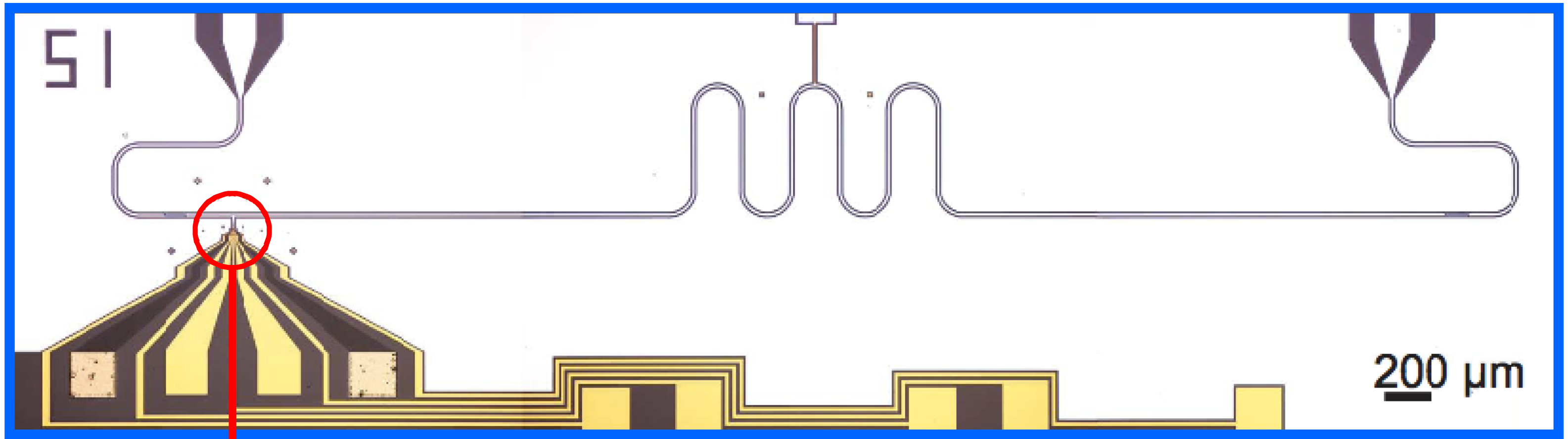
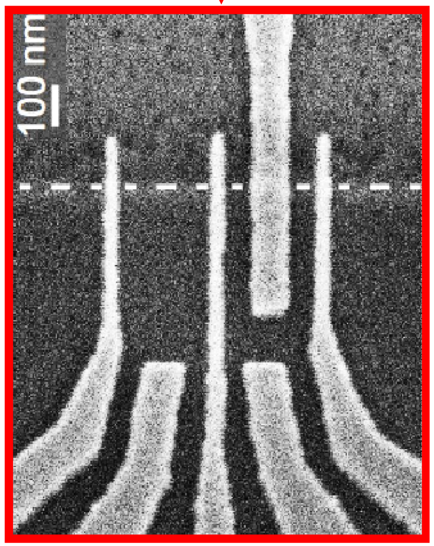
Dipole coupling of a double quantum dot to a microwave resonator





Tobias Frey, P. J. Leek, A. Blais, M. Beck, J. Basset, 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

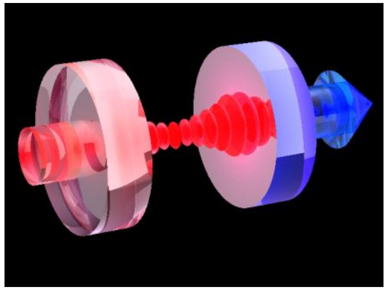
Context and motivations

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

➔ long distance exchange of quantum information, distant q-bits entanglement,…

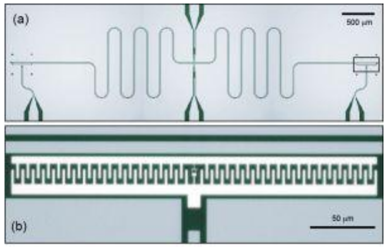
Å Very well established in the

- Cold atoms community : cavity Quantum ElectroDynamics (cavity QED)



Max Planck Institute

- Superconducting q-bit community : circuit Quantum ElectroDynamics (circuit QED)



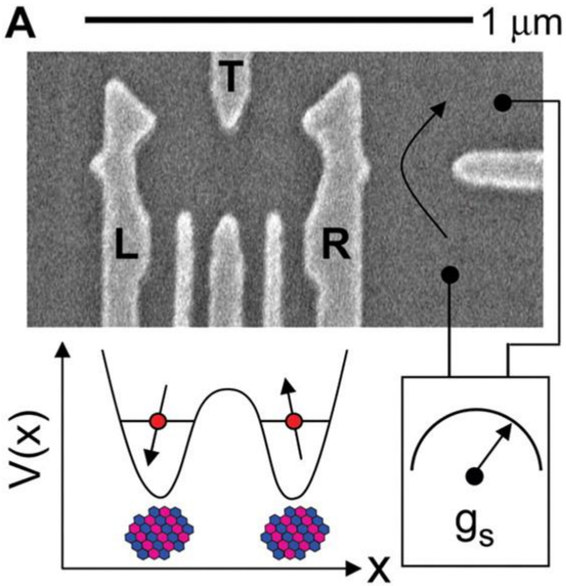
Leek et al., PRL (2010)

Å 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

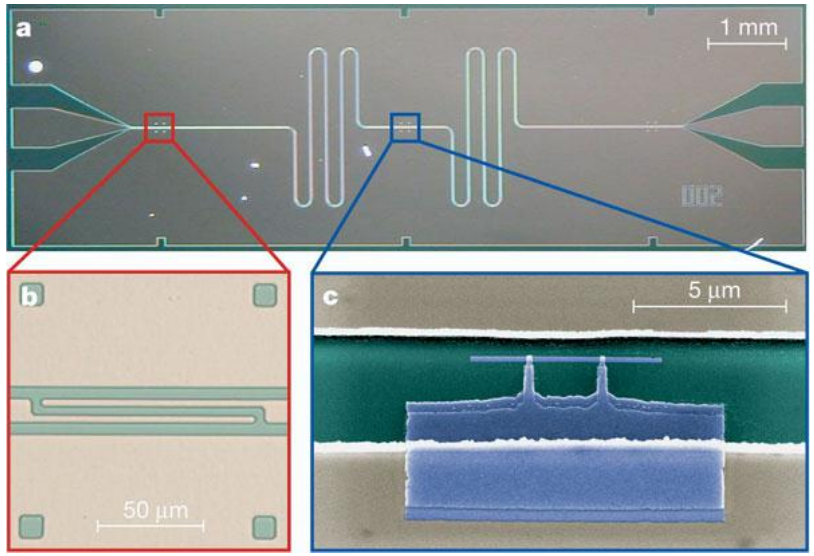
Spin qubits in quantum dots



Petta et al., Science (2005)

+

Circuit quantum electrodynamics



Wallraff et al., Nature (2004)

Potential benefits:

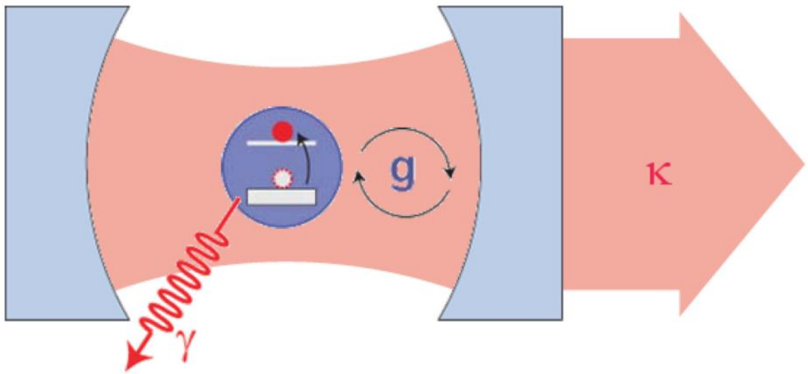
- Use electrons spins quantum bit ➔ low relaxation and dephasing rate
- Realize interfaces between different type of quantum systems

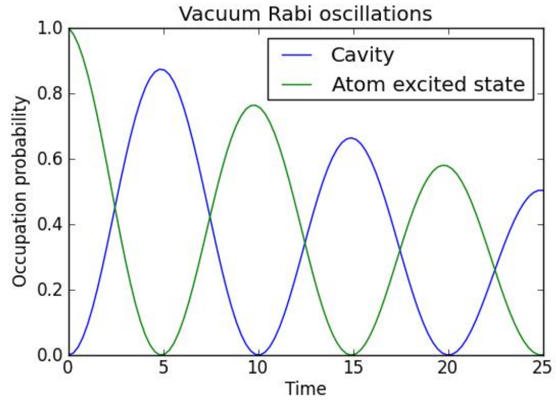
Context and motivations

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:

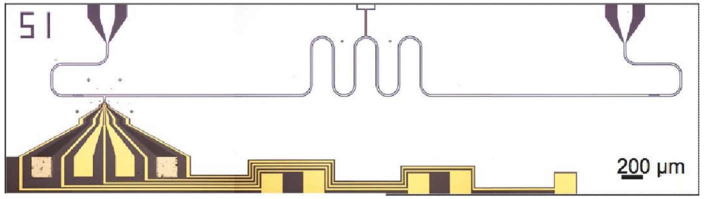
Exchange rate = g must be much higher than any other decay rates

$g/2\pi > 1/T_1$	=	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

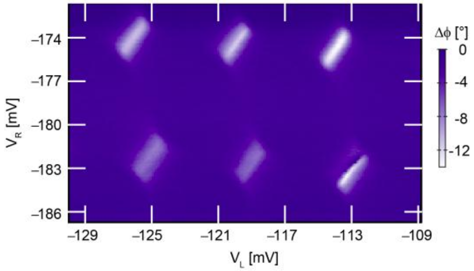
Outline

Dipole coupling of a double quantum dot to a microwave resonator

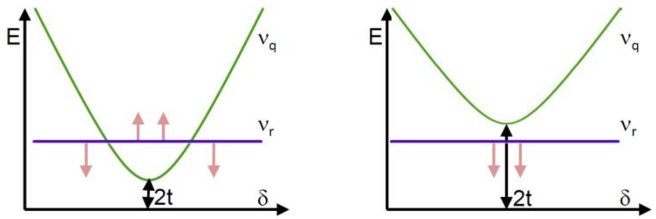
1. Hybrid quantum device and circuit QED measurement setup



2. Sensitivity of the resonator to the double quantum dot



3. A Jaynes-Cummings Hamiltonian theoretical interpretation



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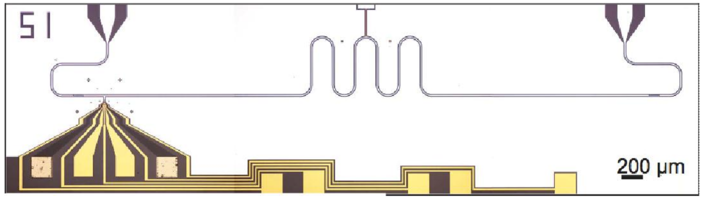

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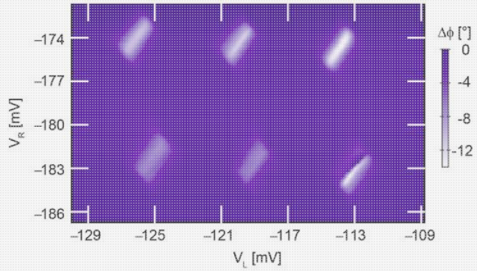

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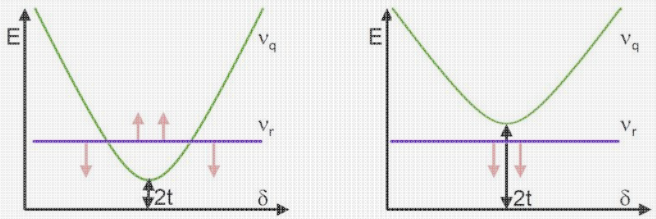
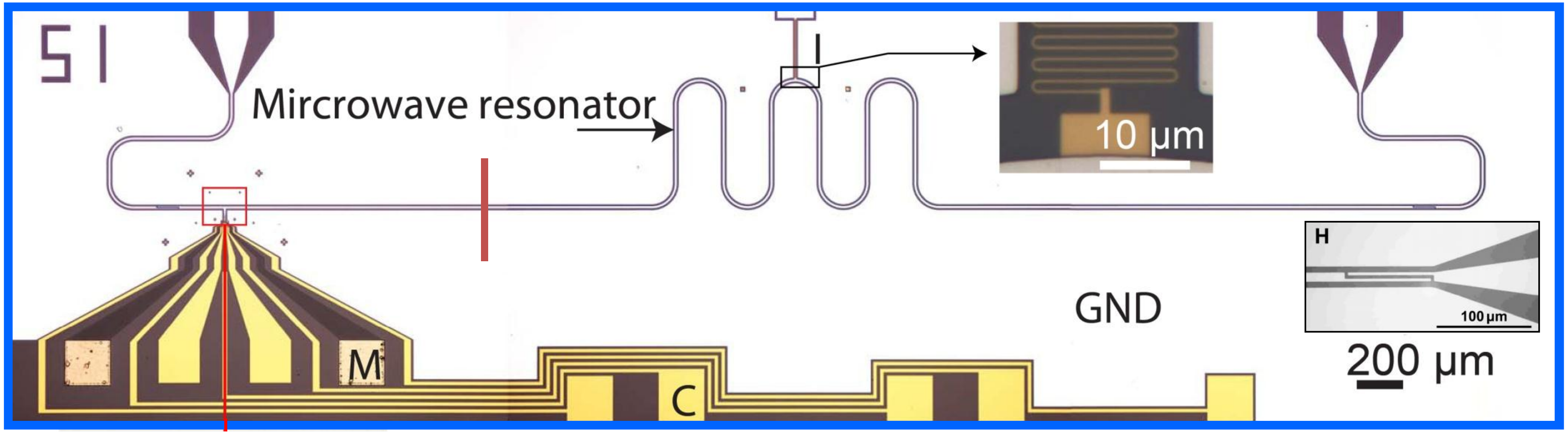
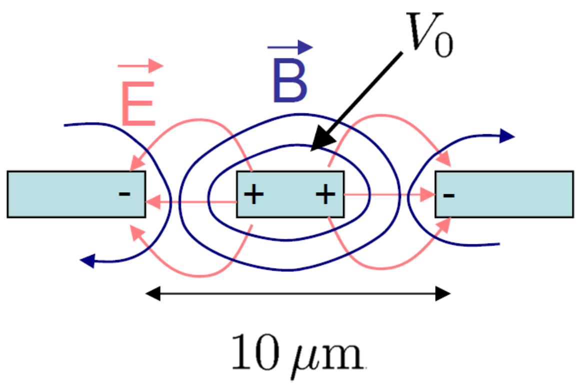


Hybrid quantum device



Cross-section of transmission line



Voltage across resonator in vacuum state (n=0)

