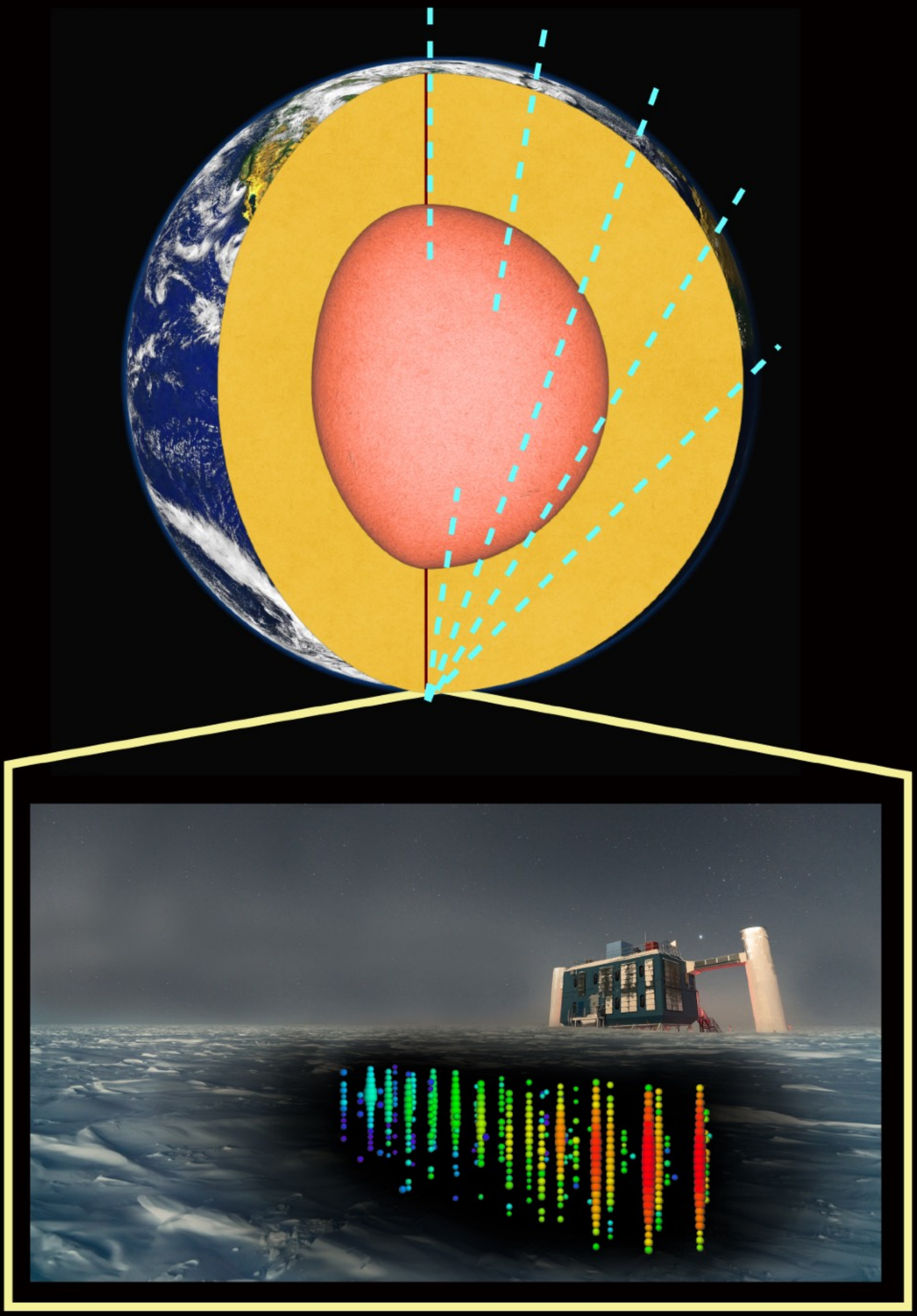
Measuring density of Earth's core using high-energy neutrinos observed by IceCube

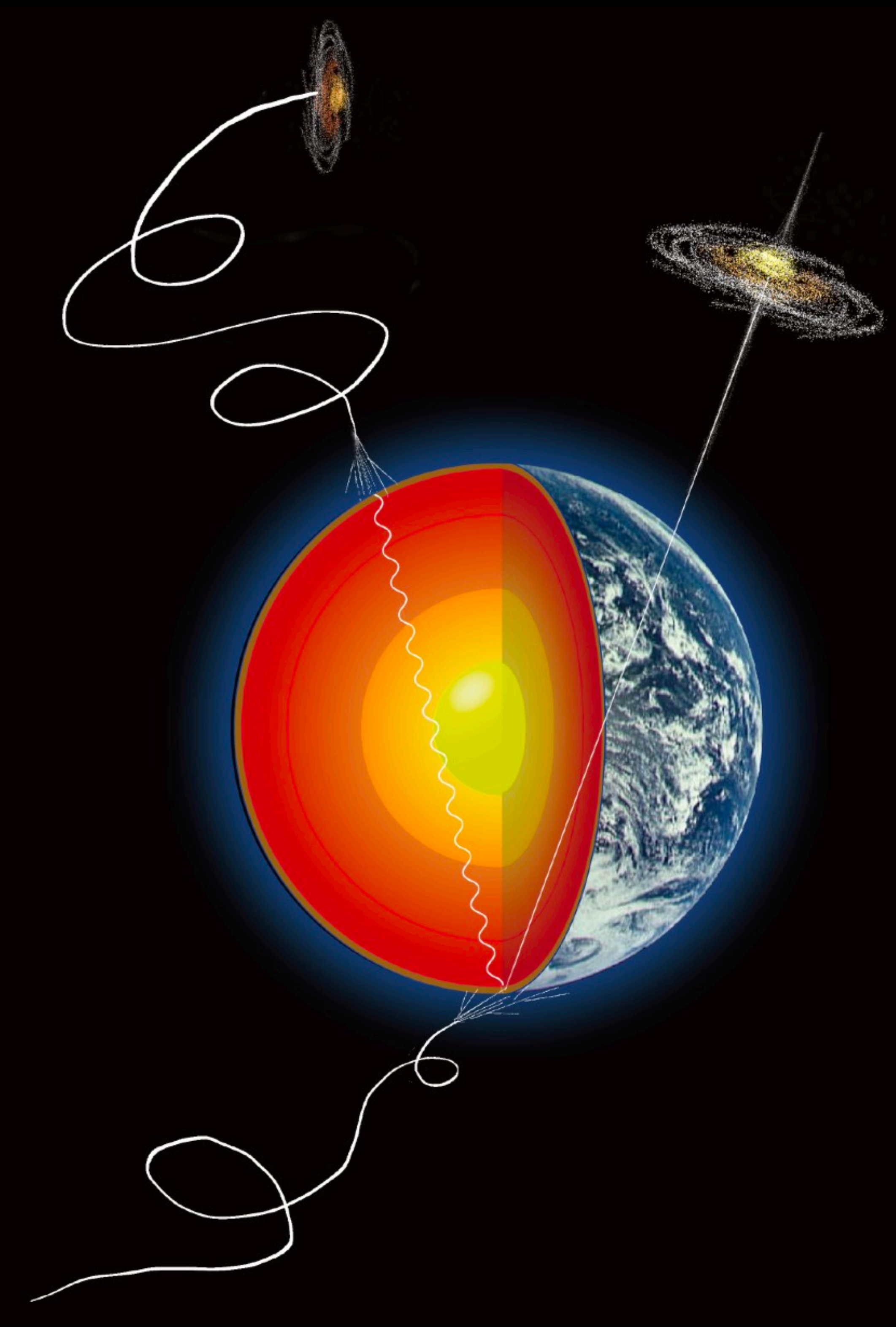


Kotoyo Hoshina for the
IceCube collaboration

June 30 2022
Multi-messenger Tomography of Earth WS
@ Snowbird, UTA

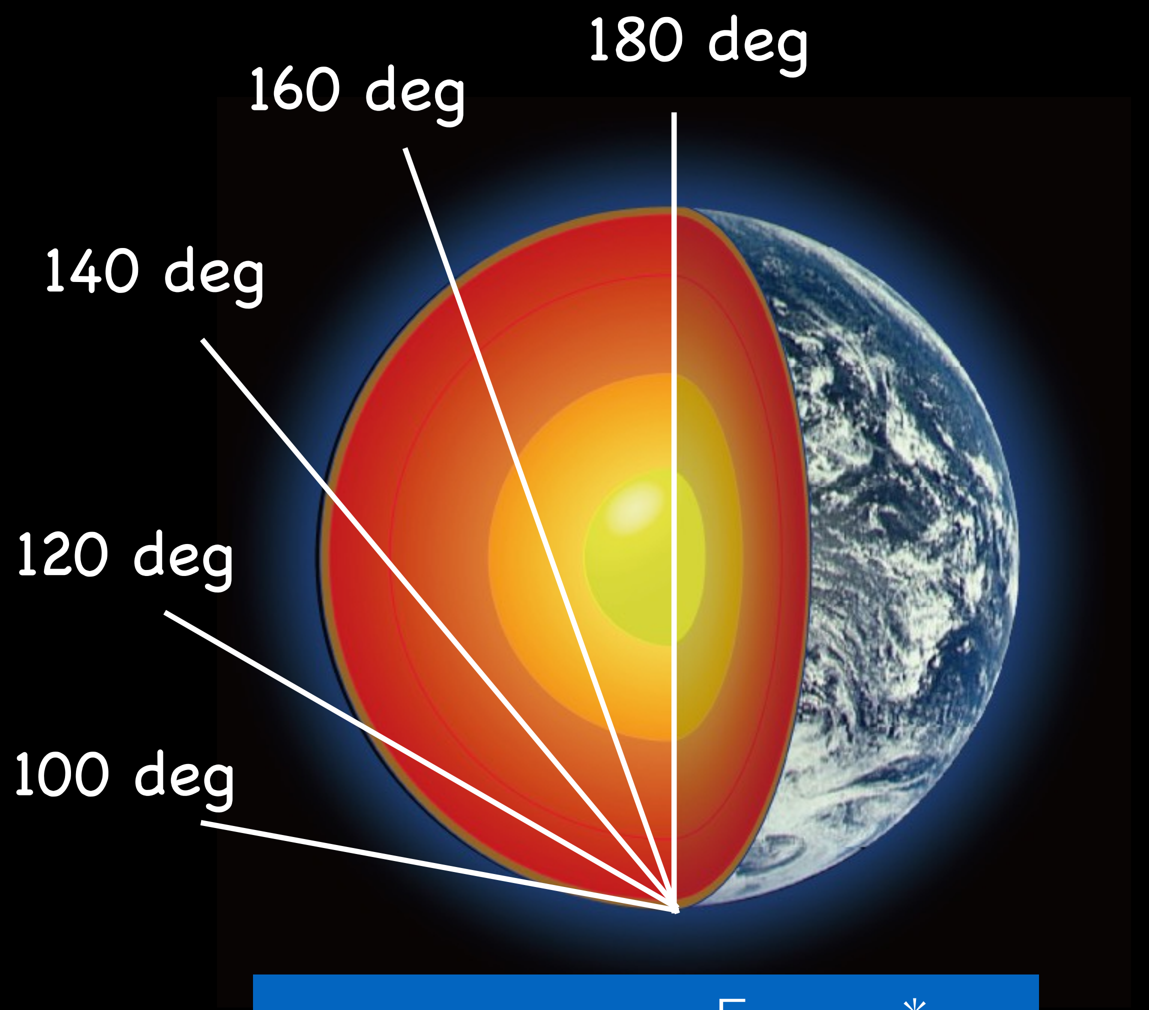
Look inside of the Earth using neutrino

- Neutrino has perfect features as a probe for investigating inside of the Earth
  - It interact with matter in two way
    - Matter effect of neutrino oscillation — see talks in tomorrow sessions
    - Weak interaction with matter (some neutrinos are absorbed by the Earth)
- This analysis detects absorption of neutrino by the Earth
  - We use atmospheric and cosmic neutrinos. Atmospheric neutrinos are generated inside atmosphere, while cosmic neutrinos are directly fly from cosmic sources such as Active Galactic Nuclei(AGN).
  - Atmospheric muons are main background events



Why we use atmospheric or cosmic neutrinos

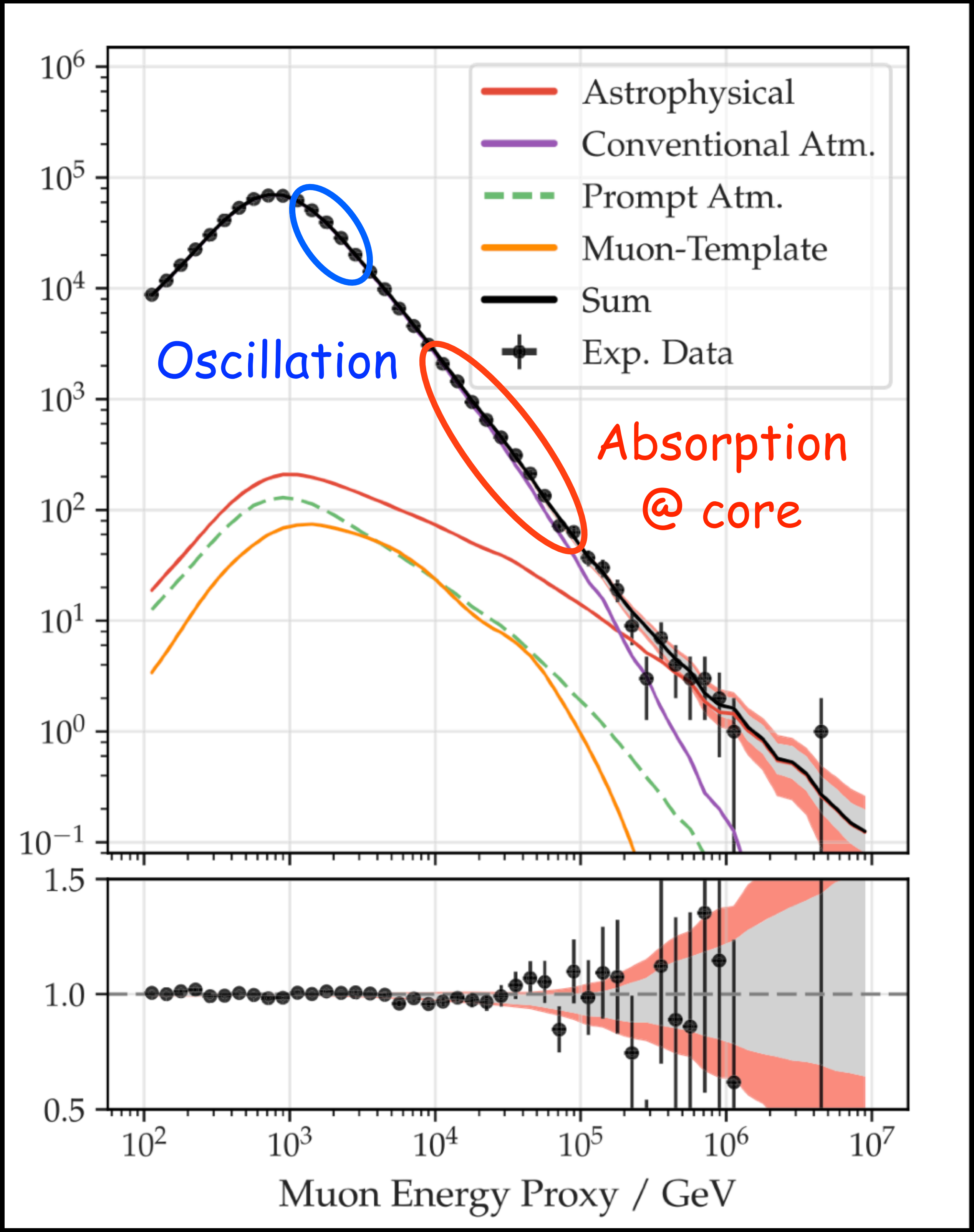
1. Multi-energy spectrum
   - Matter thickness of the Earth varies as a function of arrival zenith angle of neutrinos, thus sensitive energy for absorption varies too. Atmospheric or cosmic neutrinos have continuous energy spectrum and we can just select proper energies to detect the deficit.
2. Available anywhere on the Earth
   - We assume cosmic neutrinos are uniformly distributed
   - For atmospheric neutrino model we use Honda flux

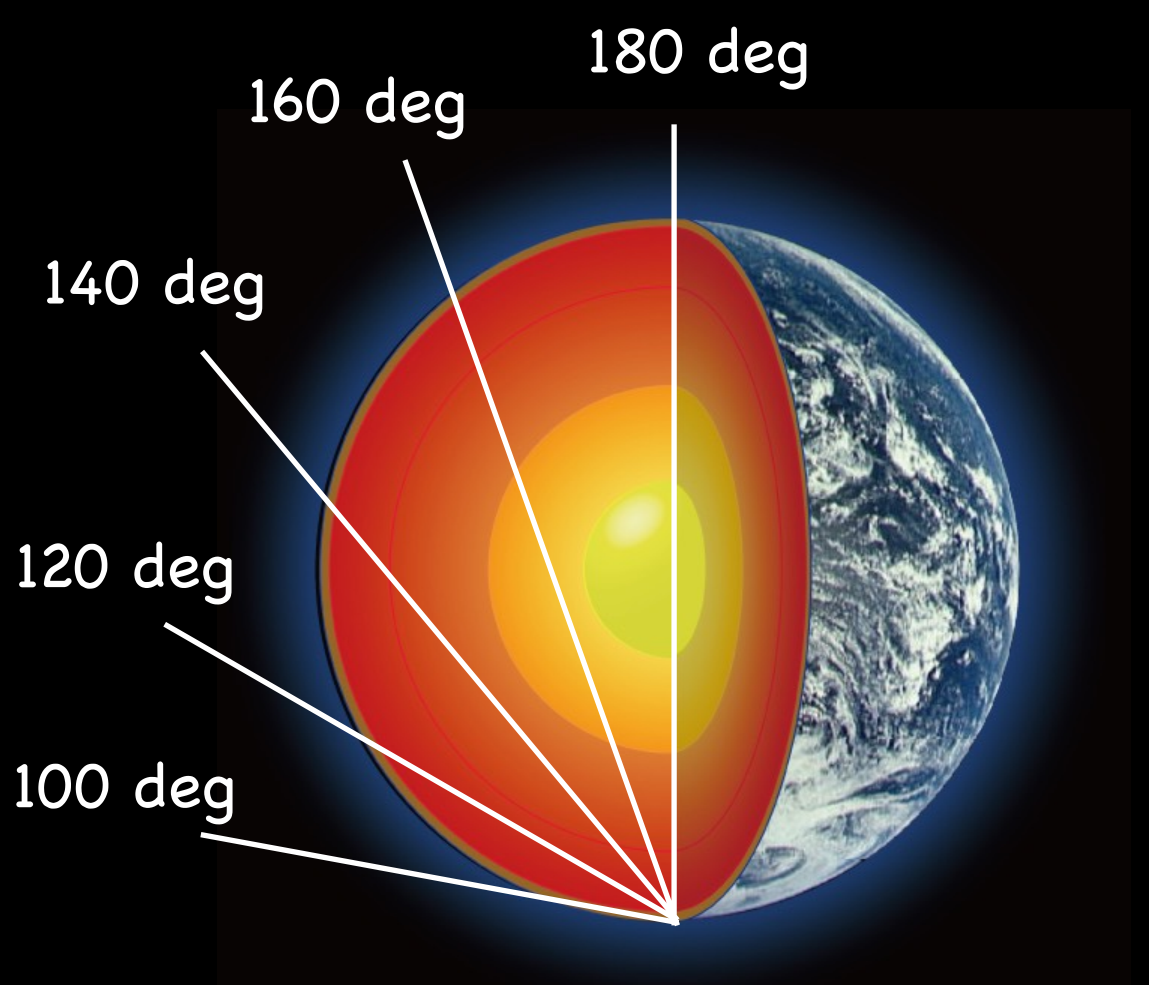


	Energy*
100 deg	7.1 PeV
120 deg	480 TeV
140 deg	150 TeV
160 deg	49 TeV
180 deg	35 TeV

*Energy of neutrino which interaction length is equivalent to the total matter thickness (column depth) along the neutrino's trajectory, with different arrival angles at detector. Assuming PREM Earth Model.

