Pacific Northwest NATIONAL LABORATORY

Suppressing high energy events in superconducting devices in a shallow underground laboratory

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U.S. DEPARTMENT of ENERGY BATTELLE

Qubits and Radiation

- Radiation deposited in qubit substrates contributes to qubit decoherence
- Large energy deposits can cause correlated errors across chip,
  - *These catastrophic error bursts cannot be fixed with error correction code*
- Gap engineering has come to the rescue!
  - Catastrophic error burst can be highly suppressed, but not quite eliminated

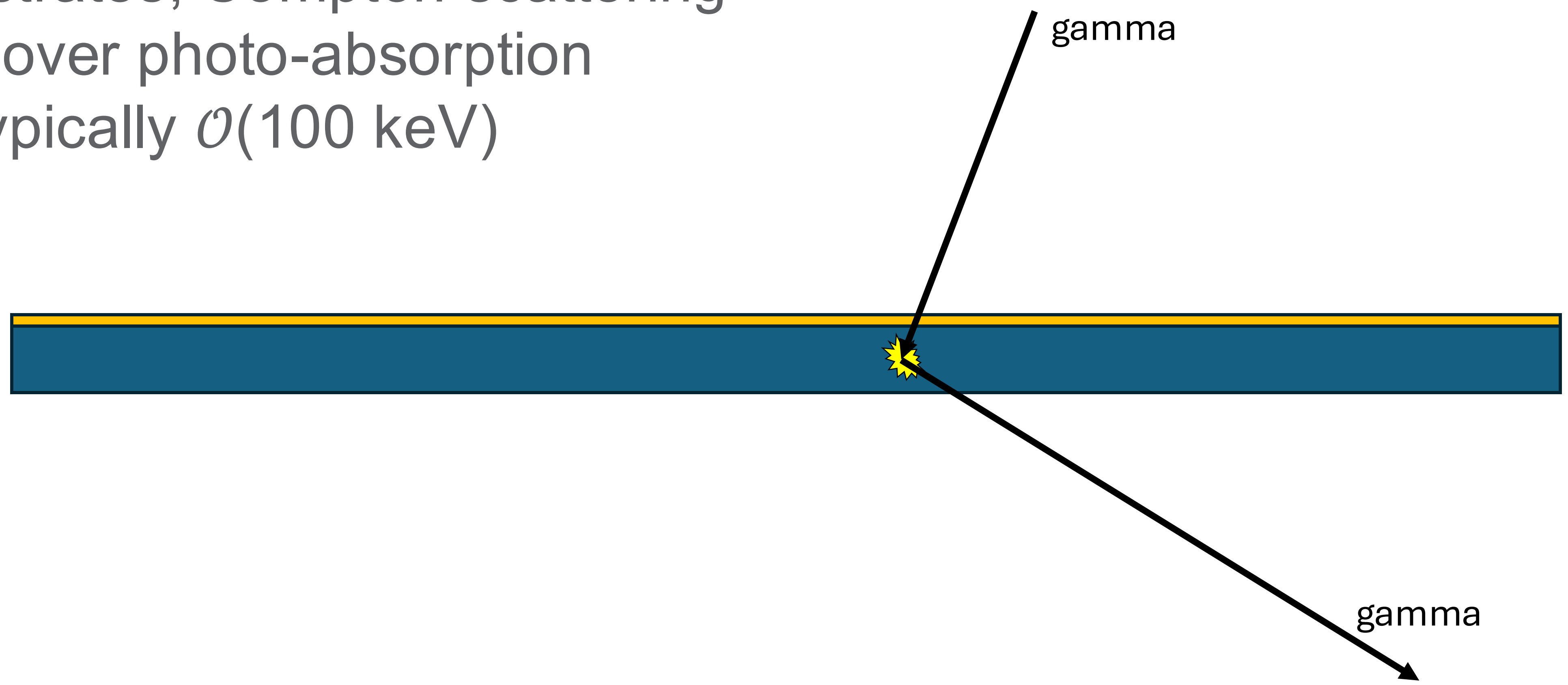
- We claim it is the ***highest energy radiation events*** which remain resistant to gap-engineering fixes

Radiation in a Qubit Substrate

Radiation in a Qubit Substrate

gamma radiation:

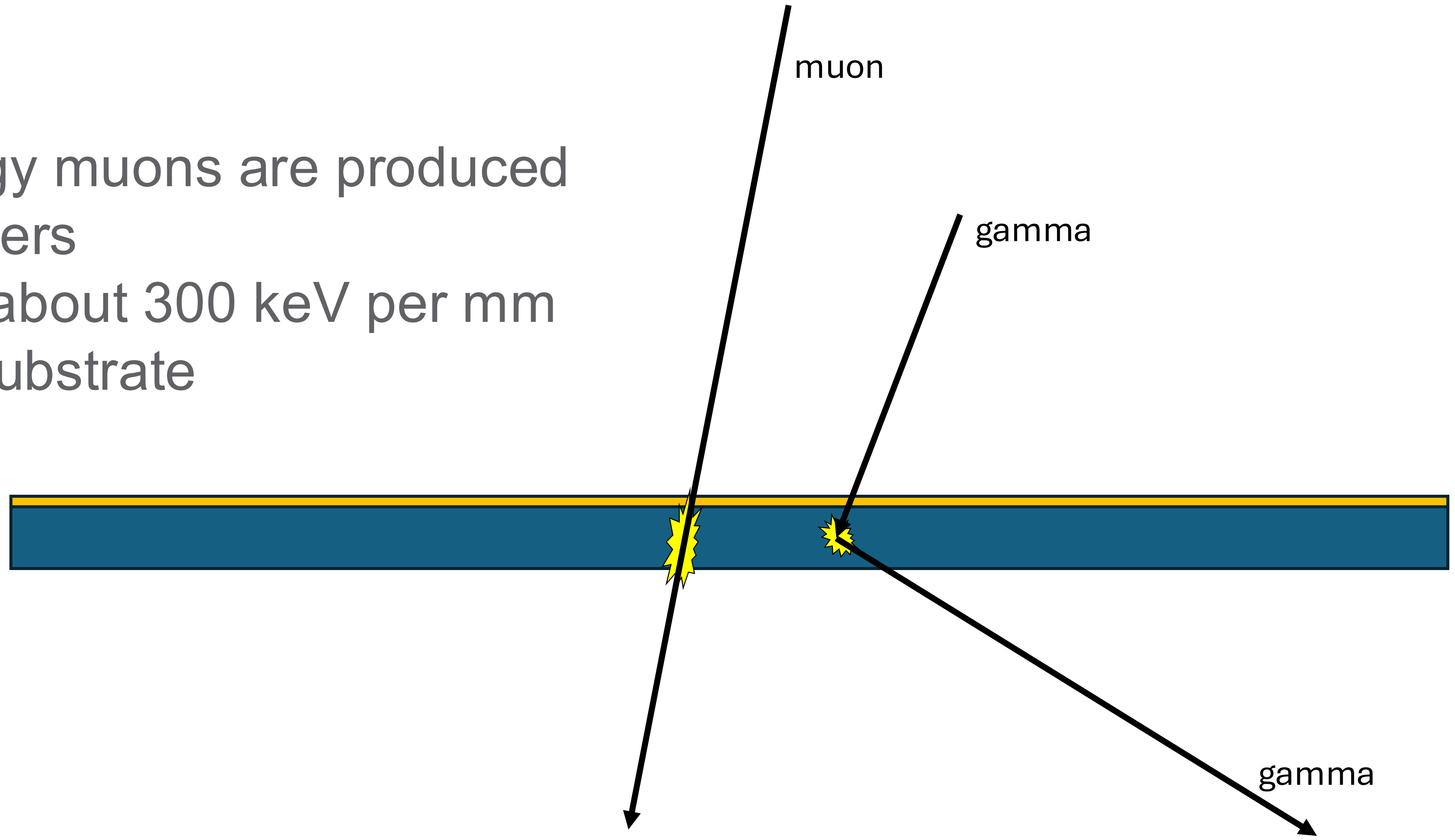
- In thin substrates, Compton scattering dominates over photo-absorption
- Energies typically $\mathcal{O}(100\ \mathrm{keV})$



Radiation in a Qubit Substrate

muons:

- High-energy muons are produced in air showers
- Energy of about 300 keV per mm of silicon substrate



