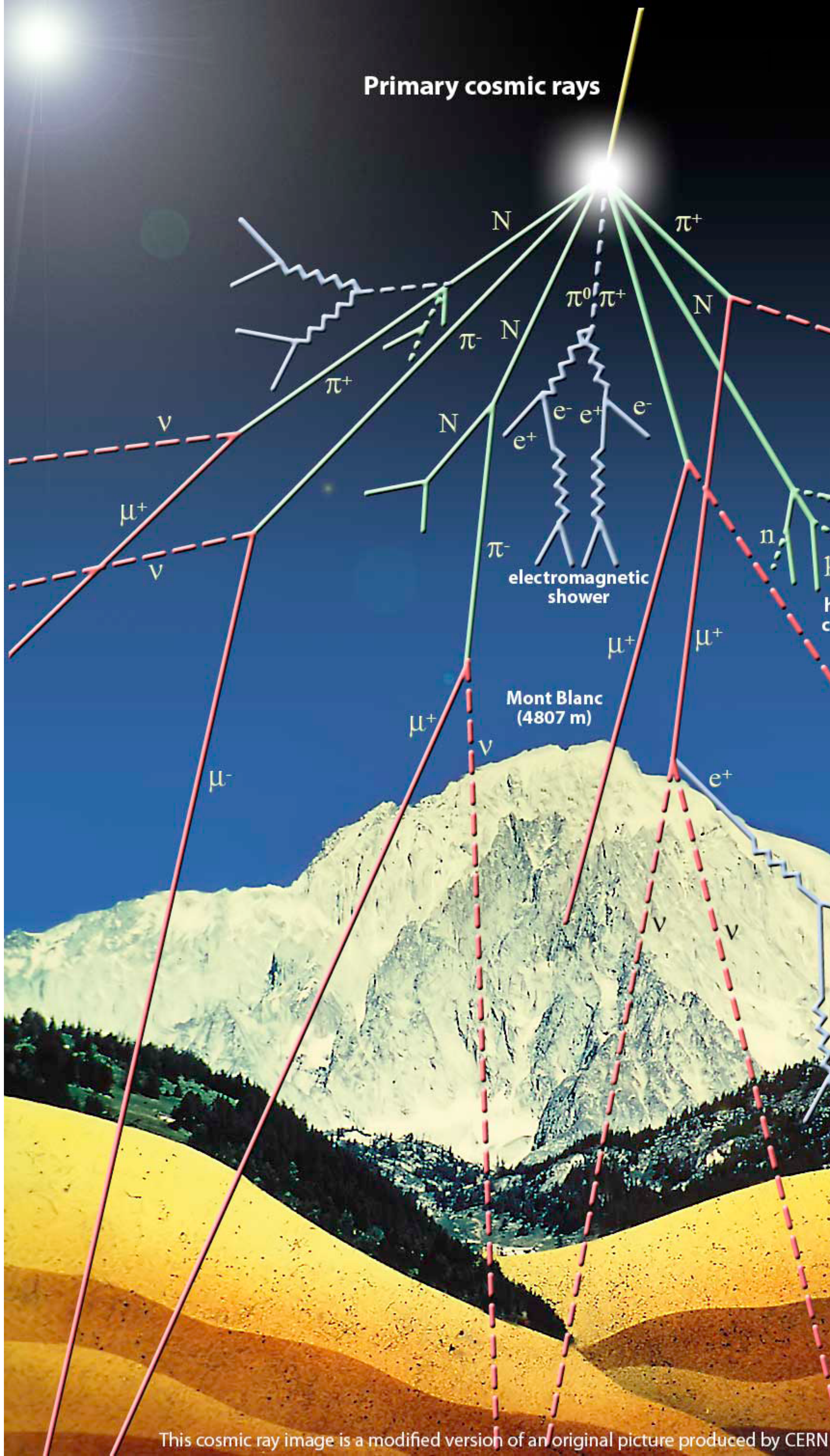
Low Energy Atmospheric Neutrino Flux Analysis with IceCube-DeepCore

Tania Wood

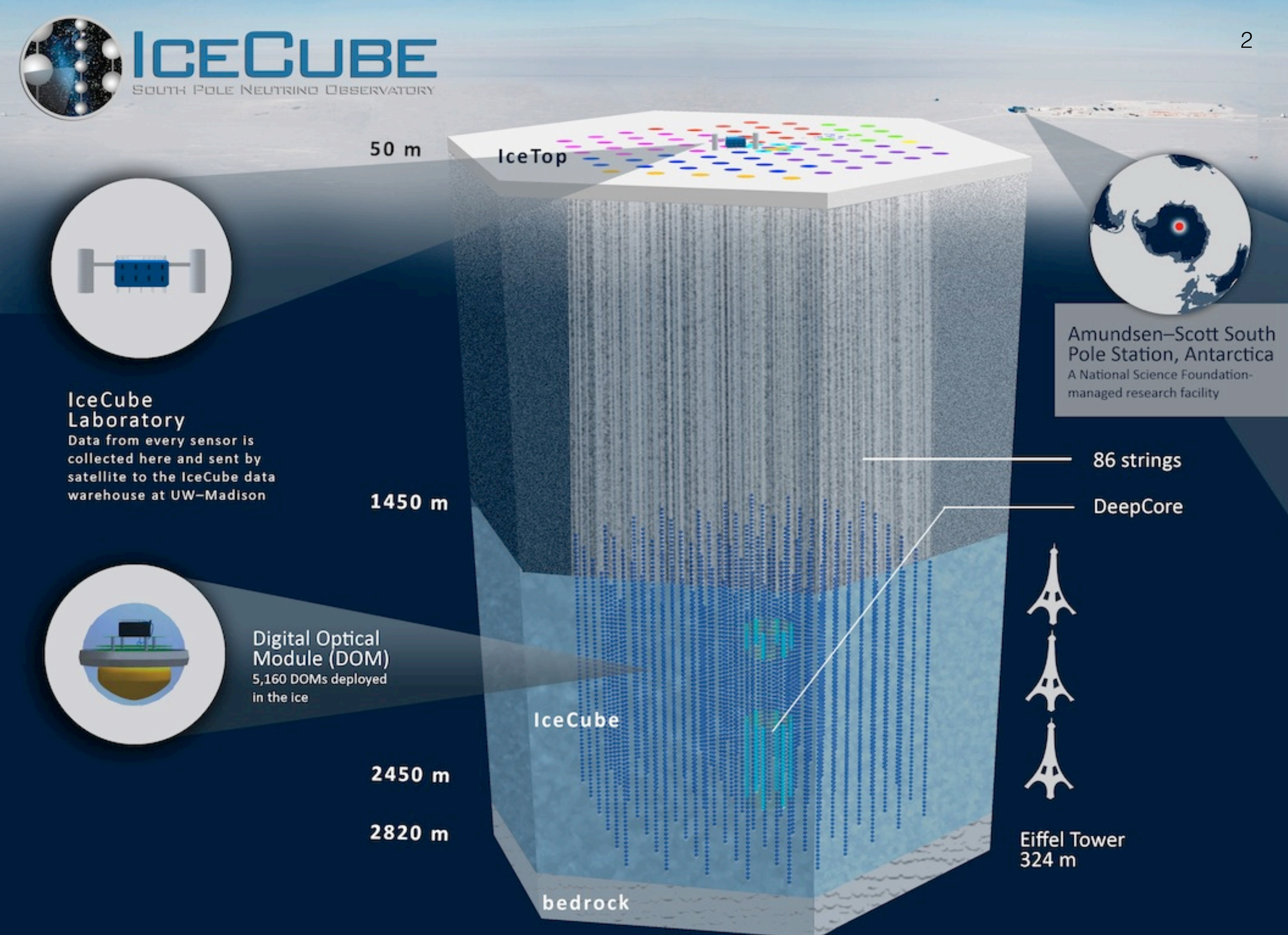
CAP 2017

UNIVERSITY OF ALBERTA

trwood@ualberta.ca



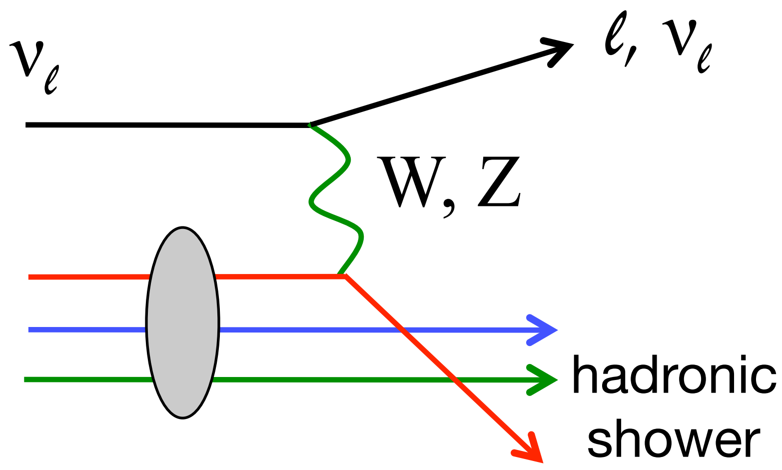
This cosmic ray image is a modified version of an original picture produced by CERN



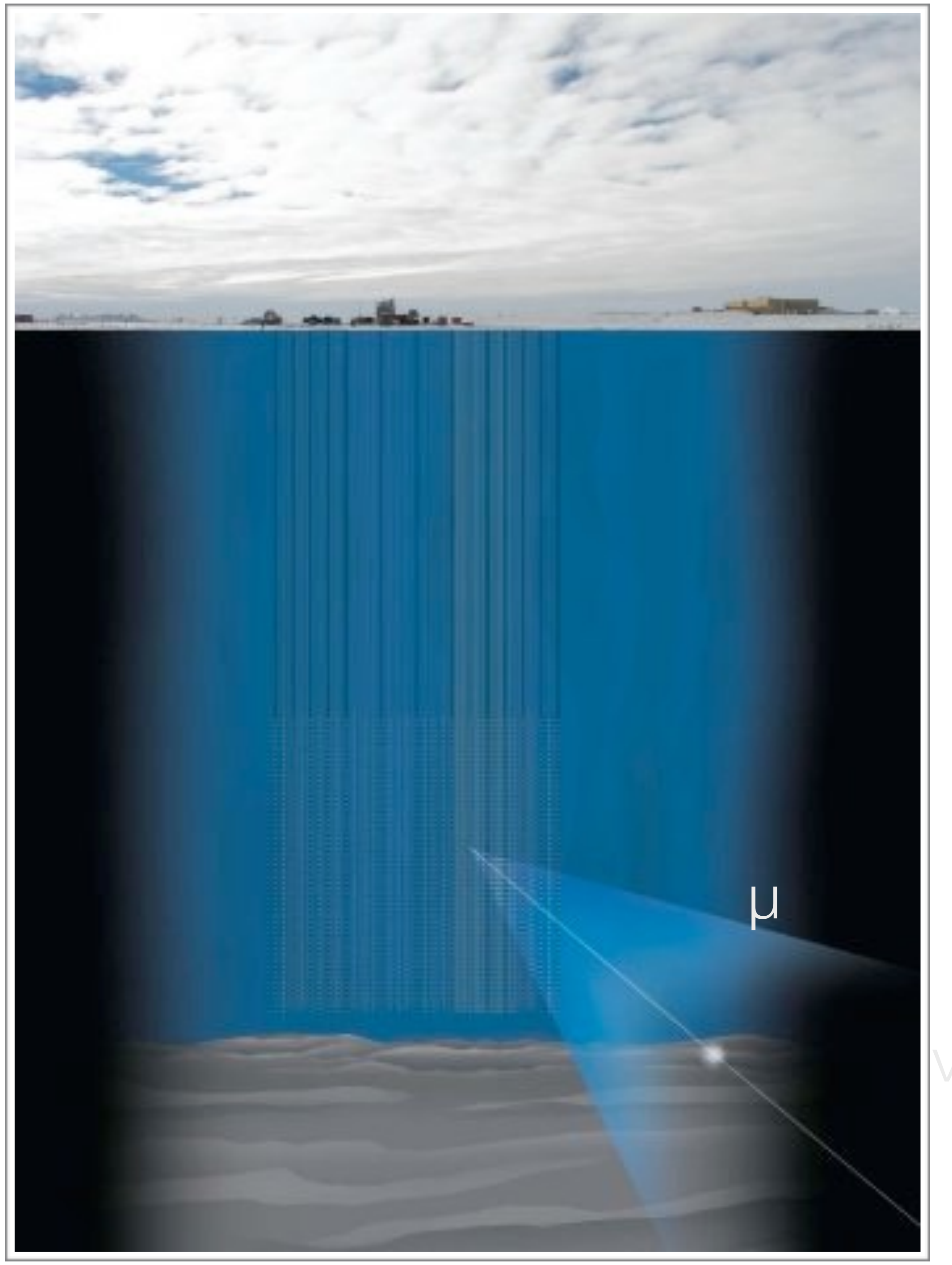
Tania R. Wood - University of Alberta

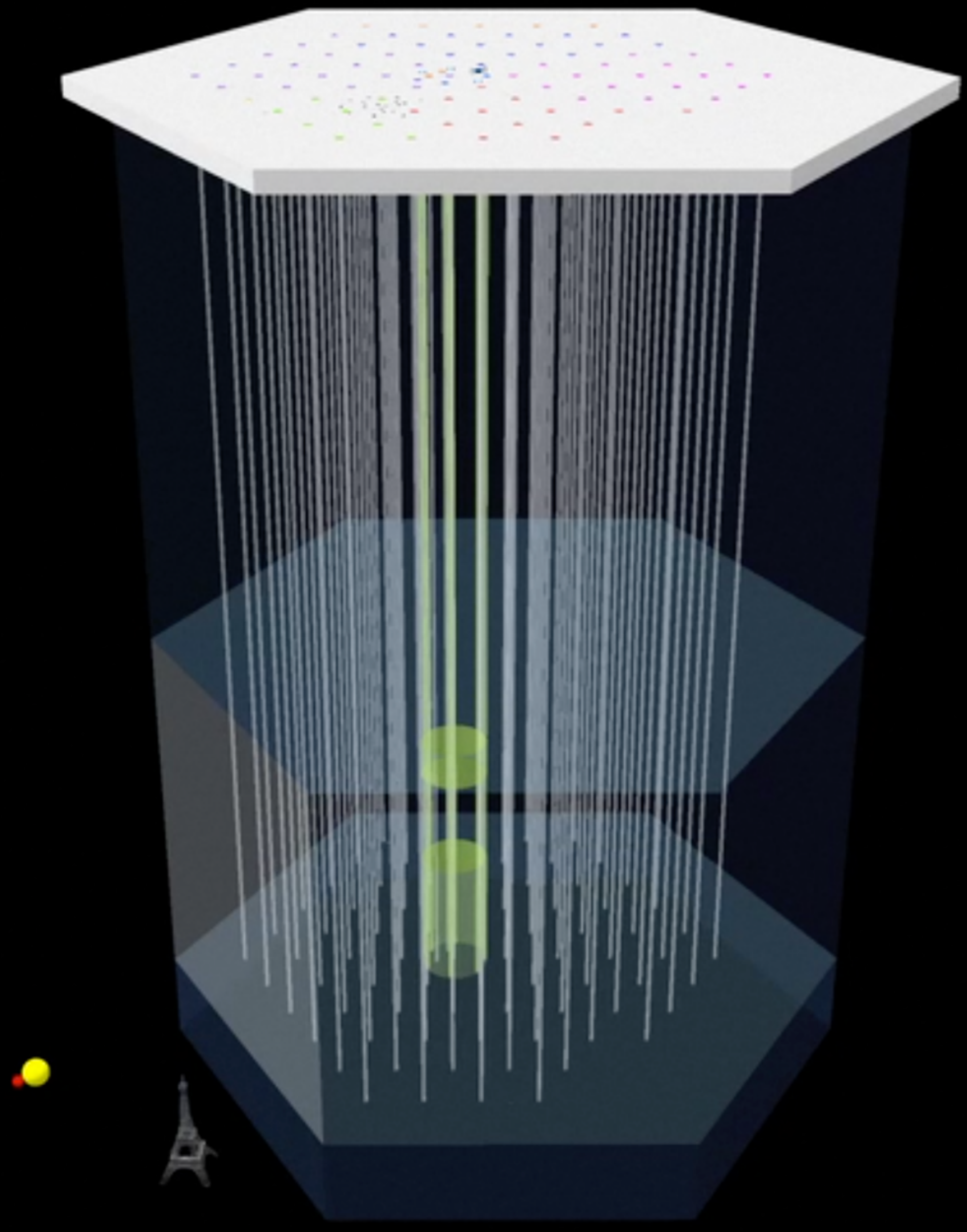
Neutrino Telescopes - Principle of Detection

- Neutrinos interact in or near the detector with nucleons in ice

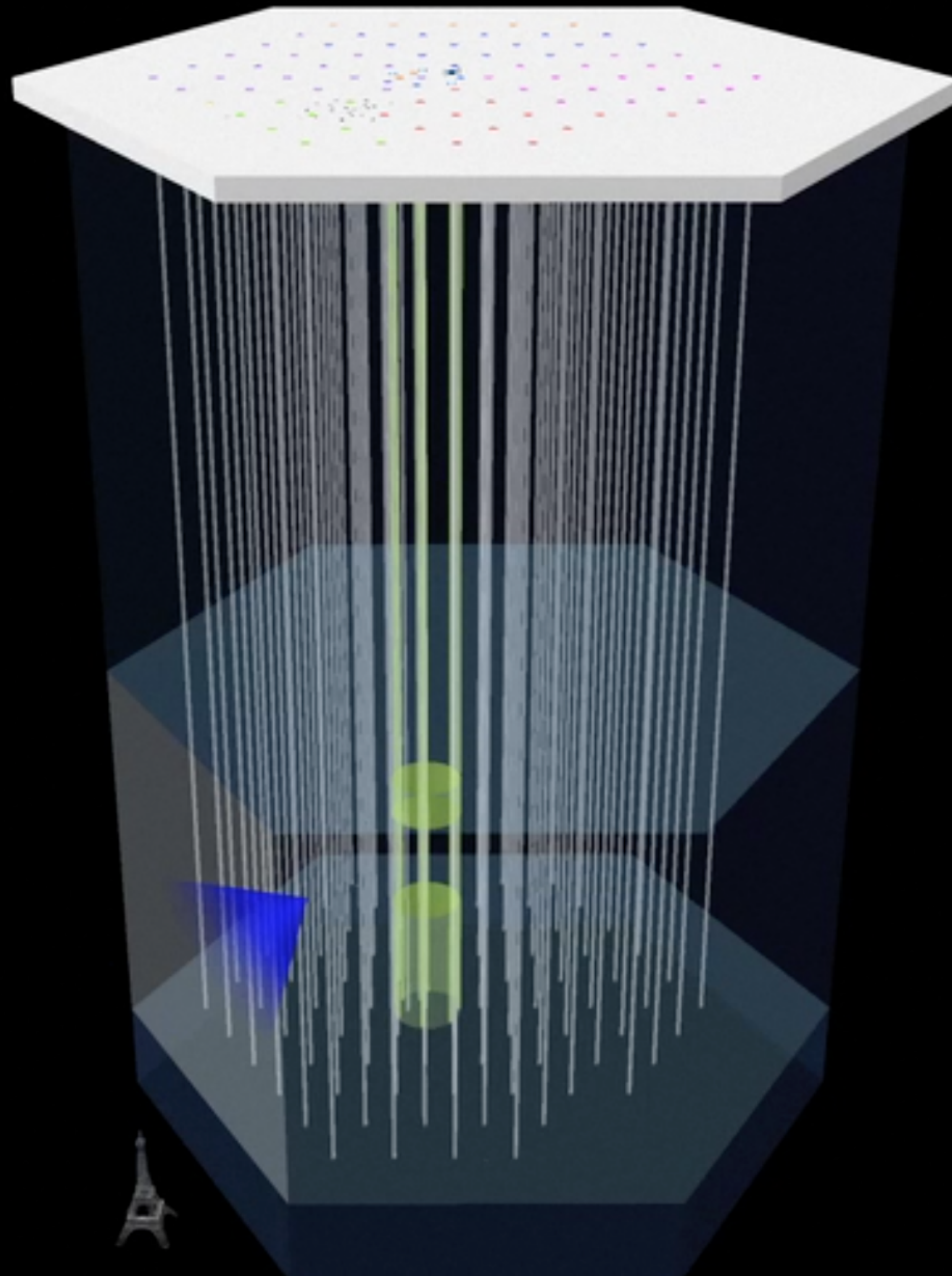


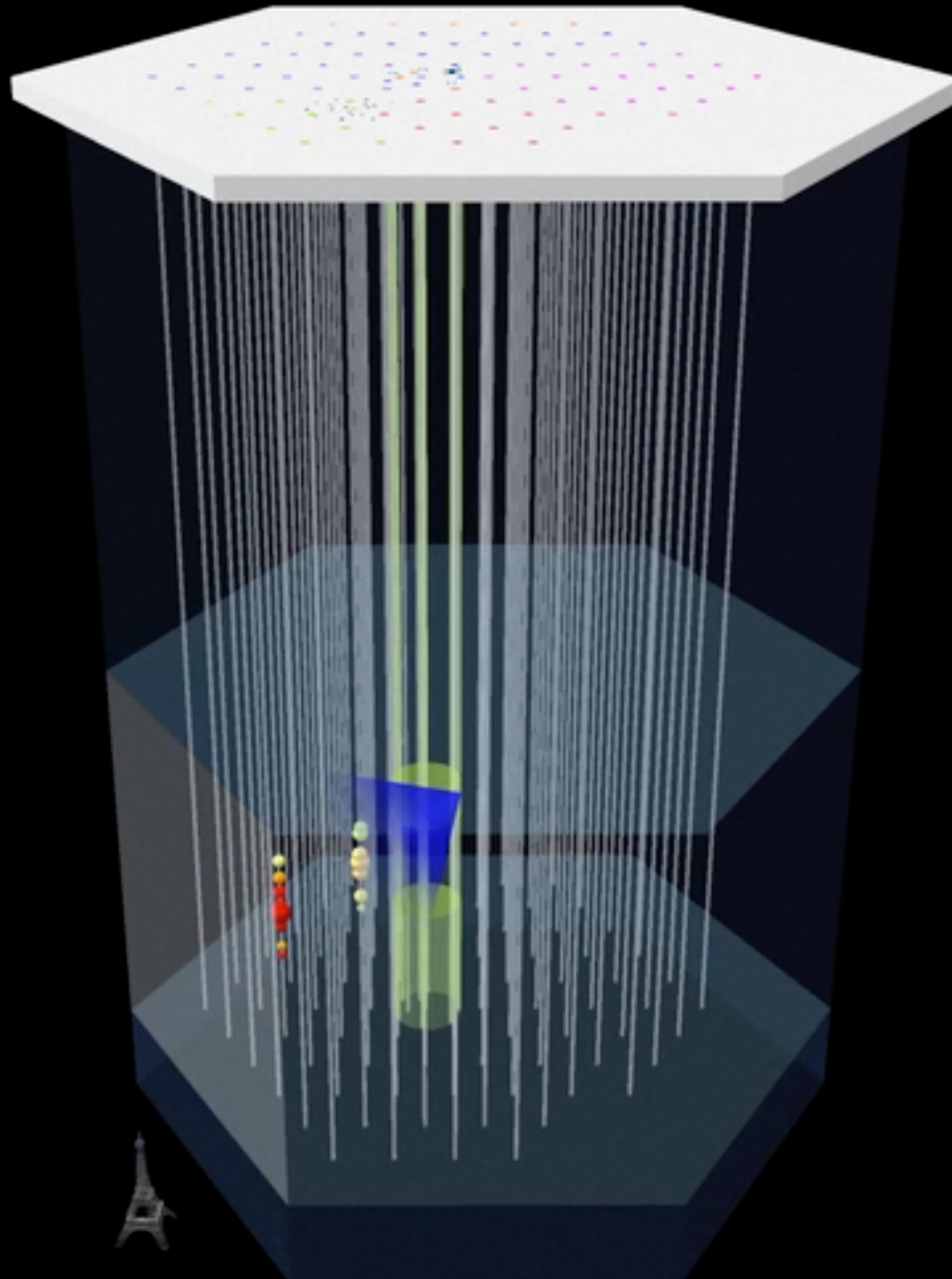
  - O(km) muon tracks from ν_μ CC
  - O(10 m) cascades from ν_e CC, low energy ν_τ CC, and ν_x NC
  - Cherenkov radiation detected by 3D array of optical sensors (OMs)



