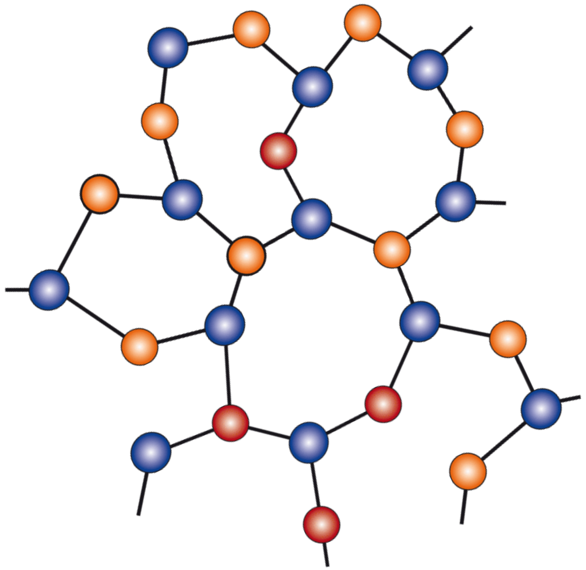
Physikalisches Institut

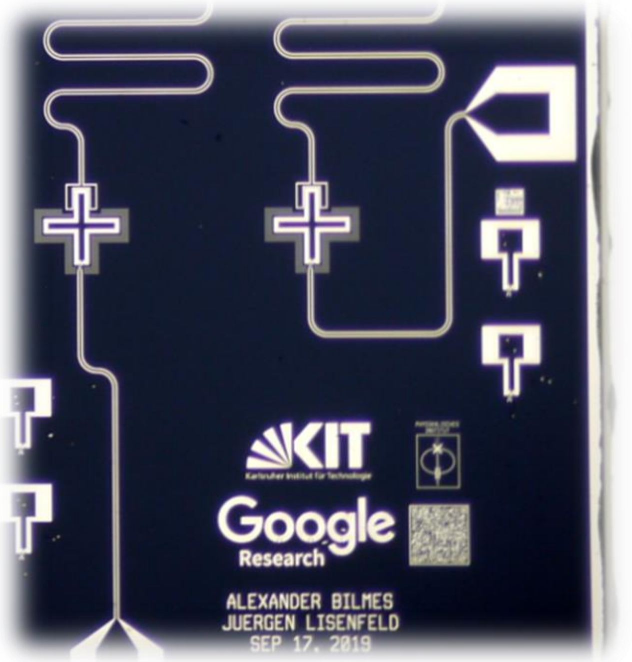
KIT Karlsruher Institut für Technologie

Material Defects in Superconducting Quantum Bits: Origins and Remedies

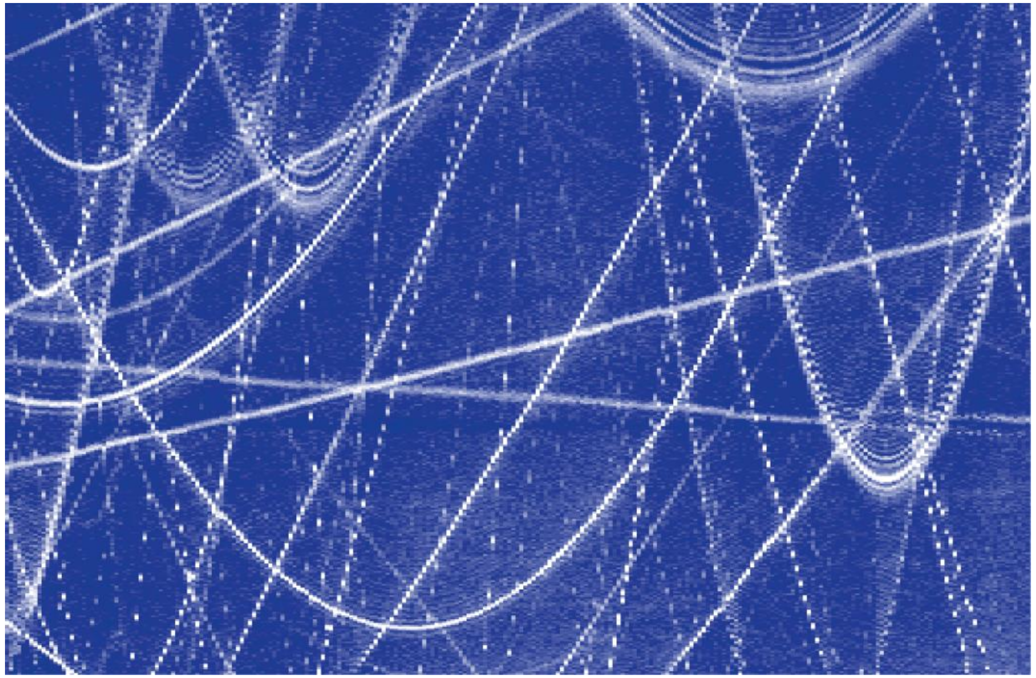
Jürgen Lisenfeld



Exploring the mysteries of glasses...



..and the sources of decoherence in superconducting qubits...

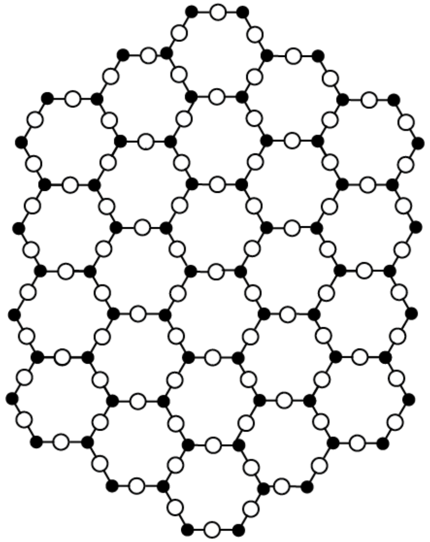


..to shed new light on atomic tunneling defects.

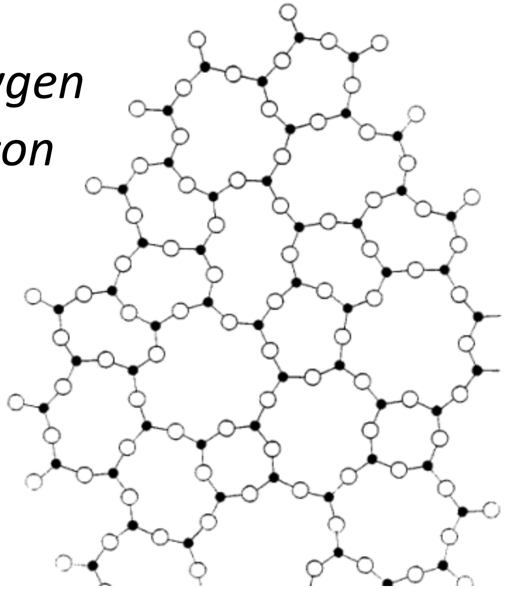
mysterious anomalies of amorphous materials

- cristalline SiO_2 ('quartz')

amorphous SiO_2 ("glass")

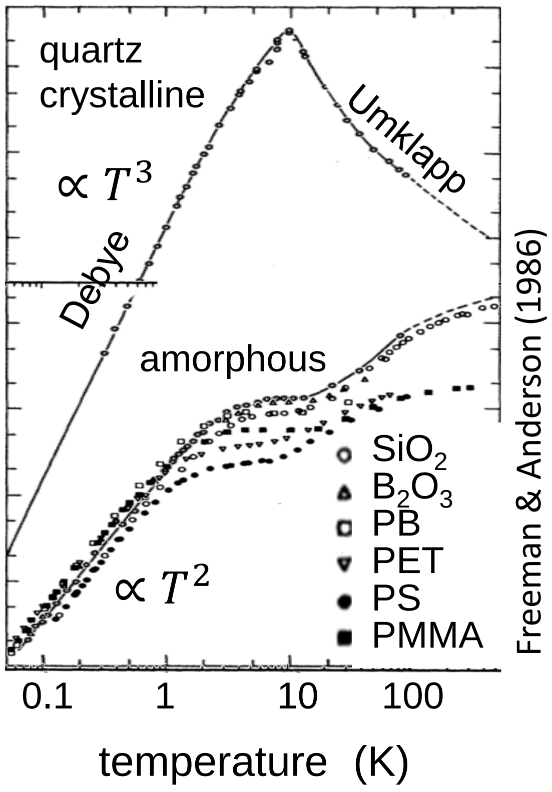


○ *oxygen*
● *silicon*

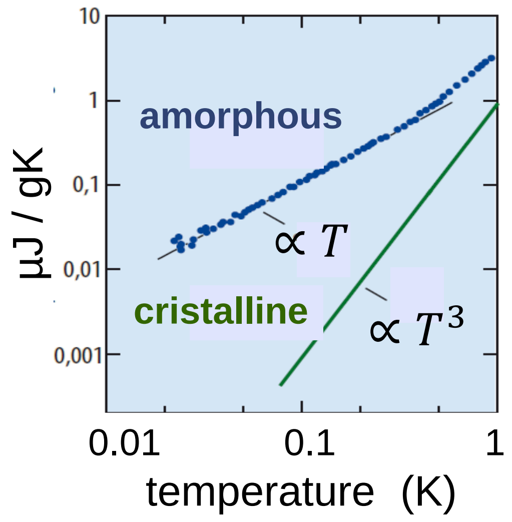


measurements in the 1970s revealed universal anomalies of glasses

thermal conductivity



specific heat

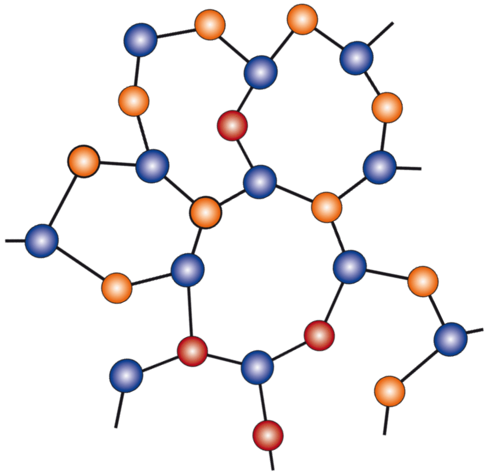


➡ glasses must **contain intrinsic states**

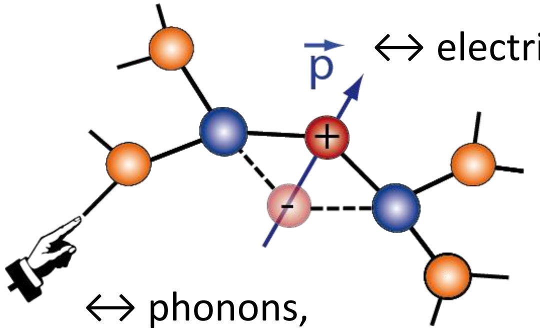
The Standard Tunneling Model

Anderson, Halperin,Varma (1973); Phillips (1973)

- **glasses contain intrinsic states**
  - (possibly) formed by atoms which can tunnel between two nearly equivalent positions



- **interaction** with **strain** & **electric field**

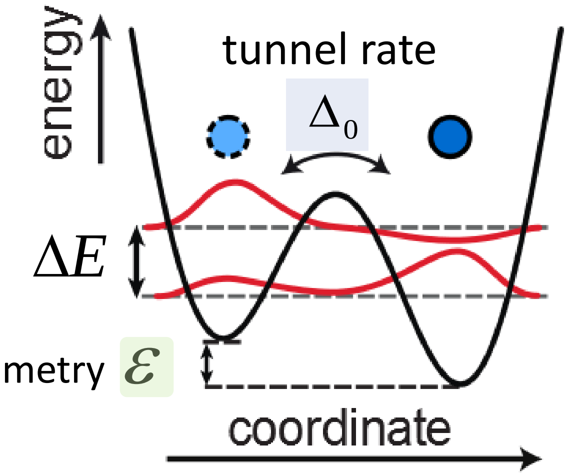


- **model by Two-Level Tunneling Systems (TLS)**

$$\hat{H}_{\mathrm{TLS}} = \frac{1}{2}\Delta_0\,\hat{\sigma}_x + \frac{1}{2}\varepsilon\,\hat{\sigma}_z$$

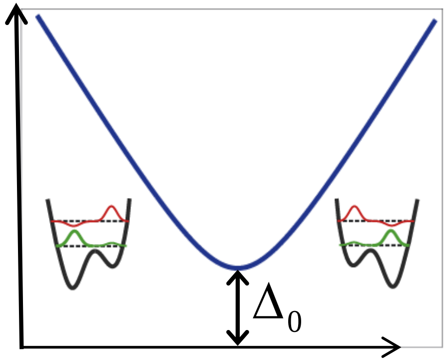
asymmetry $\varepsilon = \varepsilon_0 + \vec{p}\cdot\vec{E} + \vec{\gamma}\cdot\vec{S}$

($\vec{p}$: el. dipole moment; $\vec{E}$: E-field; $\vec{\gamma}$: deformation potential; $\vec{S}$: strain)



- **transition energy:**

$$\Delta E = \sqrt{\Delta_0^{\,2} + \varepsilon^2}$$



- expect **constant energy distribution**

$$P(E) = P_0 \approx 1000\ /\mathrm{GHz}\,\mu m^3$$

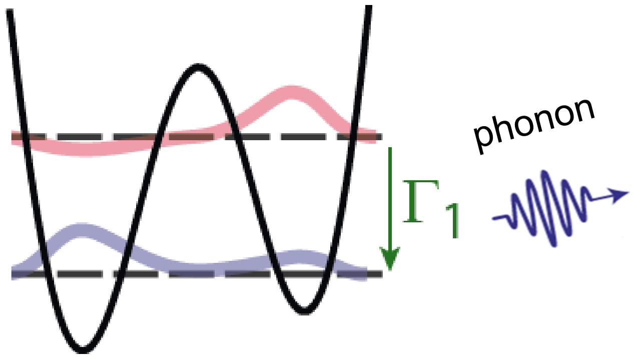
- neglects interactions between defects

TLS relaxation dynamics

- **relaxation rate**

$$\Gamma_1 = \left(\frac{\gamma_l^2}{v_l^5} + 2\frac{\gamma_t^2}{v_t^5}\right) \frac{\Delta_0^2 E}{2\pi\rho\hbar^4} \coth(E/2k_B T)$$

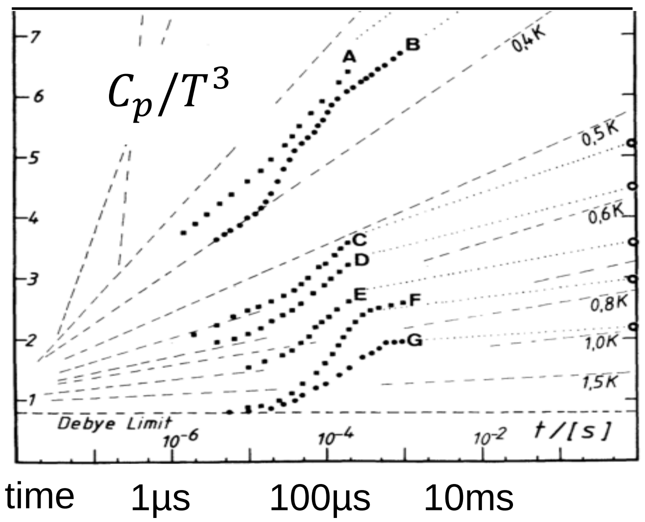
γ : phonon coupling strength
v : sound velocity
ρ : material density
p : electric dipole moment



- **internal friction** $Q^{-1} = \pi P_0 \gamma^2 / 2\rho v^2$
- **dielectric loss** $\tan\delta = \pi P_0 p^2 / 6\varepsilon_0 \varepsilon_i$

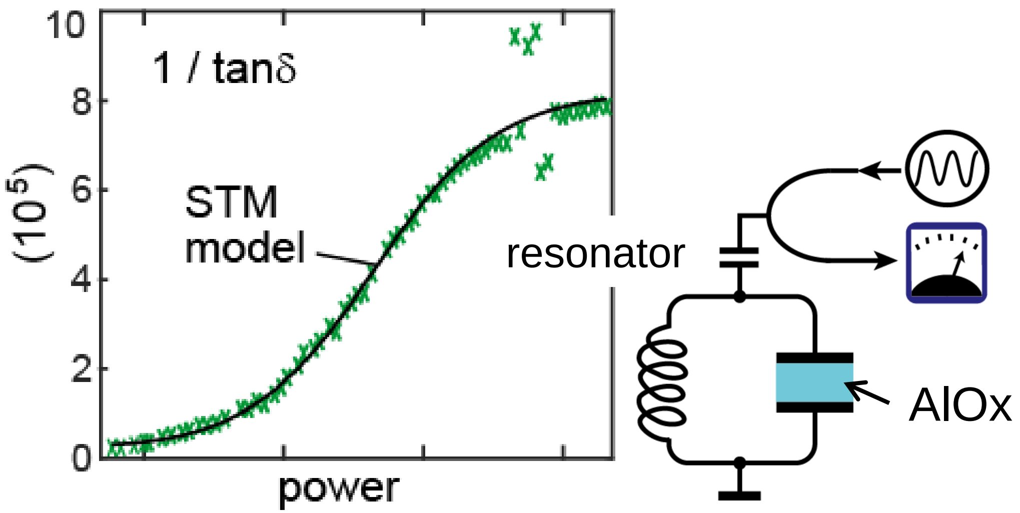
specific heat depends on time

Meissner and Spitzmann, PRL 46, 265 (1981)



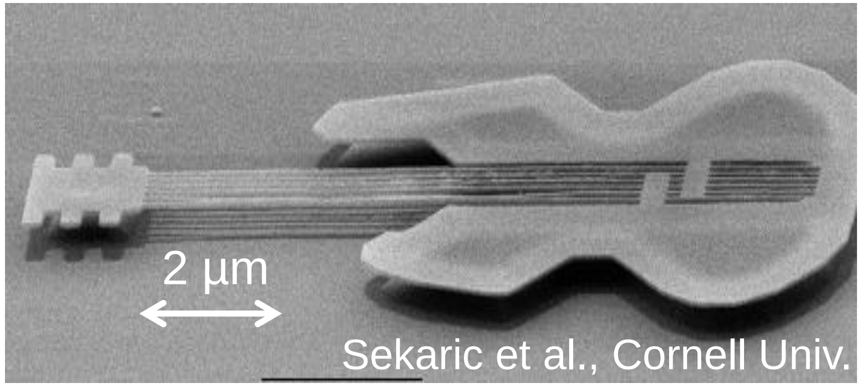
Dielectric loss depends on power

J.D. Brehm, J. Lisenfeld et al., APL 111, 12601 (2017)



Devices affected by TLS defects

- **nanomechanical resonators**

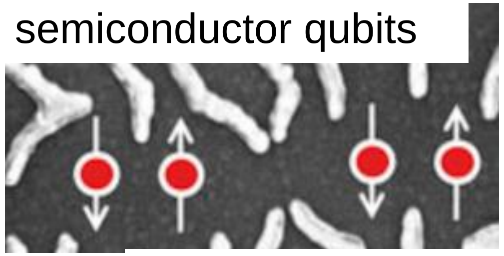


Sekaric et al., Cornell Univ.

- **quantum systems**

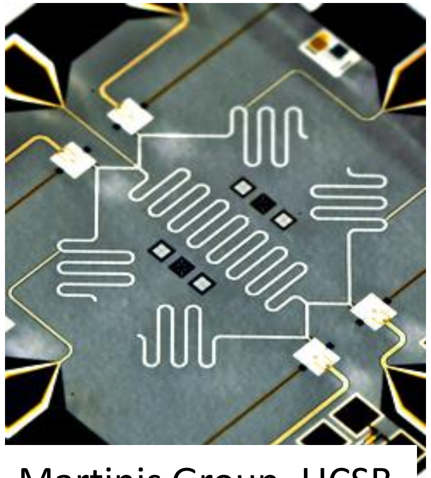
ion trap (Los Alamos)

semiconductor qubits



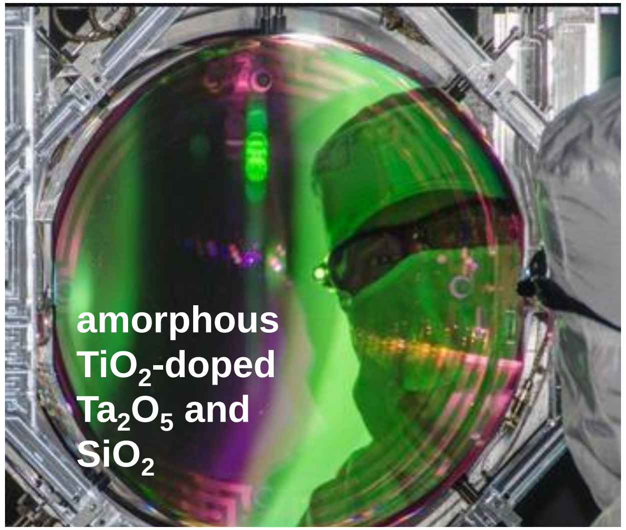
Bluhm, RWTH Aachen

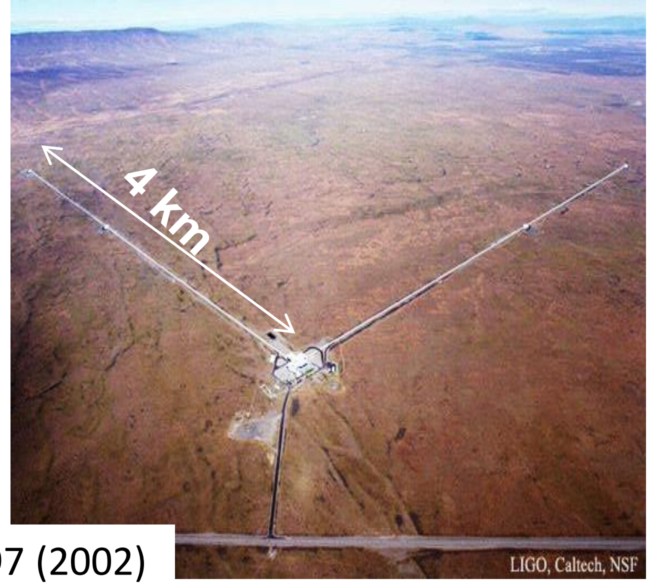
- **superconducting qubits**



Martinis Group, UCSB

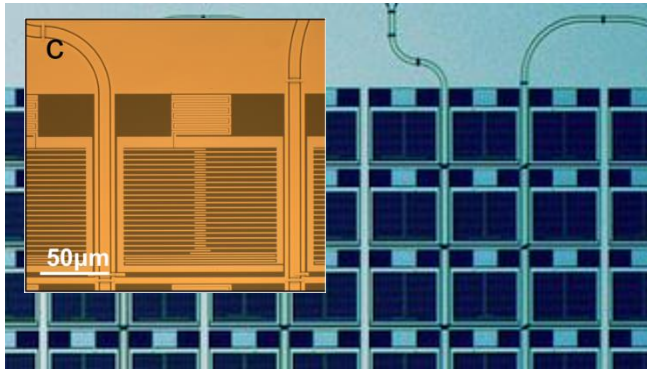
- **optical cavities (Lasers, LIGO, ...)**





Harry et al., Class. Quant. Grav. 19, 897 (2002)

