Fermilab

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UTA Center for Advanced Detector Technologies

FERMI NATIONAL ACCELERATOR LABORATORY

October, 2025

Utilizing the Quantum Zeno Effect in superconducting qubit based particle sensors

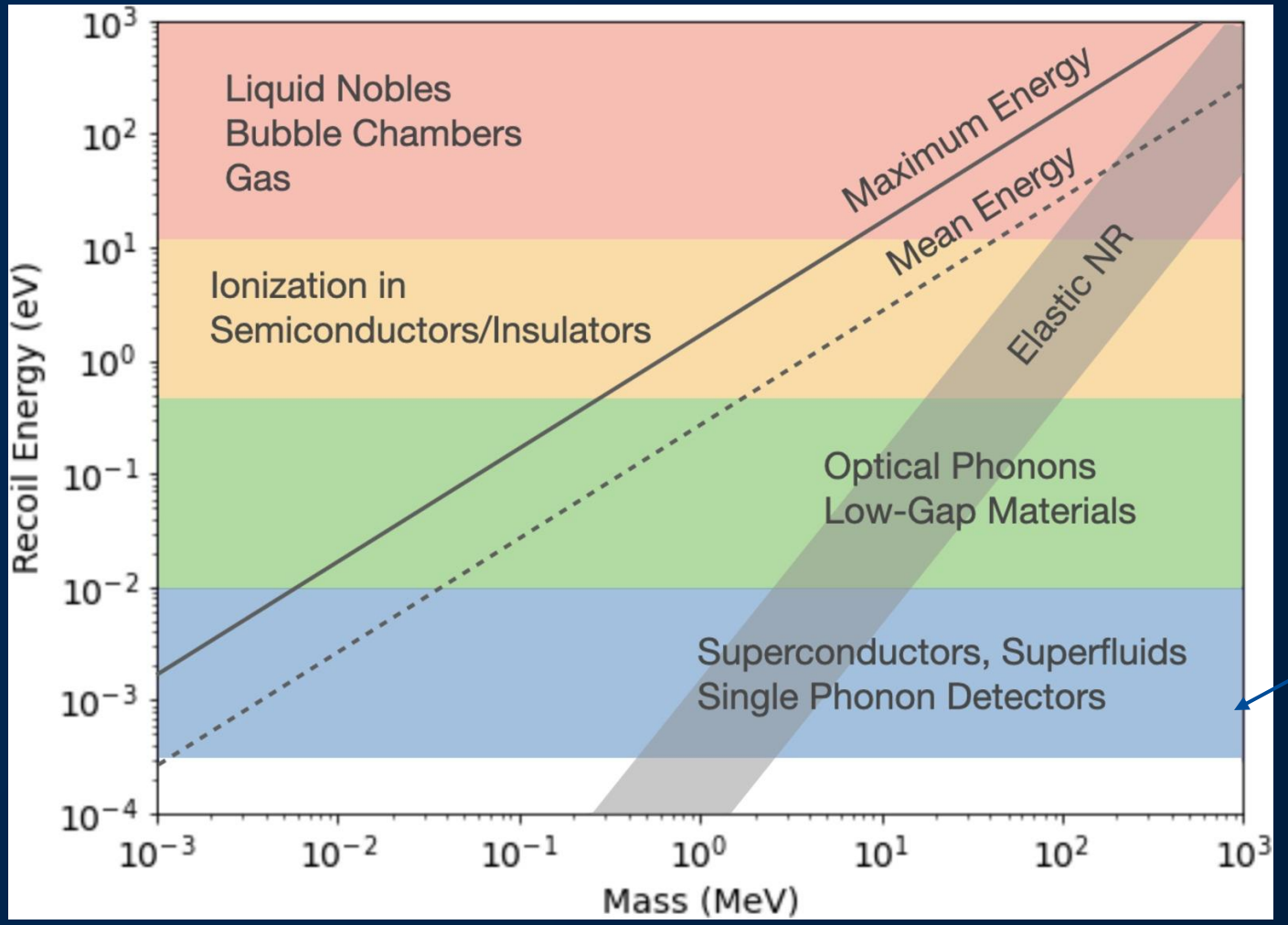
Olivia Seidel, Sara Sussman

U.S. DEPARTMENT of ENERGY

Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

Quantum based sensors for low energy detection

Direct detection dark matter techniques

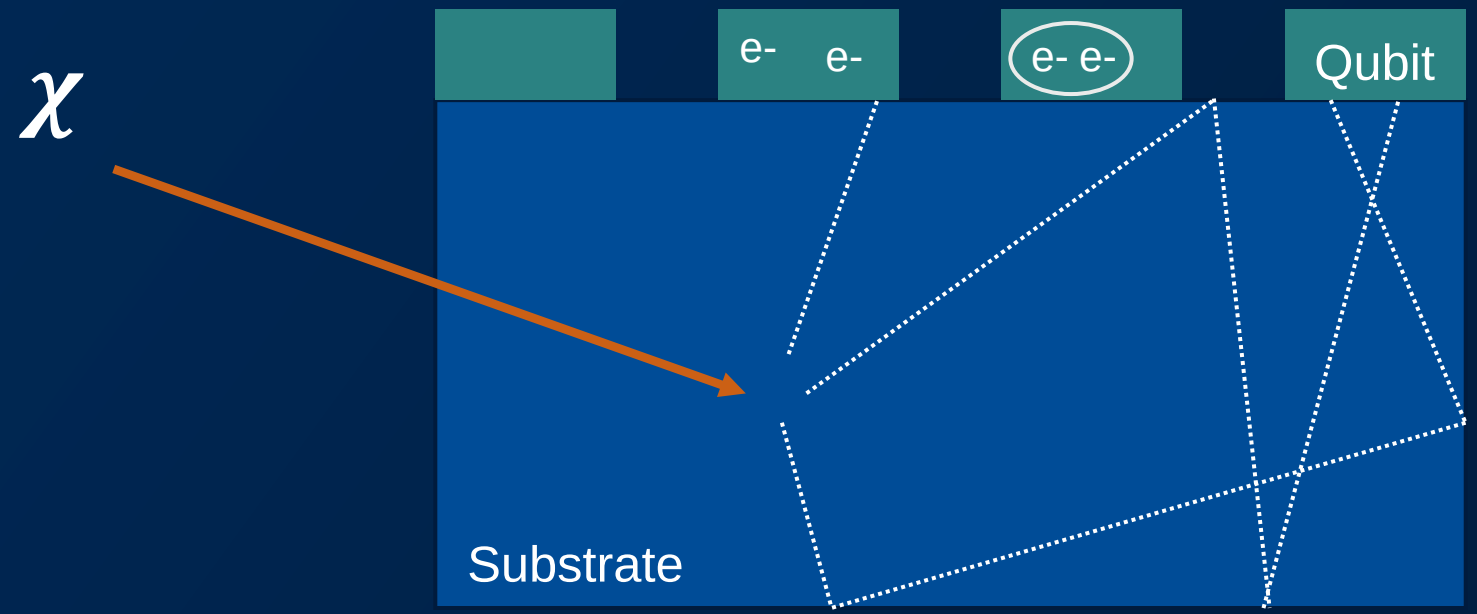


10.1016/j.nuclphysb.2024.116484

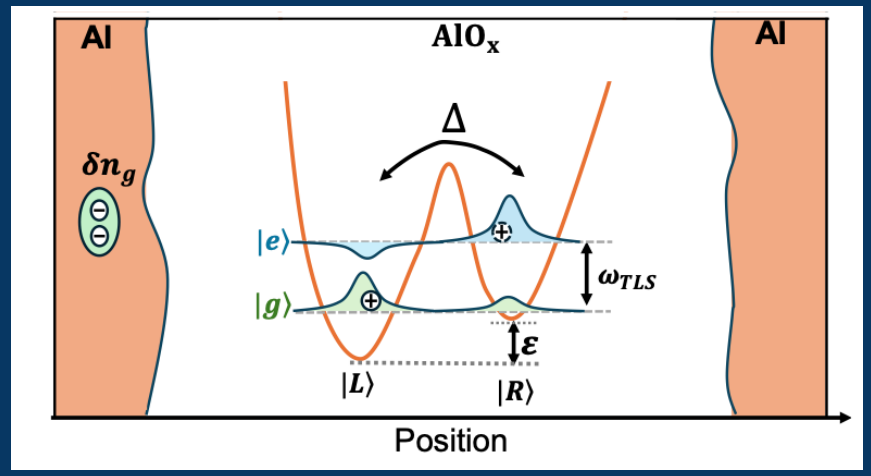
Qubit-based sensors enable meV detection

Pair-breaking leads to increased decoherence as a physics signal

Bad for quantum computing :(
Good for quantum sensing :)

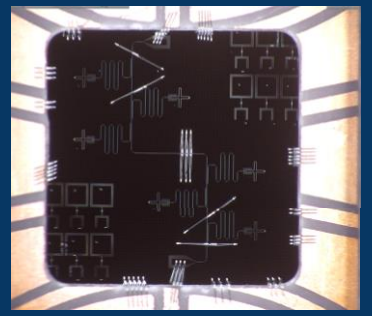


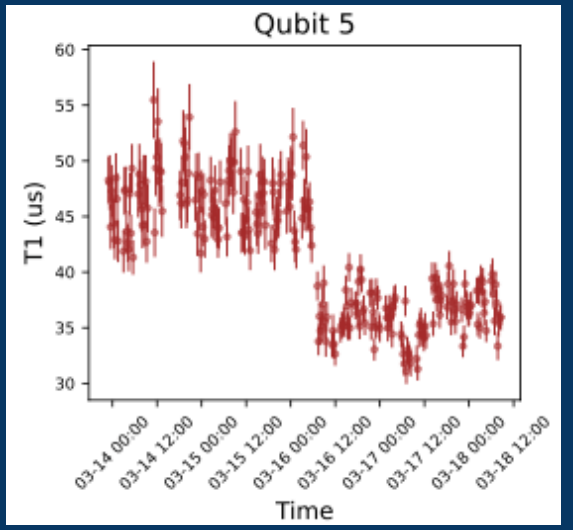
Coherence can also be affected by defect Two Level Systems (TLSes)

