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Superconducting qubits for particle detection and fundamental tests of quantum mechanics

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U.S. DEPARTMENT of ENERGY

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Superconducting qubits for particle detection and fundamental tests of quantum mechanics

Motivating questions for near-term experiments

Experimental requirements to pursue these experiments

Recent experimental work to fulfill those requirements (the Quantum Zeno Effect)

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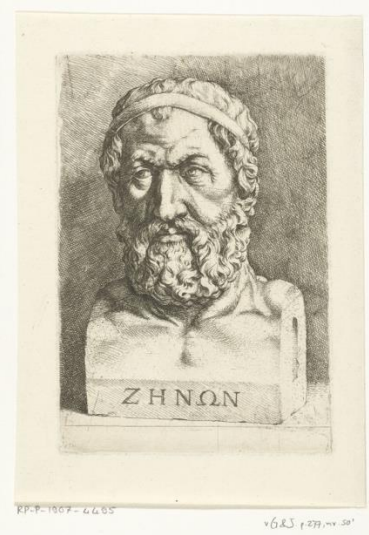
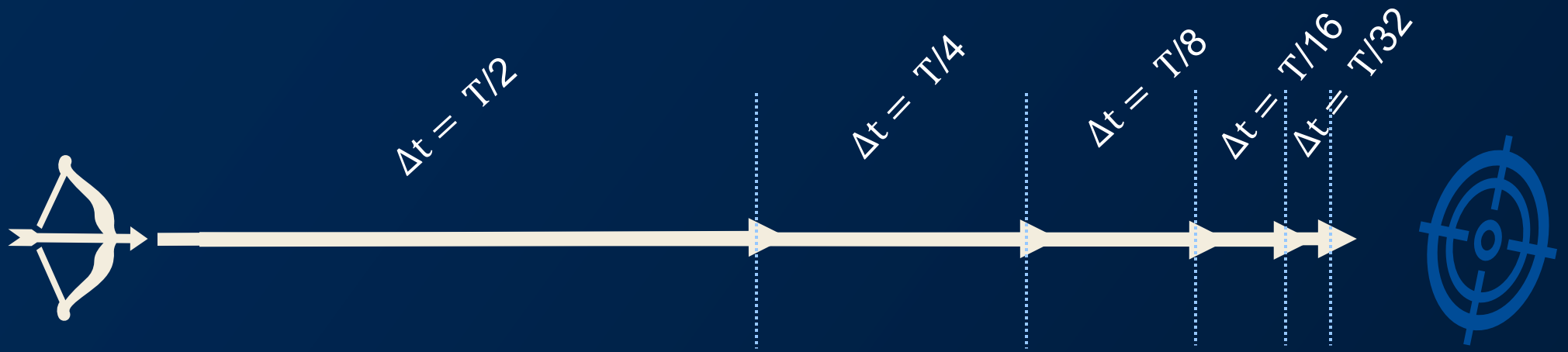
Is quantum information conserved during wavefunction collapse?

Does a quantum system in superposition experience gravitational redshift?

The Quantum Zeno Effect

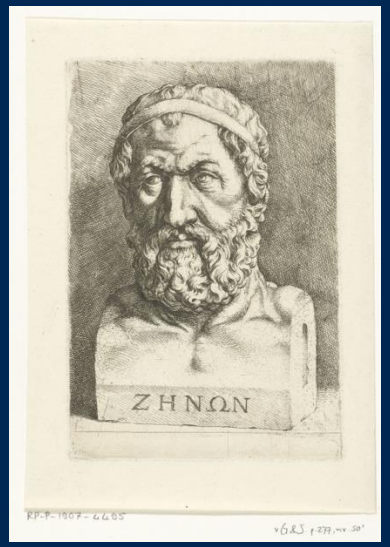


https://en.wikipedia.org/wiki/Zeno_of_Elea



How the ancient Greeks solved quantum problems

The Quantum Zeno Effect



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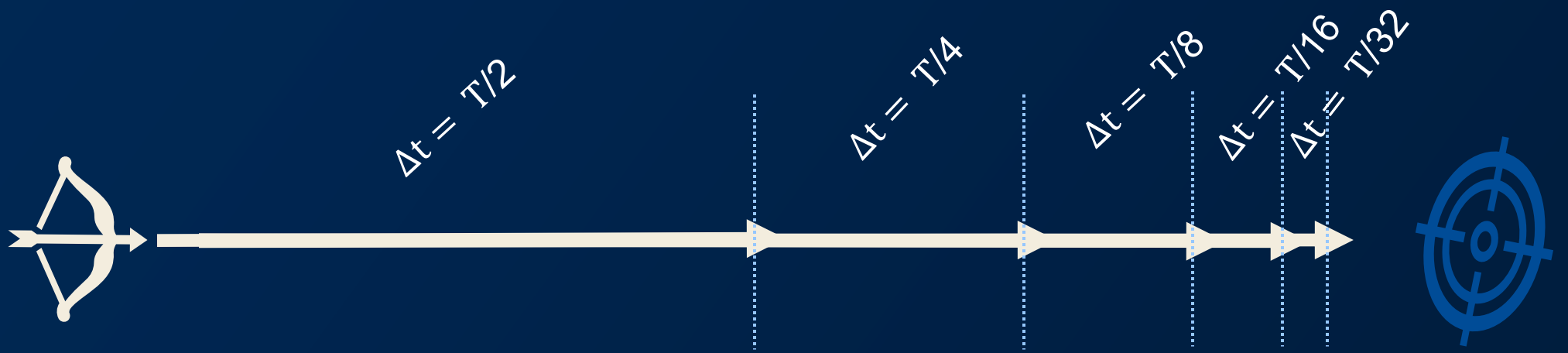
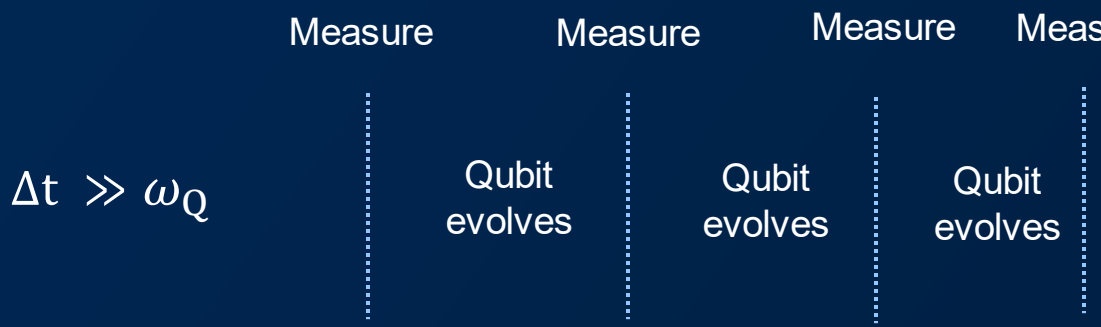


How the ancient Greeks solved quantum problems



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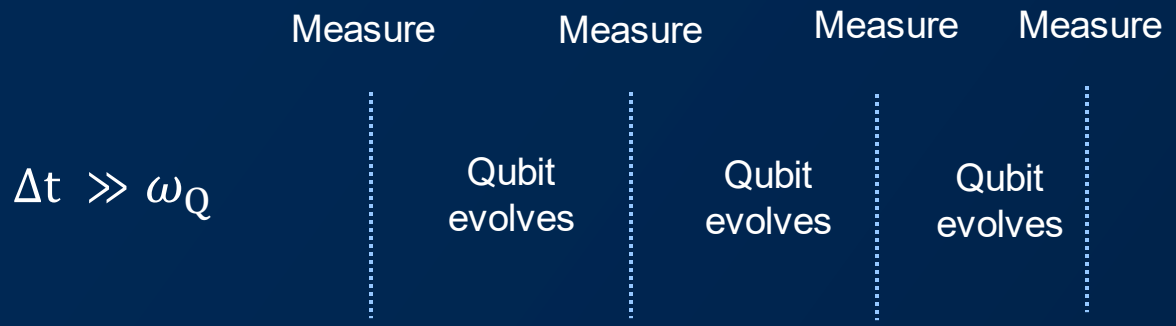
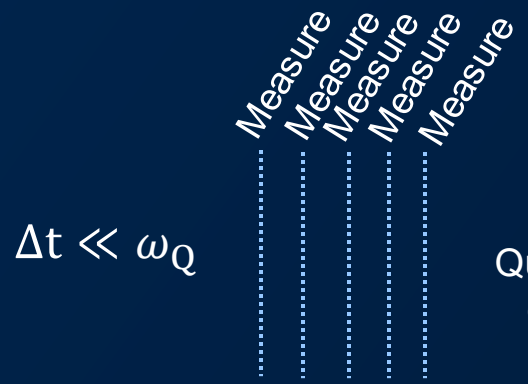
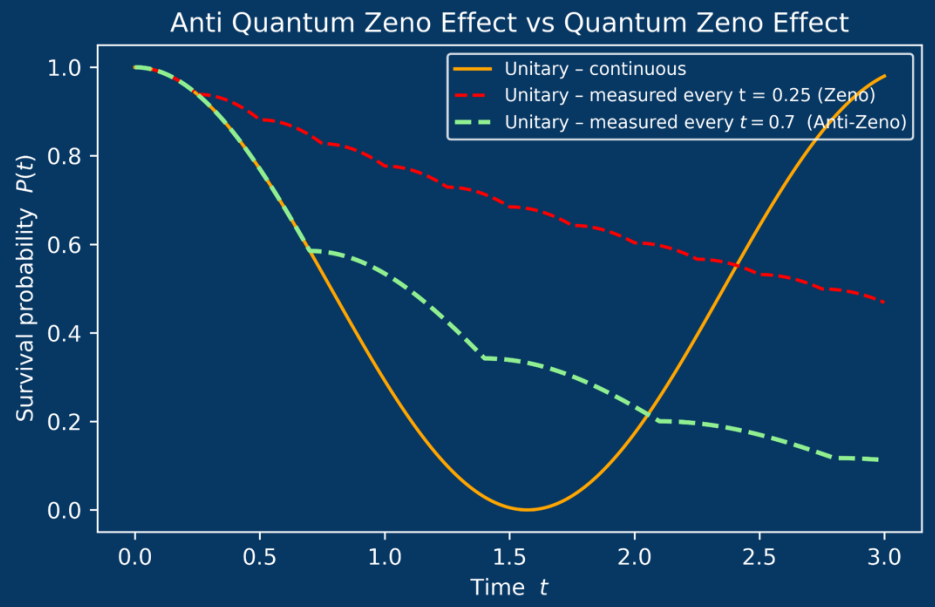
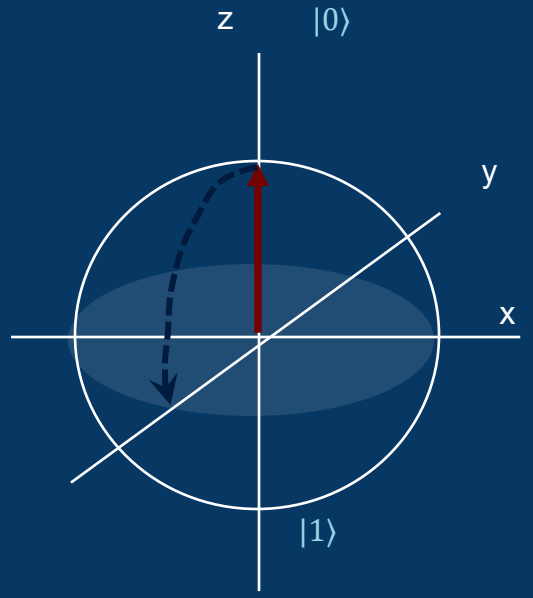




Qubit doesn't get the chance to evolve



Lab frame:



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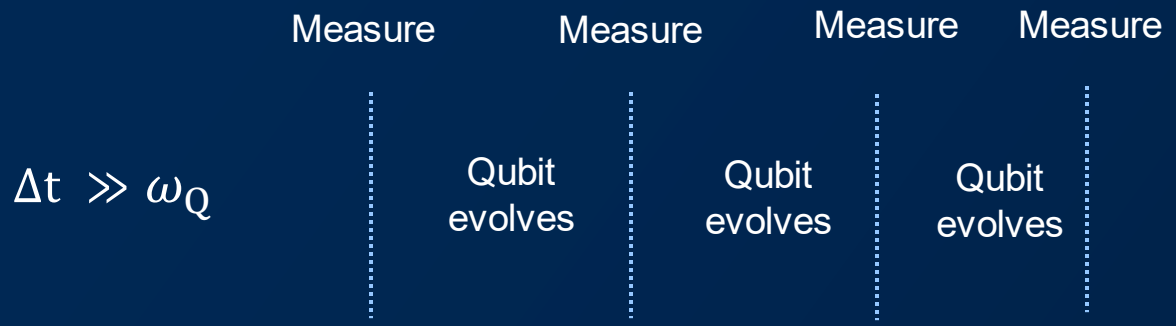

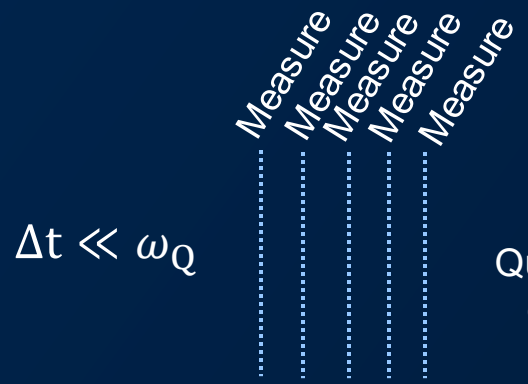

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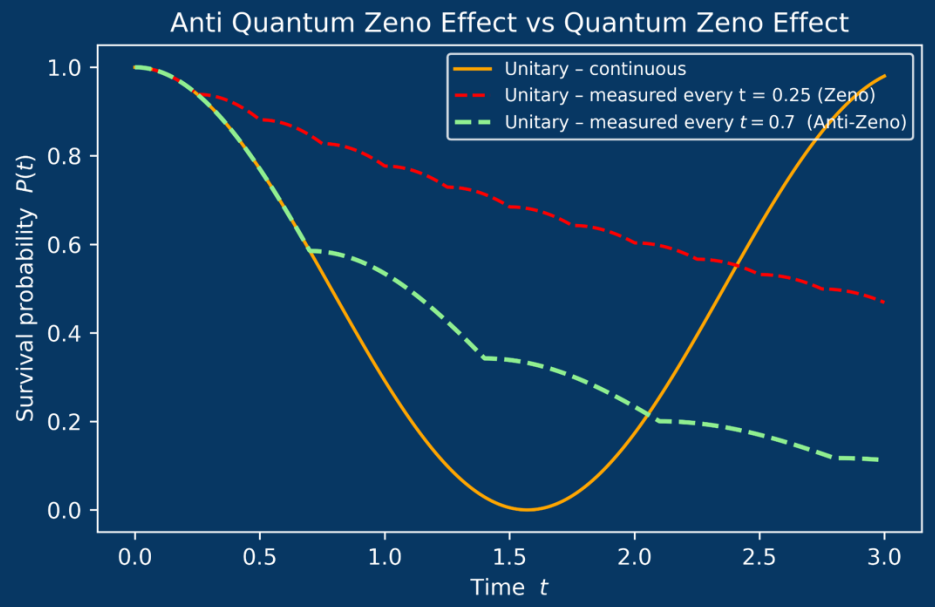

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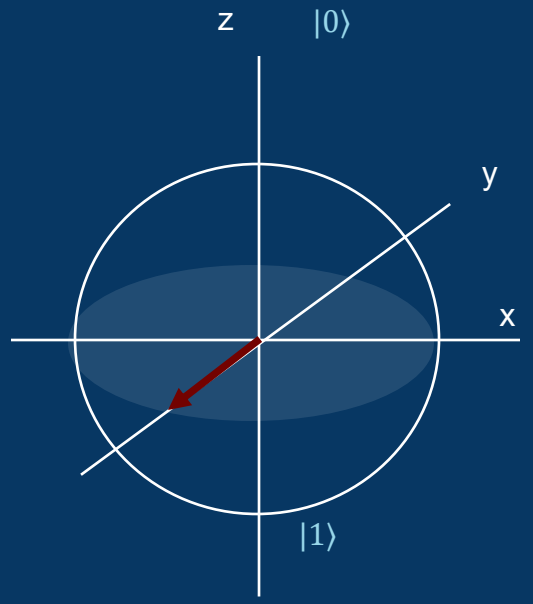

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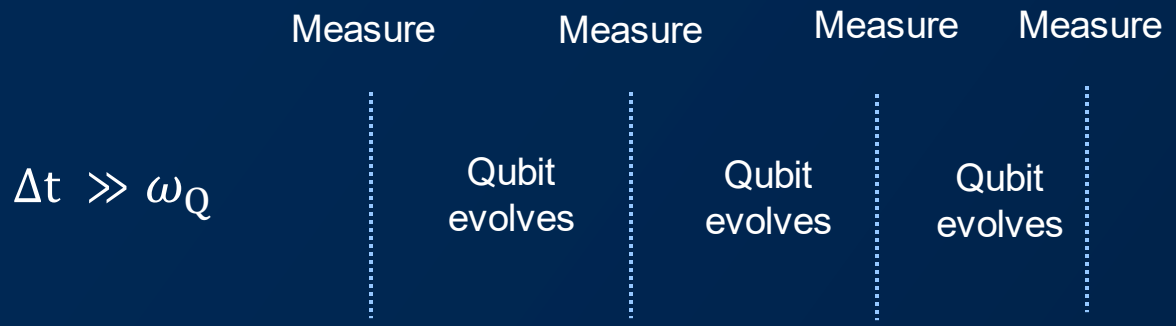

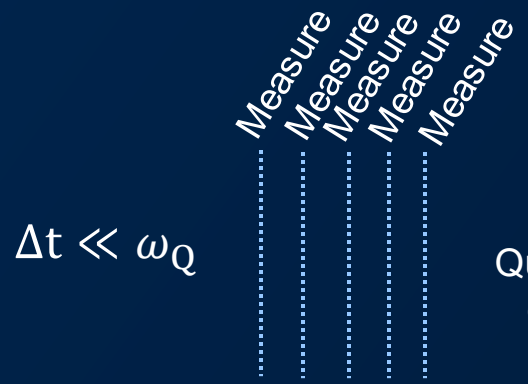

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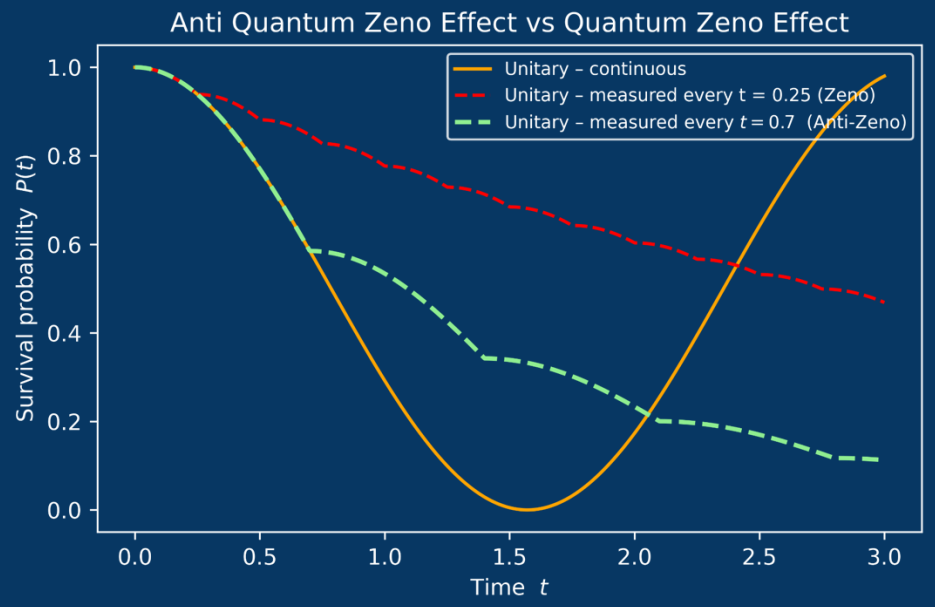

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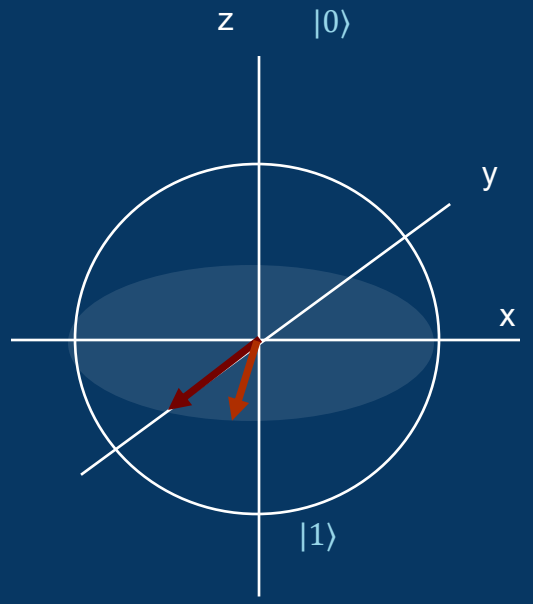

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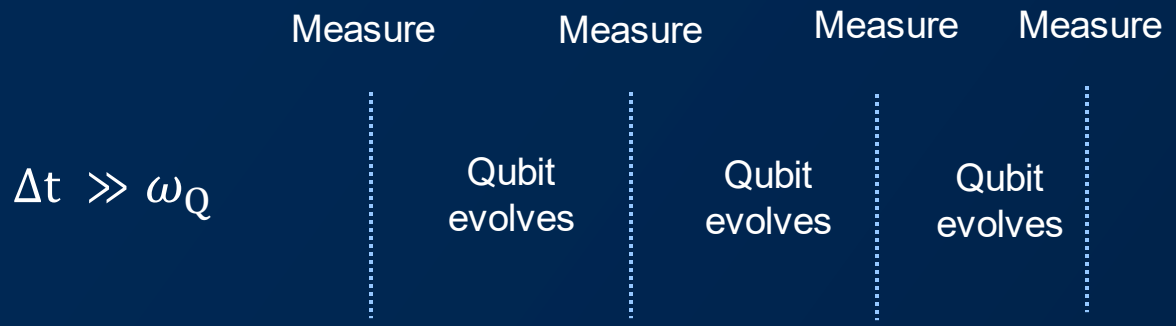

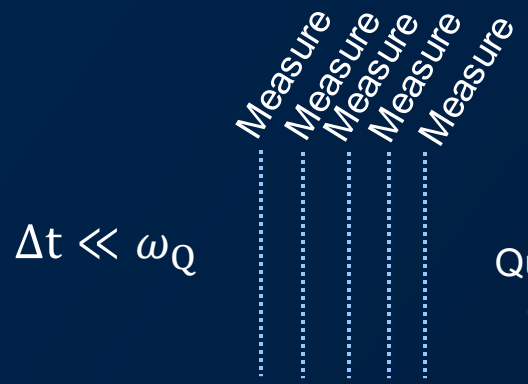

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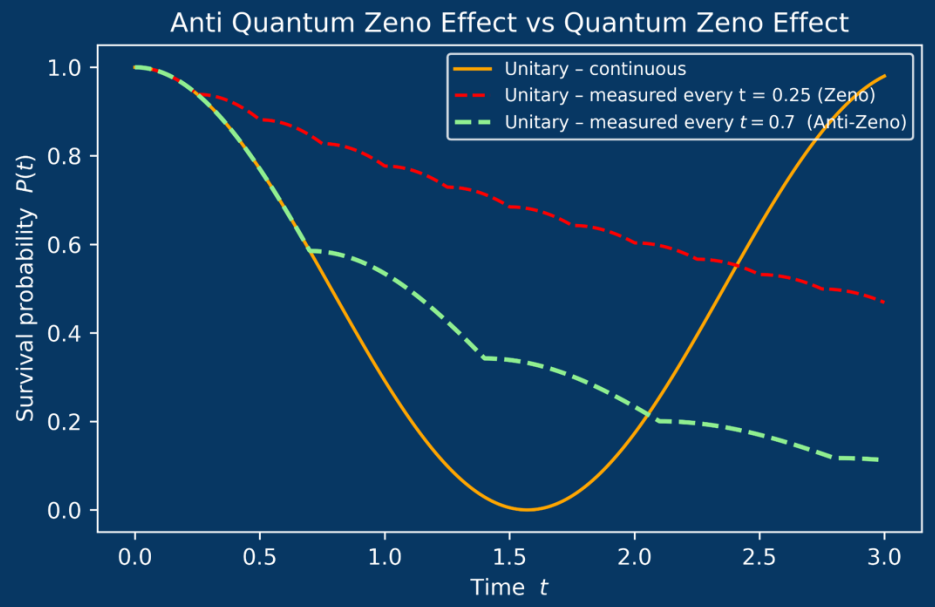

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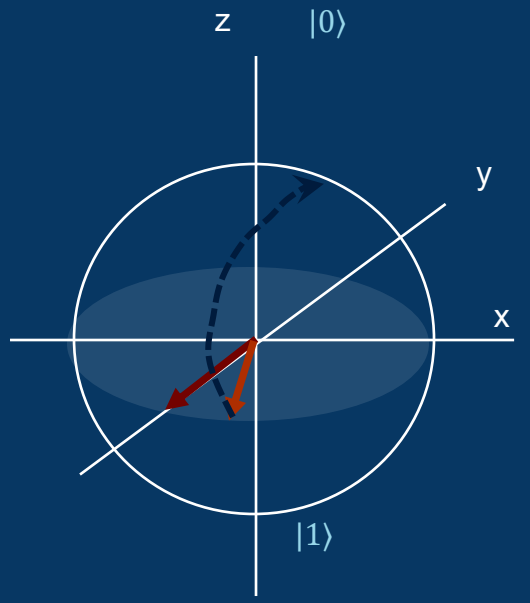

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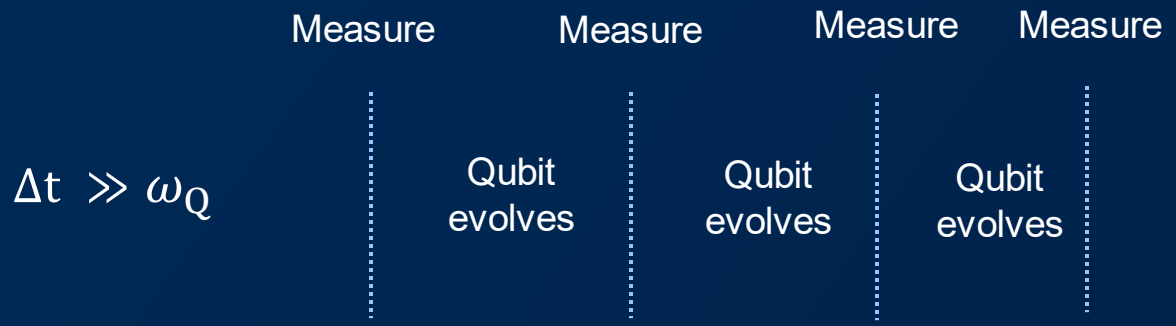

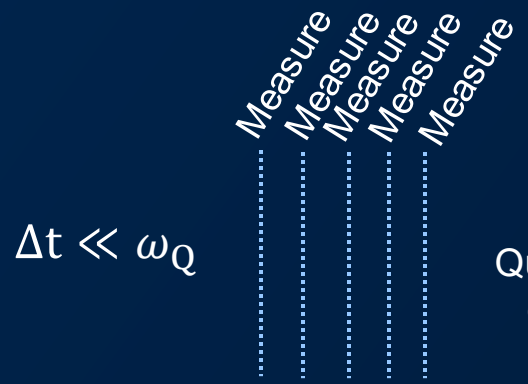

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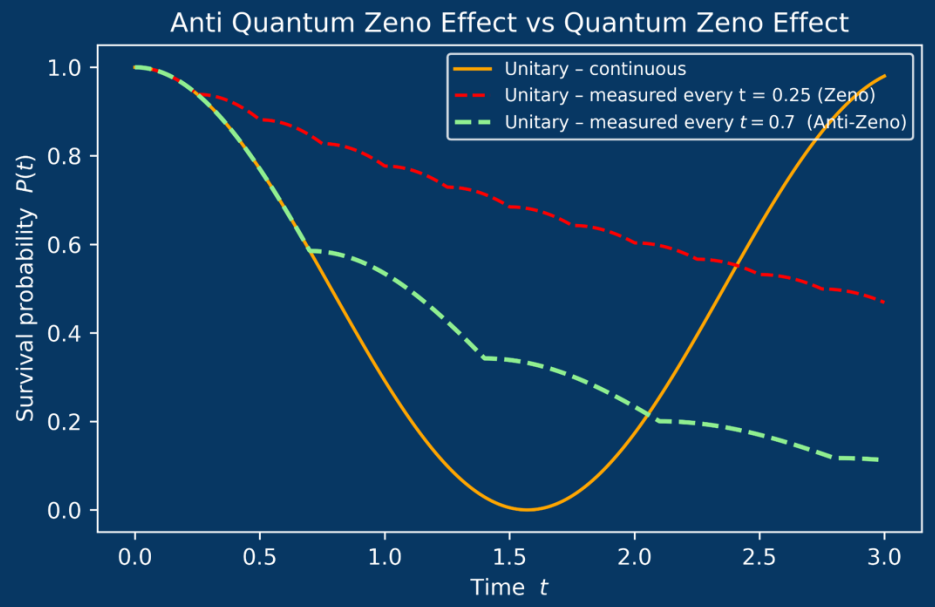

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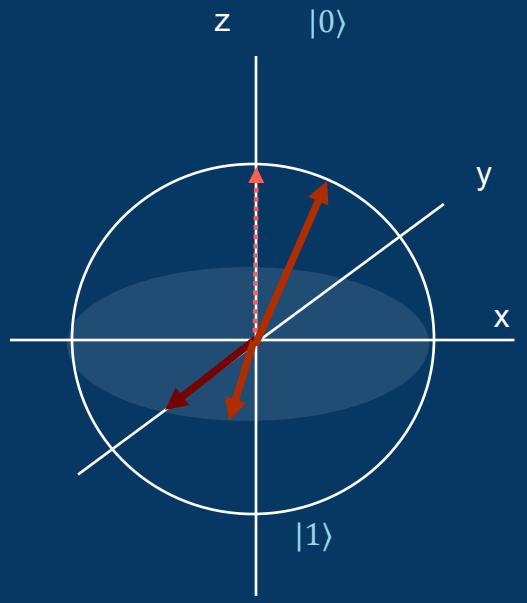

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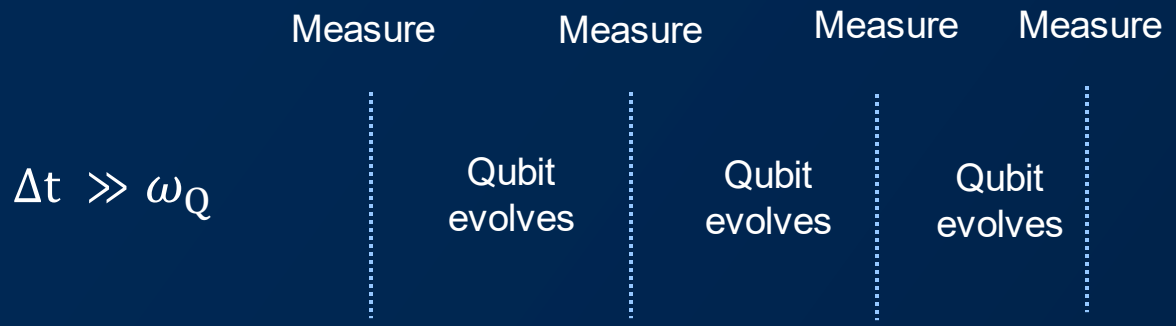

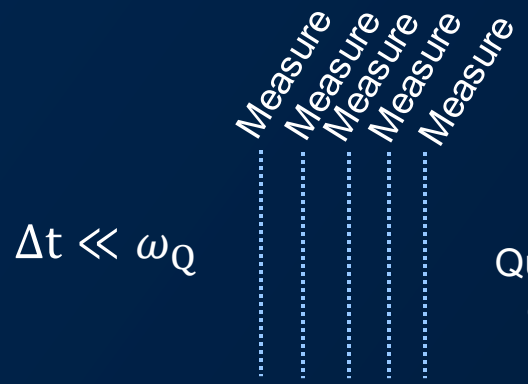

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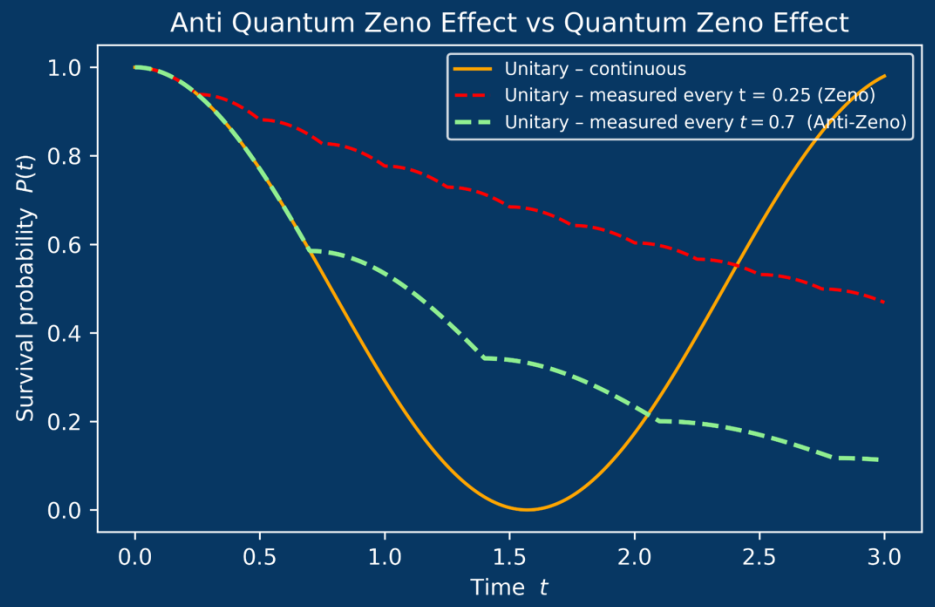

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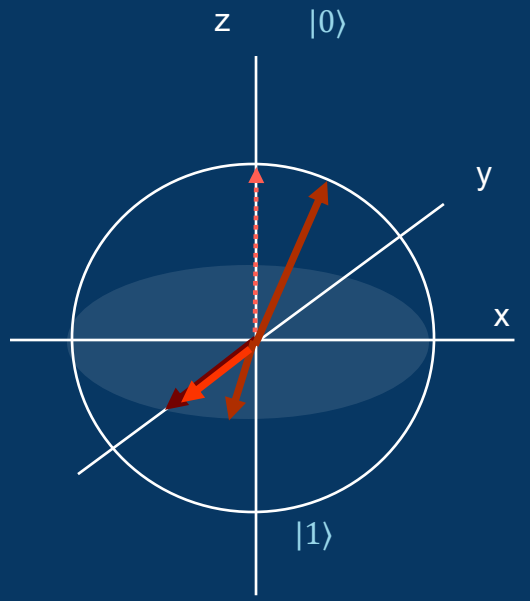


Motivating questions

How does the Quantum Zeno Effect propagate through entangled systems?

Hypothesis 1: If a stronger QZE is induced on a single quantum system, the amount of entanglement possible with other qubits will decrease

Control

Maximally entangle two qubits A and B

Measure:

$Tr(\rho_A^2) = Tr(\rho_B^2) = ½$

$Tr(\rho_{AB}^2) = 1$

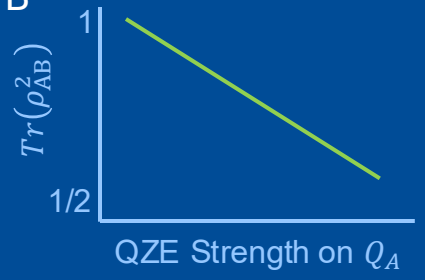
Experiment

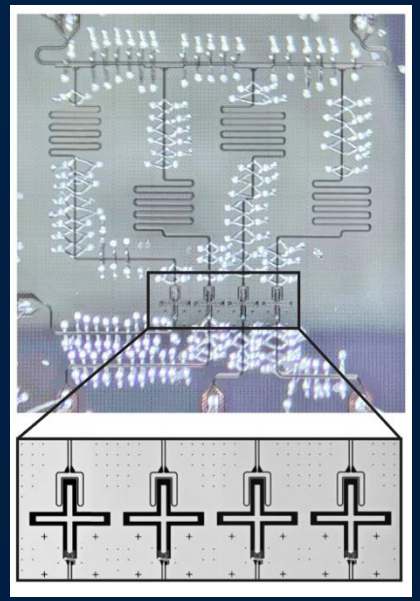
Apply projective measurements on A and then maximally entangle with B

Measure:

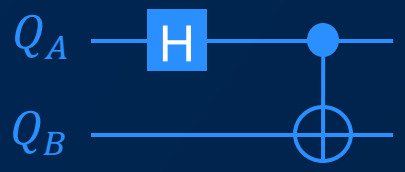
$Tr(\rho_A^2) = Tr(\rho_B^2) = ½$

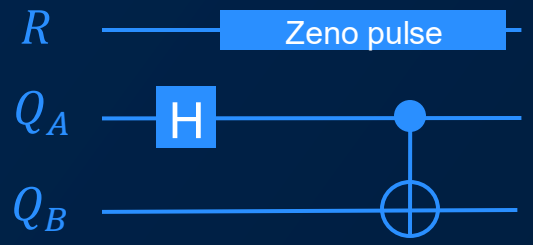
$Tr(\rho_{AB}^2) < 1$





Du PRL 133, 060601 (2024)





Hadamard gate = puts qubit in superposition

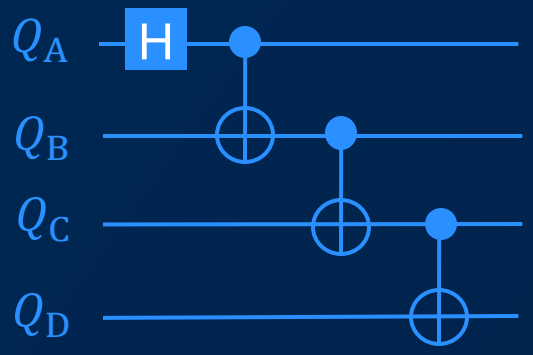
CNOT gate = maximally entangles qubits

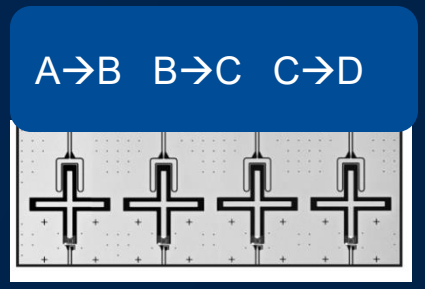
Motivating questions

How does the Quantum Zeno Effect propagate through entangled systems?

Hypothesis 2: As QZE is induced on a qubit locally that is a part of a larger system of entangled qubits, how does the Zeno freezing propagate?

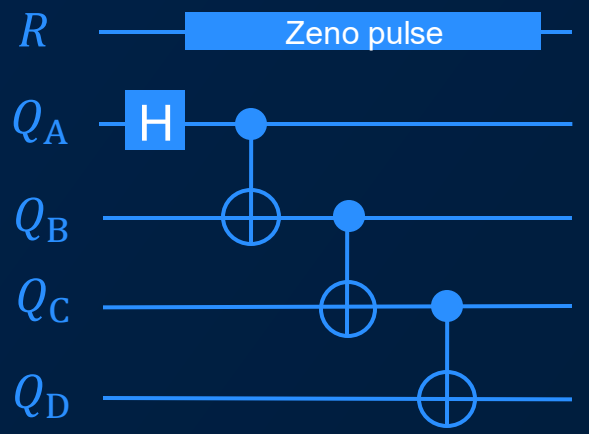
Entanglement chain of pairwise couplings across 4 qubits





Du PRL 133, 060601 (2024)

Induce the QZE on Q_A, and measure how much freezing happens on B, C and D subsequently



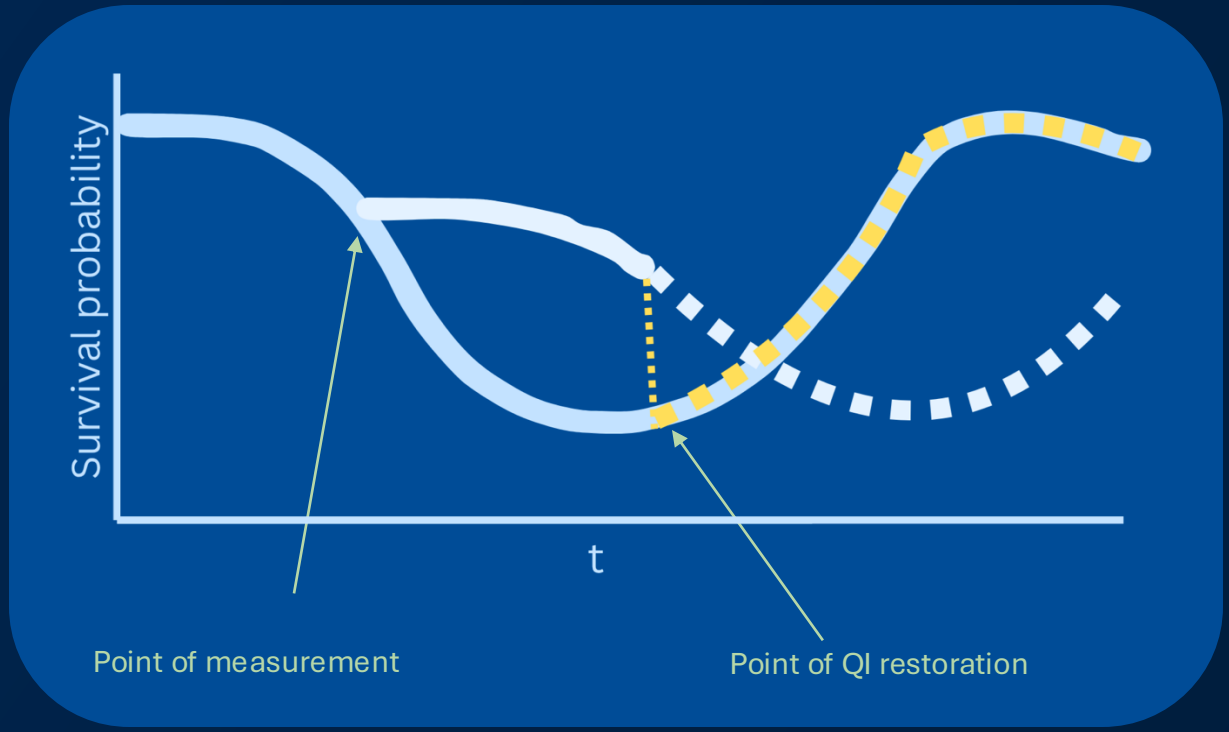
Motivating questions

Is quantum information conserved when the wavefunction collapses?

If quantum information is conserved: I should be able to restore the qubit's natural time evolution as if it were to have never become entangled with an experimenter/measurement drive.

If quantum information is not conserved: the qubit will permanently lose some information in the partial collapse/measurement process, and the qubit will never fully rebound to its natural unperturbed trajectory

QZE-inspired experiment:



Motivating questions

Can we use superconducting qubits to test if a quantum system in superposition experiences gravity?

A gravitational redshift measurable in Ramsey fringes

Ramsey fringes are caused by a phase difference between the qubits frequency and the photons used to drive the qubit (H gate)

Control:

Drive photons *generated at the same gravitational potential* = No noticeable shift

Qubit + drive 100m underground (same height) and run Ramsey– no shift in fringes.

