laboratoire pierre aigrain
électronique et photonique quantiques

Mesoscopic Quantum Electrodynamics

LPA – Ecole Normale Supérieure – Paris

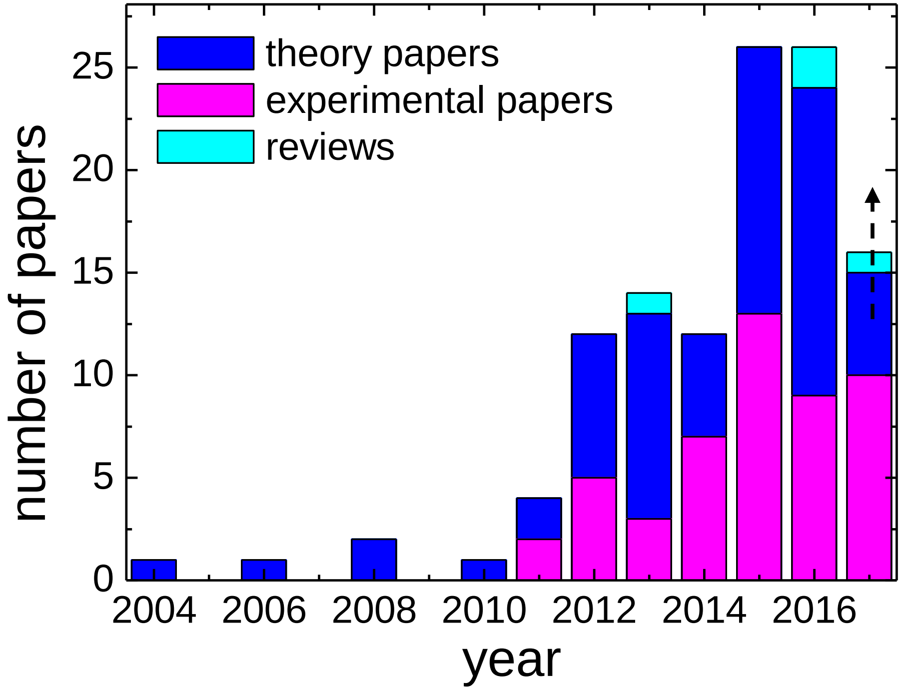
HQC team (experiments):

students/post-docs
Laure Bruhat (now in Chalmers)
Lauriane Contamin
Tino Cubaynes,
Matthieu Desjardins
Matthieu Dartiailh,
Federico Valmora,
Jérémie Viennot (now in Boulder)

permanent members:
Matthieu Delbecq
Zaki Legthas
François Mallet
PI: T. Kontos

Theory: Benoit Douçot (Jussieu)
M.-S. Choi, M. Lee (Seoul)
Audrey Cottet

Mesoscopic QED: published works

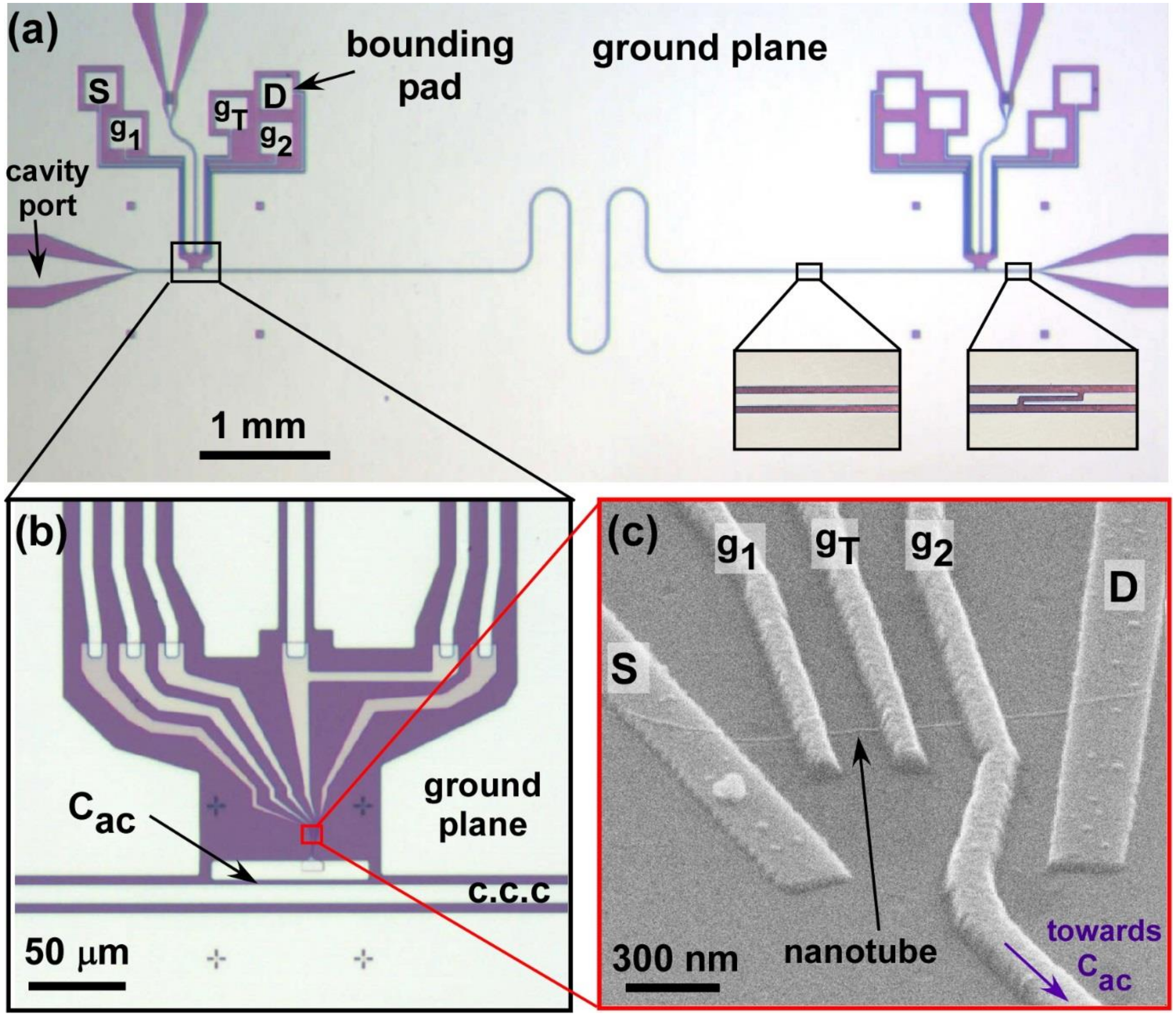


Pionneering
theory paper:
Childress et al., PRA 2004

First experiments:
Single dot with N contacts:
Delbecq et al., PRL 2011 Paris
Frey et al., PRL 2011 Zurich
Double dot with N contacts:
Frey et al., PRL 2012 Zurich
Petersson et al. , Nature 2012 Princeton

- Nanoconductors: Carbon nanotubes (Paris), GaAs/AlGaAs 2DEG (Zurich), Si/SiGe 2DEG (Princeton), semiconducting nanowires (Princeton, Copenhagen, Delft), graphene (Hefei), atomic contacts (Saclay)…
- Different types fermionic reservoirs (normal, superconducting, ferromagnetic)

Example of Mesoscopic QED device



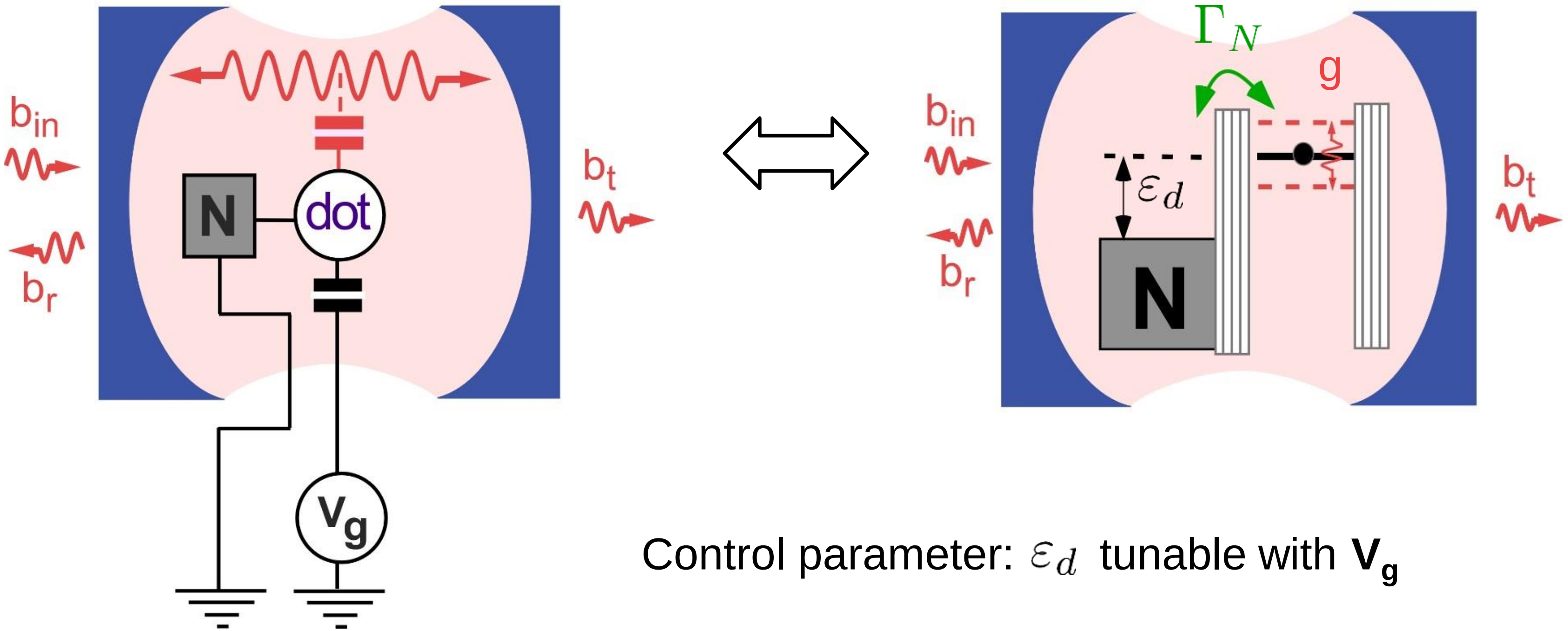
SiO_2/Si chip

OUTLINE

dot/normal metal junction in a coplanar cavity

N/dot junction in a cavity

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



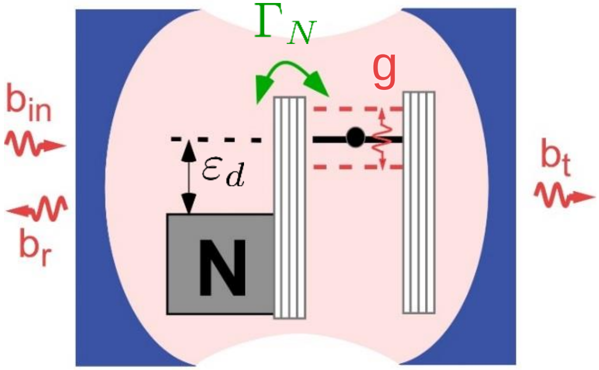
Control parameter: ε_d tunable with **V$_g$**

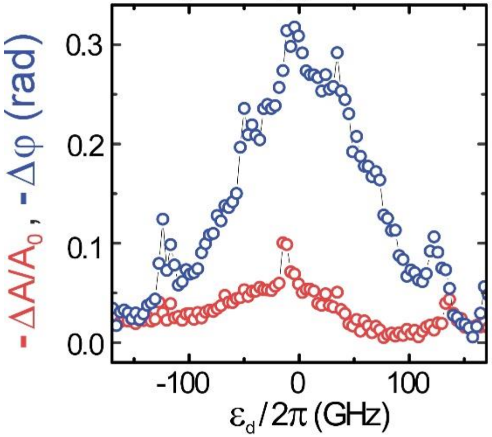
Constant parameters: dot/N tunnel rate Γ_N

dot/cavity coupling g

N/dot junction beyond the adiabatic limit

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



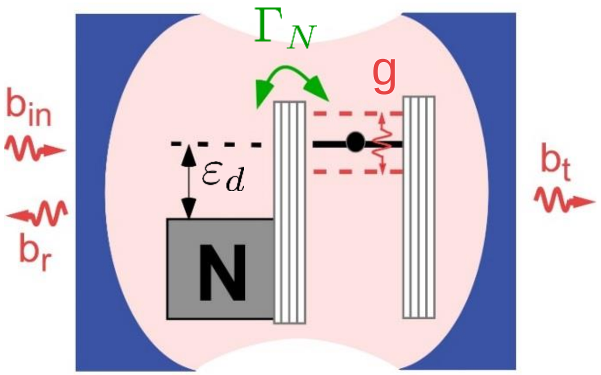


Resonances with a large Γ_N

- $\Delta A \ll A_0$ weak photon dissipation
- $\Delta\varphi \sim \Delta\omega_0/\Lambda_0 < 0$ Negative cavity frequency shift

N/dot junction beyond the adiabatic limit

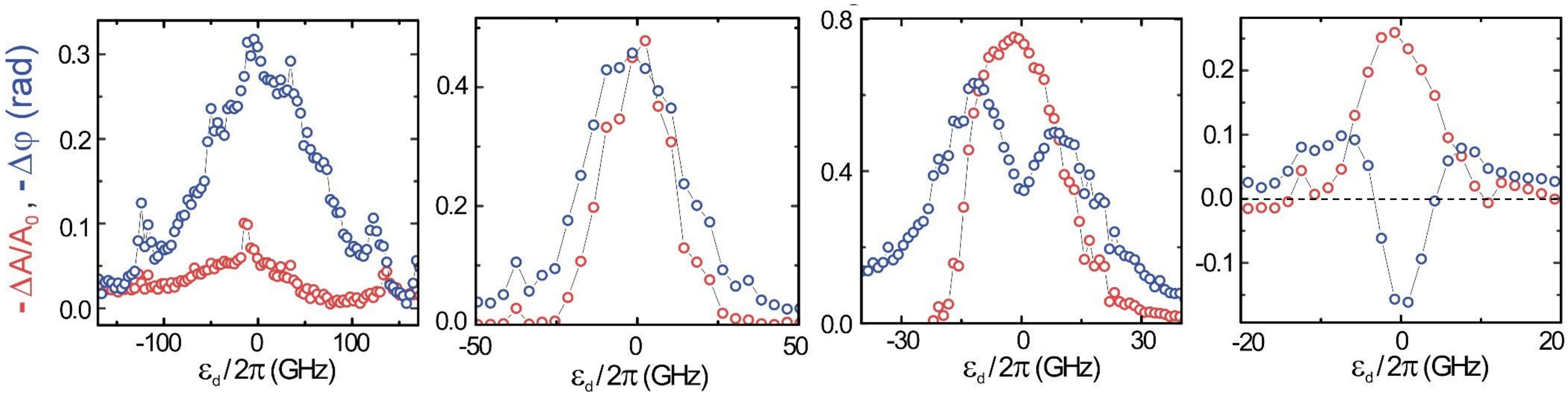
Bruhat et al., Phys. Rev. X 6, 021014 (2016)



Resonances with a smaller Γ_N

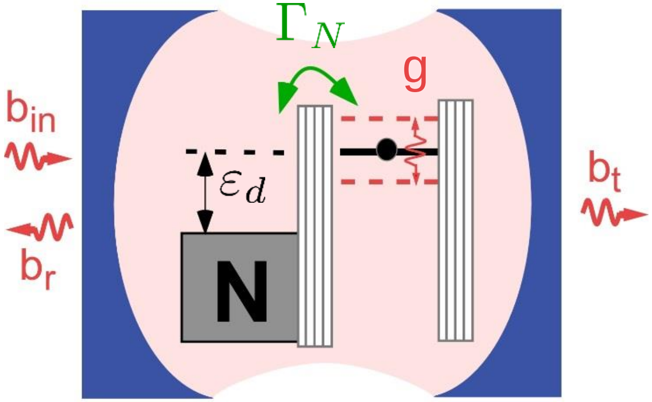
- ΔA remains negative
- sign reversal of $\Delta\varphi$! *see also PRB 86, 115303 (2012)*

Γ_N smaller



N/dot junction in cavity : data interpretation

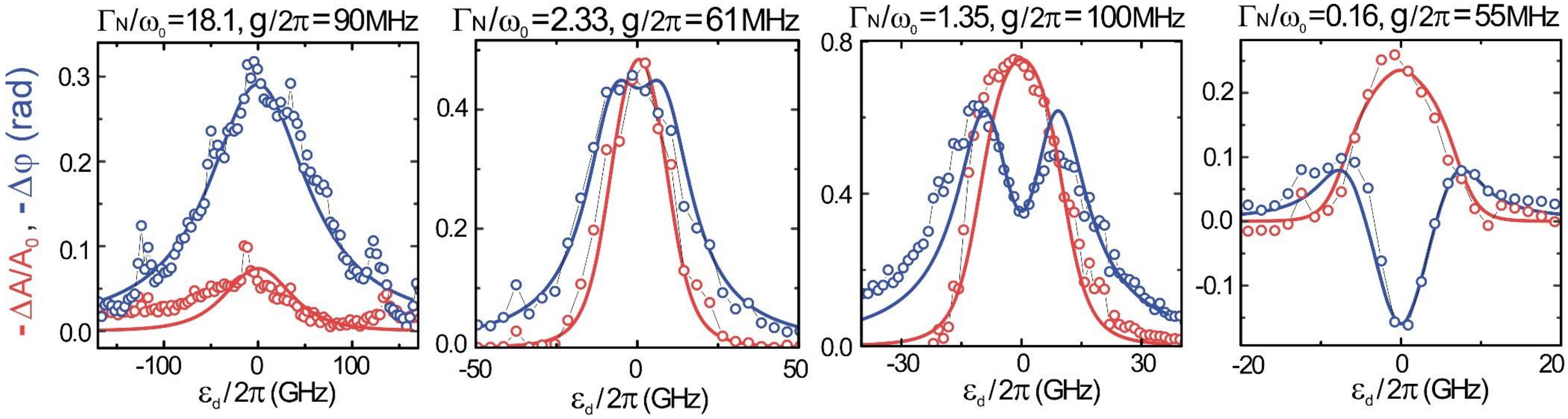
Bruhat et al., Phys. Rev. X 6, 021014 (2016)



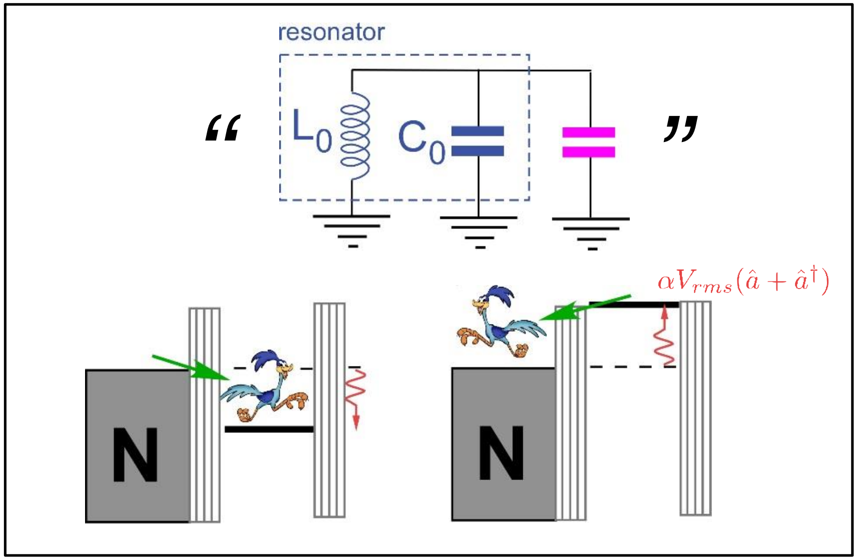
Data interpretation:

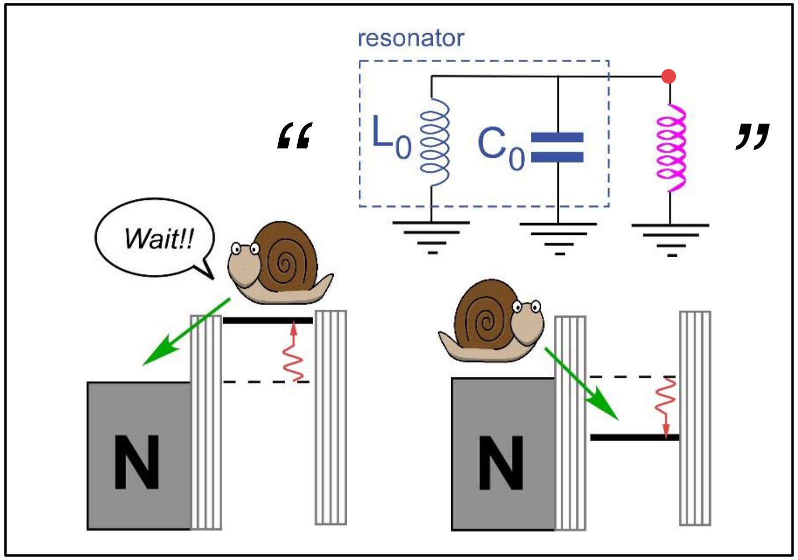
T= 60 mK for all resonances

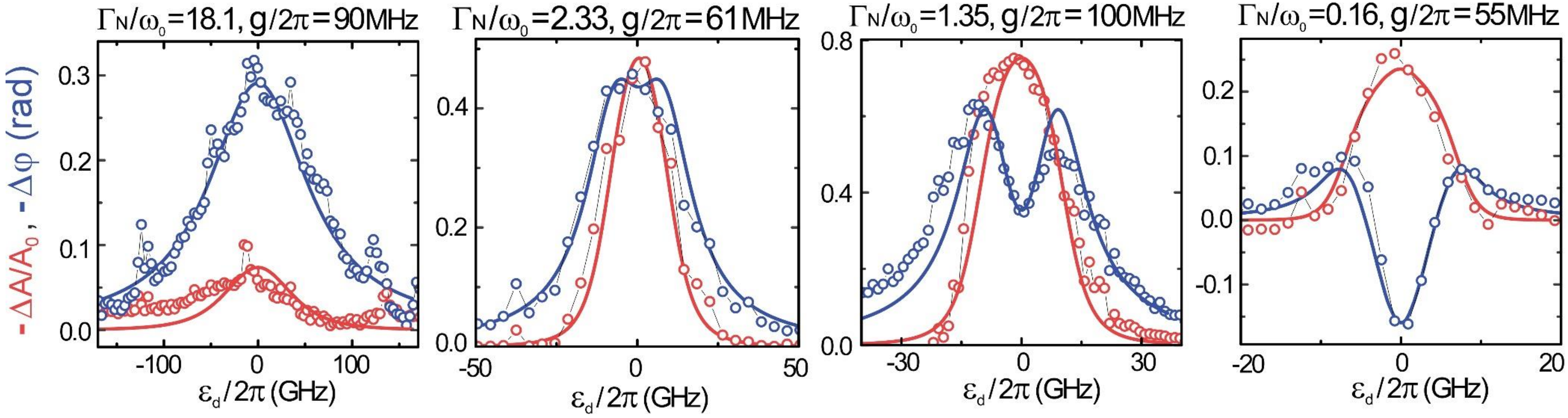
Keldysh theory, fitting parameters: Γ_N and g



From capacitive to inductive behaviors





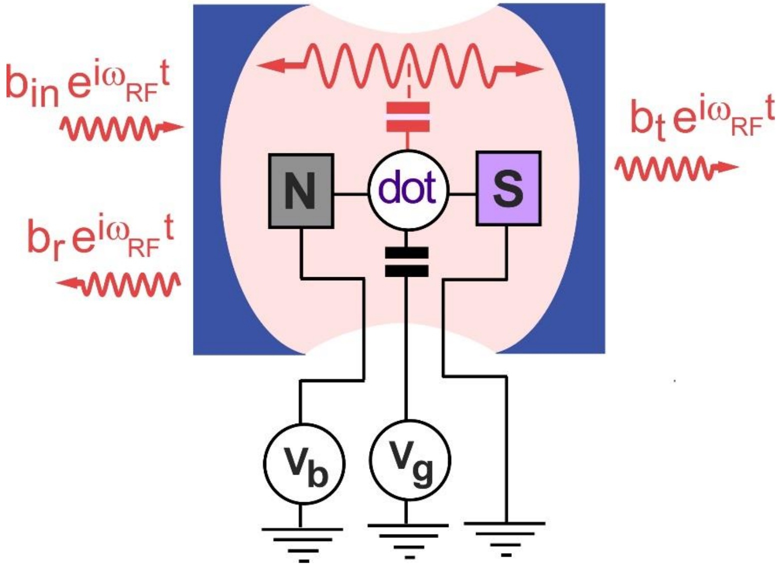


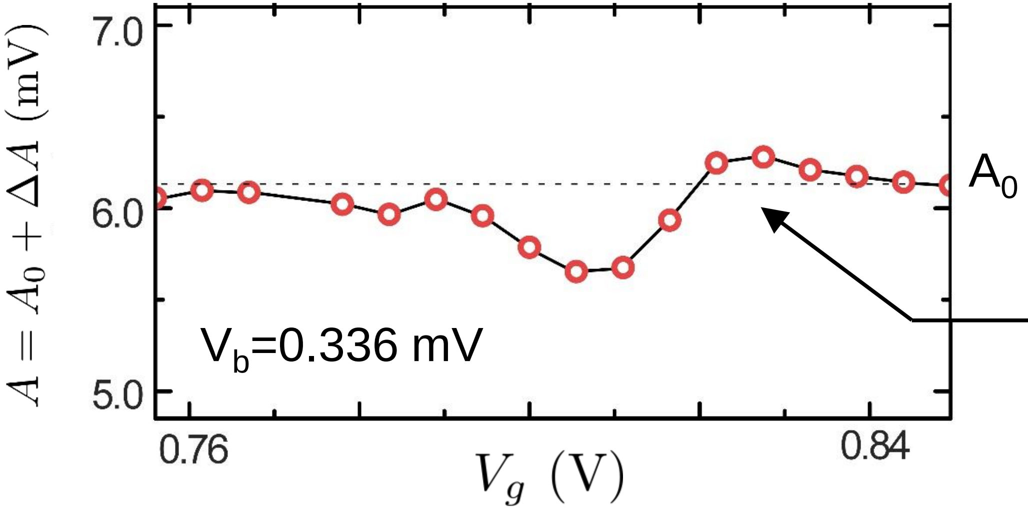
OUTLINE

Photon emission by a dot/superconductor jonction

S/dot/N bijunction at finite V_b

Bruhat, Viennot, Dartiailh, Desjardins, Kontos & Cottet, Phys. Rev. X 6, 021014 (2016)

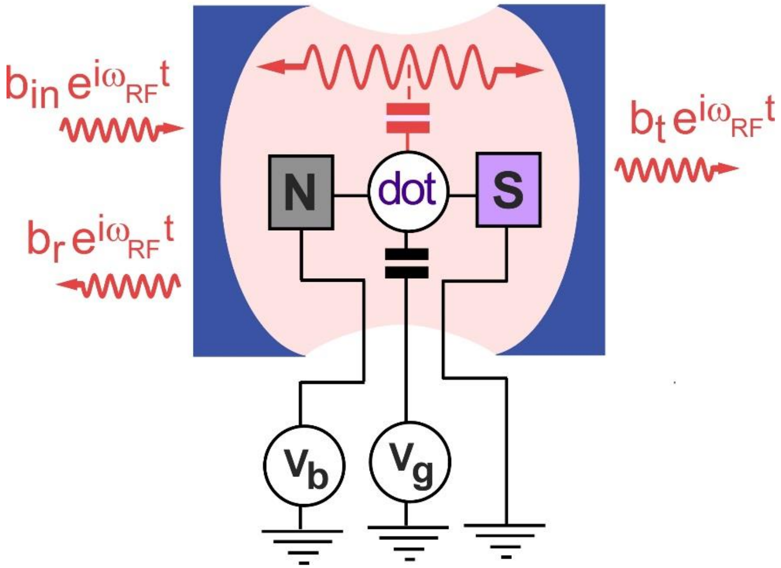


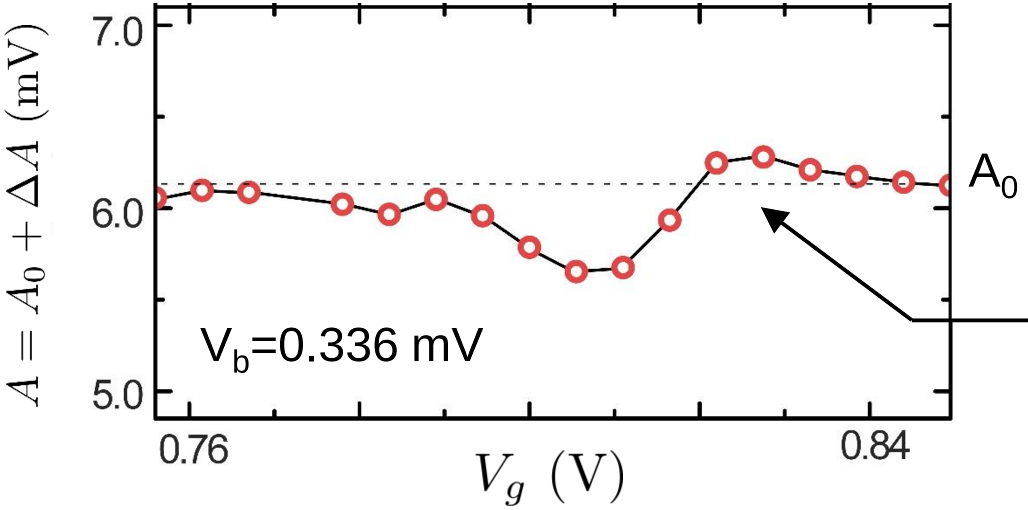


Microwave amplification $\Delta A>0$

S/dot/N bijunction at finite V_b

Bruhat, Viennot, Dartiailh, Desjardins, Kontos & Cottet, Phys. Rev. X 6, 021014 (2016)



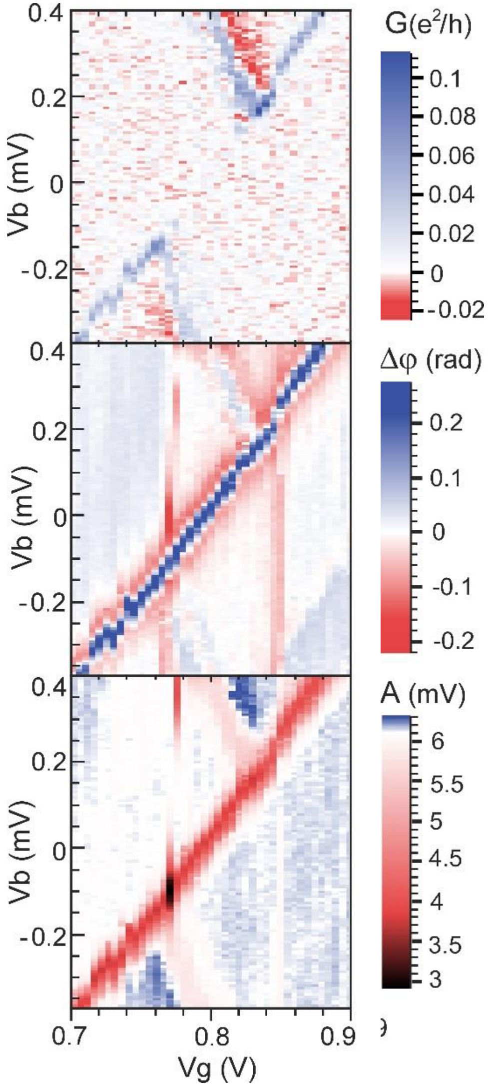


Microwave amplification $\Delta A>0$

Look at theory?

Test of theory at finite bias voltages

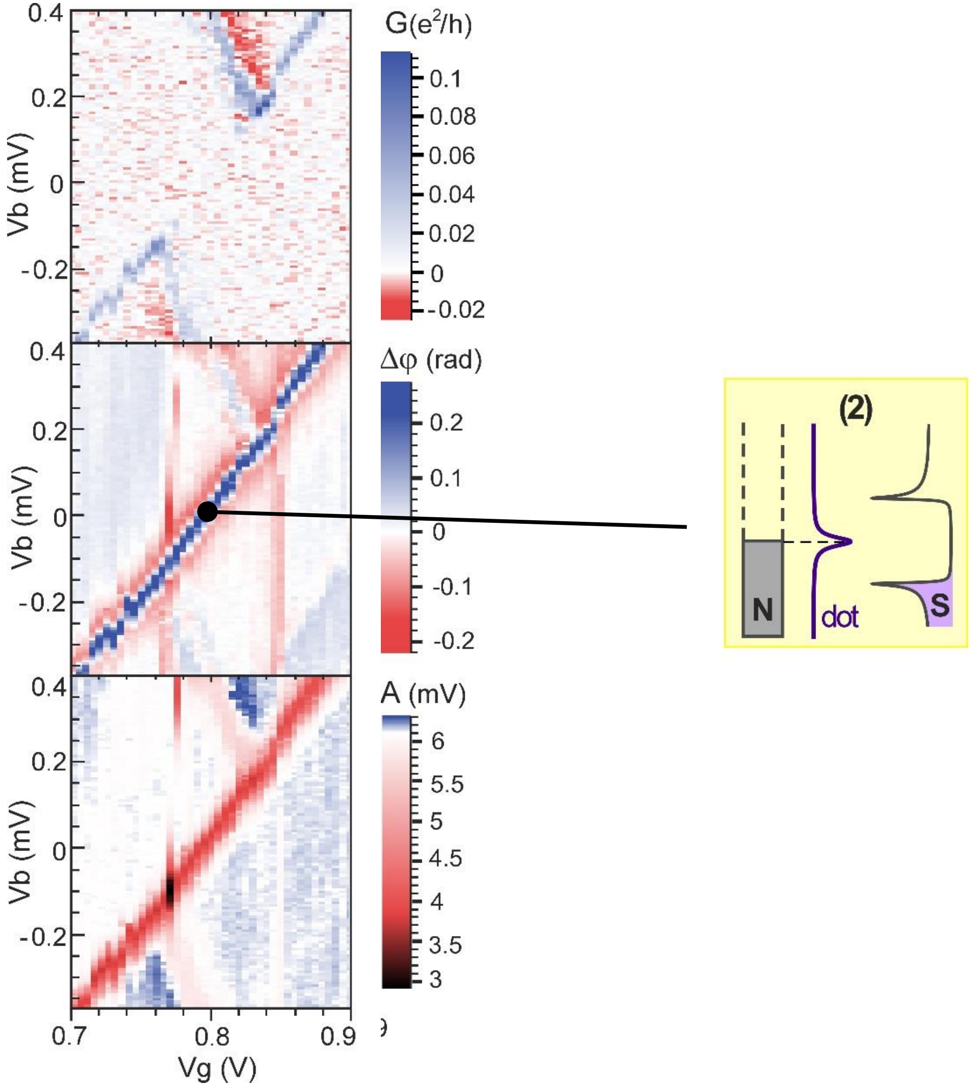
Experiment



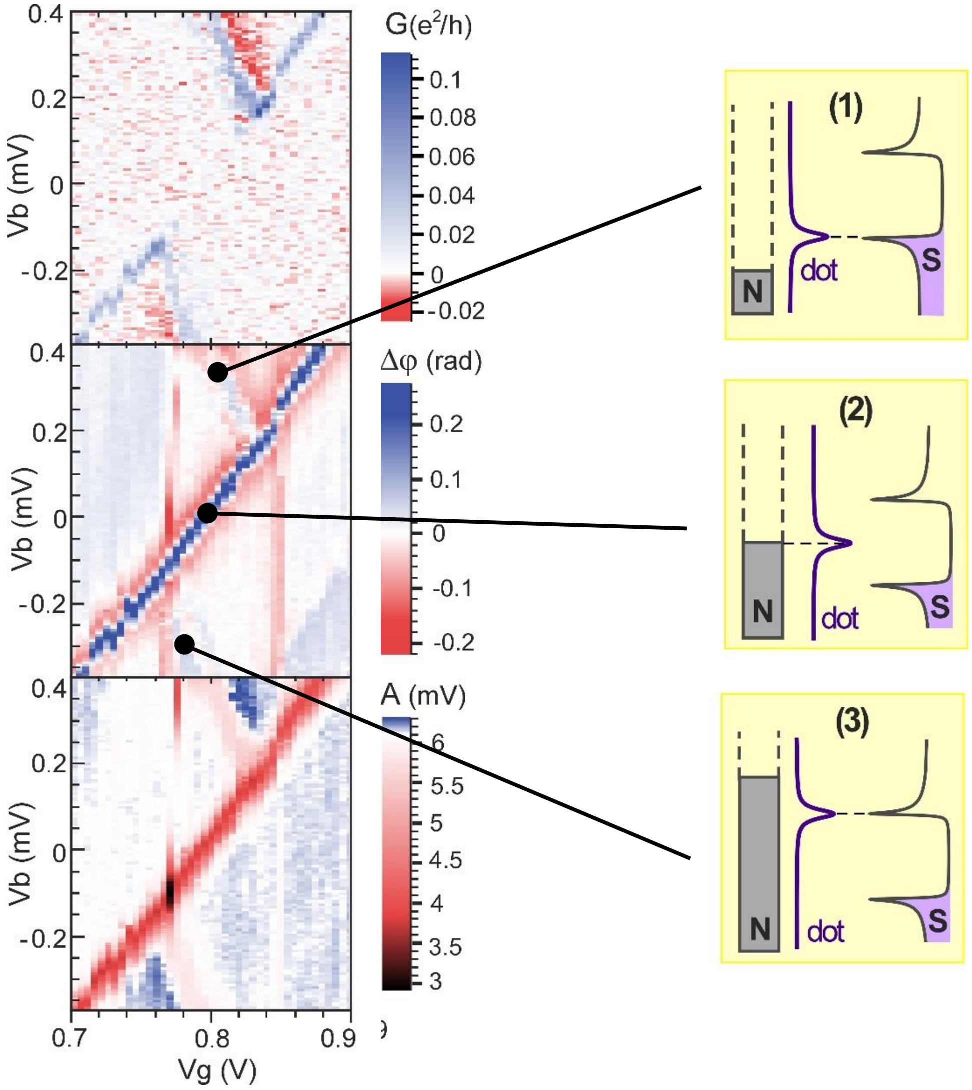
Simultaneous measurement
of conductance and cavity response
=
Two qualitatively different signals

