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Oral presentation at IWSSD 2016. No manuscript was submitted for hardcopy journal publication.

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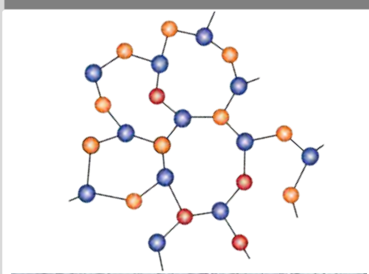
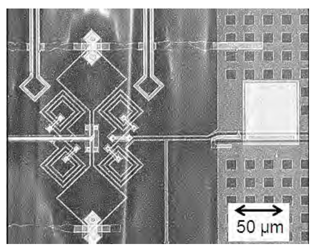
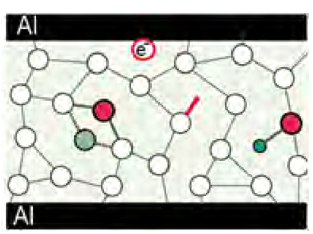
Spectroscopy and coherent Control of Defects in superconducting Films and Qubits

Jürgen Lisenfeld, Alexander Bilmes, Jan Brehm, Georg Weiss, and A.V. Ustinov

Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe, Germany ju.lis@kit.edu





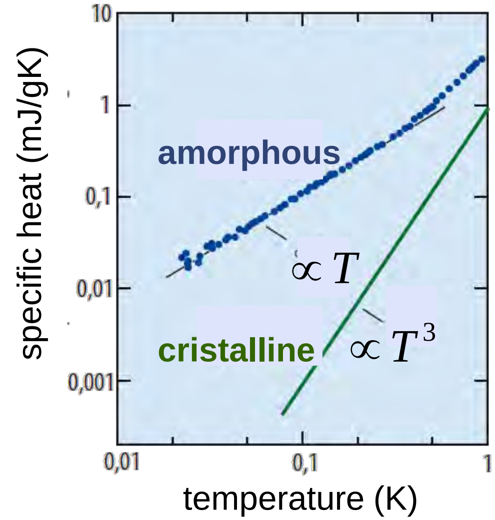


- **Two-Level-Systems (TLS):**
  a major source of noise in quantum devices
- **Using superconducting Quantum Bits to study single TLS**
  - TLS spectroscopy and mechanical strain tuning
  - mutual TLS interactions, noise spectroscopy
  - TLS - electron interaction

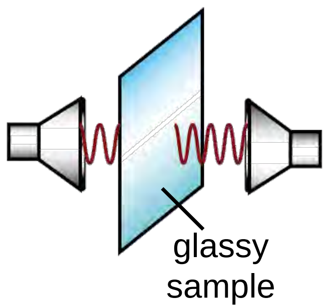
Two-Level-Systems (TLS)

measurements on glasses revealed several peculiarities:

- specific heat disagrees with Debye model
  (Zeller & Pohl 1971)



- **common signatures in amorphous materials**
  - ultrasound attenuation
  - electric field response
  - microwave response
  - thermal conductivity
  - heat capacity …



conclusion: glasses must contain **intrinsic states** having excitation energies < 1 K and which **couple to both electric fields and phonons**.

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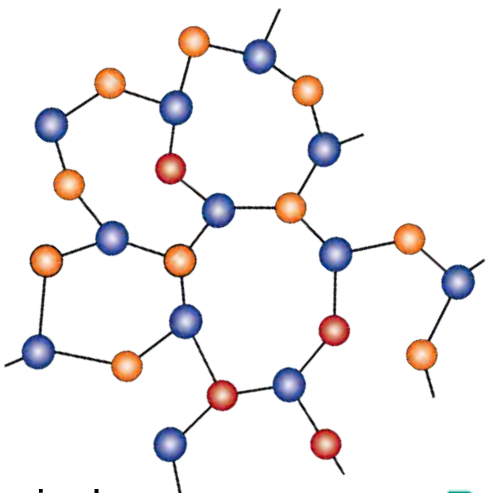
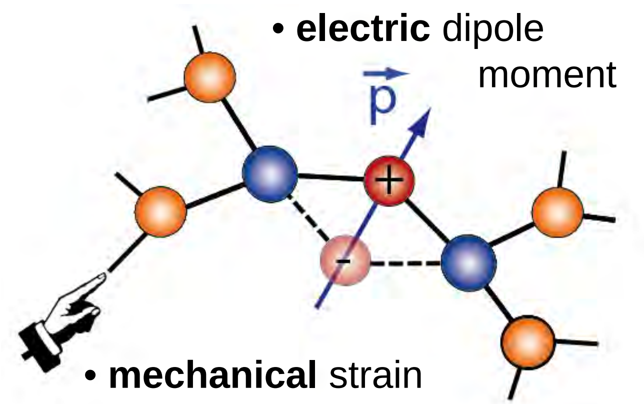
Two-Level-Systems: Tunneling Atom Model [1,2]

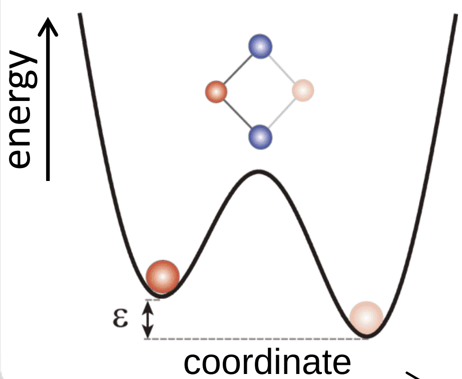
- in amorphous materials, atoms may tunnel between two positions:



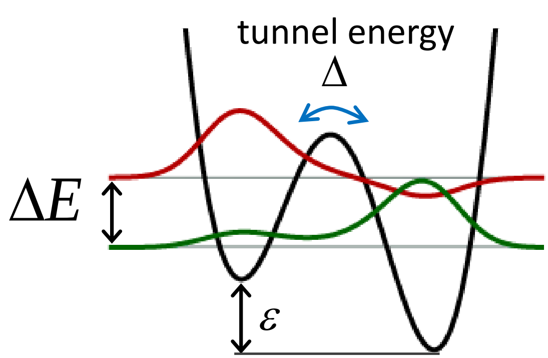
- these "tunneling systems" couple via

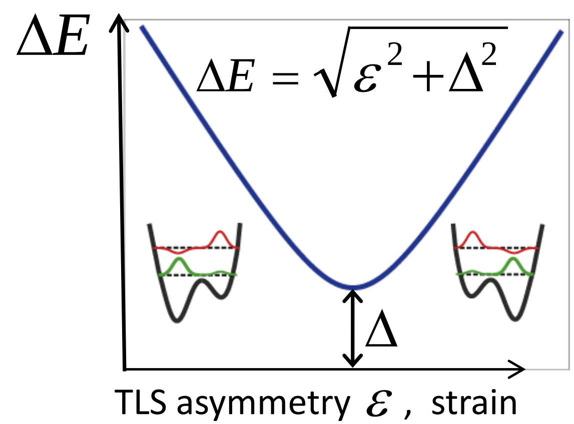


- classical



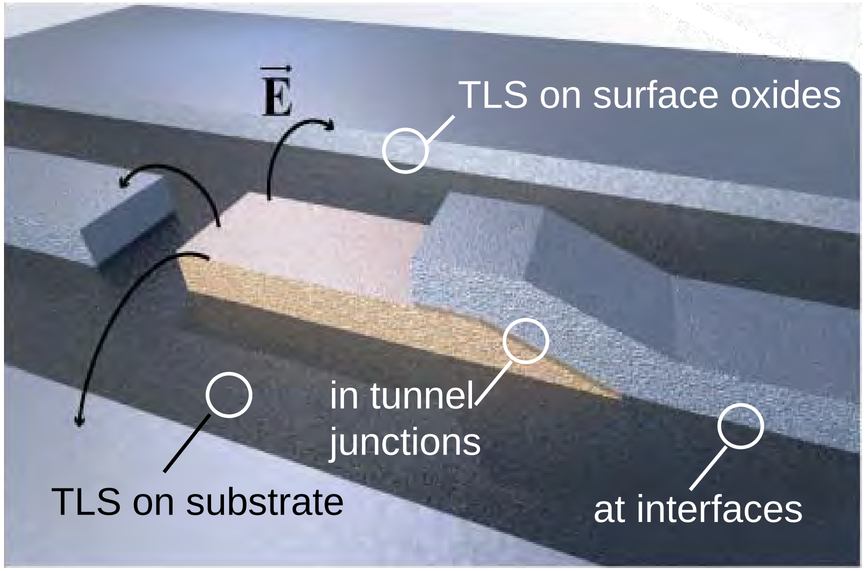
- quantum





[1] W.A. Phillips, *J. Low Temp. Phys.* **7** *351 (1972)*
[2] Anderson, Halperin, and Varma, *Philosophical Mag*. **25**, 1 (1972)

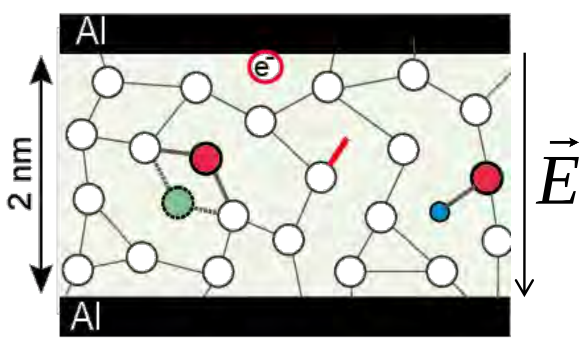
TLS in microfabricated circuits and Josephson junctions



- **TLS are found**
  - in surface oxides
  - in / on the substrate
  - at interfaces
  - in tunnel junctions

- **TLS generate noise & dissipation in**
  - MOSFETs & single-electron transistors
  - micro-mechanical resonators
  - single-photon detectors, nanowires
  - superconducting resonators and qubits
  - …

in Josephson junctions:



- **hydroxide defects** Appl. Phys. Lett. **97**, 252501 (2010)
- **dangling bonds**
- **electrons trapped at interfaces**: PRL **95**, 046805 (2005)
  Kondo- / Andreev Fluctuators PRB **84**, 235102 (2011)
- **phononically dressed electrons** PRB **87**, 144201 (2013)
- **tunneling atoms** Phys. Rev. Lett. **95**, 210503 (2005)

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The Phase Qubit

J.M. Martinis et al., PRL 93, 077003 (2004)

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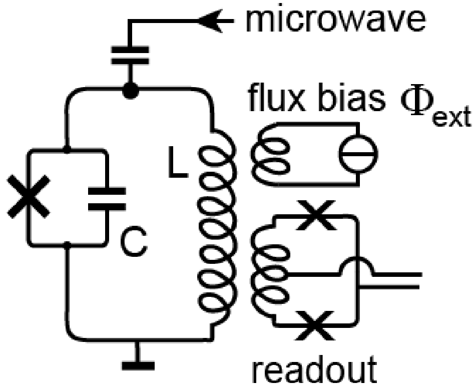
- Complete circuit



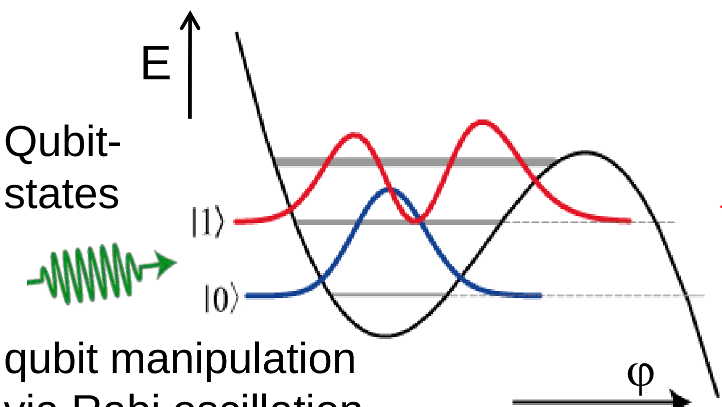
- **Hamilton-Operator**

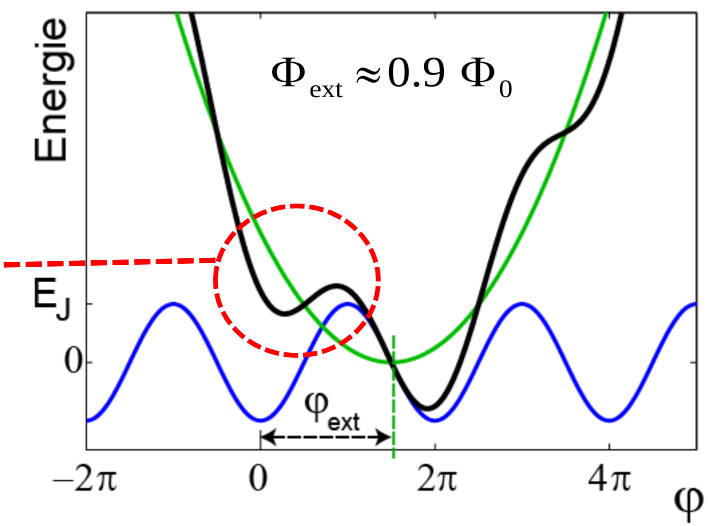
$$\hat{H} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L} - E_J \cos\hat{\varphi}$$

