Cosmogenic Background Characterization for the Colorado Underground Research Institute (CURIE)

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Topics in Astroparticle and Underground Physics

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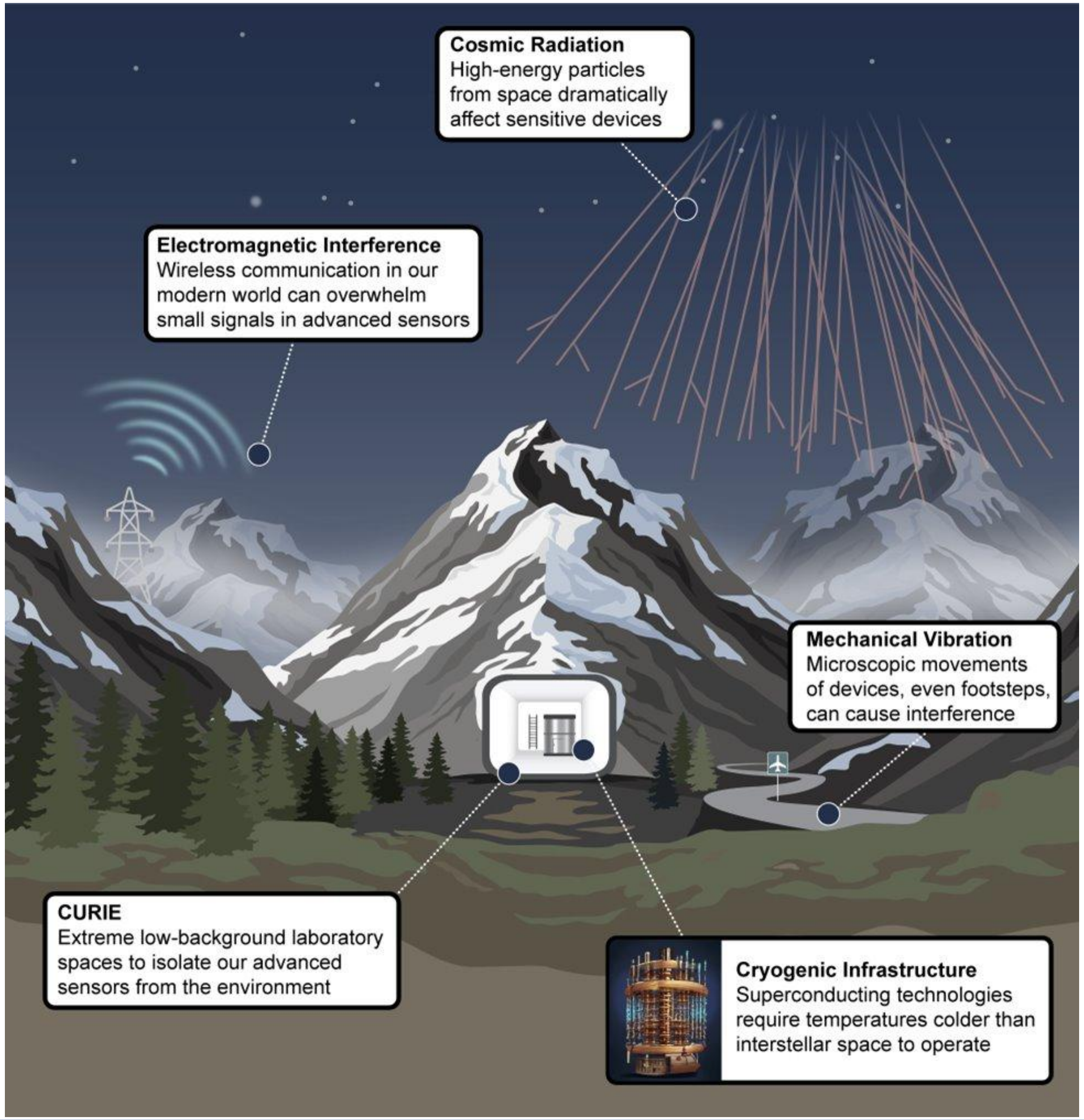
CURIE

Supported by

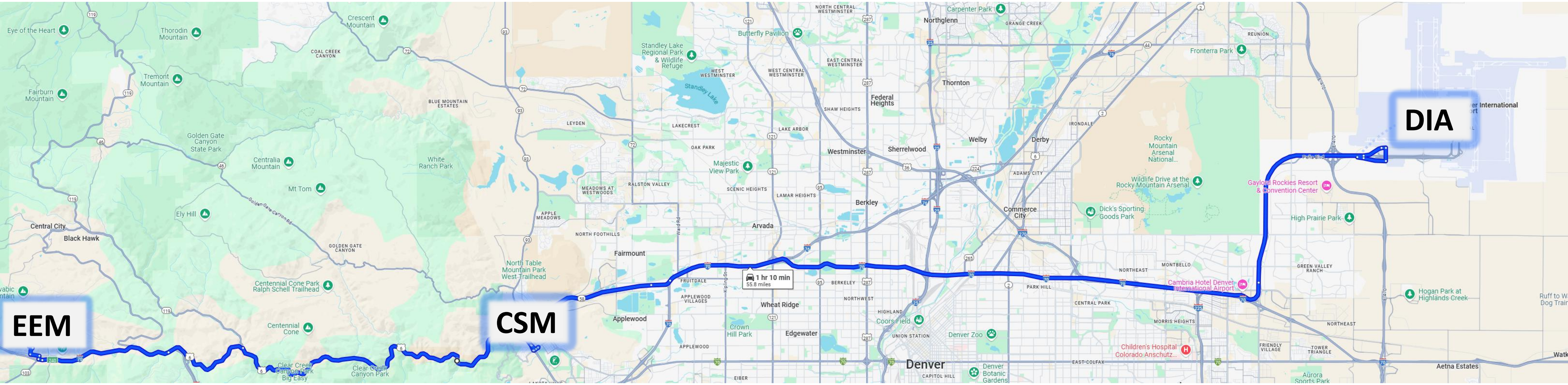
Noise in Experimental Measurements

- Many different internal and environmental noise factors
- Some easier to quantify than others
- All sources must be characterized for noise reduction, cross-correlation, etc.



CURIE @ Edgar Experimental Mine (EEM)

- Located in Idaho Springs, CO (2400m elevation)
- Approx. 1 hr. from Denver International Airport (DIA)
- Approx. 30 min from Colorado School of Mines (CSM) (Golden, CO)



