MUTE: A Modern Calculation of Deep Underground and Underwater Cosmic Ray Muons

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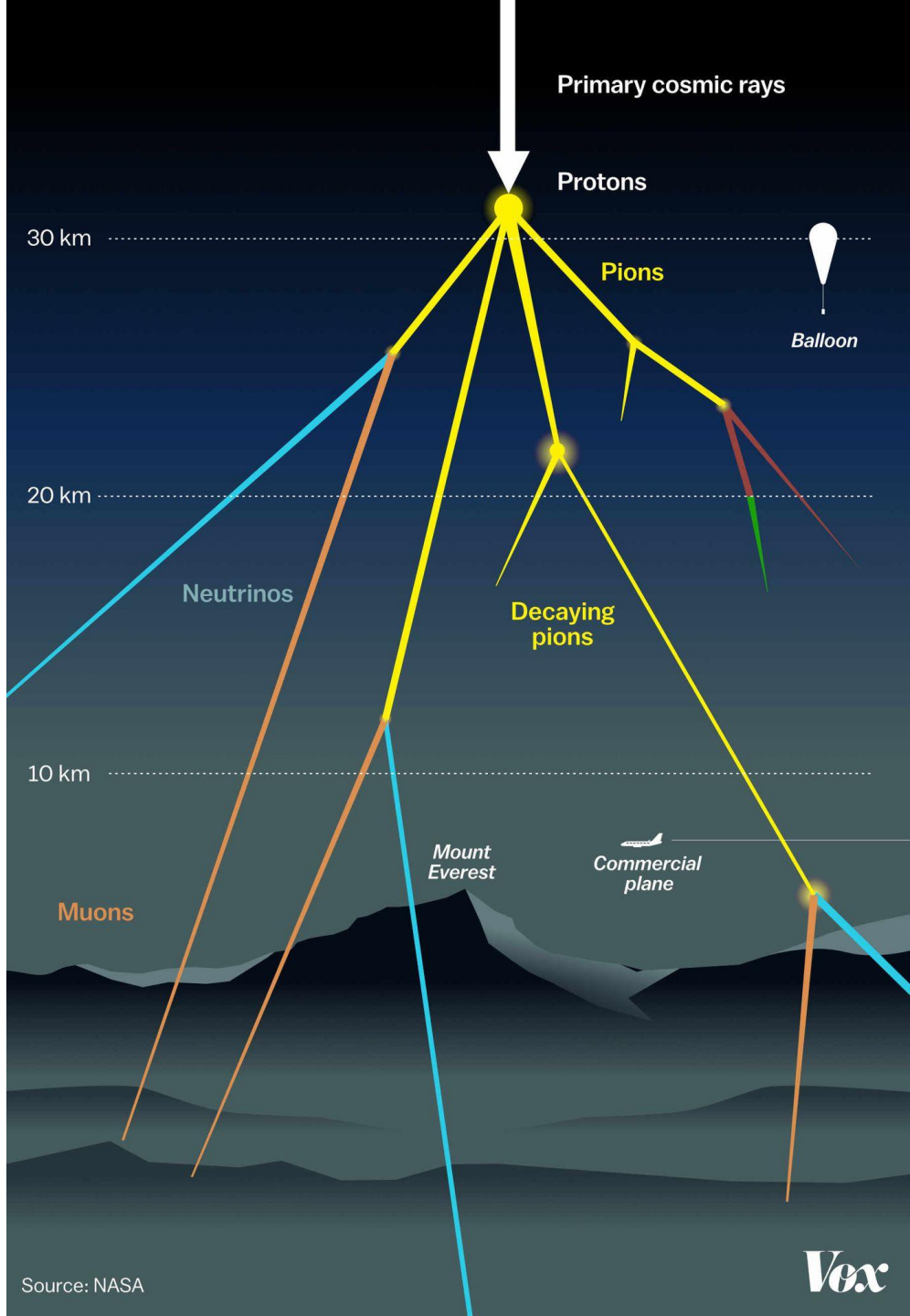
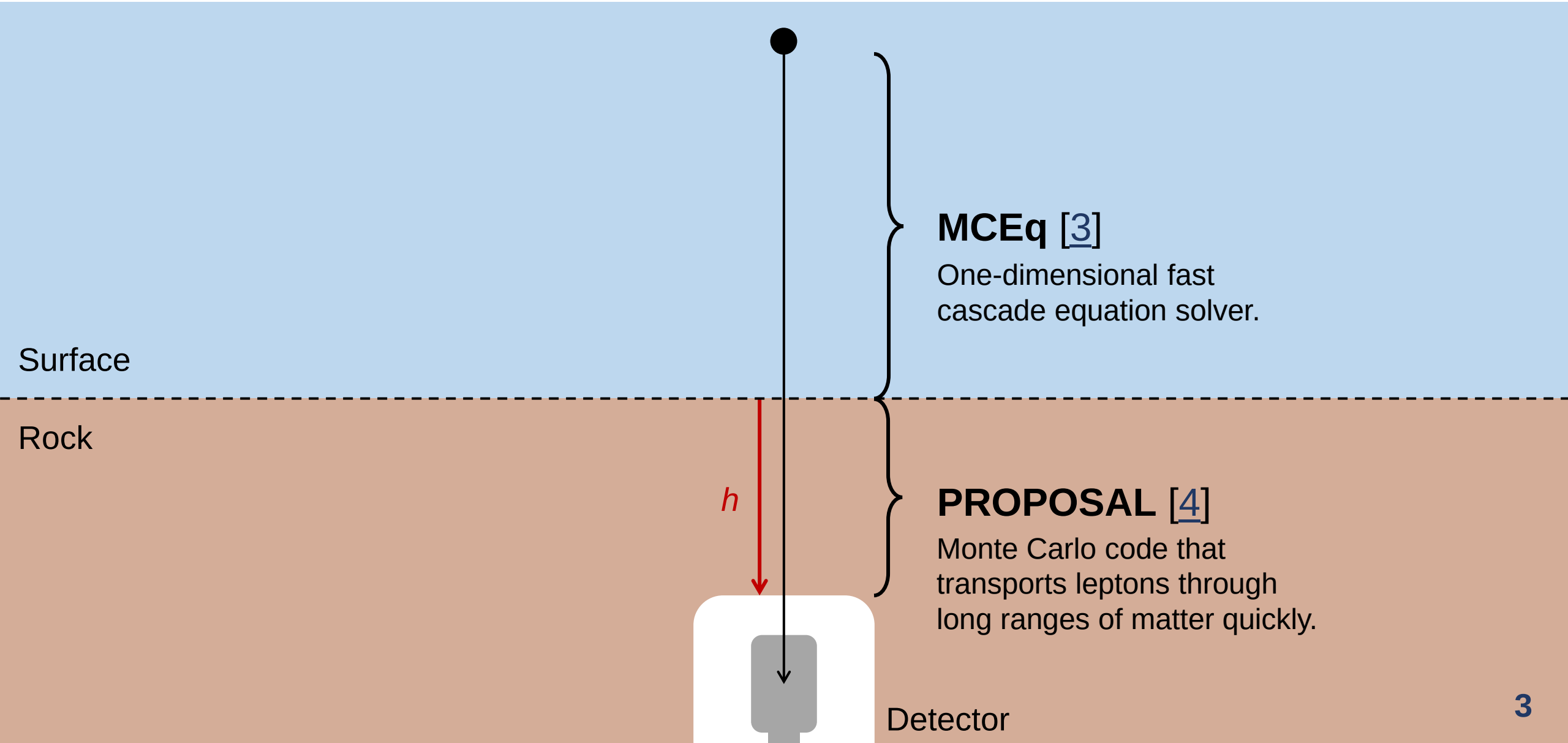
Introduction

