laboratoire pierre aigrain
électronique et photonique quantiques

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

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

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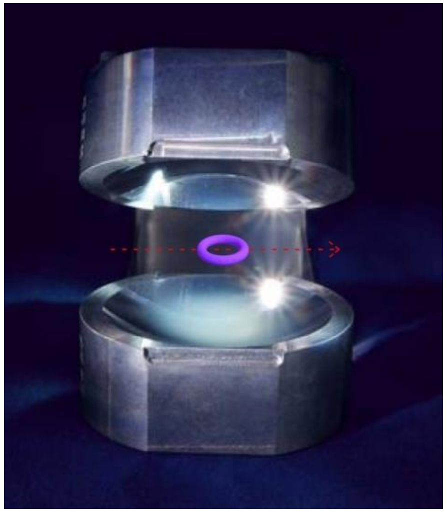
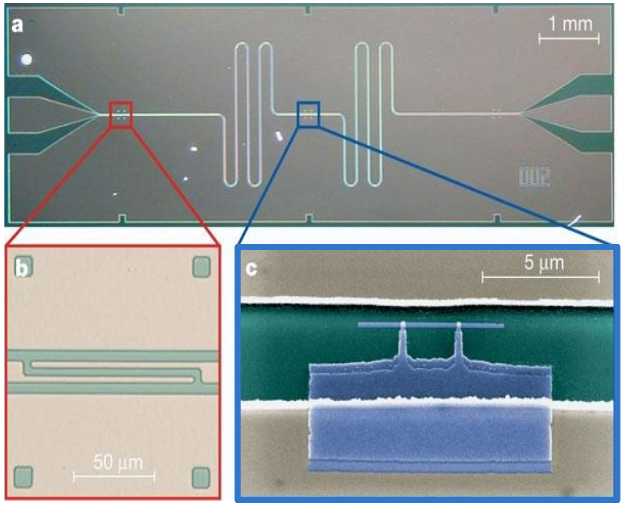
Cavity Quantum ElectroDynamics : from optical systems to superconducting chips

Atomic Cavity QED



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

Circuit QED



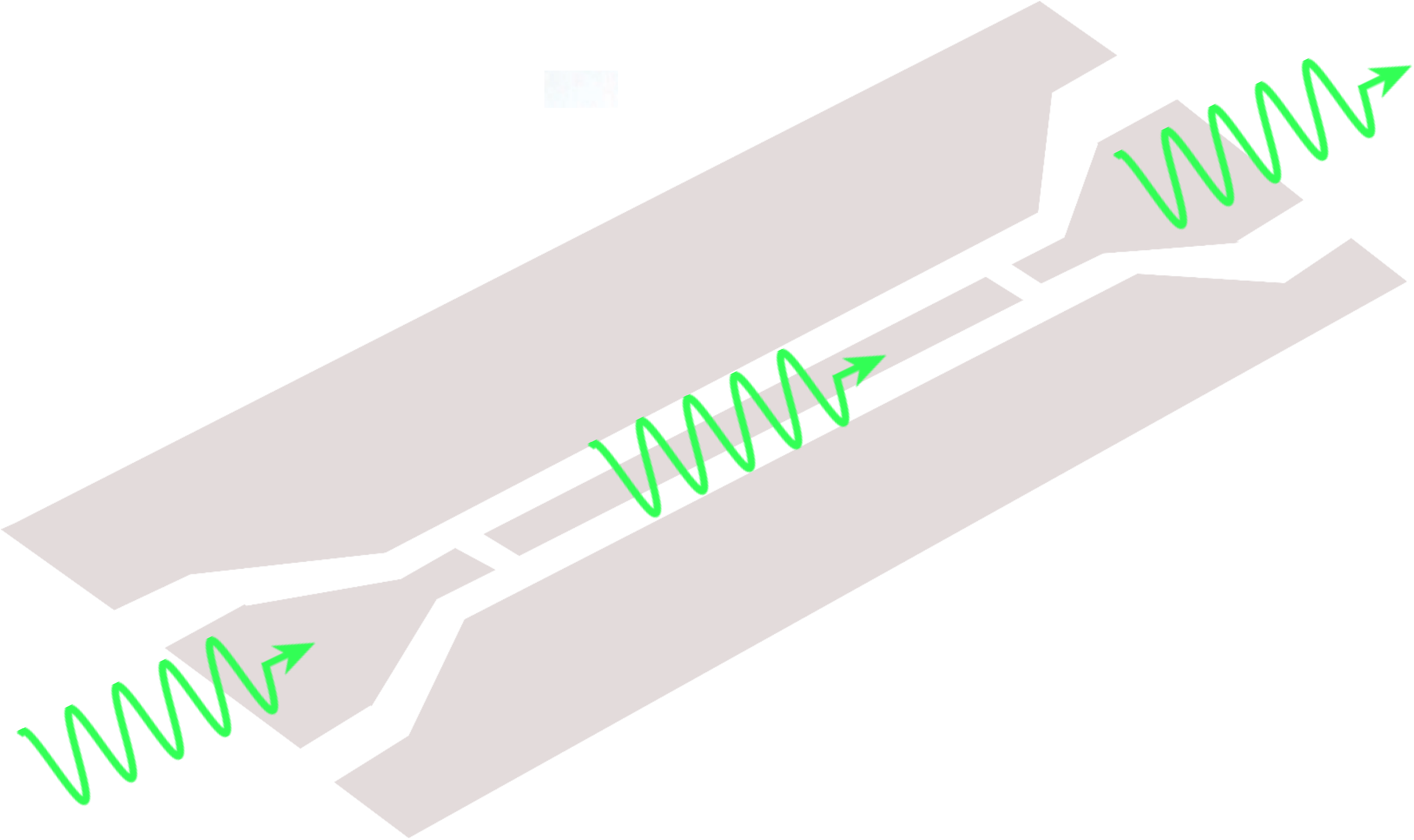
A. Wallraff et al., Nature 431, 162 (2004)

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

Two level system　Cavity photons　Coupling term

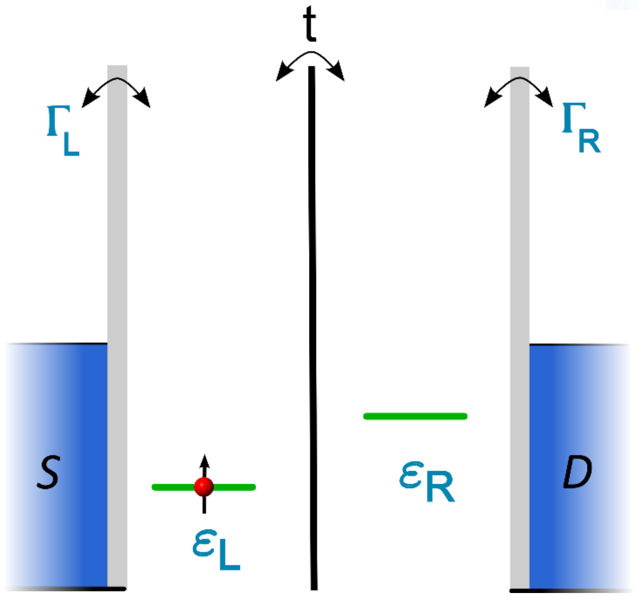
→ **Strong coupling regime = g > dissipation of photon, atom**

The cavity

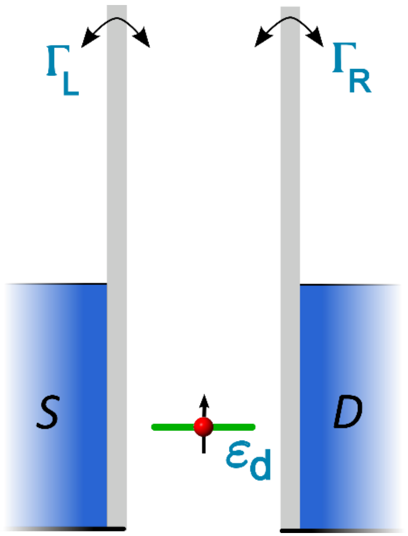


- Superconducting coplanar waveguide cavity (CPW).
- Fundamental frequency in the microwave range (6-7GHz). Q~15000
- Measurements carried out at ~20 mK-250mK

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)

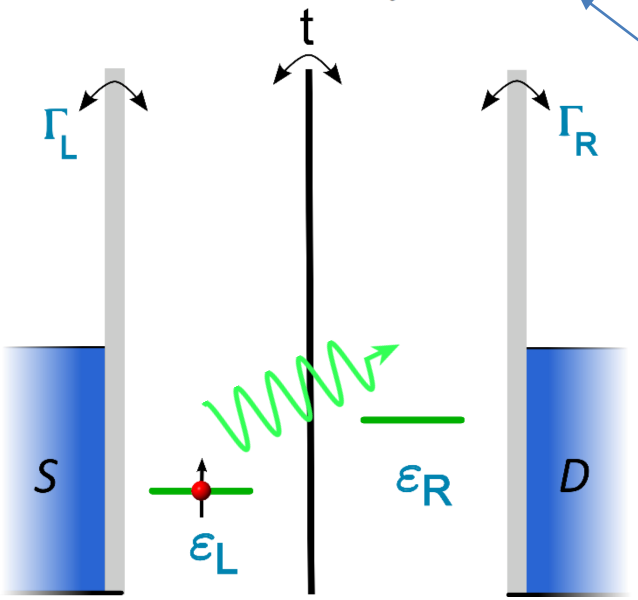
Light-matter coupling

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

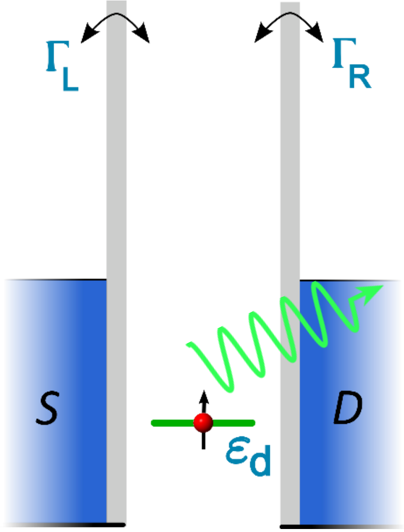
« form factor for the e.m. field»

density

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



Closed system
Quantum information



Open system
Impurity physics : condensed matter

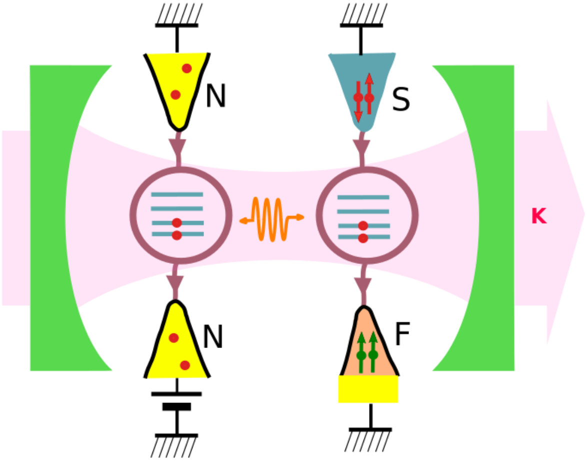
- Electric coupling to the charge density of the conductors (from gauge invariance)
- Internal transitions and transitions to leads possible (cavity to circuit QED)
- Large dipoles (g ~10-100 MHz) due to mesoscopic scale

