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# Harnessing the Quantum Zeno Effect in superconducting qubits for particle detection

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U.S. DEPARTMENT  
of ENERGY

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# Leveraging a fundamental quantum mechanics effect to develop robust qubit-based particle sensors



## Trail guide to finding a background suppressed overlook:

1. We can use qubits as particle detectors (for free, thanks quantum computing!)





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3. Nefarious backgrounds to a particle event, "Two Level Systems" 







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## Trail guide to finding a background suppressed overlook:

1. We can use qubits as particle detectors (for free, thanks quantum computing!)

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

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

3. Nefarious backgrounds to a particle event, "Two Level Systems" 

5. A background free overlook 

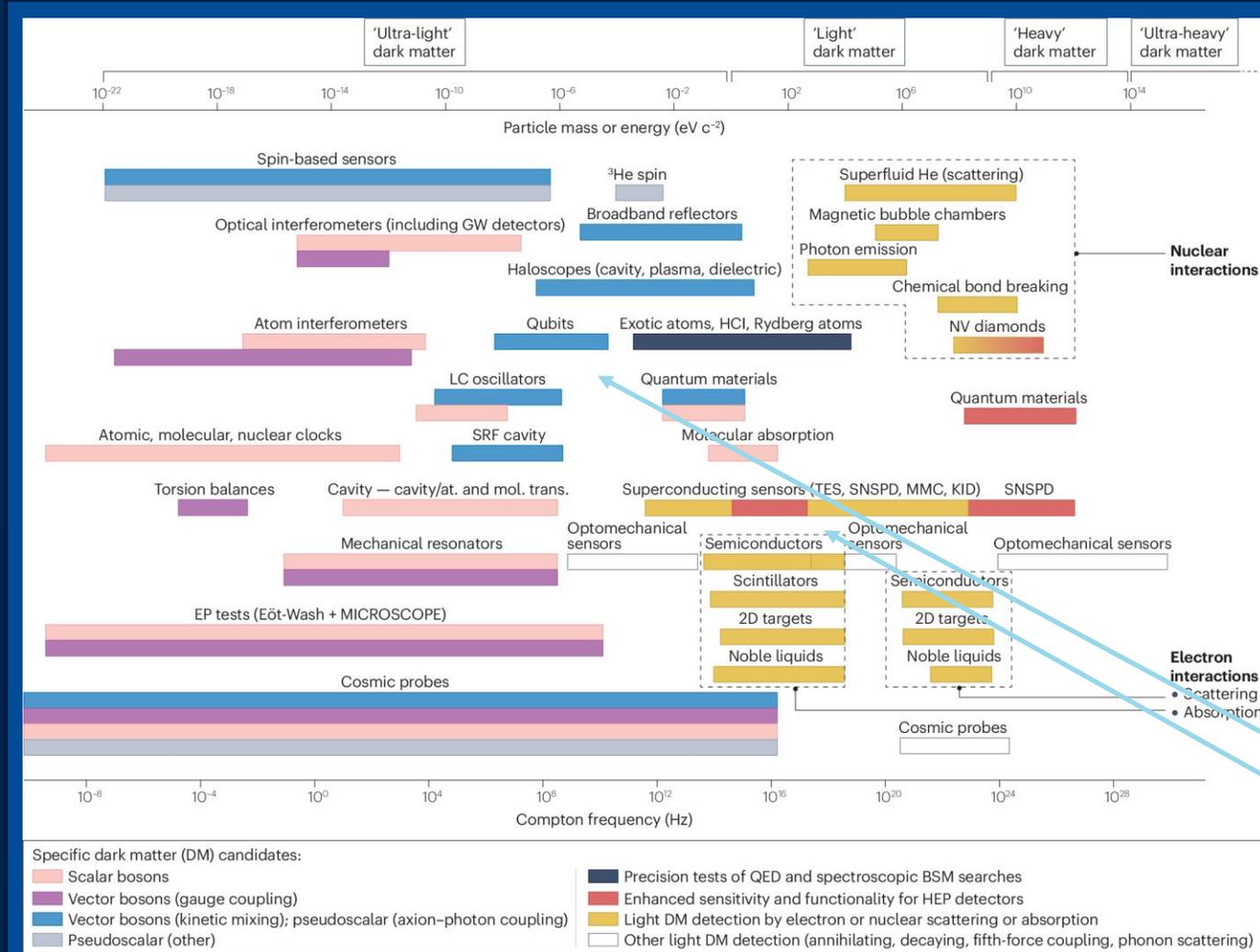




# The next generation of breakthroughs in physics will come from very sensitive detectors



Direct  
detection  
dark matter  
techniques

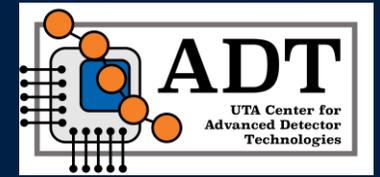


SC qubit-based  
sensors enable  
meV detection

10.1038/s42254-024-00714-3



# Superconducting qubits are promising candidates for low energy detection



### LC circuit



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

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

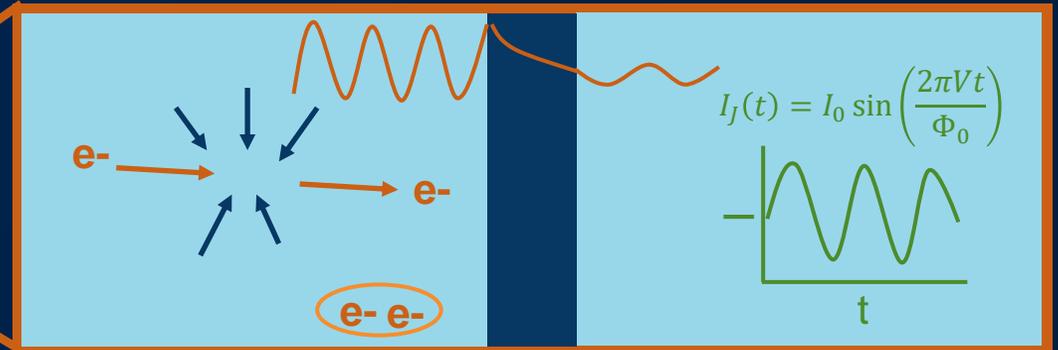


### Superconducting qubit



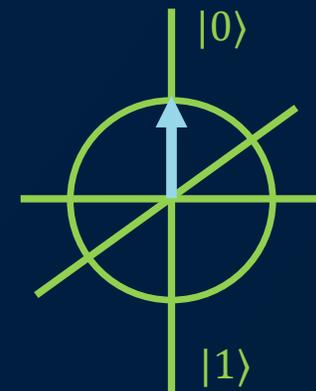
$$E_J = \frac{I_0 \Phi_0}{2\pi}$$

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



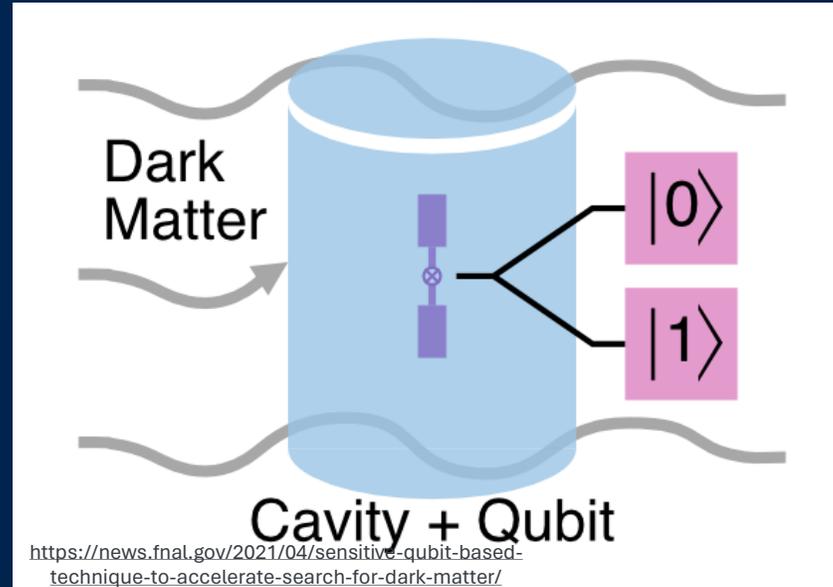
Binding energy of cooper pairs sets energy sensitivity

Supercurrent sets the qubit frequency



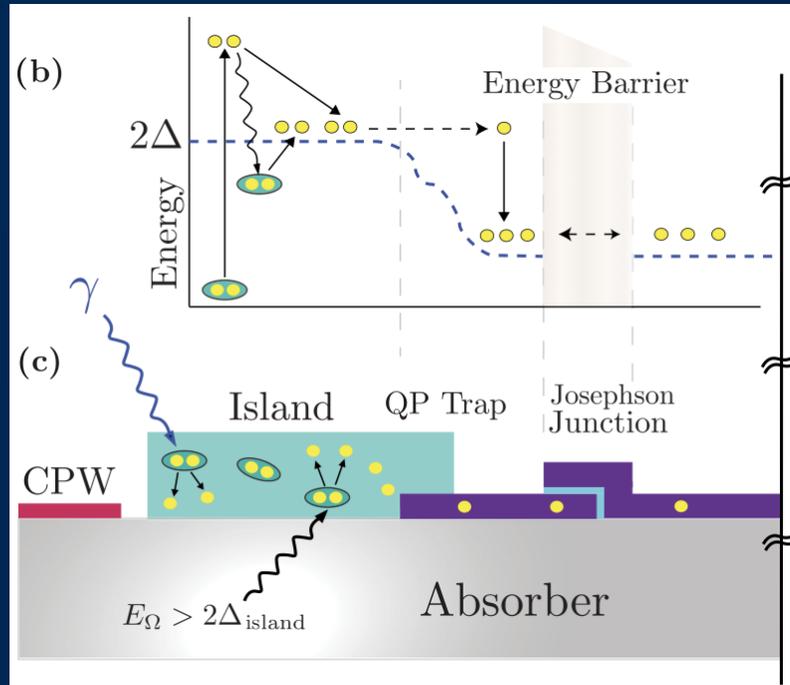
# Proposed sensing schemes using SC qubits

## Cavity based hidden photon searches



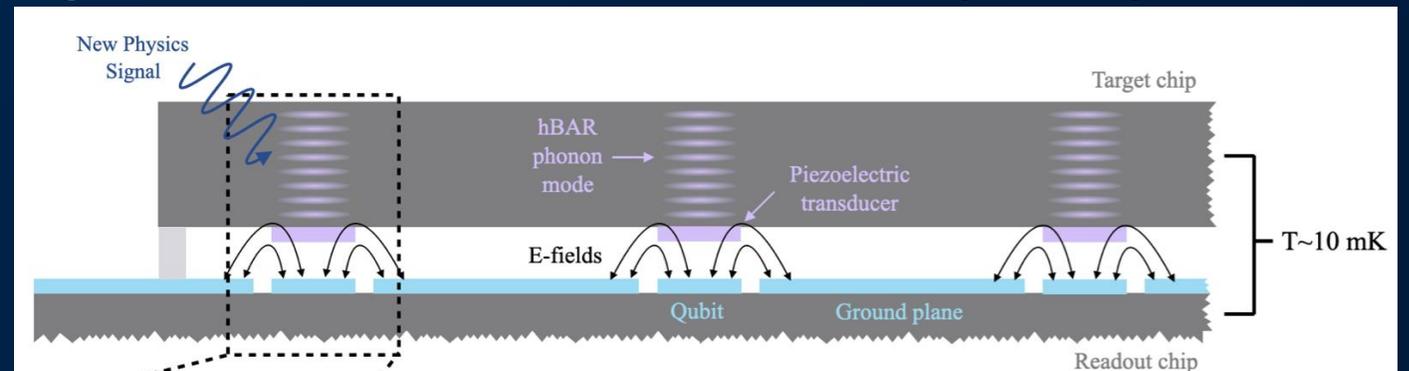
10.1103/PhysRevLett.126.141302

## Superconducting Quasiparticle-amplifying transmons (SQUATs)



10.1103/PhysRevApplied.22.054009

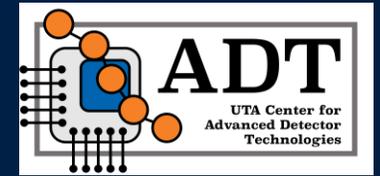
## High-overtone Bulk Acoustic Resonators (HBARs)



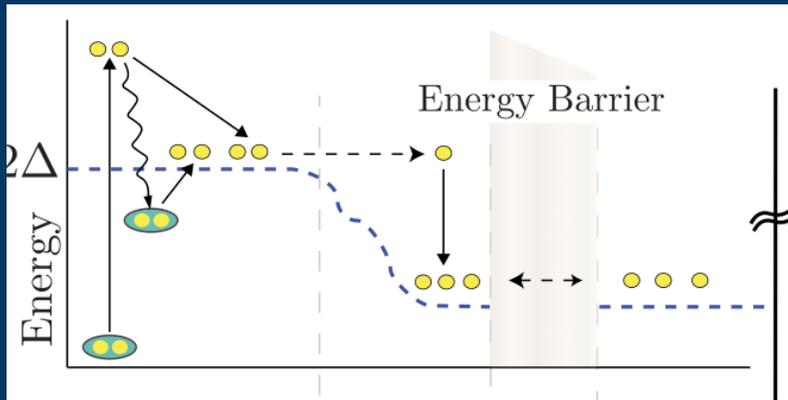
10.48550/arXiv.2410.17308



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

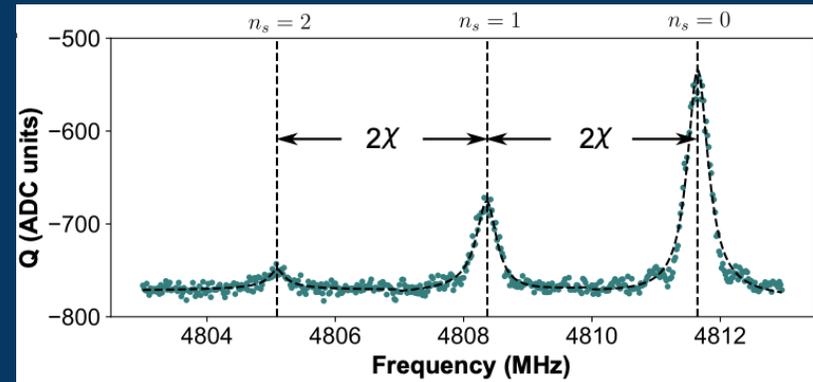


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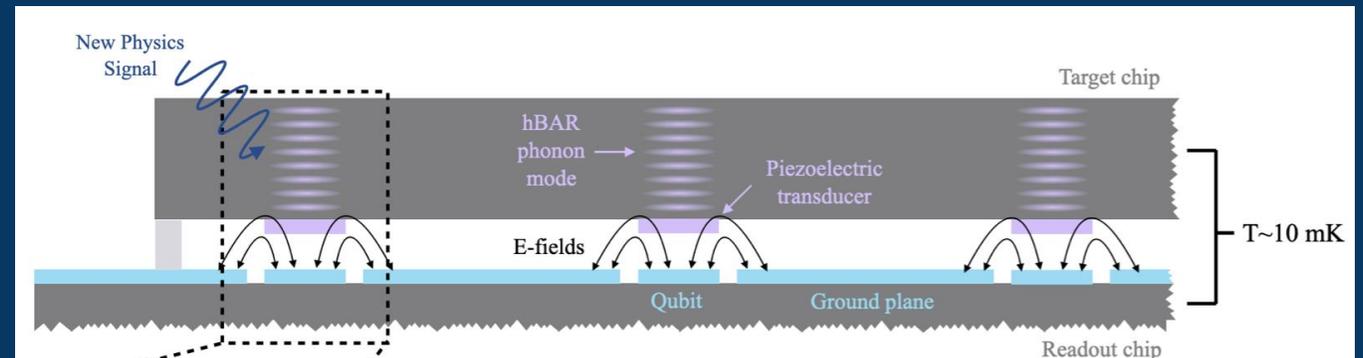
Quasiparticles shift the qubit frequency through tunnelling events  
(10.1103/PhysRevApplied.22.054009)

## 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  
(<https://arxiv.org/pdf/2501.06882>)

## High-overtone Bulk Acoustic Resonators (HBARs)



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

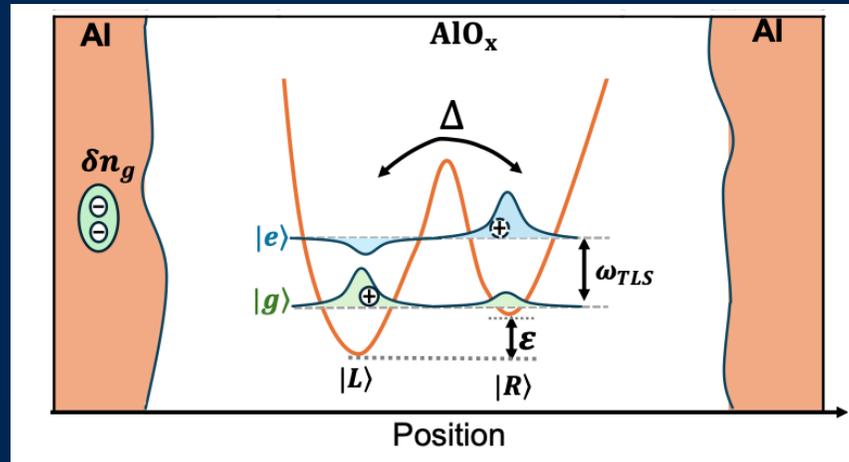


# An insidious source of backgrounds: Two Level Systems (TLSes)



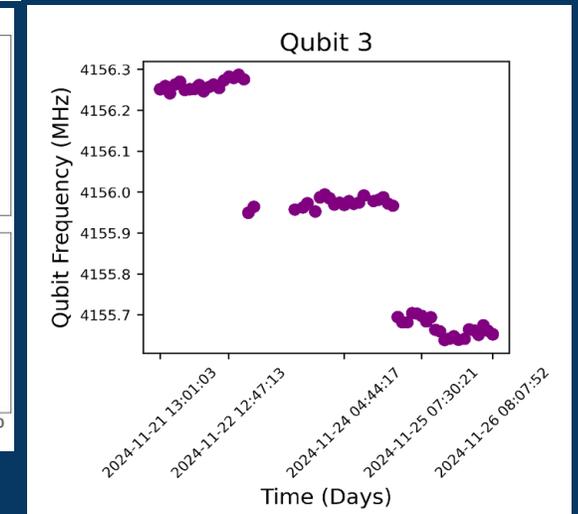
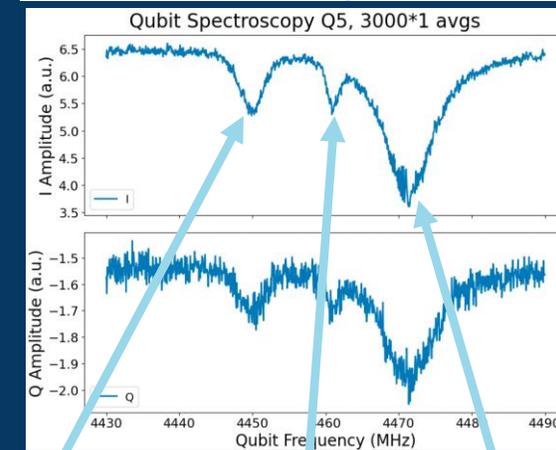
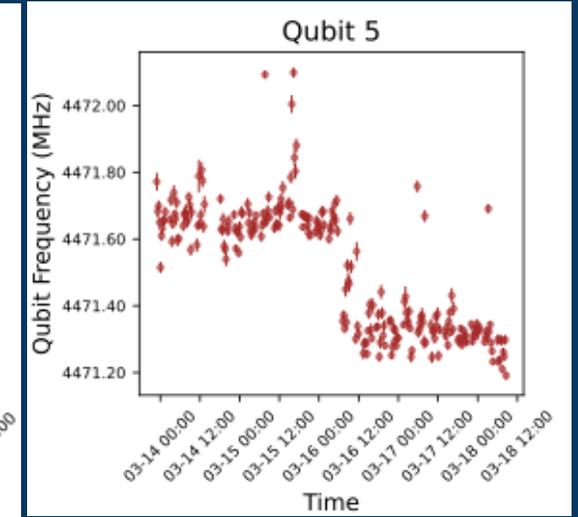
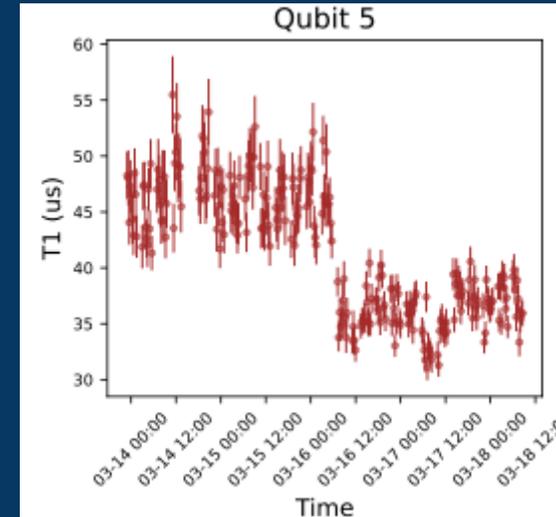
QUIET runs 4/7

