Characterizing superconducting qubits in a deep underground environment

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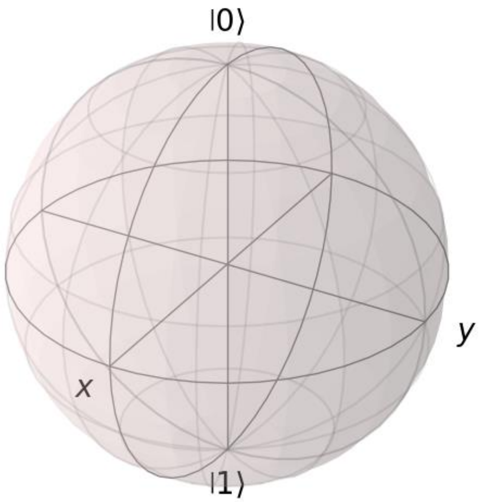
Outline



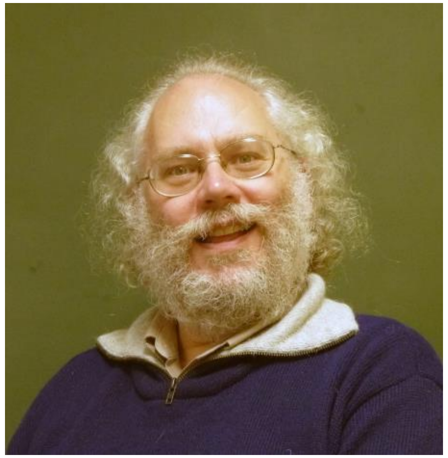
Quantum Computing

Solid State Qubits

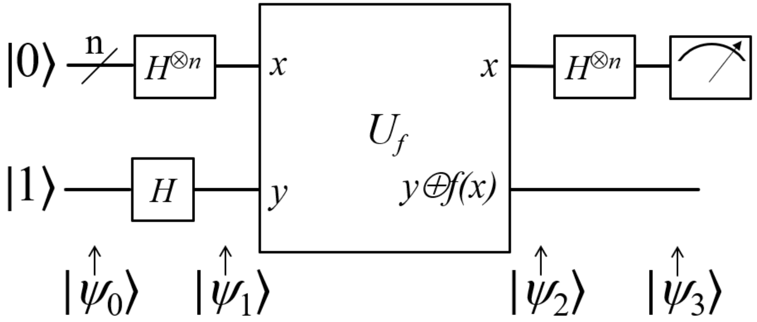
Ionizing Radiation

Measurements at CUTE

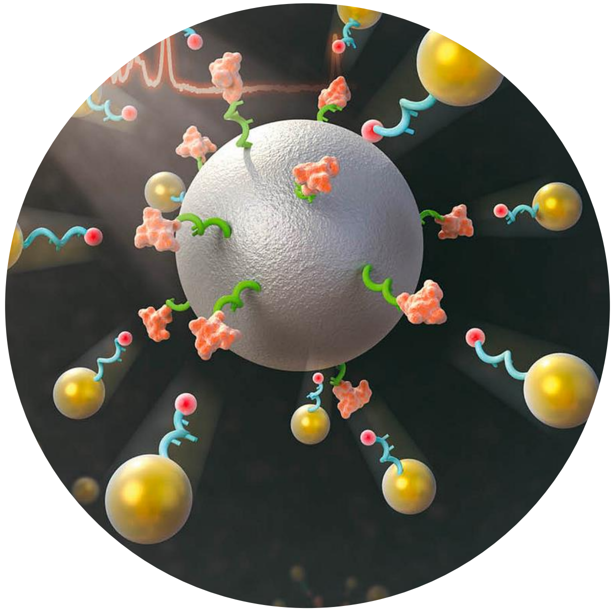
History of Quantum Computing

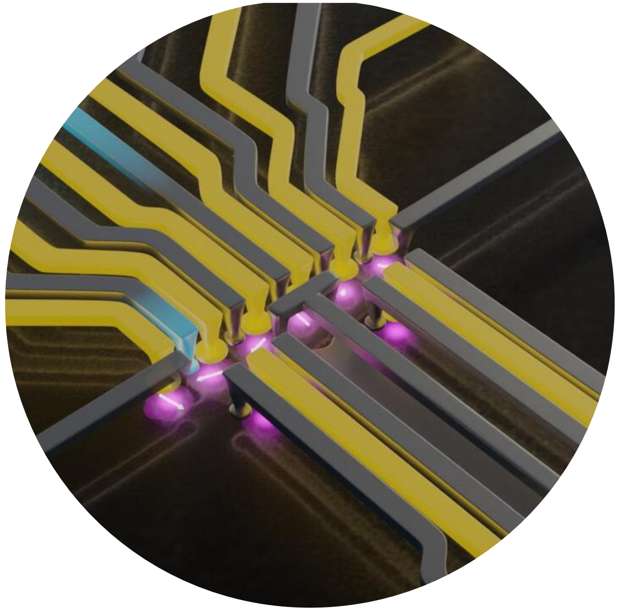


1982 | 1985 | 1994 | 1996 | 2023



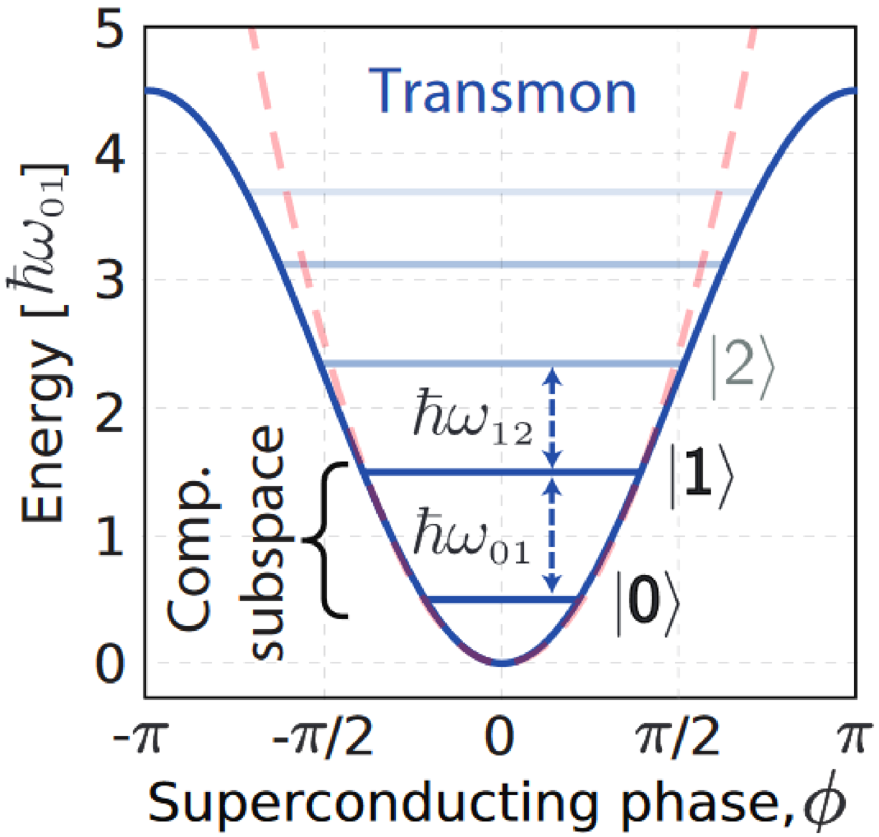
