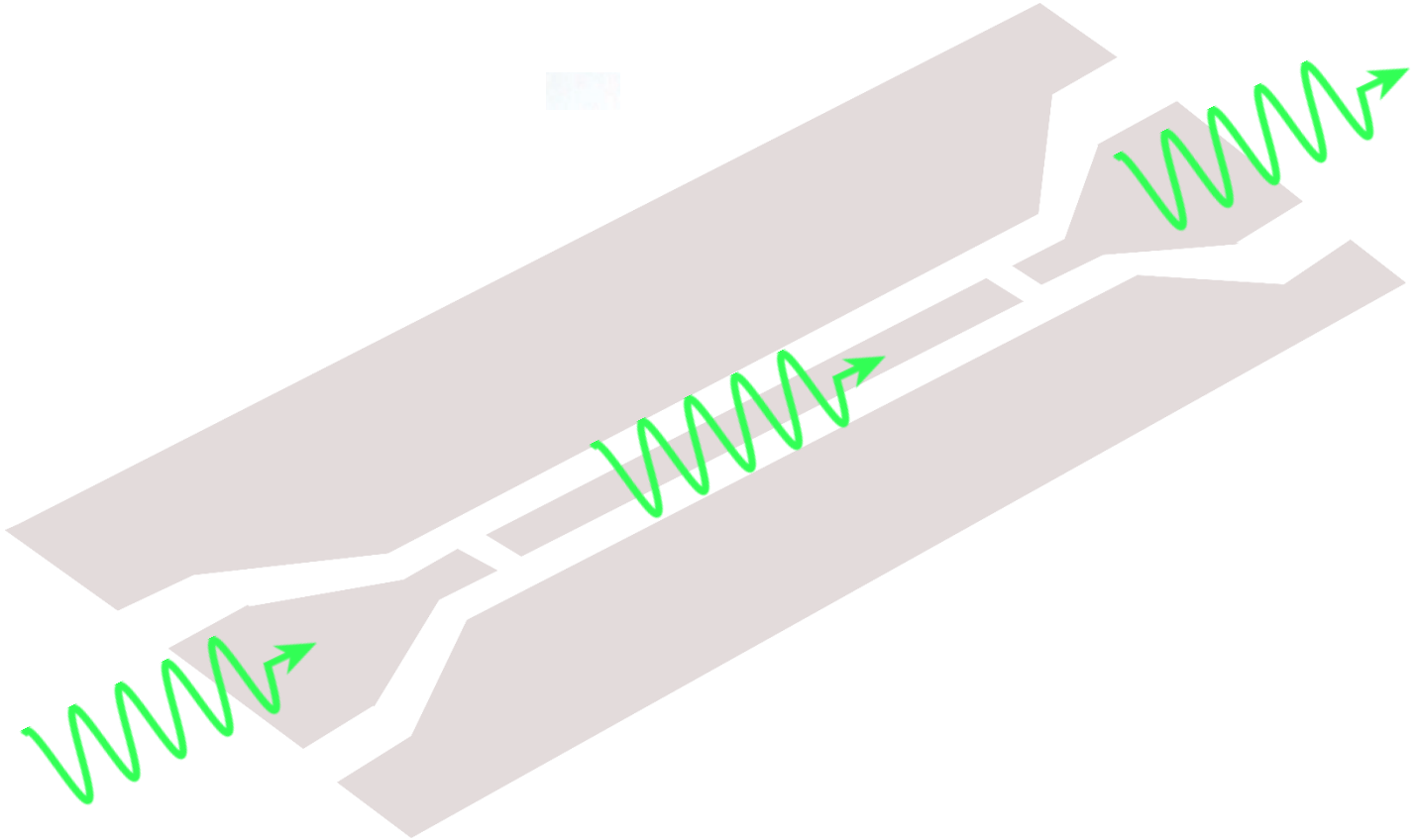
A. Wallraff et al., Nature 431, 162 (2004)

$$\hat{H}_{eff} = h\nu_{01}\hat{S}_z/2 + \hbar\omega_r a^\dagger a + \hbar g(a^\dagger \hat{S}_- + a\hat{S}_+)$$

Two level system — Cavity photons — Coupling term

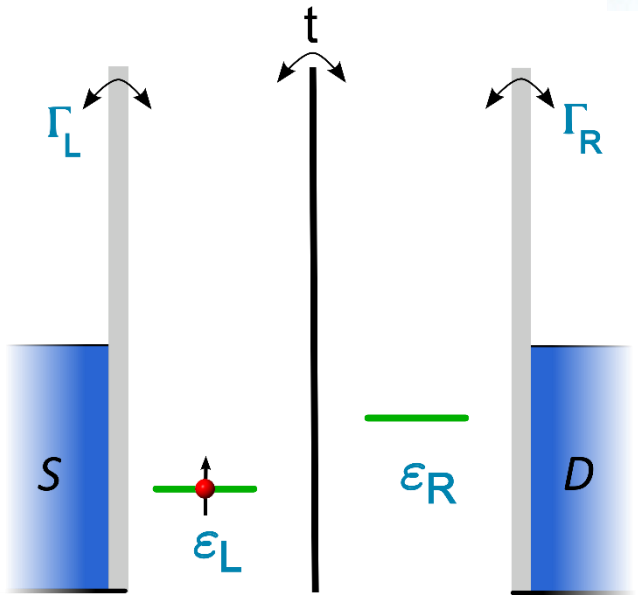
Strong coupling regime = g > dissipation of photon, atom

The cavity

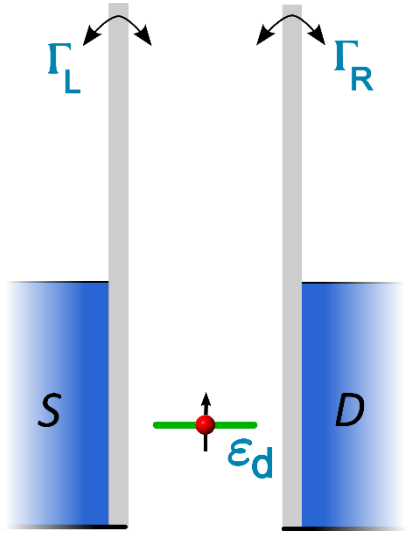


- Superconducting coplanar waveguide cavity (CPW).
- Fundamental frequency in the microwave range (6-7GHz). Q~15000
- Measurements carried out at ~20 mK-250mK

The atom



Closed system
Quantum information



Open system
Impurity physics : condensed matter

- Single quantum dots (one localized level) : artificial atom
- Double quantum dots (two coupled localized levels) : artificial molecule
- Coupled weakly or strongly to fermionic leads (closed or open quantum systems)