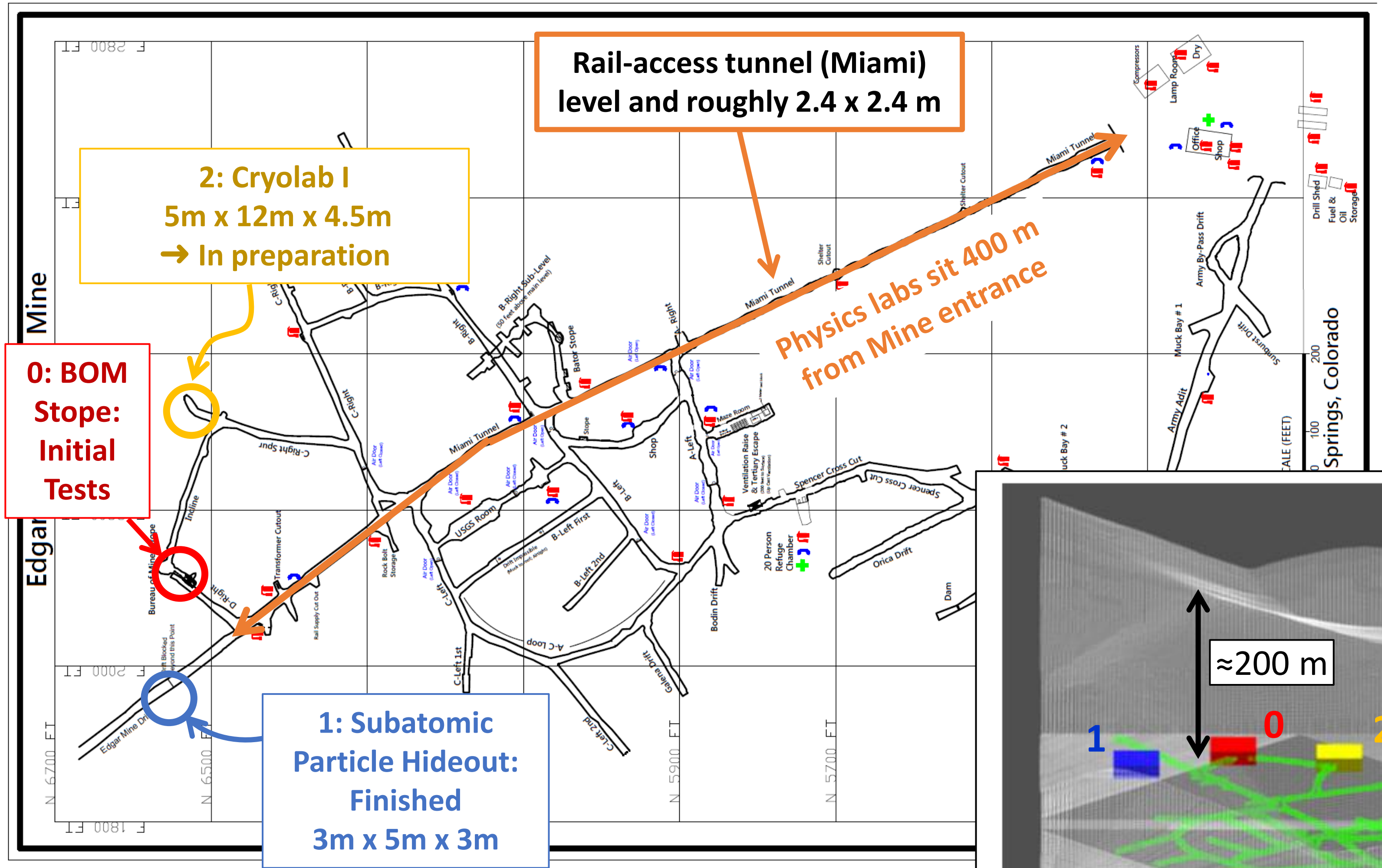
Facilities and Access

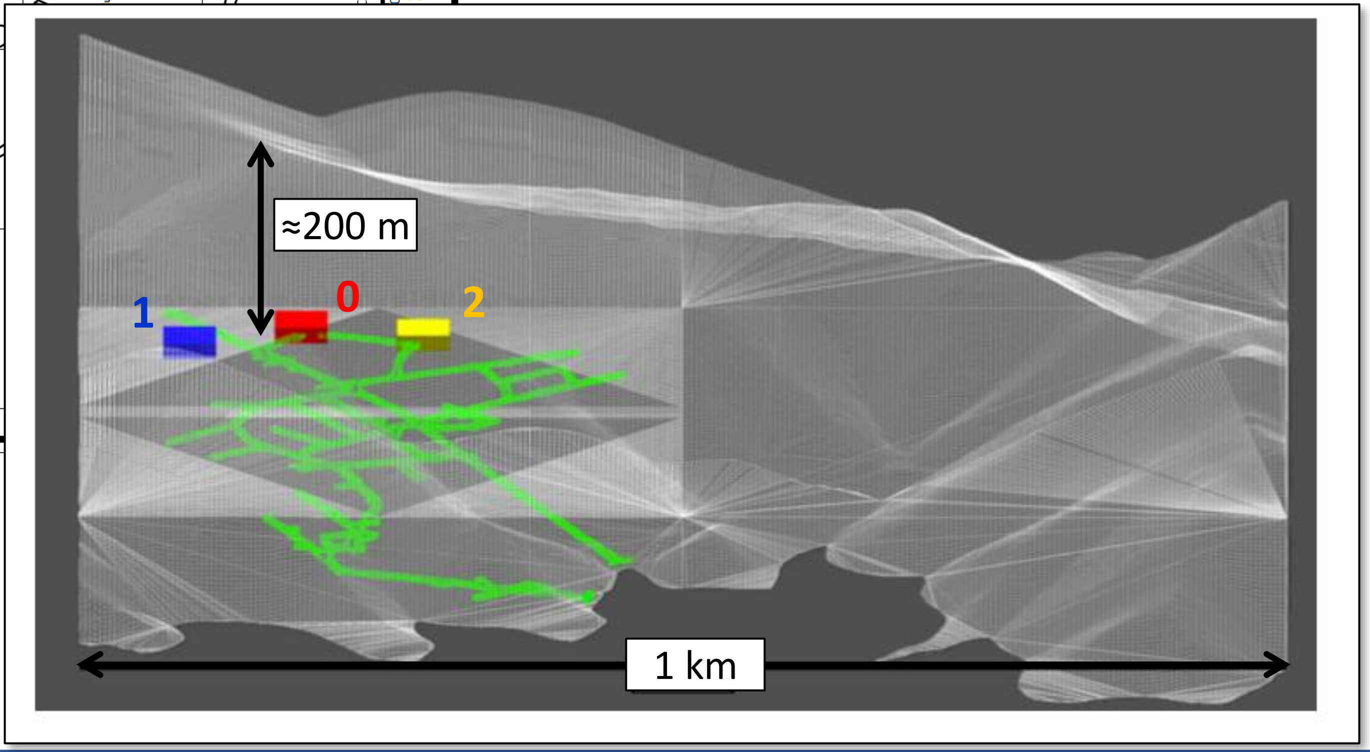
- Two main operational areas: Army tunnel and Miami tunnel (connected internally)
- Surface level, horizontal access
- Rail driven tunnels
- Near constant year-round temp. of 12 C

Available Facilities:

- single phase – 110V and 3 phase – 440V power
- Compressed air and water sources
- 1275 m^3/min exhausting silencer equipped fan for ventilation
- Internet access

Miami tunnel entrance





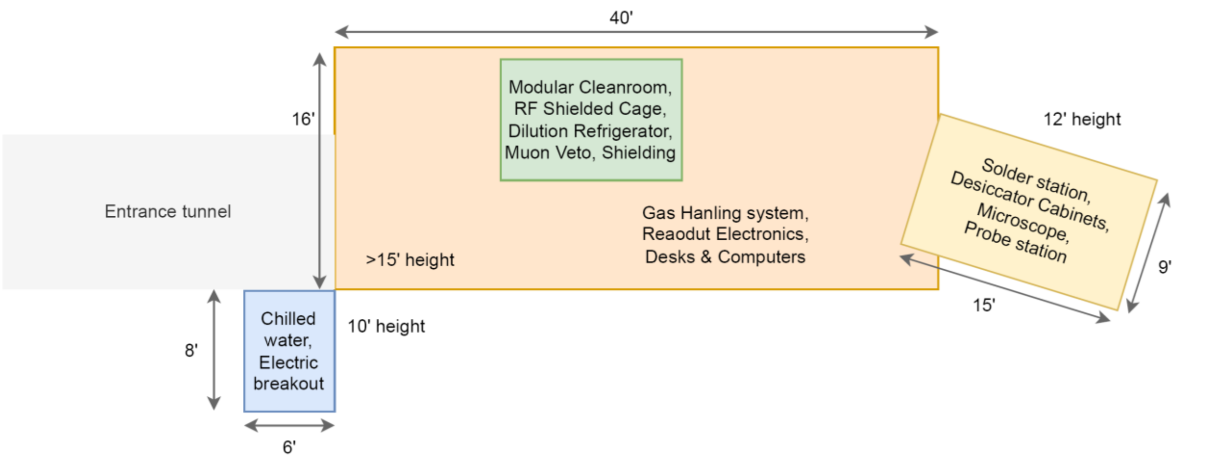
3D rendering of the EEM surface topology with the mine access ways shown in green. The relative positions of Site 0 (red), Site 1 (blue), and Site 2 (yellow) are shown.

Subatomic Particle Hideout

- Concrete floor/shotcrete walls
- 110 V power
- Ventilation
- Ethernet
- Cinder block entrance wall

Cryolab I

- Tailored to house a dilution refrigerator (Maybell Quantum)
- To receive same renovations plus 440 V power
- Compressed/chilled water hookups

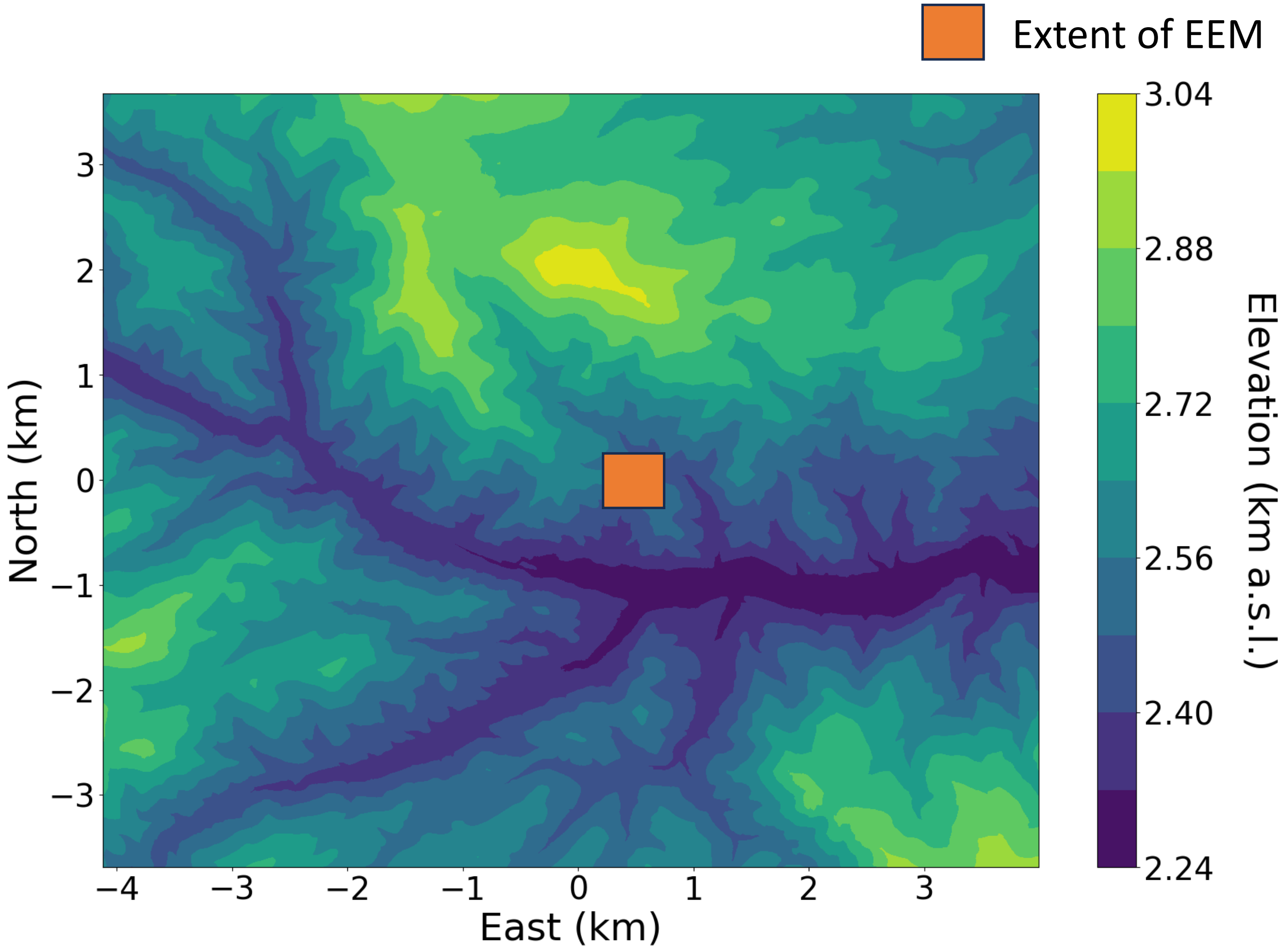


Current status and design for Cryolab I

Characterizing the Cosmogenic Background

Cosmogenic Muons

- Three locations used in analysis: Bureau of Mines (BOM) Stope, Subatomic Particle Hideout (SPH), and Cryolab I
- Site-centered overburden profiles created by coupling QGIS software to USGS DEM data [1-2]
- USGS and Colorado geologic survey data used for density profile [3-4]



