MUTE: A Modern Calculation for Deep Underground and Underwater Muons

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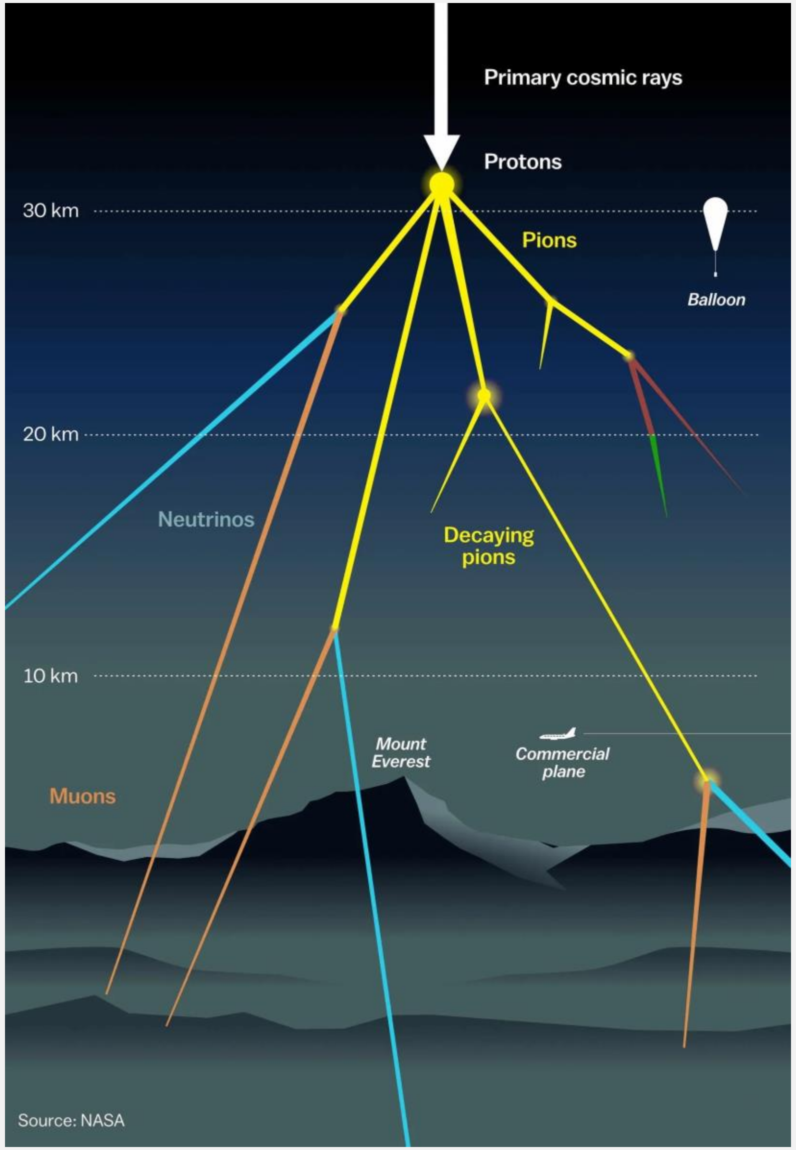
INTRODUCTION

- Underground and underwater muons are crucial in data analyses in neutrino telescopes and in the design of Dark Matter detectors.
- However, flux uncertainties have not been studied in high detail.
- **MUTE** (**MU**on in**T**ensity cod**E**) is a new computational tool written in Python that calculates atmospheric muon fluxes underground.
- It uses **MCEq** to calculate surface fluxes and **PROPOSAL** to simulate muon propagation through rock and water.