Experiment:

Drive photons *generated at a different gravitational potential* = acquired phase in fringes

Qubit 100m underground, drive on the surface and run Ramsey– any redshift? (Calibrate out drive photons redshift)

$$\phi_g = \frac{g\,\omega\,\Delta h\,T_{2Reff}}{c^2}$$

Balatsky PRA 111, 012411 (2025)

→ N entangled qubits → sensitivity approaches the Heisenberg limit, scaling with 1/N. → $N*\phi$ phase shift scaling

→ With 128 entangled qubits 100m underground and a T2 coherence time of 500ms you would see a 1 degree shift

Superconducting qubits for particle detection and fundamental tests of quantum mechanics

Motivating questions for near-term experiments

Experimental requirements to pursue these experiments

Recent experimental work to fulfill those requirements (the Quantum Zeno Effect)

Experimental requirements for near-term experiments

- A very well-shielded, well-characterized underground testbed for quantum sensing/gravitational red shift experiments
- The ability to control qubits and nearby two-level system defects with the Quantum Zeno Effect
- The ability to entangle qubits with high fidelity
- The ability to design qubit devices optimally for quantum sensing experiments

Superconducting qubits for particle detection and fundamental tests of quantum mechanics

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A walk through my research towards building robust, low background sensors to studying new physics

1. We can use qubits as particle detectors

2. What a superconducting qubit is and how it can be used for sensing

3. Backgrounds to a particle event, “Two Level Systems” and cosmic rays

4. Making better qubit designs to target specific interactions

5. A background free overlook

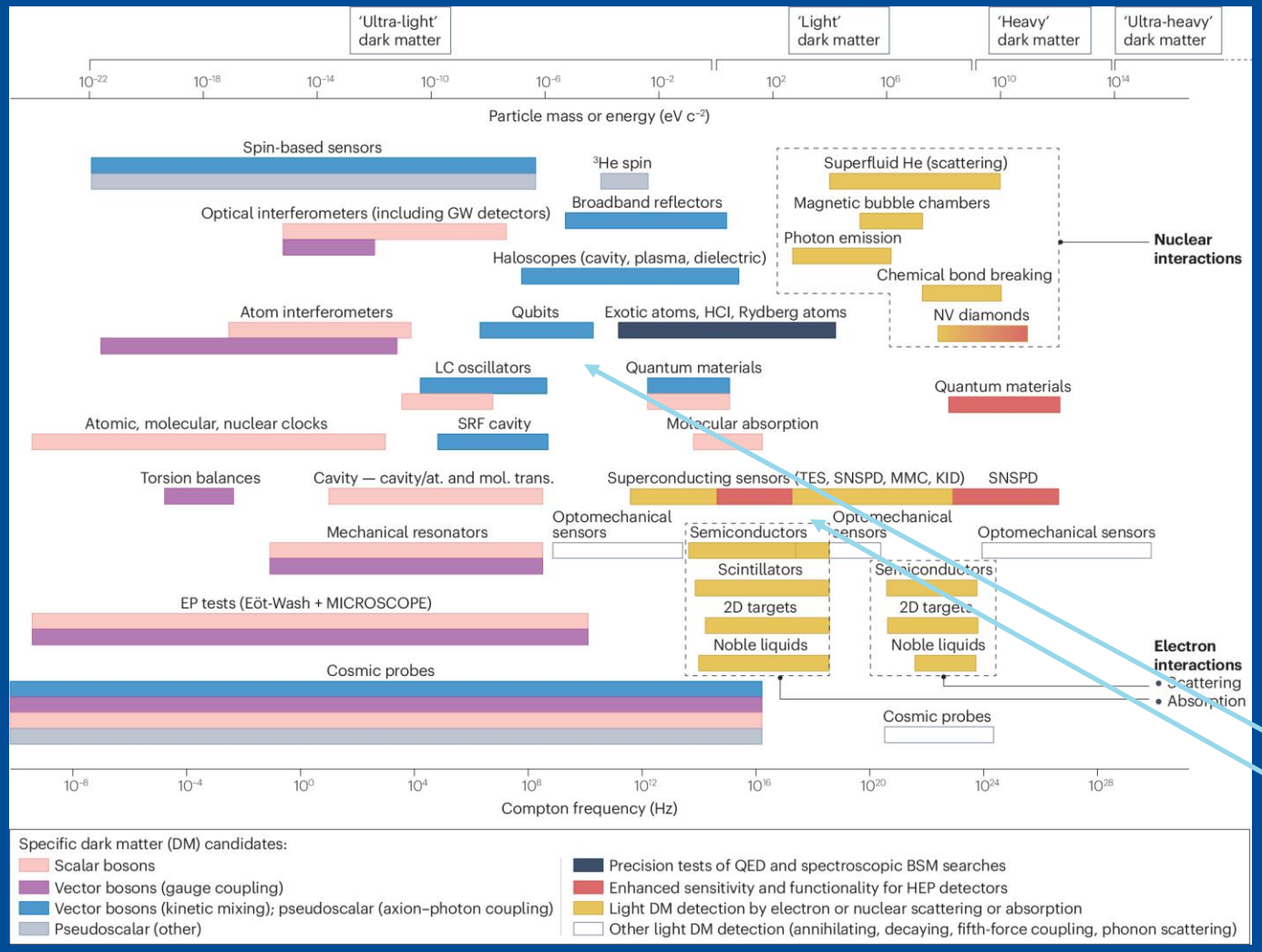
5. The Quantum Zeno Effect and how we can leverage it

A walk through my research towards building robust, low background sensors to studying new physics

1. We can use qubits as particle detectors

The next generation of breakthroughs in physics will come from very sensitive detectors

Direct detection dark matter techniques



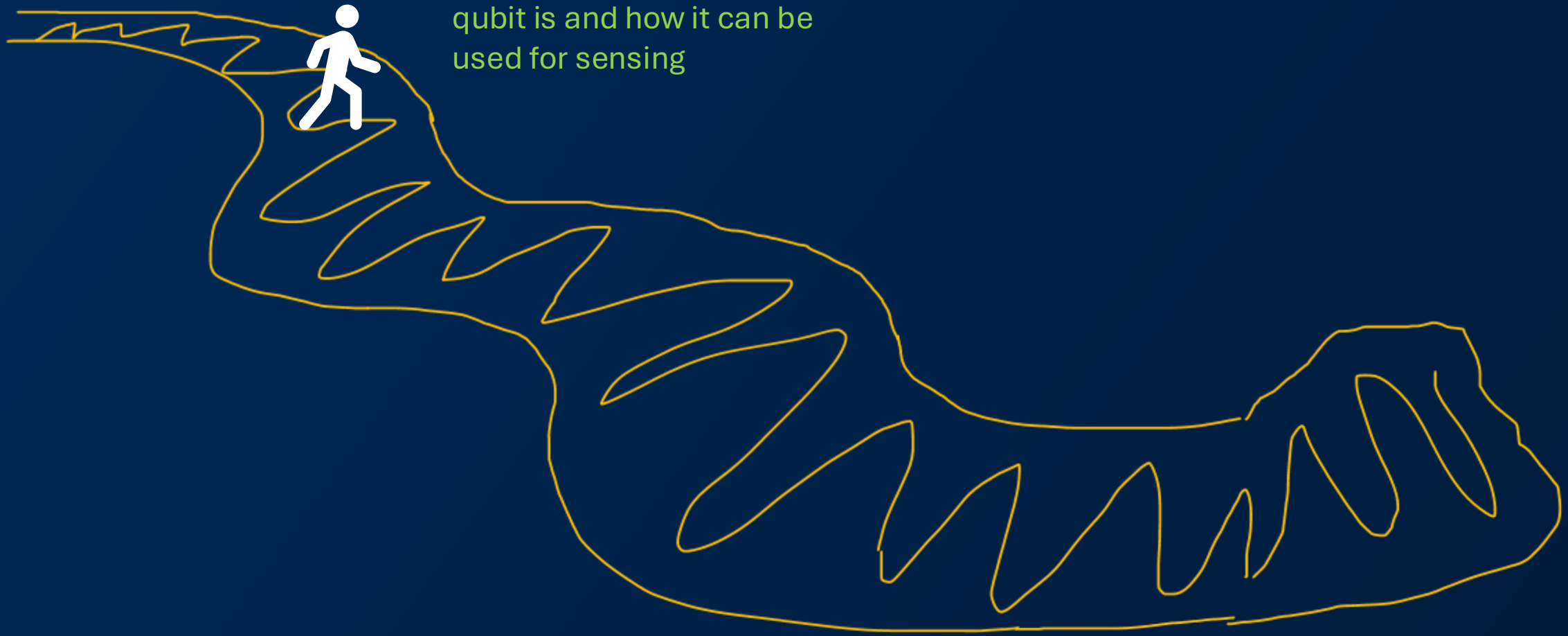
10.1038/s42254-024-00714-3

SC qubit-based sensors enable meV detection

Building robust, low background sensors to studying new physics

1. We can use qubits as particle detectors

2. What a superconducting qubit is and how it can be used for sensing



Superconducting qubits are promising candidates for low energy detection

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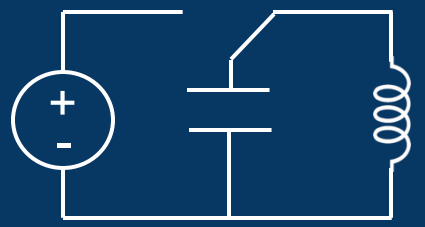
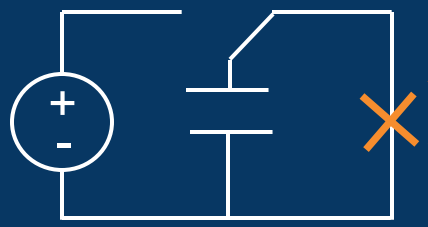
LC circuit



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

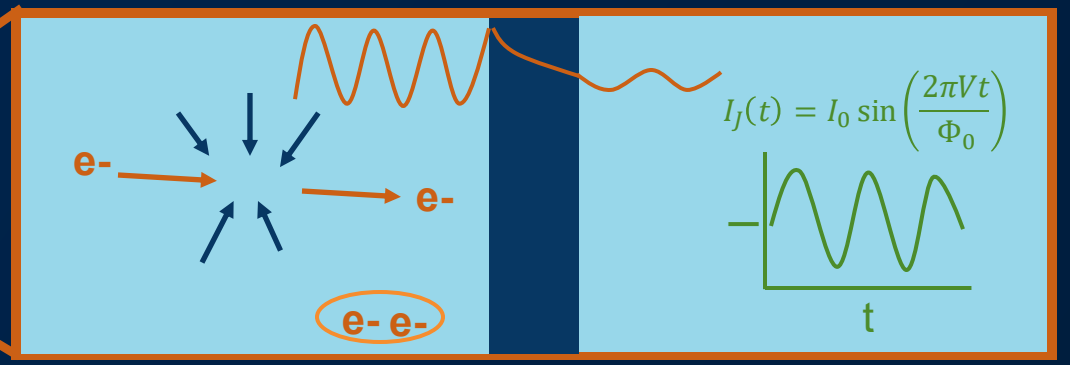
$$\hat{H} = \frac{\hat{Q^2}}{2C} + \frac{\hat{\Phi^2}}{2L}$$

Superconducting qubit



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

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

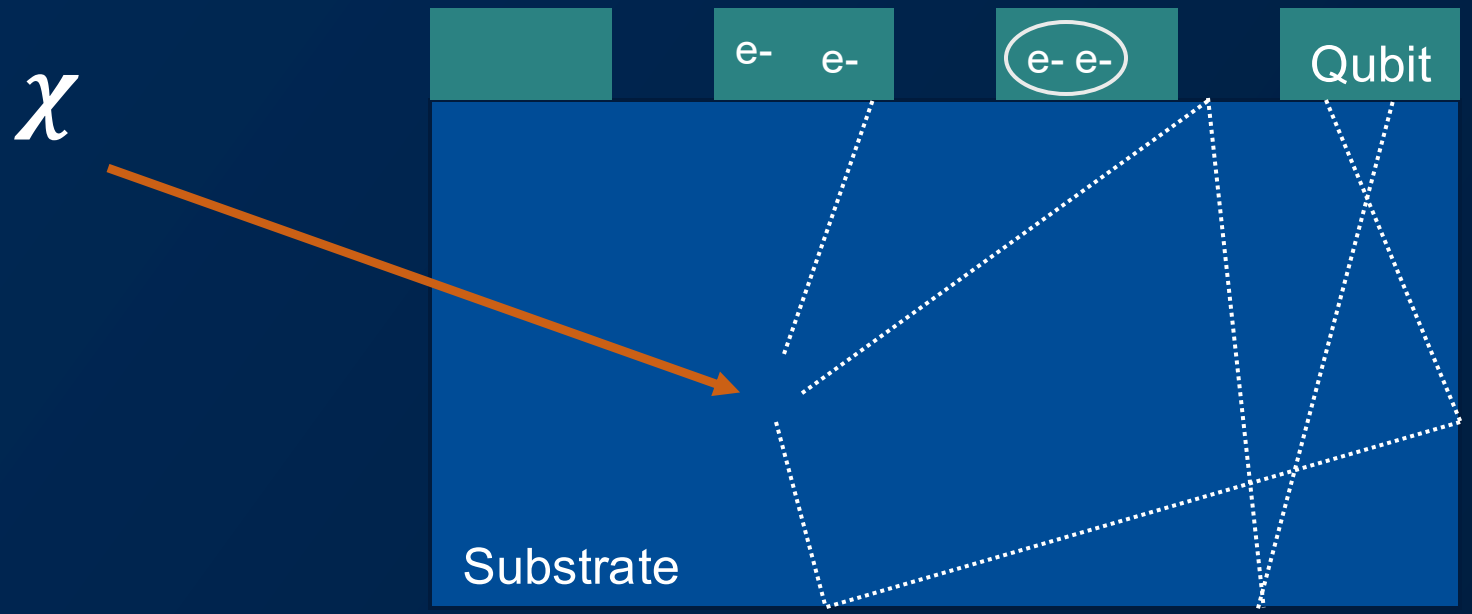


Binding energy of cooper pairs sets energy sensitivity

Supercurrent sets the qubit frequency

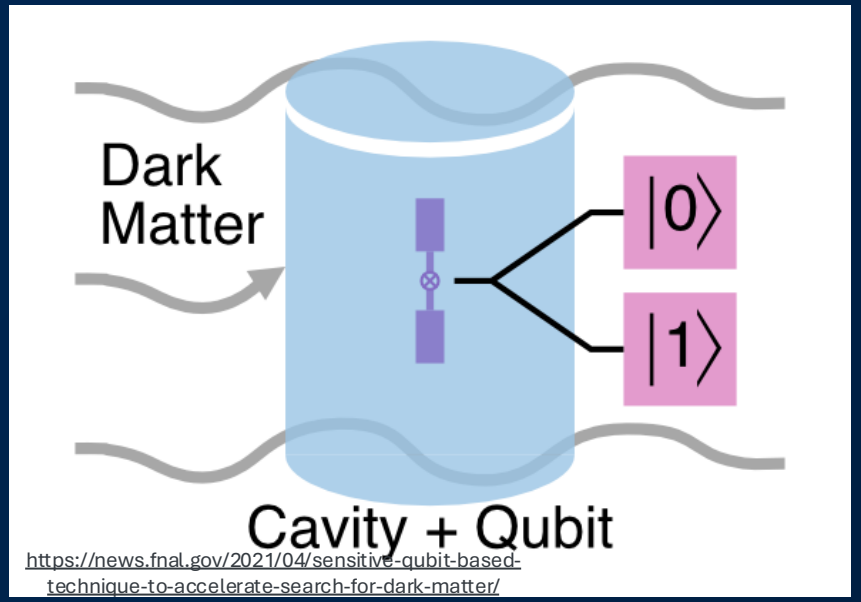
Pair-breaking leads to increased decoherence as a physics signal

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



Proposed sensing schemes using SC qubits

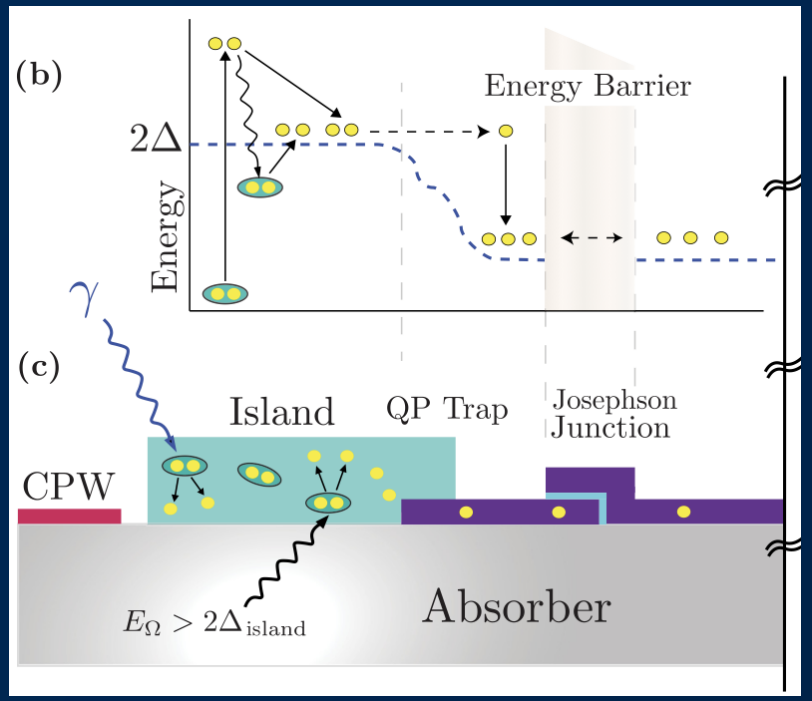
Cavity based hidden photon searches



https://news.fnal.gov/2021/04/sensitive-qubit-based-technique-to-accelerate-search-for-dark-matter/

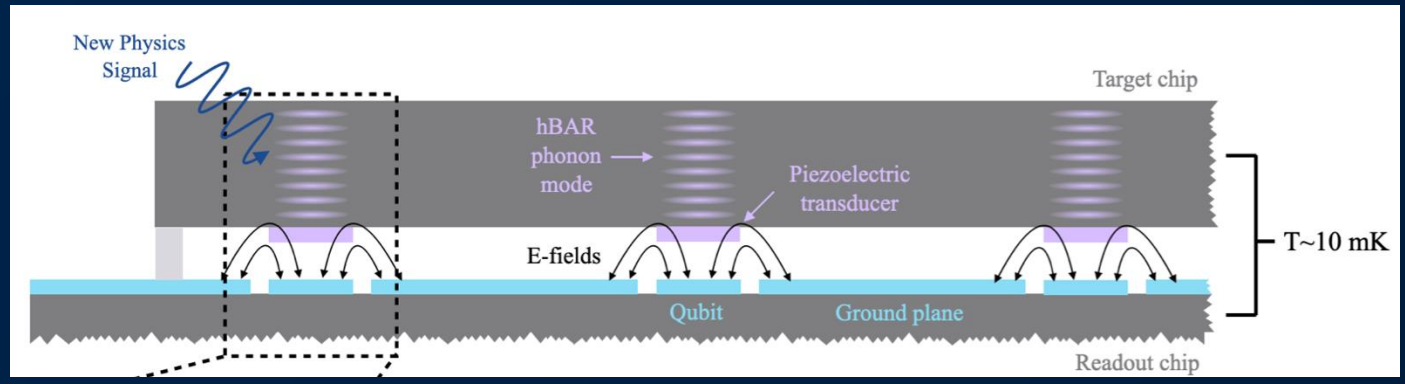
10.1103/clp9-xc2n

Superconducting Quasiparticle-amplifying transmons (SQUATs)



10.1103/PhysRevApplied.22.054009

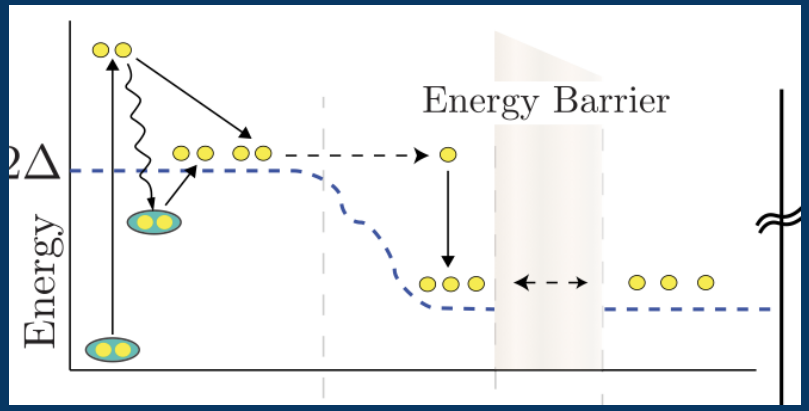
High-overtone Bulk Acoustic Resonators (HBARs)



10.48550/arXiv.2410.17308

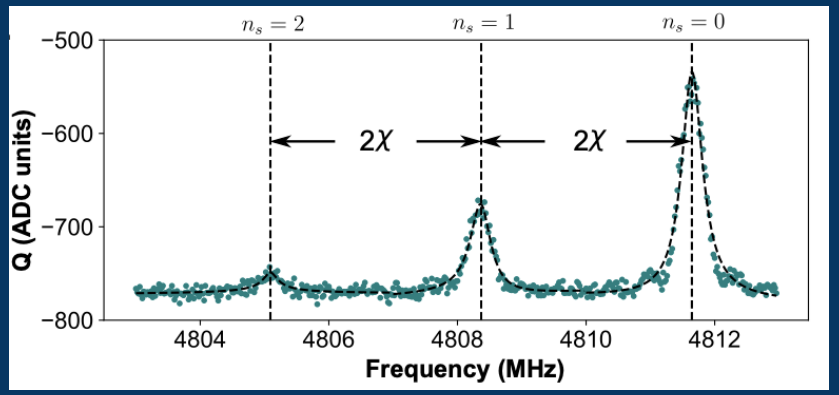
All of these sensing mechanisms use qubit frequency shifts as the detection medium

Superconducting Quasiparticle-Amplifying Transmons (SQUATs)



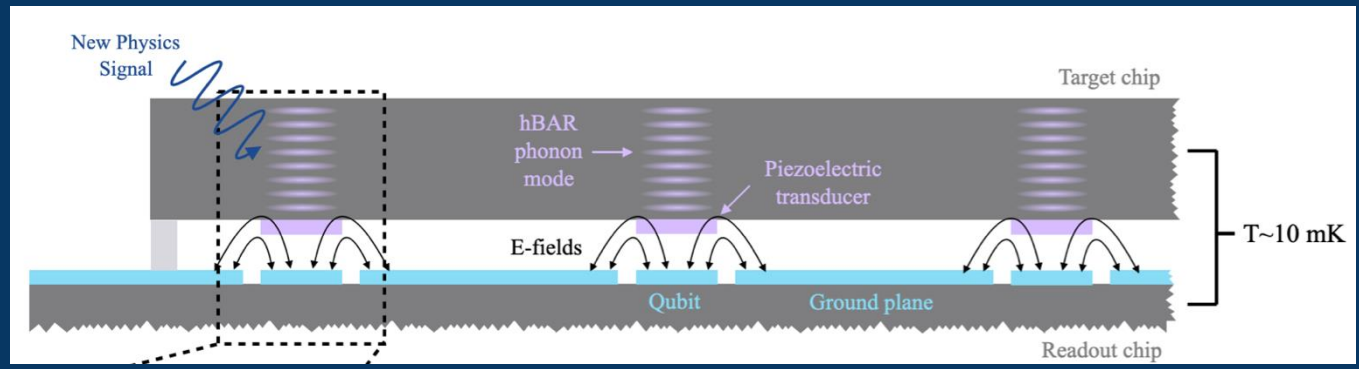
Quasiparticles shift the qubit frequency through tunnelling events (10.1103/PhysRevApplied.22.054009)

Cavity based hidden photon searches



Quasiparticles shift the qubit frequency through tunnelling The qubit frequency stark shifts by discrete amounts depending on the number of photons in the resonator (10.1103/clp9-xc2n)

High-overtone Bulk Acoustic Resonators (HBARs)



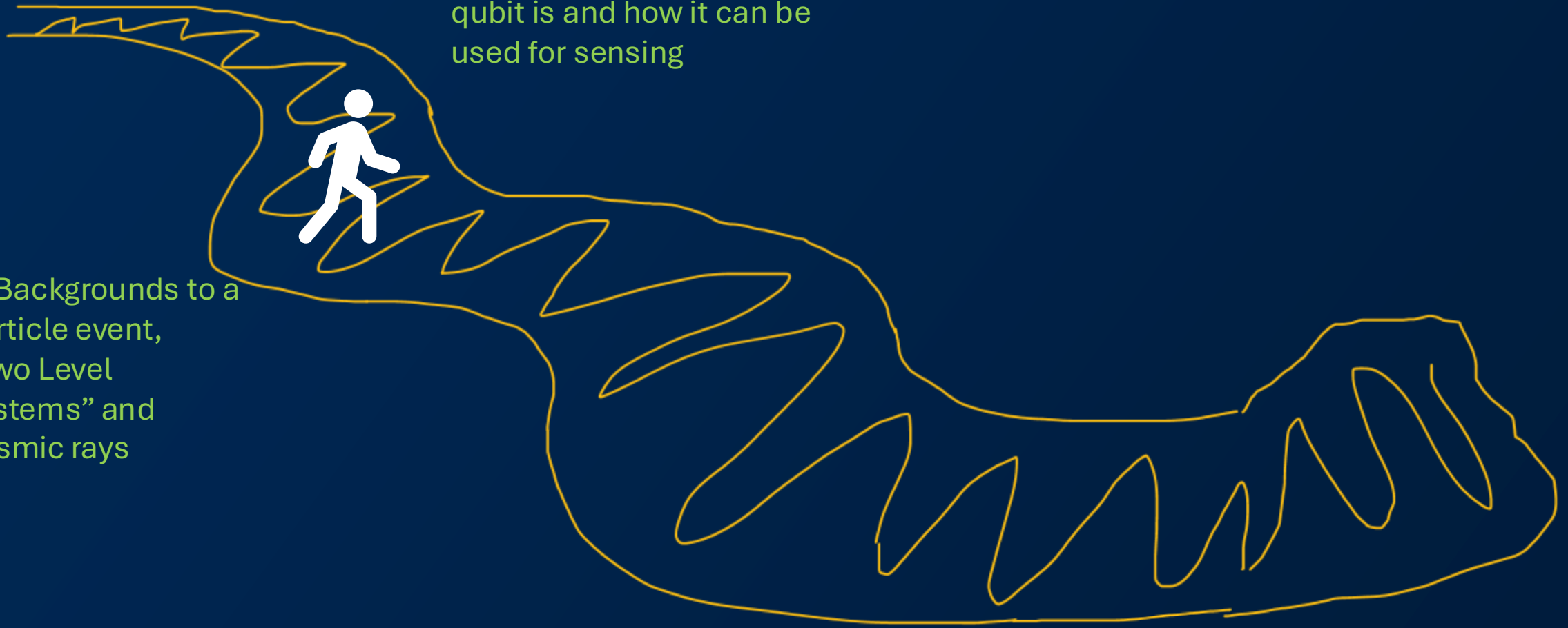
Phonons modulate the qubit frequency via piezoelectric coupling (10.1103/PhysRevX.14.031023)

Building robust, low background sensors to studying new physics

1. We can use qubits as particle detectors

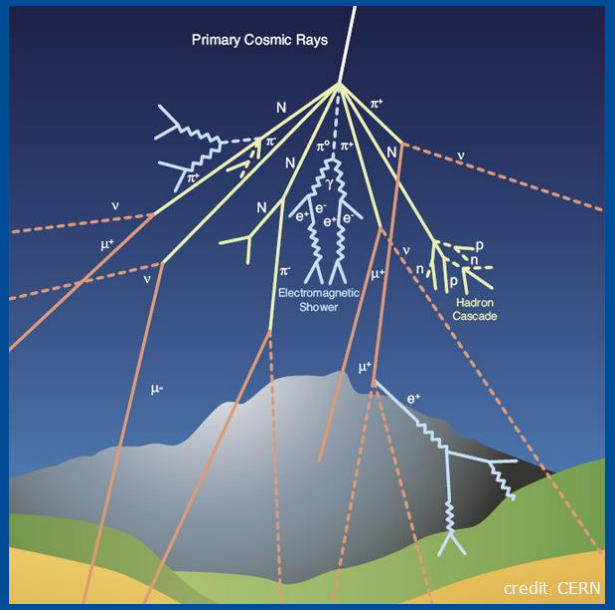
2. What a superconducting qubit is and how it can be used for sensing

3. Backgrounds to a particle event, “Two Level Systems” and cosmic rays

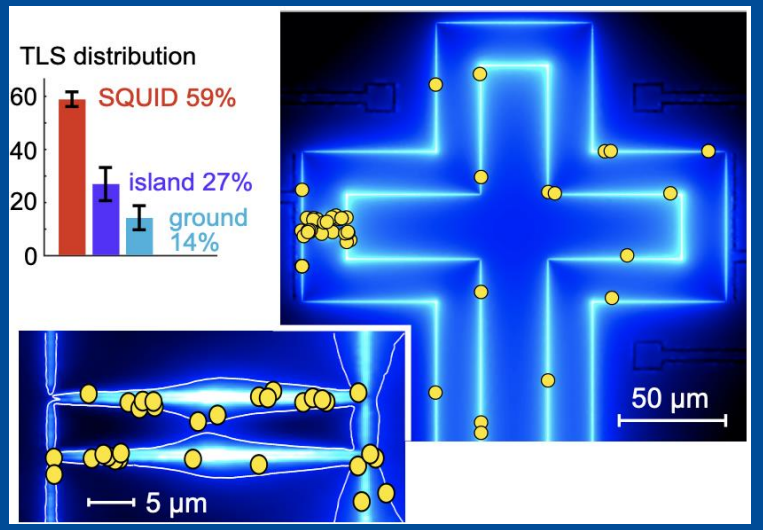


Causes of critical backgrounds in superconducting qubits/quantum sensors

1. Cosmic Rays

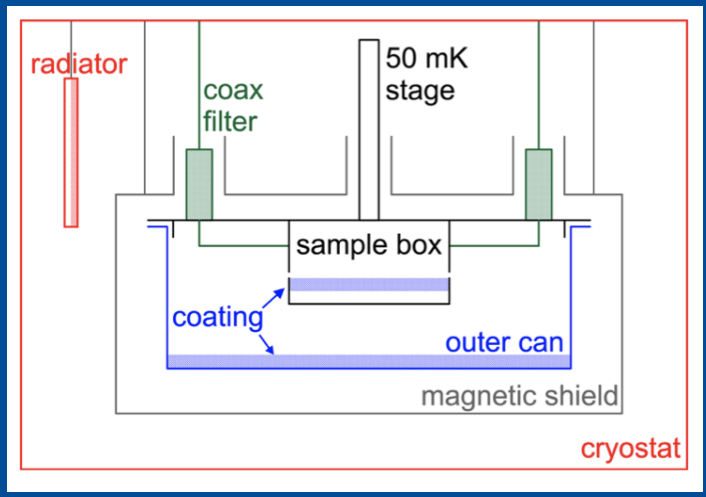


2. Defect Two level systems



10.48550/arXiv.2511.05365

3. IR

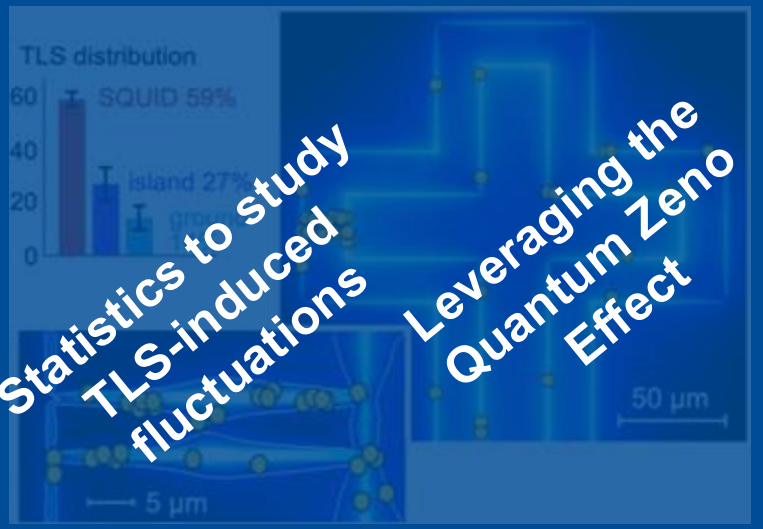


10.1063/1.3638063

Solutions

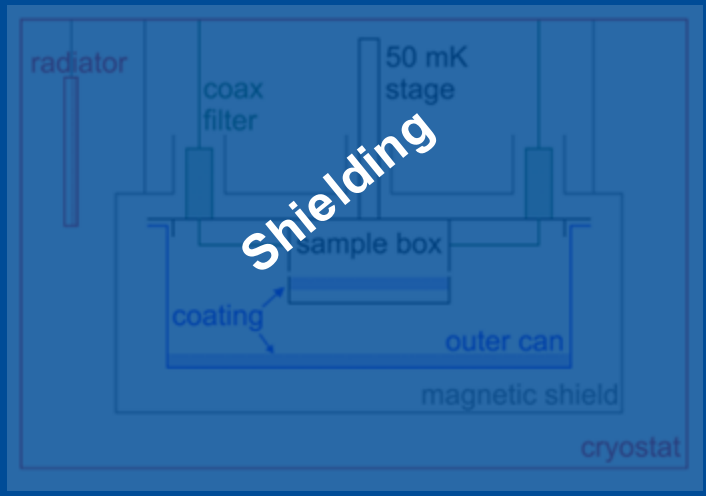
1. Cosmic Rays

2. Defect Two level systems



10.48550/arXiv.2511.05365

3. IR Shielding



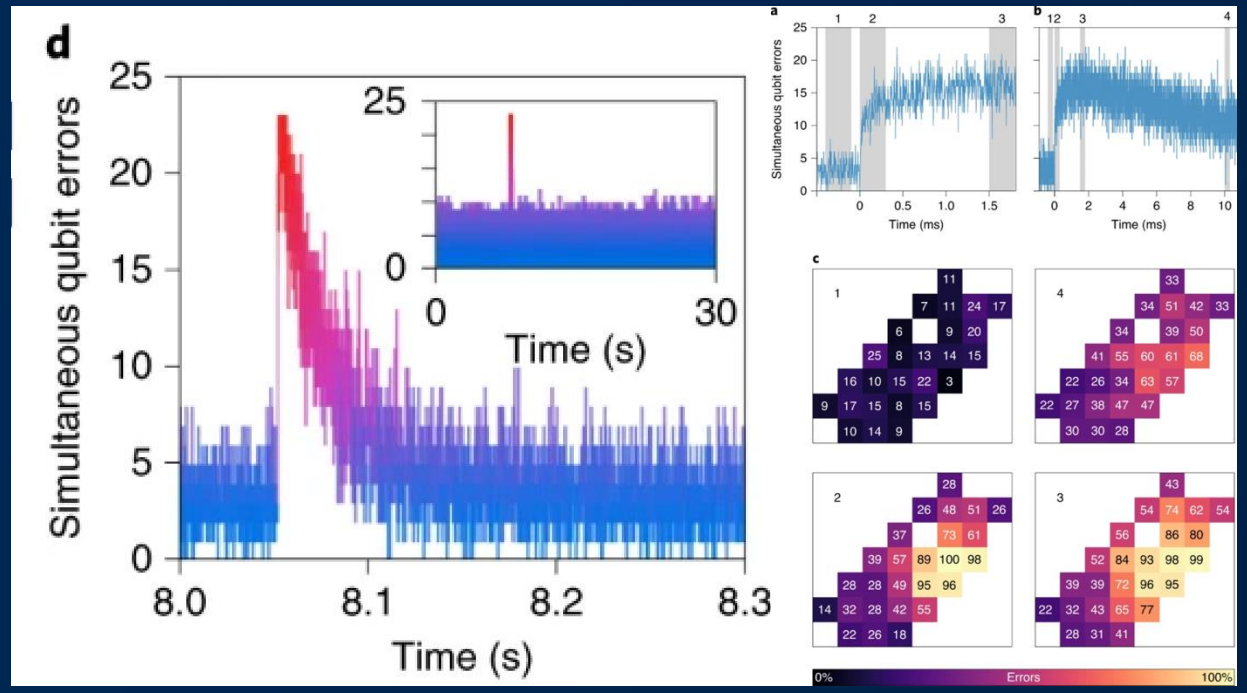
10.1063/1.3638063

Superconducting qubits are great sensors

…so good that cosmic rays become catastrophic

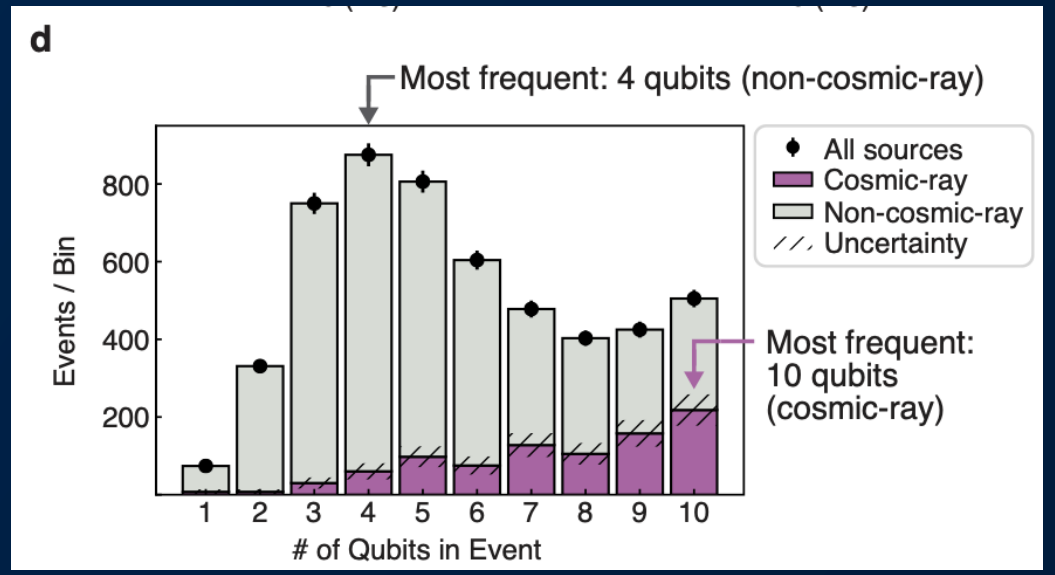
Cosmic ray induced quasiparticles → decoherence

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



10.1038/s41567-021-01432-8

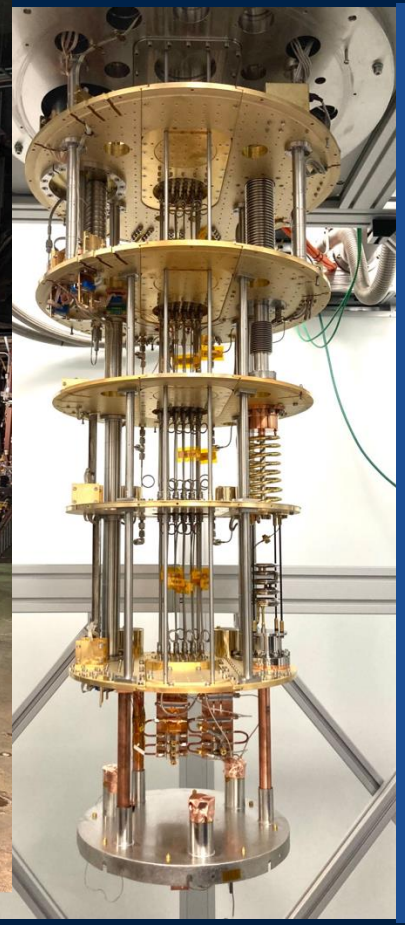
Cosmic rays found to account for 17.1 ±1.3% of spatiotemporally correlated events

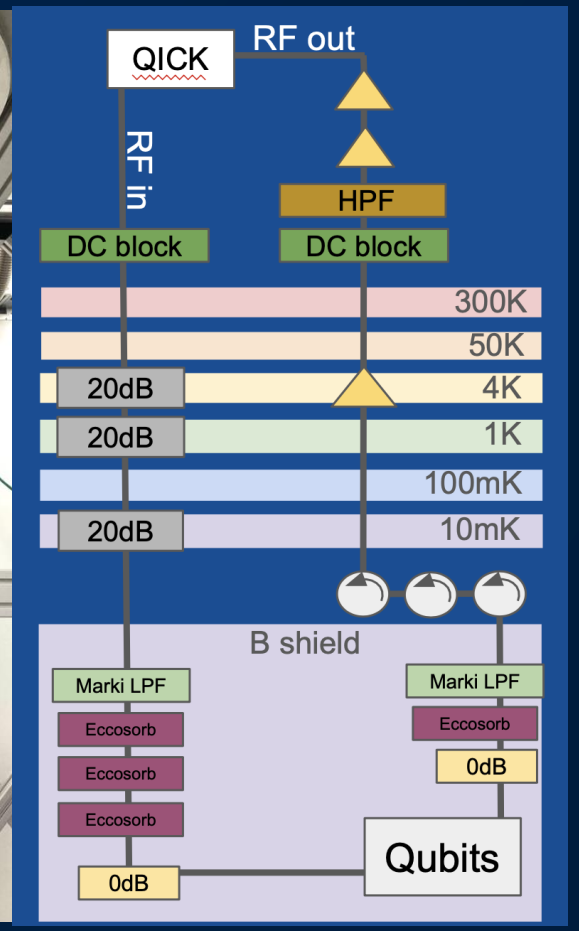


10.1038/s41467-025-61385-x

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)

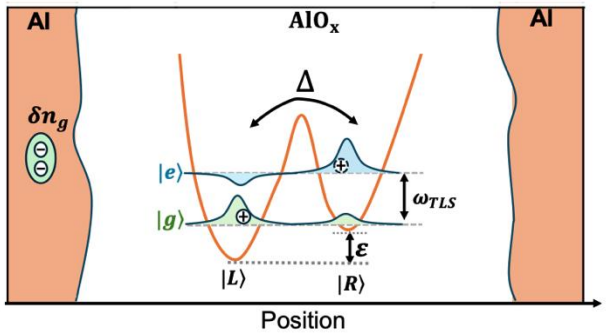




PI: Dan Baxter

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:



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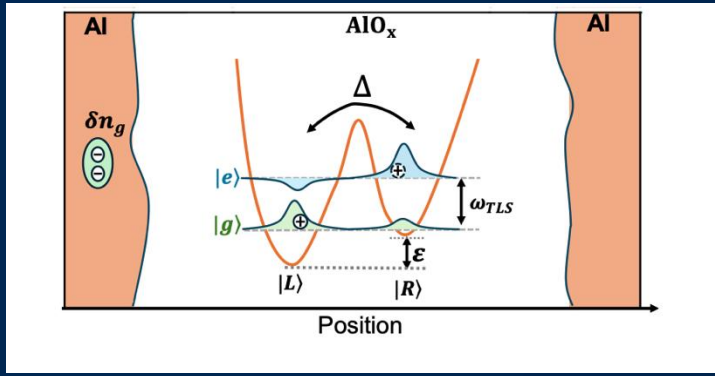
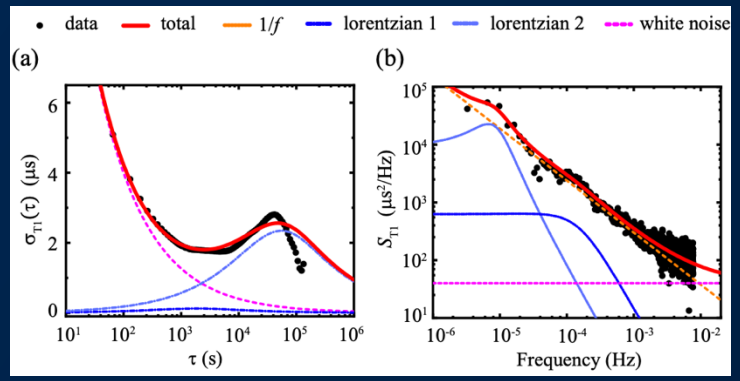
Two-Level Systems (TLSes) are quantum systems caused by material defects in the proximity of superconducting qubits:

These shift the qubit frequency around, and coherence times



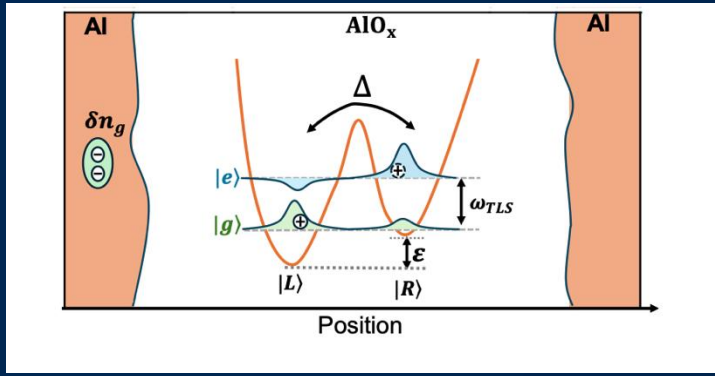


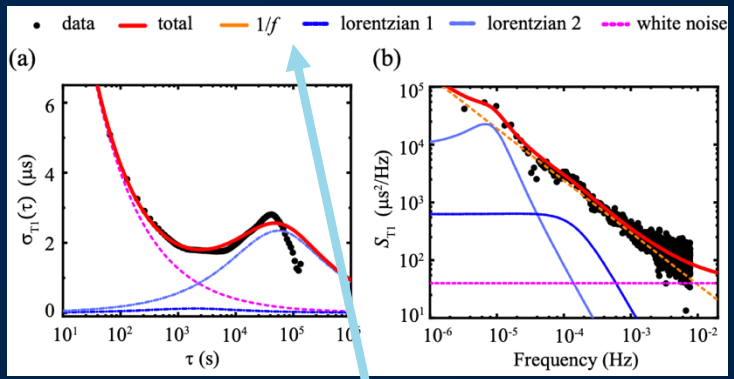
A second insidious source of backgrounds: Two Level Systems (TLSes)

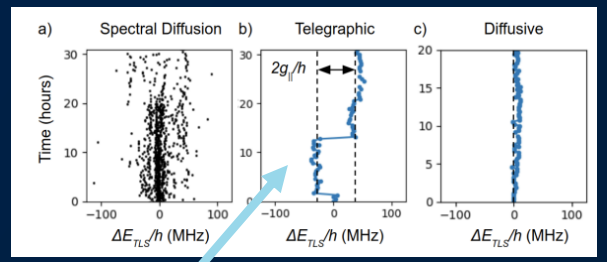
Two-Level Systems (TLSes) are quantum systems caused by material defects in the proximity of superconducting qubits:

These shift the qubit frequency around, and coherence times

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





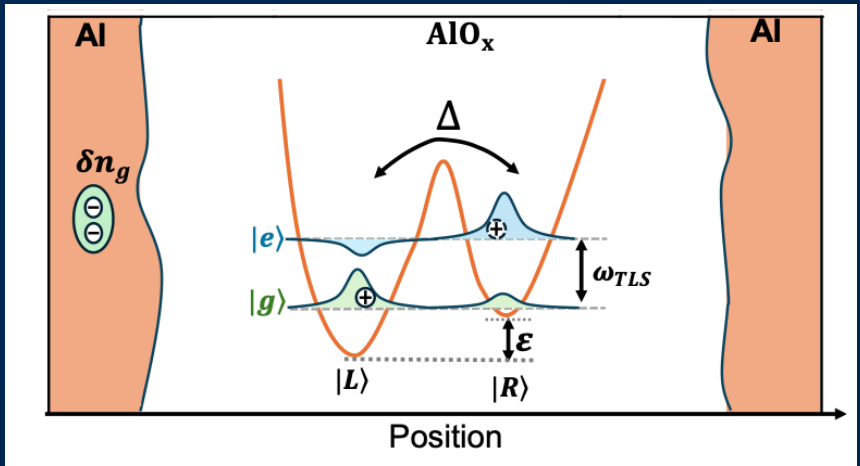


If you are lucky, they will switch at a reliable rate. However, often, this doesn't happen ☹

An insidious source of backgrounds: Two Level Systems (TLSes)

