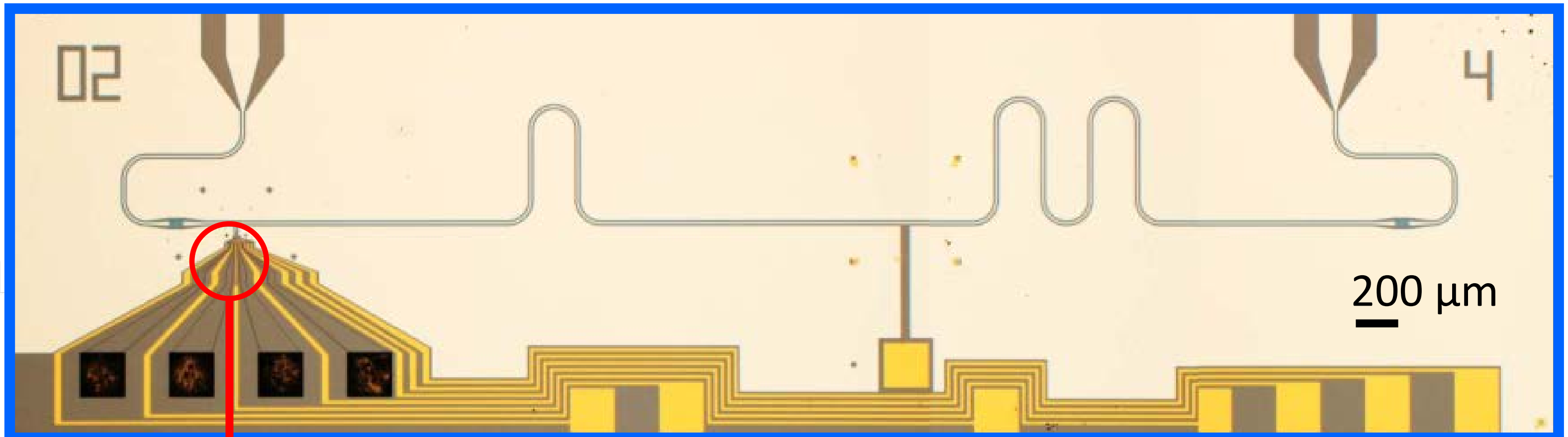
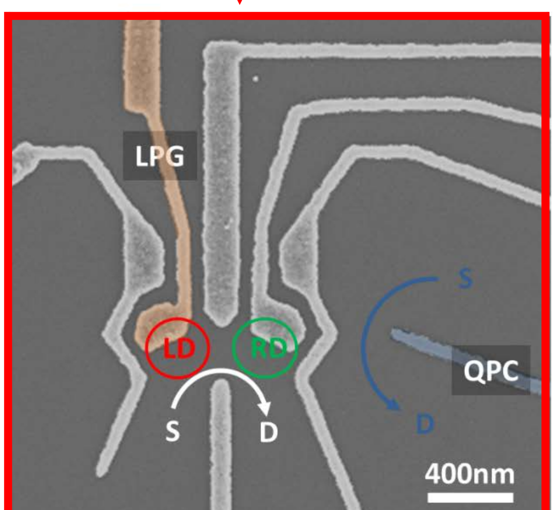
Dipole-coupling a single-electron double quantum dot to a microwave resonator





J. Basset, D.-D. Jarausch, A. Stockklauser, T. Frey, C. Reichl, W. Wegscheider, T. Ihn, K. Ensslin and A. Wallraff

Quantum Device Lab
Nanophysics Group

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

QSIT Quantum Science and Technology
National Centre of Competence in Research

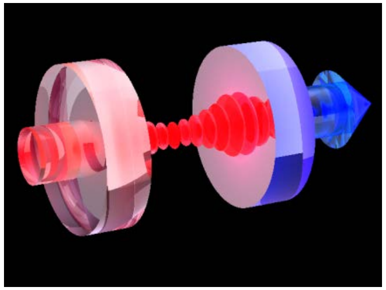
SOLID

Context and motivations

- Overall trend of coupling a Two Level System (TLS) or quantum bit to a resonant cavity

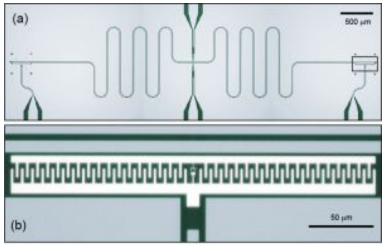
  ➔ long distance exchange of quantum information, distant qubits entanglement,…

- Very well established in the
  - Cold atoms community : cavity Quantum Electro-Dynamics (cavity QED)



Max Planck Institute

  - Superconducting qubit community : circuit Quantum Electro-Dynamics (circuit QED)



Leek et al., PRL (2010)

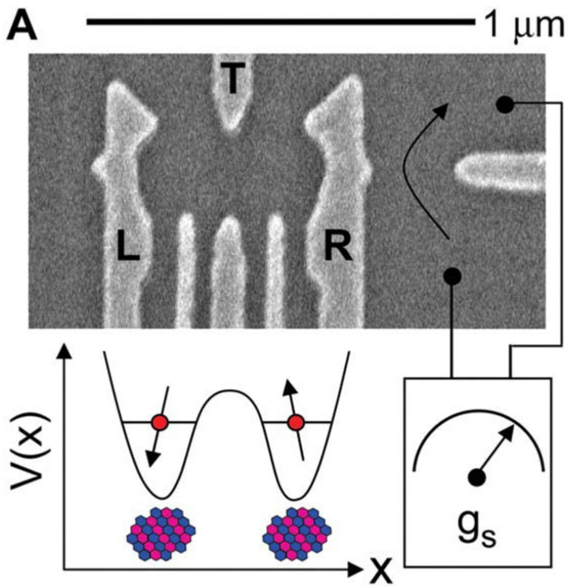
- Never realized using TLS made out of artificial atoms in semiconductor heterostructures with leads

Context and motivations

Interconnect the worlds of semiconductor and superconductor based quantum circuits

Spin qubits in quantum dots

Petta et al., Science (2005)



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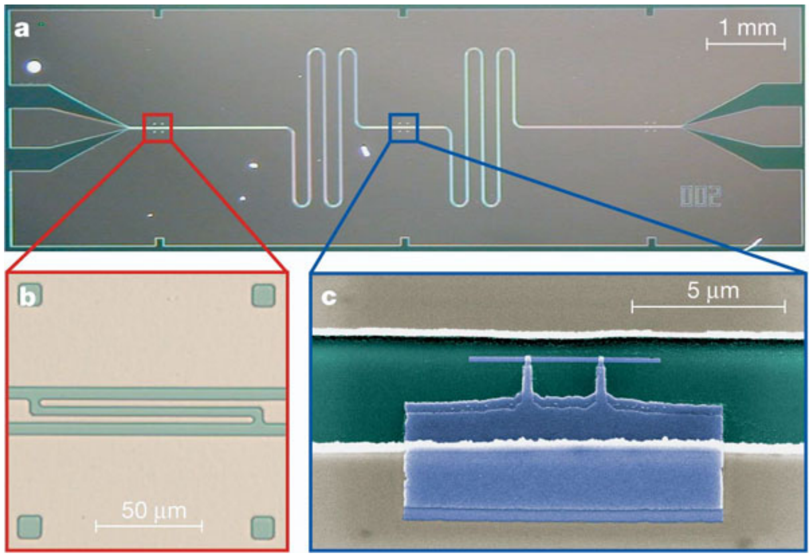
Circuit quantum electrodynamics



Wallraff et al., Nature (2004)

Potential benefits:

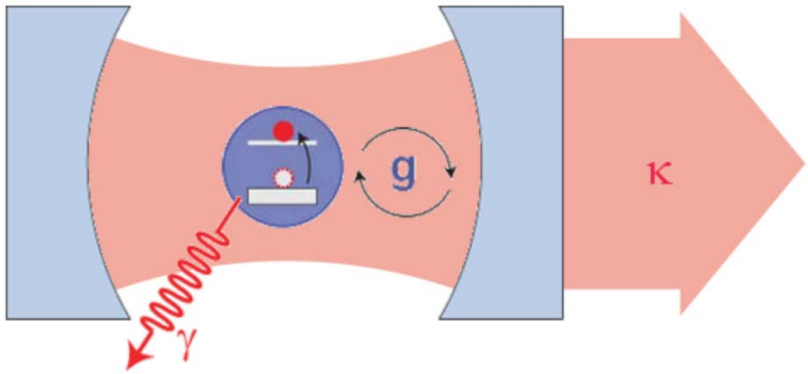
- Use electrons spins quantum bit ➔ low relaxation and dephasing rate
- Realize interfaces between different type of quantum systems

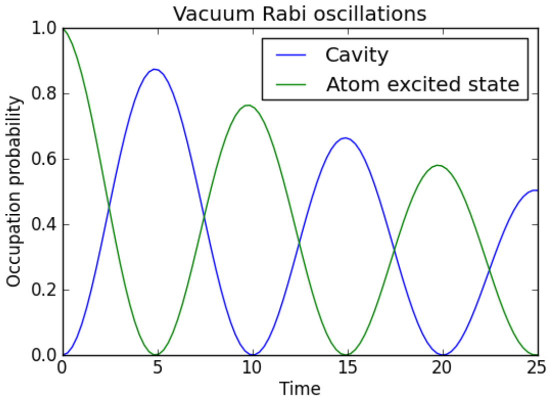
Context and motivations

First step: entanglement between a cavity and a q-bit

⇔

Coherent exchange of a single photon with a single q-bit = Vacuum Rabi Oscillations





Very challenging strong coupling regime necessary:

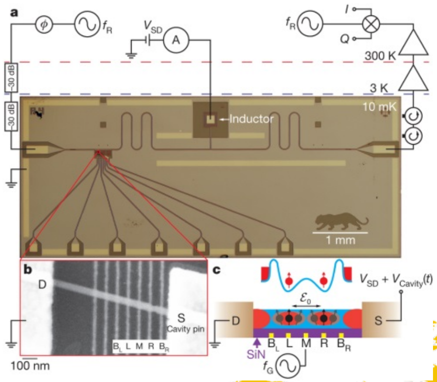
Exchange rate = g must be much higher than any other decay rates

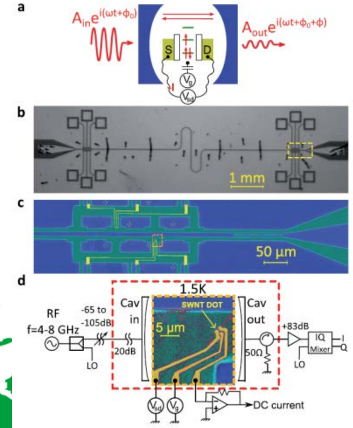
$g/2\pi > 1/T_1$ = decay rate of the excited state (relaxation rate)