Topological map of the 84 km² area centered on the EEM

[1] U.S. Geological Survey, “Vertical Accuracy of the CO-DRCOG2020B20 Digital Elevation Model,” (2020)
[2] T. Q. Foundation, “Qgis official website,” https://www.qgis.org (2024)
[3] K. S. Kellogg, R. R. Shroba, B. Bryant, and W. R.Premo, “Geologic map of the denver west 30’ x 60’ quadrangle, north-central colorado,” (2008)
[4] B. L. Widmann, R. M. Kirkham, and S. T. Beach, “Geologic map of the idaho springs quadrangle, clear creekcounty, colorado,” (2000)

Computational Framework

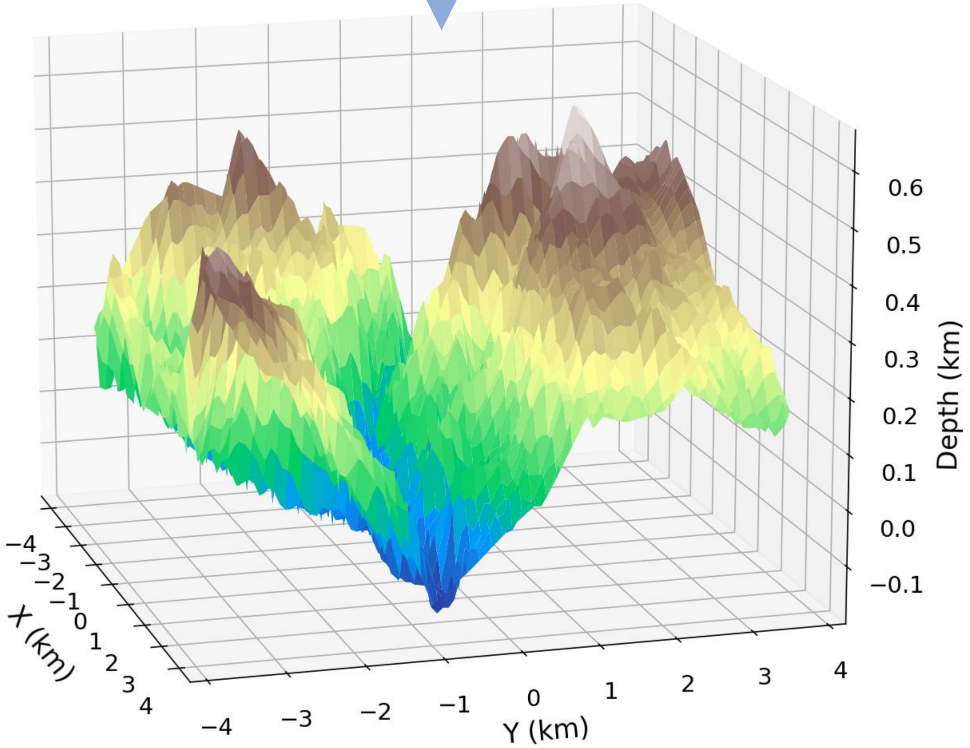
Daemonflux → **MUTE**

(DAta-drivEn MuOn-calibrated atmospheric Neutrino Flux) [5]:

- Muon sea level surface fluxes

(MUon intensiTy codE) [6]: → Underground Fluxes → Underground Intensities → Total Underground Flux

- Overburden profiles + surface fluxes



Subatomic Particle Hideout overburden profile

[5] J. P. Ya˜nez and A. Fedynitch, Phys. Rev. D 107, 123037 (2023).

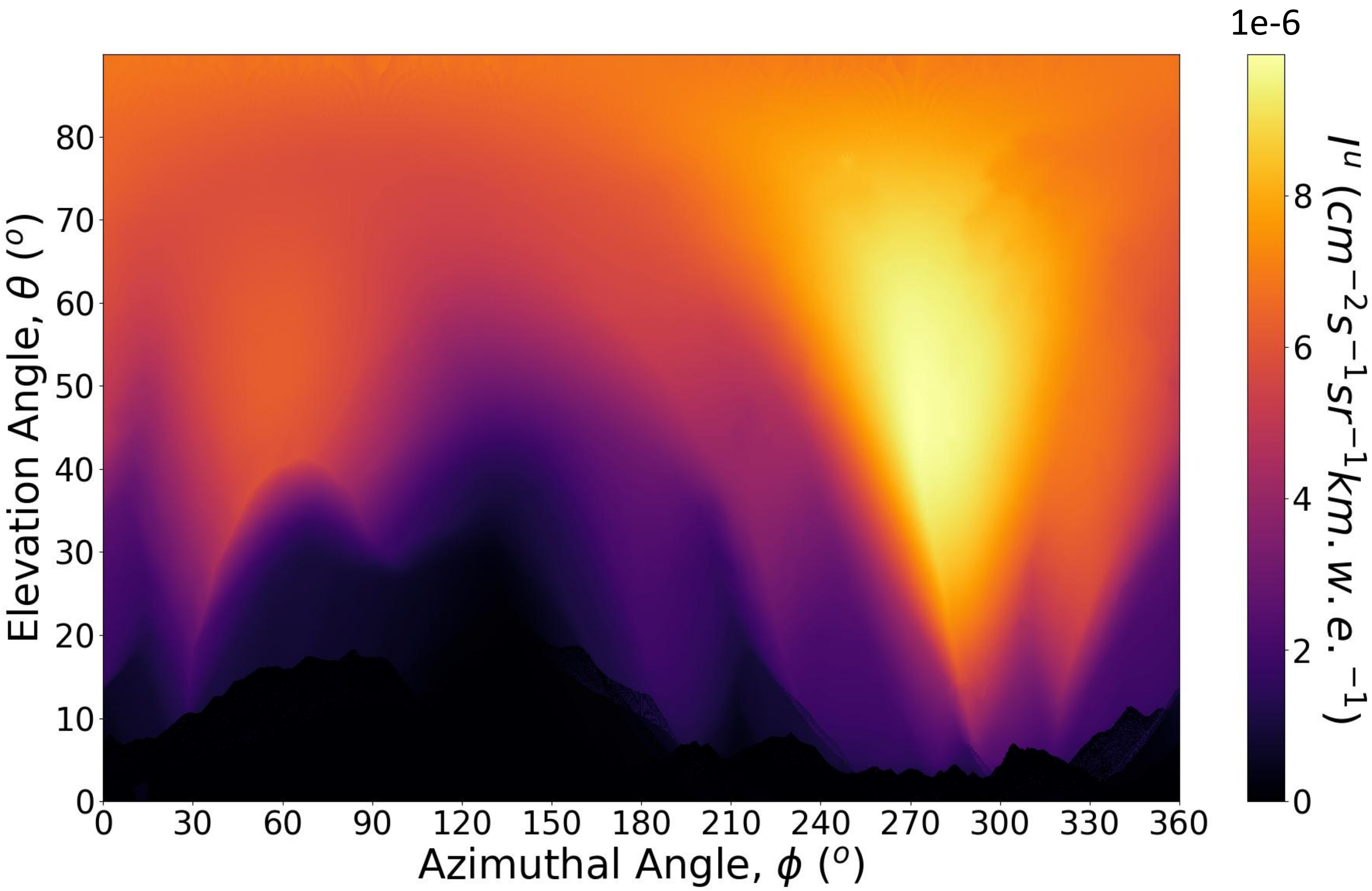
[6] A. Fedynitch, W. Woodley, and M.-C. Piro, The Astrophysical Journal 928, 27 (2022).