Qubit Platforms

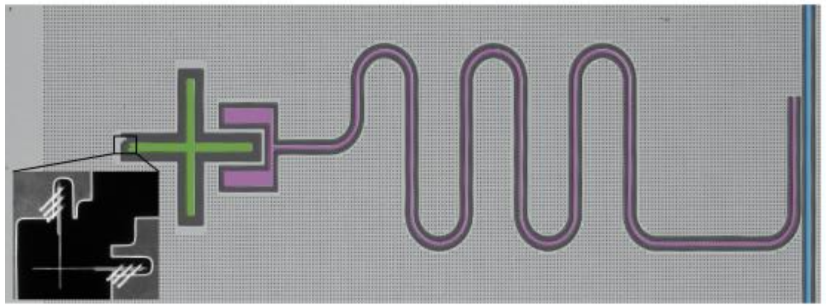




Superconducting qubits

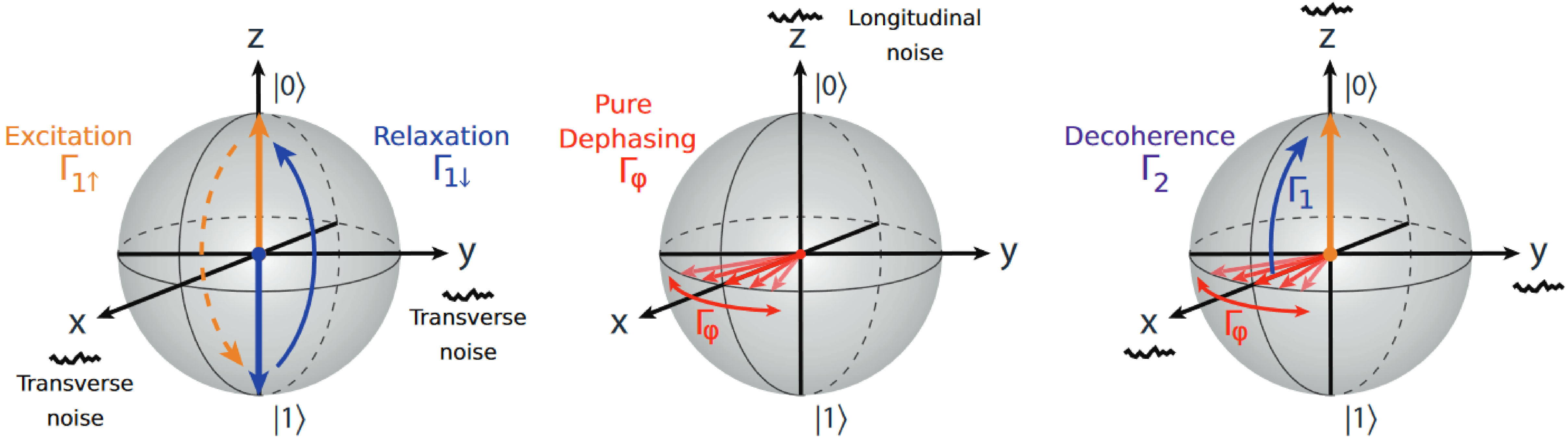
- Superconducting metals have some fraction of electrons form Cooper pairs below a critical temperature
- By introducing a nonlinear circuit element (Josephson junction), discrete energy levels are formed
- Different types: charge, flux, phase
- Readout typically done by coupling to SC resonator





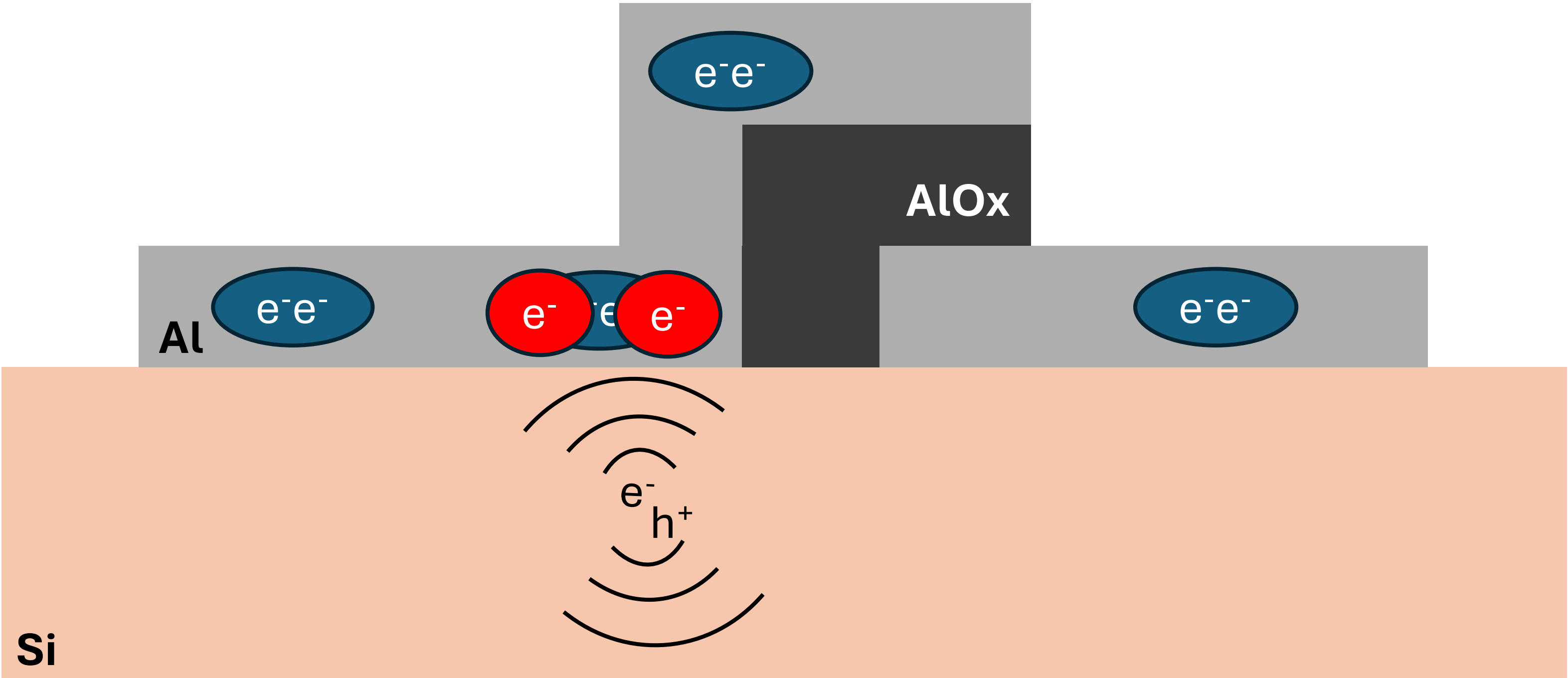
Decoherence in Qubits

Applied Physics Review **6**, 021318 (2022)



