Evidence for High Energy Astrophysical Muon Neutrinos with IceCube

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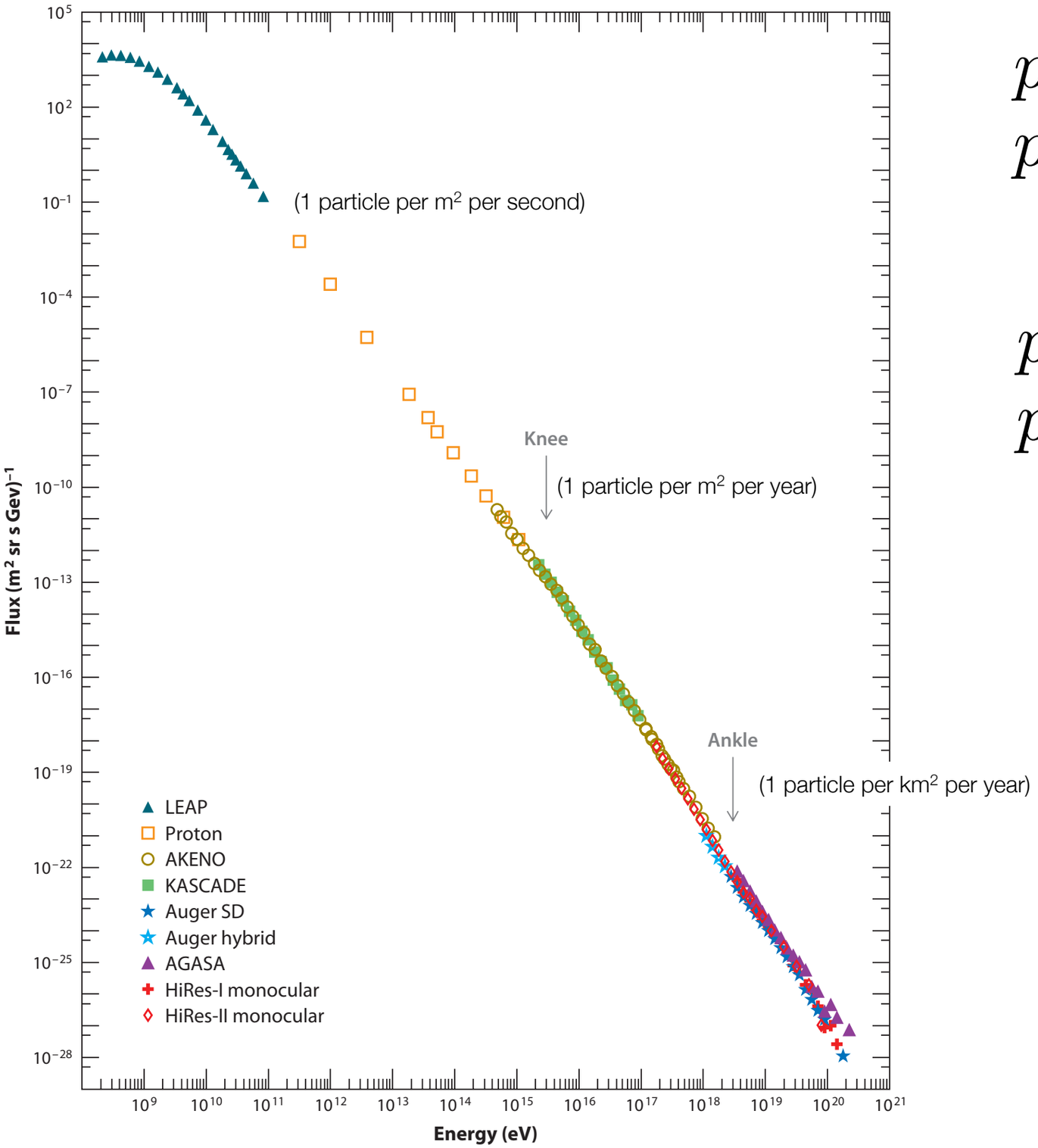
Outline

- Neutrinos in Astroparticle Physics
- The IceCube Detector
- Current IceCube Results
- This Study
- Conclusions

Neutrinos in Astroparticle Physics

Cosmic Rays



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

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

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

Any source which can make cosmic rays can also make gamma-rays and neutrinos.

Messenger Particles

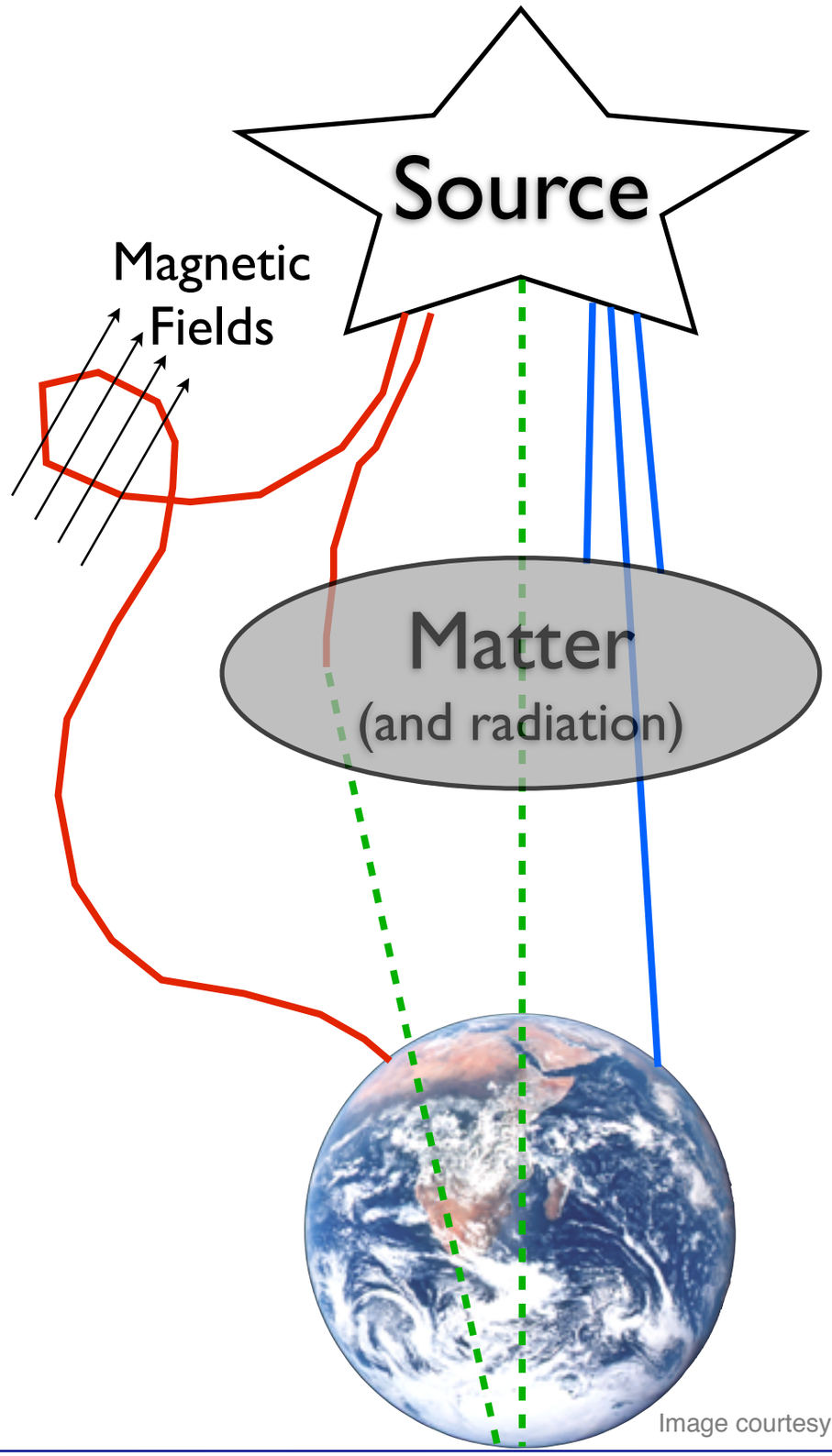
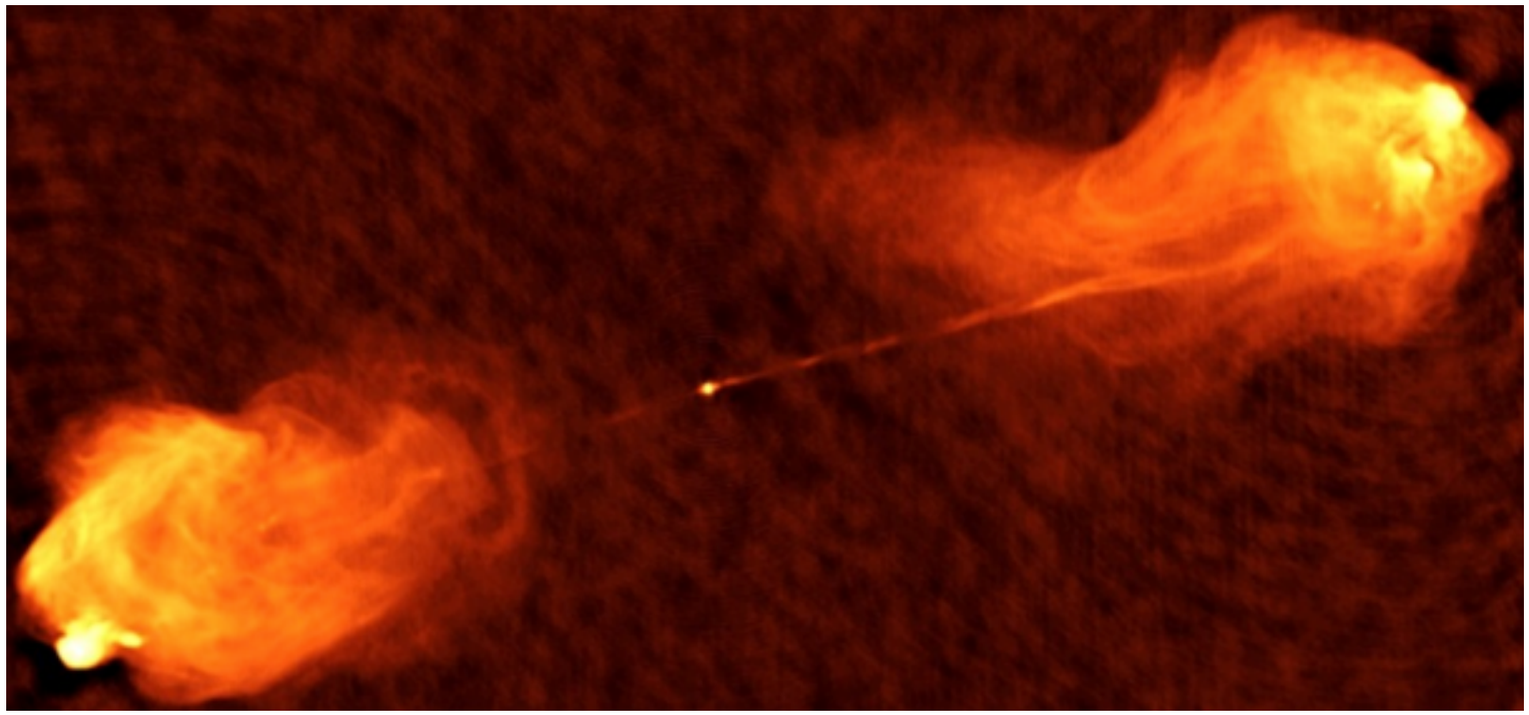


