Simulating interactions between a qubit and a resonant two-level system bath

Yaniv J. Rosen, Yujin Cho, Dipti Jasrasaria, Keith G. Ray, Daniel M. Tennant, Vincenzo Lordi, and Jonathan L DuBois

LLNL-PRES-2000031

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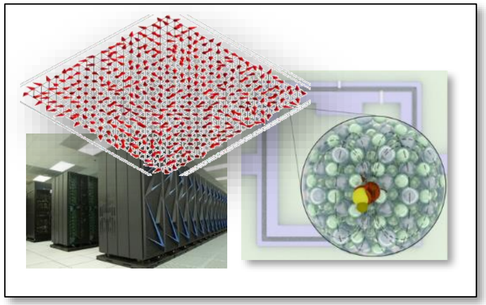
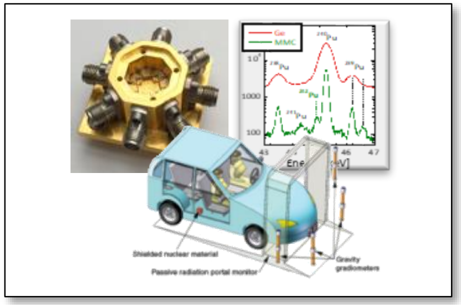
Lawrence Livermore National Laboratory

Testbed activities interface with a broad range of facilities and expertise at the lab

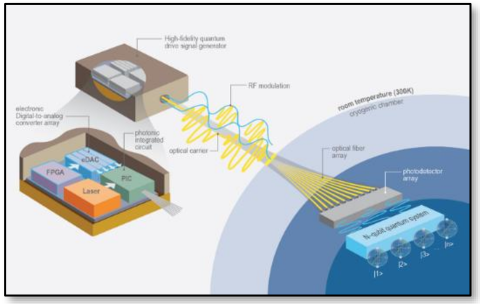


HPC & Computational Materials Science

Design, fabrication, characterization and control of superconducting quantum systems



Sensing & Detection



Photon Science & Systems Engineering

Advanced Manufacturing Lab

Center for Micro- and Nanotechnology

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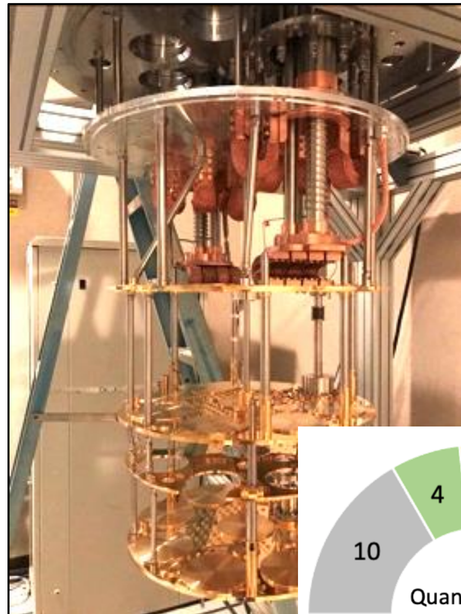
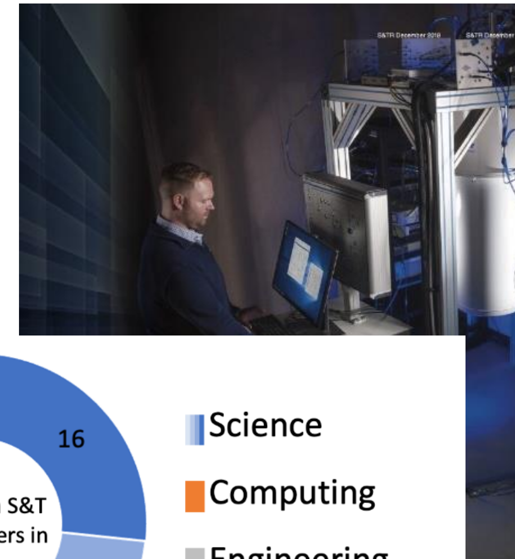
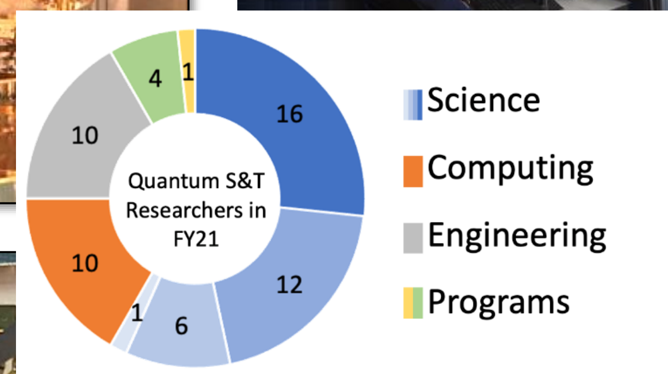
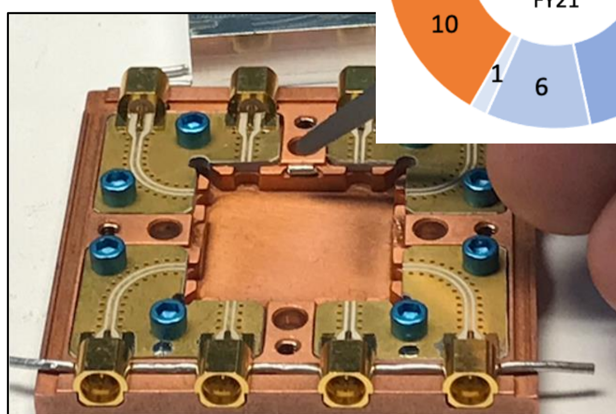
Quantum Design and Integration Testbed

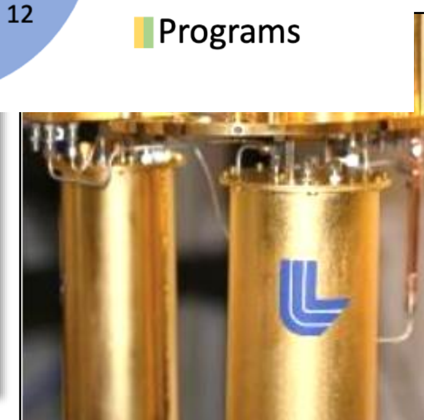
- Provides whitebox access to
  - Quantum processing platforms with state-of-the-art performance
  - Quantum device and materials characterization
- Supports ~15 teams and ~80 collaborators
  - DOE-SC, and NNSA sponsored projects including
    - NISQ Algorithm research and hardware codesign
    - Identification & amelioration of materials source of decoherence.
    - Quantum / classical control integration
    - Quantum optimal control and characterization











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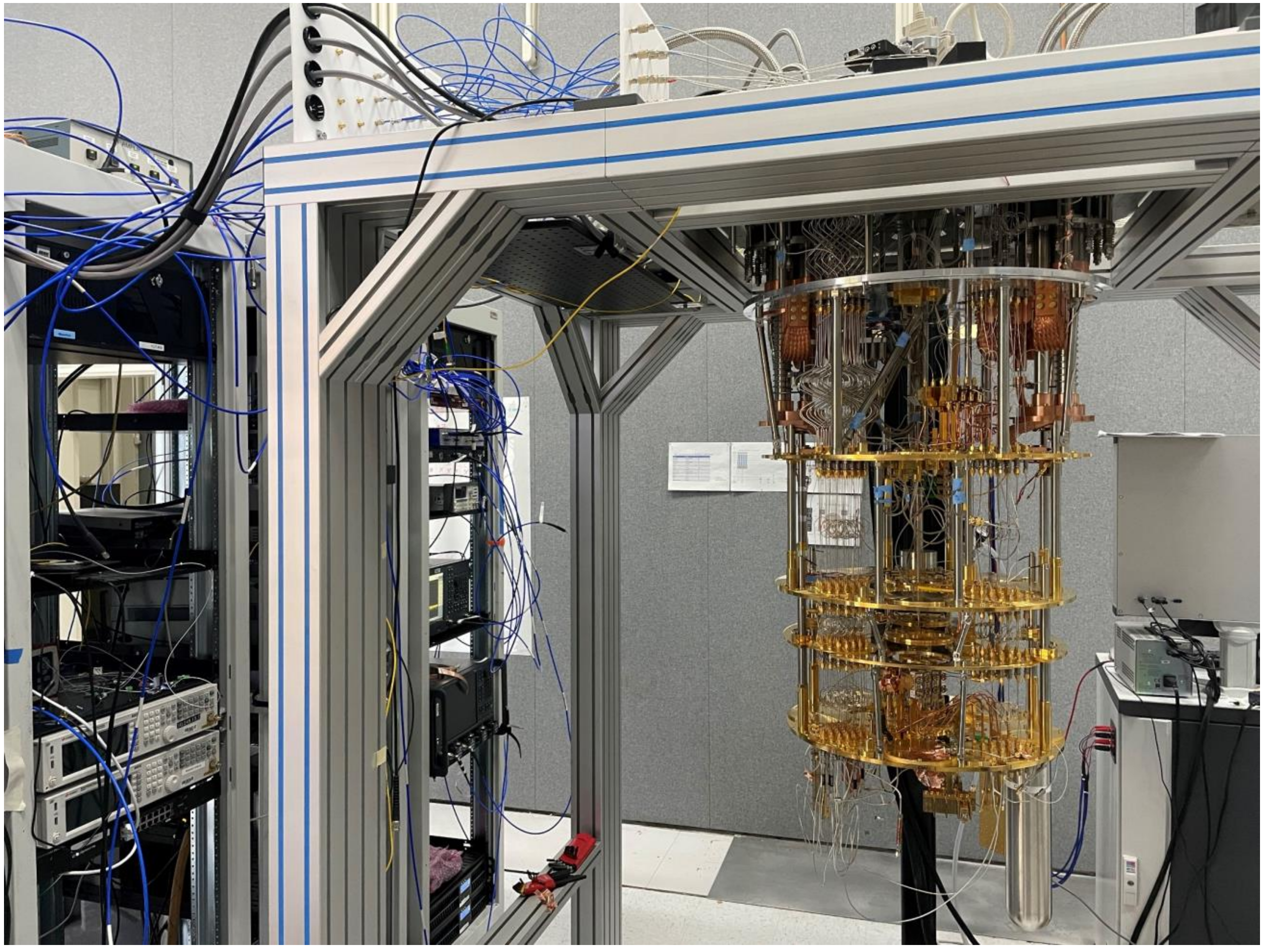
Measurement stack at LLNL

