Quantum dot circuits in microwave cavities

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Experiment: **T. Kontos**, L. E. Bruhat, J. J. Viennot, S. Datta.

Theory: A. Cottet

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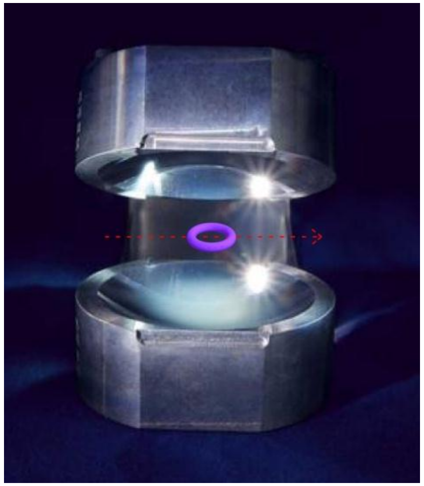
électronique et photonique quantiques

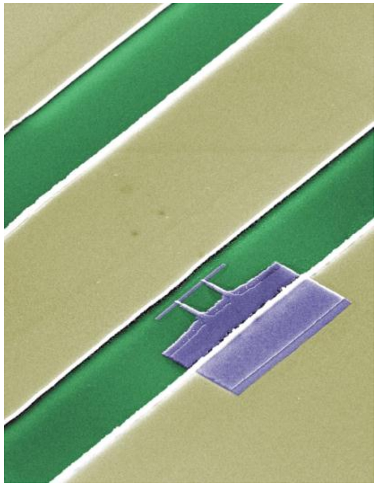
Combining cQED with quantum dots

Cavity QED



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

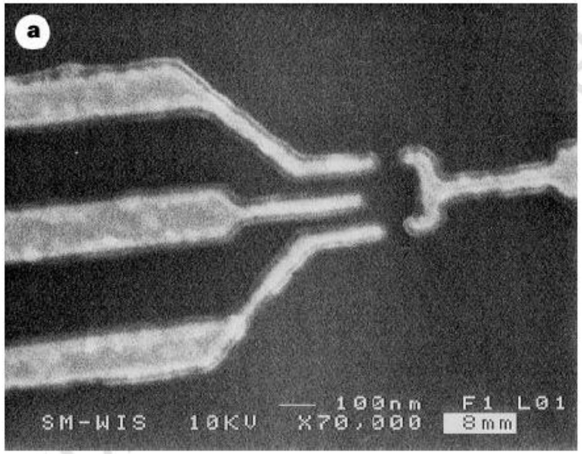
Circuit QED



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

Real or artificial two-level systems shift the resonance frequency of high finesse cavities

Quantum Dot



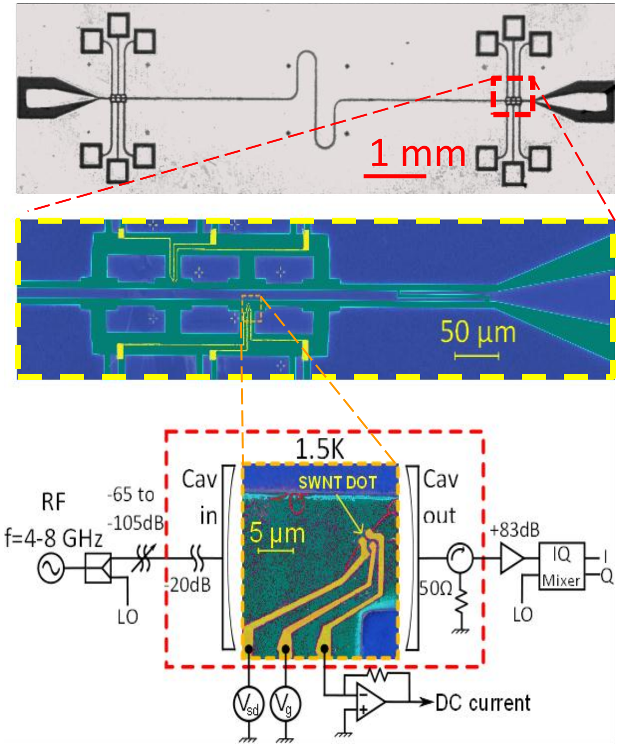
D. Goldhaber-Gordon et al., Nature 391, 156 (1998)

Various transport regimes with strong electronic interactions

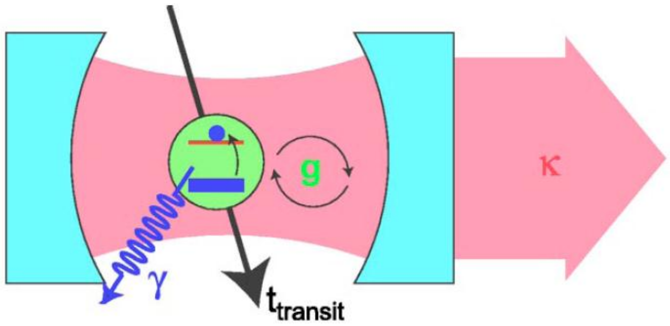
Circuit QED with quantum dots

Hybrid circuit QED

M.R. Delbecq et al. PRL ‘11. See also T. Frey et al. PRL’12



Traditional cQED



J.-M. Raimond, M. Brune, and S. Haroche, RMP **73**, 565 (2001)

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

- Hybrid circuit quantum electrodynamics

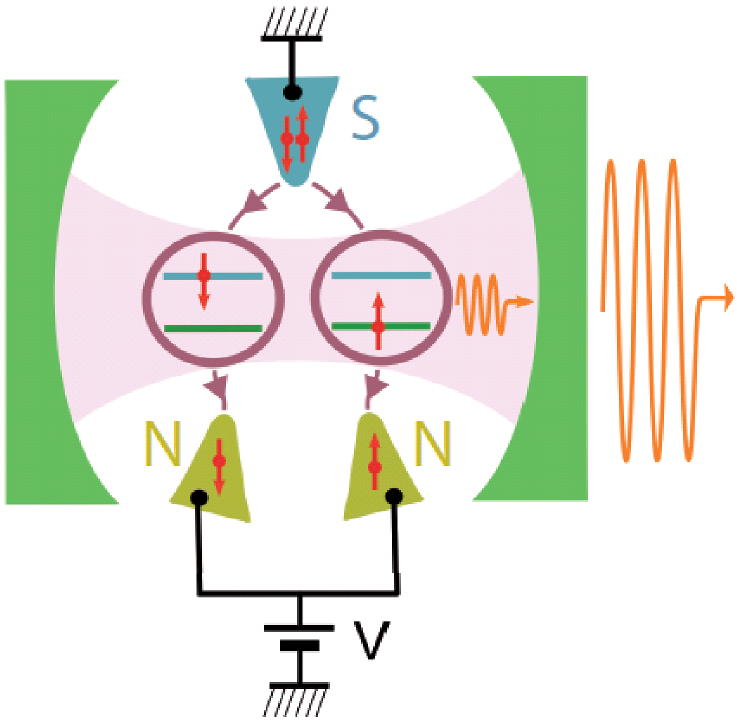
  ➡ Use of light-matter interaction to probe and manipulate nano-circuits

- Versatility of nano-circuits

  ➡ Beyond conventional atomic physics experiments

Quantum information but also condensed matter problems addressed

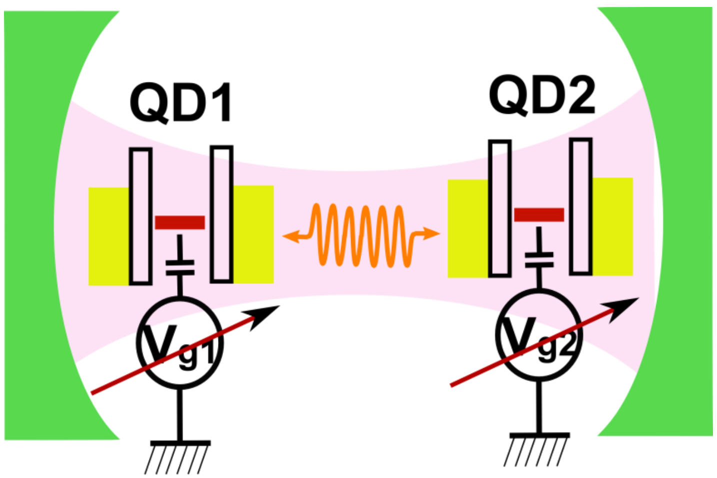
Light-matter interaction with quantum circuits



Subradiant split Cooper pairs

Probe of entanglement with electronic states

A. Cottet,T. Kontos & A. LevyYeyati, PRL'12

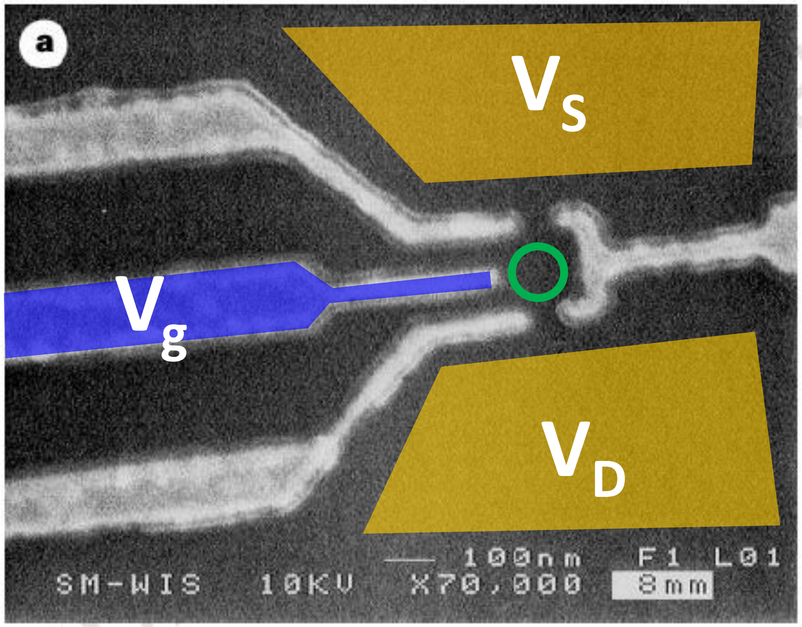


Photon mediated interaction between distant quantum dot circuits

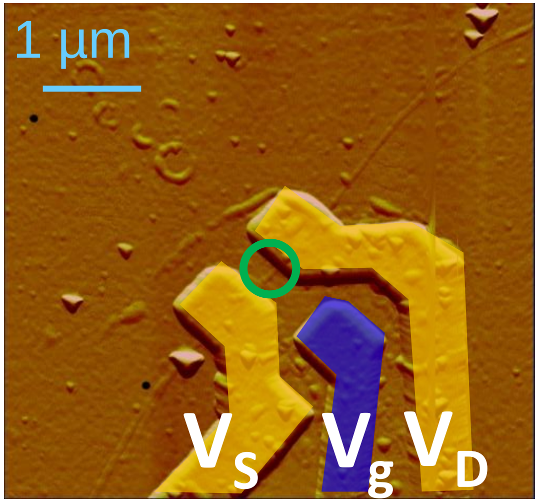
Scalability of spin quantum bits

M.R. Delbecq et al. submitted

Quantum dot geometries



Two-dimensional electronic gas QD

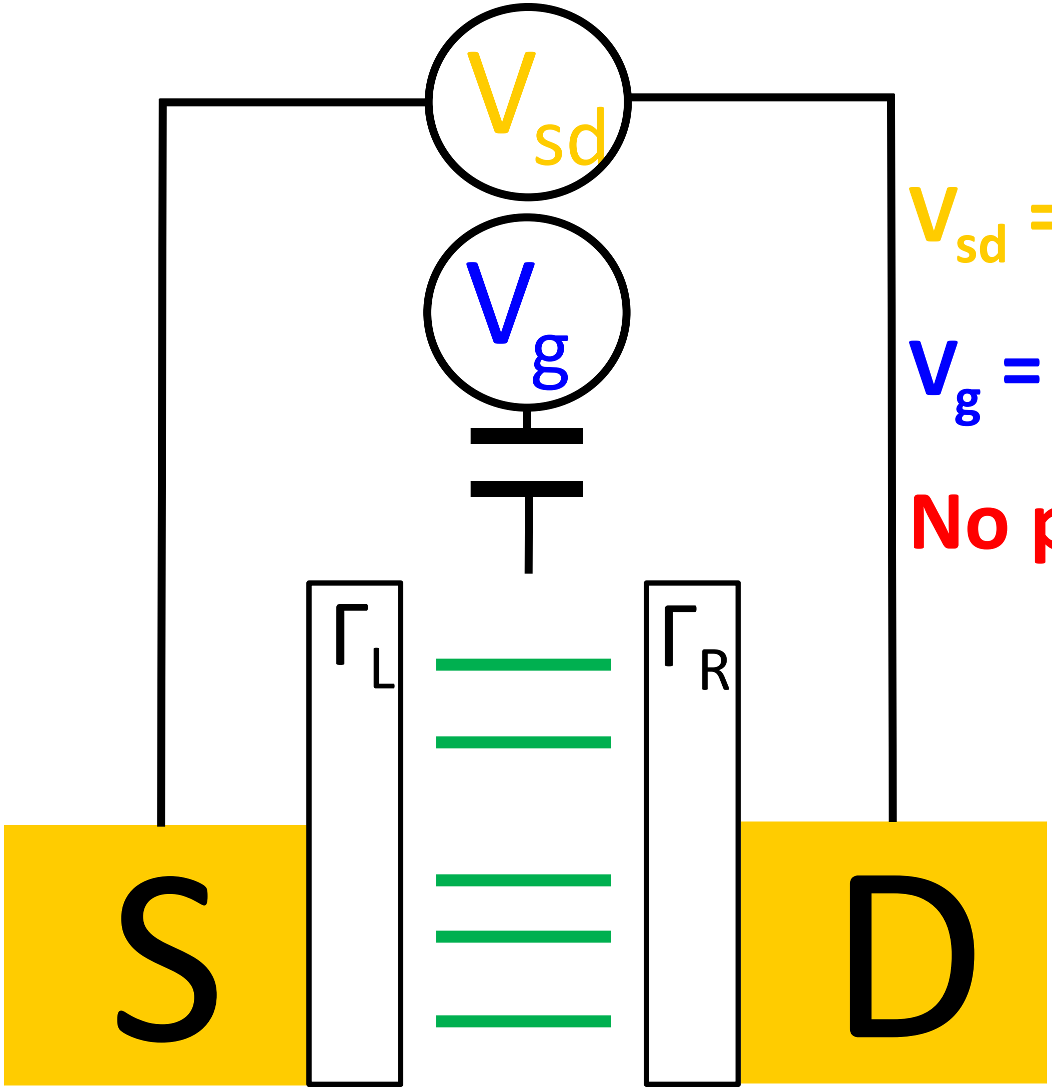


Carbon Nanotube QD

- Confinement discretizes the spectrum inside the dot
- Possibility to study two-levels system or more complex artificial atoms