$V_{0,rms}$~1μV

Aluminum resonator

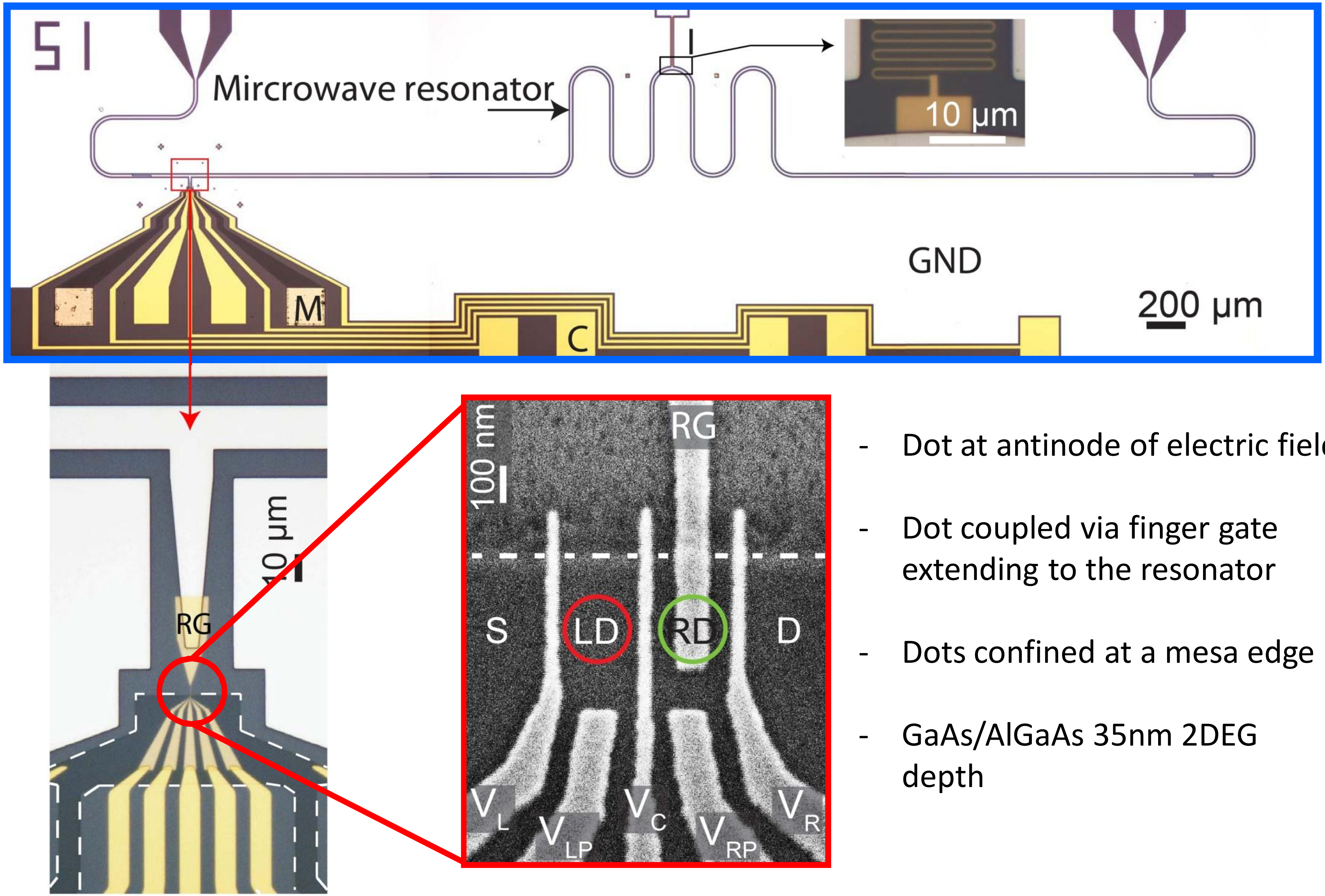
$\nu_{res} \approx 6.75$ GHz

$Q \approx 2600$

➔ Photon decay rate~2.6MHz

(not limited by substrate but by coupling to feed lines. Best Q obtained for undercoupled resonator 10^4)

Hybrid quantum device

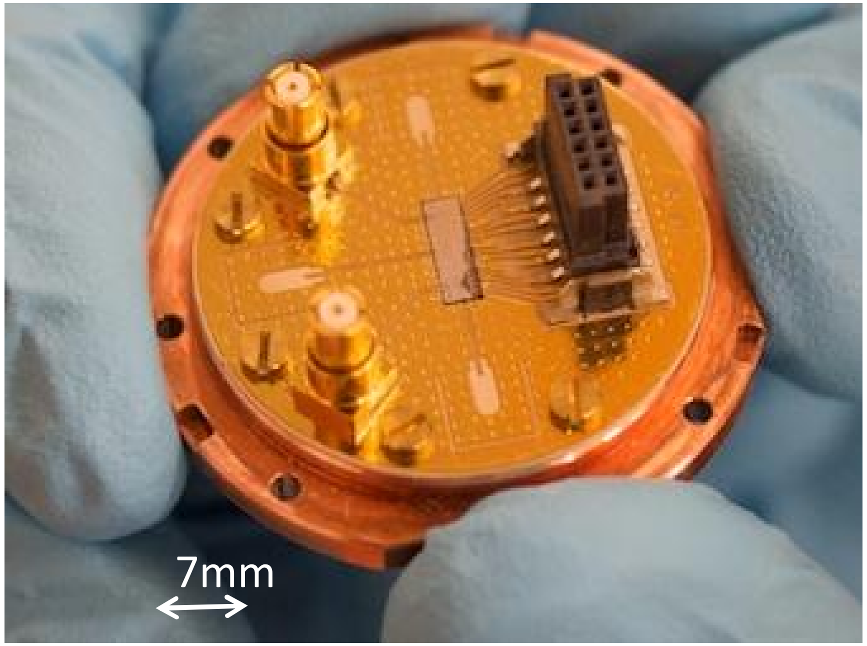


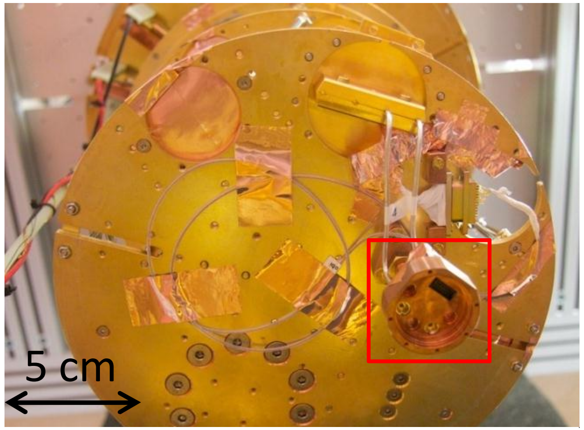
- Dot at antinode of electric field
- Dot coupled via finger gate extending to the resonator
- Dots confined at a mesa edge
- GaAs/AlGaAs 35nm 2DEG depth

T. Frey *et. al. PRL* **108**, 046807 (2012)

Hybrid Quantum Dot / Circuit QED Measurement Setup

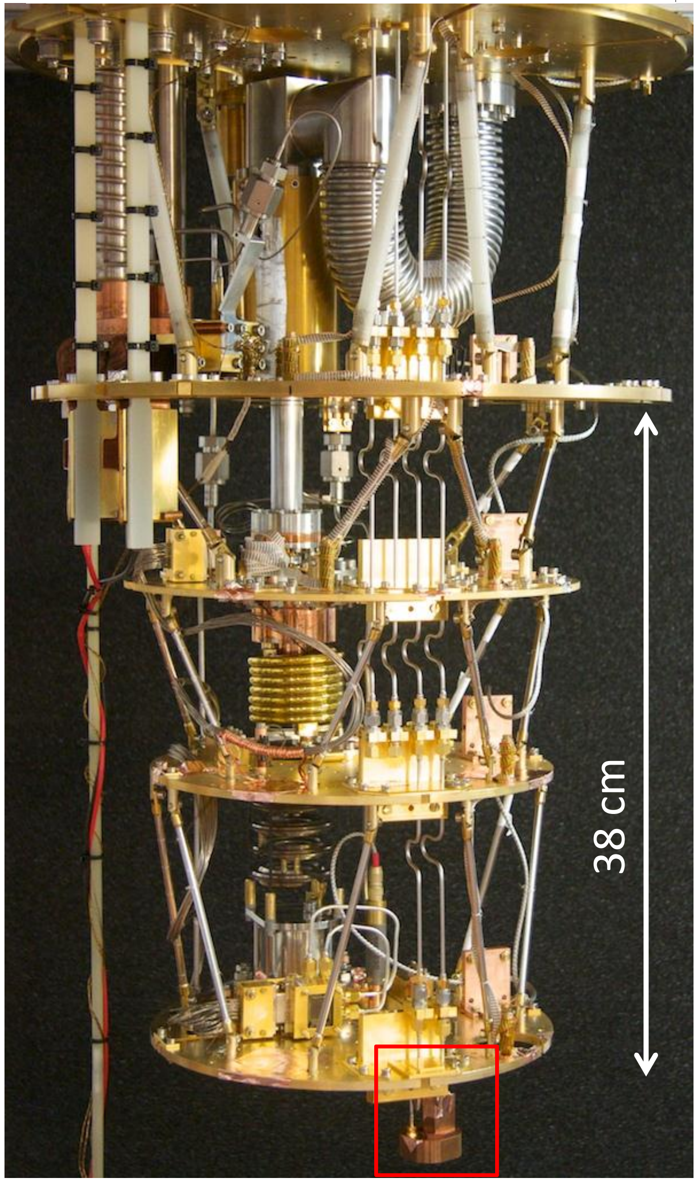
hybrid sample holder





~10 mK plate of cryostat

Pulse tube cooled cryostat



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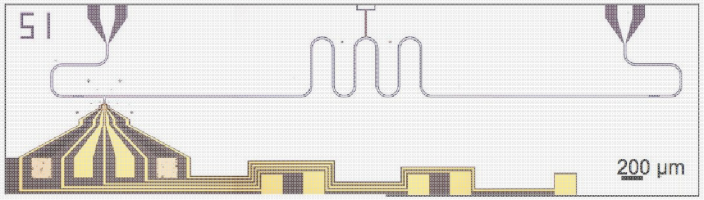

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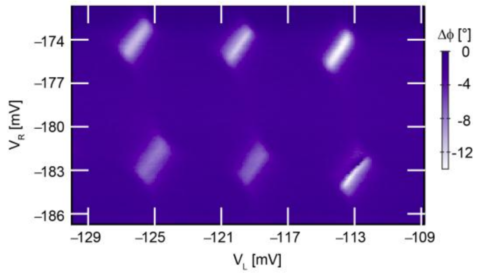

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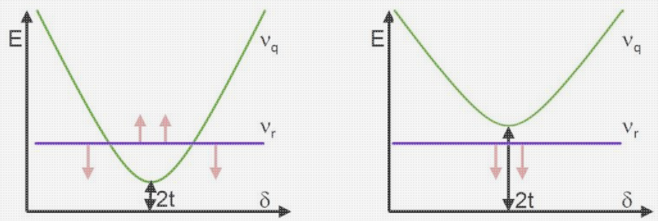
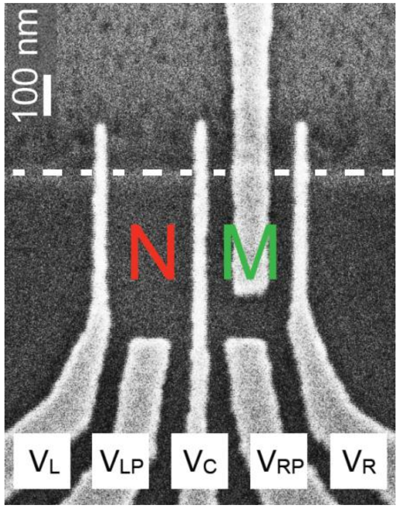
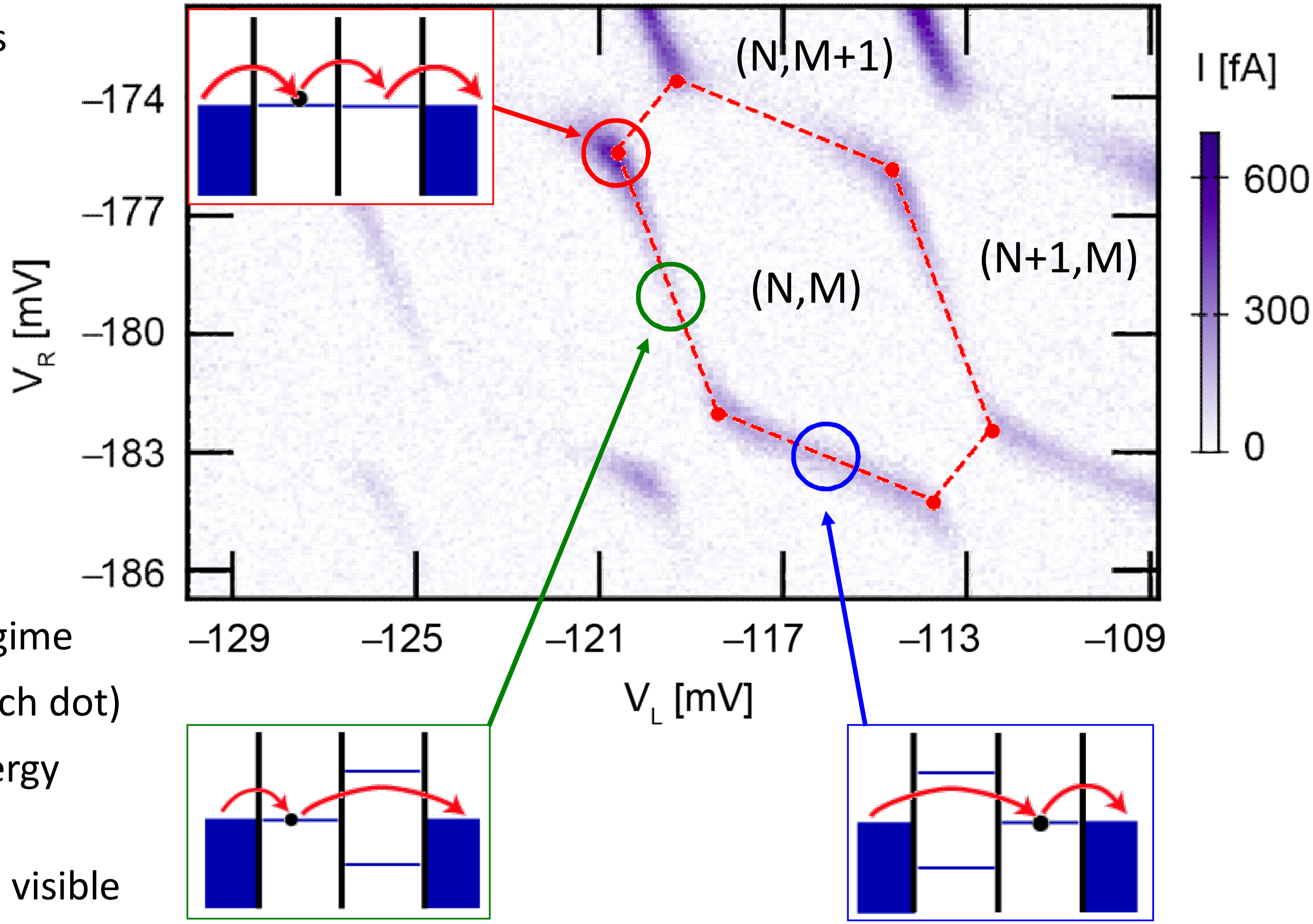


