# MUTE: A Modern Calculation for Deep Underground and Underwater Muons

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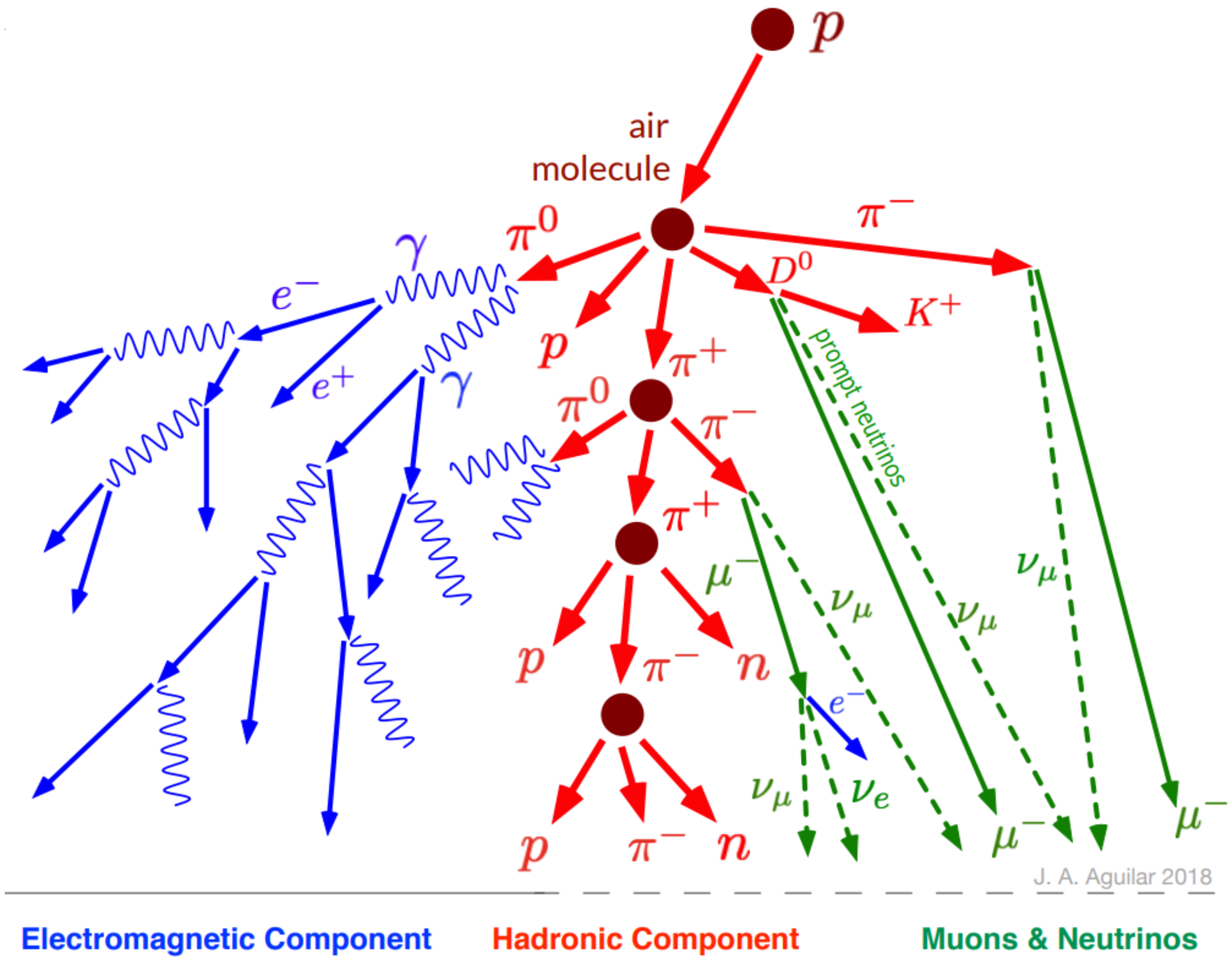
# Introduction

- Cosmic rays interact in Earth's middle atmosphere to produce muons [1].
- Muons can easily penetrate matter by multiple kilometres.
- Underground and underwater muons are crucial in data analyses and the design of Dark Matter and neutrino detectors.
- Therefore, good knowledge of their flux is important in calculations of expected muon-induced backgrounds.