- Decoherence present in all types of qubits
- Qubit becomes entangled with environment, causing a mixed state
- Nomenclature of different relaxation rates taken from NMR

Impact of ionizing radiation

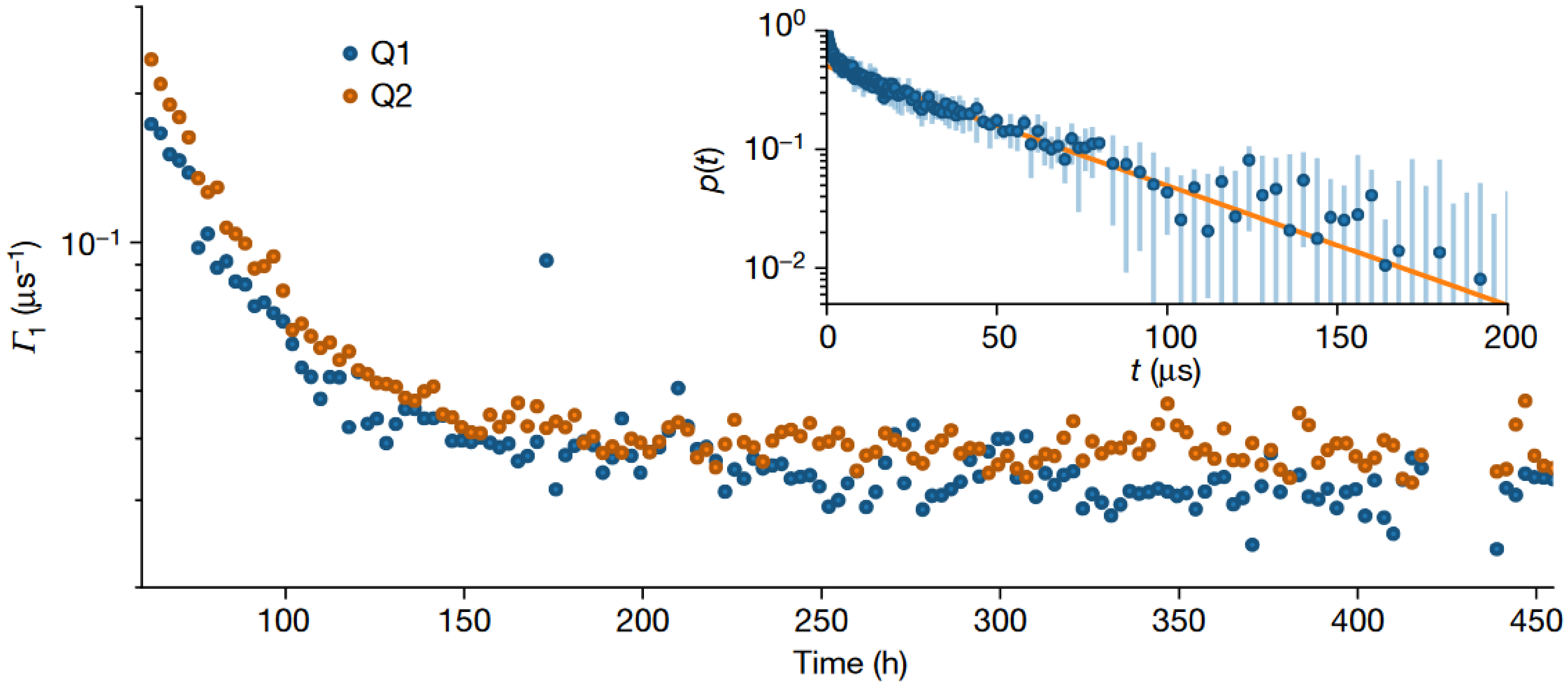


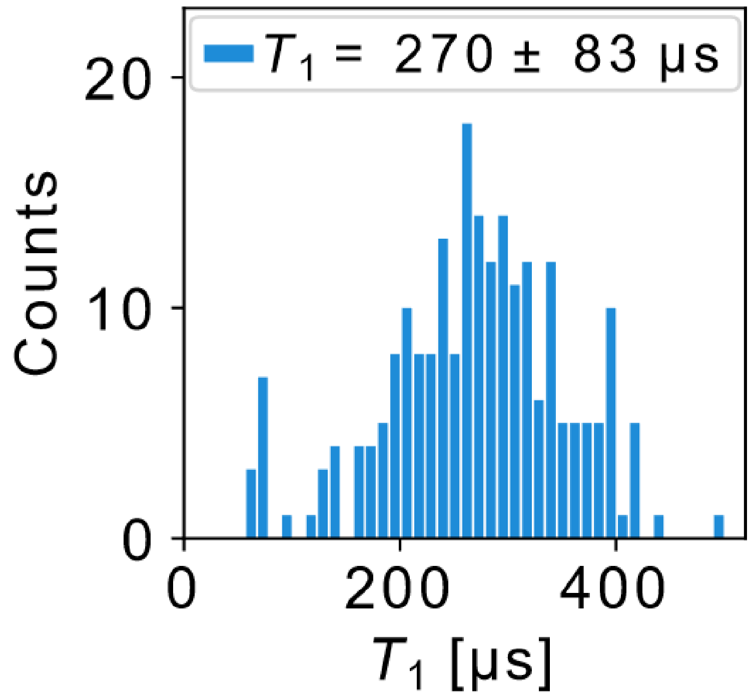
- Ionizing radiation can produce phonons in the substrate that break Cooper pairs in the superconducting film
- Photons can also be directly absorbed in the superconductor

