MUTE: A Modern Calculation for Deep Underground and Underwater Muons

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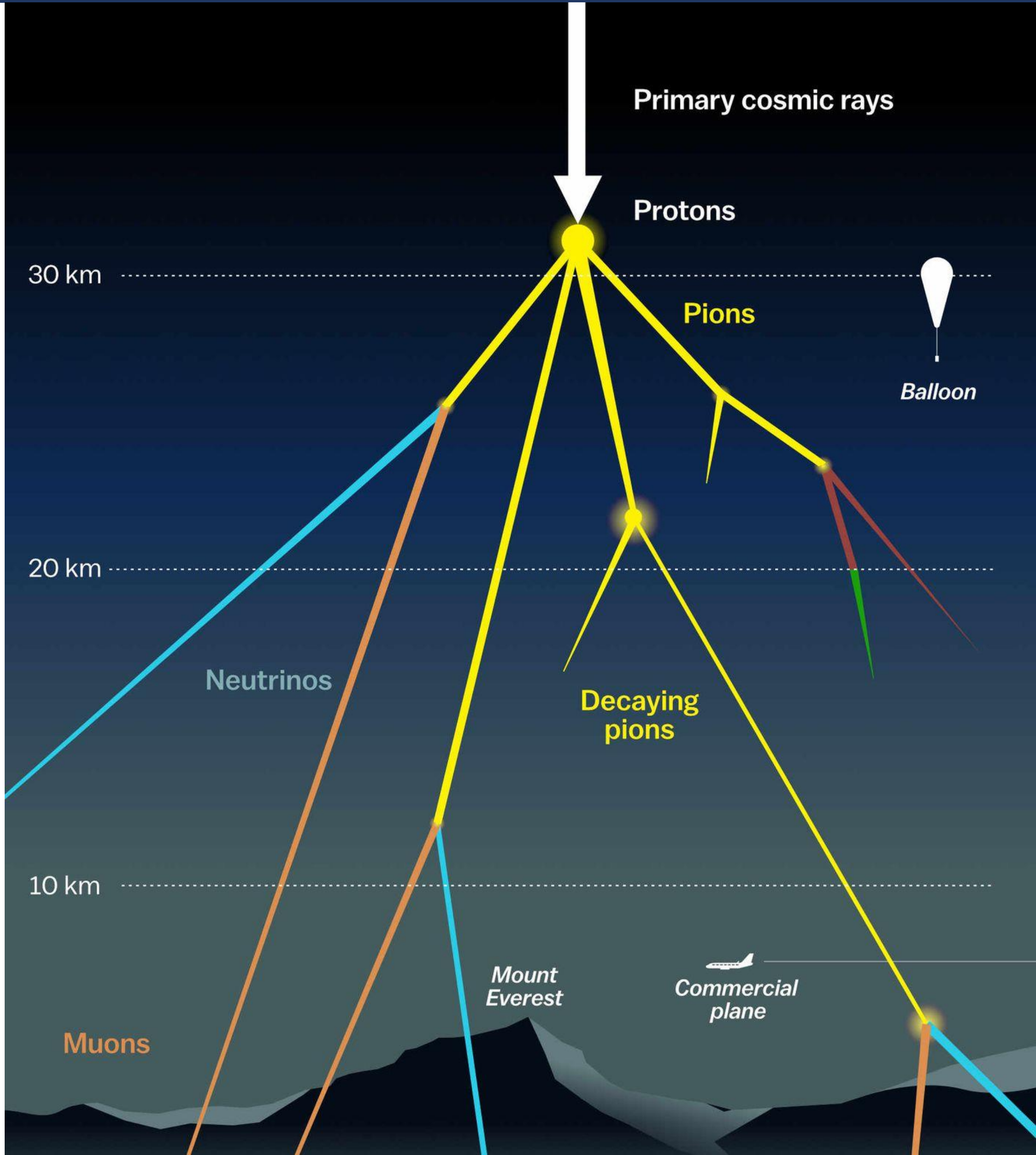
Introduction

- Underground and underwater muons are crucial in data analyses in neutrino telescopes and in the design of Dark Matter detectors.
- Mei & Hime [1] and Crouch [2] use Depth-Intensity Relations (DIRs), which may contain bias induced by systematics.
- Theoretical calculations of Bugaev [3] lack rigorous treatment of uncertainties.
- **MUTE** (**MU**on in**T**ensity cod**E**) is a new computational tool written in Python that calculates muon fluxes underground.



