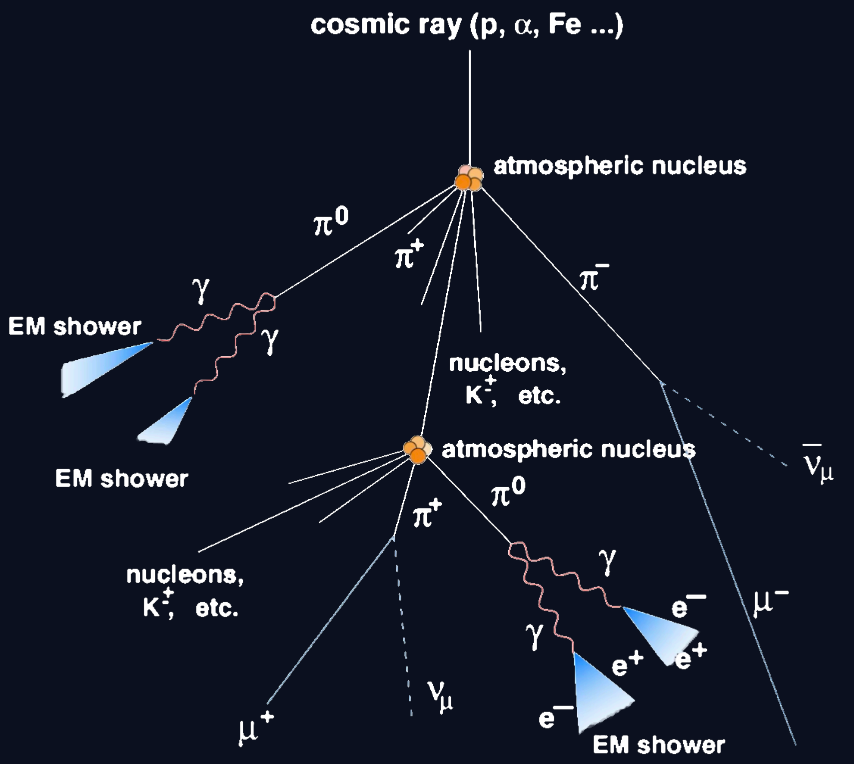
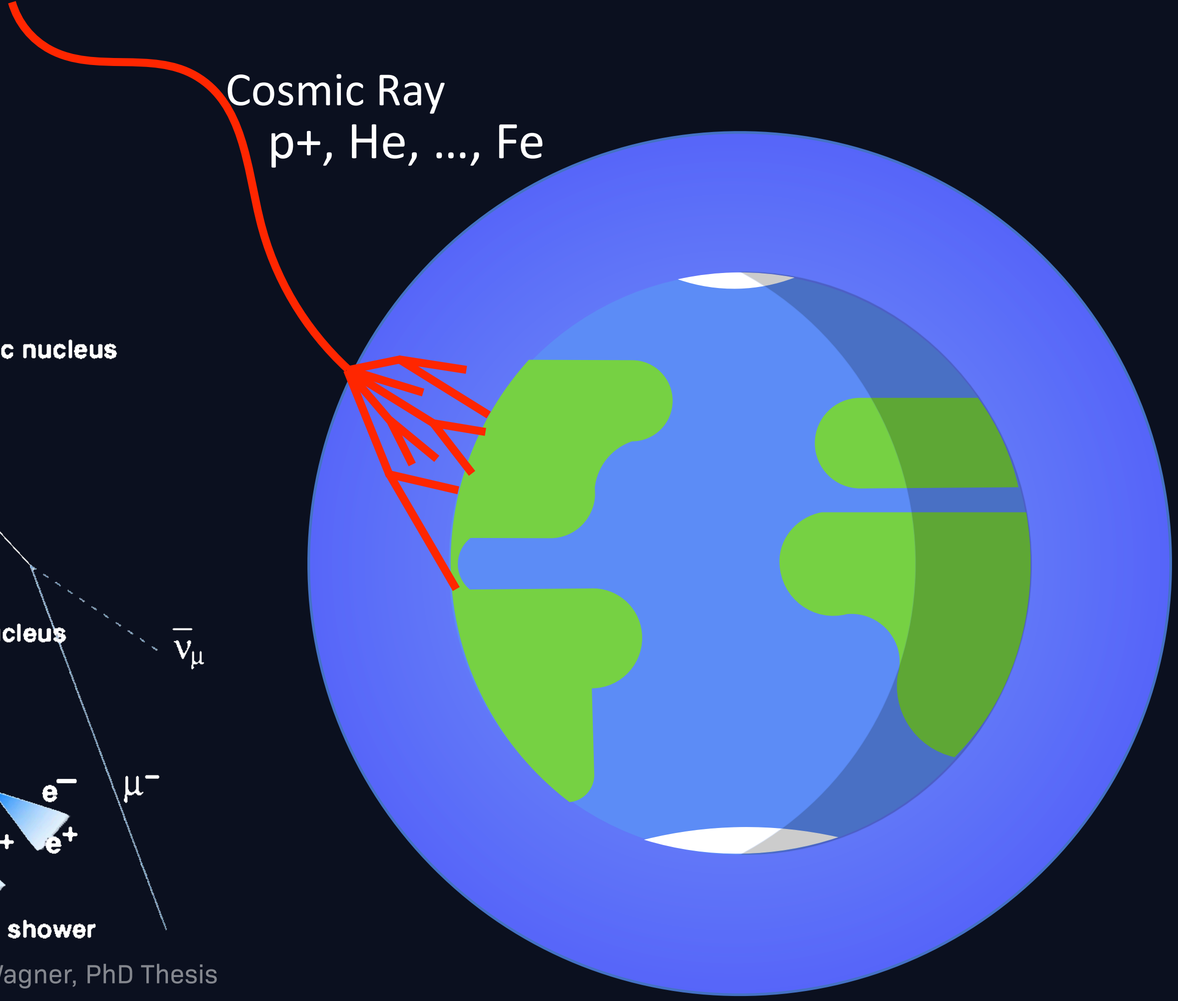
MCEq: Latest Updates and Seasonal Variations