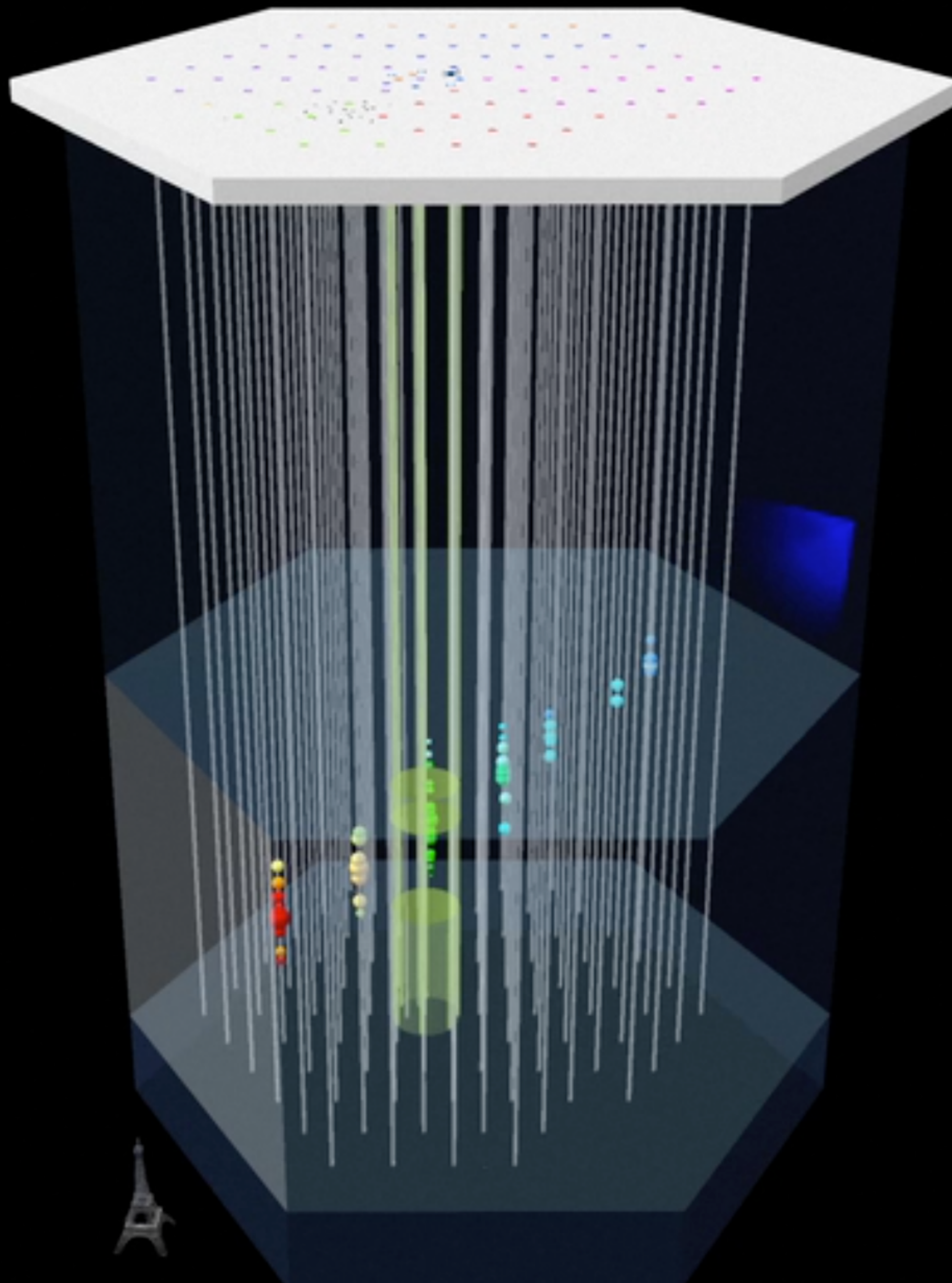


Tania R. Wood - University of Alberta





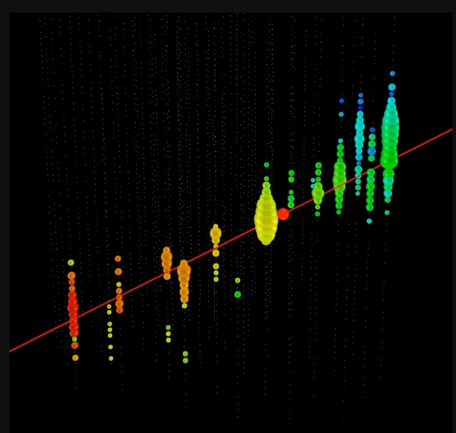
Tania R. Wood - University of Alberta

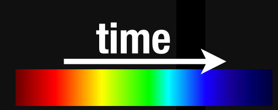


Tania R. Wood - University of Alberta

Neutrino Event Topological Signatures

‘Tracks’:



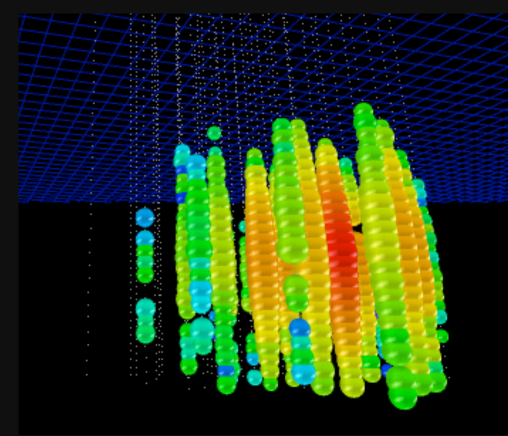


Charged Current (CC) Muon Neutrino

$$\nu_\mu + N \rightarrow \mu + X$$

factor of ≈ 2 energy resolution
$< 1°$ angular resolution

‘Cascades’:



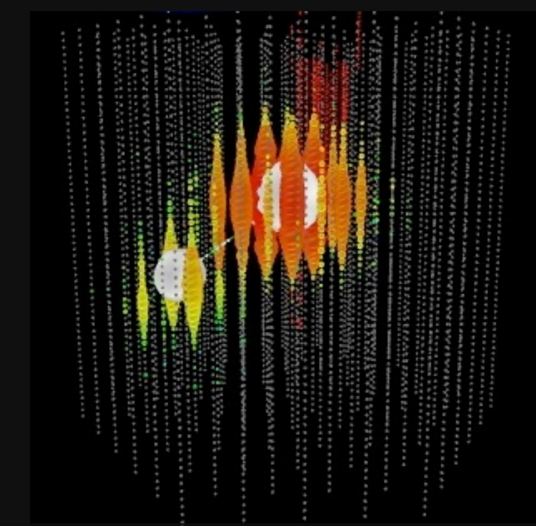
Neutral Current (NC) /Electron Neutrino

$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

$\approx \pm 15\%$ deposited energy resolution
$\approx 10°$ angular resolution
(at energies ≈ 100 TeV)

‘Composites’:



CC Tau Neutrino

$$\nu_\tau + N \rightarrow \tau + X$$

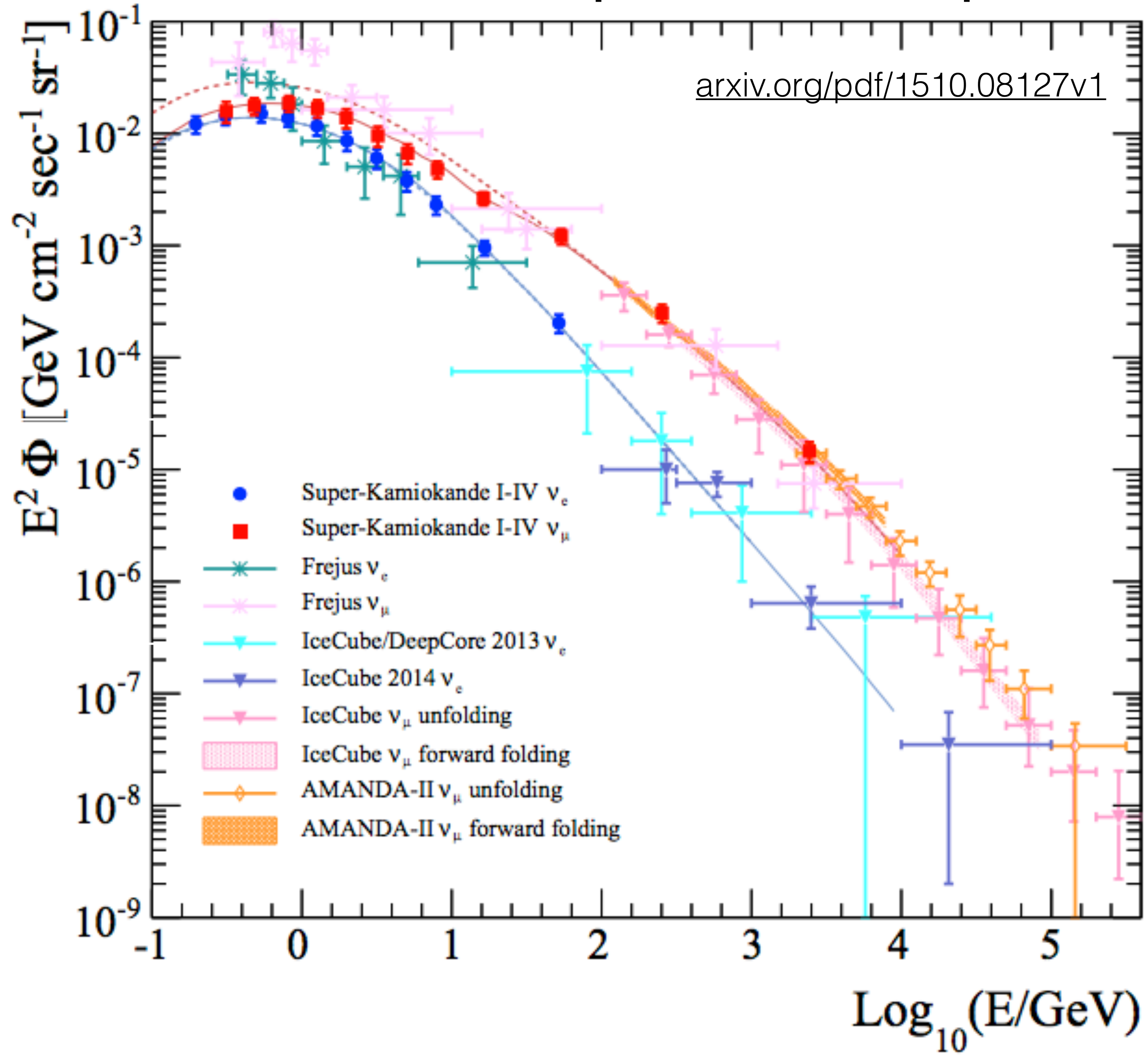
“double-bang” and other signatures (simulation)

(not observed yet)

Low-energy analyses and the atmospheric neutrino flux

- **Low-energy IceCube analyses**
  - source is the atmospheric neutrino flux

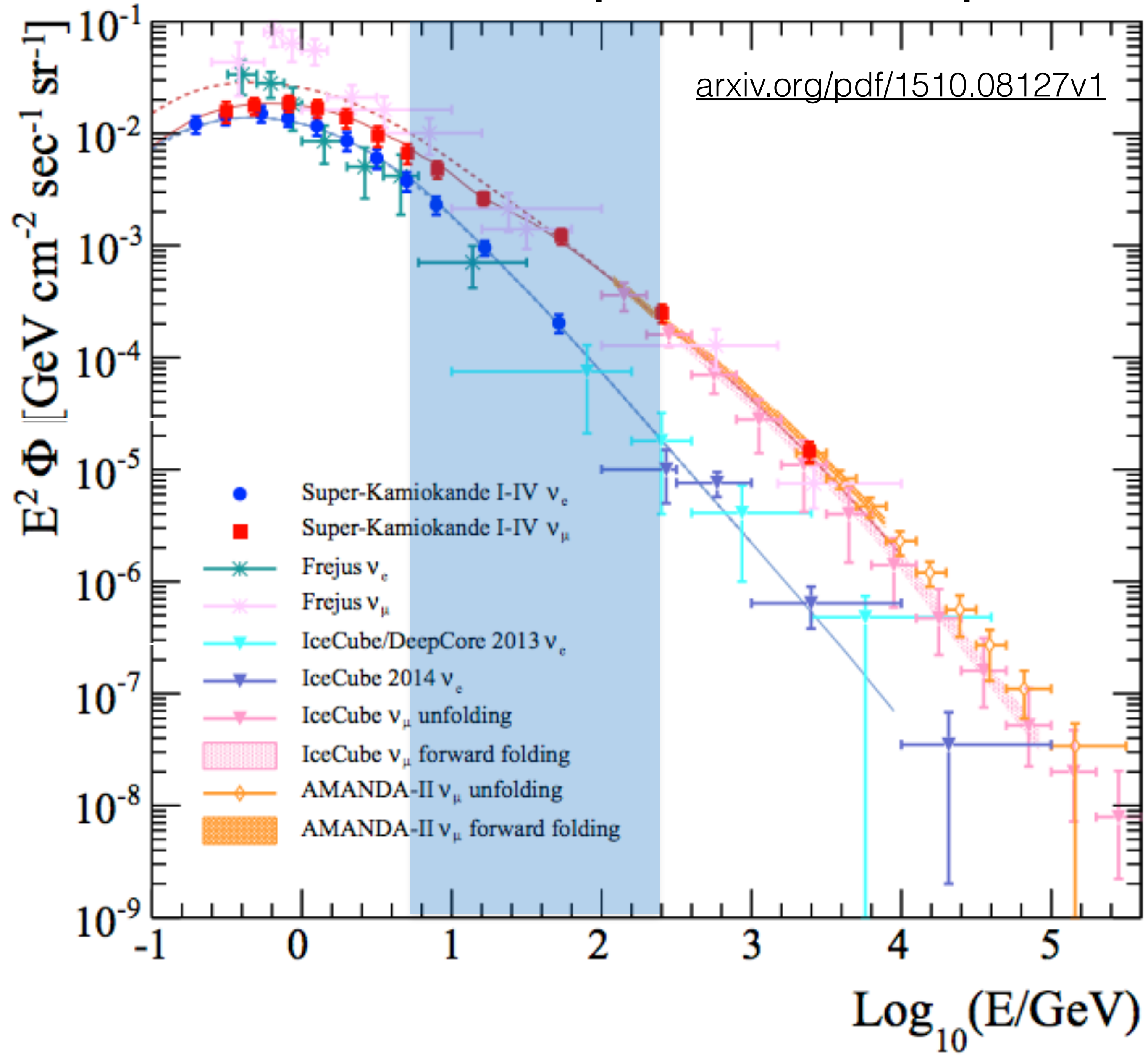
Atmospheric Neutrino Spectrum



Low-energy analyses and the atmospheric neutrino flux

- **Low-energy IceCube analyses**
    - source is the atmospheric neutrino flux
    - measurements goals include
        - neutrino oscillations

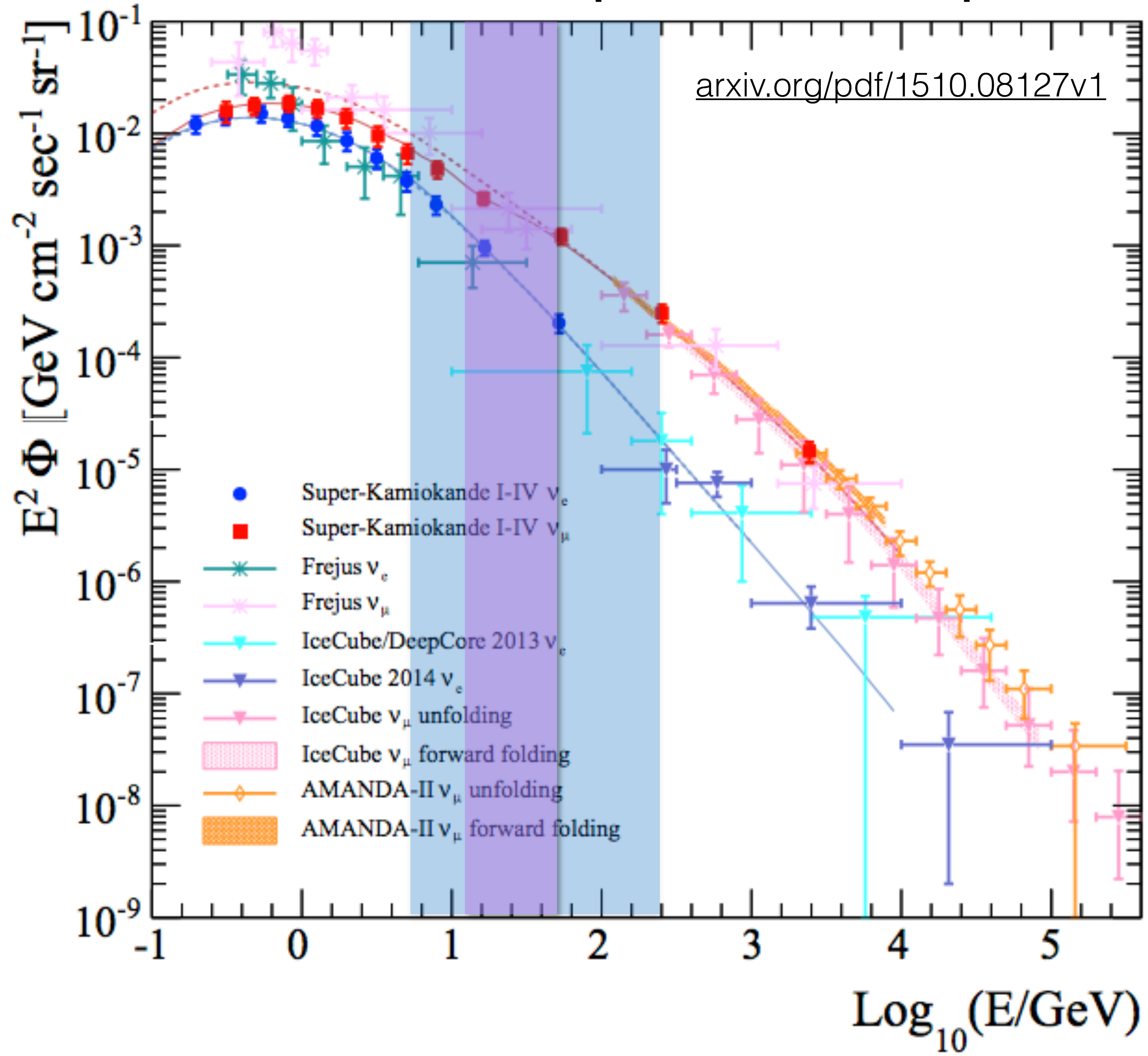
Atmospheric Neutrino Spectrum



Low-energy analyses and the atmospheric neutrino flux

- **Low-energy IceCube analyses**
  - source is the atmospheric neutrino flux
  - measurements goals include
    - neutrino oscillations
    - tau neutrino appearance

