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Abatement of ionizing radiation for superconducting quantum devices

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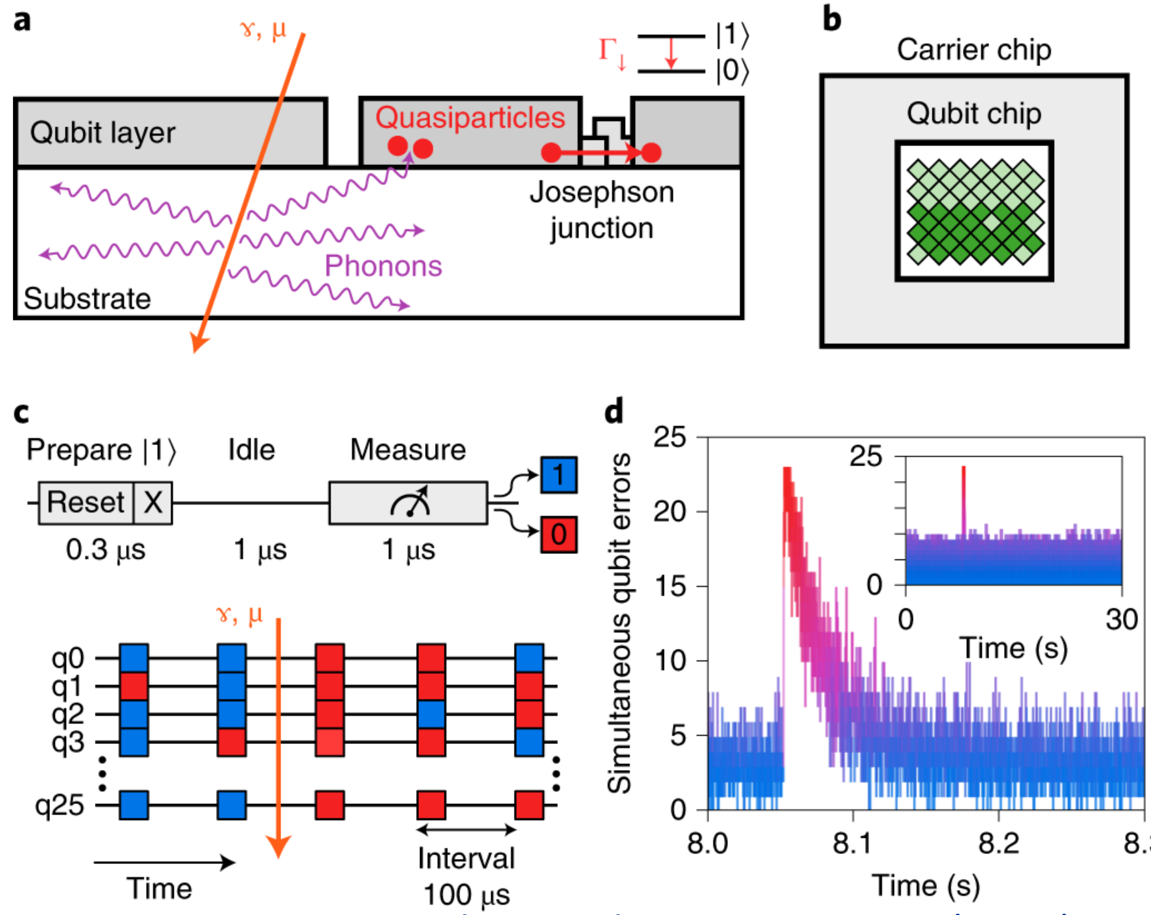
Overview

- Ionizing radiation causes faults in superconducting qubits
- Worse, may be correlated across large numbers of qubits, defeating error correction schemes



McEwen *et al. Nat. Phys.* **18**, 107–111 (2022).

- Examine the relative importance of
  - Cosmic ray secondaries
  - Environmental gamma background
  - Radioactivity inside the dilution refrigerator
- Predict performance if devices operated in the Low Background Cryogenic Facility (LBCF), a shielded dilution refrigerator in PNNL's Shallow Underground Laboratory

Sources of ionizing radiation

- External sources
  - Gammas
  - Cosmic ray secondaries (muons)
- Most mass of the fridge is:
  - Copper, gold plating
  - Aluminum (radiation shields)
  - Steel (Vacuum flange)
  - Mumetal (magnetic shielding)

Low Radioactivity
Moderate or Variable Radioactivity
High Radioactivity/Rate

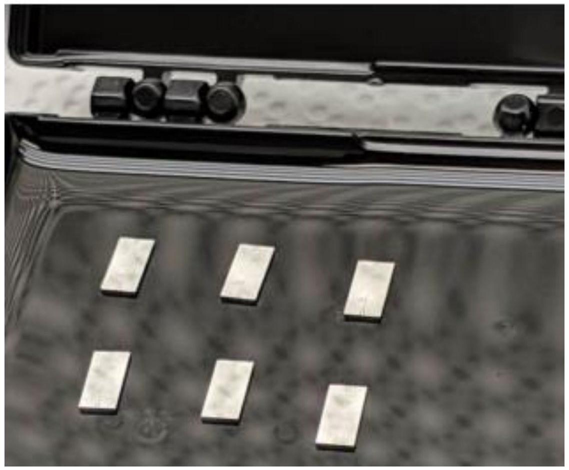
Most high radioactivity materials are very small mass
BUT
Many of them are very close to the devices

- Packaging and readout:
  - Silicon chips
  - Wirebonds
  - Indium (bump bonds)
  - Epoxy, varnish
  - FR4, ceramics (PCBs)
  - BeCu (electrical connectors)
  - Copper

assay

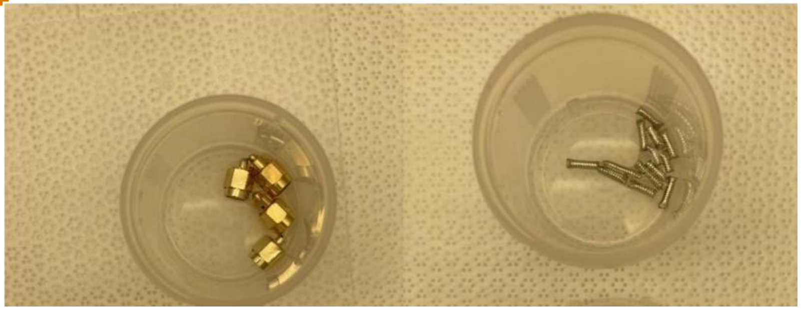
Assay of critical components

- Qubits (ICP-MS)
  - Fabricated at MIT-Lincoln Labs, each chip 2.5x5x0.3 mm
  - 3 replicates measured, only 1 above detection limit
  - Not significantly any dirtier than pure silicon

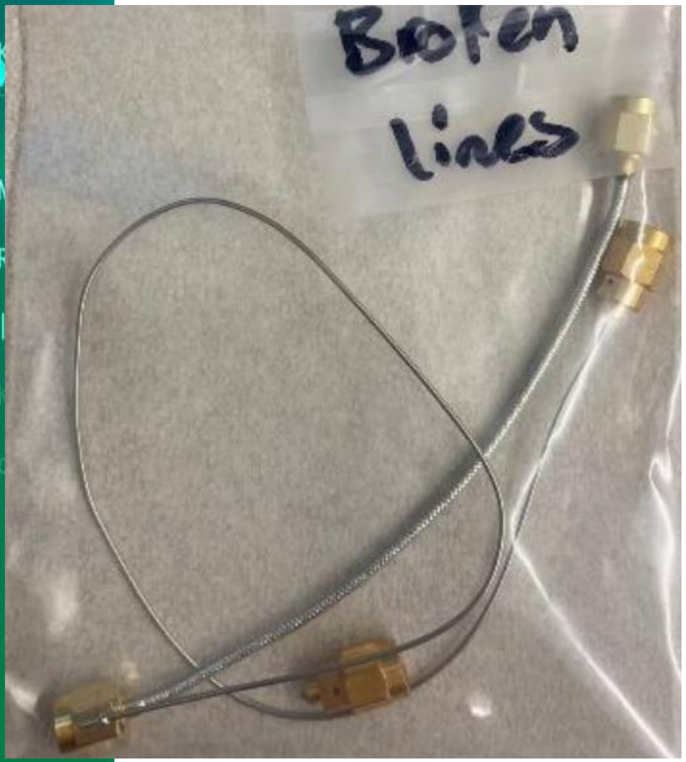


Sample	^{232}Th (mBq/kg)	^{238}U (mBq/kg)	Ref.
Qubits	0.0065 ± 0.0012	0.014 ± 0.003	This work
Silicon	<0.0073	<0.011	[38]
OFHC Cu	0.0001–0.01	0.001–0.05	[39–41]