- **Potential** for $E_J >> Q^2/2C$:

Qubit-states

qubit manipulation via Rabi oscillation





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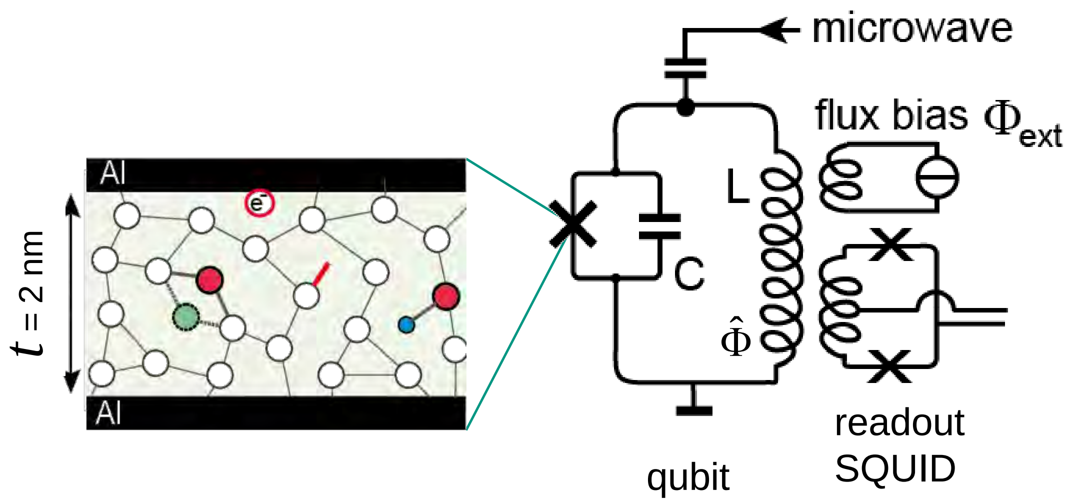
Defect-Qubit - interaction



- **Qubit-TLS interaction:**
  via TLS electrical dipole moment $\vec{p}$

Qubit:

$$\hat{H} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} + E_J$$

el. Field:

$$\vec{E} = \frac{\hat{Q}}{t\,C} \approx 1000\ \mathrm{V/m}$$

Dipole interaction:

for $\overline{p}$ = 2 D = 2 · 0.2 eÅ

$$\Rightarrow\ g = \overline{p}\,|\vec{E}| \approx h \cdot 10\,\mathrm{MHz}$$

qubit-TLS coupling strength

Defect – Qubit - Interaction

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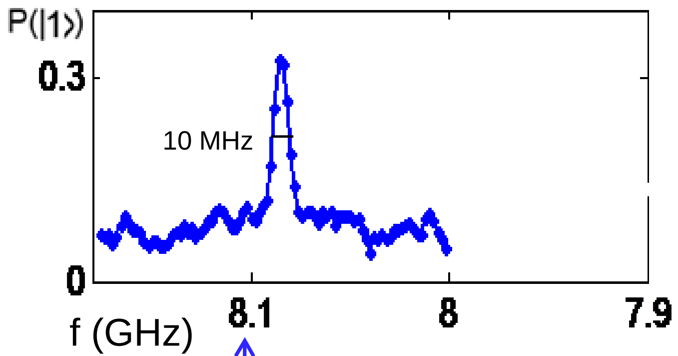
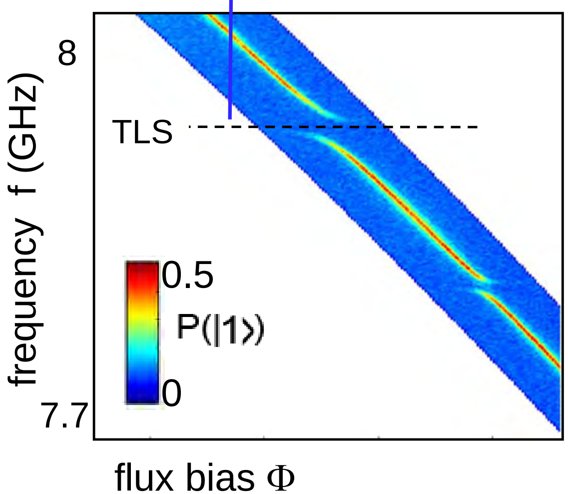
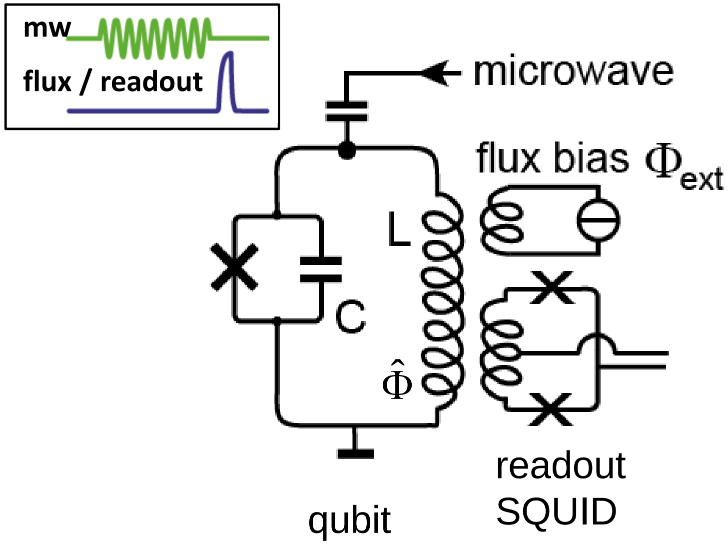
Frequency Domain:
defects cause avoided level crossings







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cf.: R.W. Simmonds, K.M. Lang, D.A. Hite, D.P. Pappas, and J.M. Martinis, PRL **93**, 077003 (2004)
Yoni Shalibo, Matthew Neeley, John M. Martinis, Nadav Katz et al., PRL **105**, 177001 (2010).

Defect – Qubit - Interaction

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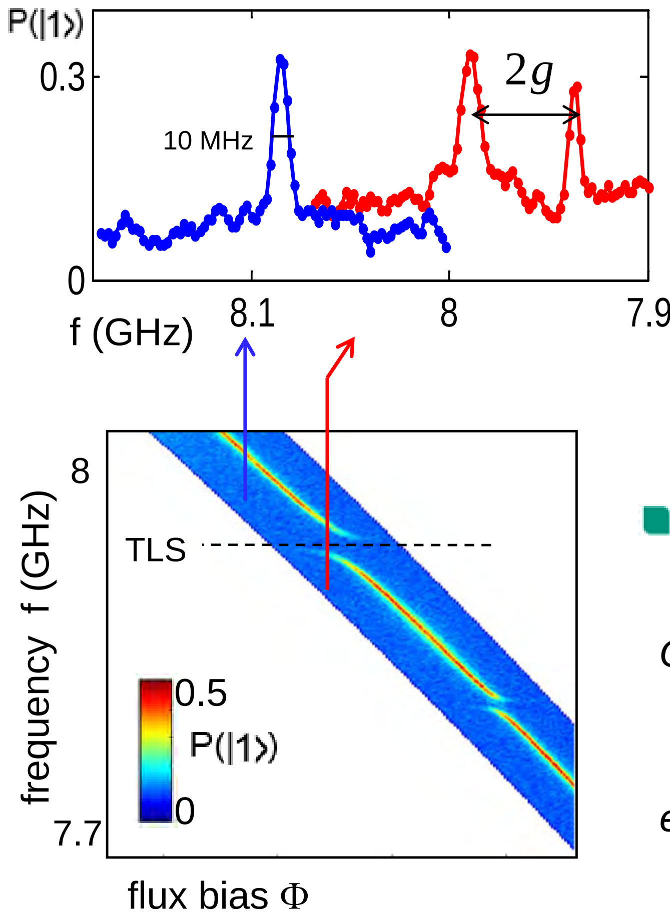

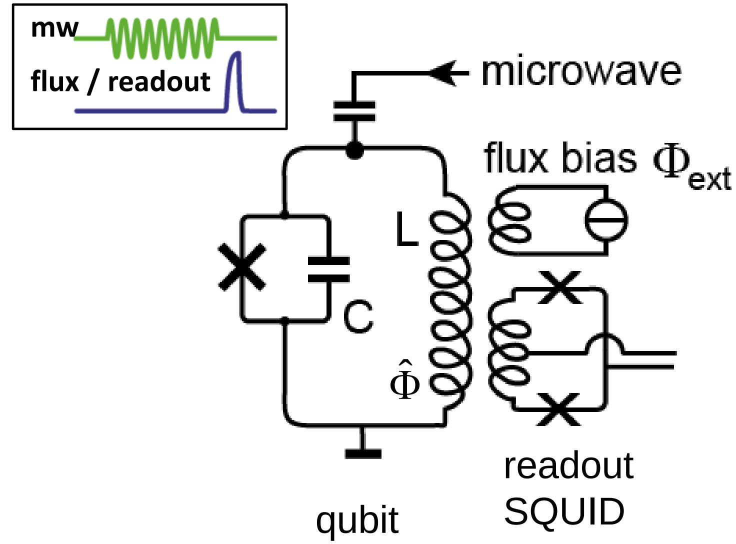

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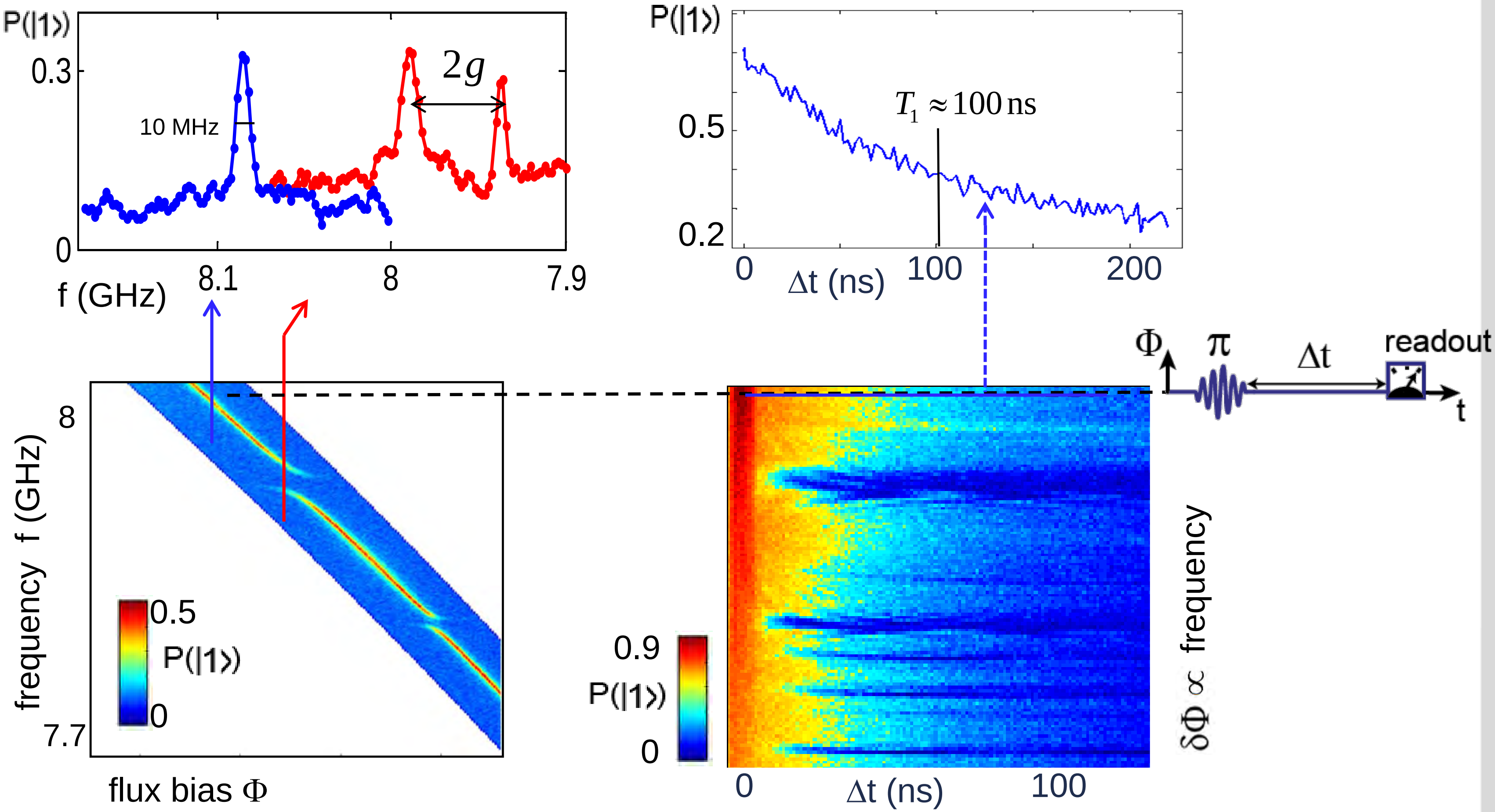
Defect – Qubit - Interaction

