Challenges and Opportunities for Predicting Muons in Underground and Underwater Labs Using MUTE

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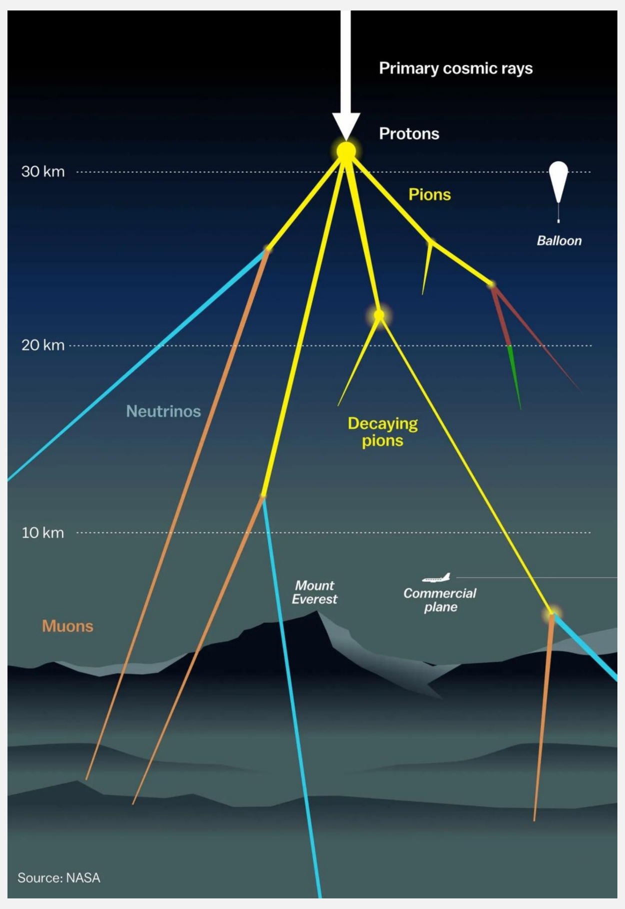
INTRODUCTION

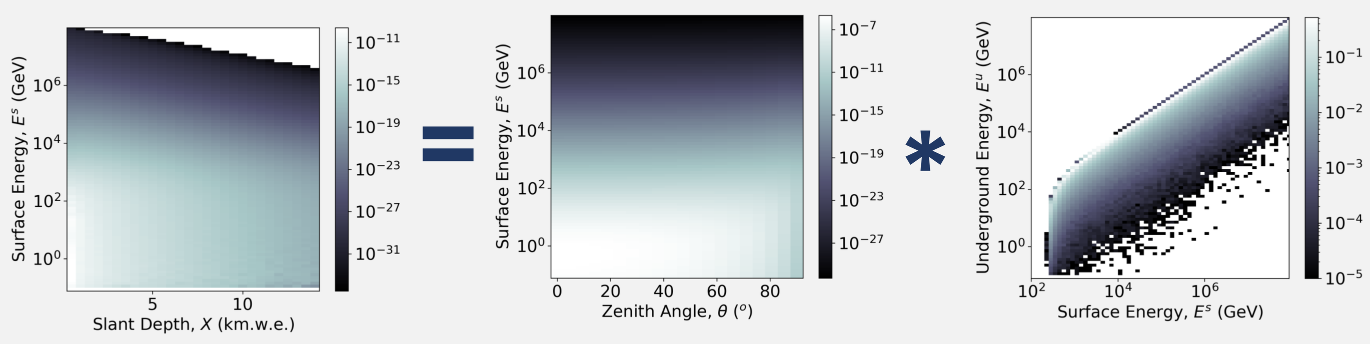
- Underground and underwater muons are crucial for data analyses in neutrino telescopes and in the design of Dark Matter detectors.
- MUTE [1] is a computational tool released in 2021 that calculates atmospheric muon fluxes.
- We now introduce MUTE v2 [2], which computes muon fluxes for labs under mountains.
- Our study employs the surface flux model DAEMONFLUX [3], which combines DDM [4] and Global Spline Fit [5].
- DAEMONFLUX is calibrated to muon flux and ratio data and gives muon and neutrino flux uncertainties of <10% up to 1 TeV.