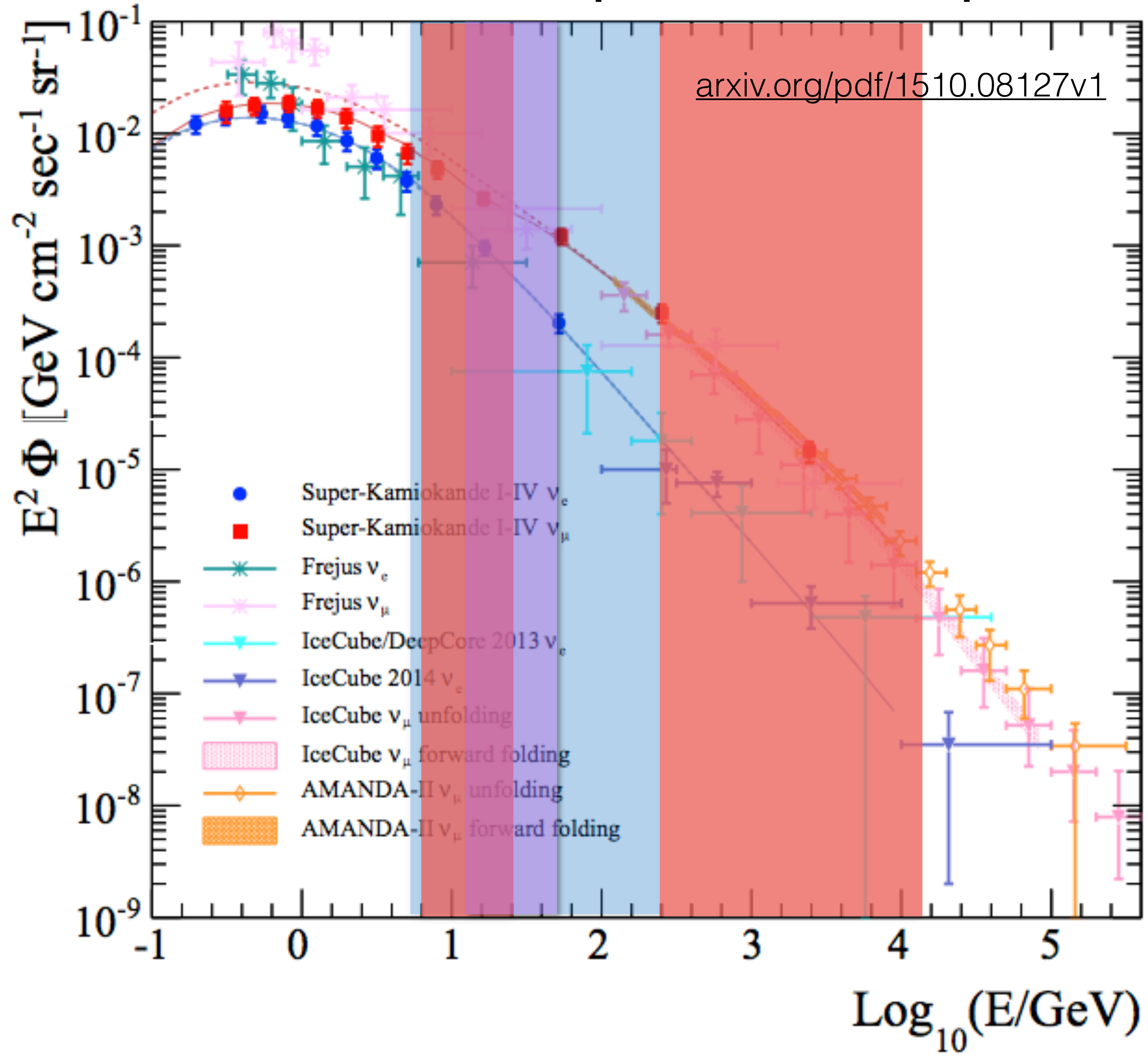
Atmospheric Neutrino Spectrum



Low-energy analyses and the atmospheric neutrino flux

- **<u>Low-energy IceCube analyses</u>**
  - source is the atmospheric neutrino flux
  - measurements goals include
    - neutrino oscillations
    - tau neutrino appearance
    - sterile neutrino searches

Atmospheric Neutrino Spectrum

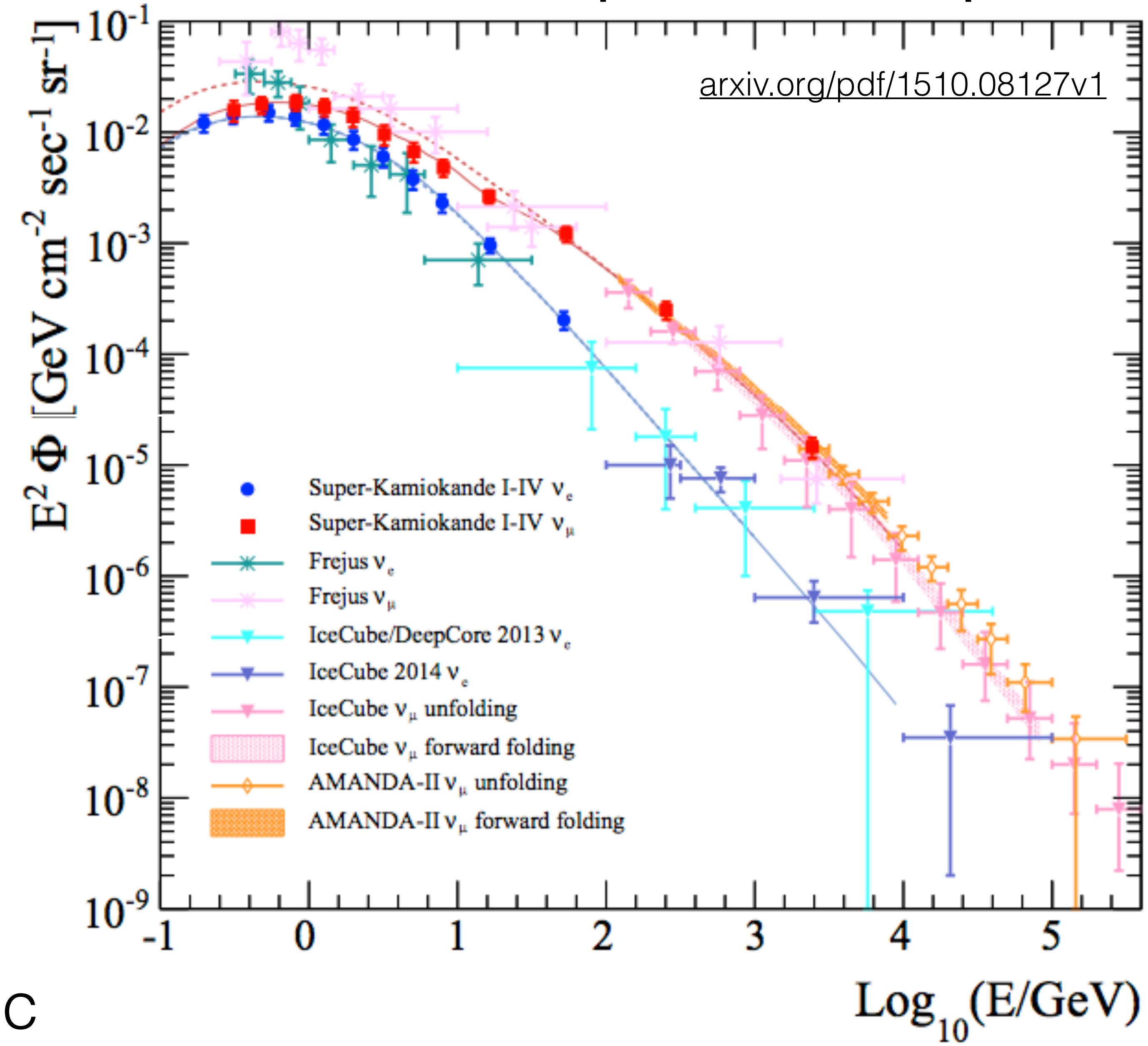


Low-energy analyses and the atmospheric neutrino flux

- **Low-energy IceCube analyses**
    - source is the atmospheric neutrino flux
    - measurements goals include
        - neutrino oscillations
        - tau neutrino appearance
        - sterile neutrino searches

- In addition to uncertainties related to our knowledge of the deep ice, the atmospheric neutrino flux represents our critical model input

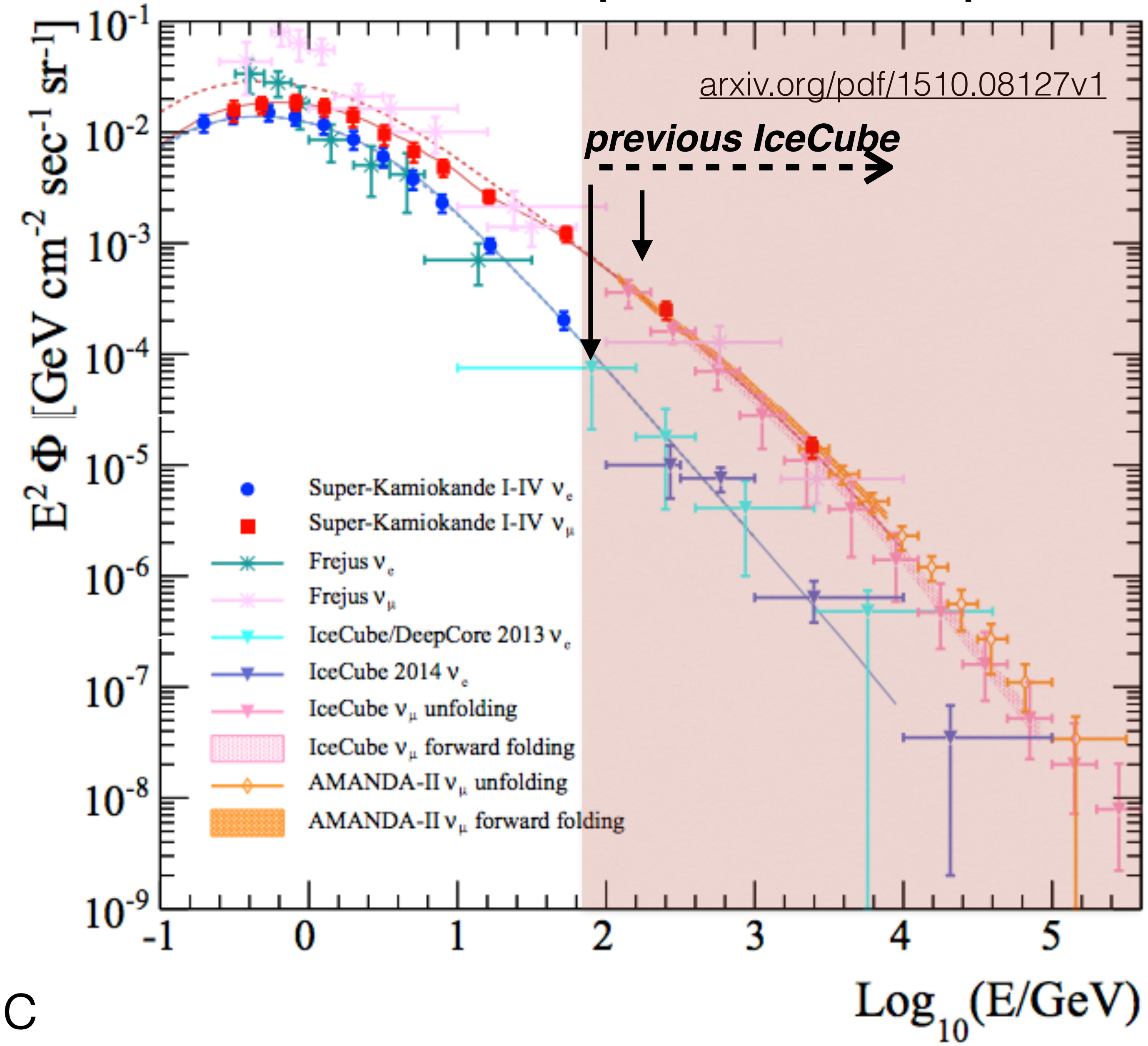
Atmospheric Neutrino Spectrum



Low-energy analyses and the atmospheric neutrino flux

- **Low-energy IceCube analyses**
    - source is the atmospheric neutrino flux
    - measurements goals include
        - neutrino oscillations
        - tau neutrino appearance
        - sterile neutrino searches
- In addition to uncertainties related to our knowledge of the deep ice, the atmospheric neutrino flux represents our critical model input

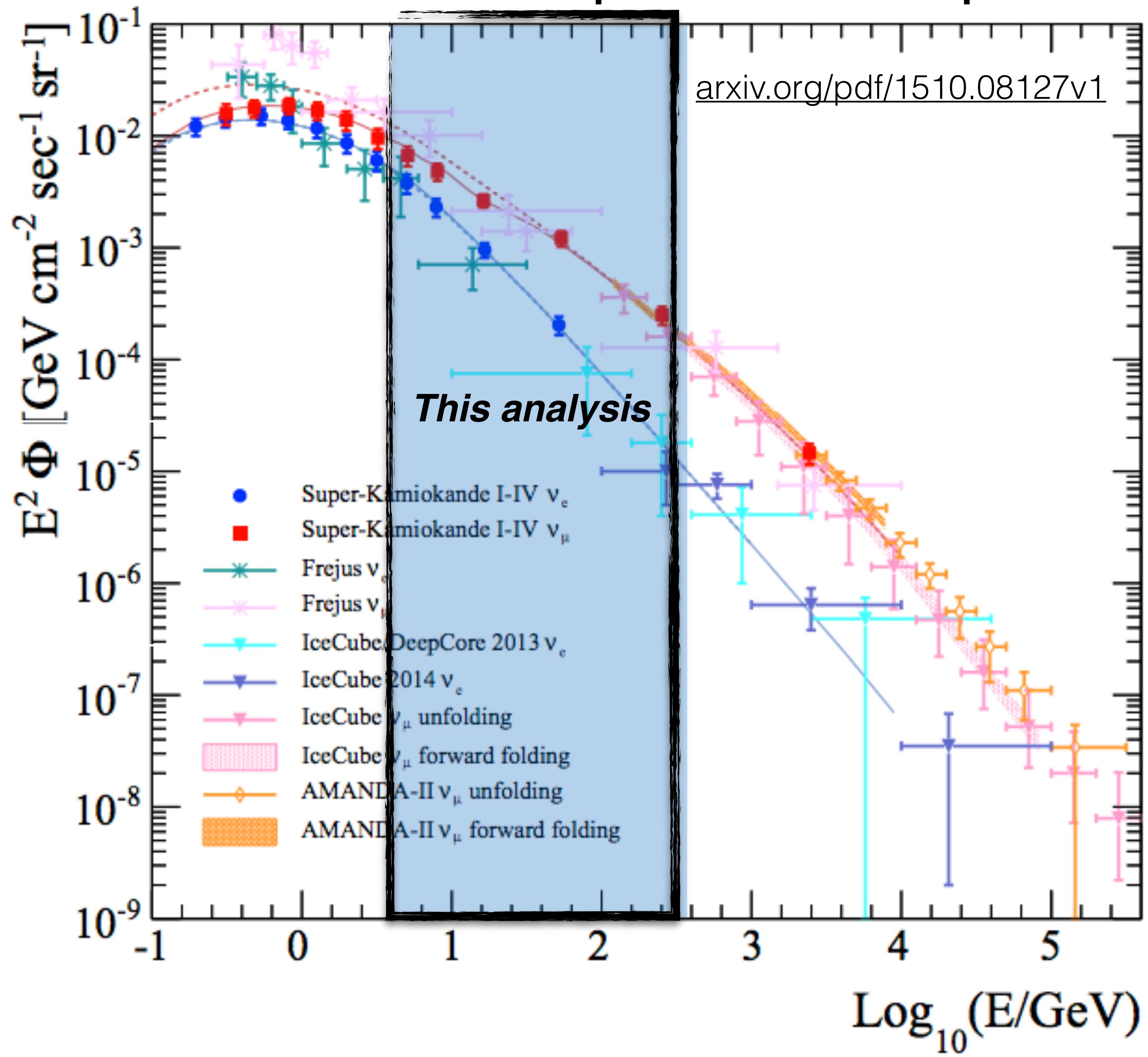
Atmospheric Neutrino Spectrum



Low-energy analyses and the atmospheric neutrino flux

- **<u>Low energy sample selection:</u>**
- Neutrino purity (90%), CosmicRays (10%), ~15,000 events/year
- Primarily Muon Neutrino (NuMu) events
- All directions allowed (<u>full sky</u>), most advanced reconstruction to date
- Energy range ~6GeV - 180GeV

Atmospheric Neutrino Spectrum



<u>Relying heavily on open source tool: MCEq</u>

Calculation of conventional and prompt lepton fluxes at very high energy A. Fedynitch, R. Engel, T.K. Gaisser, F, Rienhn, T. Stanev
<u>http://mceq.readthedocs.io/en/latest/index.html</u>

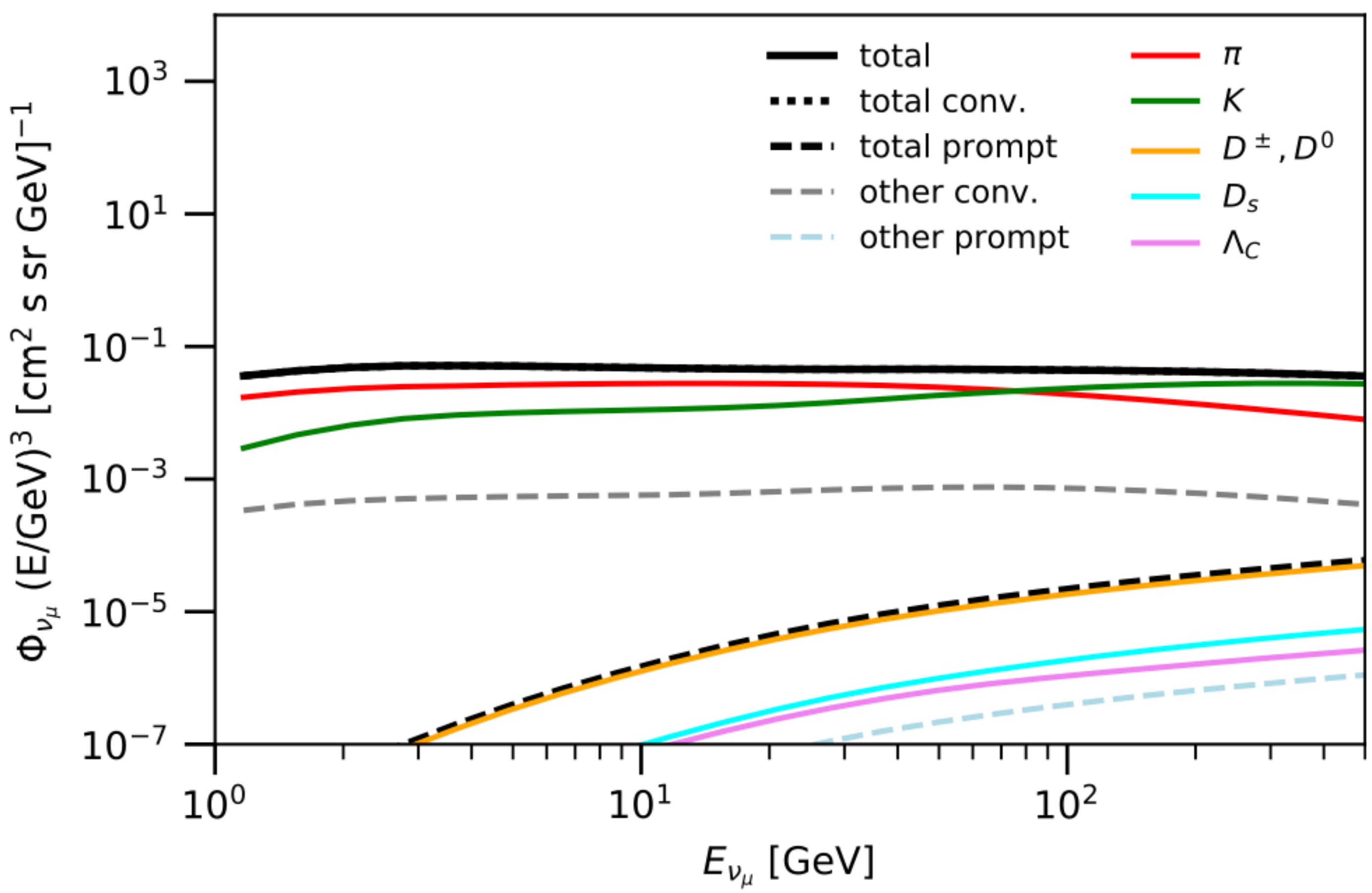
For details and development of the sample see Moriond 2017 Proceedings by João Pedro de André

Neutrino Flux Modelling:

- Want precision measurement
- Need to understand these fluxes
- Flexible modelling framework for atmospheric particle flux.
  Able to modify:
  - Cosmic ray (CR) spectrum, primaries
  - Hadronic interaction
  - Atmospheric model/geographic location/ season
- Underlying goal is to understand the uncertainties.

