Muon Flux Propagation at SNOLAB

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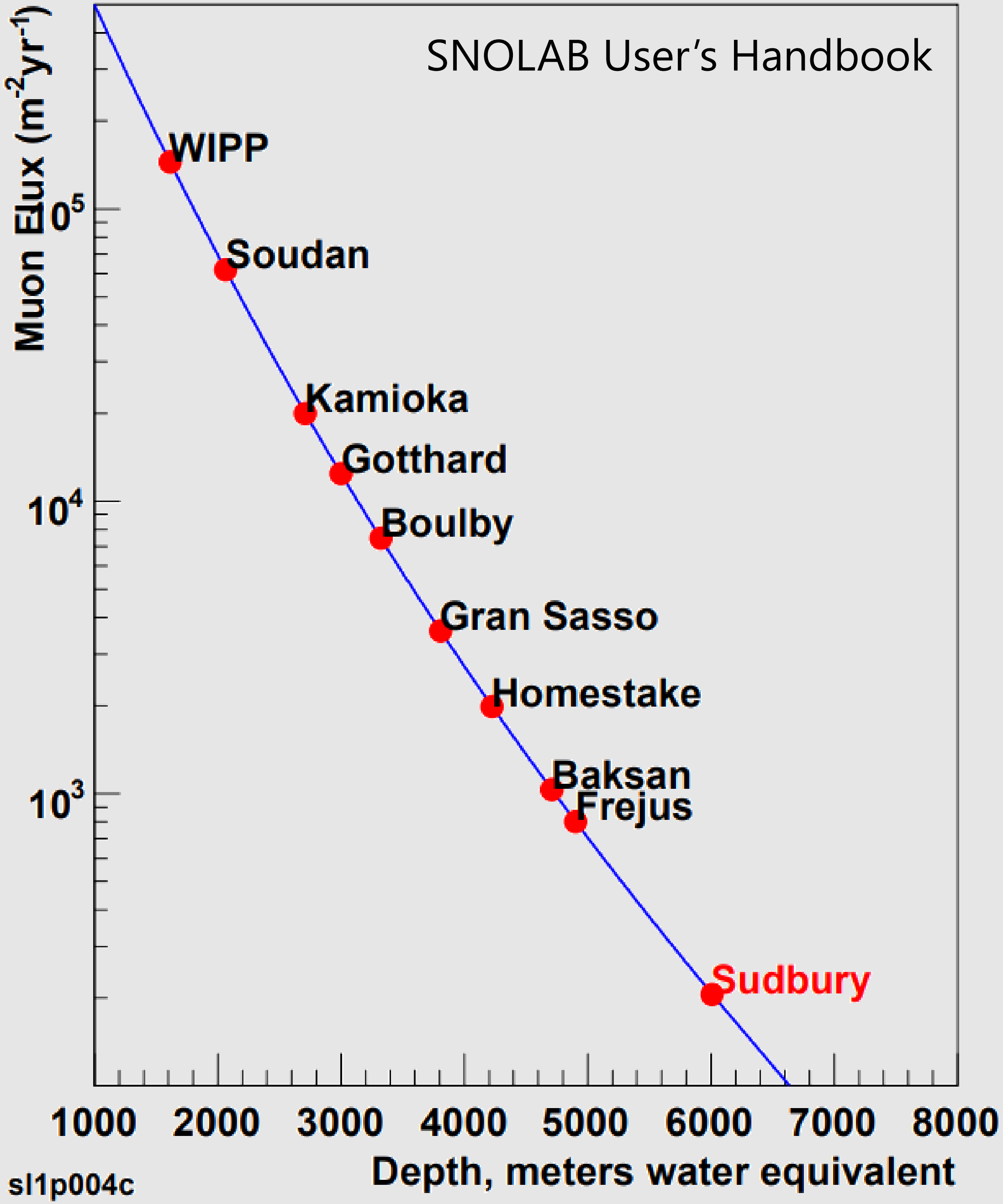
Introduction

- Despite an abundance of astronomical evidence, dark matter has not yet been found. PICO searches for dark matter in the form of WIMPs: weakly-interacting massive particles (see Colin Moore's talk tomorrow at 11:15).

- Because they are weakly-interacting, WIMP events will be rare. Neutrons are one of the main backgrounds for all rare-event search experiments.

- One source of neutrons is from interactions from cosmogenic muons. For this reason, go underground to shield from cosmic rays.



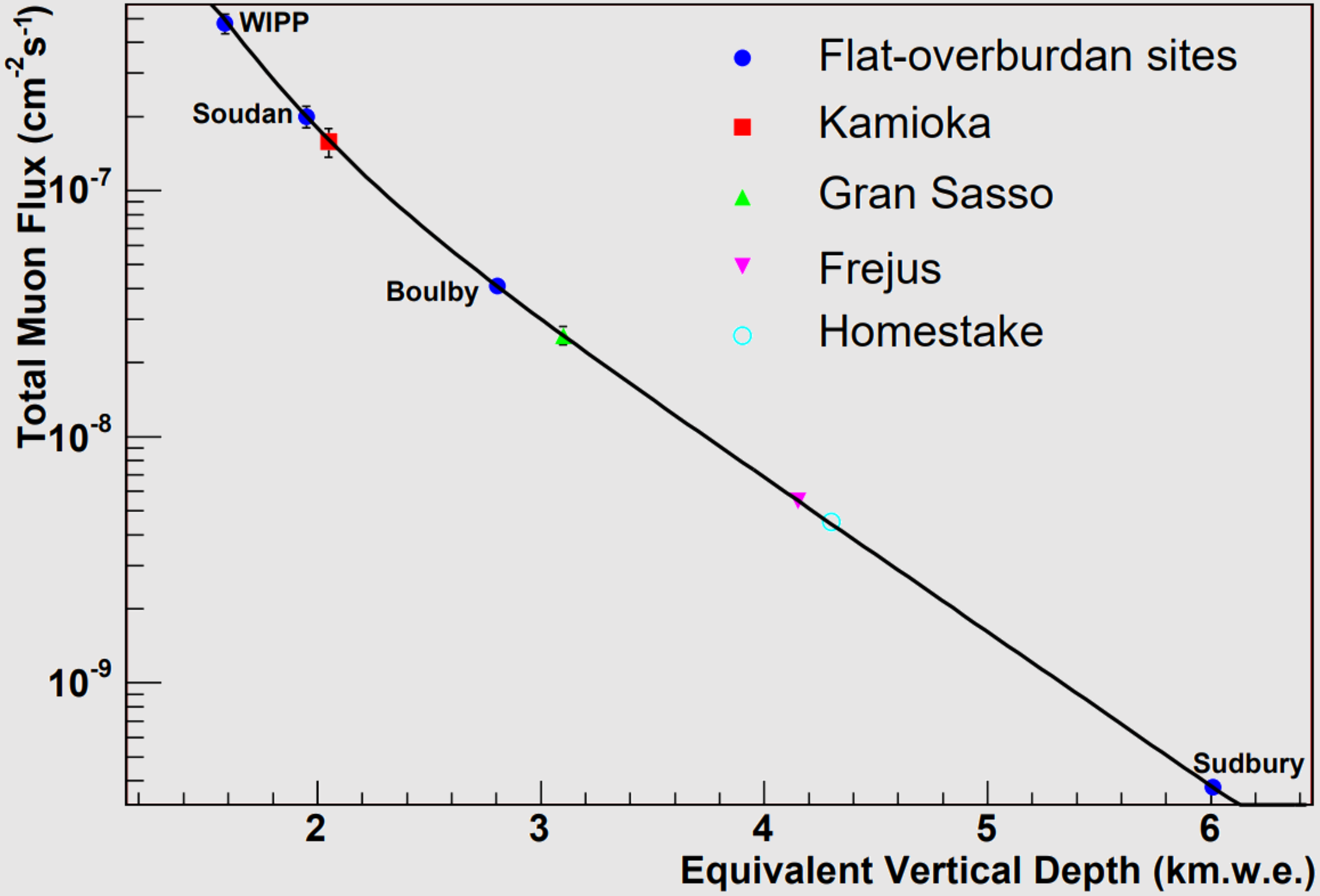
Current Literature

- Mei, D.-M. and Hime, A. (2005): Muon-Induced Background Study for Underground Laboratories.