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

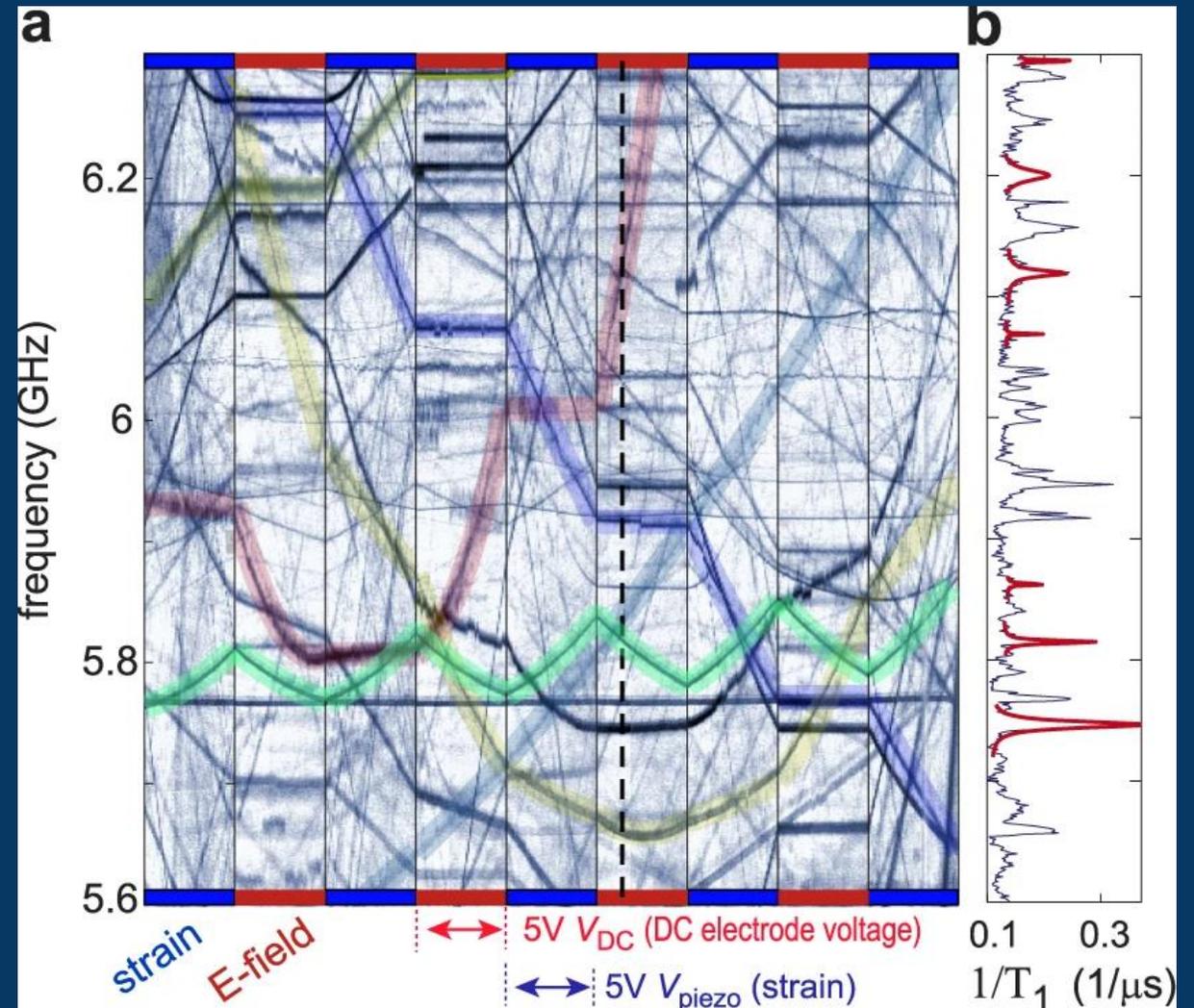
Two photon Transition

Qubit

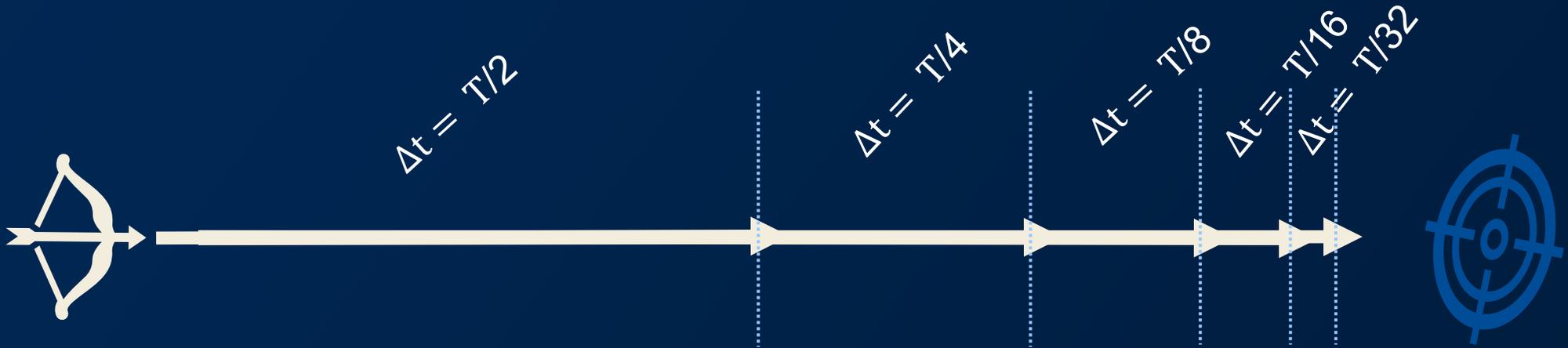
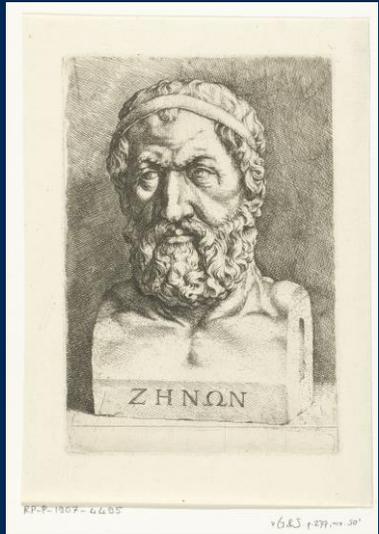
# TLses are everywhere

→ 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]



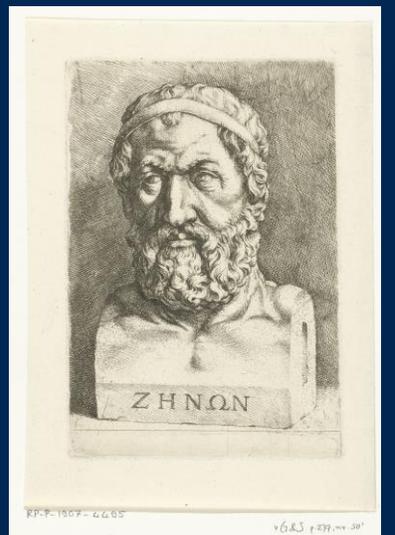
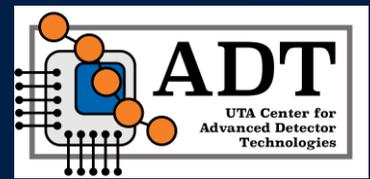
# Method to constrain quantum systems: the Quantum Zeno Effect



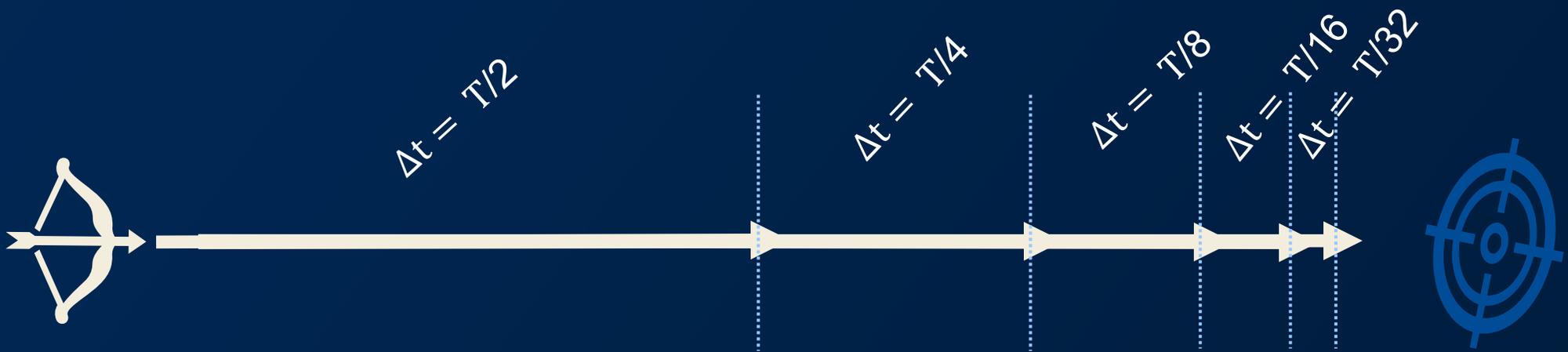
How the ancient Greeks solved quantum problems

[https://en.wikipedia.org/wiki/Zeno\\_of\\_Elea](https://en.wikipedia.org/wiki/Zeno_of_Elea)

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How the ancient Greeks solved quantum problems

$\Delta t \gg \omega_Q$

Measure

Measure

Measure

Measure

Qubit evolves

Qubit evolves

Qubit evolves

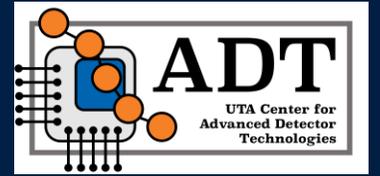
$\Delta t \ll \omega_Q$

Measure  
Measure  
Measure  
Measure  
Measure

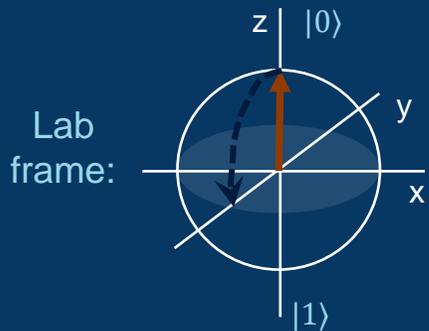
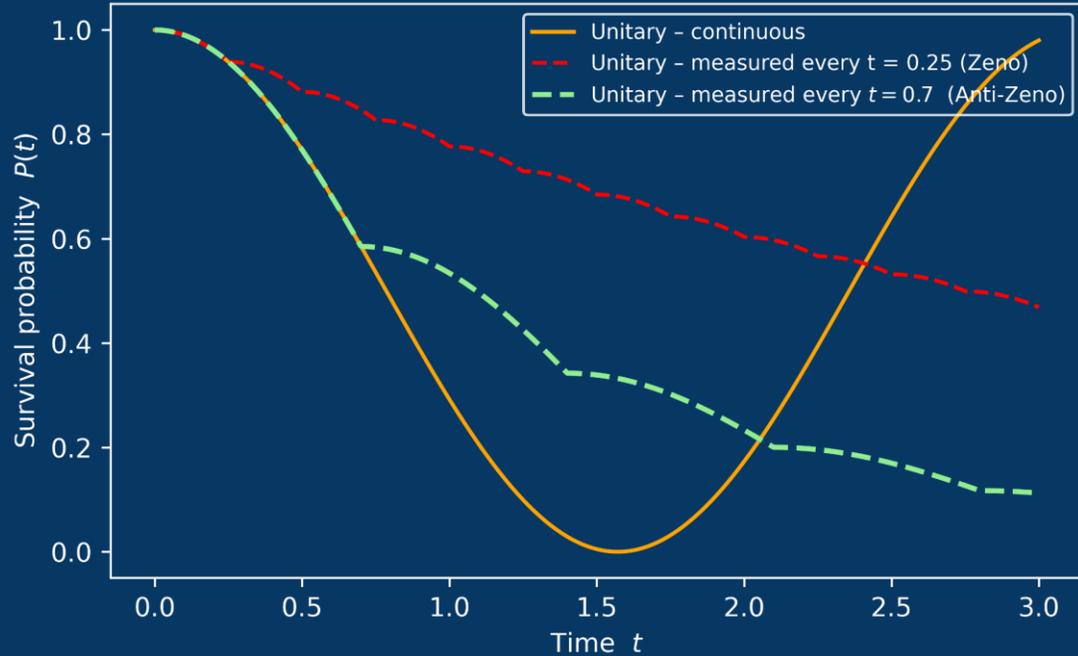
Qubit doesn't get the chance to evolve



# Method to constrain quantum systems: the Quantum Zeno Effect



Anti Quantum Zeno Effect vs Quantum Zeno Effect

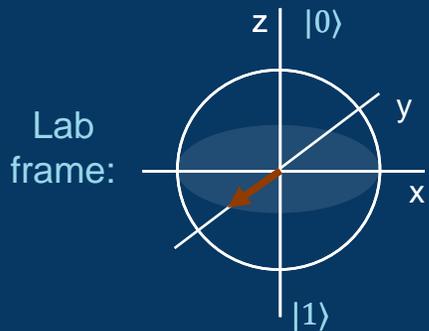
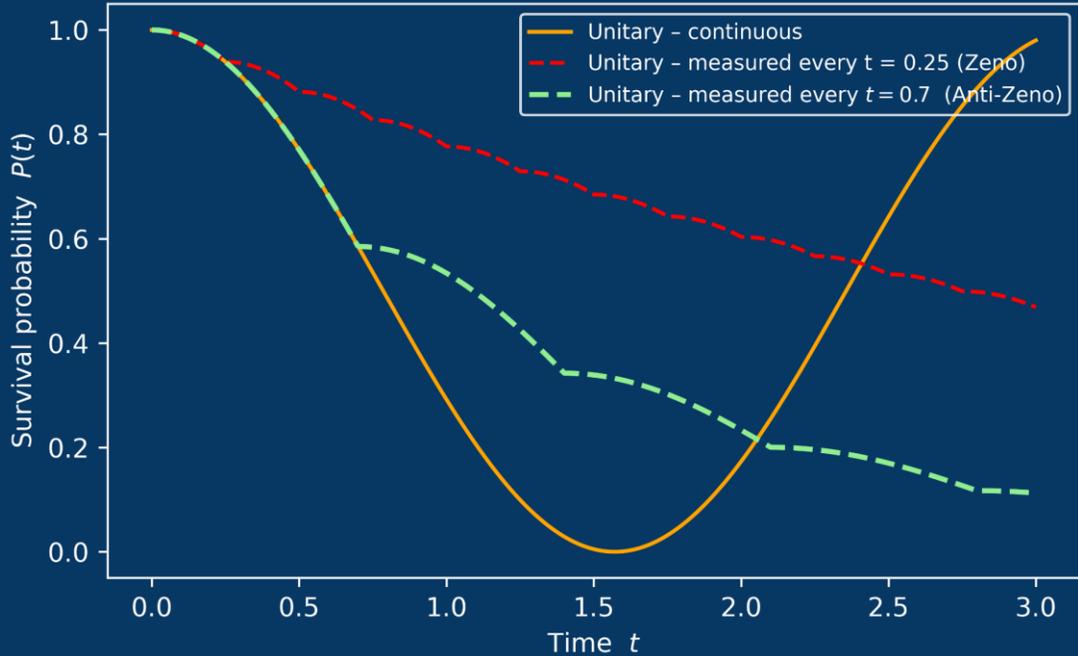




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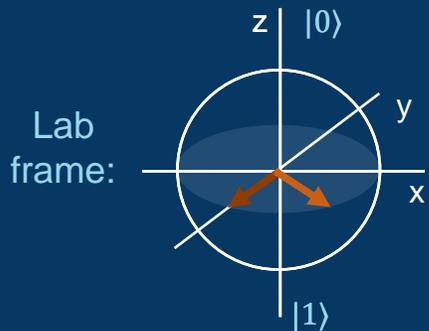
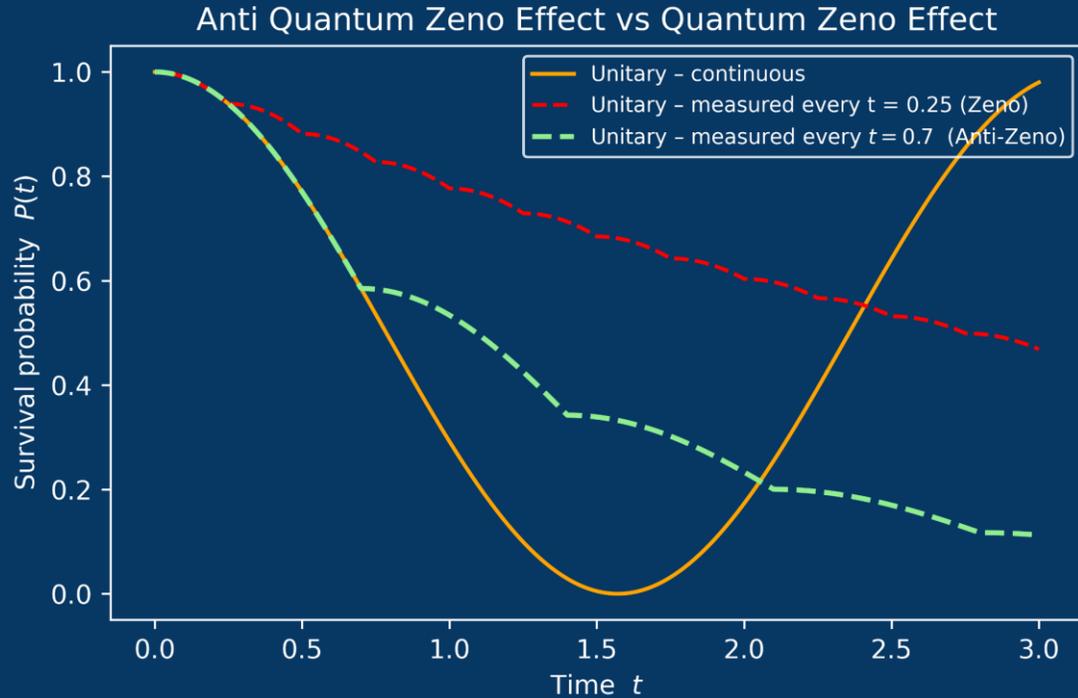


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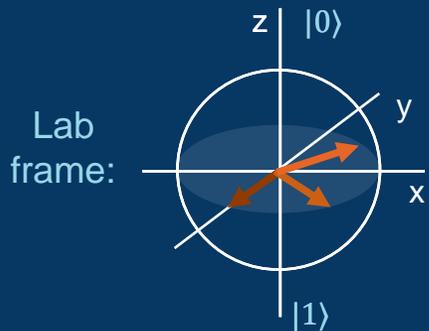
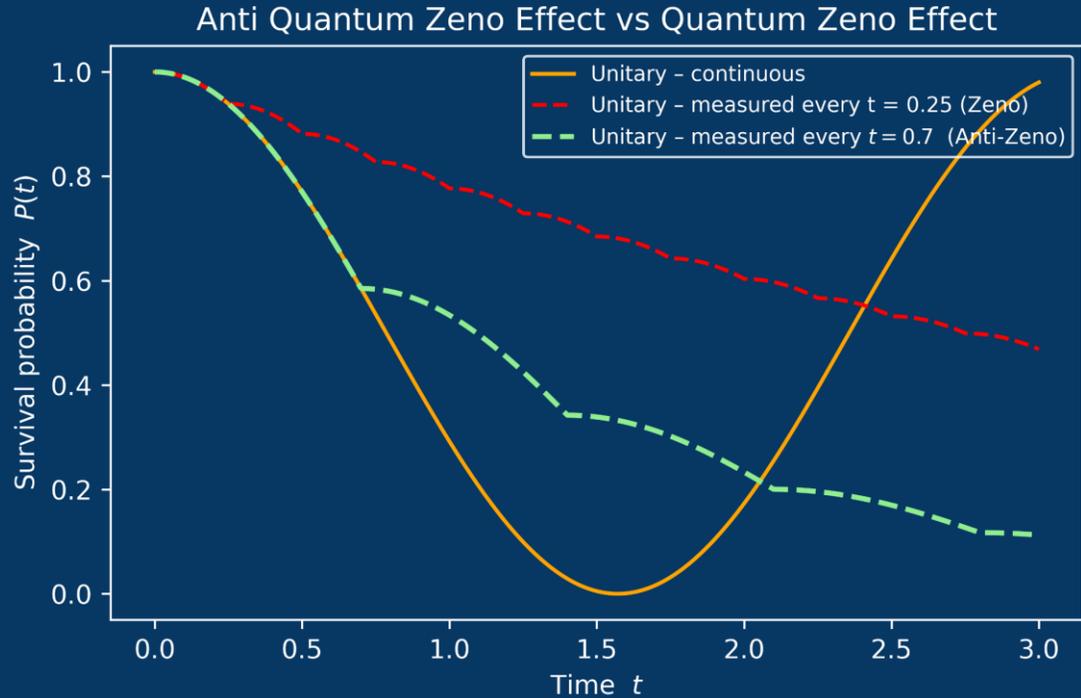
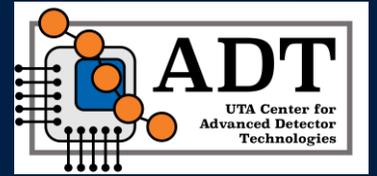