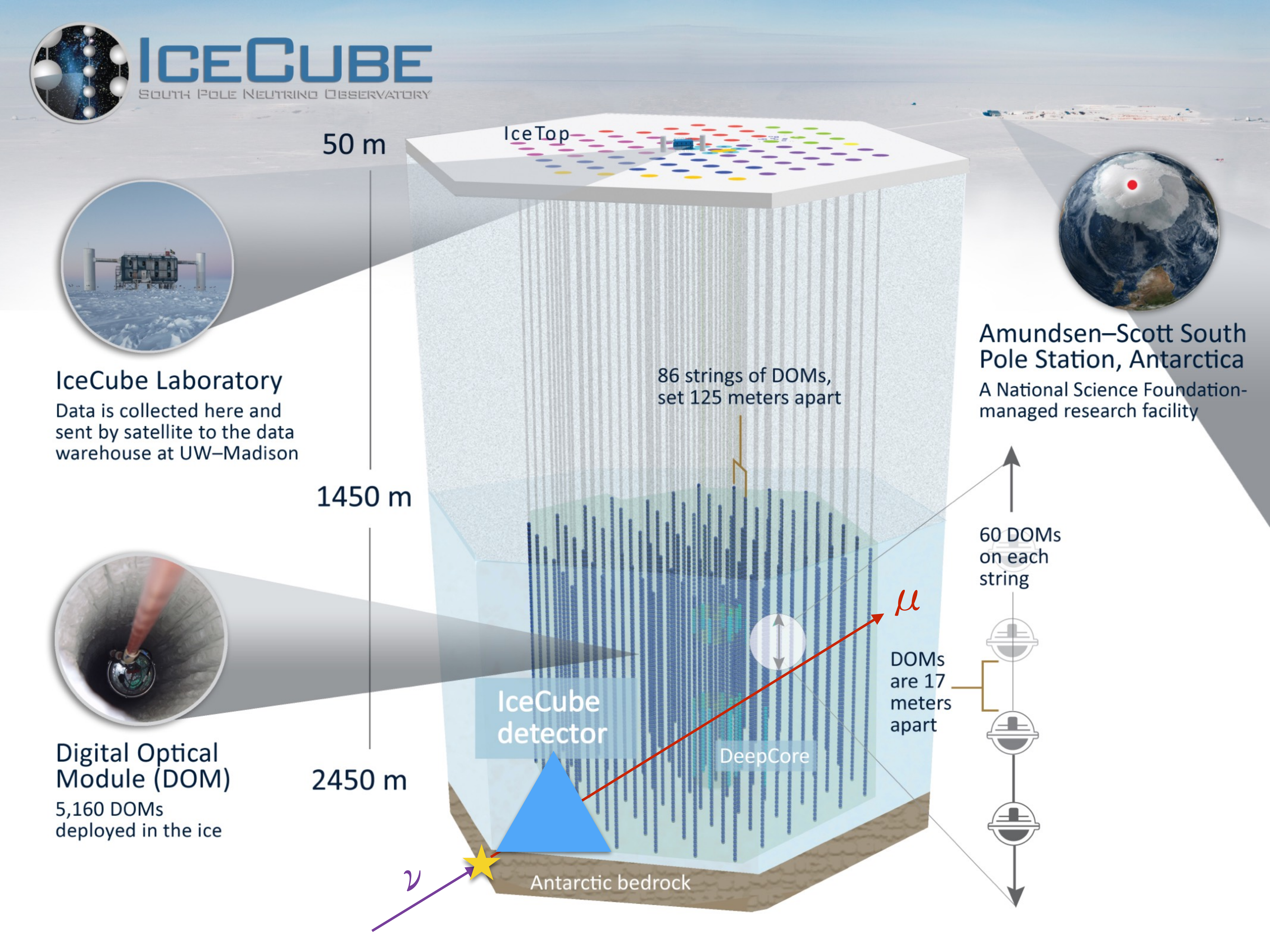
Why we use atmospheric or cosmic neutrinos





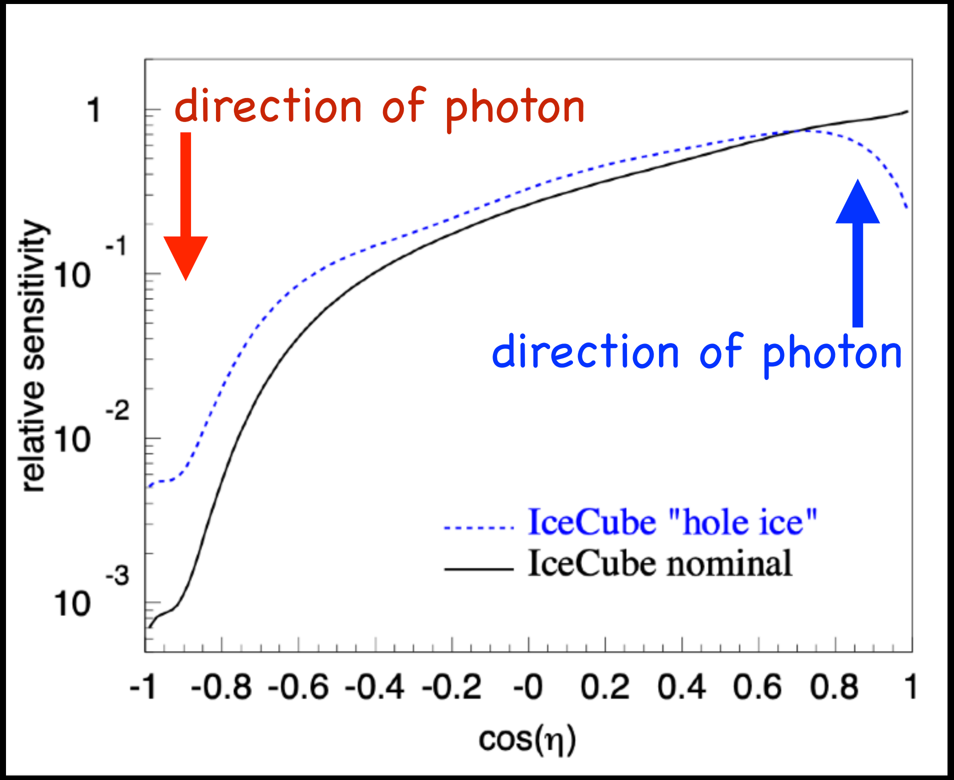
	Energy*
100 deg	7.1 PeV
120 deg	480 TeV
140 deg	150 TeV
160 deg	49 TeV
180 deg	35 TeV

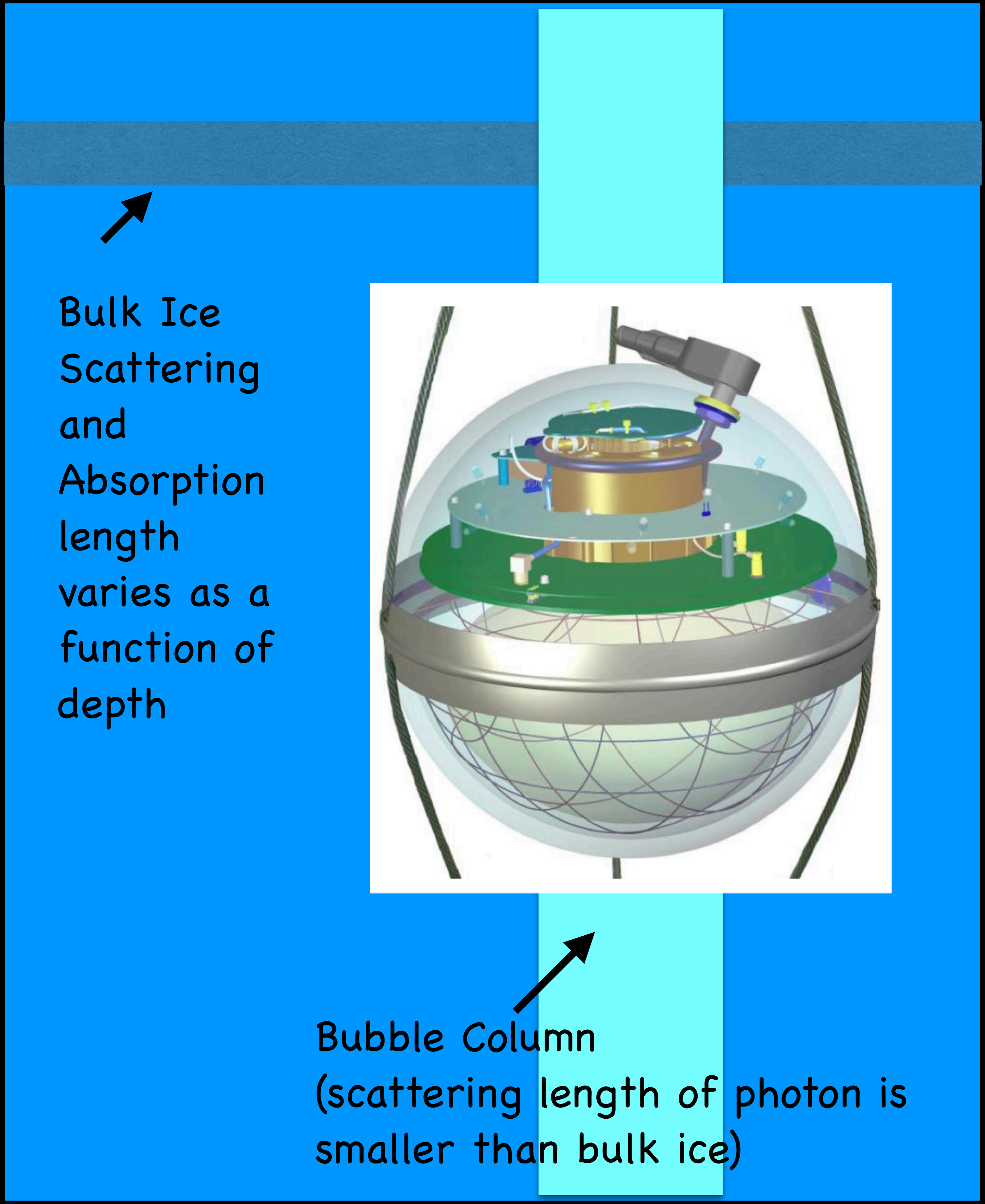
R. Abbasi et al Astrophysical Journal 928 (2022) 50
Improved Characterization of the Astrophysical Muon–neutrino Flux with 9.5 Years of IceCube Data


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
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
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
IceCube detector
DeepCore
Antarctic bedrock
μ
ν

IceCube Sensor — Digital Optical Module (DOM)

- Optical sensor is facing down, sensitivity has zenith dependence
- Also bubble column affects to the sensitivity
- Bulk ice has layered structure
- We calibrate these effects using LED lights attached to the main board

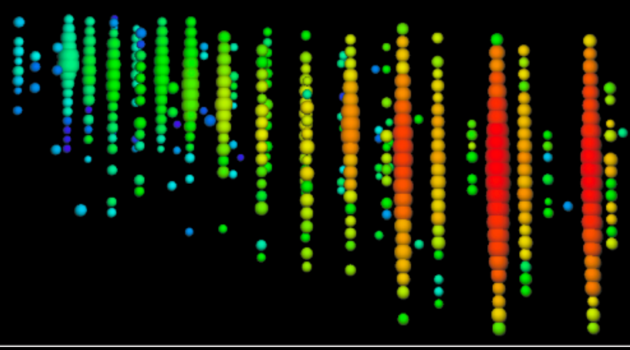


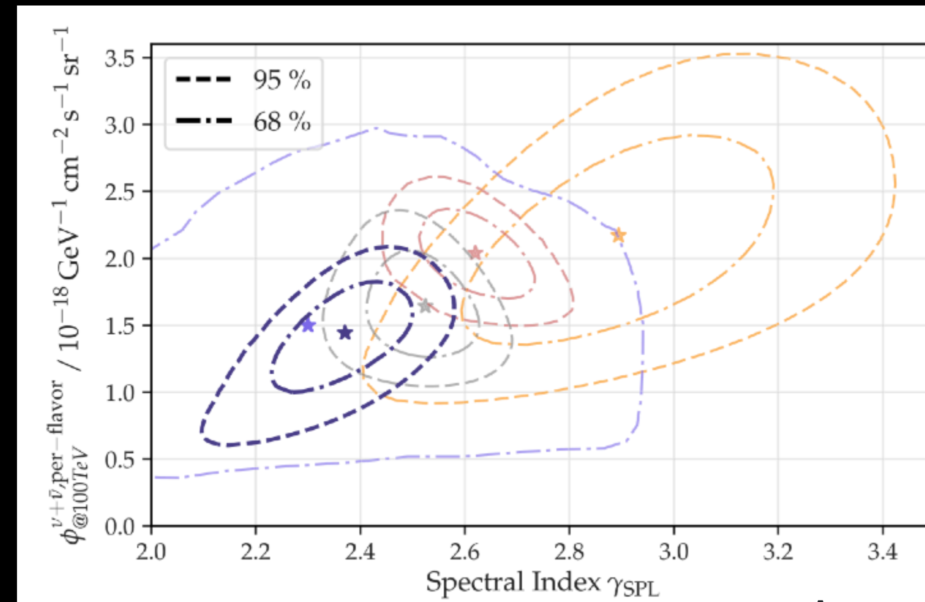


Science with IceCube

Searching Neutrino from a Source

~300 TeV neutrino located within less 0.1 degrees from TXS0506+06 blazar (September 22, 2017)



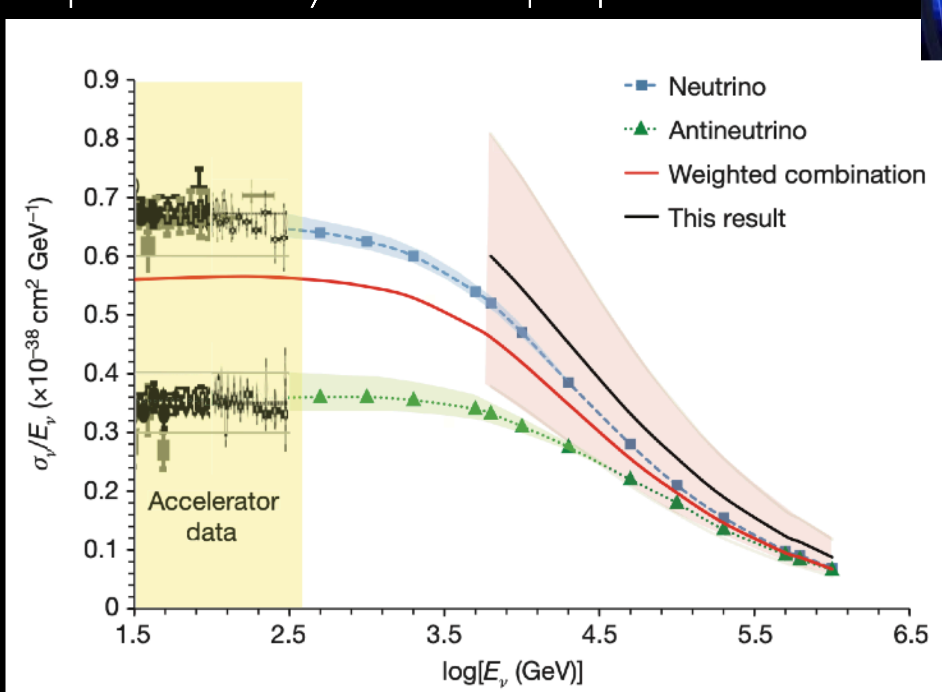


Measuring Power Law Spectral Index of Energy and Flux for Cosmic neutrino

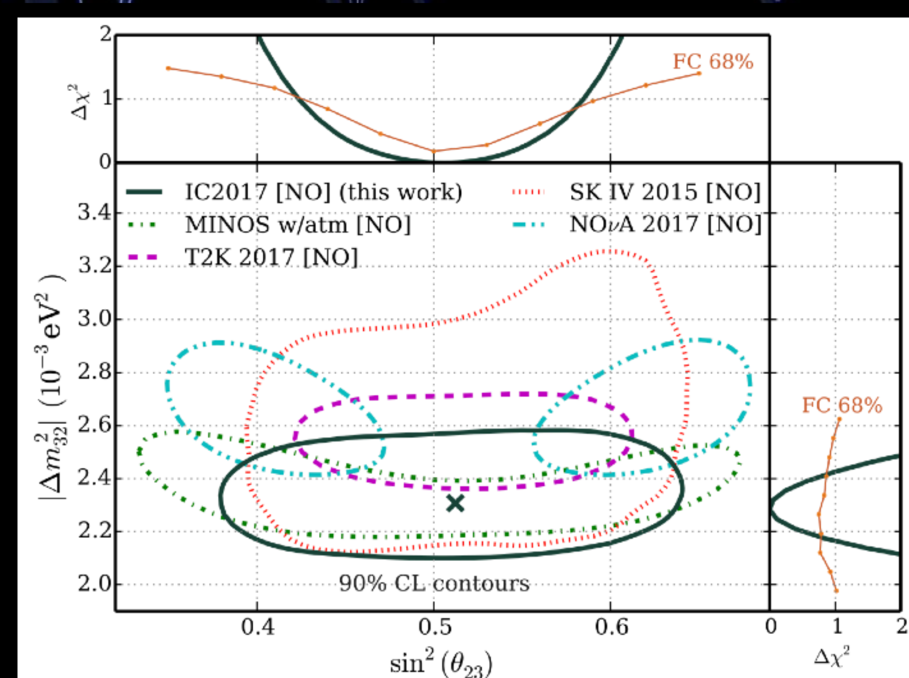
Astrophysical Journal 928 (2022) 50

Measuring Neutrino's Cross Section

Two analysis has been published, updated analysis are in preparation



Nature, 55 :596-600 (2017)



And More..

