

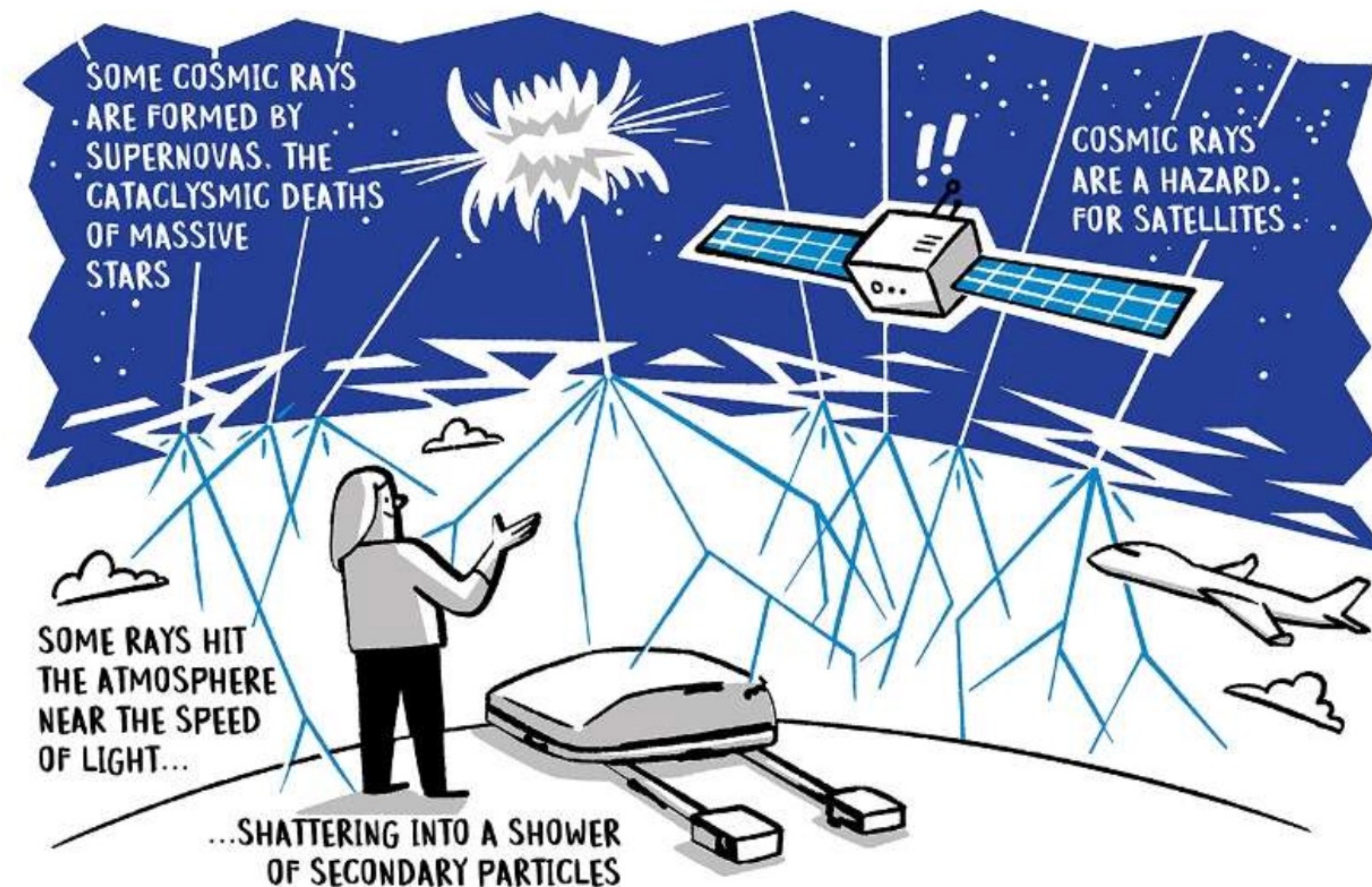
Cosmic Ray & Muon Research at SNOLAB

CRUST & COSMO

Erica Caden, SNOLAB
for the COSMO and CRUST Collaborations

Cosmic Rays

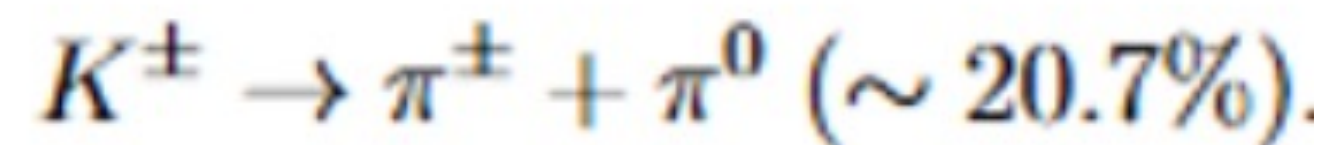
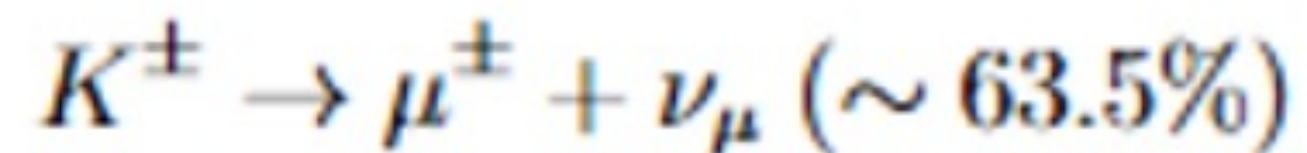
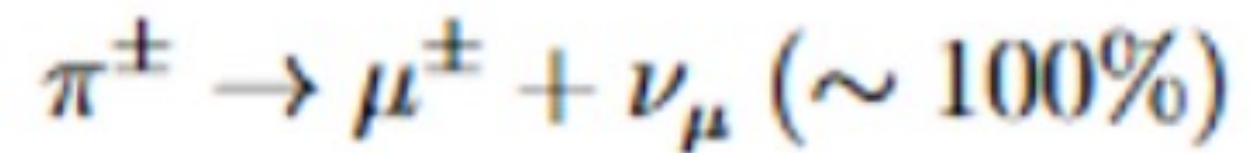
- Primary cosmic ray content is mostly protons and light nuclei
 - Heavier elements directly result from stellar evolution and death
 - Interstellar medium is host to an abundance of matter and turbulence
 - Shockwaves are viable mechanisms for accelerating particles to very high energies
- Evidence of this from decays observed using the Fermi Large Area Telescope [[10.1126/science.1231160](https://www.nasa.gov/science/10.1126/science.1231160)]
 - Cosmic ray physics has been at the energy frontier long before modern particle physics was established... and will be for the foreseeable future



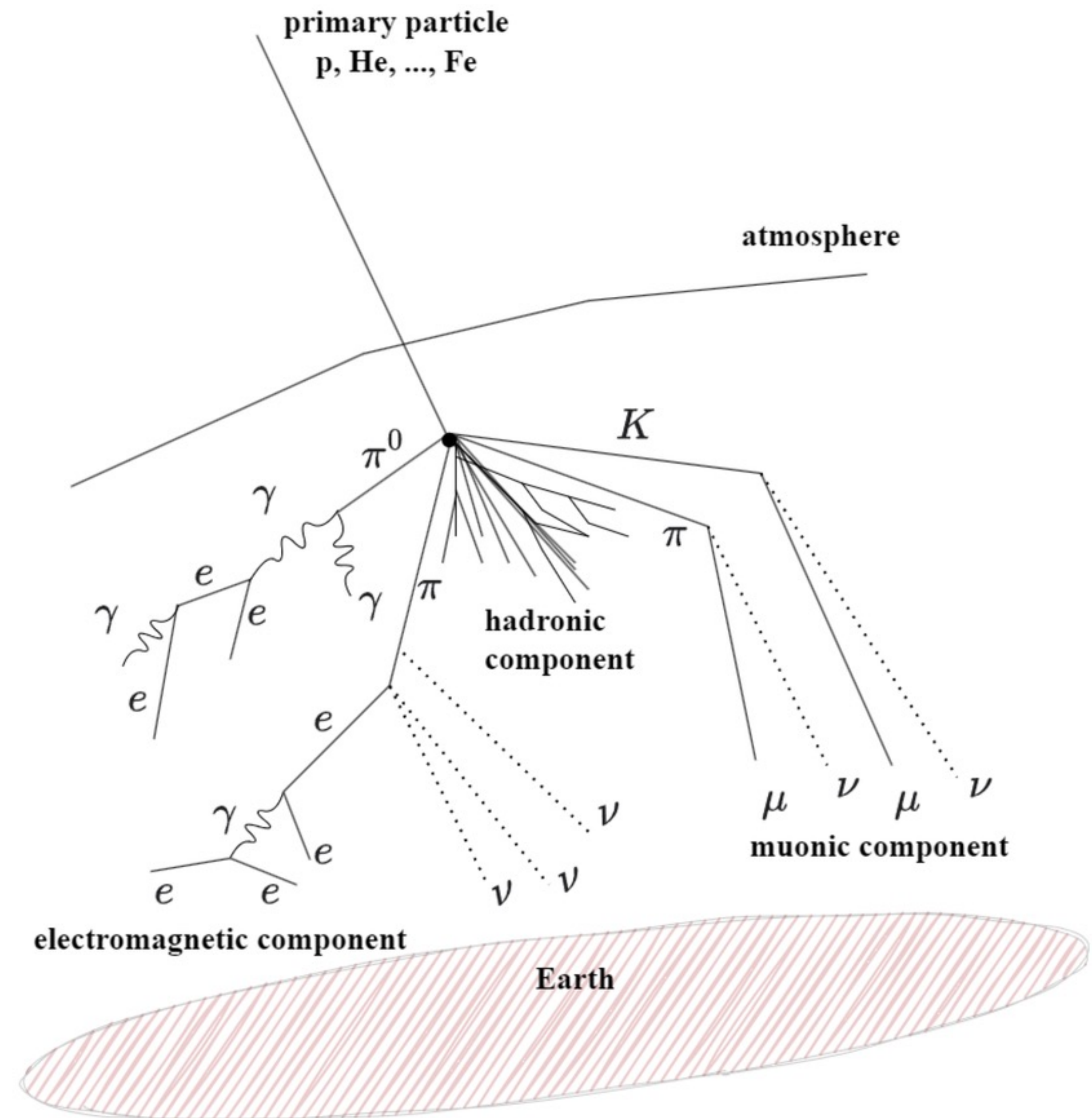
[<https://www.iop.org/explore-physics/physics-around-you/understanding-surroundings/cosmic-rays>]

Air Showers

- Primary cosmic ray interactions with the upper atmosphere create showers of secondary particles
- Conceptually identical to fixed target experiments
- π and K mesons are abundant products which decay to muons and neutrinos