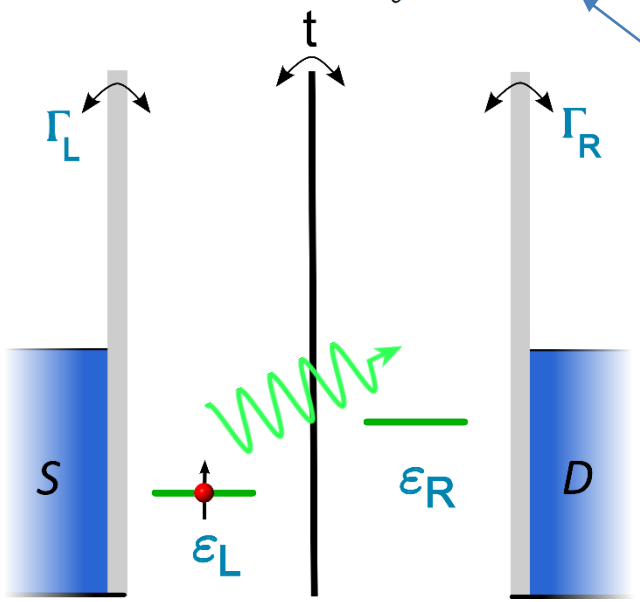
Light-matter coupling

$$\hat{\mathcal{V}} = -e \int d^3r\, V_\perp(\vec{r})\hat{\psi}^\dagger(\vec{r})\hat{\psi}(\vec{r})$$

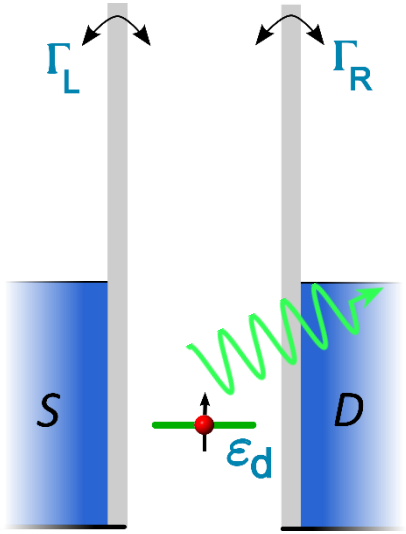
« form factor for the e.m. field»

density

$$\widetilde{H_{\rm tot}} = \int d^3r\, \hat{\psi}^\dagger(r)\tilde{h}_{\mathcal{T}}(\vec{r})\hat{\psi}(\vec{r}) + \hat{H}_{\rm Coul} + \hbar\omega_0 \hat{a}^\dagger\hat{a} + \hat{\mathcal{V}}(\hat{a}+\hat{a}^\dagger) + (\hat{\mathcal{V}}^2/\hbar\omega_0)$$



Closed system
Quantum information



Open system
Impurity physics : condensed matter

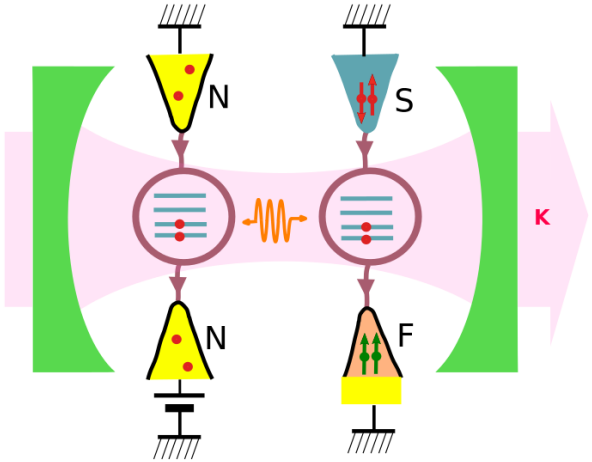
- Electric coupling to the charge density of the conductors (from gauge invariance)
- Internal transitions and transitions to leads possible (cavity to circuit QED)
- Large dipoles (g ~10-100 MHz) due to mes**osc**opic scale

A. Cottet, T. Kontos and B. Doucot, PRB'15

Hybrid circuit QED with quantum dots

J.-M. Raimond, M. Brune, and S. Haroche, RMP 73, 565 (2001)
A. Blais et al. , PRA (2004)
A. Wallraff et al. , Nature 431, 162 (2004)

→ Transfer ideas of cQED to probe/manipulate micro/macroscopic quantum states of hybrid mesoscopic circuits (e.g. quantum dot circuits)



→ **Can one achieve the strong coupling with quantum dot circuits ?**

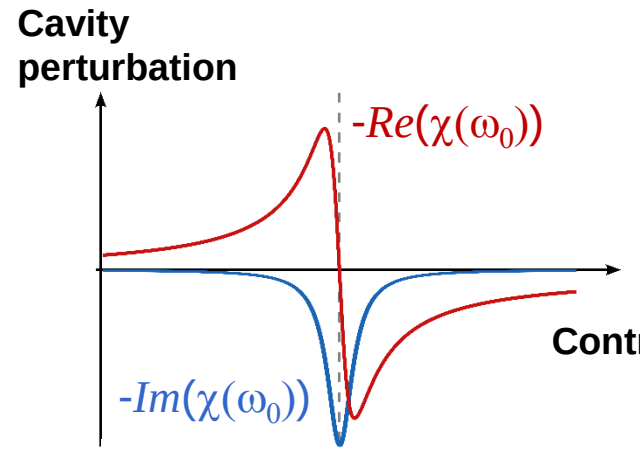
→ **Can one use that architecture for condensed matter questions ?**

M.R. Delbecq et al. PRL (2011), T. Frey *et al.* PRL (2012), K.D. Peterson et al. Nature (2012), H. Toida *et al.* PRL (2013), J. Basset et al. PRB (2013), J. Viennot et al. PRB (2014), Liu et al. Science (2015), J. Viennot et al. Science (2015).

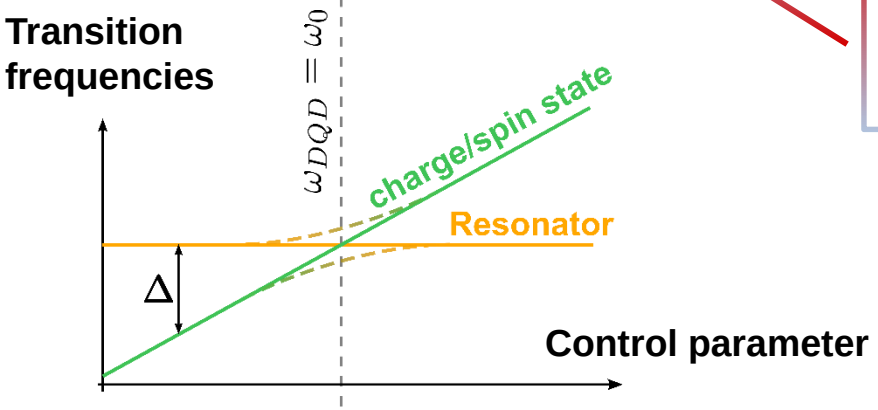
Resonator response: susceptibility I

cavity transmission $\frac{b_t}{b_{in}} = (A_0 + \Delta A)\, e^{i(\varphi_0 + \Delta\varphi)} = \frac{t_0}{\omega_{RF} - \omega_0 - i\Lambda_0 - g^2\chi(\omega_{RF})}$

DQD charge susceptibility $\chi(\omega) = \frac{1}{\omega - \omega_{DQD} - i\Gamma_2}$