Frequency Domain:
defects cause avoided level crossings

Time Domain:
qubit decays due to energy relaxation



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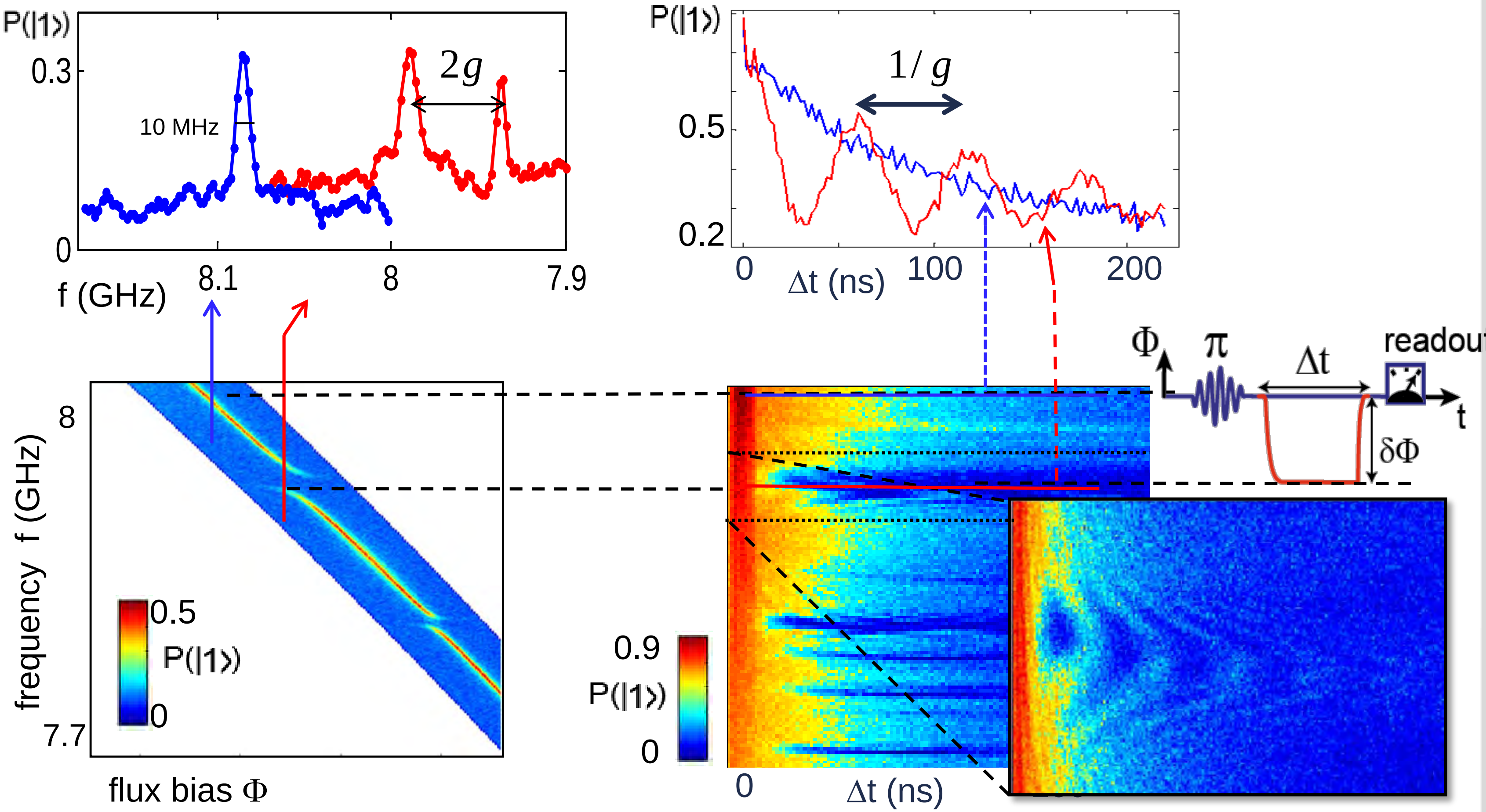
Defect – Qubit - Interaction

Frequency Domain:
defects cause avoided level crossings

Time Domain:
energy oscillates between qubit and defects



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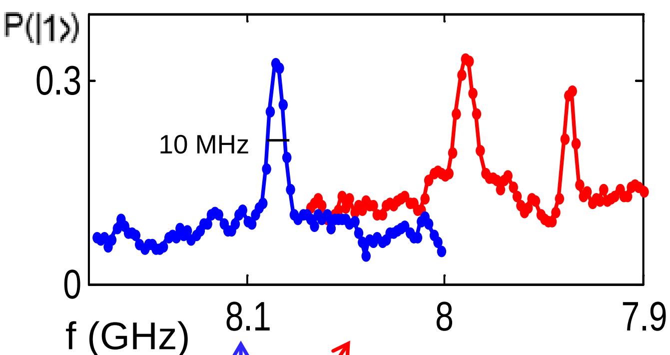

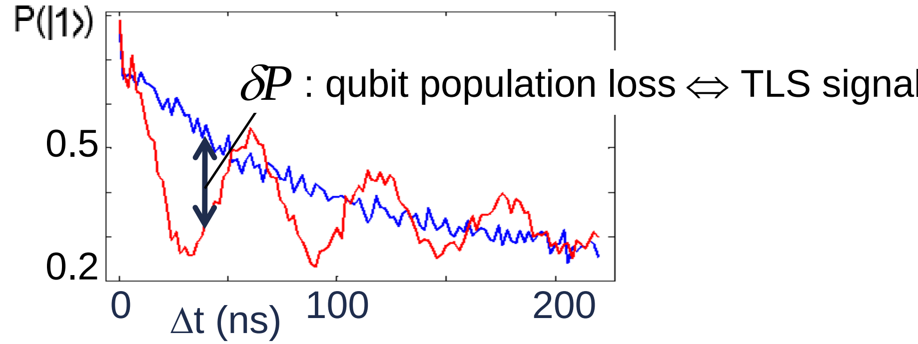

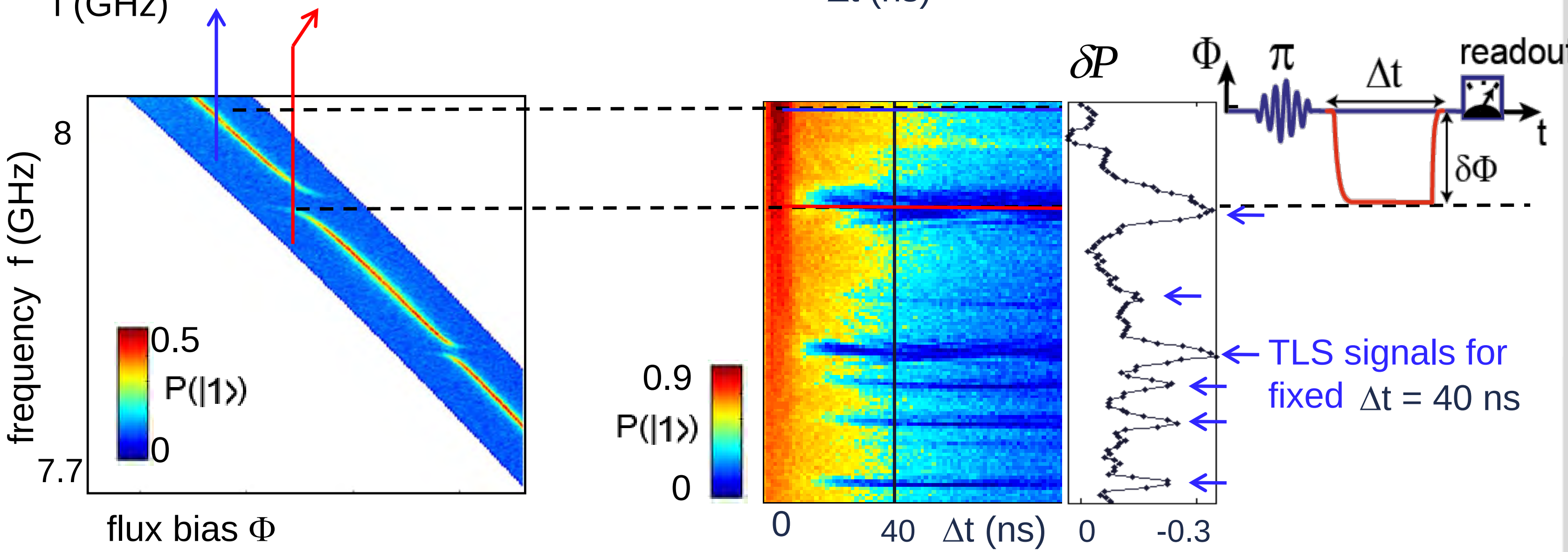

TLS Strain Spectroscopy

G. Grabovskij, J. Lisenfeld, G. Weiss, A.V. Ustinov et al., *Science* **338**, 232 (2012)

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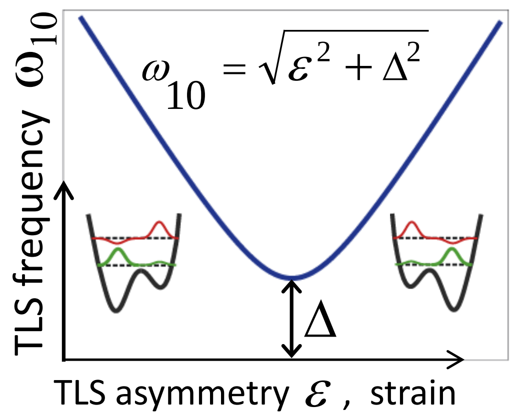
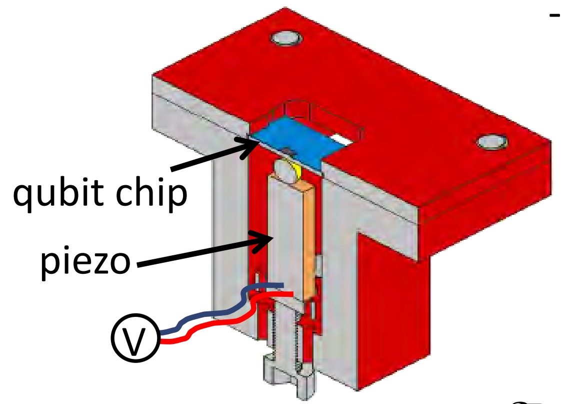


TLS strain tuning by deforming the sample using a piezo



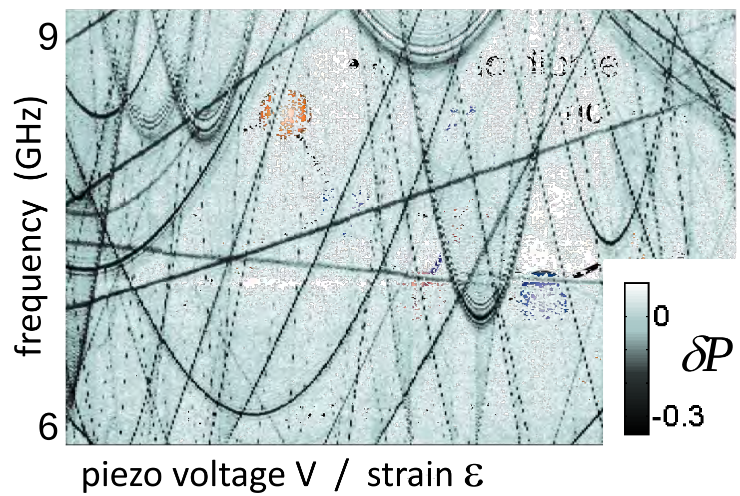
- tiny deformations

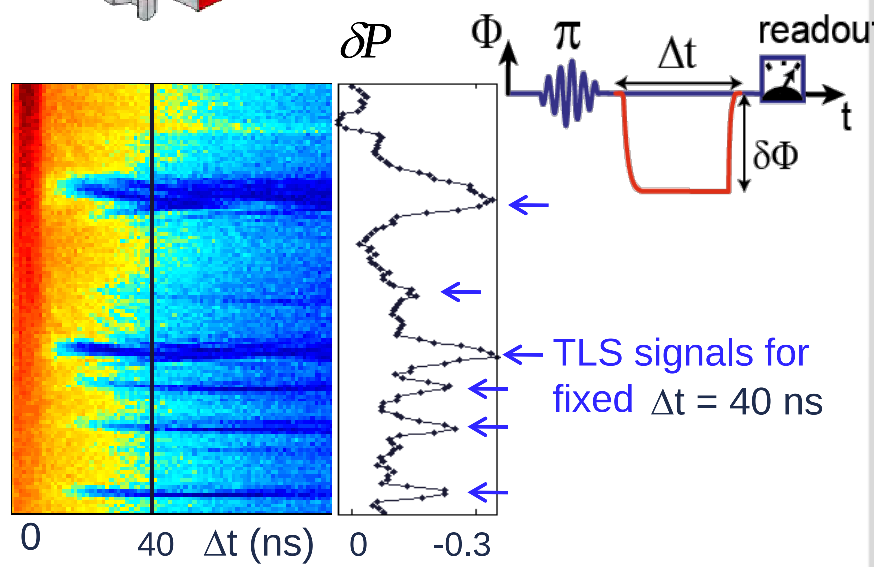
$$\frac{\Delta L}{L} \approx 10^{-7}\ /\mathrm{V}$$