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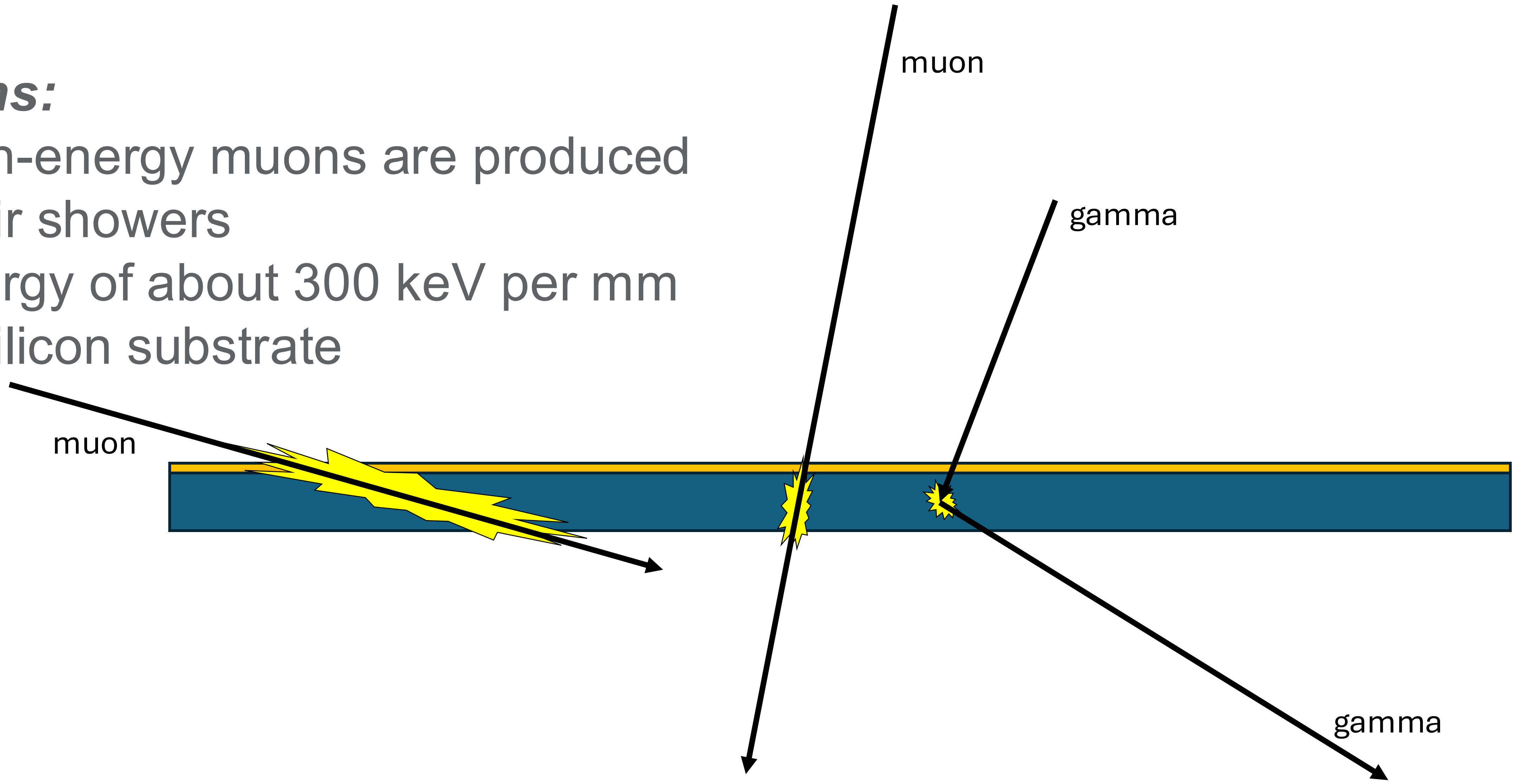
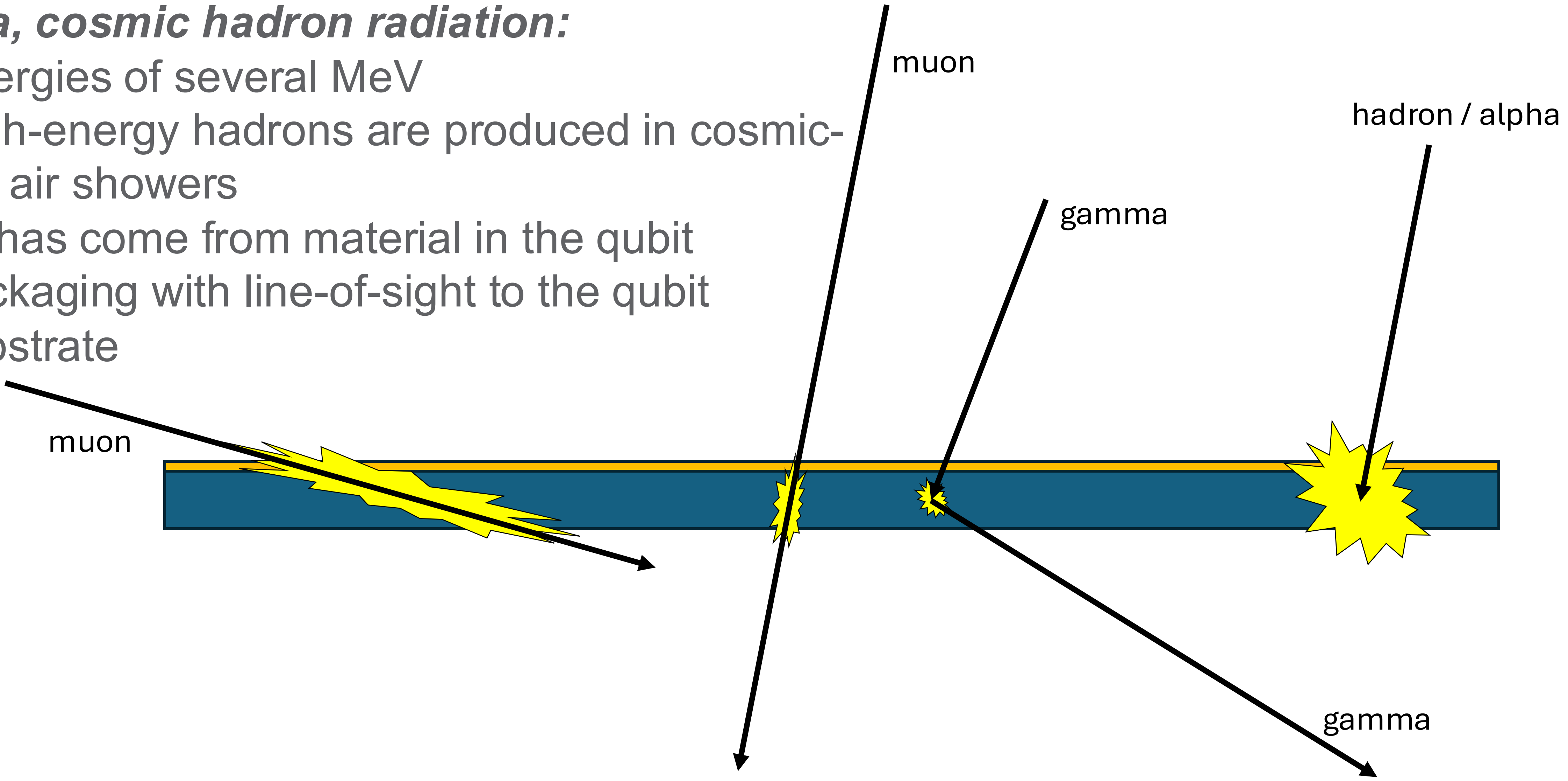