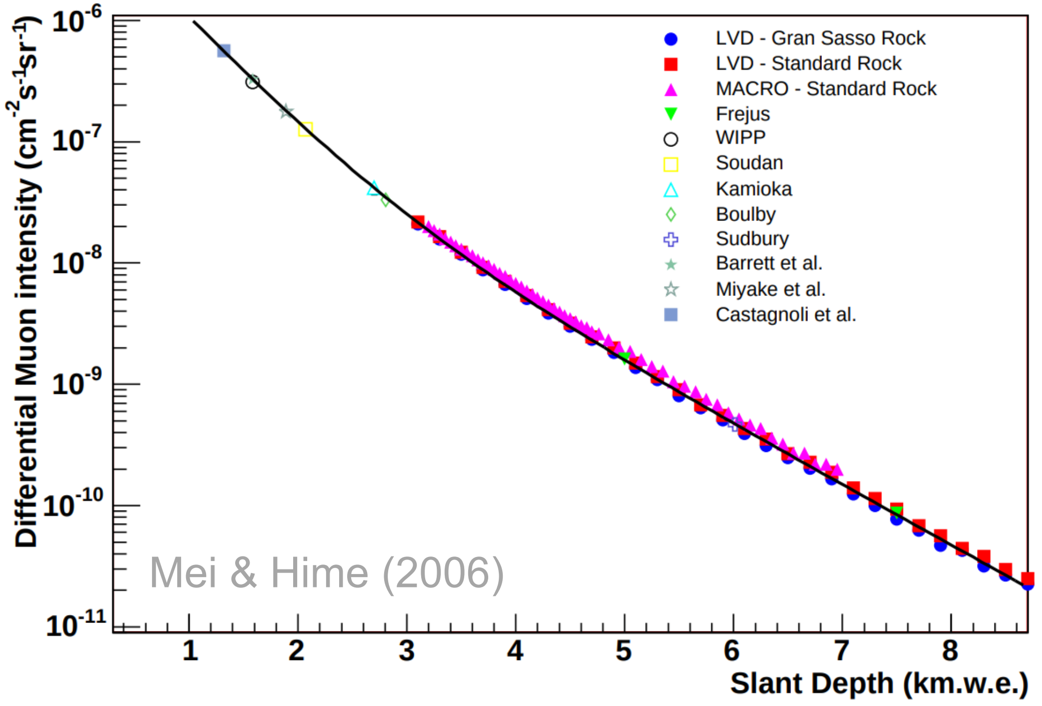

[1] J. Aguilar. *PHYS 467: Astroparticle Physics*. Lecture Notes.

# Depth-Intensity Relations

- Depth Intensity Relations [2, 3] are a common way of calculating underground muon fluxes.
- Disadvantages:
  1. They are simple parametric fits.
  2. They are susceptible to statistical errors at deep slant depths.
  3. They are approximate and introduce systematic errors for θ > ~20° [4].
- MUTE (**MU**on in**T**ensity cod**E**) solves all three of these problems.
- It is a computational tool written in Python that calculates muon spectra underground.

Continuous Losses    Discrete Losses

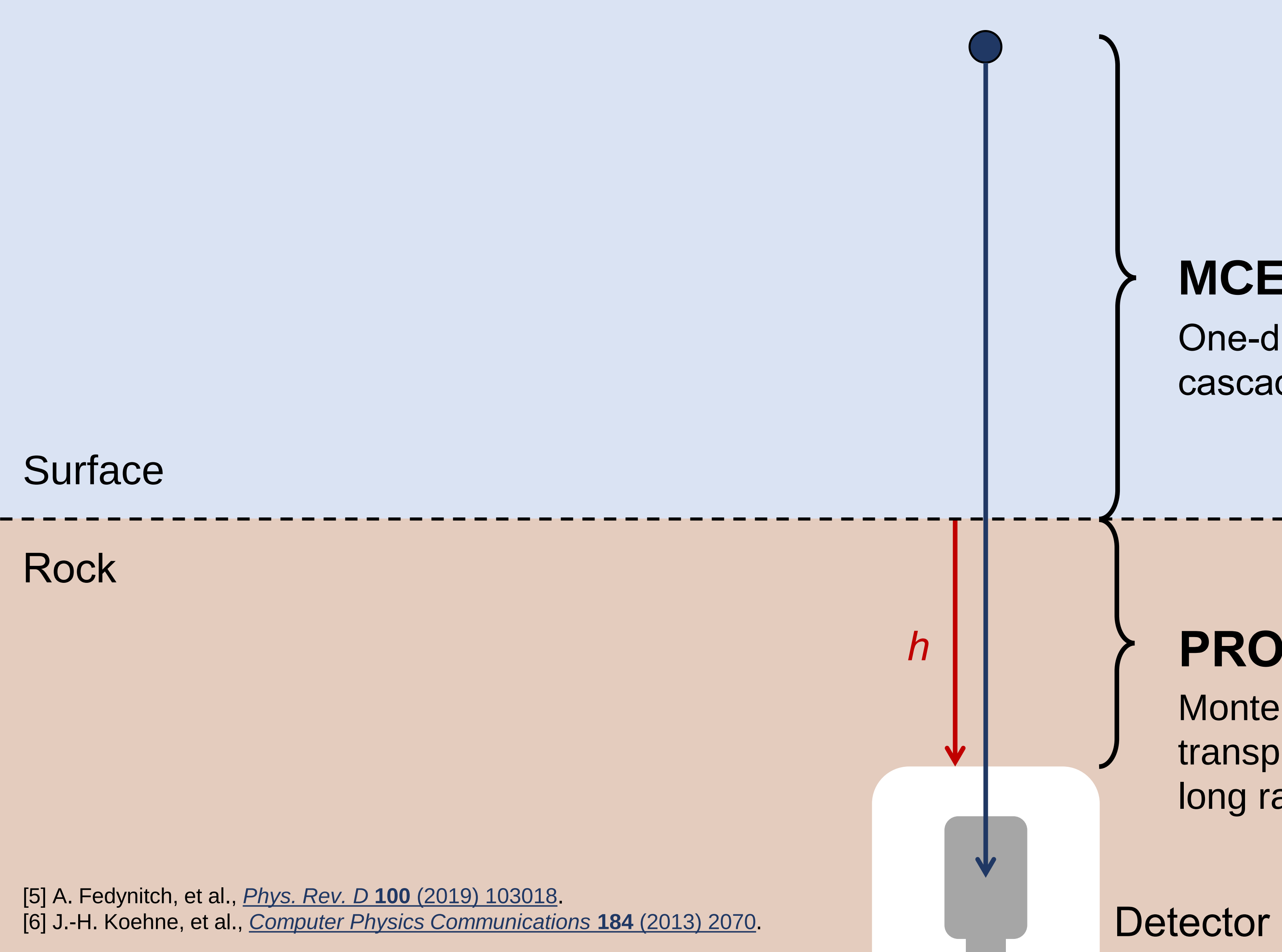
$$I(h) = I_1 e^{(-h/\lambda_1)} + I_2 e^{(-h/\lambda_2)}$$





[2] D. Mei and A. Hime, *Phys. Rev. D* **73** (2006) 053004 [astro-ph/0512125].
[3] M. Crouch, in *ICRC*, vol. 6, p. 165, Jan., 1987.
[4] A. Fedynitch, W. Woodley and M.-C. Piro, *ApJ* **928** (2022) 27.

# Method – Overview




**MCEq** [5]

One-dimensional fast cascade equation solver.