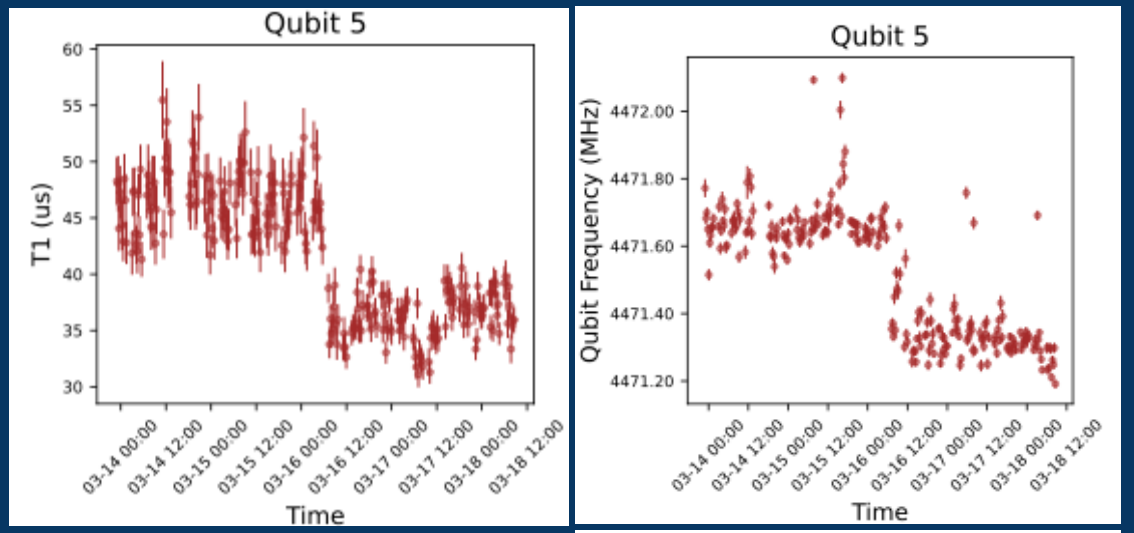
QUIET runs 4/7

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



10.1103/PhysRevLett.133.160602

They change the qubit frequency and coherence times ☹



TLS

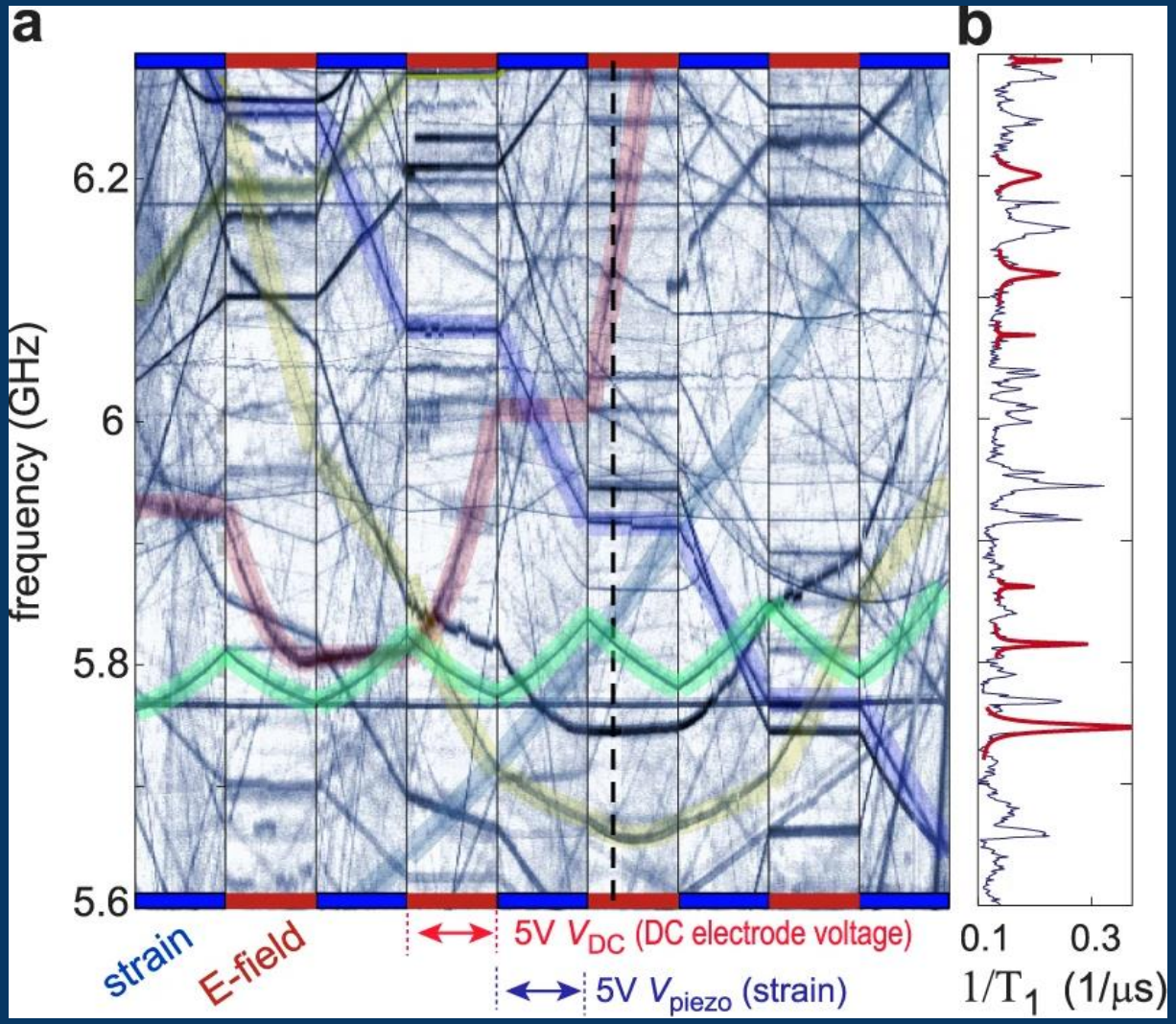
Two photon Transition

Qubit

TLSes are everywhere

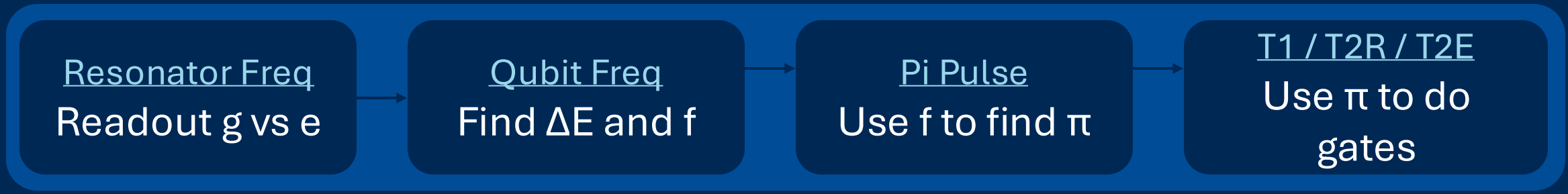
→TLSes show up at ***many frequencies*** and ***change*** depending on the local electric environment, as well as strain environments

→There have been some efforts to mitigate their effects in QC and quantum sensors, like ***cleaner fab*** or ***removing the resonator*** [1][4]



10.1038/s41534-019-0224-1

Microphysics events mess up qubits



If one of these changes, the whole measurement chain feels the effects

Qicklab

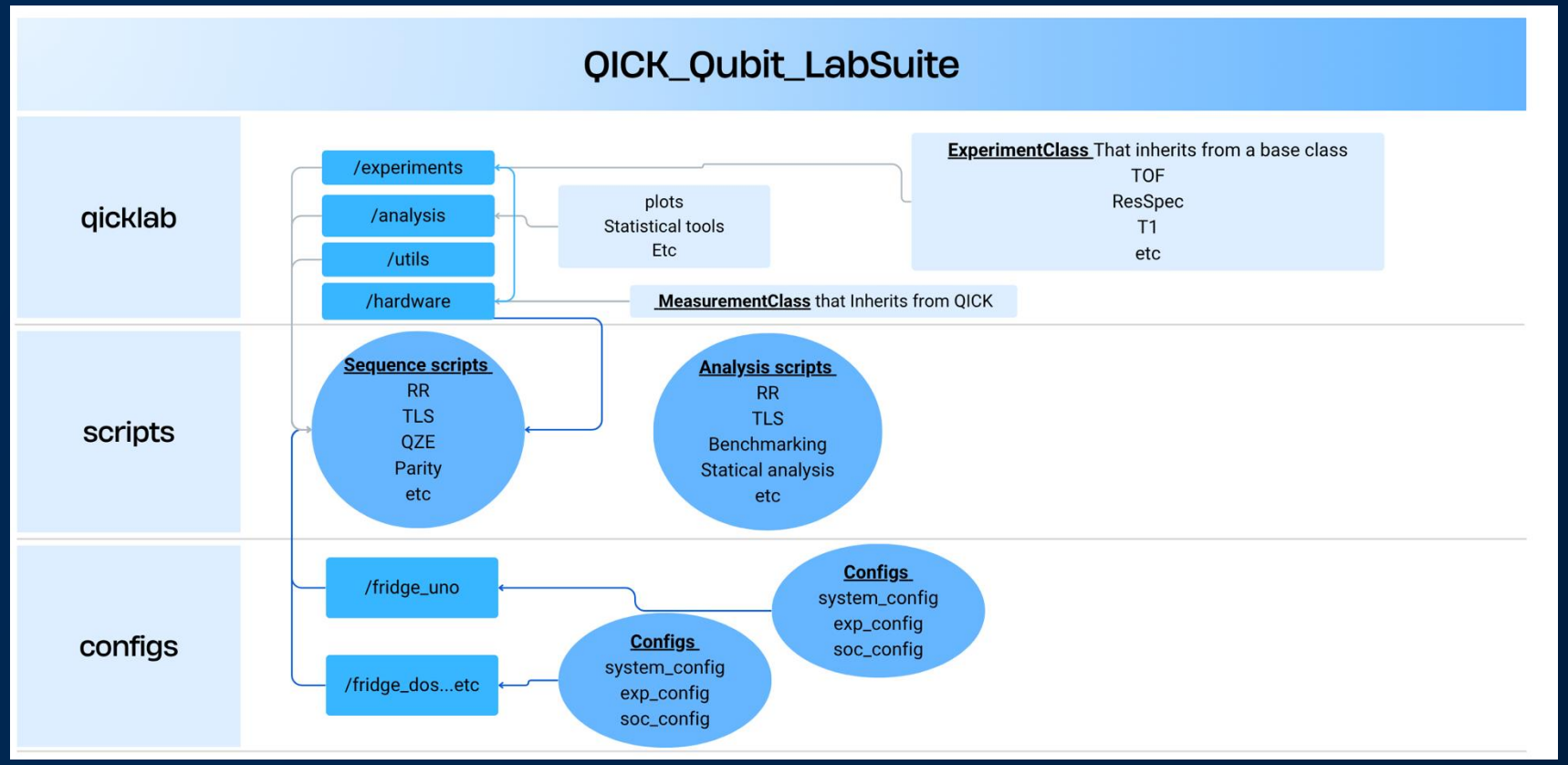
Spectroscopy & Shifts
- Qubit spectroscopy (g-e, e-f, f-h)
- Resonator spectroscopy (g, e, f)
- Bias spectroscopy
- Stark shift using offset qubit frequency
- Resonator Stark shift
- Punch-out (resonator)

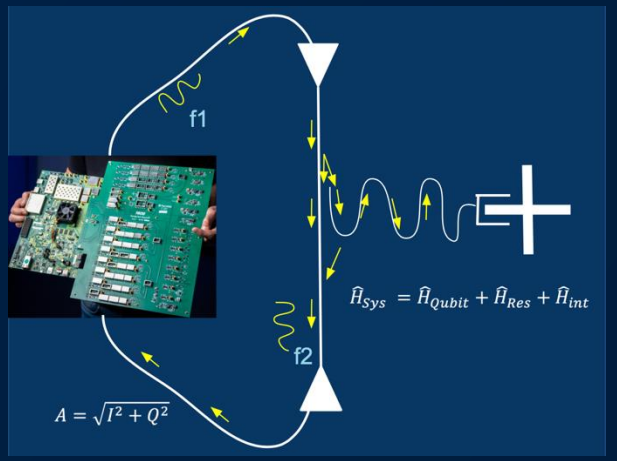
Rabi
- Amplitude (g-e, e-f, f-h)
- Length
- g and e-state Populations

Readout / Calibration
- Single-shot: g-e, g-e-f, g-e-f-h

Coherence
- T1 (g-e, e-f, f-h)
- T1/T2* with Zeno (g-e, e-f, f-h)
- T2* Ramsey (g-e)
- T2 Echo (g-e)
- Dynamical Decoupling

Tomography
- Charge tomography



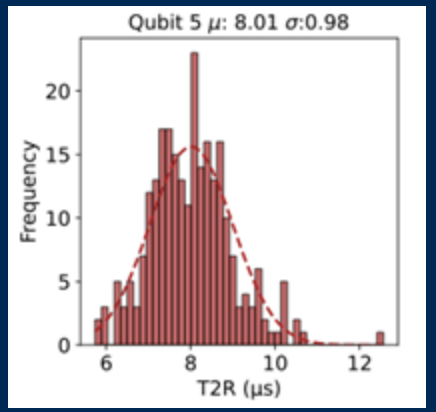


To understand microphysics….

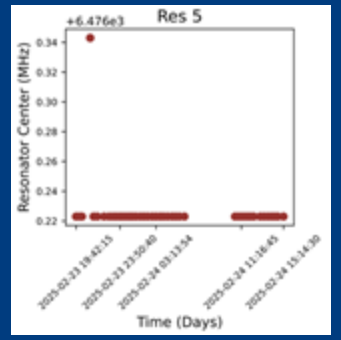
Led development of a codebase for new version of QICK tprocv2

Made a ‘Round Robin’ script - tunes up metrics and monitors over time

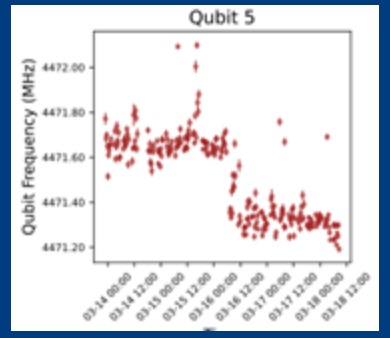
Opens doors for microphysics studies, like Two Level System (TLS) dynamics, temperature dynamics, getting statistics



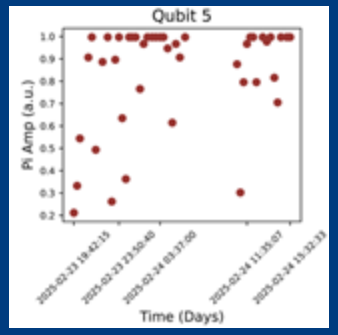
Res Frequency



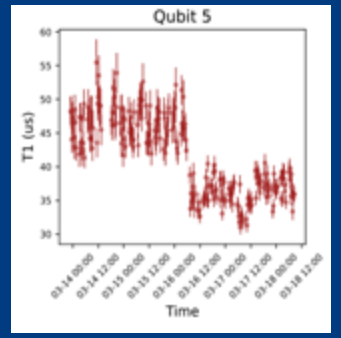
Qubit Frequency



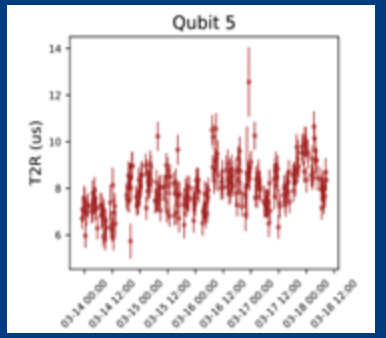
Pi Amp



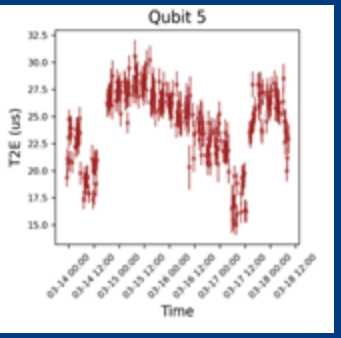
T1



T2R



T2E



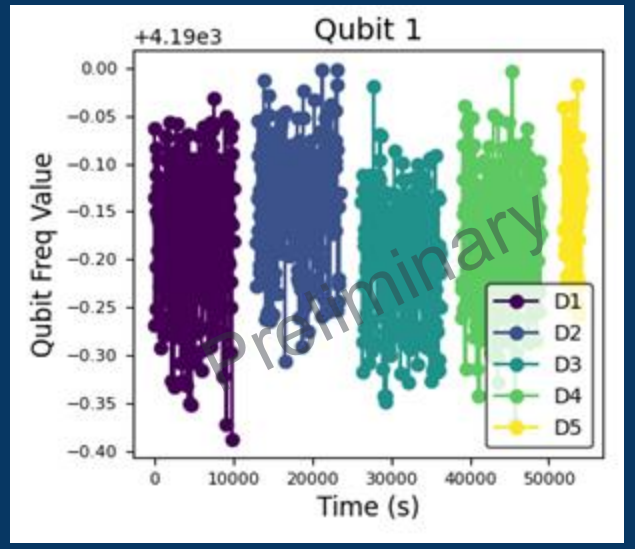
Code base used by friends at SQMS and our 3 fridges at Fermilab

QUIET is underground-- Low background studies

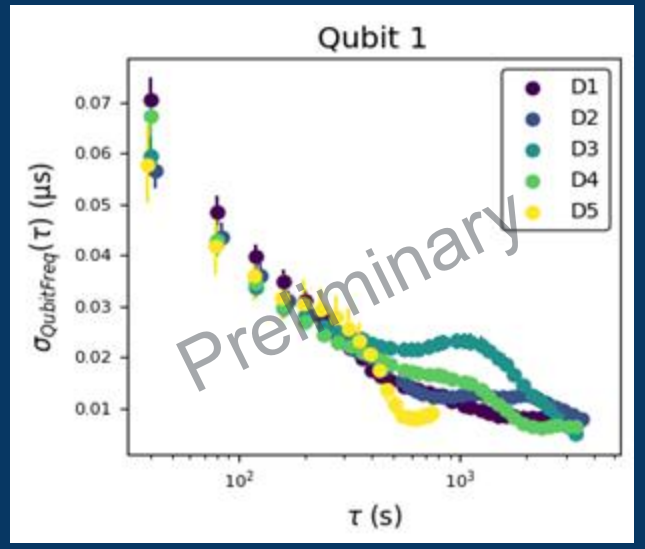
Power Spectral Density (FFT into frequency domain) and **Allan deviation (keeping it in the time domain)** to show regular switching in Qubit metrics due to TLSes

In progress: comparative studies with and without a source

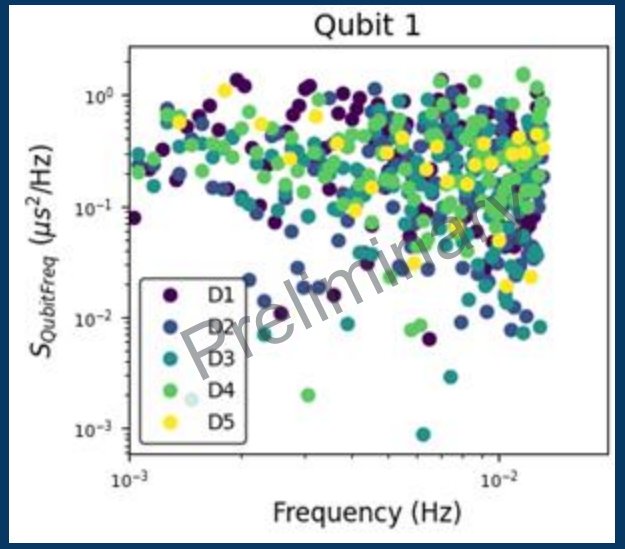
Qubit frequency with optimization between datasets



Allan Deviation of Qubit frequency values

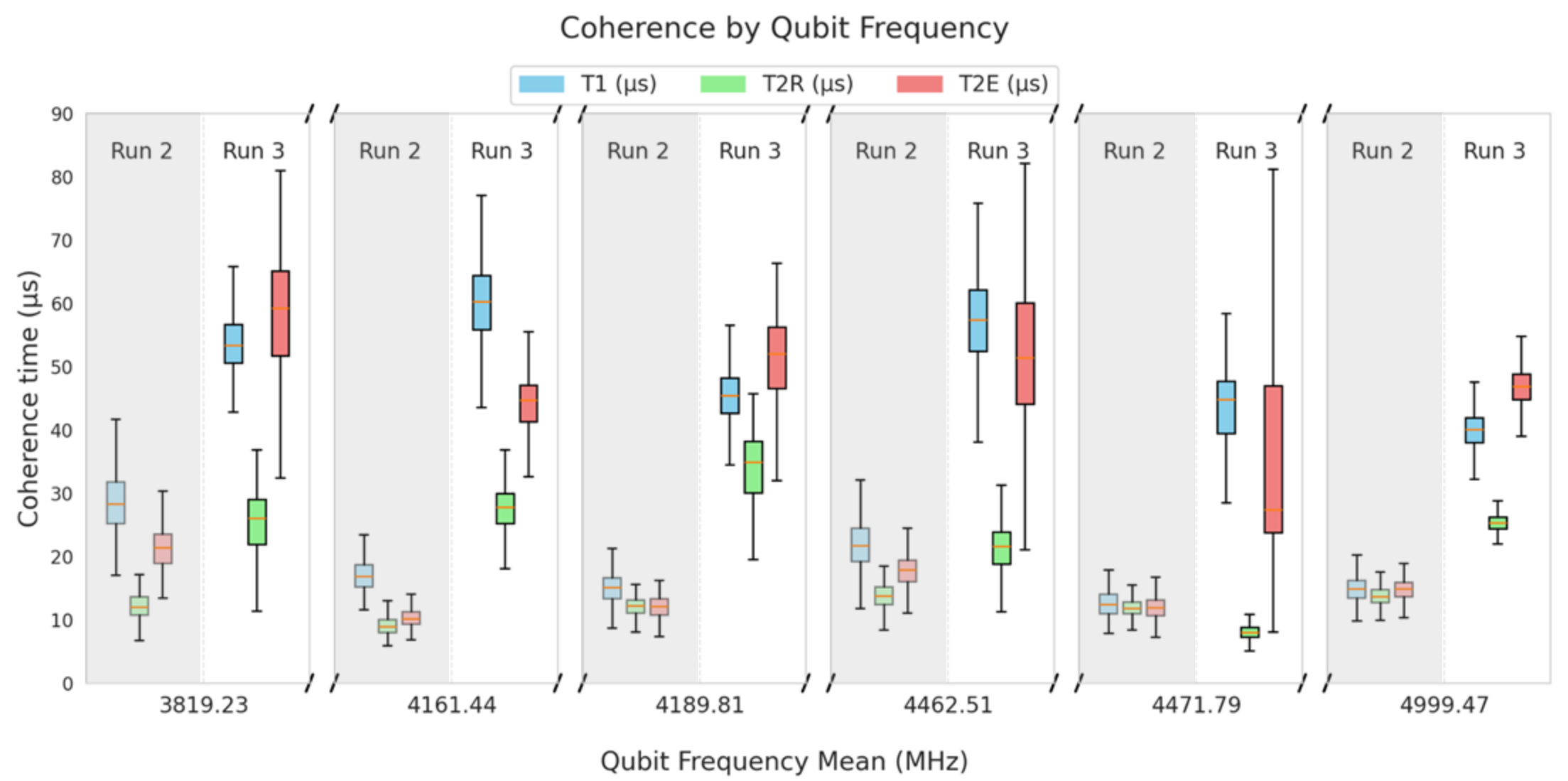


Welch Spectral Density of Qubit frequency values



Work being done in collaboration with Ryan Linehan, Joyce Christiansen-Salameh, Sara Sussman

We need coherence times to be high



We saw a 2x increase in coherence times with improved IR shielding/thermalization/filtering!

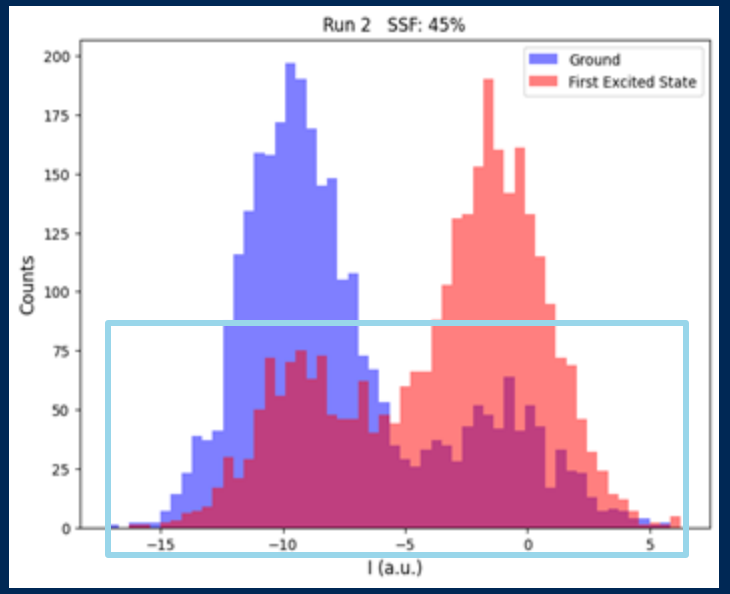
Work completed in collaboration with Sara Sussman and Arianna Colón Cesaní, Rakshya Khatiwada

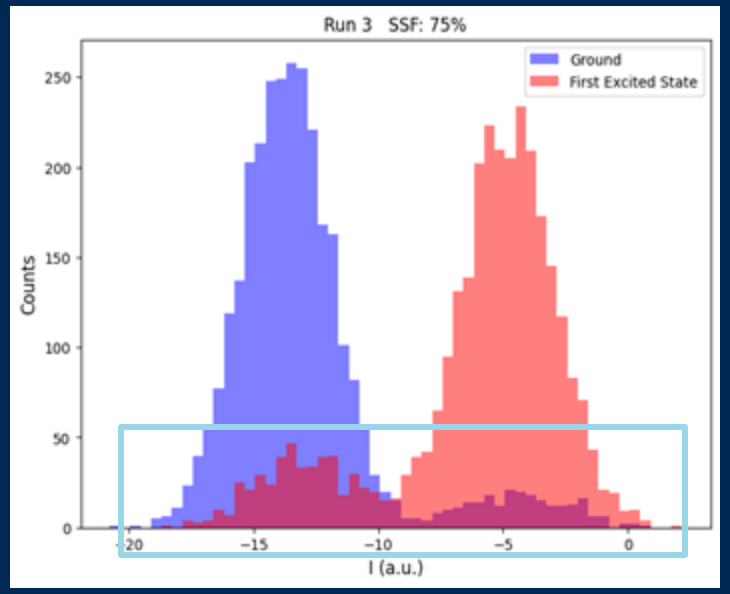
We need to measure them fast (and accurately)

Key upgrades between run 2 and 3 that improved qubit coherence:

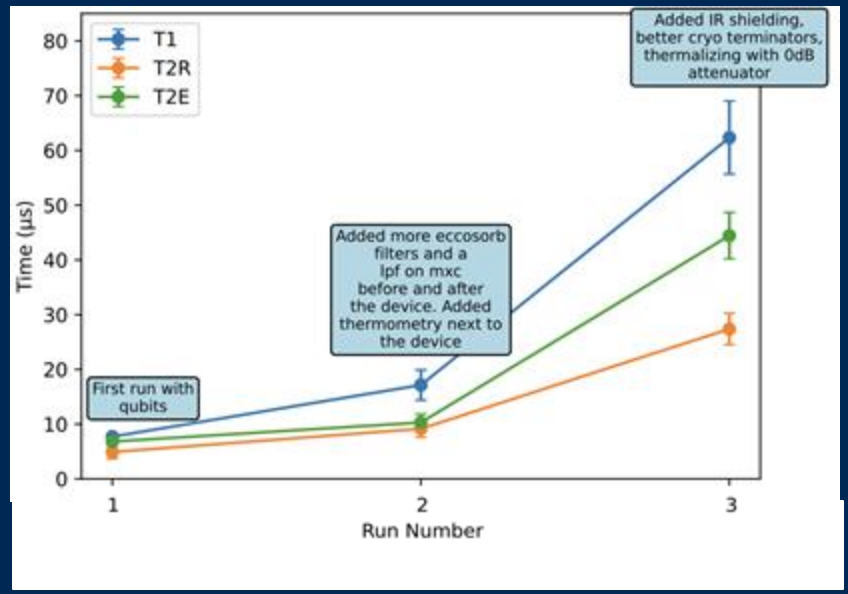
- Added 0dB attenuator before and after device to improve thermalization
- Put improved copper bodied cryo rated terminators (better thermalization) on circulators
- Improved shielding
  - IR by sealing holes and gaps
  - Shielded from higher stage radiation that was exposed previously through the mag can

We see a clear reduced thermal population due to these changes





Coherence by run



Work completed in collaboration with Sara Sussman, Arianna Colón Cesaní, Daniel Molenaar, Rakshya Khatiwada

Experimental requirements for near-term experiments

- A very well-shielded, well-characterized underground testbed for quantum sensing/gravitational red shift experiments ✅
- The ability to control qubits and nearby two-level system defects with the Quantum Zeno Effect
- The ability to entangle qubits with high fidelity
- The ability to design qubit devices optimally for quantum sensing experiments

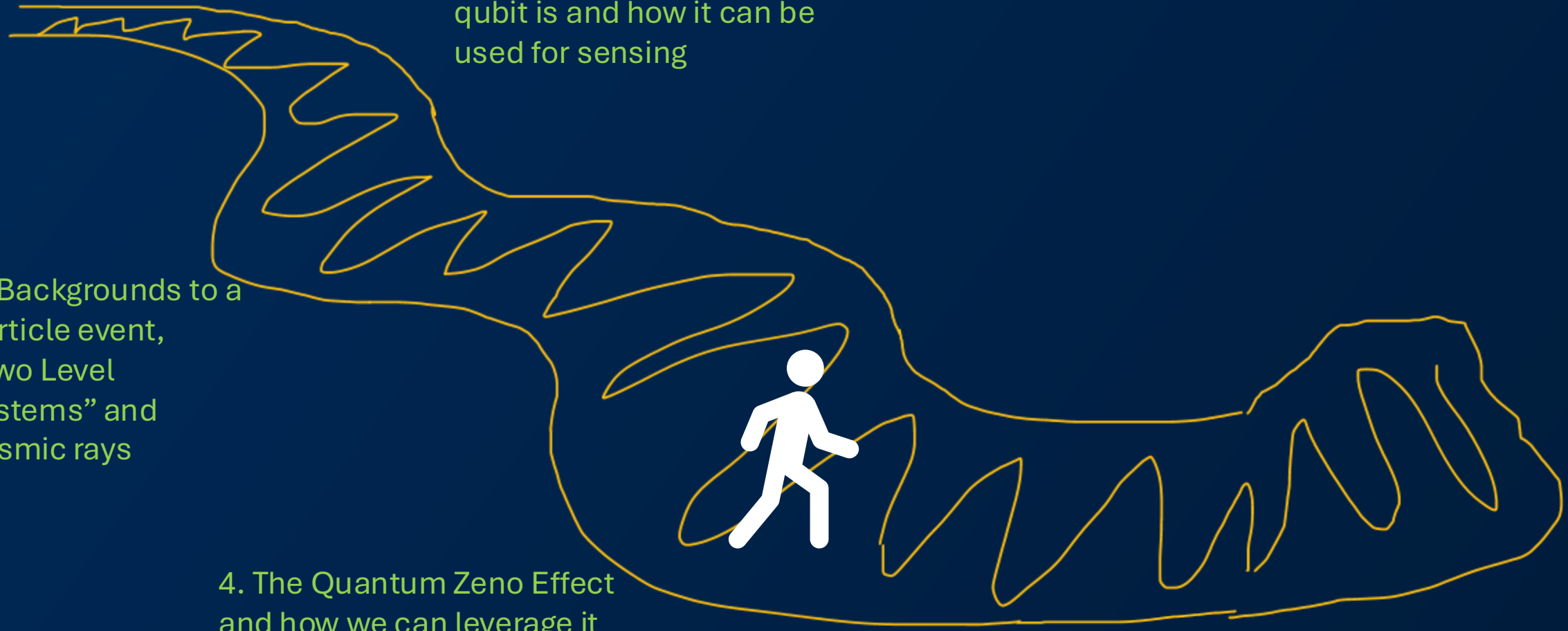
Building robust, low background sensors to studying new physics

1. We can use qubits as particle detectors

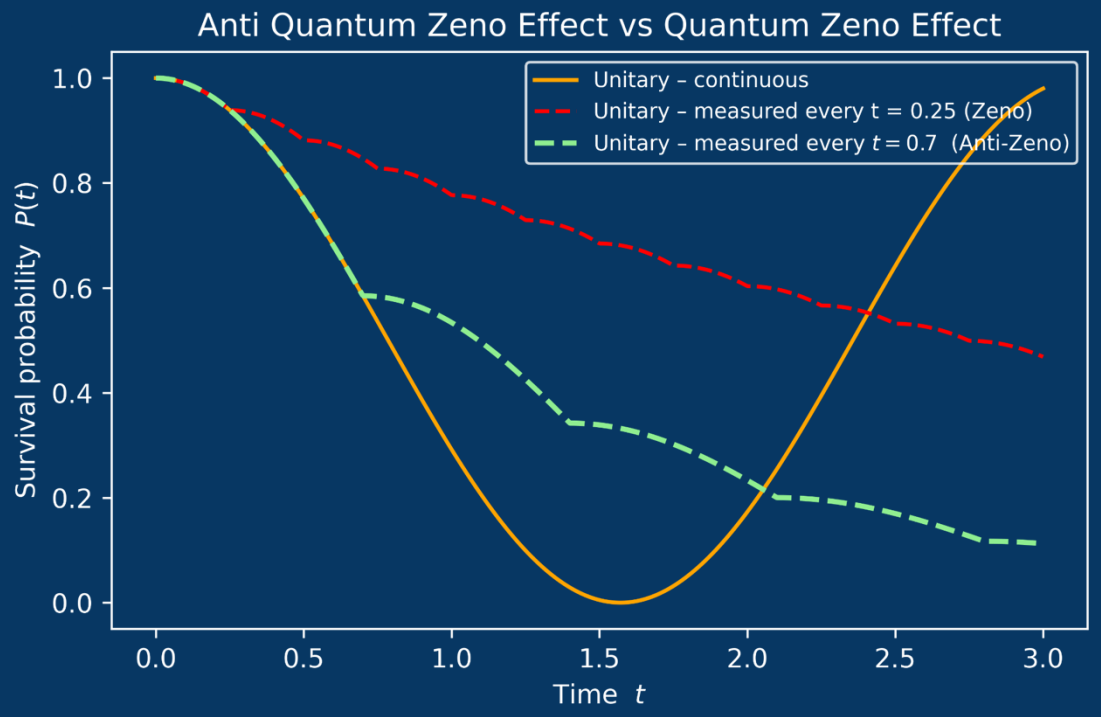
2. What a superconducting qubit is and how it can be used for sensing

3. Backgrounds to a particle event, “Two Level Systems” and cosmic rays

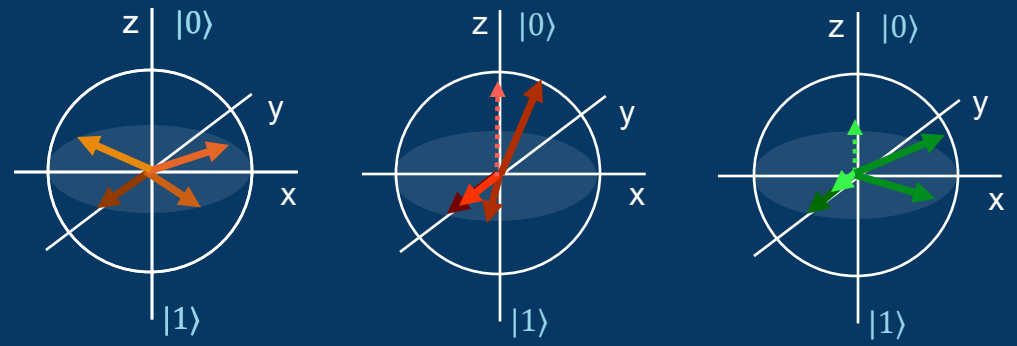
4. The Quantum Zeno Effect and how we can leverage it



Method to constrain quantum systems: the Quantum Zeno Effect

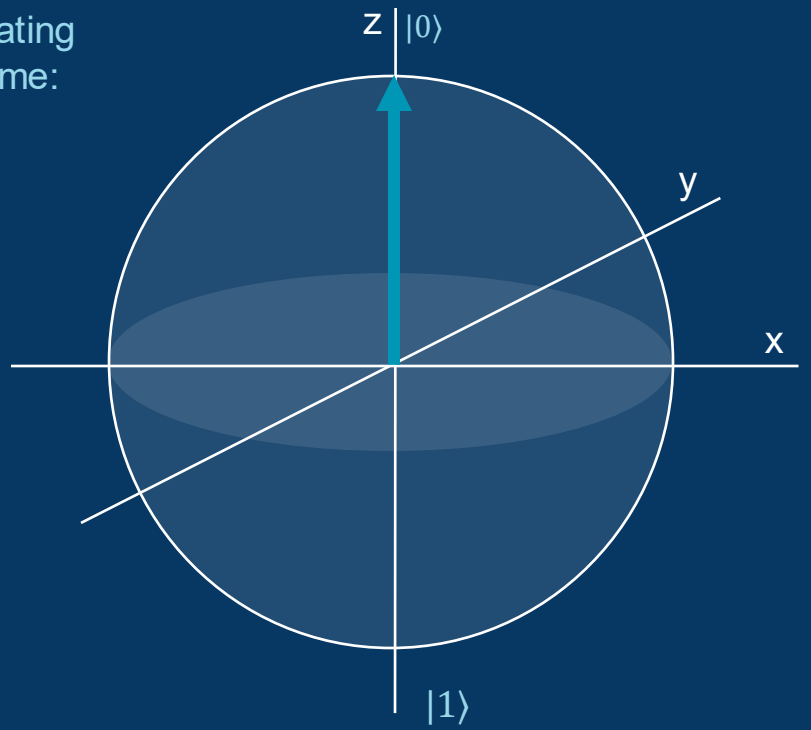


Lab frame:



We can suppress evolution our quantum system away from the poles on the Bloch sphere

Rotating frame:



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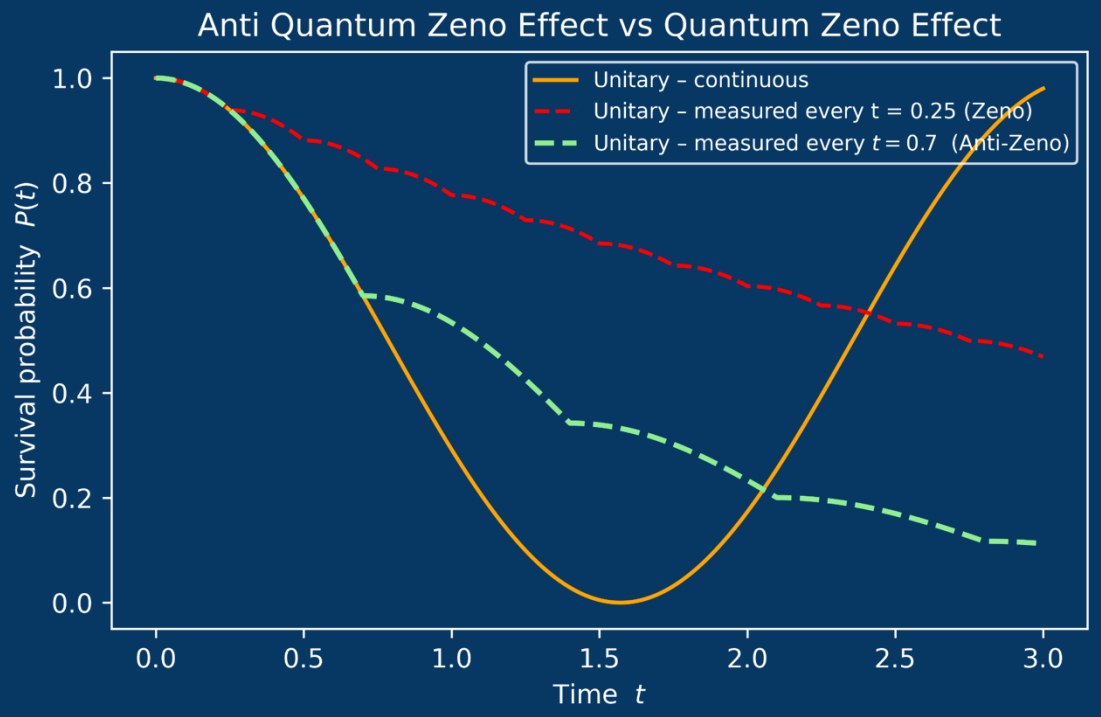

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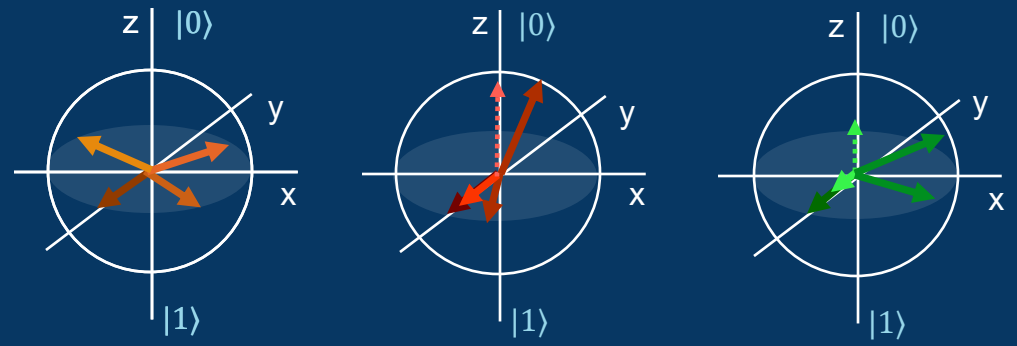

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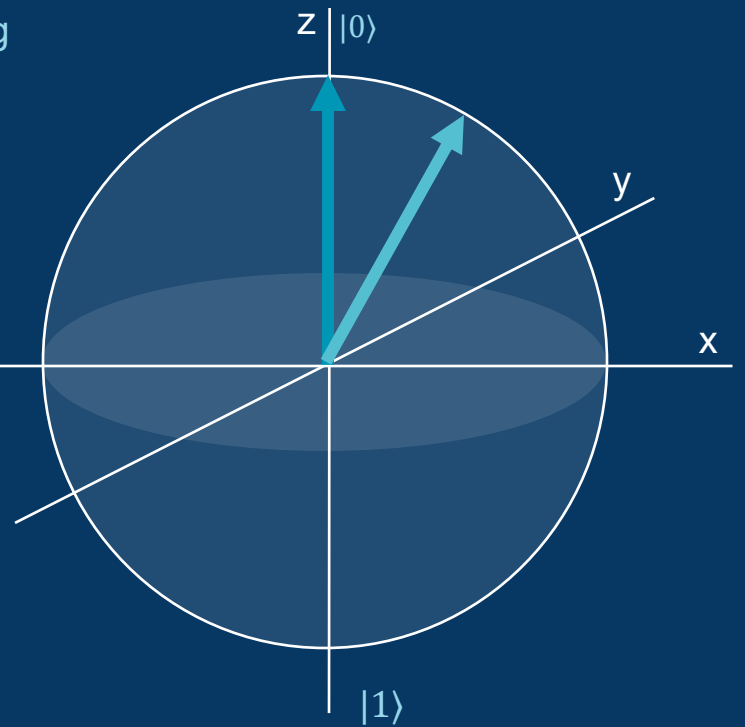
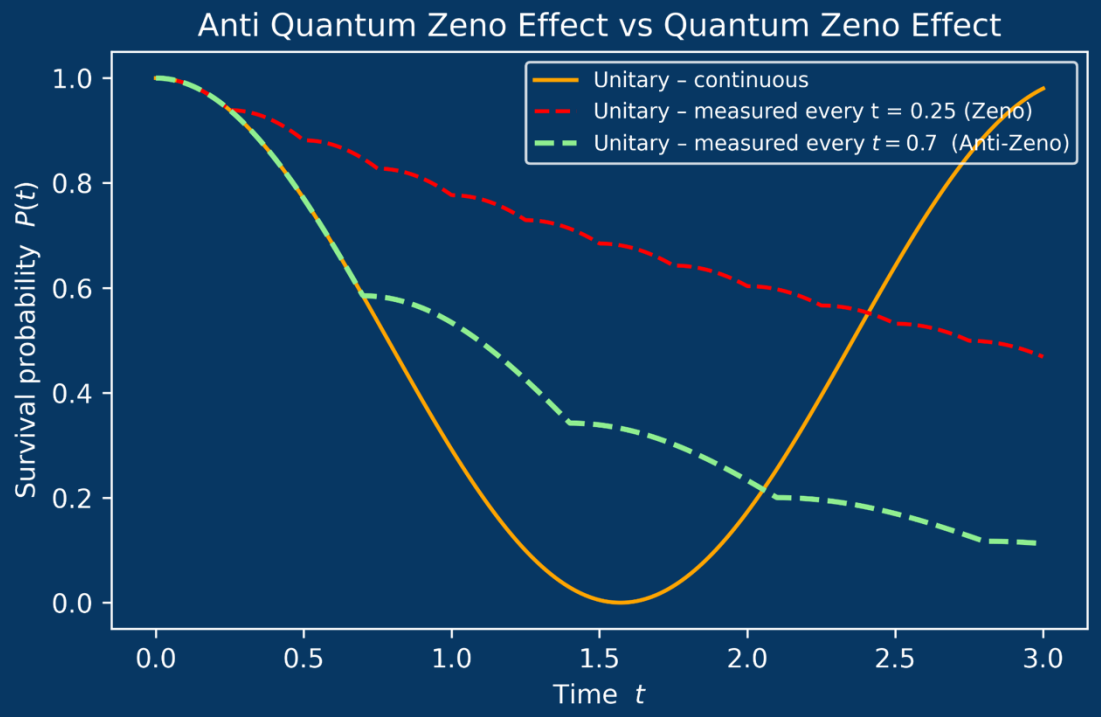
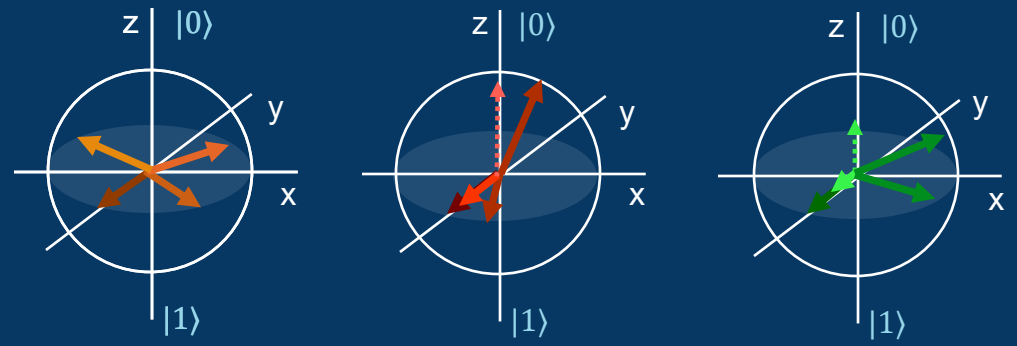