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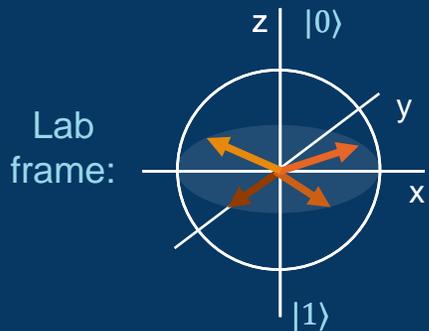
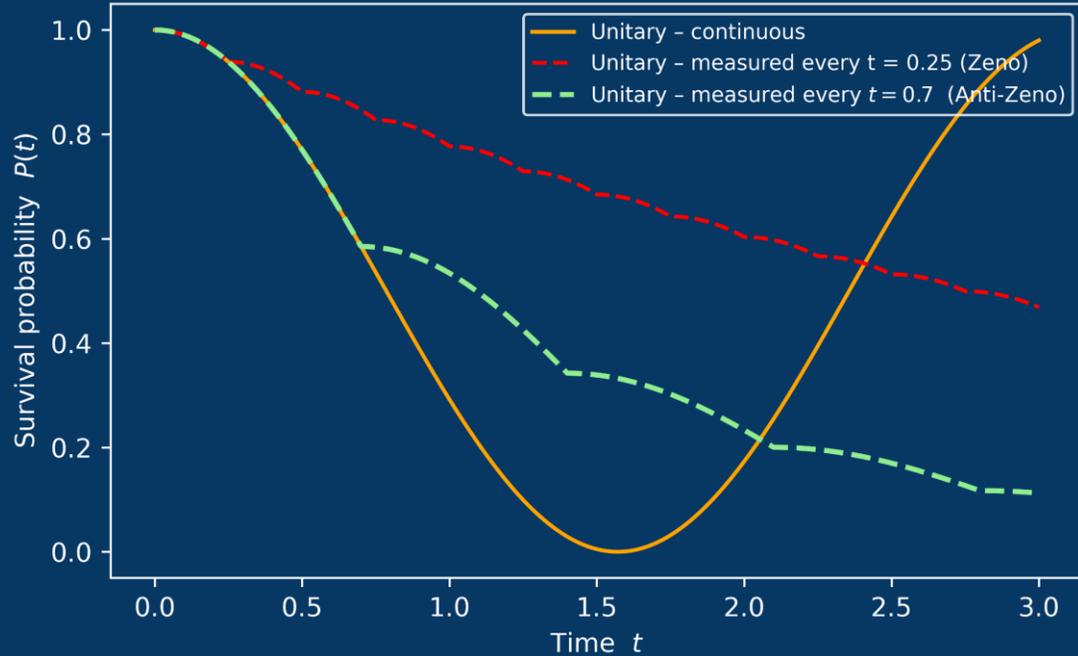




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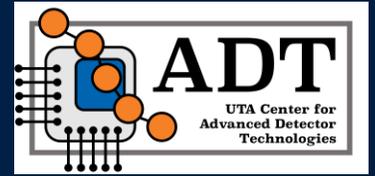


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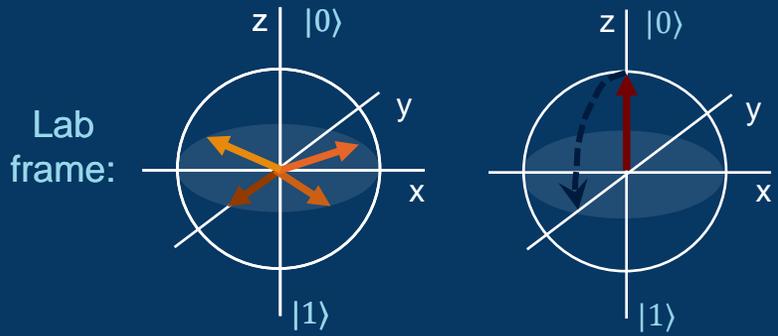
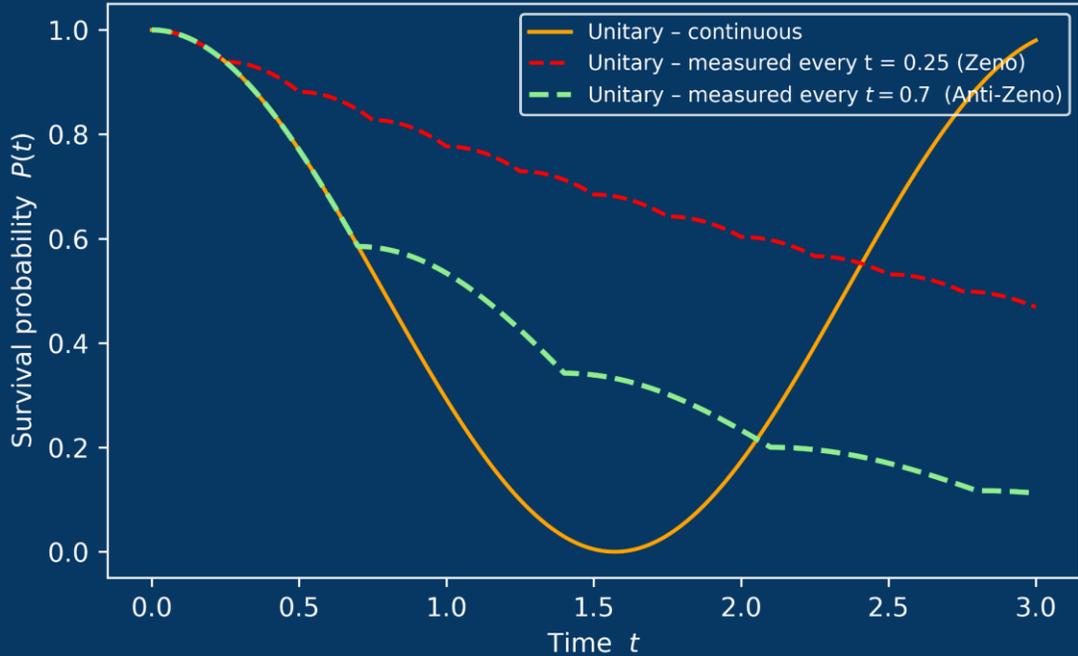




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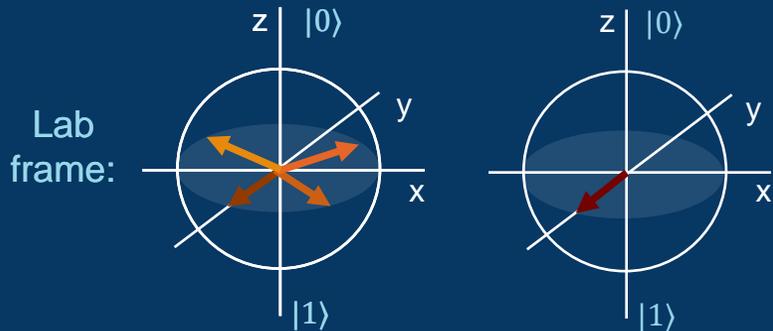
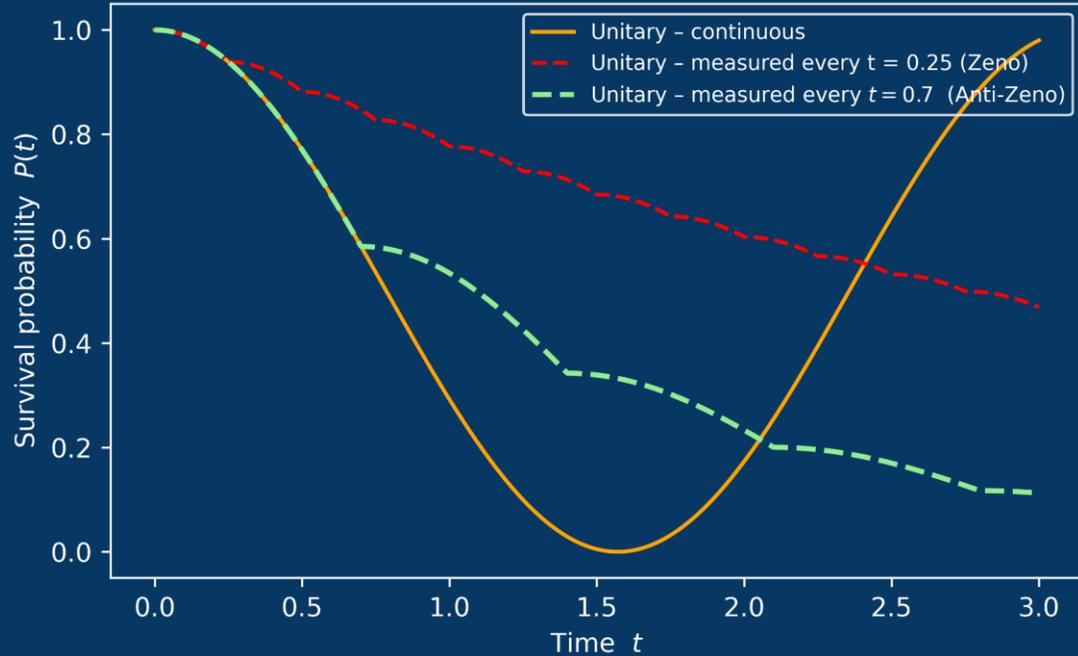




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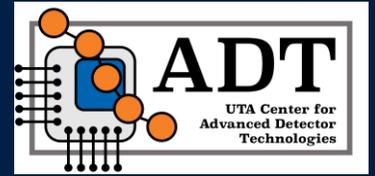


Anti Quantum Zeno Effect vs Quantum Zeno Effect

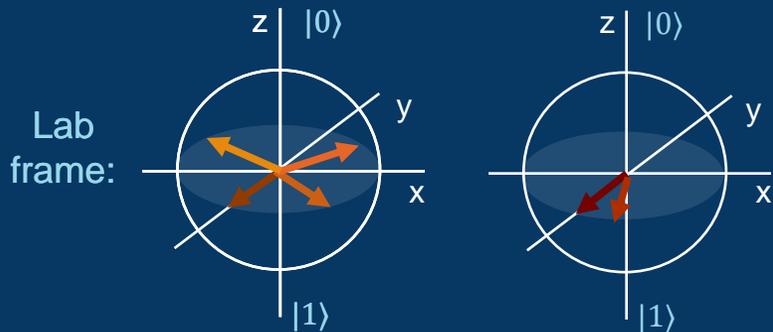
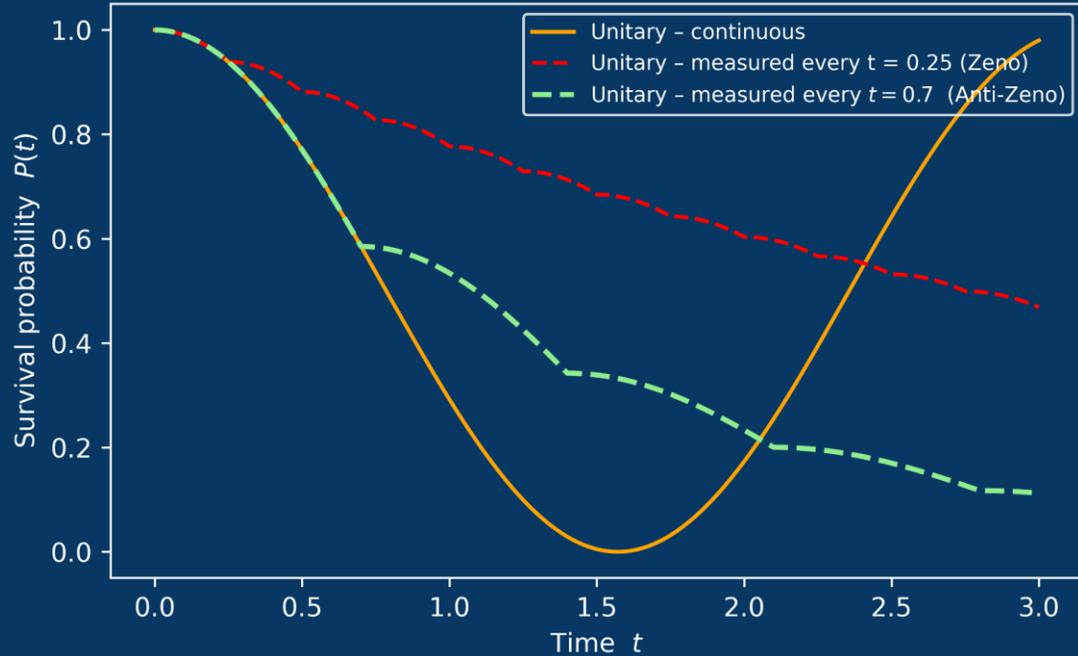




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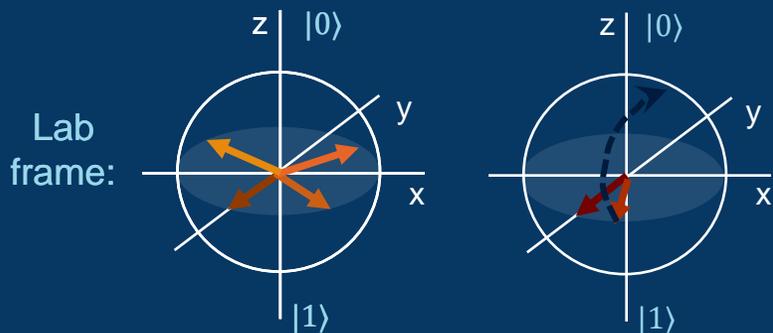
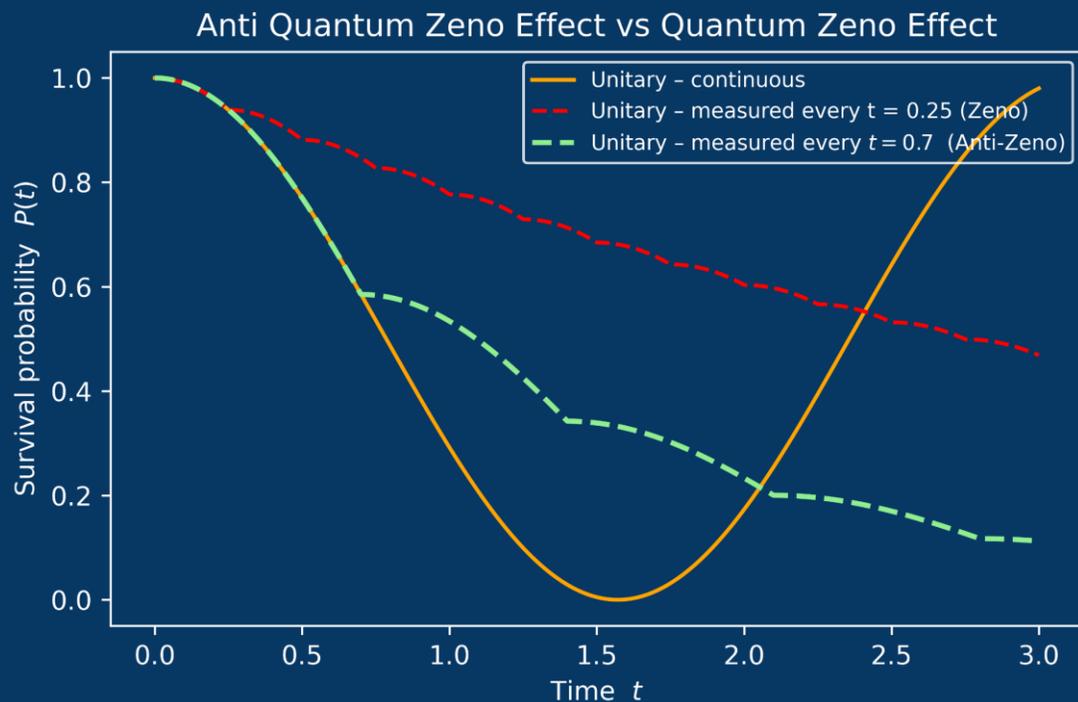


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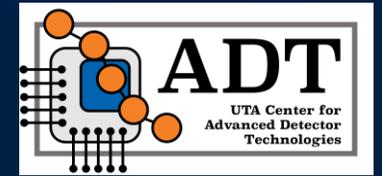


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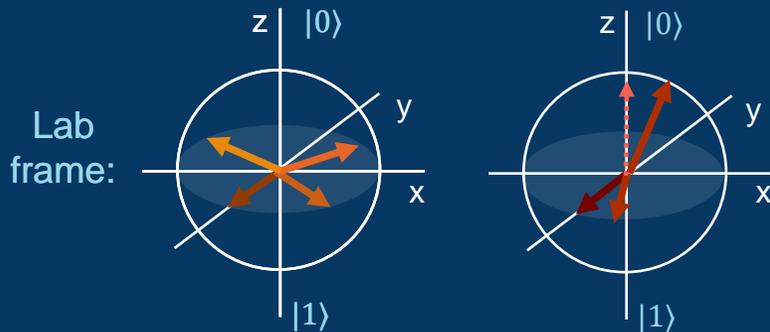
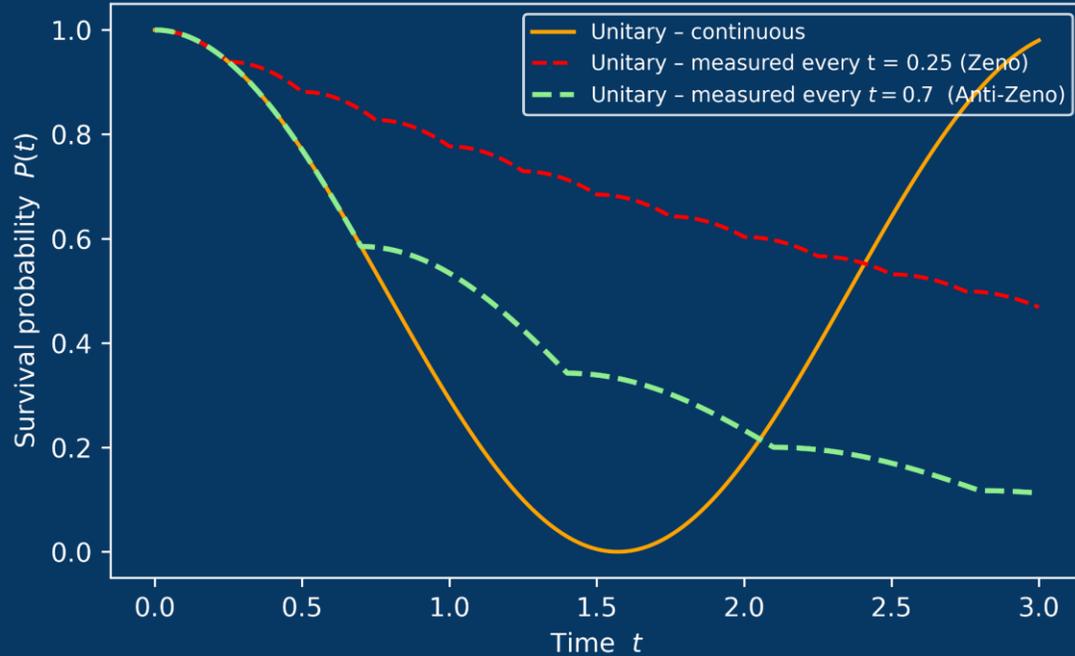




