

MUTE: A Modern Calculation for Deep Underground and Underwater Muons

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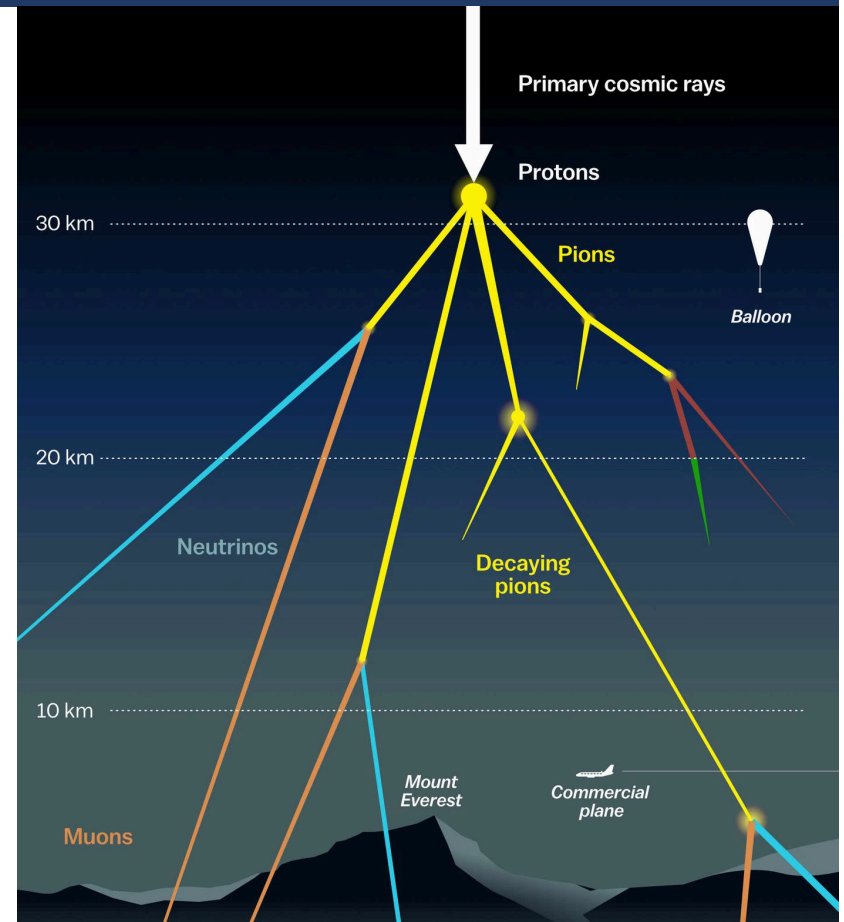
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Introduction

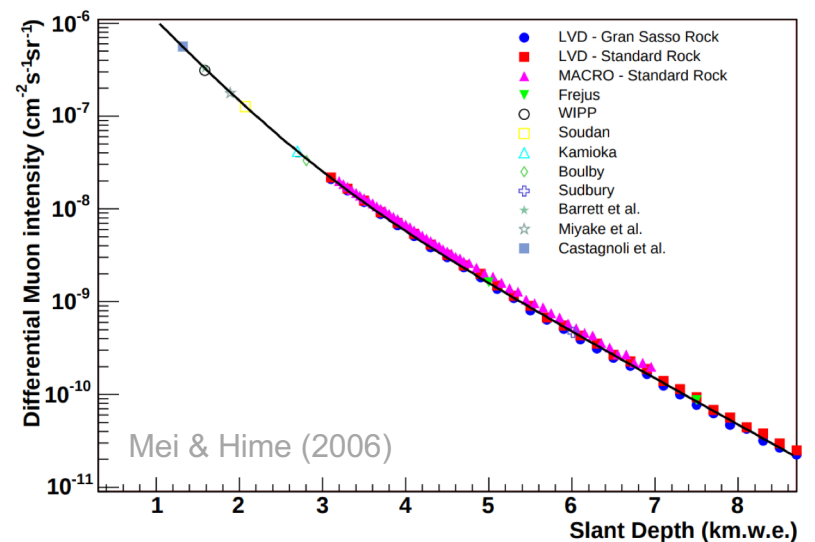
- Underground and underwater muons are crucial in data analyses in neutrino telescopes and in the design of Dark Matter detectors.
- Mei & Hime [1] and Crouch [2] use Depth-Intensity Relations (DIRs), which may contain bias induced by systematics.
- Theoretical calculations of Bugaev [3] lack rigorous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