- Co-design at LLNL
  - Algorithm requirements
  - Hardware capabilities
  - Algorithm informed hardware



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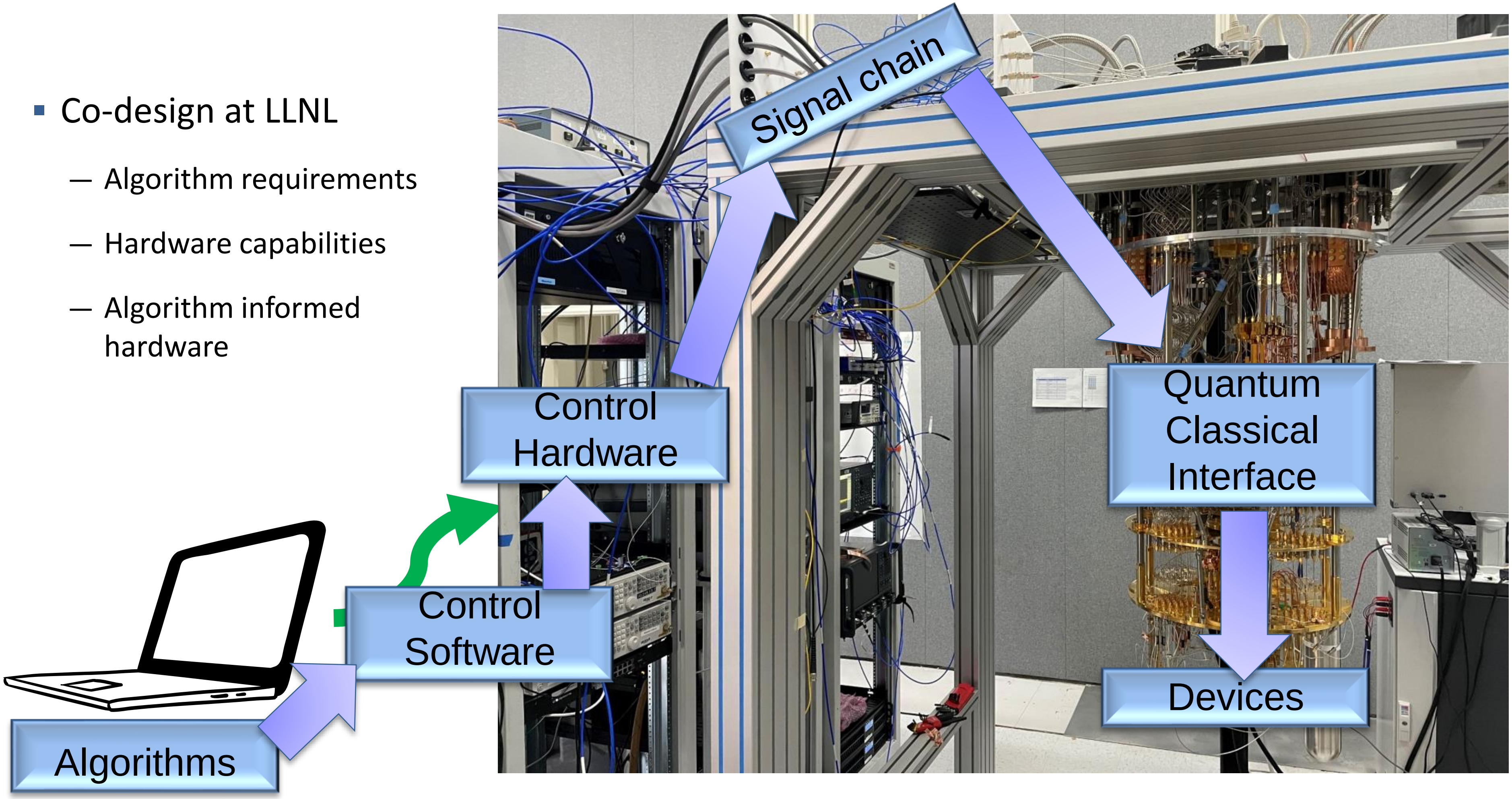

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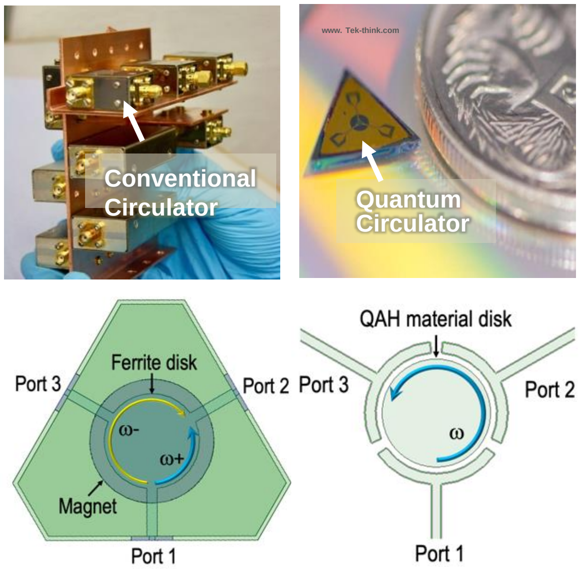
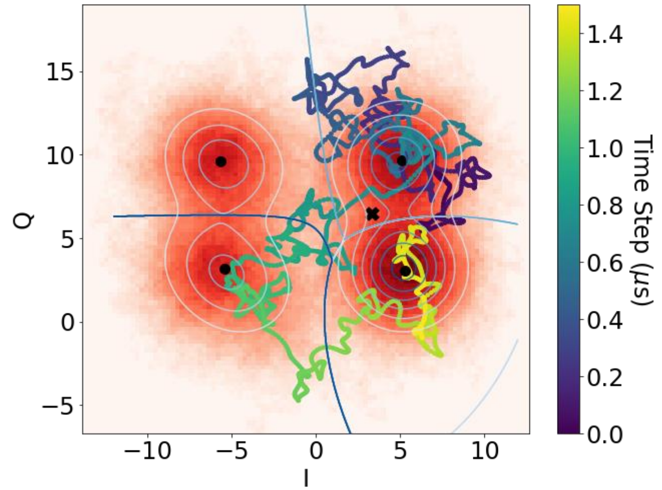
Hardware expertise for unique quantum application requirements

- On-chip topological-based non-reciprocal devices meet scalability requirements
- Increasing readout fidelity while decrease calibration time using Hidden Markov Models
- Developing RF photonic control interface
- Quantum sensing to enable large dynamic range computing gates

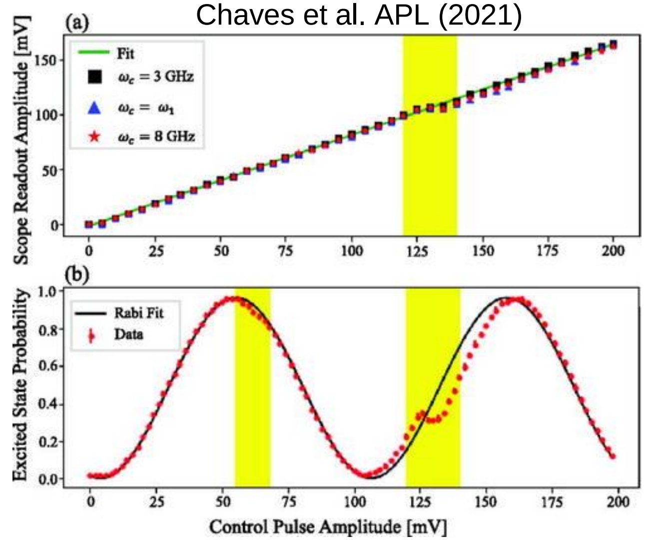
Martinez et al. PRR (2024)

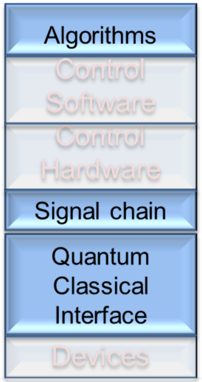


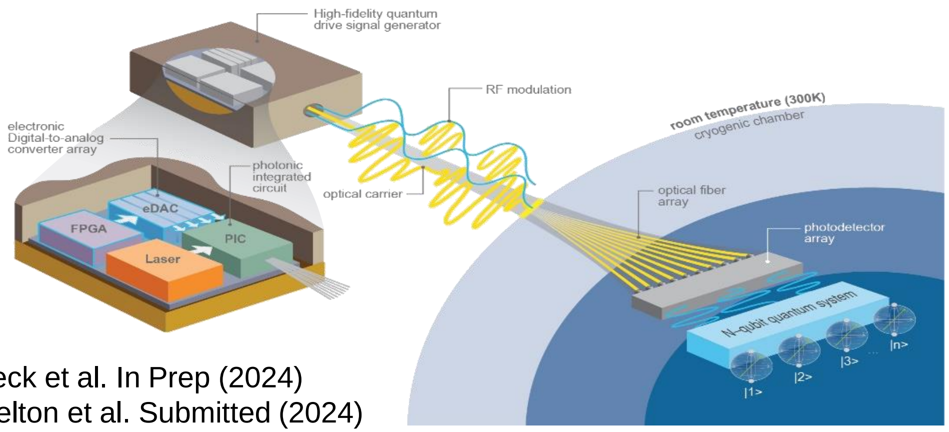
Martinez et al. PRA (2020)



Chaves et al. APL (2021)







Beck et al. In Prep (2024)
Melton et al. Submitted (2024)