Double Dot Current and Resonator Transmission

Transport measurements:

Å Charging diagrams





Dot properties:

Å Many-electron regime

(~100 electrons in each dot)

Å large charging energy E_C~1meV

Å Co-tunneling lines visible

⇔ dot quite open

Å T_{el}~135mK

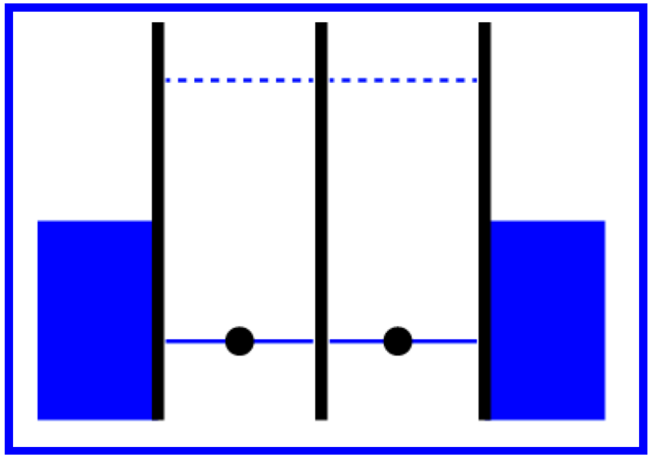
Double Dot Current and Resonator Transmission

Resonator transmission :

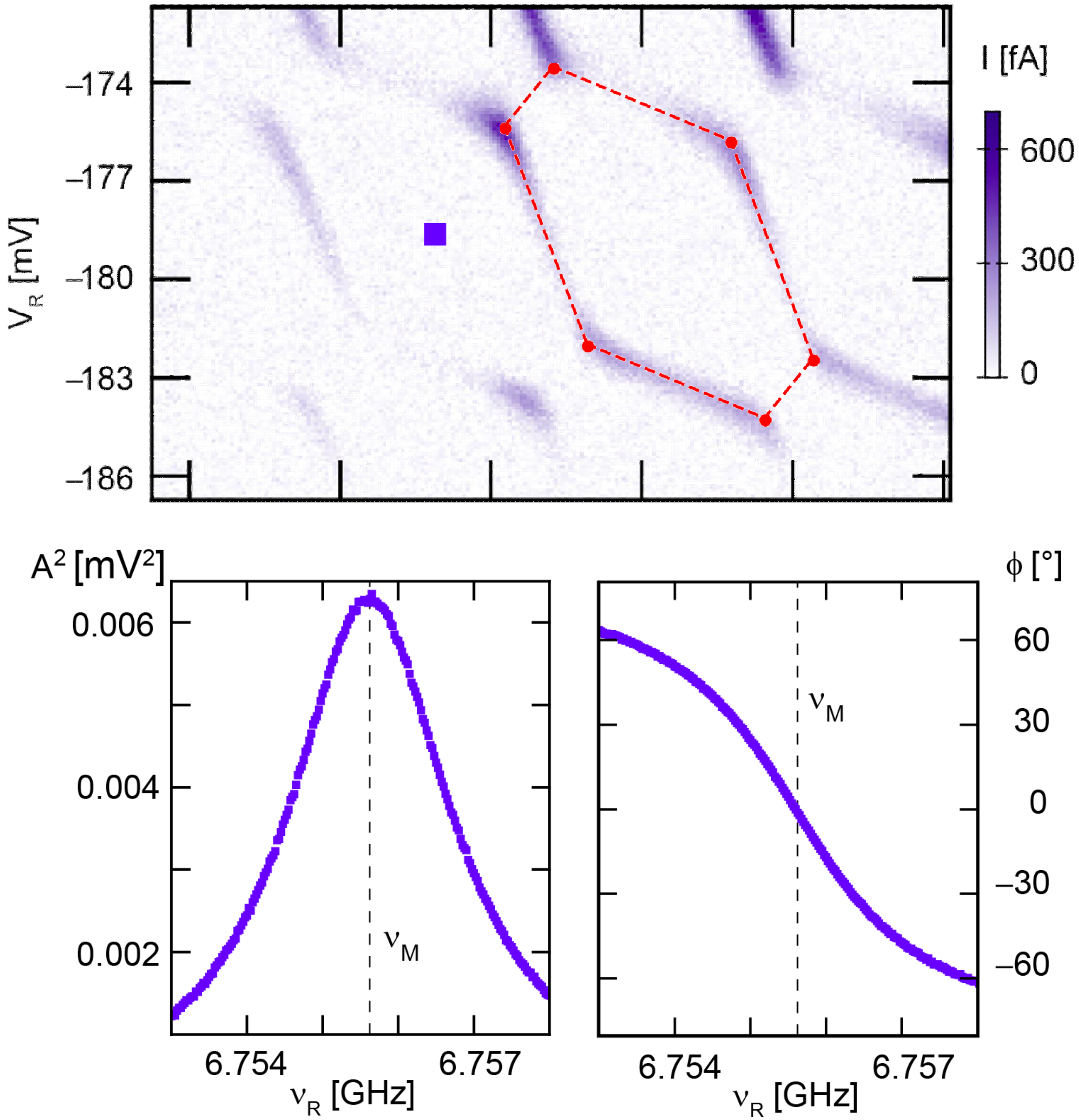
Å Amplitude A

Å Phase ϕ

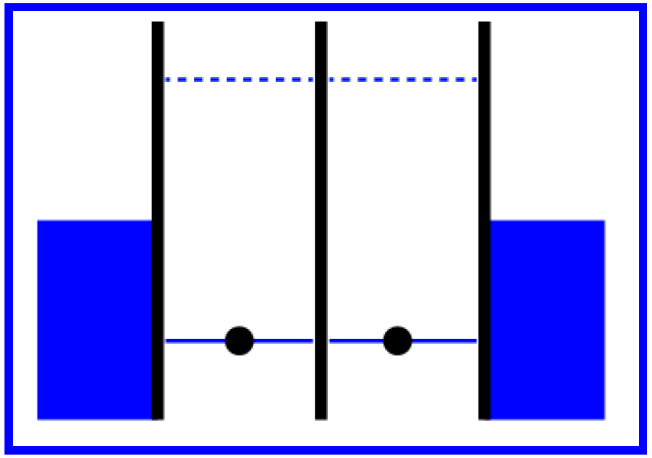
Å $Ae^{i\phi}=I+iQ$ measured into a heterodyne detection scheme.

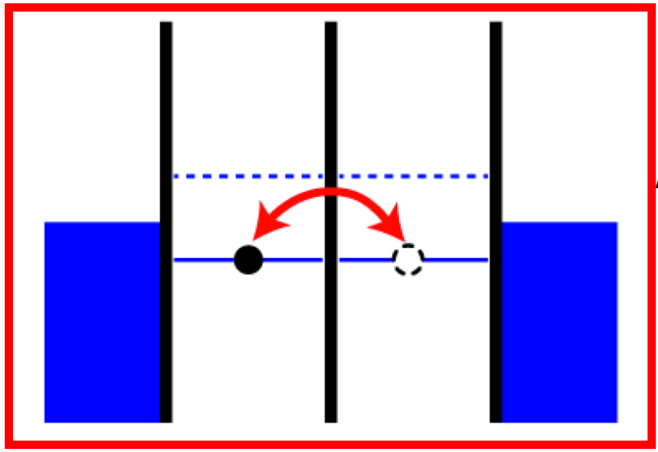


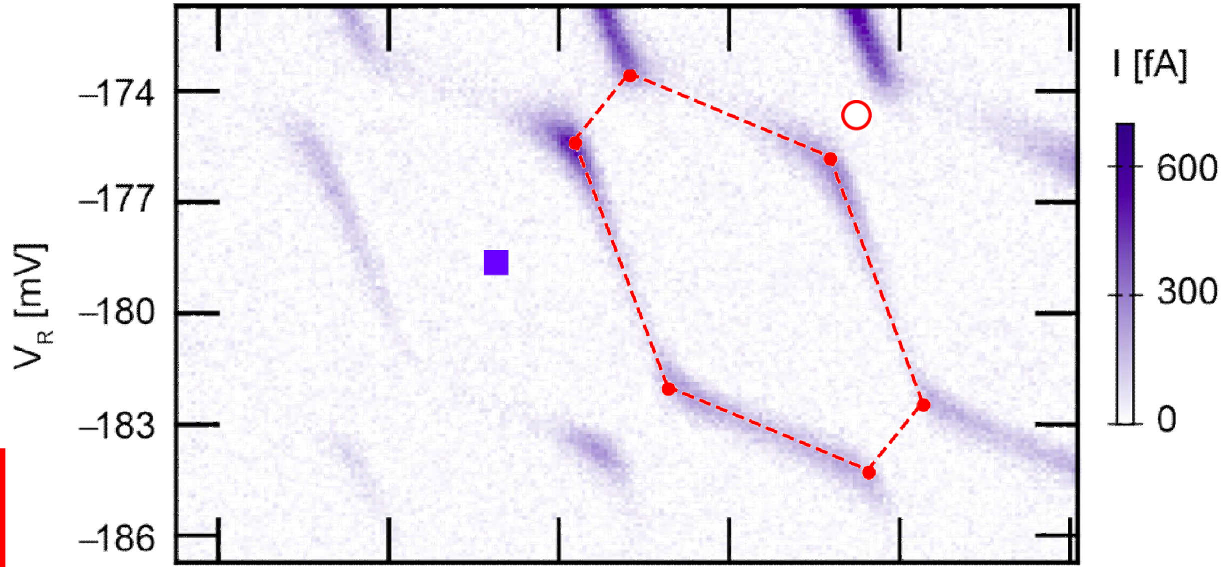
➔ Reference transmission spectra

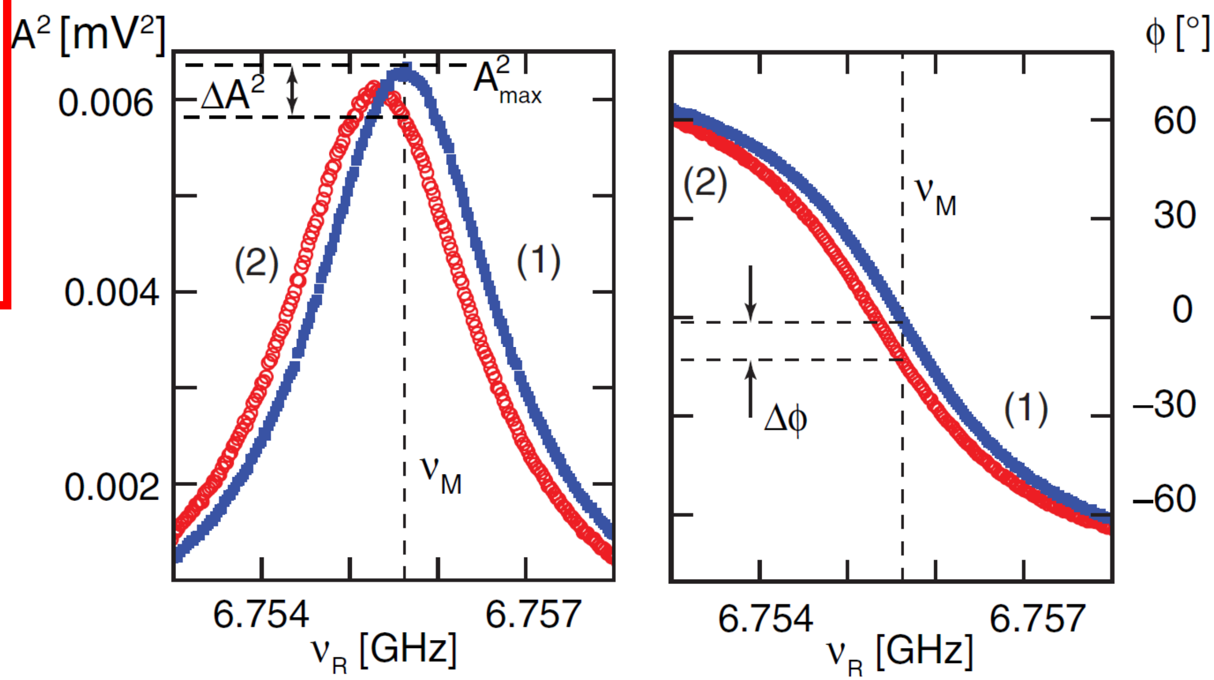


Double Dot Current and Resonator Transmission







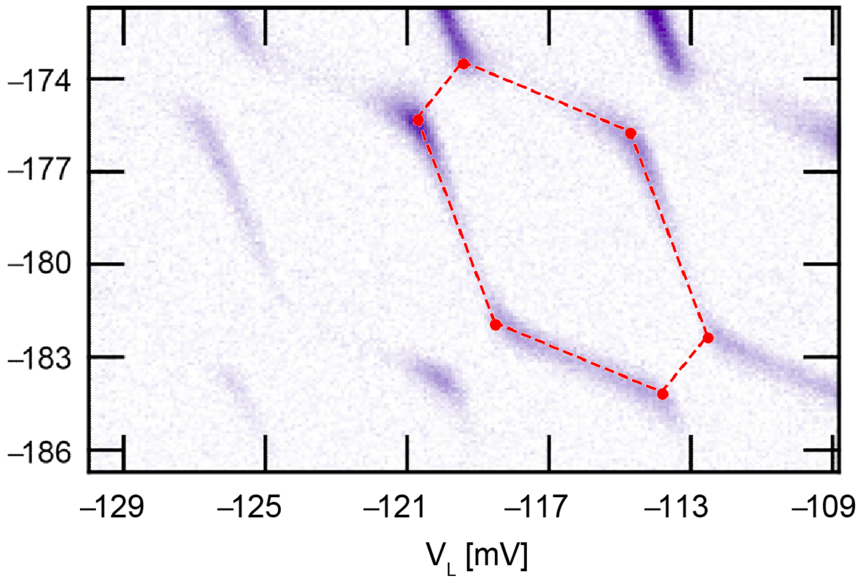


Resonator transmission

Å Measuring at a fixed frequency the amplitude and phase gives enough information