Stefan Fröse | September 2026 | TeVPa

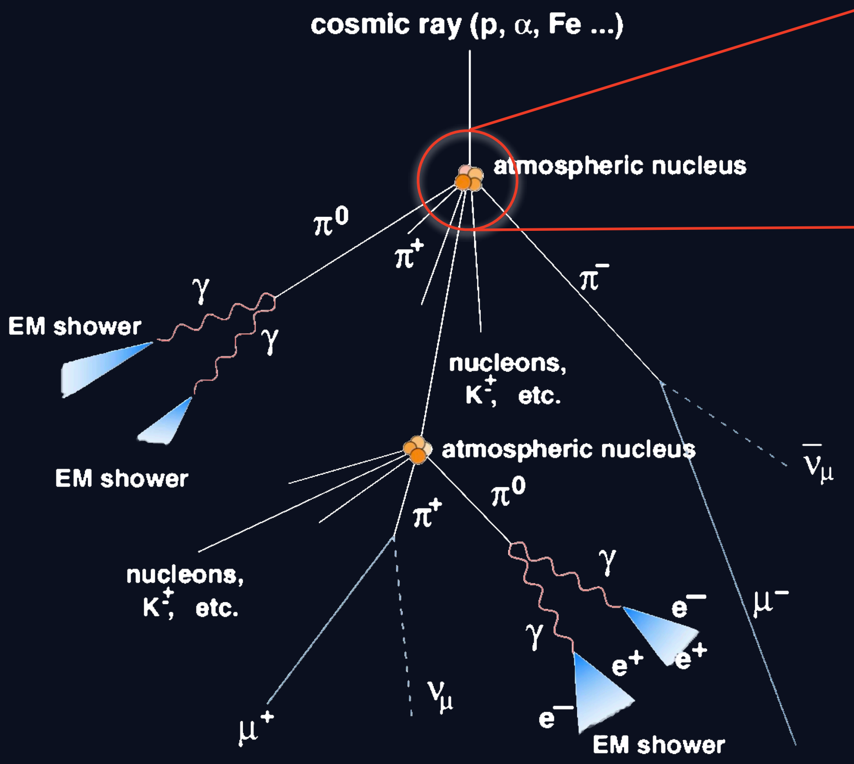
Air Shower



Credit: R.M.Wagner, PhD Thesis



Air Shower



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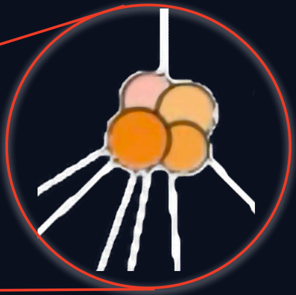
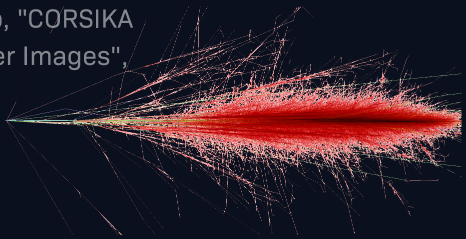


Hadronic Interaction Model

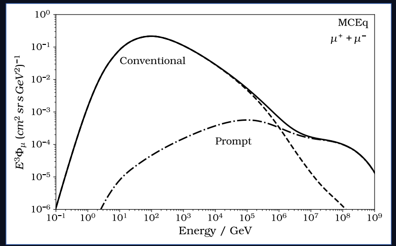
Event-by-Event Generation

Ensemble Expectation

F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005



CORSIKA



MCEq!

Cascade Equations

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{int,h}} - \frac{\Phi_h(E,X)}{\lambda_{dec,h}}$$

Sink Term

$$-\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X))$$

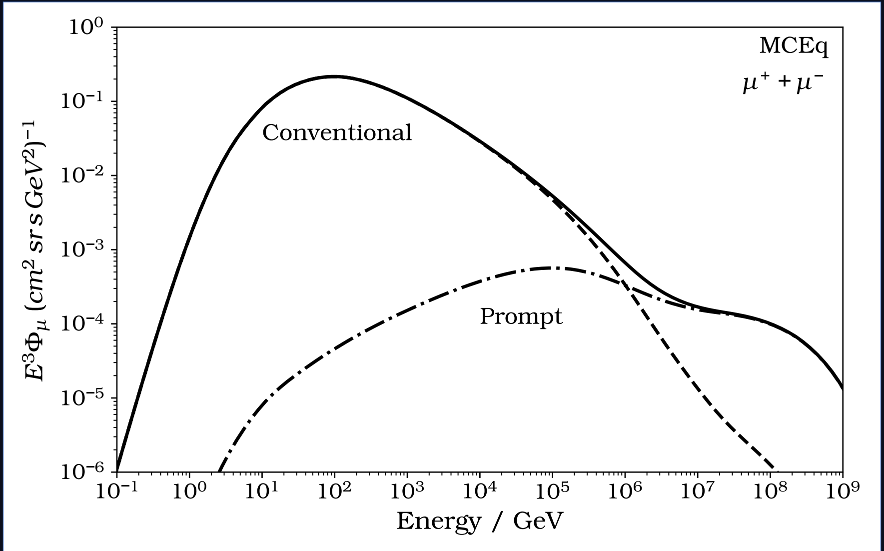
Radiative Losses

$$+\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{int,l}(E_k)}$$

$$+\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{dec}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{dec,l}(E_k)}$$

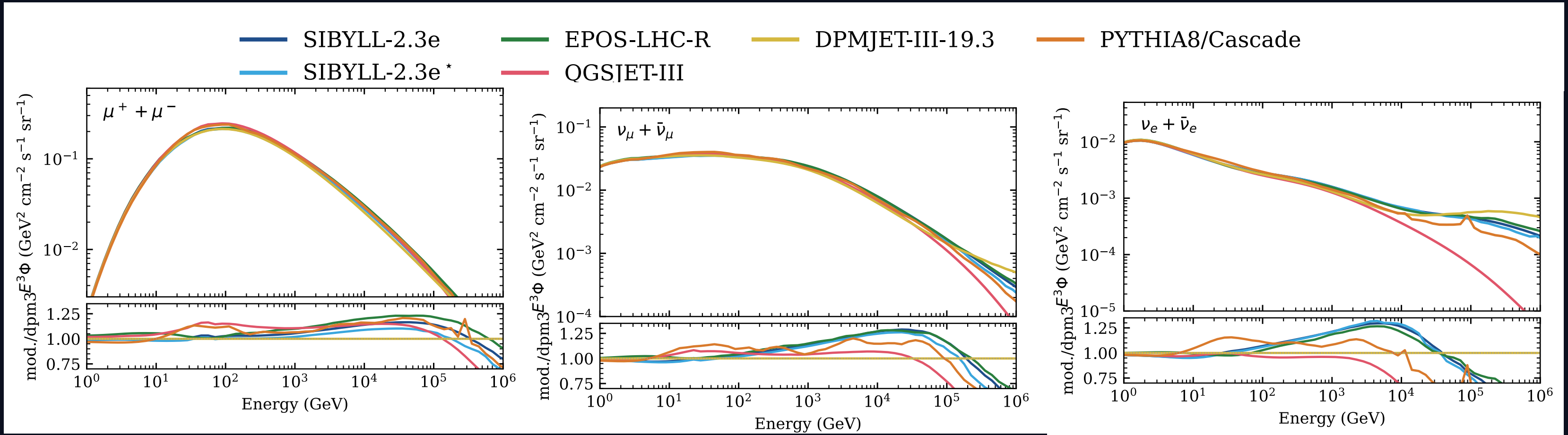
Source Terms

MCEq solves equation system and provides lepton fluxes!



