Karlsruhe Institute of Technology

Josephson junction as a tool to manipulate microscopic two-level systems

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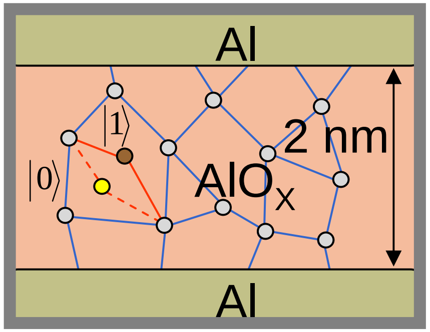
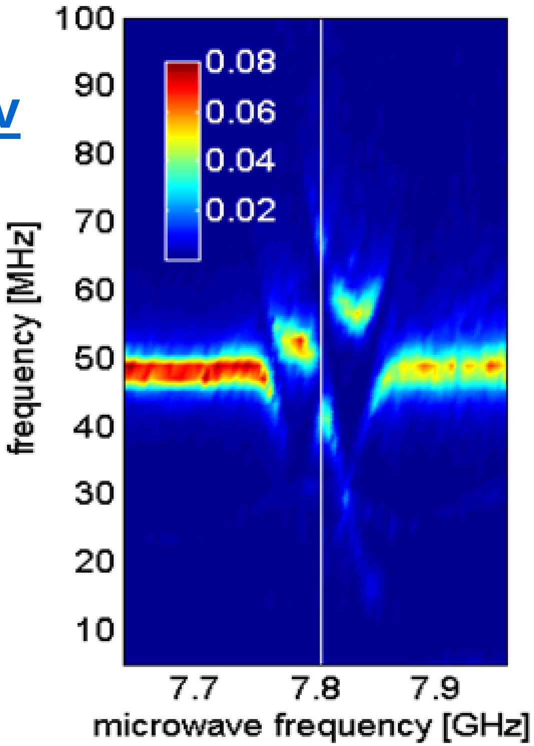
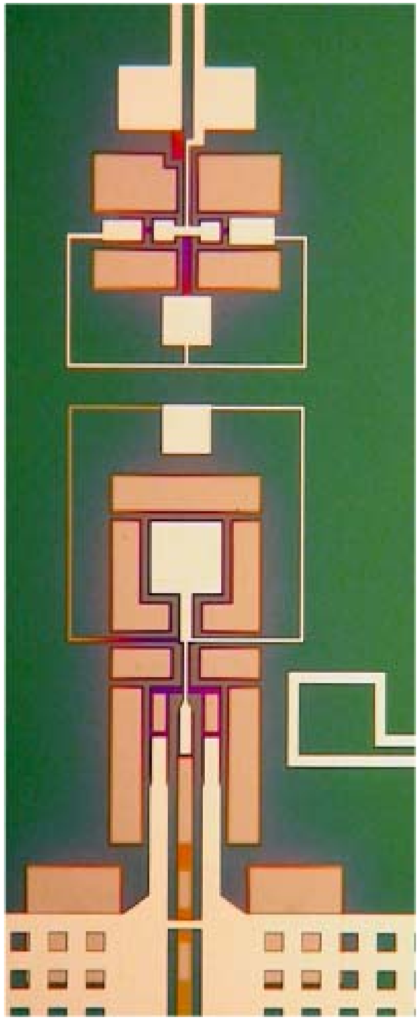
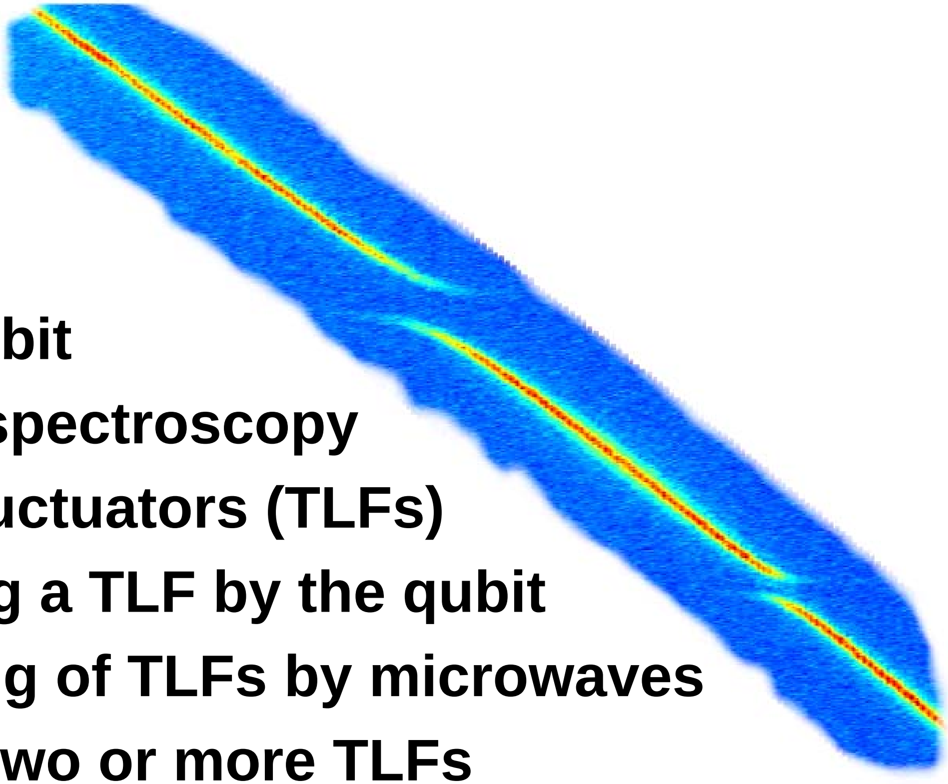




Outline

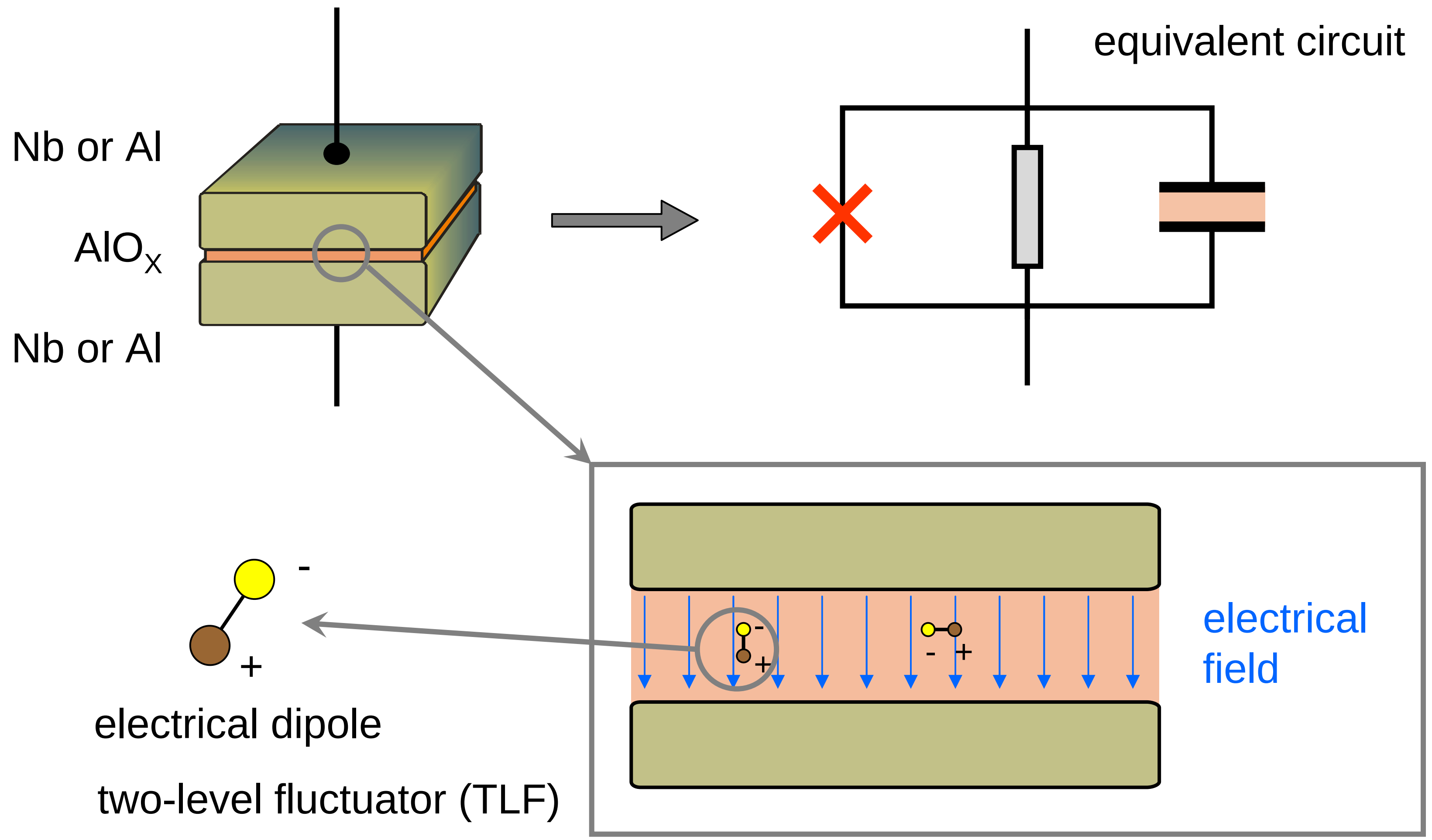




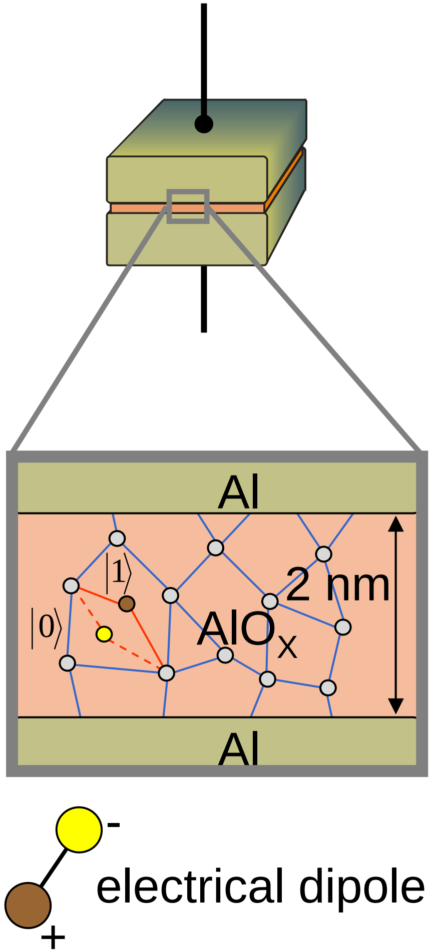
- JJ phase qubit
- Microwave spectroscopy
- Two-level fluctuators (TLFs)
- Manipulating a TLF by the qubit
- Direct driving of TLFs by microwaves
- Entangling two or more TLFs

