Electrically Protected Valley-Orbit Qubit in Silicon

- FAM talk -

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21.09.2018

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Motivation I

Zeitschrift für Instrumentenkunde.

Redaktions-Kuratorium:

Geh. Reg.-R. Prof. Dr. **H. Landolt**, Vorsitzender. **H. Haensch**, Beisitzer. Direktor Dr. **L. Loewenherz**, Schriftführer.

Redaktion: Dr. **A. Westphal** in Berlin.

XI. Jahrgang. **August 1891.** Achtes Heft.

Ein neuer Interferenzrefraktor.

Von
Dr. **L. Zehnder** in Basel.

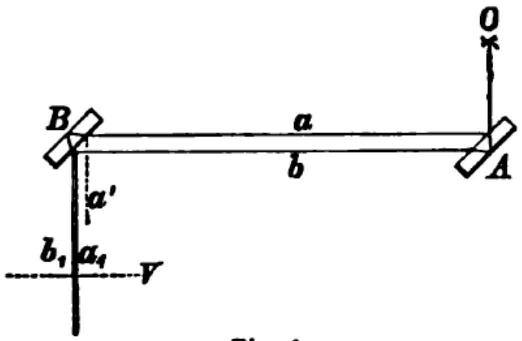


Fig. 1.

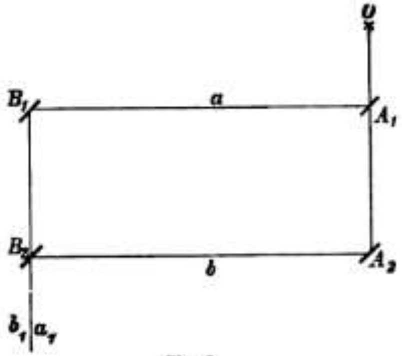


Fig. 2.

Ueber einen Interferenzrefraktor.

Von
Ludwig Mach in Prag.

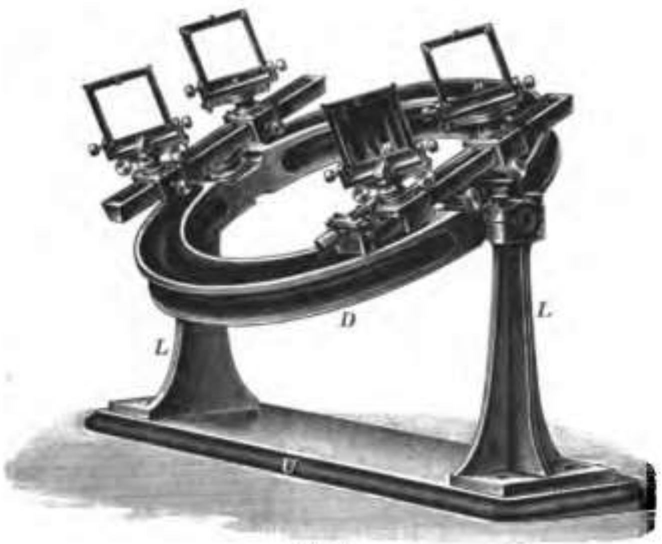


Fig. 1.

[1]) Den hier beschriebenen Apparat hatte ich bereits Ende Juli 1891 in seinen Theilen fertiggestellt, konnte jedoch denselben wegen verspäteter Lieferung einer Werkzeugmaschine erst Anfang November 1891 ganz vollenden. — Vergl. die vorläufige Mittheilung im *Anzeiger der Wiener Akademie* vom 5. November 1891.

[1] Zehnder, L., *Zeitschrift für Instrumentenkunde. 11: 275–285 (1861)*
[2] Mach, L, *Zeitschrift für Instrumentenkunde. 12: 89–93 (1862)*

Motivation II

- electrical fluctuations are omnipresent
- source of decoherence

- reduce and mitigate charge noise
  - operation at sweet spot
  - dynamic decoupling
  - hybrid qubits

- in Si: Valley-Orbit Qubit?
  - analogon to transmon qubit

Outline

Theory of LZSM interferometry

Device

Example of Application

Summary and Outlook

X. Mi, S. Kohler, J. R. Petta, arXiv:1805.04545

Quantum Two Level System

- Hamiltonian of two level system (TLS):

$$H(t) = -\frac{\Delta}{2}\sigma_x - \frac{\varepsilon(t)}{2}\sigma_z$$

- eigenstates

$$E_\pm = \pm\frac{1}{2}\Omega(t)$$

$$\Omega(t) = \sqrt{\Delta^2 + \varepsilon(t)^2}$$

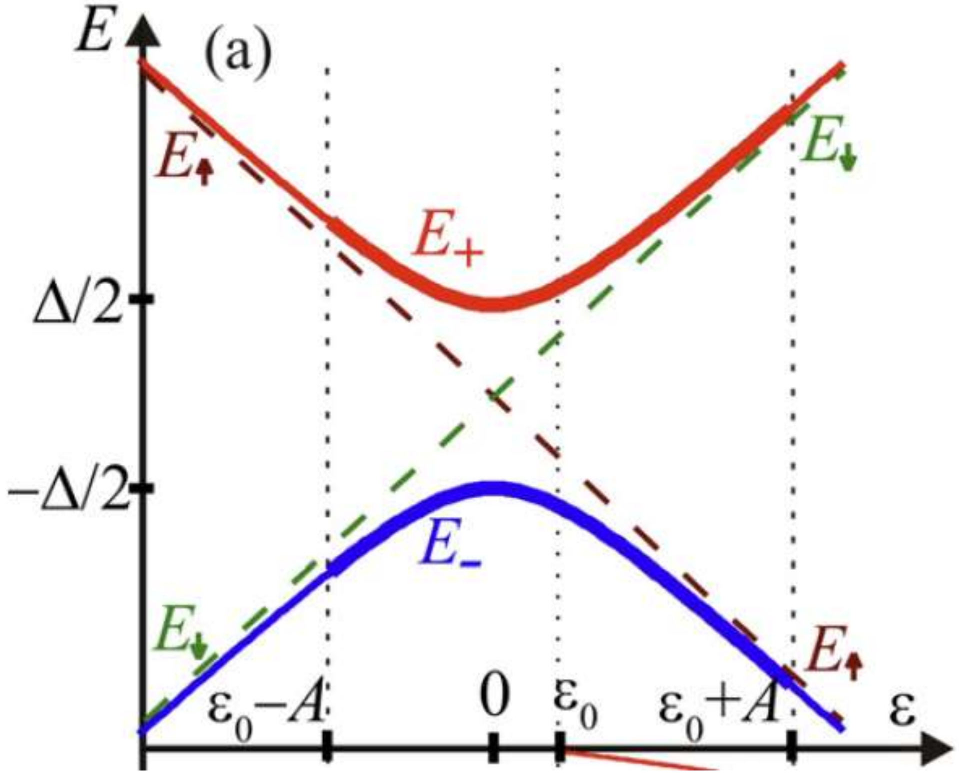


Fig: Energy levels versus detuning with avoided crossing between the two eigenstates [1]

[1] Shevchenko, S. N., Ashab, S., Nori, F., Phys. Rep. 492, 1 (2010)