(compress 1 nm by 10^{-16} m)

change TLS asymmetry:

$$\varepsilon \approx 200\ \mathrm{MHz/V}$$





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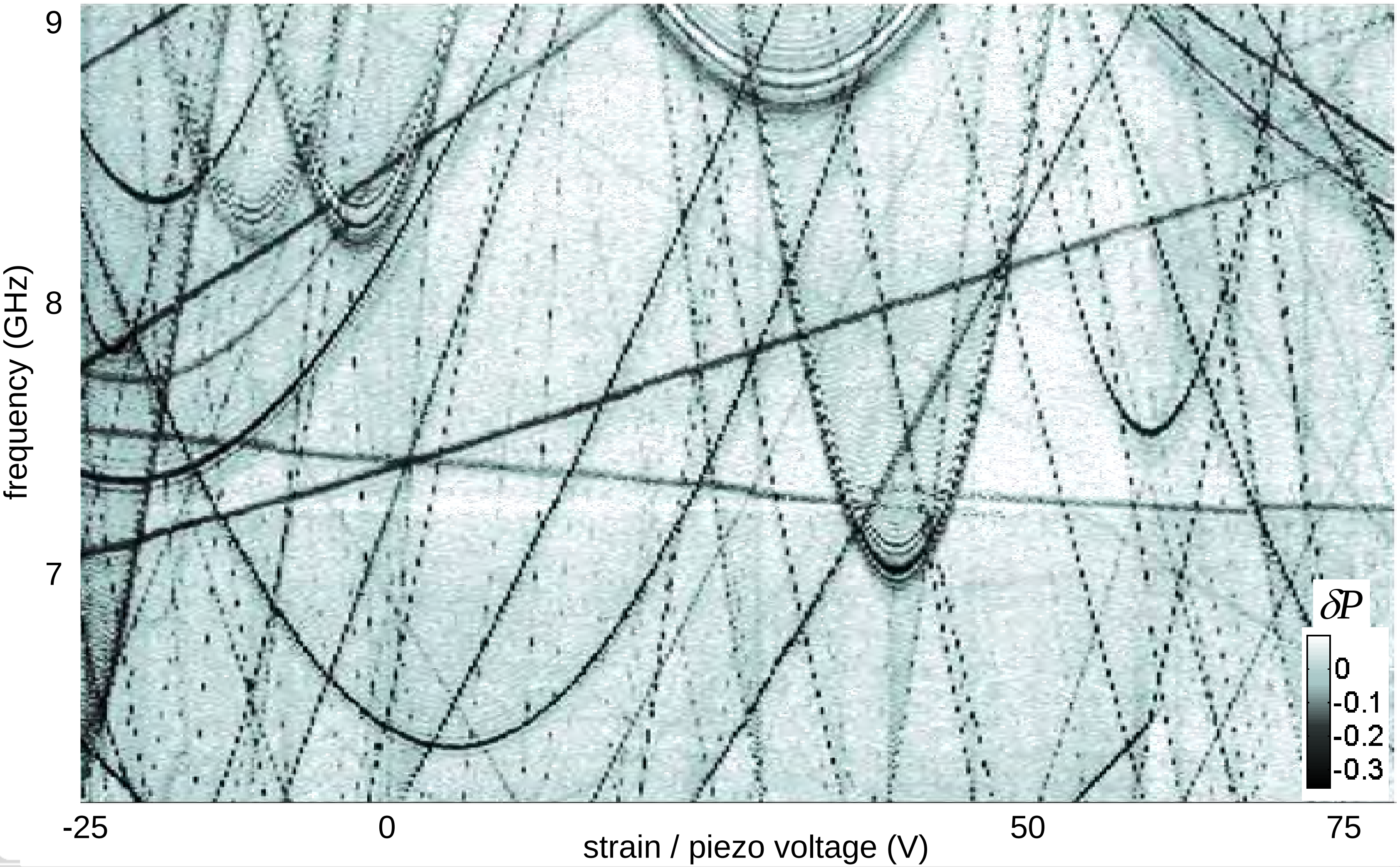

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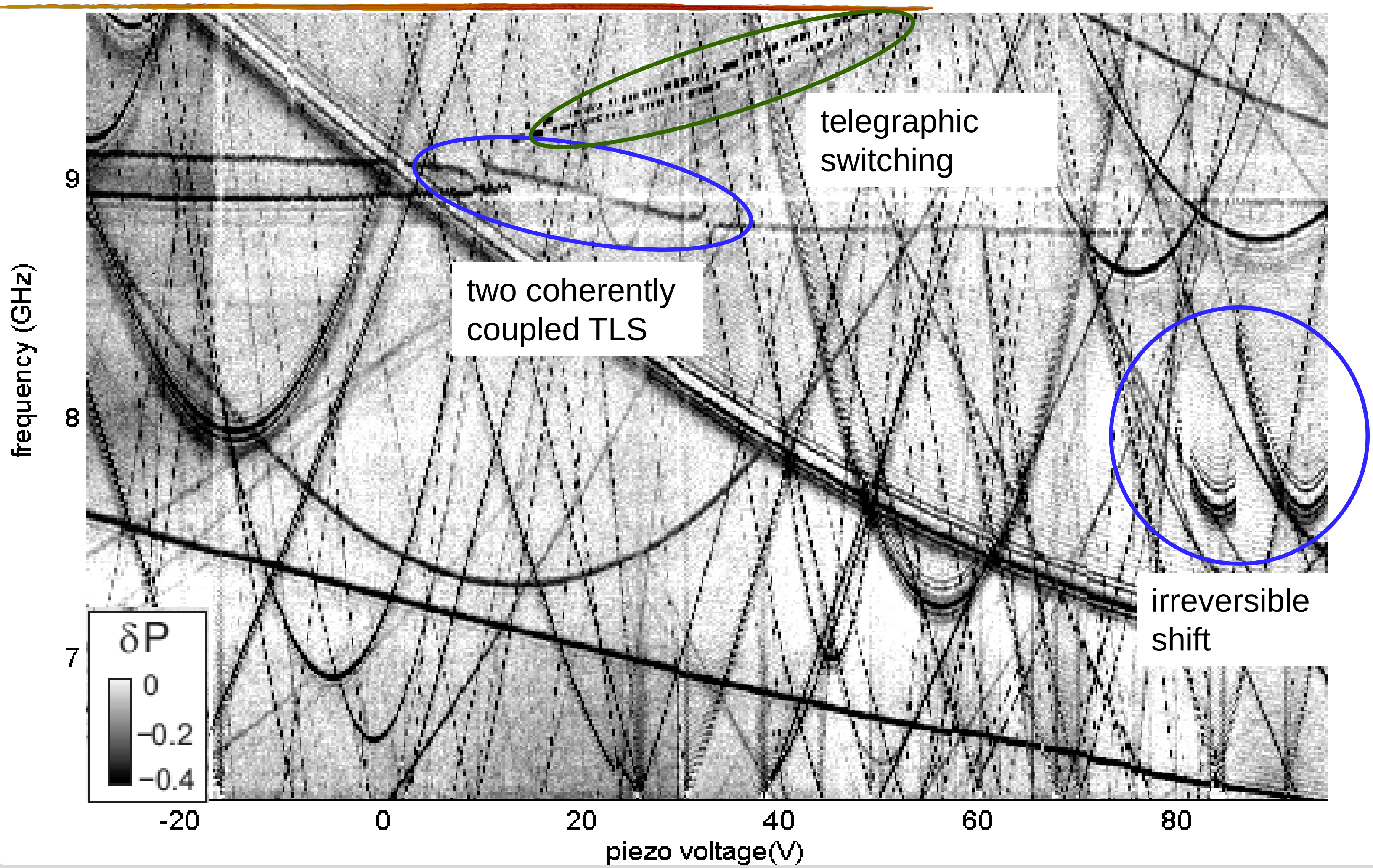

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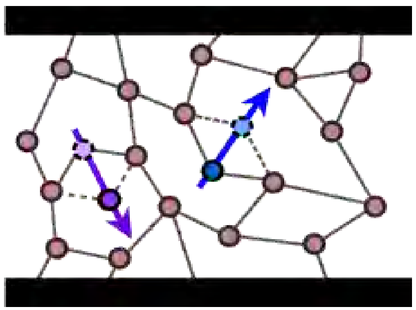
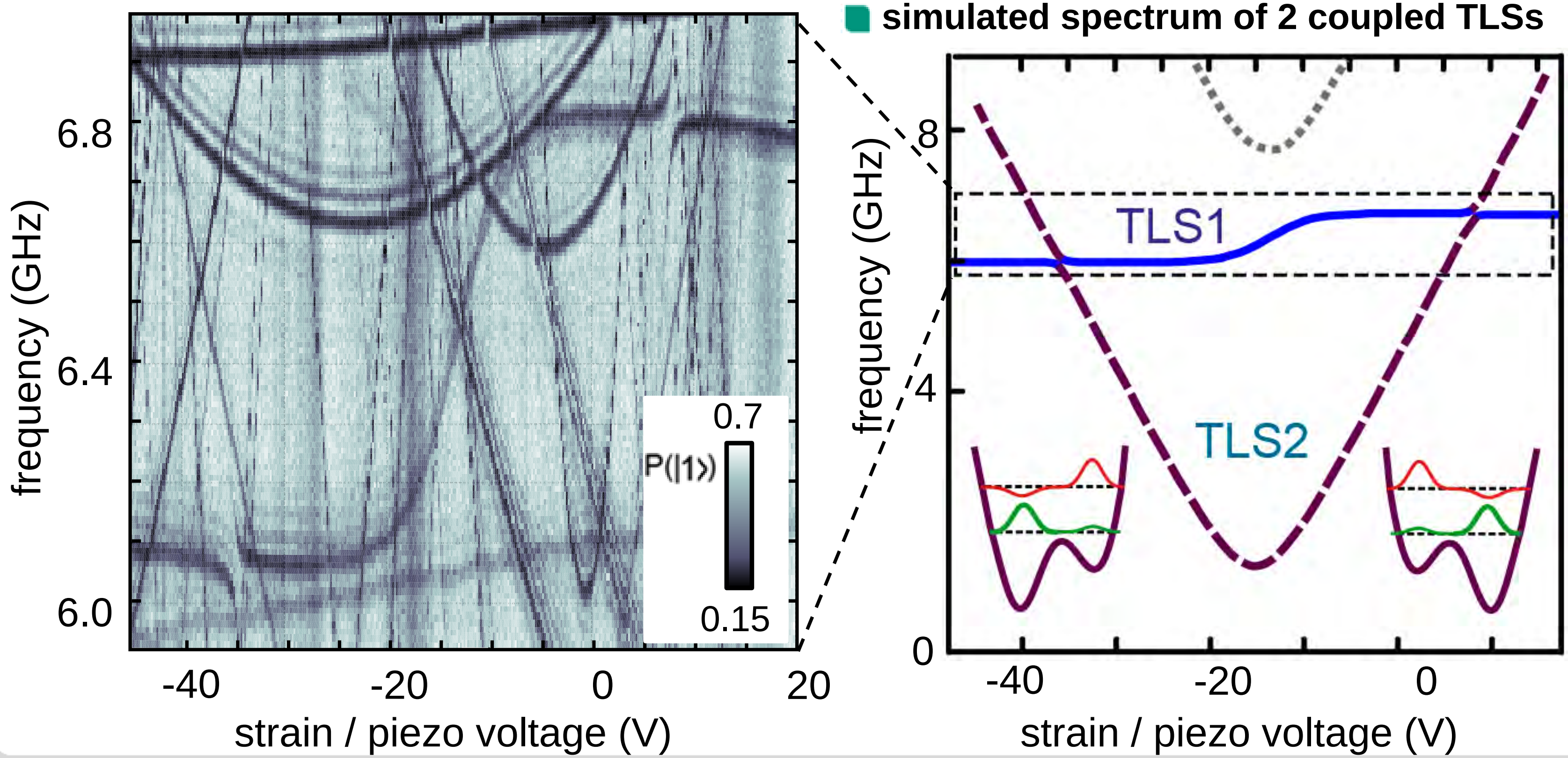
coherently interacting defects