J. Lisenfeld, C. Mueller, J. H. Cole, A. Lukashenko, A. Shnirman, and A. V. Ustinov. *ArXiv:0909.3425*

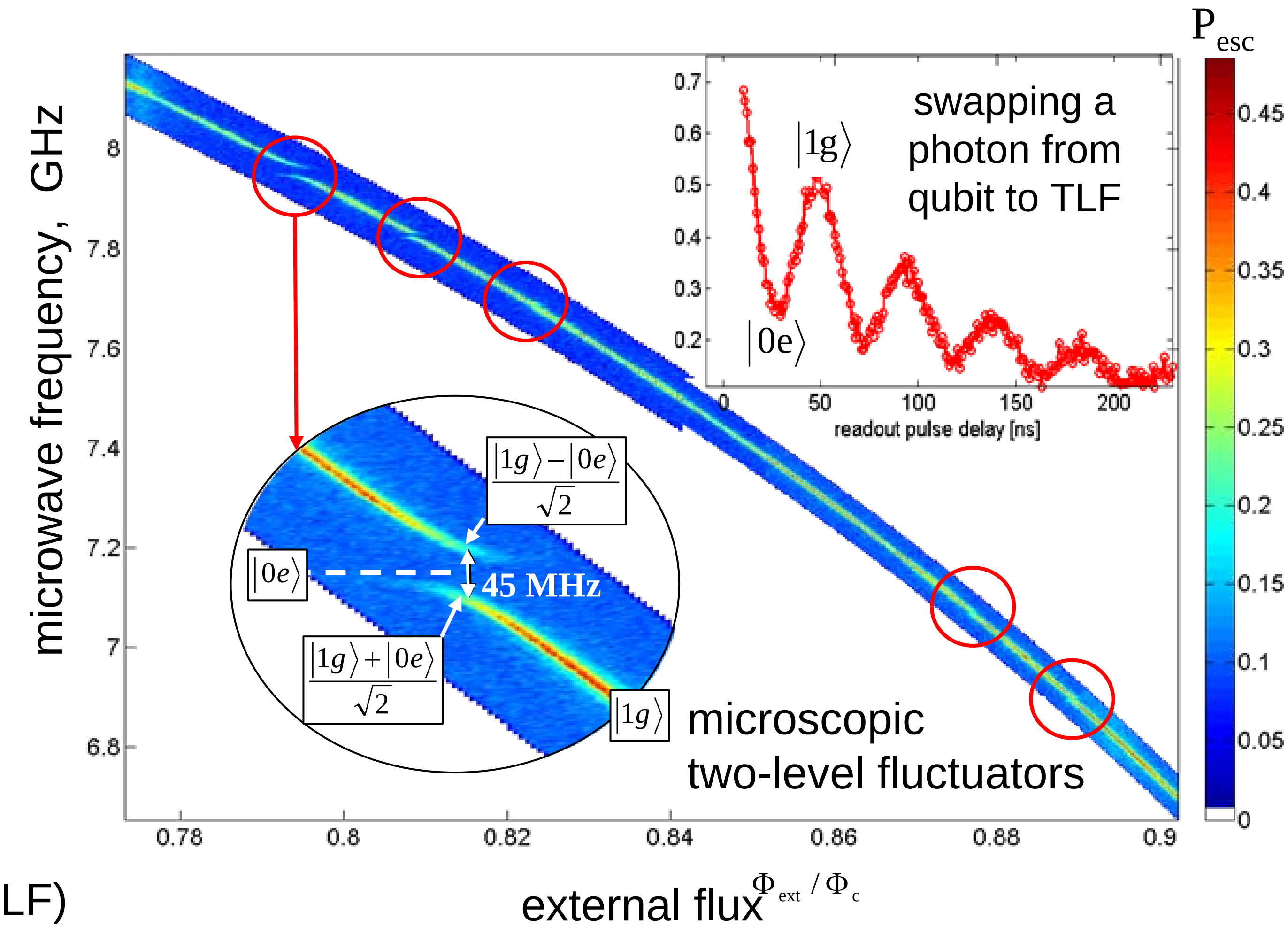
Josephson tunnel junction



Spectroscopic evidences of two-level fluctuators (TLFs)

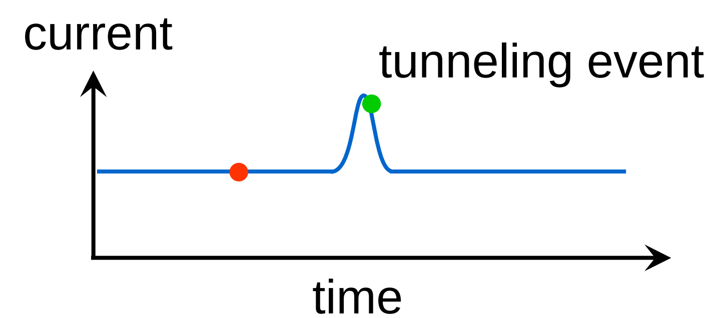


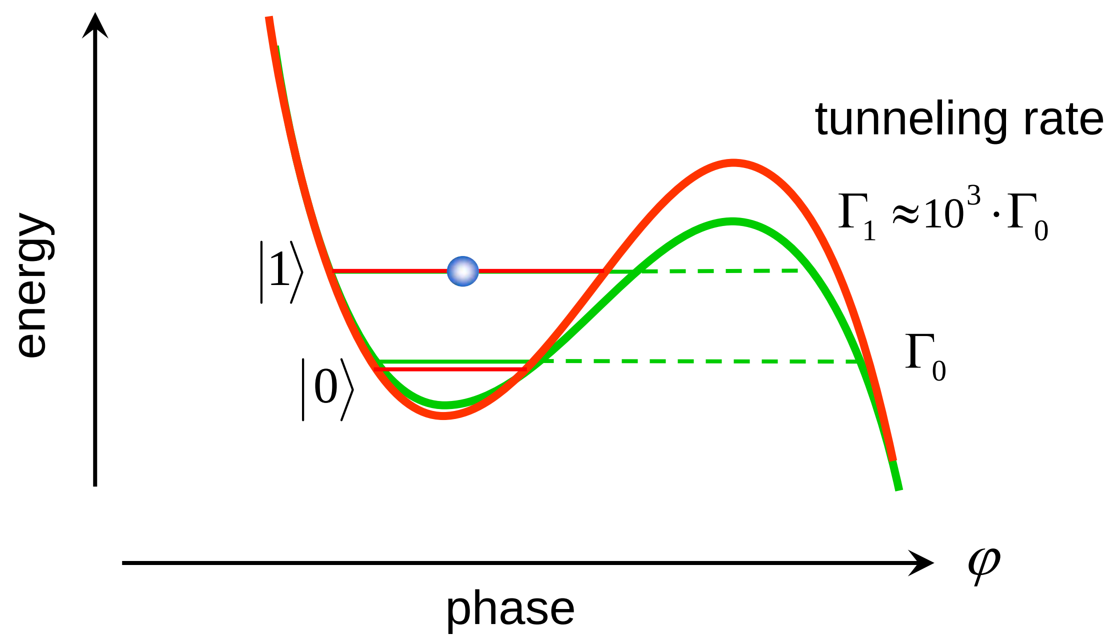
two-level fluctuator (TLF)

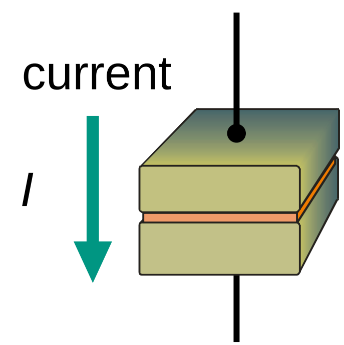


Phase qubit readout: Tunneling from the excited state

Readout by applying a tilt (current) pulse

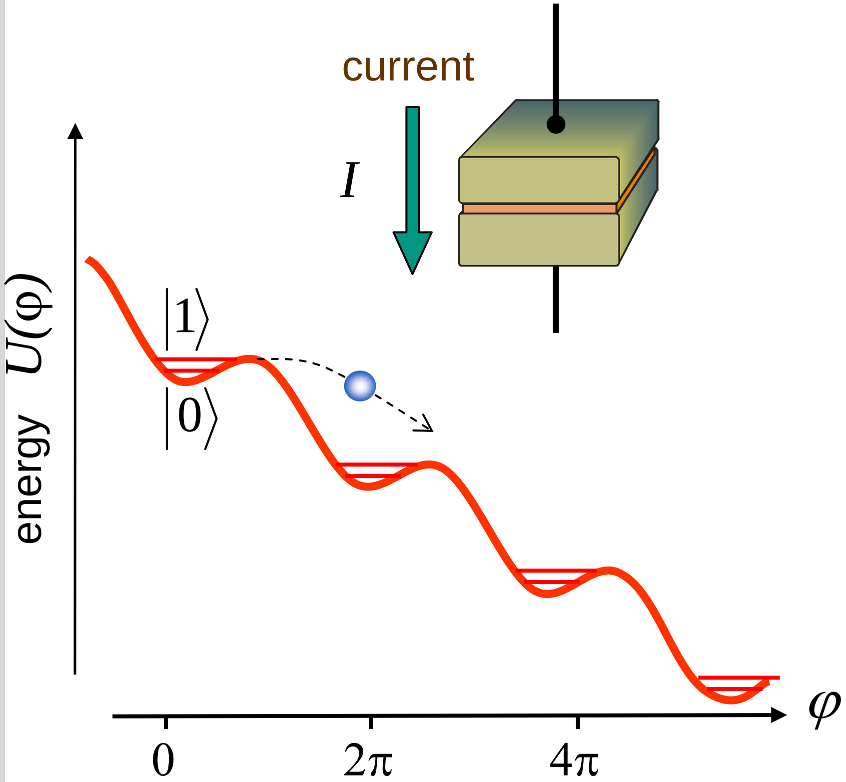




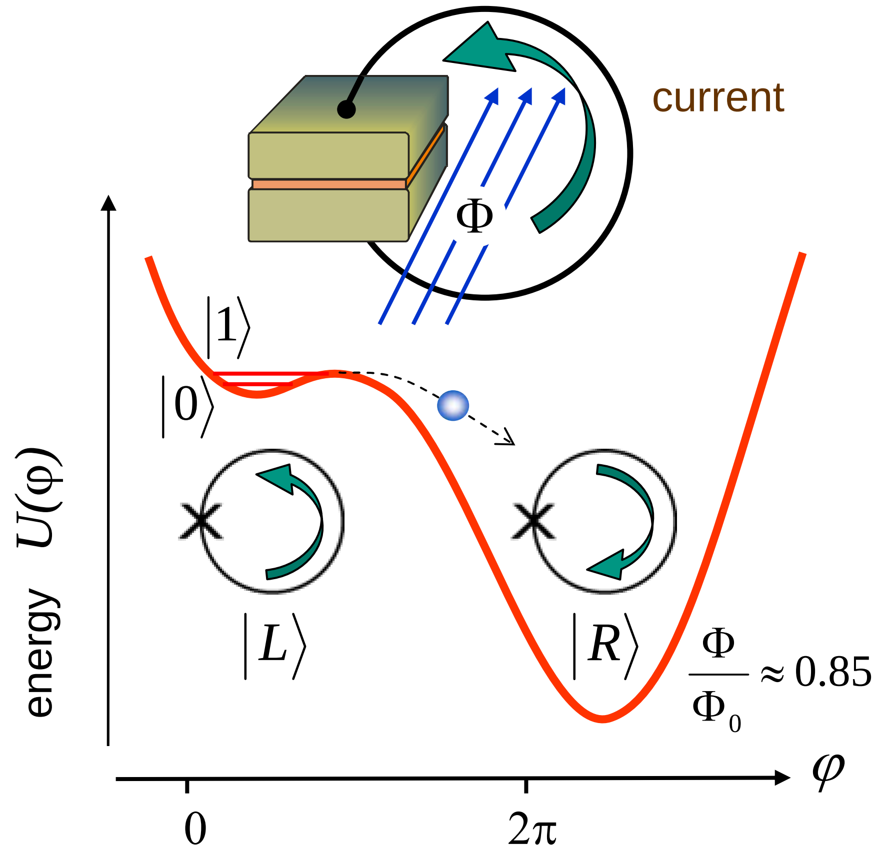


Reducing dissipation by placing the junction in a loop

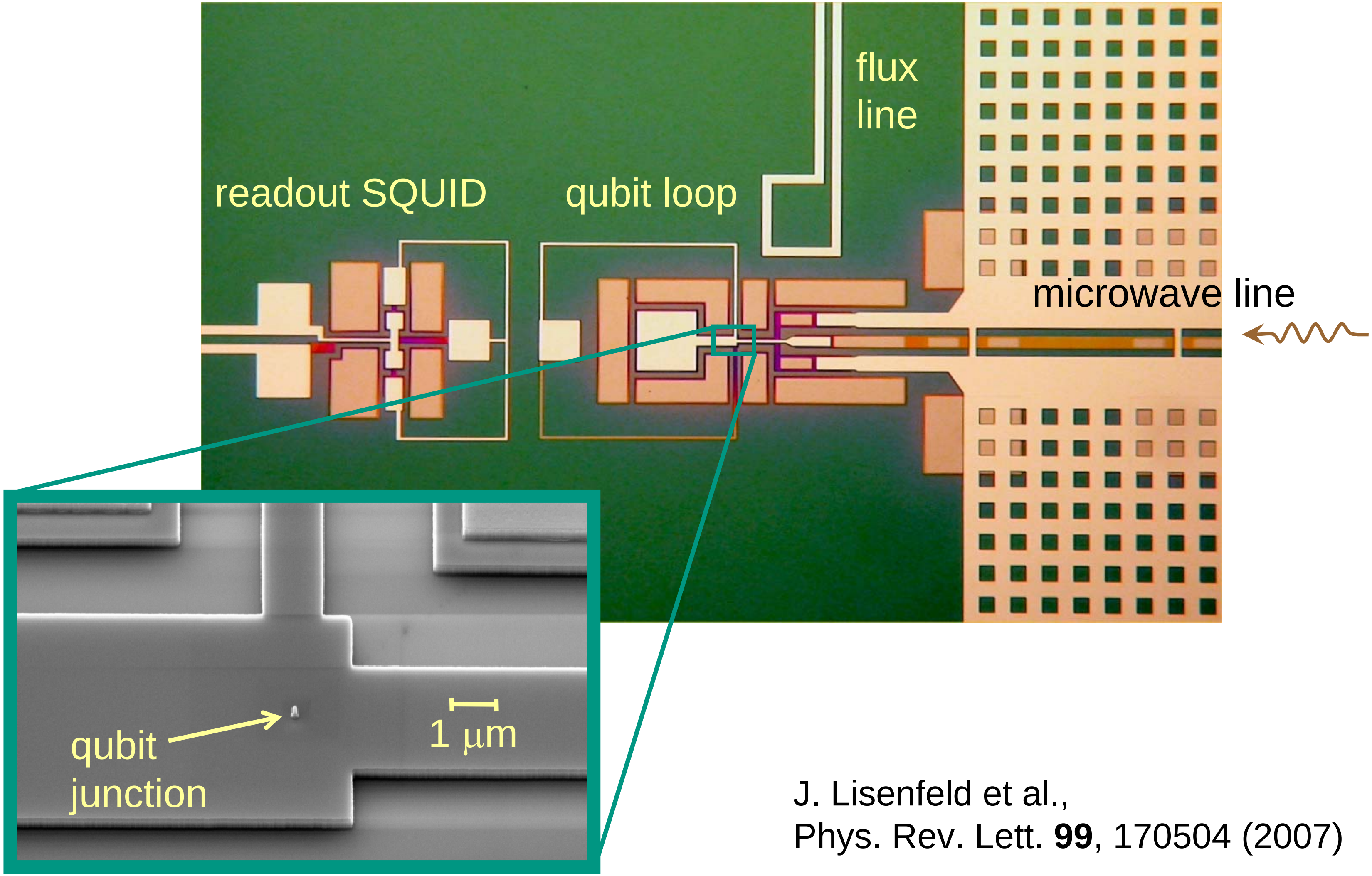
$$U(\varphi) = \frac{I_c \Phi_0}{2\pi}\left(-\frac{I}{I_c}\varphi - \cos\varphi\right)$$



$$U(\varphi) = \frac{I_c \Phi_0}{2\pi}\left[\frac{1}{2\beta_L}\left(\varphi - 2\pi\frac{\Phi}{\Phi_0}\right)^2 - \cos\varphi\right]$$