Landau-Zehner Transition

- *single* passage across avoided crossing
- assume monochromatic drive

$$\varepsilon(t) = \varepsilon_0 + A \cdot \sin(\omega t)$$

- transition probability

$$P_{\mathrm{LZ}} = \exp\left(-2\pi \frac{\Delta^2}{4v}\right)$$

- acquire Stokes phase during non-adiabatic transition

$$\varphi_{\mathrm{S}} = \frac{\pi}{4} + \delta(\ln \delta - 1) + \arg \Gamma(1 - i\delta)$$

$$\delta = \frac{\Delta^2}{4v}$$

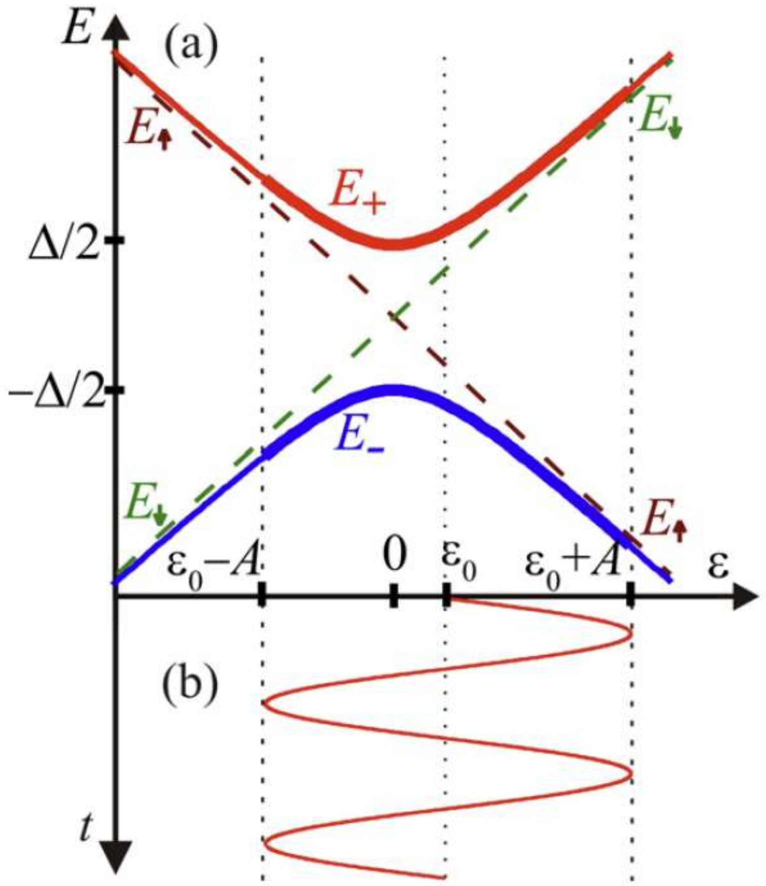


Fig: Energy levels versus detuning with avoided crossing between the two eigenstates [1]

[1] Shevchenko, S. N., Ashab, S., Nori, F., Phys. Rep. 492, 1 (2010)

Stückelberg Phase

- *double* passage across avoided crossing
- probability to end up in upper level

$$P_+ = 4P_{\mathrm{LZ}}(1 - P_{\mathrm{LZ}})\sin^2\Phi_{\mathrm{St}}$$

- with the Stückelberg phase

$$\Phi_{\mathrm{St}} = \zeta_2 + \phi_{\mathrm{S}}$$

  - ζ_2 phase acquired during adiabatic evolution
  - ϕ_S phase acquired during non-adiabatic transitions (Stokes phase)

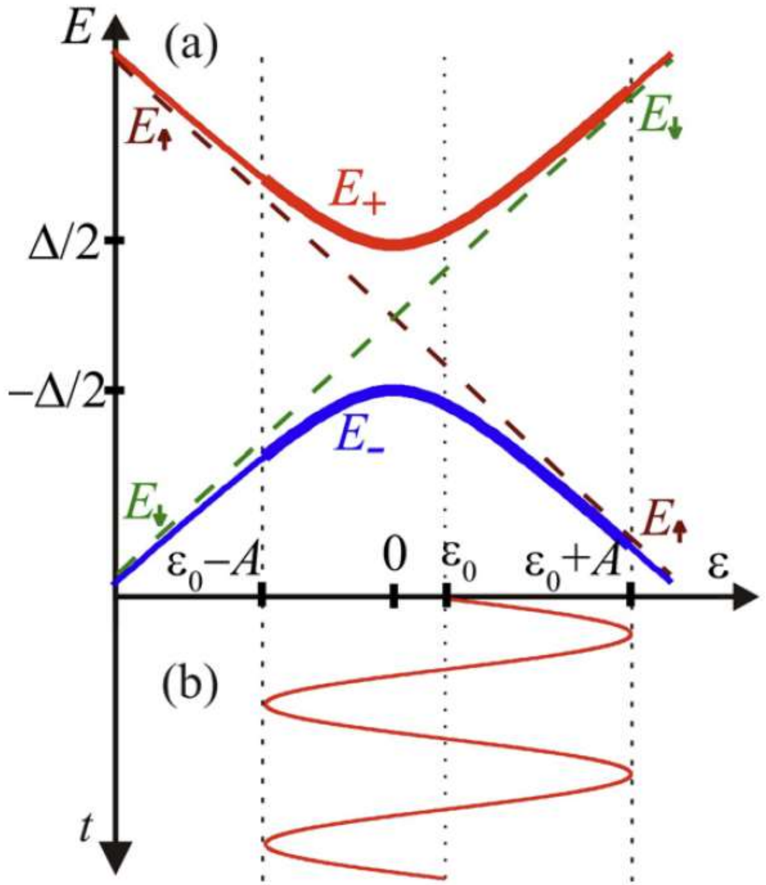


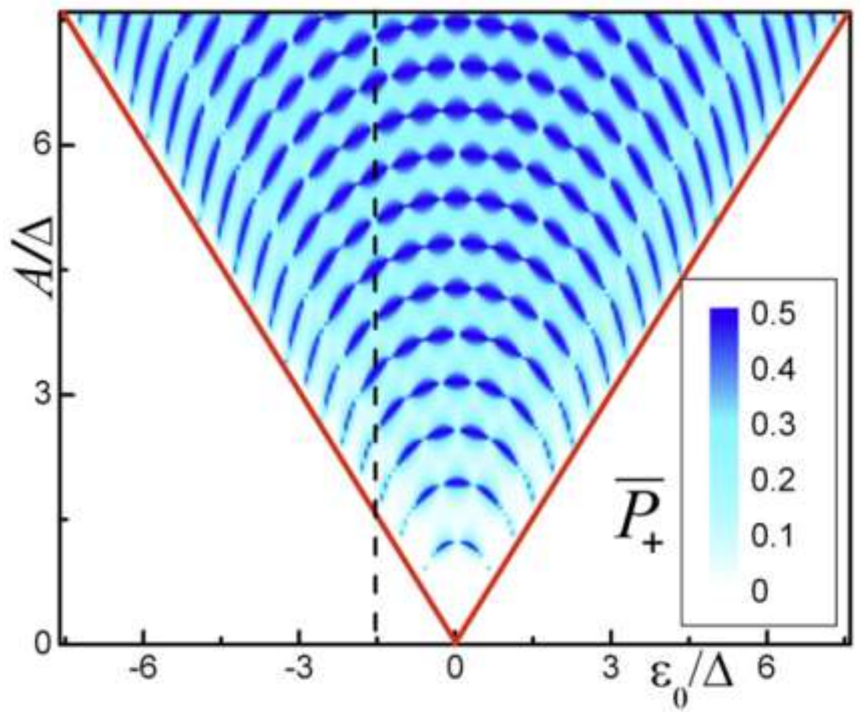
Fig: Energy levels versus detuning with avoided crossing between the two eigenstates [1]