Simulation Results

- Underground intensities suggest directional dependence
- Simulations Results:
  BOM Stope:
  0.227 ± 0.023$_{\textbf{sys.}}$ $\mu/m^2/s$

  Subatomic Particle Hideout:
  0.217 ± 0.022$_{\textbf{sys.}}$ $\mu/m^2/s$

  Cryolab I:
  0.259 ± 0.026$_{\textbf{sys.}}$ $\mu/m^2/s$

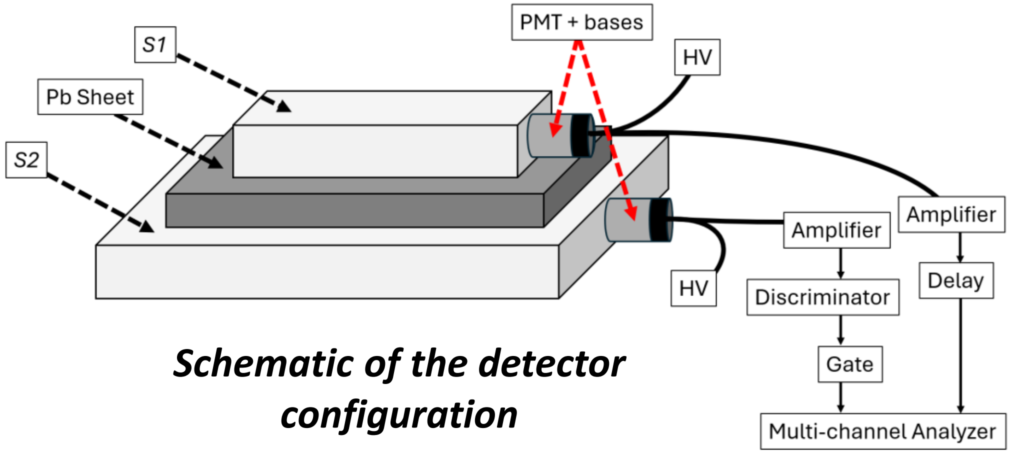


Underground muon intensities as a function of arrival angle

Experimental Measurements

- Underground muon flux measurements performed in BOM Stope and Subatomic Particle Hideout
- Used a stacked scintillator configuration ran in coincidence mode
- Detector ran in BOM Stope for 385.5 h and in SPH for 619.7 h
- Experimental Results:
  BOM Stope: $\mathbf{0.246 \pm 0.020_{sys.} \pm 0.012_{stat.}}$ μ/m²/s

  SPH: $\mathbf{0.239 \pm 0.025_{sys.} \pm 0.010_{stat.}}$ μ/m²/s

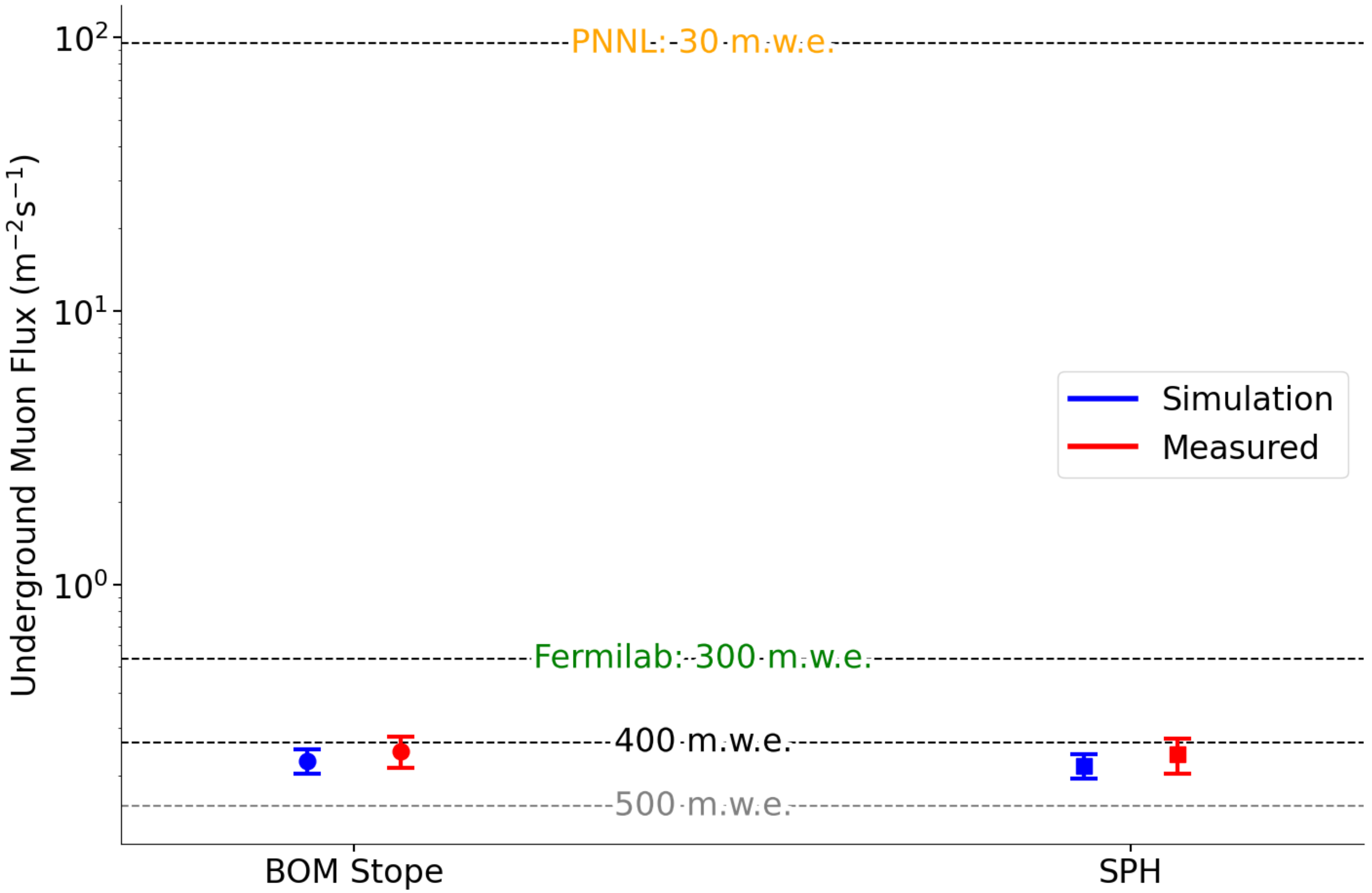


Schematic of the detector configuration

Detector operating in Subatomic Particle Hideout

Experiment vs Simulation

- Average shielding relative to a flat overburden of 415 meter-water-equivalent. [7]
- Factor of 700x reduction in muon flux compared to sea level
- Better shielding than other U.S.-based shallow facilities



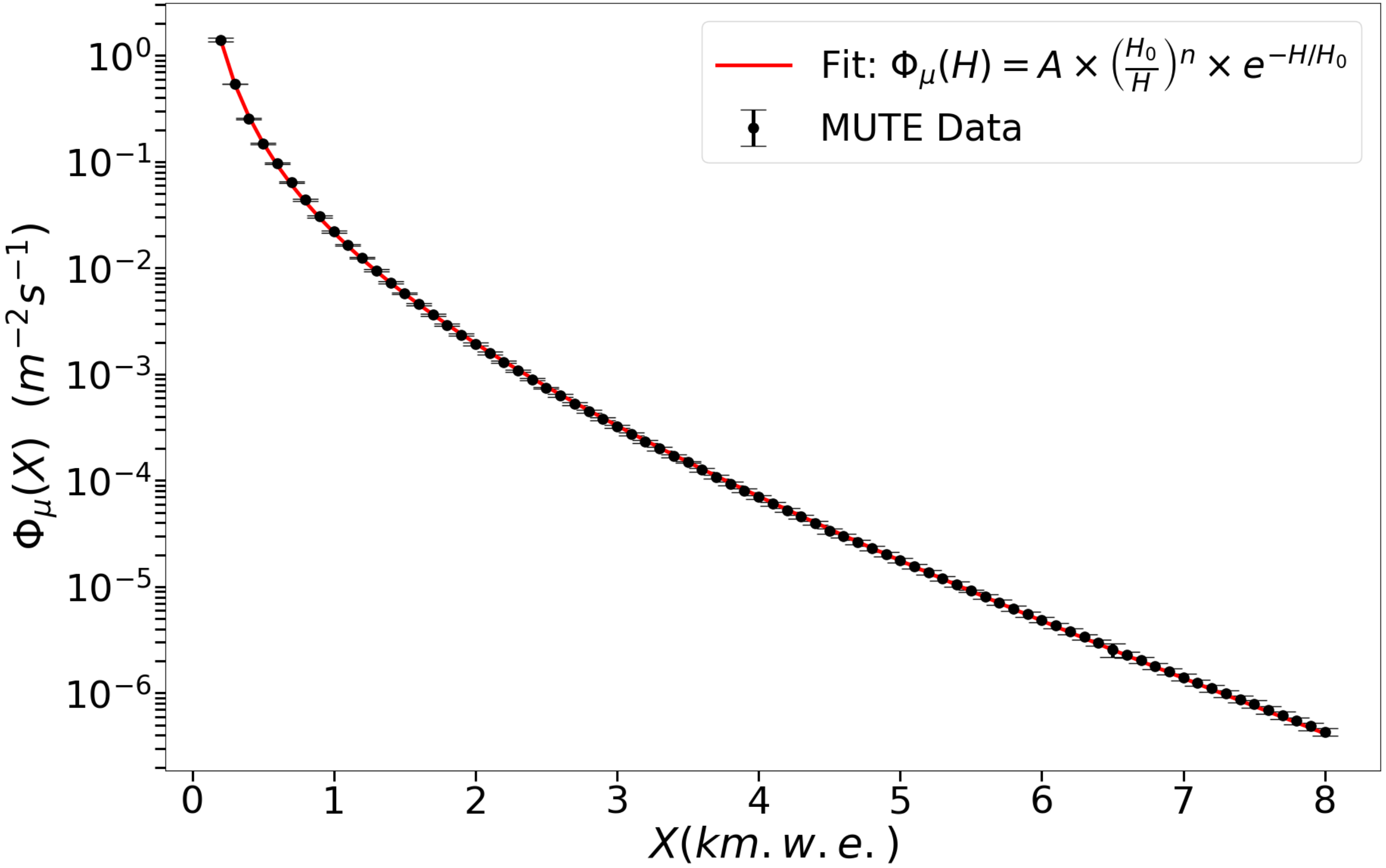
Comparison between the simulated and measured muon fluxes. The gray and black horizontal lines correspond to the flux equivalent of 500 and 400 m.w.e. flat overburdens, respectively. PNNL and Fermilab shielding is also shown for reference.