MCEq Update

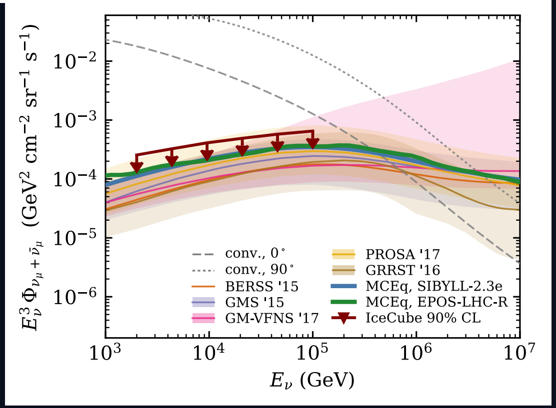
Conventional Flux



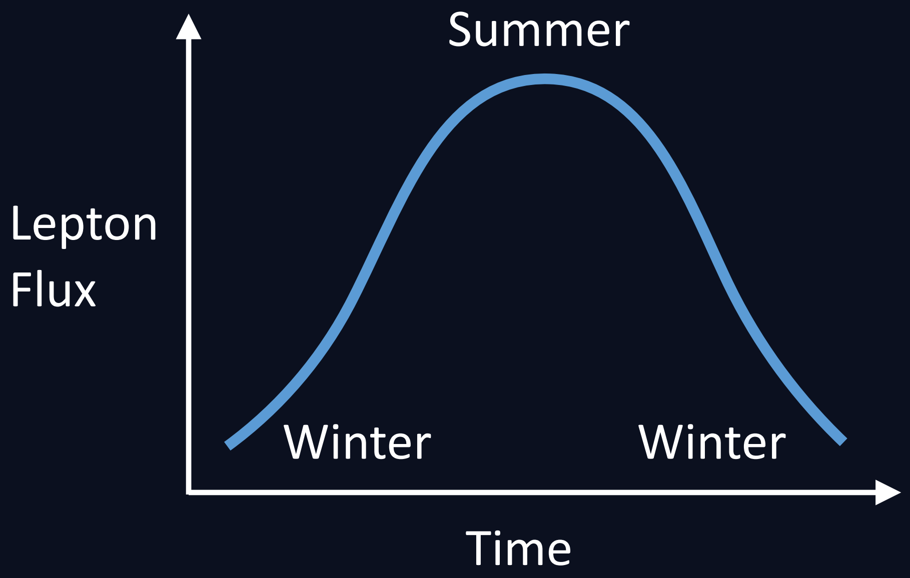
Pythia new in MCEq v2, others already available in MCEq 1.4