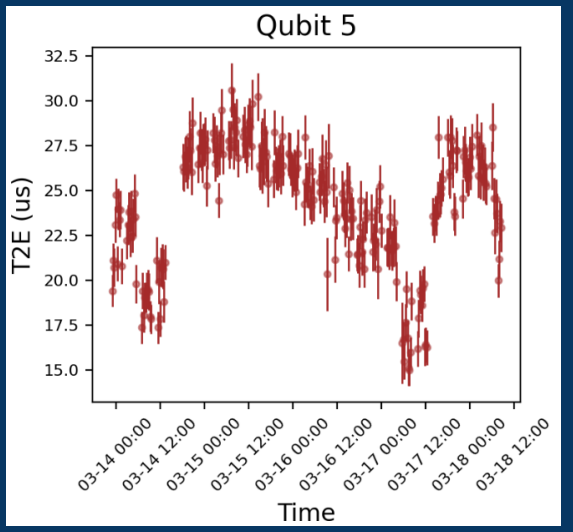


10.1103/PhysRevLett.133.160602

Data taken underground at Fermilab in QUIET:

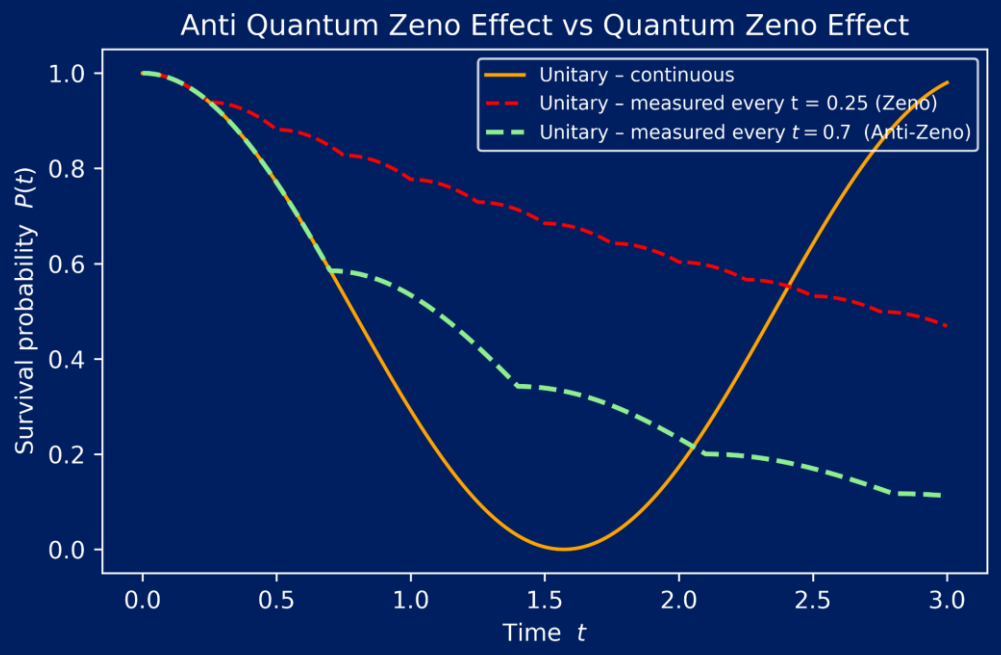






The Quantum Zeno Effect

Unitary/Closed ideal QZE



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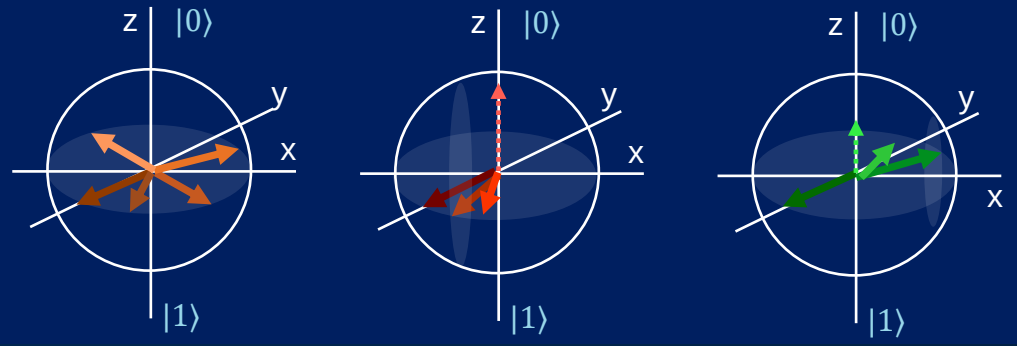

Open Quantum Systems QZE

1. Qubit-TLS entanglement → ω_Q broadening
2. Weak qubit-experimenter entanglement → photon shot noise →ω_Q broadening
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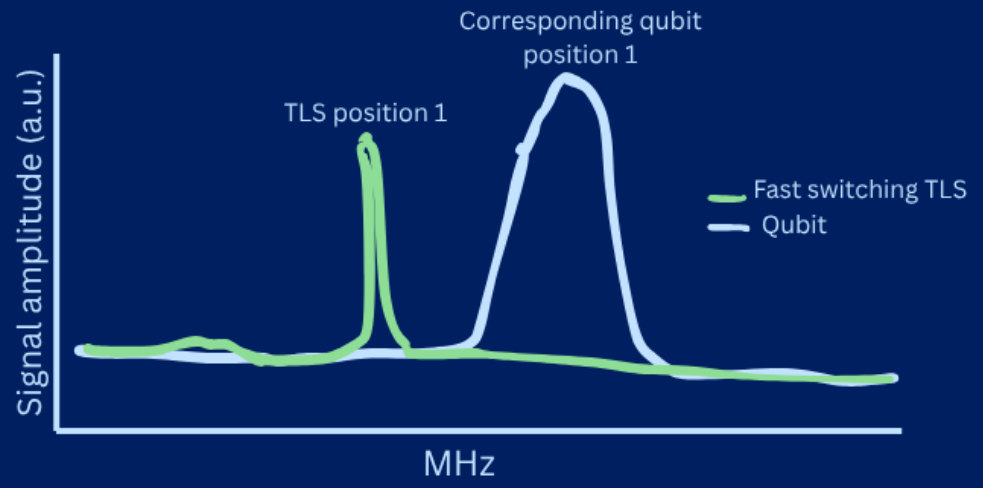
4. Strong qubit-experimenter entanglement → projects onto z repeatedly → effective dephasing



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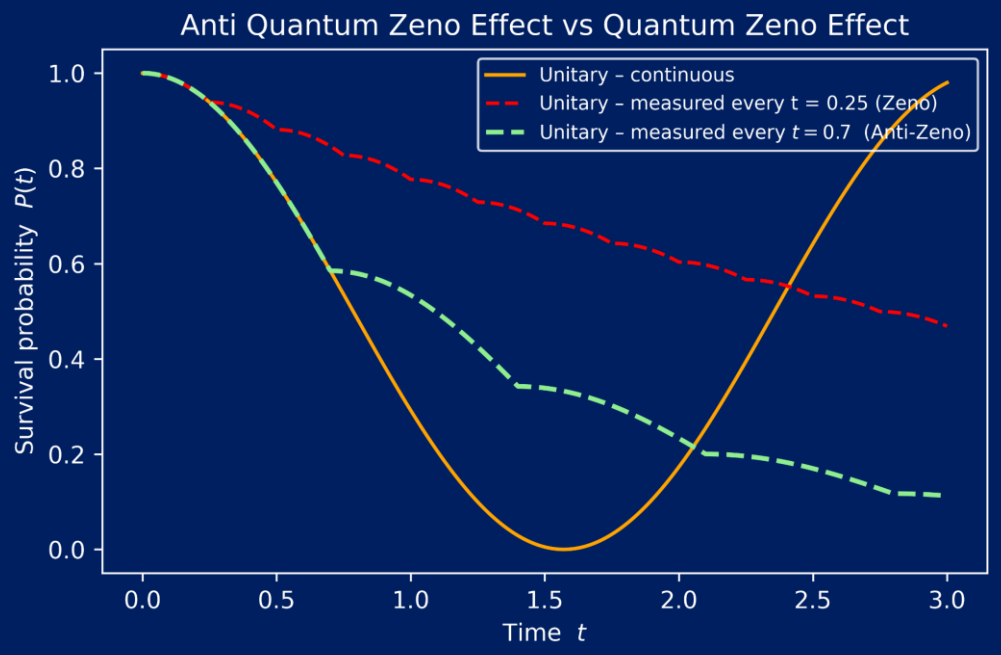

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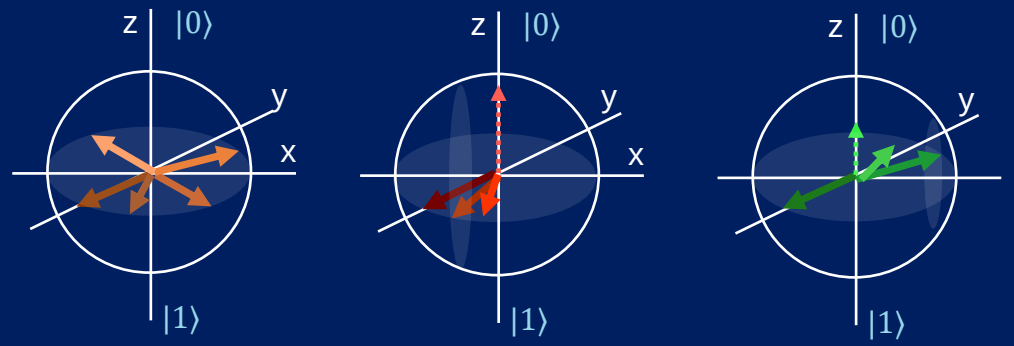

