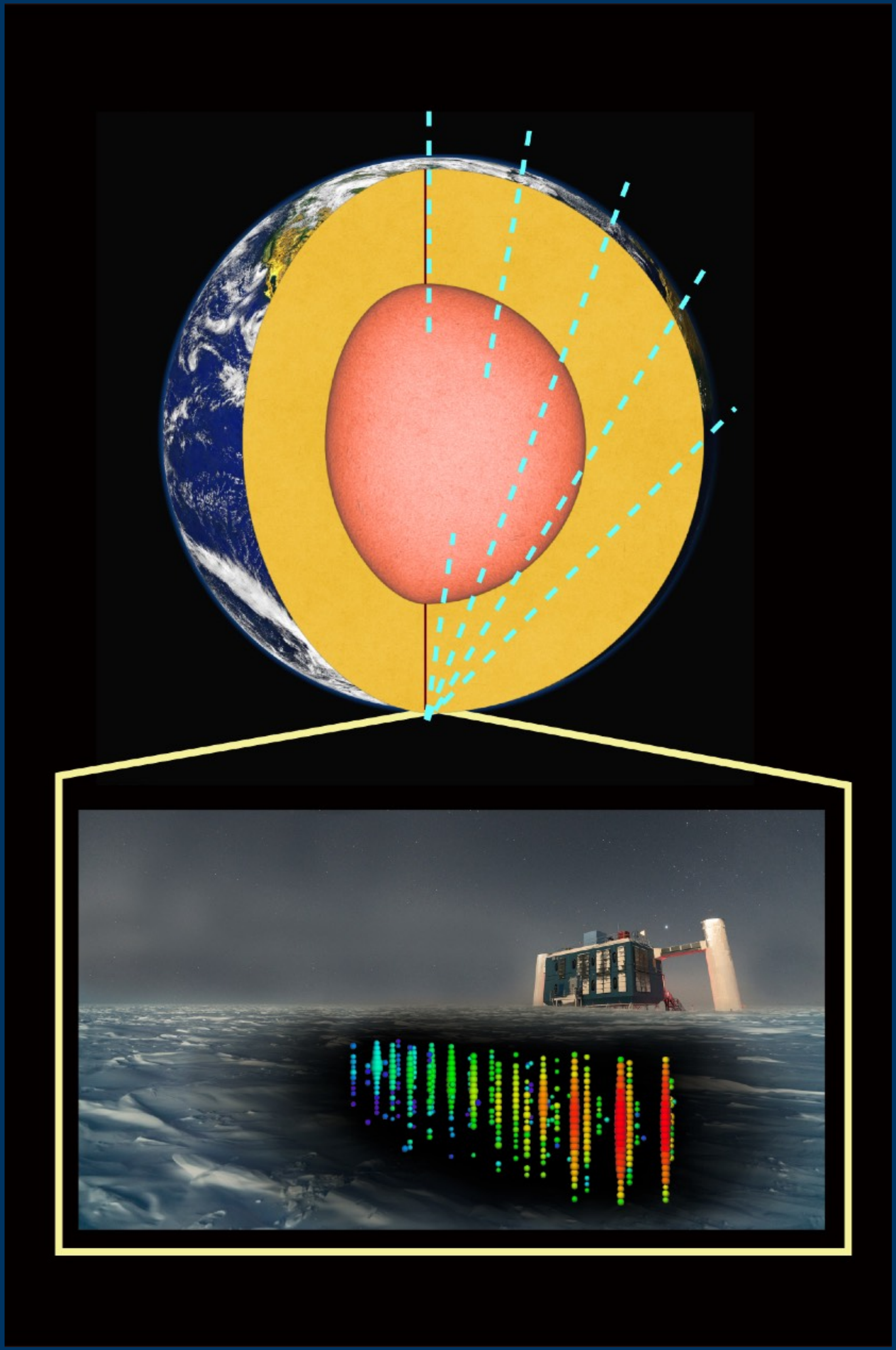
Probing Earth's Core Density with Atmospheric Neutrinos at IceCube Neutrino Observatory



Kotoyo Hoshina for the IceCube collaboration

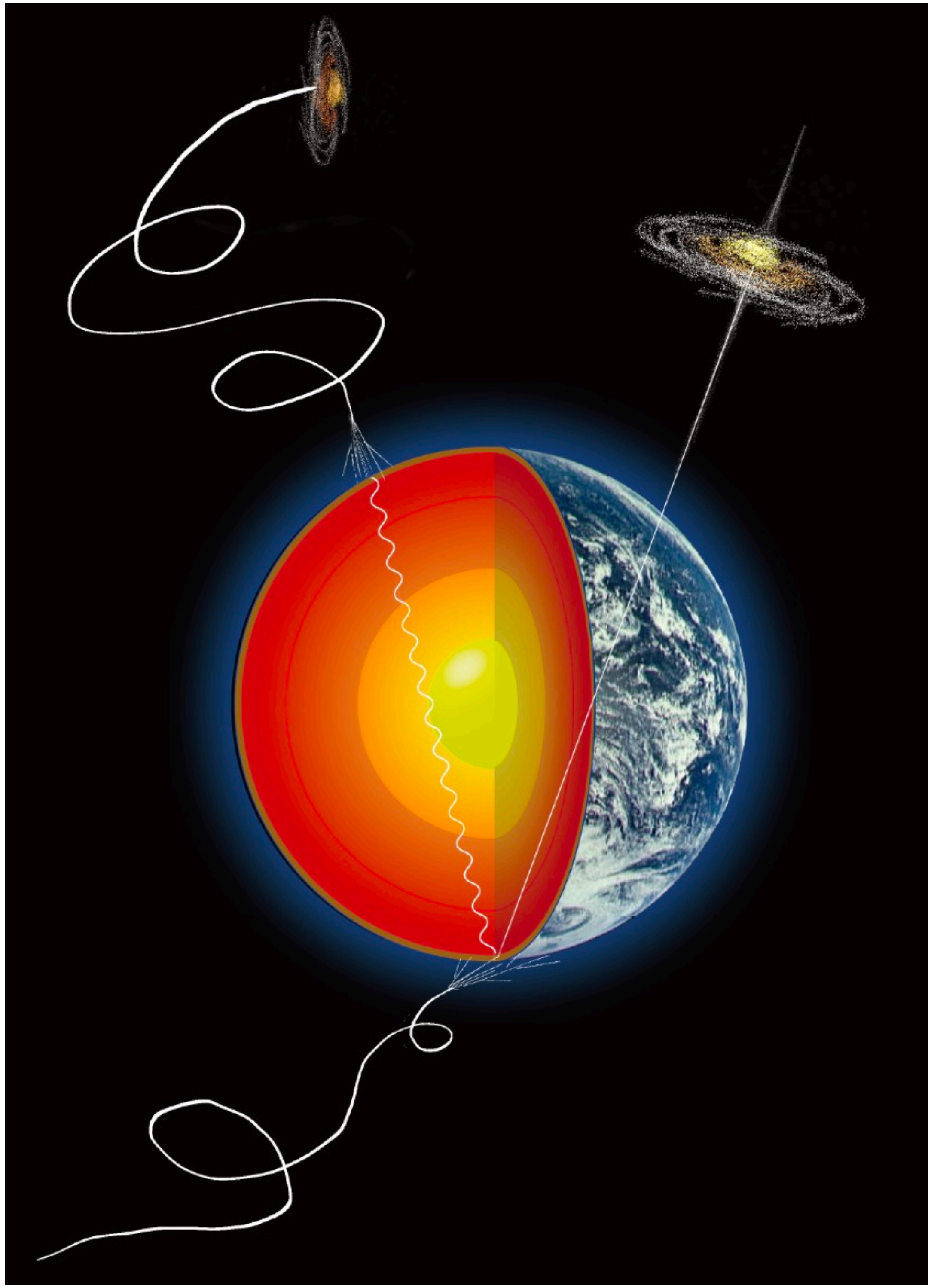
15th Conference on the Intersection of Particle and Nuclear Physics
Madison, June 9-13

Look inside of the Earth using neutrino

- Neutrino has perfect features as a probe for investigating inside of the Earth
- Neutrinos interact with matter in two way
  - Matter effect of neutrino oscillation
  - Weak interaction with matter (some neutrinos are absorbed by the Earth)
- This analysis detects matter-thickness using absorption of neutrino by the Earth

  $I = I_0 e^{-\sigma X}$

  (σ : cross section, X : column depth)



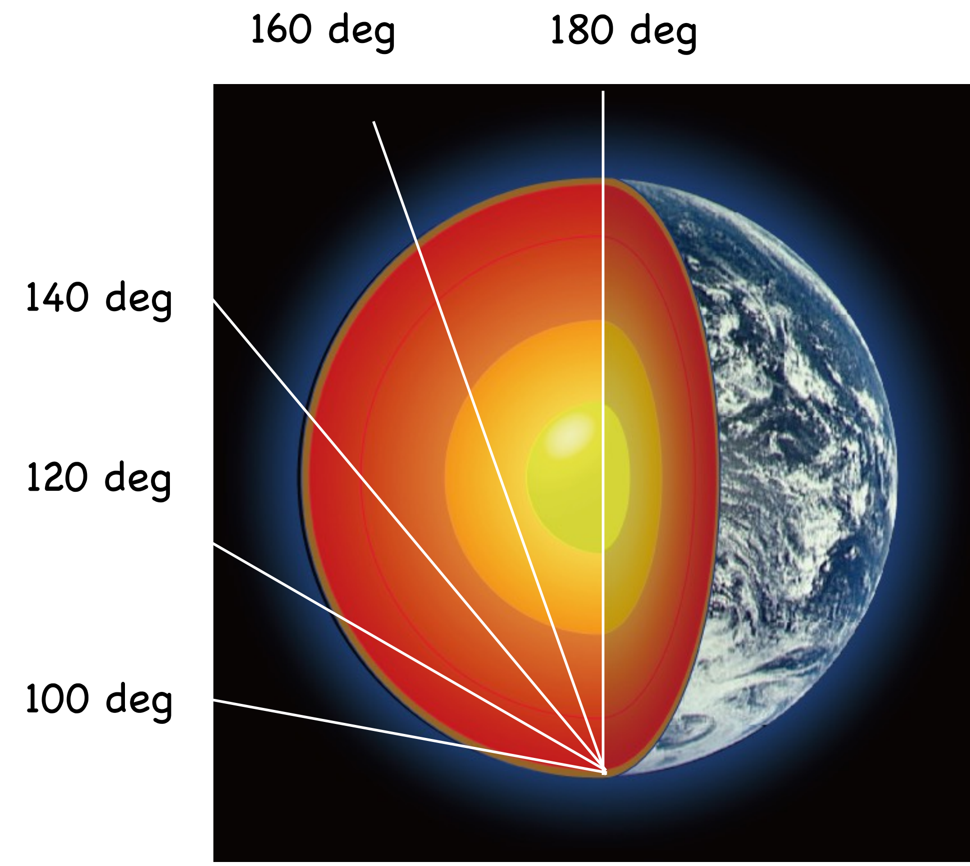
Why we use atmospheric or cosmic neutrinos

1. Multi-energy spectrum

   - Matter thickness of the Earth varies as a function of arrival zenith angle of neutrinos, thus sensitive energy for absorption varies too. Atmospheric or cosmic neutrinos have continuous energy spectrum and we can just select proper energies to detect the deficit.

