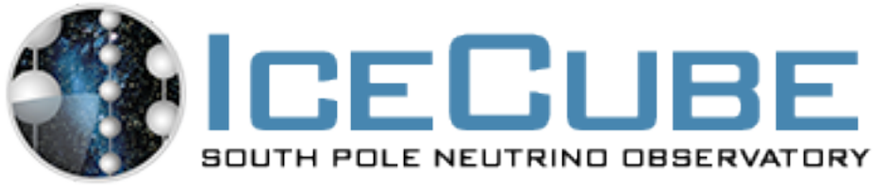
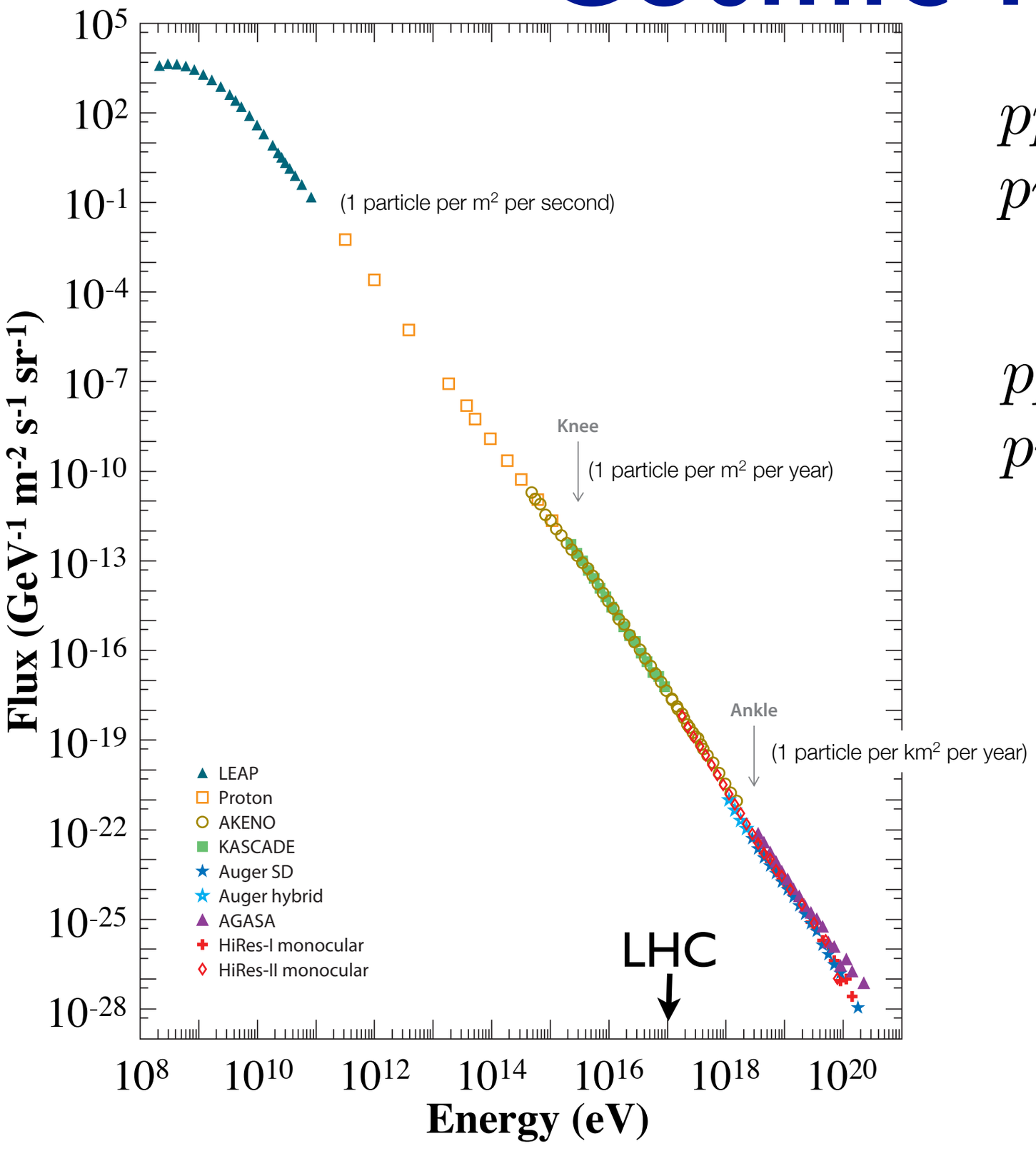
Recent Results from the IceCube Neutrino Observatory

Chris Weaver for the IceCube Collaboration

Lake Louise Winter Institute—February 20, 2015



Cosmic Rays



J. Beatty and S. Westerhoff, Ann. Rev. Nucl. Par. Sci. **59** (2009)

$$pp \to pp\pi^0$$
$$p\gamma \to \Delta^+ \to p\pi^0$$
$$\pi^0 \to \gamma\gamma$$

$$pp \to pn\pi^+$$
$$p\gamma \to \Delta^+ \to n\pi^+$$
$$\pi^+ \to \mu^+\nu_\mu$$
$$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$$

The production of cosmic rays should also lead to the production of gamma-rays and neutrinos.

Messenger Particles

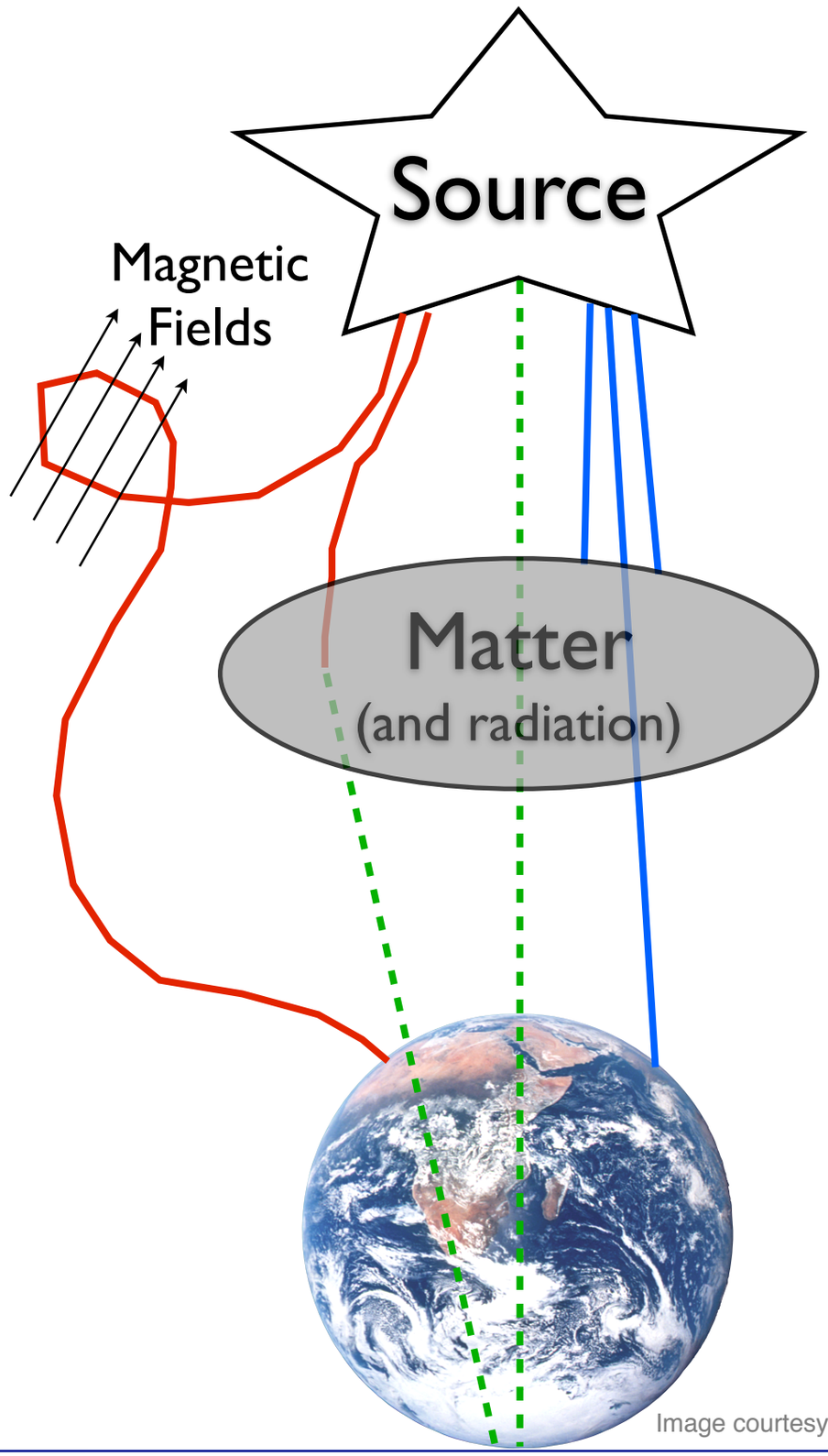
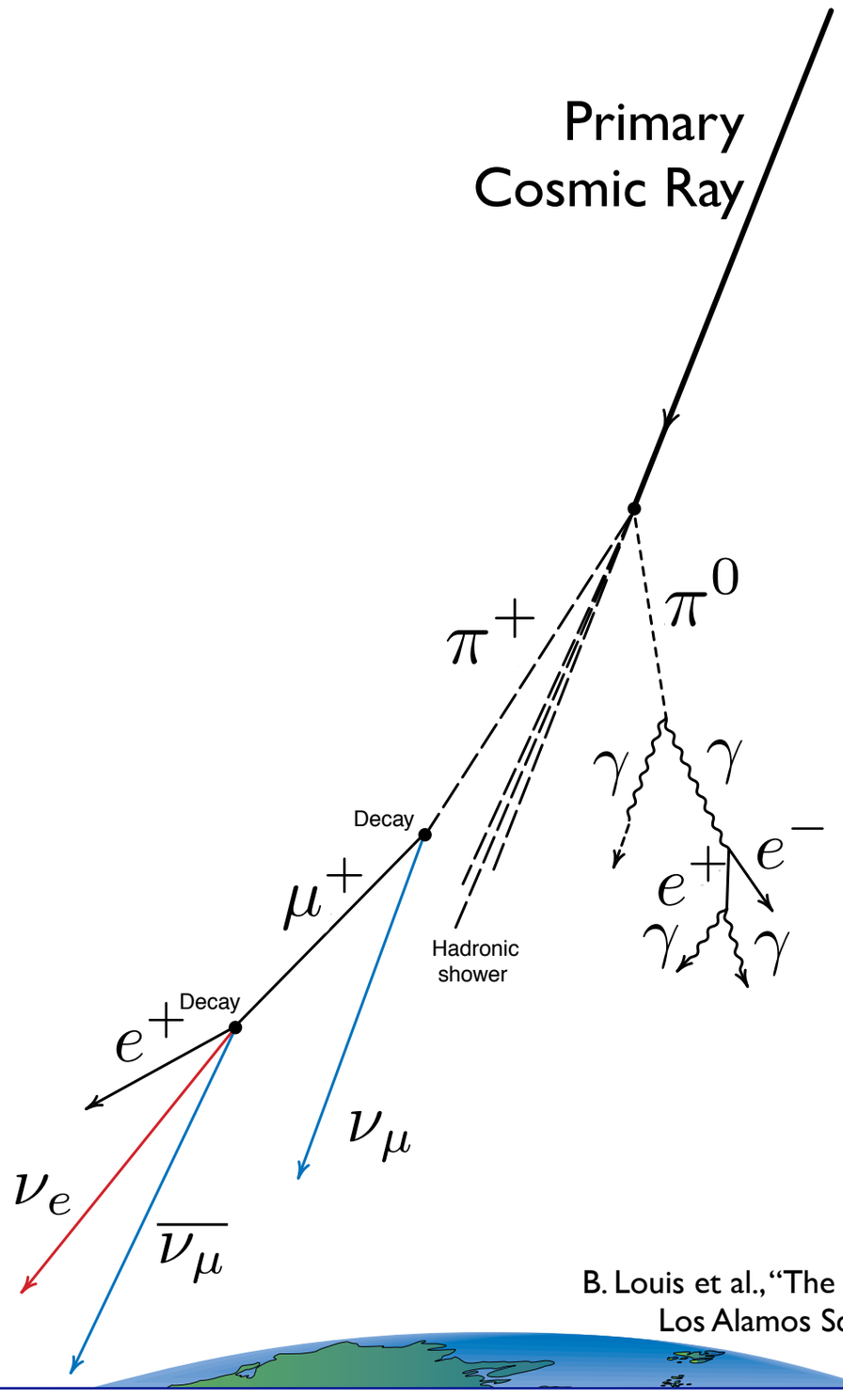