J. Lisenfeld, G. Grabovskij, C. Müller, J.H. Cole, G. Weiss, and A.V. Ustinov, Nature Communications **6**, 6182 (2015)



- **signature in defect spectroscopy**
- **simulated spectrum of 2 coupled TLSs**



coherently interacting defects

J. Lisenfeld, G. Weiss, A.V. Ustinov et al., Nature Communications **6**, 6182 (2015)

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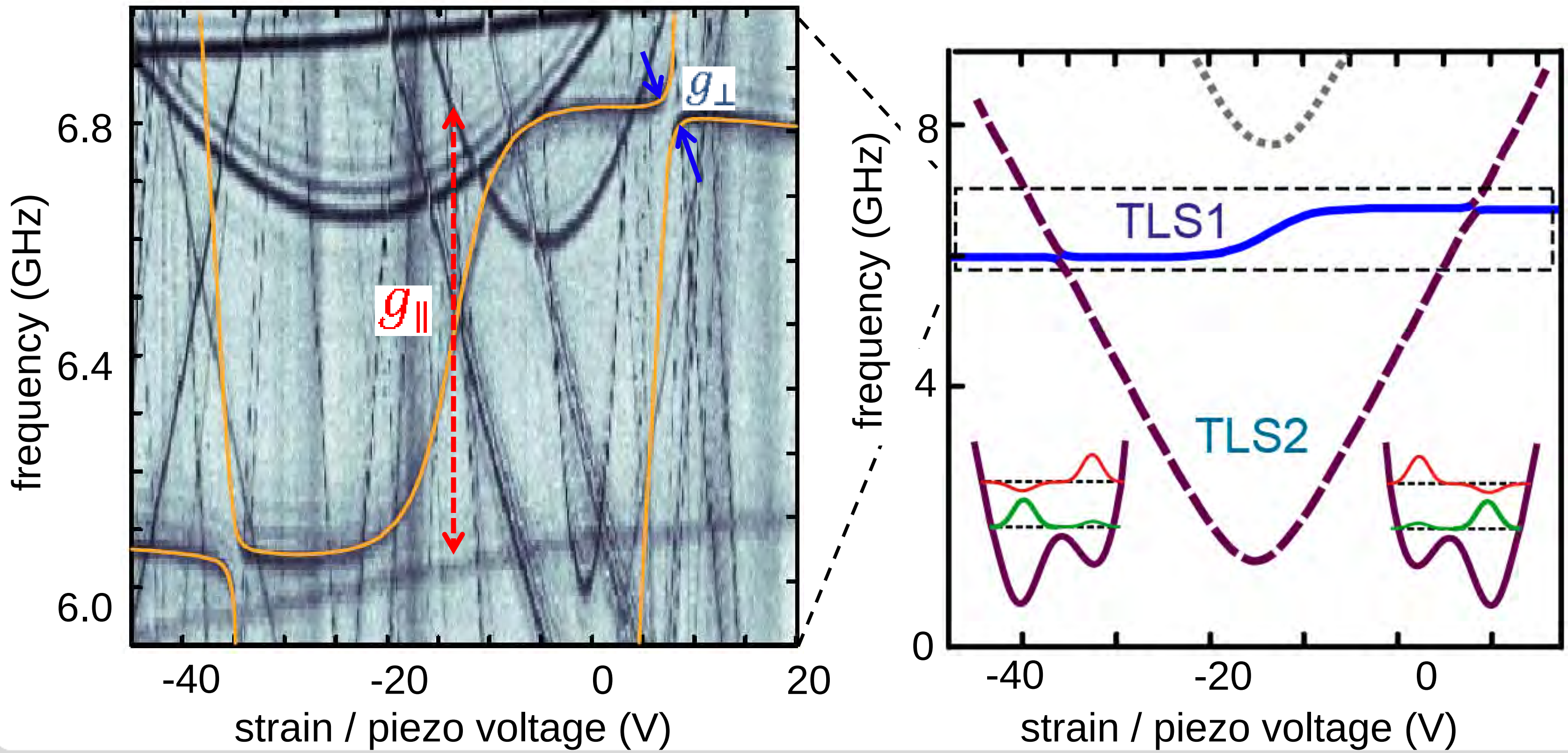
interaction Hamiltonian:

$$H_{\text{int}} = g\ \sigma_{z_1}\sigma_{z_2}$$

rotate to eigenbasis by angle θ , where $\cos\theta = \frac{\varepsilon}{E}, \quad \sin\theta = \frac{\Delta}{E}$

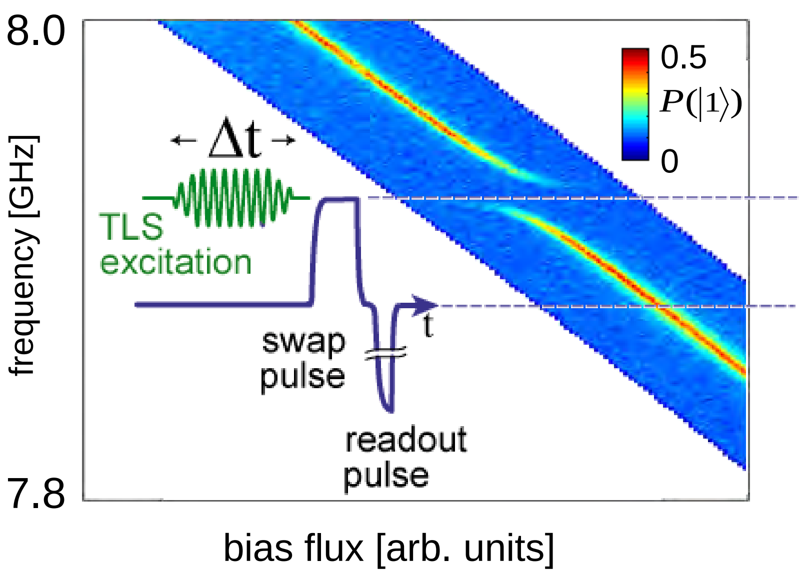
$$\Rightarrow \hat{H}_{\text{int}} = \underbrace{g\cos\theta_1\cos\theta_2}_{g_{\parallel}}\ \hat{\sigma}_{z_1}\hat{\sigma}_{z_2} + \underbrace{g\sin\theta_1\sin\theta_2}_{g_{\perp}}\ \hat{\sigma}_{x_1}\hat{\sigma}_{x_2} + \underbrace{\propto(\hat{\sigma}_x\hat{\sigma}_z + \hat{\sigma}_z\hat{\sigma}_x)}_{\text{minor contributions}}$$

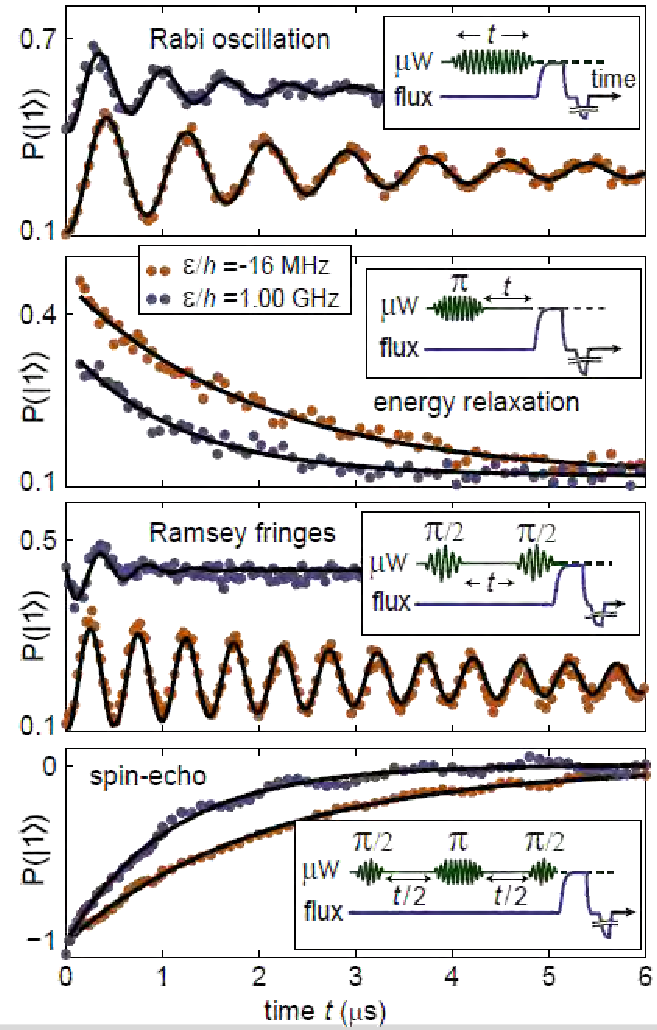


coherent control of individual TLS

J. Lisenfeld et al., Phys. Rev. B **81**, 100511 (2010)

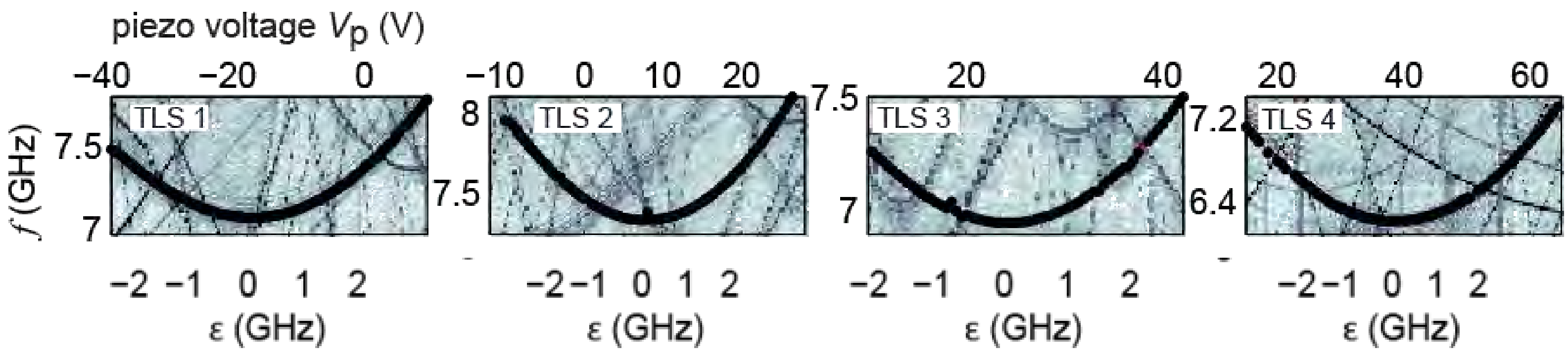
- TLS **resonantly absorbs photons** via a **Raman transition** involving a virtual qubit excitation
- ➡ full NMR-like TLS control via microwave pulse sequences
- ➡ TLS operation not degraded by qubit decoherence





Strain-dependence of TLS coherence times

J. Lisenfeld, G. Schön, A. Shnirman, G. Weiss, A.V. Ustinov et al., Scientific Reports **6**, 23786 (2015)



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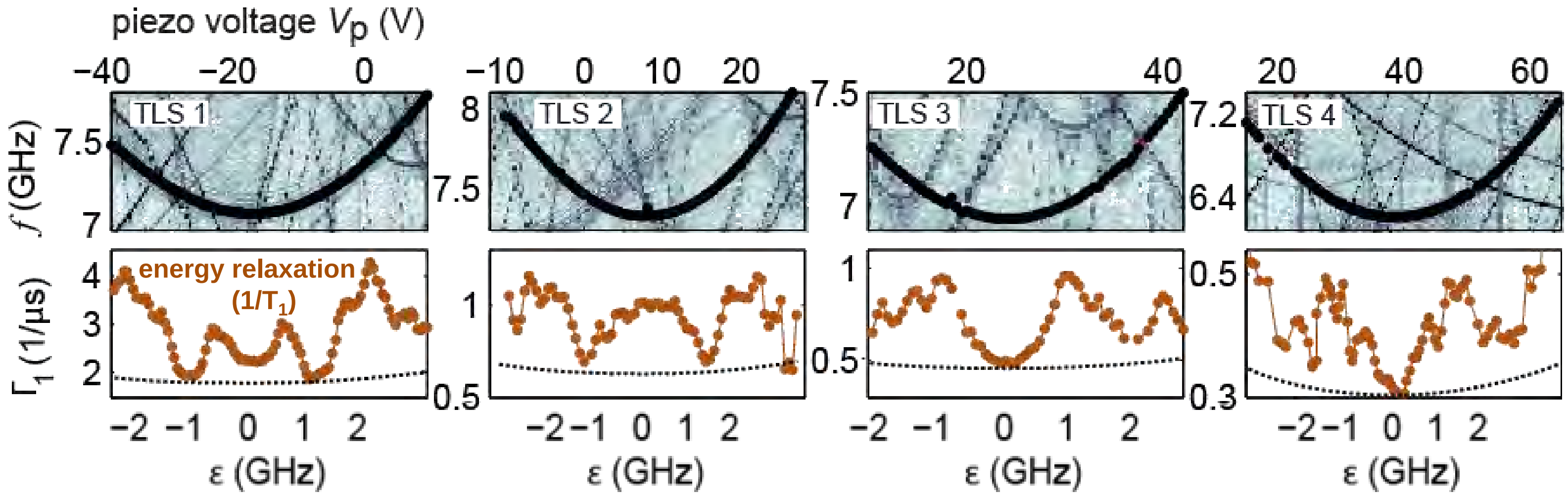
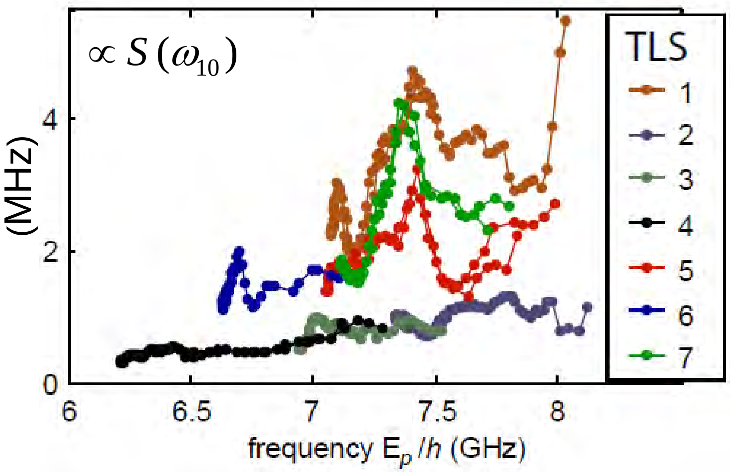