- This gives parametrisations of the muon flux underground as a function of the overburden of various underground laboratories.

$$\frac{dN}{dE_\mu} = Ae^{-bh(\gamma_\mu - 1)}\left(E_\mu + \varepsilon_\mu\left(1 - e^{-bh}\right)\right)^{-\gamma_\mu}$$

$$I_{th}(h,\theta) = \left(I_1 e^{-h_0 \sec\theta/\lambda_1} + I_2 e^{-h_0 \sec\theta/\lambda_2}\right)\sec\theta$$

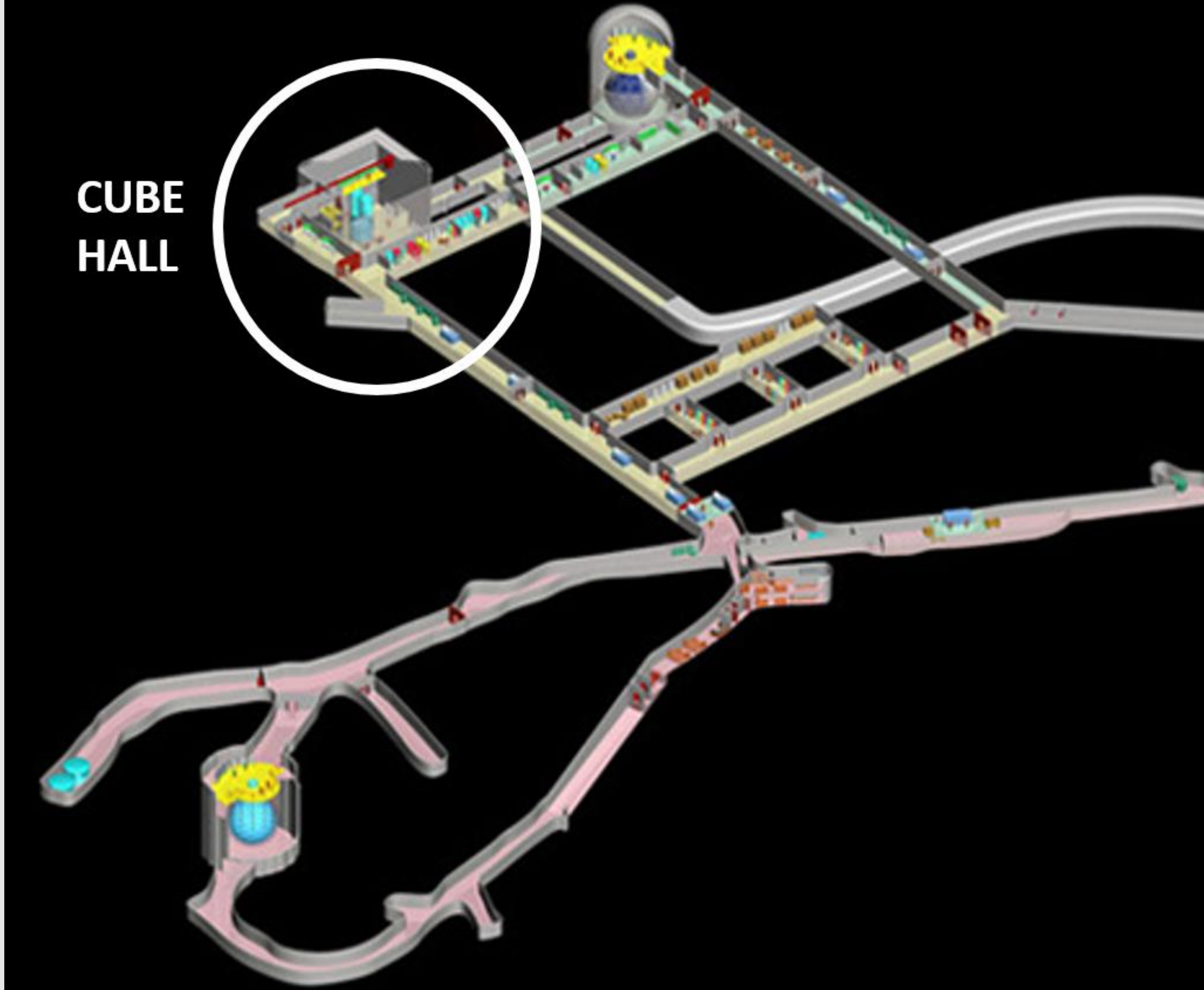


SNOLAB

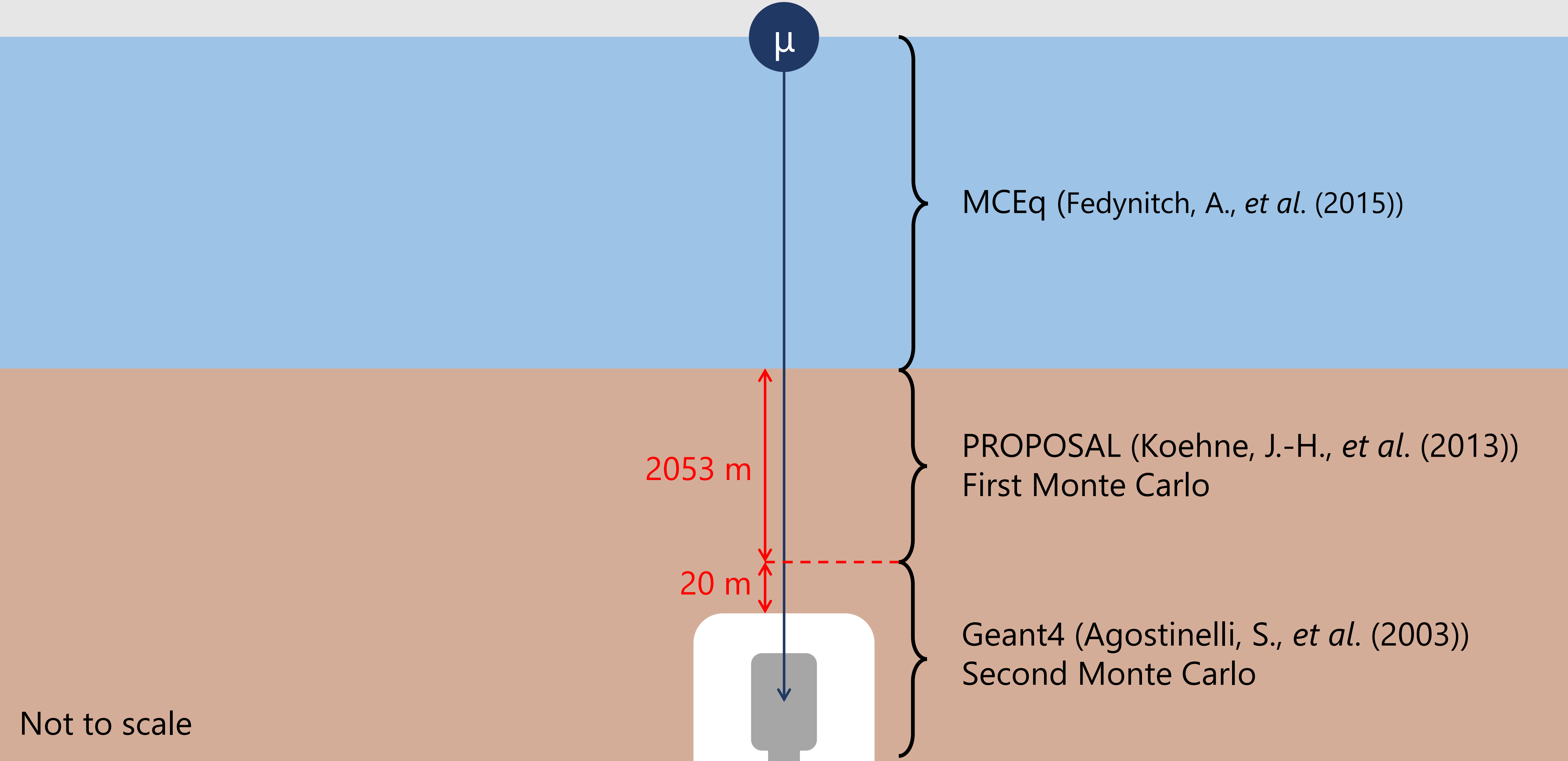
- SNOLAB is located in Sudbury, Ontario, and has a flat overburden of 2 km of uniform-density norite rock (6000 m.w.e.).

- PICO-500 is the next generation of PICO detector.

- It will be located in the Cube Hall at SNOLAB, beside DEAP-3600 and NEWS-G, where MiniCLEAN used to be.