Image courtesy NASA Johnson Space Center

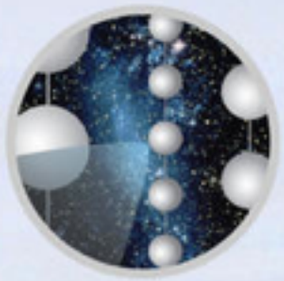
- **Cosmic Rays** are charged, and so don't travel in straight paths
- **Gamma Rays** have straight paths, but can be easily attenuated
- **Neutrinos** have straight paths and pass through nearly everything

Air Showers



B. Louis et al., "The evidence for oscillations," Los Alamos Science 25 (1997) 16.

- Many high energy neutrinos come from our own atmosphere
- Muons are produced at the same time
- These form a background when one tries to study astrophysical neutrinos (or gamma rays)



The IceCube Collaboration

Funding Agencies

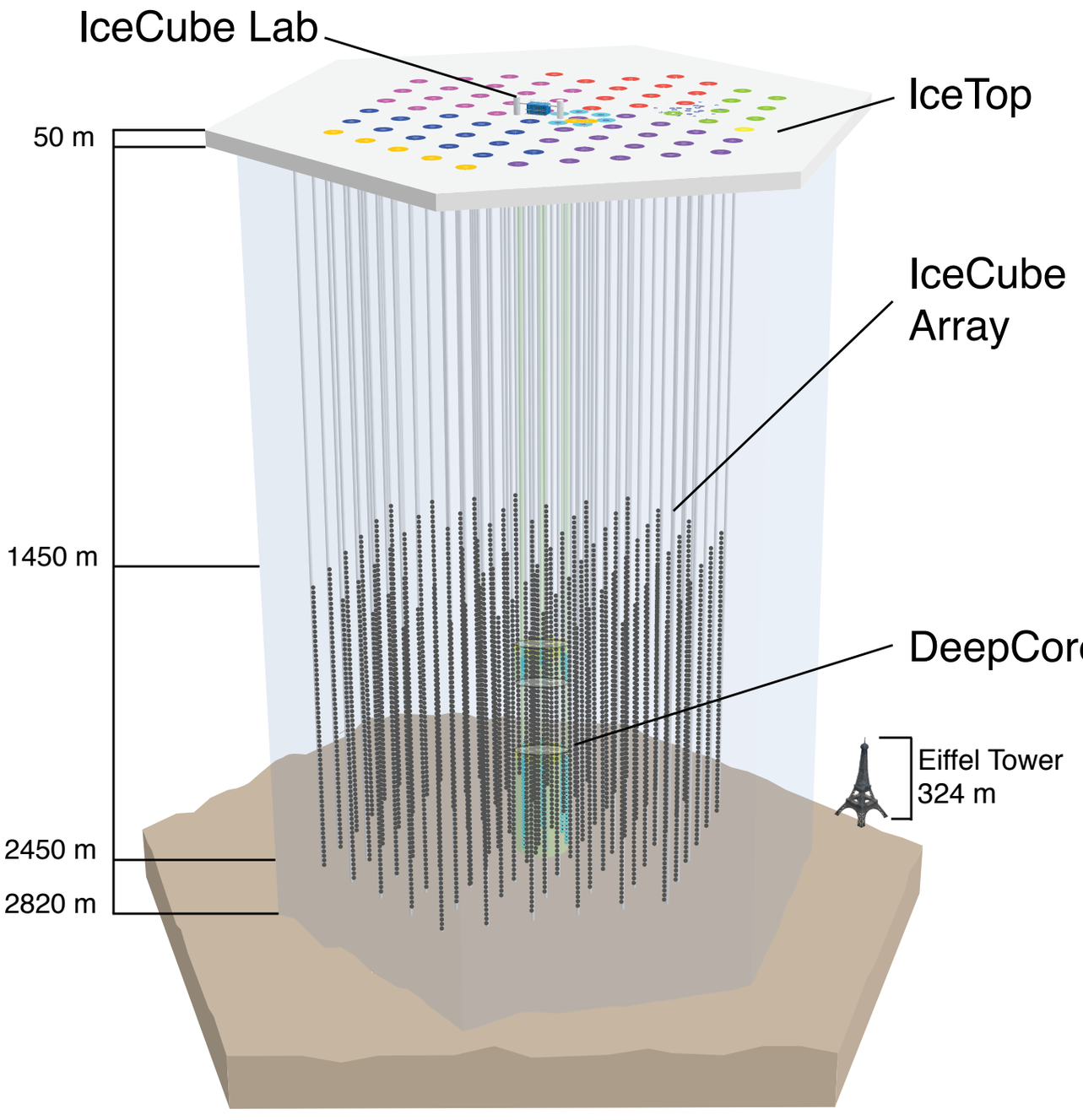
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg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