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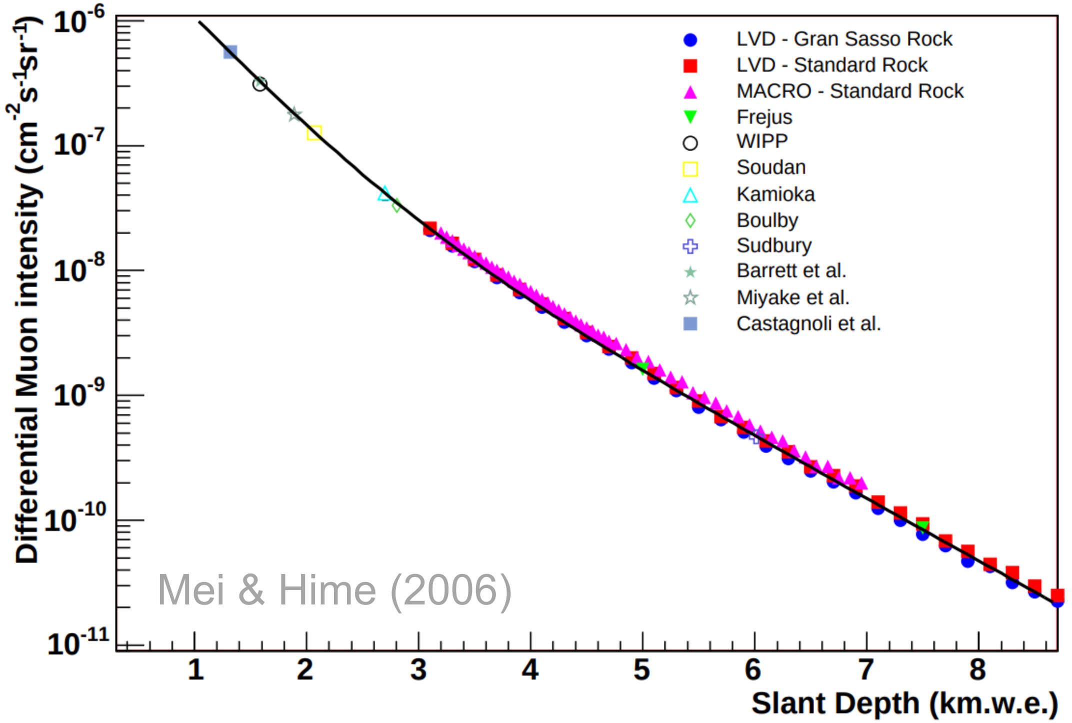
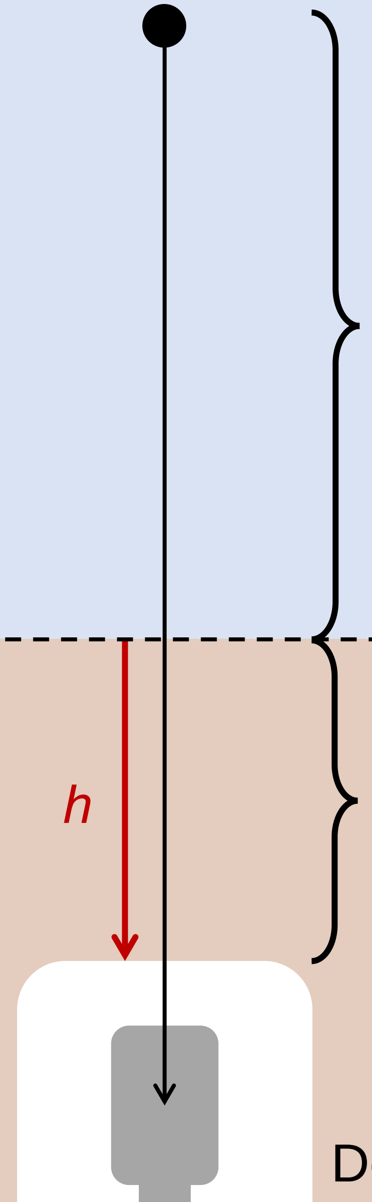
$$I(h) = I_1 e^{(-h/\lambda_1)} + I_2 e^{(-h/\lambda_2)}$$