Simulations Overview – Step 1



MCEq (Fedynitch, A., *et al.* (2015))

PROPOSAL (Koehne, J.-H., *et al.* (2013))
First Monte Carlo

Geant4 (Agostinelli, S., *et al.* (2003))
Second Monte Carlo

Not to scale

MCEq – Atmosphere to Surface

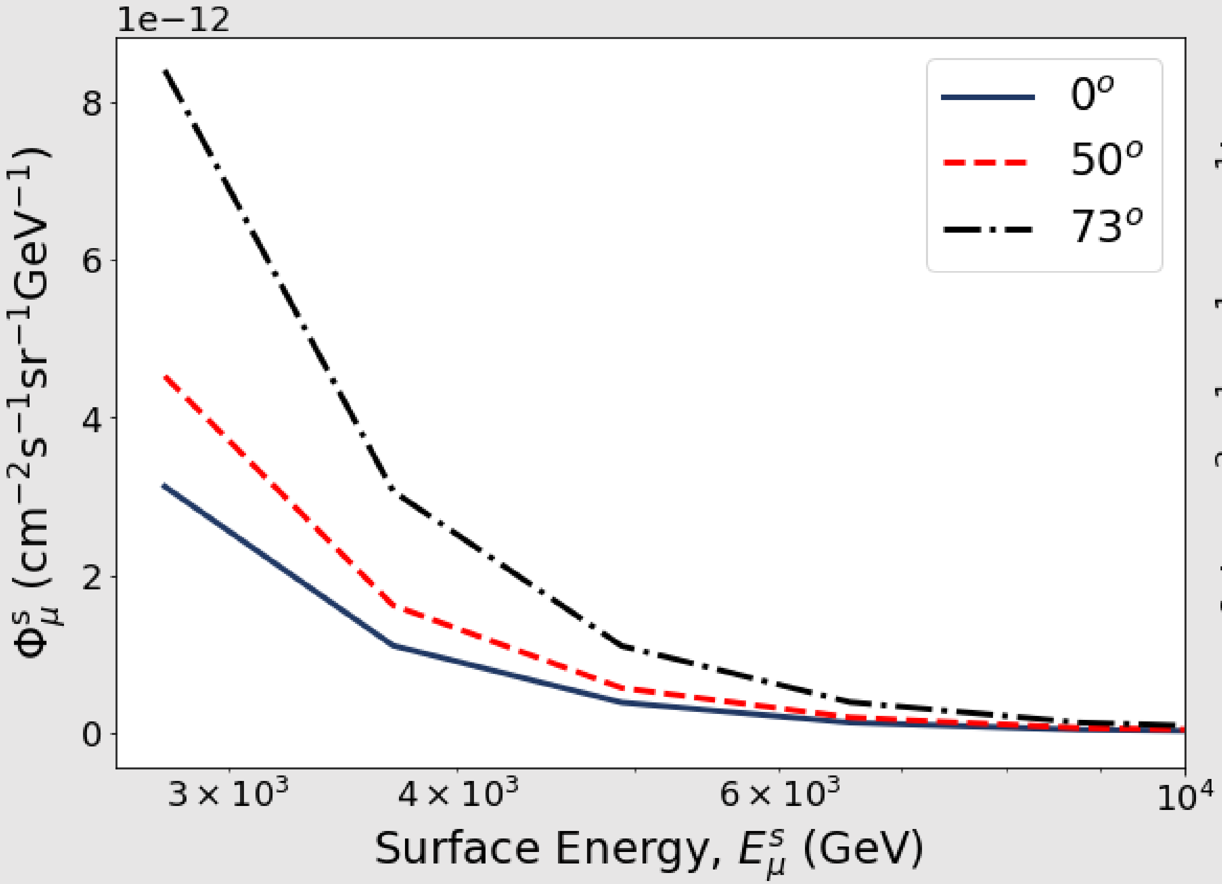
- MCEq uses NRLMSISE-00 data for the exosphere to calculate muon fluxes by solving the matrix cascade equations for cosmic rays.

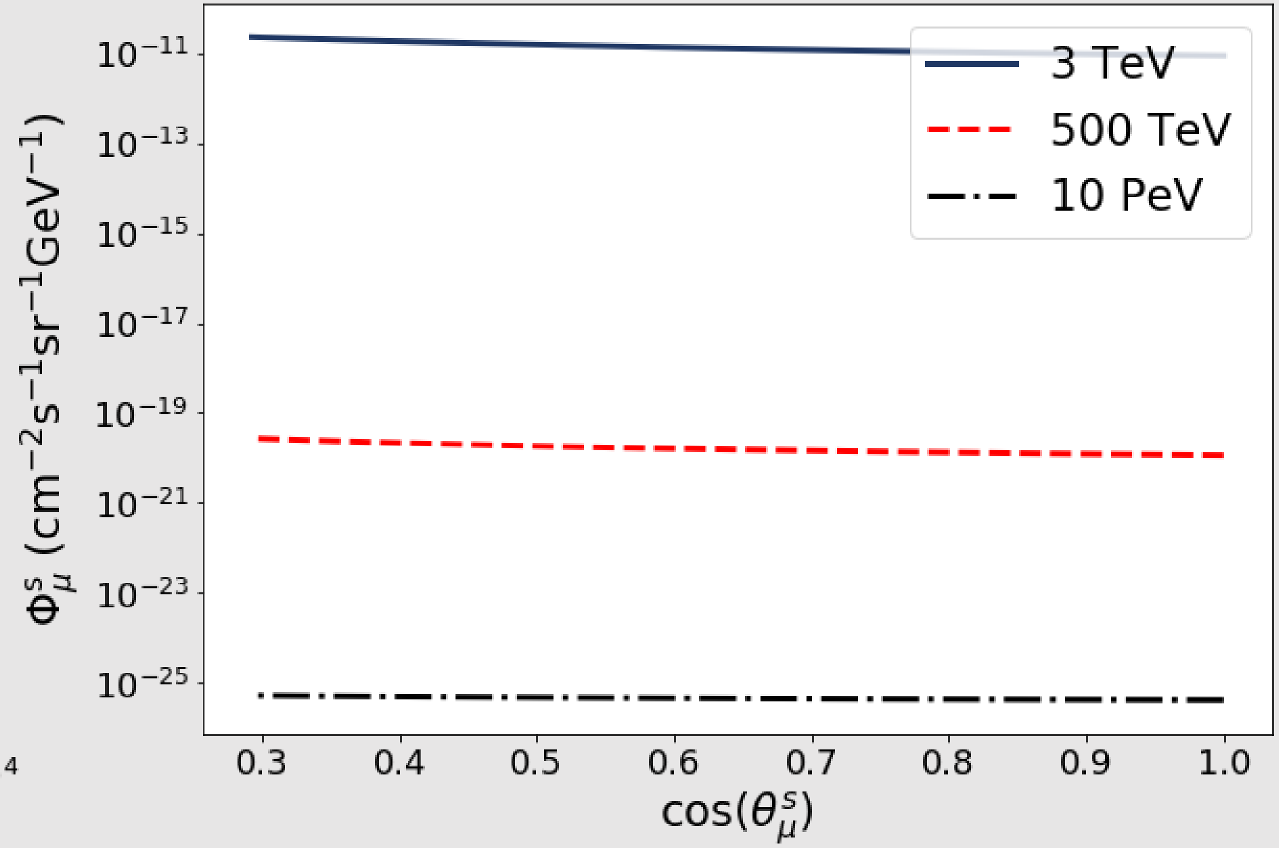
- Set the following in MCEq:
    - Location of Sudbury: (46.472°, 81.187°, 309 m)
    - Density model: NRLMSISE-00
    - Month: January, June
    - Energy bins: (3 TeV, 10 PeV)
    - Zenith angle bins: [0°, 73°]