Detector actually
~2 km below
↓

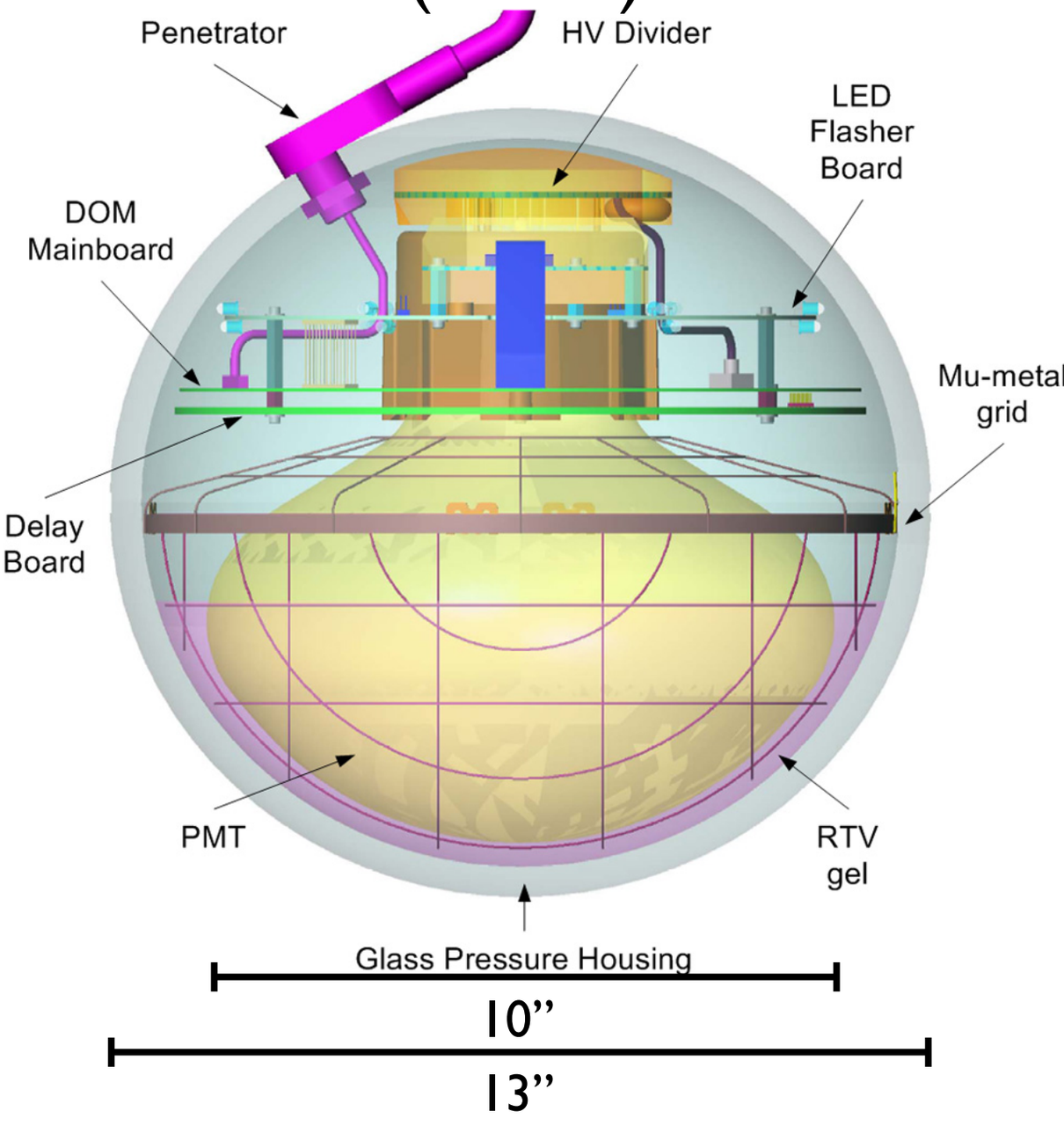
Haley Buffman & Jamie Yang. IceCube/NSF

Detector Hardware

Detector Layout

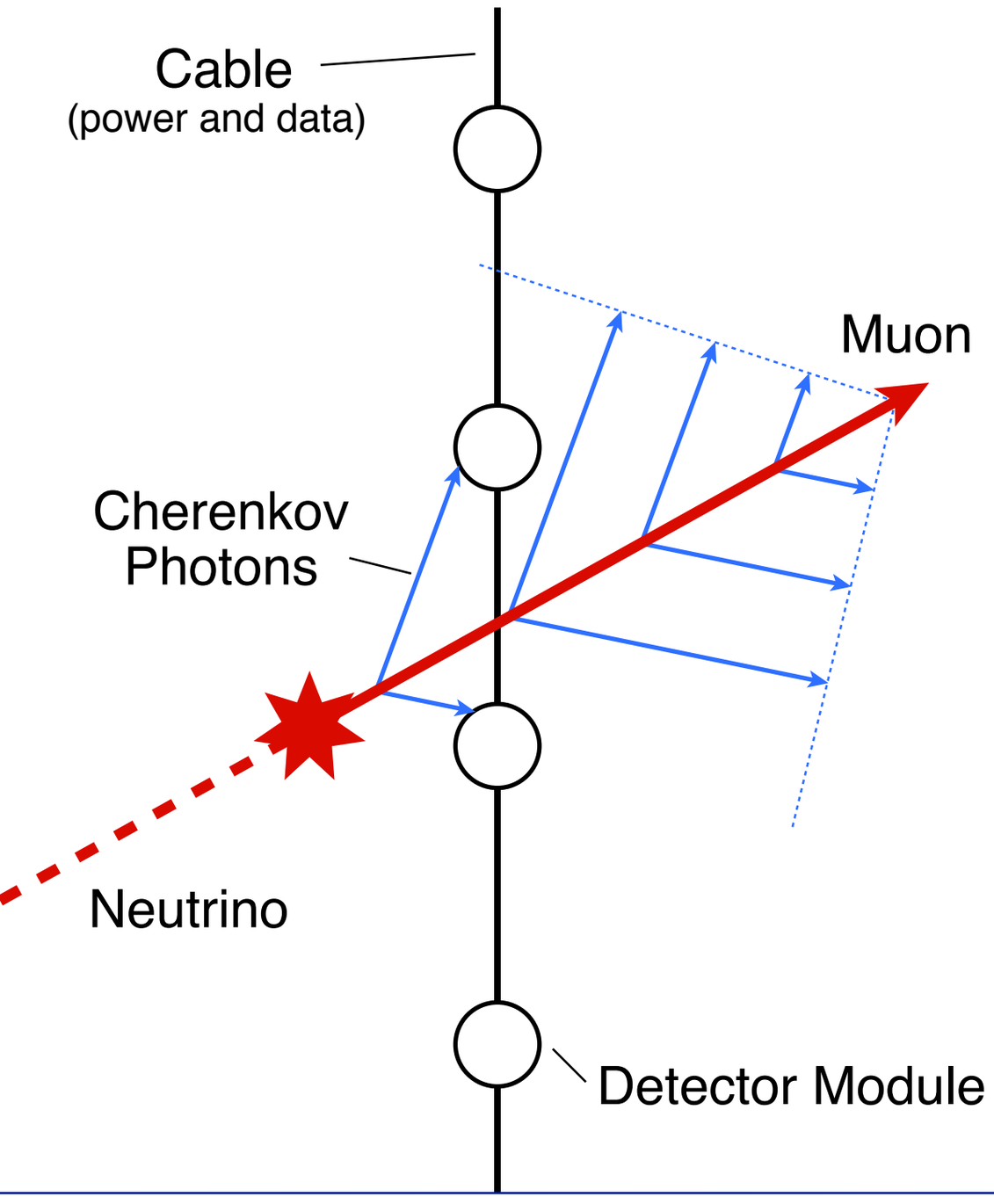


Digital Optical Module (DOM)



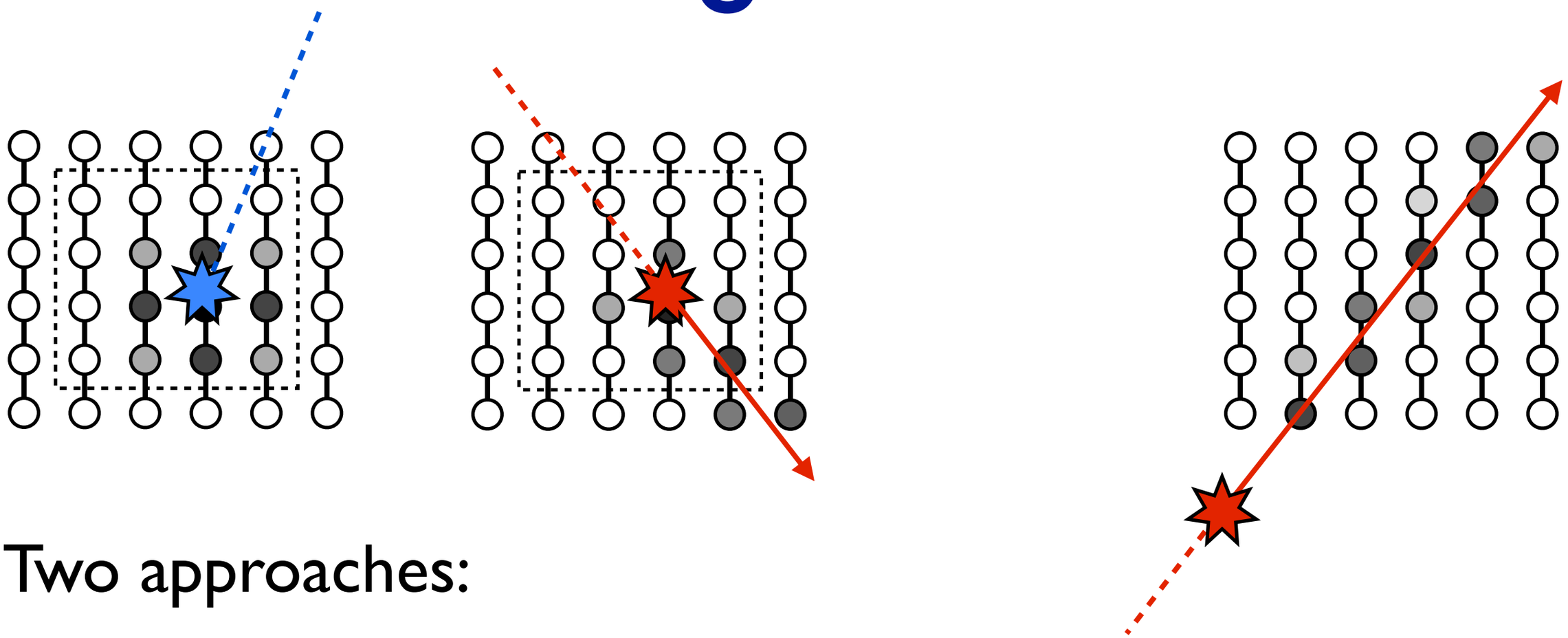
Detection Principle

Schematic of an IceCube 'String'



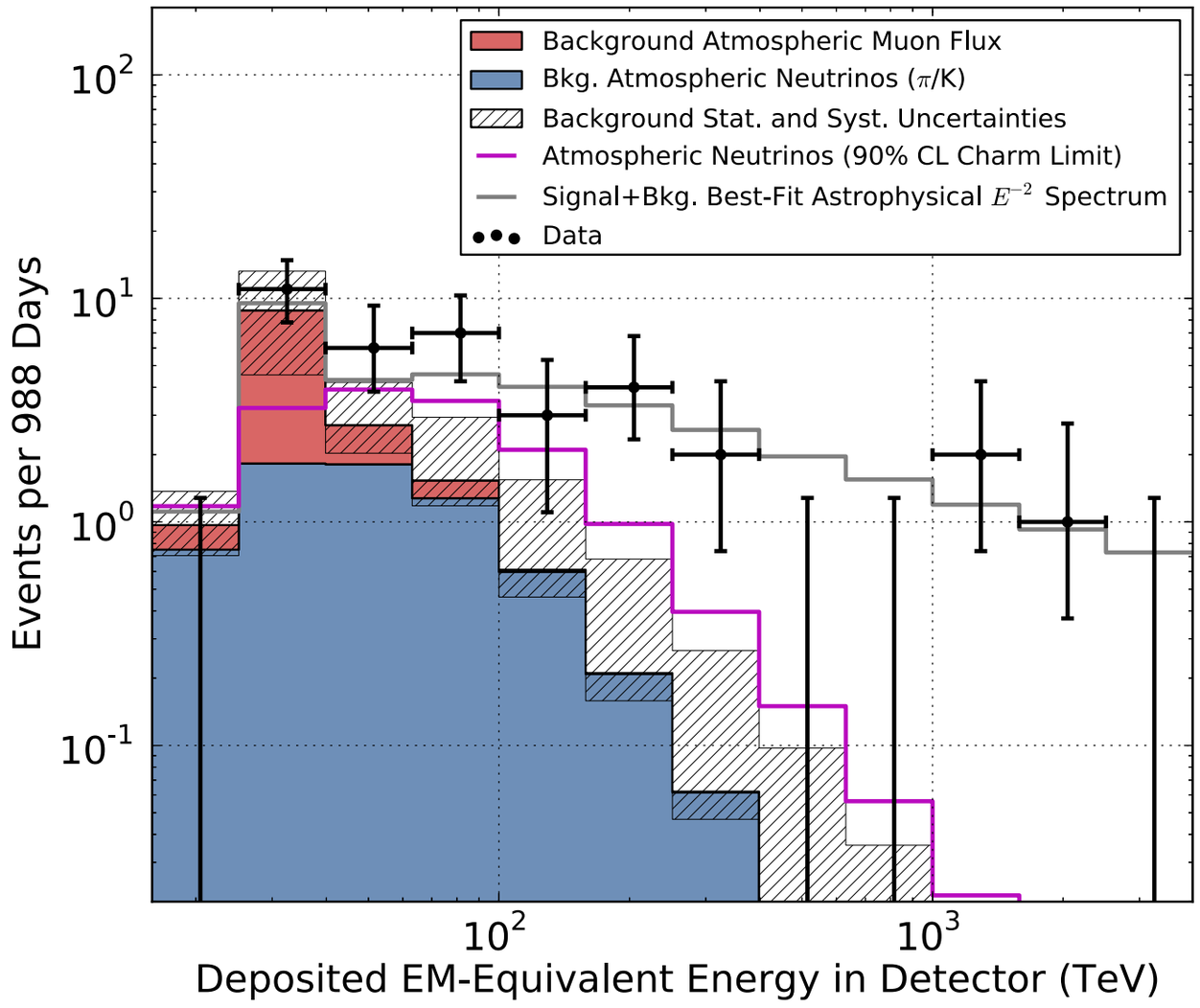
- Energetic particles produce Cherenkov light in the ice
- Modules detect photons
- Good linearity from single photon to several hundred photon level
- Absorption length for light is long (~90m) but scattering length is shorter (~25m)

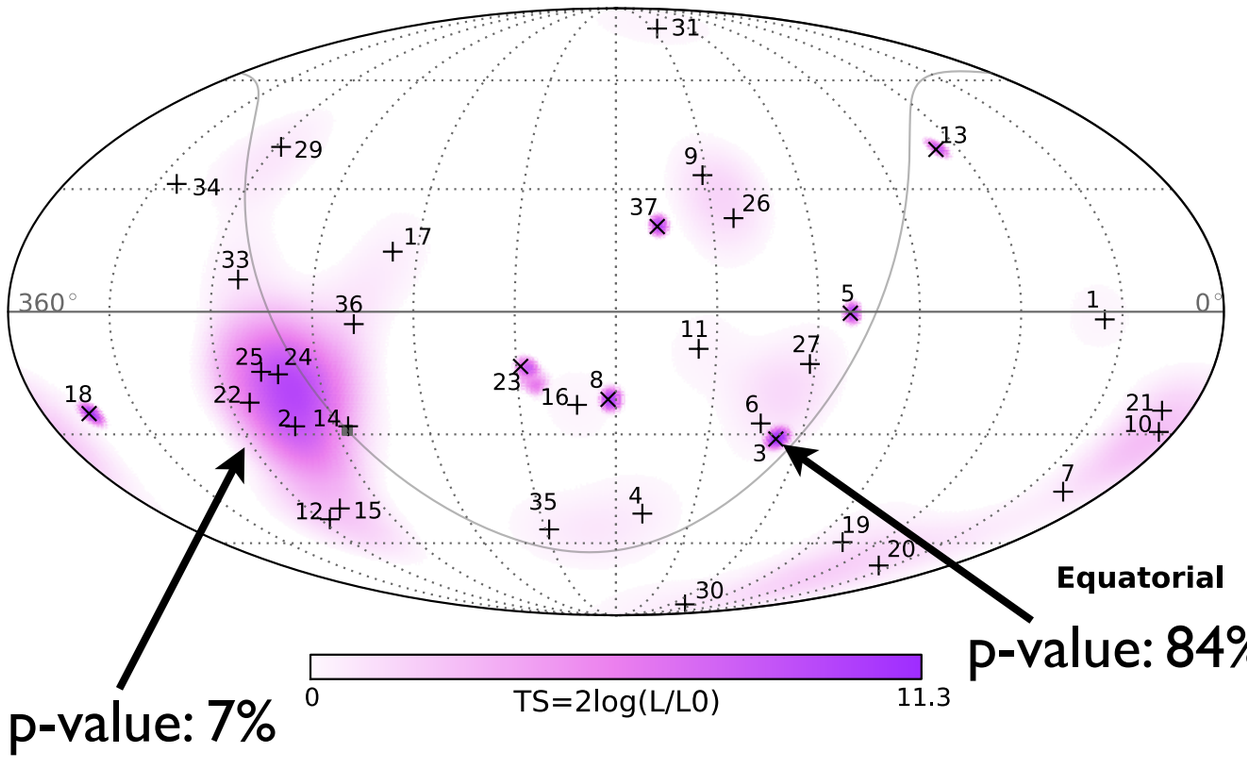
Selecting Neutrinos



- Two approaches:
  - Select events with an interaction vertex in the detector, and no visible entering particles (**starting events**)
  - Select events which have passed through the Earth, but may enter the detector after interacting (**through-going events**)