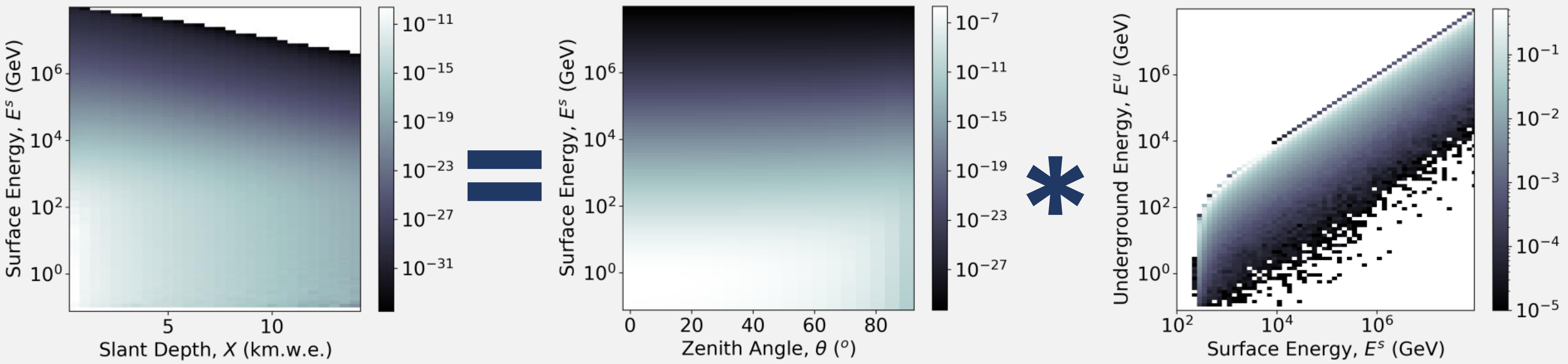


METHOD

- MCEq returns a surface flux matrix, and PROPOSAL returns a surface-to-underground transfer tensor.

- Underground fluxes are calculated by the following convolution:

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



Underground Fluxes **Surface Fluxes** **Transfer Tensor**

METHOD

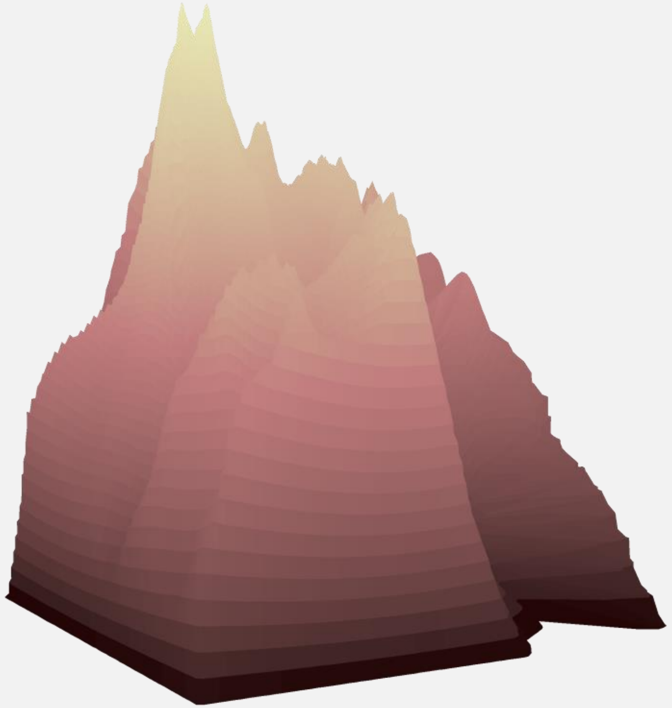
- The underground intensity is calculated by:

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

- MUTE can calculate intensities for both flat and non-flat overburdens.