Image courtesy NASA Johnson Space Center

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

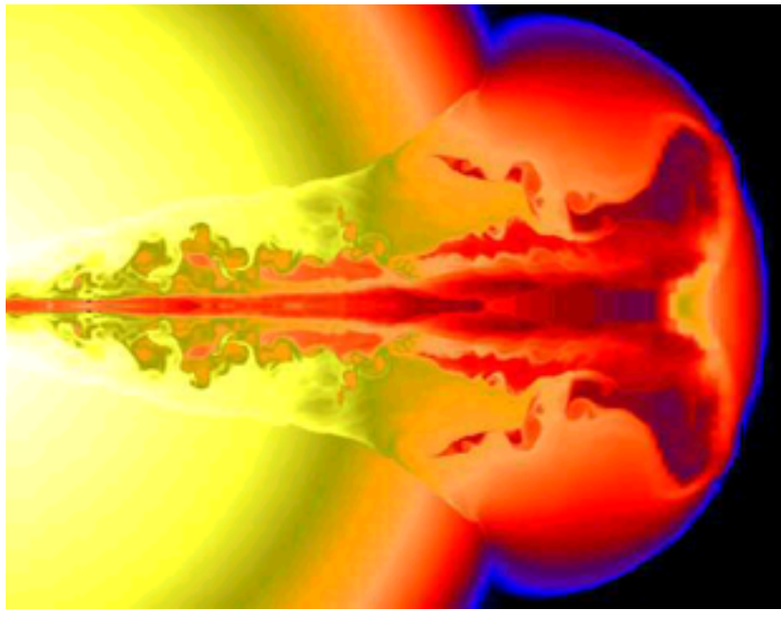
Possible Sources



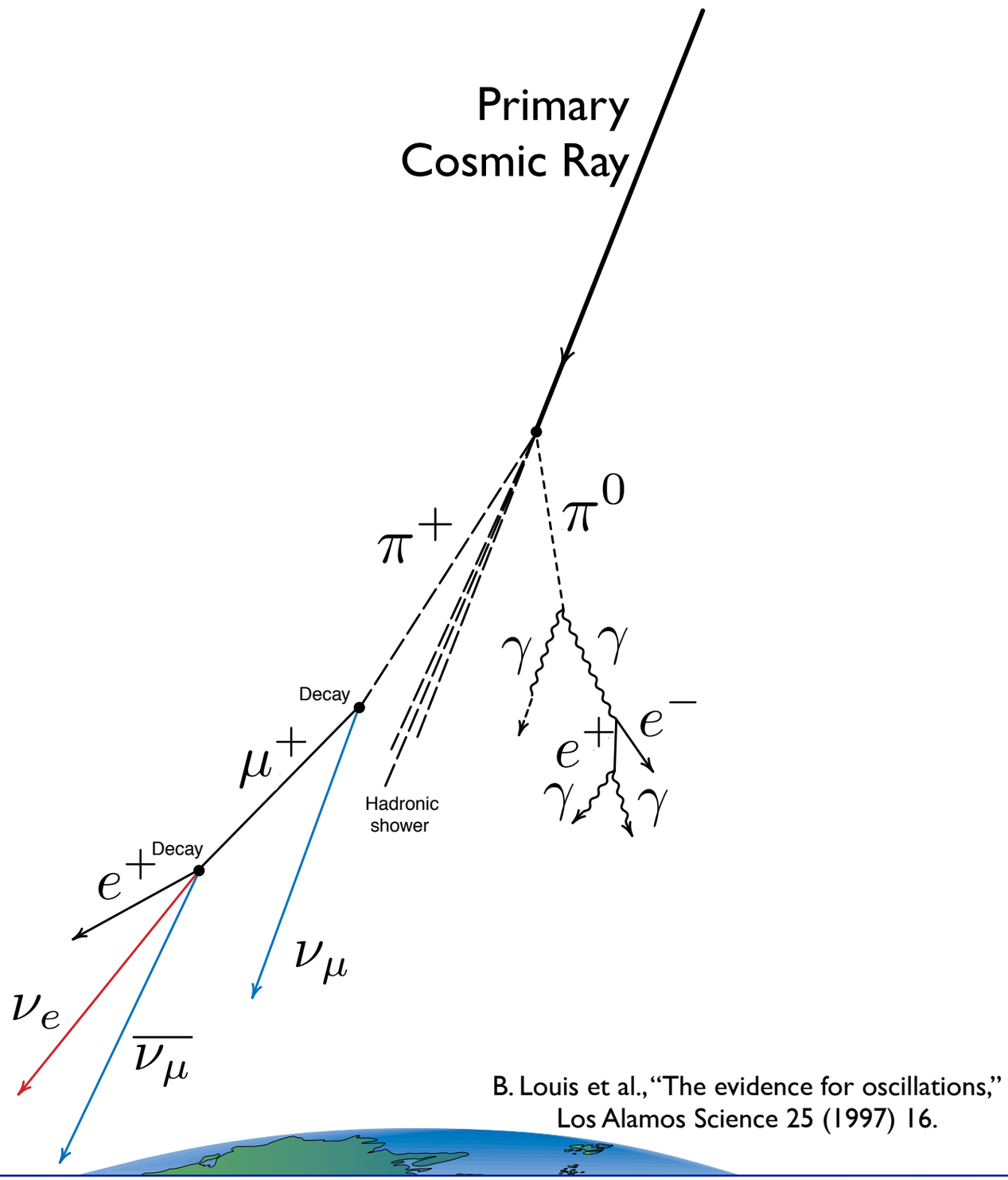
Active Galactic Nuclei

Supernova Remnants

Gamma-ray Bursts



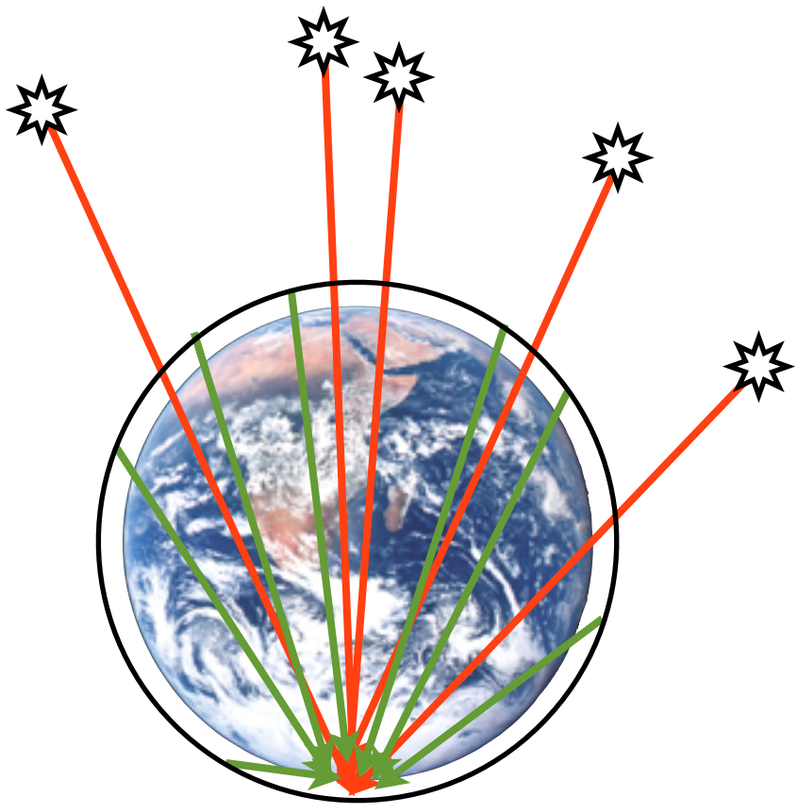
Airshowers

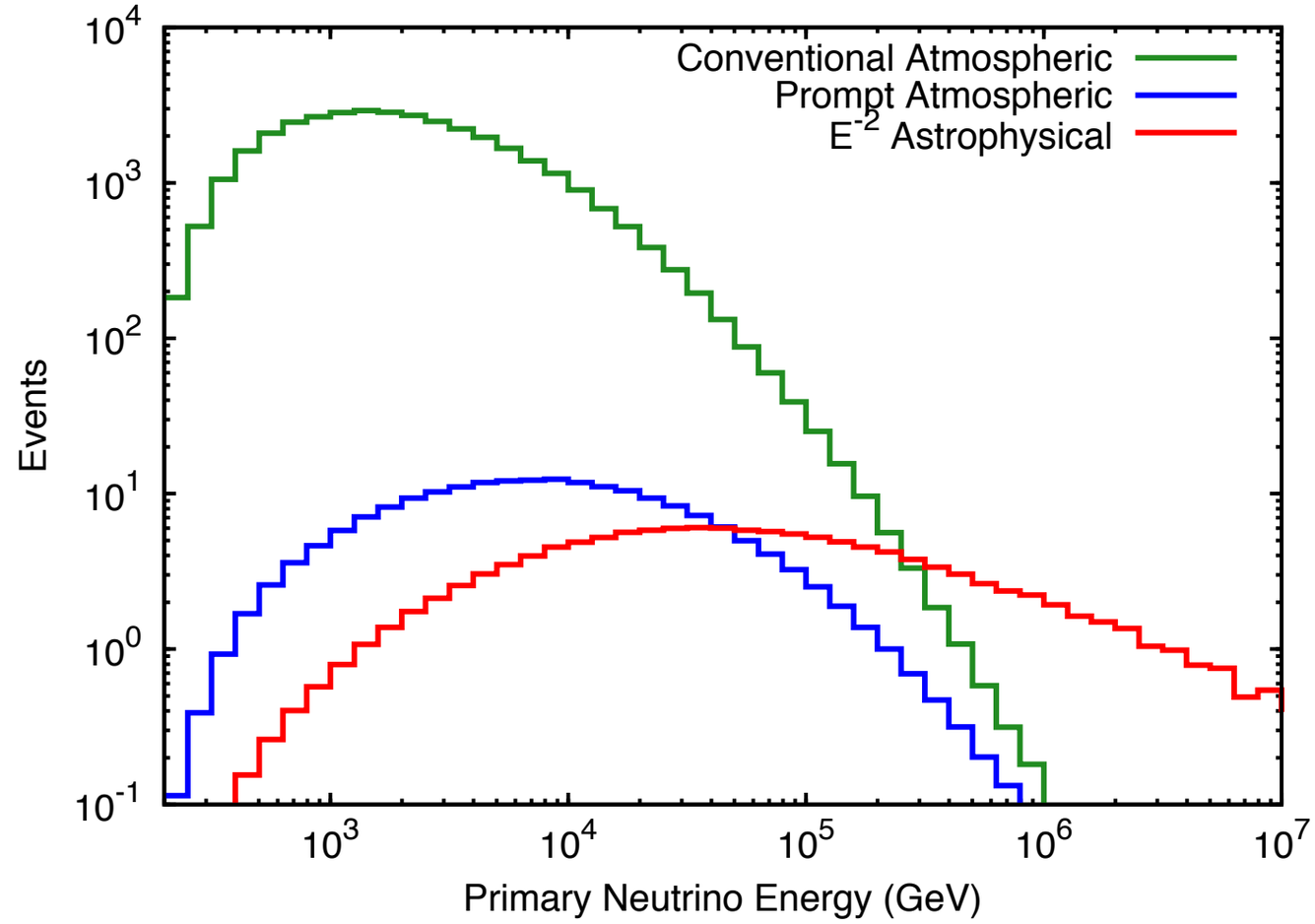


B. Louis et al., "The evidence for oscillations," Los Alamos Science 25 (1997) 16.

- Many high energy neutrinos come from our own atmosphere
- Many muons are also produced—the same processes as at a source
- These form a foreground when one tries to study astrophysical neutrinos (or gamma rays)

Diffuse Neutrino Fluxes





- Identifying neutrino sources would be ideal, but we can begin by searching for their aggregate influence
- Foreground of atmospheric neutrinos, including the 'prompt' component from heavy (charmed) meson decays
- Most models predict fluxes similar to $\phi(E) \propto E^{-2}$ which are harder than the atmospheric flux

The IceCube Detector

The IceCube Collaboration

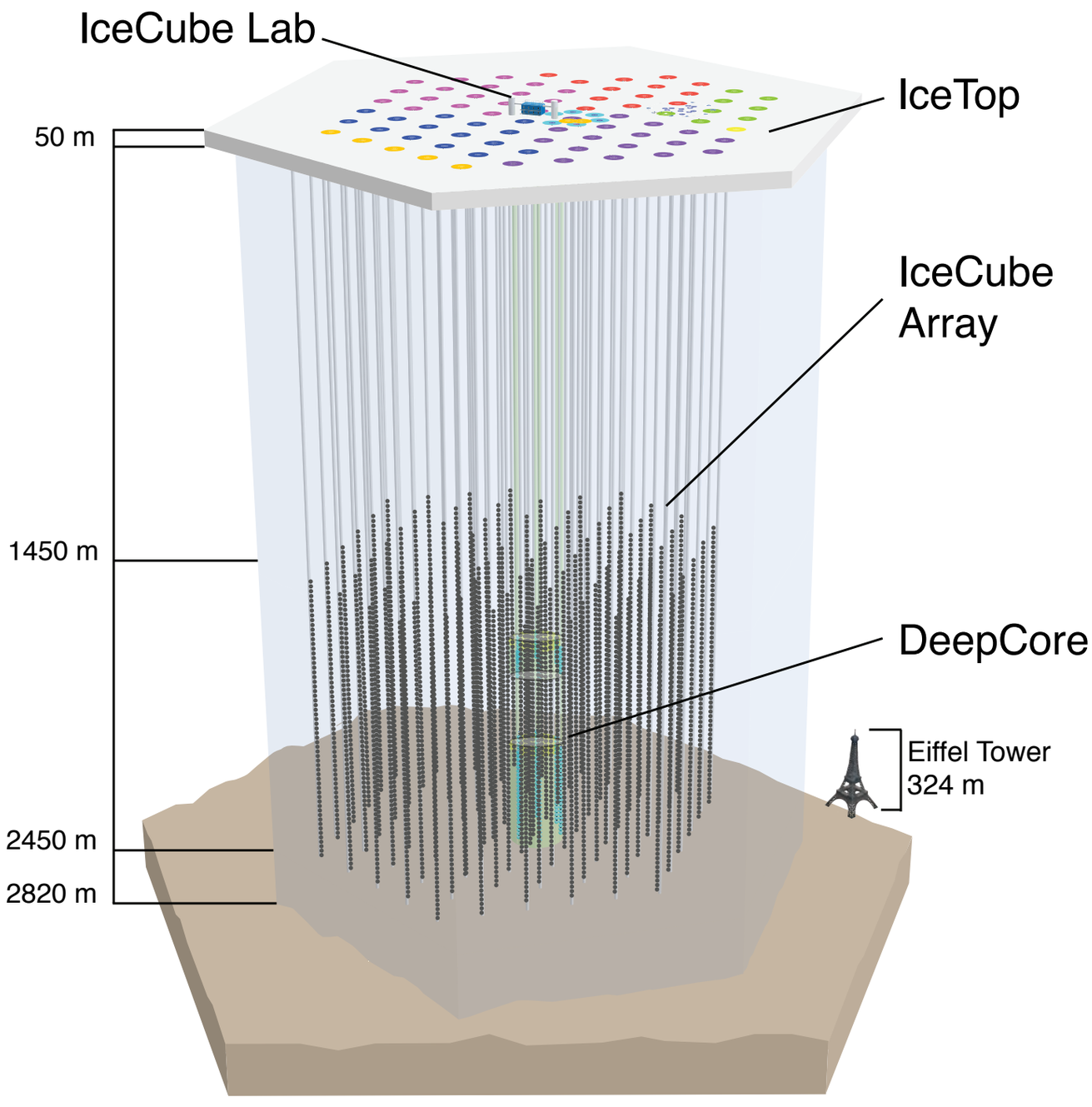
Funding Agencies

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)

