QUANTUM SCIENCE CENTER

Fermilab

Northwestern University

Developing underground facilities for qubit operations

Daniel Baxter

USQIS School – Track 1

August 11, 2023

A Brief History of Underground Science

Cosmic Rays – charged particles accelerated to nearly the speed of light which then collide with Earth's atmosphere

- 90% protons (hydrogen nuclei)
- 9% heavier nuclei (mostly helium)
- 1% electrons
- < 1% antimatter

Victor Franz Hess
1936 Nobel Prize
"for his discovery of cosmic radiation"

A Brief History of Underground Science

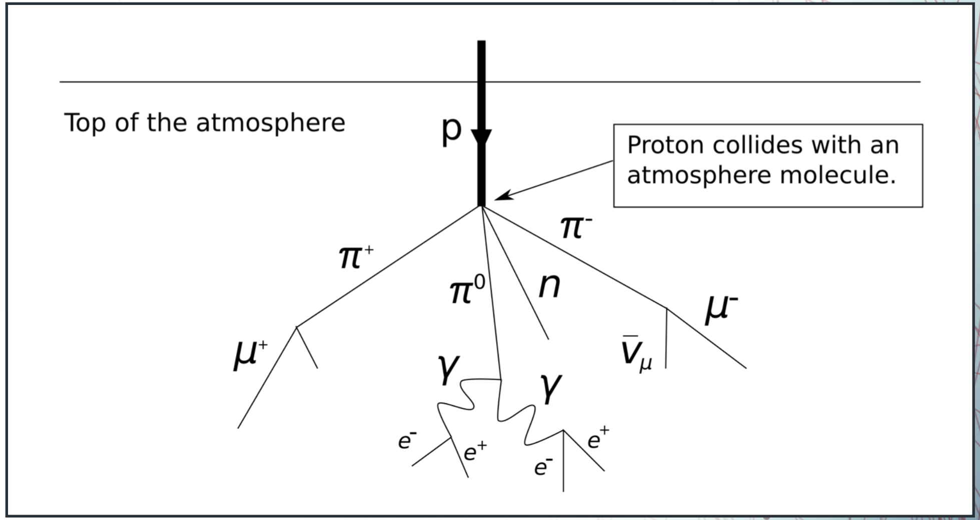
Cosmic Rays – charged particles accelerated to nearly the speed of light which then collide with Earth's atmosphere

- 90% protons (hydrogen nuclei)
- 9% heavier nuclei (mostly helium)
- **1% electrons (solar wind)**
- < 1% antimatter

A Brief History of Underground Science

Cosmic Rays – charged particles accelerated to nearly the speed of light which then collide with Earth's atmosphere

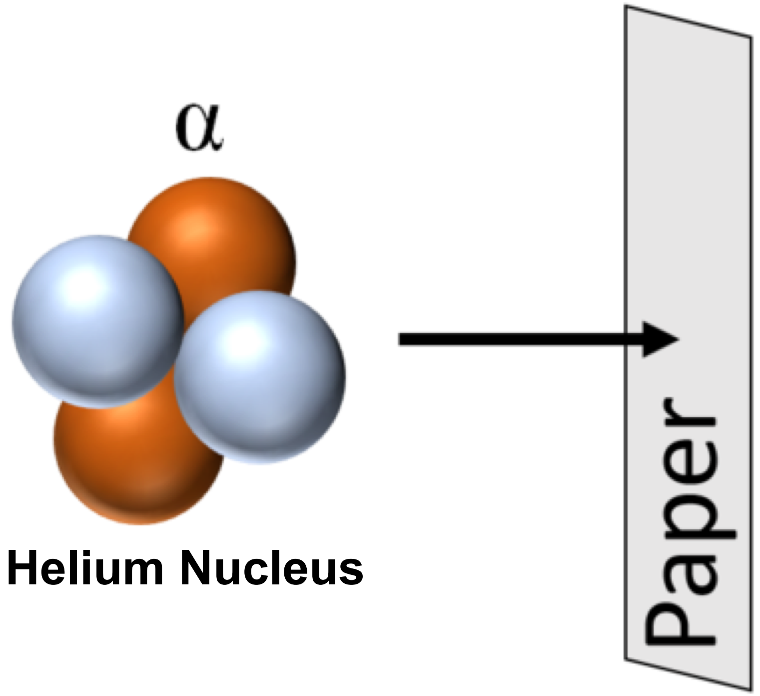
- **90% protons (hydrogen nuclei)**
- 9% heavier nuclei (mostly helium)
- 1% electrons
- < 1% antimatter