Method to constrain quantum systems: the Quantum Zeno Effect



Lab frame:



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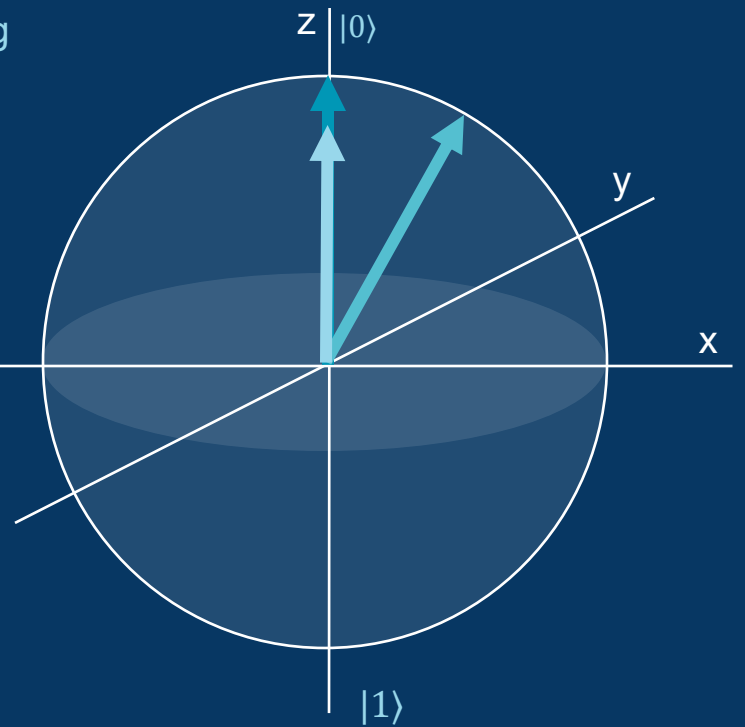
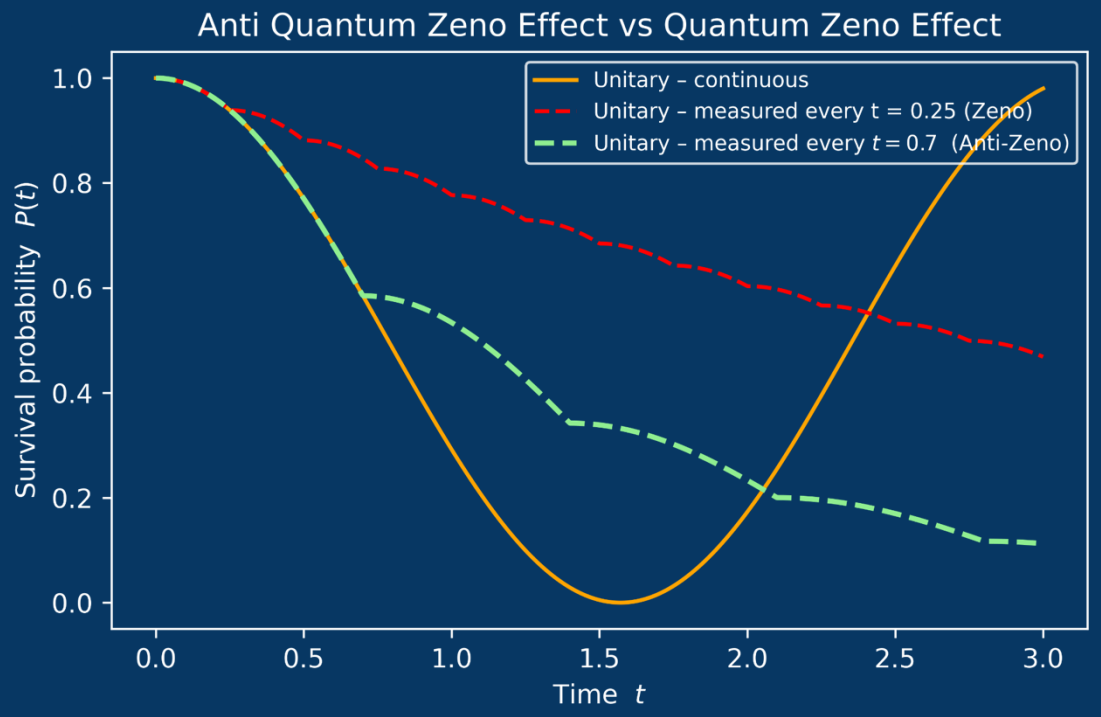
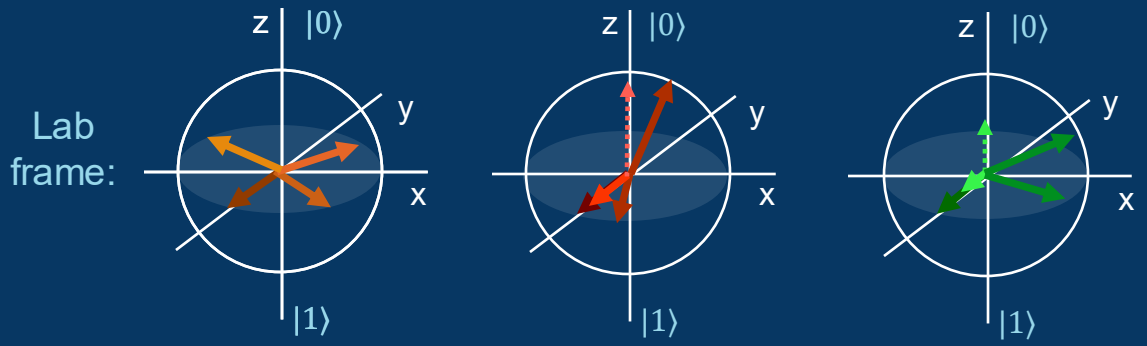


Method to constrain quantum systems: the Quantum Zeno Effect





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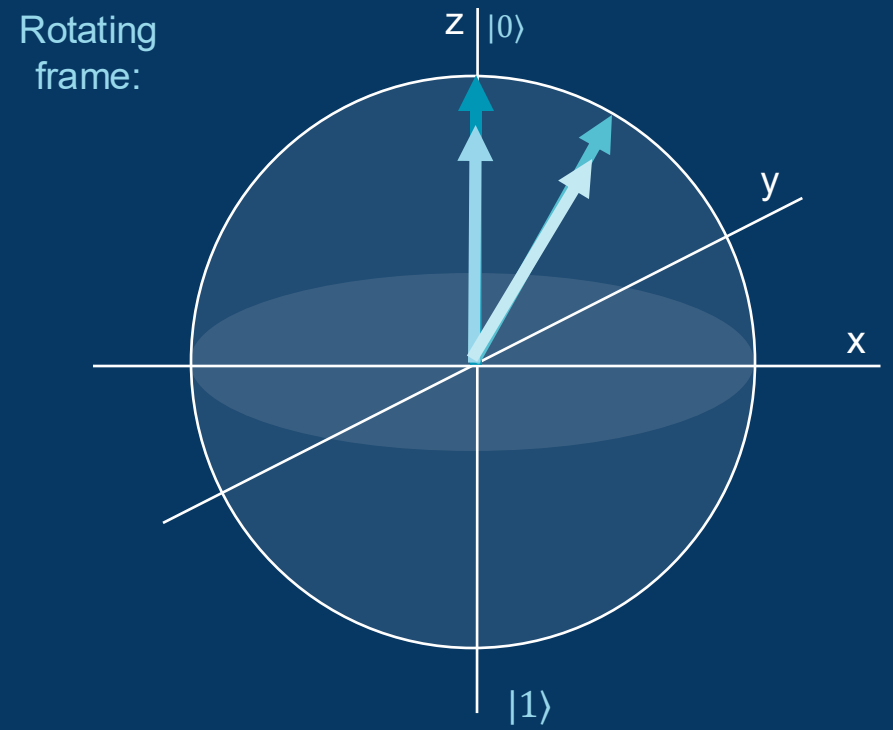

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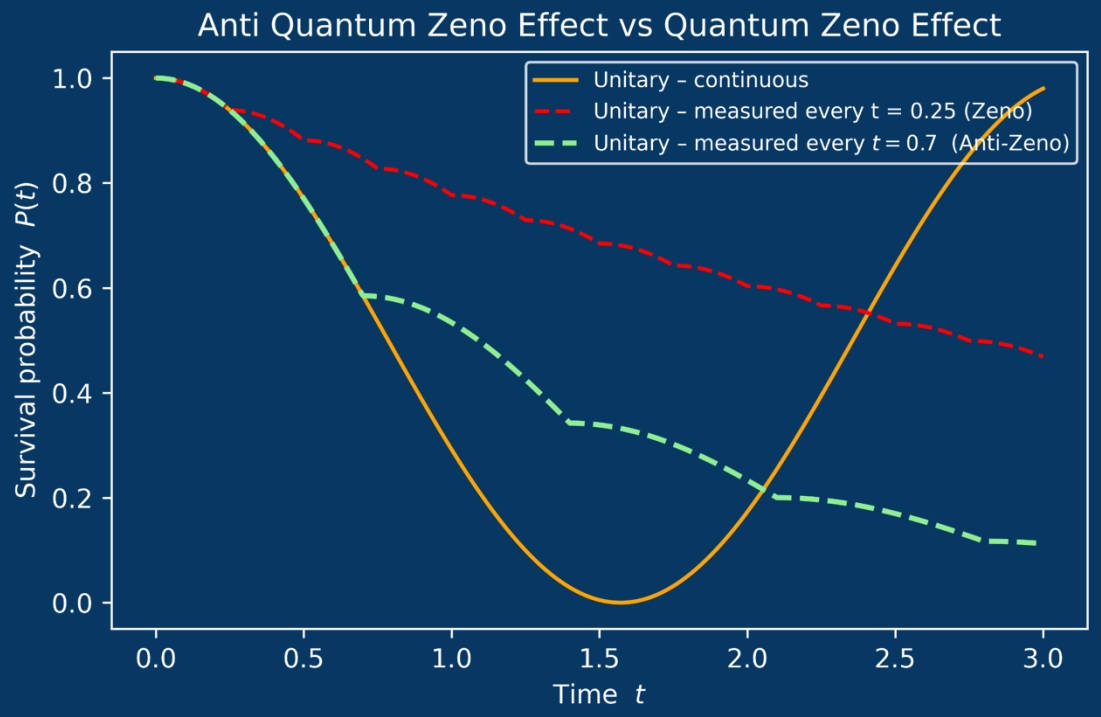

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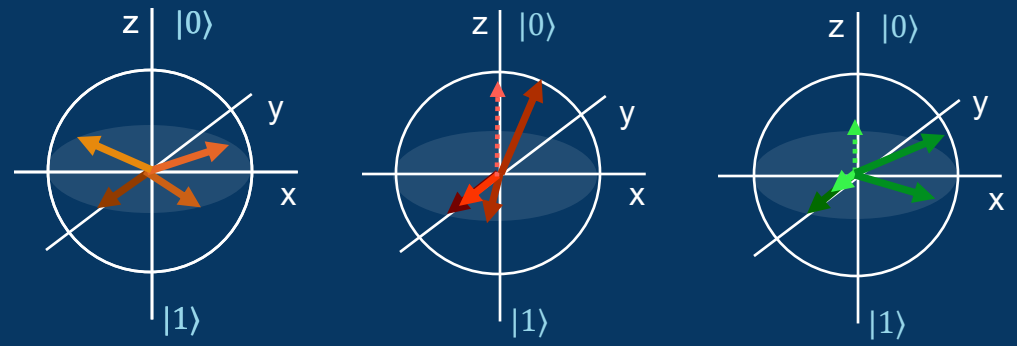

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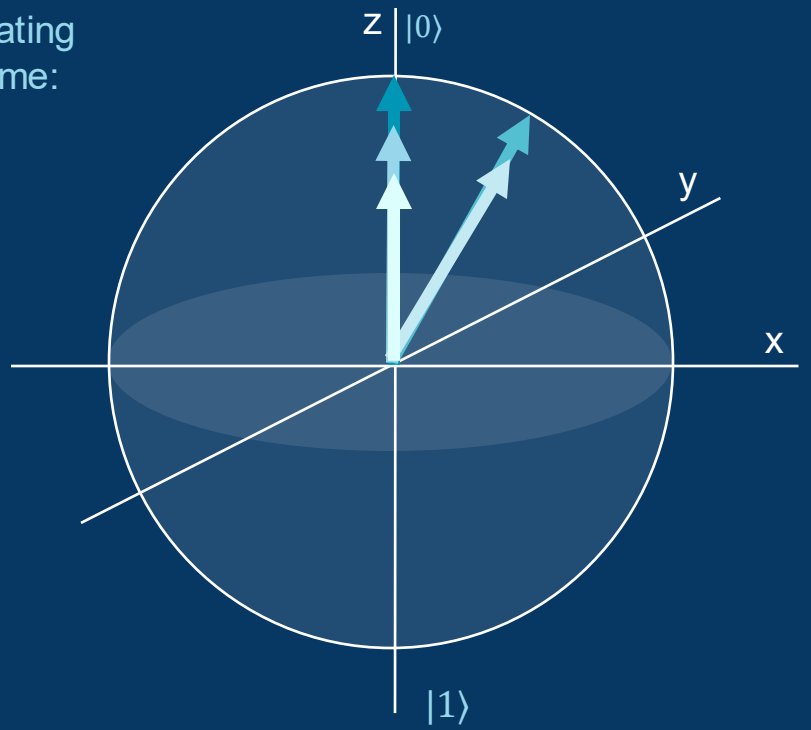

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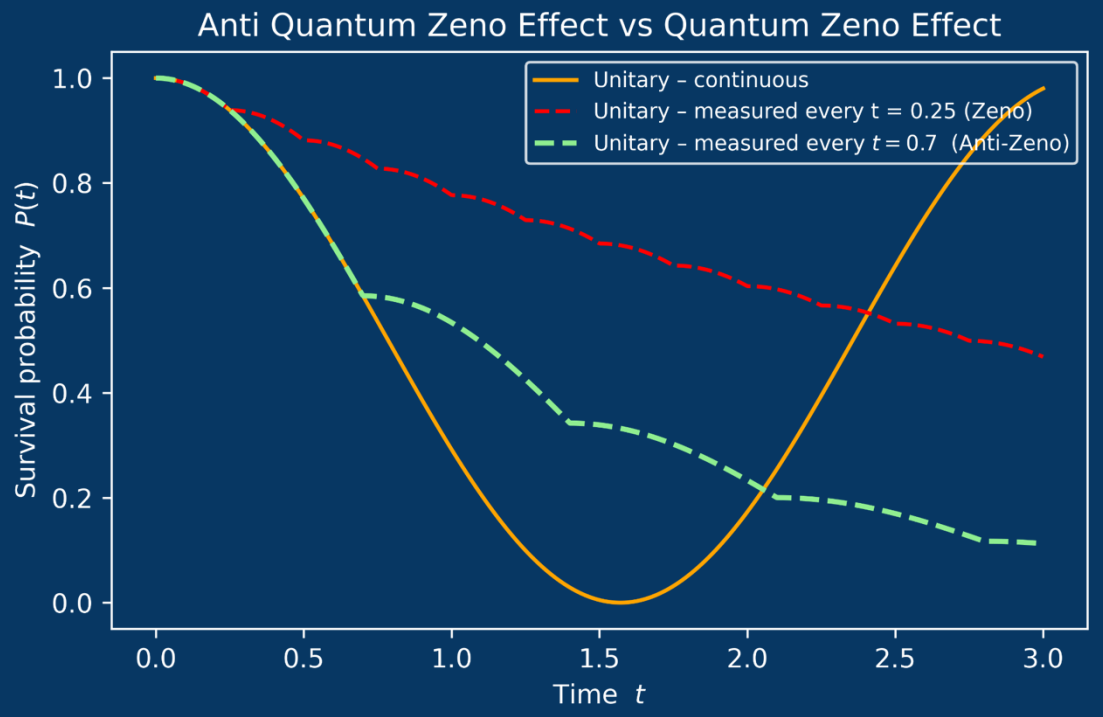

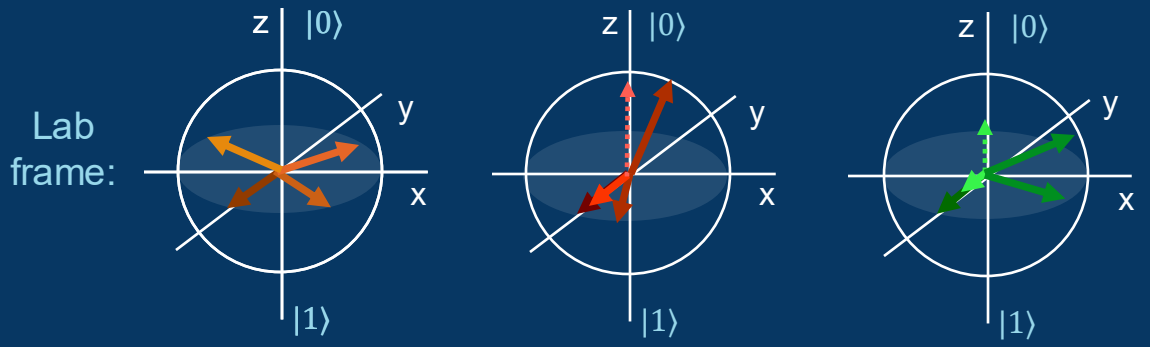

We can constrain our quantum system to a subsection of the Bloch sphere

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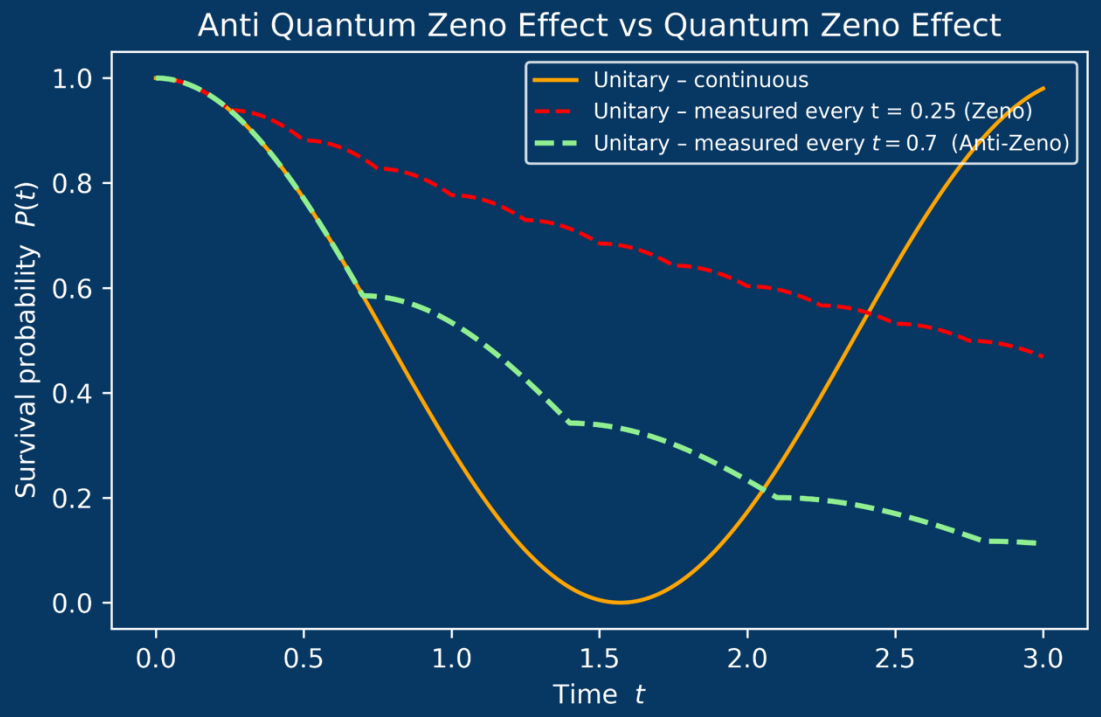

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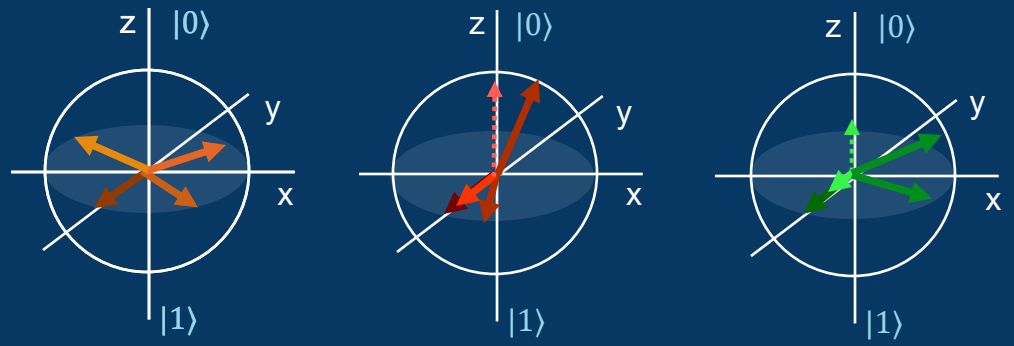

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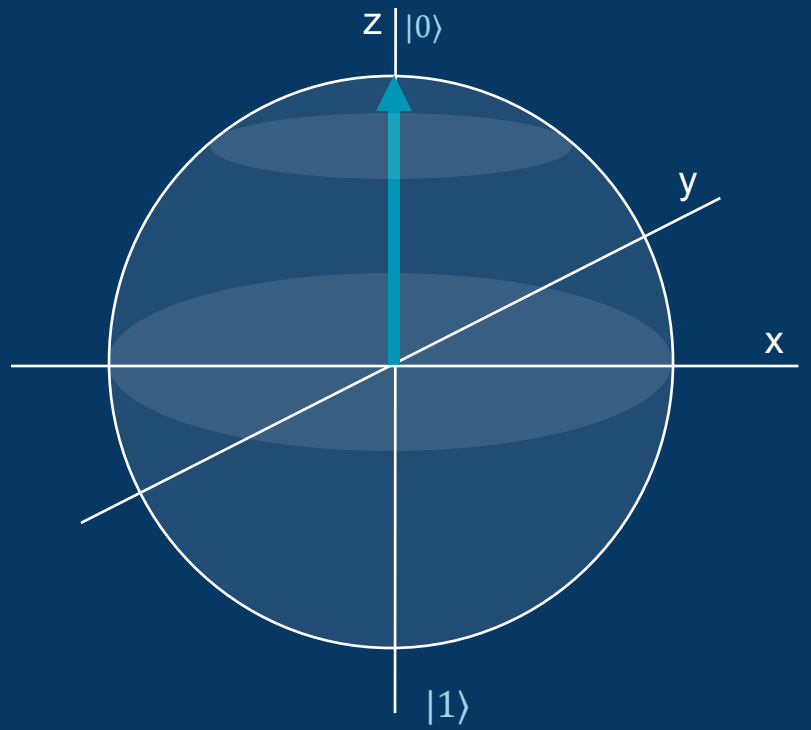

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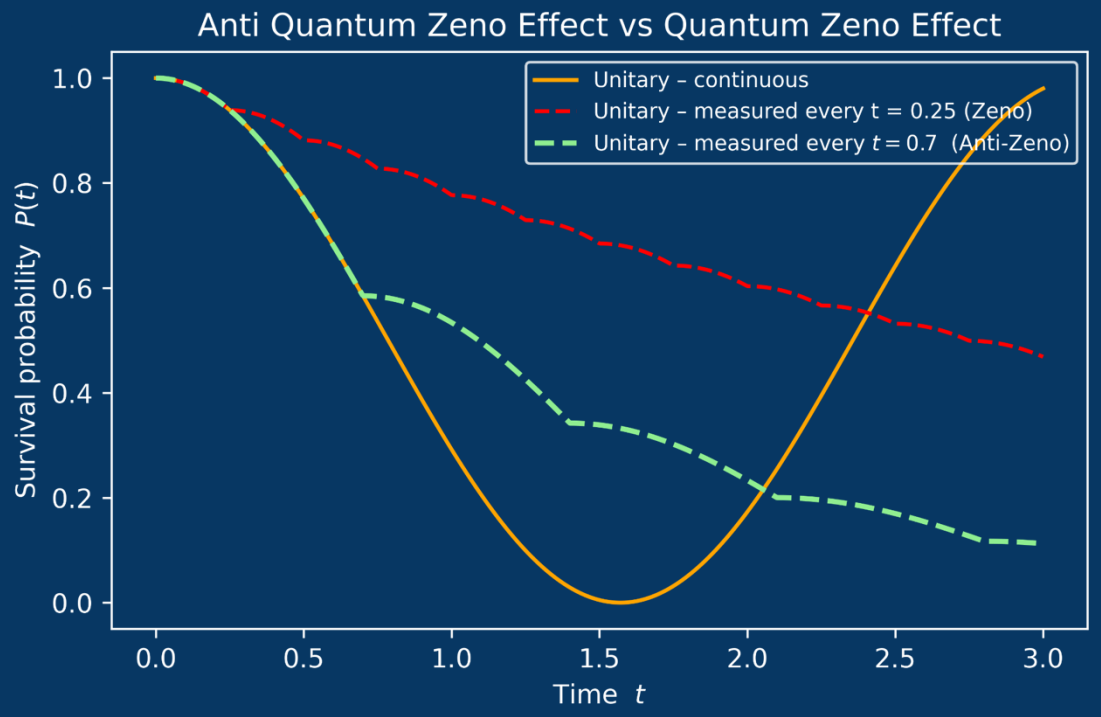

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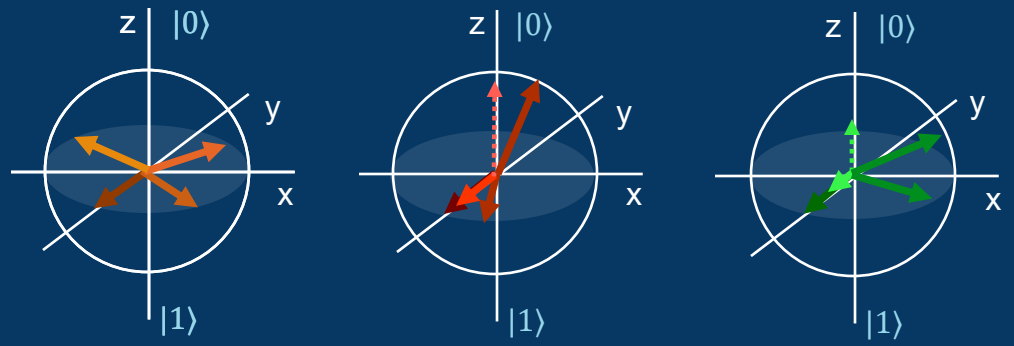

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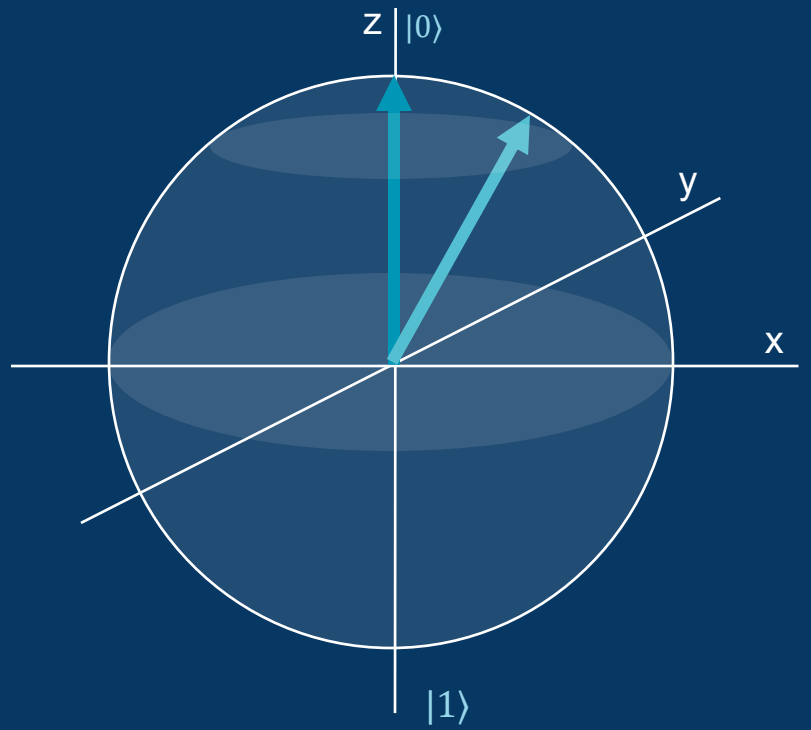

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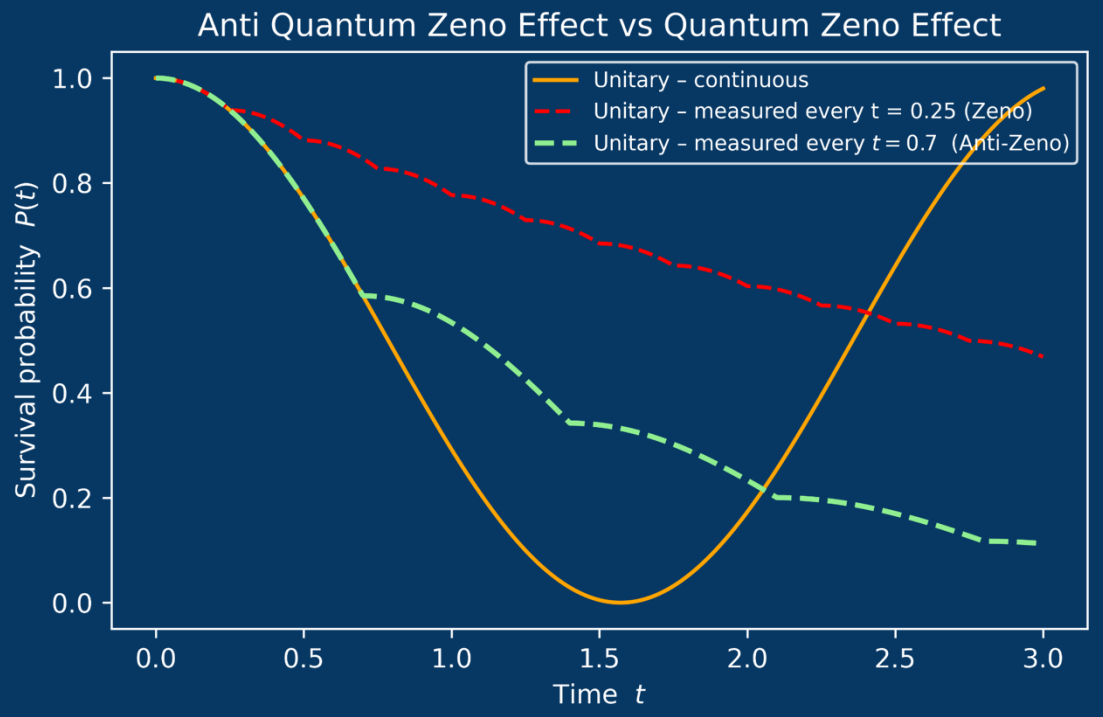

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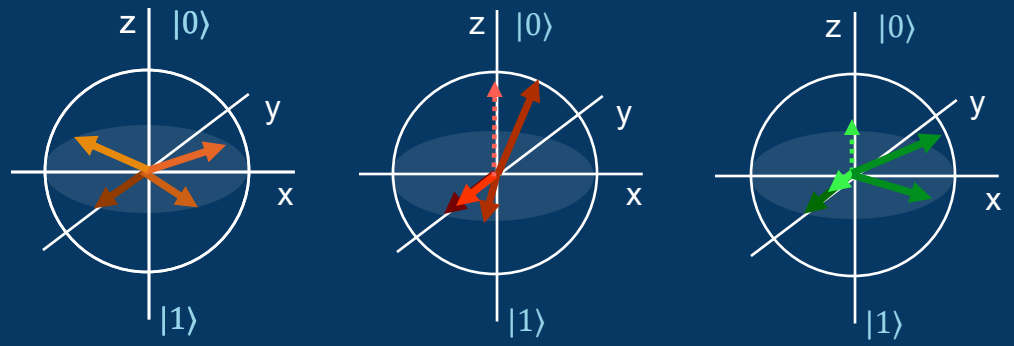

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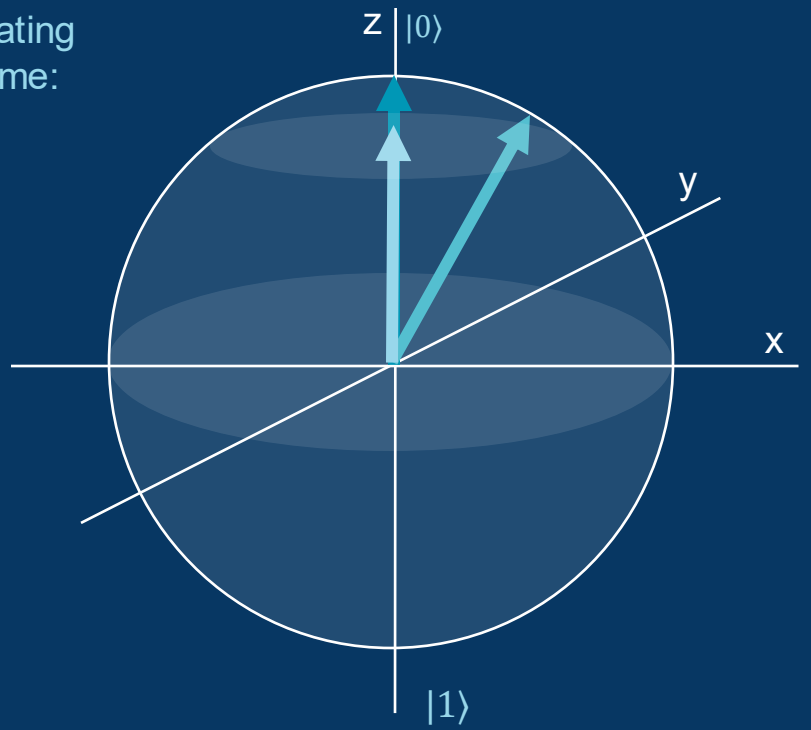

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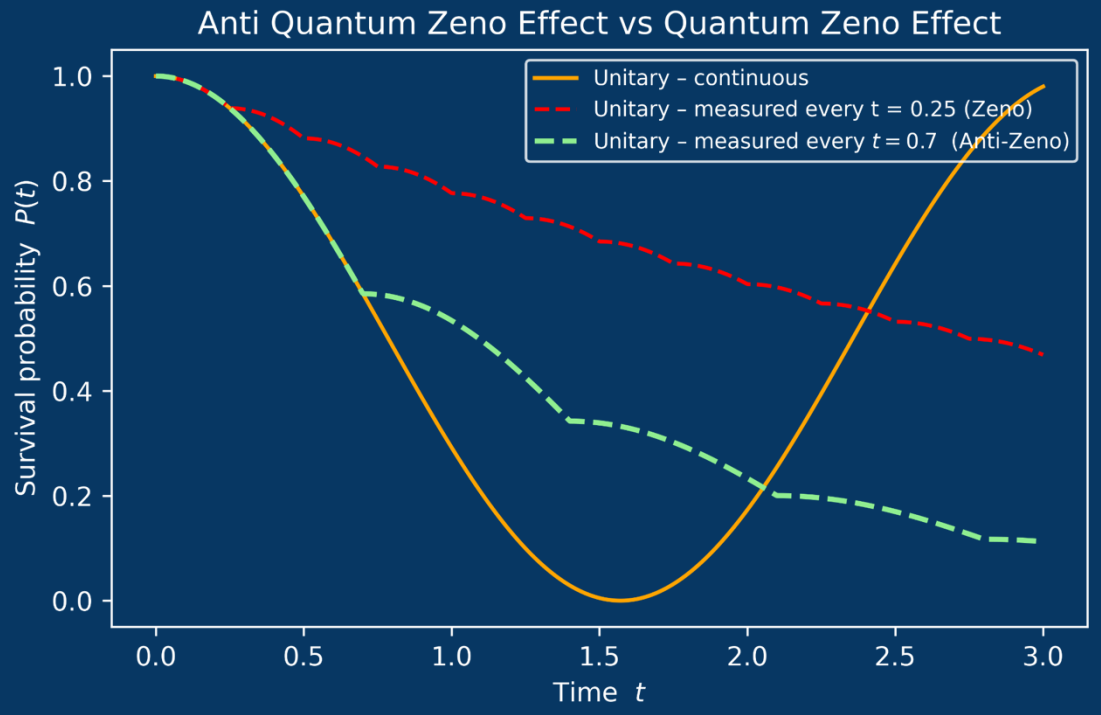

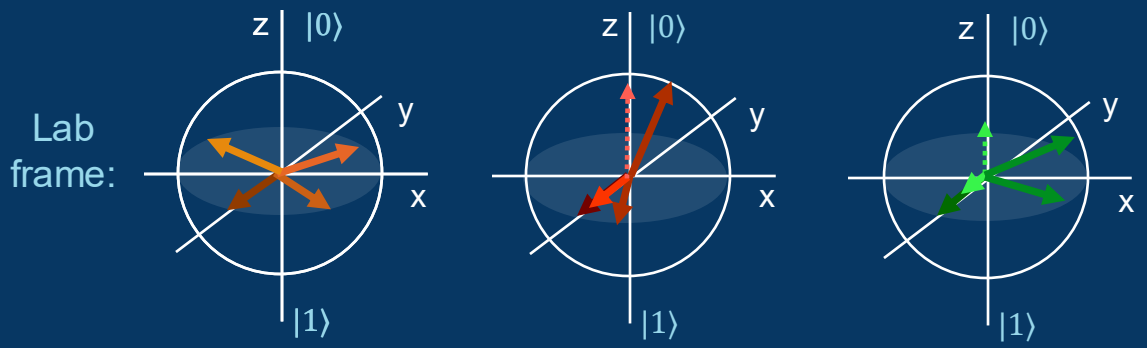

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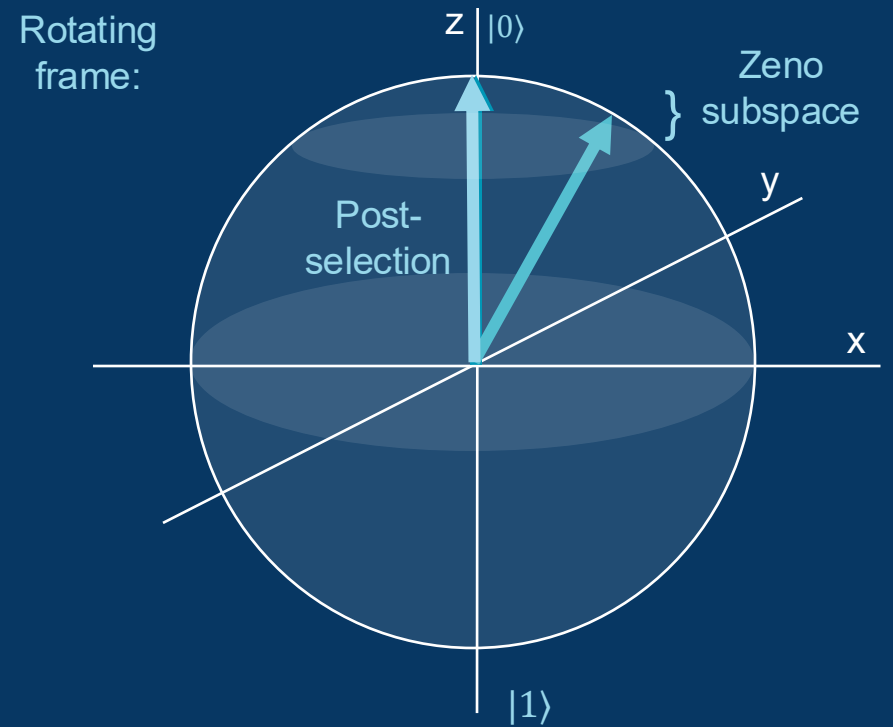
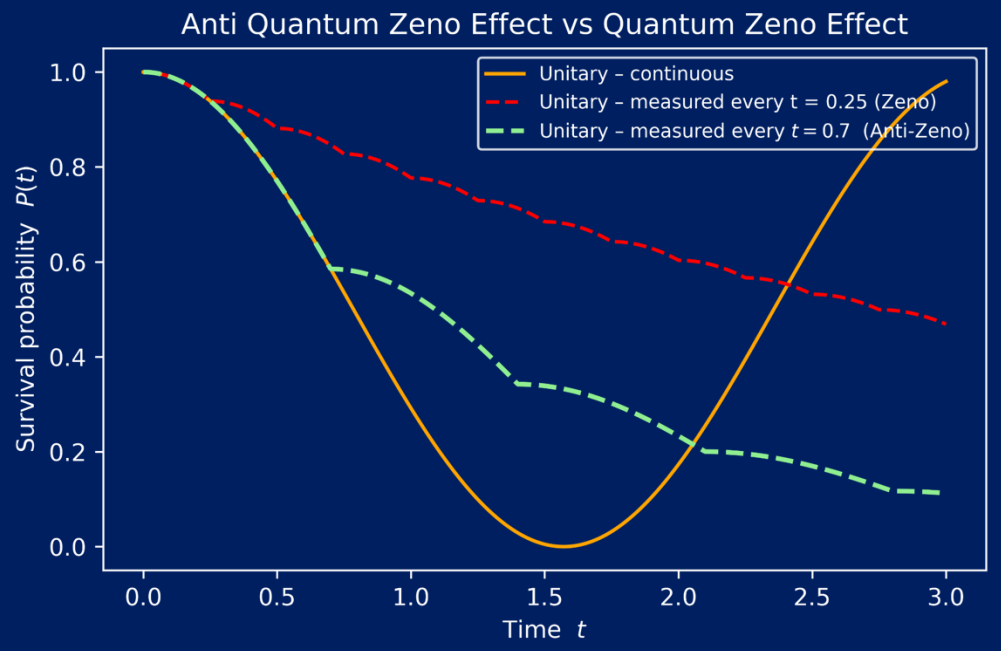


The Quantum Zeno Effect

Unitary/Closed ideal QZE



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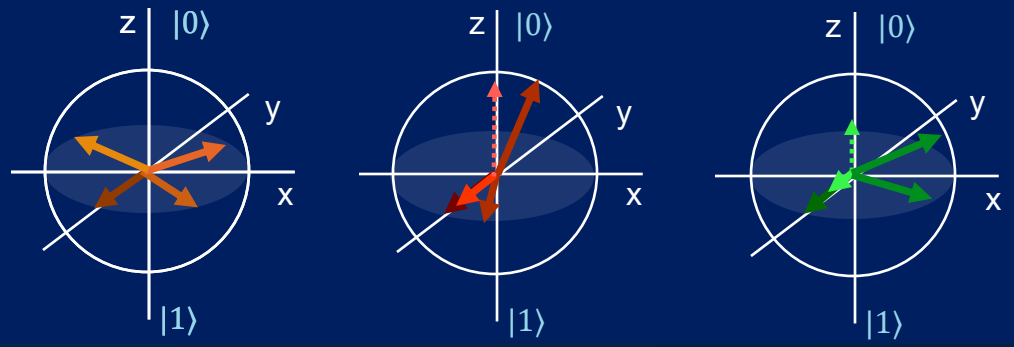

Open Quantum Systems QZE

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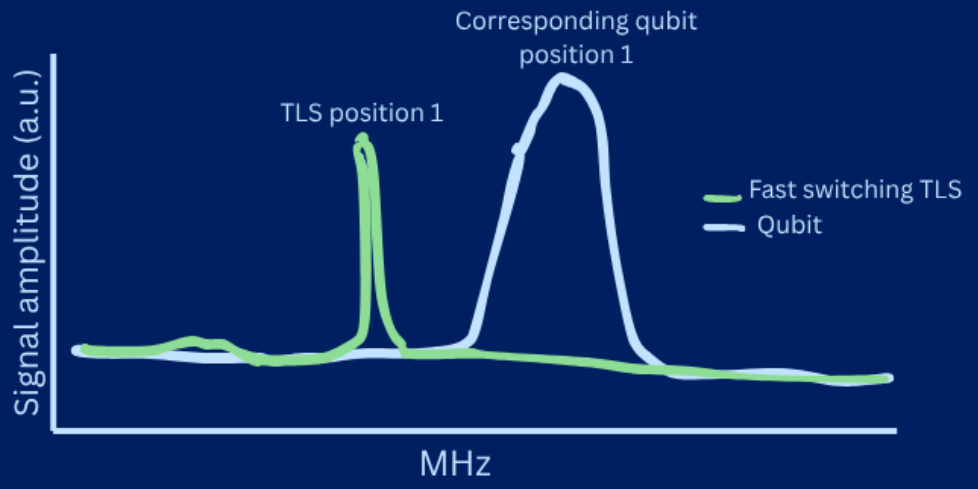