- Cosmic Ray Physics
- Dark Matter
- Beyond Standard Model

Measuring Neutrino's Oscillation Parameter using Deep Core

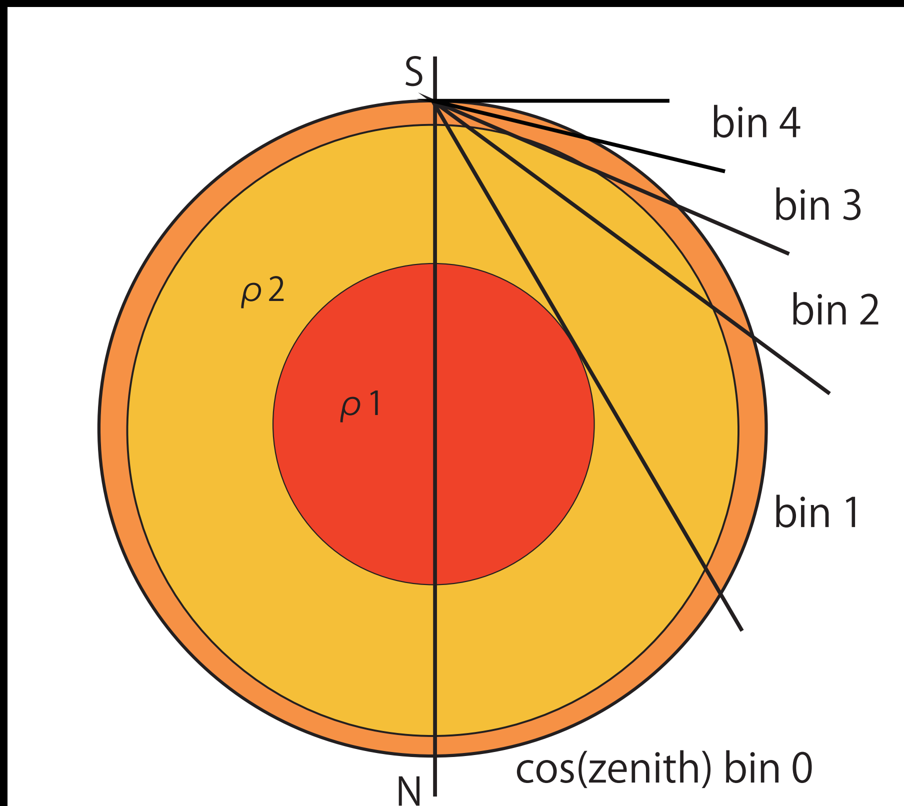
Phys. Rev. Lett. 120, 071801

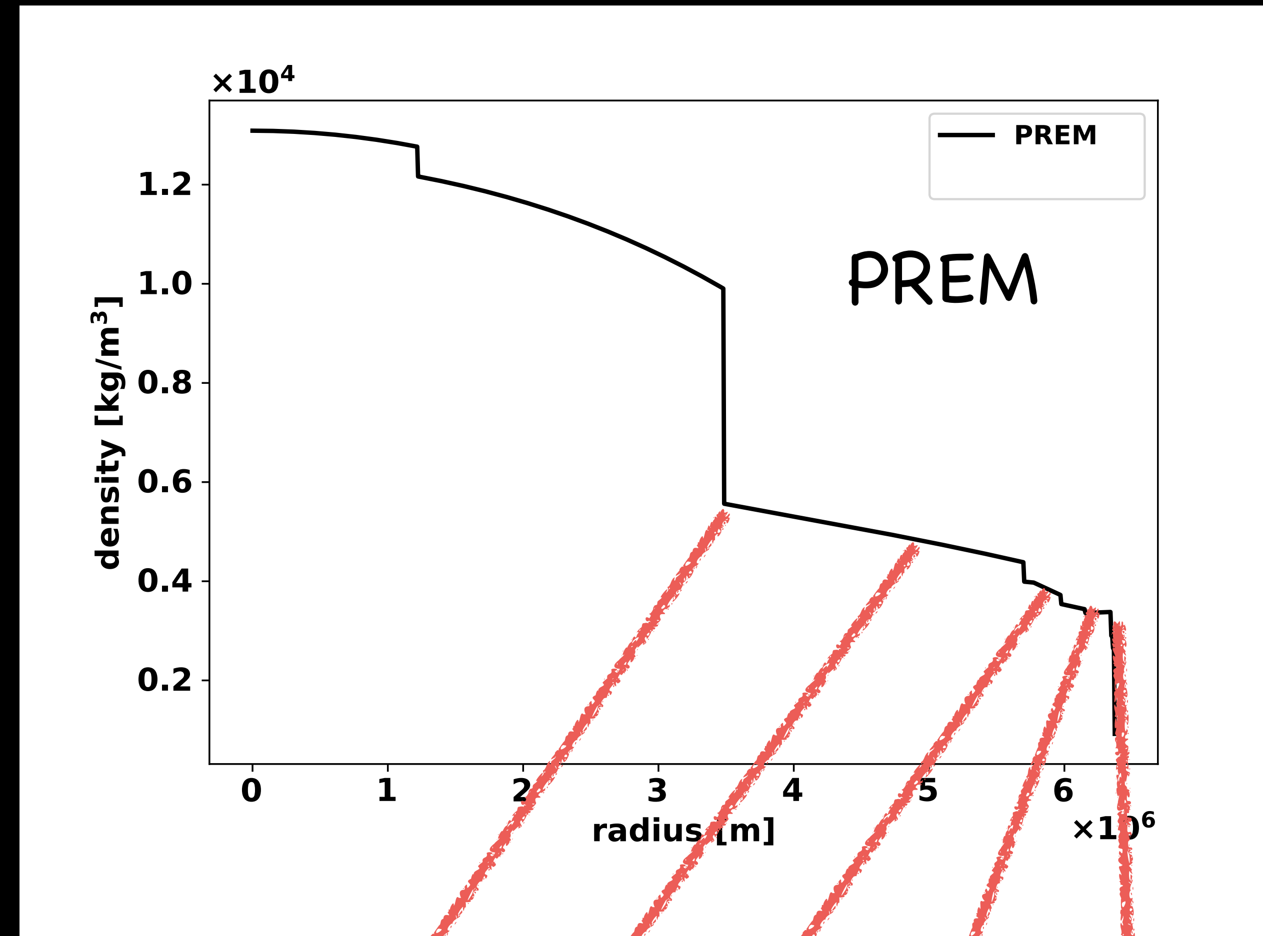
Measuring density of the Earth using Atmospheric neutrino events

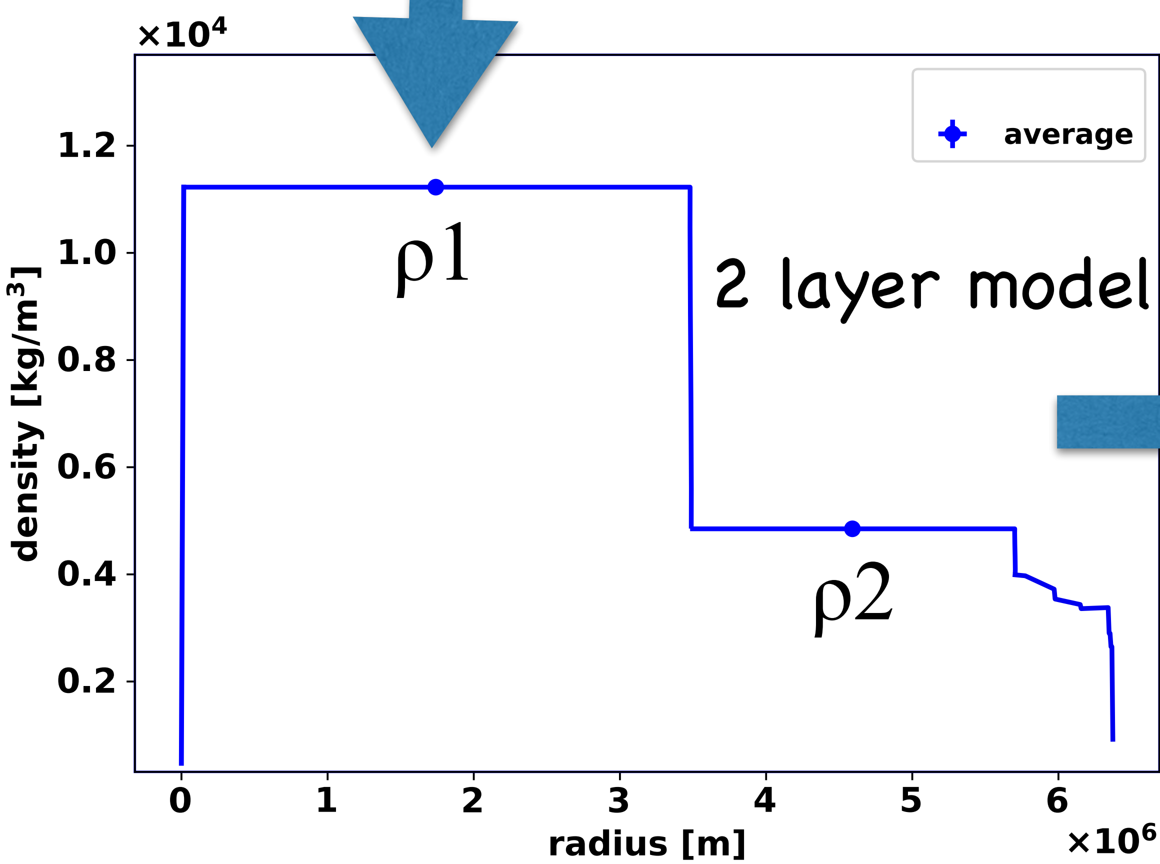
- Majority of events collected by IceCube are atmospheric neutrinos
- More than 30000 neutrinos that pass through the core region may be observed in 2010-2020 season (above TeV)
- For most of analysis they are treated as "background", but can be used for measuring Earth's core density
- Need precise control of systematics
  - Assume Standard Model neutrino cross-section based on HERA PDFs* which has ±1.5% uncertainty in the measured energy range (smaller than other sources considered here)

*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).

