MUTE: A Modern Calculation for Deep Underground and Underwater Muons

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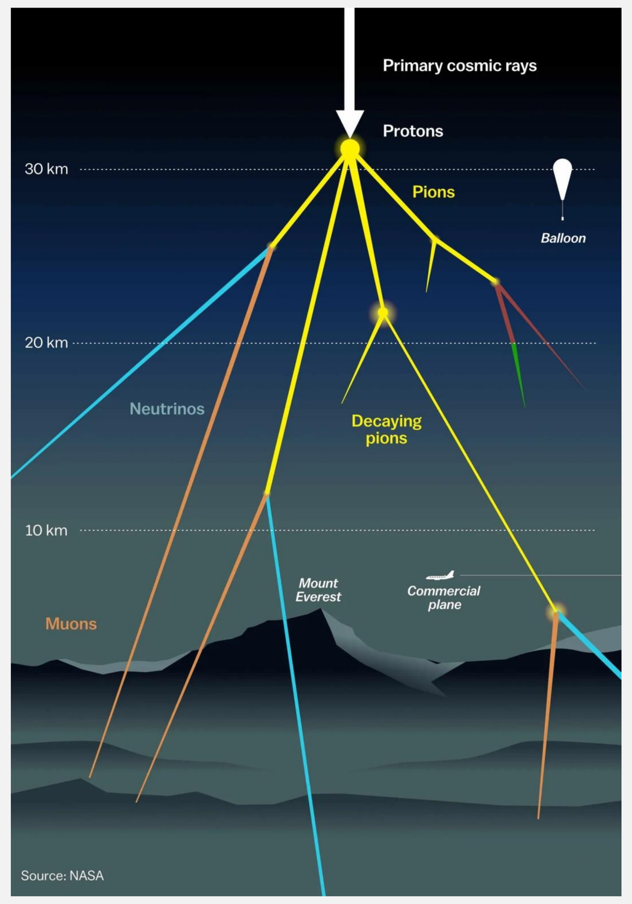
INTRODUCTION

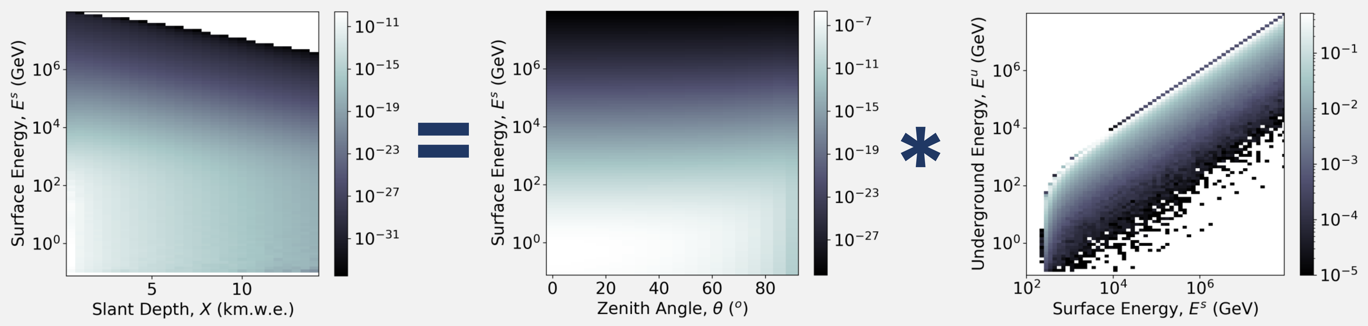
- Underground and underwater muons are crucial in data analyses in neutrino telescopes and in the design of Dark Matter detectors.
- However, flux uncertainties have not been studied in high detail.
- **MUTE** [1] is a new computational tool that calculates atmospheric muon fluxes underground.
- It uses **MCEq** [2] to calculate surface fluxes and **PROPOSAL** [3] 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:

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



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

- The underground intensity is calculated by:

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

- 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.

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

Vertical-Equivalent Intensity

$$I_{\mathrm{eq}}^{u}(X) = I^{u}(X, \theta)\cos(\theta)$$

- Used by experiments and fitting methods like Crouch [4] and Mei & Hime [5].
- Only approximate, introduces errors >20°.

