# Qubit performance meets low-mass dark matter searches

September 8-10, 2022


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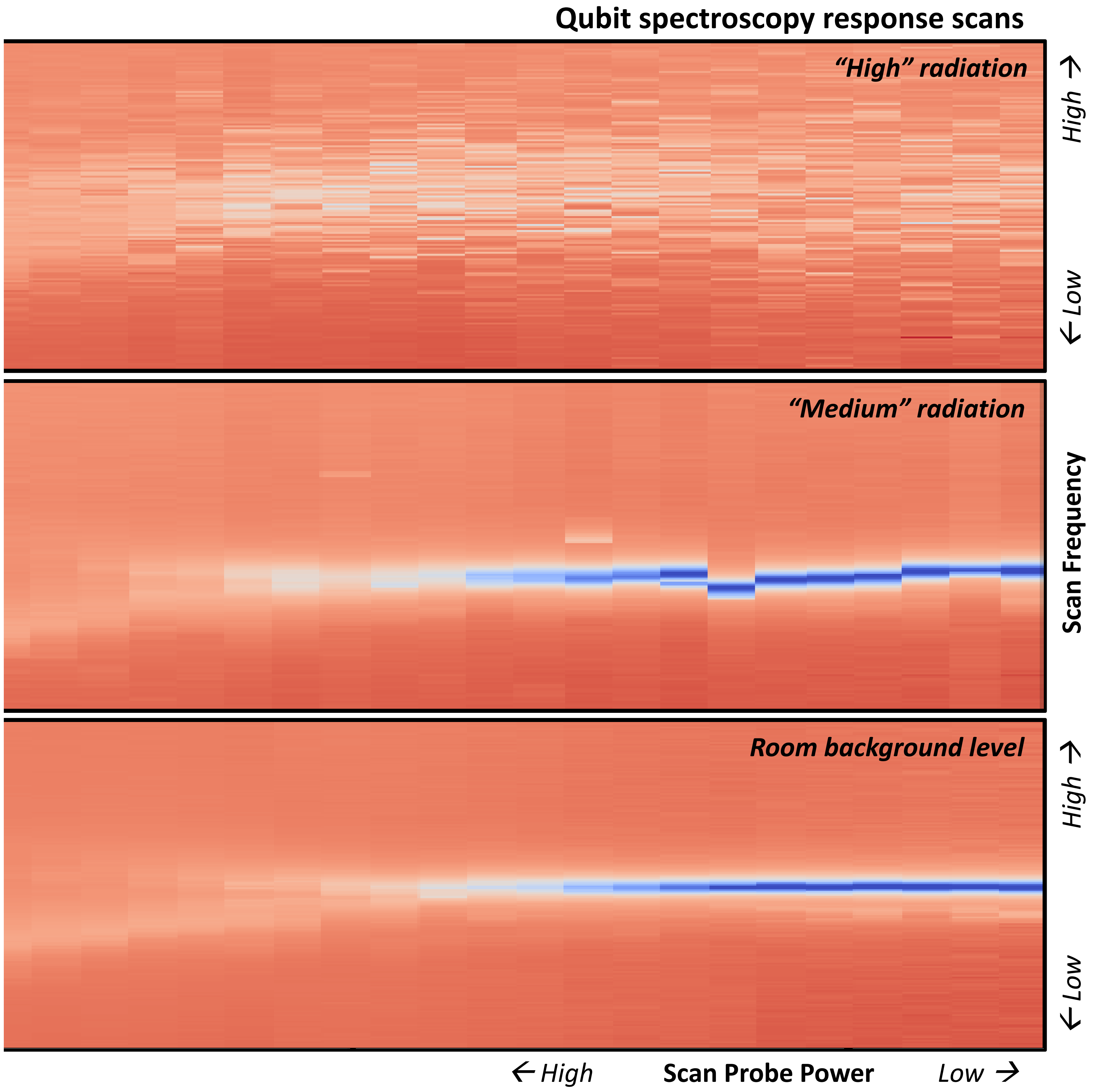
Senior Research Scientist



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# Outline

WIKIPEDIA: Knower of all things

A qubit is a two-state (or two-level) quantum-mechanical system.

- Dark matter and qubits?
- Initial observations of an *instrumentational* relationship
  - Work at LNGS
  - MIT-PNNL
  - Short history of quasiparticle poisoning
- Interesting related results of radiation & qubits
  - Wilen *et al*., Google, microfractures
- Bringing it back to dark matter
  - Particle-like dark matter…
  - Wave-like dark matter…
  - Other related ideas…
- Summary

# Dark matter and qubits?

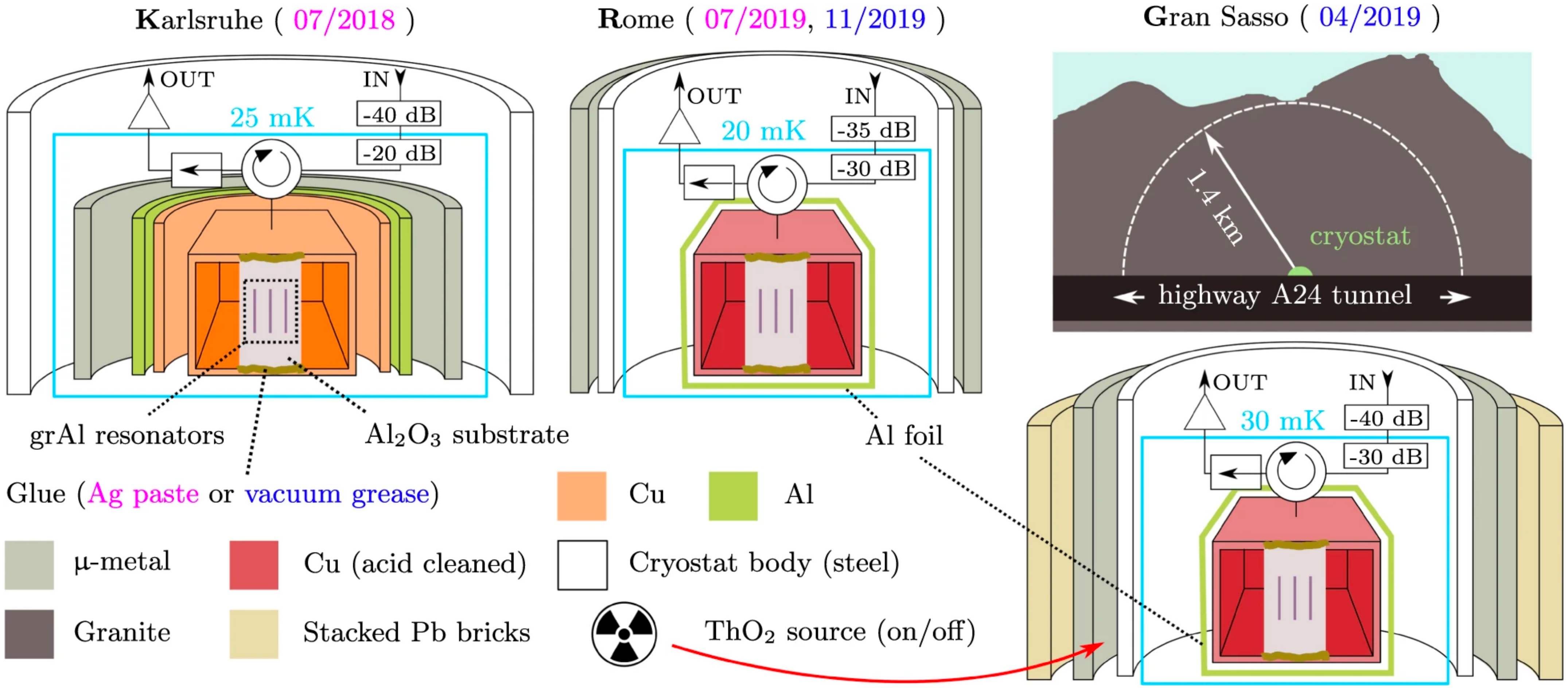
- Dark matter detectors:
  - Several experiments employ (or plan to employ) superconducting sensors
    - ✓ Particle-like dark matter: SuperCDMS
    - ✓ Wave-like dark matter: ADMX, Haystack, DM Radio, SQuAD, …
  - Sensitive to naturally occurring ionization (cosmic rays and radioactivity)
    - ✓ Mitigation: Operated in shields and deep underground

- Do quantum bits (qubits) share any of these features?
  - As we will see… "Yes"
  - But where does this lead?

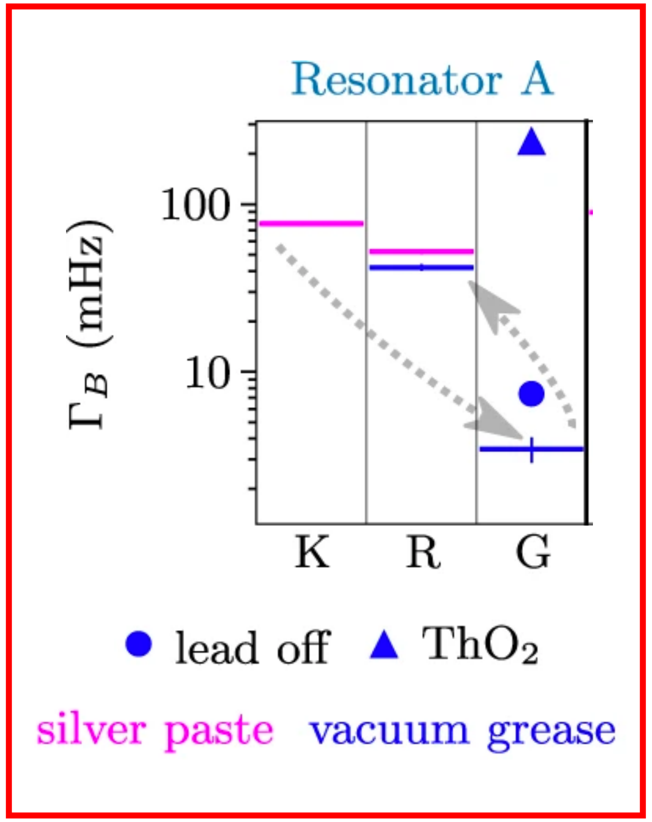
# The story begins…

<u>Key insight</u>
grAl resonators
are *very similar* to
superconducting qubits

- Using high kinetic inductance granular aluminum (grAl) superconducting resonators as a sensor for quasiparticle populations… *while underground*



