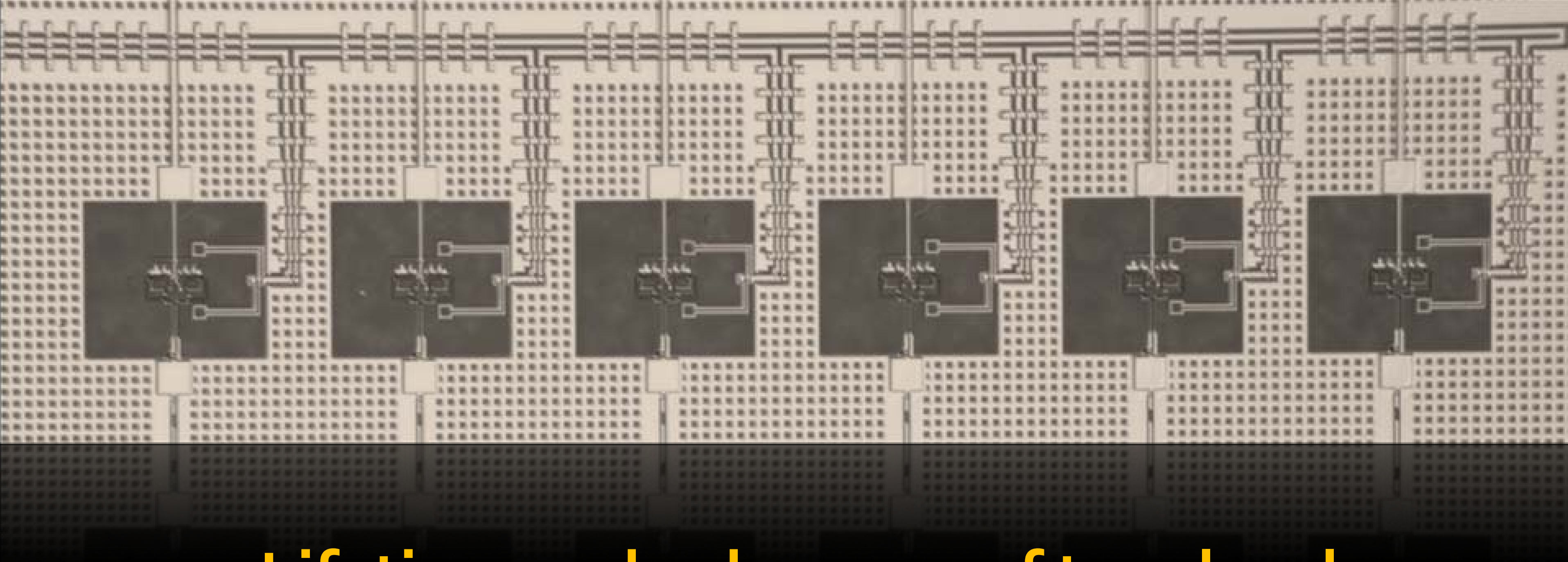


Lifetime and coherence of two-level defects within a Josephson junction

Nadav Katz (HUJI)
(collaboration with UCSB and NIST)

Racah Institute of Physics
Quantum Coherence Lab

KITP2010

Outline

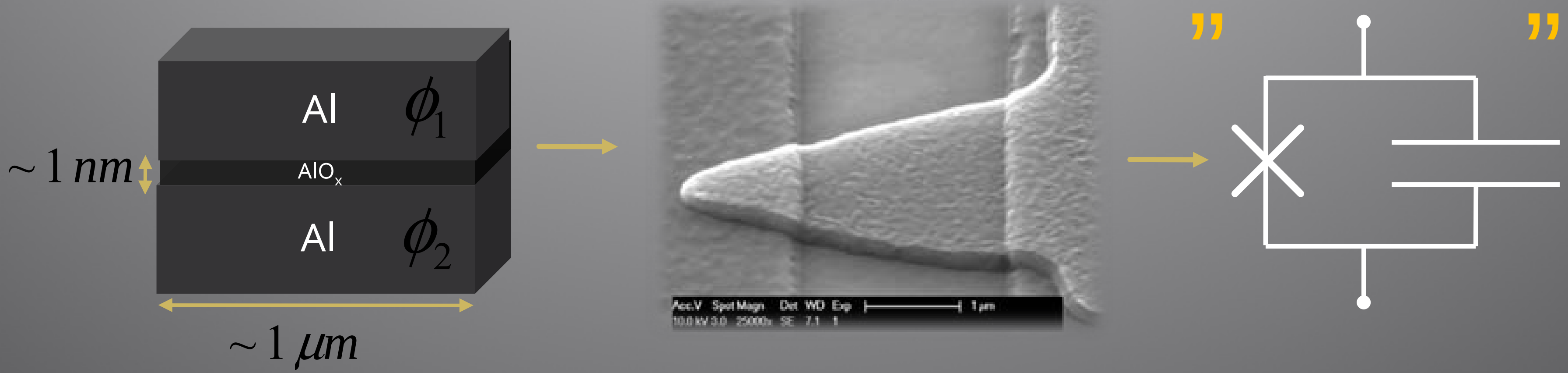
- Background – the Josephson circuit

- Decoherence from two-level defects
- The TLS model
- Probing individual defects
- TLS decoherence properties

- Feature: Quantum memory gate via TLS-Circuit interaction

Background – the Josephson junction

The Josephson tunnel junction: a nonlinear inductor



The Josephson relations:

$$I = I_0 \sin\varphi$$

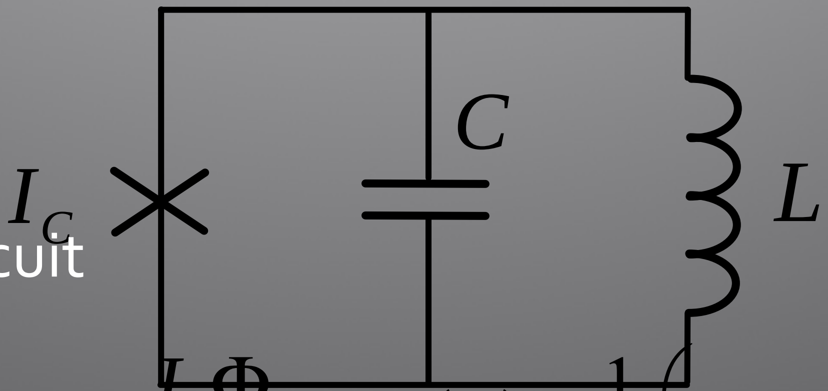
$$V = \frac{d\varphi}{dt}\frac{\Phi_0}{2\pi}$$

$\varphi = \phi_1 - \phi_2$ → "Josephson phase"

$\Phi_0 = h/2e$ → Flux quantum

Background – the Josephson phase circuit

Phys. Rev. Lett. 89, 117901 (2002)



Energy of the circuit

$$E = -\frac{2e^2}{C}N^2 - \frac{I_0\Phi_0}{2\pi}\cos(\varphi) + \frac{1}{L}\left(\Phi_{ext} - \frac{\Phi_0\varphi}{2\pi}\right)^2$$