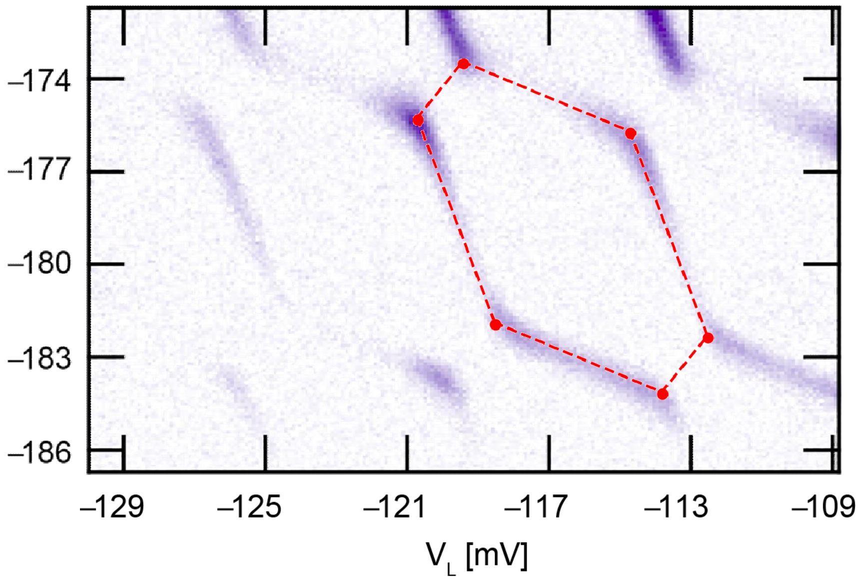
Stability diagrams in Current, Amplitude and Phase

DC current:

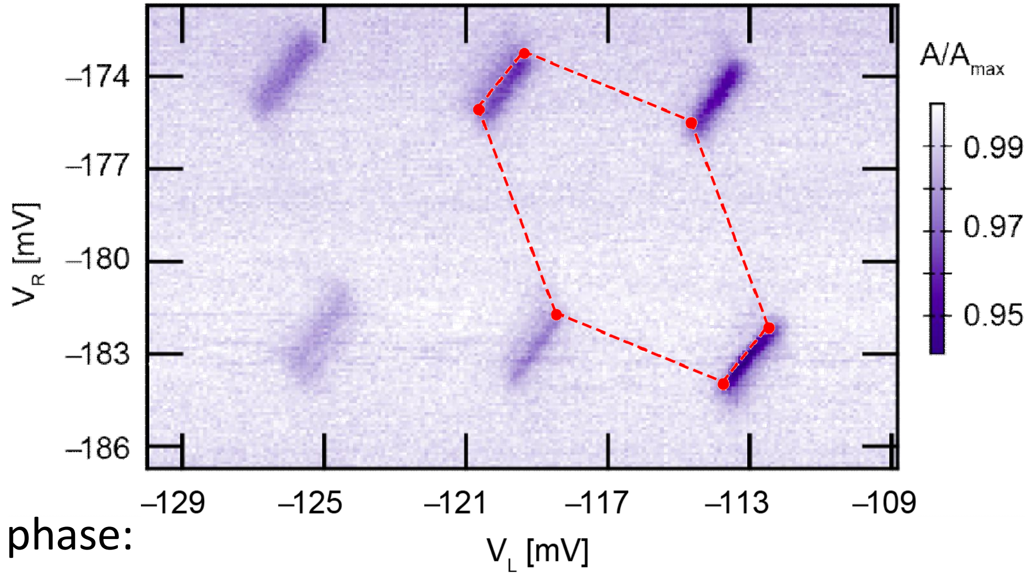


Stability diagrams in Current, Amplitude and Phase

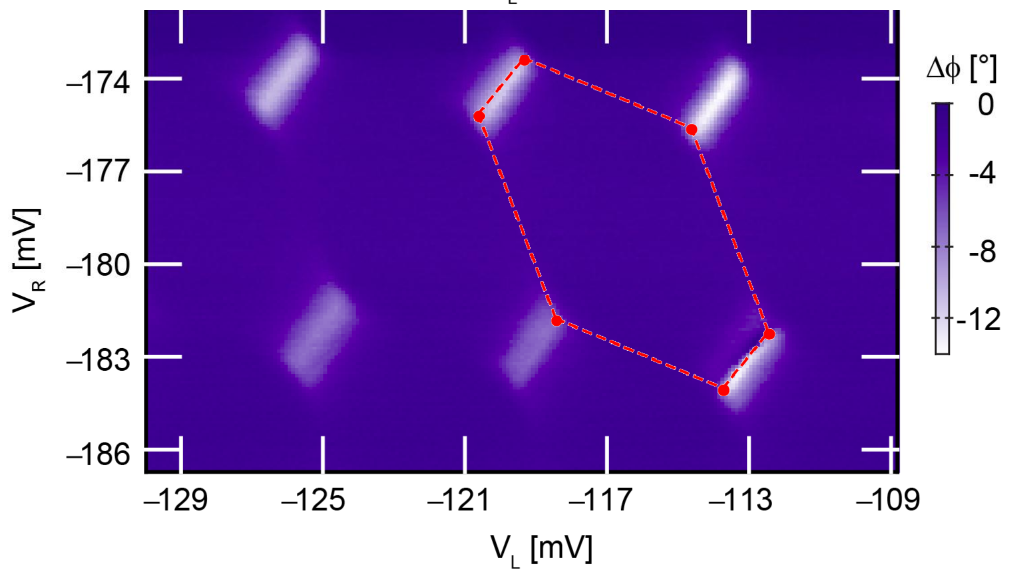
current:



amplitude:



phase:



Å systematic changes in transmission amplitude and phase

Å equivalent charging diagrams …

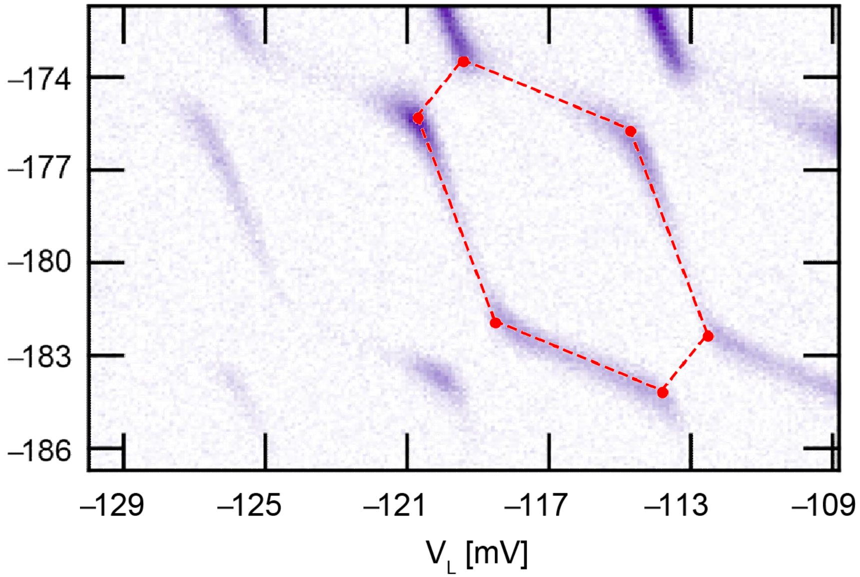
Å … but different physical signal origin

➔ Amplitude : loss through the DQD

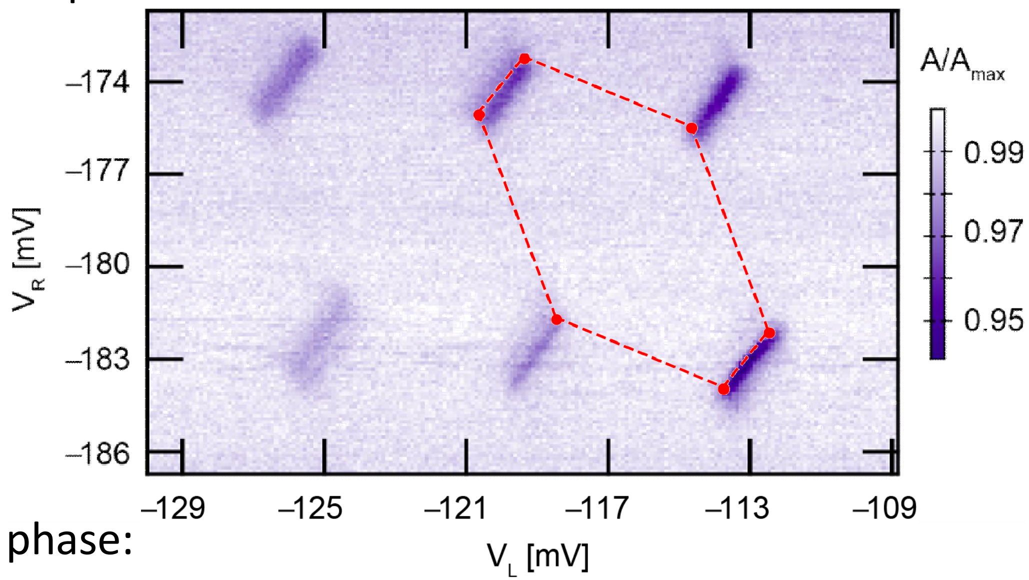
➔ Phase : Dispersive shift due to the DQD

Charging Diagrams in Current, Amplitude and Phase

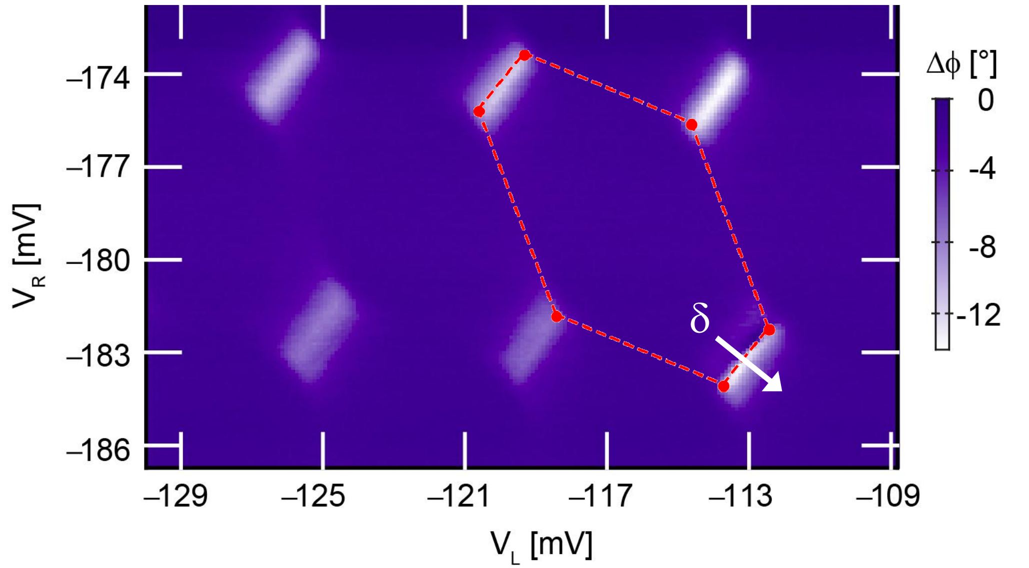
current:



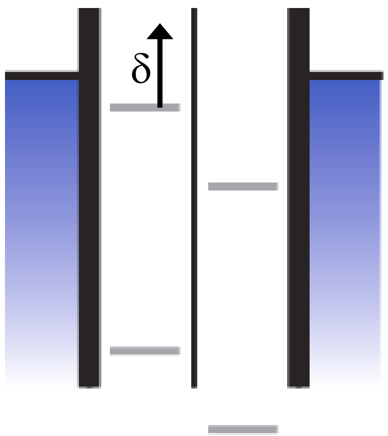
amplitude:



phase:

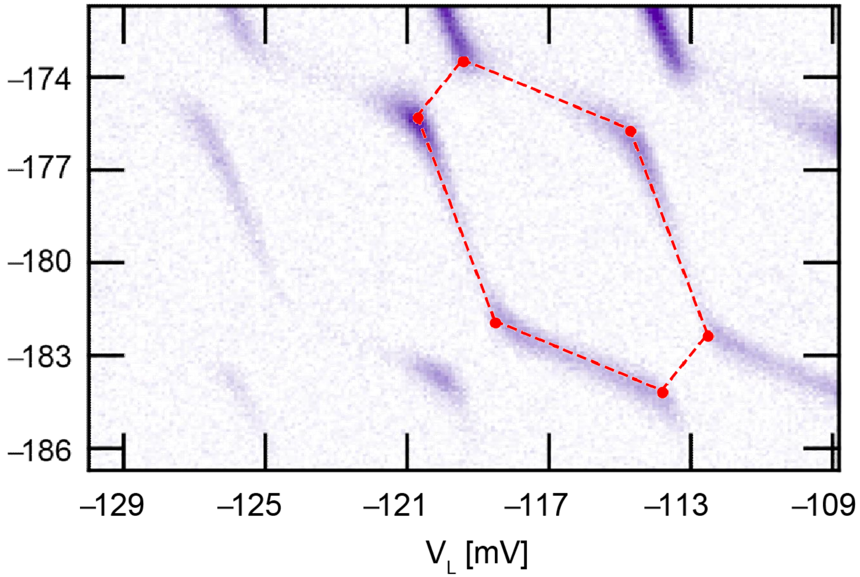


detuning δ:

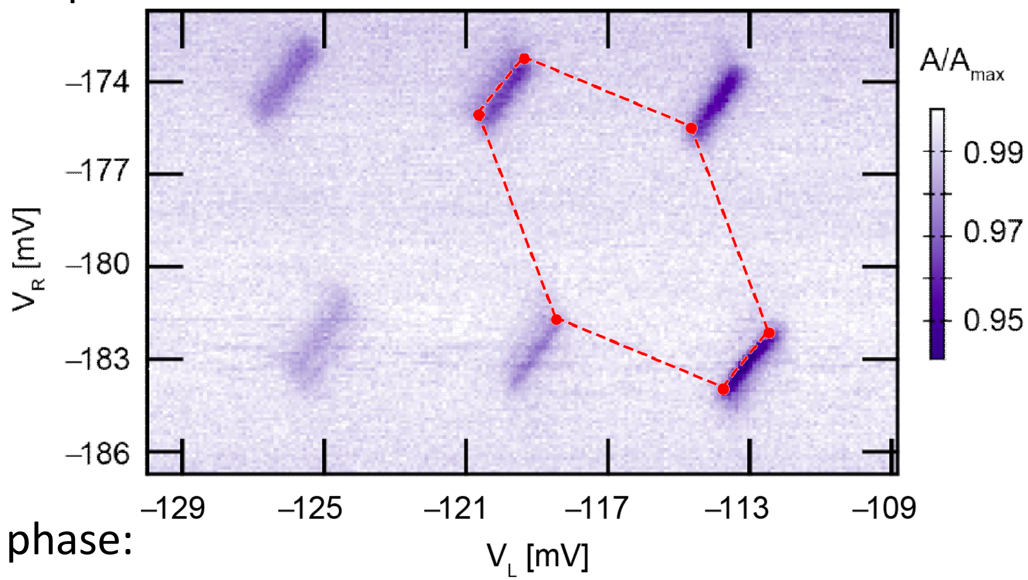


Charging Diagrams in Current, Amplitude and Phase

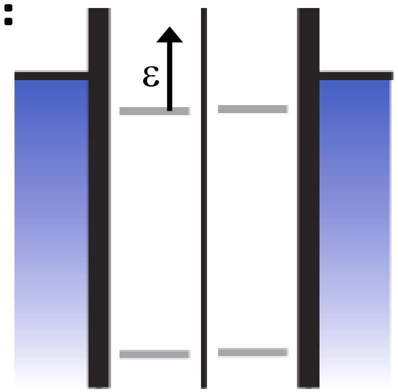
current:



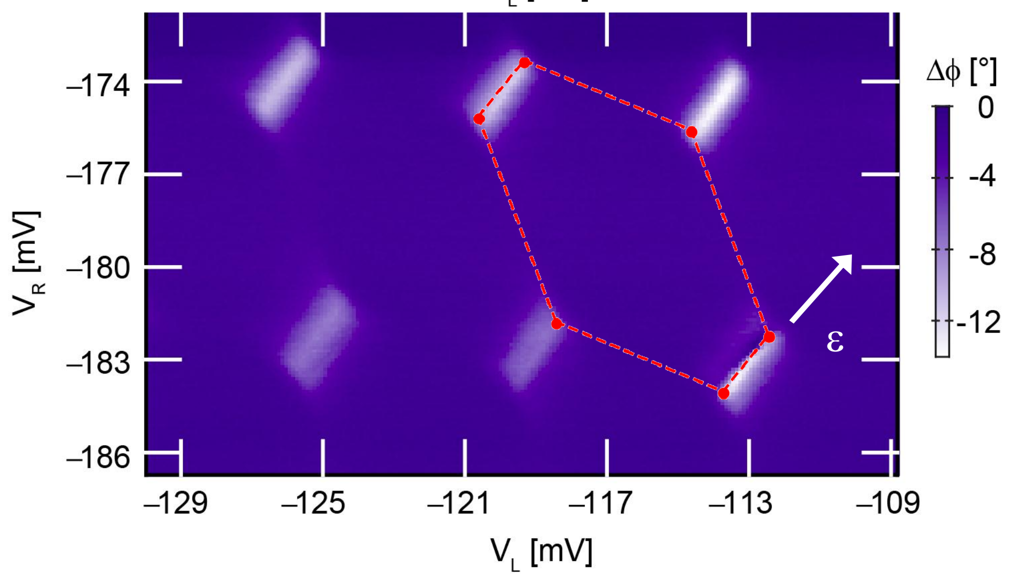
amplitude:



total energy ε:



phase:



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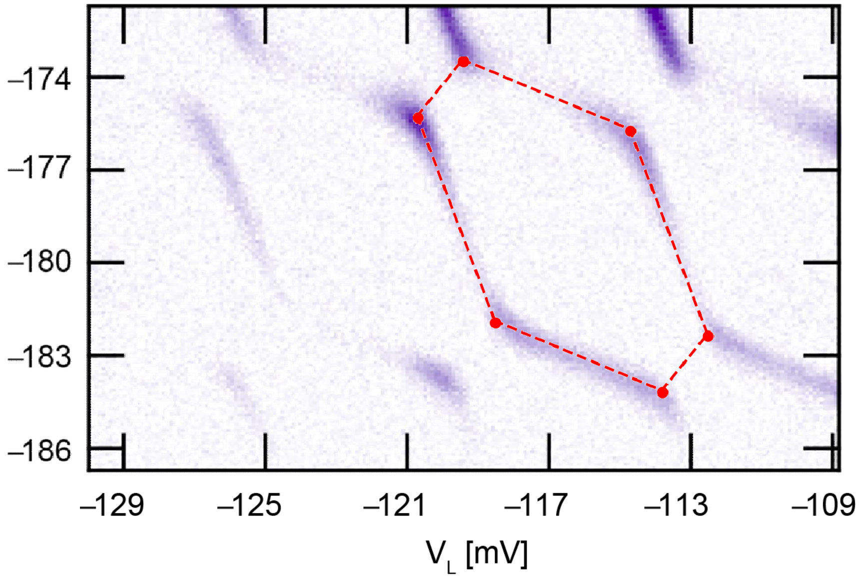
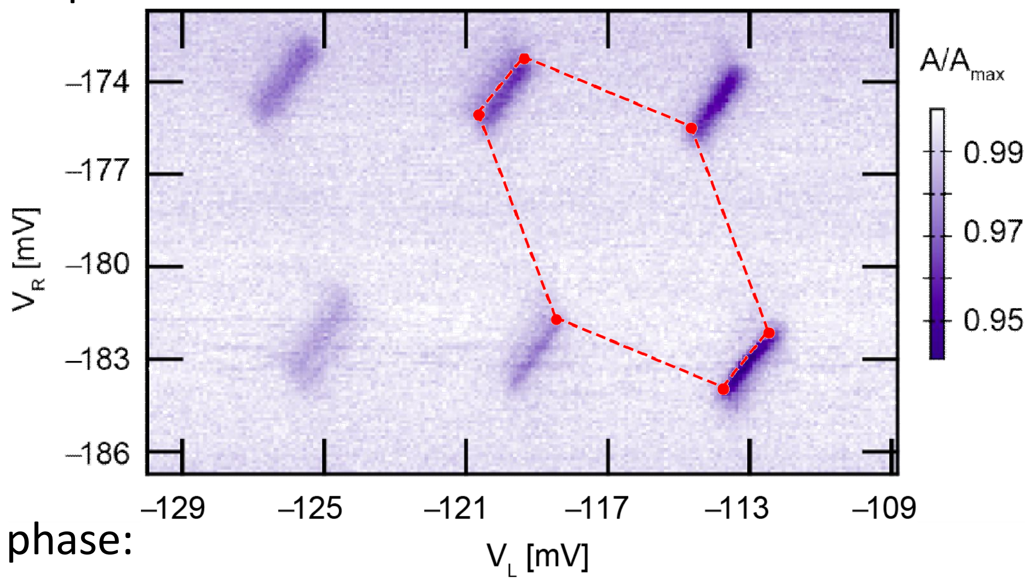
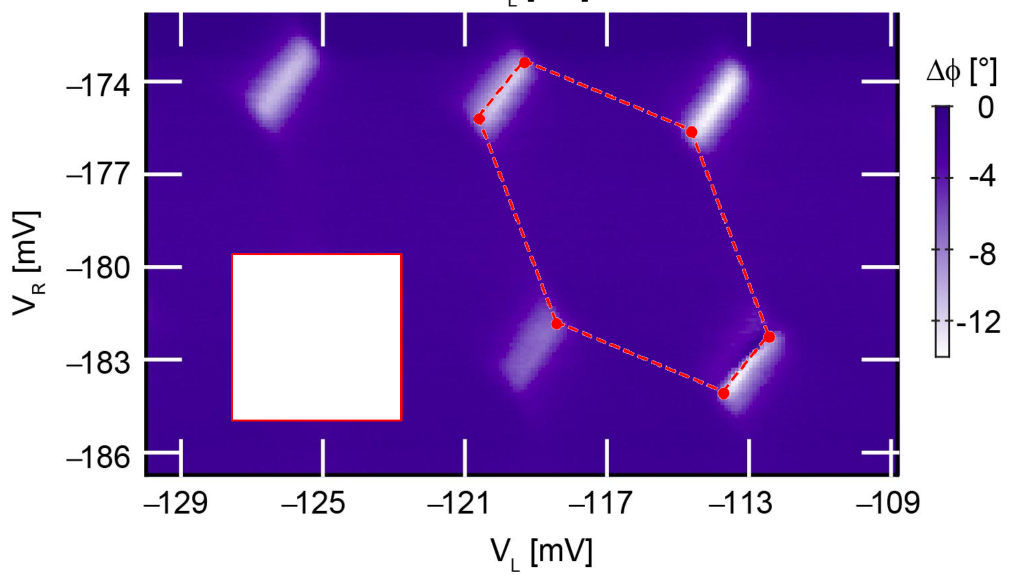
current:



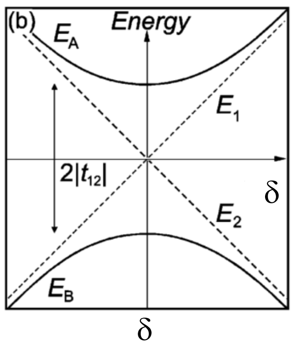
amplitude:

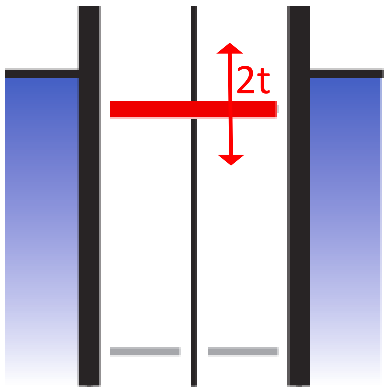


phase:



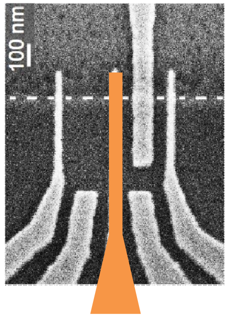
tunnel coupling t :





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

Resonator/Double-Dot Interaction
Center Gate Voltage (V_C) Influence



Tune t, with V_C

Resonator/Double-Dot Interaction
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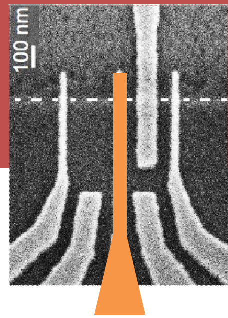
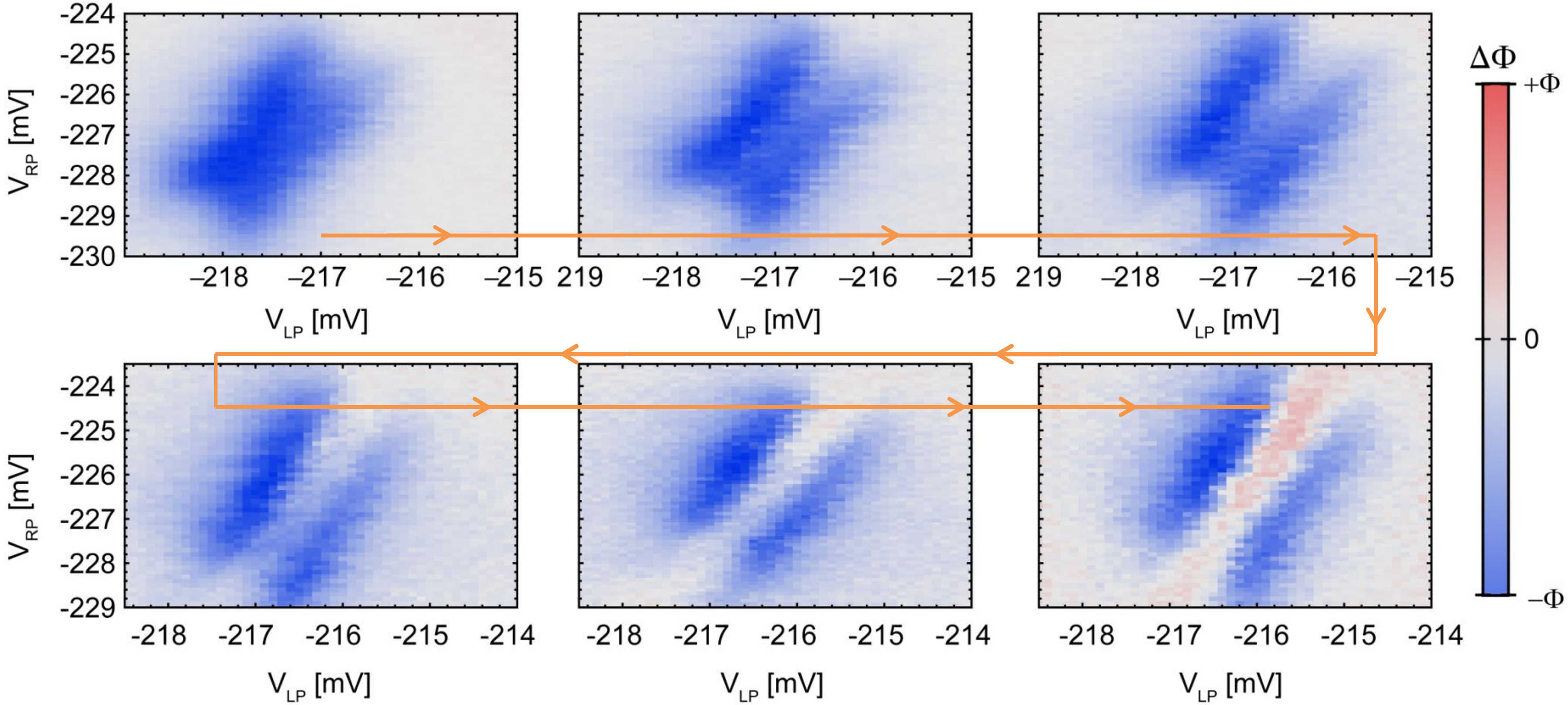