Assay of critical components



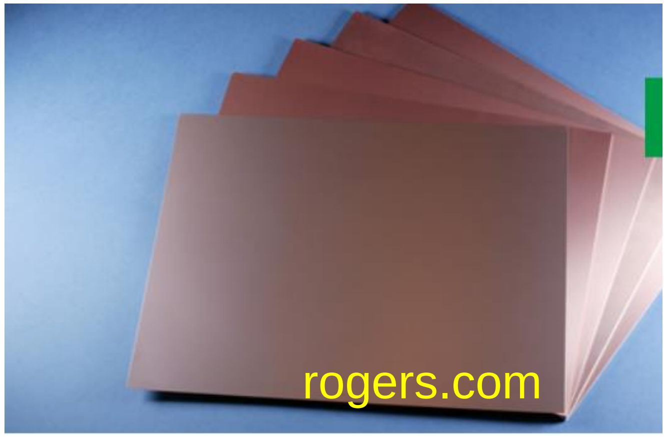
- Qubits (ICP-MS)
- Cryogenic SMA connector and semirigid coax cable (ICP-MS)
  - Only metal parts digested (e.g. not PTFE dielectric)
  - Cables fairly clean, connectors dirty (likely BeCu)



PNNL ID	Description		total sample mass [g]	measured mass [g]	mass fraction measured	^{232}Th milliBq/kg	^{232}Th ± inst	^{238}U milliBq/kg	^{238}U ± inst
			normalized to metal mass						
2023-10-01	coax connector metal	r1	2.9040	2.6336	0.907	1430	20	21000	2000
		r2	2.8953	2.6432	0.913	2240	140	25000	2000

PNNL ID	Description		total sample mass [g]	measured mass [g]	mass fraction measured	^{232}Th milliBq/kg	^{232}Th ± inst	^{238}U milliBq/kg	^{238}U ± inst
2023-10-02	coax cable metal	r1	0.1429	0.1056	0.739	<0.130	--	<0.39	--
		r2	0.1872	0.1334	0.713	<0.152	--	<0.42	--
		r3	0.1552	0.1111	0.716	<0.16	--	<0.49	--

Assay of critical components



- Qubits (ICP-MS)
- Cryogenic SMA connector and semirigid coax cable (ICP-MS)
- Low loss ceramic PCB substrates Rogers TMM10 and RO4350B (HPGe)

Sample	Mass	^{40}K	^{208}Tl	^{212}Pb	^{214}Bi	^{214}Pb	^{226}Ra	^{210}Pb
TMM10	200 g	17.3(9)	1.51(6)	5.5(3)	28.9(4)	25.4(8)	29(2)	-
RO4350B	30 g	9.1(8)	4.9(2)	15.1(9)	-	11.2(4)	8(4)	11(2)

Building a background model

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Radioactivity assays

Material	^{238}U	^{232}Th	^{40}K	^{60}Co	^{137}Cs	^{210}Pb[a]	Act.[b]	Ref.
	Isotope concentrations (mBq/kg)							
copper	0.070	0.021	0.023	0.002	-	40	6.6	[46, 50, 51]
lead	0.04	0.005	0.1	-	-	200000	-	[45, 52, 53]
steel	130	2.4	10	8.5	0.9	-	-	[46]
aluminum	66	200	2100	-	-	-	-	[46]
gold	74	19	150	-	-	-	-	[45, 54]
brass	4.9	3.5	40	-	2.6	40	6.6	[49, 55]
Kapton	10	20	60	3	-	-	-	[47, 55]
Al bonding wire	110	370	100	-	-	-	-	[45]
mumetal	20	7	15	-	-	-	-	[56]
isolator	240	190	2000					
HEMT	1000	890	10000					
K&L filter	9	23	100					
attenuator	200	52	140					
alumina	5000	66	600					
Rogers TMM10	29000	5500	17000					
Rogers RO4350B	11000	15000	9000					
SMA connector	23000	1800	-					
coaxial cable	0.4	0.15	-					
qubit chip	0.014	0.0065	-					
Indium	^{115}In: 250000							