[1] Shevchenko, S. N., Ashab, S., Nori, F., Phys. Rep. 492, 1 (2010)

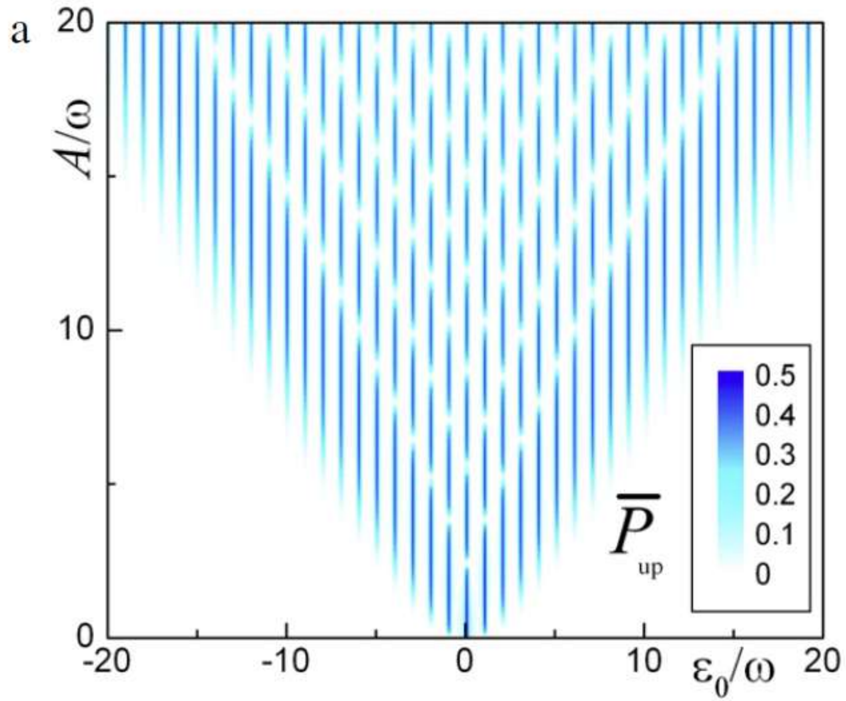
Landau-Zehner-Stückelberg-Majorana Interferometry

- *multiple* passage across avoided crossing

Slow passage limit



Fast passage limit



[1] Shevchenko, S. N., Ashab, S., Nori, F., Phys. Rep. 492, 1 (2010)

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Device Overview

- Si/SiGe double quantum dot in single electron regime
- coupled to microwave cavity
    - **strong coupling regime**

      $\kappa/2\pi = 3.3\ \mathrm{MHz}$

      $\gamma/2\pi = 4.1\ \mathrm{MHz}$

      $2g_{\mathrm{VO}}/2\pi = 16.0\ \mathrm{MHz}$
- hybrid valley-orbit state
    - strain lifts 6-fold valley degeneracy
    - $E_L = 37.5\ \mu eV$, $E_R = 38.3\ \mu eV$

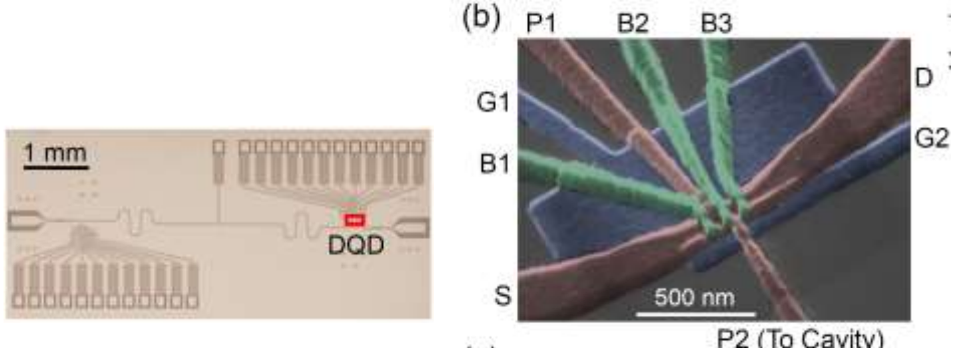

Fig: Optical image and colored SEM image of the device; cavity frequency f_c = 7.796 GHz [1]

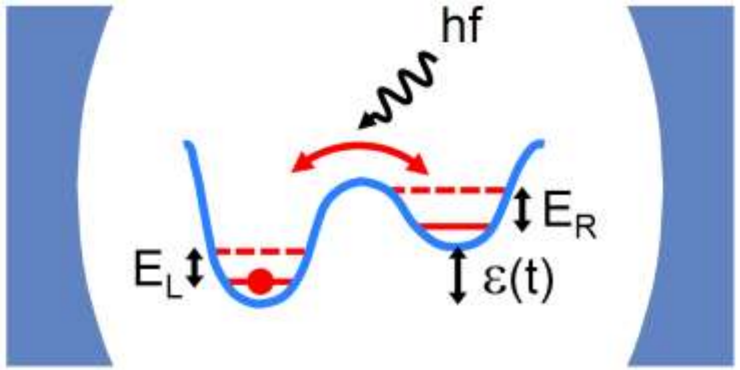

Fig: Schematic displaying the DQD in the cavity with tunable detuning ε(t) and cavity photon hf [1]