- **kinetic inductance detectors**



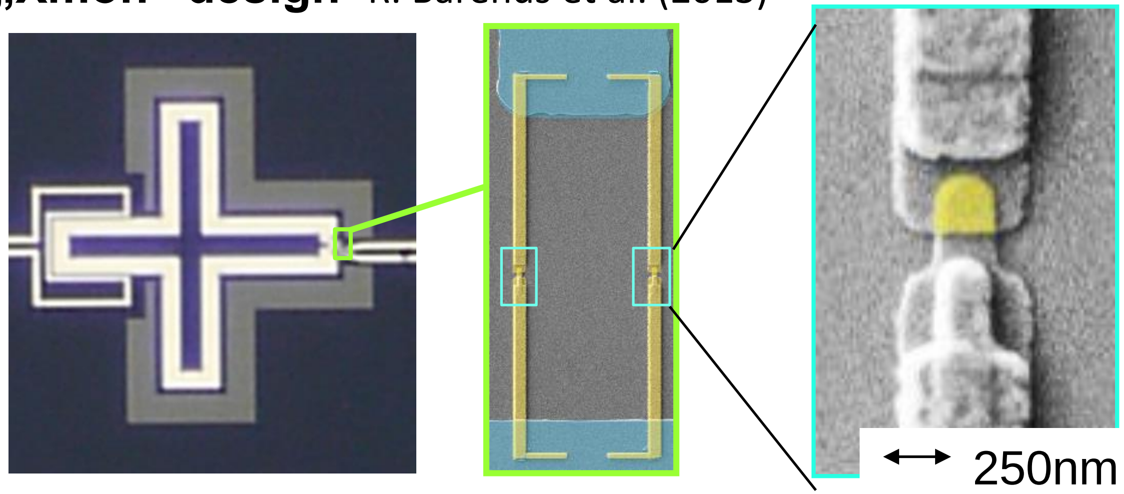
Dodkins et al., 2018

- **accelerator cavities**

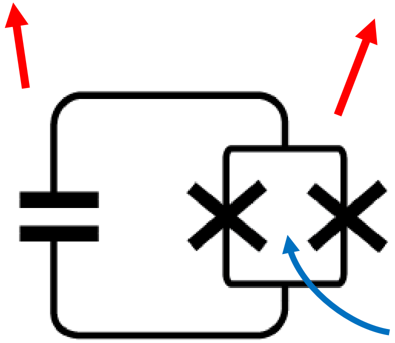
Romanenko et al., PRL 119 (2017)

Transmon Qubits

- **„Xmon“ design** R. Barends et al. (2013)



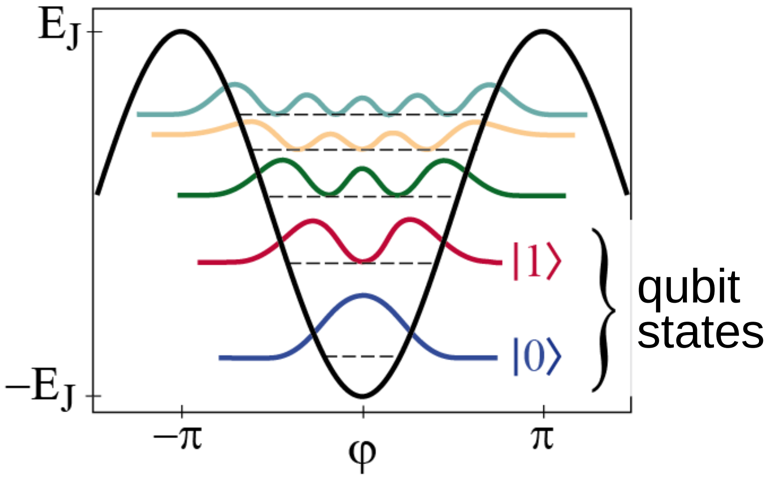
capacitor DC-SQUID Josephson junction



flux bias to
tune resonance frequency

Qubits are non-linear LC-Resonators

- **Transmon qubit energy levels**

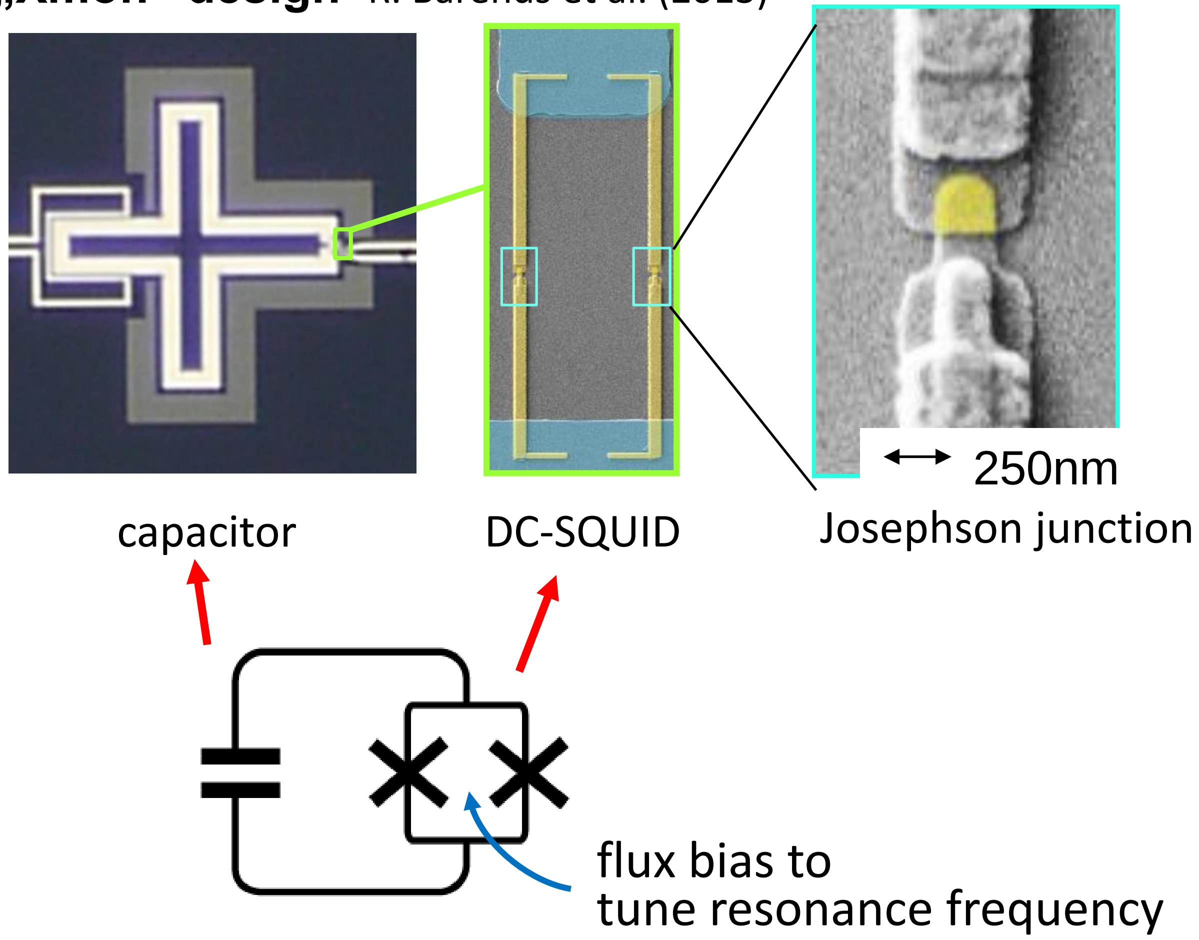


$$\hat{H} = \frac{\hat{Q}^2}{2C} - E_J \cos\varphi$$

$$E_J = \frac{\hbar I_c}{2e}$$

Transmon Qubits

- **„Xmon“ design** R. Barends et al. (2013)



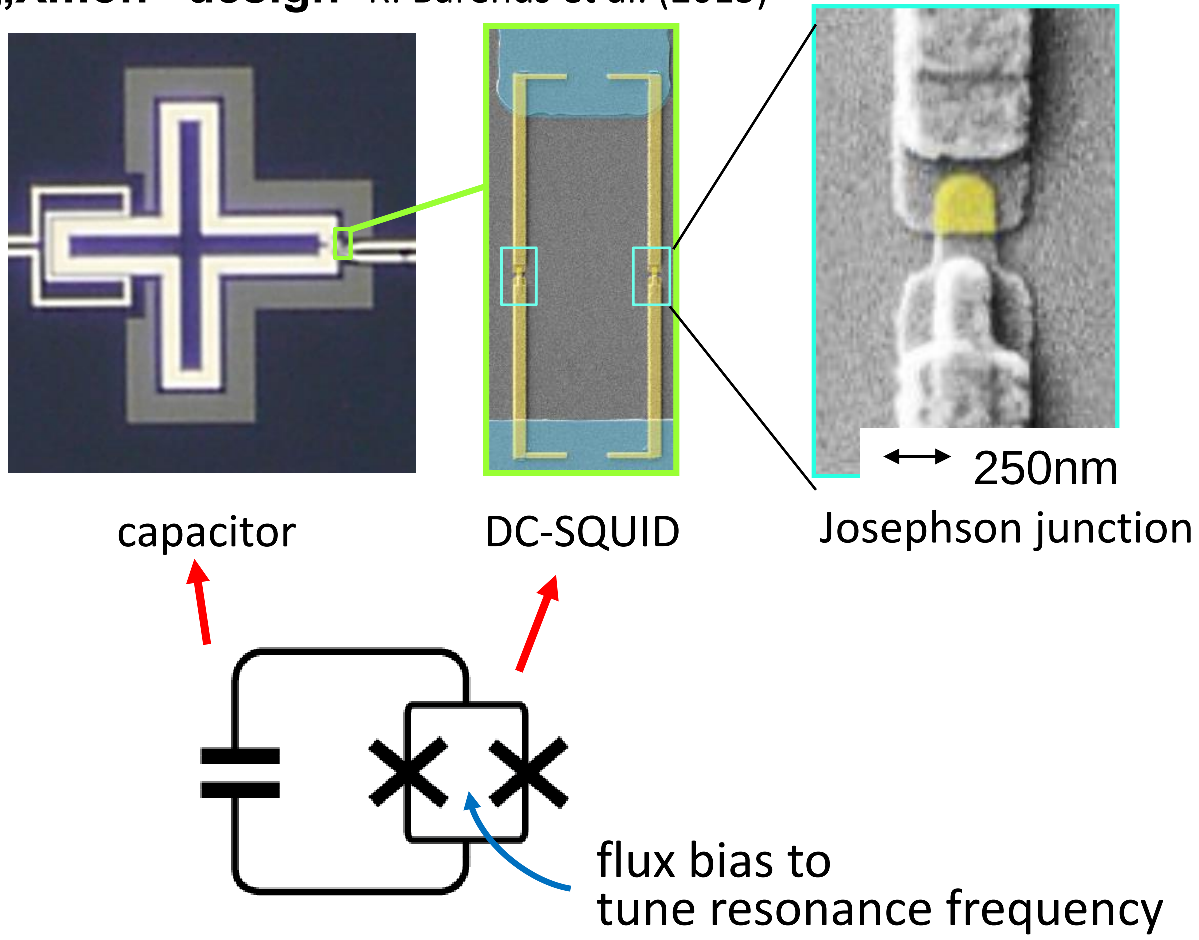
Qubits are non-linear LC-Resonators

- **Transmons made at KIT** (A. Bilmes)

- **433-qubit processor made by IBM**

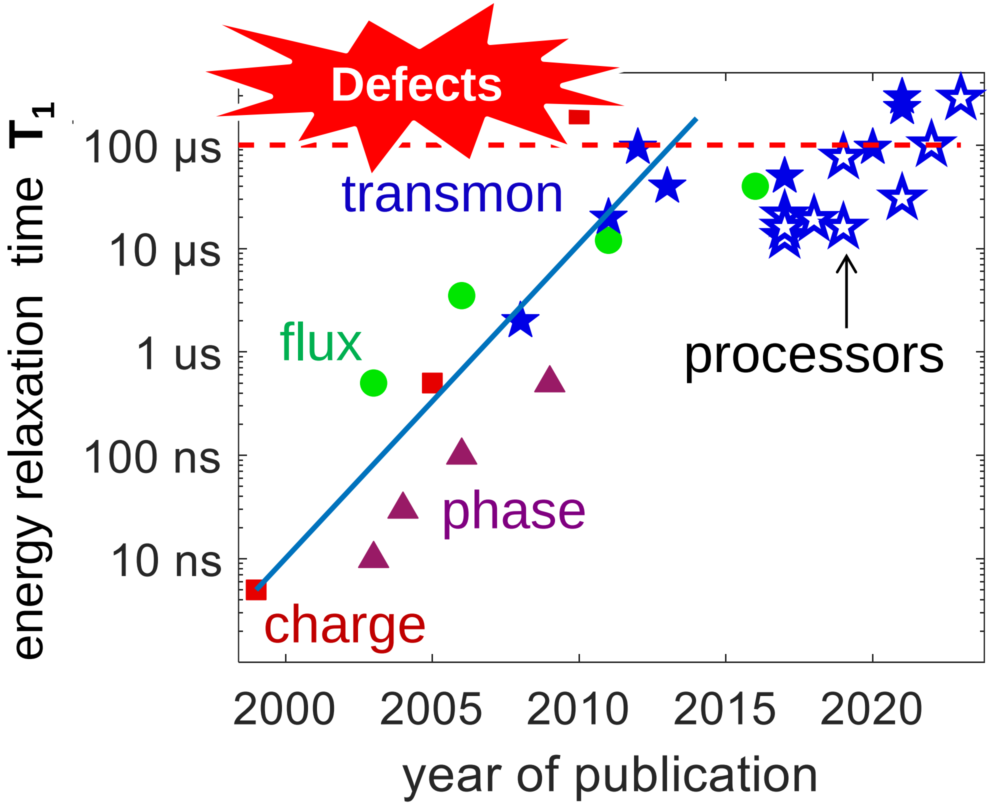
Transmon Qubits

- „Xmon“ design R. Barends et al. (2013)



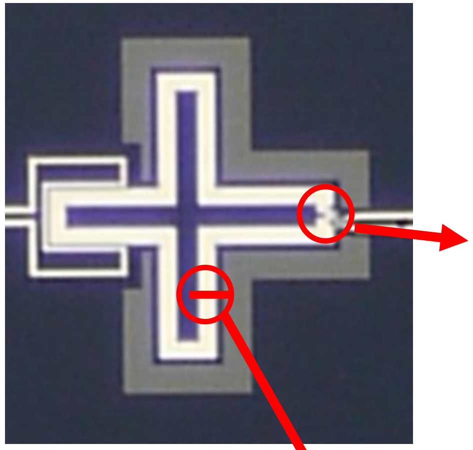
Qubits are non-linear LC-Resonators

- **qubit coherence is limited by material defects**

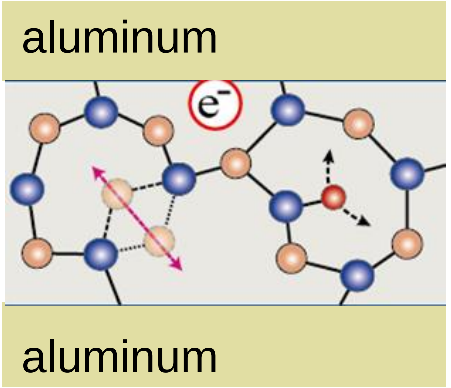


Material Defects in Qubits

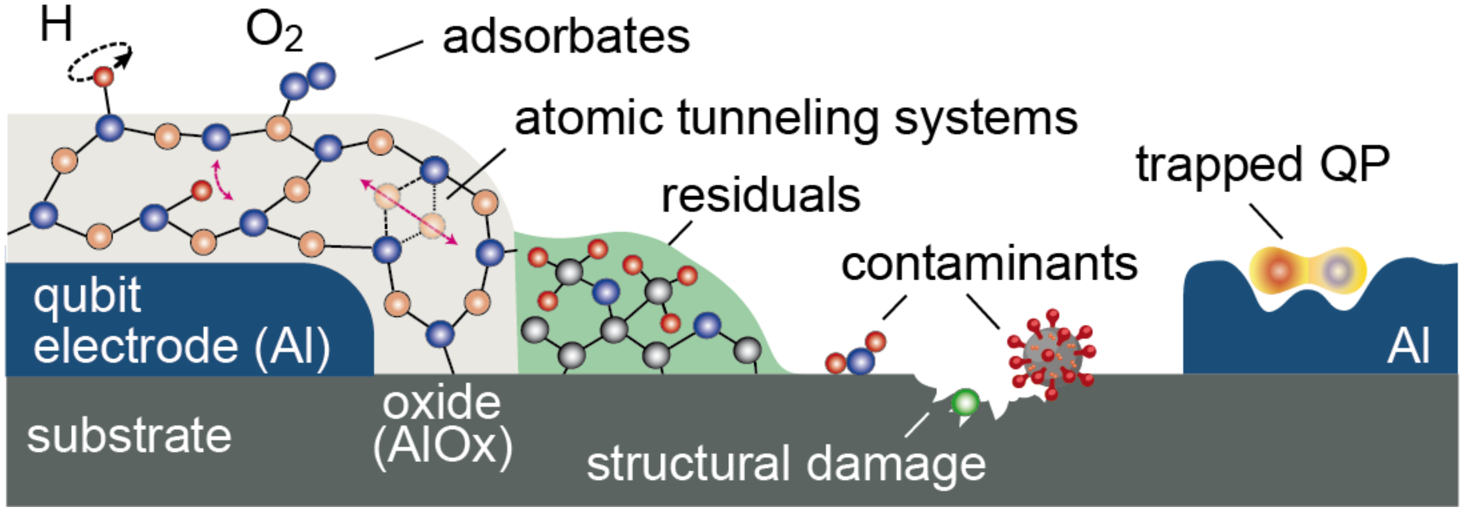
- **Transmon qubit**



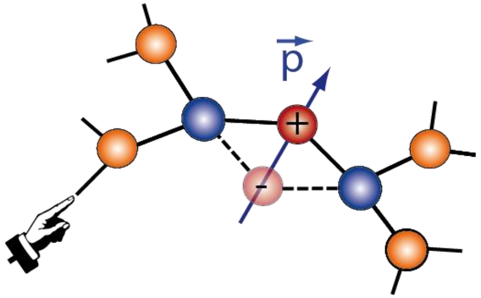
Josephson junction



circuit surface



- **TLS** couple to **the AC-electric field** of the qubit mode



- **TLS** have **random resonance frequencies**

Defect Models

Tunneling atoms
W.A. Phillips, Rep. Prog. Phys. **50**

Hydrogen rotors and interstitials
A.M. Holder et al., PRL **111**
Zhe Wang et al., PRB **98**

Andreev fluctuators
L. Faoro, L.B. Ioffe et al., PRL **95**
R. de Sousa et al., PRB **80**

Kondo resonances
L. Faoro, L.B Ioffe, PRL **96**

Metal-induced gap states
S.K. Choi et al., PRL **103**

Phonon-dressed electrons
K. Agarwal et al., PRB **87**

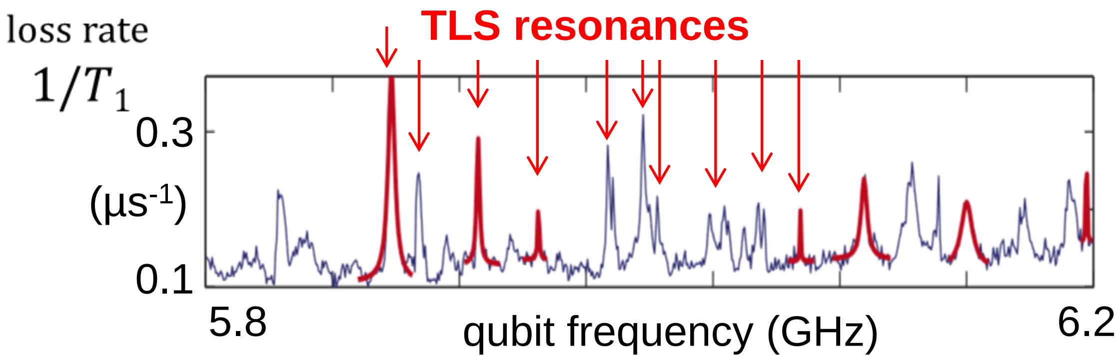
Trapped Quasiparticles
S. deGraaf et al., Sci. Adv. **6**

physisorbed Hydrogen + O_2
S. deGraaf et al., PRL **118**,
Nature Comm. **9** (2018)

Review:
C.Müller, J.Cole, J.Lisenfeld,
Rep. Prog. Phys. **82**, 24501 (2019)

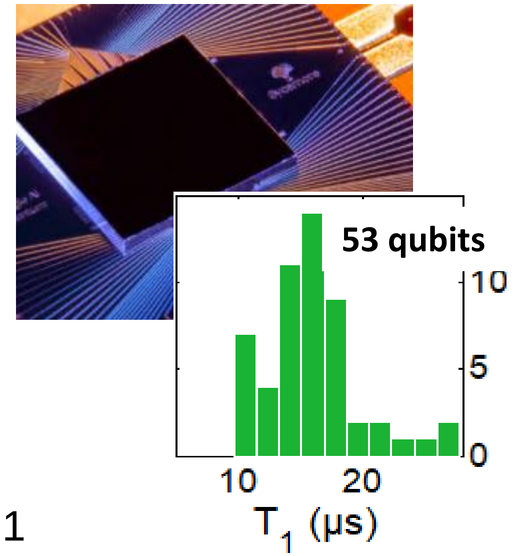
How TLS defects spoil qubit coherence

T_1 depends on qubit frequency

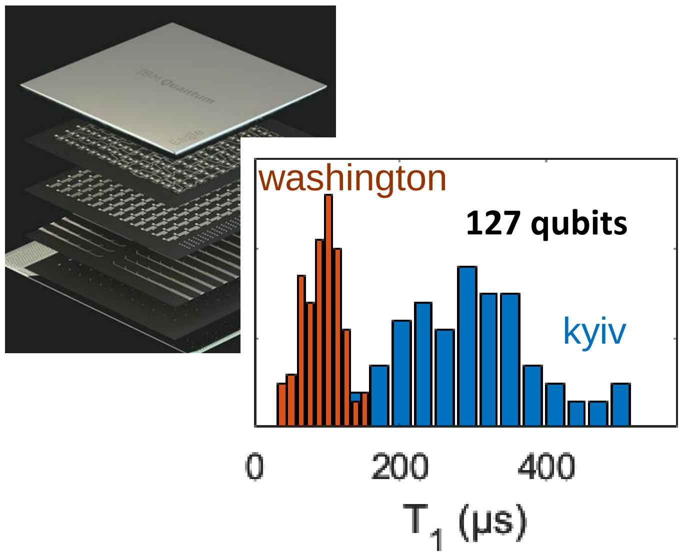


T_1 depends on the sample

- **Sycamore** (Google)
  F. Arute et al., nature (2019)

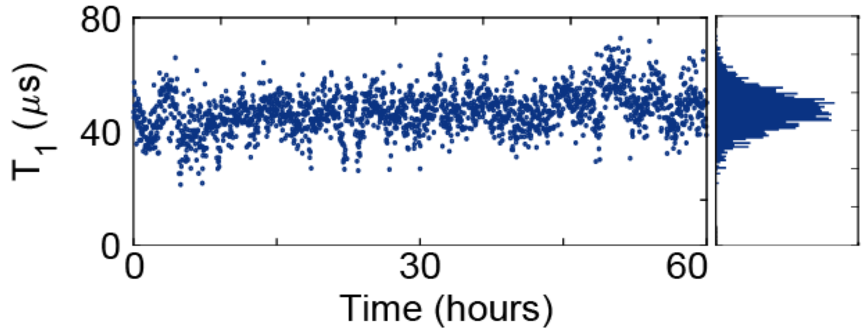


- **Eagle** (IBM, 2022)
  https://quantum-computing.ibm.com



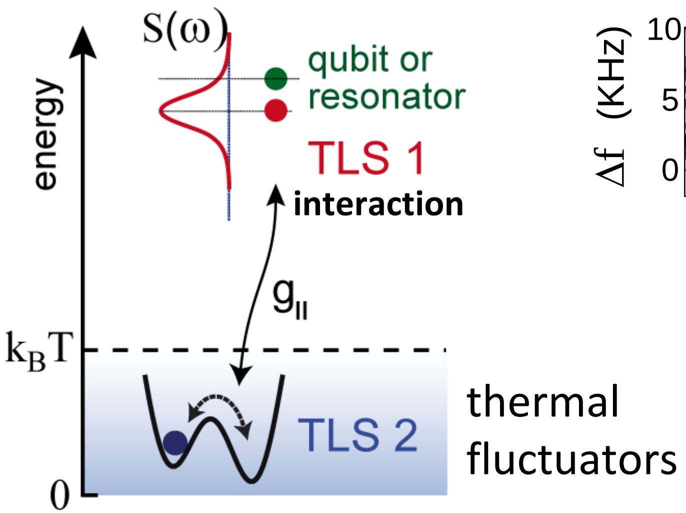
T_1 depends on time

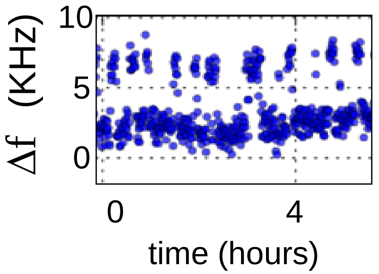
J.J. Burnett et al., npj Quant. Inf. 5 (2019)