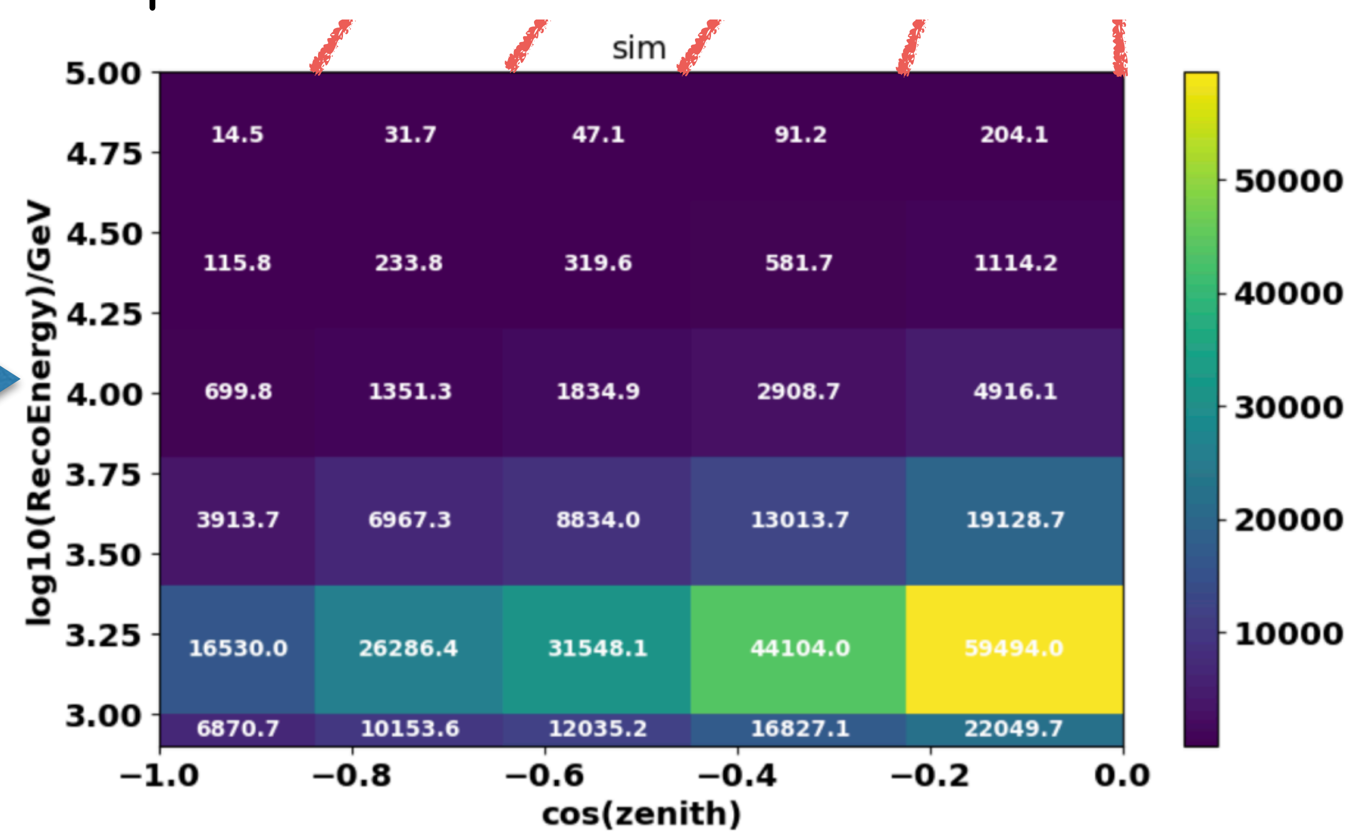
Using layered structure for Earth model





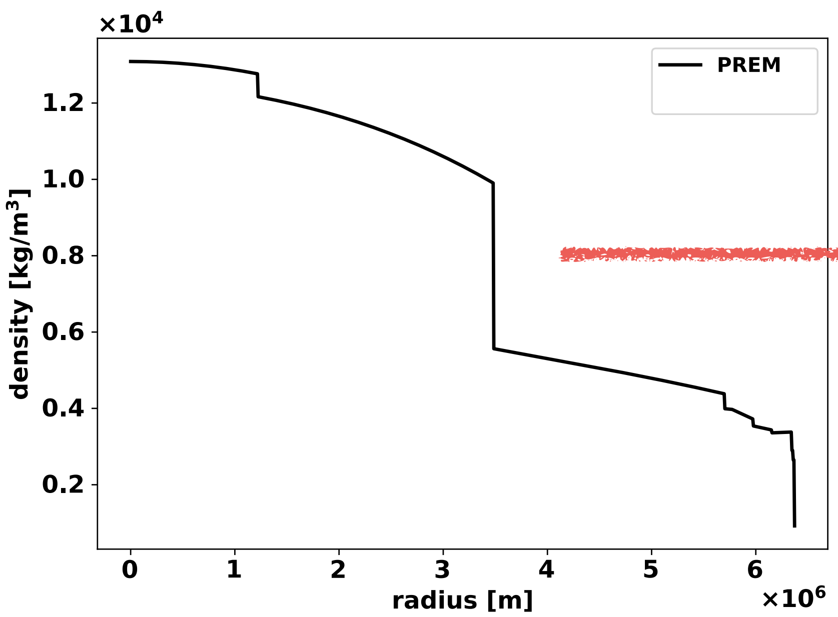


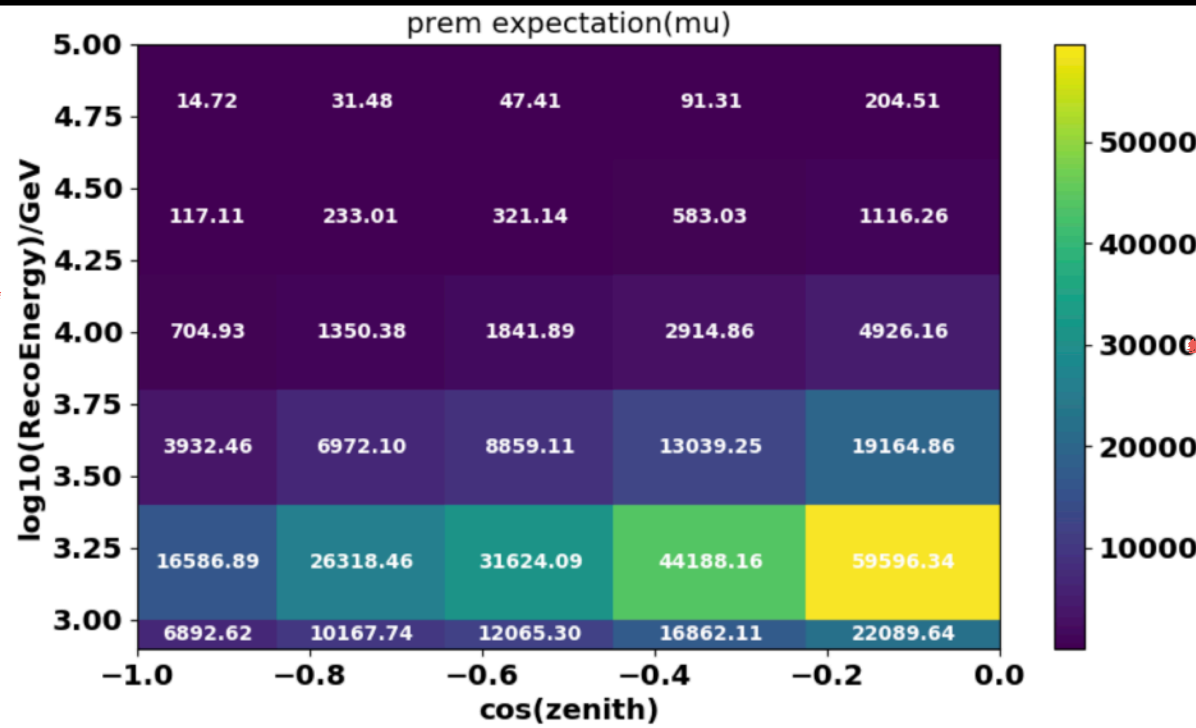
predicted number of observed events



Checking performance of the analysis — Asimov Test

making expected bin count from PREM model simulation

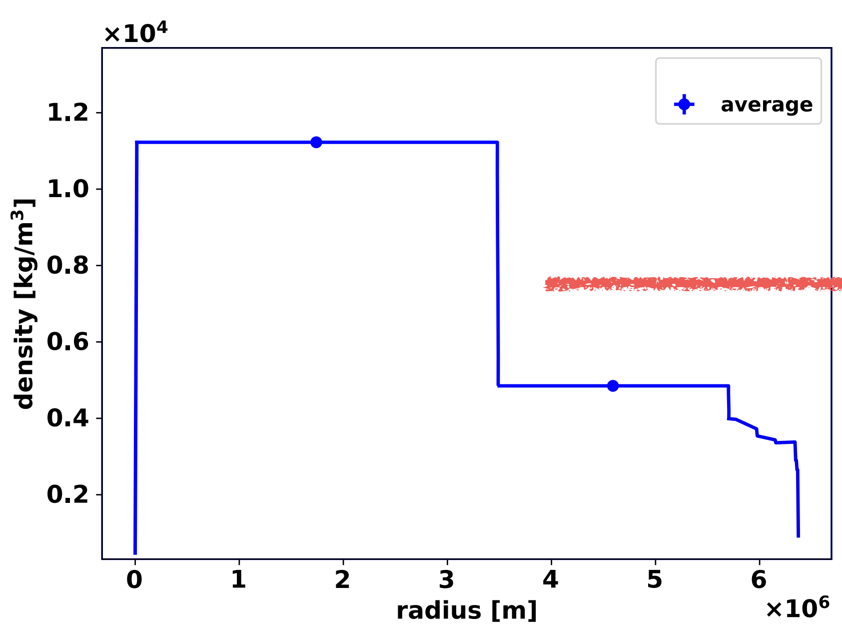


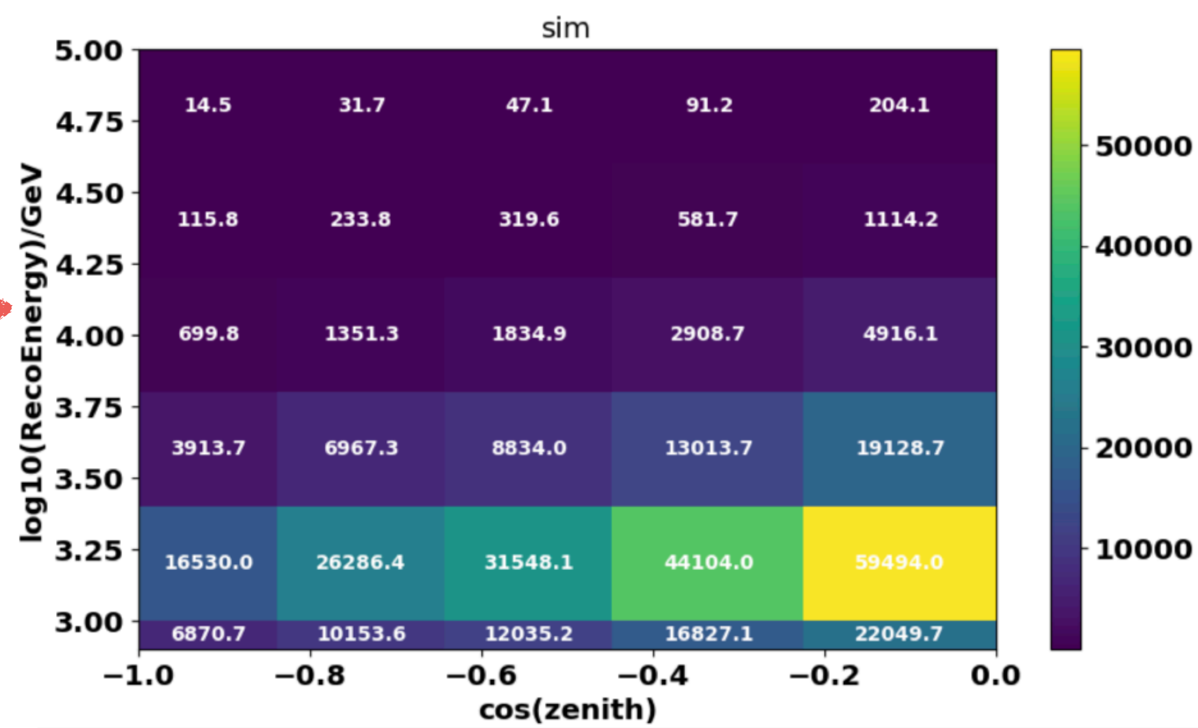


poisson sampling → Asimov data

≠

making flat density simulation





Fit density model to Asimov data.

But re-running simulation for each model is too CPU expensive!

Calculate arrival flux of neutrino at detector using NuFATE*

- NuFATE is a program that calculates arrival flux of neutrinos after total number of atoms $\boldsymbol{x}$ has been traveled through.

Eigenvalues

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

arrival flux

coefficients

Eigenvectors

number of target atoms

NUFATE

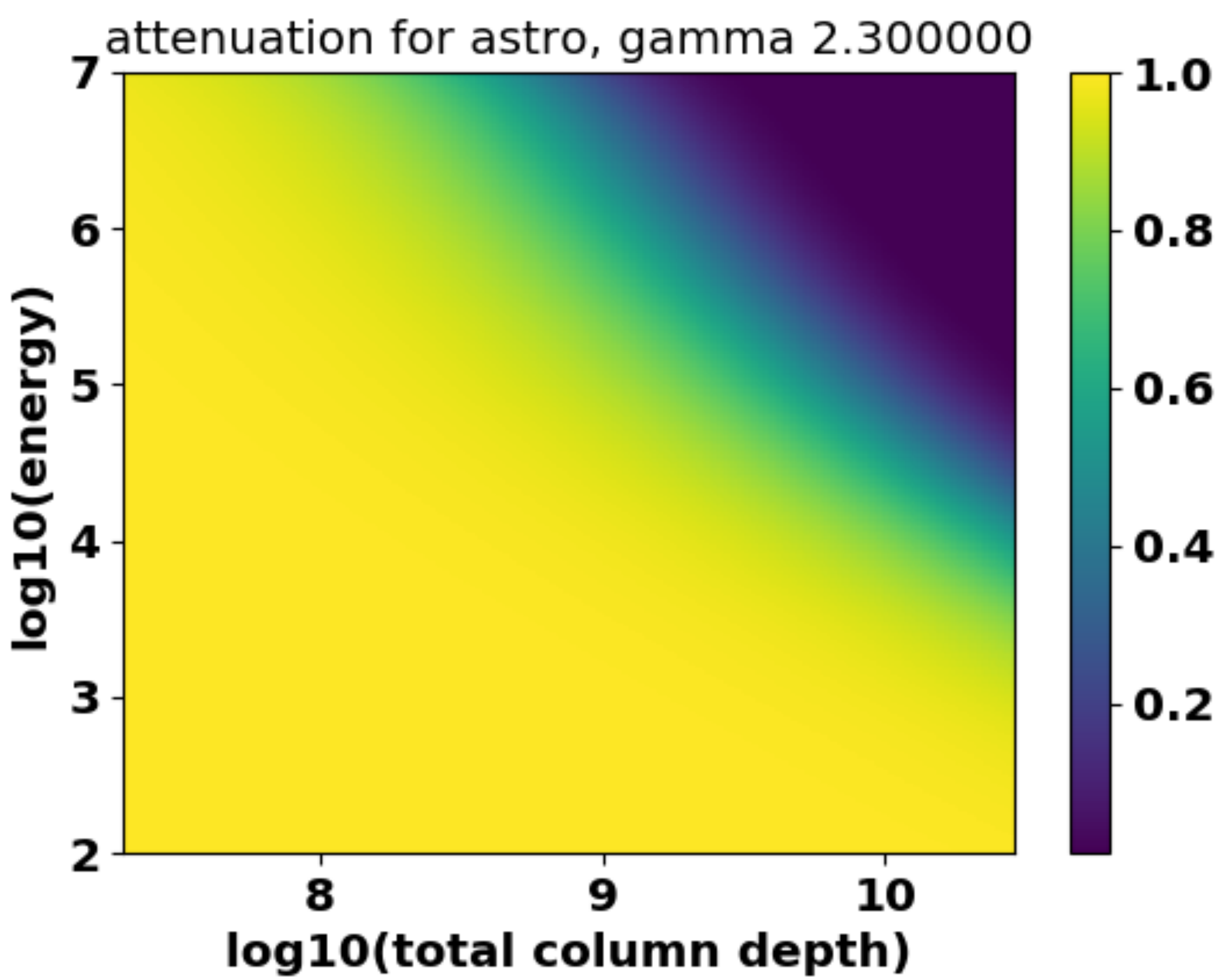
- Eigenvectors and Eigenvalues depend only on cross sections and energy nodes, therefore can be calculated at the beginning of run.

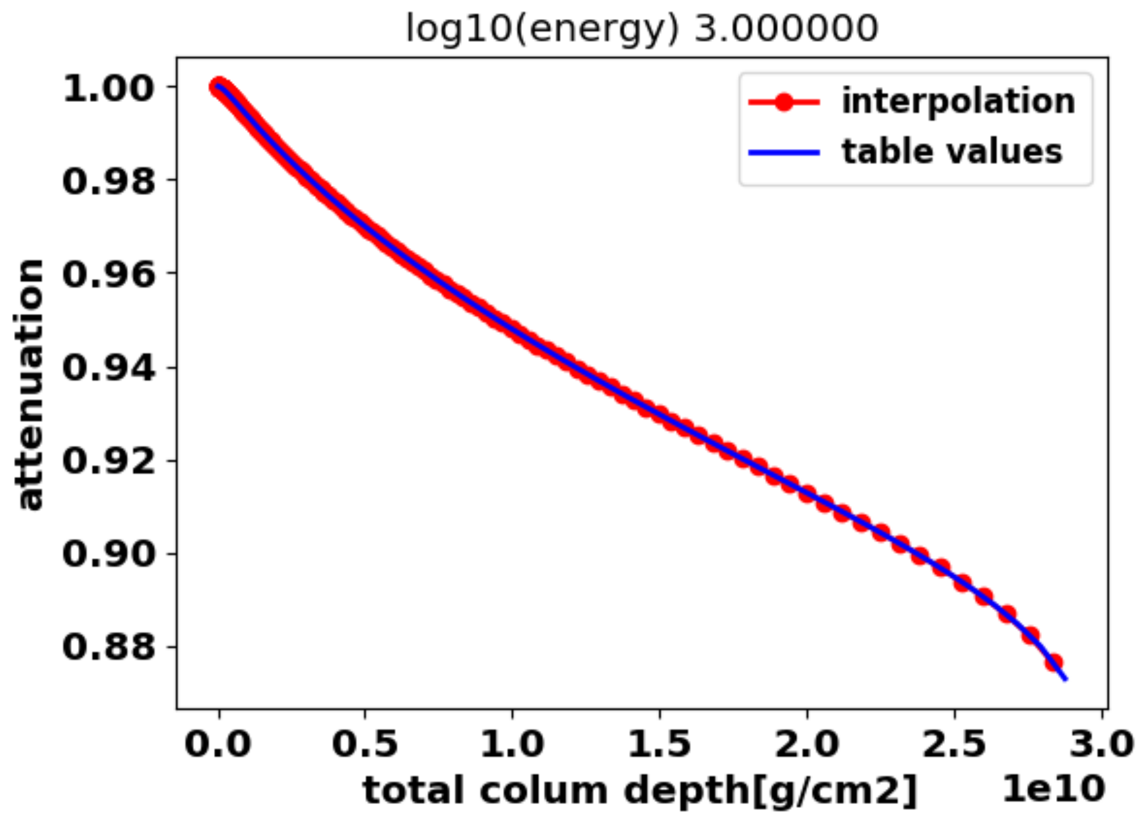
  Coefficients depend on primary energy spectrum in addition to cross section and energy nodes, so as long as the primary flux is fixed, it can be calculated only once a run.

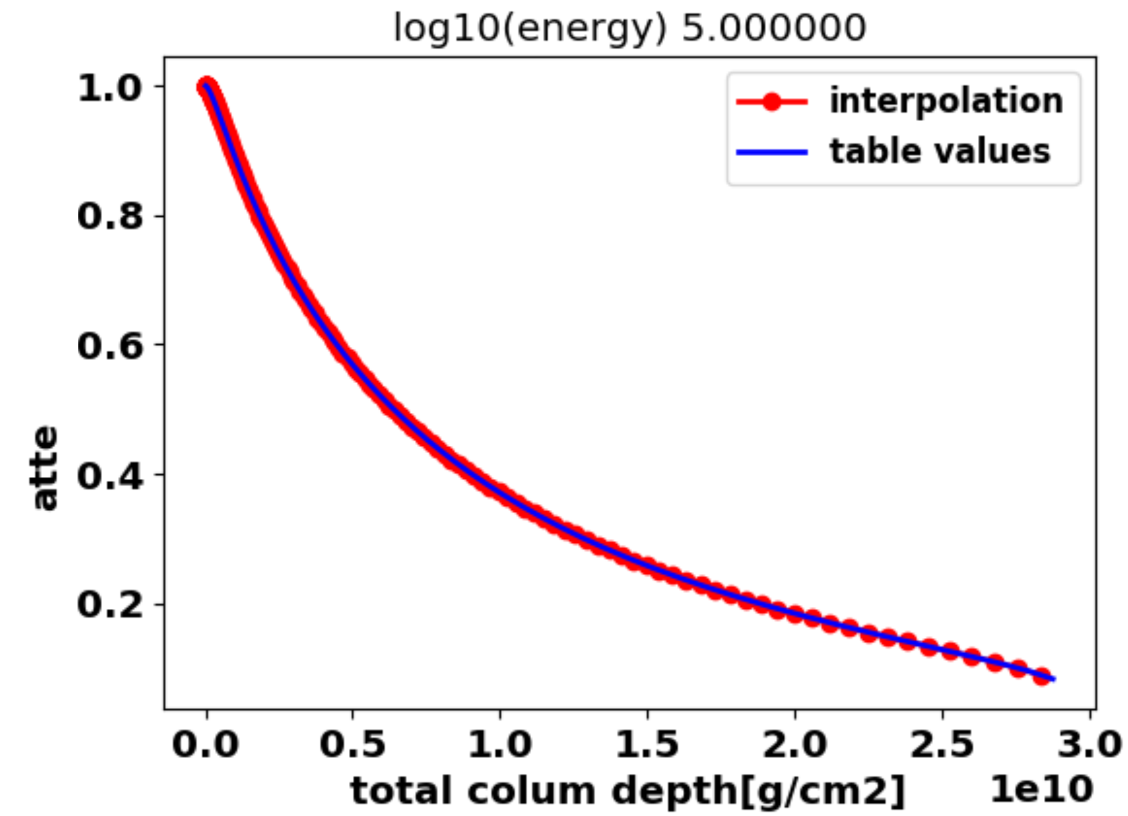
  Giving the total number of target x we get arrival flux. In fact NuFATE returns the ratio between primary flux and arrival flux, which corresponds **attenuation factor**.
  It is fast enough running in the fitting loop, but we used NuFATE to generate attenuation table in order to speed up the program even more.

*https://github.com/aaronvincent/nuFATE

2D attenuation table (generated with NuFATE)

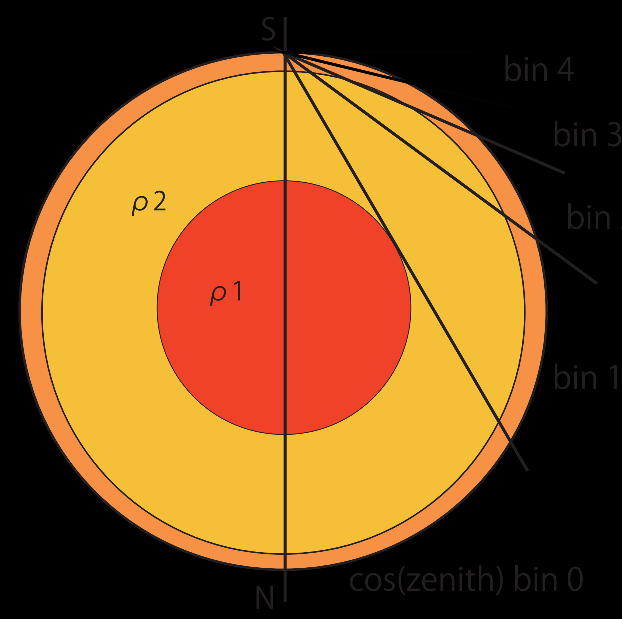






Minimum column depth corresponds 200km ice
Maximum column depth corresponds the longest path of Iridium(22.56g/cm3) Earth

Parameters for fitting



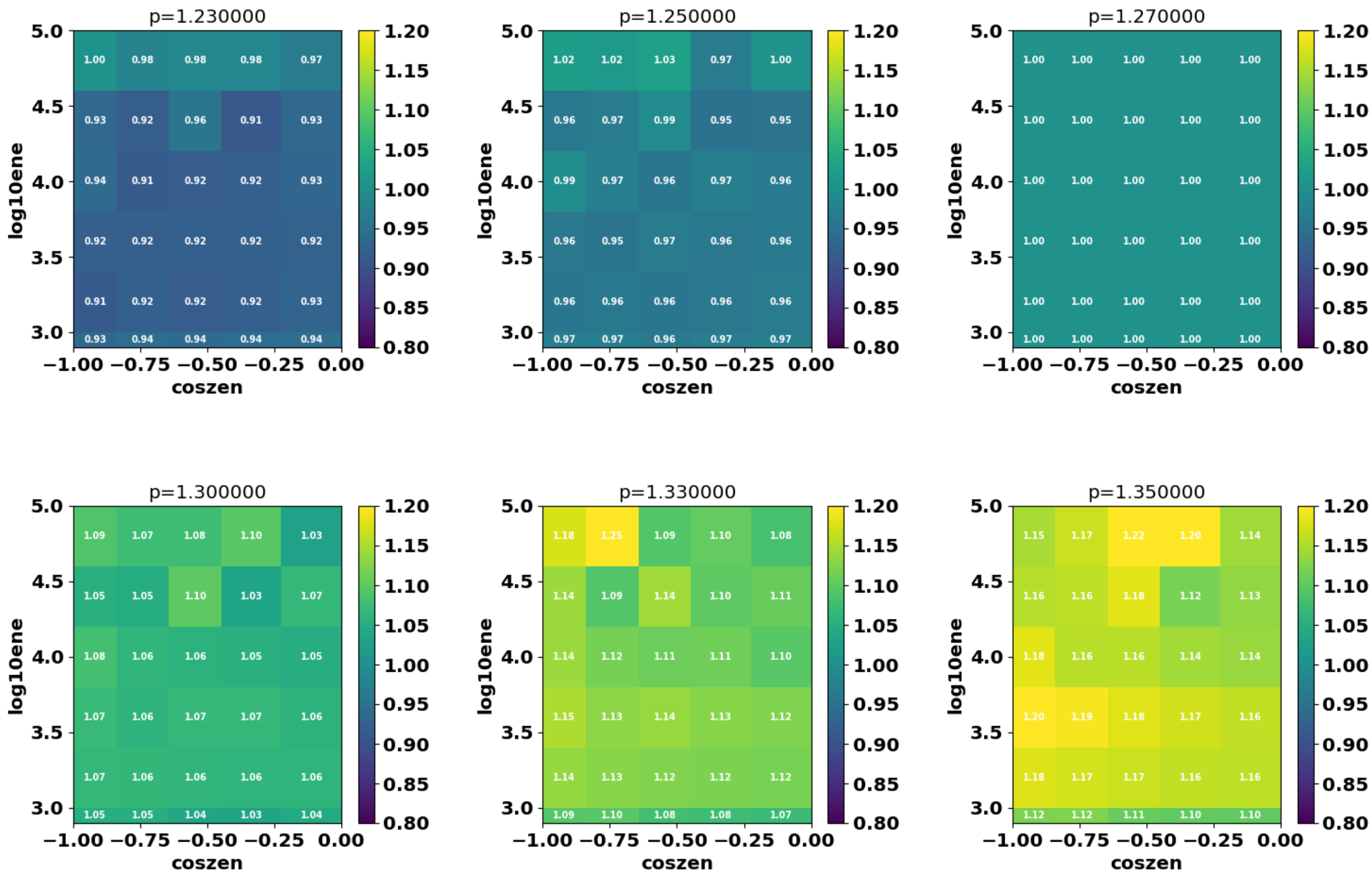
Physics parameters are :
ρ1 and ρ2 … averaged densities of each layer

However, while the fitting process we have to take into account of

- Error of normalization of 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
- Ratio of components in cosmic ray (kaon, pion, neutrino, anti-neutrino)
- Error of DOM efficiency — acceptance of Cherenkov light at DOM
- Ice Properties — ice is not uniformly transparent, because this is natural ice. In addition, bubbles generated during deployment of DOM affects angular acceptance of DOM.

