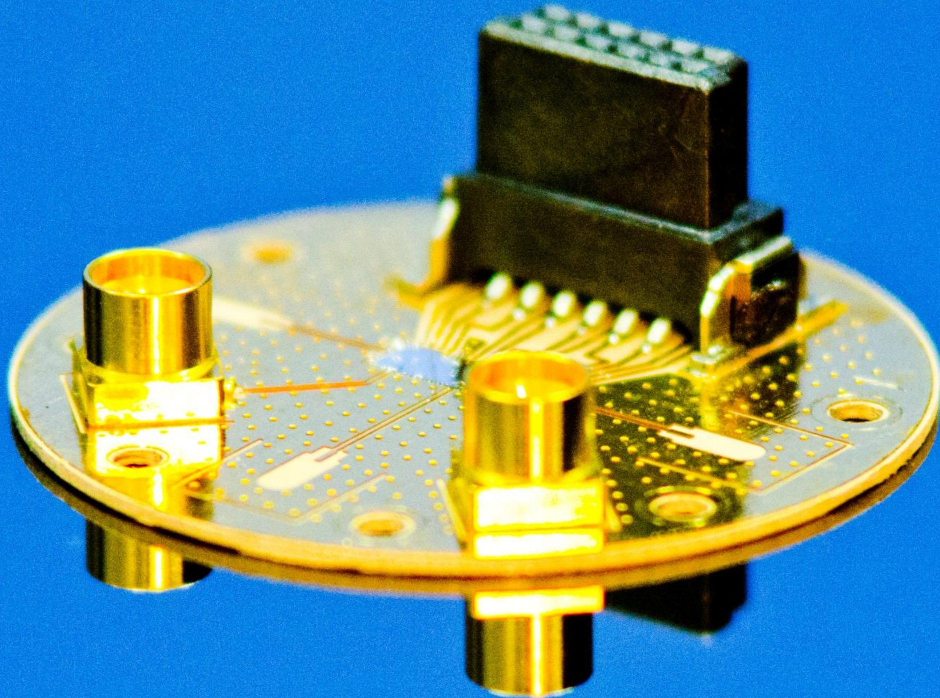
# Interaction between quantum dots and superconducting microwave resonators



Tobias Frey

Supervisors: P. J. Leek, T. Ihn, K. Ensslin, A. Wallraff

Collaborators: M. Beck, J. Faist, M. Büttiker, A. Blais

# Motivation

Interconnect the worlds of semiconductor and superconductor based quantum circuits

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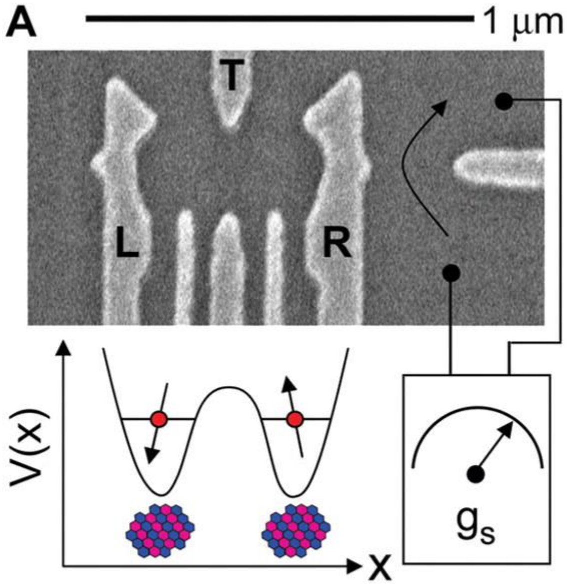
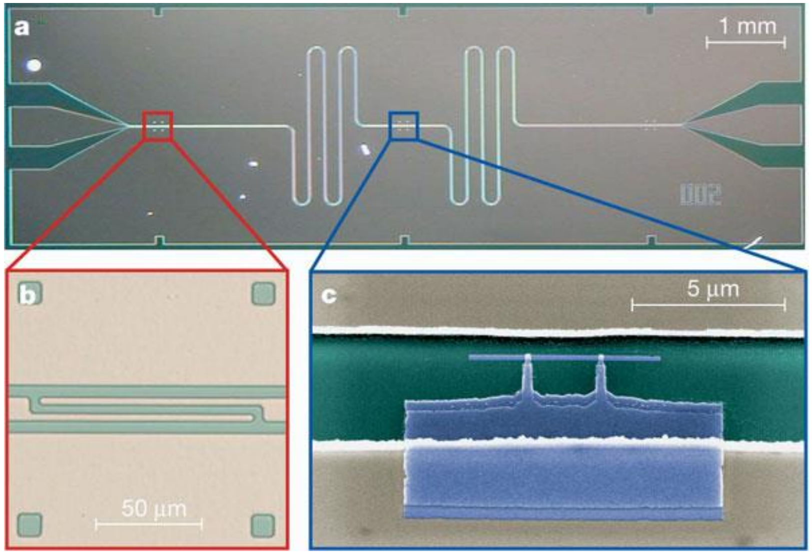
Spin qubits in quantum dots




Petta et al., Science (2005)

+

Circuit quantum electrodynamics




Wallraff et al., Nature (2004)

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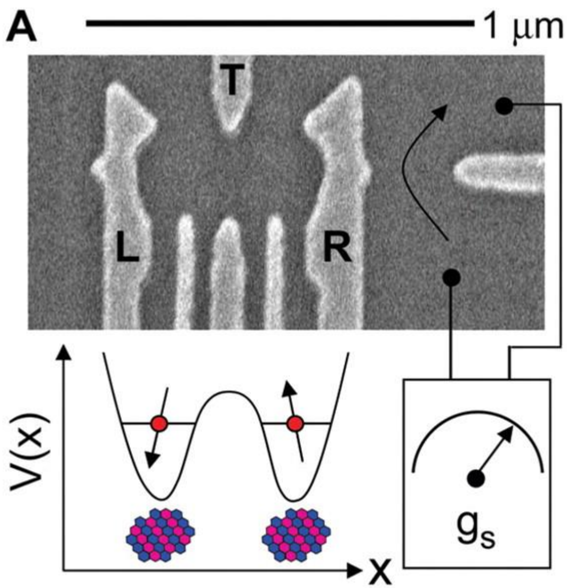
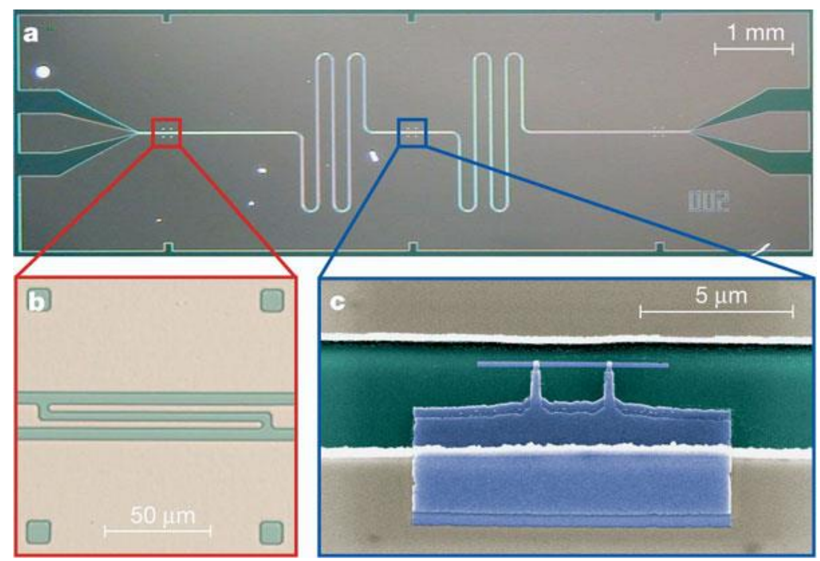
## Spin qubits in quantum dots




Petta et al., Science (2005)

+

## Circuit quantum electrodynamics

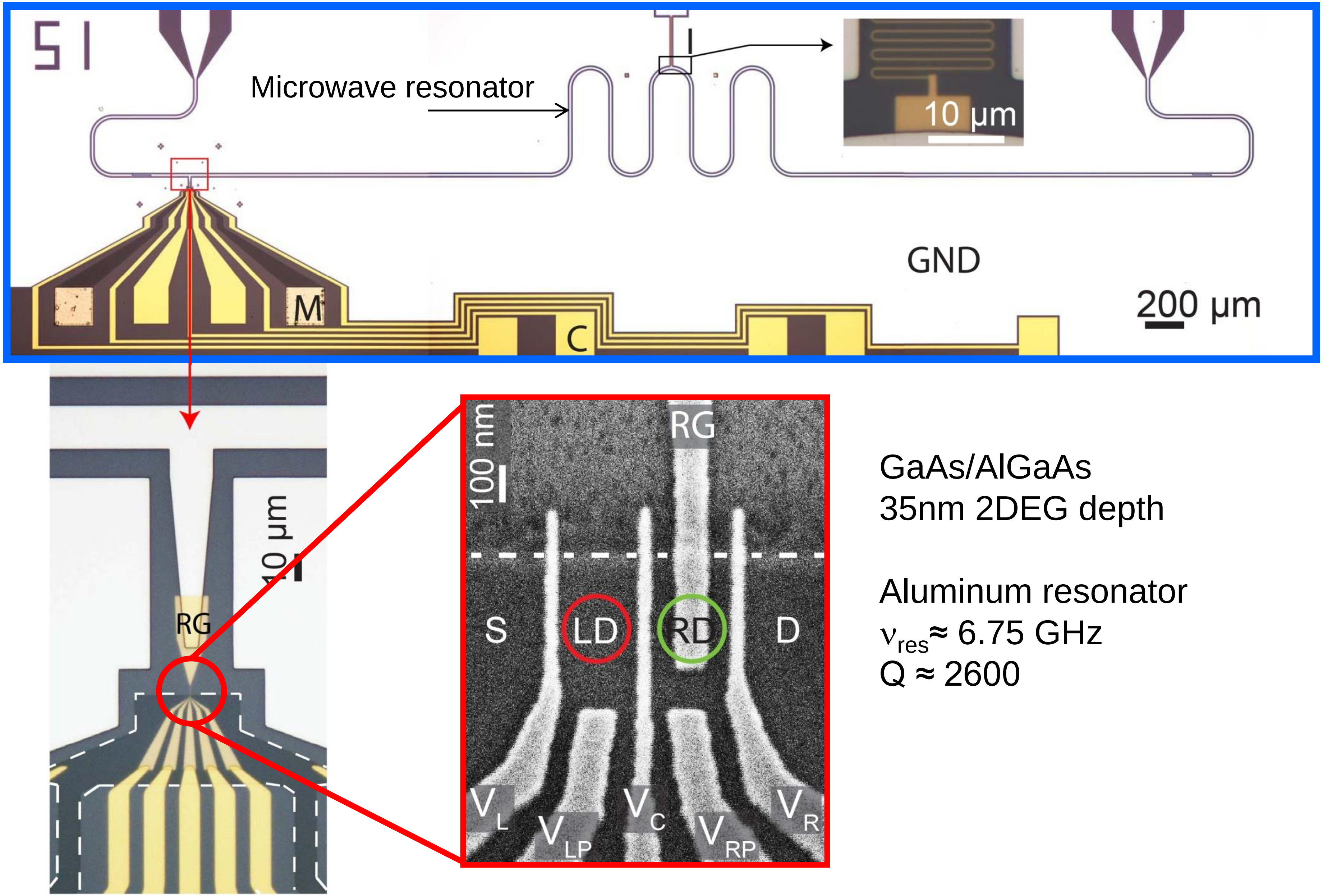



Wallraff et al., Nature (2004)

## Potential benefits:

- To enable long distance coherent coupling
- Implement alternative measurement / read-out scheme
- Realize interfaces between quantum systems

