Propagation of Muon Fluxes for PICO

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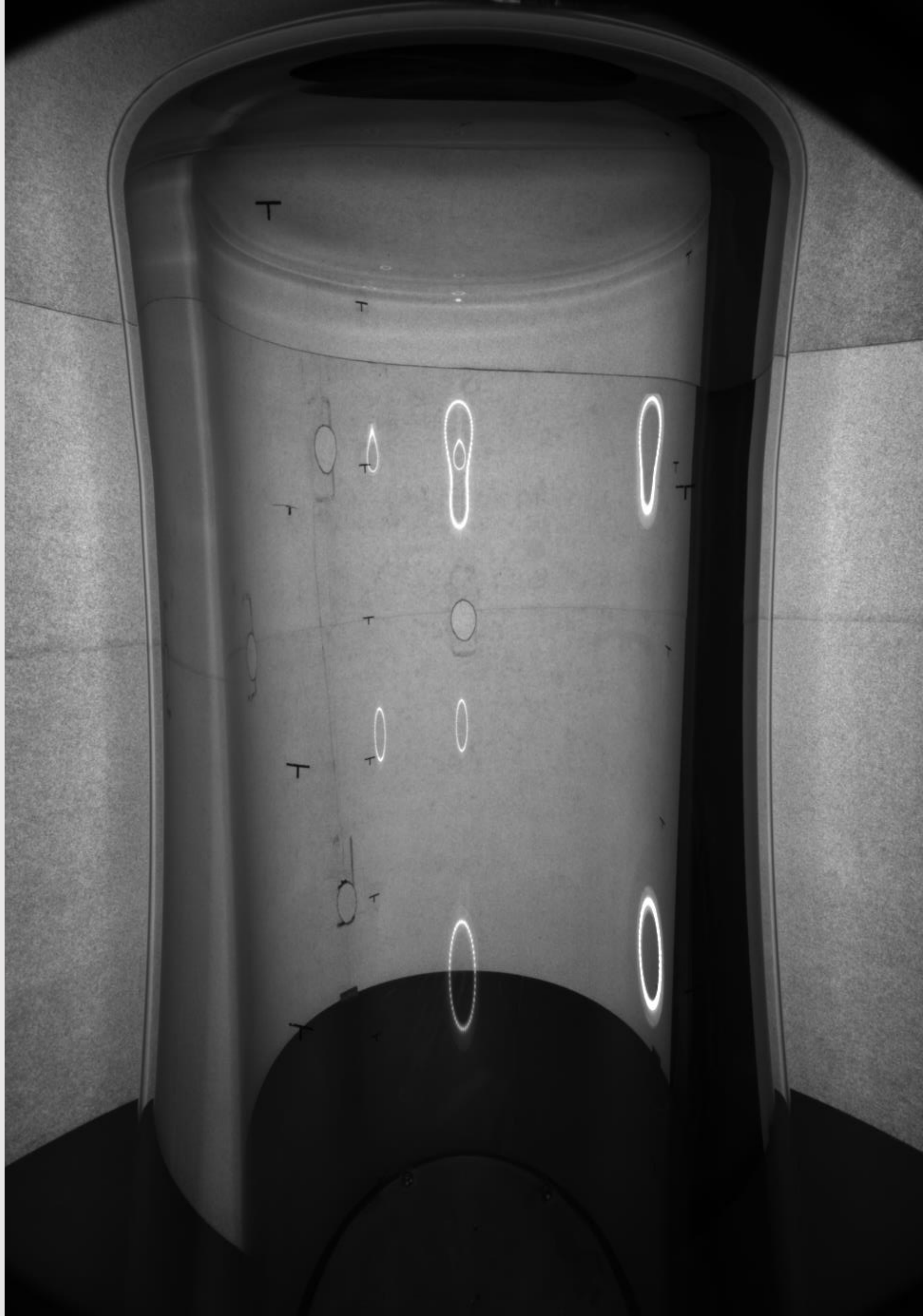
Introduction

- The PICO Experiment, installed at SNOLAB, uses bubble chamber technology to directly search for dark matter in the form of WIMPs: weakly-interacting massive particles.

- WIMPs passing through the liquid in the bubble chamber will cause bubbles to form. Neutrons, however, can also cause bubbles to form, and would be indistinguishable from those caused by WIMPs.

- One source of neutrons is from cosmogenic muons. For this reason, detectors for rare event searches are located in underground laboratories to shield from cosmic rays.

- SNOLAB is located in Sudbury, Ontario, and has a flat overburden of 2073 m (6000 m.w.e.). The next generation of PICO detector will be located in the Cube Hall at SNOLAB.



