

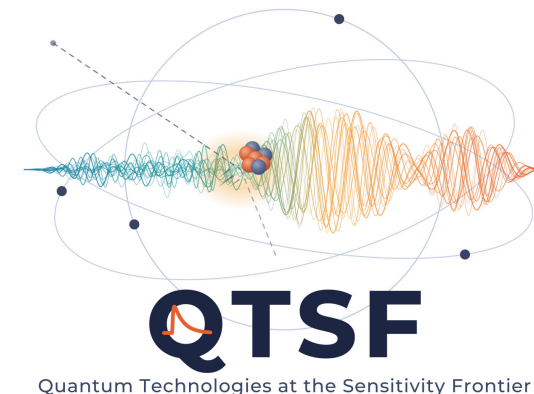
The Colorado Underground Research Institute (CURIE)

A 415 m.w.e. low-background lab for quantum sensors

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Mines Quantum Engineering Team**

¹ Colorado School of Mines * Speaker: lawanner@mines.edu

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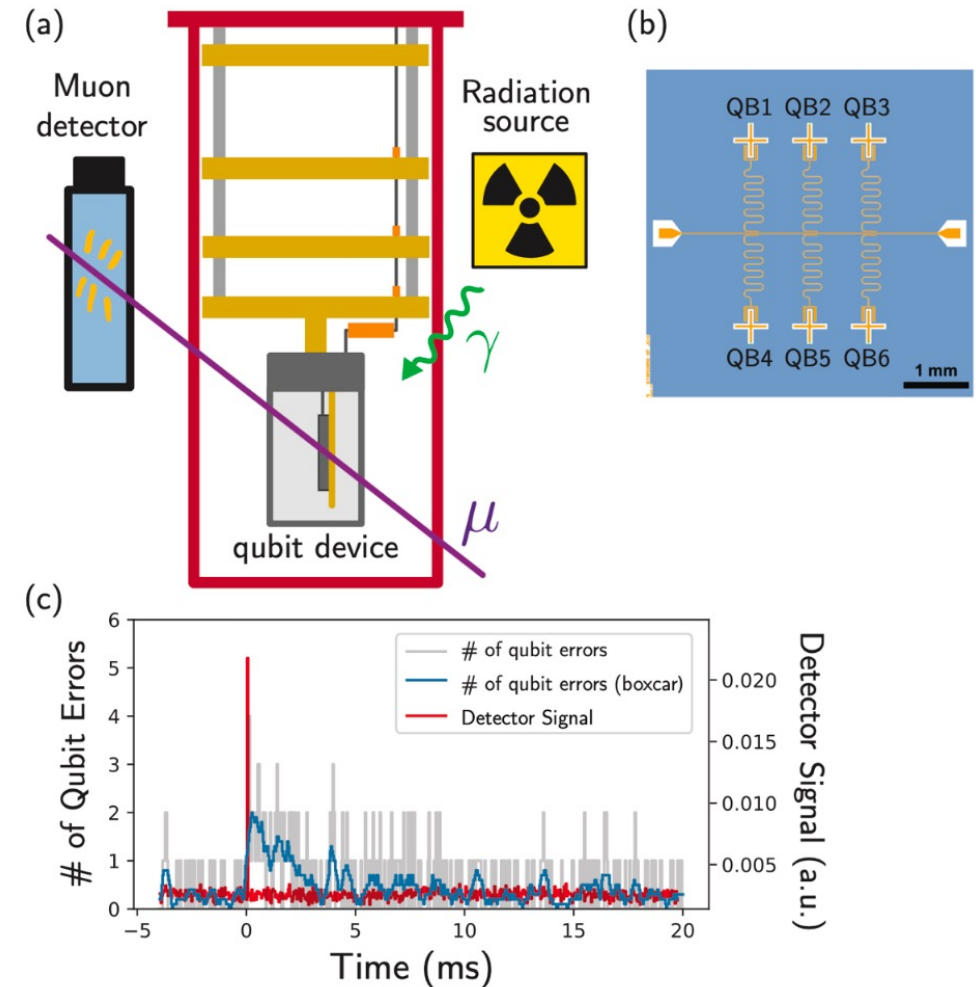


CURIE

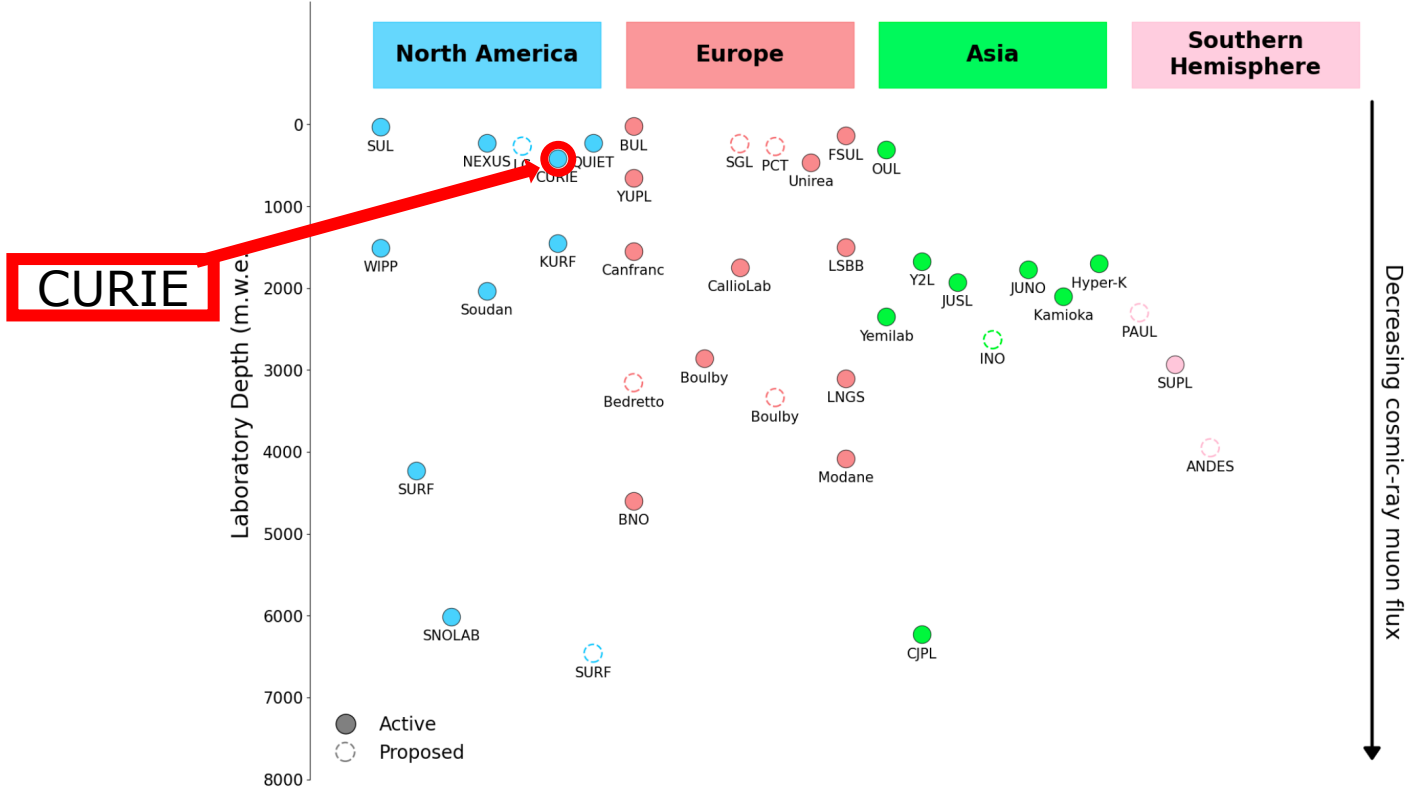
Radiation causes correlated qubit errors