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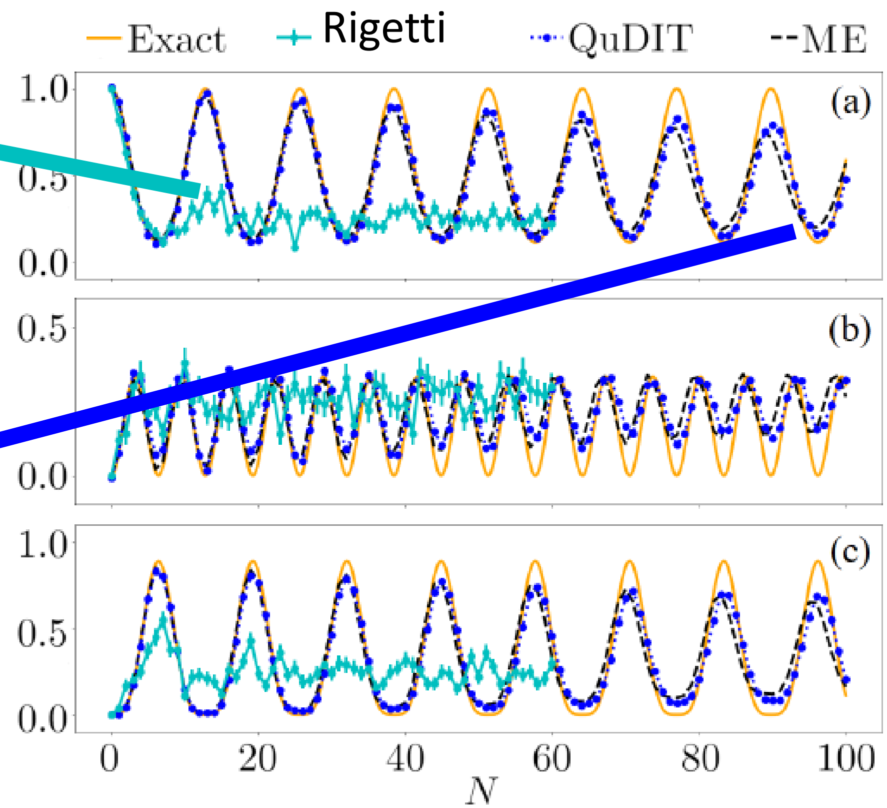
Whitebox access is a minimum requirement for codesign

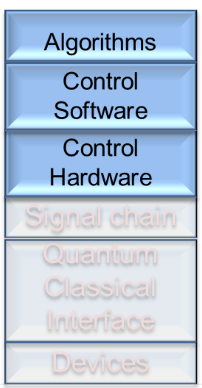
- Commercial setups
  - Gates designed for Universal quantum computation
    - Fully error corrected
    - Millions of qubits available
  - Not optimized for quantum simulation

- Conventional hardware installed in QuDIT with LLNL firmware
  - Optimized gates far superior to universal gate set.

Quantum computation of three-wave interactions with engineered cubic couplings



Shi et al. PRA (2021)



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Relaxation is due to two-level systems

https://quantumcomputingreport.com/scorecards/qubit-quality/

		T1 (µsec)		
Computer	Qubit Count	Min	Max	Ave
IBM Q System One	20	38.2	132.9	73.9
Rigetti 19Q Acorn	19	8.2	31	20.3

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- Large scatter in relaxation times

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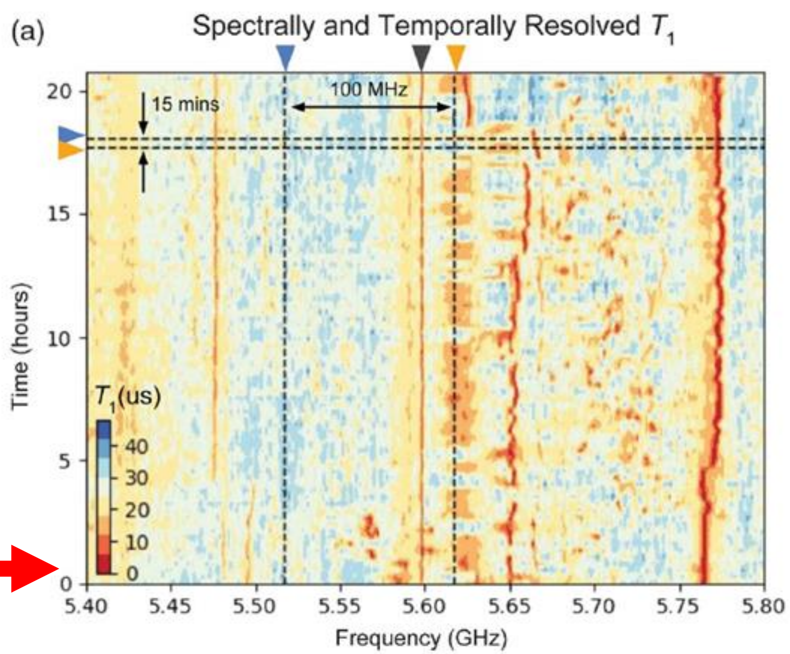
- Large scatter in relaxation times
- Defect drift over time
- Large unusable bandwidth



Google: PRL 121, 090502 (2018)

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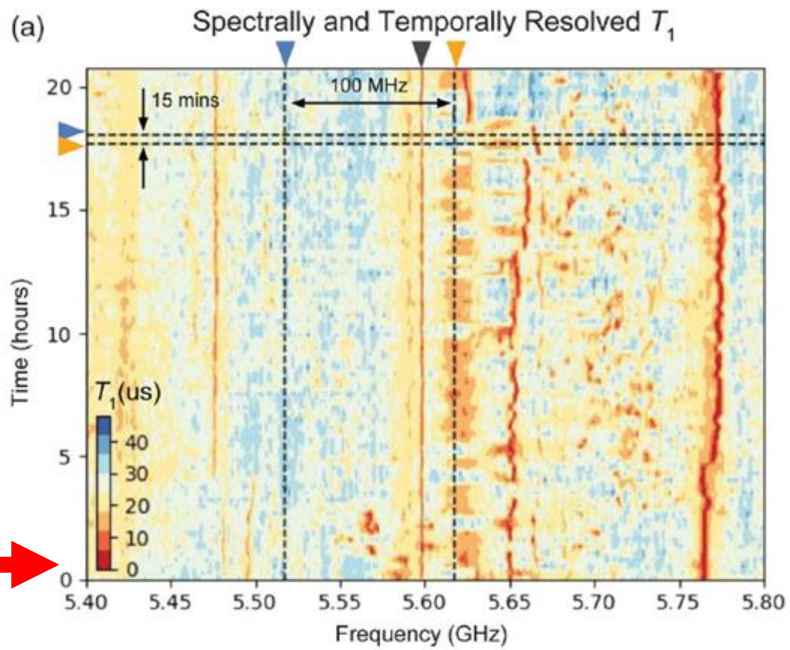
- Large scatter in relaxation times
- Defect drift over time
- Large unusable bandwidth
- Explained by standard tunneling system model?
  - Continuum of states
  - Unknown e-field coupling
  - Unknown strain-field coupling
  - Random fluctuations cause dropouts



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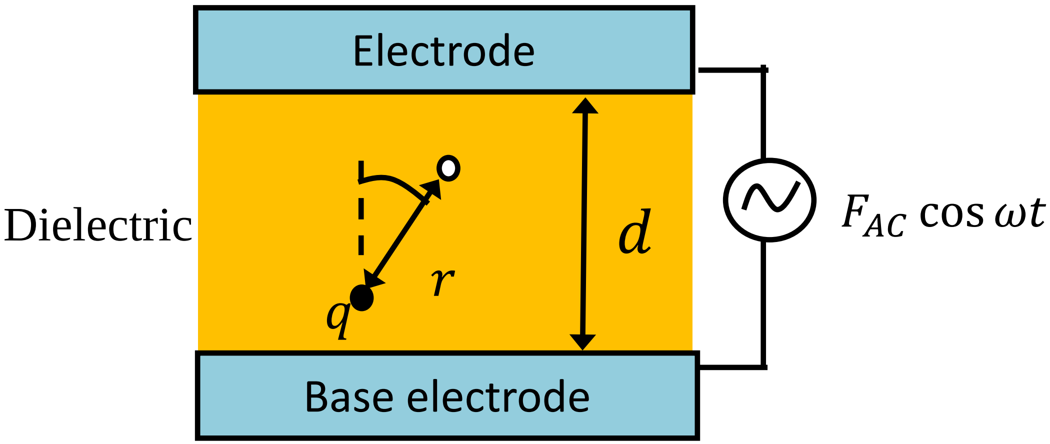
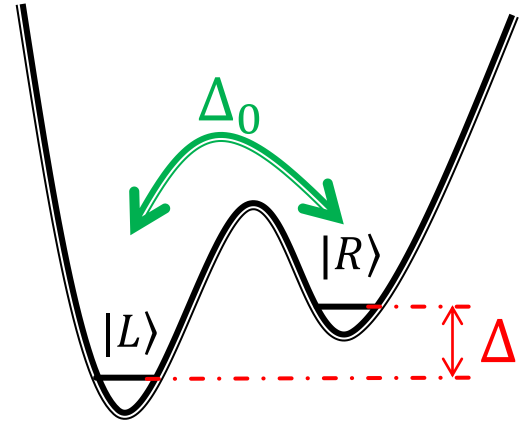
The two-level system model

Defect in capacitor



TLS Potential Energy



TLS Hamiltonian:

$$H = \frac{1}{2}\begin{bmatrix} \Delta & \Delta_0 \\ \Delta_0 & -\Delta \end{bmatrix}$$

$$\mathcal{E}_{TLS} = \sqrt{\Delta'^2 + {\Delta_0}^2}$$

W. A. Phillips, Reports on Progress in Physics 50, 1657 (1999)
P. W. Anderson et. al, *Philosophical Magazine*, *25*, 1 (1972)

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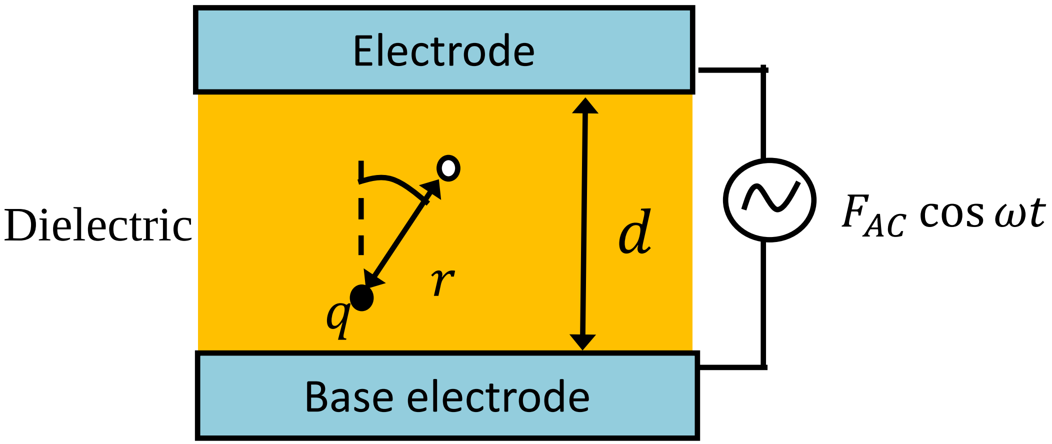