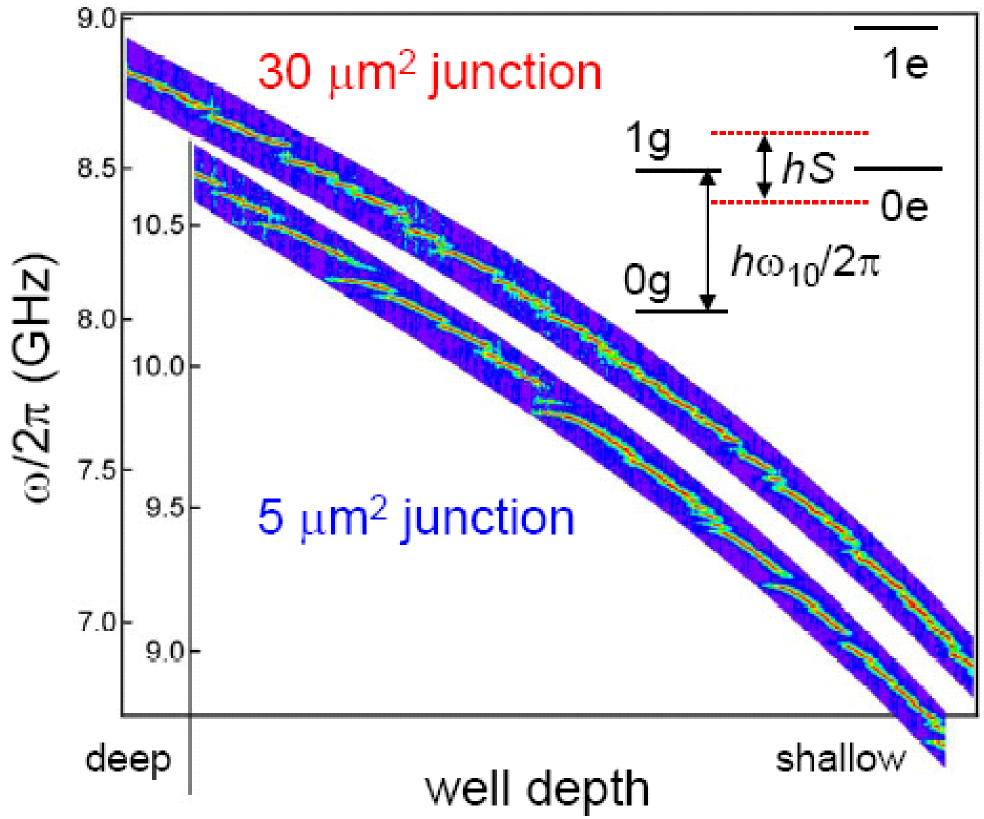


Josephson phase qubit



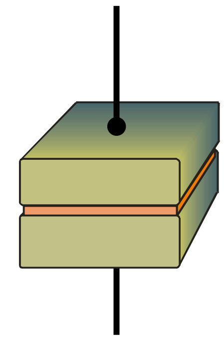
J. Lisenfeld et al.,
Phys. Rev. Lett. **99**, 170504 (2007)

Origin of decoherence in phase qubits: microscopic two-level fluctuators

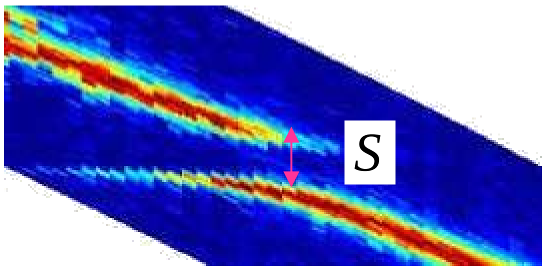


spectroscopy

$$S_{\max} \propto \sqrt{\frac{1}{A}}$$

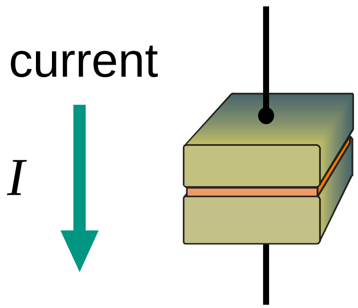


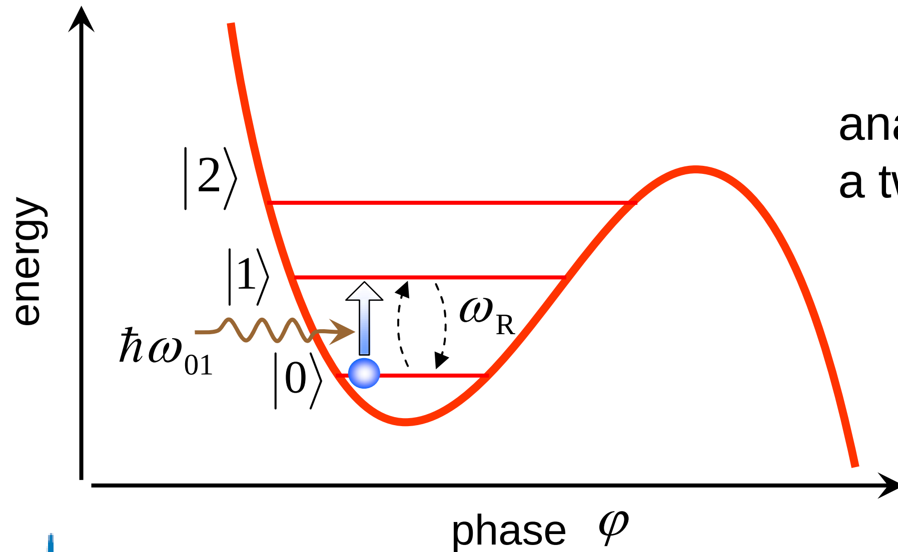
A is the junction area



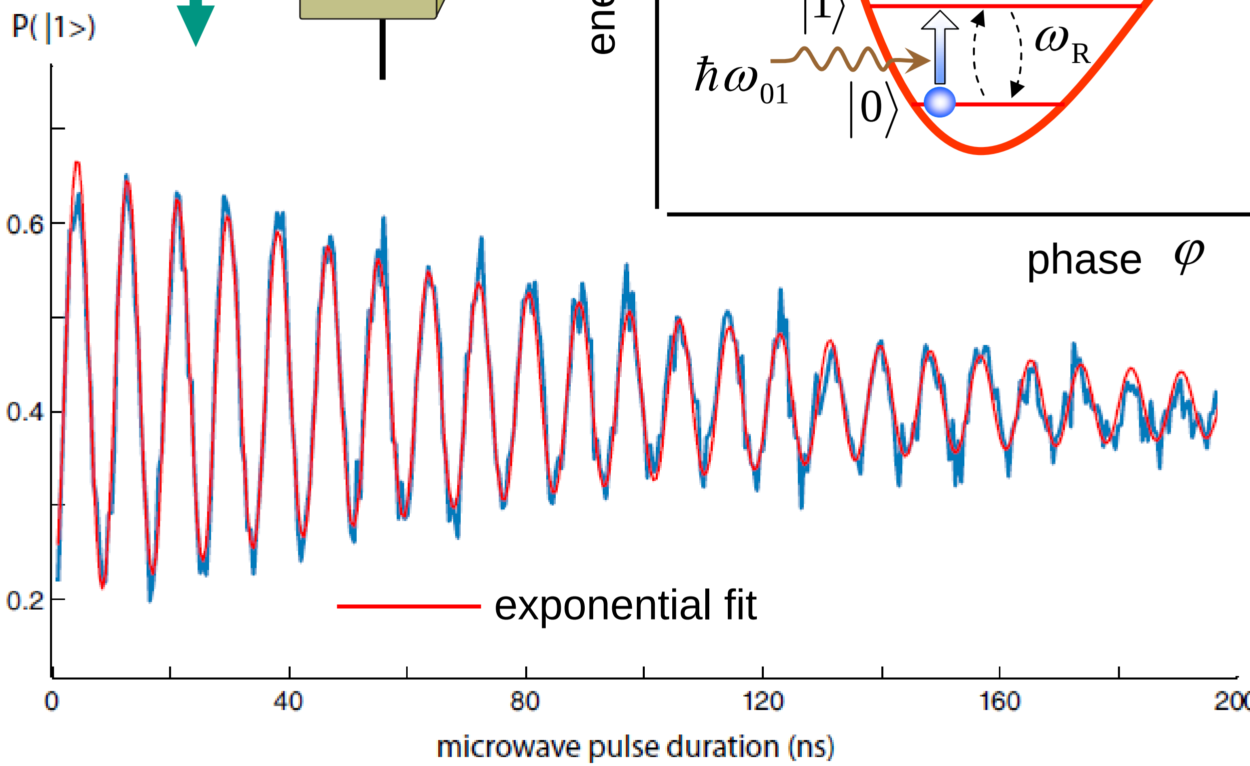
K. B. Cooper, et al., *Phys.Rev.Lett.* **93**, 180401 (2004).

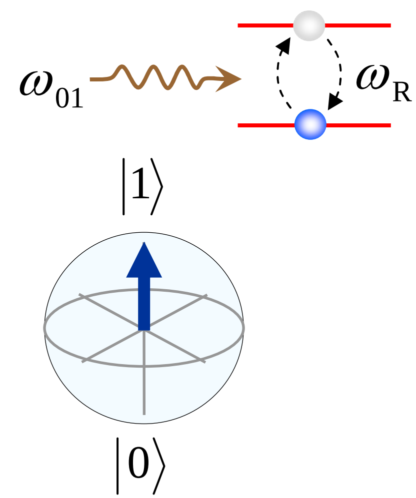
Josephson junction as a quantum system
- an artificial ‘atom’