➡ **We use SWNTs as quantum dots**

Nanotubes as quantum dots



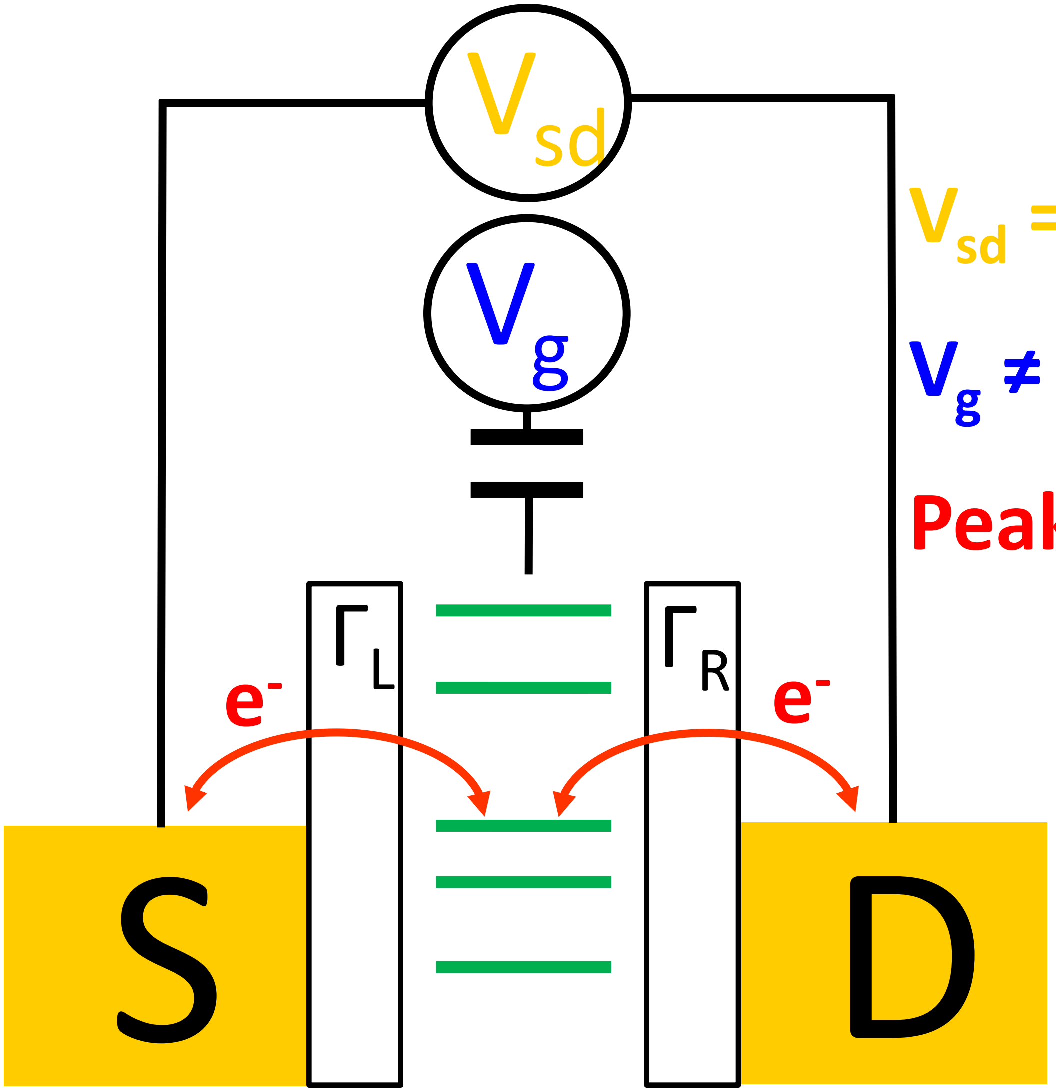
Discrete levels

$V_{sd} = 0$

$V_g = 0$

No peak in conductance

Nanotubes as quantum dots



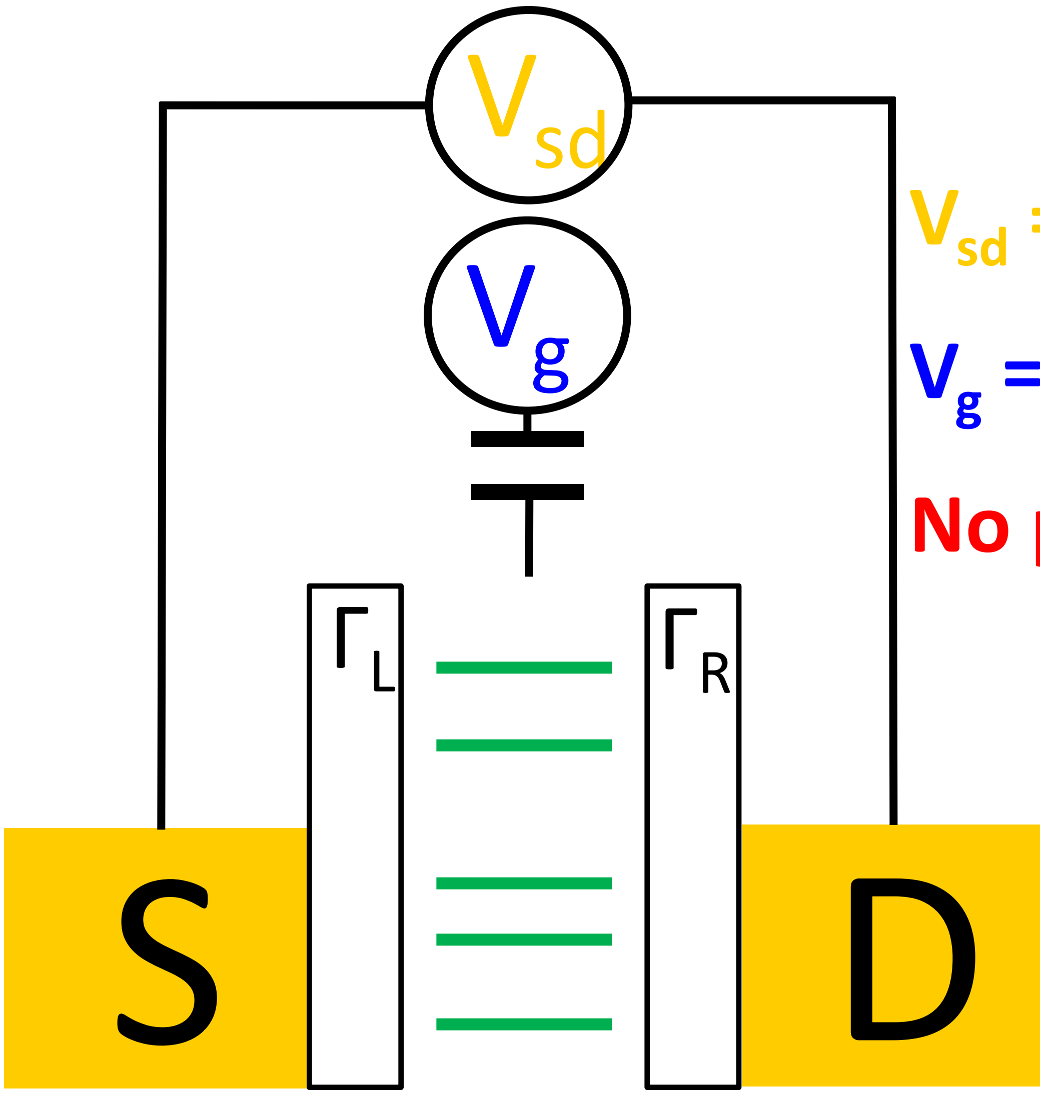
Discrete levels

V_{sd} = 0

V_g ≠ 0

Peak in conductance

Nanotubes as quantum dots



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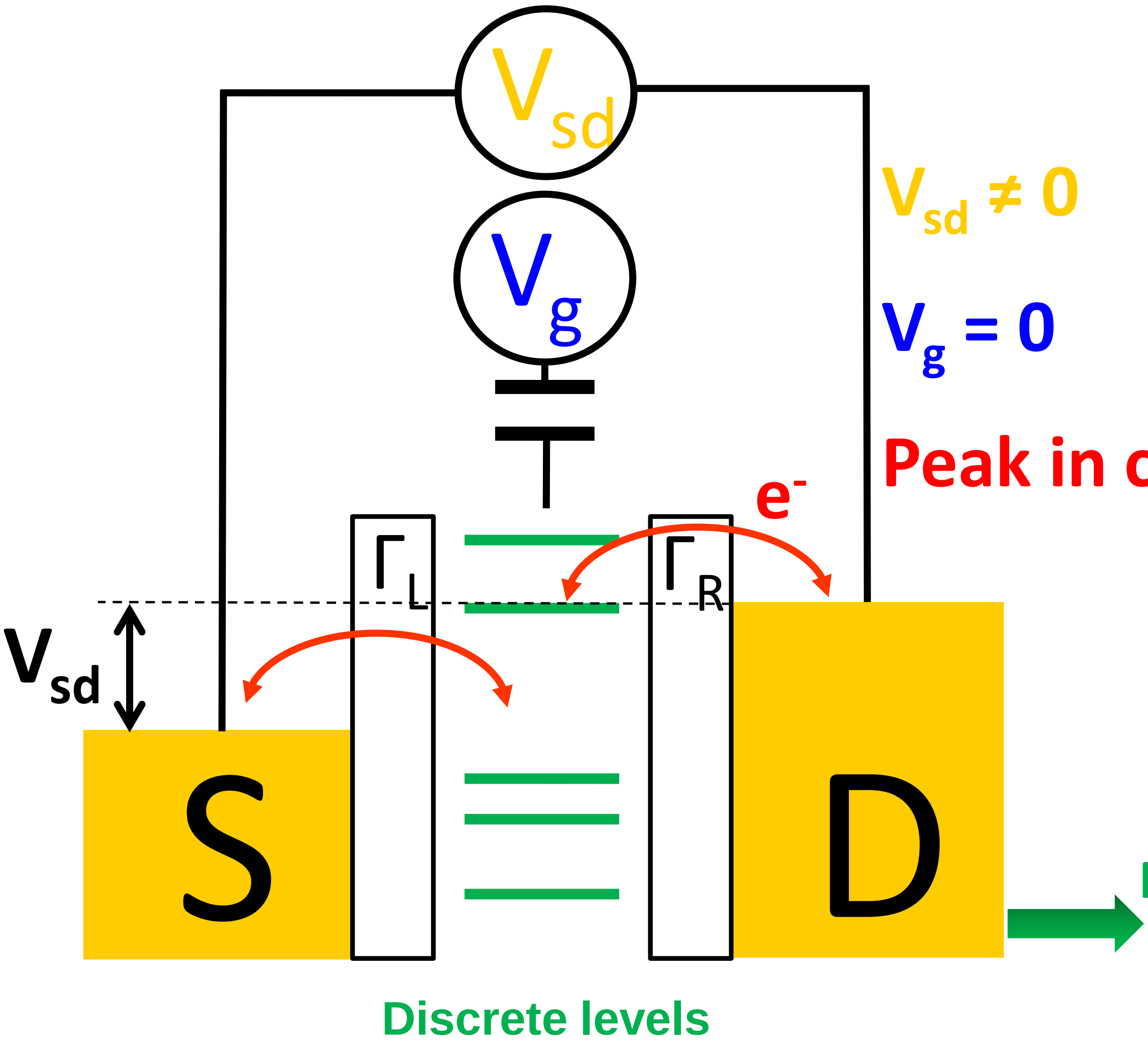