Radiation in a Qubit Substrate

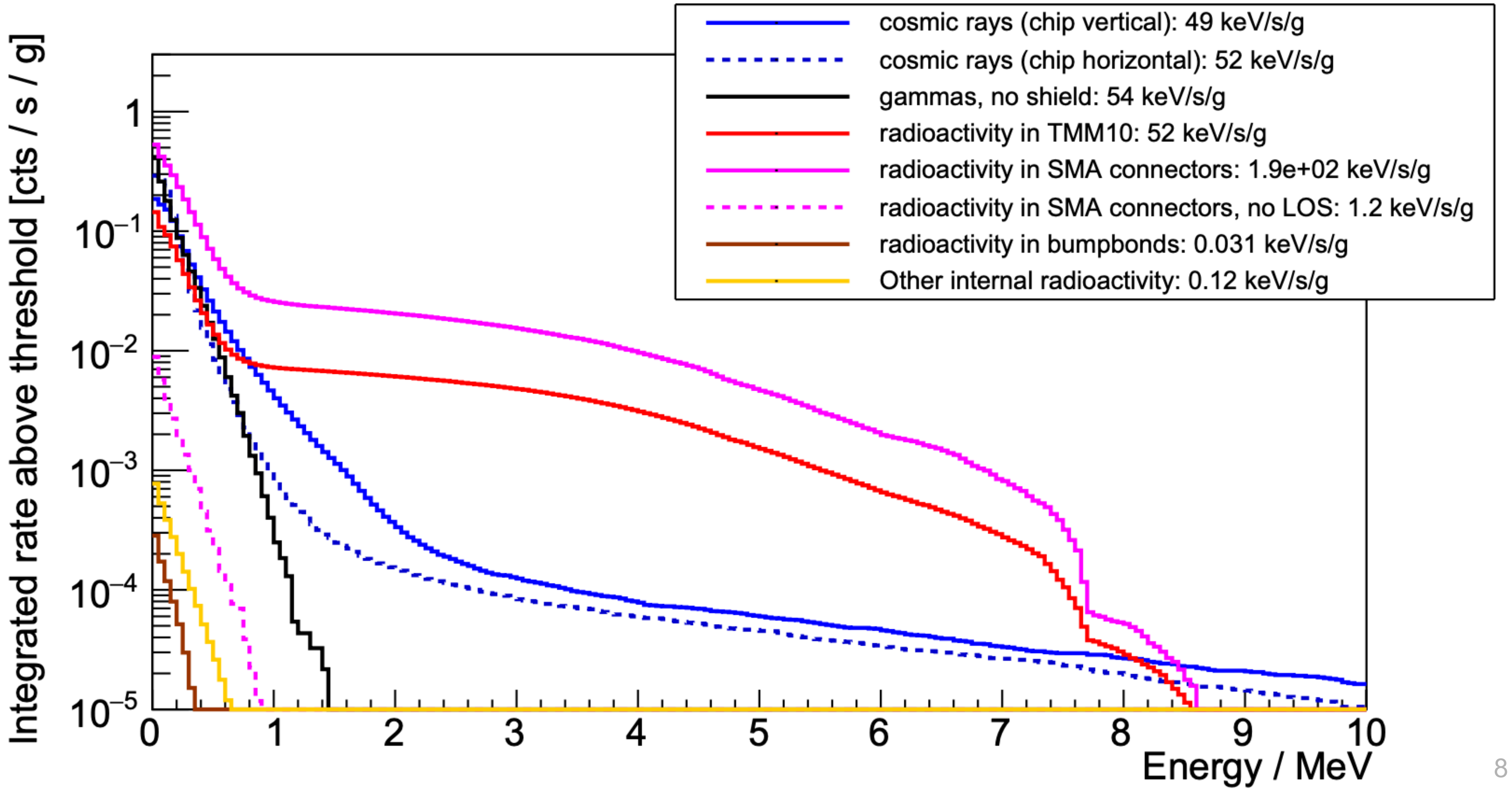
alpha, cosmic hadron radiation:

- Energies of several MeV
- High-energy hadrons are produced in cosmic-ray air showers
- alphas come from material in the qubit packaging with line-of-sight to the qubit substrate



Alphas and Radiopurity

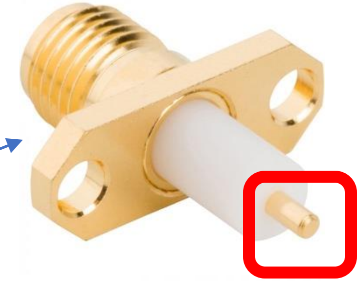
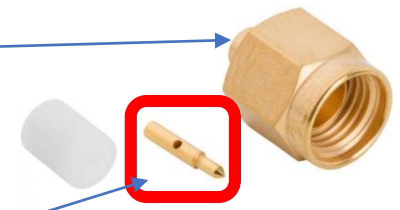
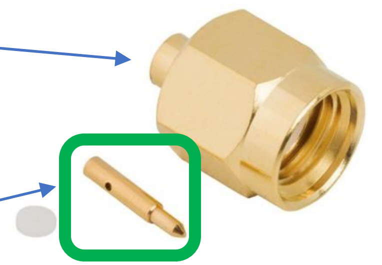
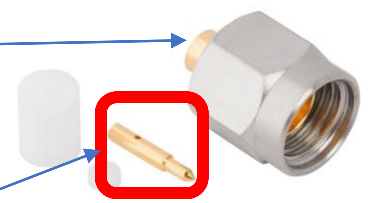
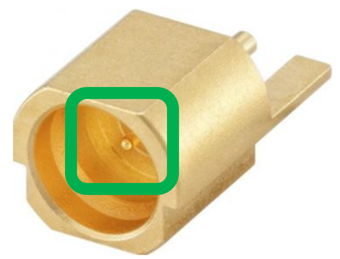
- Alphas can only reach qubit substrates by line-of-sight
- Significant sources of alphas:
  - Beryllium-copper pins on SMA connectors
  - Contamination in interposer circuit boards



[*Abatement of ionizing radiation for superconducting quantum devices*]()

SMA Connectors

			^{232}Th		^{238}U	
Product No.	**Material**	**Rep#**	**pg/g**	**+/-sd**	**pg/g**	**+/-sd**
132147-29	All dissolved (sans PTFE)	rep1	3100	200	24300	400
132147-29	All dissolved (sans PTFE)	rep2	1400	200	1510	90
132147-29	All dissolved (sans PTFE)	rep3	1070	90	1170	80
901-9201-2A	Nut Portion w/CuBe	rep1	14800	500	16200	8000
901-9201-2A	Nut Portion w/CuBe	rep2	14870	700	13100	2000
901-9201-2A	Nut Portion w/CuBe	rep3	15000	1500	15200	4000
901-9201-2A	CuBe Pin	rep1	230000	15000	2400000	18000
901-9201-2A	CuBe Pin	rep2	270000	13000	2500000	10000
901-9201-2A	CuBe Pin	rep3	250000	15000	2500000	40000
132101	Brass Nut Portion	rep1	11	3	51	4
132101	Brass Nut Portion	rep2	8	6	39	8
132101	Brass Nut Portion	rep3	<3	-	28	4
132101	Brass Pin	rep1	28	10	5	5
132101	Brass Pin	rep2	7	4	4	7
132101	Brass Pin	rep3	9	2	<1.2	-
132248	Steel Nut Portion	rep1	330	40	60	4
132248	Steel Nut Portion	rep2	540	150	290	130
132248	Steel Nut Portion	rep3	320	50	68	1
132248	CuBe Pin	rep1	60	10	250	30
132248	CuBe Pin	rep2	39	5	230	40
132248	CuBe Pin	rep3	37	12	170	30
19S202-40ML5	All (no CuBe)	rep1	4	6	3	5
19S202-40ML5	All (no CuBe)	rep2	<3	-	<0.8	-