  750 bins

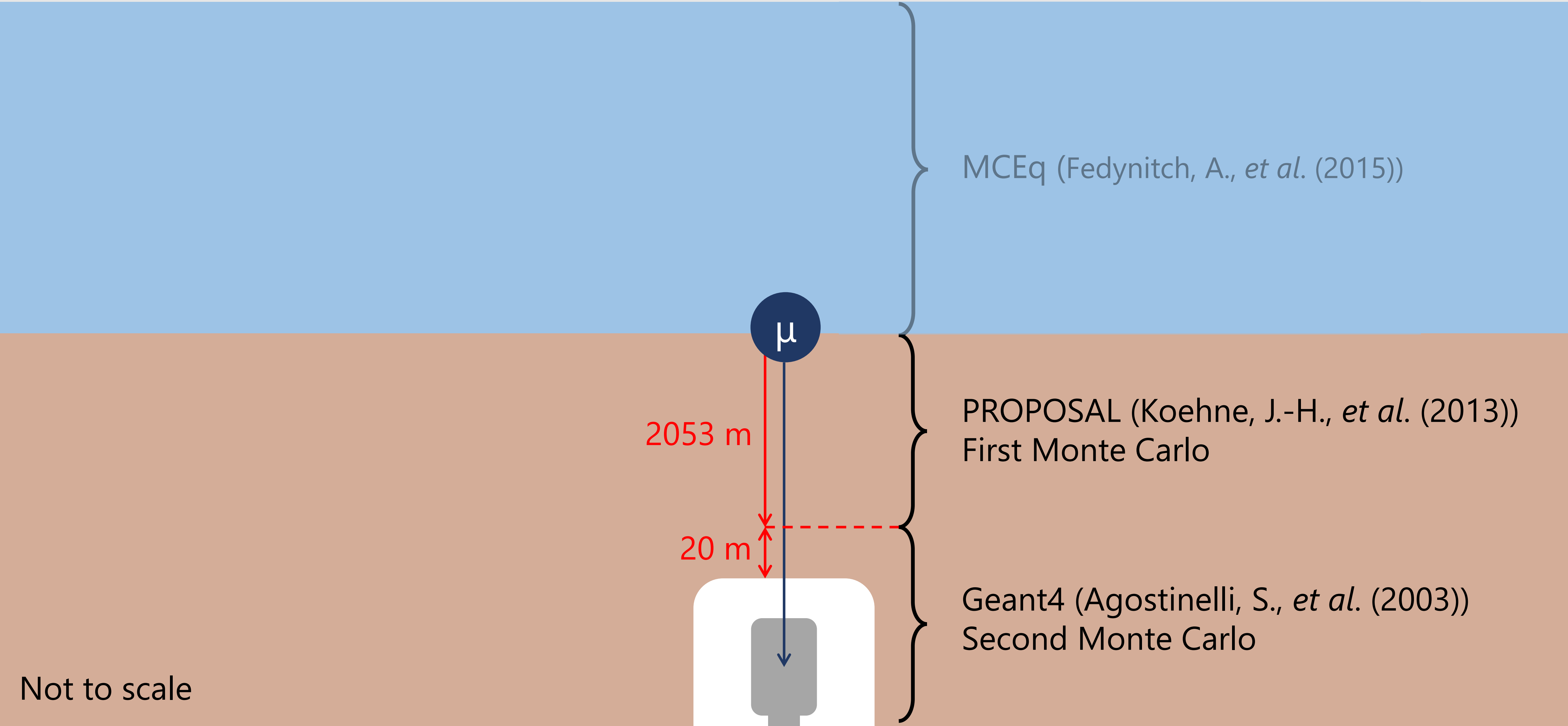
- MCEq returns surface fluxes at the location specified as a function of surface energy and surface angle: $\Phi_{\mu}^{s}\left(E_{\mu}^{s}, \theta_{\mu}^{s}\right)$.

MCEq – Surface Fluxes





Simulations Overview – Step 2



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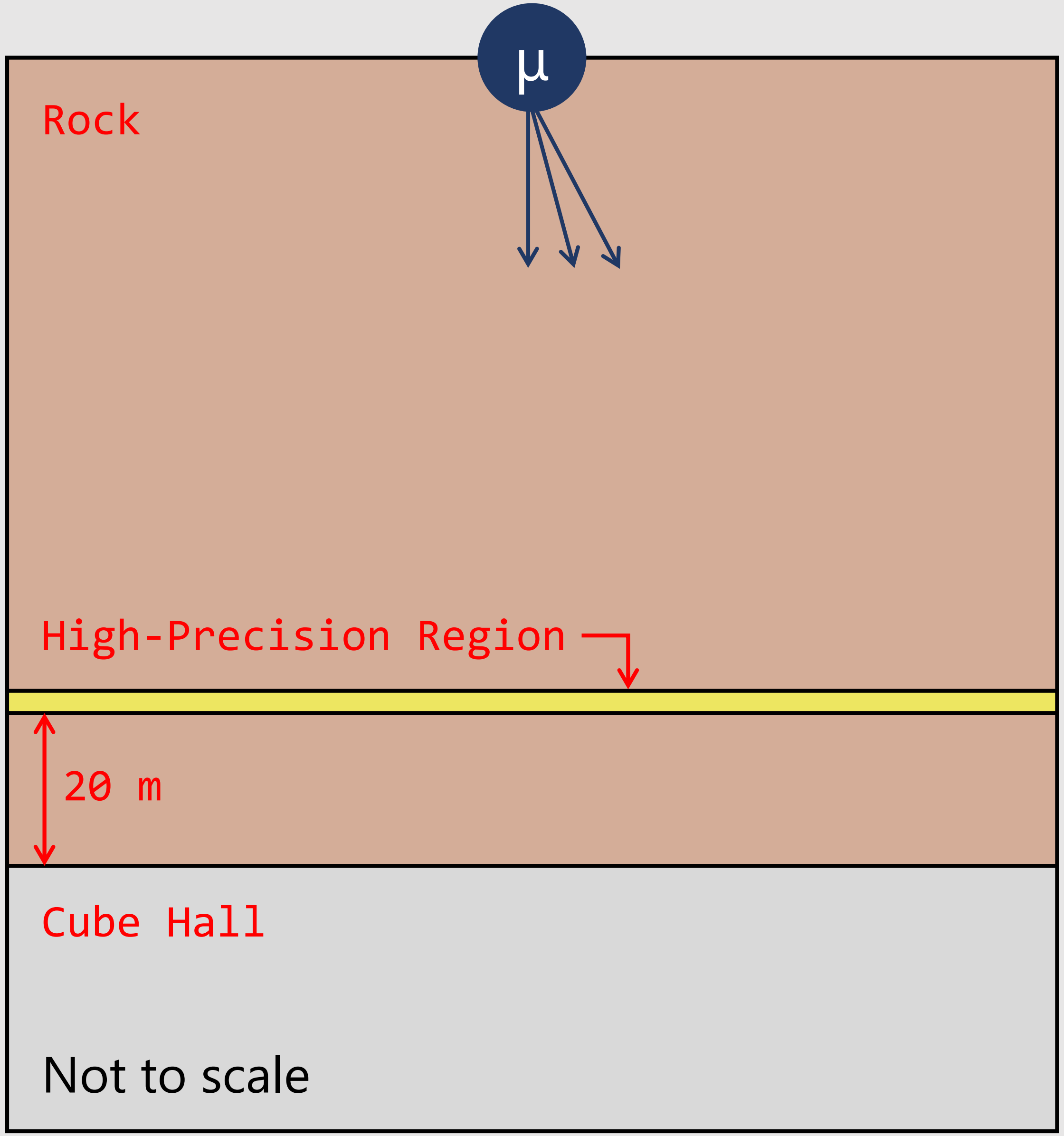
PROPOSAL – Geometry



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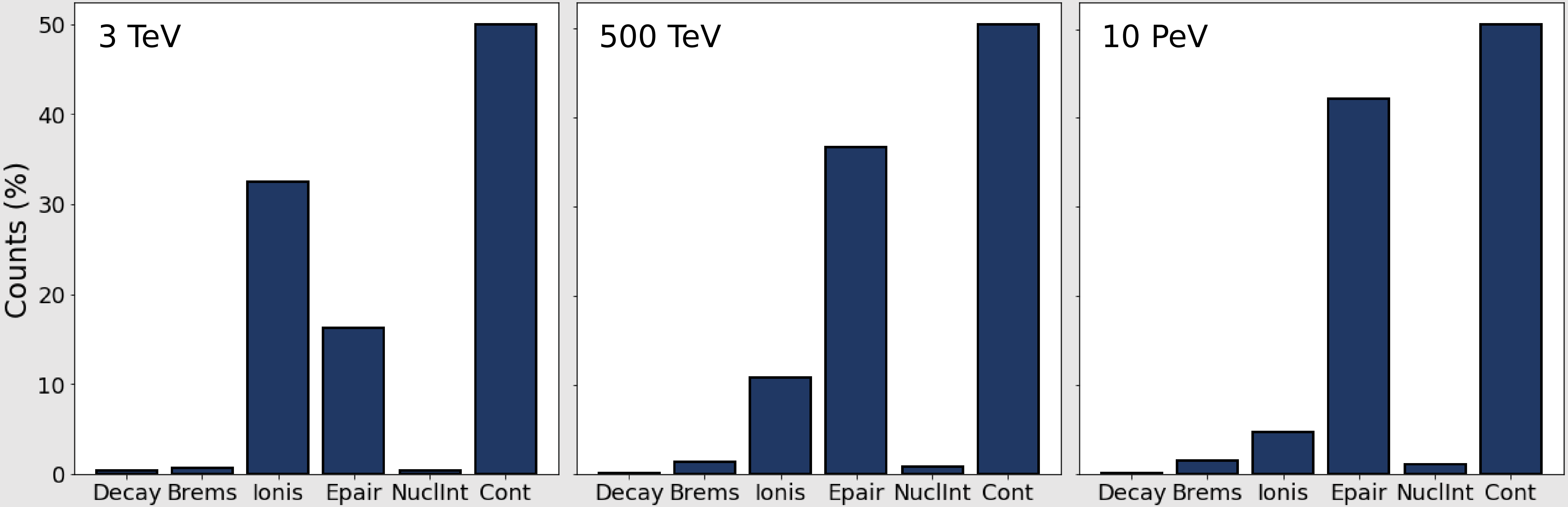
- Define a 2073 m-thick layer of norite rock for the overburden, with air at the bottom for the Cube Hall.
- Define a 0.01 cm-thick high-precision region (HPR) 20 m above the Cube Hall.
- Fire *N* muons from `(0, 0, R_E)`, where *N* is scaled per bin by the surface flux.
- Read the position of muons as they enter the HPR, and read their position and energy as they exit the HPR.