Method Overview



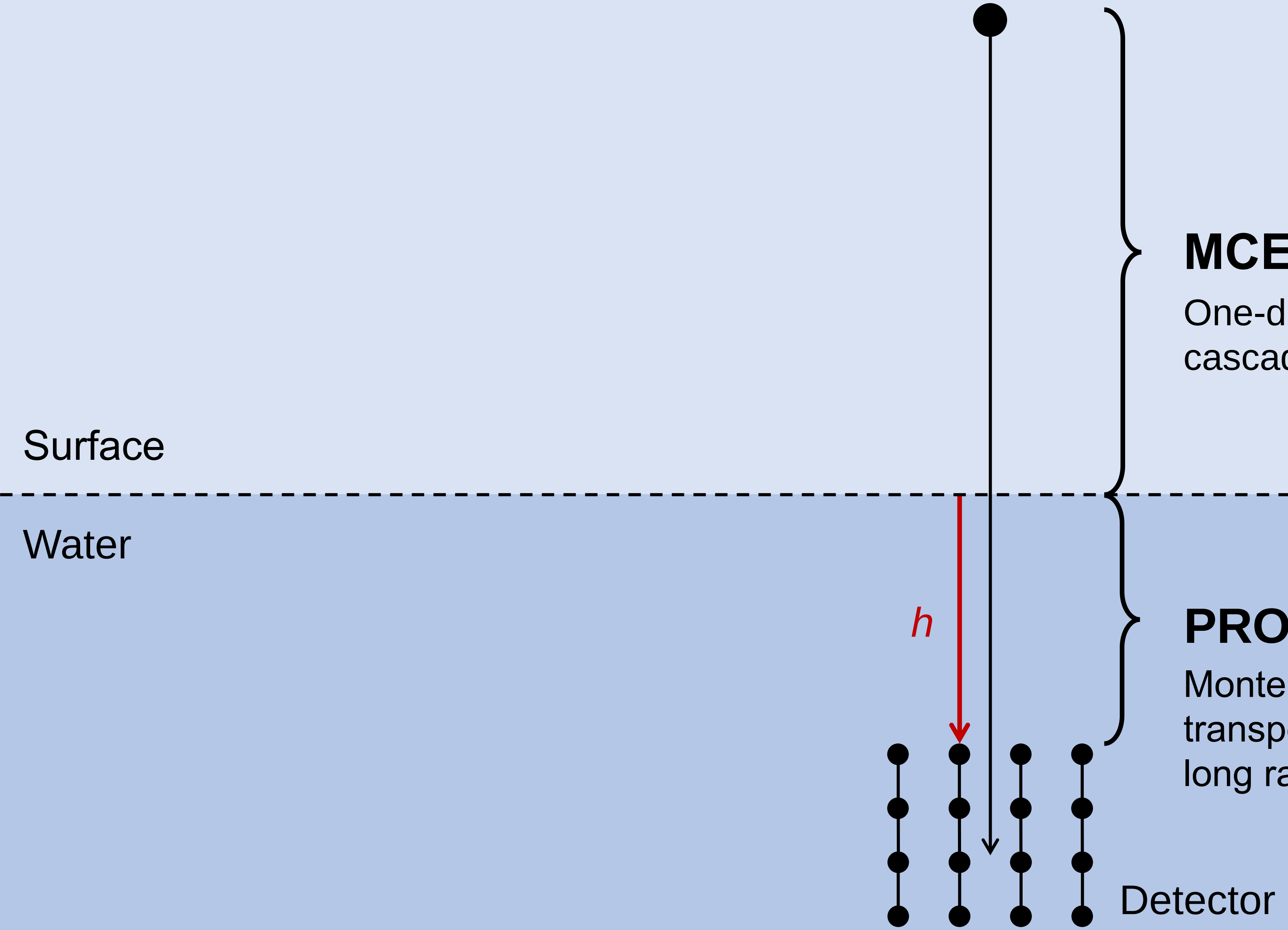
MCEq [4]

One-dimensional fast cascade equation solver.

PROPOSAL [5]

Monte Carlo code that transports leptons through long ranges of matter quickly.

Method Overview



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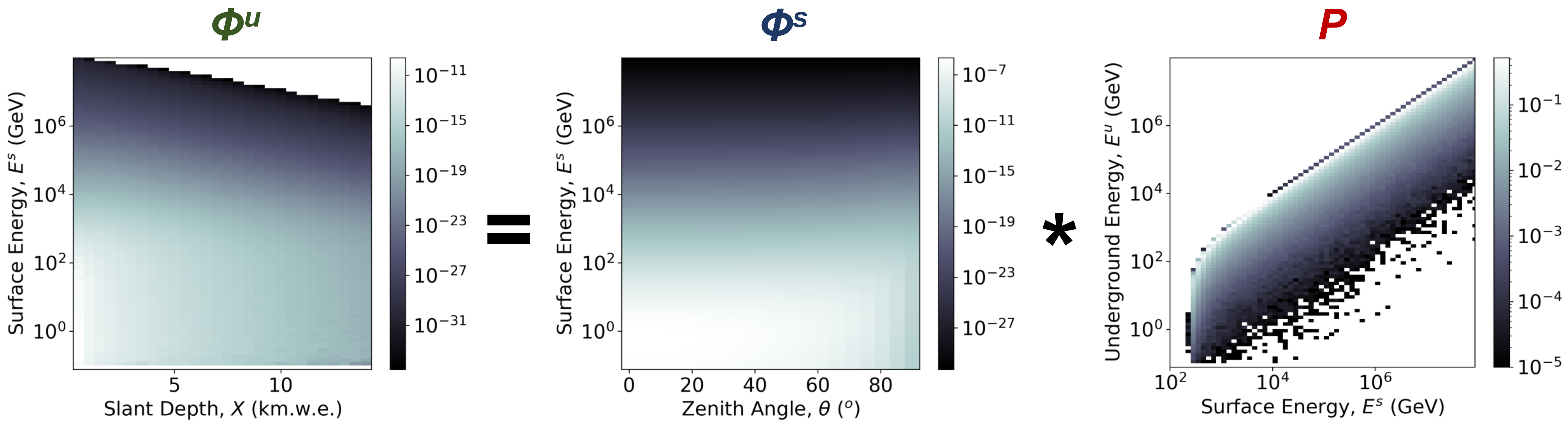
Calculations

- A convolution is performed to calculate underground fluxes:

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

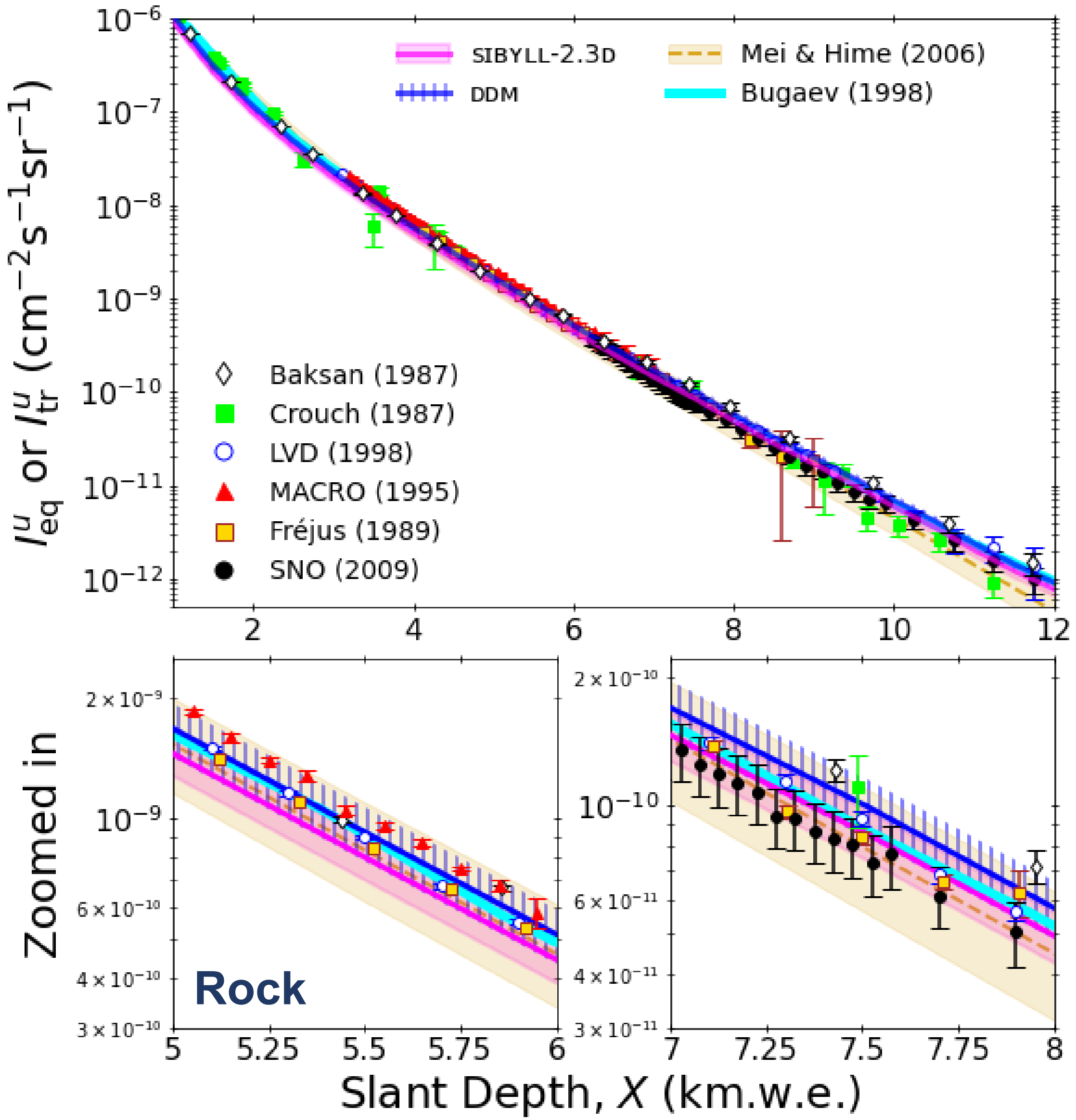


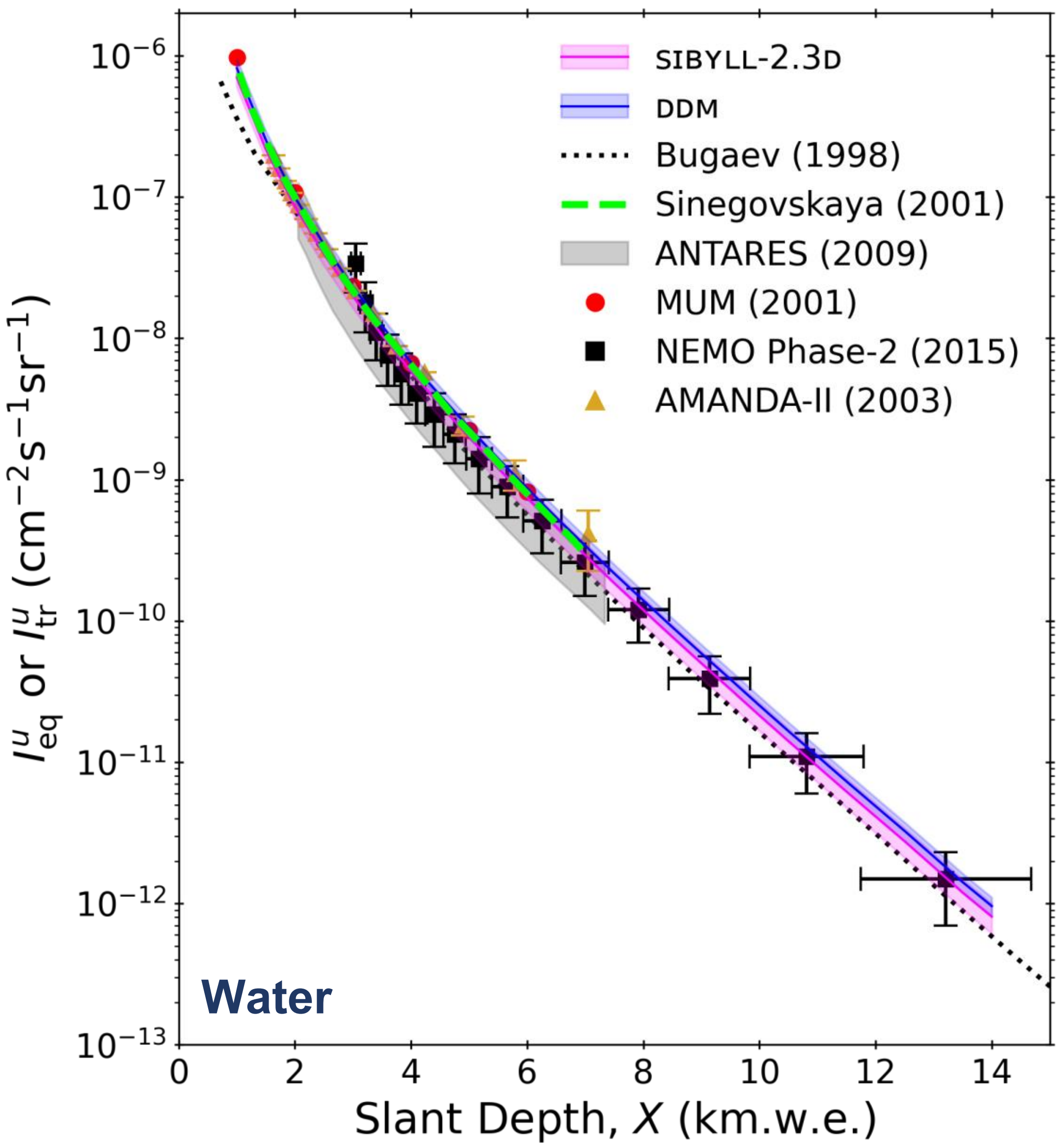
MUTE
Underground Fluxes

MCEq
Surface Fluxes

PROPOSAL
Transfer Tensor

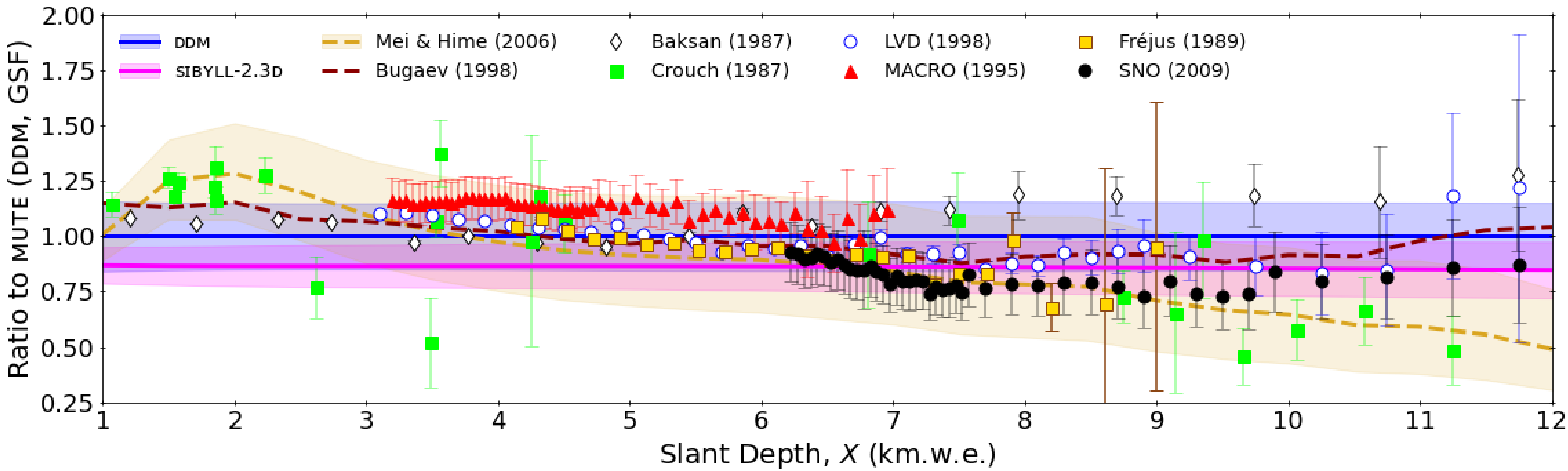
Results – Vertical Underground Intensity





Comparison to Data

- DDM is better at shallow depths, and SIBYLL is better at deep depths.
- Uncertainties on data are smaller than those on theory.
- ⇒ Theoretical uncertainties on neutrino fluxes may be able to be constrained from 40% down to ~10%.