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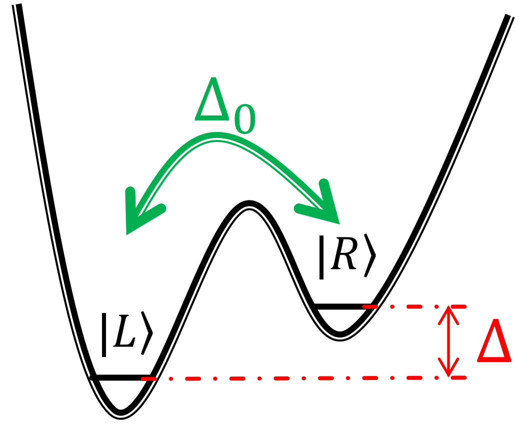

TLS Hamiltonian:

$$H = \frac{1}{2}\begin{bmatrix} \Delta & \Delta_0 \\ \Delta_0 & -\Delta \end{bmatrix} + H_{int} \qquad \mathcal{E}_{TLS} = \sqrt{\Delta'^2 + {\Delta_0}^2}$$

$$H_{int} = \left| \frac{\Delta}{E}\sigma_z + \frac{\Delta_0}{E}\sigma_x \right| \vec{p} \cdot \vec{F} + \left| \frac{\Delta}{E}\sigma_z + \frac{\Delta_0}{E}\sigma_x \right| \gamma e$$

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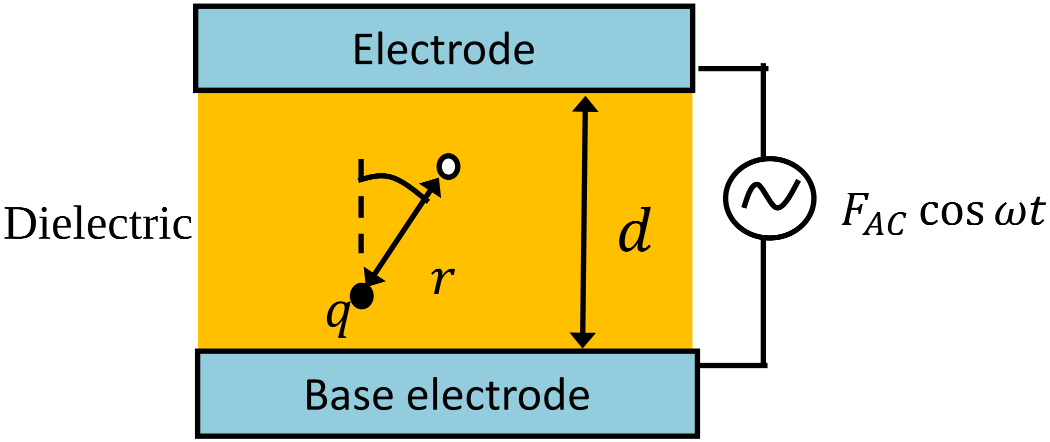

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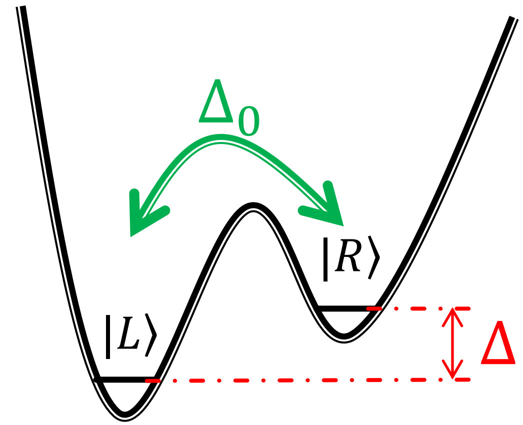

TLS Hamiltonian:

$$H = \frac{1}{2}\begin{bmatrix} \Delta & \Delta_0 \\ \Delta_0 & -\Delta \end{bmatrix} \quad \ldots_{LS} = \sqrt{\ldots}$$

Electric field coupling

Strain field coupling

$$H_{int} = \left|\frac{\Delta}{E}\sigma_z + \frac{\Delta_0}{E}\sigma_x\right| \vec{p} \cdot \vec{F} + \left|\frac{\Delta}{E}\sigma_z + \frac{\Delta_0}{E}\sigma_x\right| \gamma e$$

T_1 relaxation:

- TLS excited by a qubit photon
- TLS relaxes by emitting a phonon.

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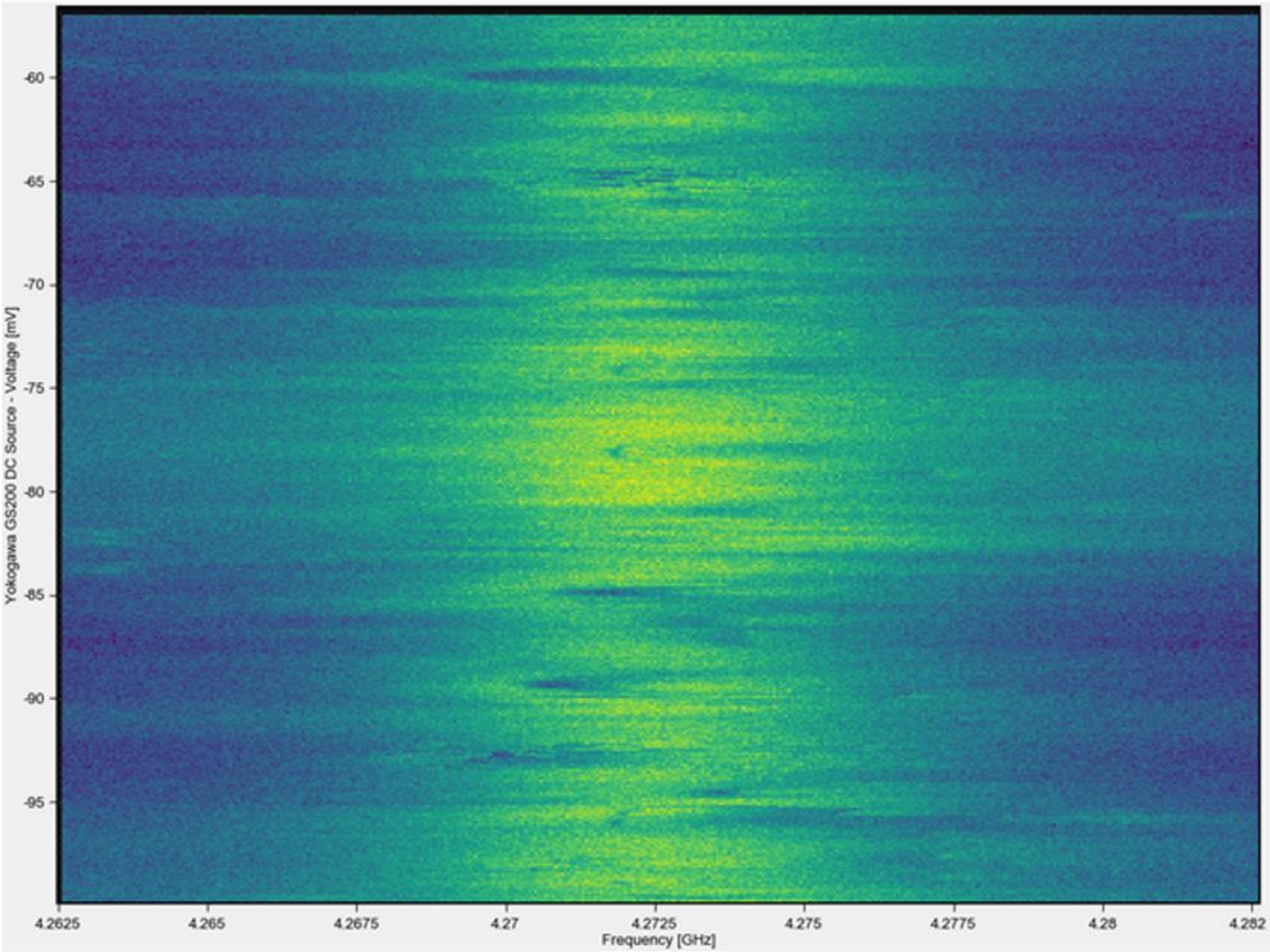
Spectroscopically imaging TLS using low capacitor-volume resonators

Gate Voltage (mV)



Frequency (GHz)

Colorbar:
$|S_{21}|$ Transmission

$$\mathcal{E}_{TLS} = \sqrt{\Delta'^2 + {\Delta_0}^2}$$

$$\Delta' = \Delta + 2\vec{p} \cdot \vec{E}$$

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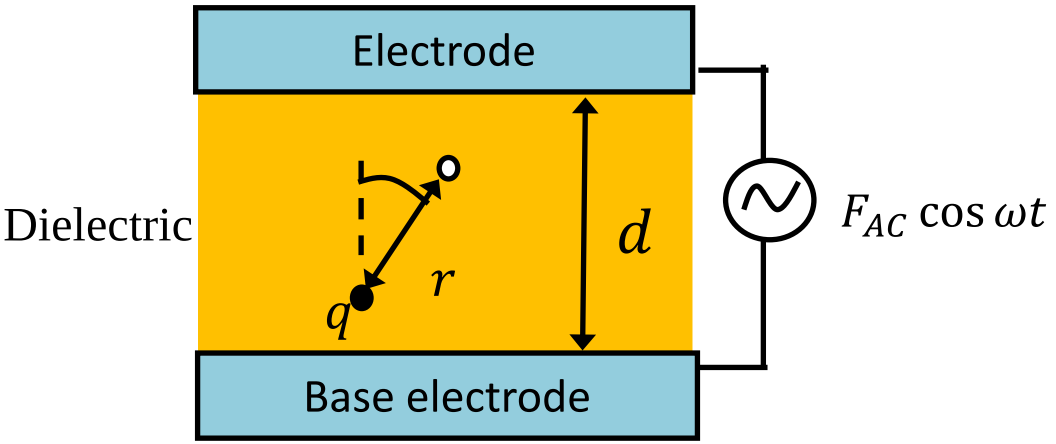

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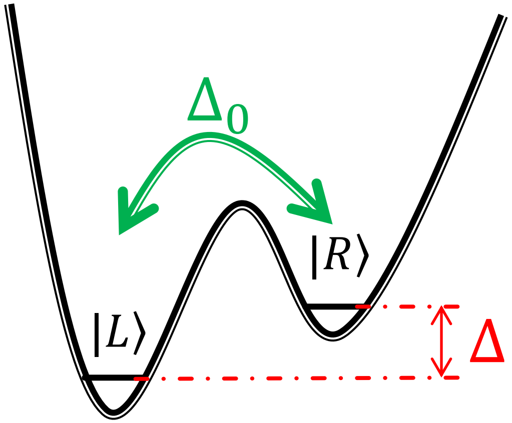

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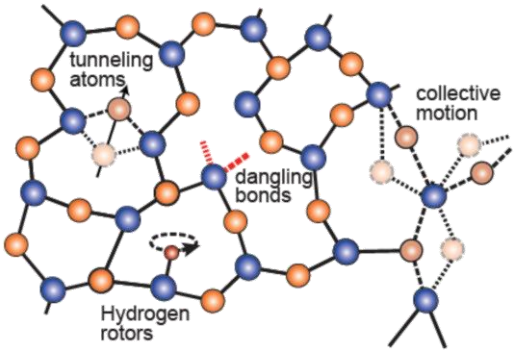
TLS locations

Rep. Prog. Phys. **82**, 124501 (2019).