$\omega_{RF} = \omega_0$

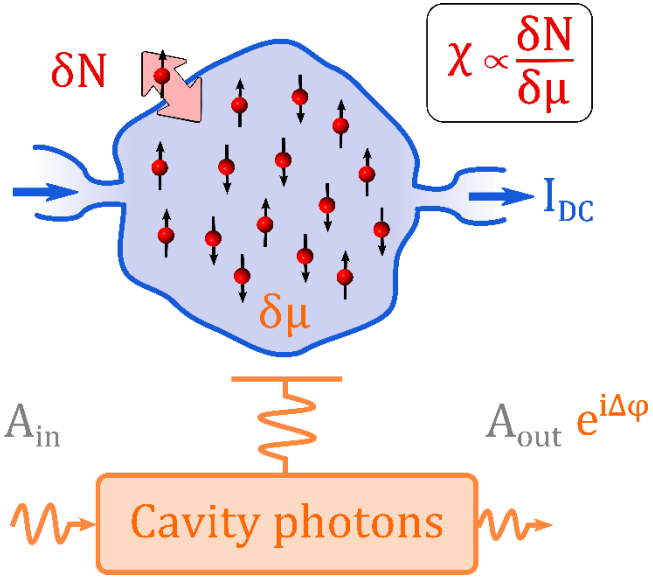


The cavity provides a cut of the hybrid DQD spectrum at $\omega_0 = \omega_{DQD}$

see also: Frey et al. PRL. (2012), Peterson et al. Nature (2012), Toida et al. PRL (2013), **...**

Resonator response: susceptibility II

cavity transmission $\frac{b_t}{b_{in}} = (A_0 + \Delta A)\, e^{i(\varphi_0 + \Delta\varphi)} = \frac{t_0}{\omega_{RF} - \omega_0 - i\Lambda_0 - g^2\chi(\omega_{RF})}$



$$\chi^*(\omega) = -i\int \frac{d\omega}{2\pi} \mathrm{Tr}\left[\check{\mathcal{S}}(\omega)\check{\mathcal{G}}^r(\omega)\check{\Sigma}^<(\omega)\check{\mathcal{G}}^a(\omega)\right]$$

$$\check{\mathcal{S}}(\omega) = \check{\tau}\left(\check{\mathcal{G}}^r(\omega+\omega_0) + \check{\mathcal{G}}^a(\omega-\omega_0)\right)\check{\tau}$$

Adiabatic regime

QD charge susceptibility $\chi(\omega) = g^2 \frac{\partial N}{\partial \epsilon_d}$

$\omega_{RF} = \omega_0$

⇒

The cavity provides a direct compressibility measurement

Bruhat, Viennot, Dartiailh, Desjardins, Kontos & Cottet, PRX 6, 021014 (2016)

Hybrid circuit QED with quantum dots

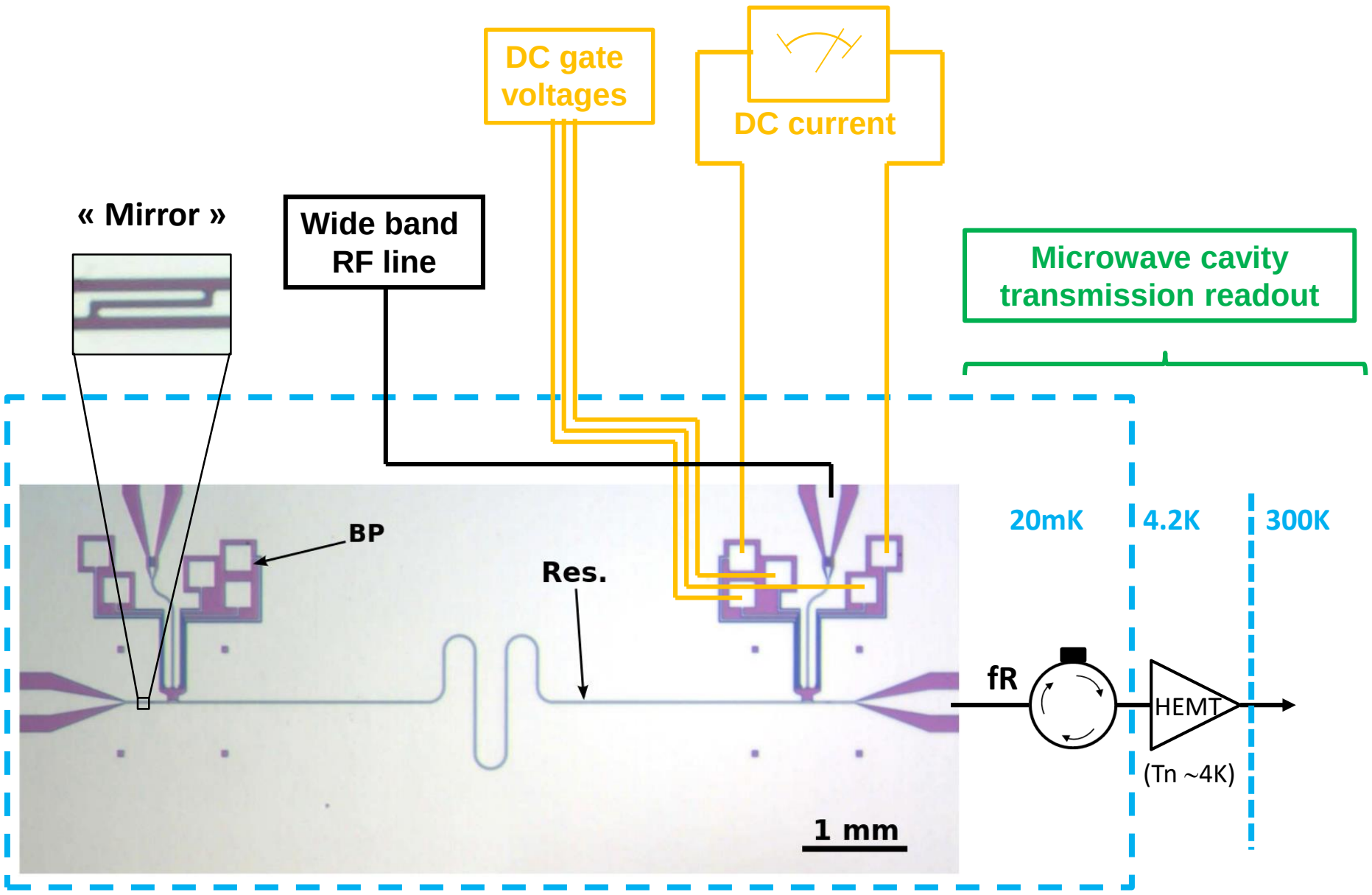
Can one achieve the strong coupling with quantum dot circuits ?

