

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

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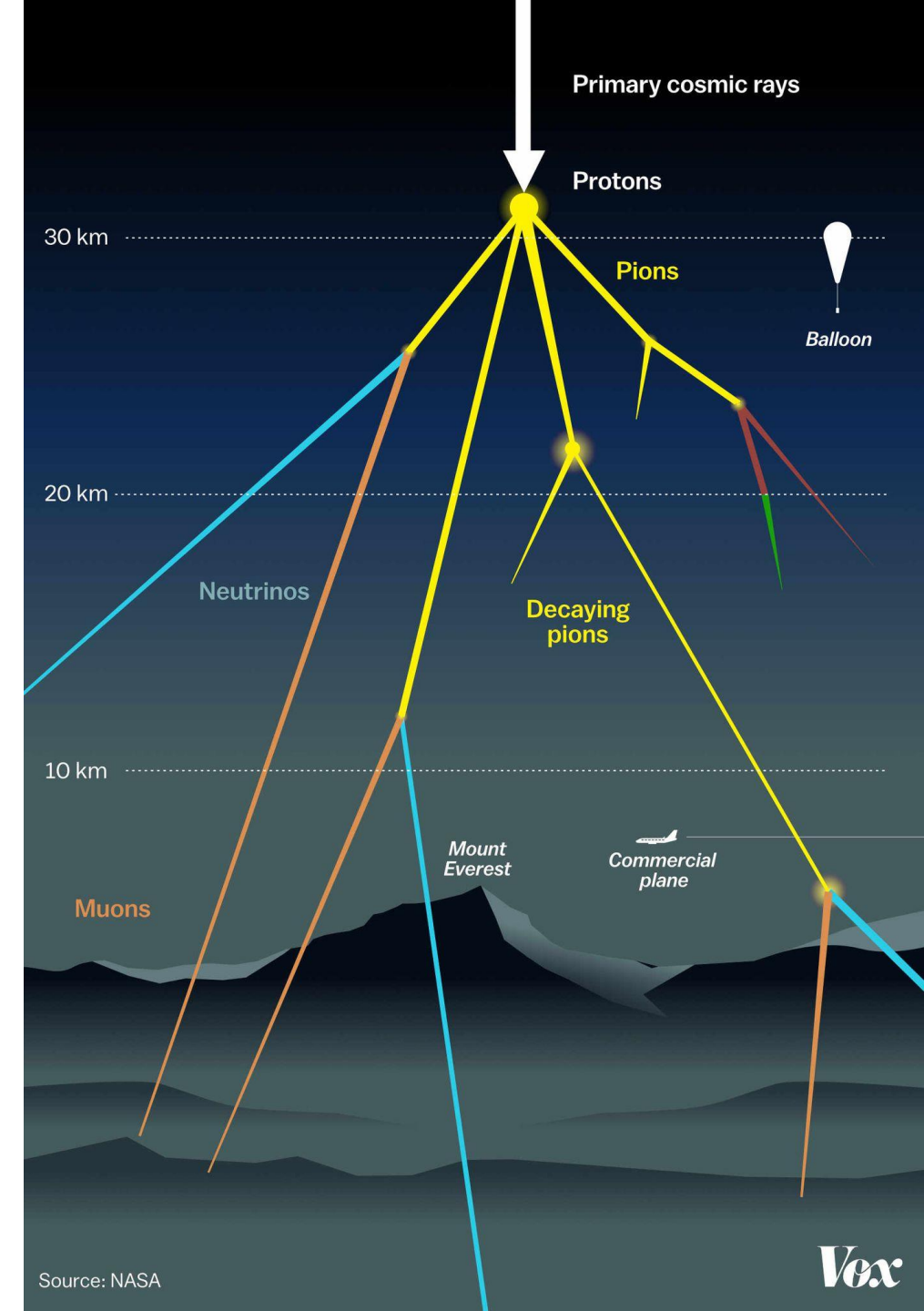
**UNIVERSITY
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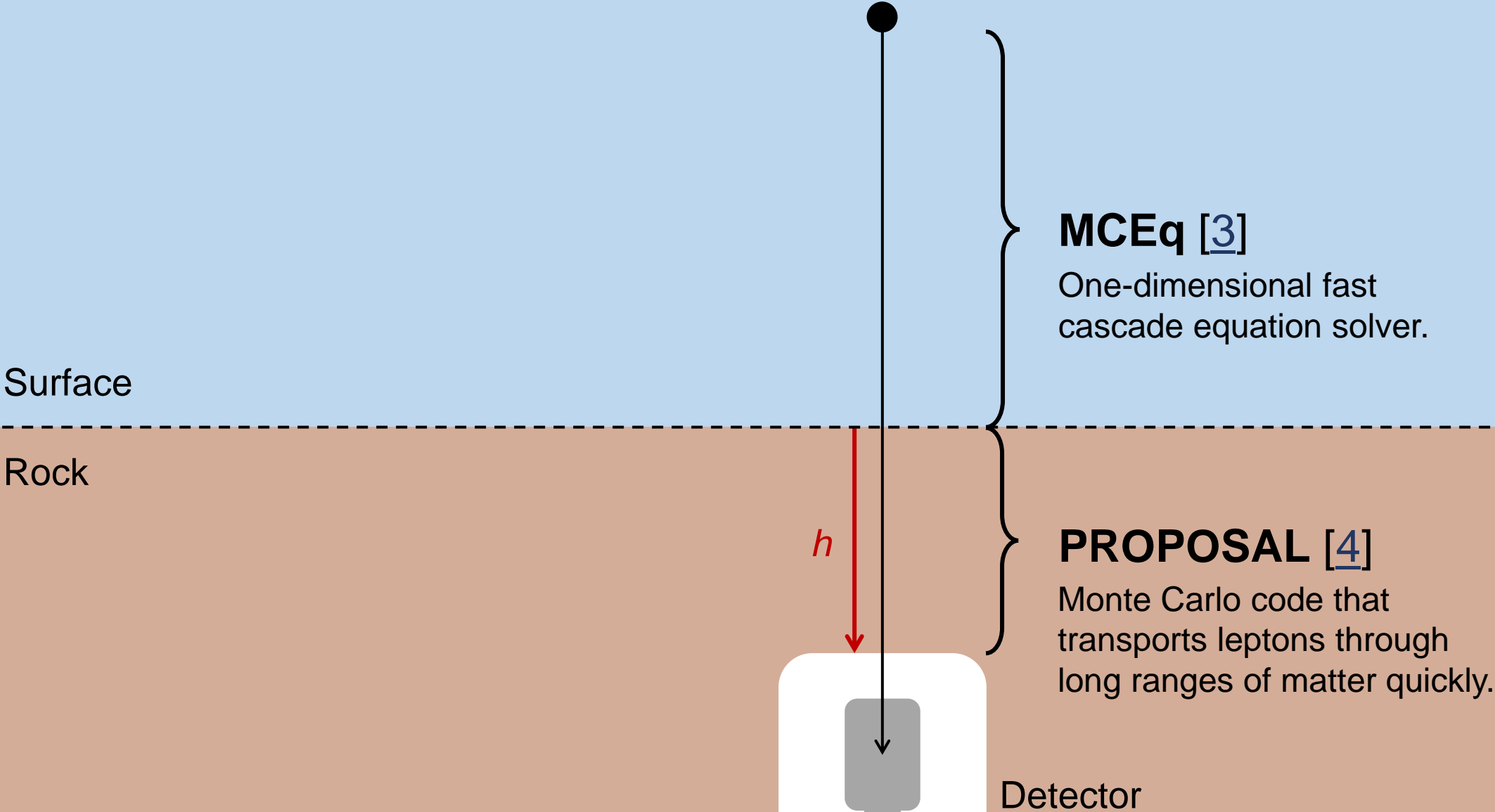


