MUTE: Calculations for Cosmic-Ray Muons in Deep Underground Laboratories

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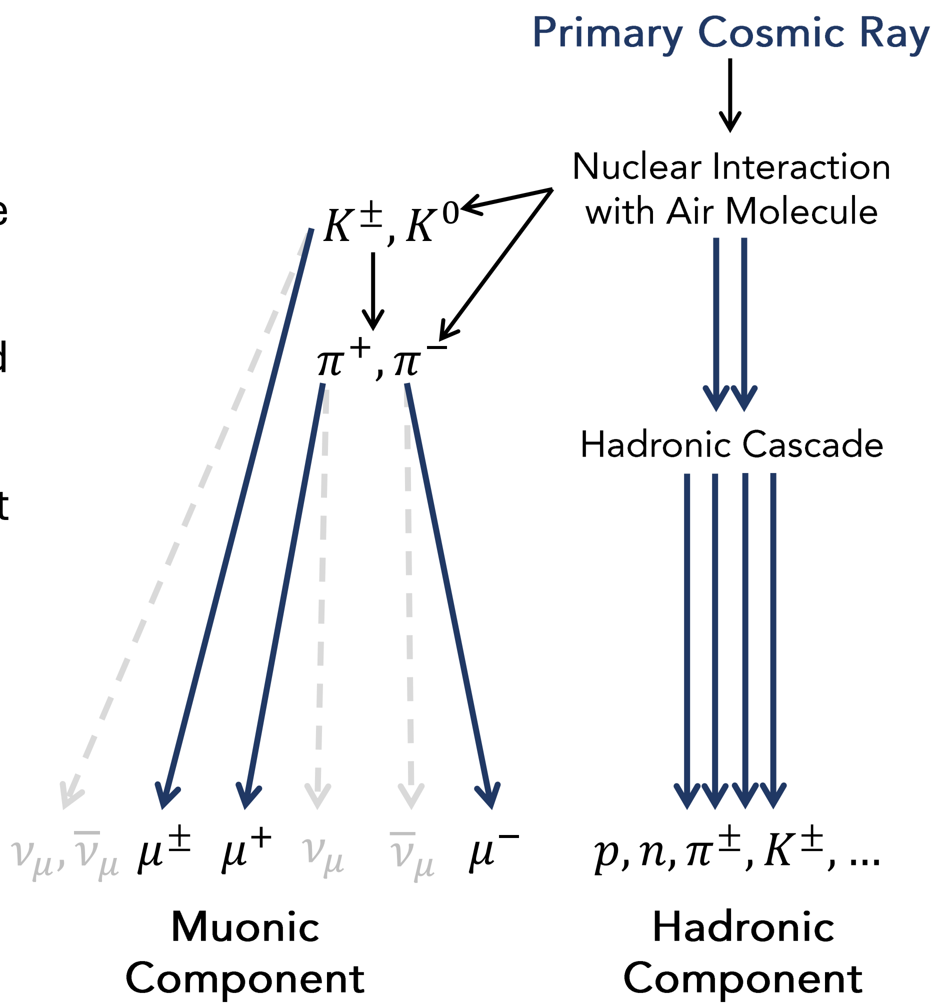
TAUP 2025
25 August 2025

Introduction

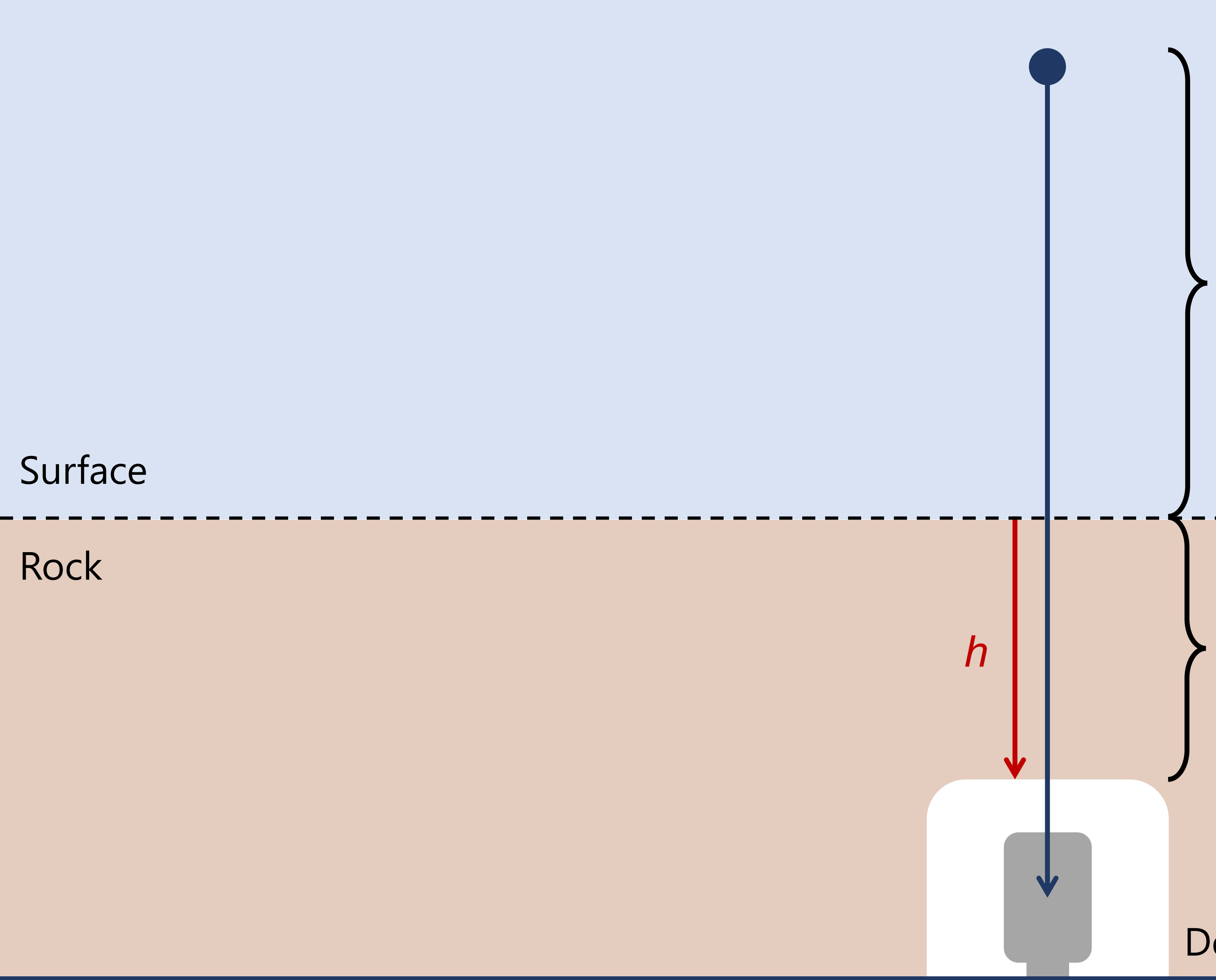
- Underground muons are crucial for data analyses in neutrino telescopes and in the design of dark matter detectors.
- Previous methods for CR muon calculations have many disadvantages:
    - **Analytical Formulas and Parametric Fits:** Missing comprehensive treatment of the uncertainties, contain systematic biases.
    - **Muon Propagator Codes:** Rely on outdated models or slow and inaccesible tools.
- MUTE is an open-source Python program first released in 2021 that calculates atmospheric muon fluxes.