A. Cottet, T. Kontos and B. Douçot, 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)



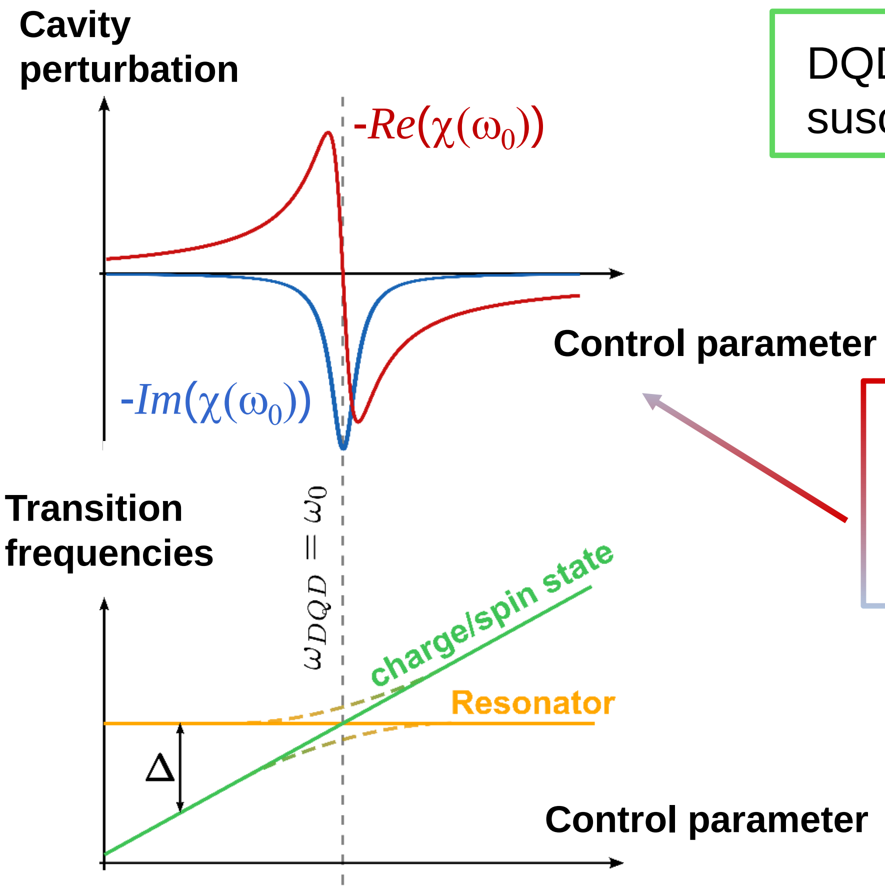
➡ **Can one achieve the strong coupling with quantum dot circuits ?**

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

$$\omega_{RF}=\omega_0$$

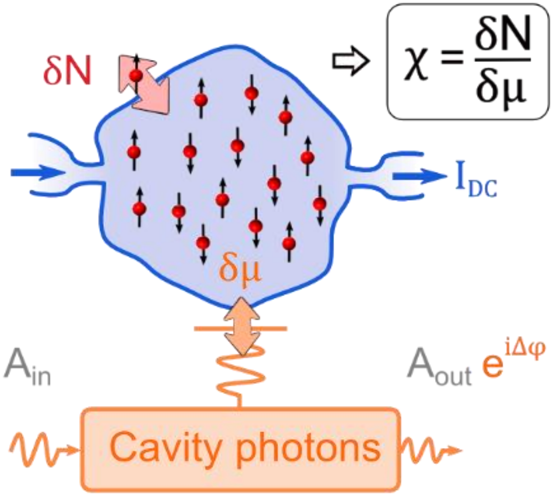
$$\Rightarrow$$

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), **…**

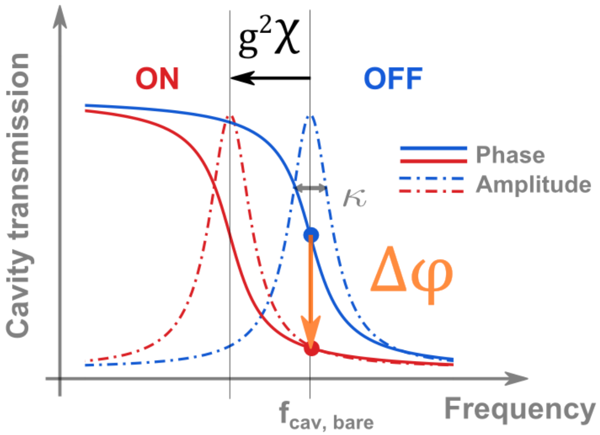
Resonator response: susceptibility II

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



Adiabatic regime

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



⇨

The cavity provides
a direct compressibility
measurement

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

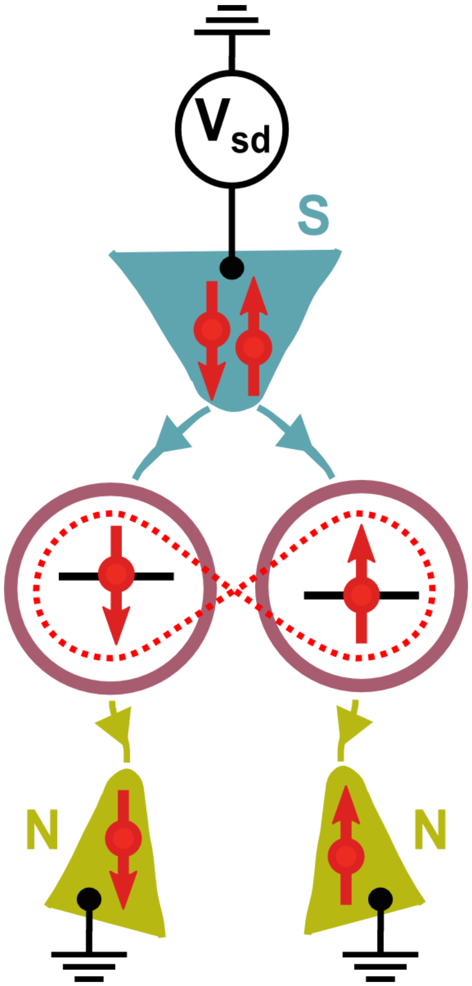
Hybrid circuit QED with quantum dots

➡ Can one achieve the strong coupling with quantum dot circuits ?

L. E. Bruhat et al. submitted ‘16

Cooper pair splitter device

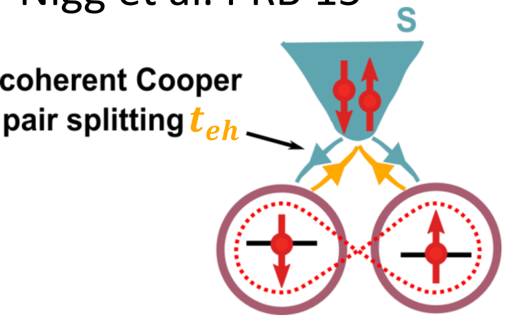
Beamsplitter geometry



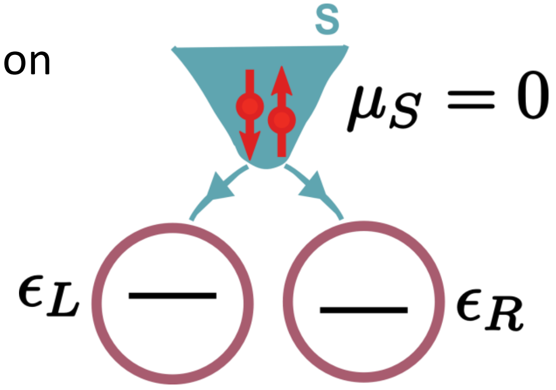
➡ Physics of Cooper pair splitting studied by transport so far (CNT, SC nanowires, graphene).