[1] Mi, X., Kohler, S., Petta, J. R., arXiv:1805.04545

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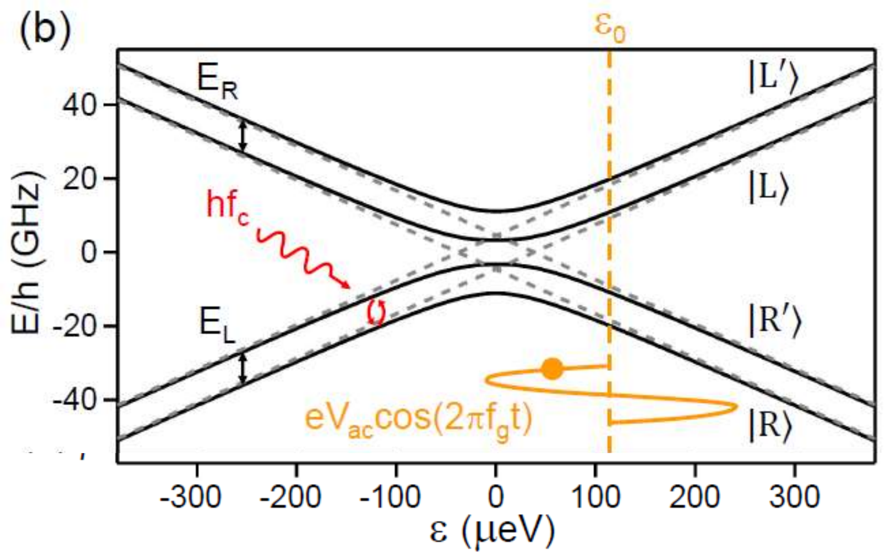
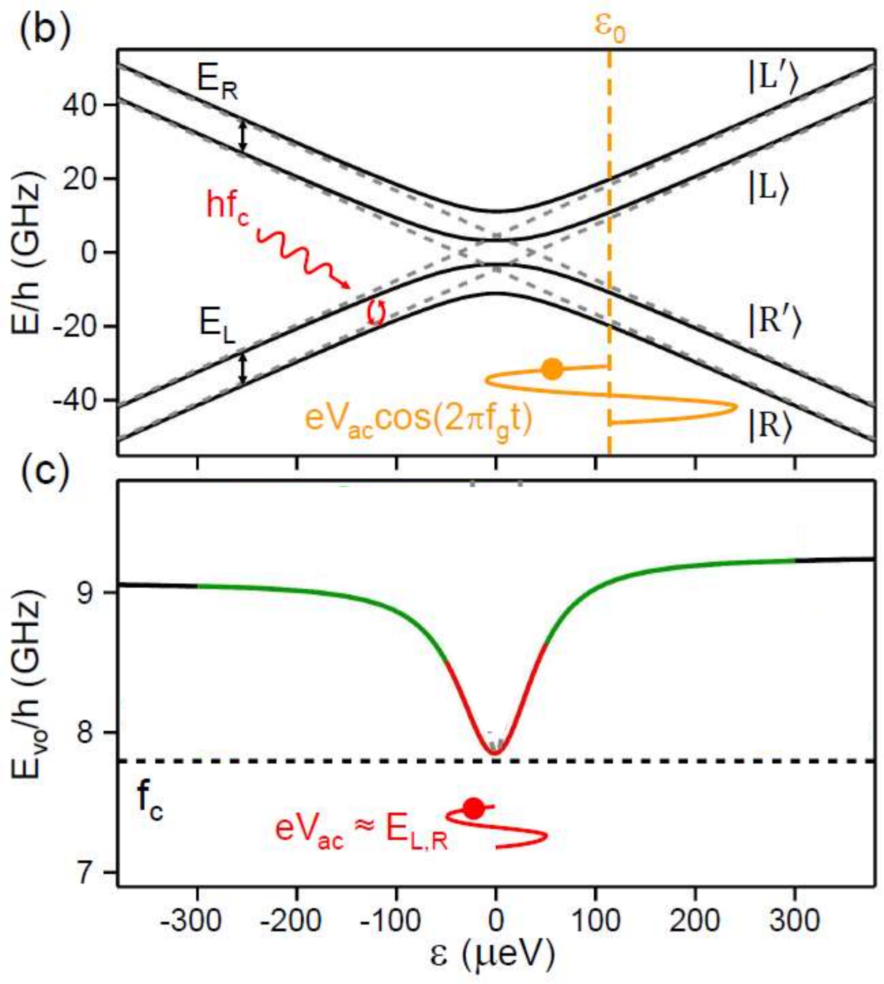
Landau-Zehner-Stückelberg-Majorana Interferometry

- DQD energy level diagram



[1] Mi, X., Kohler, S., Petta, J. R., arXiv:1805.04545

Landau-Zehner-Stückelberg-Majorana Interferometry



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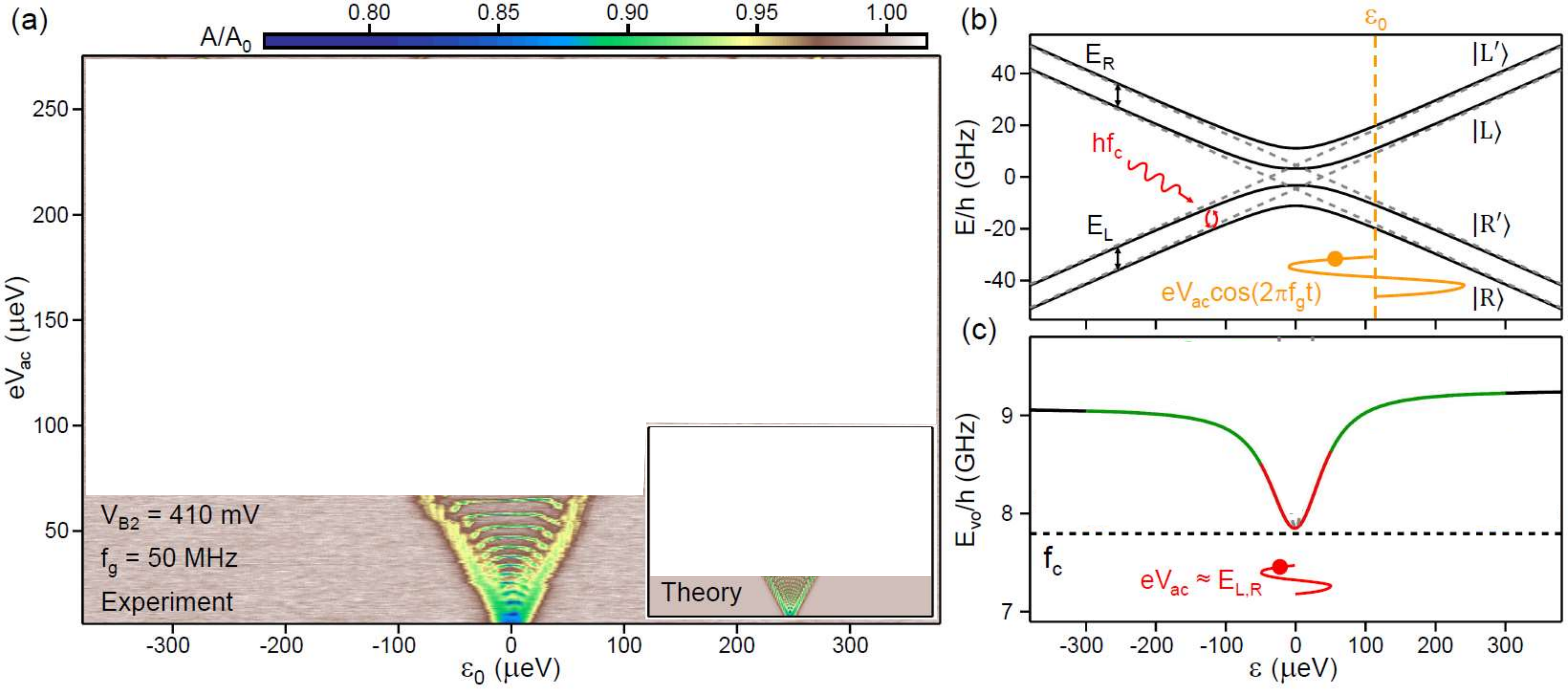