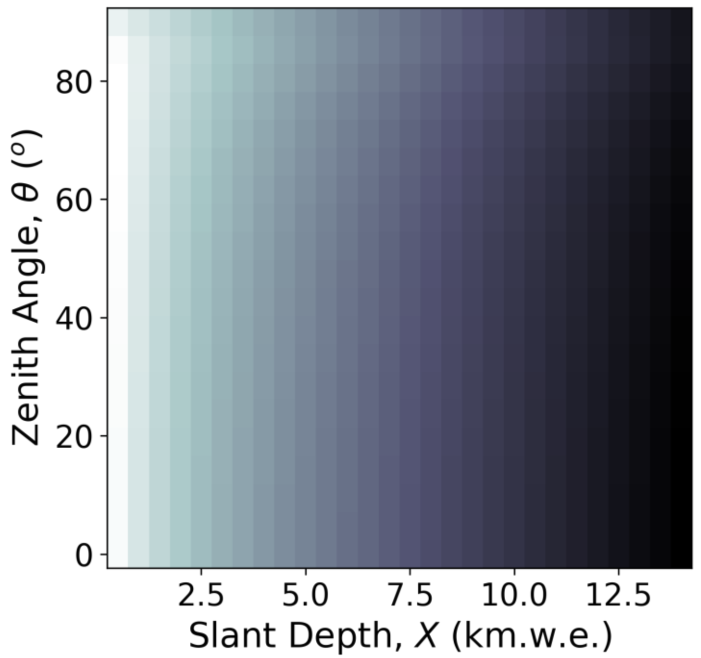


Labs under Mountains

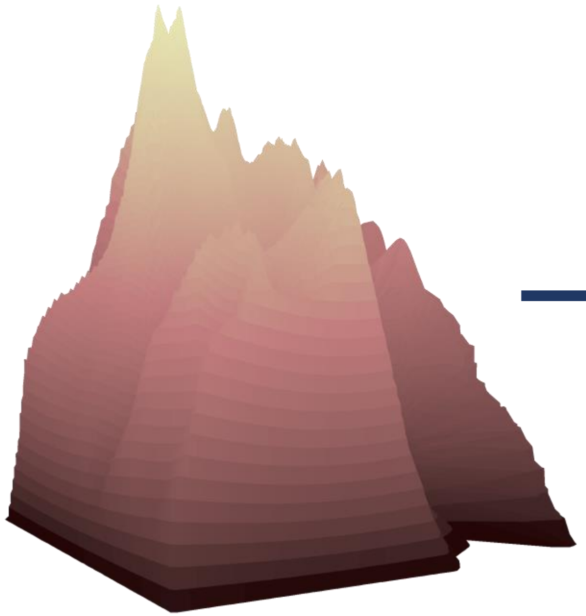
- Underground intensities for mountains are first calculated on a grid of constant zenith angles and slant depths.

- Using a map of the mountain profile, these intensities are then interpolated to the slant depths $X(\theta,\ \phi)$ that define the mountain.