# Hybrid quantum device

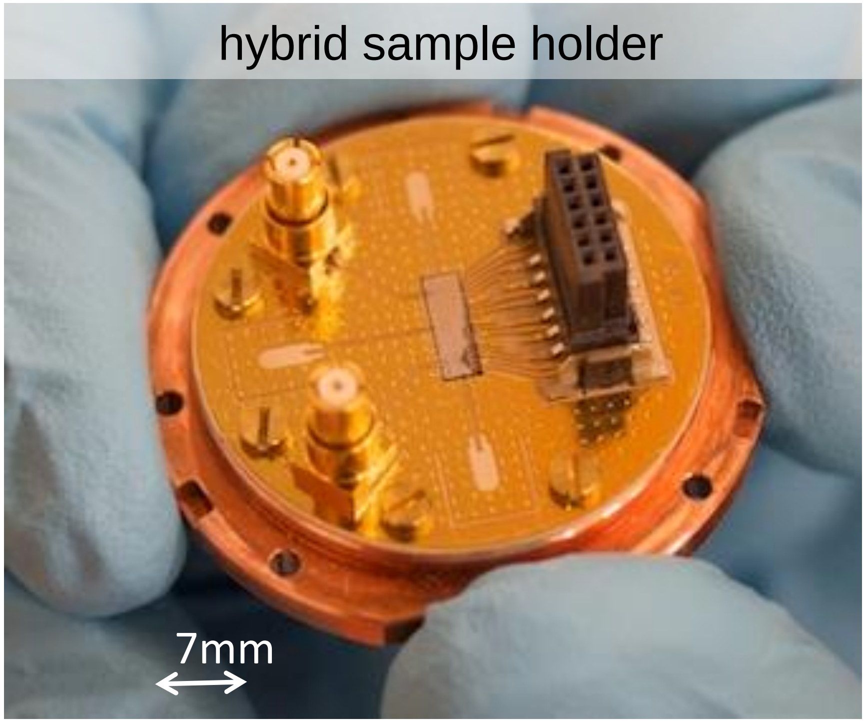



GaAs/AlGaAs
35nm 2DEG depth

Aluminum resonator
$\nu_{res} \approx 6.75$ GHz
Q ≈ 2600

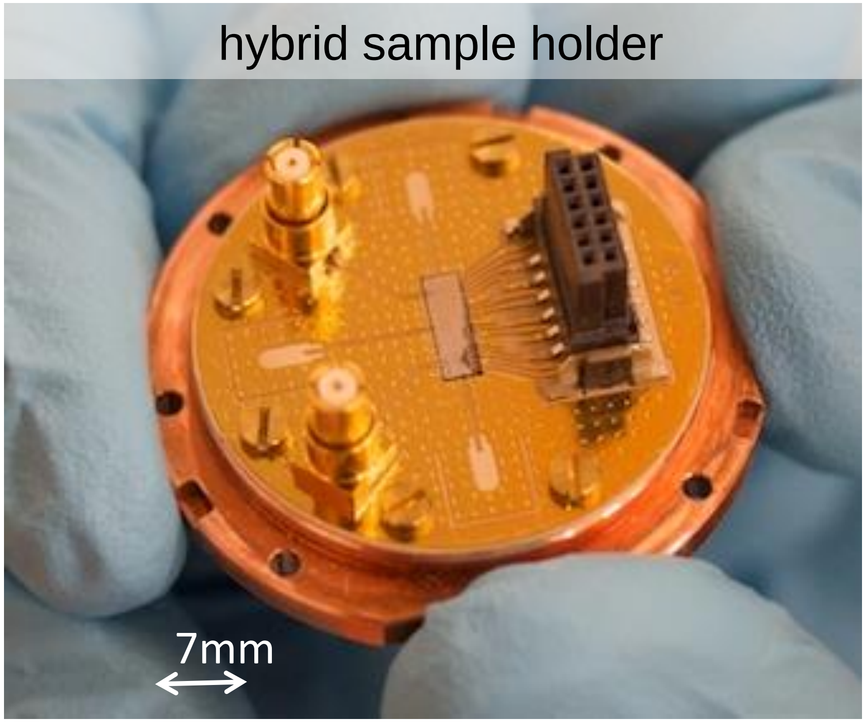
T. Frey *et al*, *PRL* **108**, 046807 (2012)

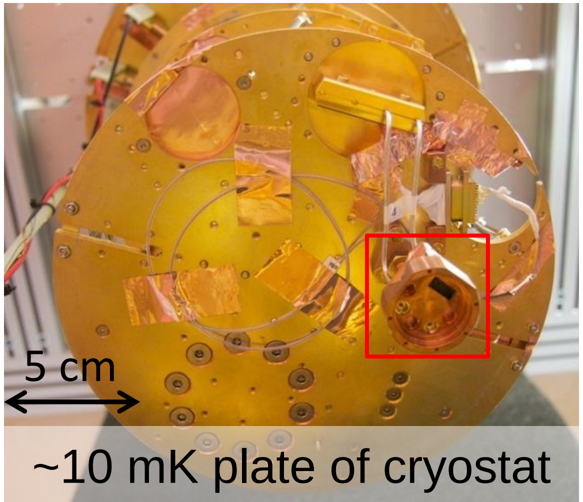
# Hybrid Quantum Dot / Circuit QED Measurement Setup