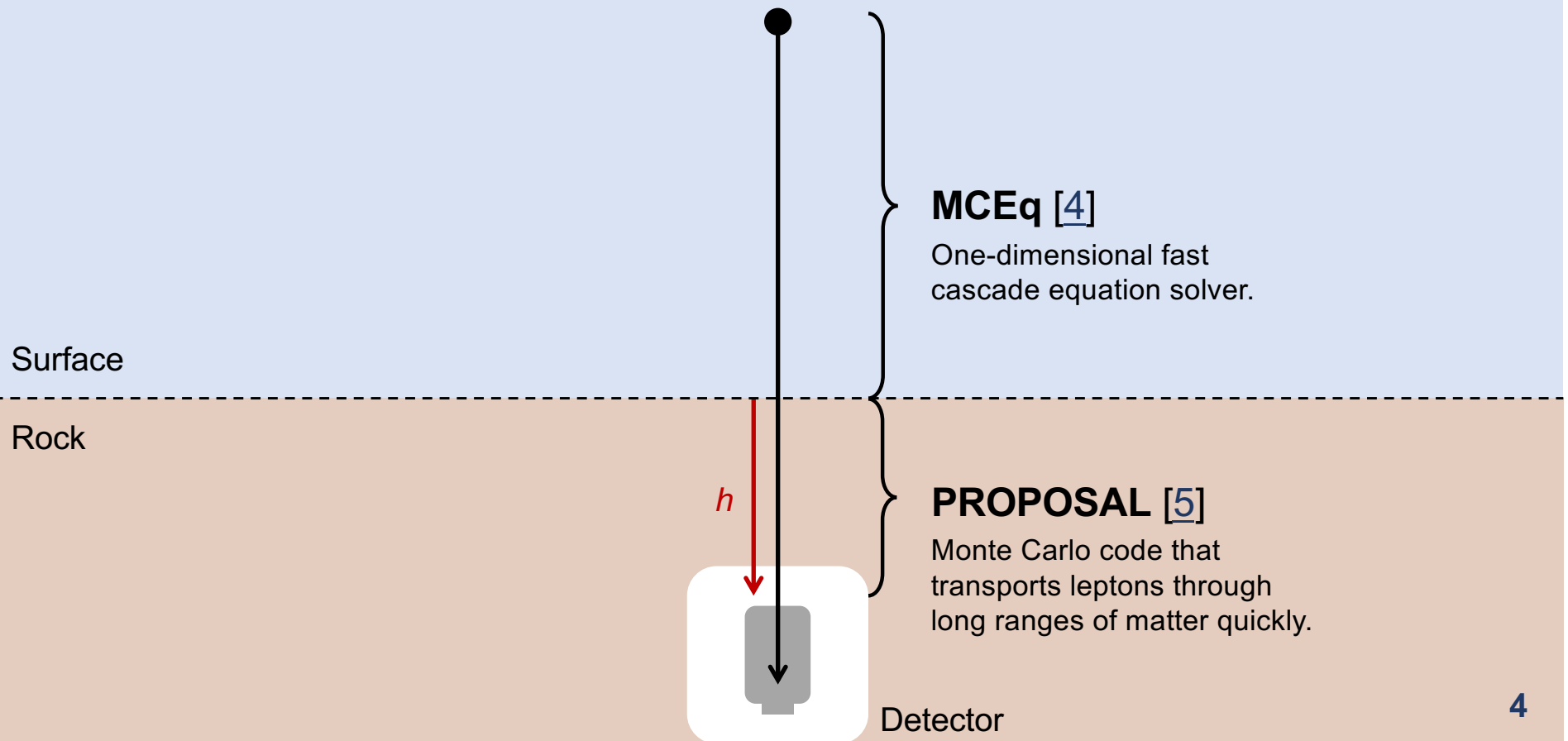
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