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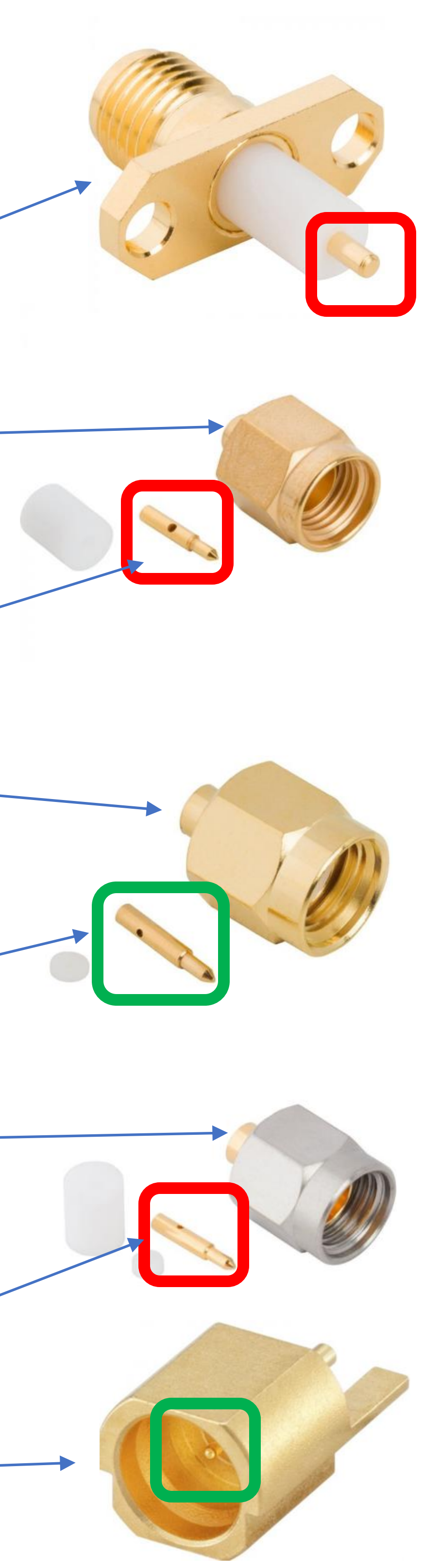
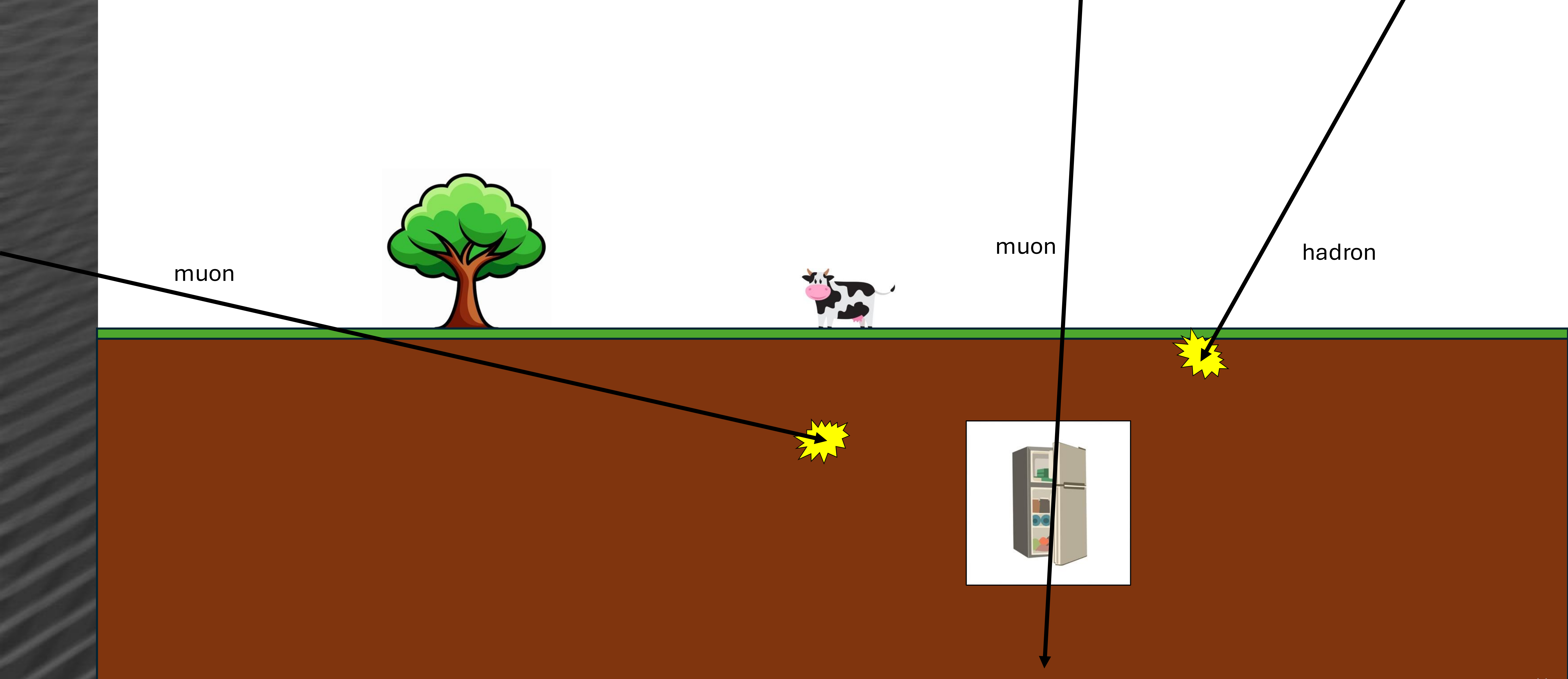
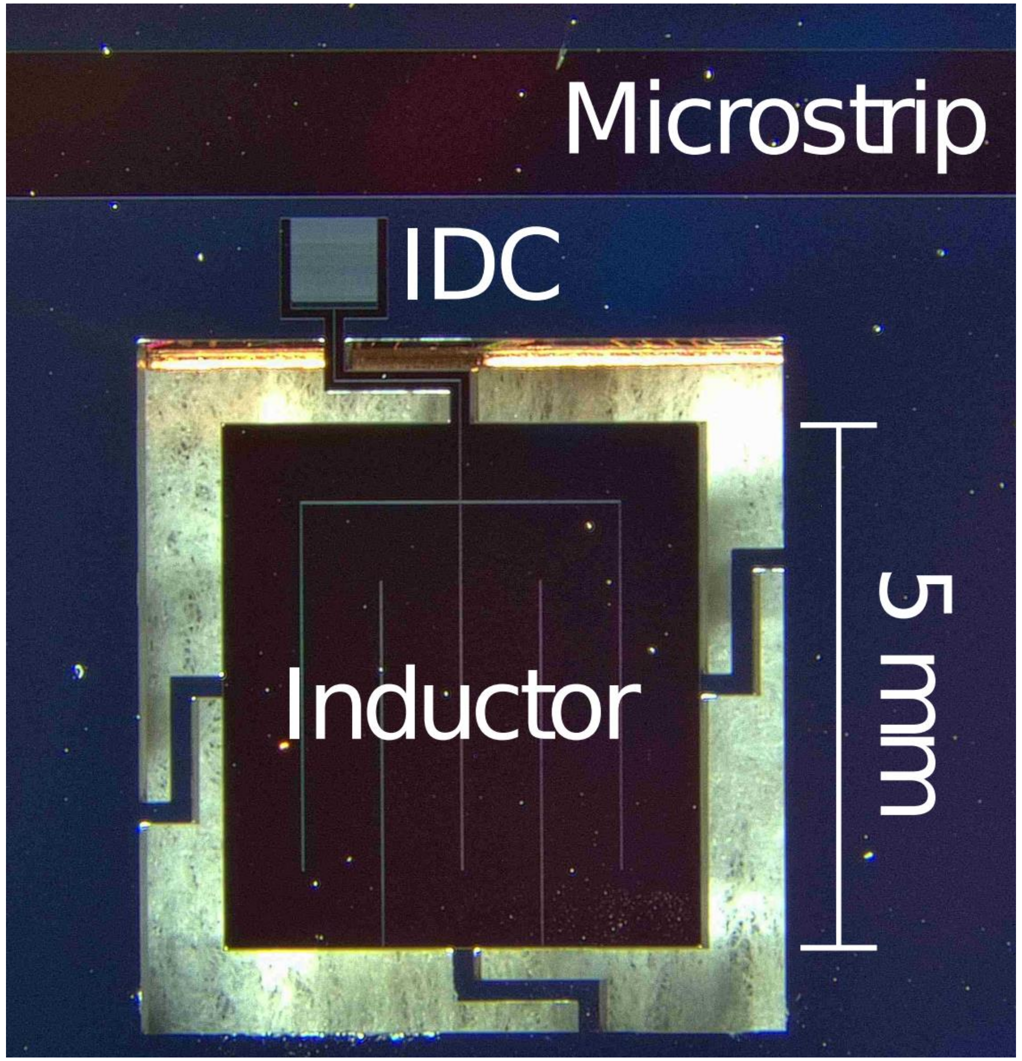


A shallow underground lab



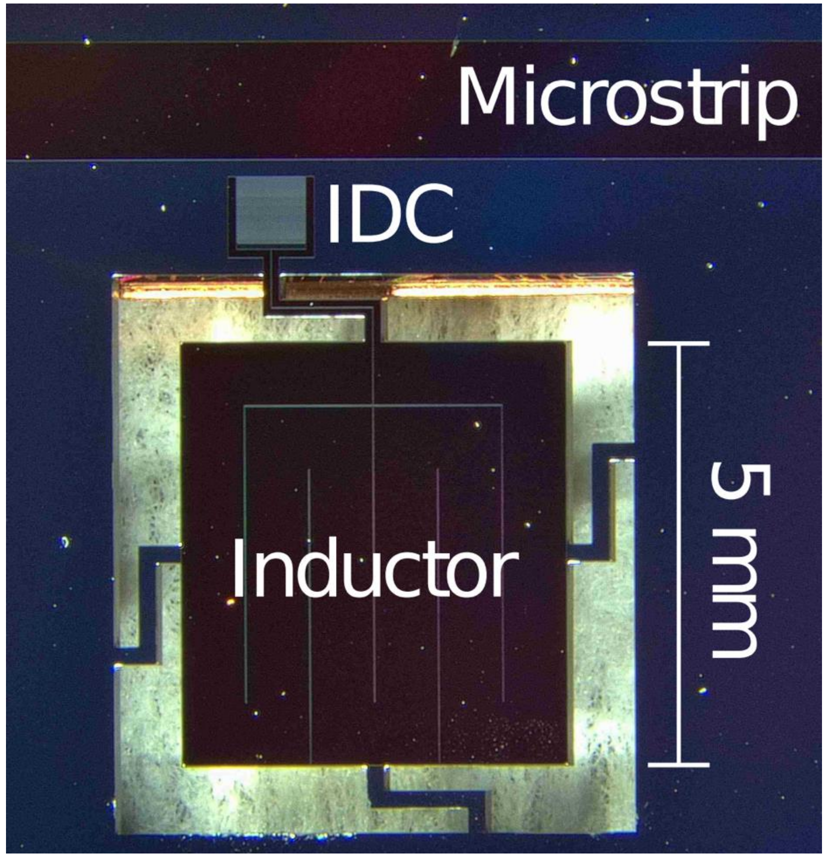
Spectral Measurements in Qubit-like substrates