Produce muons, photons, electrons, and neutrinos…

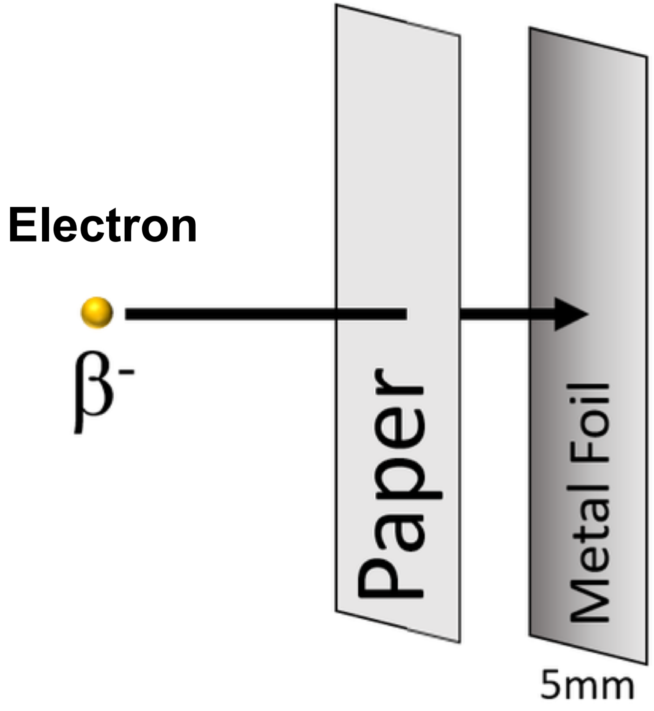
A Brief History of Underground Science

Radiation Penetration Depths



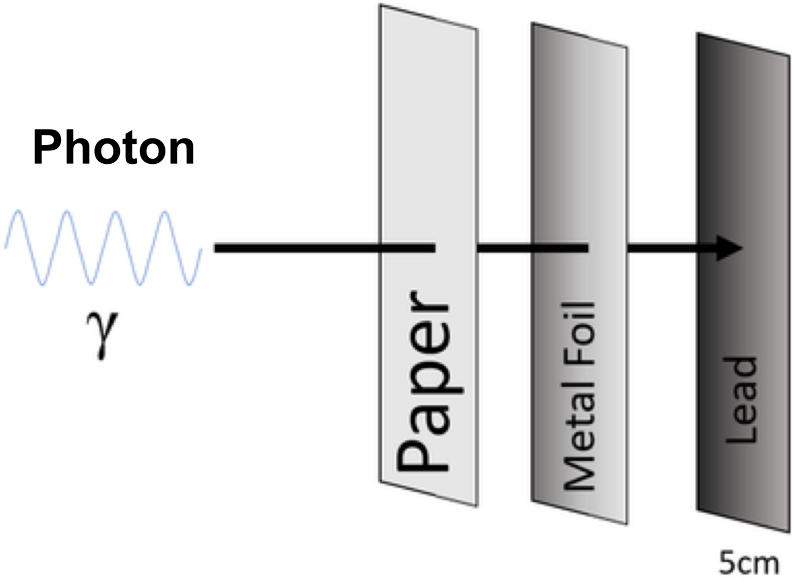
A Brief History of Underground Science

Radiation Penetration Depths



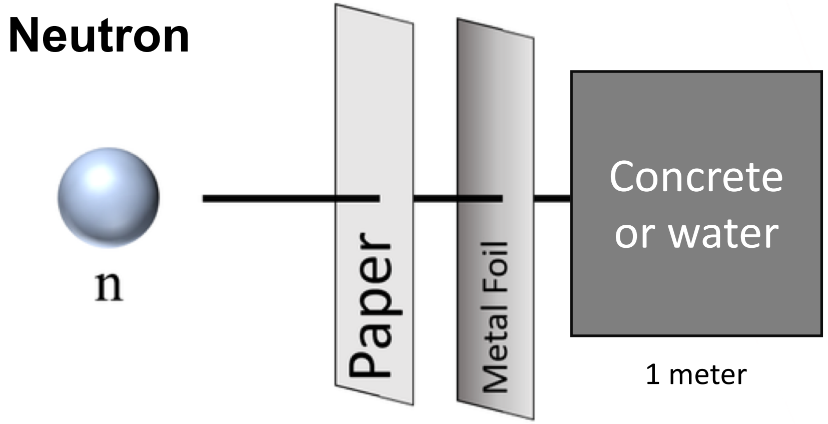
A Brief History of Underground Science

Radiation Penetration Depths



A Brief History of Underground Science

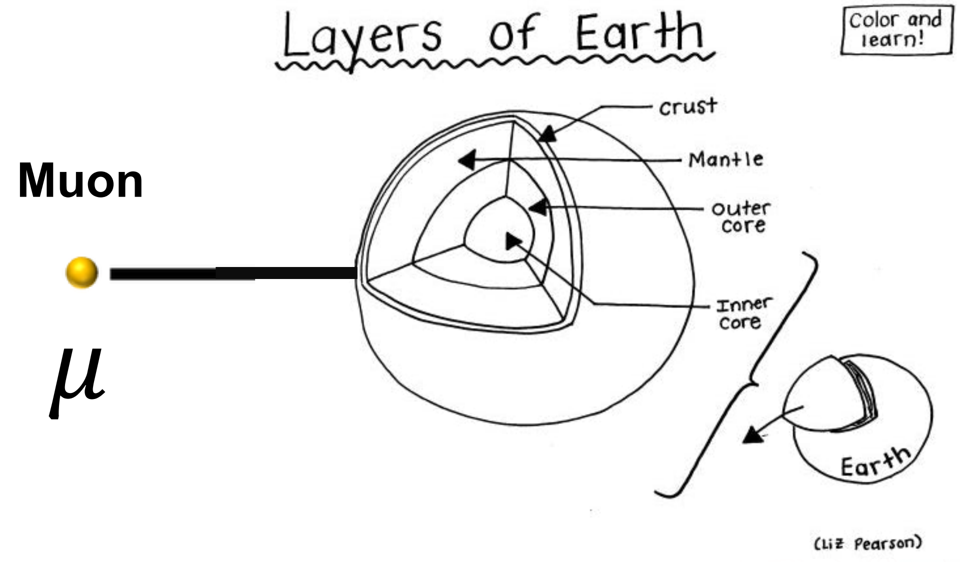
Radiation Penetration Depths



A Brief History of Underground Science

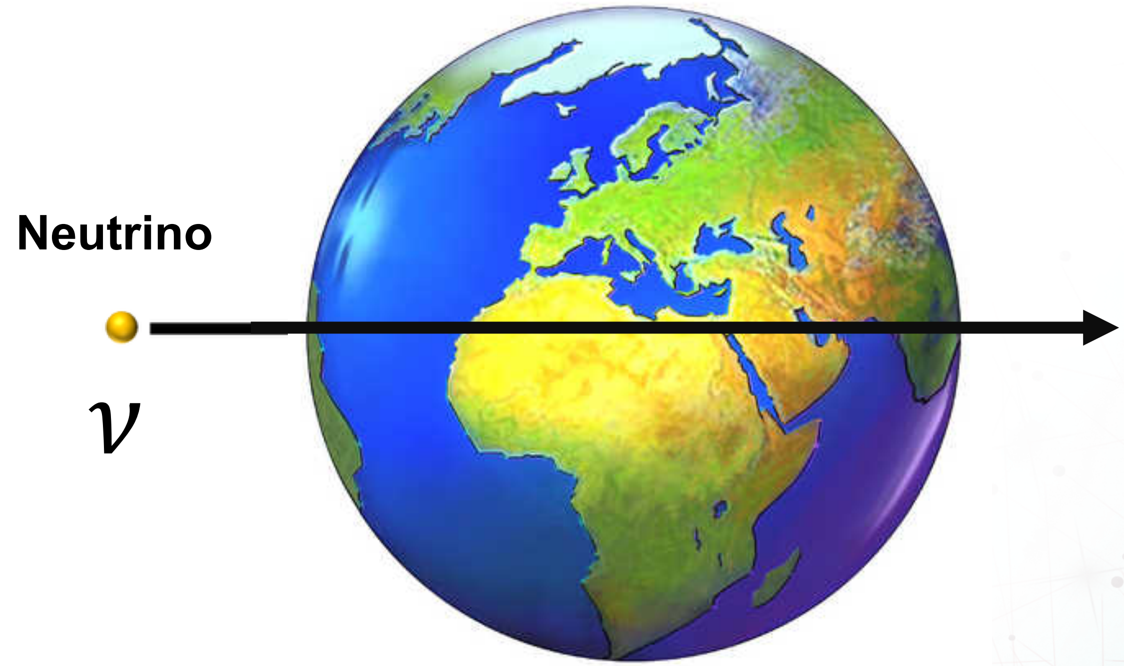
Radiation Penetration Depths

We'll come back to this



A Brief History of Underground Science

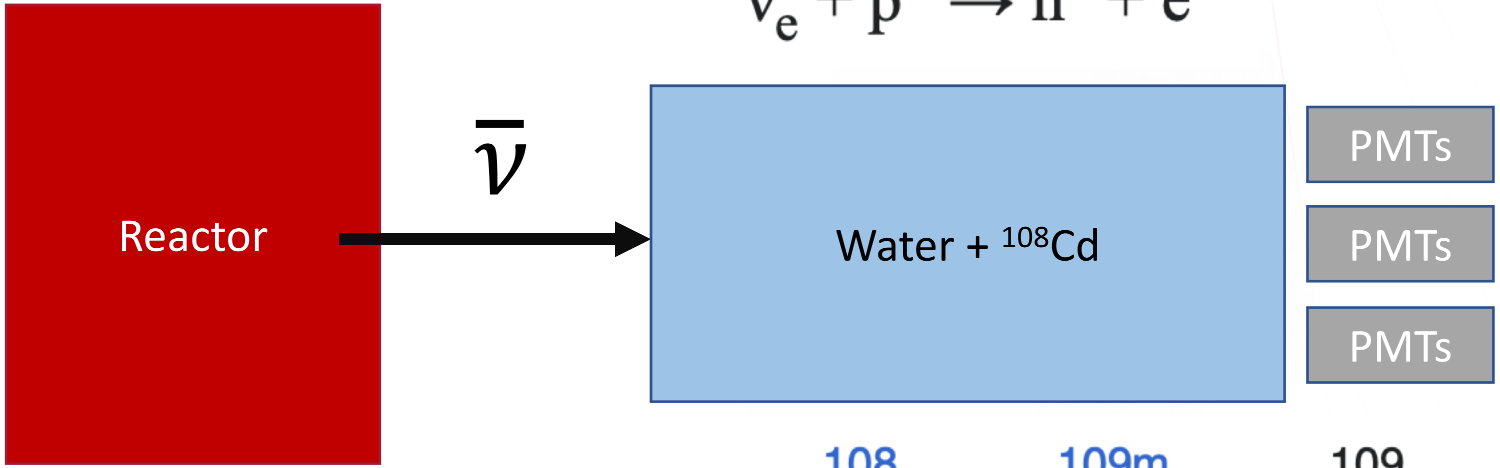
Radiation Penetration Depths



A Brief History of Underground Science

Neutrino Detection:

$$\bar{\nu}_e + p^+ \rightarrow n^0 + e^+$$



$$n + {}^{108}\mathrm{Cd} \rightarrow {}^{109m}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd} + \gamma$$

Frederick Reines
1995 Nobel Prize
"for the detection of the neutrino"

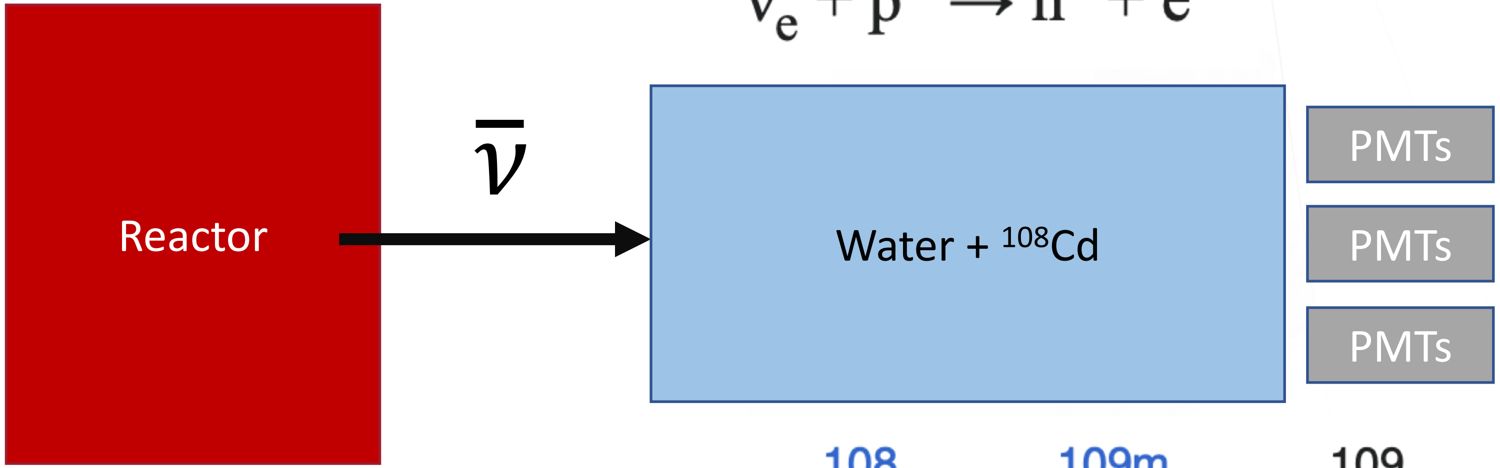
Cowan-Reines Experiment (1956) was performed 12m underground to remove cosmic rays!