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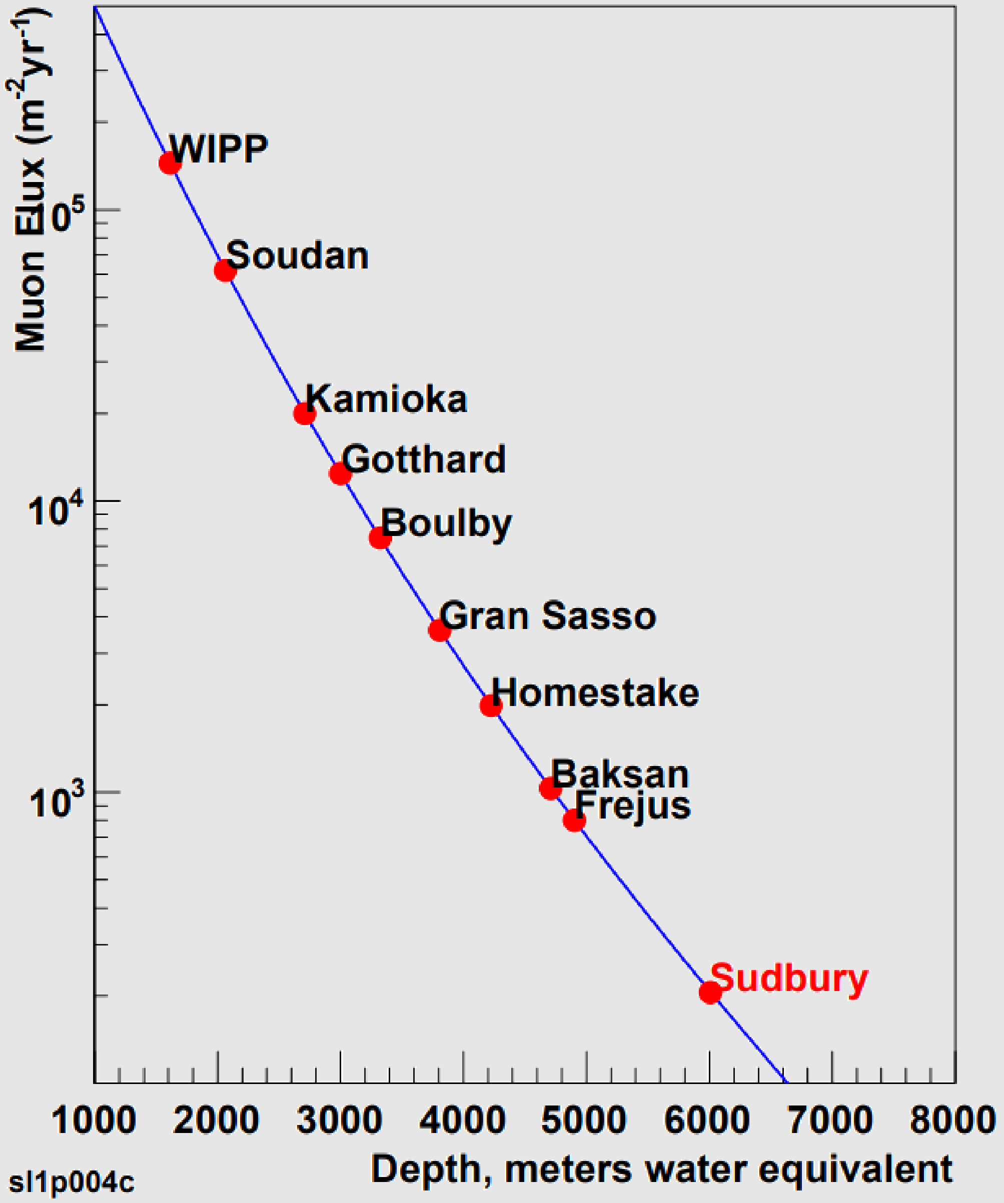
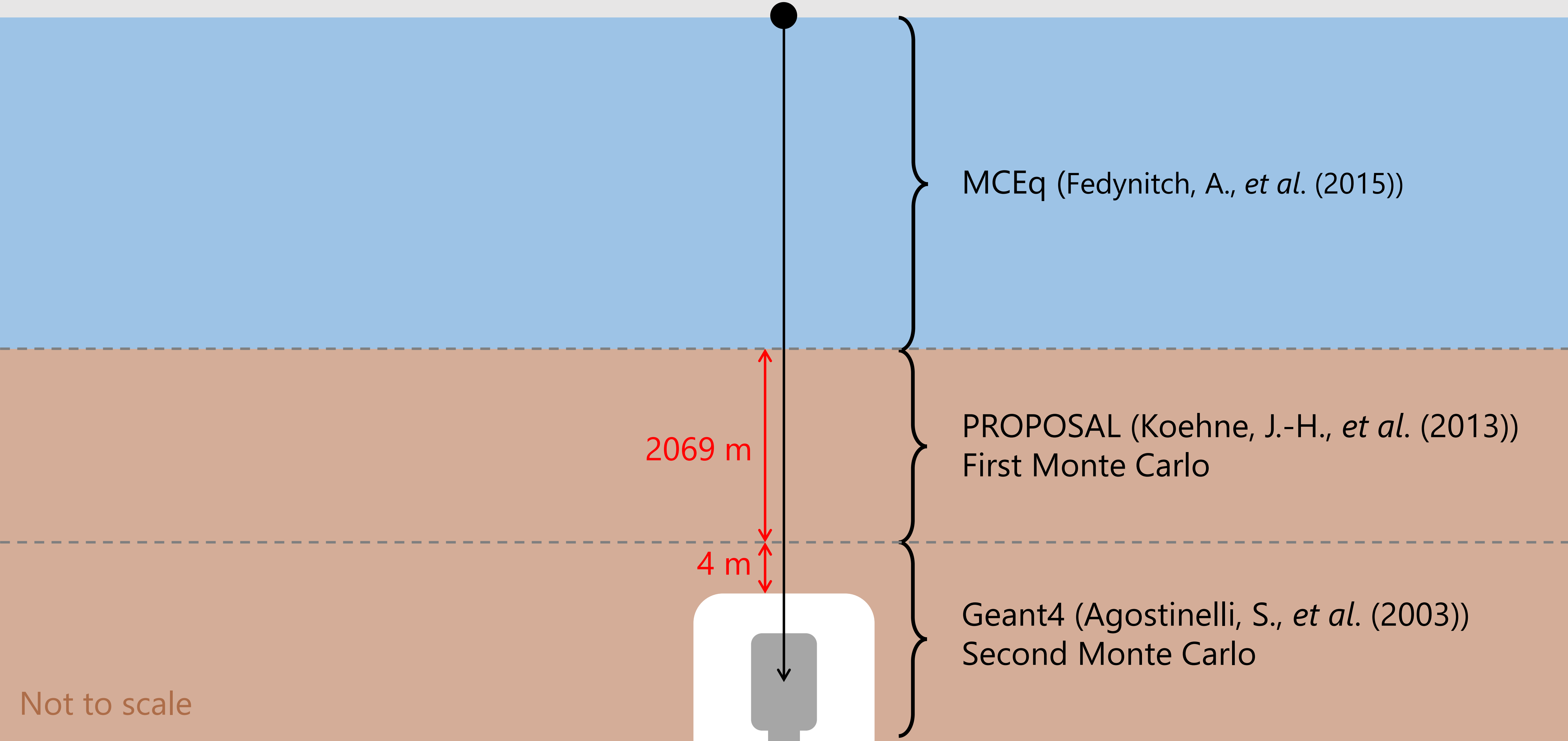
SNOLAB User's Handbook