T. Frey, *ETH PhD thesis* (2013)

# Hybrid Quantum Dot / Circuit QED Measurement Setup

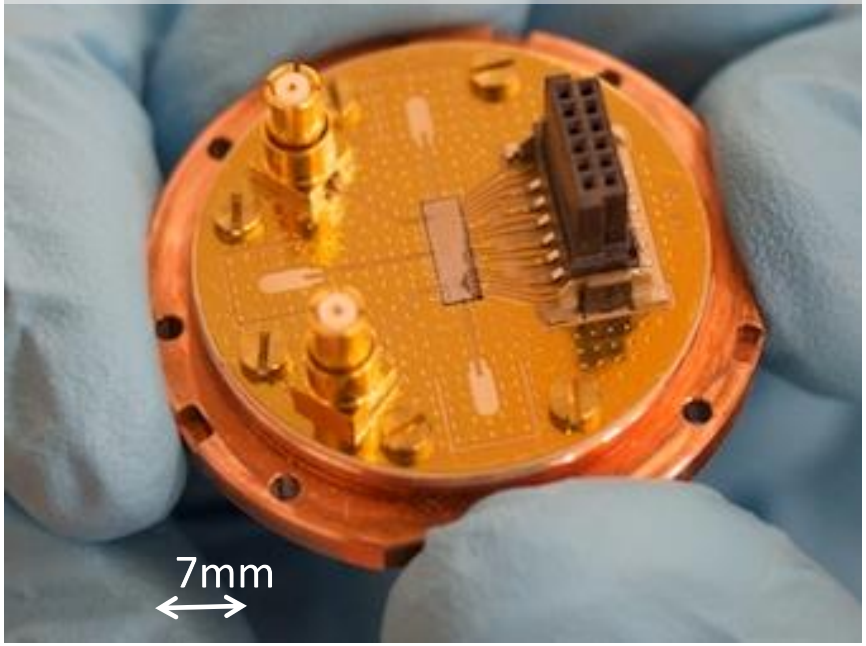


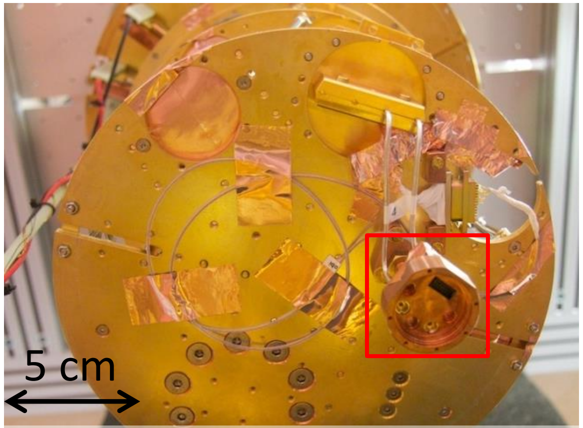




T. Frey, *ETH PhD thesis* (2013)

# Hybrid Quantum Dot / Circuit QED Measurement Setup

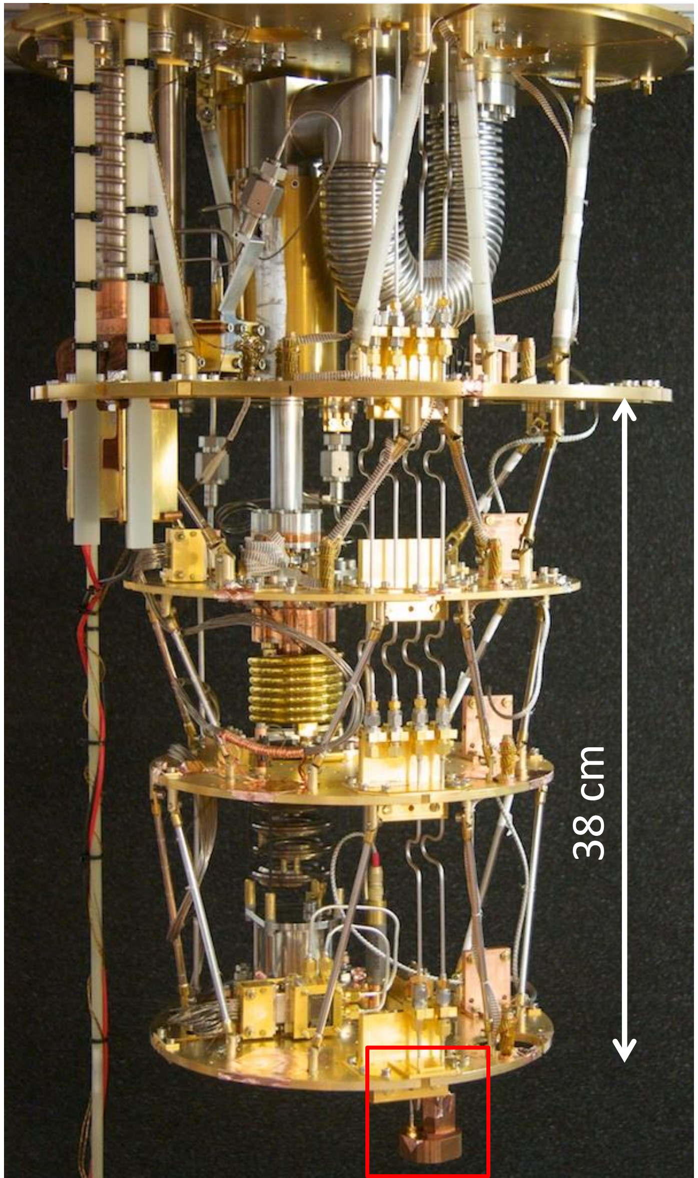
hybrid sample holder



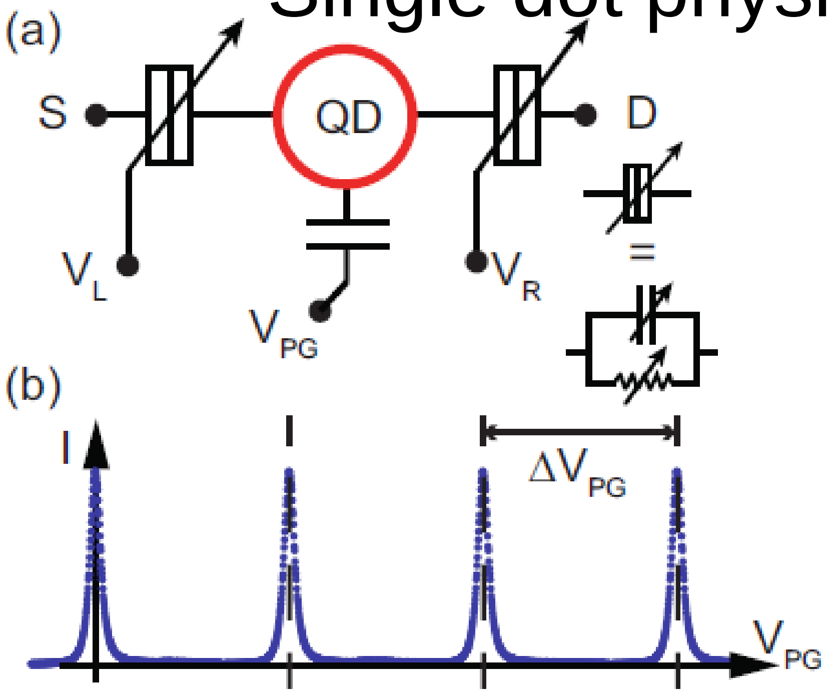

~10 mK plate of cryostat

Pulse tube cooled cryostat




T. Frey, *ETH PhD thesis* (2013)

# Single dot physics




T. Frey, *ETH PhD thesis* (2013), more details T. Ihn, Oxford University Press (2010)

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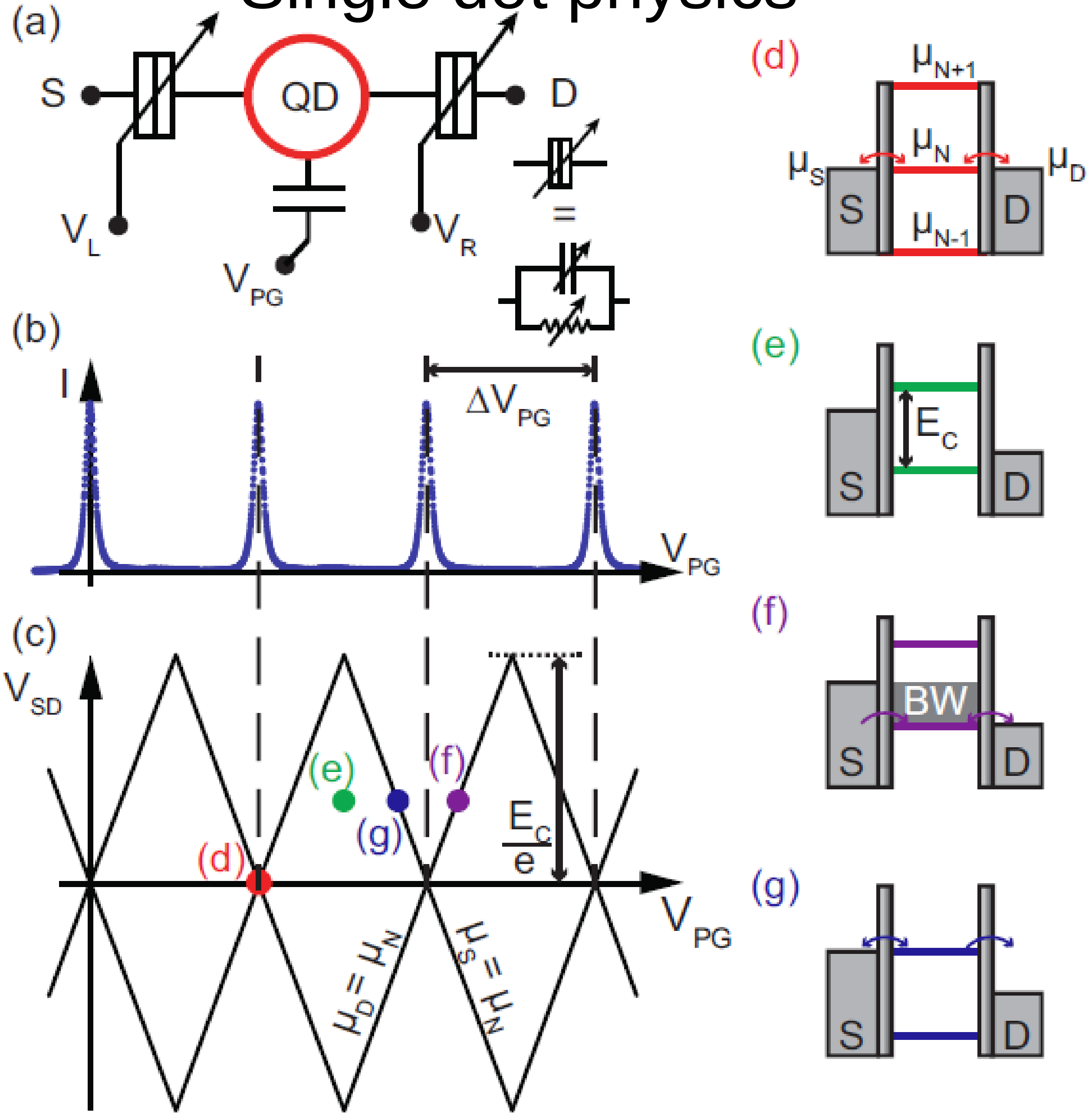
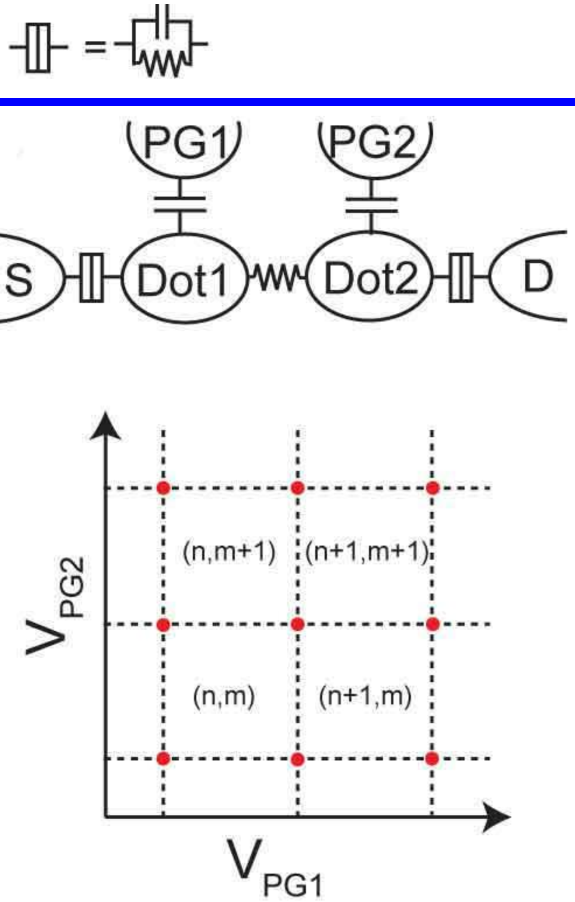



T. Frey, *ETH PhD thesis* (2013), more details T. Ihn, Oxford University Press (2010)

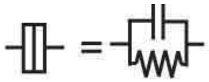
# Charge stability diagram: double dot

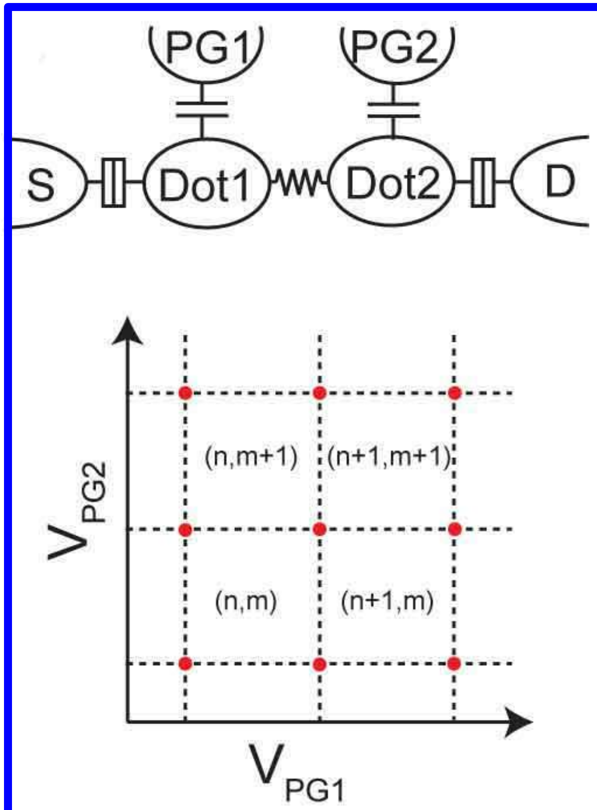



each dot coupled **only** to its gate

Slide courtesy of Klaus Ensslin

# Charge stability diagram: double dot



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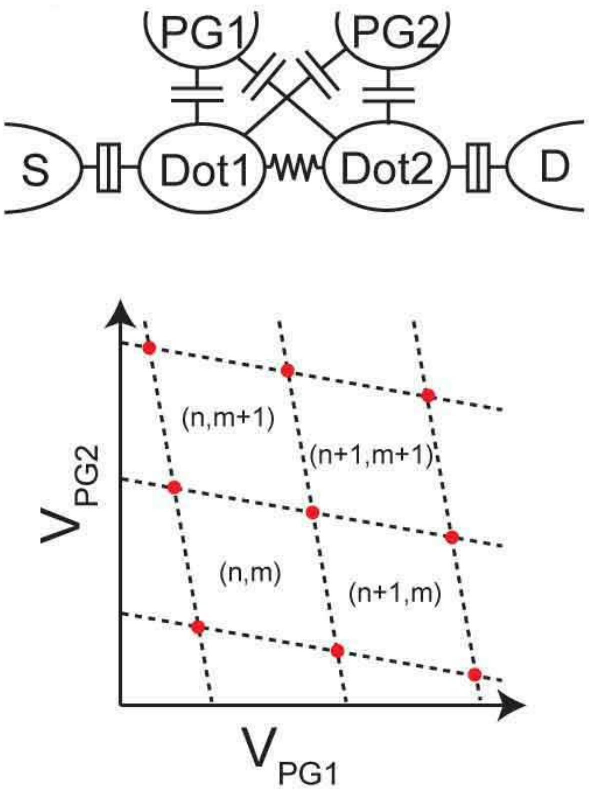
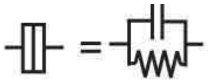
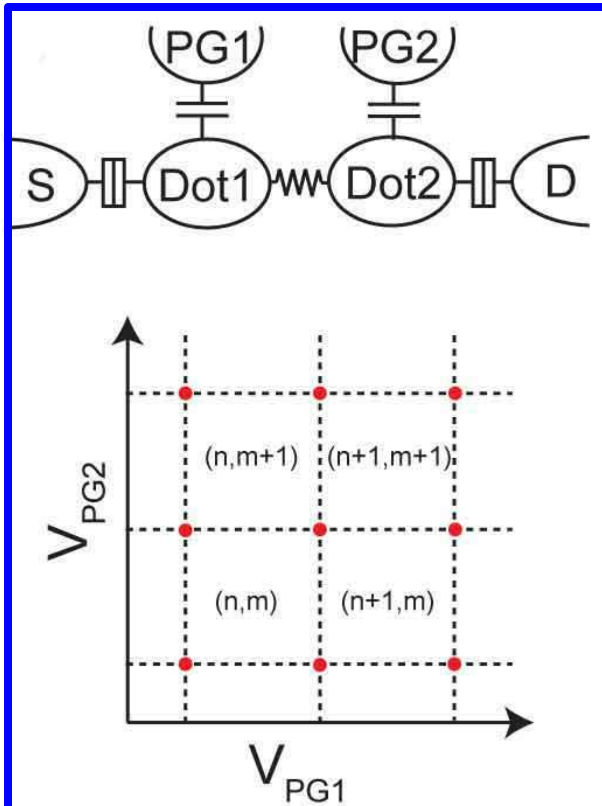



each dot coupled to **both gates**

Slide courtesy of Klaus Ensslin

# Charge stability diagram: double dot



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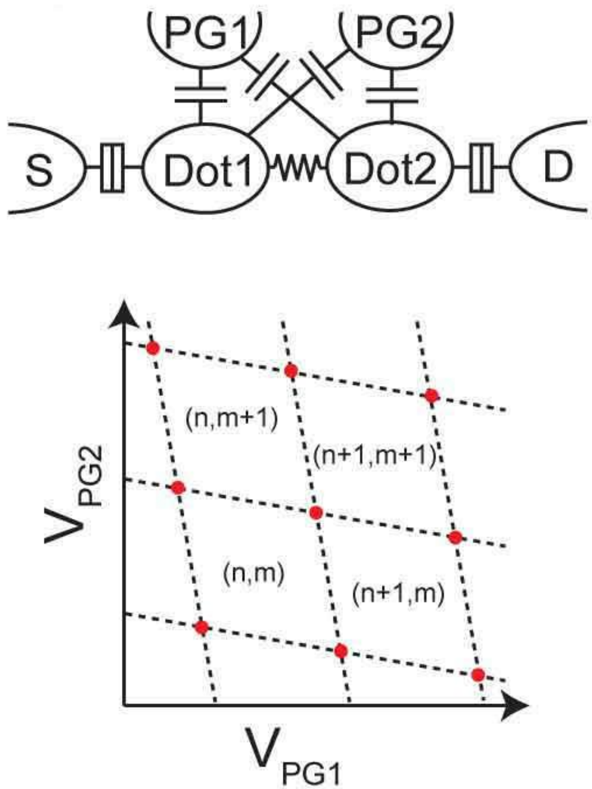
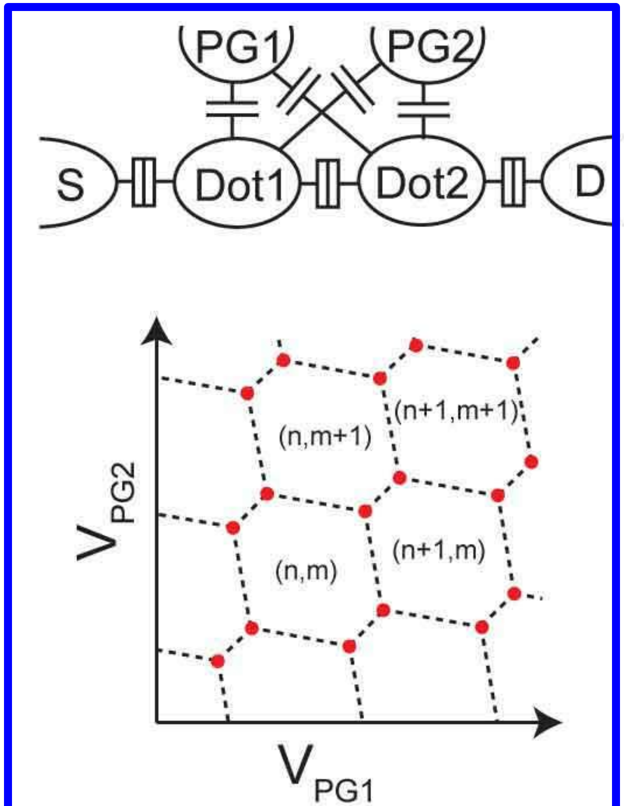
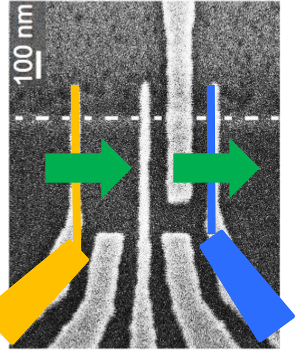