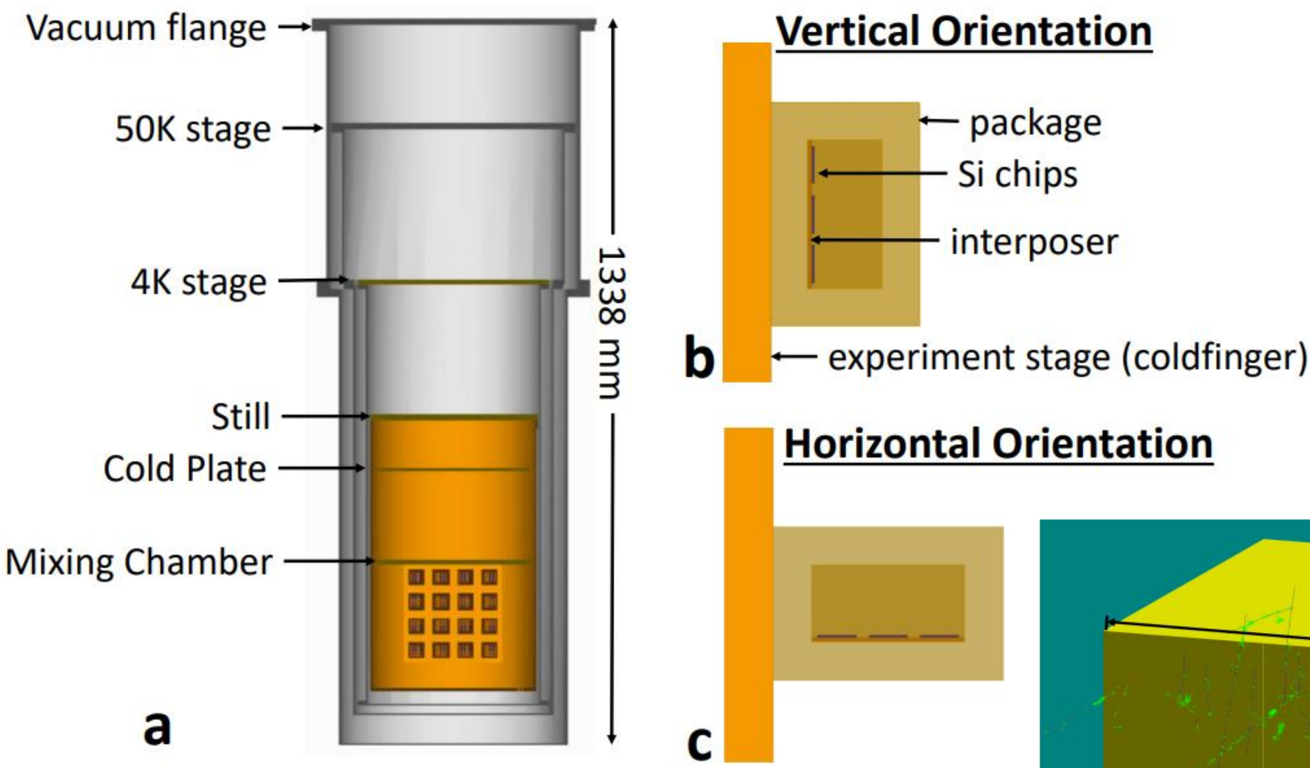
Bill of materials

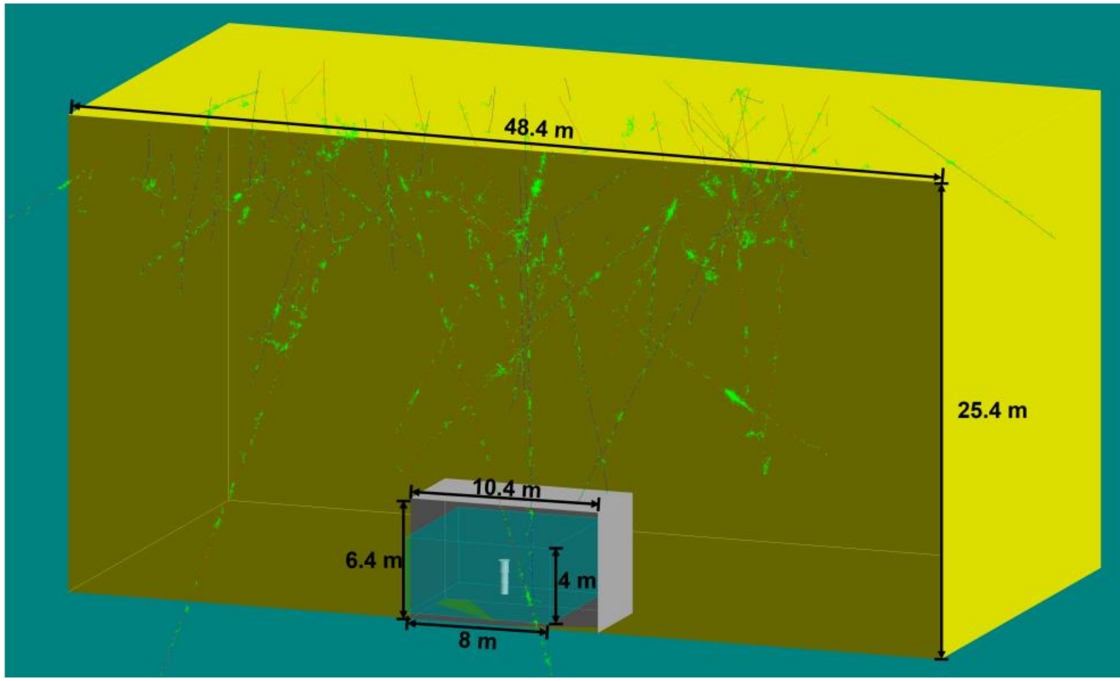
Component	Material	Mass (kg)
Cosmic rays (chip horizontal)		
Cosmic rays (chip vertical)		
Ambient Gammas		
Ceramic PCB interposers		
	alumina	780 mg
	RO4350B	370 mg
	TMM10	550 mg
Coax connectors on package		
inside (line-of-sight)	SMA	10 × 2.3 g
outside (no line-of-sight)	SMA	10 × 2.3 g
Bump bonds	indium	20 μg
All other components (itemized below)		
Fridge stages and shields		
MXC stage	Cu	4.6
CP stage	Cu	3.3
Still stage	Cu	5.9
4K stage	Cu	8.7
50K stage	Cu	5.1
Vacuum flange	steel	21
Still can	Cu	6.3
4K can	Al	4.1
50K can	Al	5.7
Vacuum can	Al	21
Gold plating	gold	0.5
Experiment readout		
Wirebonds	Al/Si	10 × 0.1 mg
Package	Cu	0.1
Package Fasteners	brass	10 × 0.3 g
Cryo filters	K&L	10 × 15 g
Closest coax cable	semirigid	10 × 10 cm
Coldfinger	Cu	1.8
Inner shield		
	Cu	1
	Al	1
	mumetal	1
MXC DC feedthroughs	BeCu	100 pins
MXC RF feedthroughs	SMA	10 × 2.3 g
MXC RF attenuators		10 × 5 g
MXC isolators		10 × 145 g
4K HEMT amplifiers		10 × 17 g

Simulated hit efficiencies

Source location	^{238}U	^{232}Th	^{40}K	^{60}Co	^{137}Cs	^{210}Pb
	Hit efficiency, 1/g/s/Bq					
Bump bonds	8.3E+2	6.6E+2	5.4E+1	5.6E+1	6.4E+1	^{115}In:
Interposer board	7.3E+0	5.2E+0	1.5E+0	3.1E-1	8.3E-1	1.5E+0
Package	7.3E-2	6.0E-2	1.2E-2	2.1E-2	9.8E-3	8.0E-3
Package Connector Inside	8.4E-1	5.2E-1	1.8E-1	5.3E-2	7.5E-2	
Package Connector Outside	1.4E-2	1.7E-2	9.4E-4	1.4E-2	4.8E-3	
Experiment stage	7.3E-4	1.0E-3	4.5E-5	9.1E-4	2.3E-4	2.5E-6
Experiment shield	2.2E-4	2.8E-4	1.3E-5	2.5E-4	8.1E-5	0.0E+0
Mixing Chamber Stage	1.2E-4	1.6E-4	8.8E-6	1.5E-4	4.4E-5	1.8E-7
Cold Plate Stage	1.7E-5	2.3E-5	1.1E-6	2.3E-5	6.8E-6	1.4E-8
Still Stage	7.3E-6	9.3E-6	5.8E-7	9.5E-6	2.6E-6	4.8E-9
4K Stage	1.6E-6	2.3E-6	1.3E-7	2.7E-6	4.1E-7	0.0E+0
50K Stage	4.6E-7	7.4E-7	2.1E-8	8.2E-7	1.9E-7	3.1E-9
Vacuum Flange	2.6E-7	3.3E-7	1.5E-8	4.0E-7	8.6E-8	0.0E+0
Still Can	6.0E-5	8.1E-5	4.3E-6	7.4E-5	2.1E-5	7.5E-8
4K Can	3.0E-5	3.9E-5	2.1E-6	3.6E-5	1.1E-5	9.7E-9
Lower 50K Can	2.5E-5	3.1E-5	1.8E-6	2.9E-5	9.1E-6	9.7E-9
Upper 50K Can	9.3E-7	1.3E-6	3.6E-8	1.5E-6	4.4E-7	0.0E+0
Lower Vacuum Can	1.7E-5	2.3E-5	1.4E-6	2.1E-5	7.6E-6	0.0E+0
Upper Vacuum Can	6.3E-7	1.0E-6	8.7E-8	1.1E-6	2.1E-7	0.0E+0