- Alpha, electron and muon tests all show **spatially correlated errors** across the chip
- **Gap engineering** is less effective against phase errors
- **Error correction and vetoes** help, but correlated bursts overwhelm standard codes and vetoes cost dead time
- **Going underground** removes nearly all muons; radon and rock radioactivity remain and must be measured
- RISQ Conference on these issues

Source: Radiation Impacts on Superconducting Qubits (RISQ 2026);
Nature Communications 16, 6428 (2025)



CURIE joins the world's underground labs at 415 m.w.e.



415 m.w.e.
overburden at Cryolab I

700x
fewer cosmic-ray muons than at the surface

m.w.e. = meters water equivalent.
Source: CURIE depth and muon reduction: Kehlbeck et al., Phys. Rev. D (2025)

Edgar Mine offers expandable, fully serviced lab space

- **History:** silver, copper and gold mine since the 1900s, now maintained to modern safety standards for Mines teaching and research
- **Characterized:** hill profile mapped with USGS LiDAR data
- **Expandable:** the mining-engineering training program blasts new rooms at low cost
- **Power:** 480 V 3-phase, 100 A per section, expandable
- **Network:** high-speed Ethernet and Wi-Fi throughout the mine
- **Access:** 30 min from the Mines campus, CSM has full control over operation



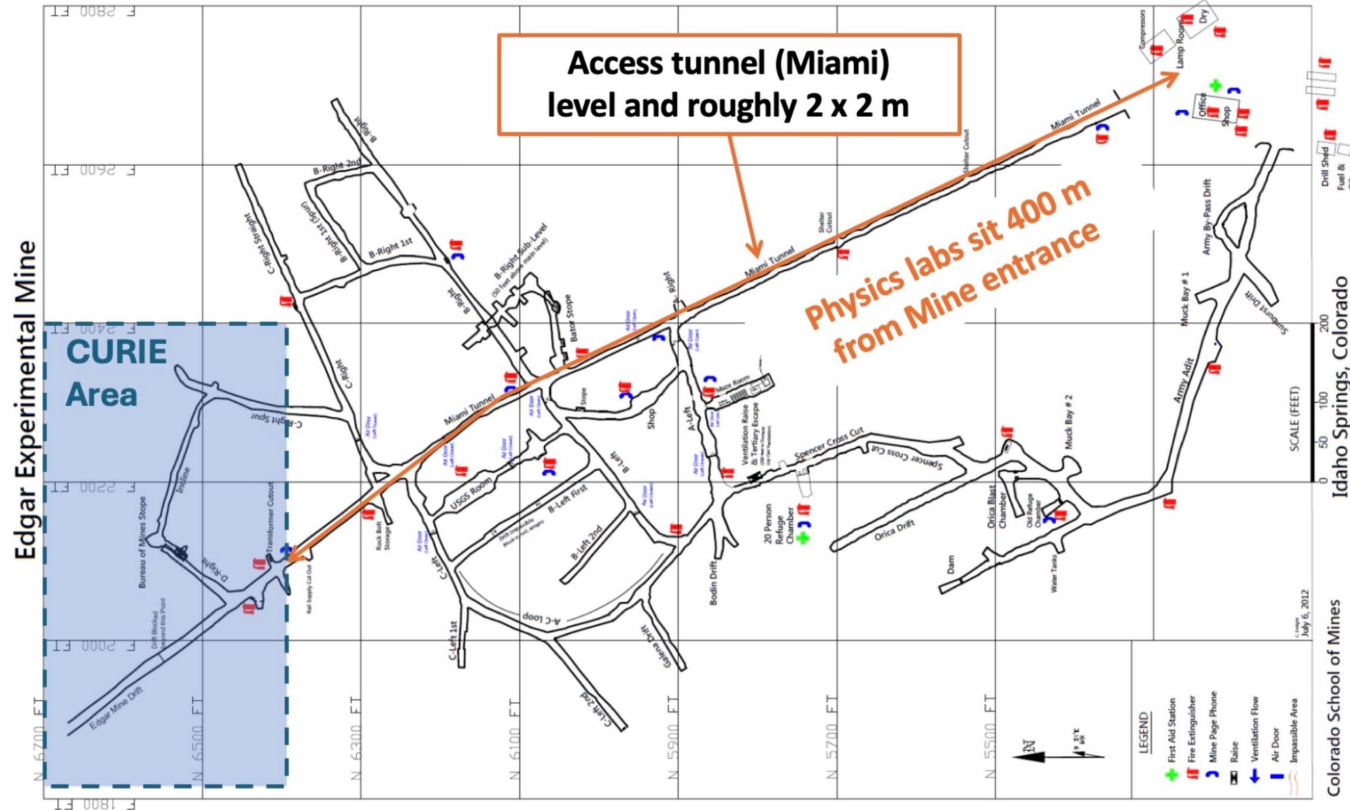
200 m

of rock overburden
(415 m.w.e.)