See talk of M. Dartiailh

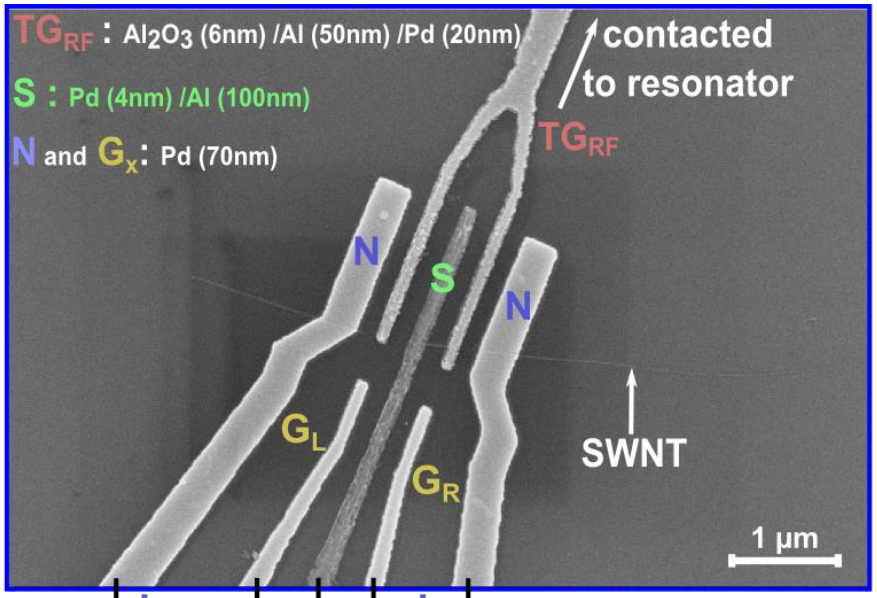
Hybrid circuit QED with quantum dots

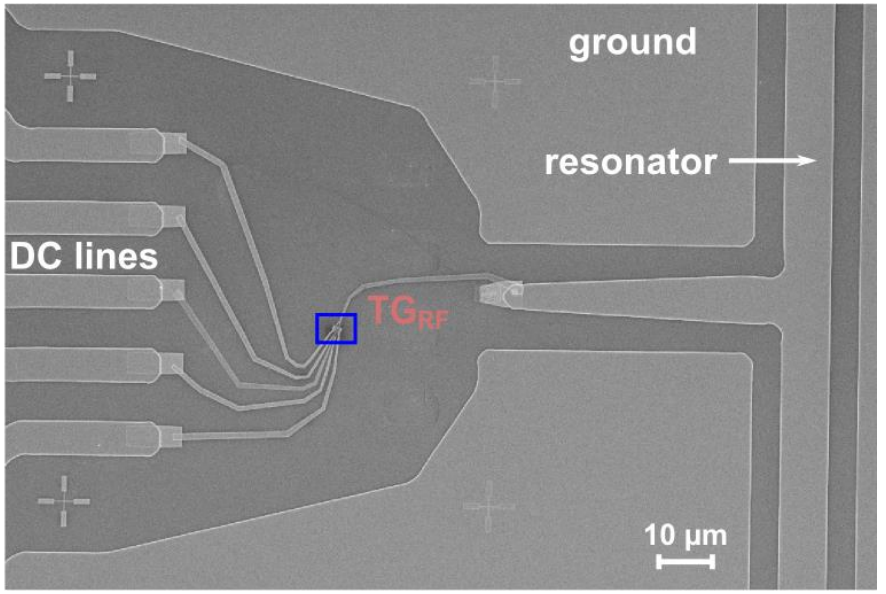
➡ **Can one use that architecture for condensed matter questions ?**

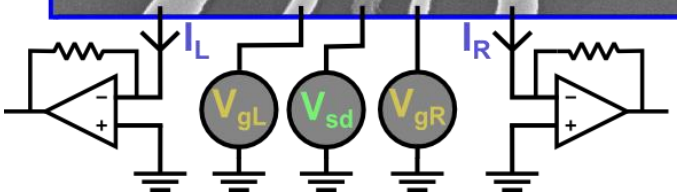
Measurement setup



S-dot-N in a cavity







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

Nb resonator parameters :

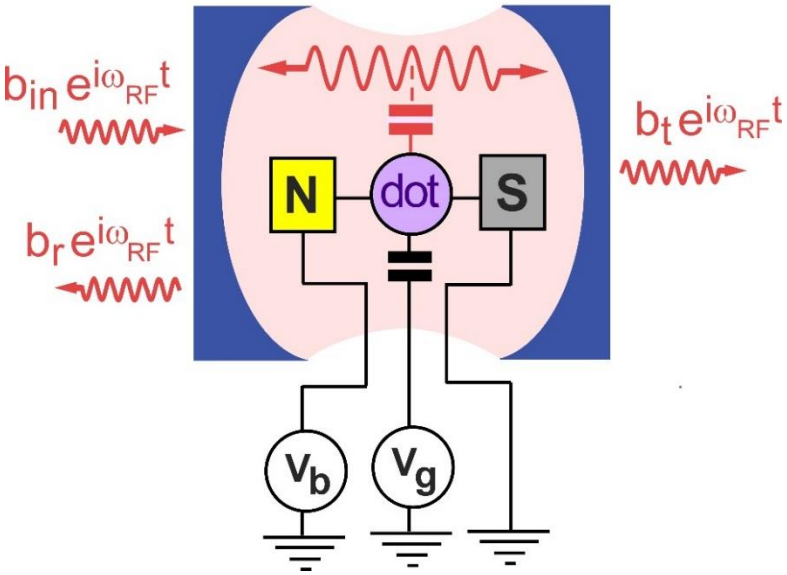
Q ≈ 10000

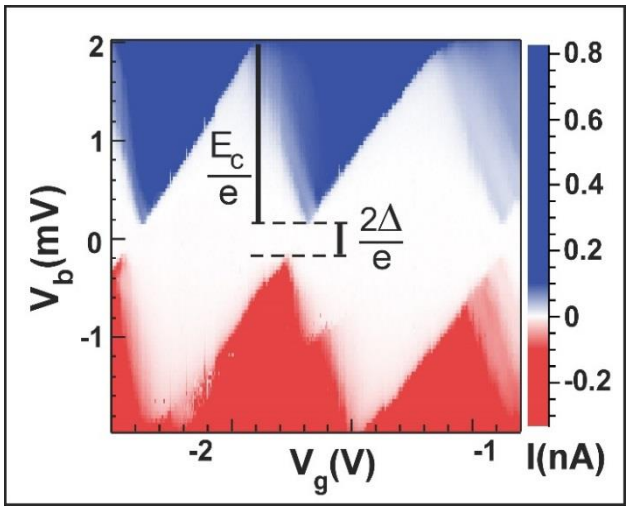
f_c = 6.6480 GHz

Measurements :

- Current : I
- Resonator transmission : amplitude and phase

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





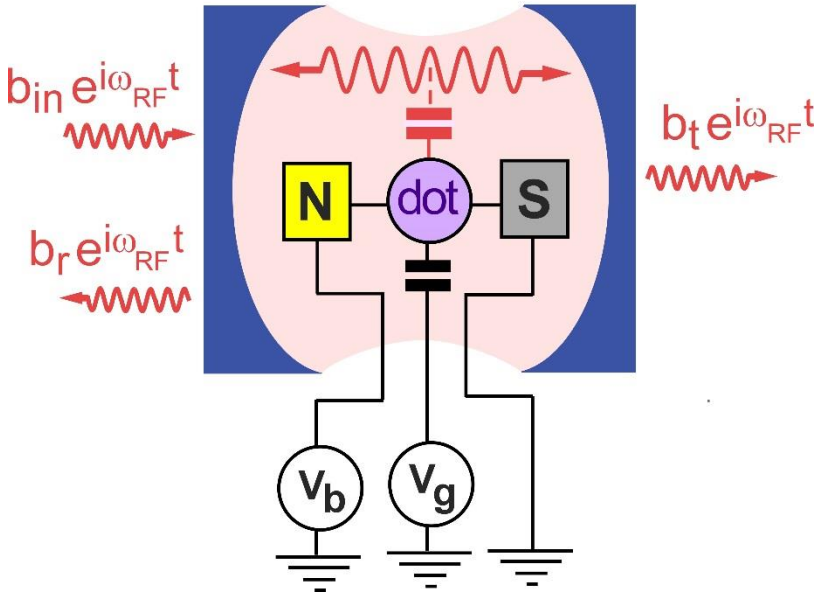
- Strong Coulomb blockade
- No Andreev reflections