$V_{sd} \neq 0$

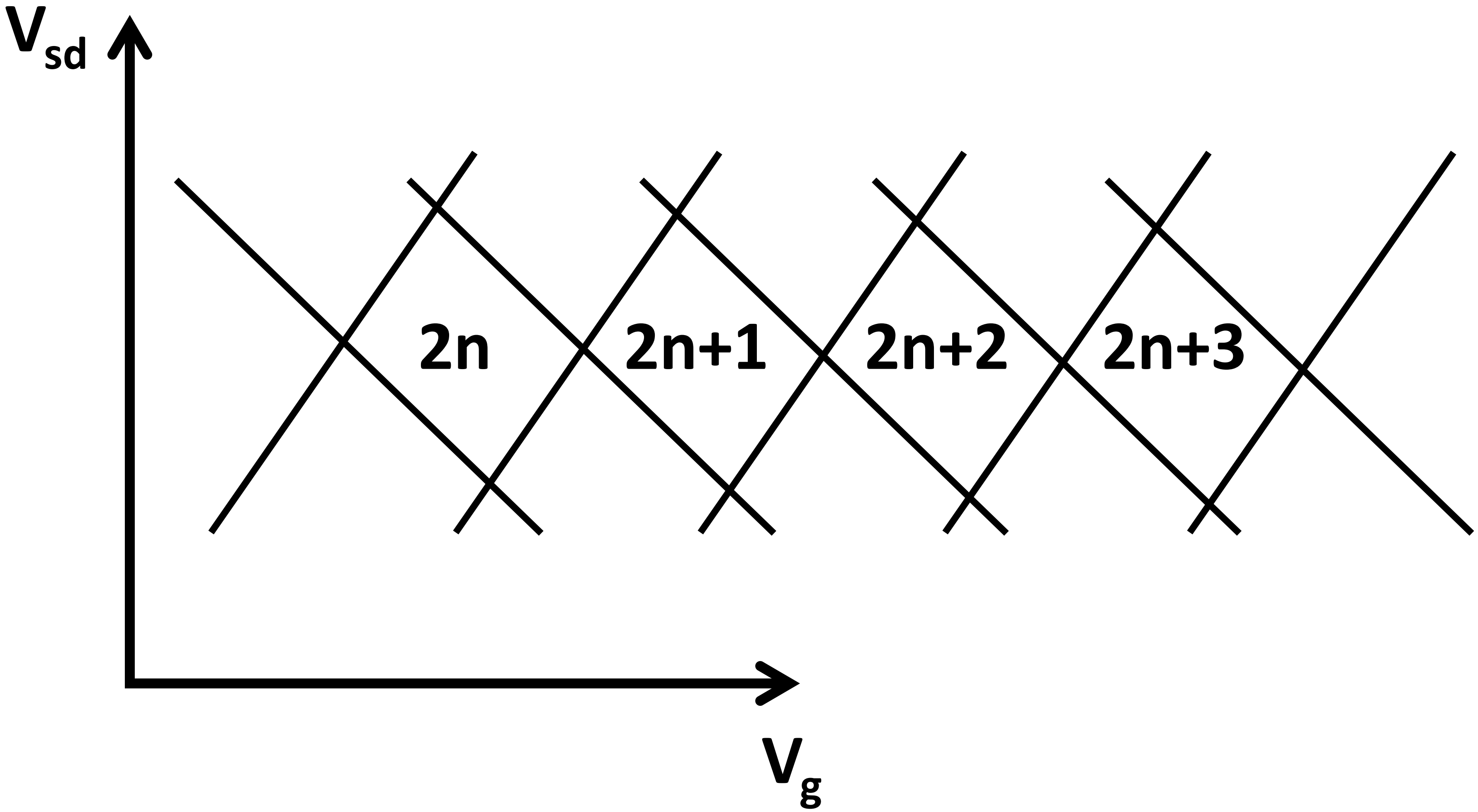
$V_g = 0$

Peak in conductance

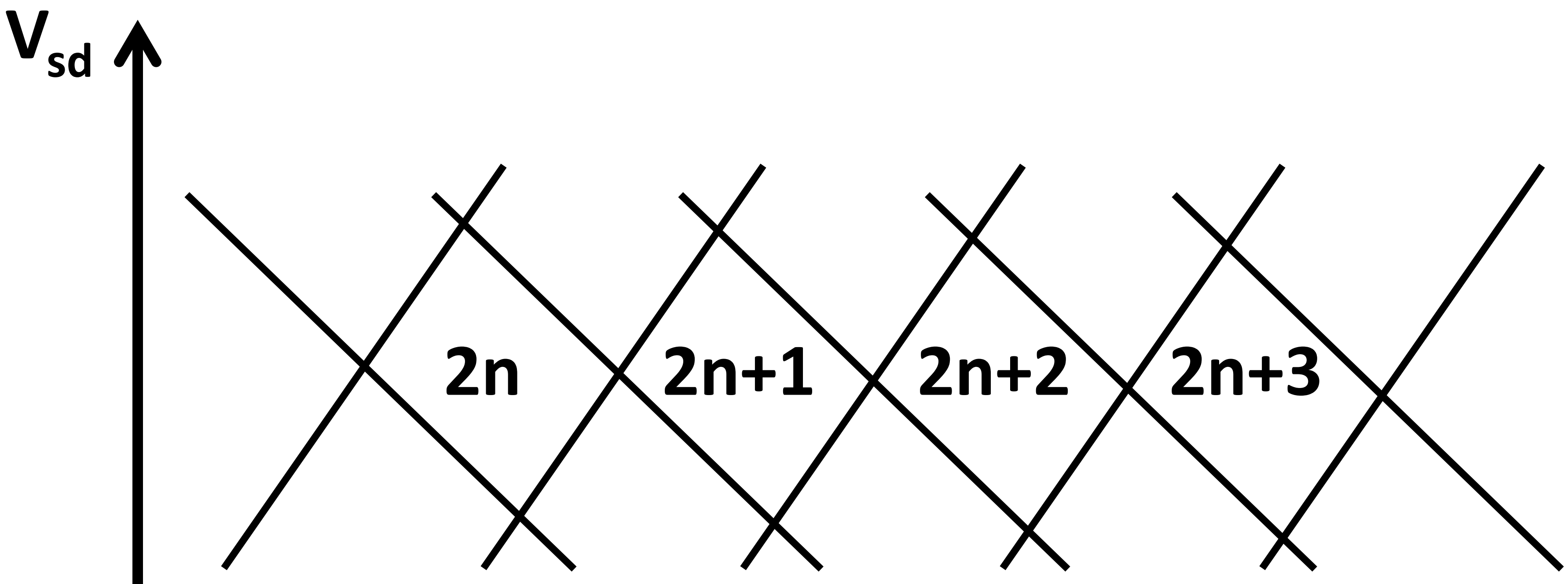
Resonances on lines

$V_{sd} + \alpha\, V_g = cste$

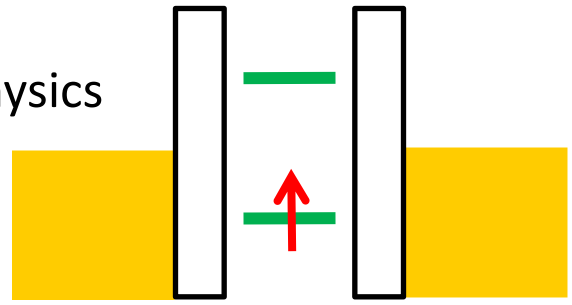
Coulomb diamonds and Kondo ridge



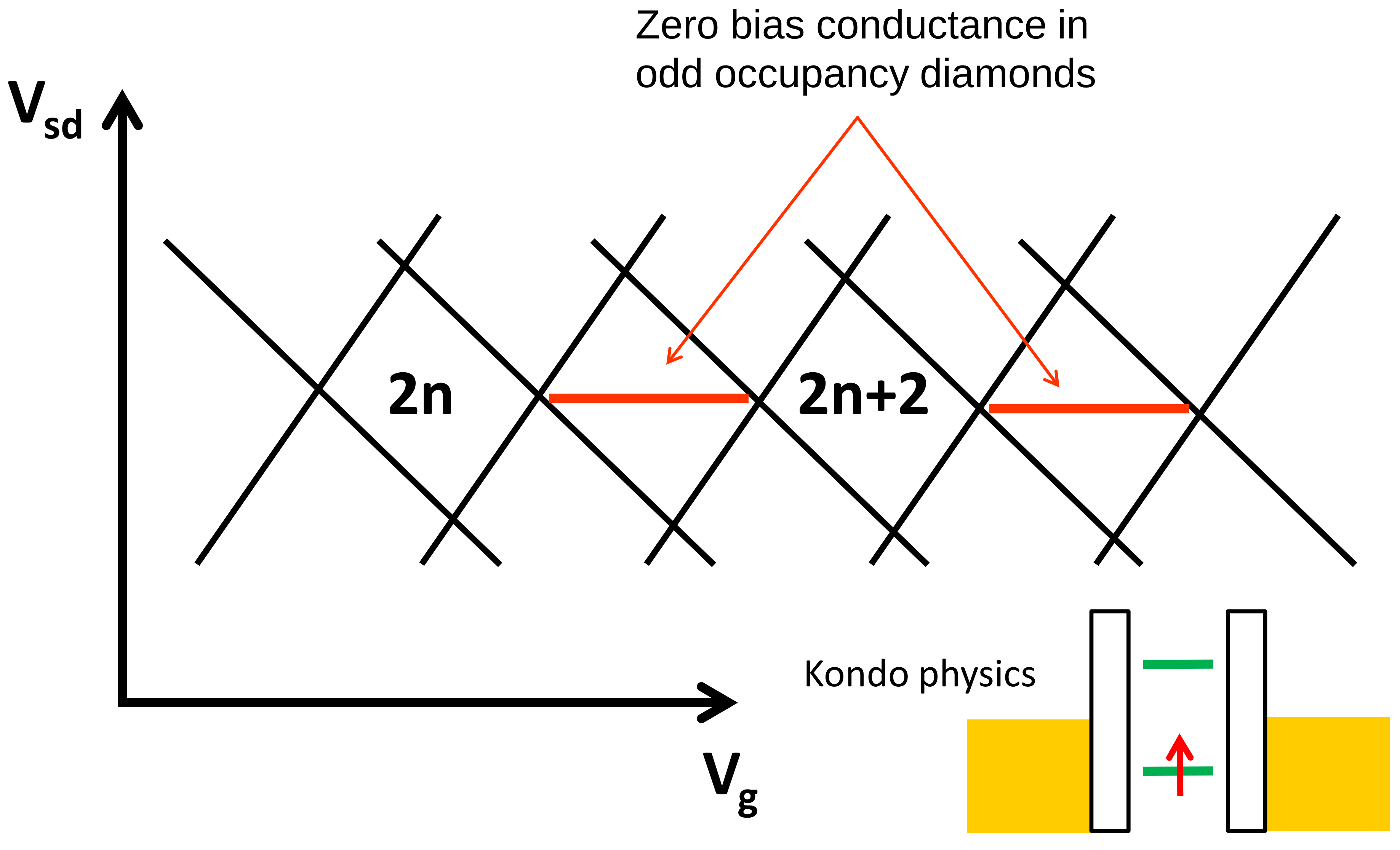
Coulomb diamonds and Kondo ridge



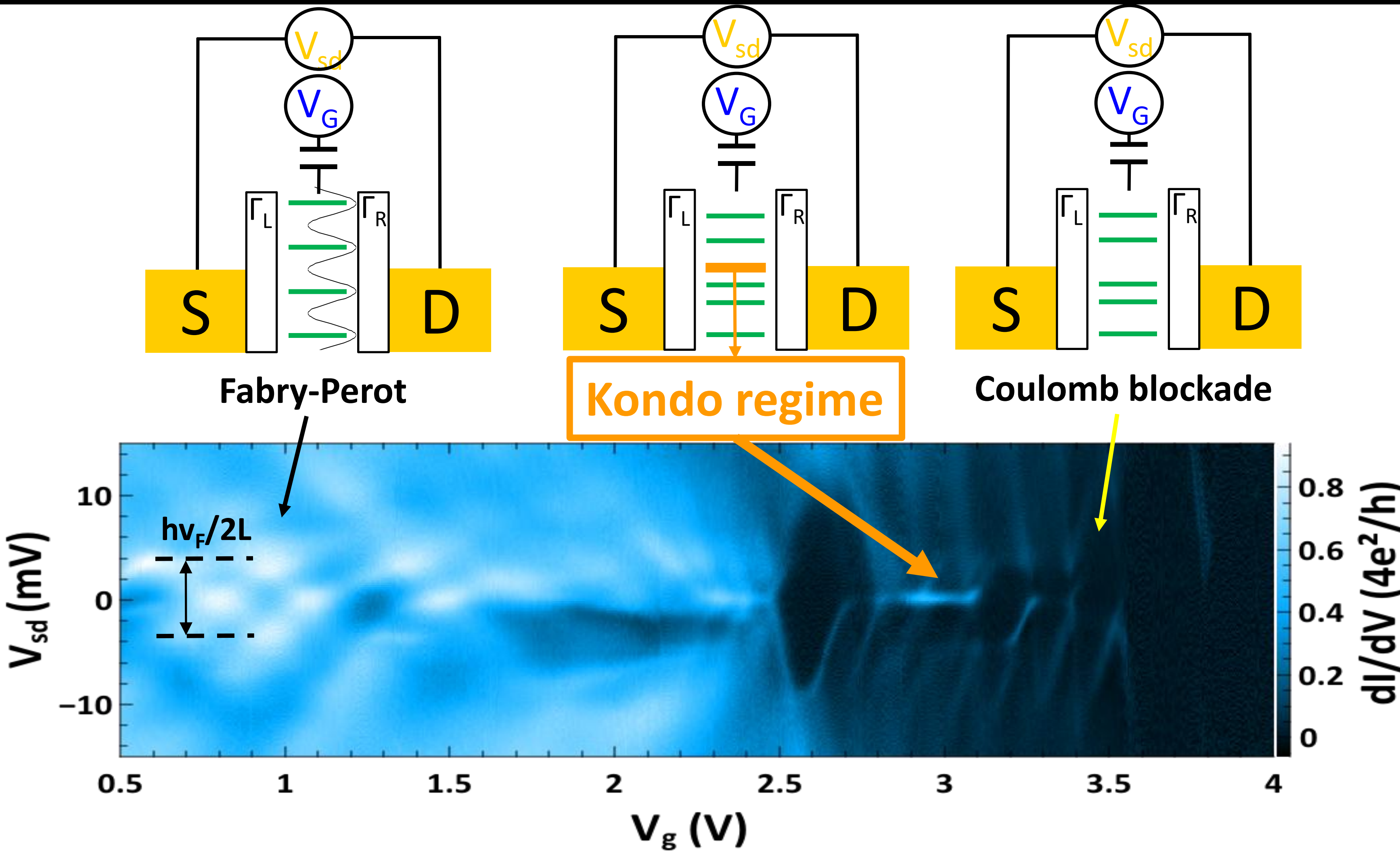
Kondo physics



Coulomb diamonds and Kondo ridge



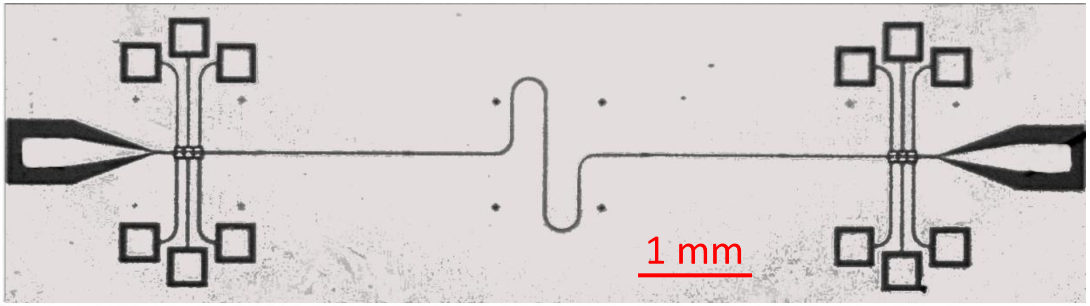
Transport spectroscopy of semiconducting SWNTs