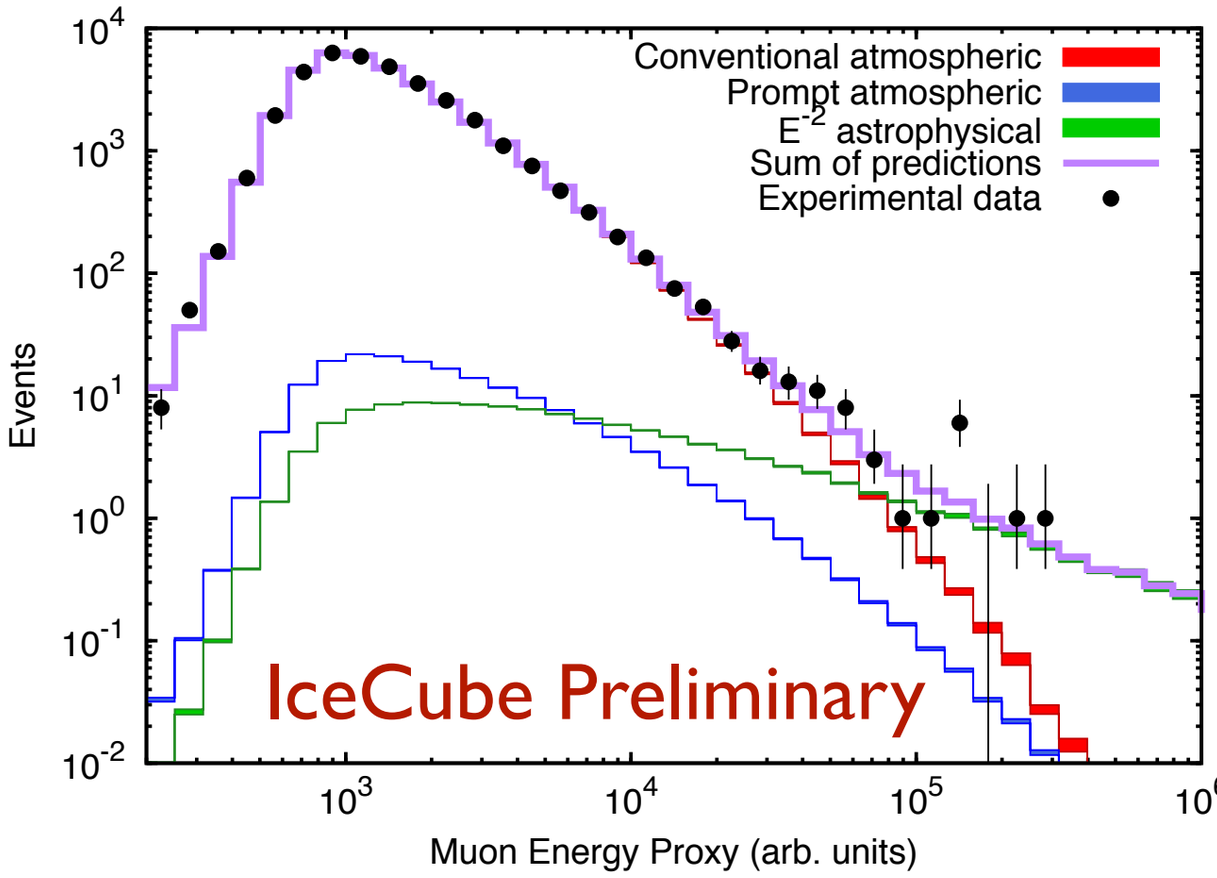
All-Flavor, All-Sky with Starting Events

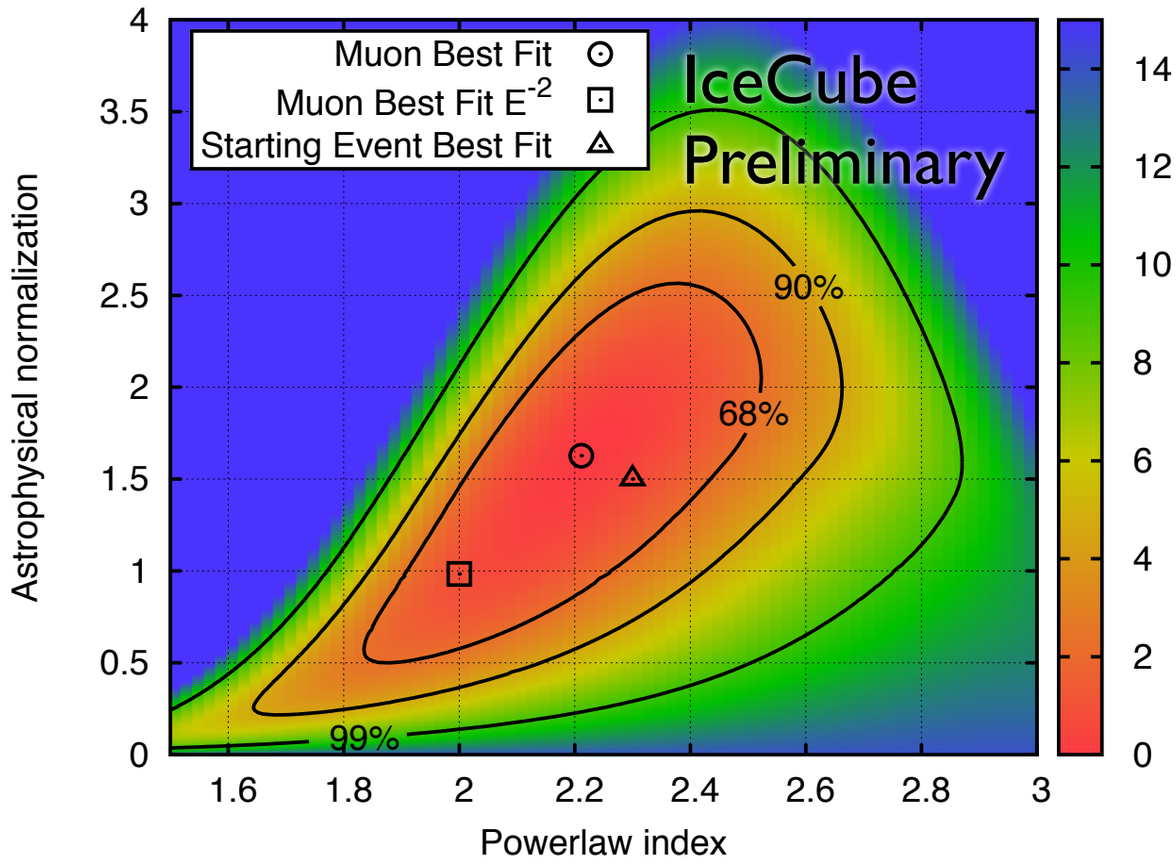




- Phys. Rev. Lett. 113, 101101: Analysis of starting events depositing >60 TeV or more using 3 years of data, observes events up to ~2 PeV
- Mostly ν_e charged current and neutral current interactions, mostly sensitive in the southern sky
- Clear excess over background (5.7σ), no clear clustering on the sky