[7] D. Keblbeck et al., Phys. Rev. D 111, 023036 (2025)

Depth-Intensity Relationship

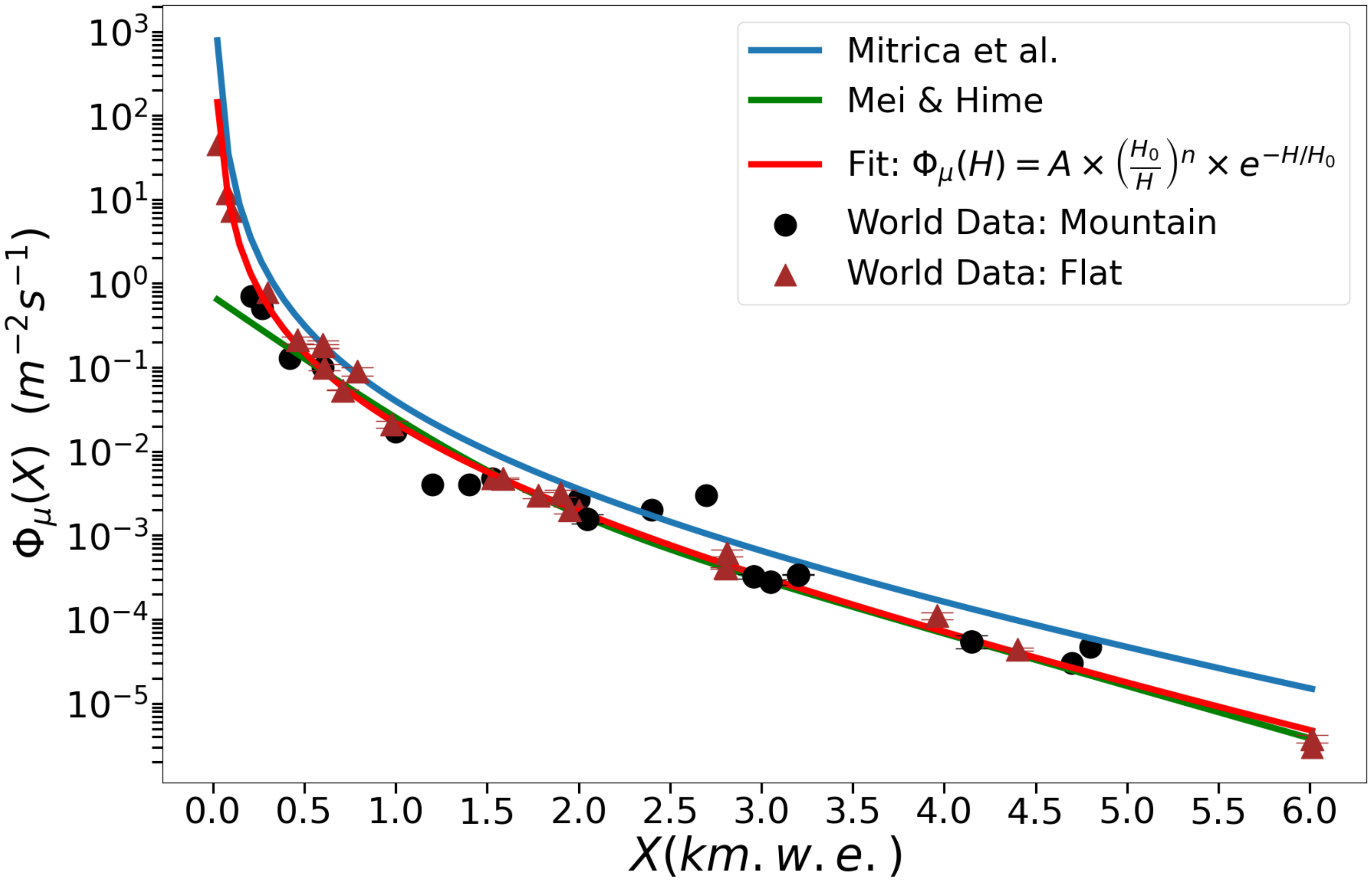
- Developed a new DIR to directly compare facilities under mountains to those with flat overburdens

$$\Phi_\mu(H) = A \times \left(\frac{H_0}{H}\right)^n \times e^{-H/H_0}$$



Fit function applied to the MUTE simulated underground muon flux data for flat overburden depths of 0.2 – 8.0 km.w.e.

- New DIR directly compared to existing models [8, 9] using experimental world data
- Corrected Akaike Information Criterion chosen for comparative analysis – accounts for goodness of fit and number of model parameters



M&H and Mitrica et al. muon flux models compared to Φ_μ(H), plotted against experimental data from worldwide facilities

	X [0.075, 0.98] km.w.e.		X [1.53, 6.0] km.w.e.		X [0.075, 6.0] km.w.e.	
Model	AICc	Weight	AICc	Weight	AICc	Weight
$\Phi_\mu(H)$	-30.57	1.0	-26.51	0.99	-105.20	1.00
Mei & Hime	39.56	0.0	-17.17	0.01	8.22	0.00
Mitrica et al.	23.46	0.0	23.08	0.00	56.10	0.00

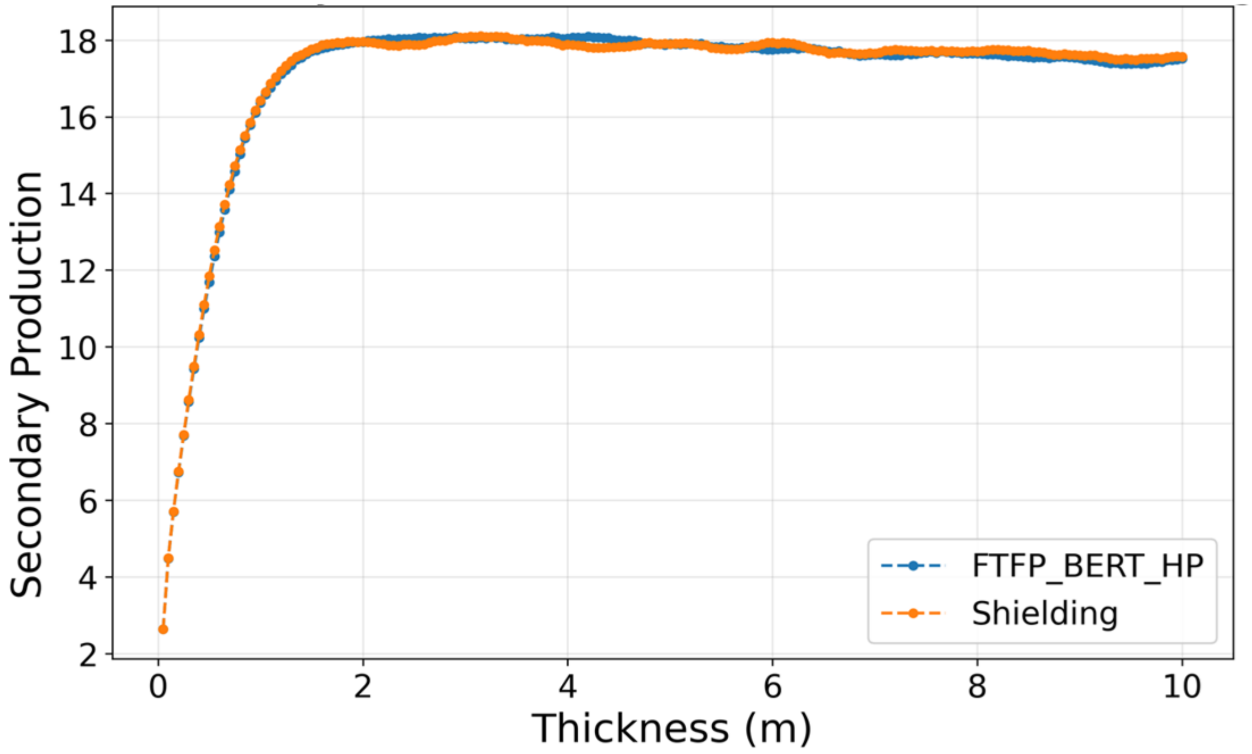
Comparison of AICc values and Akaike weights between all models for three separate depths ranges