→ Interaction with thermal fluctuators

L. Faoro, L. Ioffe, PRB **91**, 014201 (2014)
C. Müller, J.L. et al., PRB **92**, 035442 (2015)
S. Schlör, J.L. et al., PRL **123**, 190502 (2019)

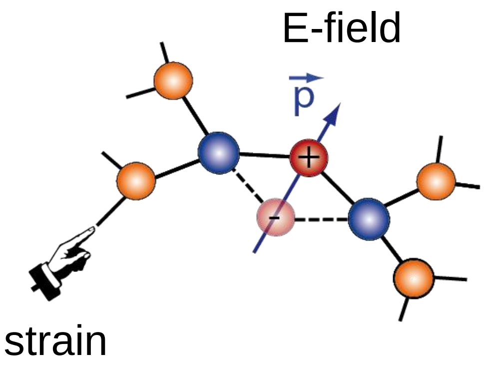


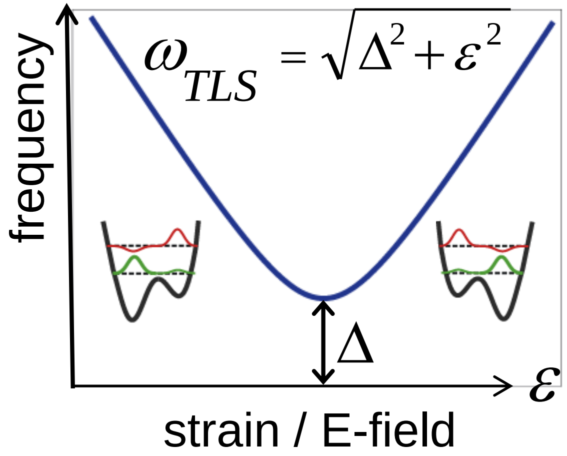


controlling TLS by mechanical strain and electric fields

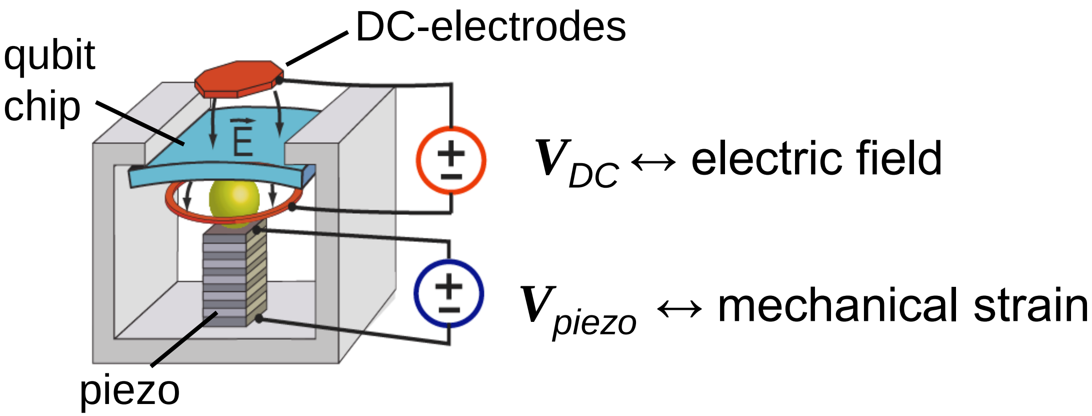
J. Lisenfeld, A. Bilmes et al., npj Quant. Inf. 5, 105 (2019)

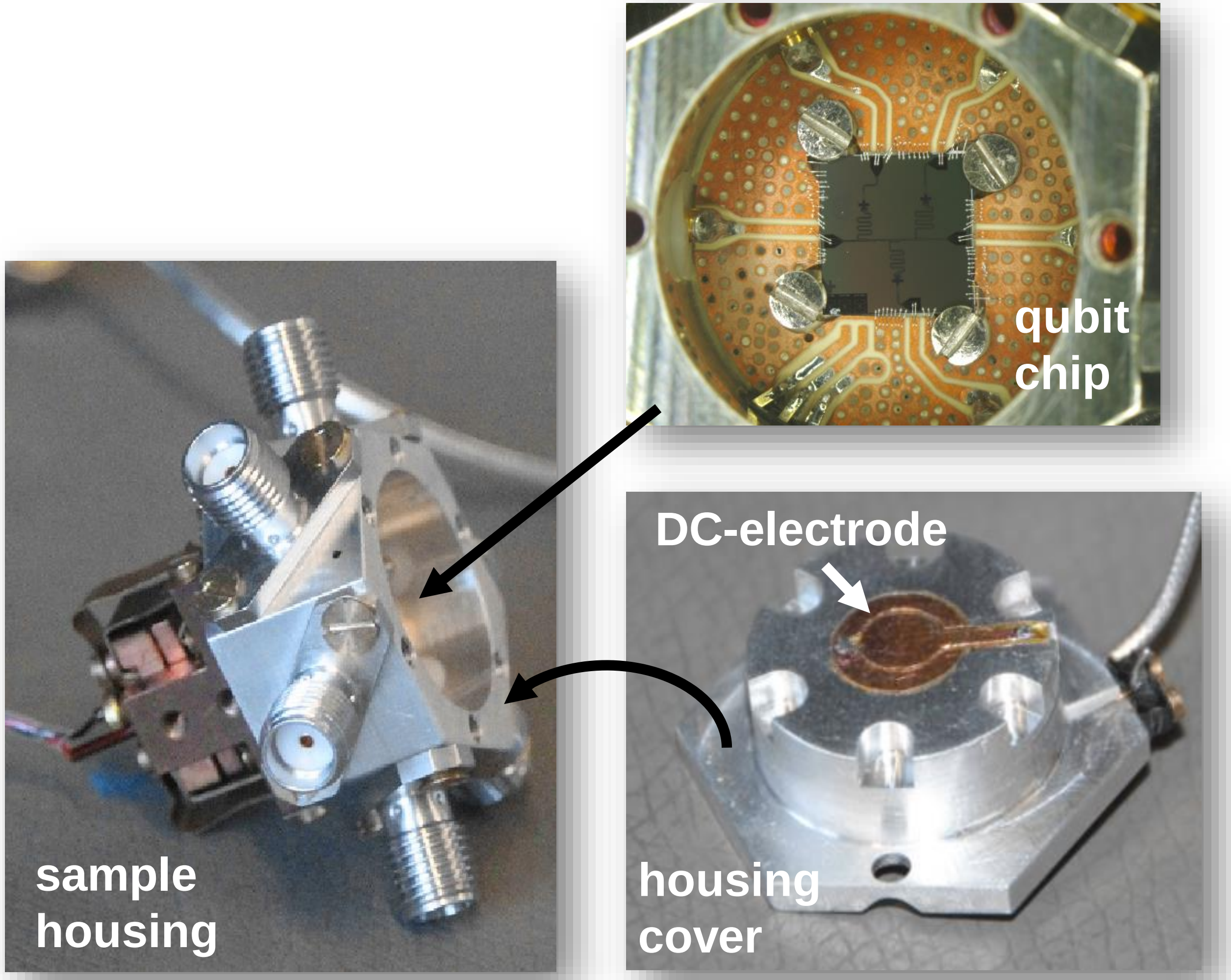
- **tune TLS resonance frequency**





- **strain- and electric-field tuning**





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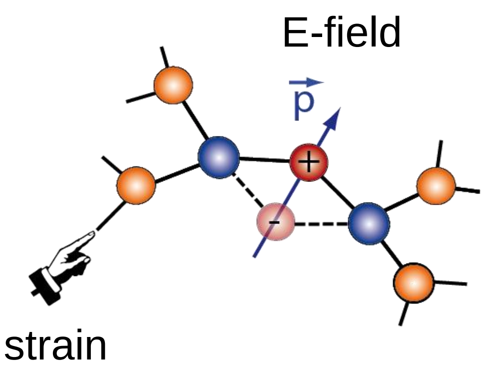
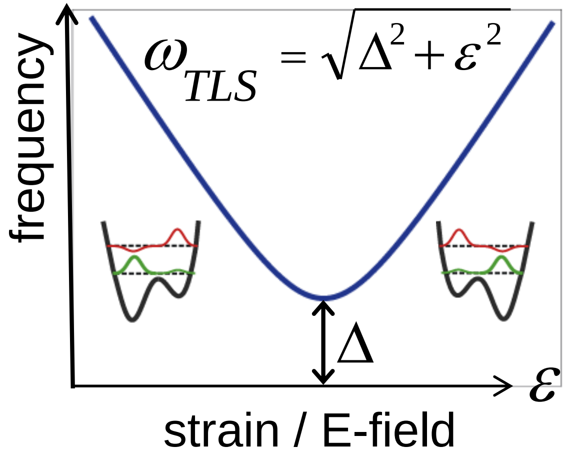
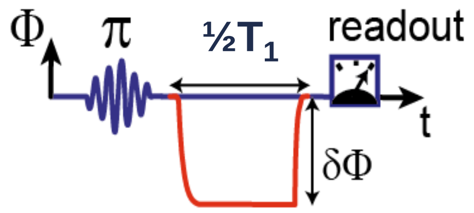
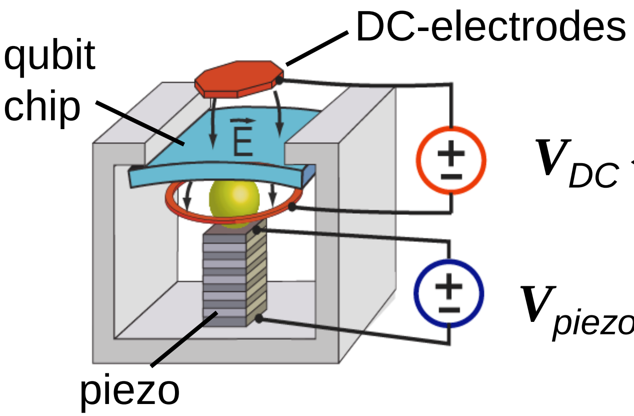




- **Detect TLS by swap spectroscopy**



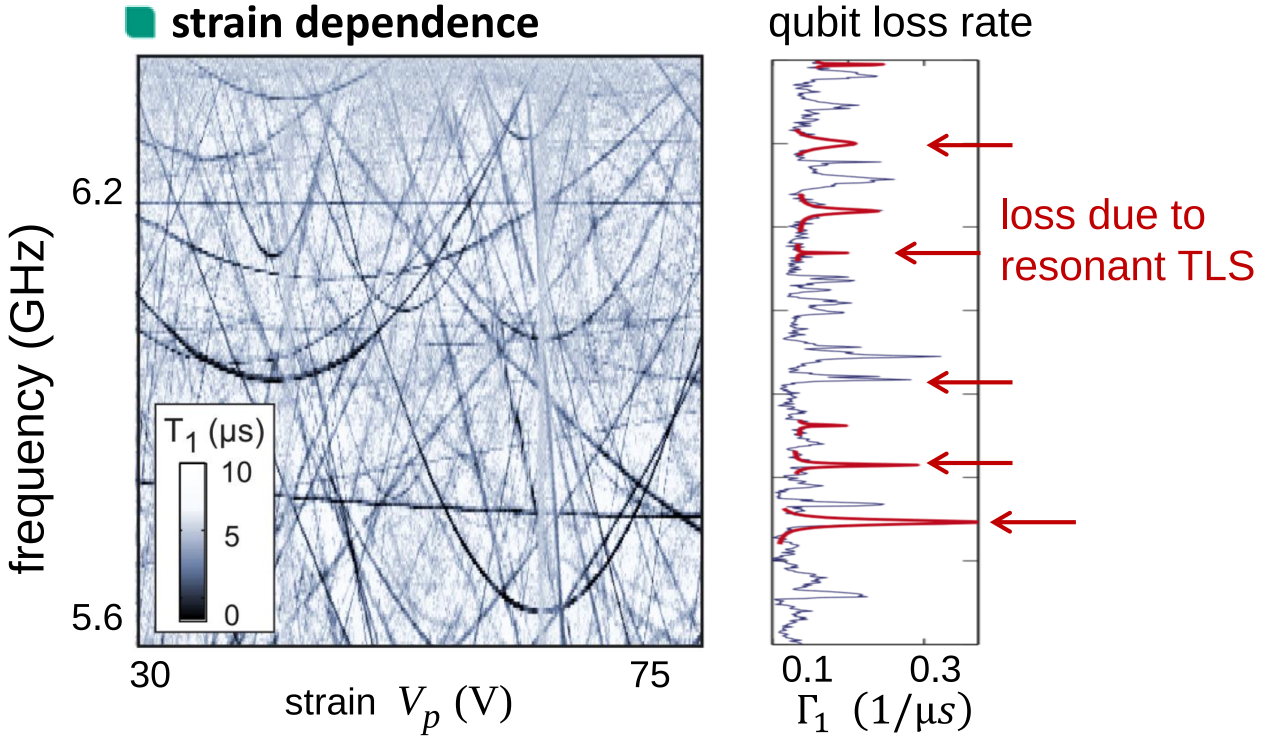
- **strain- and electric-field tuning**



$V_{DC} \leftrightarrow$ electric field

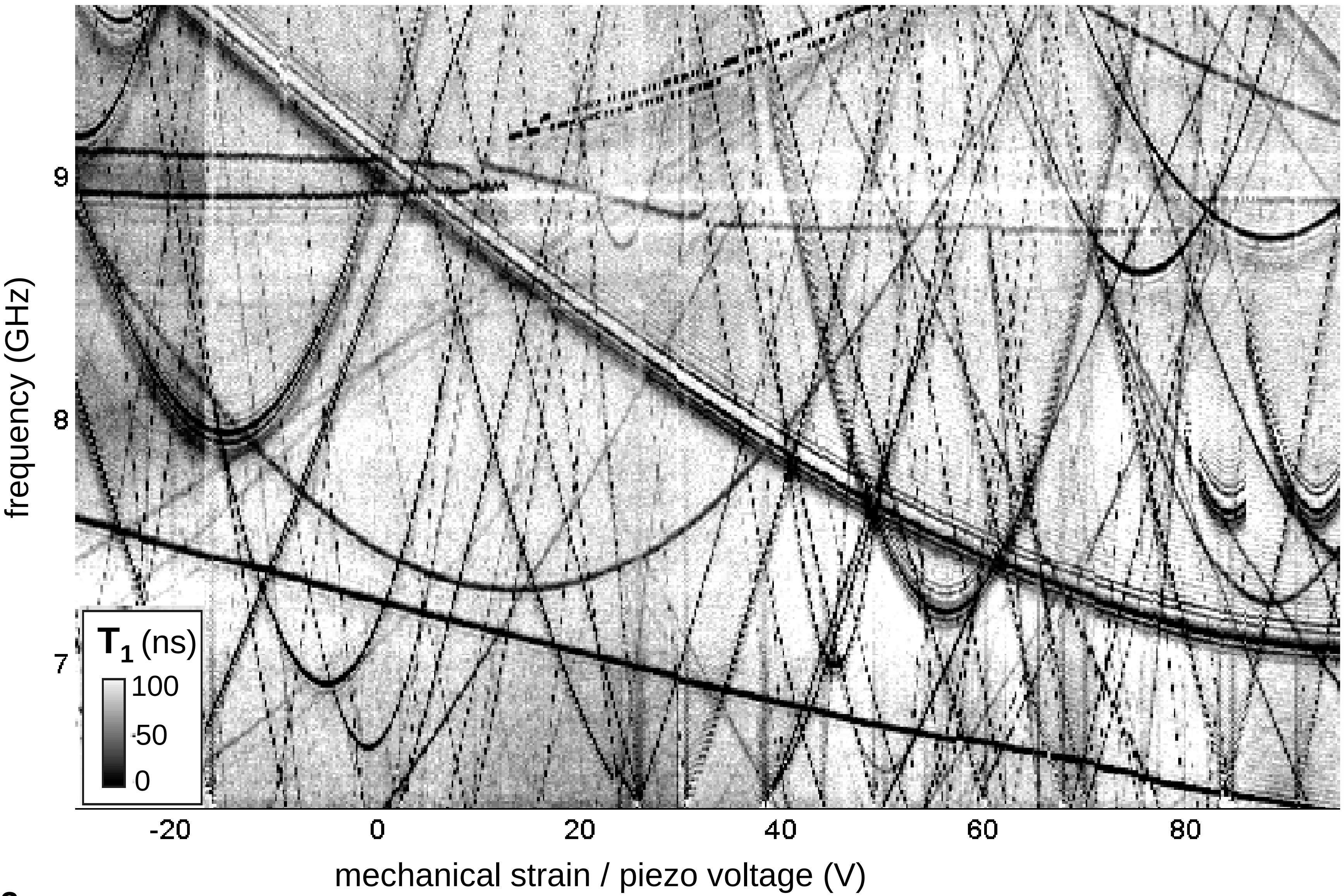
$V_{piezo} \leftrightarrow$ mechanical strain

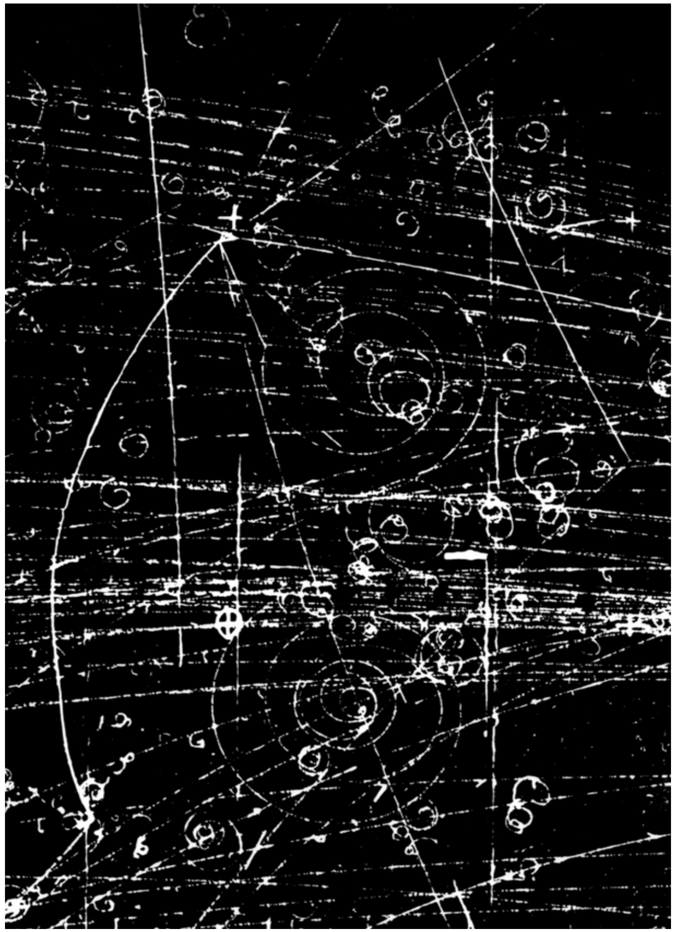
- **strain dependence**



TLS strain spectroscopy

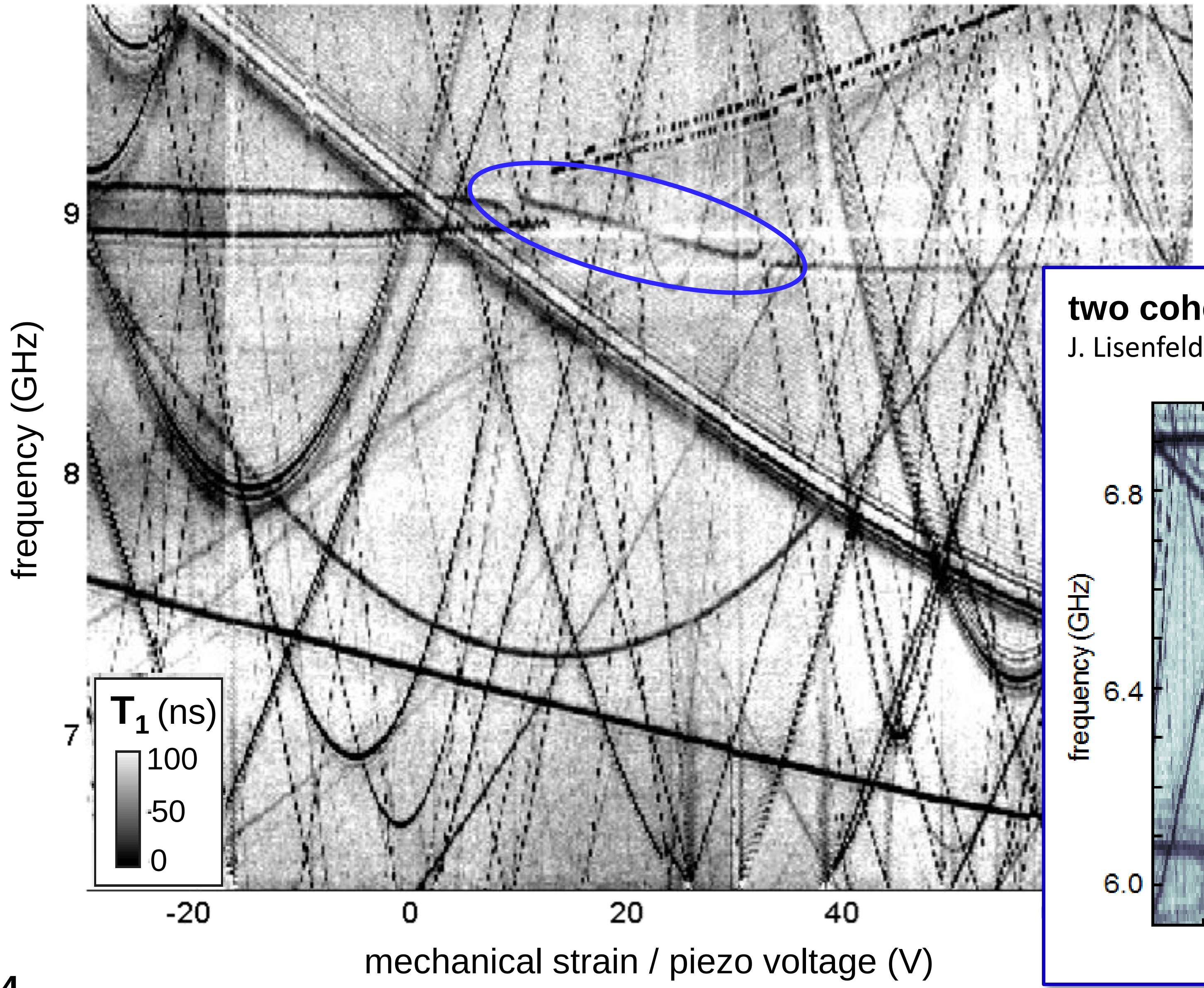
J. Lisenfeld, G. Grabovskij, C. Müller, J. Cole, A.V. Ustinov et al., Nat. Comm. **6**, 6182 (2015)