12 °C

constant year-round
(54 °F)

Two labs are operational, with more being excavated



Subatomic Particle Hideout (SPH)

$\sim 15 \text{ m}^2$

Particle-background characterization lab,
 $3 \times 5 \times 3 \text{ m}$

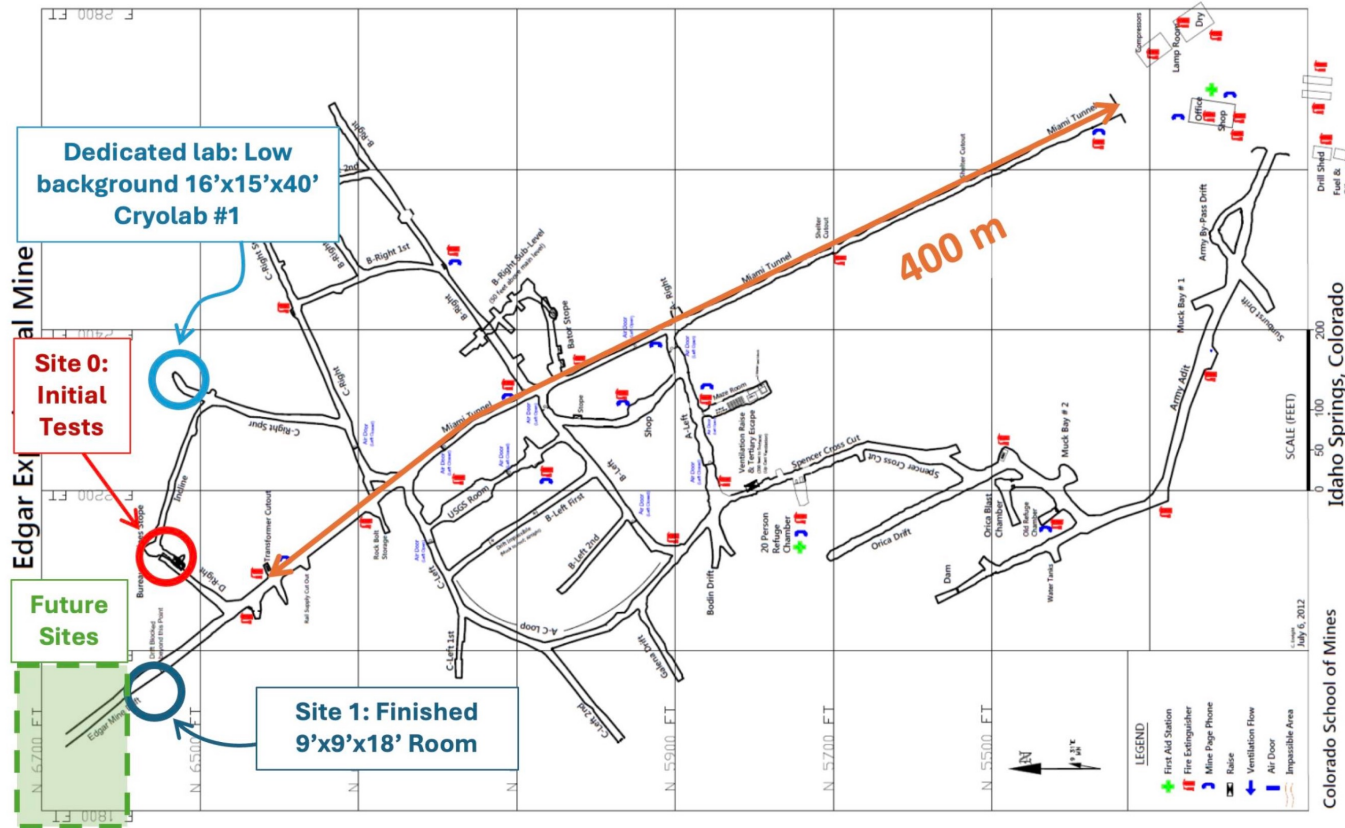
Cryolab I

$\sim 50 \text{ m}^2$

Planned: cleanroom, ventilation, 480 V 3-phase power, closed-loop chilled water

Next: additional labs being blasted beside the SPH

Two labs are operational, with more being excavated



Subatomic Particle Hideout (SPH)