- Transition from Fabry-Perot to Coulomb blockade as transmission is lowered
- Kondo regime (horizontal lines in the middle of Coulomb diamonds) in between
- More exotic possibilities in SWNTs (SU(4), pure orbital, two particle Kondo)

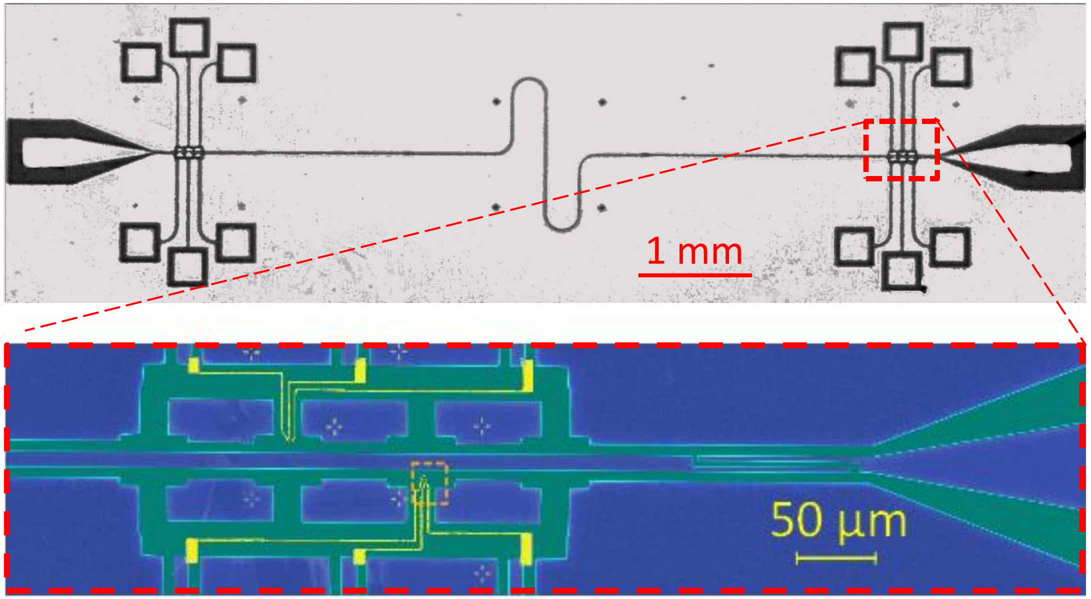
Jarillo-Herrero et al. Nature '05, Makarovski PRL '07, T. Delattre et al. Nature Phys. '09

Embedding SWNTs in microwave cavities



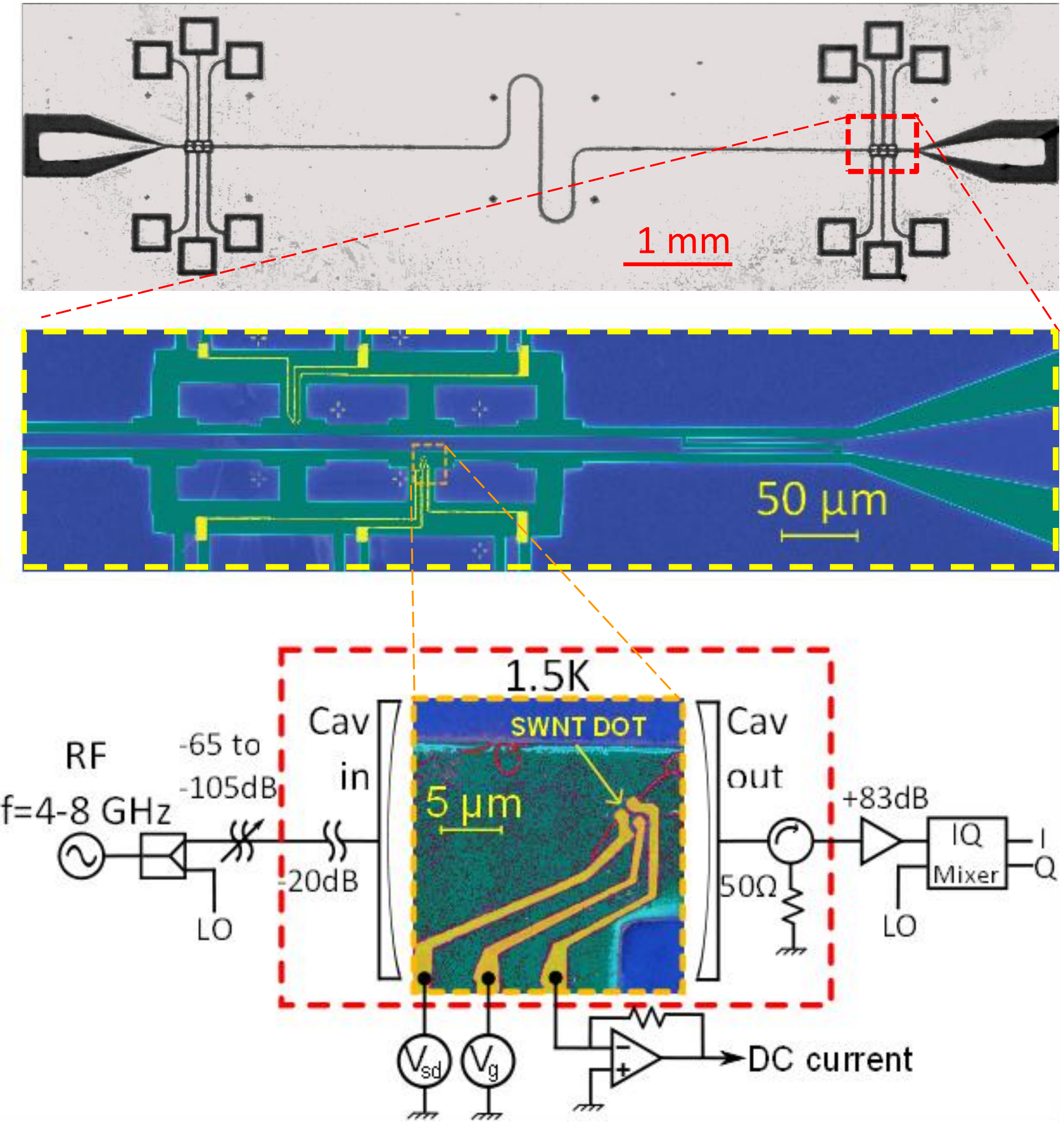
- 10 µm gaps or 1+1 50µm fingers (“mirrors” of the cavity)
- SF6 RIE etching of Nb (superconductor for high finesse cavity)

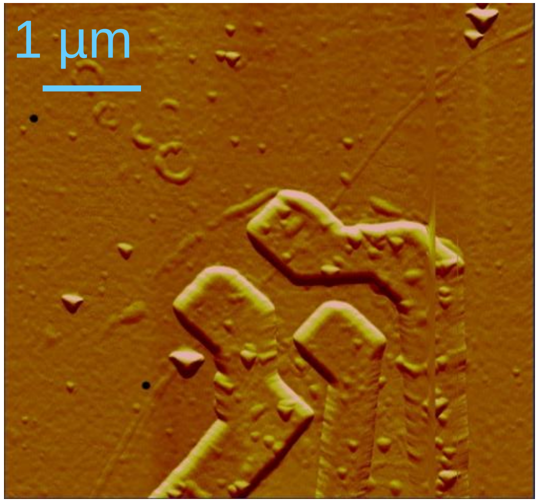
Embedding SWNTs in microwave cavities



- 10 µm gaps or 1+1 50µm fingers (“mirrors” of the cavity)
- SF6 RIE etching of Nb (superconductor for high finesse cavity)
- Growth of CNT by CVD after the etching
- Contacted CNTs with Pd electrodes inside the cavity (openings in ground)
- Use of reversed process (optical lithography for Al resonator at the end) to enhance yield

Embedding SWNTs in microwave cavities





Phase = Arctan(I/Q)

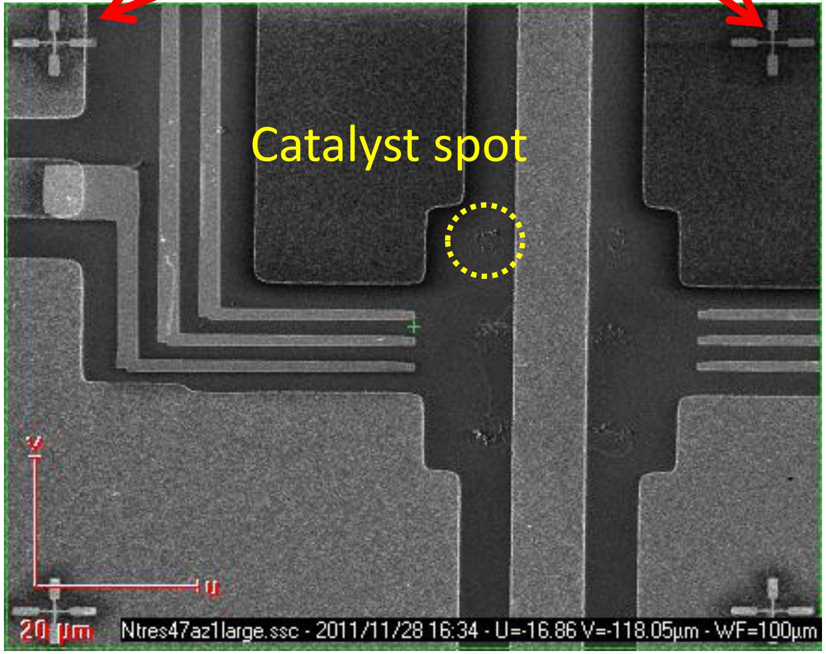
Modulus = $\sqrt{I^2+Q^2}$

CNT growth and contacting

CVD growth (methane process)

CNT growth and contacting

CVD growth (methane process)



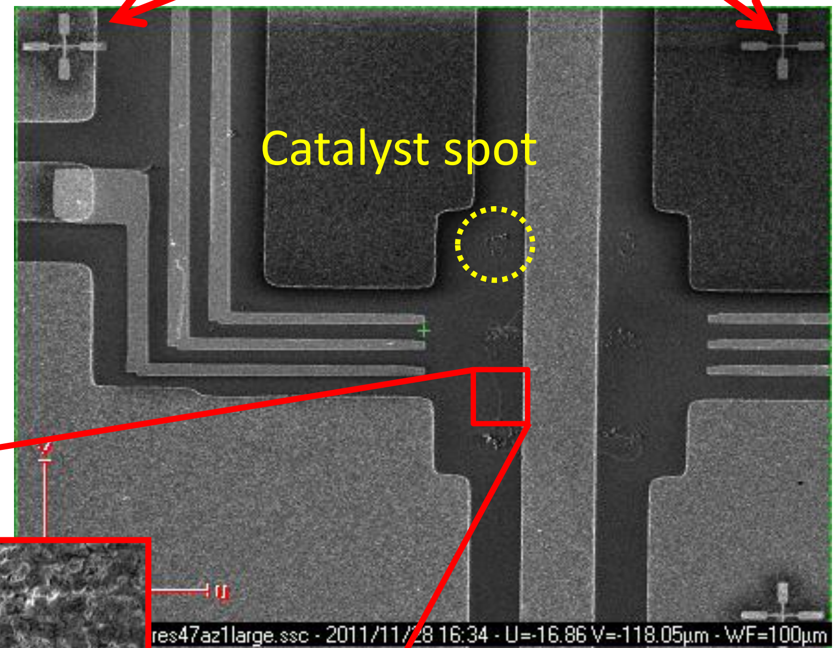
Localization with SEM

CNT growth and contacting

CVD growth (methane process)