**PROPOSAL** [6]

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

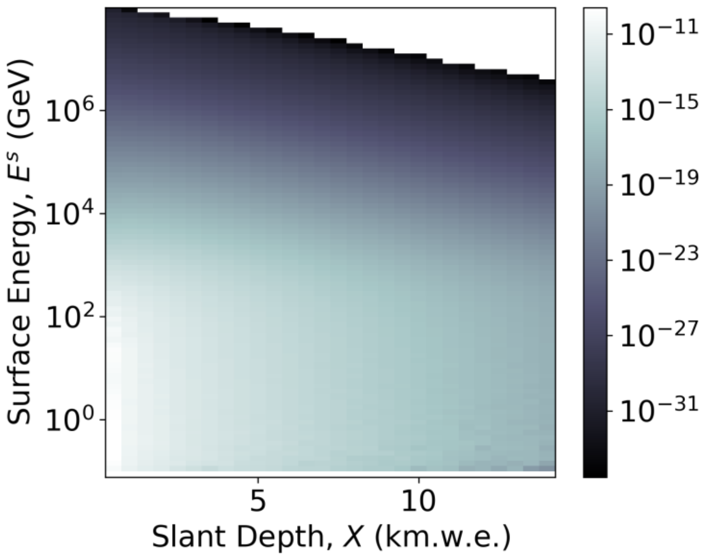
[5] A. Fedynitch, et al., *Phys. Rev. D* **100** (2019) 103018.
[6] J.-H. Koehne, et al., *Computer Physics Communications* **184** (2013) 2070.

# Method – Convolution

- A convolution is performed to calculate underground fluxes:

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

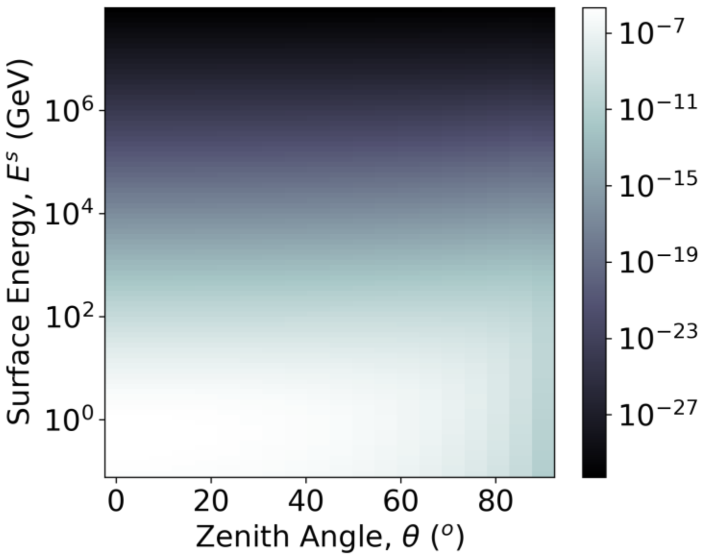
$\Phi^u$




**MUTE**
Underground Fluxes

=

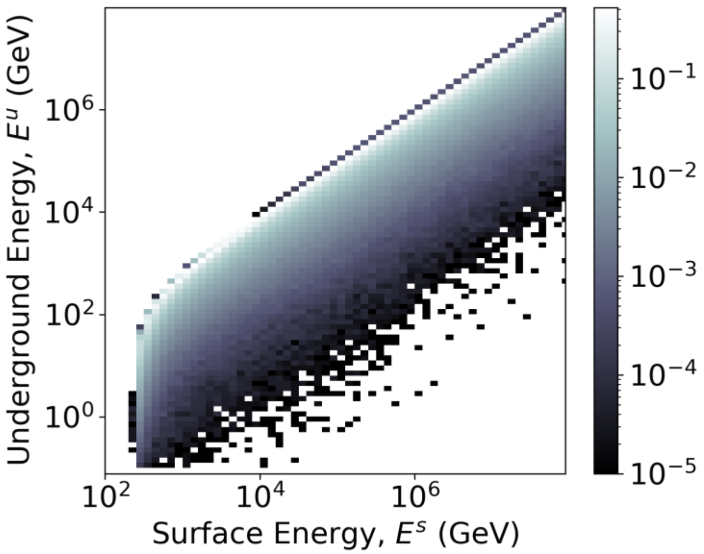
$\Phi^s$




**MCEq**
Surface Fluxes

*

$P$

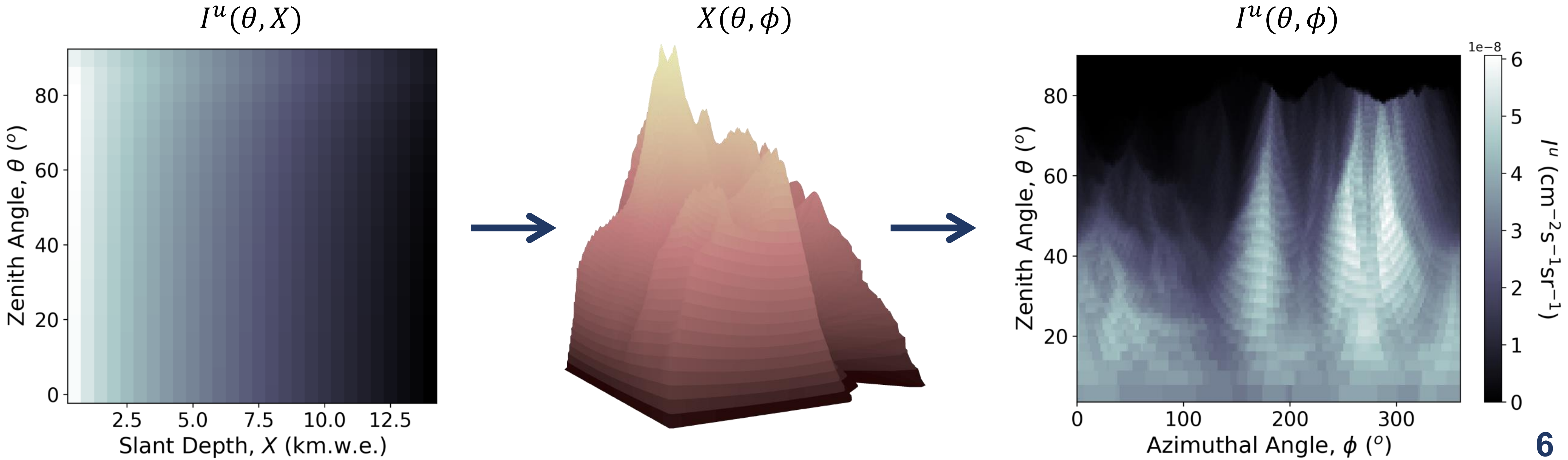