~15 m²

Particle-background characterization lab,
3 × 5 × 3 m

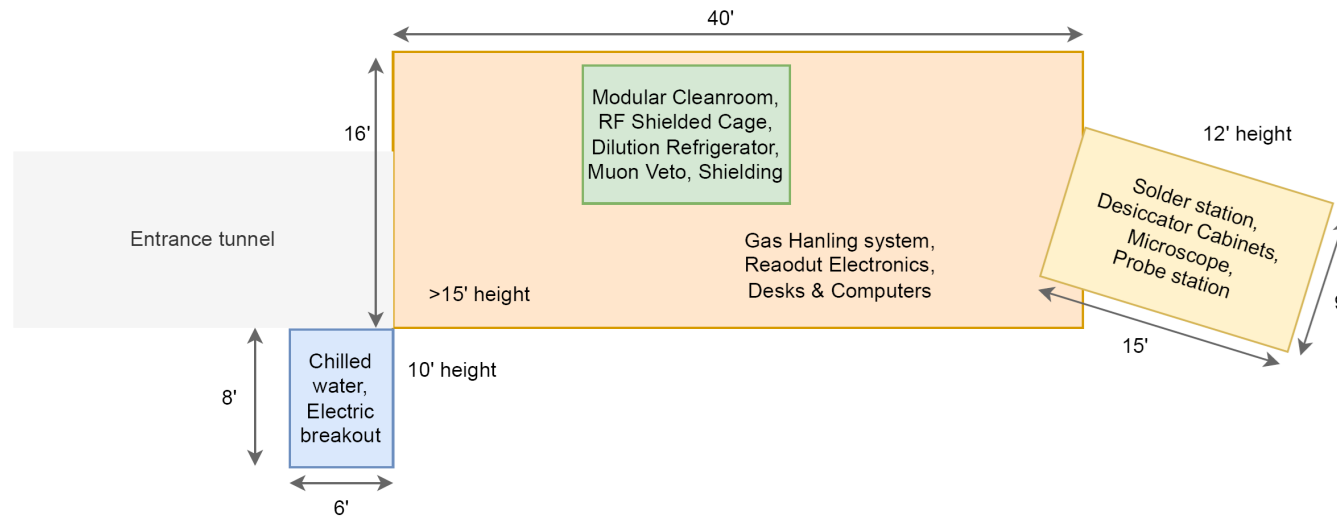
Cryolab I

~50 m²

Planned: cleanroom, ventilation, 480 V 3-phase power, closed-loop chilled water

Next: additional labs being blasted beside the SPH

Subatomic Particle Hideout and the Cryolab I



Particle Hideout (SPH)
~15 m² particle-background characterization lab

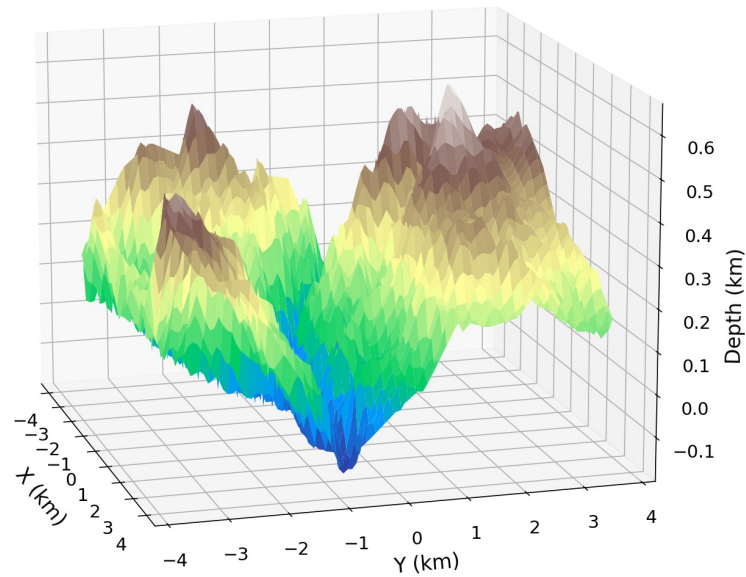


Cryolab I (CLI)
Cryogenic sensing experiments

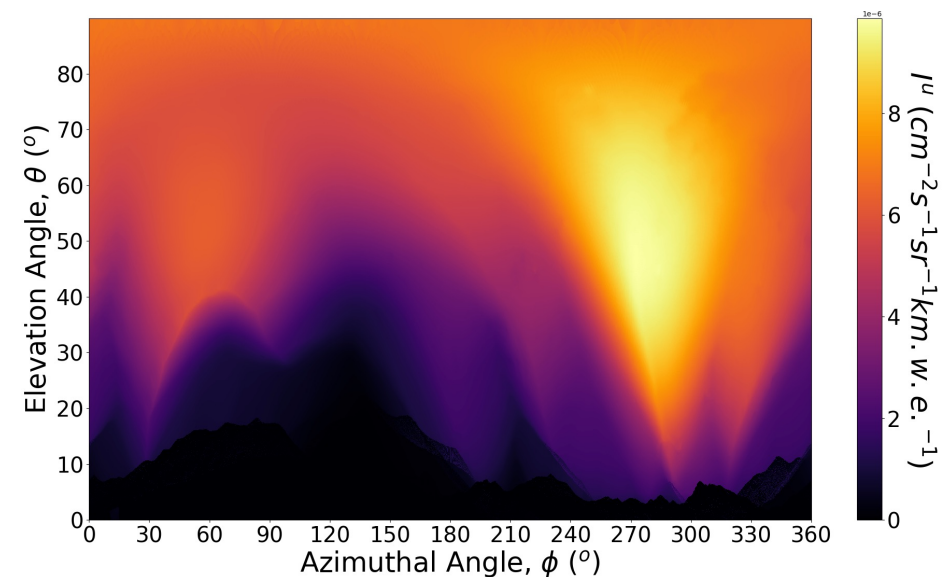
Simulation predicts muon arrival direction at each site

Input: sea-level flux (DaemonFlux¹) + LiDAR terrain

Output: intensity by angle (MUTE²)



Overburden above the SPH



Simulated muon intensity seen from the SPH

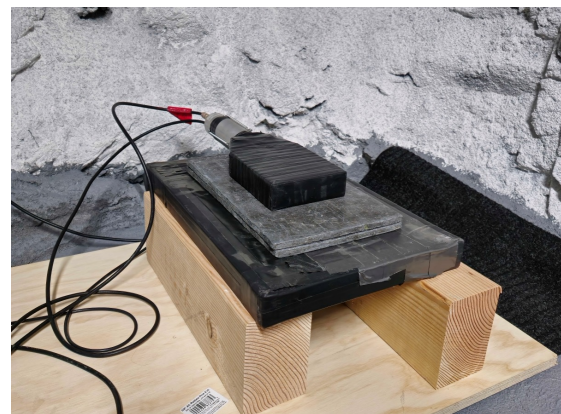
1 J. P. Yañez and A. Fedynitch, Phys. Rev. D 107, 123037 (2023). 2 A. Fedynitch, W. Woodley and M.-C. Piro, Astrophys. J. 928, 27 (2022).
Simulation: D. Keblbeck et al., Phys. Rev. D 111, 023036 (2025)

Measured muon flux matches simulation within 1σ

Underground muon flux, $\mu/\text{m}^2/\text{s}$

Site	Simulated	Measured
Cryolab I*	0.227 ± 0.023	0.246 ± 0.023
SPH	0.217 ± 0.022	0.239 ± 0.027

- **Coincidence scintillators:** 385 hrs in CLI, 620 hrs in SPH
- **Motorized telescope:** maps arrival direction, moves between sites
- **Result:** 415 m.w.e. average shielding, 700× fewer muons than sea level