A Brief History of Underground Science

Neutrino Detection:

Notice this is only electron neutrinos!

$$\bar{\nu}_e + p^+ \rightarrow n^0 + e^+$$

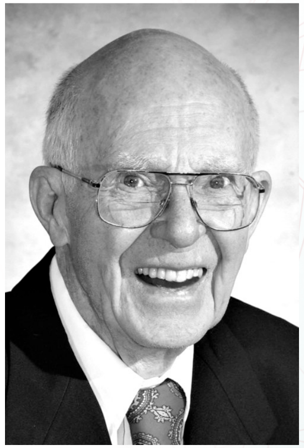


$$n + {}^{108}Cd \rightarrow {}^{109m}Cd \rightarrow {}^{109}Cd + \gamma$$

But experiments did not find the expected flux of electron neutrinos from the Sun… “the solar neutrino problem”

A Brief History of Underground Science

To detect solar electron-neutrinos, Ray Davis Jr. and John Bahcall went **4,850 feet** deep in the Homestake Gold Mine in Lead, South Dakota, where they built a 100,000 gallon water neutrino detector (1960's)

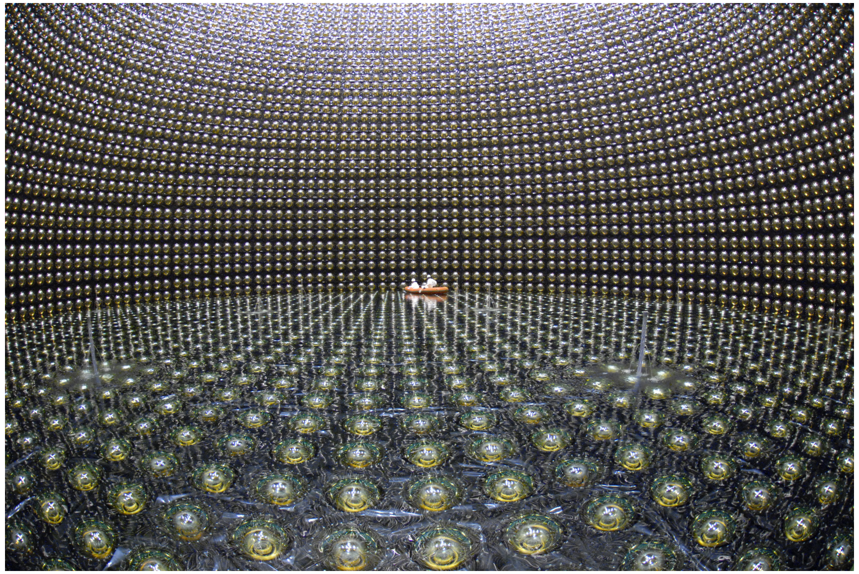


Raymond Davis Jr.
Masatoshi Koshiba
2002 Nobel Prize
"…for the detection of cosmic neutrinos"

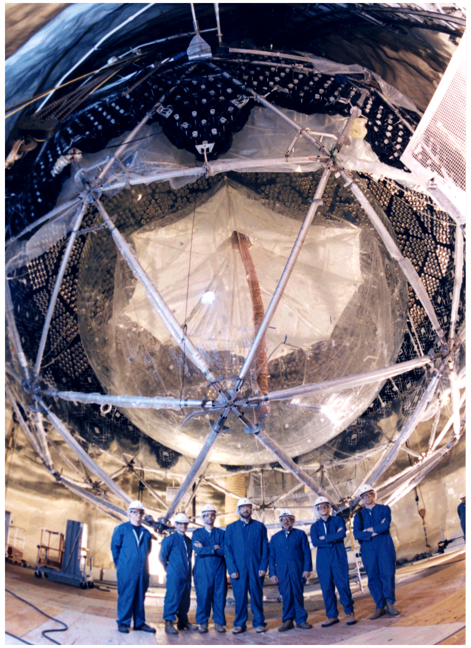
A Brief History of Underground Science

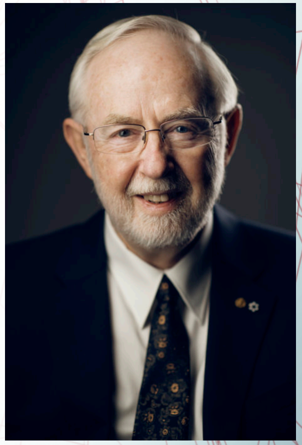
- The deficit of solar neutrinos observed is now explained by oscillations into non-electron flavors

Super-Kamiokande: 3,300 ft



SNO: 6,800 feet





Takaaki Kajita
Arthur B. McDonald
2015 Nobel Prize
"for the discovery
of neutrino oscillations…"

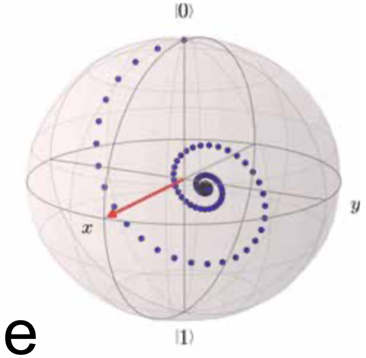
Dan… this is a quantum computing school.

What does this have to do with qubits?

Radiation and Superconducting Qubits

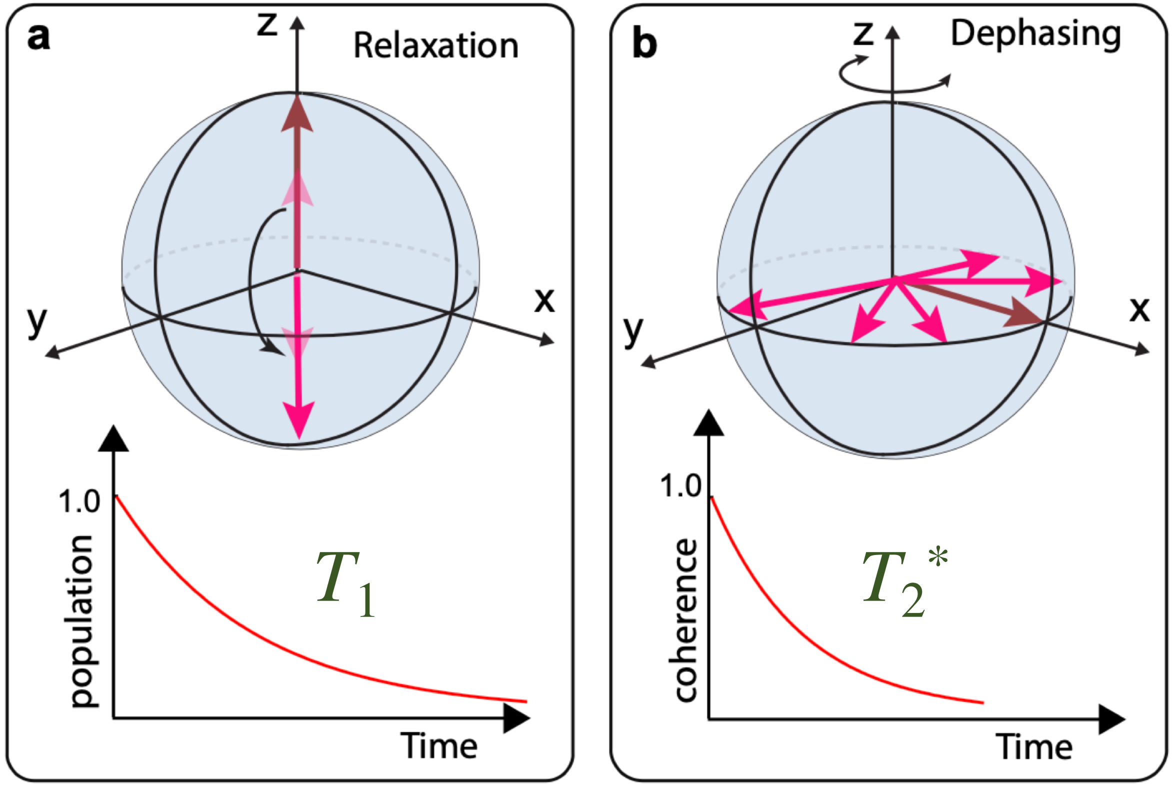
Quantum Coherence

- a quantum state, as in a qubit, can only exist so long as it remains isolated from its environment



- T1 = Relaxation Time timescale for loss of the energy of the qubit state (ie, 1 → 0)