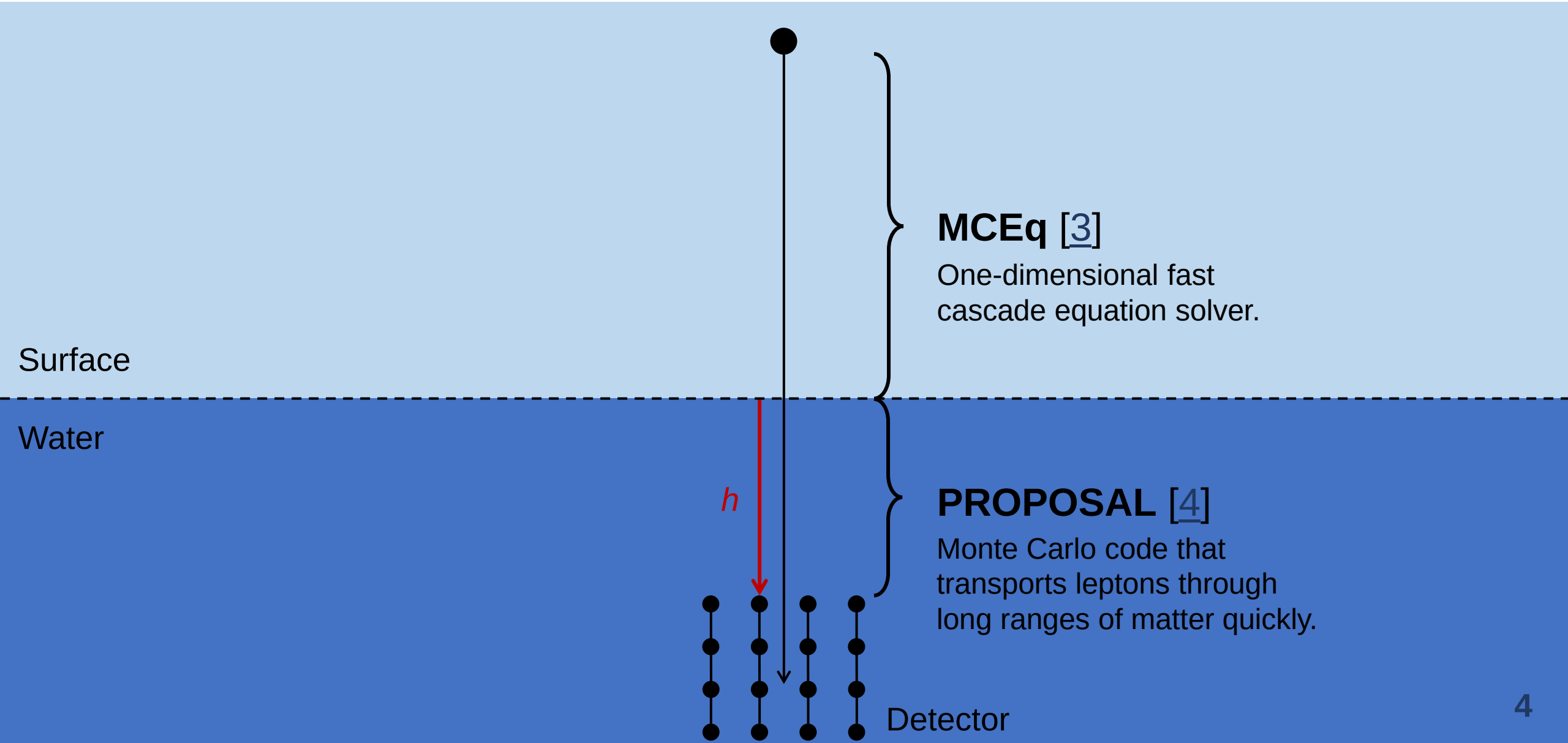
- Underground muons are important for DM and neutrino experiments because they can produce neutrons.
- They can give us information about cosmic rays and neutrinos.
- Not much work has been done in the past 16 years [1, 2].
- Current programs are difficult to use, slow, and depend on fits to data.