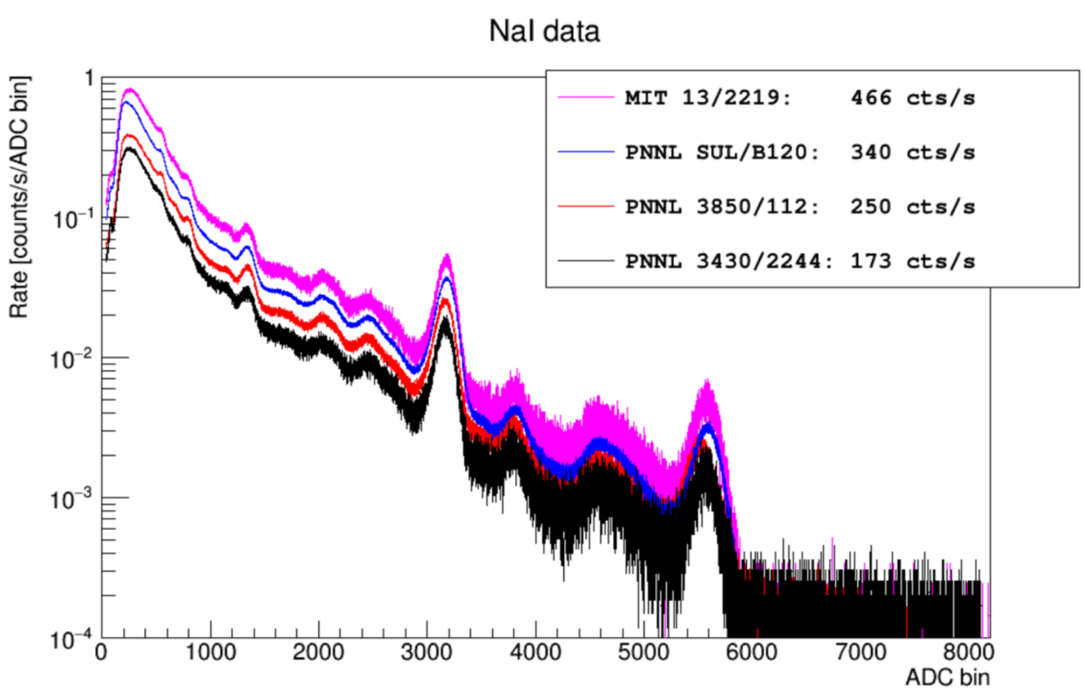
Simulation setup

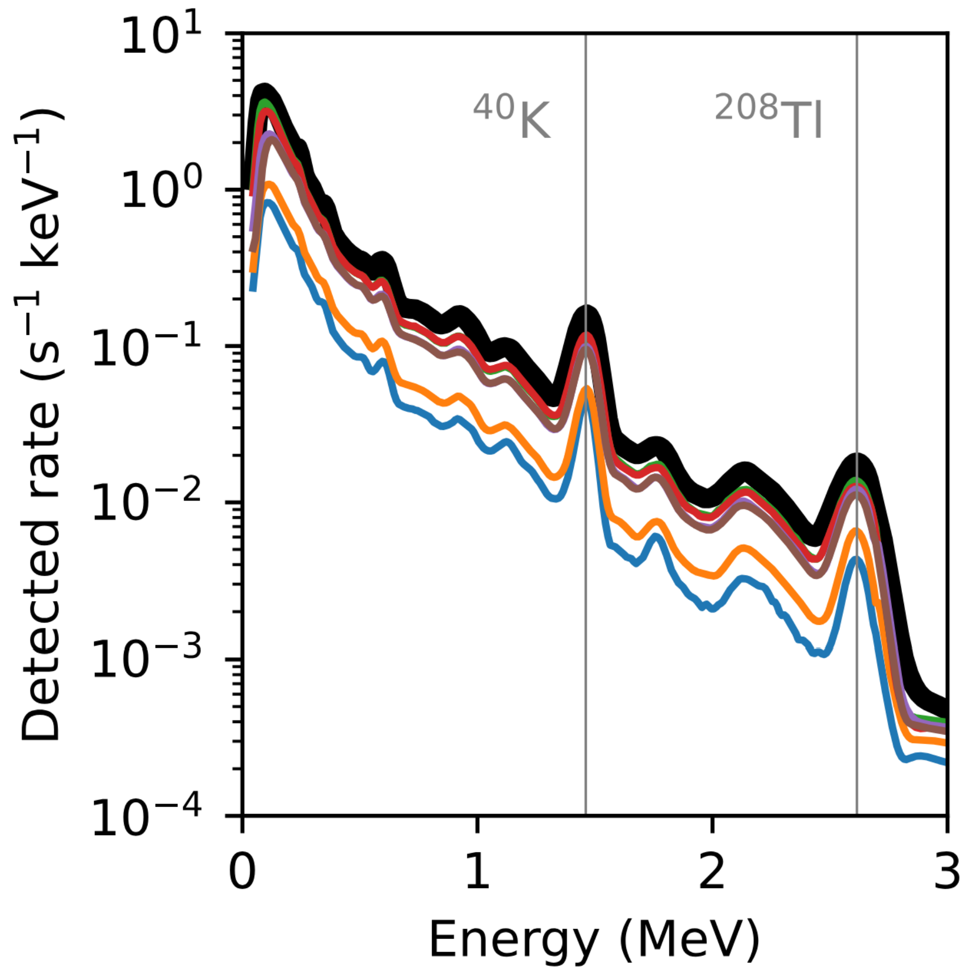




Common Gamma Backgrounds

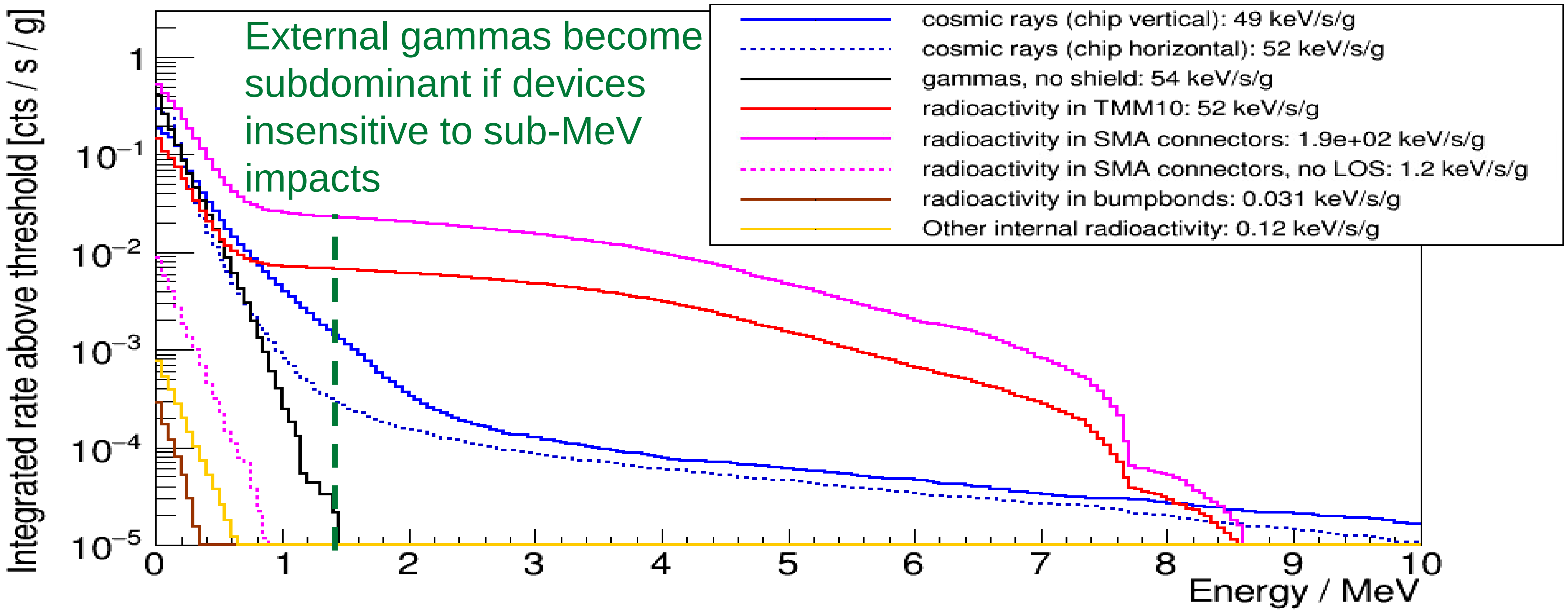
- Environmental gamma and muon rates measured in multiple buildings, laboratories, and institutions with same instrument
- All within factor of ~5