Cloud chamber photograph (1958)
U.S. National Archives

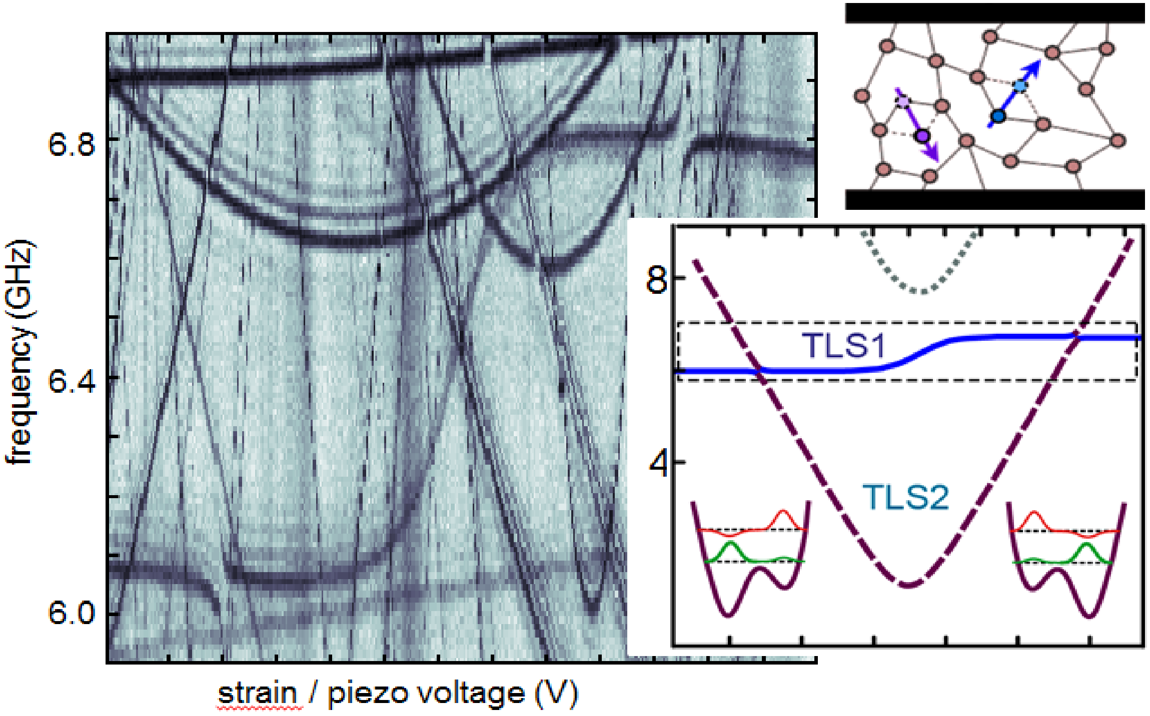
TLS studies at KIT



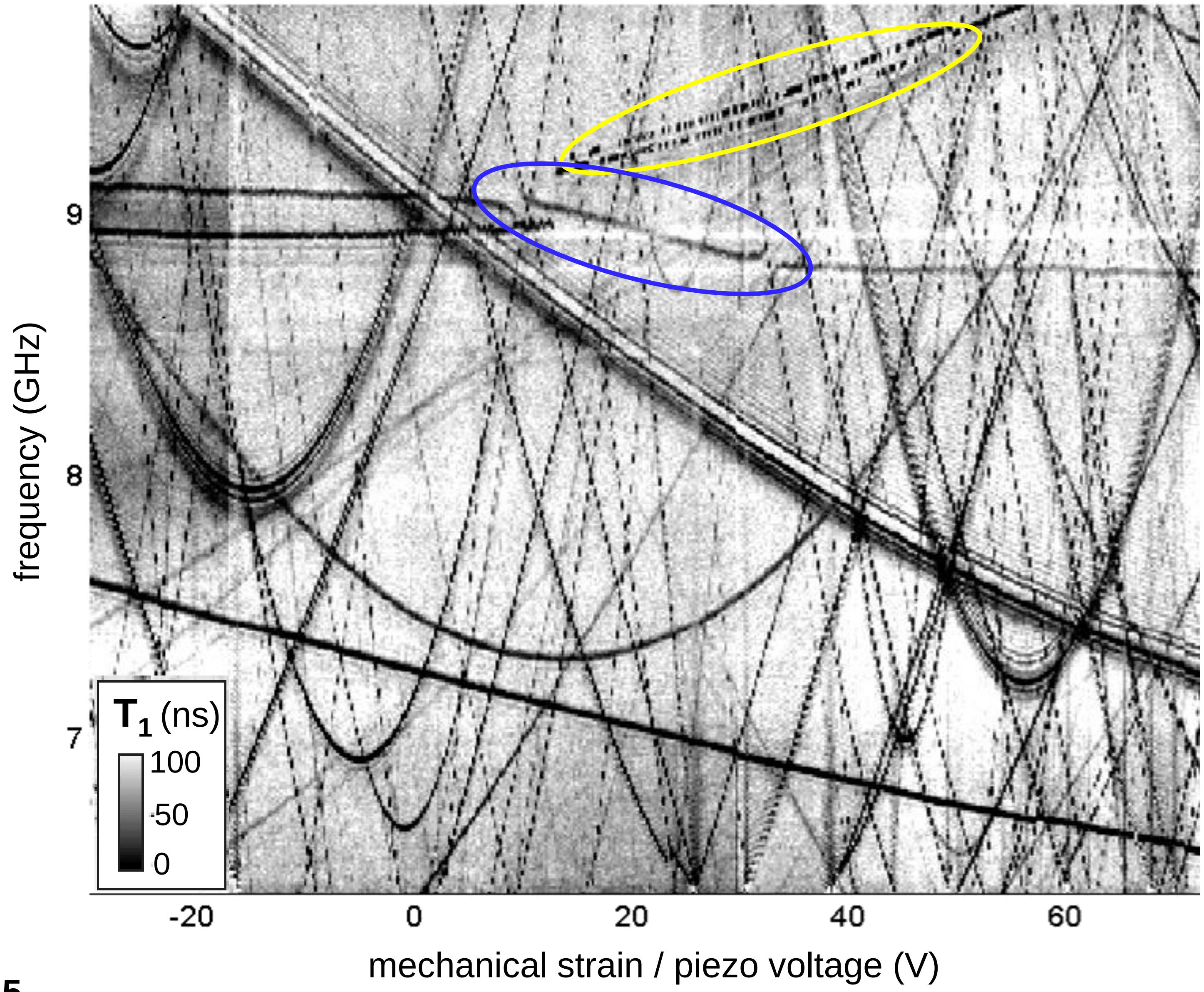
TLS strain spectroscopy
Grabovskij et al., Science 338, 232 (2012)

coherently coupled TLS
Grabovskij et al., NJP 13, 063015 (2011)
Lisenfeld et al., nature comm. **6**, 6182 (2015)

two coherently coupled TLS
J. Lisenfeld et al., Nat. Commun. **6**, 6182 (2015)



TLS studies at KIT



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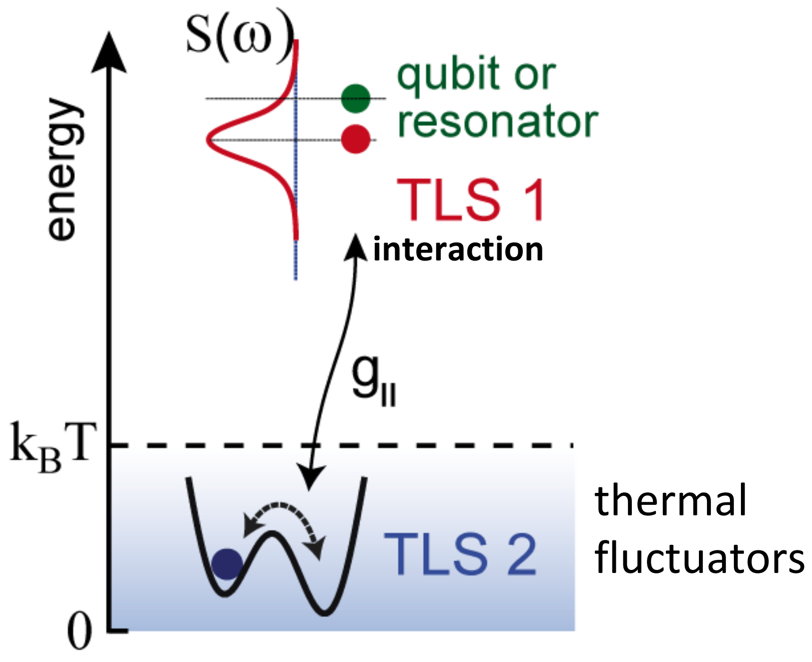
Lisenfeld et al., nature comm. **6**, 6182 (2015)

noise from thermal TLS
Müller et al., PRB 92, 035442 (2015)
Brehm et al., APL 111, 112601 (2017)
Meissner et al., PRB 97, 180505 (2018)
Schlör et al., PRL 123, 190502 (2019)



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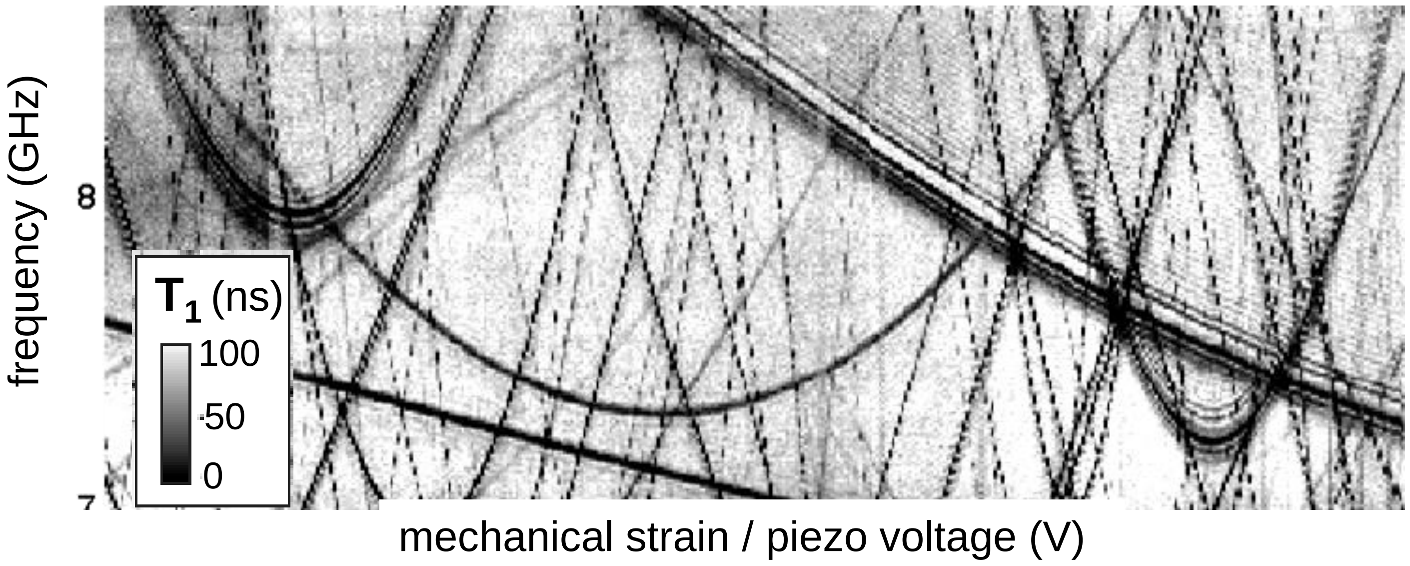
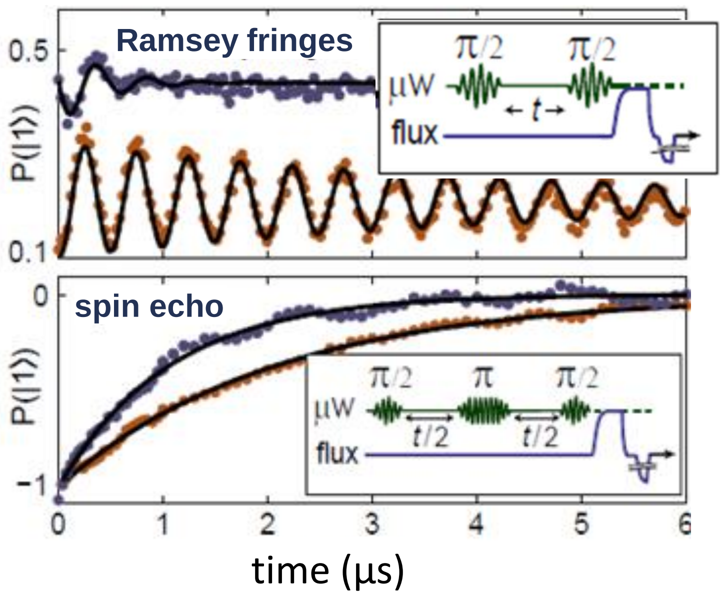
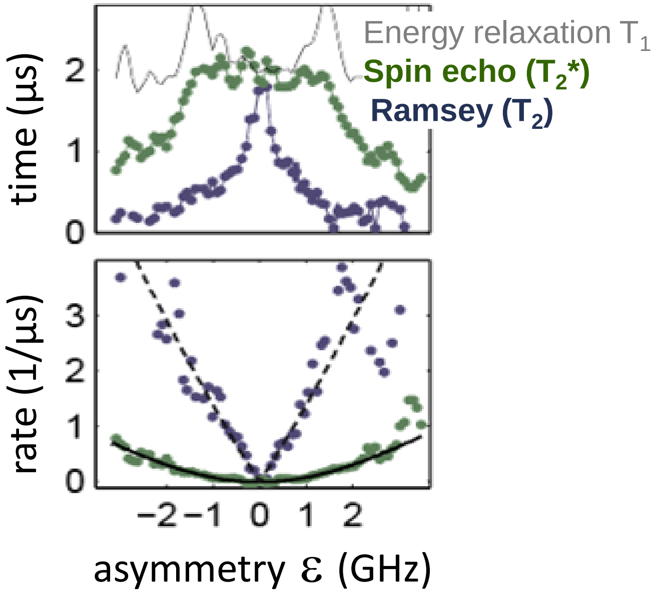


coherent TLS control and readout



Decoherence spectroscopy



TLS strain spectroscopy
Grabovskij et al., Science 338, 232 (2012)

coherently coupled TLS
Grabovskij et al., NJP 13, 063015 (2011)
Lisenfeld et al., nature comm. **6**, 6182 (2015)

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Müller et al., PRB 92, 035442 (2015)
Brehm et al., APL 111, 112601 (2017)
Meissner et al., PRB 97, 180505 (2018)
Schlör et al., PRL 123, 190502 (2019)

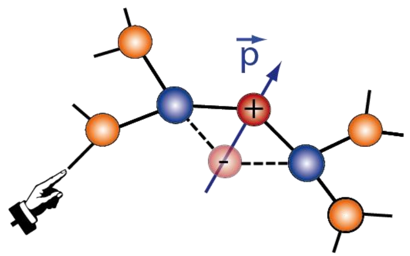
testing microscopic models
Cole et al., APL **97**, 252501 (2010)
Bushev et al., PRB **82**, 134530 (2010)

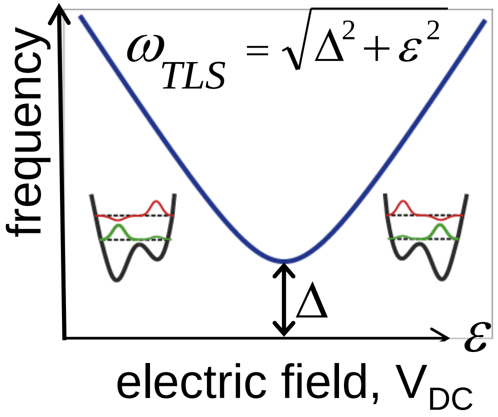
coherent TLS control & readout
Lisenfeld et al., PRL **12**, 230504 (2010)
Lisenfeld et al., PRB **81**, 100511 (2010)
Lisenfeld et al., Sci. Rep. **6**, 23786 (2016)
Bilmes et al., PRB **96**, 064504 (2016)
Matityahu et al., PRB **95**, 241409(R) (2017)

electric-field tuning of TLS
Lisenfeld et al., npj Quant. Inf. 5, 105 (2019)
Bilmes et al., Sci. Rep. 10, 3090 (2020)
Lisenfeld et al., npj Quant. Inf. 9, 8 (2023)

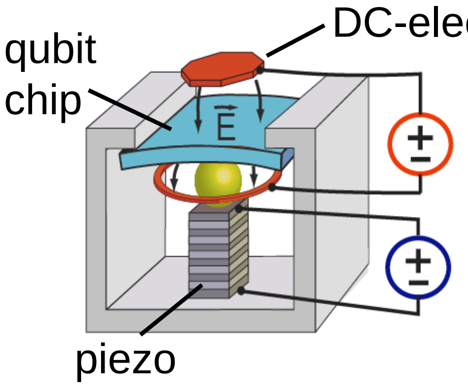
Controlling defects by Electric Fields

- **tune TLS resonance frequency**





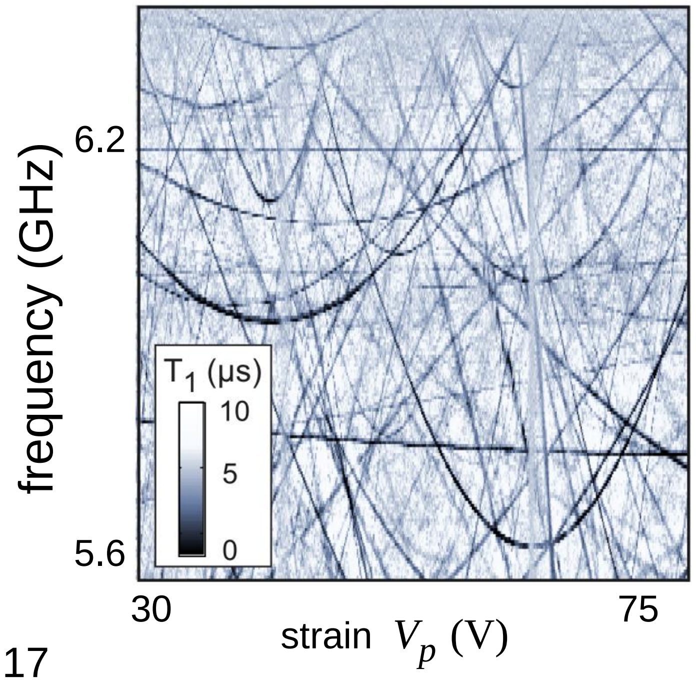
- **strain- and electric-field tuning**



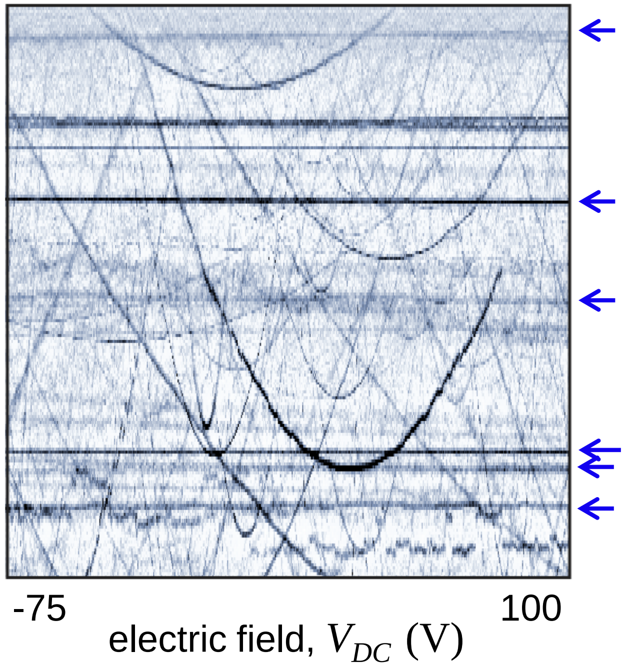
V_{DC} : electric field

V_{piezo} : mechanical strain

- **strain dependence**



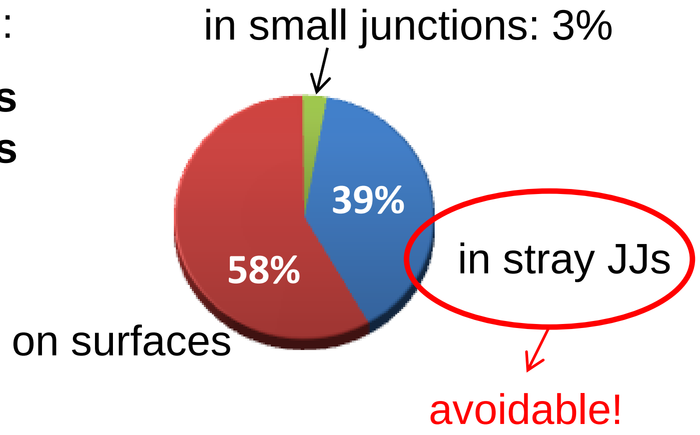
- **electric field dependence**



no E-field coupling:

identifies defects
In tunnel barriers

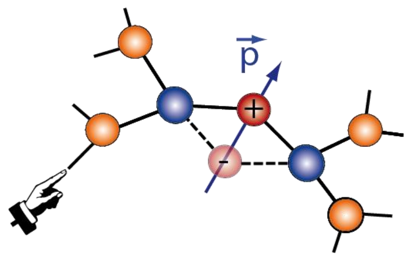
➡ **TLS locations:**

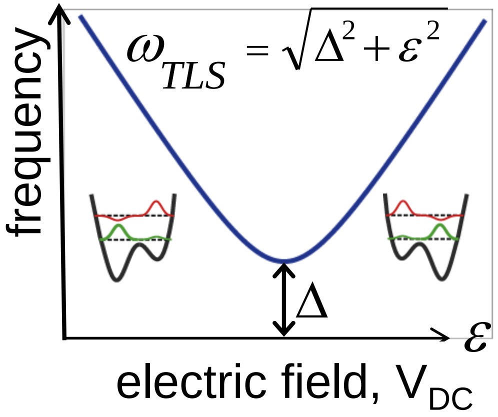


J. Lisenfeld, A. Bilmes et al., npj Quant. Inf. 5, 105 (2019)

Controlling defects by Electric Fields

- **tune TLS resonance frequency**





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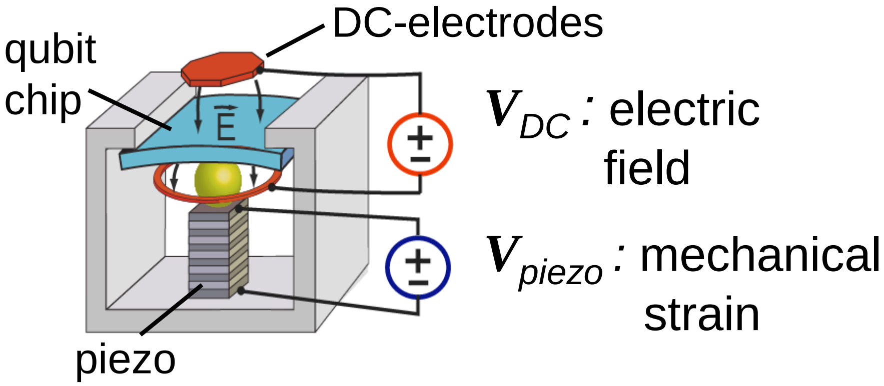
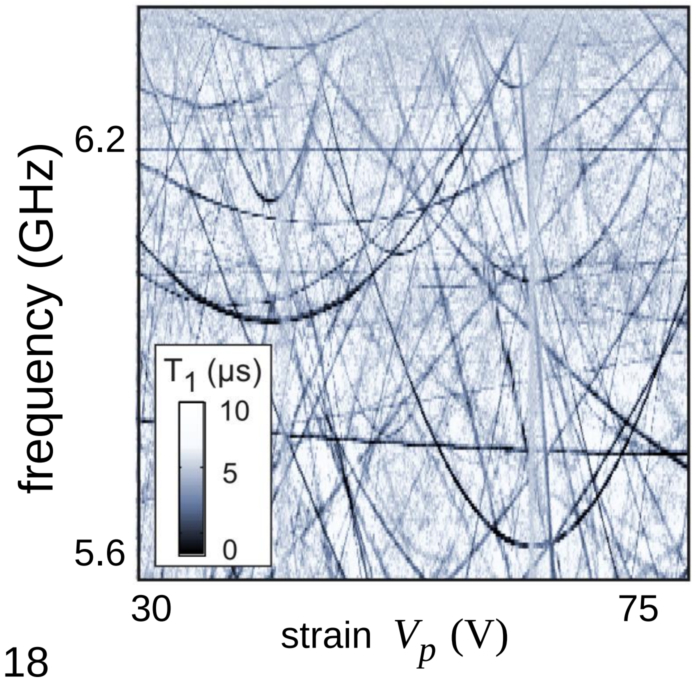
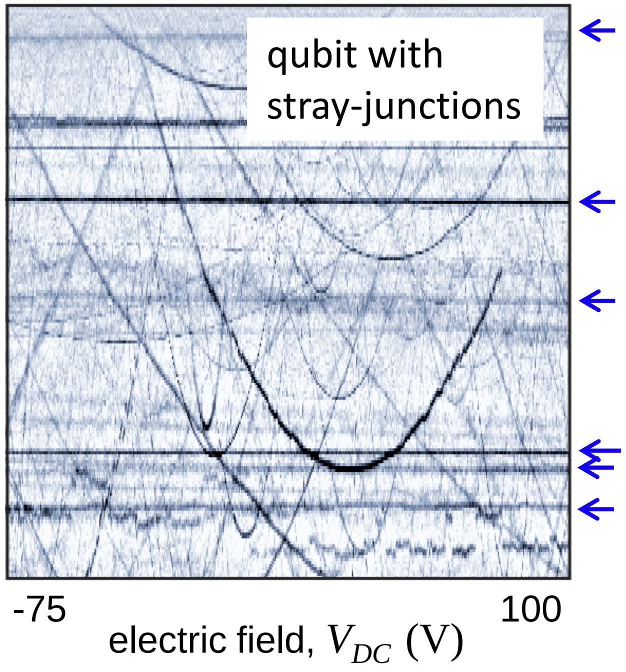
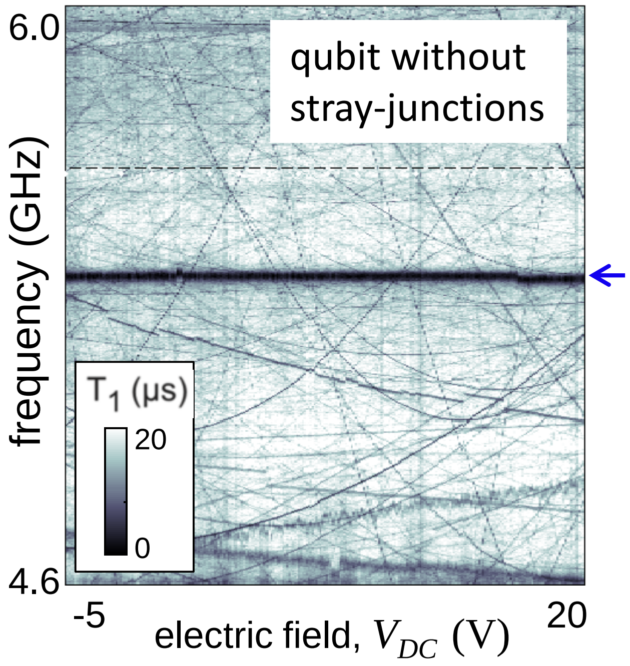