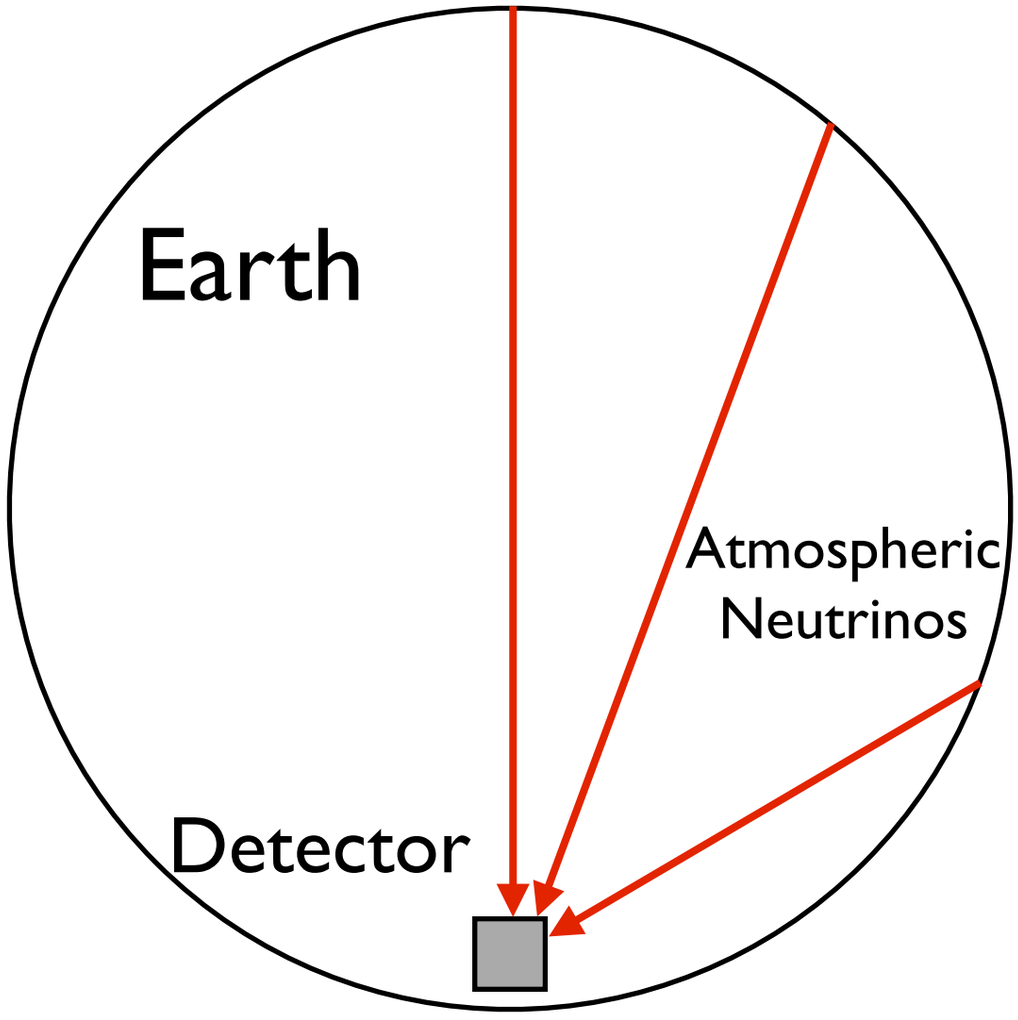
Northern Sky Through-going Events

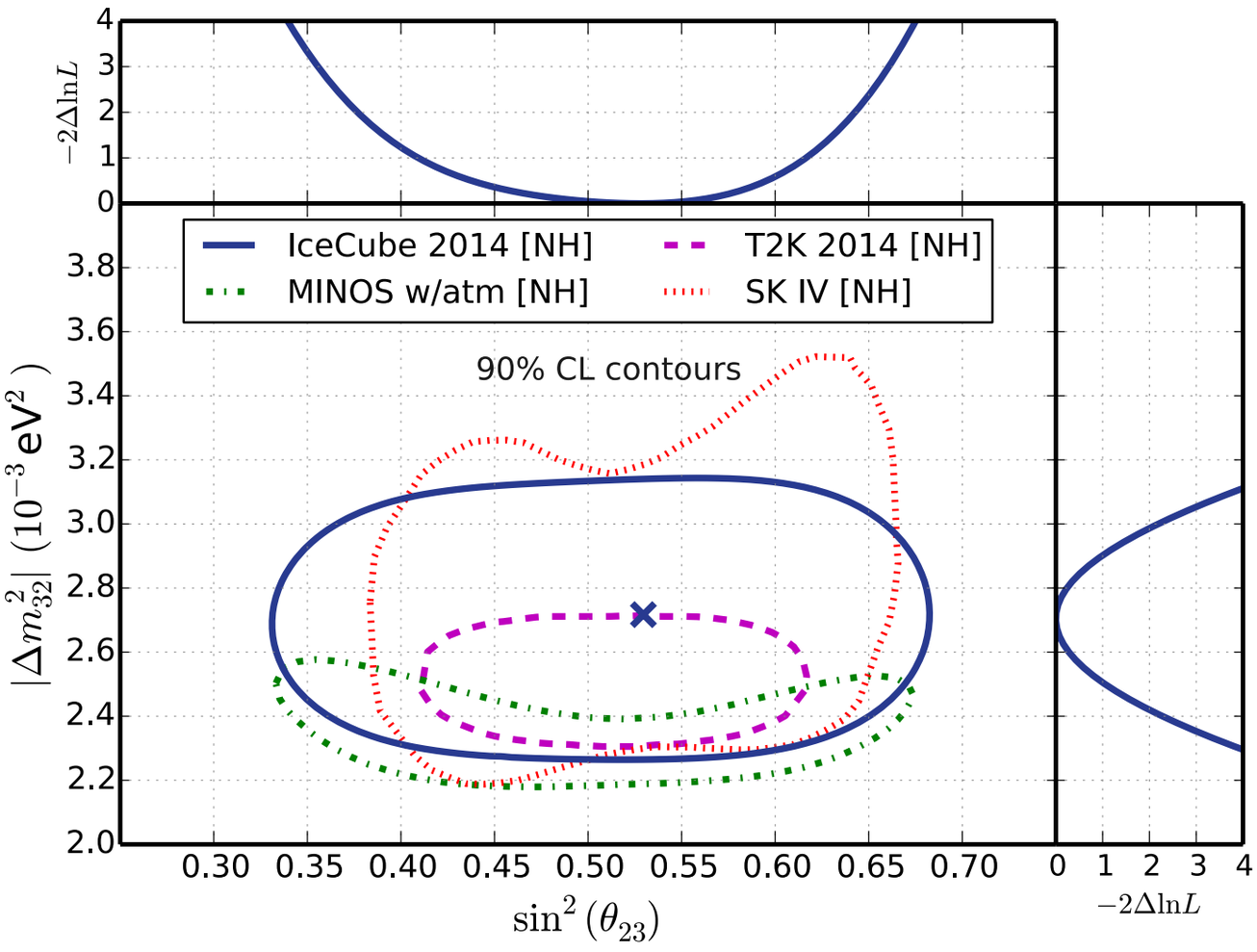




- (Paper in internal review) Analysis of through-going events from the northern sky using 2 years of data—ν_μ charged current only, >1 TeV
- Excess over atmospheric background of 3.7σ
- Signal looks similar in different channels and different parts of the sky

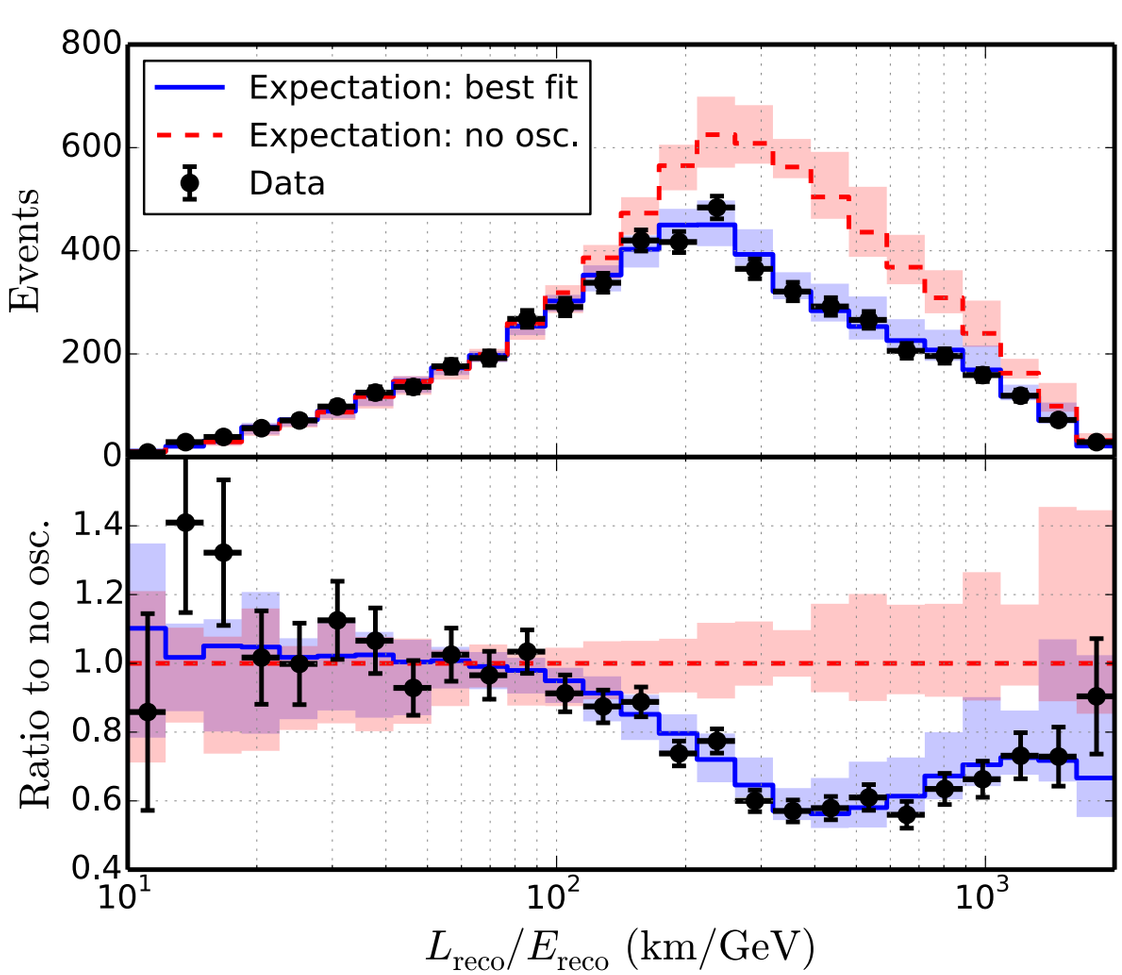
Neutrino Oscillation

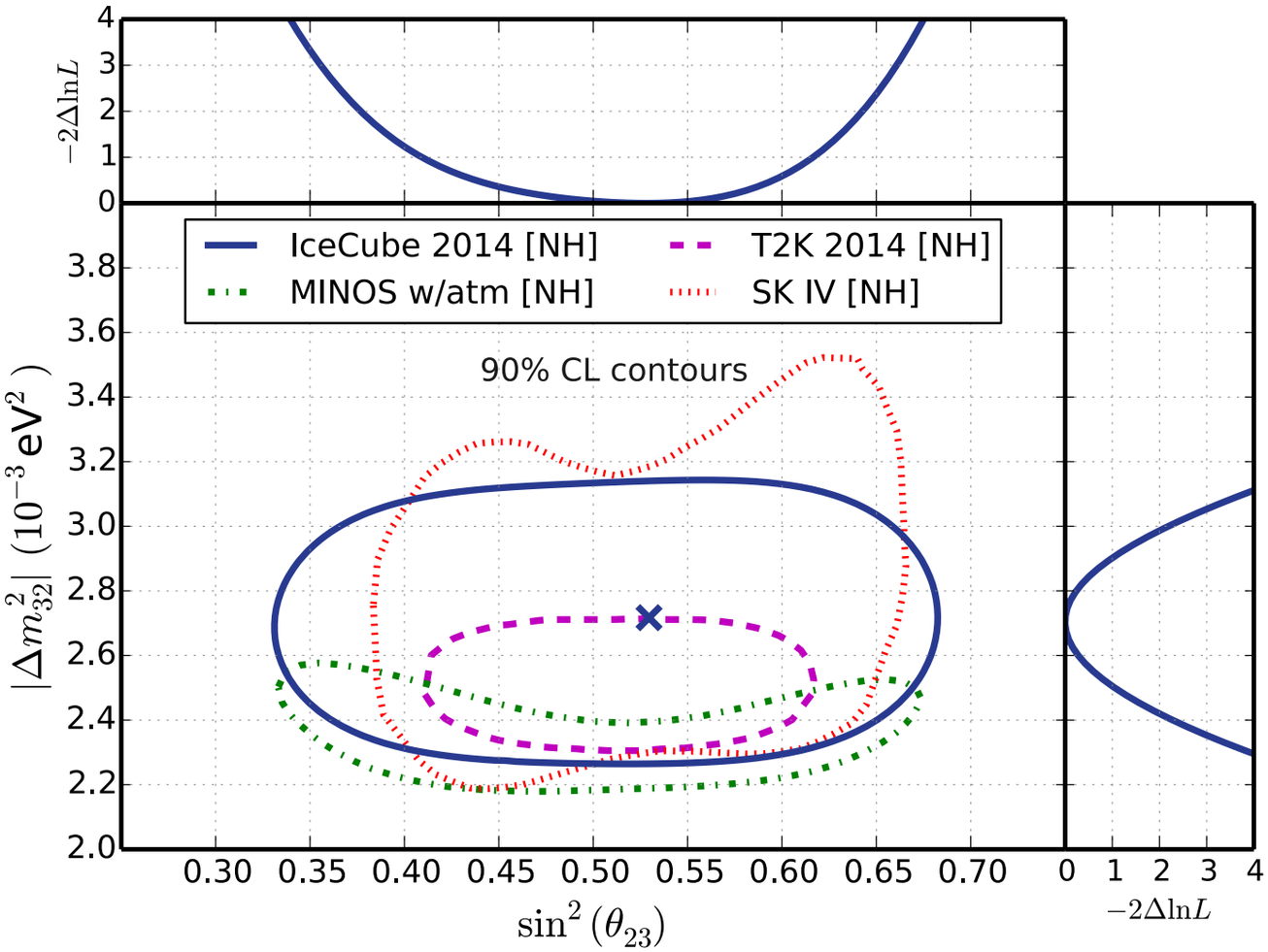




- arXiv:1410.7227: Disappearance analysis of ~10 GeV-100 GeV atmospheric ν_μ with 3 years of data
- Obtains $\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$ and $|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\mathrm{eV}^2$ for the normal hierarchy.