Impact on coherence time

Nature **584**, 551-556 (2020)

arXiv: 2310.06797

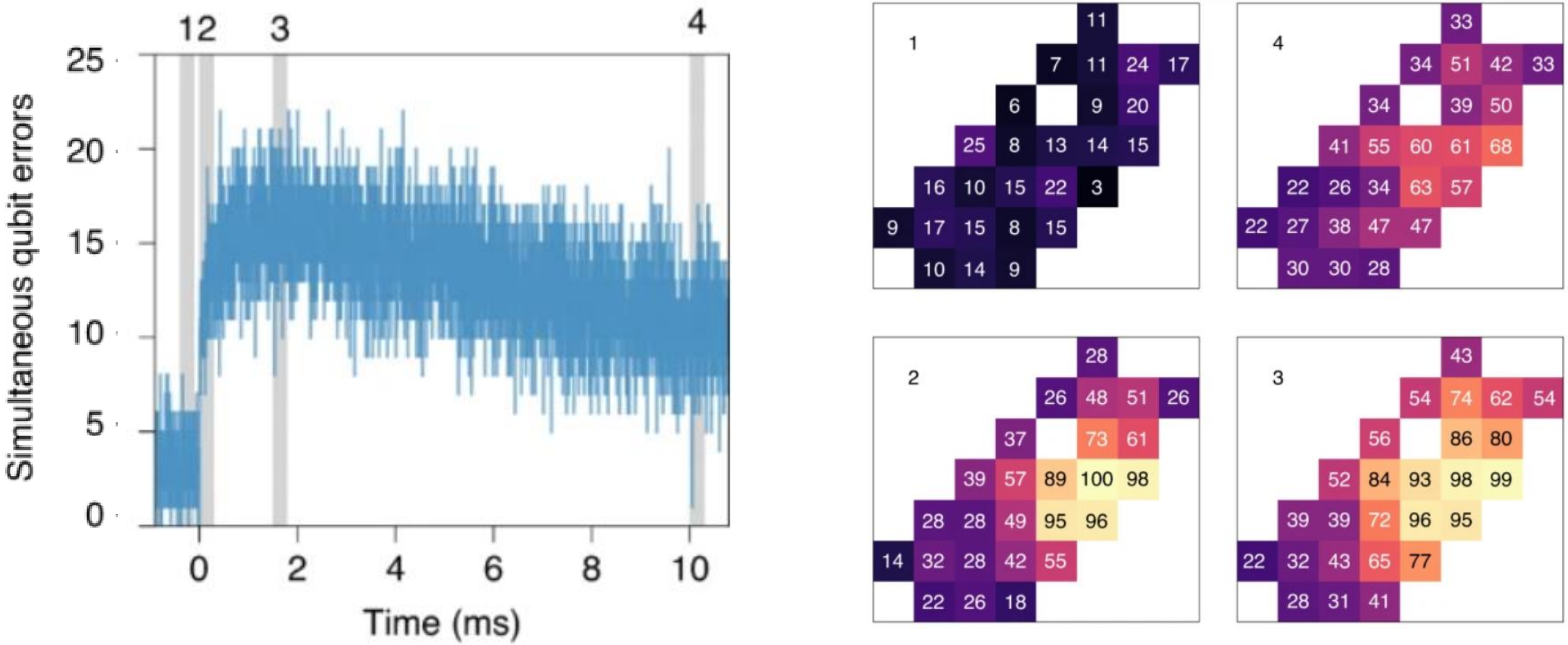




- Coherence time has been shown to worsen in presence of radioactive source
- Study fluctuations of coherence times above and below ground and in presence of radioactive sources

Correlated Errors

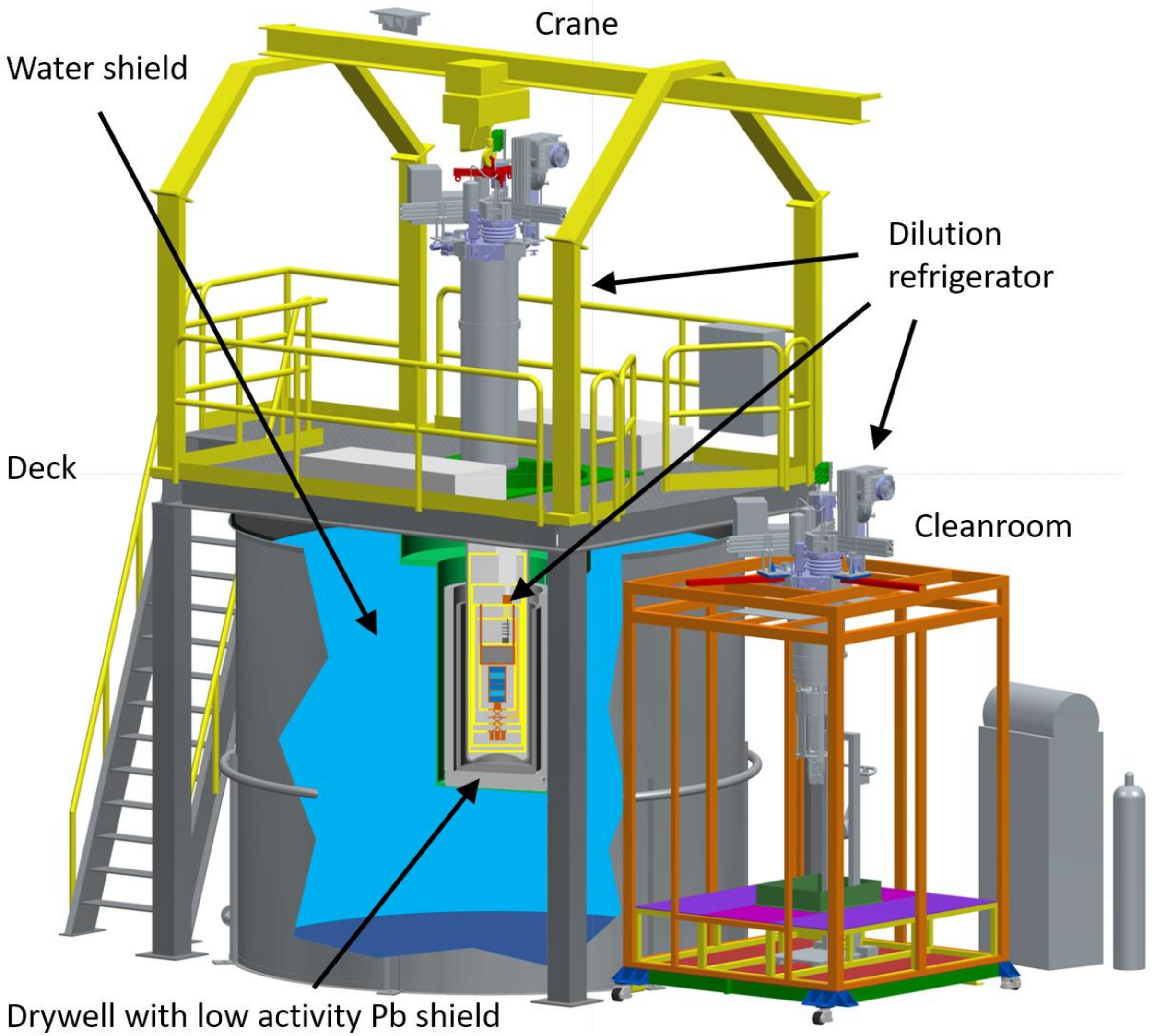
Nature Physics **18**, 107-111 (2022)