$g/2\pi > 1/T_\phi$ = dephasing rate

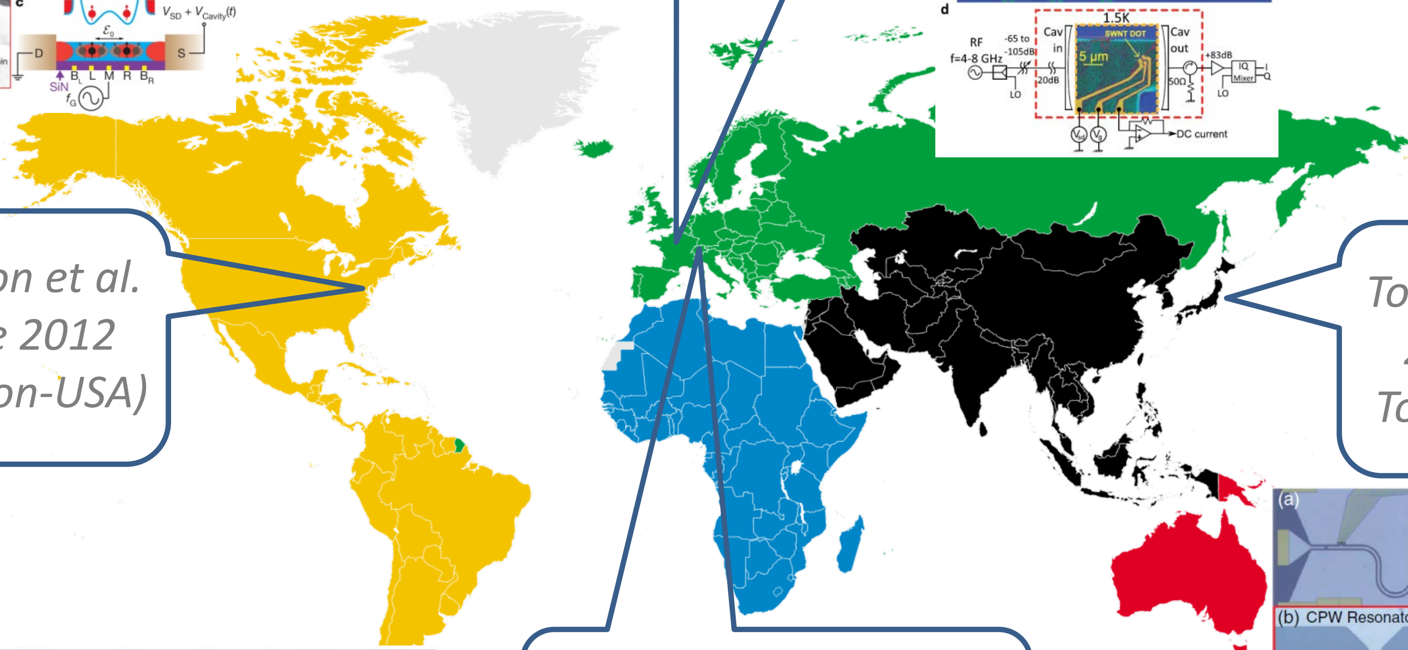
$g/2\pi > \kappa/2\pi$ = decay rate of the photon in the cavity

A very timely experiment….



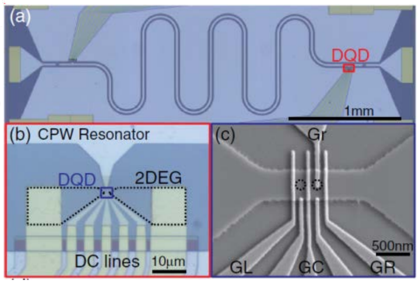


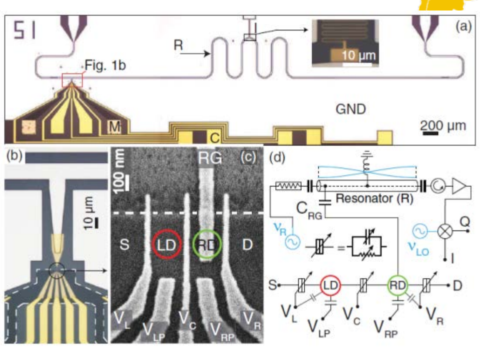
Delbecq et al. PRL 2011 (ENS Paris - France)



Petersson et al. Nature 2012 (Princeton-USA)

Toida et al. PRL 2013 (Univ. Tokyo - Japan)





Frey et al. PRL 2012 (ETH Zurich - Switzerland)

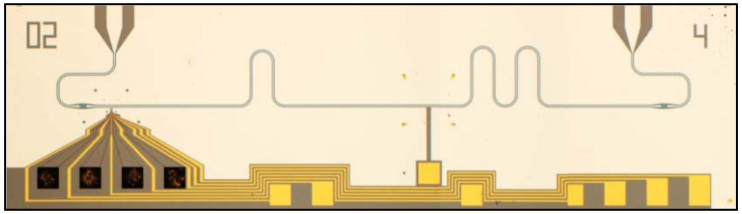
No Strong Coupling between Resonator and <u>Charge qubit</u>

➔ Dephasing too high (GHz) compared to coupling (50 MHz)

➔ Is the number of electrons relevant?

Outline

1. Last-electron dedicated hybrid quantum device and circuit QED measurement setup



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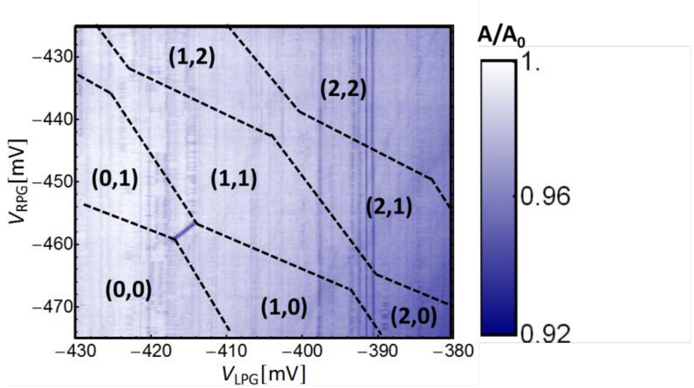
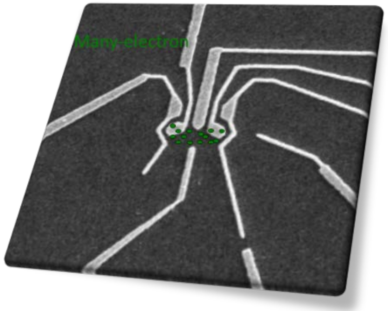


3. Single-electron vs many-electron decoherence



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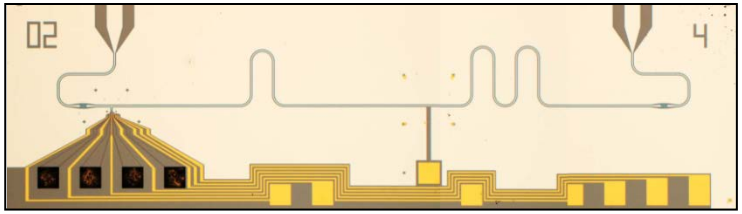

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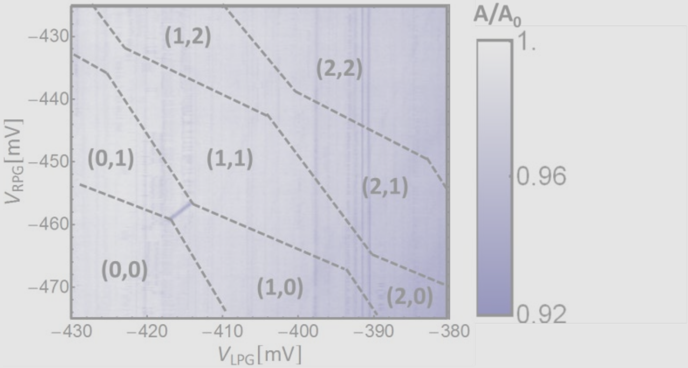

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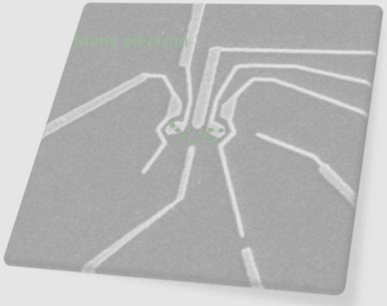
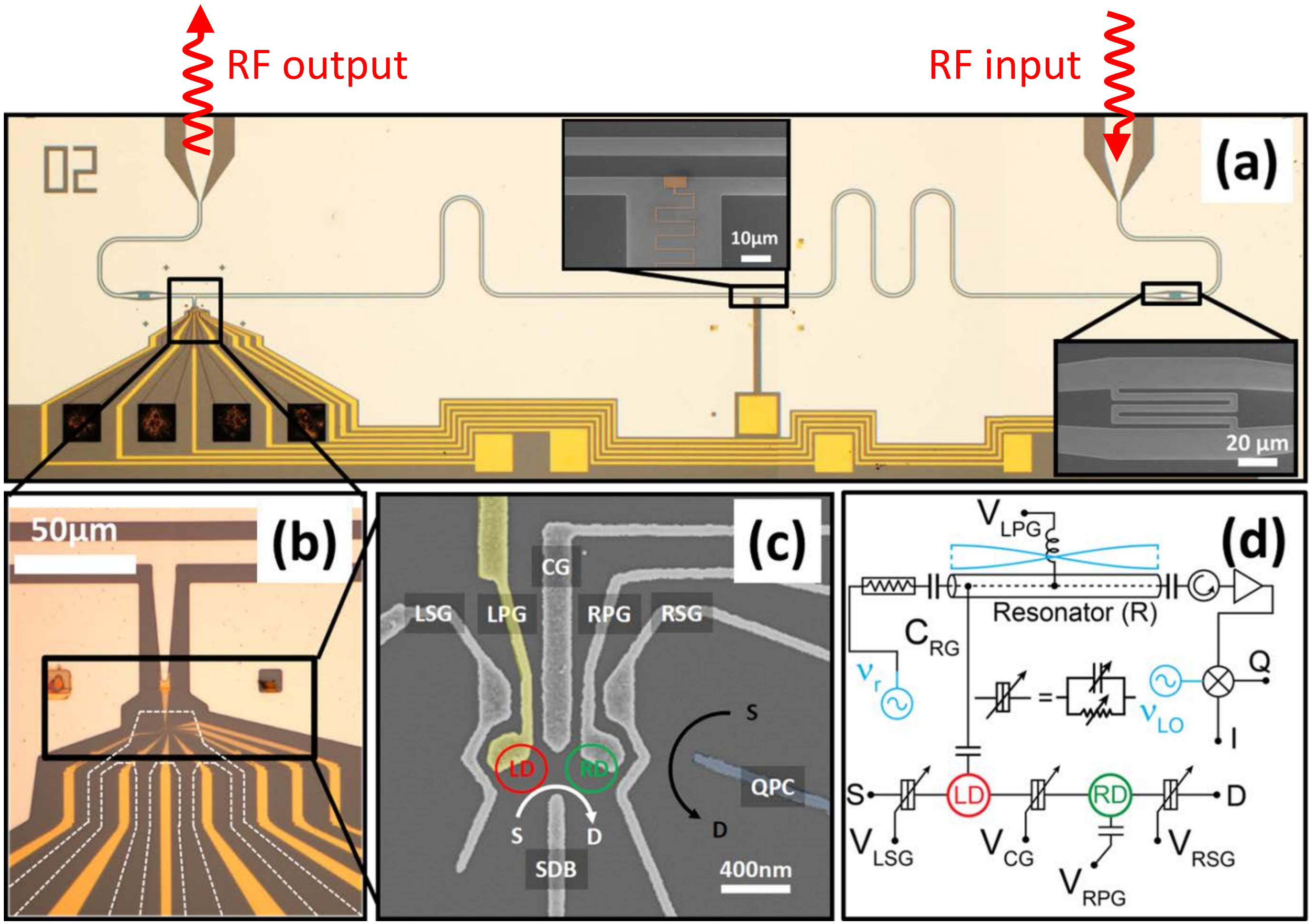
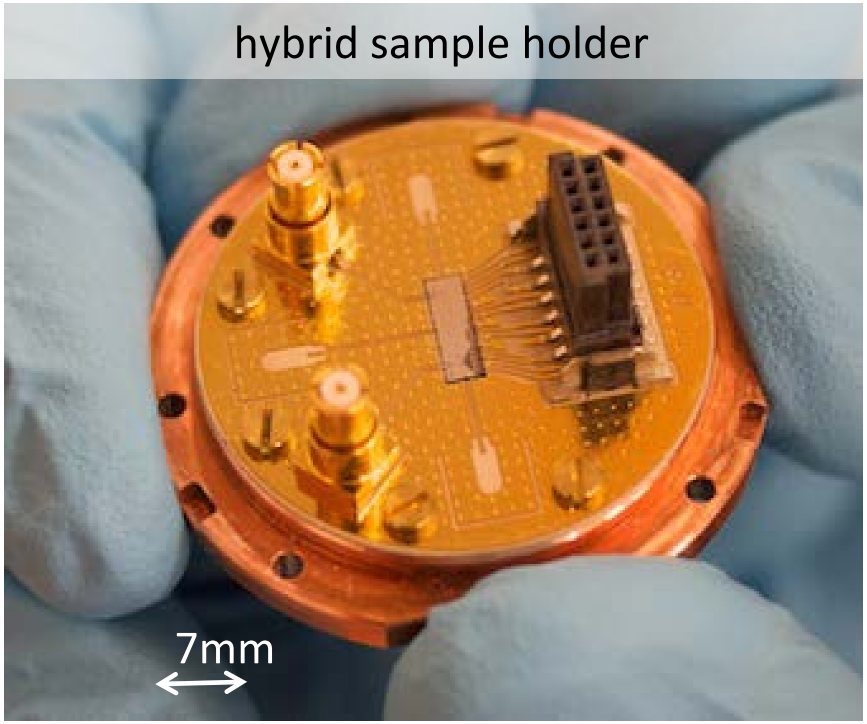