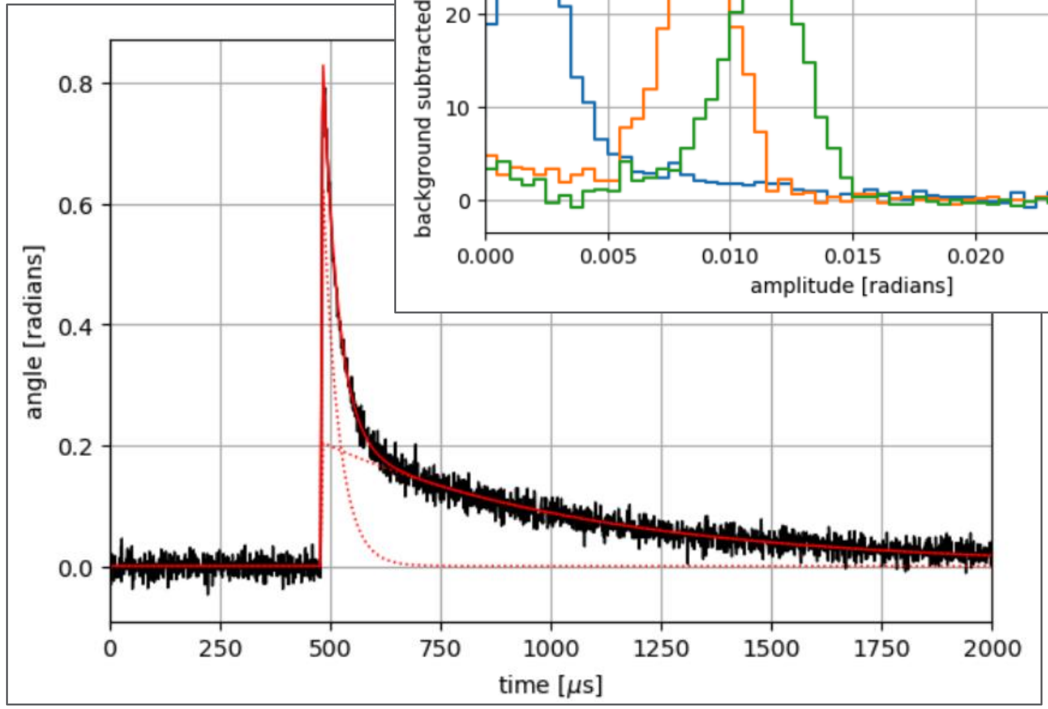
- Kinetic Inductance Detectors make a great energy-resolving qubit proxy!
  - Similar substrate / absorber material ✓
  - Similar substrate form-factor ✓
  - Similar superconducting film ✓
  - Bonus - similar RF readout ✓

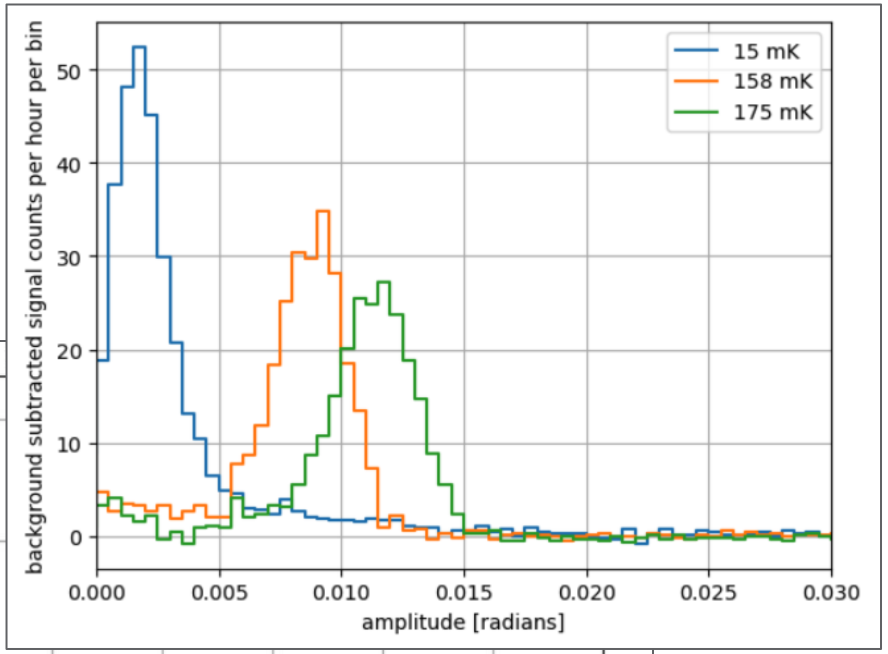


NIST Thermal Kinetic Inductance Detector

What is a TKID?