- Ionizing radiation has been shown to generate correlated errors in arrays of superconducting qubits
- Such errors are not easily corrected with error-correction protocols

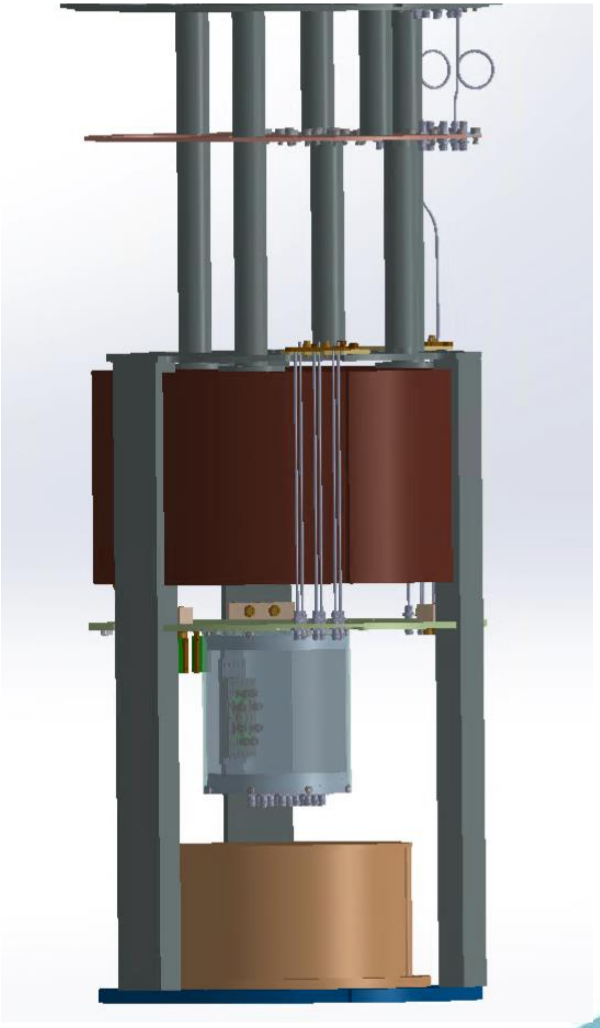
The CUTE Facility

- Cryogenic Underground TEst (CUTE) facility at SNOLAB
- Dilution refrigerator situated in shielded dry-well
- Adjacent cleanroom for payload changes
- Suspension system to minimize vibrations
- Gamma and neutron calibration sources
- Developed for testing SuperCDMS detectors



CUTE Upgrades

- Some modifications to CUTE cryostat required to facilitate qubit measurements
- Incorporate new copper plate below the inner lead shield
- Develop cryogenic magnetic shield
- Install microwave cabling and components
- Plan is to use QBlox electronics for control and readout of qubits, finish developing software for experiments



Assay Measurements at SNOLAB

Component	Mass [g]	Rate [mHz]	^{238}U [mBq/kg]	^{235}U [mBq/kg]	^{232}Th [mBq/kg]	^{210}Pb [mBq/kg]	^{137}Cs [mBq/kg]	^{60}Co [mBq/kg]	^{40}K [mBq/kg]
Packaged qubit sample	220.0	275.1	t: 1100 ± 200 b: 20 ± 3	29 ± 3	38 ± 5	-	< 3.0	< 0.8	60 ± 30
Copper sample holder	126.1	5357.4	t: 60 ± 20 b: 1 ± 1	1.3 ± 0.5	7 ± 2	< 42000	< 0.5	< 1.1	30 ± 10
Si Wafer 2" Type 010	2.677	80.5	t: < 520 b: < 13	< 22	< 29	30000 ± 20000	10 ± 20	< 18	< 340
EPIG PCBs (ELCO)	7.835 (2 units)	89.4	t: 6000 ± 2000 b: 1500 ± 100	110 ± 30	2200 ± 100	-	< 38	< 26	1400 ± 600
Non-magnetic connectors and screws	3.2 (5 units)	136.0	t: 35000 ± 1000 b: 4000 ± 3000	1500 ± 100	540 ± 80	-	-	-	1100 ± 500
Aluminum pellets	4.25	8.5	t: < 130 b: < 14	< 6.7	20 ± 10	< 970	< 90	< 13	< 750
NbTi cable	6.2	183.8	t: 20000 ± 10000 b: 60 ± 10	350 ± 10	510 ± 30	11000 ± 400	< 58	< 9.3	100 ± 200
EZForm cables	20.2 (2 units)	22.9	t: 800 ± 1000 b: < 38	< 14	< 39	-	< 21	< 2.8	200 ± 300
Amumetal shield	49.6	1416.9	t: 800 ± 100 b: < 1.2	13 ± 2	10 ± 4	30000 ± 20000	< 2.4	< 1.9	50 ± 30

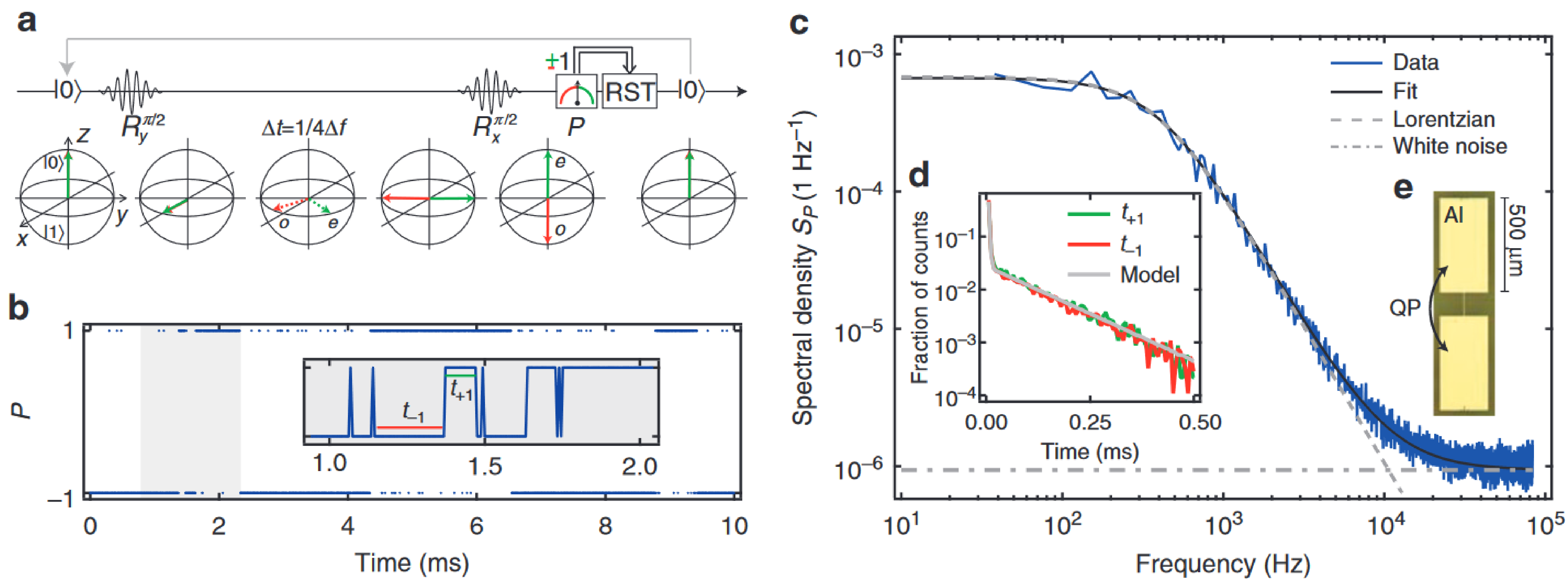
- Performed assays of qubit materials and common microwave components in the underground gamma counting facility