Test of theory at finite bias voltages

Experiment

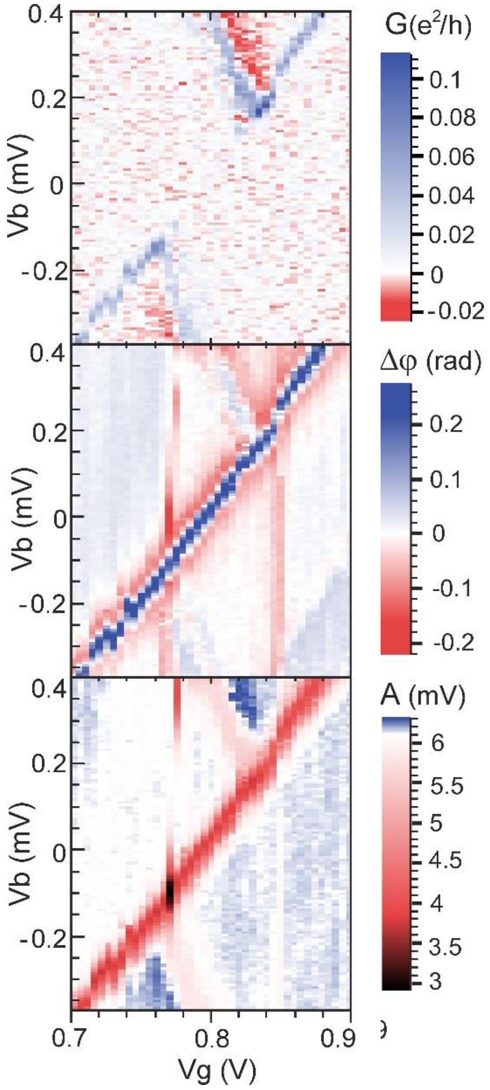


Test of theory at finite bias voltages


Experiment

Test of theory at finite bias voltages

Experiment



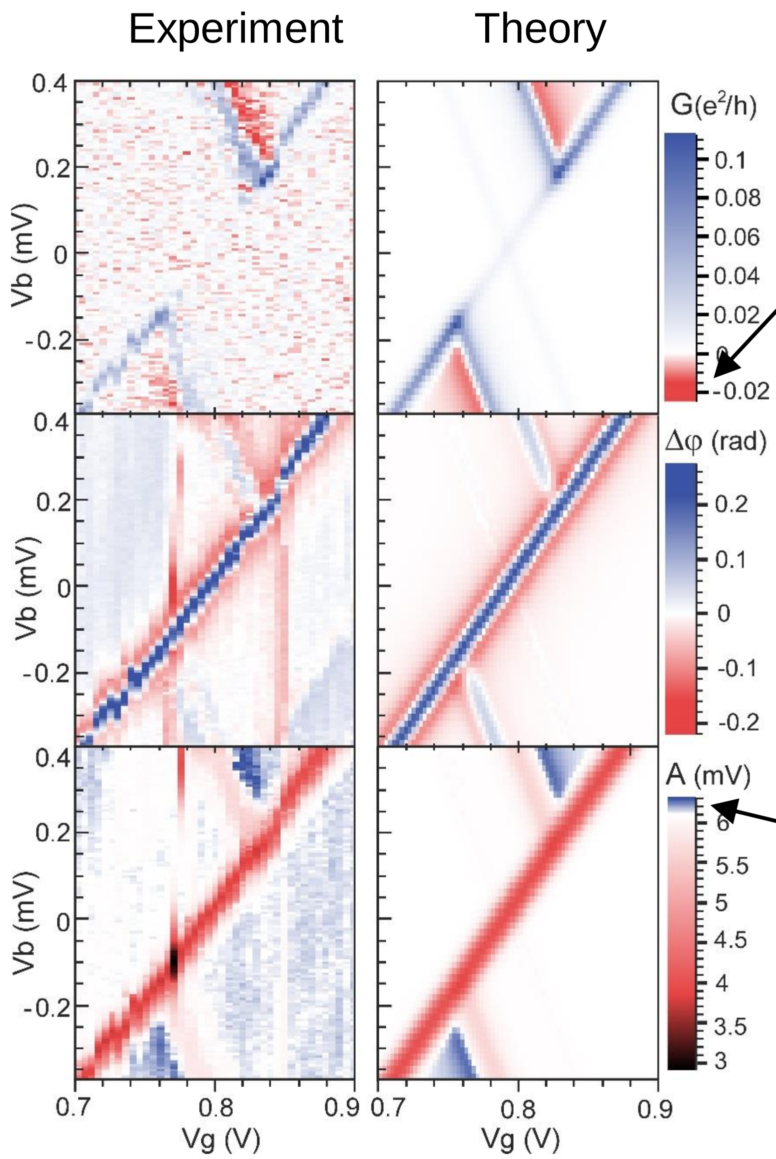
Theory

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

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

⇨ *simultaneous fit of three 2D plots*

Test of theory at finite bias voltages

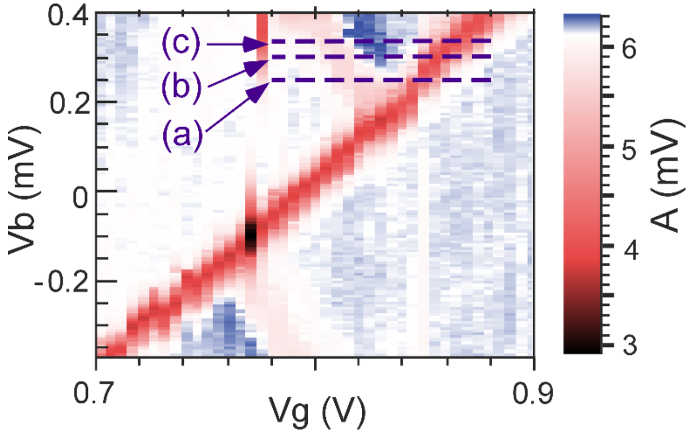


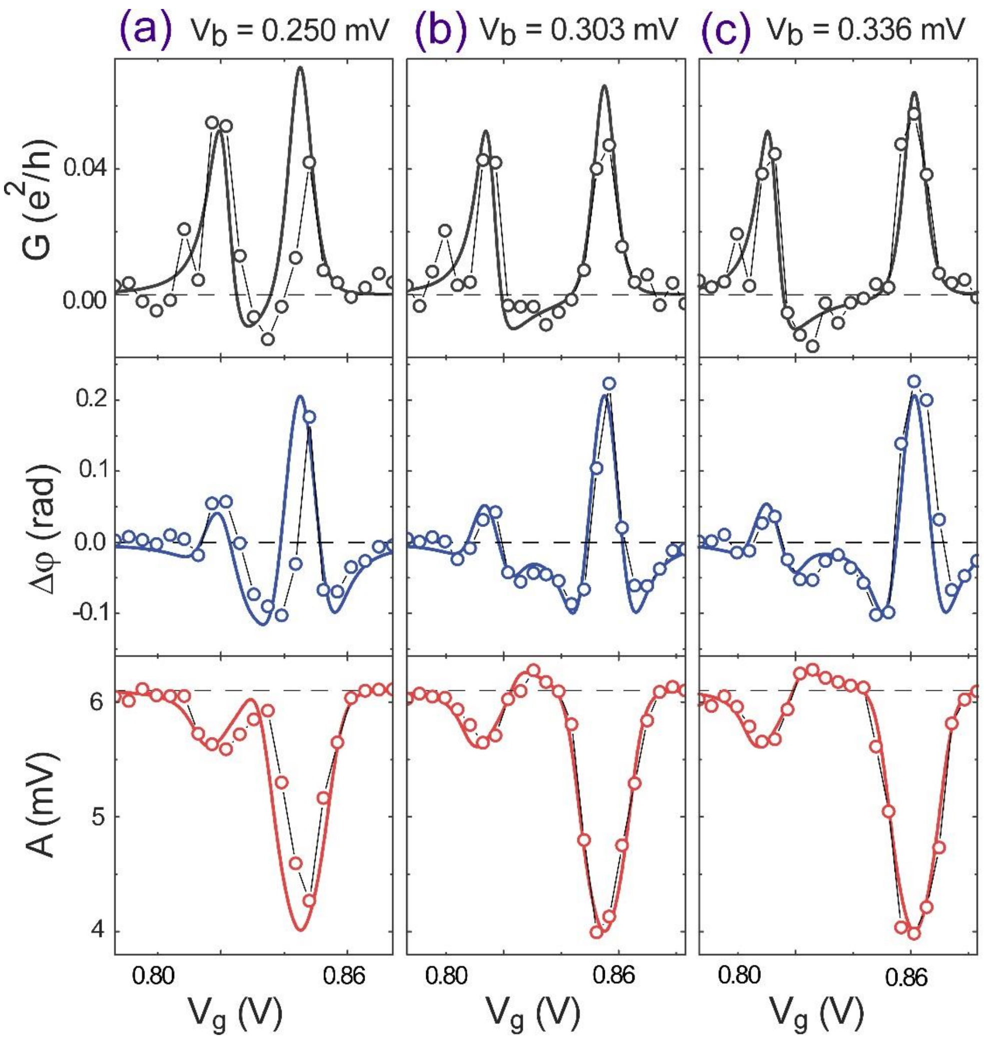
Negative differential conductance

Δφ ≷ 0
Inductive response of quantum dot circuit

Microwave amplification ΔA>0

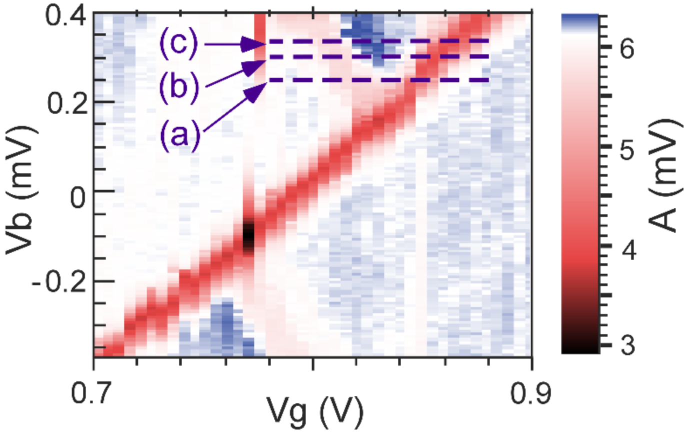
Test of theory at finite bias voltages

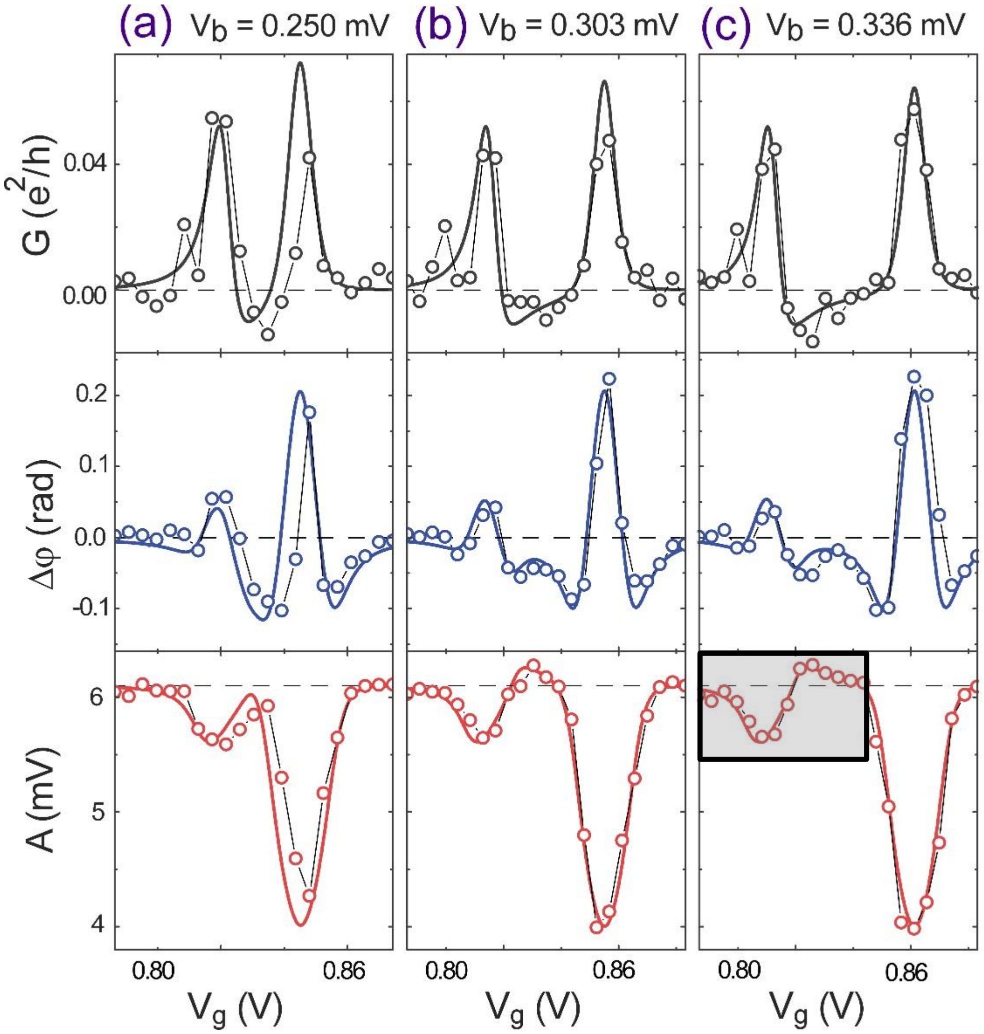




Quantitative modelling of the data

Test of theory at finite bias voltages

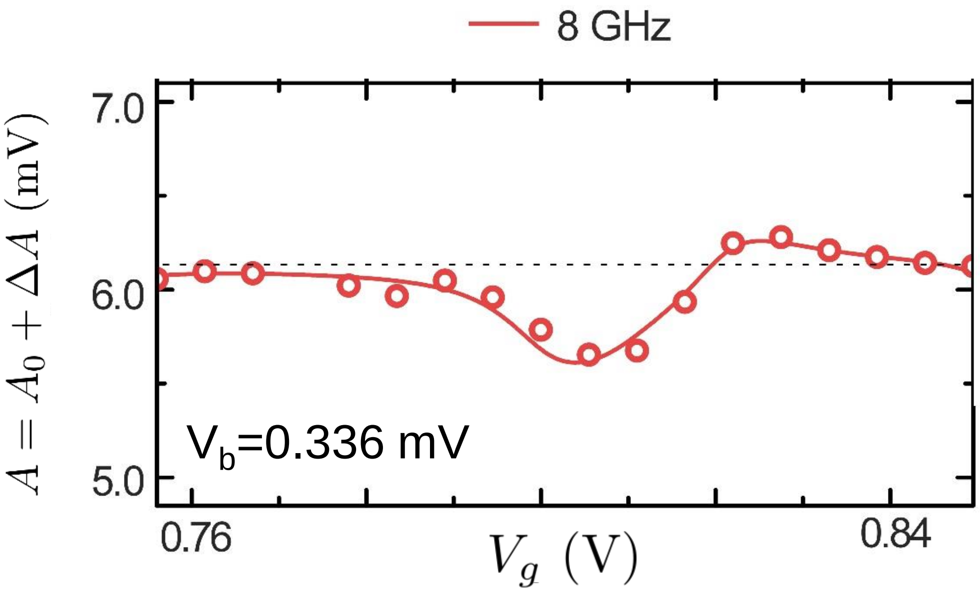




Quantitative modelling of the data

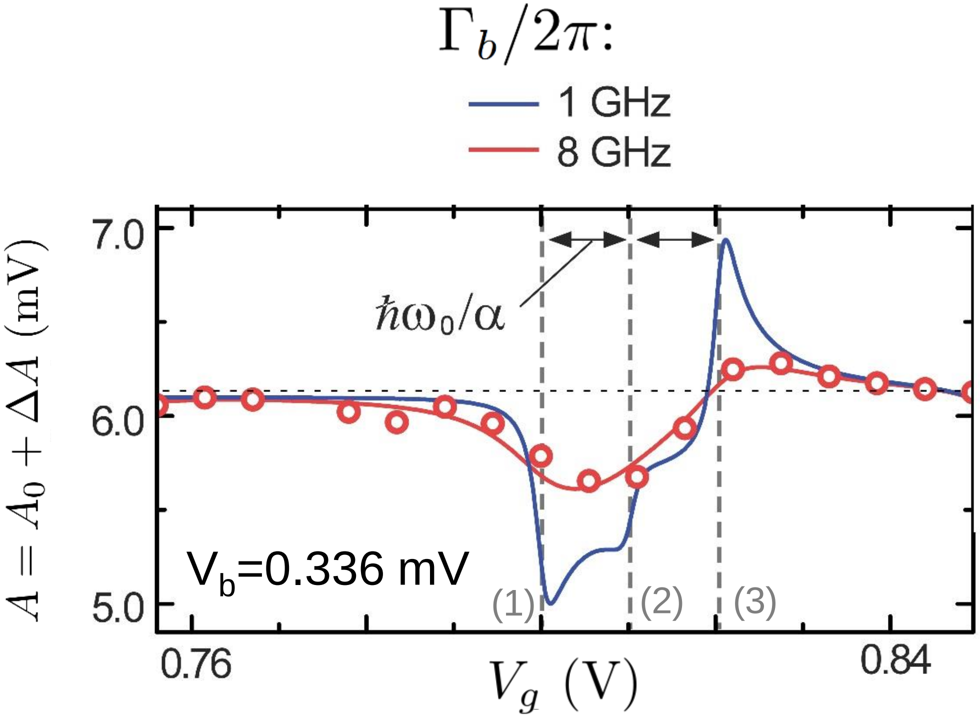
Inelastic tunneling between dot and S

$\Gamma_b/2\pi$:



Inelastic tunneling between dot and S

ω_0 : cavity frequency
α : DC-gate lever arm



Inelastic tunneling between dot and S

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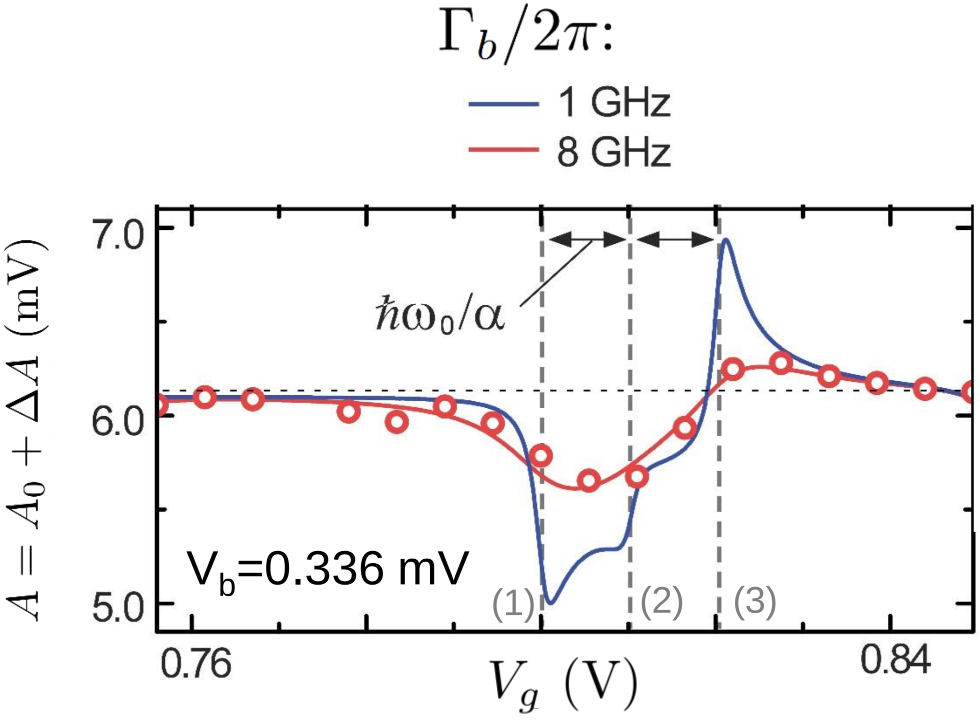
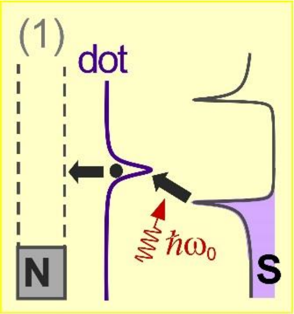
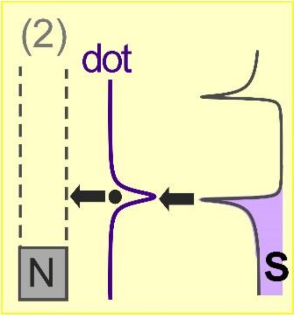


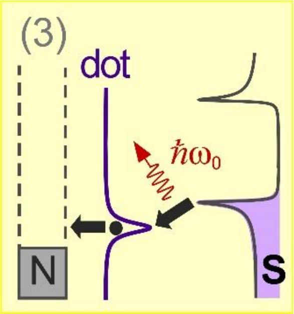
Photon-emission
visible only through cavity!