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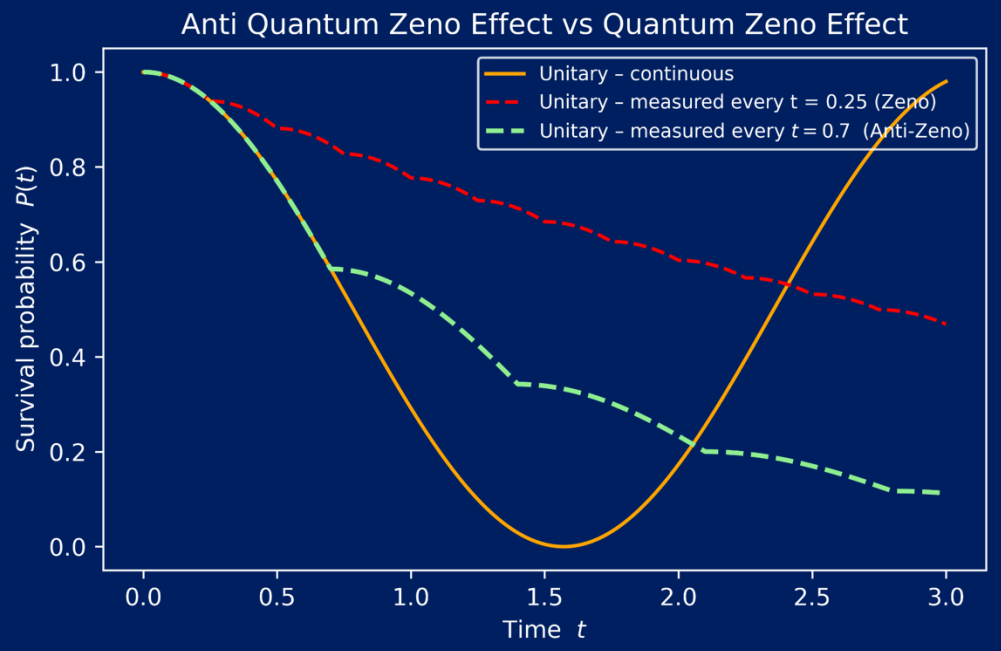

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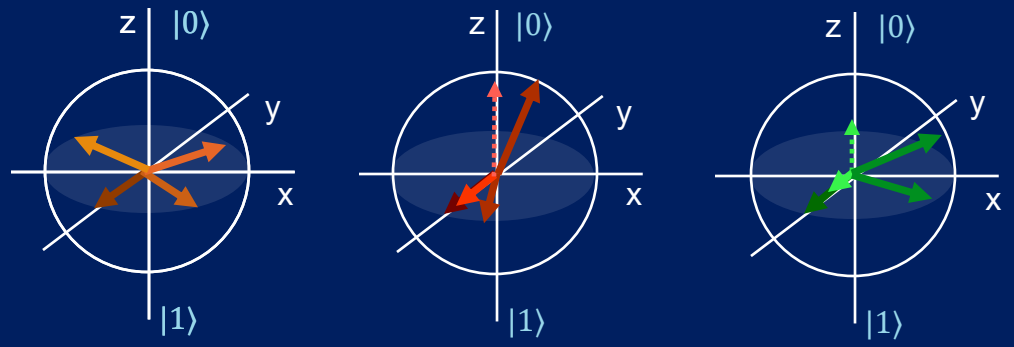

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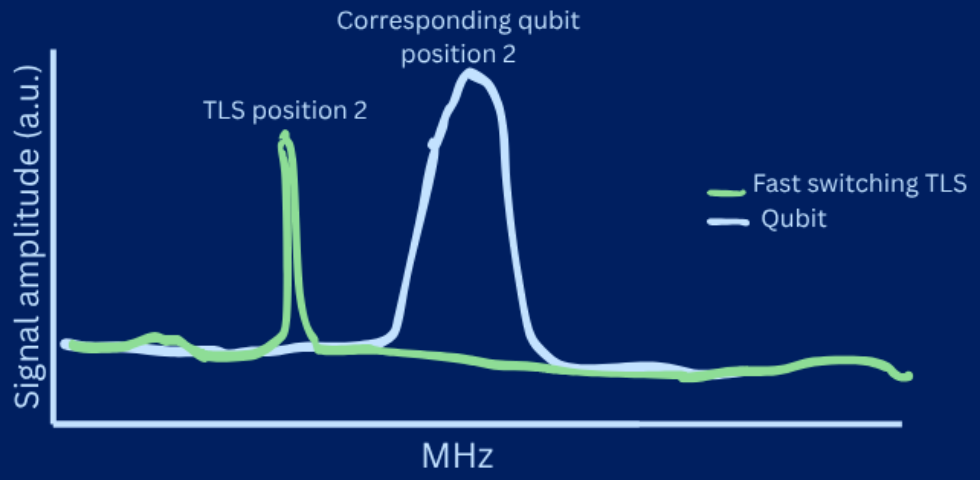

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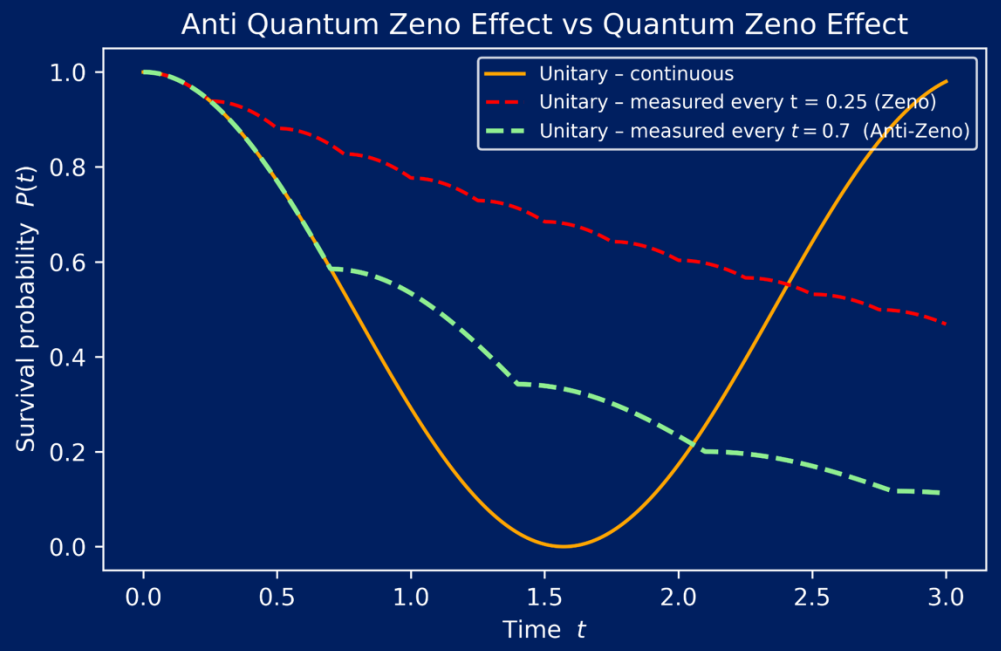

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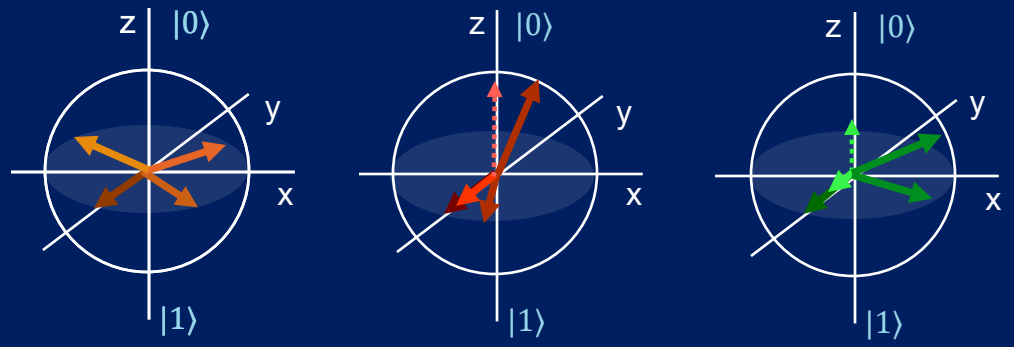

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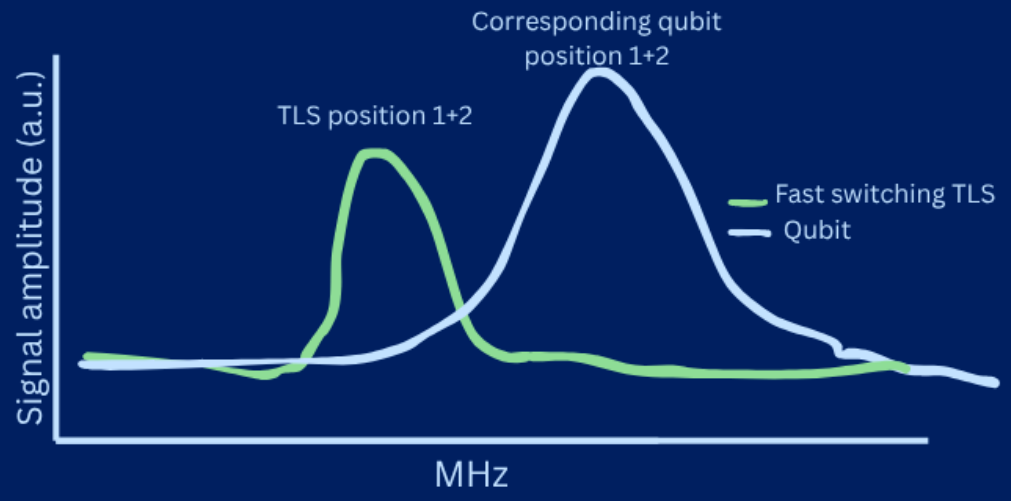

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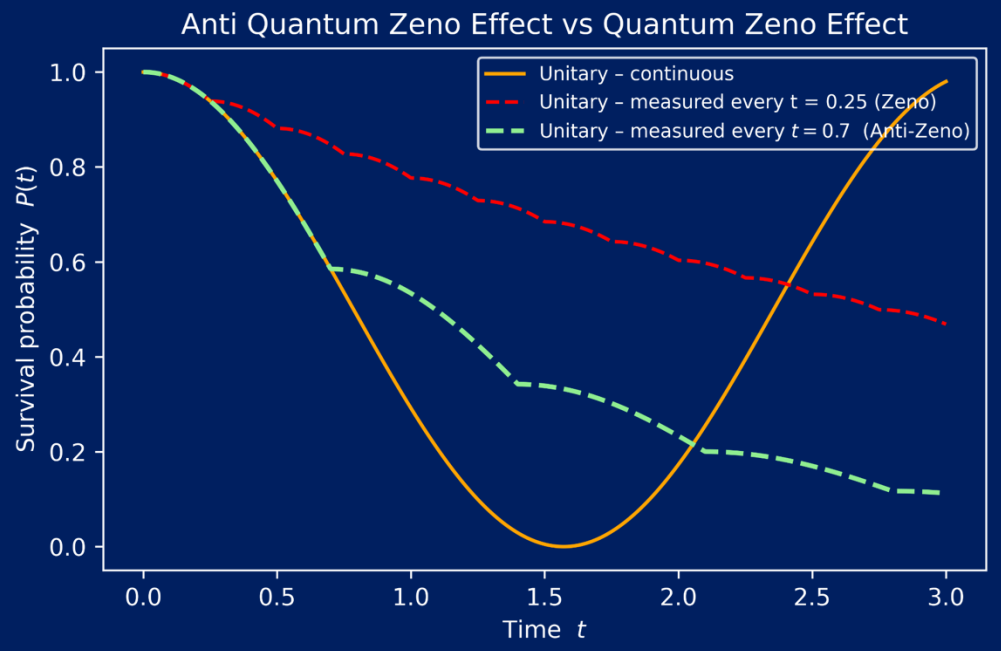

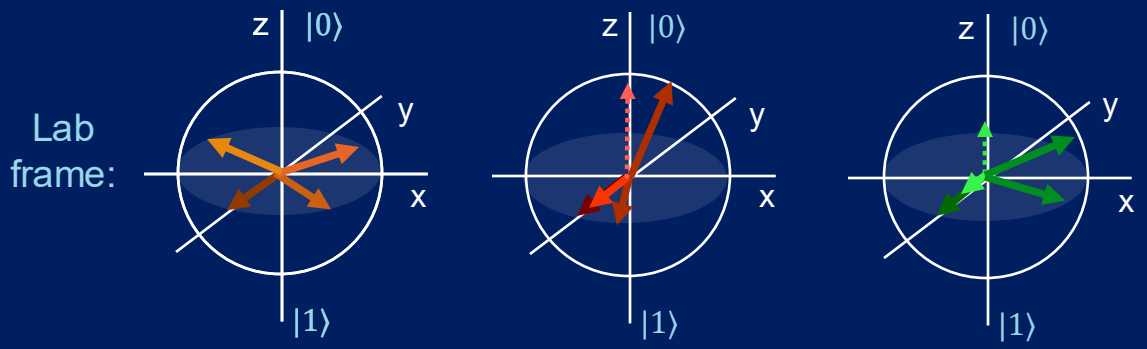

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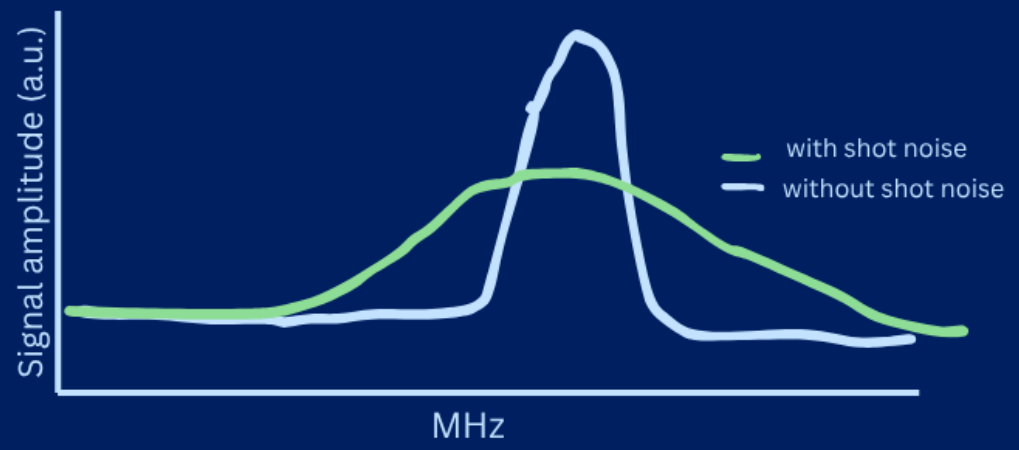

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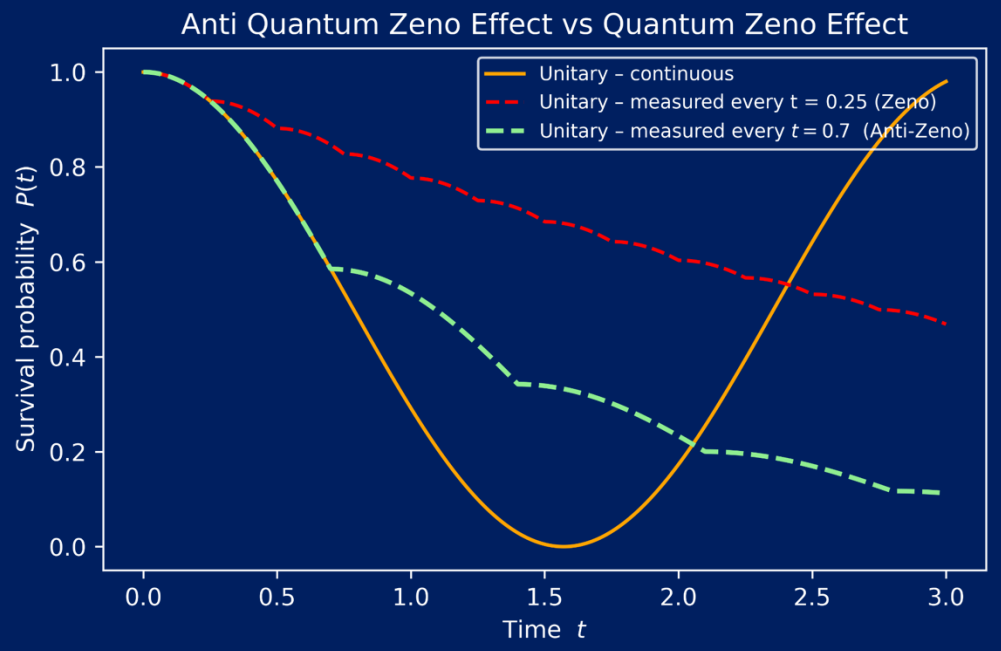

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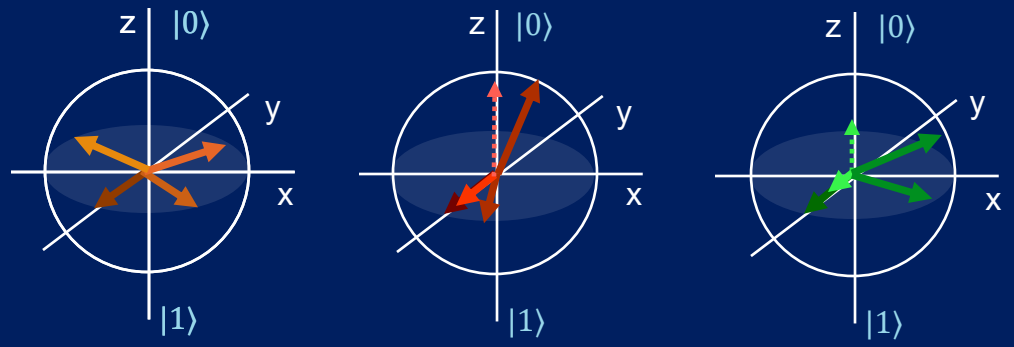

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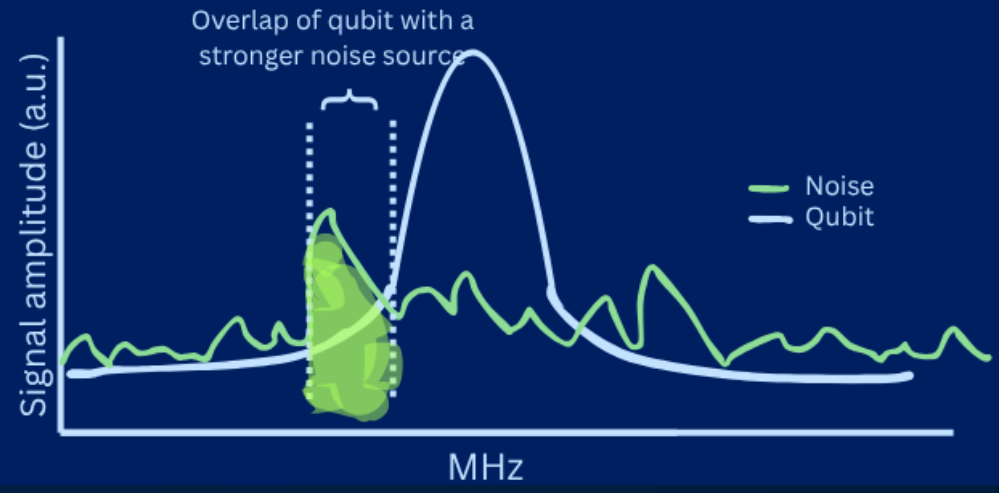

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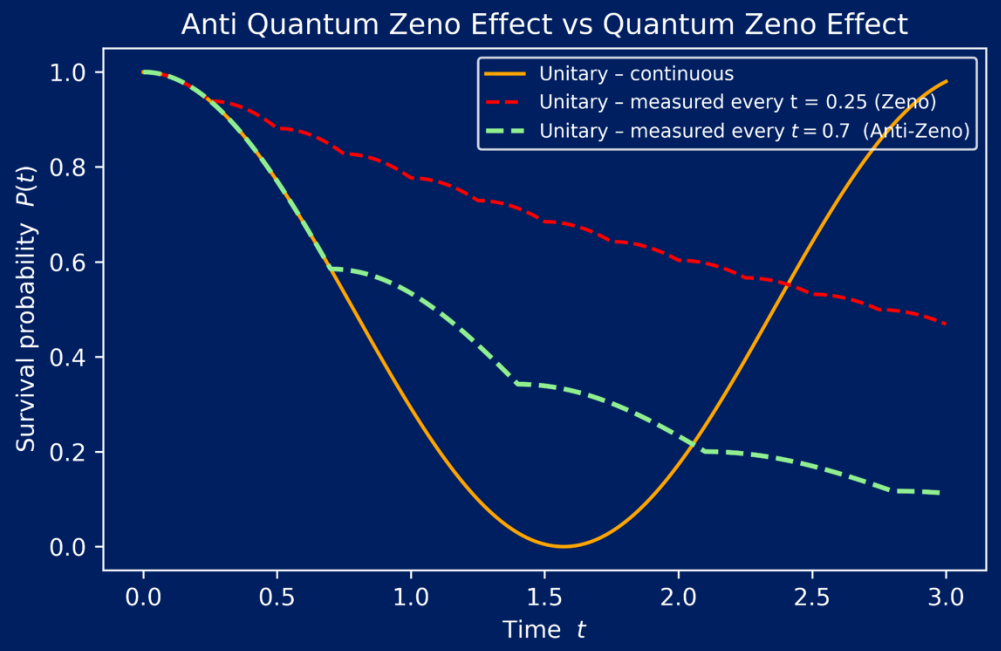

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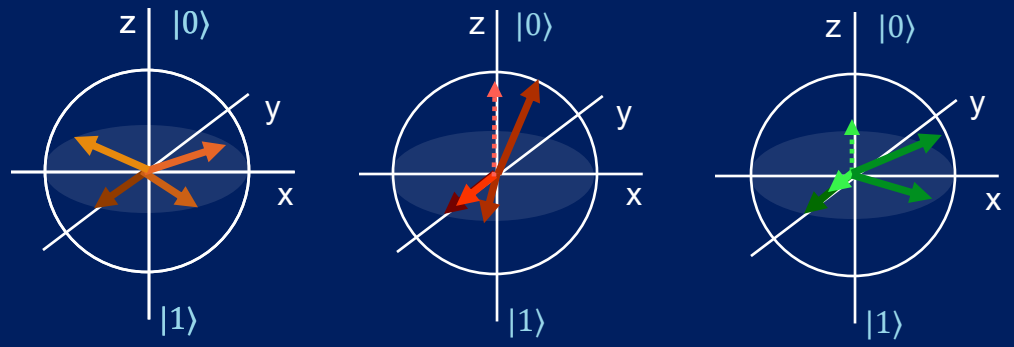

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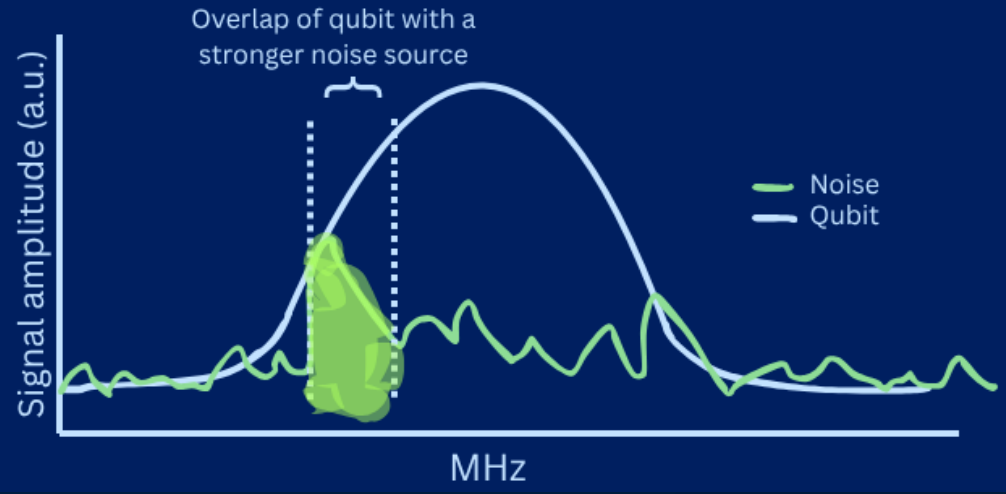

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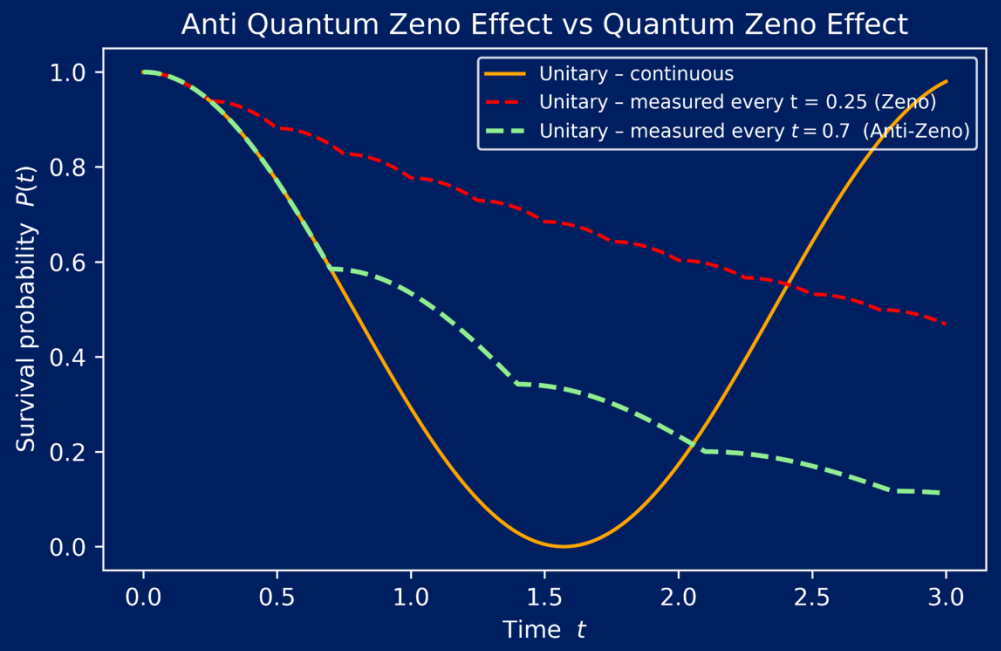

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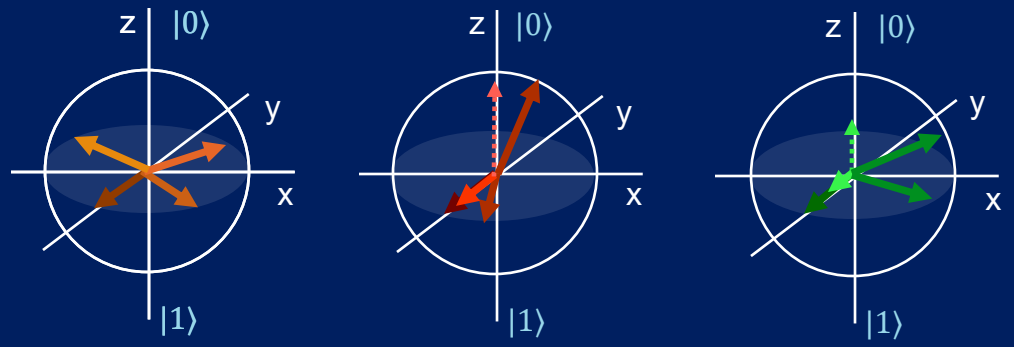

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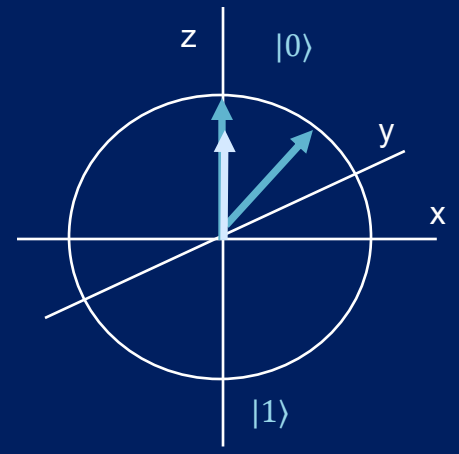
Rabi in the rotating frame



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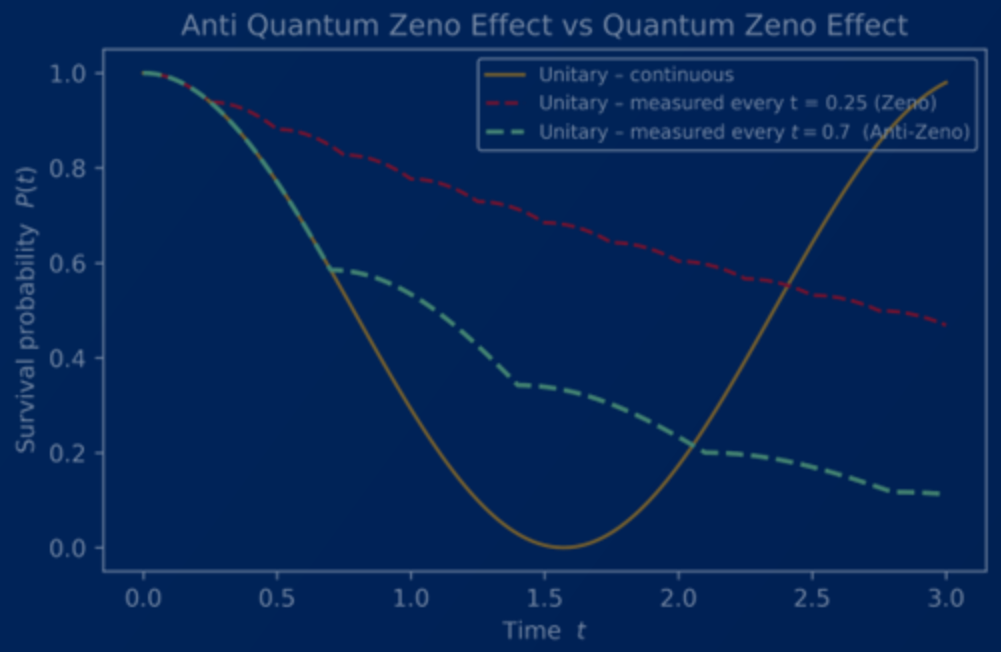

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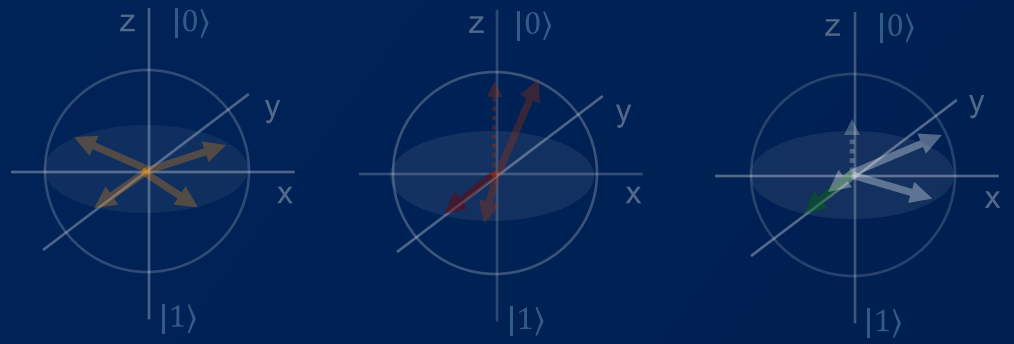

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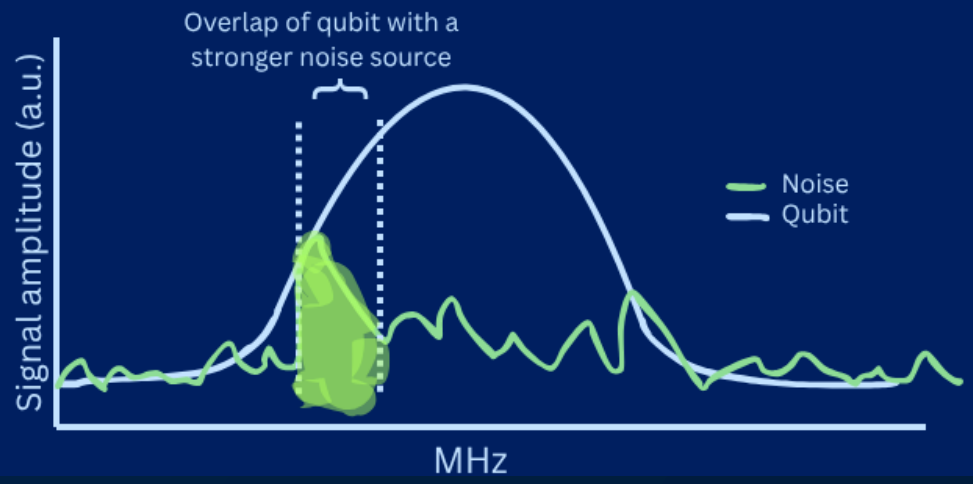

Expected total decay rate of the qubit

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

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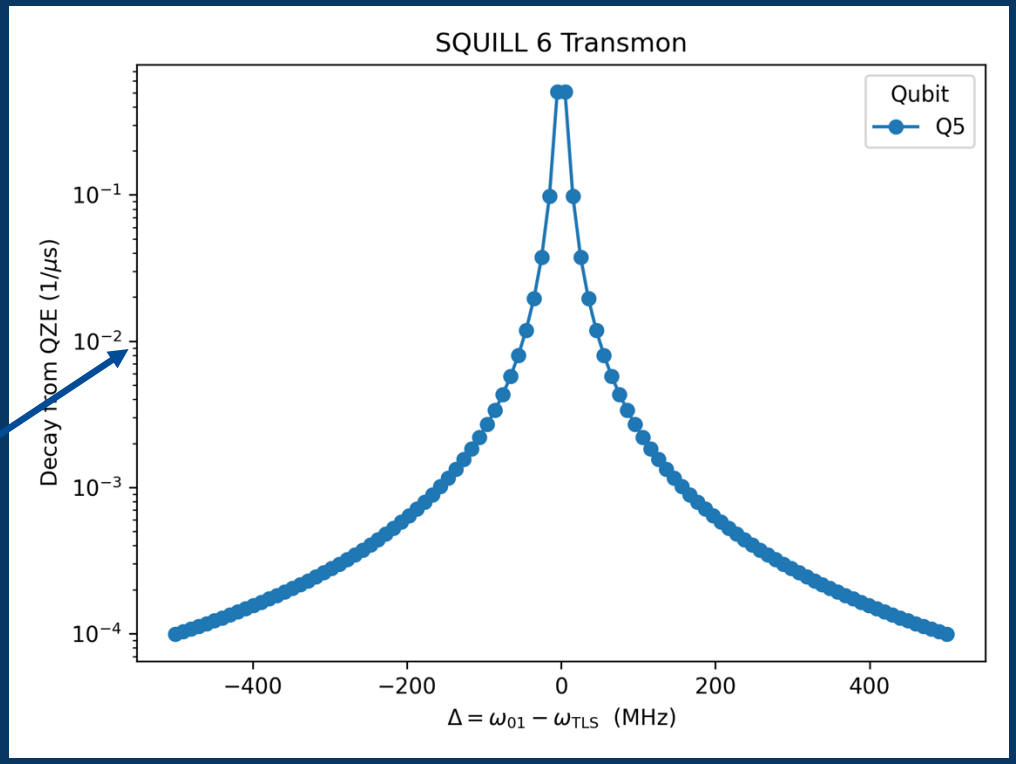
- 0.009 (1/us) is 1/T1 for this qubit, for reference



Initial results

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

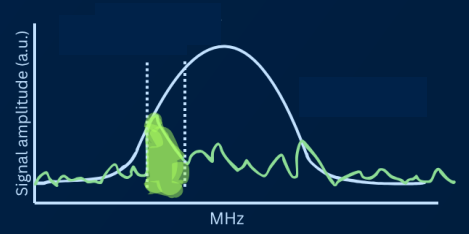
π pulse to excite to $|1\rangle$ at ω_Q

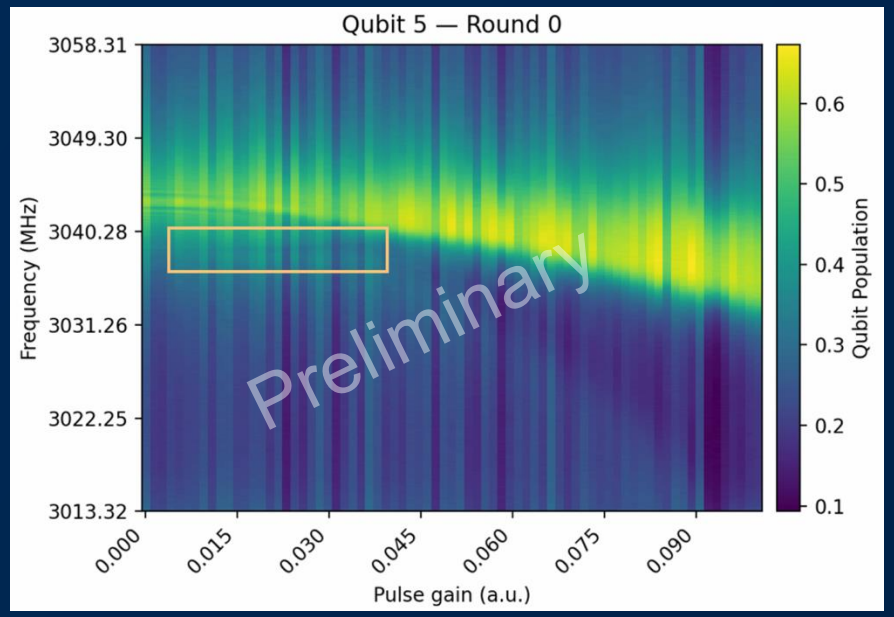
Delay time

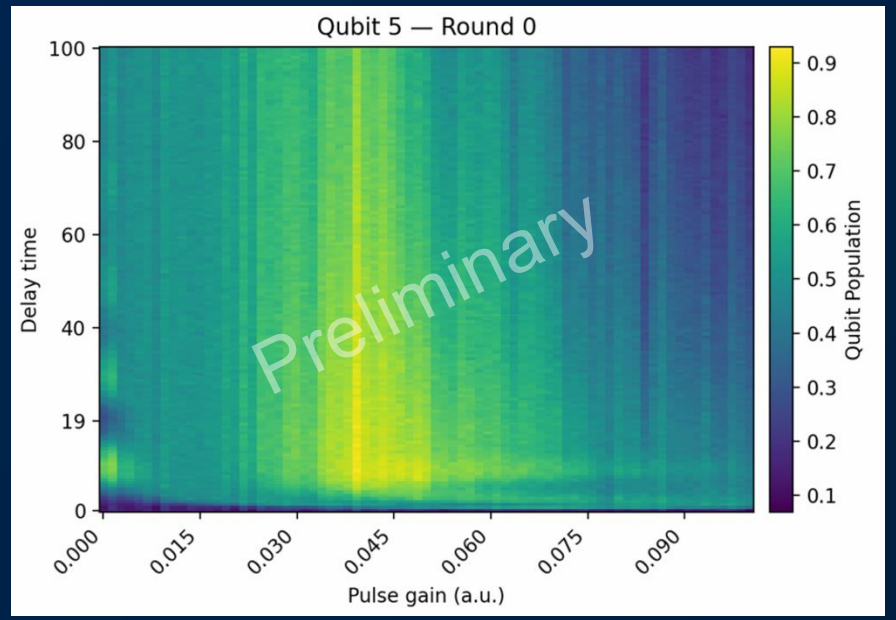
Readout pulse in resonator at ω_R

Zeno pulse in resonator at ω_R

Ring down time for resonator



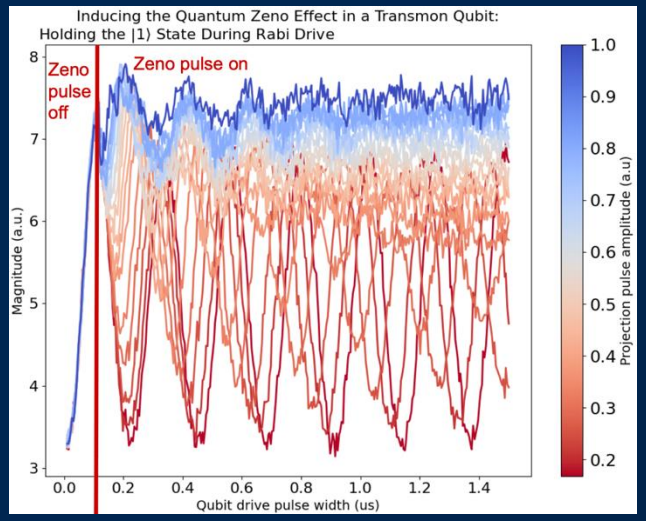




Ongoing work

Using the QZE to stabilize TLSes to better enable reliable quantum sensors:

Induce the QZE on the qubit
Induce the QZE on the qubit using photons in the resonator



Ongoing work

Using the QZE to stabilize TLSes to better enable reliable quantum sensors:

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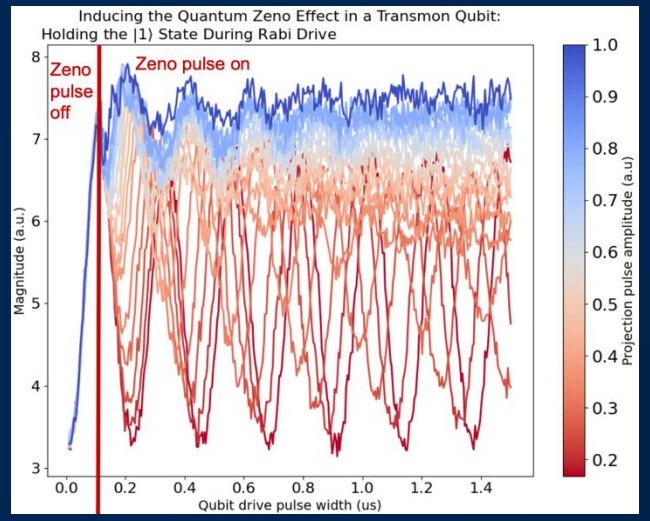
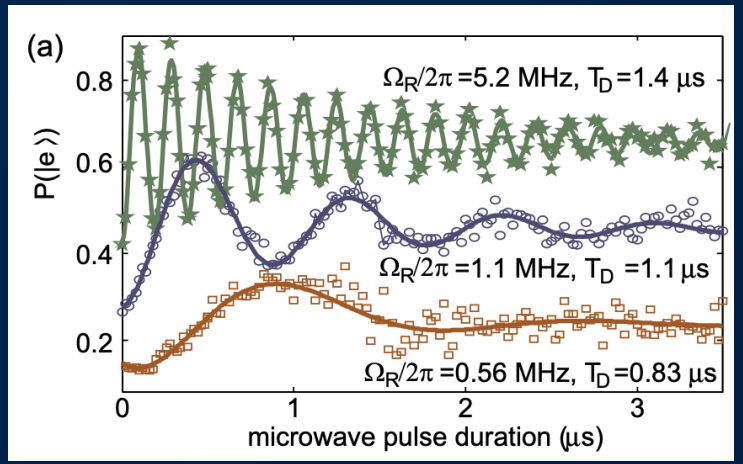
Characterize a TLS
Rabi a TLS and get its T1 time,
Track the amount of its instability





Rabi oscillations of a TLS
(10.1103/PhysRevB.95.241409)

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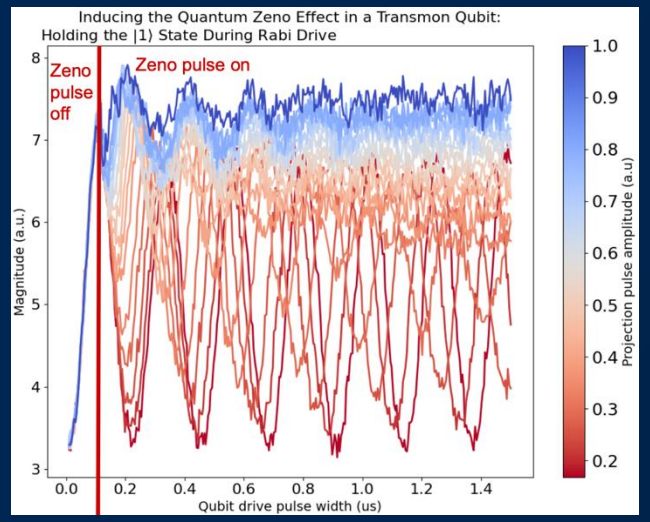
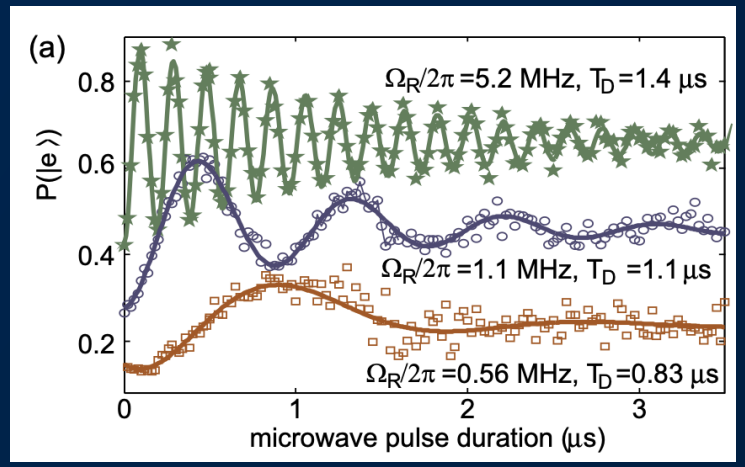
Stabilize TLS
Induce the QZE on The TLS and benchmark stabilization on the qubit frequency





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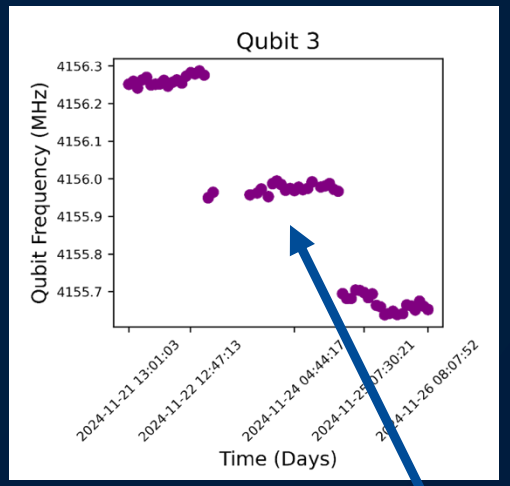