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Anti Quantum Zeno Effect vs Quantum Zeno Effect

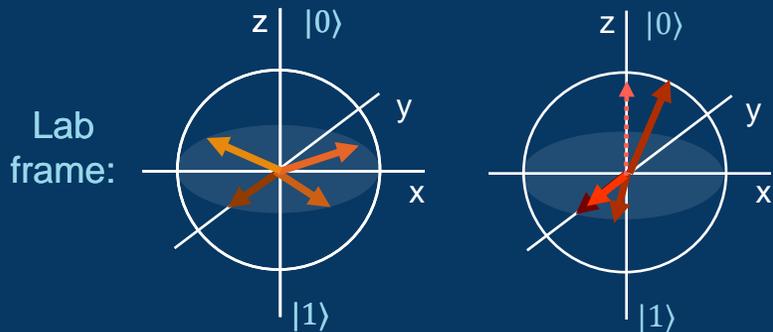
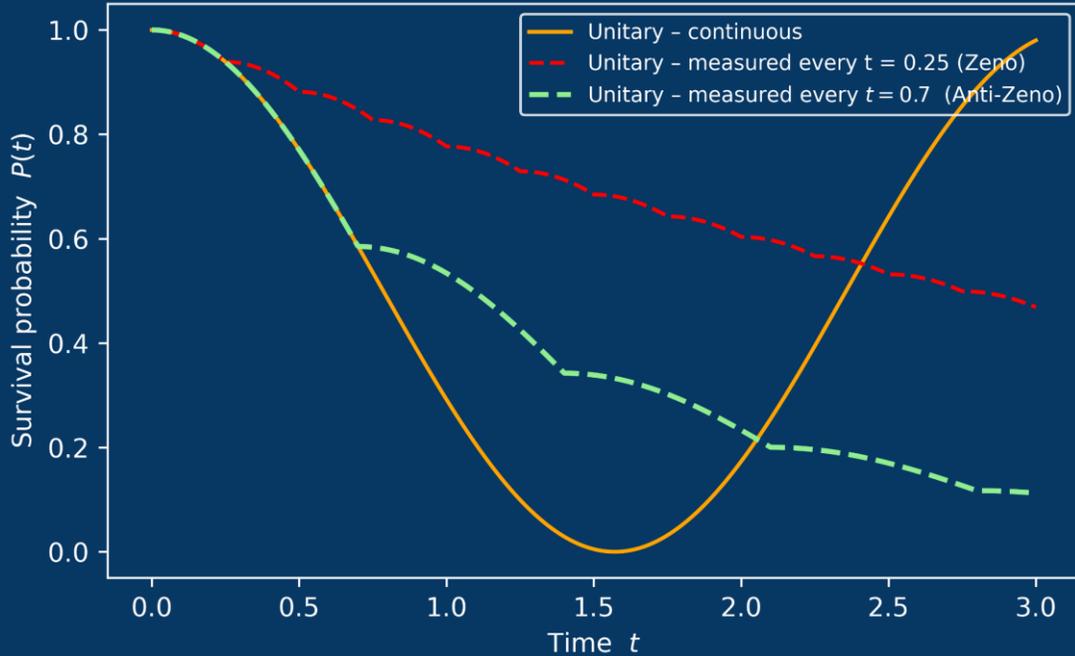




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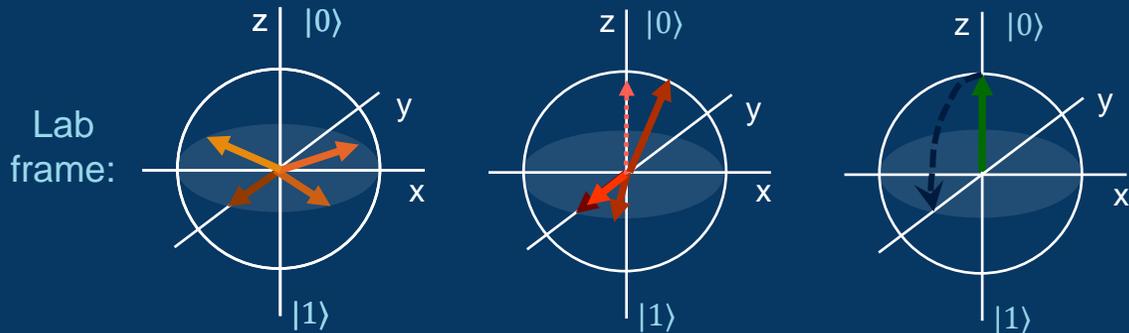
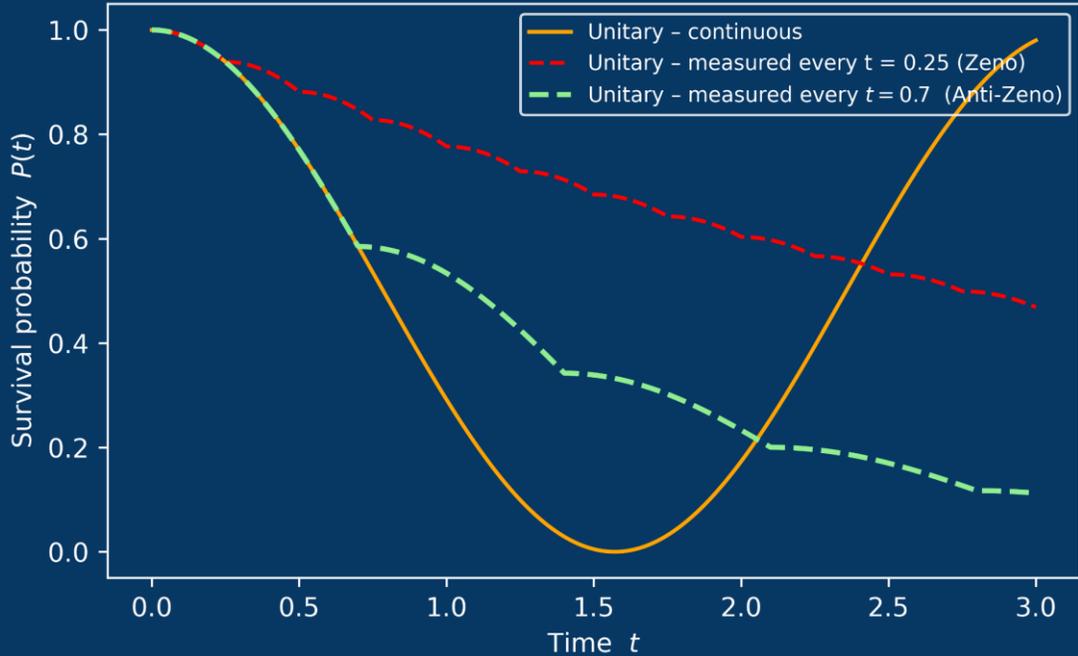




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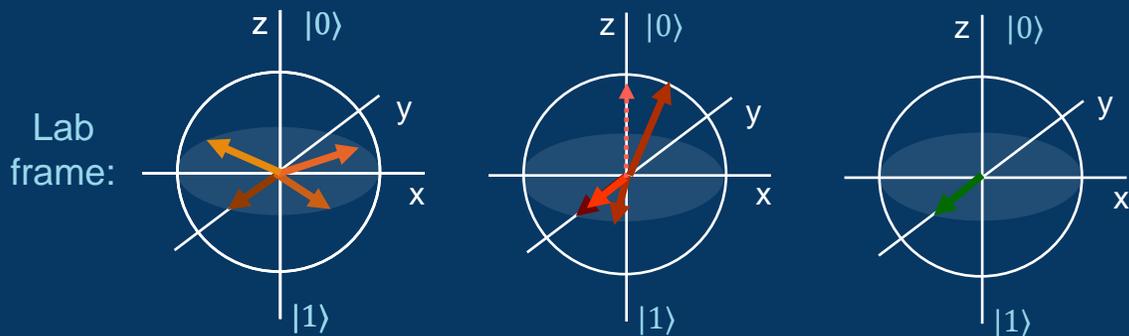
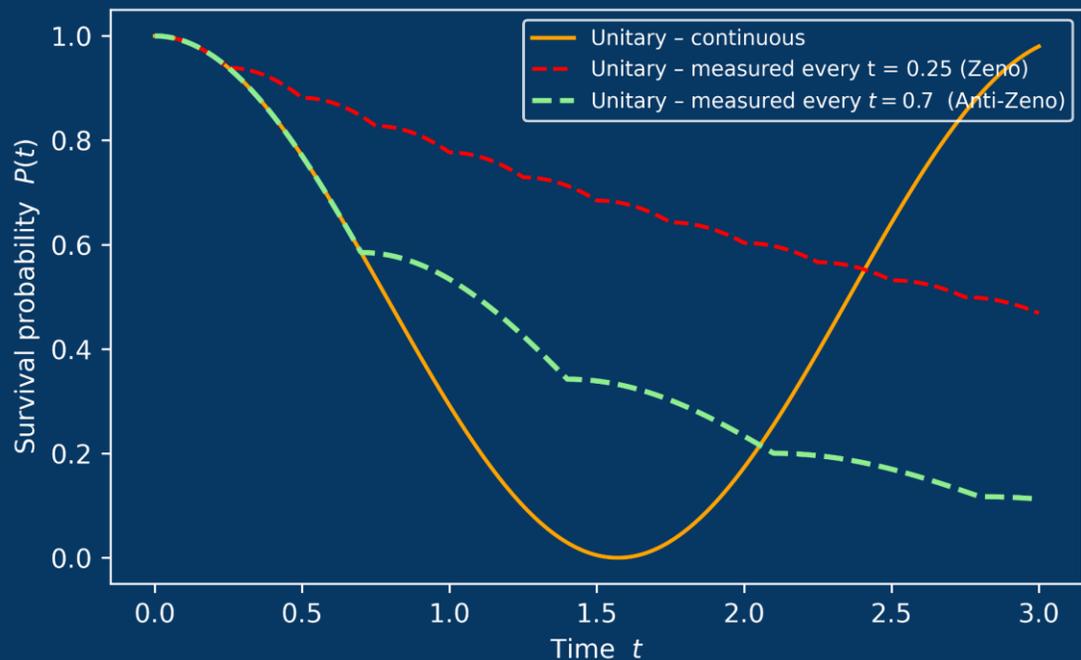




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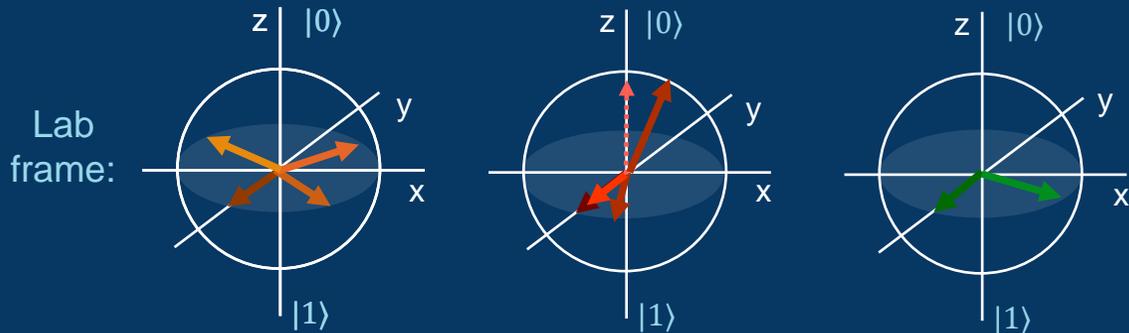
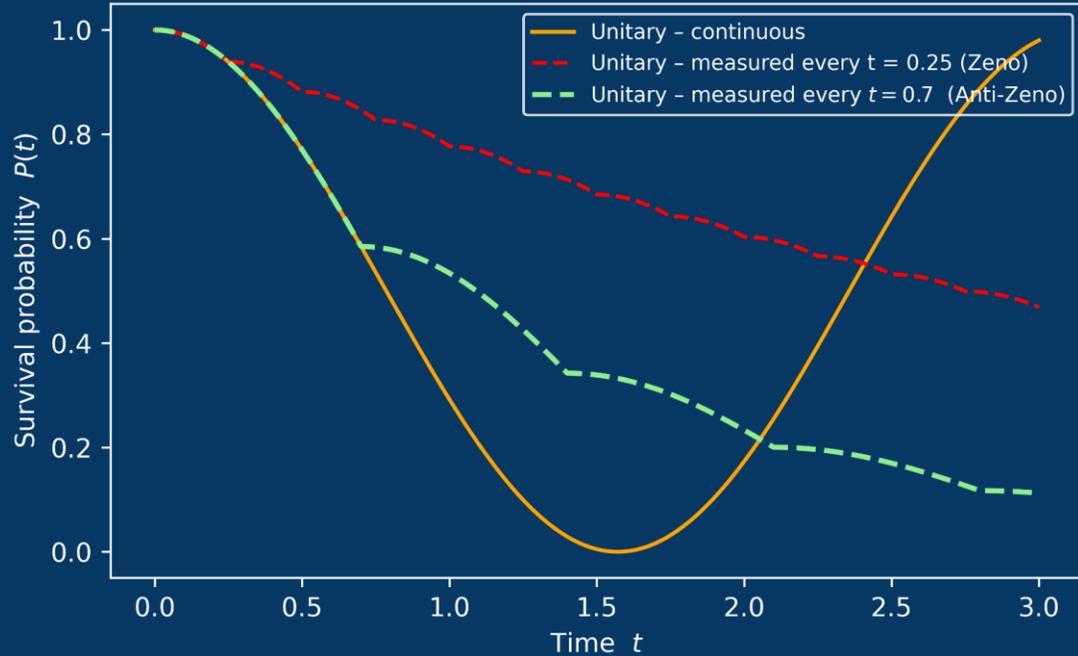




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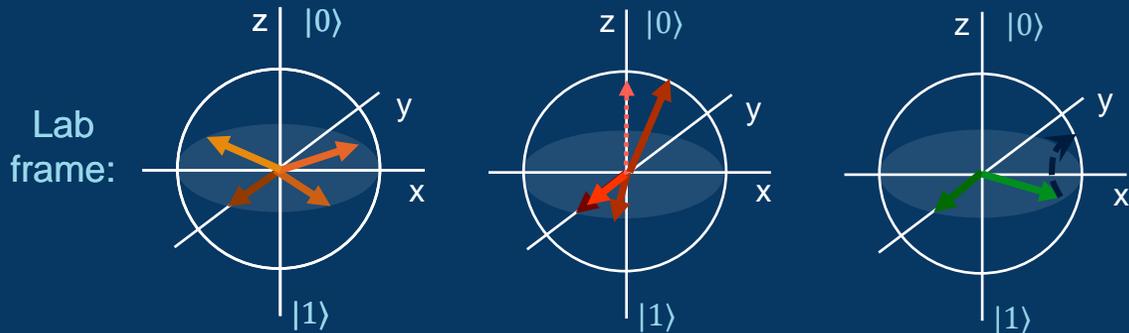
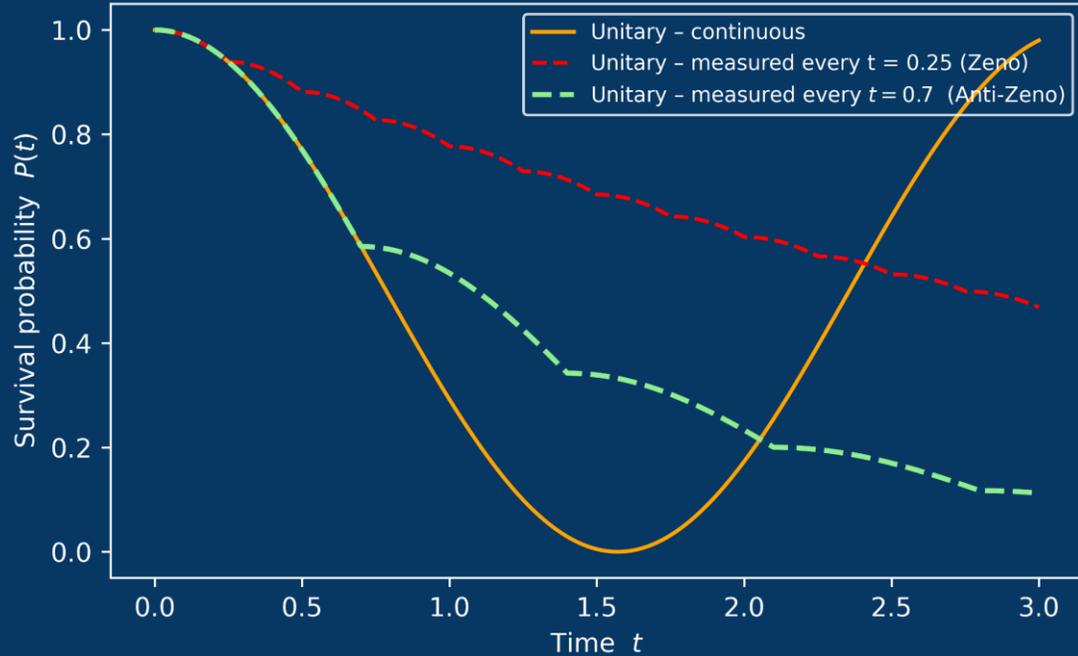




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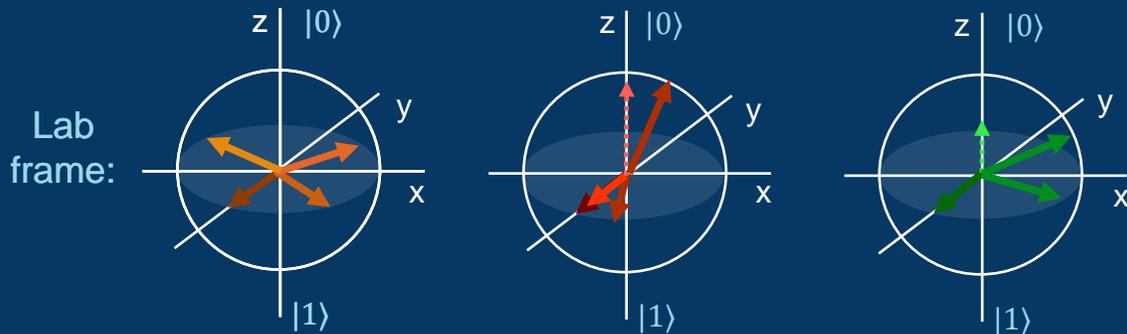
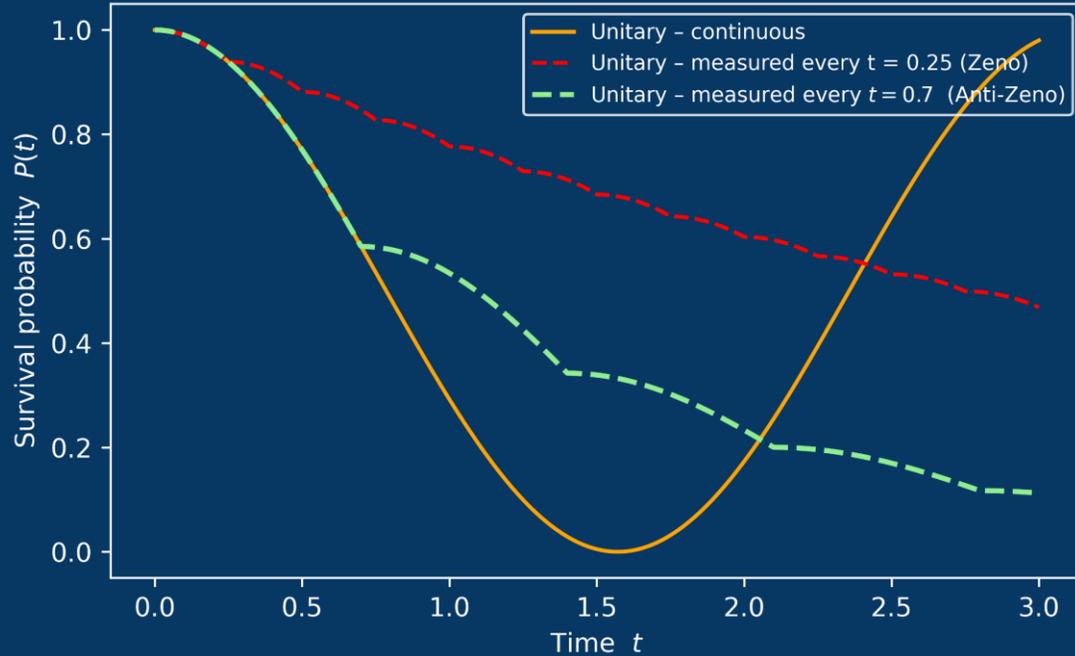