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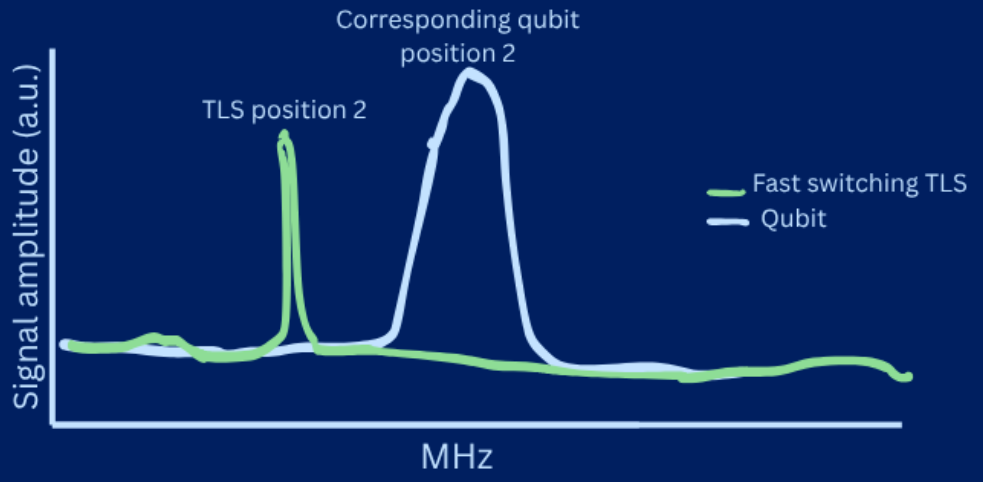

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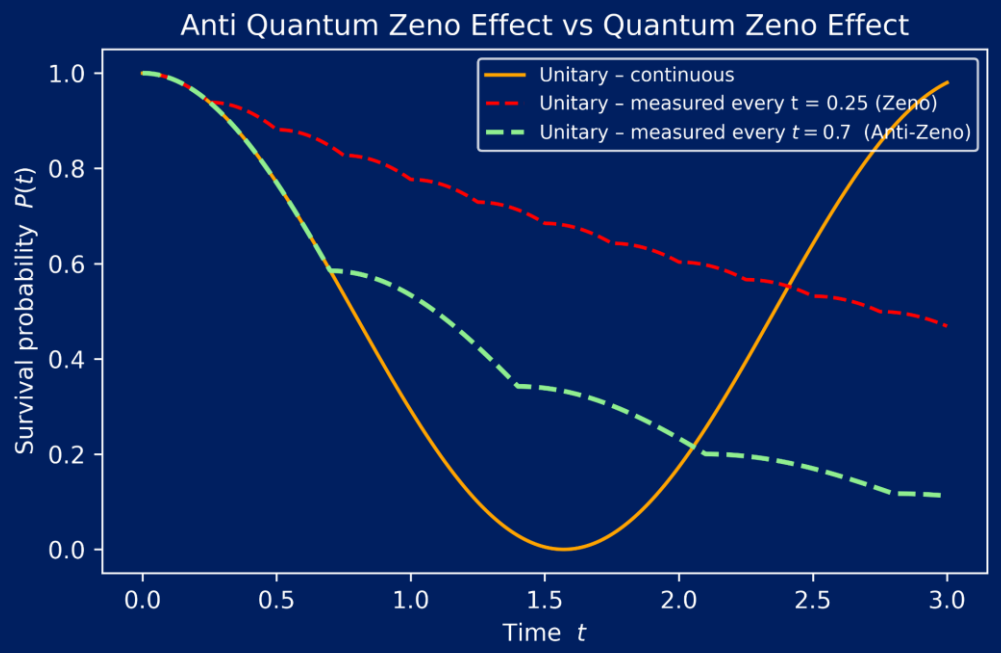

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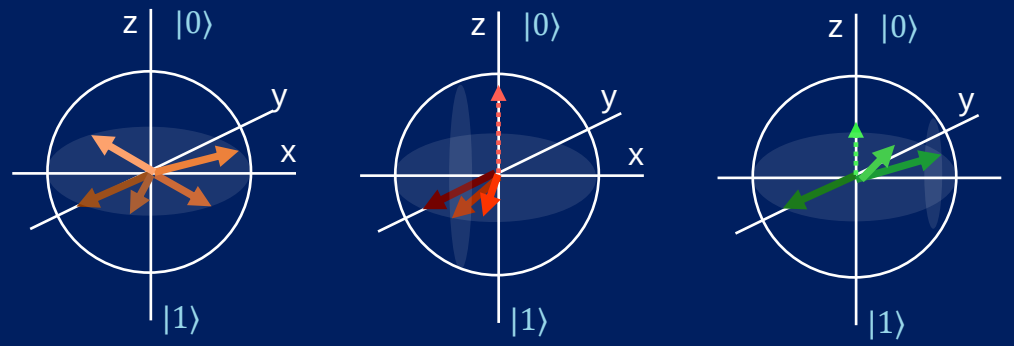

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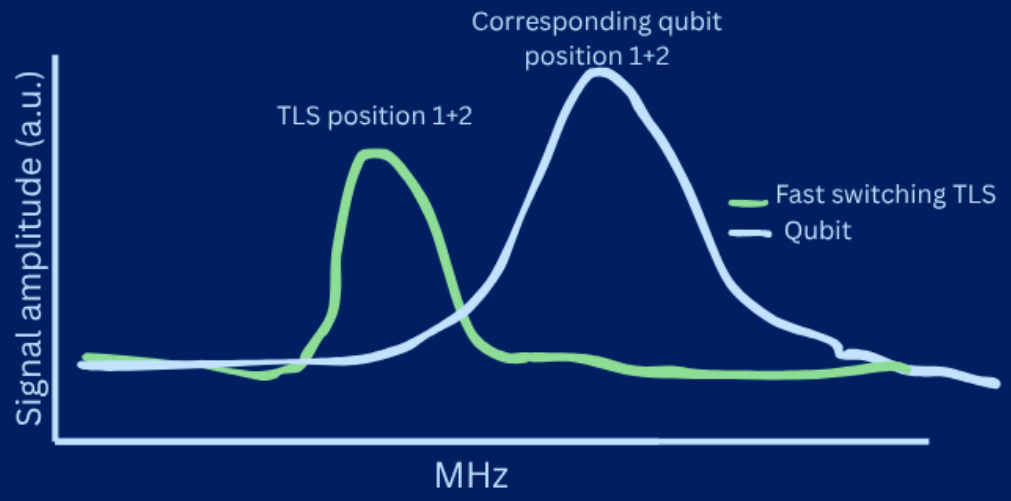

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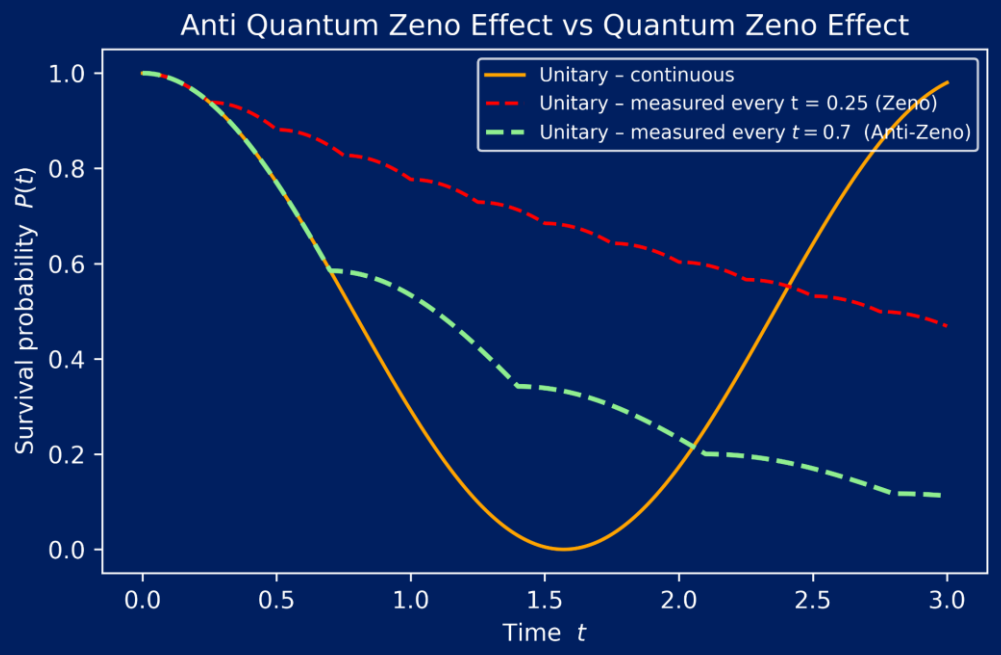

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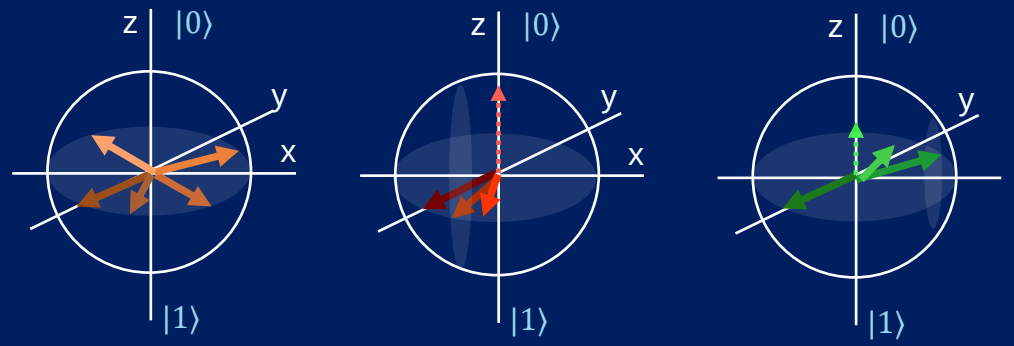

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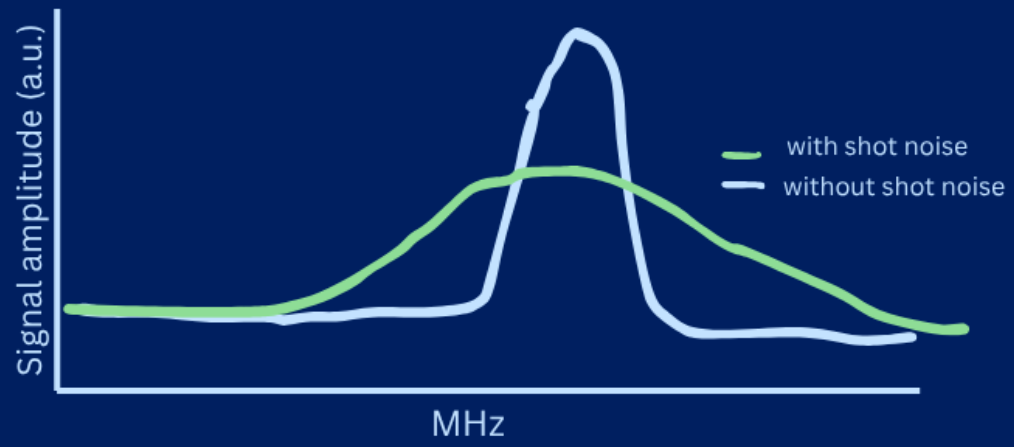