Typical Radiation budget at surface

Count rate above threshold



Key Takeaways

- Three dominant sources of ionizing radiation events:
  - Cosmic ray secondaries
  - Ambient gammas
  - Line-of-sight “dirty” components (ceramic PCBs, BeCu coax connectors)
- If devices are sensitive to low energy impacts, these sources contribute roughly equally
- If there is a significant threshold effect, line-of-sight alphas are the biggest concern, followed by cosmic rays, and gammas are very subdominant

In Situ Measurements

Spectroscopic measurements and models of energy deposition in the substrate of quantum circuits by natural ionizing radiation

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(Dated: April 18, 2024)

arXiv:2404.10866

Accepted to PRX Quantum

In Situ Measurements

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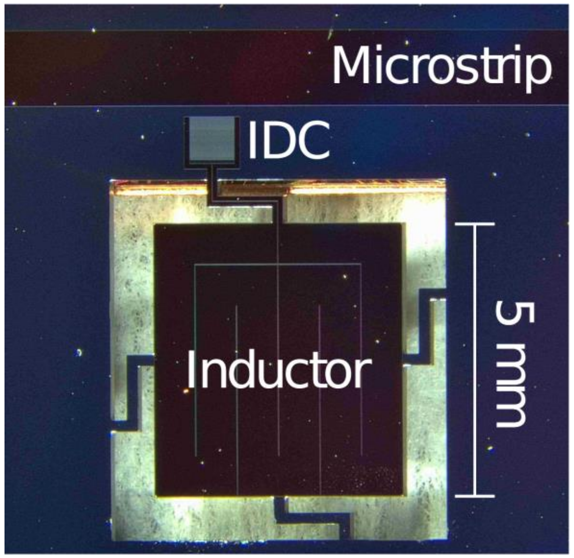
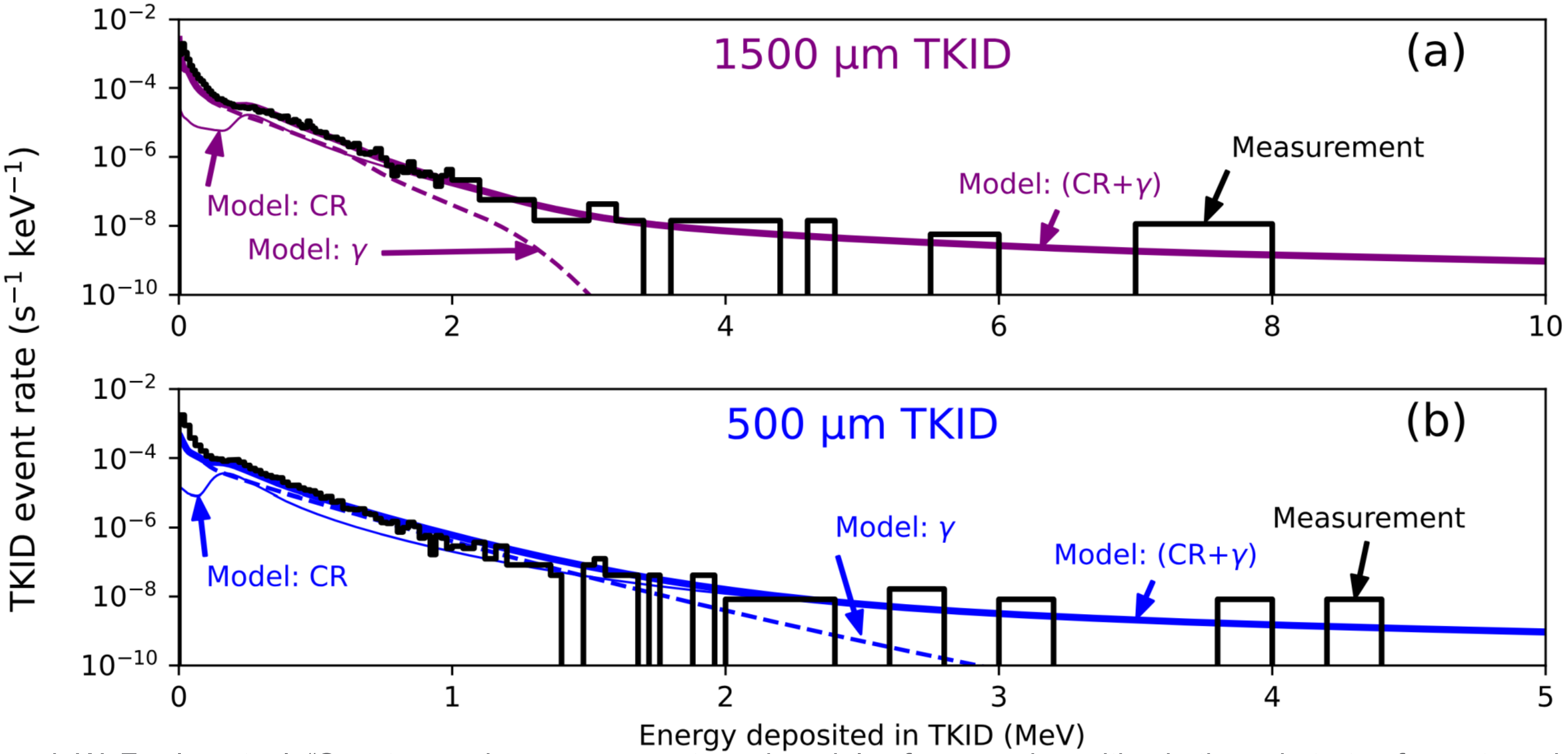
Spectrum of pulses recorded in 5x5 mm^2 Thermal KID microcalorimeter agrees well with predictions. Only Cu and Al have line-of-sight to sensor.





Joseph W. Fowler, et. al. "Spectroscopic measurements and models of energy deposition in the substrate of quantum circuits by natural ionizing radiation." arXiv:2404.10866

North American Underground QIS Facilities

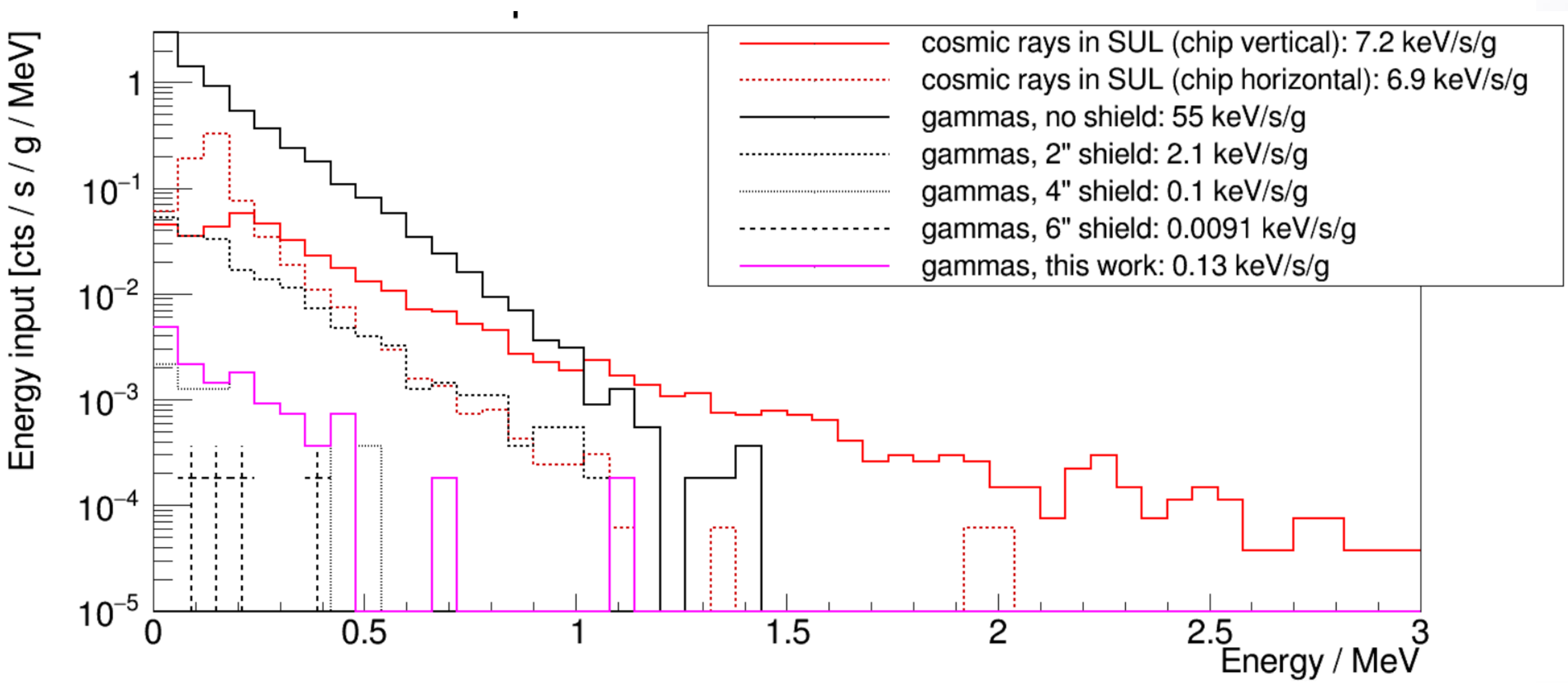
- PNNL
- Fermilab
- SNOLAB
- SURF
- Colorado School of Mines