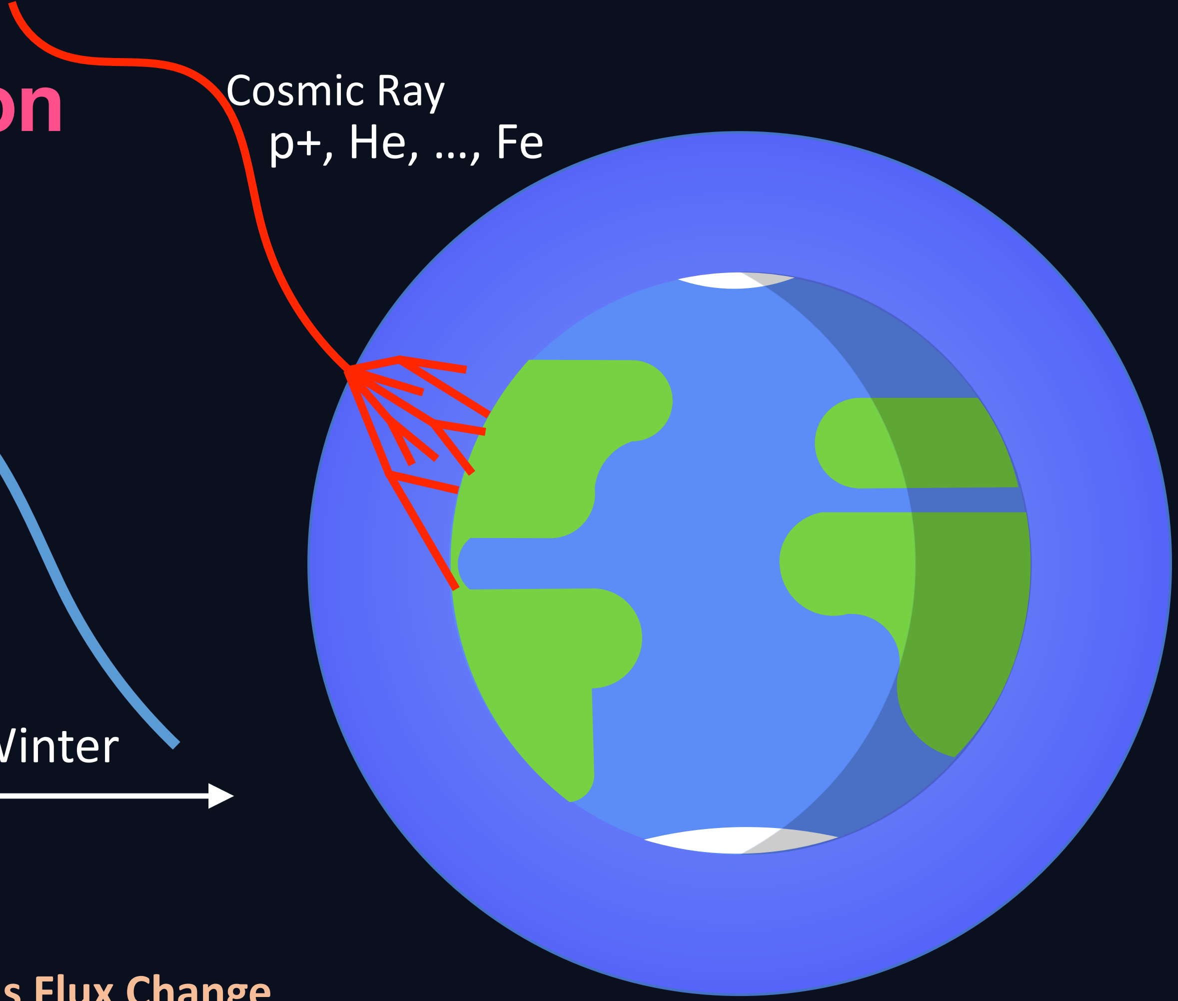
Angantyr and FLUKA on the way

Prompt Flux

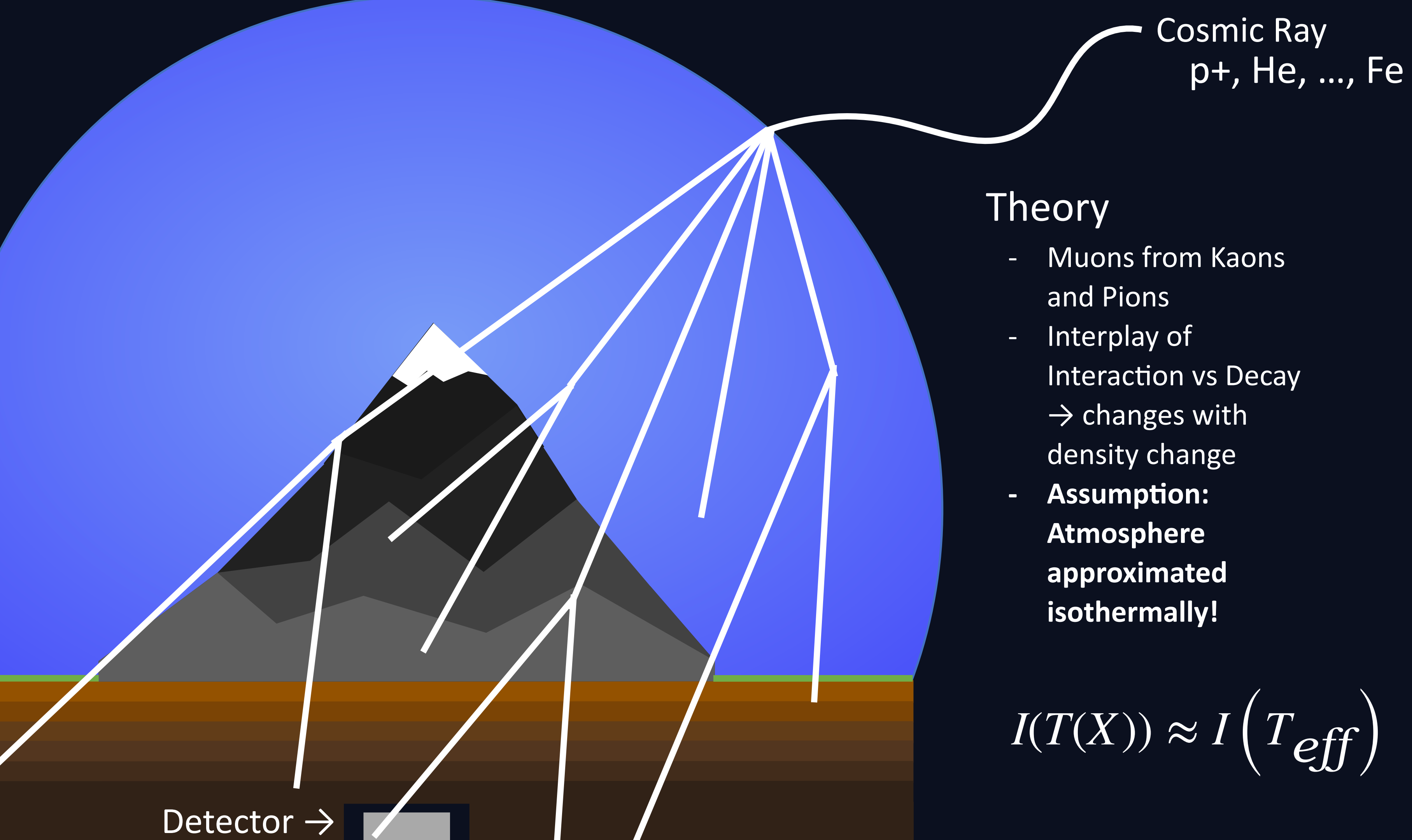


Seasonal Variation





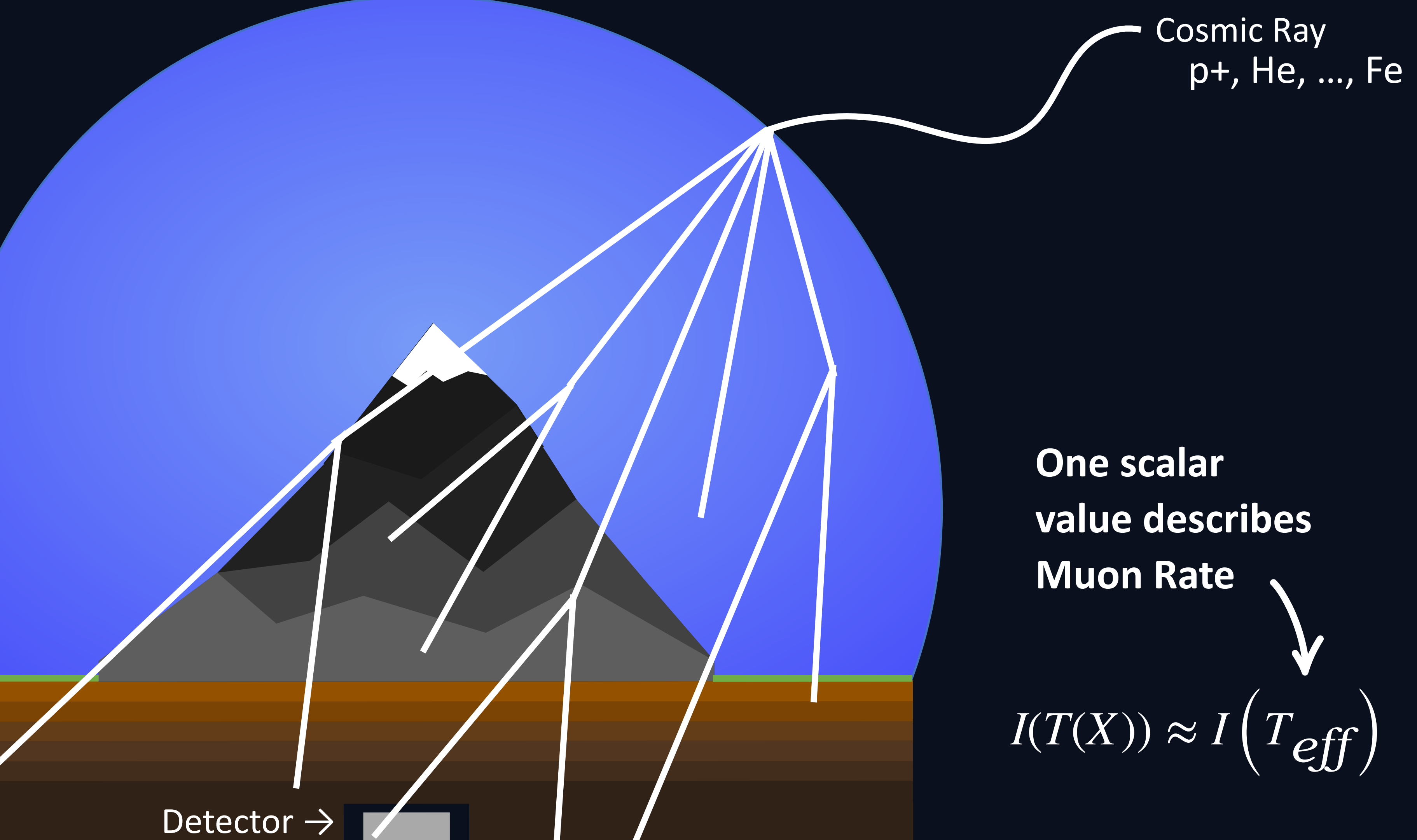
Temperature Change yields Flux Change



Theory

- Muons from Kaons and Pions
- Interplay of Interaction vs Decay → changes with density change
- **Assumption: Atmosphere approximated isothermally!**