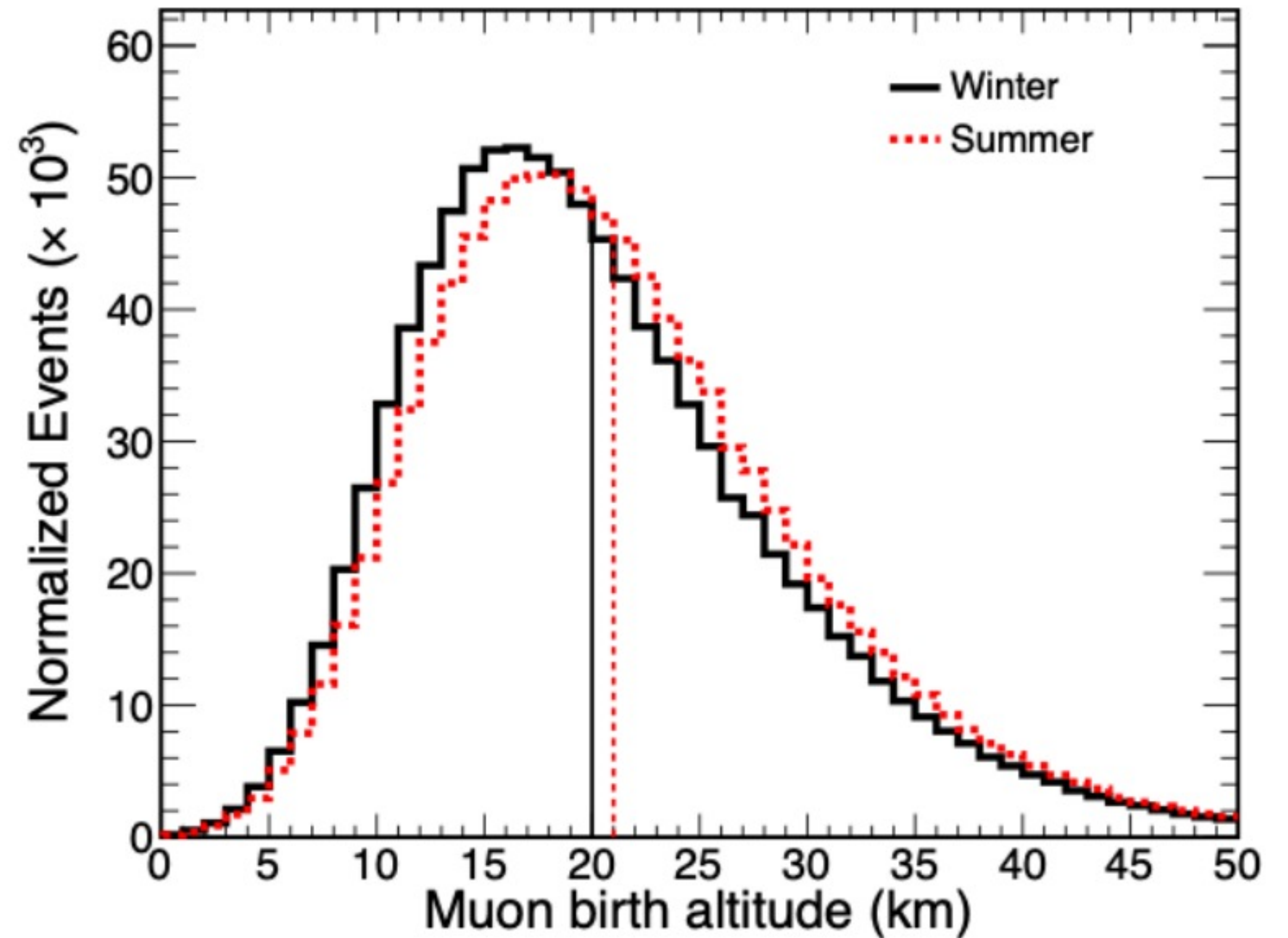


- Both shower products are observable at deep underground laboratories



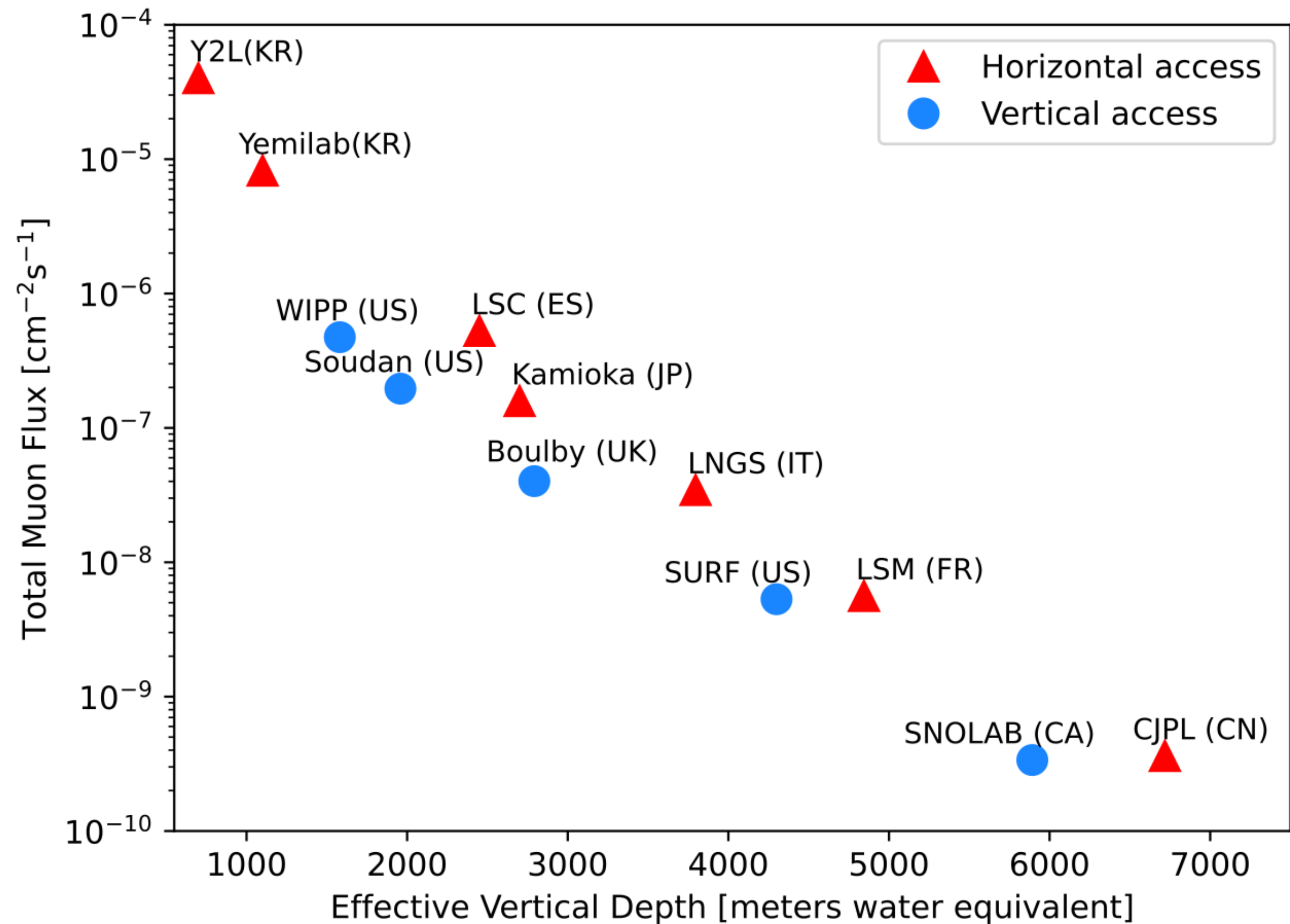
π and K Decay

- The altitude at which cosmic rays interact with the atmosphere depends on the scale height
 - During the warm season, the atmosphere is taller, and cosmic rays interact sooner - opposite happens during the winter
 - More time for mesons to decay during summer
- Muons produced most directly by the parent cosmic ray will have systematically higher energies
- Pion interaction length: $\Lambda_{\pi} = 180 \text{ g/cm}^2$
- Kaon interaction length: $\Lambda_K = 160 \text{ g/cm}^2$



Muons underground

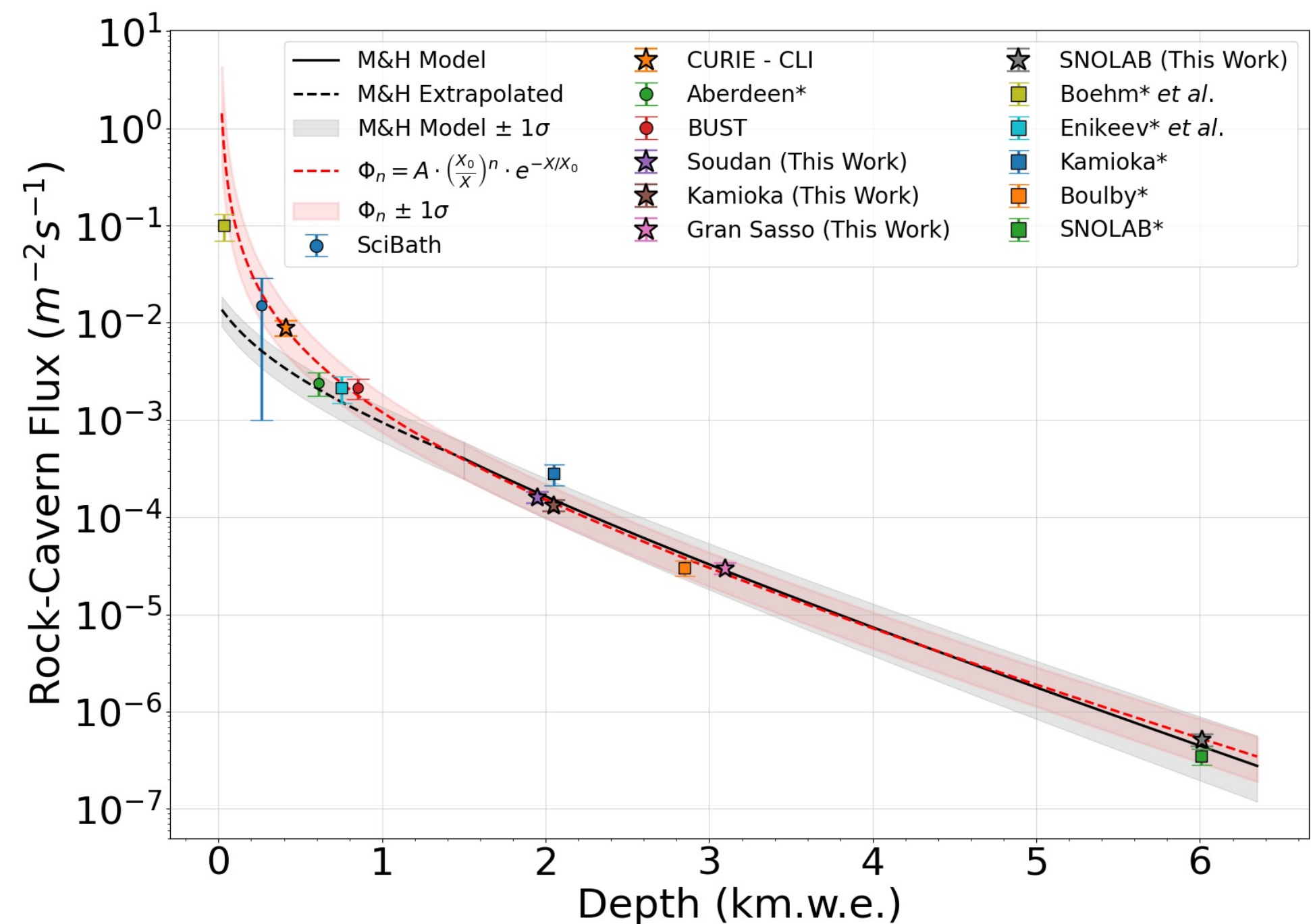
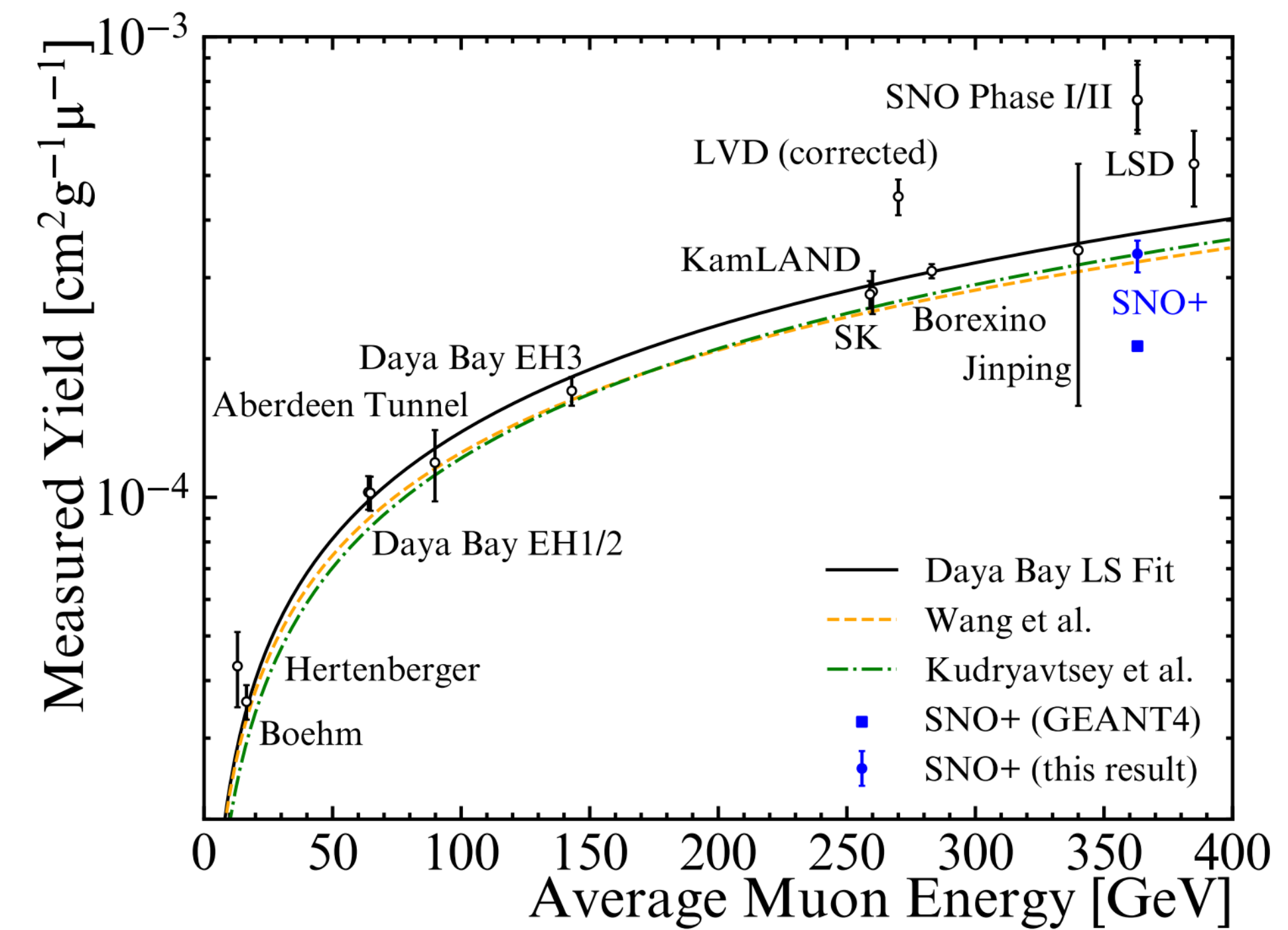
- Overburden filters all muons below a depth-dependent threshold
- Local energy spectrum underground is hard - depends on depth
- Convenient parameterizations exist (e.g.: Mei & Hime, 2006 & Keblbeck et al, 2025)
- Cosmogenic backgrounds studied extensively by rare event searches across the world
- Each underground site is unique: Amount of overburden, topology, rock composition, location on the planet
- SNOLAB's flat overburden and deep vertical depth will allow for the deepest measurement of the π/K ratio and test of the latest meson/muon production and transportation models



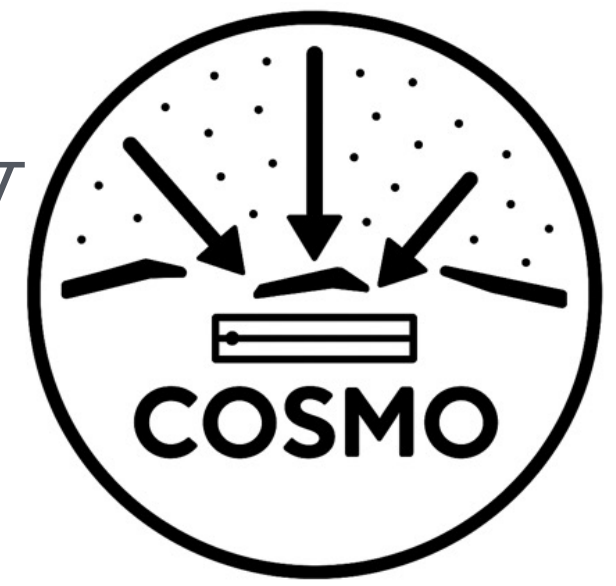
adapted from [Chin. Phys. C 45.2 \(2021\)](#)

Muon-induced bkgds

- High average muon energy at ~6 km.w.e is effective at producing hadronic showers in rock
- Hadronic showers themselves lead to neutrons, isotopes, and electromagnetic backgrounds
- Improved knowledge/monitoring of muons underground can better inform models for predicting backgrounds
- SNO and SNO+ recently published cosmogenic neutron yields for D2O ((w/wo salt) and H2O and find varying levels of agreement between Geant4 and FLUKA [<https://doi.org/10.1103/vs3y-sbb2>]
- Discrepancies indicate that there's room for improvement
- Keblbeck et al have developed a tool to couple MUTE and Geant4 which enables detailed lab-specific studies of muons and muon-induced backgrounds [<https://doi.org/10.1103/7n8l-pr2g>]