Alignments crosses

Catalyst spot



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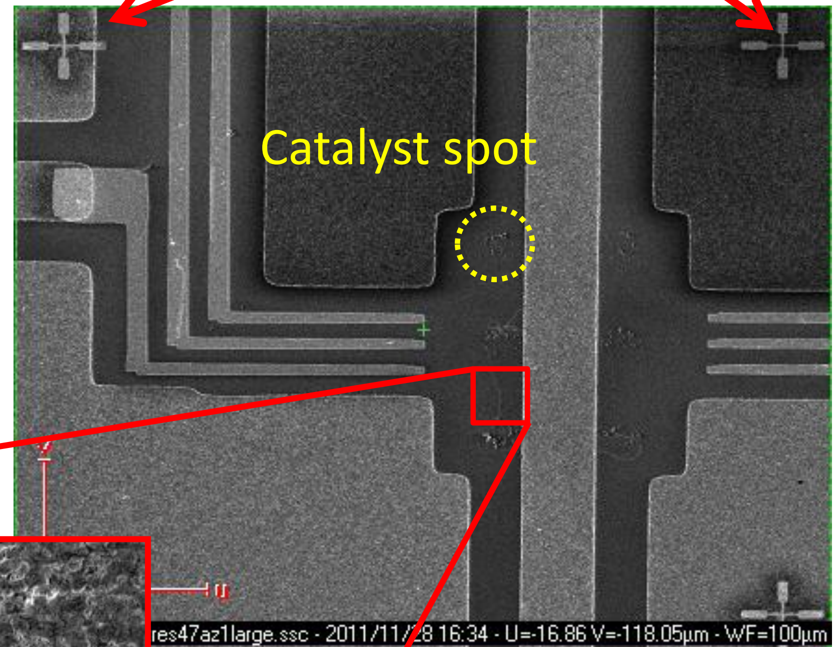
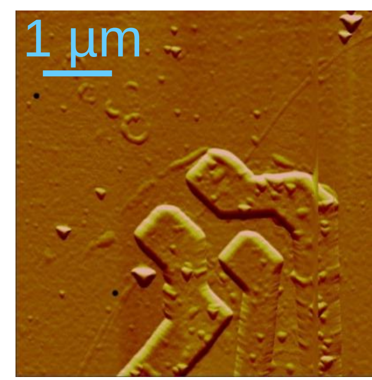
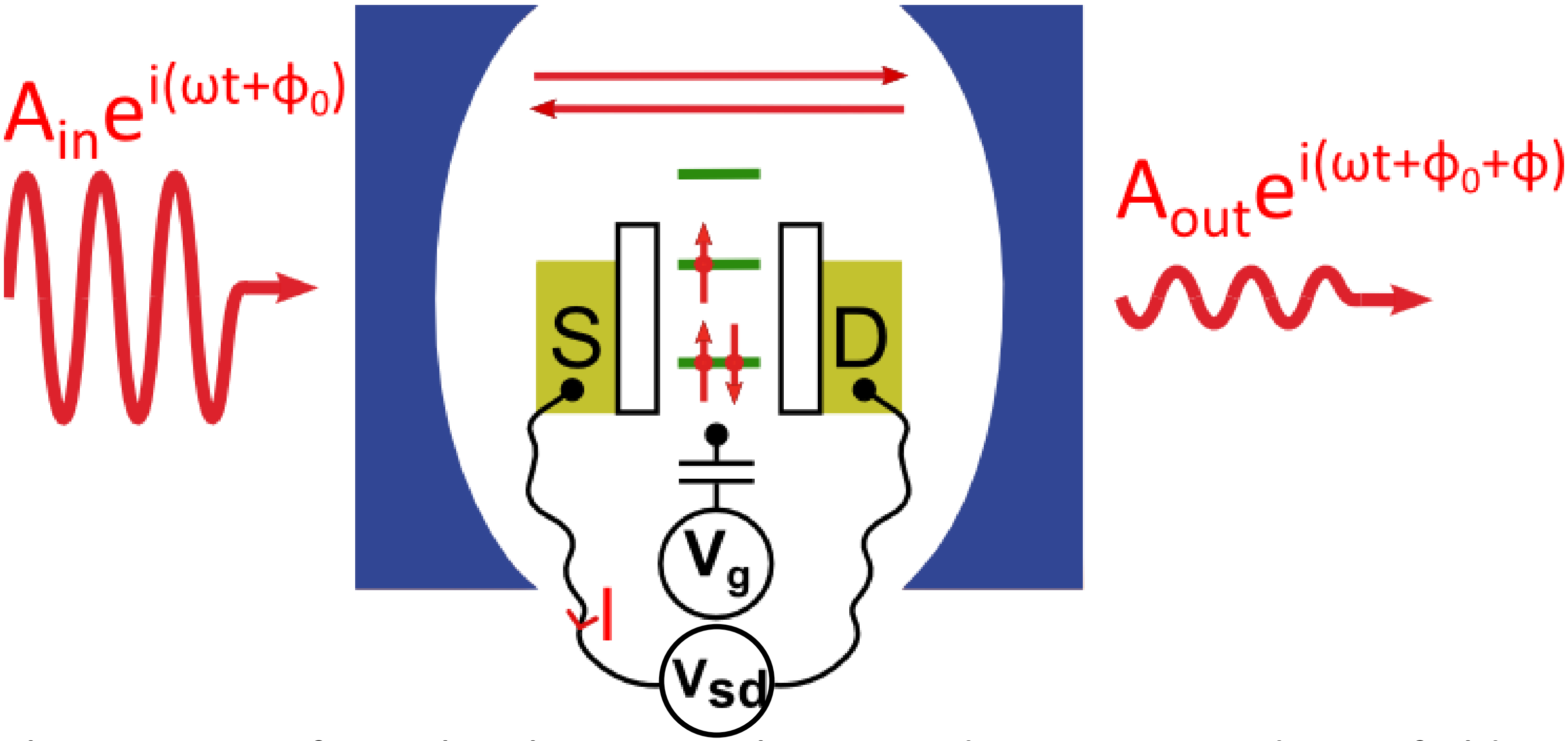


Localization with SEM

Pd contacts



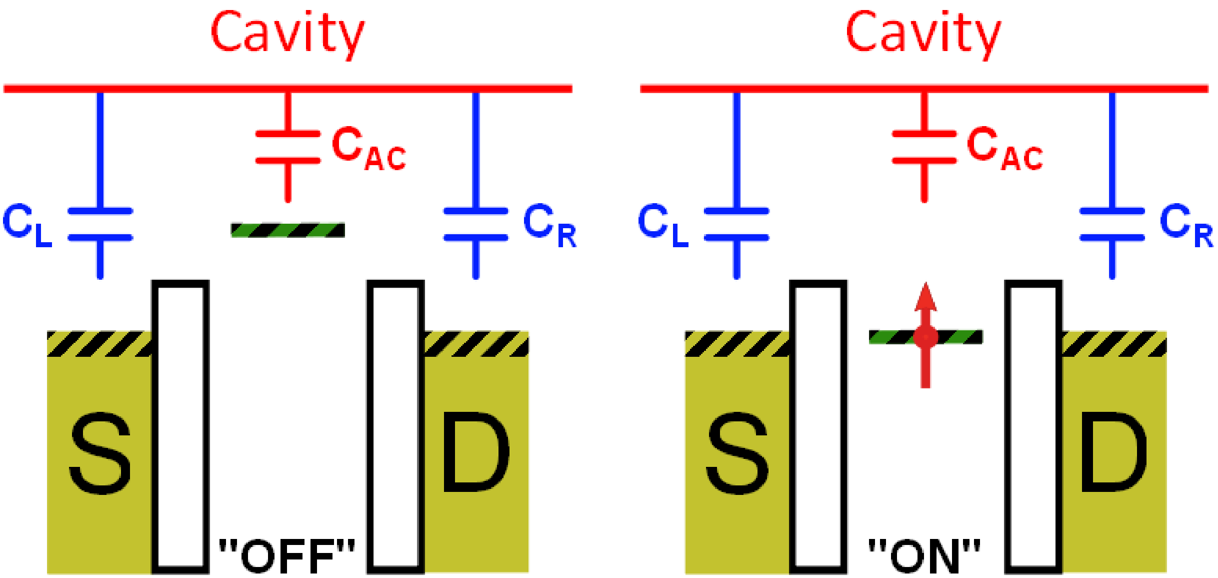
A Kondo impurity in a microwave cavity



- Enhancement of coupling between photon and « impurity » due to field confinement
- Should affect both amplitude and phase of the signal
- More complex situation than in standard cavity QED setup a priori

Kondo = Many-body system **Photons coupled to open quantum system**

Coupling of the cavity with the quantum dot



At -60dBm, ~ 10000 resident photons

Classical regime for cavity

$$Y_{Dot}(\omega) \approx i\omega C_{Dot} + \frac{\alpha}{R_{Dot}}$$

On-chip « photonic » Anderson-Holstein model [1]

$$H = H_{dot} + H_{cav} + \sum_{K,K'} (\lambda_K \hat{N}_K + \lambda_{K'} \hat{N}_{K'})(\hat{a} + \hat{a}^+)$$

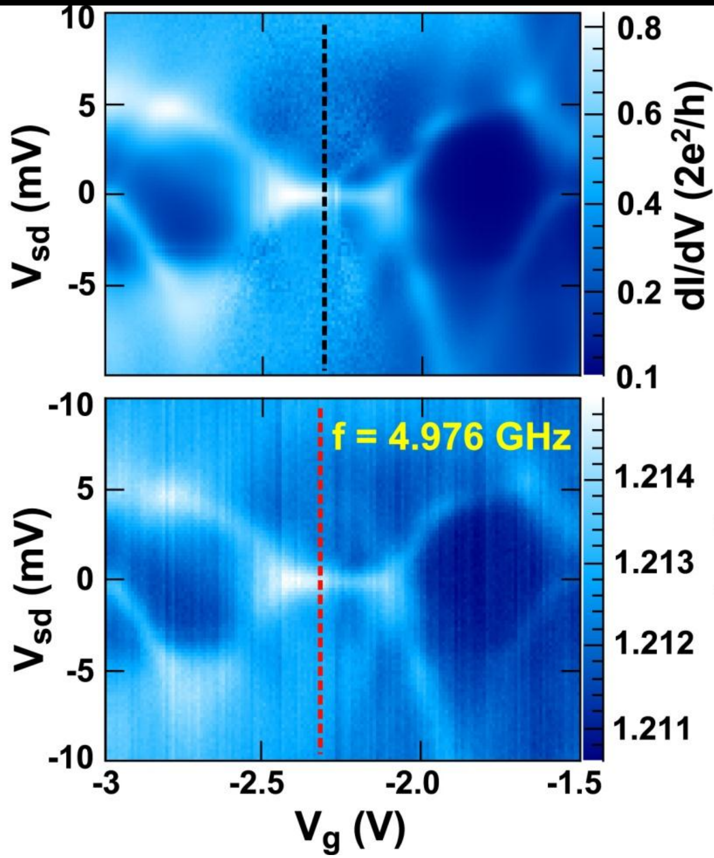
- We probe the charge susceptibility with the classical EM field
- A priori also sensitive to orbital susceptibility

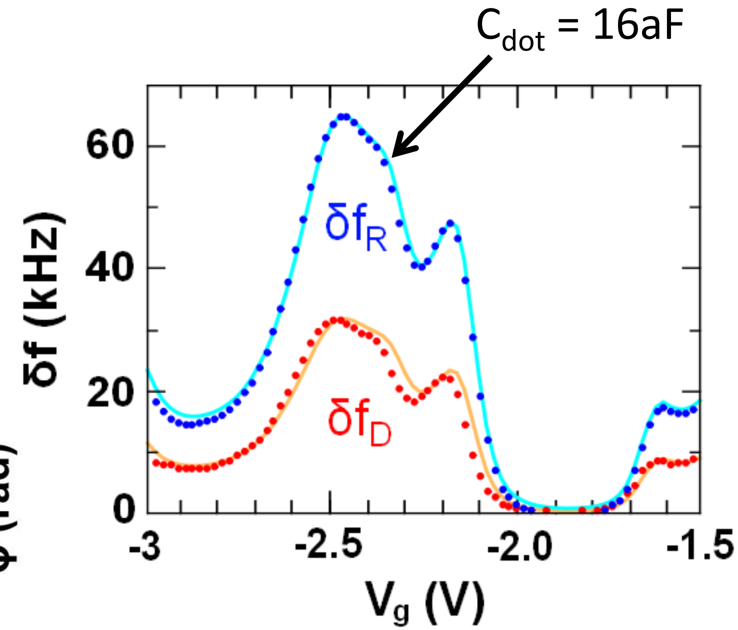
[1] C. Bergenfelfd & P. Samuelsson PRB'12

Transport and phase spectroscopy

Low frequency conductance

Phase of the transmitted microwave signal @ resonance





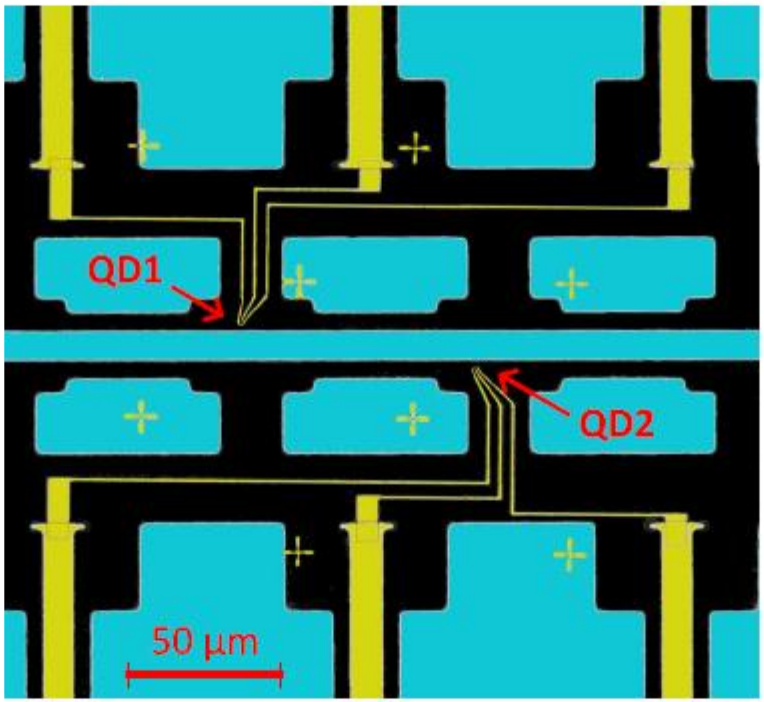
- Kondo resonance appears as horizontal lines in the Coulomb diamonds
- Similar spectroscopic features in the phase of the microwave signal