Kinetic energy

Charging energy

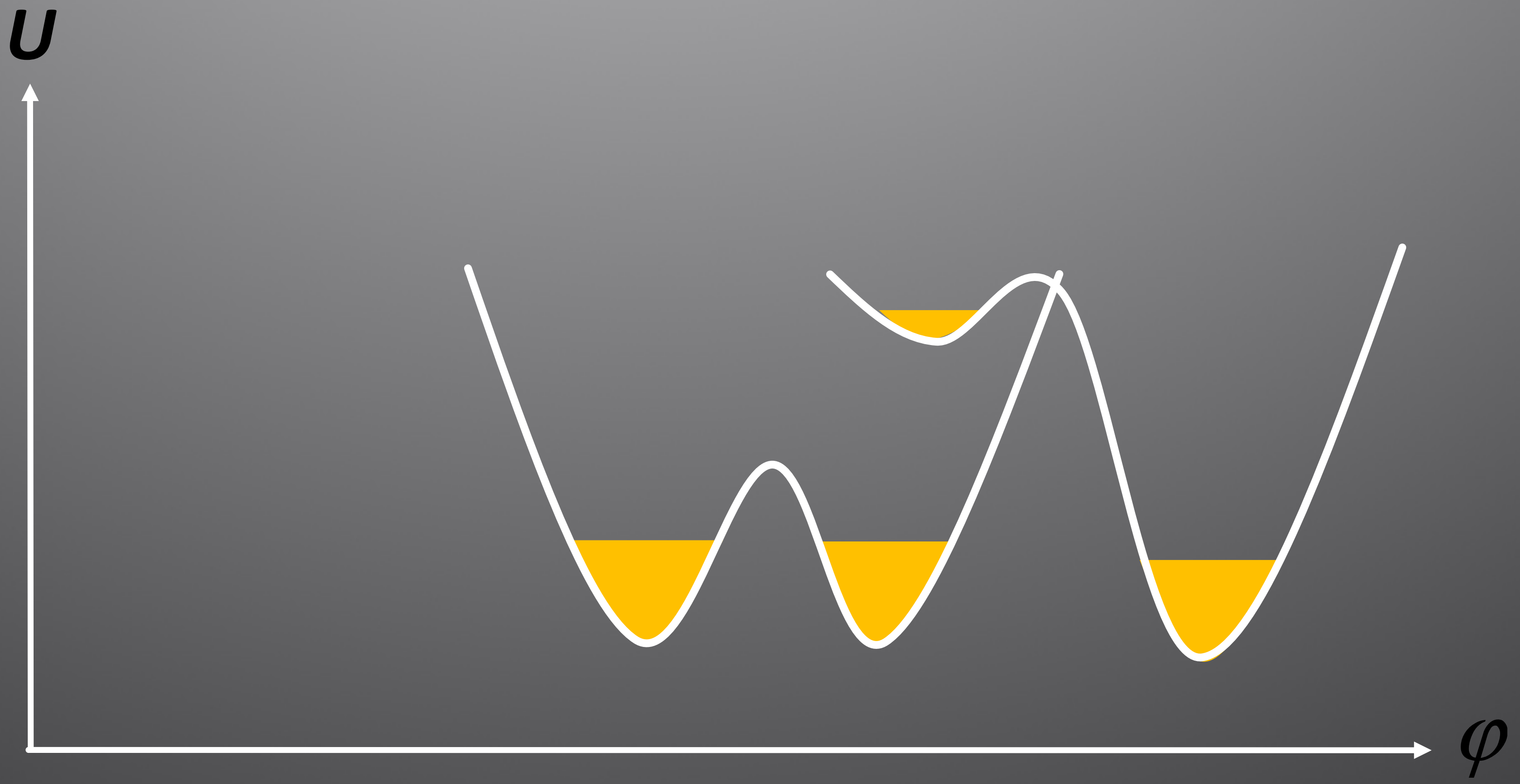
Josephson energy

Potential energy

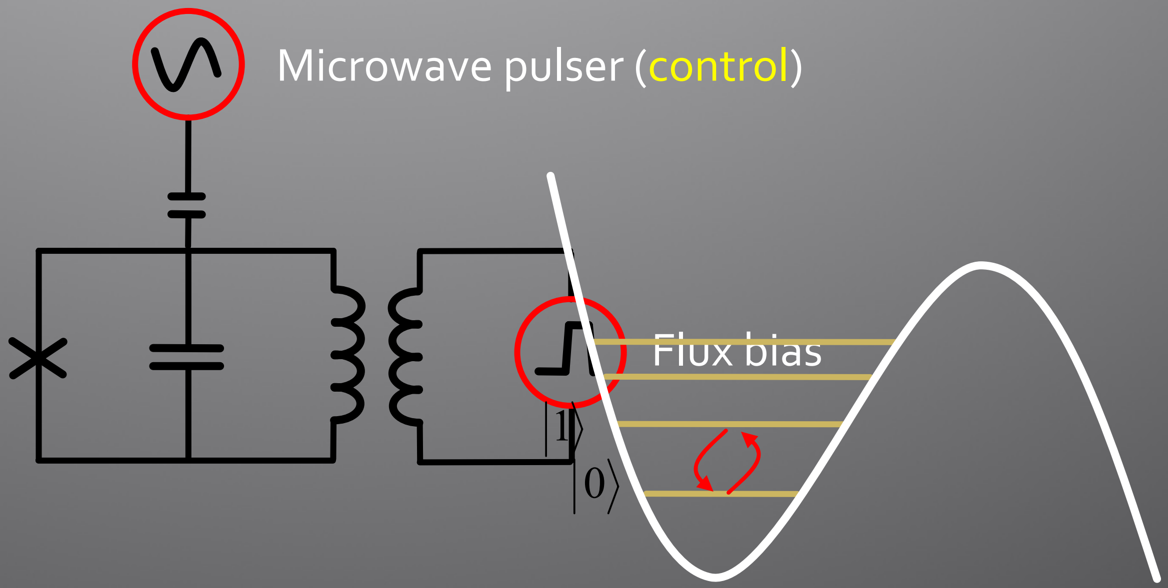
Magnetic energy

Background – the Josephson phase circuit

$$U = -\frac{I_0\Phi_0}{2\pi}\cos\hat{\varphi} + \frac{1}{L}\left(\Phi_{ext} - \frac{\Phi_0\hat{\varphi}}{2\pi}\right)^2$$



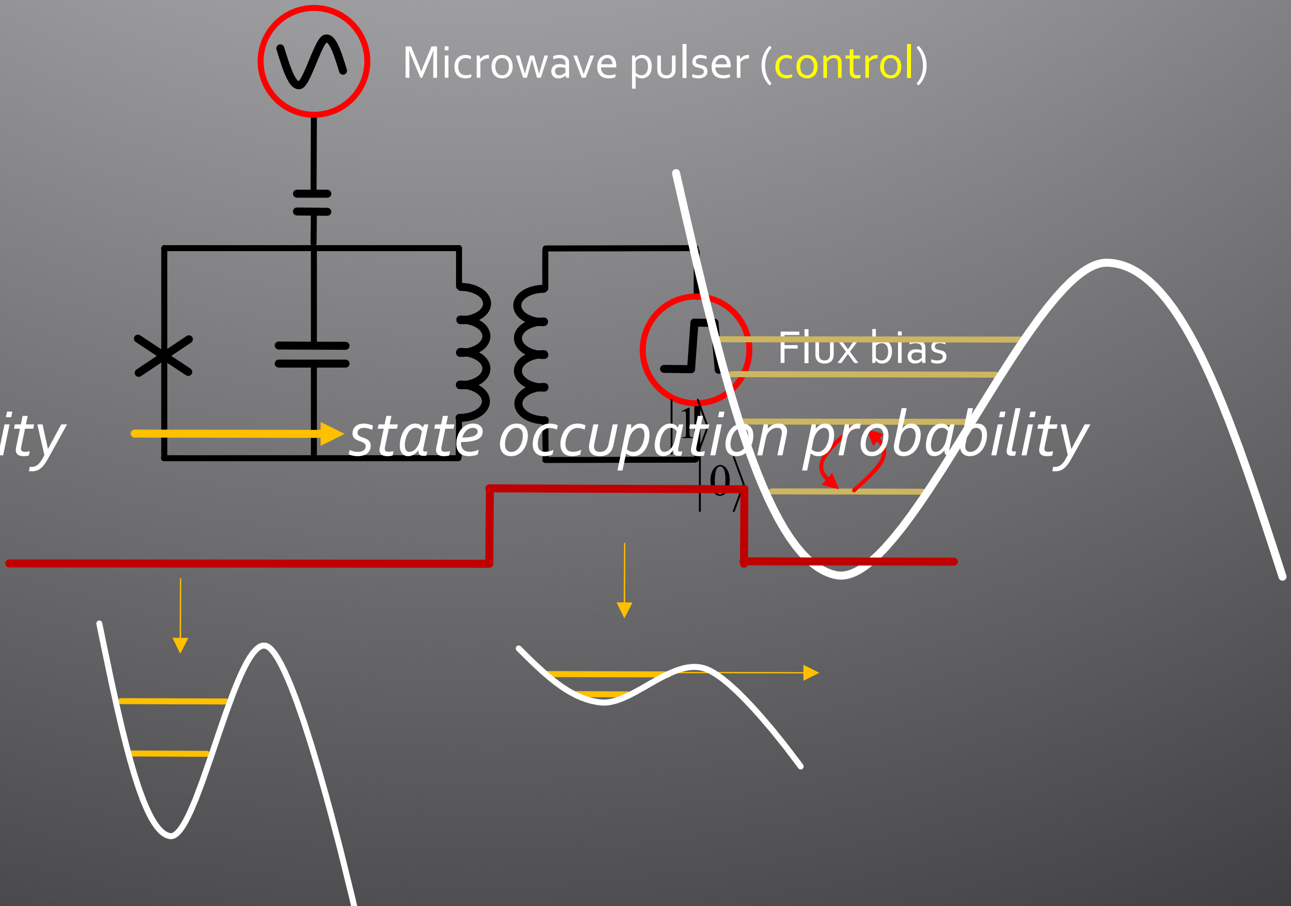
Background – the Josephson phase circuit