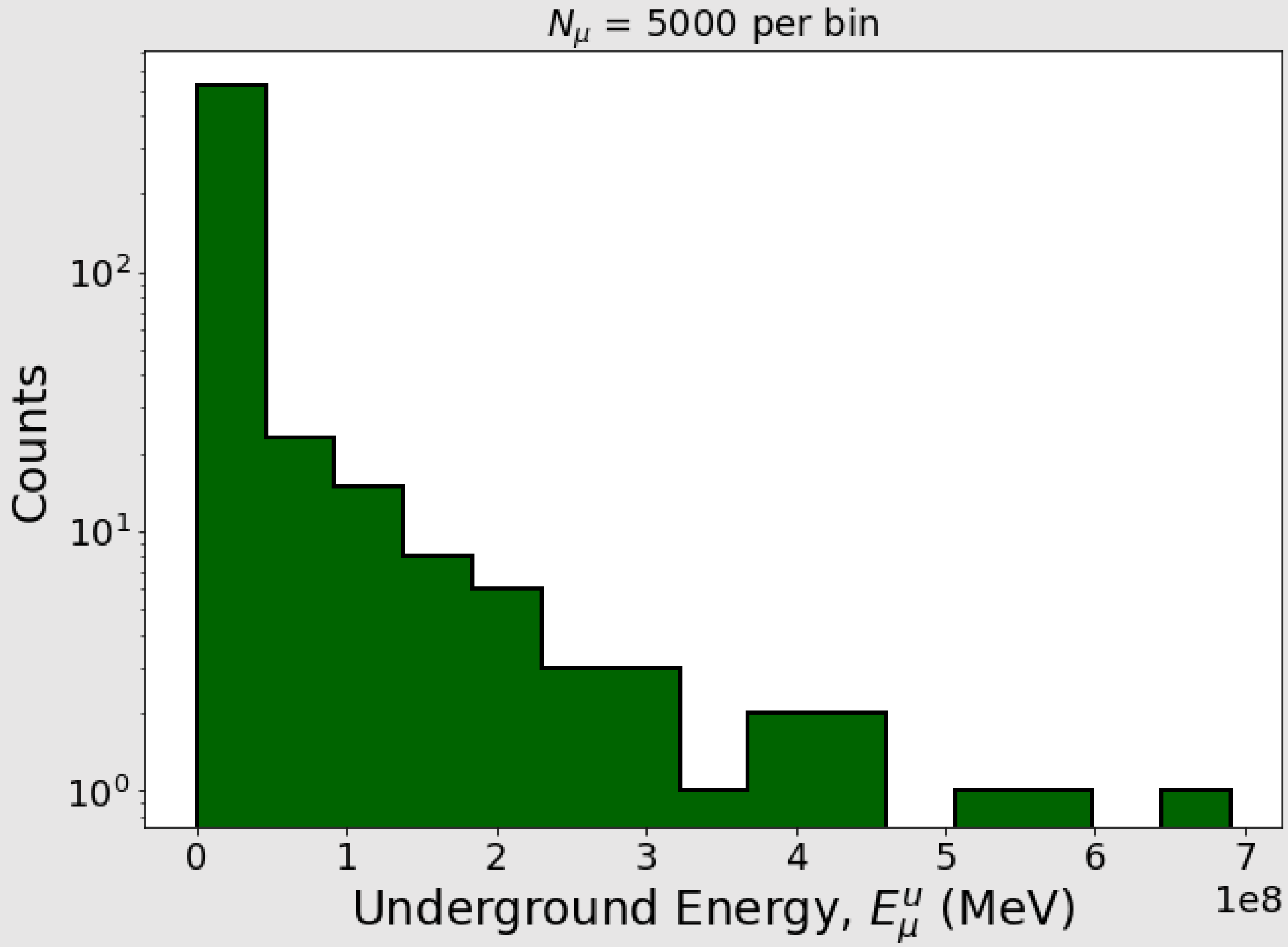
PROPOSAL – Interactions Underground

- Low-energy muons lose most of their energy to ionisation, whereas high-energy muons lose most of their energy to electron-positron pair production (Cont = continuous energy loss).



PROPOSAL – Energy Distribution

- Most muons lose most of their energy as they make their way underground.



PROPOSAL – Survival Probability

- Define a muon that survives (*s*) as a muon that:
  1. Does not decay at all
  2. Does decay, but with $r < R_{HPR}$ (meaning it has made it past the HPR)

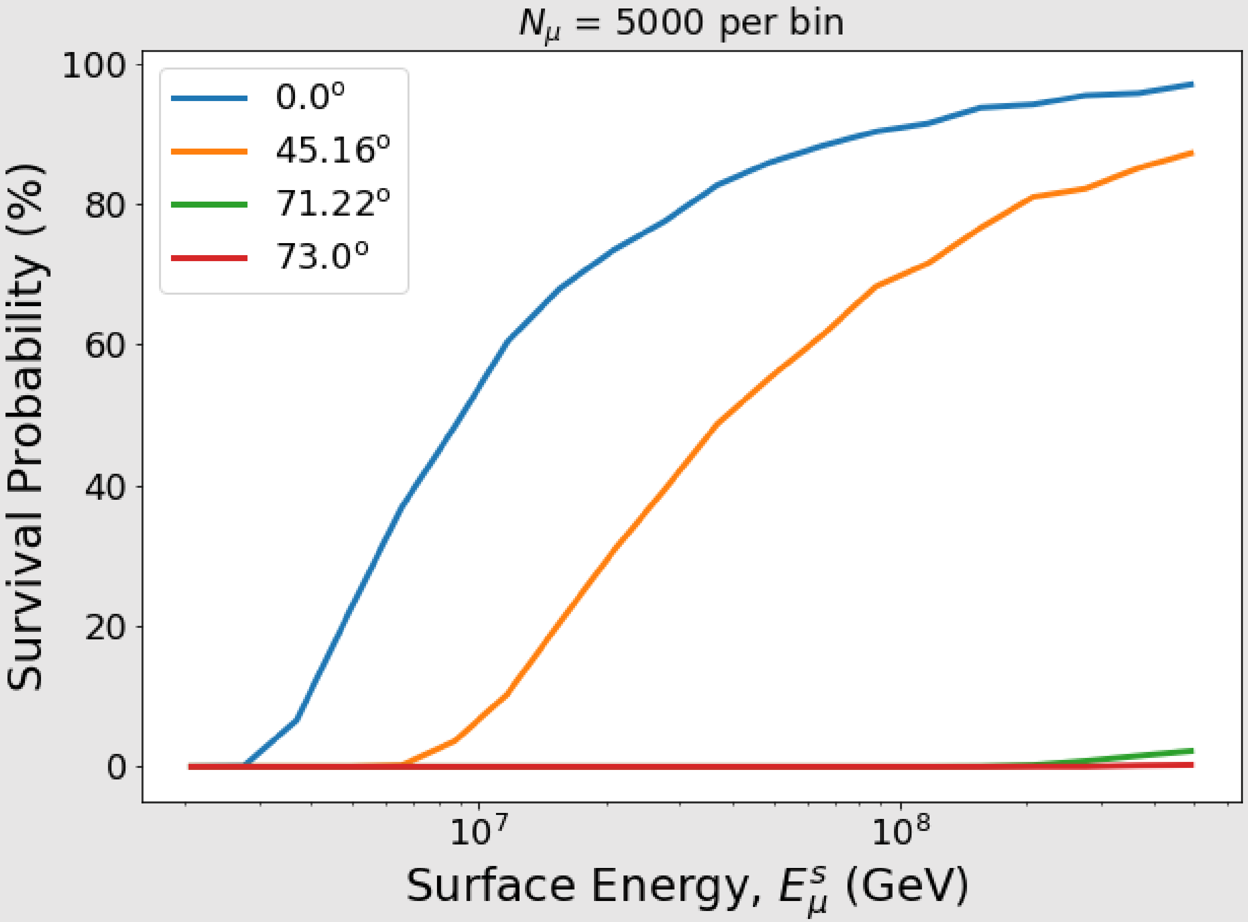
- Survival probability, *S*, is then given by:

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

- Return a survival probability for each $\left(E_{\mu}^{s}, \theta_{\mu}^{s}\right)$ surface bin, and use these to calculate the underground muon flux.