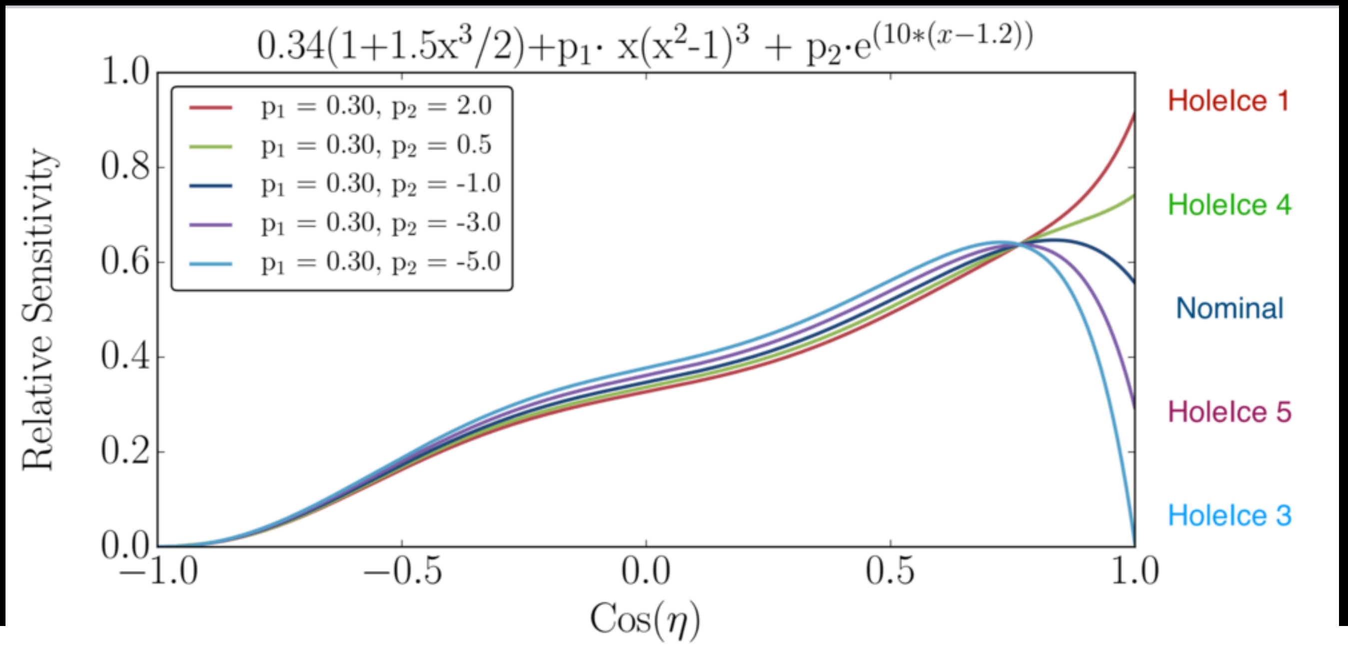
DOM efficiency table (ratio to nominal value p=1.27)

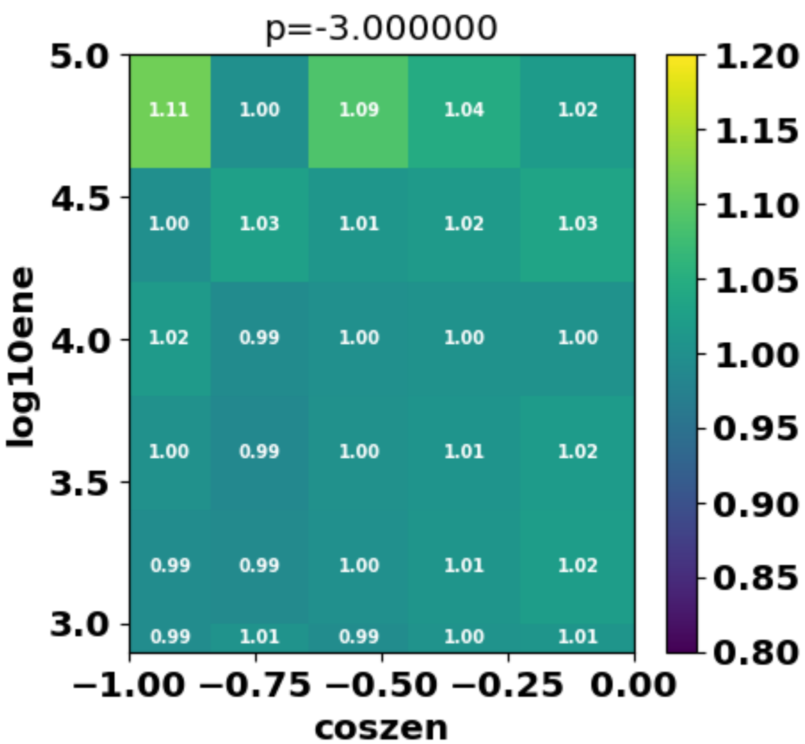
- multiplied as scale parameter for each bin while fitting loop (linear interpolation is used)



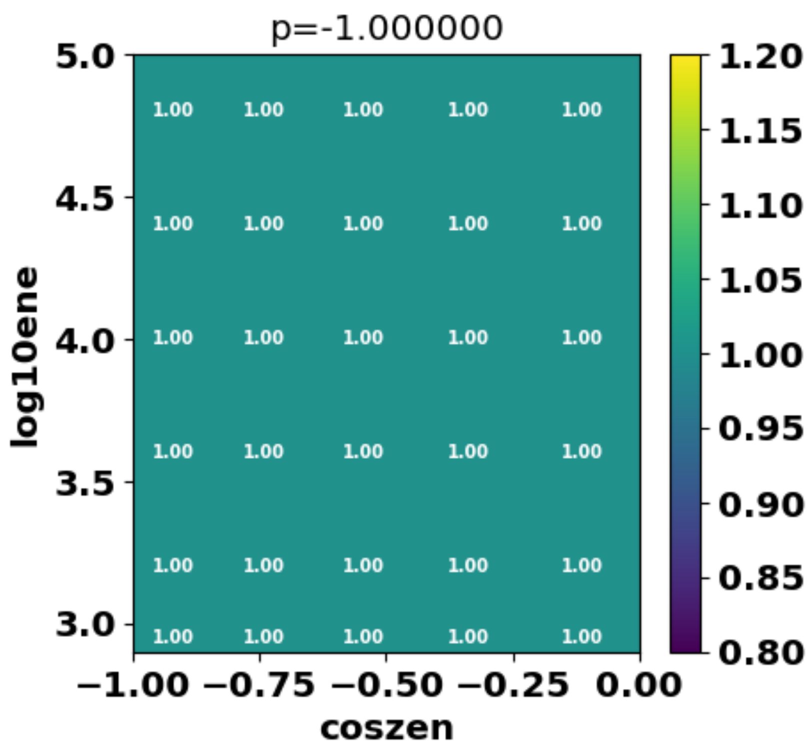
hole ice table (ratio to nominal value -1.0)

- multiplied as scale parameter for each bin while fitting loop (linear interpolation is used)