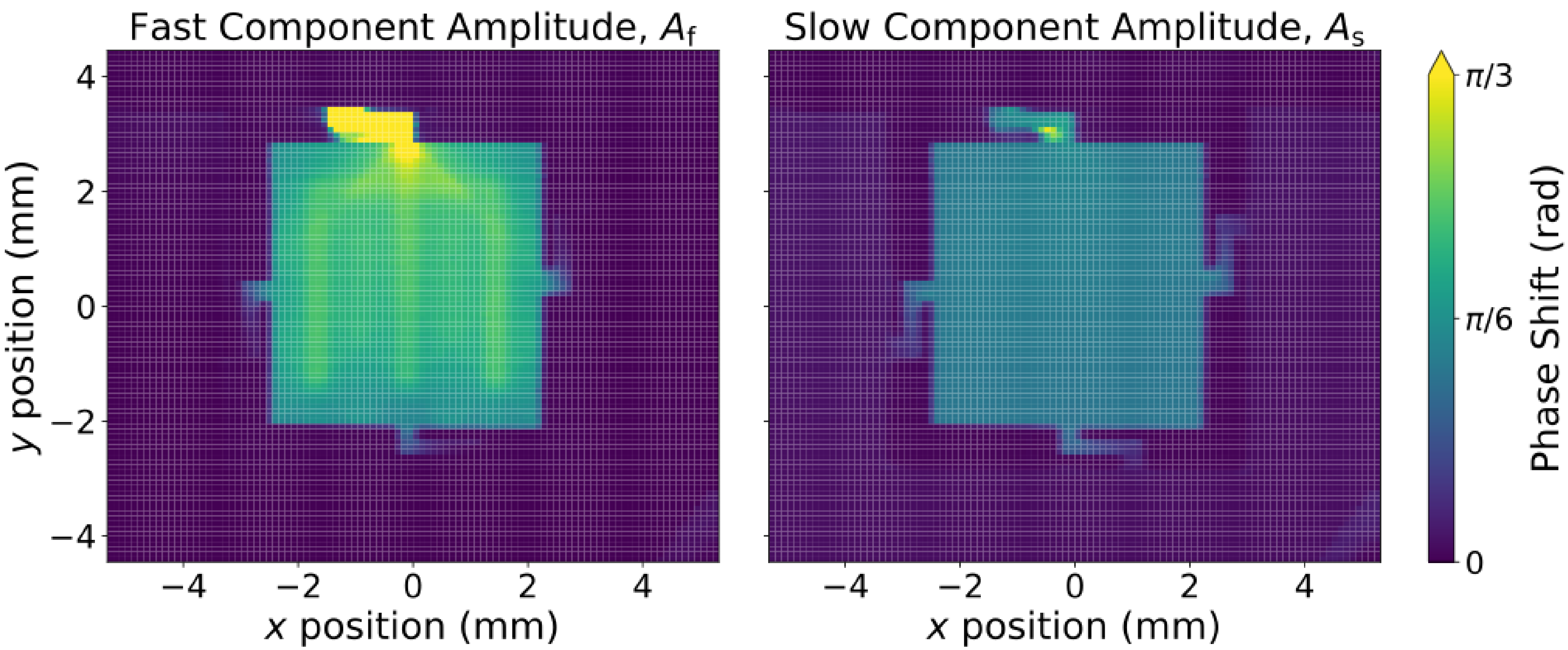


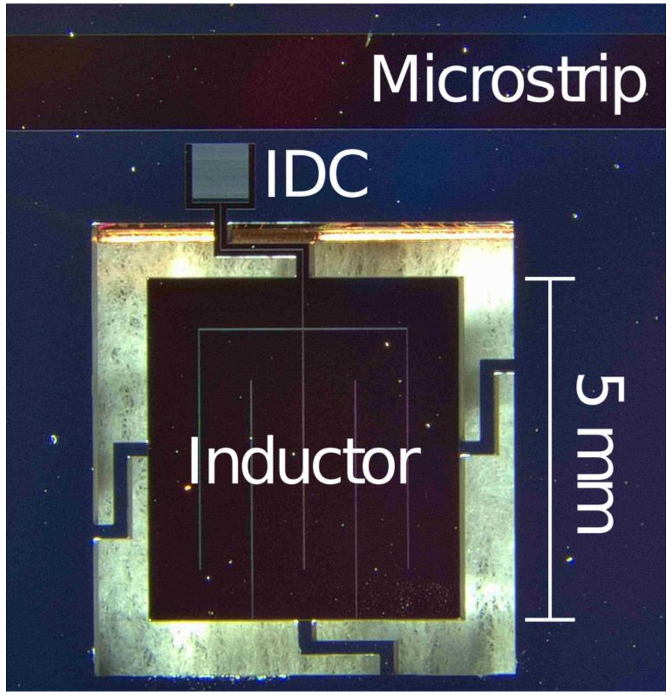


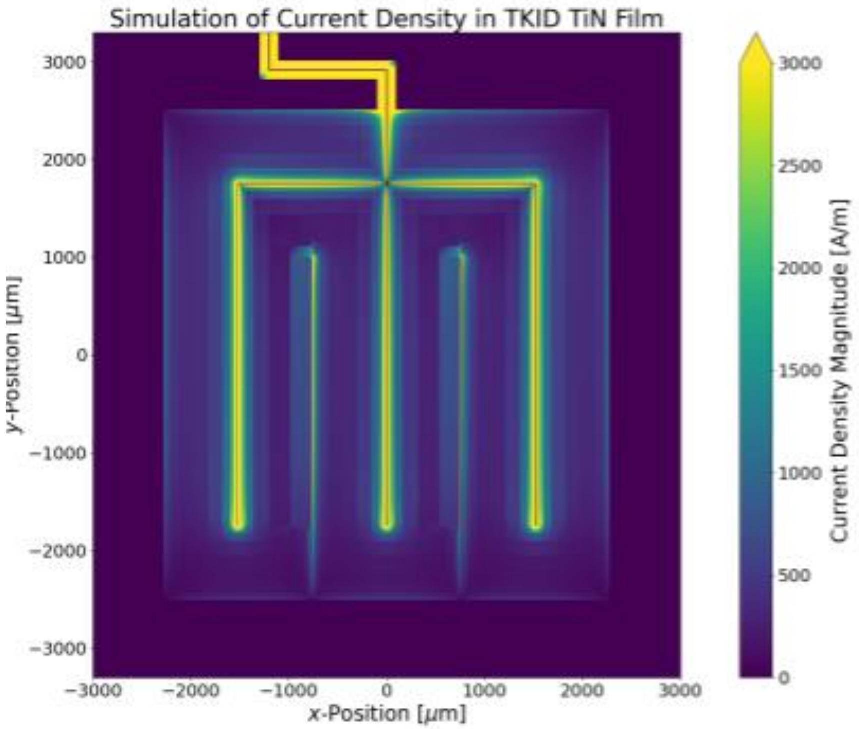


Why use a *thermal* KID???

Reduced position-dependence!





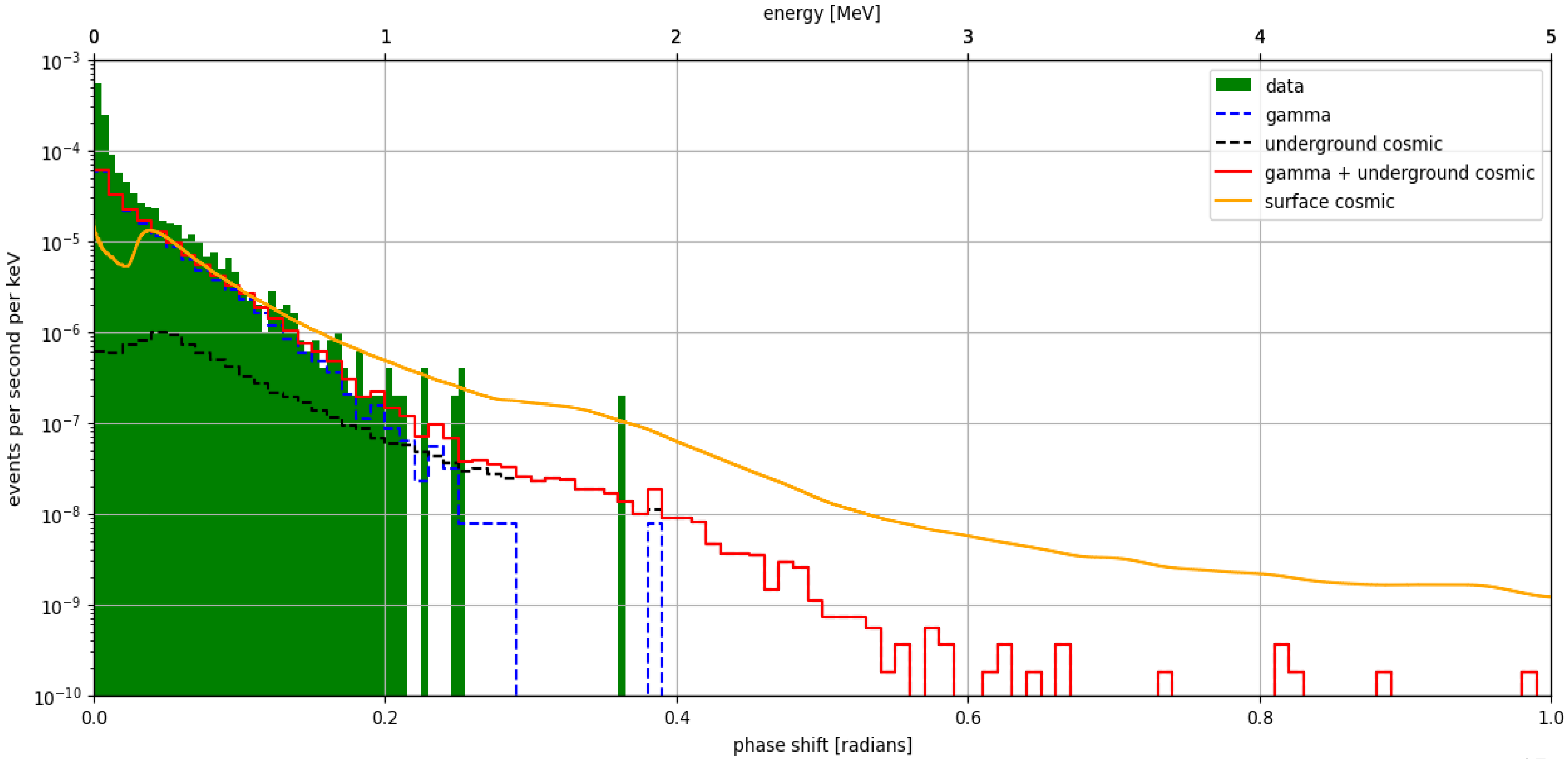


A study of the position-dependent response of thermal kinetic inductance detectors through the use of cryogenic beam steering, *in preparation, Ian Flogarty et. al.*