Introduction

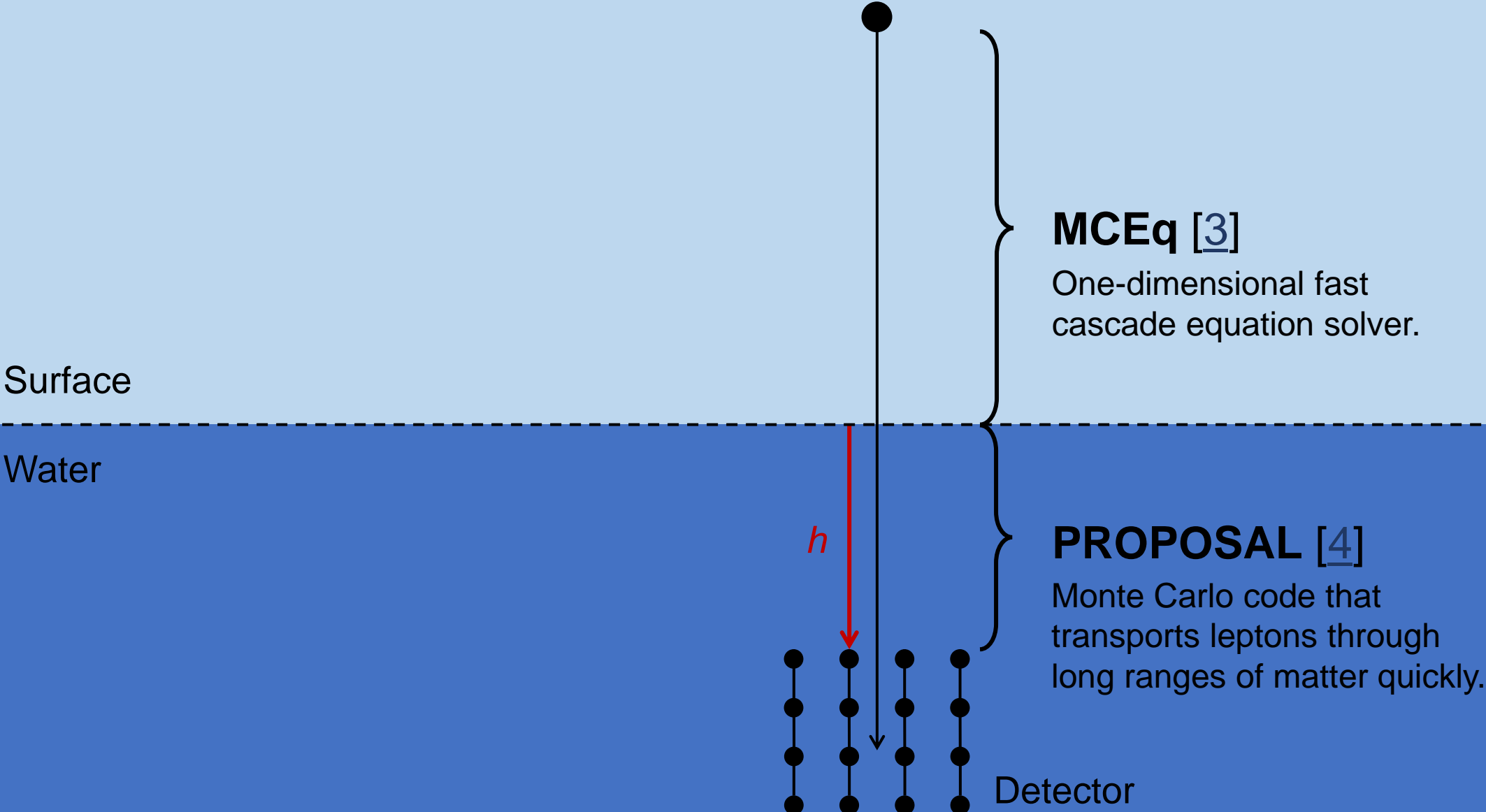
- Underground muons are important for DM and neutrino experiments because they can produce neutrons.
- They can give us information about cosmic rays and neutrinos.
- Not much work has been done in the past 16 years [[1](#), [2](#)].
- Current programs are difficult to use, slow, and depend on fits to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