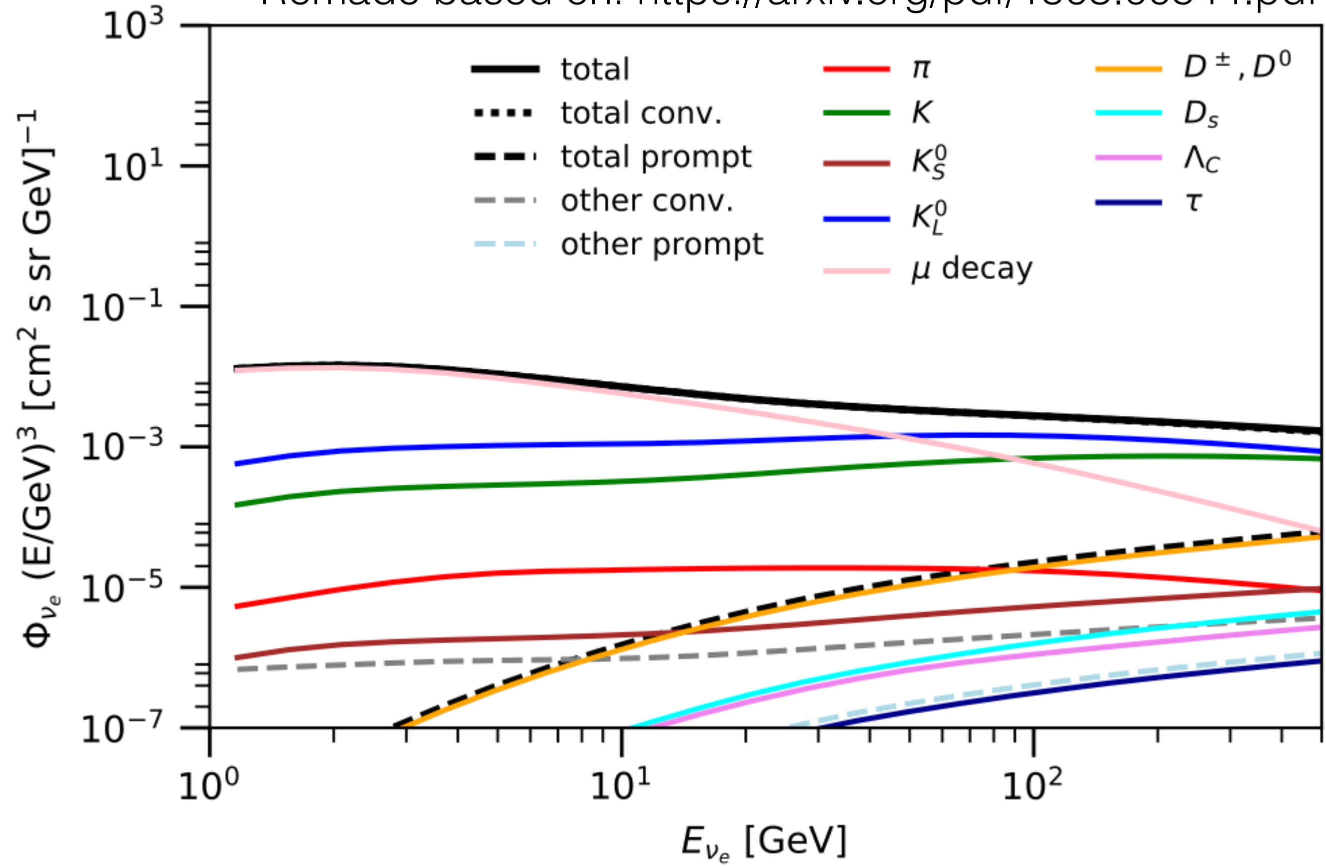
- Using open source tool: MCEq
  - *Calculation of conventional and prompt lepton fluxes at very high energy A. Fedynitch, R. Engel, T.K. Gaisser, F, Rienhn, T. Stanev* *http://mceq.readthedocs.io/en/latest/index.html*

CosmicRays > Mesons > Neutrinos



NuMu

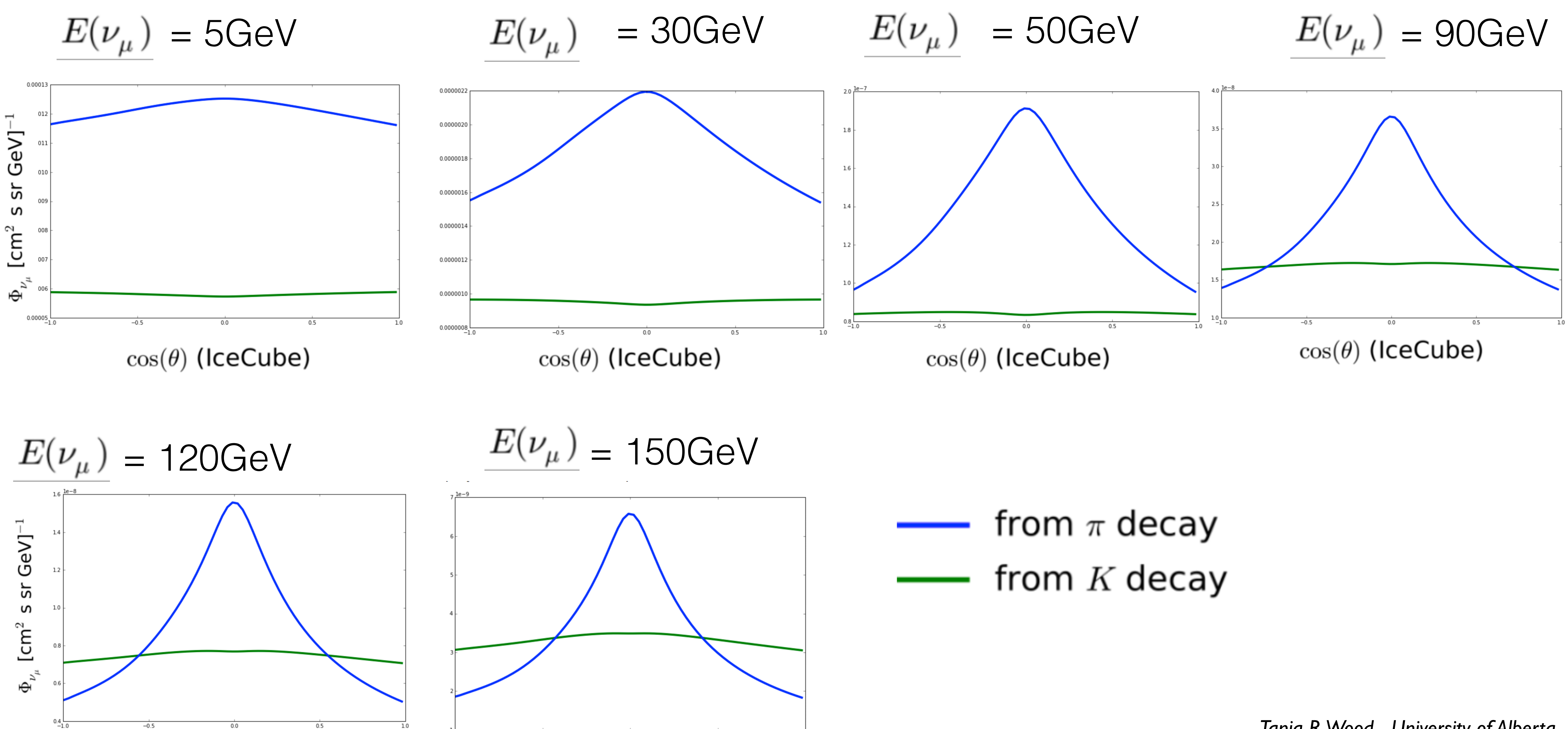
Remade based on: https://arxiv.org/pdf/1503.00544.pdf



NuE

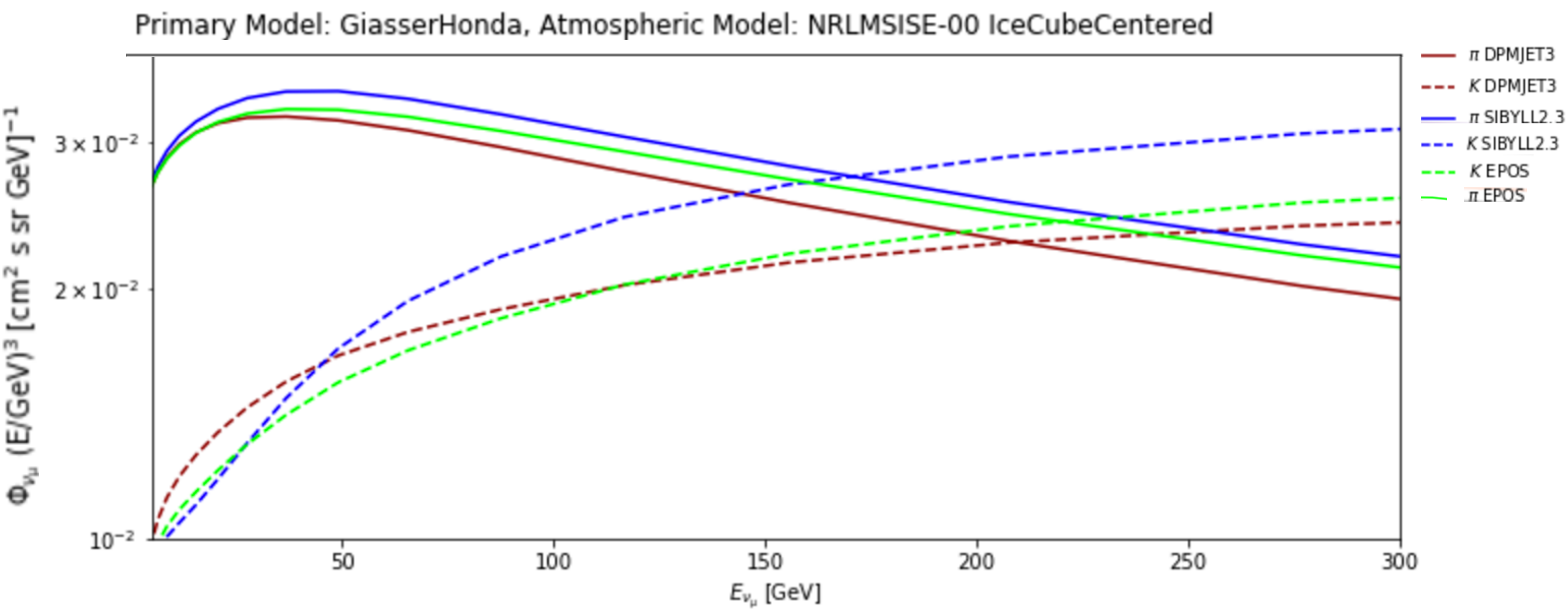
Neutrino Flux Measurement of Kaon/Pion Ratio:

- Flux changes depending on angle and secondary (meson) energy



Comparisons of NuMu Predictions:

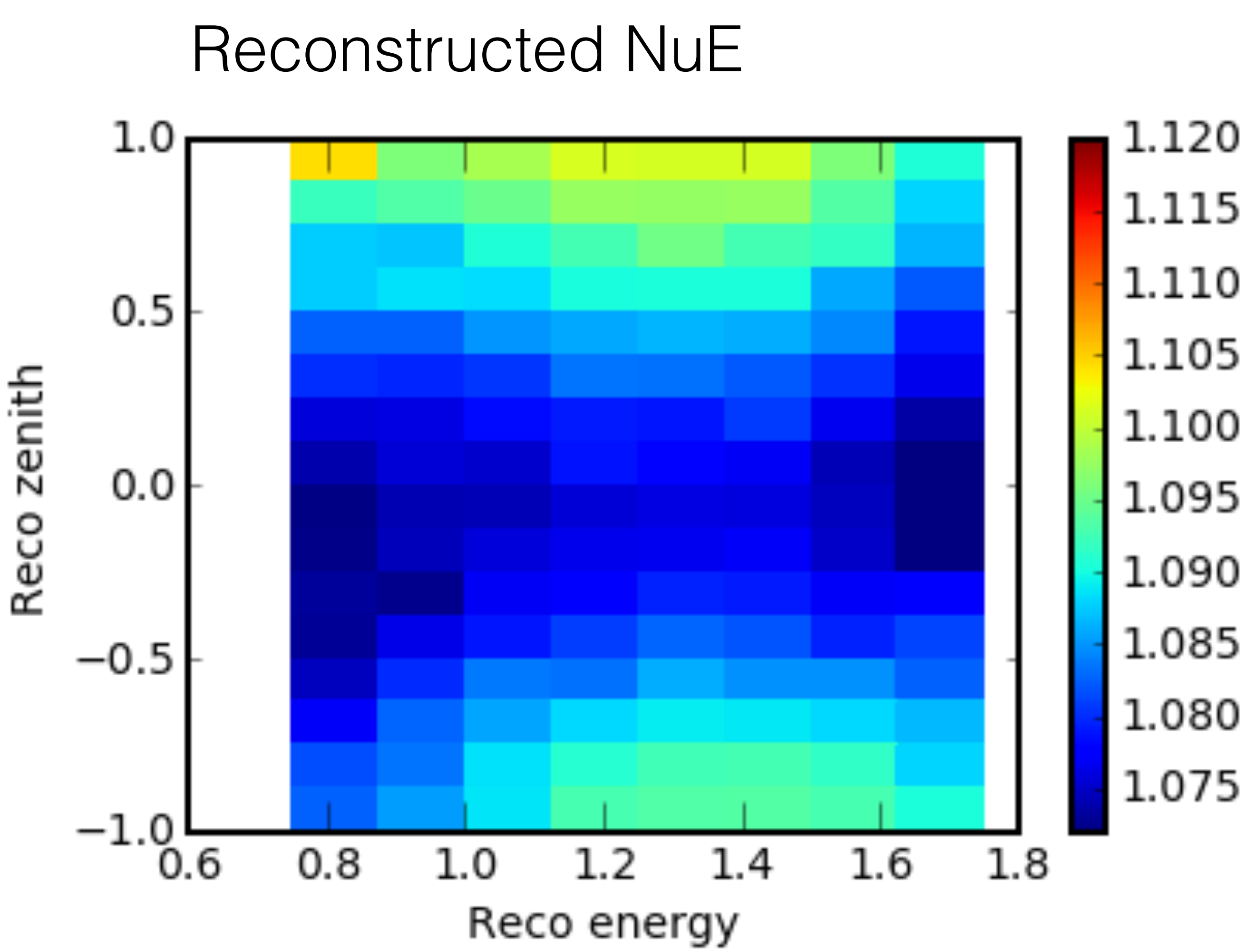
- Here we see Kaon and Pion contributions to NuMu flux, changing only the interaction model.
- Shapes are very similar in dominant regions.

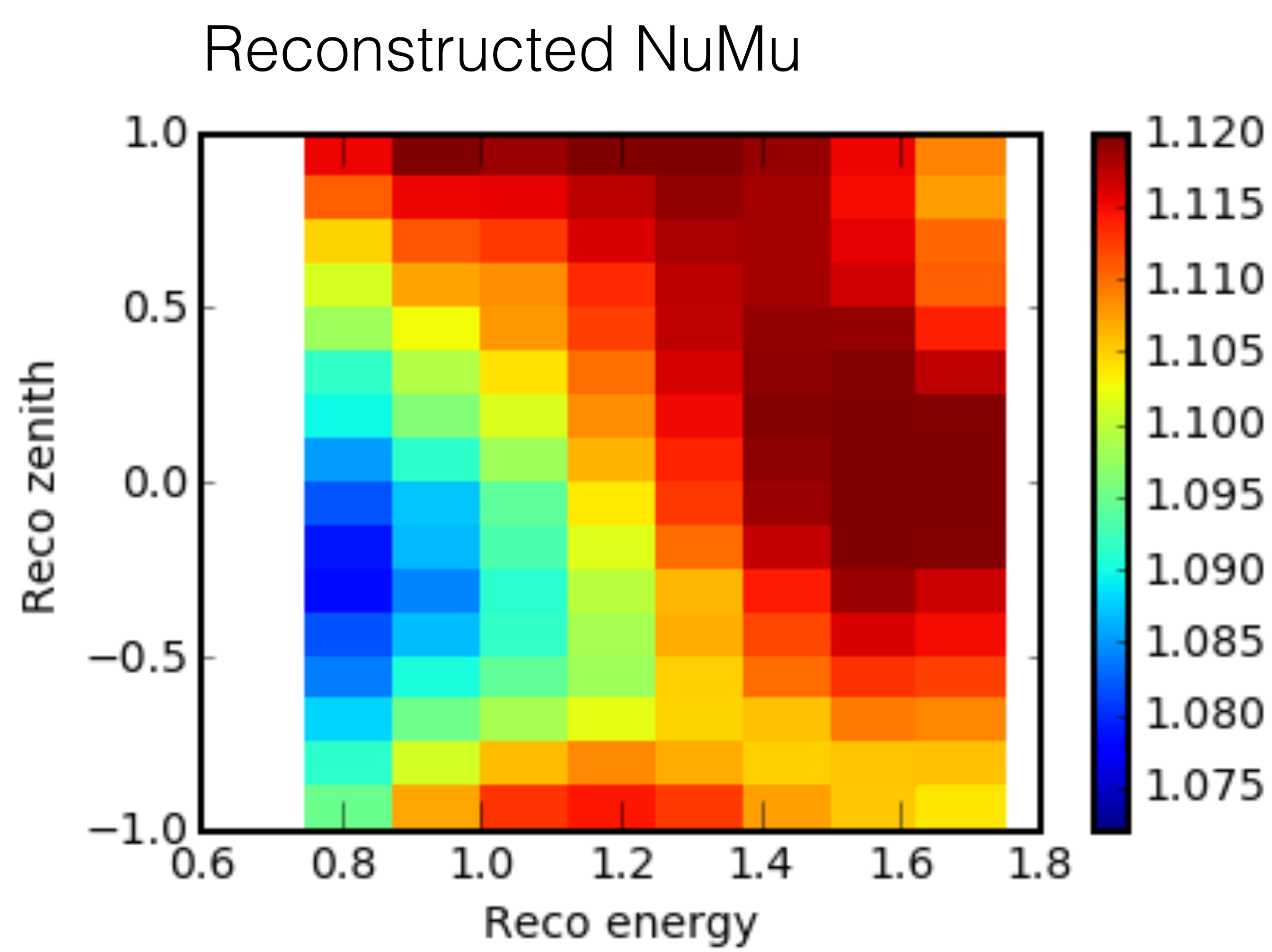


- Keep template of NuMu from kaons constant and scale the Numu from pions.
- Scaling allows for moving of cross over point where kaons begin to dominate as source for NuMu

Reminder:

Ratio of numu_from_pi scaled up by 1.2/1

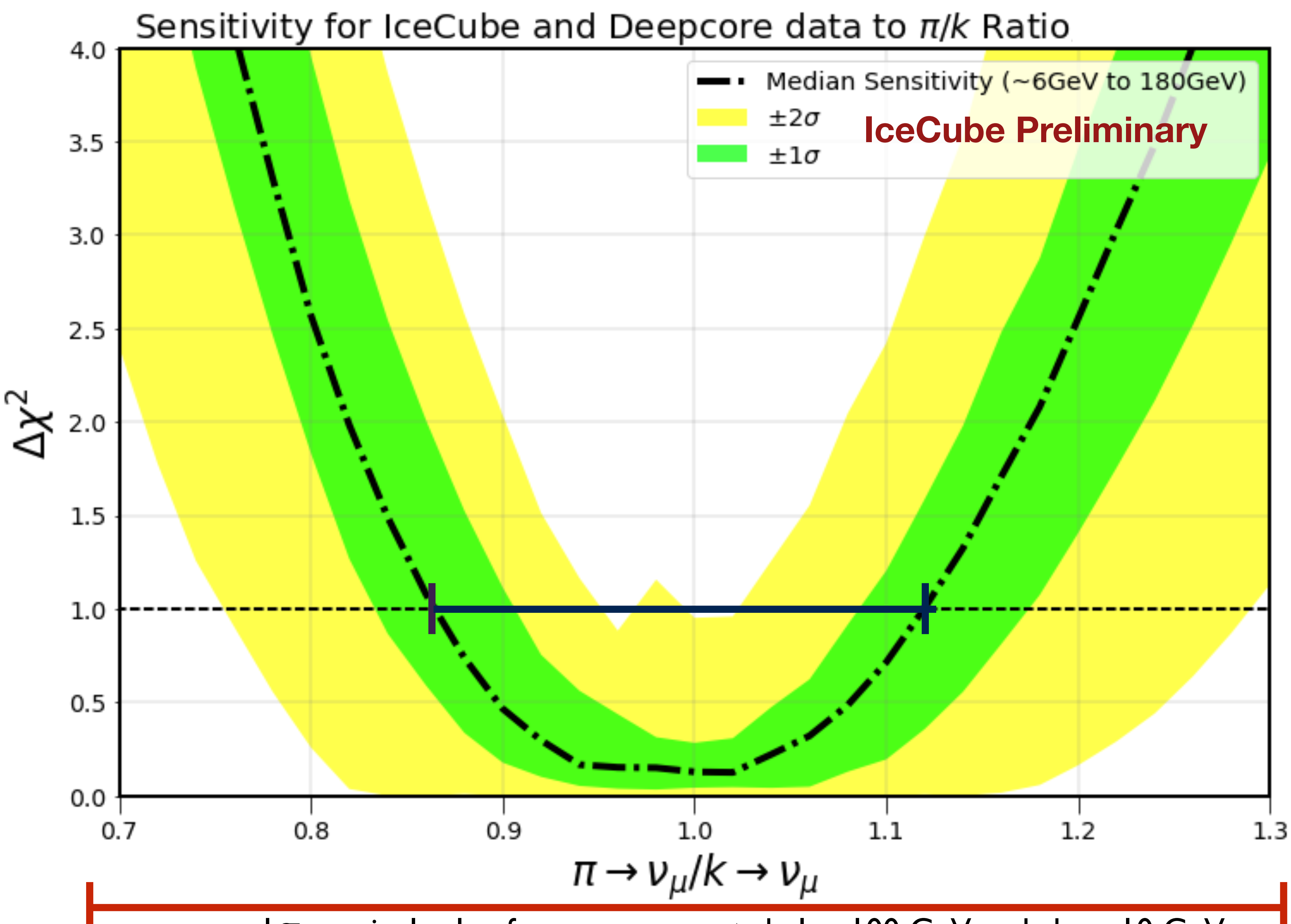




Take away: Yes we should be able to see this effect at a level that will likely interest the community