MUTE (MUon inTensity codE)

https://github.com/wjwoodley/mute



MUTE Method Overview



daemonflux or MCEq

Surface muon flux model calibrated to experimental data; uncertainties to percent level up to 1 TeV.

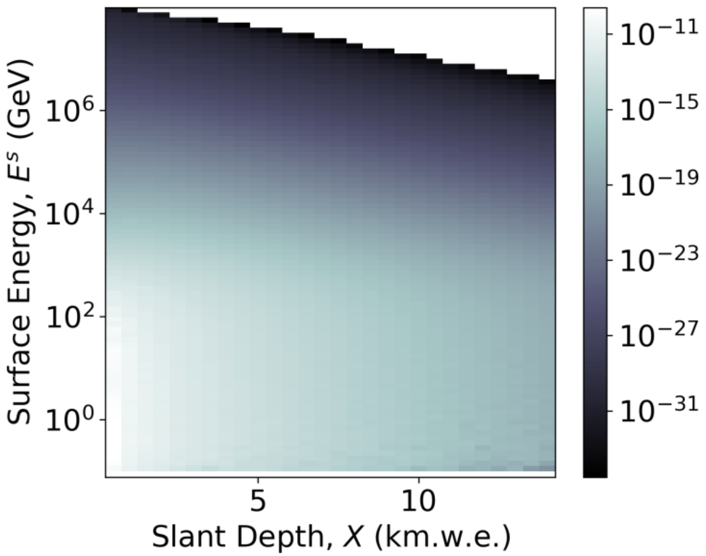
PROPOSAL

Monte Carlo code optimised to transport leptons through long ranges of matter quickly.

MUTE Method

$$\Phi^u(E_j^u, X_k, \theta_k) = \sum_i \Phi^s(E_i^s, \theta_k) P(E_i^s, E_j^u, X_k) \left(\frac{\Delta E_i^s}{\Delta E_j^u}\right)$$

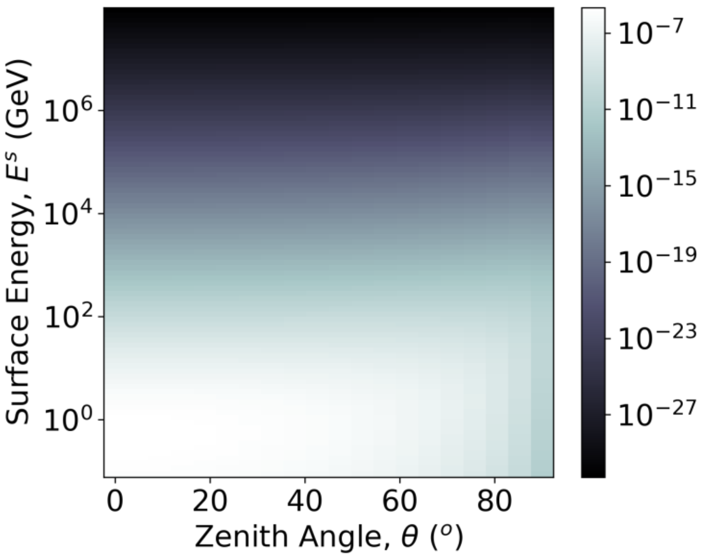
$\boldsymbol{\Phi^u}$



MUTE
Underground Fluxes

=

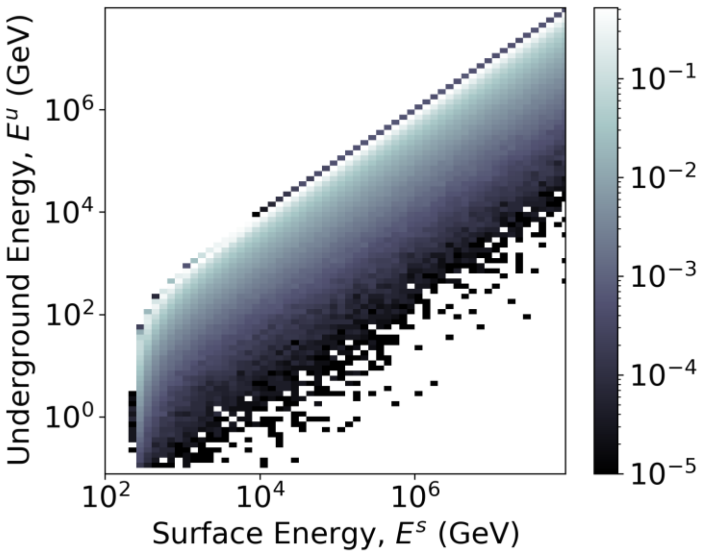
$\boldsymbol{\Phi^s}$



MCEq
Surface Fluxes

*

$\boldsymbol{P}$



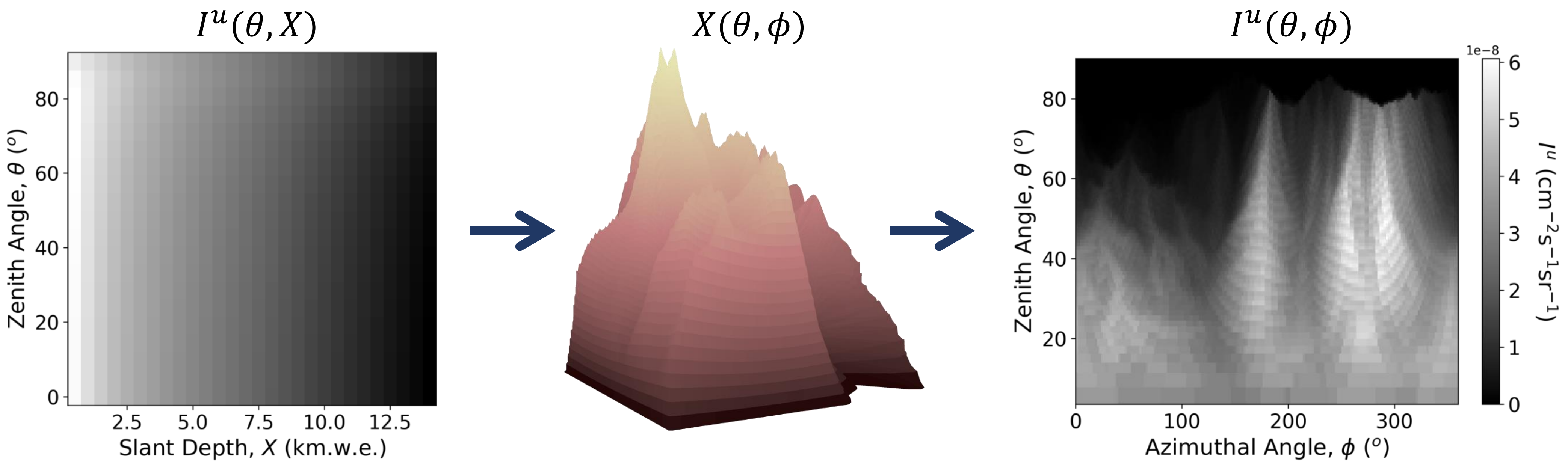
PROPOSAL
Transfer Tensor

Defining Laboratory Parameters – Overburden

- Intensities are calculated by integrating underground muon flux over all energies:

$$I^u(X,\theta) = \int_{E_{\rm th}}^{\infty} \Phi^u(E^u, X, \theta)\mathrm{d}E^u$$