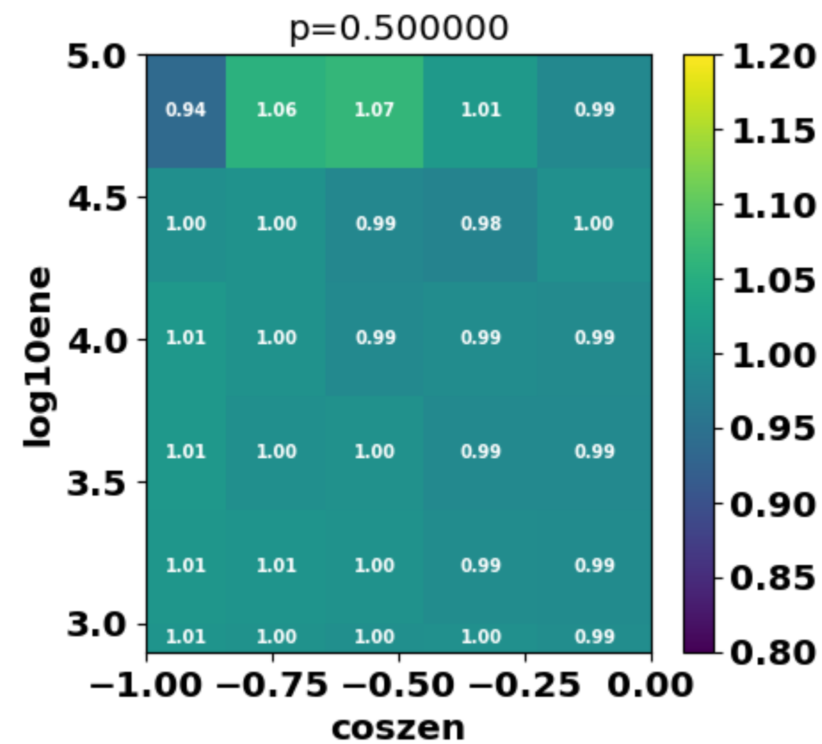




HoleIce5



Nominal

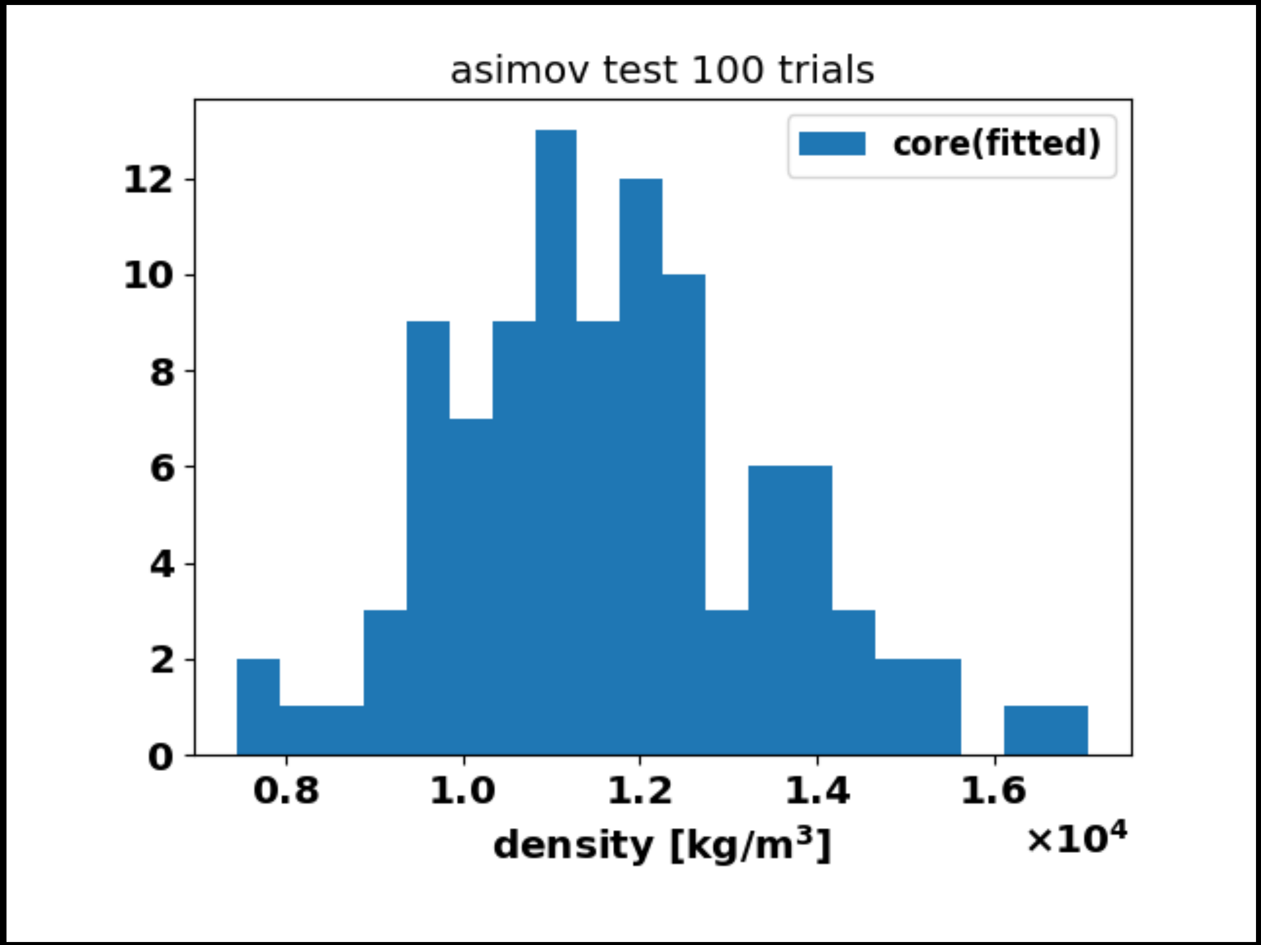


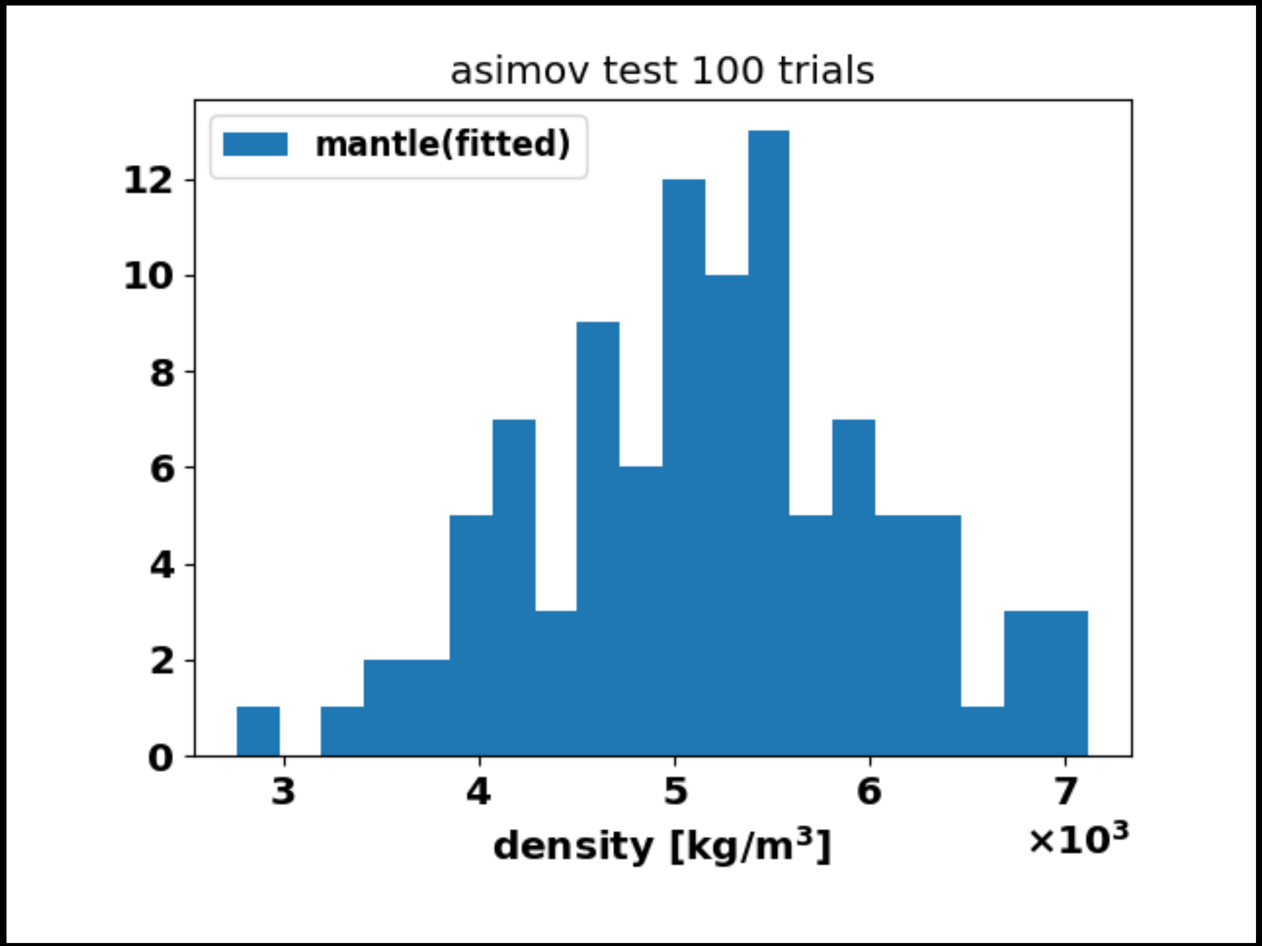
HoleIce4

using 3~4million simulations each, may be increased x10

Results from 100 Asimov Tests

Scaled for 11 years of IceCube data





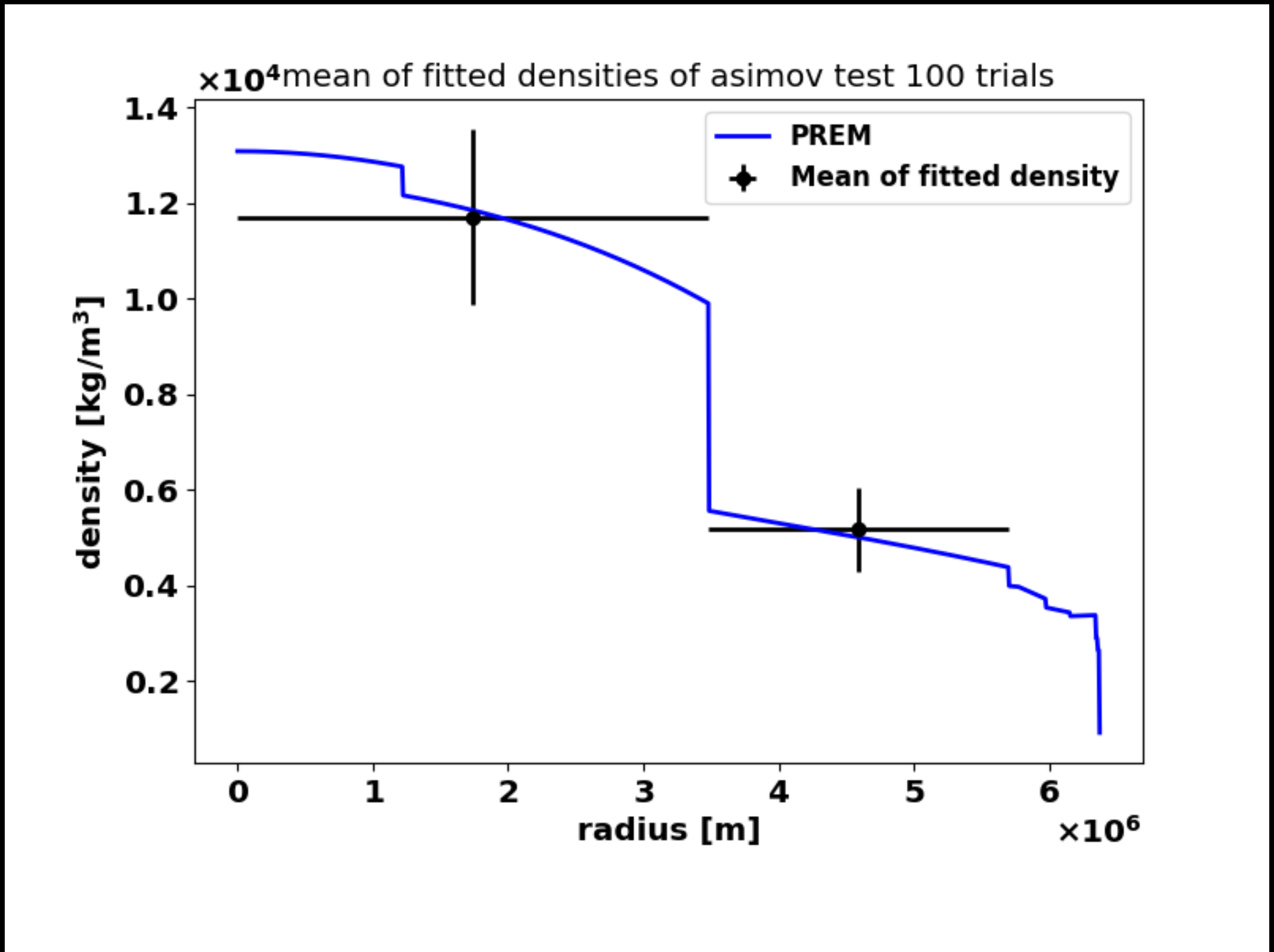
Systematics studies are still ongoing

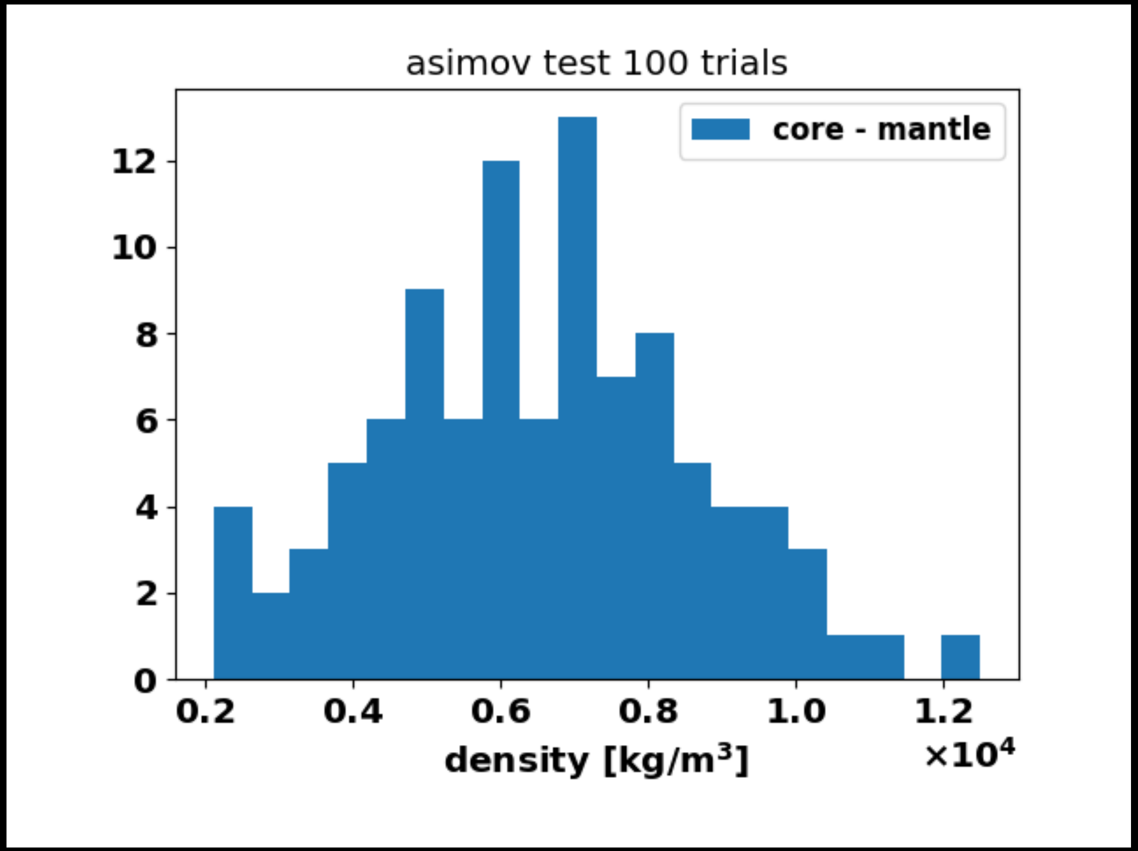
- Atmospheric spectrum will be updated with new MCEq* program
- Error of bulk ice properties are not included in these plots

*https://github.com/afedynitch/MCEq

Results from 100 Asimov Test

Scaled for 11 years of IceCube data





Y-axis error bars represent standard deviations of fitted densities of 100 trials

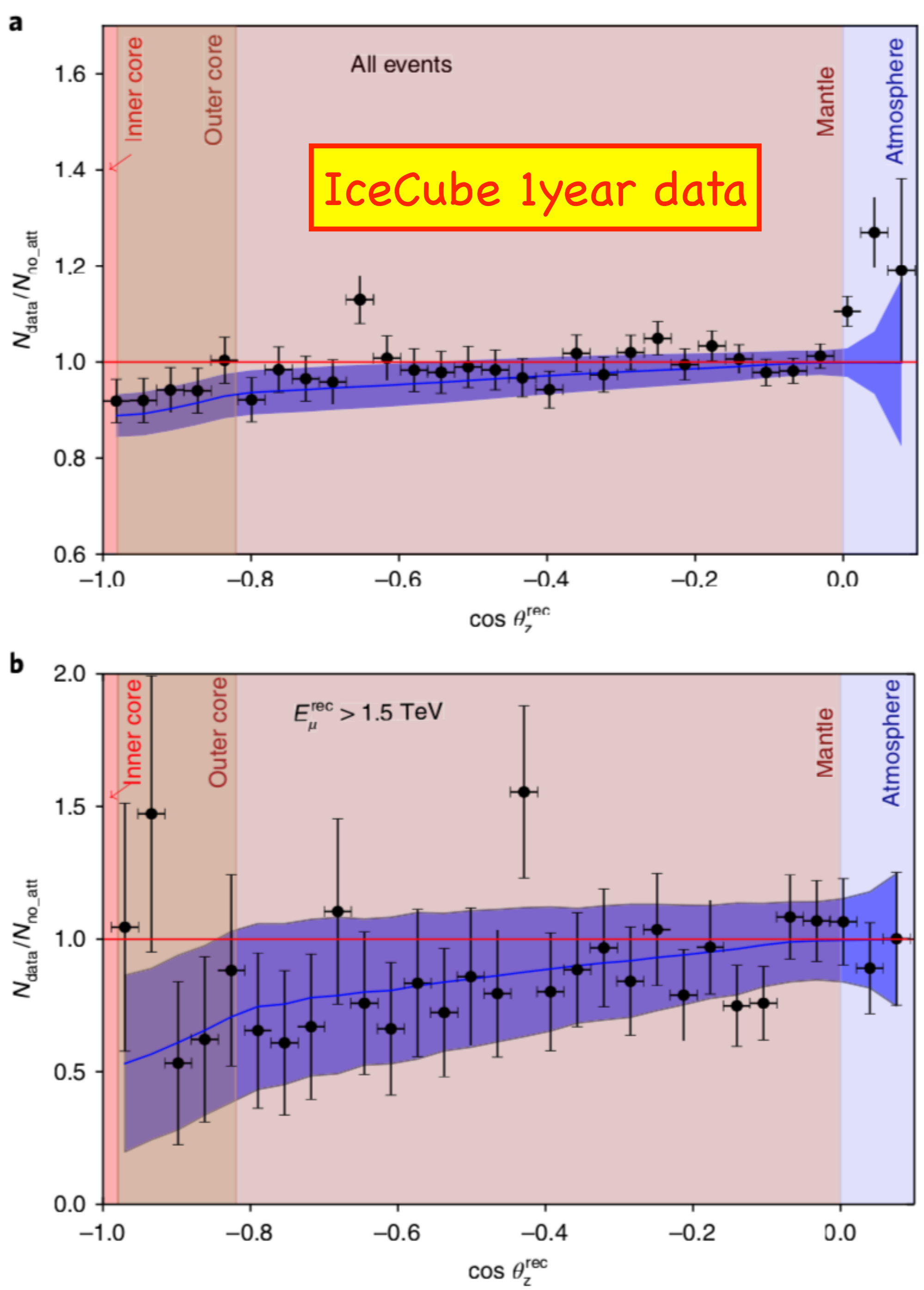
Systematics studies are still ongoing

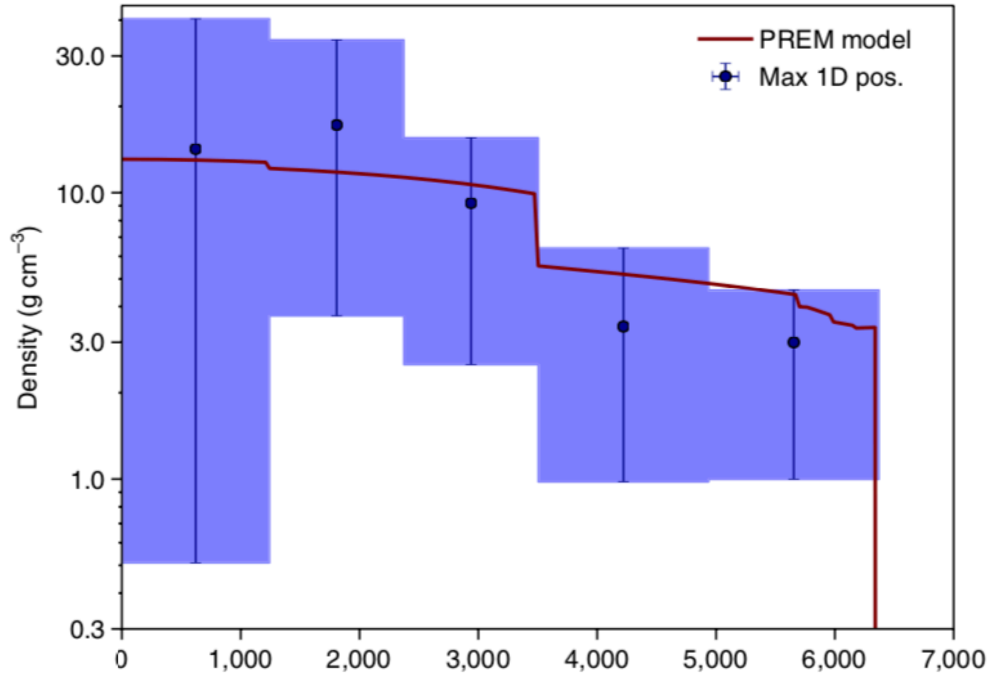
- Atmospheric spectrum will be updated with new MCEq* program
- Error of bulk ice properties are not included in these plots