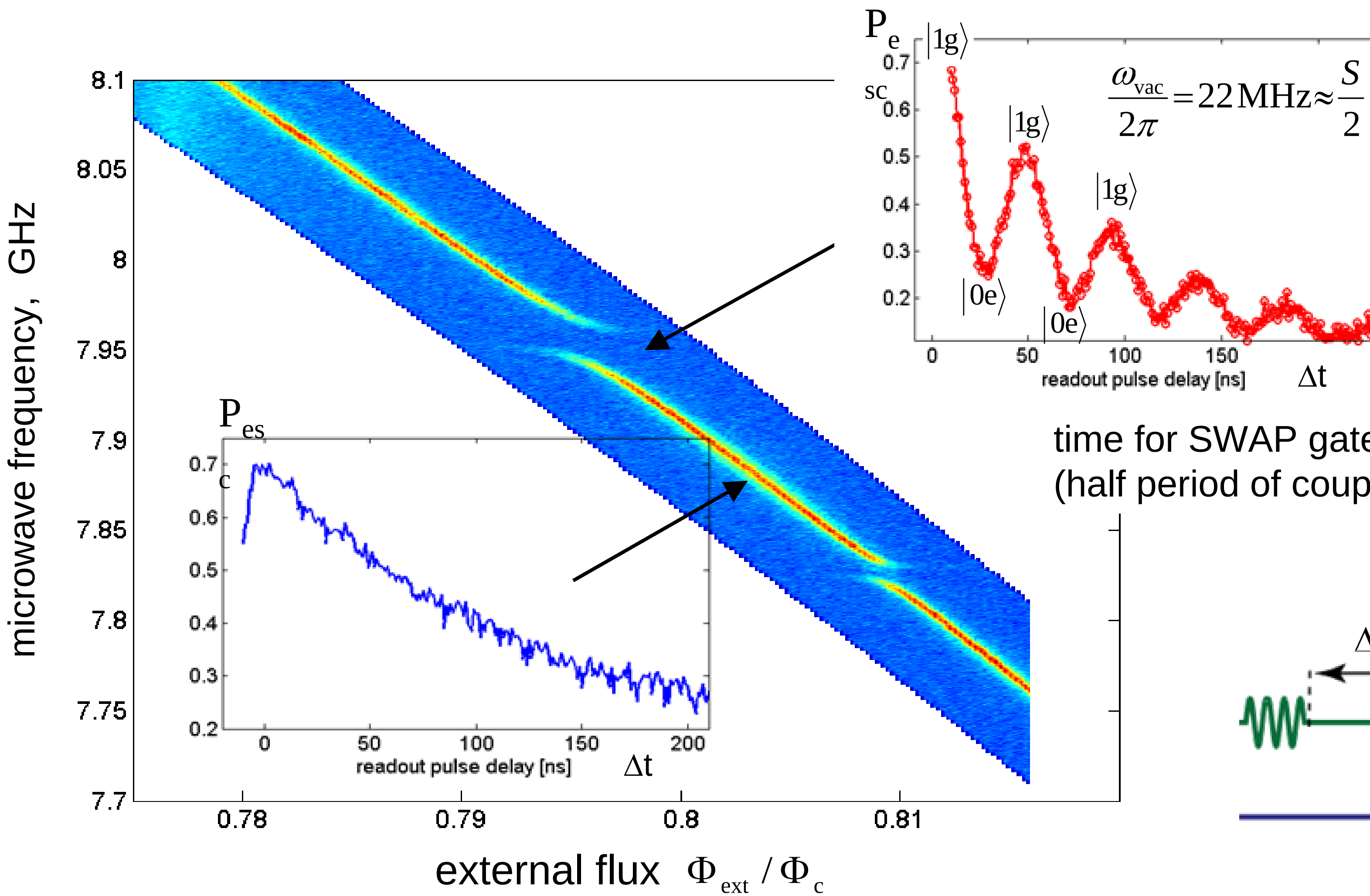


analog of
a two-level atom

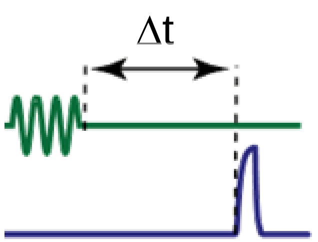




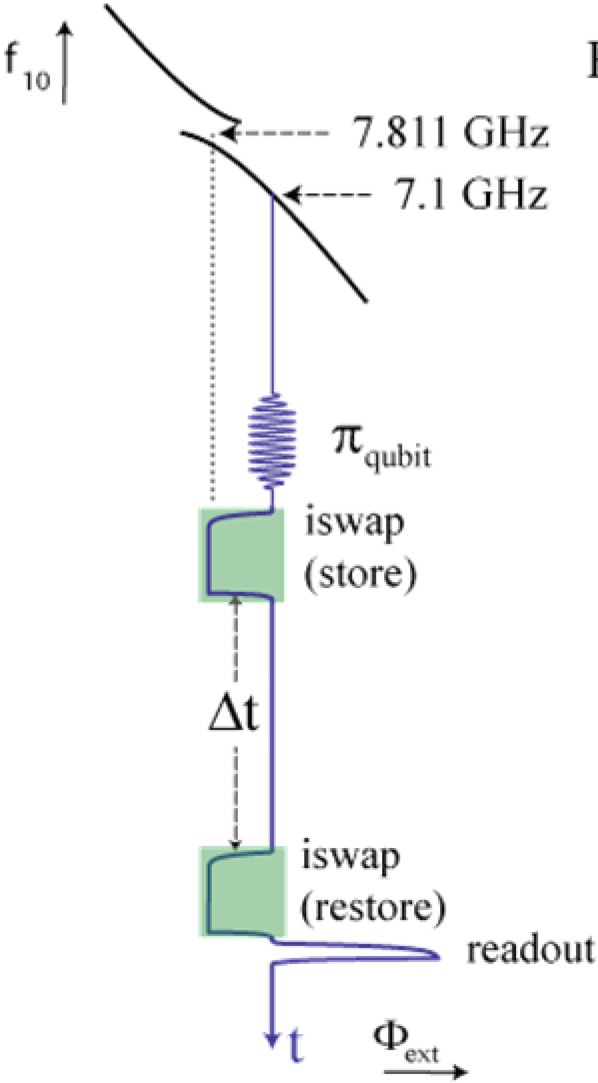
Swapping a quantum state of qubit with the state of two-level fluctuator

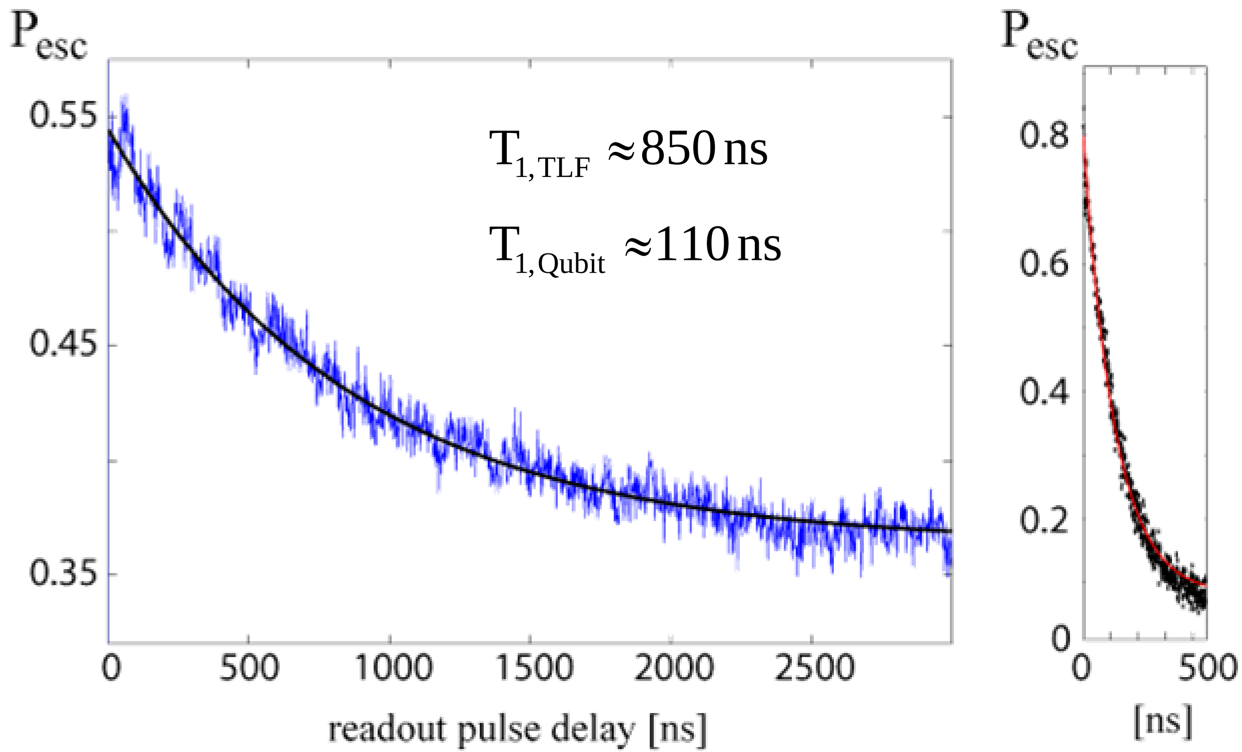


time for SWAP gate: 23ns (half period of coupled osc.)



Using a two-level fluctuator as a quantum memory



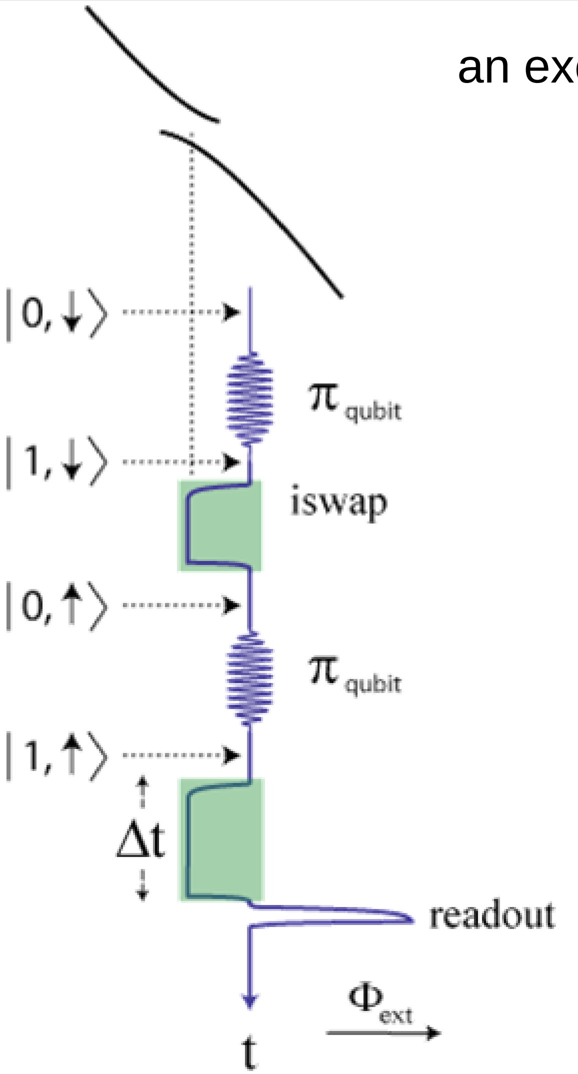


<u>see also:</u>

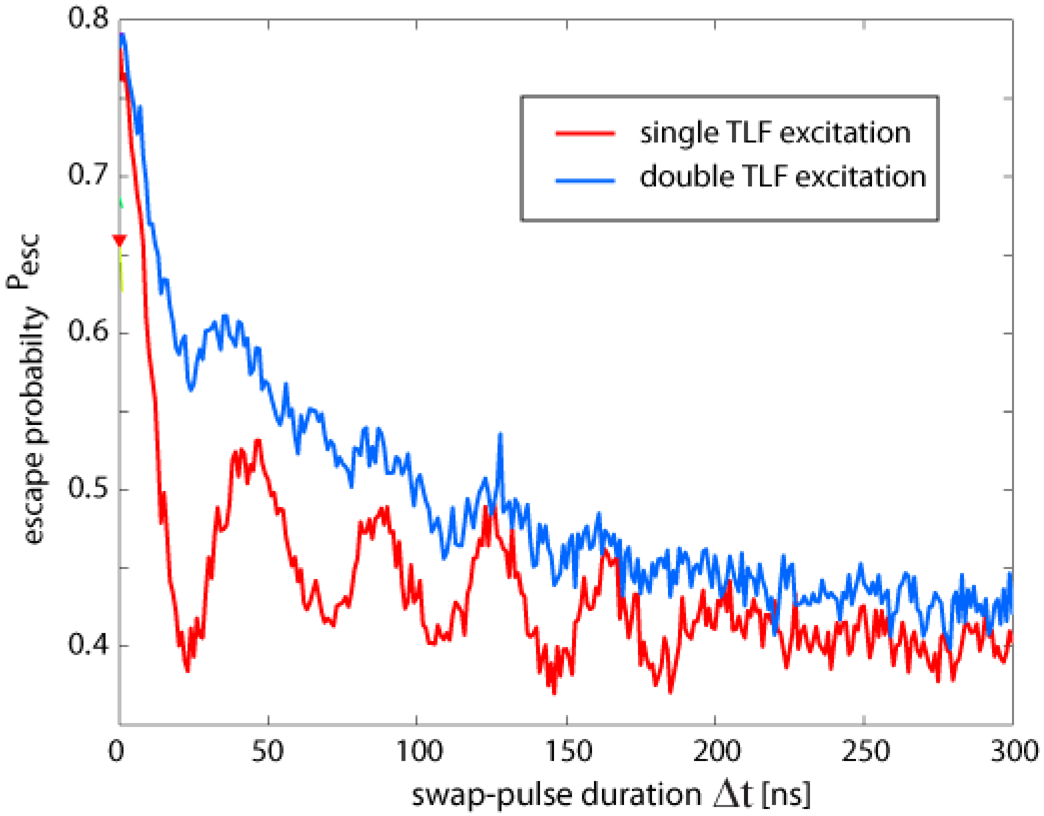
M. Neeley, M. Ansmann, J. Martinis, et. al., *Nature Physics* **4**, 523 (2008)

$T_{1,Qubit} \approx 400\,ns$, $T_{1,TLF} \approx 1.2\,\mu s$, $T_{2,TLF} \approx 210\,ns$

Is TLF really a two-level system ?
Yes, it is.