Neutrino Oscillation





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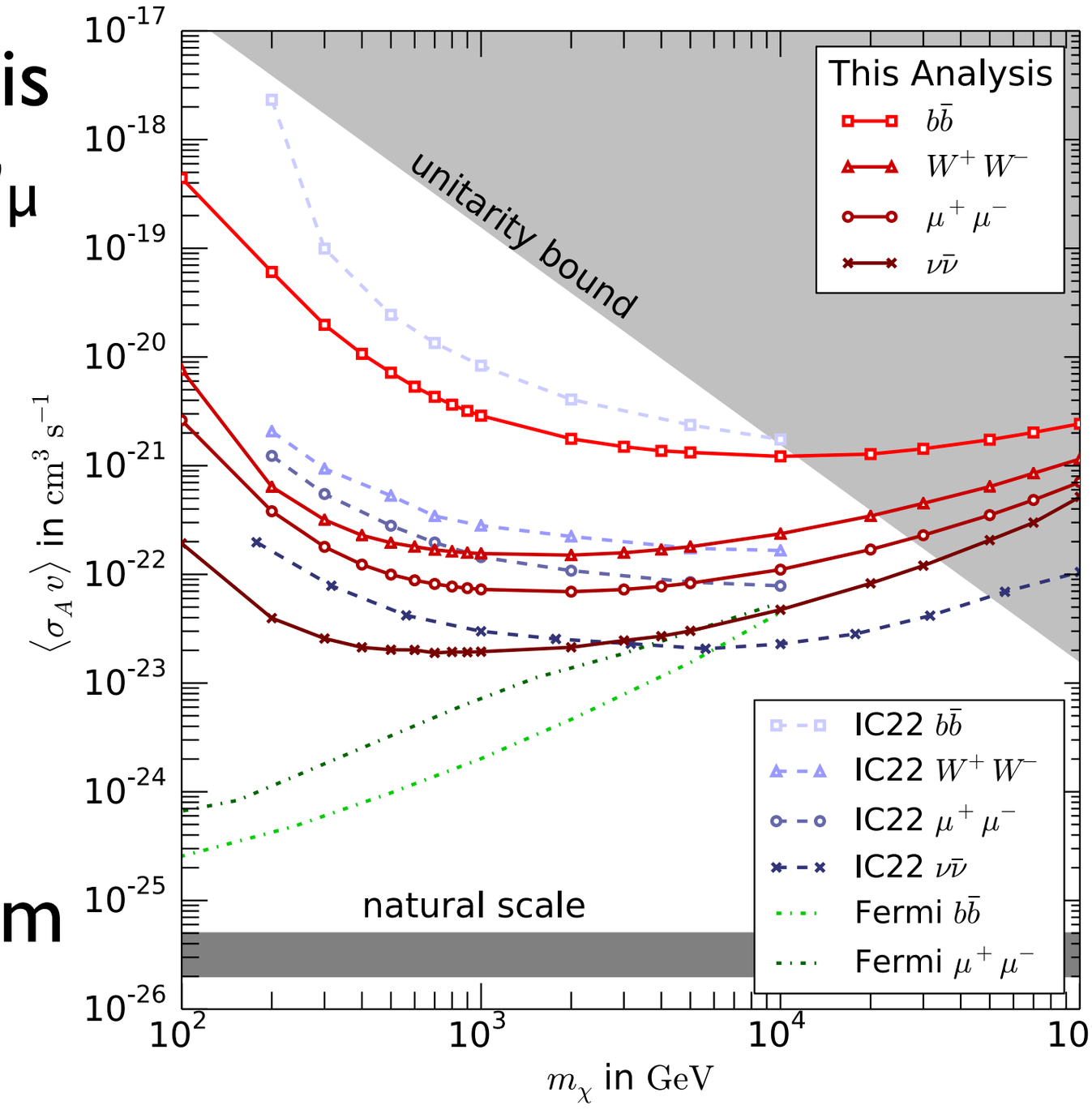
WIMP Annihilation

- arXiv: 1406.6868: Analysis of arrival directions of ν_μ to look for correlation with the expected signature of WIMP annihilations in the Galactic halo
- Used 1 year of data, events with energies from ~100 GeV to 10 TeV

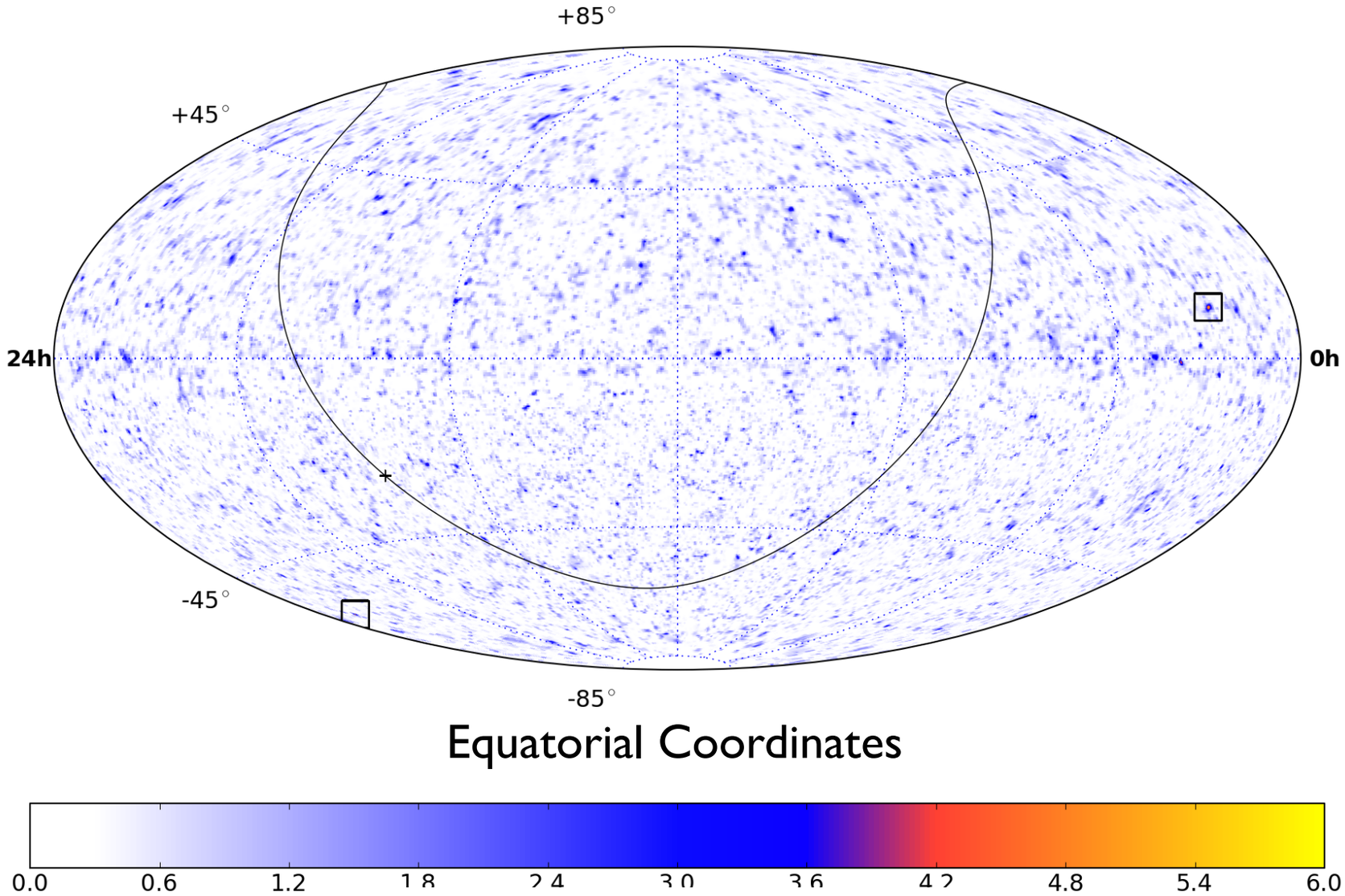


Summary

- For astrophysical neutrinos IceCube sees:
  - A consistent diffuse flux in all detection channels
  - No clear association with known sources
- Also lots of work in other areas:
  - Neutrino oscillations
  - Dark matter
  - Supernovae
  - Monopoles

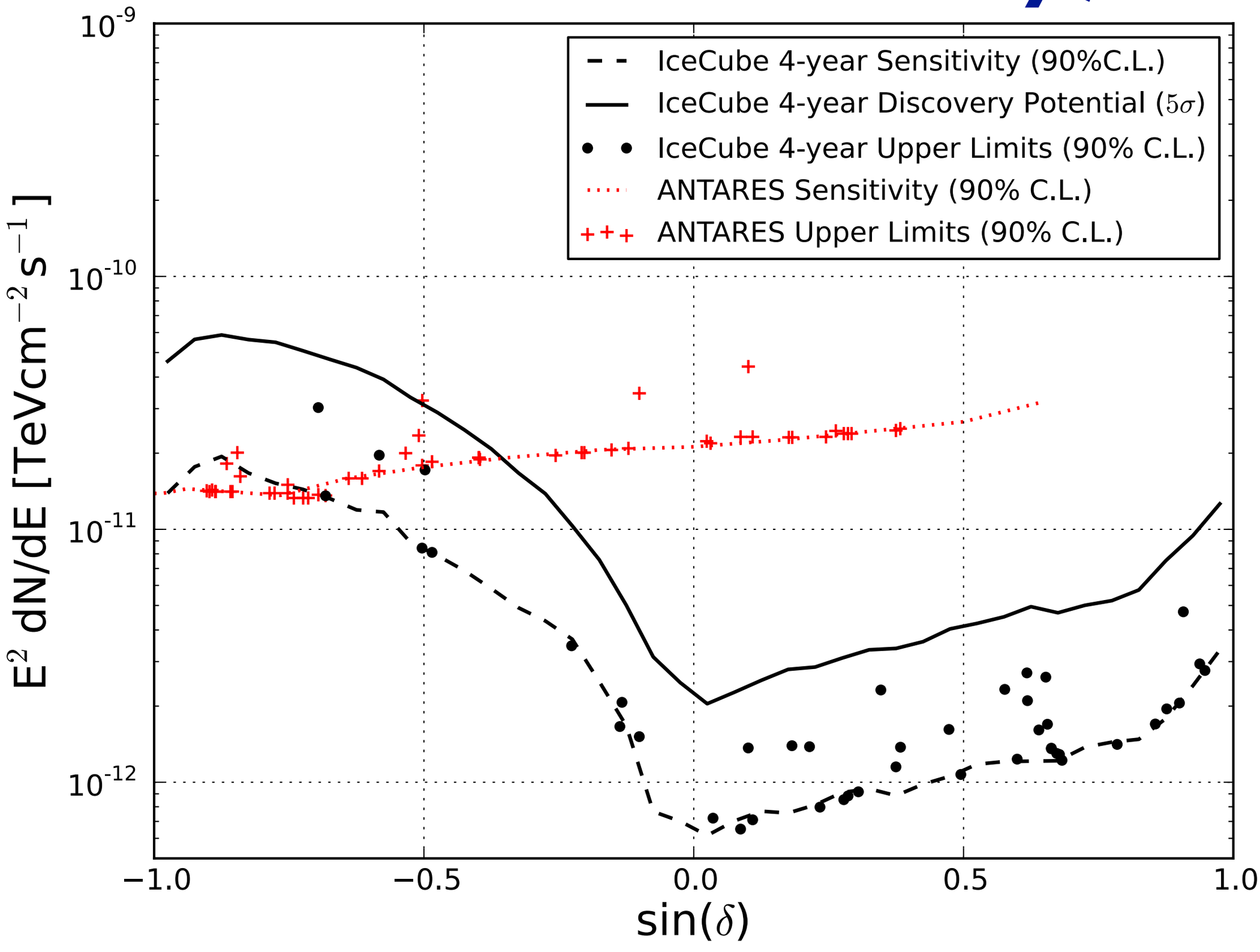
Questions?