each dot coupled to **both gates**

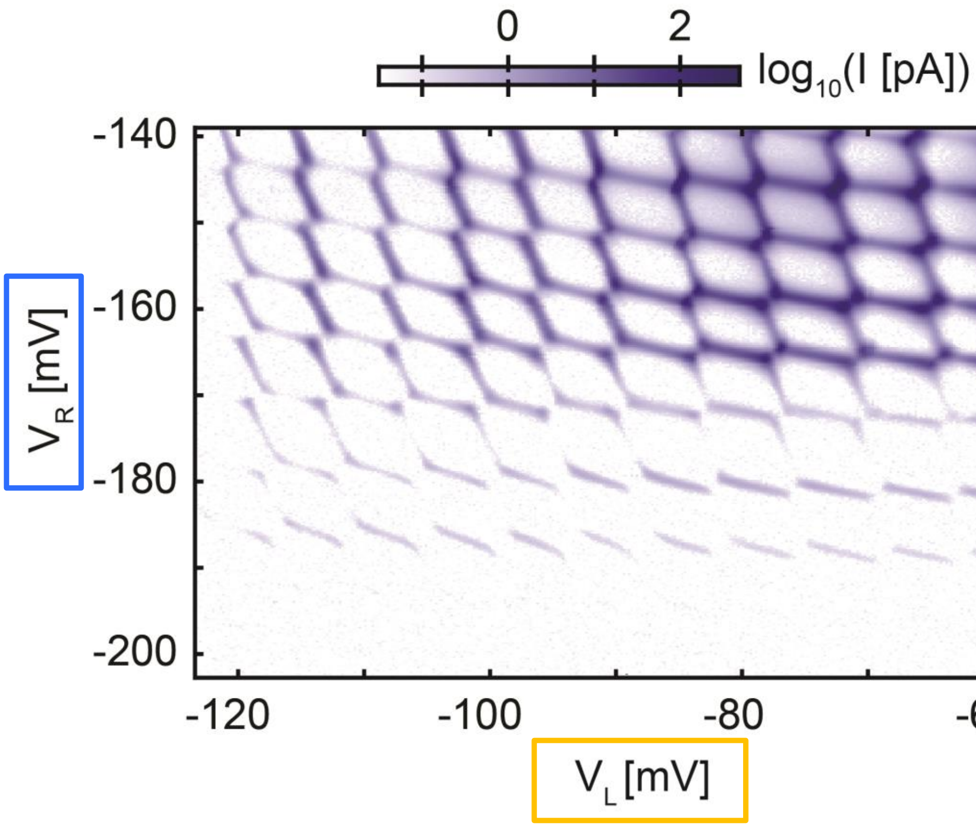



**both dots** coupled to each other

Slide courtesy of Klaus Ensslin




# Transport through the double quantum dot




charging energy ~1 meV;
many electron regime

T. Frey *et al*, *PRB* **86**, 115303 (2012)

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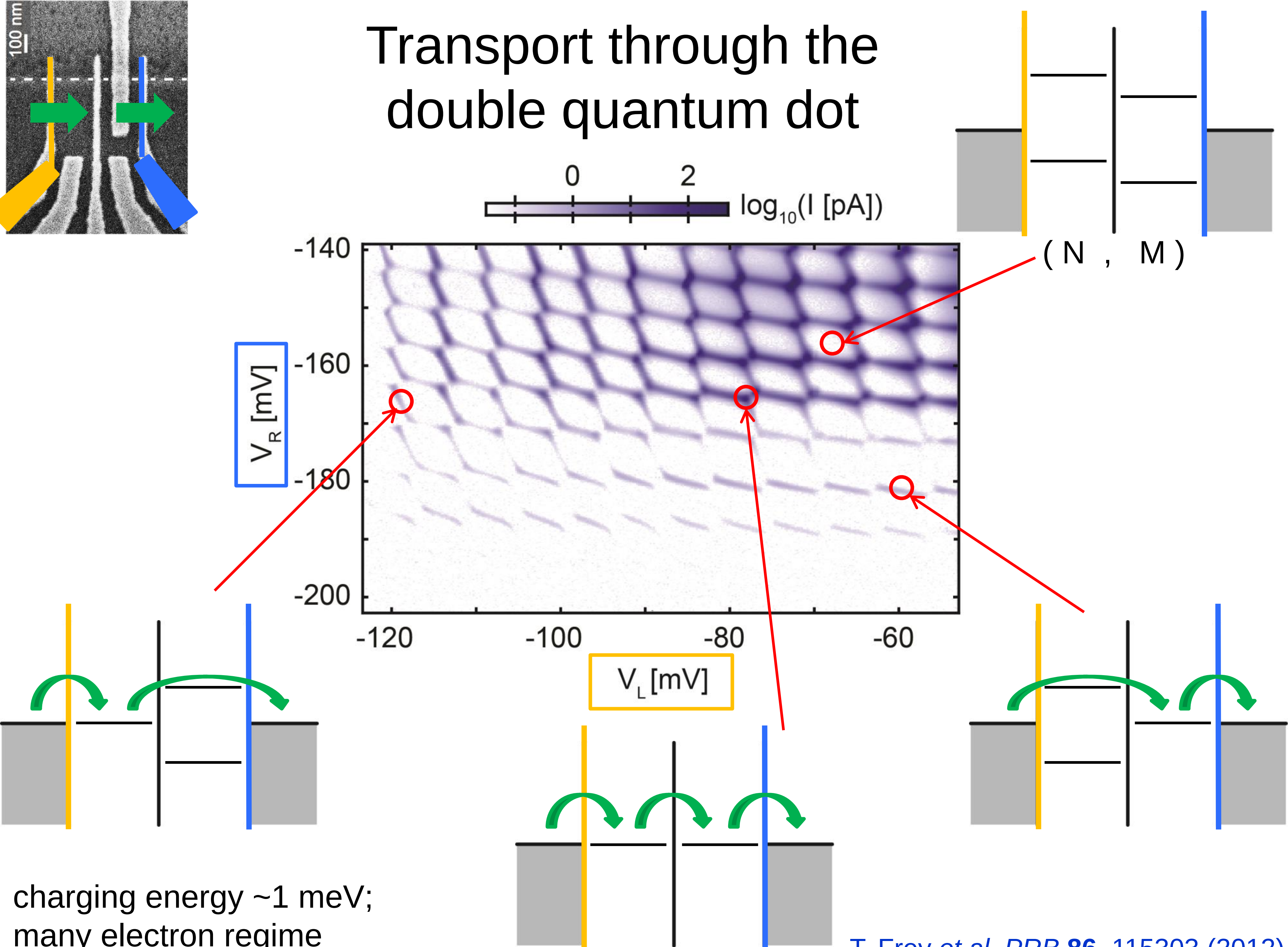


charging energy ~1 meV;
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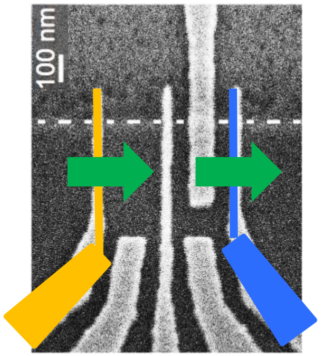
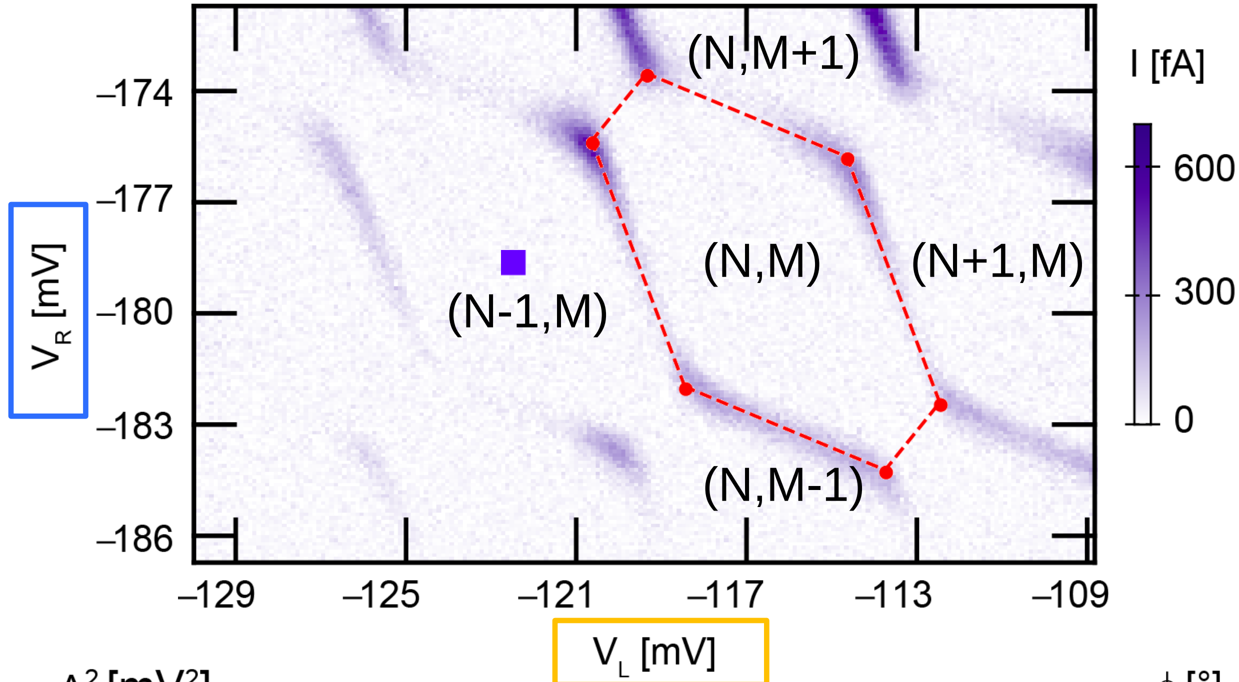
# Double Dot Current and Resonator Transmission

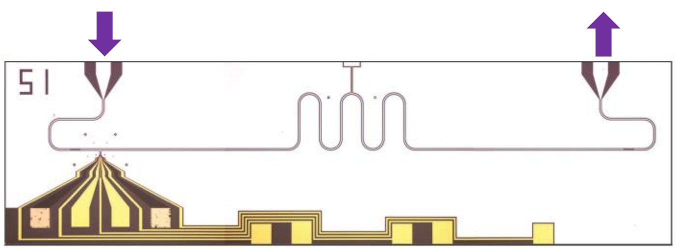
**Transport measurements:**

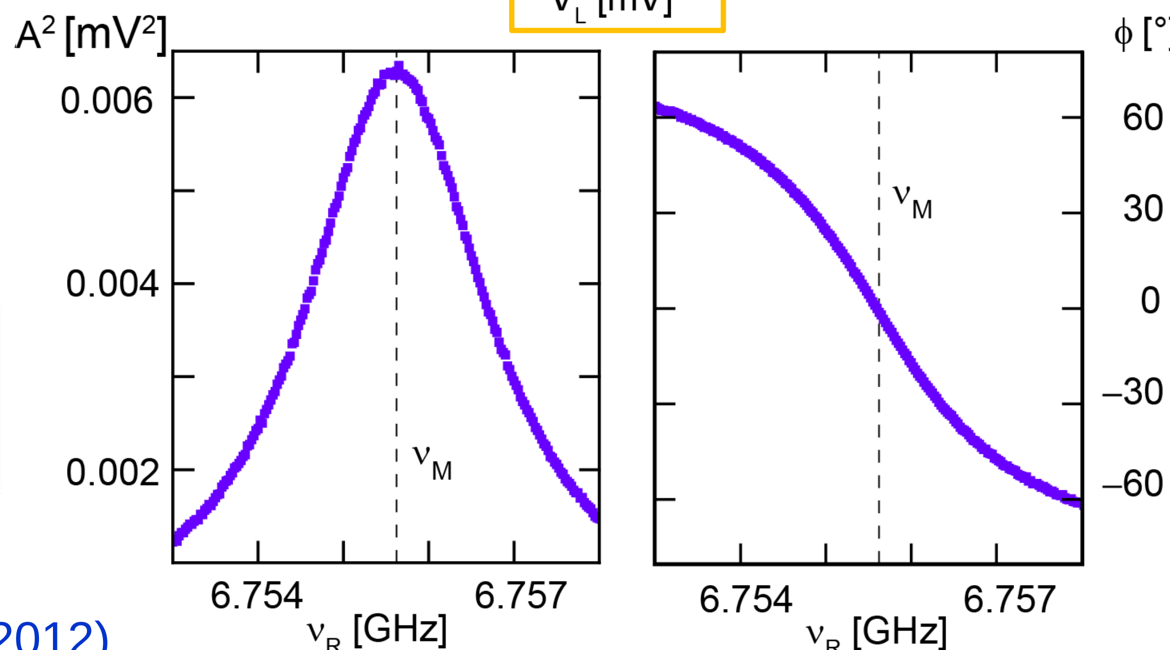



**Resonator transmission :**

- amplitude
- phase




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

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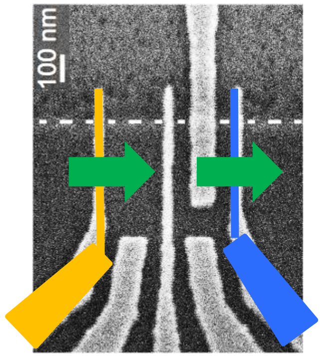