PROPOSAL – Survival Probability

- Survival probability increases as energy increases (minimum: 3 TeV).
- Survival probability increases as angle decreases (maximum: 73°).



Underground Muon Flux

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

$$\begin{array}{cl} & \theta \longrightarrow \\ E \Big\downarrow & \underbrace{\begin{bmatrix} \Phi^s_{11} & \cdots & \Phi^s_{1m} \\ \vdots & \ddots & \vdots \\ \Phi^s_{n1} & \cdots & \Phi^s_{nm} \end{bmatrix}}_{\text{MCEq Output}} \circ \underbrace{\begin{bmatrix} S_{11} & \cdots & S_{1m} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nm} \end{bmatrix}}_{\text{PROPOSAL Output}} = \begin{bmatrix} \Phi^u_{11} & \cdots & \Phi^u_{1m} \\ \vdots & \ddots & \vdots \\ \Phi^u_{1n} & \cdots & \Phi^u_{nm} \end{bmatrix} \end{array}$$

Underground Muon Rate

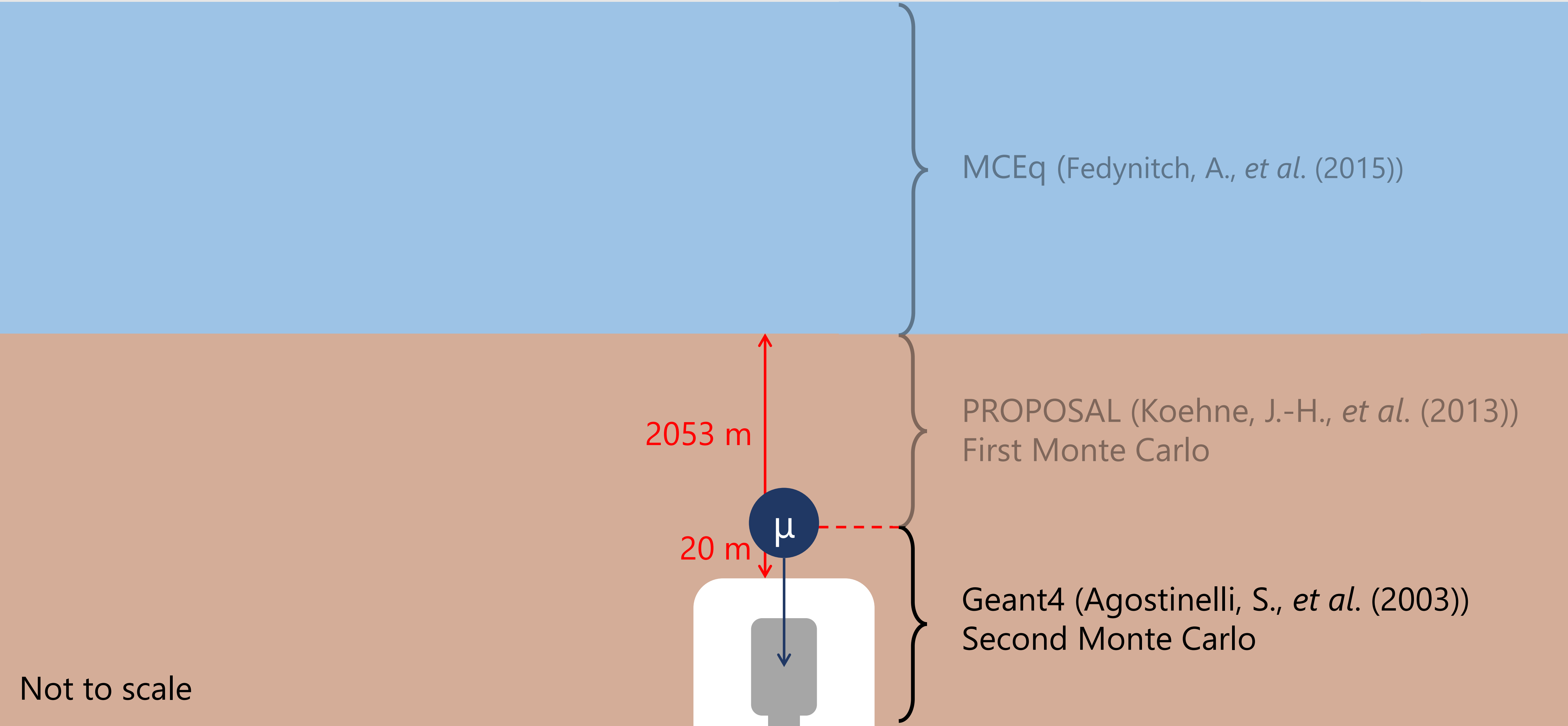
- Integrate the underground muon flux over all surface energies and angles to obtain a total rate for muons entering the Cube Hall.

$$R_\mu^u = A_{CH} \int_{3\,TeV}^{10\,PeV} \int_0^{2\pi} \int_{0^\circ}^{73^\circ} \Phi_\mu^u\left(E_\mu^s, \theta_\mu^s\right) \sin \theta_\mu^s \, \mathrm{d}\theta_\mu^s \, \mathrm{d}\phi \, \mathrm{d}E_\mu^s$$

- For the area of the top of the Cube Hall, $A_{CH} = 2.763\times10^6$ cm^2:

• Calculated muon rate:	9.1×10^{-4} s^{-1}
• SNOLAB muon rate:	8.6×10^{-4} s^{-1}

Simulations Overview – Step 3



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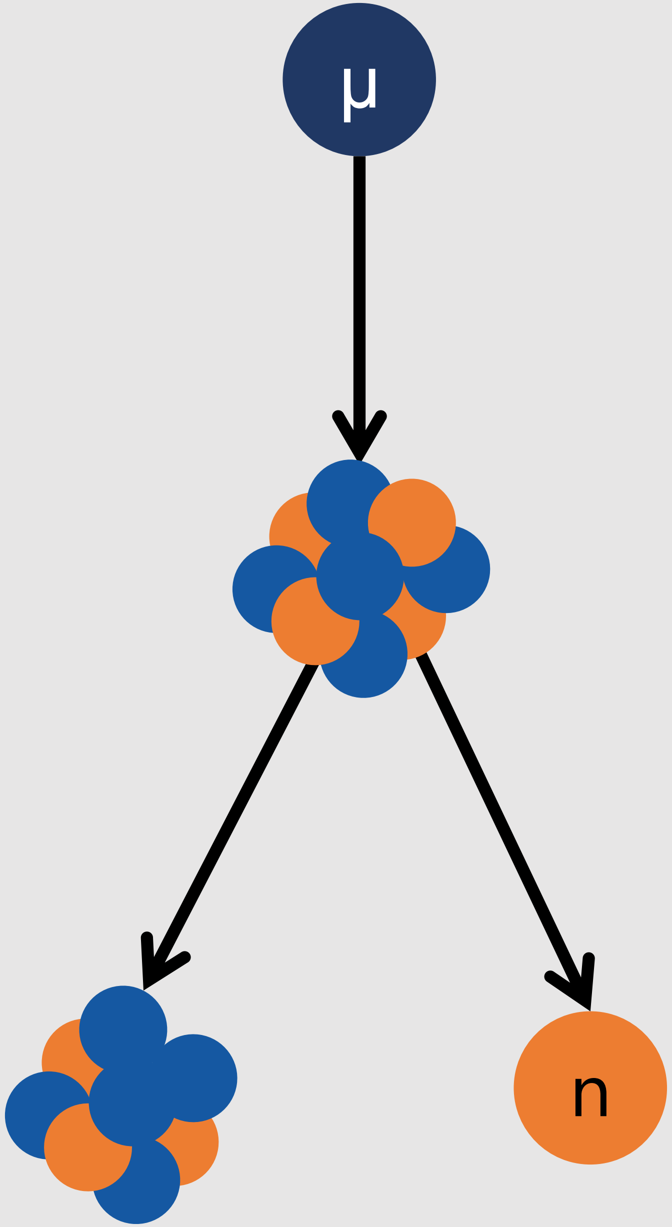
Muon-Induced Neutrons



- As muons travel through the rock, they can produce neutrons through spallation or muon capture.