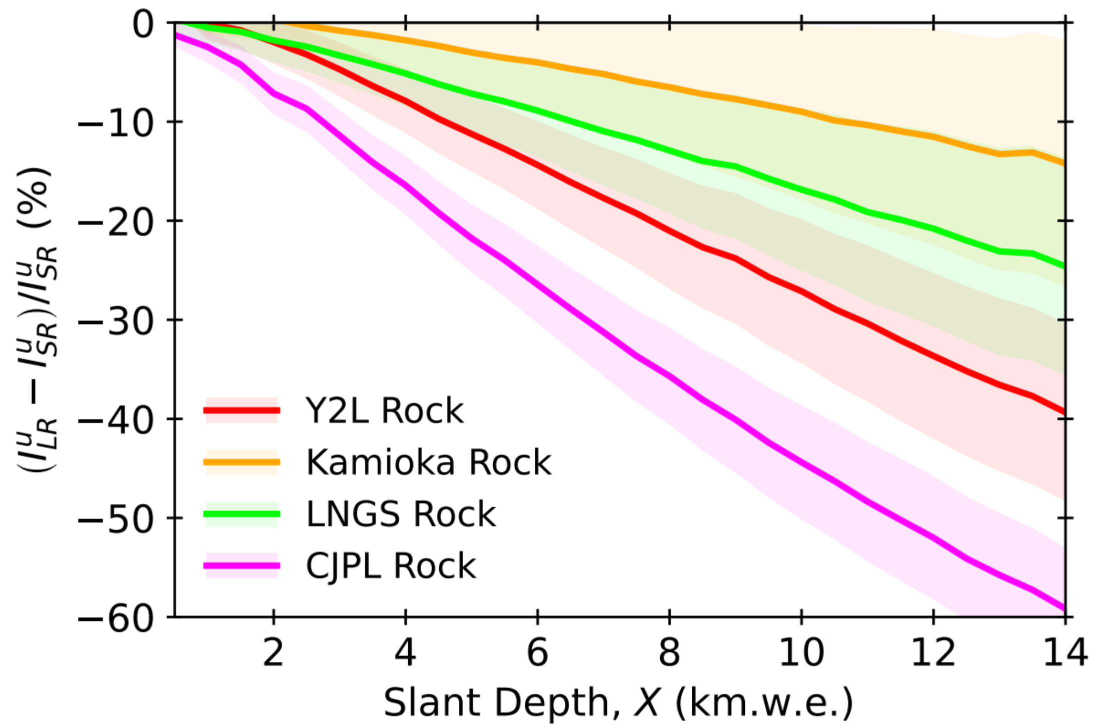
- Laboratory overburden shapes can be specified in MUTE by setting one of the following parameters:
  - Vertical Depth (for labs under **flat overburdens**)
  - Mountain Profile in $X(\theta,\phi)$ (for labs under **mountains**)