Point Sources Muon Neutrinos

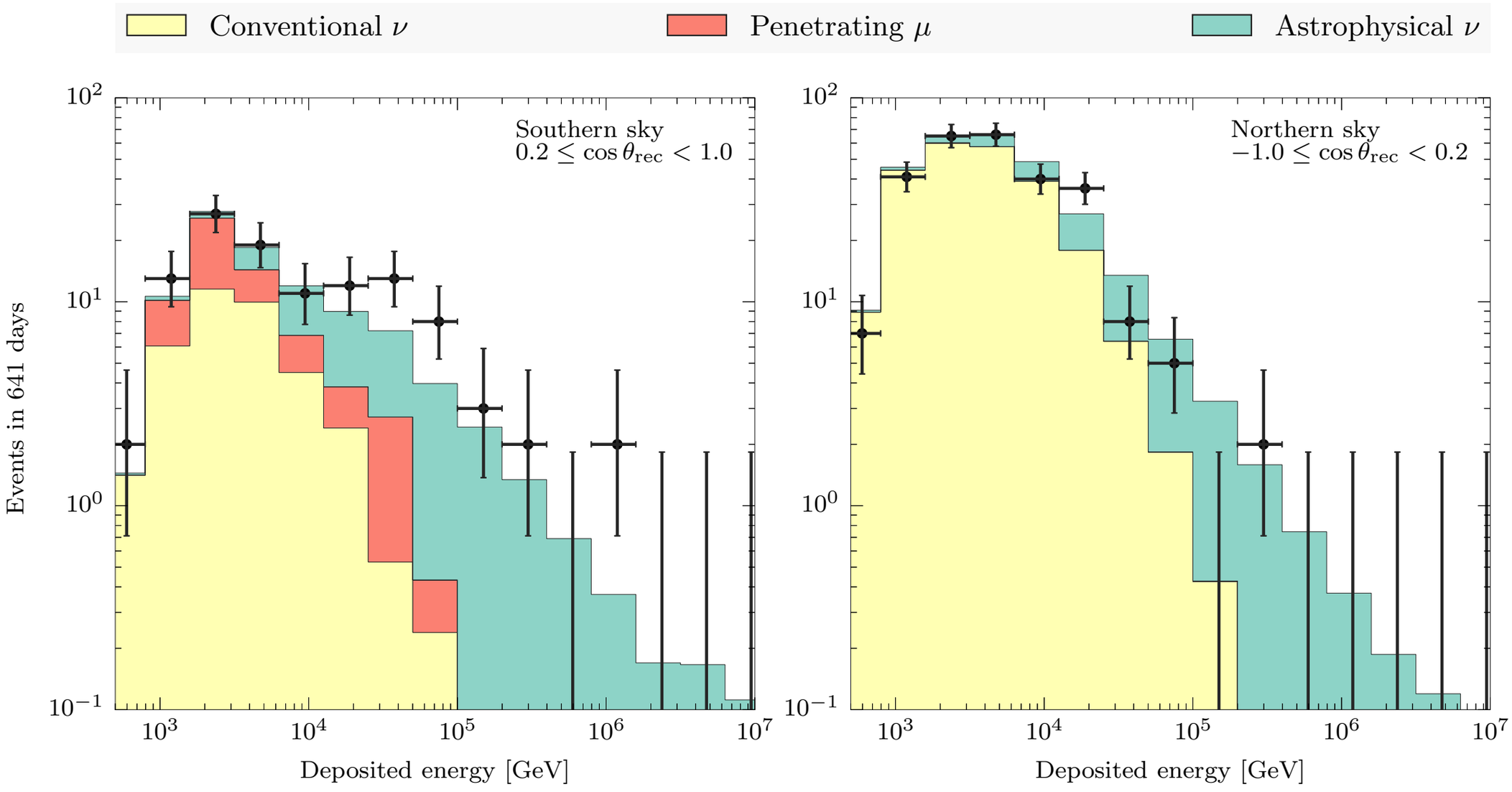


- arXiv:1406.6757: Analysis of through-going events from the whole sky—ν_μ and μ using 4 years of data
- No significant features observed (post-trial p-values of 0.23 and 0.44 for the best points on the sky pre-trial)

Point Source Sensitivity/Limits

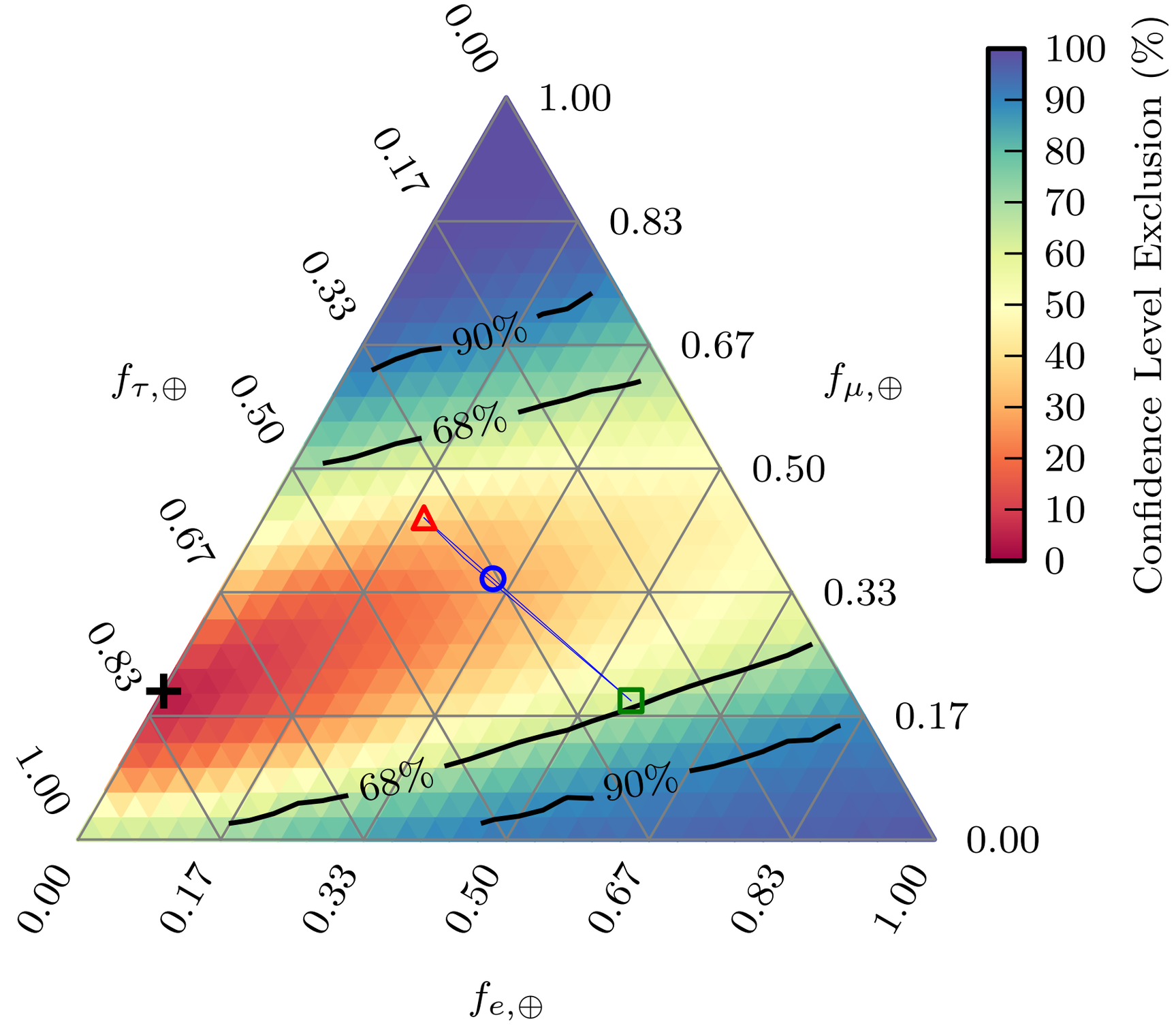


All-Flavor, All-Sky with Starting Events



- Phys. Rev. D 91, 022001: Extends analysis of starting events down to ~1 TeV, using 2 years of data
- Astrophysical spectrum seems to continue down to a few TeV