Coincidence scintillators



Muon telescope

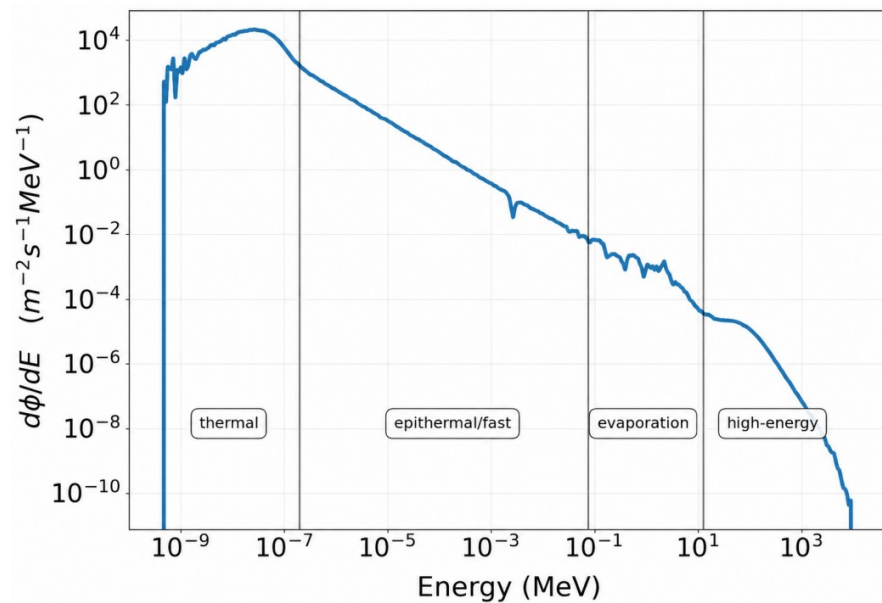
Simulated: systematic uncertainty. Measured: systematic and statistical combined in quadrature.

Source: D. Kehlbeck et al., Phys. Rev. D 111, 023036 (2025)

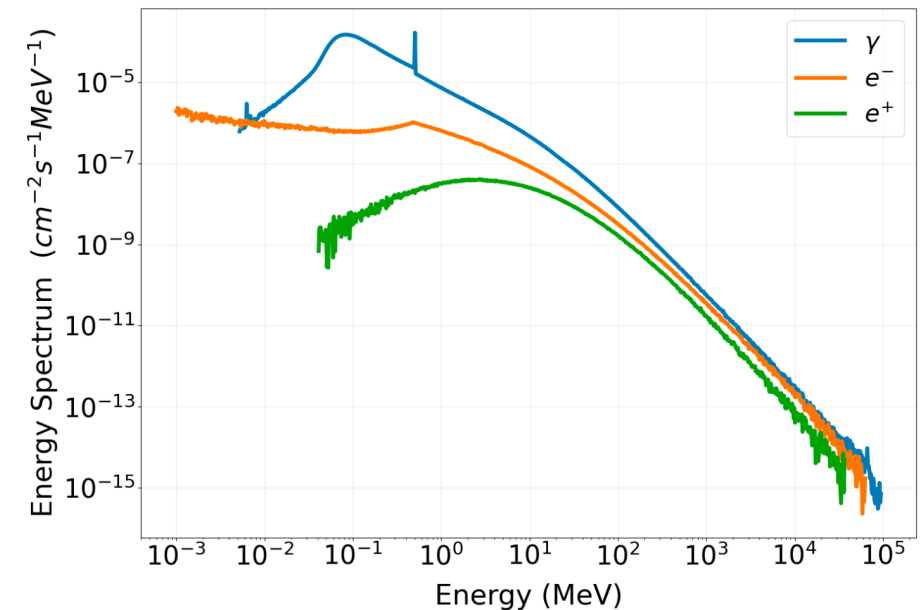
*right outside of it

Gamma flux is 65× the neutron flux in the SPH

Method: MUTE muon spectra → Geant4 rock hemisphere → secondaries at cavern wall



Muon-induced neutrons, SPH
Total: $8.5 \times 10^{-3} m^{-2}s^{-1}$

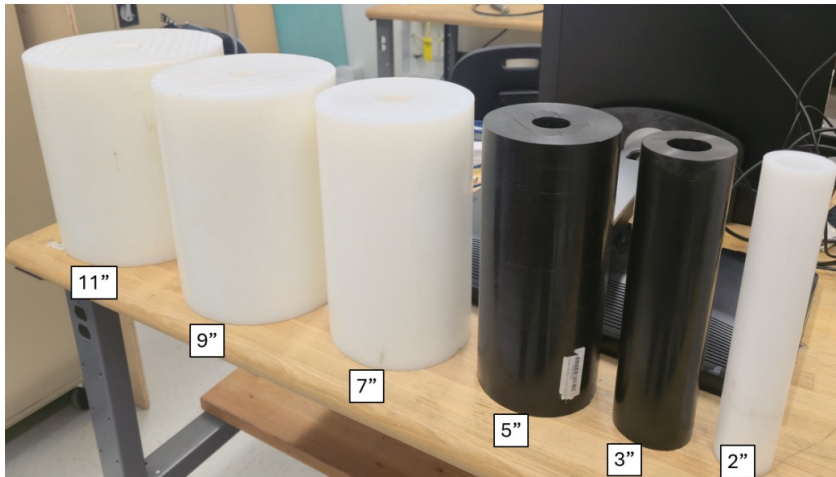


Muon-induced γ , e^- and e^+ , SPH
 γ 0.55 · e^- 0.044 · e^+ 0.011 $m^{-2}s^{-1}$