Microwave pulser (control)

Flux bias

Background – the Josephson phase circuit



Microwave pulser (control)

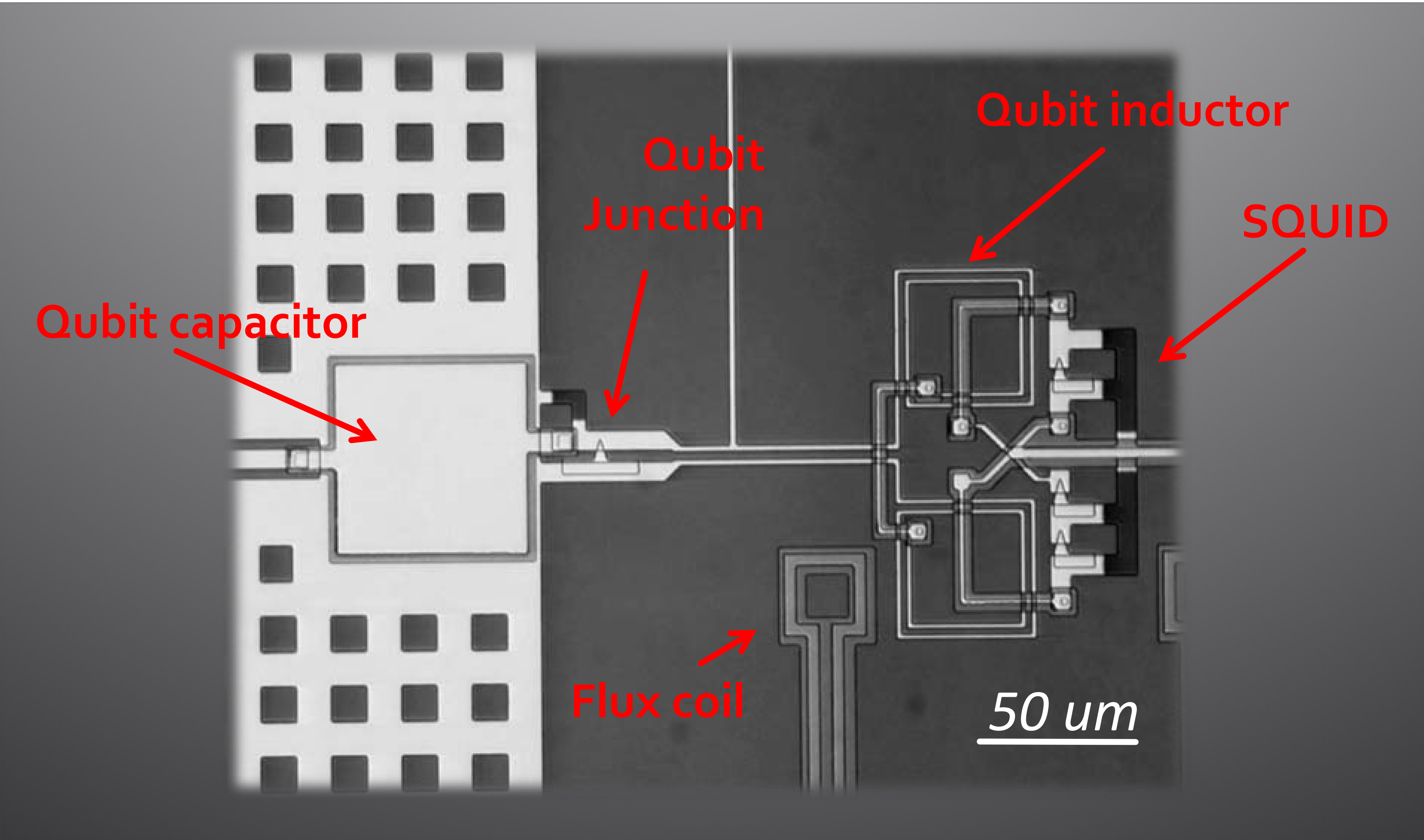
Flux bias

Escape probability → *state occupation probability*

Flux bias:

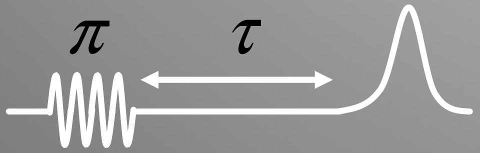
Background – the Josephson phase circuit

Devices fabricated by Martinis group (UCSB)

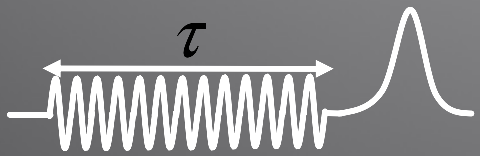


Phase Qubit Decoherence

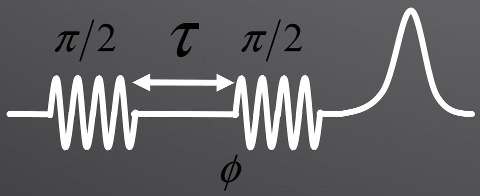
T_1:

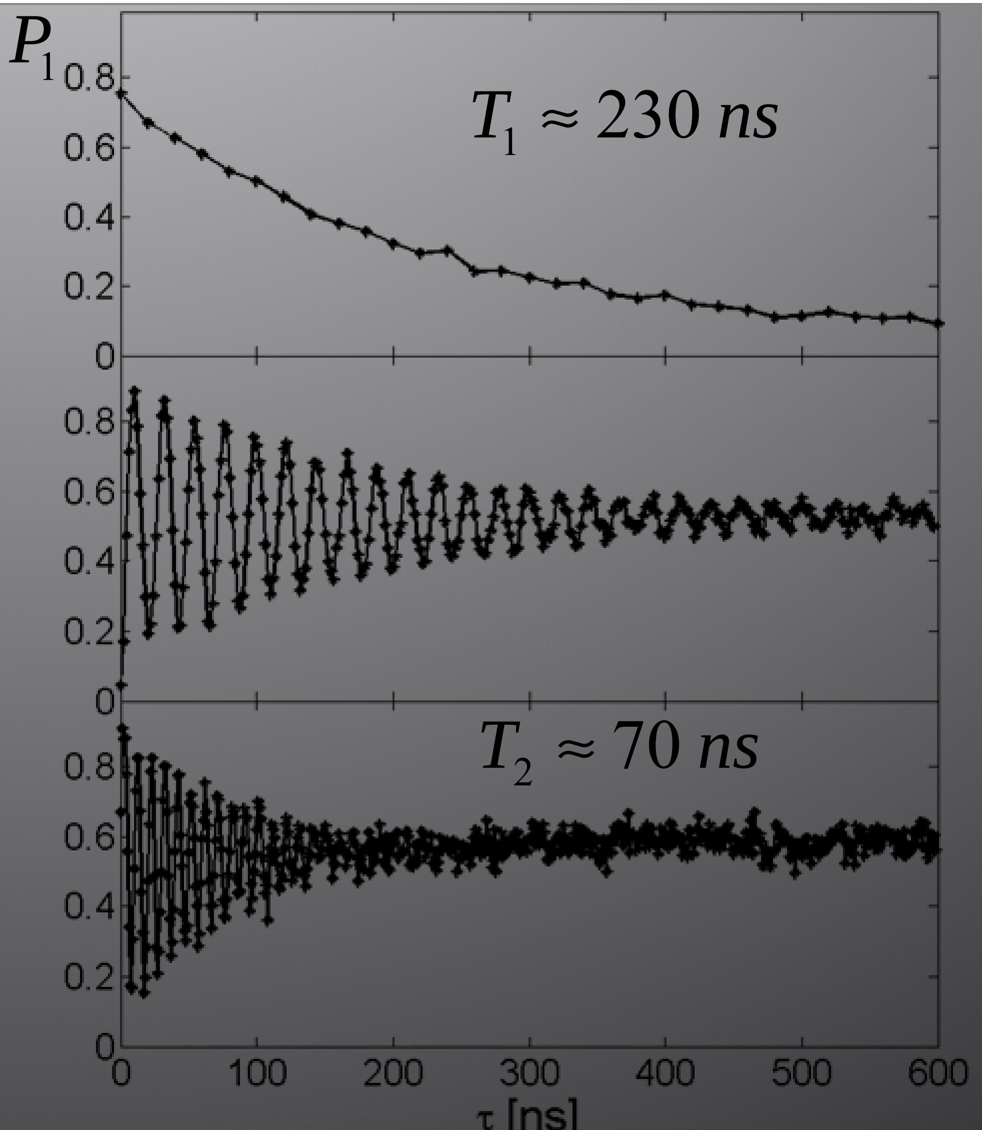


Rabi:



Ramsey:





Phase Qubit Decoherence

Decay and dephasing mechanisms:

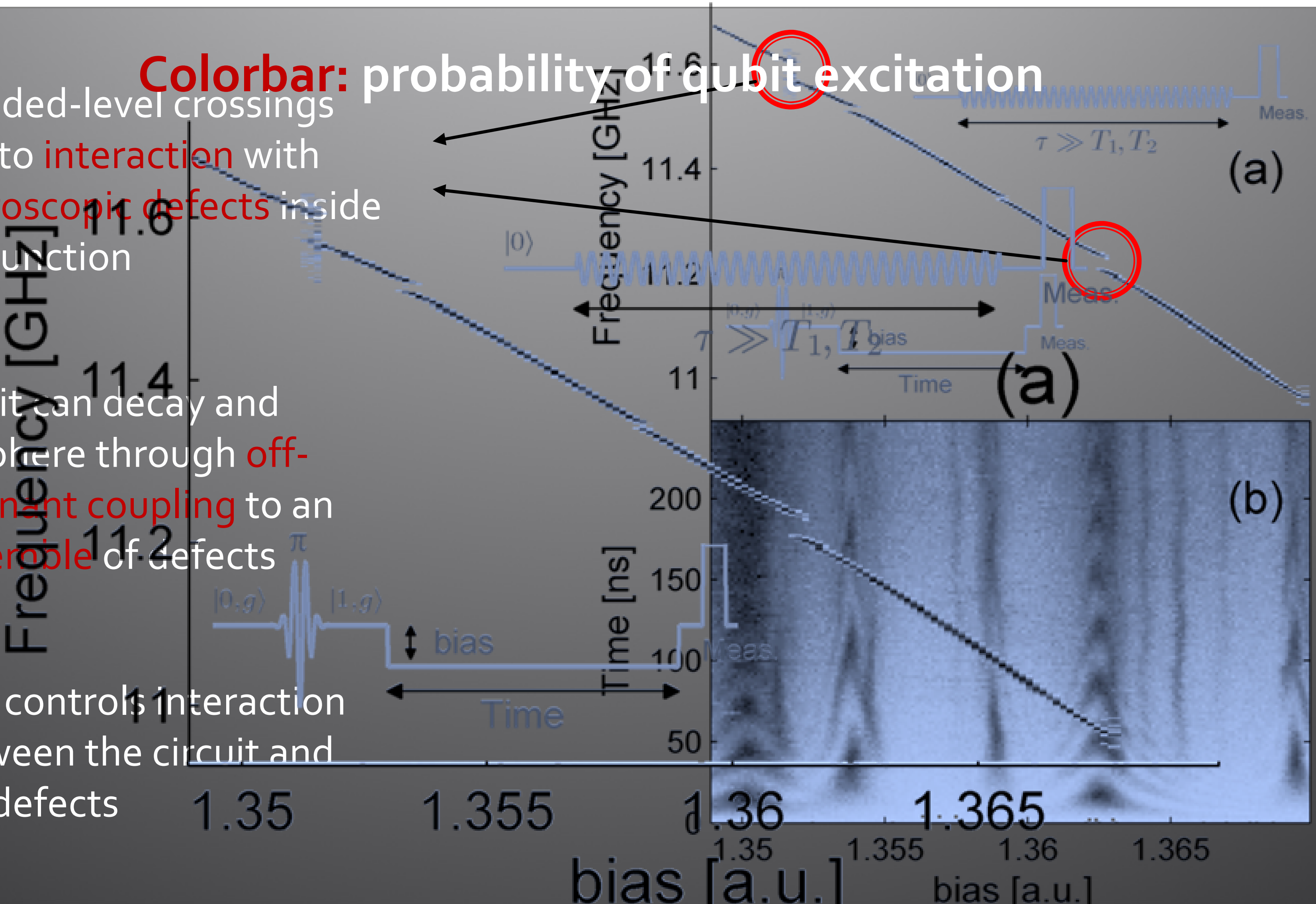
- Dielectric loss
- Nonequilibrium quasiparticles
- Coupling to external circuitry
- Coupling to microscopic defects

(TLSs)

- Magnetic flux noise
- External circuitry noise
- TLSs

Coupling to TLSs

Colorbar: **probability of qubit excitation**



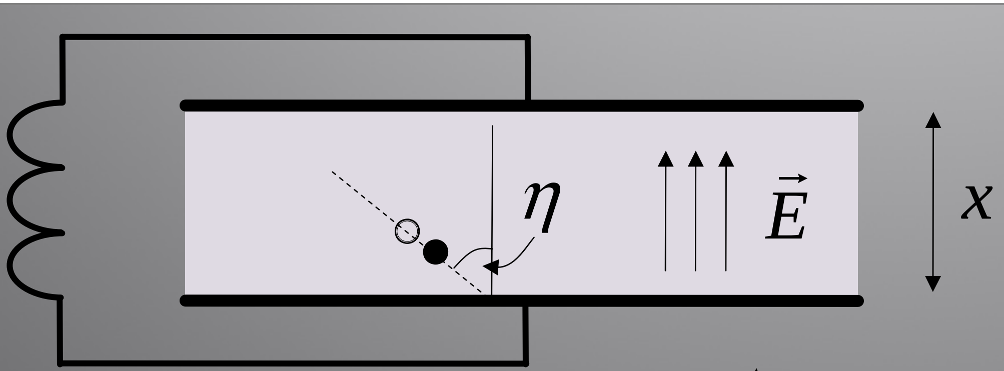
Avoided-level crossings due to interaction with microscopic defects inside the junction

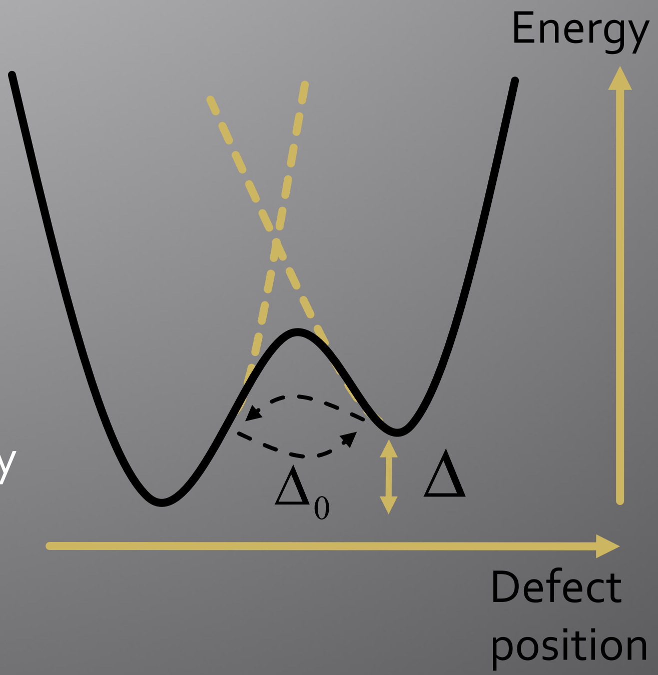
Qubit can decay and decohere through off-resonant coupling to an ensemble of defects

Bias controls interaction between the circuit and the defects

The TLS model

J Martinis et.al, PRL 95, 210503 (2005)