METHOD

- DAEMONFLUX returns a surface flux matrix, and PROPOSAL [6] returns a surface-to-underground transfer tensor.
- Underground fluxes are calculated by the following convolution:

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



- The underground intensity is calculated by:

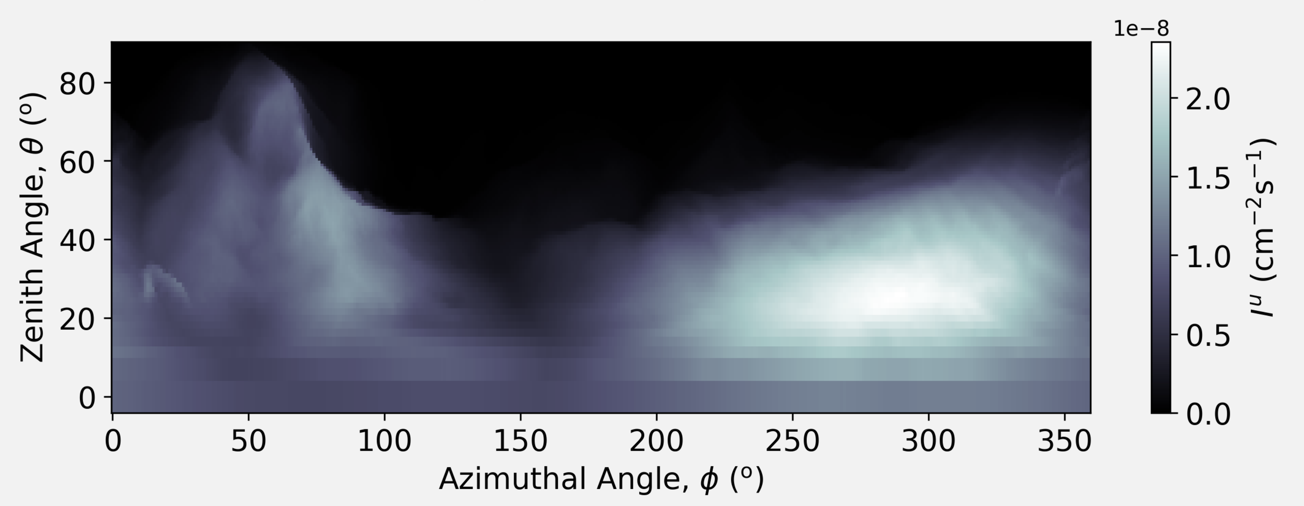
$$I^u(X, \theta) = \int_{E_{\rm th}}^{\infty} \Phi^u(E^u, X, \theta) \mathrm{d}E^u$$

- 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.

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

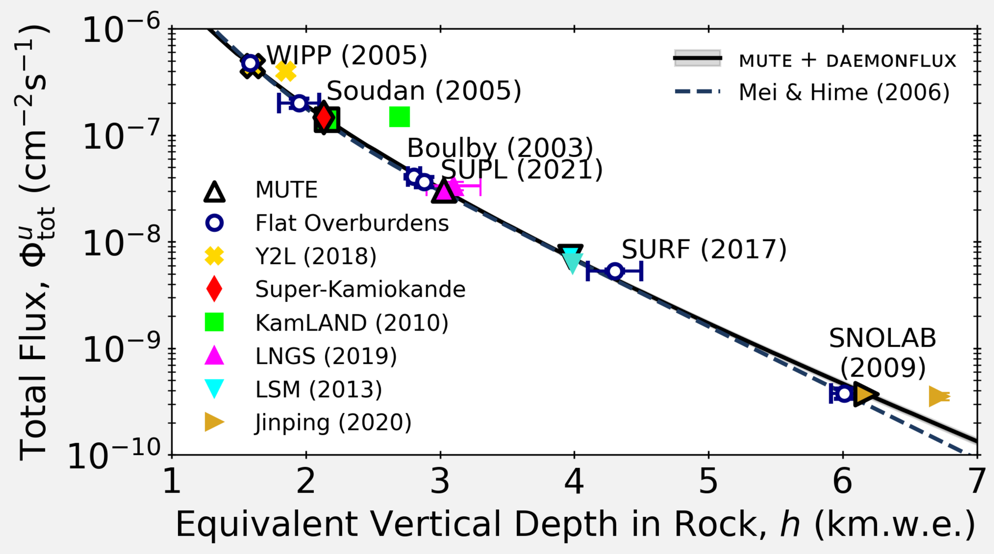
Gran Sasso Mountain

- The result is a matrix of underground intensities as a function of zenith and azimuthal angle:



TOTAL FLUX

- The total muon flux is the main observable of interest for muon-induced backgrounds and has been calculated for labs underground and underwater with DDM and DAEMONFLUX.