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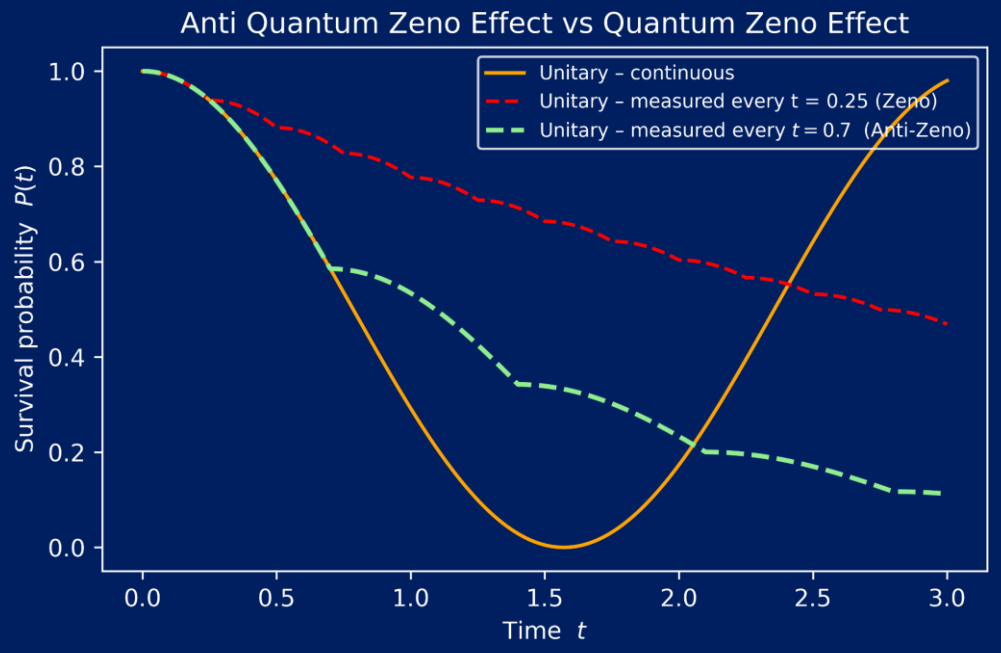

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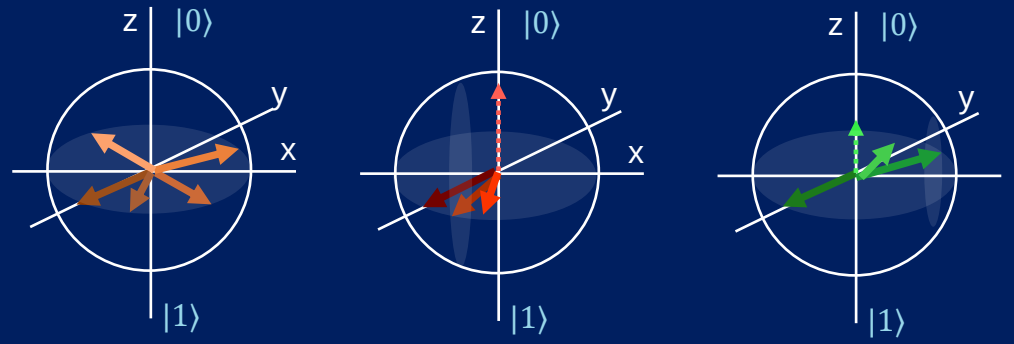

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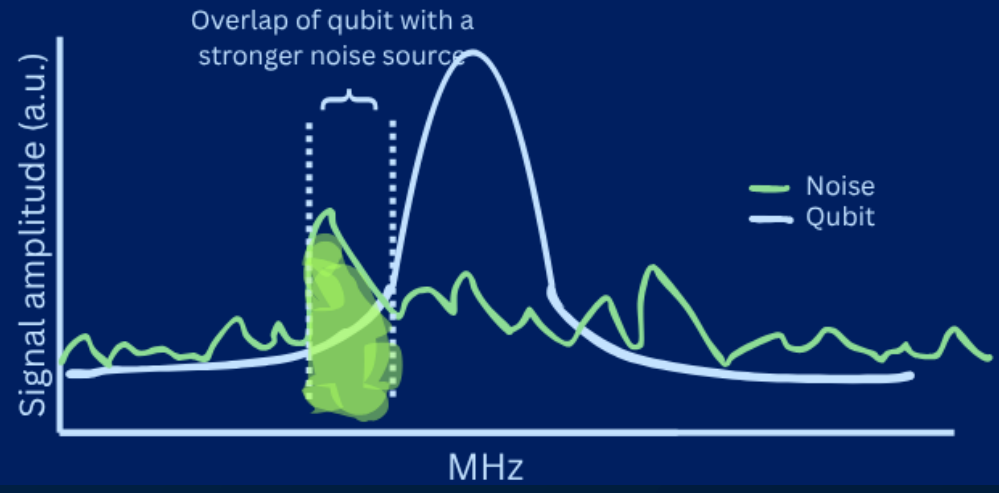

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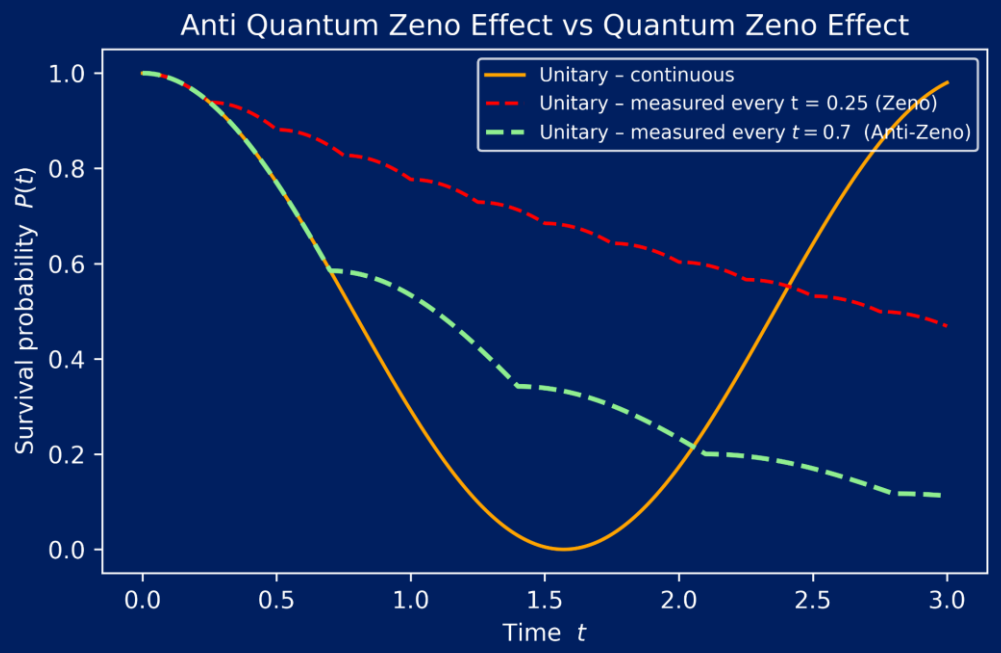

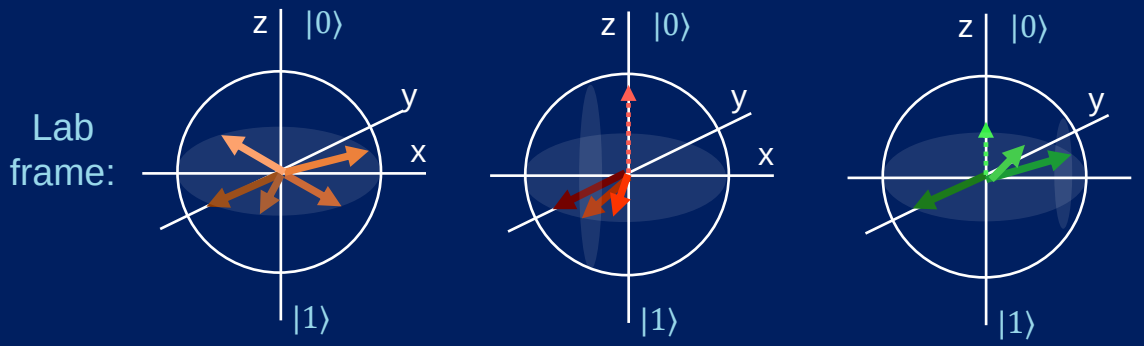

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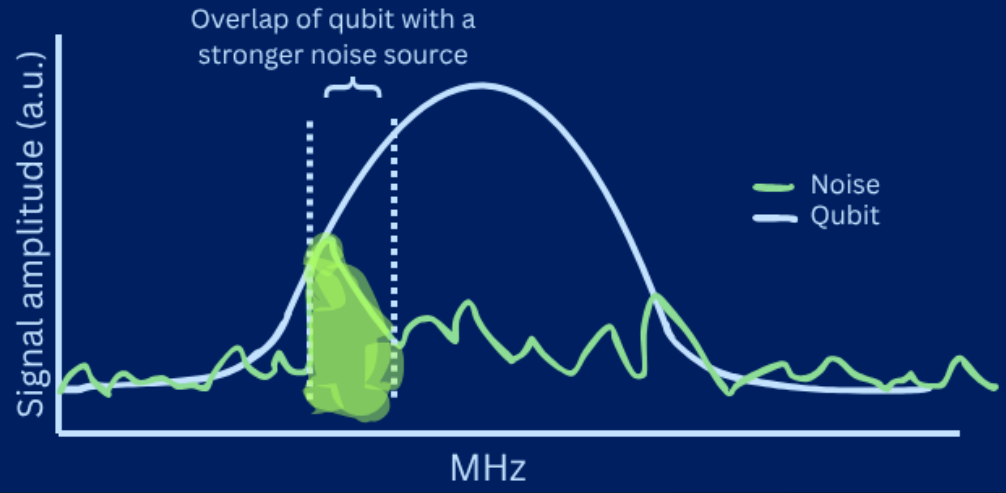