2. Available anywhere on the Earth

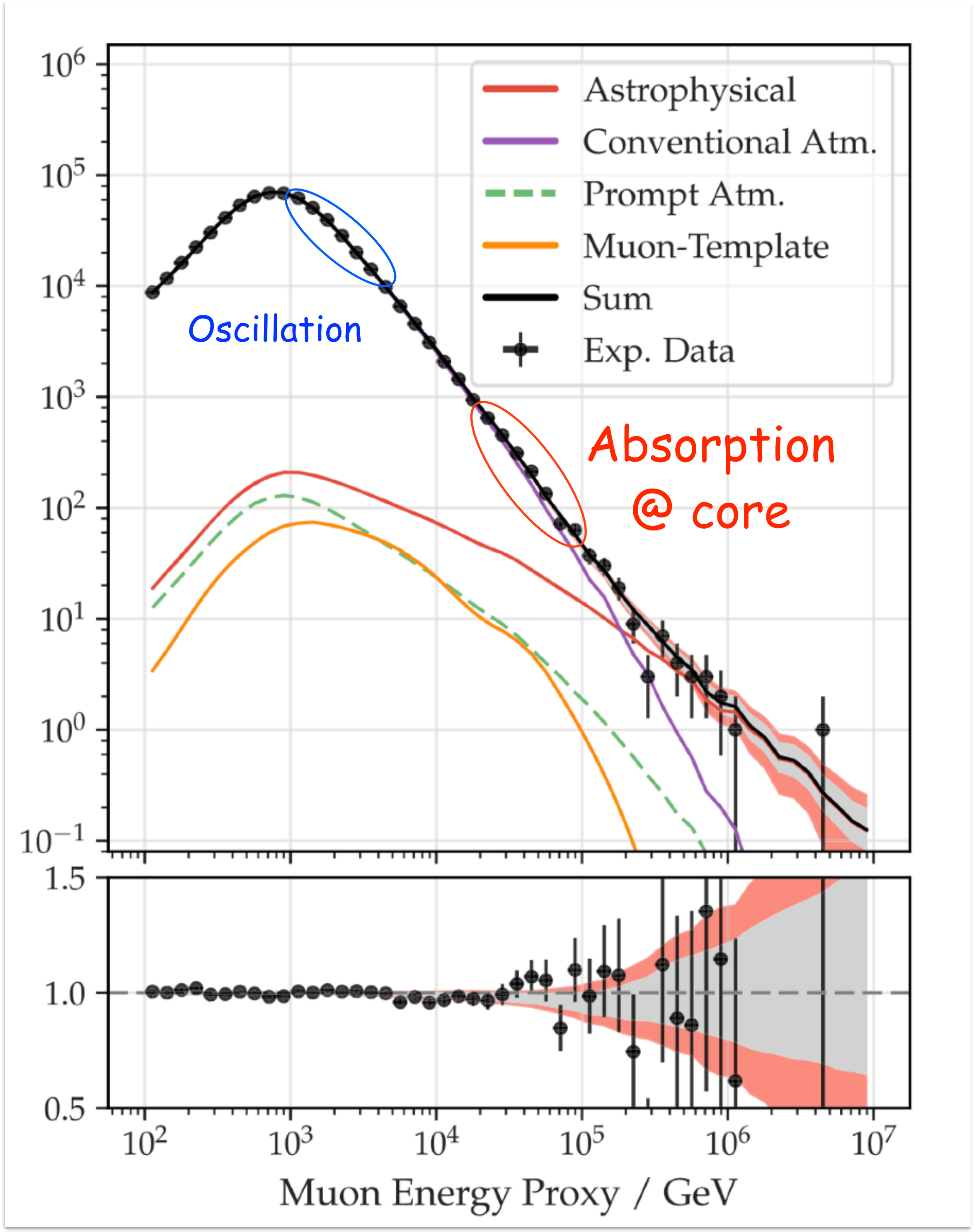
3. For cosmic neutrinos, we assume uniform distribution for sources

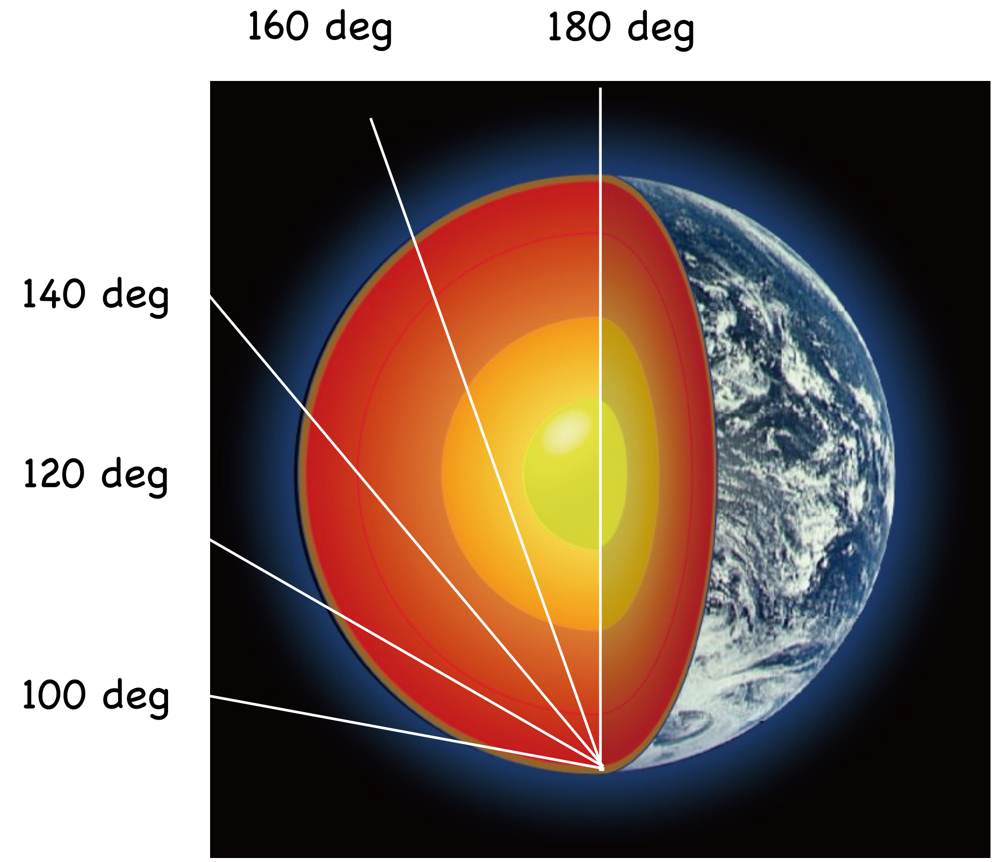


	Energy*
100 deg	2.2 PeV
120 deg	132 TeV
140 deg	51 TeV
160 deg	36 TeV
180 deg	32 TeV

*Energy of neutrino which interaction length is equivalent to the total matter thickness (column depth) along the neutrino's trajectory, Assuming PREM Earth Model. Only CC interaction is took into account.

Why we use atmospheric or cosmic neutrinos





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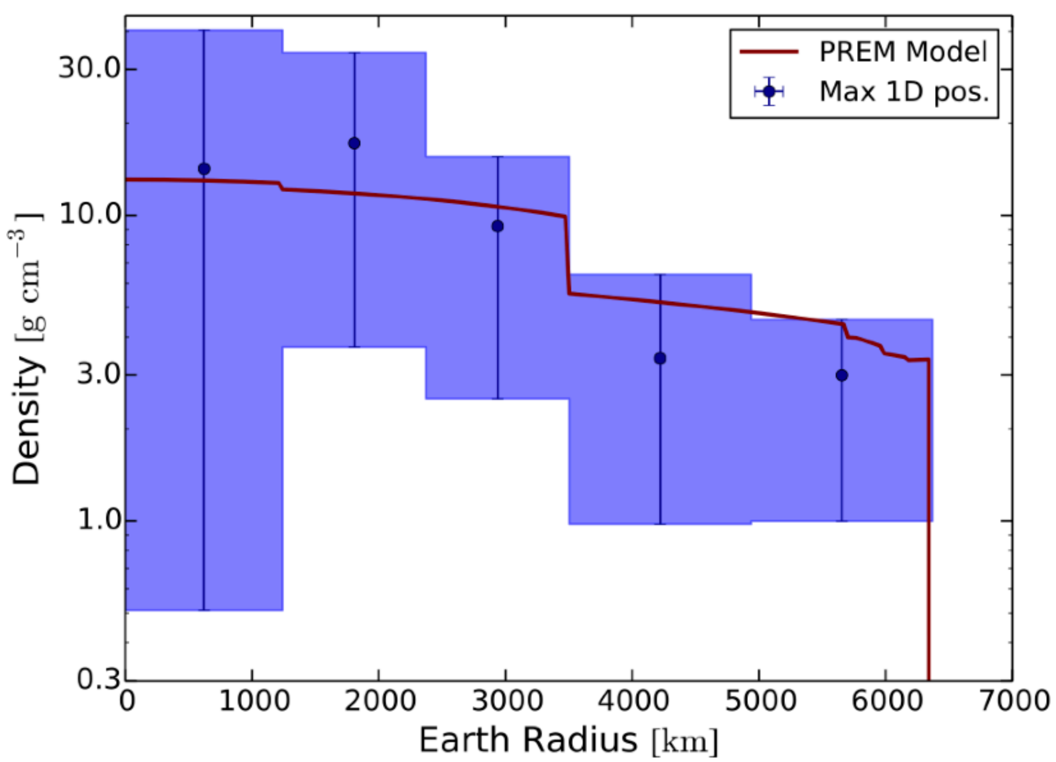
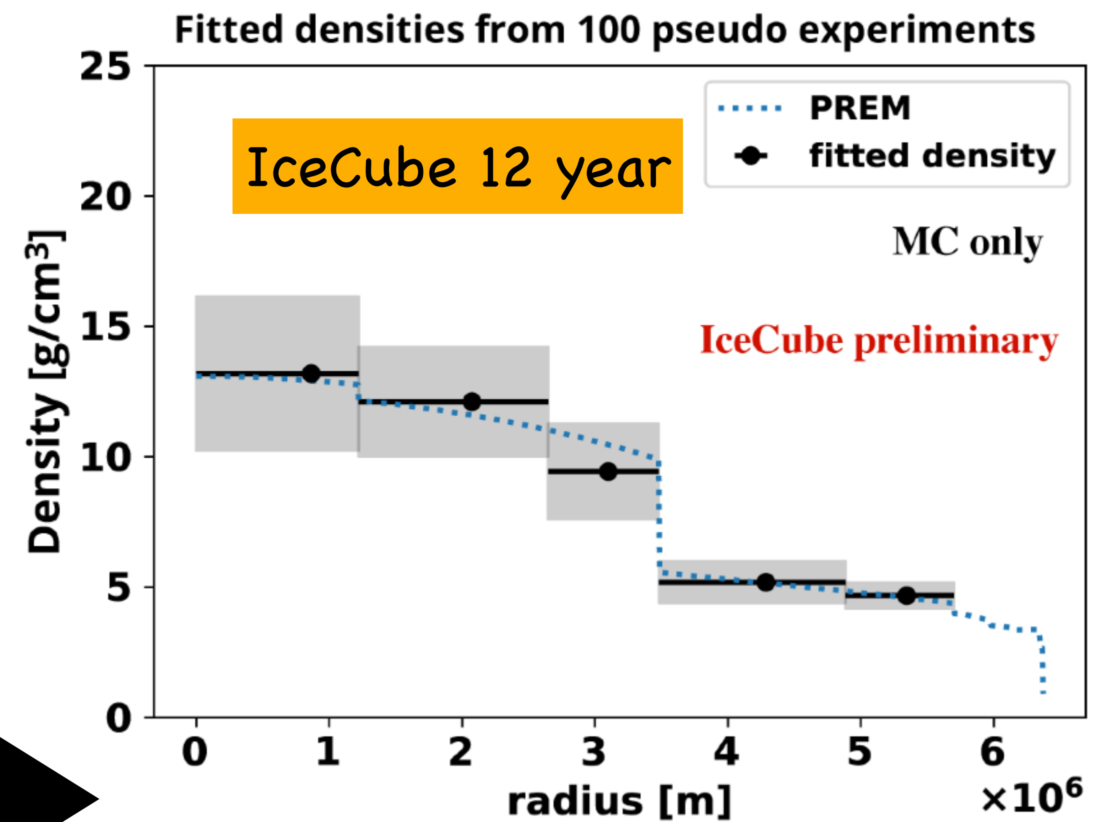
R. Abbasi et al Astrophysical Journal 928 (2022) 50
Improved Characterization of the Astrophysical Muon-neutrino Flux with 9.5 Years of IceCube Data