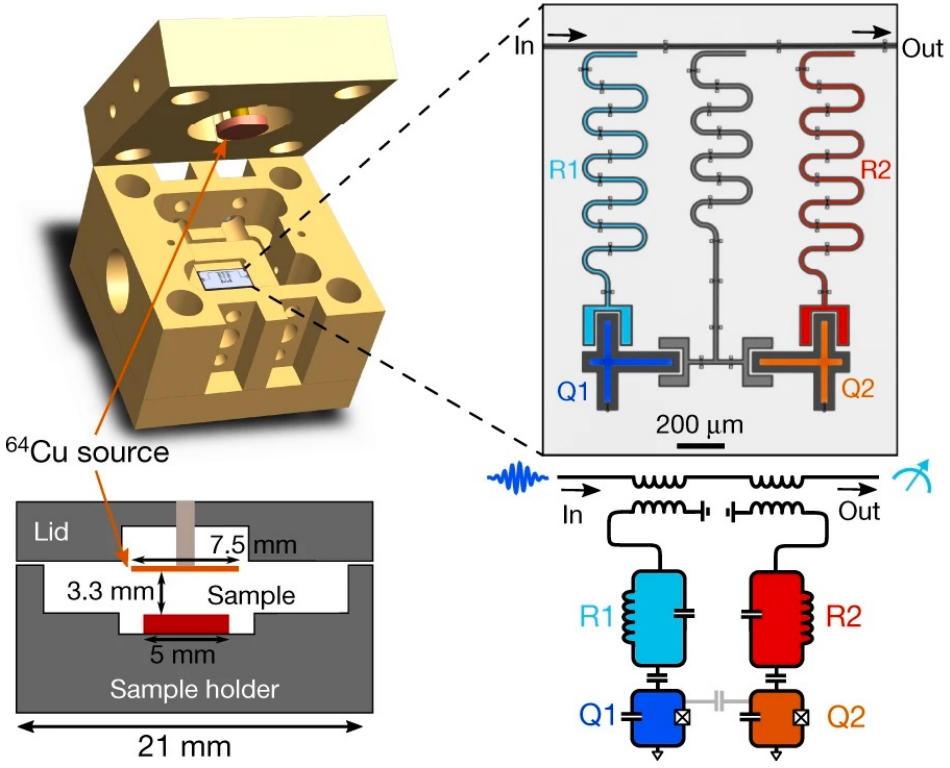

Results

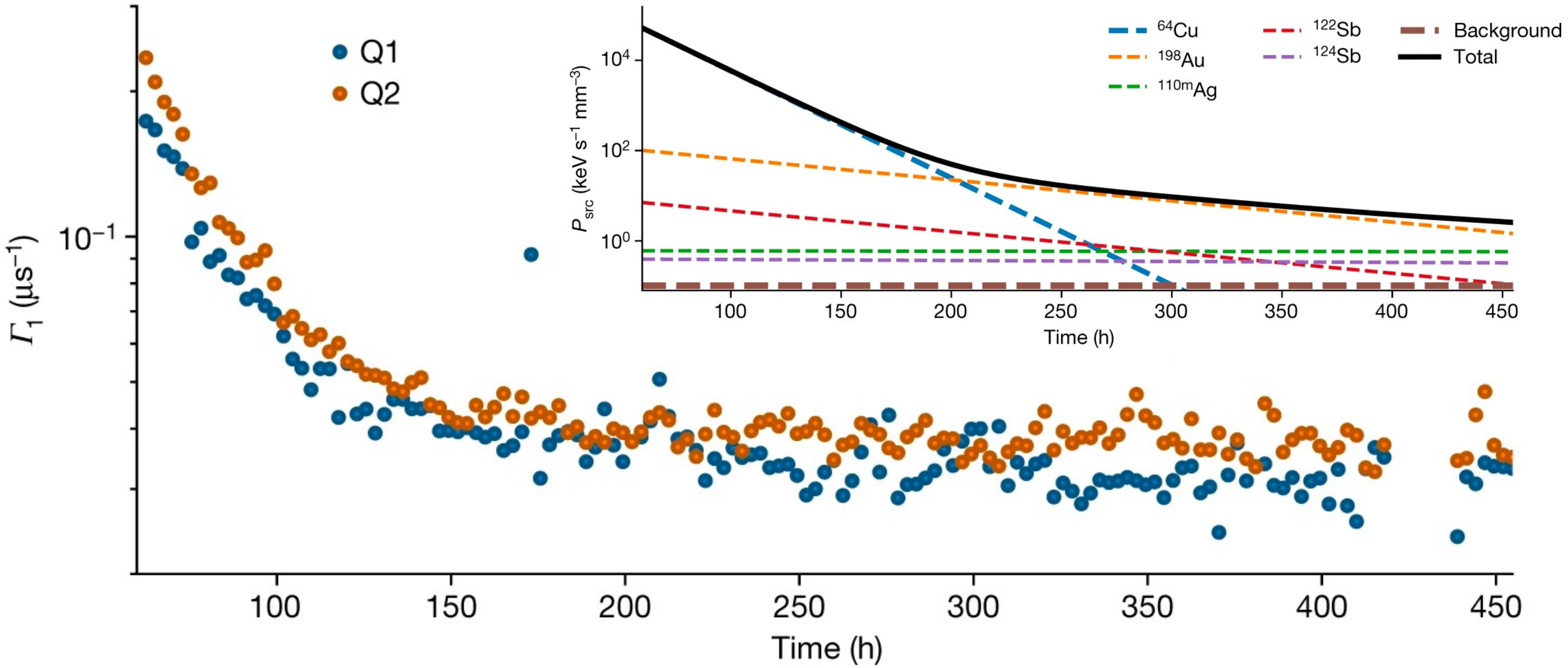



L. Cardani *et al.*, *Nature Communications* 12, Article: 2733 (2021)

# Superconducting quantum bits (qubits) sense ionizing radiation

- Operation of superconducting transmon qubits under *variable* ionizing radiation exposure ($^{64}$Cu source with $T_{½}$ = 12.7 hours)
  - Hypothesis: Ionizing radiation "poisons" transmon via superconducting quasiparticles

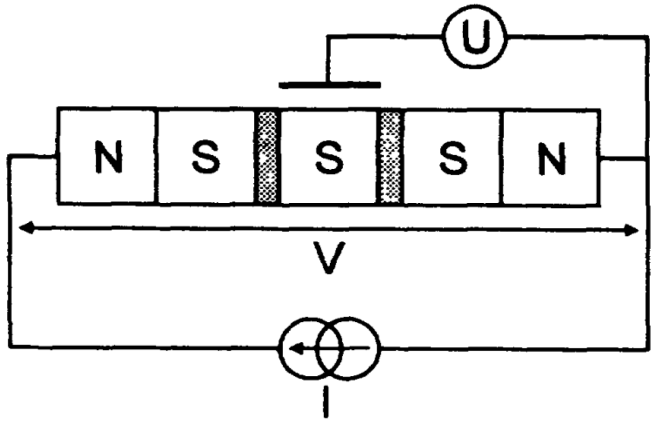


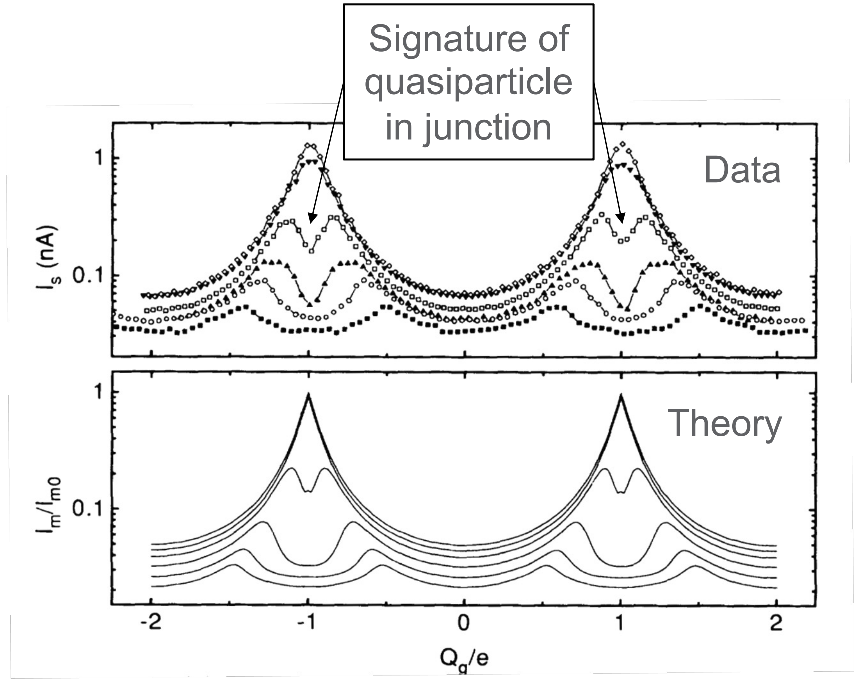

A.P. Vepsäläinen *et al.*, Nature 584, pgs 551–556 (2020)