Photon-absorption



Elastic transport



Photon-emission

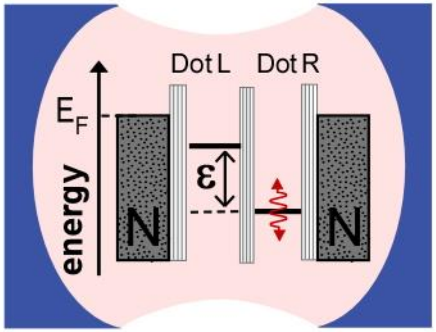
$$\text{rate} \sim 2MHz$$
$$\sim 0.3 \text{ pA}$$

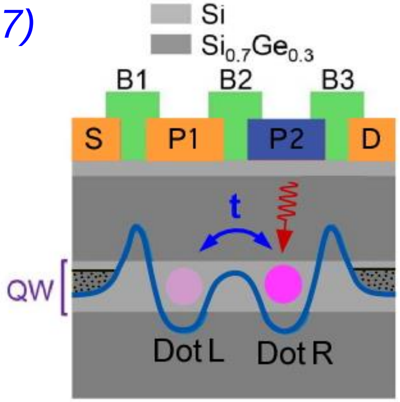
OUTLINE

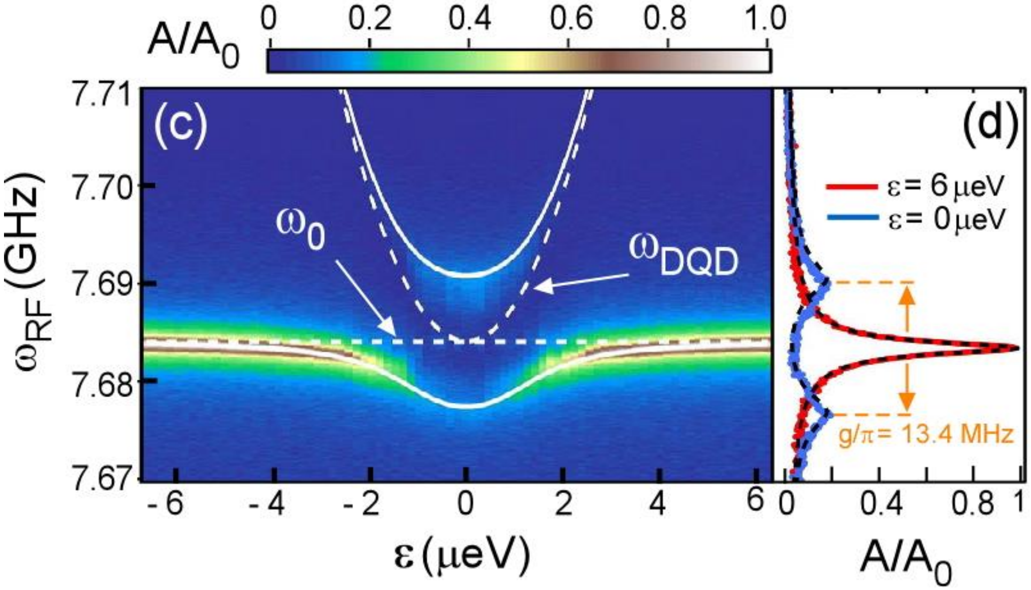
double dot in a cavity:
strong coupling to charge degree of freedom

double dot in a cavity: strong coupling to charge degree of freedom

Mi et al., Science 355, 156 (2017)





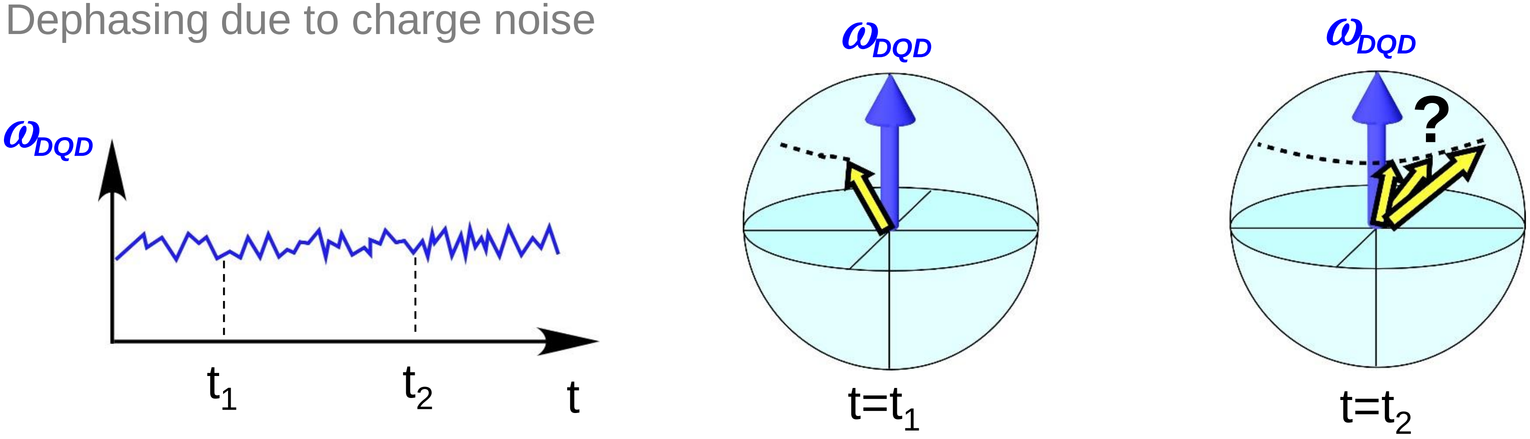


see also:
Stockklauser et al.,
PRX 7, 011030 (2017)

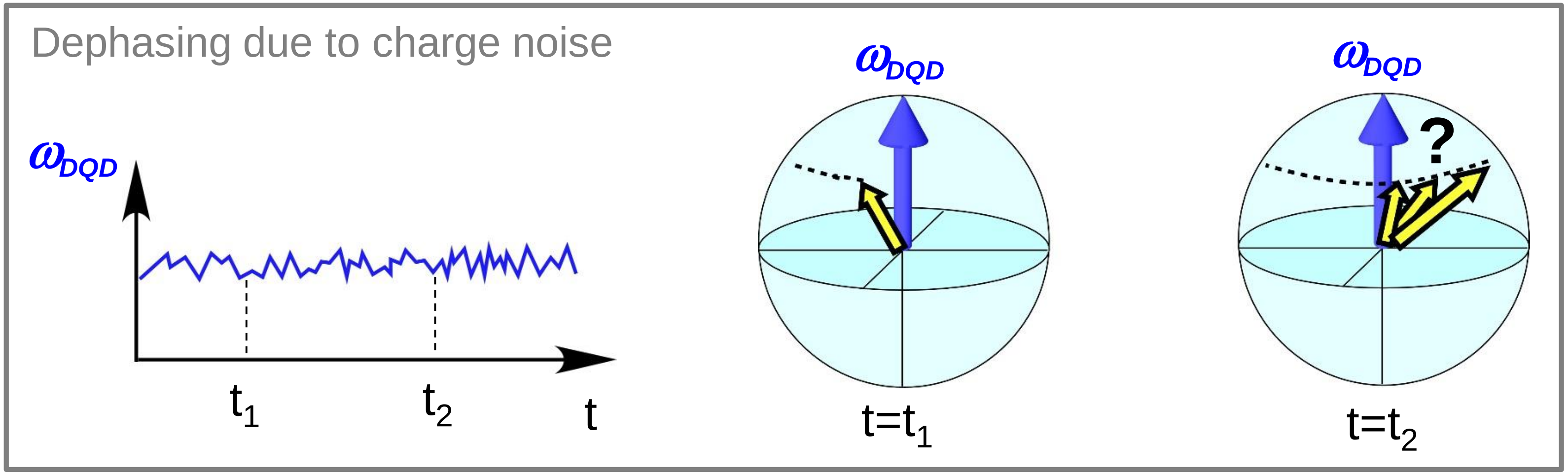
Bruhat et al.,
arXiv:1612.05214

Reaching the strong coupling regime

Dephasing due to charge noise



Reaching the strong coupling regime



Dephasing due to charge noise

$$g_\perp \gg \Gamma_2\,, \Lambda_0$$

$$\Gamma_2 \sim \frac{1}{\pi}\frac{\partial^2 \omega_{+-}}{\partial \varepsilon^2} E_c^2 (\delta n)^2$$

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

increase $g_\perp$

Stockklauser et al., PRX 2017

$g_\perp / \Gamma_2 = 1.27$

decrease E_c

Bruhat et al., arXiv 2016

$g_\perp / \Gamma_2 = 2.5$

decrease charge noise

Mi et al., Science 2017

$g_\perp / \Gamma_2 = 2.57$

OUTLINE

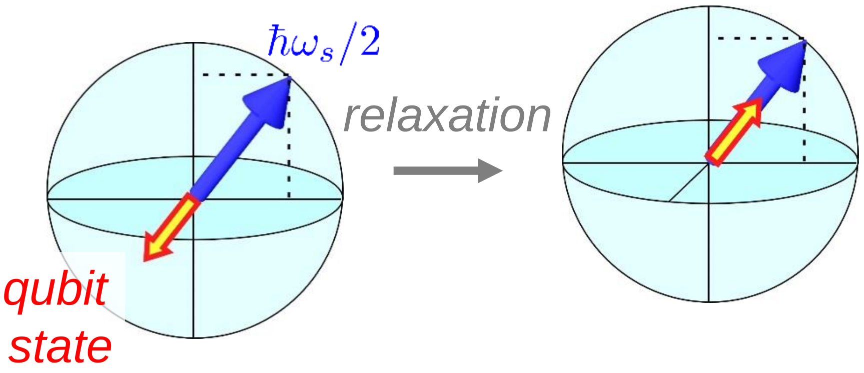
Coherent spin-photon coupling in a hybrid device

Quantum dot circuits potentialities?

Superconducting qubits :

Coherence limited by relaxation T_1<100 μs

Review: Devoret and Schoelkopf, Science (2013)



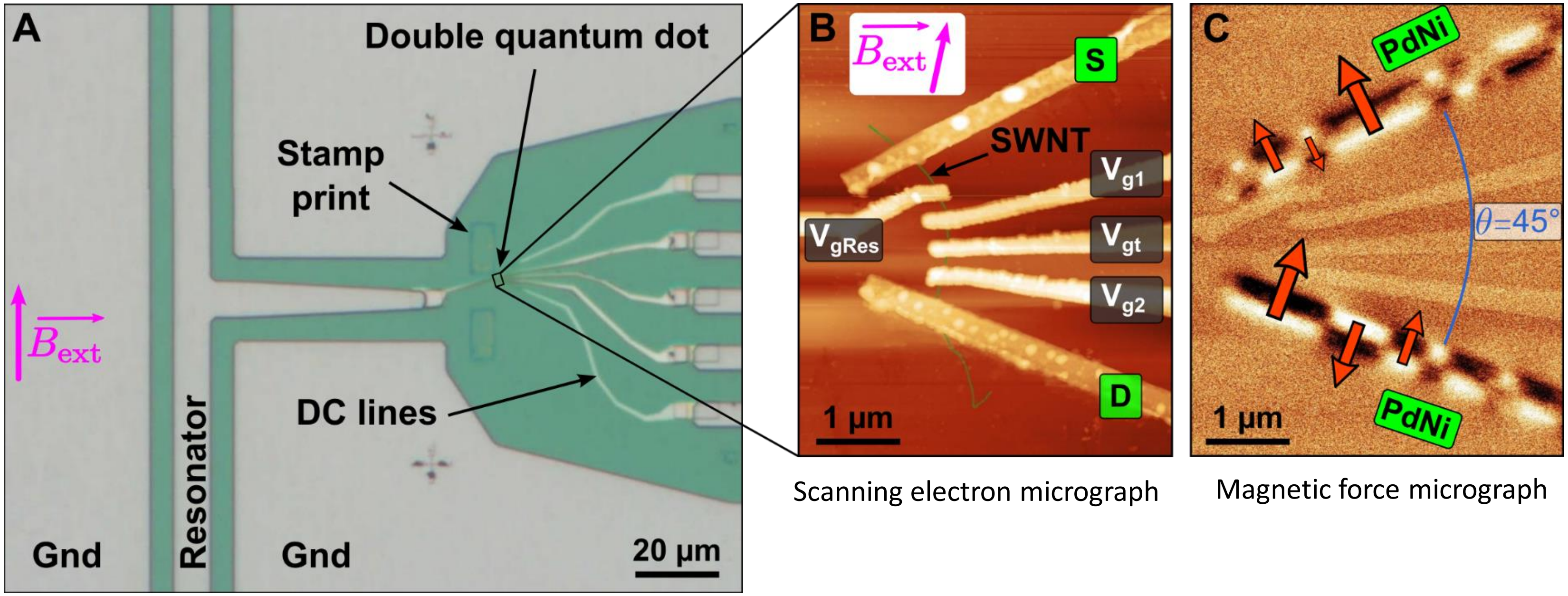
Spin in a quantum dot :

- GaAs (single dot) @ 130mK:
  T_1~80 ms *Scarlino et al., PRL 2014*
- Si/SiGe (double dot) @ 15mK:
  T_1~3 s *Prance et al., PRL 2012*
- Carbon nanotube (bulk) @ 4K:
  T1~170 μs *Rice et al. PRB 2013*

⇨ quantum dot circuit or a hybrid nanocircuit in a microwave cavity?

Experiment: carbon nanotube and PdNi contacts

*Viennot, Dartiailh, Cottet, & Kontos, Science **349**, 6246 (2015)*



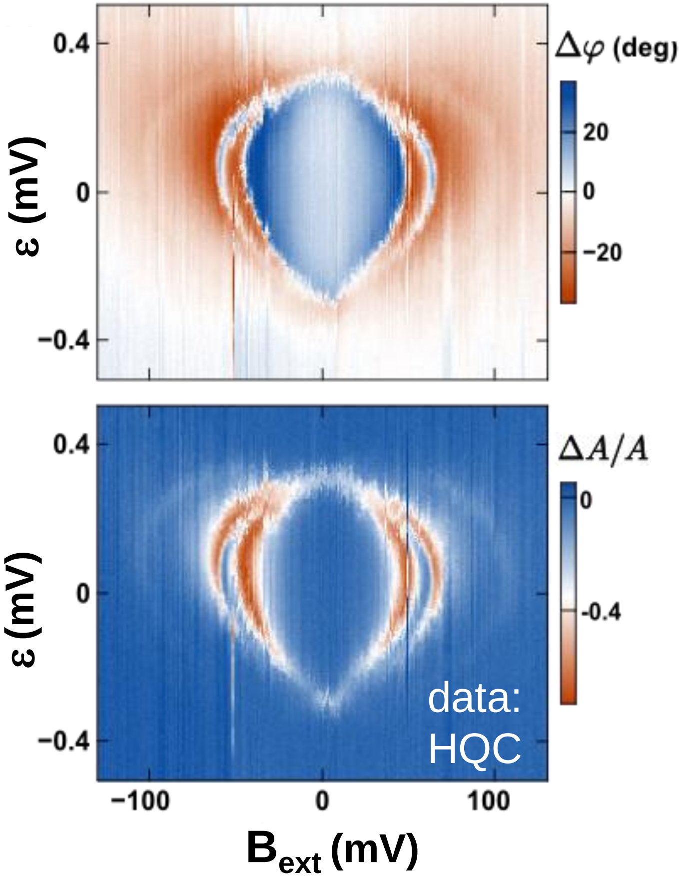
Scanning electron micrograph

Magnetic force micrograph

- Non-colinear magnetizations imposed by contacts shape
- Magnetic field applied to bring cavity and DQD in resonance
- Resonator $\omega_0 /2\pi = 6.72GHZ$, quality factor $Q \simeq 10^4$ up to $B_{ext} = 100mT$

Magneto-spectroscopy

***Viennot, Dartiailh**, Cottet, & Kontos, Science **349**, 6246 (2015)*



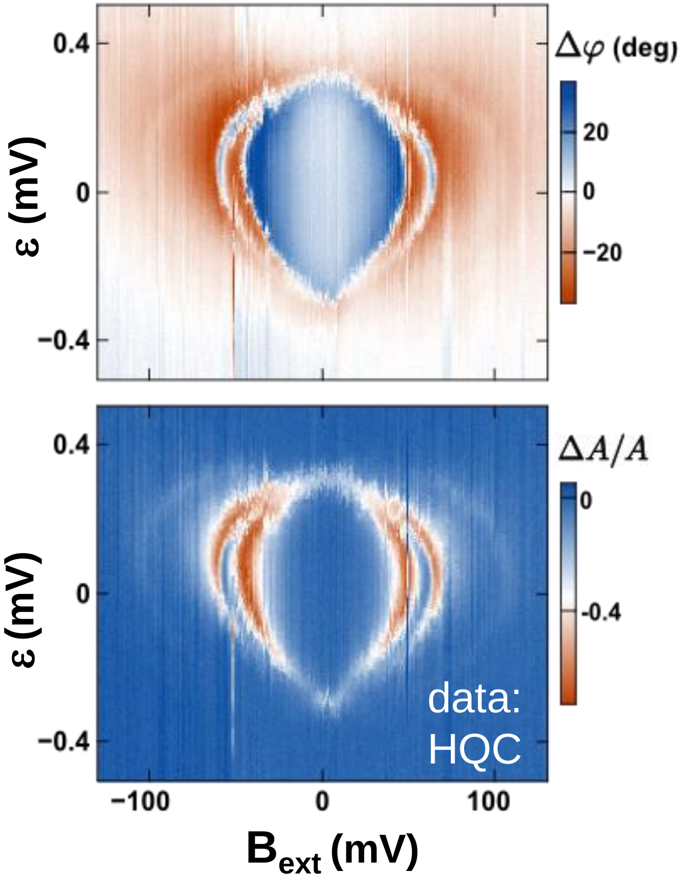
data: HQC

These resonances strongly move with B_{ext} !