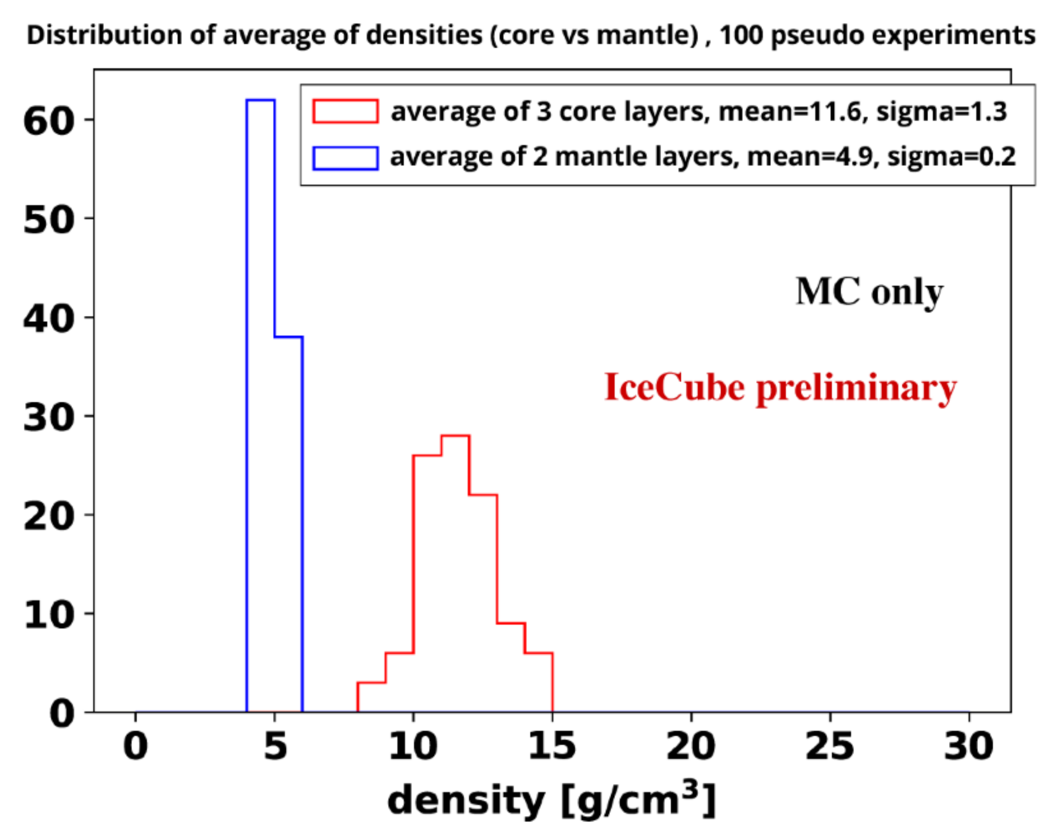
What we are trying to see

IceCube 1 year



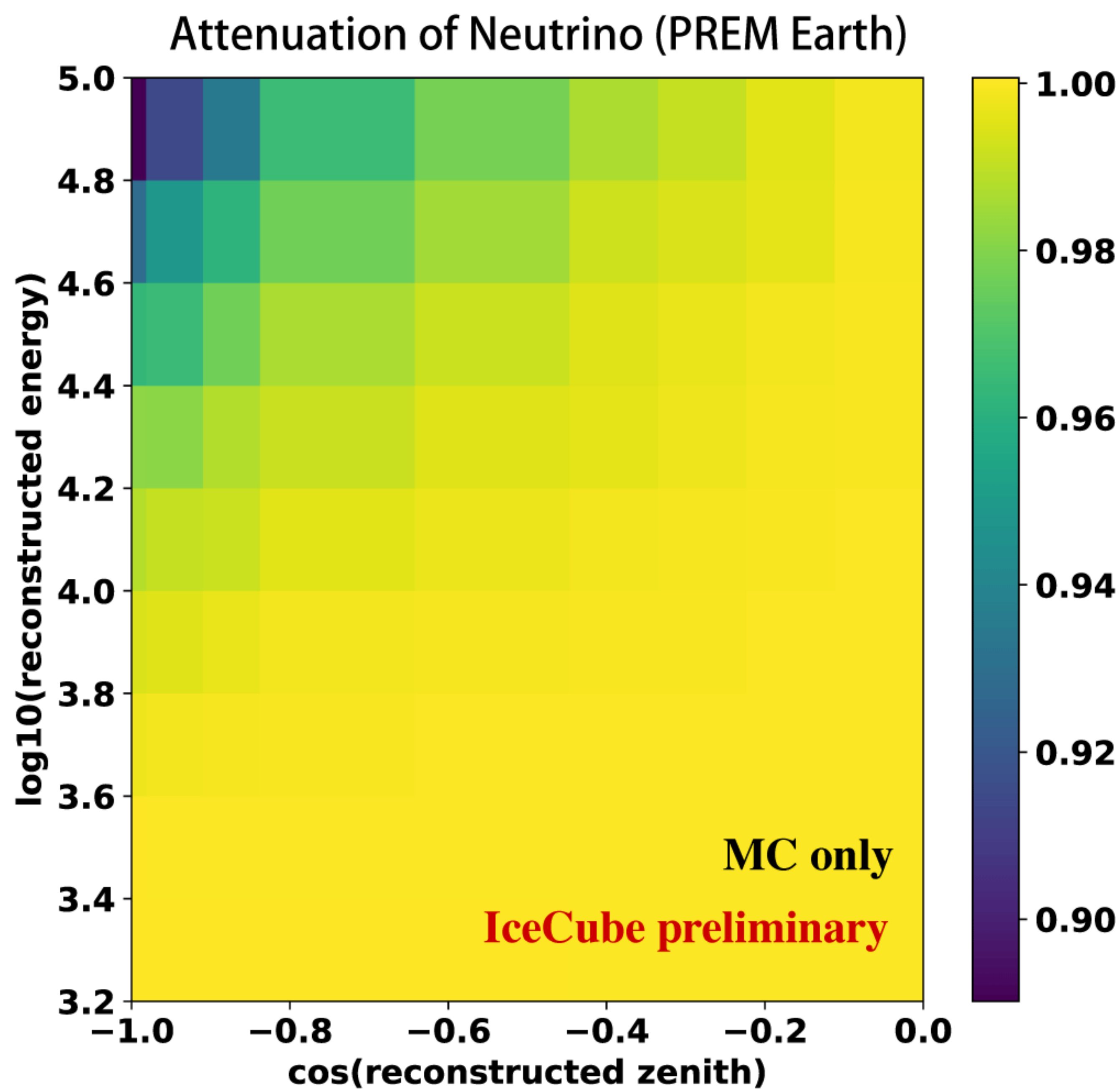
Andrea Donini, Sergio Palomares-Ruiz, and Jordi Salvado
"Neutrino tomography of Earth" Nature Phys. 15, 37 (2019)