Project Goals

- Quantify effect of radiation on qubit decoherence
  - Correlated qubit measurements
  - Identify particle interactions on multiple substrates
- Identify sources of decoherence using alternative sensors
  - Charge qubits
  - Superconducting resonators
  - Phonon-sensitive sensors (SAW resonators, MKIDs, etc.)
- Identify and implement mitigation techniques
  - Phonon absorbers
  - Gap-engineered qubits
  - Substrate modifications

Charge-Parity Fluctuations

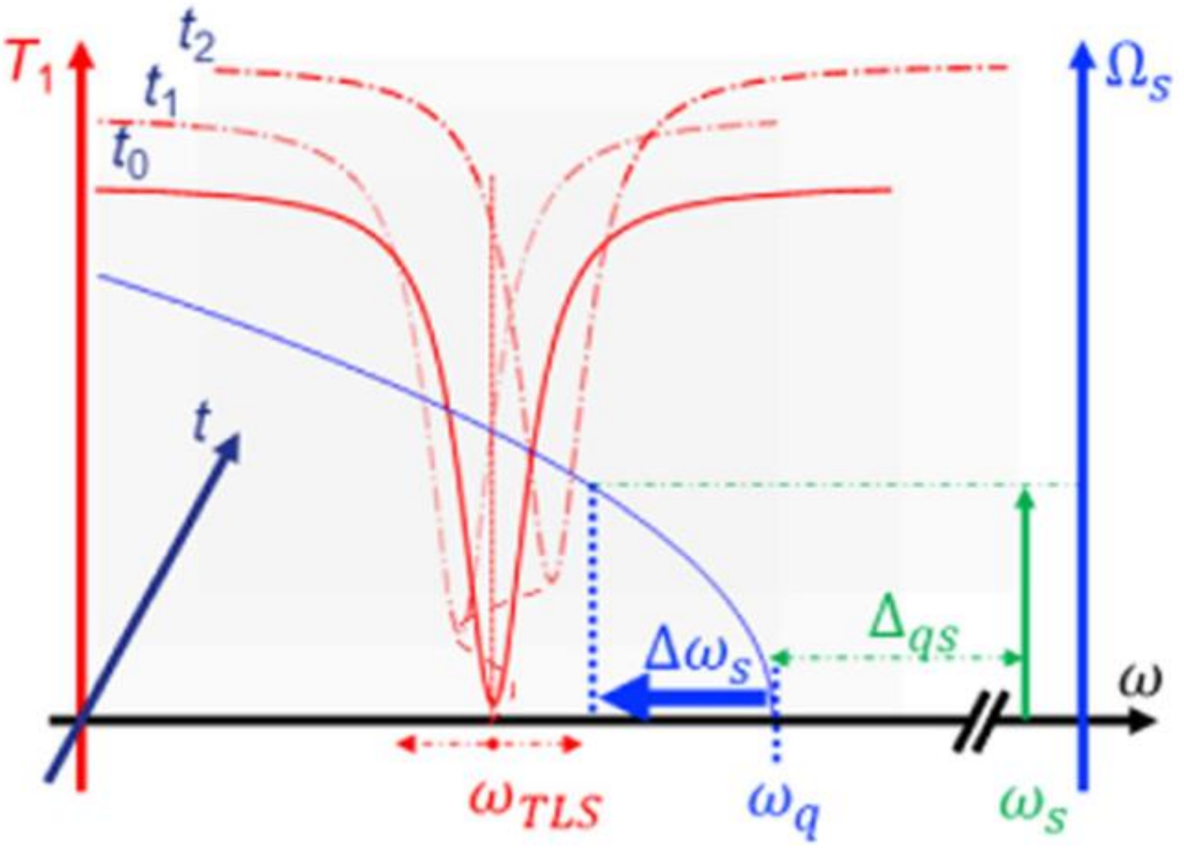
Nature Communications **4**, 1913 (2013)