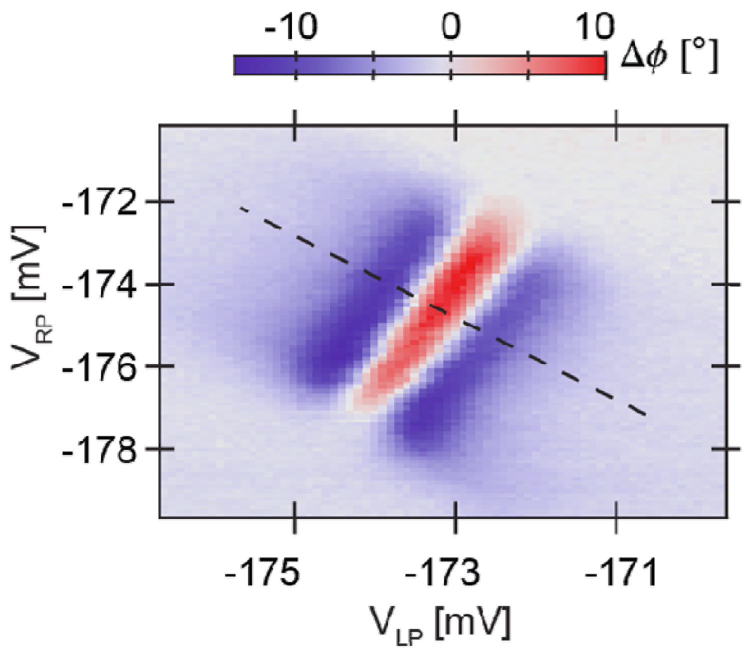
Tune t, with V_C

V_C more negative

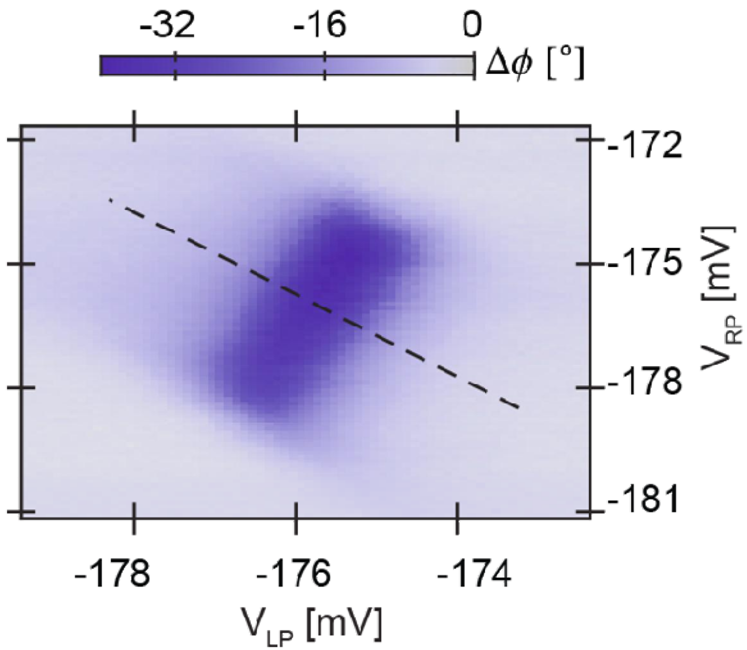


V_C more negative

Detailed Resonator/Double-Dot Interaction

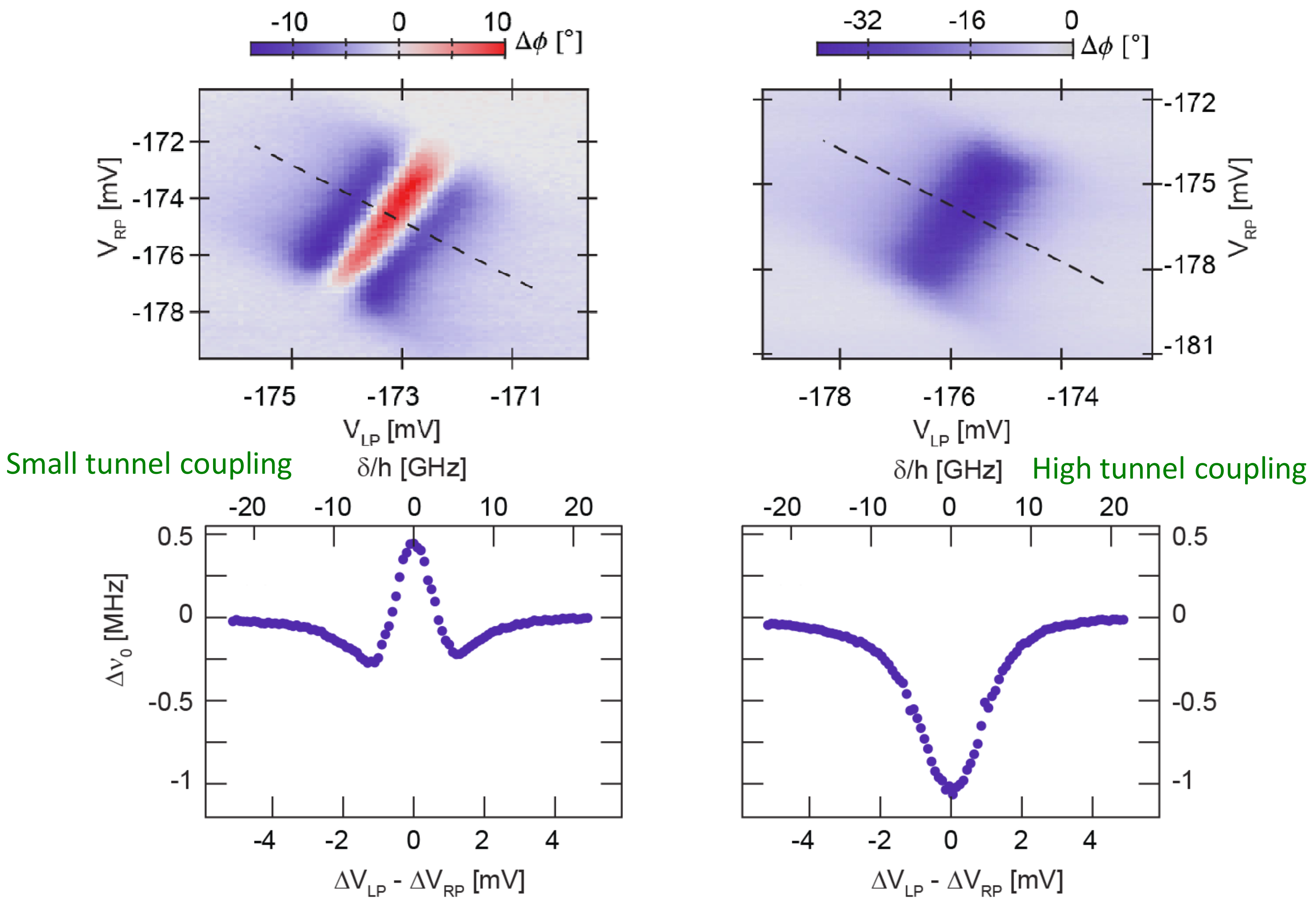


Small tunnel coupling



High tunnel coupling

Detailed Resonator/Double-Dot Interaction



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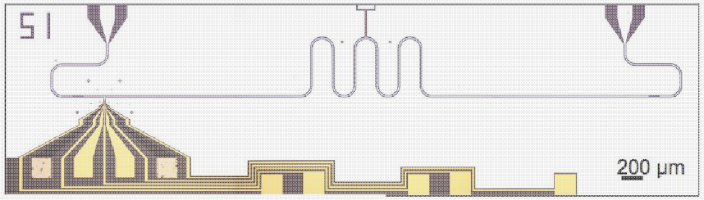

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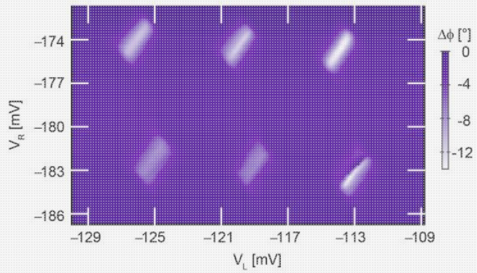

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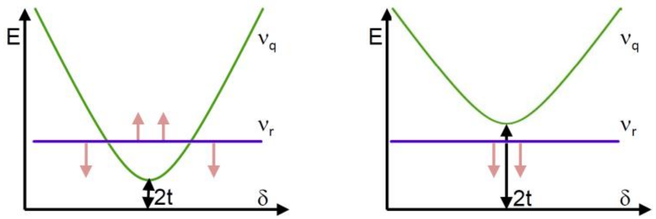
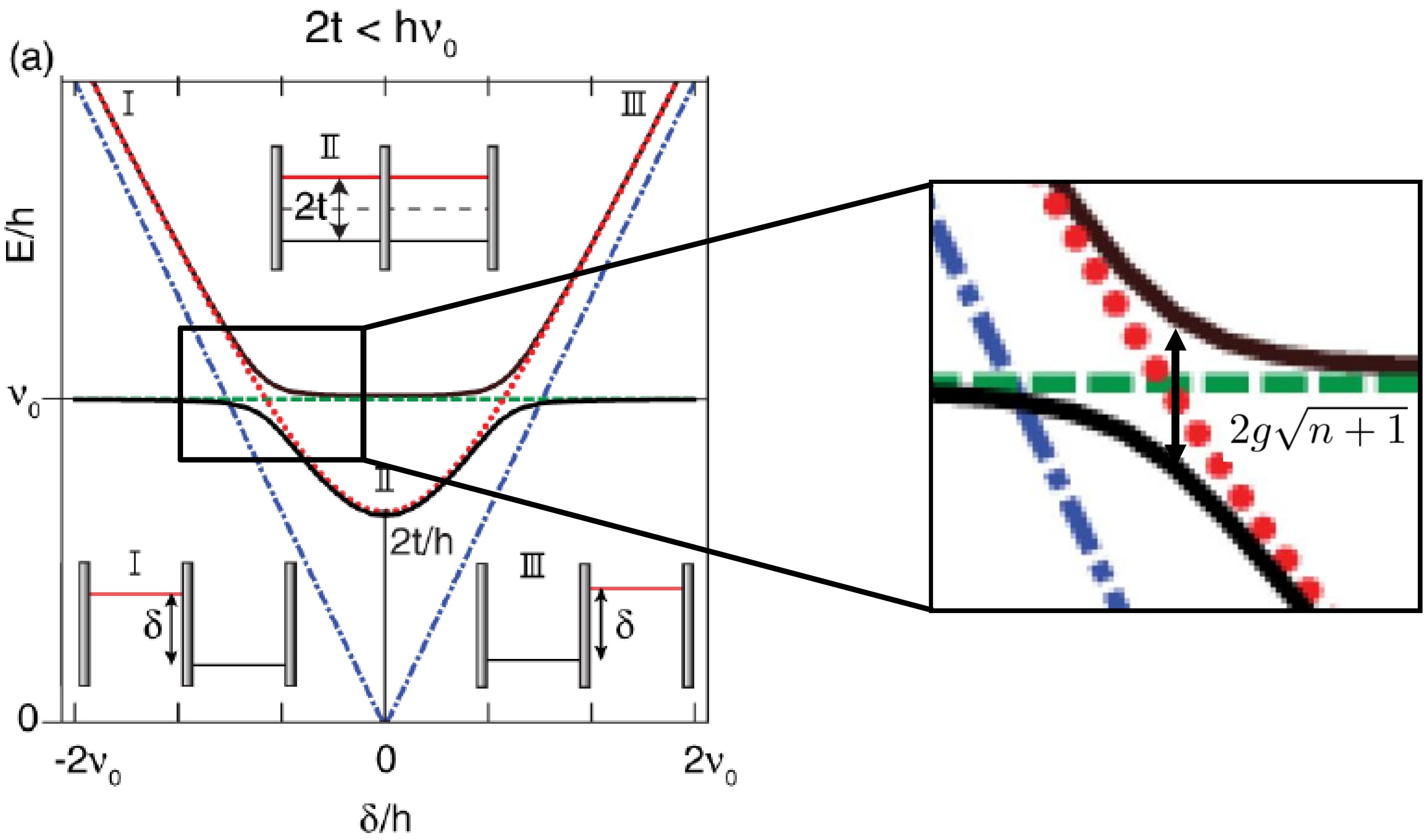


Jaynes-Cummings Hamiltonian modeling the dipolar interaction

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

$$\nu_q = \sqrt{\delta^2 + 4t^2} \qquad \sin\theta = 2t/\sqrt{\delta^2 + 4t^2}$$



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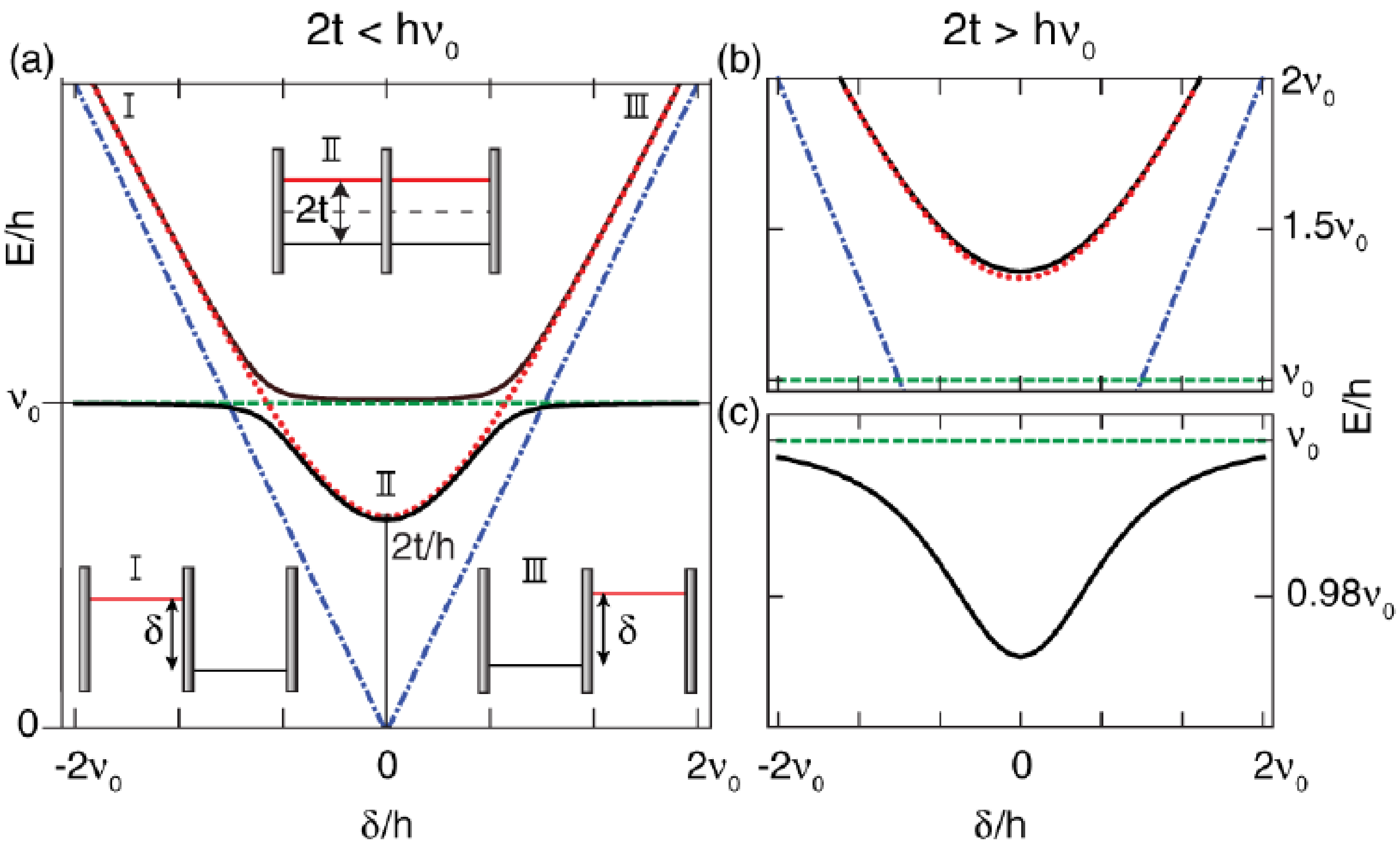