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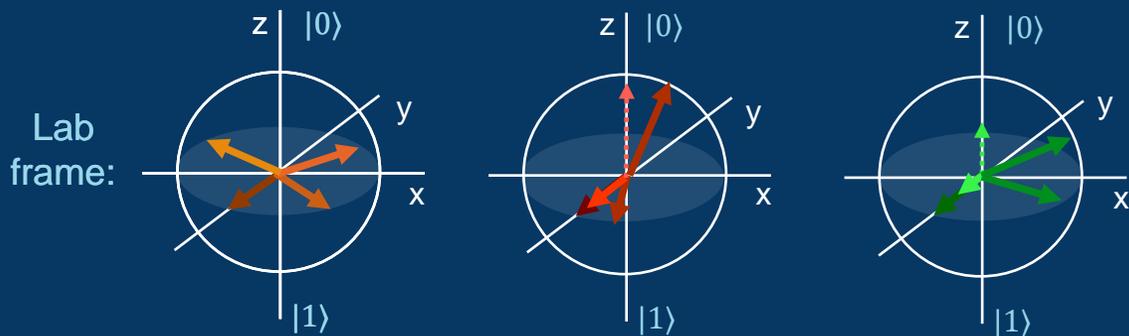
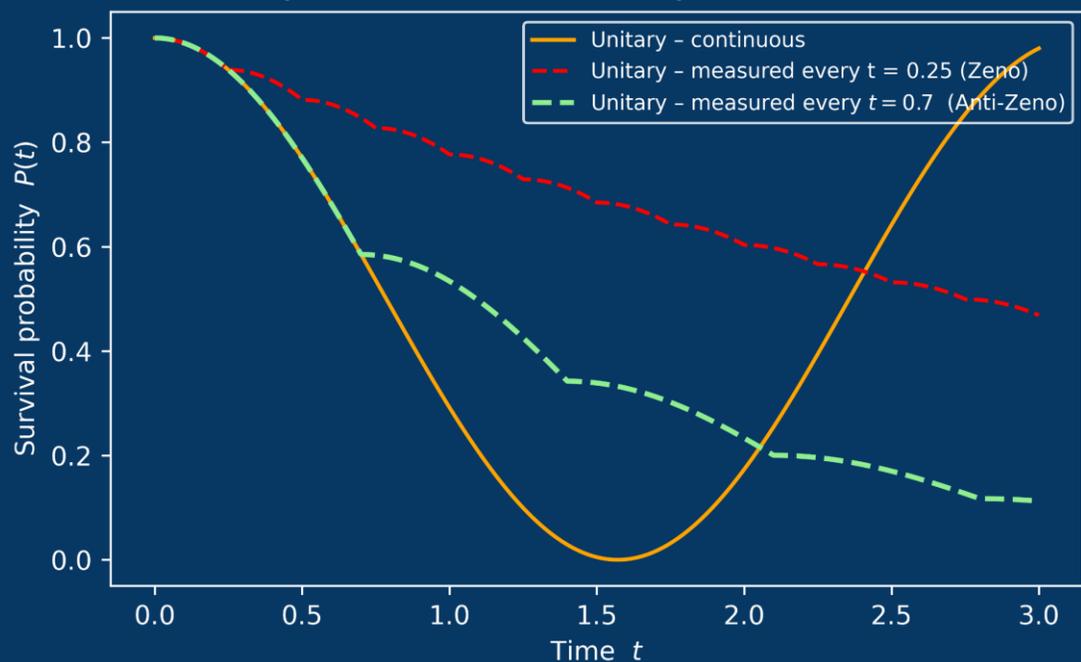




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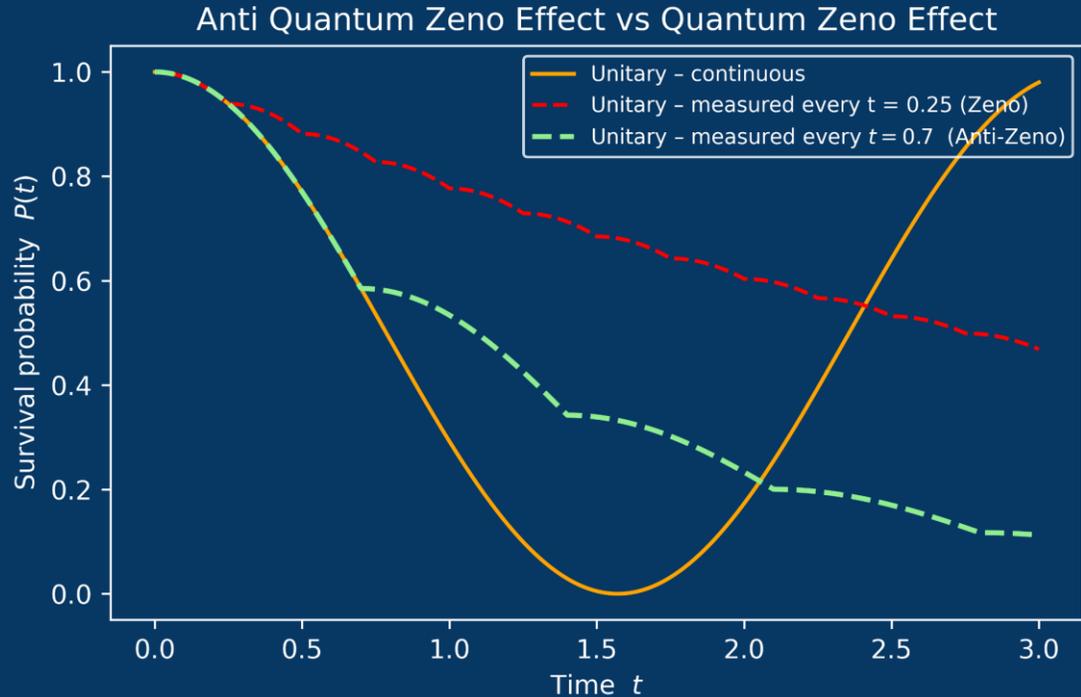


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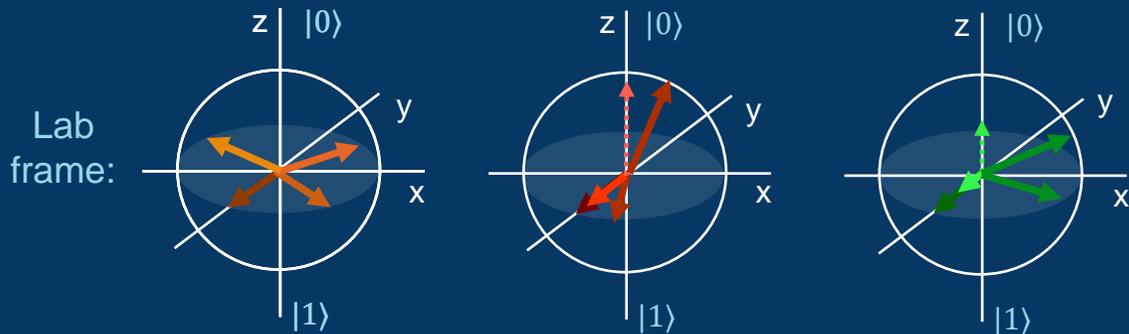




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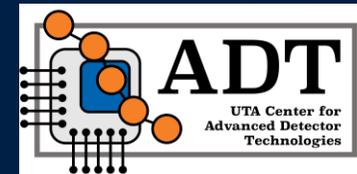


We can suppress evolution our quantum system away from the poles on the Bloch sphere

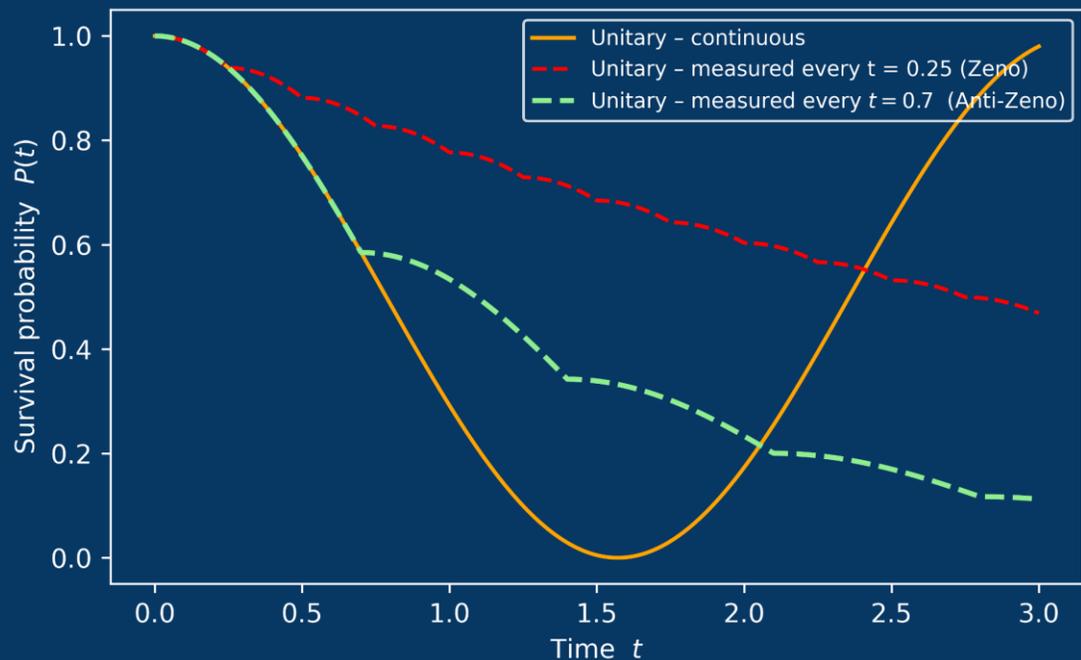




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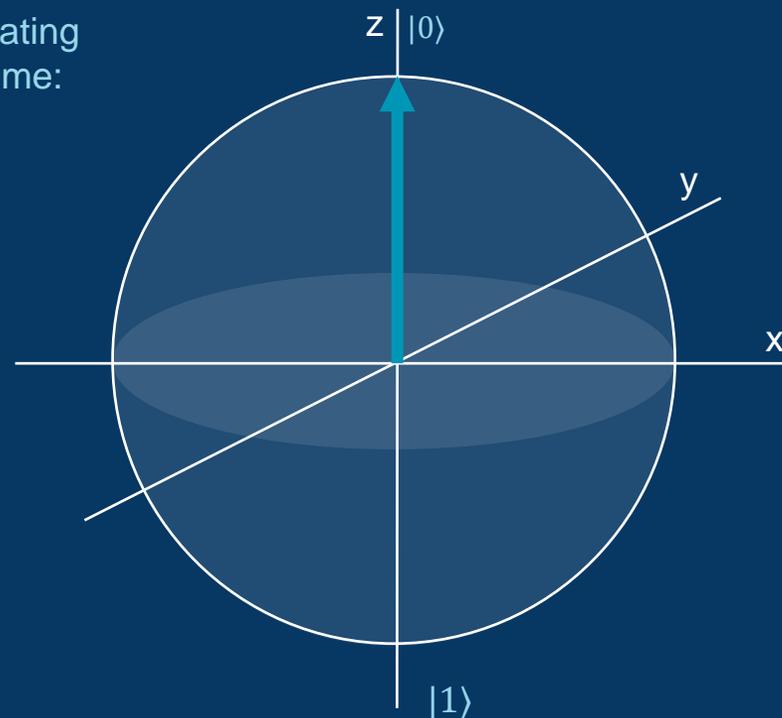


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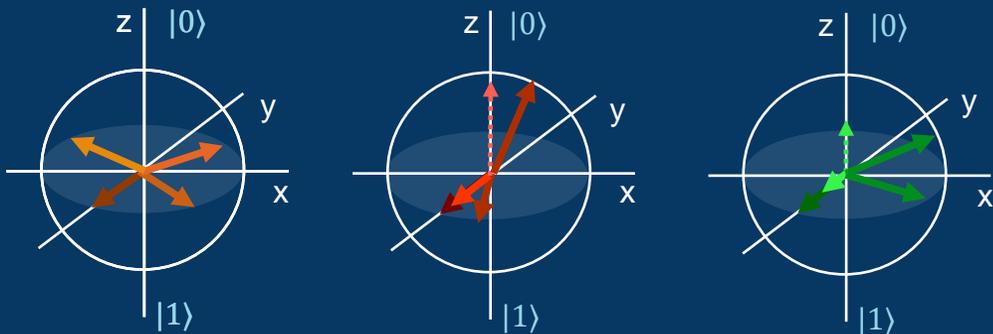


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Rotating frame:

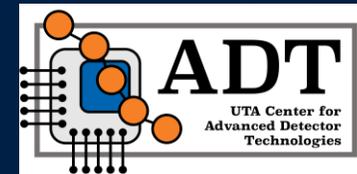


Lab frame:

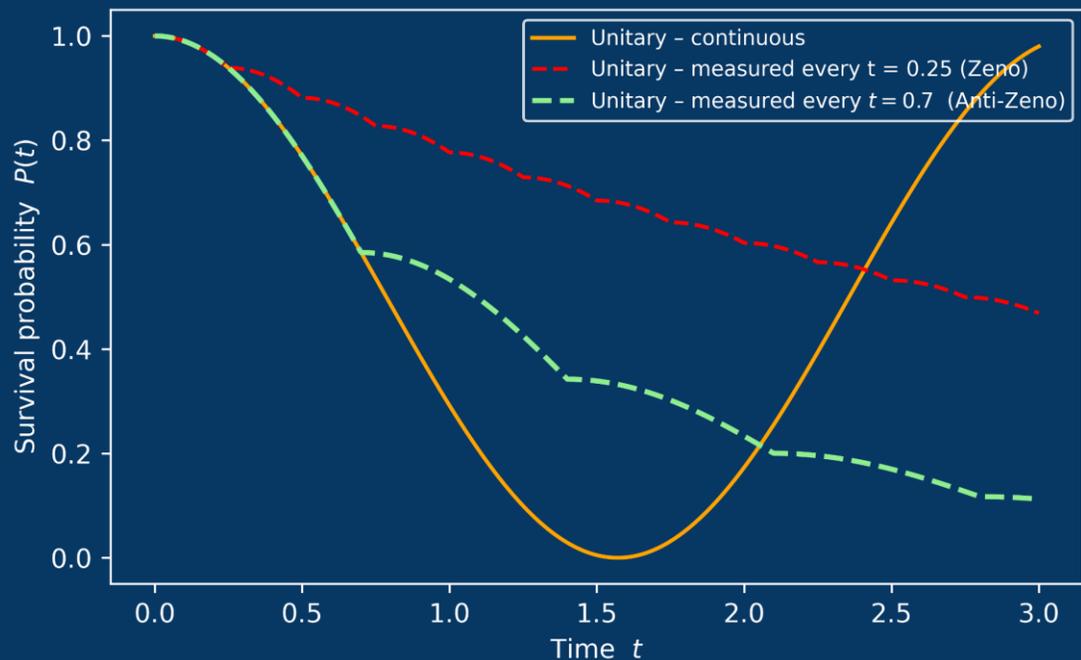




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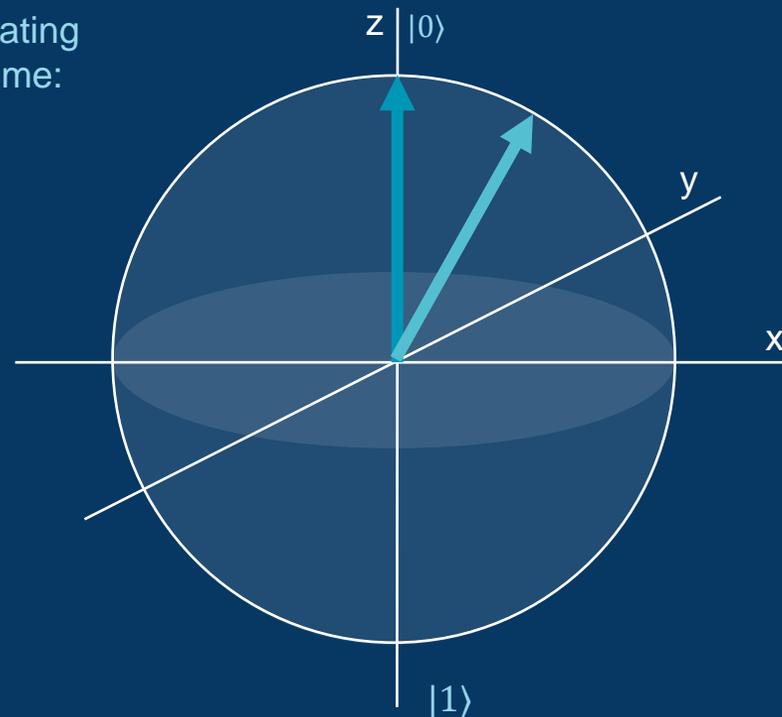


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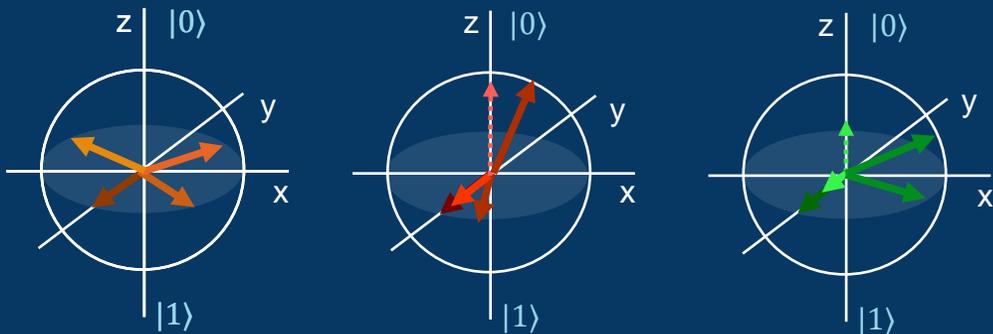


We can suppress evolution our quantum system away from the poles on the Bloch sphere

Rotating frame:



Lab frame:

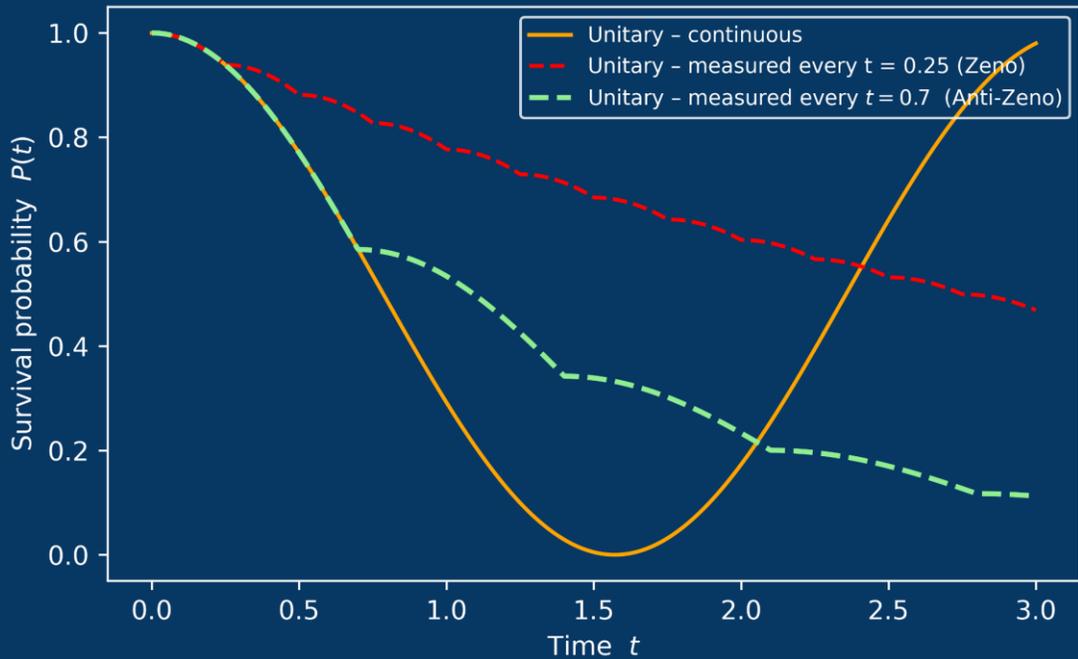




# Method to constrain quantum systems: the Quantum Zeno Effect

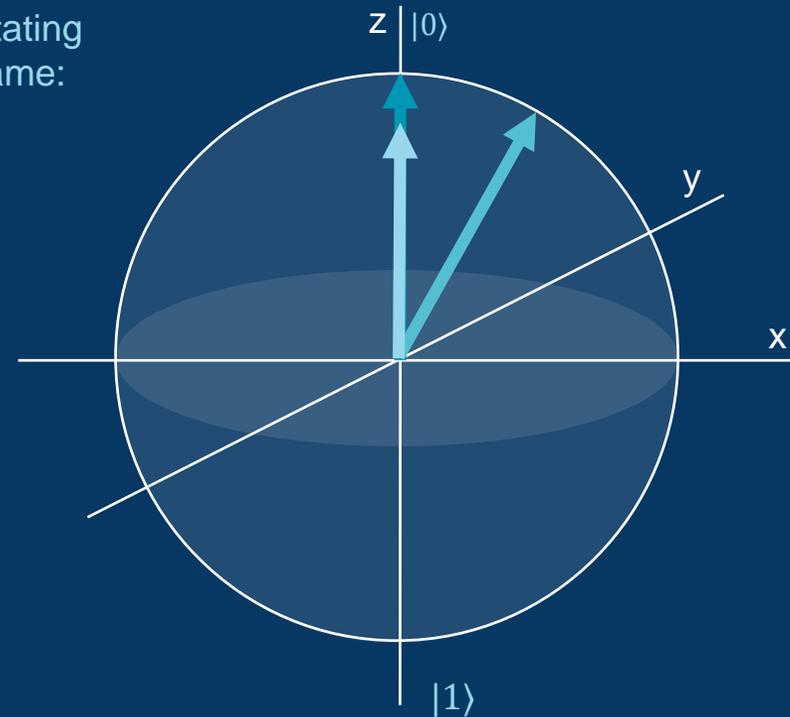


Anti Quantum Zeno Effect vs Quantum Zeno Effect

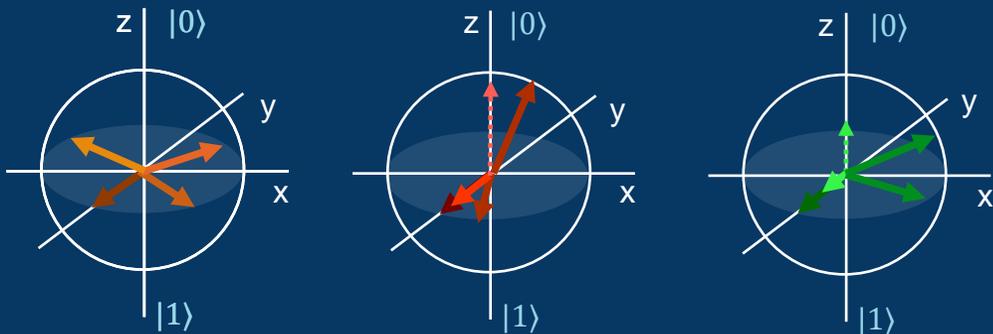


We can suppress evolution our quantum system away from the poles on the Bloch sphere

Rotating frame:

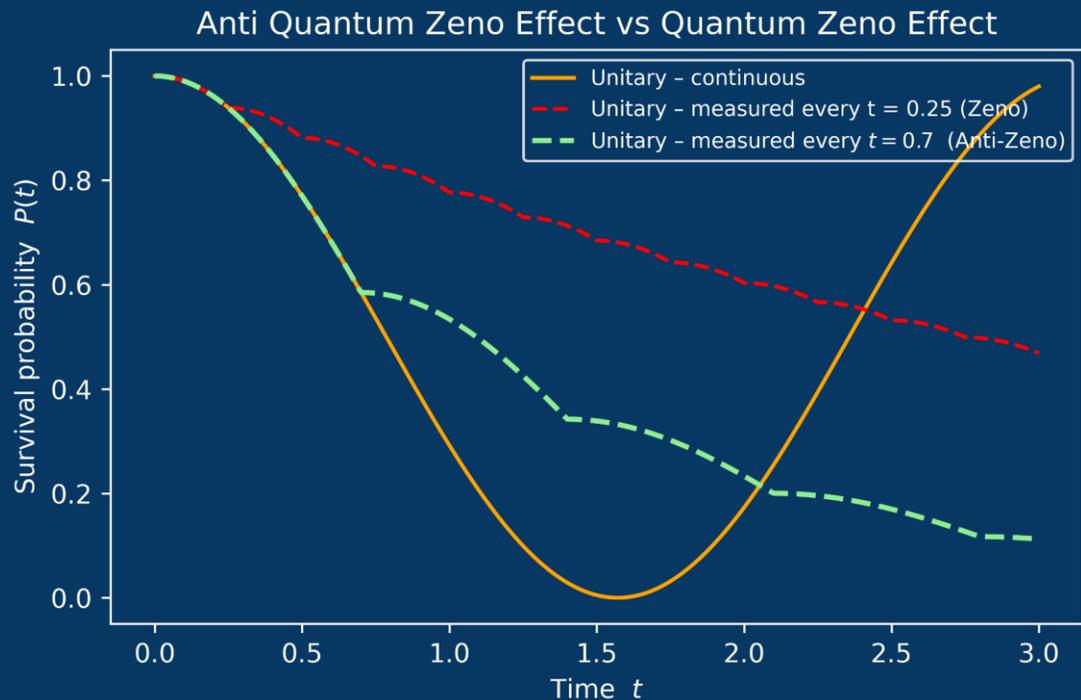


Lab frame:



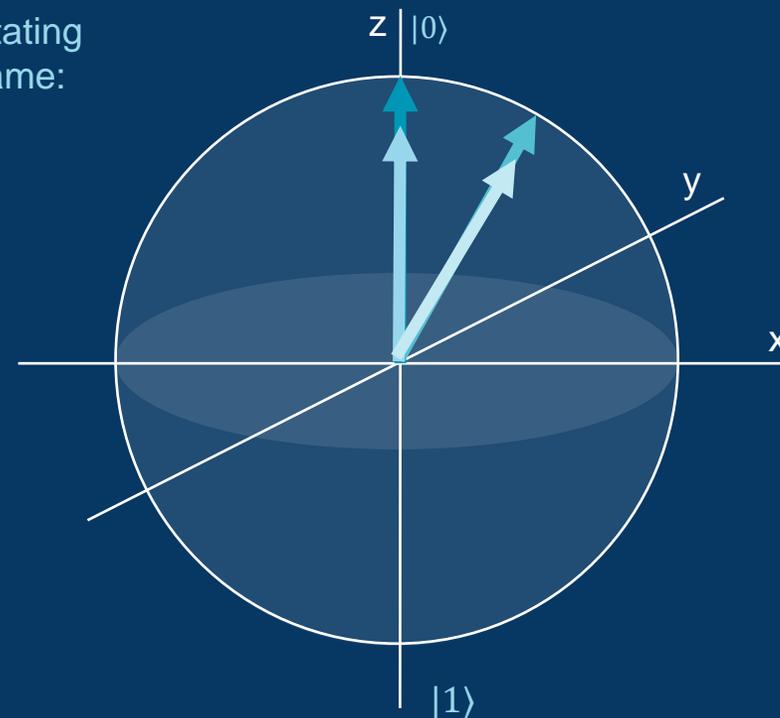


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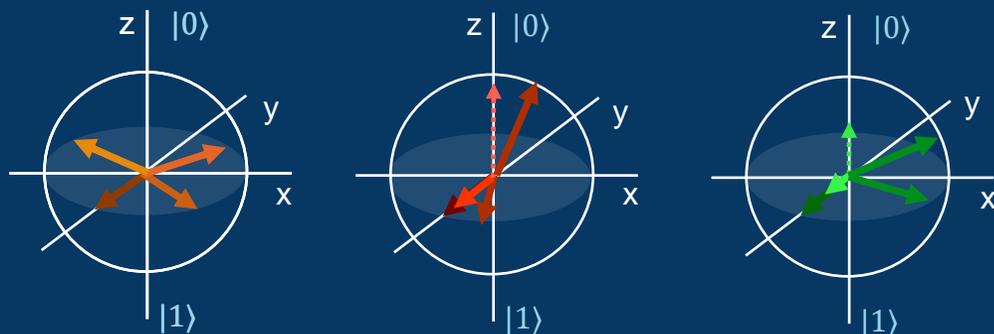


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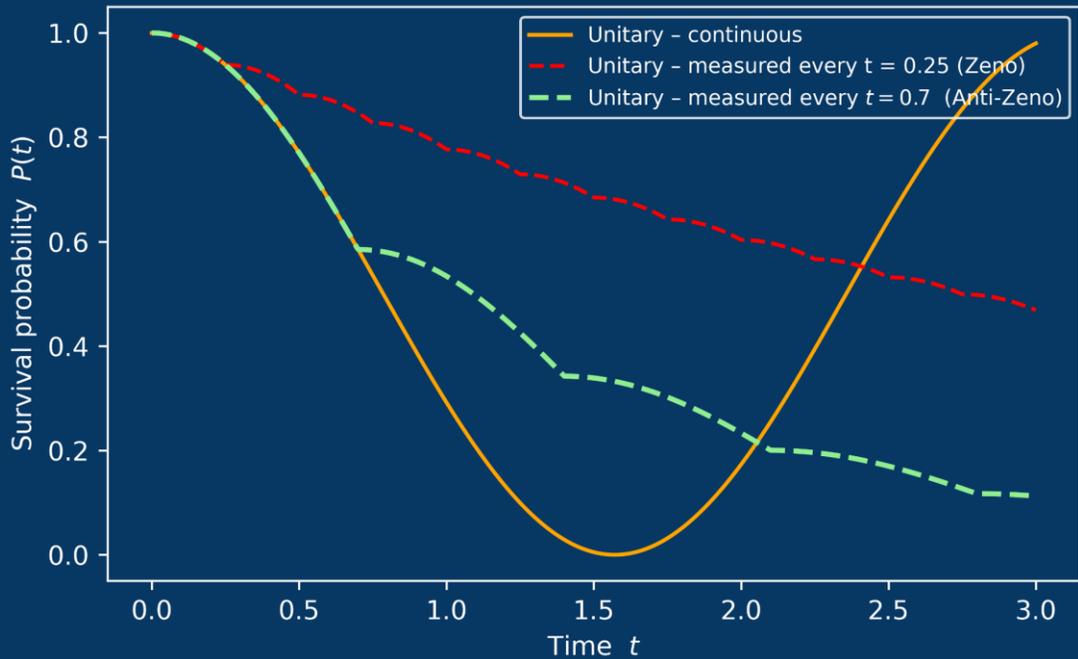




# Method to constrain quantum systems: the Quantum Zeno Effect

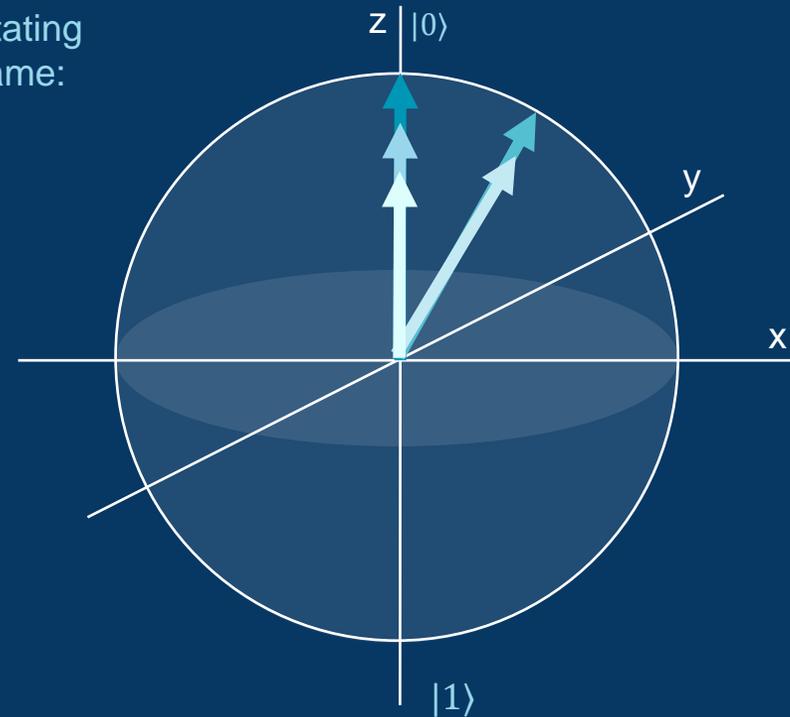


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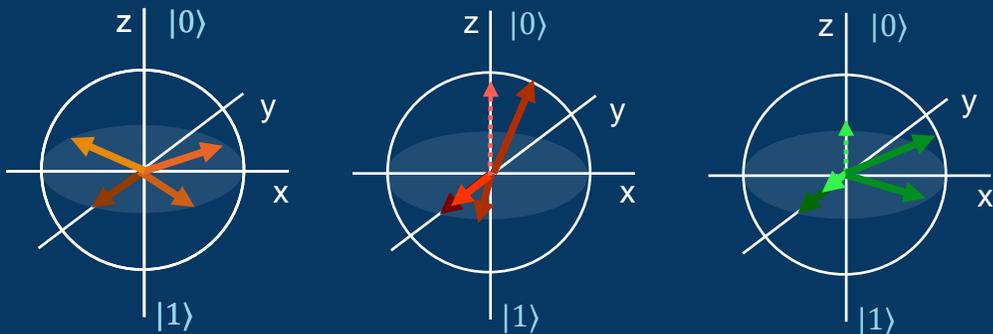


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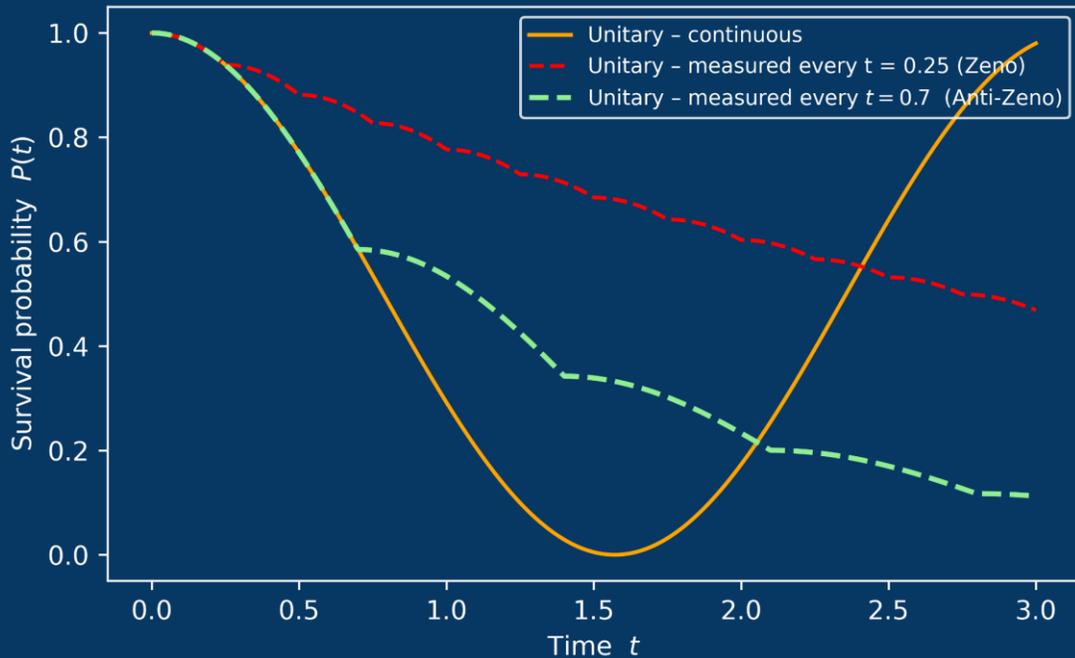




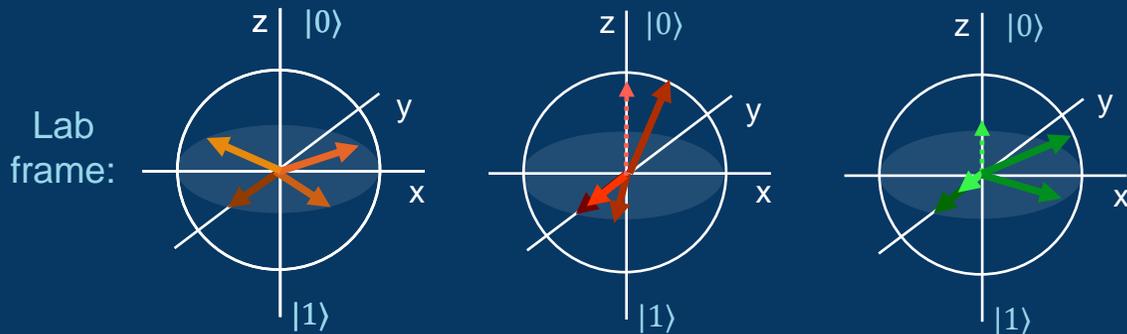
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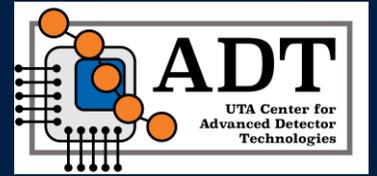


We can constrain our quantum system to a subsection of the Bloch sphere

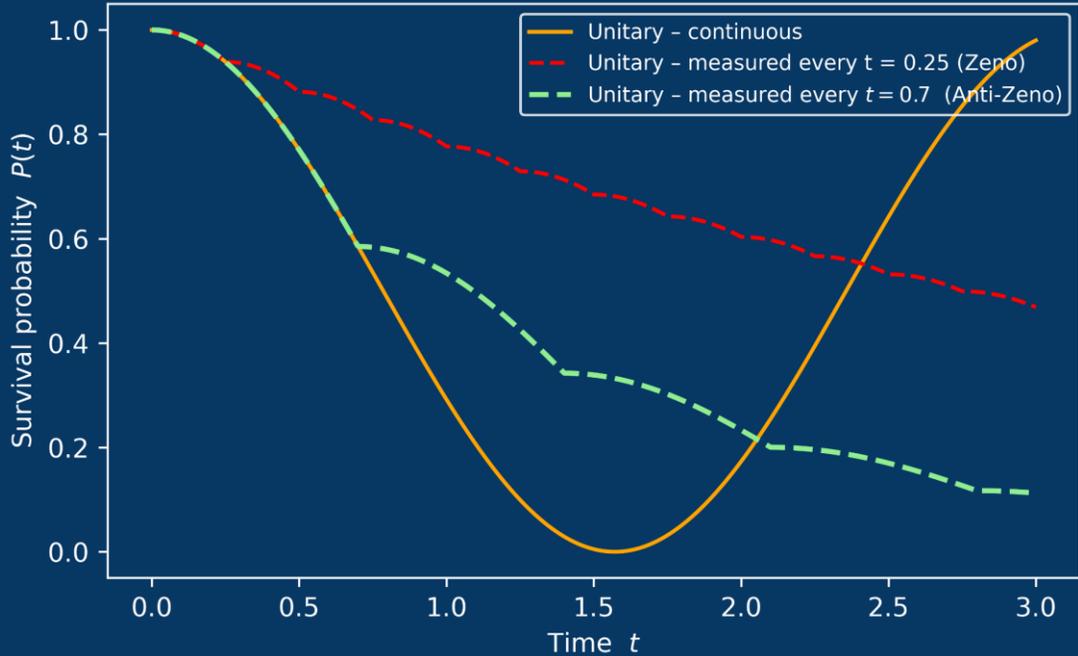




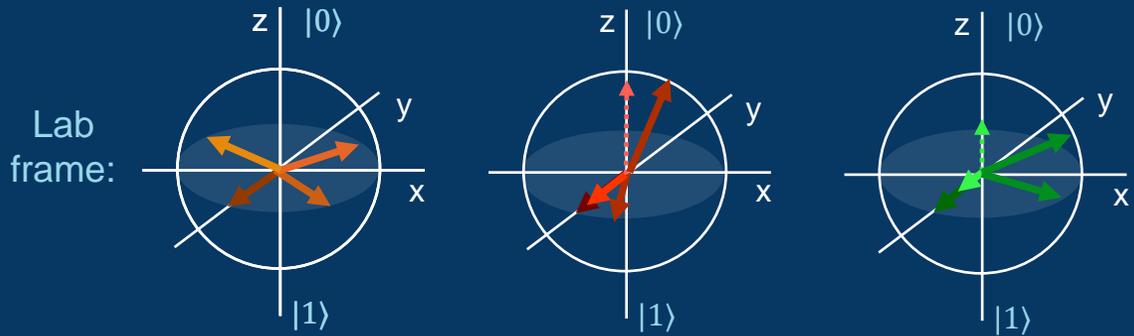
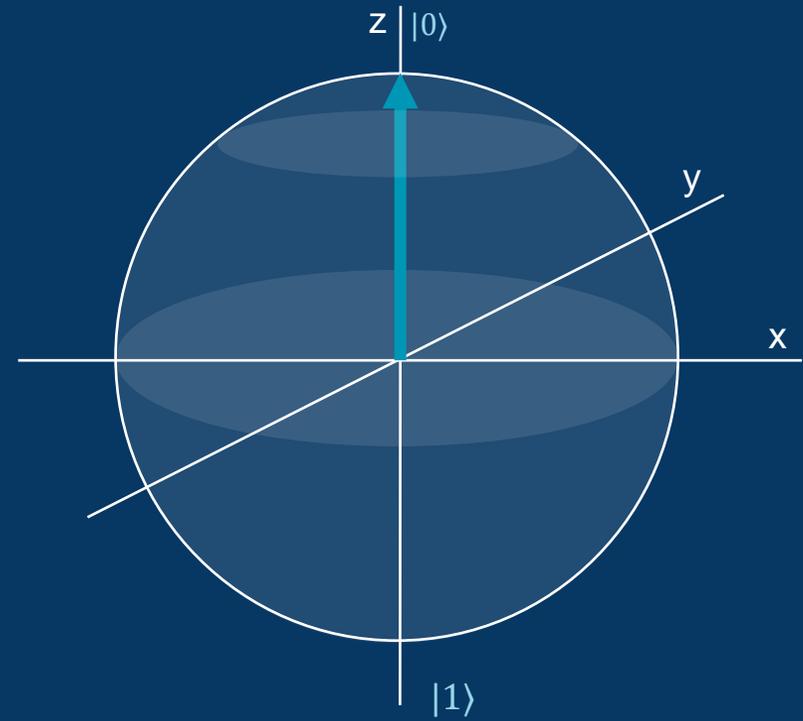
# Method to constrain quantum systems: the Quantum Zeno Effect