- **strain dependence**
- **electric field dependence**

A. Bilmes, JL et al., *Supercond. Sci. Tech.* **34,** 125011 (2021)



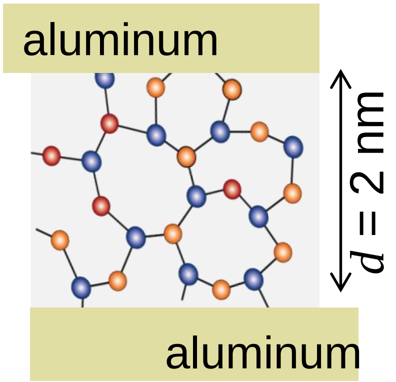


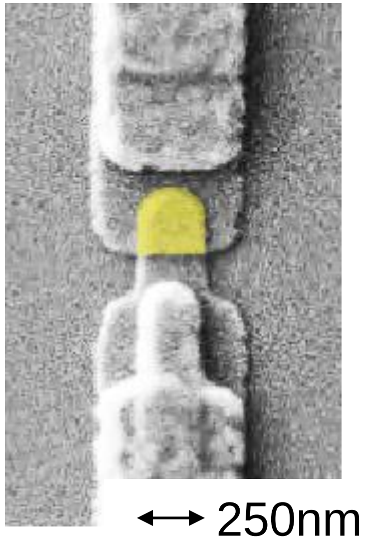


Typical number of Junction-TLS:
~ 0.1 TLS / GHz
(200nm x 250nm JJ)

Decoherence due to junction-TLS

- **TLS in the tunnel barrier**





A. Bilmes, KIT

- **qubit decay rate** due to a single junction-TLS:

$$\Gamma_1 \approx g^2 \frac{\Gamma_{TLS}}{\Gamma_{TLS}{}^2 + \delta^2}$$

$\Rightarrow$ $\Gamma_1 \approx (125\ \mu s)^{-1}$

for 2 TLS at detuning $\delta \pm 5$ GHz and 2 junctions in parallel at typical TLS densities

- $g = \left(\frac{\Delta_0}{E}\right)\ \vec{p}\cdot\vec{E} \approx 50$ MHz

TLS-qubit coupling strength

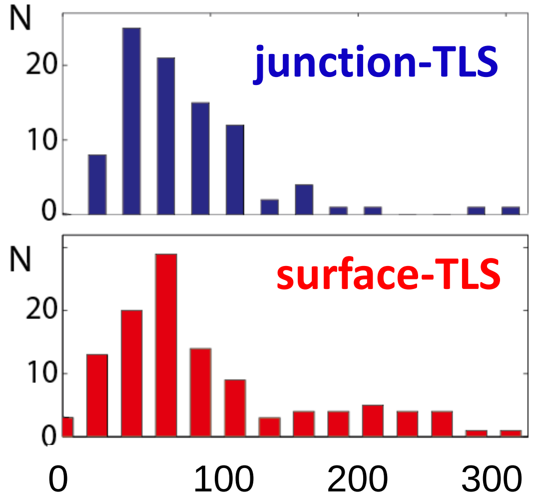
E-field in tunnel barrier:

$$|\vec{E}| = \sqrt{\frac{h\omega}{2C}}\frac{1}{d} \approx 2\ \mathrm{kV}/m$$

TLS dipole moment $\vec{p} \approx 1e\text{Å}$

- $\Gamma_{TLS} \approx$ 10 MHz

TLS decoherence rate

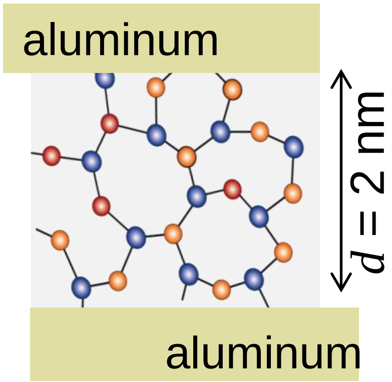


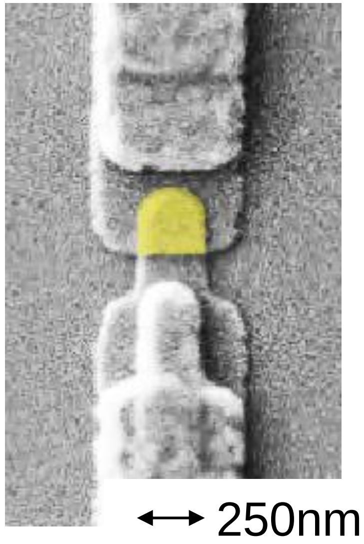
$(\Gamma_1/2 + \Gamma_\phi)^{-1}$

(Lisenfeld et al., npj quant. Inf. 5 (2019))

Decoherence due to junction-TLS

- **TLS in the tunnel barrier**





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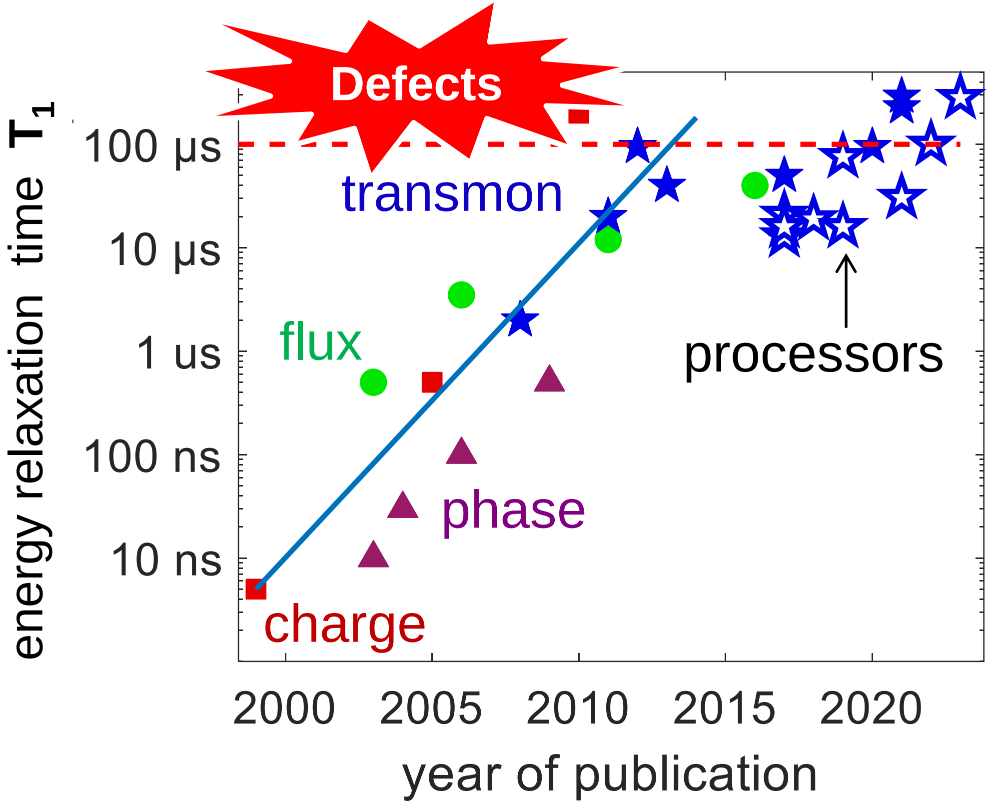
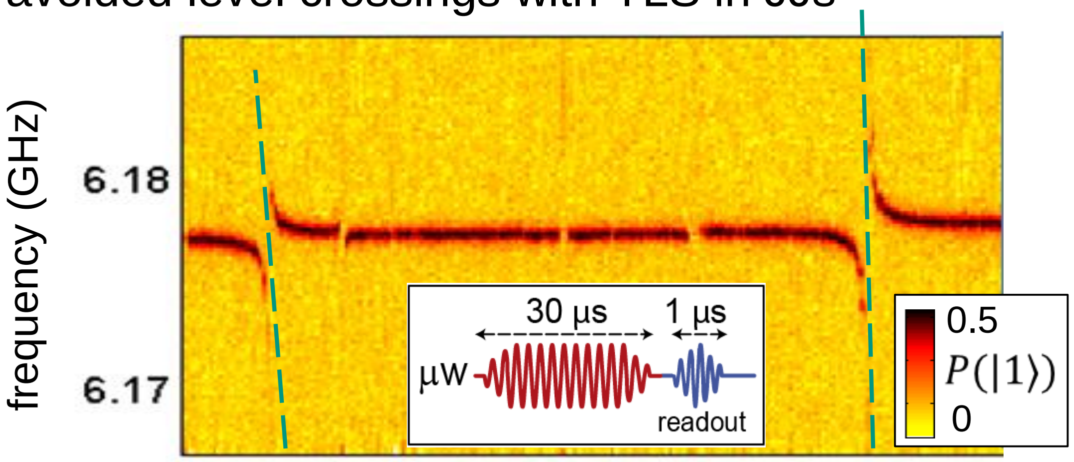
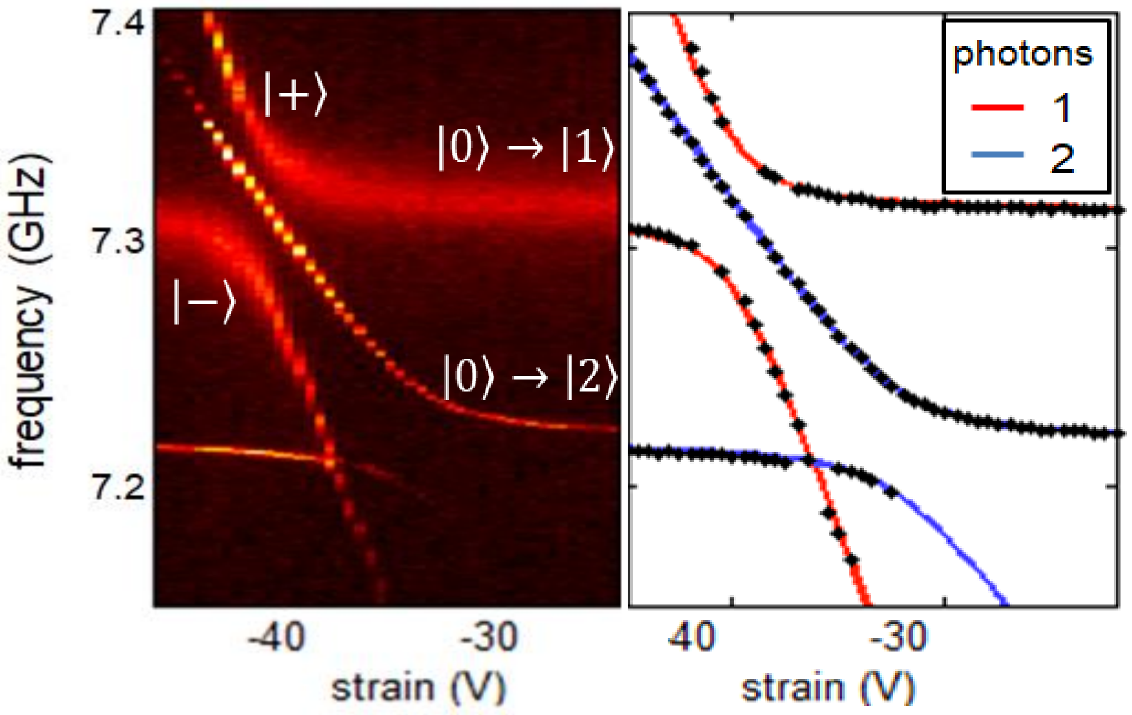


qubit resonance with junction-TLS

avoided level crossings with TLS in JJs



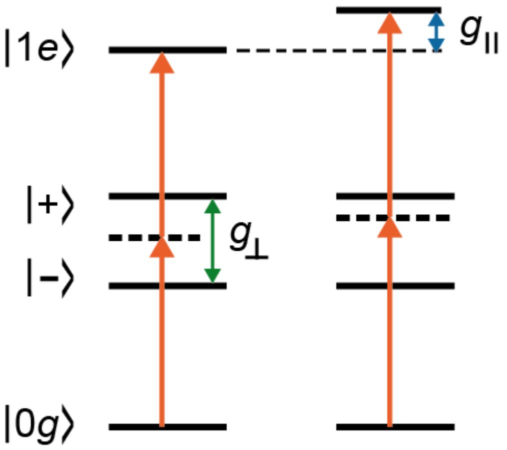
- higher power: **multi-photon transitions**