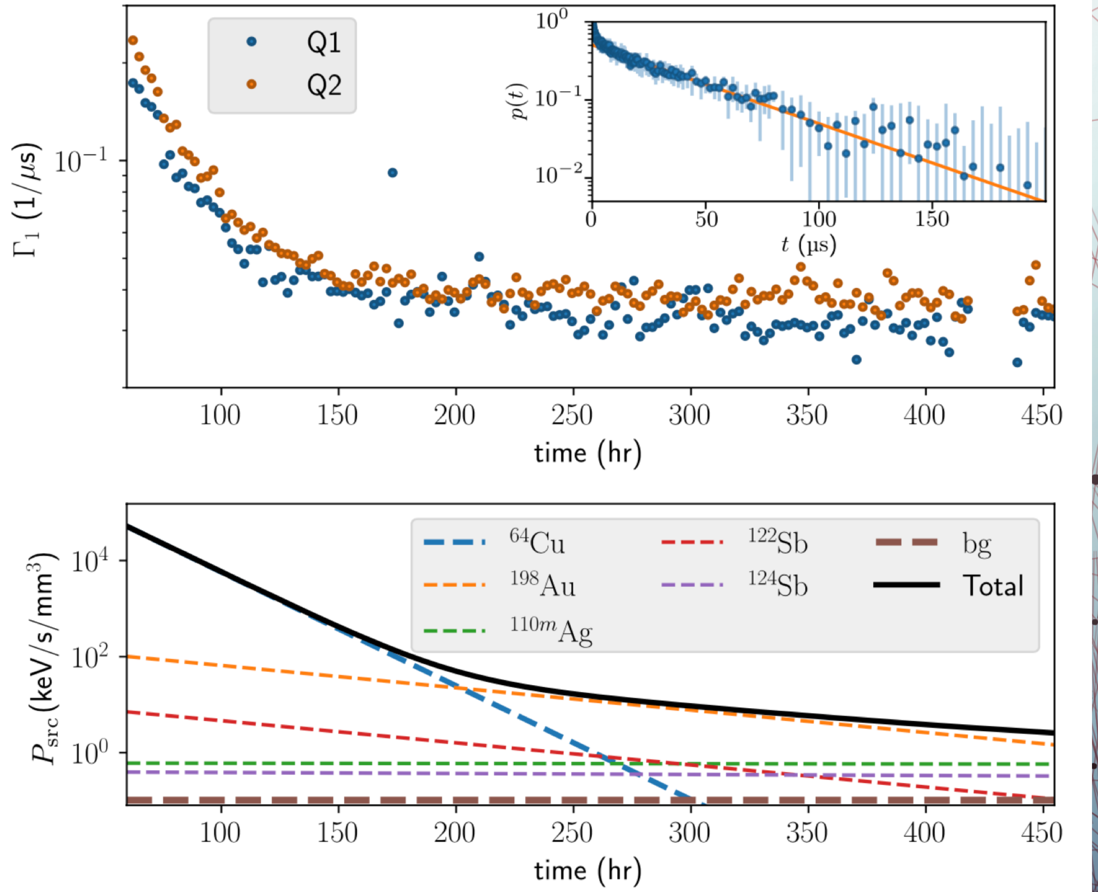
Mahdi Naghiloo, (2019) [arXiv:1904.09291]



Radiation and Superconducting Qubits

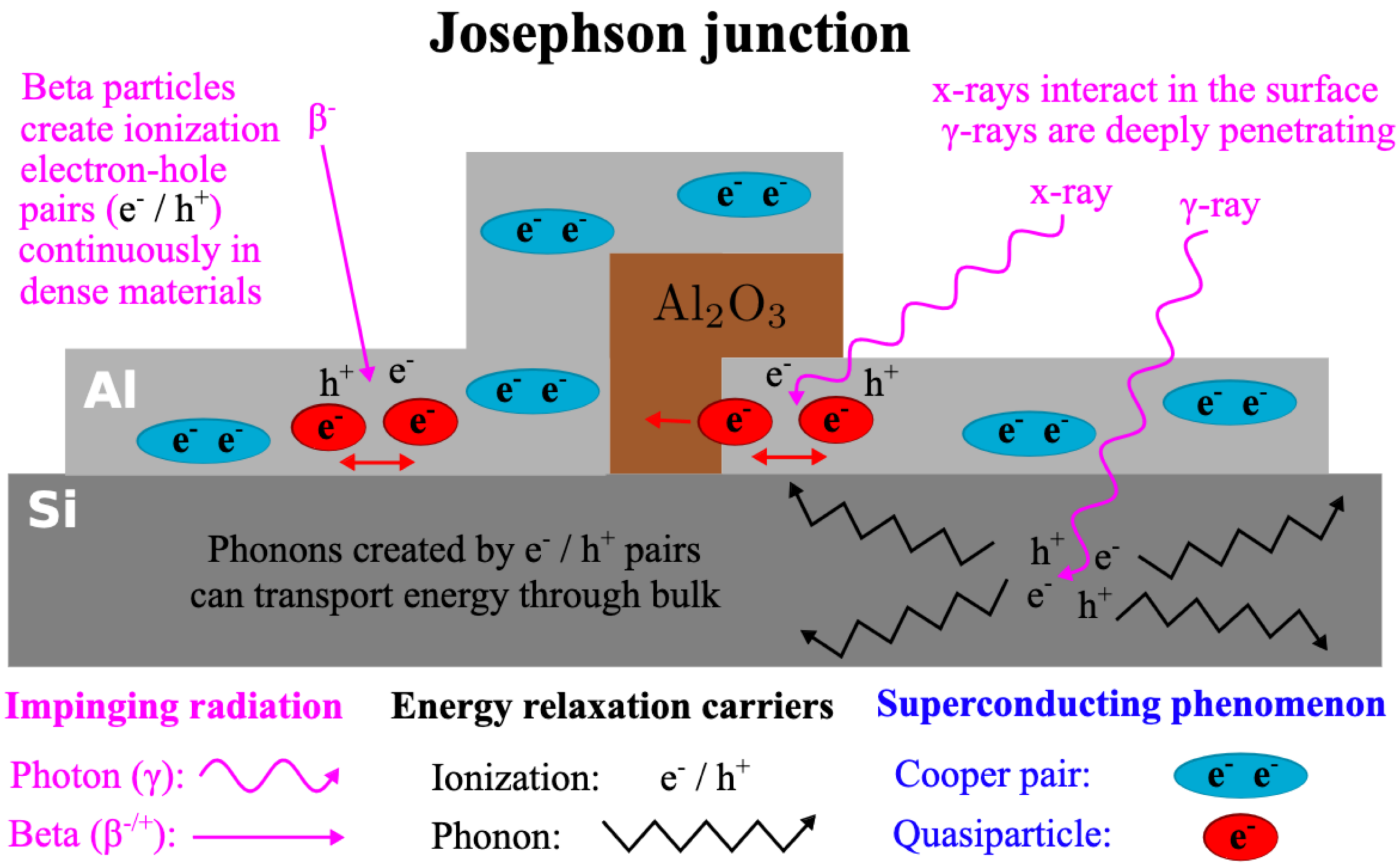
- Measurements of decoherence relaxation rates (1/T1) in the presence of a ^{64}Cu source
- Clear correlation between T1 and decay of ^{64}Cu source in two separate qubit sensors!
- Strong evidence that quasiparticle poisoning due to radiation breaking Cooper pairs is a limiting factor in superconducting qubits for QIS

Vepsäläinen et al, Nature 584, 551 (2020) [arXiv:2001.09190]



Radiation and Superconducting Qubits

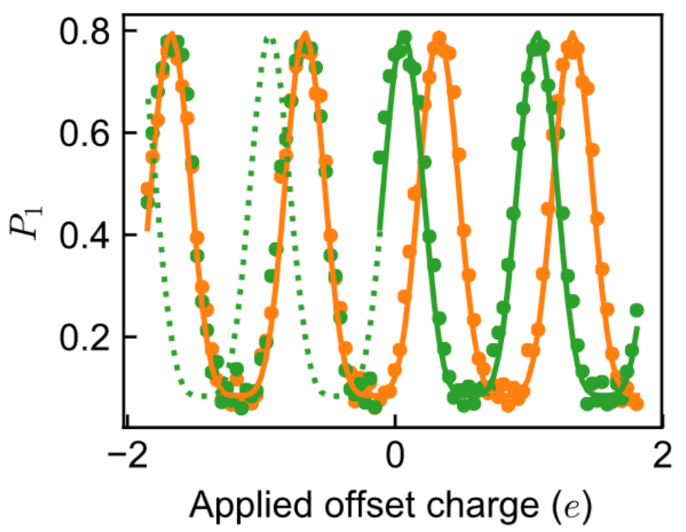
Vepsäläinen et al, Nature 584, 551 (2020) [arXiv:2001.09190]