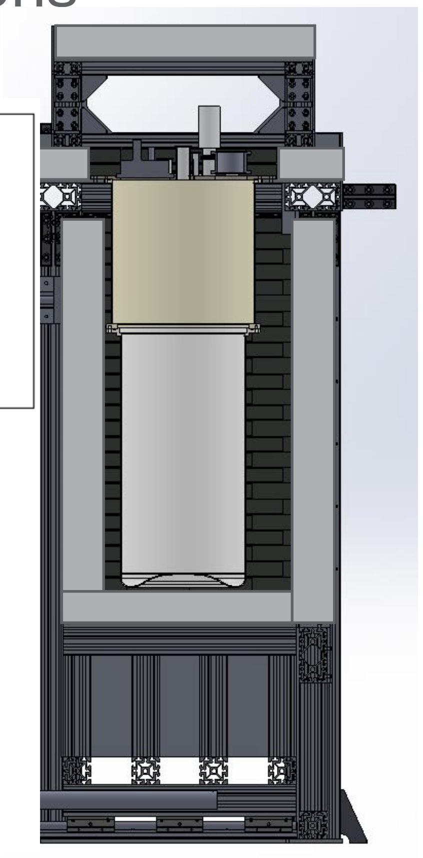
PNNL Shallow Underground Laboratory

- SUL houses clean rooms (class 10,000 and 1,000) , world-leading ultra-pure material growth and characterization capability
- 19 m overburden reduces muon flux by 6X, neutron and proton flux by >100X
- Bluefors LD-400 operating for ~1.5 years

Low Background Cryogenic Facility (LBCF) shield design approach

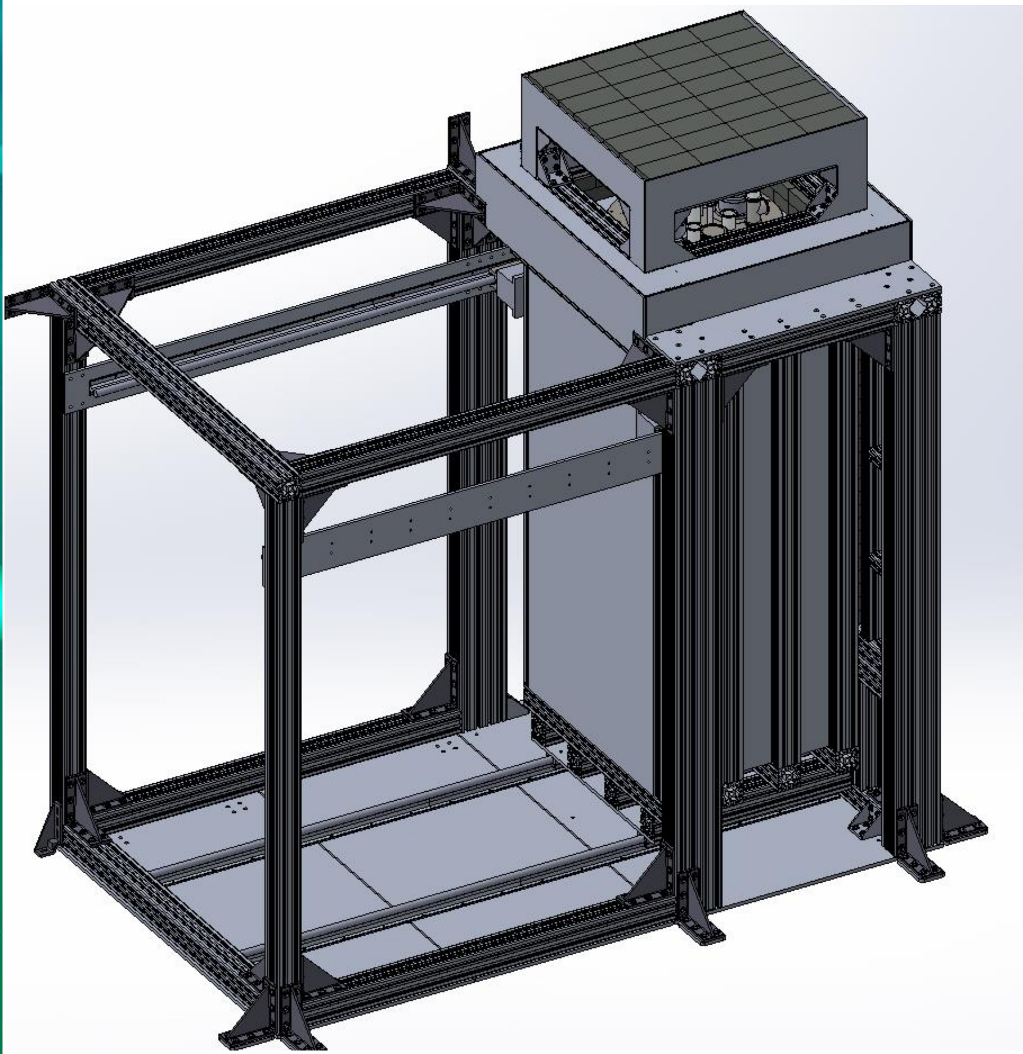
- Surround dil fridge model floating in space with hermetic lead shield of different thickness
- "Done" when residual gamma rate is below ~10% residual muon rate at 4" thick
- Then add holes for access, framing, seams between sections