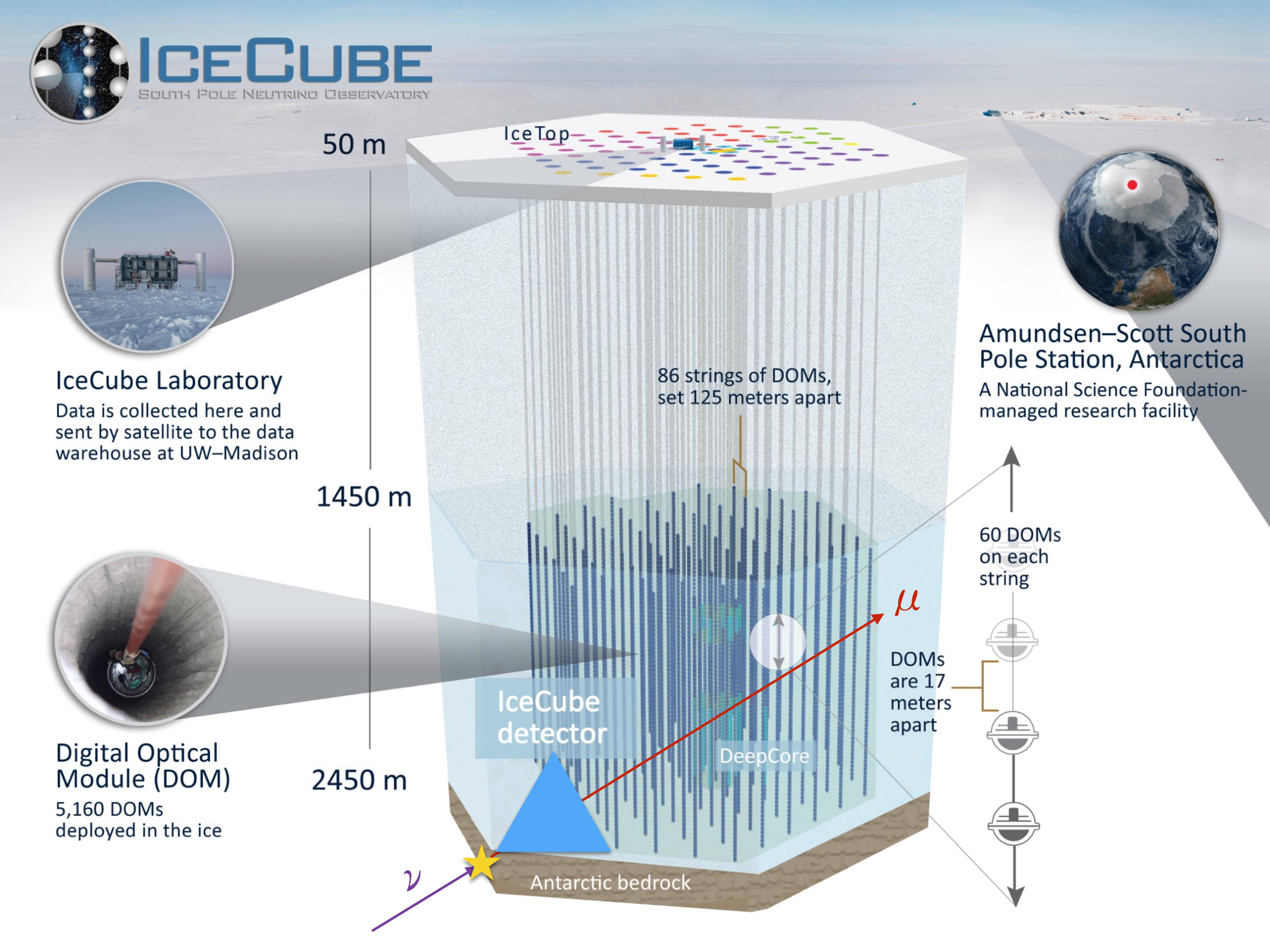


Measuring density of the Earth using Atmospheric neutrino events

- At less than 100TeV, Majority of events collected by IceCube are atmospheric neutrinos
- More than 30000 neutrinos that pass through the core region will be observed in 2010-2022 season
- This analysis is trying to see less than 10% effect



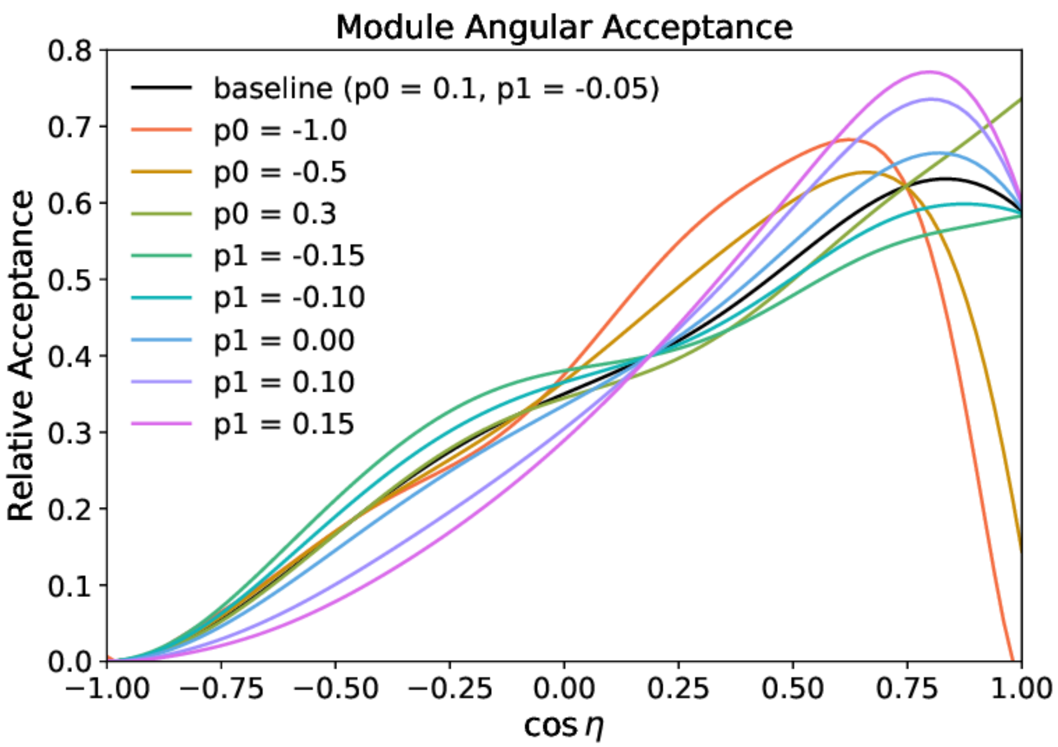
This analysis requires precise control of systematics



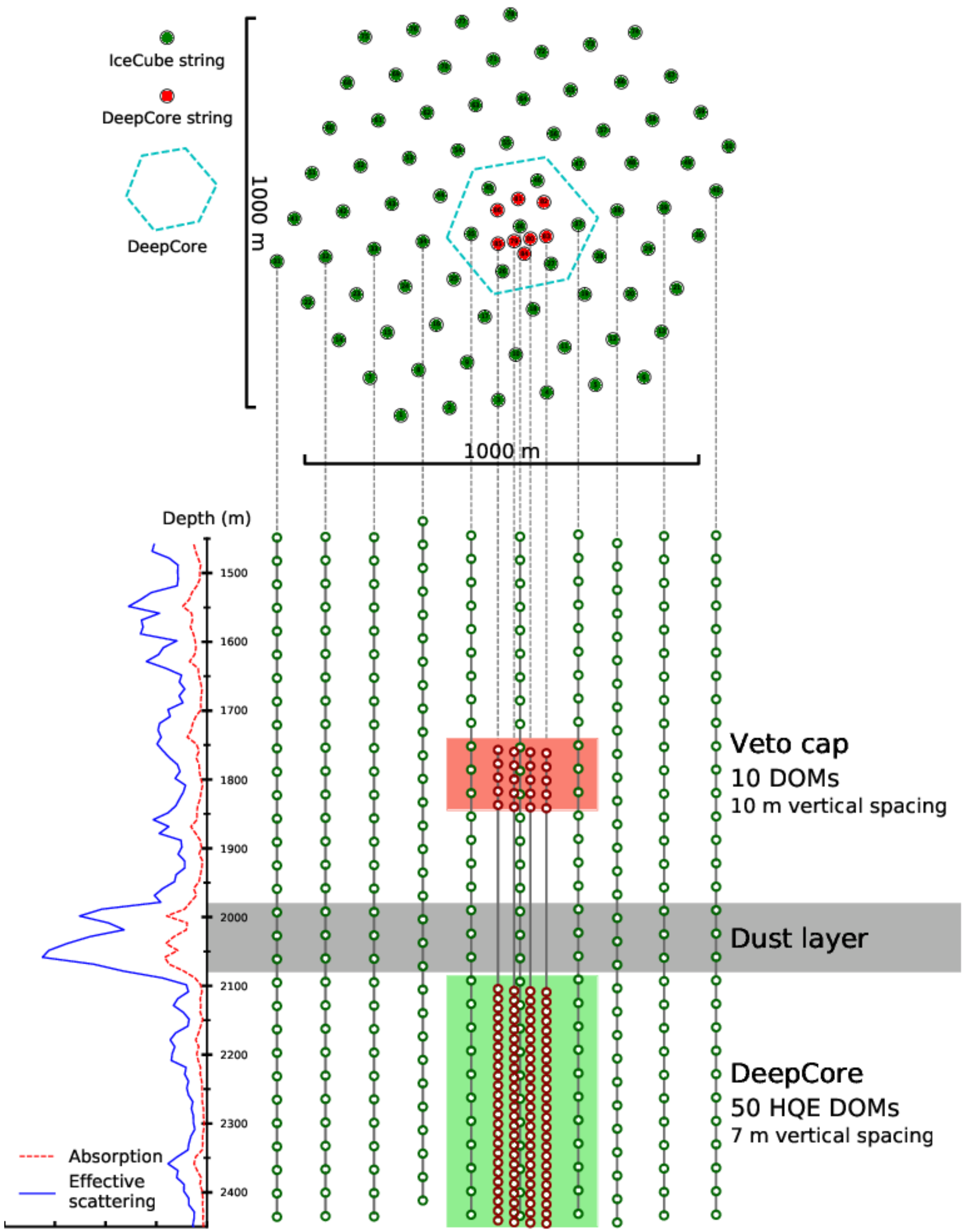
IceCube
South Pole Neutrino Observatory
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
μ
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
ν
Antarctic bedrock

Detector systematics

- Optical sensor is facing down, sensitivity has zenith dependence
- Also bubble column affects to the sensitivity
- Bulk ice has layered structure
- DOM sensitivity



R. Abbasi *et al* 2022 *JINST* **17** P11003



Uncertainty of Atmospheric Neutrino Fluxes

- Hadron production in shower process will affect to the flux of neutrinos

- This effect is also zenith-dependent

- Estimating uncertainty of atmospheric flux as a function of arrival zenith and energy is essential to see 10% effect of attenuation of neutrinos!