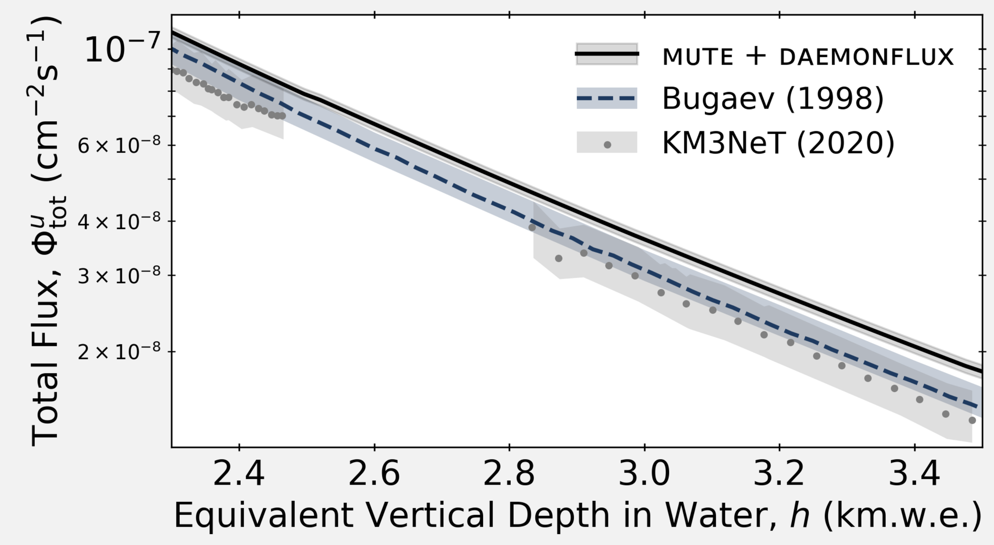


Standard Rock

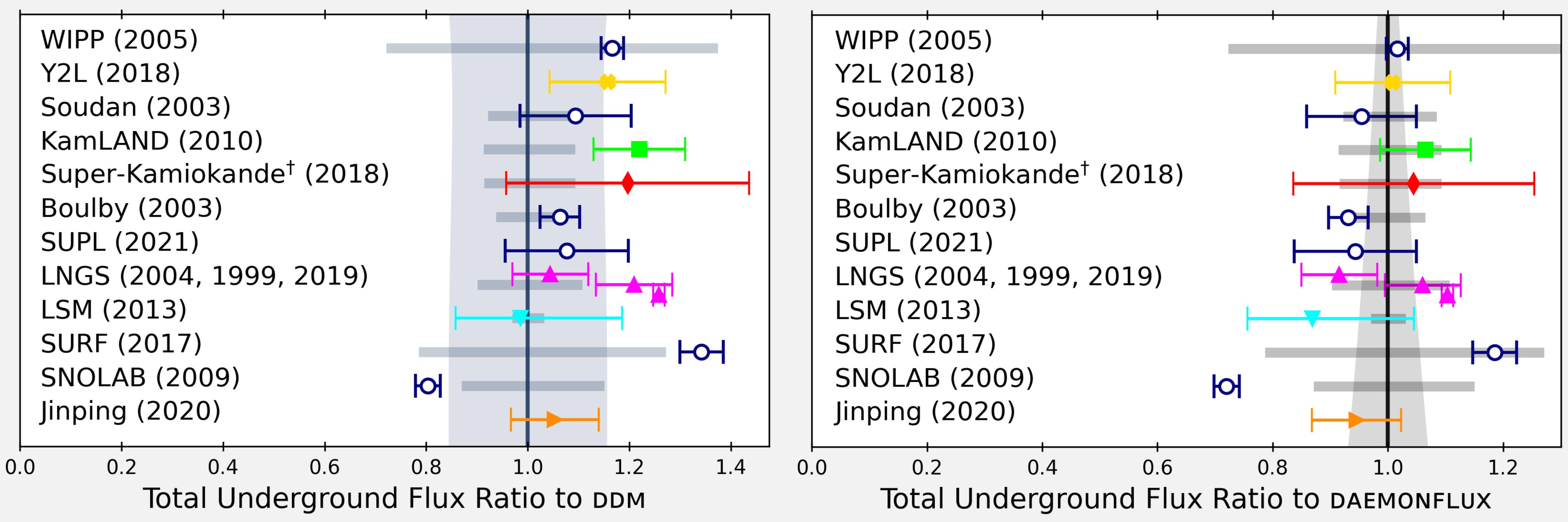
- We observe almost no systematic shift with DAEMONFLUX, compared to DDM, which has noticeably larger error bars and appears systematically lower than the data (see below).
- MUTE with DAEMONFLUX provides a satisfactory description of the data, with the only exception being SNOLAB.