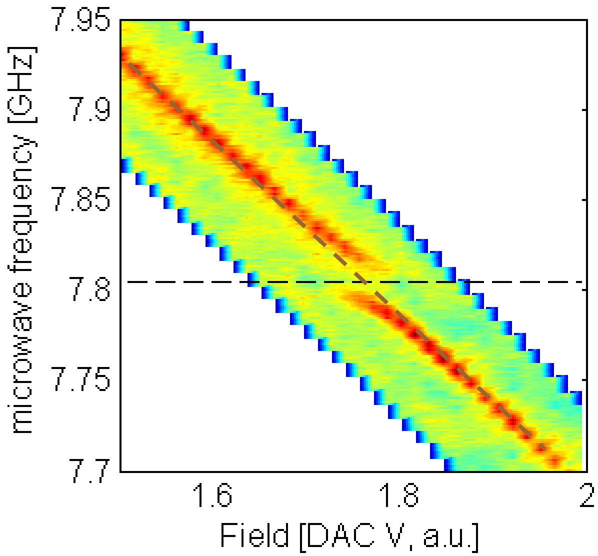


an excited multi-level system could absorb additional photons

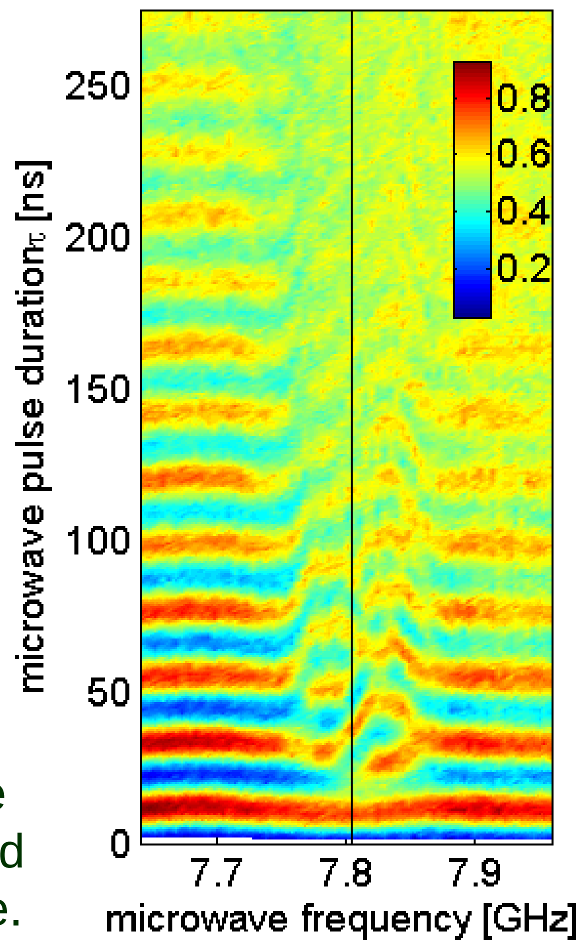


Outcome: no oscillations when *both* TLF and qubit are in their excited states and coupled

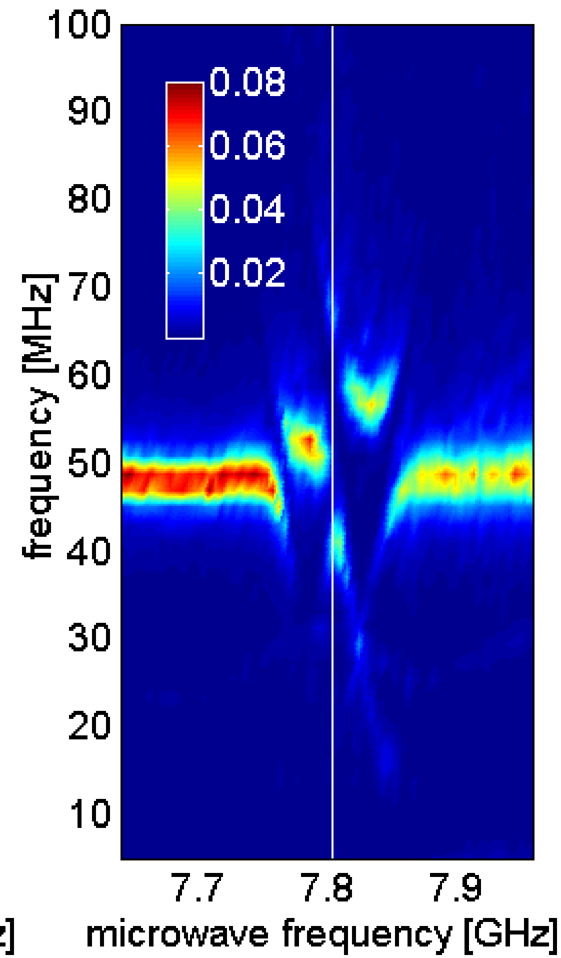
Rabi oscillations of the qubit in the vicinity of a TLF: Data



time domain data



frequency domain data



Sweeping flux through splitting, at each flux adjusting microwave frequency to qubit resonance and recording a Rabi oscillation trace.

Transitions in the driven 4-level system: qubit coupled to TLF

Hamiltonian: $H = H_s + H_I + H_{em}$

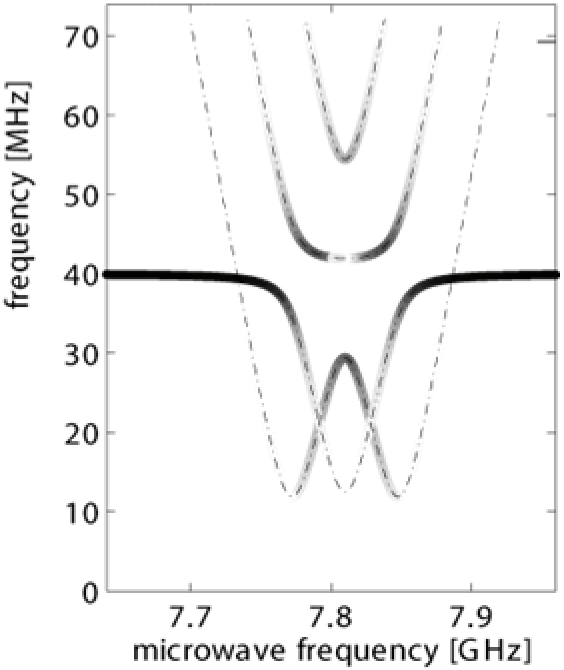
$$H_s = -\tfrac{1}{2}\varepsilon_q\sigma_z \; -\tfrac{1}{2}\varepsilon_f\tau_z \; + \tfrac{1}{2} S\,\sigma_x\tau_x$$

qubit — TLF — qubit-TLF coupling

field: $H_{em} = \hbar\omega_d\left(a^+a + \tfrac{1}{2}\right)$

$$H_I = \tfrac{1}{2}\Omega_q\left(a\sigma_+ + a^+\sigma_-\right) + \tfrac{1}{2}\Omega_f\left(a\tau_+ + a^+\tau_-\right)$$

qubit-field coupling — TLF-field coupling

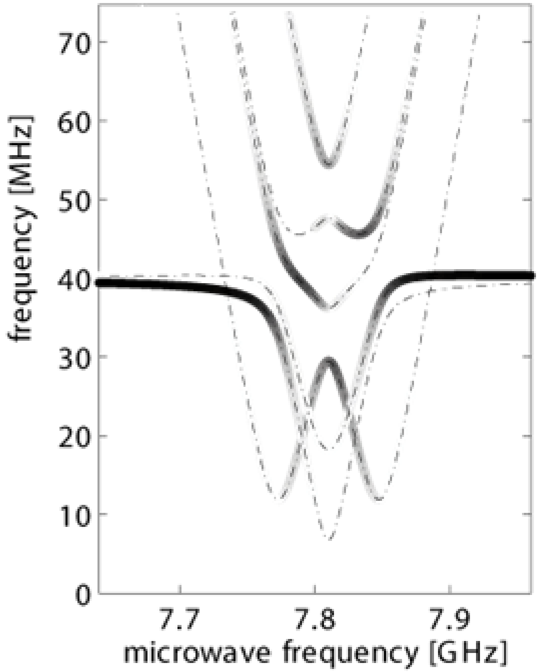


$\Omega_f = 0$

symmetric

$\Omega_f = 0.1$

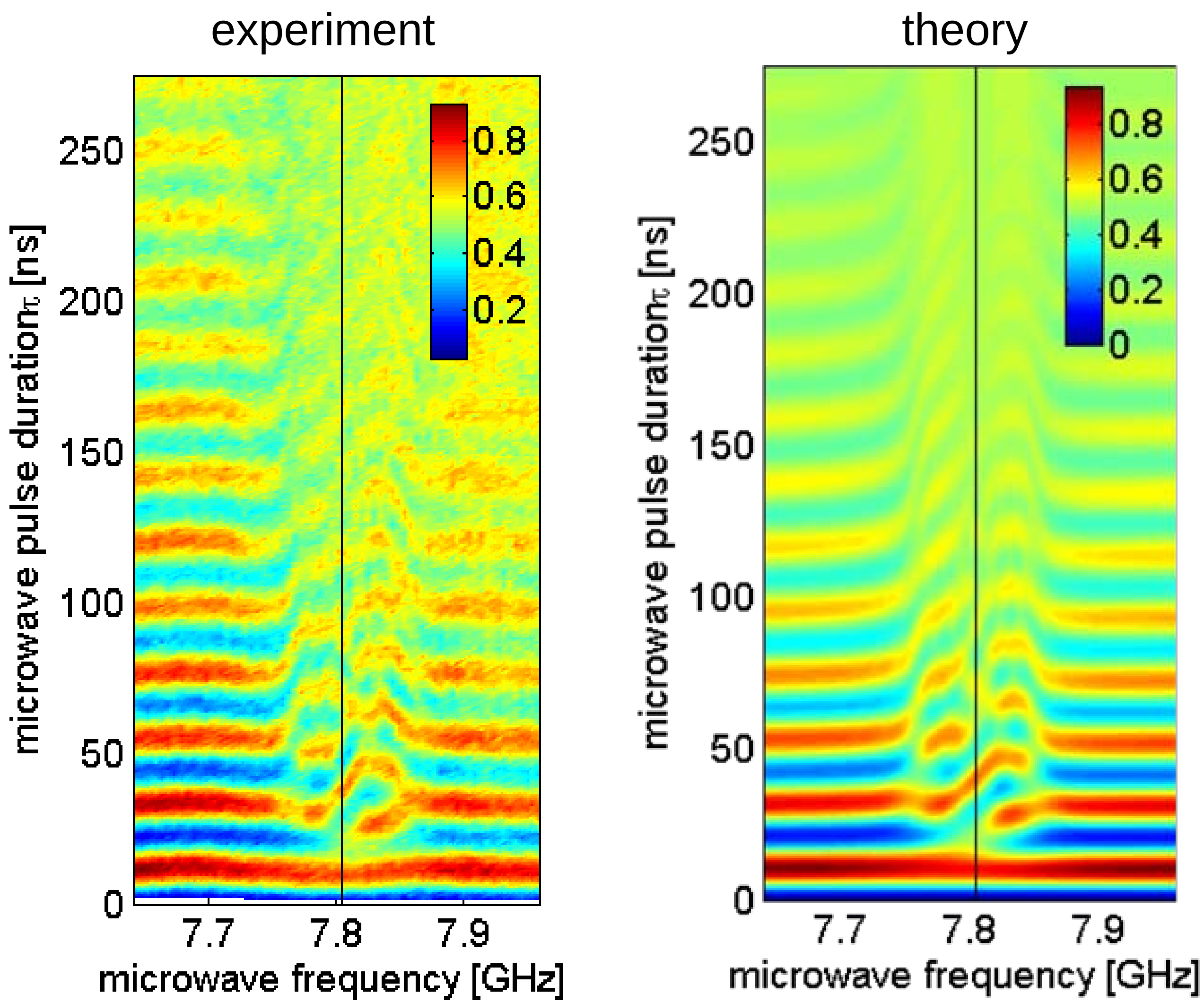
not symmetric



Theory:
C. Müller, J. H. Cole, and
A. Shnirman (Karlsruhe)

Rabi oscillations of the qubit in the vicinity of TLF: Comparison in time domain

<u>Theory</u>:
C. Müller
J. H. Cole
A. Shnirman
(Karlsruhe)