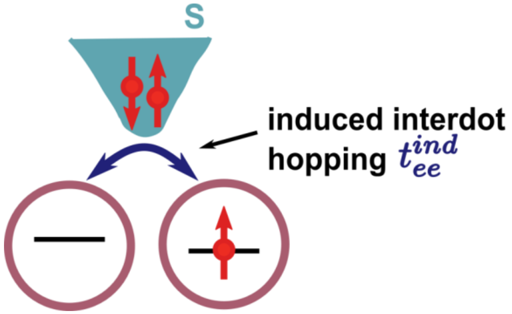
Interfacing dots and superconductors

From Schrieffer-Wolf transformation
Nigg et al. PRB'15



(0,0)/(1,1) sector





(1,0)/(0,1) sector

$$t_{eh} \sim -\pi\sqrt{\Gamma_{SL}\Gamma_{SR}}\cos(k_F\delta x)\, e^{-\frac{|\delta x|}{\xi_0}} f\left(\frac{\epsilon_\Sigma}{\Delta},\frac{\epsilon_\delta}{\Delta}\right) + \frac{2t}{\Delta}(\Gamma_{SL}+\Gamma_{SR}) \qquad t_{eh}|0\rangle\langle S| + \text{h.c.}$$

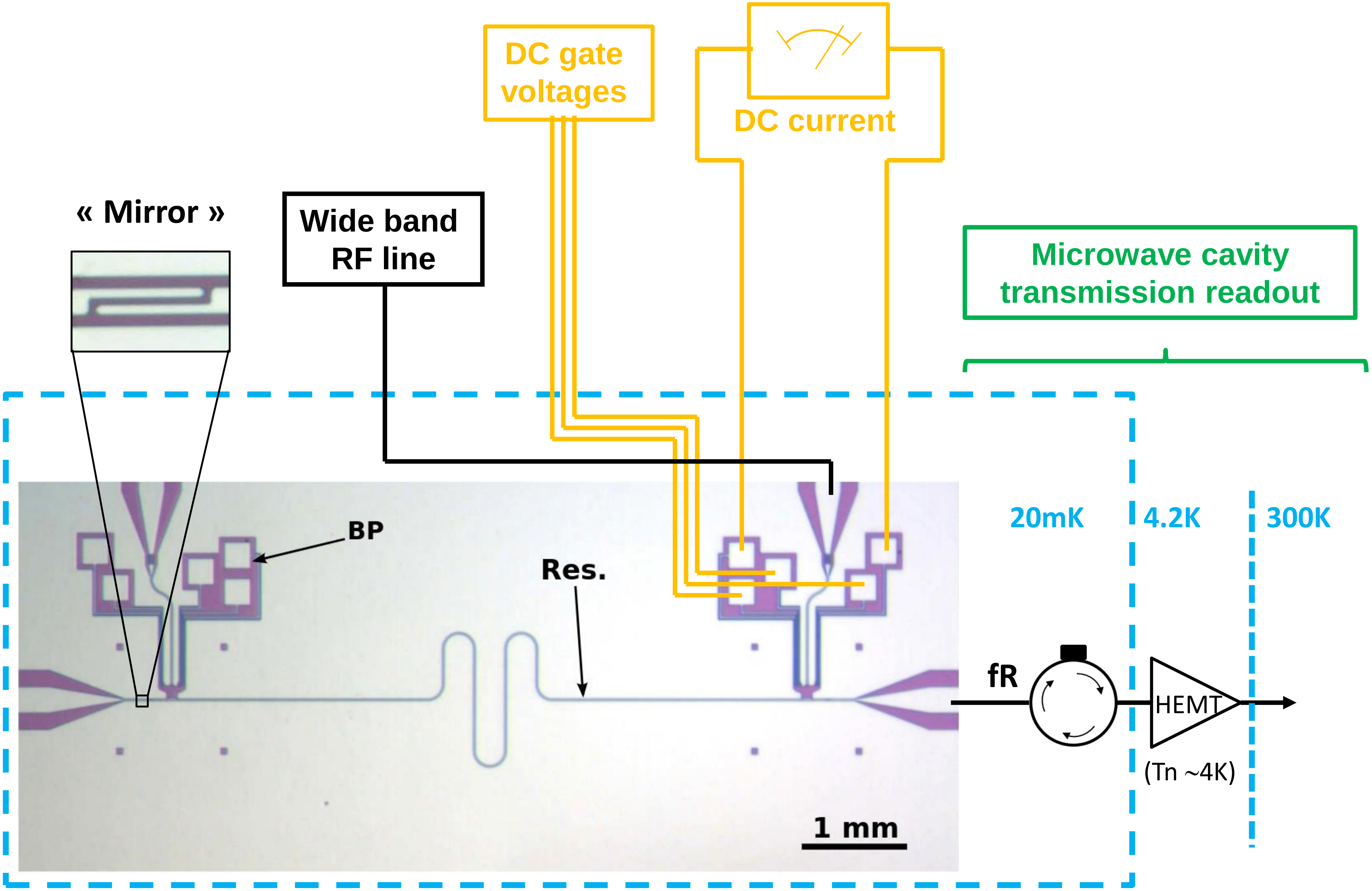
$$t_{ee}^{ind} \sim -\pi\sqrt{\Gamma_{SL}\Gamma_{SR}}\cos(k_F\delta x)\, e^{-\frac{|\delta x|}{\xi_0}} g\left(\frac{\epsilon_\Sigma}{\Delta},\frac{\epsilon_\delta}{\Delta}\right) + \frac{2t}{\Delta}(\Gamma_{SR}-\Gamma_{SL})\, h\left(\frac{\epsilon_\Sigma}{\Delta},\frac{\epsilon_\delta}{\Delta}\right) \qquad t_{ee}^{ind}|B\rangle\langle AB| + \text{h.c.}$$

$$\epsilon_\Sigma = \epsilon_R + \epsilon_L + U_m \qquad \epsilon_\delta = \epsilon_R - \epsilon_L$$

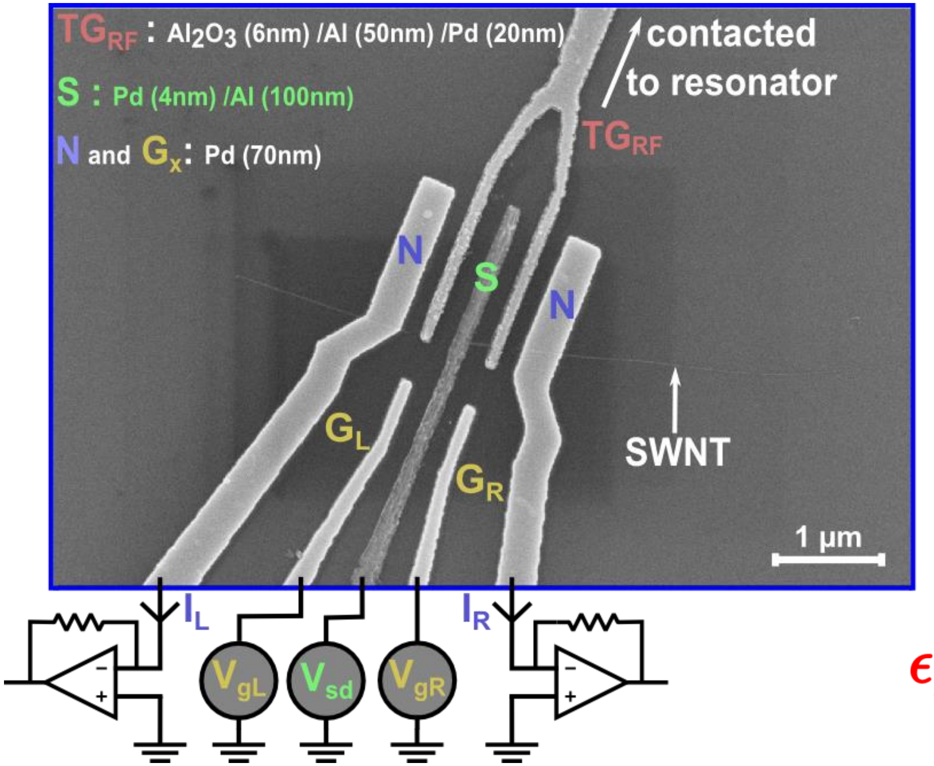
➡ t_{eh} and t^{ind}_{ee} both depend on ϵ_Σ and ϵ_δ as a result of Cooper pair splitting

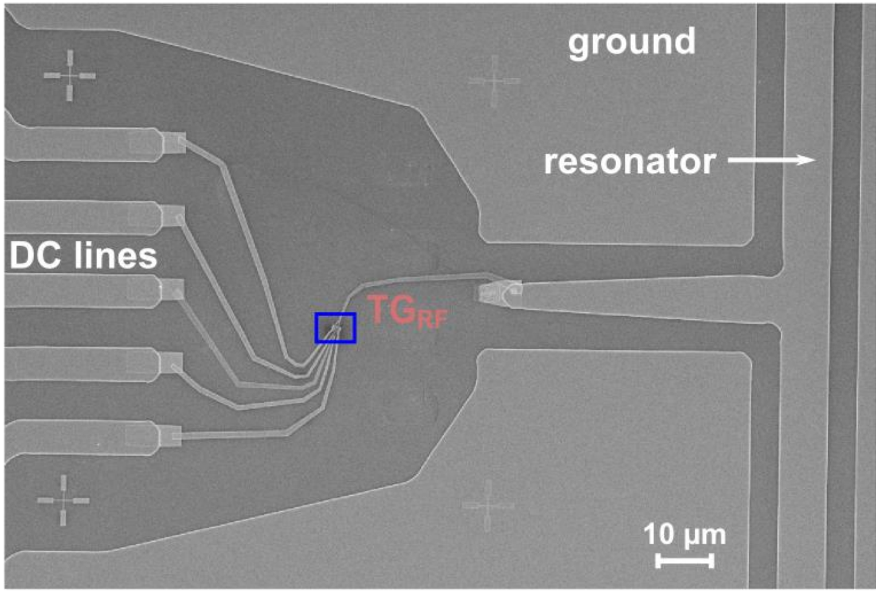
Hofstetter et al. Nature'09, L.G. Herrmann et al., PRL'10, Das, A. et al., *Nat. Com.*'12, Z. B. Tan et al. PRL'15, I. V. Borzenets et al. arXiv:1506.04597, R. S. Deacon et al. Nat. Com **6**, 7446 (2015) J. Schindele et al. PRL'13, M.-S. Choi et al. PRB'00, J. Eldridge et al. PRB'10, P. Burset et al. PRB'11 , T. Martin, Phys. Lett'96 , G. Deutscher and D. Feinberg, APL'00, P. Recher et al. '01….