Anti Quantum Zeno Effect vs Quantum Zeno Effect

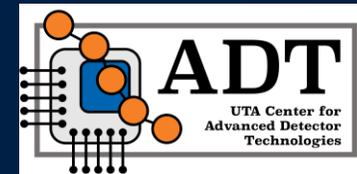


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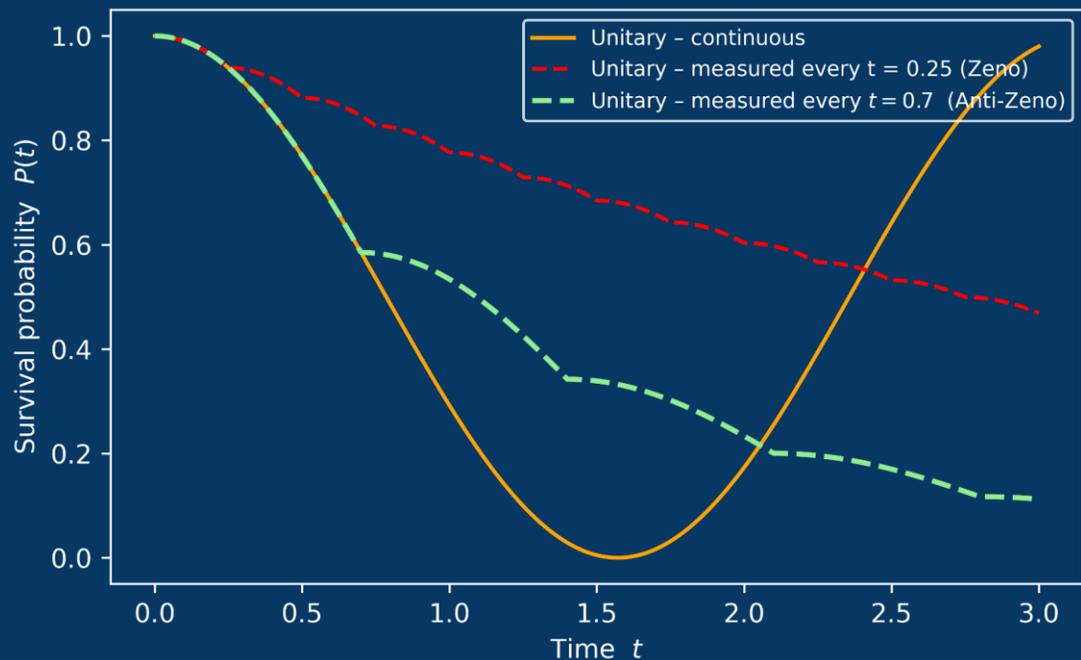




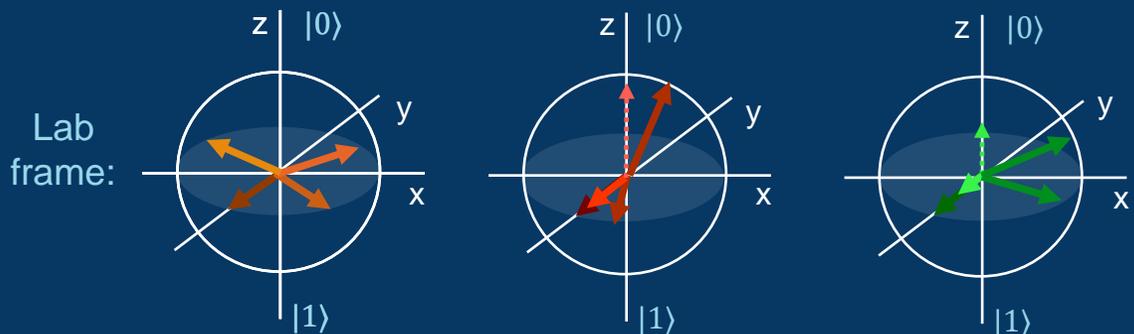
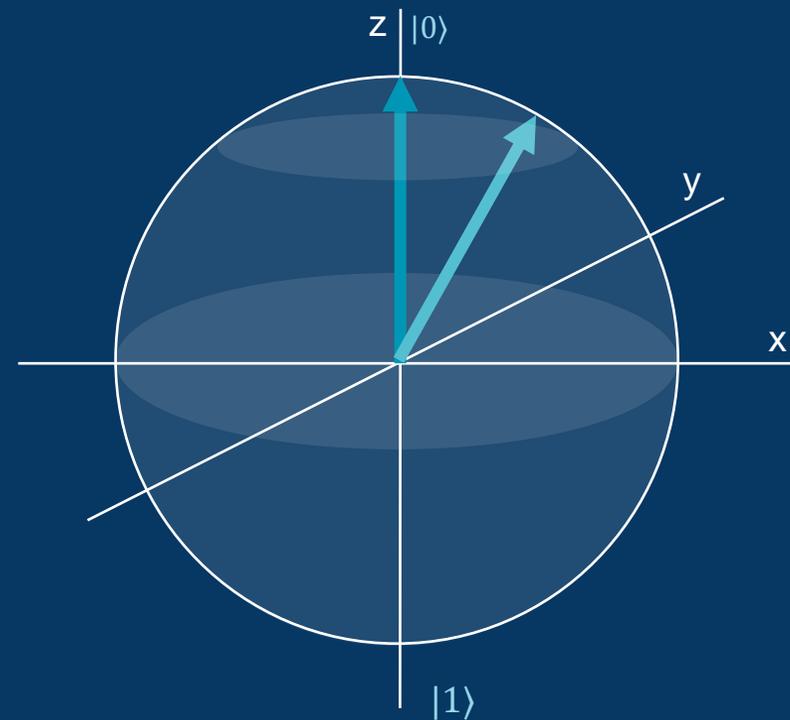
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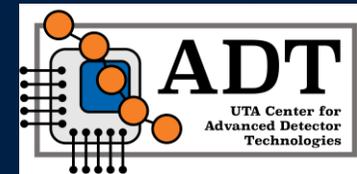


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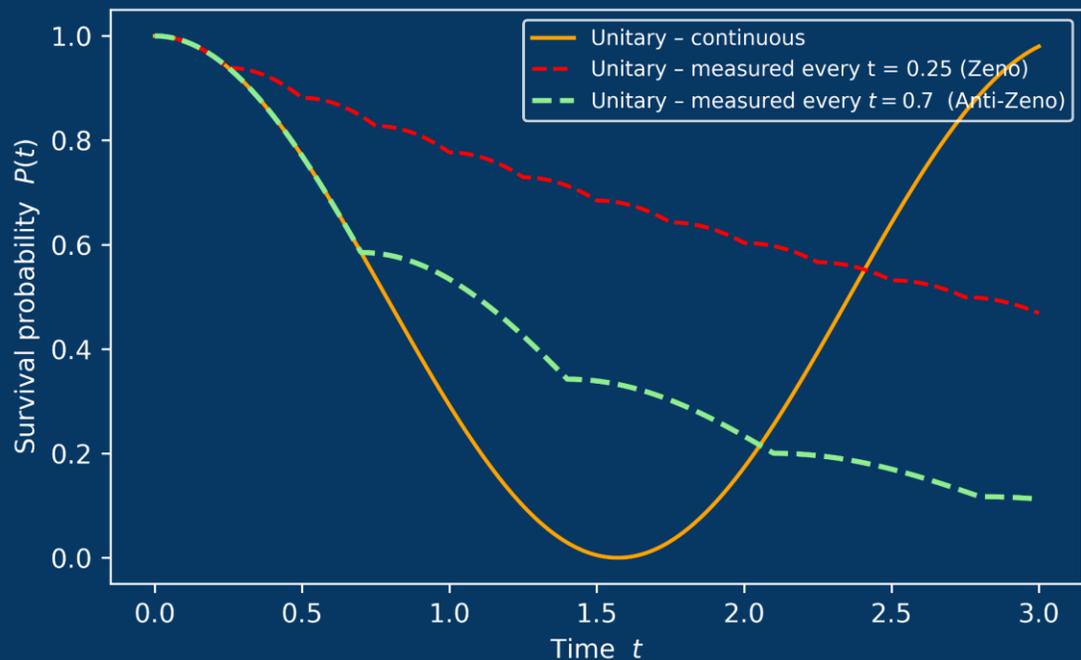




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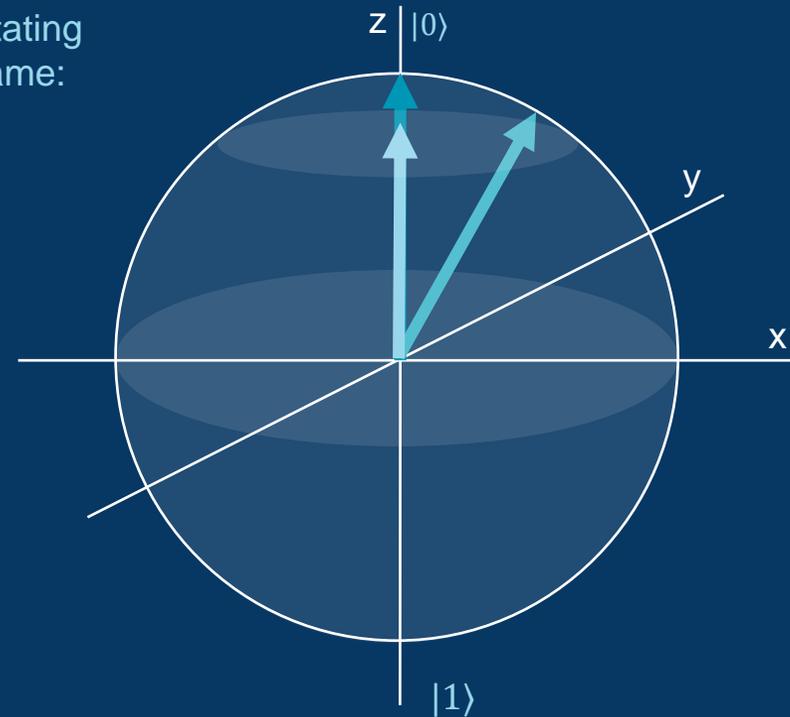


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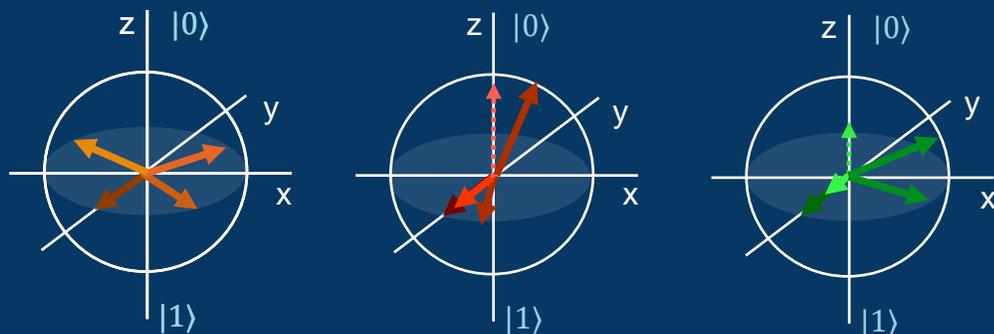


We can constrain our quantum system to a subsection of the Bloch sphere

Rotating frame:



Lab frame:

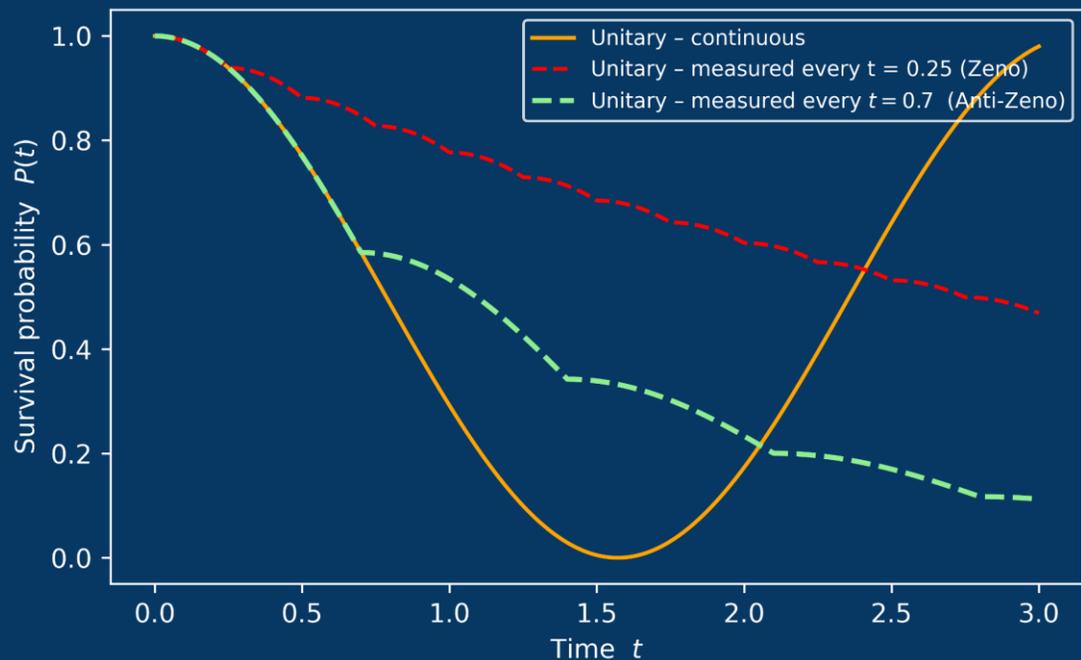




# Method to constrain quantum systems: the Quantum Zeno Effect

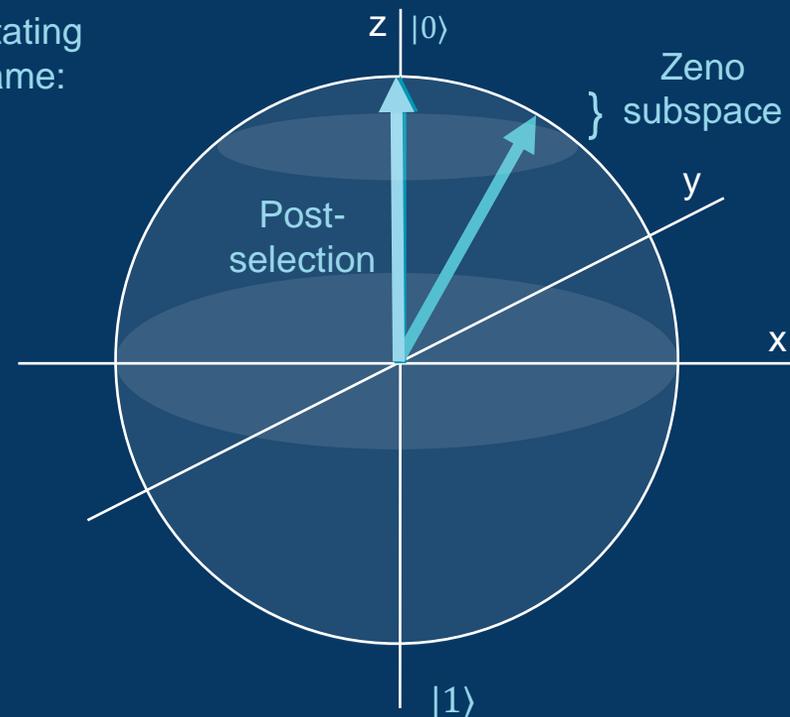


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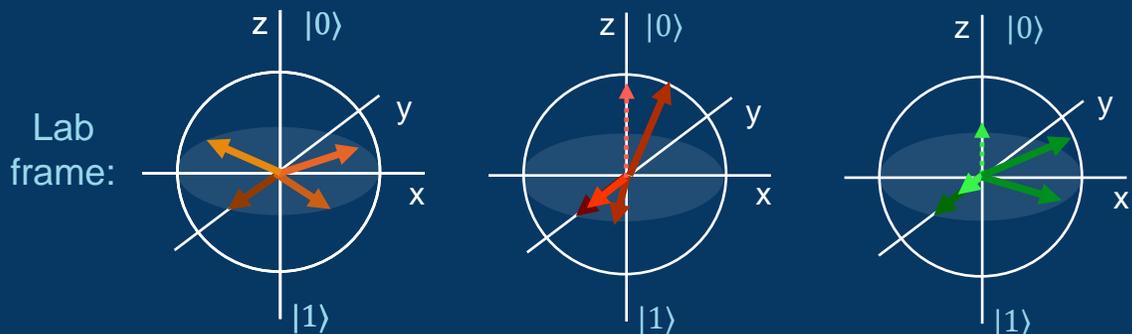


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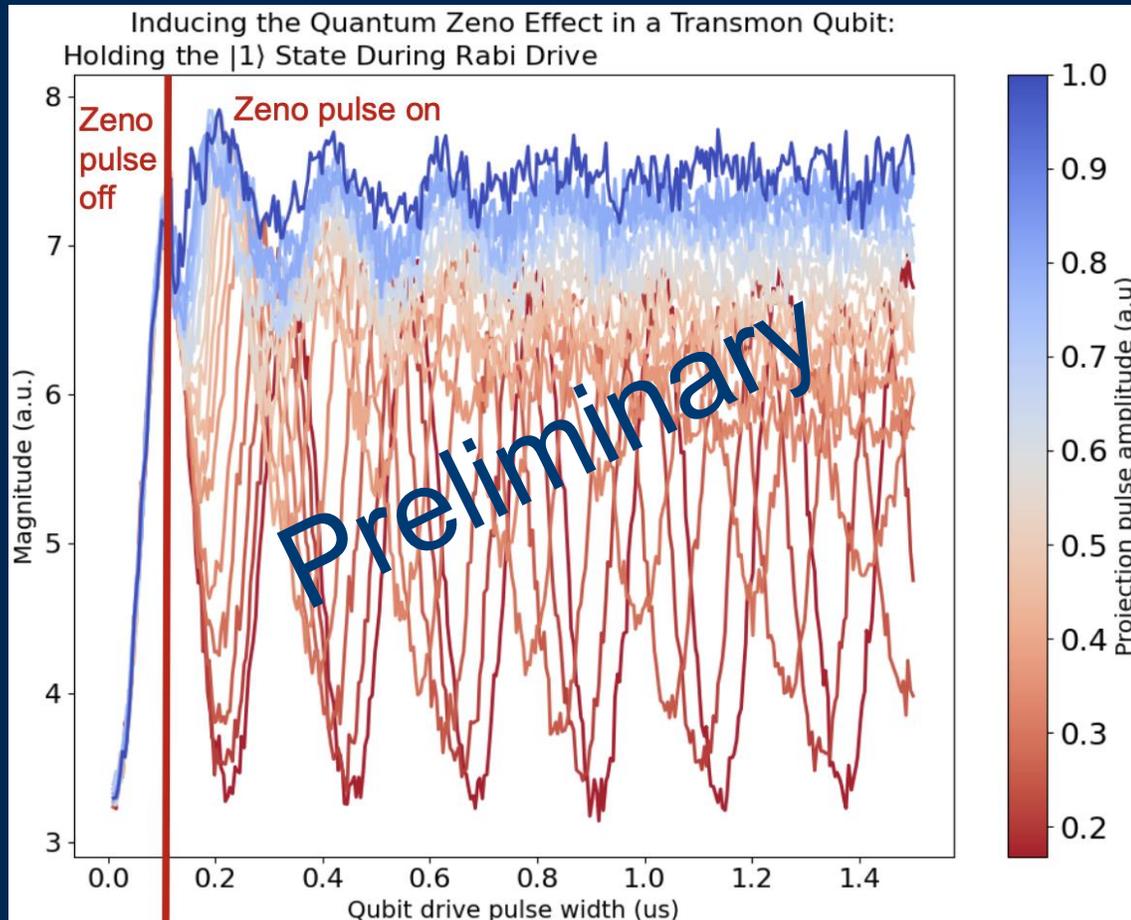


Can we do this with a TLS?