This shouldn't happen while freezing the TLS

Experimental requirements for near-term experiments

- A very well-shielded, well-characterized underground testbed for quantum sensing/gravitational red shift experiments ✅
- The ability to control qubits and nearby two-level system defects with the Quantum Zeno Effect **(Work in progress, preliminary data)**
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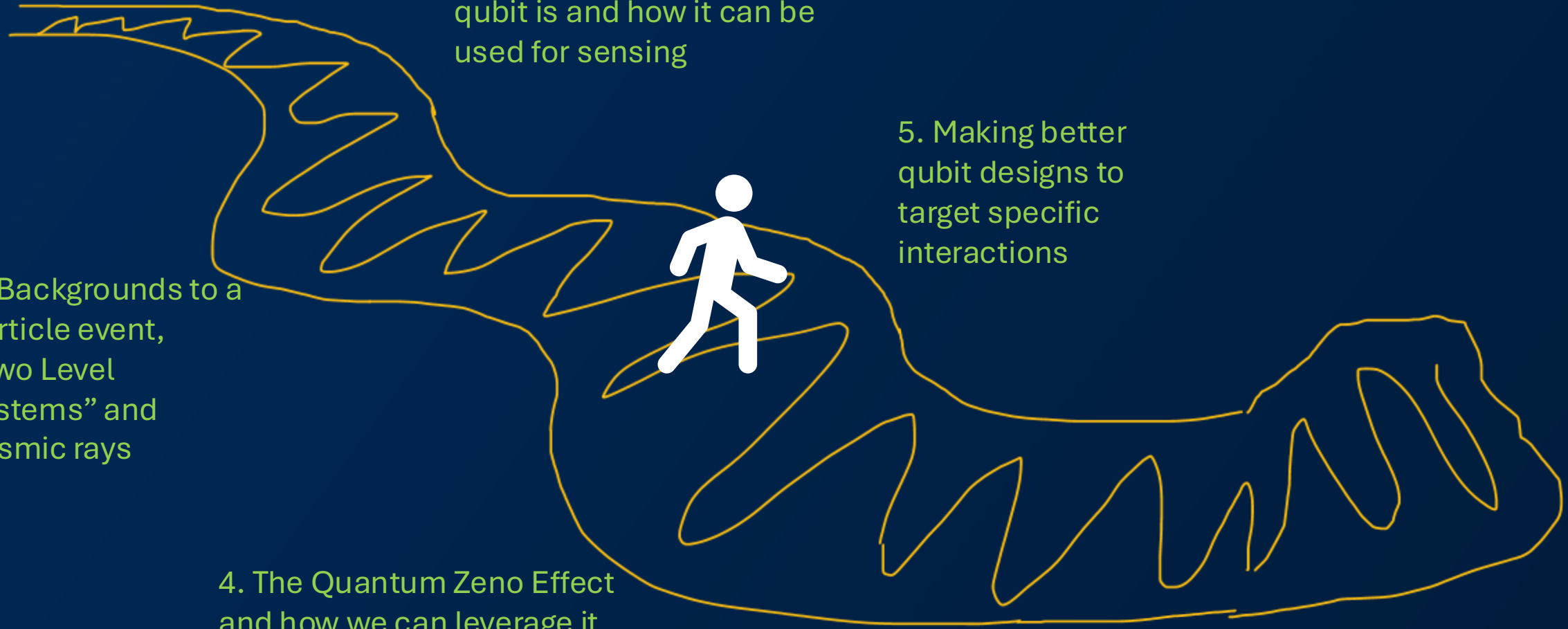
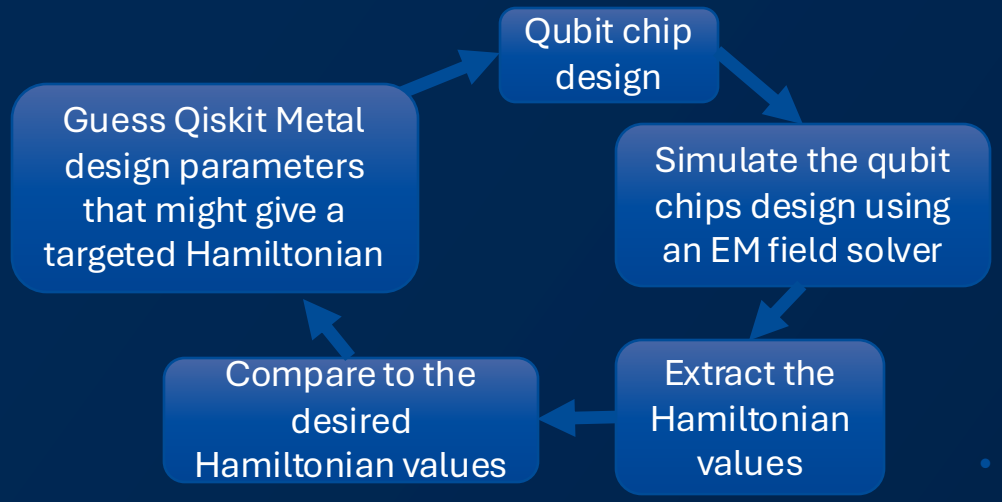
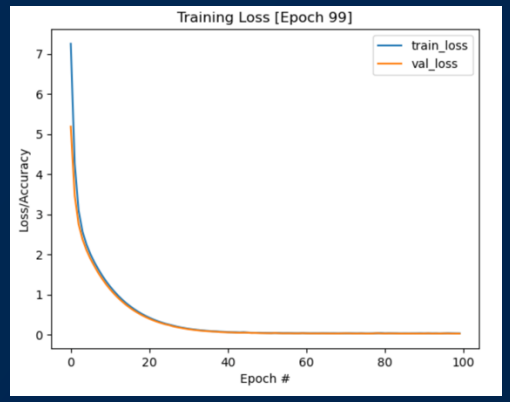
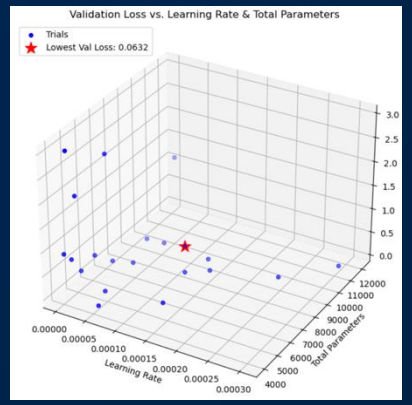


We need specific Hamiltonians to target given energy ranges







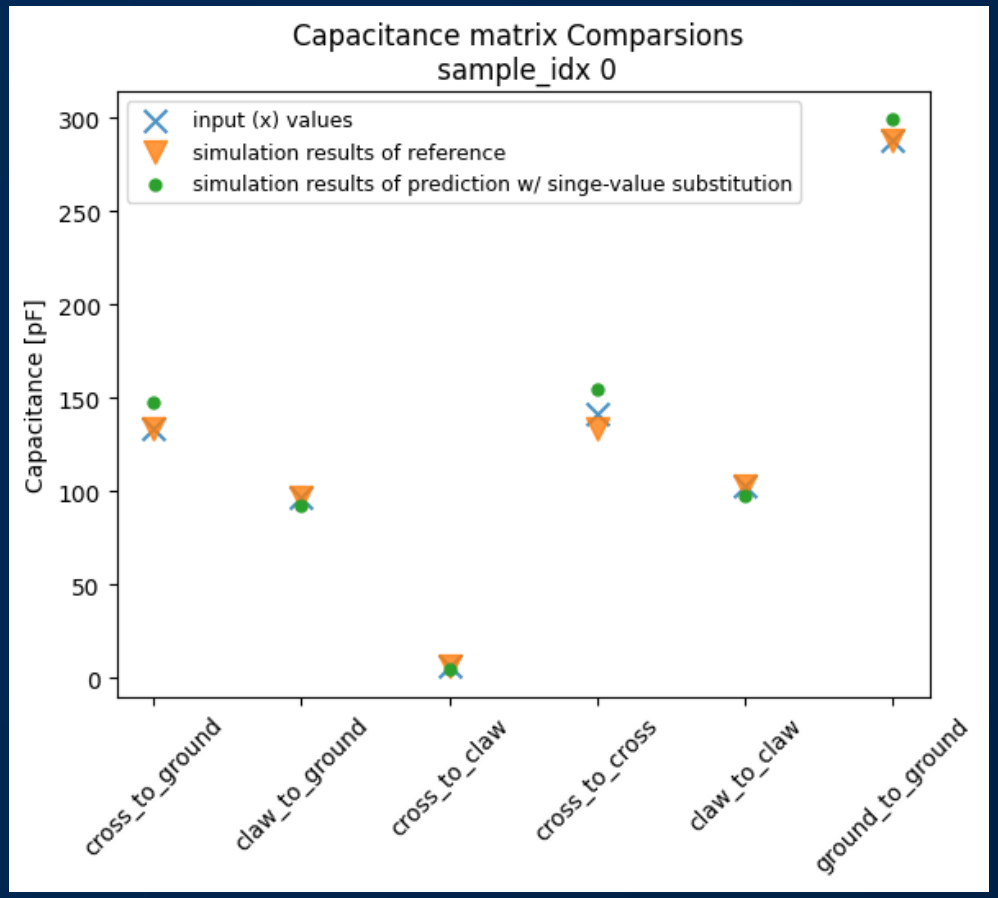
- Three models, one for the Transmon Cross, the capacitive coupling claw, and the readout resonator.
- **X values:** Hamiltonian parameters
- **Y values:** Qiskit Metal design parameters (geometrical/layout variables) for the specific part of the chip that the MLP should predict (lengths, gap sized, widths, etc)

Model: "sequential_1"

Layer (type)	Output Shape	Param #
fc0 (Dense)	(None, 2500)	17,500
leaky_relu0 (LeakyReLU)	(None, 2500)	0
dropout0 (Dropout)	(None, 2500)	0
fc1 (Dense)	(None, 300)	750,300
leaky_relu1 (LeakyReLU)	(None, 300)	0
dropout1 (Dropout)	(None, 300)	0
fc2 (Dense)	(None, 4000)	1,204,000
leaky_relu2 (LeakyReLU)	(None, 4000)	0
dropout2 (Dropout)	(None, 4000)	0
fc3 (Dense)	(None, 2700)	10,802,700
leaky_relu3 (LeakyReLU)	(None, 2700)	0
dropout3 (Dropout)	(None, 2700)	0
fc_output (Dense)	(None, 29)	78,329

Total params: 38,558,492 (147.09 MB)
Trainable params: 12,852,829 (49.03 MB)
Non-trainable params: 0 (0.00 B)
Optimizer params: 25,705,663 (98.06 MB)

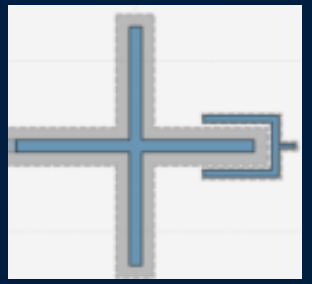
We need specific Hamiltonians to target given energy ranges



Test values simulated using HFSS pipeline by Firas Abouzahr

Reference test coupling claw:

ML predicted coupling claw:



Work completed in collaboration with Sara Sussman, Firas Abouzahr, Enectali Figueroa

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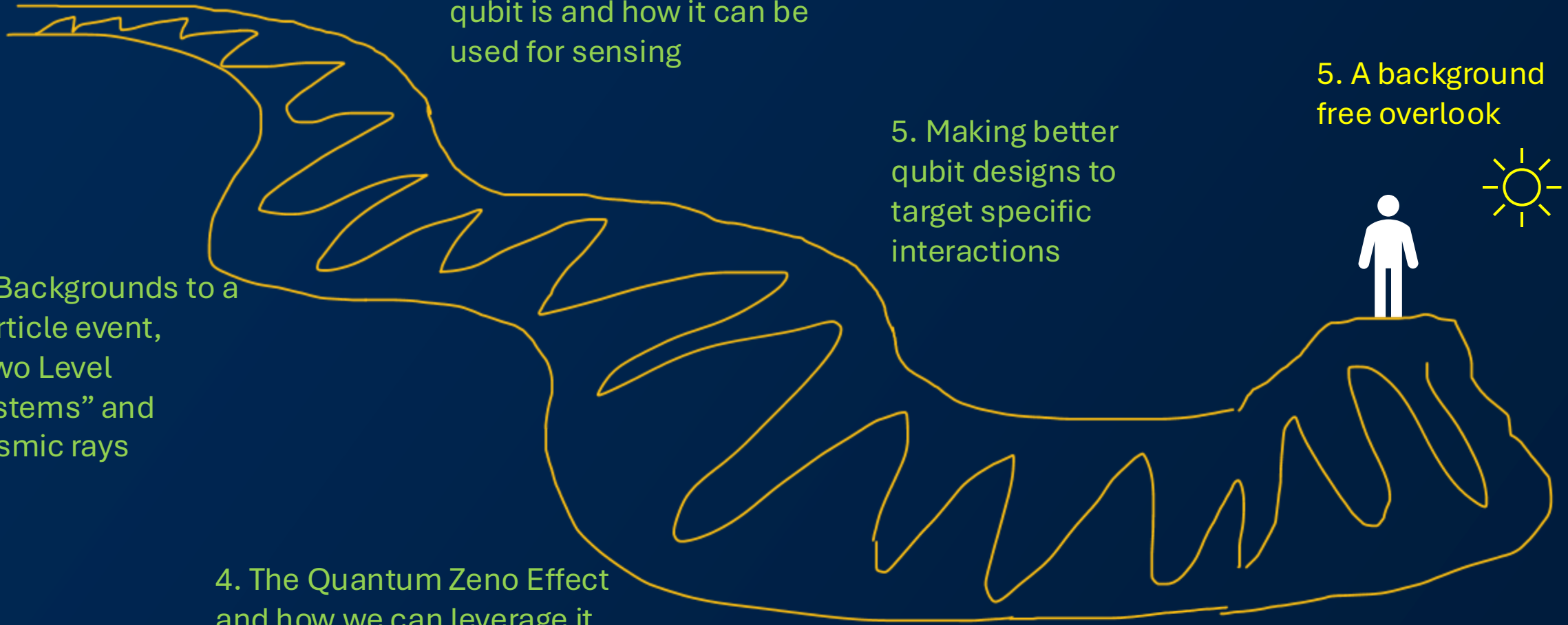
5. A background free overlook

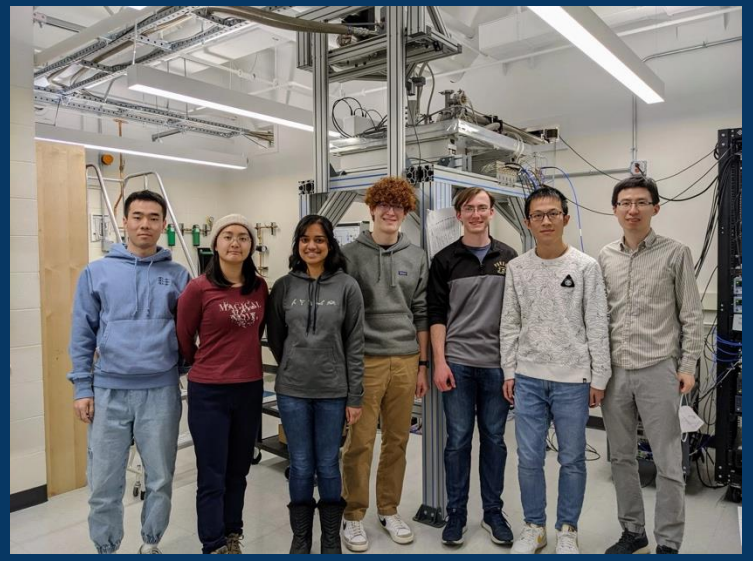


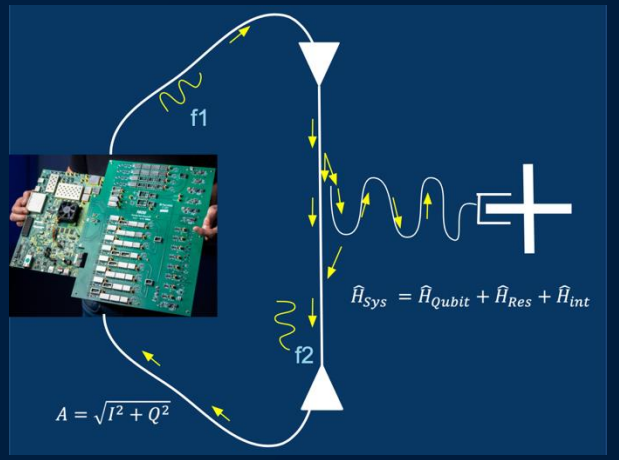
Conclusion

- Superconducting based qubits offer potential for ultra-low energy particle detection
- Two of the leading known sources of backgrounds:
  1. Cosmic rays
  2. Defect Two Level Systems
- (1) can be mitigated by going underground, (2) remains a limiting background to qubit-based sensing, so we can try to constrain them and quantify their fluctuations
- We can leverage SC qubits for tests of fundamental quantum mechanics like:
  - How the QZE propagates through entangled systems
  - Unitarity of quantum mechanics and conservation of quantum information
  - If systems in superposition experience gravity

Thank you to the Graduate Instrumentation Research Award for supporting this work!

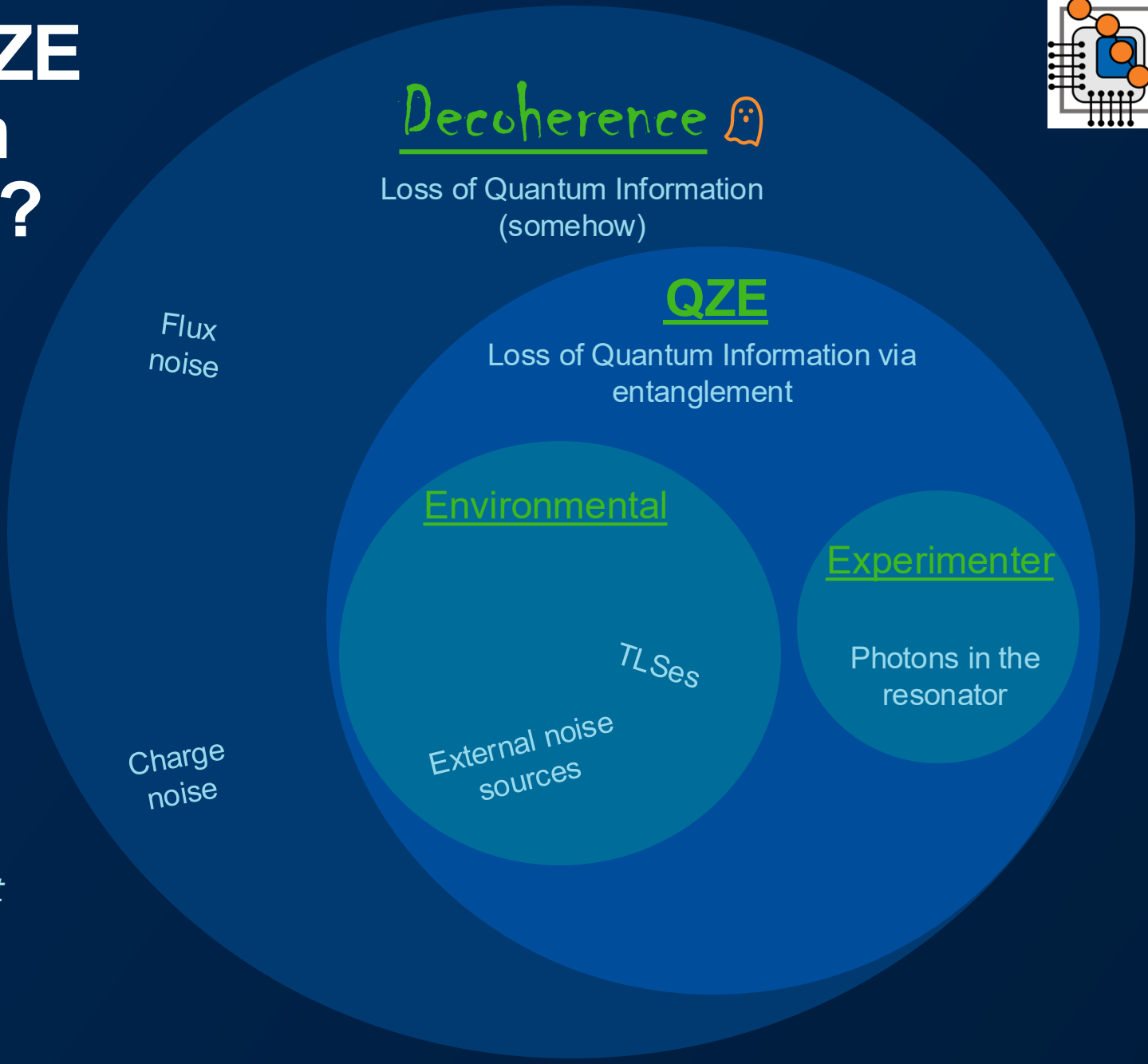
Huge thank you to Alex Ma's Lab (Ma Lab), Archana Kamal's group (QUEST), the Fermilab CosmiQ and QICK teams!





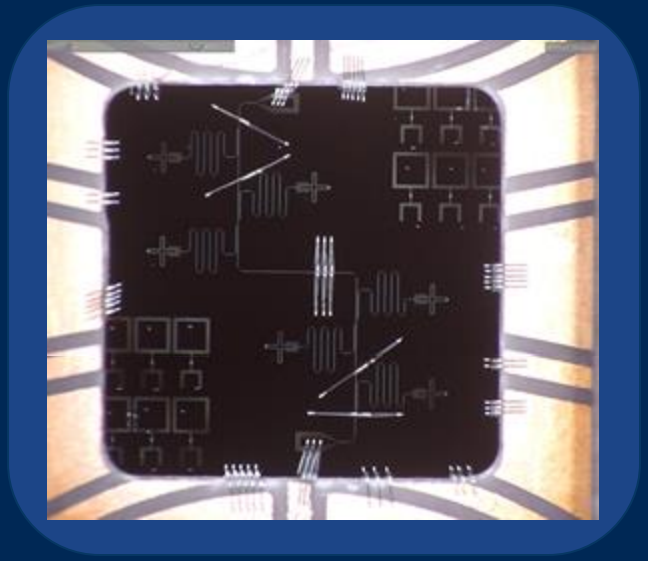
Backups

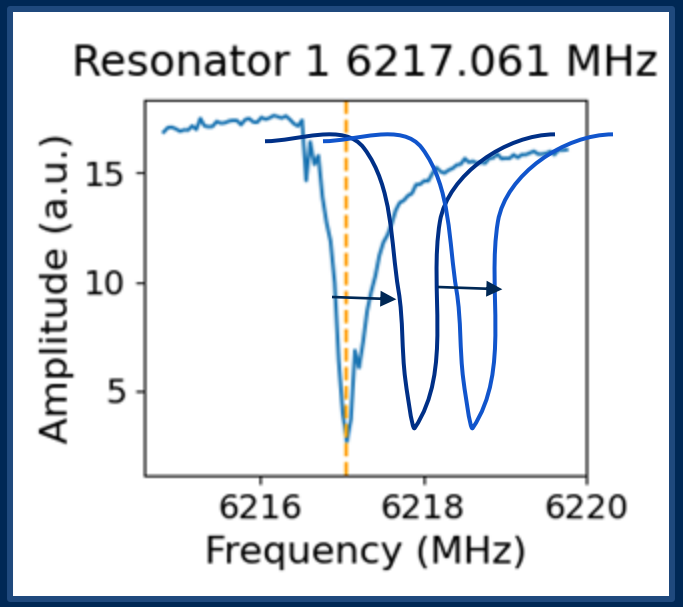
How is the QZE different than decoherence?

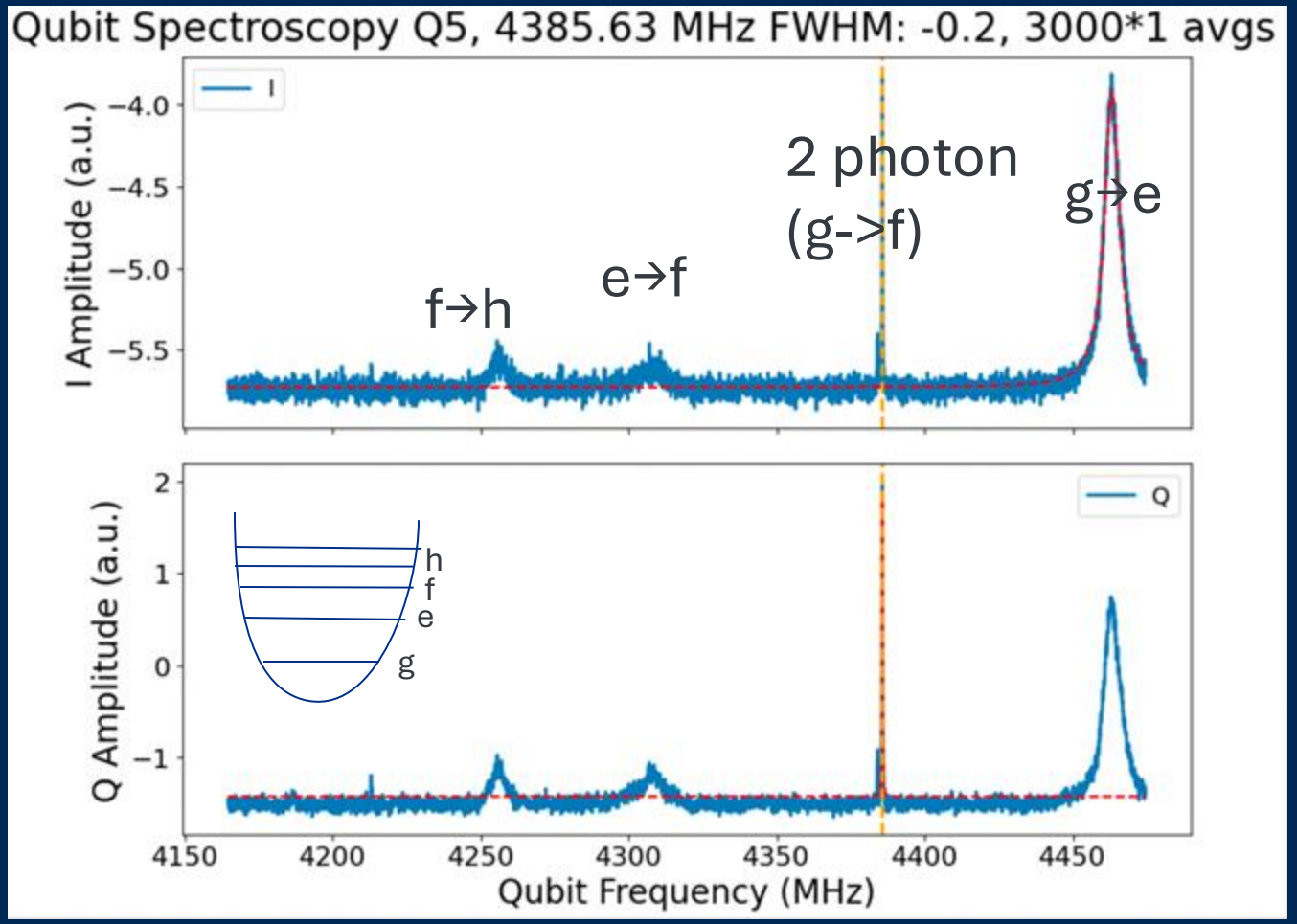


Pure dephasing is most fundamentally the loss of quantum information from the qubits perspective, and if it happens through entanglement its the QZE

Foundational Measurements: Step 0

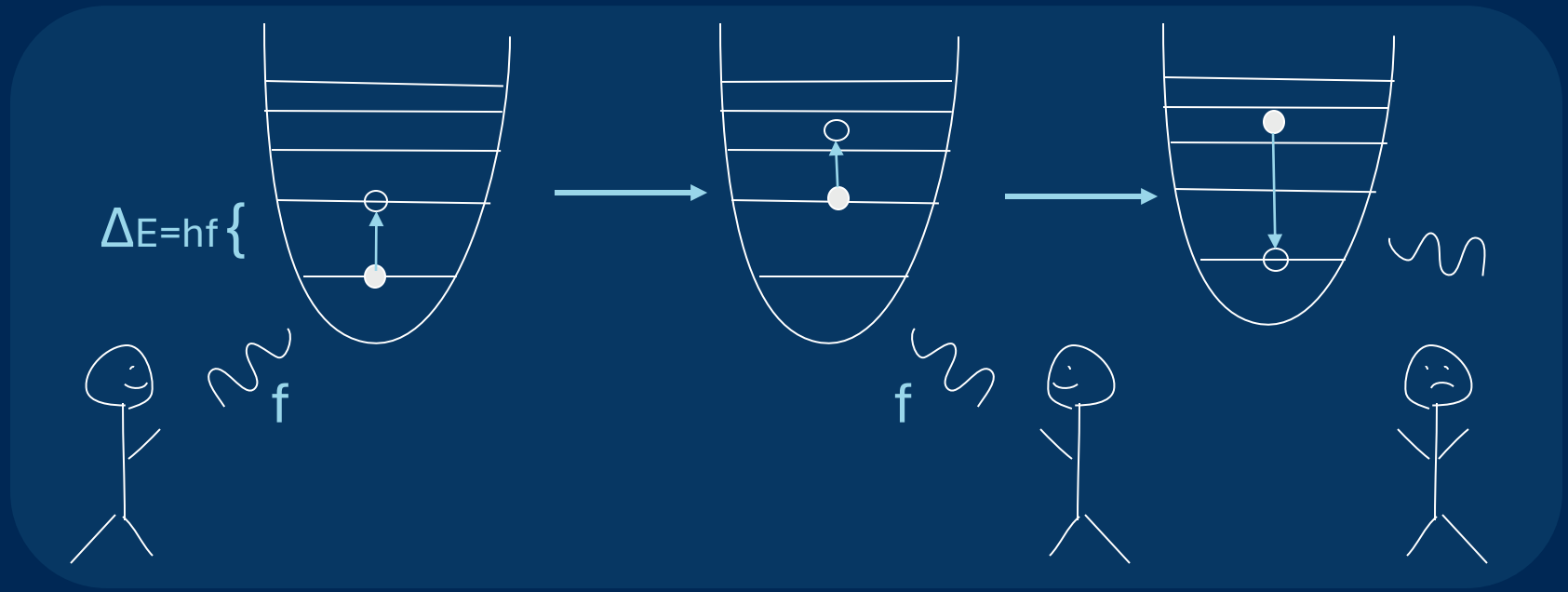




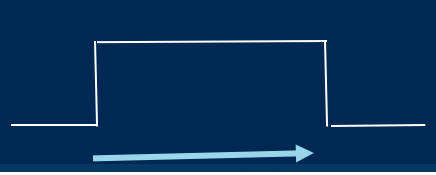


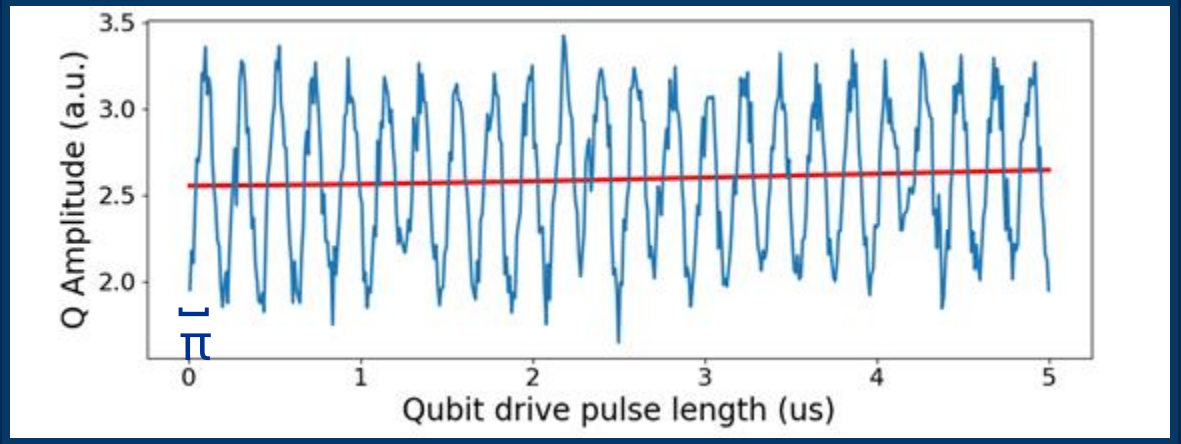
FERMI NATIONAL ACCELERATOR LABORATORY

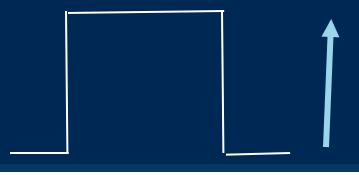
Foundational Measurements: Step 1

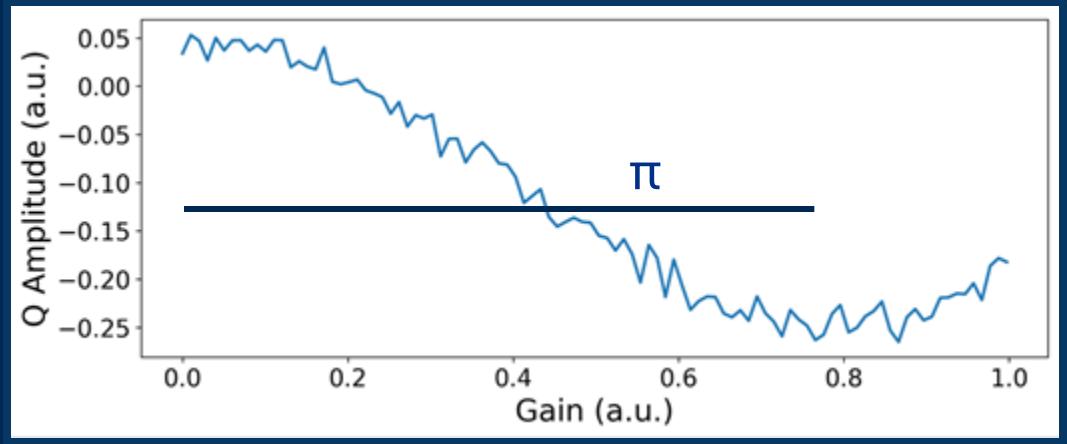


Rabi Oscillations

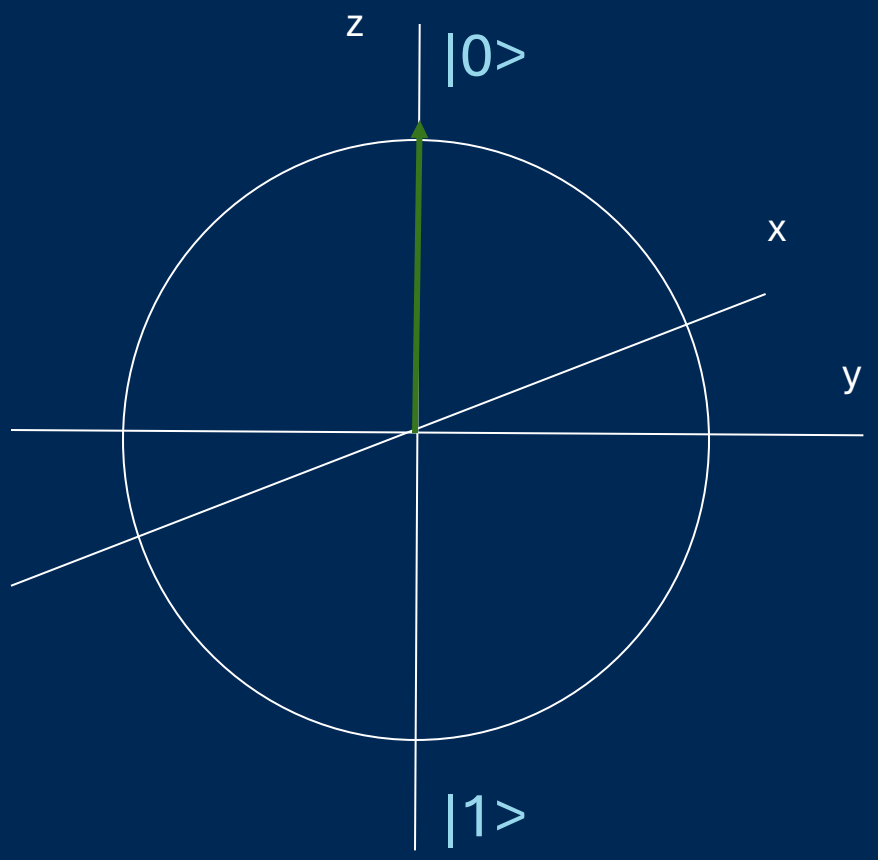








Foundational Measurements: Bloch Sphere

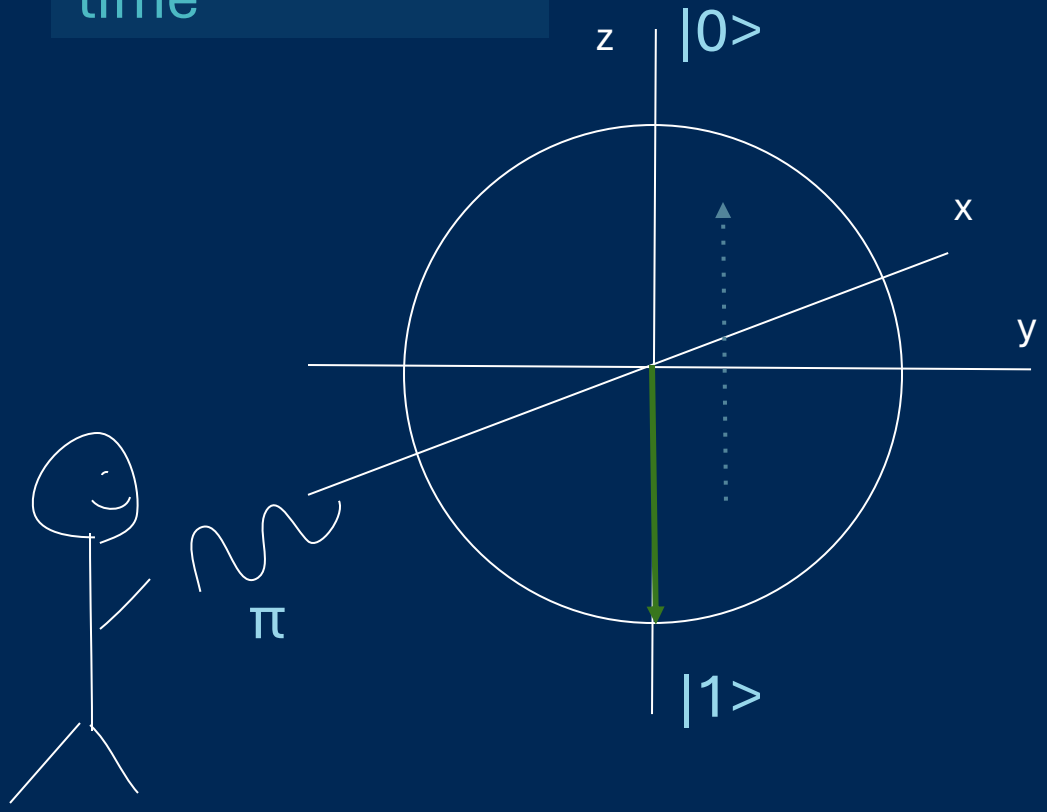


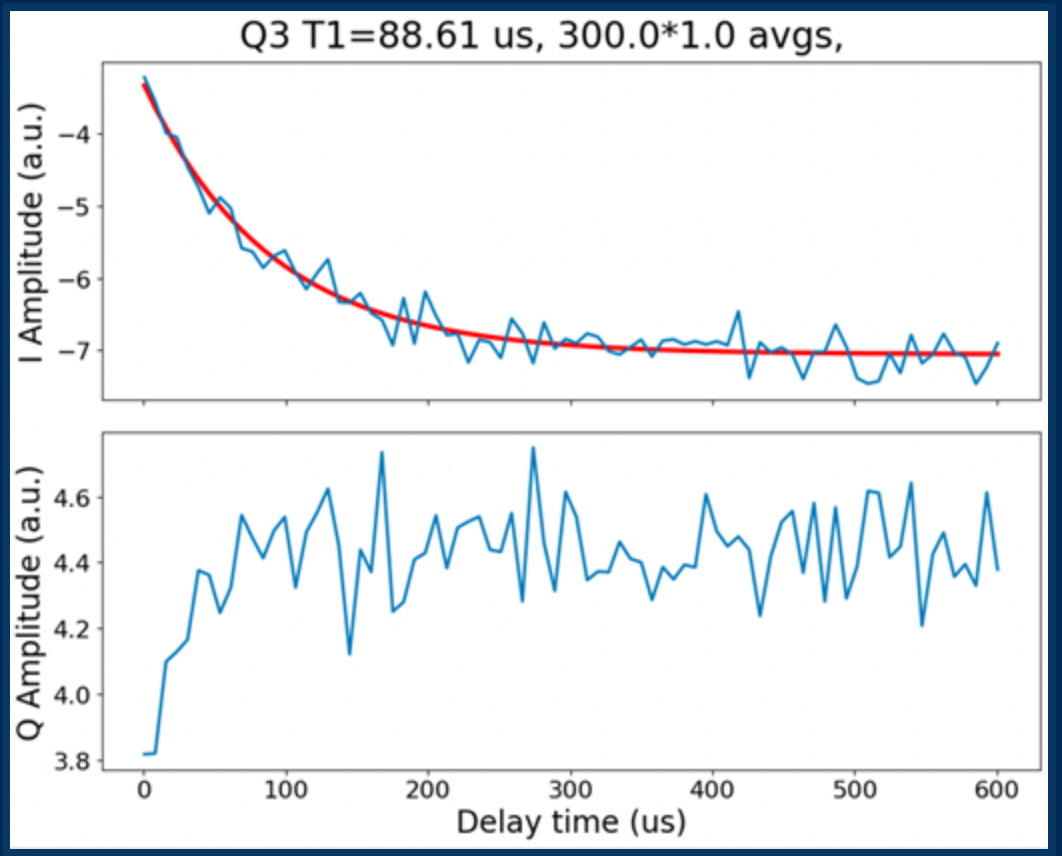
Quantum Phase Information

I can only ever measure here

Foundational Measurements: Step 2

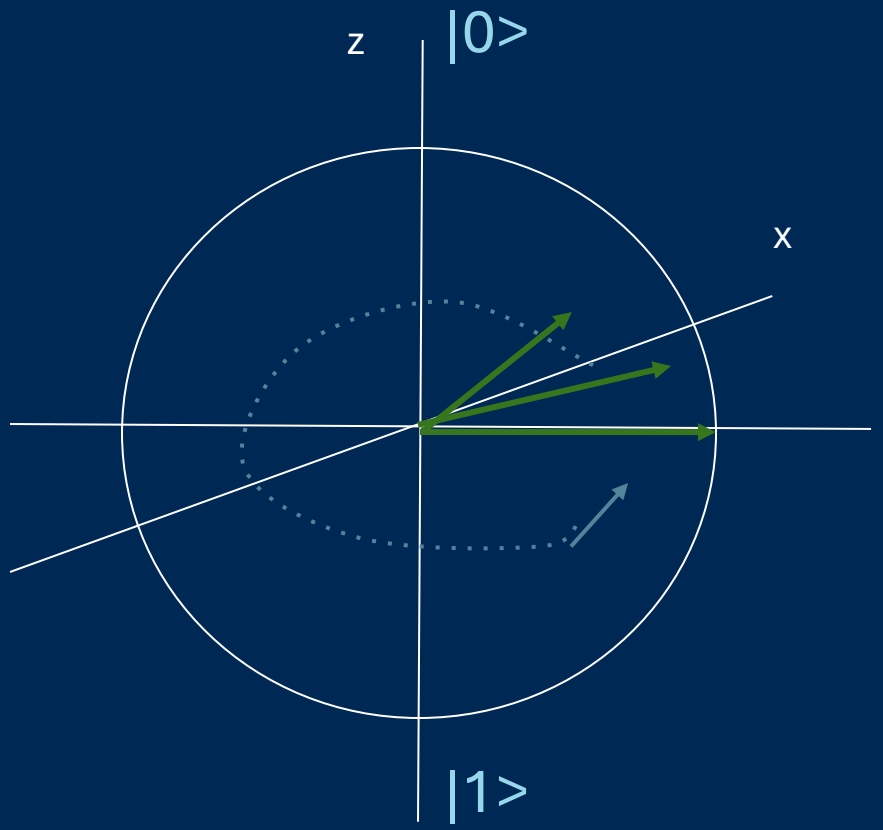
T1: “Relaxation time”