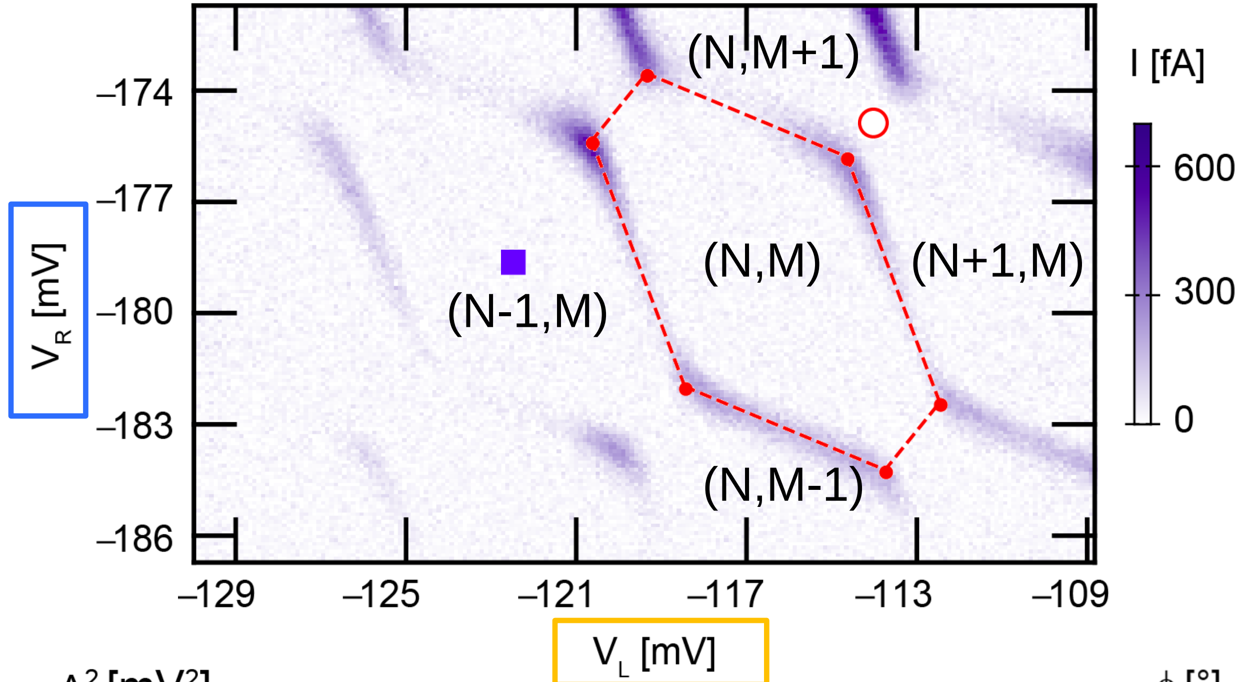


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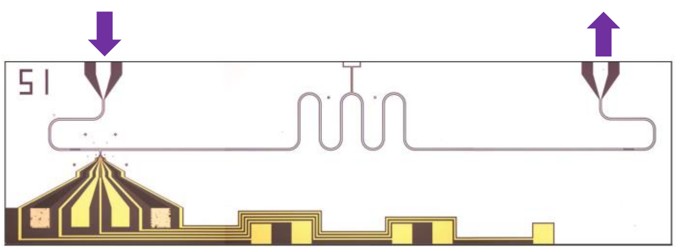
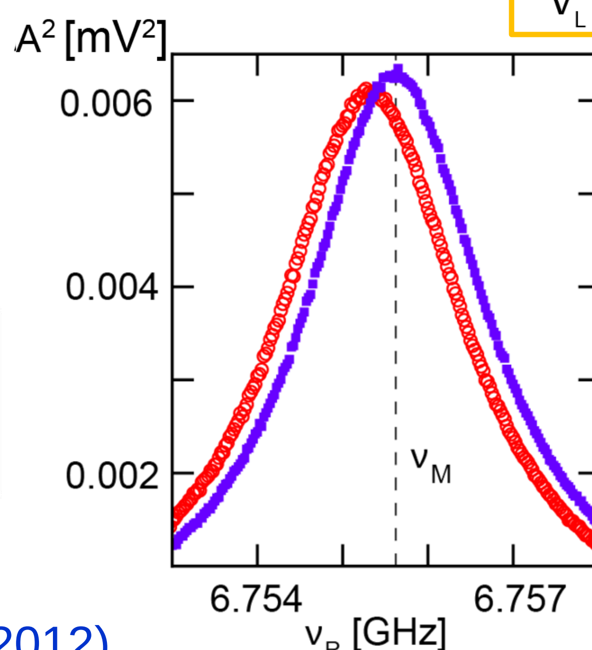
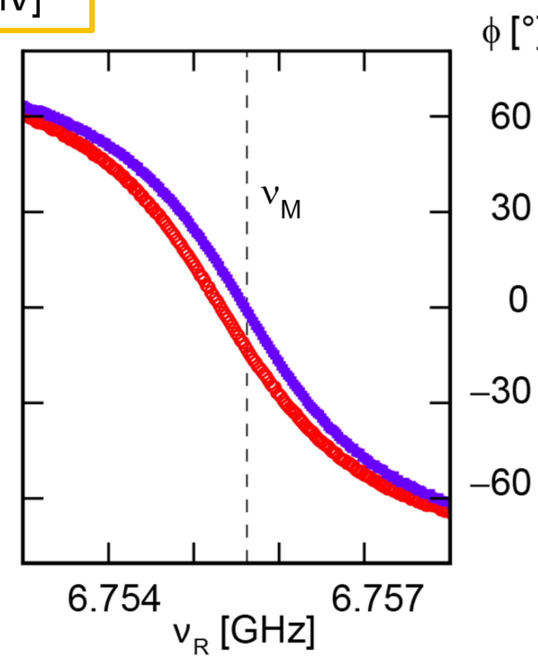


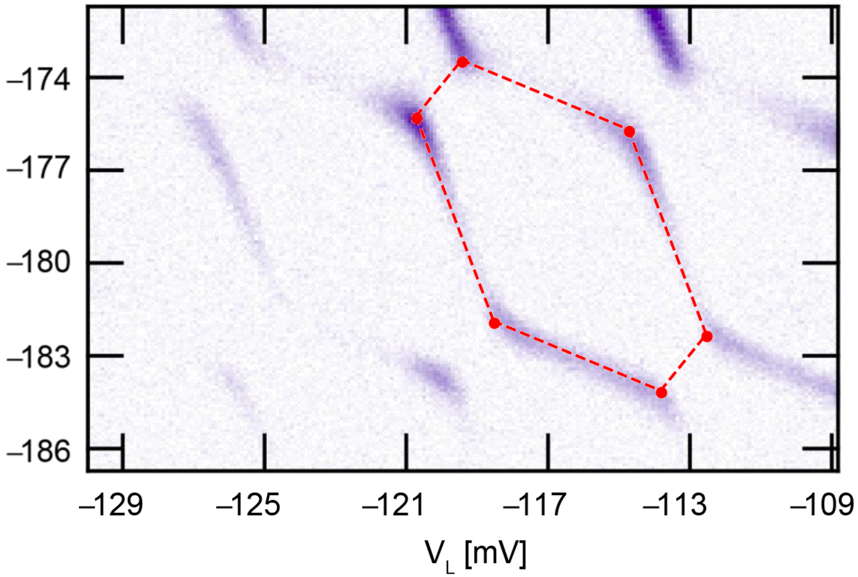



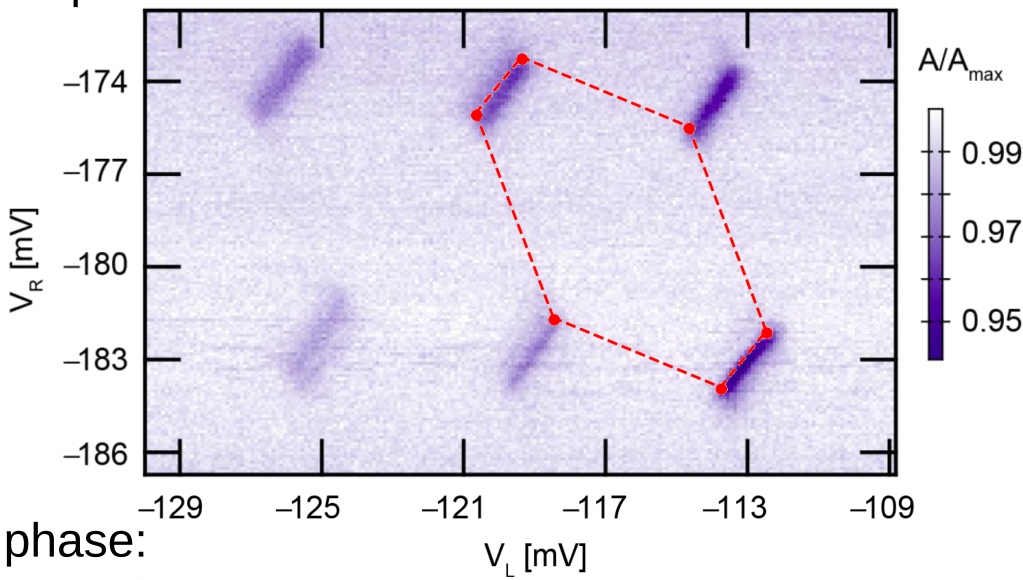

T. Frey *et al*, *PRL* **108**, 046807 (2012)

# Charging Diagrams in Current, Amplitude and Phase

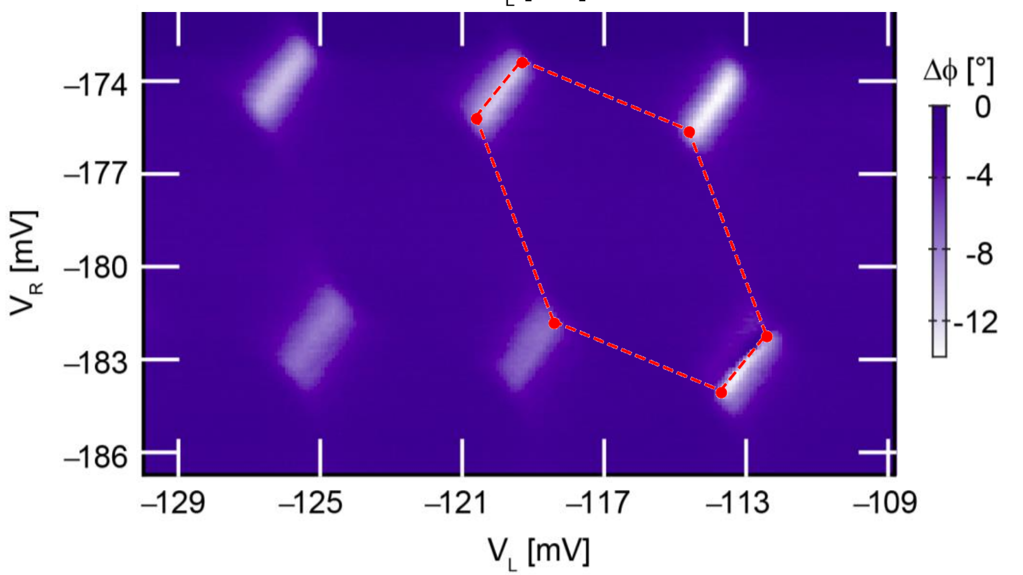
current:




amplitude:




phase:

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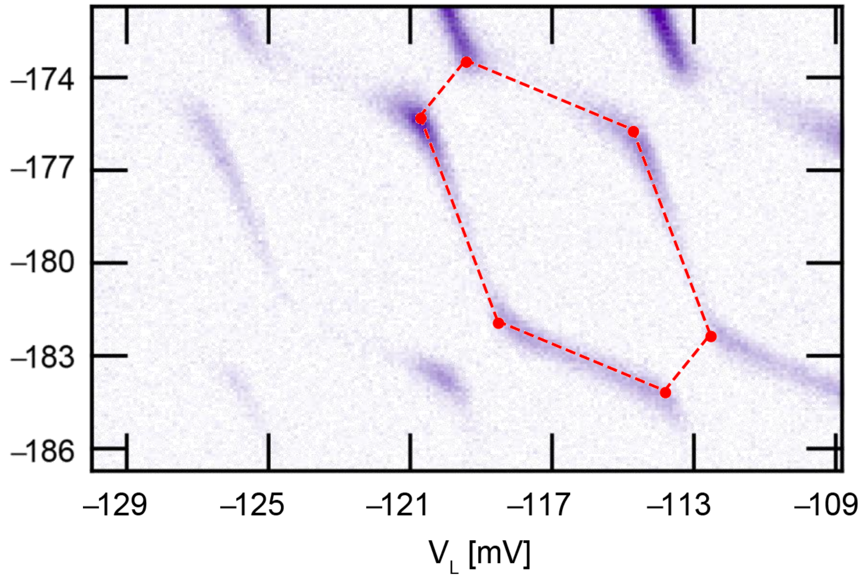
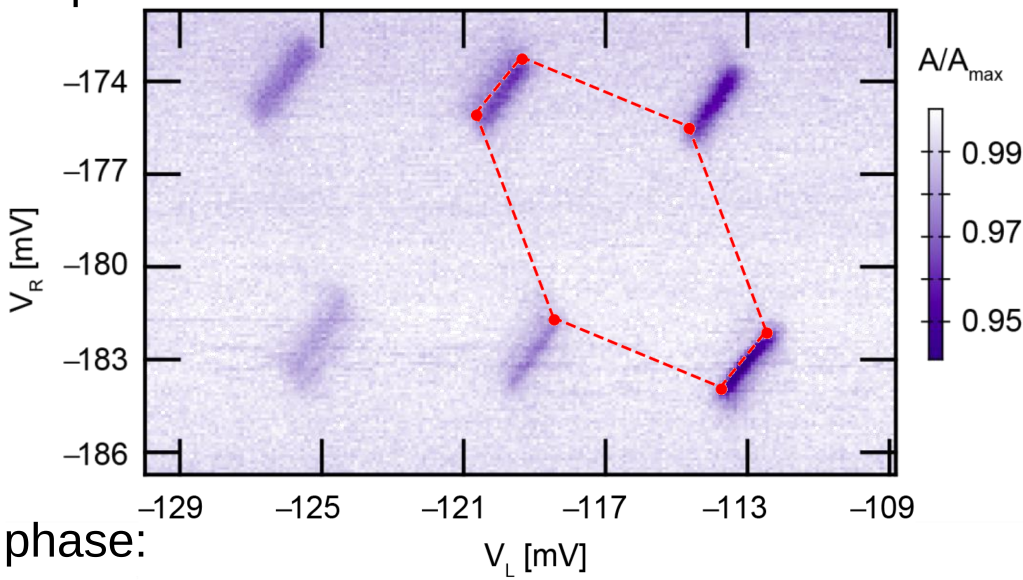
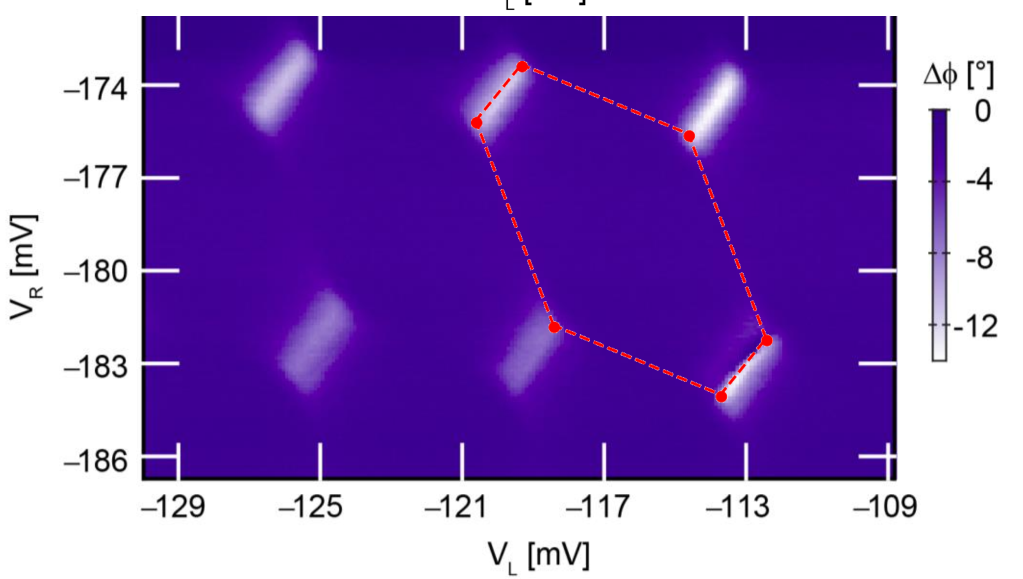



amplitude:




phase:

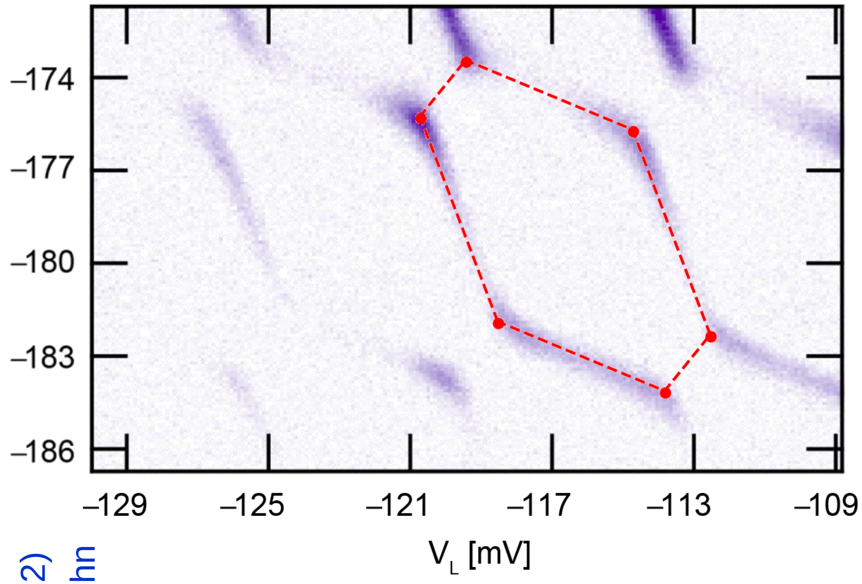



- systematic changes in transmission amplitude and phase
- equivalent charging diagrams …
- … but different physical origin of signal

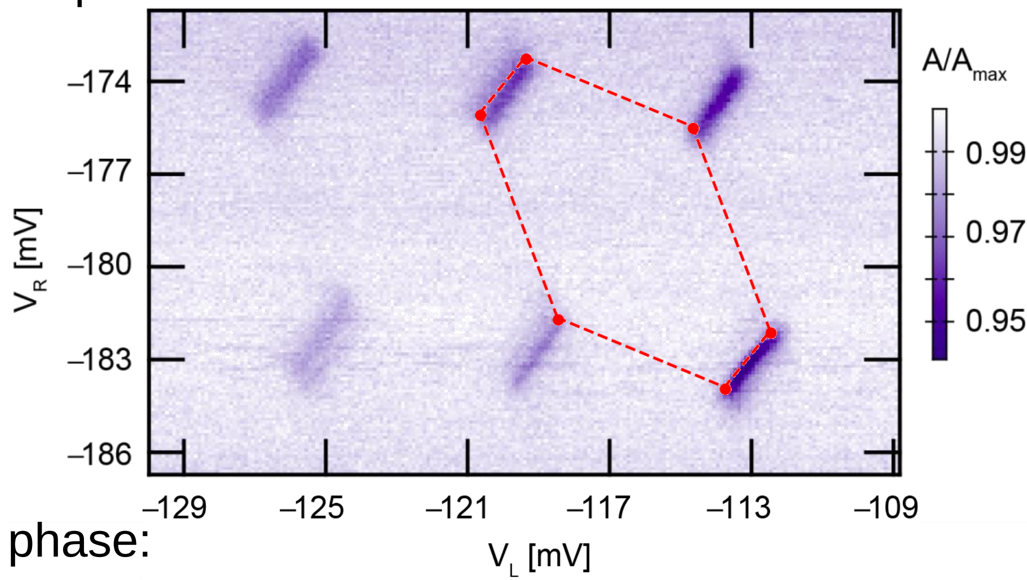
T. Frey *et al*, *PRL* **108**, 046807 (2012)

# Charging Diagrams in Current, Amplitude and Phase

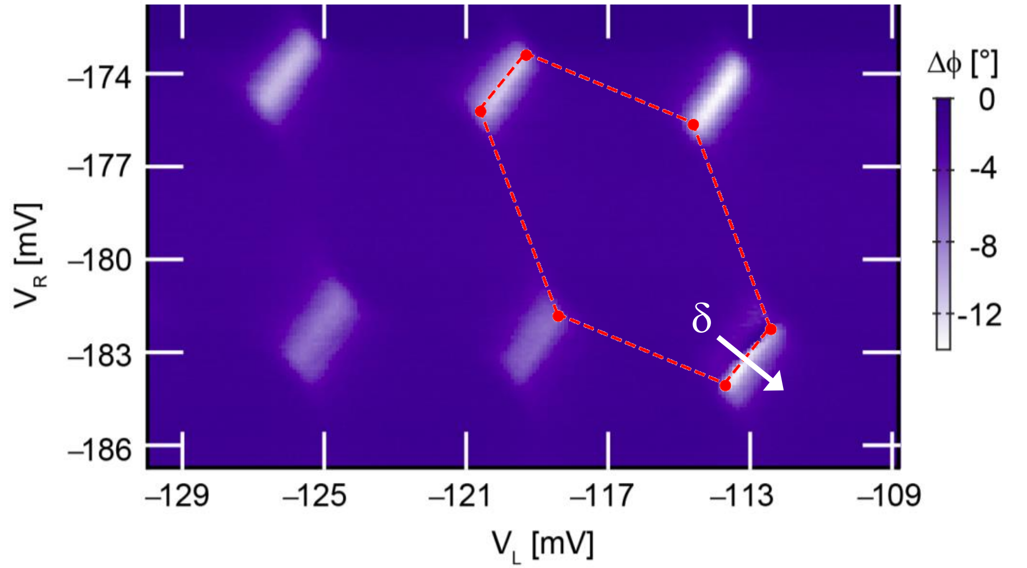
current:



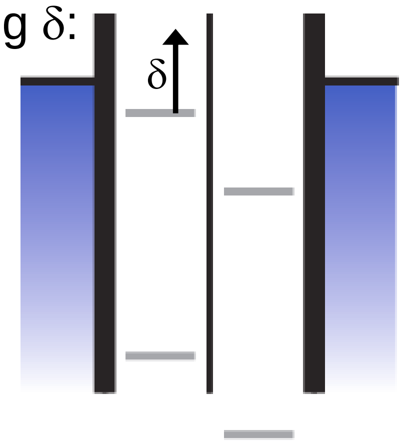

amplitude:




phase:




detuning δ:

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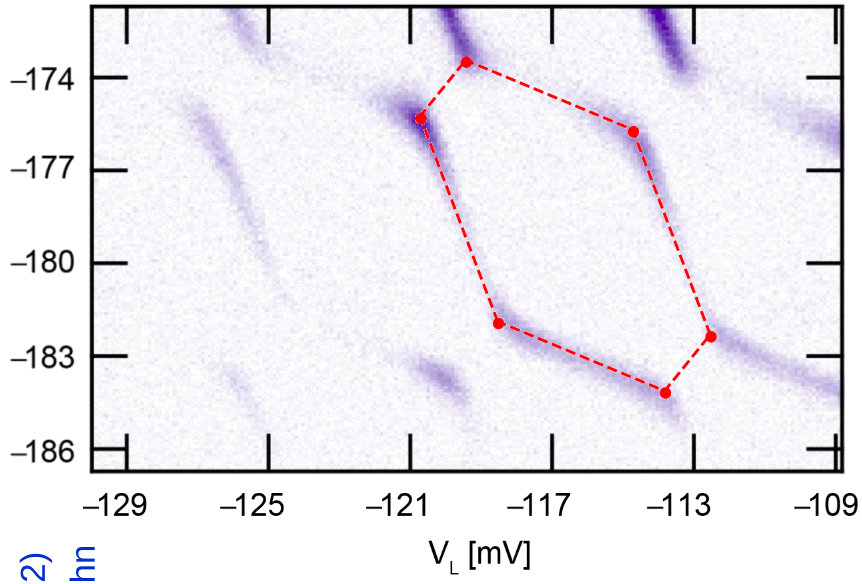
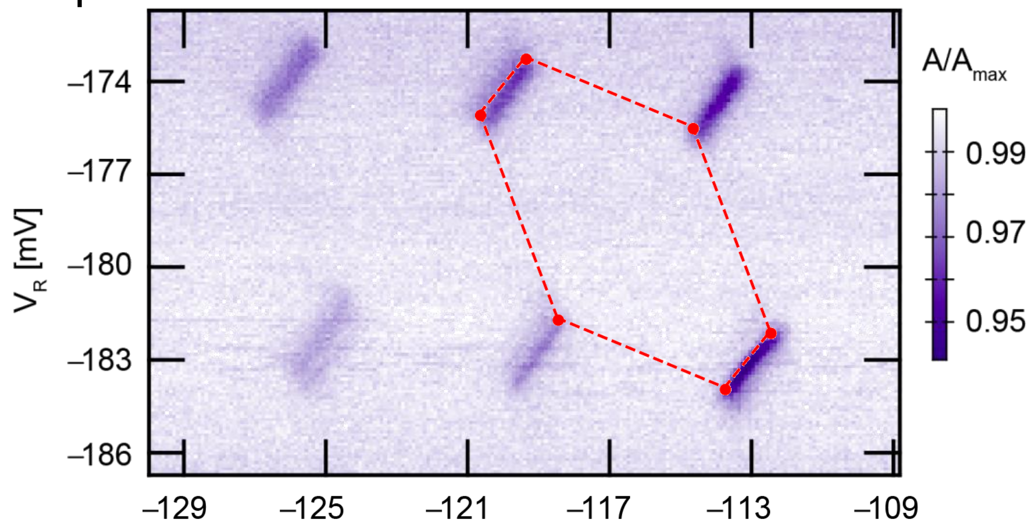
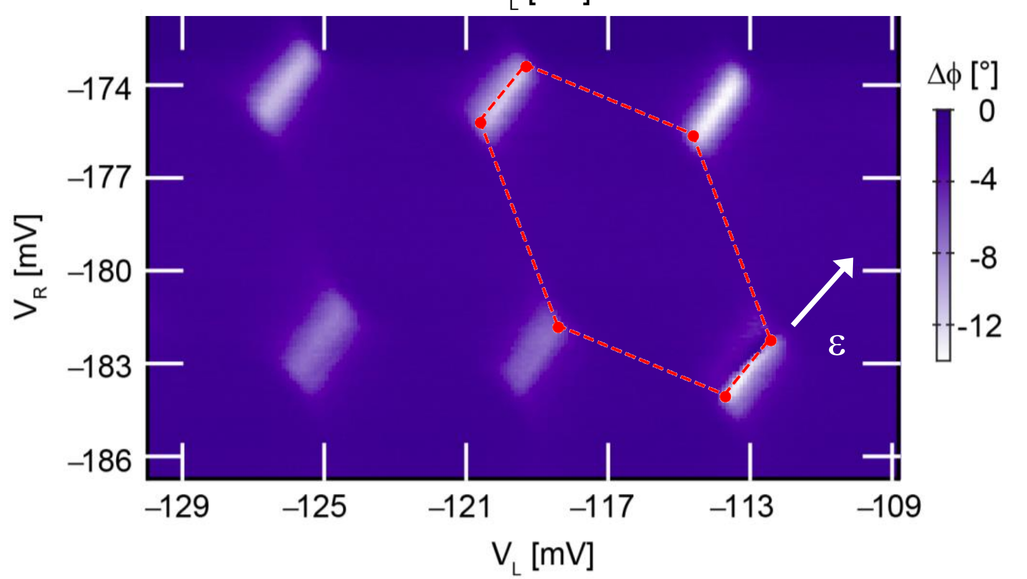


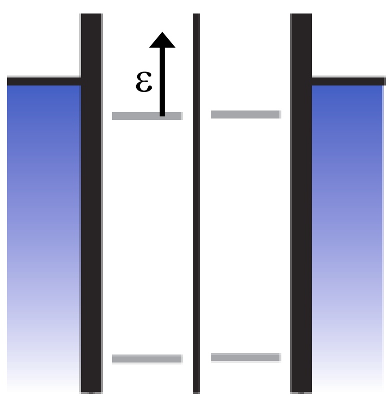

amplitude:




phase:




total energy ε:

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parts of slide courtesy of Thomas Ihn

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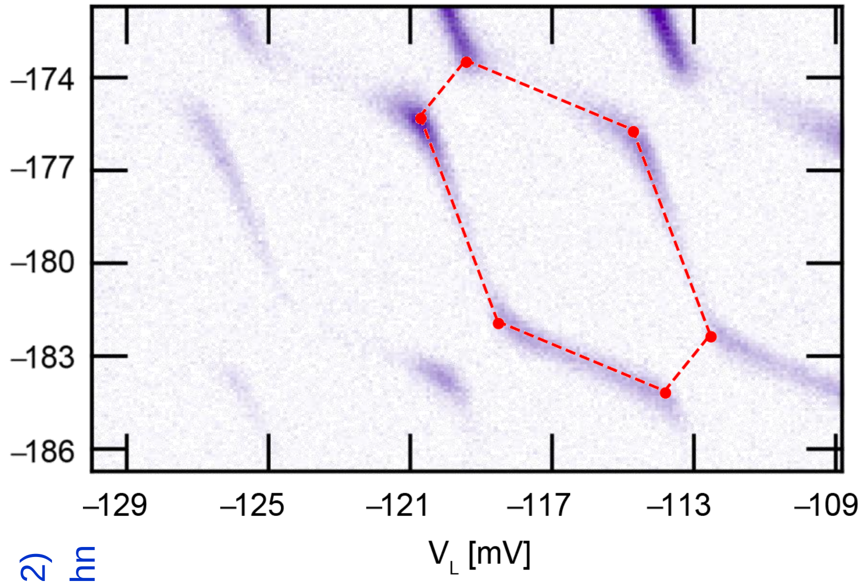
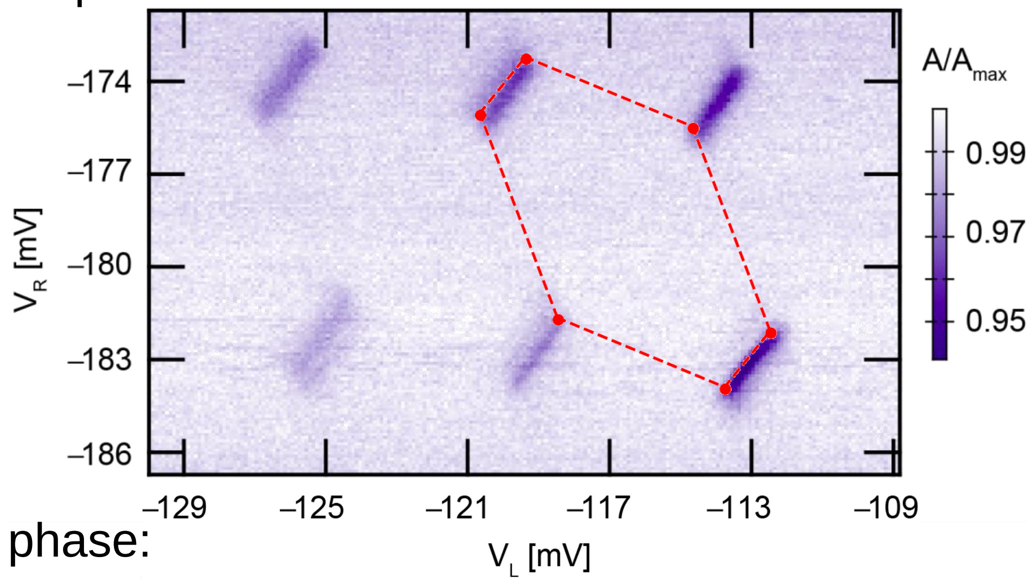
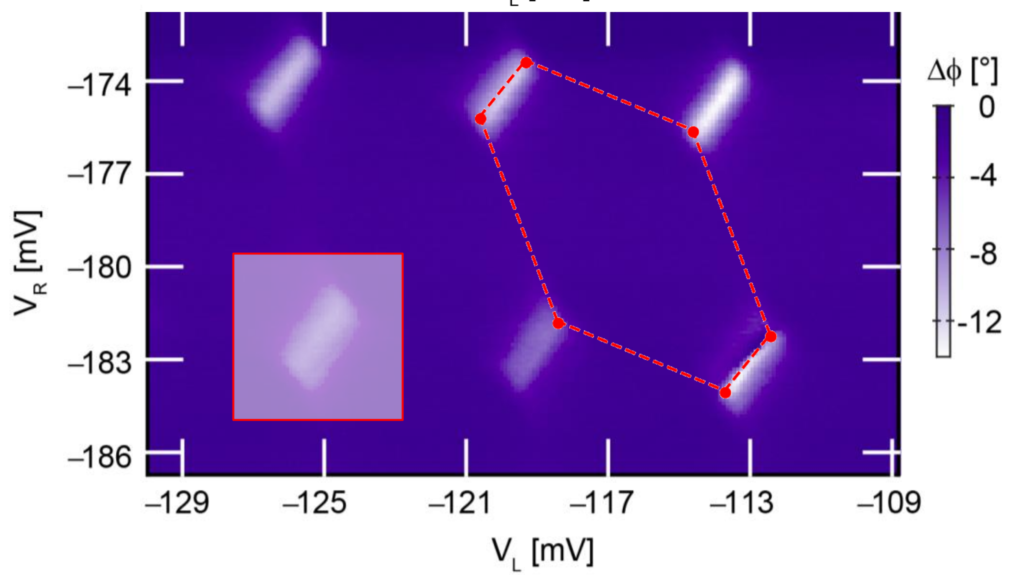


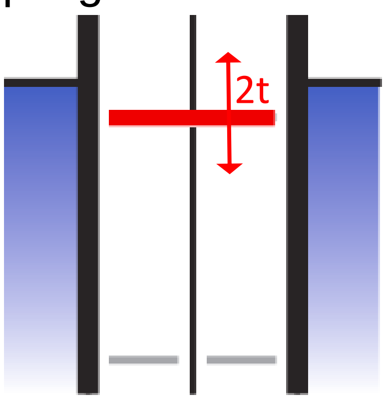

amplitude:




phase:




tunnel coupling t :

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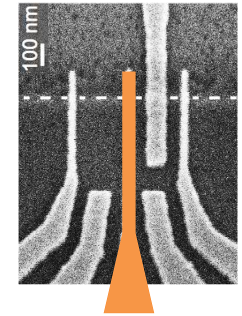
# Resonator/Double-Dot Interaction
## Center Gate Voltage ($V_C$) Influence



Tune t, with $V_C$

T. Frey, *ETH PhD thesis* (2013)

# Resonator/Double-Dot Interaction
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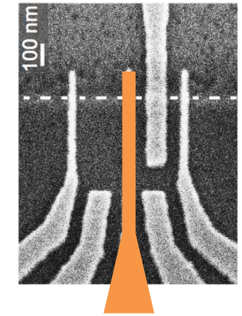
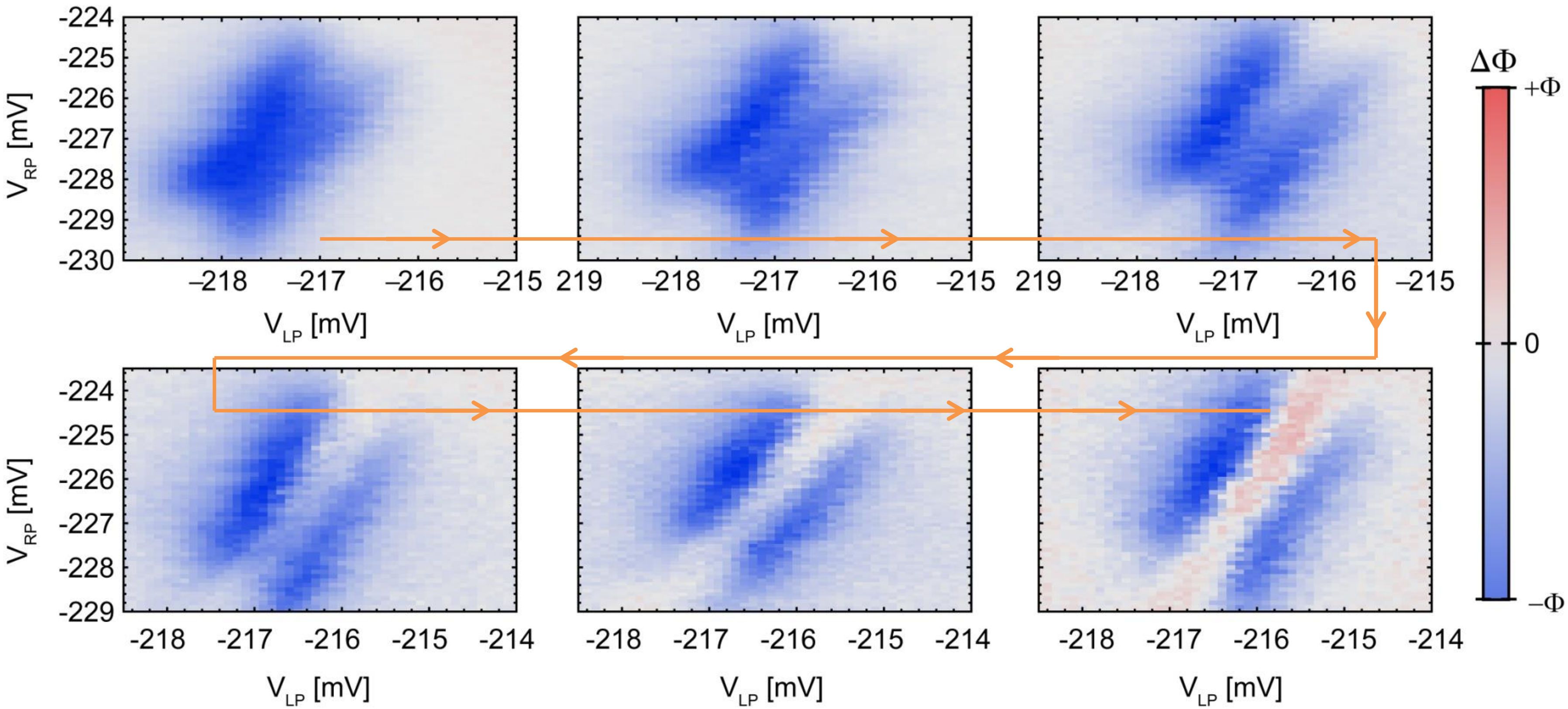