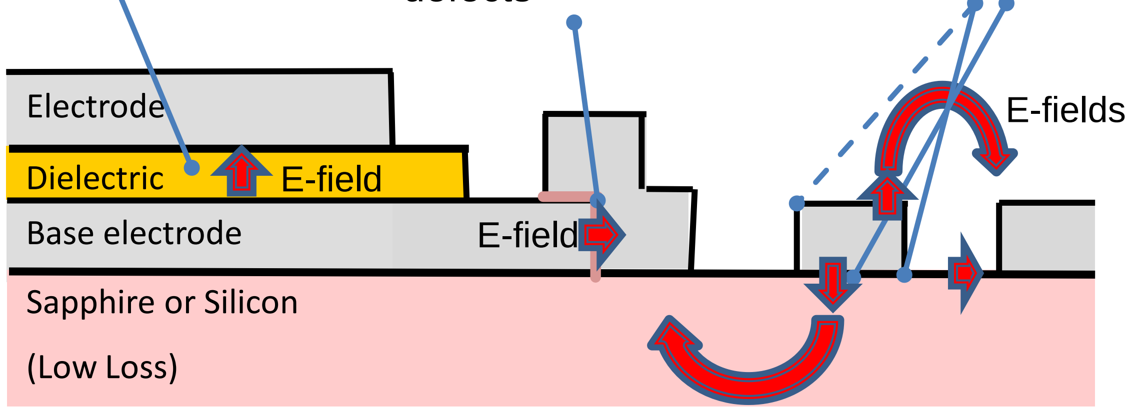


Chemical Residues And Particles Couple to E-Fields

Imperfect Dielectrics: microstrips, capacitors, and crossovers

a-Al_2O_3 Josephson Junction Barrier: possibly OH^- defects

Surface Oxides: e.g., native oxide on the surfaces of SCs and substrates



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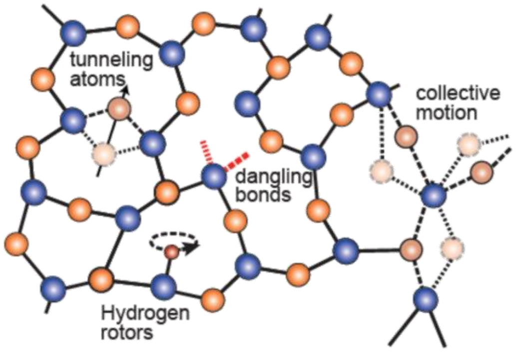

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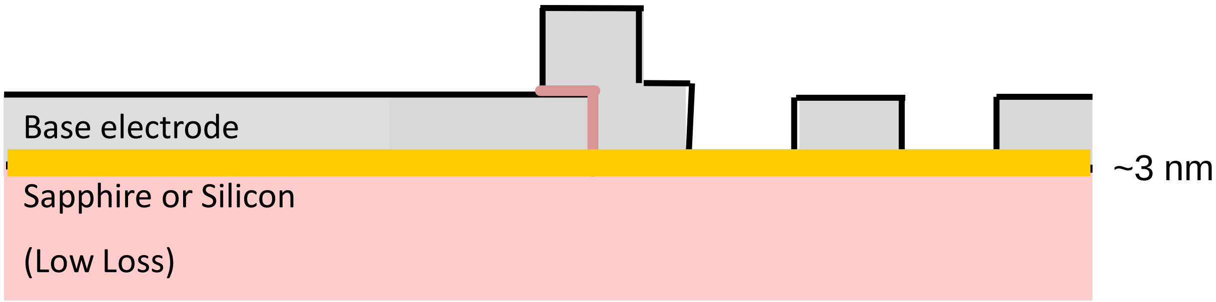

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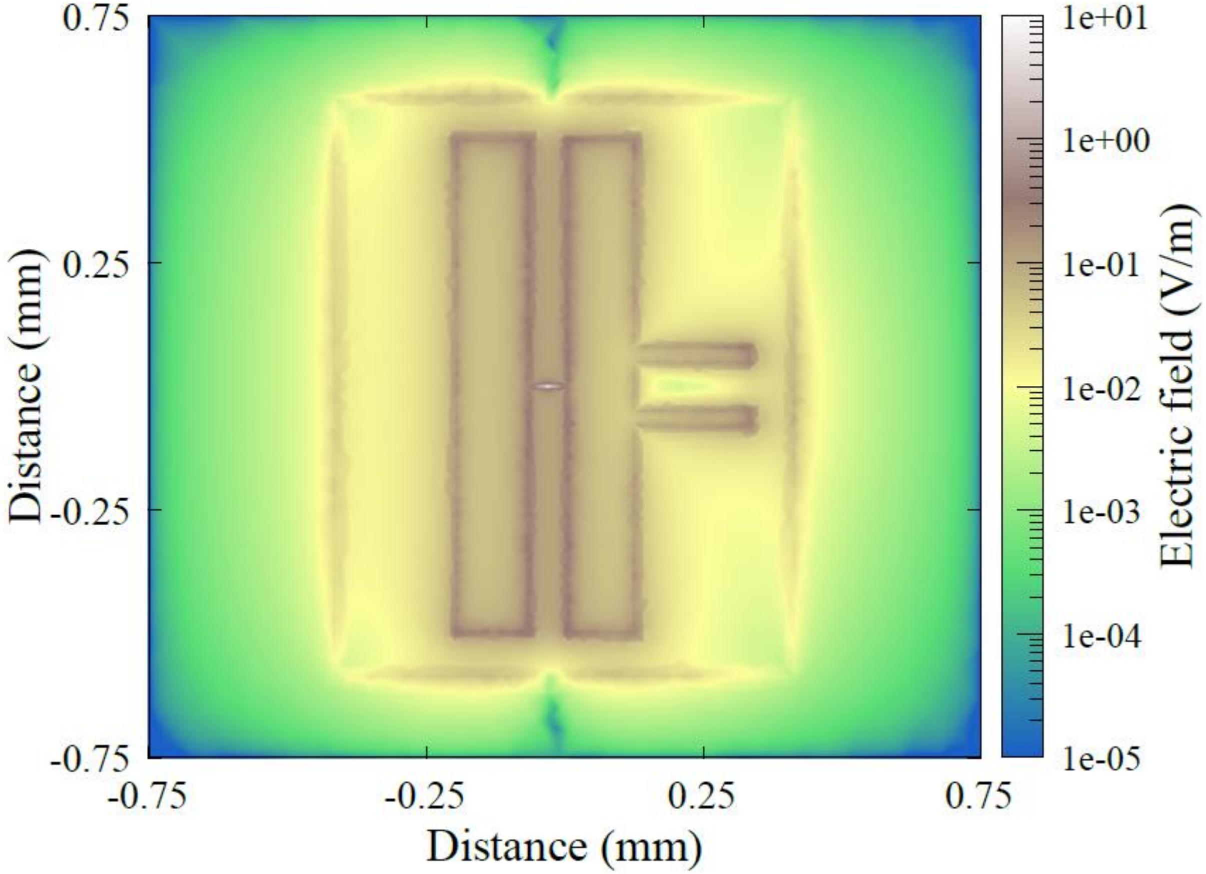
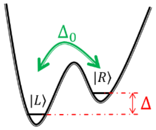
Step 1: Model electric fields of a device

TLS ~$0.5/\mu m^2$





Coupling:

$$\Omega_i = \frac{\vec{p} \cdot \vec{E}_i}{\hbar} \frac{\Delta_0^i}{Energy}$$

arXiv:2211.08535

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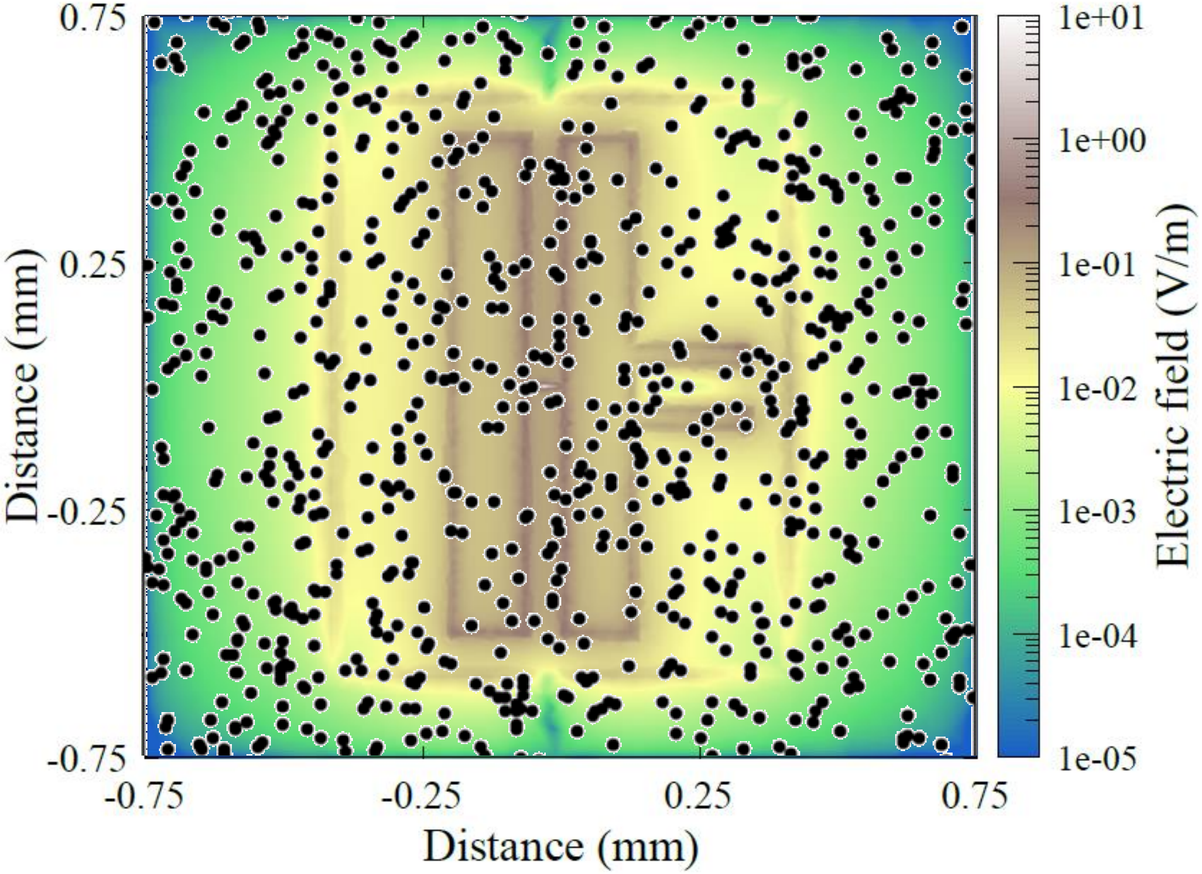
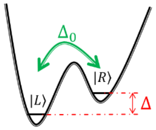
Step 2: Place one million TLS

TLS ~$0.5/\mu m^2$





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Number of TLS

$$N = \int \int \frac{P_0 V}{\Delta_0} d\Delta_0 \, d\Delta$$

arXiv:2211.08535

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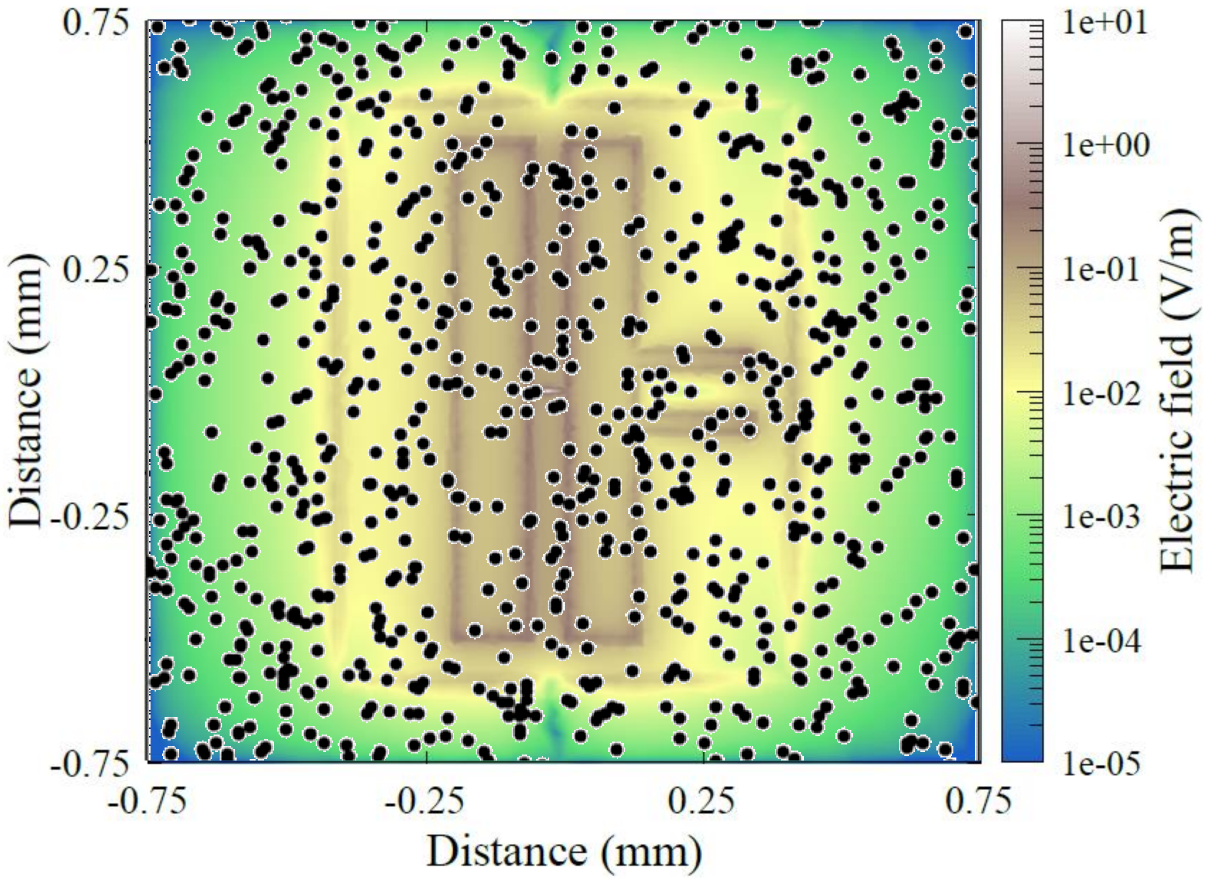
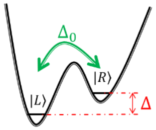
Step 2: Place one million TLS -> select 200 with highest couple

TLS $\sim 0.5/\mu m^2$





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Number of TLS

$$N = \int \int \frac{P_0 V}{\Delta_0} d\Delta_0 \, d\Delta$$
$$= \int_d^{\pi/2} \int_{\hbar\omega-\delta}^{\hbar\omega+\delta} \frac{P_0 V}{\sin\theta} dE \, d\theta$$

$P_0 = 10^{44}/\mathrm{Jm}^3$

$V = 3nm \times (1.5mm)^2$

$\min\left(\frac{\Delta_0}{E}\right) \cong d \cong 10^{-50}$

$\delta = h \times 10\ MHz$

$\omega = 2\pi \times 5\ GHz$

arXiv:2211.08535

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Step 3: Simulate 200 TLS using full Lindblad

Full Lindblad Simulation

- Discard Hilbert space with > 1 photon
  - initialized qubit with 1 photon
  - Only include loss due to TLS-phonon coupling
- Simulation uses 200 TLSs
  - $\Omega_{TLSi} = \frac{\vec{p}\cdot\vec{F}_i}{\hbar}\frac{\Delta_0^i}{\hbar\omega}$, where $|\vec{p}|$ is adjustable
  - $T_{1,TLSi} = \frac{T_{1,min}}{\left(\Delta_0^i\right)^2}$, where $T_{1,min}$ is adjustable

$|g>$ $|q>$ $|TLS1>$ $|TLS2>$ $|TLSN>$

$$\hat{H} = \hbar \begin{pmatrix} 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & \omega_q & \Omega_{TLS1} & \Omega_{TLS2} & \dots & \Omega_{TLSN} \\ 0 & \Omega_{TLS1} & \omega_{TLS1} & 0 & \dots & 0 \\ 0 & \Omega_{TLS2} & 0 & \omega_{TLS2} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \Omega_{TLSN} & 0 & 0 & \dots & \omega_{TLSN} \end{pmatrix}$$

$$L_i = \begin{pmatrix} 0 & 0 & \dots & 1/\sqrt{T_{1,TLSi}} & \dots & 0 \\ 0 & 0 & \dots & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 & \dots & 0 \end{pmatrix}$$

arXiv:2211.08535

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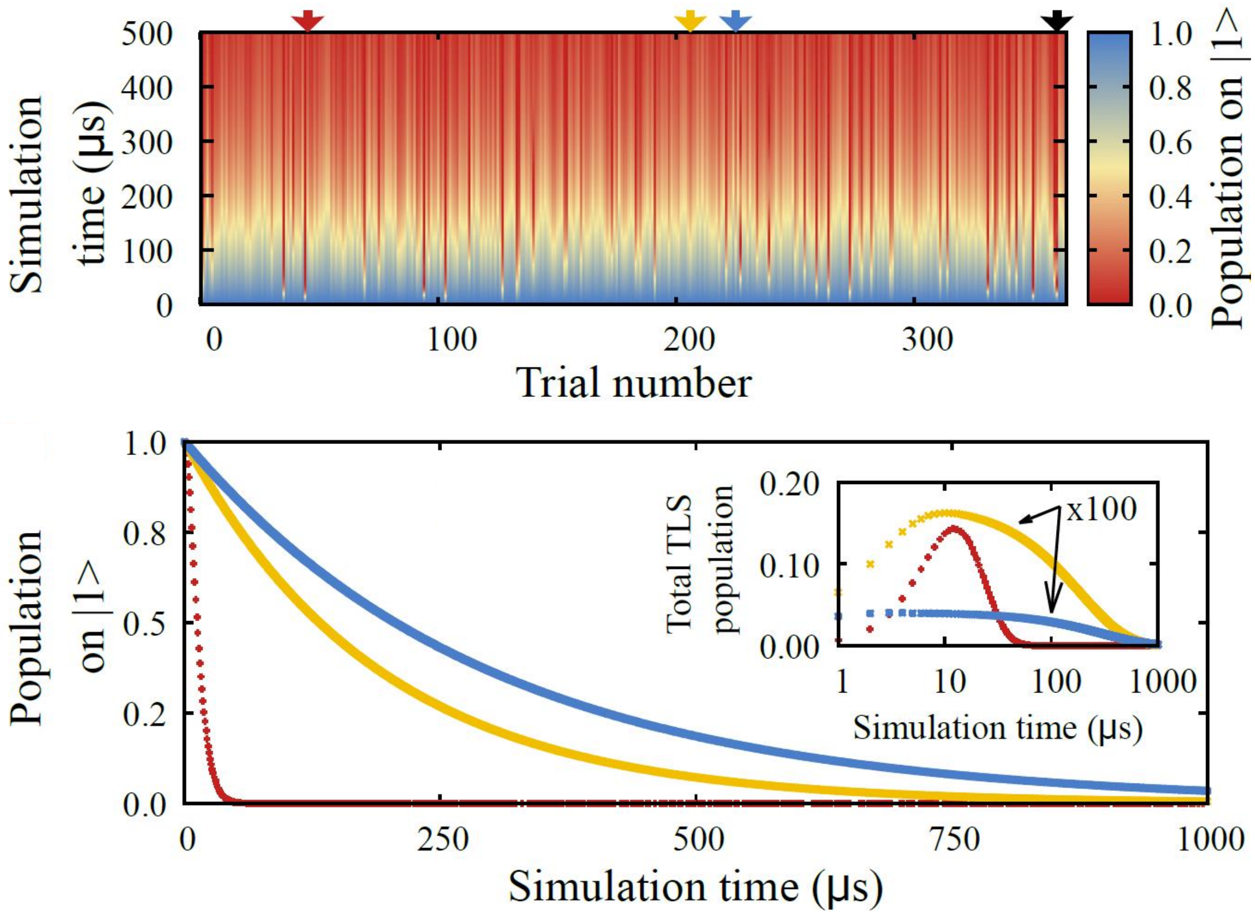
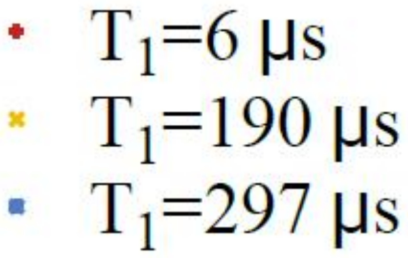
High T_1 with occasional dropouts for different TLS configurations