➡ position of two-photon line reveals couplings between qubit and TLS

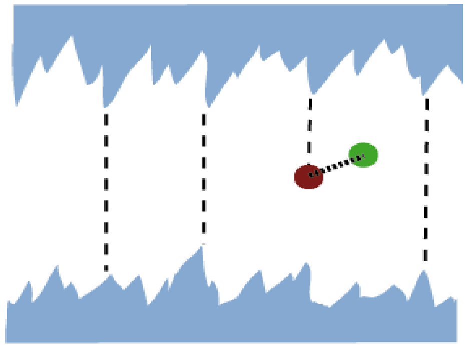
$g_\perp$: transversal / charge or

$g_\parallel$: longitudinal / critical current



➡ no detectable critical current coupling

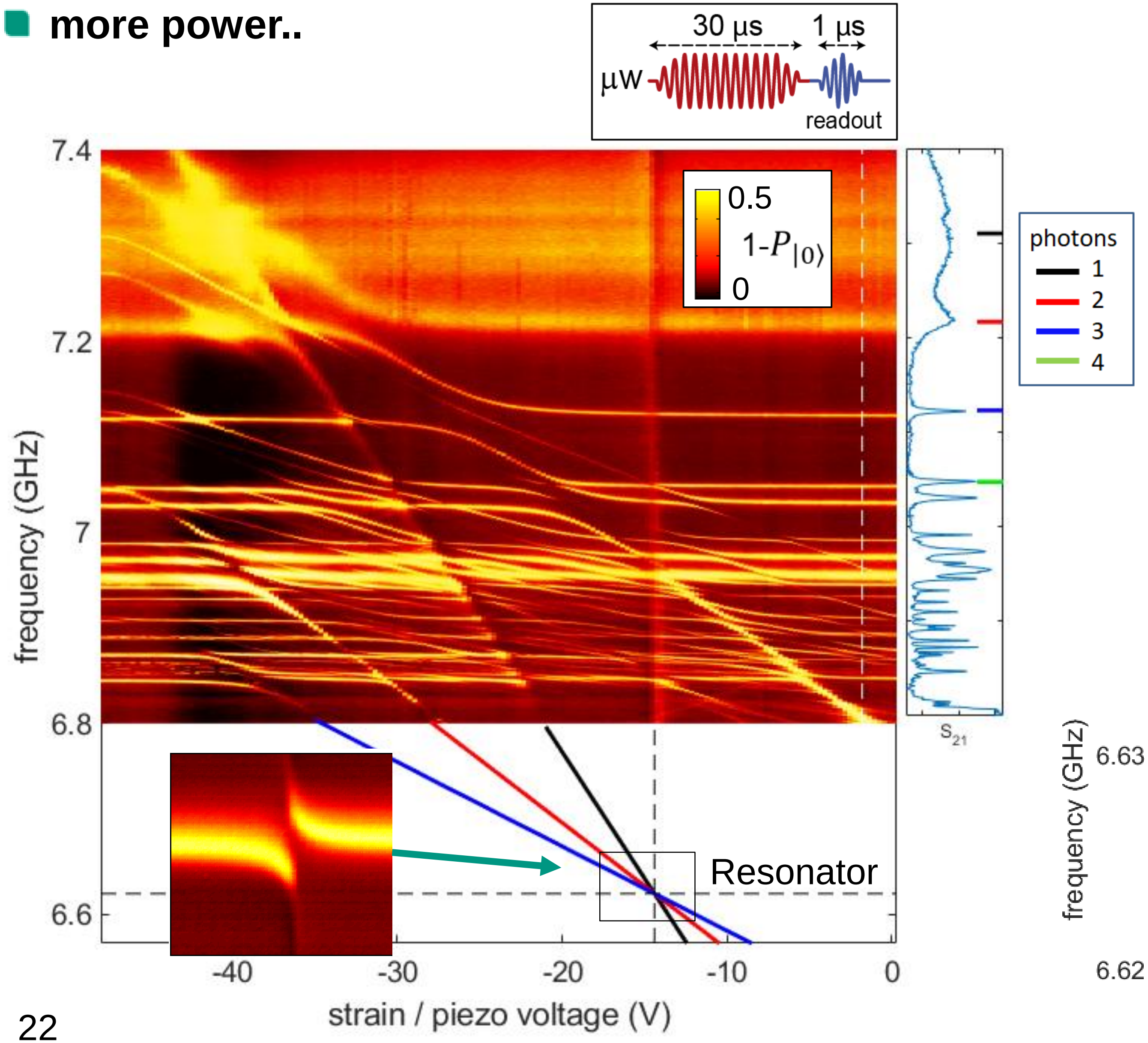
$g_\perp = 31.9$ MHz, $g_{||} <$ 1 MHz



TLS blocking tunneling channels in a JJ

Spectrum of TLS-Qubit-Resonator interactions

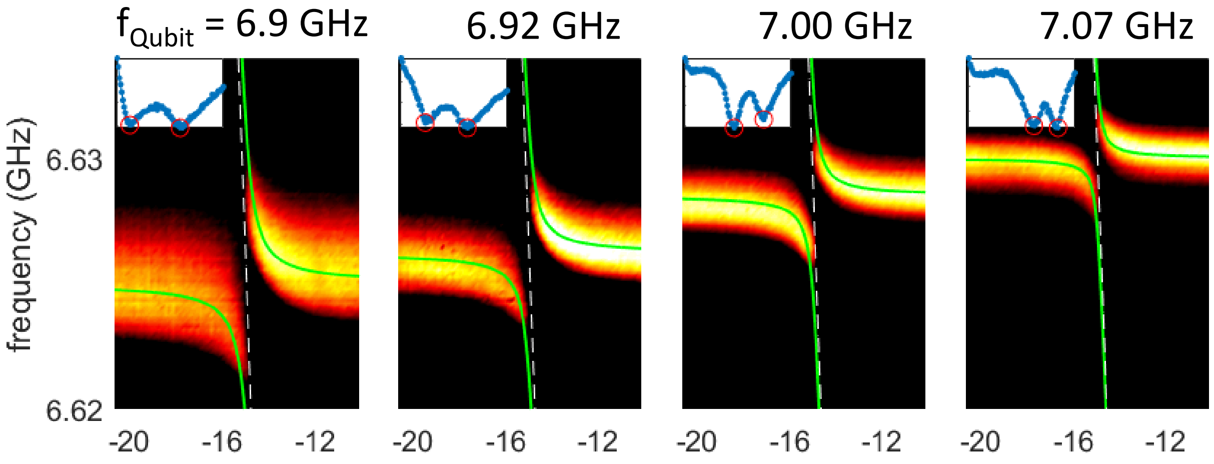
- **more power..**



➡ strong coupling of TLS to resonator mediated via qubit

➡ reveals new decoherence channel

TLS-resonator coupling strength vs. qubit detuning



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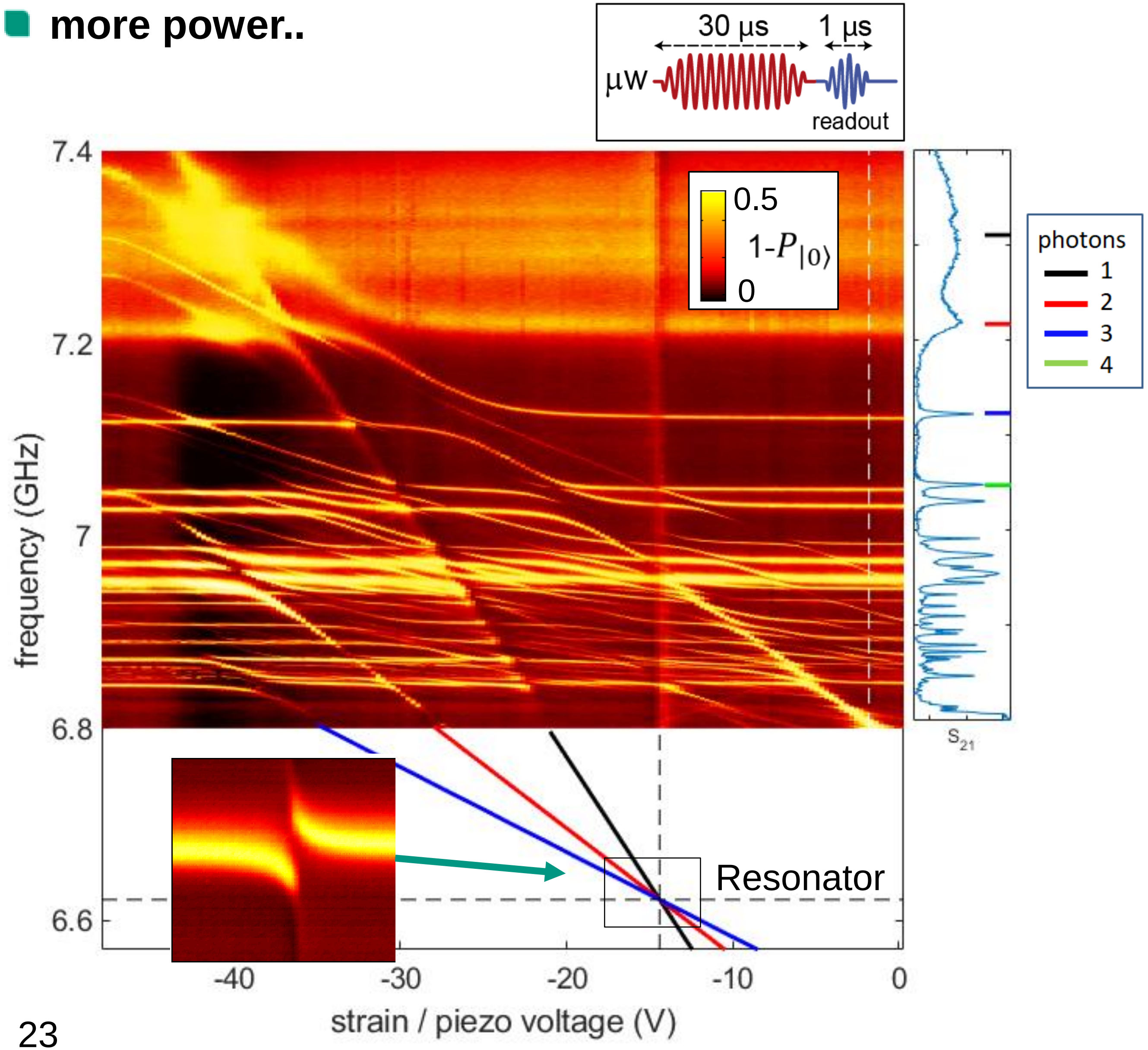
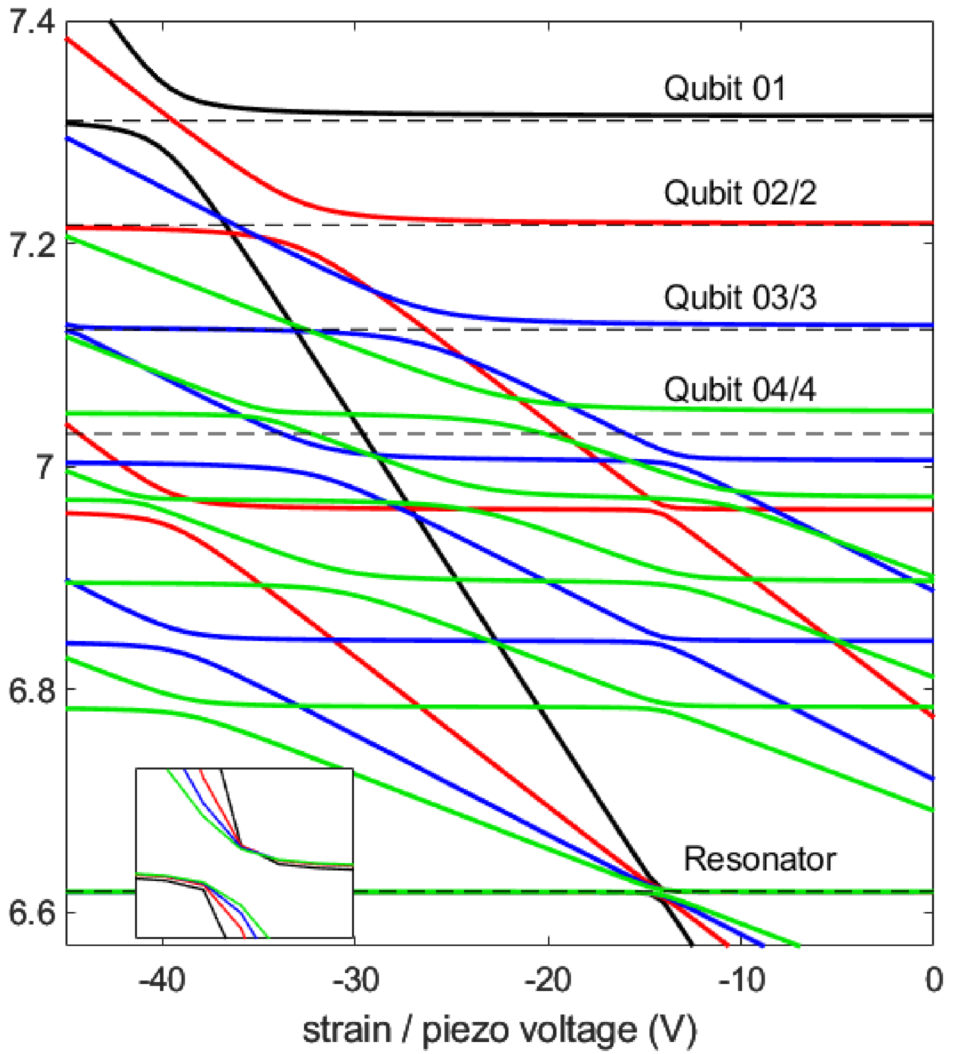


Eigenvalues of Hamiltonian



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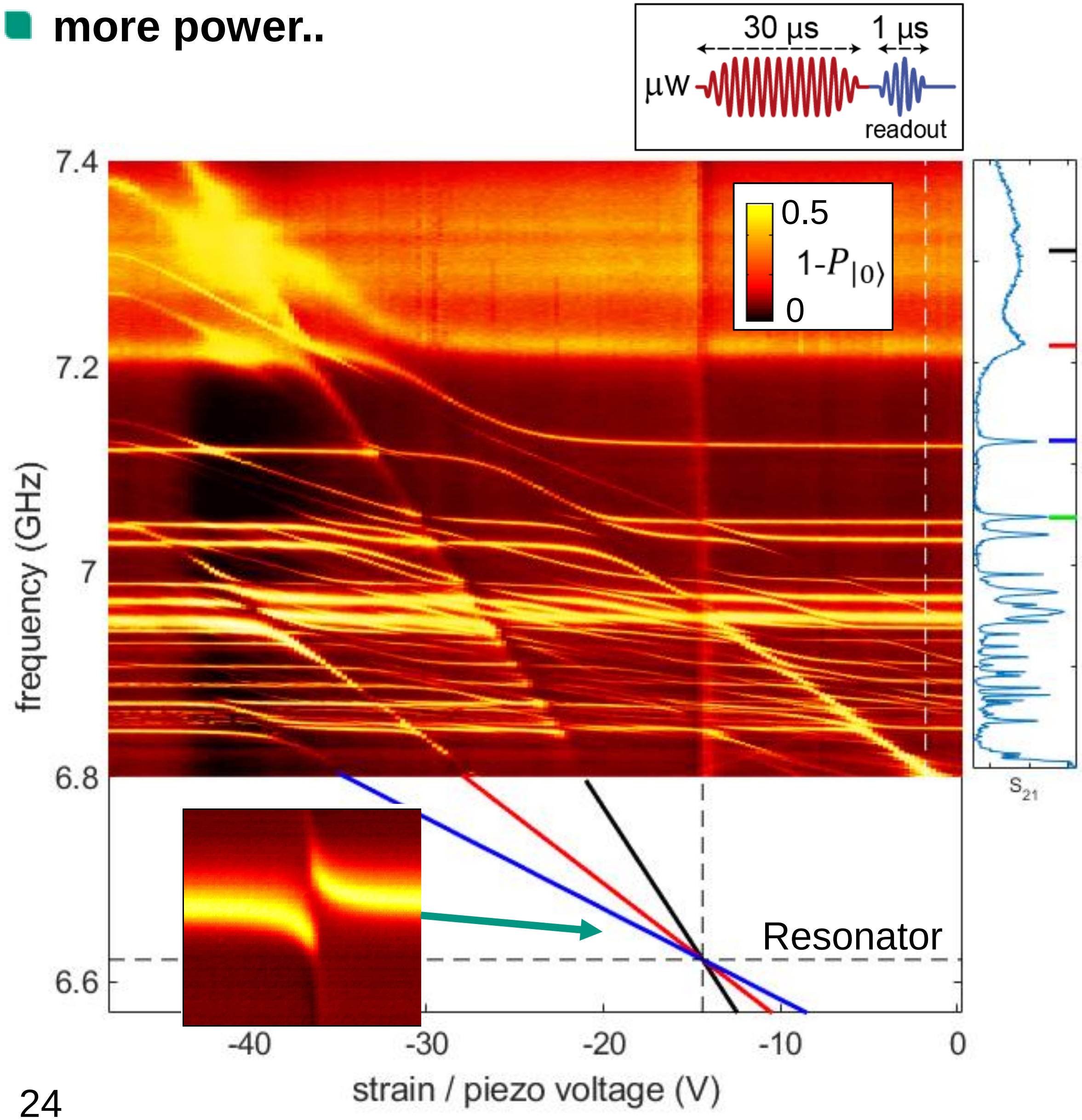
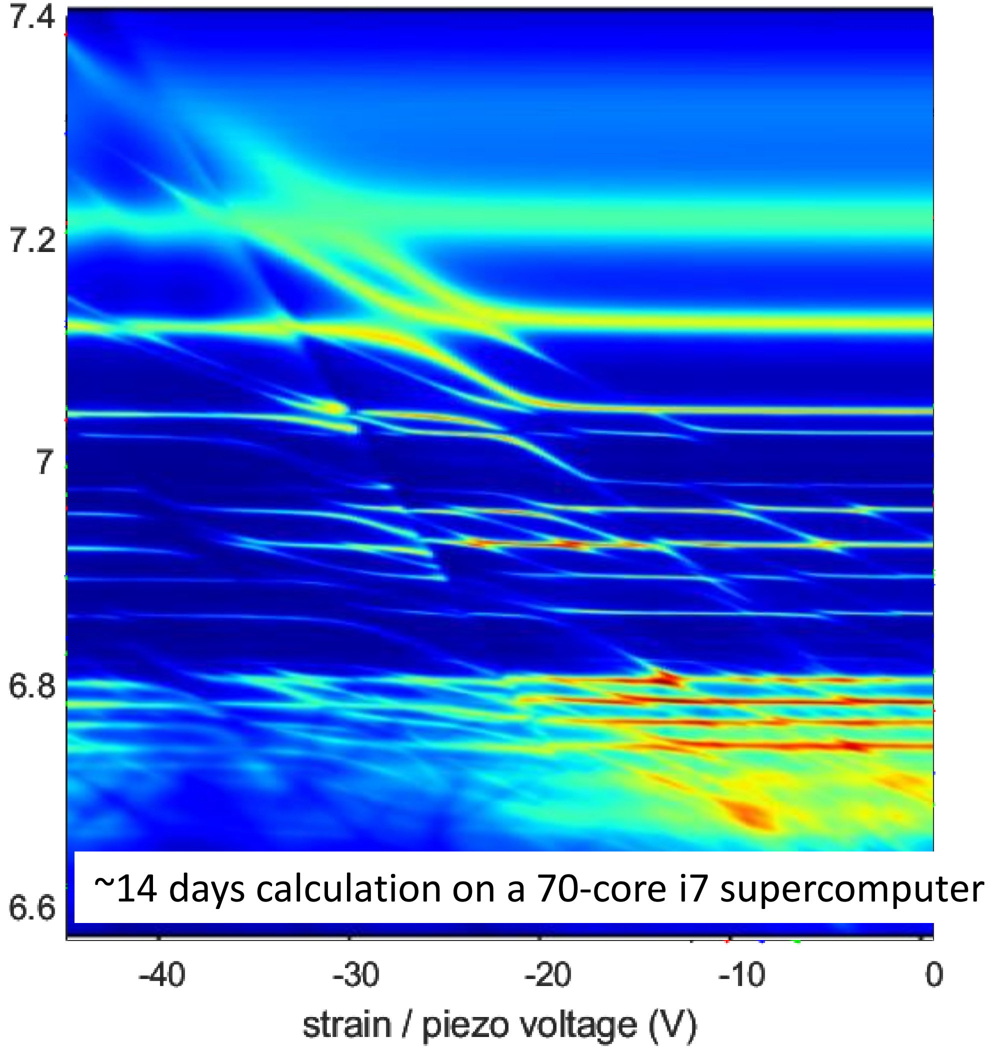


simulation of driven system´(Qutip)

qubit expectation value



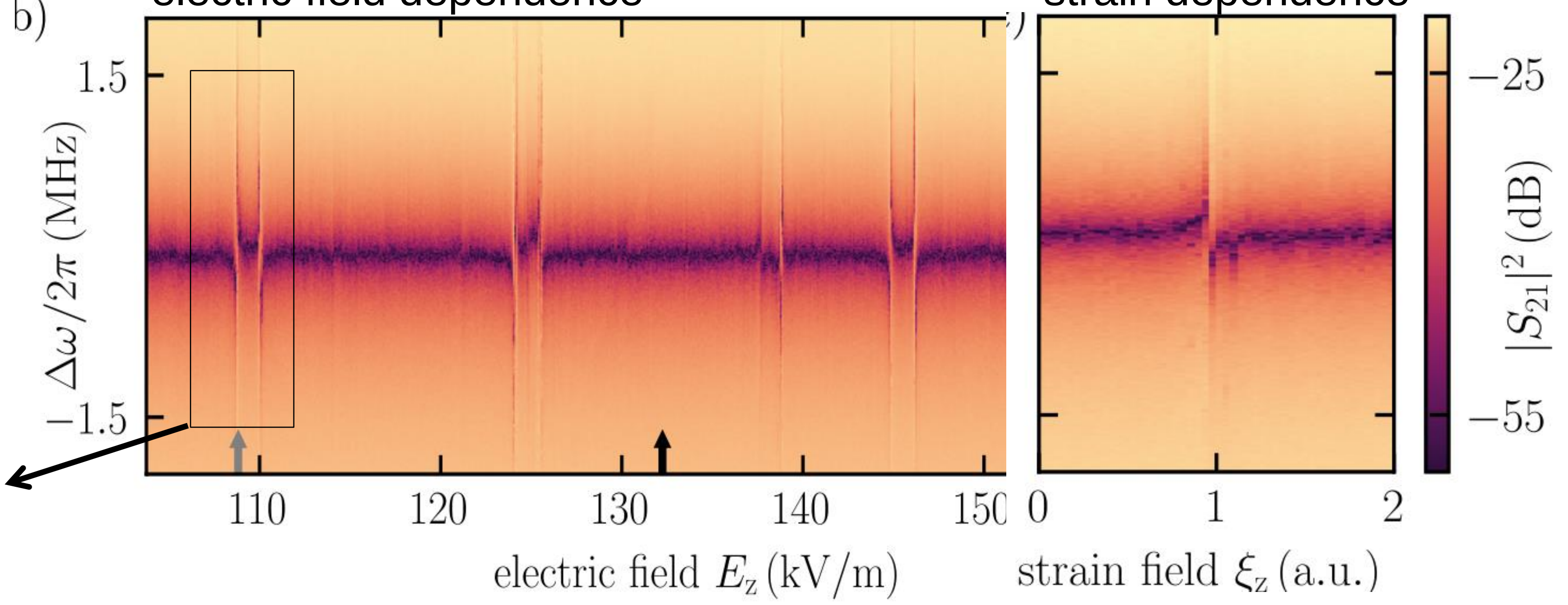
TLS in granular aluminum resonators

M. Kristen, N. Voss, M. Wildermuth, J. Lisenfeld, H.R. Rotzinger and A.V. Ustinov, in prep. (2023)

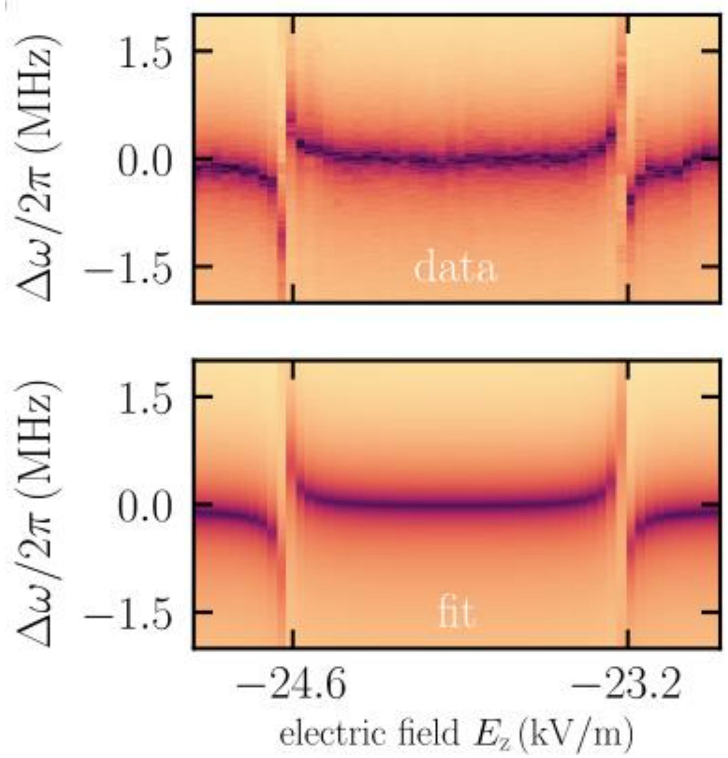
- stripline resonator:
  - ~25 nm-thick grAl on Sapphire
  - width = 2 µm, length=505 µm
  - R_n: 0.68 kΩ/□
  - resonance at 7.48 GHz

electric field dependence

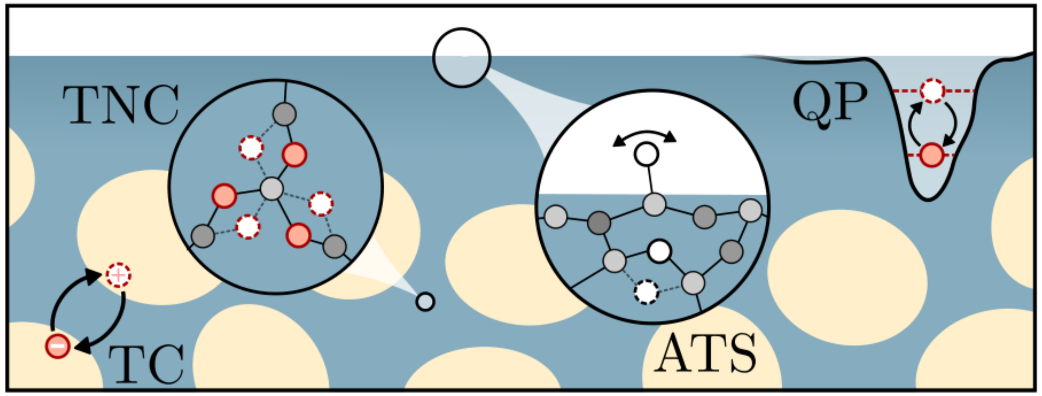
strain dependence



avoided level crossings



TLS models in grAl



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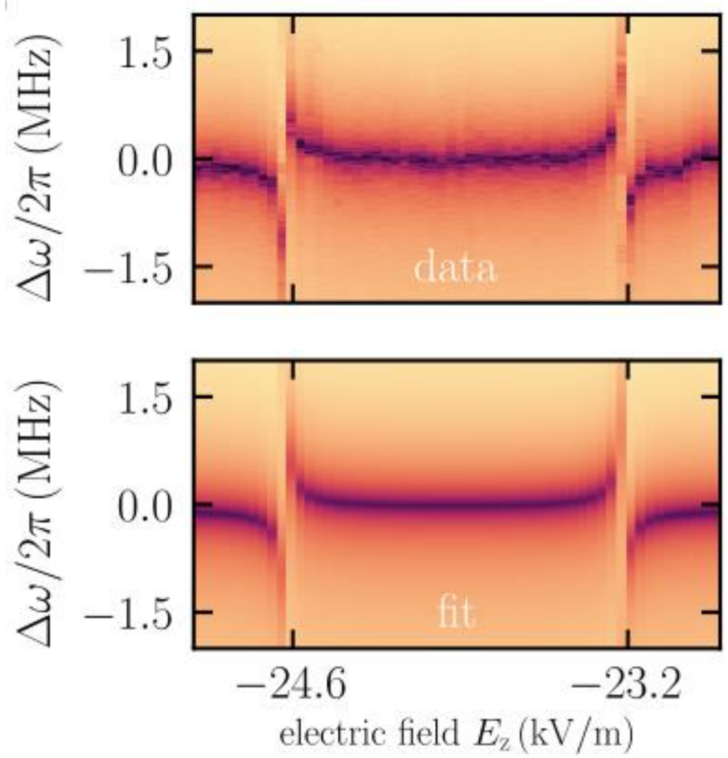
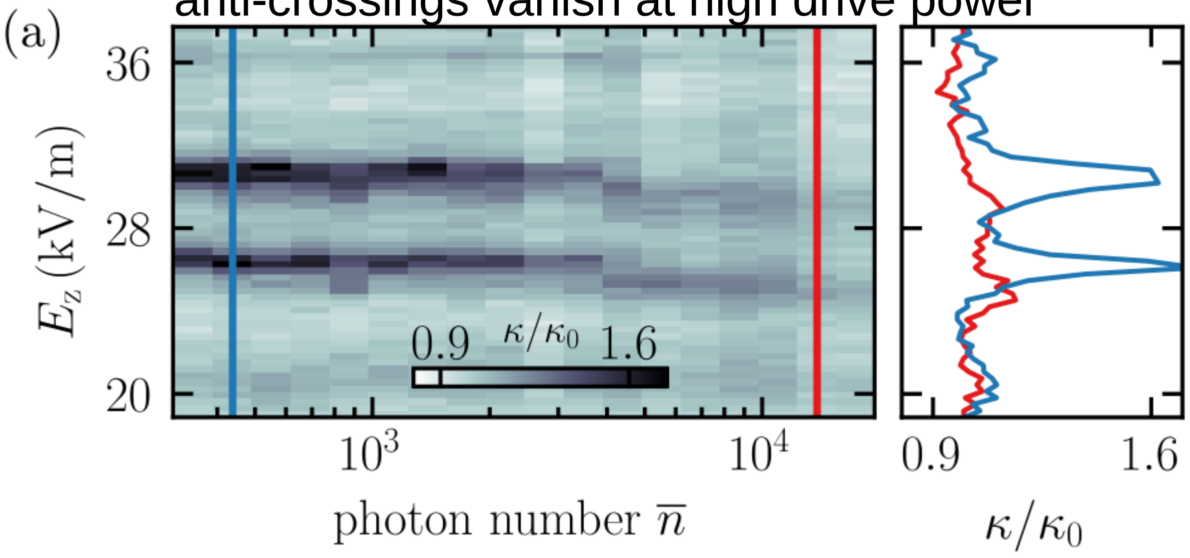
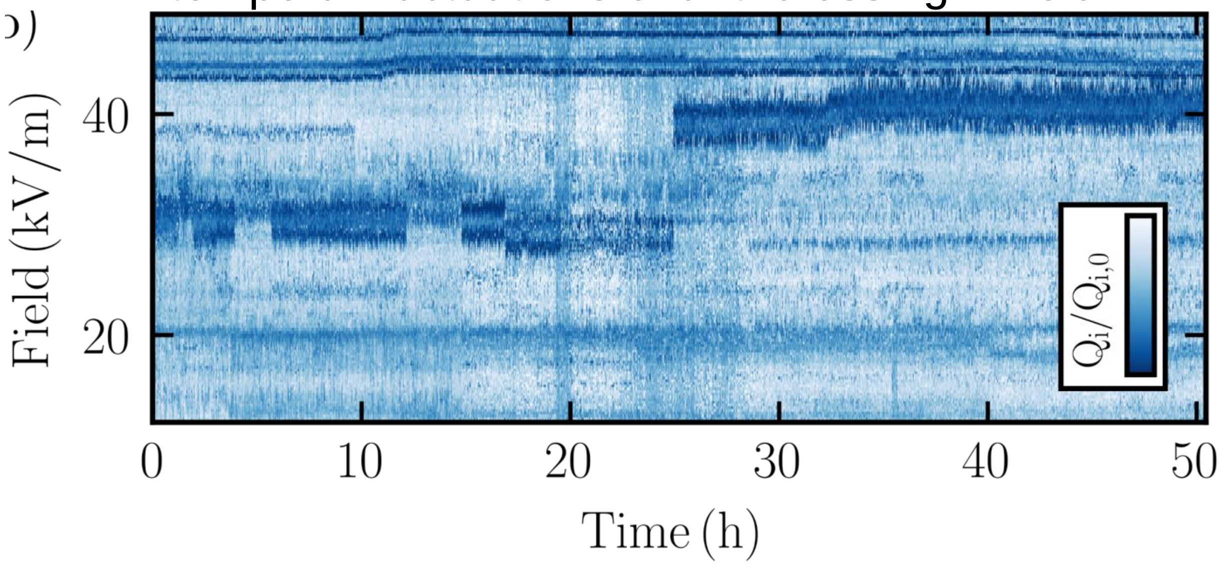


anti-crossings vanish at high drive power



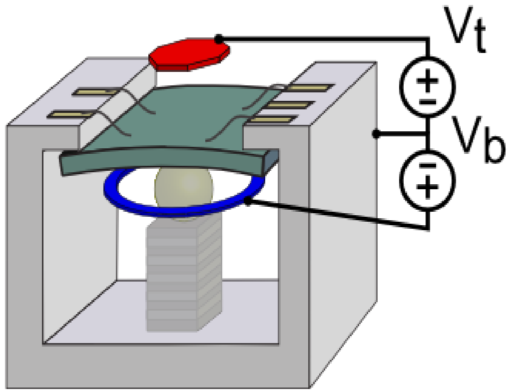
temporal fluctuations of anti-crossing E-field



determine locations of surface-TLS

A. Bilmes, A. Megrant, P. Klimov, G. Weiss, J.M.Martinis, A.V. Ustinov, and J. Lisenfeld., Scientific Reports 10, 3090 (2020)