**PROPOSAL**
Transfer Tensor

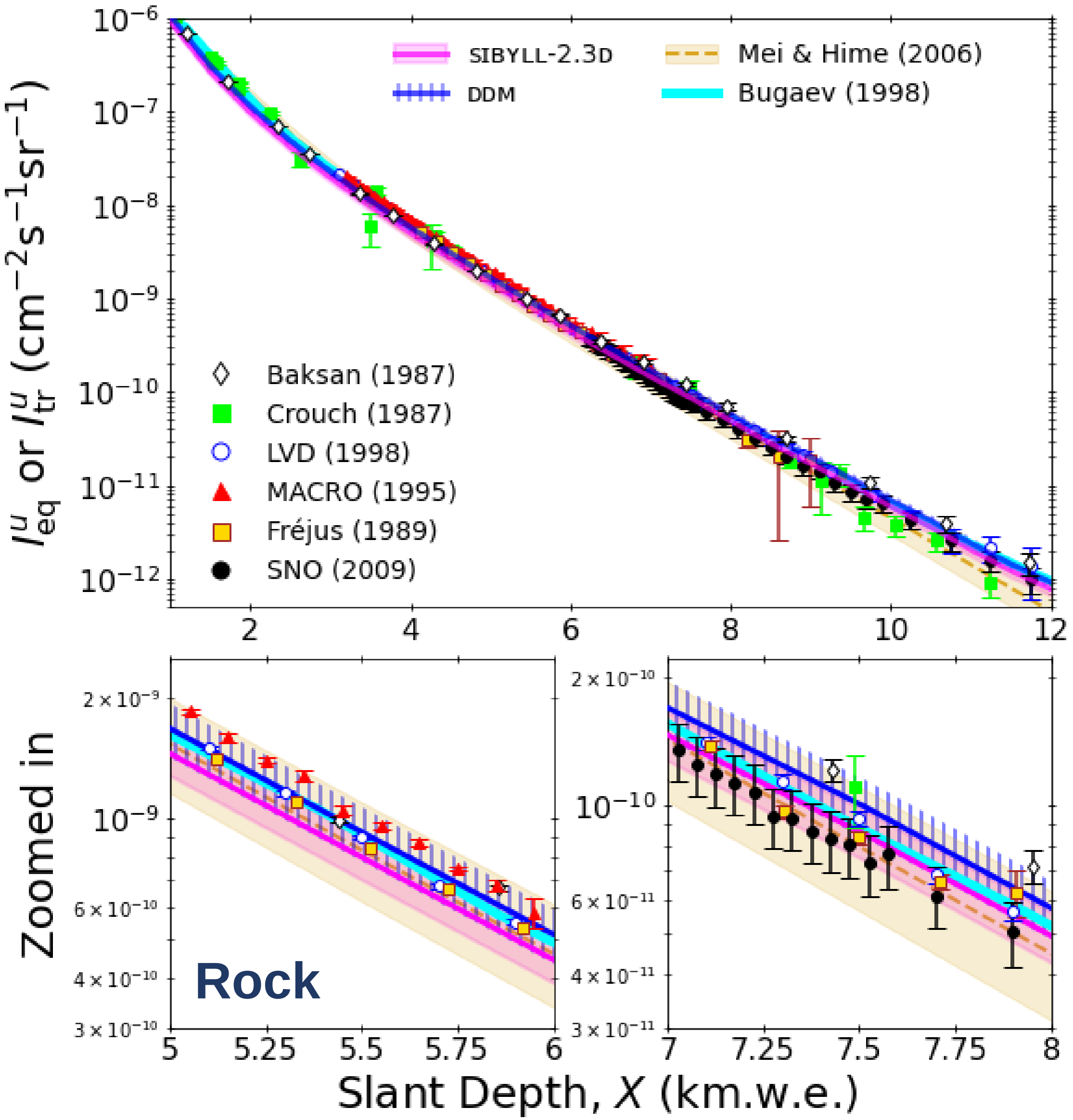
# Method – Labs under Mountains

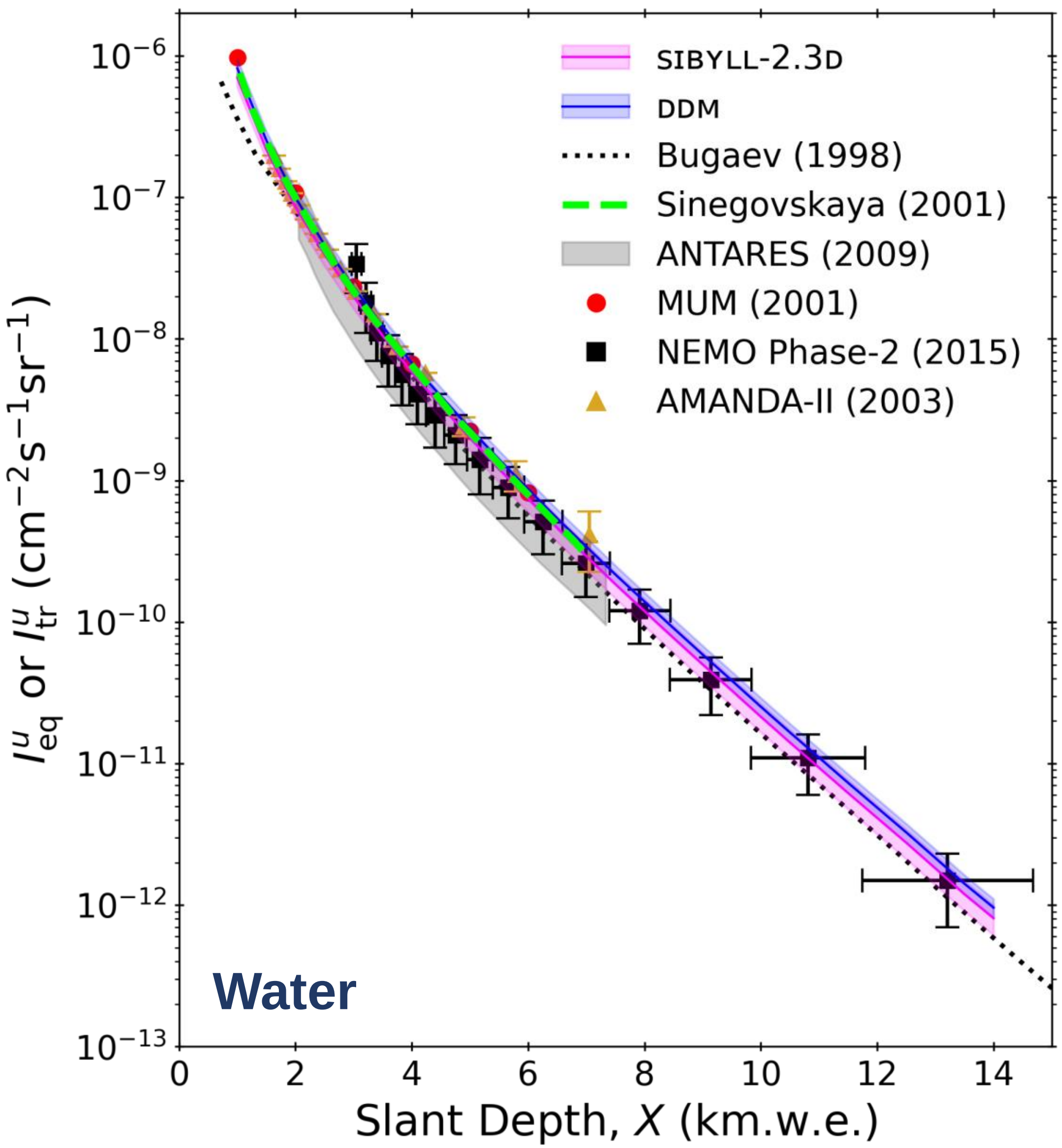
- Underground intensities for mountains are first calculated on a grid of constant zenith angles and slant depths.