- symmetric pattern in Γ_1 can not originate in mutual TLS interactions

- golden rule: $$\Gamma_1 \propto \left(\frac{\Delta}{\sqrt{\Delta^2+\varepsilon^2}}\right)^2 \cdot S(\omega_{10})$$

several TLS have a common maximum in Γ_1 around 7.4 GHz

- possibly coupling to same phonon mode



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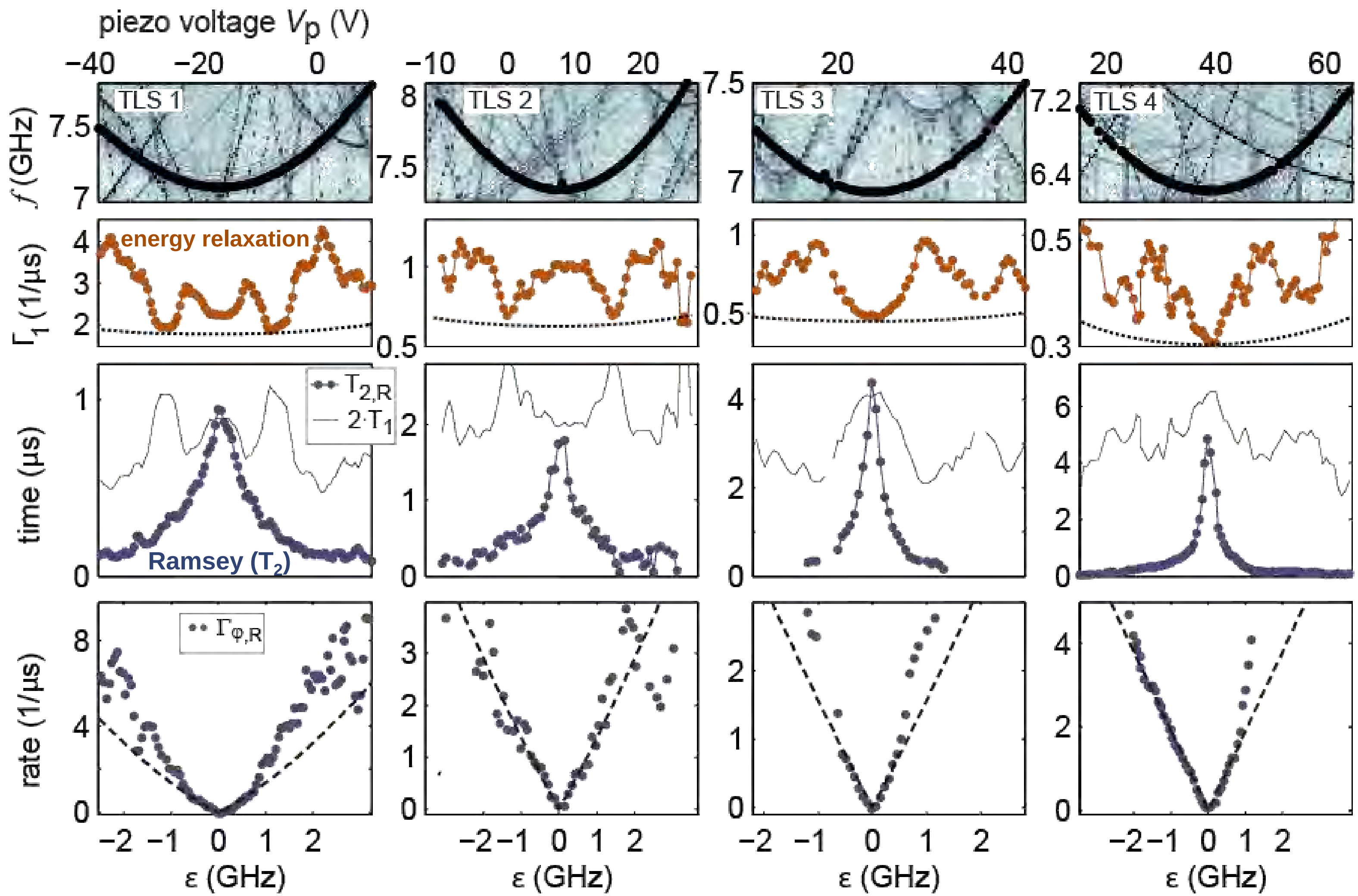

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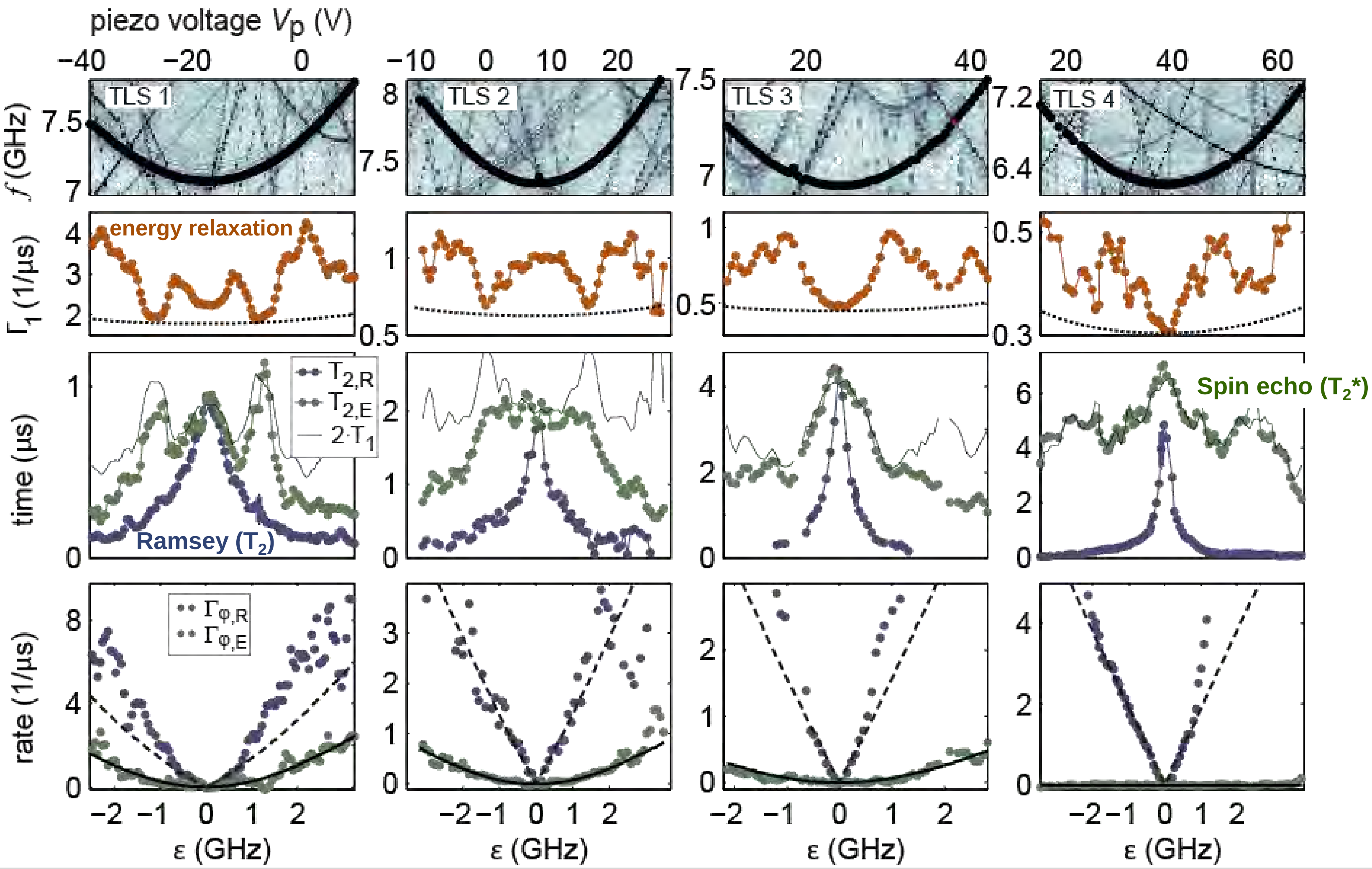
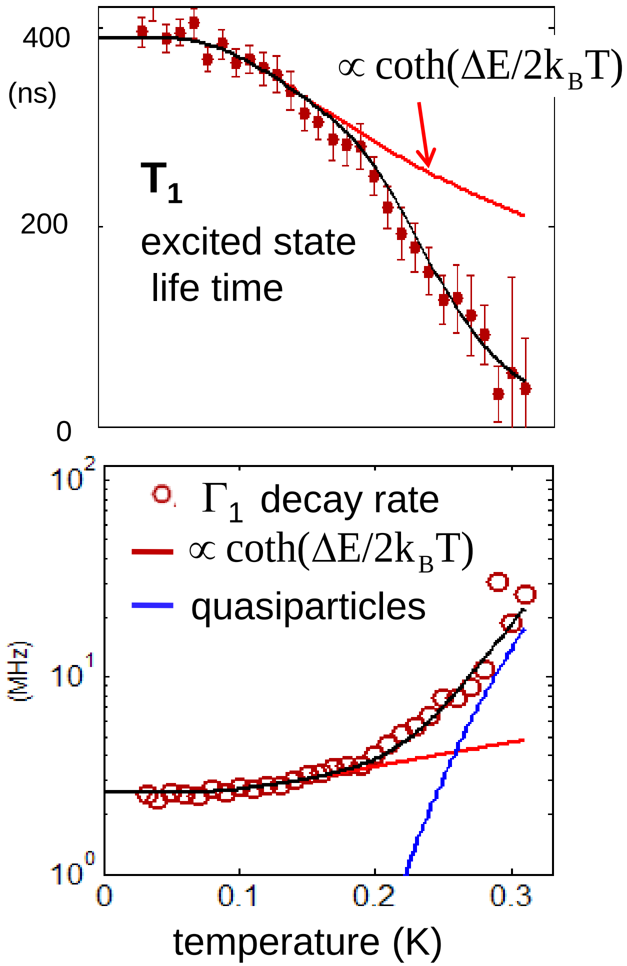


Temperature dependence of TLS coherence

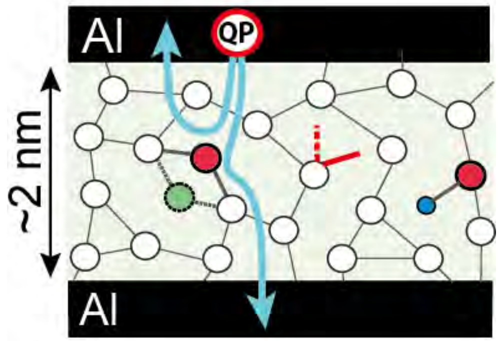
J. Lisenfeld et al., Phys. Rev. Lett. **105**, 230504 (2010)

- TLS energy relaxation rate exceeds phonon contribution



- TLS decay at higher temperatures [1] caused by **quasiparticles** ?

  c.f. J. L. Black, Glassy Metals I, Topics in Applied Physics 46, 167 (1981).