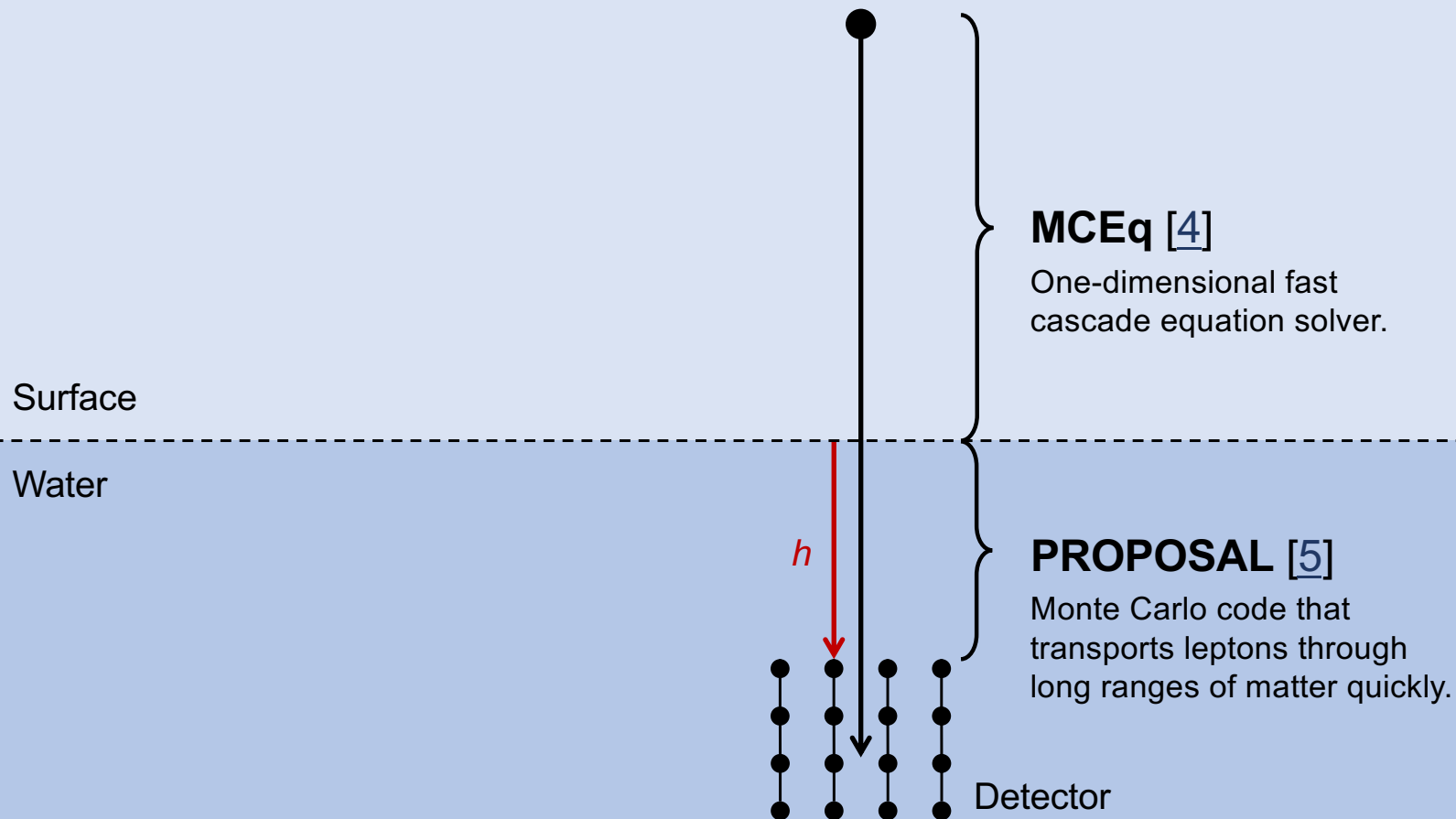
$$I(h) = I_1 e^{-h/\lambda_1} + I_2 e^{-h/\lambda_2}$$