True Vertical Intensity

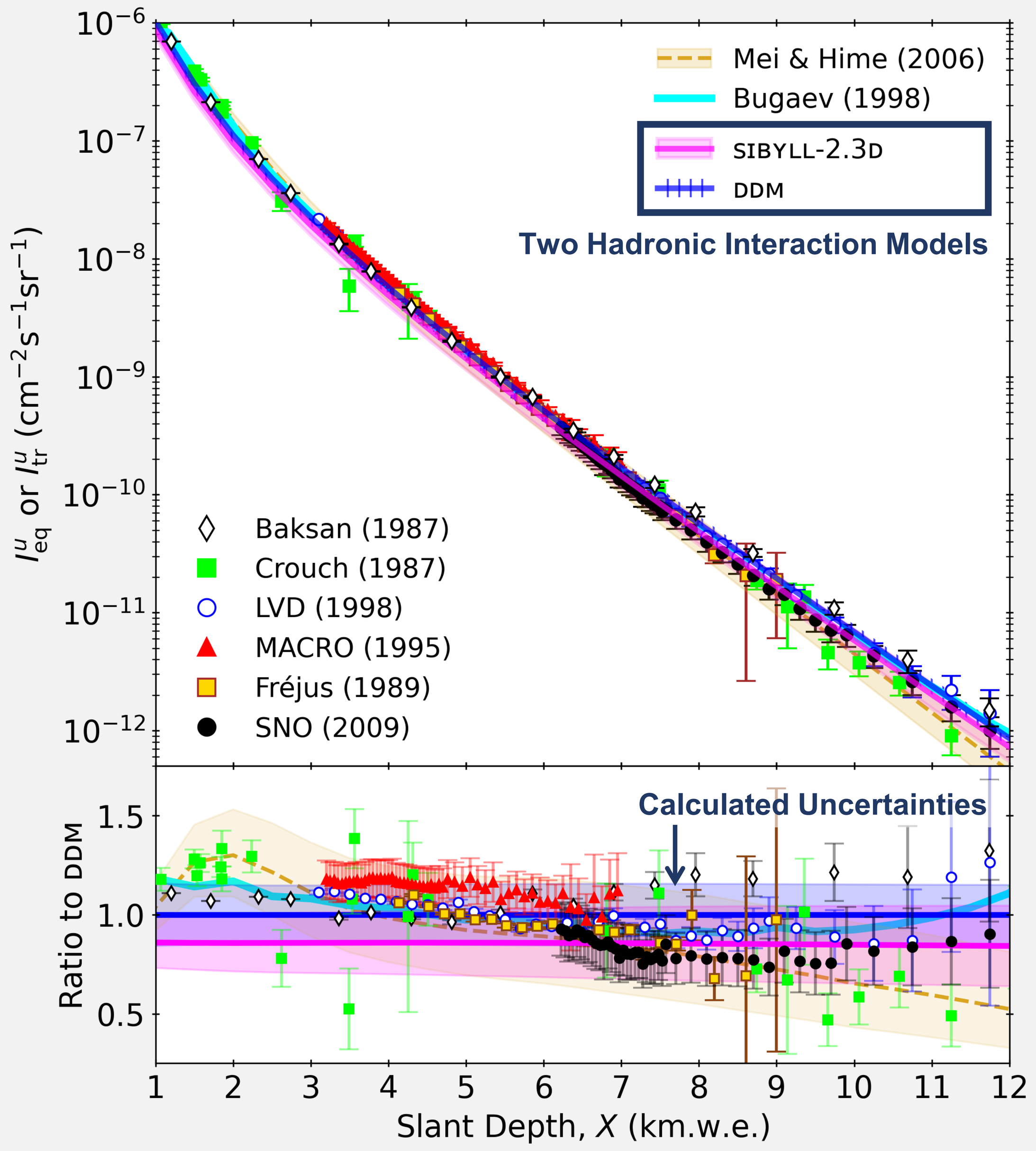
$$I_{\mathrm{tr}}^{u}(X) = I^{u}(X, \theta = 0)$$

- Used by MUTE and theoretical calculation by Bugaev, et al. [6].
- Defined exactly, so contains no additional error.