Simulation Method



Simulation Method



MCEq [3]

One-dimensional fast cascade equation solver.

PROPOSAL [4]

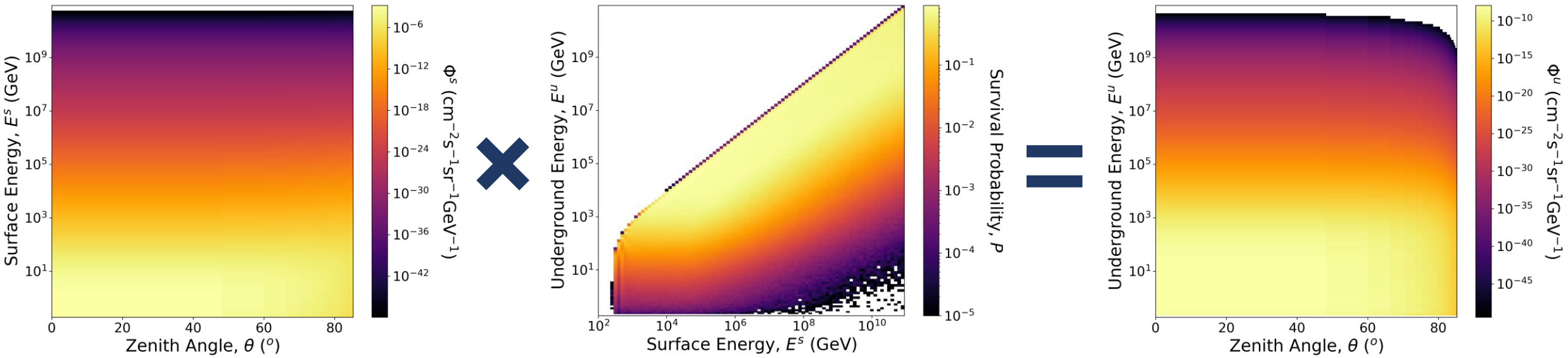
Monte Carlo code that transports leptons through long ranges of matter quickly.

Calculations

- Underground fluxes are calculated using a convolution:

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

Φ^s P Φ^u



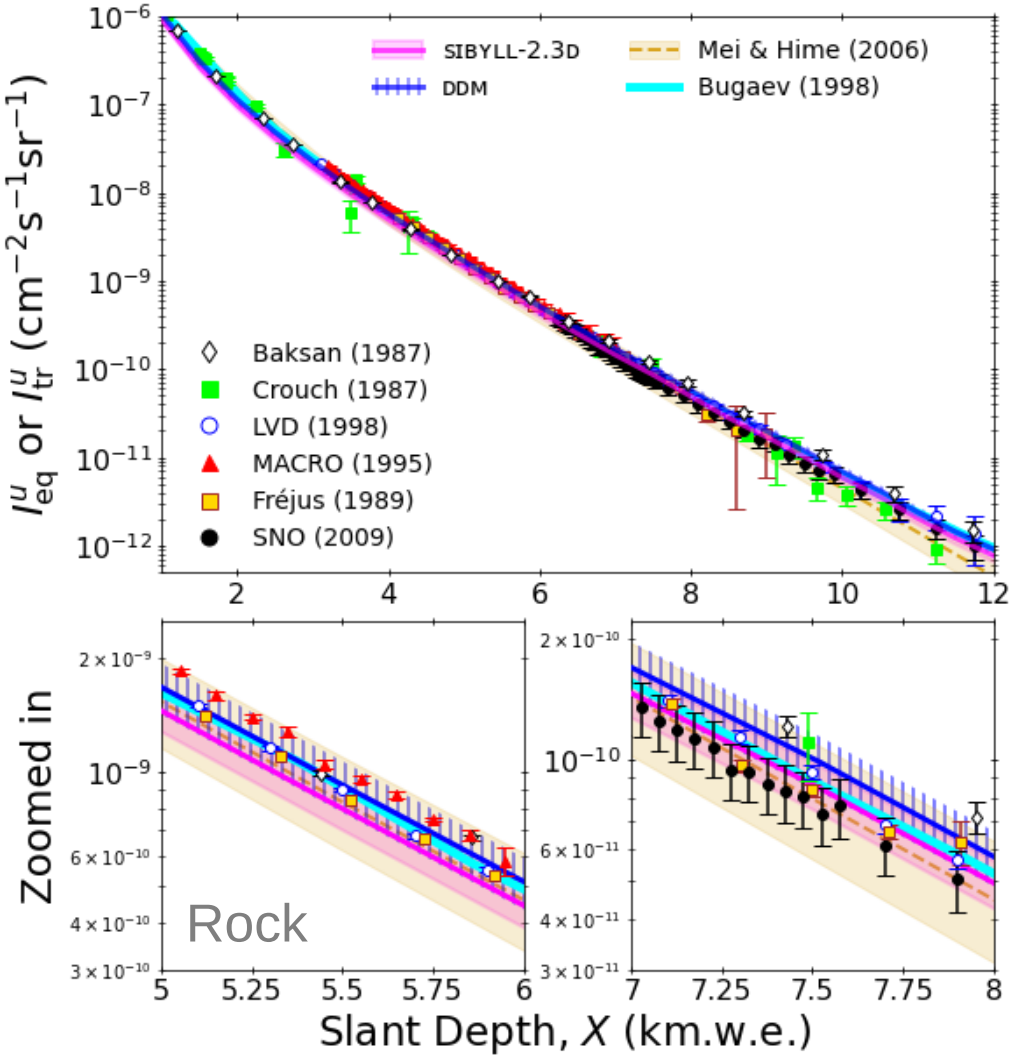
Surface Flux
From MCEq

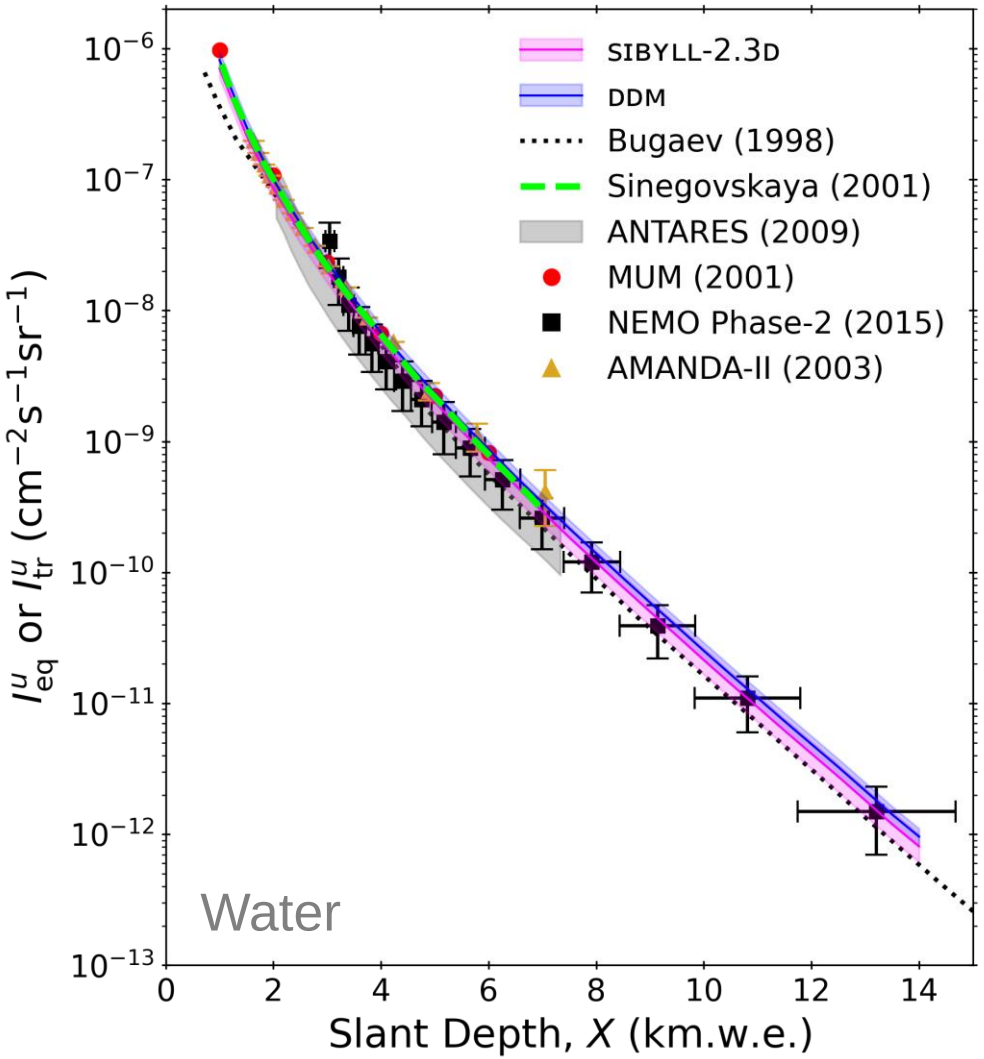
Transfer Tensor
From PROPOSAL

Underground Flux

Results

- Interaction models: DDM [5], SIBYLL-2.3d [3] + Bartol errors [6].