Δ Well asymmetry

Δ_0 Tunneling energy

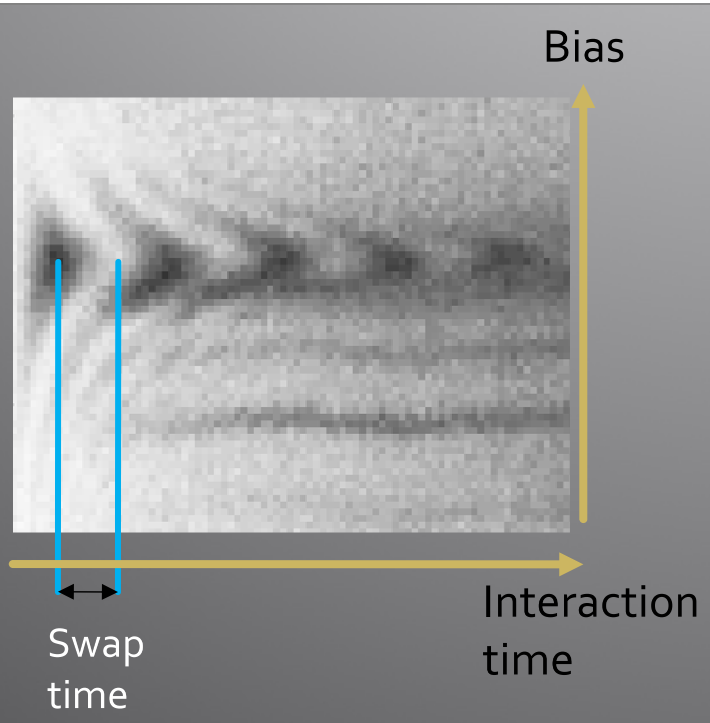
TLS energy: $E_{ge} = \sqrt{\Delta^2 + \Delta_0{}^2}$

Qubit-TLS coupling strength: $S = S_{\max} \dfrac{\Delta_0}{E} \cos\eta$ ← Dipole – Electric field interaction

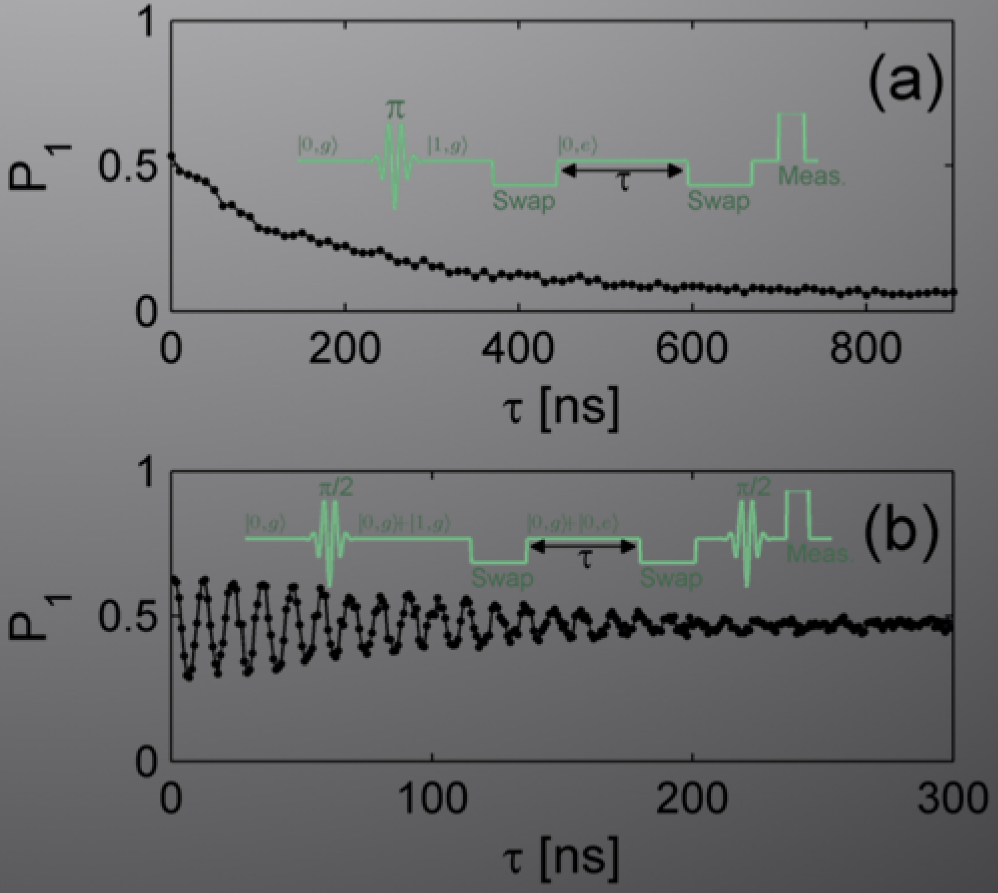
$$S_{\max} = 2\frac{d}{x}\sqrt{\frac{E_{10}e^2}{2C}}$$

Probing individual defects

M Neeley et.al Nat Phys 4, 523 (2008)



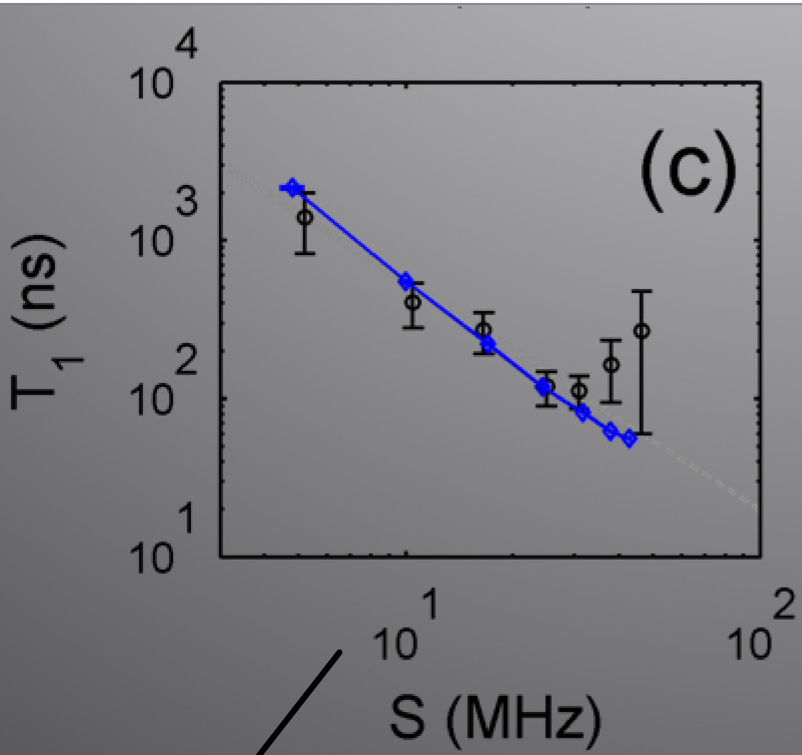
Method



- Extract energy relaxation and dephasing times of each TLS
- TLS can be used as a quantum memory via swap gate

TLS decoherence results

Y. Shalibo et.al, arXiv:1007.2577 (2010)

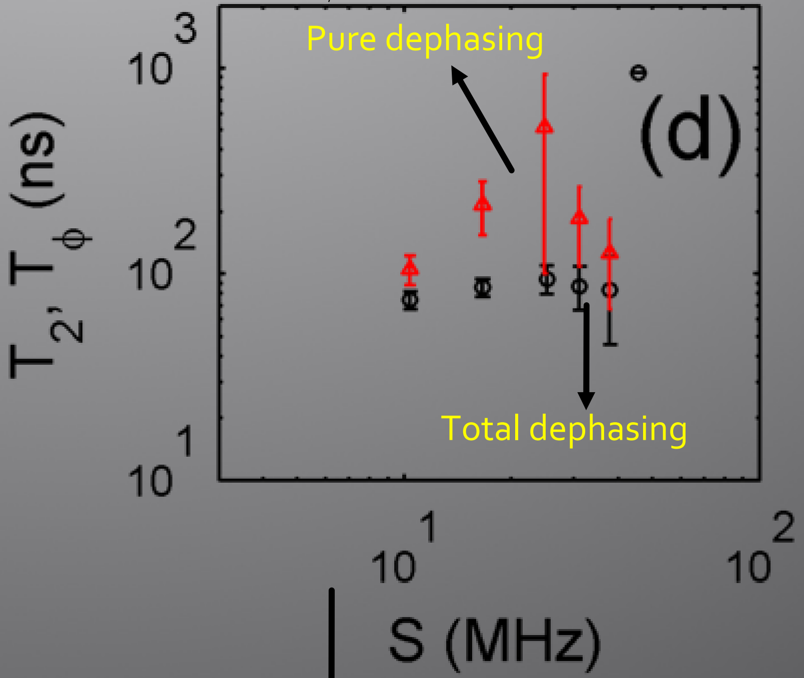


Lifetime fits a power law -

$$\langle T_1 \rangle \propto \langle S \rangle^{-\alpha}$$

$$\alpha \approx 1.44 \pm 0.15$$

$$T_\phi = \left(1/T_2 - 1/2T_1\right)^{-1}$$



Pure dephasing time is optimized at intermediate couplings

TLS relaxation model

Energy relaxation by dipole-phonon coupling

$$T_1^{-1} = \frac{E_{ge}^{3}\left(\frac{S}{S_{\max}\cos\eta}\right)^{2}}{2\pi\rho\hbar^{4}}\sum_k \frac{\gamma_k^{2}}{v_k^{5}}$$