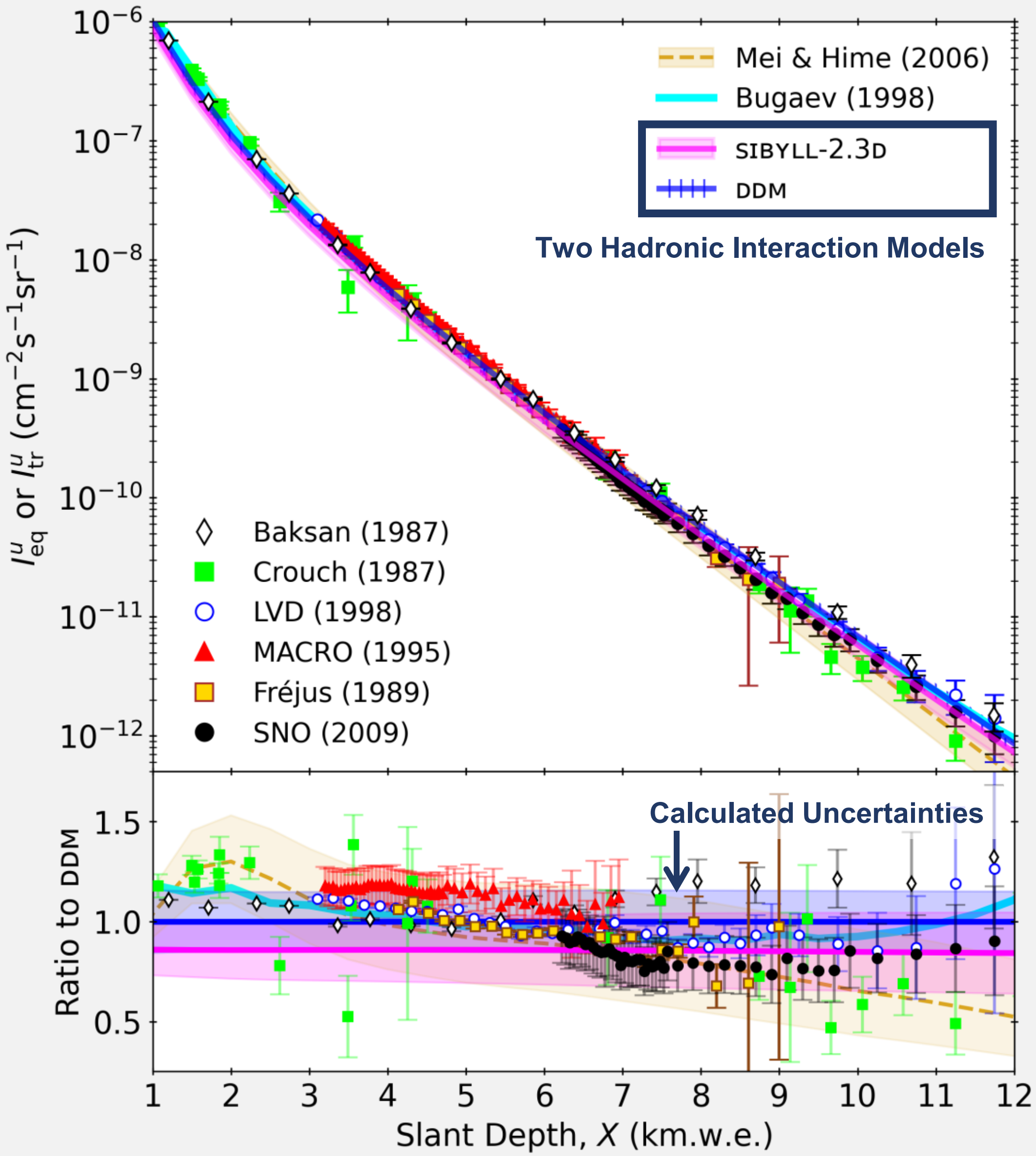
- For labs under mountains, a grid of intensity values is calculated, and is then interpolated to the mountain profile read in from a geometry file.

$$\Phi^u_{\mathrm{tot}} = \iint_{\Omega} I^u(X(\theta,\phi),\theta)\,\mathrm{d}\Omega$$



RESULTS

- MUTE gives excellent agreement with vertical underground intensity data over the entire depth range.
- For both rock and water, DDM is better at describing lower slant depths, and SIBYLL-2.3D is better at higher slant depths, as expected.
- Calculated uncertainties on models are smaller than those on data, suggesting neutrino flux uncertainties could be significantly reduced from 40% to ~10%.