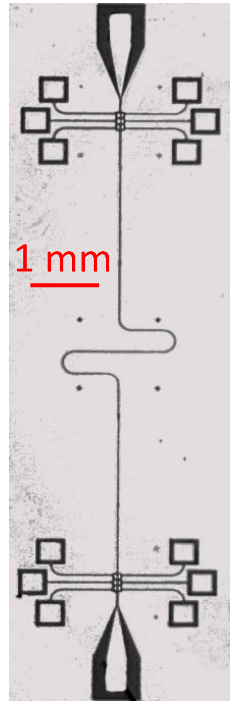
Measurement of electron-photon coupling

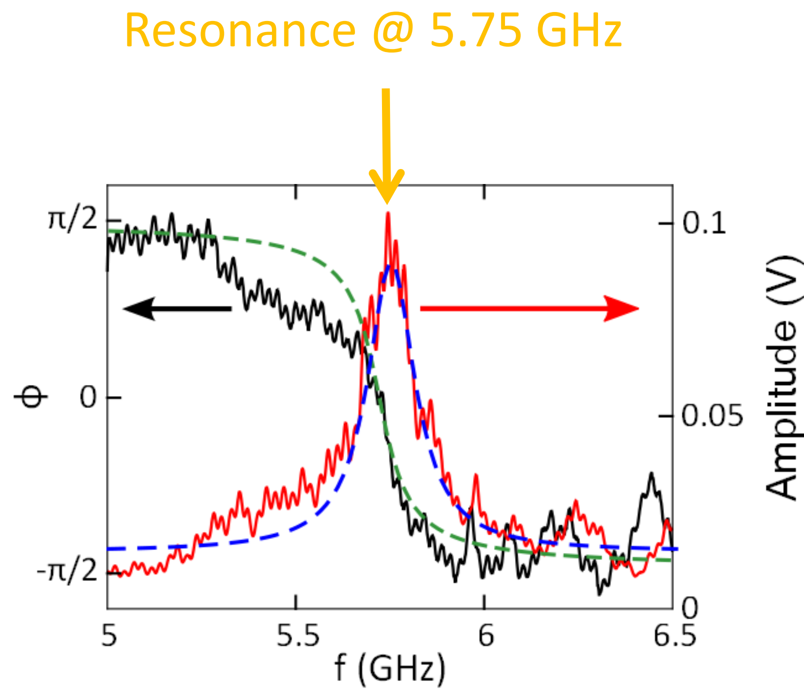
100 MHz → OK for circuit QED experiments

M.R. Delbecq et al. PRL '11

Two SWNTs quantum dots in a microwave cavity



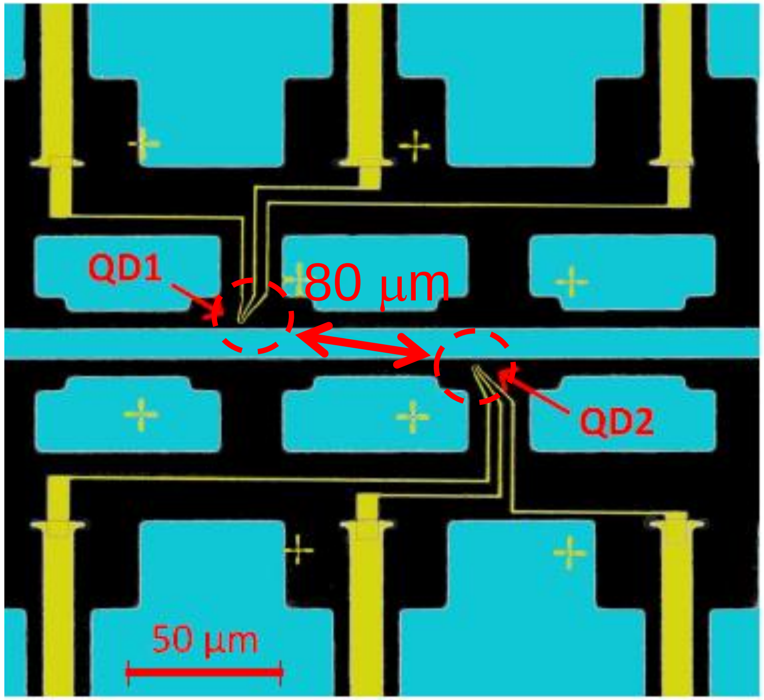


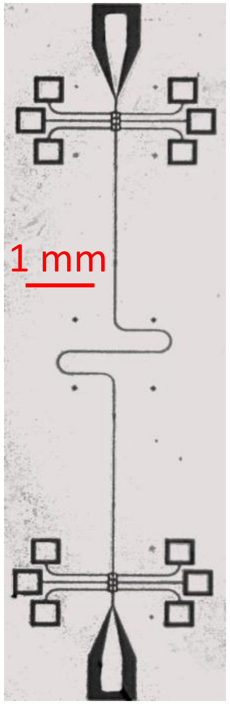


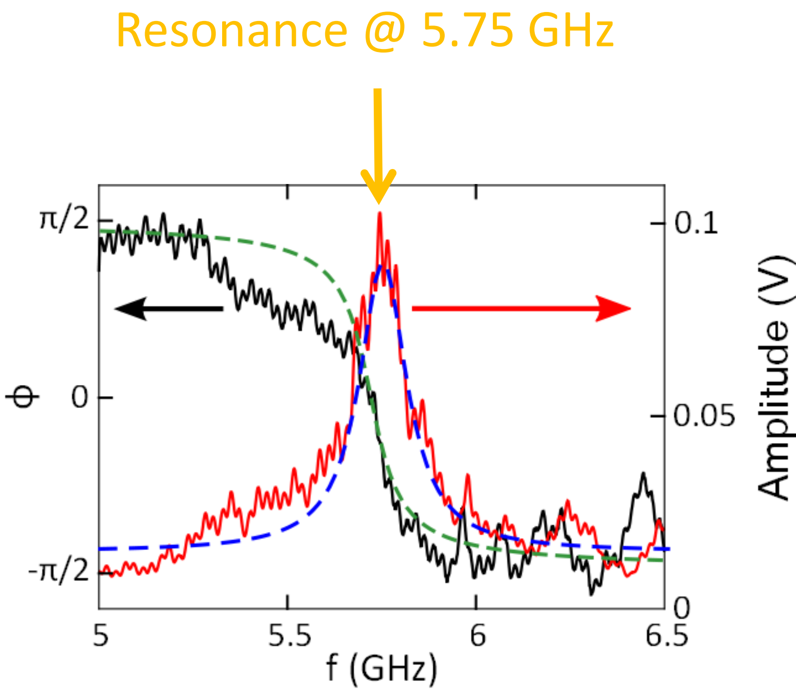
- Both quantum dots share the same anti-node of the electric field
- Distant from about 80 µm (direct coupling not possible)

➡ Each quadratures (I,Q) of the transmitted field and the two conductances G_1 and G_2 of the dots are measured simultanueously

Two SWNTs quantum dots in a microwave cavity







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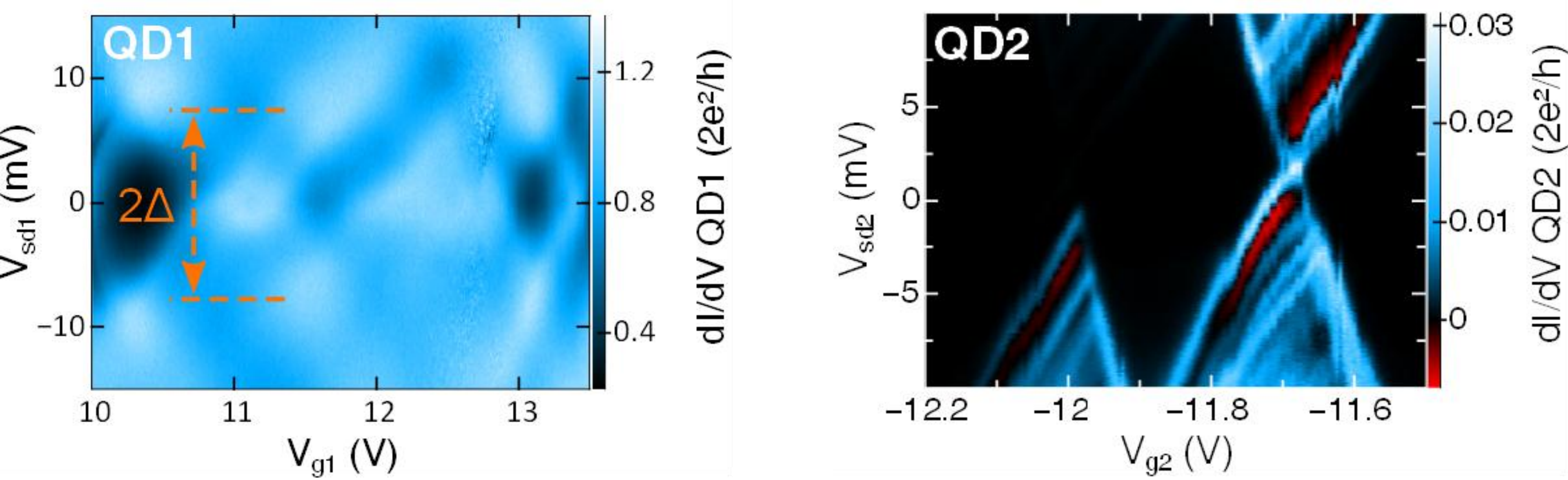
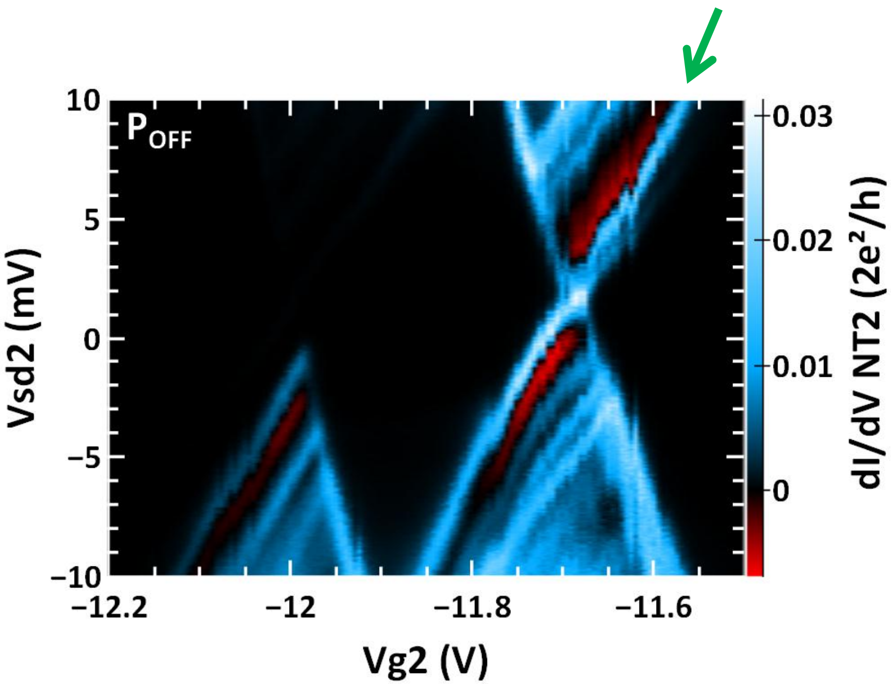
Transport spectroscopy of each quantum dot

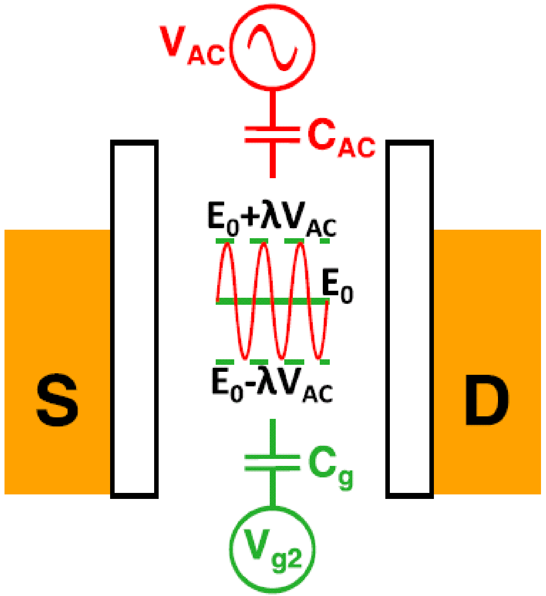


- Quantum dot 1 in the Fabry-Perot limit (more open)
- Quantum dot 2 in the Coulomb blockade (more closed)

Do they both « talk » to the cavity photons and do they talk with each other ?