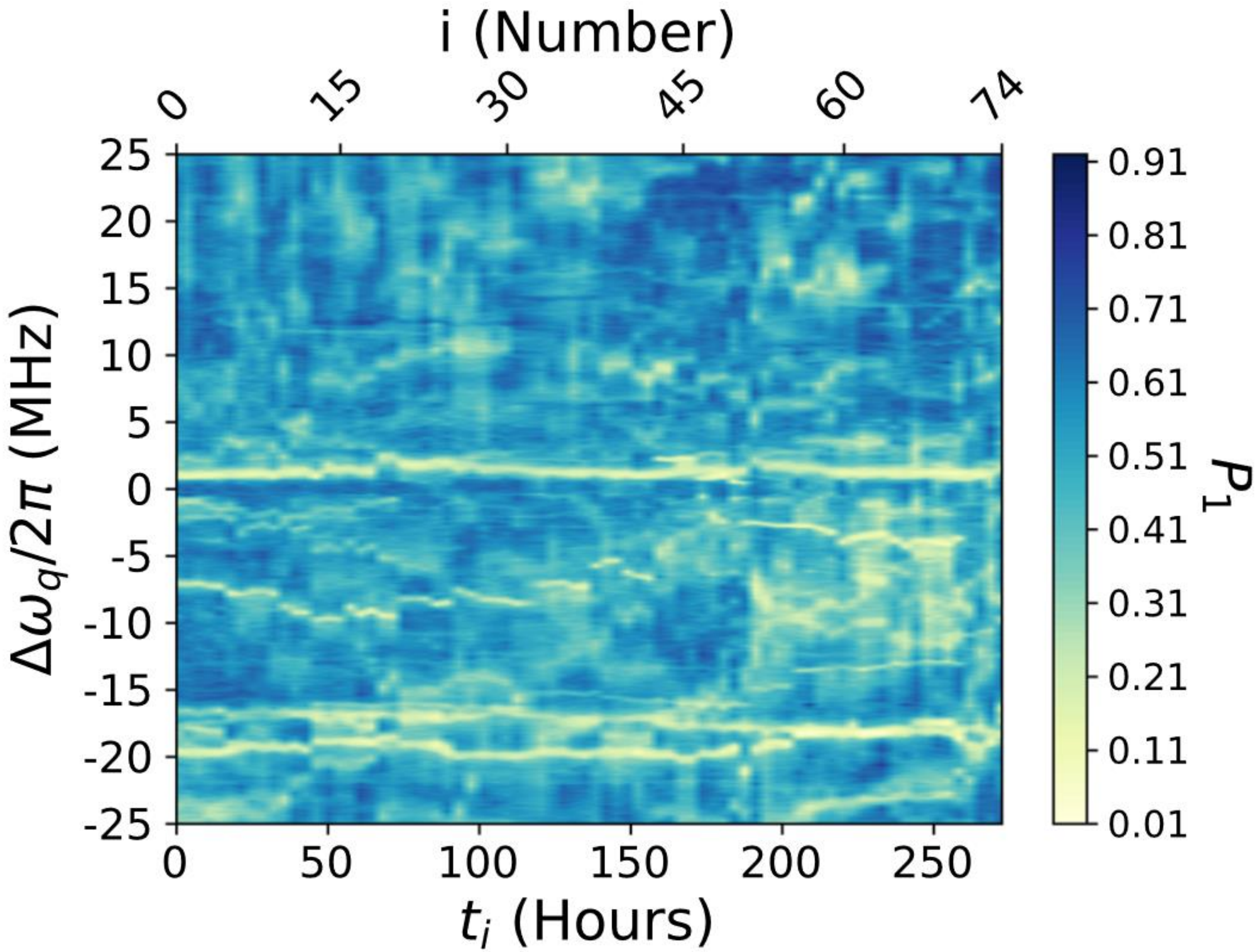


- Charge-parity measurements can detect quasiparticle tunneling rate
- Requires charge-sensitive qubits, but can also be performed by using higher qubit levels

TLS Spectroscopy

npj Quantum Information **8**, 132 (2022)

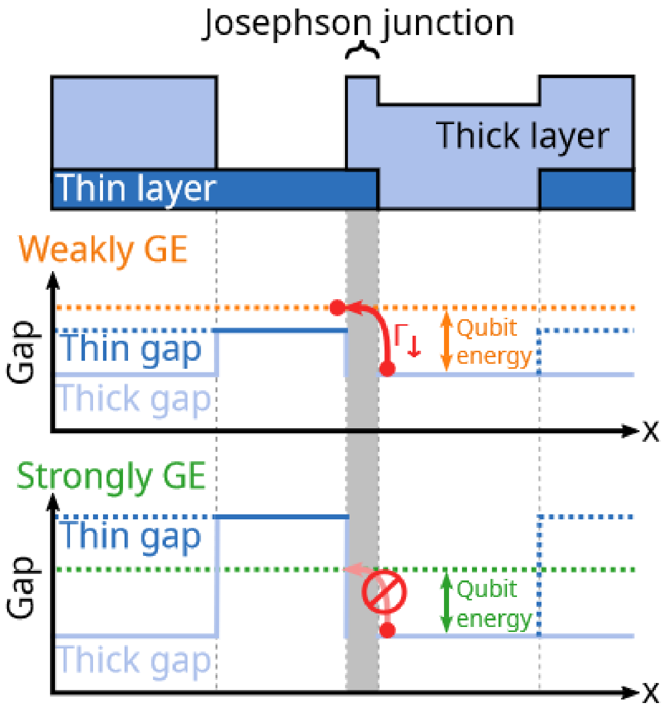


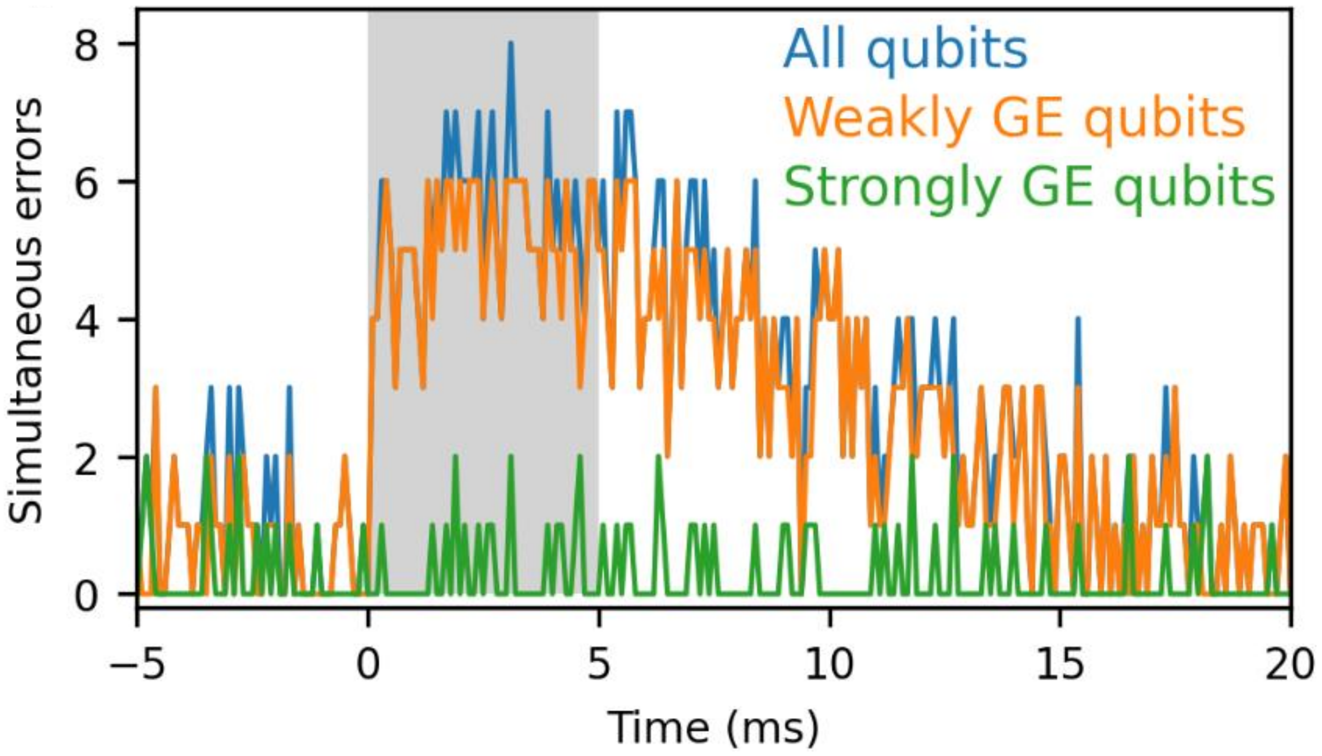


- Two-level systems (TLS) are defects typically found at interfaces
- Sweeping the qubit frequency can identify TLSs
- Study how TLSs behave on surface and underground