Simulations Overview



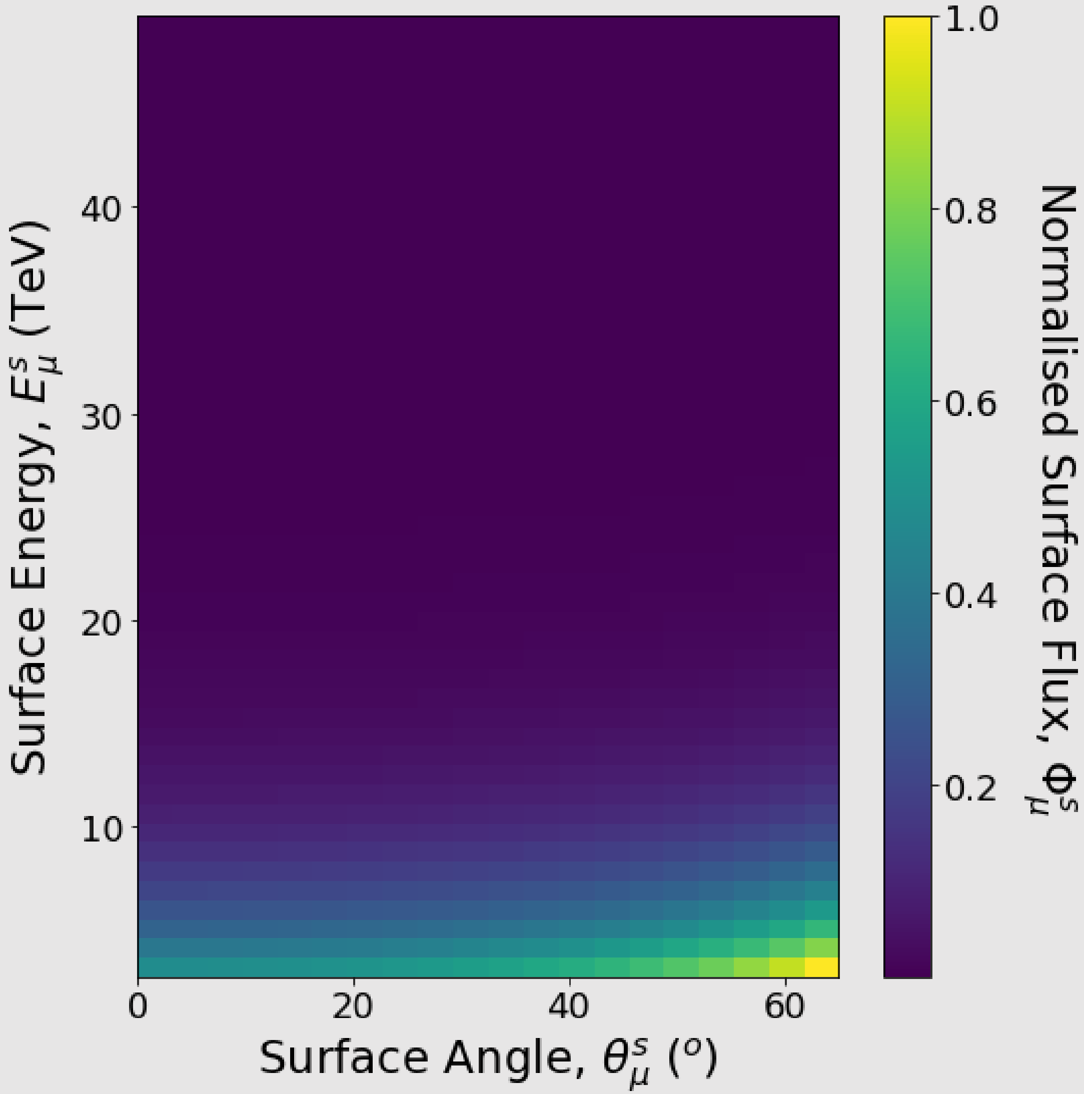
MCEq – Atmosphere to Surface

- MCEq uses NRLMSISE-00 data for the exosphere to calculate muon fluxes by solving the matrix cascade equations for cosmic rays.