Water

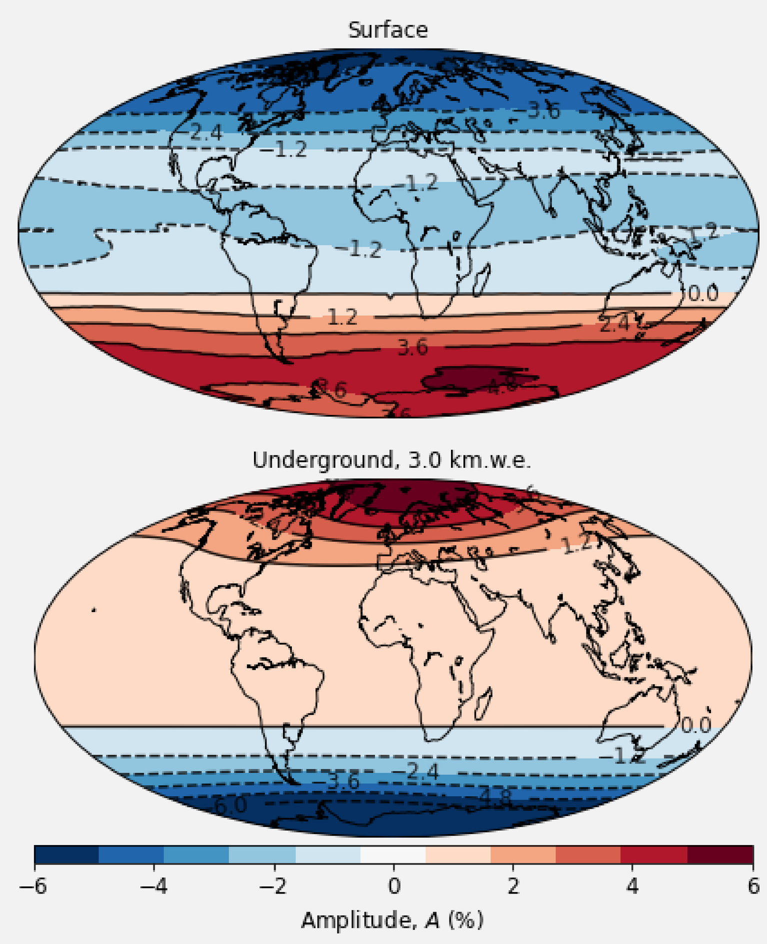
- We note that KM3NeT data is a factor of 2 below the prediction for water, but expect the level of precision of MUTE that we observe for rock to be applicable to water as well.



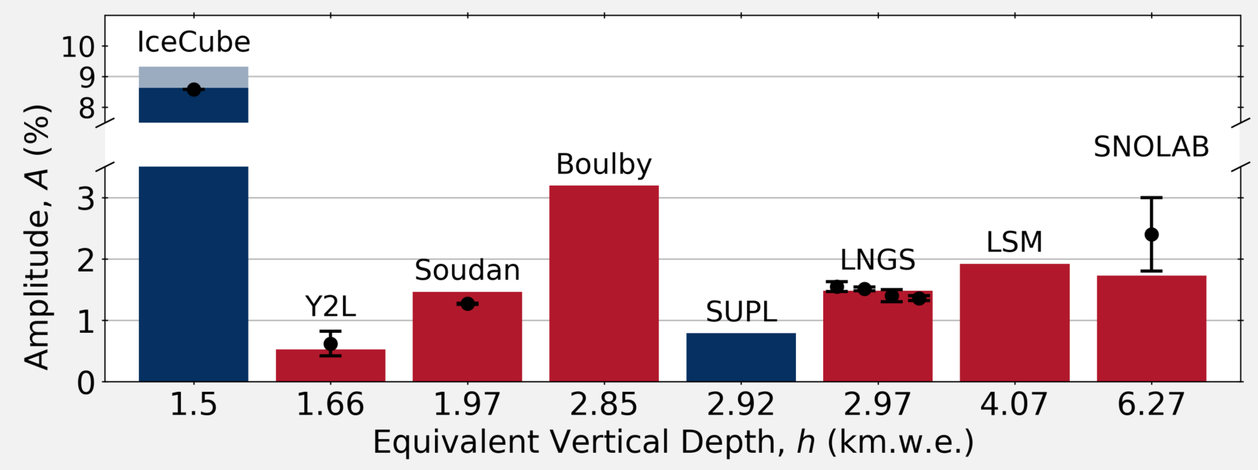
Ratios to Predictions for Standard Rock



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 (see left).
- MUTE calculates these amplitudes to high precision for labs in the **northern** and **southern** hemispheres (see below).



CONCLUSION

- MUTE provides a **robust basis** for exploring underground muon flux data.
- We match total flux data for most locations within uncertainties for rock and await more data for water.
- We observe **good compatibility** with available data for amplitudes of seasonal variations.

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 are given on the GitHub page: https://github.com/wjwoodley/mute.

References

[1] A. Fedynitch, et al., ApJ 928 (2022) 27.
[2] W. Woodley and A. Fedynitch, 10.5281/zenodo.5791812.
[3] J. P. Yañez and A. Fedynitch, PRD 107 (2023) 123037.
[4] A. Fedynitch and M. Huber, PRD 106 (2022) 083018.
[5] H. P. Dembinski, et al., PoS ICRC2017 (2018) 533.
[6] J.-H. Koehne, et al., CPC 184 (2013) 2070.

Acknowledgements

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