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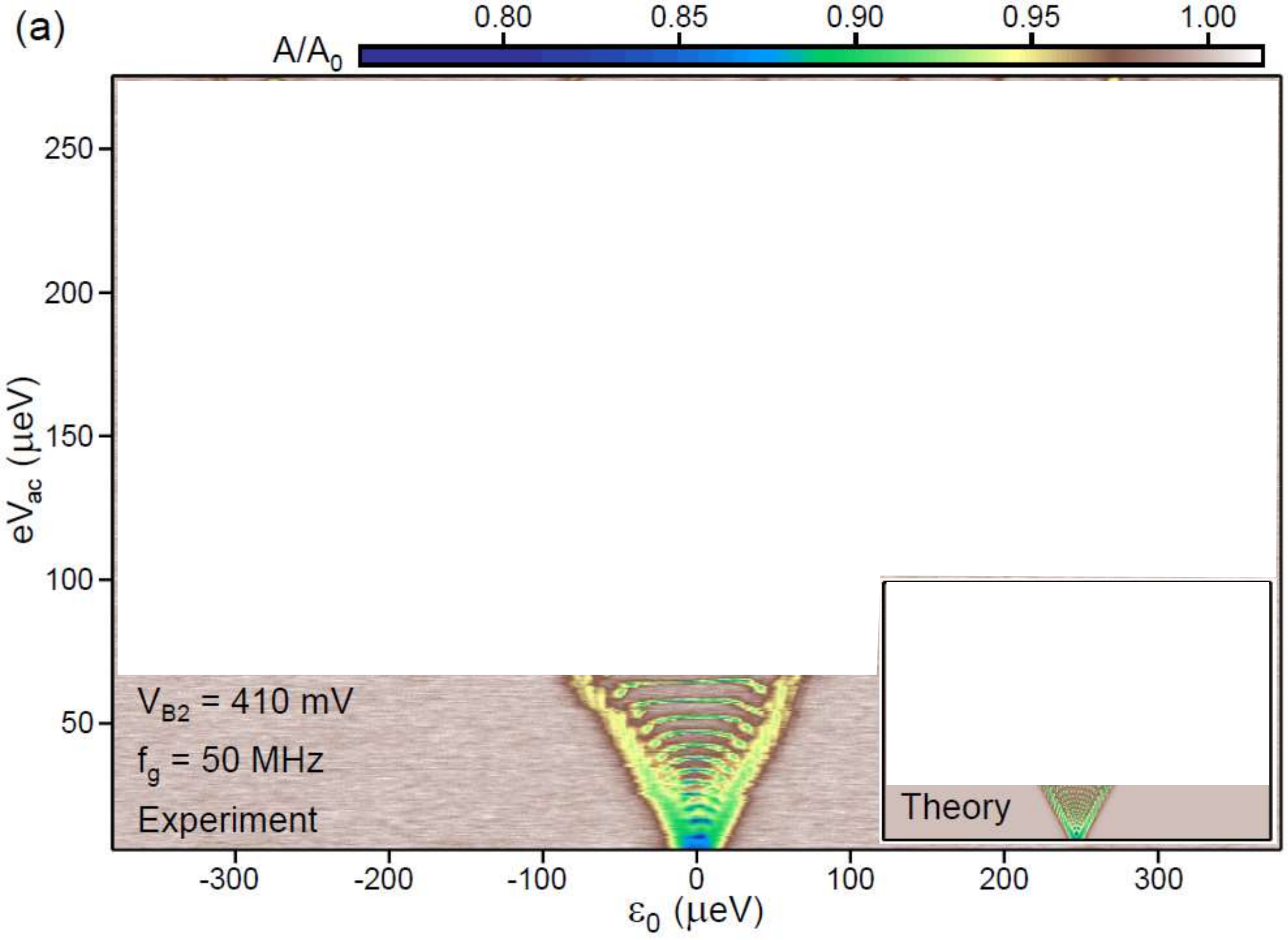
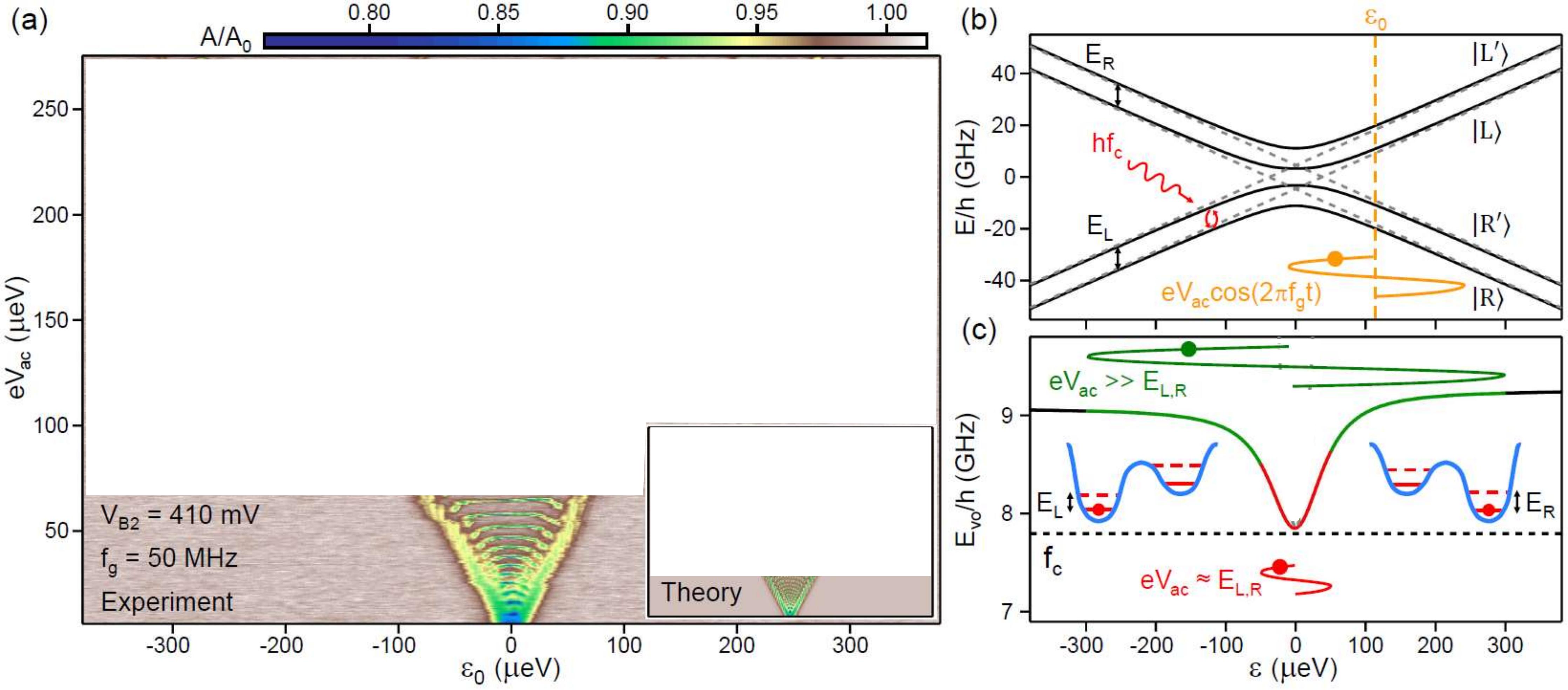


- for small detuning $|\varepsilon| \leq E_{\mathrm{L,\,R}}$
  - hybridized valley-orbit states
- LZSM pattern resembles case of conventional two level system