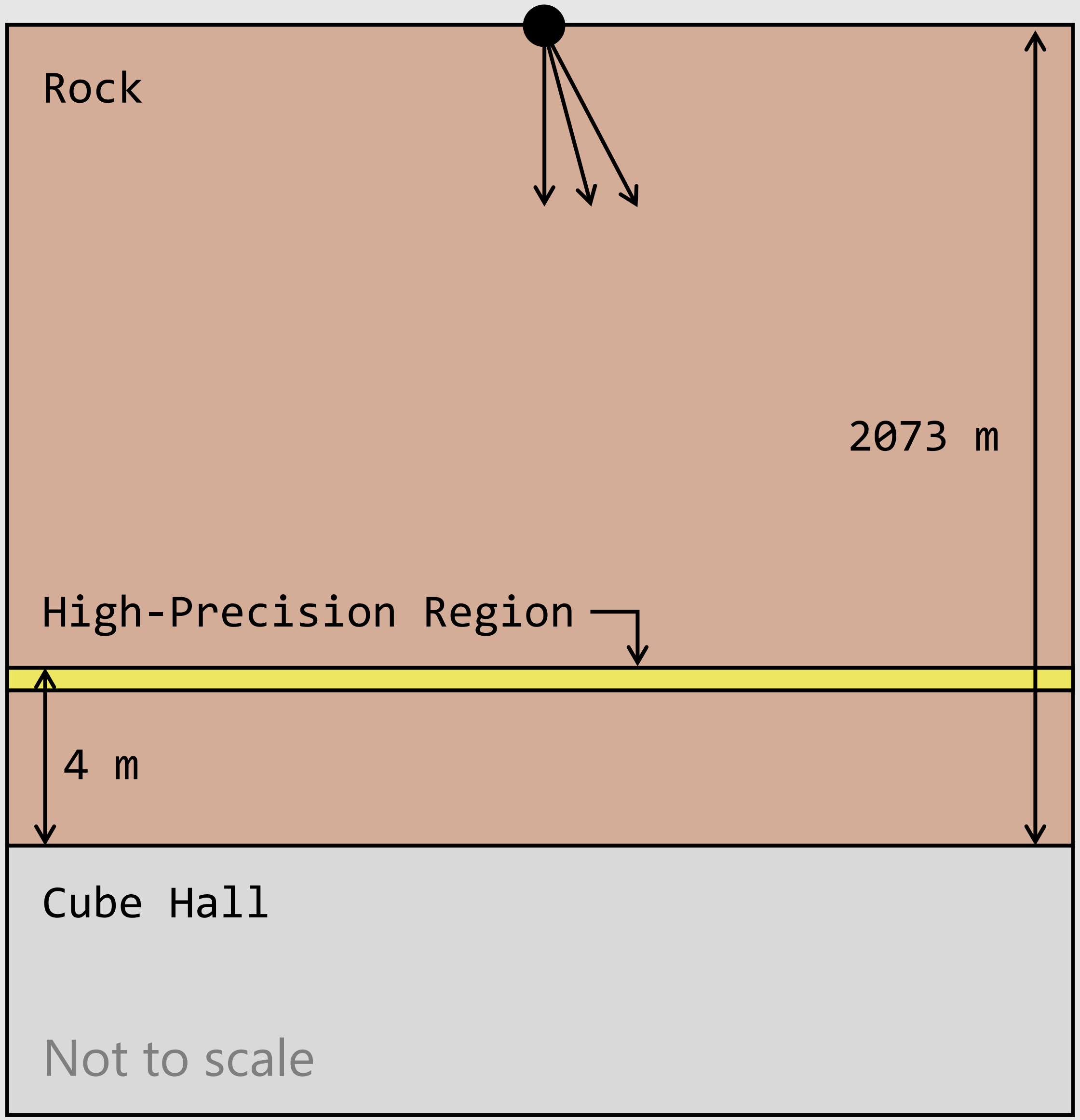
- Set the following in MCEq:
  - Location of Sudbury: (46.47°, 81.19°, 309 m)
  - Month: January, July
  - Energy bins: (2.8 TeV, 50 TeV)
  - Zenith angle bins: [0°, 65°]

- MCEq returns surface fluxes at the location specified as a function of surface energy and surface angle: $\Phi_\mu^s(E_\mu^s, \theta_\mu^s)$.

- Surface flux increases as zenith angle increases, as expected, due to suppression of pion interactions at larger zenith angles.