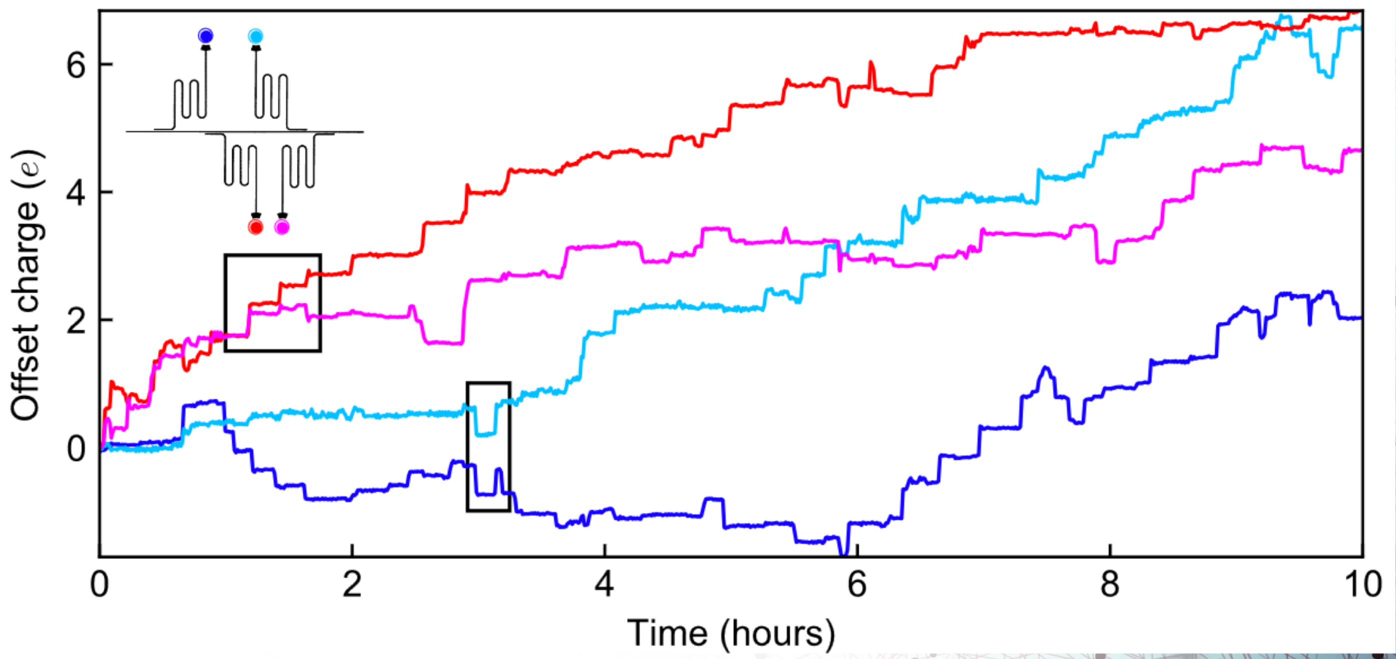


Radiation and Superconducting Qubits

Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]

Chip w/ four weakly charge-sensitive transmon qubits demonstrates clear correlated charge jumps over long times



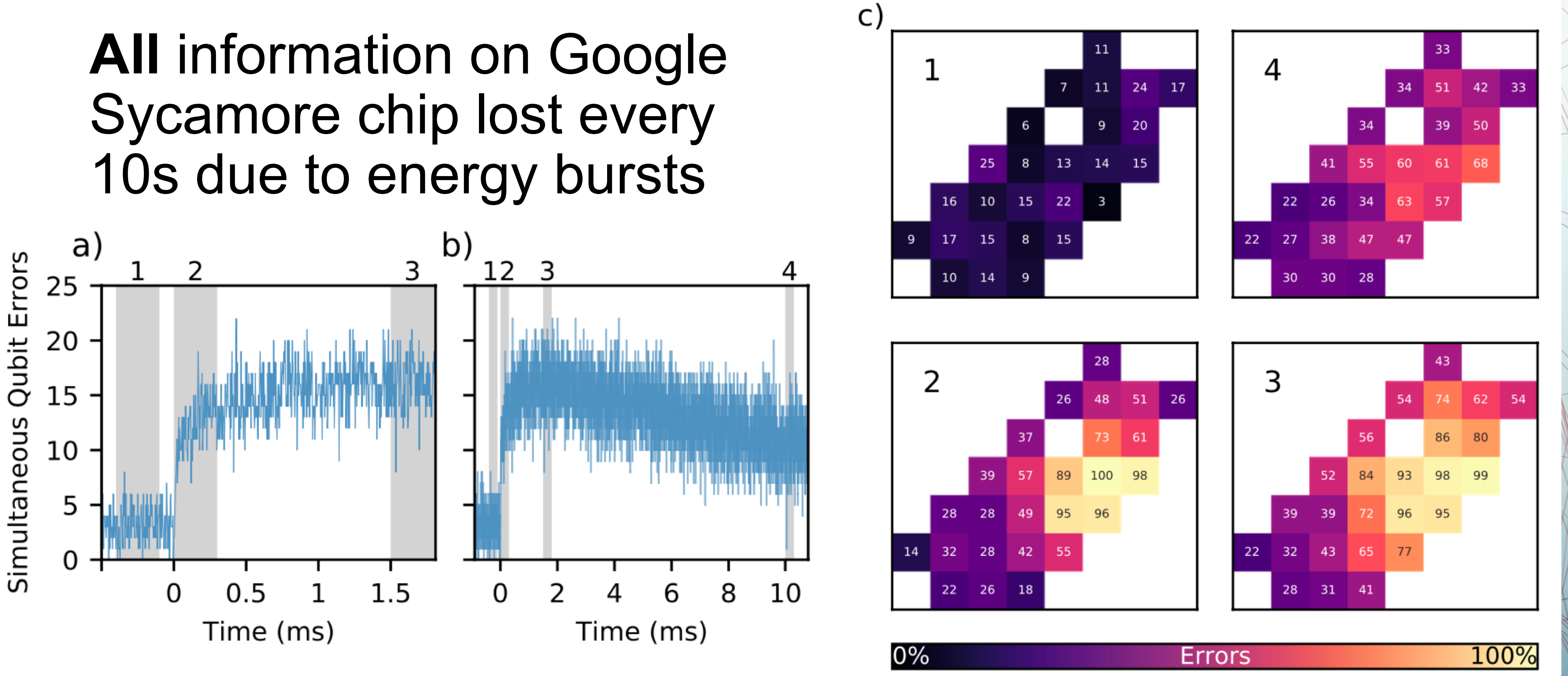


QUANTUM SCIENCE CENTER

Radiation and Superconducting Qubits

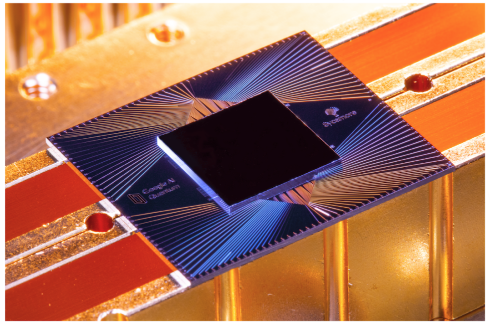
McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]

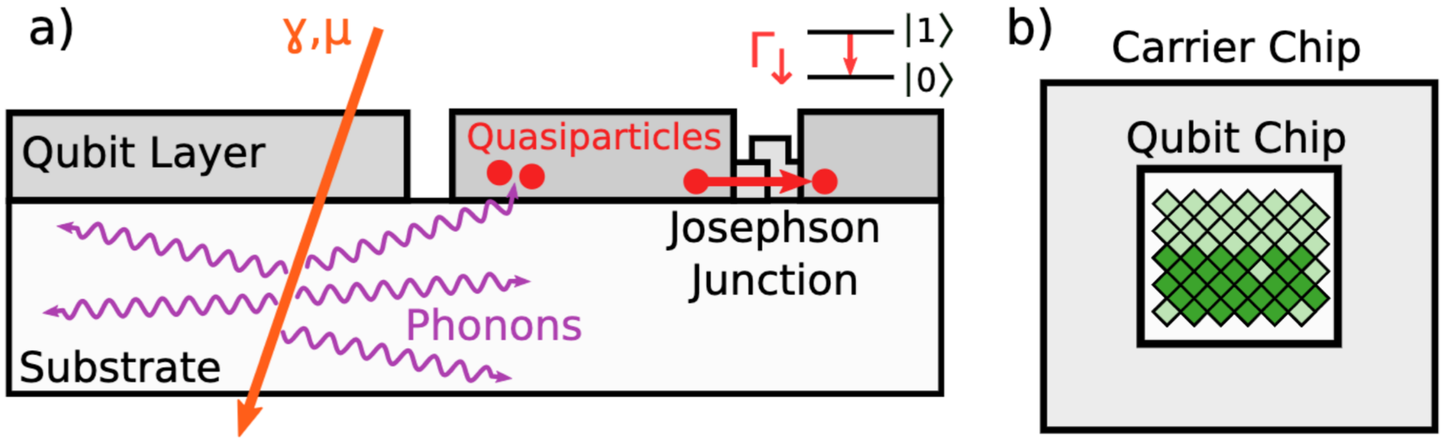
All information on Google Sycamore chip lost every 10s due to energy bursts