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

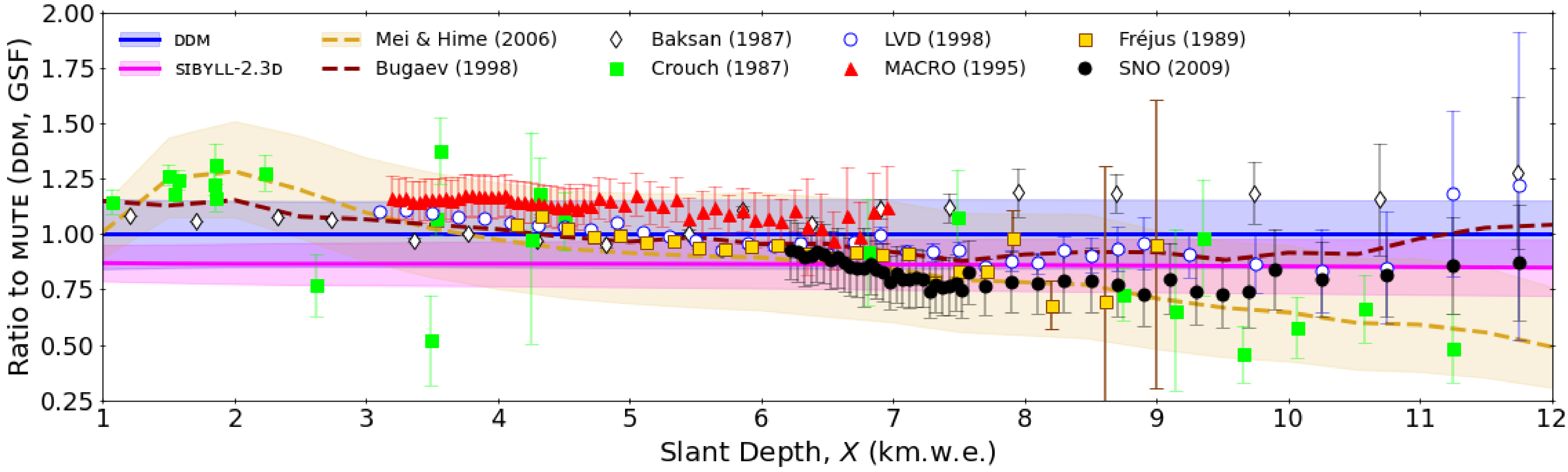


# Results – Vertical Underground Intensity



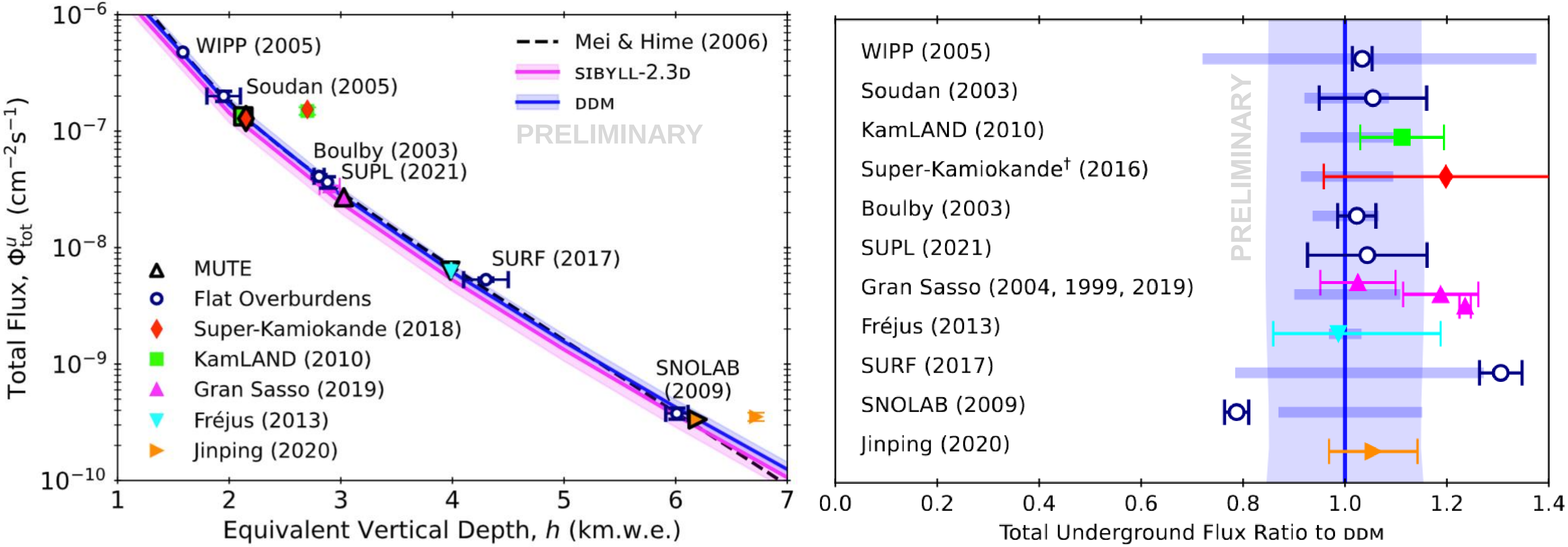
# Results – Comparison to Data




- DDM is better at shallow depths, and SIBYLL is better at deep depths.
- Uncertainties on data are smaller than those on the theory, meaning data can be used to constrain the models.

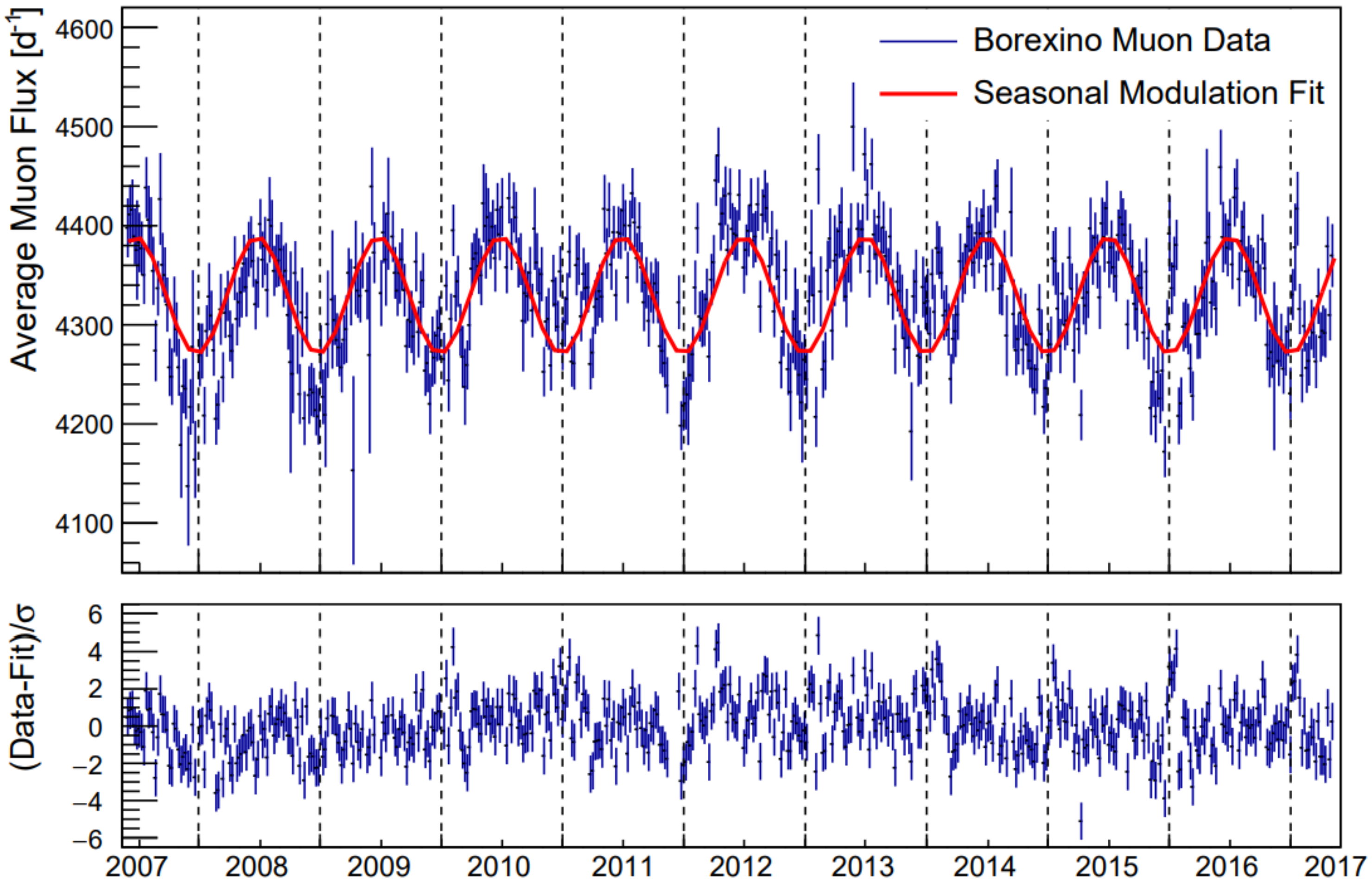
# Results – Total Underground Flux

- Total flux calculations are consistent with measurements for labs under flat overburdens and mountains within theoretical errors in nearly every case.