# Quasiparticle poisoning is nothing new…
# Neither is ionization radiation as a cause…

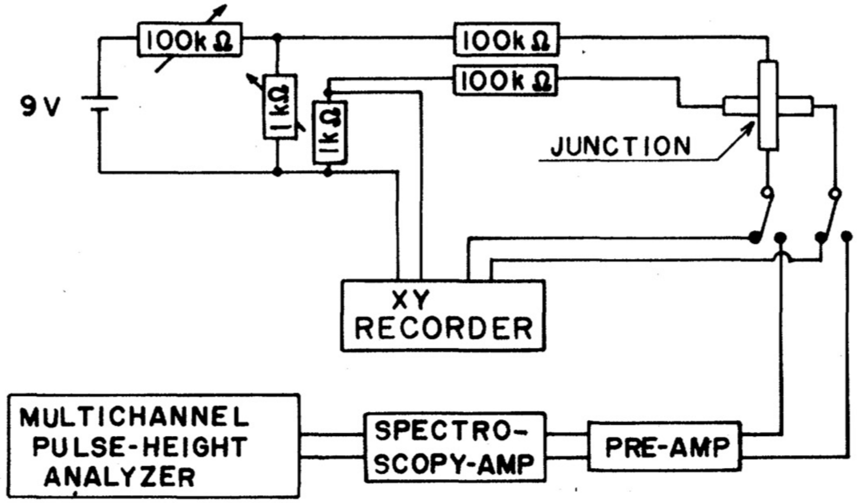
- Observation of Parity-Induced Suppression of Josephson Tunneling in the Superconducting Single Electron Transistor
  - P. Joyez *et al.*, Phys. Rev. Lett. 72, 2458 (**1994**)

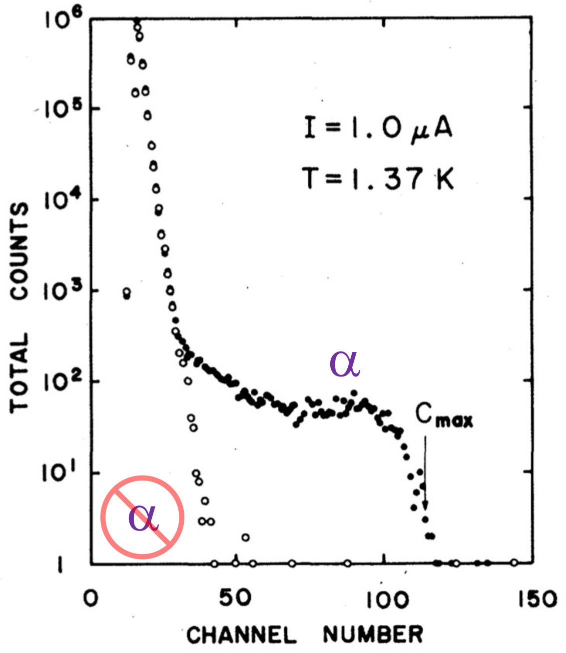



*Non-thermal quasiparticles attributed to Normal electrodes*



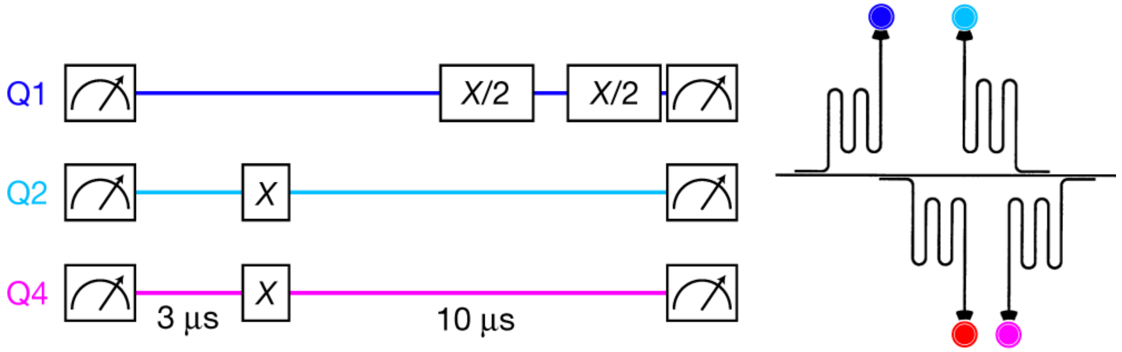

- Quasiparticle excitation in a superconducting tunnel junction by α particles
  - M. Kurakado *et al.*, Phys. Rev. B 22, 168 (**1980**)



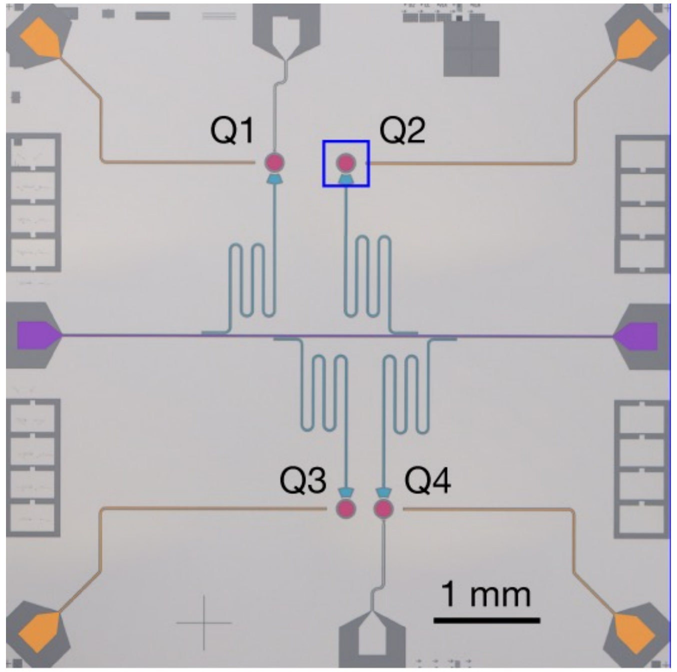



# Detour #1:
## Ionizing radiation & superconducting qubits

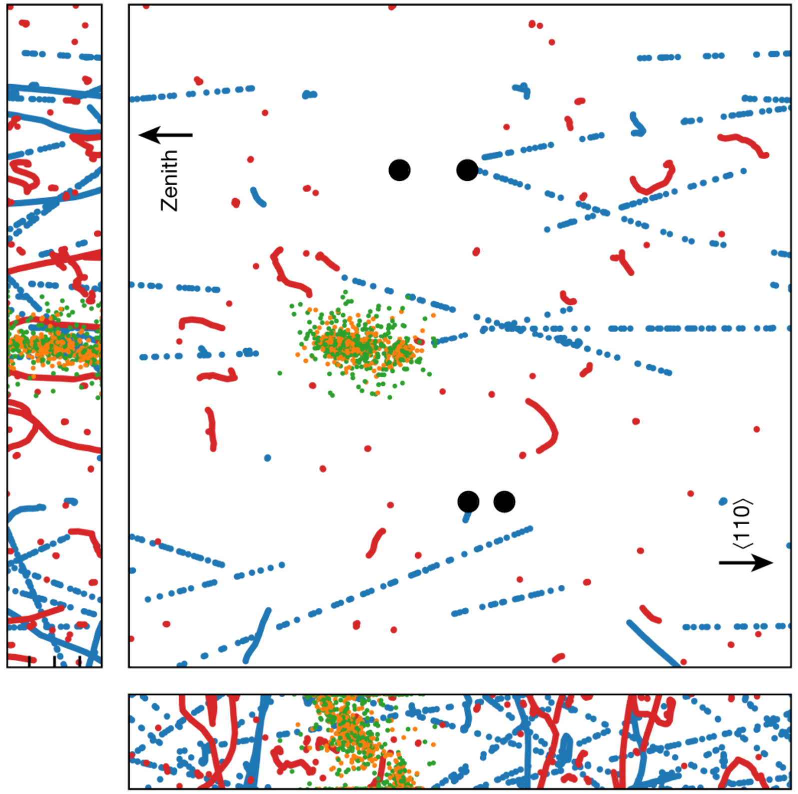
- Correlated charge noise and relaxation errors in superconducting qubits
  - C.D. Wilen *et al.*, *Nature* 594, 369–373 (2021)