With thanks to the SLAC DMQIS group for providing the steerable MEMS mirror

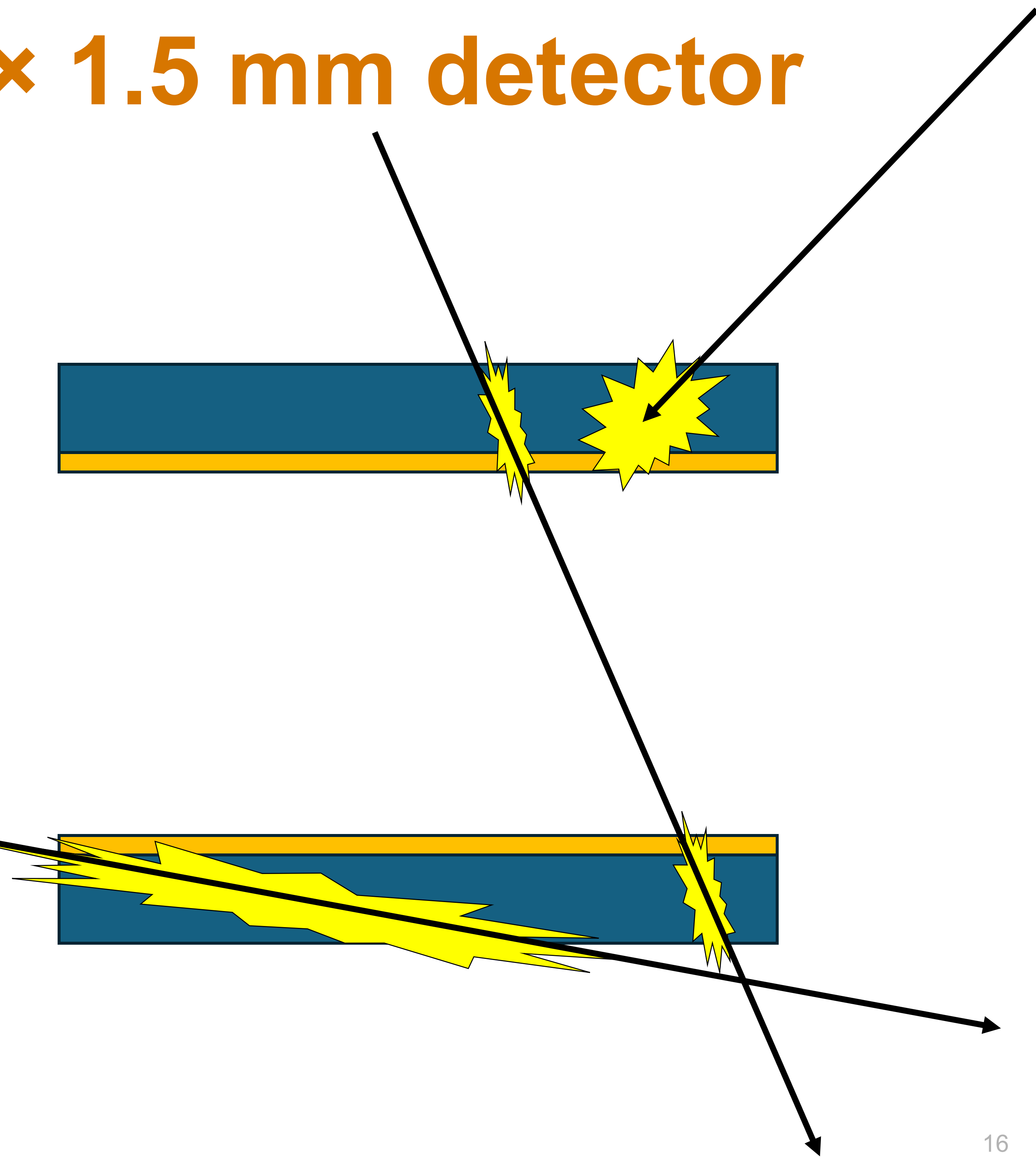
Preliminary run with 5 mm × 5 mm TKID

- In PNNL's Shallow Underground Lab we demonstrated we can calibrate and operate a TKID with sufficient dynamic range
- Data is consistent with our model of our underground radiation environment
- We are ready for high - stats measurements

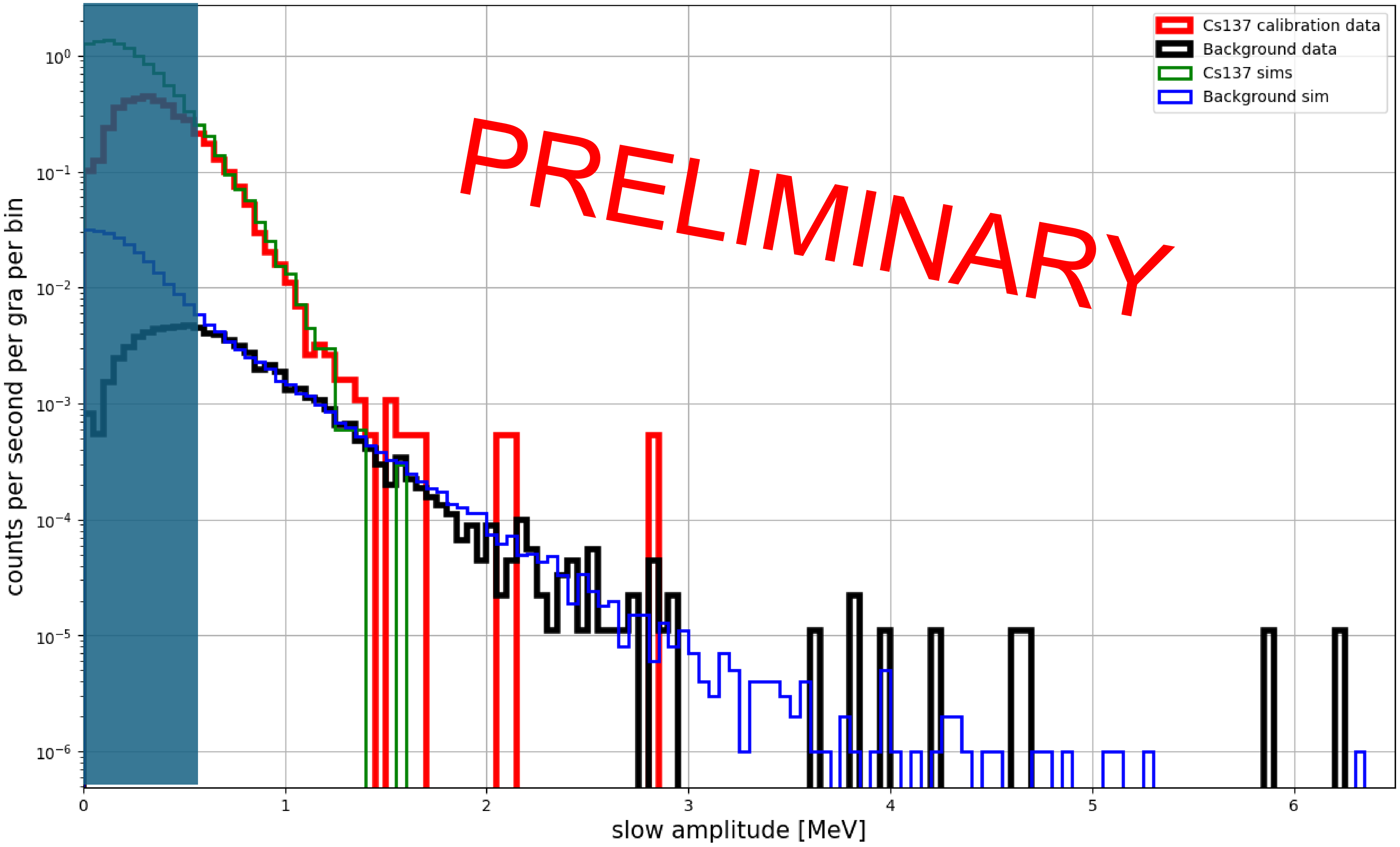


Ongoing: 10 mm × 10 mm × 1.5 mm detector

- Now using horizontal orientation
- Increased active mass → higher-stats measurement of highest-energy events
- Two stacked detectors allow for tagging of downward muons