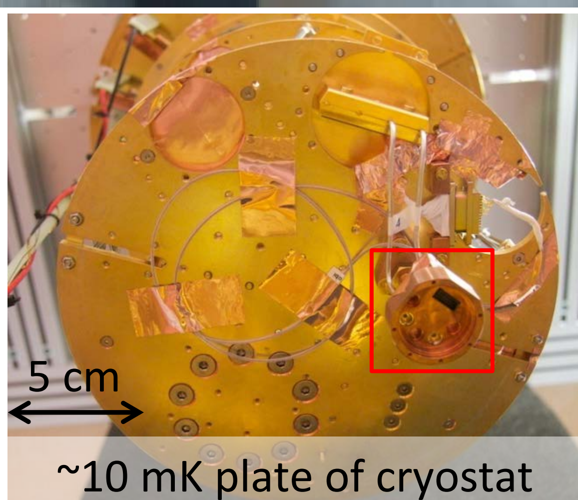
Last-electron dedicated quantum device



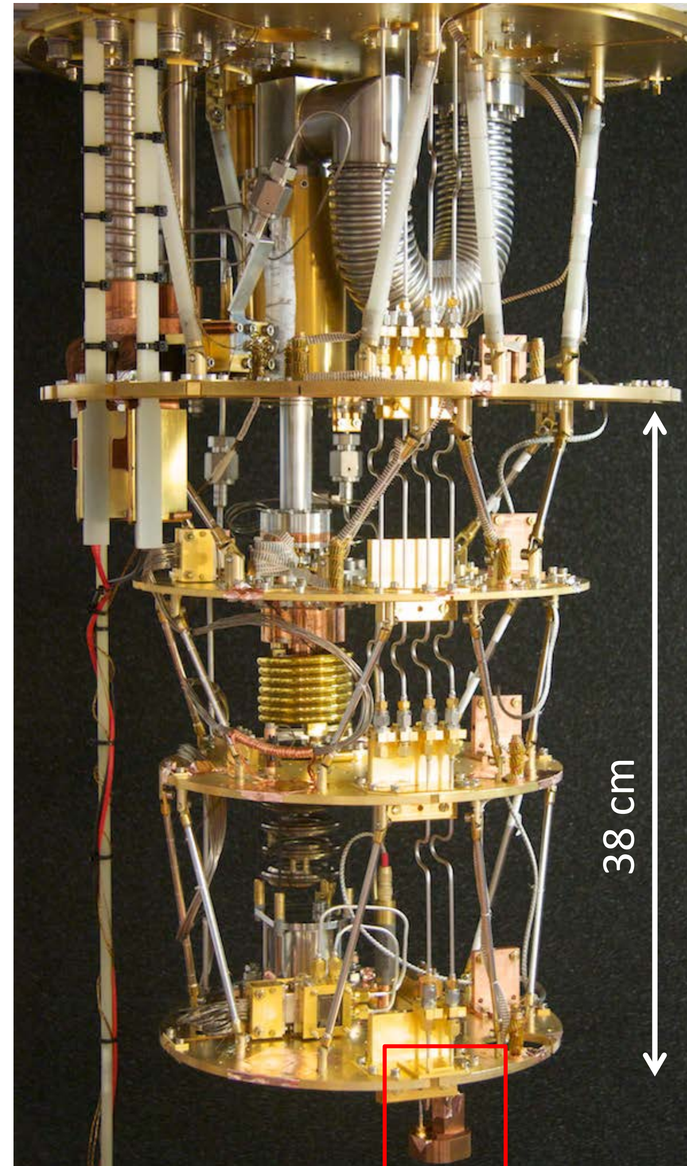
- Superconducting overcoupled resonator (Al) ν_0=6.7GHz Q~900
- Inductor at the center of the resonator
- 2D Gas in GaAs/GaAlAs 90 nm below surface
- All gated DQD sample with a quantum point contact charge readout
- Heterodyne detection scheme of Amplitude and phase with FPGA

Hybrid Quantum Dot / Circuit QED Measurement Setup





Pulse tube cooled cryostat



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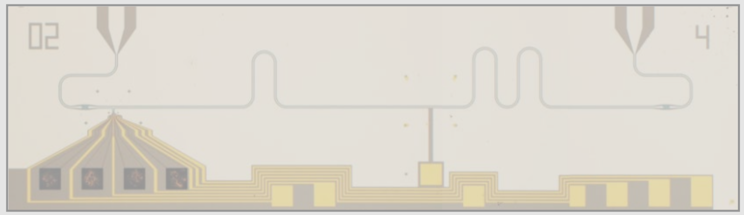

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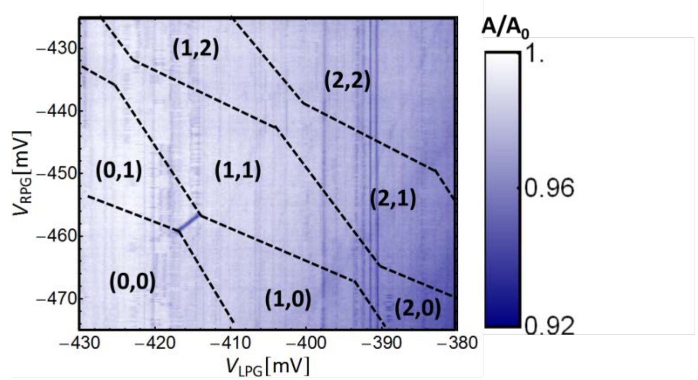

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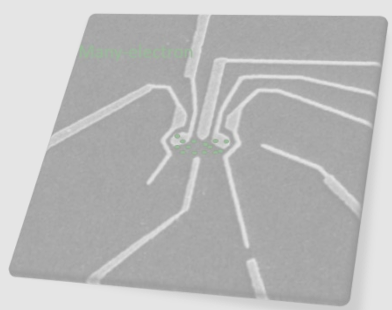
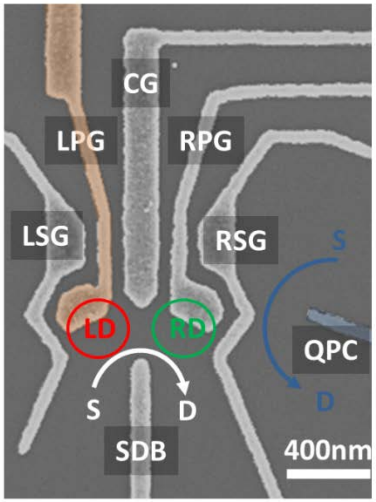


Double Dot Charge state

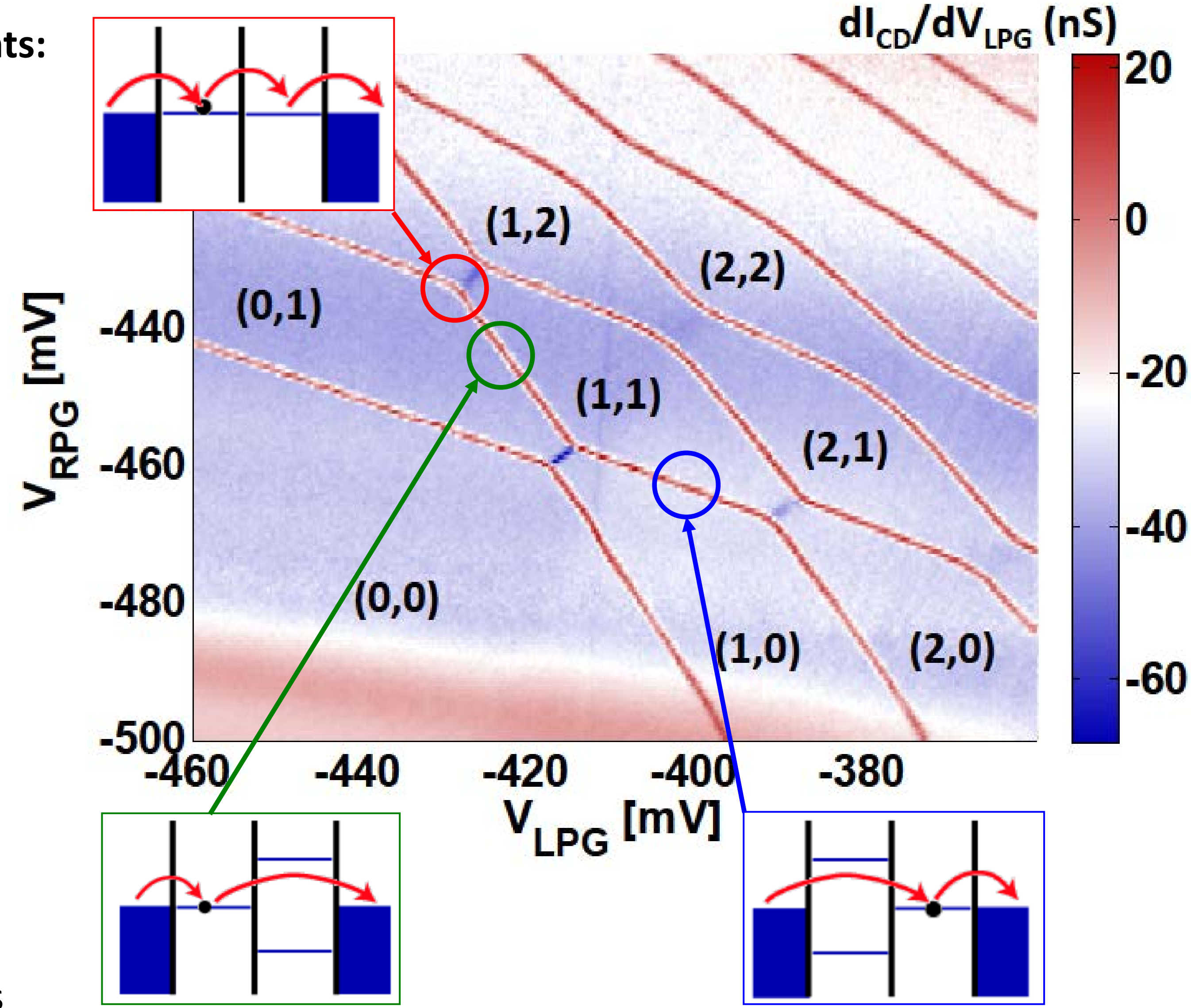
Charge state measurements:

- Charging diagrams



Dot properties:

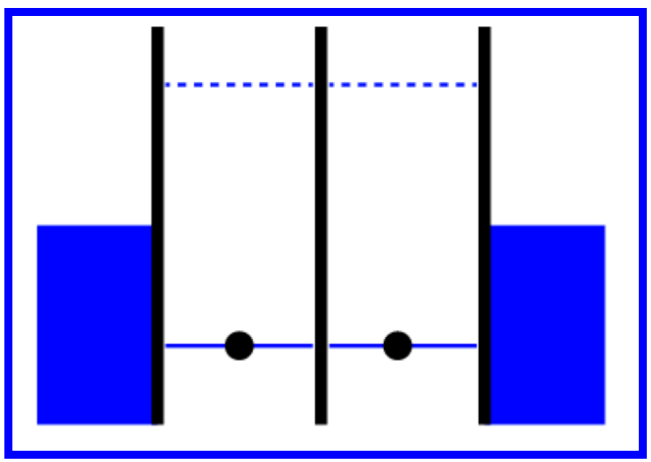
- Single-electron regime
- large charging energy E_C~3meV
- Mean level spacing $\Delta\varepsilon$~110μeV=26GHz
- Strong cross-talk of PGs on tunnel coupling
- T_{el}~130mK



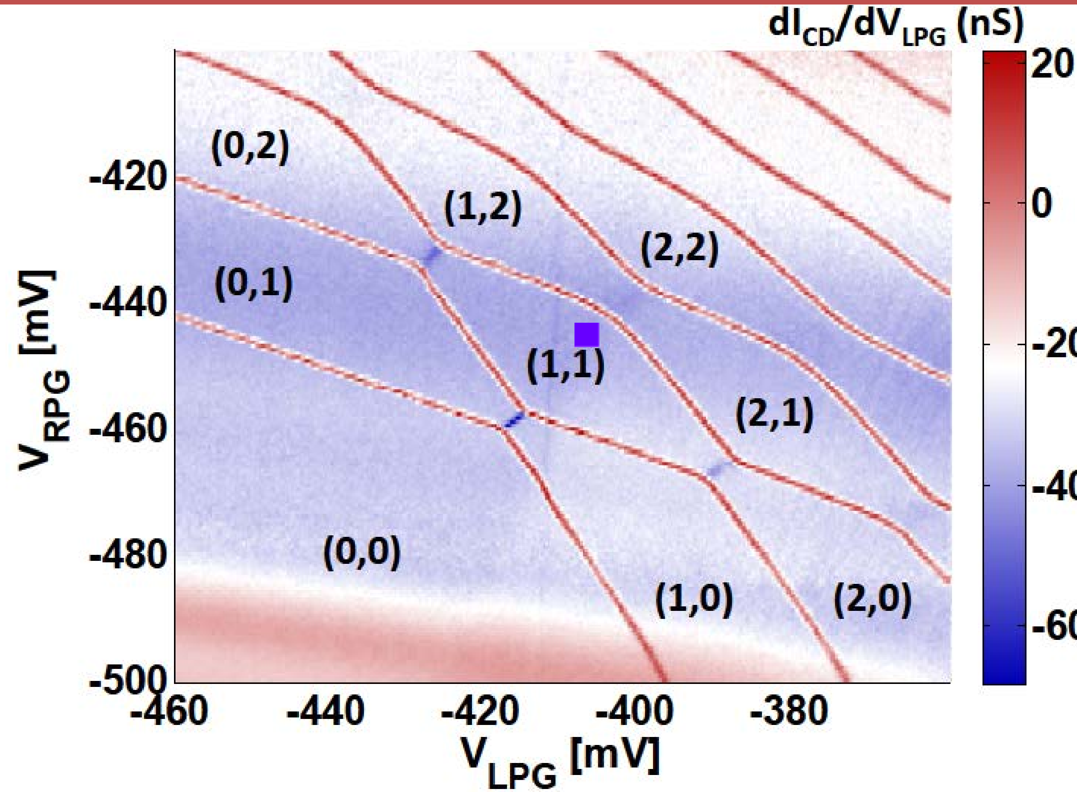
Double Dot Current and Resonator Transmission

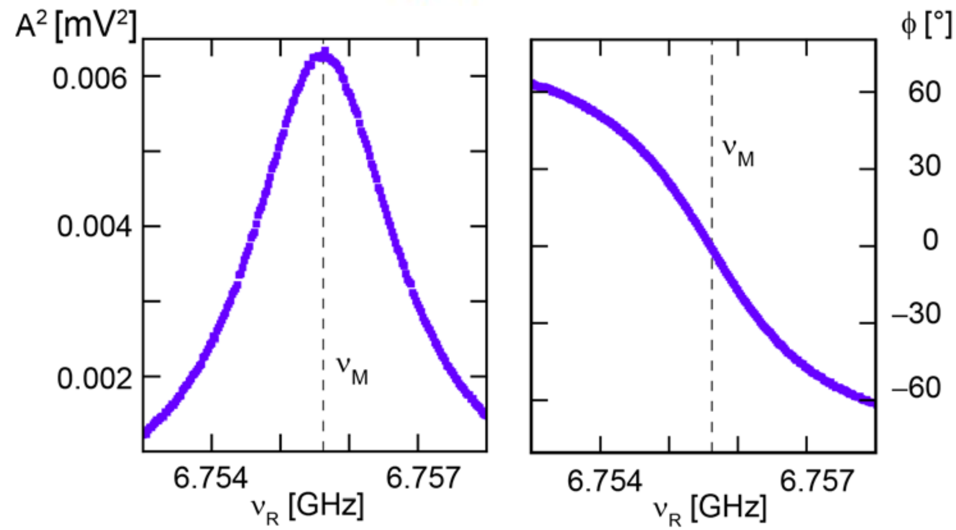
Resonator transmission :

- Amplitude A
- Phase ϕ
- $Ae^{i\phi}=I+iQ$ measured into a heterodyne detection scheme.



➔ Reference transmission spectra





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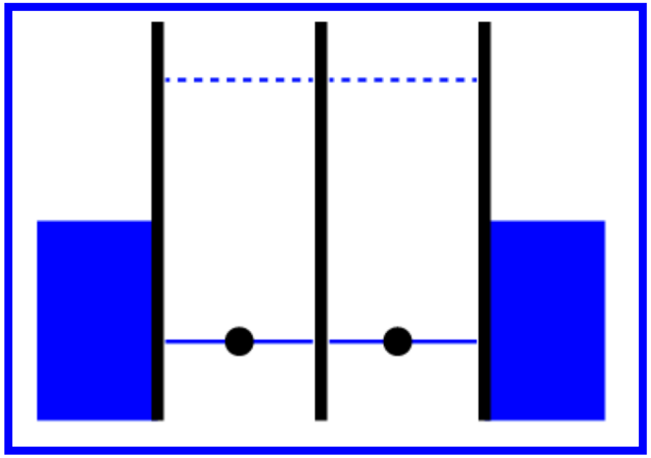
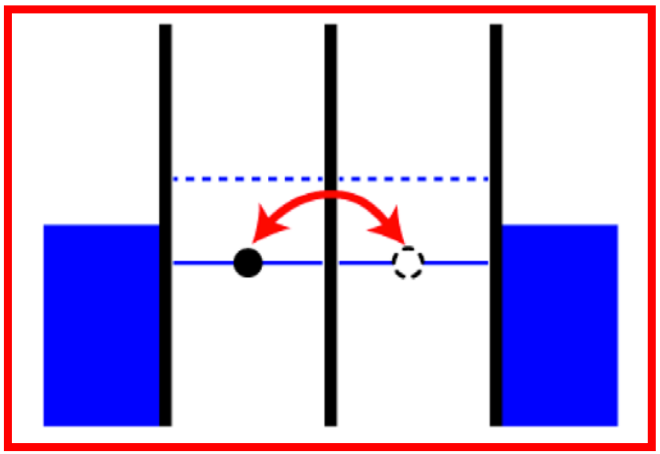
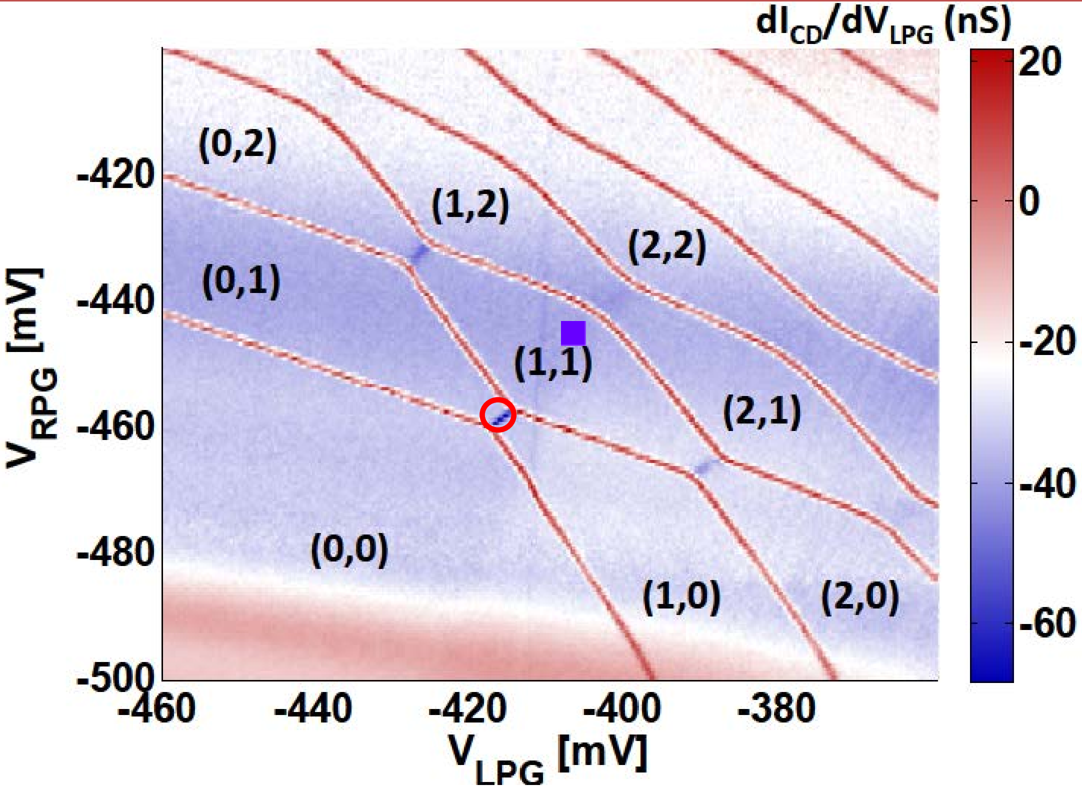
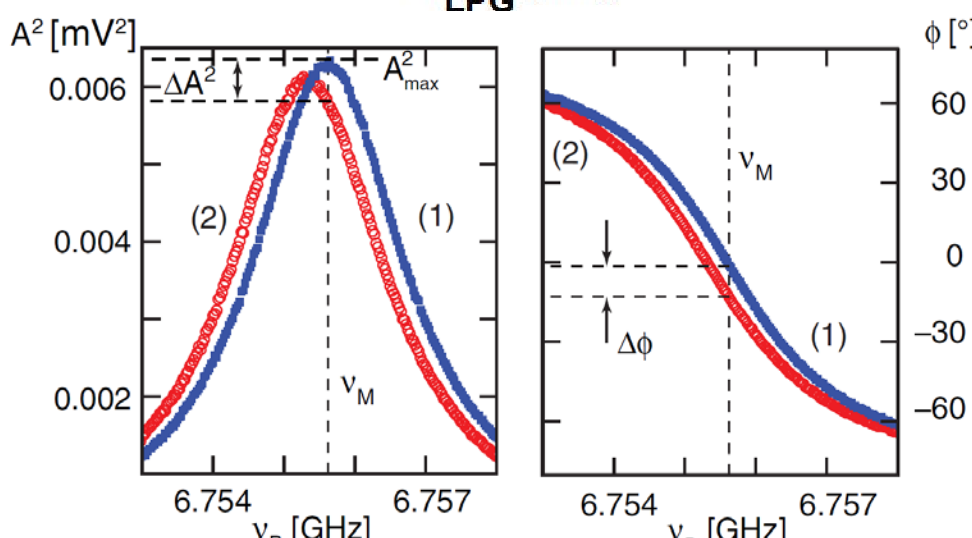