Simulation Method



Simulation Method

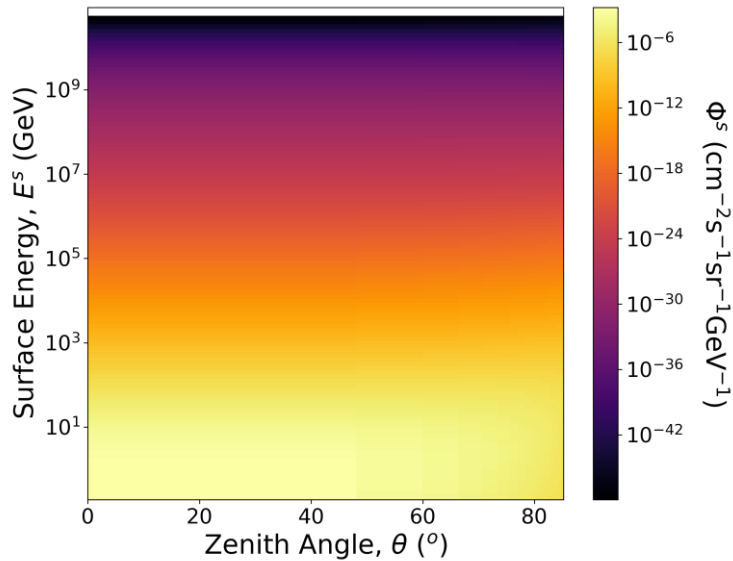


Calculations

- Underground fluxes are calculated using a convolution:

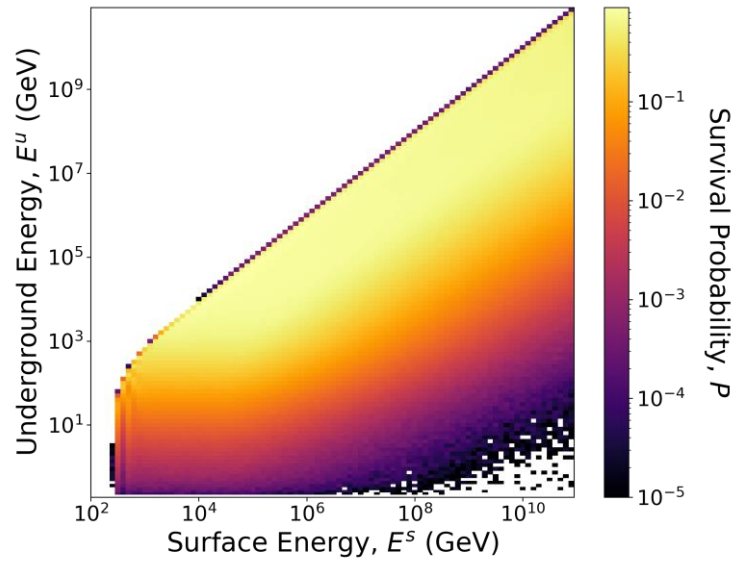
$$\Phi^u(E_j^u, X_k, \theta_k) = \sum_i \Phi^s(E_i^s, \theta_k) P(E_i^s, E_j^u, X_k) \left(\frac{\Delta E_i^s}{\Delta E_j^u} \right)$$