# Seasonal Variations

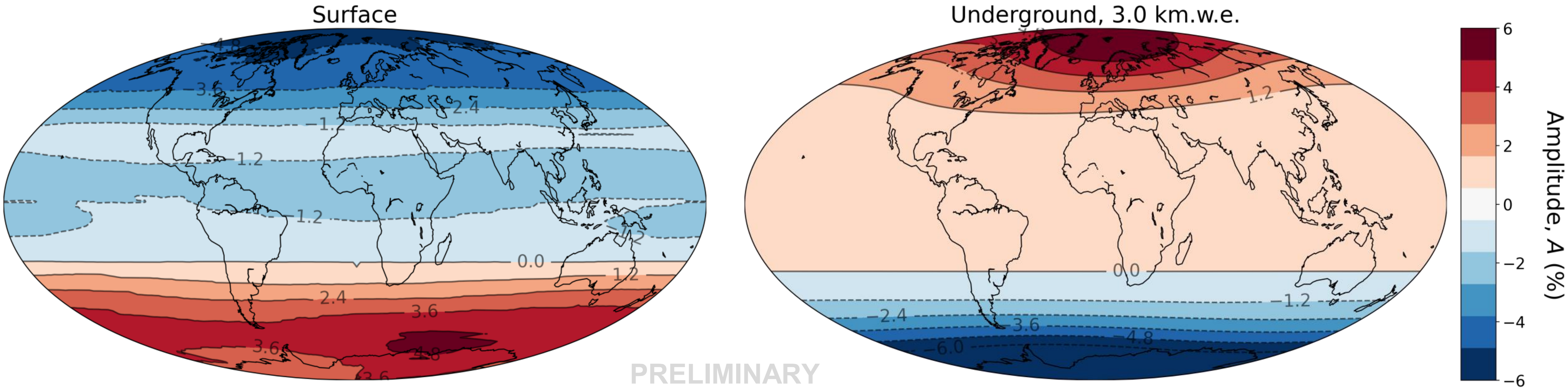
- The phenomenon of seasonal modulations in the muon flux is well-known [7]:




[7] M. Agostini, *et al.*, *Journal of Cosmology and Astroparticle Physics* **2019** (2019) 046.

# Seasonal Variations – Results

- I have calculated the amplitude of seasonal variations around the globe:

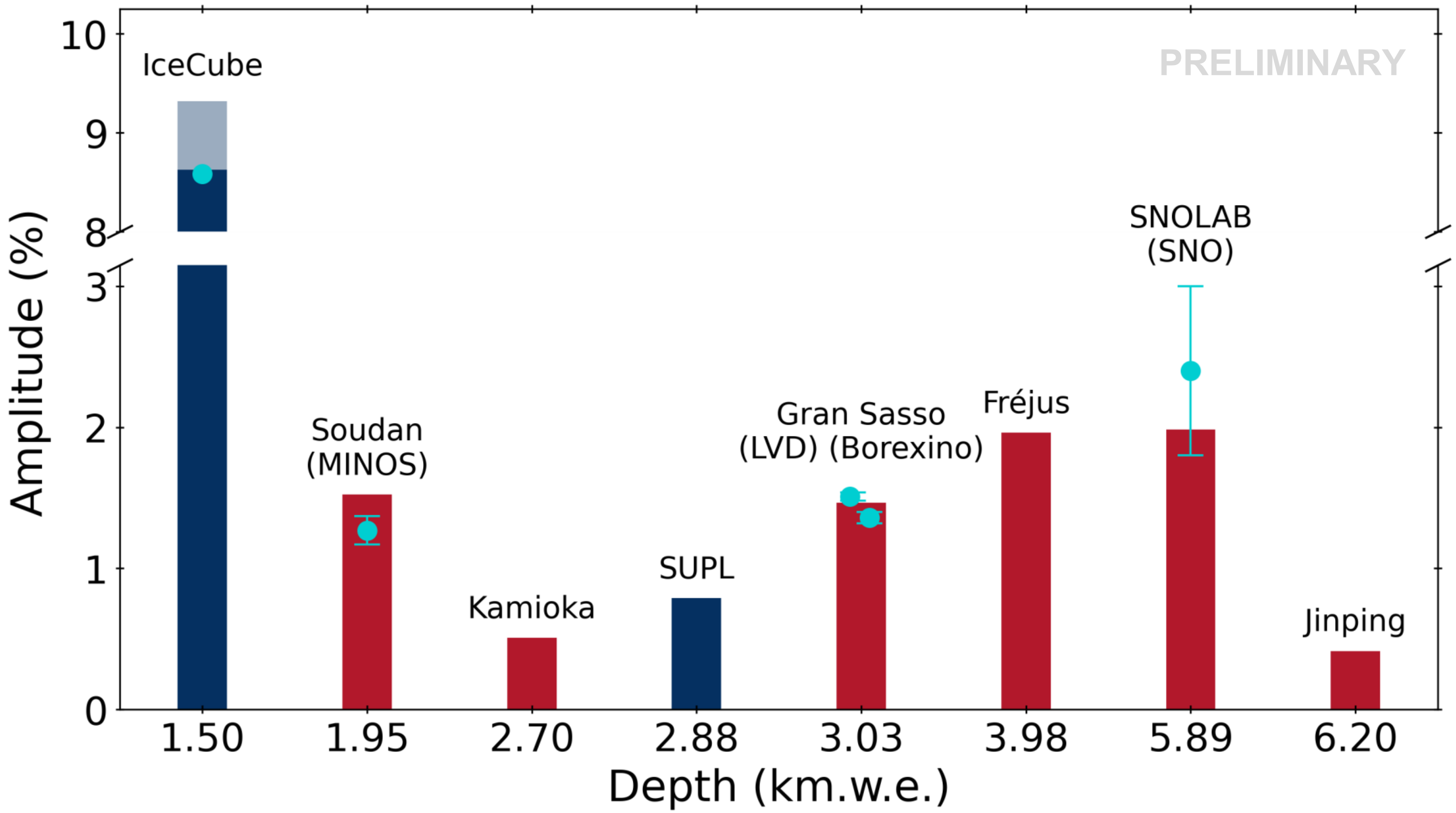



- The muon flux is **lower** at the surface in summer in the **northern hemisphere**.