Driving dot 2 with the cavity field

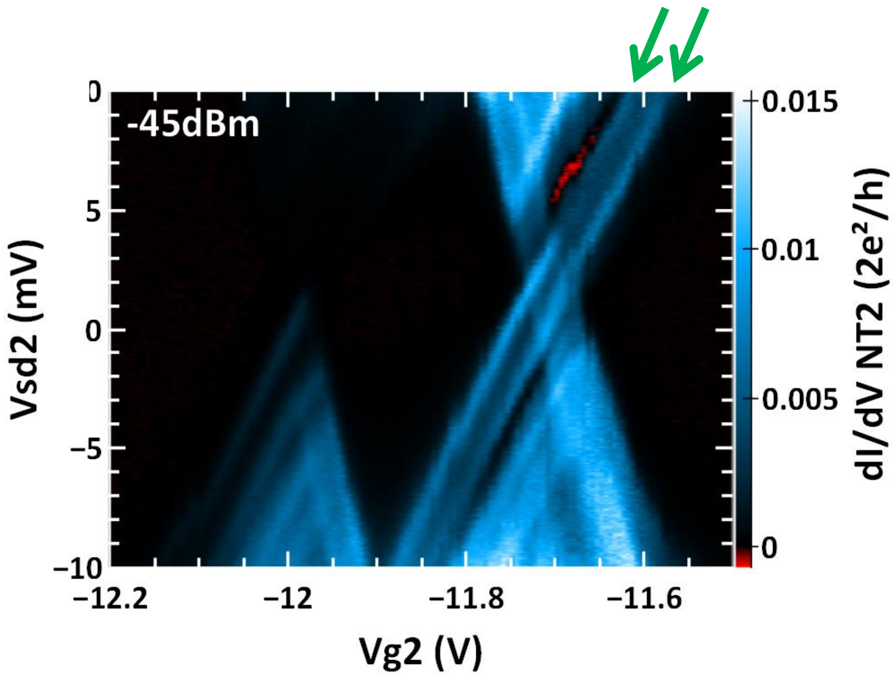


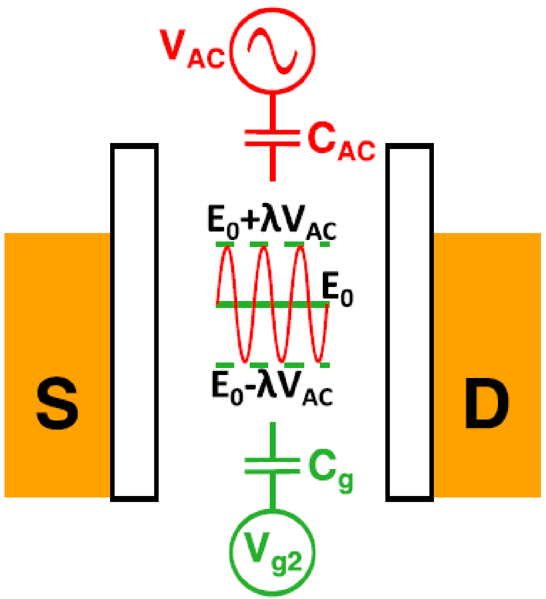


- Coupling to the leads of electronic levels ~ 1 meV >> ω_0 cavity frequency
- Electronic system relaxes much faster than times scale of photons

→ How does the spectroscopy change when one increases the number of photons in the cavity ?

Driving dot 2 with the cavity field





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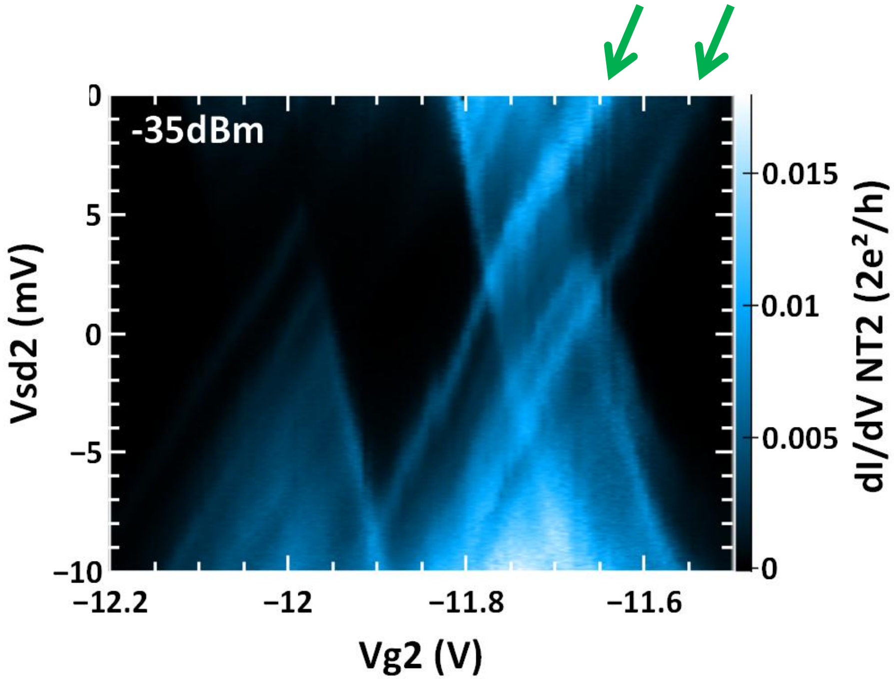

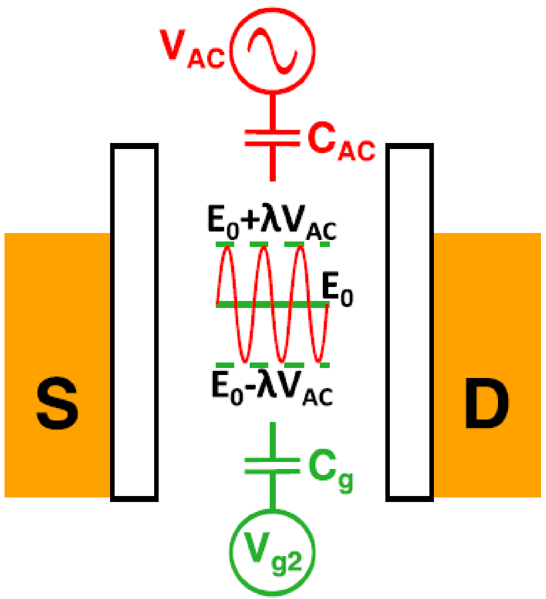

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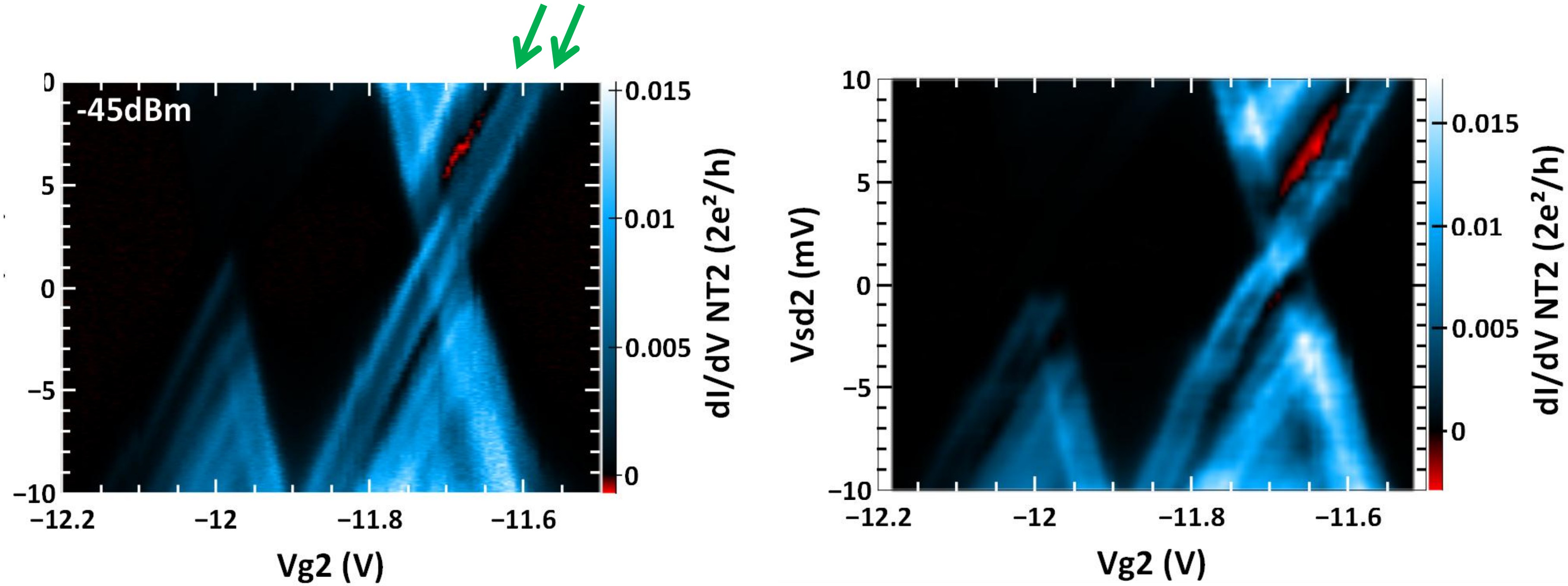
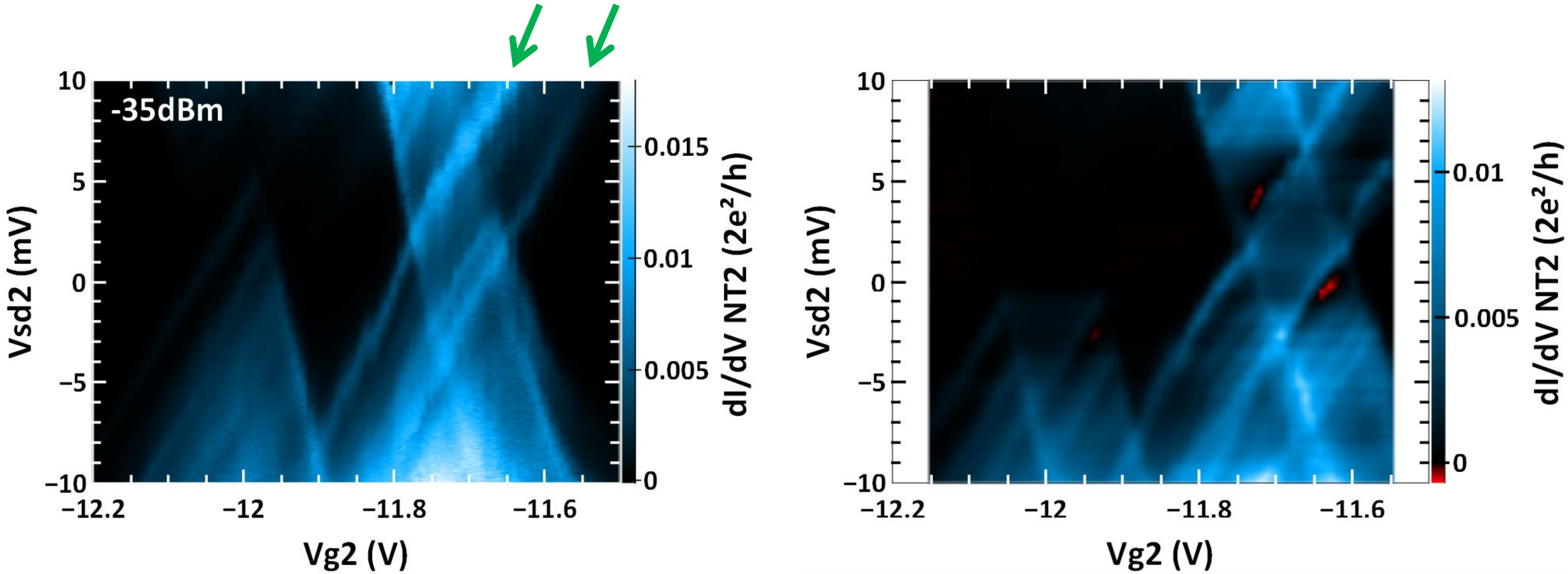


$$G_{on} = \frac{1}{2\pi}\int_0^{2\pi} G_{off}(V_G + \lambda V_{AC}\cos(2\pi f_0 t)\,, V_{sd})dt$$

How does the spectroscopy change when one increases the number of photons in the cavity ?