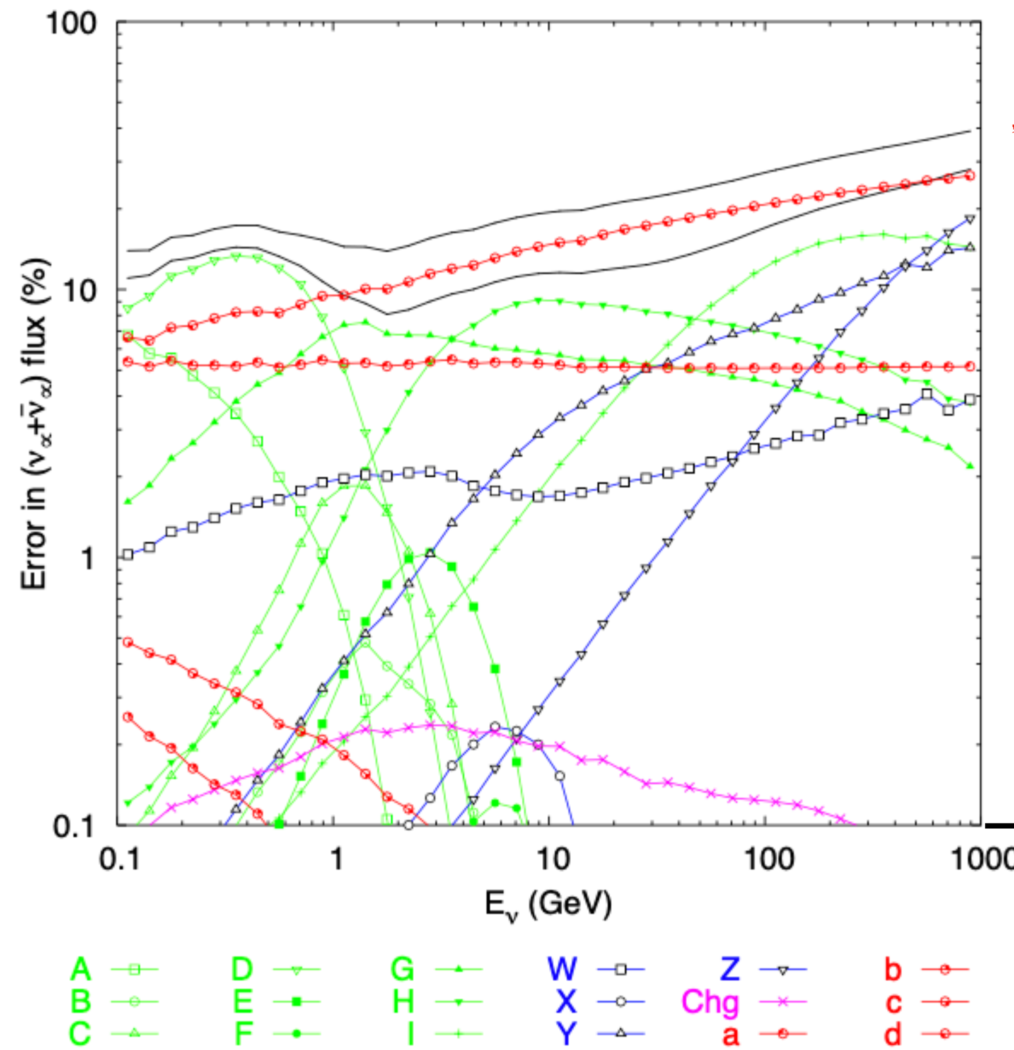


FIG. 10: (color online) Breakdown of flux uncertainties (shown here for angle averaged muon neutrinos) with different regions of hadron production as a function of neutrino energy. The capital letters in the key correspond with the hadron production uncertainty zones in figure 3 and the one labeled 'Chg' represents the pion charge ratio uncertainty. The lower case letters in the key correspond to variation of the flux parameters in table (I). See text for more information. The topmost thick (black) line with no points is the total error on the flux and the lower line of the same style is the total hadronic error (i.e. excluding the uncertainty from the primary flux).

G.D. Barr *et al* *Phys.Rev.D* 74 (2006) 094009

...?

use MCEq* to calculate fluxes and estimate uncertainty!

MCEq: Matrix cascade equations
https://github.com/mceq-project/MCEq

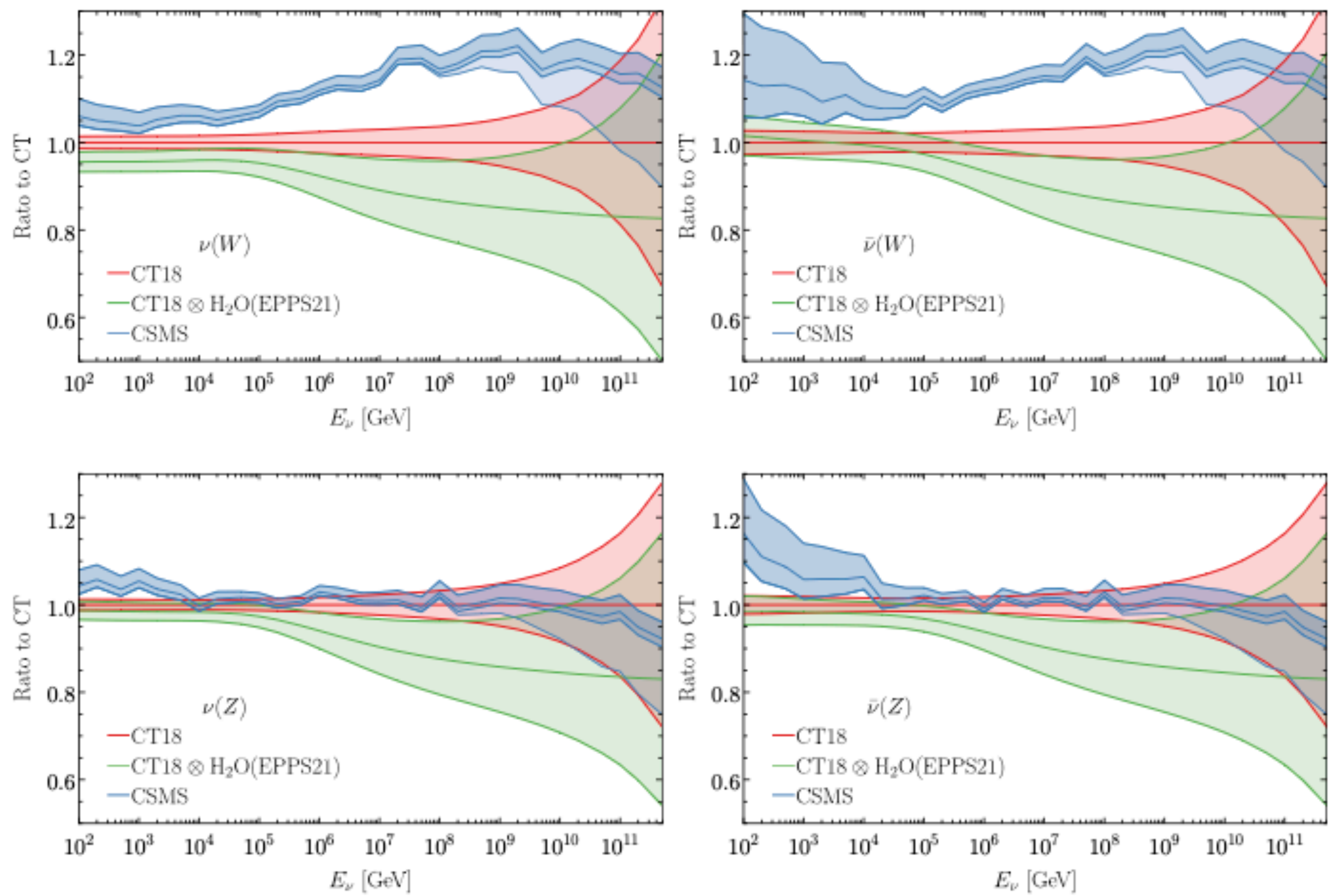
10TeV 100TeV

Cross section model dependence

- IceCube default cross section model is CSMS* cross section with model uncertainty ~5% or less at 100TeV

- However, variations between different models may be larger.

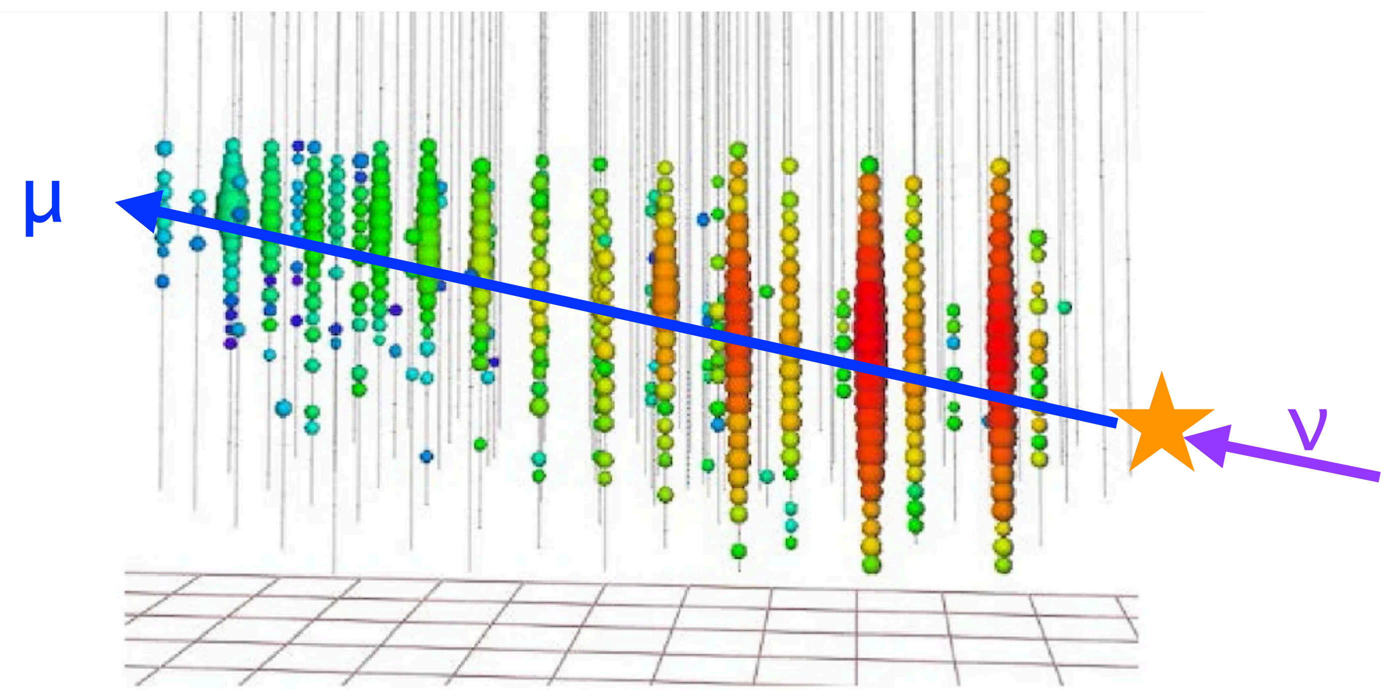
  - Cross section scaling parameter is added to nuisance parameter (could be optimized with a better handlings)