⇨ Spin degree of freedom involved

Magneto-spectroscopy

***Viennot, Dartiailh**, Cottet, & Kontos, Science **349**, 6246 (2015)*



Cavity transmission at $\omega_{RF} = \omega_0$

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

$$= \frac{t_0}{i\Lambda_0 - \chi(\omega_0)}$$

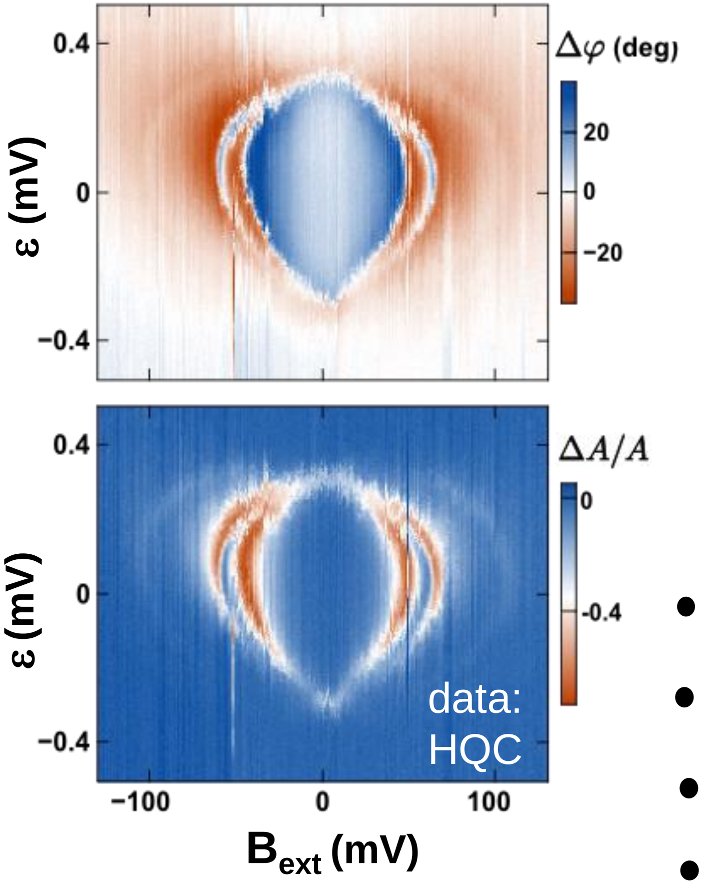
$$\chi(\omega_0) = \sum_{ij} \frac{g_{ij}^2}{\omega_0 - \omega_{ij} + i\Gamma_{ij}}$$

Multiple transitions due to L/R, spin and K/K' degrees of freedom

The cavity provides a cut of the DQD spectrum at frequency ω_0

Magneto-spectroscopy

Viennot, Dartiailh*, Cottet, & Kontos, Science* ***349****, 6246 (2015)*



Hamiltonian:

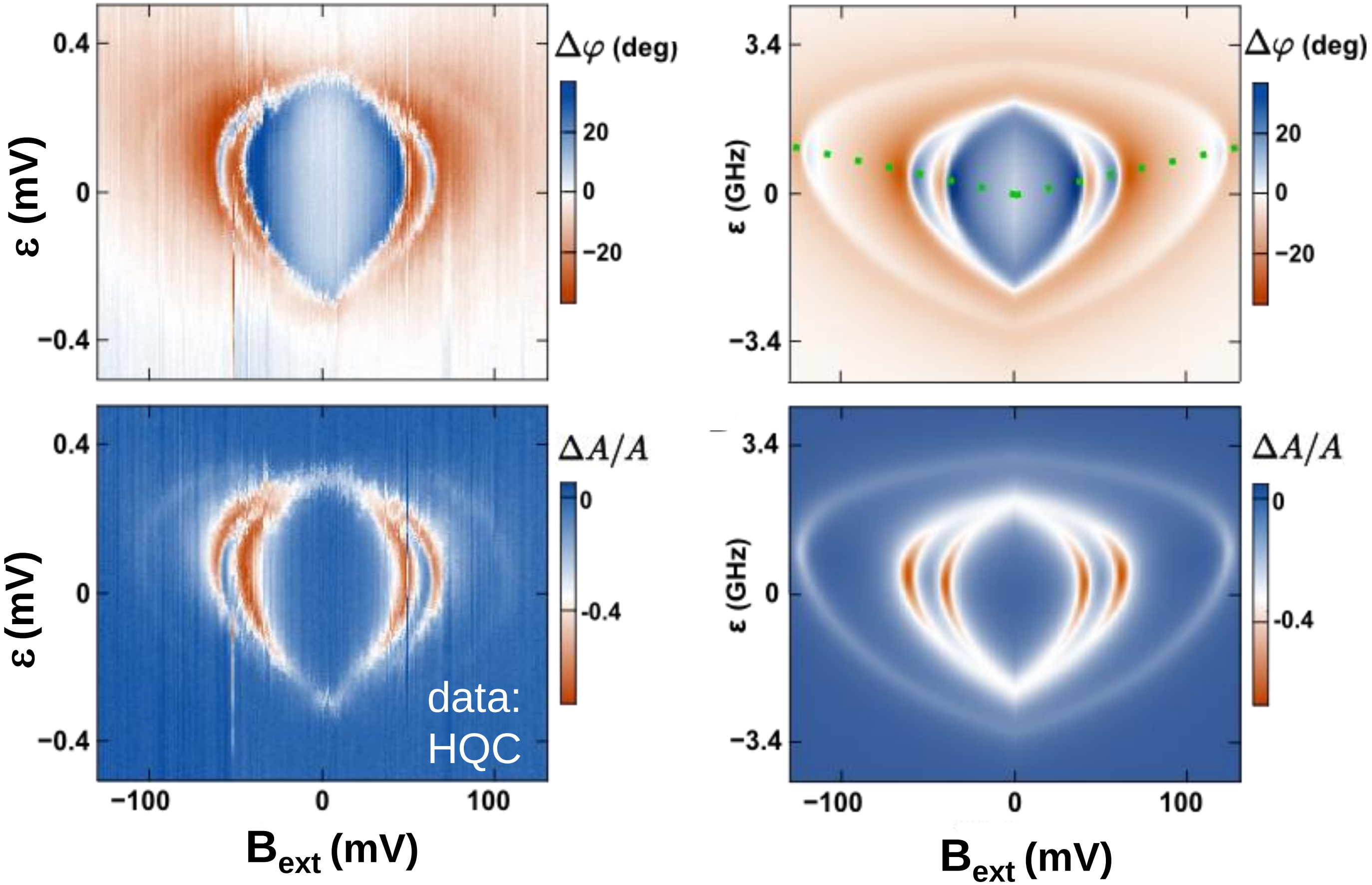
$$\widetilde{\hat{H}_{tot}} = \hat{H}_{DQD}(\varepsilon^{DC}, B_{ext}) + \hbar\omega_0 \hat{a}^\dagger \hat{a} + \hbar(g_L \hat{n}_L + g_R \hat{n}_R)(\hat{a} + \hat{a}^\dagger)$$

Ingredients:

- Non-collinear contact-induced Zeeman fields
- Charge-noise dephasing (dependent on level dispersion)
- Atomic disorder in the nanotube => small K/K’ coupling
- Constant relaxation rate for all transitions

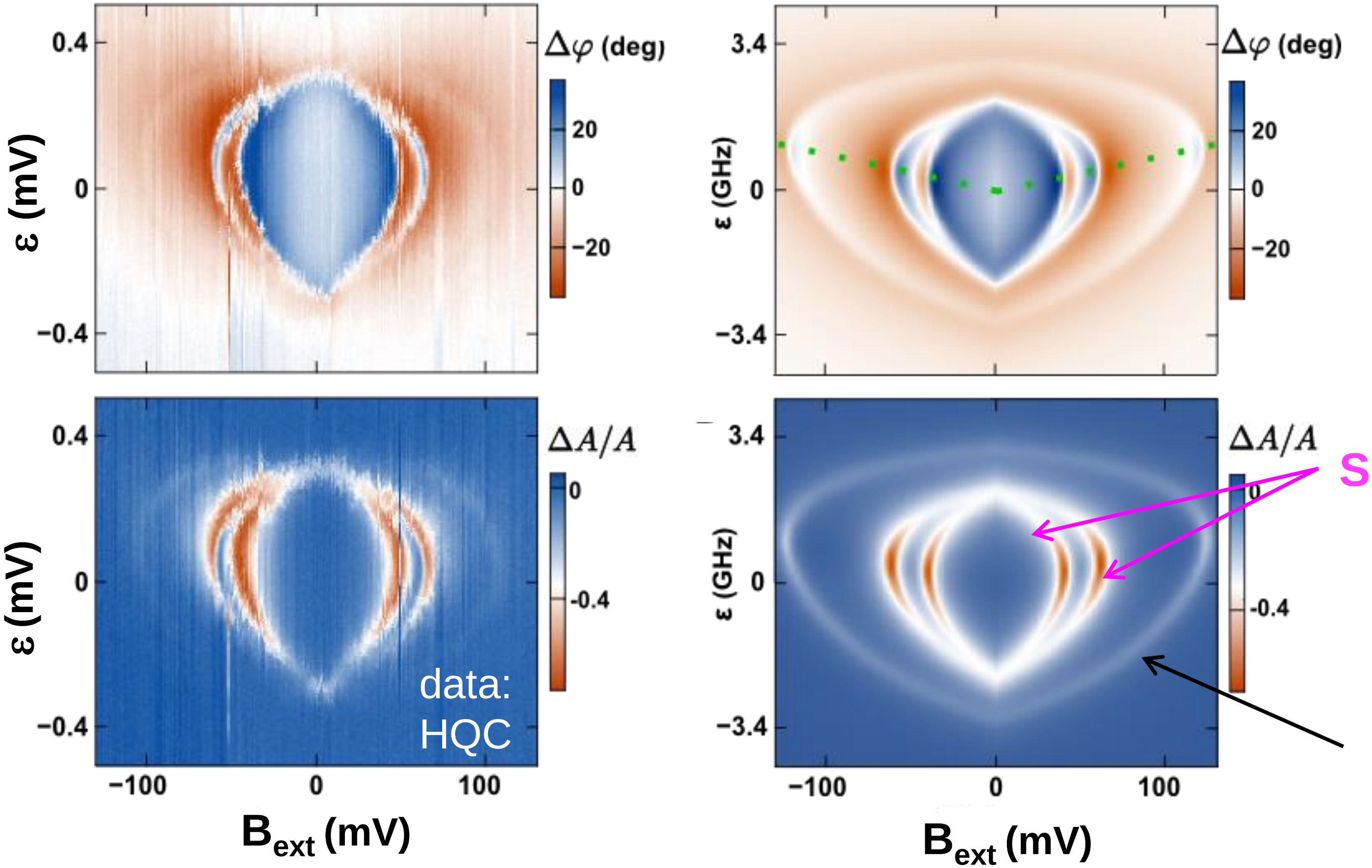
Magneto-spectroscopy

__Viennot, Dartiailh__, Cottet, & Kontos, Science __349__, 6246 (2015)



Magneto-spectroscopy

__Viennot, Dartiailh__, Cottet, & Kontos, Science __349__, 6246 (2015)



Spin-flip transitions

$|K,\uparrow\rangle \leftrightarrow |K,\downarrow\rangle$

$|K',\uparrow\rangle \leftrightarrow |K',\downarrow\rangle$

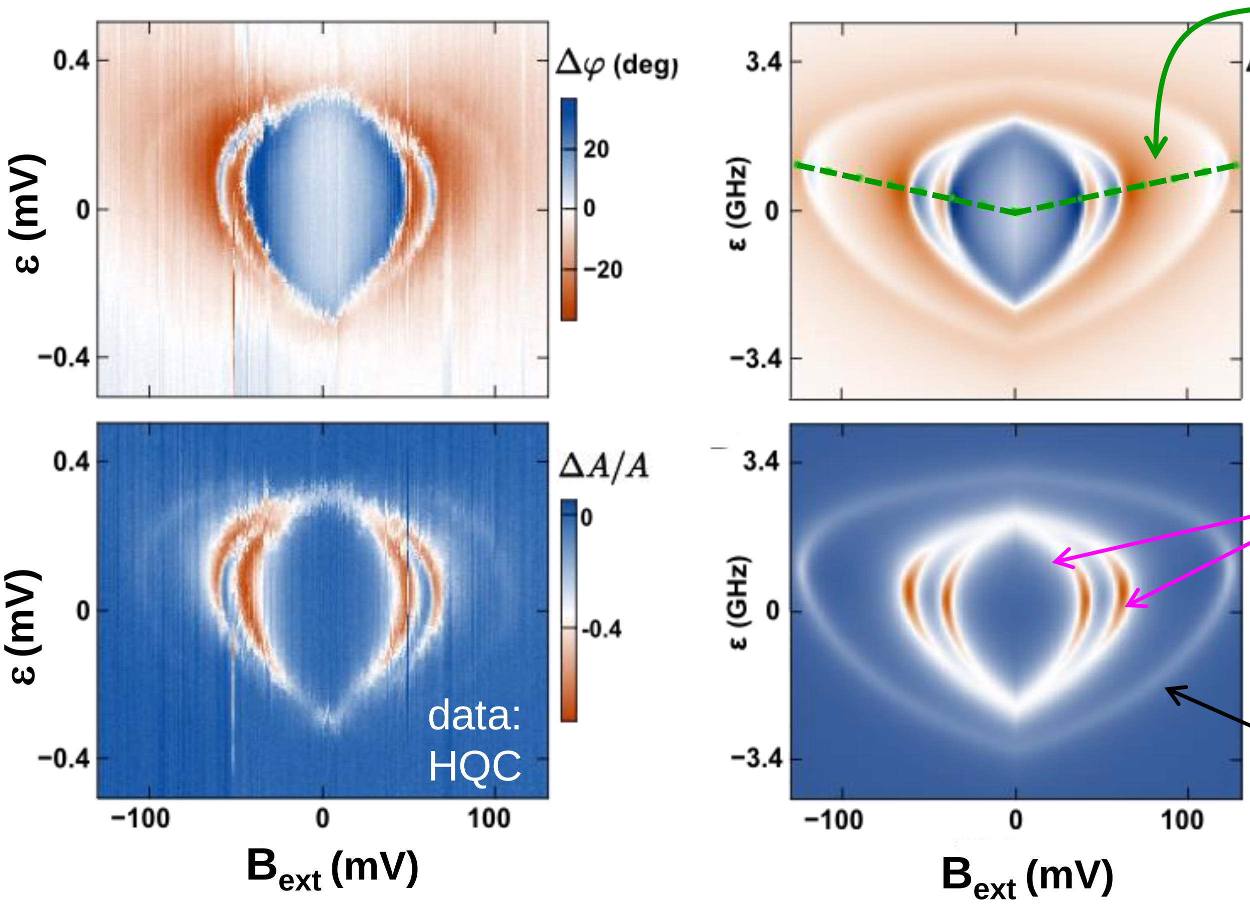
Spin and K/K' flip

$|K',\uparrow\rangle \leftrightarrow |K,\downarrow\rangle$

- The two brightest transitions (more coherent) are 80% spinfull in our model

Magneto-spectroscopy

Viennot, Dartiailh*, Cottet, & Kontos, Science* ***349****, 6246 (2015)*



Sweet line $\frac{\partial \omega_{ij}}{\partial \varepsilon} = 0$

Spin-flip transitions

$|K,\uparrow\rangle \leftrightarrow |K,\downarrow\rangle$

$|K',\uparrow\rangle \leftrightarrow |K',\downarrow\rangle$

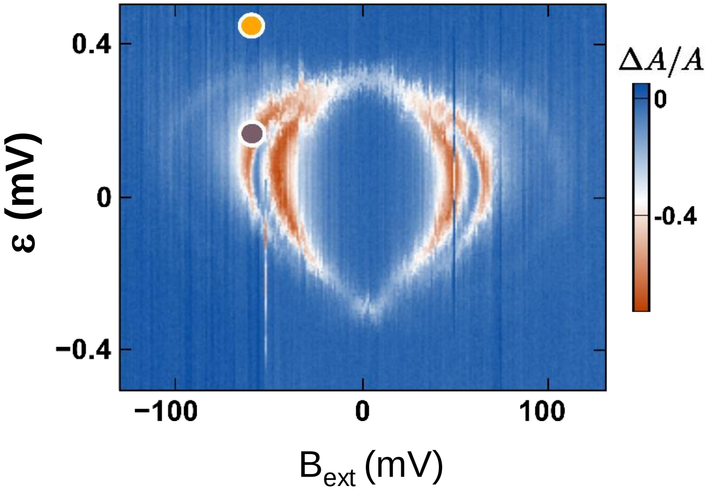
Spin and K/K' flip

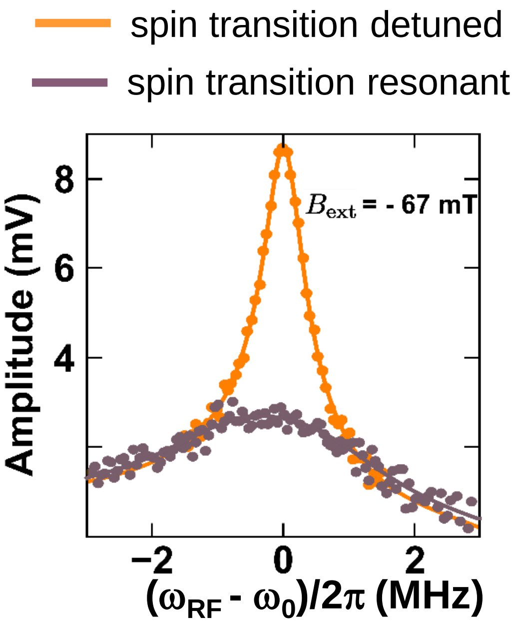
$|K',\uparrow\rangle \leftrightarrow |K,\downarrow\rangle$

- The two brightest transitions (more coherent) are 80% spinfull in our model
- Charge noise gives an important contribution to decoherence

Almost strong spin/photon coupling

*Viennot, Dartiailh, Cottet, & Kontos, Science **349**, 6246 (2015)*





$\Gamma^*_{2,\,\mathrm{spin}} \approx 2\pi \times 2.5$ MHz $g_{\mathrm{spin}} \approx 2\pi \times 1.3$ MHz

- Previous experiments with same E_c: $\Gamma^*_{2,\,\mathrm{charge}} \approx 2\pi \times 500$ MHz
- *Almost strong coupling regime* $\Gamma^*_{2,\,spin} < g_{spin}$ *!*

Cooperativity

$$C = \frac{\left(g^*_{spin}\right)^2}{\Lambda_0 \Gamma_{2,spin}} = 2.3$$

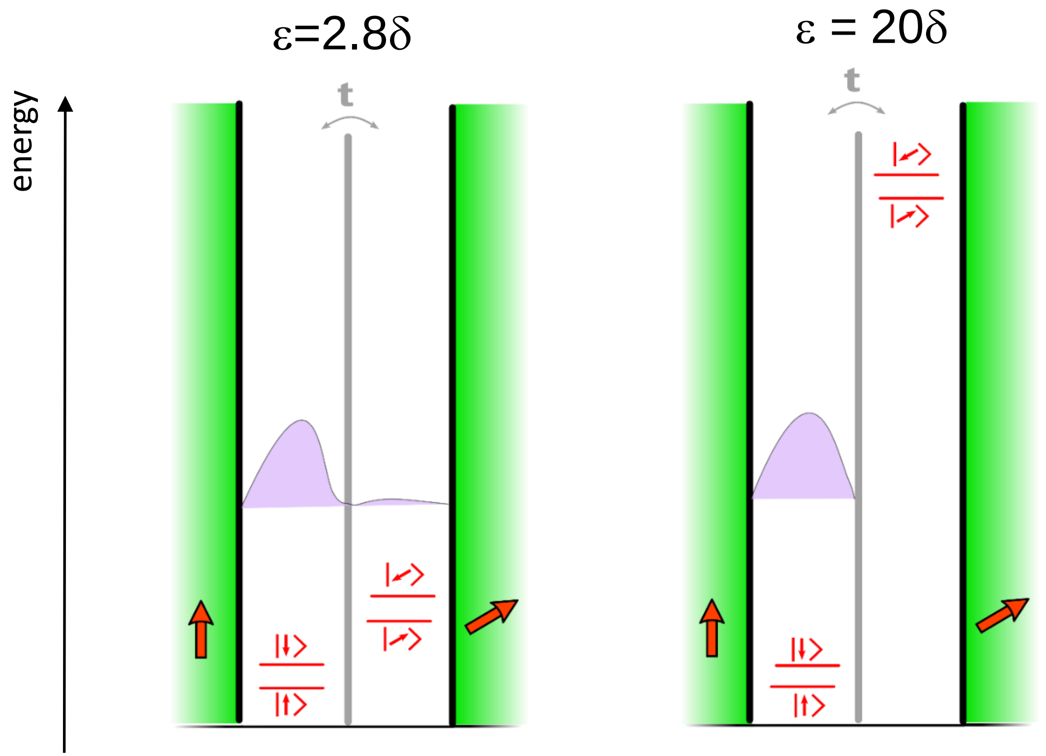
Optimization of the spin/photon coupling

Theory proposal:
Cottet & Kontos,
*PRL **105**, 160502 (2010)*

<u>Main sources of decoherence</u>:

- charge noise => dephasing

- phonons => relaxation



ON POINT
(theory proposal)

$g_\perp = 5.6$ MHz

$\Gamma_2^* = 1$ MHz

Strong coupling limit

OFF POINT
(theory proposal)

$g_\perp = 13$ kHz

$\Gamma_2^* = 0.5$ kHz

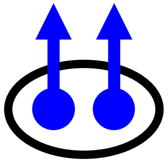
pure spin limit
= quantum memory?