$$I(T(X)) \approx I\left(T_{eff}\right)$$



One scalar value describes Muon Rate

$$I(T(X)) \approx I\left(T_{eff}\right)$$

Cosmic Ray
p+, He, ..., Fe

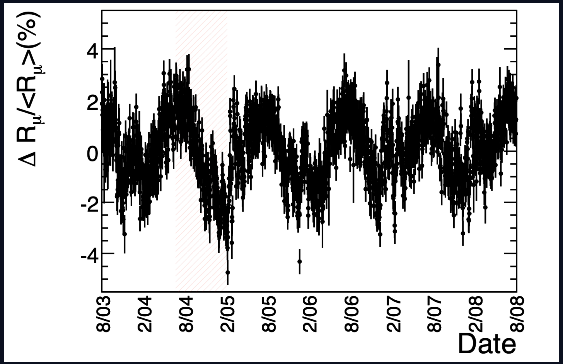
$$\boxed{\frac{\Delta I}{I} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}}}$$

One scalar value describes Muon Rate

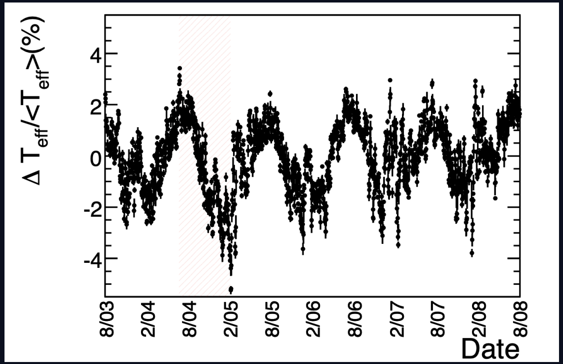
$$I(T(X)) \approx I\left(T_{eff}\right)$$

How do you measure α_T?

1. Detector measures muon rate over time

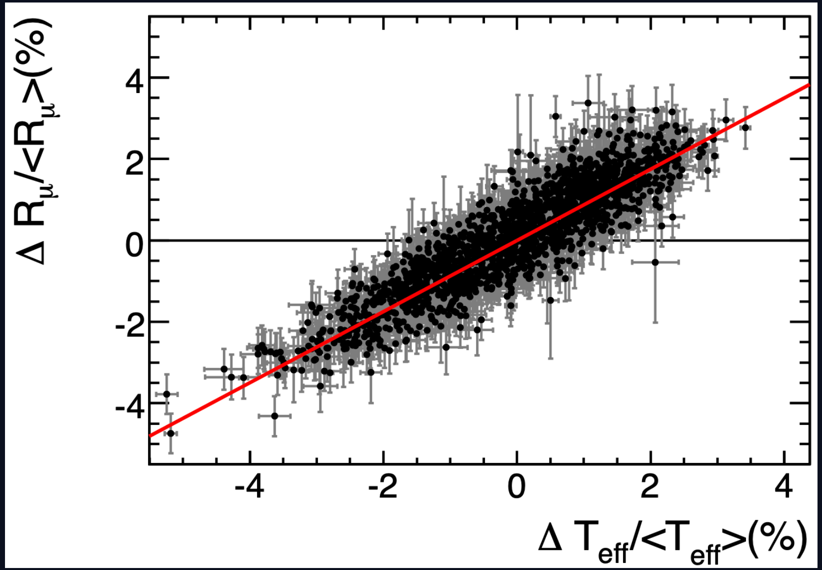


2. Calculate T_{eff}



3. Fit the slope

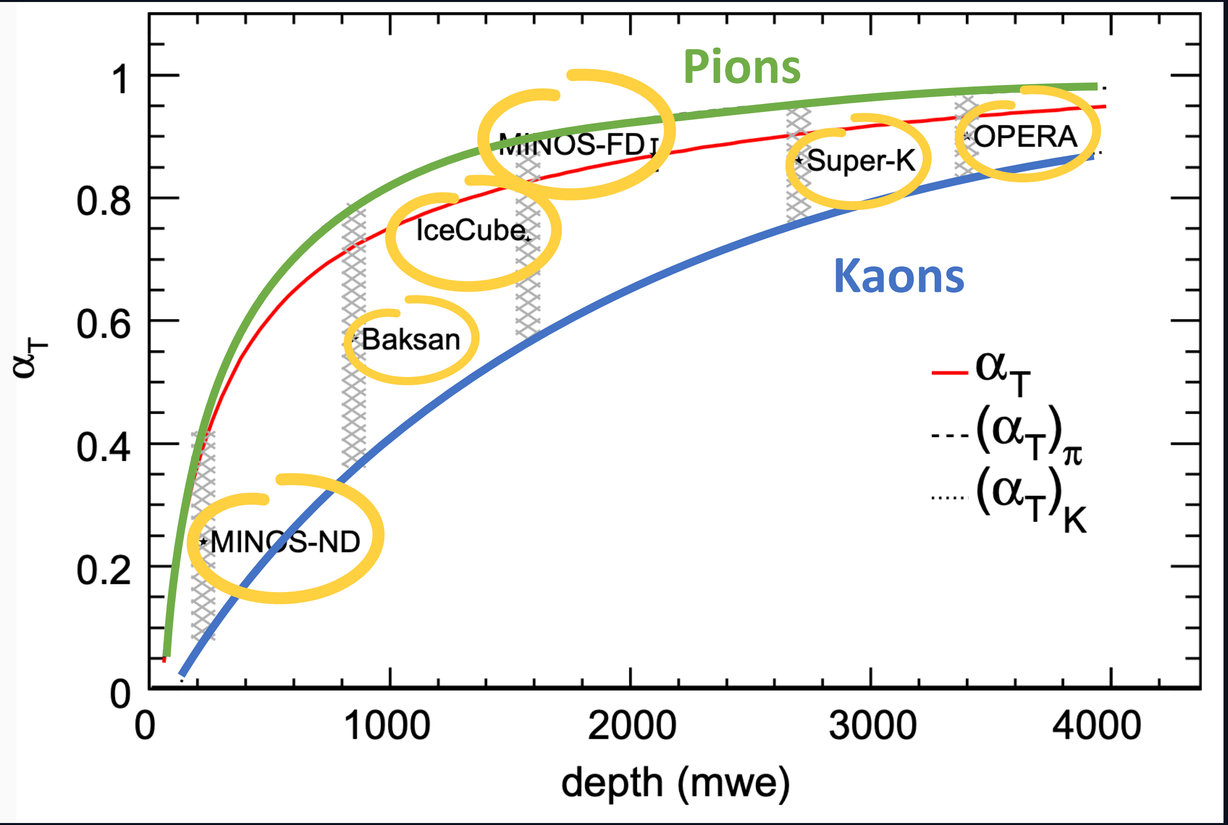
$$\frac{\Delta I}{I} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}}$$