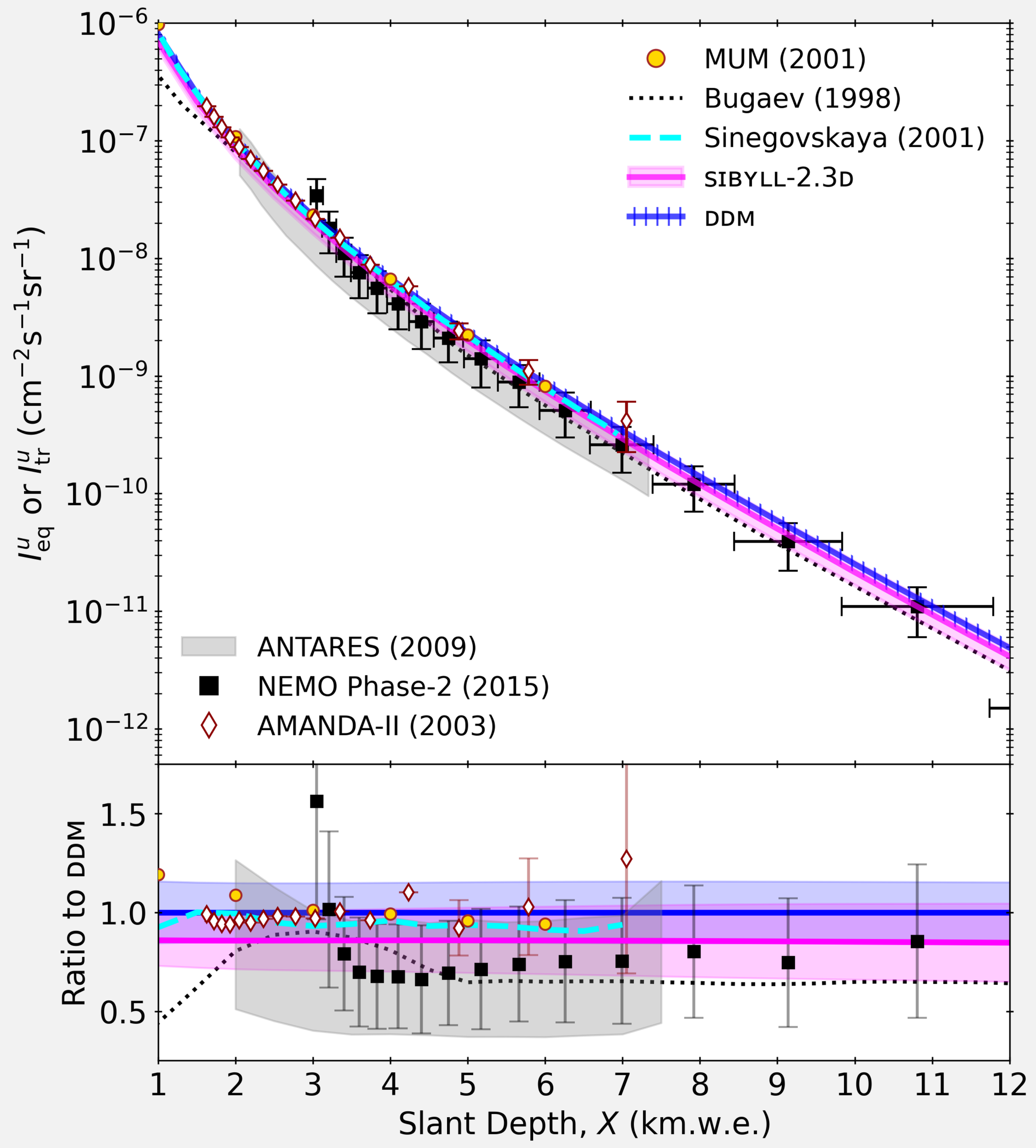
RESULTS

- MUTE gives excellent agreement with vertical underground intensity data over the entire depth range.
- For both rock and water, DDM [7] is better at describing lower slant depths, and SIBYLL-2.3D [4] 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 around 10%.