- In spallation, high-energy muons can collide with atomic nuclei and cause the nuclei to break into pieces, some of which will be high-energy neutrons.

- In muon capture, protons in atomic nuclei capture muons, which causes the emission of neutrons.

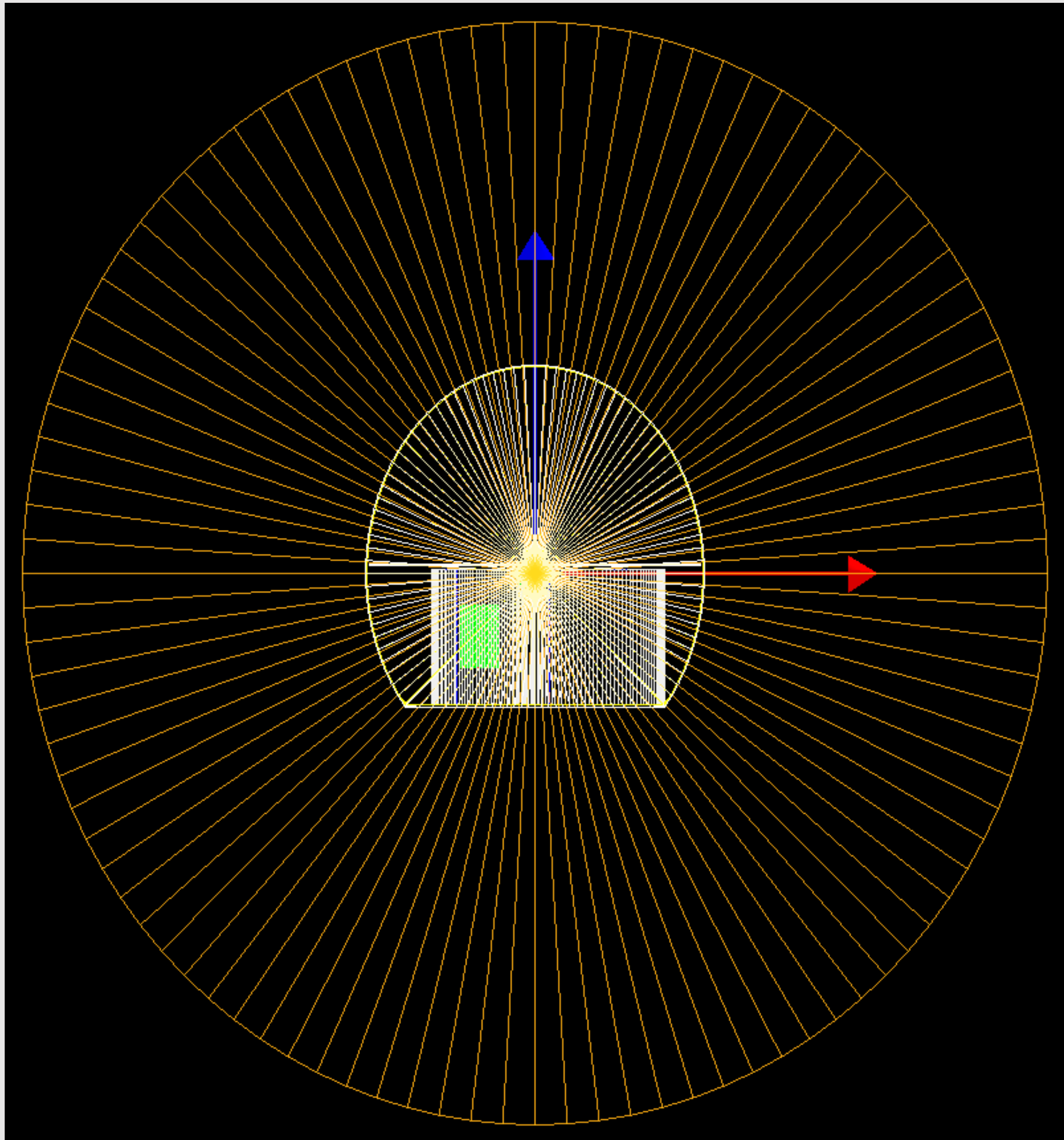
- Because neutrons are background for PICO, it must be ensured that the number of muon-induced neutrons is low.

Geant4 – Underground to PICO

- Use the PICO-500 Geant4 geometry for the second Monte Carlo.

- Drawing from the energy distribution from PROPOSAL, fire muons from 20 m 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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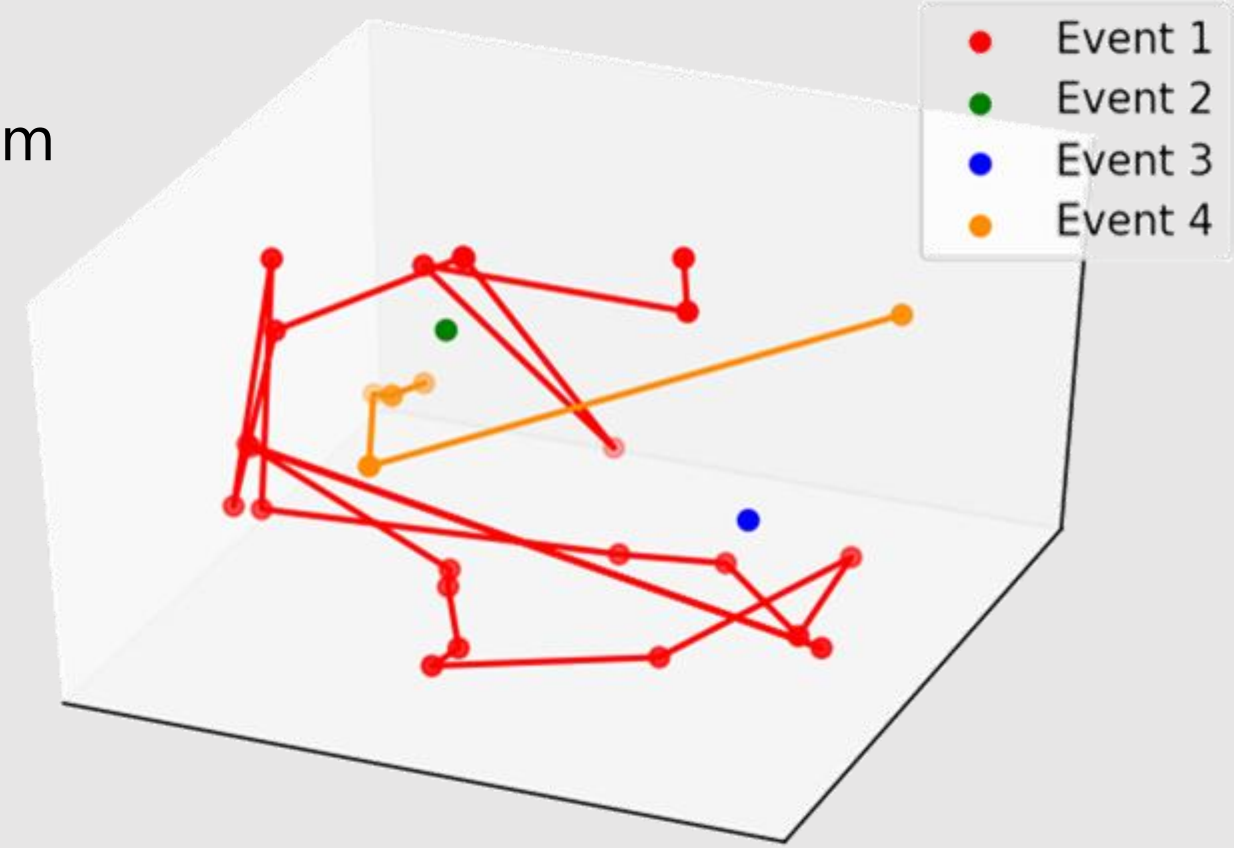