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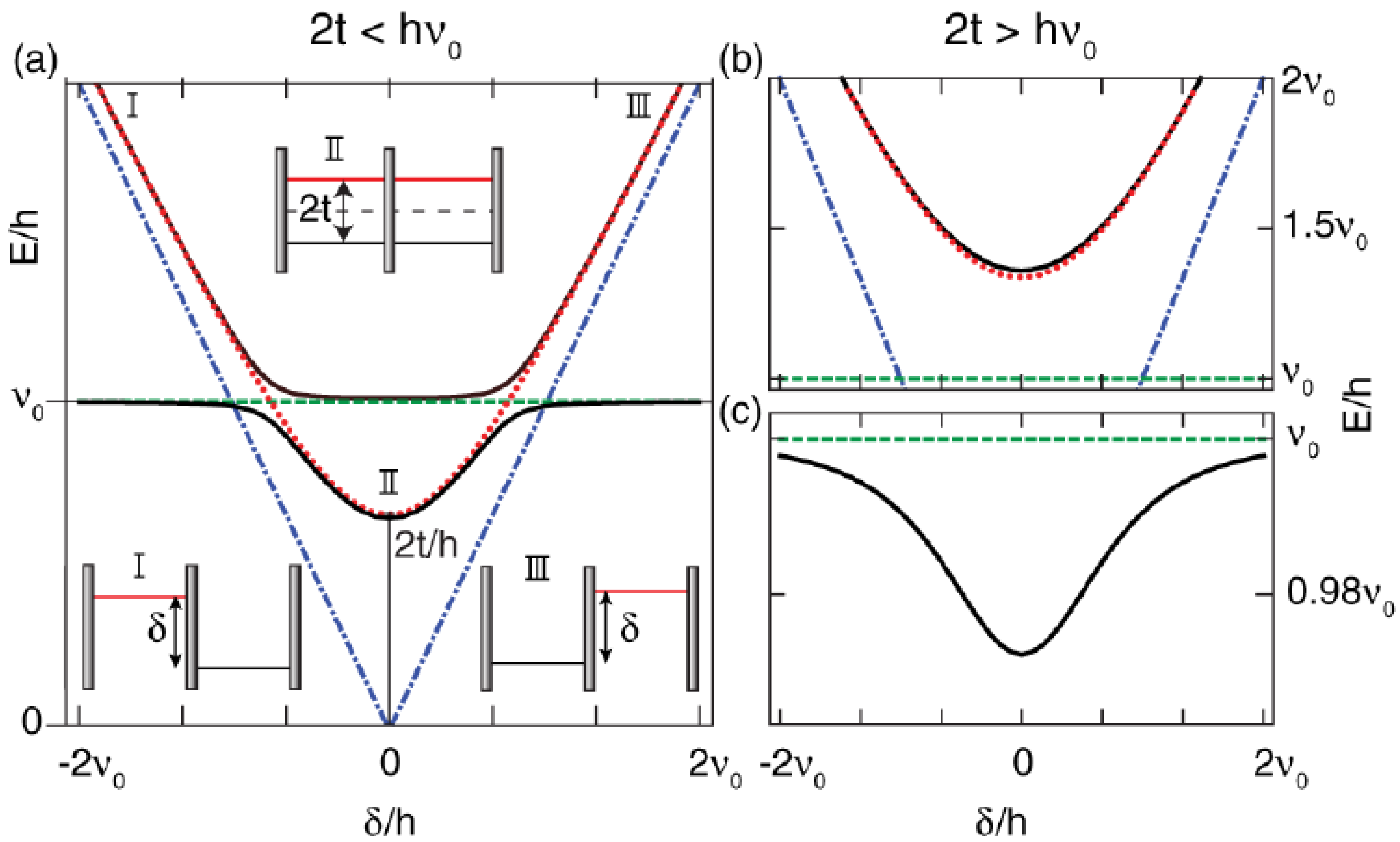


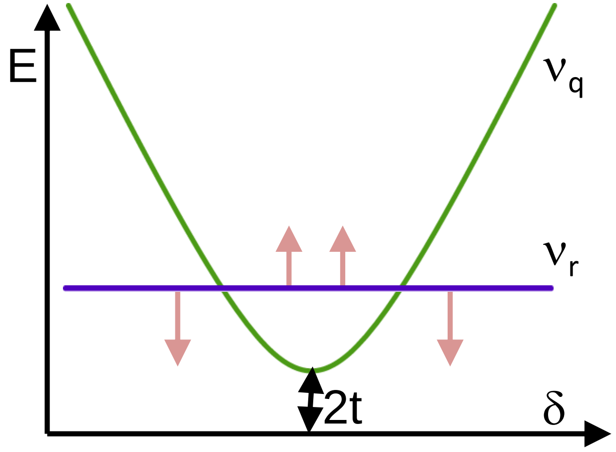
- To fit the experimental data:

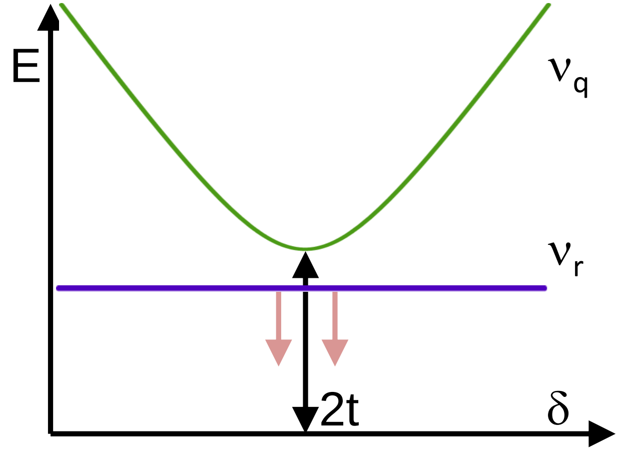
  Å Jaynes-Cummings Hamiltonian + q-bit relaxation + q-bit dephasing

  ➔ Markovian master equation approach (Alexandre Blais – Sherbrooke University)

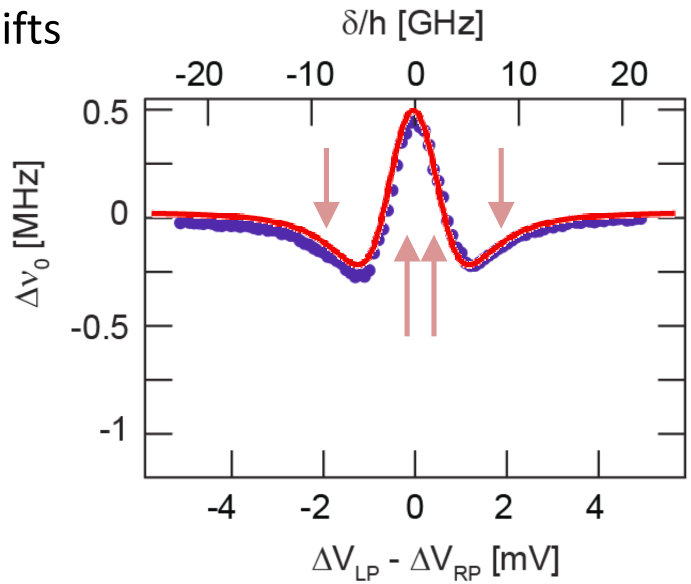
Non-Resonant Frequency Shifts

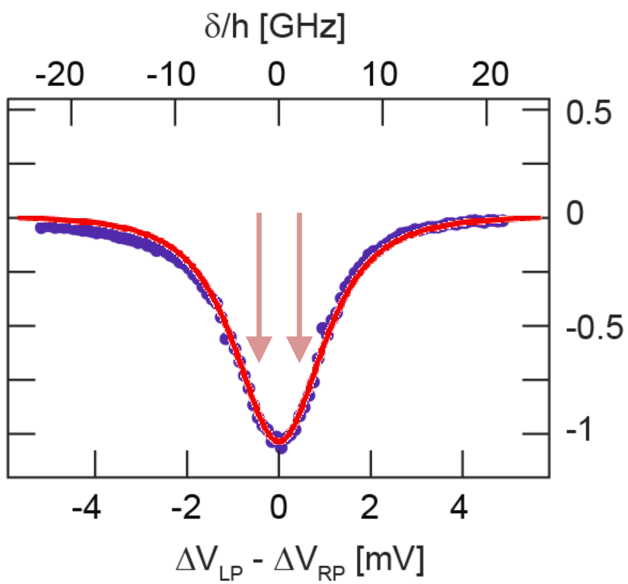
Energy diagrams





Frequency shifts





$\gamma_1/2\pi$=100MHz

Petta et al. PRL (2004)

$2t/h$=6.1GHz < ν_0	$2t/h$=9GHz > ν_0
$g/2\pi$=50MHz	$g/2\pi$=50MHz
$\gamma_\phi/2\pi$=3.3GHz	$\gamma_\phi/2\pi$=0.9GHz

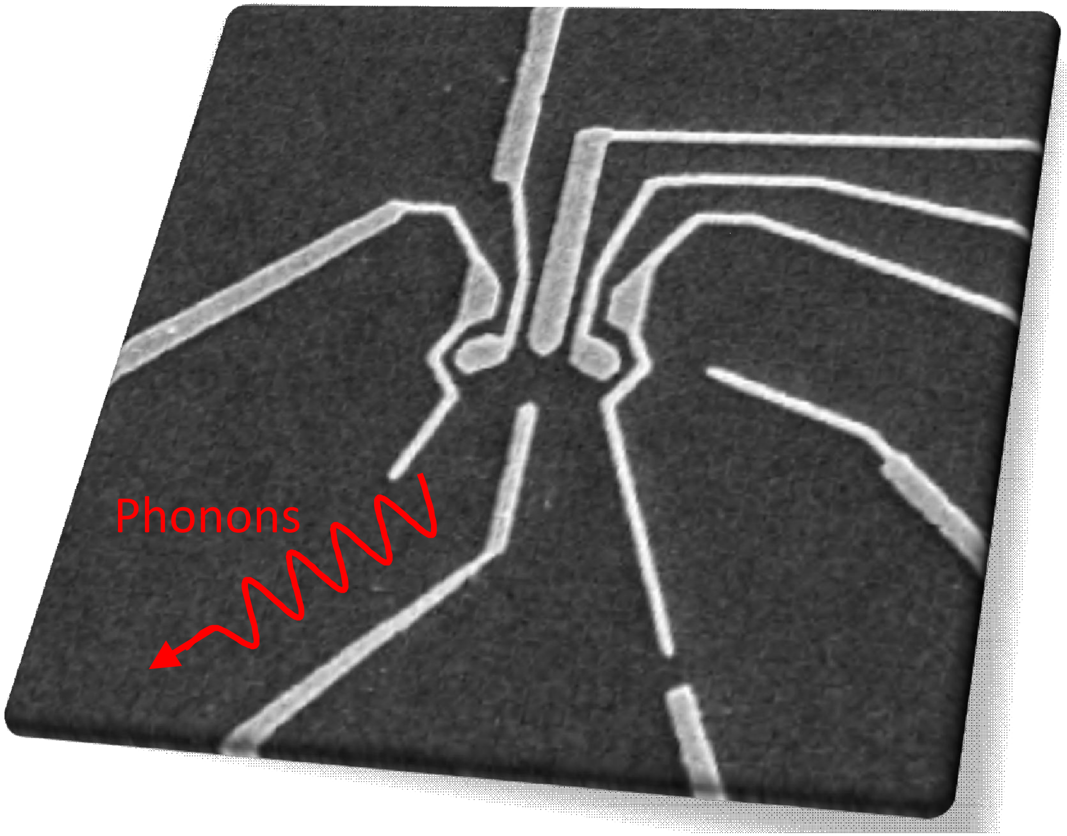
Possible sources of decoherence

- Phonon decoherence *Vorojtsov et al. PRB 71, 205322 (2005)*

  Å longitudinal piezoelectric phonons : maximum effect when 2t/h~s/a

  S : phonon velocity (~5.10^3m/s) ; a : dot size (~50nm); s/a ~100GHz >2t/h

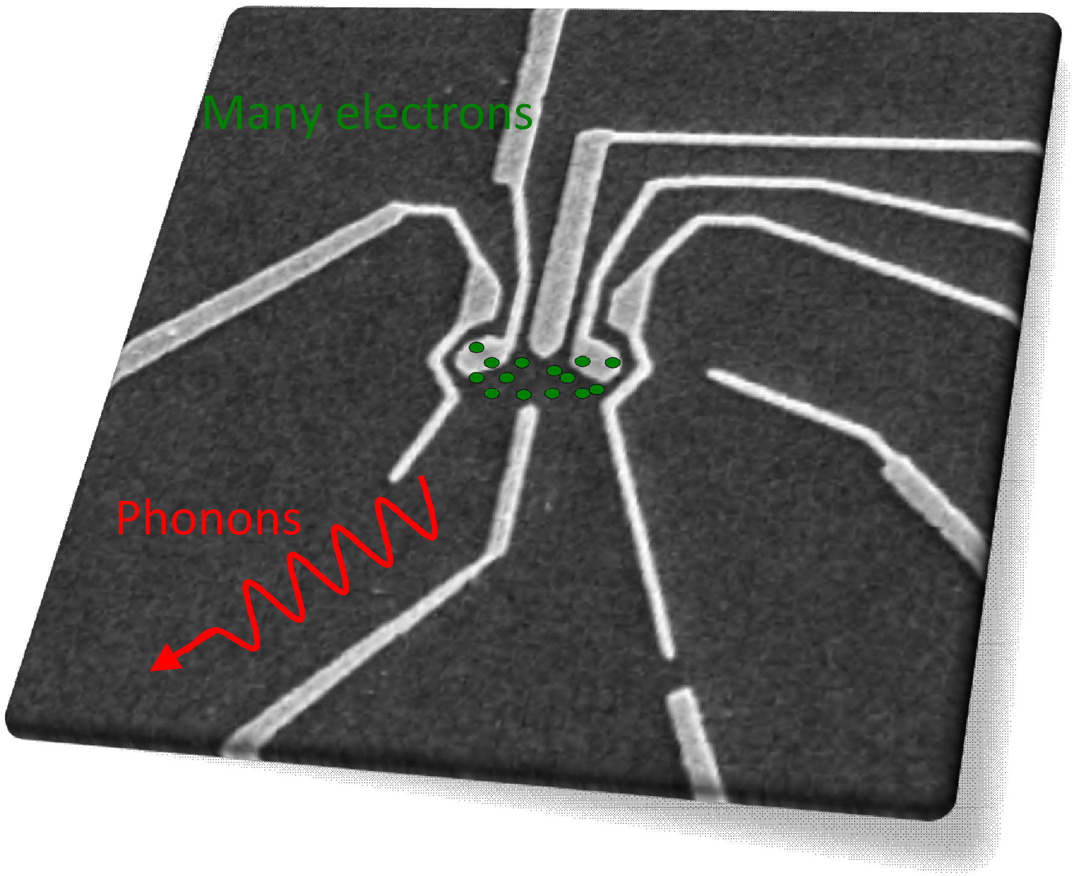
  Å Theory predicts 1 to 2 orders of magnitude smaller decoherence rate (10-100MHz) than observed in the experiment (GHz)



Possible sources of decoherence

- Excited states close in energy due to the large number of electrons and electronic temperature T=135mK