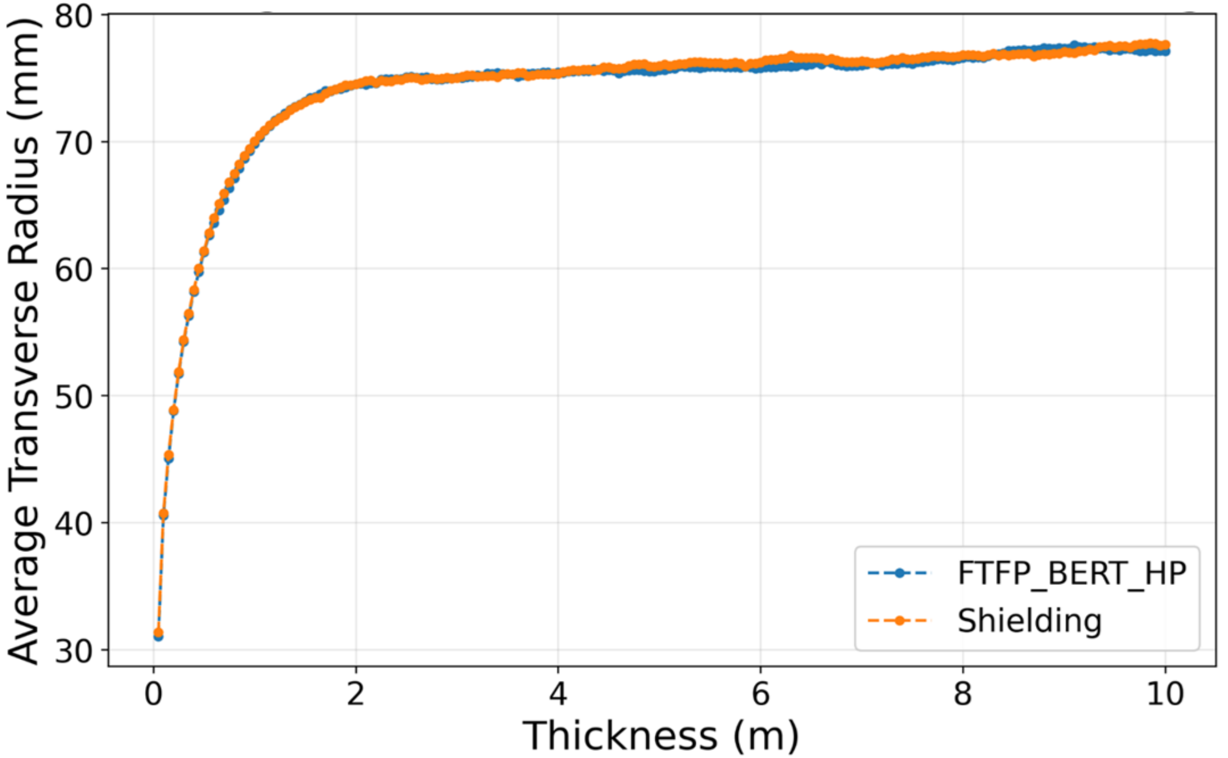
[8] D.-M. Mei and A. Hime, Phys. Rev. D 73, 053004 (2006)

[9] B. Mitrica et al., Advances in High Energy Physics 2013,256230 (2013)

Muon-induced Secondaries

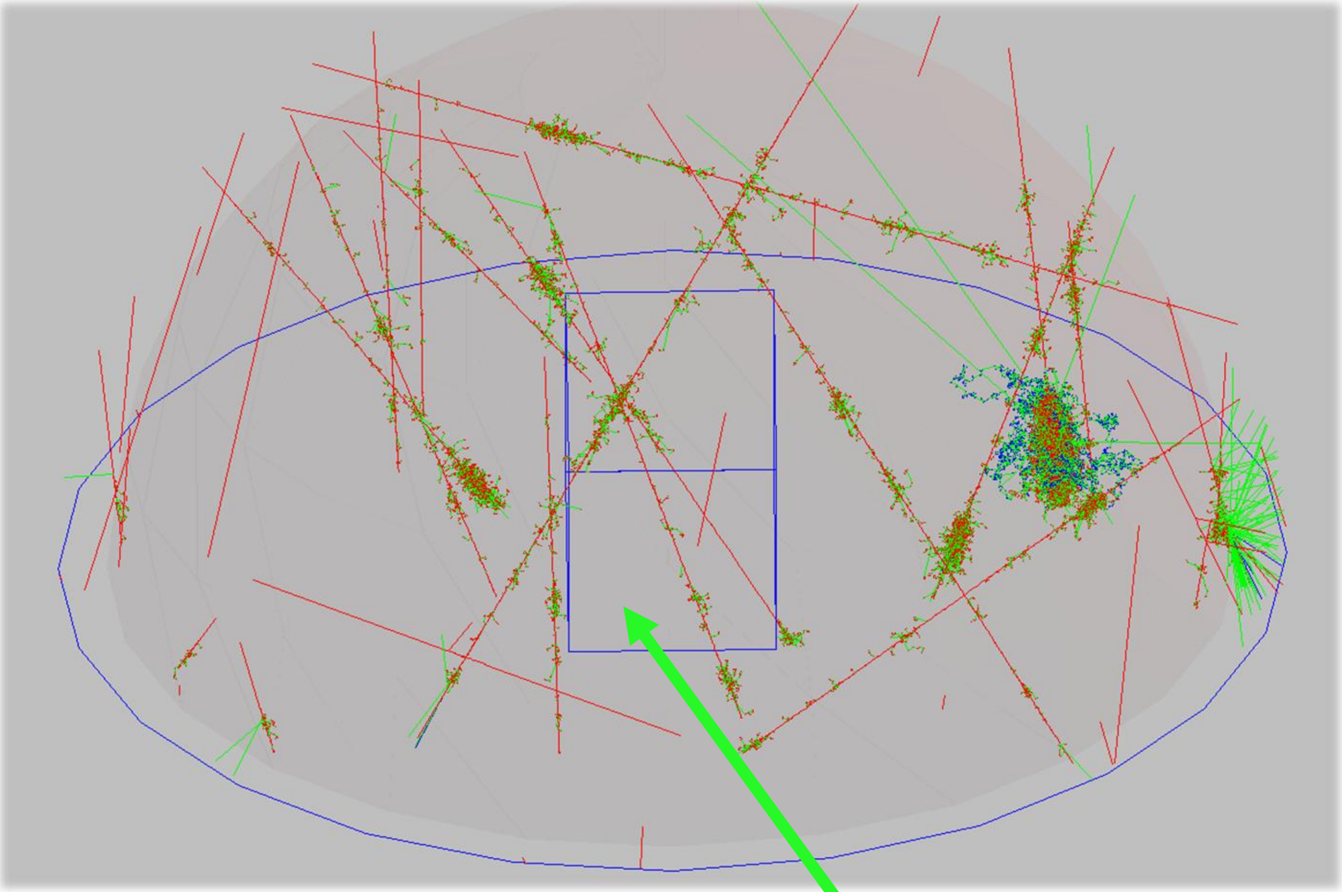
- Approximate topology with hemisphere of rock
- Muon-induced equilibrium study done using Geant4
- Rock thickness of 4m chosen to ensure muon-induced shower equilibrium





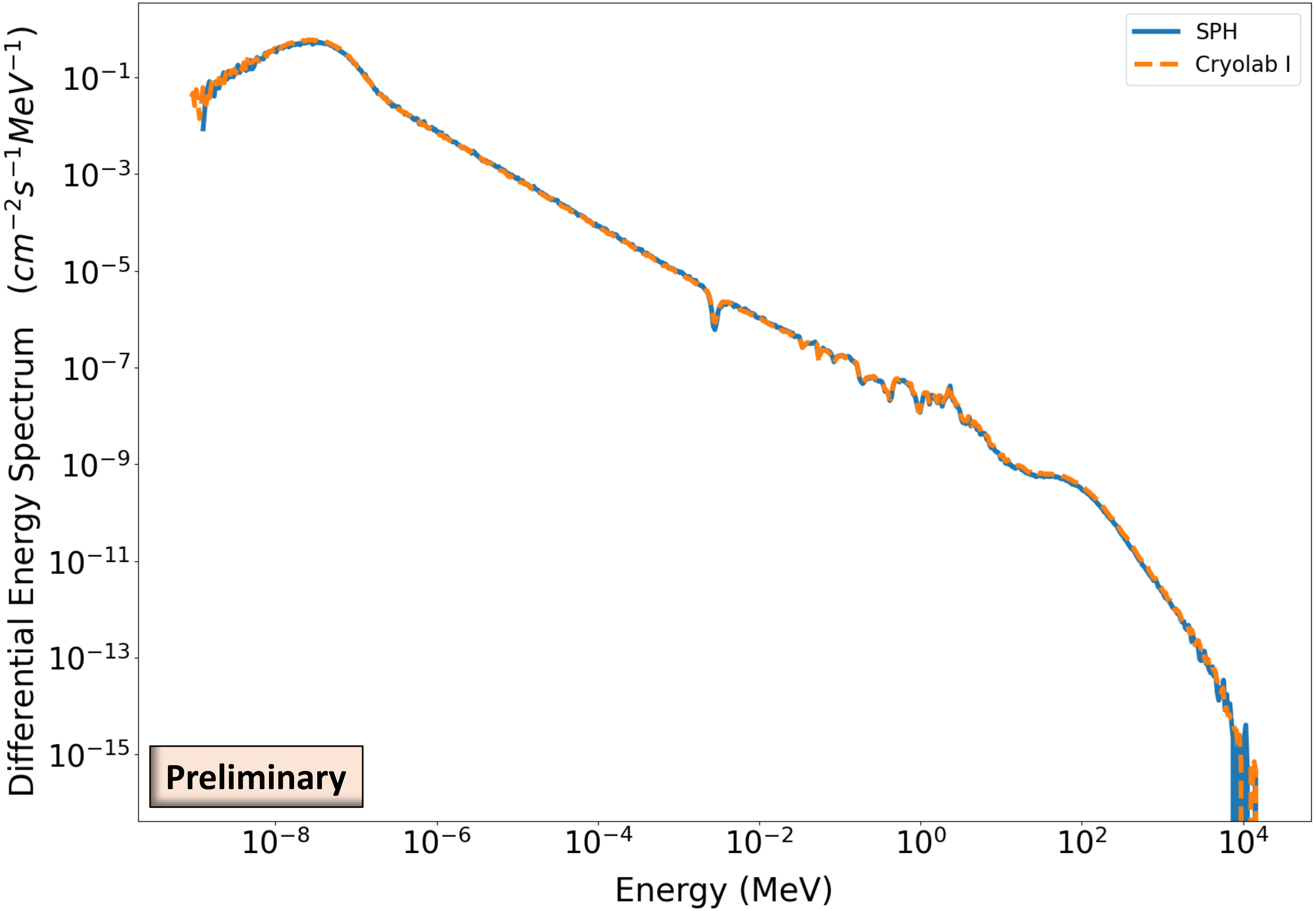
Muon-induced Secondaries

- MUTE energy and angular distributions coupled to Geant4
- Tag secondaries crossing rock-cavern boundary
- Estimate rock-cavern flux and energy distributions