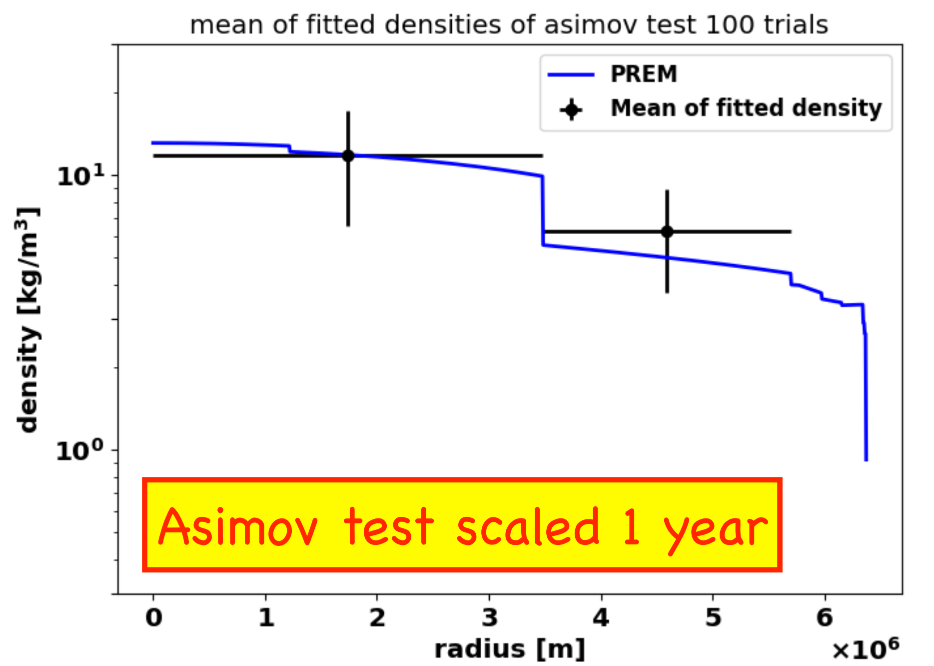
https://github.com/afedynitch/MCEq

Comparison with the past analysis

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





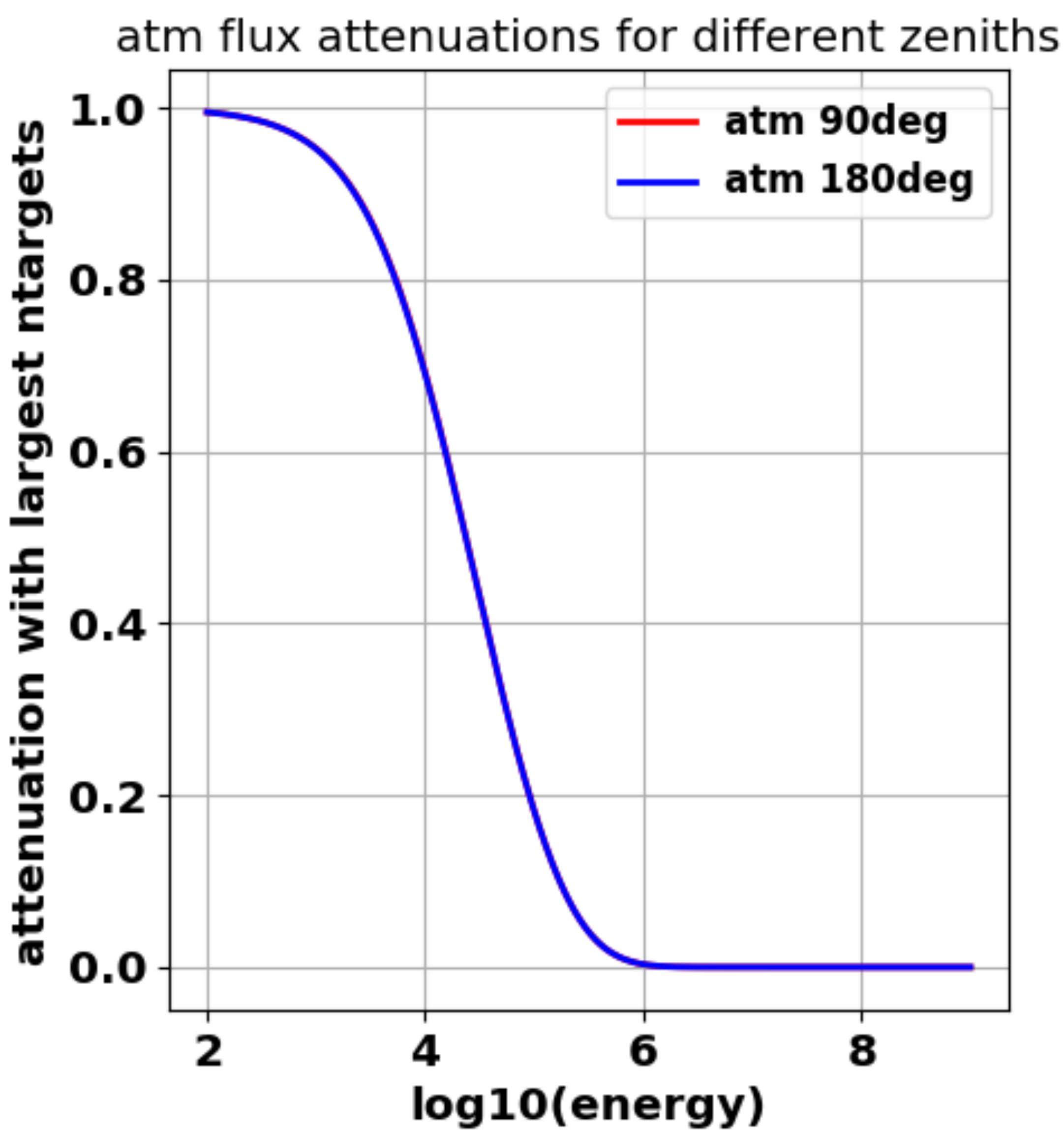


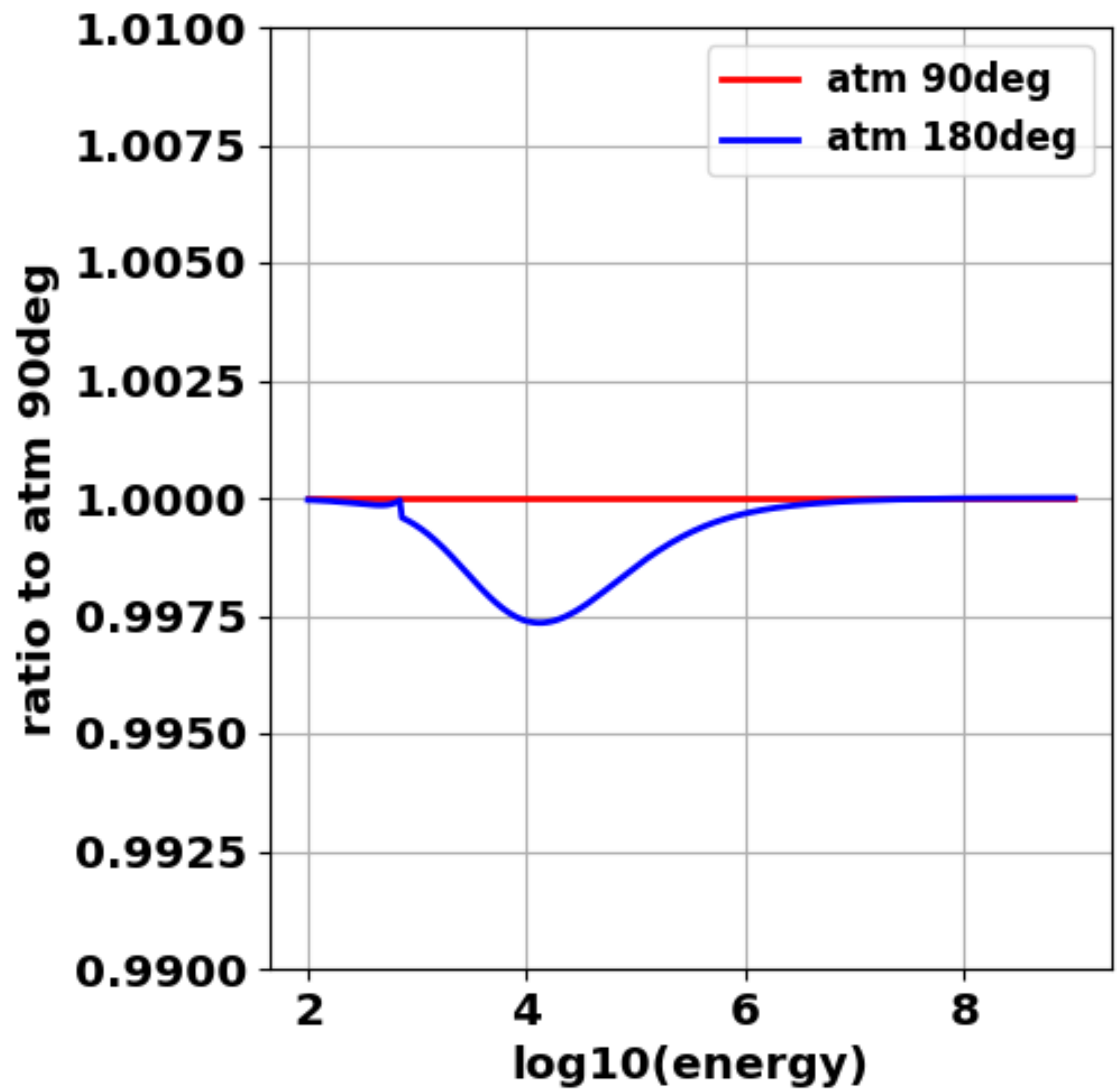
Summary

- Performance of measuring Earth's core and mantle density using IceCube 11years data is presented with Asimov Test under current knowledge of systemic errors.
    - Study of systemic errors will be updated in next 6 months, and the new systemic errors and atmospheric model prediction may decrease the error bars.
- Using the same analysis framework and assumed cross-section, the performance for 1 year IceCube data is estimated for comparison with the published results by Andrea Donini, Sergio Palomares-Ruiz, and Jordi Salvado. The simulation set, event selection, and analysis programs and binning is different from their result, but the size of error bars looks consistent with their study.

backup

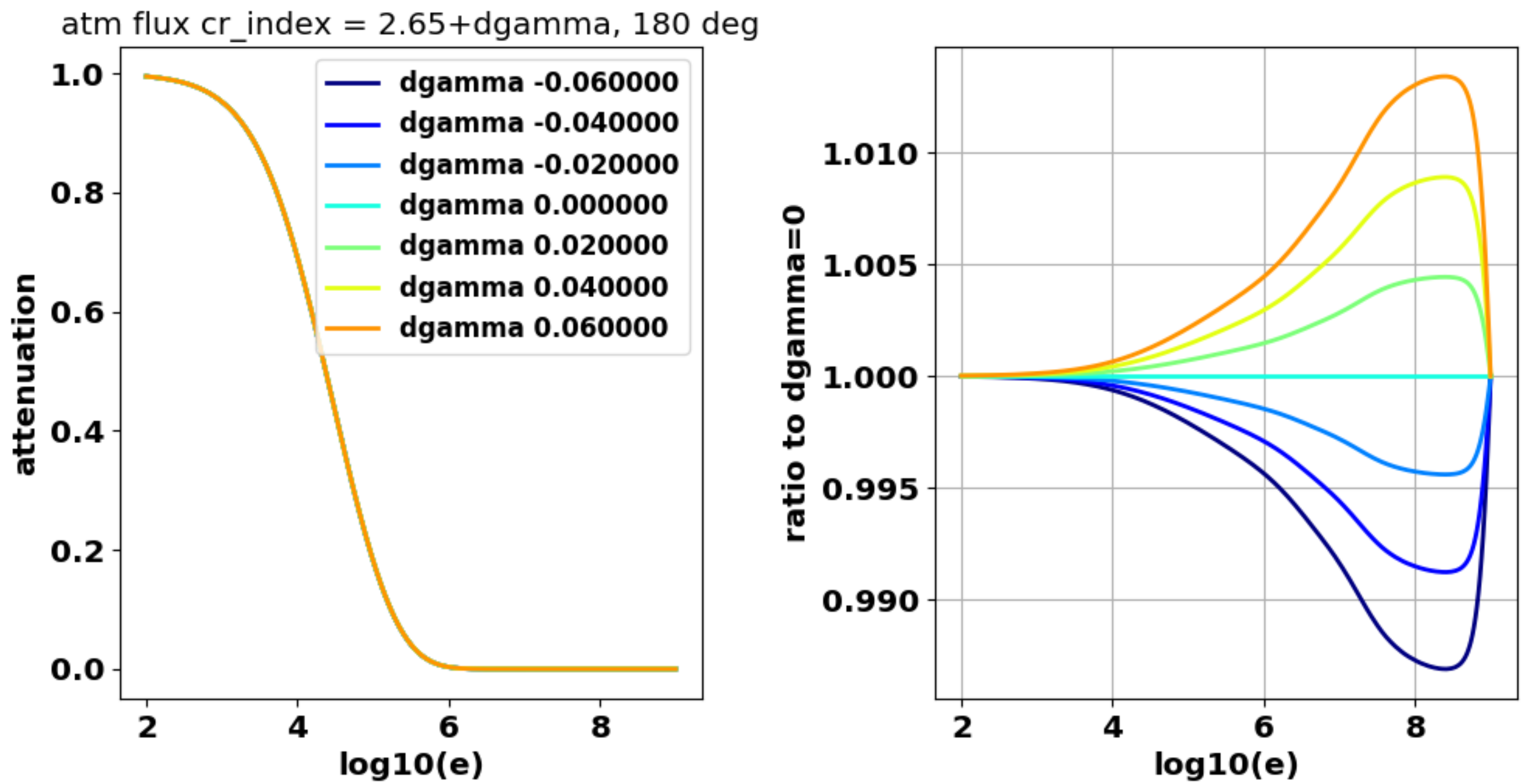
Attenuation of atmospheric spectrum with PREM model for SAME number of targetsTARGETS





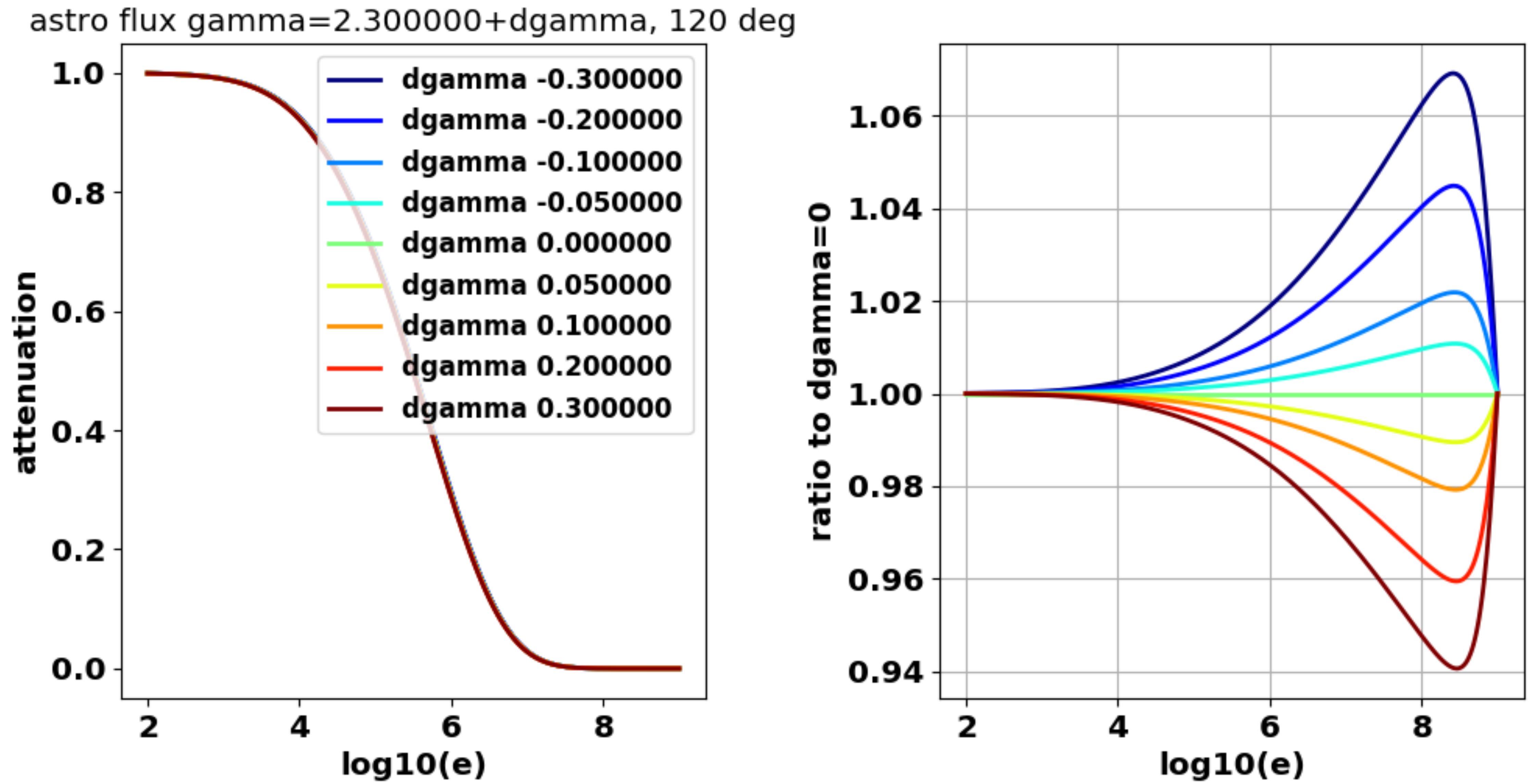
- We initialized two nuFATE objects with different zenith angles, but fed the same number of targets (number of atoms) because this parameters can be calculated easily on the fly.
- The effect is less than 1% and much smaller than other systematics, thus I ignored the zenith dependence of the propagation weight. We calculate the propagation weight with 145 deg at the beginning of the run, and use it for all zenith angles.

Deviation of propagation weight of atmospheric neutrinos when we change primary cosmic-ray gamma parameter



- usually we take within 0.05 for deviation of gamma, thus the effect is negligible. Same situation for prompt flux either.
- highest energy point is fixed, need to use proper energy range for actual analysis

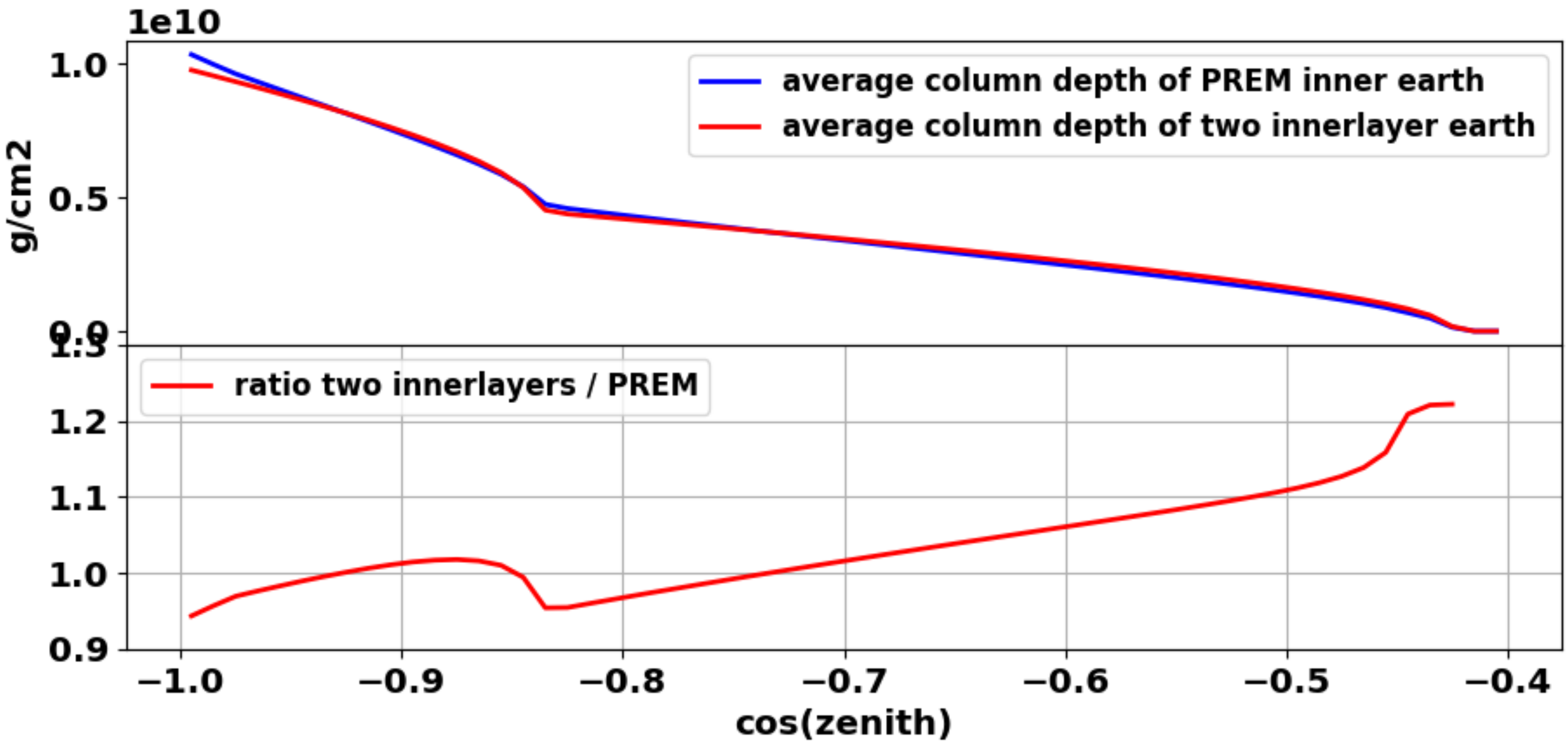
Deviation of propagation weight of astrophysical neutrinos when we change the gamma factor of the power law



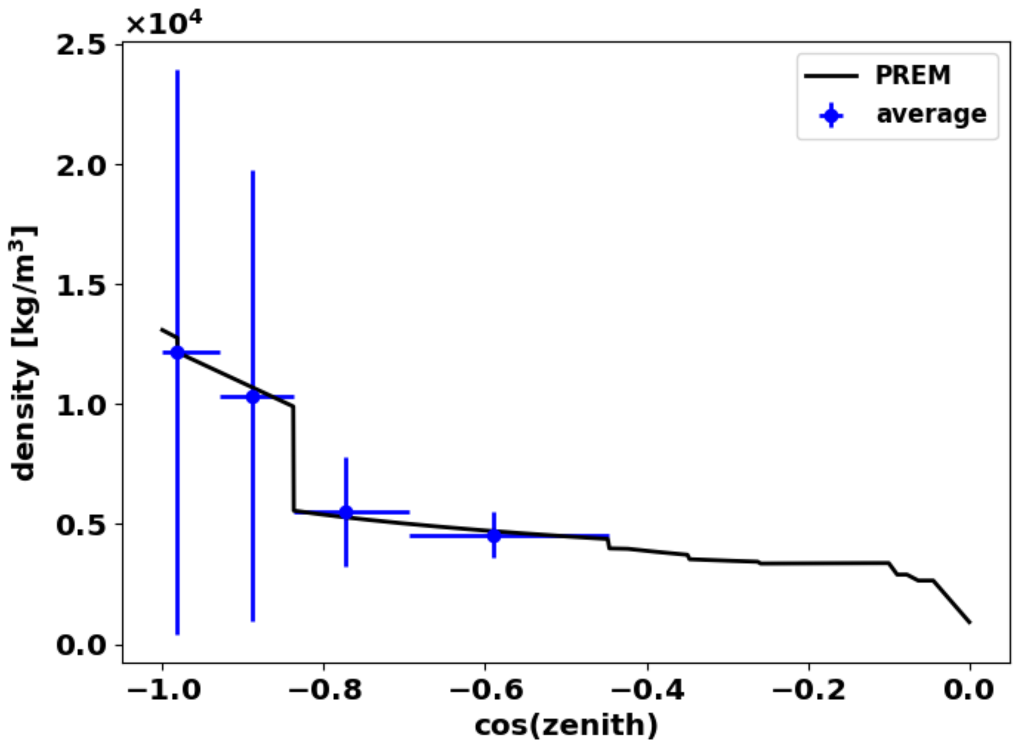
- Astrophysical flux have wider range for delta gamma, but still 1% effect below 100 TeV.
- For this analysis(below 100TeV) astrophysical flux is not dominant and the effect to the final fitting is smaller than other systematics, thus this effect is ignored. For higher energy, though, I recommend to treat the issue properly.