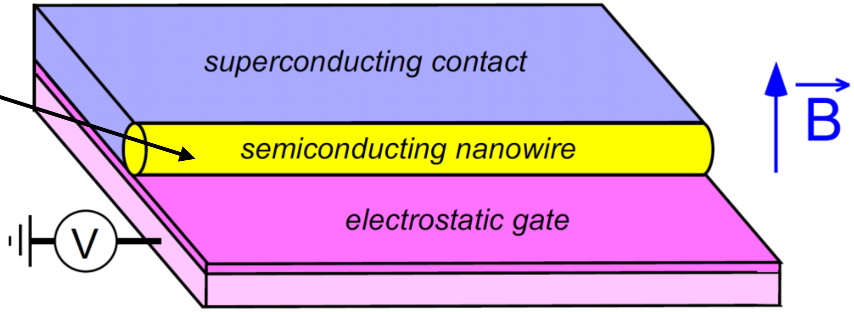
OUTLINE

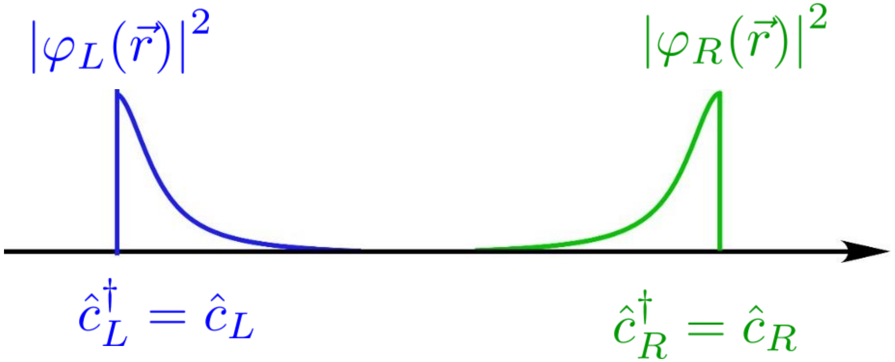
Majorana bound states in a cavity

Majorana fermions in a nanowire

Synthetic
topological
superconductivity

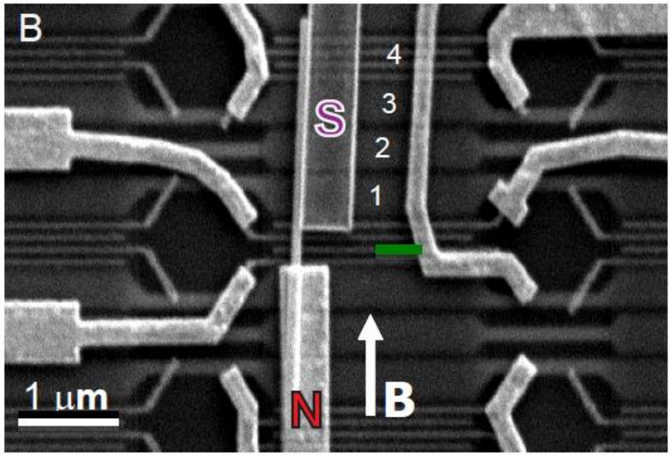




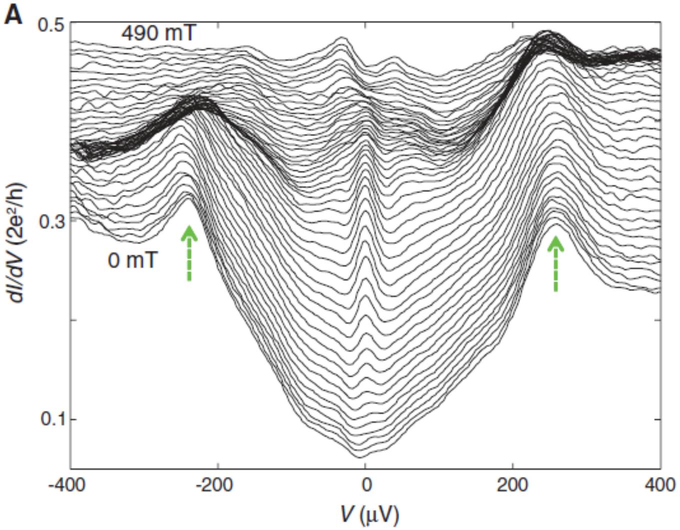


two low-energy self-adjoint quasiparticle states

Observation of zero bias conductance peaks in semiconducting nanowires



Density of states measurement



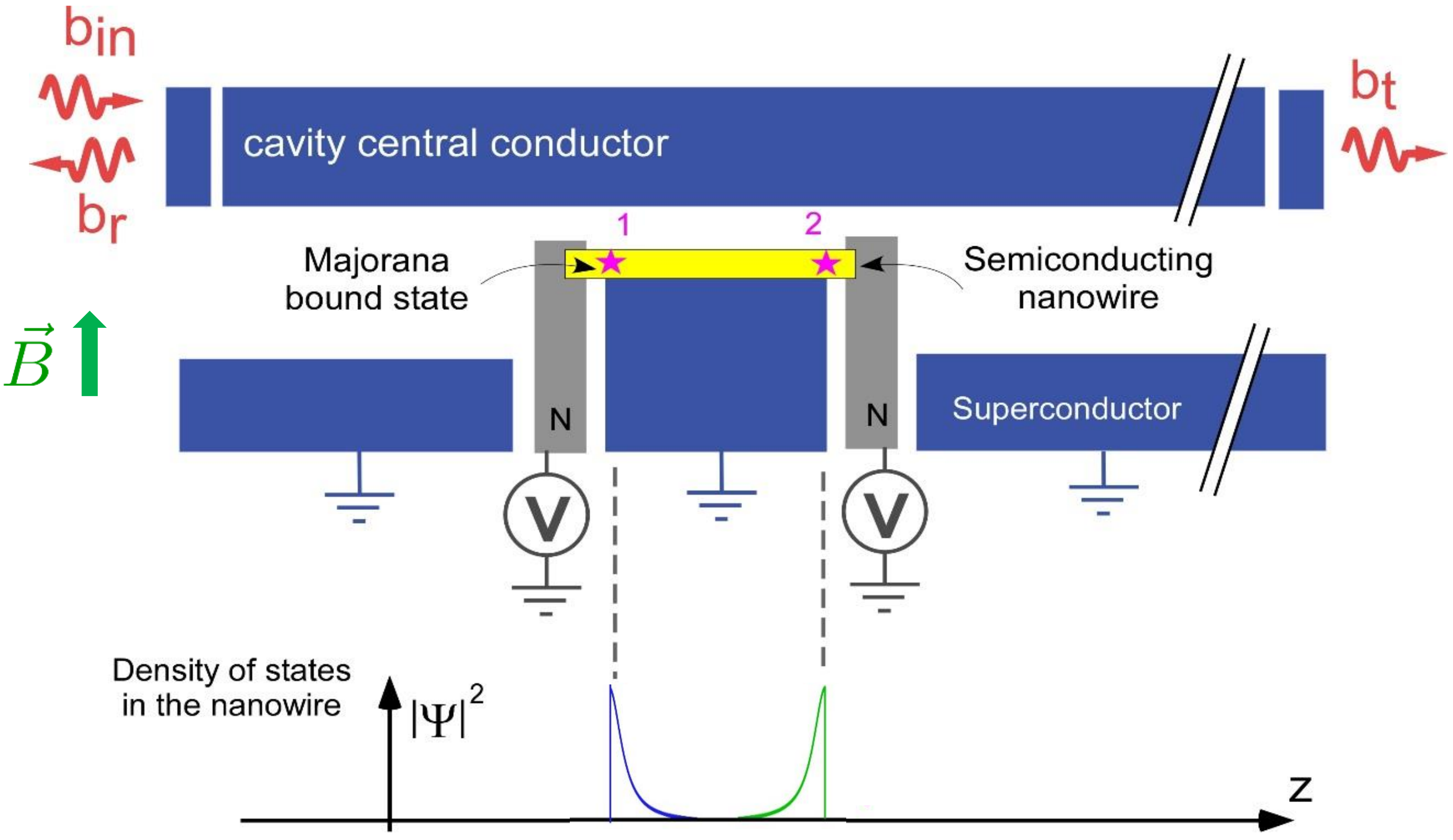
Mourik, et al., Science 336, 1003 (2012)
Williams, et al., PRL (2012)
Das, et al., Nature Phys. (2012).
Deng, et al., Nano Lett. (2012),
Rokhinson et al., Nature Phys. (2012)
etc…

⇒

Majorana bound state

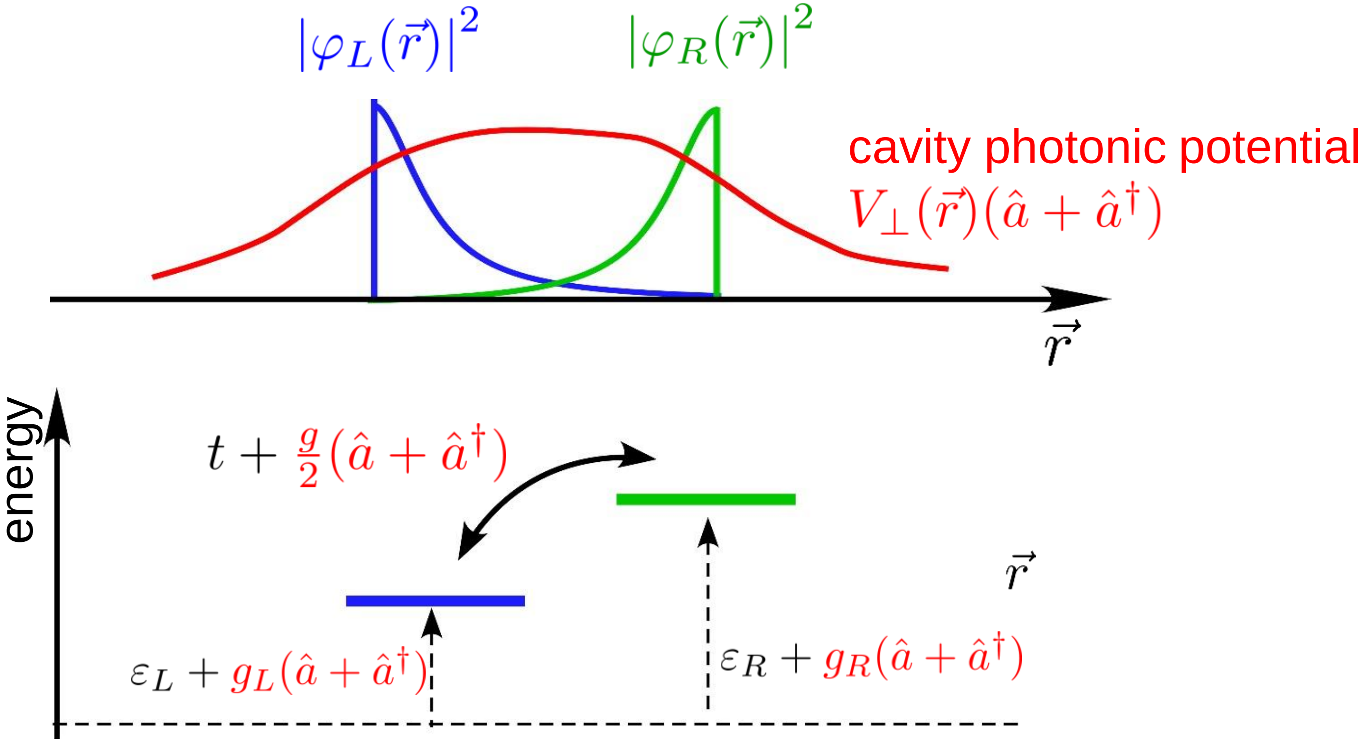
$$\gamma^\dagger = \gamma \quad ?$$

Majorana nanowire in a cavity



Majorana creation operators: $\hat{c}_L$ $\hat{c}_R$

Majorana pair in a cavity



$|\varphi_L(\vec{r})|^2$

$|\varphi_R(\vec{r})|^2$

cavity photonic potential

$V_\perp(\vec{r})(\hat{a}+\hat{a}^\dagger)$

$\vec{r}$

energy

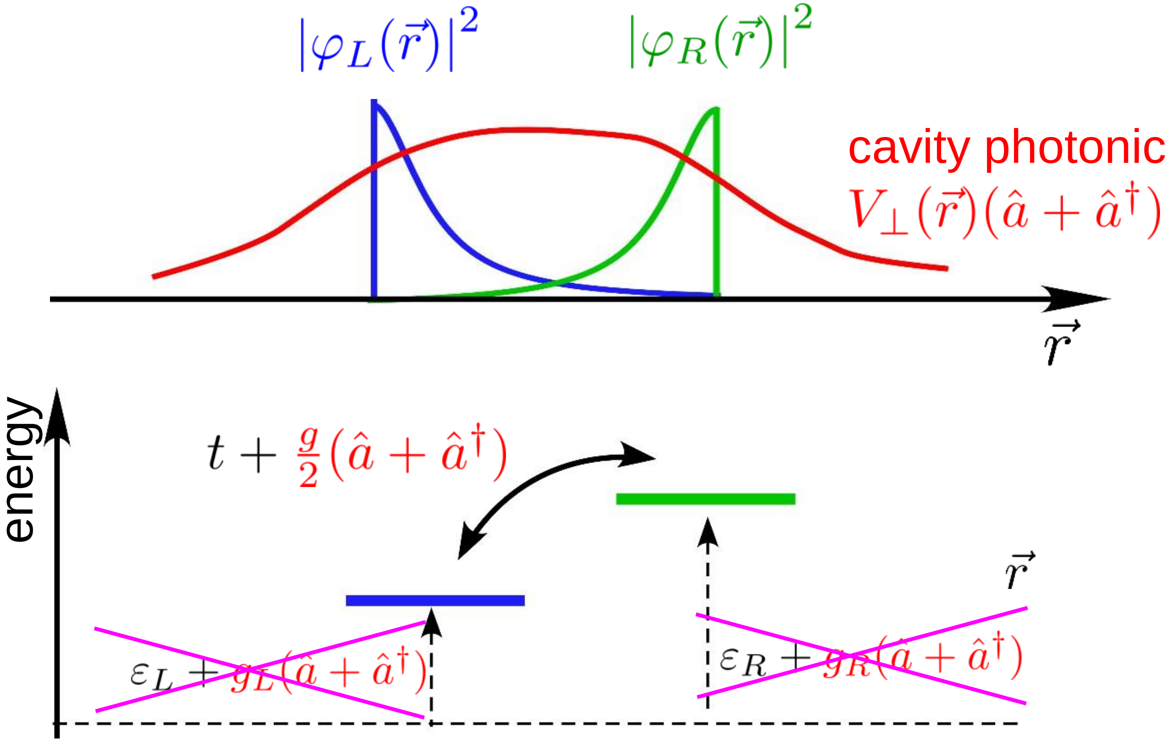
$t+\frac{g}{2}(\hat{a}+\hat{a}^\dagger)$

$\vec{r}$

$\varepsilon_L+g_L(\hat{a}+\hat{a}^\dagger)$

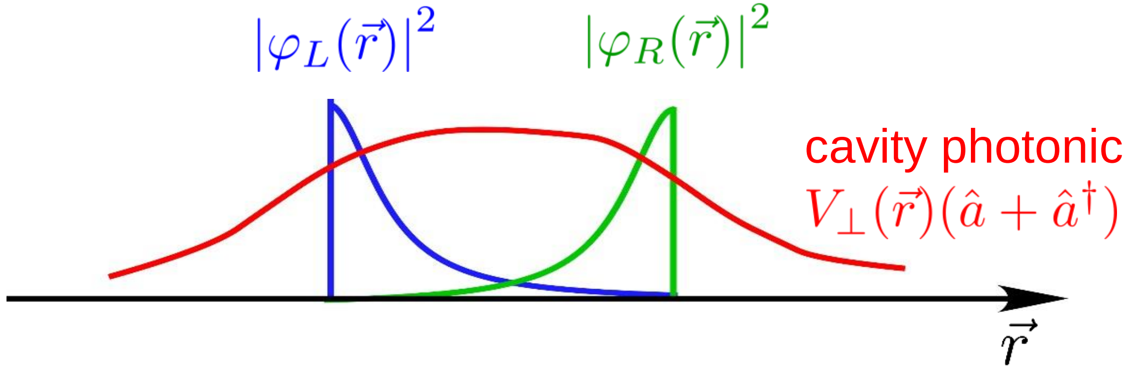
$\varepsilon_R+g_R(\hat{a}+\hat{a}^\dagger)$

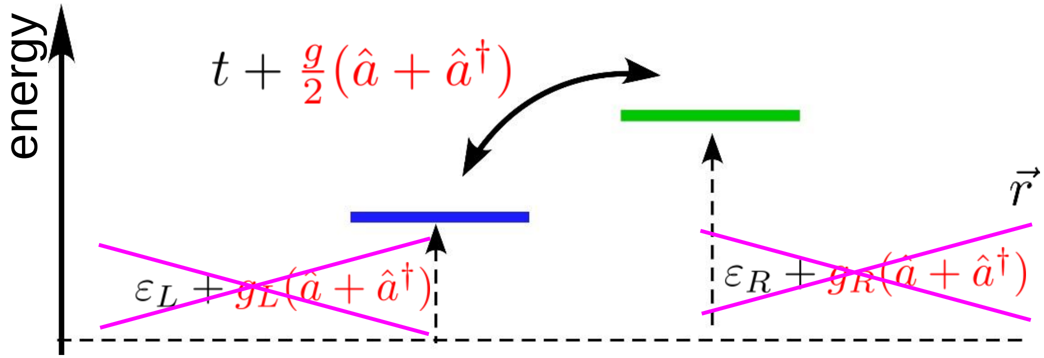
Majorana pair in a cavity



$$\boxed{\begin{array}{c} \hat{c}^\dagger_{L(R)} = \hat{c}_{L(R)} \\ \Downarrow \\ \hat{c}^\dagger_L \hat{c}_L = \hat{c}^\dagger_R \hat{c}_R = 1 \end{array}}$$

Majorana pair in a cavity



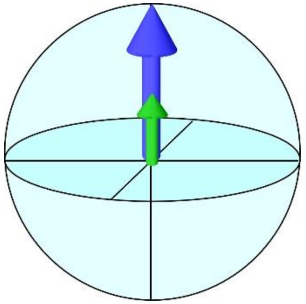


$$\hat{c}^\dagger_{L(R)} = \hat{c}_{L(R)}$$

$$\Downarrow$$

$$\hat{c}^\dagger_L \hat{c}_L = \hat{c}^\dagger_R \hat{c}_R = 1$$

$$\boxed{\hat{H} = 2it\hat{c}_L\hat{c}_R + ig(\hat{a}+\hat{a}^\dagger)\hat{c}_L\hat{c}_R + \hbar\omega_0\hat{a}^\dagger\hat{a}}$$



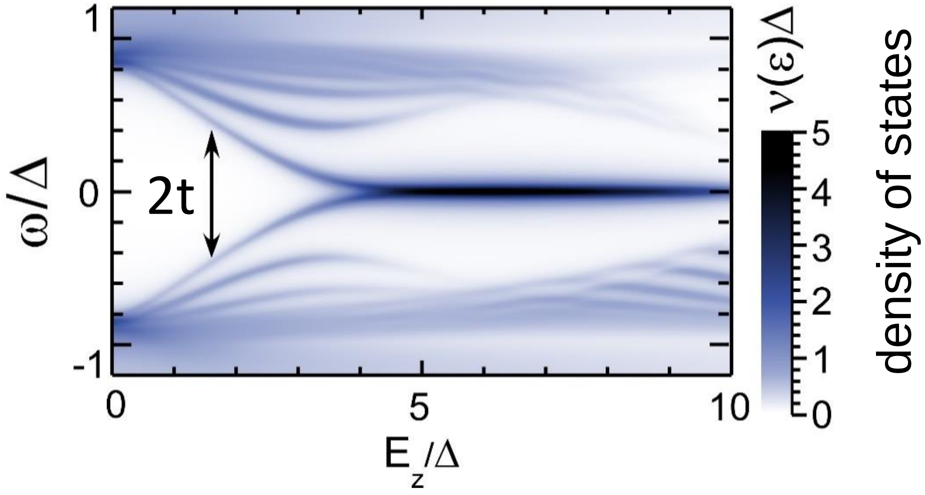
no cavity signal?