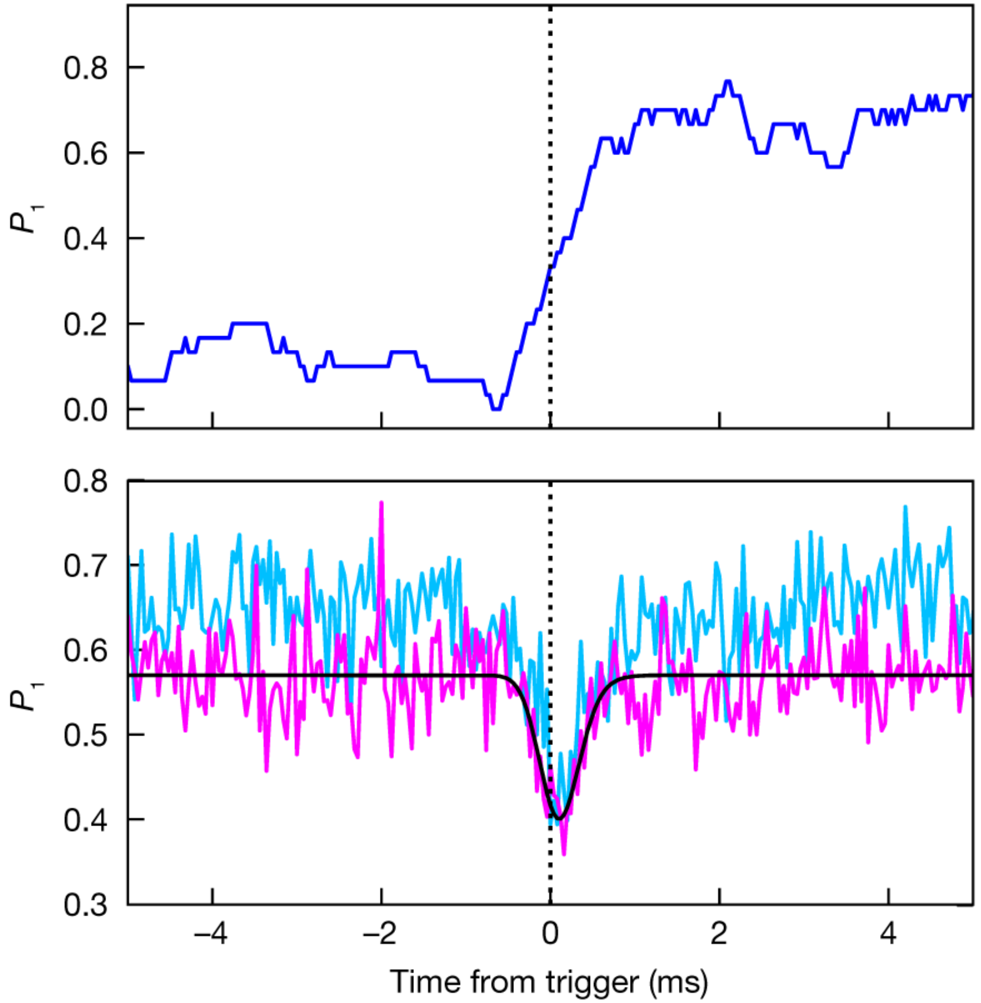



Simulation of γ- and cosmic rays



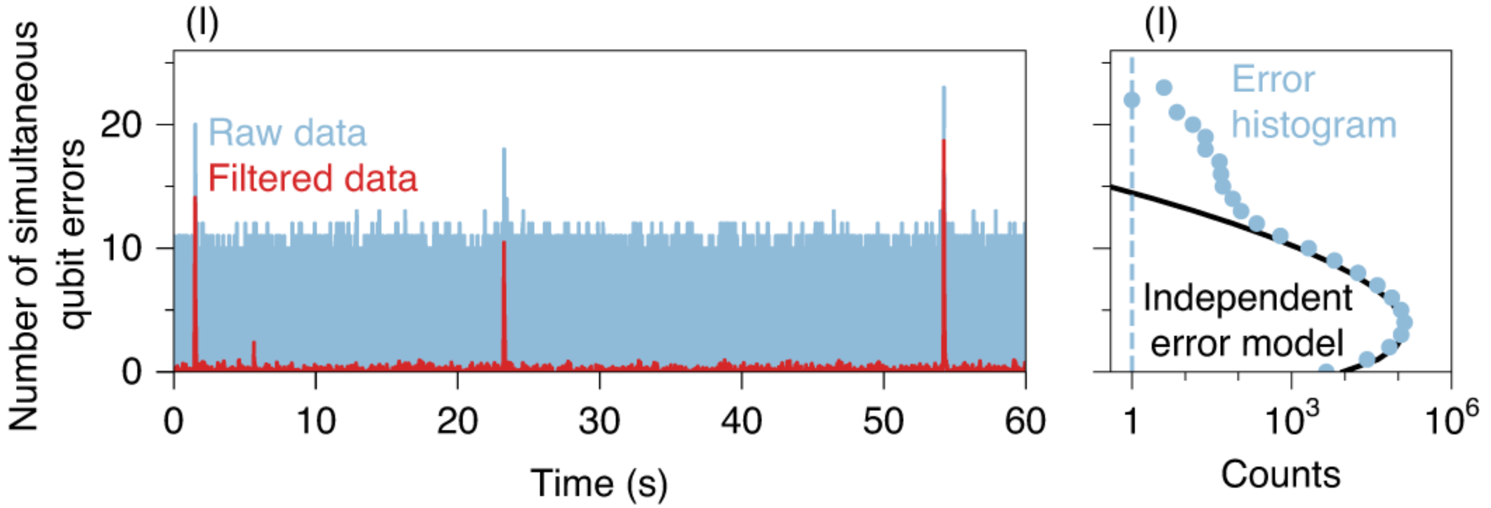

4-qubit chip layout

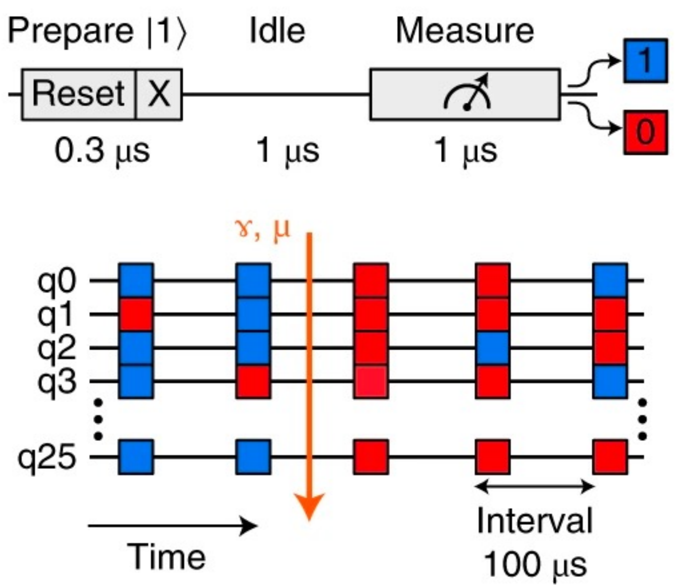


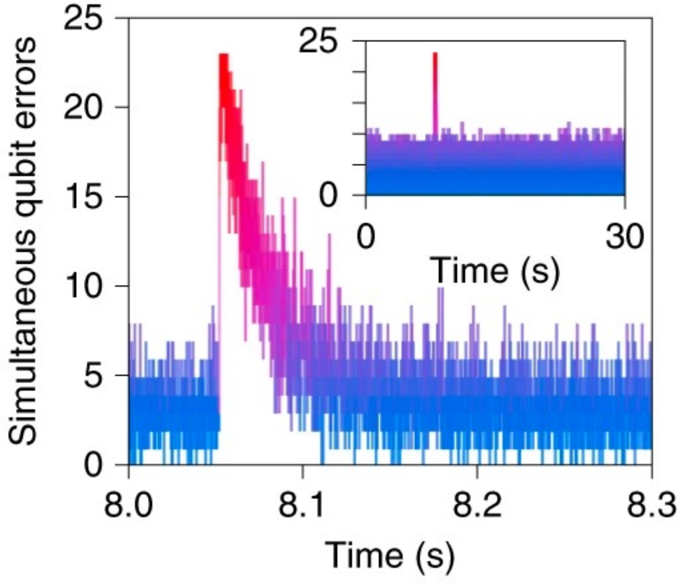



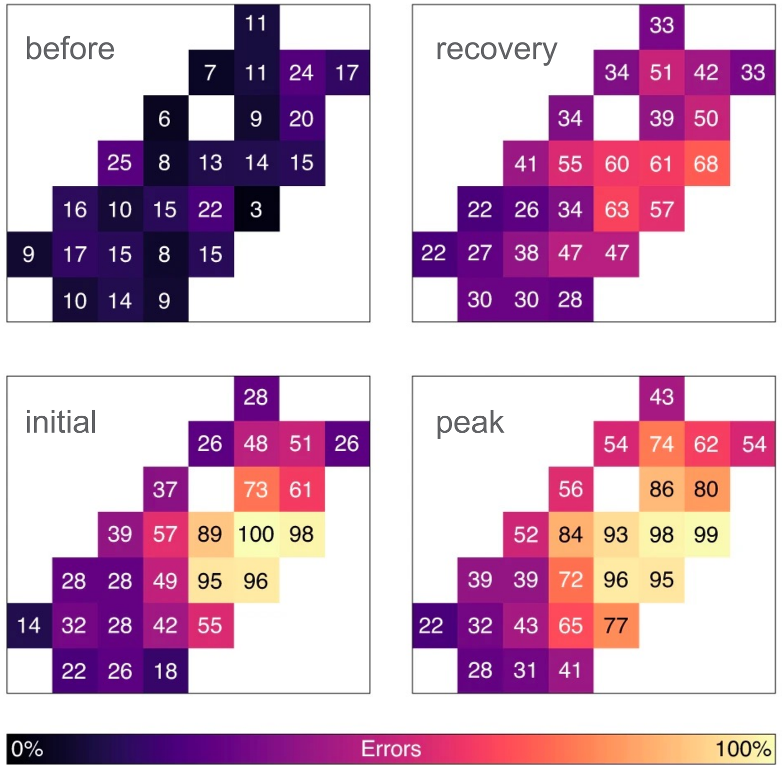
# Detour #2:
# Ionizing radiation & superconducting qubits

- Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits
  - M. McEwen *et al.*, *Nature Physics* 18, 107–111 (2022)