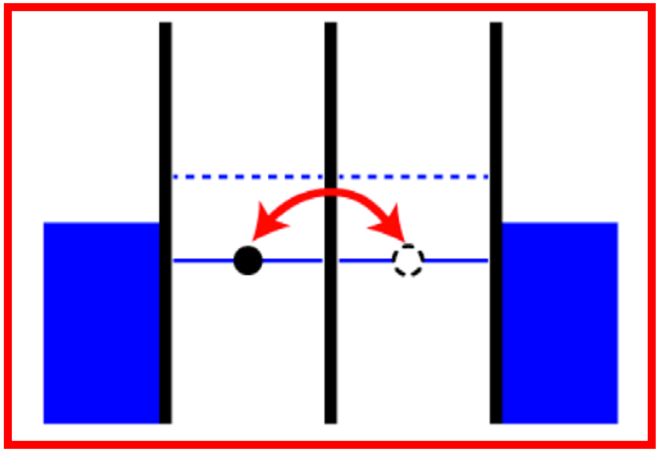




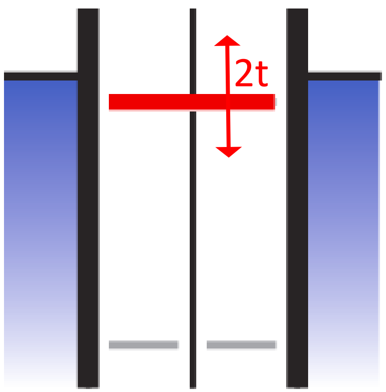
Resonator transmission

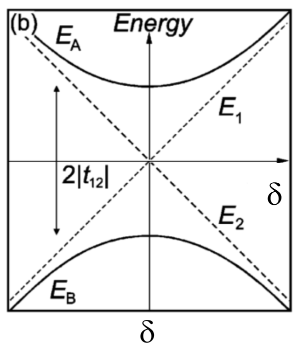
- Measuring at a fixed frequency the amplitude and phase gives a lot of information

Double Dot Current and Resonator Transmission



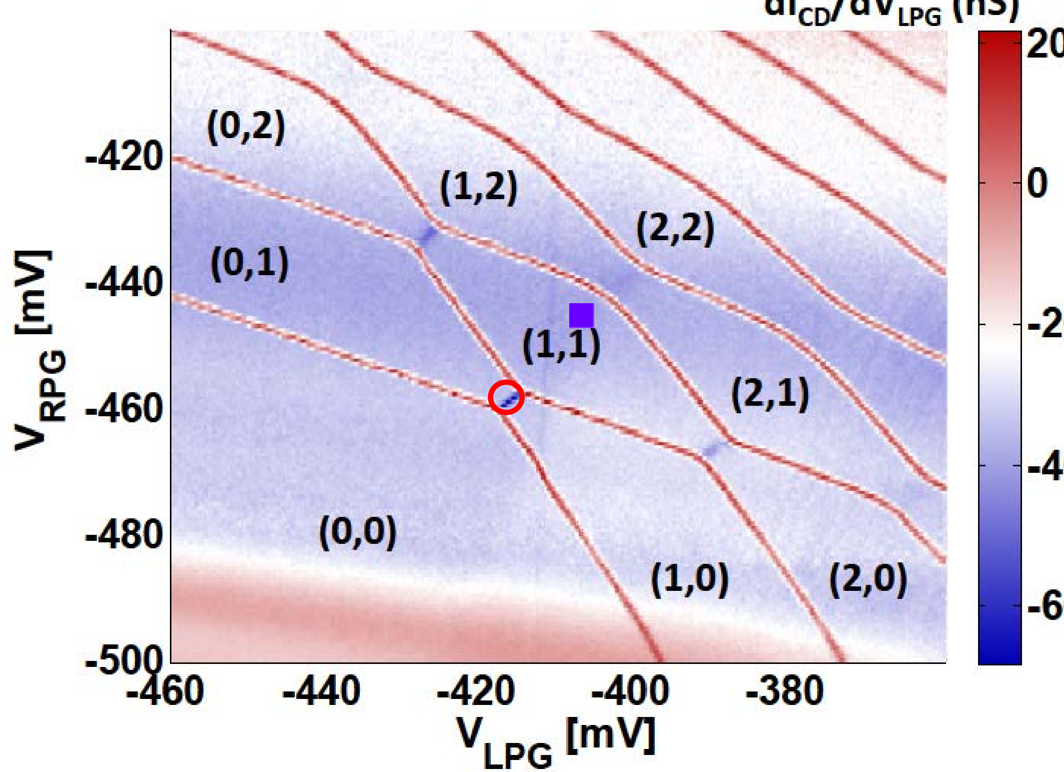
tunnel coupling t :

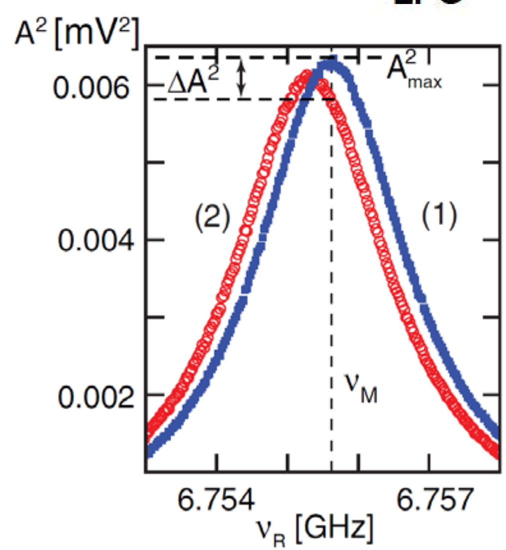


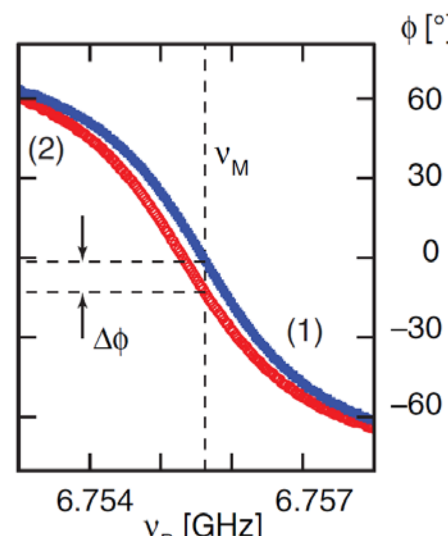


$$E_A - E_B = \sqrt{(\delta)^2 + (2|t_{12}|)^2}$$

- Single-electron charge qubit: bonding and antibonding charge states of the delocalized electron
- Qubit energy depends on detuning δ and tunnel coupling t