- **two independent DC-electrodes**



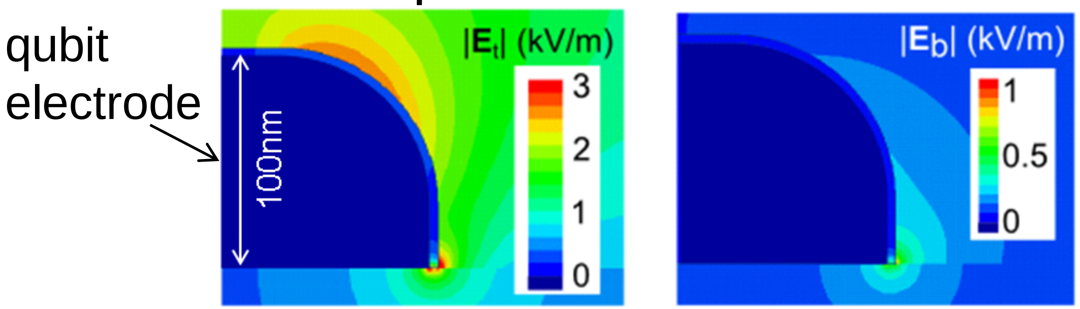
measure simulate

$$\frac{\gamma_t V_t}{\gamma_b V_b} = \frac{d\boldsymbol{E}_t(\boldsymbol{x})}{d\boldsymbol{E}_b(\boldsymbol{x})}$$

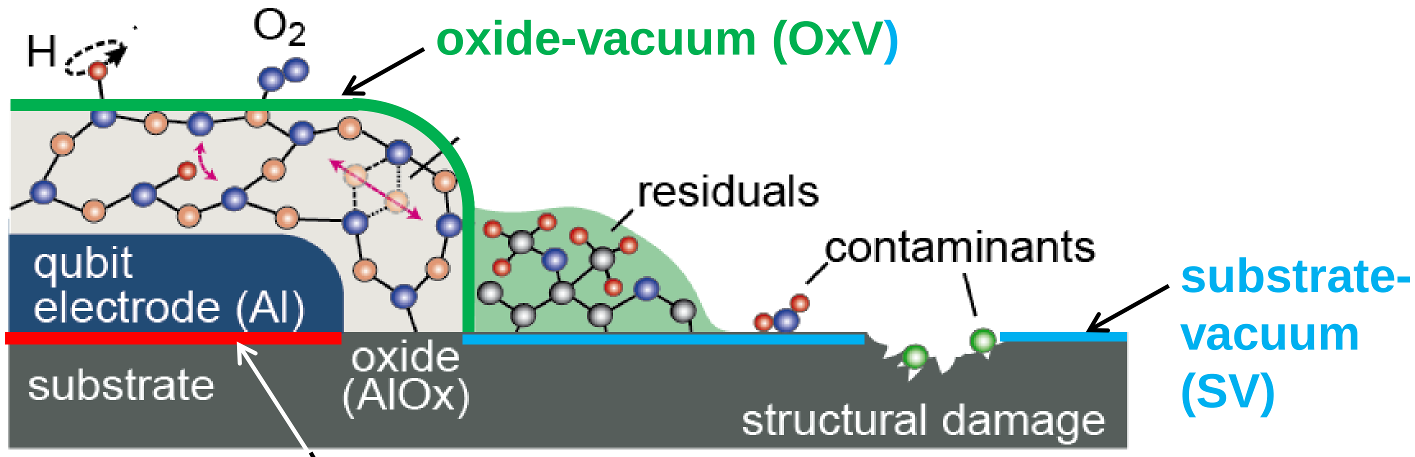
then solve for location x

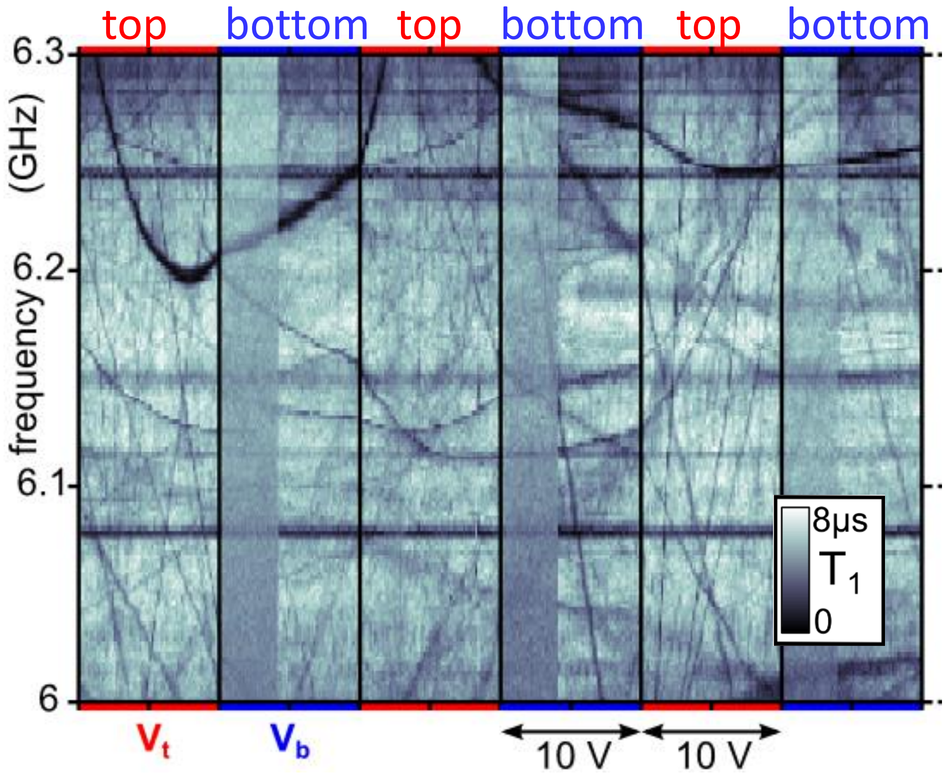
E-field simulations

0.5 V on **top electrode** on **bottom electrode**



distinguish TLS at different circuit interfaces





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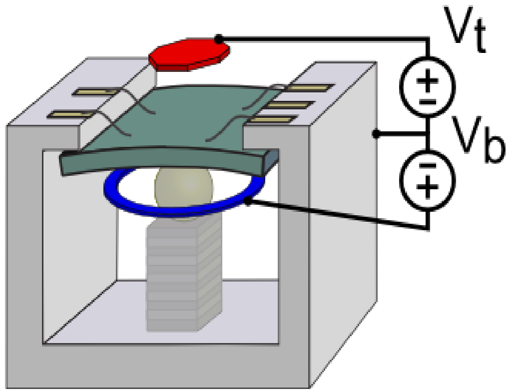

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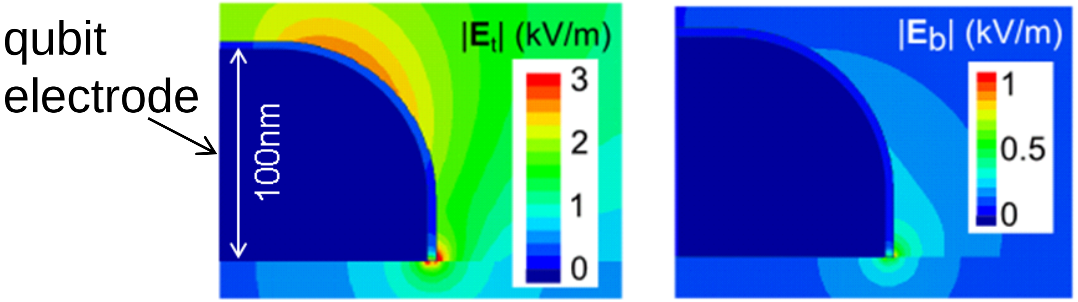

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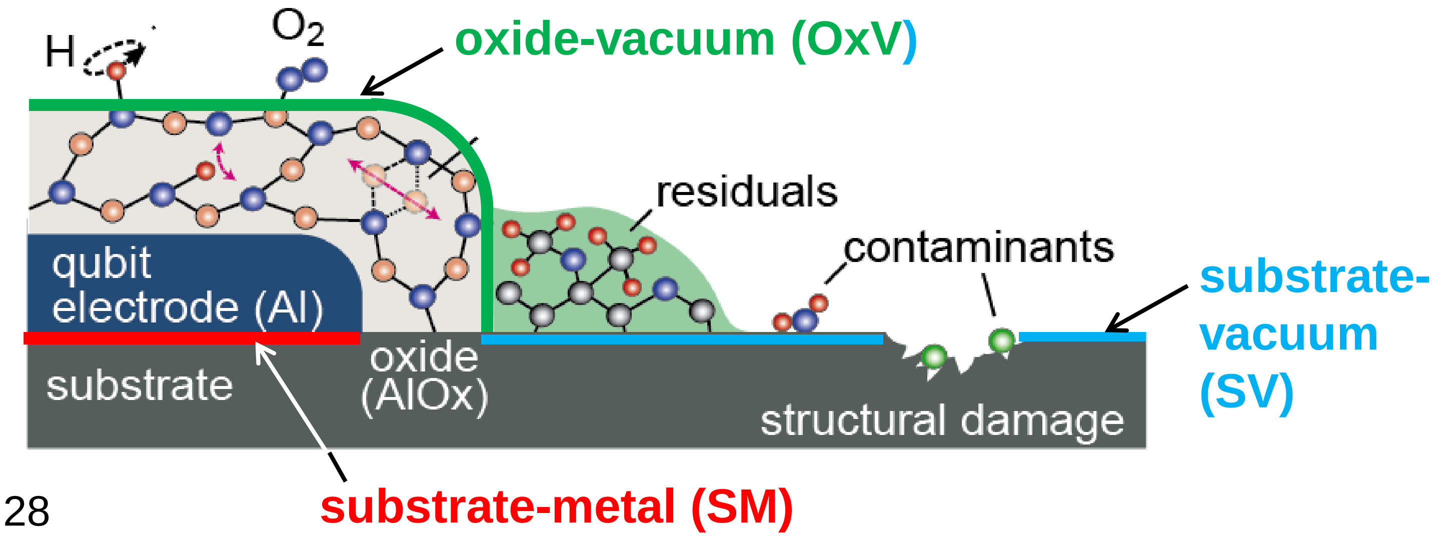
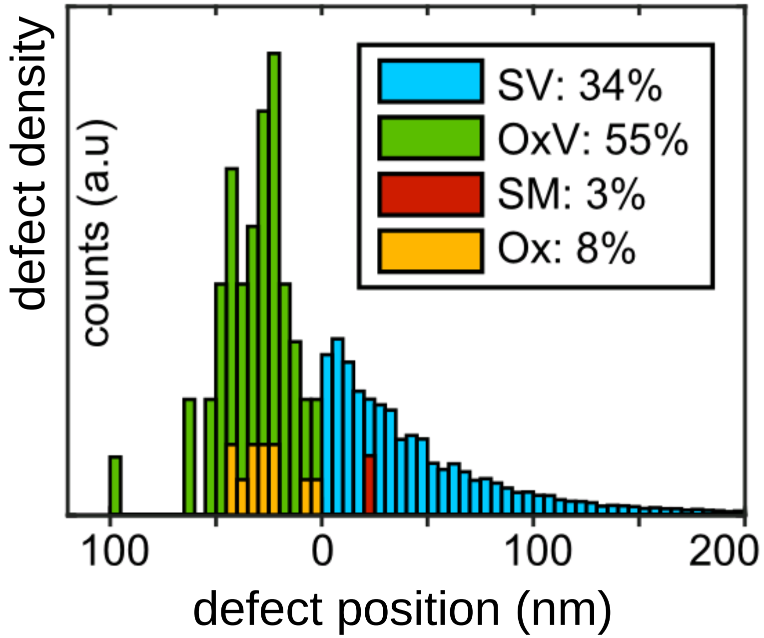
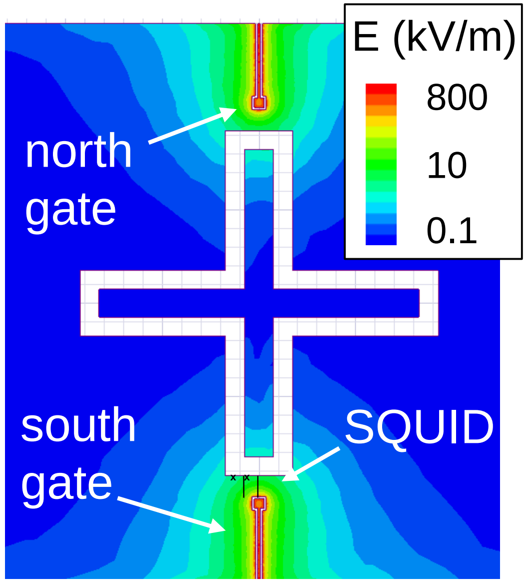


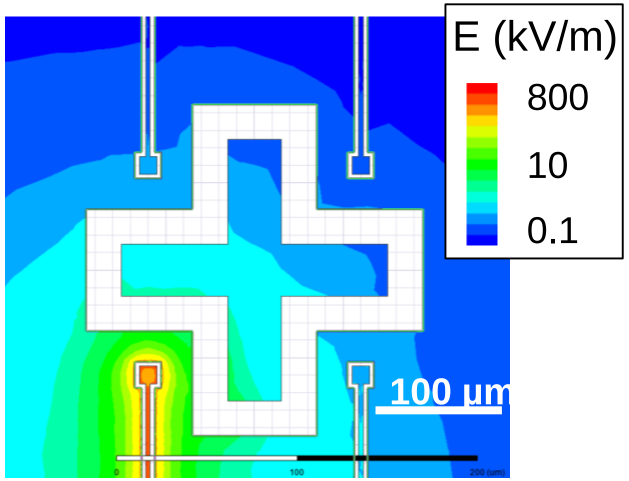
- **locations of TLS along film edge**

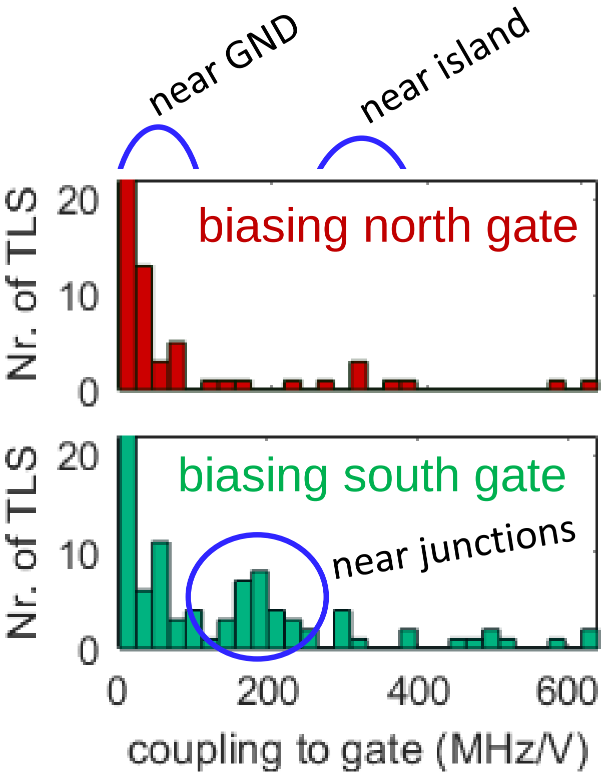


mapping TLS locations

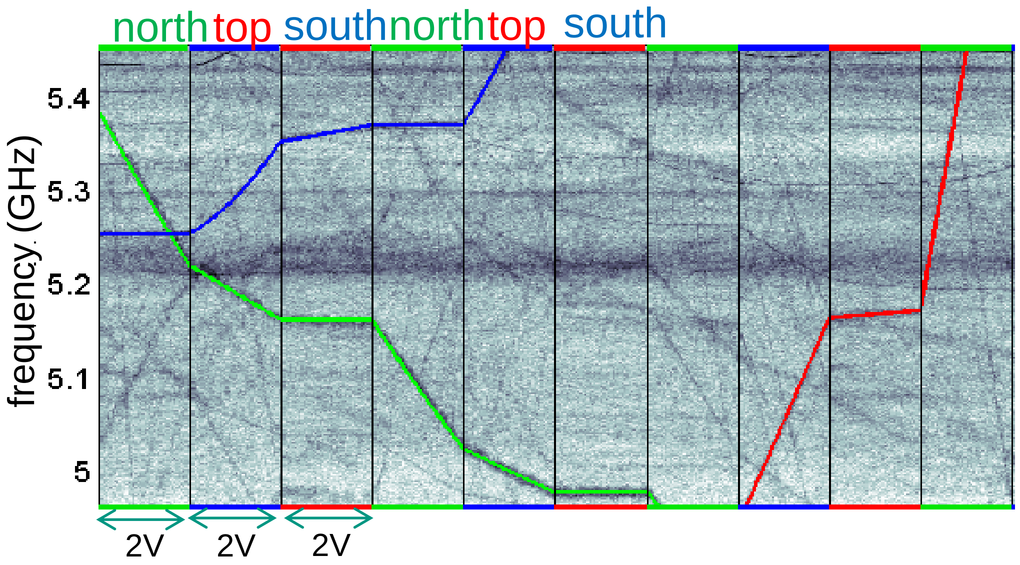
- on-chip gate electrodes







- measure response of TLS to each electrode

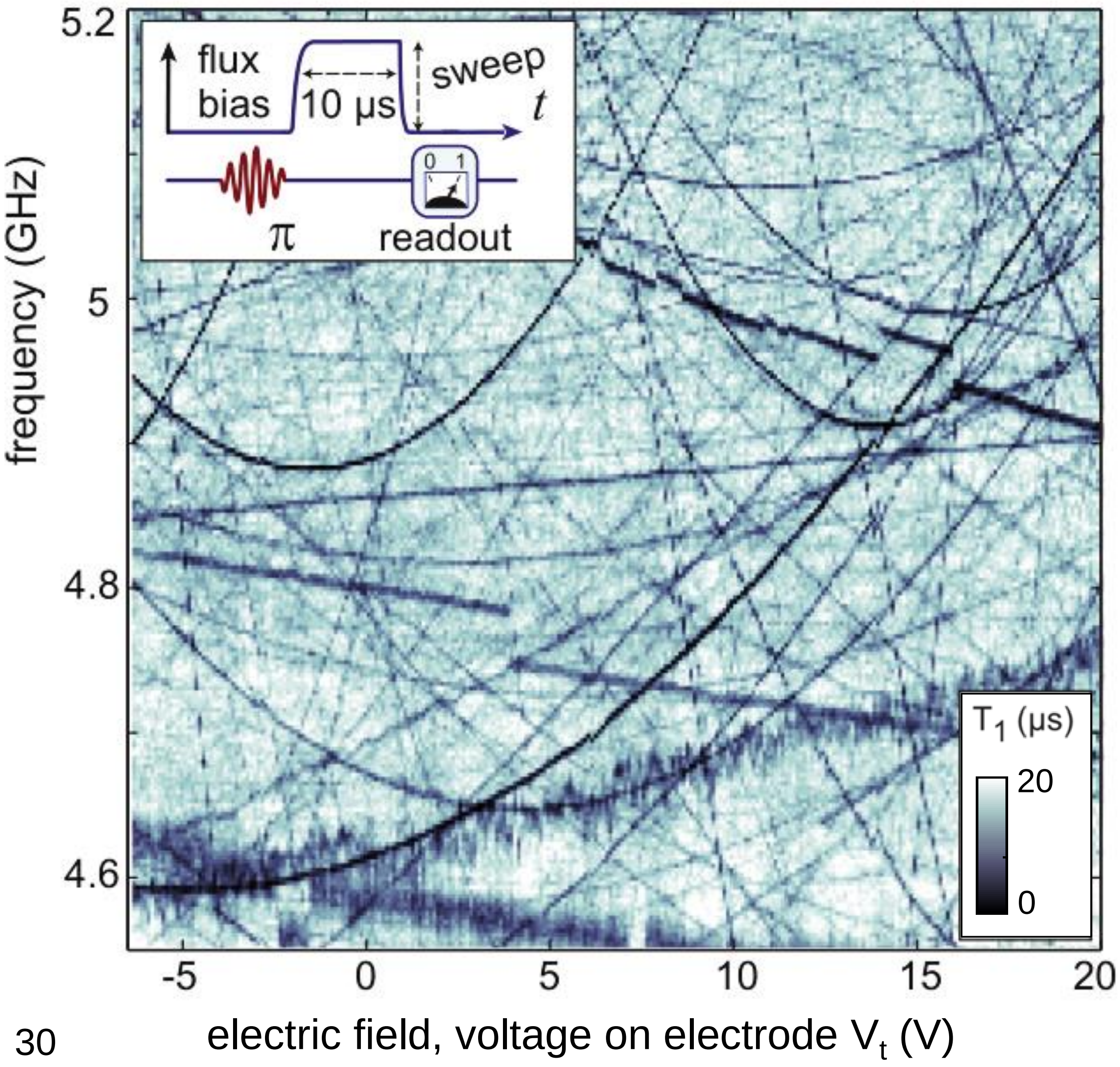


Goals:

- obtain 2D-maps of defect positions
- clarify role of TLS on junction leads
- compare TLS formation by optical and eBeam lithography, Ion-milling, residuals

Enhancing the T_1-time of qubits by E-fields

J. Lisenfeld, A. Bilmes et al.,
npj Quant. Inf. 9, 8 (2023)



- **Idea:**

  increase T_1 – time by tuning defects away from qubit resonance

- **Demo:**

  Enhancing the Coherence of Superconducting Qubits with Electric Fields

  J. Lisenfeld, A. Bilmes, and A.V. Ustinov,
  npj Quant. Inf. 9, 8 (2023)

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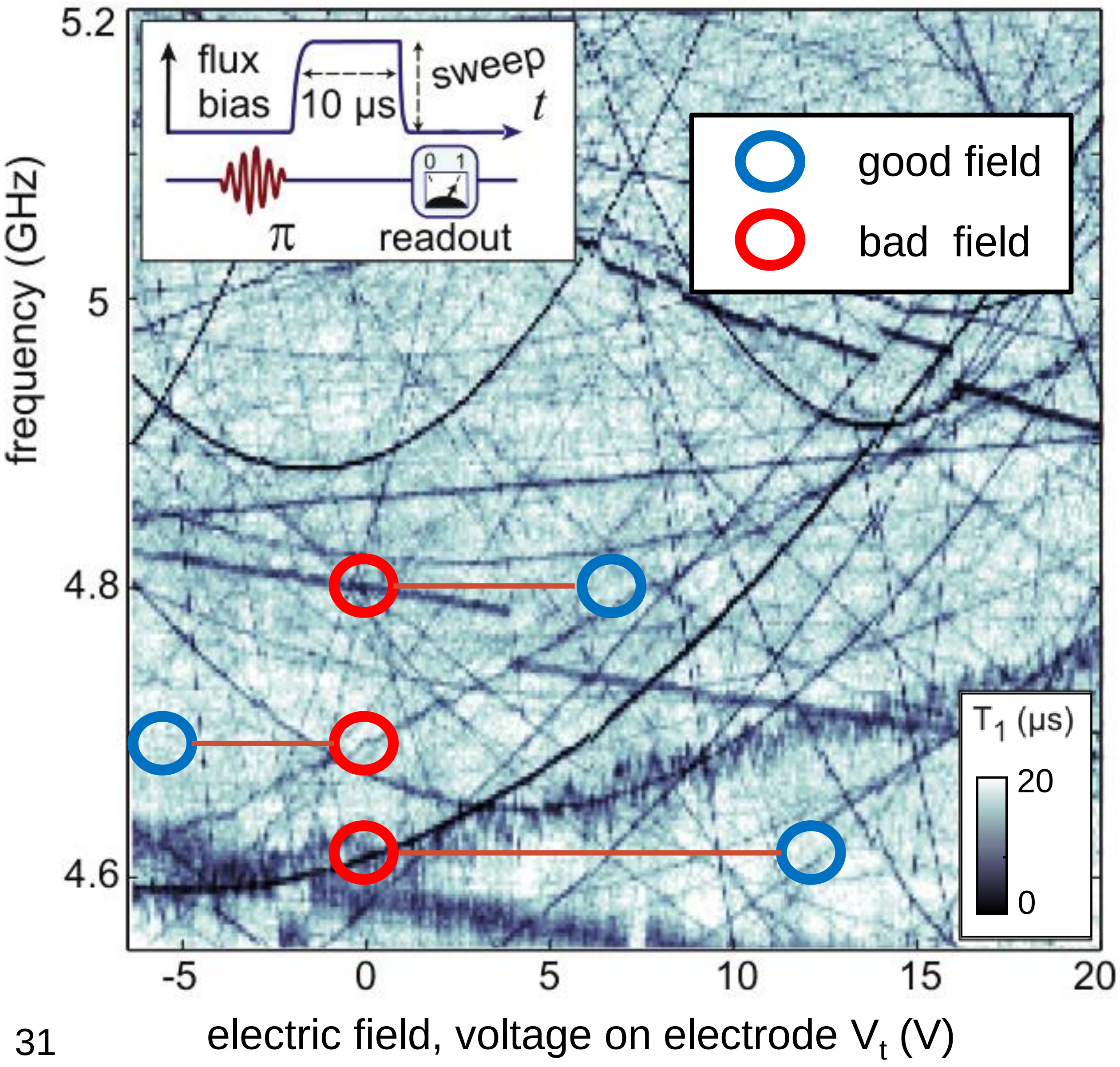