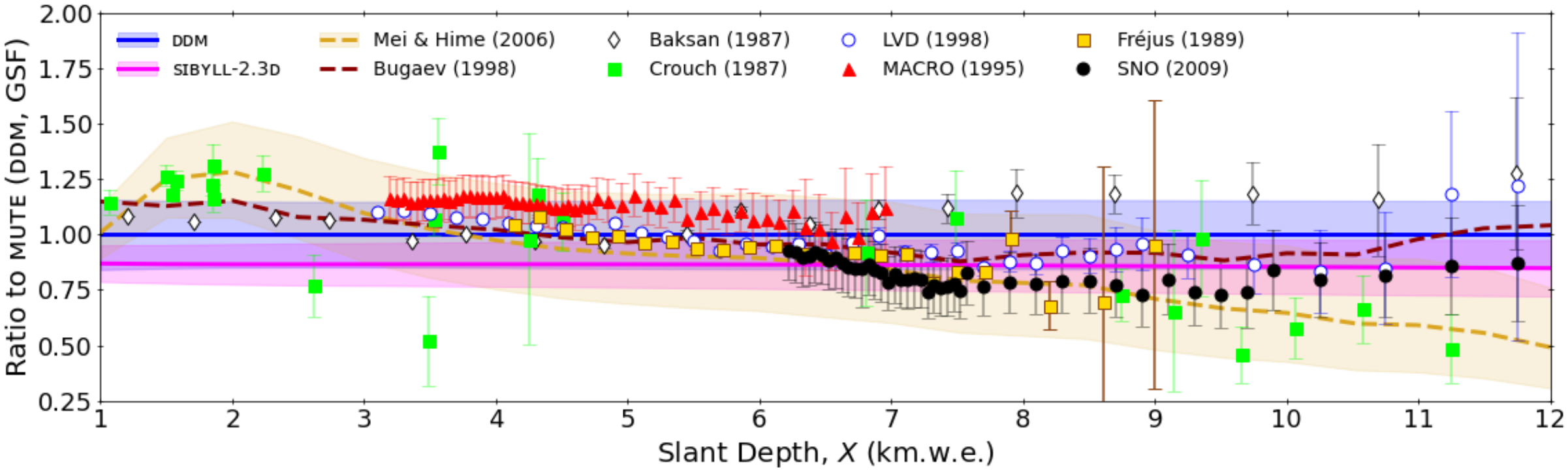




Comparison to Data

- DDM is better at shallow depths, and SIBYLL is better at deep depths.
- Uncertainties on data are smaller than those on theory.

⇒ Theoretical uncertainties on neutrino fluxes may be constrained from 40% down to 10%.



MUTE

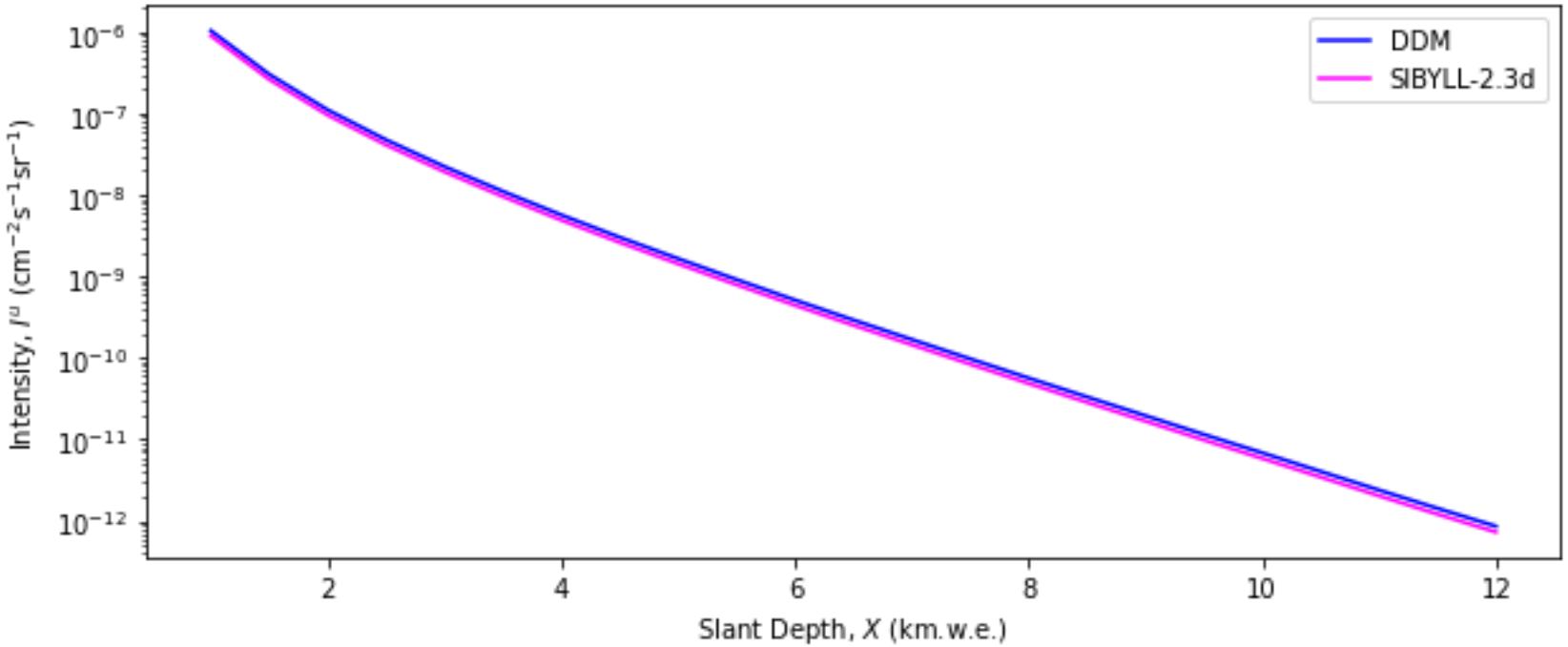
- **MU**on in**T**ensity cod**E**
  - Pure Python
  - Open-source
  - Available to use at https://github.com/wjwoodley/mute

- The computational scheme is described in arXiv:2109.11559, which has been accepted for publication in *The Astrophysical Journal*.