Flux Measurements of Kaon/Pion ratio: Sensitivity

- 100 pseudo experiments with statistical fluctuations, all systematics.
- This plot is a profile scan that gives us an indication of our sensitivity to changes in the spectral index

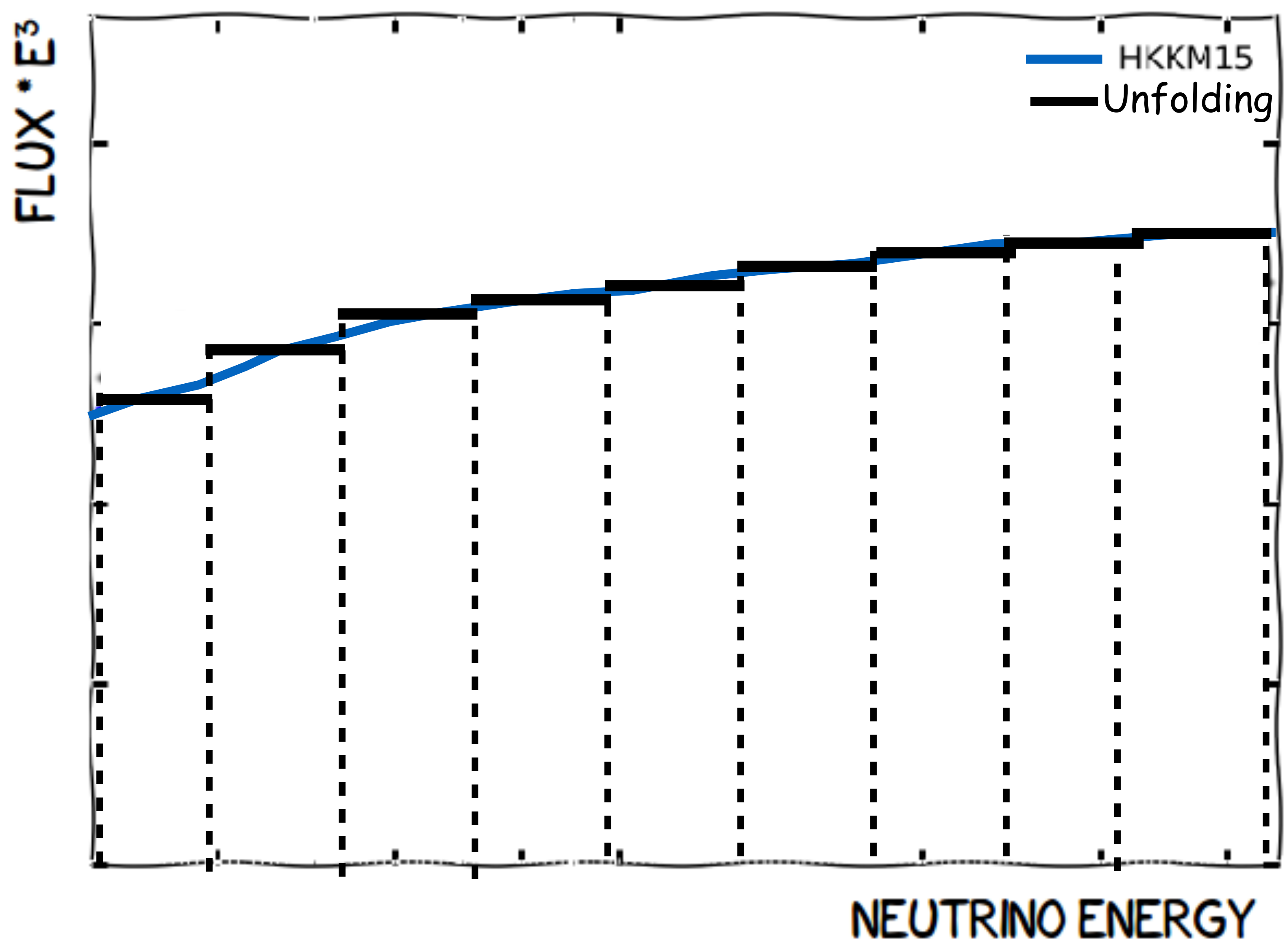


1σ nominal value for measurements below100 GeV and above10 GeV, G. D. Barr et al. Phys. Rev. D74 (2006) 094009.

Identifying the Atmospheric Neutrino Spectrum: Unfolding

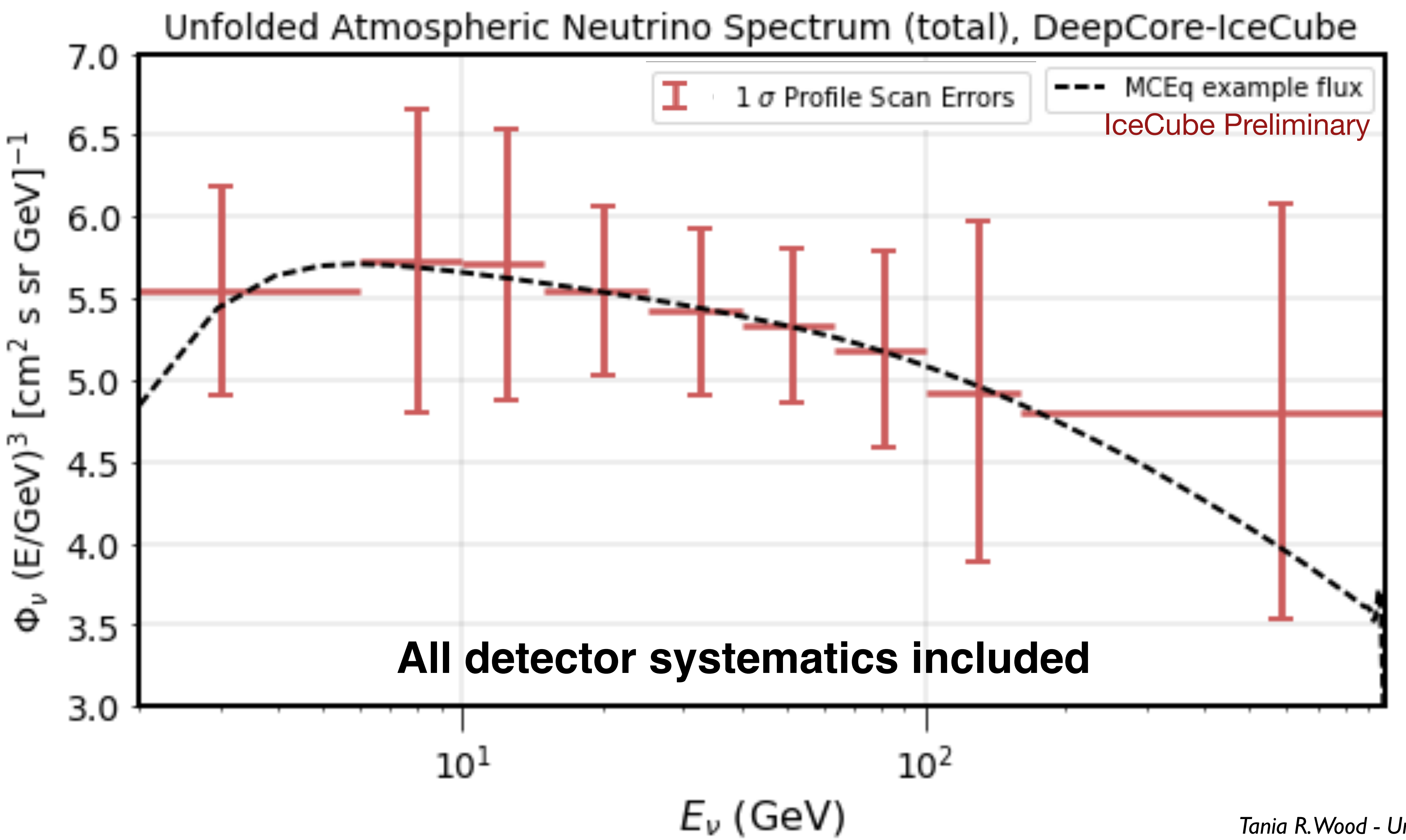
- Would like to do ‘semi’ model independent unfolding
- Models appear relatively flat in E^-3 spectrum
- Use weighting scheme that gives flat E^-3 Spectrum but preserves zenith angle dependence.
- *Note: conserve Nu/NuBar ratios, allow scaling up and down of ratio shape only*

Unfolding in ’n’ bins



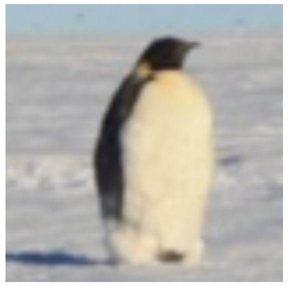
Identifying the Atmospheric Neutrino Spectrum: Unfolding

- With the 'faked data' we assign the underlying spectrum seen here in '---' ; for the unfolding of the bins we assume a flat spectrum.
- Energy bin error is taken from the 1sigma of a profile scan done for each bin. Note this plot is MC only.



Summary:

- Advanced flux modelling tools are in place and fully tested
- Key parameters that guide the systematic uncertainties of the flux measurement have been studied and demonstrate the potential to reach precision values
- First indications from the simulation studies show separability of the leading flux models
- IceCube has accumulated one of the world's largest atmospheric neutrino datasets for which to execute the measurement
- Expect results later this summer (ICRC)
- Future work from these studies to include a joint analysis of IceCube and Super-Kamiokande datasets in the low-energy overlap region to provide a single flux measurement over 6 orders of magnitude



Thanks!

UNIVERSITY OF ALBERTA

ICECUBE

The IceCube Collaboration

Funding Agencies

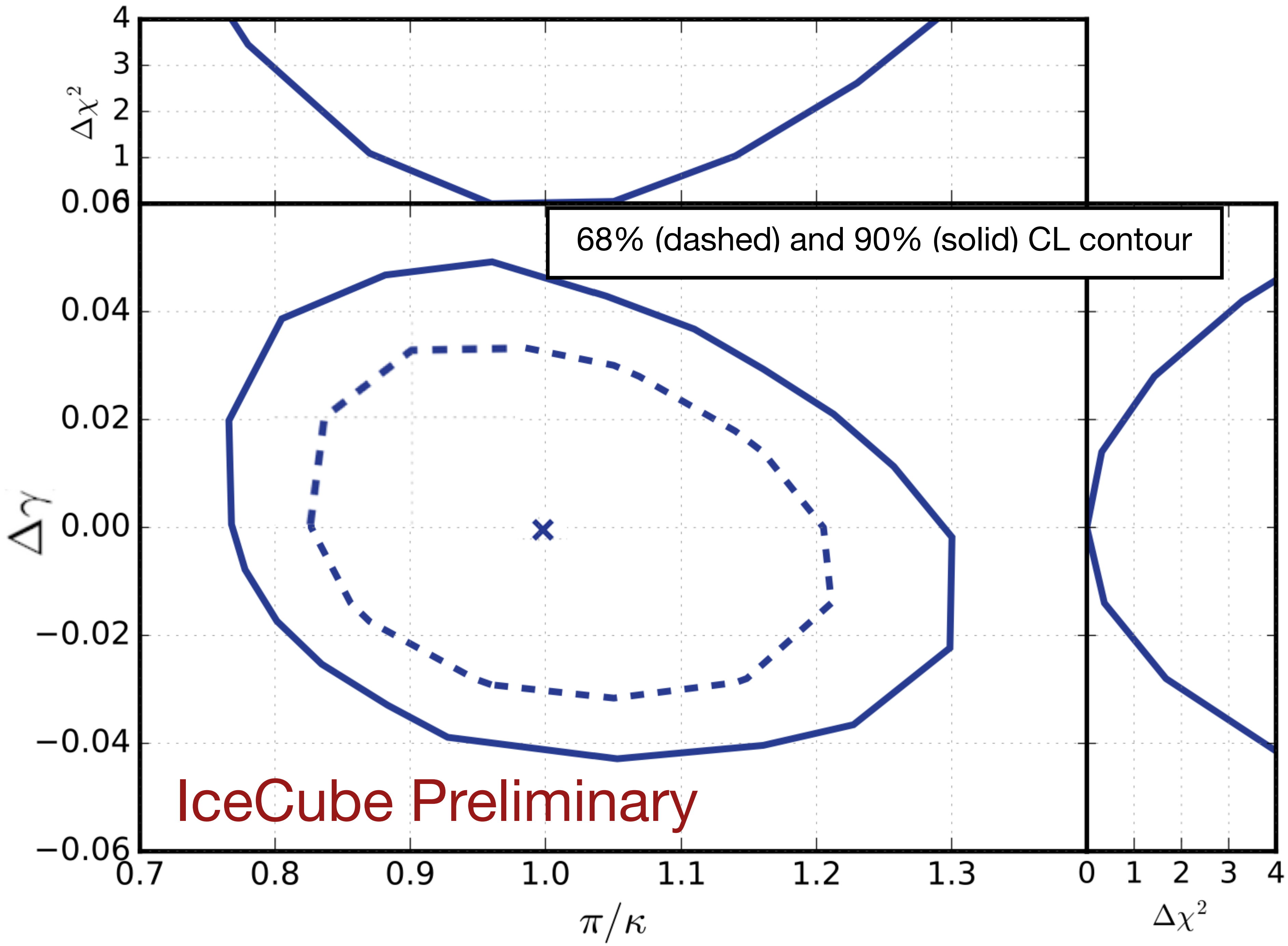
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)


BACK UP

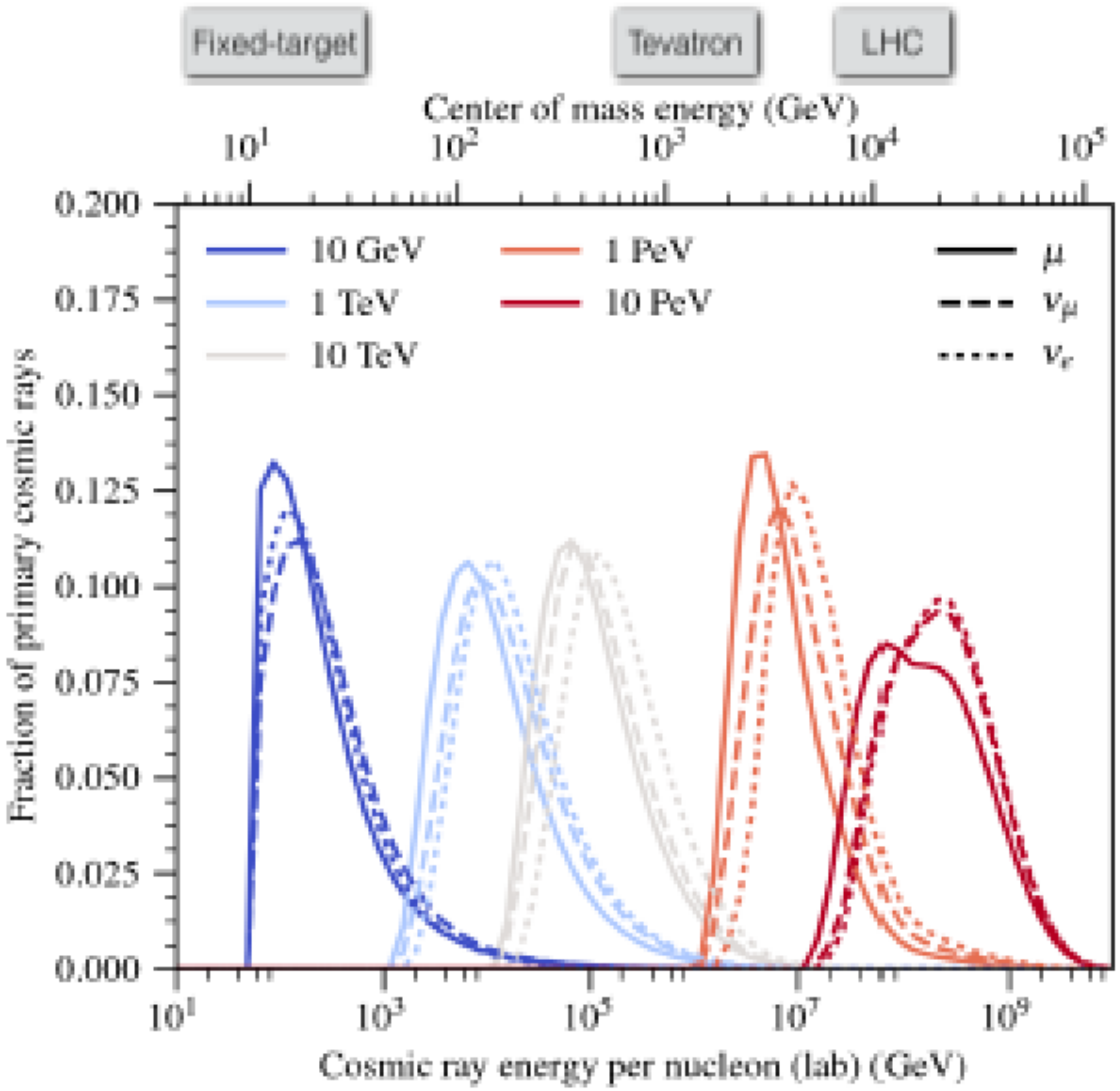
Key parameters towards a precision flux measurement

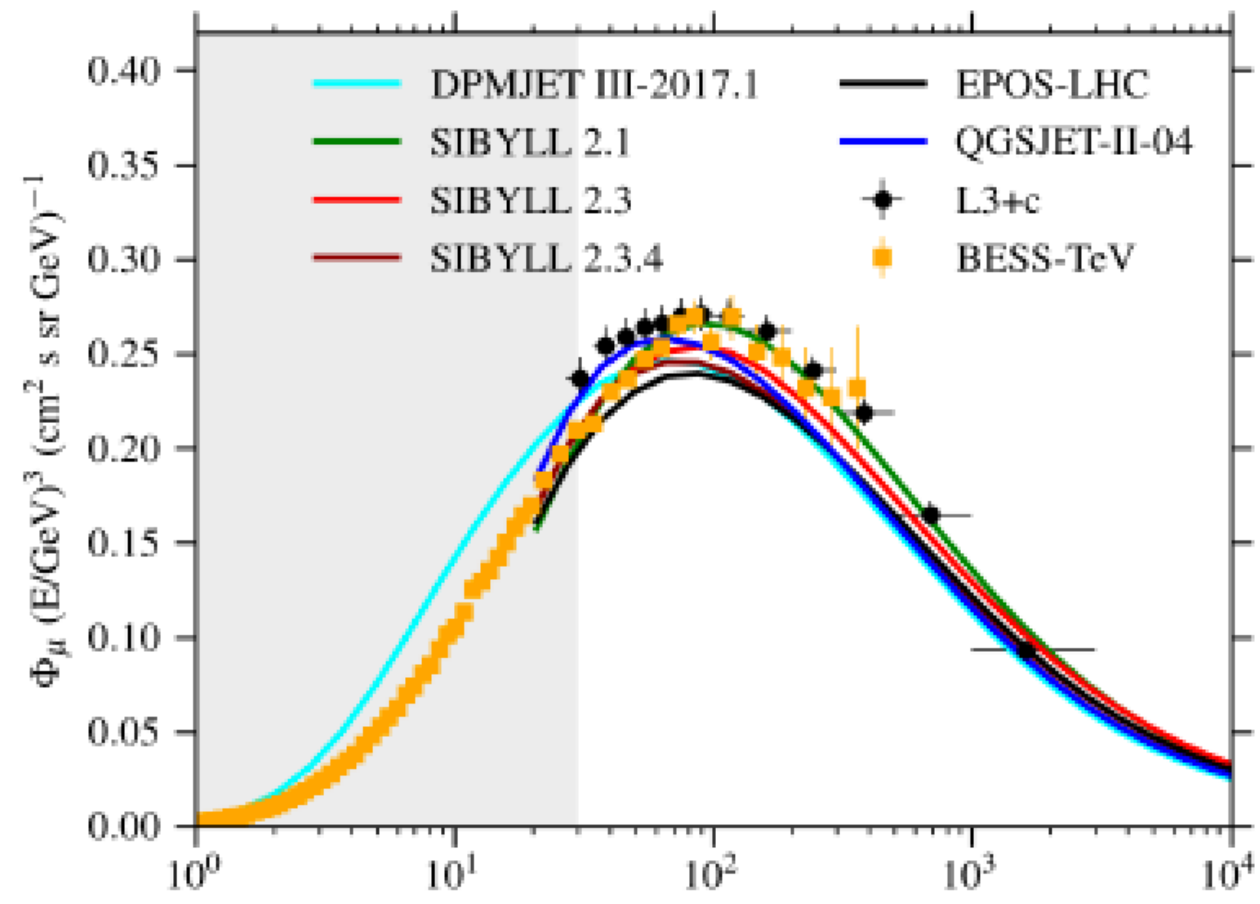
68% (dashed) and 90% (solid) CL contours