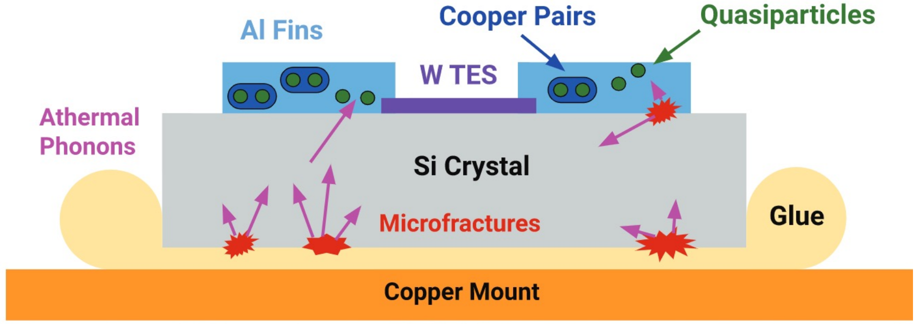



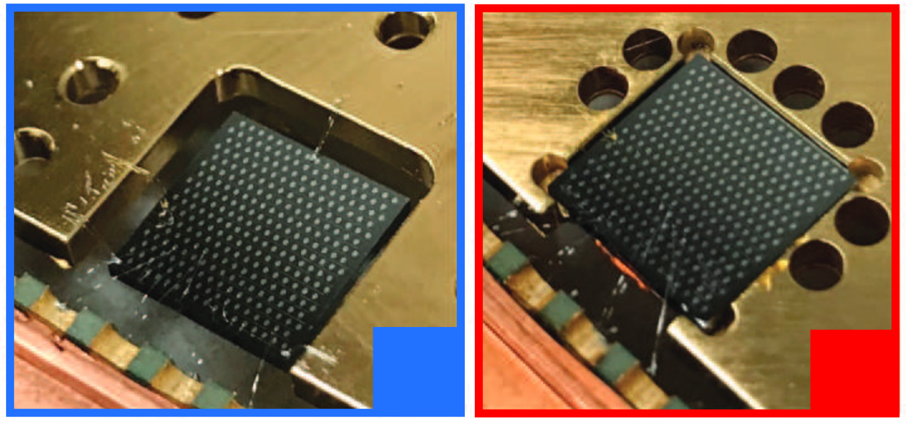




Error bursts spread through the multi-qubit chip

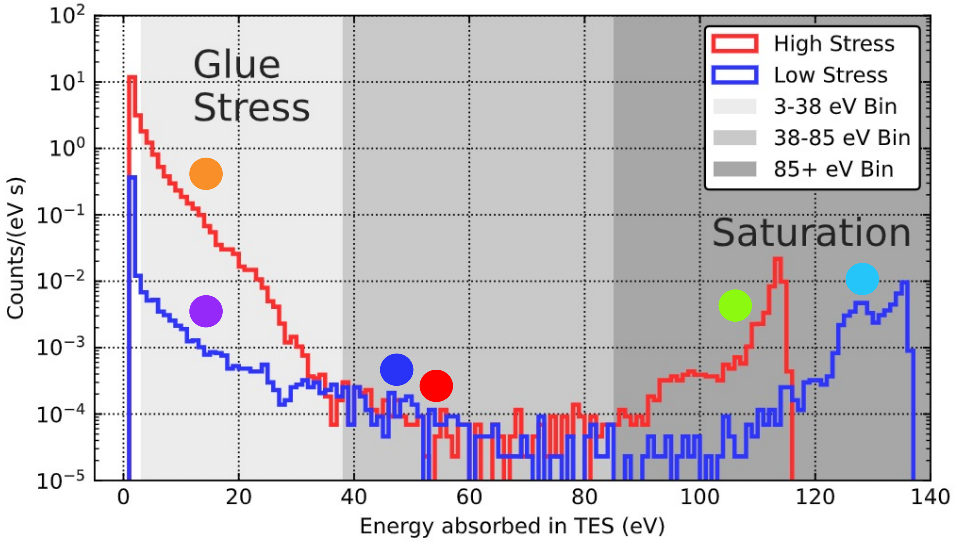
# Detour #3:
# ***Not just*** ionizing radiation & superconducting qubits

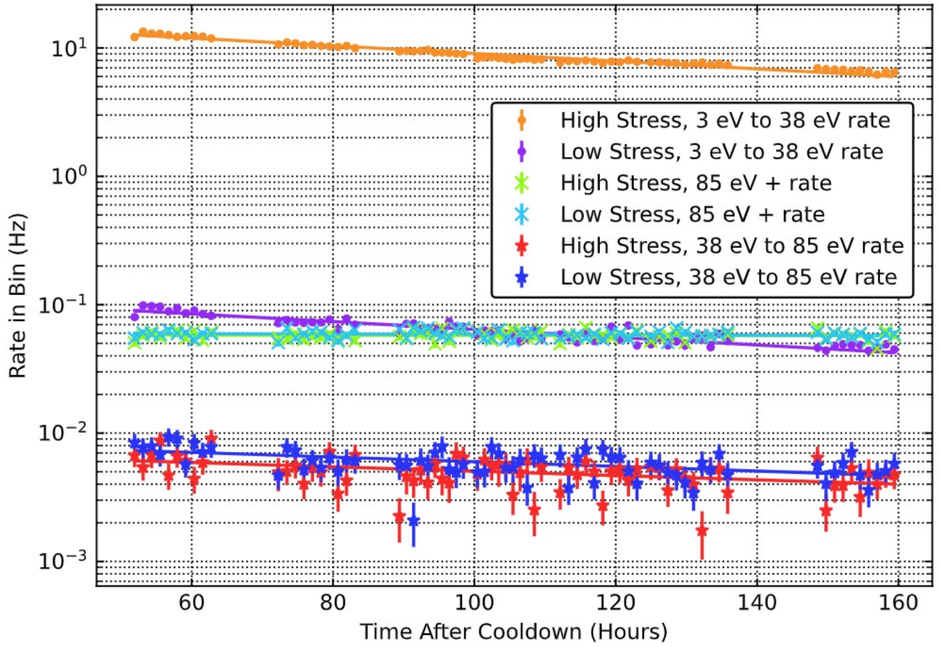
- A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning
  - R. Anthony-Petersen et al., arXiv:2208.02790 (2022)



Low stress (wire bonds) High stress (glue)




Observation
High-stress mounting produces low energy events (bursts of quasiparticles)

Clencher
Effect decreases from the time of cooldown implying a *relaxation* effect

# GUINEAPIG 2022

## New ideas and direct search methods for lighter, sub-GeV, particle dark matter

- I want to *try*** to get this talk back to a *dark matter* focus…

- Revelatory statement up-front:
  - I’m not aware of anyone building qubit instruments to detector *particle-like* dark matter

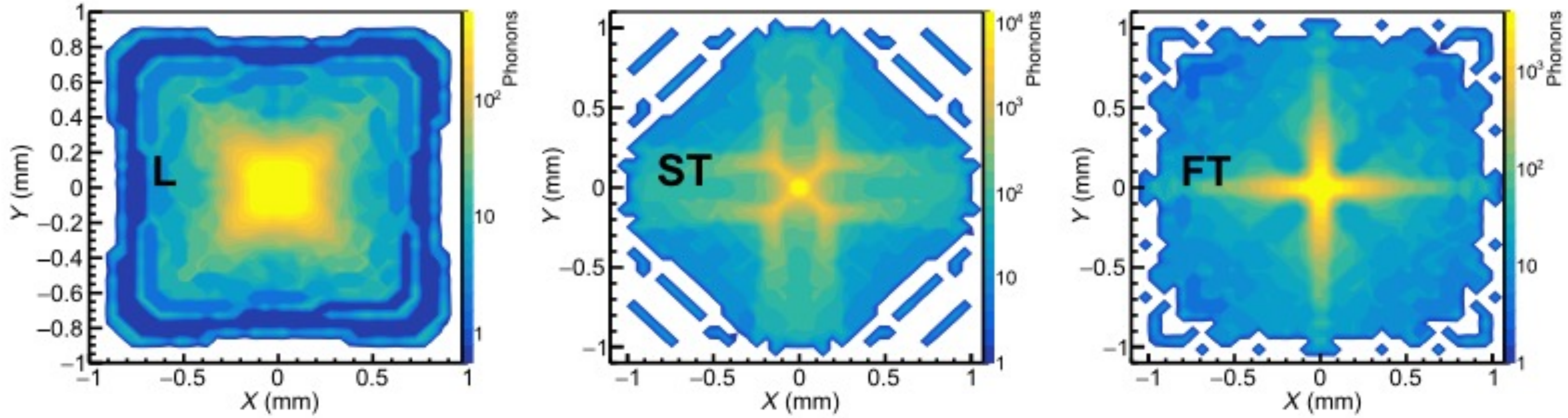
- However:
  - There is great *synergy* between particle-like dark matter sensors and qubits
  - There are proposals to use qubits in detection of *wave-like* dark matter
  - …
  - I’ll try to cover both and some!

** My continuing interest is in quantum error correction… but I *will not* digress…

# Synergy #1
## Superconducting device design and modeling

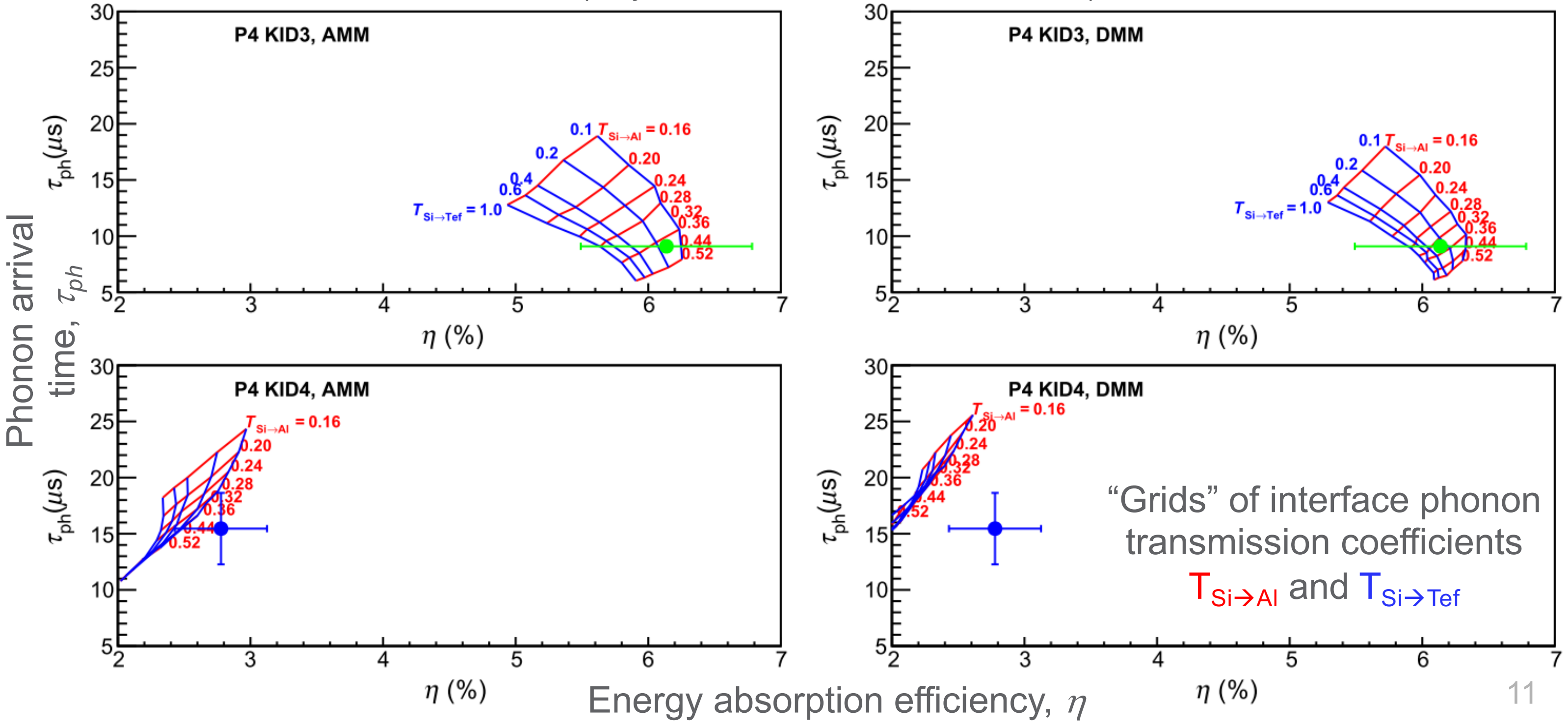
- Measurements and Simulations of Athermal Phonon Transmission from Silicon Absorbers to Aluminum Sensors
  - M. Martinez *et al.*,
  - Phys. Rev. Applied 11, 064025 (2019)