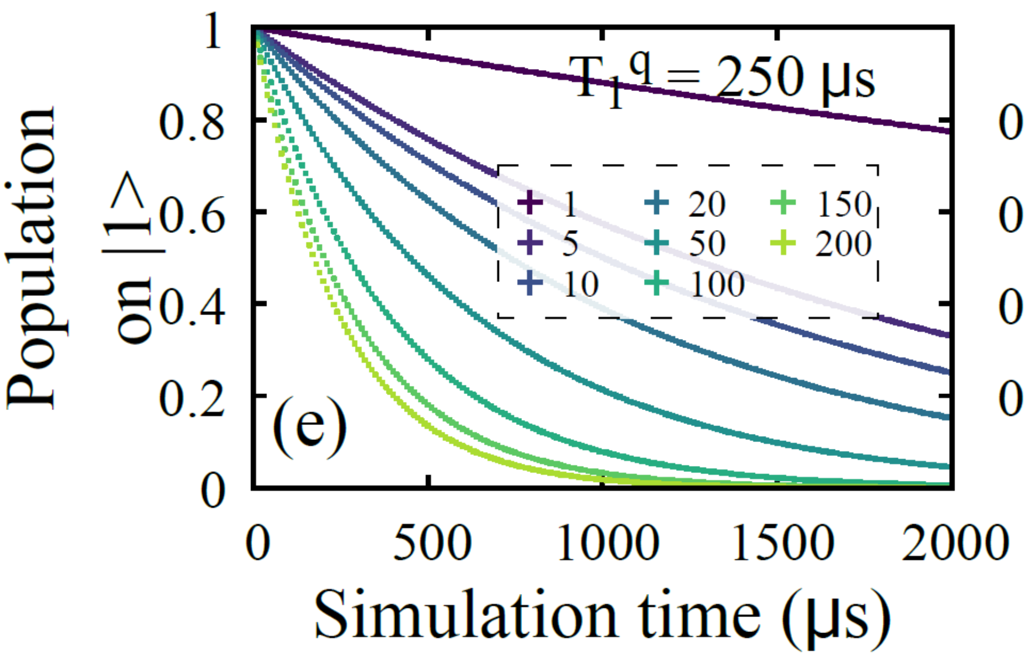


arXiv:2211.08535

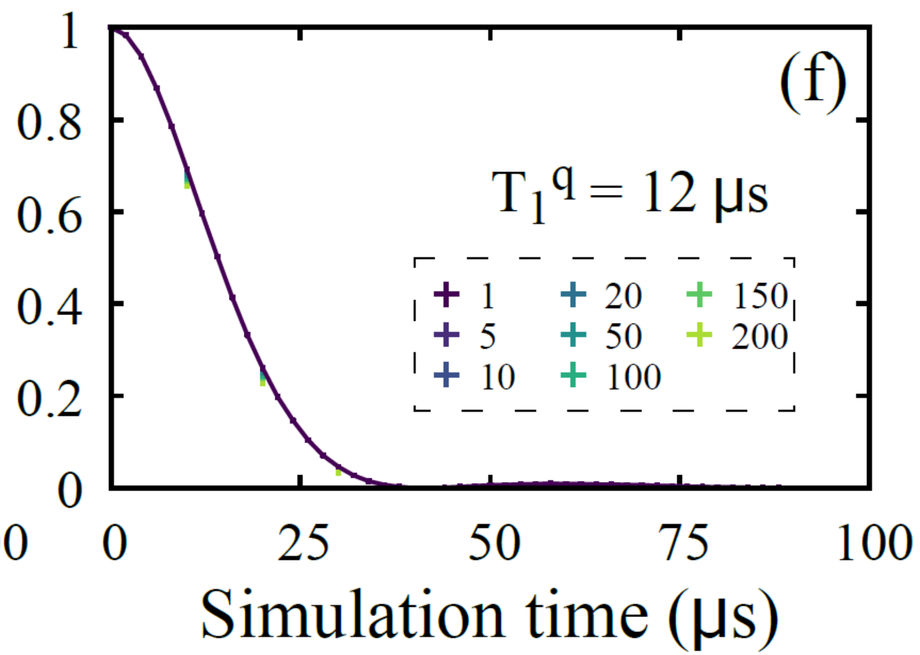
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Qubit dynamics dominated by between 1 and 150 TLS

T_1 average



T_1 Dropout



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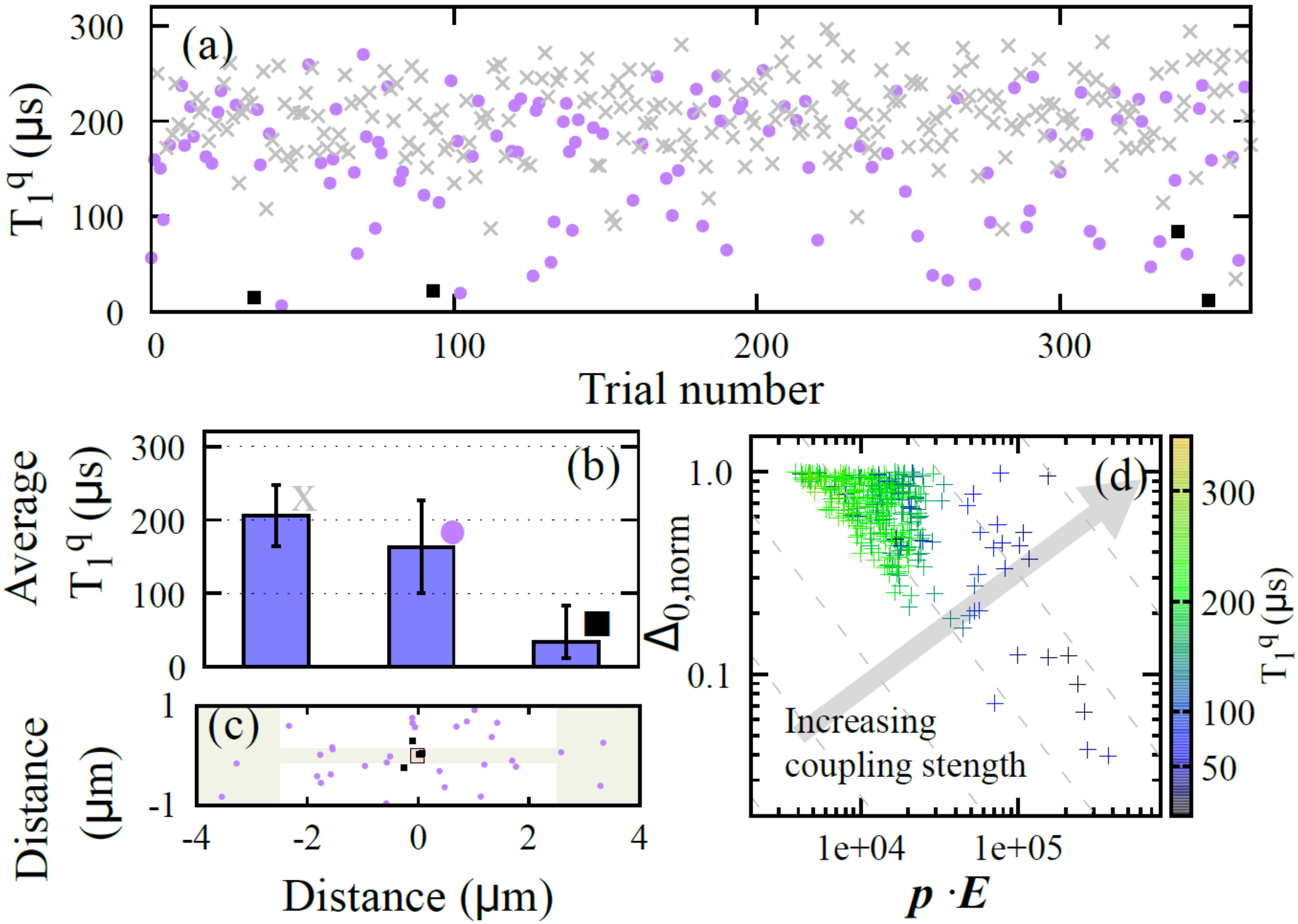
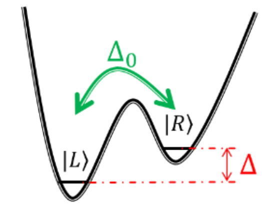
Dropouts dominated by high E-field, *not* coupling strength