Tune t, with Vc

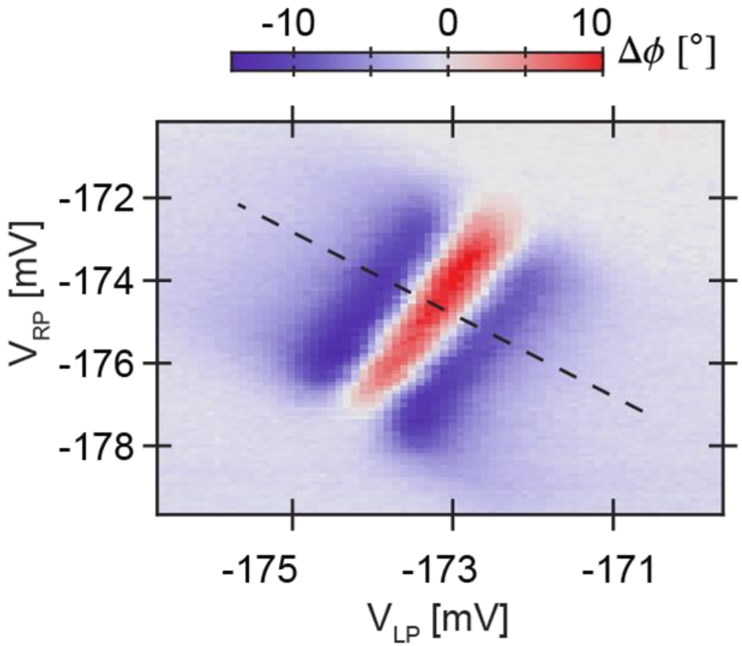
Vc more negative →

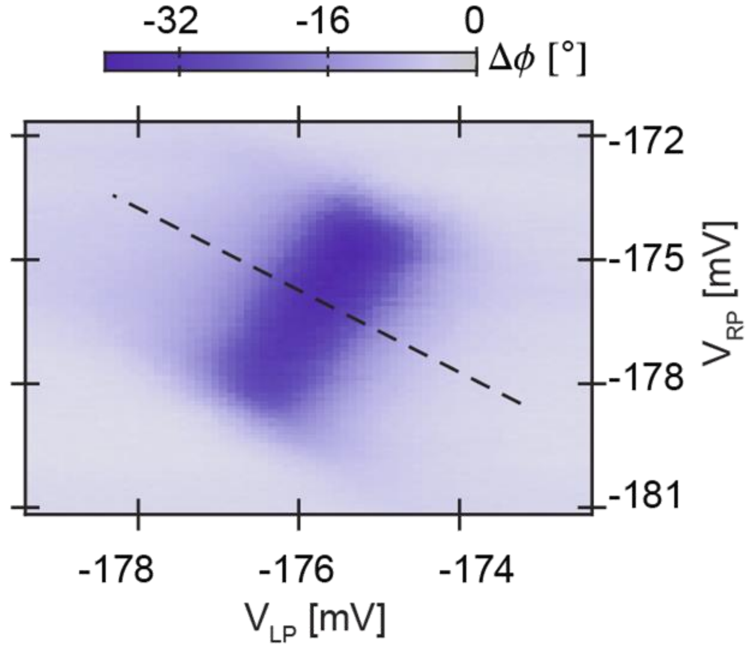



Vc more negative →

T. Frey, *ETH PhD thesis* (2013)

# Detailed Resonator/Double-Dot Interaction




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

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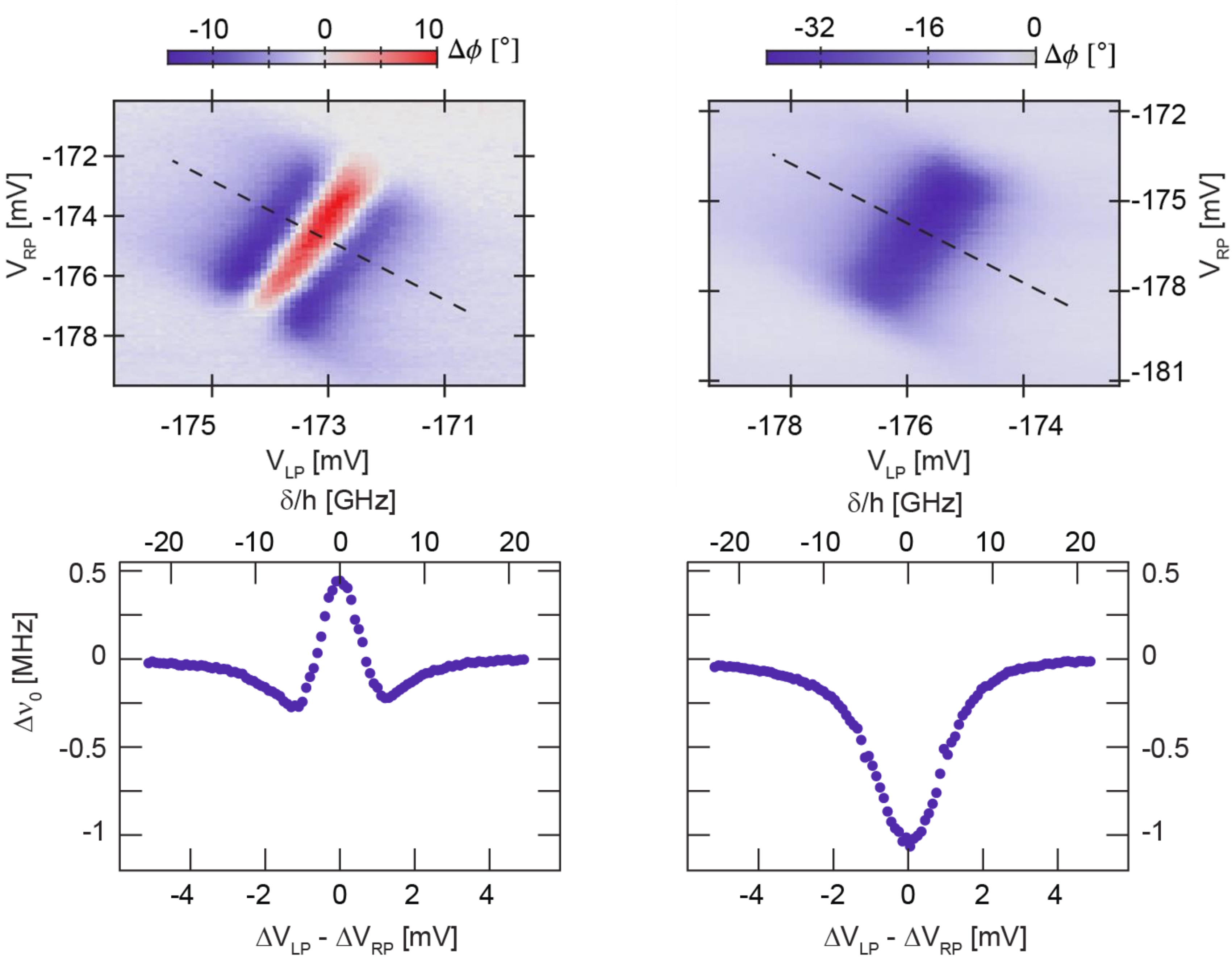
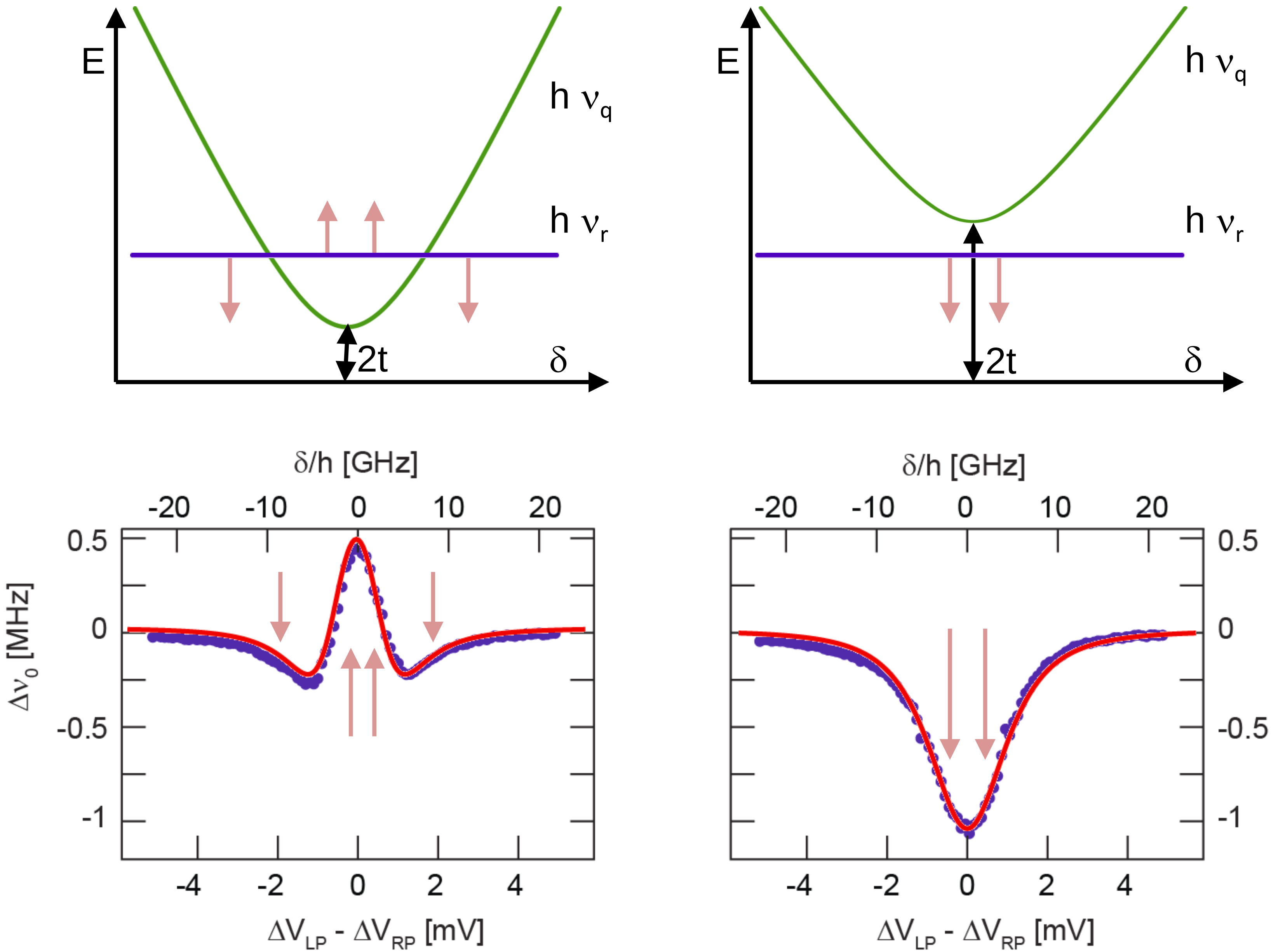



T. Frey *et al*, *PRL* **108**, 046807 (2012)

# Non-Resonant Frequency Shifts




T. Frey *et al*, *PRL* **108**, 046807 (2012)
parts of slide courtesy of Thomas Ihn

# Summary

- Fabricated integrated semiconductor/superconductor device
- Explored novel measurement scheme for quantum dots
- Observed first indications of controlled resonator/quantum dot dipole-coupling

# Outlook

- Explore limits of coherence
- Work towards coherent interface
- Evaluate potential to investigate spin physics
- Use resonator as a coupling bus in semiconductor-based QIP

T. Frey, P. J. Leek, M. Beck, A. Blais, T. Ihn, K. Ensslin and A. Wallraff,
*PRL* **108**, 046807 (2012)