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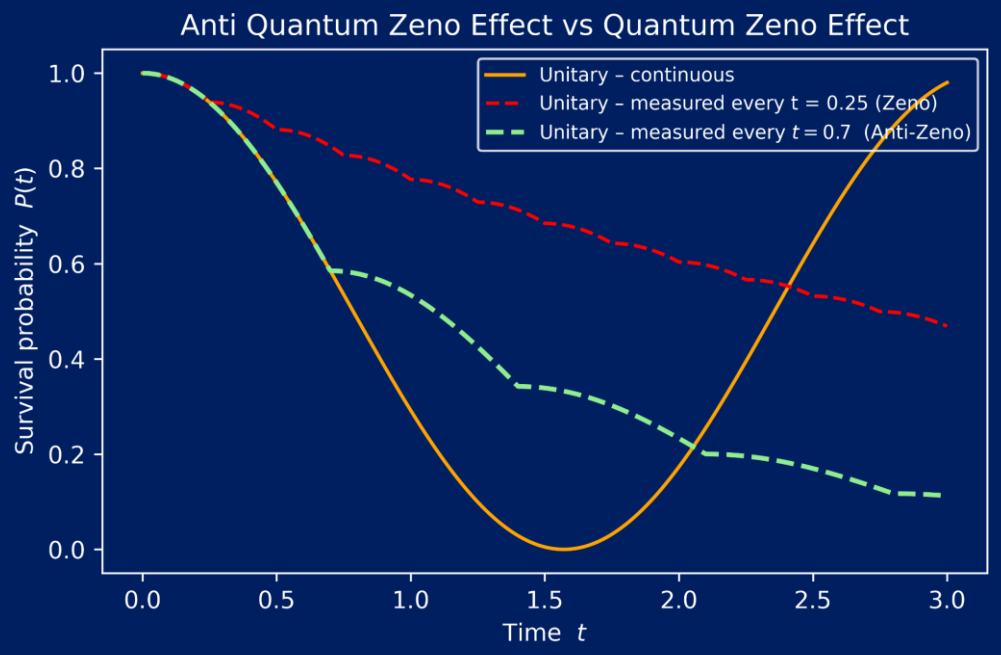

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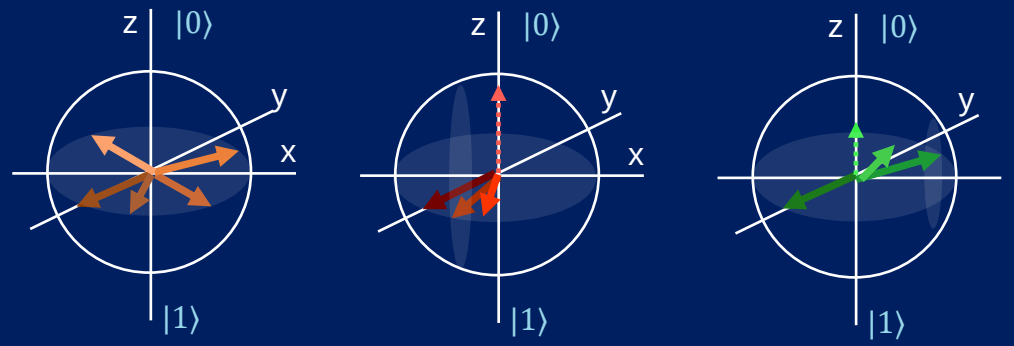

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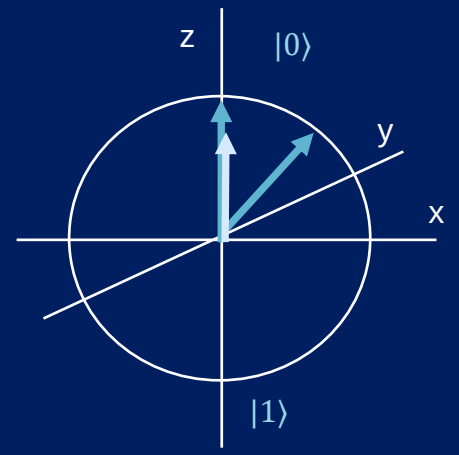
Rabi in the rotating frame



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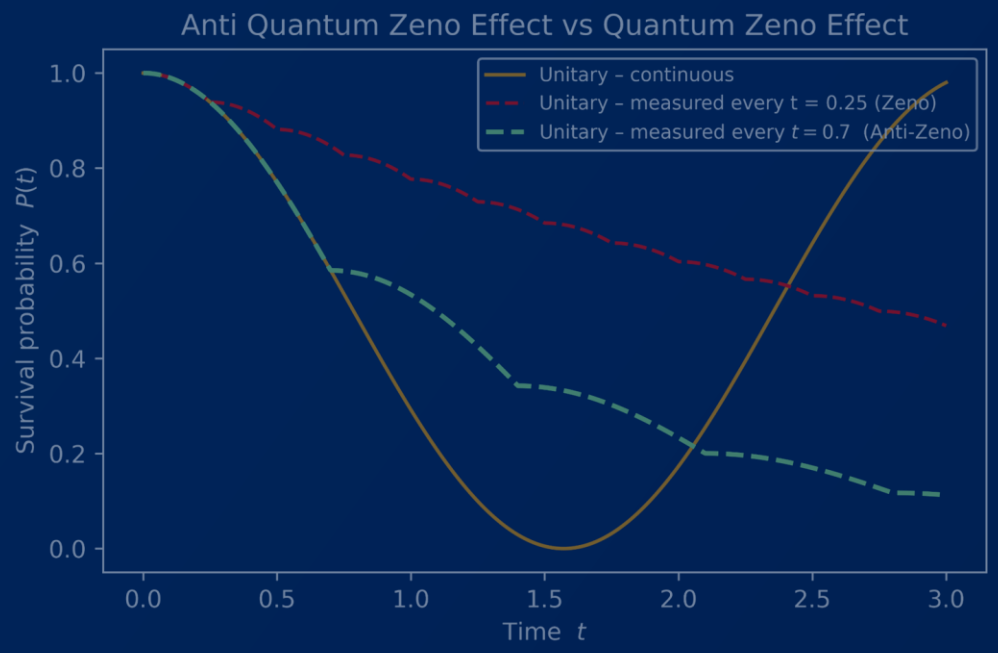

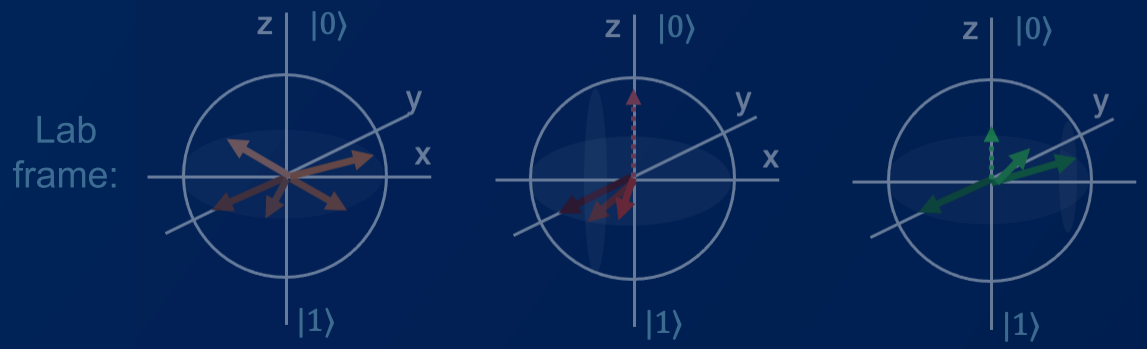

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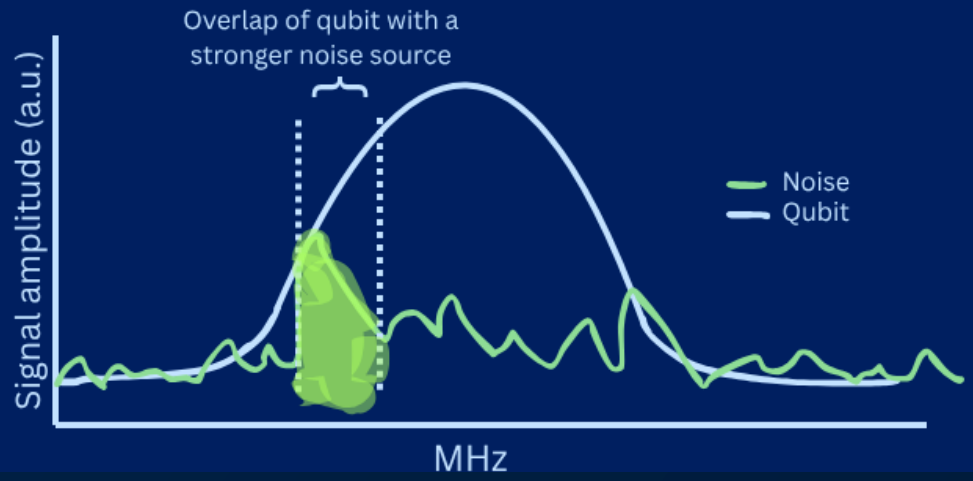

Expected total decay rate of the qubit

$$\Gamma = \gamma_q + 2g_D^2 \frac{\gamma_\phi + \gamma_{1,D}/2 - \gamma_q/2}{\left(\gamma_\phi + \gamma_{1,D}/2 - \gamma_q/2\right)^2 + \left(\omega_q - \omega_D\right)^2}$$