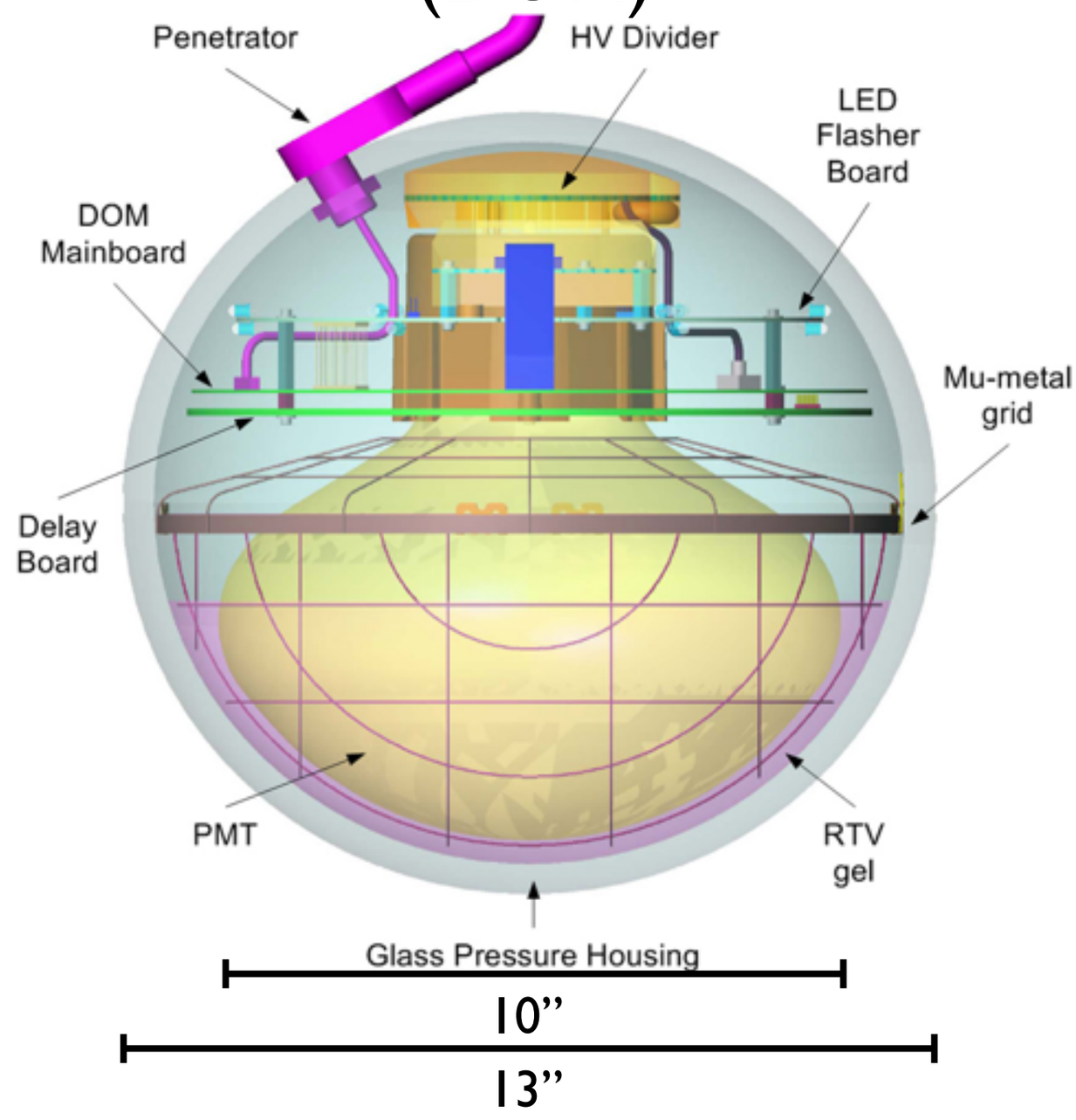
Haley Buffman & Jamie Yang. IceCube/NSF

Detector Hardware

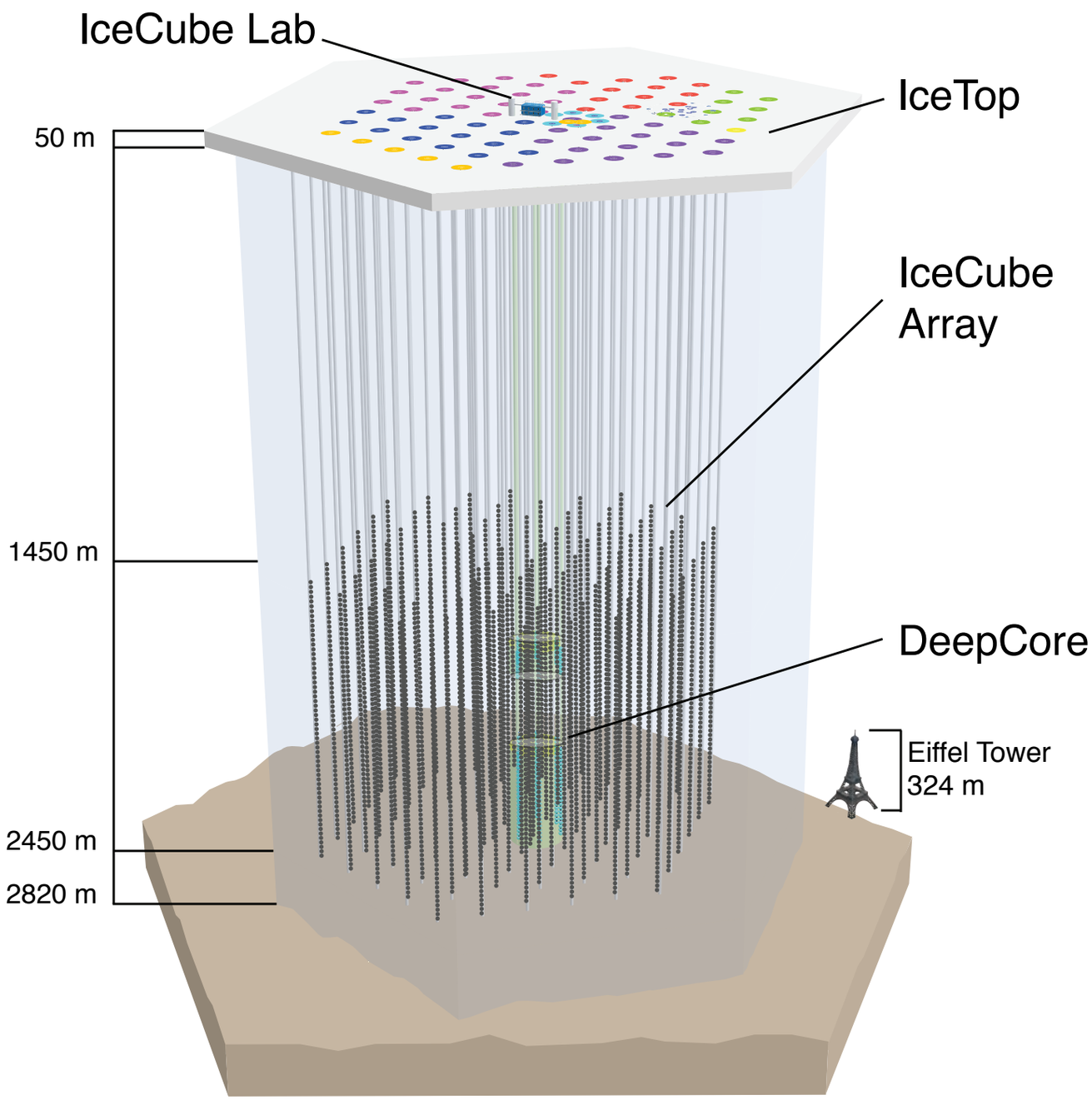
Detector Layout



Digital Optical Module (DOM)



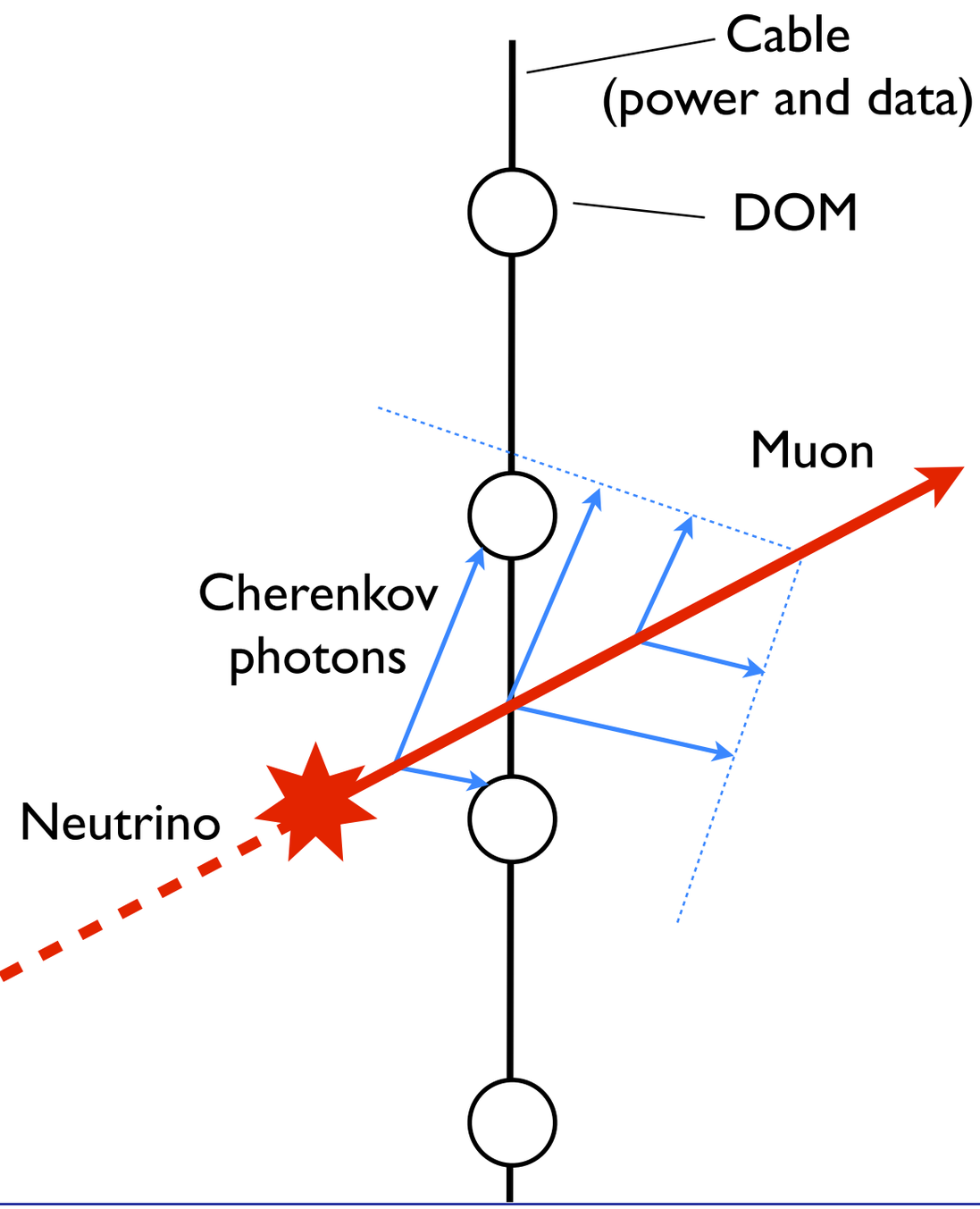
Detector Hardware



- Detector has ~1 km^3 of (sparsely) instrumented volume (sensor spacing 17m vertically, 125m horizontally)
- Construction completed in Dec. 2010
- Data collected continuously during construction with partial configurations

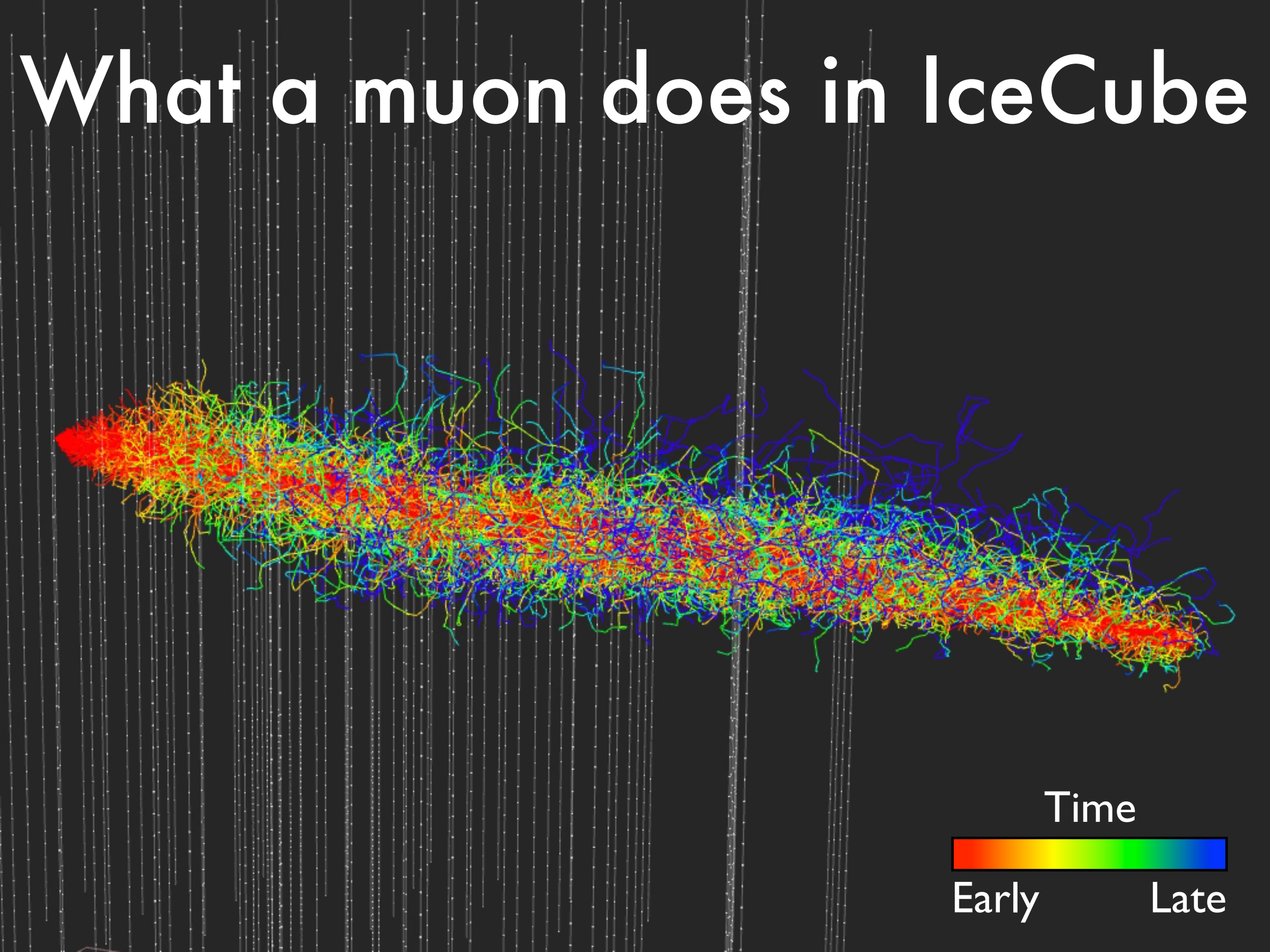
Detection Principle

Schematic of an IceCube 'String'