- This plot shows the correlation in the sample between changes in spectral index and the kaon/pion ratio

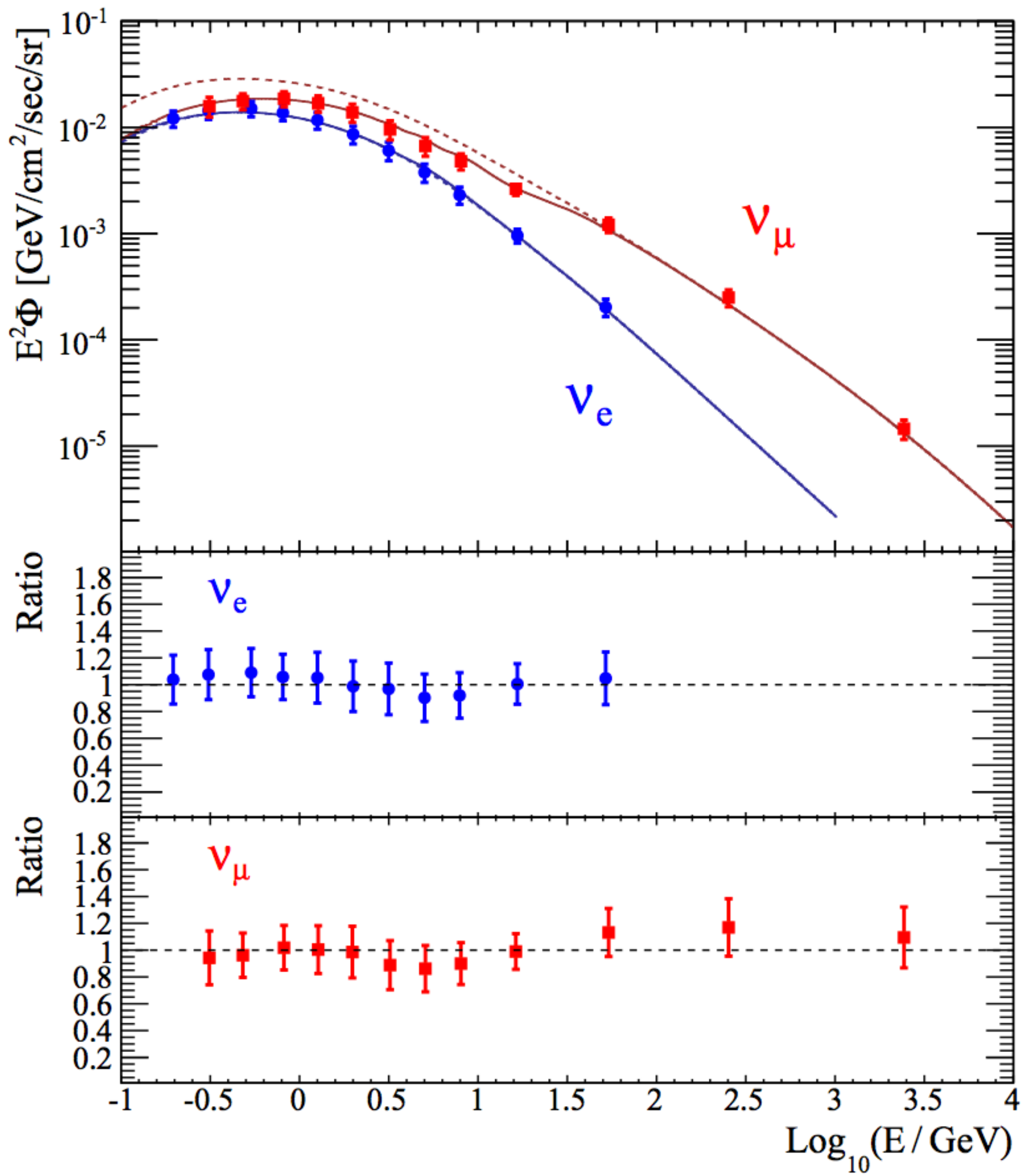


Relation between lepton and cosmic ray energy





The Super-Kamiokande Collaboration
Measurements of the atmospheric neutrino flux by Super-Kamiokande: energy spectra, geomagnetic effects, and solar modulation
https://arxiv.org/pdf/1510.08127.pdf



The Super-Kamiokande Collaboration
Measurements of the atmospheric neutrino flux by Super-Kamiokande: energy spectra, geomagnetic effects, and solar modulation
https://arxiv.org/pdf/1510.08127.pdf

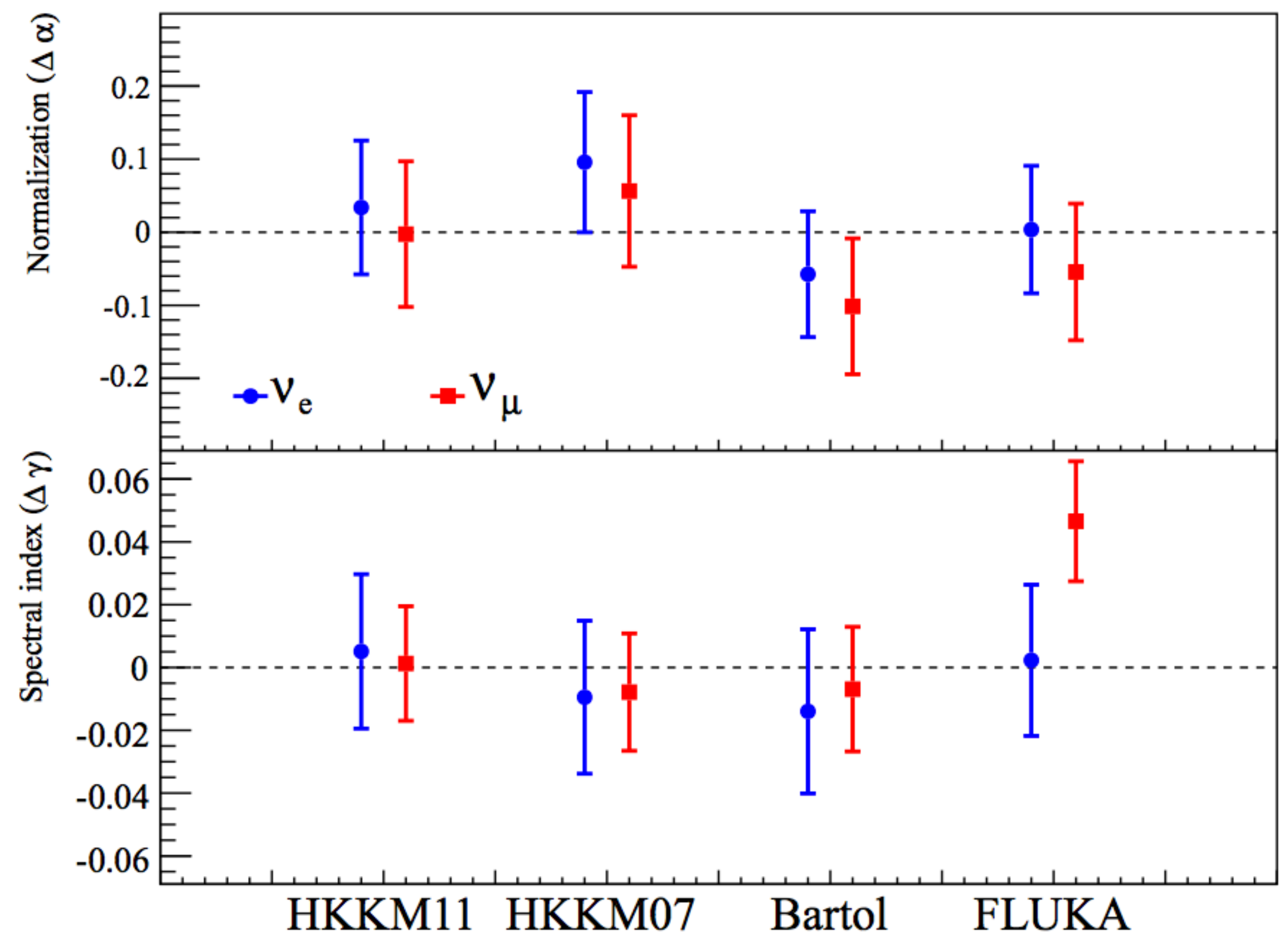
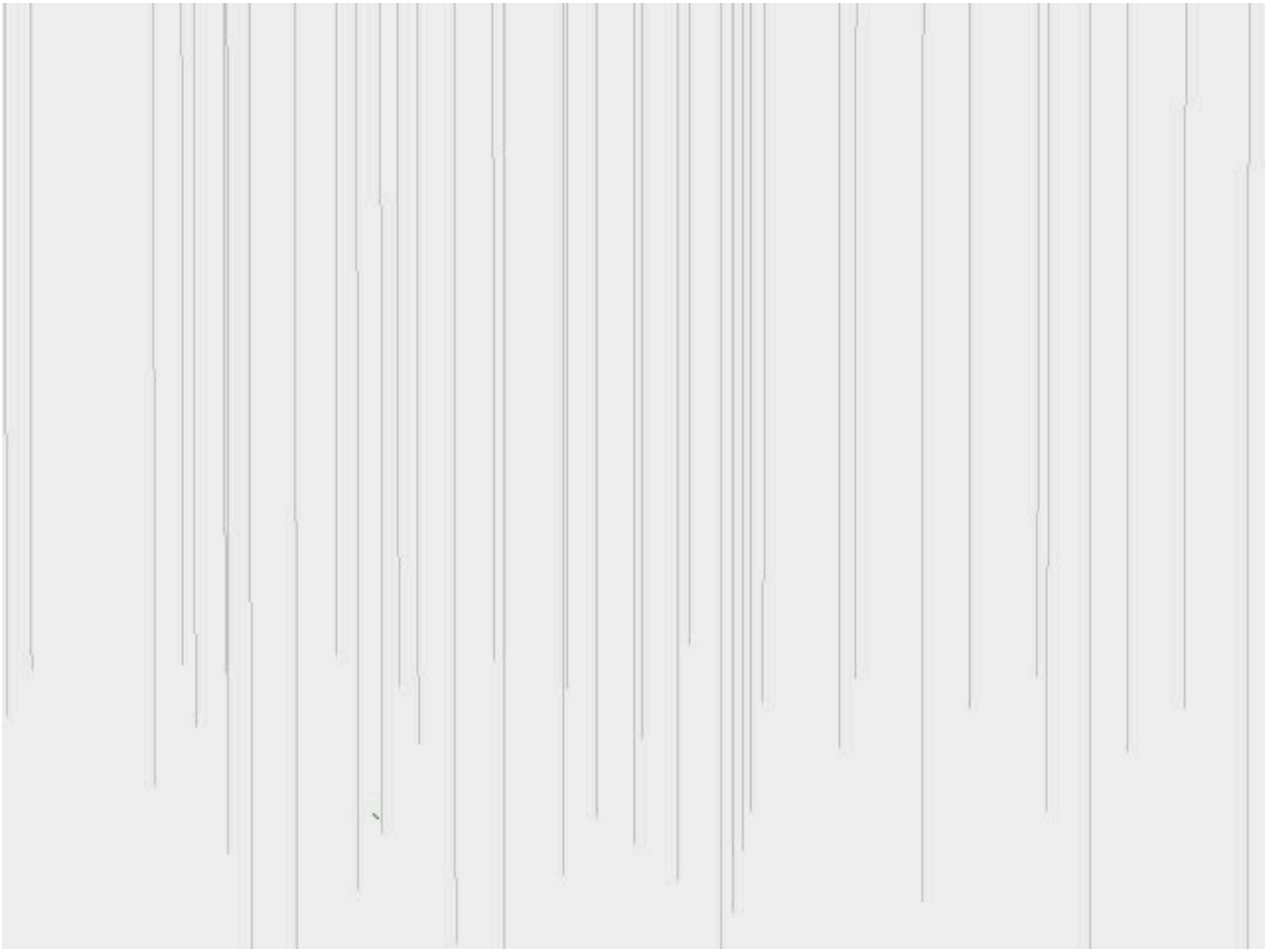


FIG. 10. (color online) Best-fit and 1 σ error of $\Delta\alpha$ and $\Delta\gamma$ parameters for each flux model by χ^2 calculation, representing the deviation in normalization and spectral index from the flux prediction, respectively.

Average NuMu charged current (NuMu CC) event



Position: vertex (15,-40,-402)m
i.e. around the center of
DC depth, direction
'toward' DC strings

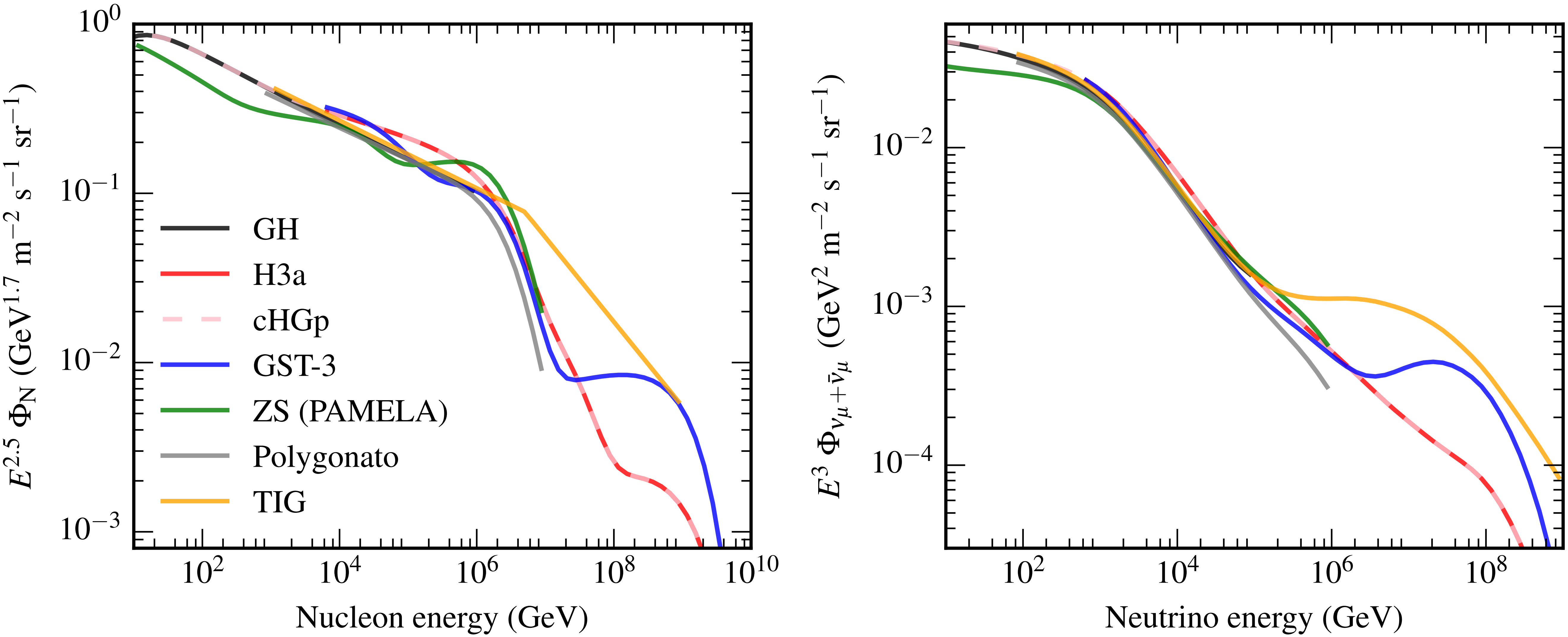
-> for experts i.e. between string 36 and two or three DC strings

->Cone represents Cherenkov Cone

NuMuCC with a 26GeV muon and 4GeV hadronic cascade

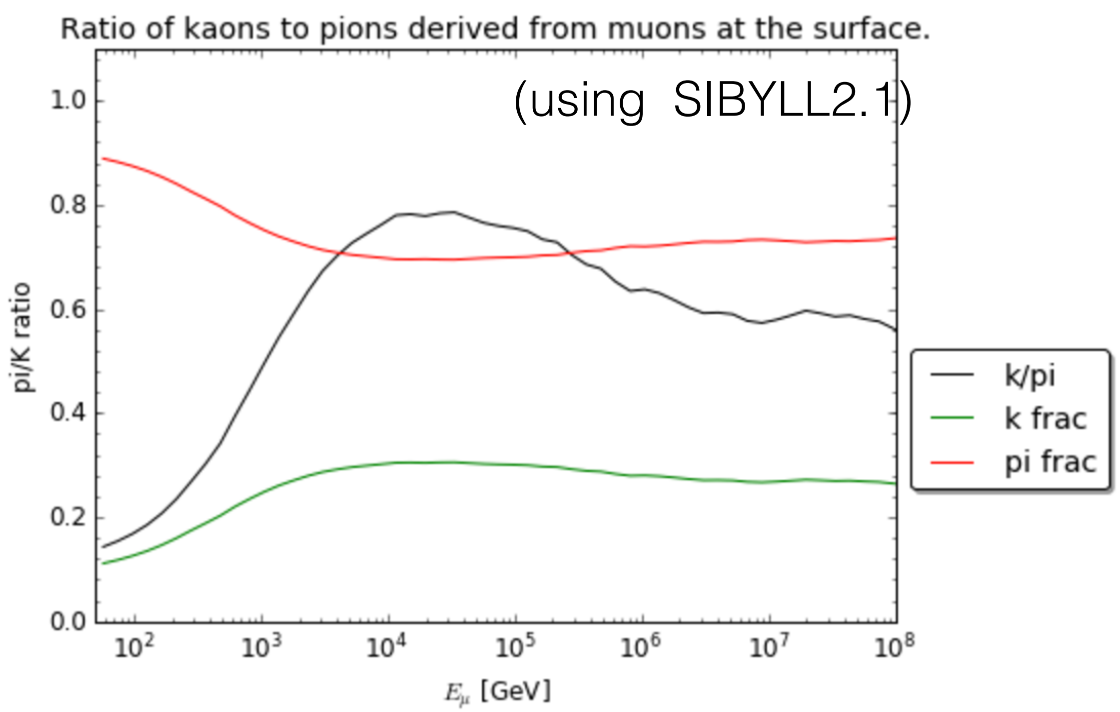
**the hadronic cascade is always the same approximation with 4 pions (2 charged, 2 neutral) taking away 90% of the cascade energy

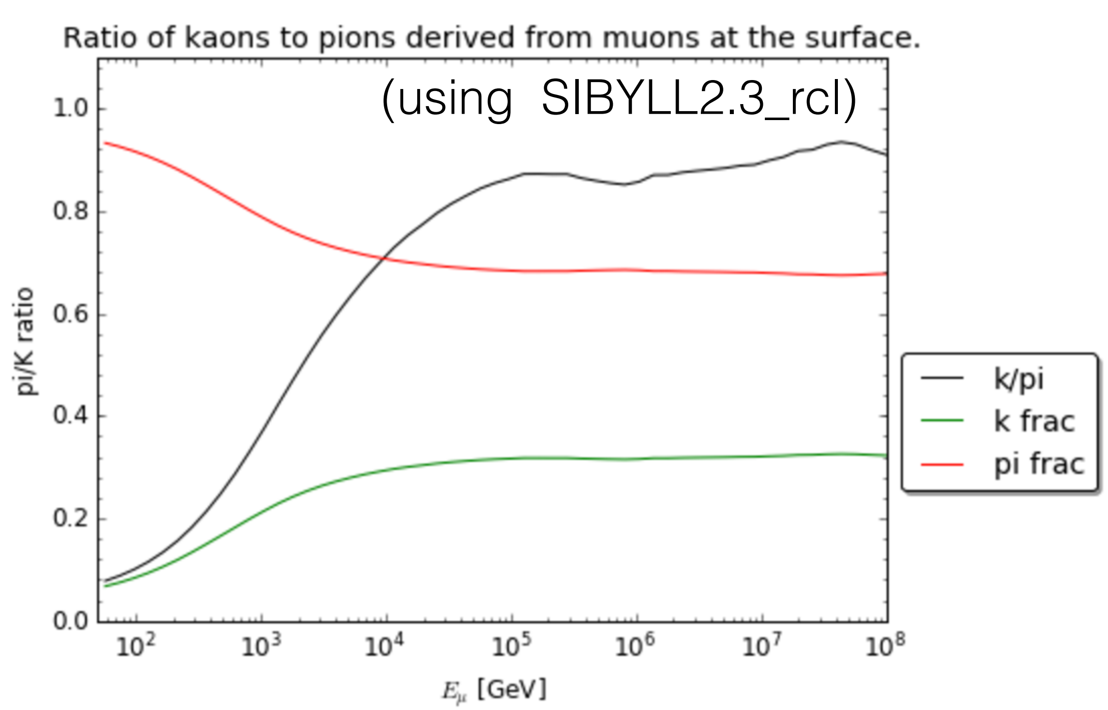
Available CR Models:



A. Fedynitch

Neutrino Flux Measurement of Kaon/Pion Ratio:



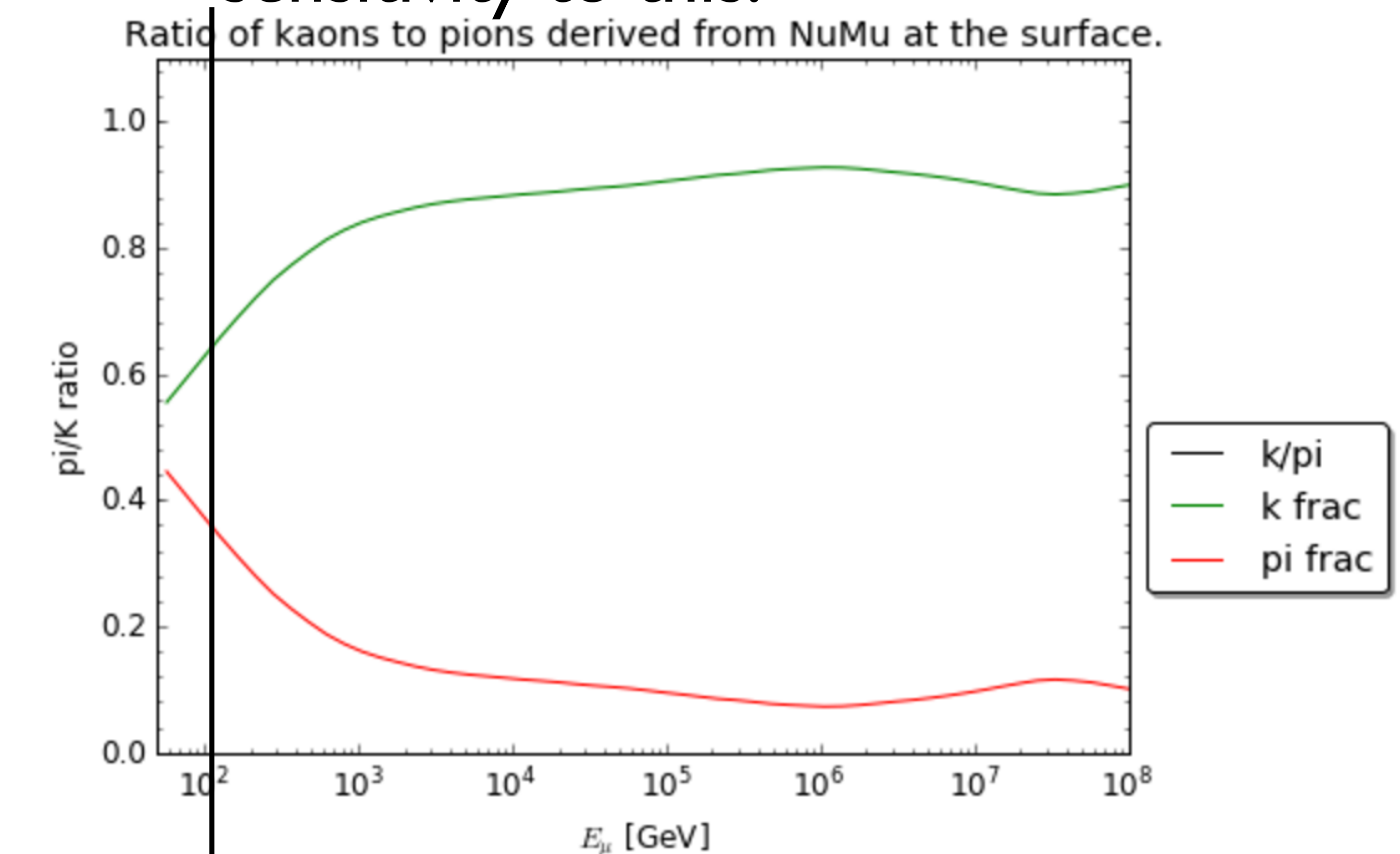


Plots made with MCEq

- It depends entirely on the shape of the inclusive particle production cross-section and not only on its absolute value, for example; so for the hadronic interaction the pi/K ratio is ambiguous where these are not well known.
- Working to adjust meson production predictions by scaling to muon charge-ratio experiments.

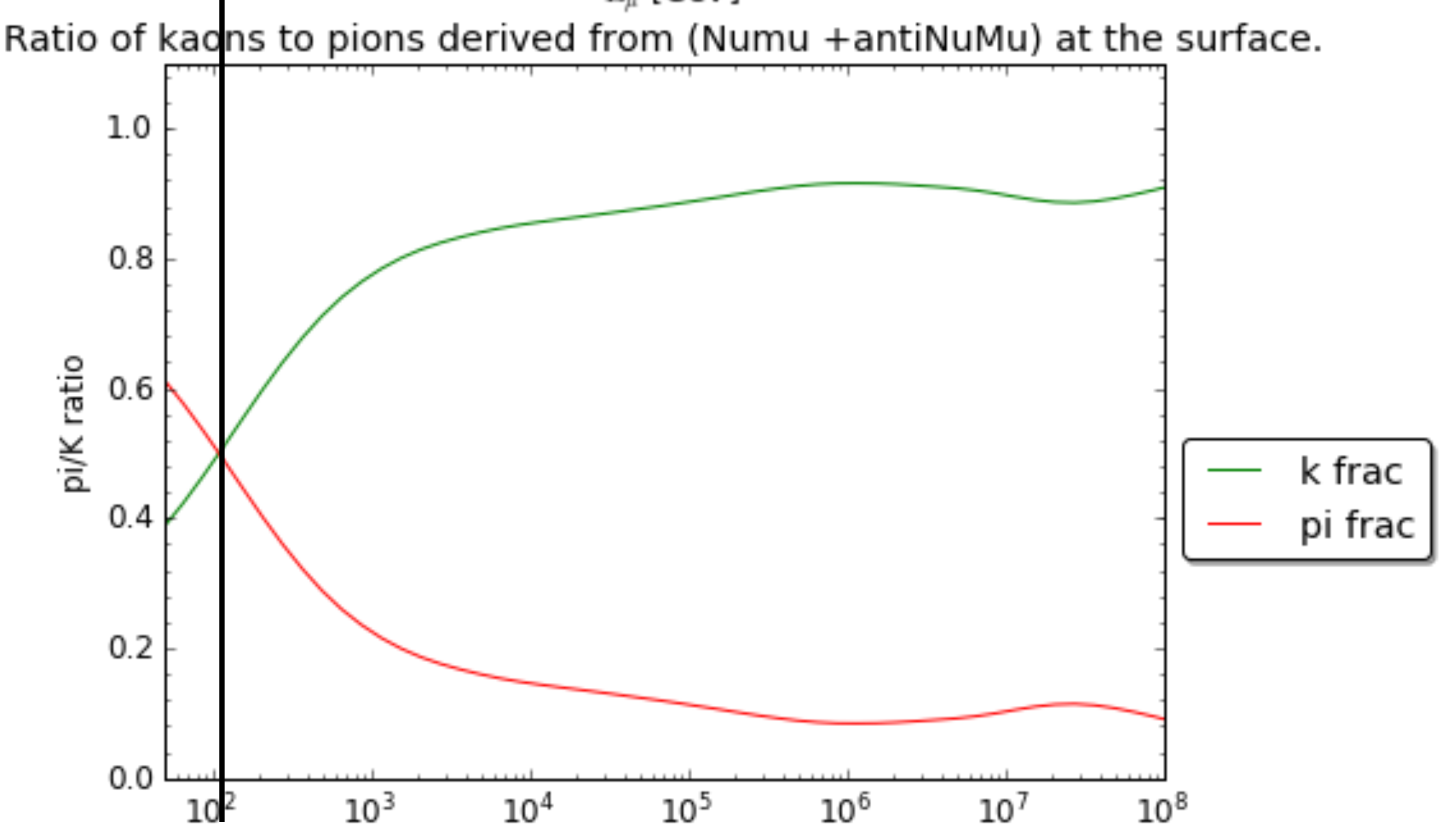
Neutrino Flux Measurement of Kaon/Pion Ratio:

- Different hadronic models move the k/pi fraction crossing point. May have sensitivity to this.



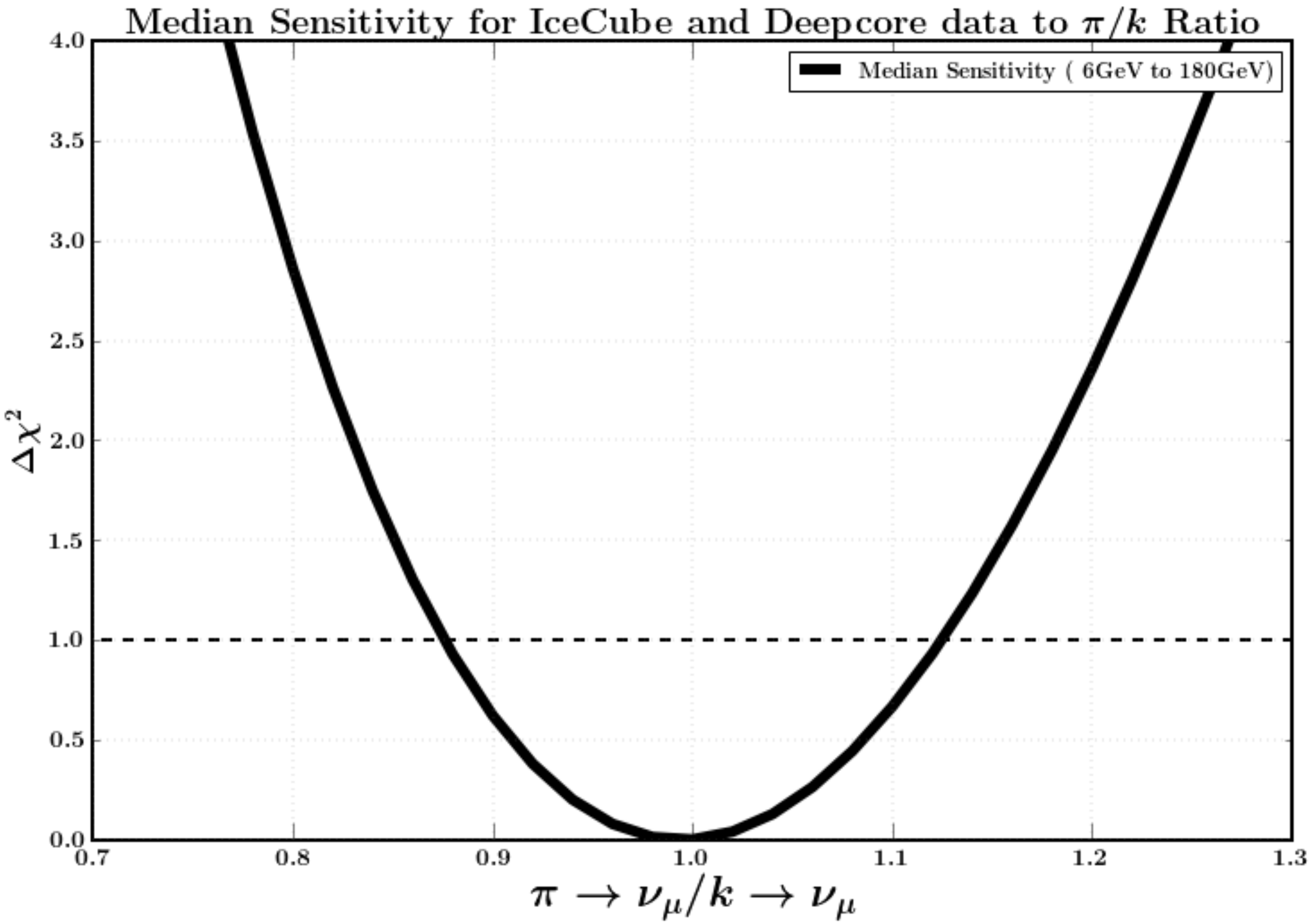
k/pi ratio:

plot made with SIBYLL2.3

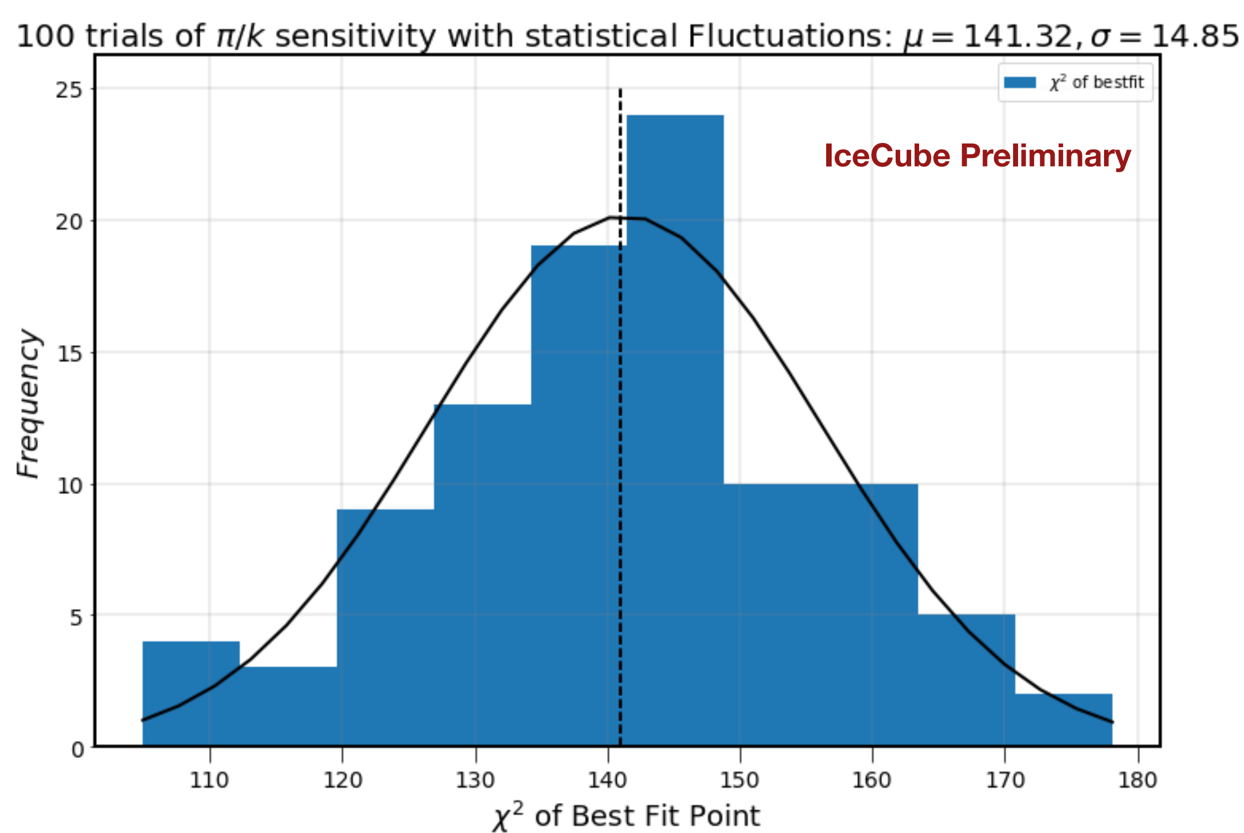


k/pi ratio:

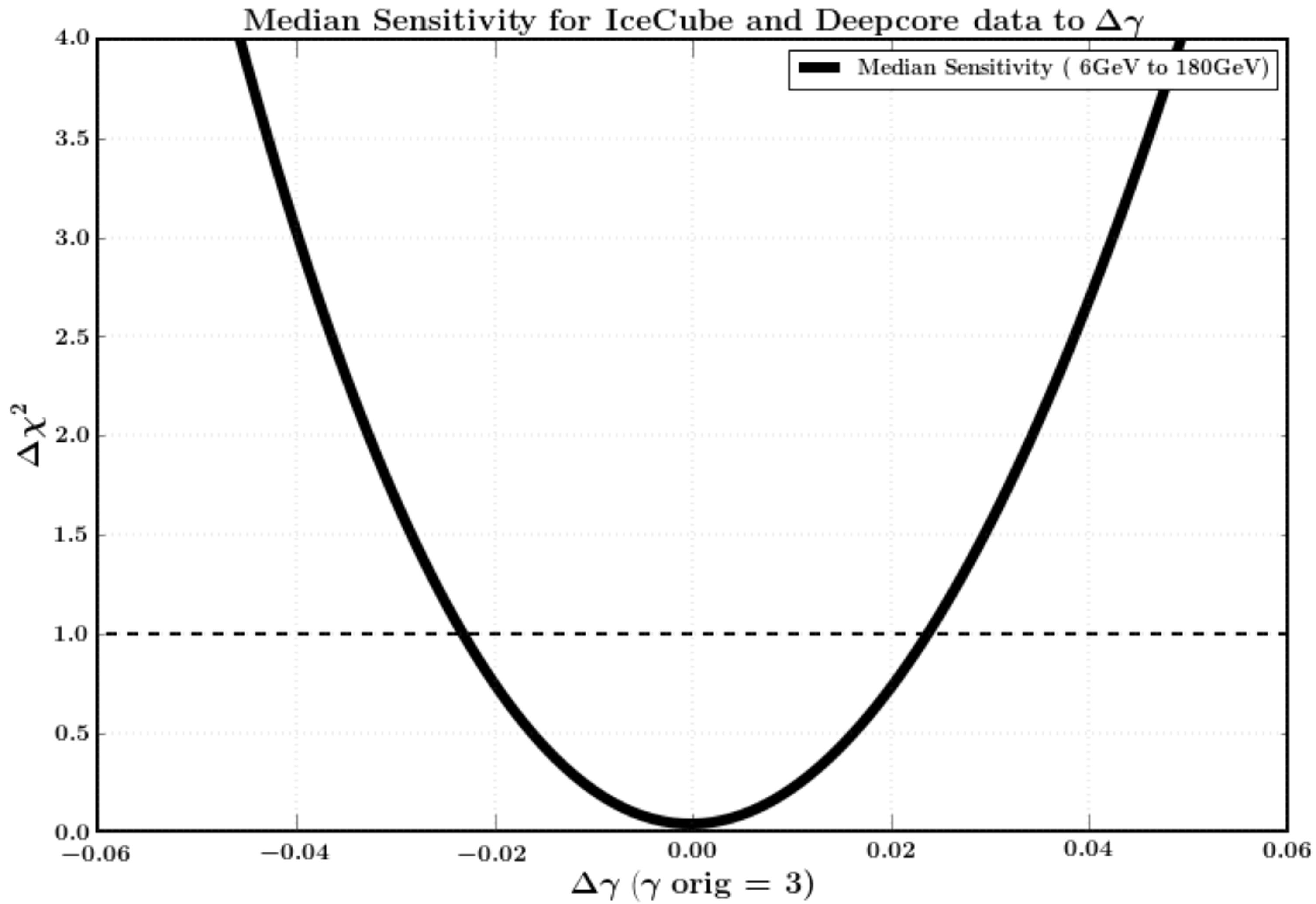
plot made with DPMJET-III, (shown only to 50GeV for ease of comparison)