Φ^s



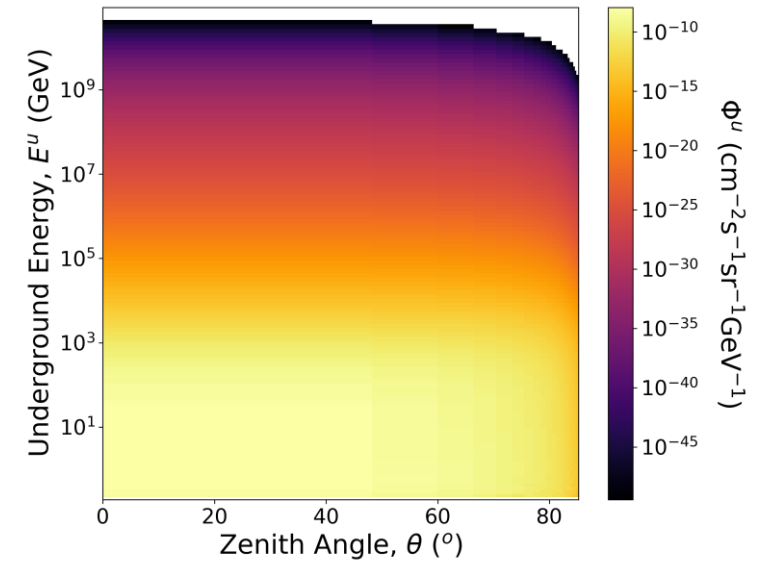
Surface Flux
From MCEq

P



Transfer Tensor
From PROPOSAL

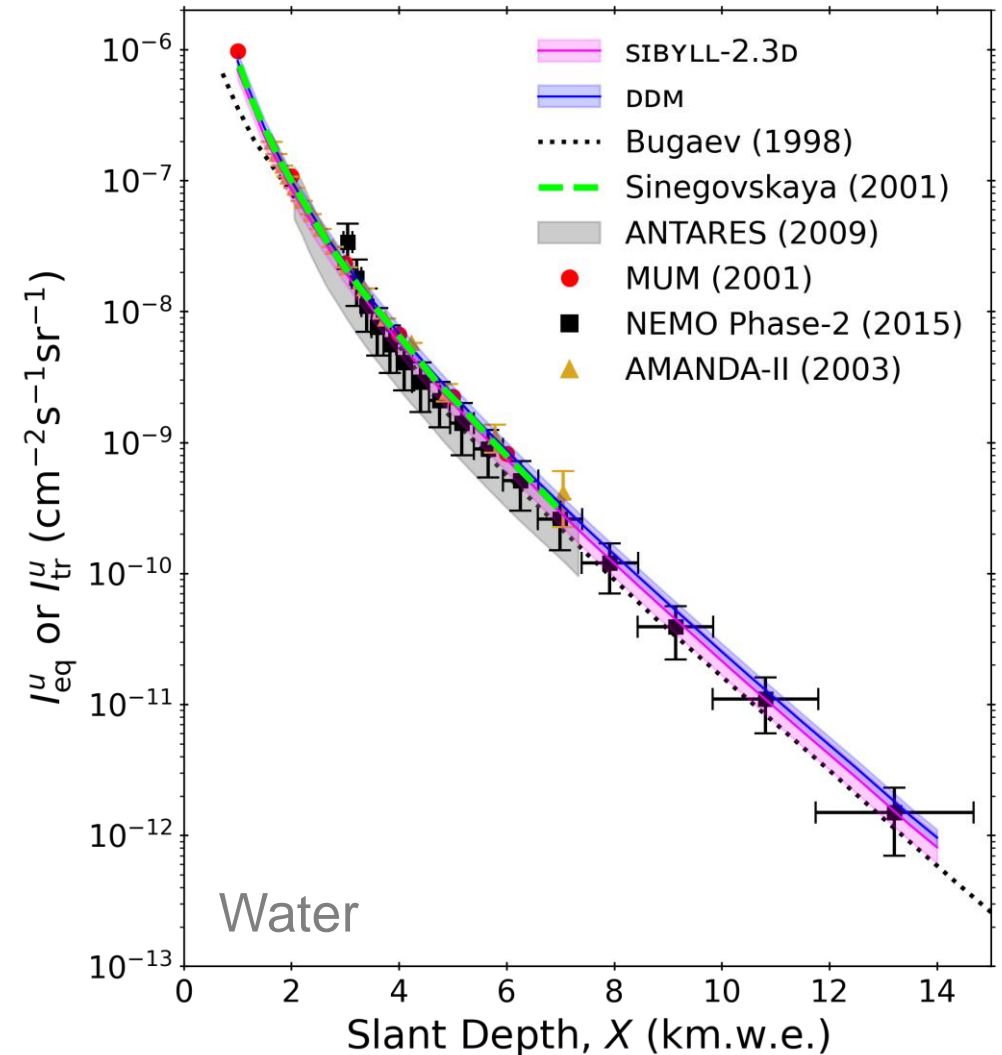
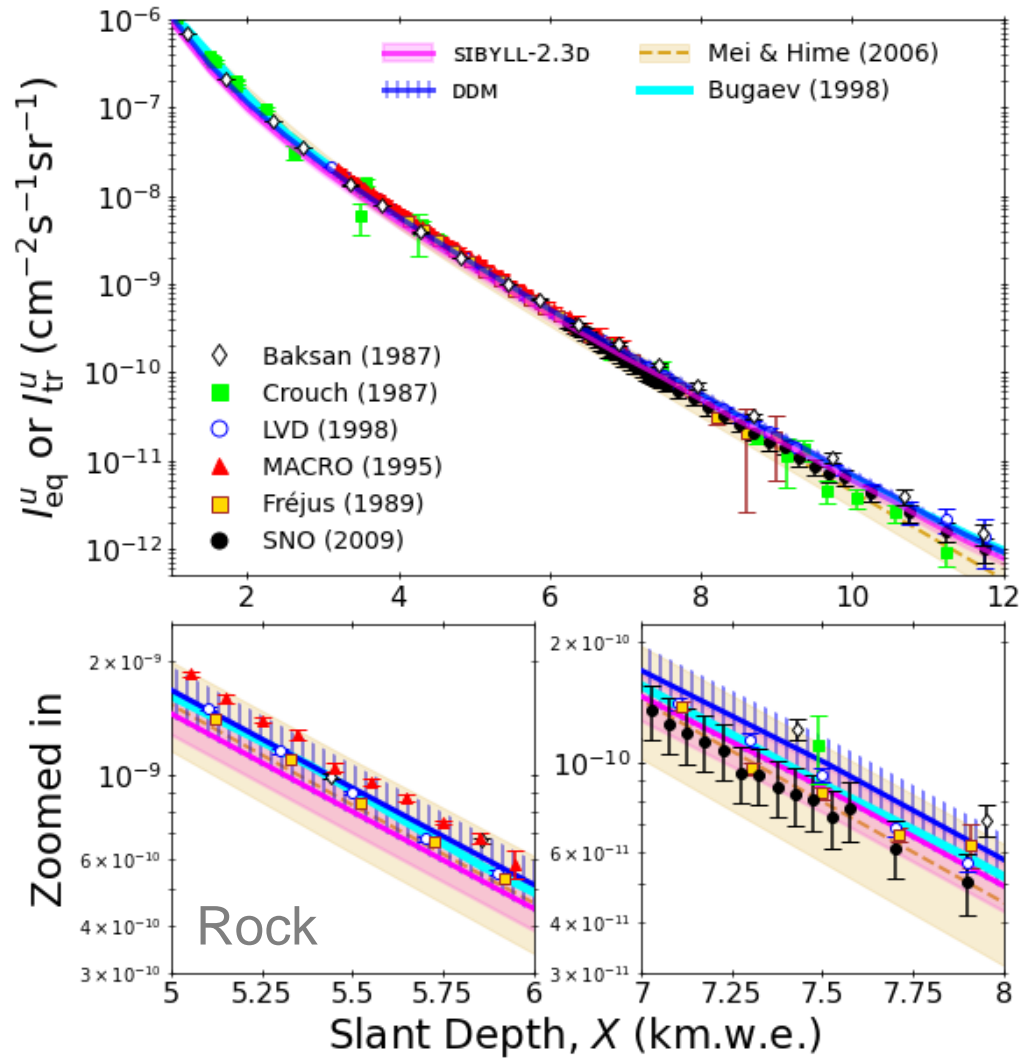
Φ^u