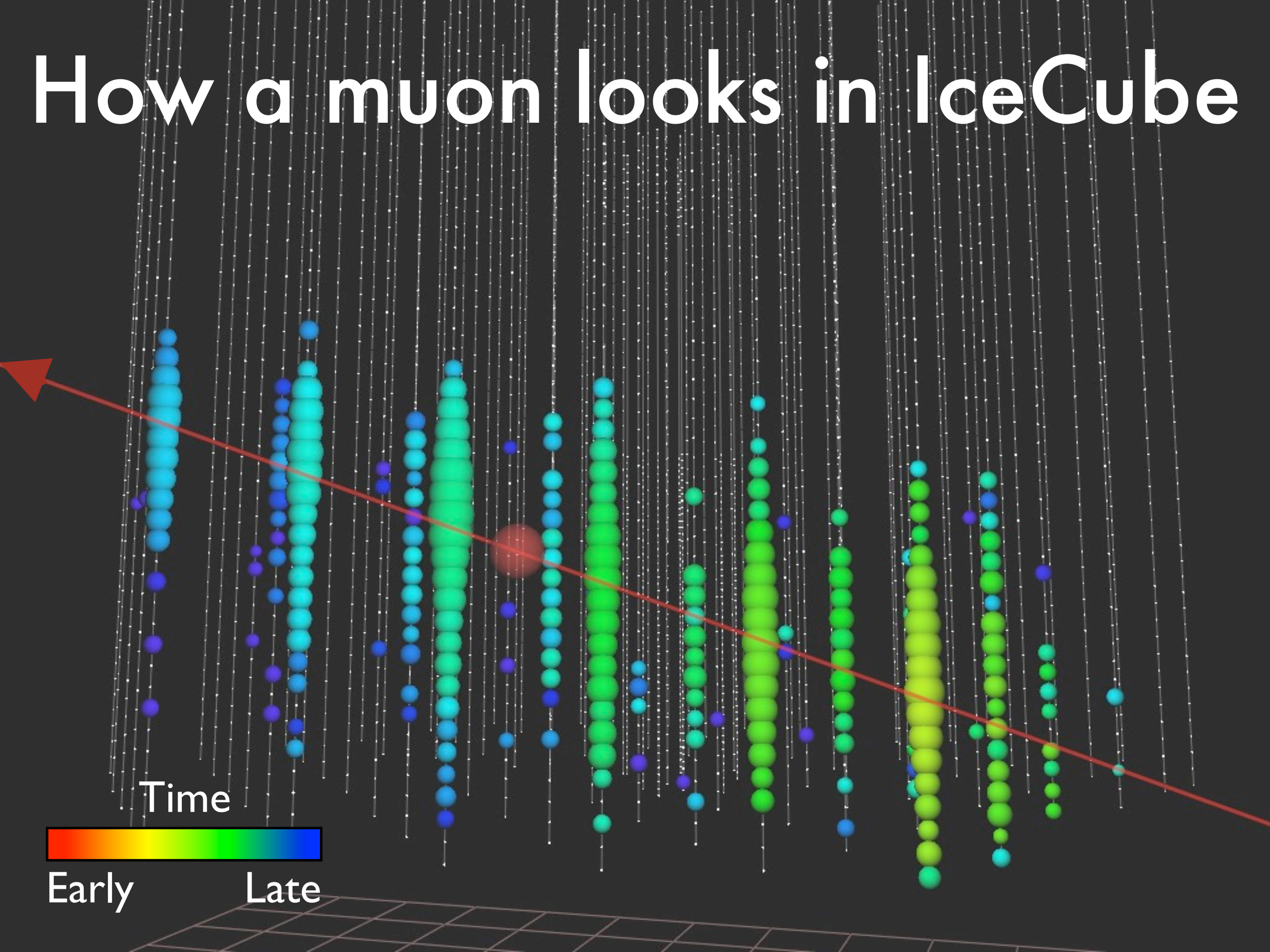


- Energetic particles emit Cherenkov light in the ice
- DOMs detect photons
  - single photon sensitivity
  - digitization of PMT waveforms with precise timing
- Absorption length for light is long (~90m) but scattering length is shorter (~25m)

What a muon does in IceCube

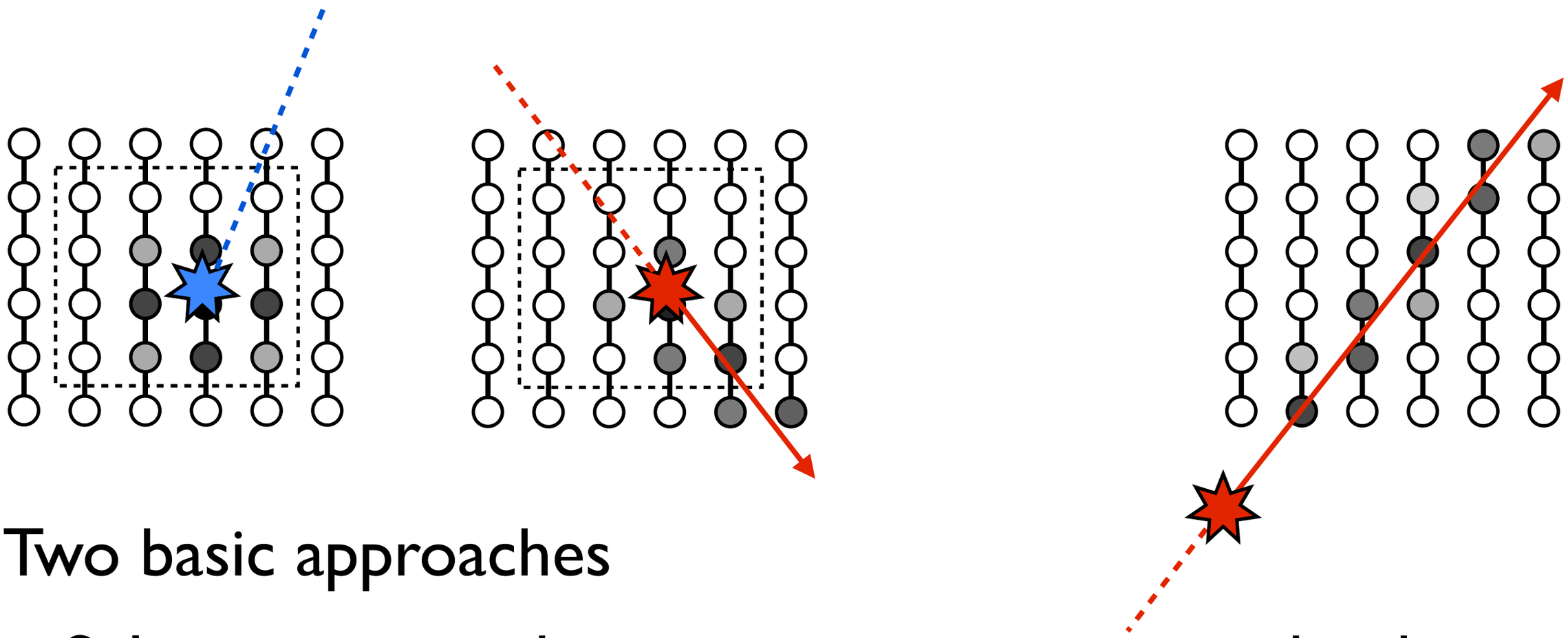


How a muon looks in IceCube



Current IceCube Results

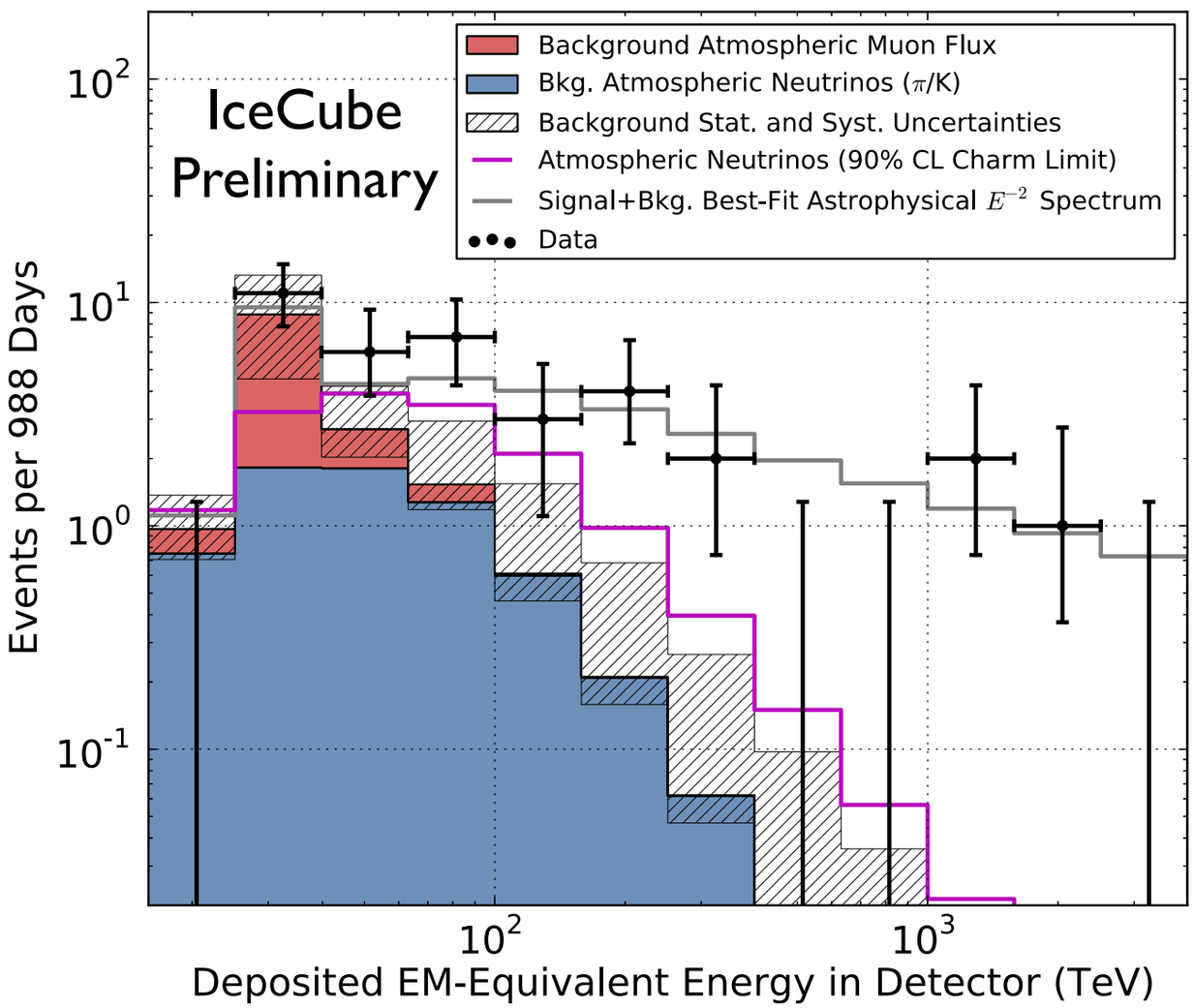
Selecting Neutrinos



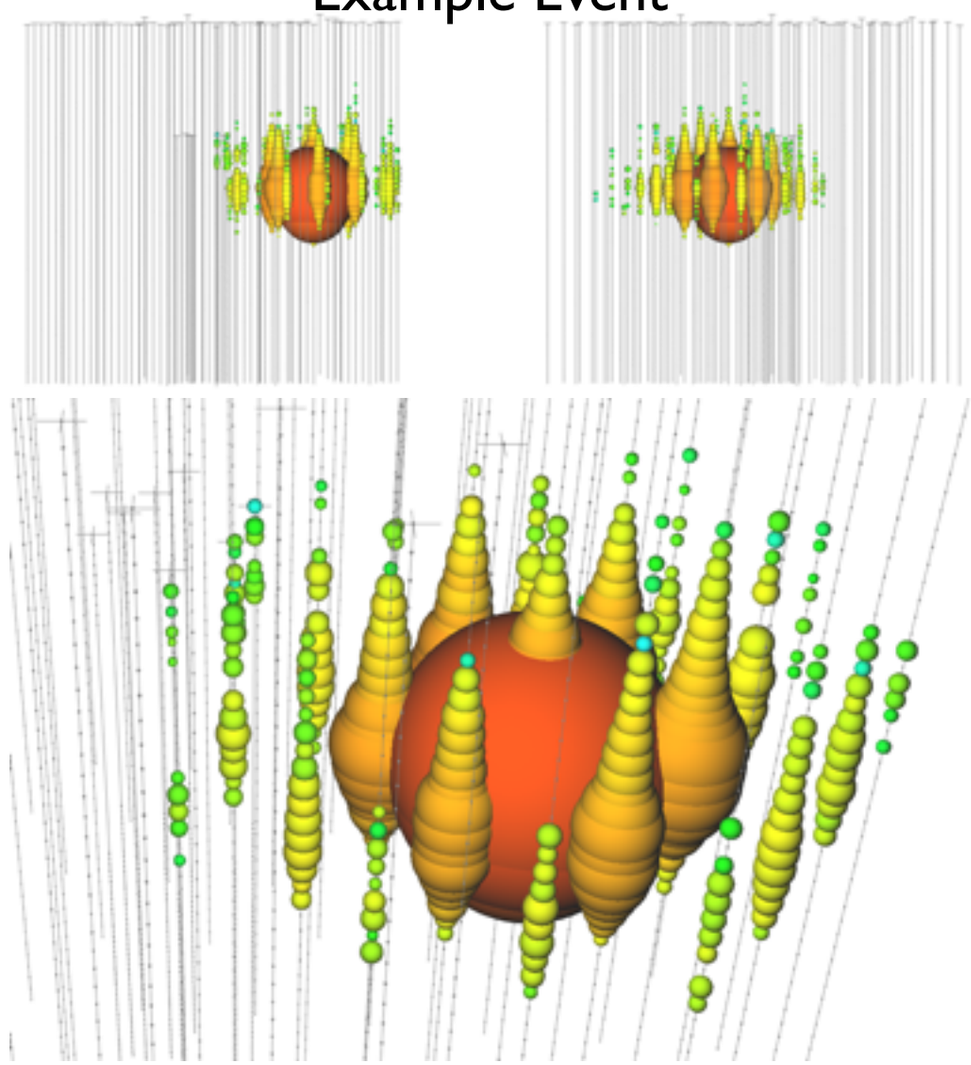
- Two basic approaches
  - Select events with an interaction vertex in the detector, and no visible entering particles (**starting events**)
  - Select events which have to have passed through the Earth, but enter the detector after interacting (**through-going events**)