MINOS Collaboration, 2010, PRD , arxiv:0909.4012

α_T as a probe for hadronic physics

- Depends on Depth, because it changes the energy threshold
- Separate theoretical Solution for Kaons and Pions

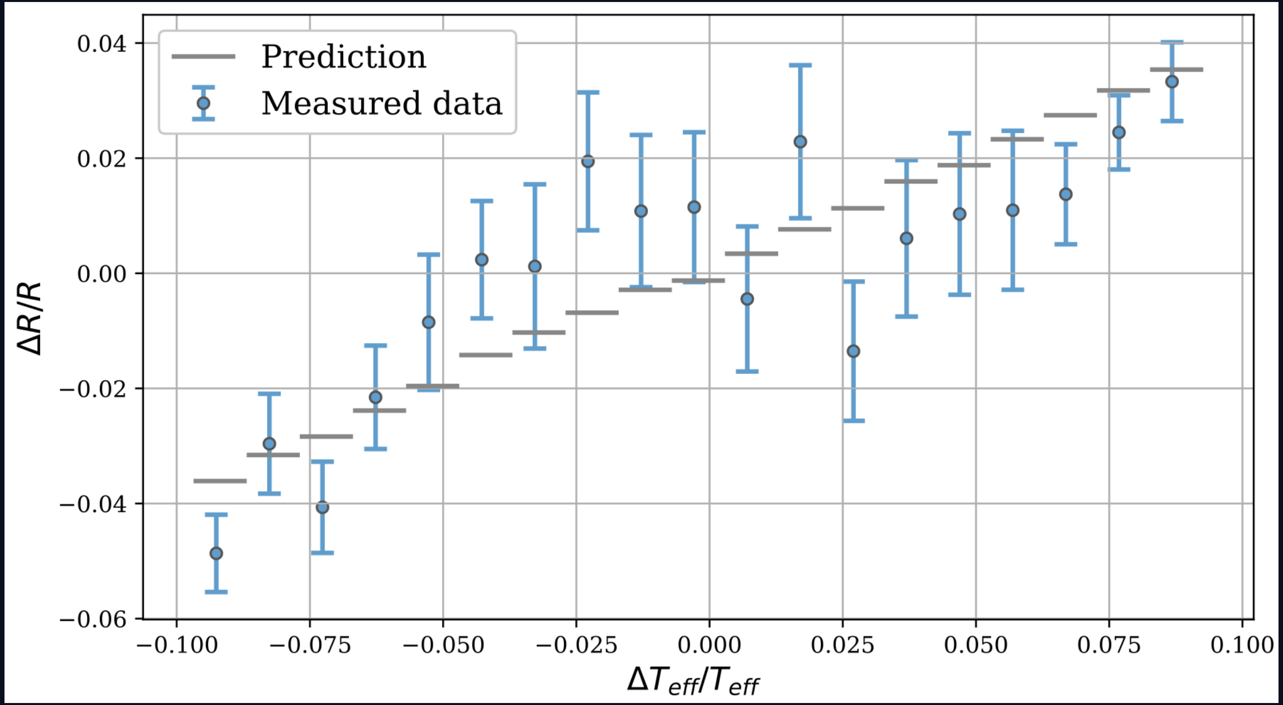


- Different Detectors have different overburden therefore measure different α_T

Grashorn et al., 2010, Astropart. Phys., arxiv: 0909.5382

The Tension