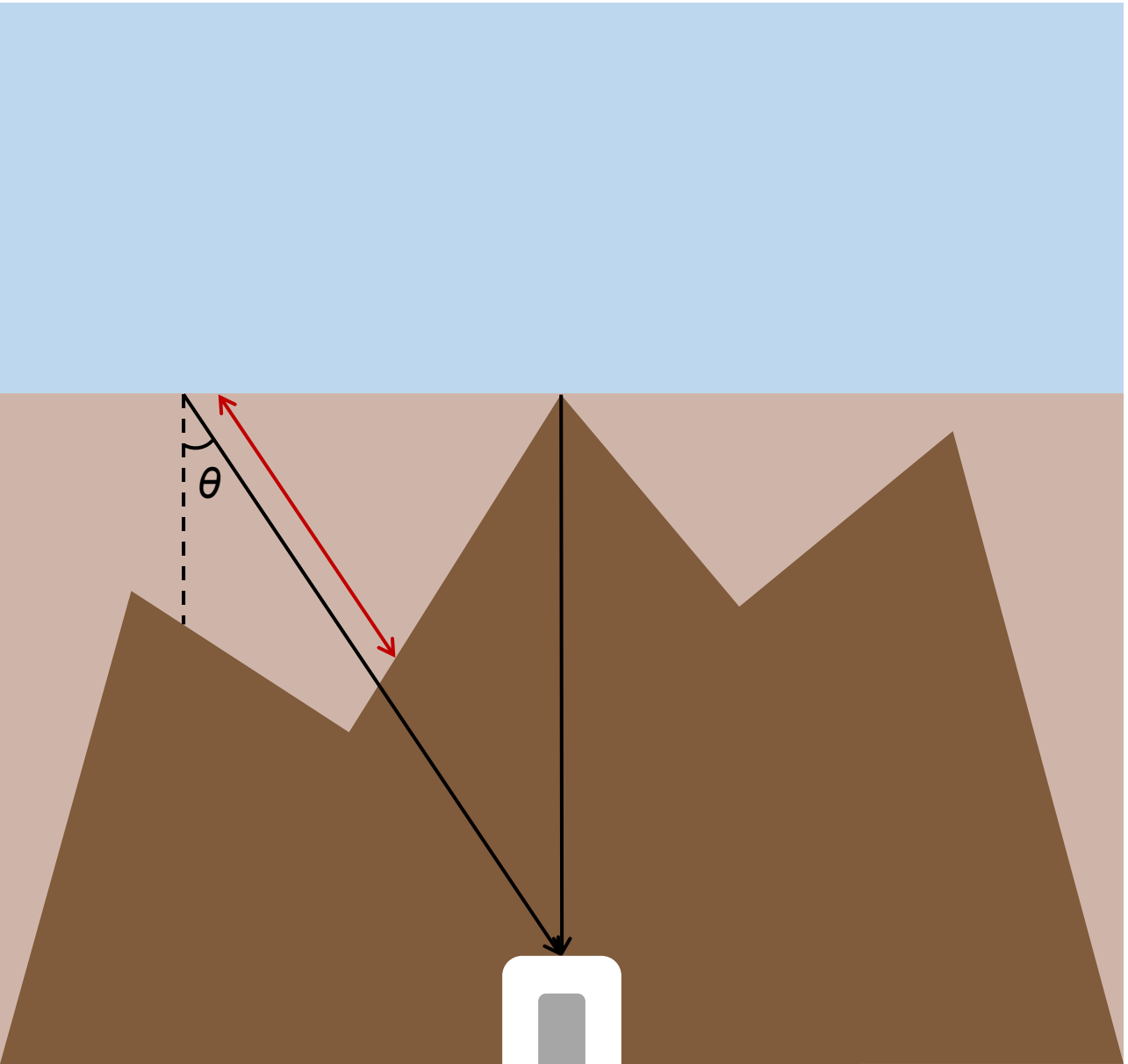
MUTE – Example

```
import mute.constants as mtc
import mute.underground as mtu

mtc.set_overburden("flat")
mtc.set_medium("rock")
mtc.set_density(2.65)

intensities_DDM    = mtu.calc_u_intensities_tr(interaction_model = "DDM")
intensities_SIBYLL = mtu.calc_u_intensities_tr(interaction_model = "SIBYLL-2.3d")
```