Starting Events

Energy Distribution



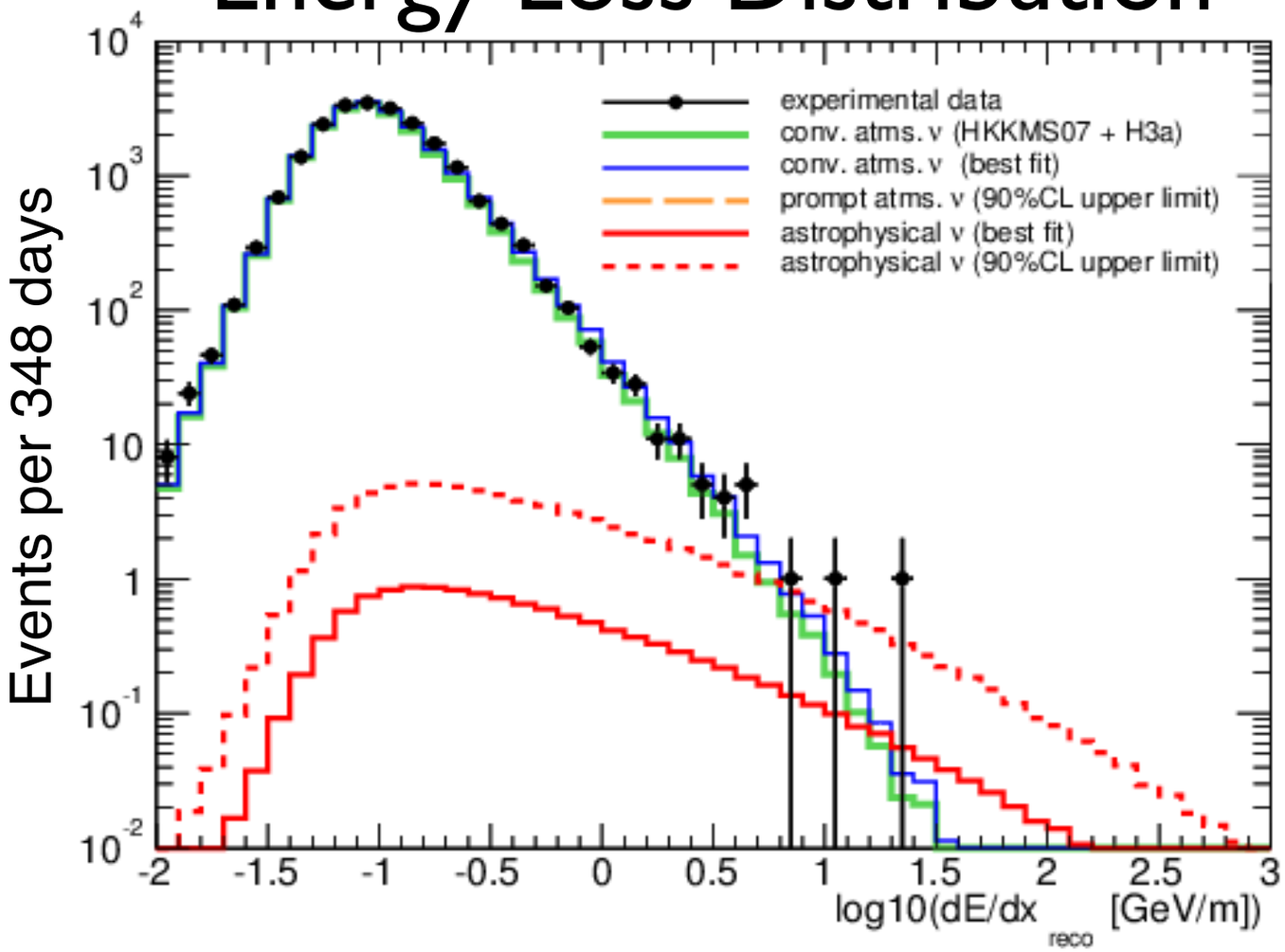
Example Event



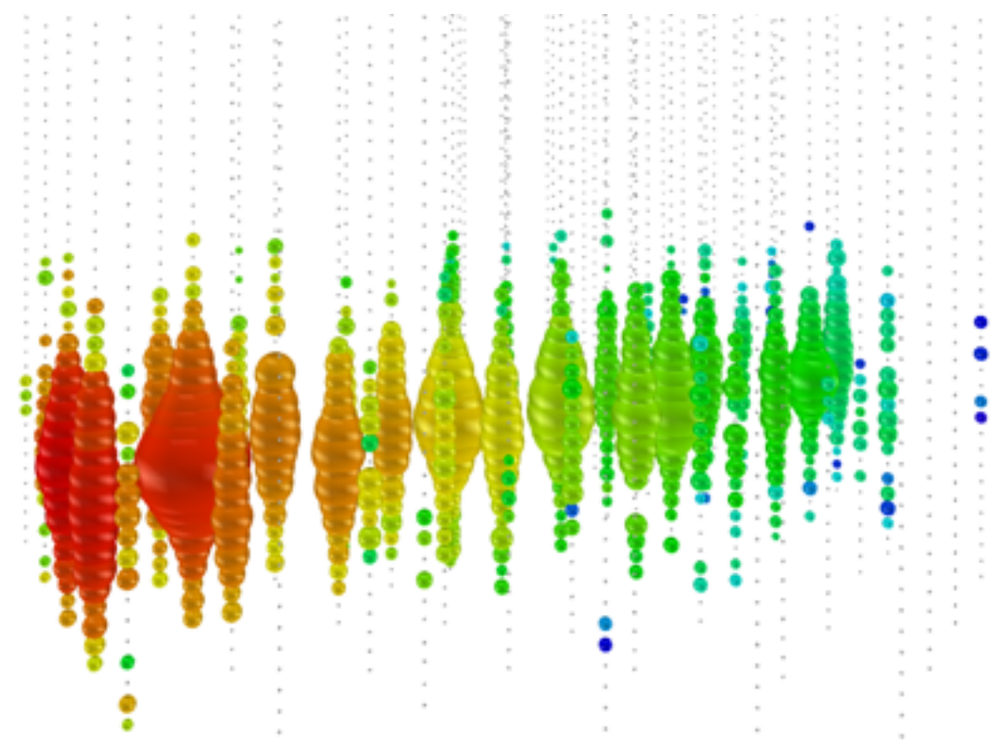
- Data from 3 years of the complete detector
- A clear excess of high energy events over background expectations (5.7 σ)
- This technique works over 4π , but is most sensitive in the southern sky

Through-going Events

Energy Loss Distribution



Example Event

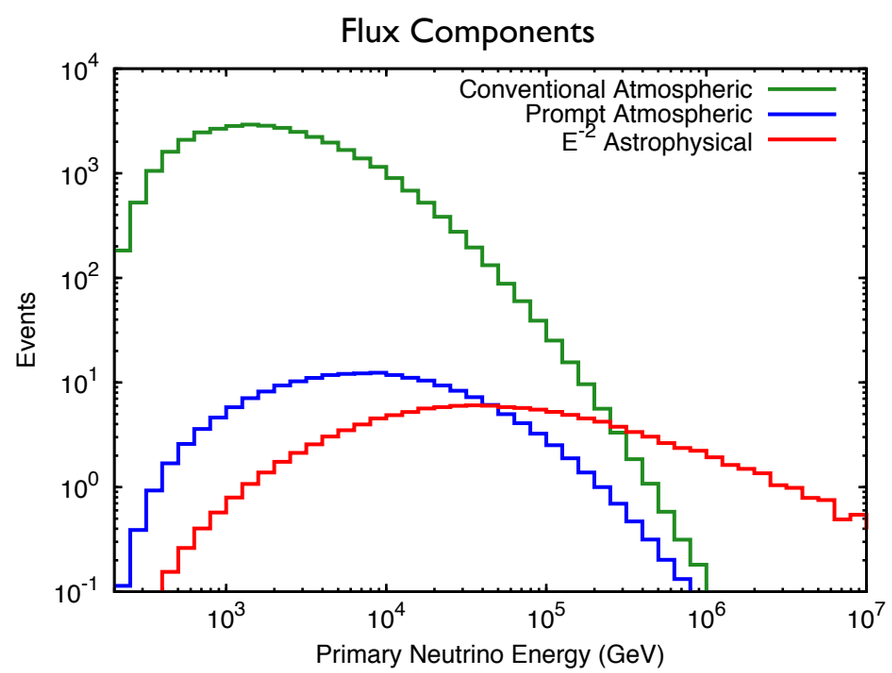


- Data from one year of the 3/4 complete IceCube detector
- Best fit E^{-2} flux is nonzero (2.7×10^{-9} GeV^{-1} cm^{-2} s^{-1} sr^{-1}), but is not significant (incompatible with background at only 1.8 σ)
- This technique is effective only for the northern sky

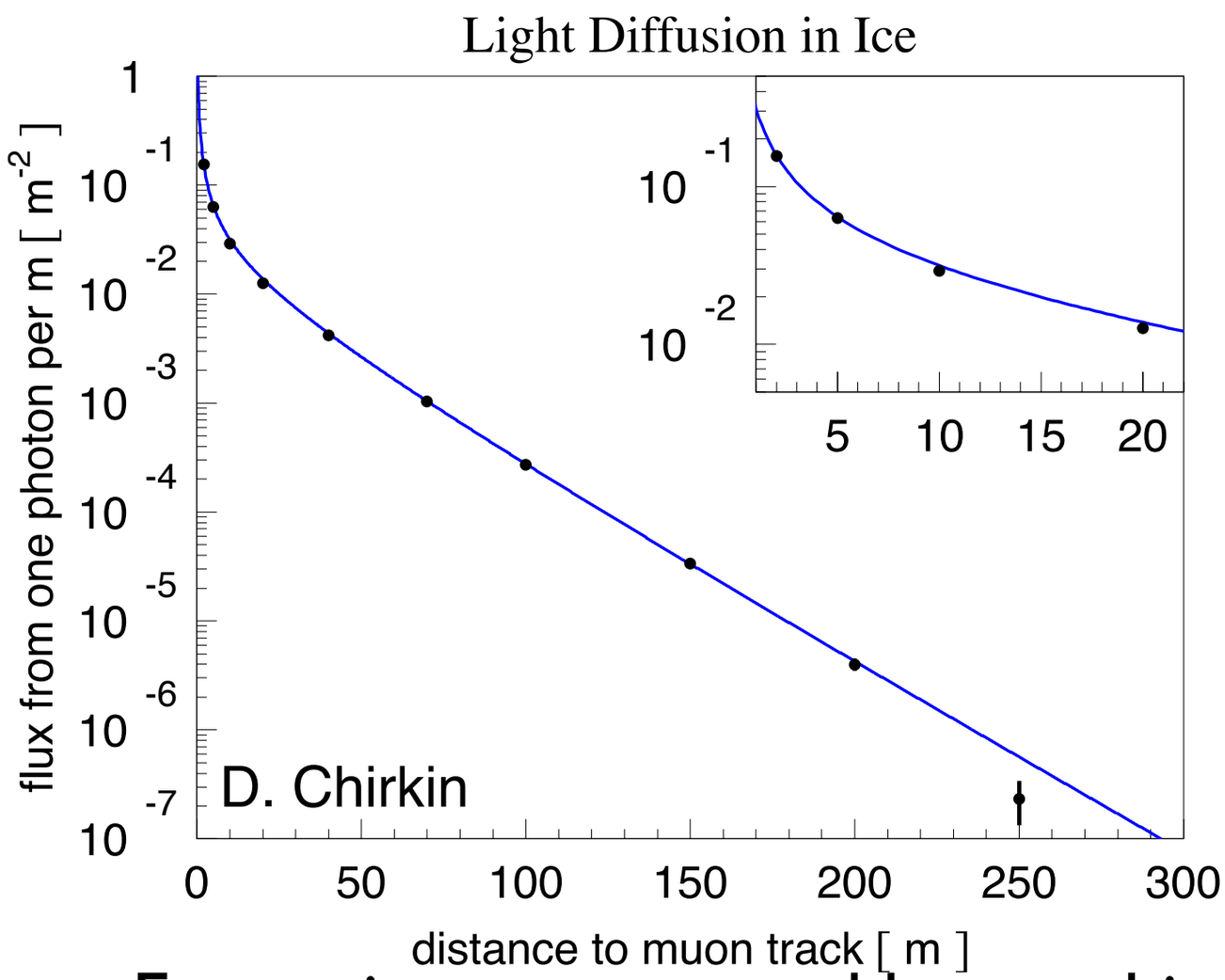
A New Through-going Event Analysis

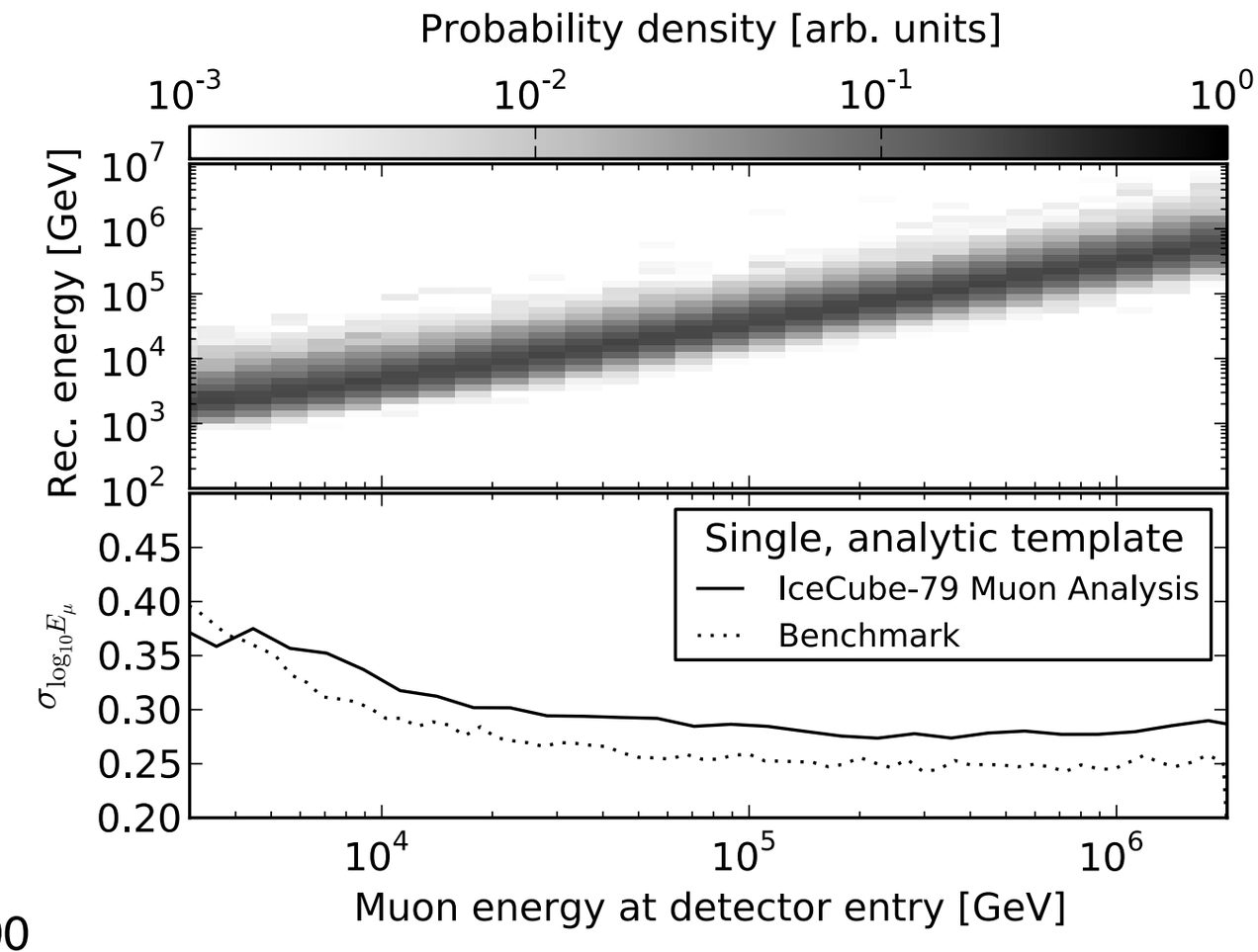
Plan

- Use two years of data (May 2010-May 2012) with the (more-or-less) complete detector
- Fit for a non-atmospheric component of the flux!
  - Forward-folding binned likelihood fit
  - Bin data by zenith angle, energy, and data-taking period