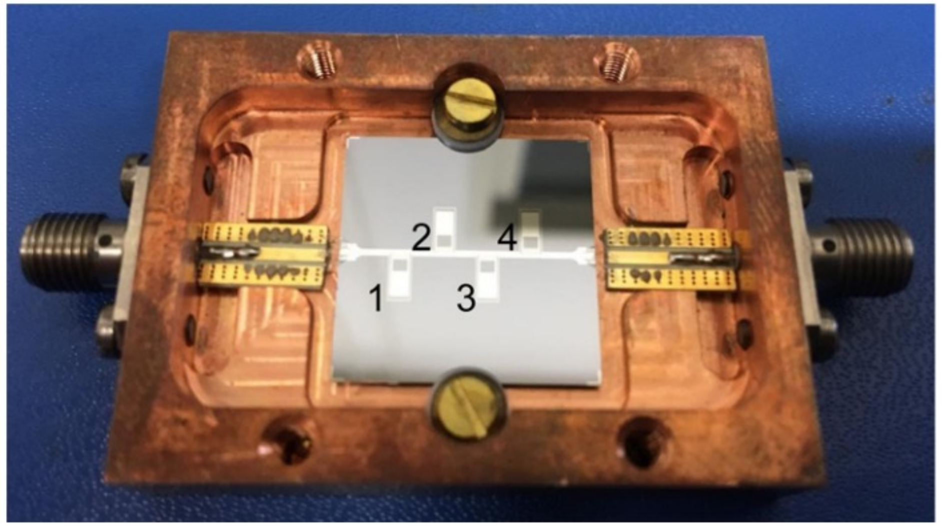
Geant 4 (G4CMP) simulation of phonon transport in silicon chip



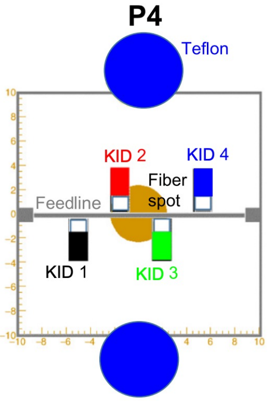

G4CMP modeling parameters and measured KID response

(only half of the data are shown here)




Chip model

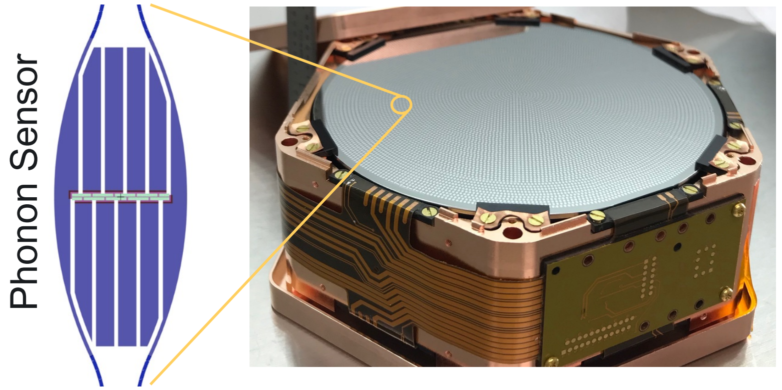



Not qubits! - Four kinetic inductance devices (KIDs)

# Synergy #1.5
# Superconducting device design and modeling

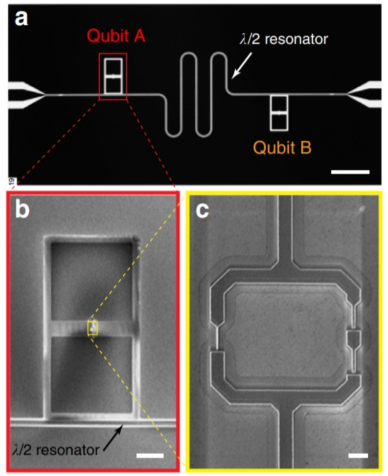
- Phonon transport & quasiparticle production in chip-based cryogenic devices

## Dark matter detector




see also R. Agnese et al., *PRD* **95** (2017)

## Qubit device

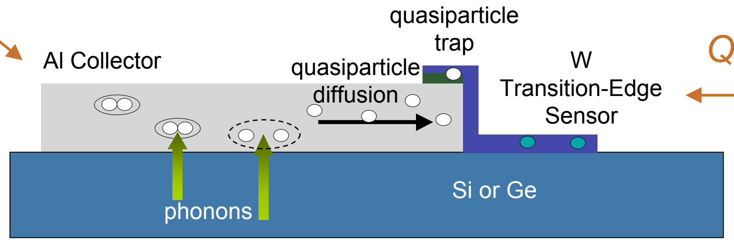



F. Yan et al., *Nature Communications* **7** (2016)

<u>Several parallels</u>

*Superconducting circuit film*

*Crystal substrate*




*Quasiparticle sensitive component, e.g., Josephson junction or TES*

Take advantage of equivalence to develop tools for optimization of device performance:

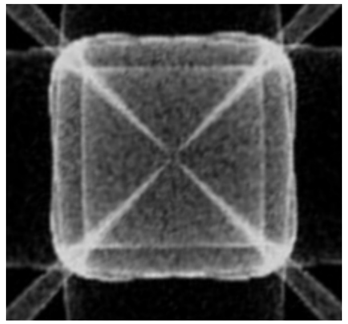
- Fabricate & test devices with varying physical properties
- Model phonon & quasiparticle response with dark matter detector Monte Carlo (G4CMP)
- Use results to optimize designs & develop science applications

## G4CMP-inspired devices to measure phonon caustics

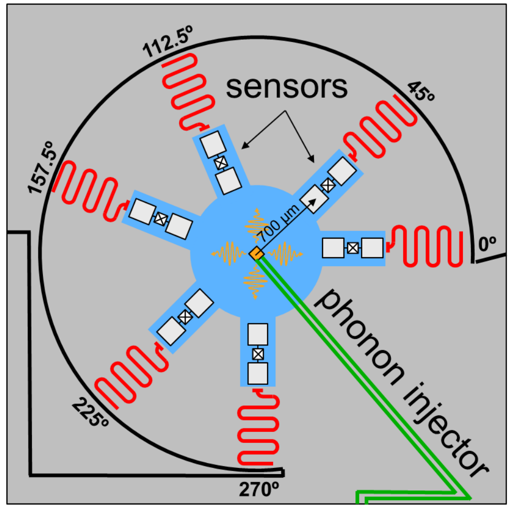
Research plans (in progress):

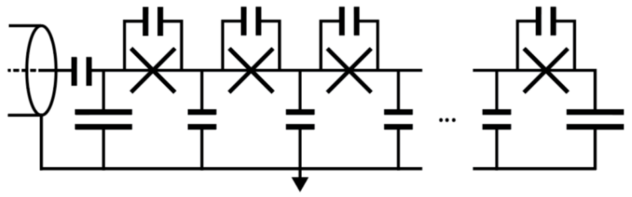
- Measurement of phonon caustics
- Characterization of novel sensors
- Expansion of quasiparticle processes and tracking in G4CMP
- Device and sensor development for HEP science applications

G4CMP-simulated phonon caustics pattern in silicon

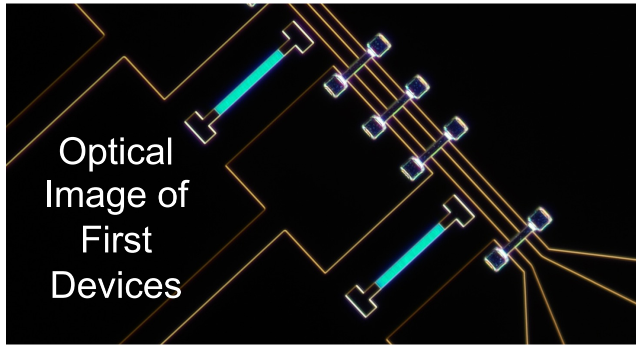


Caustics measurement chip layout with SNIS'S phonon injector



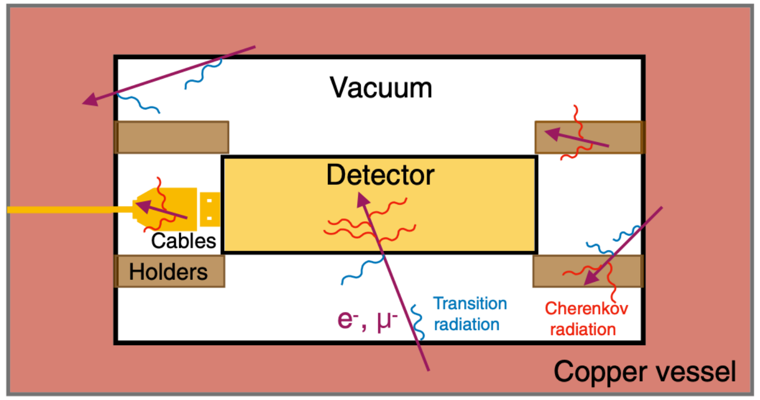
Instrumented with novel JAMKID sensors

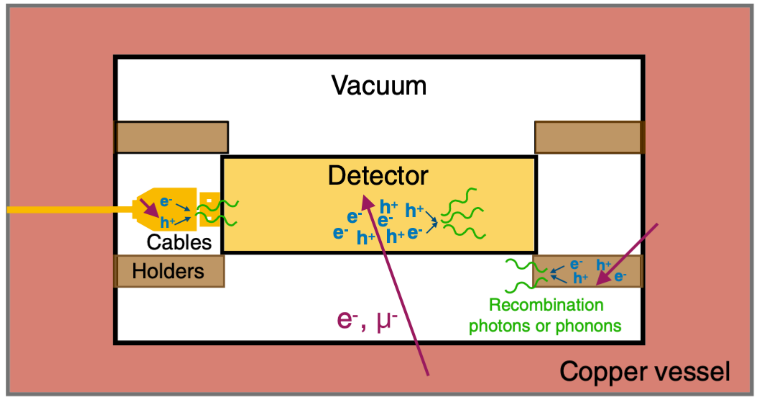


# Synergy #2
## Environmental disturbances & “Low-energy excesses”

- Concerns about low energy phenomenon (often quasiparticle producing)
  - Low energy ionizing radiation (e.g., low-energy forward scattering)
  - Secondary emission process (e.g., Cerenkov, transition, fluorescence)