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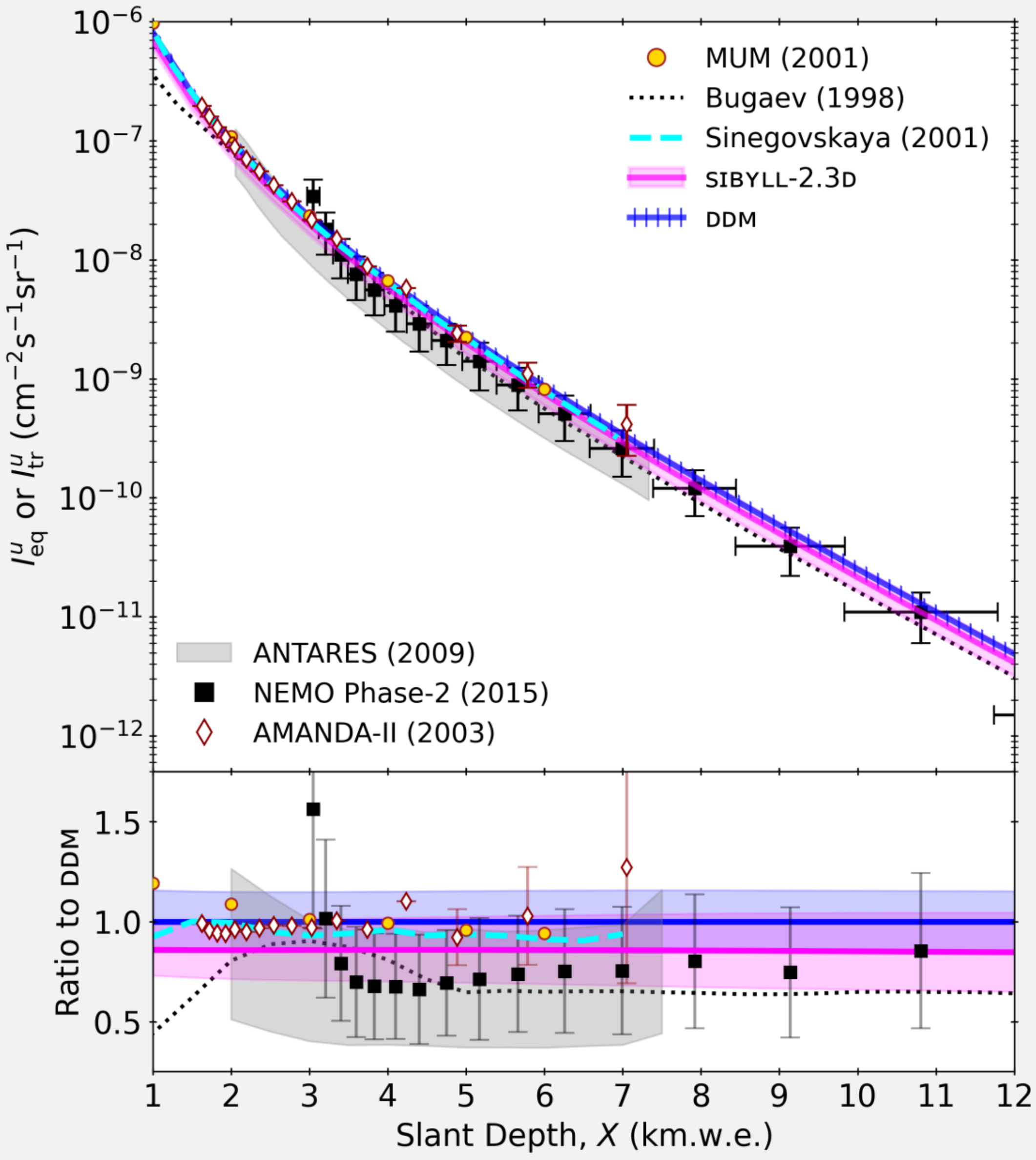
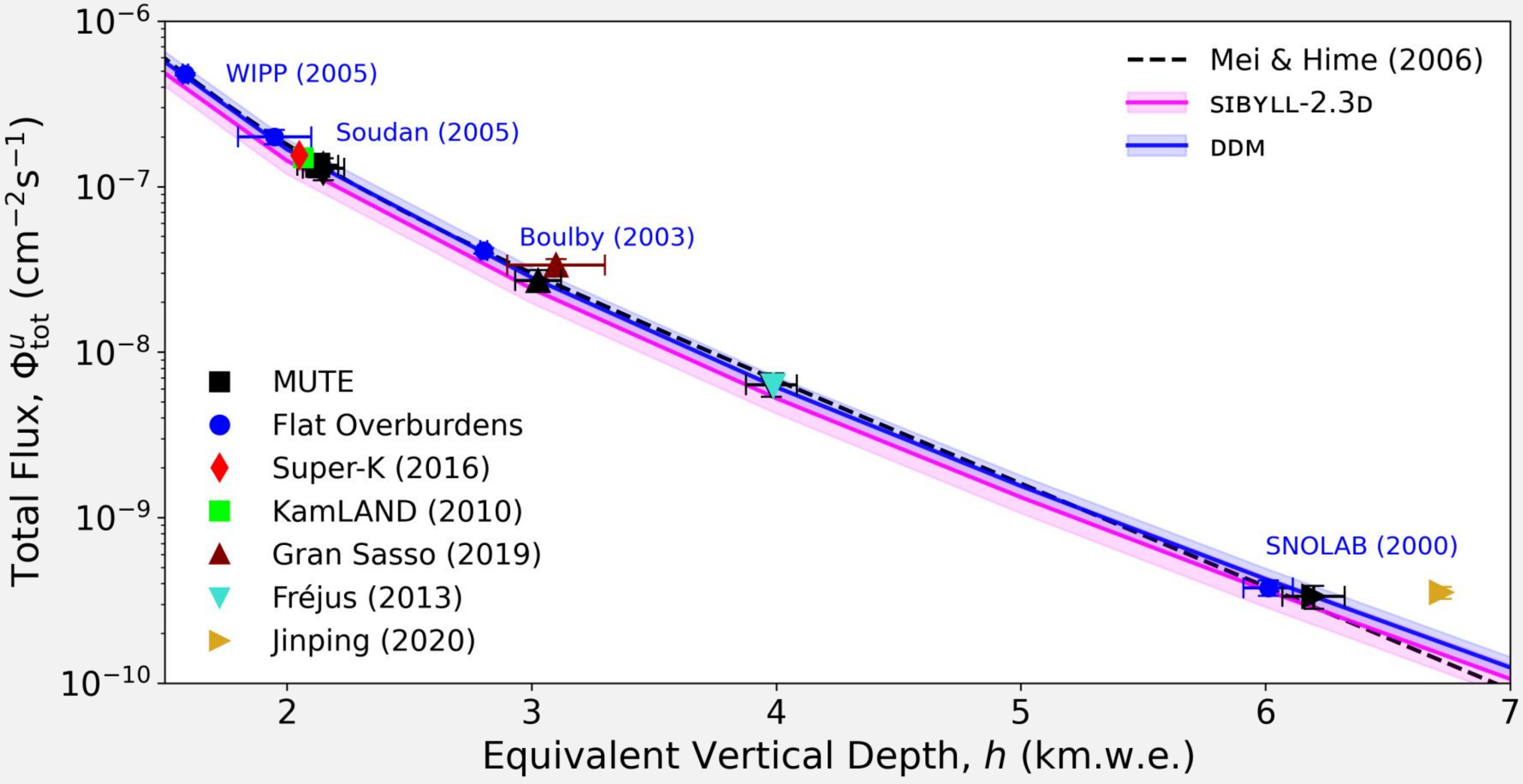