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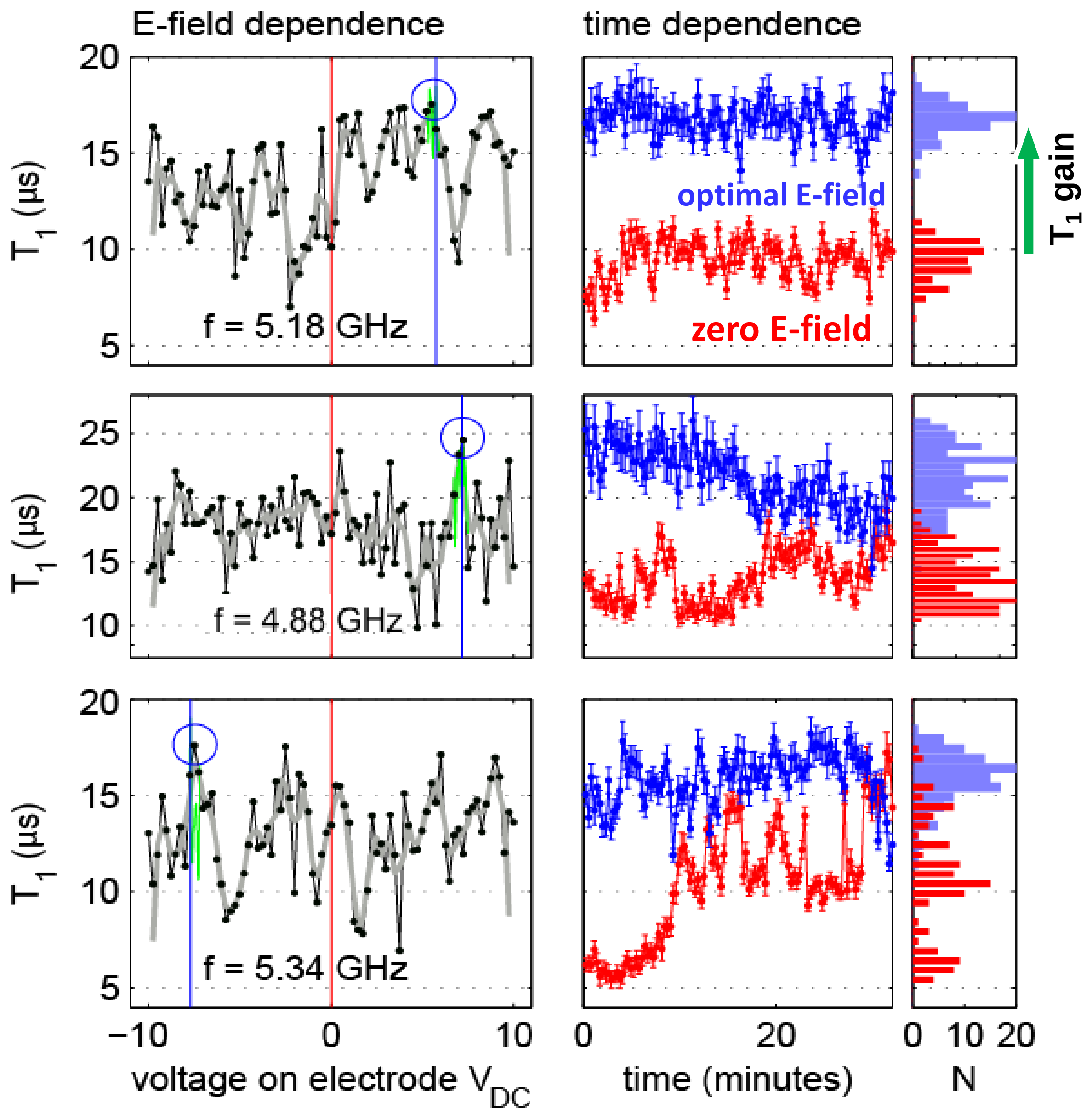


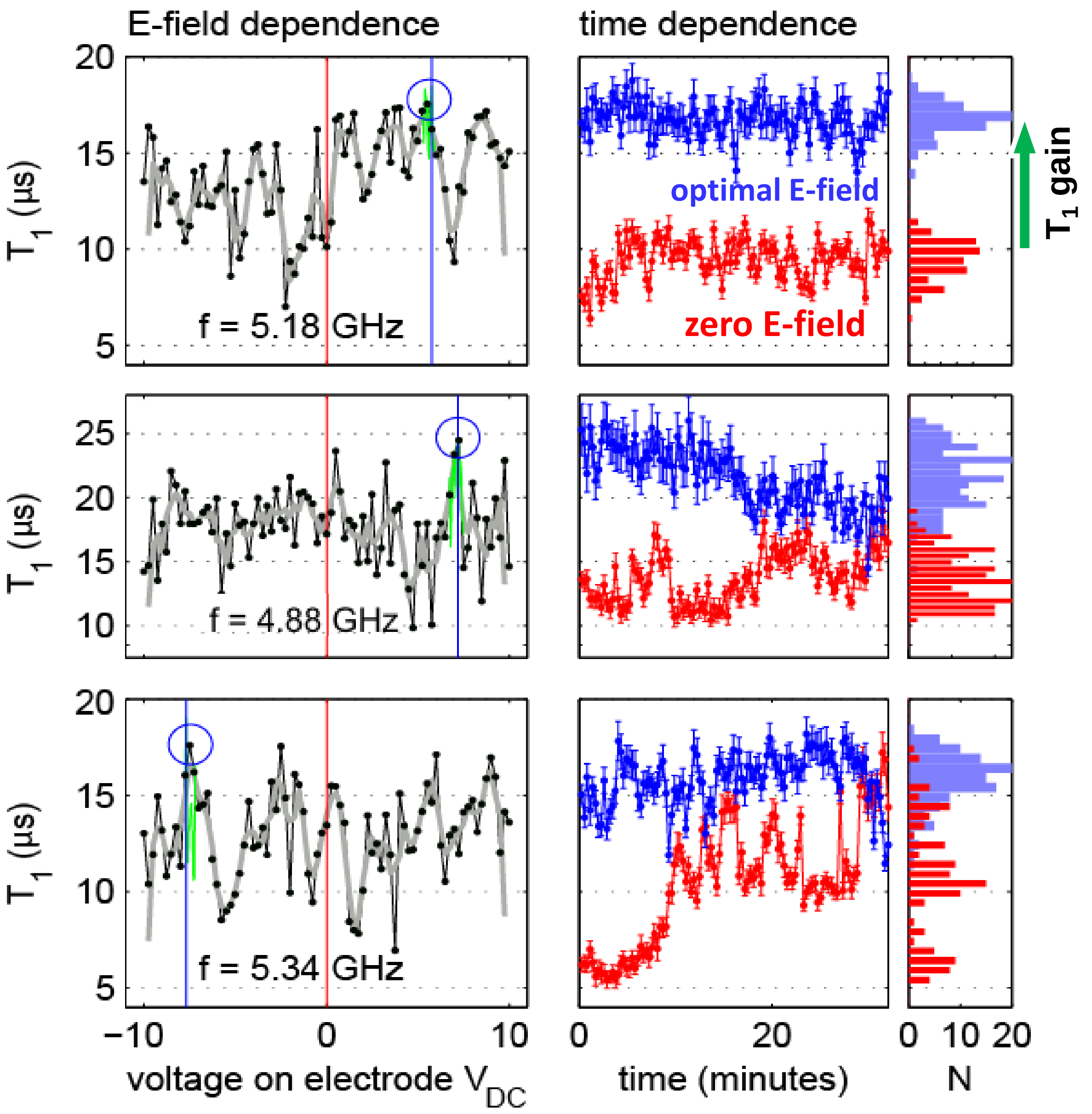
- **Method**:
  Measure T_1 vs. applied E-field,
  find optimal E-field where T_1 reaches maximum

- **Benchmark:**
  Monitor T_1 for 30 minutes
  at zero and optimal E-fields

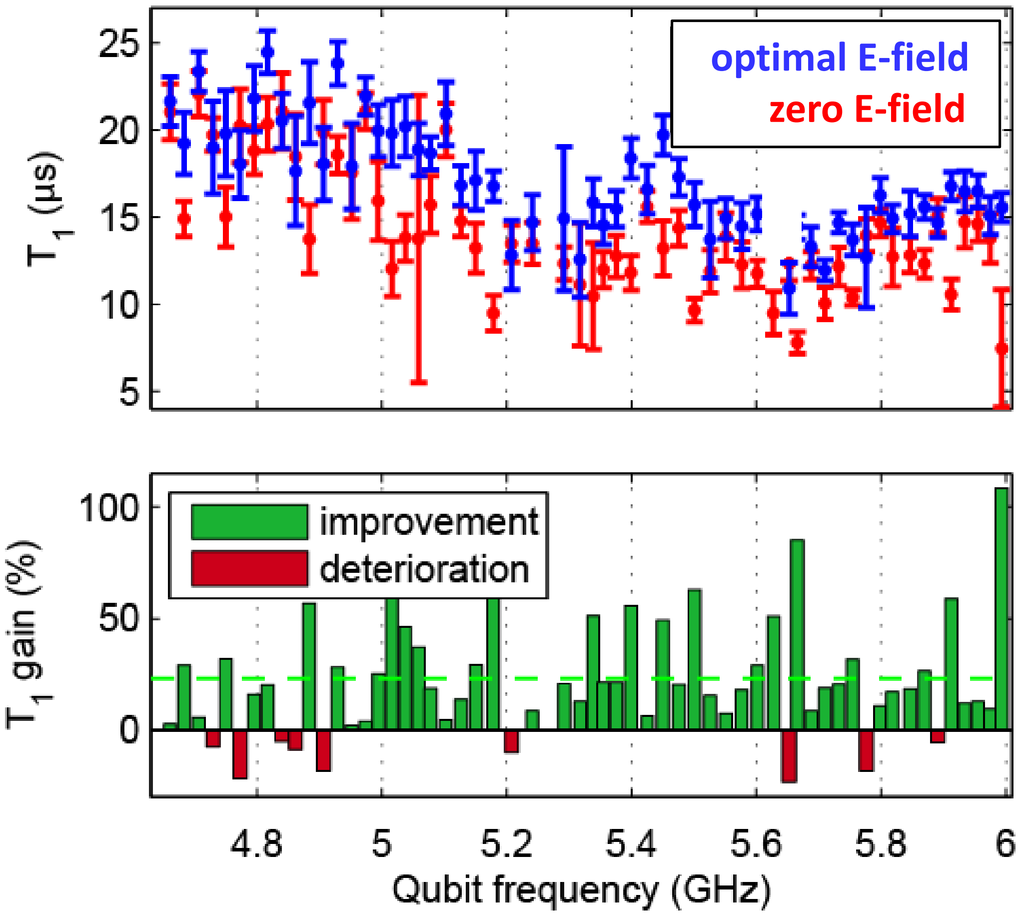
  repeat at various frequencies

Enhancing the T_1-time of qubits by E-fields

J. Lisenfeld, A. Bilmes et al., npj Quant. Inf. 9, 8 (2023)



- **Results:** automatically enhanced T_1 times

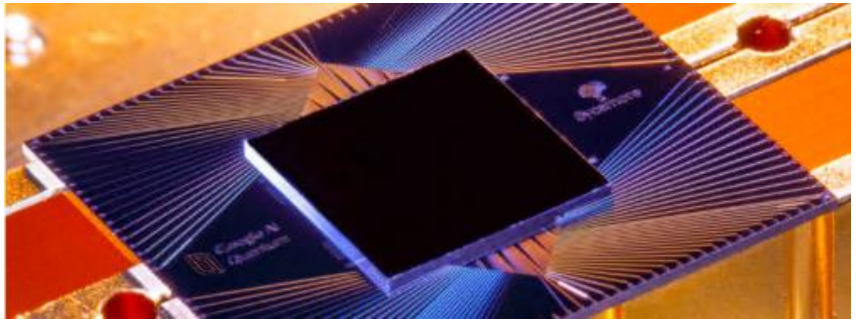


➡ T_1 enhanced by ~ 23% on average

E-field tuning: Integration in quantum processors

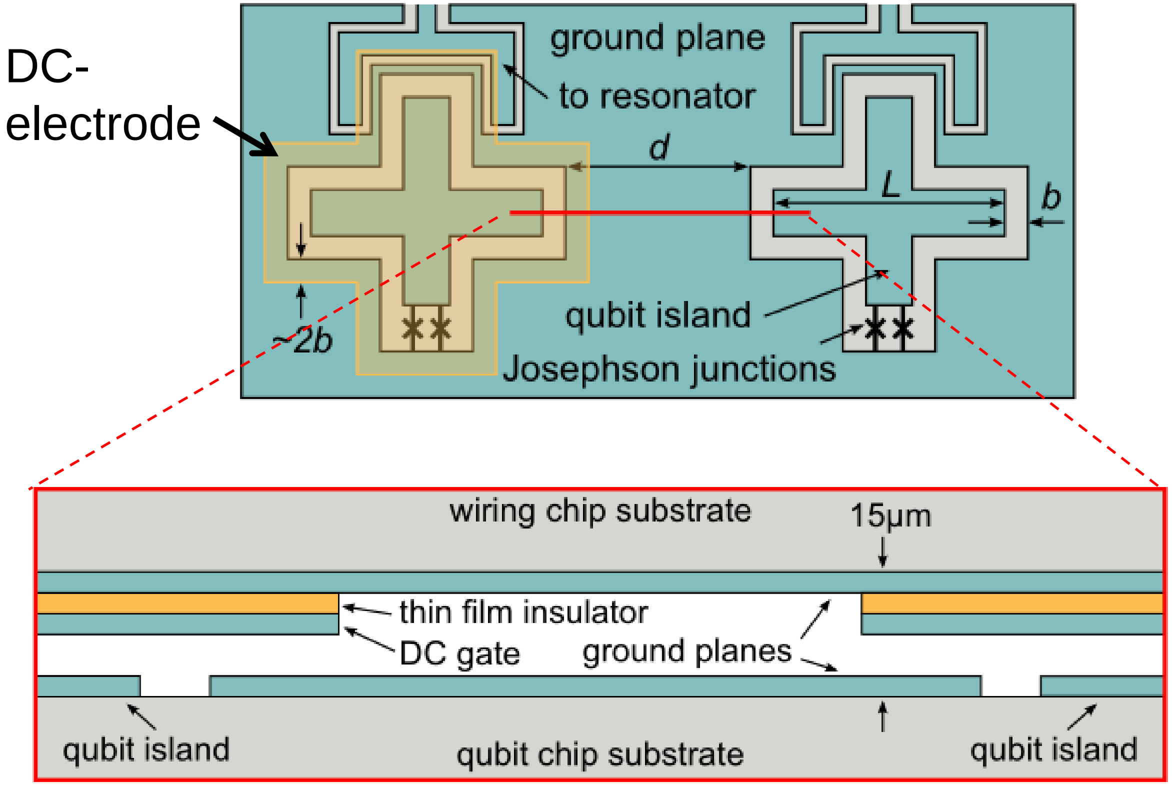
Flip-Chip architecture

- **Sycamore, 53-qubits, 86 tunable couplers** (Google)
  F. Arute et al., nature **574**, 505 (2019)



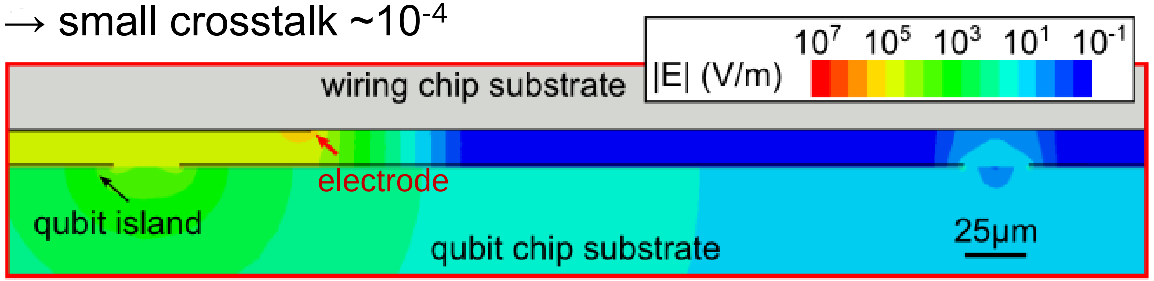
- easy to implement
- efficient (20+% more T_1 time)
- fast (<1 minute or on-the-fly)
- scalable to multi-qubit processors

Integration of DC-electrodes

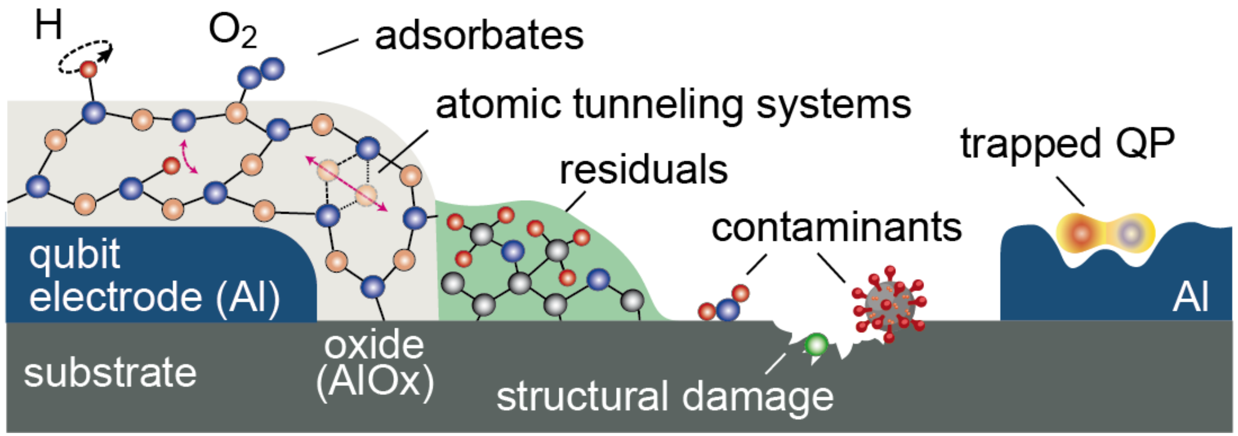


E-field simulation

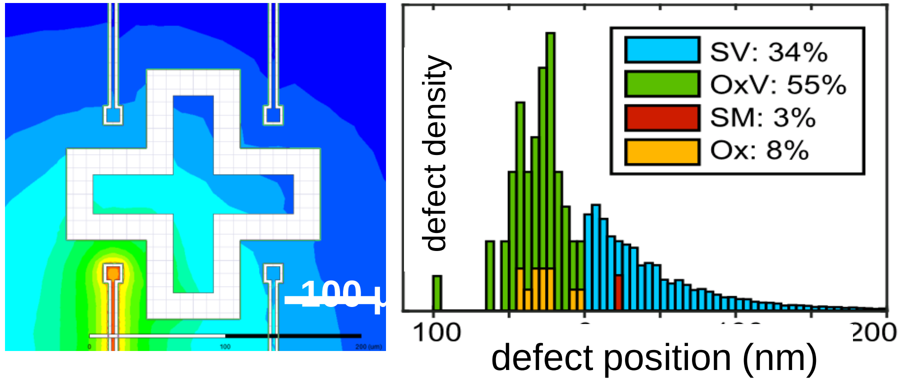
→ small crosstalk ~10^{-4}



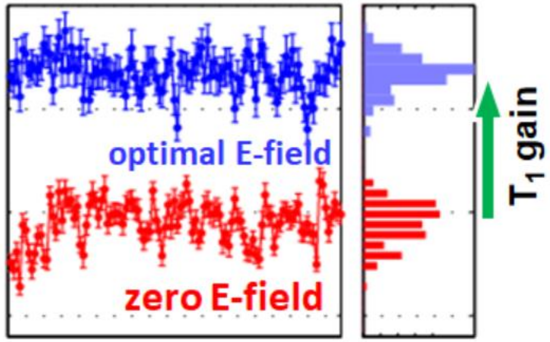
Summary



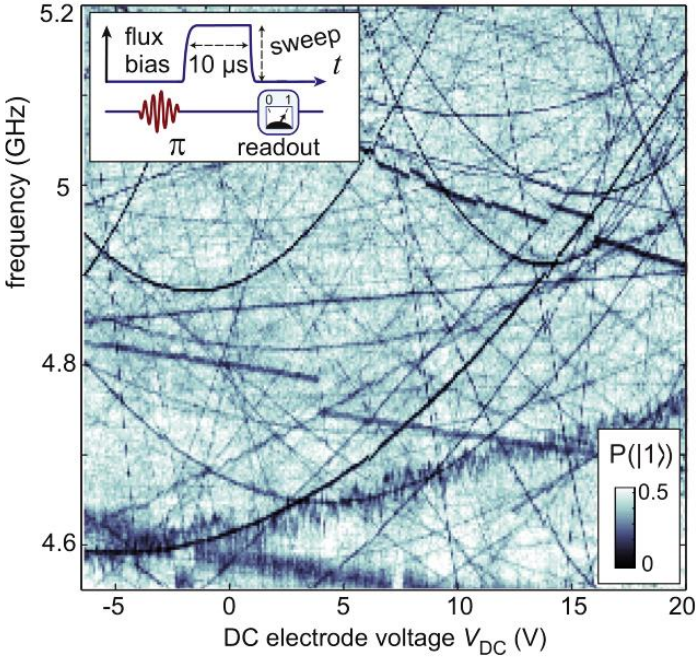
mapping TLS positions



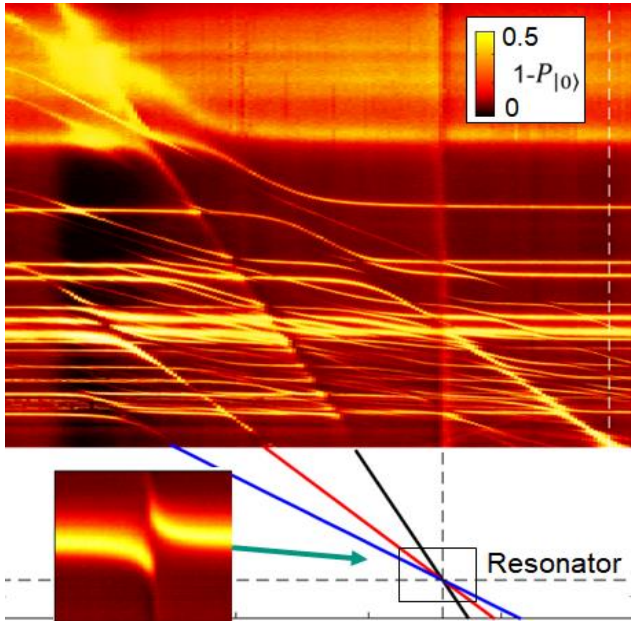
Improve qubit T_1 time



strain- & E-field spectroscopy



TLS-resonator coupling



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