Measurement setup



Cooper pair splitter in a cavity





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

Nb resonator parameters :

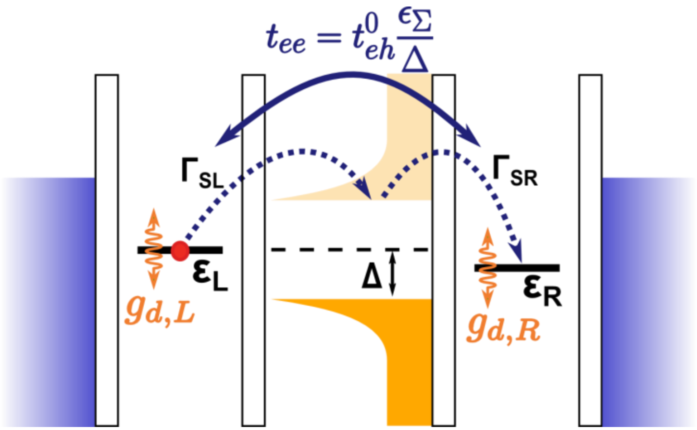
$Q \approx 10000$

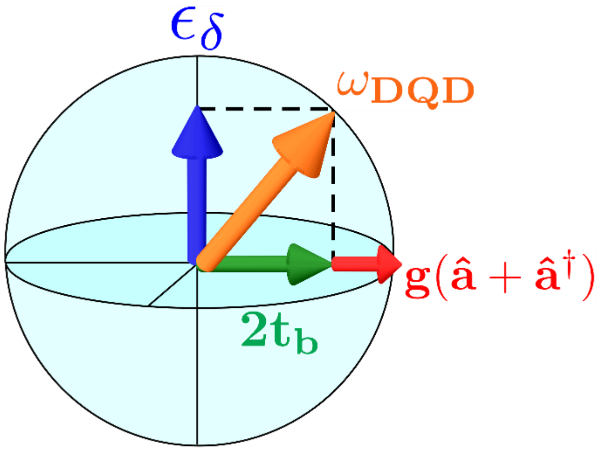
$f_c = 6.6480$ GHz

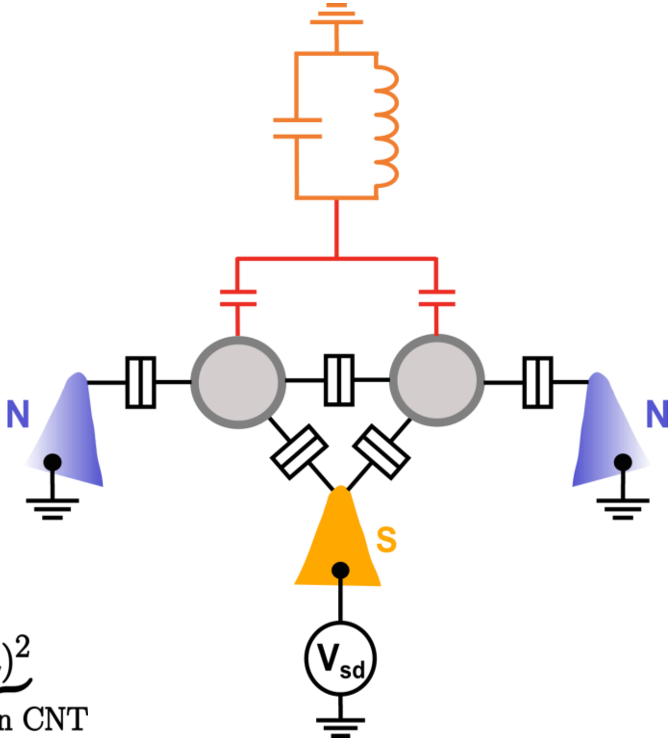
Measurements :

- Currents : I_L, I_R
- Resonator transmission : amplitude and phase

Coupling scheme vs dephasing







$$\Gamma_2^* \sim \underbrace{\frac{\partial^2 E}{\partial \epsilon_\delta^2}}_{\sim\frac{1}{2\omega_c}} E_c^2 \underbrace{(\delta n)^2}_{\sim 10^{-8}\text{ in CNT}}$$

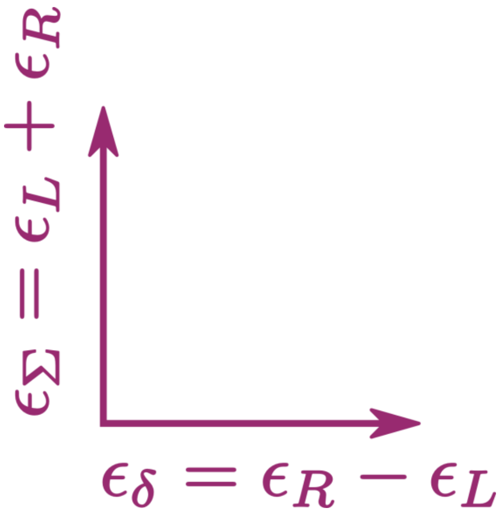
For Ec ≈ 10 meV, $\Gamma_2 \approx$ 550MHz

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

Here Ec ≈ 1 meV, $\Gamma_2 \approx$ 5MHz

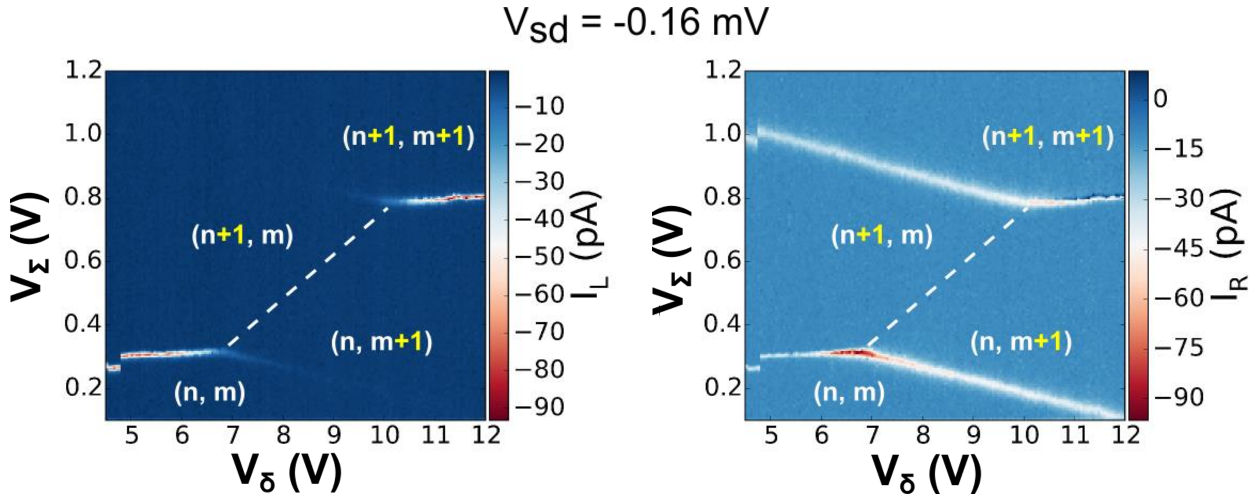
- Renormalization of L/R hoping from elastic cotunnelling through superconductor
- Induce large transverse coupling via symmetric coupling to em field
- Lower charge noise than in other setups

Transport measurement



$\epsilon_\Sigma = \epsilon_L + \epsilon_R$

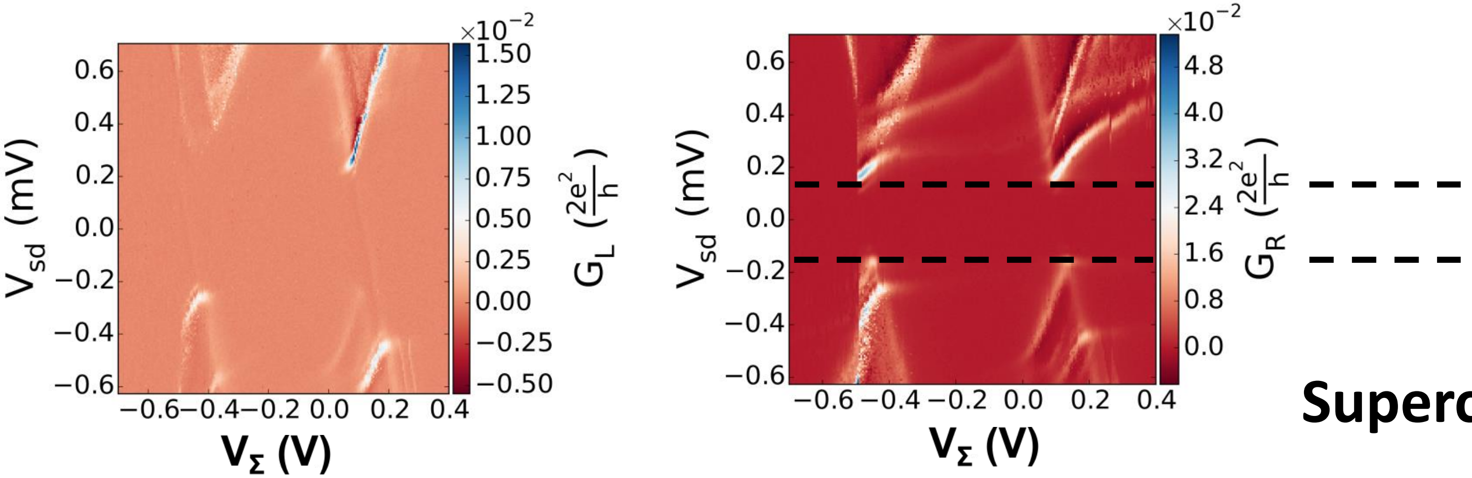
$\epsilon_\delta = \epsilon_R - \epsilon_L$



V_{sd} = -0.16 mV

Double dot stability diagram :