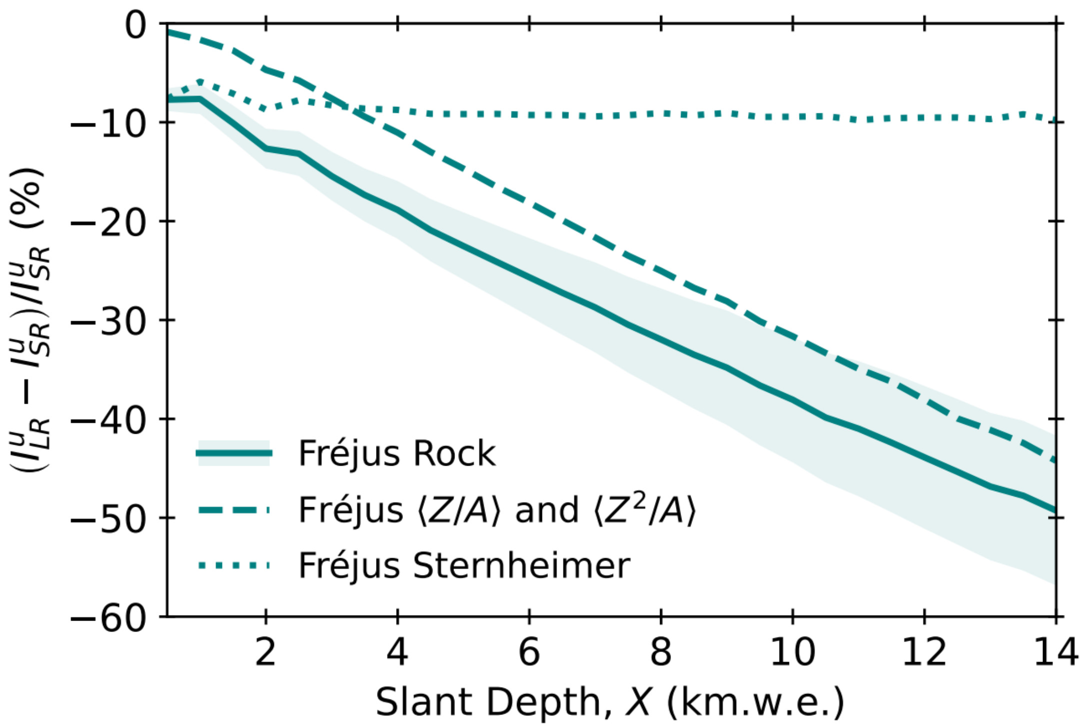


Defining Laboratory Parameters – Rock Composition

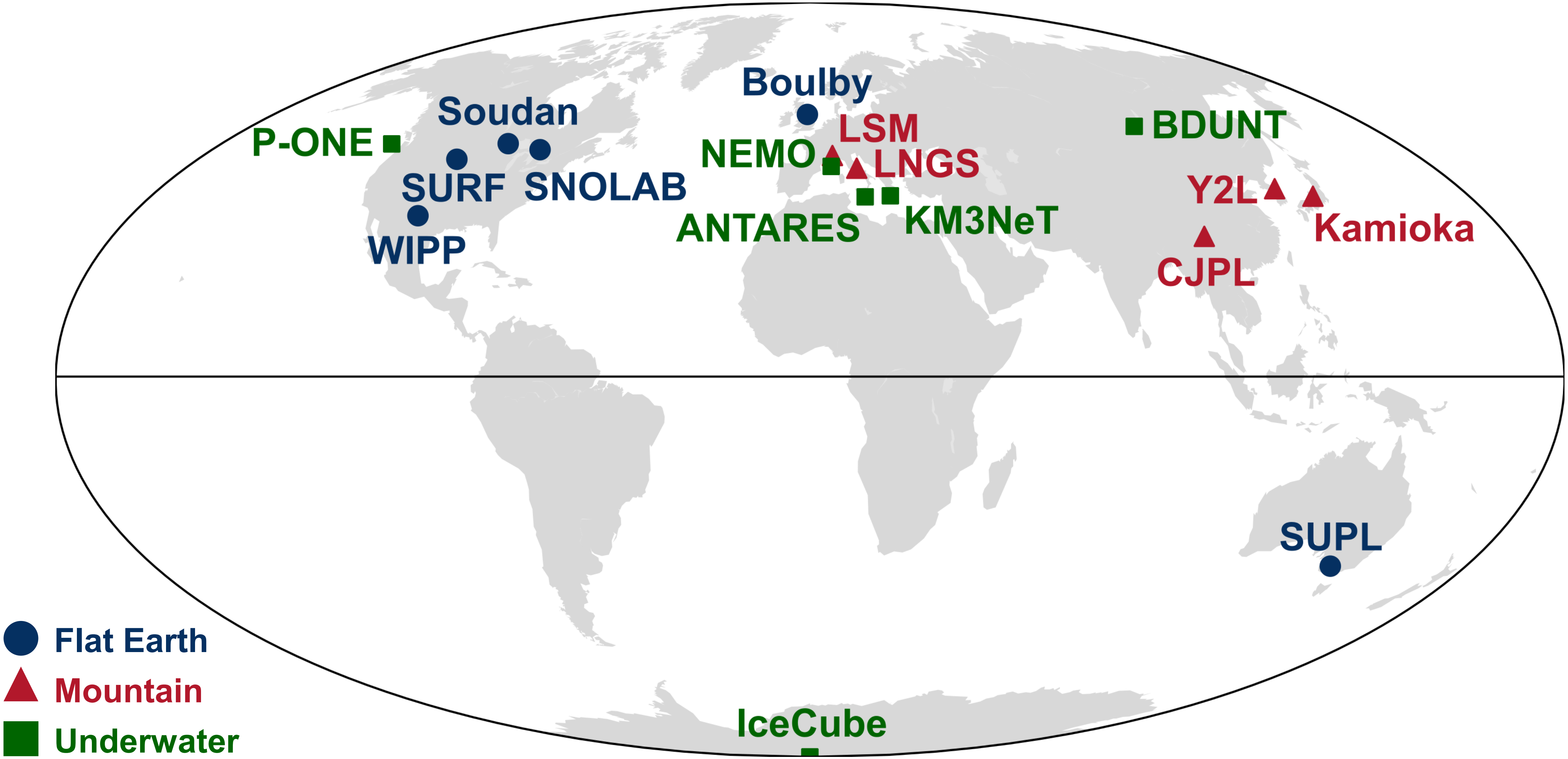
- Rock composition plays a significant role in modelling the energy loss of muons travelling through rock. MUTE and PROPOSAL require details of the rock for accurate modelling (recommendations in PRD 110 (2024) 6, 063006):

1. Rock Density
2. <*Z*> and <*A*> of Rock from Minor or Major Components
3. Sternheimer Parameters for Ionisation Losses