- Seasonal Variations of muon neutrinos measured by IceCube

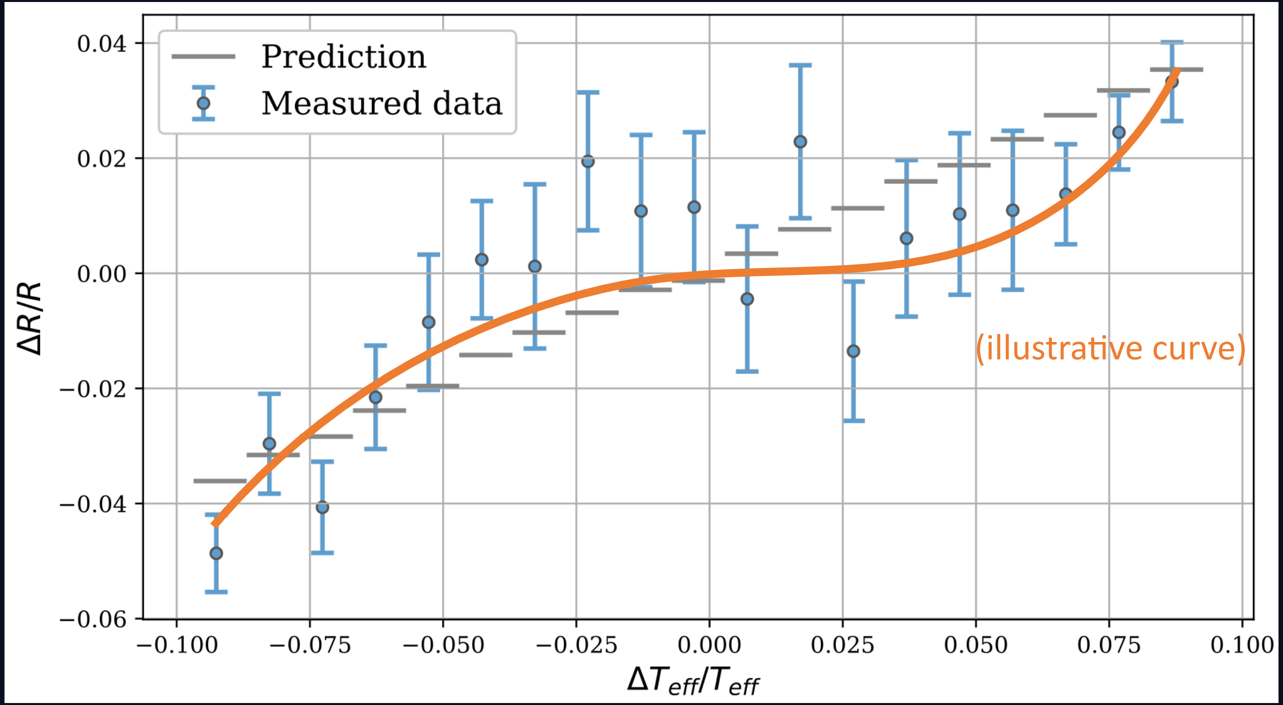


IceCube Collaboration, 2023, EPJC 83, 2303.04682

The Tension

Also called: Salsa Curve

- Seasonal Variations of muon neutrinos measured by IceCube



IceCube Collaboration, 2023, EPJC 83, 2303.04682

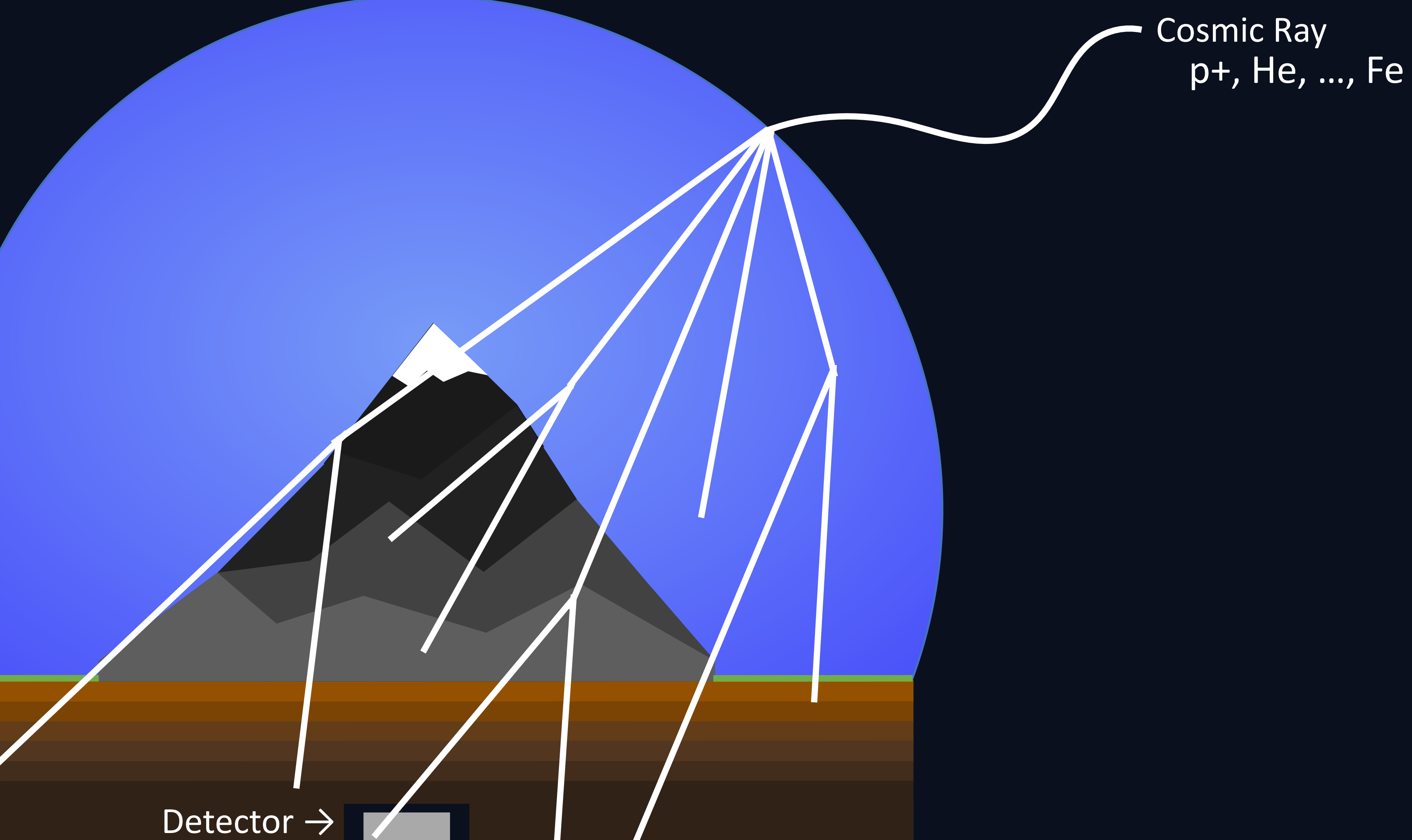
Not Linear as Expected!

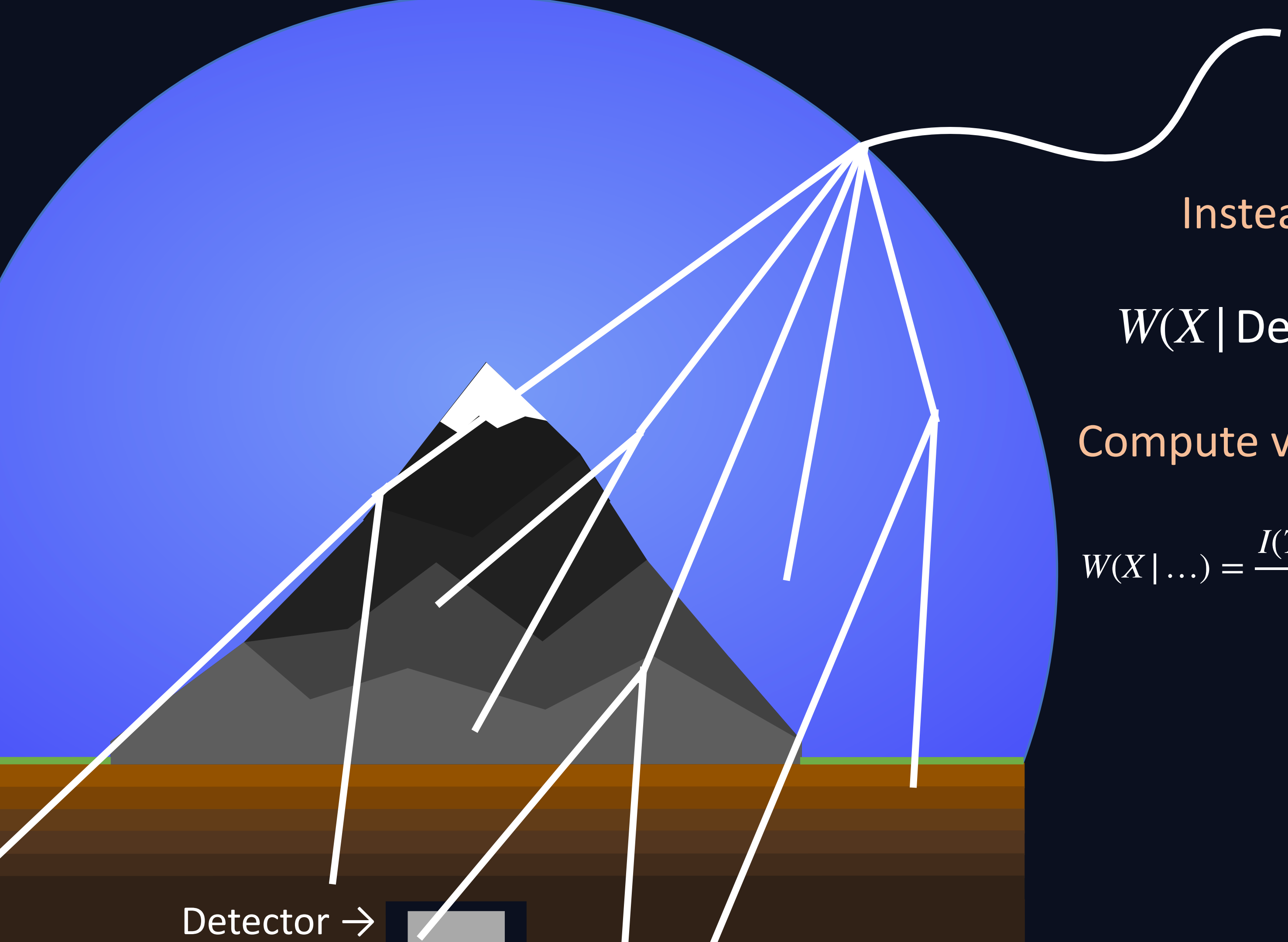
So what now?