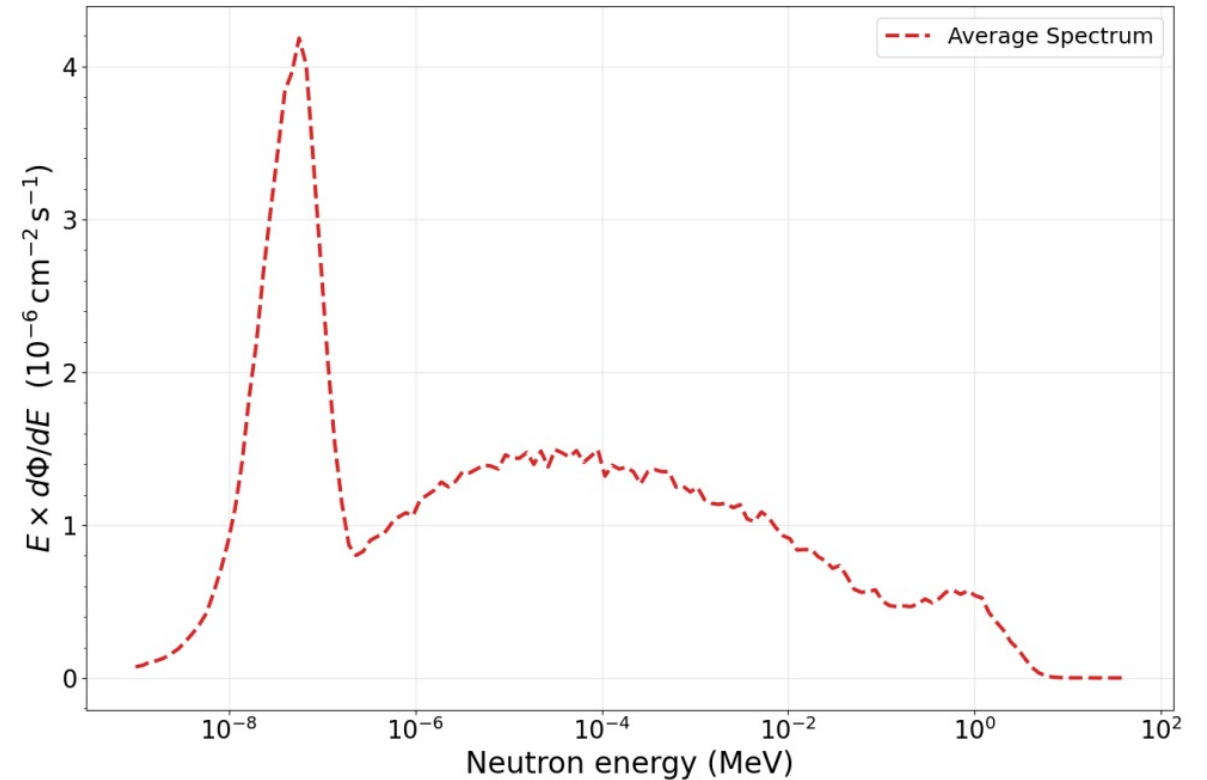
Integrated fluxes, ~15% systematic uncertainty. Spectra are per MeV, so peak heights are not comparable across species. Source: D. K. Keblbeck et al., arXiv:2510.06150 (2025)

Radiogenic neutrons measured

- **Radiogenic neutrons** are generated in Th/U decay in rock
- Spectrum measured using custom **Bonner Cylinder Spectrometer**
- ^3He counter and polyethylene cylinder moderators, calibrated using ^{239}Pu - ^9Be



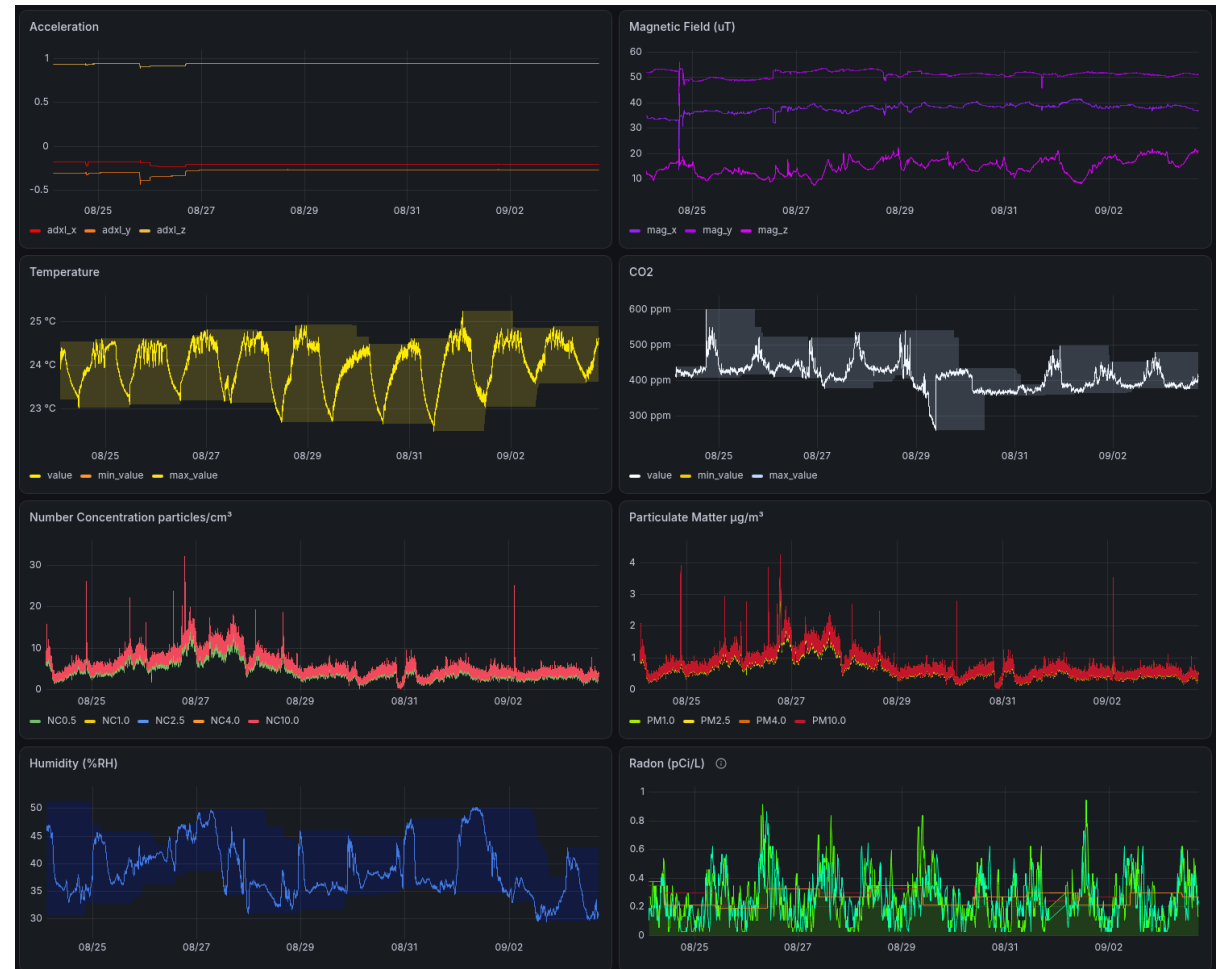
Source: D. K. Keblbeck et al., arXiv this week!