Underground Flux

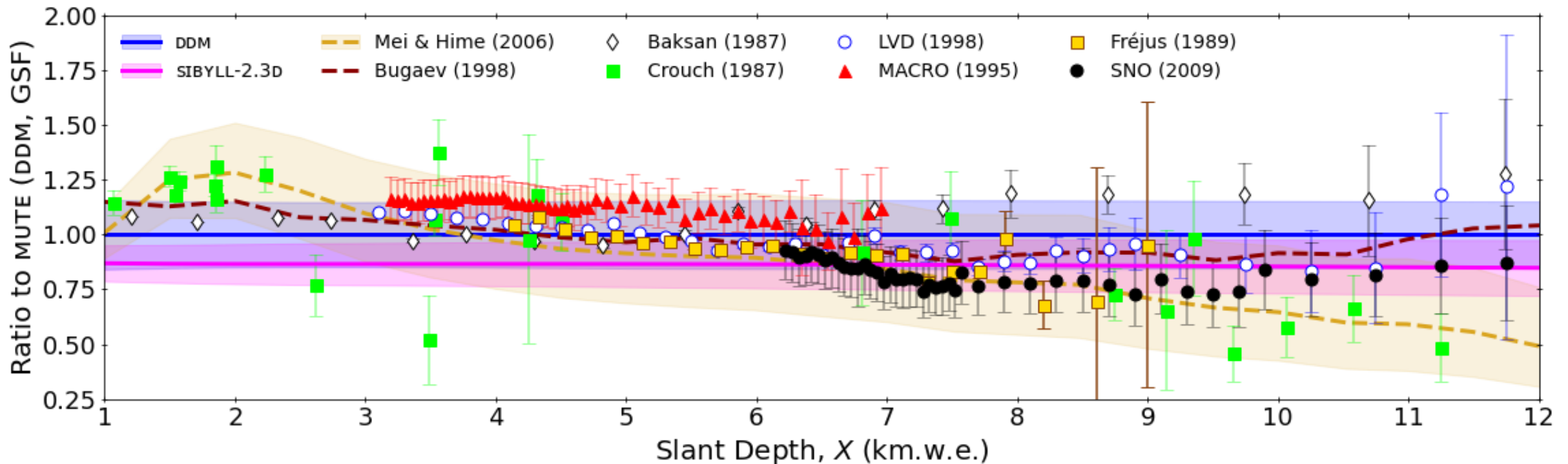
Results

- 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 code**E**
 - Pure Python
 - Open-source
 - Available to use at <https://github.com/wjwoodley/mute>
- The computational scheme is described in [arXiv:2109.11559](https://arxiv.org/abs/2109.11559), which has been accepted for publication in *The Astrophysical Journal*.