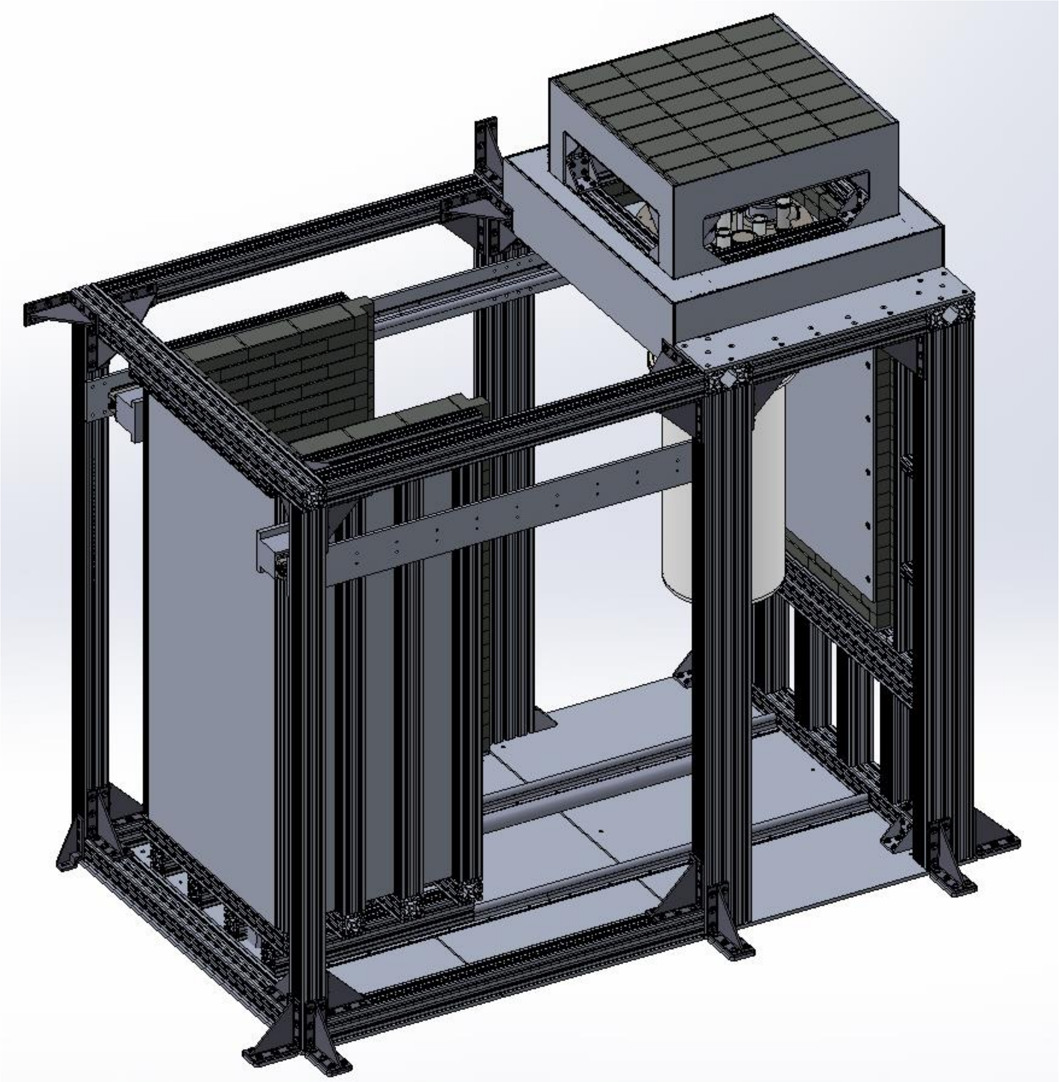




LBCF Shield design

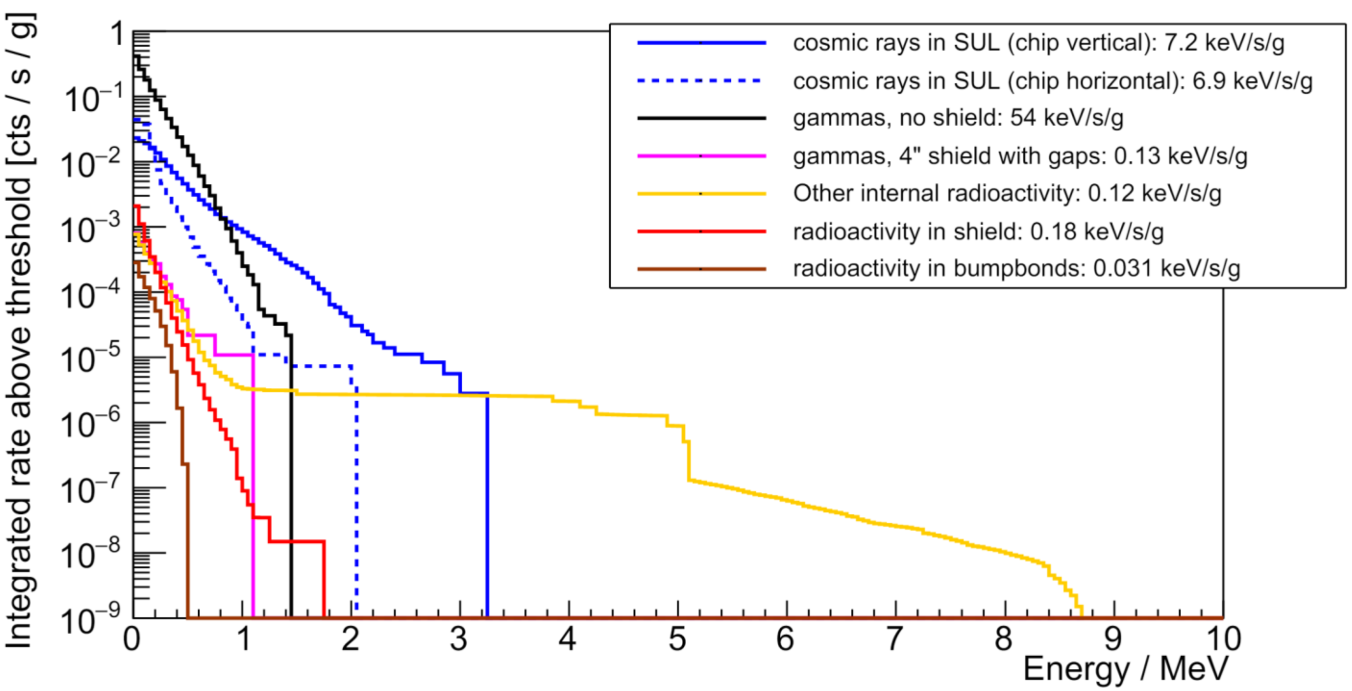
- Reduces gamma rate by ~99.8%
- Automated cage door open/close enables A/B tests for ambient radiation
- Expected completion late Summer 2024





Devices running in the LBCF

- McEwen et. al. observed “catastrophic” error bursts with rate ~1/(10s)
- Estimated radiation dose in LBCF ~5% of “typical” surface lab if care paid to line-of-sight components
- If McEwen error rate is 100% radiation-driven, naïve scaling suggests error burst rate in LBCF would be ~1/(2 minutes)
- Cosmic ray muons dominate at low-to-medium energy
- ^{210}Pb in copper housings likely dominates at high energy (~few/year)



QIS @ Fermilab

QUIET

Quantum Underground Instrumentation Experimental Testbed

QUIET was built to significantly enhance our capabilities in underground quantum work, with the following advantages over NEXUS:

- NEXUS is very high-demand and not dedicated to qubit operations
- Dedicated qubit experimental volume is limited
- Once the DD neutron generator turns on, NEXUS will switch from being a low-background facility to a neutron-calibration (activated) facility