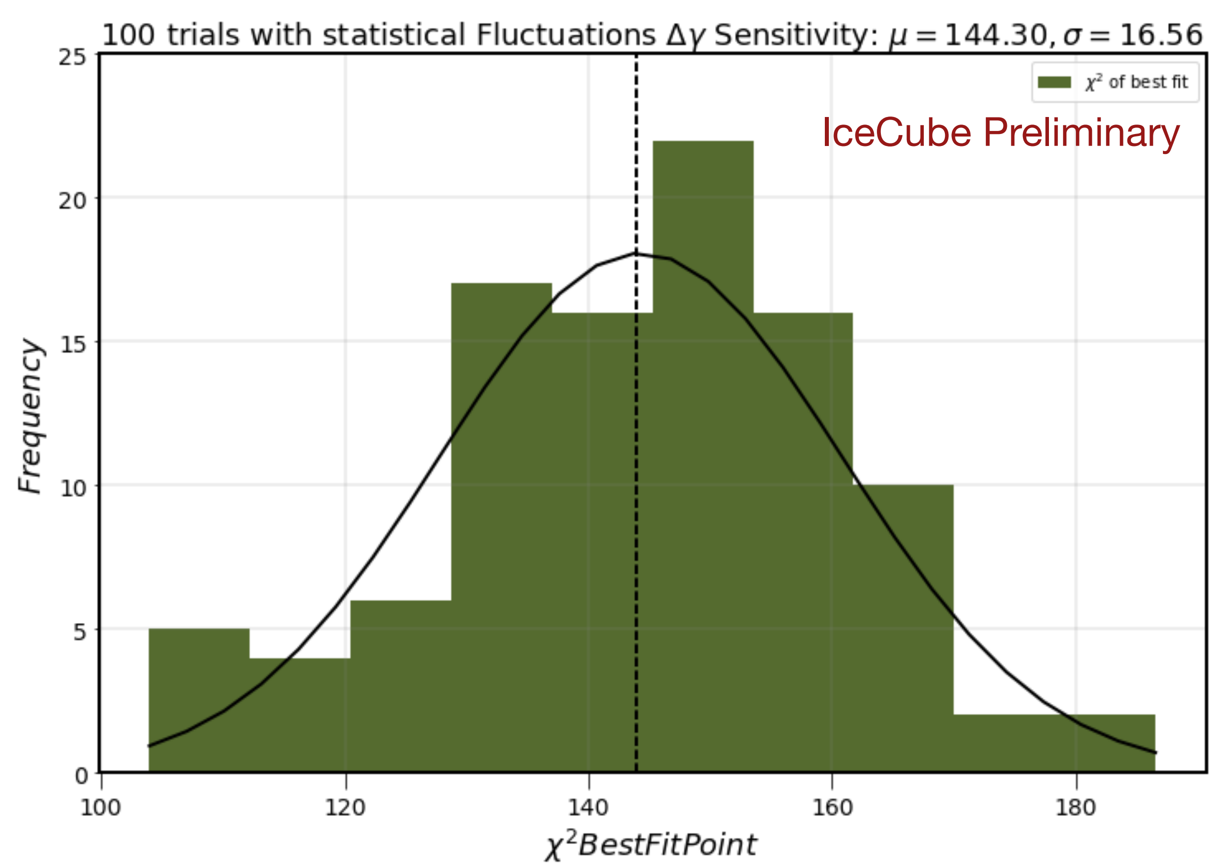


Median Sensitivity for IceCube and Deepcore data to π/k Ratio
Median Sensitivity (6GeV to 180GeV)
$\Delta\chi^2$
$\pi \rightarrow \nu_\mu / k \rightarrow \nu_\mu$



100 trials of π/k sensitivity with statistical Fluctuations: $\mu = 141.32, \sigma = 14.85$
χ^2 of bestfit
IceCube Preliminary
Frequency
χ^2 of Best Fit Point


Median Sensitivity for IceCube and Deepcore data to Δγ
Median Sensitivity (6GeV to 180GeV)
Δχ²
Δγ (γ orig = 3)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06


100 trials with statistical Fluctuations Δγ Sensitivity: μ = 144.30, σ = 16.56
χ² of best fit
IceCube Preliminary
Frequency
χ²BestFitPoint
25
20
15
10
5
0
100
120
140
160
180

Honda 2015 Model Pieces:

As implemented in MCEq

- Background:
  Can put in individual model pieces to 'recreate' Honda flux

  - Ingredients : Muon Calibration of inclusive DMPJET-III

  - IGRG (3D Geomagnetic model.. not significant effects above ~ 1 GeV and not included in MCEq

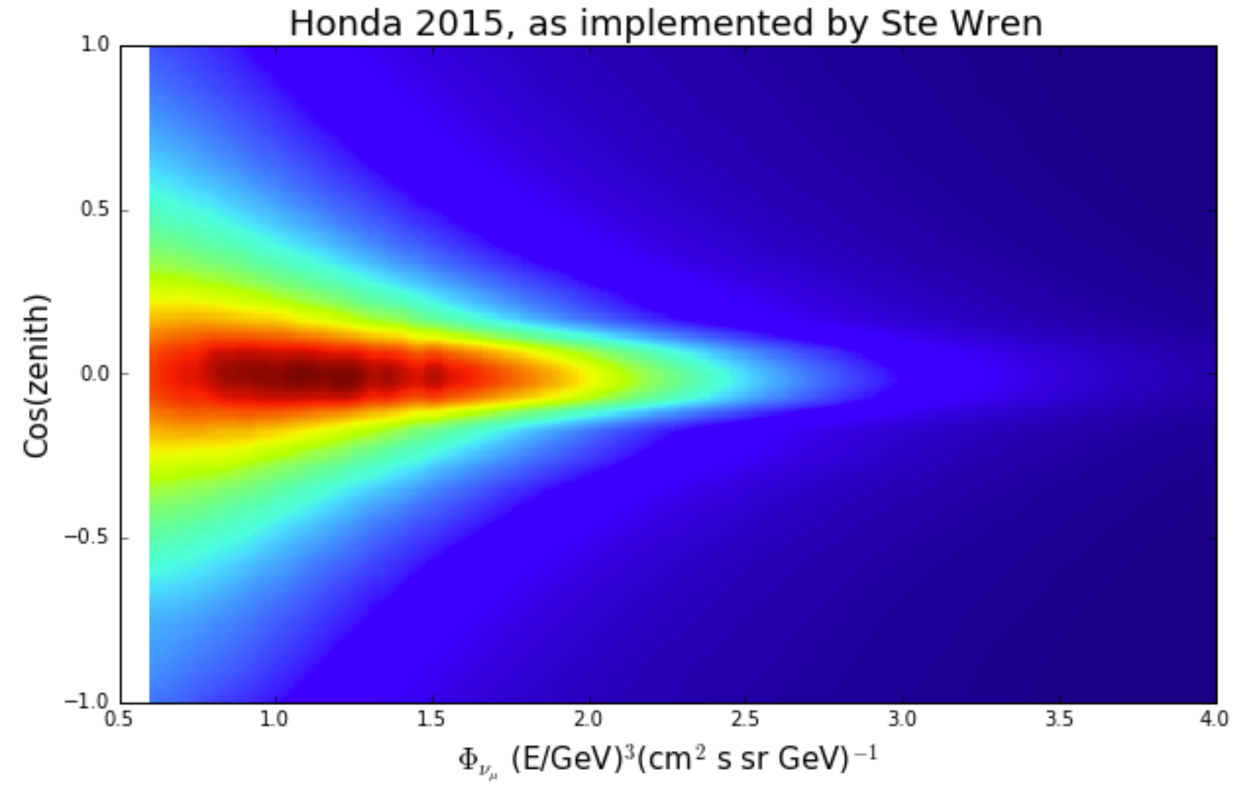
  - NRL(MSISE-00) Atmosphere model — location South pole ..

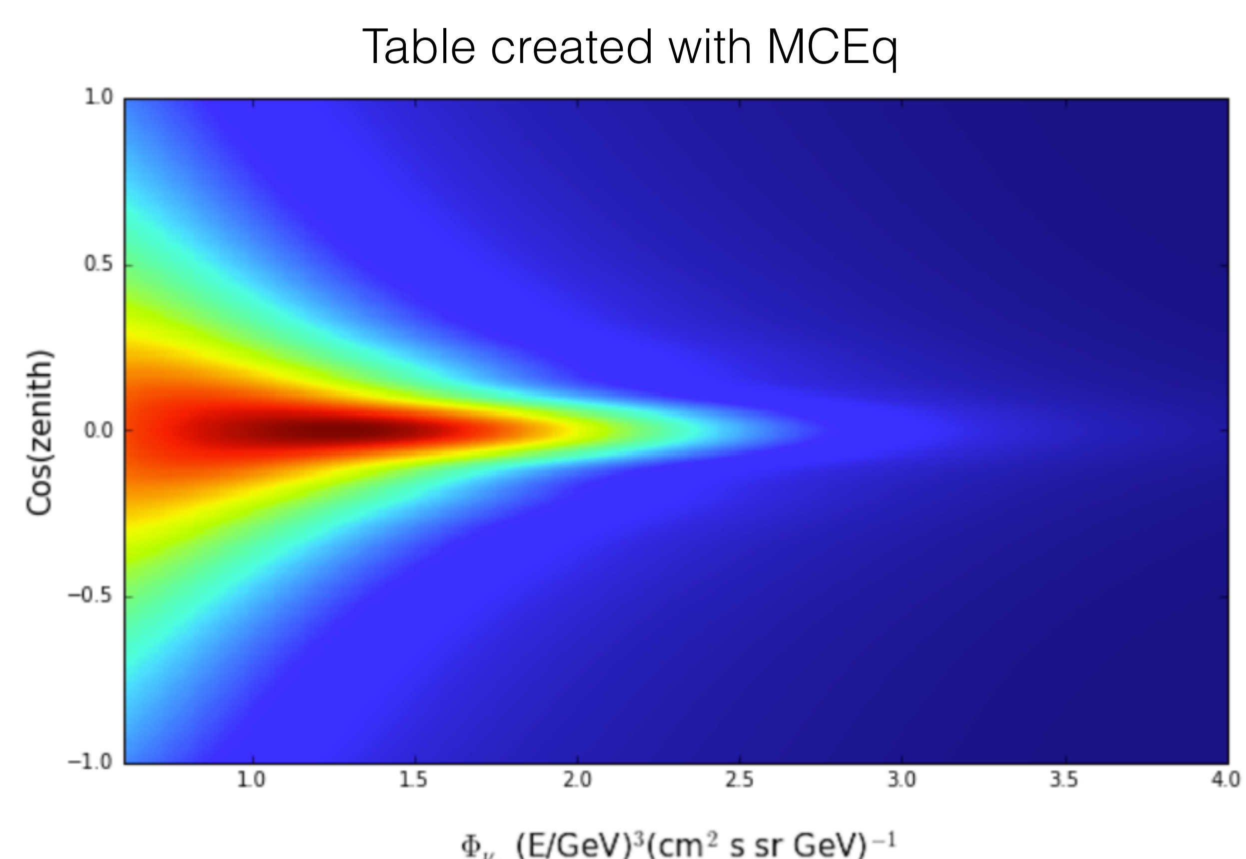
  - CRModel: ' HondaGiasser'

**Version of DPMJET-III parameterized for MCEQ_dev does not have the Muon Calibration. Handling this by allowing scaling of kaon and pion flux templates

MCEq Neutrio Flux Tables:

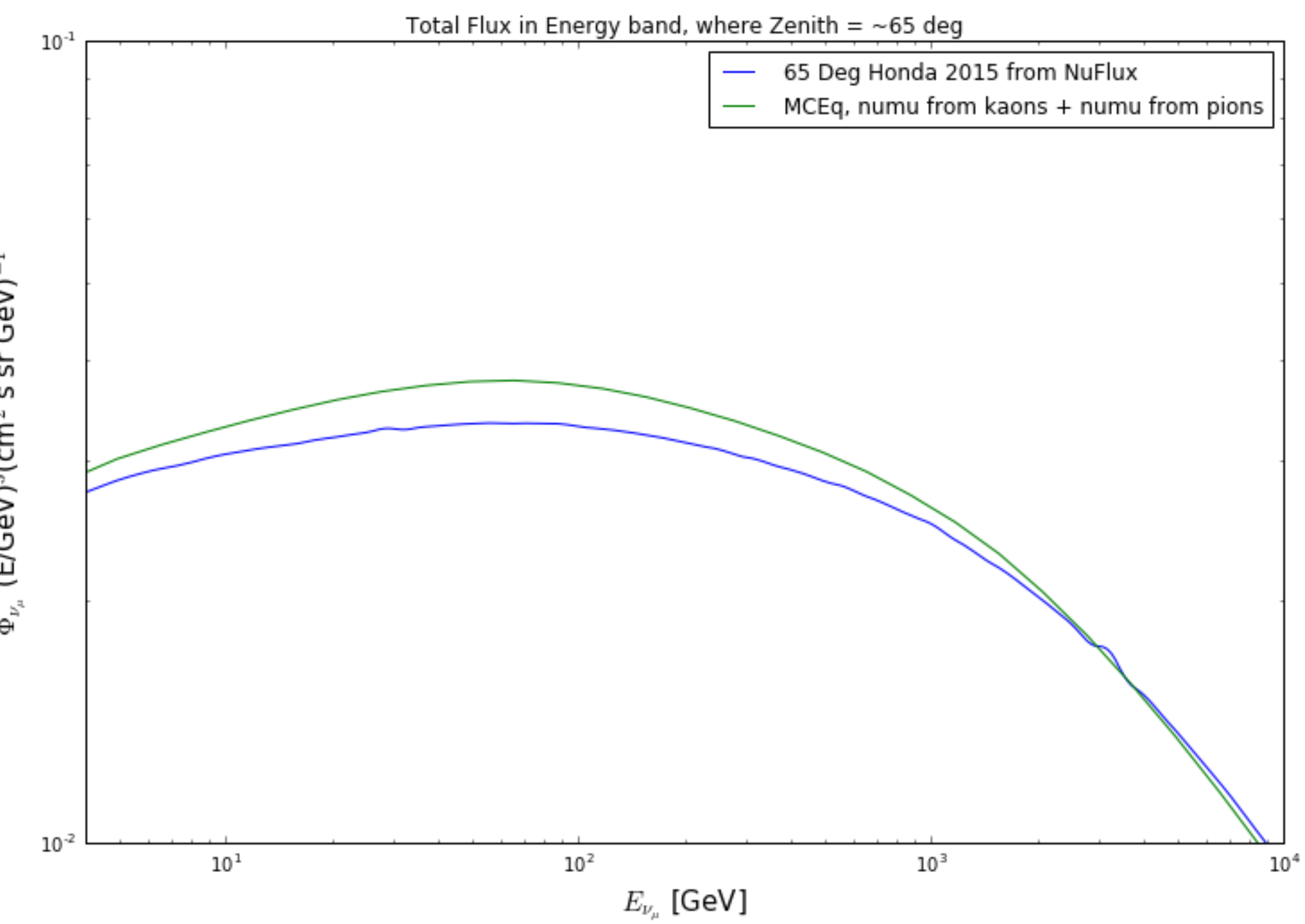
- A. Fedynitch has expanded MCEq to energies relevant for DeepCore and has provided wonderful support
- Now able to create tables using any components you want
  - ie. can create tables for various CRModels, hadronic, and atmospheric models

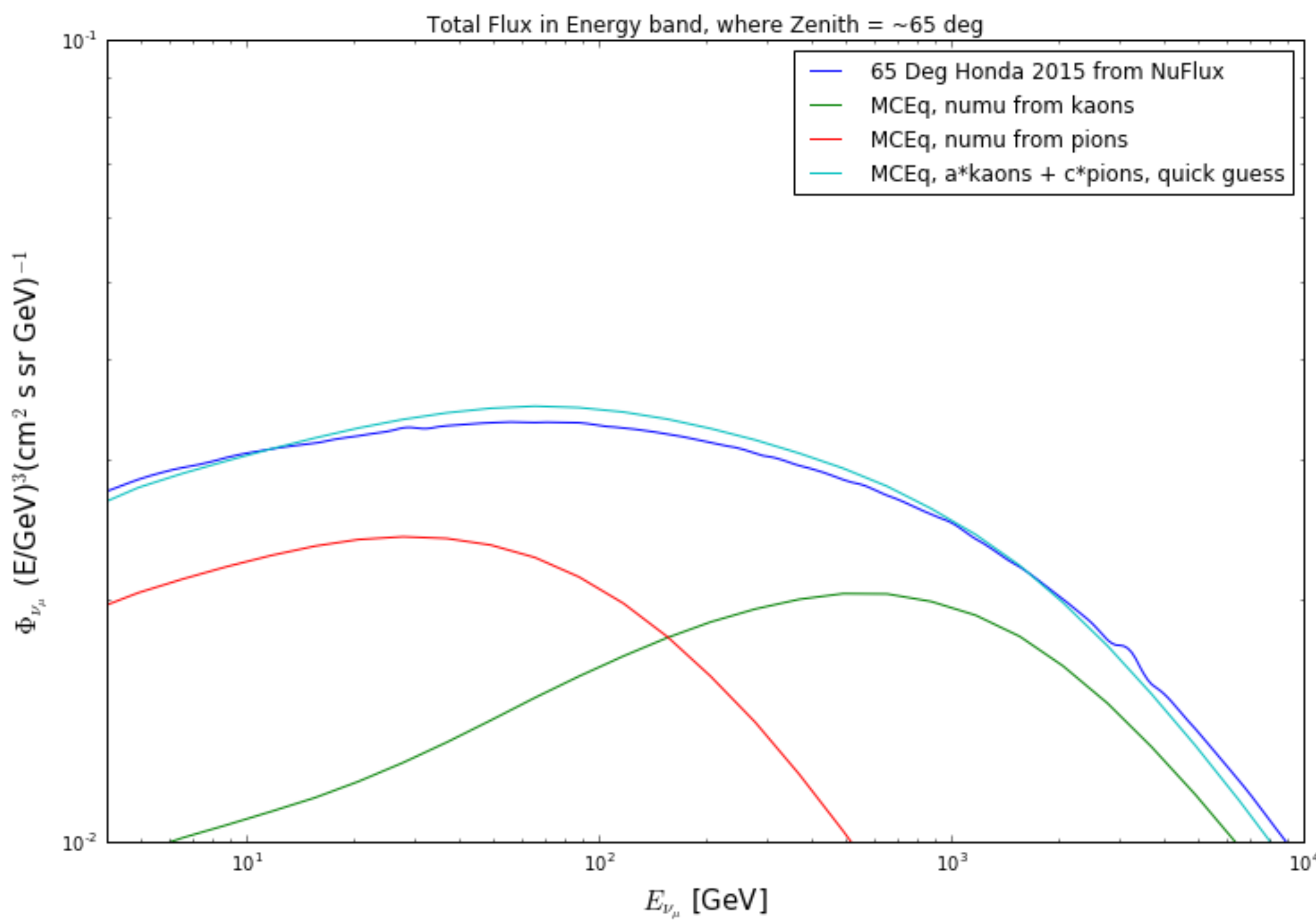




Kaon/Pion ratio: Details

- Adding functionality:
  - Scaling factors for the various flux spectrum components to 'create' a Honda spectrum.





- Here modification of the kaon and pion components lead to a much better fit to Honda

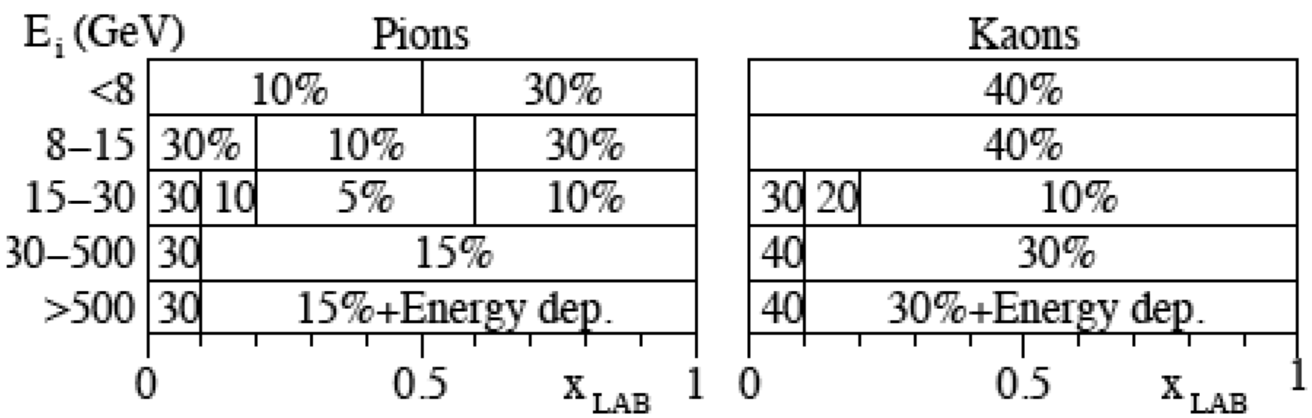


FIG. 2: Uncertainties assigned to the production rate of charged pions (left) and charged kaons (right) as a function of x_{lab}. The uncertainties are shown for various ranges of incident particle energy E_{i} for interactions of protons on light nuclei.

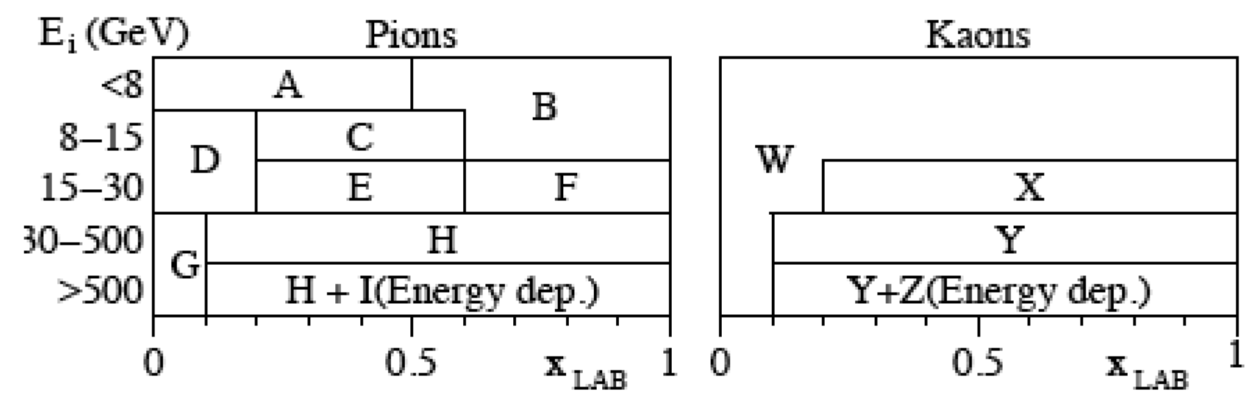


FIG. 3: Uncertainty sources for hadron production. The uncertainties which are applied are fully correlated within each region shown and completely uncorrelated between regions. The letters used to label each region are used on subsequent figures. The levels of uncertainties applied are shown in figure 2.