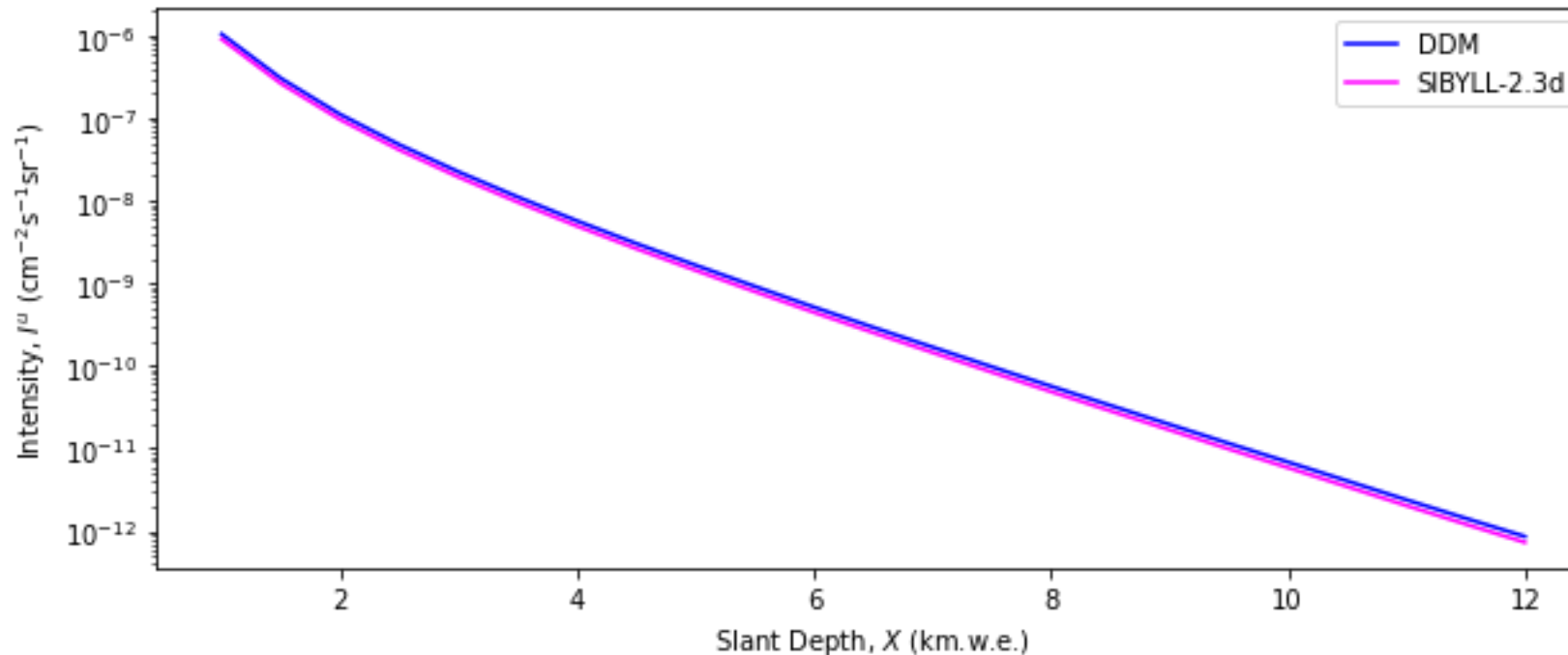
MUTE – Example

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

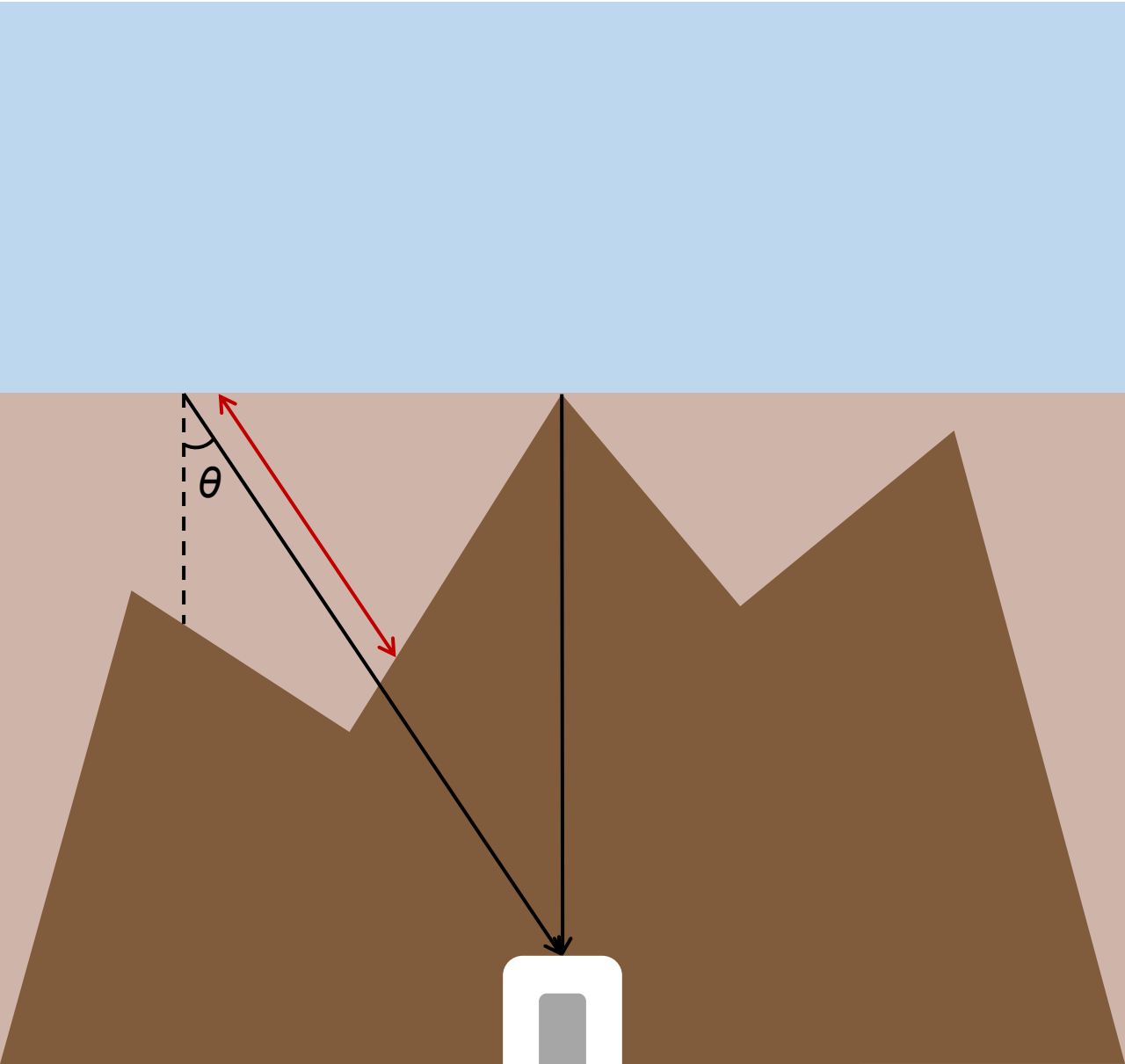
```
mtc.set_overburden("flat")
mtc.set_medium("rock")
mtc.set_density(2.65)
```