10.1103/PhysRevLett.132.090602

- γ_q = intrinsic decay rate of the qubit (1/T1)
- γ_ϕ = 1/ T_ϕ
- $\gamma_{1,D}$ = 1/T1 of the TLS
- g_D = coupling strength of qubit to TLS defect
- The second term is the contribution from the QZE, as it is induced from spectral overlap with a coupled TLS

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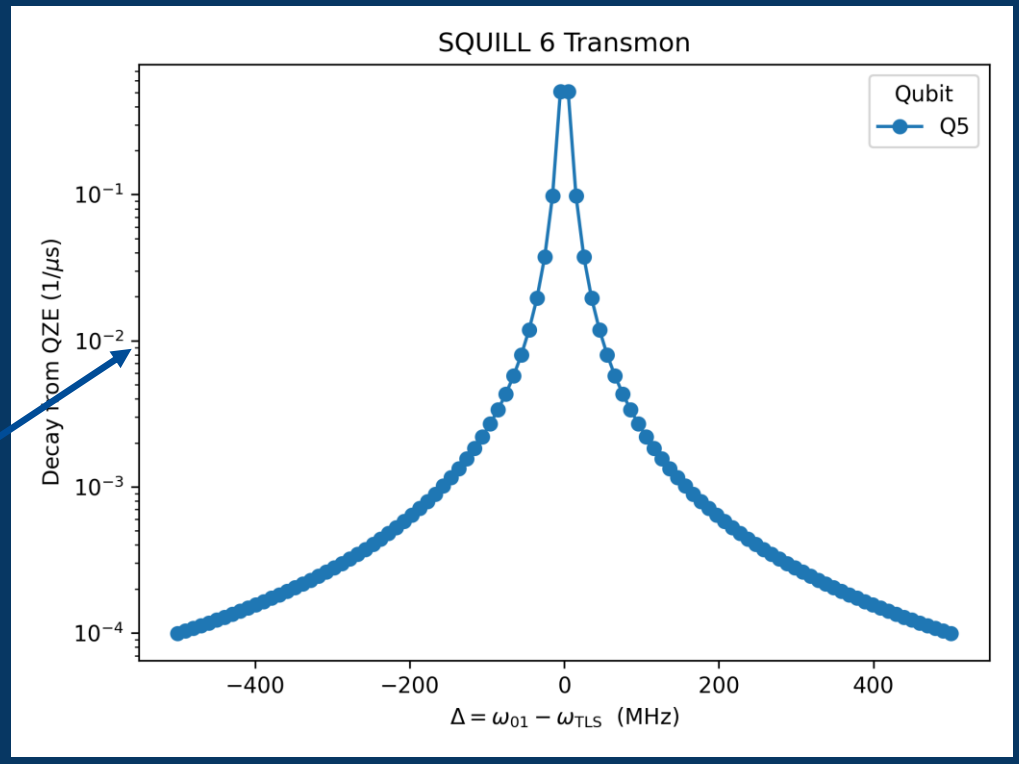
- 0.009 (1/us) is 1/T1 for this qubit, for reference