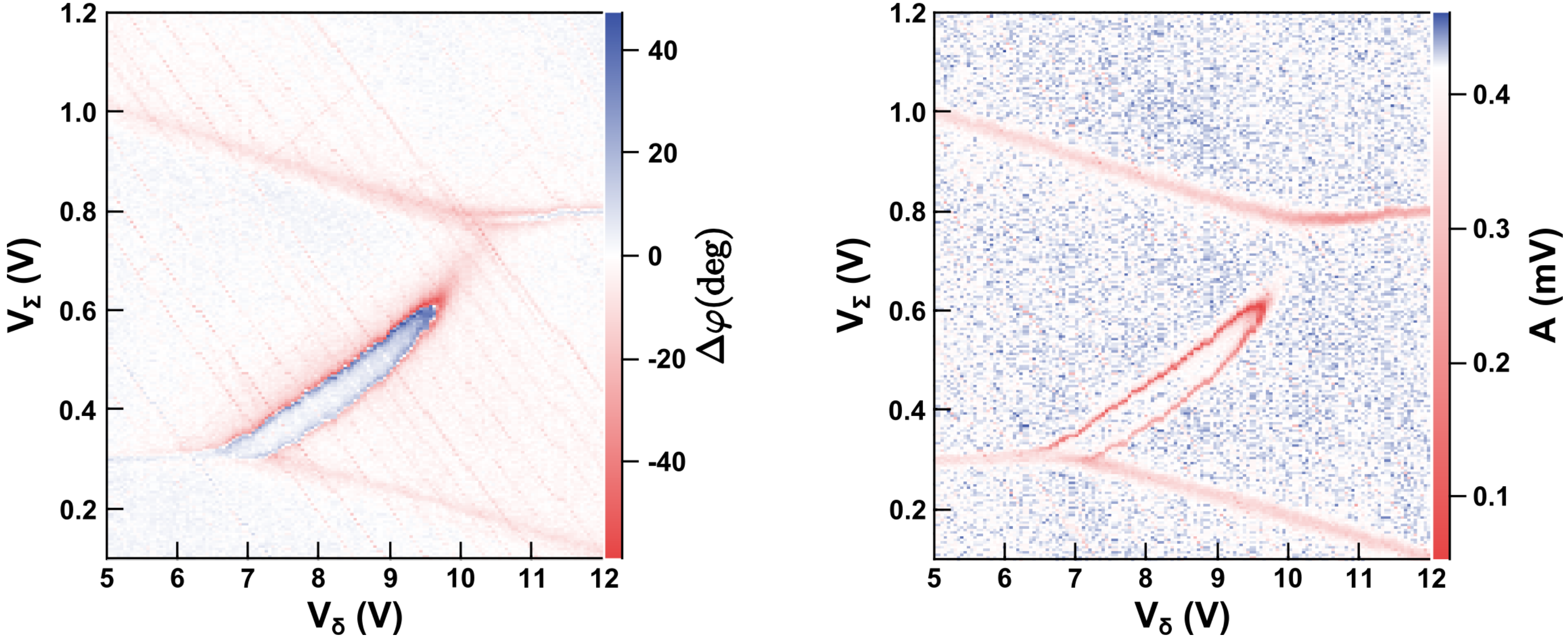
2 spatially separated orbitals



Δ = 150 µV

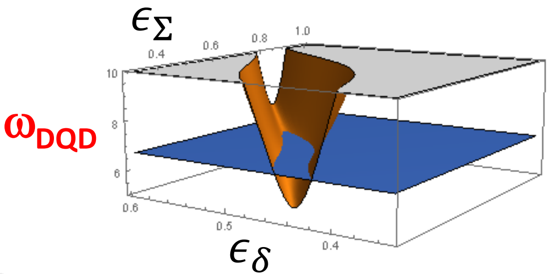
Superconducting gap

Cavity measurement



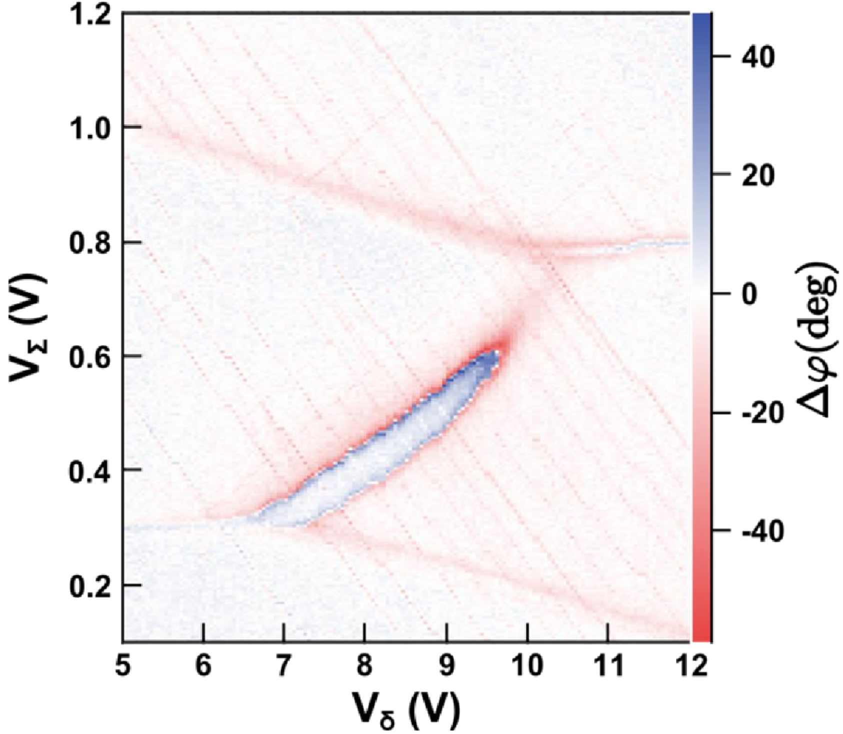
- Resonant interaction between cavity and hybrid superconducting-quantum circuit
- Internal transitions depend both on ϵ_Σ and ϵ_δ. Distortions in detuning (different from variable barrier see A. Stockklauser et al . PRL'15)

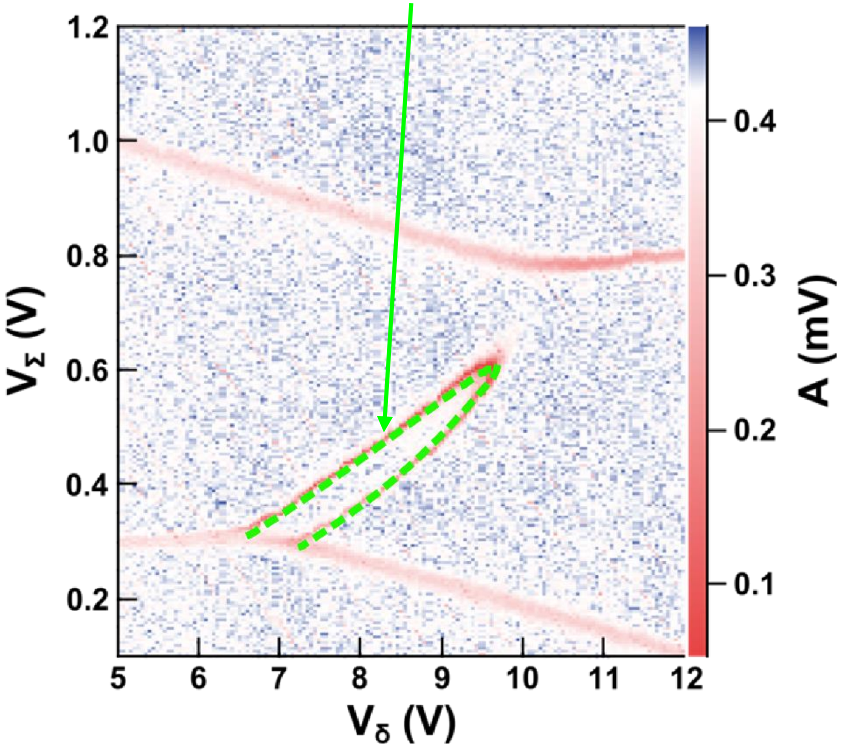
Cavity measurement



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

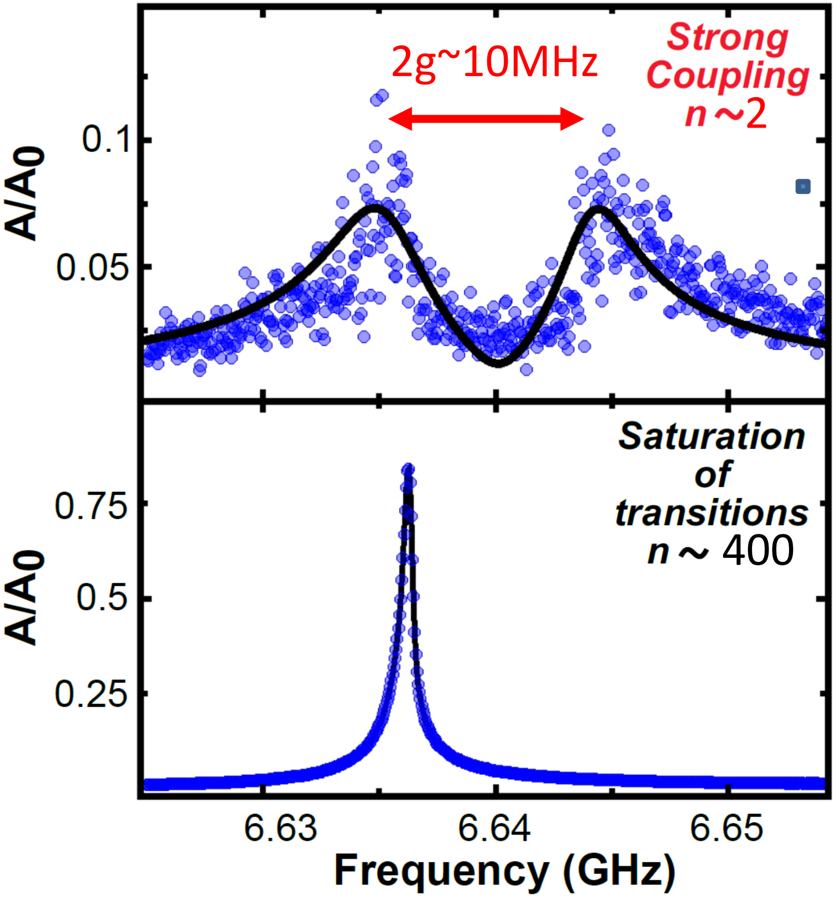
$$\sqrt{(\epsilon_\delta{}^2 + 4t^2)Z(\epsilon_\Sigma, \epsilon_\delta)^2 + 4t_{ee}^{ind}(\epsilon_\Sigma, \epsilon_\delta)^2}$$