Method Overview



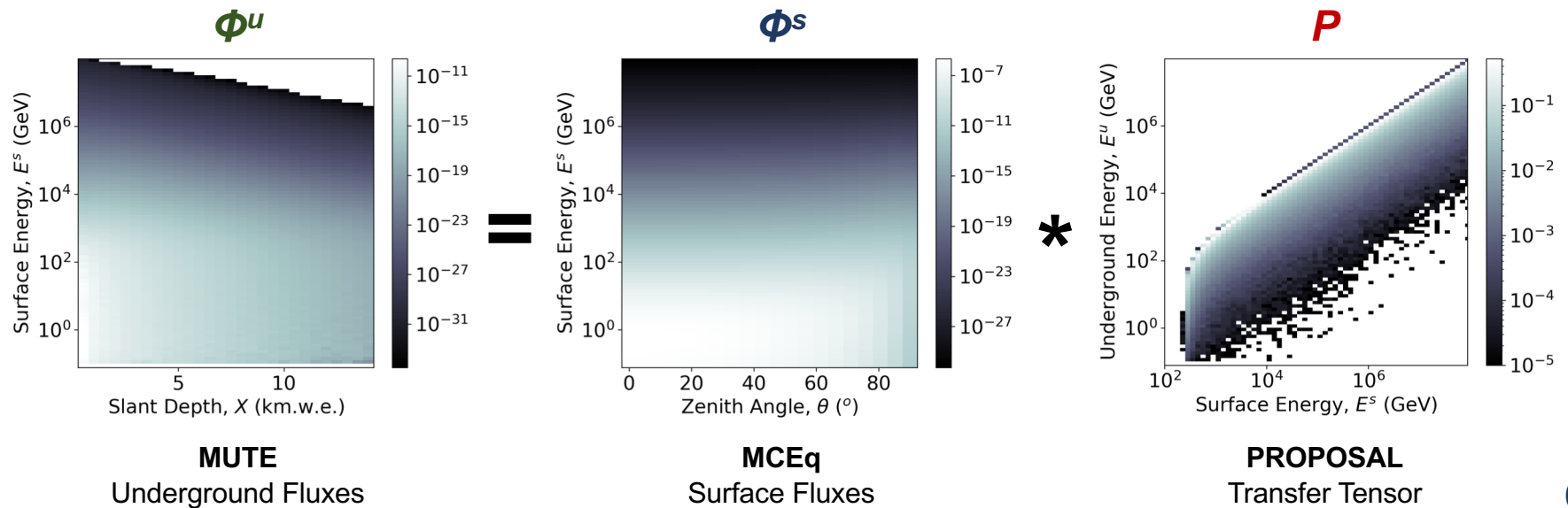
Method Overview



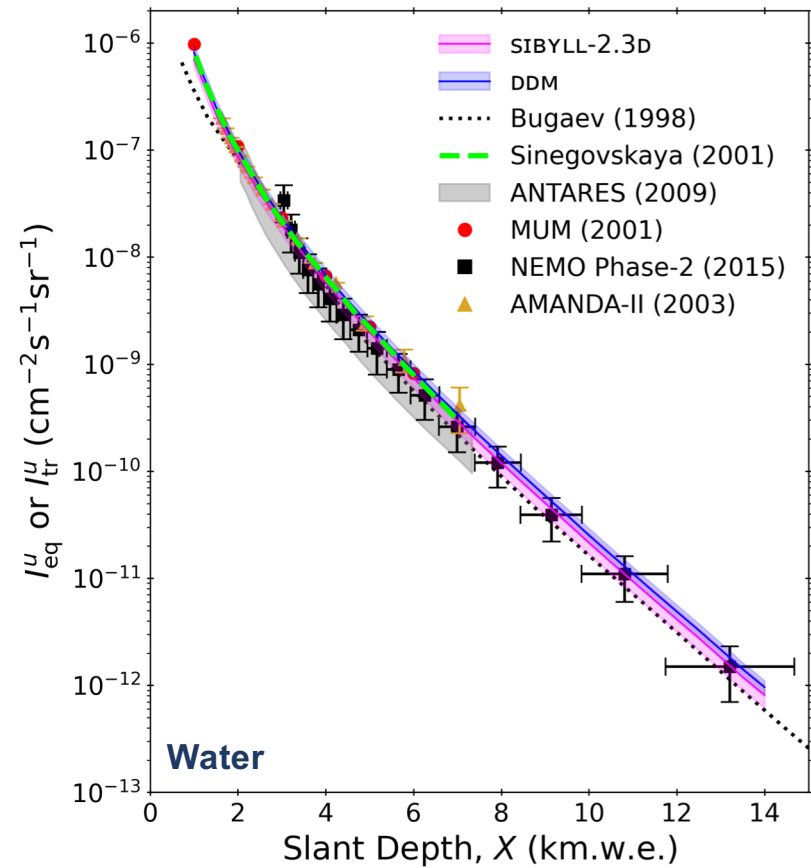