COsmic ray Seasonal Modulation Observatory



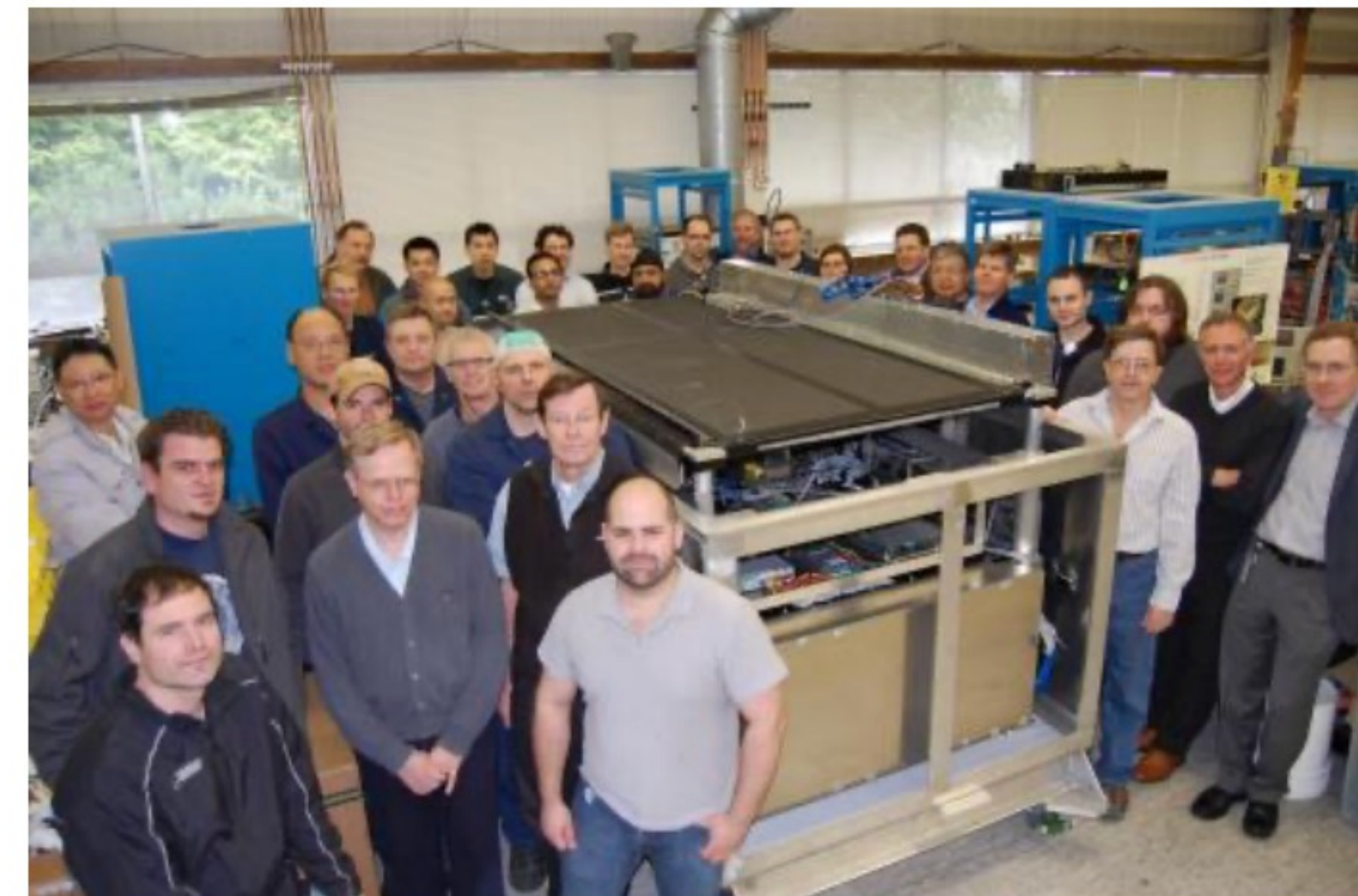
- Eight robust muon geotomography detectors based on extruded plastic scintillator technology
 - 2 m² footprint per detector
 - ~10 mrad angular resolution
 - High efficiency, low data storage requirements
 - Analysis infrastructure very mature
- Measure cosmic ray muons at SNOLAB in a dedicated way to probe cosmic ray and atmospheric physics at the depth frontier
- Develop new expertise in cosmic ray physics, muon-induced backgrounds



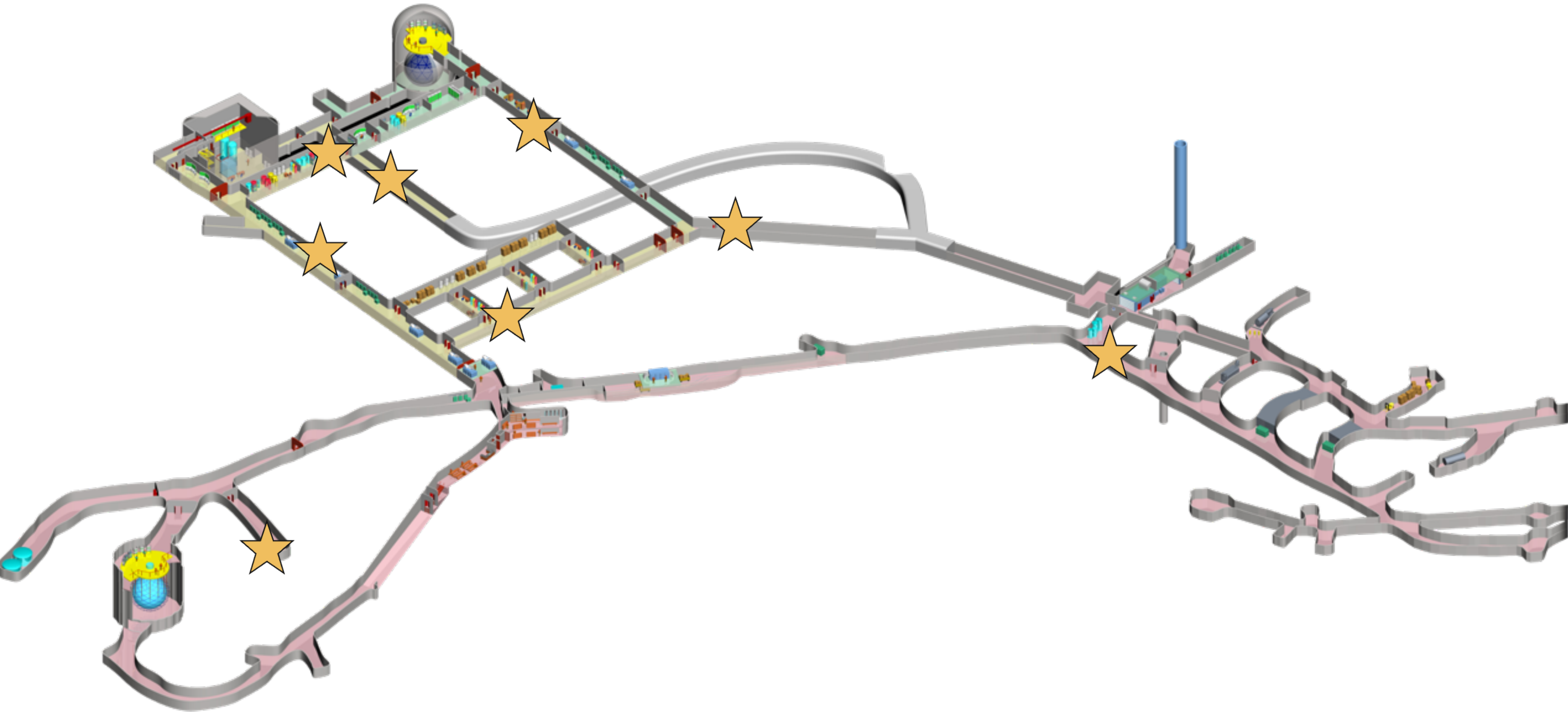
Source: <https://ideon.ai/about/our-story/>

COSMO's "v1" Muon Detectors

- Commercial detectors produced by spin-off of TRIUMF for muon geotomography applications
 - Advanced Applied Physics Solutions → CRM GeoTomography → Ideon Technologies (ideon.ai)
 - Ideon has since developed new deployable muon technology and CNL subsequently acquired the V1 hardware
 - Deployed next generation muon tracking technology (borehole and panel detectors) at Totten and Creighton mines
- Track reconstruction methods identical to those used in scattering tomography by CNL
 - v1 detectors are essentially different configurations of CNL's CRIPT detector [[NIM.A. 798 \(2015\) 12-23](#)]
 - Require modest physical space due to rugged enclosure
 - ~900 kg of mass from enclosure/skid, interior frame, plastic scintillator

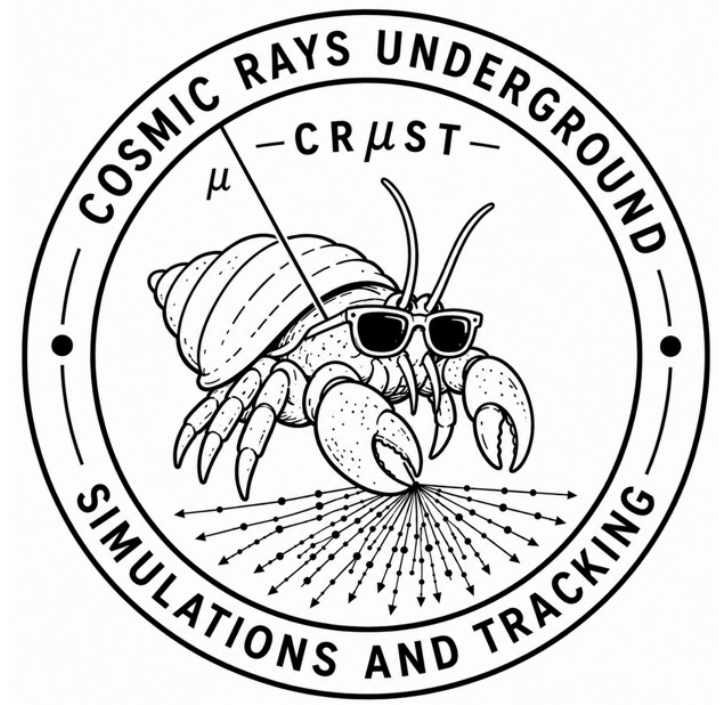


Possible Locations

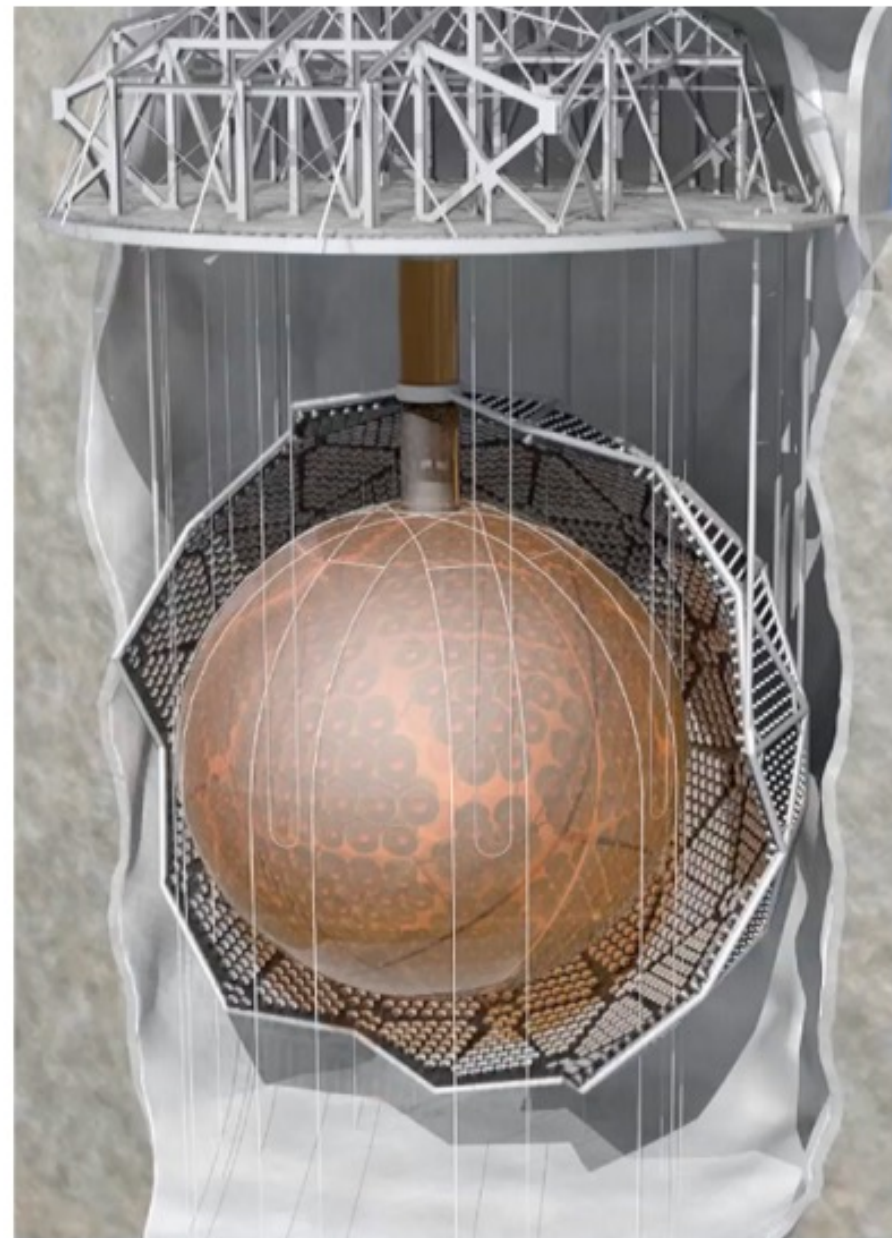


Cosmic Rays Underground Simulations and Tracking

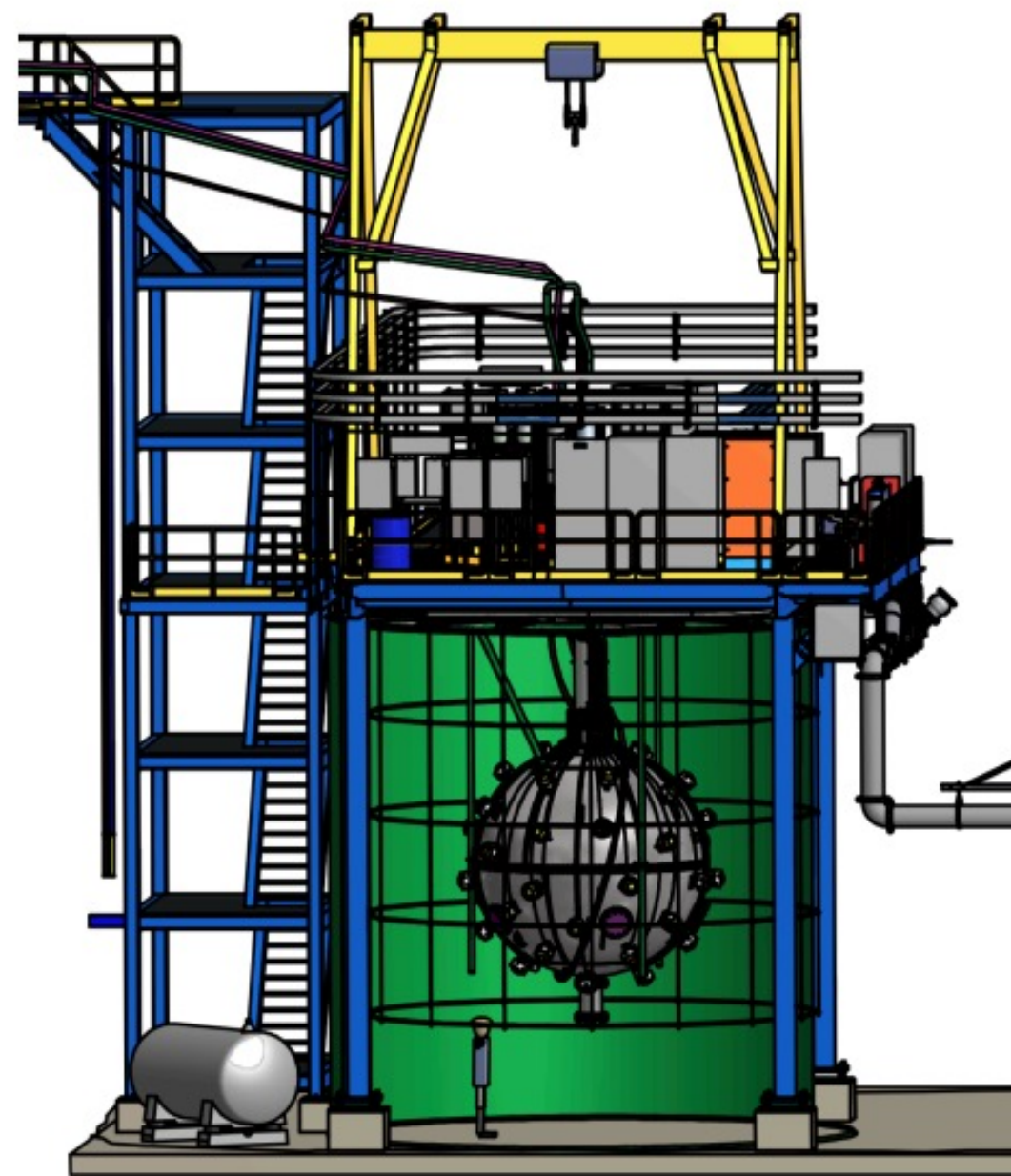
- Highly complementary effort underway to facilitate more cooperation between SNOLAB experiments
- Neutrino and Dark Matter searches either have dedicated Muon Vetos or the ability to identify muons
- Aggregating this muon data, accounting for detector/experiment-specific systematics, will allow the creation of a large sample of muons at SNOLAB
- Aiming to foster technical discussions and share latest developments in computational tools