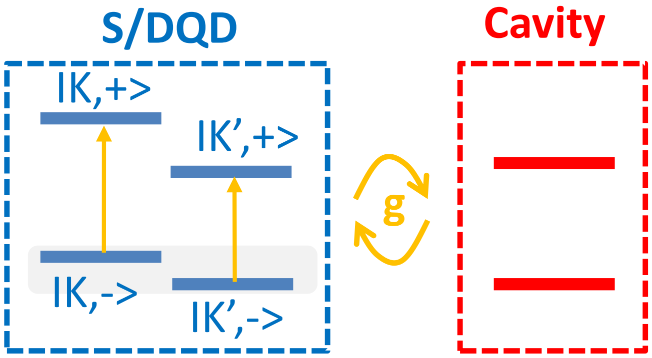


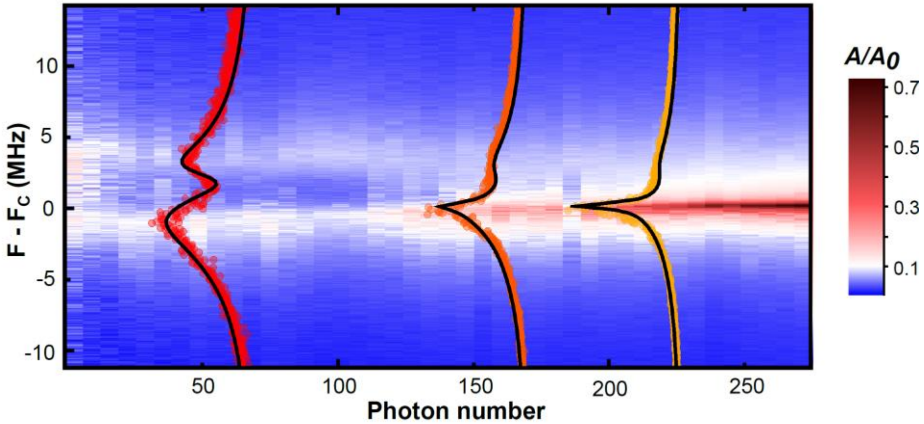


- Resonant interaction between cavity and hybrid superconducting-quantum circuit
- Internal transitions depend both on ϵ_Σ and ϵ_δ!
- Quantitative agreement with S-induced low energy spectrum.

Engineering strong coupling with hybrid S/dot circuit







- Largest Vacuum Rabi splitting about 10 MHz ~ 3 line widths
- Power dependence consistent with saturation of B/AB transitions
- Quantitative agreement with theory + 2 B/AB transitions

➡ First observation of strong coupling between a quantum dot circuit and a microwave cavity

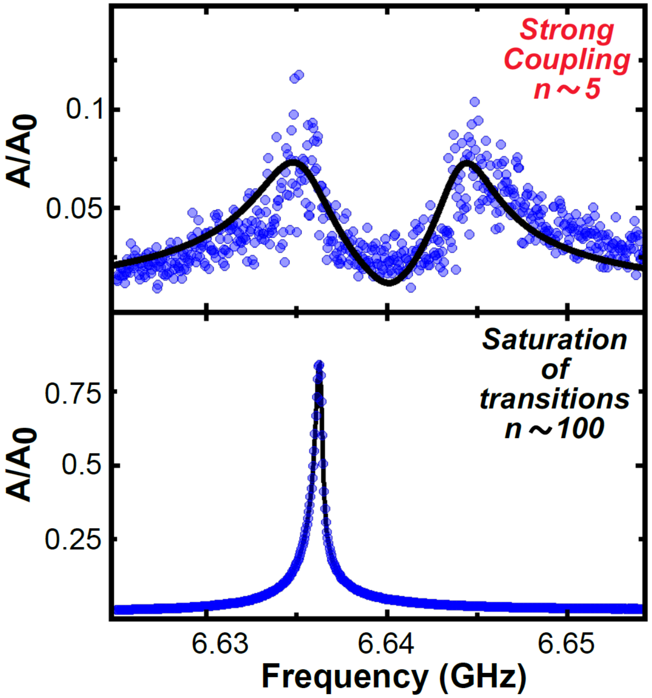
Conclusion I

✓ **First observation of strong coupling between a quantum dot circuit and cavity photons (could be generalized to many other setups RX qubits,...)**

✓**Cavity QED with a hybrid superconductor-quantum dot circuit**

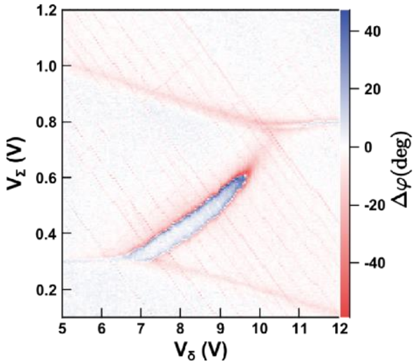
✓ **Study of Cooper pair splitting physics (t^0_{eh}~400MHz)**

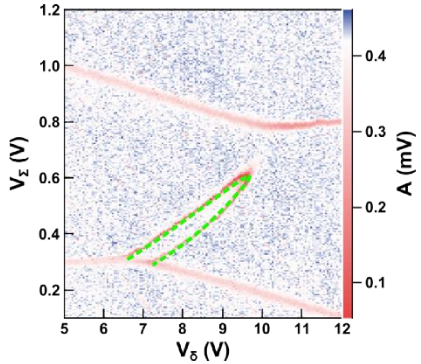
L. E. Bruhat et al. submitted '16



Perspectives

- ✓ Ultra-long distance coupling of double quantum dots. **(G. Burkard, A. Immamoglu PRB'06)**
- ✓ Entanglement in condensed matter (Cooper pair splitting)





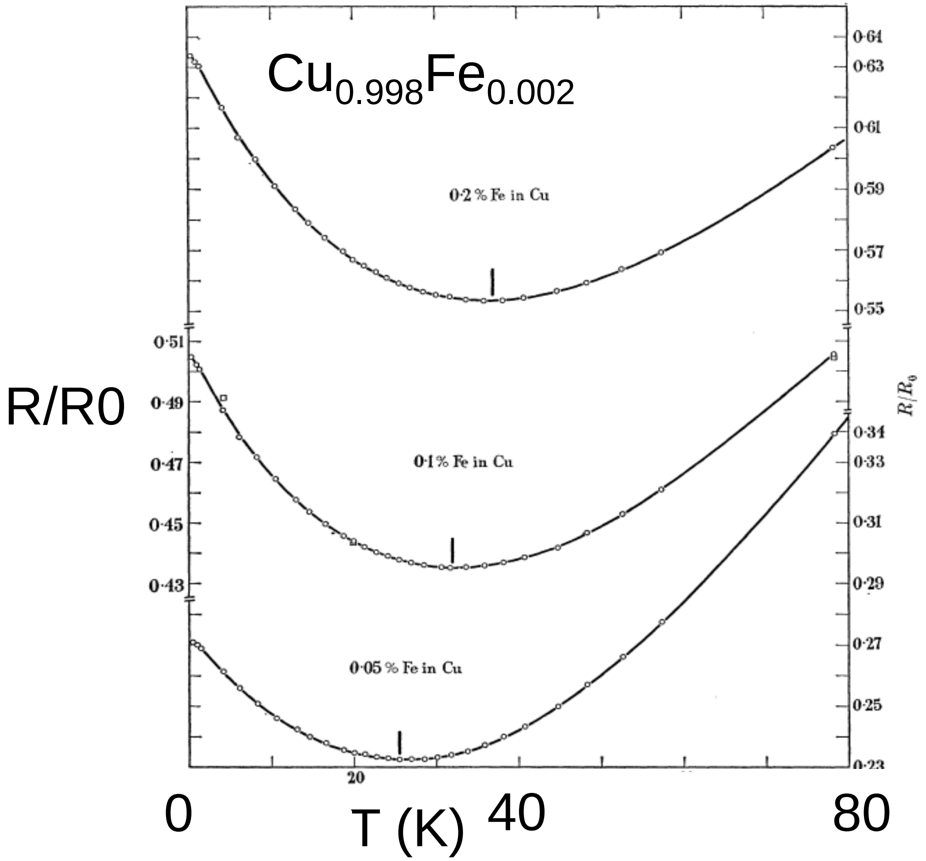
Hybrid circuit QED with quantum dots

➡ Can one use that architecture for condensed matter questions ?