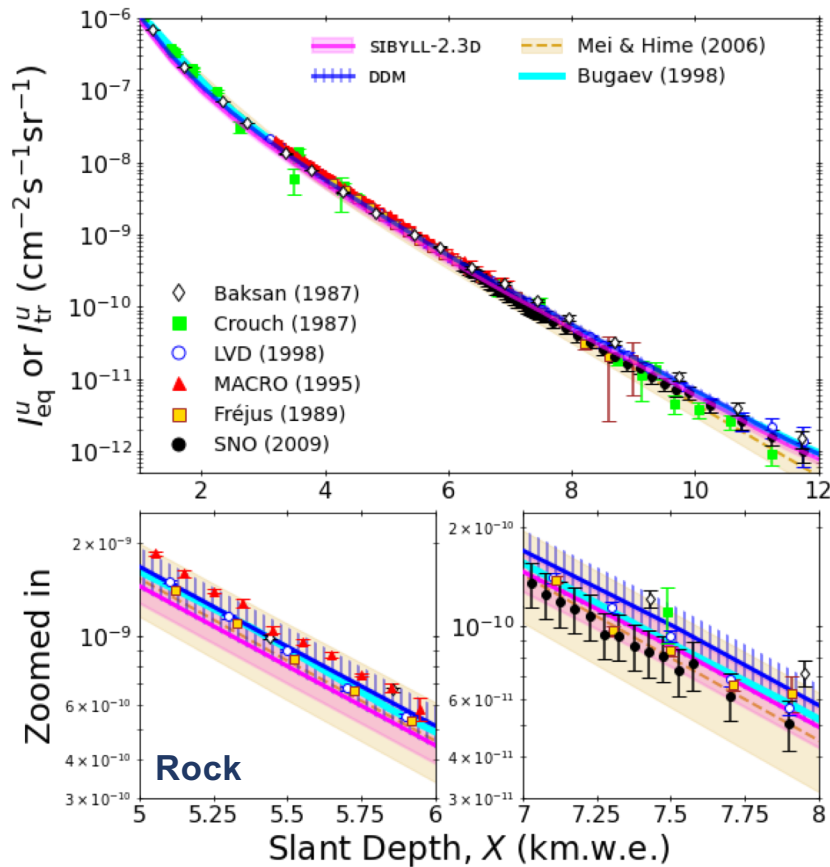
Calculations

- A convolution is performed to calculate underground fluxes:

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

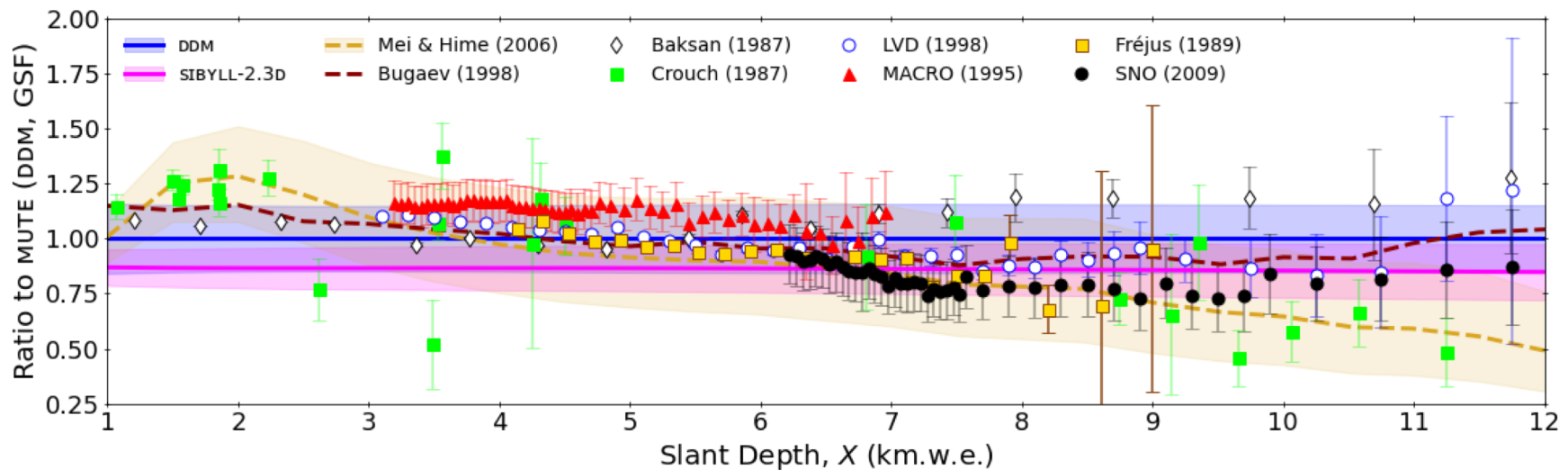


Results – Vertical Underground Intensity



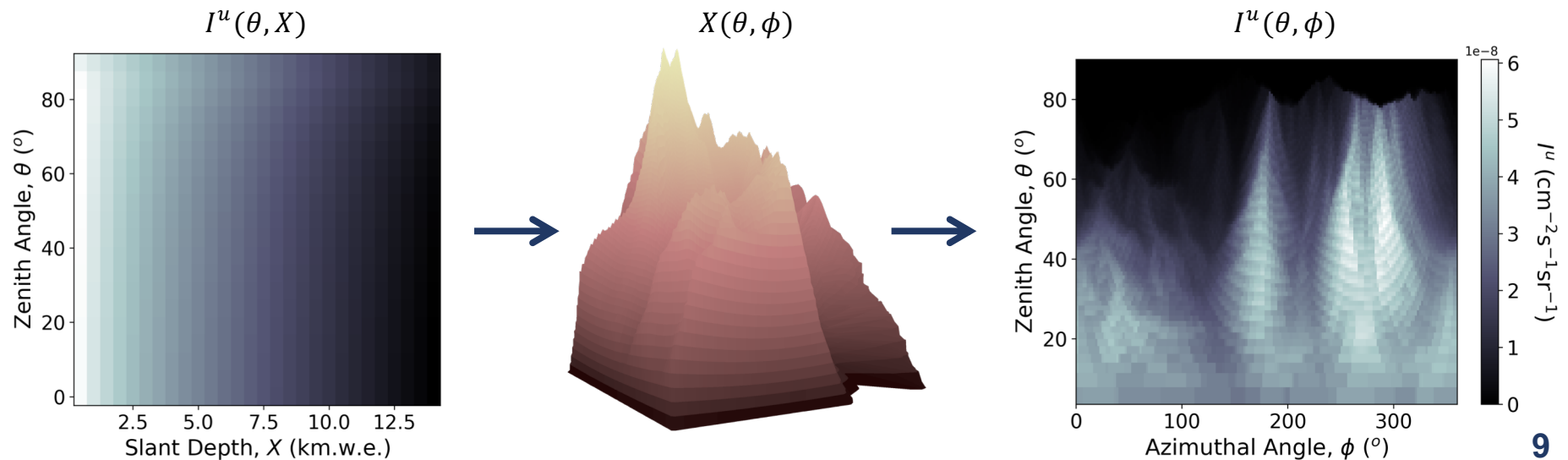
Comparison to Data

- DDM is better at shallow depths, and SIBYLL is better at deep depths.
- Uncertainties on data are smaller than those on theory.
- \Rightarrow Theoretical uncertainties on neutrino fluxes may be able to be constrained from 40% down to $\sim 10\%$. [6]