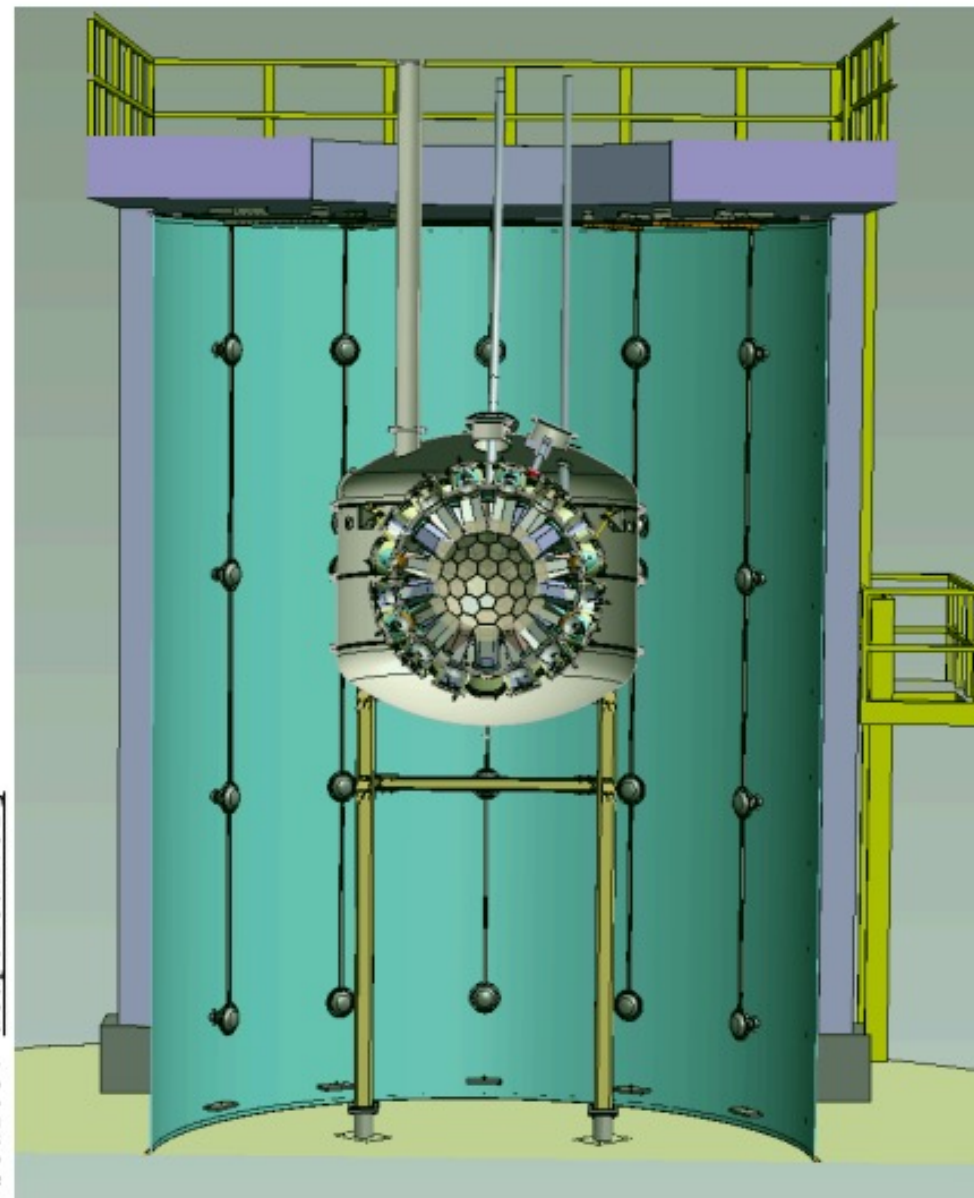
Source: <https://snoplus.phy.queensu.ca/about.html>



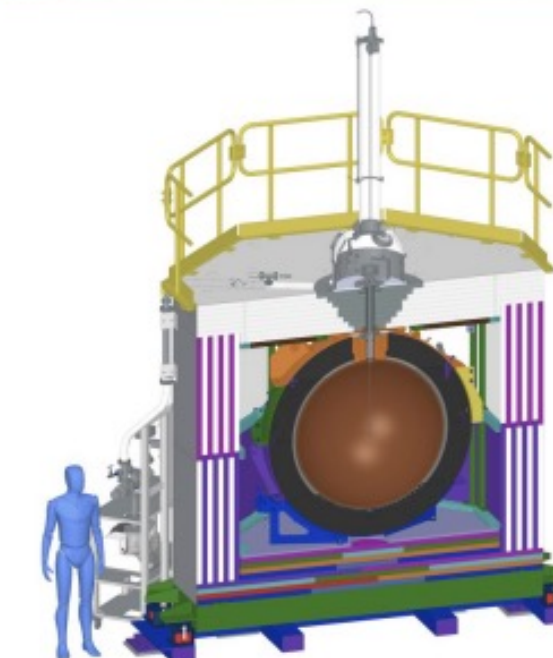
Source: <https://doi.org/10.1016/j.astropartphys.2018.09.006>



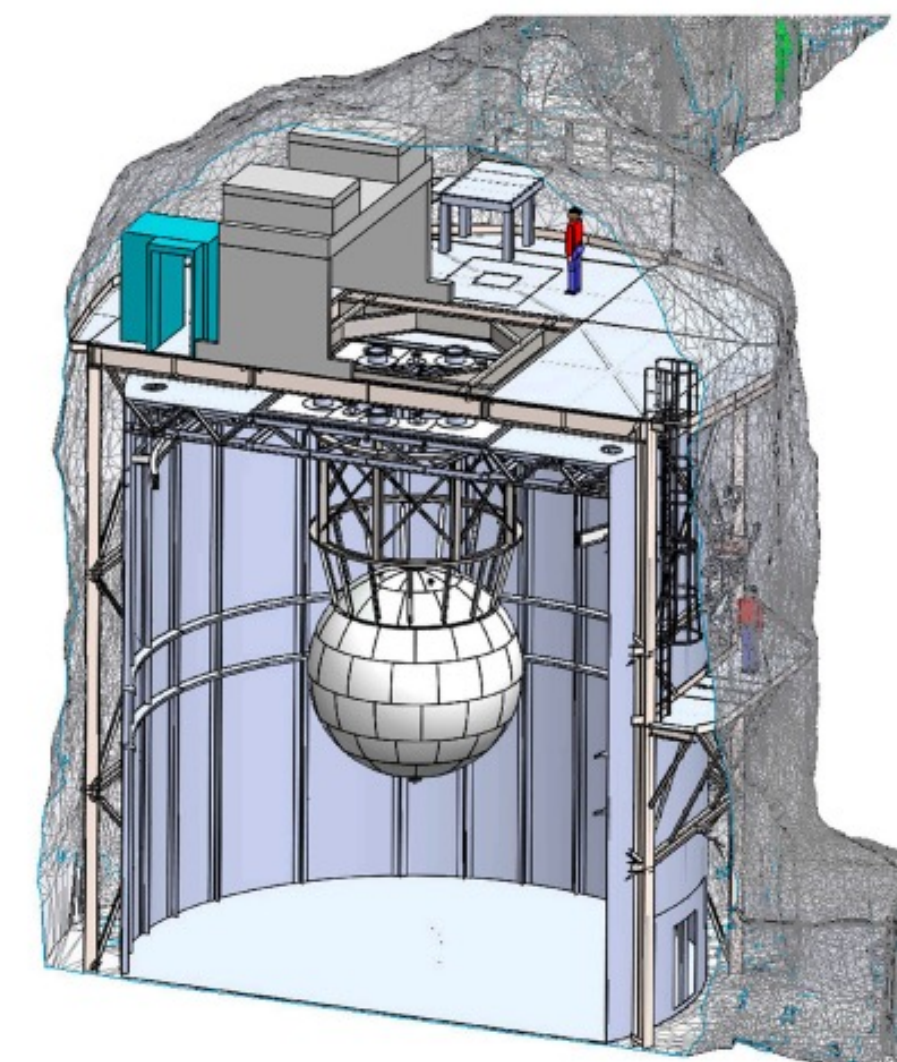
Source: deapclean.org



Source: SNOLAB

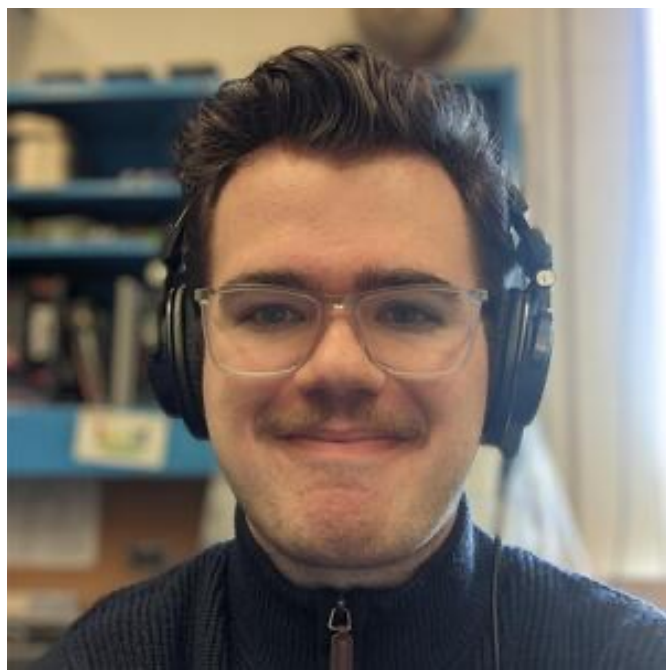
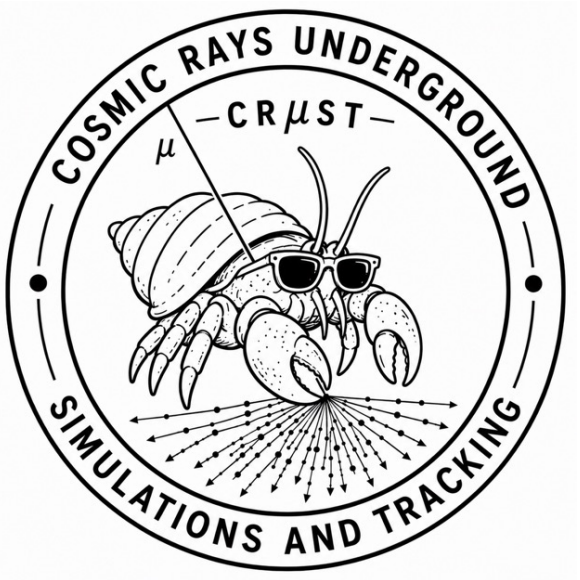


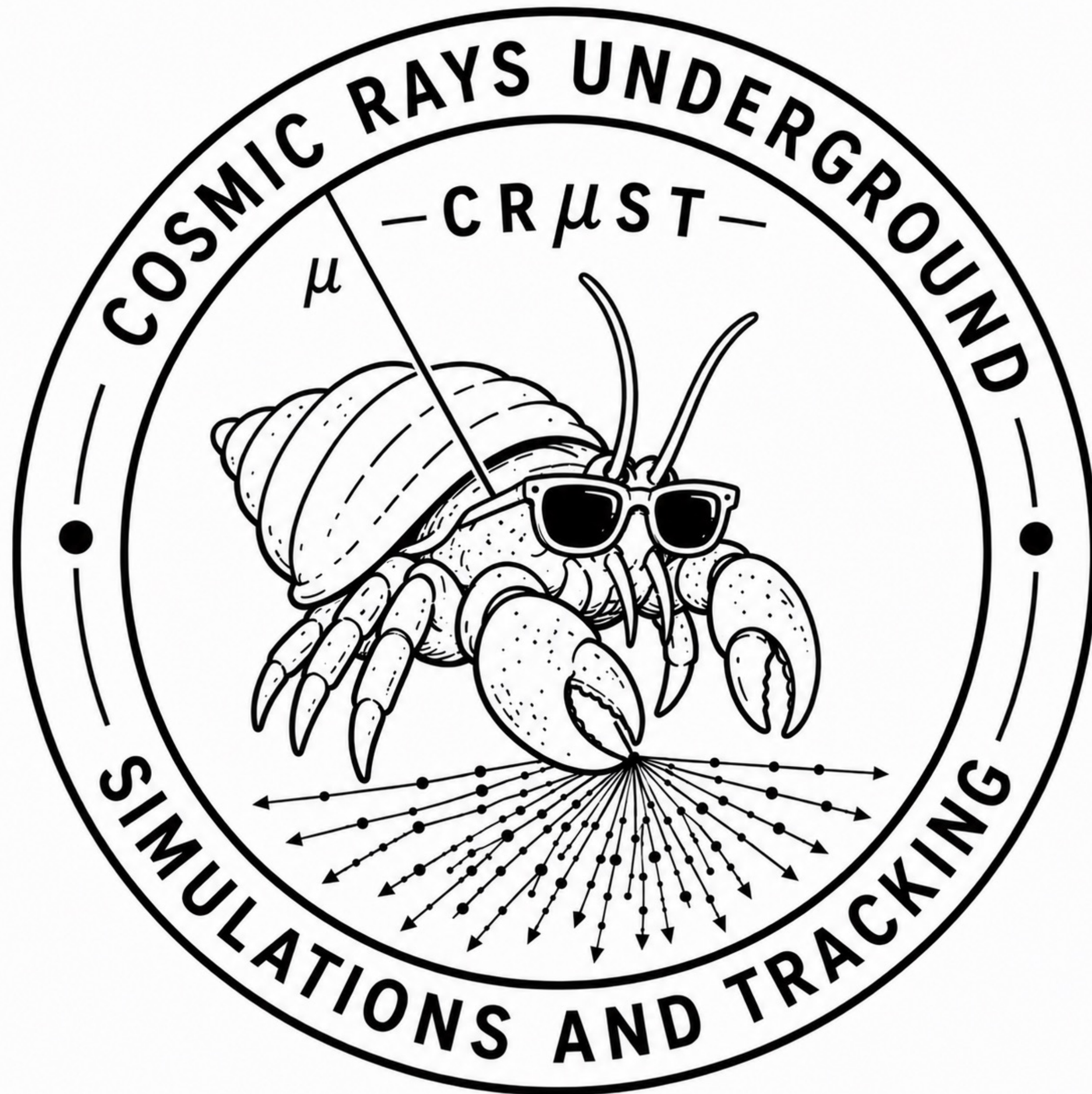
Source: <https://arxiv.org/pdf/2205.15433>