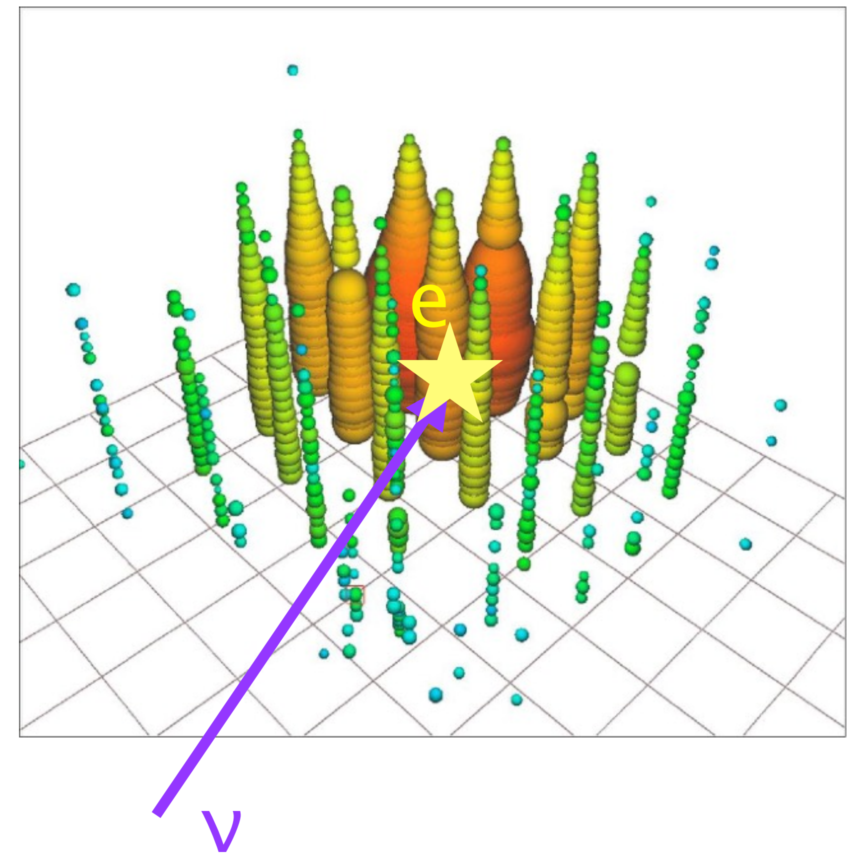


Keping Xie, Jun Gao, T. J. Hobbs, Daniel R. Stump, and C.-P. Yuan (CTEQ-TEA Collaboration)
High-energy neutrino deep inelastic scattering cross sections, Phys. Rev. D 109, 113001

*Cooper-Sarkar, A., Mertsch, P. & Sarkar, S. The high energy neutrino cross-section in the Standard Model and its uncertainty. *J. High Energ. Phys.* **2011**, 42 (2011).

Track events and Cascade events





ν_μ Charged current interaction

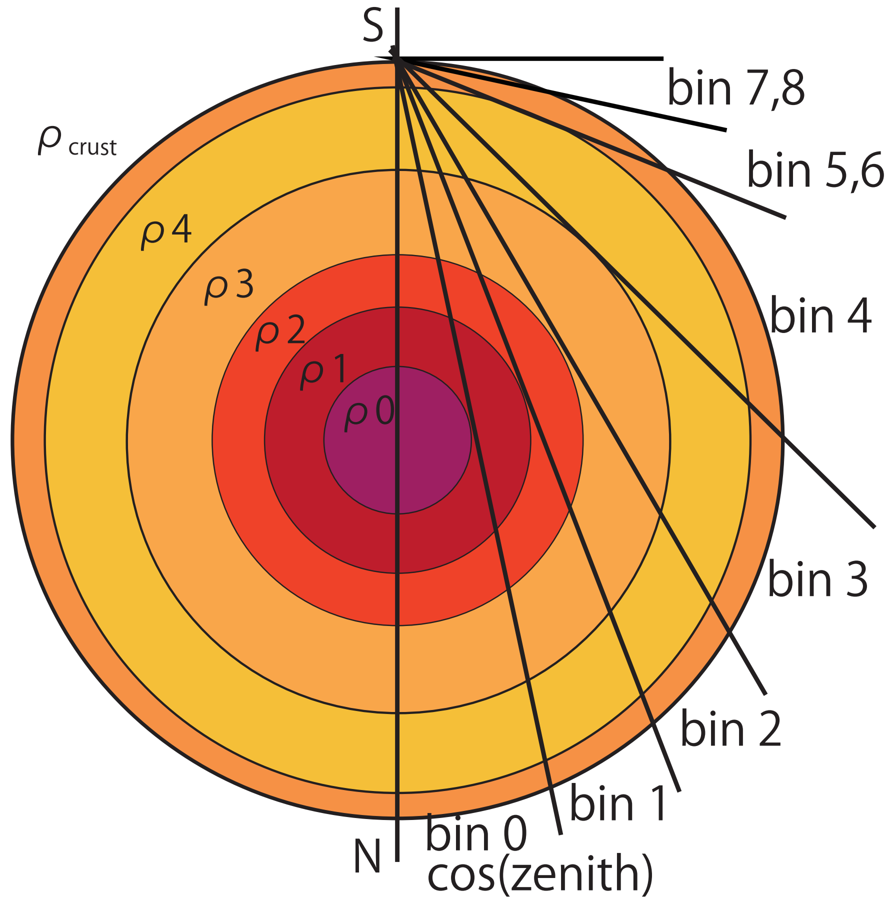
ν_τ Charged current interaction

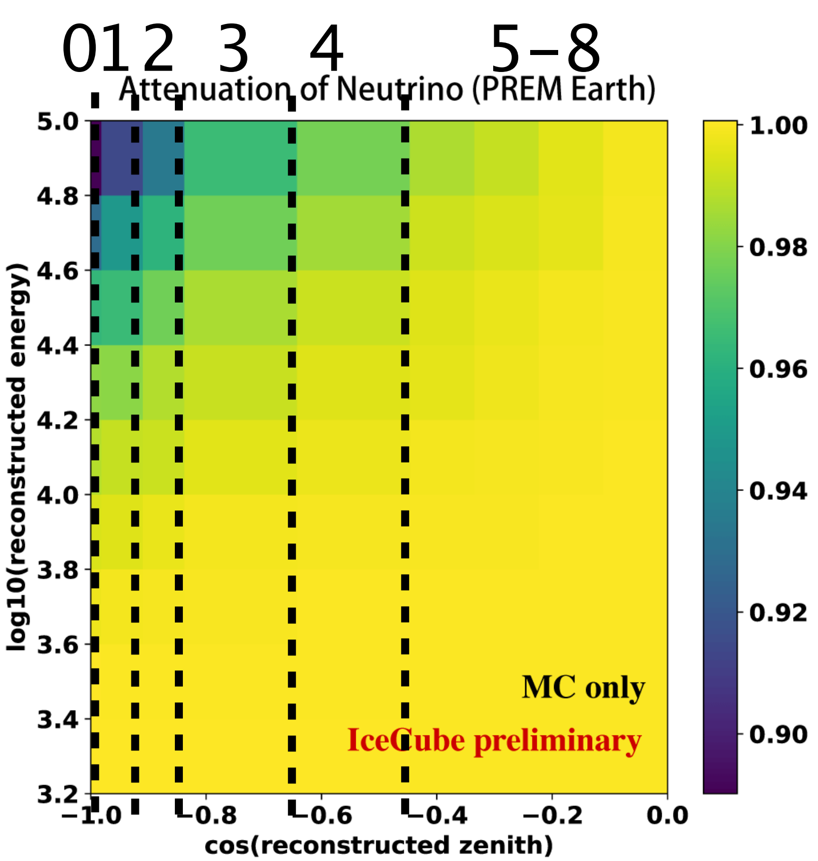
ν_e Charged current interaction

All neutral current interaction

This analysis uses well-reconstructed, upward going track events only

Density layers and analysis method



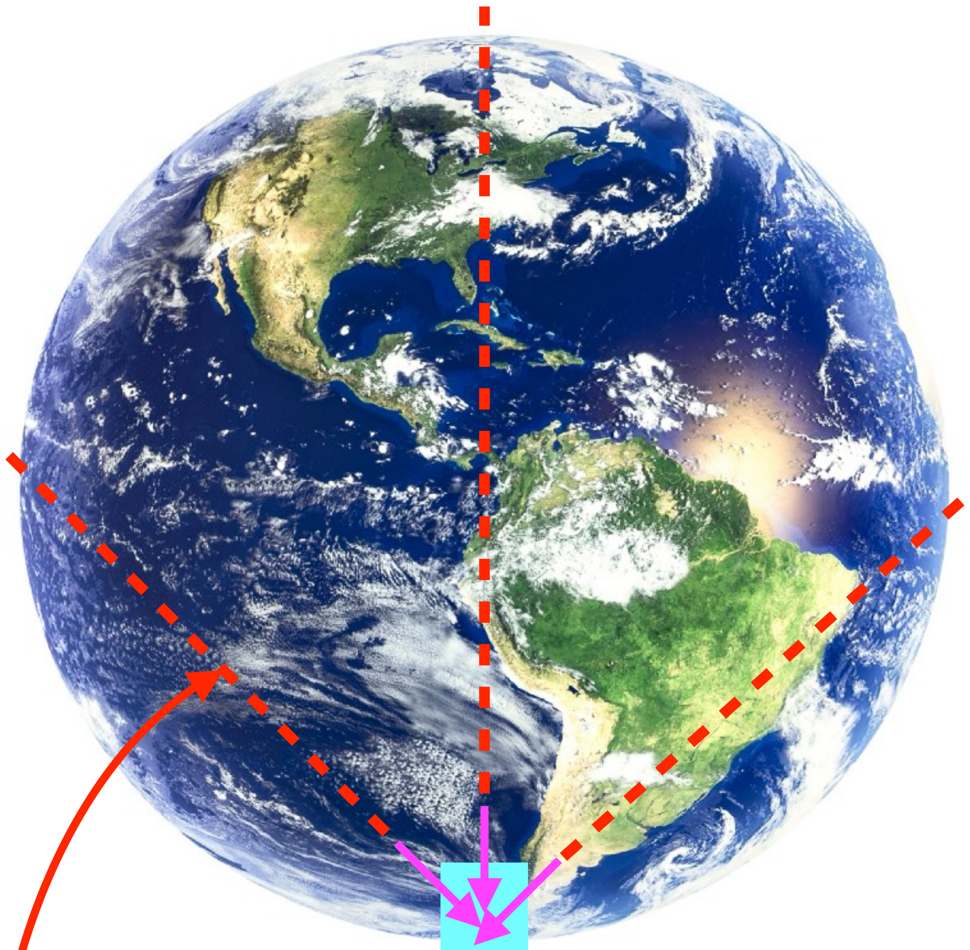


- Crust layer is fixed to PREM model
- Arrived neutrino events are plotted in 2D histogram of cos(reconstructed zenith) vs log10(reconstructed energy)
- Then, the observed counts are compared with simulated expectations (μ_θ) as a function of nuisance parameters and layer densities(θ), by minimizing the log-likelihood :

$$-2\ln\lambda(\boldsymbol{\theta}) = 2\sum_{i=1}^{N}\left[\mu_i(\boldsymbol{\theta}) - n_i + n_i \ln\left(\frac{n_i}{\mu_i(\boldsymbol{\theta})}\right)\right] - \alpha S_{MaxEnt}$$