Need a low-background facility dedicated to RF and qubit operations → QUIET

Fermilab

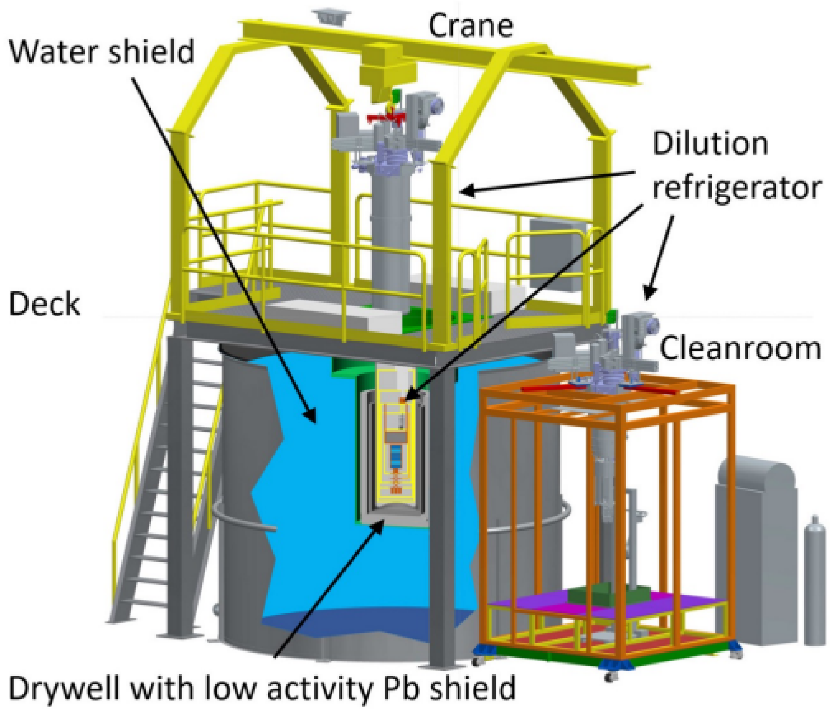
[Tali Figueroa, RISQ 2024](#)

QIS @ SNOLAB: CUTE
Cryogenic Underground TEst Facility

Facility Overview

What the CUTE Facility can offer:

- SNOLAB operated facility (accepting proposals)
- Operational temperature as low as 12 mK
- Low overall radioactive background
- Minimal mechanical vibrations thanks to cryostat suspension system
- Low level of electromagnetic interference
- Availability of calibration sources (gamma, neutron)
- Full remote operations
- Low-radon, class 300 cleanroom to change payload
  - Typical Rn level < 15 mBq/m^3



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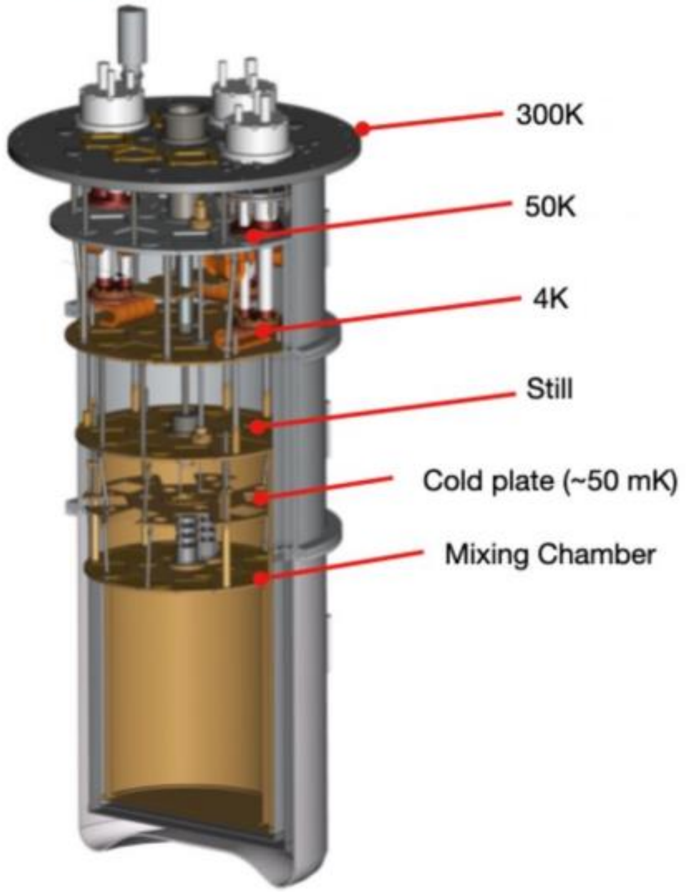
[Andrew Kubik, RISQ 2024]

QIS @ SURF

SURF Cryogenic User Facility

Proposal inline with becoming DOE scientific user facility

- **Multi-user, low-background, ultra-low temperature test facility for cryogenic detectors:**
  - Applications in **fundamental nuclear and particle physics research** (neutrinos and dark matter)
  - Detectors with extremely low energy thresholds and excellent energy resolution require **isolation from ionizing radiation** at deep facility like SURF to be effective
  - Detectors often rely on quantum thermal sensors with operating **temperatures in milli-Kelvin range** requiring dilution refrigerator
- **Cryogenic User Facility at SURF:**
  - **No deep underground cryogenic test facility in U.S.** (recent shallow sites addressing general shortage of underground cryogenic test infrastructure in U.S. – PNNL & FNAL!)
  - **Significant interest from U.S.-based groups**: low-mass dark matter (TESSERACT, SPLENDOR), neutrinoless double-beta decay (CUPID), quantum information systems (MIT, UIUC); collaborating with Virginia Tech
  - Underground cleanroom, cooling infrastructure available; clean shielding Pb and surface lab space possible.



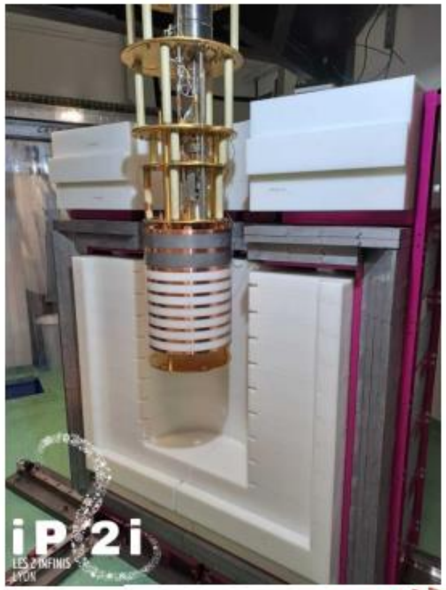
Proposing Bluefors XLD1000SL dilution refrigerator to accommodate large payload (detectors/shielding)

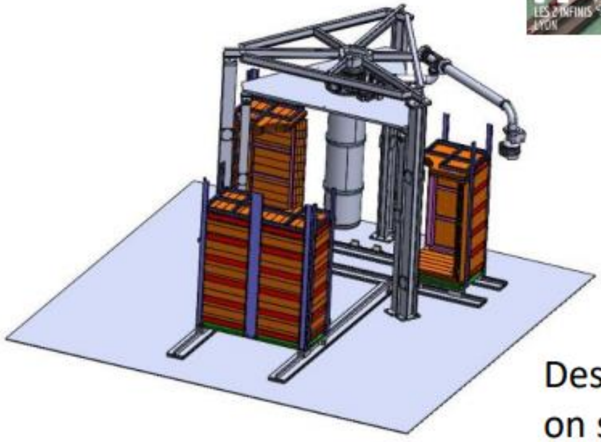
[Janet Heise, RISQ 2024]

QIS @ Colorado School of Mines
Edgar Mine

mK Testing Platform

- mK platform built around dilution fridge
- Surrounded by scintillators for active muon veto
- Layered shell of lead and borated polyethylene for gamma and neutron reduction
- Inside of fridge to have cryogenic muon veto, additional lead shielding, and superconducting magnetic shielding
- Thermometry and advance sensors off well-understood noise environment
- Quantum-limited MW amplifiers will read out devices under development





Design to be based on schematic

 PHYSICS COLORADOSCHOOLOFMINES

For more information: Wouter Van De Pontseele wvdp@mit.edu
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PHYSICS.MINES.EDU

[Dakota Keblbeck, RISQ 2024]

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Summary

- PCBs and BeCu connectors dominate radiation budget if within direct line-of-sight of device, especially at high energy
- Otherwise ambient gammas and cosmic ray muons contribute roughly equally
- Therefore both shielding and overburden are necessary to achieve reduction
- PNNL Low Background Cryogenic Facility achieves 85% reduction in cosmic ray muons, expects 99.8% reduction in internal gammas, total 95% reduction in ionizing radiation event rate for typical chips
- Expected error burst rate ~2 minutes

Thank you