Source: <https://doi.org/10.1139/cjp-2024-0300>

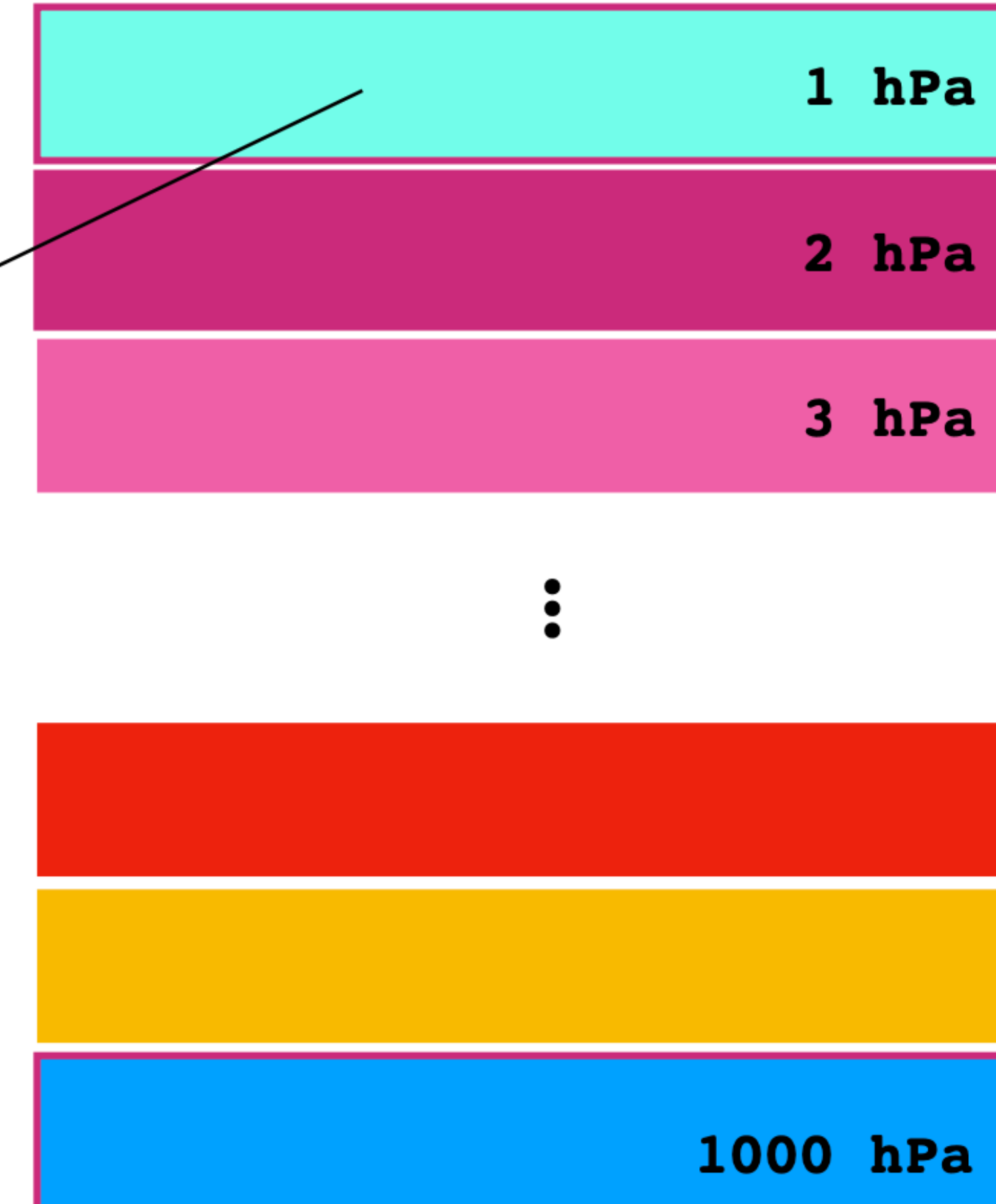
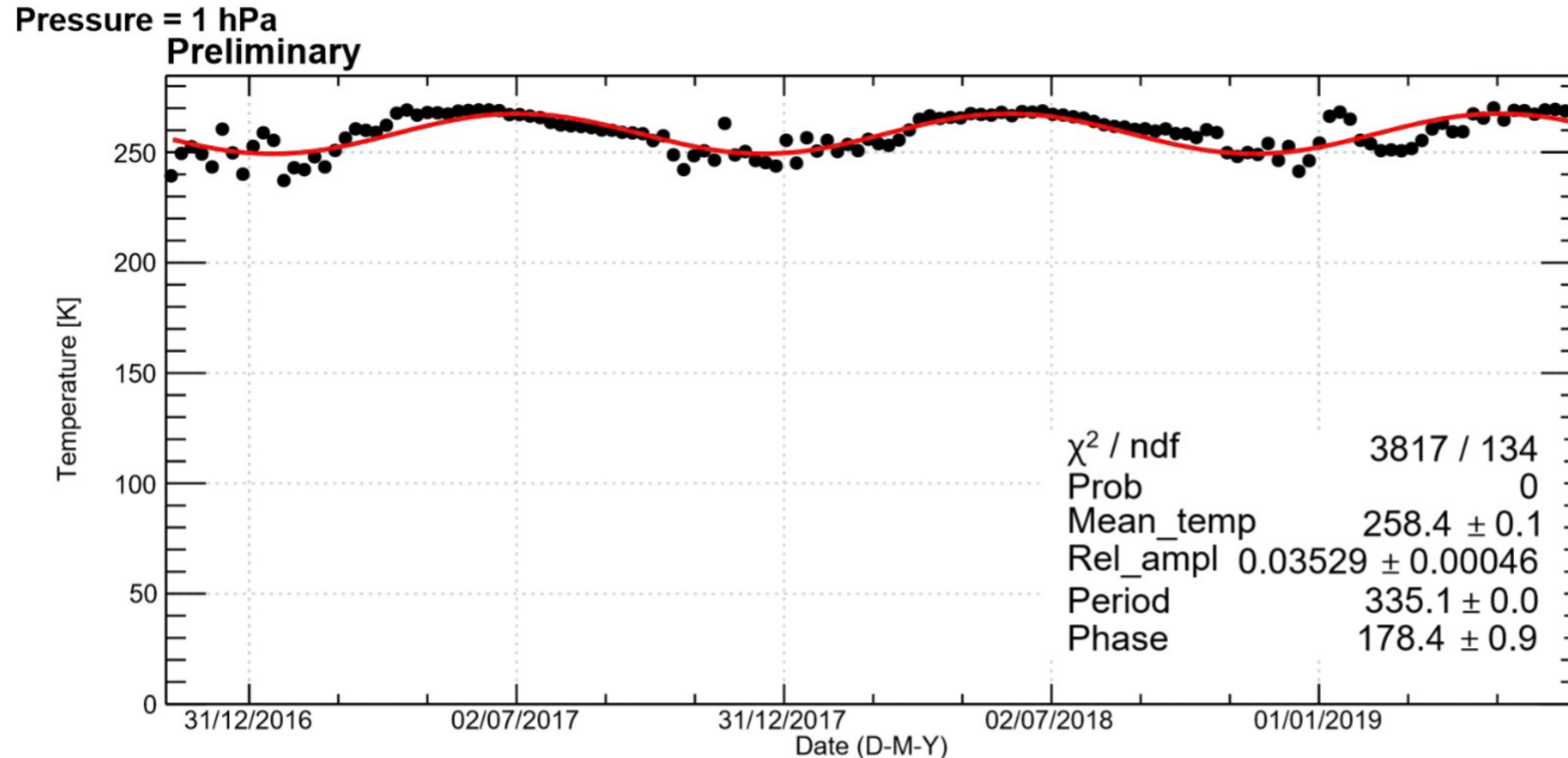
CRUSTaceans





Muon Intensity Modulation

- Changes in the atmospheric conditions drive the energy spectrum of muons
 - More (less) decays \rightarrow higher (lower) muon energy
 - Higher (lower) energy \rightarrow More (less) muons at slant depth, d
- Atmosphere is not a single monolithic column of some temperature, T
 - More realistic to represent it as discrete pressure levels
 - Temperature measurements are also taken at discrete heights
- Temperature for each level can be obtained from ECMWF data



Muon Intensity Modulation

- Simple model describing correlation between muon intensity and atmospheric temperature provided by the MACRO experiment ([https://doi.org/10.1016/S0927-6505\(97\)00011-X](https://doi.org/10.1016/S0927-6505(97)00011-X)) based on Barrett *et al* (<https://doi.org/10.1103/RevModPhys.24.133>)

$$\frac{\Delta I_{\mu}}{I_{\mu}^0} = \int_0^{\infty} dX \alpha(X) \frac{\Delta T(X)}{T(X)}$$

- Leveraging the atmospheric stack model, the complicated integral can be re-expressed as

$$\frac{\Delta R}{\langle R \rangle} = \alpha_T \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

- Intensity is proportional to the rate and rather than evaluating some arbitrarily difficult integrals over the atmosphere, the effective temperature is used
- Effective temperature also covers the fact that meson/muon production doesn't happen at any specific height

Effective temperature

- The effective atmospheric temperature can be computed using an approximation provided by Grashorn *et al* (<https://doi.org/10.1016/j.astropartphys.2009.12.006>)

$$T_{eff} \simeq \frac{\sum_{n=0}^N \Delta X_n T(X_n) (W_n^\pi + W_n^K)}{\sum_{n=0}^N \Delta X_n (W_n^\pi + W_n^K)}$$

$$W^{K,\pi}(X) \simeq \frac{(1 - X/\Lambda'_{\pi,K})^2 e^{-X/\Lambda_{\pi,K}} A_{\pi,K}^1}{\gamma + (\gamma + 1) B_{\pi,K}^1 K(X) (\langle E_{th} \cos\theta \rangle / \epsilon_{\pi,K})^2}$$

$$K(X) = \frac{(1 - X/\Lambda'_{\pi,K})^2}{(1 - e^{-X/\Lambda'_{\pi,K}}) \Lambda'_{\pi,K} / X}$$