M.M. Desjardins et al. submitted ‘16

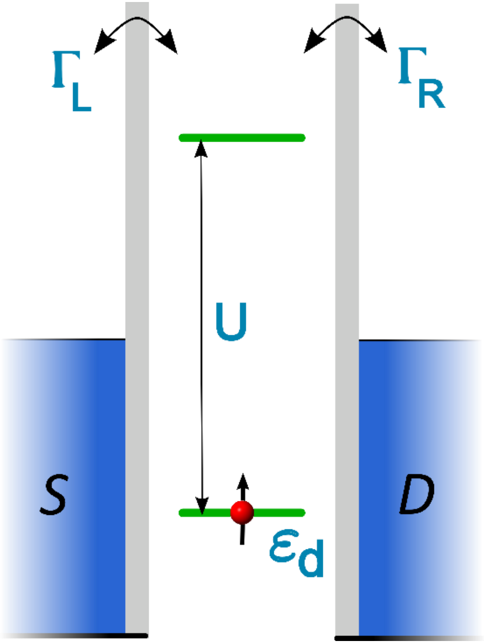
Kondo physics in alloys

J. P. Franck et al. Proc. Roy. Soc. **A263**, 494 (1961)



- Resistance of a metal usually decreases as temperature lowered.
- Increase of resistance in some magnetic alloys even though tiny amount of magnetic impurities added !
- Discovered as early as in the 1930’s

Anderson model for a magnetic impurity



P.W. Anderson '61

ε_d = energy level of the quantum dot

U = charging energy

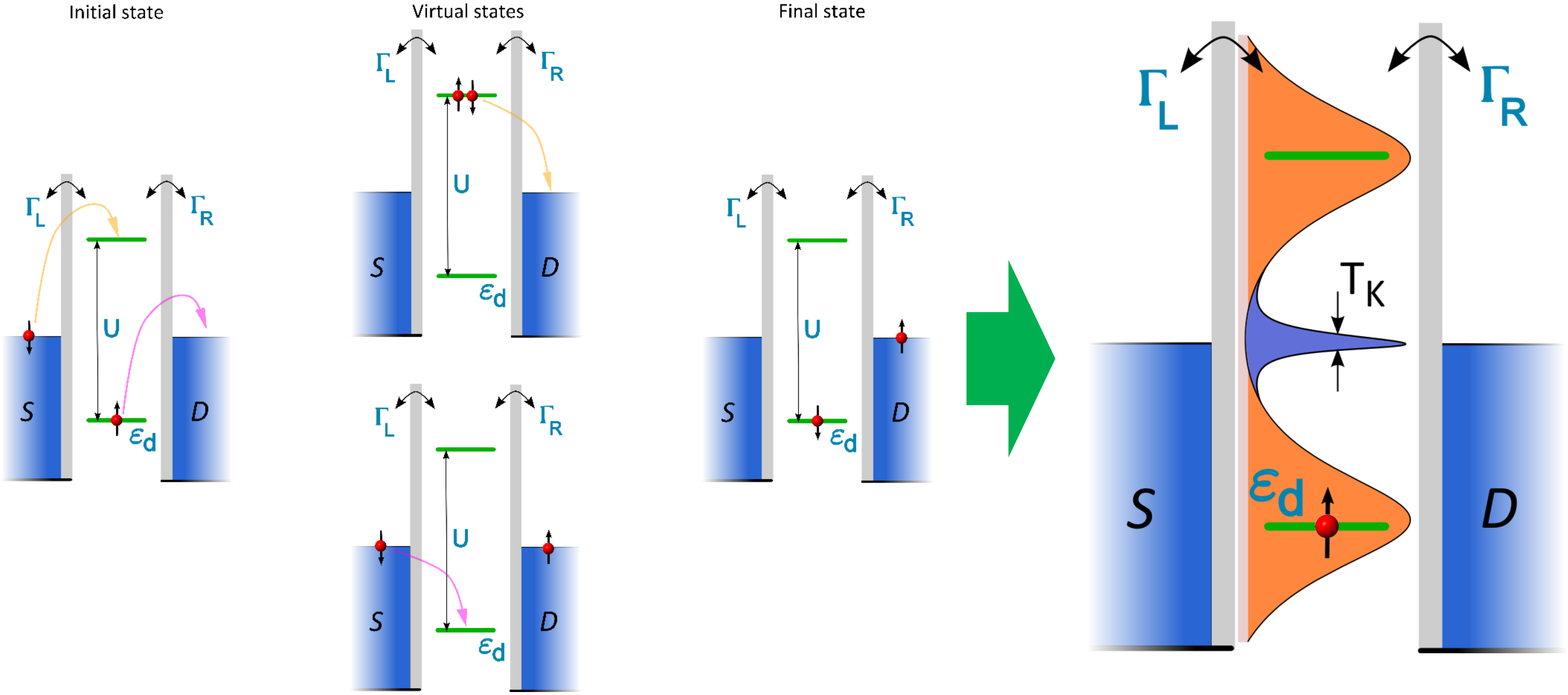
Γ's = coupling to Fermi sea of host matrix

- Simplest model of a magnetic impurity… U favors magnetic moment.
- Can be mapped onto Kondo (spin) problem at low energy (Schrieffer-Wolf)

➡ « Simplest » many body problem (energy level with coulomb +Fermi sea)

➡ Physics relevant for many condensed matter systems (« test bench »)

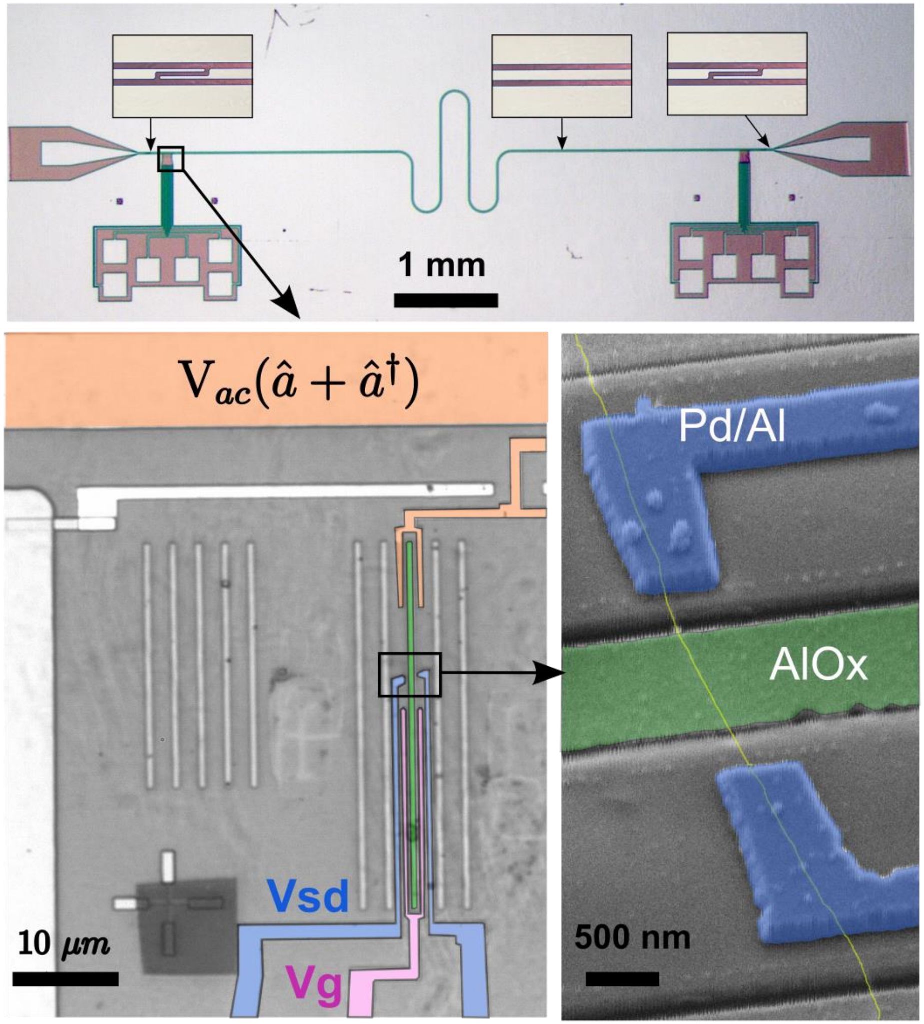
Virtual processes and Kondo/AS resonance



- Virtual processes quantum mechanically allowed at equilibrium
- Decoupling of spin and charge degrees of freedom (not usual resonant level)

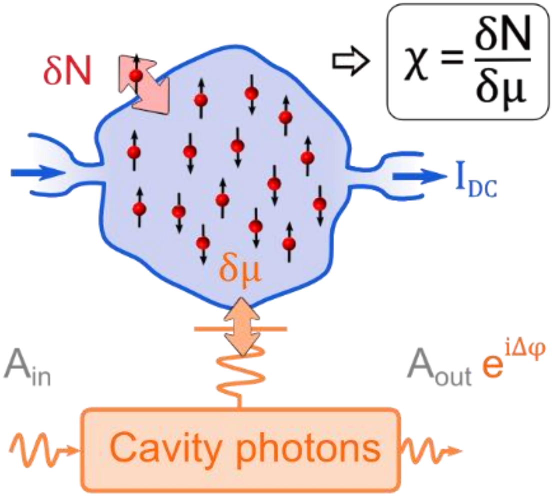
➡ Contribute to current through impurity although charge frozen

The experimental setup



Carbon nanotube based quantum dot

Stamped single wall carbon nanotubes in high finesse Nb microwave cavity (Q~15000)



Cavity measures directly the compressibility of the electronic system

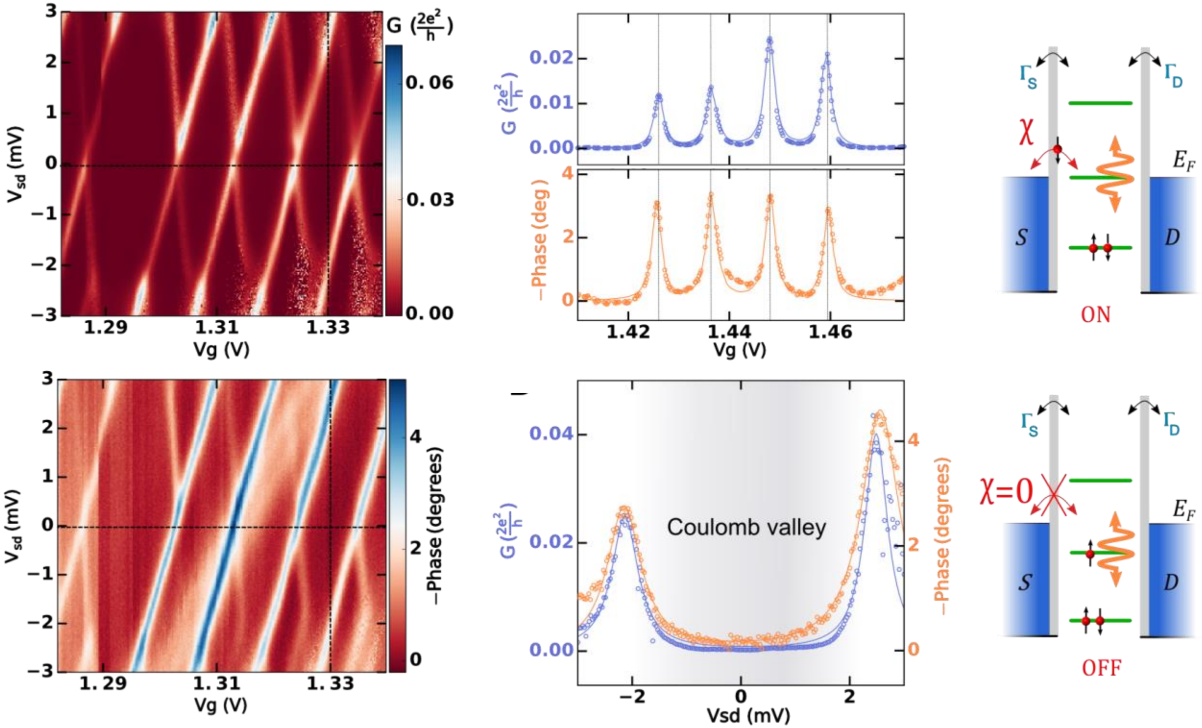
Simultaneous measurement of conductance and compressibility