γ_k	Strain-phonon coupling Coefficient for phonon mode k
v_k	Speed of sound for phonon mode k
ρ	Dielectric mass density

Stochastic simulation yields:

$$\alpha \approx 1.63$$

Minimal lifetime calculated for Aluminum phonons:

$$T_1^{\min} \approx 30ns$$

TLS dephasing model

Dephasing due to energy fluctuation:

$$E_{ge} = \sqrt{\Delta^2 + \Delta_0^{\,2}}$$

Exponential sensitivity of Δ_0 (tunneling energy) on P:

$$\Delta_0 \propto \exp(-P/P_0) \longrightarrow \delta\Delta_0 \approx -\Delta_0 \frac{\delta P}{P_0}$$

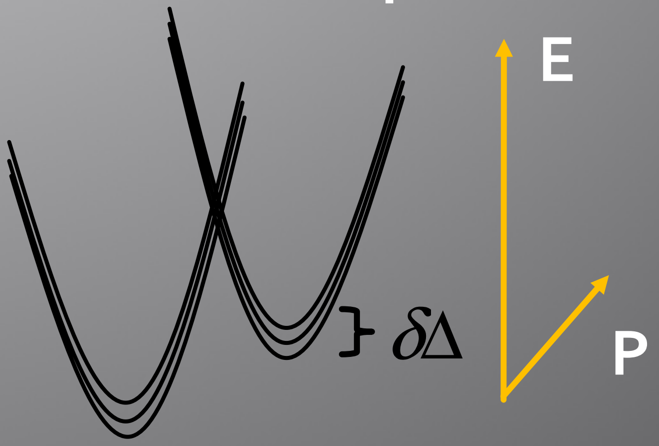
Linear sensitivity of Δ on P:

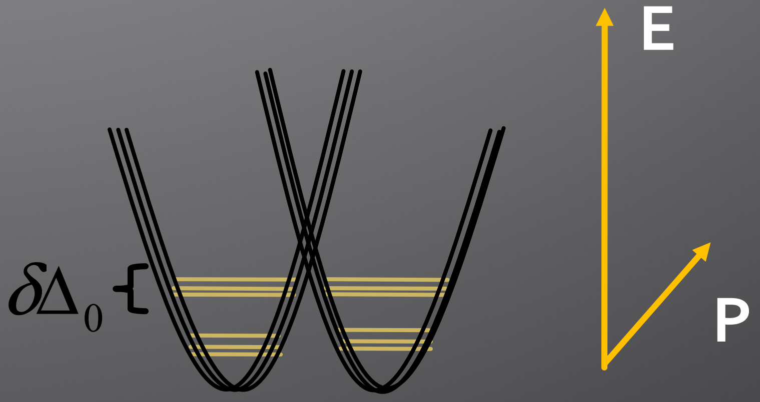
$$\Delta \propto P \longrightarrow \delta\Delta \approx \Delta \frac{\delta P}{P_1}$$

To first order in δP :

$$\delta E_{ge} \approx \frac{\delta P}{E_{ge}} \left(\Delta^2 / P_1 - \Delta_0^{\,2} / P_0 \right)$$

P = environmental param.