➡ test :

1) generate quasiparticles by injection or by raising the sample temperature
2) calibrate QP density using the qubit
3) measure TLS coherence times

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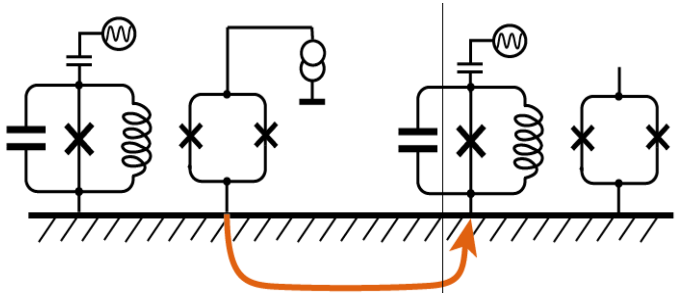
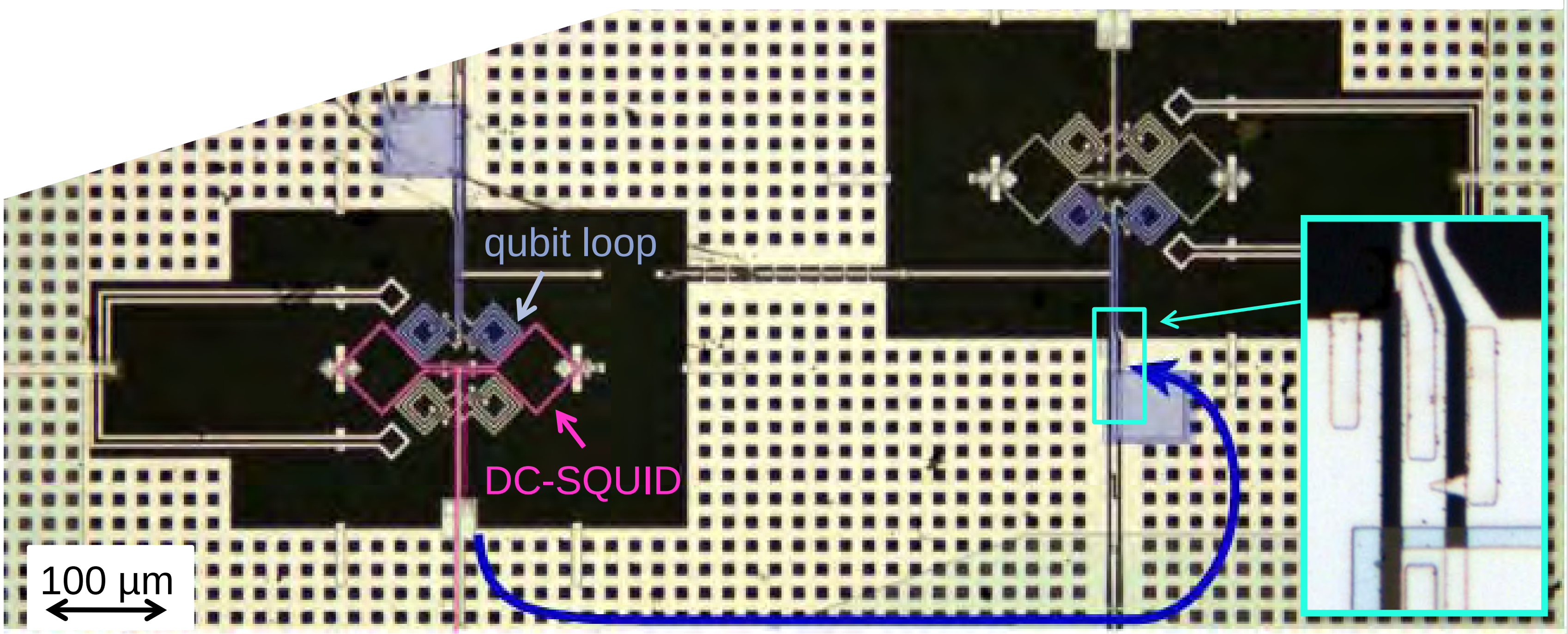
injection of quasiparticles

cf. M. Lenander et al., PRB **84**, 024501 (2011)



- drive 2nd on-chip DC-SQUID with current $I_b > I_C$
- → generated QPs diffuse to qubit's Josephson junction where they interact with TLS
- → we expect a difference in QP density on the two JJ electrodes because of the sample layout

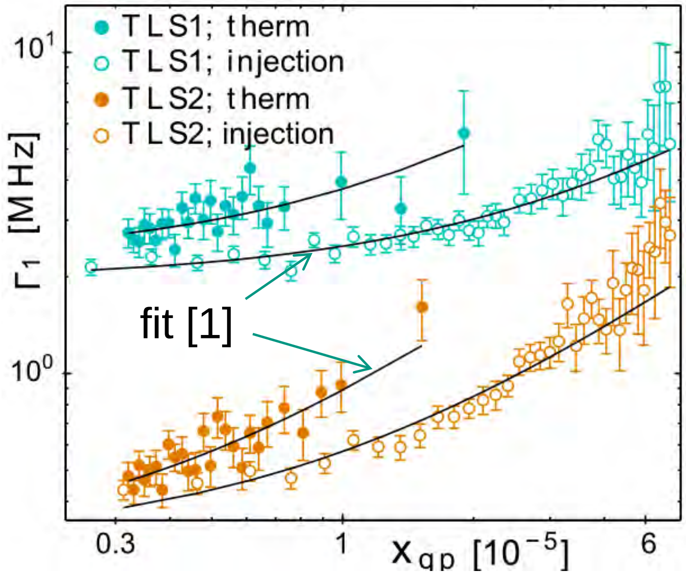


QP-induced decoherence of Two-Level Systems

A. Bilmes, J. Lisenfeld, G. Weiss, A.V. Ustinov et al., arXiv:1609.06173

- Korringa-like QP-TLS-interaction:

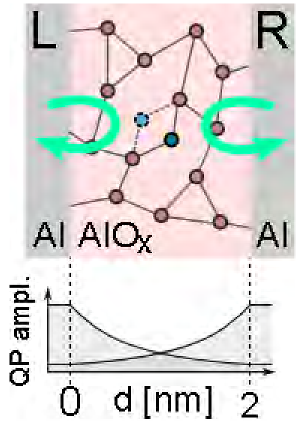
$$\Gamma_1 = S x_{qp} + \Gamma_1^{(0)}$$



- we observe:

$$\Gamma_1^{therm} > \Gamma_1^{inject}$$

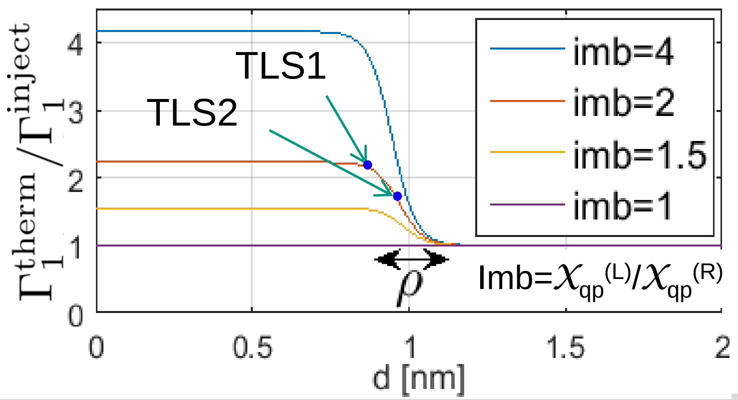
- QP-TLS coupling depends on TLS location



- QP densities differ in injection experiment:

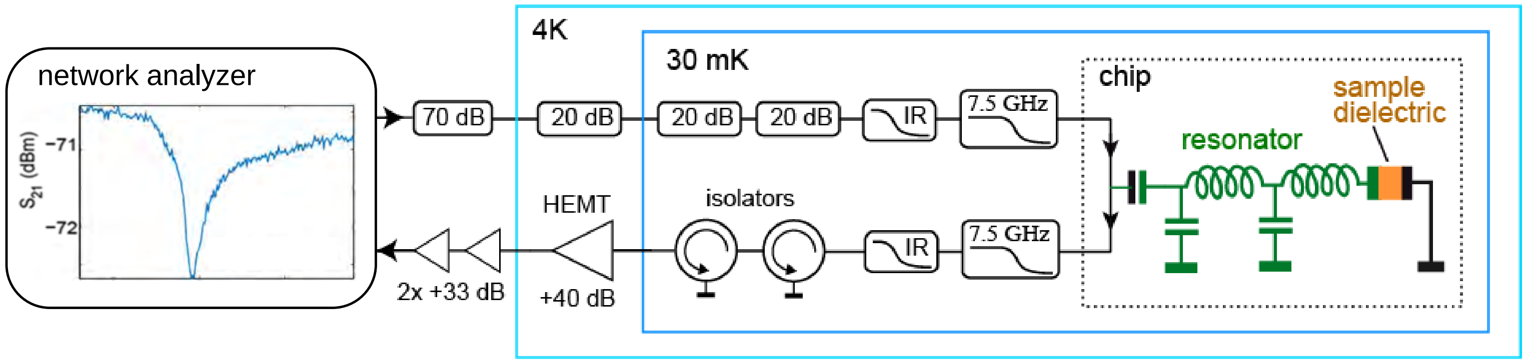
$$x_{qp}^{(L)} \approx x_{qp}^{(R)}/2$$

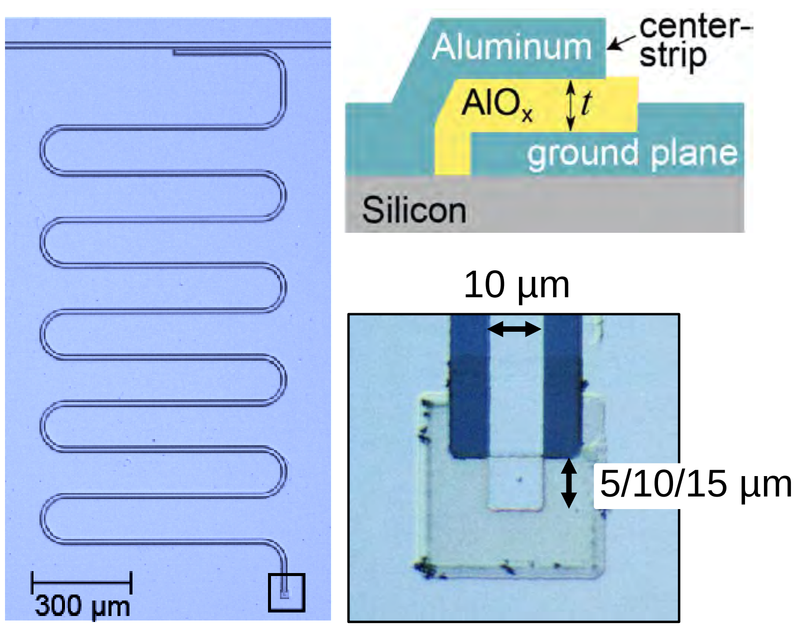
➡ estimation of TLS location



coupling TLS to a transmission-line resonator

J. Brehm, A. Bilmes, J. Lisenfeld, to be published (2016)





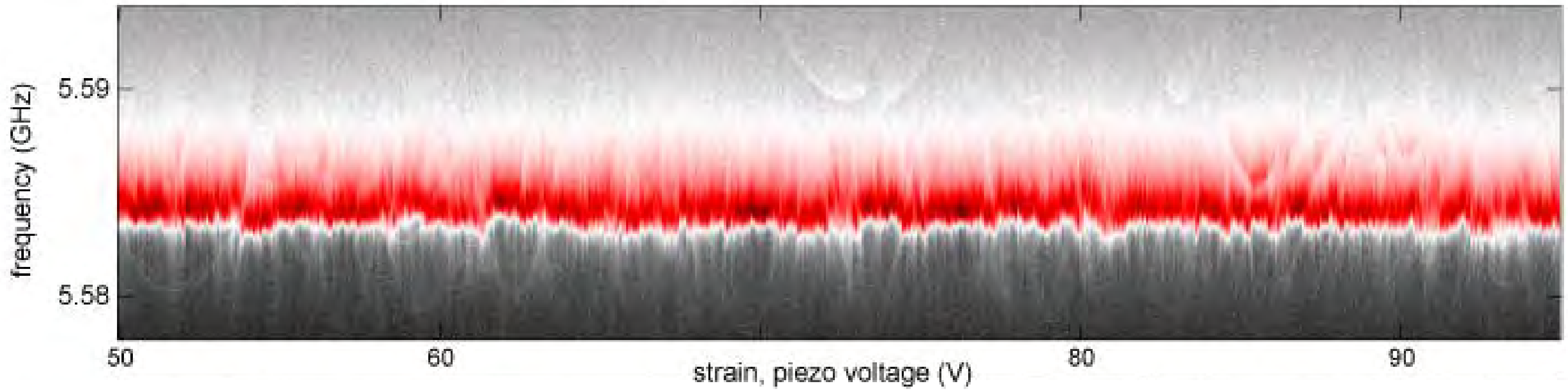
- AlOx fabricated using anodization
  t =50 nm, area 10µm x (5/10/15)µm
- choose a dielectric volume to have ~1 TLS within 1-MHz-window
  $\rho \approx 100\ \mathrm{TLS}/(\mu m^3 \cdot GHz) \Rightarrow V \approx 10 \mu m^3$
- coupling strength resonator-TLS g:

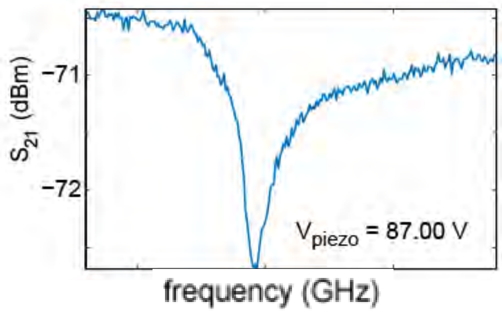
$$hg = p_{\|} \left| \vec{E} \right| \approx \frac{p_{\|}}{t} \sqrt{\frac{hf_{res}}{2\,(C_{res} + C_{cap})}}$$

$$C_{res} \approx 1.4\, pF, \quad C_{cap} \approx 0.2\, pF$$

TLS coupled to a resonator: strain-spectroscopy

J. Brehm, A. Bilmes, J. Lisenfeld, to be published (2016)



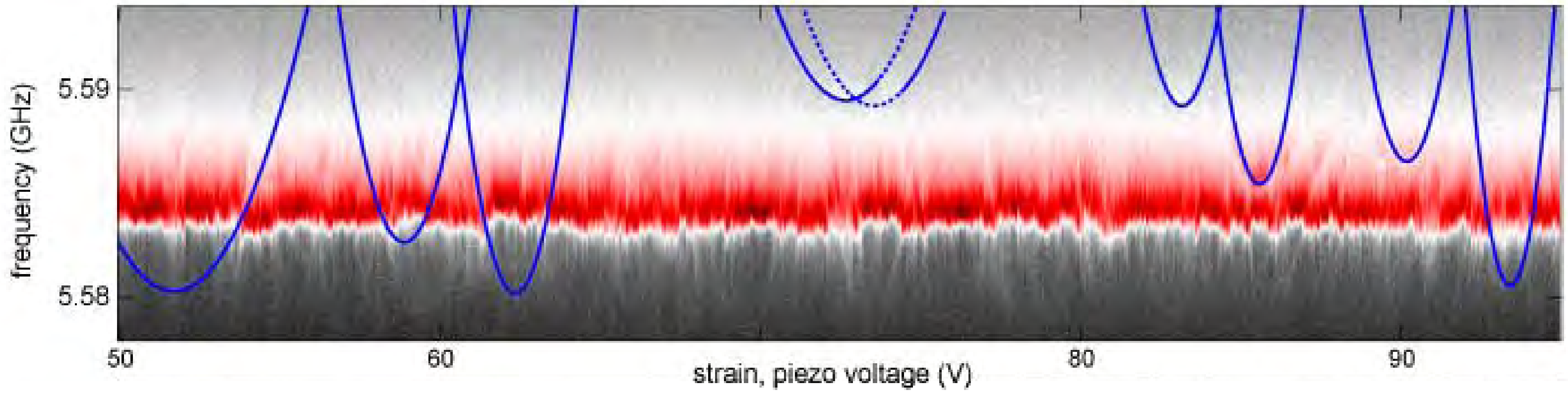


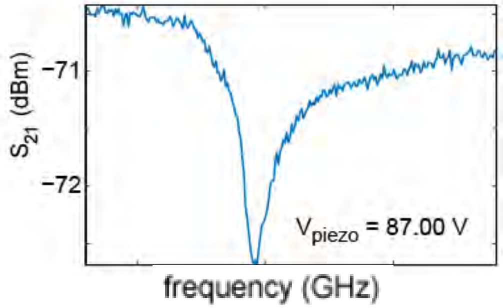
[1] E. Rephaeli et al., 'Few-photon single-atom cavity QED with input-output formalism in Fock space, arXiv:1208.6053 (2012)

TLS coupled to a resonator: strain-spectroscopy

J. Brehm, A. Bilmes, J. Lisenfeld, to be published (2016)

Karlsruhe Institute of Technology





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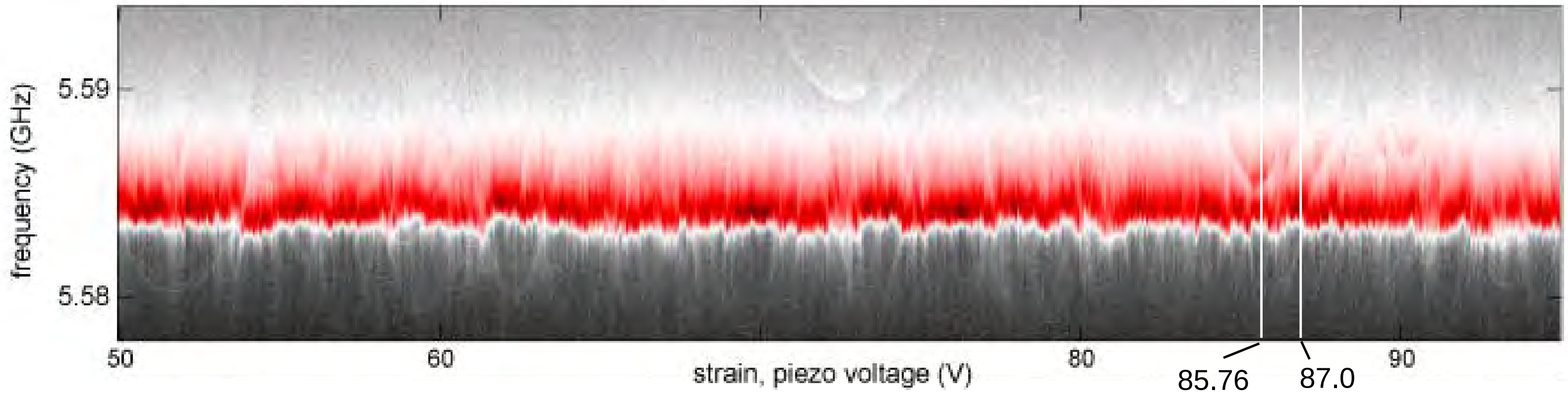
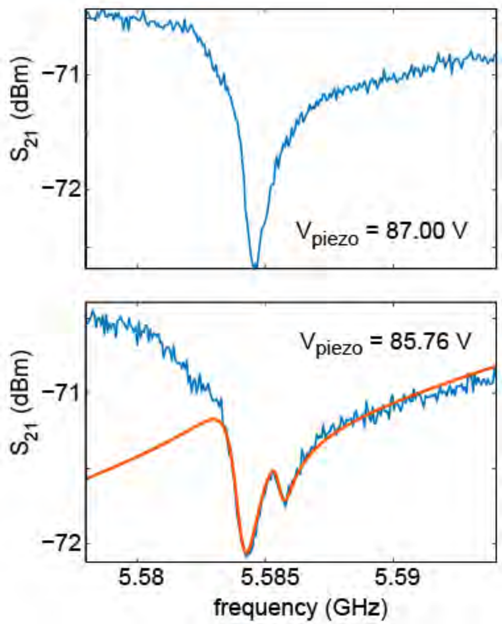


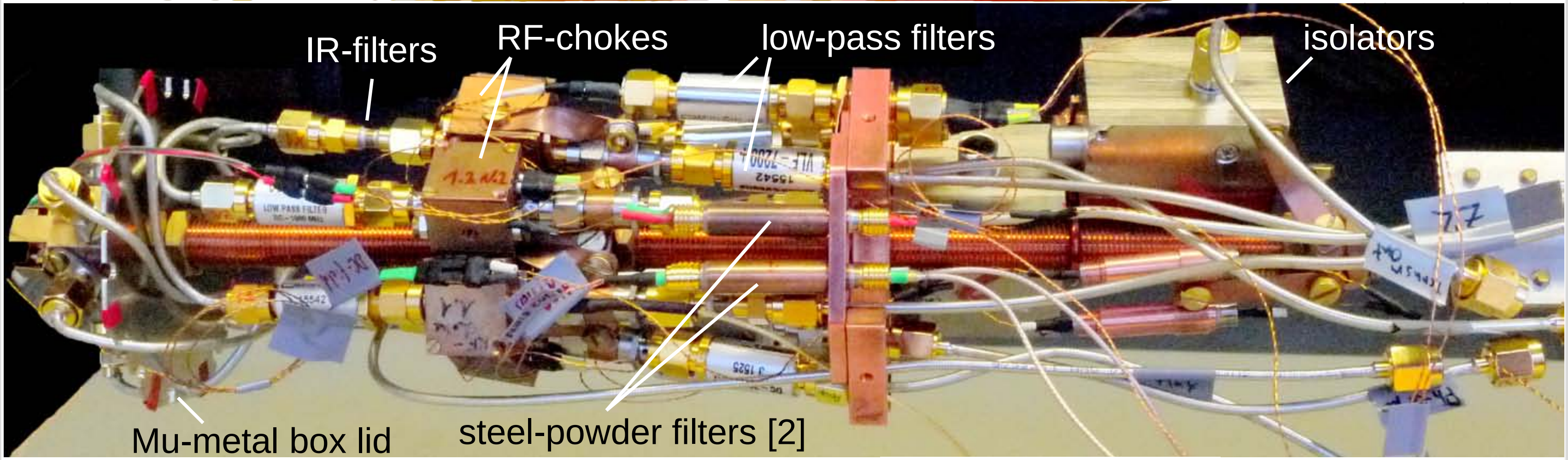


- individual TLS are resolved
  double-peaks in resonance with strongly coupled TLS
- fit to model provides TLS parameters [1]:

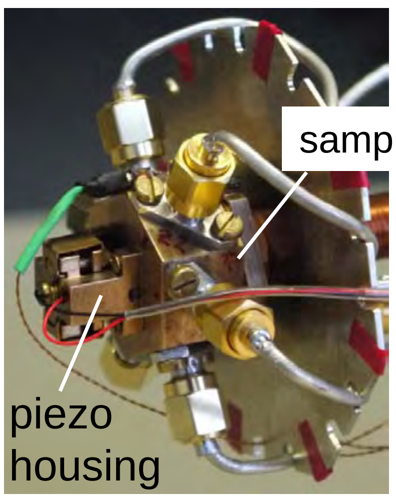
  example:
  - T_1 = 1.6 μs, energy relaxation rate
  - g = 540 kHz, coupling strength
  - $p_{||}$ = 1.0 eÅ, dipole moment

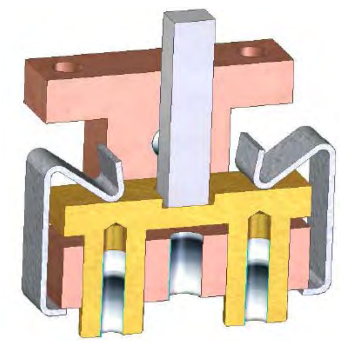
[1] E. Rephaeli et al., 'Few-photon single-atom cavity QED with input-output formalism in Fock space, arXiv:1208.6053 (2012)

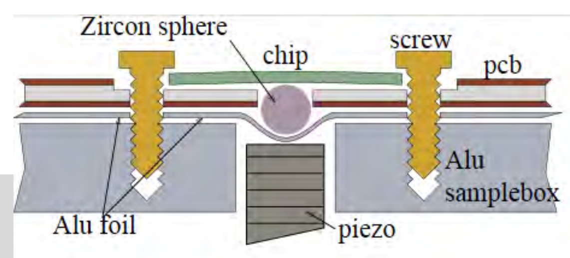
mechanical-strain tuning of TLS: setup[1]



piezo housing





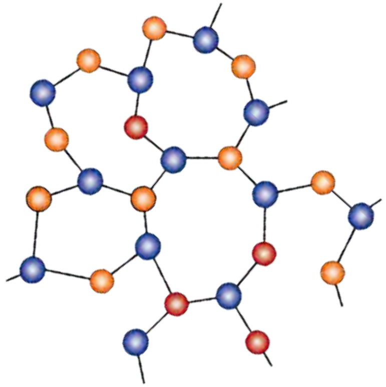


[1] design and assembly by A. Bilmes, PhD Thesis (KIT, 2018)
[2] A. Lukashenko and A.V. Ustinov, Rev. Sci. Instr. 79, 014701 (2008)

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2017.
Oral presentation at IWSSD 2016. No manuscript was submitted for hardcopy journal publication.

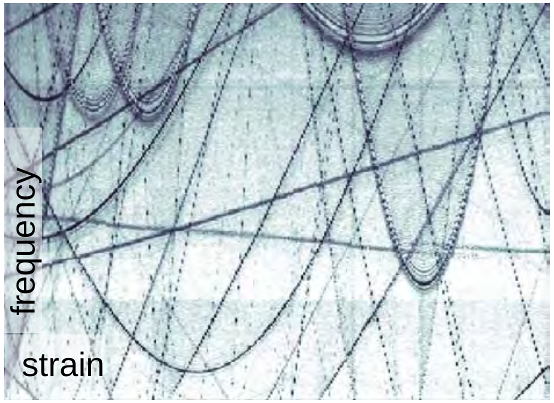
Summary: exploring TLS with superconducting Qubits

- **TLS** are a **major decoherence source** which affects various microfabricated devices
  - ➡ it is vitally important to understand emergence of TLS in fabrication

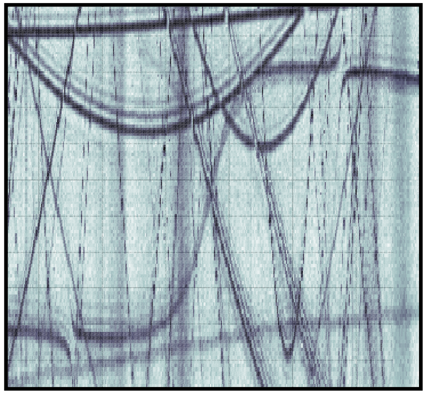


- it is now possible to **address single TLS coherently** with superconducting circuits

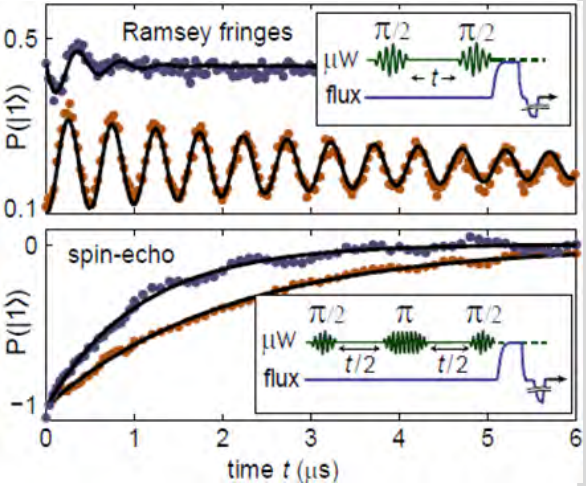
TLS strain spectroscopy



coherently coupled TLS



TLS quantum dynamics



➡ Superconducting qubits (and resonators) are **ideal tools** for the **characterization of materials** and **defect properties.**