Weight Kernel
W(X)

$$T_{\text{eff}} = \frac{\int T(X)W(X)dX}{\int W(X)}$$

Does not depend on systematic parameters like: detector depth, overburden, zenith angle, time of year


Cosmic Ray
p+, He, ..., Fe
Detector →

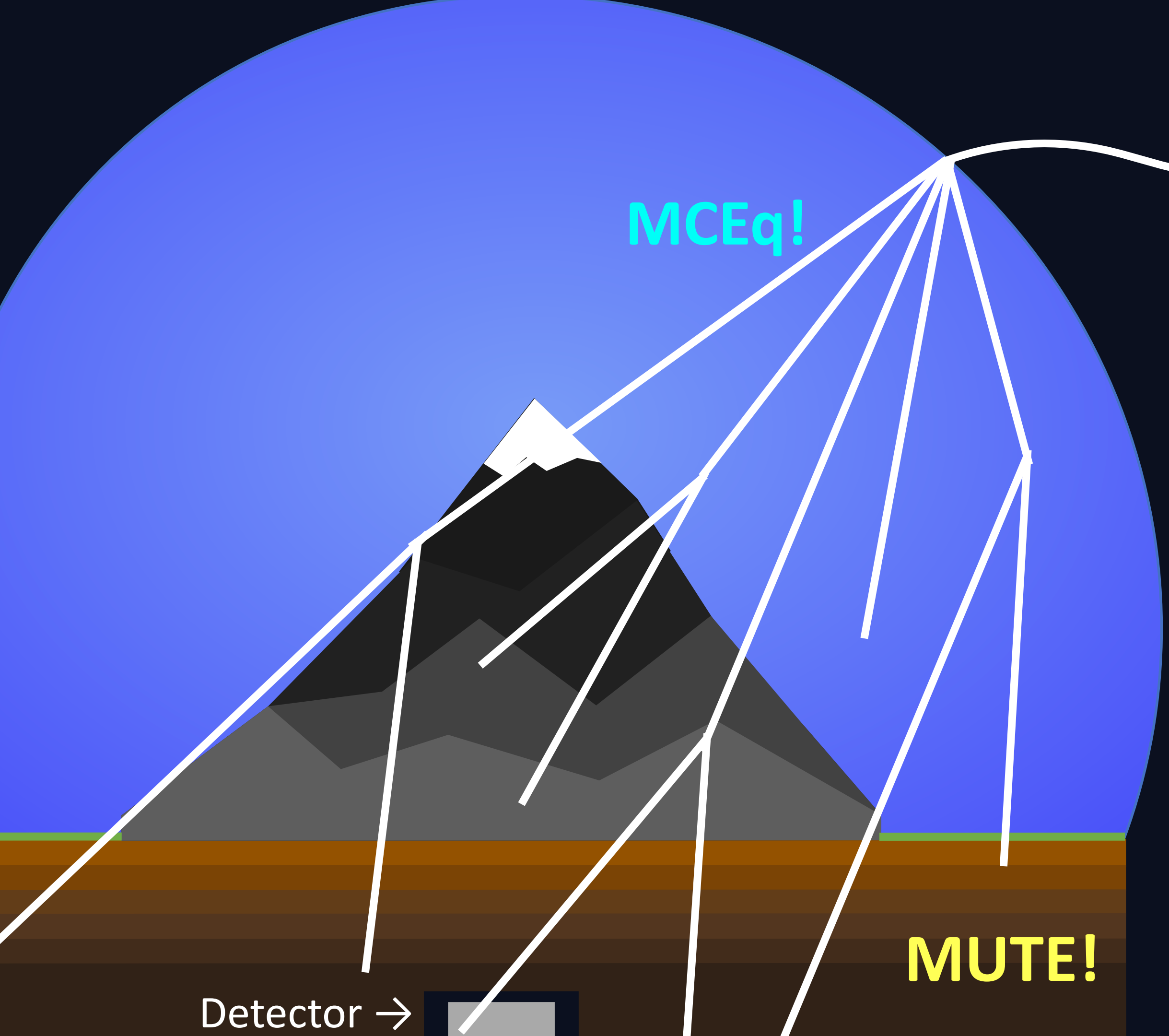


Instead of W(X):

$$W(X \mid \text{Depth, Zenith, ...})$$

Compute via perturbation:

$$W(X \mid \ldots) = \frac{I(T+\delta \mid \ldots) - I(T-\delta \mid \ldots)}{2\delta}$$



GSF 2025!

Instead of W(X):

$W(X\,|\,\text{Depth, Zenith, ...})$

Compute via perturbation:

$$W(X\,|\,\ldots) = \frac{I(T+\delta\,|\,\ldots) - I(T-\delta\,|\,\ldots)}{2\delta}$$

We have the framework!

What’s to come

1. MCEq has been updated to new Hadronic Interaction Models
   ➡New Features to come are 2D, 3D, New Hadronic Models, EM-Model, Geomagnetic Cutoff
2. Seasonal Variations Theory is studied in regards to systematics of the measurement setup
   ➡Weight profile characterization by moments of the distribution (mean, variance, …)
   ➡Quantify which parameters have largest effects