Gap engineering

arXiv: 2402.15644

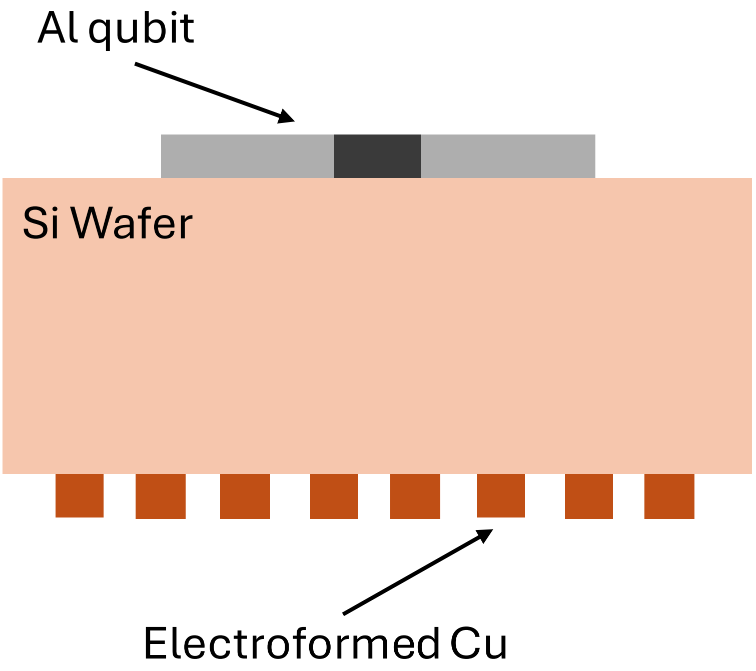


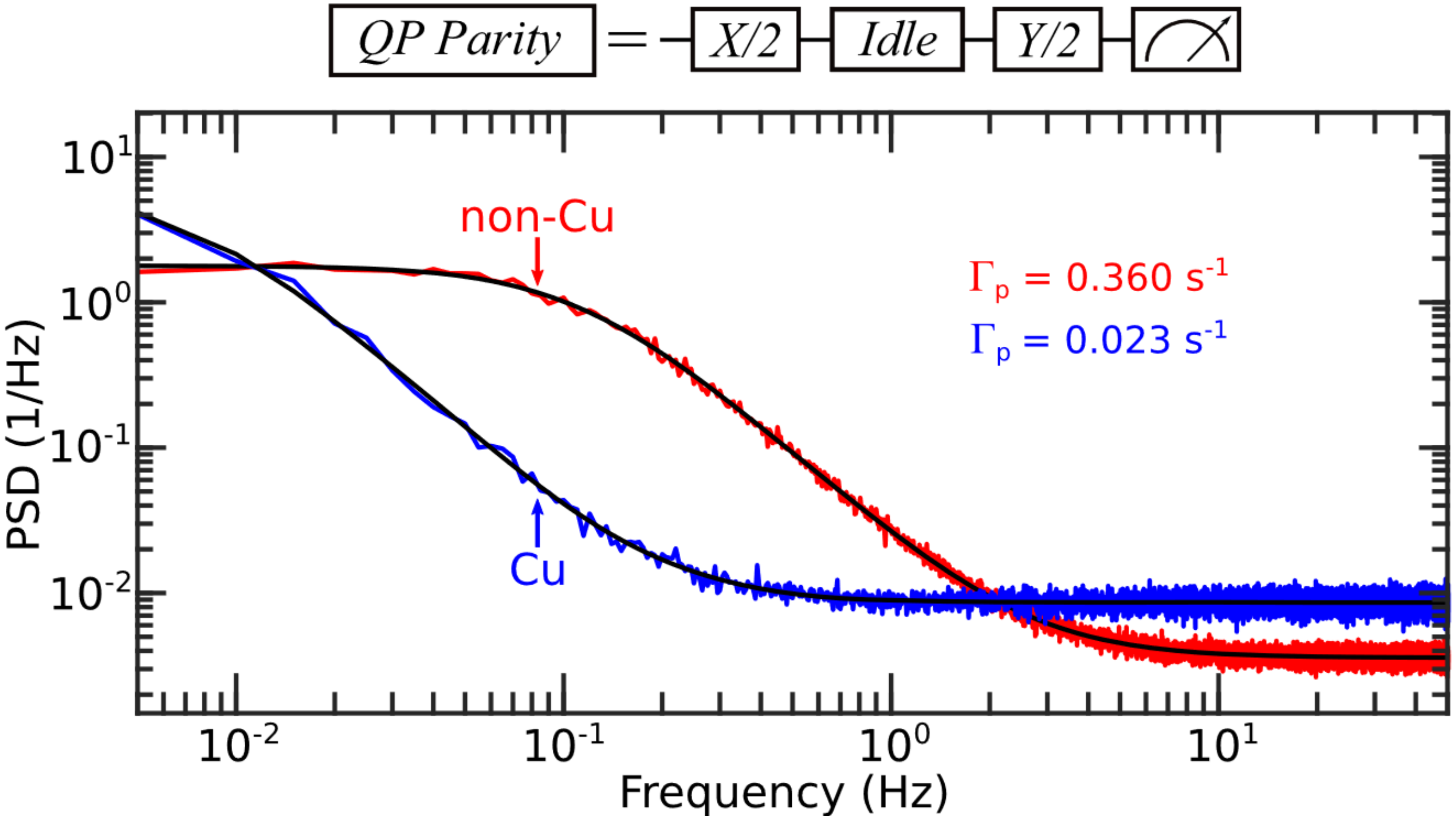


- Engineering the superconducting gap across the junction can prevent the tunneling of quasiparticles
- Achieved by modifying the film thickness or introducing impurities

Phonon Absorbers

Nature Communications **13**, 6425 (2022)





- Normal metal backing on substrate causes phonons to down-convert below superconducting gap
- Can also use a lower-gap superconducting film

Conclusion

- Quantum computing is a transformative technology that could have profound impact on the world
- Superconducting qubits are a leading candidate to form the basis of a quantum computer
- Ionizing radiation has been shown to degrade the coherence time and cause correlated errors in multiple qubits
- This project aims to use state-of-the-art qubits in the CUTE facility to study the underlying mechanisms for the degradation
- Upgrades to the CUTE facility will start at the end of summer, and data taking should begin by end of year