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

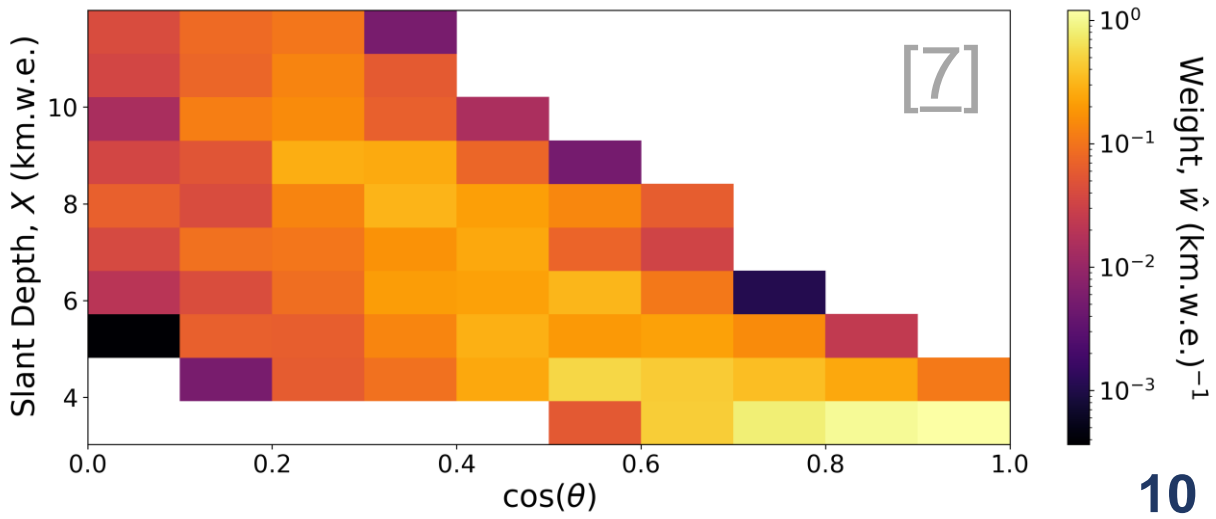
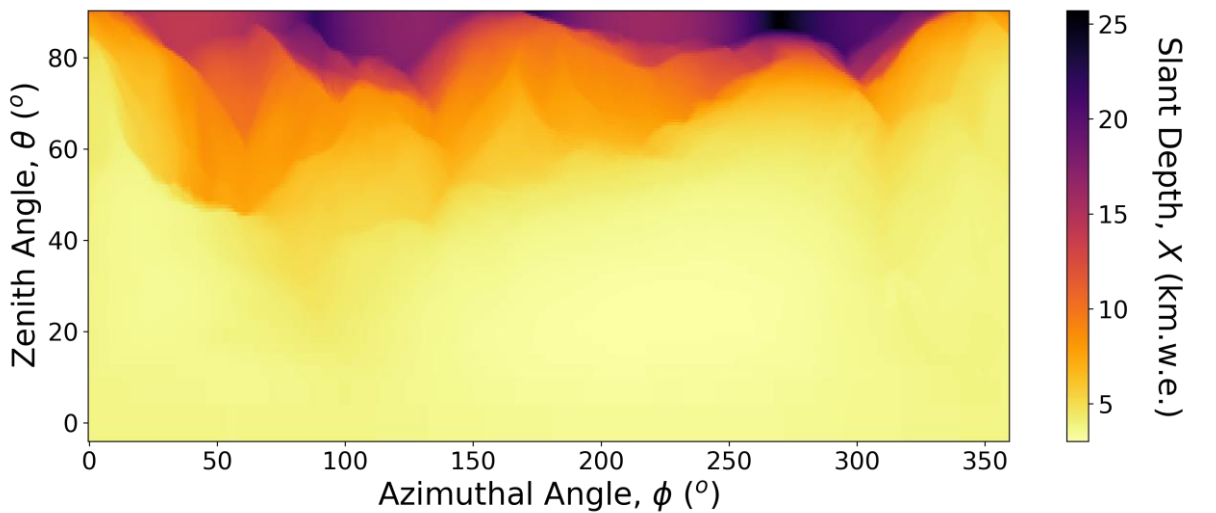
6 seconds