Energy Reconstruction

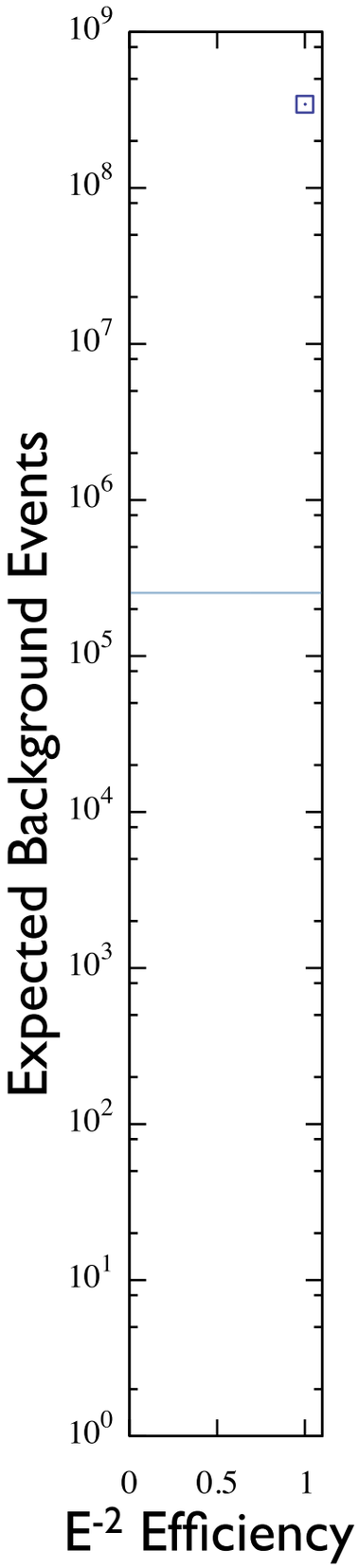


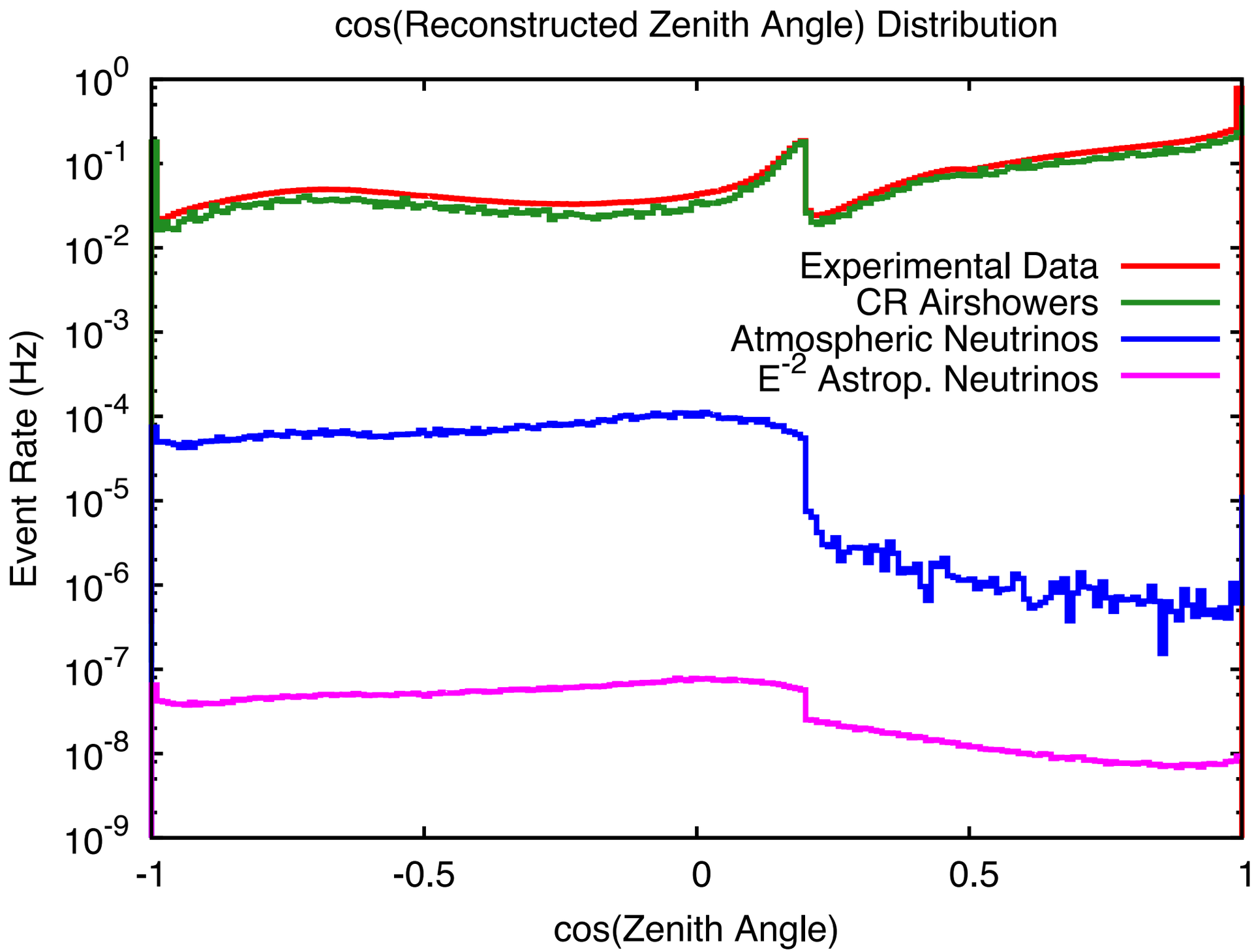


- Energy is reconstructed by matching the expected light yield for a muon to the observed amount of light
- Only energy deposited in (or near) the detector can be measured
- Muons may travel long distances, losing energy in the process, so only a high energy muon at the detector is proof of a high energy neutrino