Radiogenic Neutron Spectrum

Other backgrounds: 9 continuous sensor streams

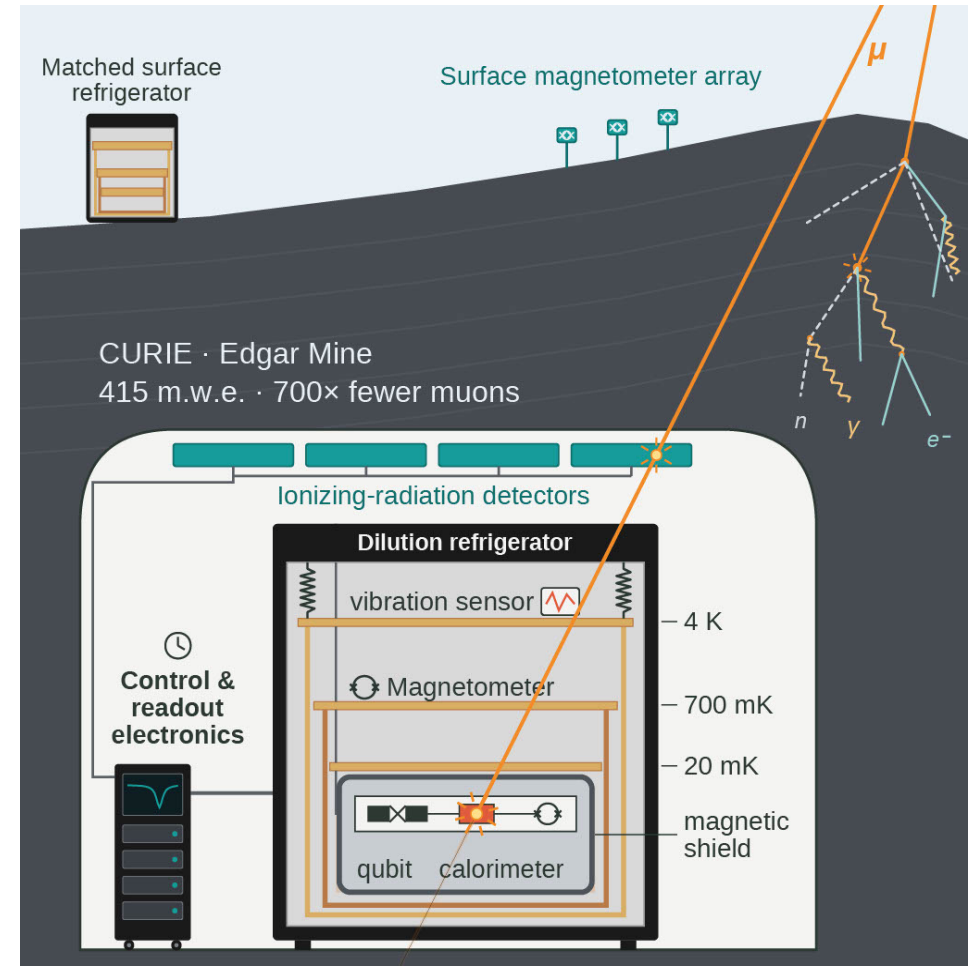
- **Vibration:** 3-axis accelerometer
- **Magnetic field:** 3-axis magnetometer
- **Radon:** two RadonEye monitors
- **Air:** CO₂, temperature, humidity, particulates, VOC/NO_x
- **Data:** ~1 Hz to Grafana, weeks of uptime, offline buffering



Sensor package and dashboard: J. Aldrich

Next: a cryogenic qubit testbed underground

- **Vericold ADR:** available now; may move underground
- **Dilution refrigerator:** funding being pursued
- **KASCADE 2x2m muon panels:** being acquired for underground and surface runs to study muon multiplicity and bundles
- **Muon telescope data campaigns:** MUTE depth study, angular characterization
- **More lab space:** new rooms being blasted beside the SPH



Concept: planned qubit testbed at CURIE

Summary

700×

fewer muons than at the surface, under 415 m.w.e. of rock

Cosmogenic Muons and Neutrons

Measured to within 1σ of simulations

Radiogenic Neutrons

Th/U source neutrons measured underground

~65 m²

of lab space today, with more rooms being blasted now

CURIE is open to collaborators

480 V power, Ethernet and Wi-Fi, live environmental monitoring, and a public background-simulation framework. Contact us with any questions!: lawanner@mines.edu