$$1/\Lambda'_{\pi,K} = 1/\Lambda_N - 1/\Lambda_{\pi,K}$$

$$A_K^1 = 0.38 \times r_{K/\pi}$$

$$A_\pi^1 = 1$$

$$r_{K/\pi} = 0.149 \pm 0.06$$

$$B_K^1 = 1.740 \pm 0.028$$

$$B_\pi^1 = 1.460 \pm 0.007$$

$$\Lambda_N = 120 \text{g/cm}^2$$

$$\Lambda_K = 160 \text{g/cm}^2$$

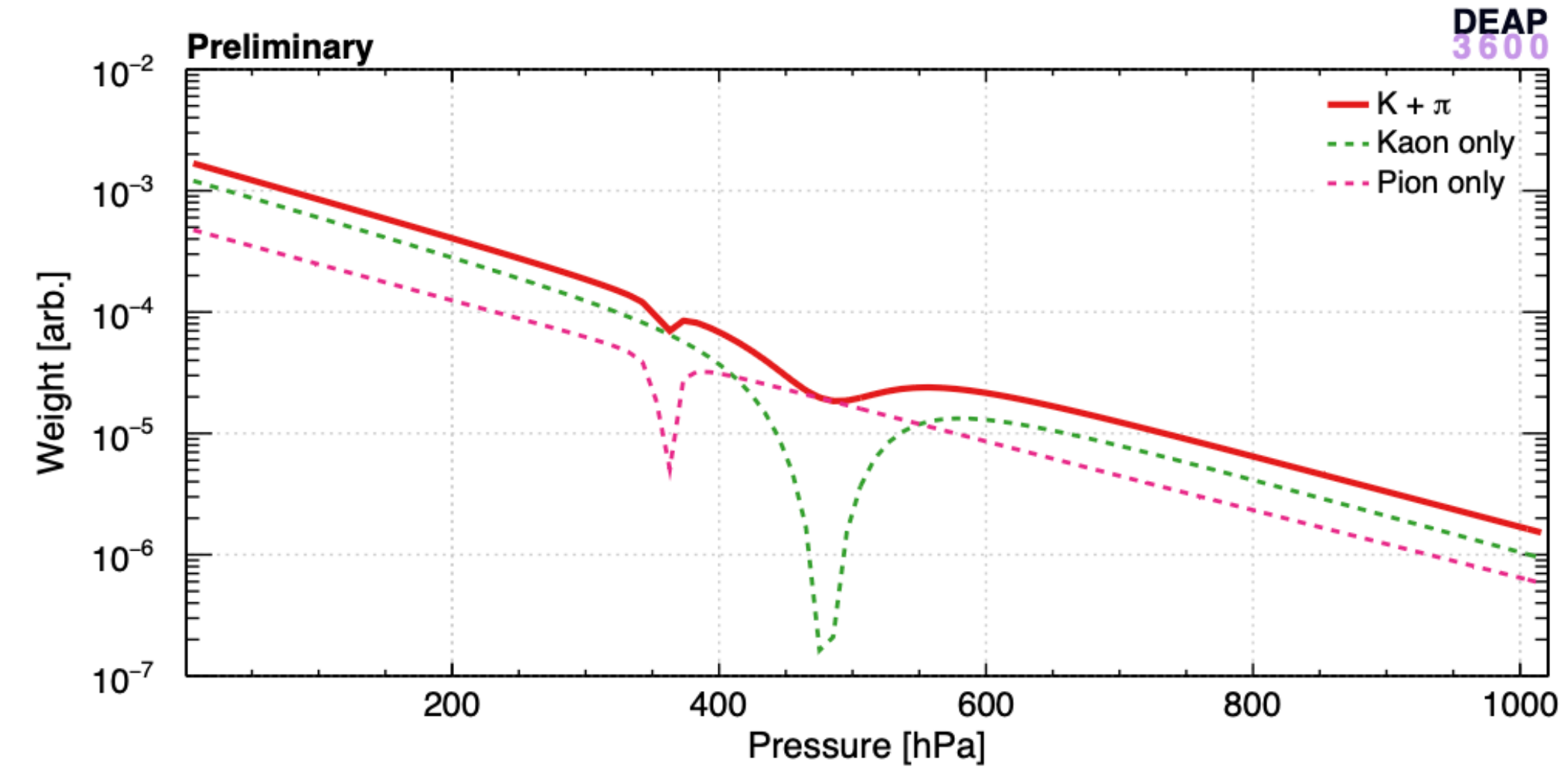
$$\Lambda_\pi = 180 \text{g/cm}^2$$

$$\langle E_{th} \cos\theta \rangle = (2.58 \pm 0.41_{sys}) \text{ TeV}$$

$$\gamma = 1.7 \pm 0.1$$

$$\epsilon_K = (0.851 \pm 0.014) \text{ TeV}$$

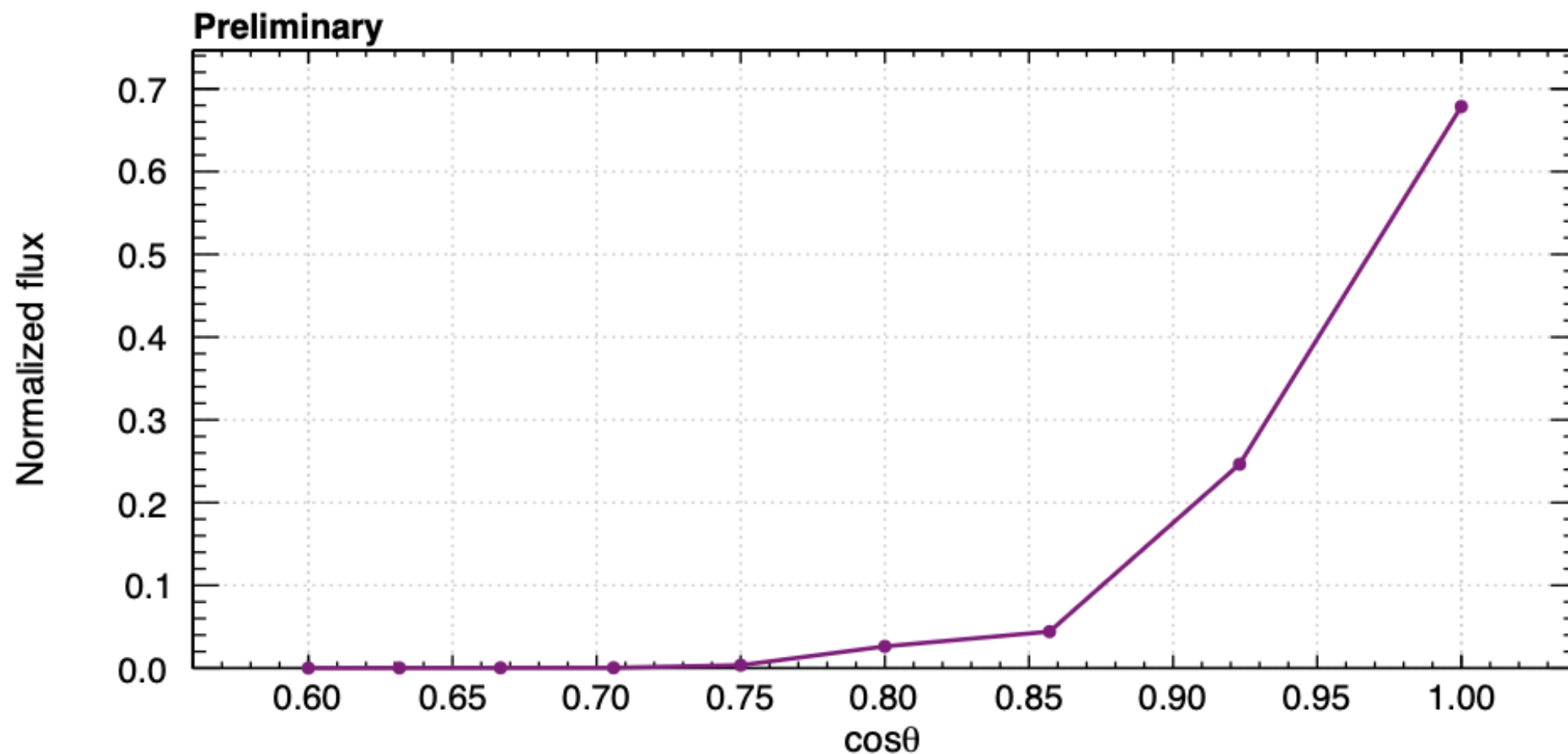
$$\epsilon_\pi = (0.114 \pm 0.003) \text{ TeV}$$



for SNOLAB

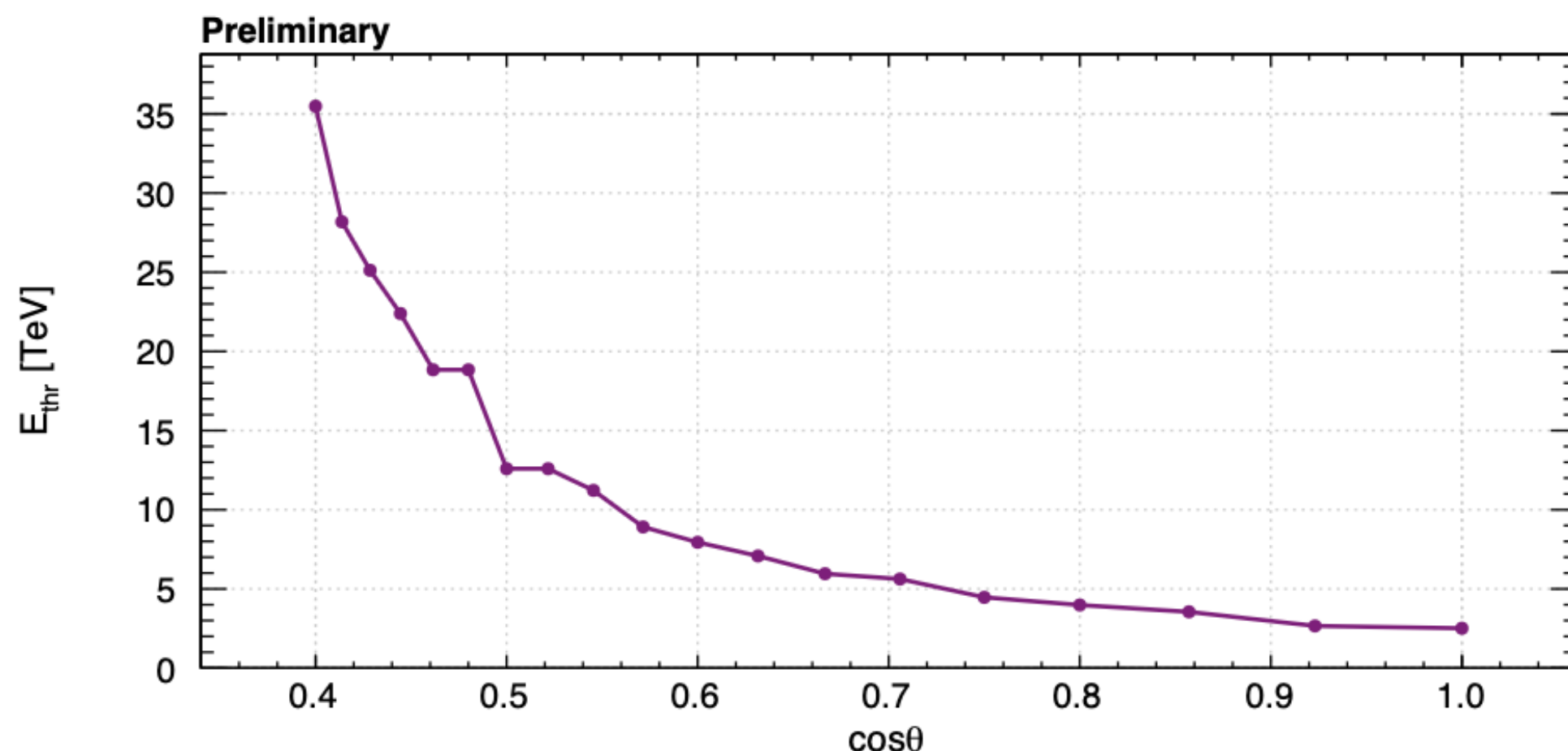
Threshold Energy

- Lab-dependent parameter in calculating π and K weights is the depth, expressed as the angle-averaged threshold energy for muons to survive to the lab
- Calculation for SNOLAB (~6 km.w.e) done using MUSIC/MUSUN



- Averaging over the normalized flux (top) and the threshold for a given amount of rock (bottom):

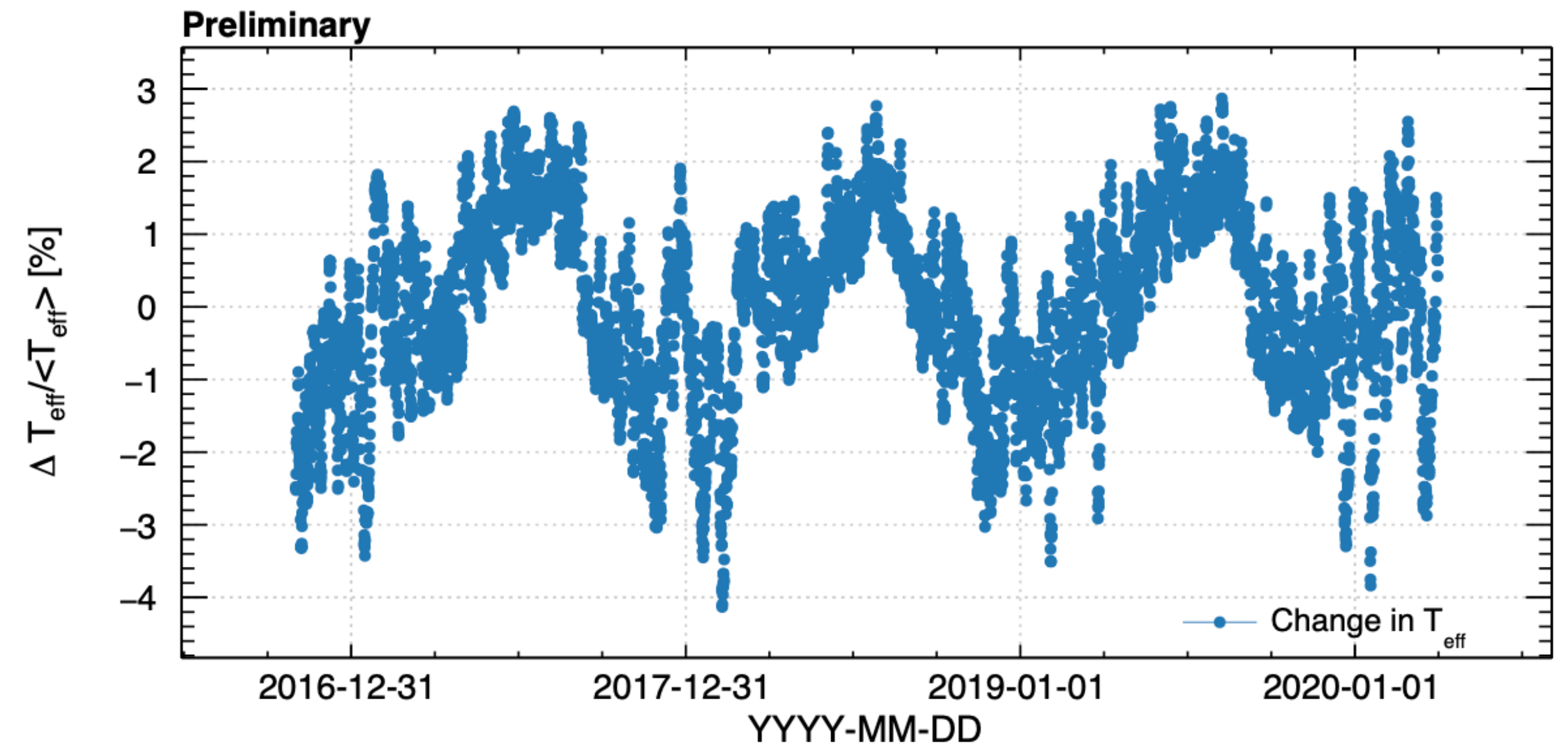
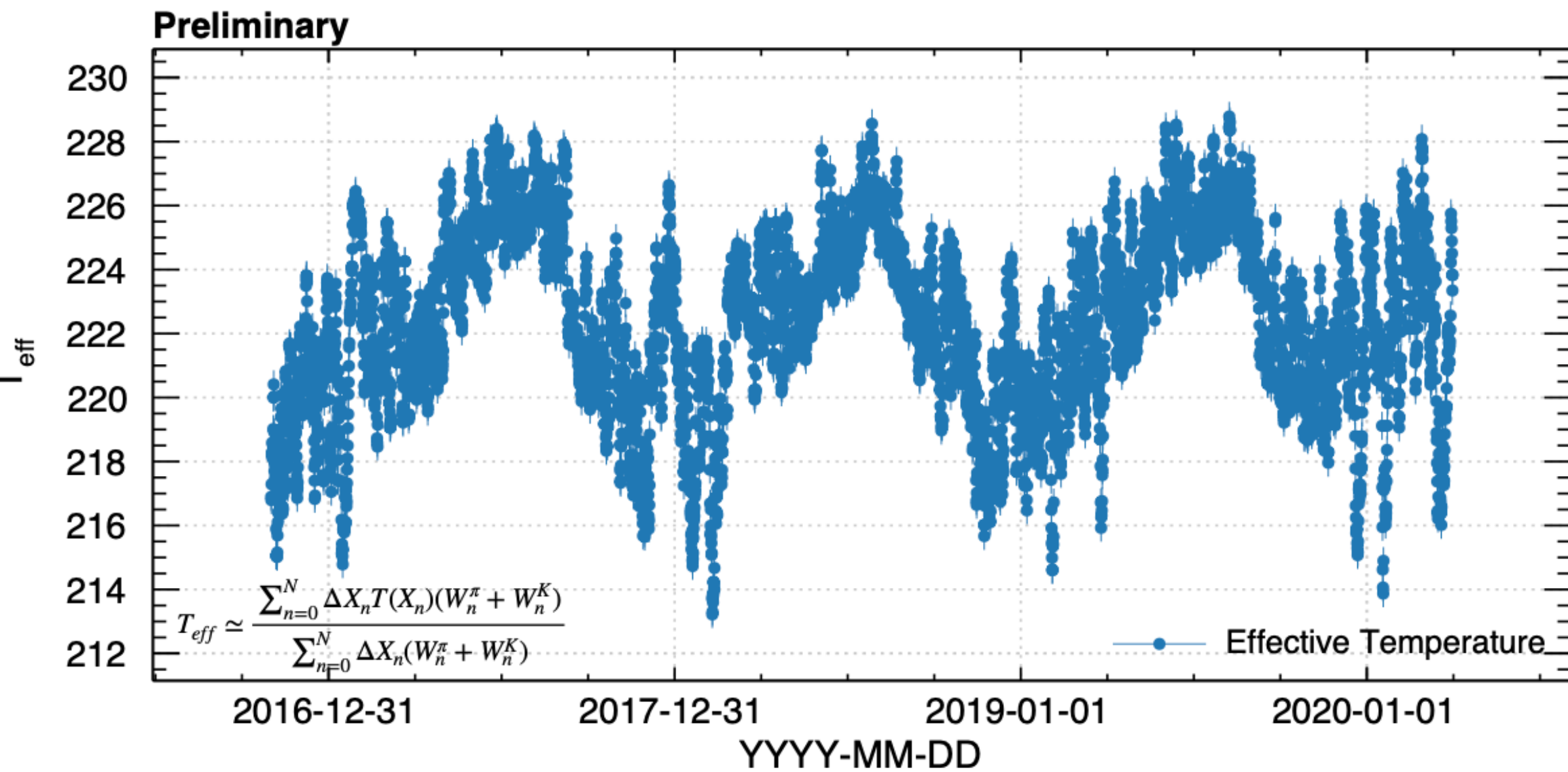
$$\langle E_{thr} \cos\theta \rangle = (2.58 \pm 0.41) \text{ TeV}$$