Laboratory Locations



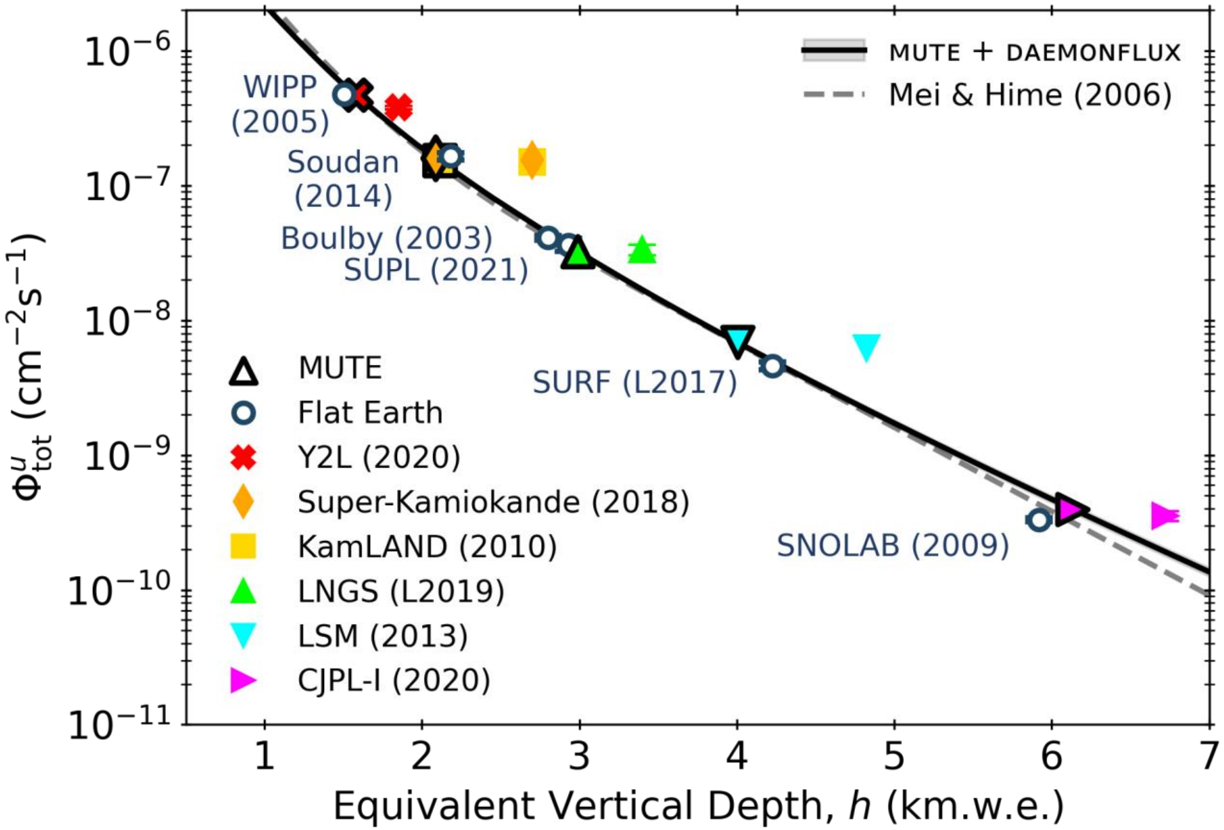
Total Underground Muon Flux

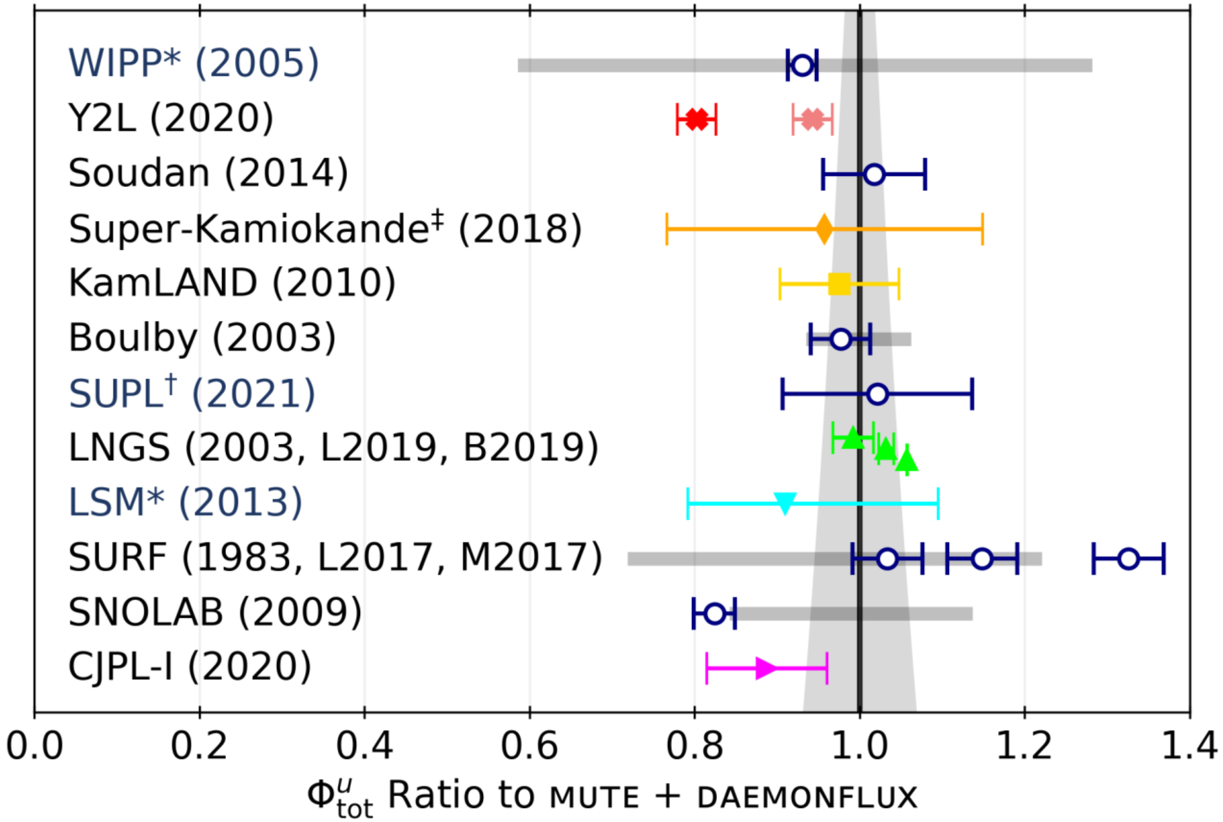
- The total muon flux is the main observable of interest for muon-induced backgrounds and it has been calculated for various deep underground labs using daemonflux.

Laboratory	Experiment	Φ^u_{tot} (cm^{-2} s^{-1}) Measured	Φ^u_{tot} (cm^{-2} s^{-1}) Predicted by MUTE	$\overline{h}_{SR}$ (km.w.e.) Inferred from MUTE
WIPP	- (2005)	$(4.77 \pm 0.09) \times 10^{-7}$ [30]	$(5.17 \pm 0.11) \times 10^{-7}$ [a]	1.54 ± 0.01
Y2L	COSINE-100 (2020)	$(3.795 \pm 0.110) \times 10^{-7}$ [68] $(4.459 \pm 0.132) \times 10^{-7}$ [b]	$(4.73 \pm 0.11) \times 10^{-7}$	1.58 ± 0.01
Soudan	- (2014)	$(1.65 \pm 0.10) \times 10^{-7}$ [69]	$(1.66 \pm 0.04) \times 10^{-7}$	2.07 ± 0.01
Kamioka	Super-Kamiokande (2018)	$(1.54 \pm 0.31) \times 10^{-7}$ [33] [c]	$(1.61 \pm 0.04) \times 10^{-7}$	2.09 ± 0.01
	KamLAND (2010)	$(1.49 \pm 0.11) \times 10^{-7}$ [27]	$(1.53 \pm 0.04) \times 10^{-7}$	2.11 ± 0.01
Boulby	ZePLiN 1 (2003)	$(4.09 \pm 0.15) \times 10^{-8}$ [34]	$(4.19 \pm 0.13) \times 10^{-8}$	2.83 ± 0.02
SUPL	SABRE (2021)	$(3.65 \pm 0.41) \times 10^{-8}$ [70]	$(3.58 \pm 0.11) \times 10^{-8}$ [d]	2.93 ± 0.02
LNGS	MACRO (2003)	$(3.22 \pm 0.08) \times 10^{-8}$ [42]		
	Borexino (B2019)	$(3.432 \pm 0.003) \times 10^{-8}$ [43]	$(3.25 \pm 0.11) \times 10^{-8}$	2.99 ± 0.02
	LVD (L2019)	$(3.35 \pm 0.03) \times 10^{-8}$ [44]		
LSM	EDELWEISS (2013)	$(6.25 \pm 0.2^{+0.6}_{-1.0}) \times 10^{-9}$ [71]	$(6.87 \pm 0.28) \times 10^{-8}$ [a]	4.00 ± 0.03
SURF	Homestake (1983)	$(4.14 \pm 0.05) \times 10^{-9}$ [72]		
	MAJORANA (M2017)	$(5.31 \pm 0.17) \times 10^{-9}$ [38]	$(4.01 \pm 0.17) \times 10^{-9}$	4.38 ± 0.03
	LUX (L2017)	$(4.60 \pm 0.33) \times 10^{-9}$ [73]		
SNOLAB	SNO (2009)	$(3.31 \pm 0.10) \times 10^{-10}$ [25]	$(4.02 \pm 0.24) \times 10^{-10}$	6.13 ± 0.05
CJPL-I	JNE (2020)	$(3.53 \pm 0.29) \times 10^{-10}$ [29]	$(3.98 \pm 0.24) \times 10^{-10}$	6.13 ± 0.05

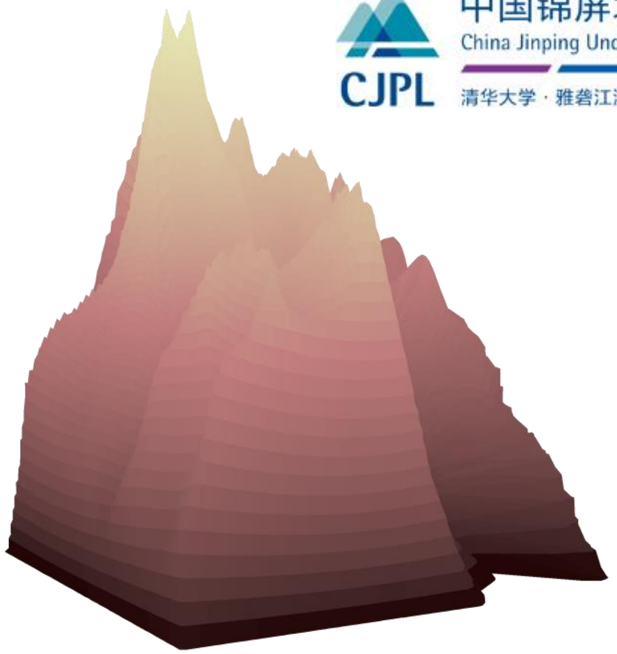
Total Underground Muon Flux

- The total muon flux is the main observable of interest for muon-induced backgrounds and it has been calculated for various deep underground labs using daemonflux.
- MUTE with daemonflux provides a satisfactory description of the data in all cases, with small uncertainties.