Rock



Water



OPEN-SOURCE PYTHON CODE

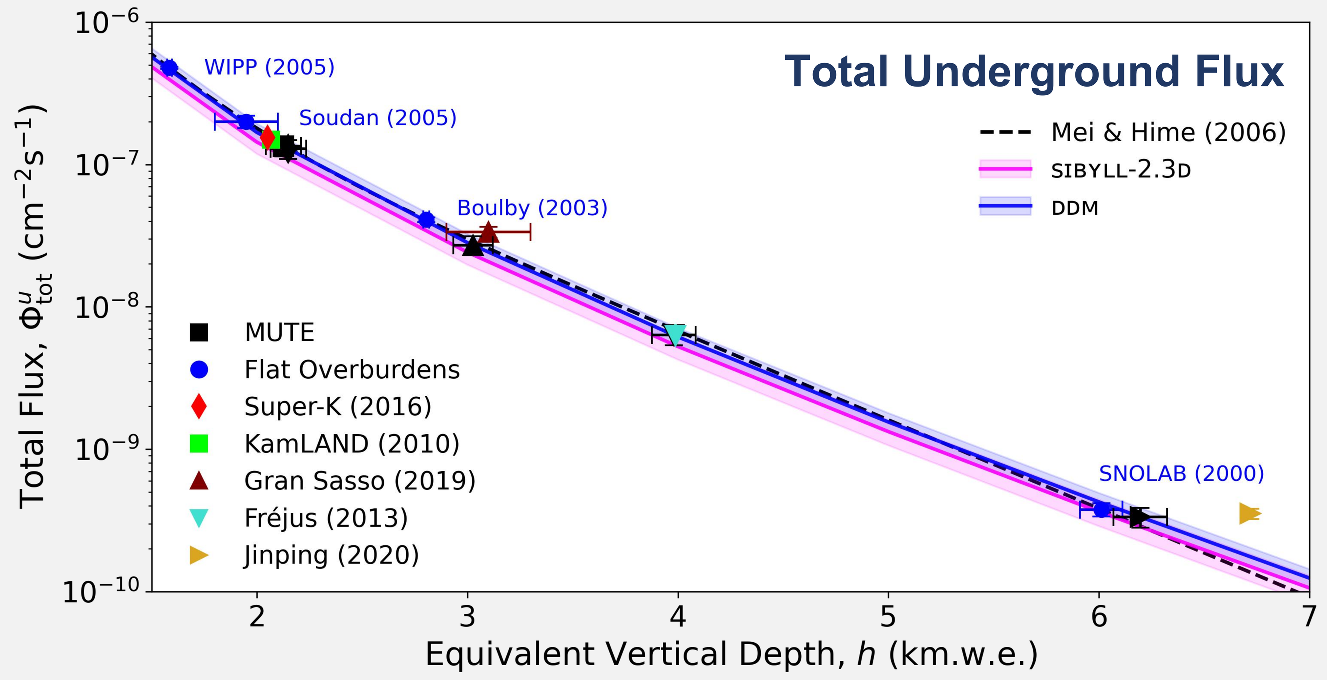
MUTE can be installed via pip:

```
$ pip install mute
```

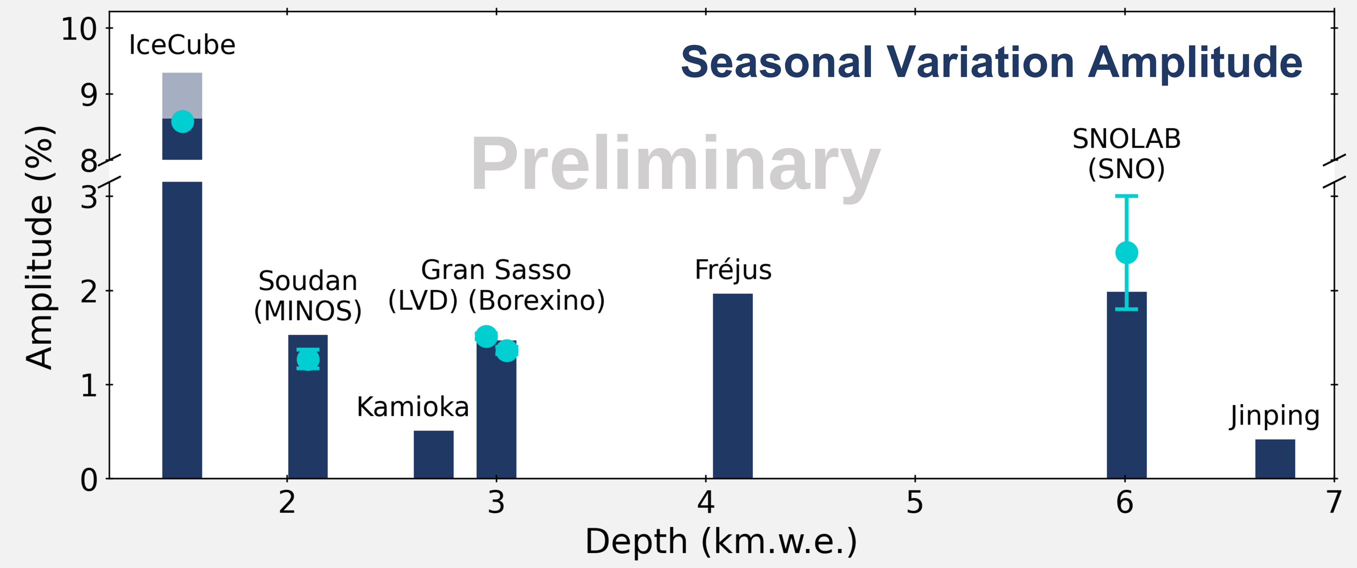
PROPOSAL will need to be installed in order to generate custom transfer tensors. Full installation instructions given on the GitHub page: **https://github.com/wjwoodley/mute**.

NEW DEVELOPMENTS

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



- 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.

REFERENCES

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Acknowledgements

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