- To date, the deepest measurement of the atmospheric temperature correlation coefficient, α_T , is ~1.8 TeV at LNGS
- SNOLAB's flat overburden and deep vertical depth will allow for the deepest measurement of the π/K ratio and test of the latest meson/muon production and transportation models

Effective temperature

- Using the atmospheric layer model, the local threshold energy, and the ECMWF data, an example of the effective temperature for a ~3.5 year window was computed



- Modulation of the effective temperature is % level, thus we expect the muon flux to change nearly identically on average

Temperature coefficient

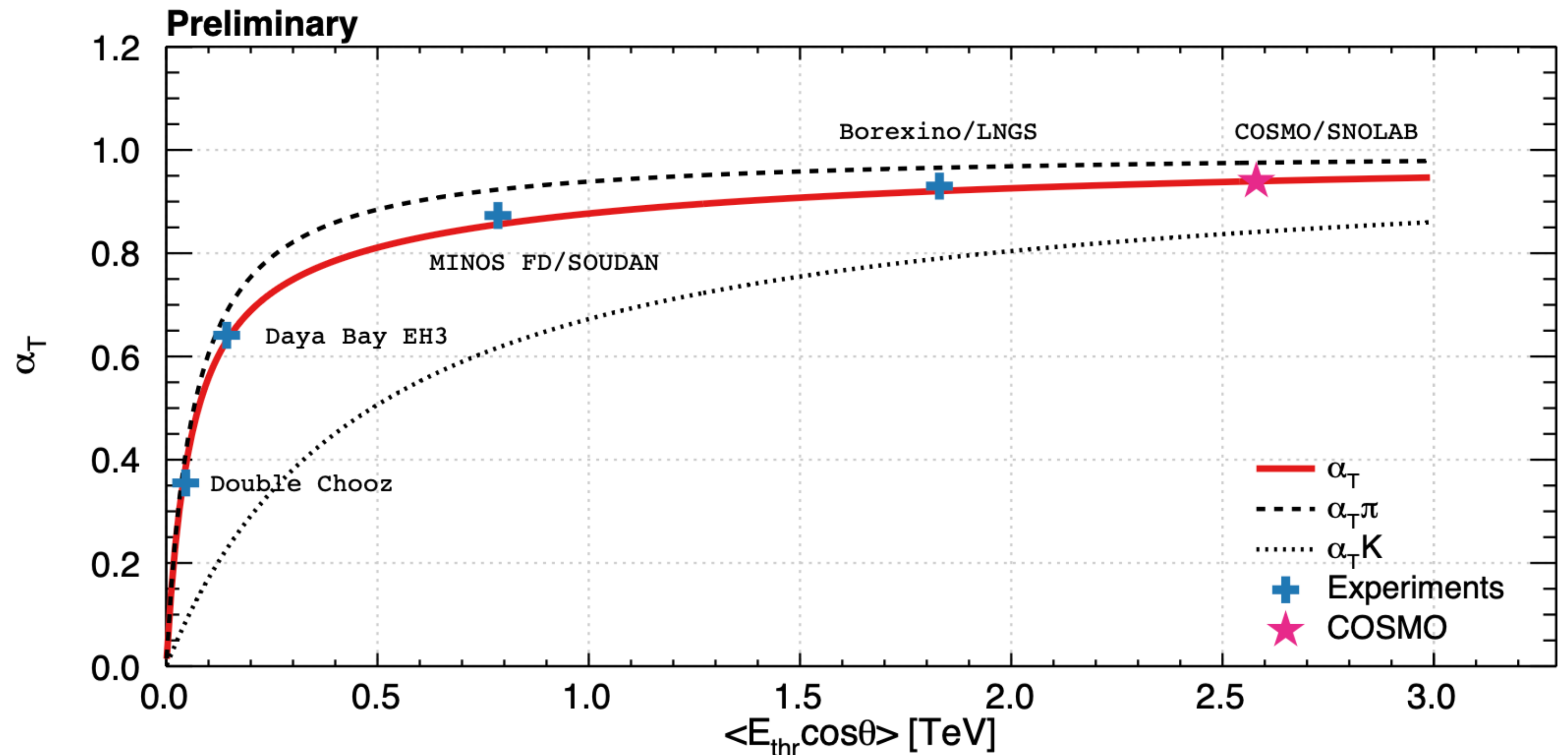
- Grashorn *et al* have provided a simple parameterization of the theoretical expectations for α_T , $\alpha_T(K)$, and $\alpha_T(\pi)$
- Muons from Kaon decay become more significant proportion of those observed underground as depth increases

$$\alpha_T = \frac{1}{D_\pi} \frac{1/\epsilon_K^0 + A_K^1 (D_\pi/D_K)^2 / \epsilon_\pi^0}{1/\epsilon_K^0 + A_K^1 (D_\pi/D_K) / \epsilon_\pi^0}$$

$$D_{\pi,K} = \frac{\gamma}{\gamma + 1} \frac{\epsilon_{\pi,K}^0}{1.1 \langle E_{thr} \cos\theta \rangle} + 1$$

$$(\alpha_T)_{\pi, K} = \frac{1}{D_{\pi,K}}$$

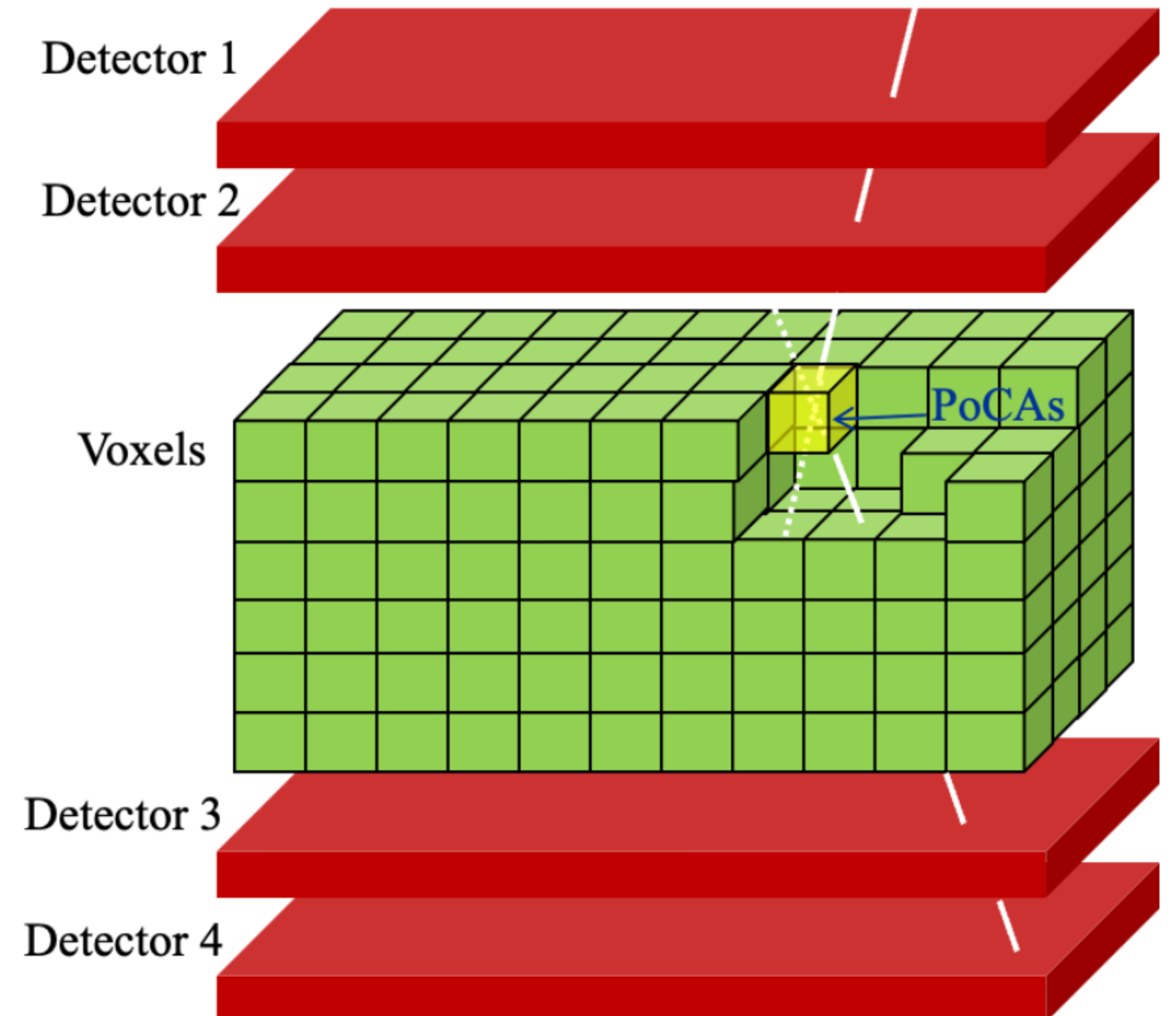
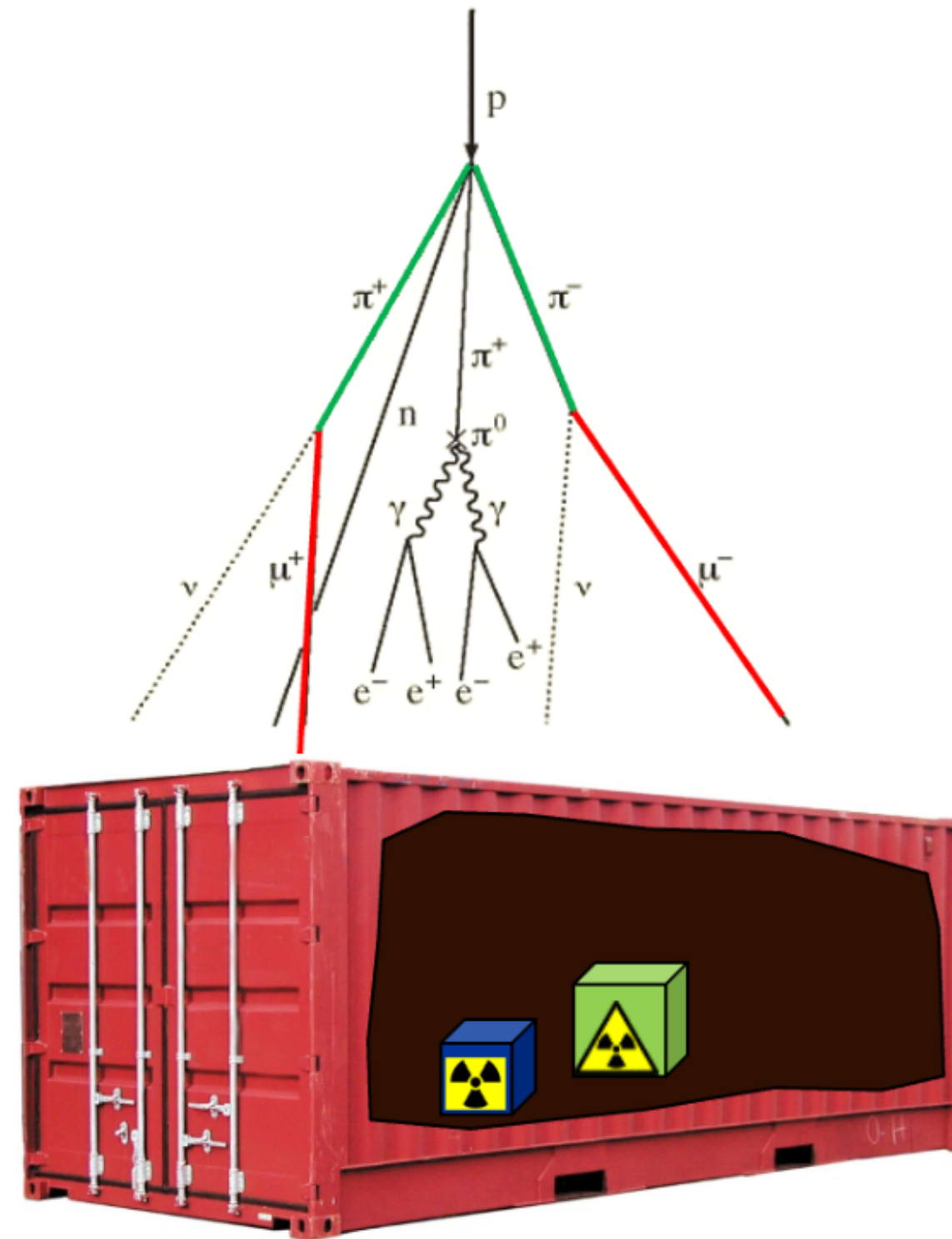
- Combining COSMO data with existing and future data from SNOLAB experiments will produce a very unique data set