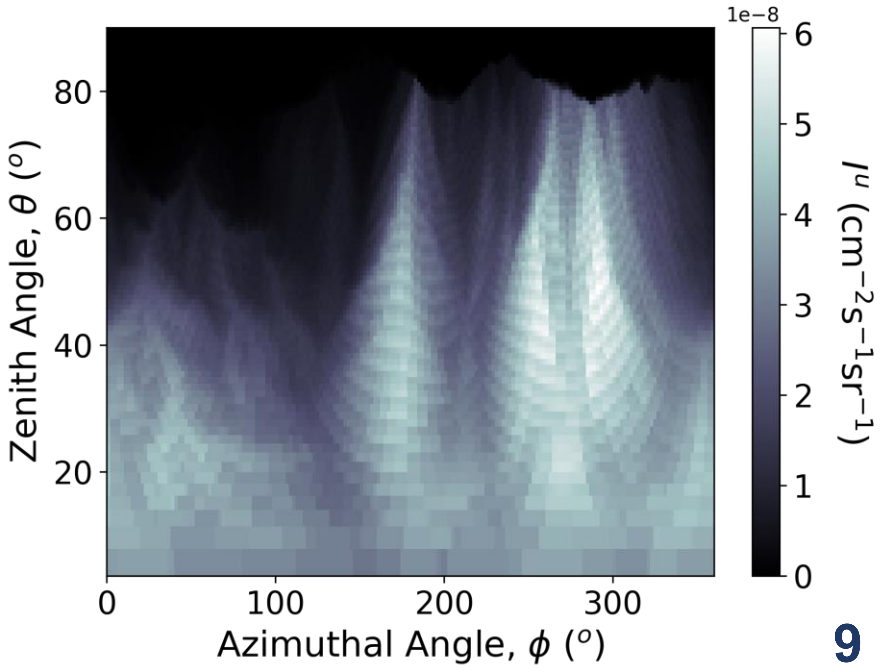
$I^u(\theta, X)$



$X(\theta, \phi)$

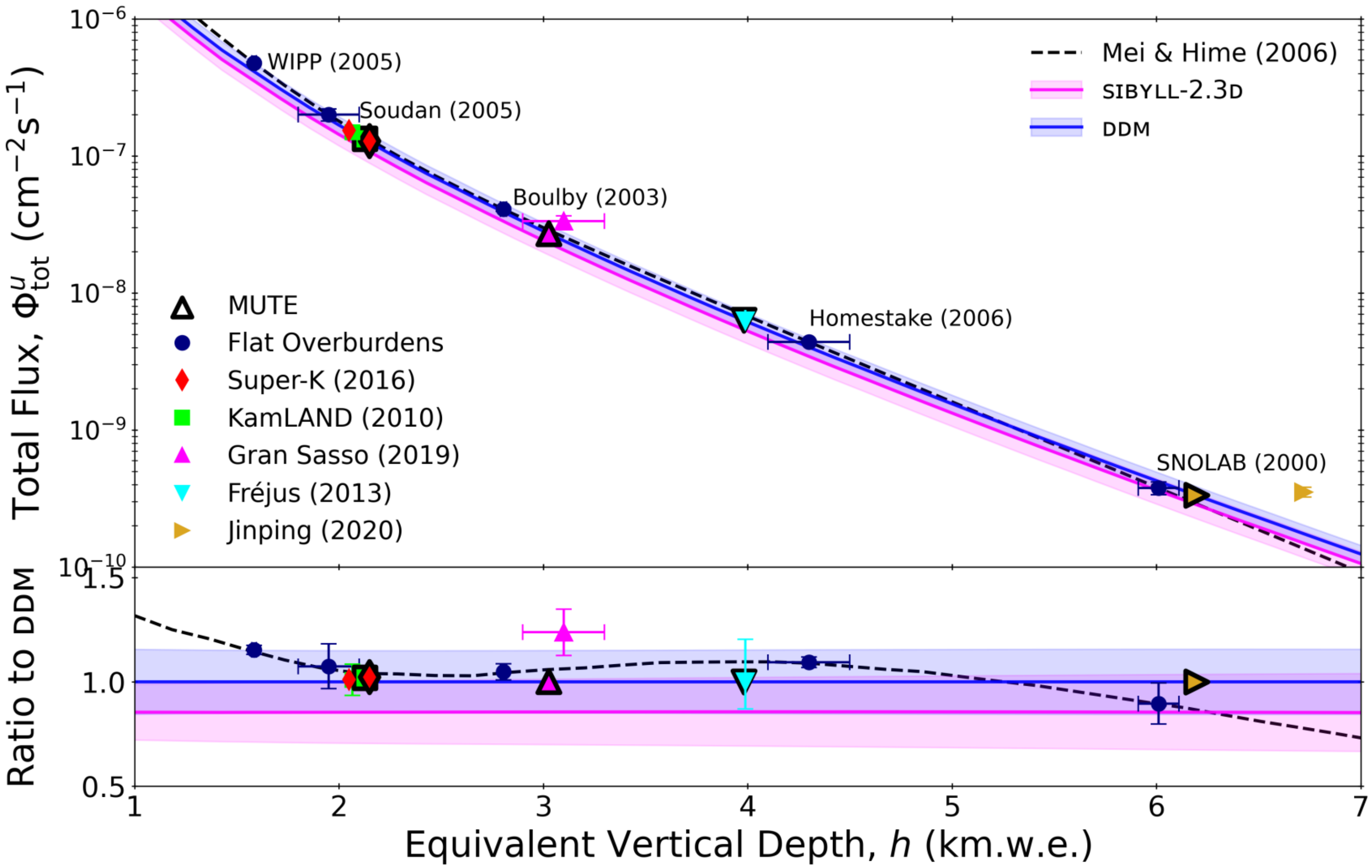


$I^u(\theta, \phi)$



Results – Total Underground Flux

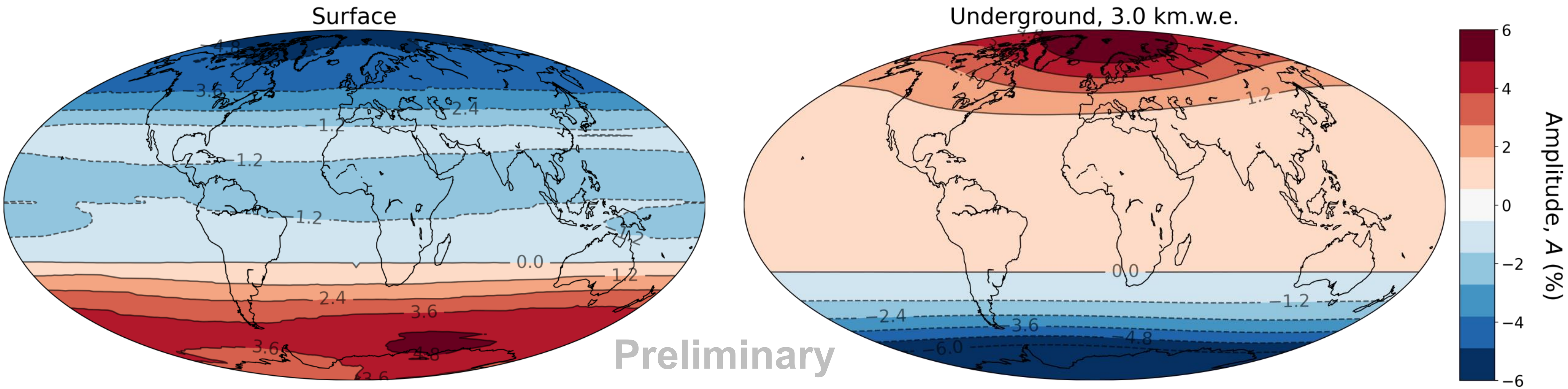
- Our calculation reproduces total underground flux measurements excellently.