[1] Mi, X., Kohler, S., Petta, J. R., arXiv:1805.04545

Landau-Zehner-Stückelberg-Majorana Interferometry



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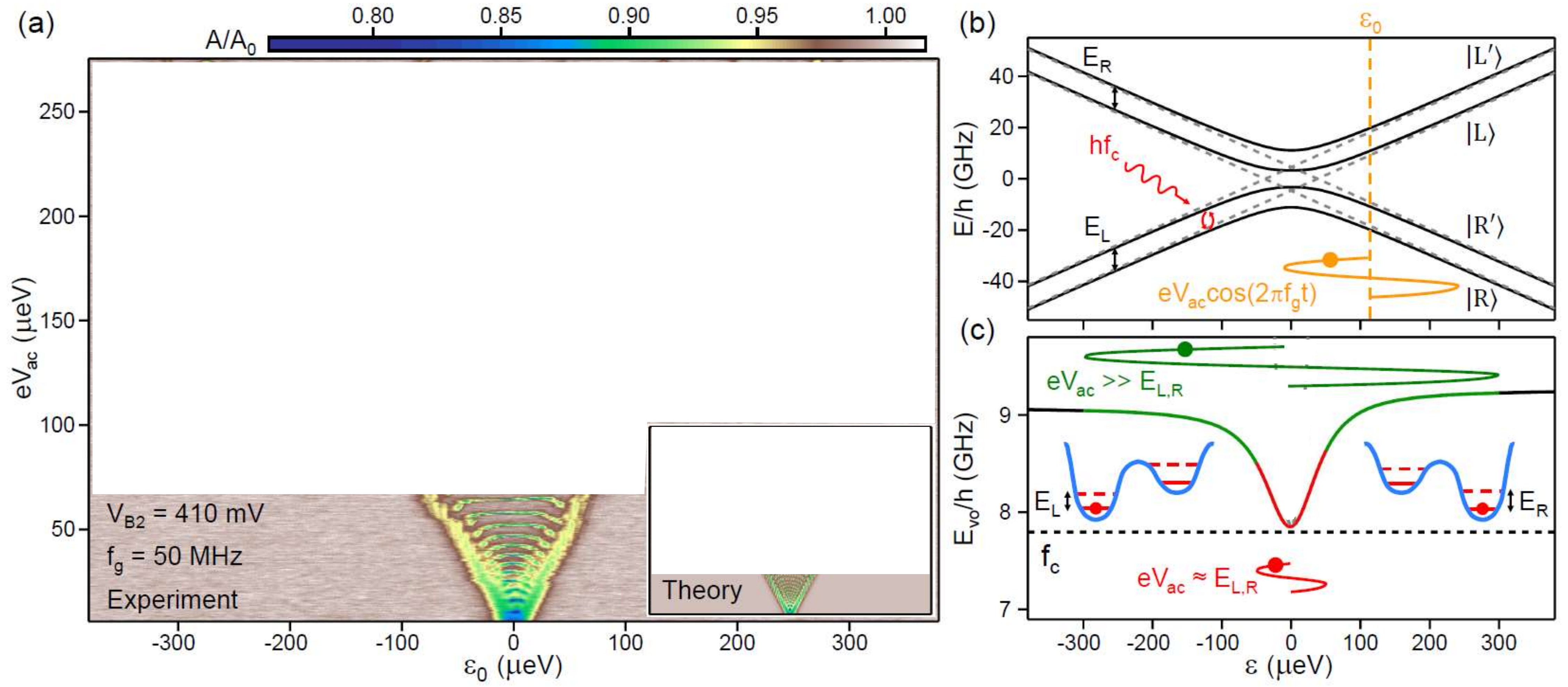

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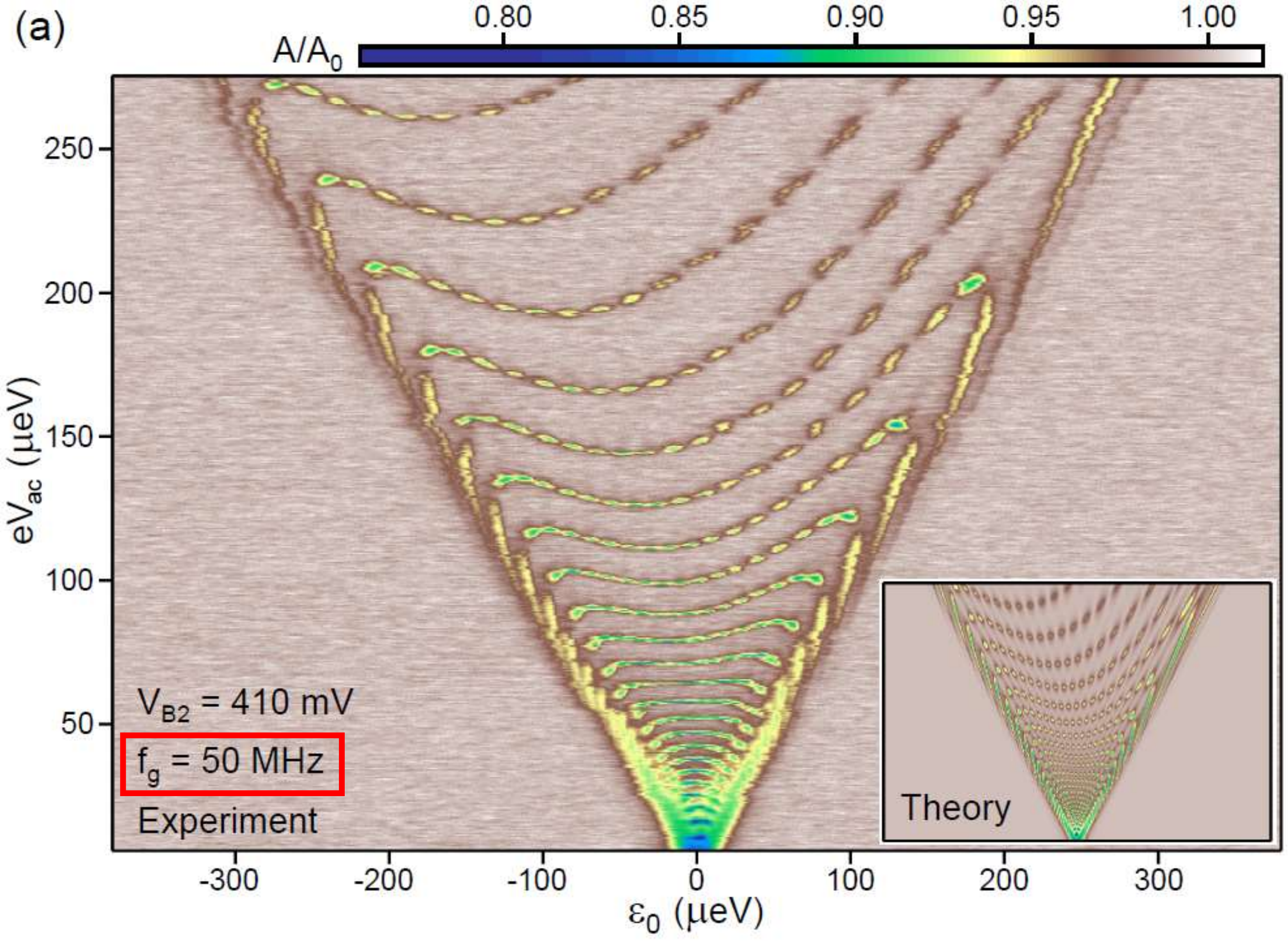
Landau-Zehner-Stückelberg-Majorana Interferometry