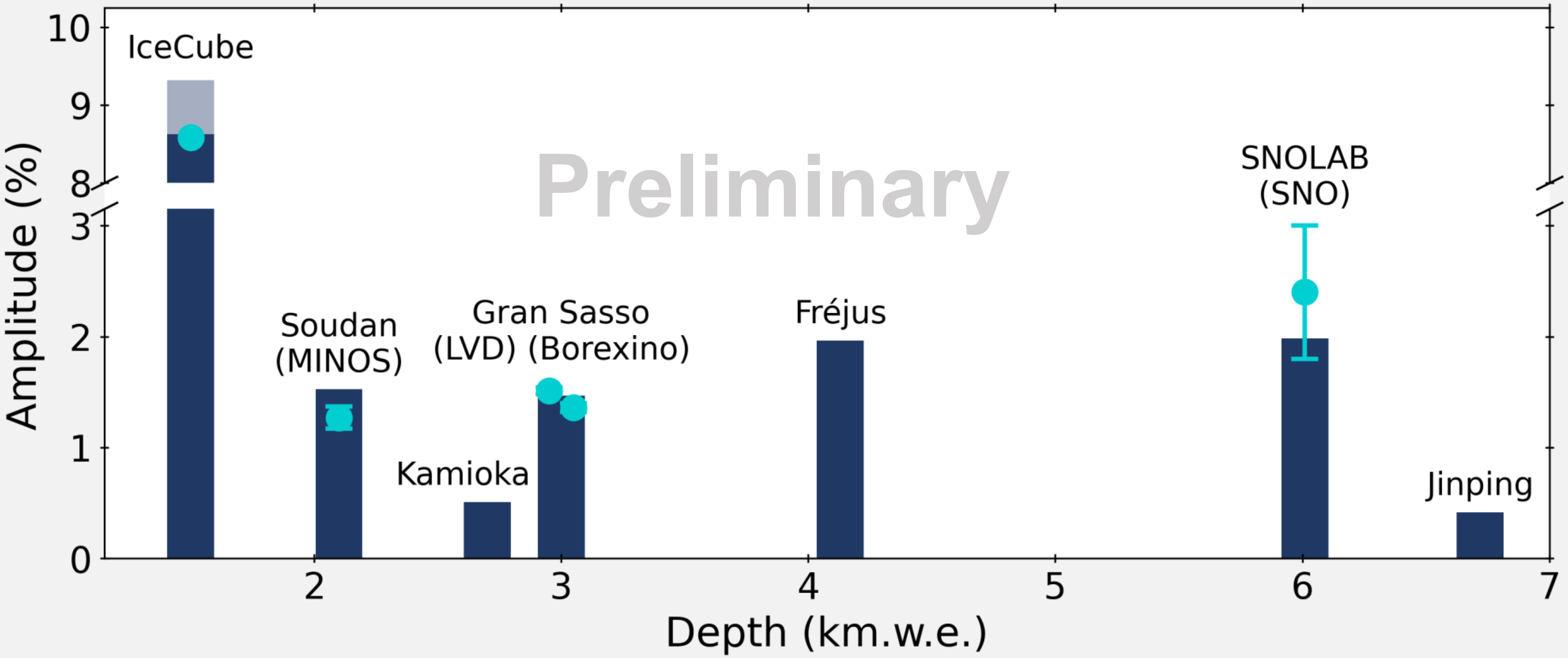
NEW DEVELOPMENTS

- Total flux calculations are consistent with measurements for flat overburdens and under mountains within theoretical errors.



NEW DEVELOPMENTS

- Seasonal variations in the underground muon flux can also be calculated to high precision.



CONCLUSION

- MUTE can calculate **forward predictions** for underground muon fluxes and intensities to very high precision.

- Uncertainties on data are smaller than those on theory.

- **New constraints** on CR fluxes and hadronic models can be obtained by leveraging measurements of the vertical and total fluxes from underground and underwater facilities.

- MUTE can be installed via pip (`pip install mute`). Full installation instructions are given on the GitHub page: **https://github.com/wjwoodley/mute**.