Results – Seasonal Variations

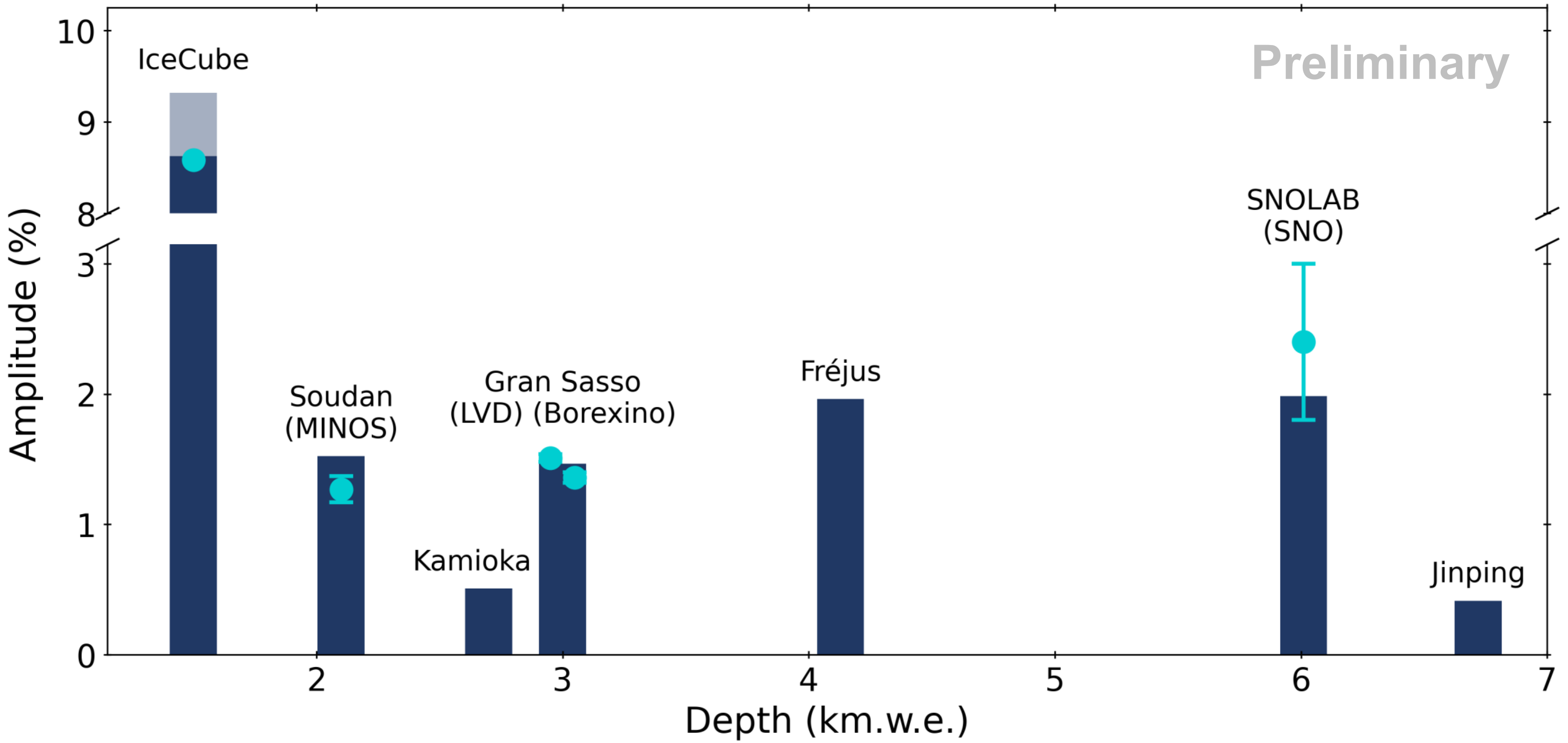
- In the summer, the atmosphere is taller, meaning muons travel longer distances and decay more often ⇒ the muon flux is **lower** at the surface in summer.

- However, there are also more higher-energy muons in the summer, which reach deeper underground ⇒ the muon flux is **higher** underground in summer.



Results – Seasonal Variations

- MUTE can calculate seasonal variation amplitudes to very high precision.



MUTE

- MUTE can be installed via pip (`pip install mute`). Computational scheme and detailed documentation are given in our recent paper [6] and on the GitHub page:

doi:10.3847/1538-4357/ac5027

https://github.com/wjwoodley/mute

- **Flexible:**
  - Flat or mountain
  - Location on Earth
  - Month
  - Medium (Standard Rock)
  - Density of medium (2.65 gcm^{-3})
  - Energy threshold
  - Primary model (GSF)
  - Interaction model (DDM)
  - Level of statistics

- **Fast:**
  - MUTE comes with pre-calculated transfer tensors at installation.
  - Calculations take seconds to complete.

Applications

- MUTE can give full definitions of muon spectra:
  - Energy spectra
  - Angular spectra
  - Total muon rate

- Results from MUTE can be used as input into general particle transport codes like Geant4 and FLUKA to study muon-induced backgrounds in underground and underwater detectors.

- This can be used by Dark Matter and neutrino experiments to design effective shielding strategies for muon-induced neutrons.

Conclusion

- By combining MCEq and PROPOSAL, MUTE can calculate **forward predictions** for underground muon fluxes and intensities.
- The program is flexible, fast, and precise, and the results match experimental data very well.
- Uncertainties on data are smaller than those on theory. **New constraints** on cosmic ray fluxes and hadronic models can be obtained by leveraging measurements of the vertical and total fluxes from underground and underwater facilities.
- MUTE is public and available to be used by Dark Matter and neutrino experiments in labs under flat overburdens and mountains.

Thank you

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