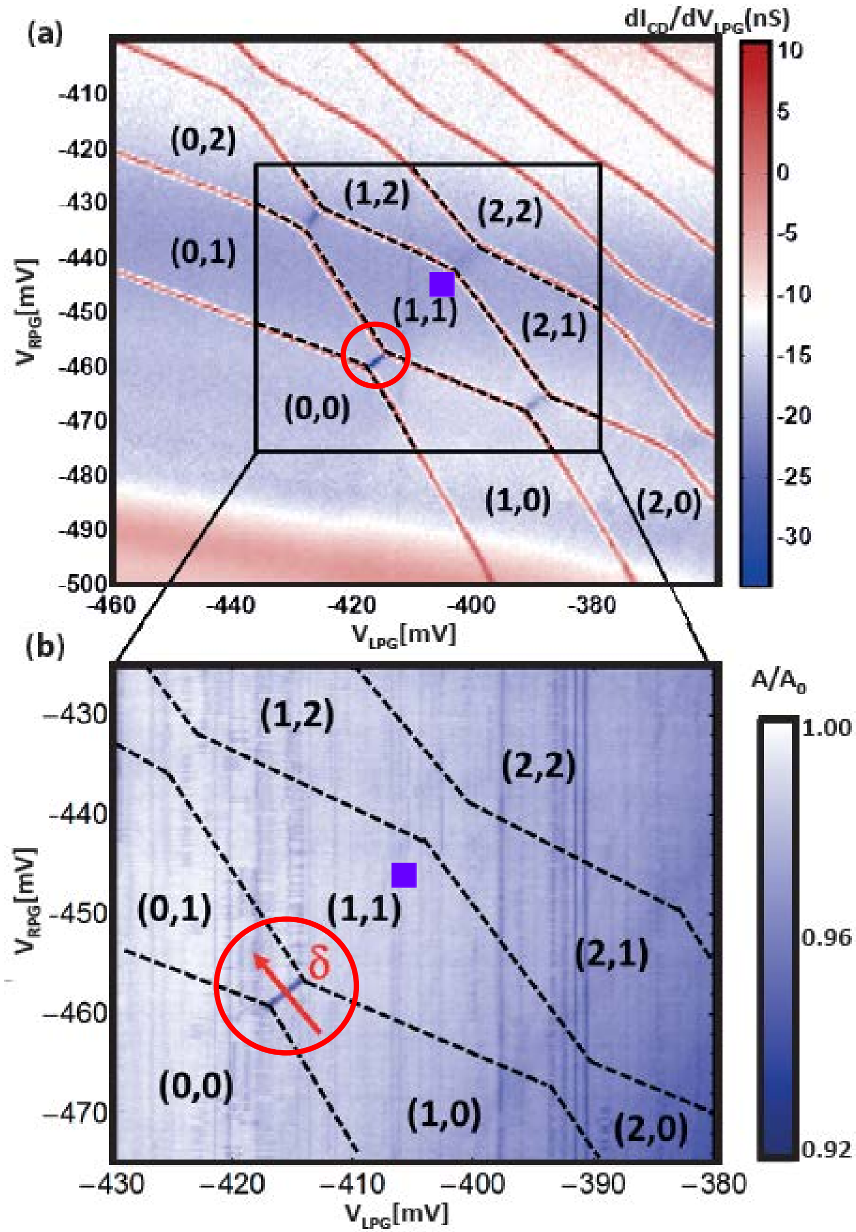




Last electron: Resonator vs QPC readout

QPC readout

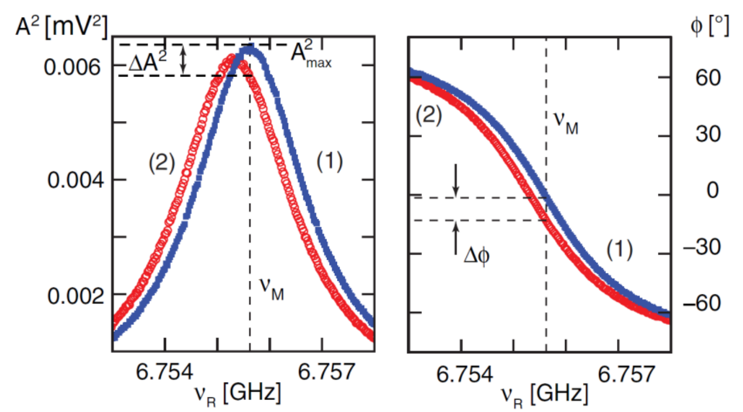
Microwave readout

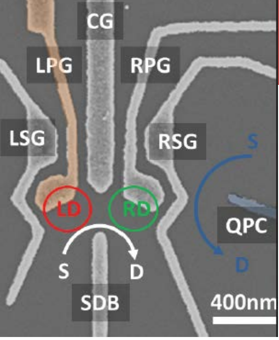


- QPC readout is an easy tool to determine the absolute charge occupancy

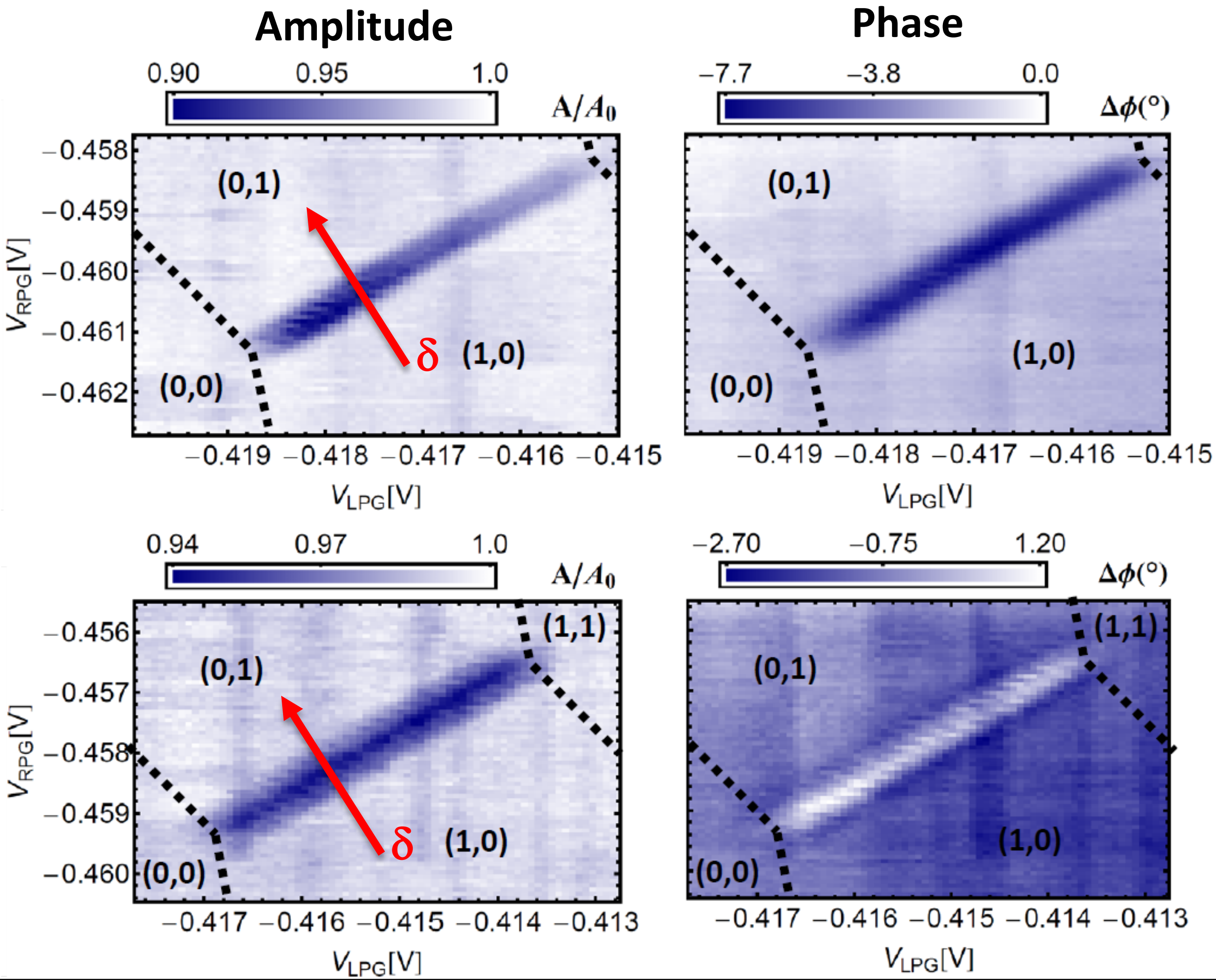
- Microwave signal change visible only at the (0,1) ⇔ (1,0) transition

➔ limited range of sensitivity





Microwave readout vs tunneling



V_{CG}=-360mV

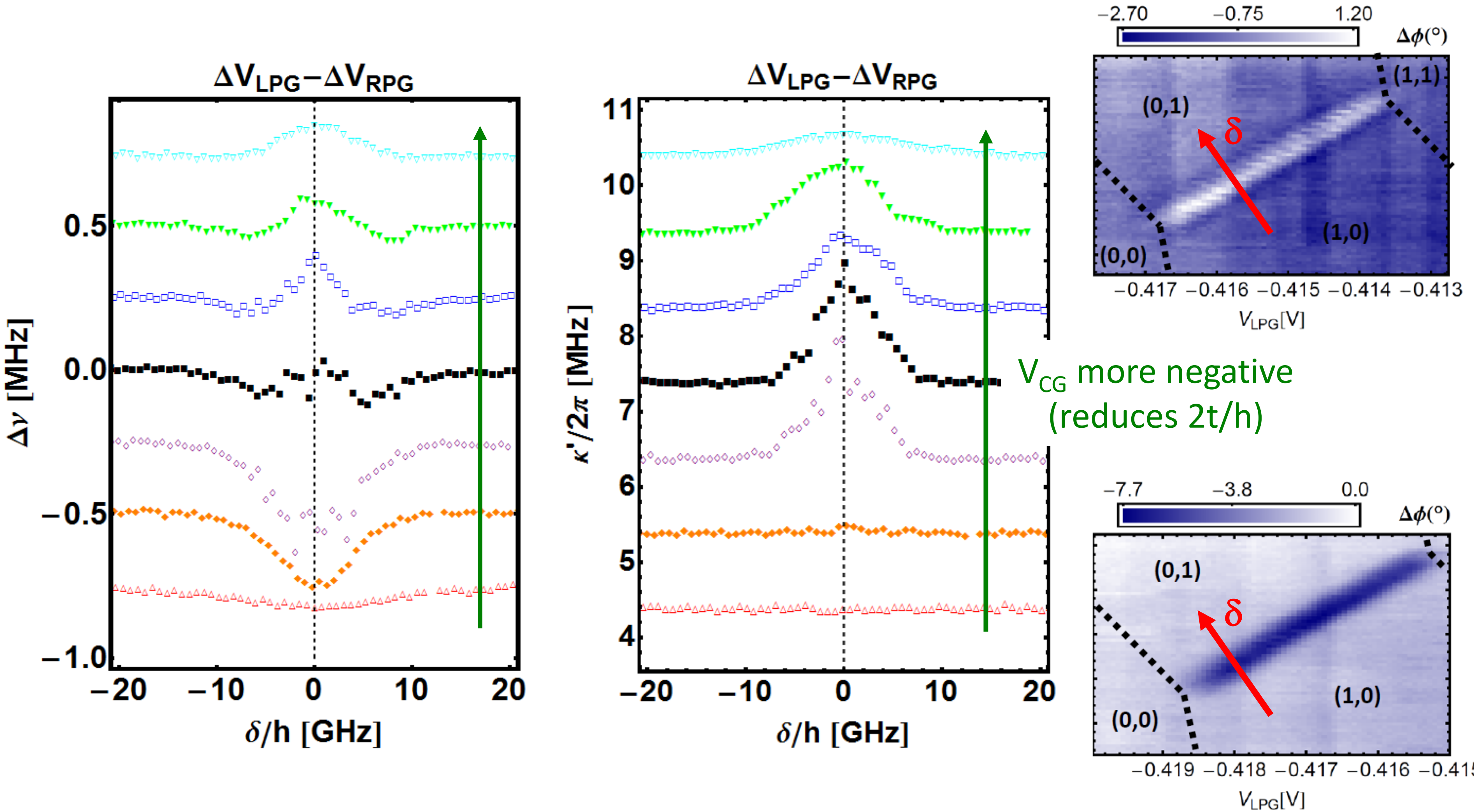
V_{CG} more negative reduces 2t/h

V_{CG}=-370mV

- Changes in transmission amplitude and phase
  - ➔ Amplitude : loss through the DQD
  - ➔ Phase : Dispersive shift due to the DQD
- Strong changes in phase behaviour depending on tunnel coupling ($2t/h\nu_0$)
  - ➔ Determine tunneling

Frey *et al.* PRL (2012)

Frequency shift and linewidth broadening measurement



- Entire spectra acquisition along detuning δ+ Lorentzian fit ➔ Δν and κ/2π
- Acquired for different tunneling V_{CG} i.e. different tunneling t

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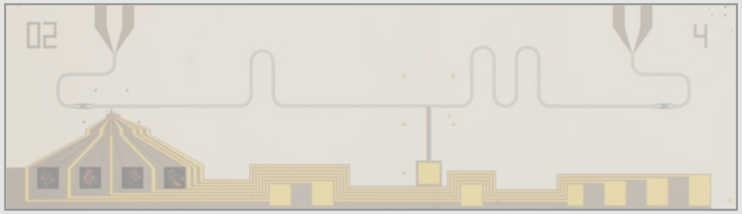

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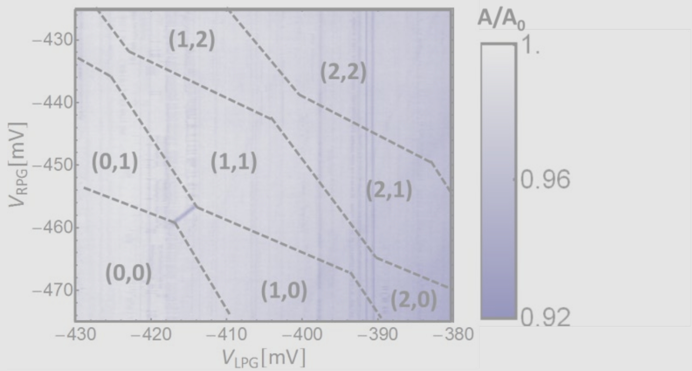

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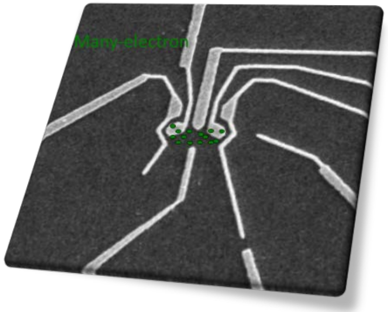


Jaynes-Cummings + Master equation

$$\boxed{H = h\nu_0\left(\hat{n} + \frac{1}{2}\right) + \frac{h\nu_q}{2}\hat{\sigma}_z + \hbar g \sin\theta(\hat{a}^\dagger\hat{\sigma}^- + \hat{a}\hat{\sigma}^+),}$$

$$\underbrace{h\nu_0\left(\hat{n} + \frac{1}{2}\right)}_{\text{Resonator}} \quad \underbrace{\frac{h\nu_q}{2}\hat{\sigma}_z}_{\text{Qubit}} \quad \underbrace{\hbar g \sin\theta(\hat{a}^\dagger\hat{\sigma}^- + \hat{a}\hat{\sigma}^+)}_{\text{Qubit-Resonator coupling}}$$

Qubit frequency :