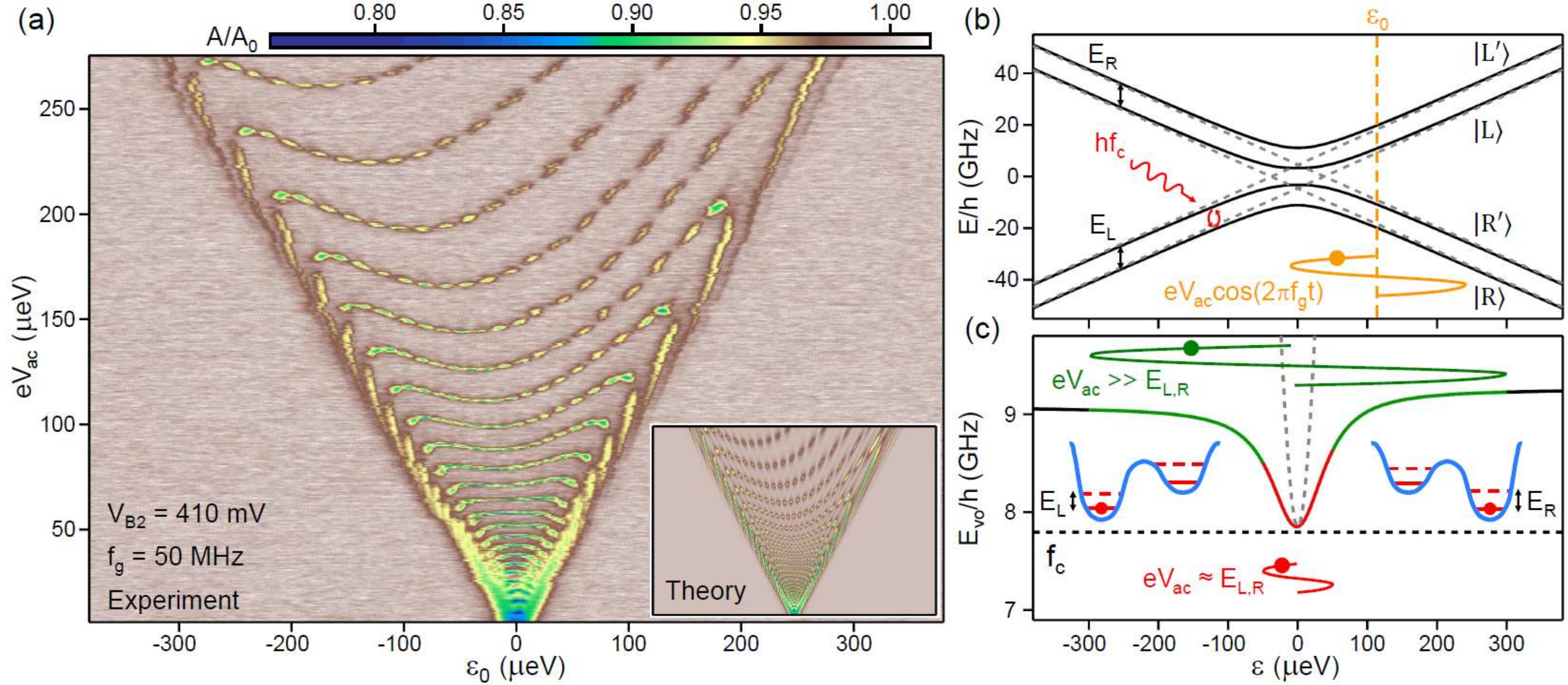
- at large detuning $|\varepsilon| \gg E_{\mathrm{L,\ R}}$
  - single-dot valley splitting dominates
  - leads to asymmetric interference pattern
- long charge coherence
  - due to flat dispersion relation of valley-orbit qubit

$$\left|\frac{\mathrm{d}E_{\mathrm{VO}}}{\mathrm{d}\varepsilon}\right| < 0.08$$

$$\left|\frac{\mathrm{d}E_{\mathrm{CQ}}}{\mathrm{d}\varepsilon}\right| \approx 1$$

[1] Mi, X., Kohler, S., Petta, J. R., arXiv:1805.04545

Landau-Zehner-Stückelberg-Majorana Interferometry



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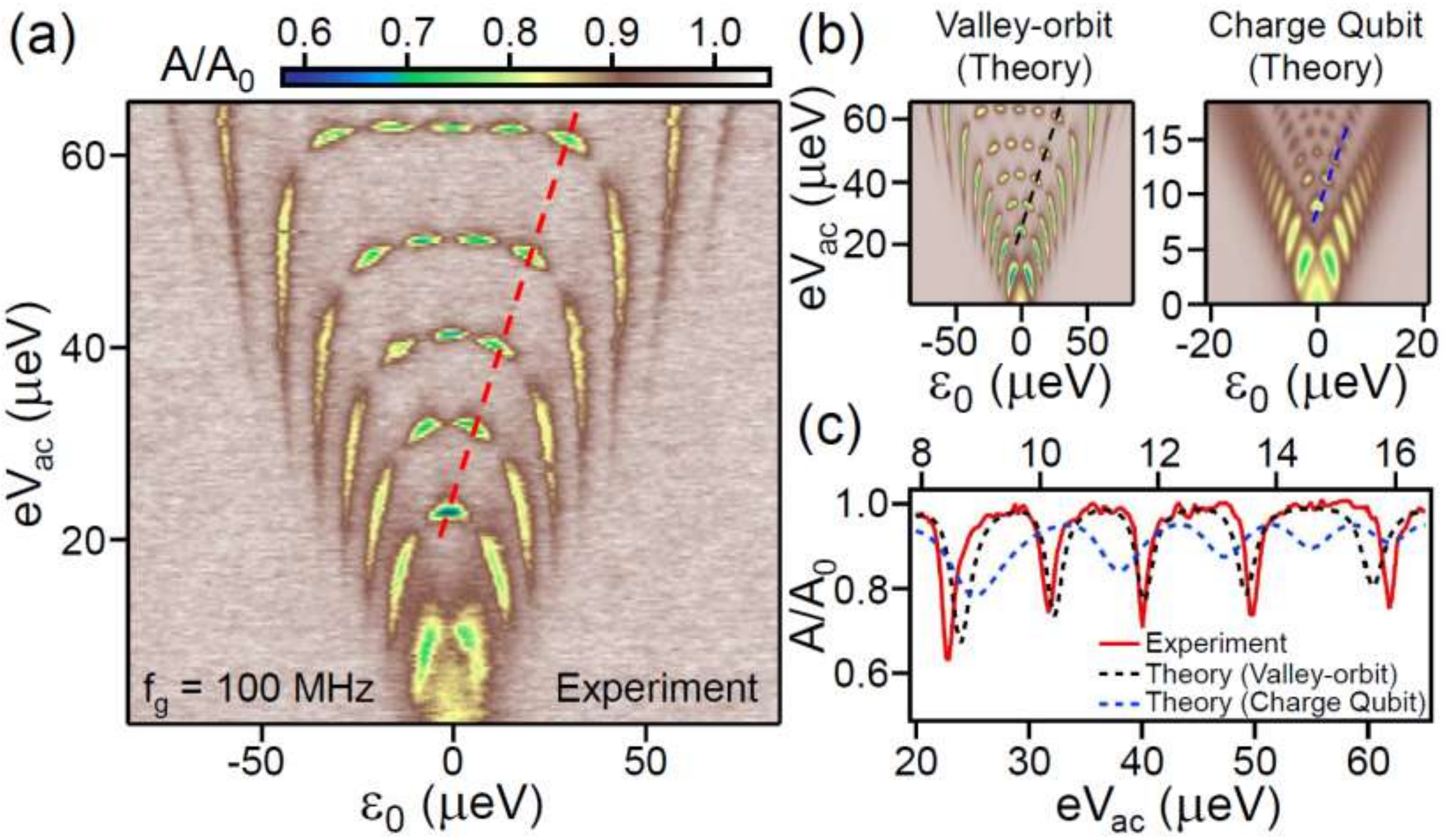
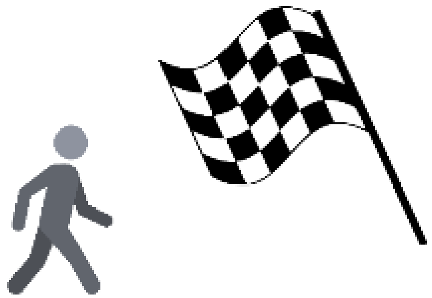
Valley-Orbit Qubit Advantage