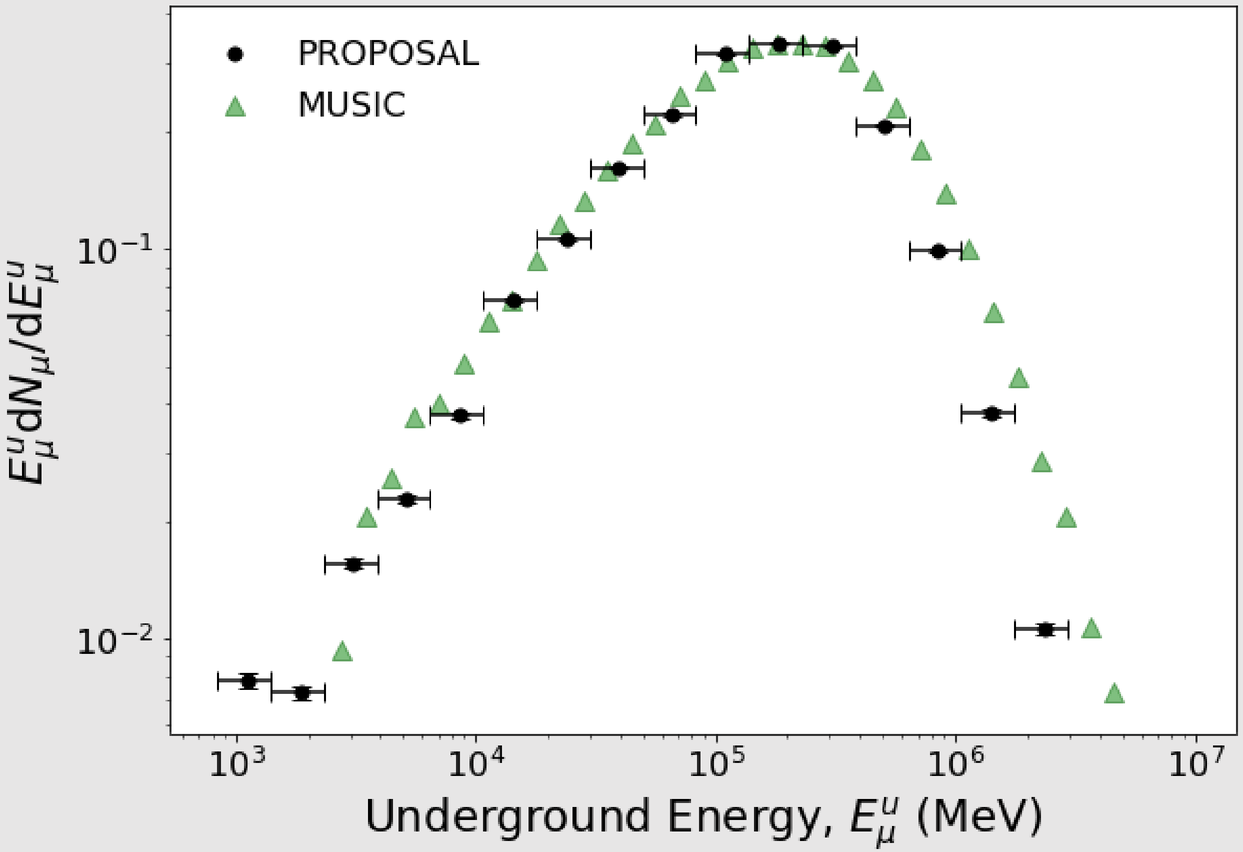


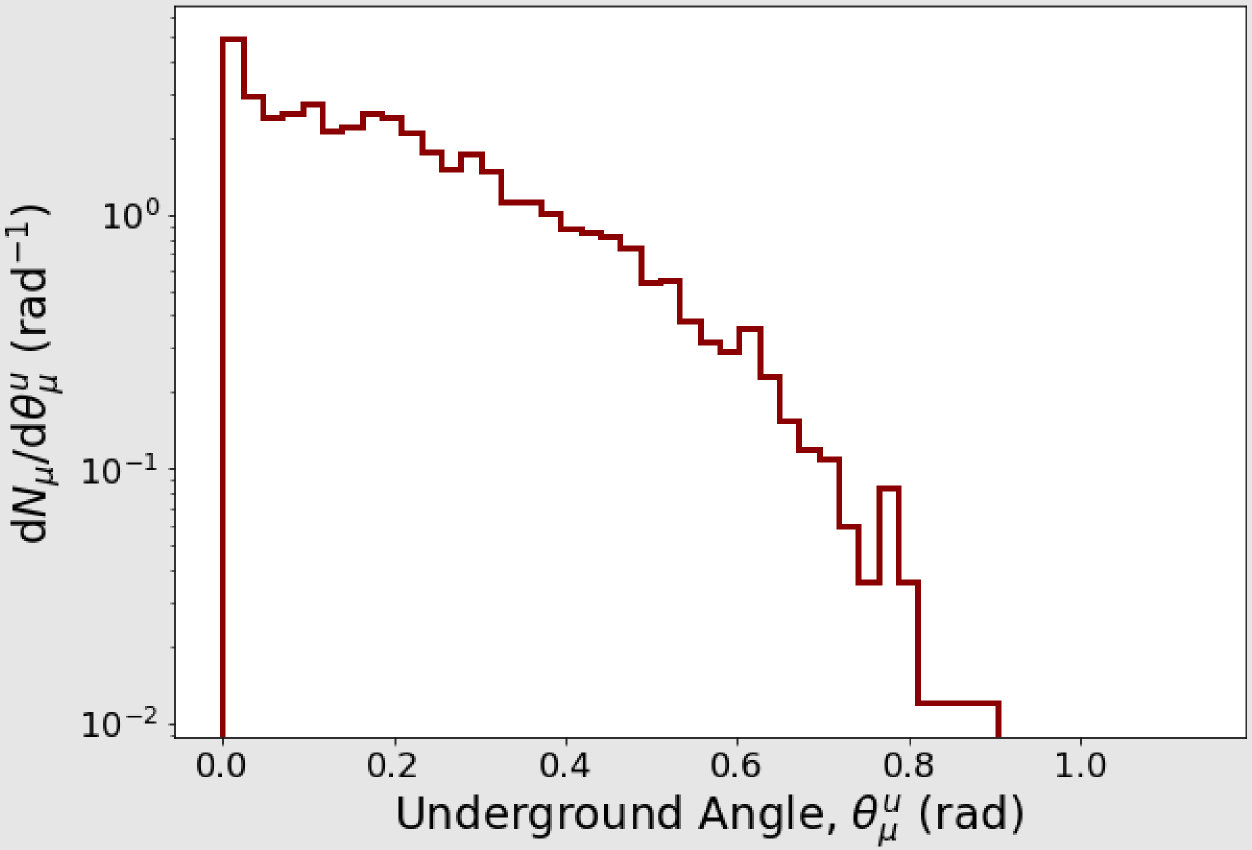
PROPOSAL – Geometry



- PROPOSAL is a program that can propagate leptons like muons through matter, and is optimised for very large distances.
- To build a geometry for SNOLAB, define a 2073 m-thick layer of standard rock with the density of rock corrected to match that of the norite that makes up the SNOLAB overburden.
- Define a 0.01 cm-thick high-precision region (HPR) 4 m above the Cube Hall.
- Fire *N* muons from the top center, where *N* is scaled per bin by the surface flux.
- Read the energy, position, and time of muons as they enter the HPR, and their position as they exit.