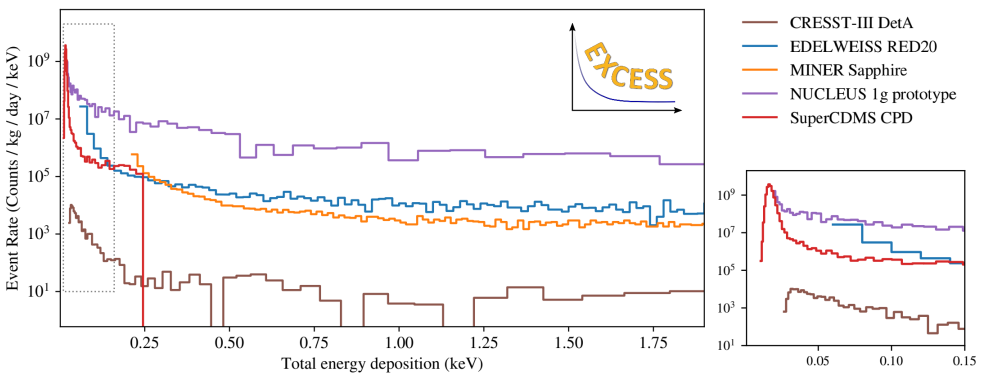
- Sources of Low-Energy Events in Low-Threshold Dark-Matter and Neutrino Detectors
  - P. Du *et al.*, Phys. Rev. X **12**, 011009 (2022)



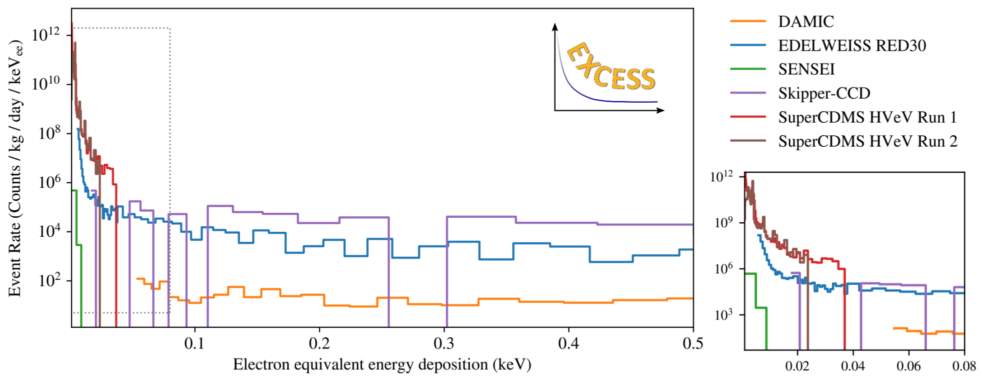




- EXCESS workshop: Descriptions of rising low-energy spectra
  - P. Adari *et al.*, SciPost. Phys. Proc. 9 001 (2022)

Total energy deposition

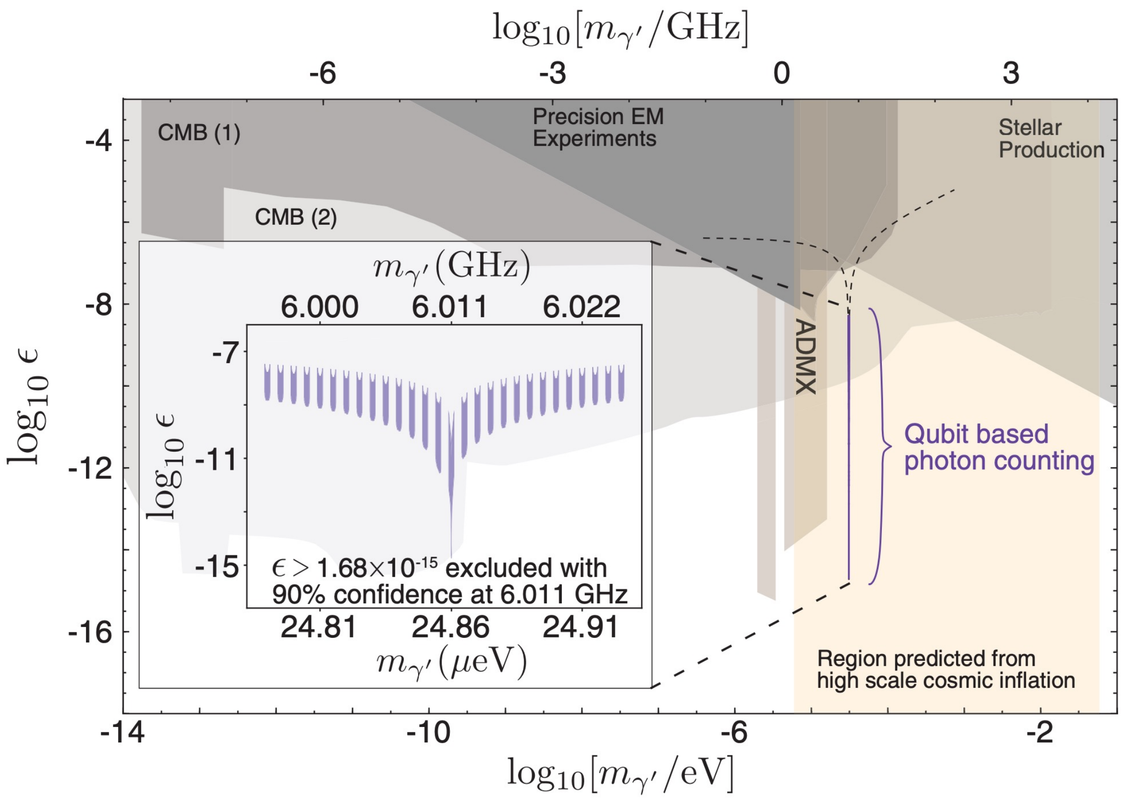



Electron-equivalent energy deposition



# Wave-like dark matter searches & Qubits

- Searching for Dark Matter with a Superconducting Qubit
  - A.V. Dixit *et al.*, Phys. Rev. Lett. 126, 141302 (2021)




Key concepts:

- Use a cavity to convert axion dark matter to photons
- Use a qubit coupled to cavity to assess occupancy

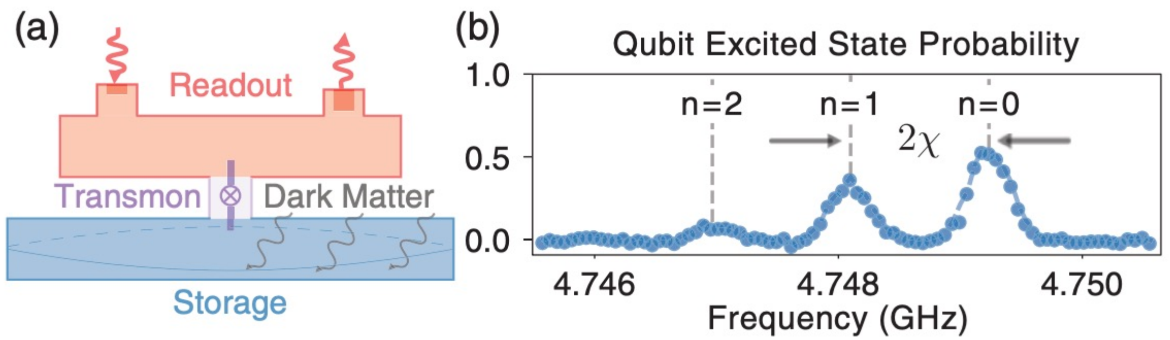



FIG. 1. Superconducting transmon qubit dispersively coupled to high $Q$ storage cavity. (a) Schematic of photon counting device consisting of storage and readout cavities bridged by a transmon qubit [29]. The interaction between the dark matter and electromagnetic field results in a photon being deposited in the storage cavity. (b) Qubit spectroscopy reveals that the storage cavity population is imprinted as a shift of the qubit transition frequency. The photon-number-dependent shift is $2\chi$ per photon.