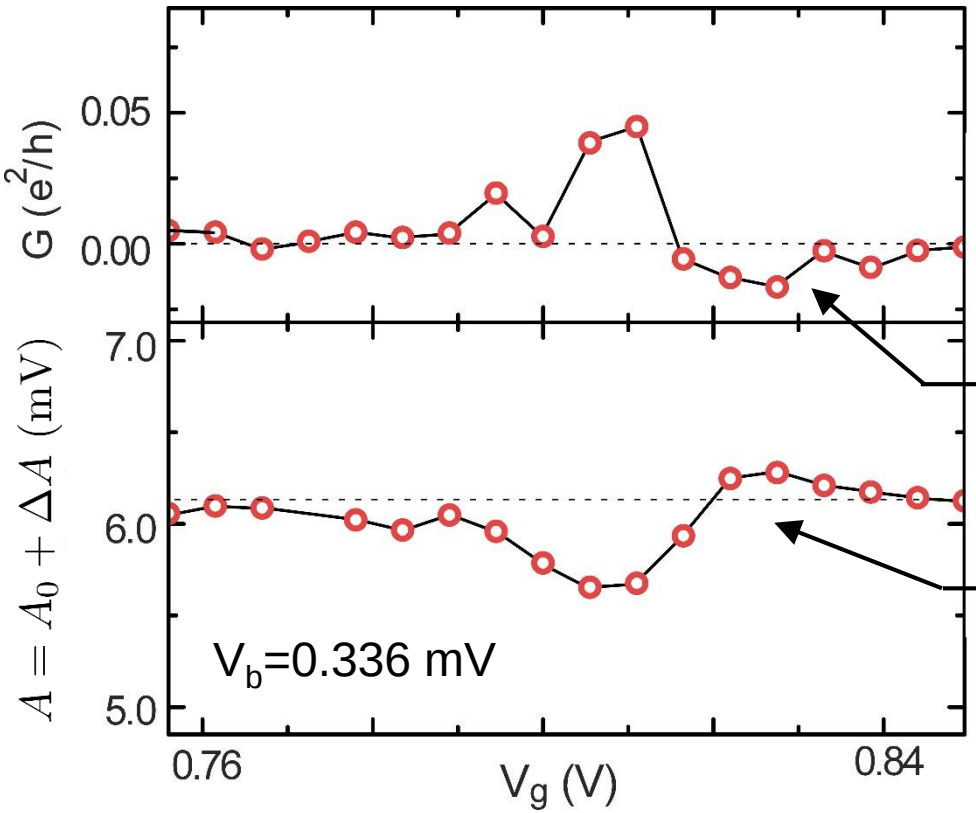
$\Rightarrow$ At V_b=0, effective dot/N junction

$\Rightarrow$ At V_b finite, S/dot/N bi-junction

S/dot/N bijunction at finite V_b

*Bruhat, Viennot, Dartiailh, Desjardins, Kontos & Cottet, PRX **6**, 021014 (2016)*





Negative differential conductance

A_0

Microwave Amplification $\Delta A>0$

Reminiscent of : Liu et al., Science 347, 285 (2015)
See also: Liu et al., PRL 113, 036801 (2014),
A. Stockklauser et al., PRL 115, 046802 (2015)