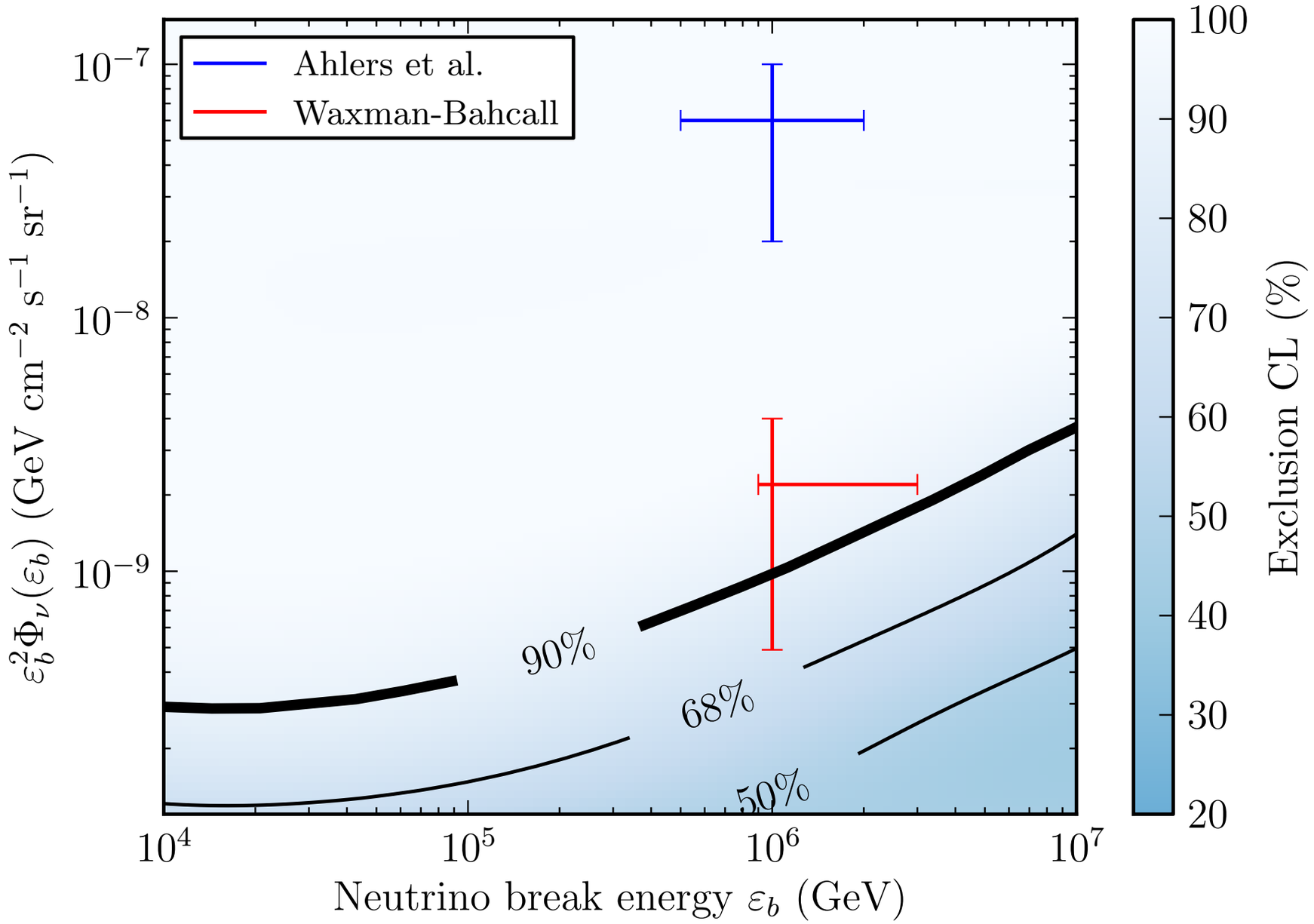
Flavor Fit



- arXiv: 1502.03376: Used 3 years of starting events with energies >35 TeV

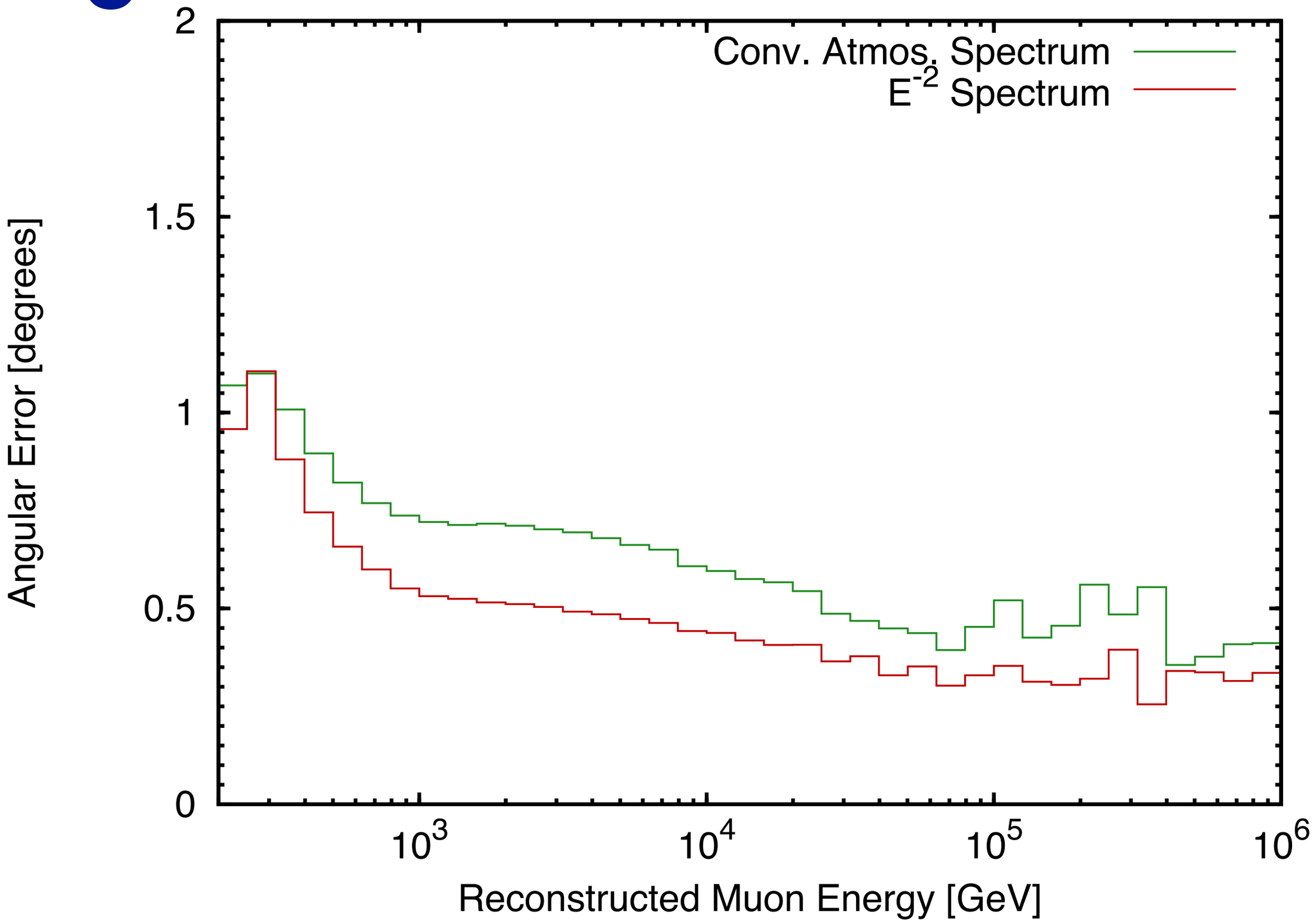
GRB Limits

IceCube Preliminary

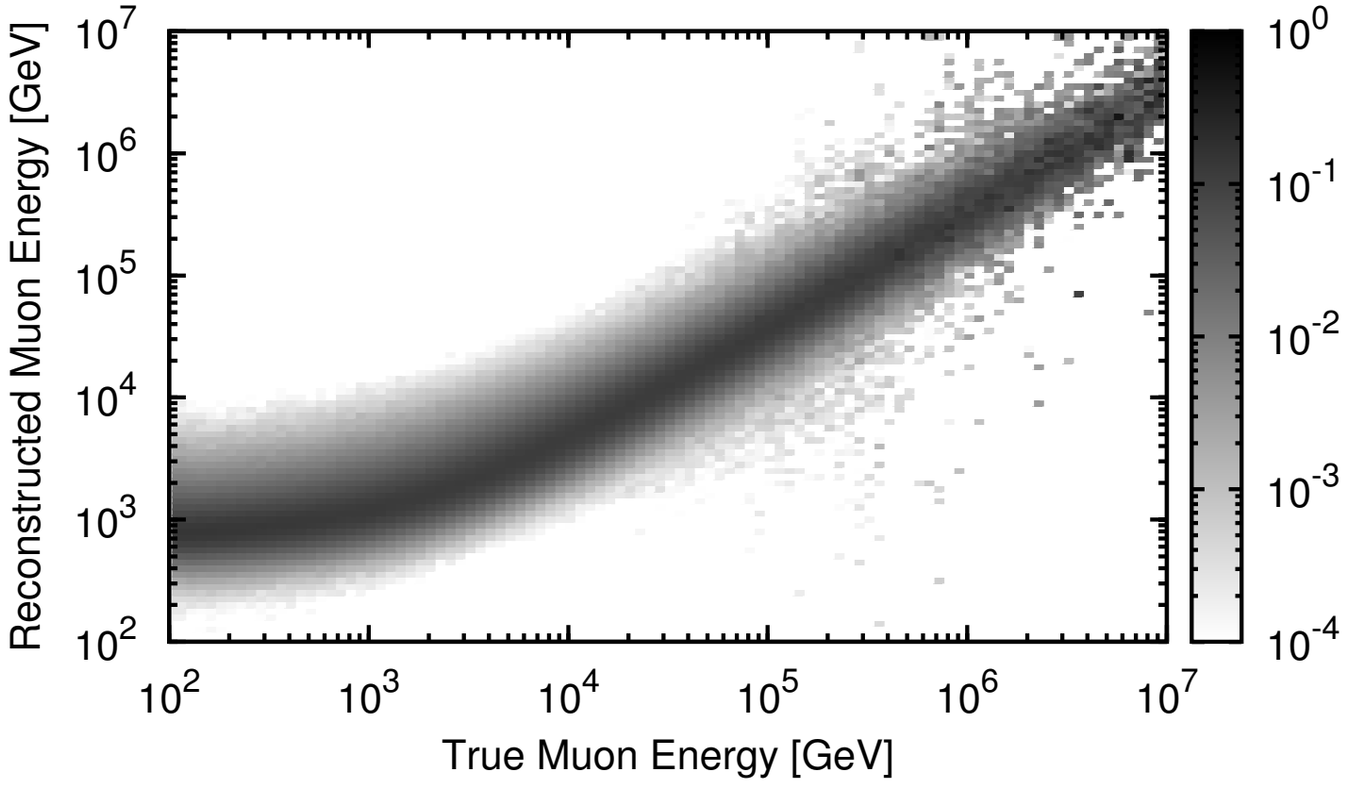


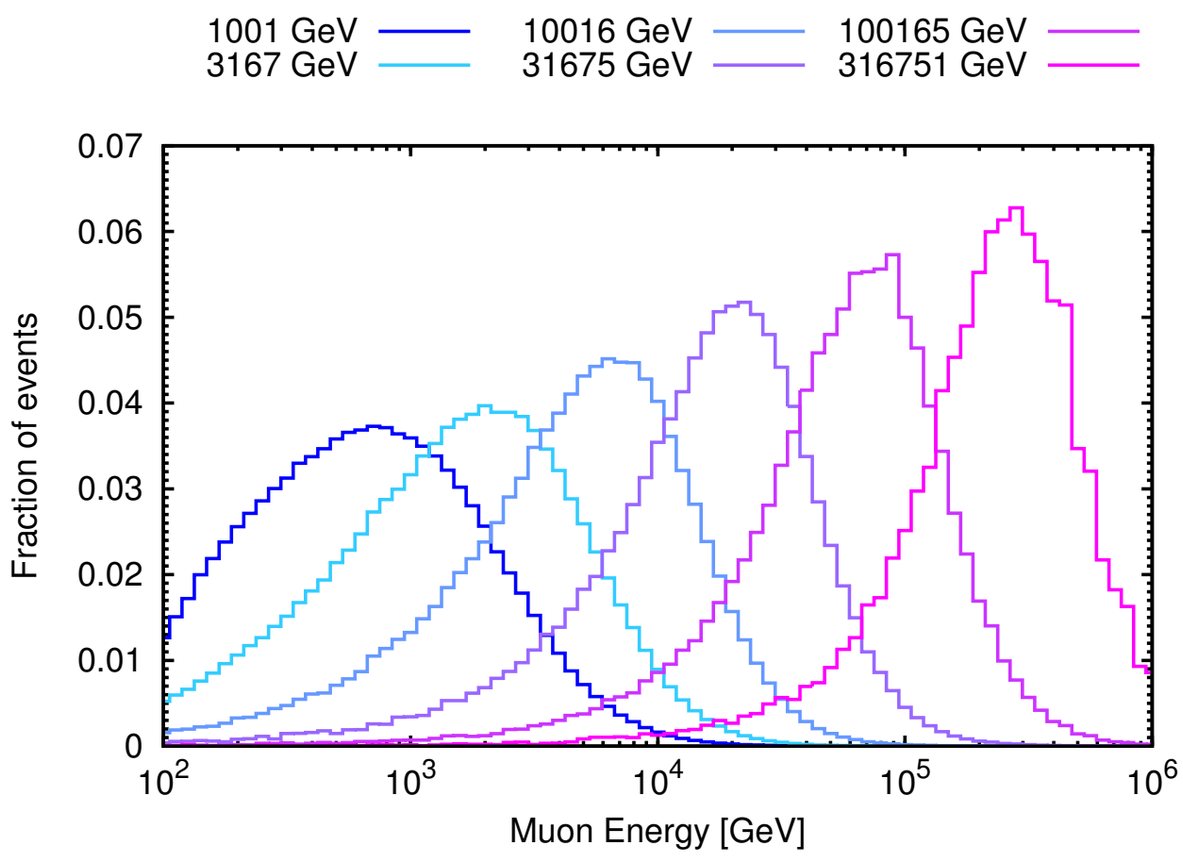
- (Paper in internal review): Using 4 years of through-going ν_μ from the northern hemisphere

Angular Resolution for Muons



Energy Resolution for Muons





How a muon looks in IceCube