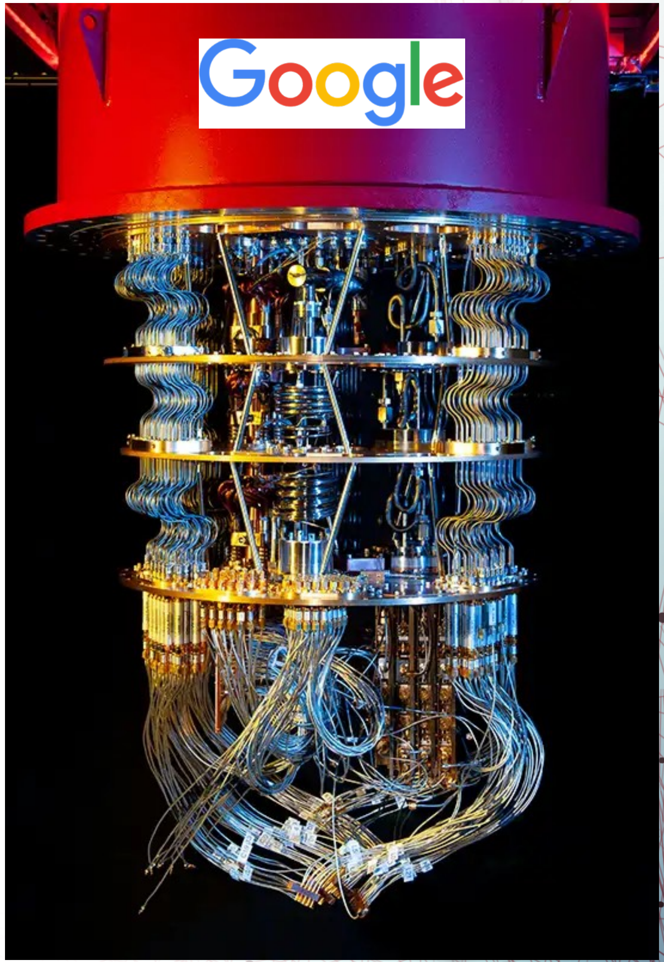
Radiation and Superconducting Qubits

Several studies have shown that background radiation is very disruptive to superconducting qubits (quasiparticle poisoning causing coherent errors)





Google Sycamore team: [arXiv:2104.05219](https://arxiv.org/abs/2104.05219)

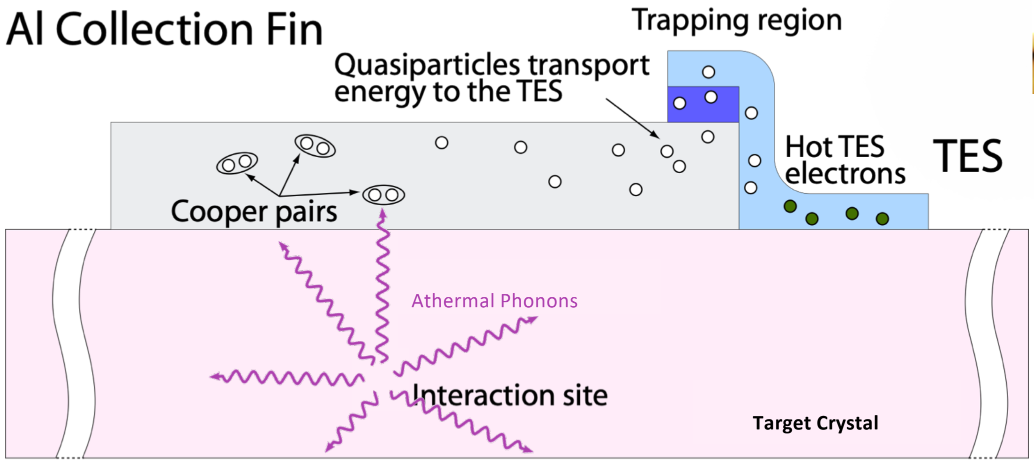


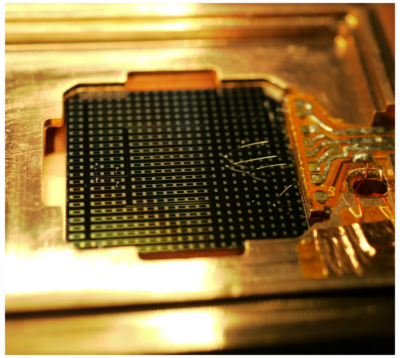
Radiation and Superconducting Qubits

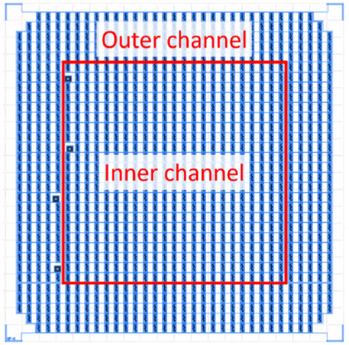
We have all the tools to work on this problem!

Our dark matter detectors work by measuring phonons in silicon through TES detectors and Al superconducting collectors films

We are bringing our knowledge of cryogenics, background reduction, particle detection, phonon and quasiparticle physics, and superconducting readout to Quantum Computing Problem







Ambient Radiation

In a typical surface environment:

- Alpha, beta radiation can't penetrate dilution refrigerator walls
- Neutron radiation is a concern, but rates are lower
- Sea-level muon flux is about **= 1 /cm^2 /min**
- Typical gamma background is about **= 10^5 interactions /kg /day /keV**

Typical qubit chip is about 1 cm^2 in area of silicon on 0.5mm thick substrate (100 mg)

Muon rate ≈ 1 /min

Photon rate ≈ 7 /min /MeV

Ambient Radiation

In a typical surface environment:

- Alpha, beta radiation can't penetrate dilution refrigerator walls
- Neutron radiation is a concern, but rates are lower
- Sea-level muon flux is about **= 1 /cm^2 /min**
- Typical gamma background is about **= 10^5 interactions /kg /day /keV**

Typical qubit chip is about 1 cm^2 in area of silicon on 0.5mm thick substrate (100 mg)

Muon rate ≈ 1 /min

Increases with altitude!

Photon rate ≈ 7 /min /MeV

For MeV-scale gammas, this is almost exactly the decoherence rate of the Google chip

Ambient Radiation

10s is still a lot of time to do calculations; why is this a problem? World-leading individual qubits have T1 ≤ 1 ms

1. Quantum Error Correction is used to correct for qubit decoherence and quantum noise, but fundamentally relies on losses of information being **uncorrelated**

2. Superconducting qubits can only be fabricated so close together without interference, which means that getting to larger numbers of qubits (ie: hundreds → millions) requires going to larger chips (larger event rates)

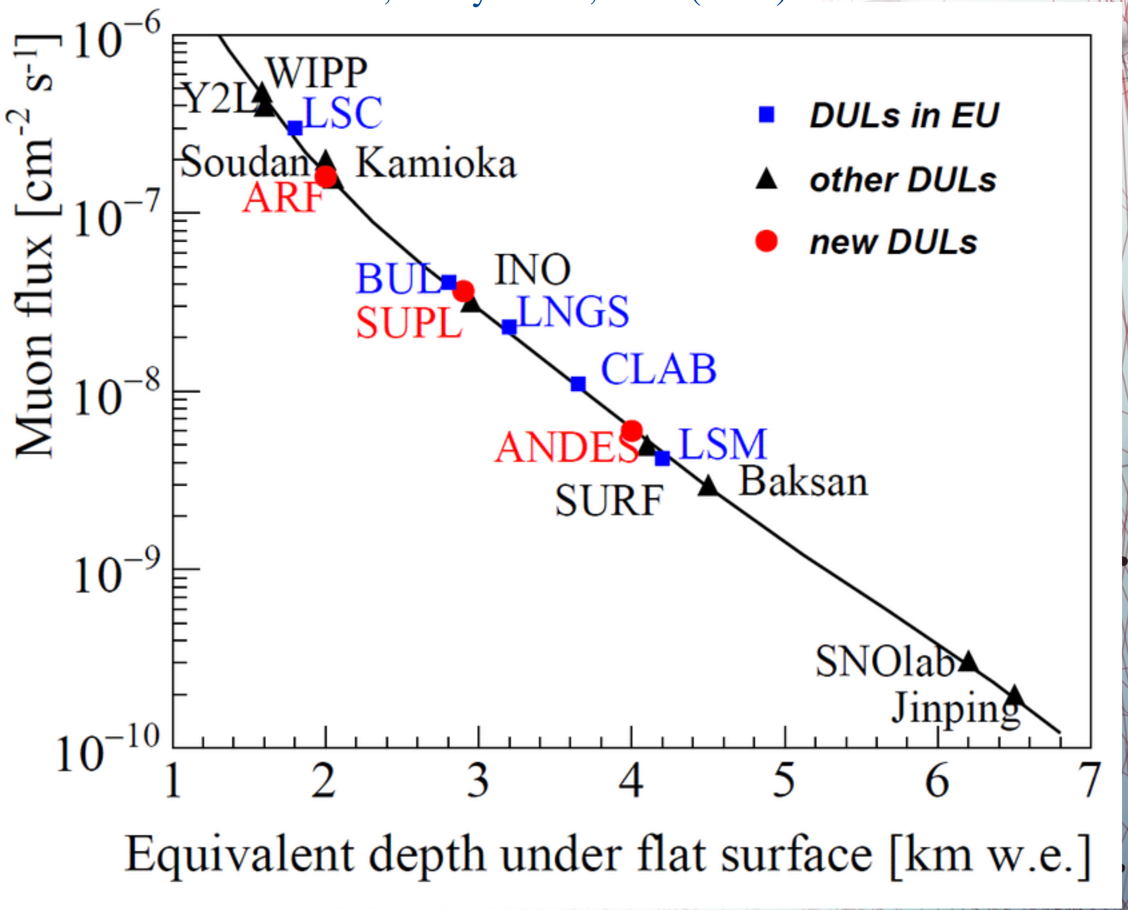
Ambient Radiation

Deep underground labs are now common-place in the particle astrophysics community to reduce muon rates to less than one per year in monolithic, ton-scale detectors