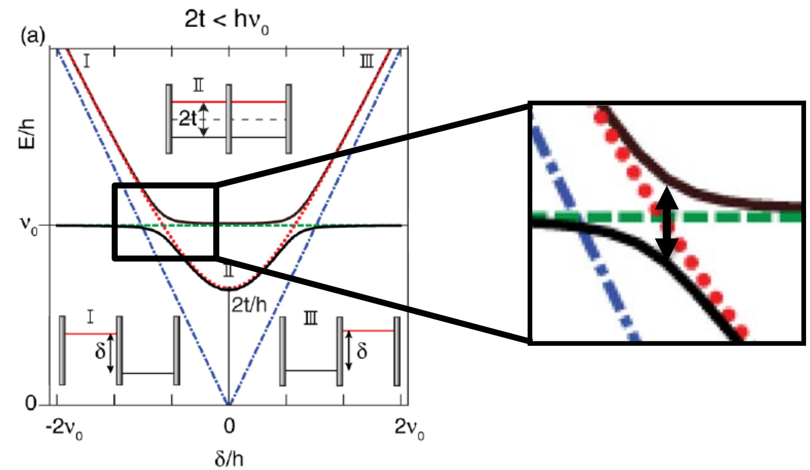
$$\nu_q = \sqrt{\delta^2 + 4t^2}$$

Inhomogenous decoherence rates:

$$\gamma_1 = \sin^2\theta\gamma_\varphi^b + \cos^2\theta\gamma_1^b$$

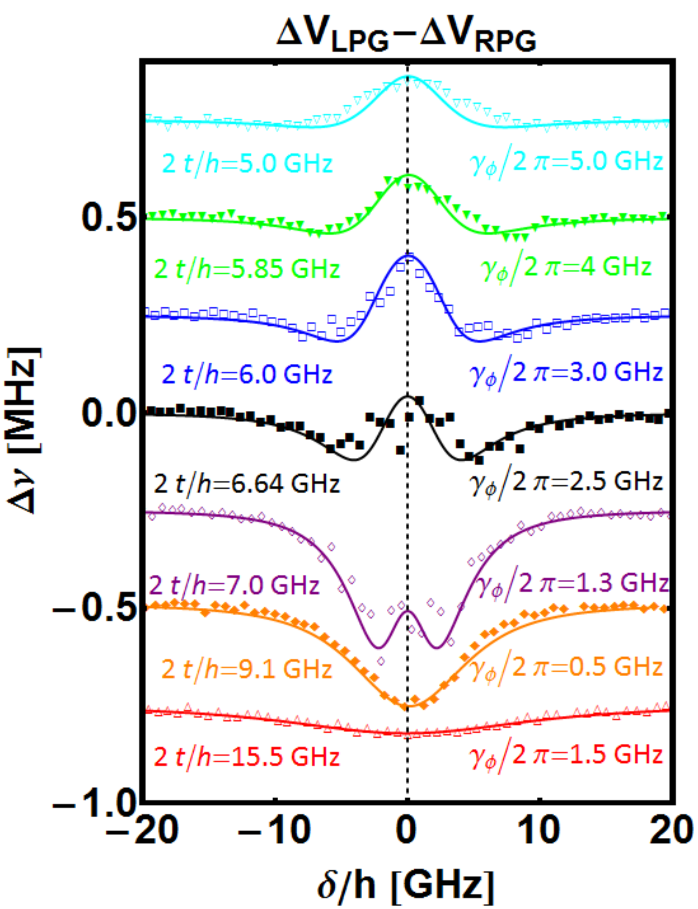
$$\gamma_\varphi = \cos^2\theta\gamma_\varphi^b + \sin^2\theta\gamma_1^b.$$

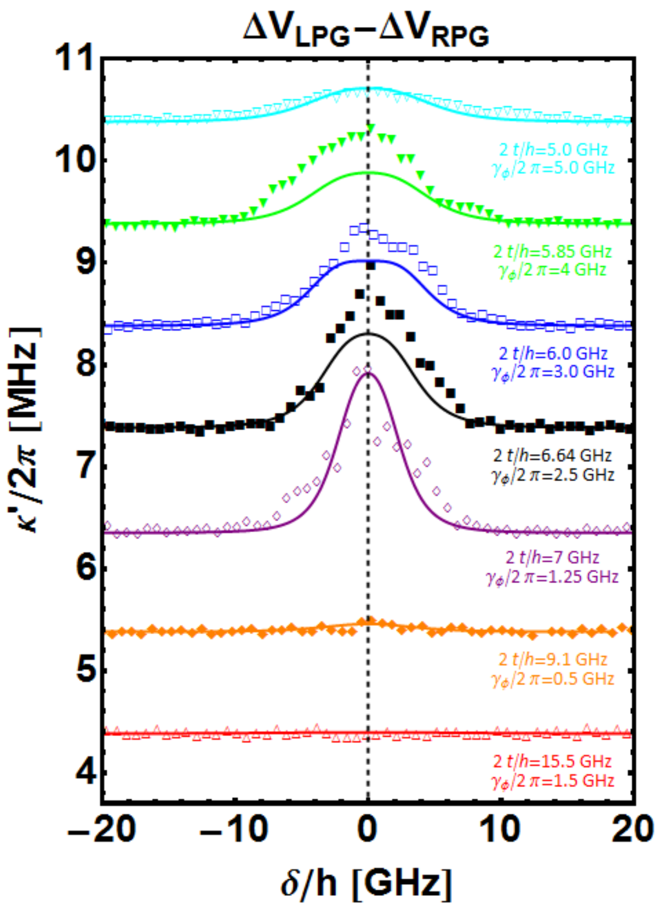
Mixing angle : $\sin\theta = 2t/\sqrt{\delta^2 + 4t^2}$

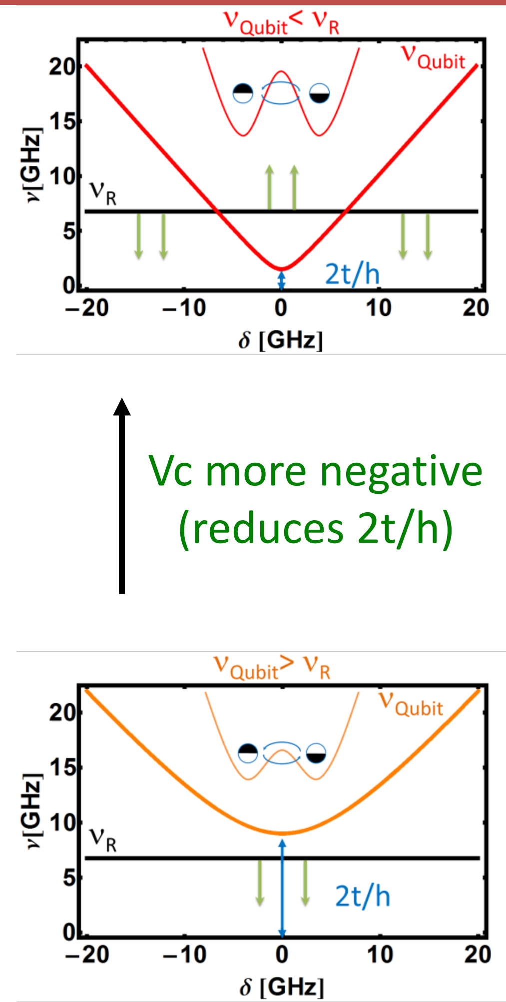


- Fixed parameters set by the experiment or according to literature:
  - ✓ Qubit/Resonator coupling: $g/2\pi$=25 MHz
  - ✓ Resonator frequency ν_0=6.75GHz
  - ✓ Relaxation rate: $\gamma_1^b/2\pi$=100MHz
- Fitting parameters:
  - ✓ Tunnel coupling between dots $2t/h$
  - ✓ Dephasing rate: $\gamma_\varphi^b/2\pi$

Frequency shift and linewidth broadening analysis

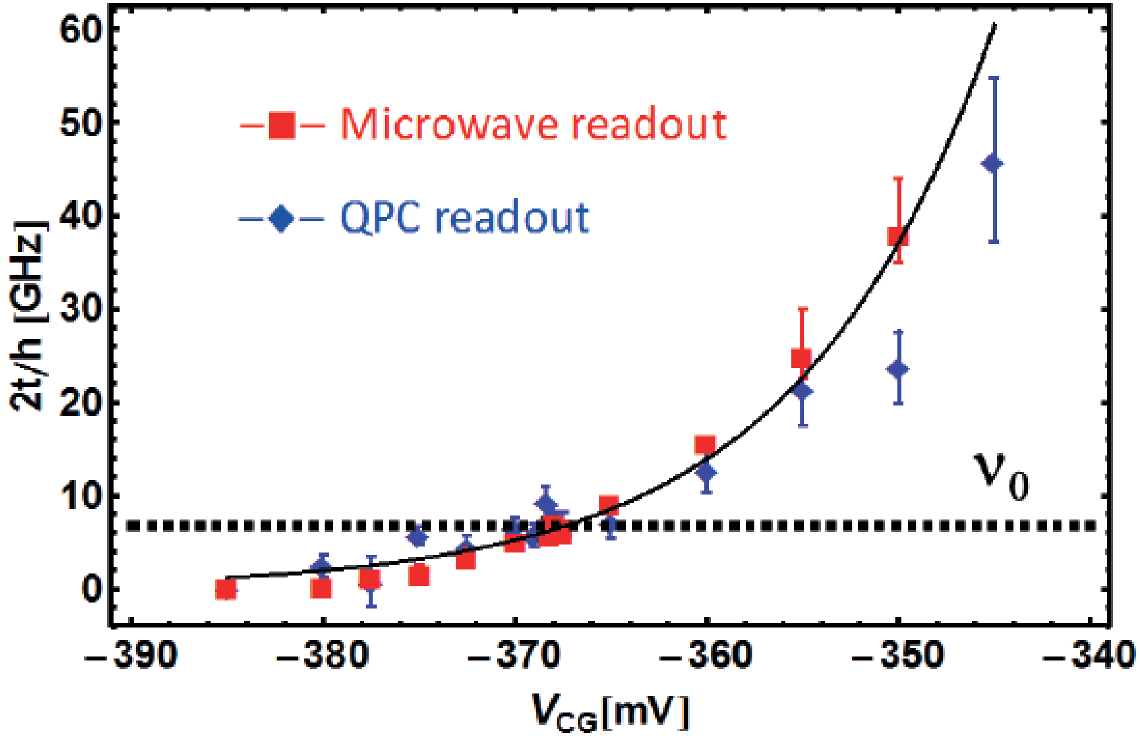






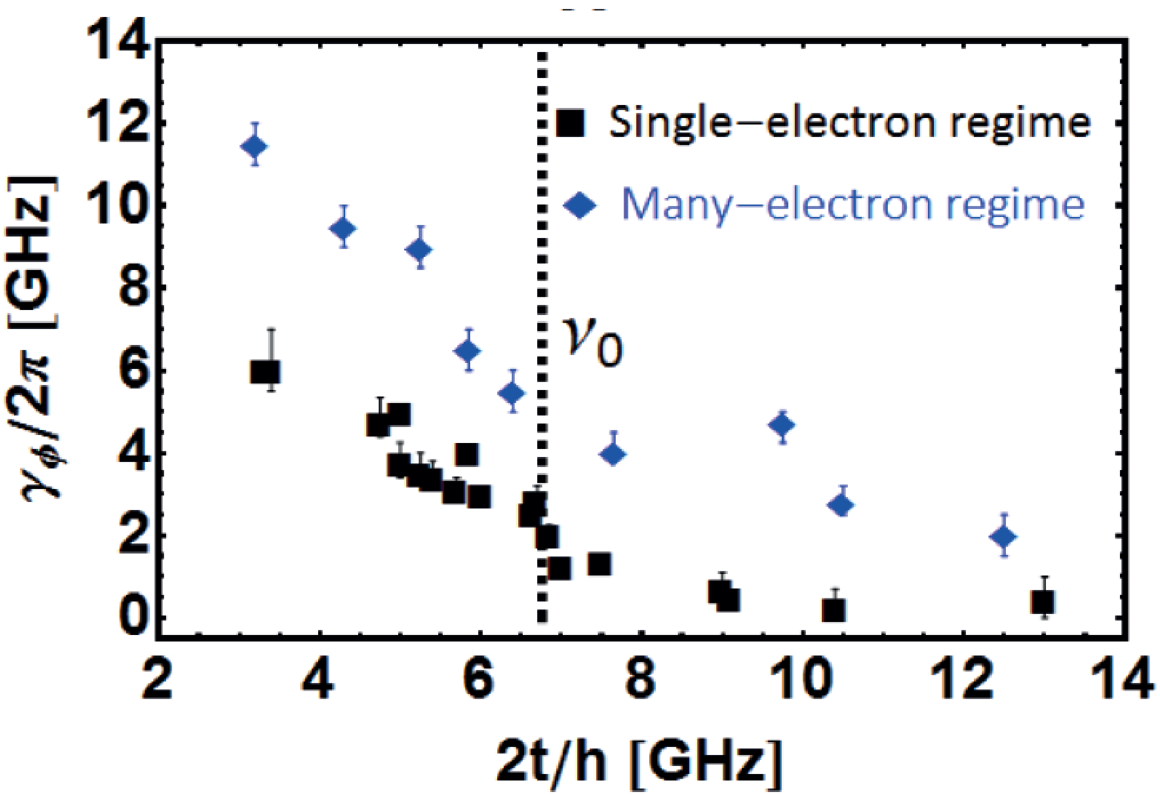
- Data simulation with Jaynes-Cummings Hamiltonian + q-bit relaxation + q-bit dephasing
  ➔ Markovian master equation approach (Alexandre Blais – Sherbrooke University)