Modelling the Muon Flux at CJPL

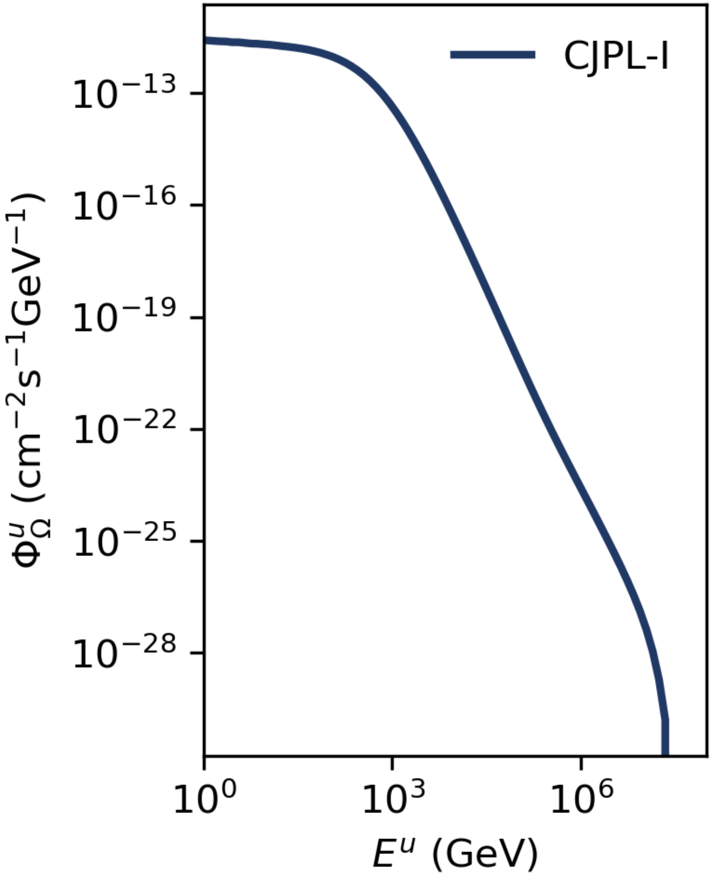


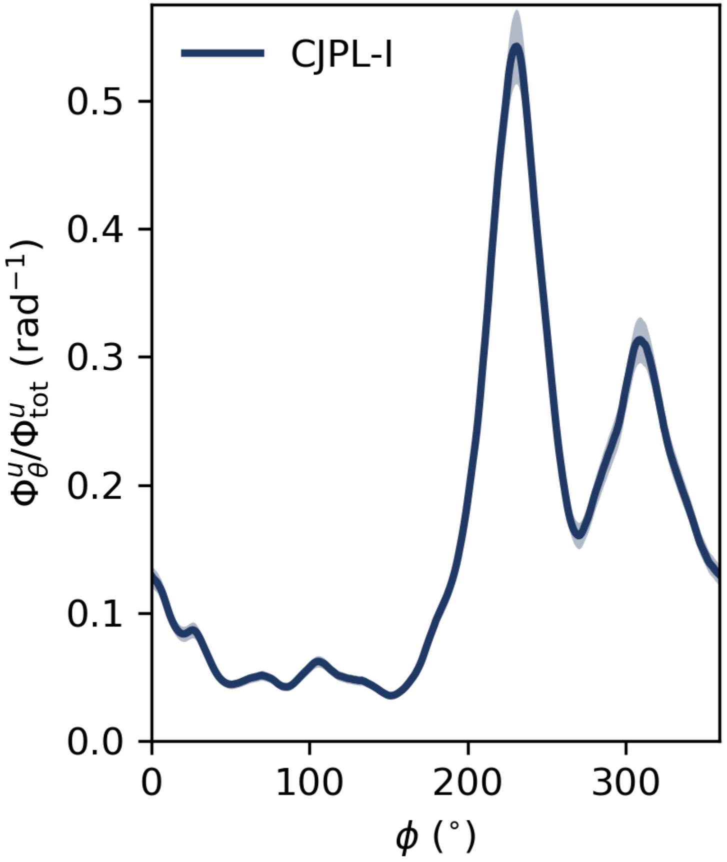
C	O	Mg	Al
9.59	46.42	11.50	0.15
Si	**K**	**Ca**	**Fe**
0.19	0.07	31.96	0.10

<*Z*> = 12.15; **<*A*>** = 24.30; ***ρ*** = 2.8 gcm^{-3}

- CJPL-I mountain map provided by Shaomin Chen at Tsinghua University.

$$\Phi_{\mu,\mathrm{tot}}^{u,\mathrm{CJPL}} = (3.98 \pm 0.24) \times 10^{-10}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$





Modelling the Muon Flux at CJPL

1. Install MUTE in the terminal.

```
pip install mute
```

2. Import MUTE in Python.

```python
import mute.constants as mtc
import mute.underground as mtu
```

3. Define parameters for CJPL through global constants.

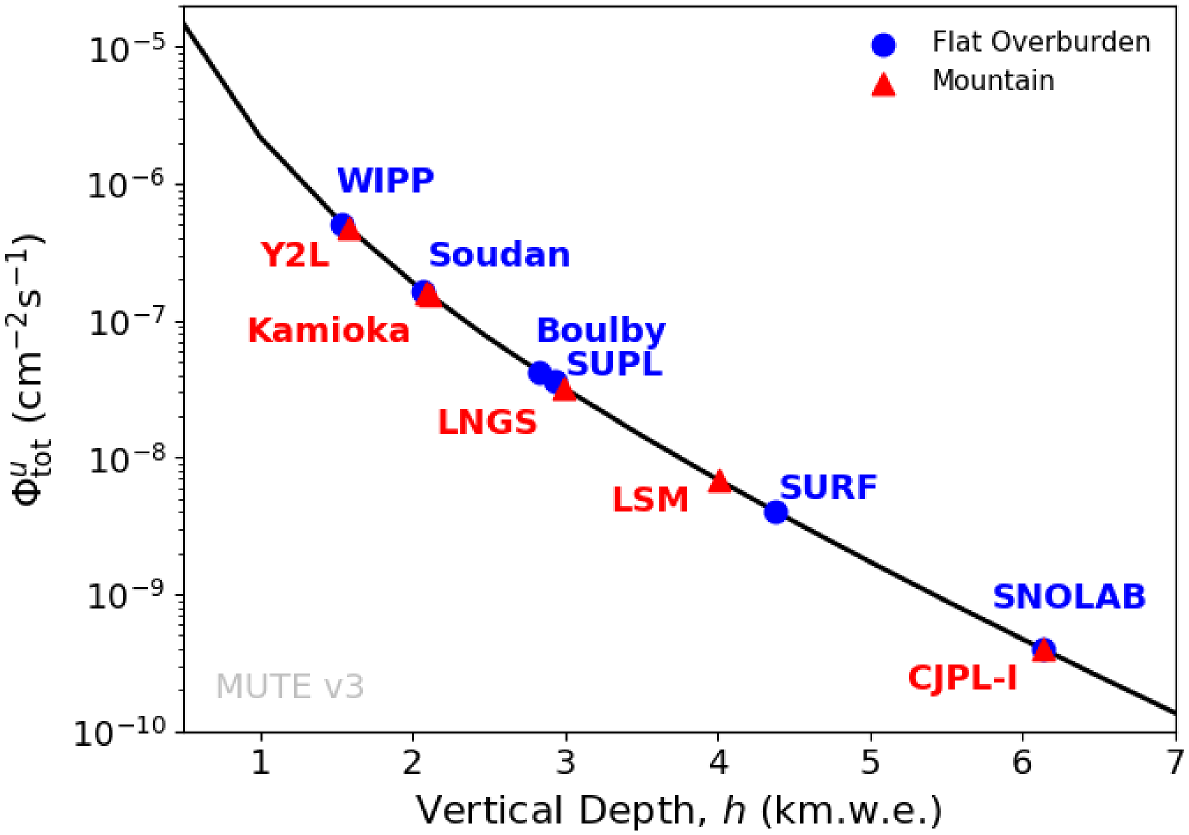
```python
mtc.set_overburden("mountain") # Do calculations for a lab under a mountain
mtc.set_reference_density(2.8) # Set rock density to 2.8 g/cm^3
mtc.load_mountain("CJPL")      # Load the profile of the mountain above CJPL
```