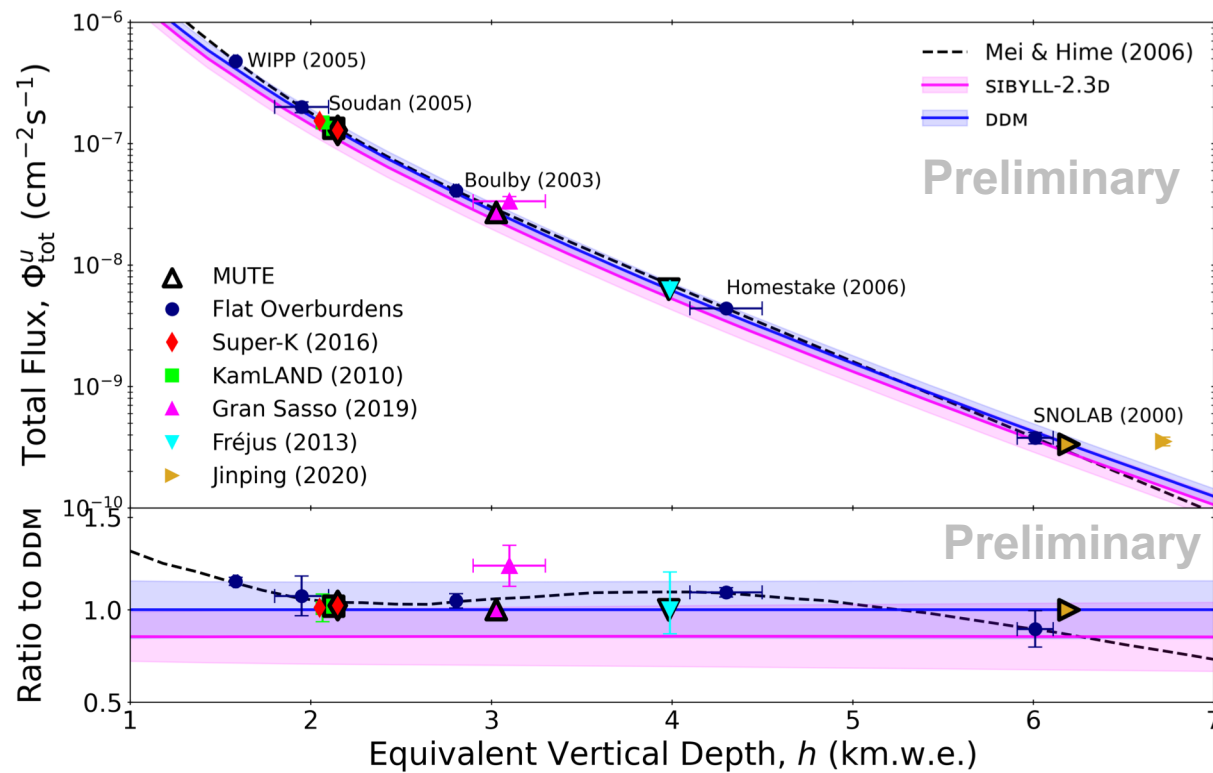
Labs under Mountains

- 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.



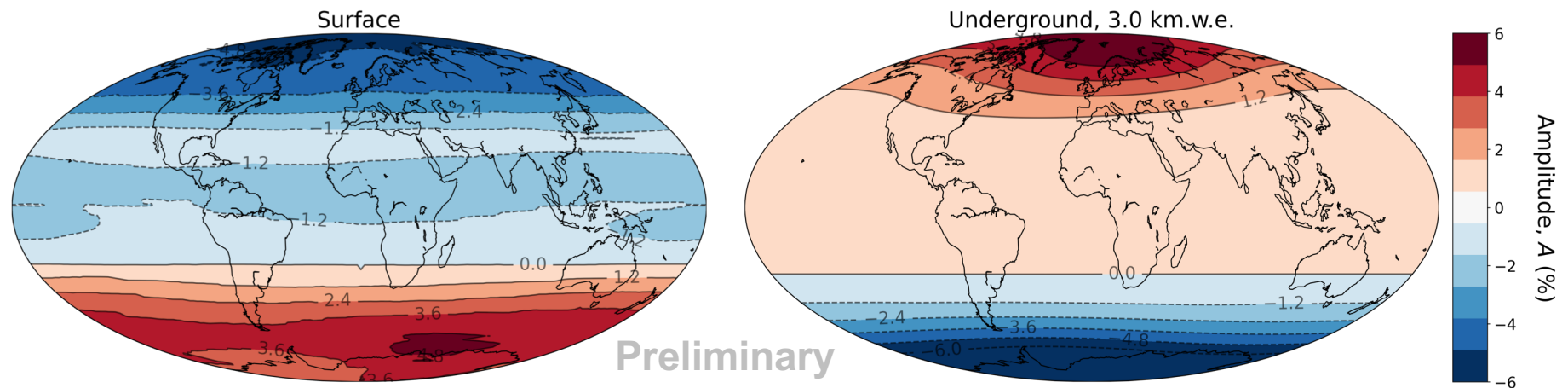
Results – Total Underground Flux

- Our calculation reproduces total underground flux measurements excellently.