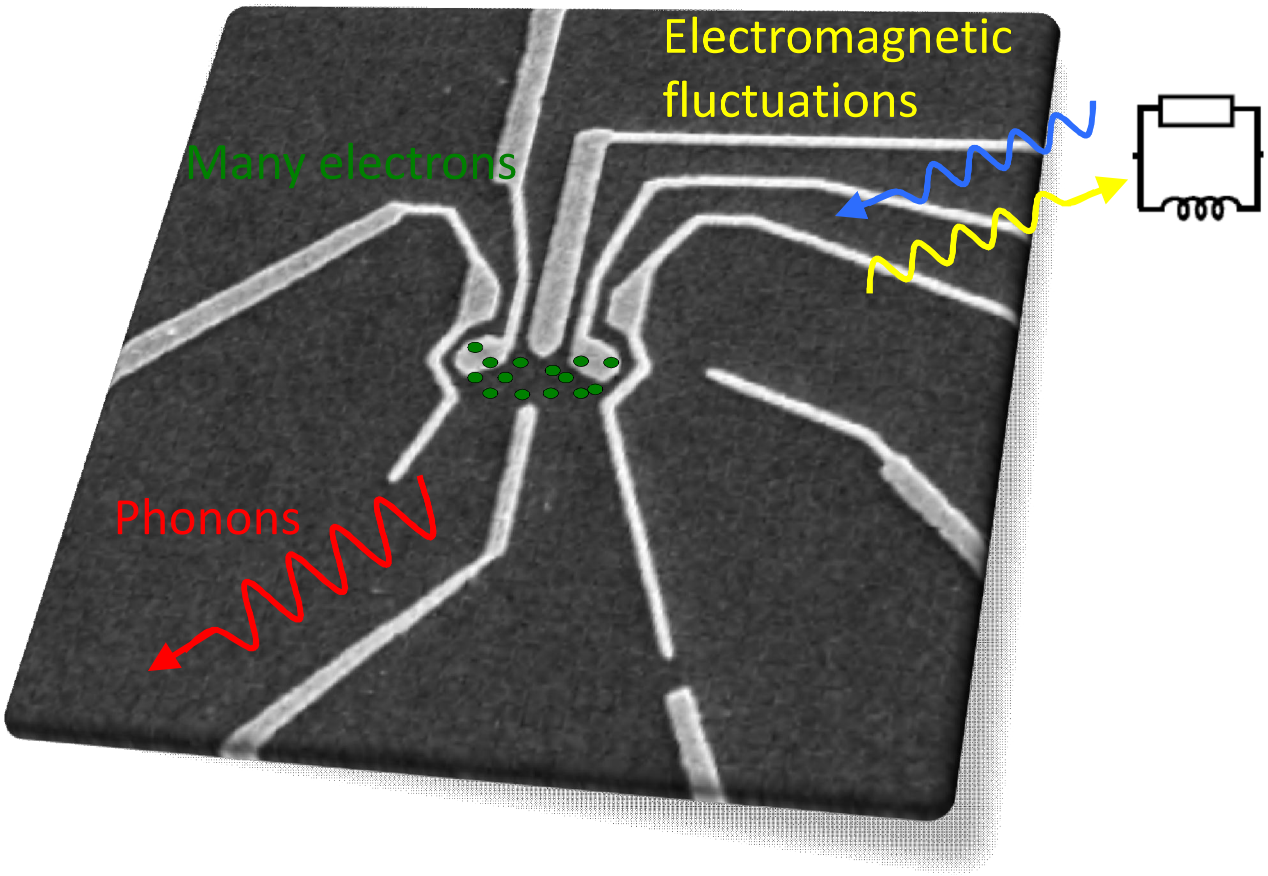
  Å *Petersson et al. PRL 105, 246804 (2010)* obtained a decoherence rate ~100MHz in the few electron regime



Possible sources of decoherence

- Decoherence by electromagnetic fluctuations Valente et al. PRB 82, 125302 (2010)

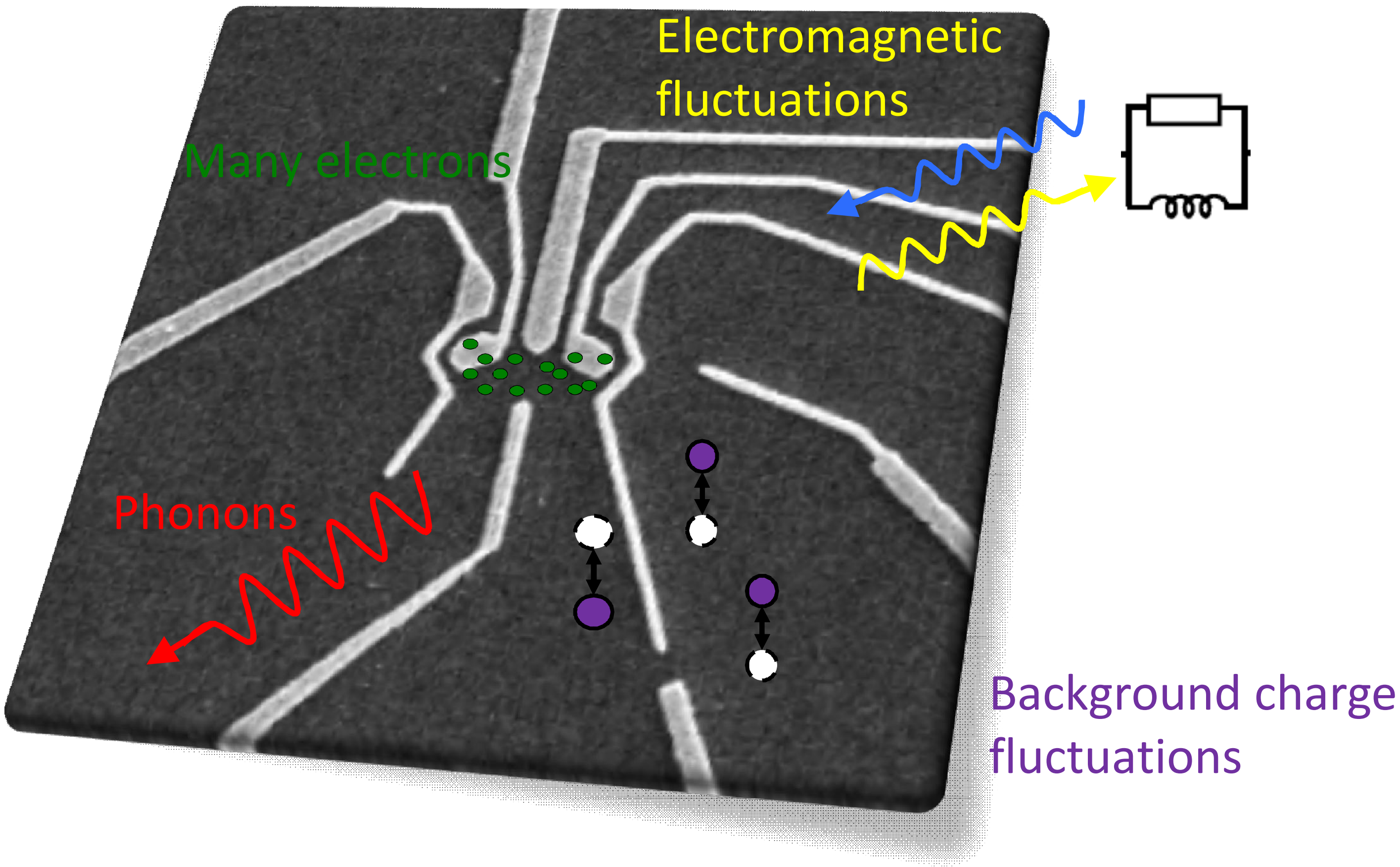
  Å Approximately 4 times less critical than phonons (~25MHz) ; can be reduced by decreasing the interdot charge coupling



Possible sources of decoherence

- Dephasing due to background charge fluctuations *Itakura et al. PRB 67, 195320 (2003), Abel et al.PRB 78, 201302 (2008), Yurkevich et al. PRB 81, 121305 (2010)*

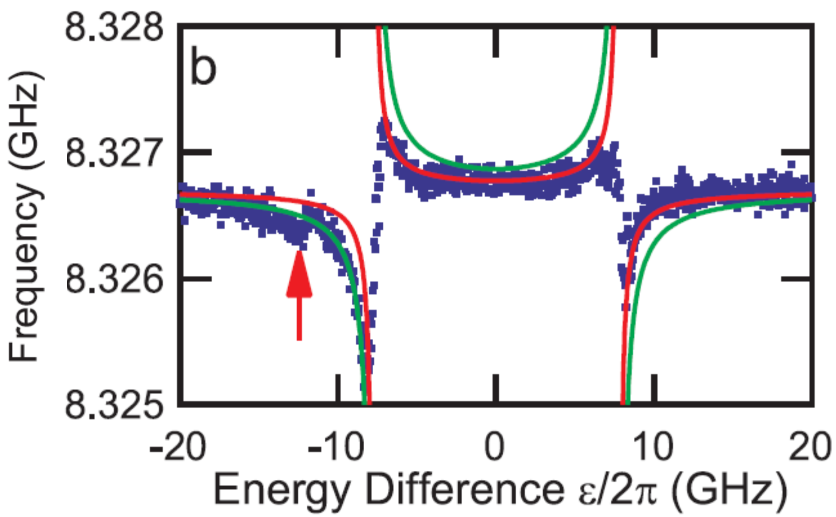
  Å Sample dependent decoherence that might be reduced from one wafer to the other (MHz to GHz)



A very timely experiment….

Toida et al. arXiv 2012 (Japan)

Same experiment with GaAs DQD

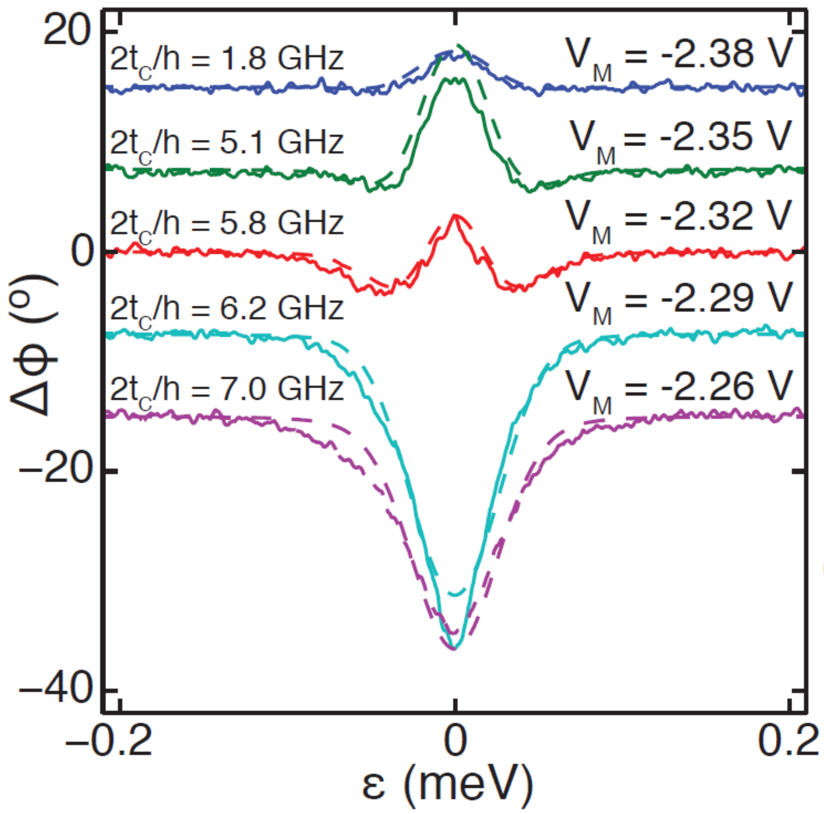


Longer relaxation and decoherence times without fundamental difference

➔ Wafer to wafer fluctuations

Petersson et al. arXiv 2012 (USA)

InAs nanowires



Roughly similar data

Possible improvements

Å Possible improvements:

- Emptying the double dot system down to the last electron

  ➔ $1/T_1$, $1/T_\varphi$ $\searrow$

- Increasing the lever arm of the gate coupled to the resonator
- Decrease the cross-talk between the resonator gate and the second dot

  ➔ g $\nearrow$

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Å Limitations :

- Imply the use of a purely gated system (no mesa edge)
  - ➔ 2DEG depth~95nm instead of 35nm ; g $\searrow$
  - ➔ Cross-talk increase; g $\searrow$
  - ➔ Confinement of the wave function enhanced; g $\searrow$

- Best ever decoherence rate (*Petersson et al. PRL 105, 246804 (2010)*) $1/T_\varphi$ = 1/10ns ⇔ 100MHz > g

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Conclusions:

➔ Issue on g increase is not clear yet

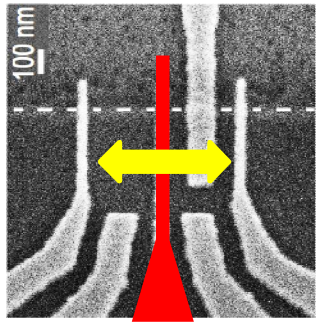
➔ The strong coupling regime seems difficult to reach with charge states even though calculations have shown that it may work

Natural perspectives, next steps :

➔ SPIN STATES due to their insensitivity to electric types of fluctuations

see *K.D. Petersson et al. arXiv 1205.6767 (2012) at Princeton*

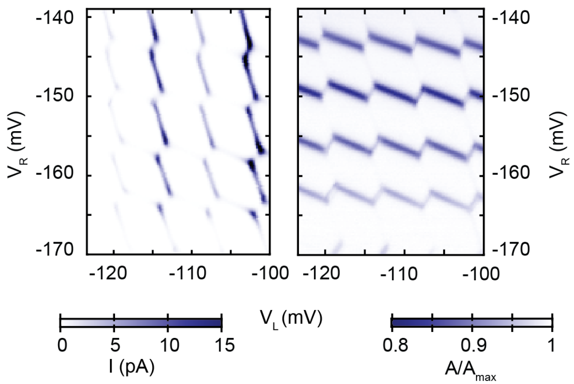
Conclusions and perspectives

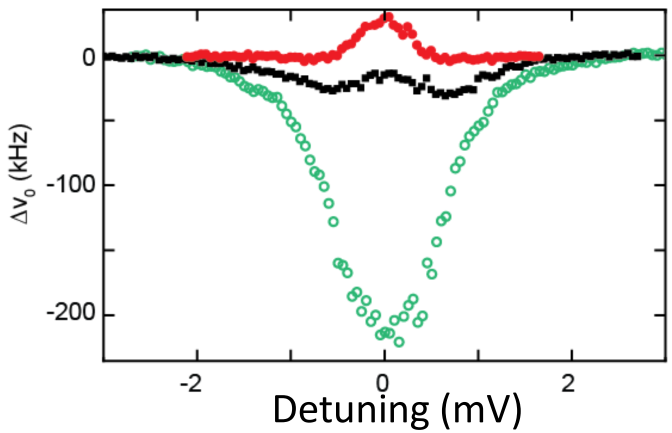


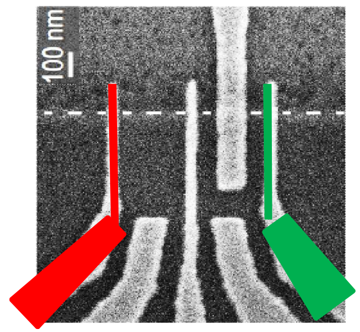
- Dipole coupling of a double quantum dot to a microwave resonator
  T. Frey, P. J. Leek, M. Beck, A. Blais, T. Ihn, K. Ensslin, A.Wallraff,
  PRL **108**, 046807 (2012)

Outlook

- Reach the single electron regime
- Explore limits of coherence
- Work towards coherent interface
- Evaluate potential to investigate spin physics
- Use resonator as a coupling bus in semiconductor-based QIP
- Quantum dot admittance probed at microwave frequencies with an on-chip resonator







T. Frey, P. J. Leek, M. Beck, J. Faist, M. Büttiker, A. Wallraff, K. Ensslin, T. Ihn PRB 86, 115303 (2012)