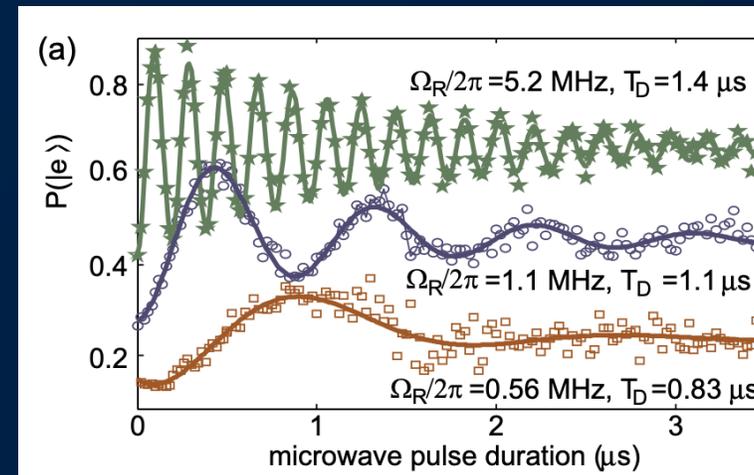




# We have measured the QZE in the qubit's 'two levels'



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



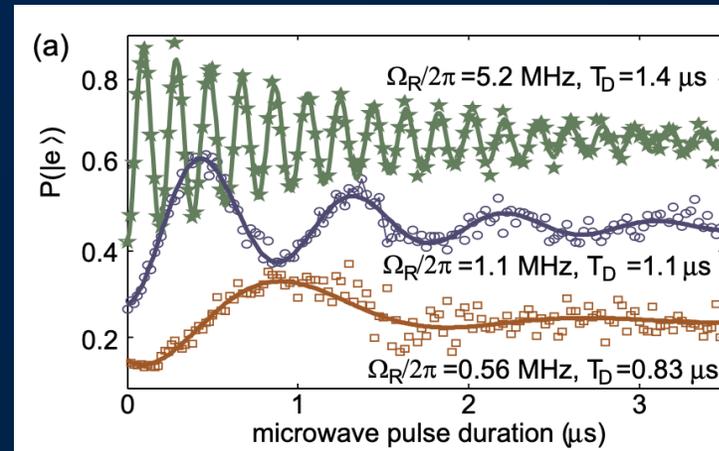
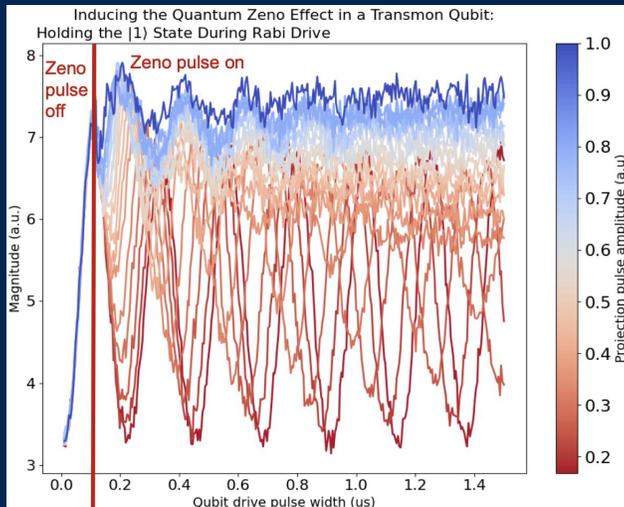
Rabi oscillations of a TLS  
(10.1103/PhysRevB.95.241409)  
10.1126/sciadv.ado6240

Steps towards stabilizing TLSes to better enable reliable quantum sensors:

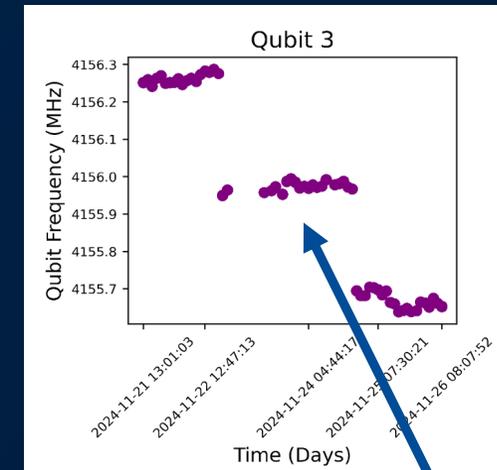
Induce the QZE on the qubit  
 Induce the QZE on the qubit using photons in the resonator

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

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



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



This shouldn't happen while freezing the TLS



# Conclusion

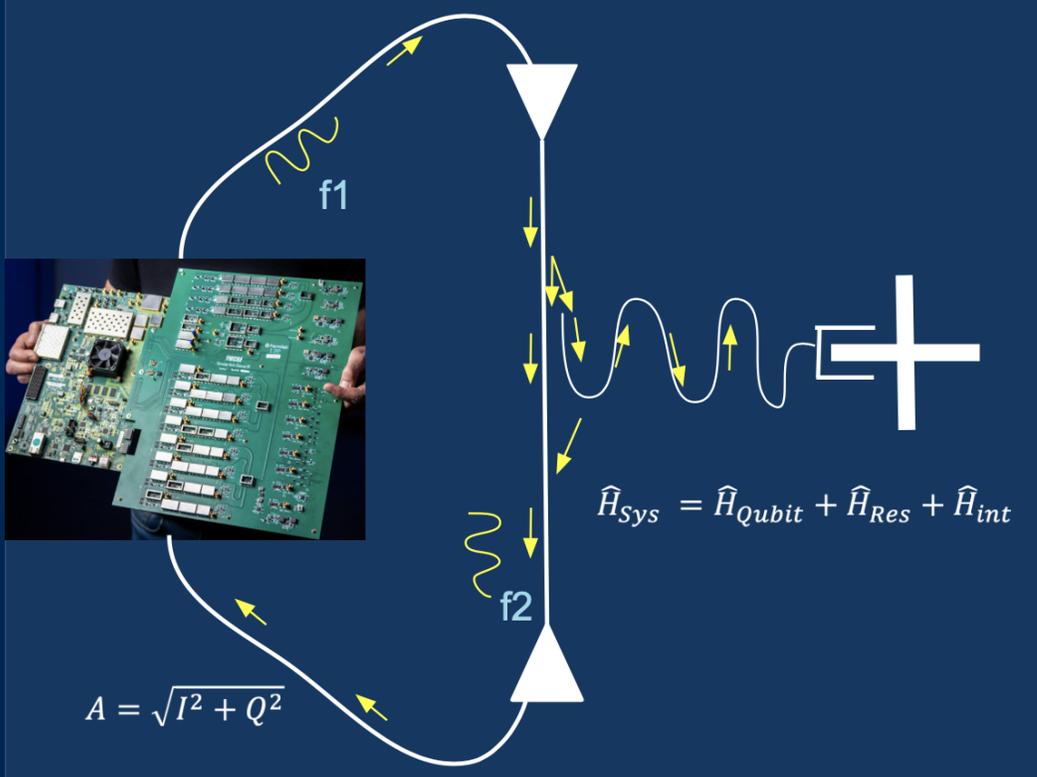
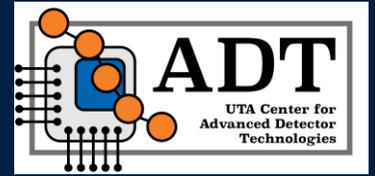


- Superconducting based qubits offer potential for ultra-low energy particle detection
- Two of the leading known sources of backgrounds:
  1. Cosmic Rays
  2. Defect Two Level Systems
- (1) can be mitigated by going underground, (2) remains a limiting background to qubit-based sensing
- The Quantum Zeno Effect constrains a quantum system, and could provide a method for constraining Defect Two Level Systems
- This work aims to prove this idea

***Thank you to the DOE and the Graduate Instrumentation Research Award committee for supporting this work!***

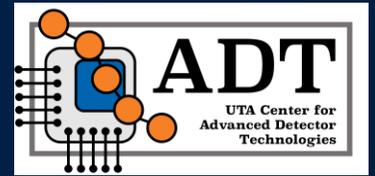


# Thank you to the **Fermilab CosmiQ** and **QICK** teams!

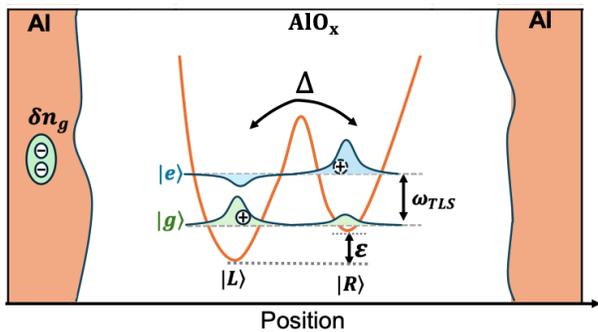




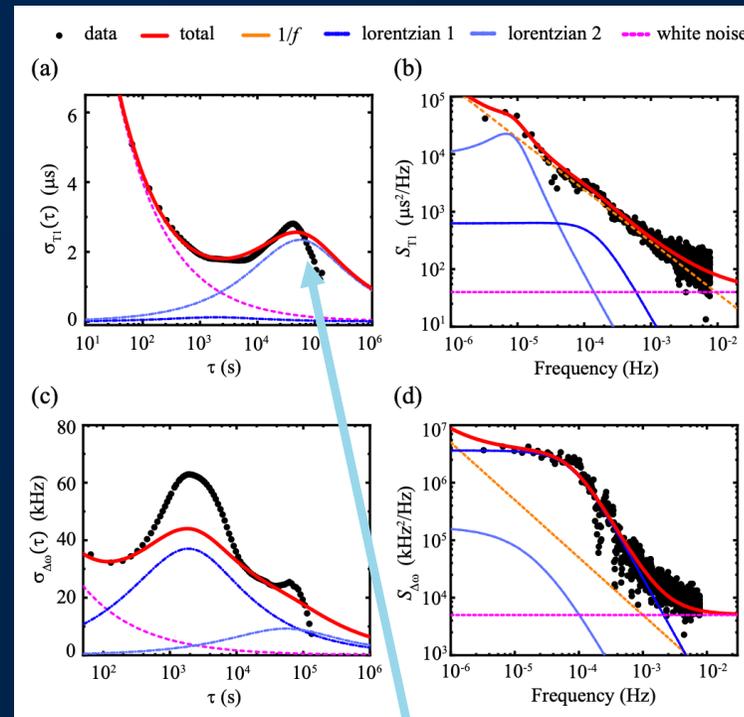
# A second insidious source of backgrounds: Two Level Systems (TLSes)



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

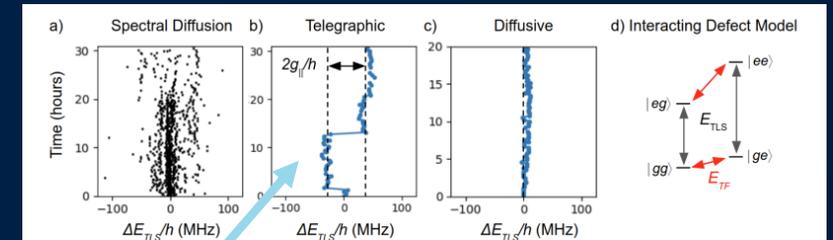


These shift the qubit frequency around, and coherence times



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

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  $2g_i/h$ , 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.



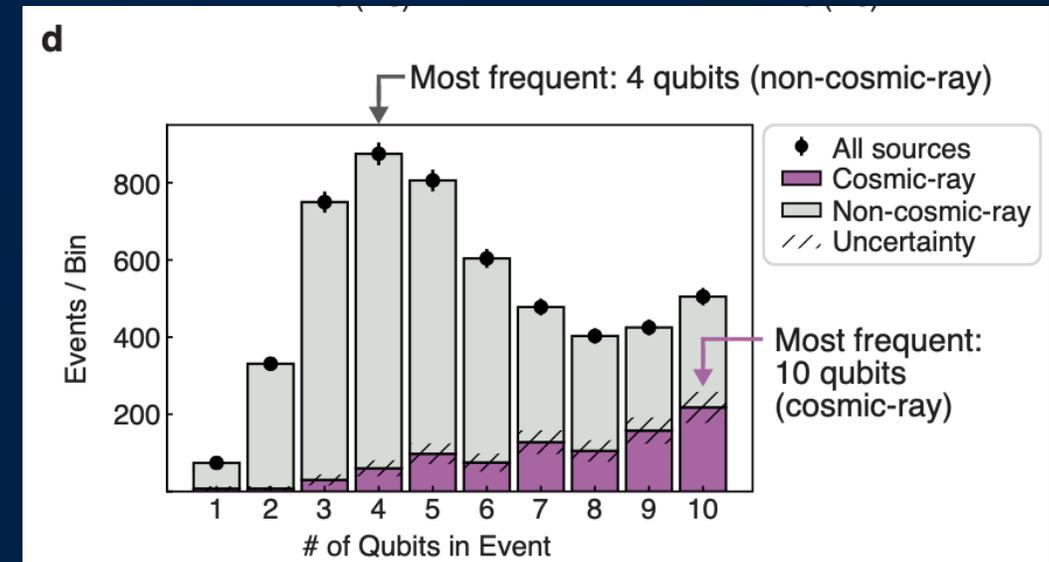
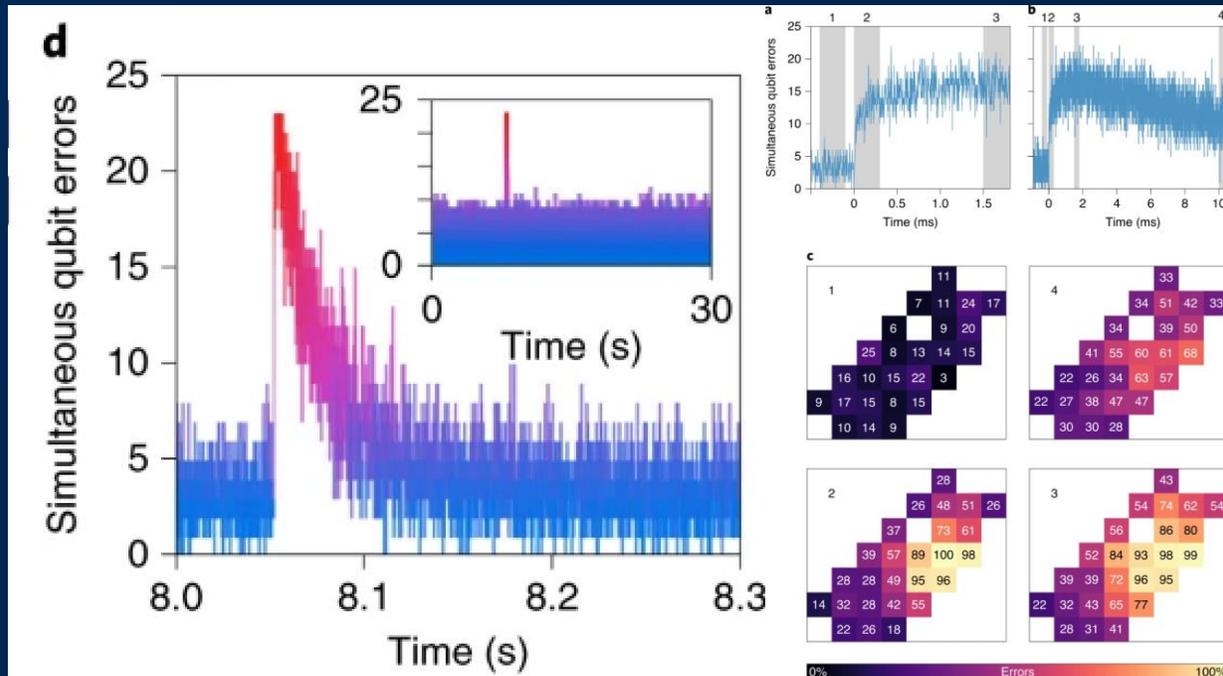
# Qubits are great sensors, and are extra sensitive to cosmic rays



## Cosmic Ray Induced Quasiparticles → Decoherence

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

*Cosmic rays found to account for  $17.1 \pm 1.3\%$  of spatiotemporally correlated events*



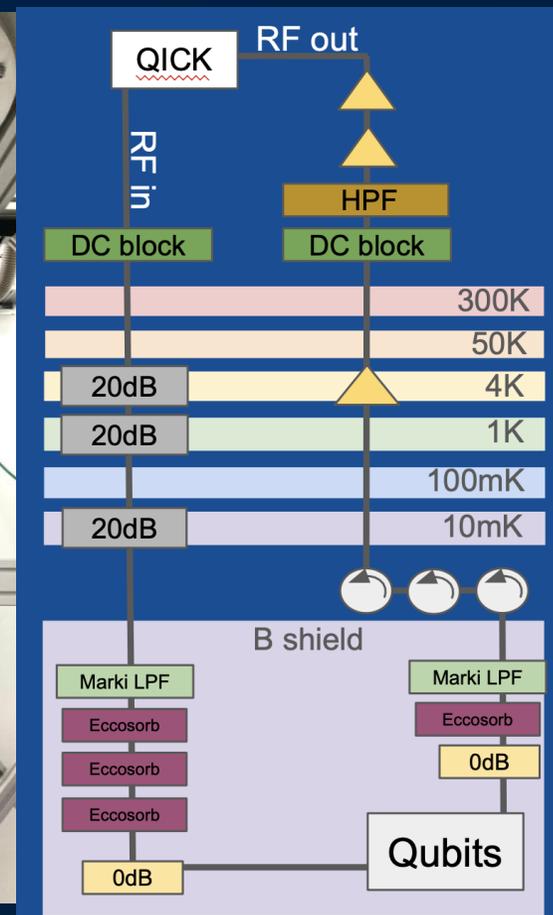
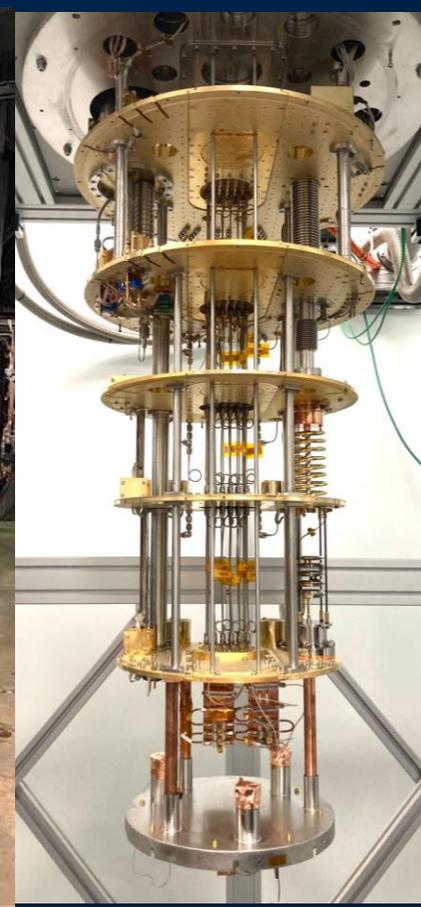
[6]



# 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)*

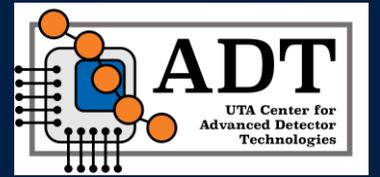


# Overview of current Qubit hardware

	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



# How is the QZE different than decoherence?



## Decoherence

Loss of Quantum Information (somehow)

## QZE

Loss of Quantum Information via entanglement

## Environmental

## Experimenter

Flux noise

Charge noise

External noise sources  
TLses

Photons in the resonator

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