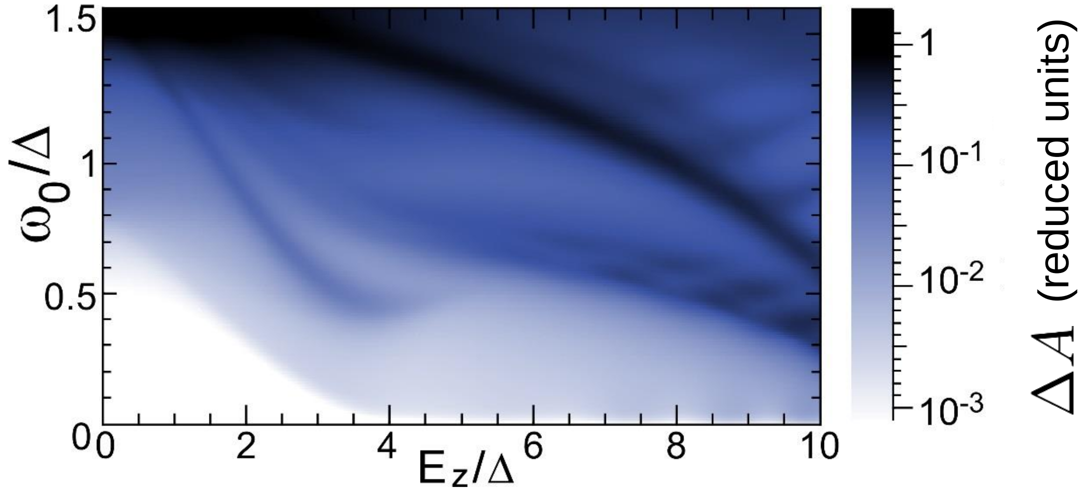
Dissipative response of the cavity (theory)

__Dartiailh__, Kontos, Douçot & Cottet, PRL 118, 126803 (2017)

Theory

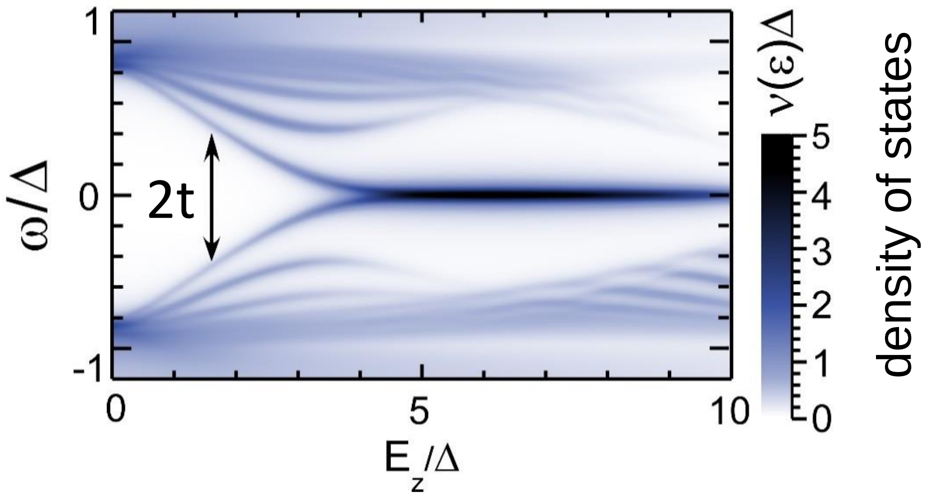
$$\frac{b_t}{b_{in}} = \frac{t_0}{-i\Lambda_0 - g^2\chi(\omega_0)}$$

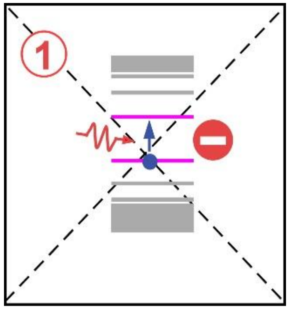


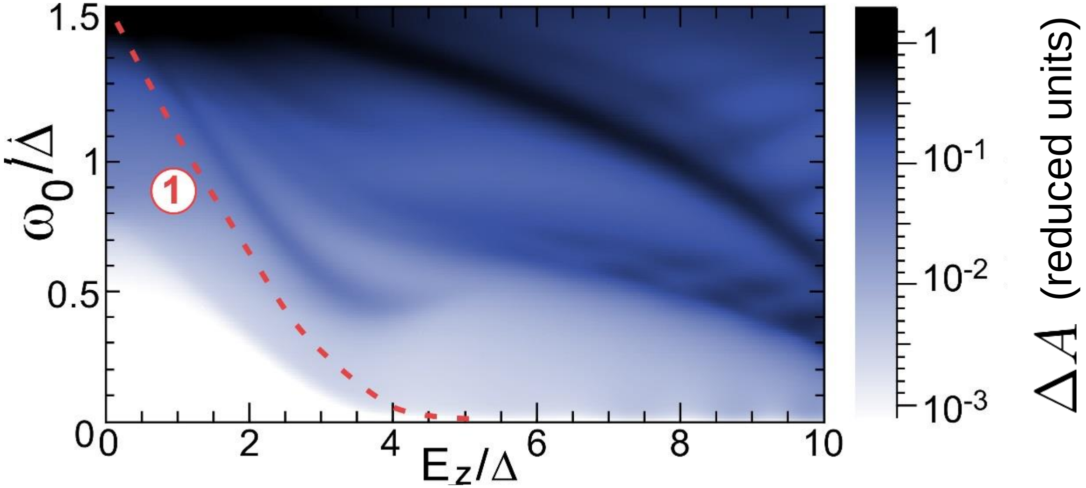


Dissipative response of the cavity (theory)

***Dartiailh**, Kontos, Douçot & Cottet, PRL 118, 126803 (2017)*



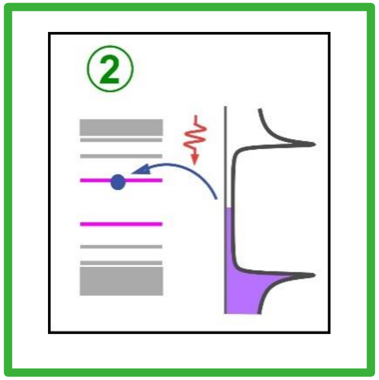


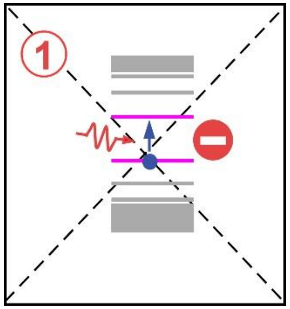


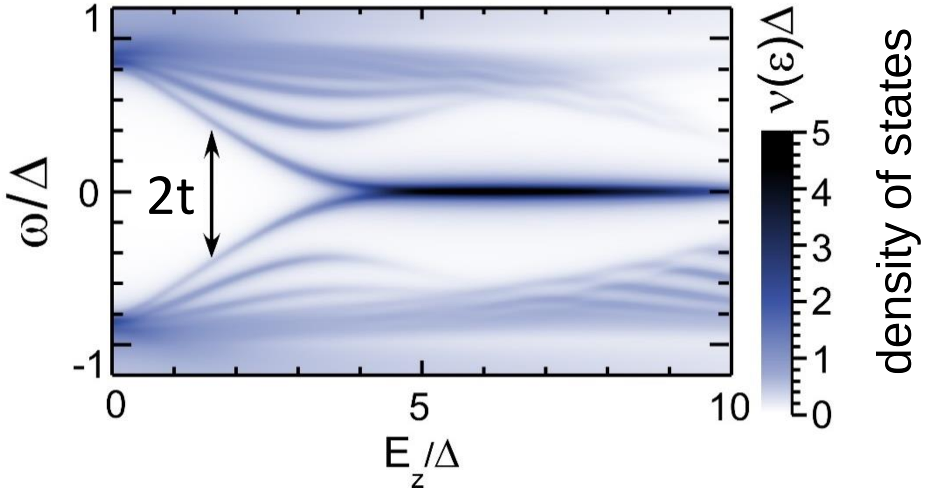
Dissipative response of the cavity (theory)

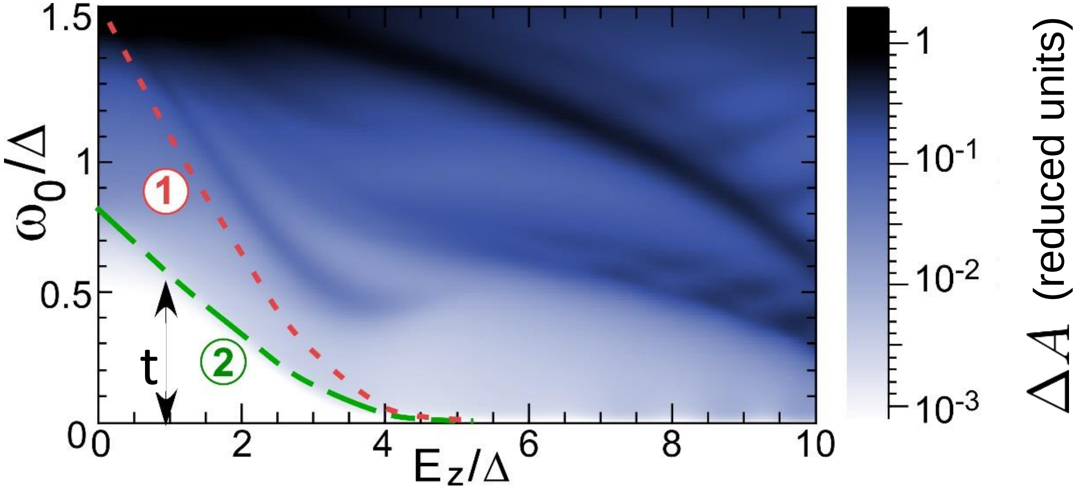
__Dartiailh__, Kontos, Douçot & Cottet, PRL 118, 126803 (2017)

$g \neq 0$









Dissipative response of the cavity (theory)

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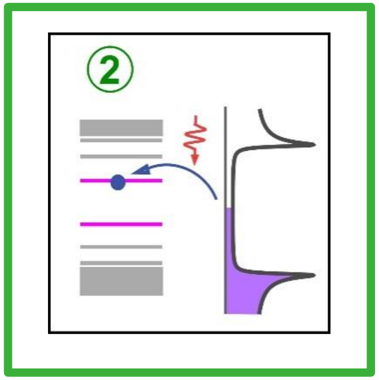
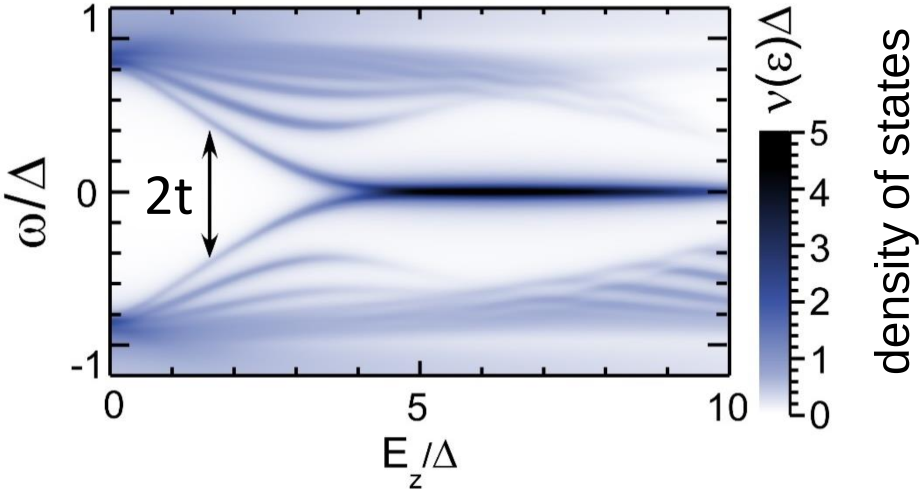
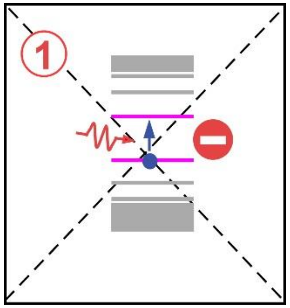
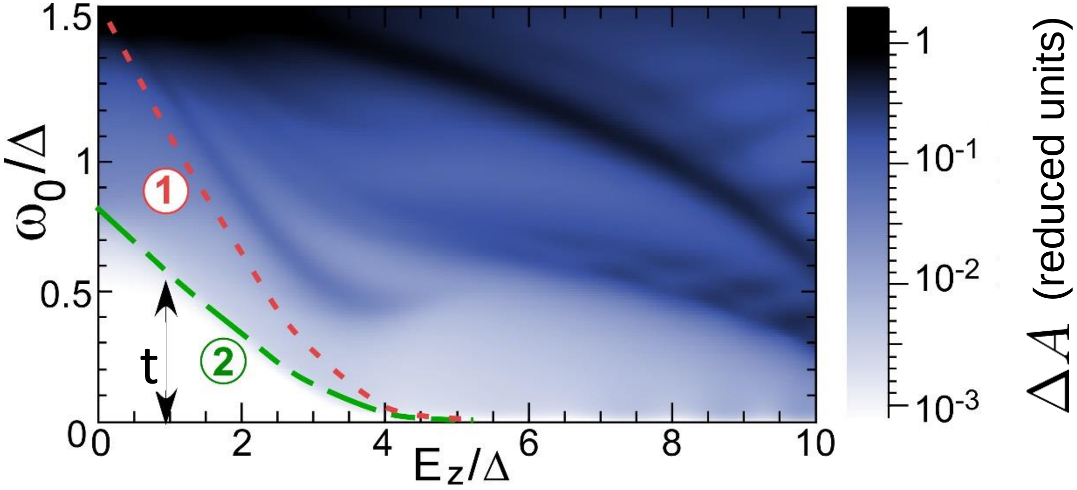
$g \neq 0$







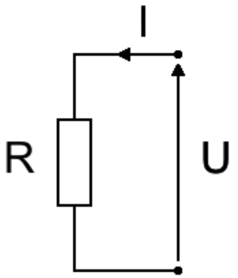
dark transition due to self-adjoint property



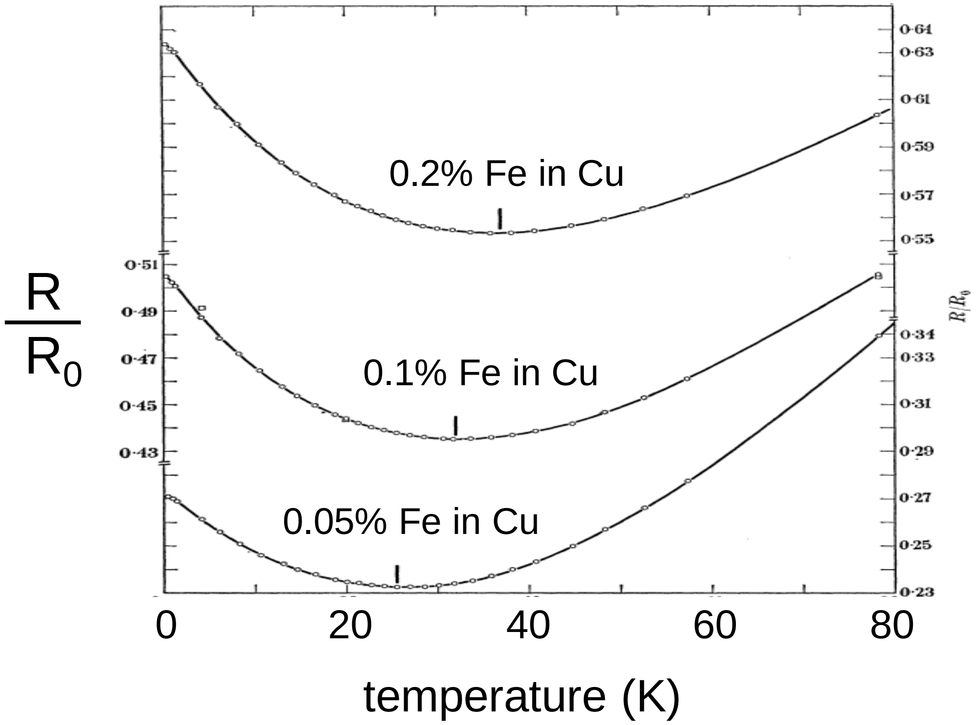
OUTLINE

Charge freezing in a Kondo impurity

Kondo physics in alloys

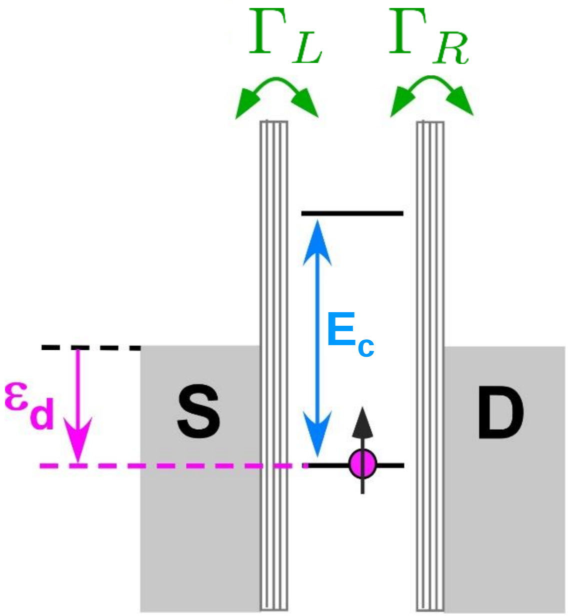


J. P. Franck et al. Proc. Roy. Soc. **A263**, 494 (1961)



- Resistance of a metal usually decreases as temperature lowered
- Increase of resistance when tiny amount of magnetic impurities added !
- Effect observed since the 1930’s, theoretical explanation by Jun Kondo in 1964

A quantum dot as an artificial magnetic impurity



P. W. Anderson, Phys. Rev. 124, 41 (1961)

E_c charging energy

$\Gamma_{L(R)}$ coupling to reservoirs

ε_d energy level of the dot

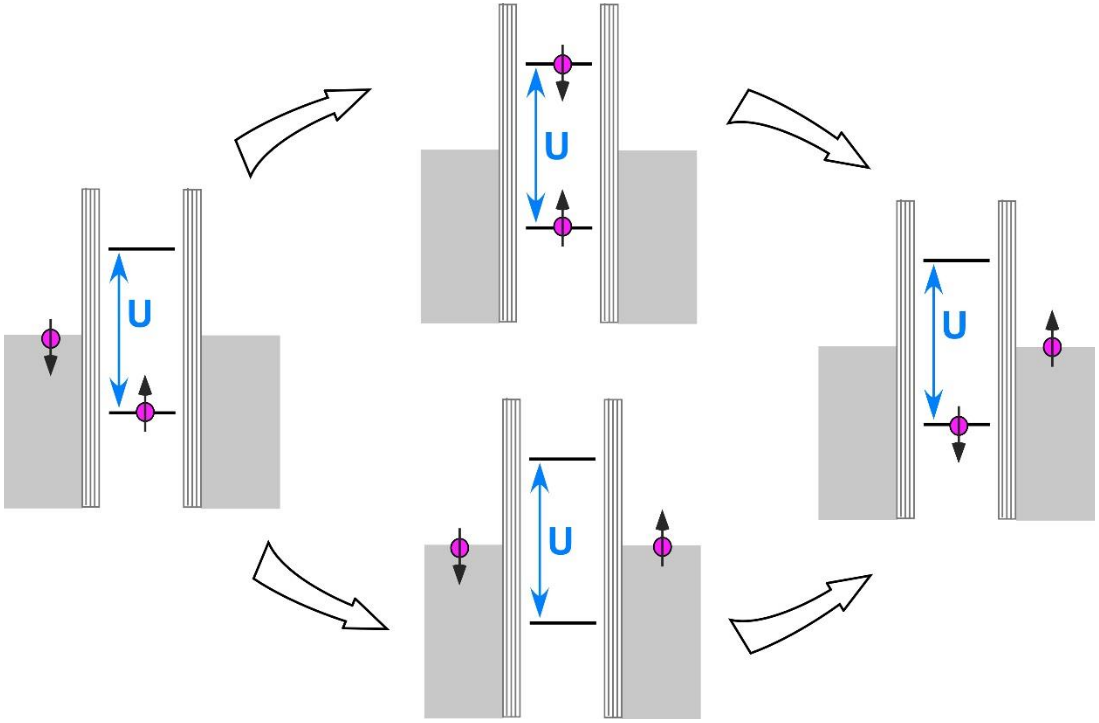
- **E_c** favors dot magnetic moment for $-E_c < \varepsilon_d < 0$
- $\Gamma_{L(R)} \neq 0 \Rightarrow$ mapping on Kondo problem at low energy (Schrieffer-Wolf)
- « Simplest » many body problem (energy level with Coulomb + Fermi sea)