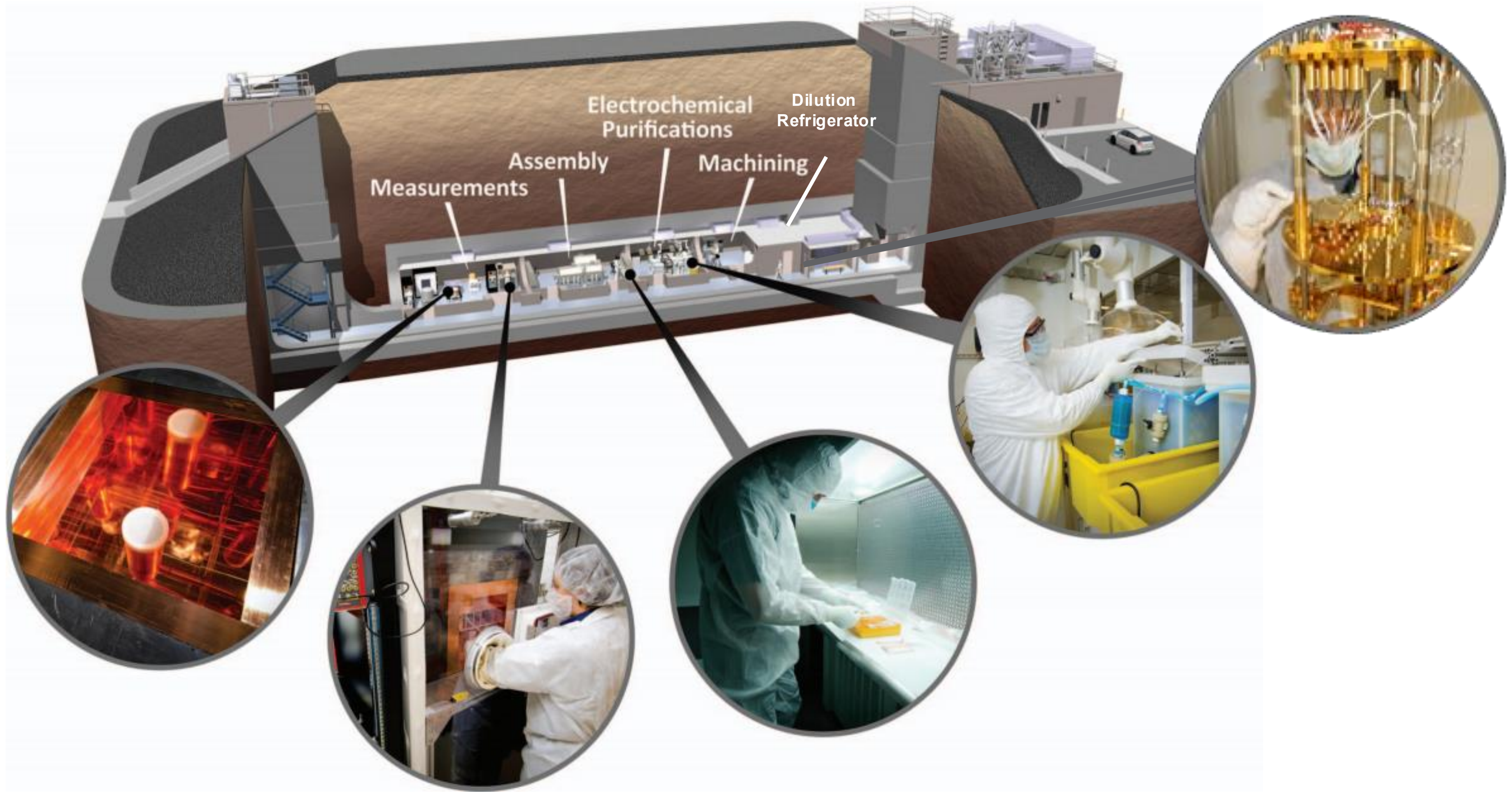


10 mm × 10 mm first data



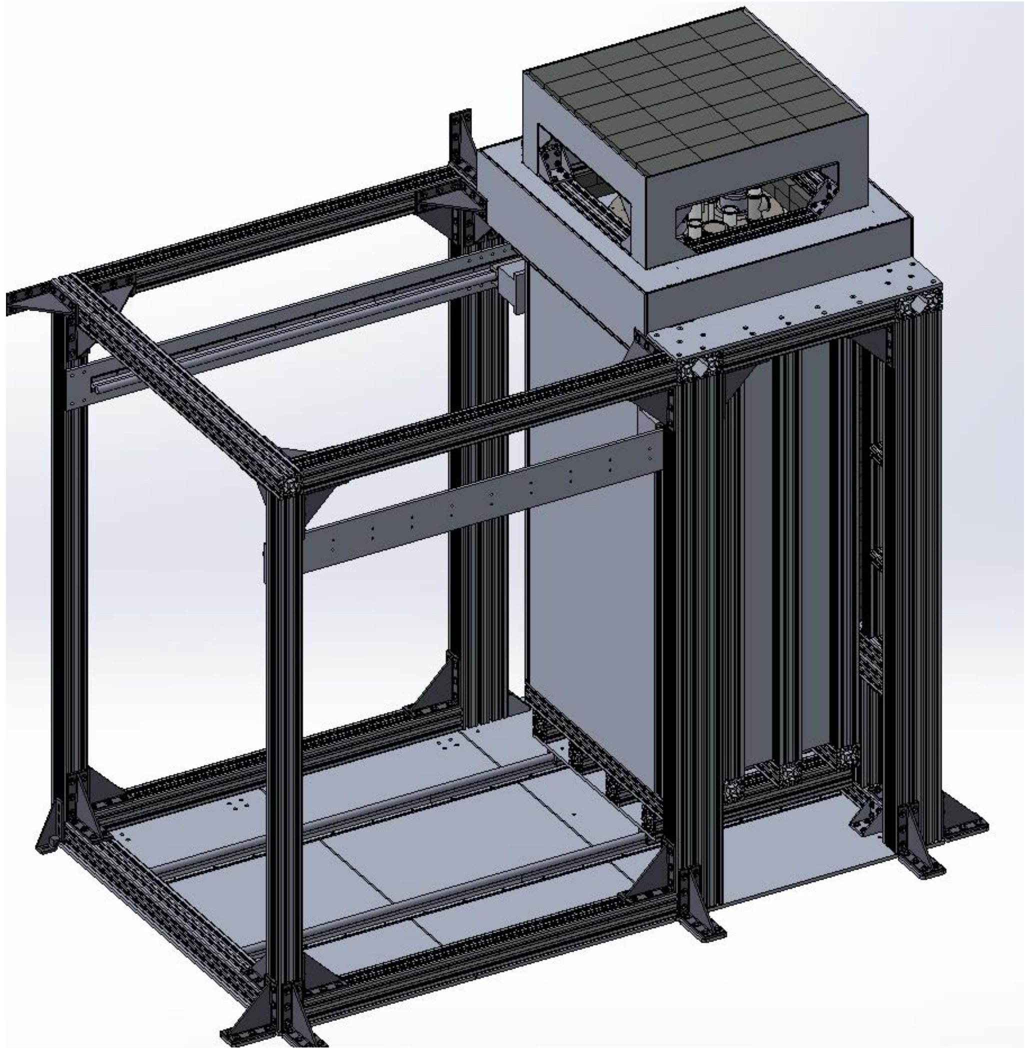
PNNL Shallow Underground Laboratory and Low Background Cryogenic Facility (LBCF)

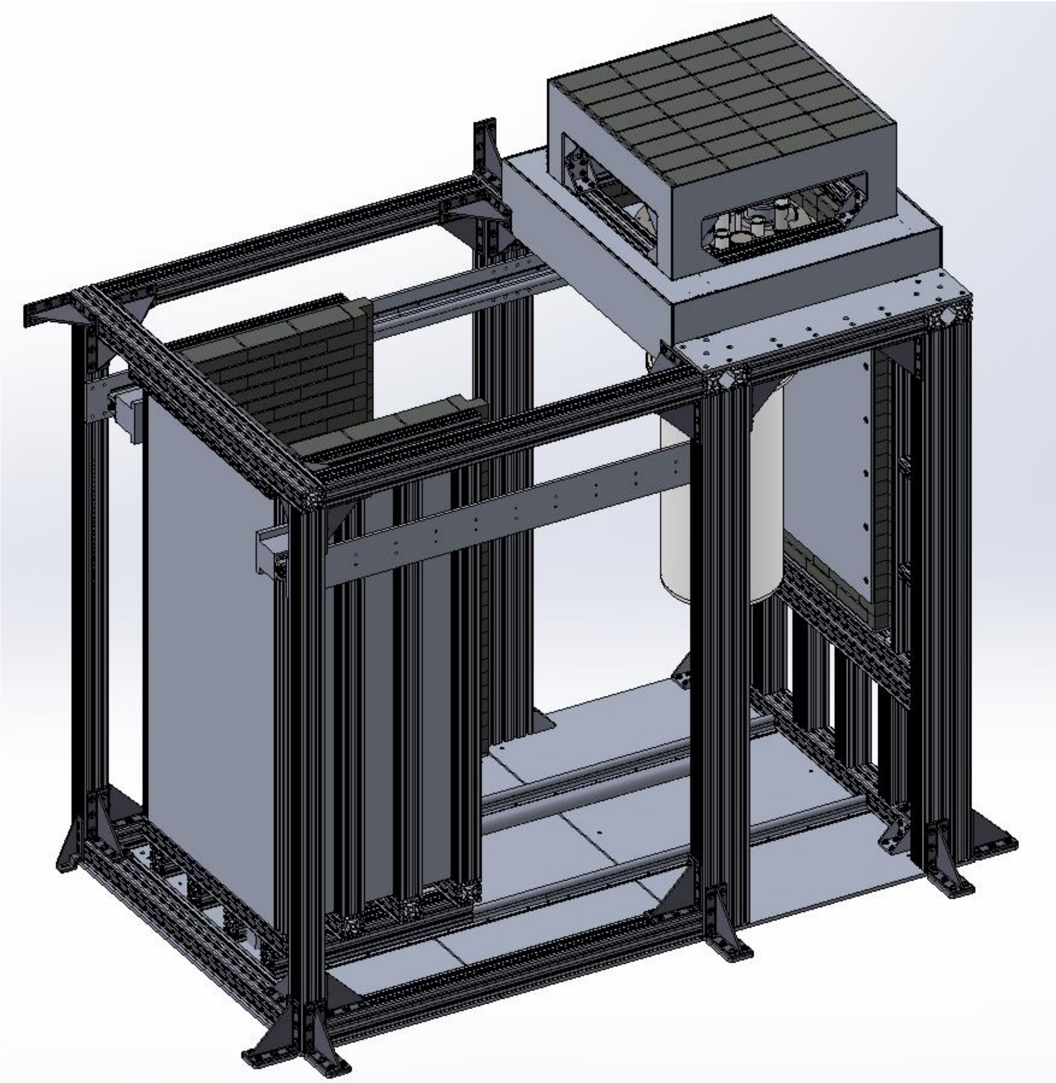
- SUL houses clean rooms (class 10,000 and 1,000) , world-leading ultra-pure material growth and characterization capability
- 19 m overburden reduces muon flux by 6X, **neutron and proton flux by >100X**
- Bluefors LD-400 dilution fridge with external gamma shield



LBCF Shield

- Reduces gamma rate by ~99.8% -> dominated by residual cosmic ray muons
- Automated cage door open/close enables A/B tests for ambient radiation
- Expected completion Fall 2025





Thank you

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