Electron-photon coupling calibration

Coulomb blockade :
U ~ 3meV and Γ~0.7 meV

Compressibility contrast ~1000 eV^{-1}
Piece of metal of 1µm^3 ~10^{10} eV^{-1}

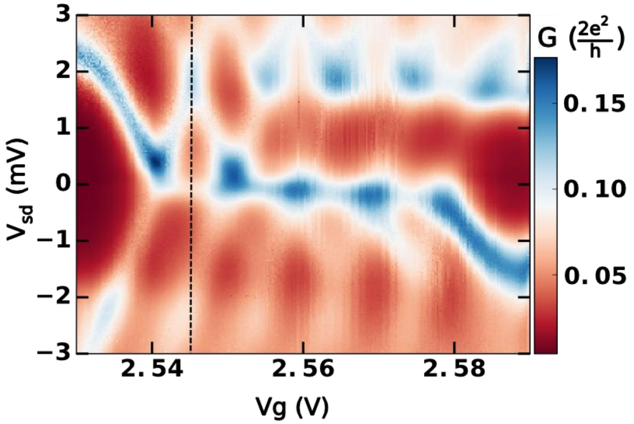
Charge sensitivity ~2. 10^{-4} e

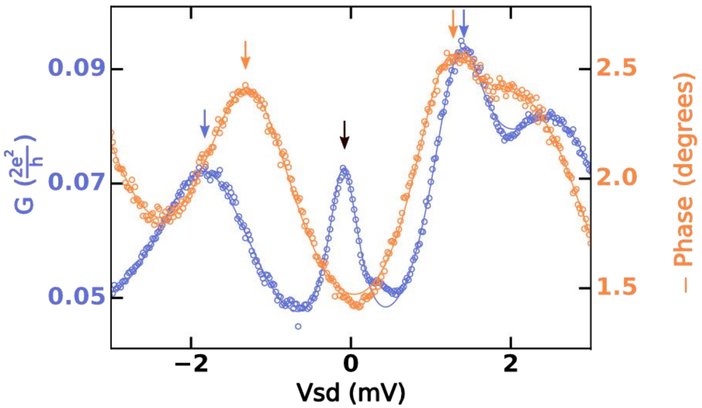


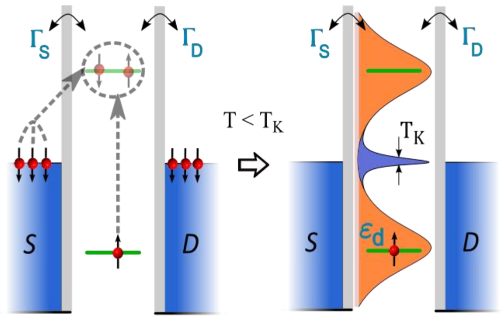
- Coulomb peaks visible both in conductance and phase (both measure the same physics)
- Amplitude of phase contrast allows to measure g ~100 MHz

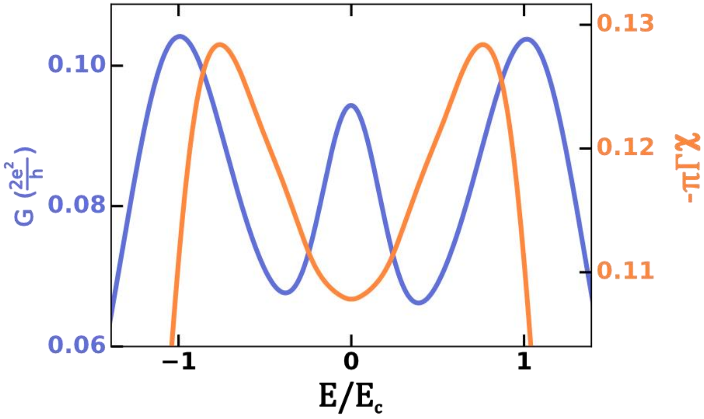
➡ Electronic and photonic systems are well coupled : what about in the Kondo regime ?

‘Transparent’ Kondo/AS resonance







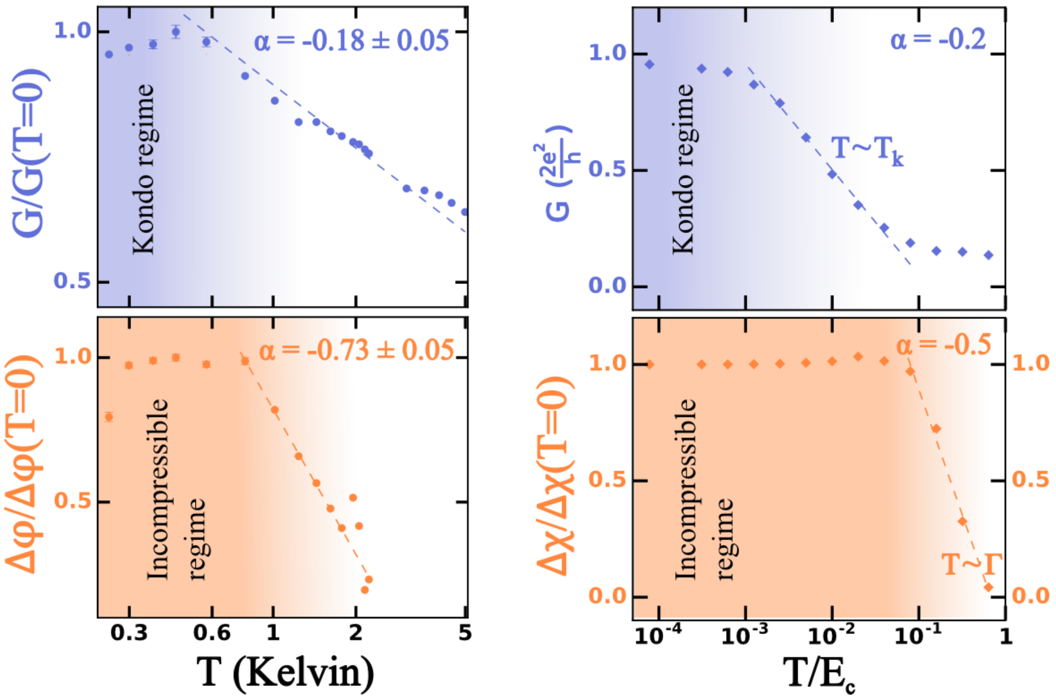


- Phase and conductance *do not* measure the same physics !
- Kondo resonance is ‘transparent’ to photons while charge peaks visible. Zero charge susceptibility and shifts well reproduced by NRG (M. Lee, M.-S. Choi)

➡ **Illustrates the separation of spin and charge degrees of freedom in a Kondo system.**

M.M. Desjardins et al. submitted ‘16

Temperature dependence



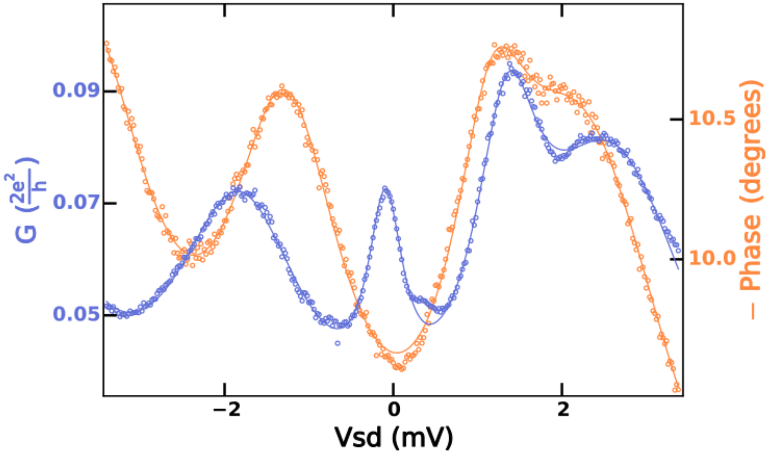
- Phase and conductance do not have the same temperature dependence
- G evolves on temperature scale given by T_K whereas phase on temperature scale given by Γ
- Experimental logarithmic slopes are in good agreement with NRG data.

➡ **Illustrates the separation of spin and charge degrees of freedom in a Kondo system.**

M.M. Desjardins et al. submitted '16

Conclusion II

✓**cQED architecture can be used to study condensed matter problems**
✓**Large charge-photon coupling**
✓**Observation of separation of spin and charge degrees of freedom in a Kondo system.**
M.M. Desjardins et al. submitted'16



Perspectives of this setup

- Probe of transport in mesoscopic circuits
L.E. Bruhat et al., PRX 6, 021014 (2016)
- Quantum quench of Kondo cloud
- Quantum simulation of fermion-boson systems.
- Probe of Majorana fermions in condensed matter **(A. Cottet, T. Kontos and B. Douçot PRB'13, M.C Dartiailh et al. submitted)**