Subatomic Particle Hideout

Muon-induced Secondaries



Neutron energy spectrum at SPH and Cryolab I

Muon-induced Secondaries

- Neutron flux in agreement with estimation from Mei & Hime [8]
- Electromagnetic component dominates

Preliminary

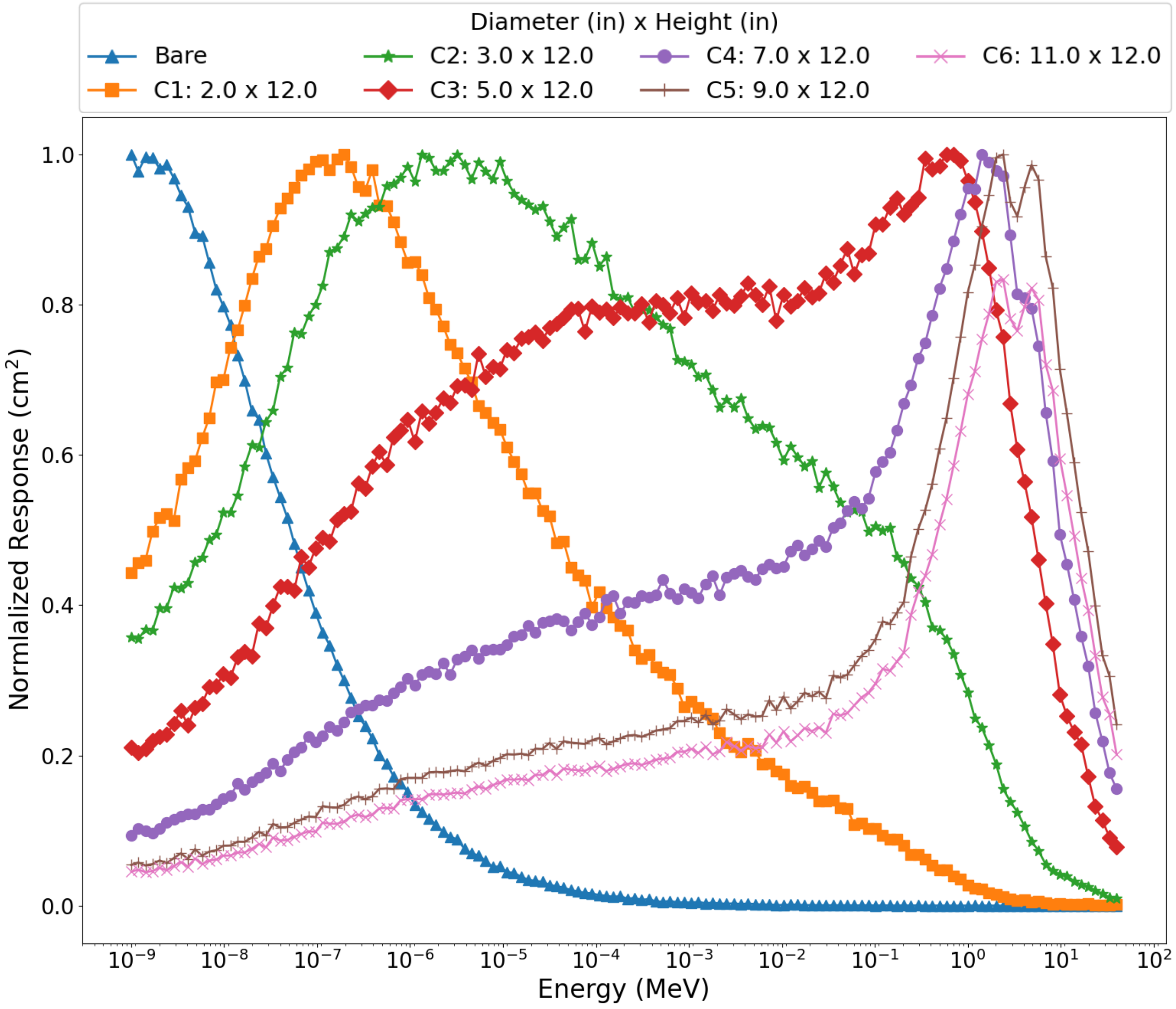
Rock-Cavern Flux $[1/(\mathrm{m}^2\ \mathrm{s})]$

Location	Primary Muon $[\times 10^{-1}]$	Neutron $[\times 10^{-3}]$	Gamma $[\times 10^{-1}]$	Electron $[\times 10^{-2}]$	Positron $[\times 10^{-2}]$
SPH	$(2.39 \pm 0.25_{sys.})$	$(3.78 \pm 0.43_{sys.})$	$(5.54 \pm 0.63_{sys.})$	$(4.39 \pm 0.49_{sys.})$	$(1.08 \pm 0.12_{sys.})$
Cryolab I	$(2.59 \pm 0.26_{sys.})$	$(3.97 \pm 0.43_{sys.})$	$(6.51 \pm 0.71_{sys.})$	$(5.28 \pm 0.58_{sys.})$	$(1.29 \pm 0.14_{sys.})$

[8] D.-M. Mei and A. Hime, Phys. Rev. D 73, 053004 (2006)

Ongoing Efforts

- Ongoing neutron background characterization
  - 3He neutron spectrometer
  - Liquid scintillator for neutron/gamma PSD
- Characterize environmental factors including vibrations, electromagnetic, ambient radon, etc.



Summary

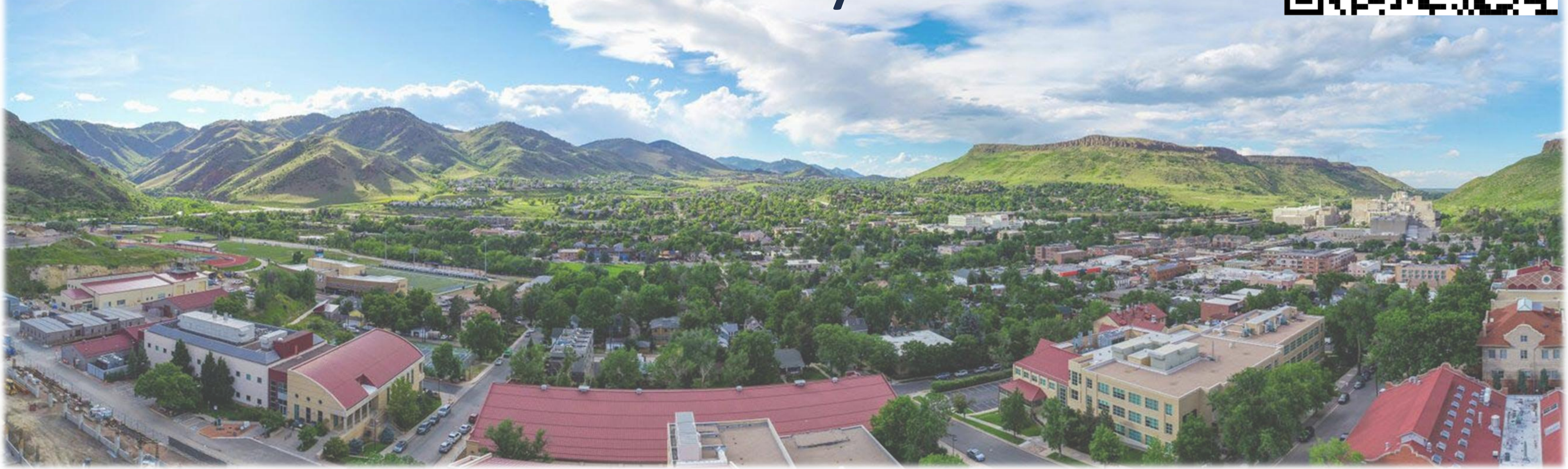
- Good cosmogenic radiation shielding and facility access and infrastructure
- Progressing toward a well characterized facility
- Many opportunities for new collaborations and research

Facility	Overburden (m.w.e.)	Sea level muon reduction
CURIE	415	700x
PNNL [10]	30	6x
Fermilab [11, 12]	225 - 300	200x – 400x

[10] C. E. Aalseth et al., Review of Scientific Instruments 83, 113503 (2012).
[11] P. Figueroa, "Fermilab underground facilities,"https://indico.fnal.gov/event/63132/contributions/289832/attachments/178491/243304/Fermilab_Underground_Facilities_Figueroa.pdf (2024)
[12] D. Temples, "20th conference on low temperature devices,"https://lss.fnal.gov/archive/2023/slides/fermilab-slides-23-163-etd-ppd.pdf (2023)

Physical Review D™

Thank you!