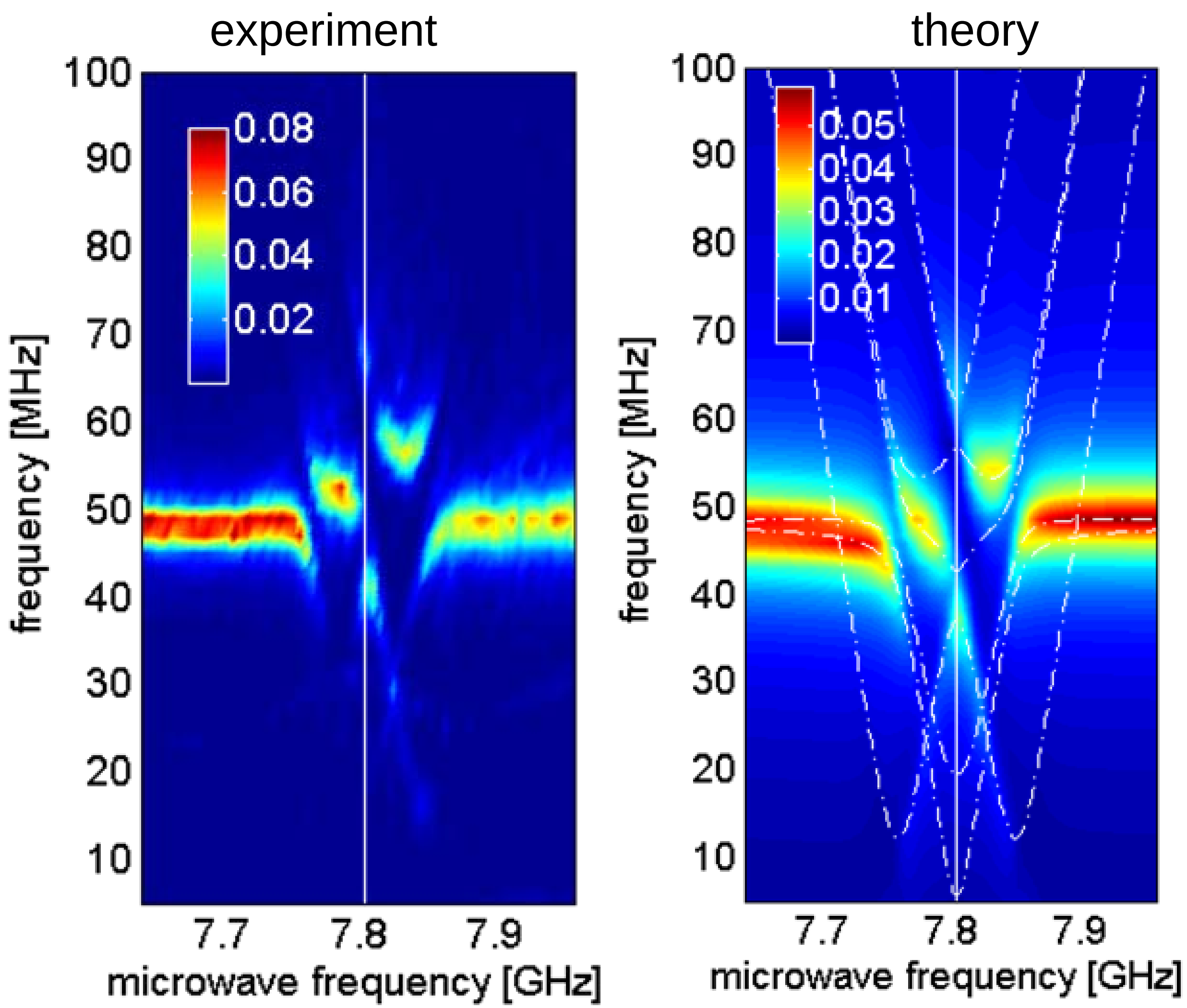
Rabi oscillations of the qubit in the vicinity of TLF: Comparison in frequency domain

Asymmetric picture indicates **direct coupling** of TLF to driving field

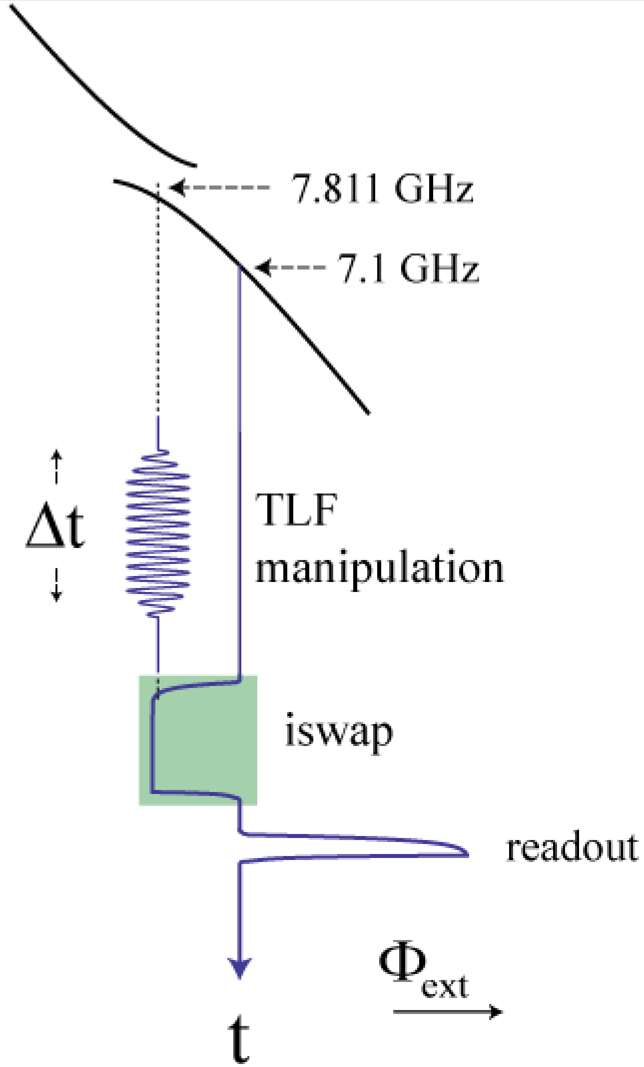
Dipole size fit from theory:

$$p \approx 0.06\,\mathrm{d} \approx 0.12\,\mathrm{nm}$$

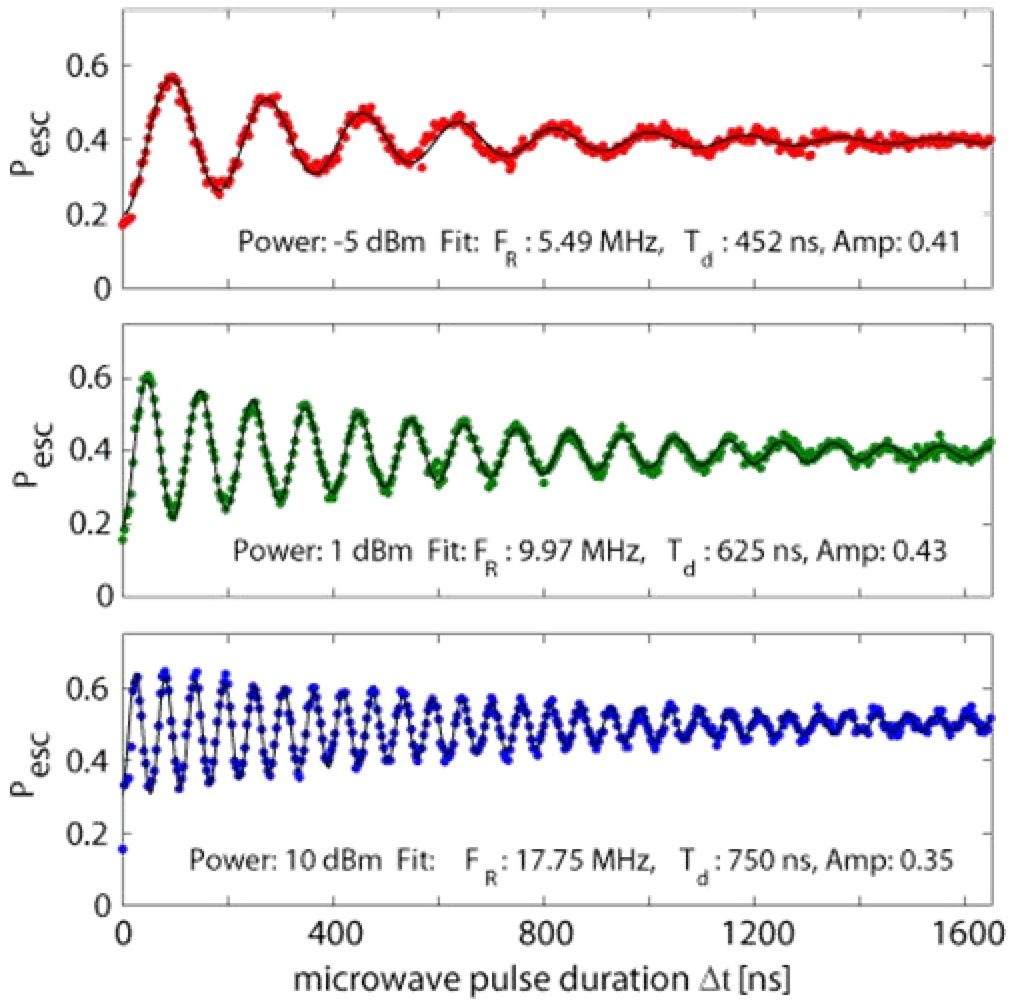
with $\mathrm{d} \approx 2\,\mathrm{nm}$ dielectric thickness



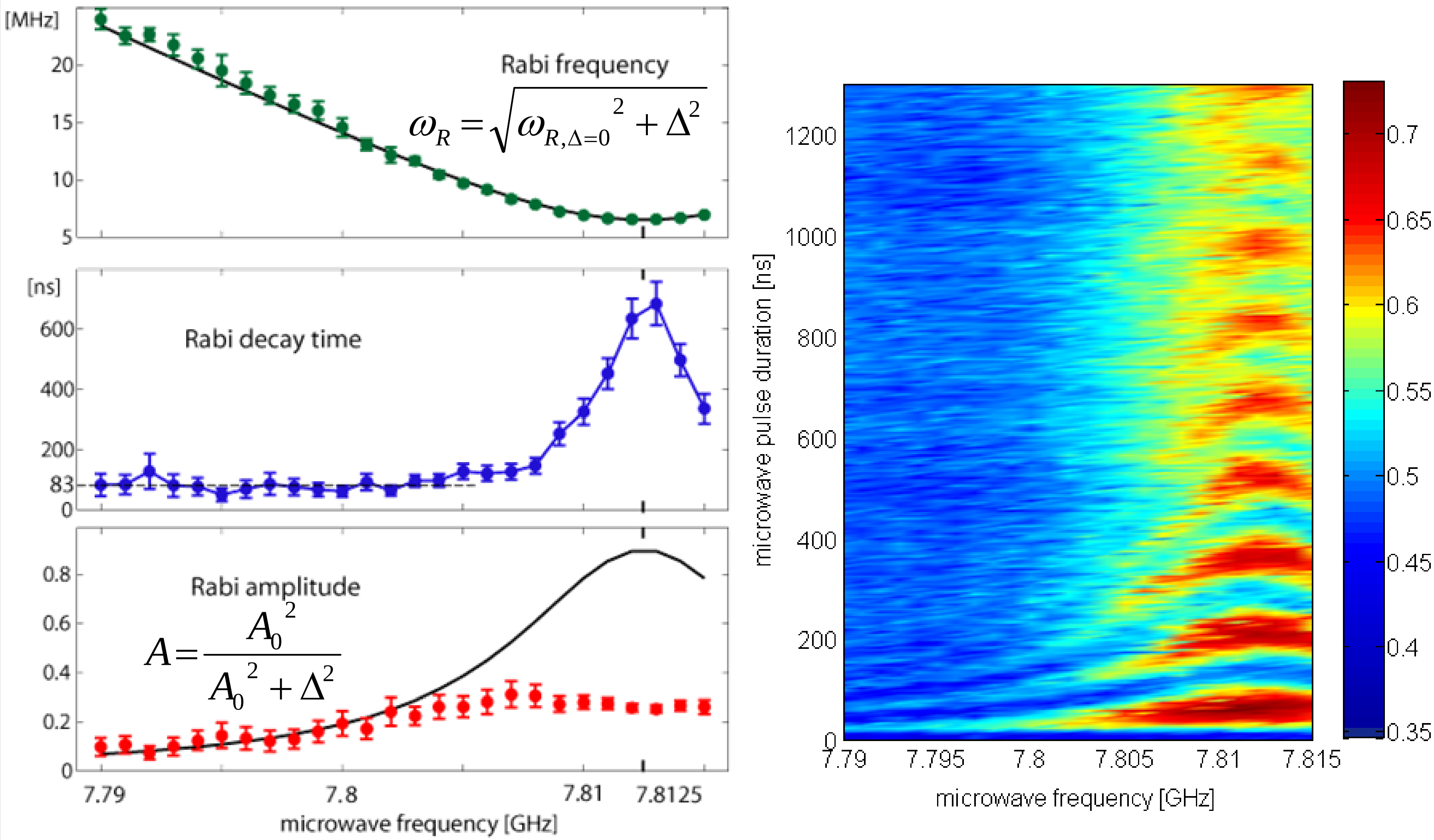
Direct excitation of a TLF by applying microwaves