PROPOSAL – Energy and Angular Spectra





PROPOSAL – Survival Probability

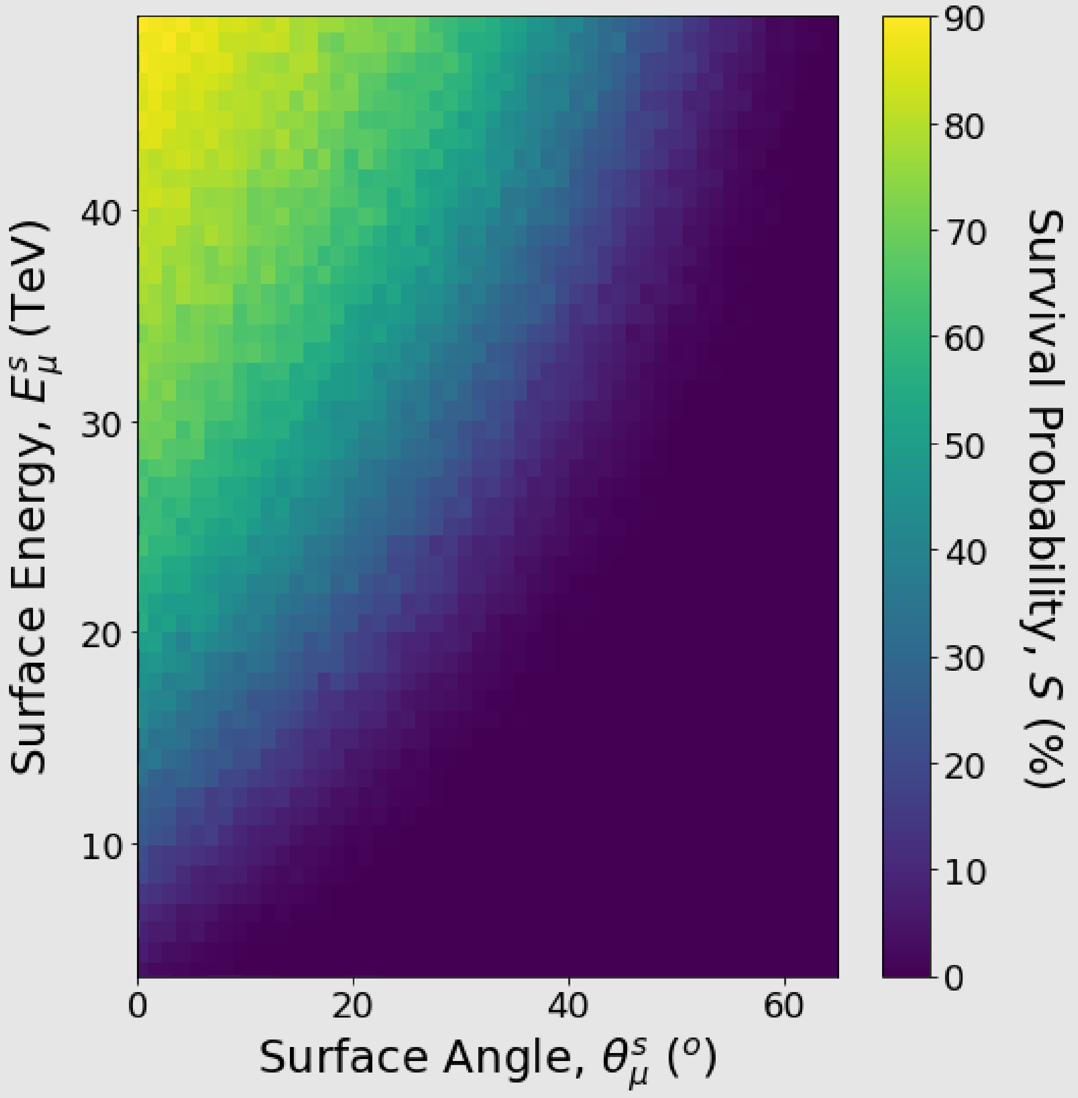
- Define a muon that survives (*s*) as a muon that either:
    1. Does not decay at all
    2. Does decay, but beyond the HPR

- Survival probability, *S*, is given by:

$$S = \frac{s}{N}$$

- *S* increases as energy increases, as expected, because muons with more energy have a better chance at making it underground.

- *S* decreases as zenith angle increases, as expected, because muons coming in at larger angles have more rock to travel though.



Underground Muon Flux

- Multiply the surface fluxes from MCEq by the survival probabilities from PROPOSAL to obtain underground muon fluxes:

$$\begin{bmatrix} \Phi^s_{11} & \cdots & \Phi^s_{1m} \\ \vdots & \ddots & \vdots \\ \Phi^s_{n1} & \cdots & \Phi^s_{nm} \end{bmatrix} \circ \begin{bmatrix} S_{11} & \cdots & S_{1m} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nm} \end{bmatrix} = \begin{bmatrix} \Phi^u_{11} & \cdots & \Phi^u_{1m} \\ \vdots & \ddots & \vdots \\ \Phi^u_{1n} & \cdots & \Phi^u_{nm} \end{bmatrix}.$$