1. Operate in a mine (vertical)
2. Go under a mountain (horizontal)

- **SURF** (Sanford Underground Research Facility) in SD includes the same cavern that Ray Davis used to detect solar neutrinos!
- **SNOLAB** in ON, Canada is the deepest clean laboratory in North America

Ianni, J. Phys. Con, 1342 (2020) 012003



Ambient Radiation

Only 5cm of lead can dramatically cut gamma flux by x10^3

Only 300 feet of rock can cut the muon flux by x$10^{2\text{-}3}$

Typical qubit chip is about 1 cm^2 in area of silicon on 0.5mm thick substrate (100 mg)

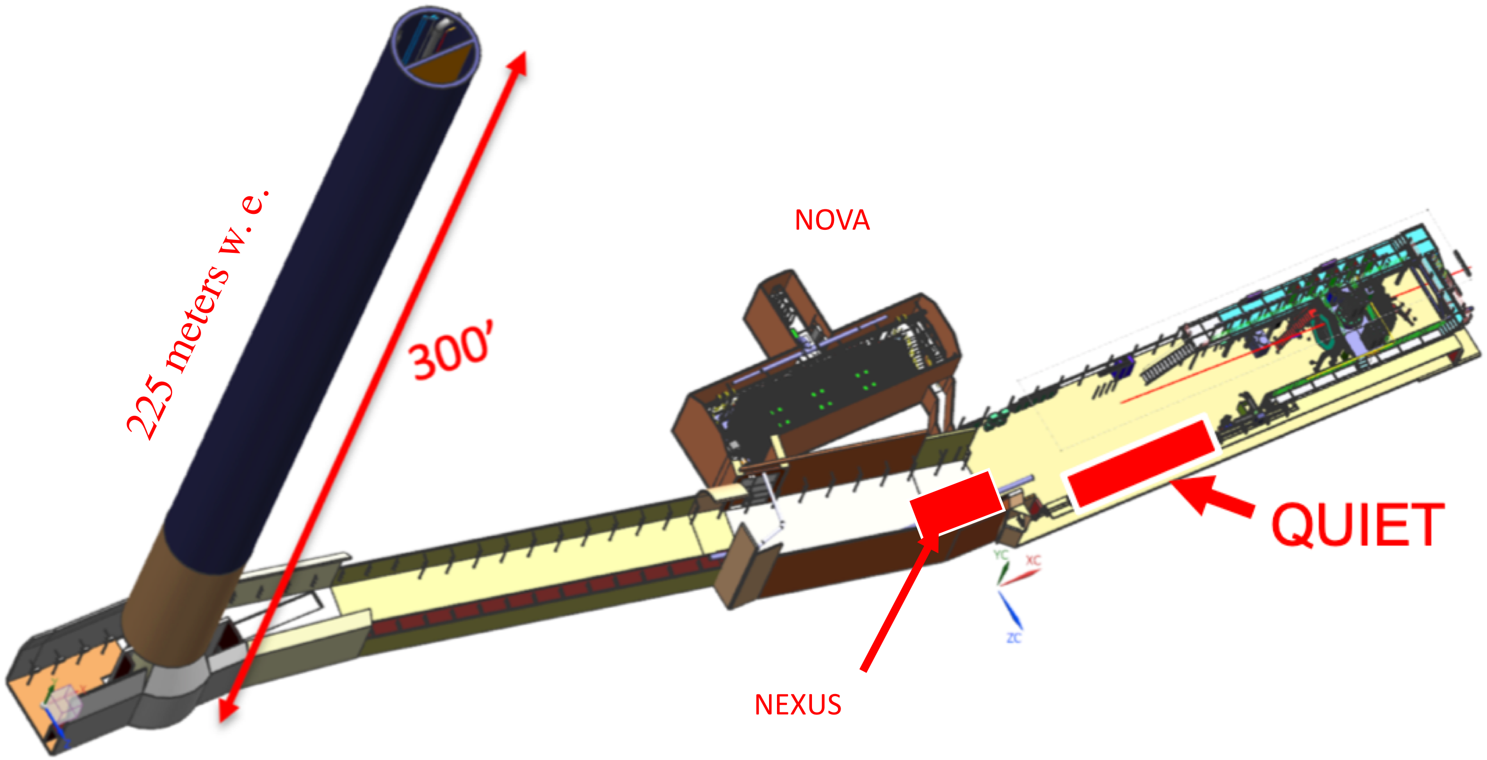
Muon rate ≈ 10 /day

Increases with altitude!

Photon rate ≈ 10 /day /MeV

This is very tolerable for long computations!

Ambient Radiation



Cosmic Quantum (CosmiQ) – NEXUS

Northwestern **EX**perimental **U**nderground **S**ite

Originally developed for calibration of dark matter detectors, now retrofit for RF to run superconducting qubits

– $4\boldsymbol{\pi}$ lead shield provides 10^3 reduction in ambient backgrounds
– Ongoing measurements with the same chip from *Wilen et al* exploring correlated information loss in an underground environment

Cosmic Quantum (CosmiQ) – QUIET

Quantum **U**nderground **I**nstrumentation
Experimental **T**estbed

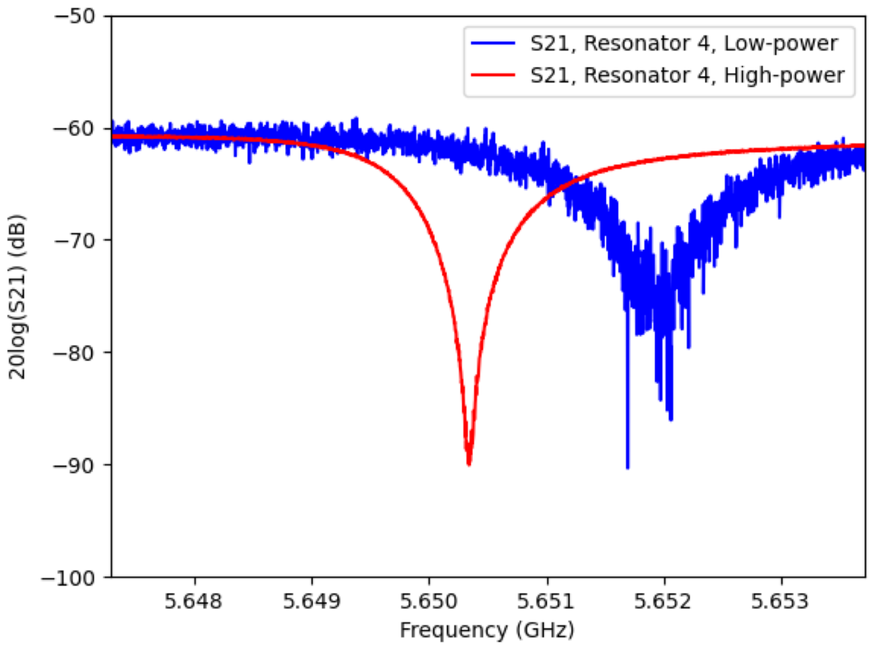
This QSC facility, once complete, will house one of the only dedicated, low-background cryostats for superconducting qubit operations

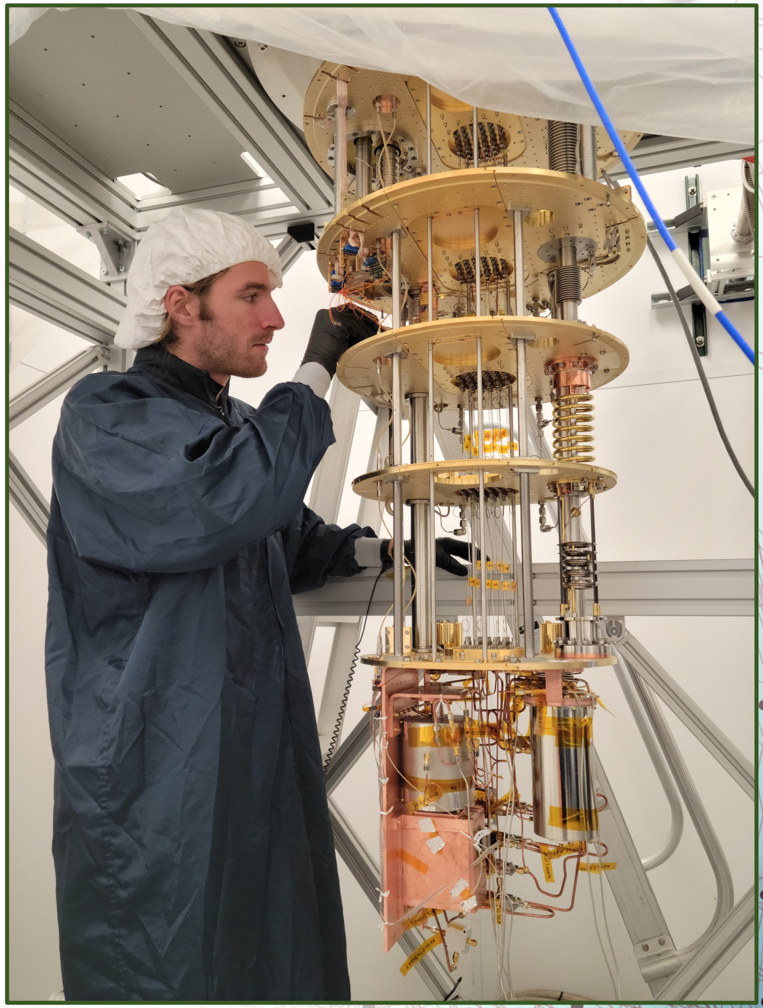
- Class 10,000 clean room
- 50 ft^2 antechamber for gowning and material cleaning
- 250 ft2 main room will contain a shielded Oxford dil. fridge w/ up to 16(48) NbTi(SS) RF lines
- Design of the QUIET radiation shield and muon veto is underway in parallel
- Utility installation is now proceeding, including power, chilled water, fiber internet, and fire suppression systems