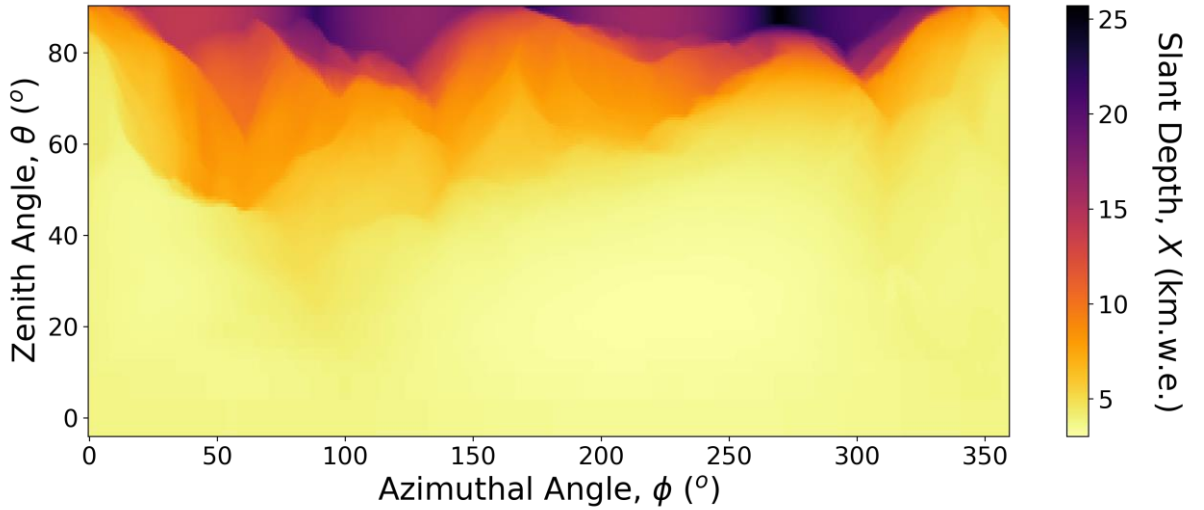
6 seconds

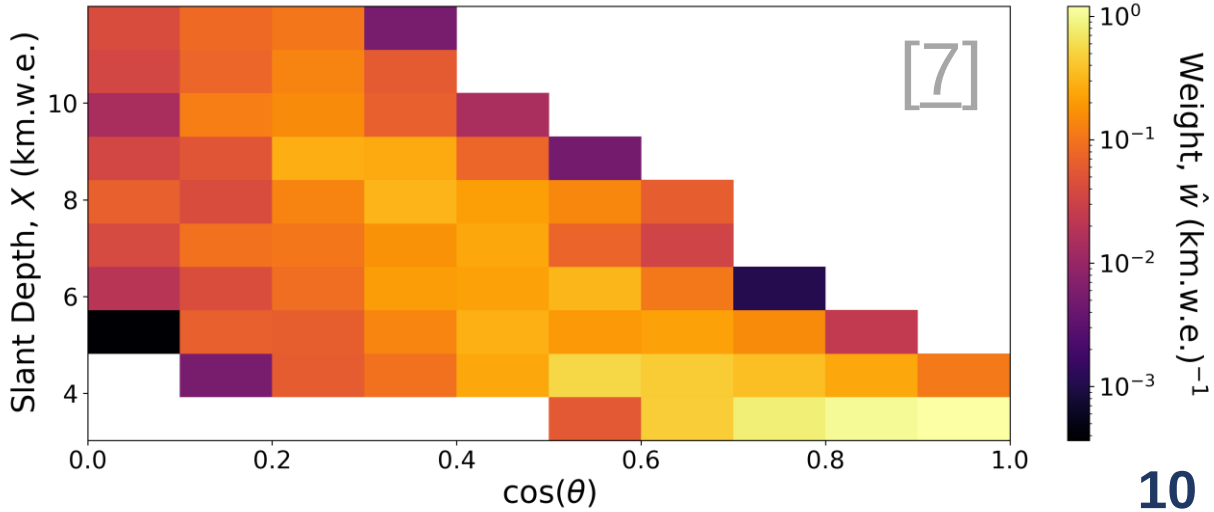


Calculations for Mountains



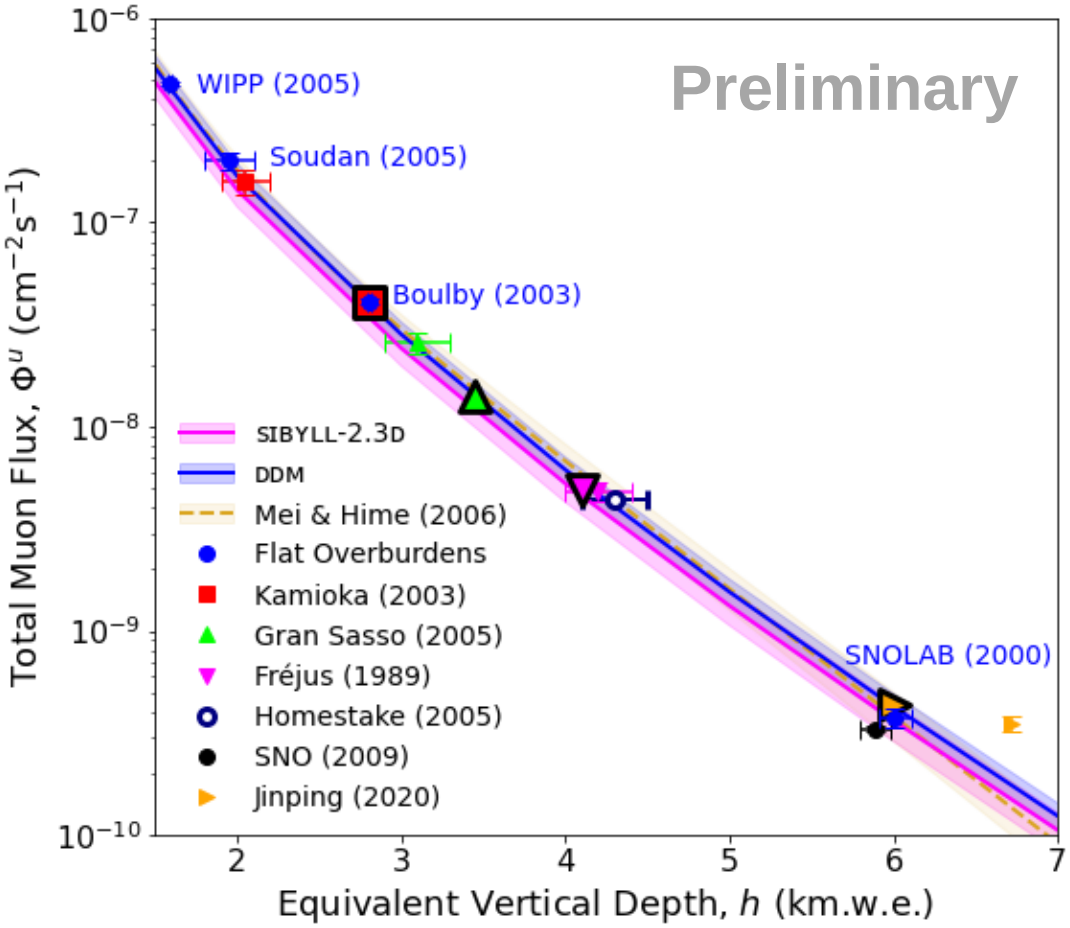
Gran Sasso



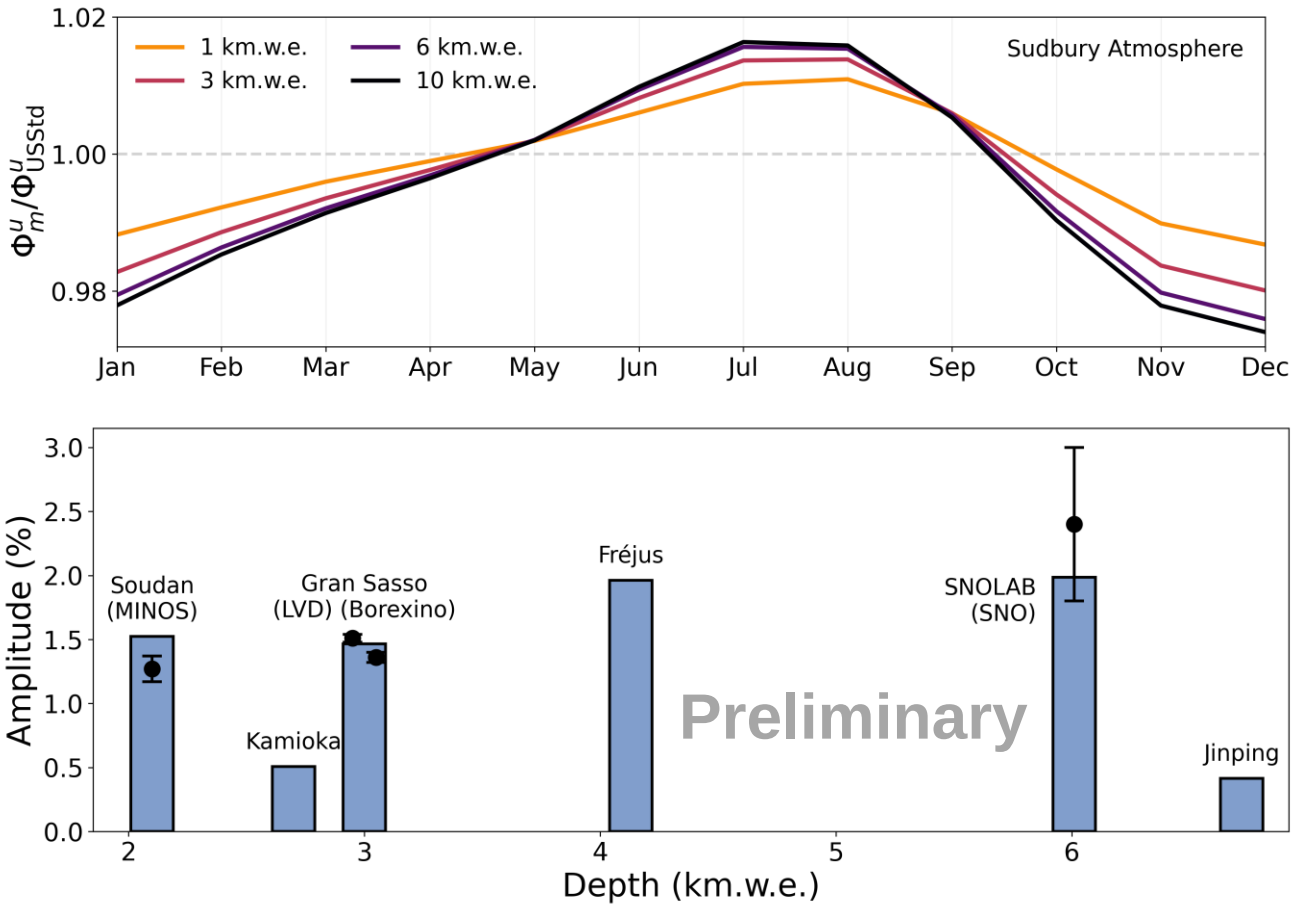


Other Features – Work in Progress

Total Muon Fluxes [7]



Seasonal Variation [7]



Conclusion

- MUTE combines MCEq and PROPOSAL to make predictions for atmospheric muons deep underground and underwater.

- The program is fast, precise, and flexible and the results match experimental data very well.

- It can be used to constrain hadronic and cosmic ray uncertainties, possibly leading to a reduction in the atmospheric neutrino flux uncertainty from 40% to 10%.

- It can currently be used by dark matter and neutrino experiments in labs under flat overburdens and soon mountains. Please use it!

Thank you

References

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Data

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