Virtual processes and Kondo resonance

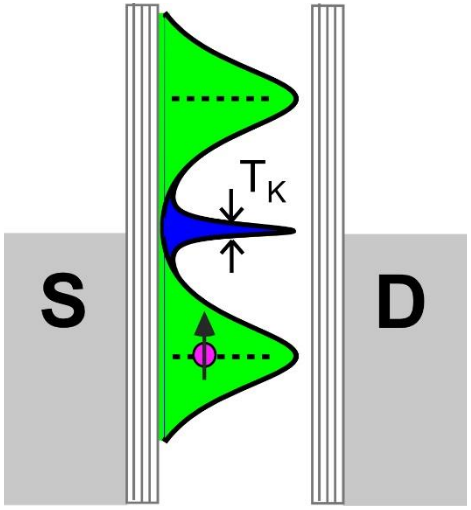
Initial state

Virtual state

Final state

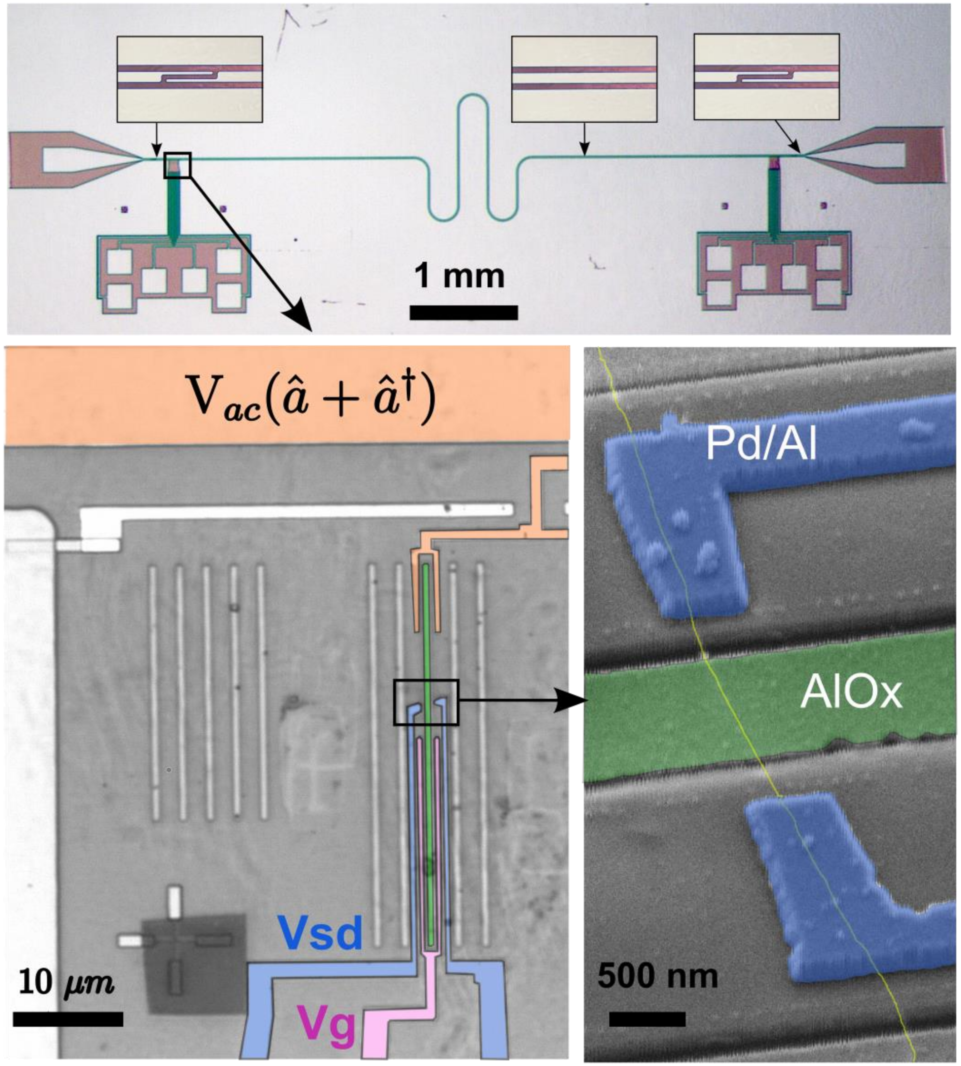


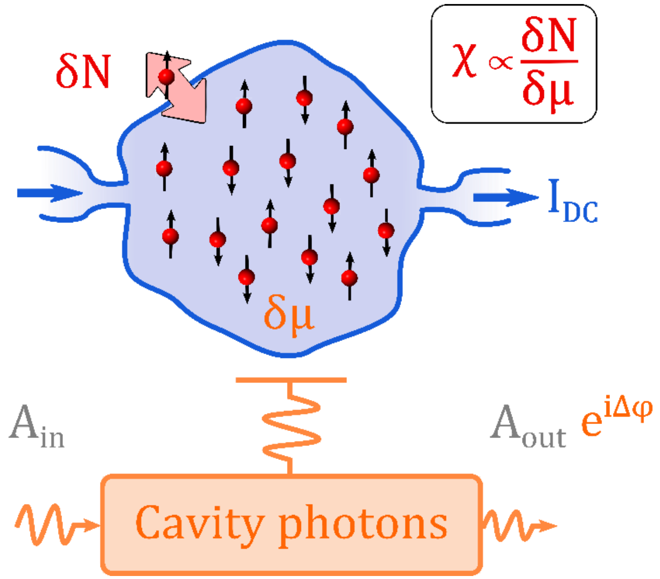
Dressed DOS



- Virtual processes quantum mechanically allowed
- Current through impurity although charge frozen
- Decoupling of spin and charge degrees of freedom

The experimental setup

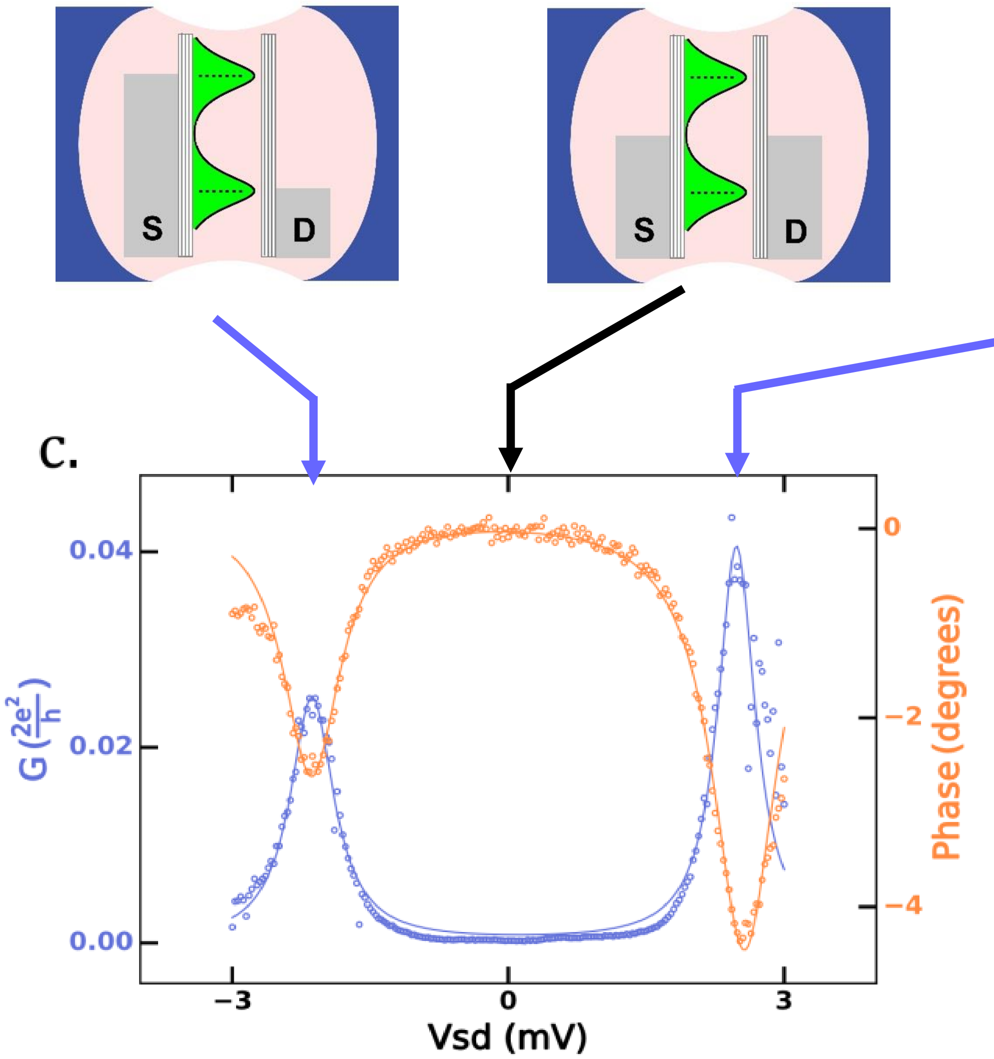




- Simultaneous measurement of conductance and microwave response
- Cavity measures Re $[\chi(\omega_0 = 0)]$
  = quantum capacitance of the dot
  = compressibility of the electronic system

Electron-photon coupling calibration in Coulomb blockade regime

M. M. Desjardins, et al., Nature 545, 71 (2017)

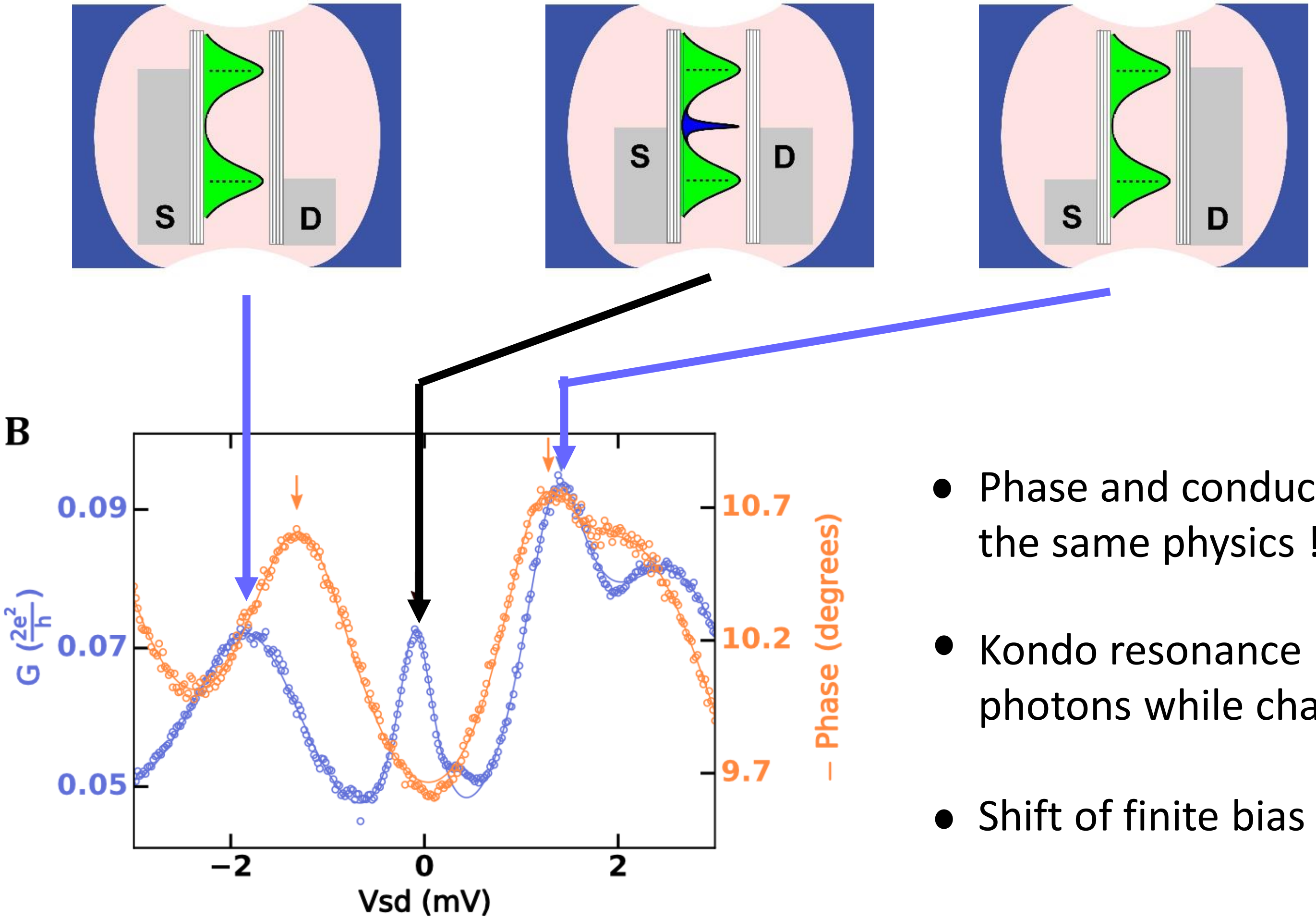


- Coulomb peaks visible both in conductance and microwave phase
- Amplitude of phase contrast => g ~100 MHz

U ~ 3meV, $\Gamma_L+\Gamma_R$~0.7 meV

‘Transparent’ Kondo resonance

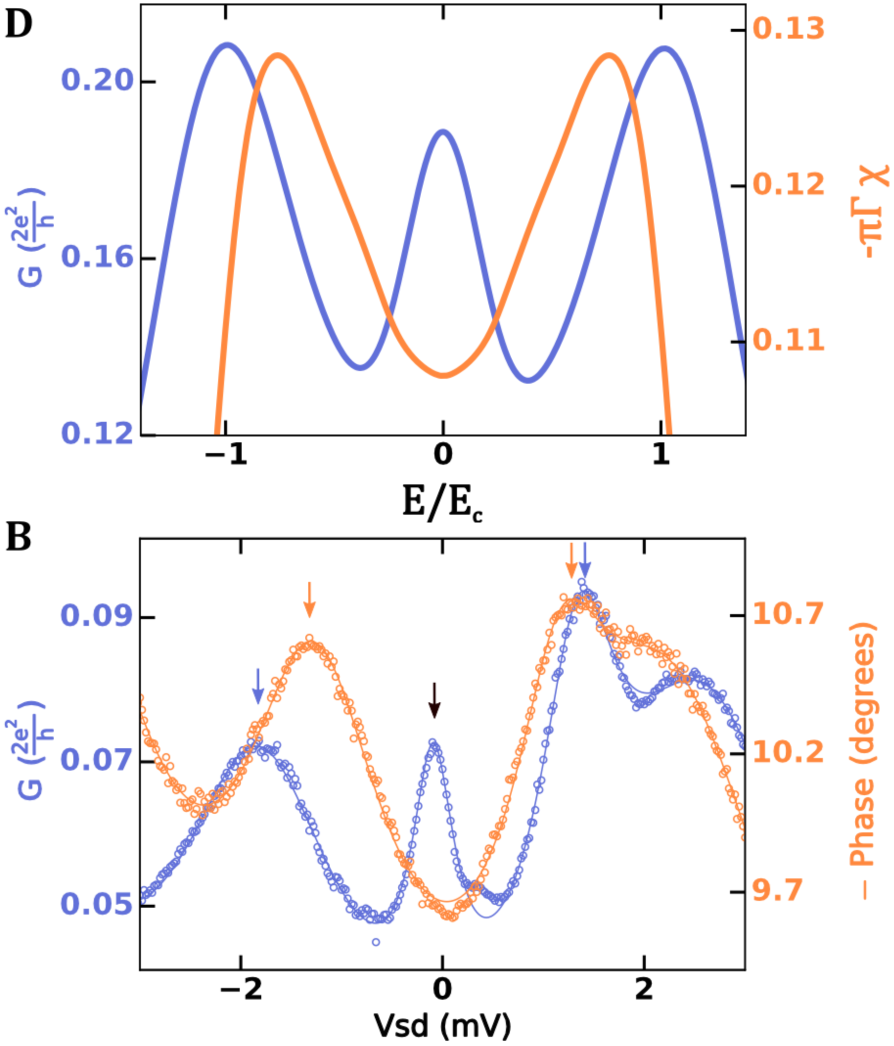
M. M. Desjardins, et al., Nature 545, 71 (2017)



- Phase and conductance do not measure the same physics !
- Kondo resonance is ‘transparent’ to photons while charge peaks visible
- Shift of finite bias voltage peaks

‘Transparent’ Kondo resonance

M. M. Desjardins, et al., Nature 545, 71 (2017)



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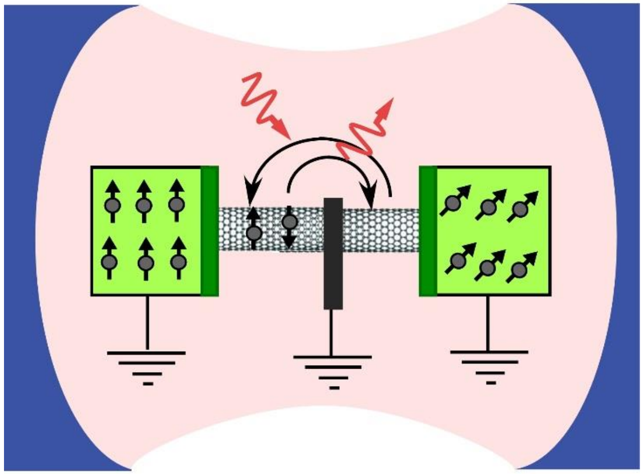
- Numerical Renormalization Group theory by M. Lee and M.-S. Choi, reproduces:
  - Peaks shifts
  - Zero charge susceptibility

➡ *Separation of spin and charge dynamics confirmed*

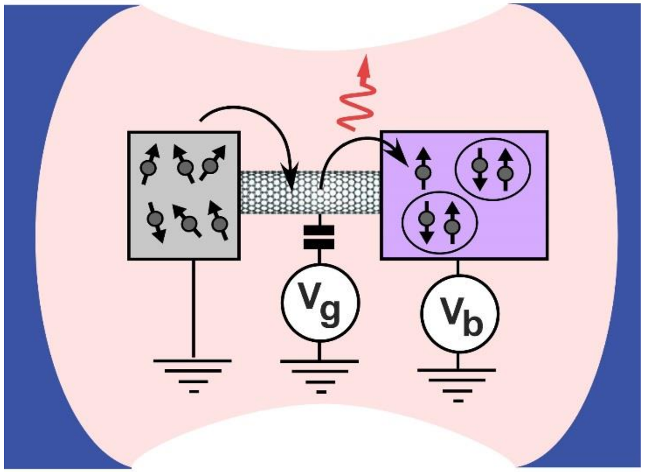
SUMMARY



Closed mesoscopic circuits:

Transverse coupling between cavity photons and different degree of freedom (charge, spin, ….)

=> atomic-like physics



Open mesoscopic circuits:

Dynamical aspects of tunneling:

- Capacitive/inductive cavity frequency shifts
- Photon assisted tunneling to/from BCS peak

Characterization of different exotic states:

- Majorana bound states
- Kondo cloud

The end