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

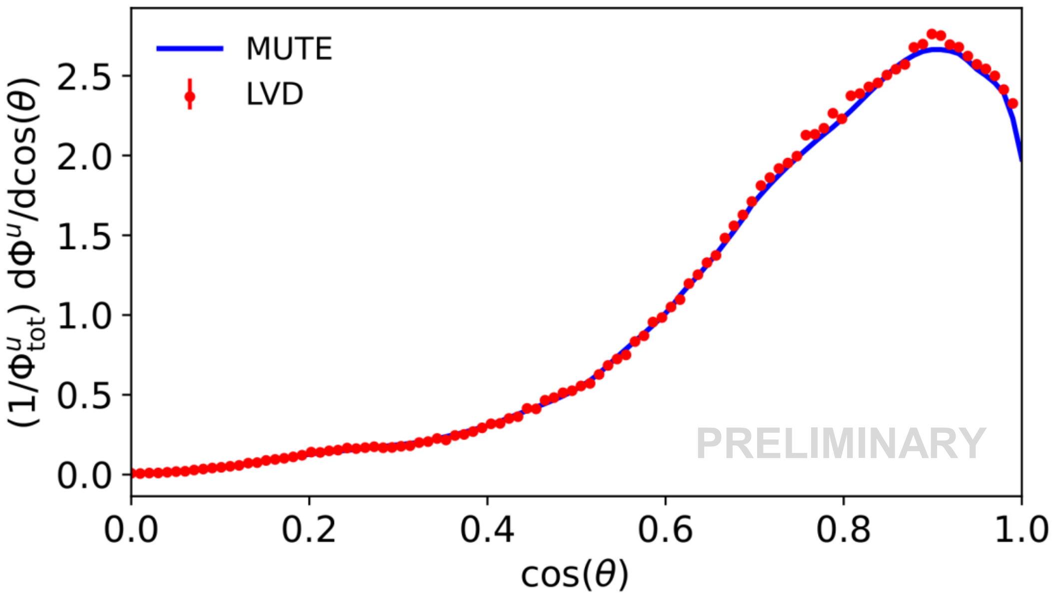
# Seasonal Variations – Results

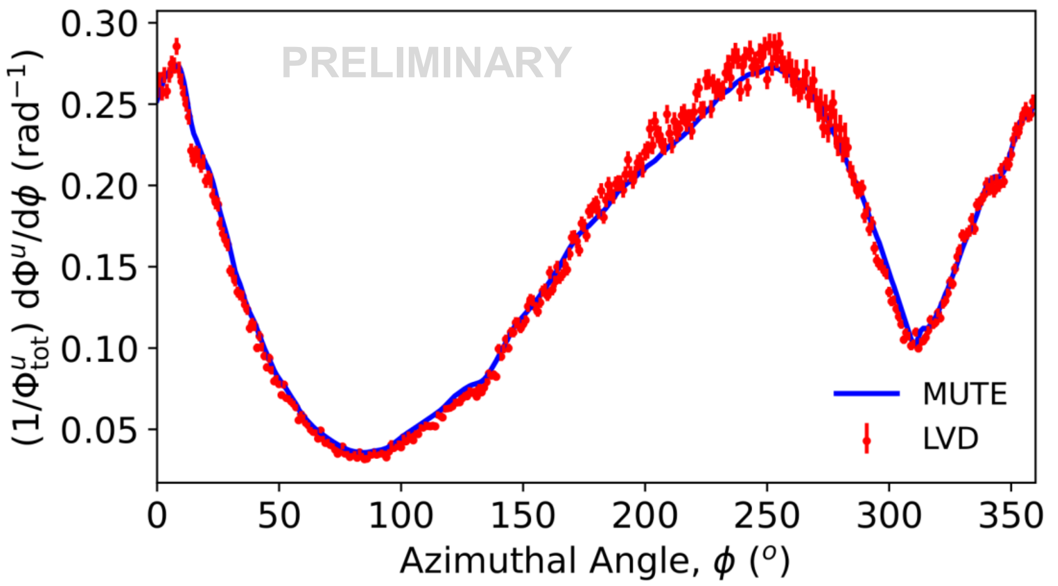
- MUTE can calculate seasonal variation amplitudes to high accuracy.



# Applications – Angular Distributions

- MUTE can also calculate one-dimensional angular distributions for labs under mountains in the $\theta$ and $\phi$ directions.
- Results for the Gran Sasso mountain have been compared to data from the LVD experiment.
- We obtain very good agreement for the muon spectrum and flux, and for the shape of the mountain.
- This serves as a way of verifying the data analysis of the LVD experiment.



# Conclusion

- MUTE is flexible, fast, and precise. It gives a full description of muon distributions underground and underwater, and can provide forward predictions for total muon fluxes.

- The results match experimental data very well for all physical observables. This can be used to cross-check data analyses.

- It can also be used to constrain hadronic and cosmic ray uncertainties, which is ongoing work at the moment.

- MUTE is public and available (`pip install mute`) to be used by experiments in labs under flat overburdens and mountains.

doi:10.3847/1538-4357/ac5027

https://github.com/wjwoodley/mute

# Thank you