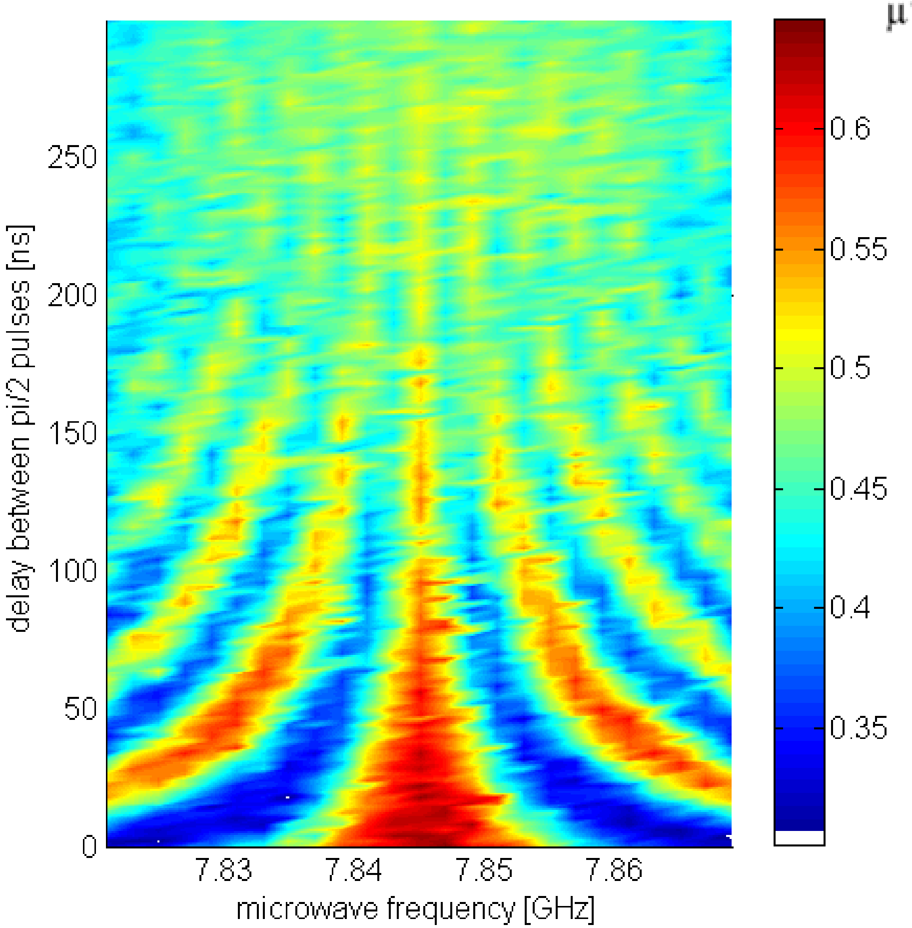
Rabi oscillations in TLF

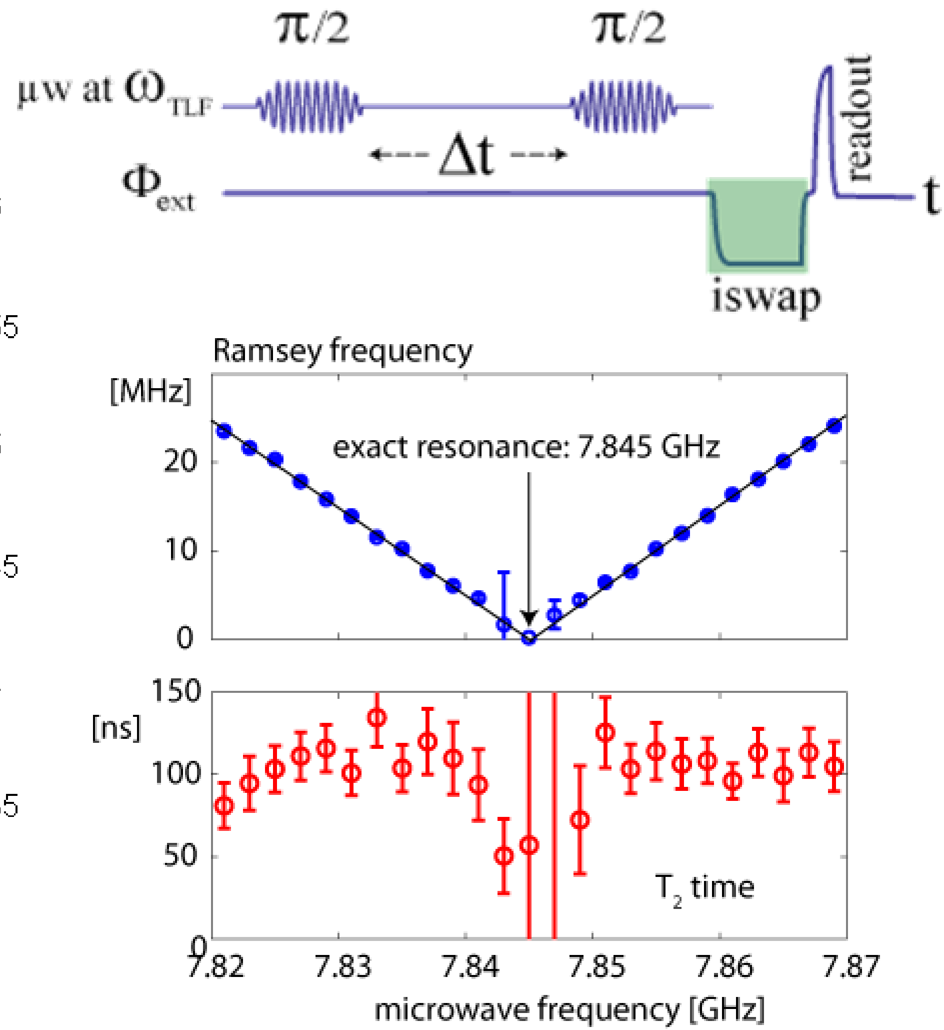


Rabi oscillations in a directly driven TLF : Dependence on driving field detuning

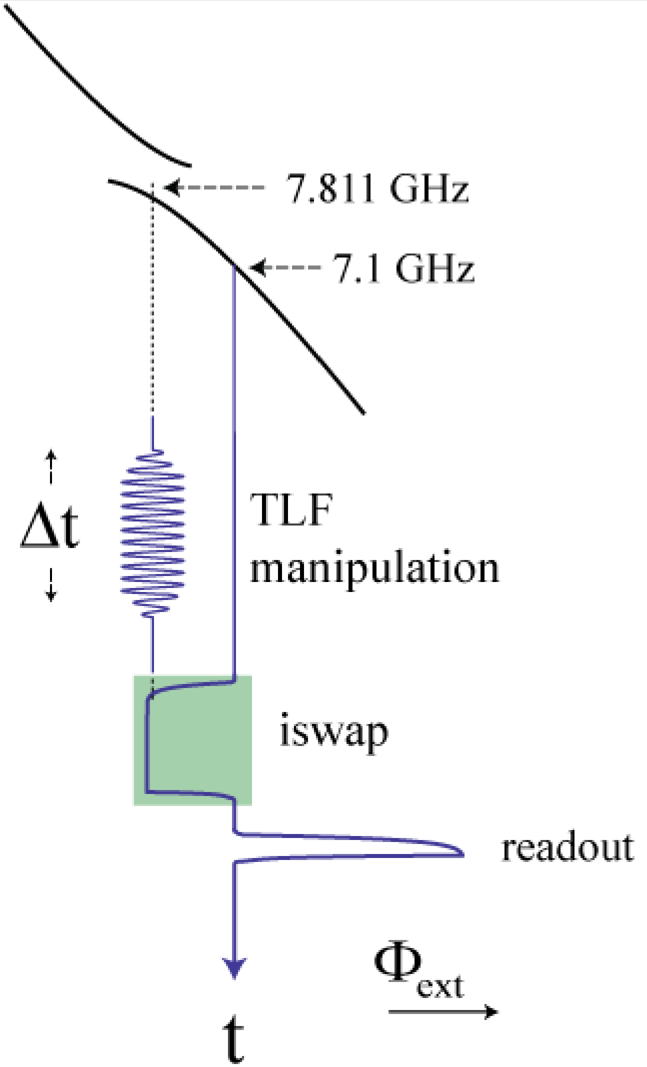


Ramsey oscillations in a directly driven two-level fluctuator: Dephasing time T_2



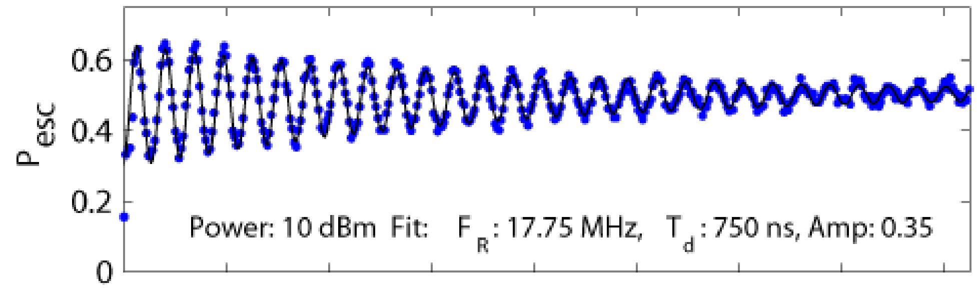


Two-level fluctuator has much longer T_1 time than the JJ qubit

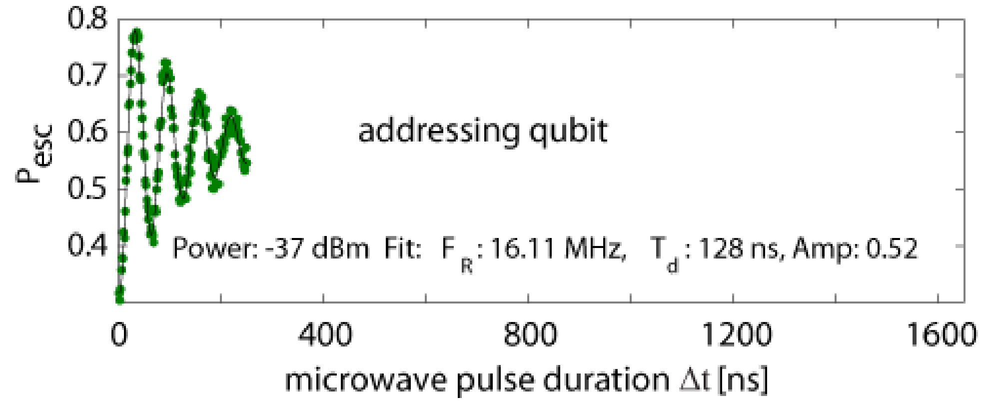


TLF is a better qubit than JJ ...