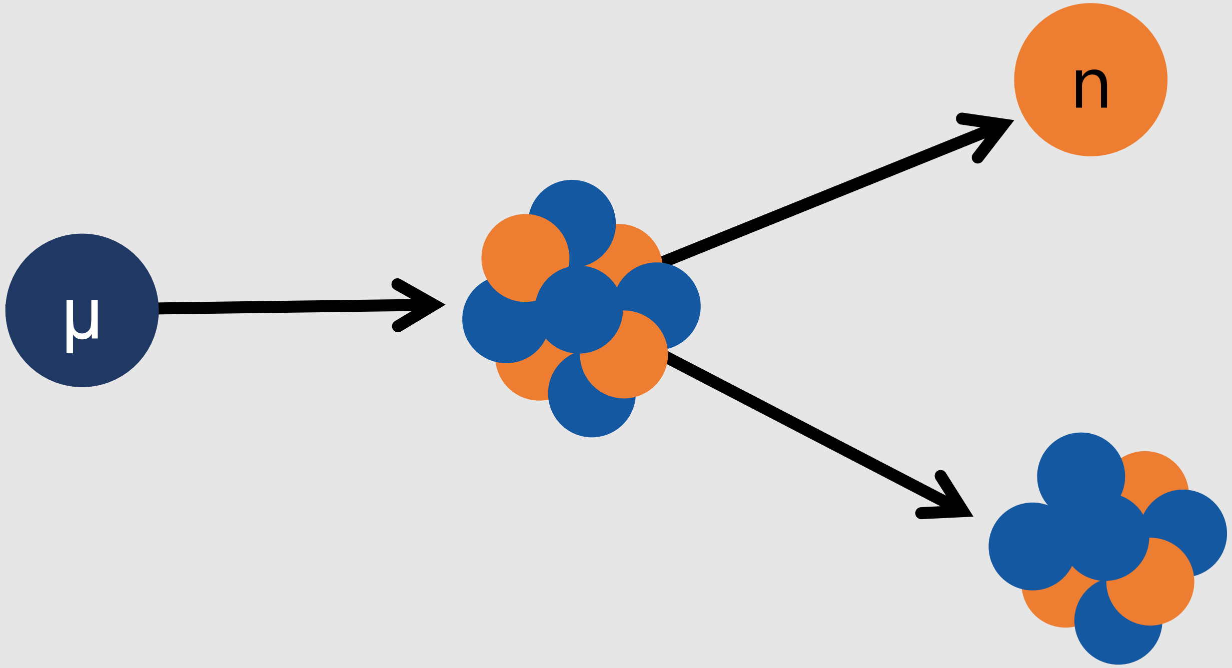
- Calculate the total muon rate underground by integrating over surface energy and surface angle:

$$R^u_\mu = A_{CH} \int_{2.8\,TeV}^{50\,TeV} \int_0^{2\pi} \int_{0^\circ}^{65^\circ} \Phi^u_\mu(E^s_\mu, \theta^s_\mu) \sin\theta^s_\mu \, \mathrm{d}\theta^s_\mu \, \mathrm{d}\phi \, \mathrm{d}E^s_\mu.$$

Calculated muon rate:	8.4×10^{-4} s^{-1}
SNOLAB measured rate:	8.6×10^{-4} s^{-1}