4. Calculate muon fluxes.

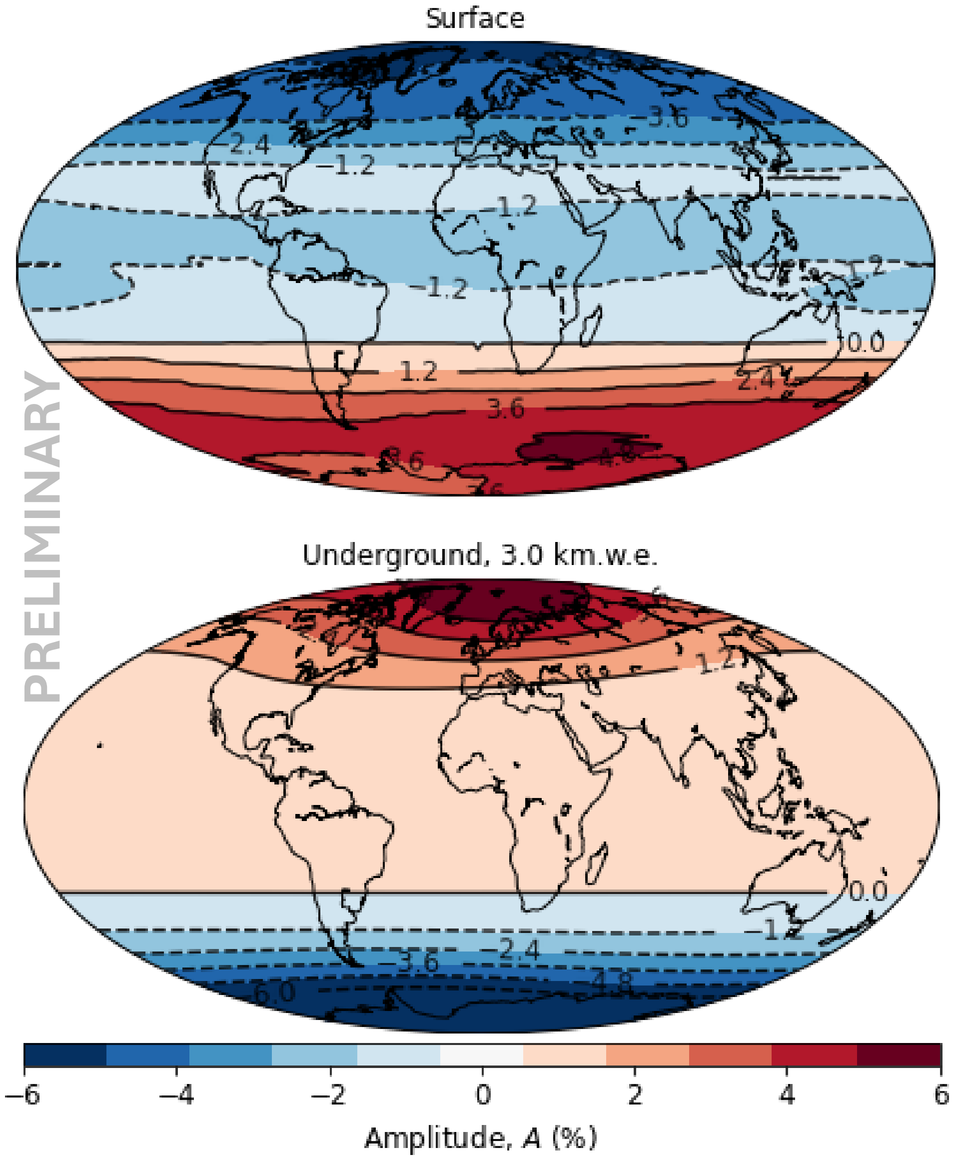
```python
mtu.calc_u_tot_flux(model = "daemonflux") # Calculate total underground flux
mtu.calc_u_e_spect(model = "daemonflux")  # Calculate underground energy spectrum
mtu.calc_u_ang_dist(kind = "azimuthal", model = "daemonflux") # Calculate angular distribution
```

MUTE v3

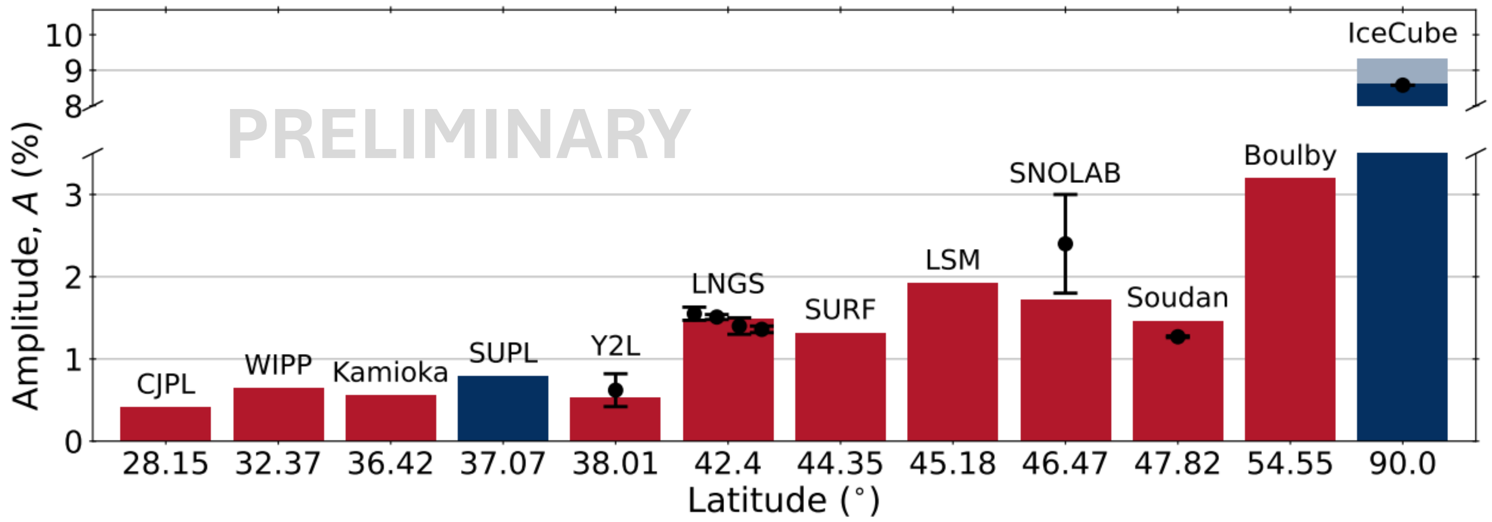
- MUTE v3.0.0 was released on 25 May 2025.
- This release included a number of new features and improvements:
  - Integration of **daemonflux** for surface muon fluxes into the computation chain.
  - Functions to compute **energy spectra**.
  - Functions to compute **angular distributions**.
  - Built-in **mountain maps** provided for DULs:
    - Y2L (COSINE-100)
    - Kamioka (Super-Kamiokande)
    - Kamioka (KamLAND)
    - LNGS (LVD)
    - LSM (Fréjus)
    - CJPL-I (JNE)
  - Detailed **propagation media** for individual labs.
  - More precise control over (latitude, longitude).
  - Better statistics (10^6) in default transfer tensors.
- Results published in [PRD 110 (2024) 6, 063006](PRD 110 (2024) 6, 063006).