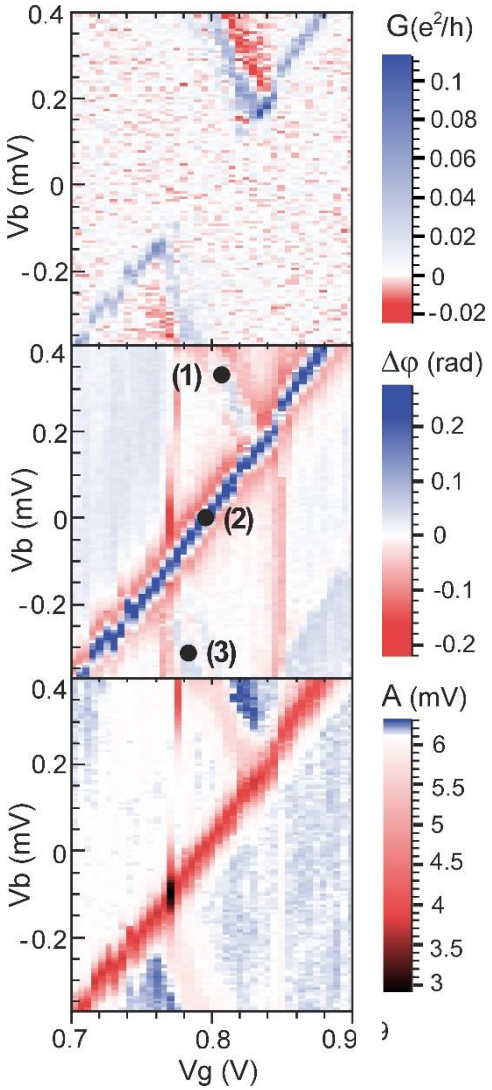
S/dot/N : data on large scale

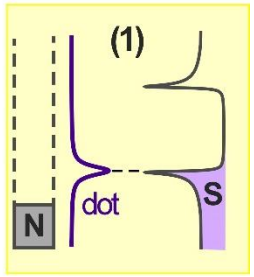
Negative differential resistance

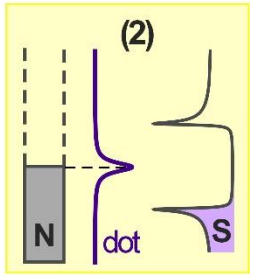
Sign changes in $\Delta\varphi$

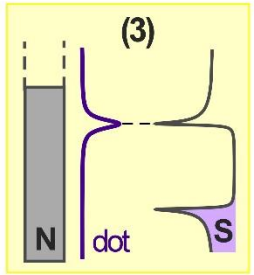
Microwave amplification $\Delta A>0$

Experiment









Test of theory at finite bias voltages

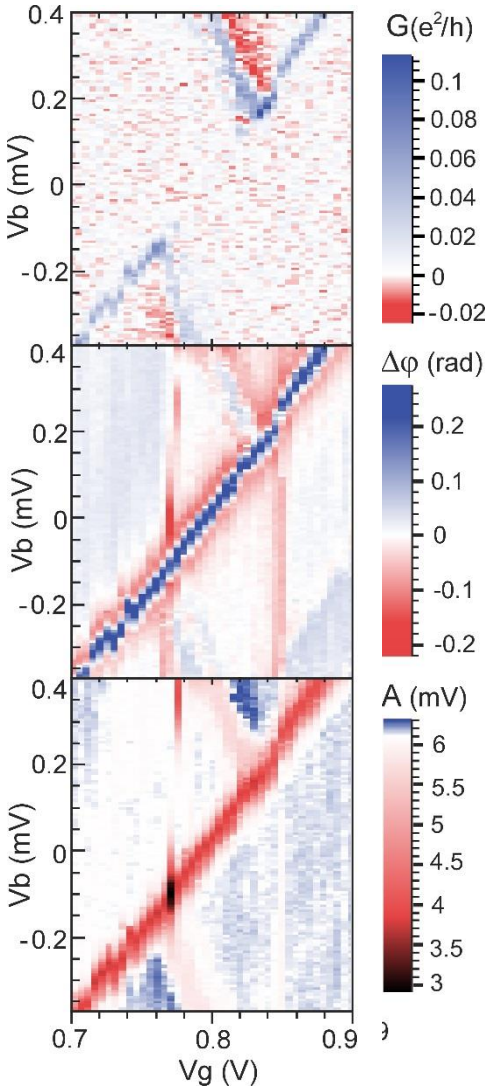
Experiment

Theory

Negative differential resistance

Sign changes in $\Delta\varphi$

Microwave amplification $\Delta A>0$



$$\frac{b_t}{b_{in}} = \frac{t_0}{\omega_{RF} - \omega_0 - i\Lambda_0 - g^2\chi(\omega_0)}$$

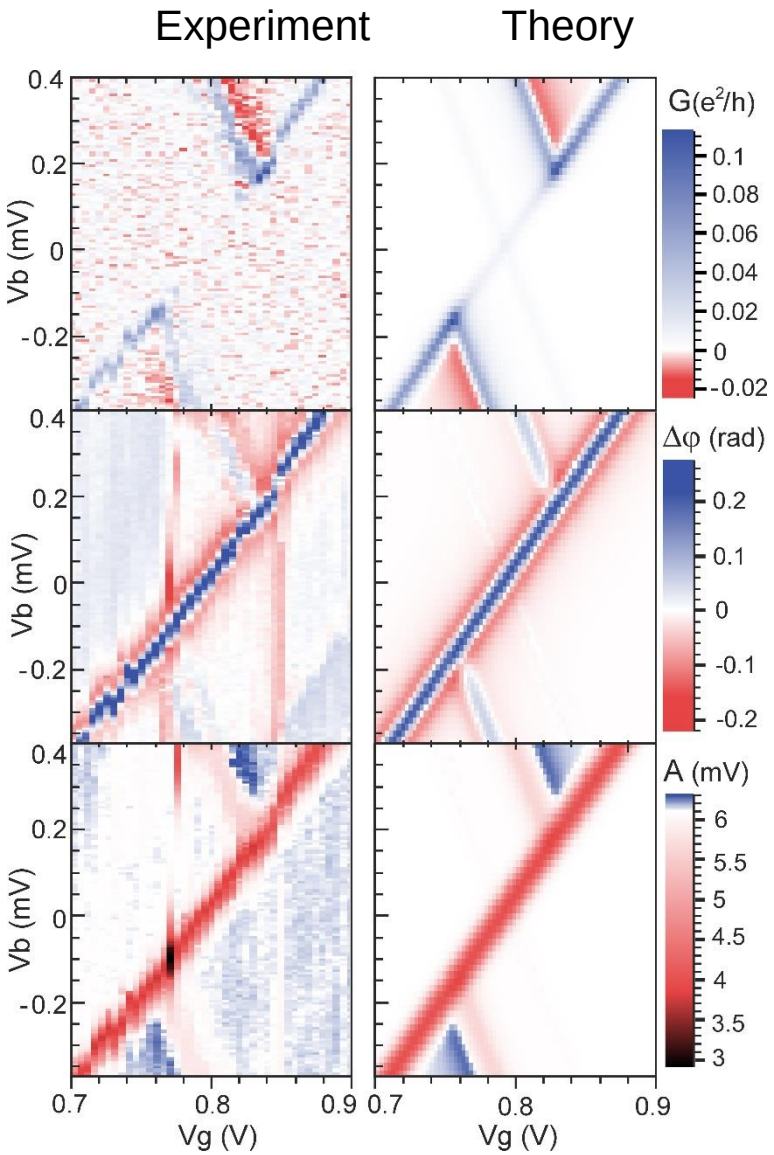
gap of S	$\Delta = 0.17$ meV
Temperature	$T = 90$ mK
dot/N tunnel rate	$\Gamma_N/2\pi = 0.6$ GHz
dot/S tunnel rate	$\Gamma_S/2\pi = 65$ MHz
BCS peaks broadening	$\Gamma_n/2\pi = 8$ GHz
dot/cavity coupling	$g/2\pi = 99$ MHz