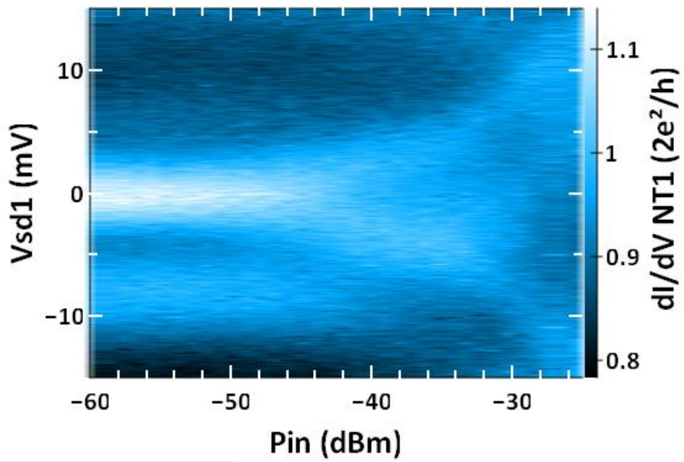
Driving dot 2 with the cavity field

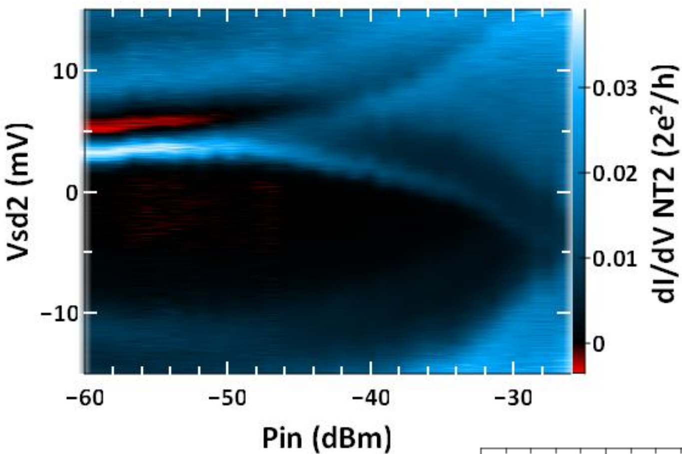


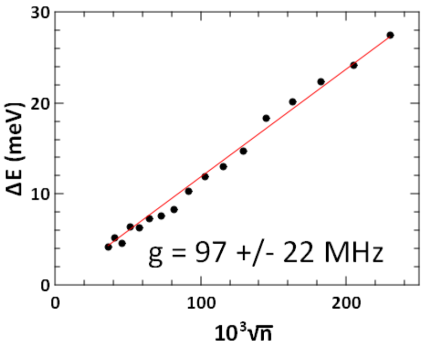
$$G_{on} = \frac{1}{2\pi}\int_0^{2\pi} G_{off}(V_G + \lambda V_{AC}\cos(2\pi f_0 t)\,, V_{sd})dt$$

Dynamical splitting of states of dot 2 by the photons in the cavity

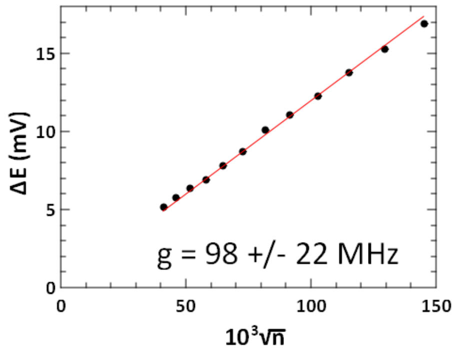
Dynamic splitting of states







Energy level splitting $\Delta E = 2g\sqrt{\bar{n}}$

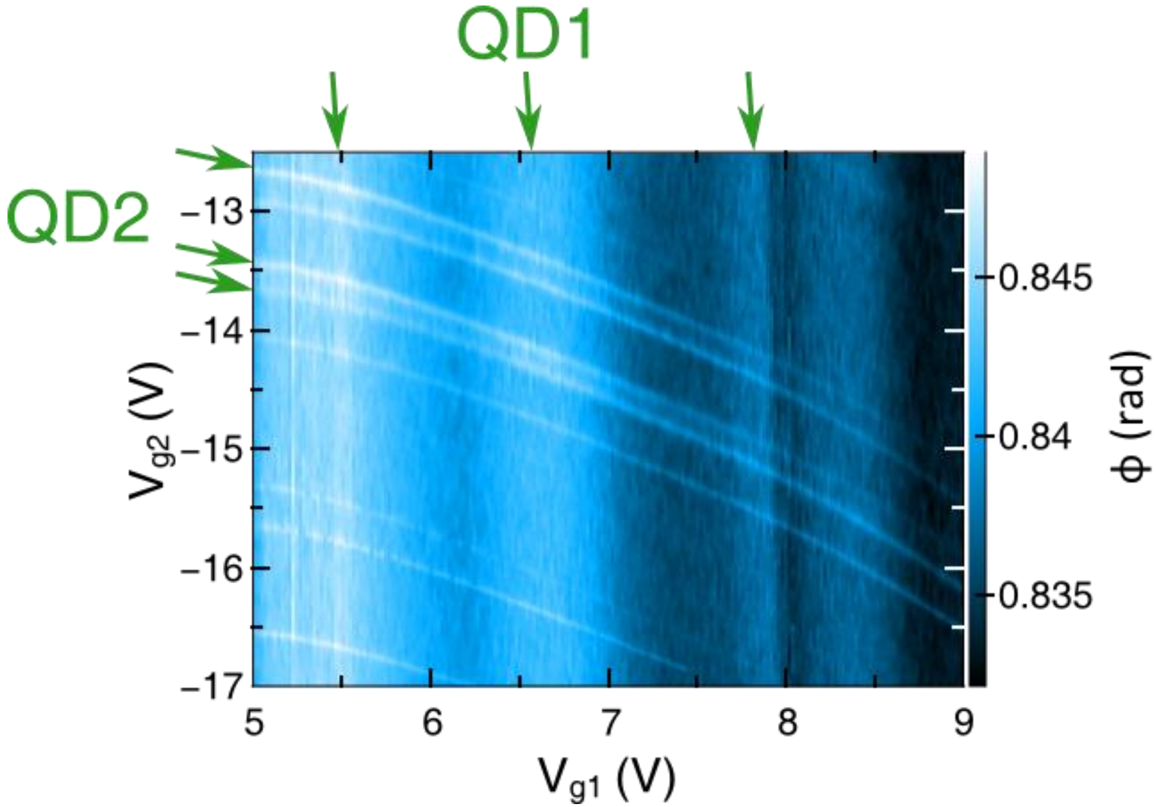


- « Funnel » shaped splitting as a function of power
- Splitting scales with square root of number of photons

→ Confirmation of the level coupling and allows a direct measurement of it

$g_1, g_2 \approx$ 100 MHz

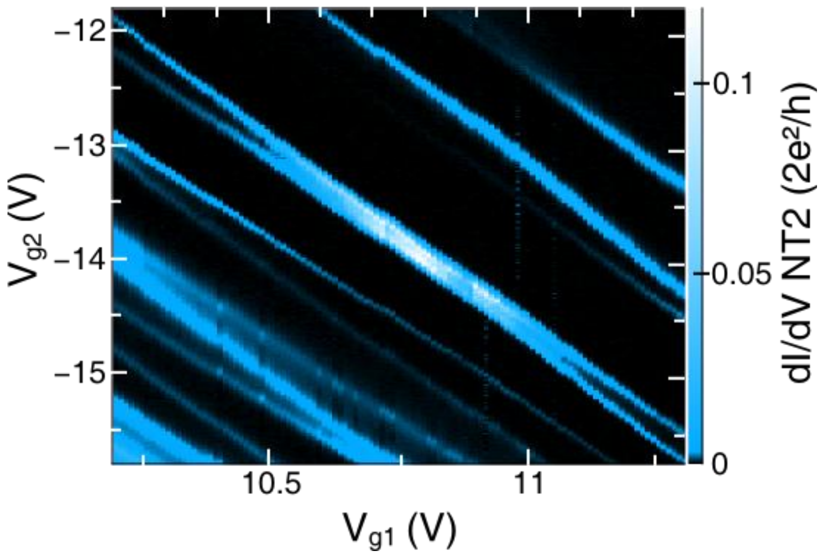
Joint read-out of the two quantum dots

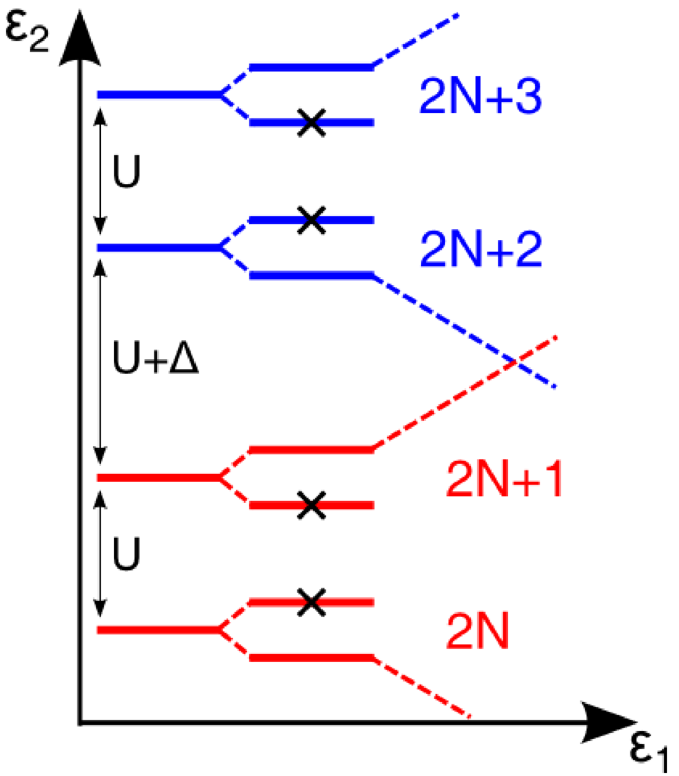


- The energy levels of dot 1 and dot 2 are read-out via the phase of microwave signal
- Vertical (dot 1) lines slightly tilted
- Dot 2 levels are controlled both by gate 2 and distant gate 1

➡ The slope of dot 2 levels versus gate 1 shows the interaction between dot 1 and dot 2

Distant interaction between dot 1 and dot 2





- Closed dot used as detector of energy states of the whole system
- Closed dot (2) « feels » the distant gate acting on dot 1
- Crossing and anticrossings show that states of dot1 and dot2 are coupled

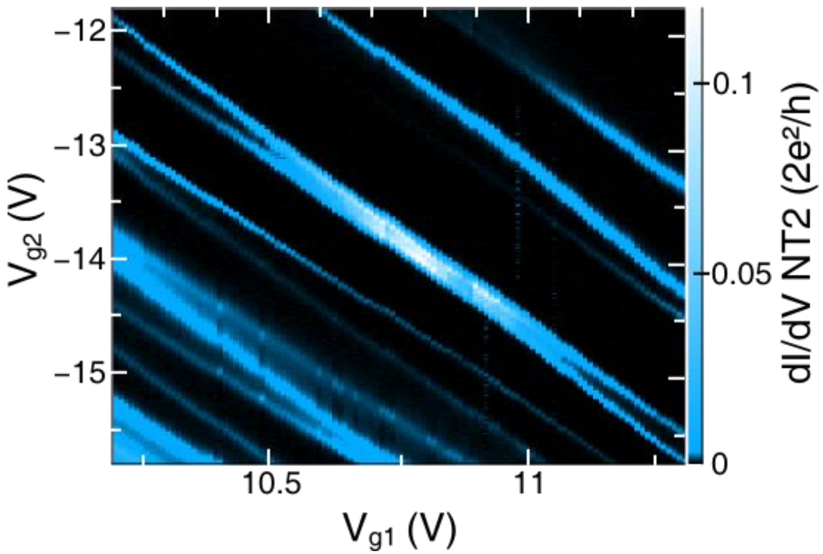
➡ Non-local coupling of the two dots mediated by the cavity photons (real and virtual photons involved)

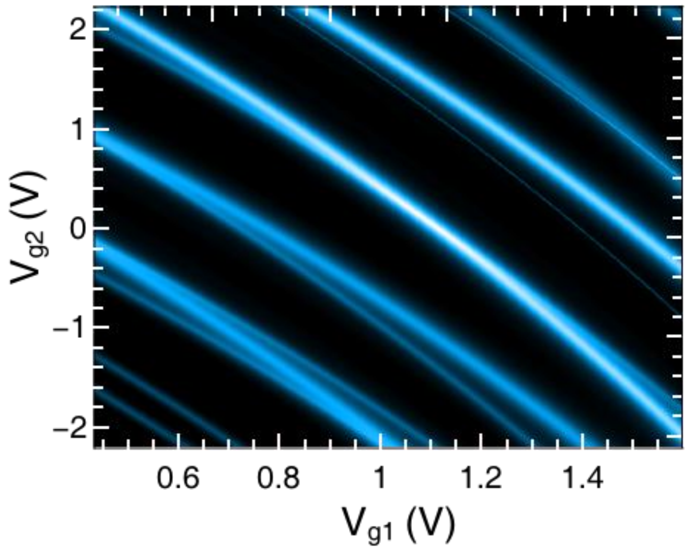
A. Cottet et al. PRL’12, Palyi and Burkard PRL’11

Distant interaction between dot 1 and dot 2

Polaronic shift of energy levels

$$\delta\varepsilon_2 = -4\pi \frac{g_1 g_2}{\omega_0} N_{el,QD1} \approx 1meV$$





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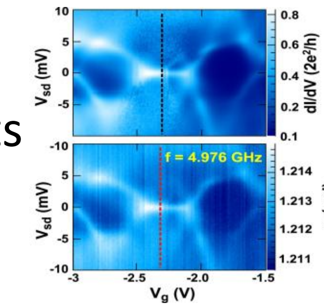
Conclusion

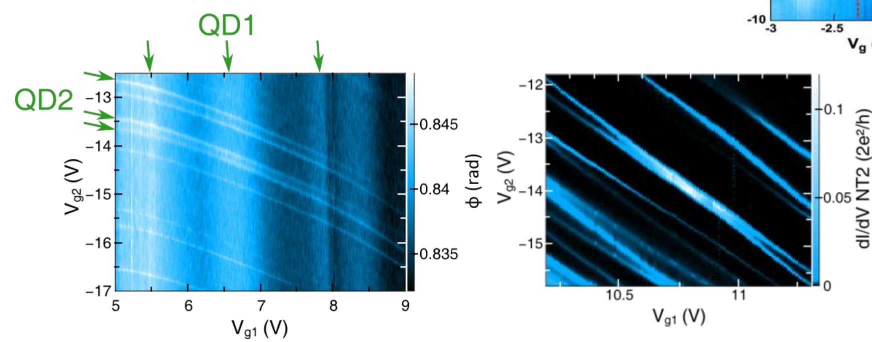
- Use of the cavity QED tools to probe and couple quantum dot circuits



M.R. Delbecq et al. PRL ‘11

- Coupling of distant quantum dots

M.R. Delbecq *et al.* submitted



➡ Can be used to probe coherence in quantum circuits

(Cottet, Kontos Levy Yeyati’ 12)

➡ Use this interaction for gate operations between distant dots

(Burkard, Immamoglu’ 06)

➡ Scaling up such an architecture to make complex quantum gates for Spin Qbits

➡ Double quantum dot in cavity for spin Qbit

(Cottet and Kontos’10)