Context

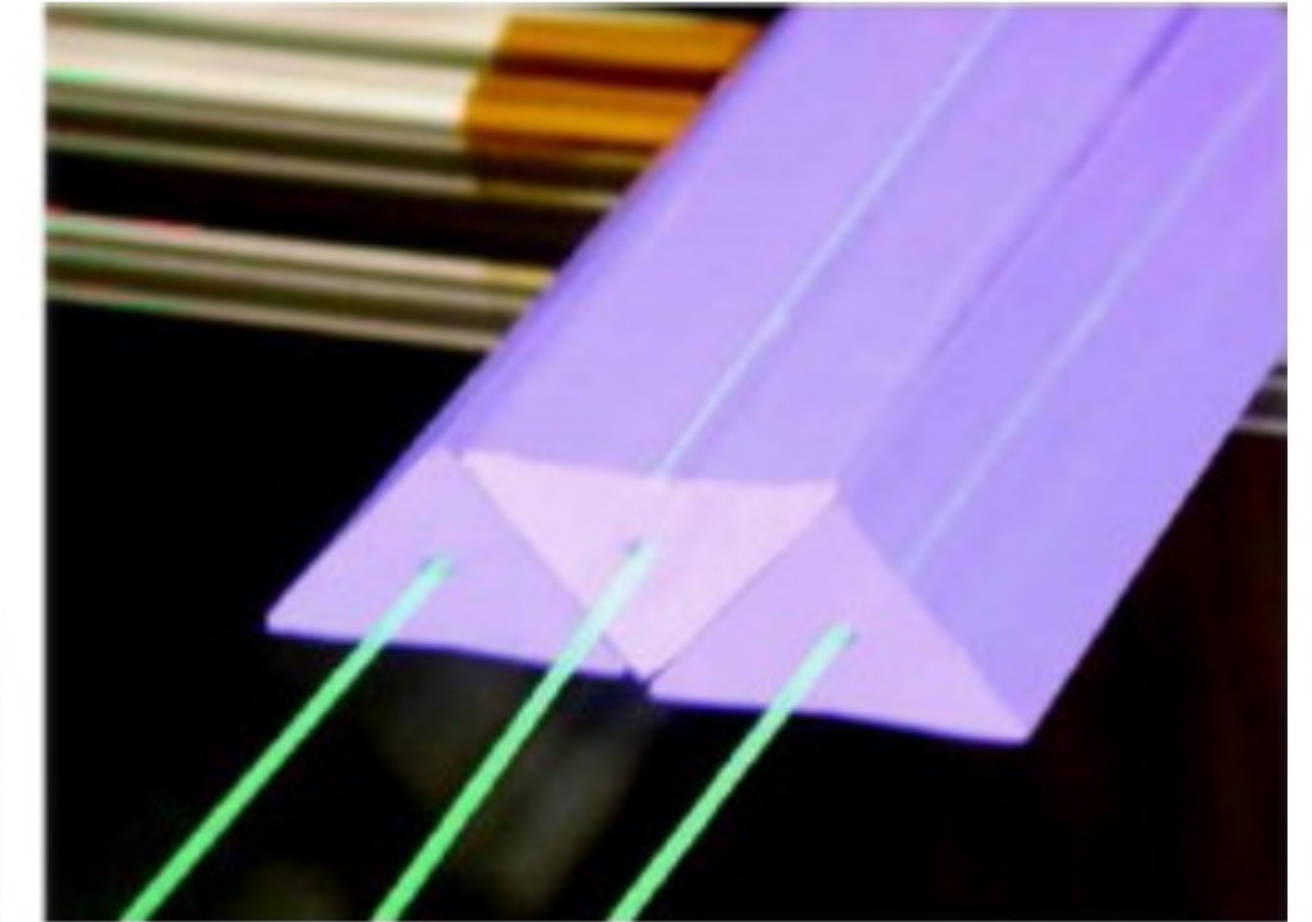
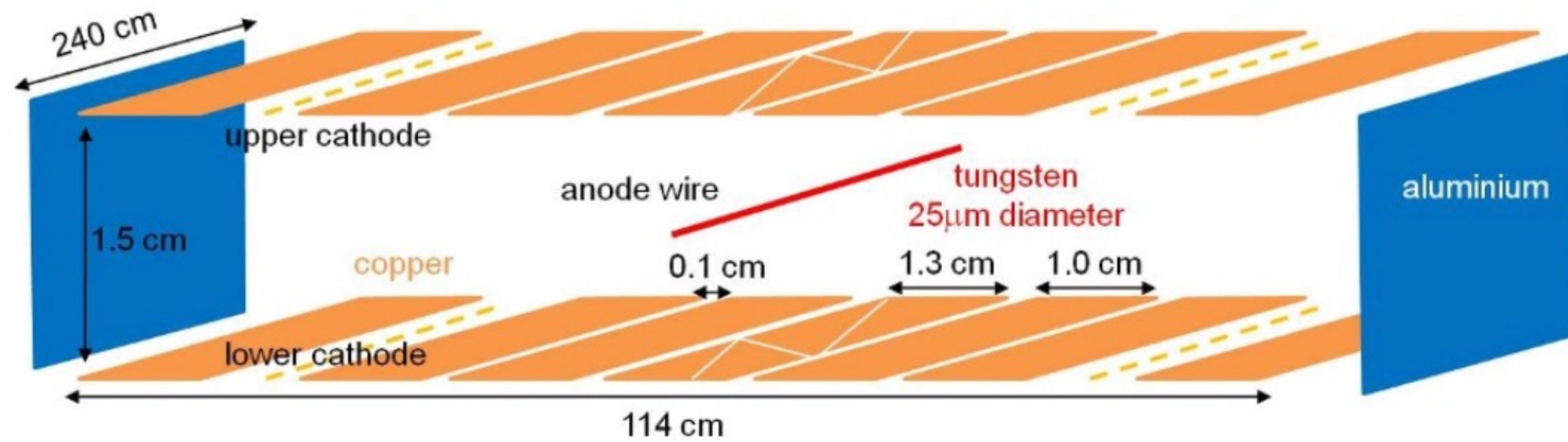
- Government of Canada sought ways to detect illicit radiological/nuclear materials at borders to prevent nuclear terrorism
- Collaboration formed to leverage HEP technology for this application (many SNO alum)
 - Concept of "Muon Scattering Tomography" established by Los Alamos National Laboratory

- By tracking individual muons, 3D images of dense materials can be located and described
- Multiple viable technology choices exist from collider experiments



Tracking technology

- Project explored muon tracking detector technologies (drift chambers and extruded plastics) for muon tomography
 - Drift chambers offered excellent resolution, coverage, and minimal DAQ costs
 - Plastics are physically robust, excellent timing, and very stable over long periods of time

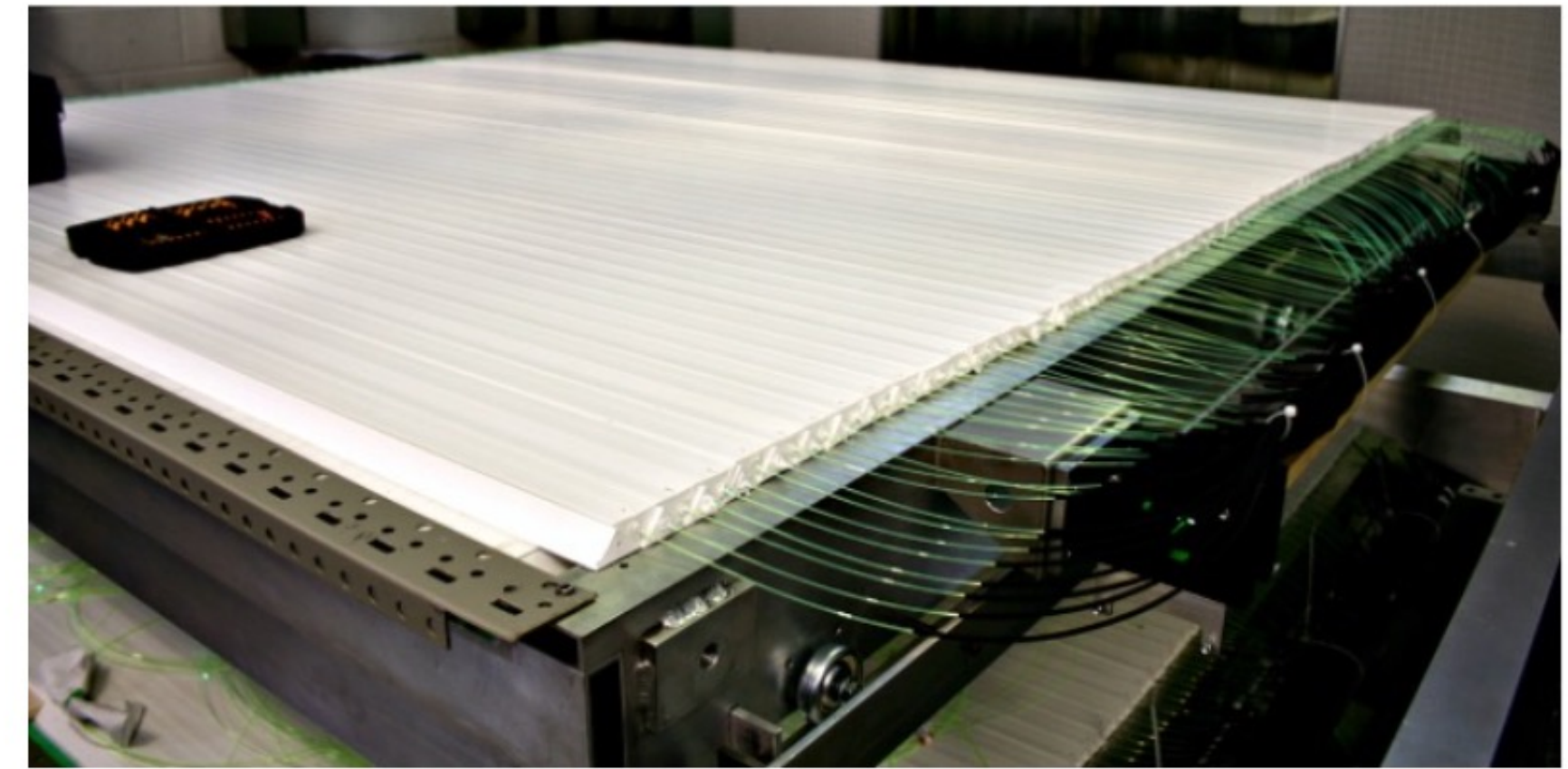
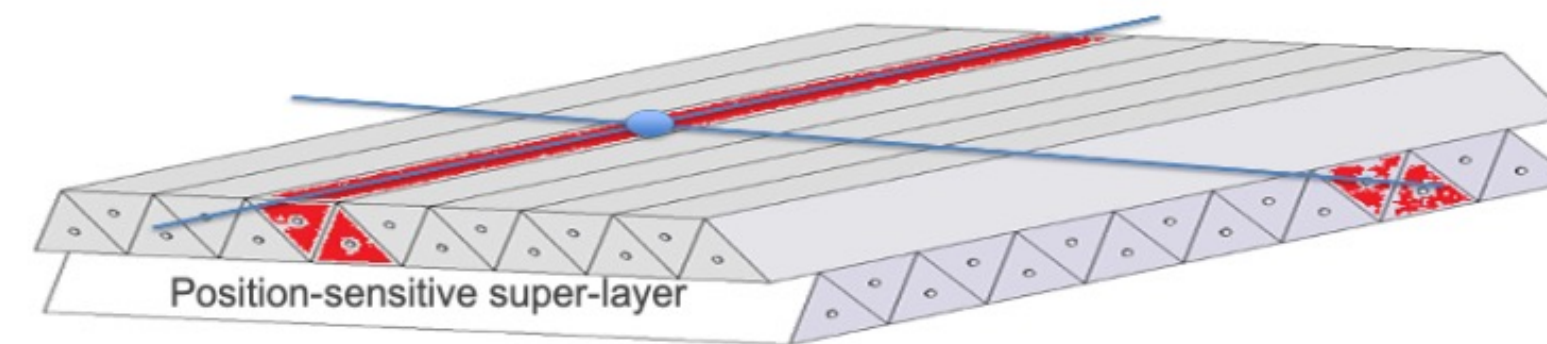
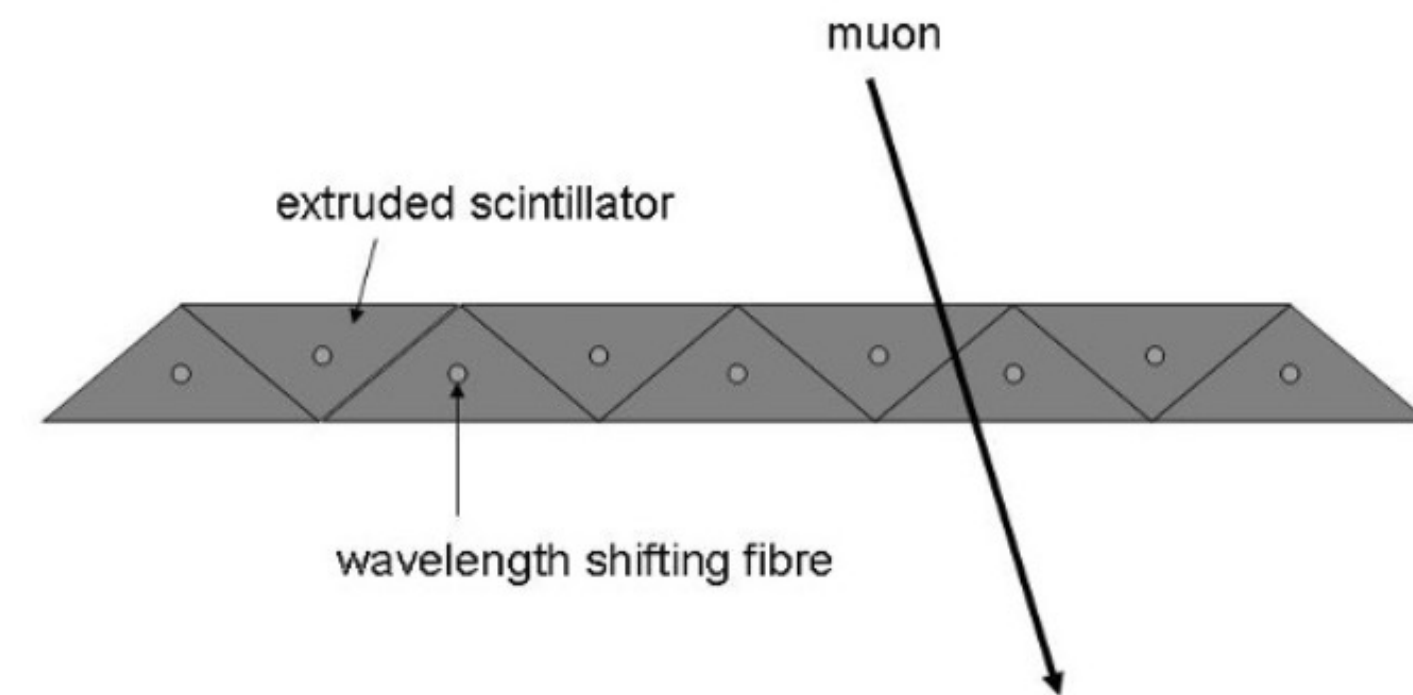


Source: <https://doi.org/10.1016/j.nima.2013.12.053>

- Left: Drift chamber concept using a single anode wire, offset zig-zag cathode pads
- Right: Extruded plastics with wavelength shifting fibers arranged in a small plane
- Collaboration decided to proceed with extruded plastics based on thorough evaluations and demonstration

Extruded plastics

- Triangular extruded plastics produced by Fermilab, based on bars produced for Minerva
 - Dow Styron 663, doped with 1% PPO, and 0.03% POPOP
 - Co-extruded with TiO_2 coating and central hole for WLS fibre
- Kuraray Y11 fibres (2.5 mm diameter) used for WLS and transportation of light
 - Photons detected with Hamamatsu H8804 64-channel PMTs
 - Non-instrumented end capped with reflective coating



- Shape/arrangement ensures muons hit pairs of bars (1D position)
- Two orthogonal planes placed together create a super layer (2D position)
- Pairs of super layers used for tracking (3D tracks)
- 2/3 of CNL's muon tracking systems are based on this technology