[1] Mi, X., Kohler, S., Petta, J. R., arXiv:1805.04545

Outline



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X. Mi, S. Kohler, J. R. Petta, arXiv:1805.04545

Summary and Outlook

- Landau-Zehner-Stückelberg-Majorana Interferometry
  - allows determination of important parameters of Hamiltonian
- LZSM interference pattern in Si/SiGe DQD
  - very low driving frequency of 50 MHz (compared to GHz in other systems)
- valley-orbit qubit less sensitive to charge noise
  - use valley degree of freedom for enhanced silicon qubits?
  - deterministic tailoring of valley splitting necessary

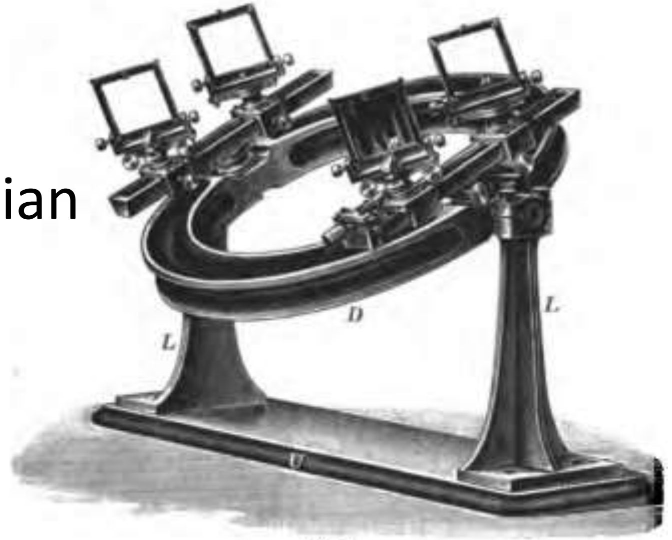


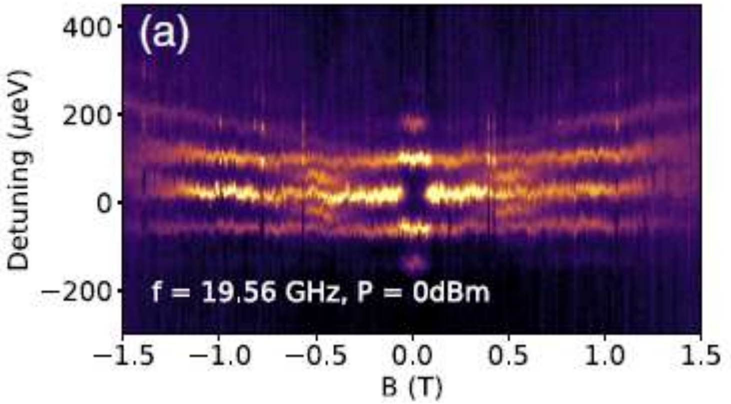
Fig. 1.

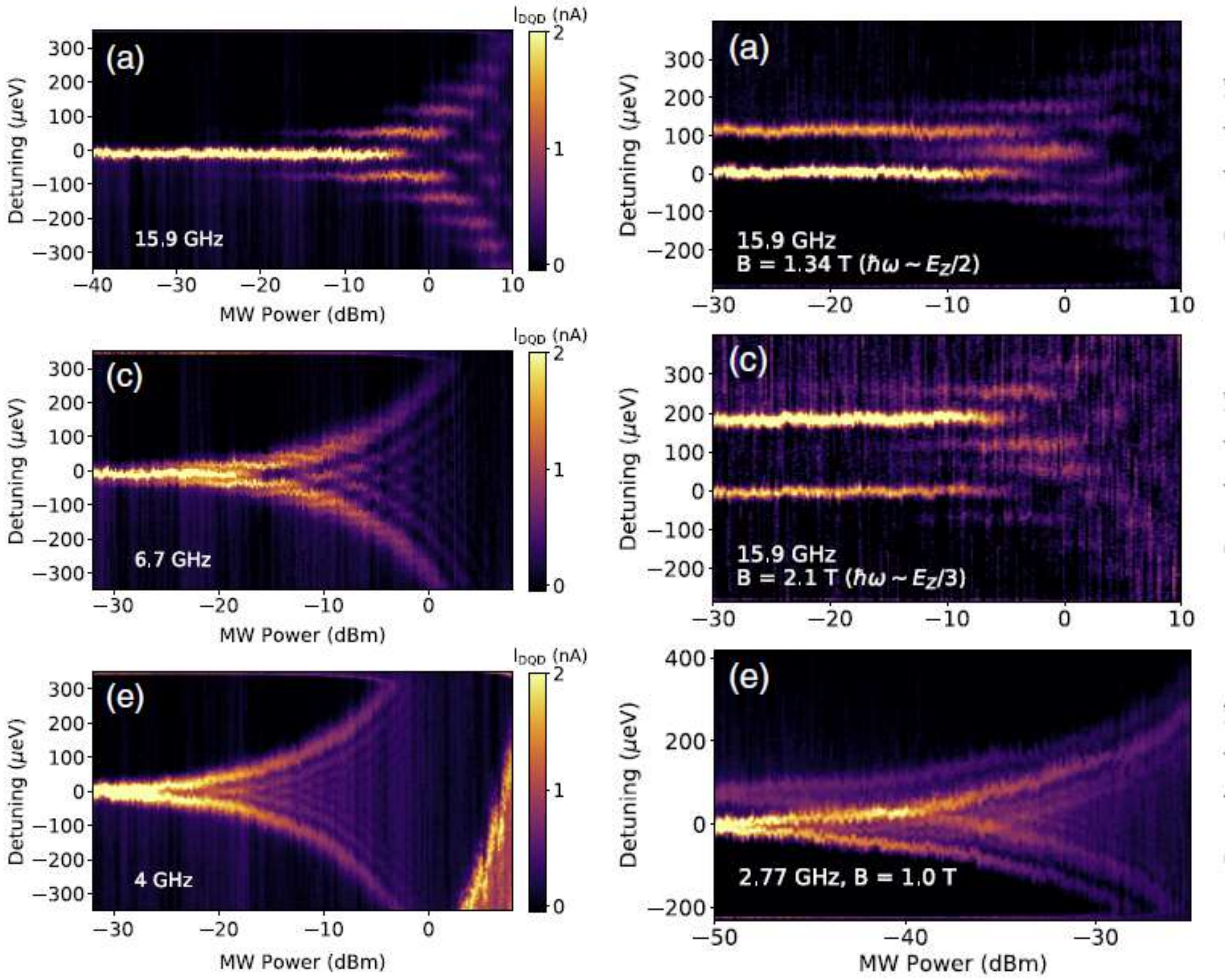
Additional Slides

- LZSM interferometry of Single Hole in GaAs

LZSM Interferometry of Single Hole in GaAs

- Single hole in GaAs DQD
- strong SOI
- two tunneling processes
  - spin conserving
  - spin flipping





[1] A. Bogan *et al.*, PRL **120**, 207701 (2018)