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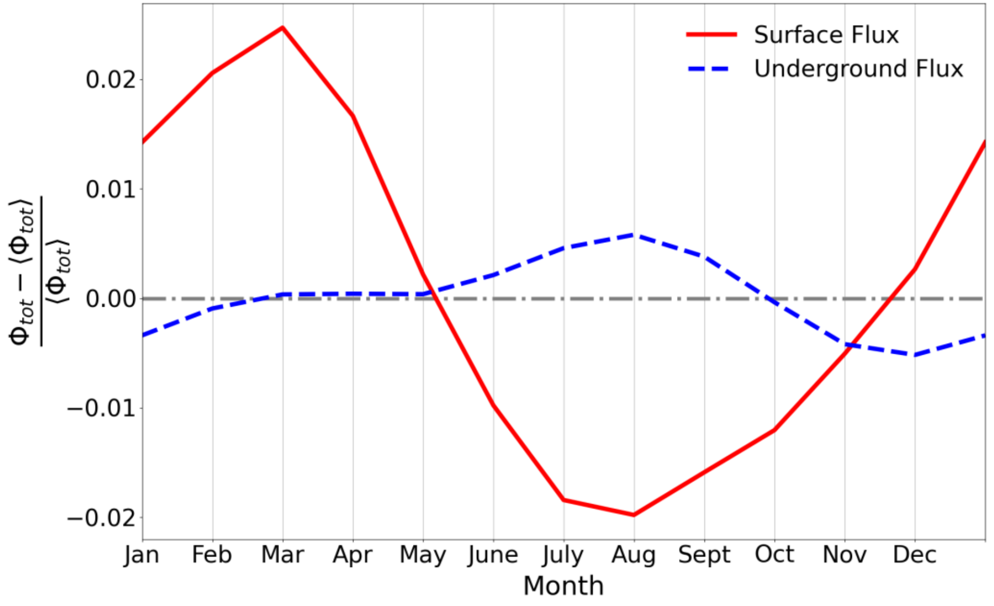
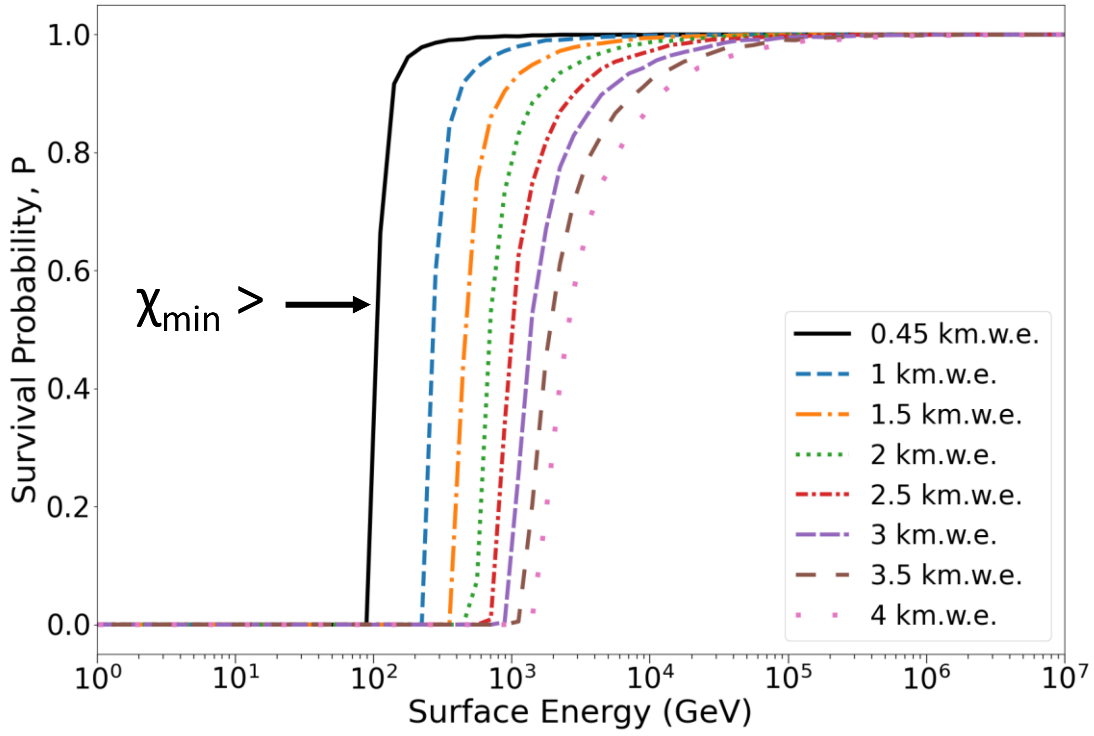
Supplemental Slides

Surface Muon Flux

- The surface and underground muon flux varies with both altitude and season [13-14]
- Only low energy muons added to the surface spectrum at 2400m altitude
- Underground flux expected to vary by less than 1% throughout the year and can be neglected



Estimated seasonal surface and underground muon fluxes



Underground muon survival probability as a function of surface energy for various slant depths

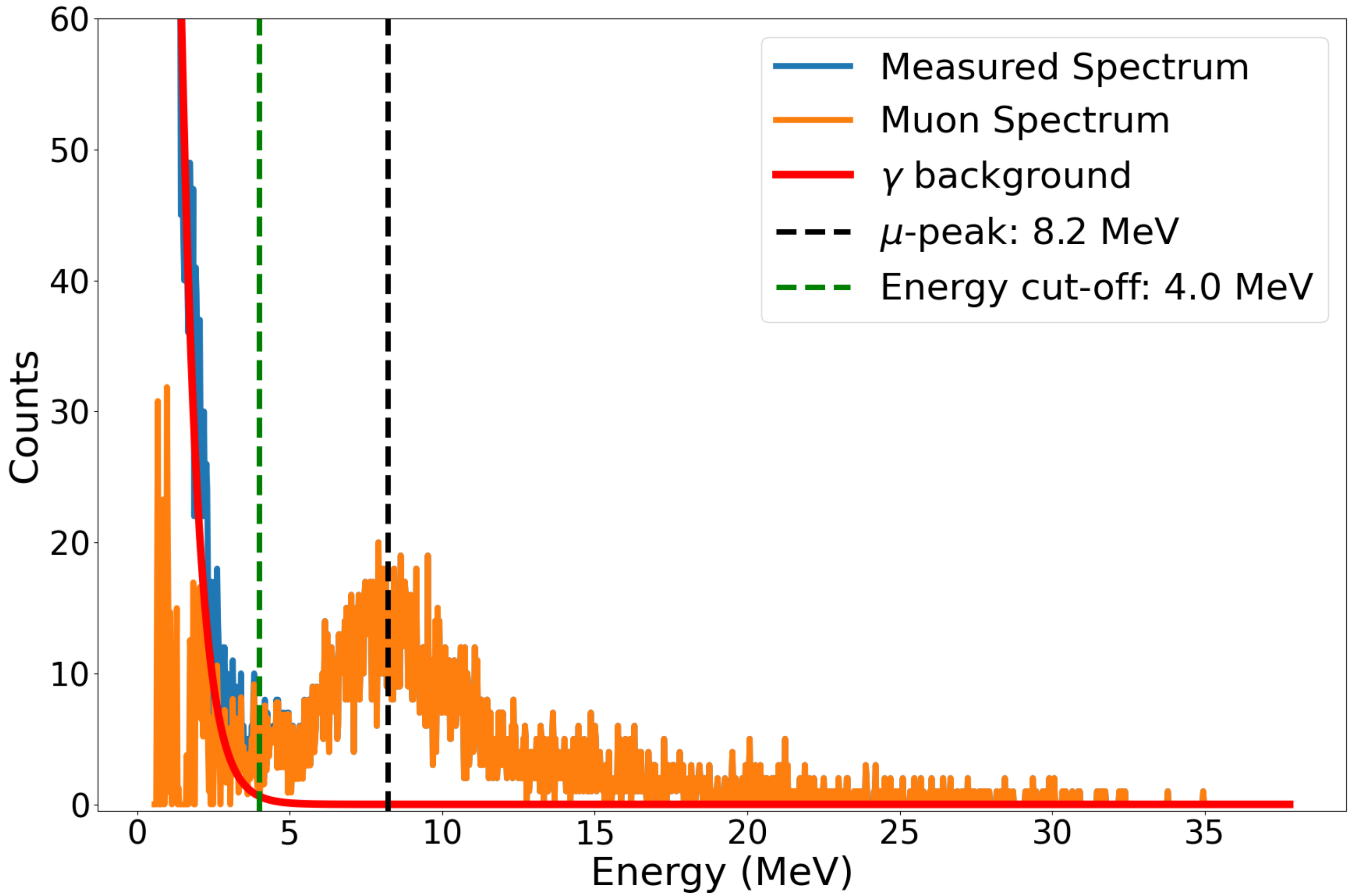
- Found no contribution to the underground flux below ≈ 90 GeV surface energy
- Sea level surface muon flux appropriate to use

[13] S. Verpoest, D. Soldin, and P. Desiati, Astroparticle Physics 161, 102985 (2024).

[14] P. Hansen, P. Carlson, E. Mocchiutti, S. J. Sciutto, and M. Boezio, Phys. Rev. D 68, 103001 (2003).

Gamma Background

- Gamma background from naturally occurring sources obscures the low energy muon counts – typically below 3 MeV of deposited energy
- An exponential fit to the gamma background was applied up to the energy cutoff of 4 MeV
- Gamma background subtracted to estimate total muon count N_{tot}



Results of the channel-to energy-conversion and γ background subtraction from the measured spectrum in Site 1. The estimated energy cut-off, μ-peak, and γ background are also shown