αS_{MaxEnt} : regularization term to suppress oscillating behavior of unfolding problems

Generating simulation



LeptonInjector (Detector Simulation)

https://github.com/icecube/LeptonInjector

NUFATE

Eigenvalues

$$\vec{\phi} = \sum c_i \hat{\phi}_i e^{\lambda_i x}$$

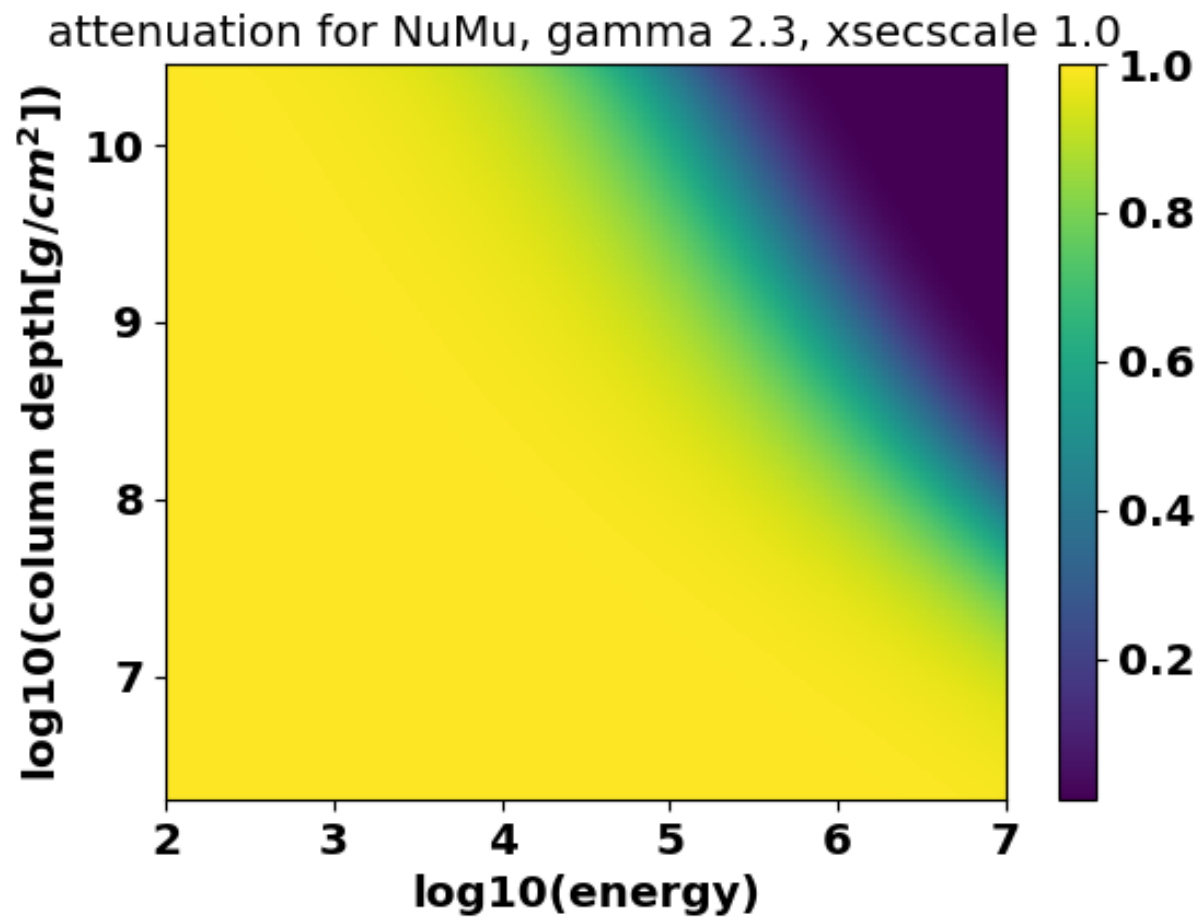
coefficients

Eigenvectors

column depth along the neutrino track * N_A

https://github.com/aaronvincent/nuFATE

Attenuation calculated with NUFATE



Minimum column depth corresponds 20km ice
Maximum column depth corresponds 12742km Iridium(22.56g/cm3)

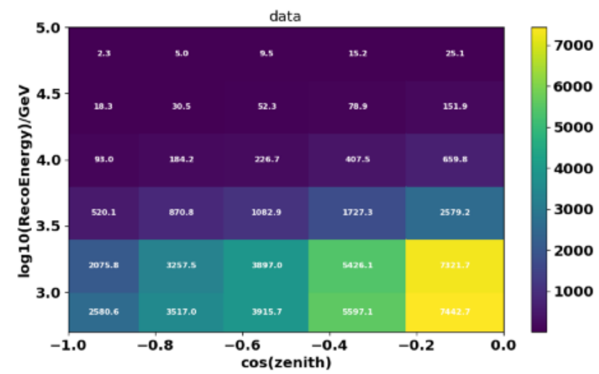
Fitting Parameters

- Nuisance parameters
  - Error of normalization of conventional atmospheric flux
  - Error of normalization of prompt flux
  - Error of normalization of astrophysical (cosmic) flux
  - Error of power law spectrum of cosmic ray (affects to atmospheric and prompt)
  - Error of power law spectrum of astrophysical flux
  - Errors for shape of conventional atmospheric flux (4 parameters : h, w, y, z)
  - Error of DOM efficiency — acceptance of Cherenkov light at DOM
  - Ice Properties — scattering, absorption, holeice parameter p1 and p2
  - cross section scale
- Physics parameters
  - Density of each layer from 0 to 4 (total 5 layers)