Cosmic Quantum (CosmiQ) – LOUD

Error 404 – Acronym not found

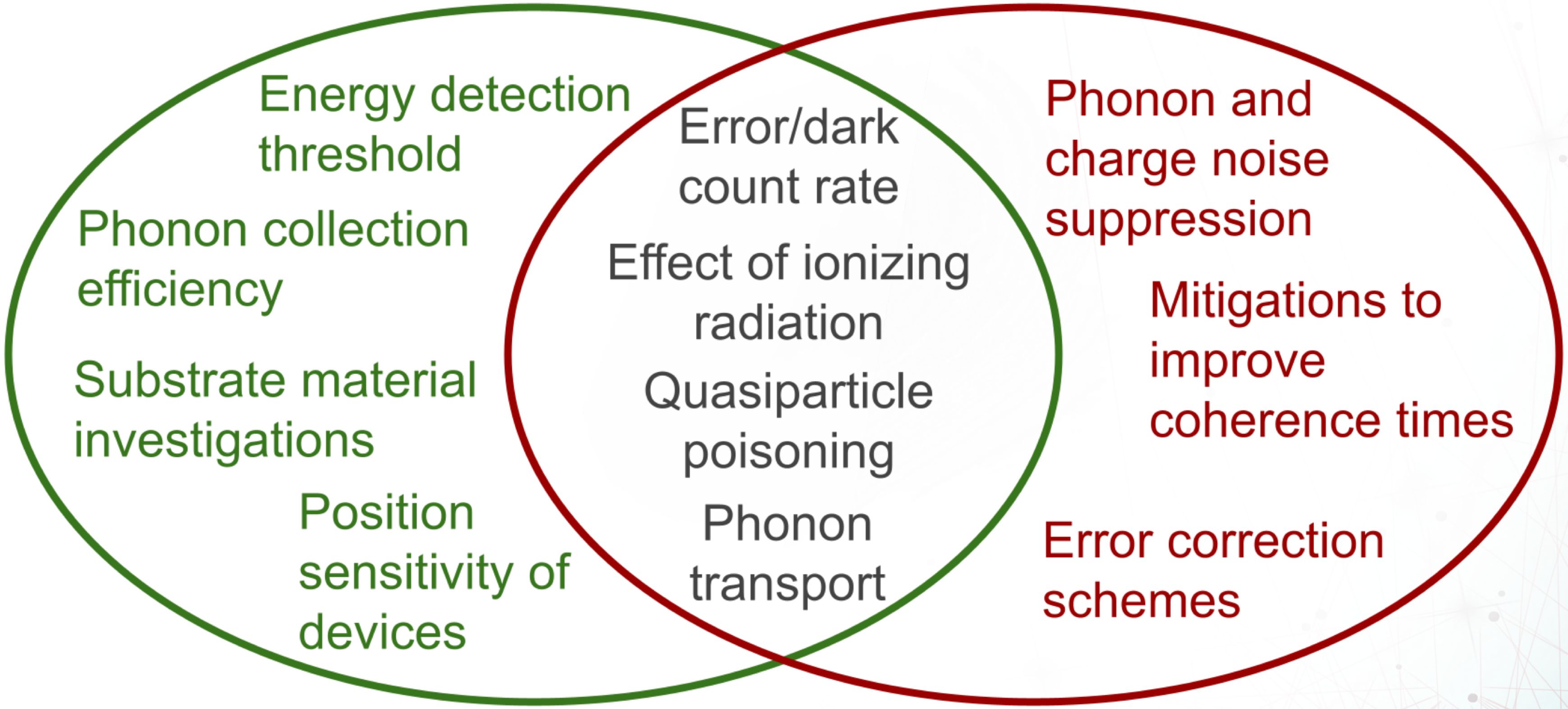
Underground facilities are great, but sometimes you just want somewhere easy to work

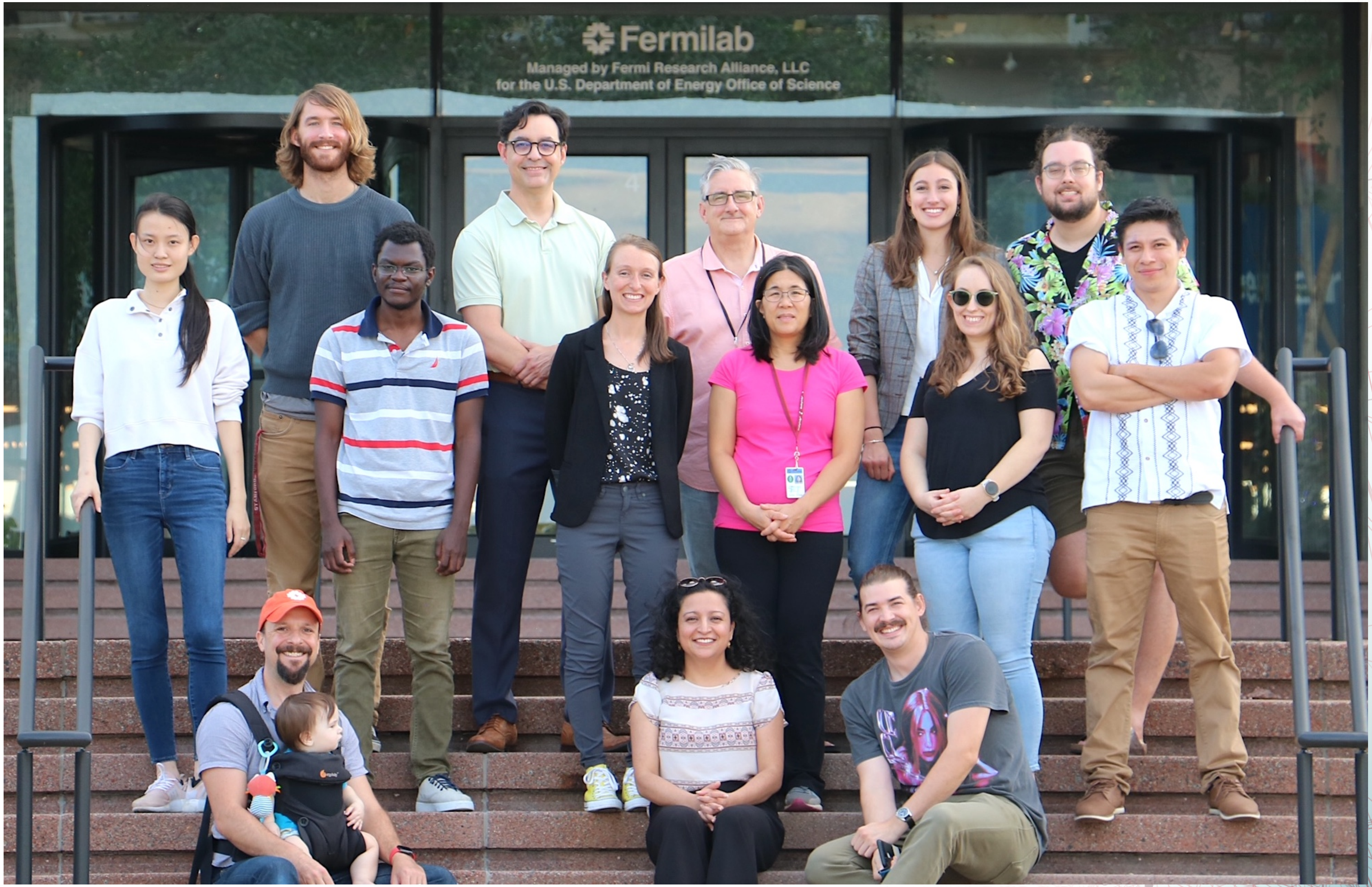




Cosmic Quantum (CosmiQ)

SC Qubits for Dark Matter **SC Qubits for Quantum Computing**




Fermilab
Managed by Fermi Research Alliance, LLC
for the U.S. Department of Energy Office of Science