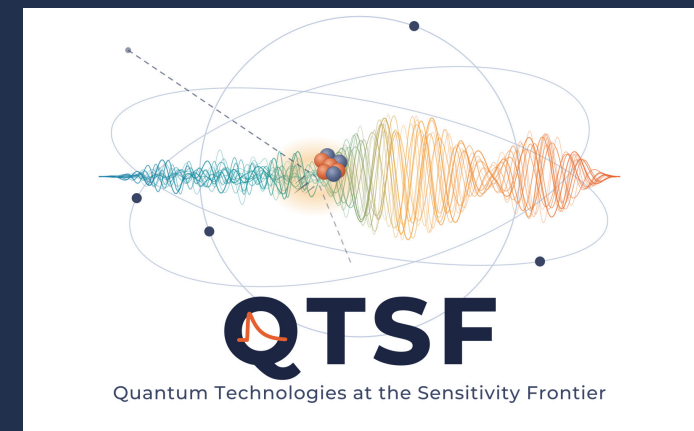
<https://CURIE.mines.edu>



COLORADO SCHOOL OF
MINES

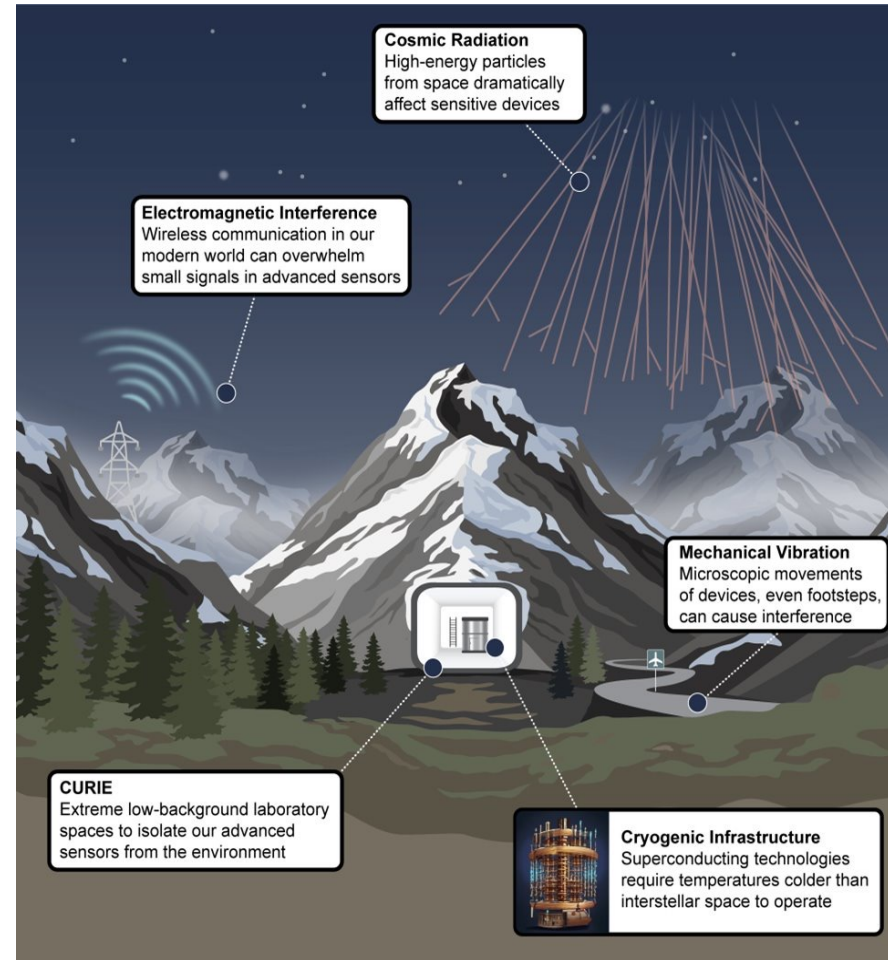
Questions?

→ <https://CURIE.mines.edu>
lawanner@mines.edu



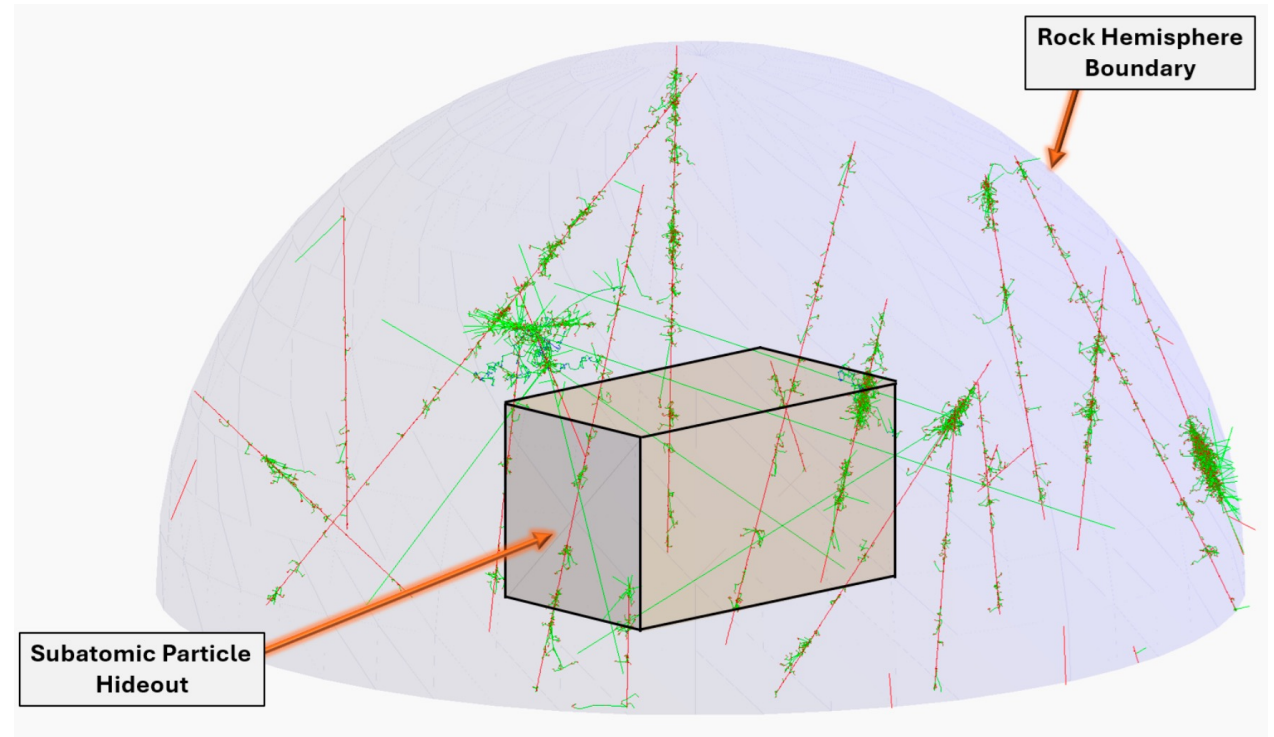
Supplemental Slides

Backup: environmental backgrounds at CURIE



Backup: Geant4 secondaries simulation

- **Input:** MUTE muon energy and angle spectra
- **Tags** every secondary crossing the rock-cavern boundary
- **Output:** secondary flux and energy spectra in each lab
- **Measured with:** ^3He neutron spectrometer, HPGe detector, large liquid scintillator



Backup: neutron depth-intensity relation

$$\Phi_n(H) = A (H_0 / H)^n e^{-H / H_0}$$

$$A = 0.003 \pm 0.001 \text{ m}^{-2} \text{ s}^{-1}$$

$$H_0 = 1.015 \pm 0.083 \text{ km.w.e.}$$

$$n = 1.562 \pm 0.192$$

Plot vs. Mei & Hime and data: paper Fig. 10

- **Predicts:** muon-induced neutron flux at the rock-cavern boundary vs. lab depth
- **Fit to:** simulated CURIE neutron fluxes
- **Why new:** the Mei & Hime extrapolation deviates below ~ 0.6 km.w.e., where shallow labs sit
- **Agrees with:** SciBath and BUST measurements

H = depth in km.w.e. Source: D. K. Keblbeck et al., arXiv:2510.06150 (2025), Eqn. 6 and Fig. 10