Initial results

Longer coherence times means we have more "active time" for our quantum sensors

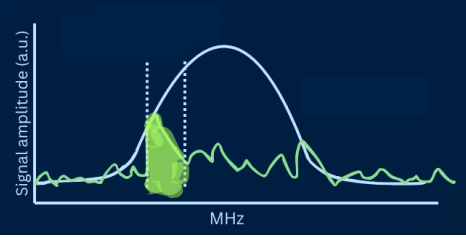
π pulse to excite to $|1\rangle$ at ω_Q

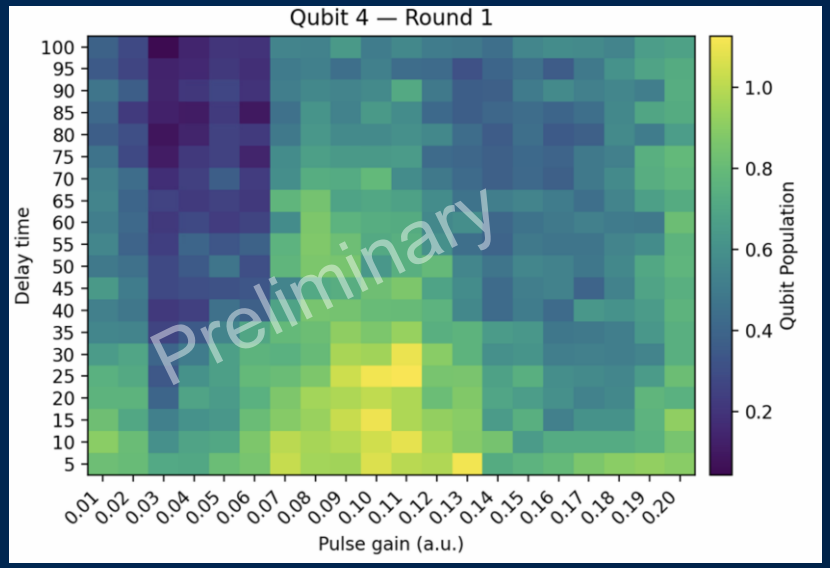
Delay time

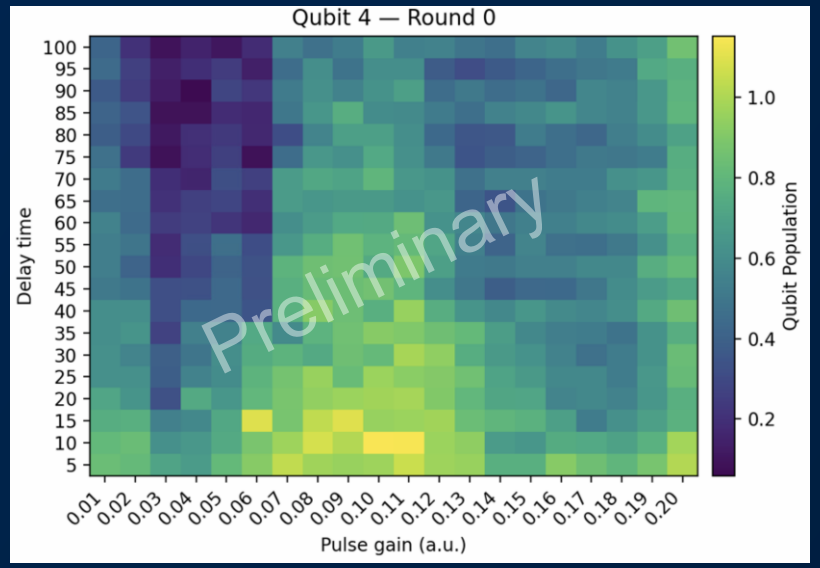
Readout pulse in resonator at ω_R

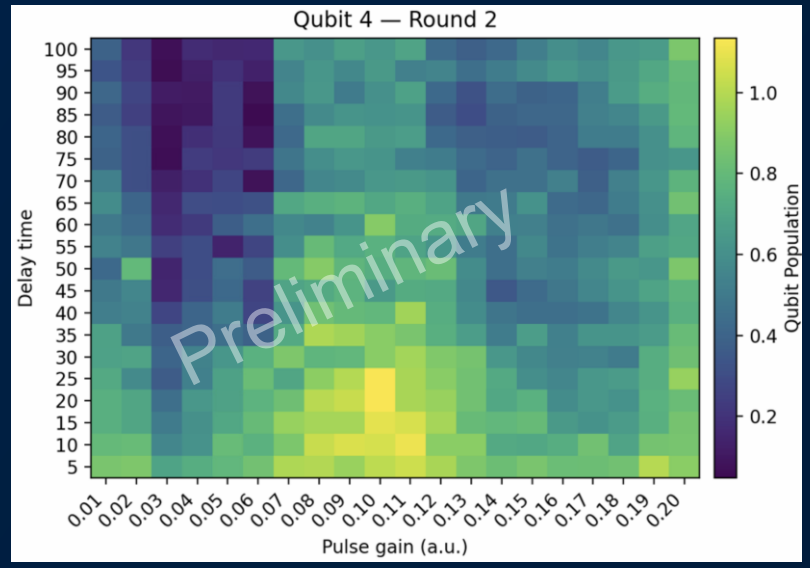
Zeno pulse in resonator at ω_R

Ring down time for resonator









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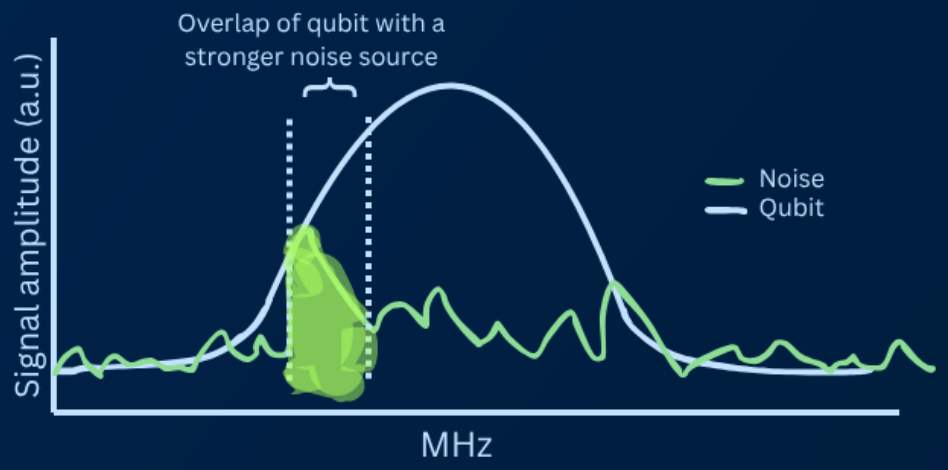
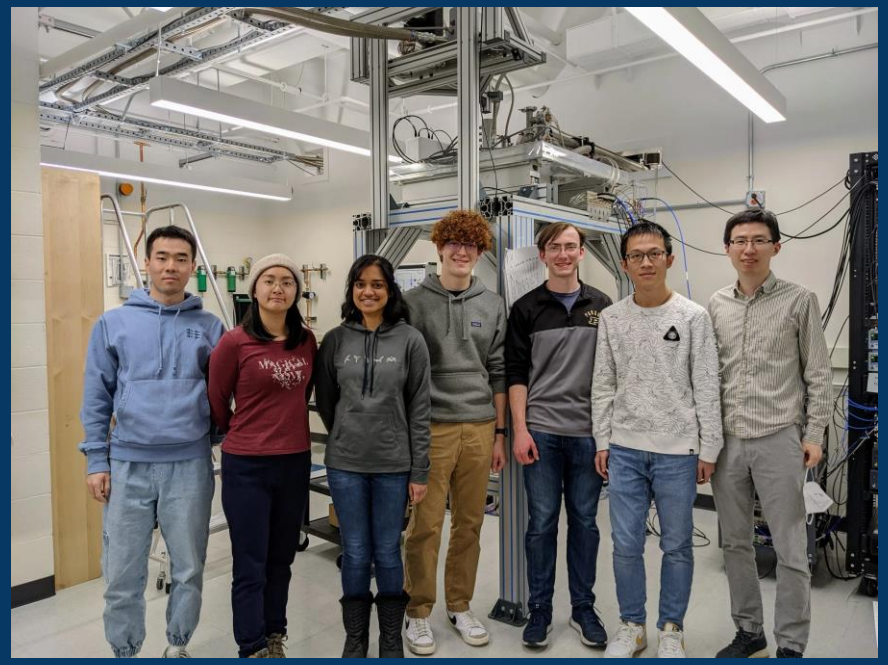
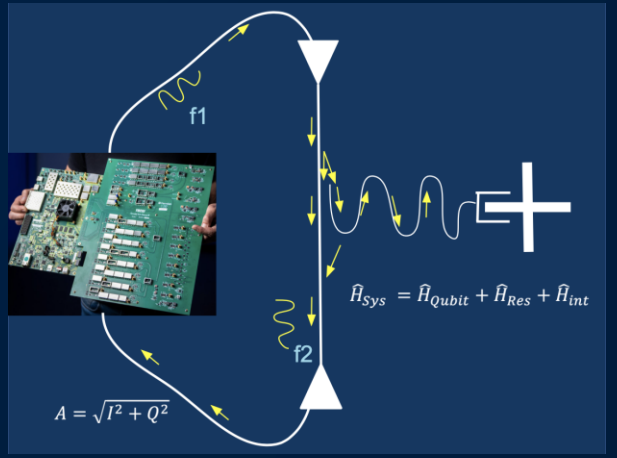
Conclusion

- Superconducting qubits make great low energy particle detectors
- The longer the coherence time, the longer we have an active quantum sensor for
- We can enhance the coherence times of superconducting qubits by leveraging the Quantum Zeno Effect



Huge thank you to Alex Ma's Lab (Ma Lab), Archana Kamal's group (QUEST), the Fermilab CosmiQ and QICK teams!





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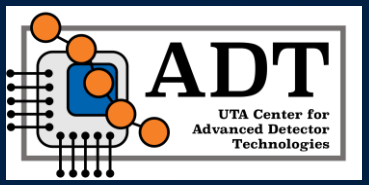
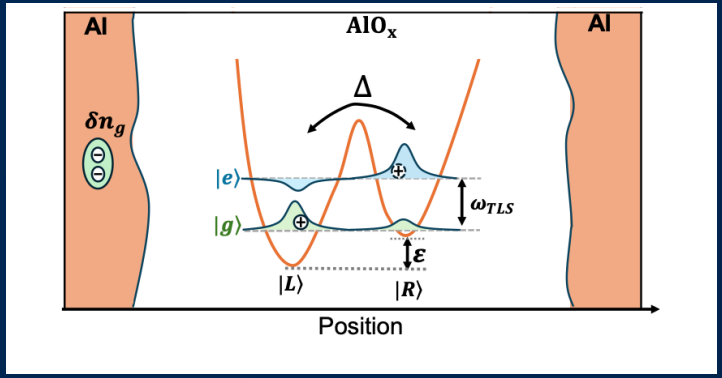


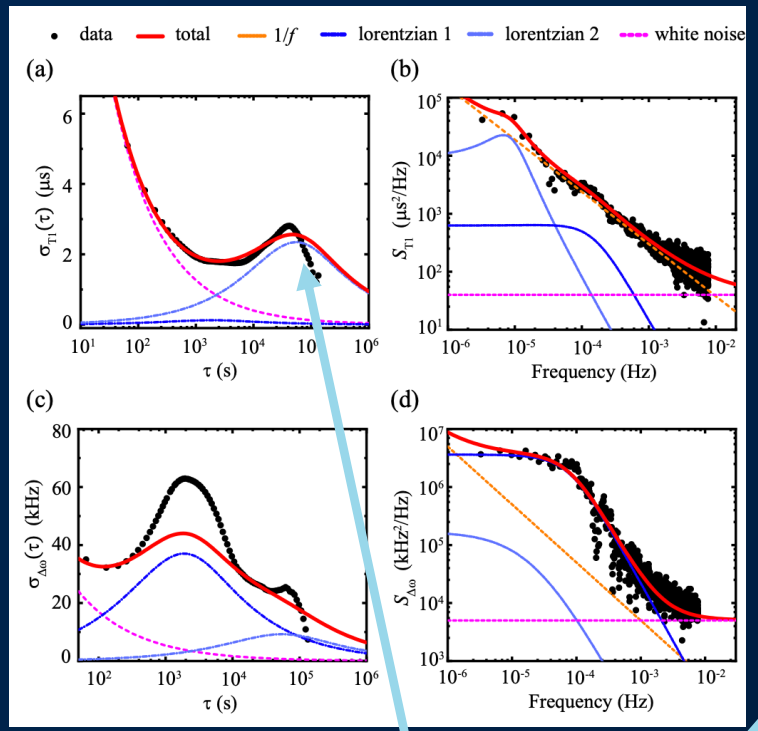
Thank you!

A second insidious source of backgrounds: Two Level Systems (TLSes)

Two-Level Systems (TLSes) are quantum systems caused by material defects in the proximity of superconducting qubits:



These shift the qubit frequency around, and coherence times



They can exhibit various types of TLS behavior (Diffusive, telegraphic, etc)

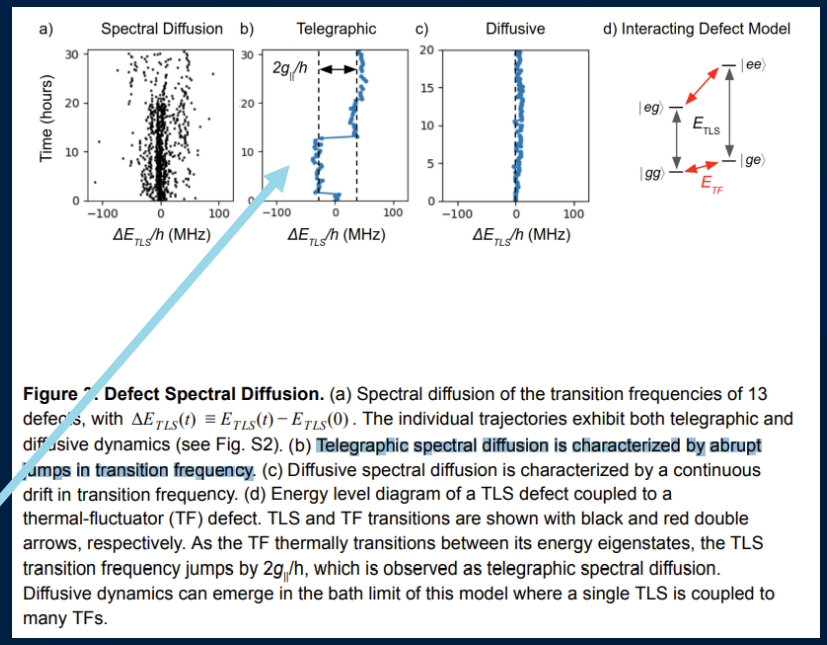


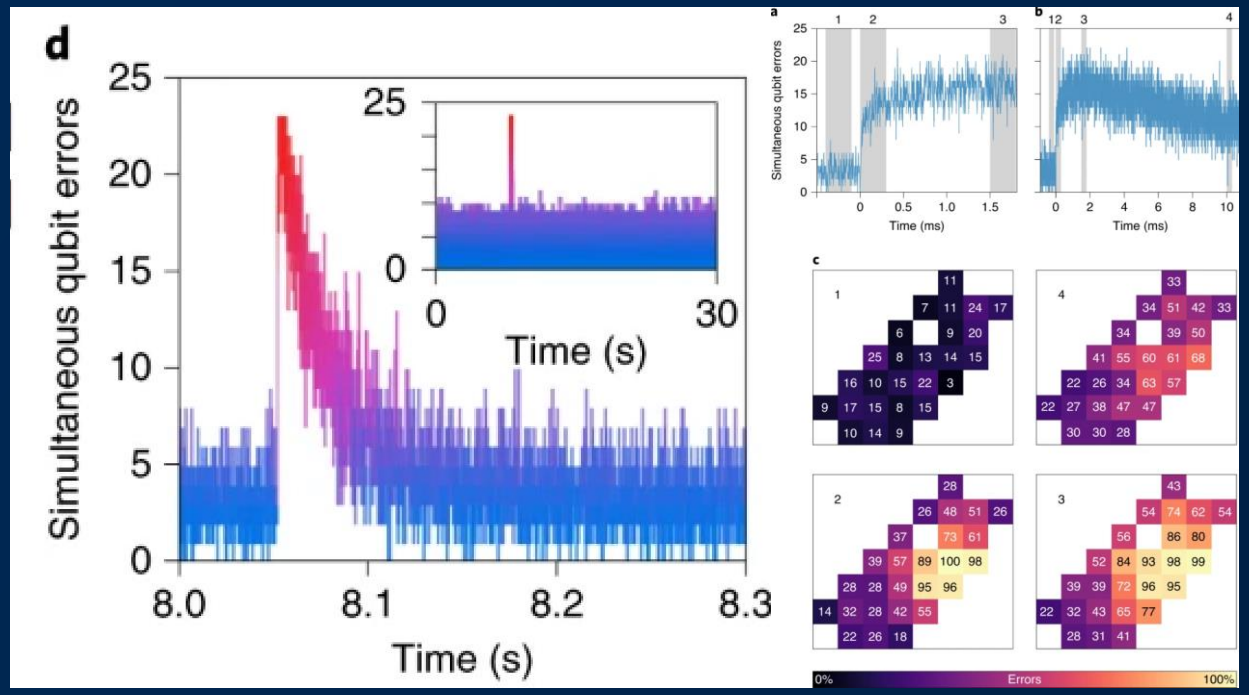
Figure 2. Defect Spectral Diffusion. (a) Spectral diffusion of the transition frequencies of 13 defects, with $\Delta E_{TLS}(t) \equiv E_{TLS}(t) - E_{TLS}(0)$. The individual trajectories exhibit both telegraphic and diffusive dynamics (see Fig. S2). (b) Telegraphic spectral diffusion is characterized by abrupt jumps in transition frequency. (c) Diffusive spectral diffusion is characterized by a continuous drift in transition frequency. (d) Energy level diagram of a TLS defect coupled to a thermal-fluctuator (TF) defect. TLS and TF transitions are shown with black and red double arrows, respectively. As the TF thermally transitions between its energy eigenstates, the TLS transition frequency jumps by $2g_{\parallel}/h$, which is observed as telegraphic spectral diffusion. Diffusive dynamics can emerge in the bath limit of this model where a single TLS is coupled to many TFs.