Calculations for Mountains

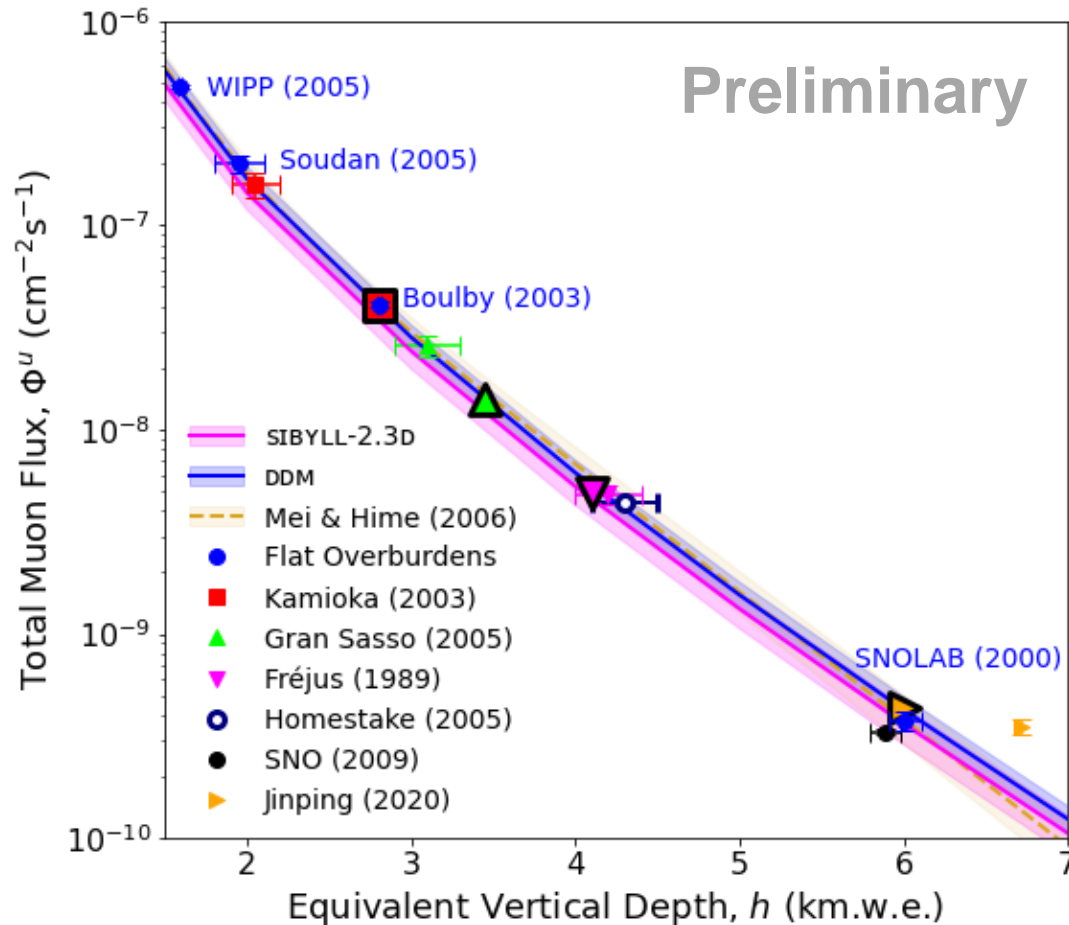


Gran Sasso

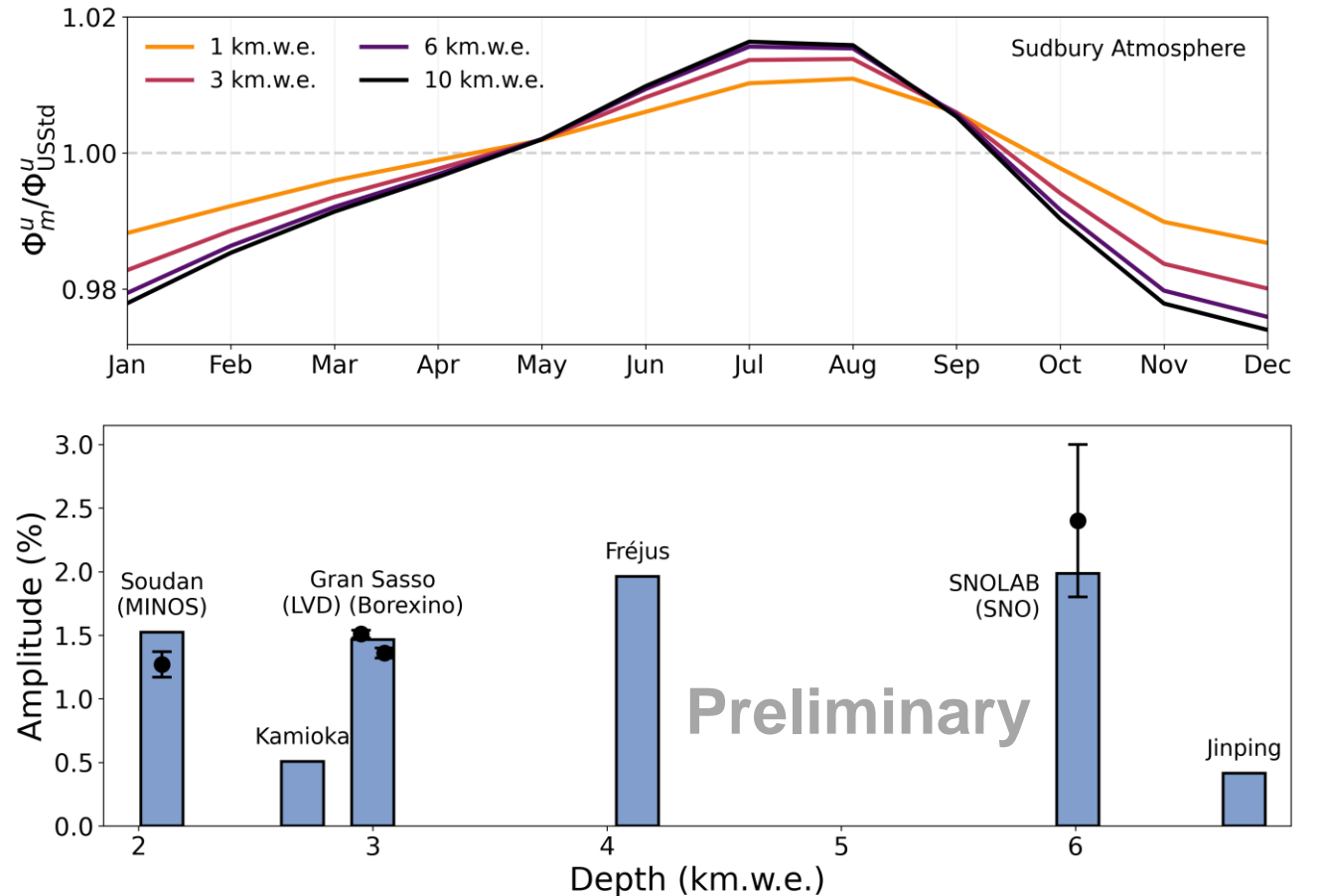


Other Features – Work in Progress

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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