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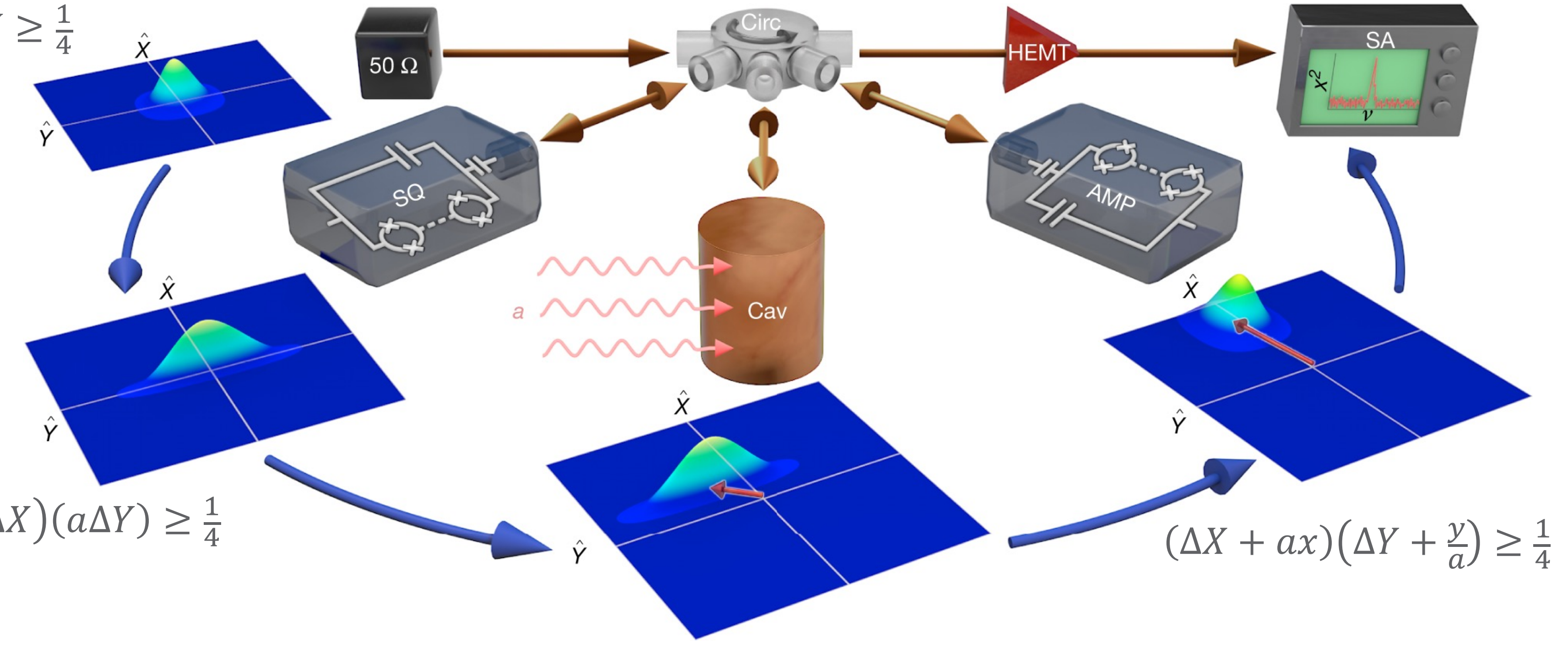
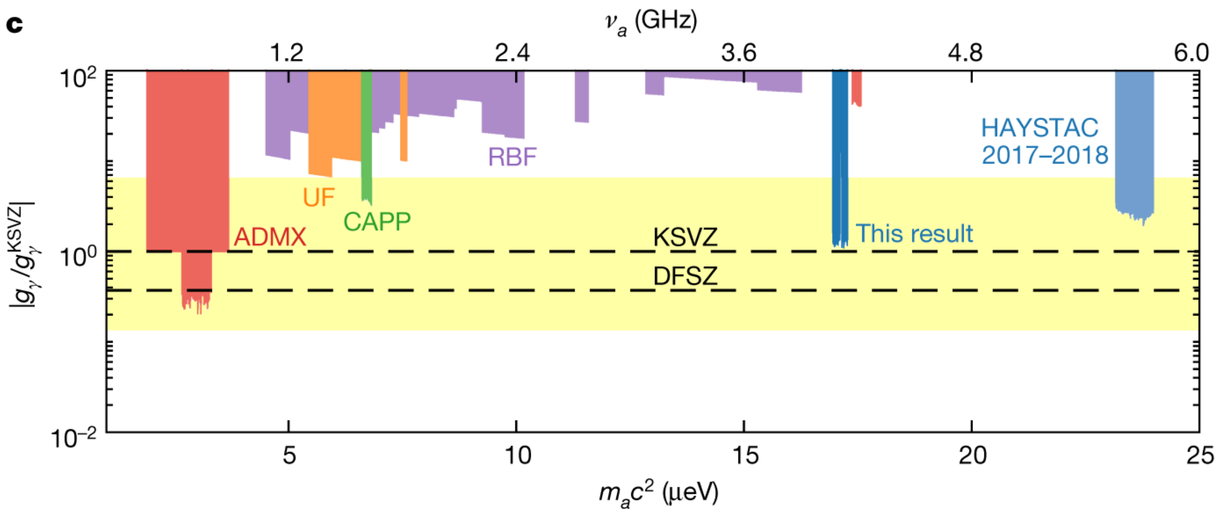
# Wave-like dark matter searches & "Quantum"

- HAYSTACK:
  - Quantum state squeezing
- A quantum enhanced search for dark matter axions
  - K.M. Backes *et al.*, Nature 590, 238–242 (2021)

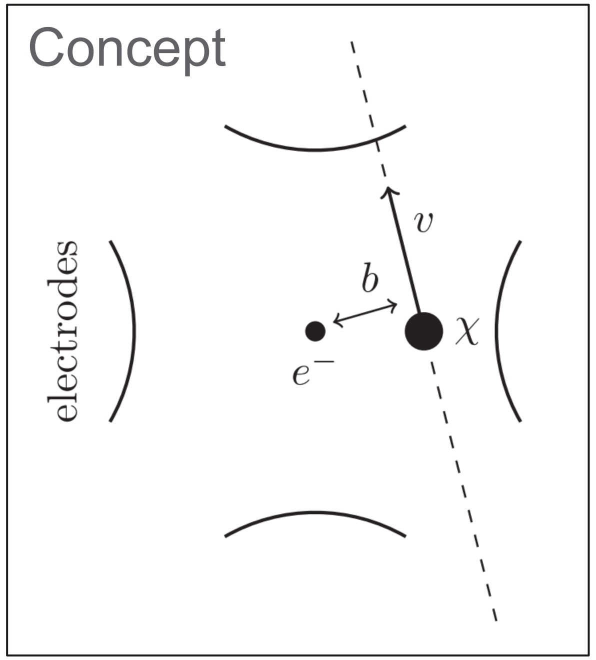



- Squeezable quantum state:
  - State with two non-commuting quantum observables having continuous eigenvalues
  - For example: $\Delta X \Delta Y \geq \frac{1}{4}$



# Something different…

- Detecting "milli-charge" dark matter with trapped ion-based 'qubits'
- Trapped Electrons and Ions as Particle Detectors
  - Daniel Carney et al., Phys. Rev. Lett. **127**, 061804 (2021)

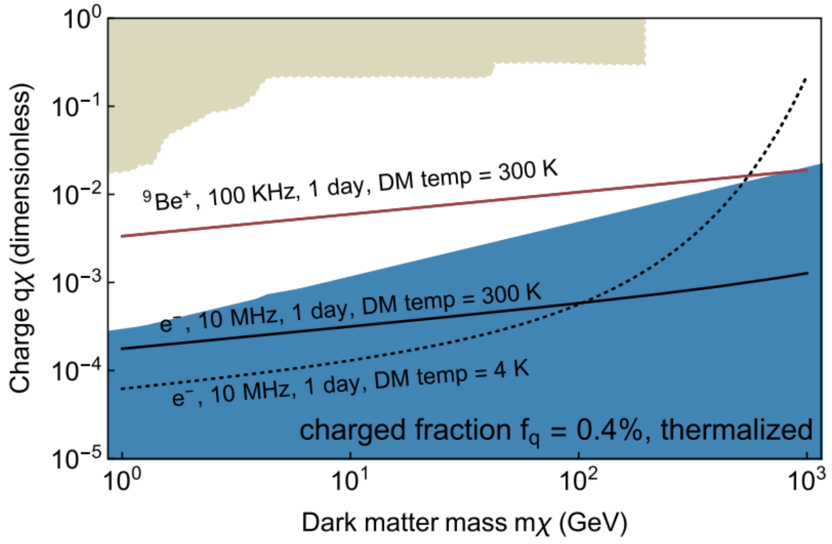



Kinematics of a scattering event in a Paul trap. The charged particle $\chi$ impinges on the trapped electron with impact parameter $b$ and velocity $v$.

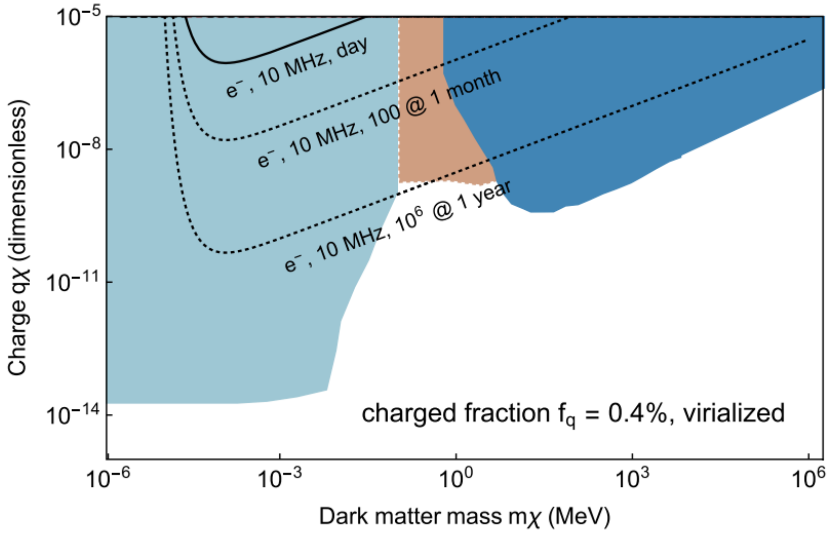
Three step duty cycle:

1. Initialize ion into ground state $|0\rangle$
2. Wait a dwell time $\Delta$t
3. Interrogate if ion is in excited state

DM captured and thermalized into the Earth




DM virialized with the galaxy



# Summary

- Quantum computing bits are very sensitive to “environmental disturbances”
- Recent observations have shown superconducting qubits are sensitive to normal environmental levels of ionizing radiation
  - This shows a synergy in device design and performance for superconducting detectors
  - Currently this is driving modeling developments (Geant and G4CMP)
- Will qubits be used in direct detection of dark matter?
  - Axions: Likely, yes.
  - WIMPs: Less clear, but device-synergies are strong
- Regardless:
  - Quantum sensing for direct detection of dark matter seems an inevitable approach

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# Thank you!

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