If you are lucky, they will switch at a reliable rate. However, often, this doesn't happen ☹

Qubits are great sensors, and are extra sensitive to cosmic rays

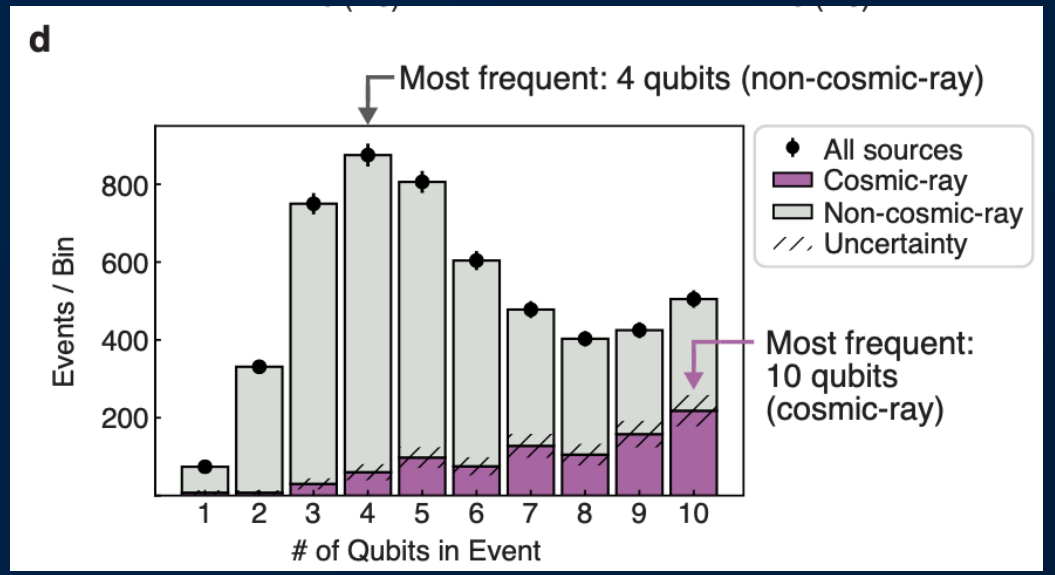
[Cosmic Ray Induced Quasiparticles → Decoherence]

Phonons break cooper pairs, which tunnel to JJ and cause suppression of T1



[5]

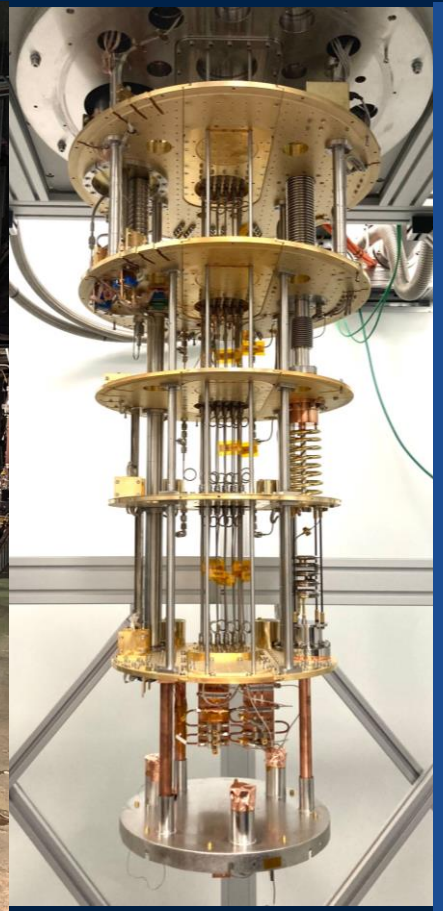
Cosmic rays found to account for 17.1 ±1.3% of spatiotemporally correlated events

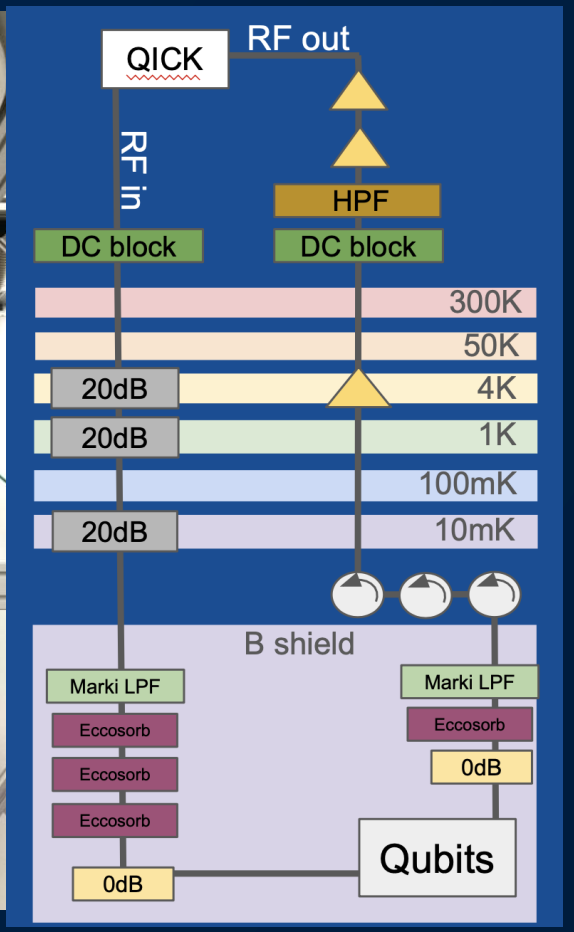


[6]

Cosmic ray solution: go 100m underground

Low background facility
99% reduction in muon flux when compared to surface level fridges!
Deepest QIS fridge in US (that we know of)





Superconducting qubits are promising candidates for low energy detection

ADT
UTA Center for Advanced Detector Technologies

LC circuit

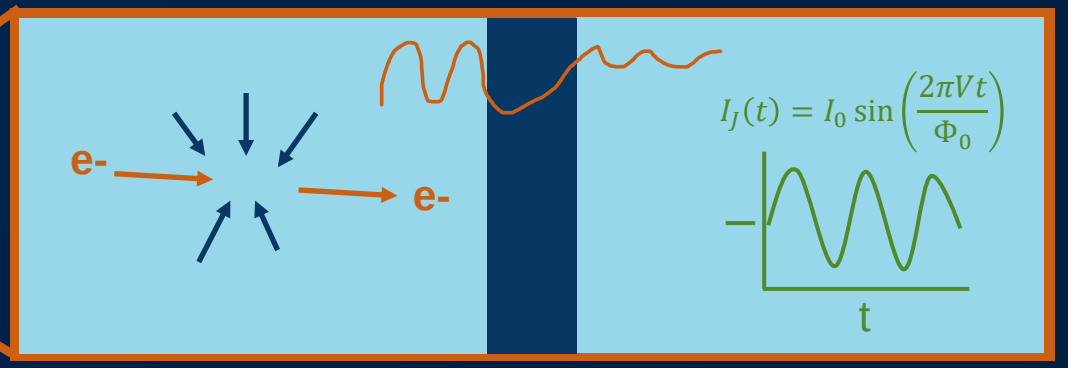
$$\Delta E = \hbar\omega = \frac{\hbar}{\sqrt{LC}}$$

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

Superconducting qubit

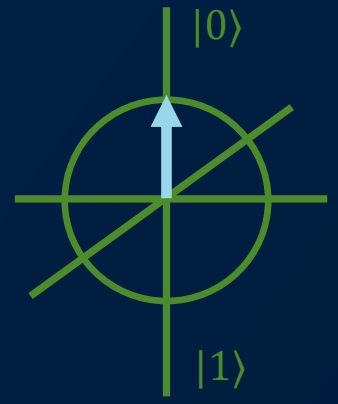
$$E_J = \frac{I_0 \Phi_0}{2\pi}$$

$$\hat{\mathrm{H}} = \frac{\hat{Q^2}}{2C} + E_J \cos(\hat{\delta})$$



Binding energy on cooper pairs sets energy sensitivity

Supercurrent sets the qubit frequency



Overview of current Qubit hardware

	Superconducting	Trapped Ion	Neutral atom (Rydberg, alkali)	Spin	Photonic
Key components	JJs, resonators	Ions in a vacuum chamber controlled using em fields	Atoms trapped using laser tweezers	Electron or nuclear spin in solid state materials, controlled with B or E fields	Quantum states of light encoded in photons
Disadvantages	Low temps needed, fast decoherence time, QP poisoning	Hard to access, sparse density and hard to scale/entangle as a result	Scaling to large number of qubits	Scaling to large numbers	Complicated control architecture
Advantages	Easier scalability, leverages current fab techniques	high coherence, high fidelity	High coherence, high fidelity	Compatibility with semiconductor manufacturing	Room temp
Coherence times	Few milliseconds	Seconds to minutes	Seconds	Seconds	Photon loss is limit here
Single qubit Gate operation times	10s of ns	10s of microseconds	1-10us for rydberg (higher for others)	10s of ns for electrons, 1-10us for nucleus	nanoseconds