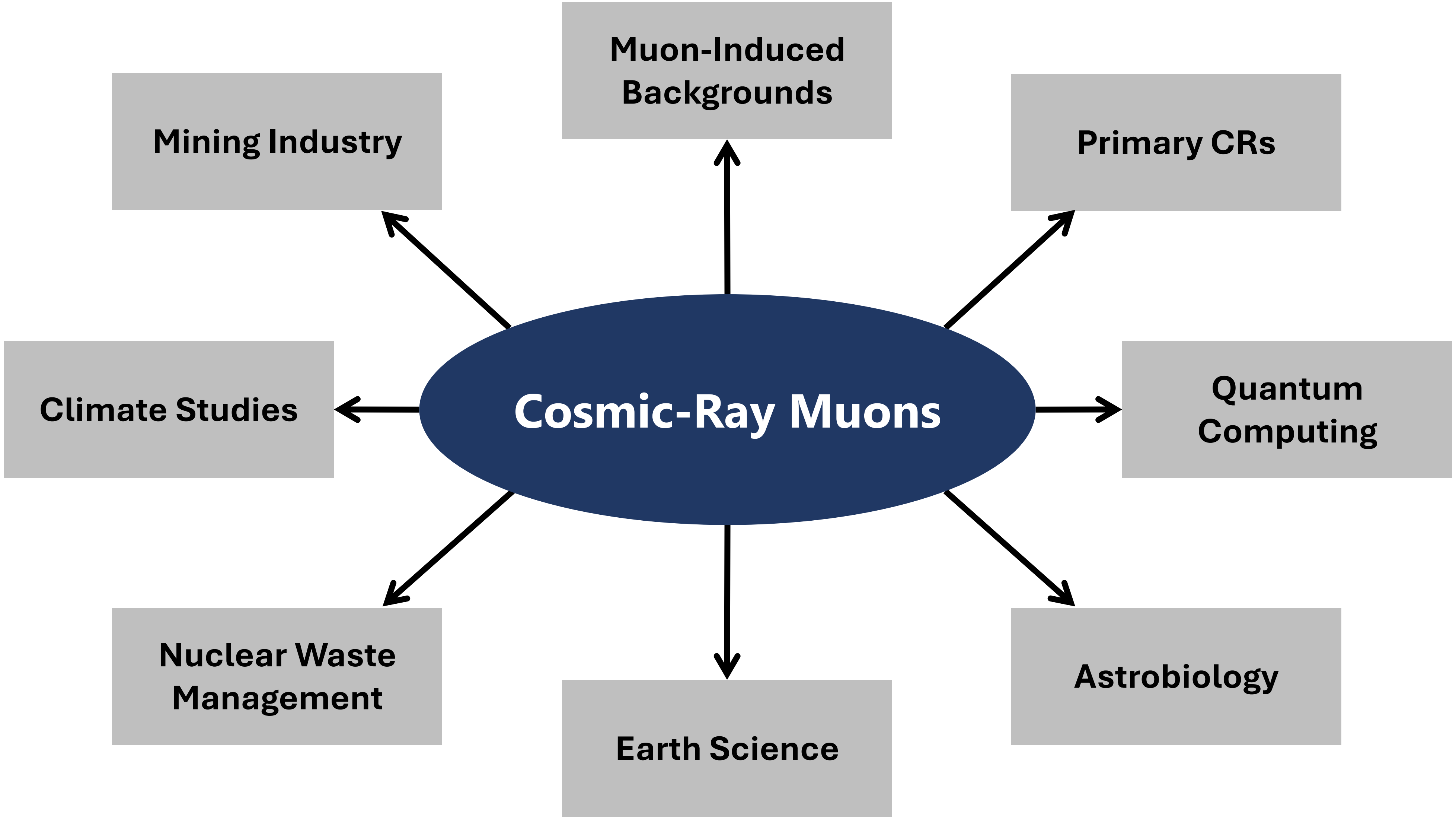
Seasonal Variations



- The muon flux varies over the seasons due to changes to the temperature and density of the atmosphere.
- Energy-dependence of the decay and interaction processes means the **sign of the amplitude of these variations inverts** from surface to underground.
- MUTE calculates these amplitudes to high precision for labs in the **northern** and **southern** hemispheres.
- It can provide predictions to new experiments, like SABRE.



Other Applications



Upcoming Releases

v3.0 → v3.1 → v3.2 → v4.0

- Future releases of MUTE are planned to accommodate these applications.
- New features planned:
    - Integration of latest primary crflux models (GSF) and hadronic interaction models (SIBYLL-2.3e, EPOS-LHC-R, QGSJET-III.01) though MCEq.
    - Propagation to shallow depths (< 0.5 km.w.e.).
    - Arbitrary medium definition for any rock composition.
    - Built-in mountain map generator.
    - More efficient calculations.
- Stay tuned!
- Please feel free to reach out if you are interested in applications of MUTE.

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Summary

- MUTE uses state-of-the-art models and codes to provide precise estimates of muon spectra underground.
- It can compute forward predictions for muon fluxes, intensities, energy spectra, and angular distributions for underground laboratories located at depths between 0.5 km.w.e. and 14.0 km.w.e.
- Results have been compared against data from various experiments and we find very good agreement in almost all cases. Full details are published in PRD 110 (2024) 6, 063006.
- MUTE v3 is available to be installed via pip with documentation on GitHub: https://github.com/wjwoodley/mute.
- Future releases of MUTE are being planned for various interdisciplinary applications, including updates to include the most recent CR and hadronic models.

Thank You