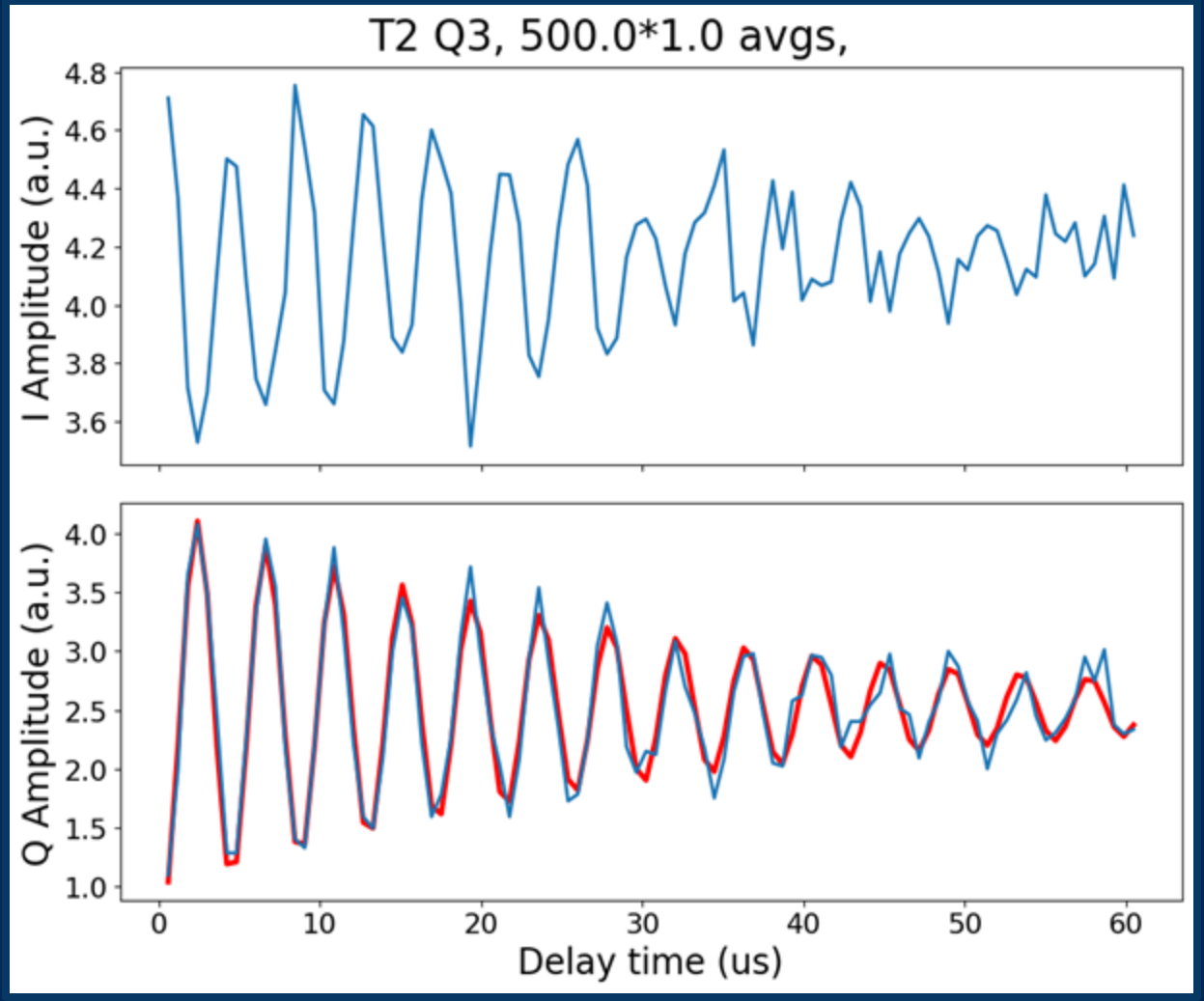




Foundational Measurements: Step 3

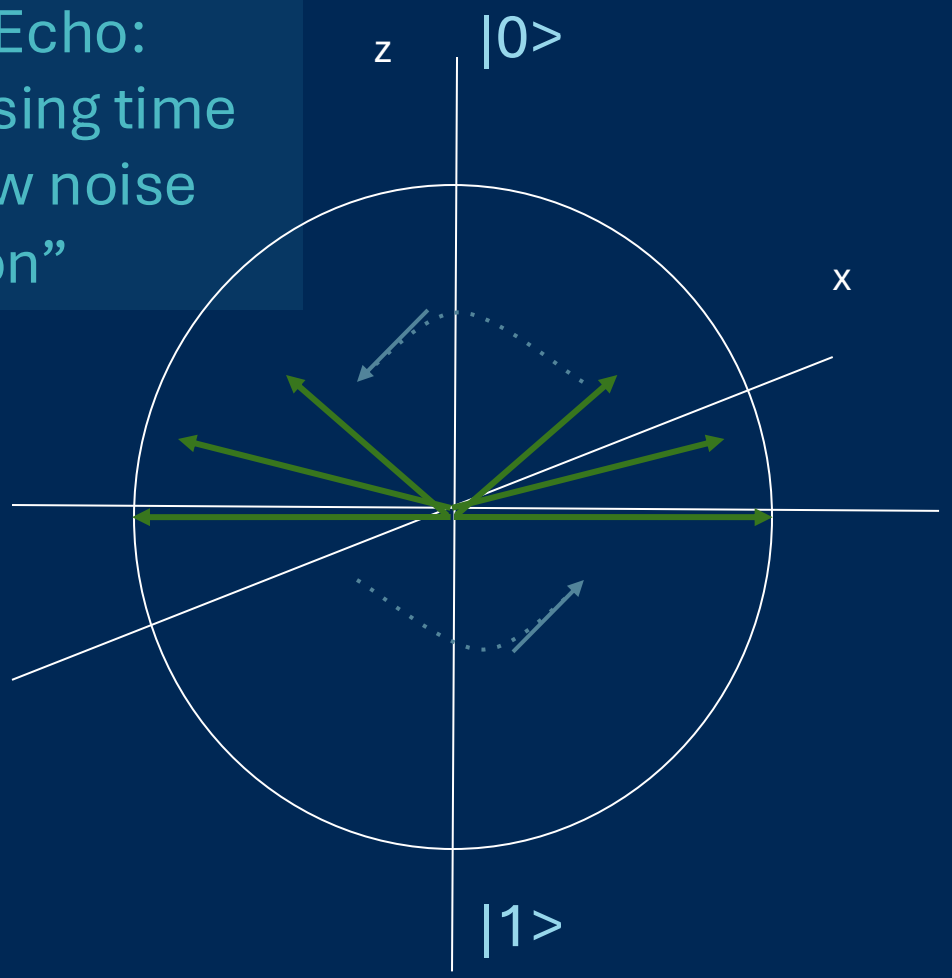
T2 Ramsey:
"Dephasing time"

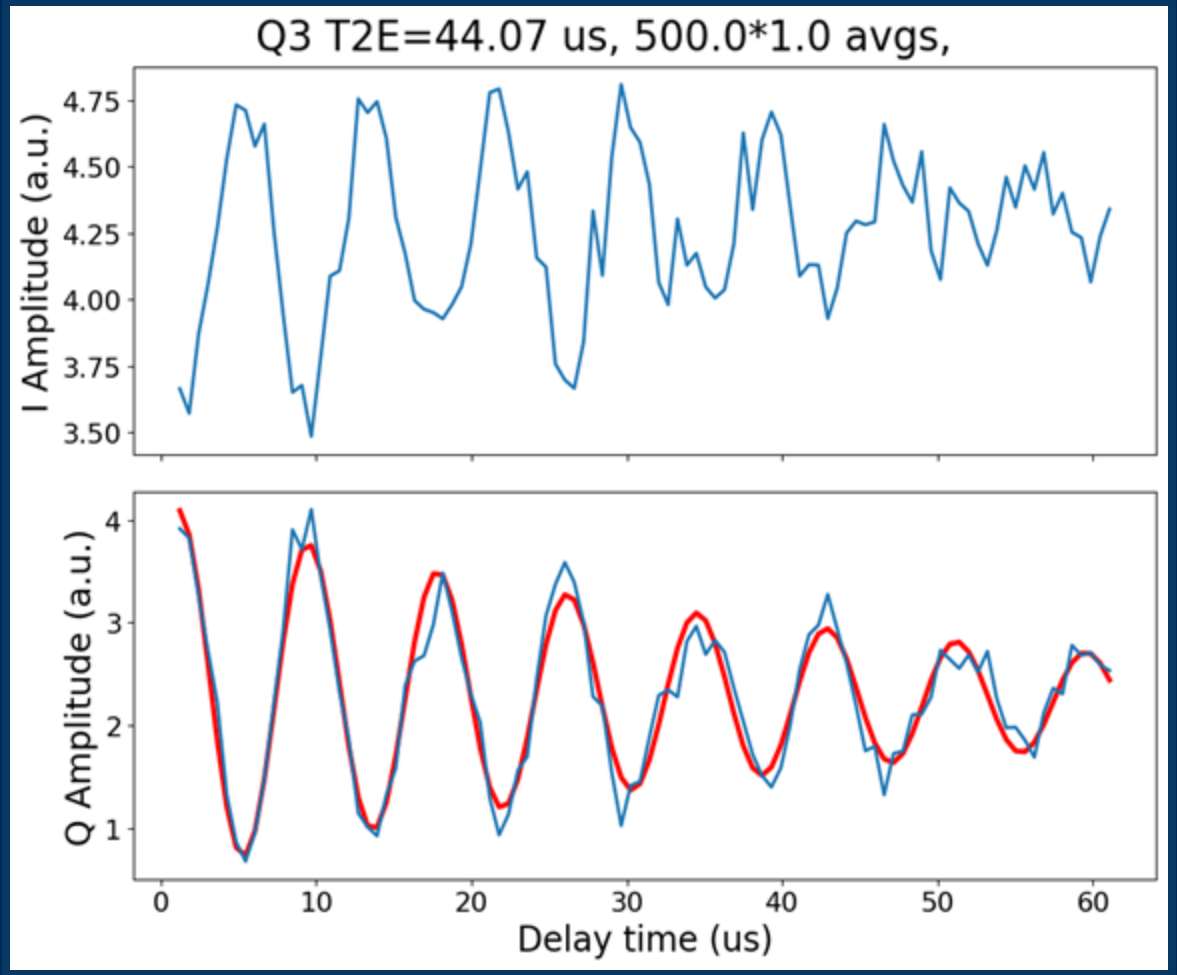




Foundational Measurements: Step4

T2 Spin Echo: “Dephasing time with slow noise reduction”

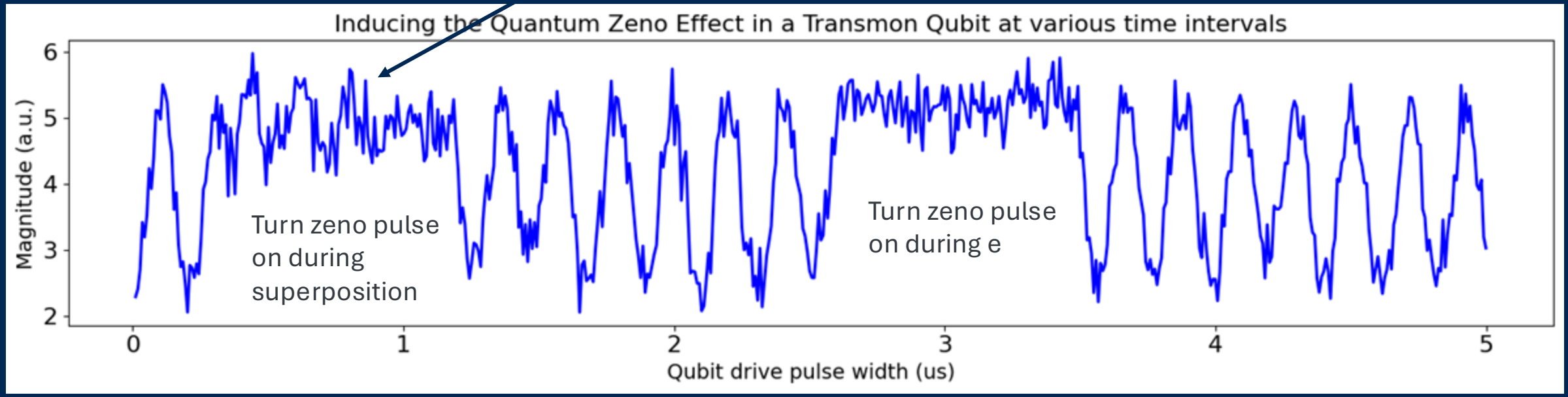




Validating measurements of the QZE

If the qubit is indeed being frozen to the first excited state, it should immediately start undergoing spontaneous emission regardless of where I stop zeno-ing in the natural rabi cycle

Confined quantum system

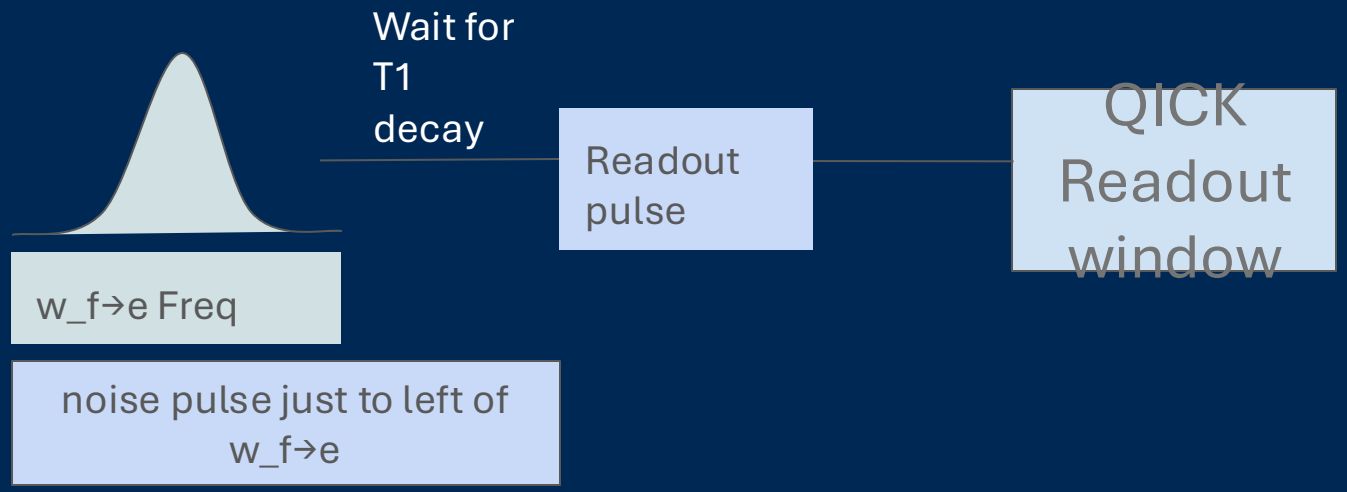


Measuring the impact of QZE on higher energy transitions

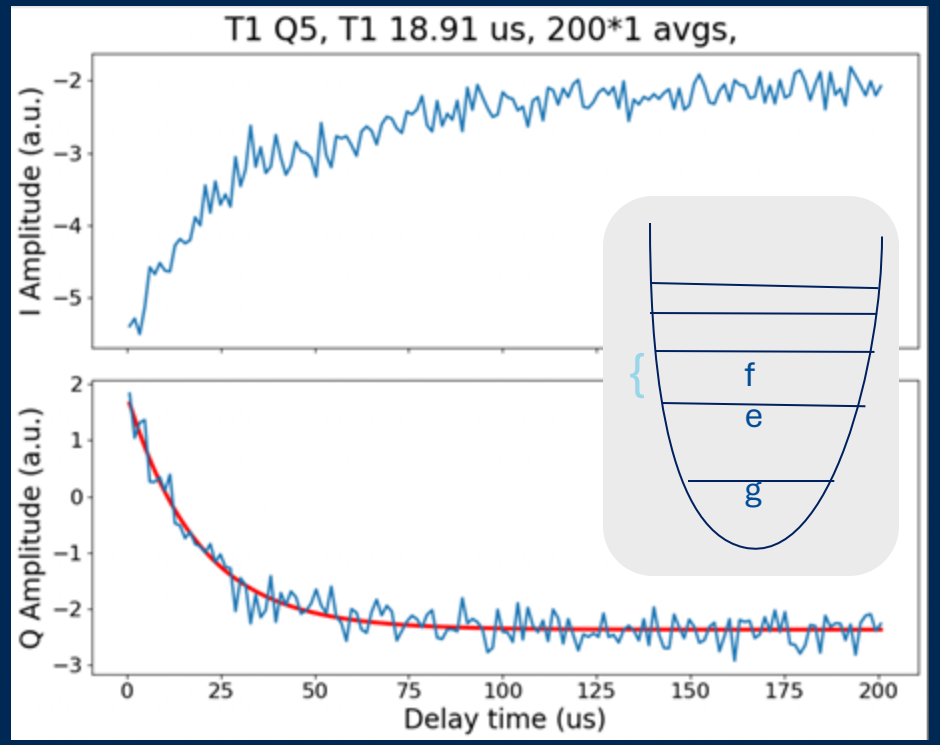
Initial steps towards paper measurement

Question-- can you freeze higher energy levels without disturbing the lower transitions??

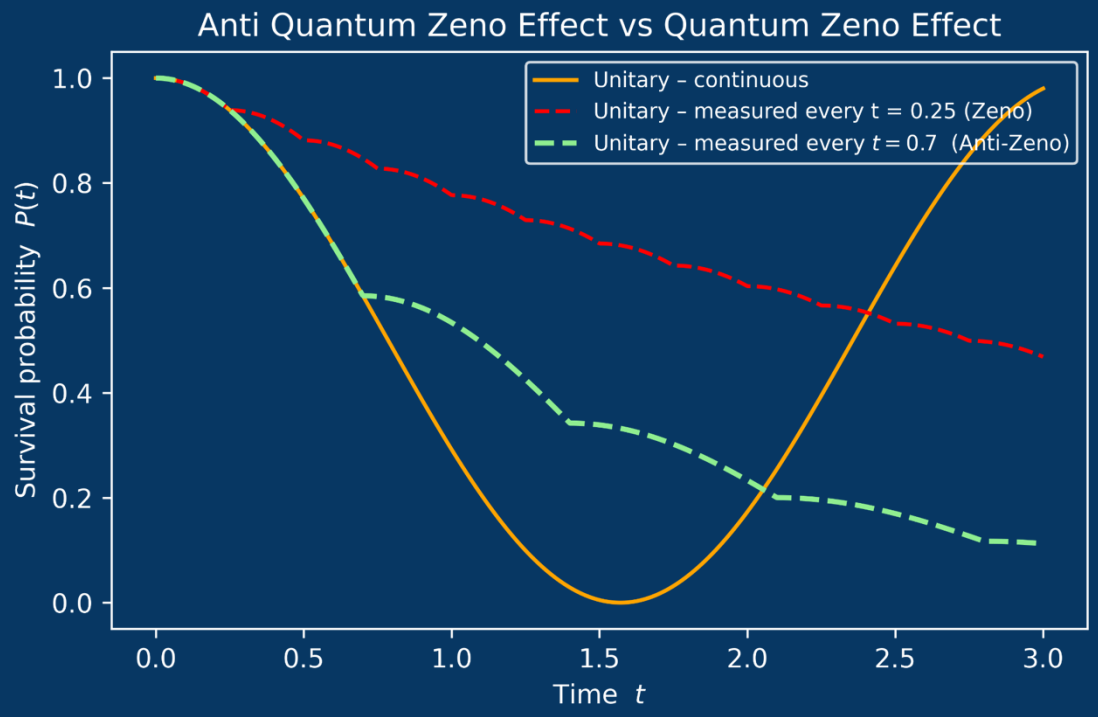
I have measured T1 from F→e to make sure they are long enough to see this effect-- and they are!



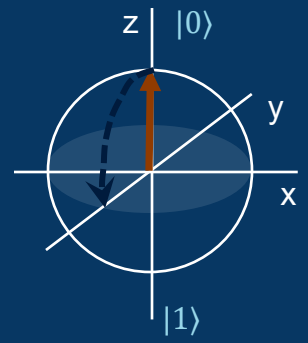
T1 from F→e



Method to constrain quantum systems: the Quantum Zeno Effect



Lab frame:



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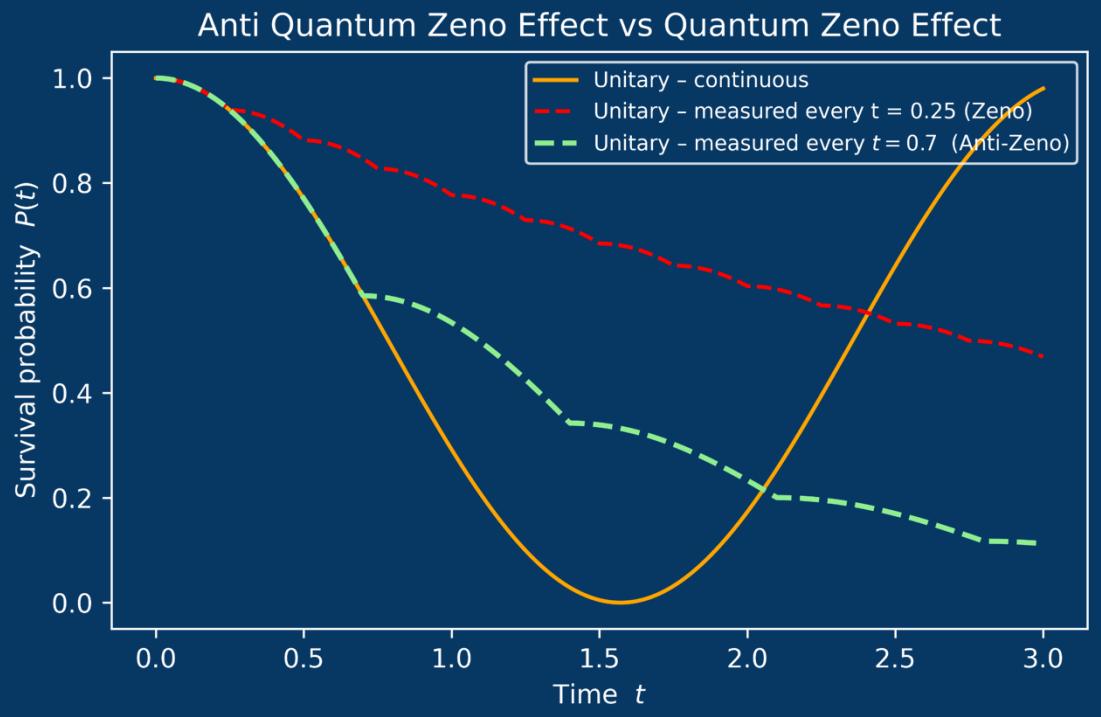

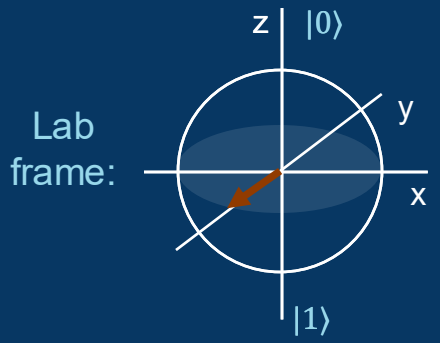

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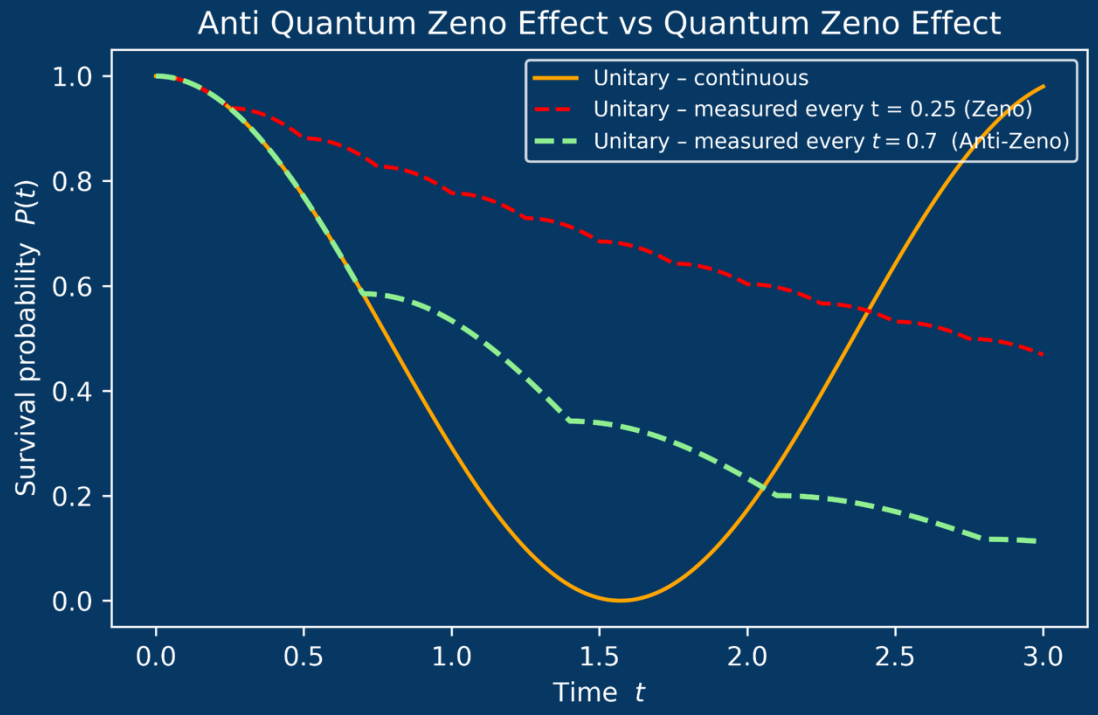

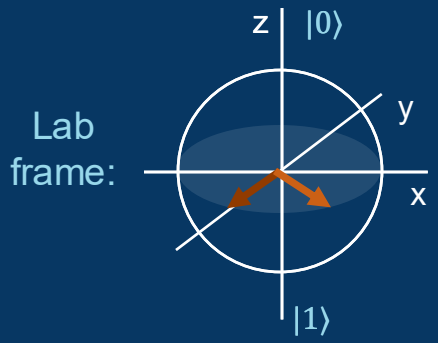

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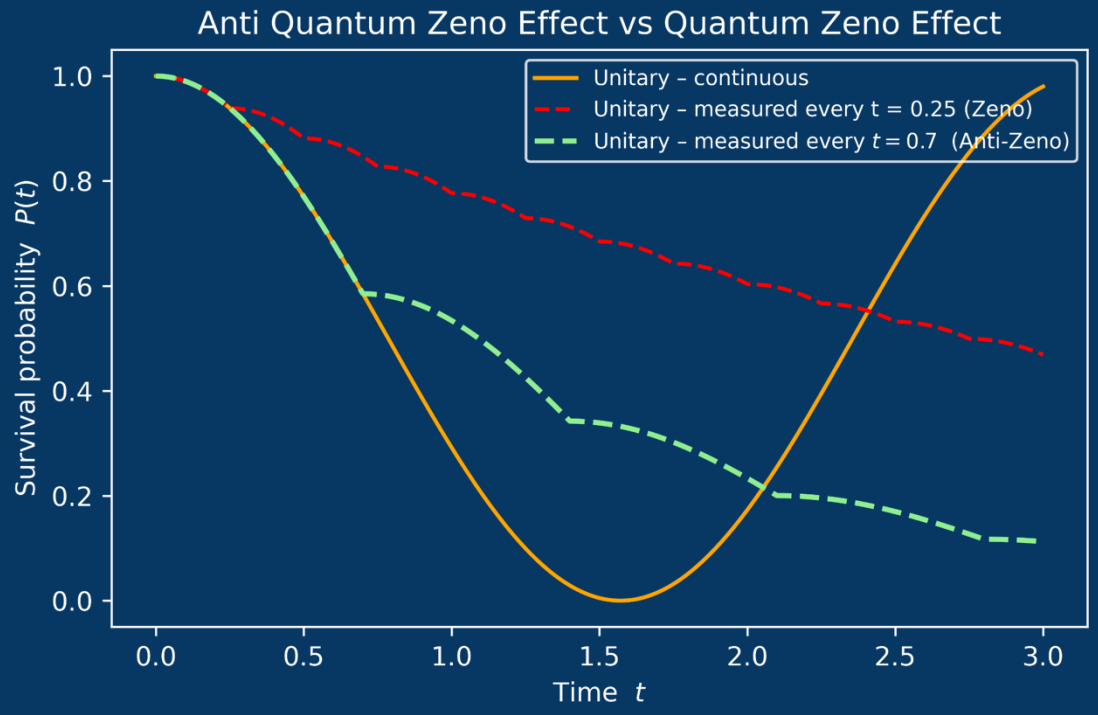

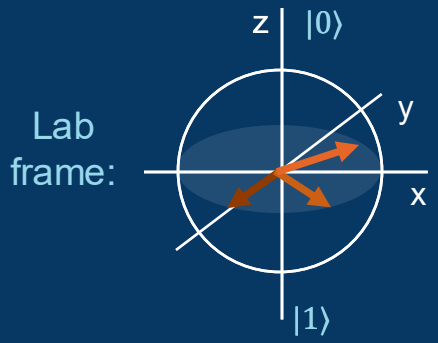

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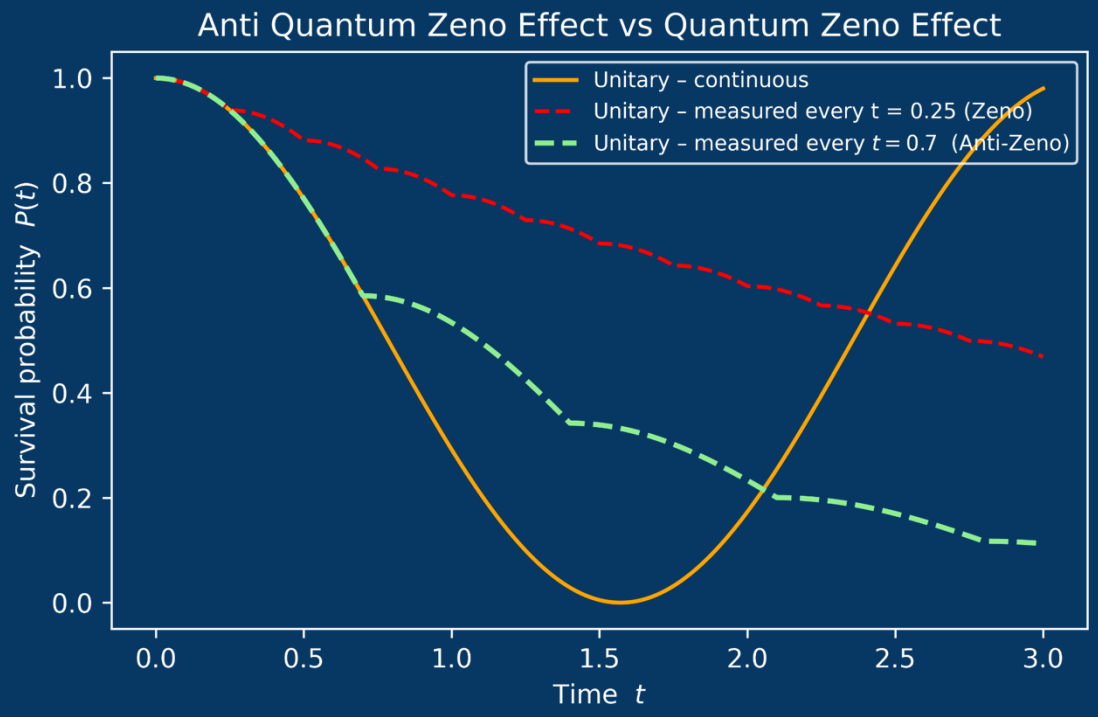

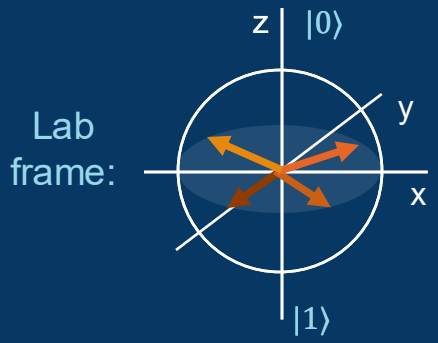

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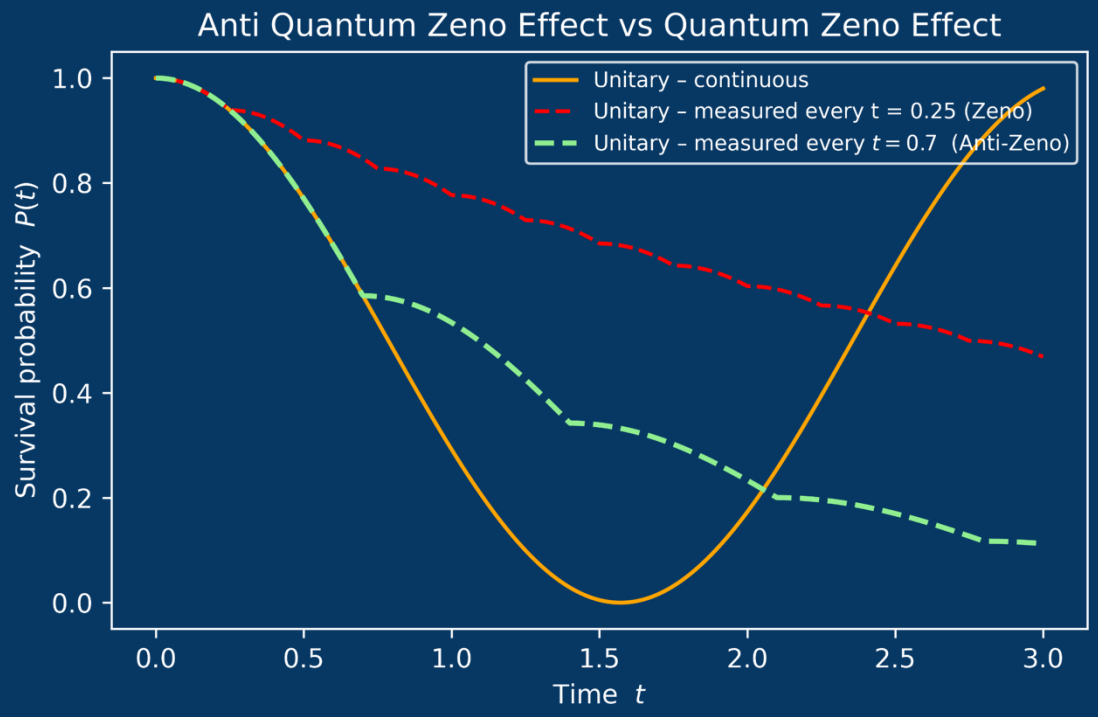

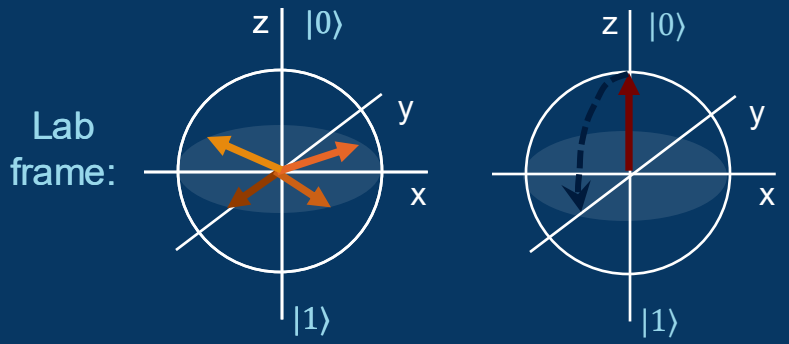

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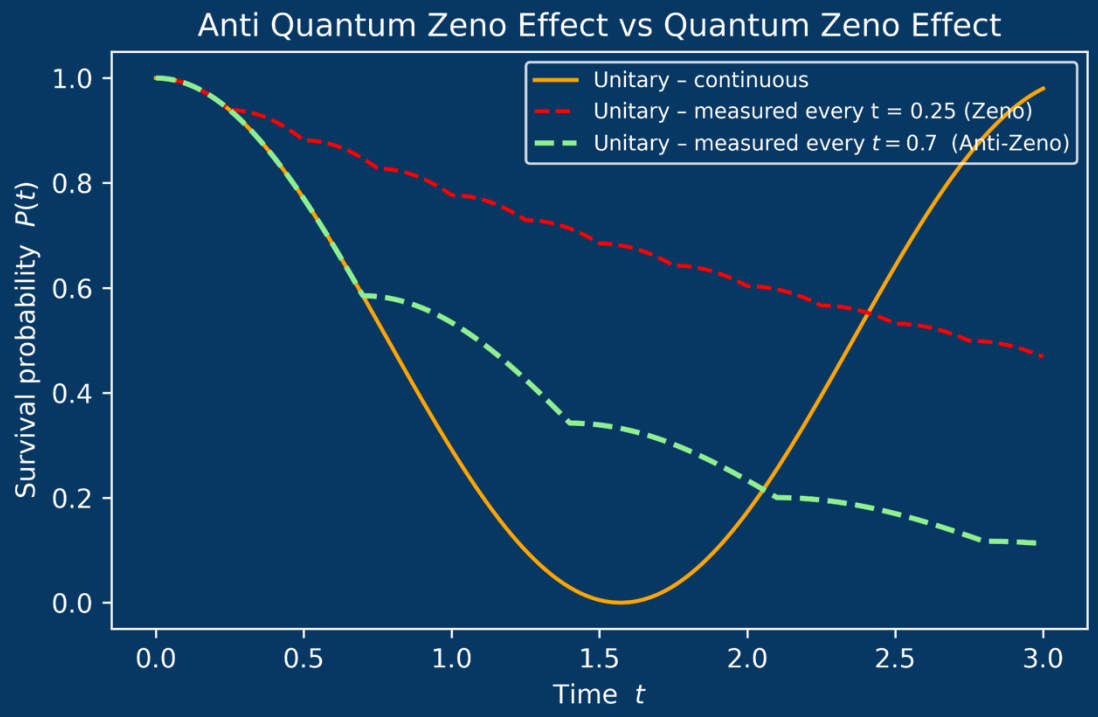
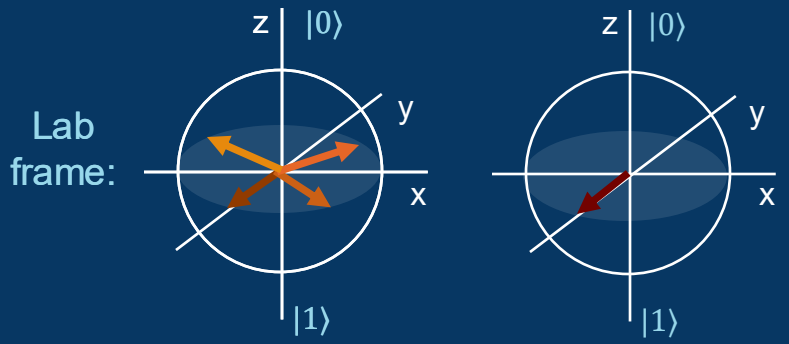
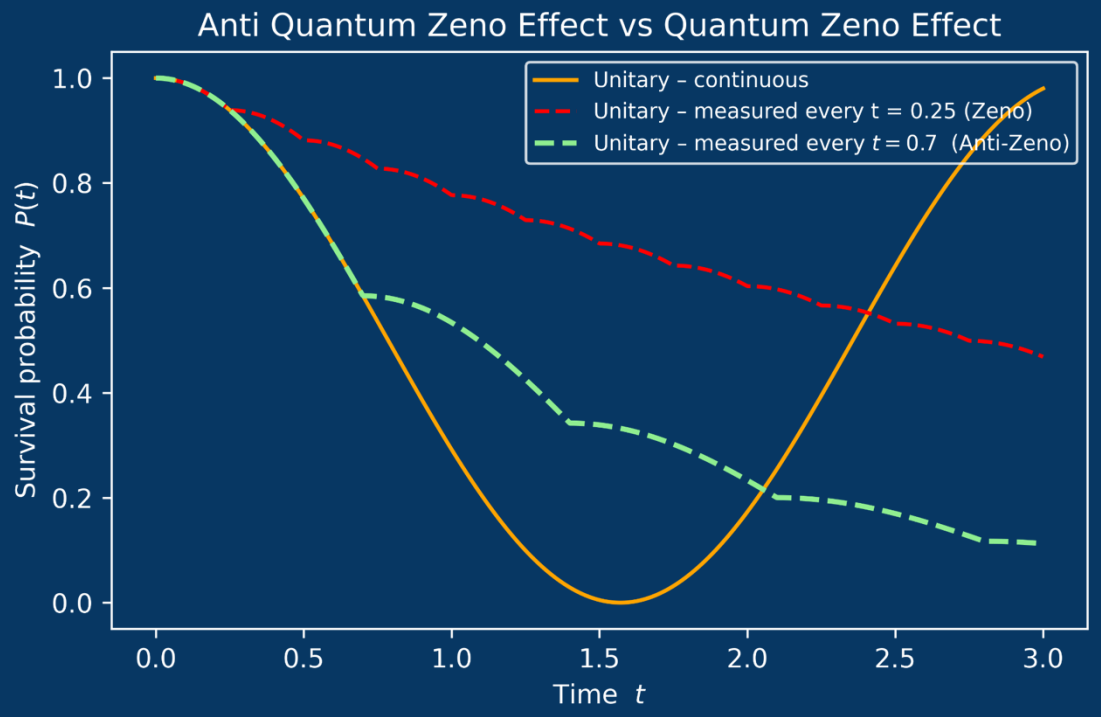
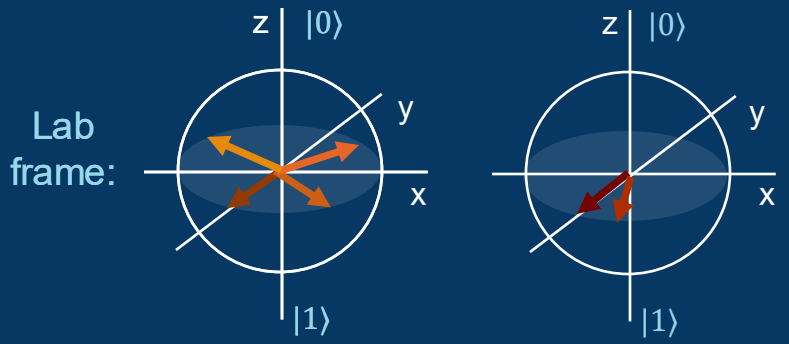




Method to constrain quantum systems: the Quantum Zeno Effect





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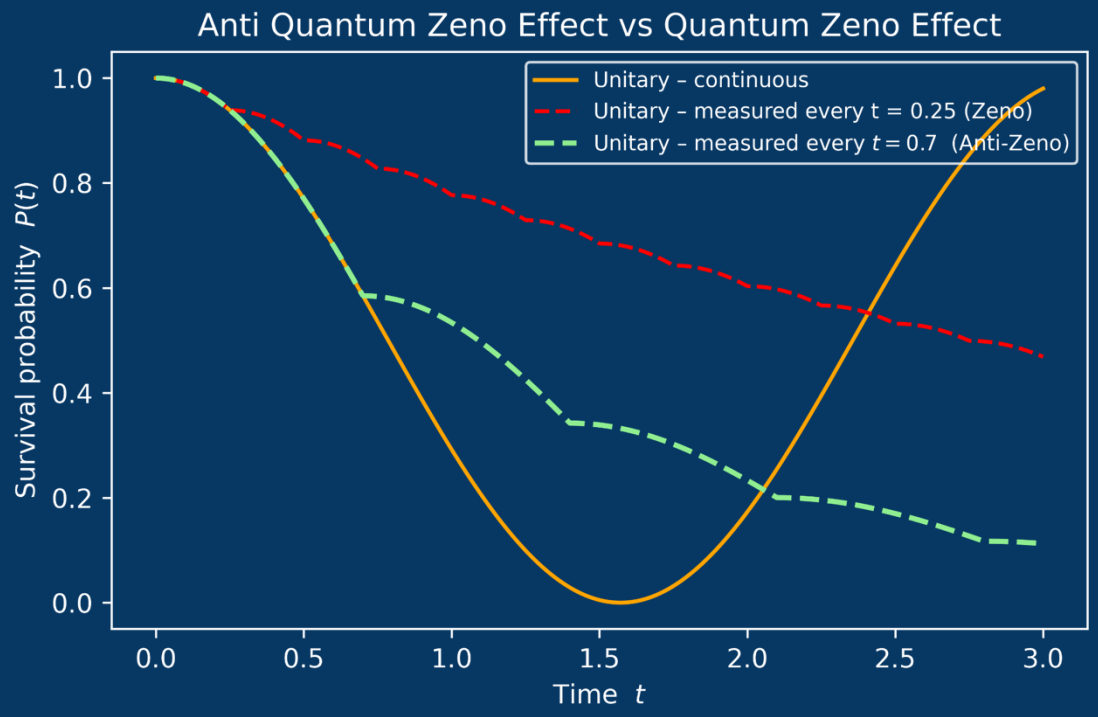

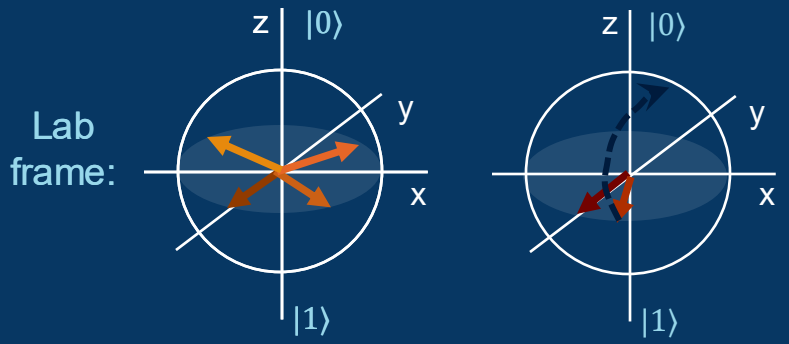

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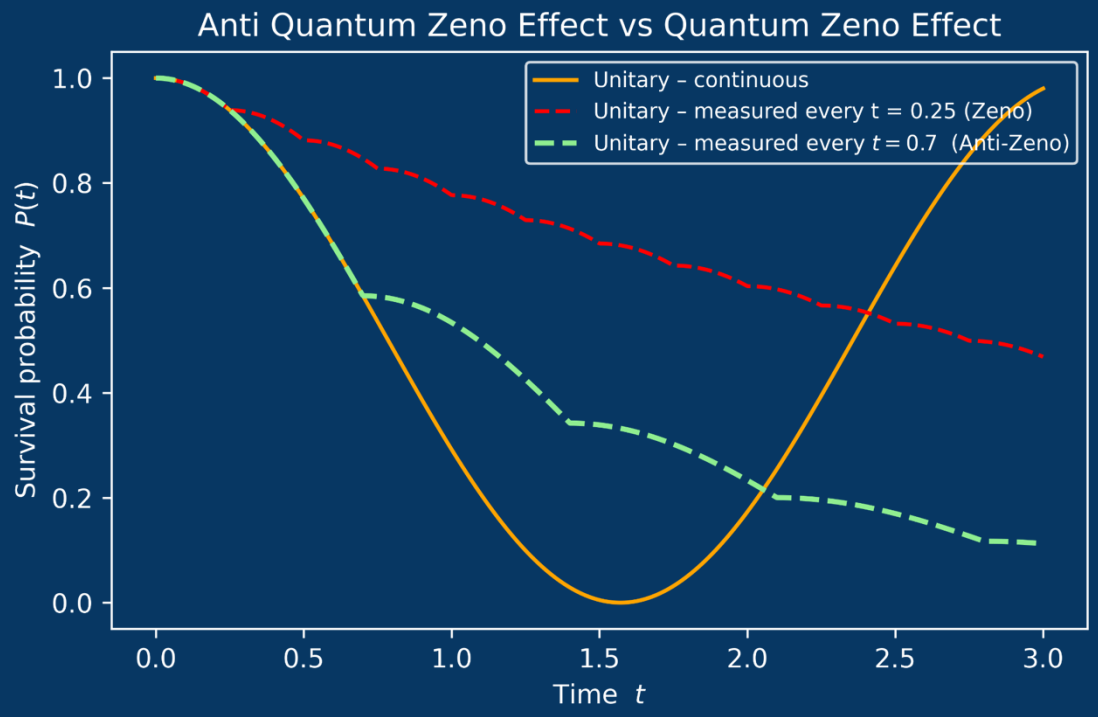