Coupling:

$$\Omega_i = \frac{\vec{p} \cdot \vec{E}_i}{\hbar} \frac{\Delta_0^i}{Energy}$$

$$T_1^{TLS} \propto \frac{1}{\Delta_0^2}$$

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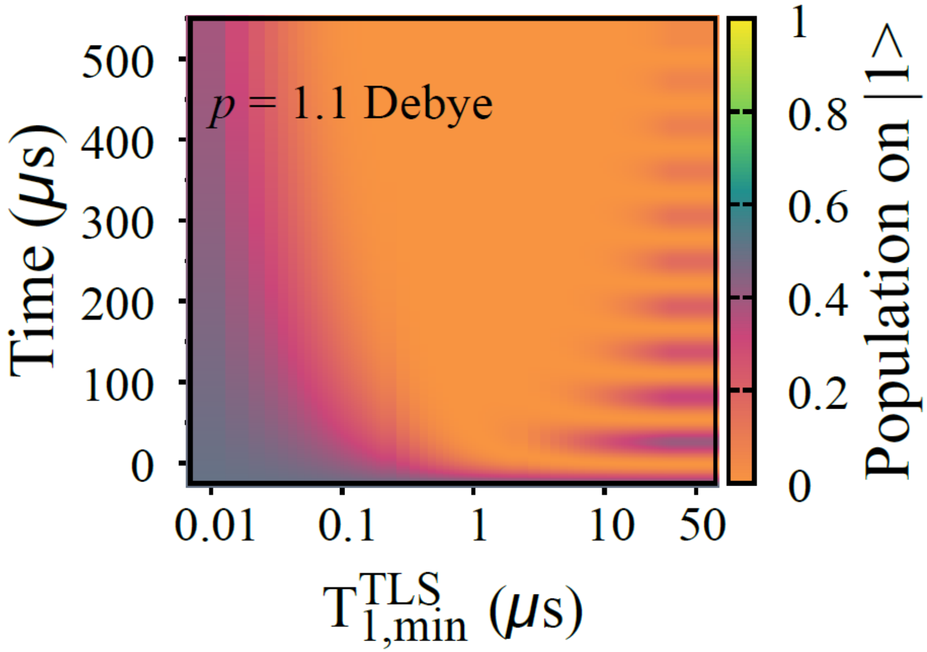
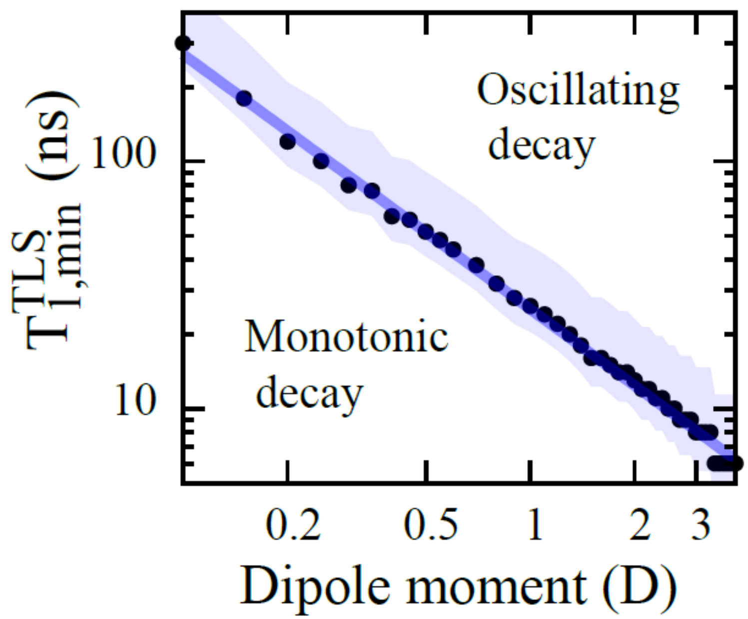
We place limits on TLS T_1 times depending on Dipole moment





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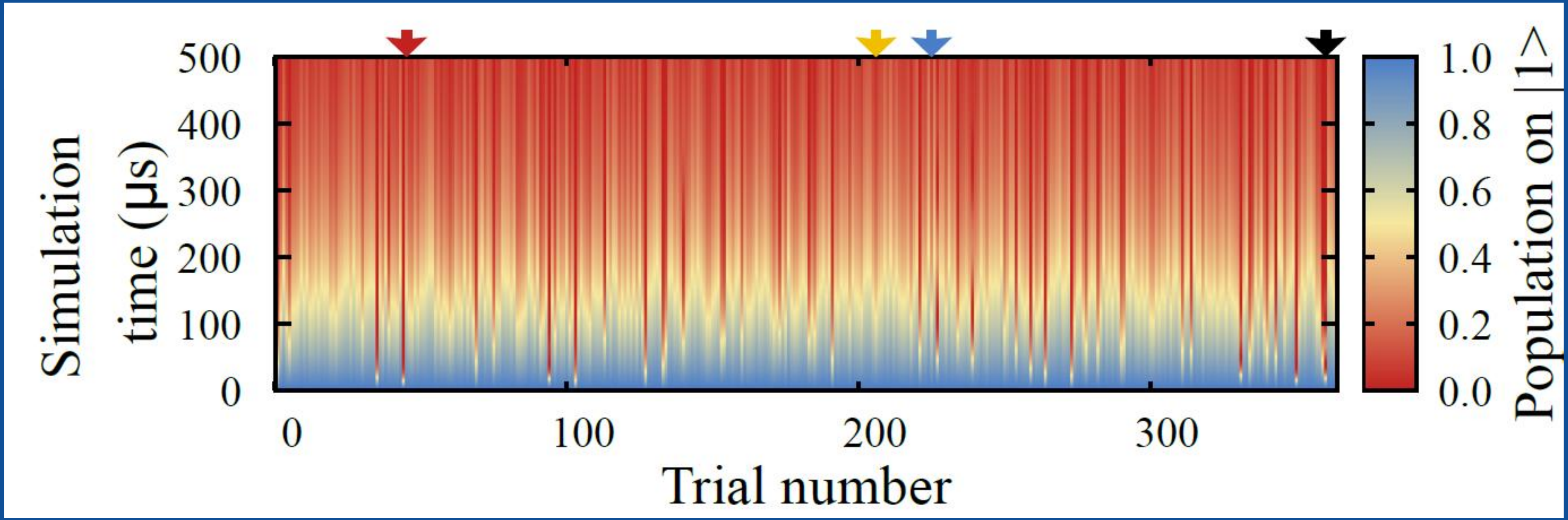

Simulating the standard TLS model:

- Reproduced T_1 dropouts
- Dropout indicator is E-Field, not coupling strength
- Put bounds on dipole moment and $T_{1,min}$

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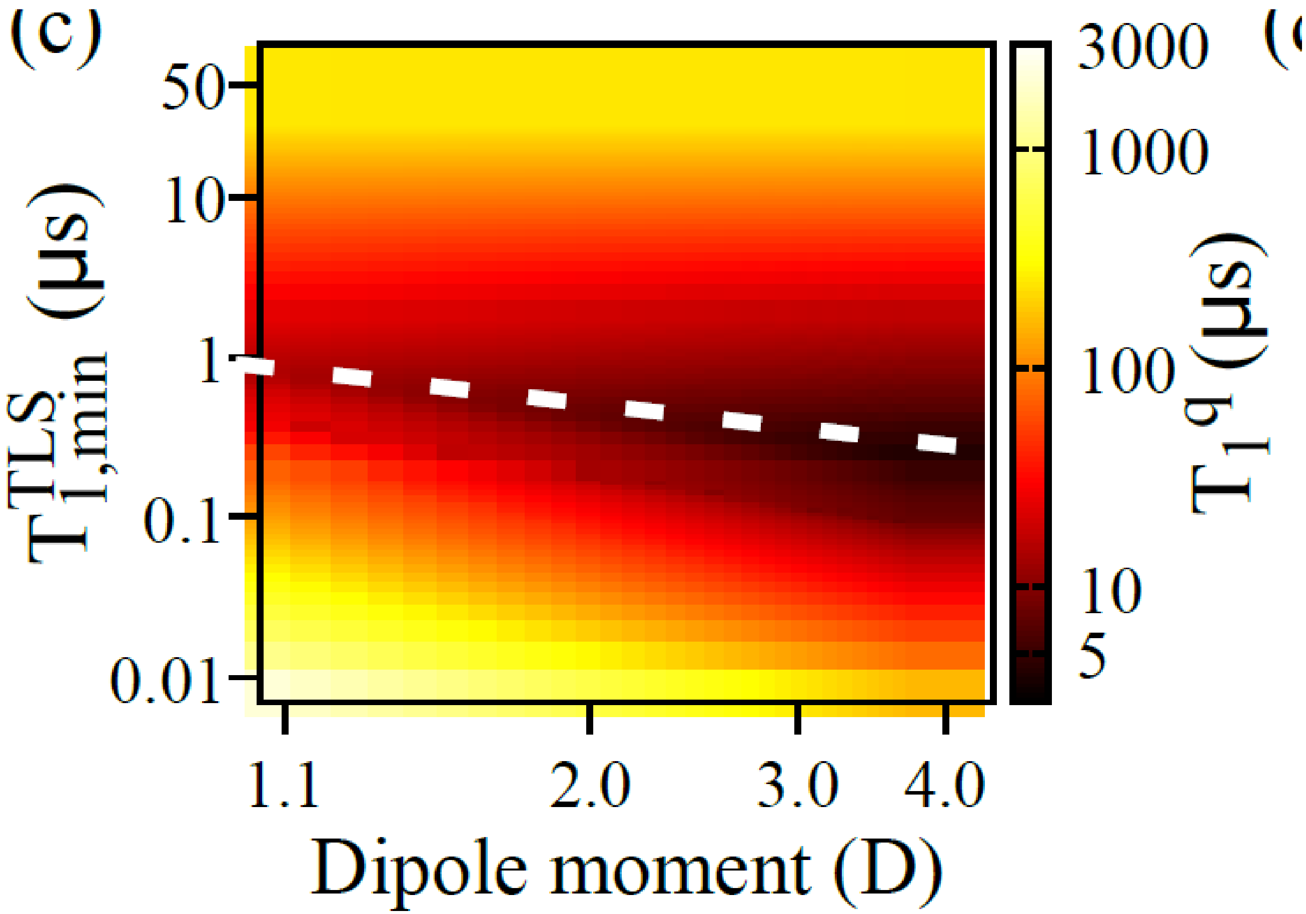
Quantum Sci. Technol. 8 045023 (2023)

Supplemental



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