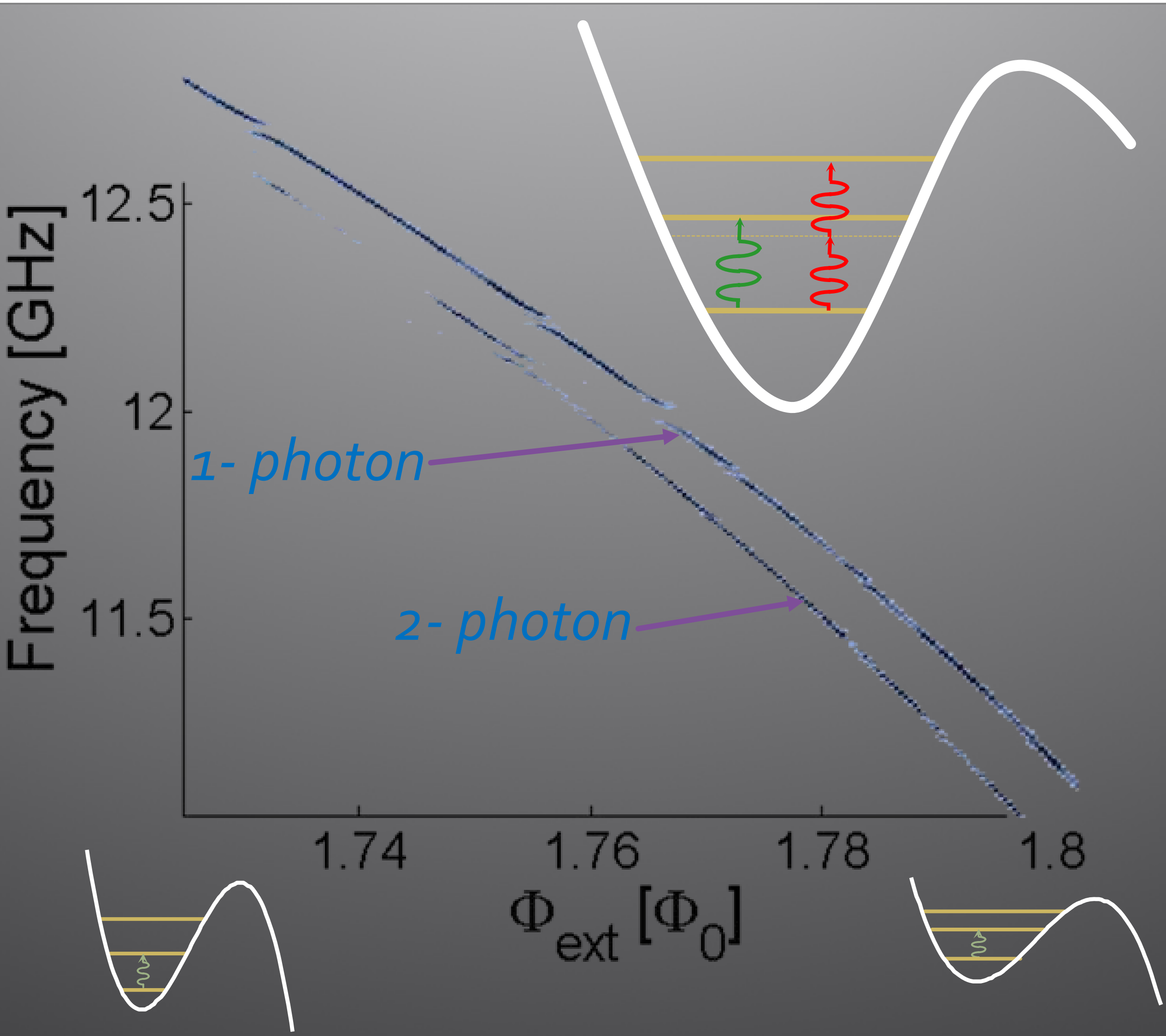




Energy fluctuation vanishes for $\Delta^2 / P_1 \approx \Delta_0^{\,2} / P_0$

This happens at intermediate couplings since $\Delta_0 \propto S$

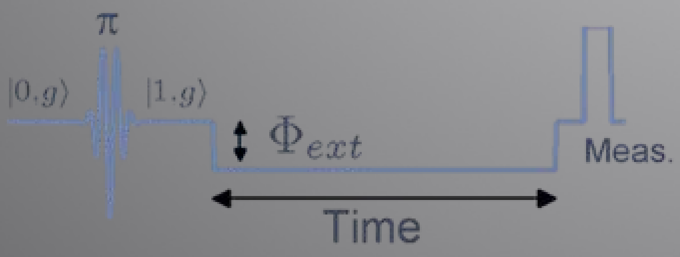
Two-level spectroscopy

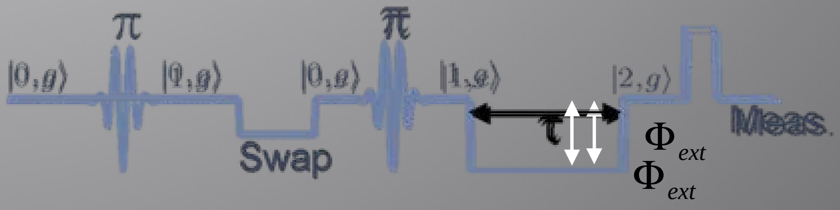


1- photon

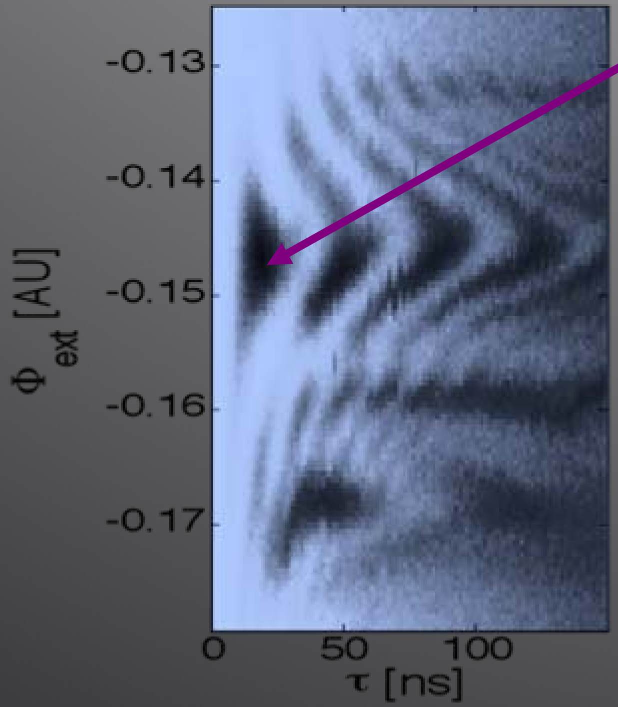
2- photon

Circuit-TLS logic



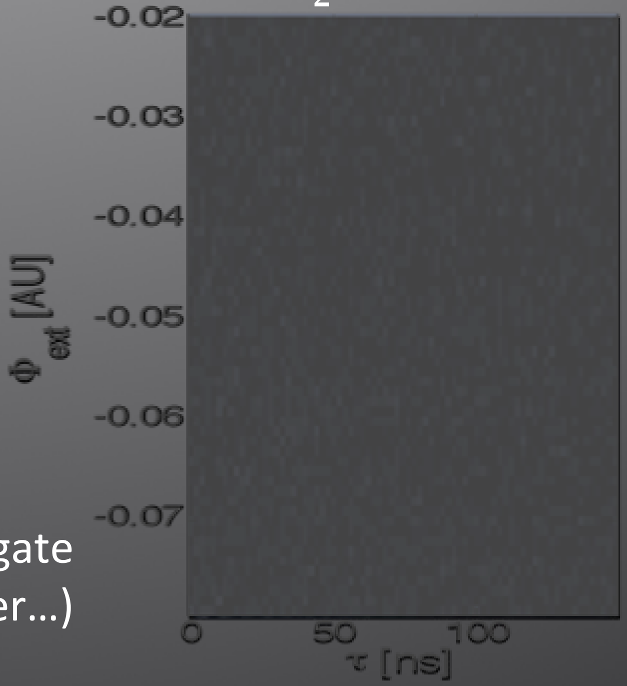


P_1 = colorscale



Qubit excitation fully Swapped into the TLS

P_2 = colorscale



Qutrit-TLS gate

(oscillates times $\sqrt{2}$ faster…)

Controlled Quantum memory

Circuit	TLS	State after gate
|0>	|0>	|0,0>
|1>	|1>	|1,1>
|1>	|0>	|0,1>
|1>	|1>	|2,0>

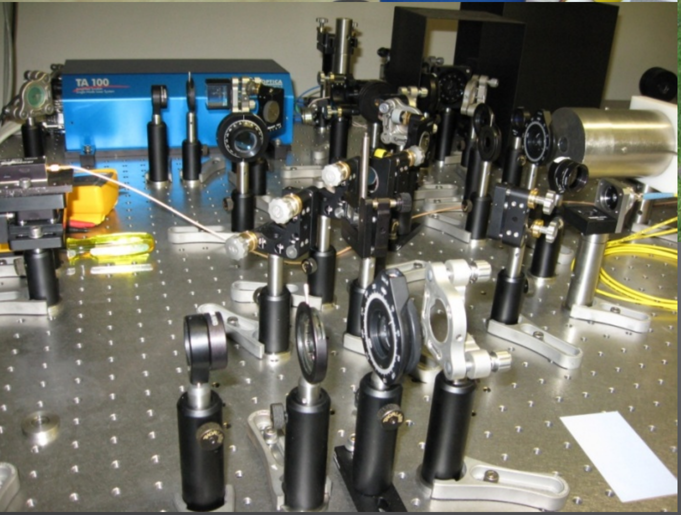
Only if the circuit contains an excitation, the state of the system will change:

- If the memory (TLS) is cleared, the gate will load it (register data)
- if the memory is not cleared, the gate will load the circuit (memory readout)

Conclusion

- We demonstrated how the phase circuit (a macroscopic object) can be used as a probe for studying microscopic systems – an impedance transformer
- We utilized the controlled interaction between these systems to perform a quantum memory logic operation.
- Possible application: engineer long-lived defects into the chip as a designed memory.

Our Lab



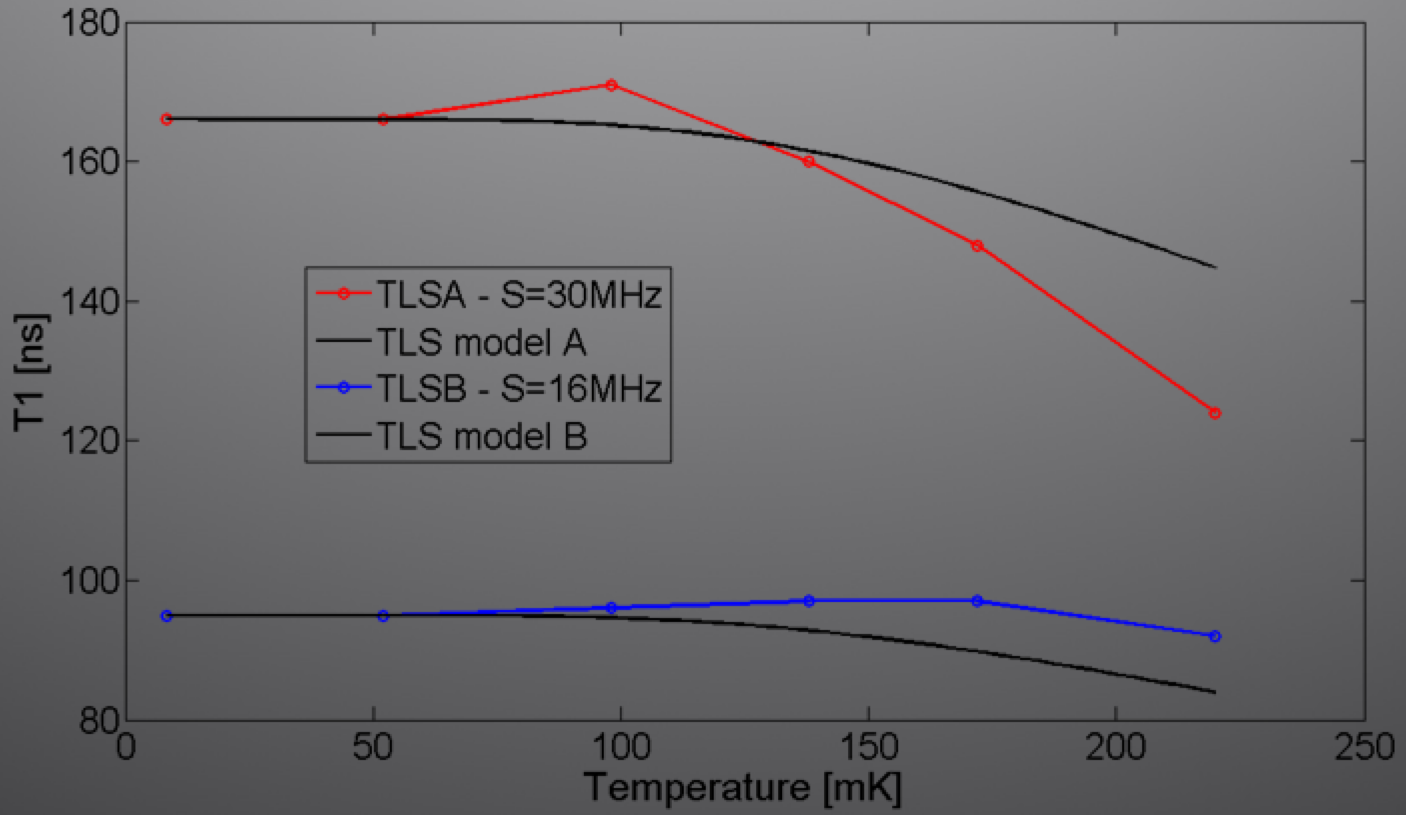
From left to right:

Avraham Klein, Yoni Shalibo, Nadav Katz, Felix Zeides, David Shwa, Ya’ara Rofe, Uri Vool

Temperature dependence

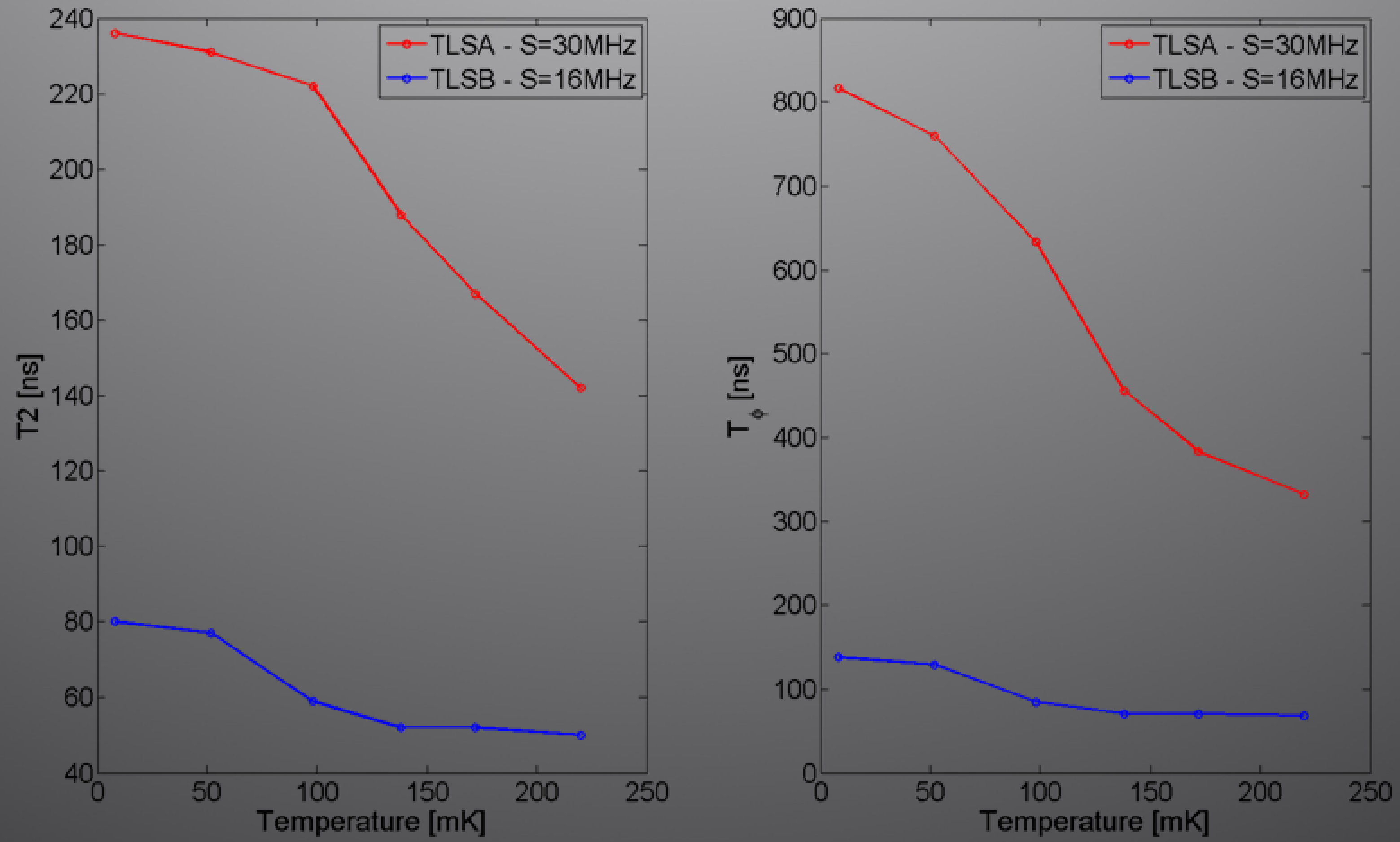
Relaxation time is consistent with the TLS model:

$$T_1^{\text{model}} \propto \tanh(E_{ge} / 2k_B T)$$



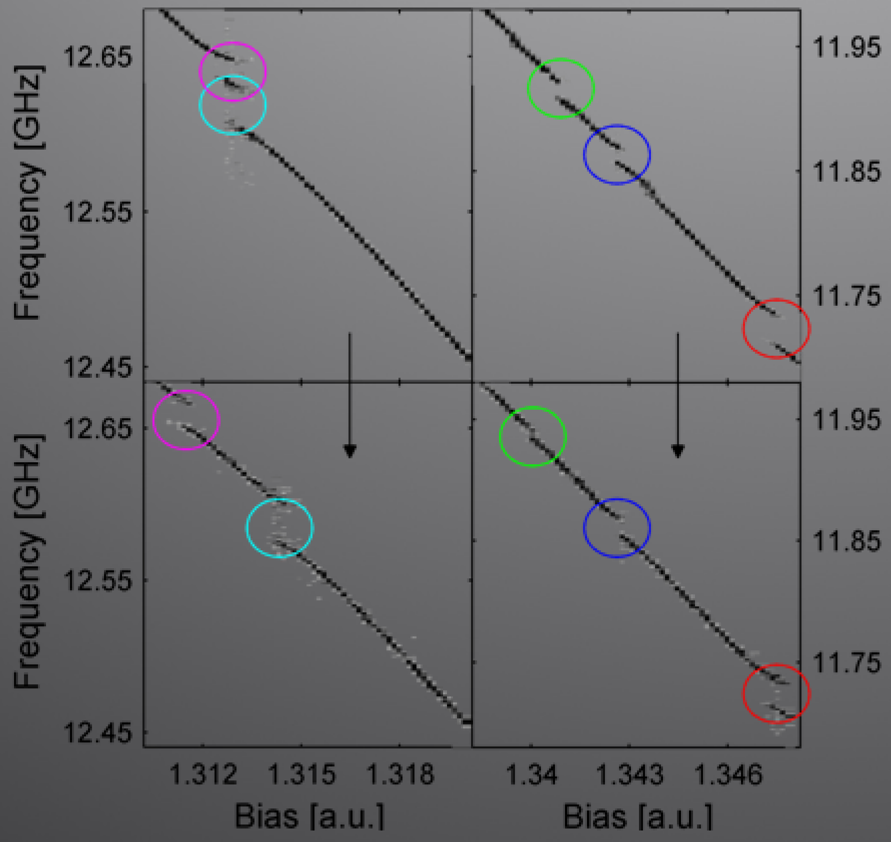
Temperature dependence

Dephasing times are reduced above 50 mK:



Temperature dependence

Spectrum before and after partial warmup to 1.5K (both measurements are taken at T=10 mK):



Some of the TLSs are not fully reset after warmup.