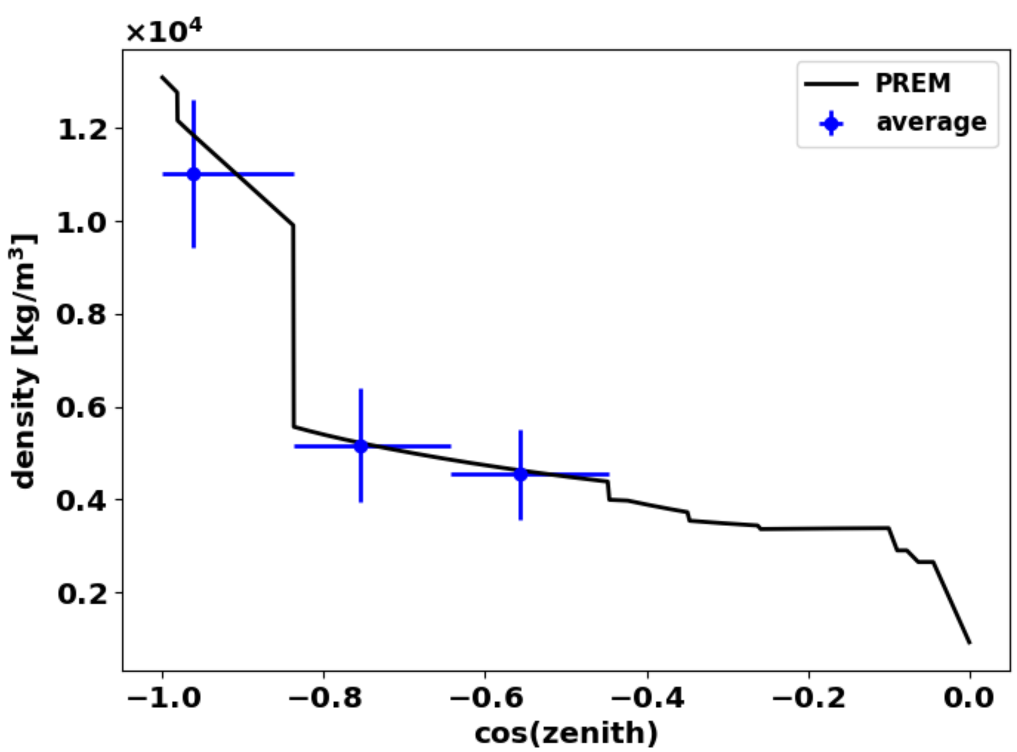
Total column depth : PREM vs 2-layers model

Difference of total column depth between true PREM and 2-layers flat density model at core region is 5%. At larger cos(zenith) anyway Earth is transparent for atmospheric neutrinos, so the effect due to simplifying the layer structure will be less than the statistical error.

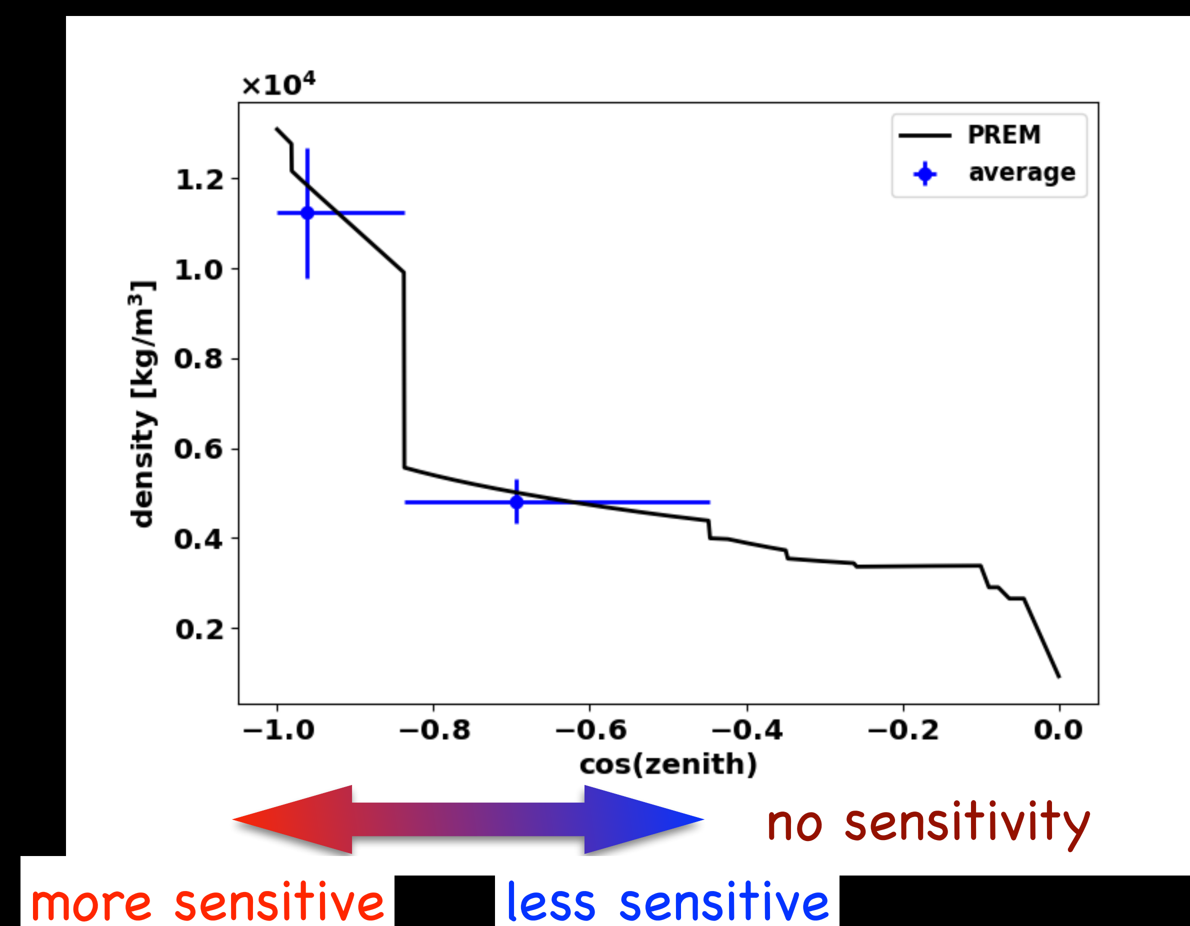


Fit results vs number of layers

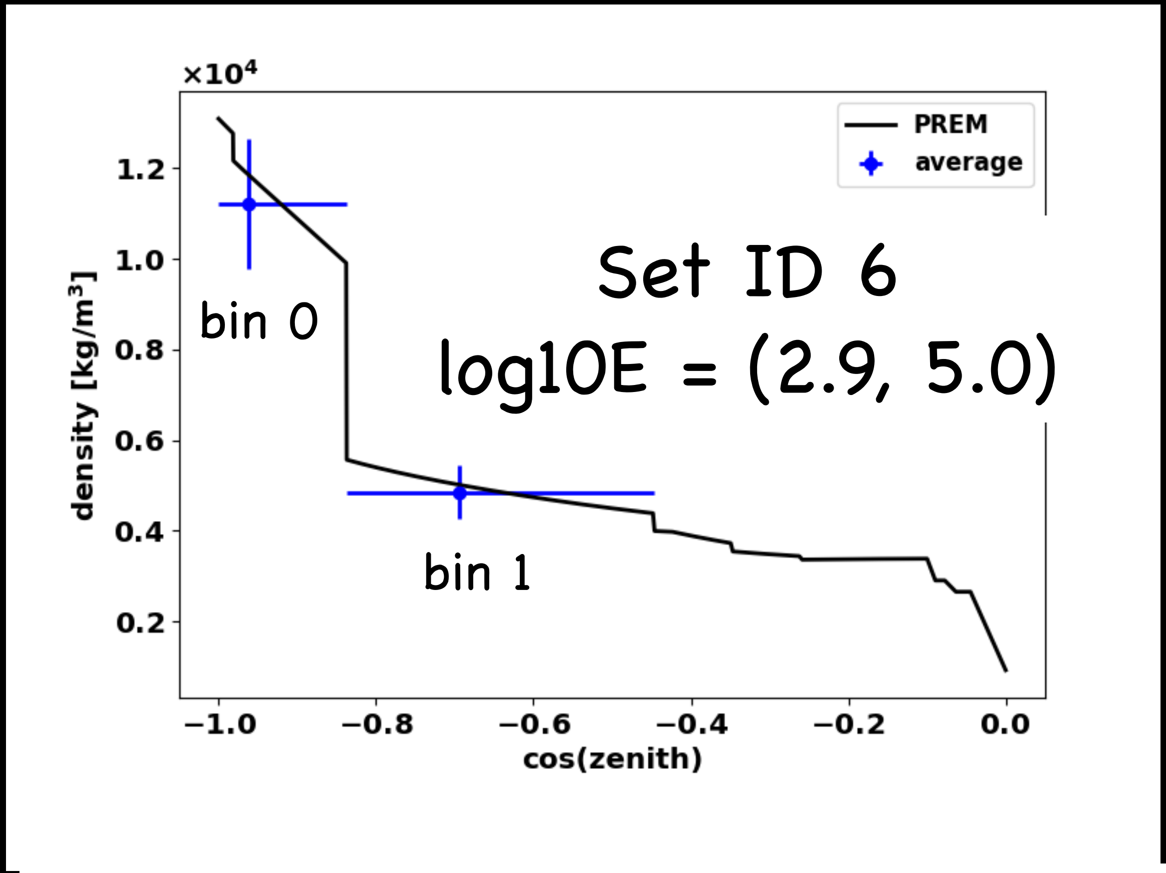


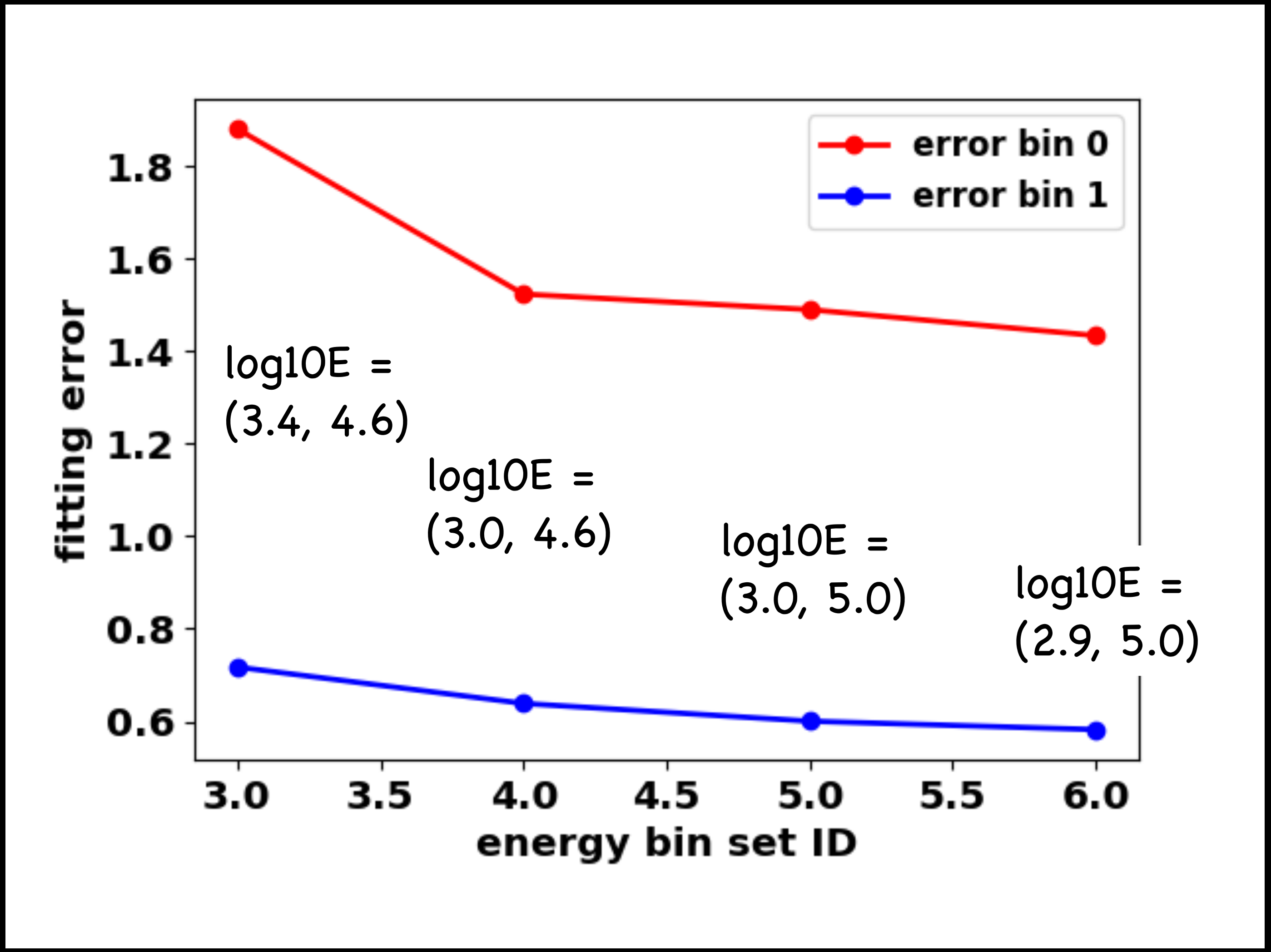


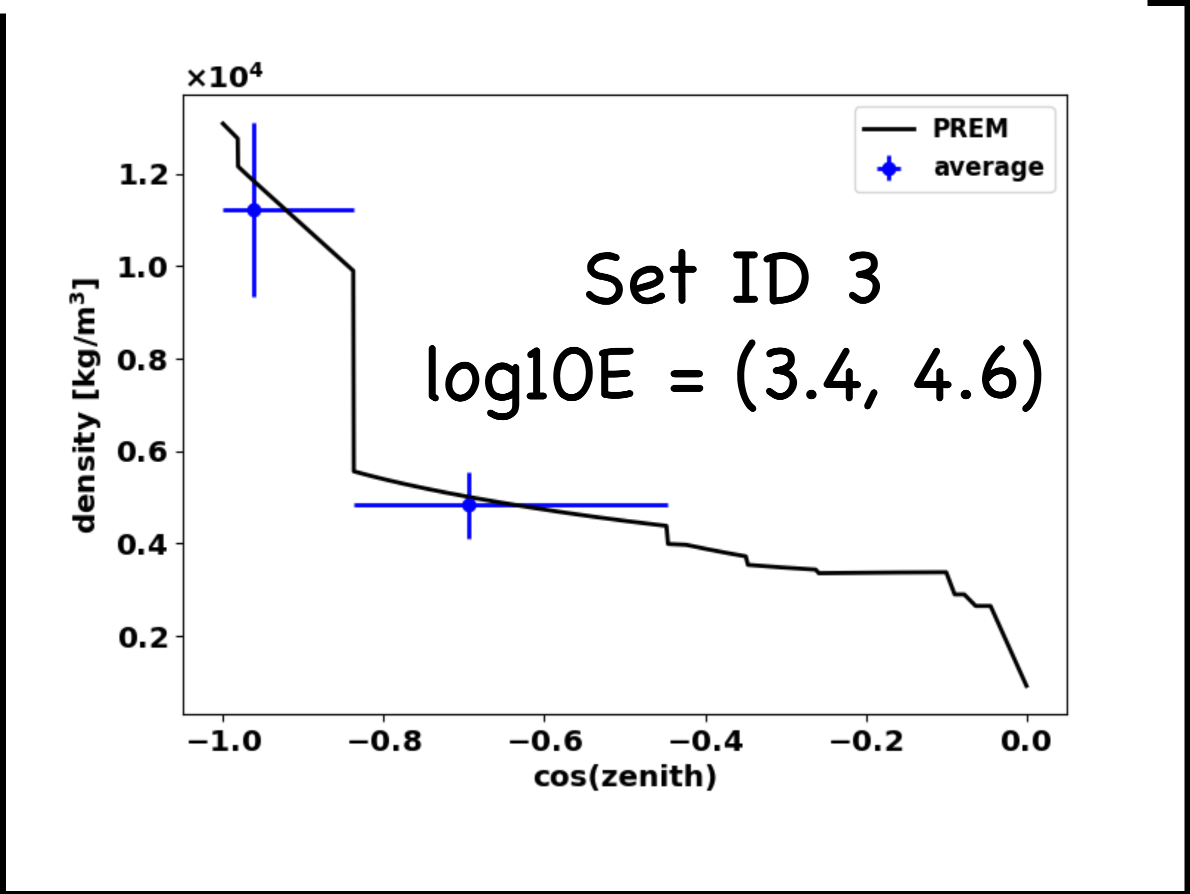
- 4 layers : no separation
- 3 and 2 layers : 1 sigma or more if systematics is perfectly understood
- This is density layers, not analysis bins in coszenith



Fit results vs energy ranges







- Reducing energy ranges helps…
  - Shrink simulation size
  - Avoid using unknown sources at high energy end (uniform diffuse assumption may not be true)
  - Avoid lower energy data pulls fit results when systematics are not fully understood