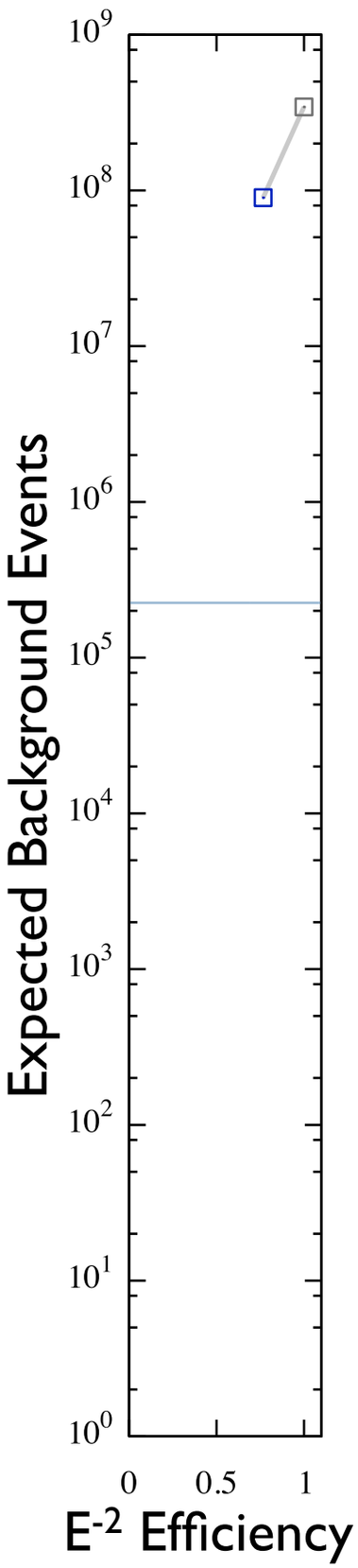
Data Selection

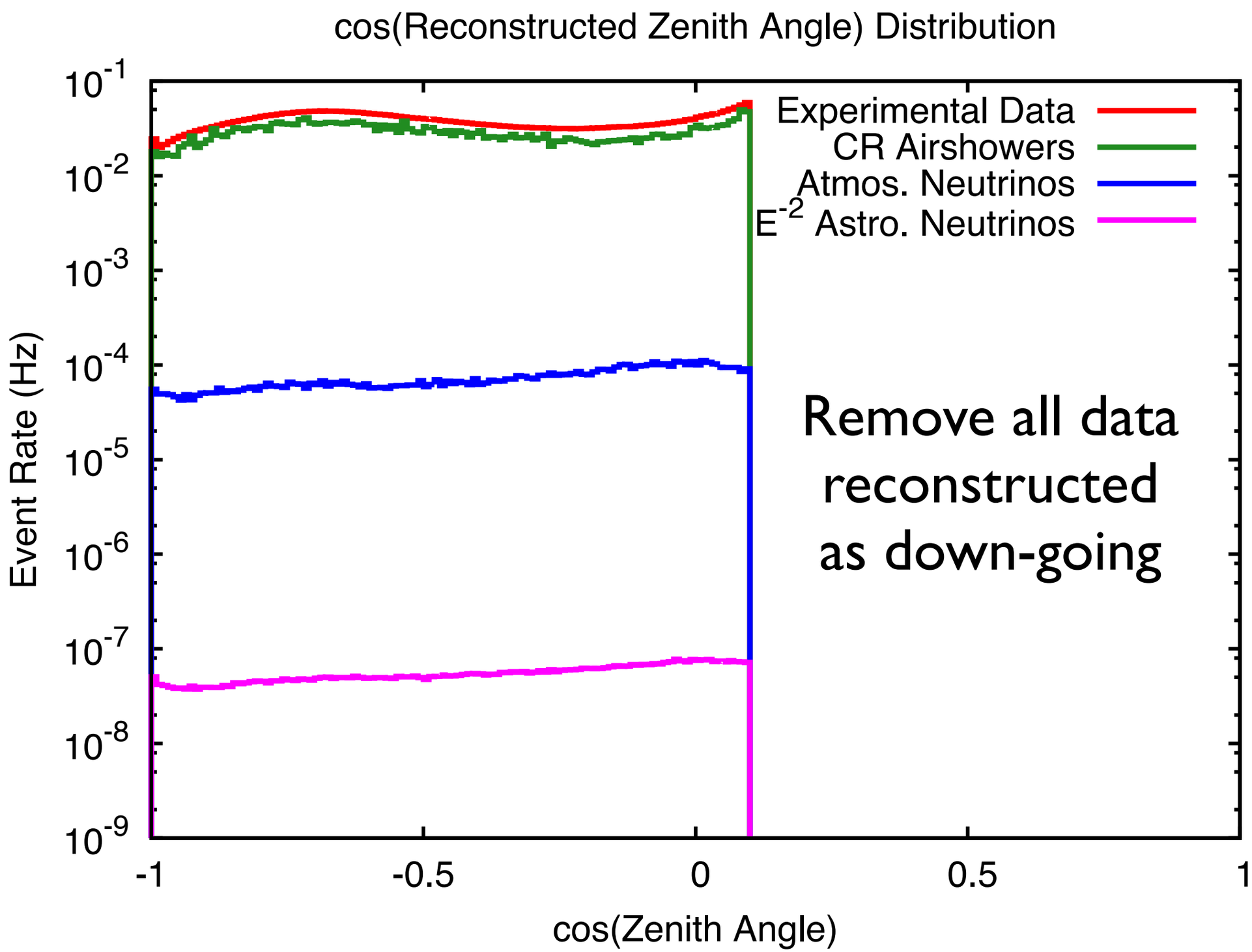
Initial Data





Up-going Data Only

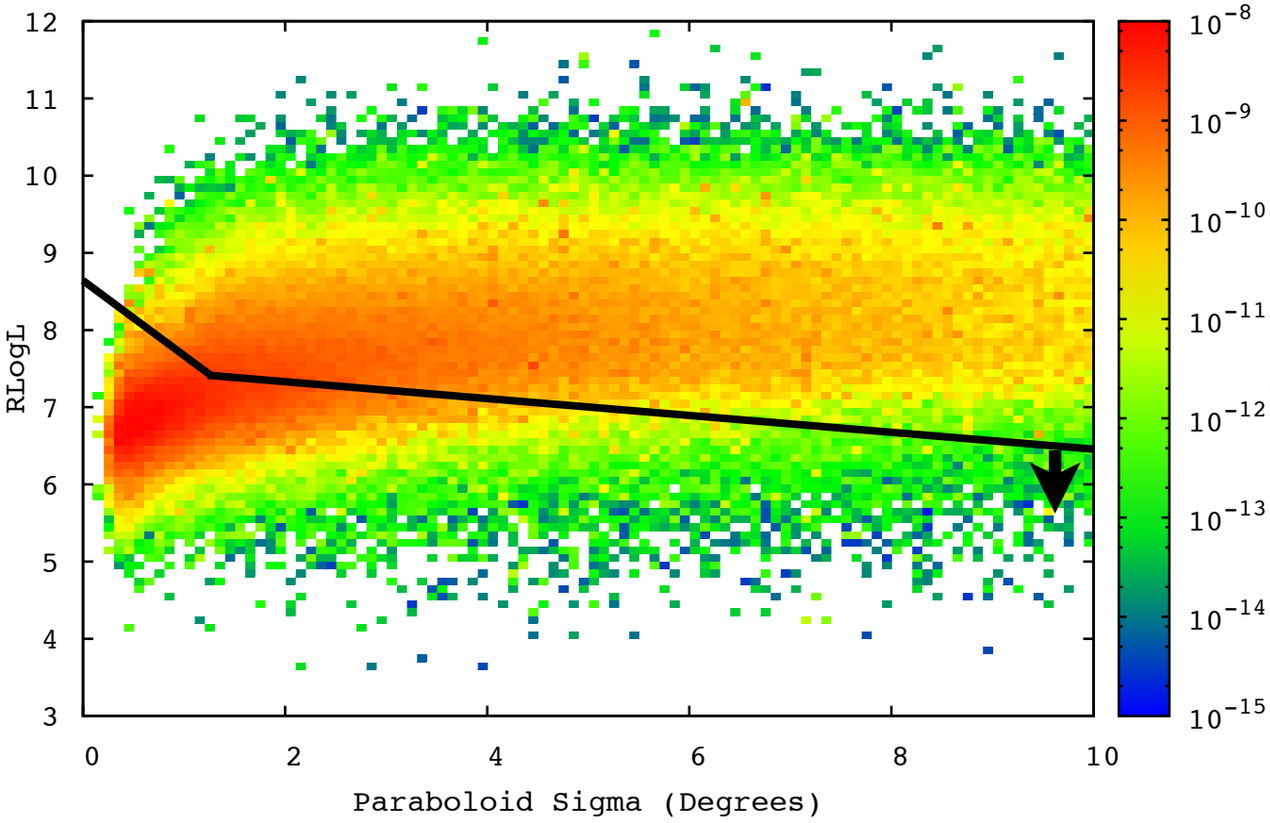




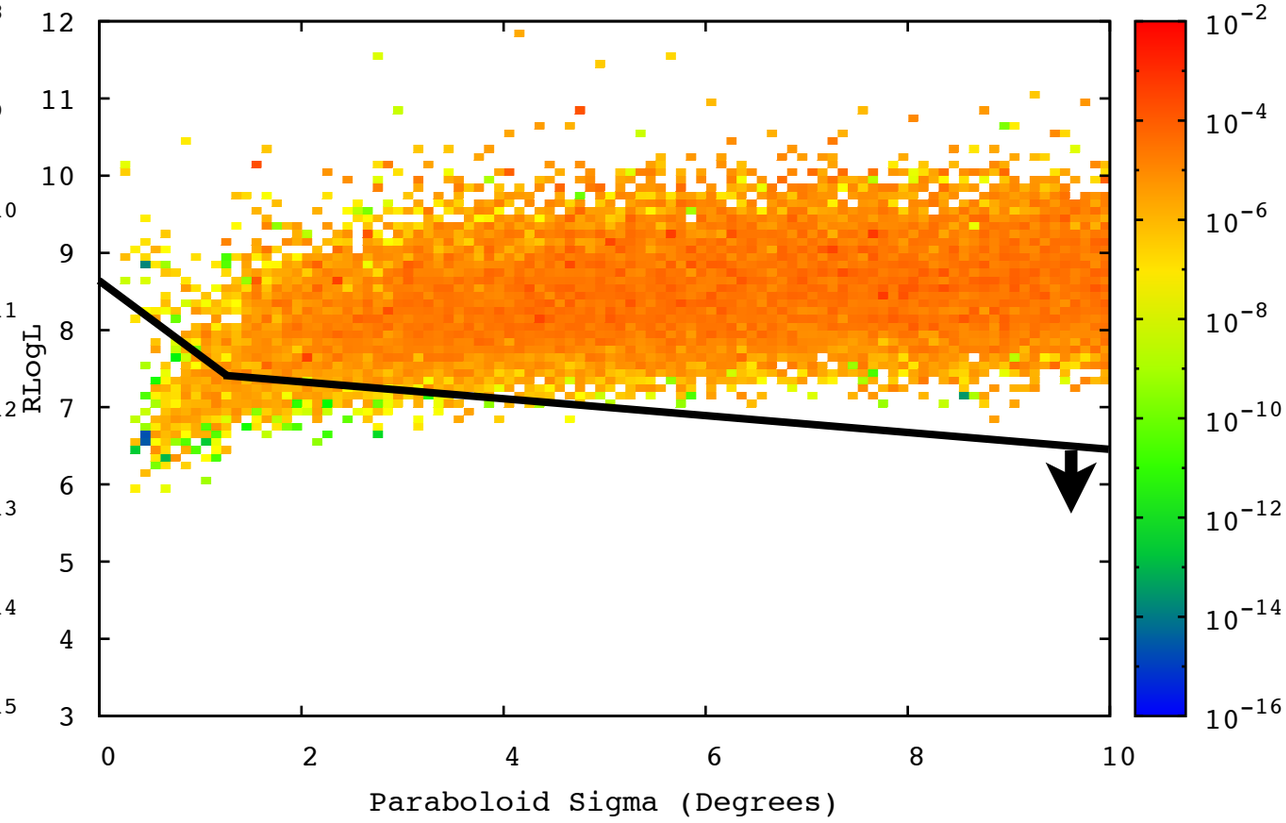
Remove all data reconstructed as down-going

Reconstruction Quality Cuts

E^{-2} Neutrinos

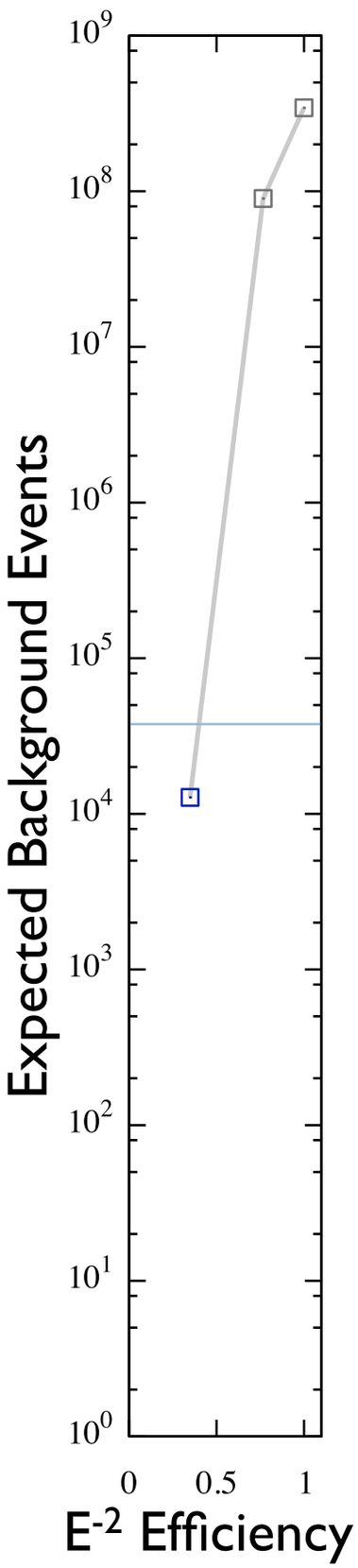


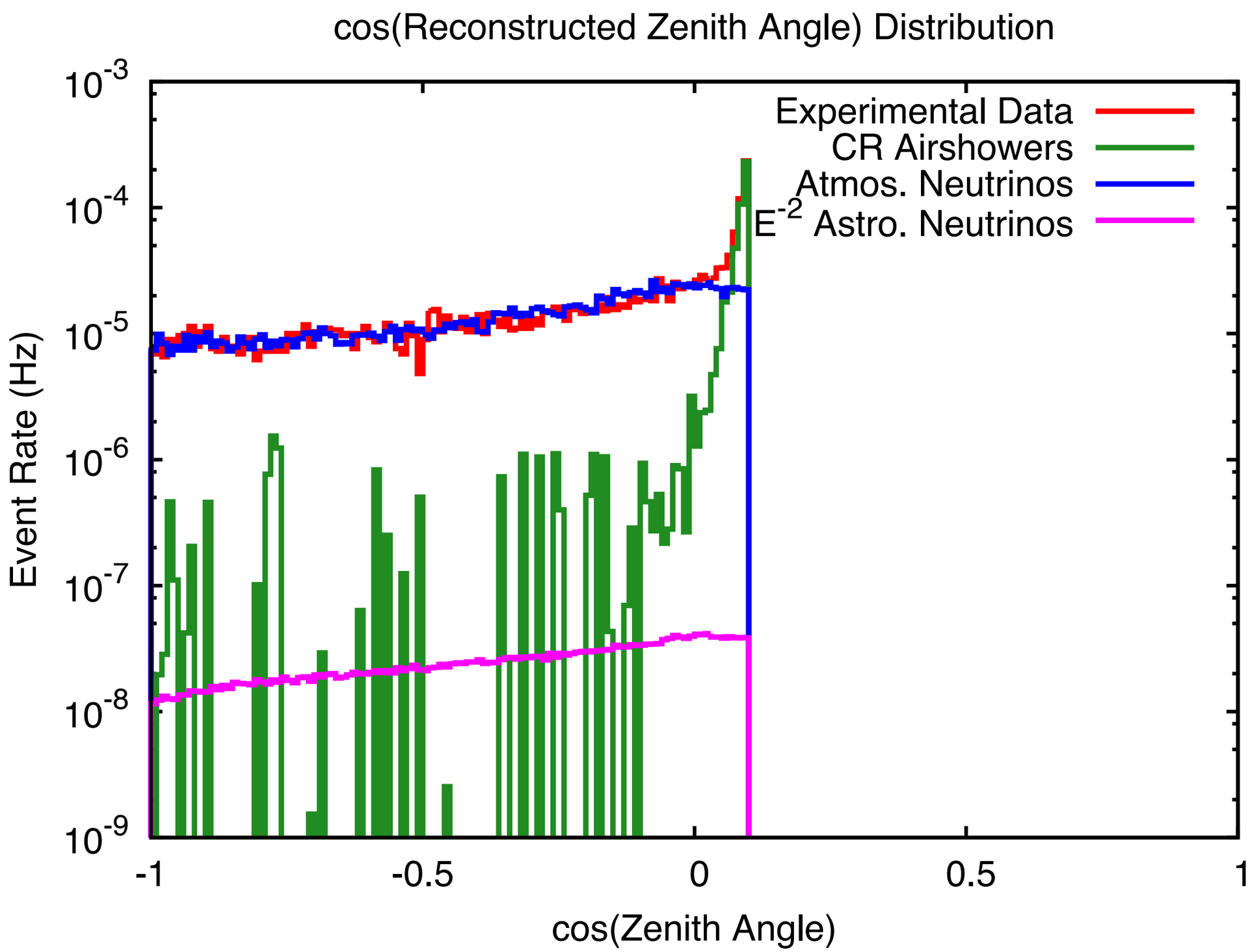
Simulated Airshowers



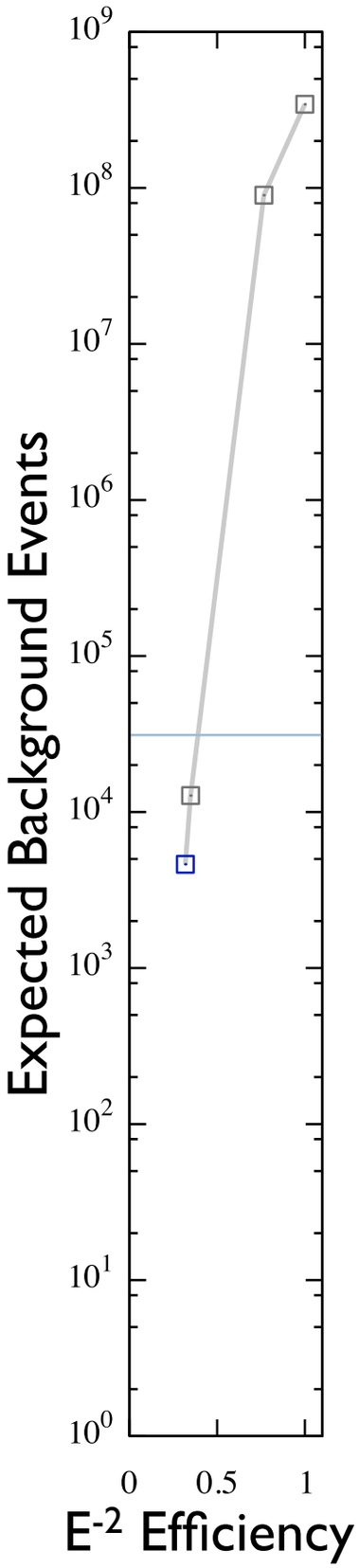
- 'RLogL' (reduced log likelihood) is a quality measure from the directional reconstruction
- 'Paraboloid' is a profile likelihood estimate of the angular error of the reconstruction.