Conclusion

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

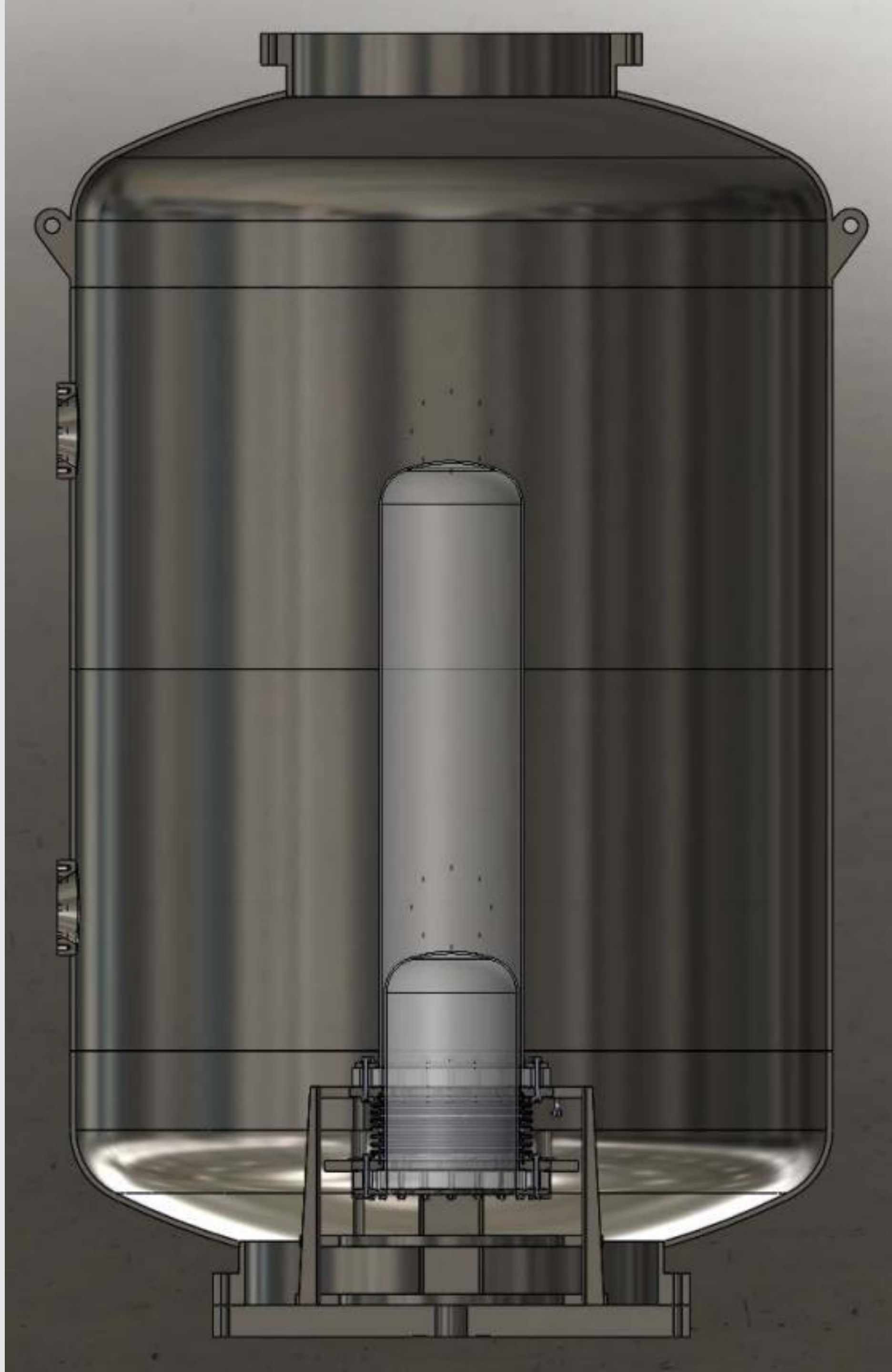
- With the use of MCEq, PROPOSAL, and Geant4, the energy and angular spectra of muons underground can be calculated, which can be used to inform decisions about PICO-500's muon veto system, and can be used to calculate the rate of neutrons entering the detector.

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

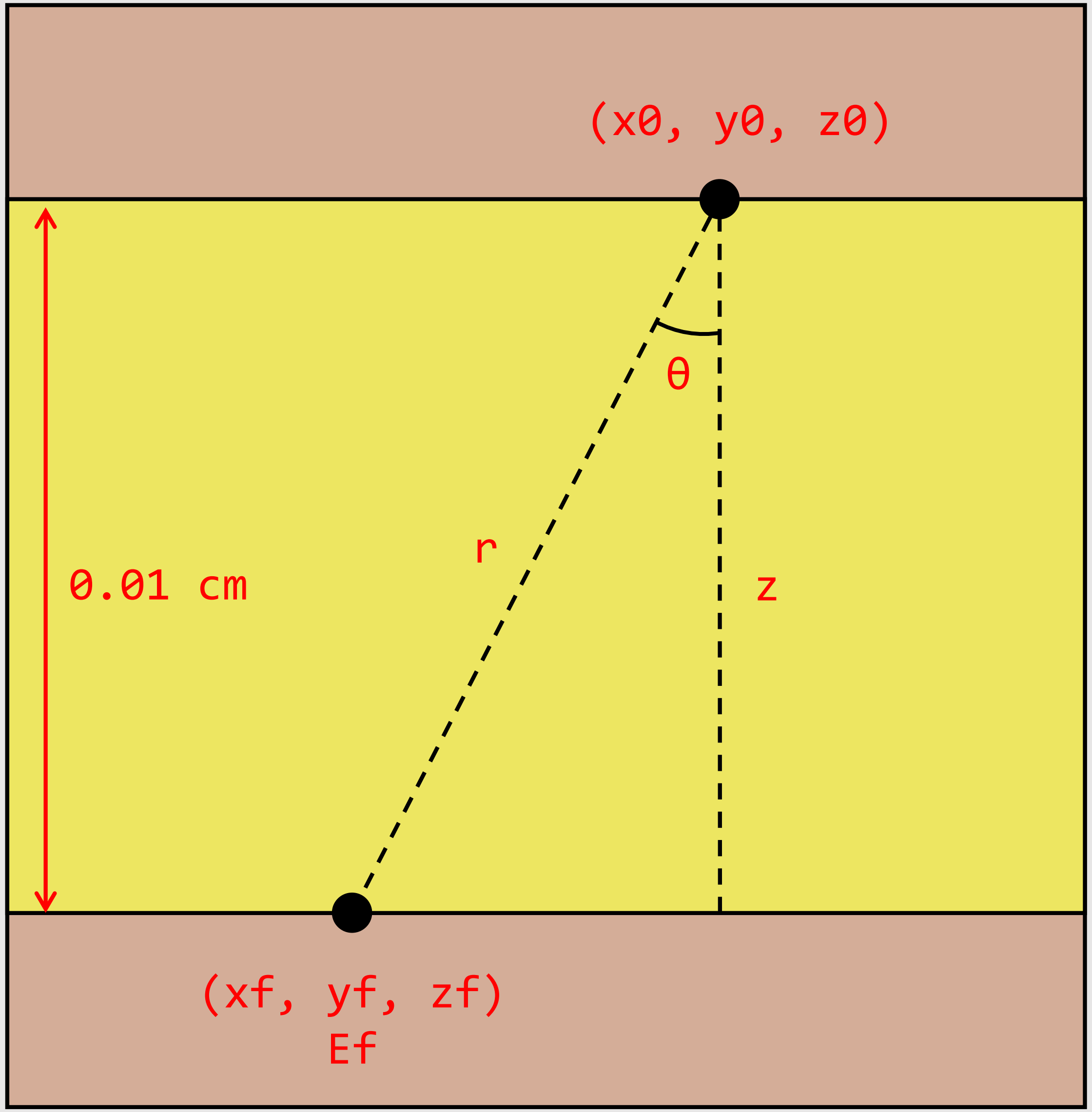
- Although this is still a work-in-progress, it looks like the background for PICO-500 will not be dominated by muon-induced neutrons.

Dark Matter Detection

- PICO is an experiment installed in SNOLAB that searches for WIMPs using bubble chambers filled with superheated C_3F_8.
- The WIMP signature is a **single-bubble** event. Because WIMPs interact so weakly, WIMP-induced bubbles will be very rare, making PICO a low-background experiment.
- **Neutrons** are one of the main backgrounds, as they can cause WIMP-like single-bubble events.
- PICO-500 will be installed in the Cube Hall.



PROPOSAL – Geometry



- Convert to an underground angle:

$$\underline{r} = (x, y, z) = \underline{r}_f - \underline{r}_0$$

$$\theta_\mu^u = \left|\left(\frac{180°}{\pi}\right)\cos^{-1}\left(\frac{z}{r}\right) - 180°\right|$$

- This gives an error of about 0.5%.