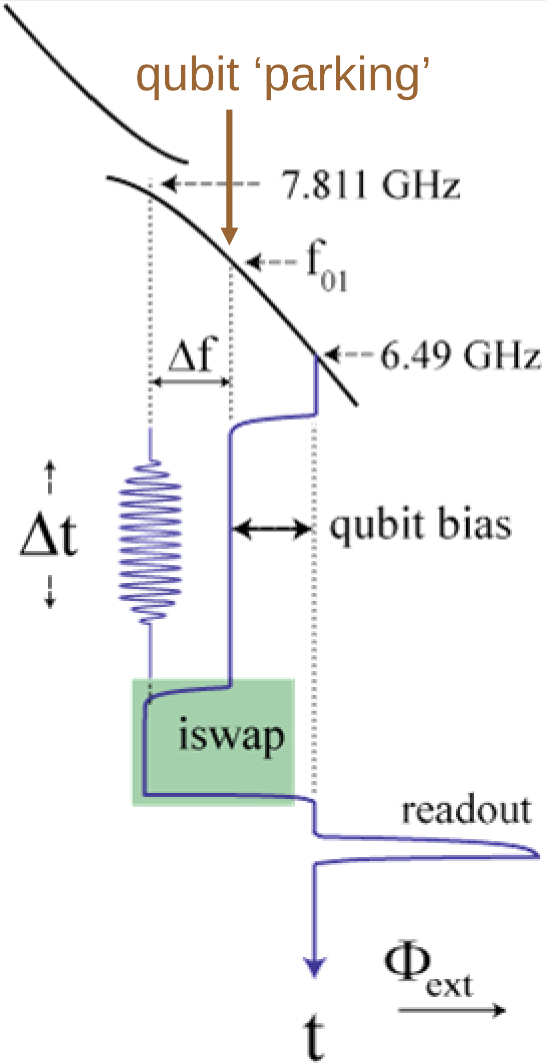
Rabi oscillations of TLF

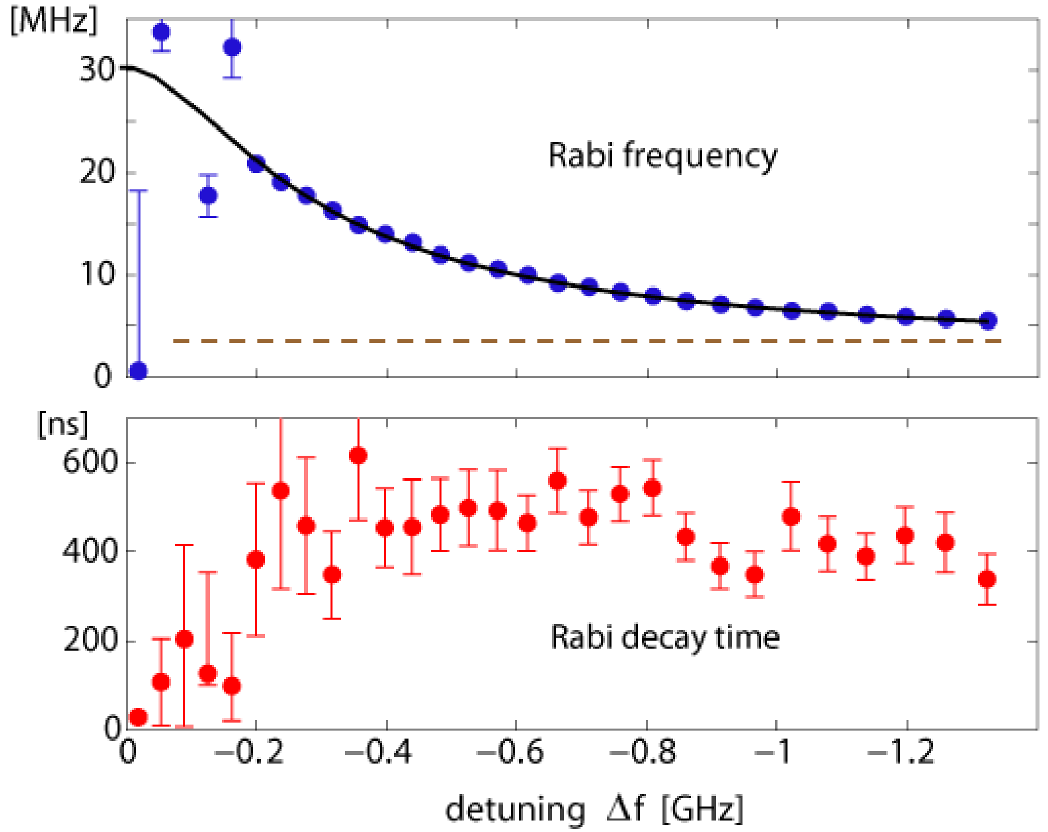


Rabi oscillations of the qubit



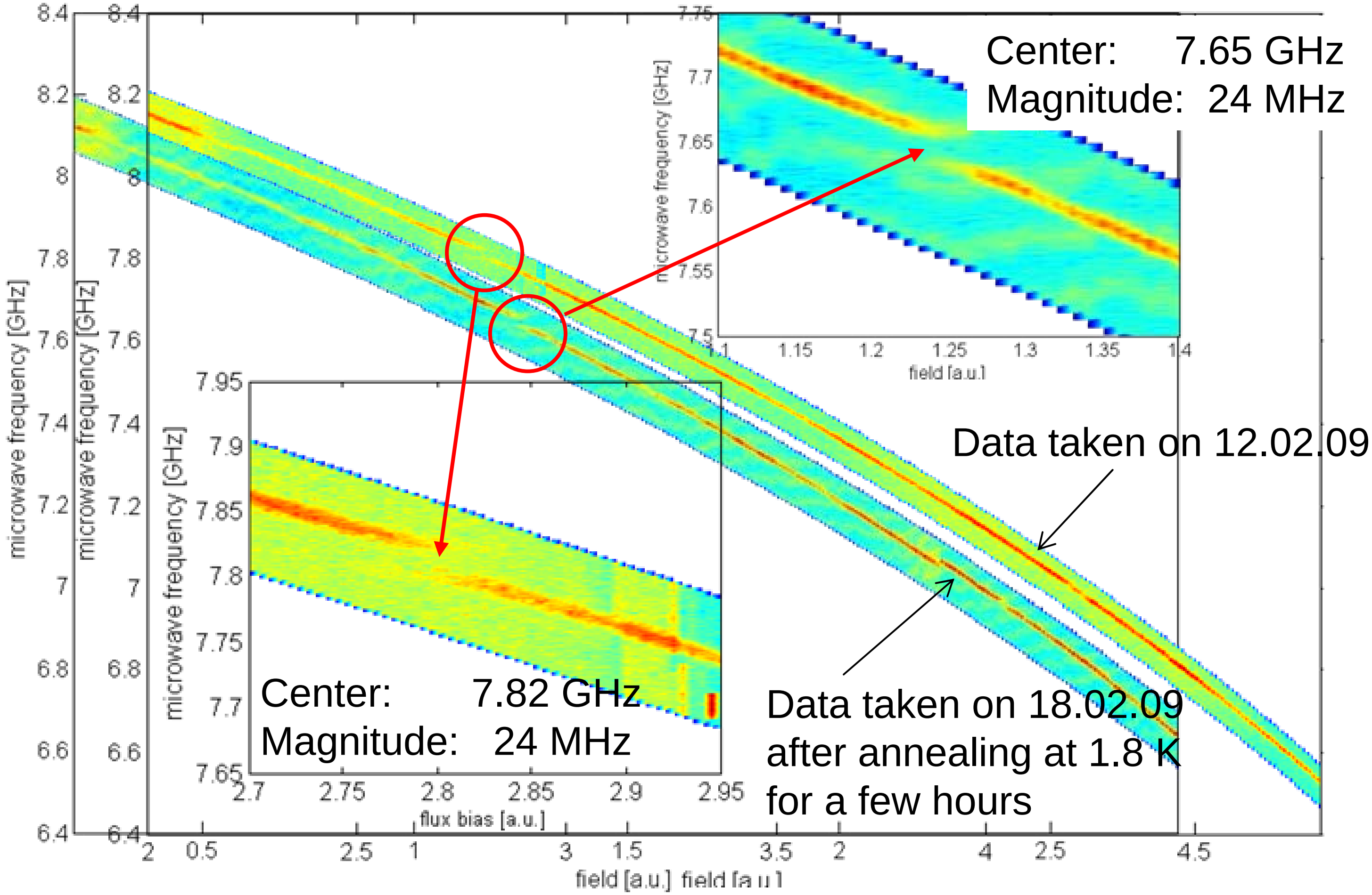
Rabi oscillation in TLF versus qubit ‘parking’ position



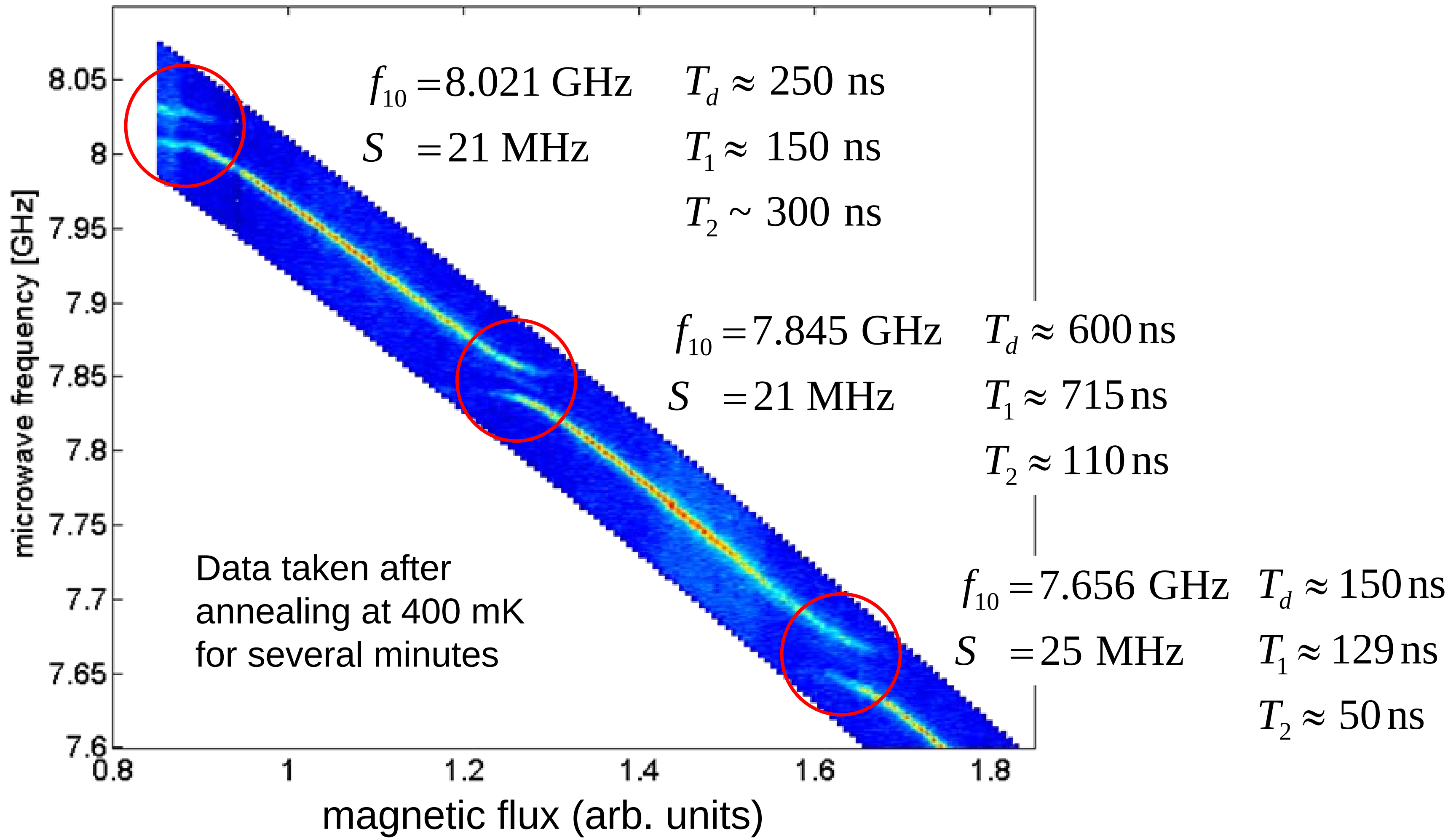


microwave field strength ‘seen’ by TLF depends on the qubit resonance frequency

Migration of fluctuators due to thermal annealing

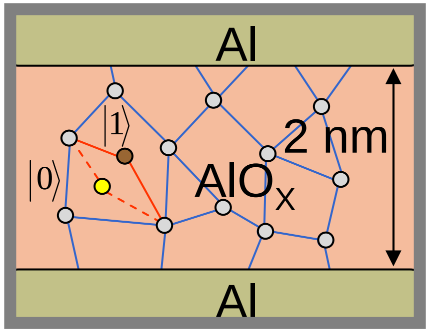


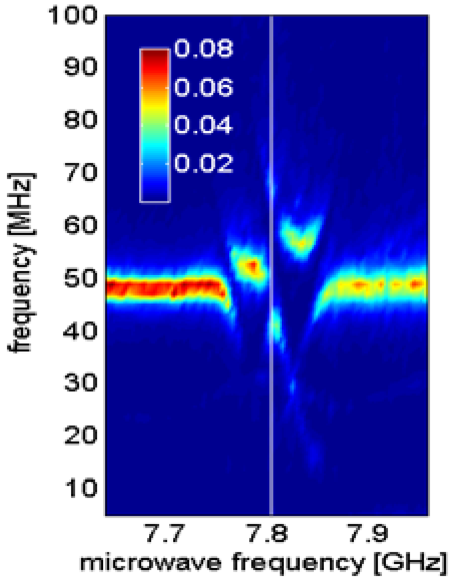
Possibility to entangle two or more TLFs



Conclusions

- **TLFs may have longer coherence times than qubits**
  - **they can be used as a built-in quantum memory**
  - **they allow to entangle a macroscopic object with microscopic defect and study a coupled quantum system**
- **TLFs show direct coupling to the electrical ac field in the junction**
  - **they can be directly controlled by microwaves**
  - **a qubit is only necessary to measure them**
- **Full quantum control and characterization of individual TLFs is readily possible**





Thanks to my collaborators

- **J. Lisenfeld, P. Bushev, A. Lukashenko (experiment)**
- **C. Müller, J. H. Cole, A. Shnirman (Karlsruhe, theory)**
- **J. M. Martinis, M. Ansmann (UCSB, sample fab)**

J. Lisenfeld, C. Mueller, J. H. Cole, A. Lukashenko, A. Shnirman, and A. V. Ustinov. *ArXiv:0909.3425*

Karlsruhe experimental team