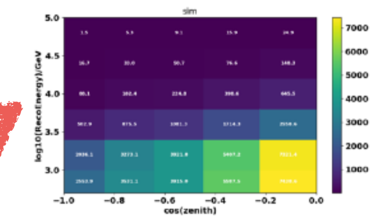
Asimov Test

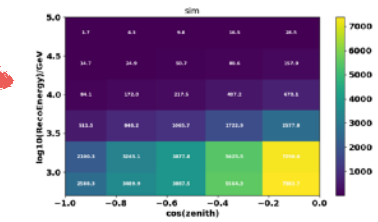
Asimov data

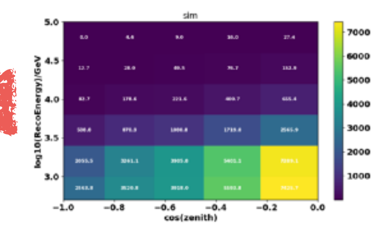
MCTruth

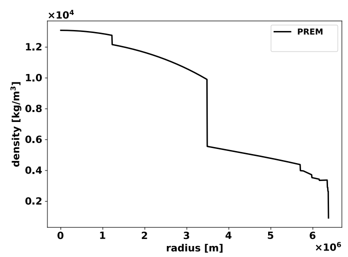


poisson sampling





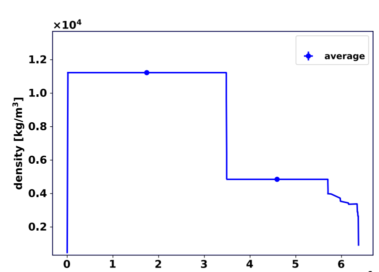




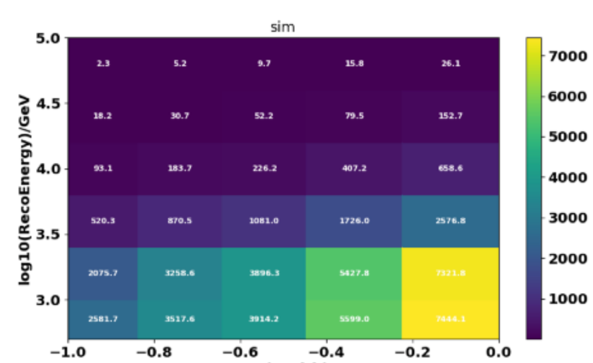
Weight with PREM model

LeptonInjector Simulation

① Fit to MCTruth



Weight with Layered density model



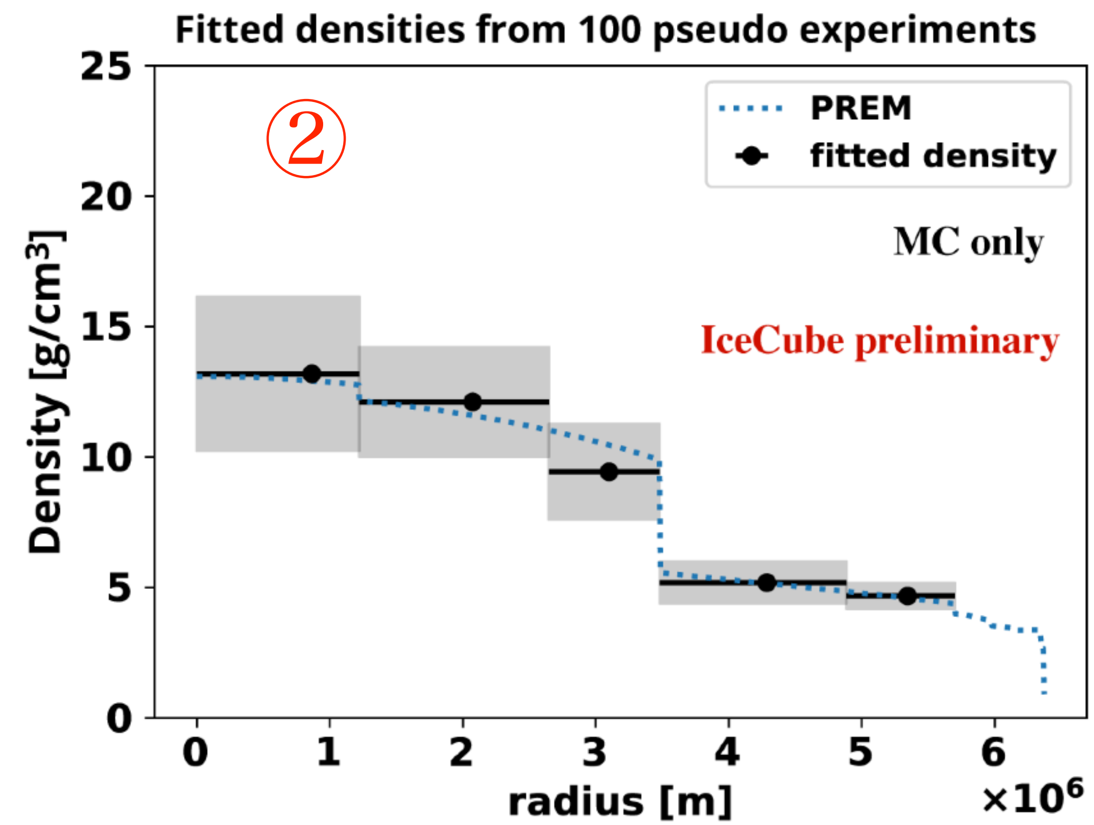
② Fit to Asimov data

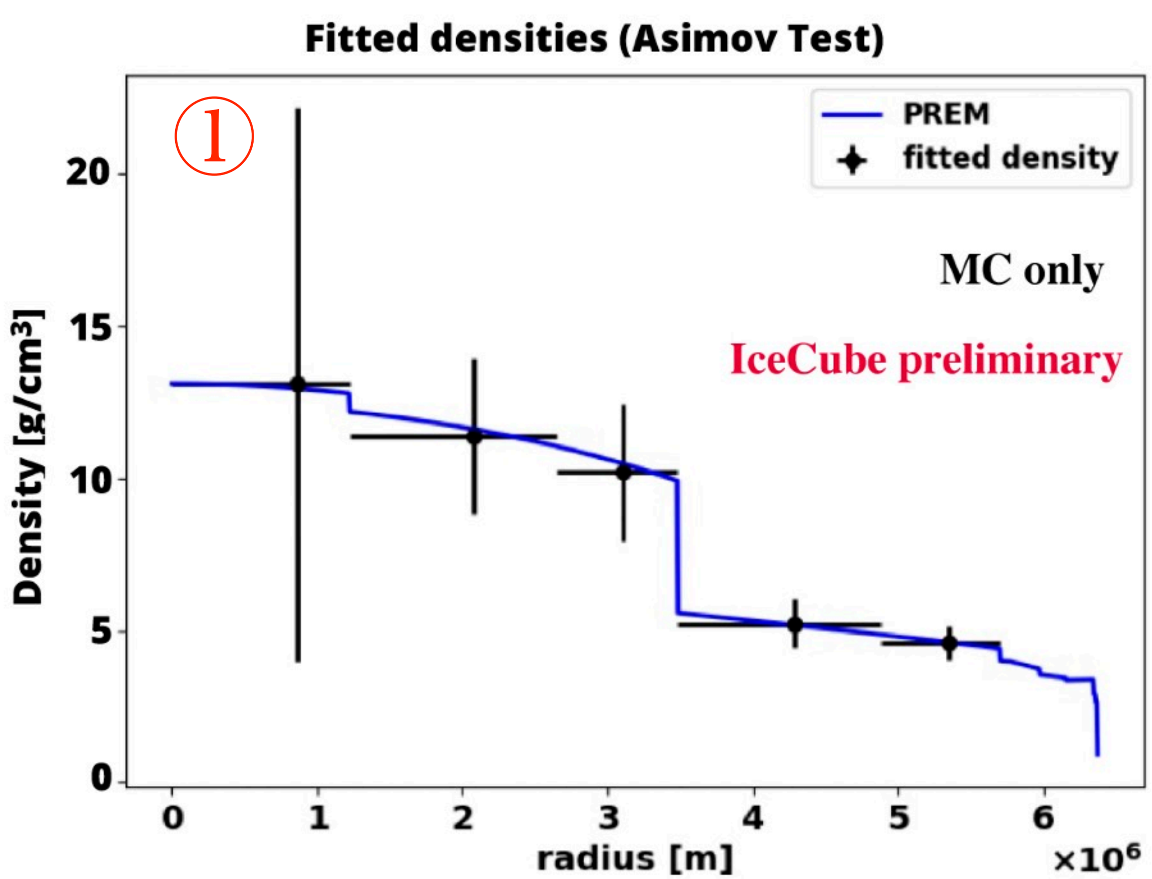
Program check with Asimov Test

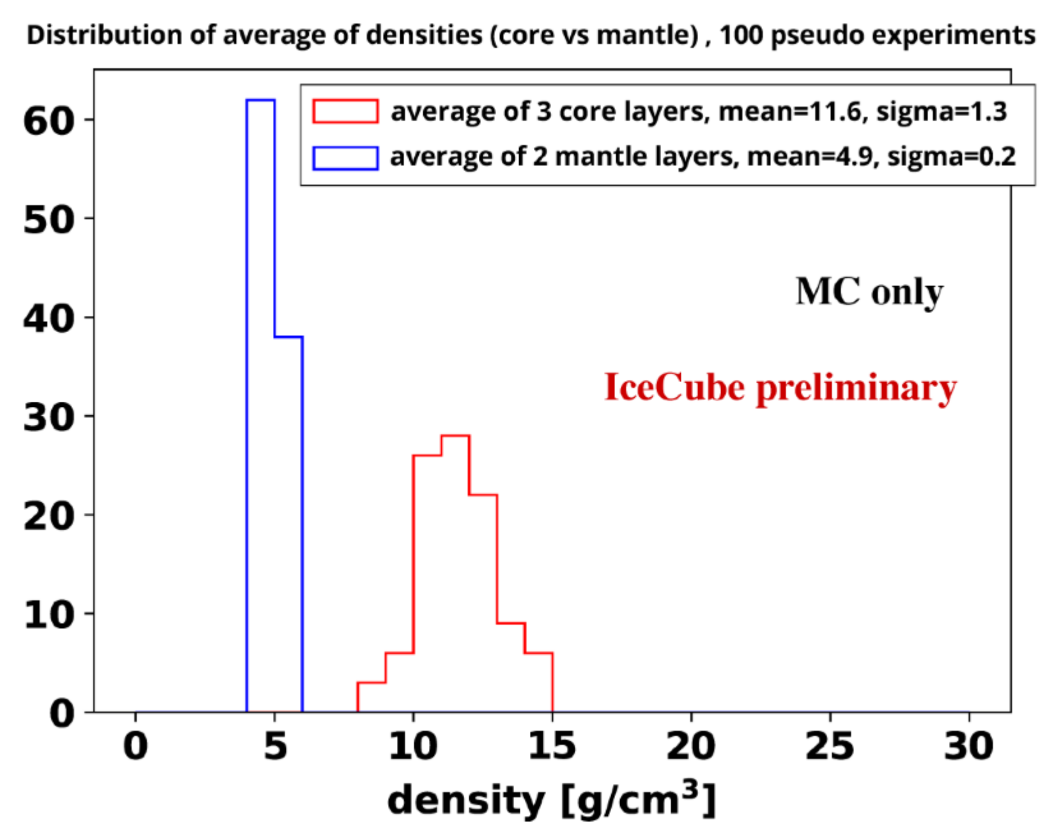
①Fit to MCTruth works.

②Average of 100 Asimov Test:

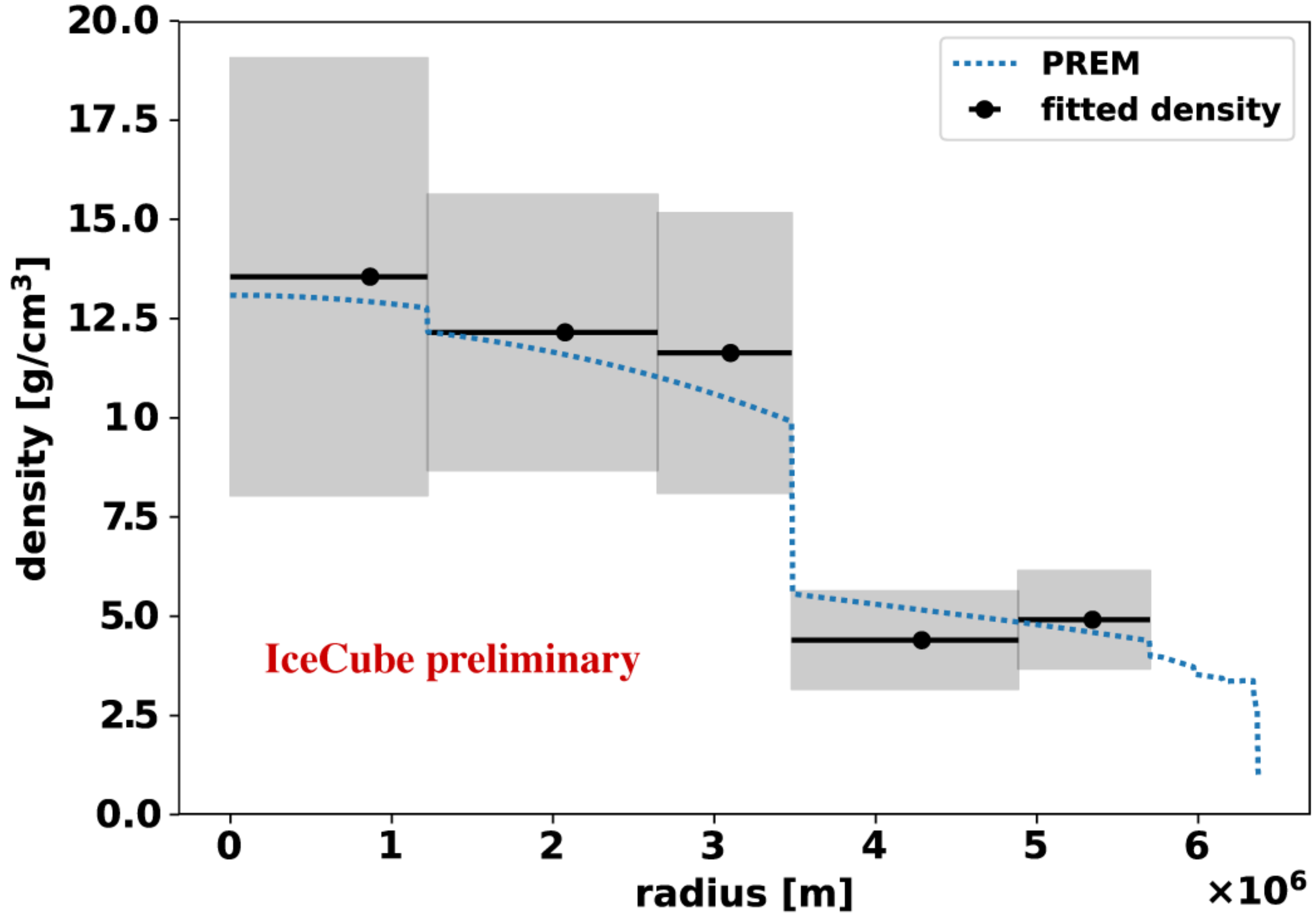
Distribution of Average of core layers and mantle layers are separated







Fitted result with 10% data



Live time 312.2 days

- Error bars are 1 sigma fitting errors
- Regularization strength alpha = 10 is used which may be optimized

Summary

- Method of measuring Earth's core and mantle density using IceCube 12years data is almost finalized except for a few optimization options:
  - treatment of cross-section model differences
  - regularization term
- Currently working hard to open full data by this summer