Tunnel coupling extraction + comparison with charge detector



- Two methods are consistent
  - ✓ Tunnel coupling roughly depends exponentially with center gate voltage V_{CG}
  - ✓ More precise determination (x20) of 2t/h with microwave when 2t/h ν_0~1

Dephasing: Single vs Many-electron

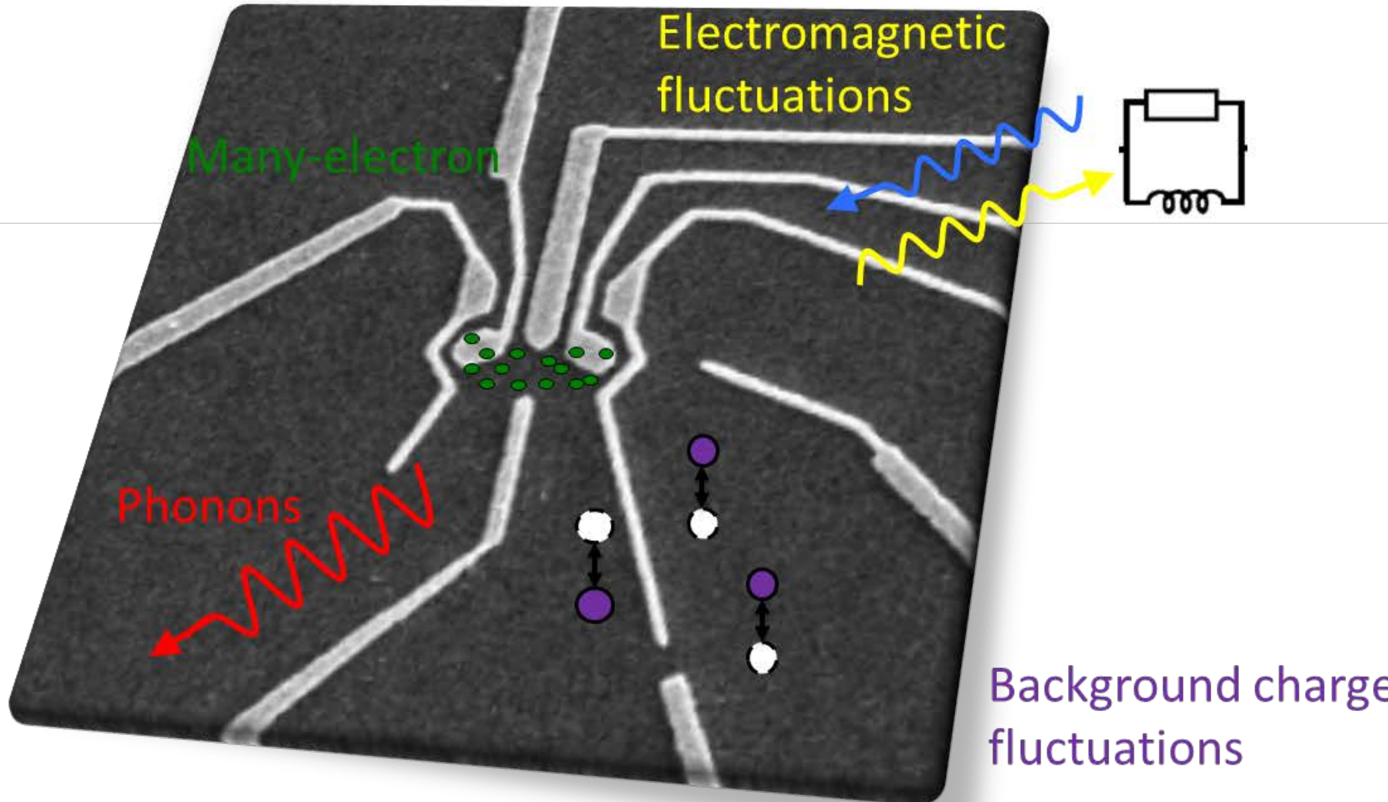


- Single electron DQD:
  - ✓ g/2π=25MHz
  - ✓ Dephasing increases at low tunnel coupling and ranges from 0.4GHz to 8GHz
- Many-electron DQD (~50 electrons in each dot):
  - ✓ g/2π=50MHz
  - ✓ Dephasing increases at low tunnel coupling and ranges from 1GHz to 17GHz
- Dephasing 2-3 orders of magnitude larger than coupling : $\gamma_\varphi/2\pi >> g/2\pi = 25\text{MHz}$

Possible sources of decoherence

Petersson *et al. PRL 105, 246804 (2010)*
Exp: $\gamma_\varphi/2\pi$~ 100MHz

Valente *et al.* PRB 82, 125302 (2010)
Th: $\gamma_\varphi/2\pi$ ~25MHz



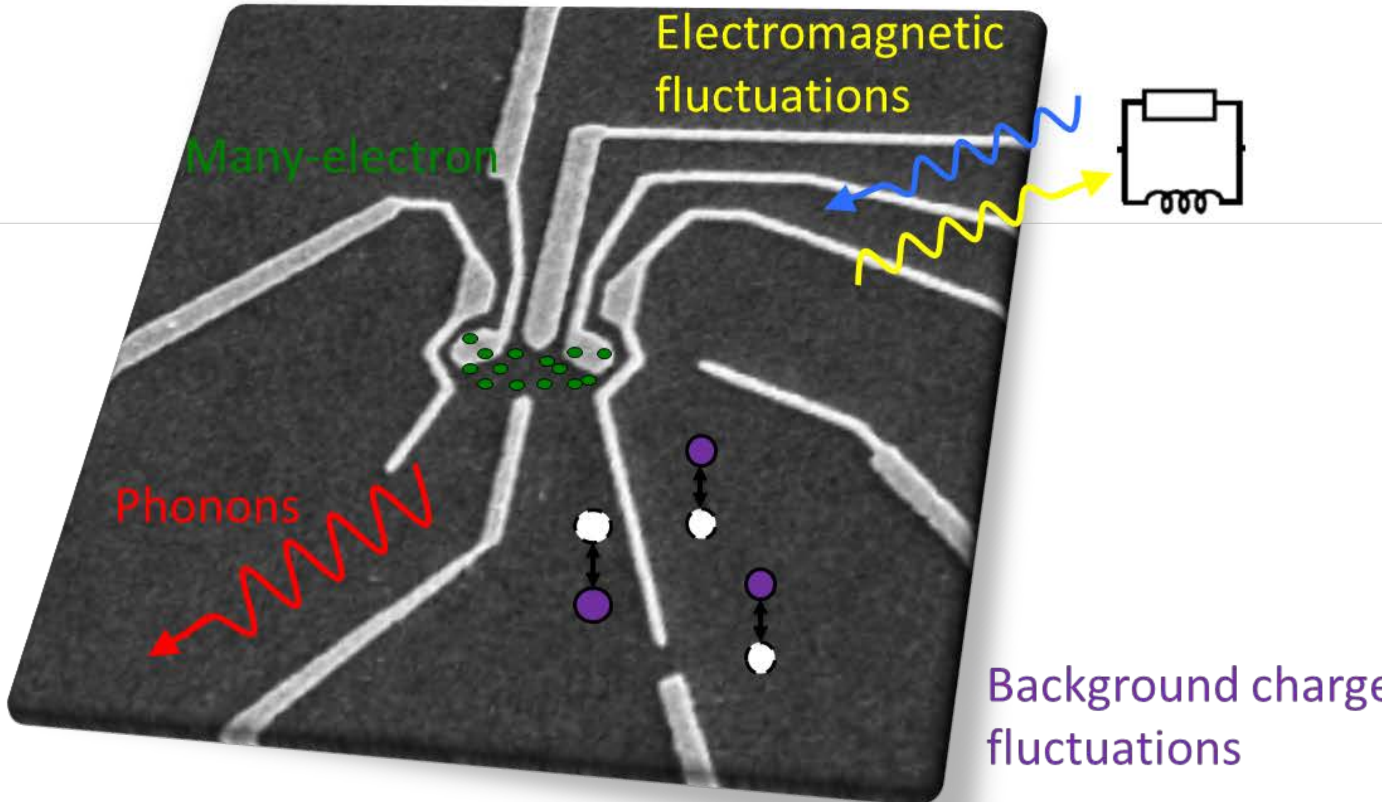
Vorojtsov *et al. PRB 71, 205322 (2005)*
Th: $\gamma_\varphi/2\pi$~10-100MHz

Itakura *et al. PRB 67, 195320 (2003), Abel et al. PRB 78, 201302 (2008)*, Yurkevich *et al. PRB 81, 121305 (2010)* Th/Exp: MHz to GHz

Possible sources of decoherence

Petersson *et al. PRL 105, 246804 (2010)*
Exp: $\gamma_\varphi/2\pi$~ 100MHz

Valente *et al.* PRB 82, 125302 (2010)
Th:$\gamma_\varphi/2\pi$ ~25MHz



Vorojtsov *et al. PRB 71, 205322 (2005)*
Th: $\gamma_\varphi/2\pi$~10-100MHz

Itakura *et al. PRB 67, 195320 (2003), Abel et al. PRB 78, 201302 (2008)*, Yurkevich *et al. PRB 81, 121305 (2010)* Th/Exp: MHz to GHz

➔ **Our results are consistent with BCF:**
Strong detuning noise = Charge noise that changes the asymmetry of the qubit's double-well potential

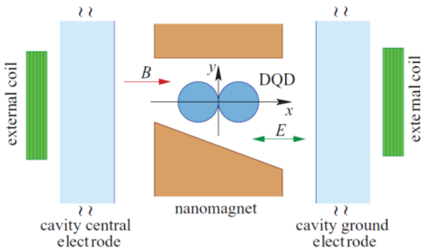
Conclusions and perspectives

- Dipole-coupling a single-electron double quantum dot to a single photonic mode

J. Basset *et al.* arXiv 1304.5141 (2013)

Outlook

- Evaluate potential to investigate spin physics
  - ✓ Trif *et al.* PRB (2008), Nori *et al.* PRB (2012), Cottet *et al.* PRL (2010), Jin *et al.* PRL (2012)
  - ✓ Petersson *et al.* Nature (2012)



- Full counting statistics of photons emitted from the DQD to the resonator
  - ✓ Xu *et al.* arXiv (2013)
- Full counting statistics of electrons in a DQD in a controlled microwave environment
  - ✓ Lambert *et al.* PRB (2008)
- Non local electron transport properties with two S/DQDs coupled via the resonator
  - ✓ Bergenfeldt *et al.* PRB (2013), arXiv (2013), Lambert *et al.* EPL (2013)
  - ✓ Delbecq *et al.* Nat. Comm. (2013)