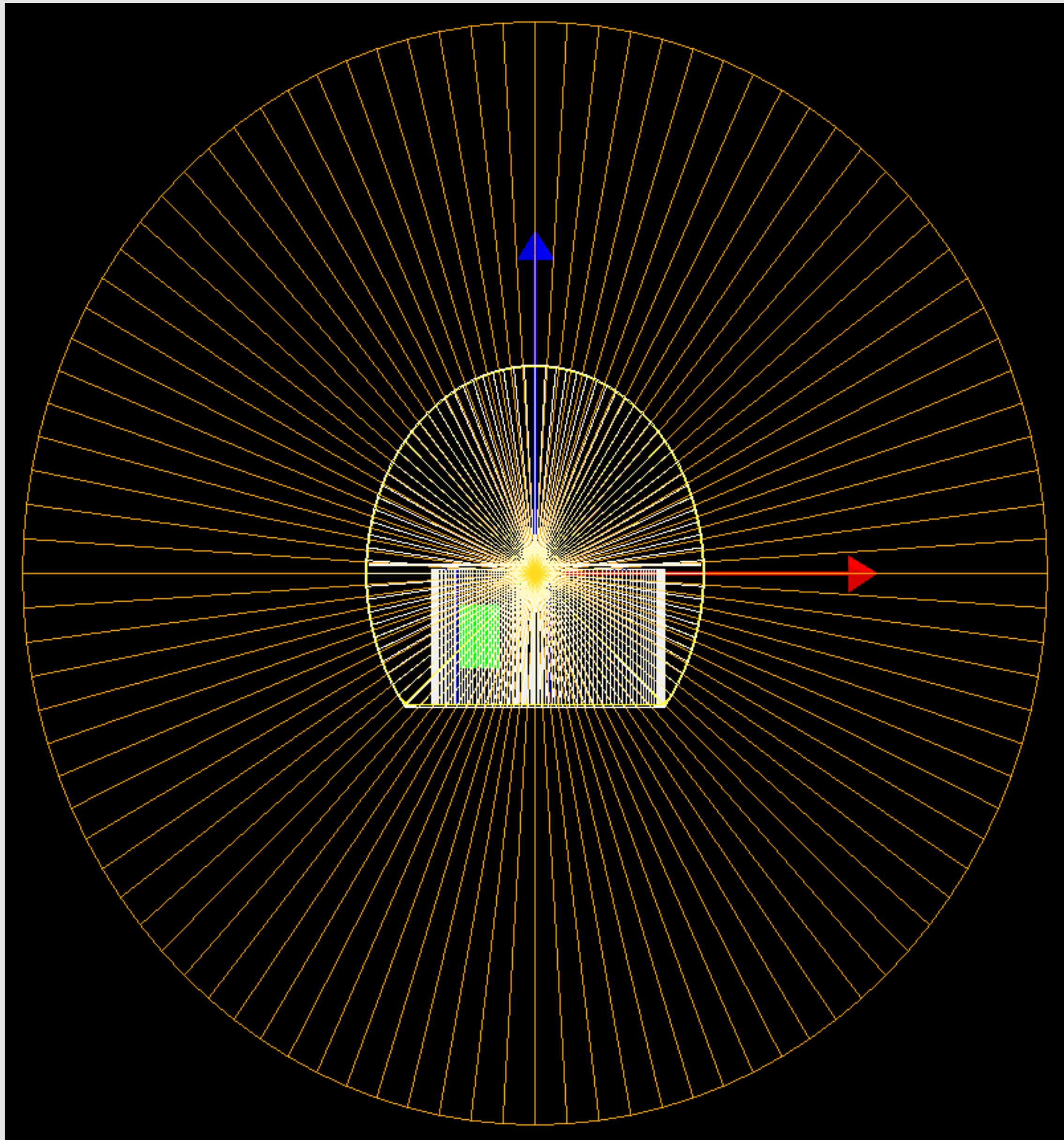
Muon-Induced Neutrons

- As muons travel through the rock, they can produce neutrons through spallation or muon capture.
- In spallation, a high-energy muon collides with an atomic nucleus and causes the nucleus to break into pieces, some of which will be high-energy neutrons (see below).
- In muon capture, a proton in a nucleus captures a muon, which causes the emission of a neutron.



Geant4 – Underground to PICO

- For the second Monte Carlo, use Geant4, with a detailed geometry for PICO-500.
- Drawing from the energy distribution from PROPOSAL, fire muons from the rock above the top of the Cube Hall.
- Preliminary test:
    - Energies: [0, 1 TeV]
    - Angle: 0°
    - Number of muons: 10 million
    - Results: 4 events
2 multi-bubble
2 single-bubble



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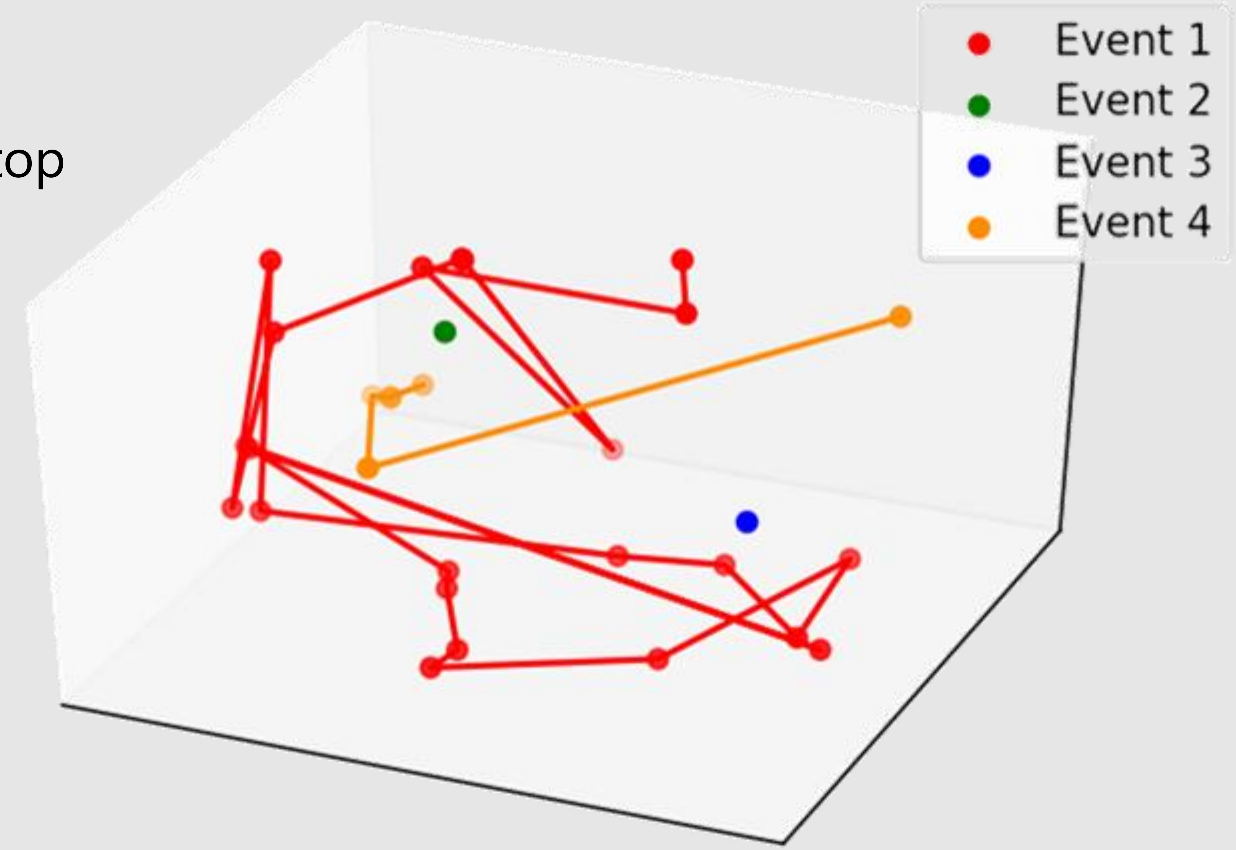

Conclusion

- An efficient new method to propagate muon fluxes from atmosphere to underground has been developed.

- With the use of MCEq, PROPOSAL, and Geant4, the underground energy and angular spectra of atmospheric muons can be calculated. This information is used to calculate the expected external neutron background rate, and can be used to inform decisions about a muon veto system for the PICO-500 detector.

- This method can easily be adapted to other experiments or underground laboratories.

- Although this is still a work-in-progress, it looks like the background for PICO-500 will not be dominated by muon-induced neutrons.

Thank you