Test of theory at finite bias voltages

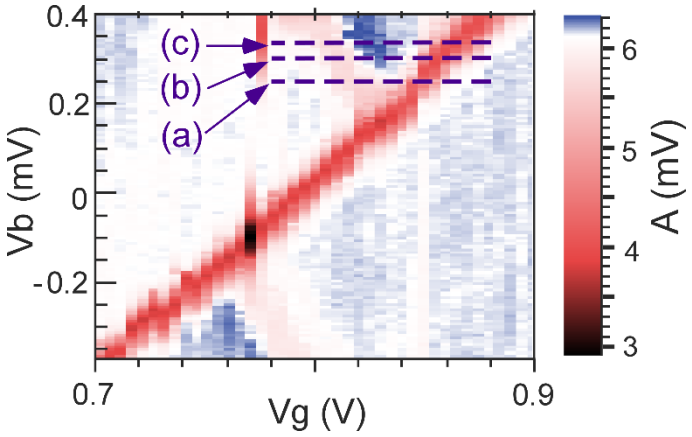
Negative differential resistance

Sign changes in $\Delta\varphi$

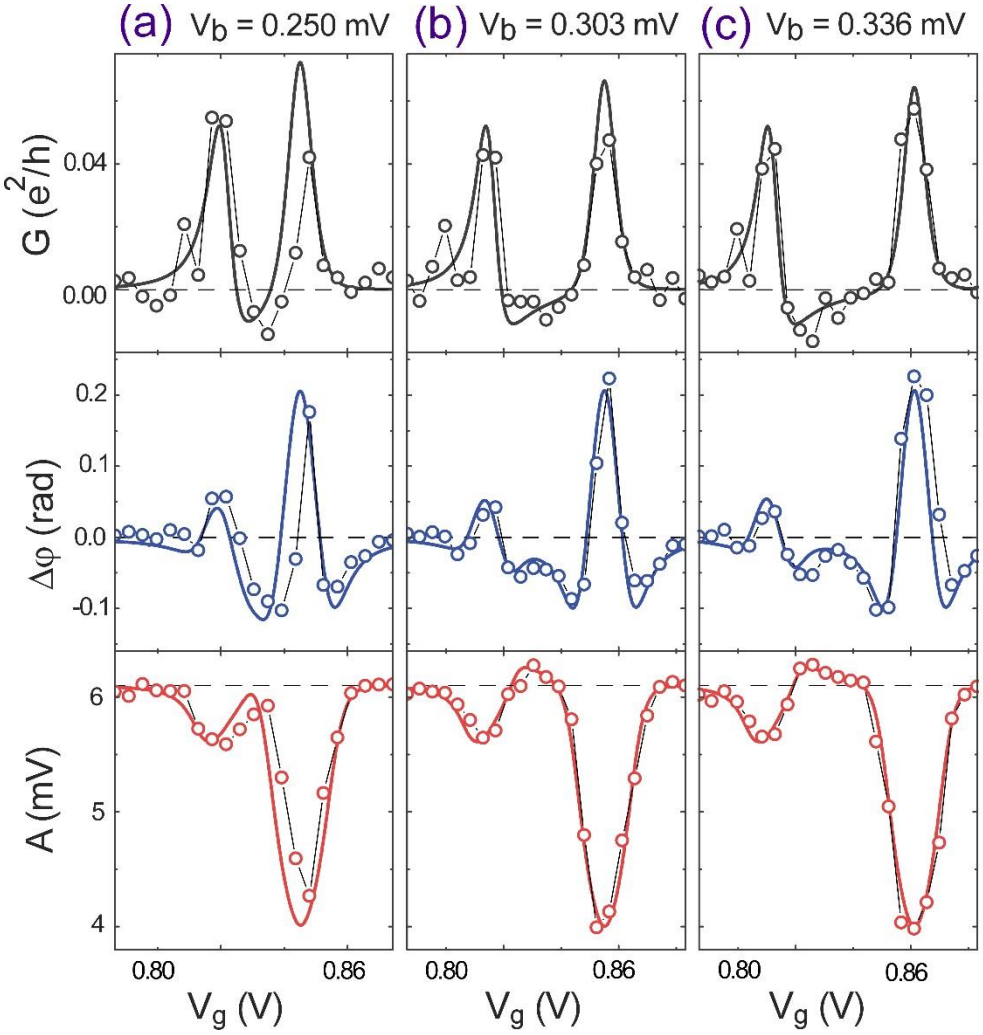
Microwave amplification $\Delta A>0$



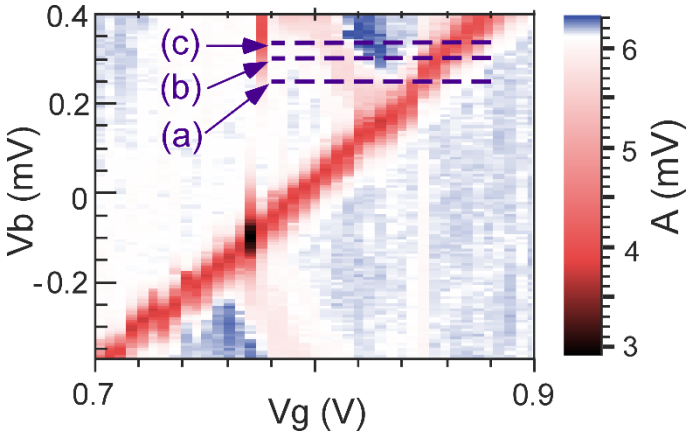
Test of theory at finite bias voltages



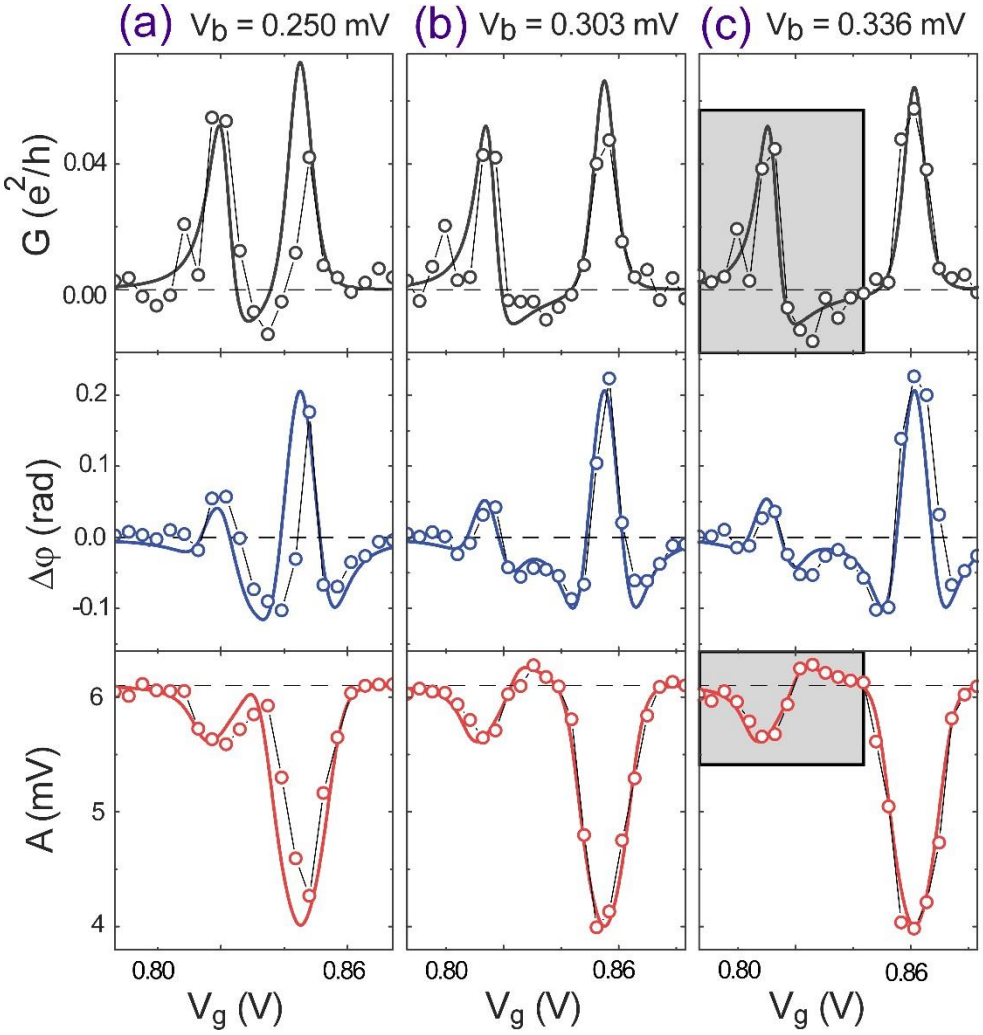
Quantitative modelling of the data



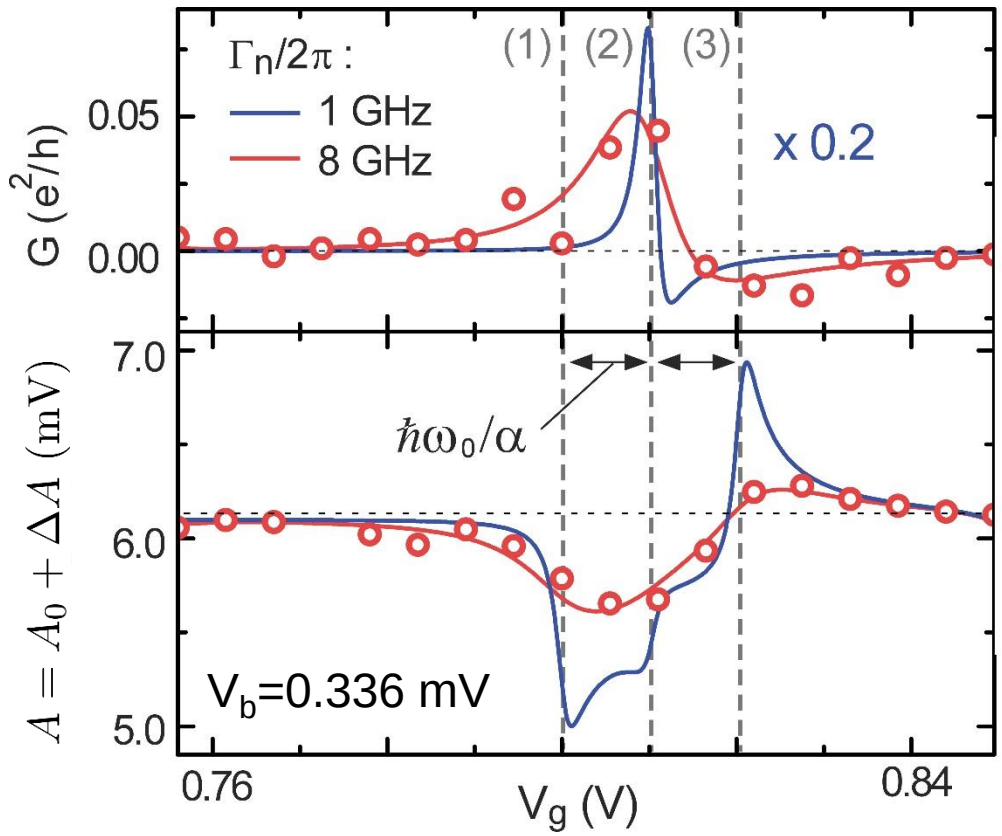
Test of theory at finite bias voltages



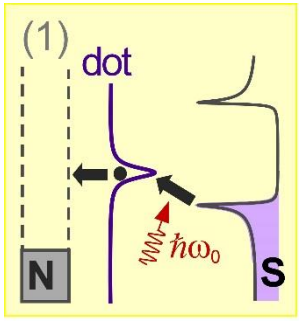
Quantitative modelling of the data



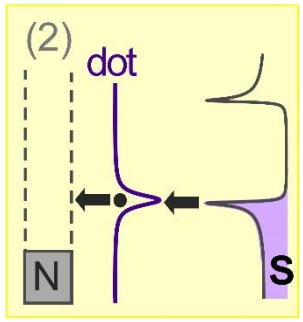
Inelastic tunneling between dot and S