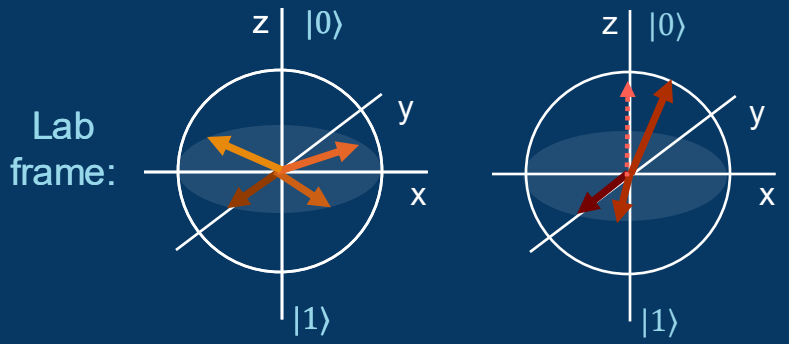

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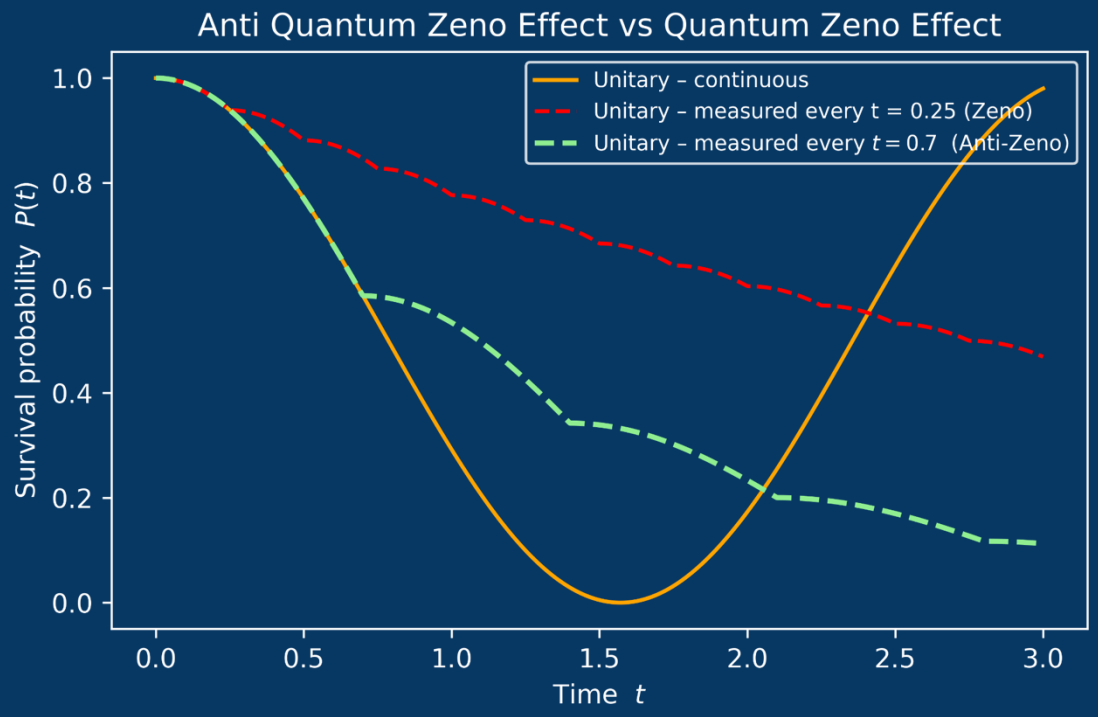

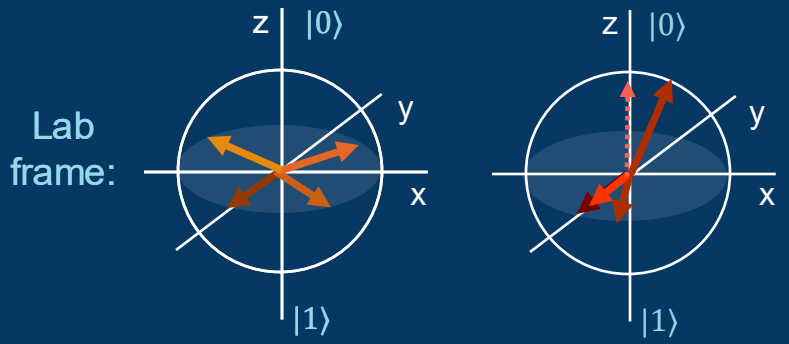

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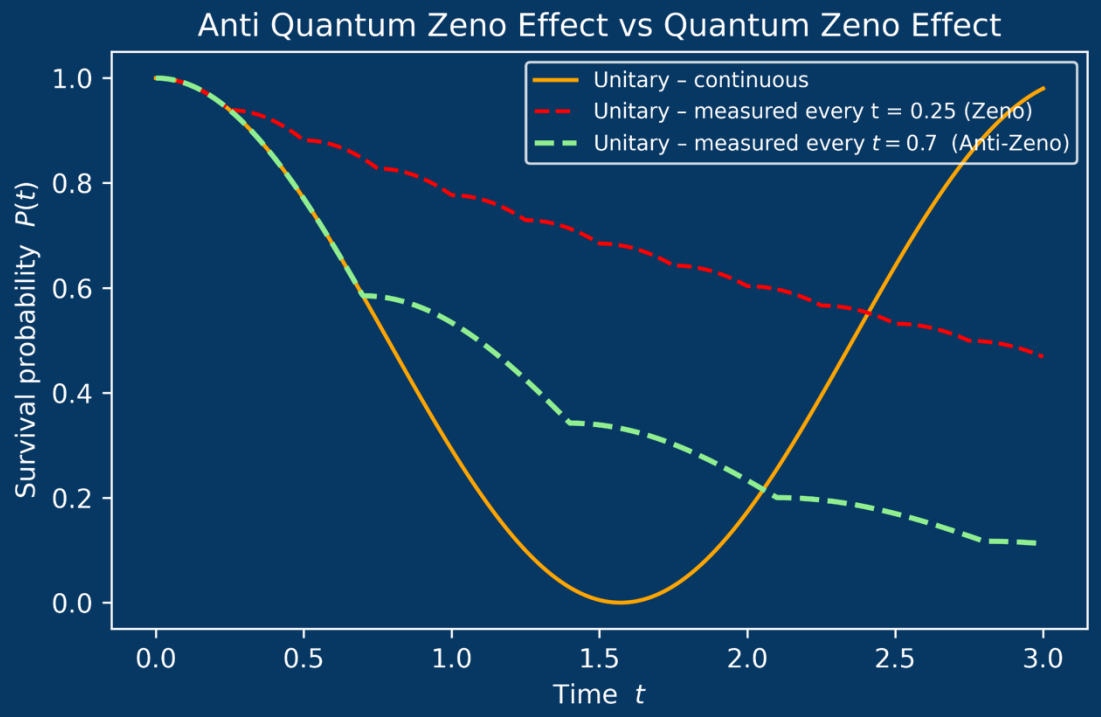

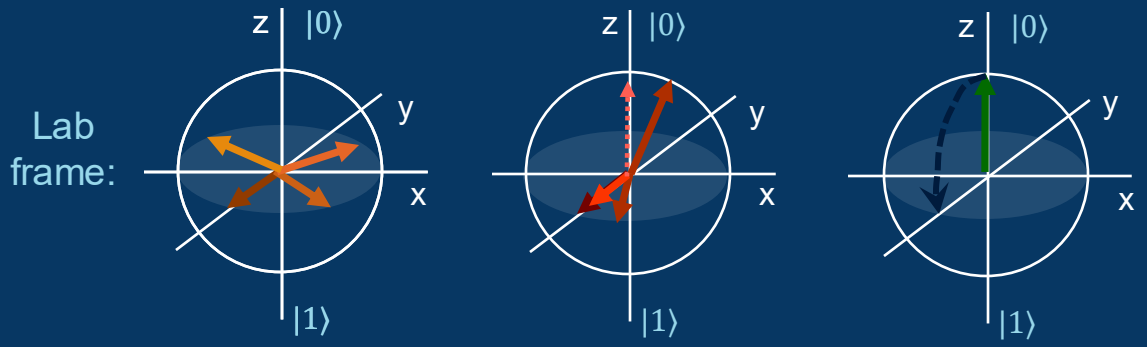

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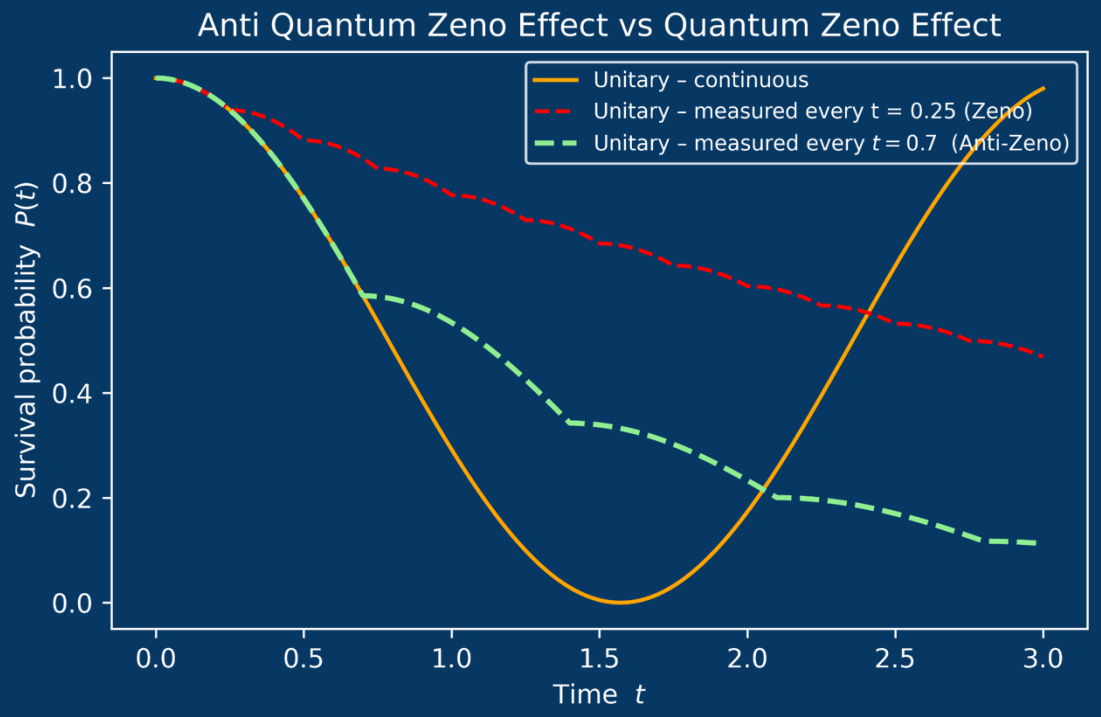

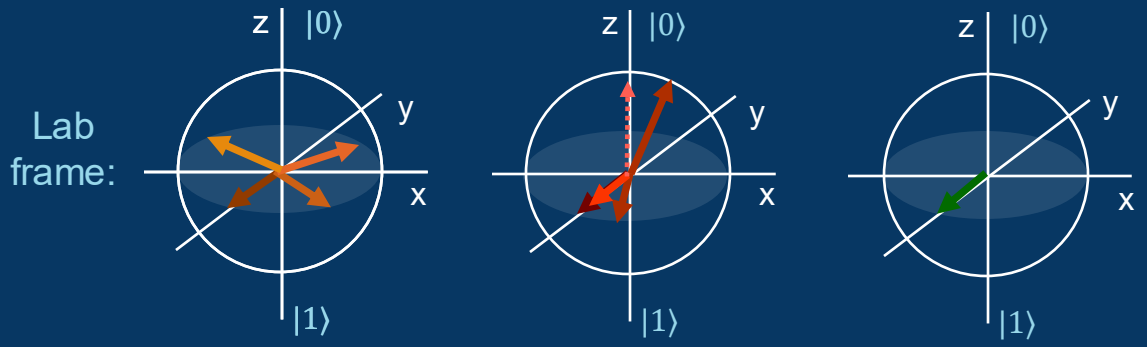

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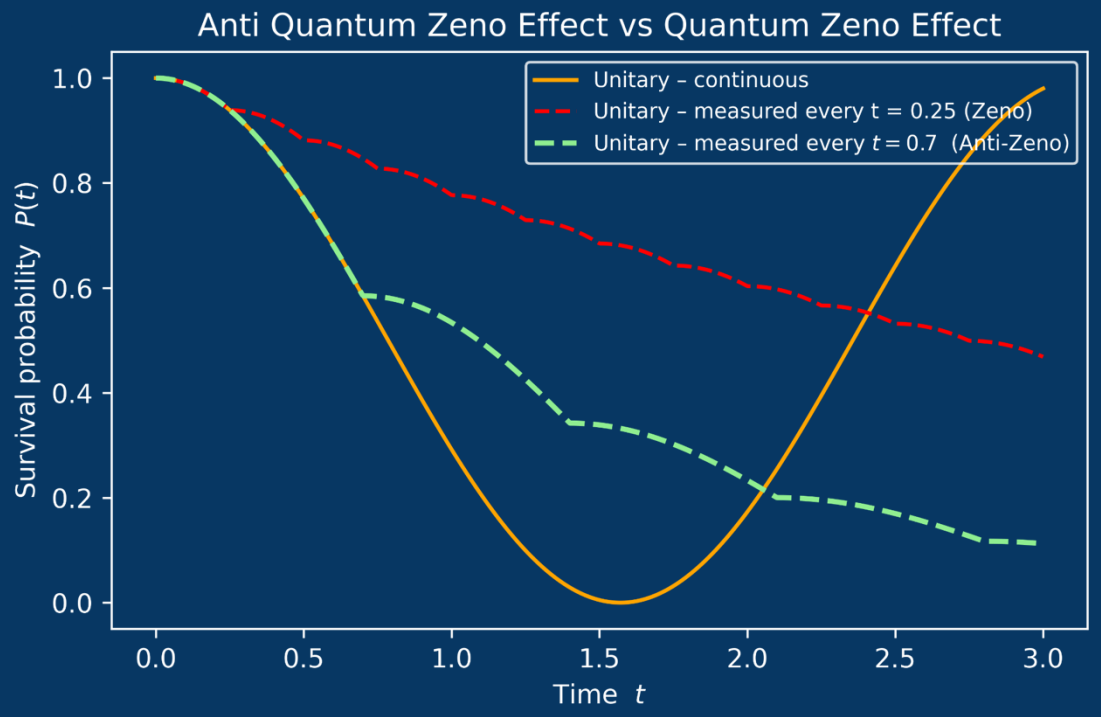

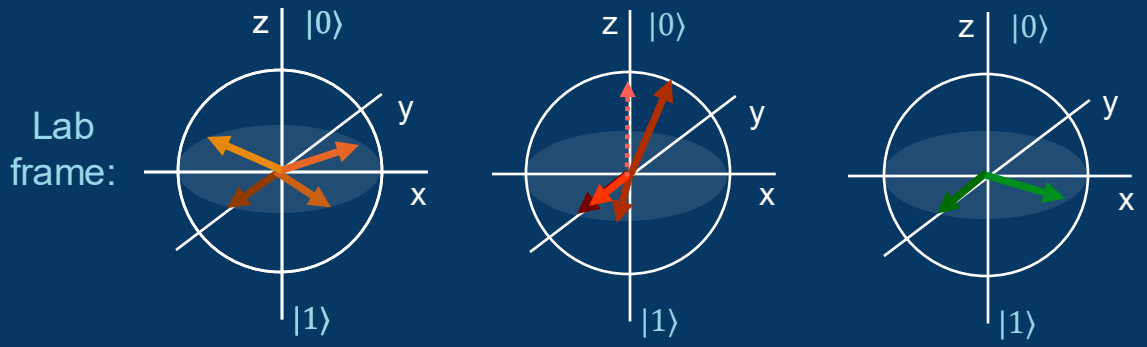

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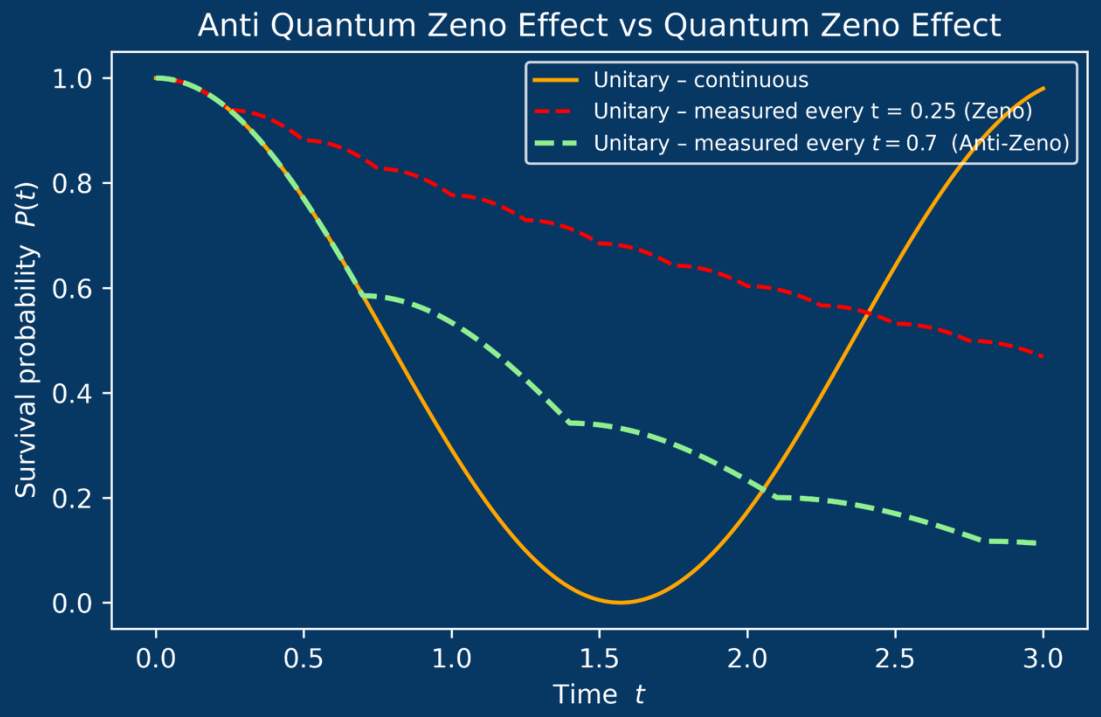

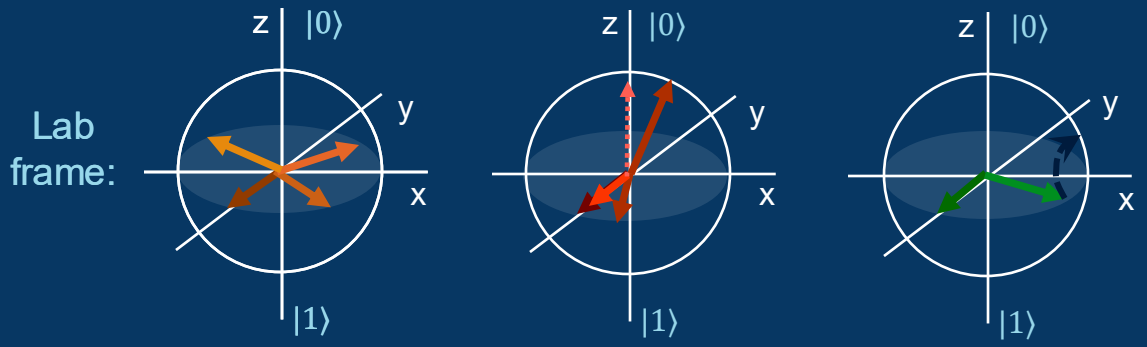

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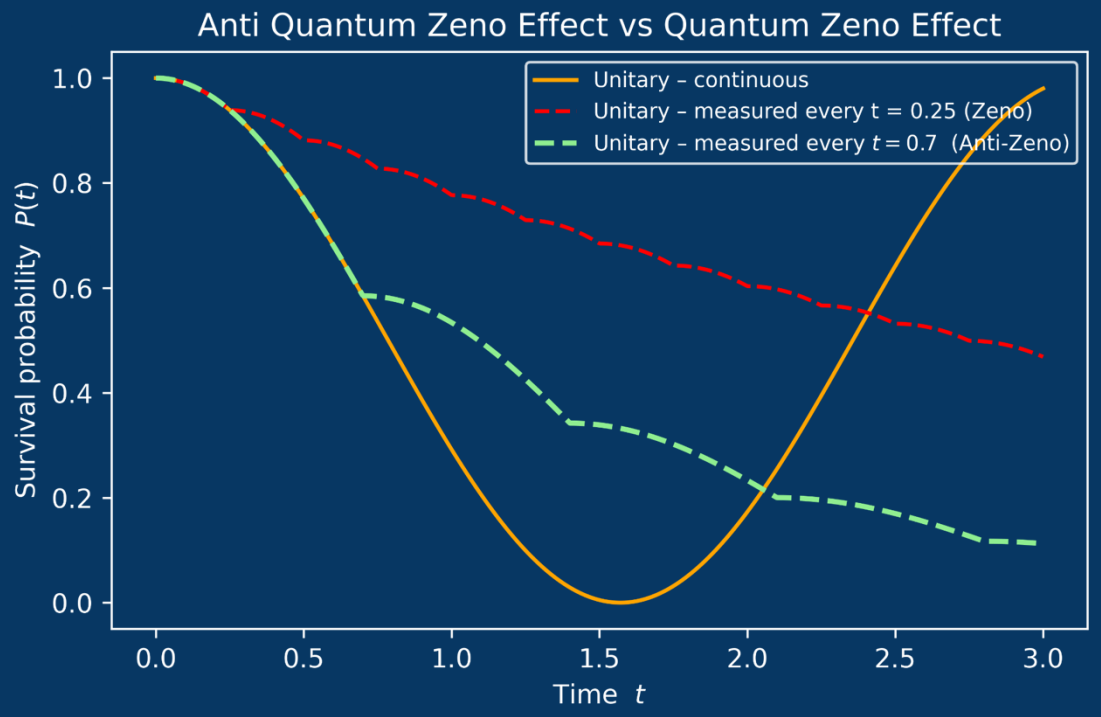

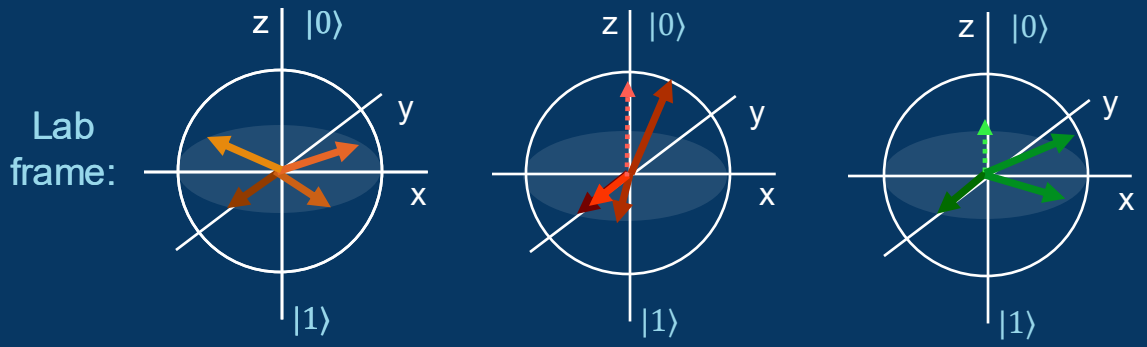

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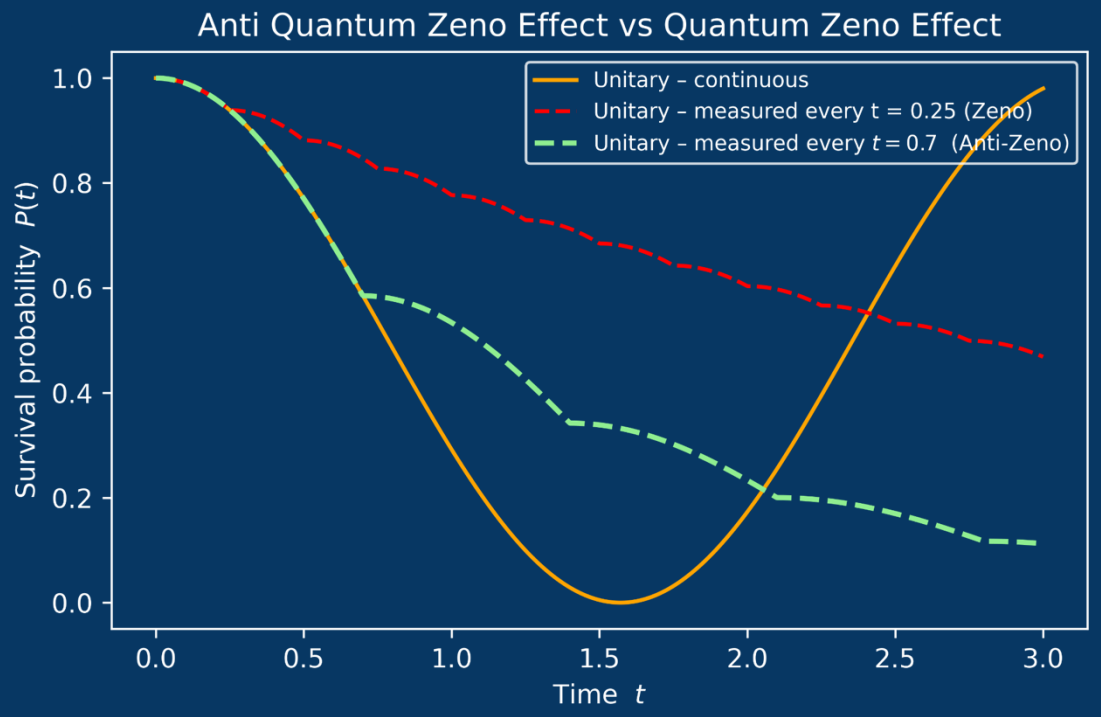

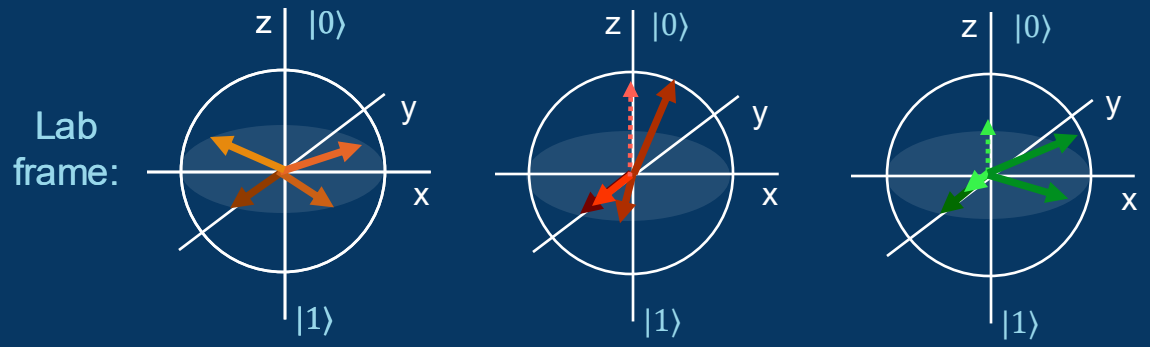

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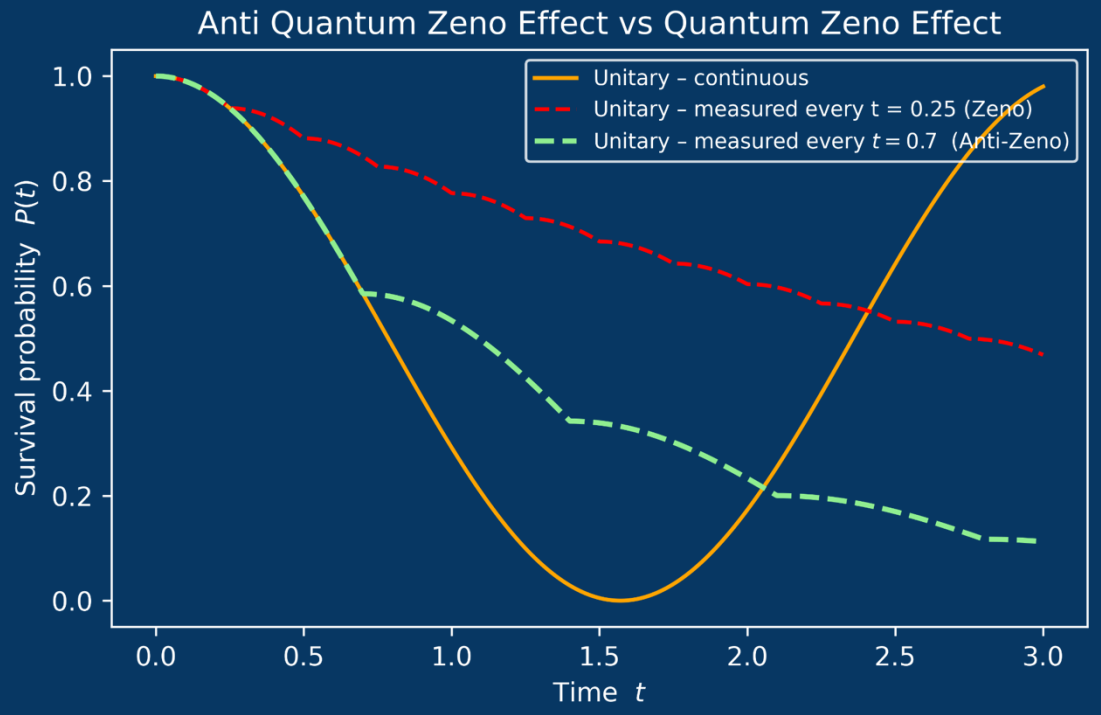
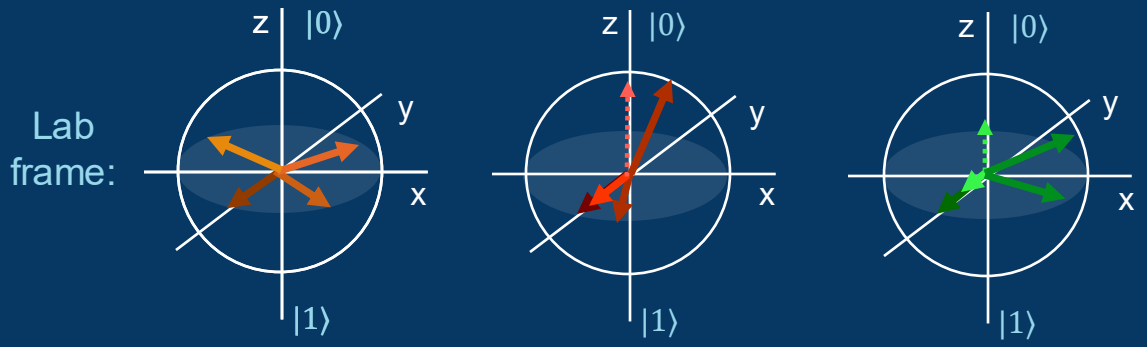
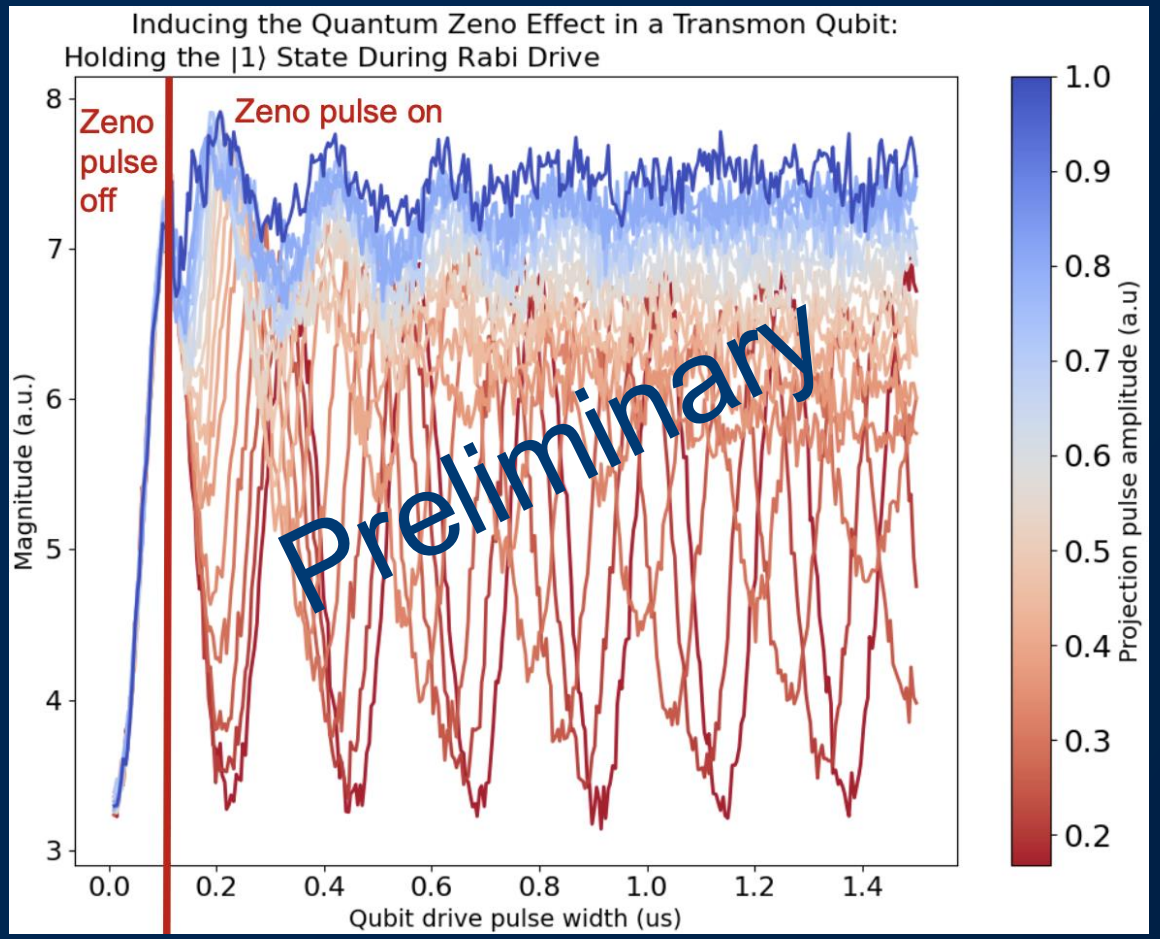


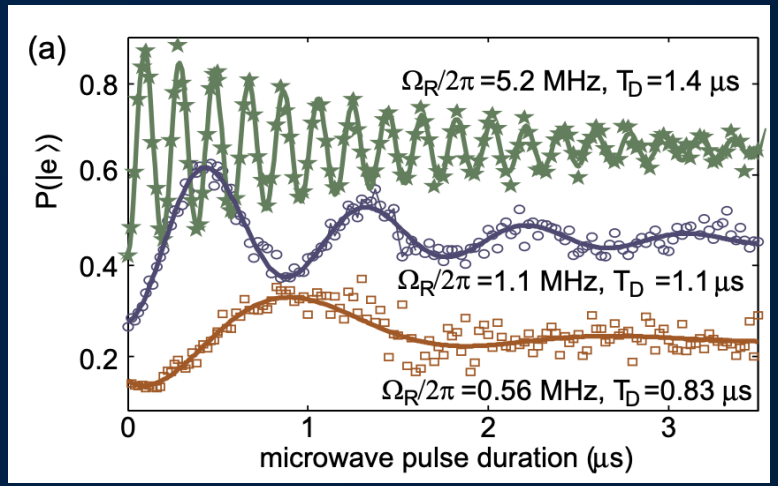


We can suppress evolution our quantum system away from the poles on the Bloch sphere

We have measured the QZE in the qubit's 'two levels'



Similar to the qubit, a TLS is also a two level quantum system with a coherence time, and frequency



Rabi oscillations of a TLS (10.1103/PhysRevB.95.241409) 10.1126/sciadv.ado6240

Fermilab

November, 2025

Qicklab

A pip installable package for superconducting qubit measurements and analysis using QICK

U.S. DEPARTMENT of ENERGY

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

FERMI NATIONAL ACCELERATOR LABORATORY

Goals of this project

1. To gather various types of qubit measurements and experimental sequences in one place, along with the tools to analyze those measurements

2. To have a sustainable contribution pipeline with rules that allows it to be long lasting past grad students leaving projects

3. To be an open source resource for QICK users who do superconducting qubit readout and control

4. To have lasting documentation for new users to jump in and use

https://github.com/CosmiQuantum/QICK_Qubit_LabSuite/tree/development

Notable features: Qubit Measurements

Coherence
- T1 (g-e)
- T1 with longitudinal drive / Zeno (g-e)
- T2* Ramsey (g-e)
- T2 Echo (g-e)
- Dynamical Decoupling

Readout / Calibration
- Single-shot: GE
- Single-shot: GEF
- Single-shot: GEFH

Tomography
- Charge tomography

Diagnostics / Misc
- Time-of-flight
- TWPA consistency
- TOF Oscilloscope example

Rabi
- Amplitude (g-e, e-f, f-h)
- Length
- f→resonator
- g and e-state Populations

Spectroscopy & Shifts
- Qubit spectroscopy (g-e, e-f, f-h)
- f→resonator spectroscopy
- Bias spectroscopy
- Stark shift (1D)
- Stark shift (2D)
- Resonator Stark shift (1D)
- Resonator Stark shift (2D)
- Punch-out (resonator)

https://github.com/CosmiQuantum/QICK_Qubit_LabSuite/tree/development

Notable features: Experiment sequences

Readout / Calibration

- Combined readout optimization (g-e)
  - Readout length, resonator gain, readout frequency, etc.

Rabi

- Rabi chevron (g-e)

Spectroscopy & Shifts

- Punch-out test (resonator)

Round-Robin / TLS / Benchmarking

- Round-robin — TLS comprehensive
- Round-robin — benchmark
- Round-robin — e-f studies

https://github.com/CosmiQuantum/QICK_Qubit_LabSuite/tree/development

Notable features: Analysis tools

- Boxplots
- PSDs
- Comparing metrics vs each other
- Cumulative plots
- Histograms
- Fitting functions
- Analysis for all the qubit measurements (Coherences, Rabi, Qubit spectroscopy, SSF, etc)

https://github.com/CosmiQuantum/QICK_Qubit_LabSuite/tree/development

Notable features: Analysis Sequences

- TLS statistics
- TLS comprehensive
- Stark analysis
- Effective qubit temperatures
- Metrics vs time plotting
- Comparing statistics run to run

https://github.com/CosmiQuantum/QICK_Qubit_LabSuite/tree/development

Notable features: Adjustable configurations

- Measurement config
- SoC proxy config
- System config

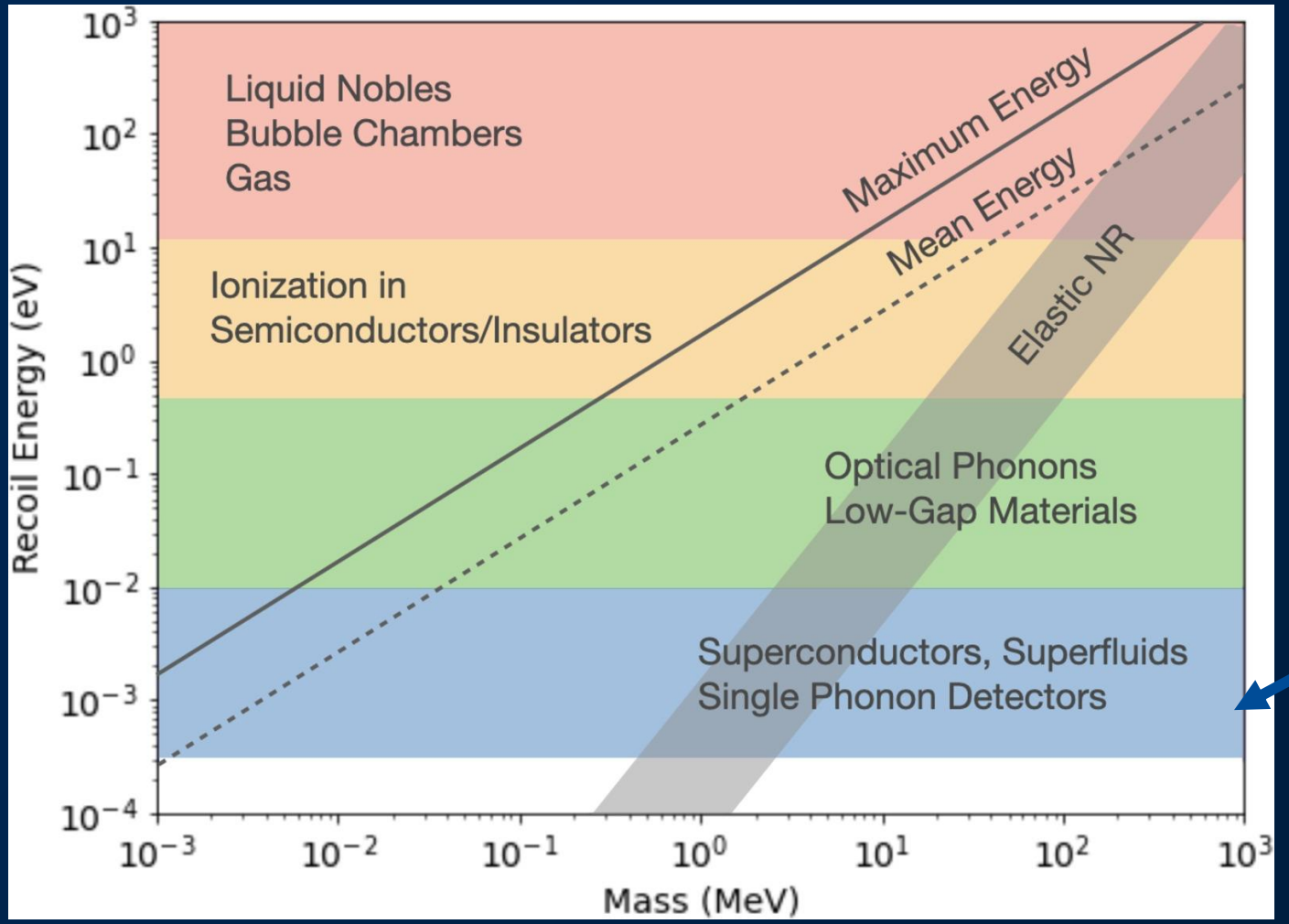
https://github.com/CosmiQuantum/QICK_Qubit_LabSuite/tree/development

Current Status

- Developed the initial Qicklab package “skeleton” and migrated all major *tprocv2* experiment and analysis scripts into the new structure
  - Improved readability, organization, and functionality
- Systematic testing has not yet begun
- Next phase includes full validation of the package (targeting December), followed by refinement/cleanup and continued efforts to generalize the experiment and analysis pipelines so they run seamlessly for other fridges.

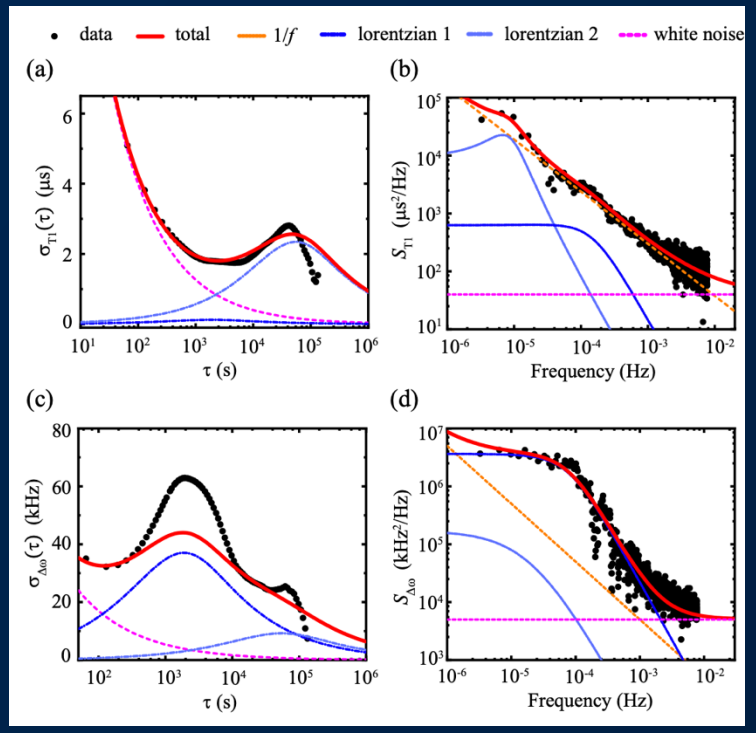
Quantum based sensors for low energy detection

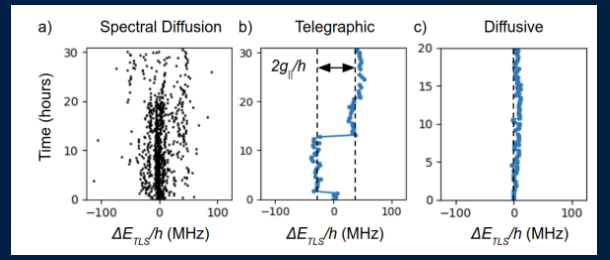
Direct detection dark matter techniques



10.1016/j.nuclphysb.2024.116484

Qubit-based sensors enable meV detection


data
total
1/f
lorentzian 1
lorentzian 2
white noise
(a)
(b)
(c)
(d)
τ (s)
Frequency (Hz)


a) Spectral Diffusion
b) Telegraphic
c) Diffusive
Time (hours)
2g||/h
ΔE_TLS/h (MHz)