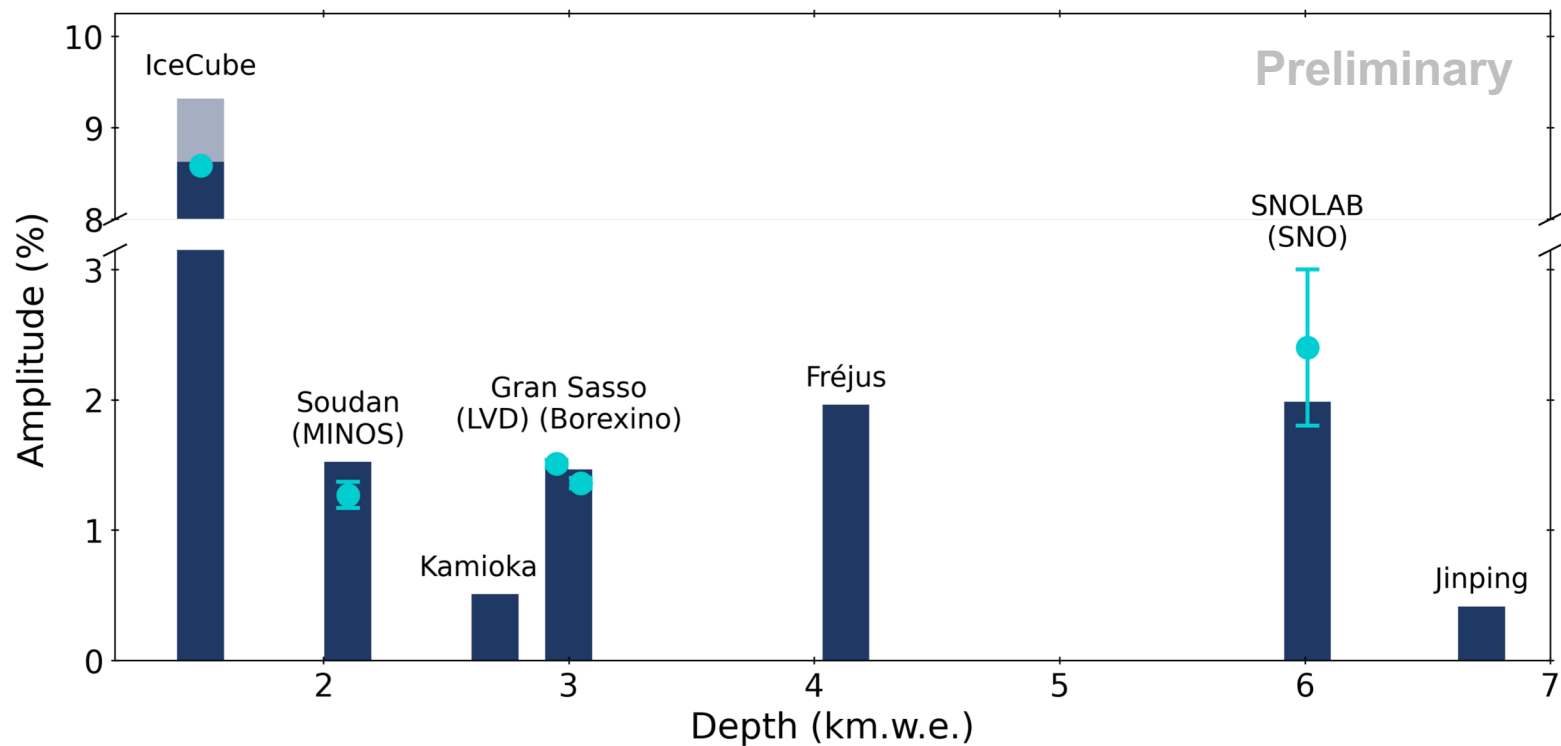
Results – Seasonal Variations

- In the summer, the atmosphere is taller, meaning muons travel longer distances and decay more often \Rightarrow 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 \Rightarrow 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://doi.org/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