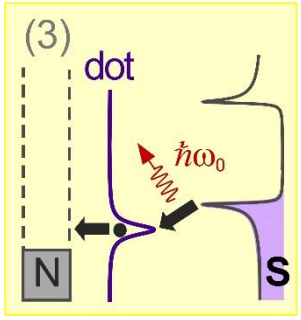
Photon-emission visible only through cavity!



Photon-absorption



Elastic transport



Photon-emission

$\Gamma_{e/a} \sim 2MHz$

~ 0.3 pA

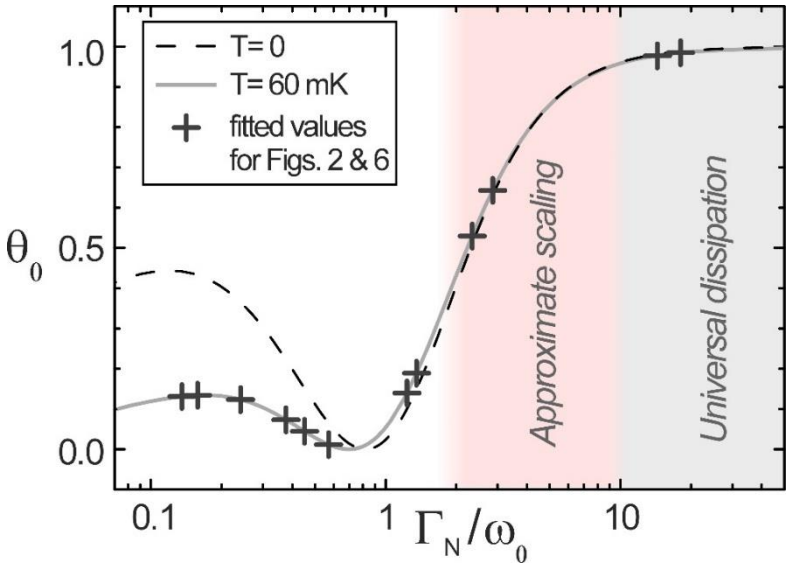
Conclusion

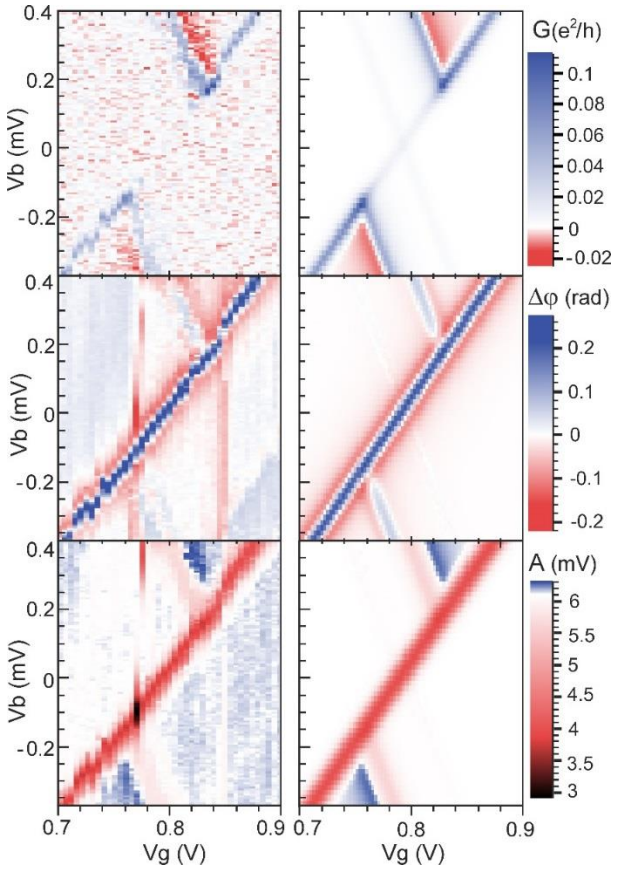
✓**cQED architecture can be used to study transport in quantum dots.**

✓**Study charge relaxation between a discrete level**

✓**Photon assisted tunneling between a quantum dot and a superconductor.**

L.E. Bruhat et al. Phys. Rev. X 6, 021014 (2016).





Perspective of this setup

- Probe of topological superconducting/Majorana fermions in S-wire hybrids