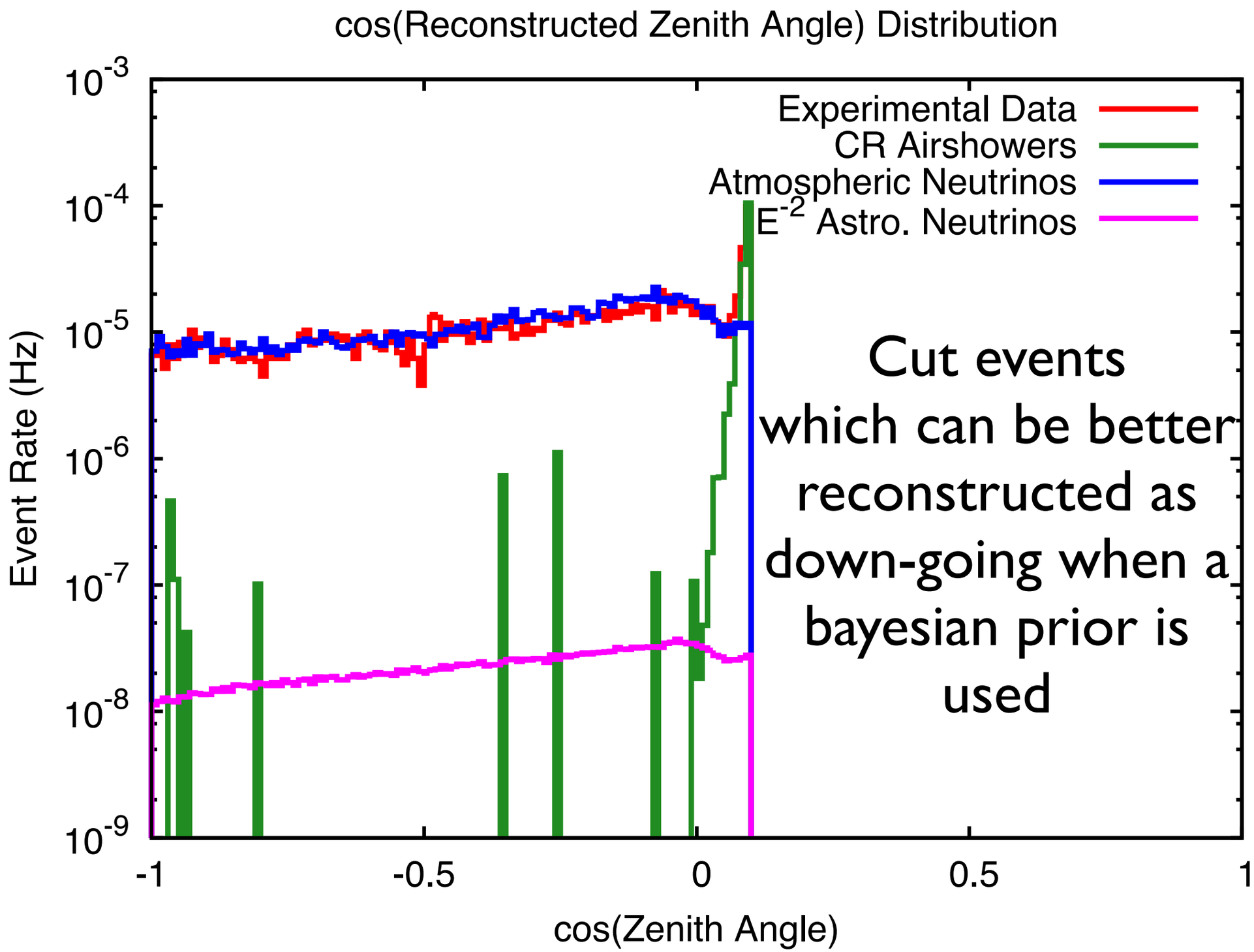
Neutrino-dominated Data





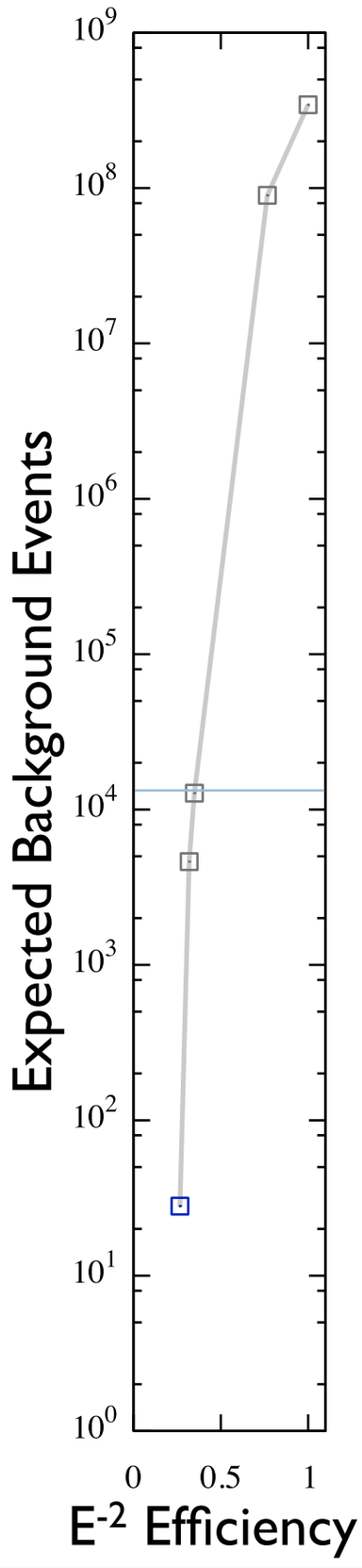
Getting cleaner. . .

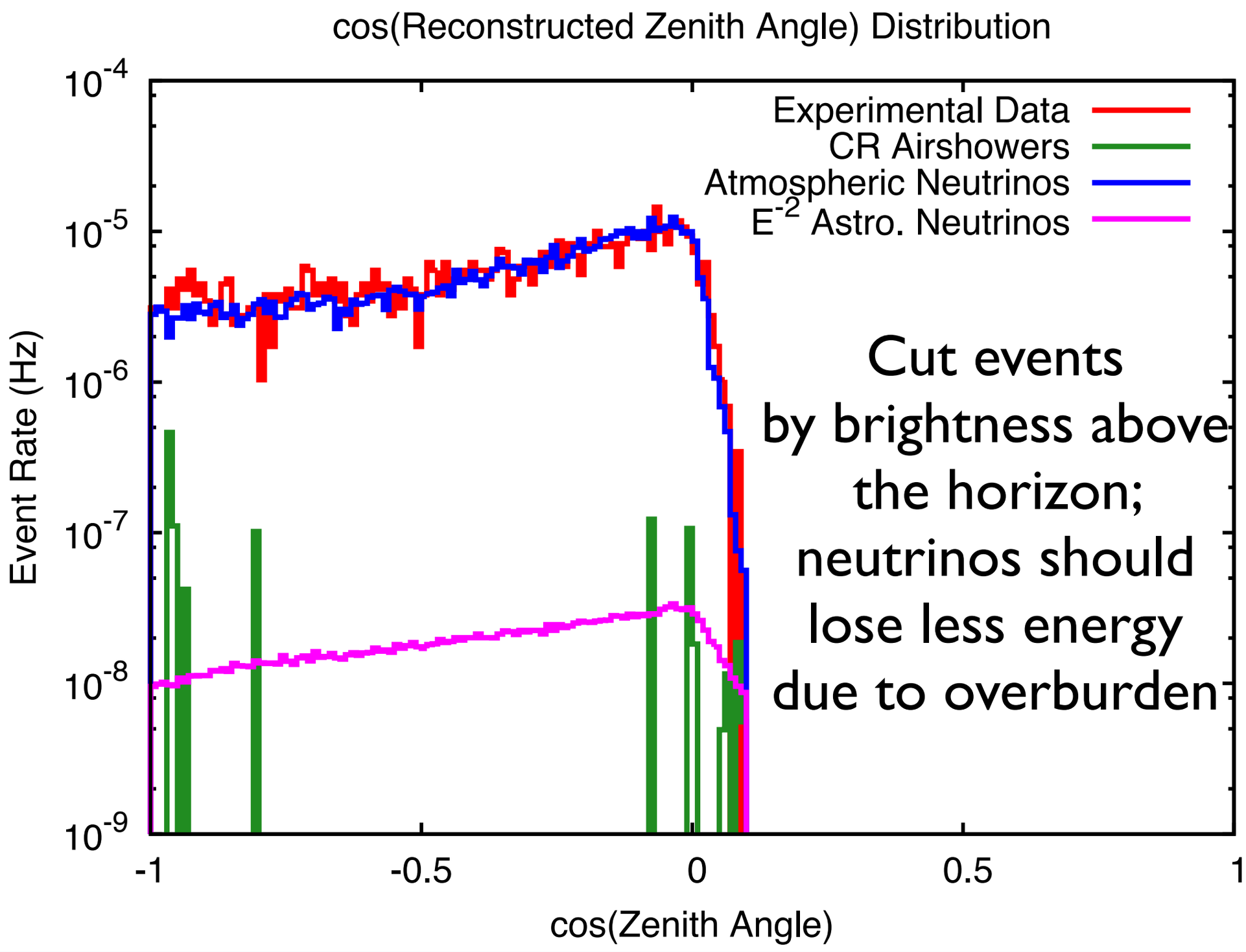




Cut events which can be better reconstructed as down-going when a bayesian prior is used

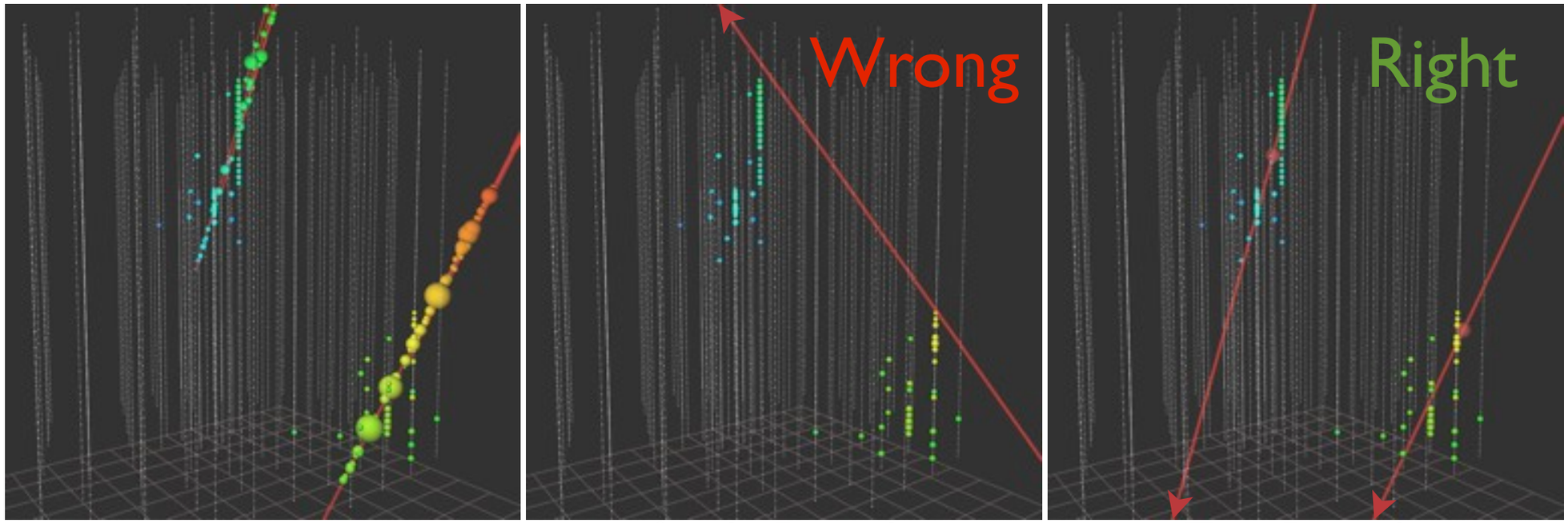
Nearly pure. . .





Cut events by brightness above the horizon; neutrinos should lose less energy due to overburden

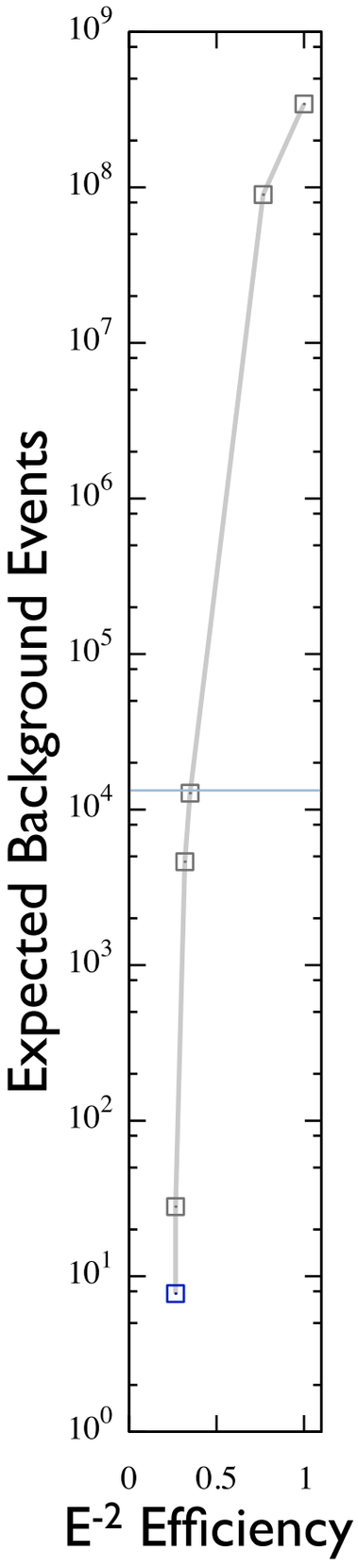
Remove Coincident Events

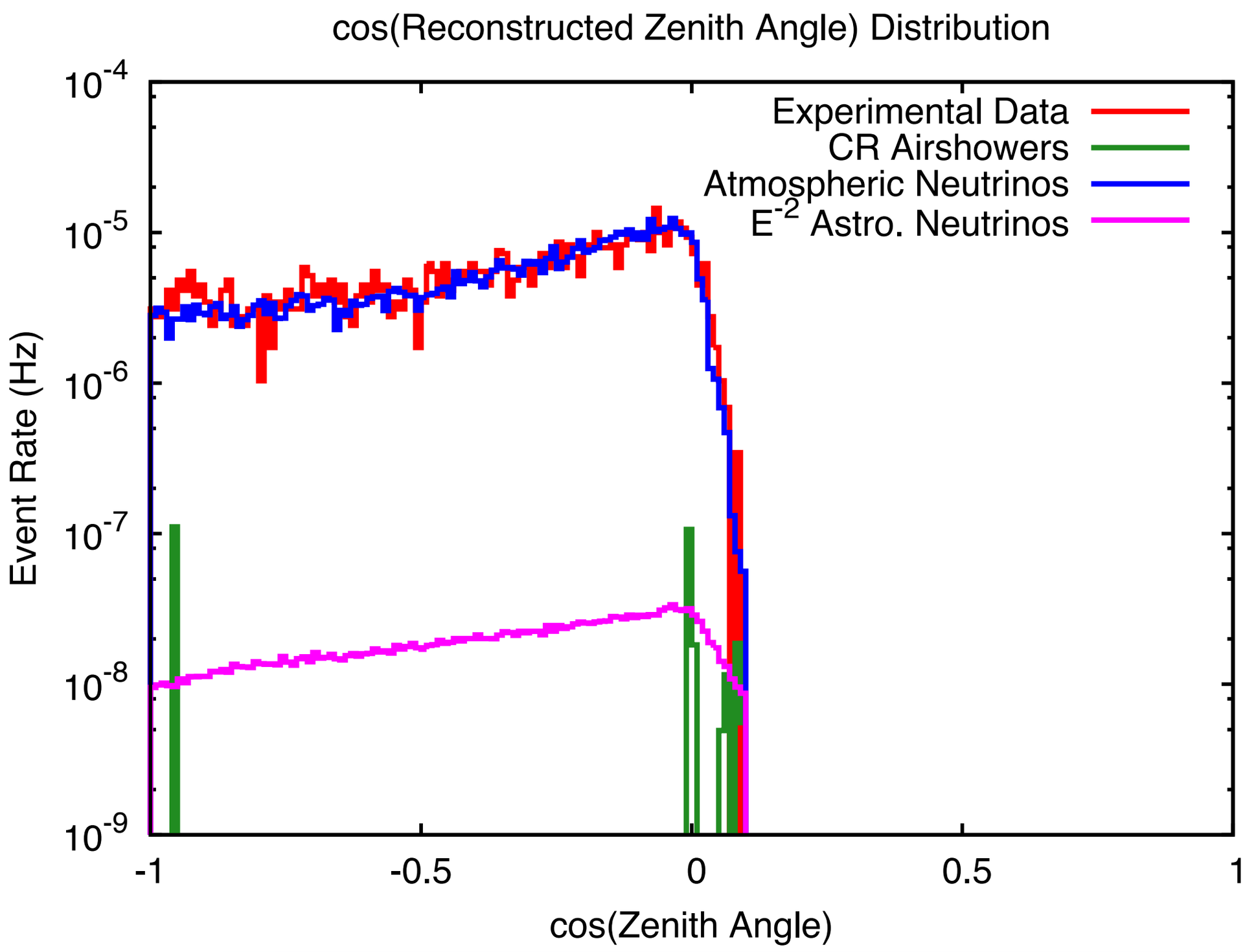


Truth | Single Particle Reconstruction | Two Particle Reconstruction

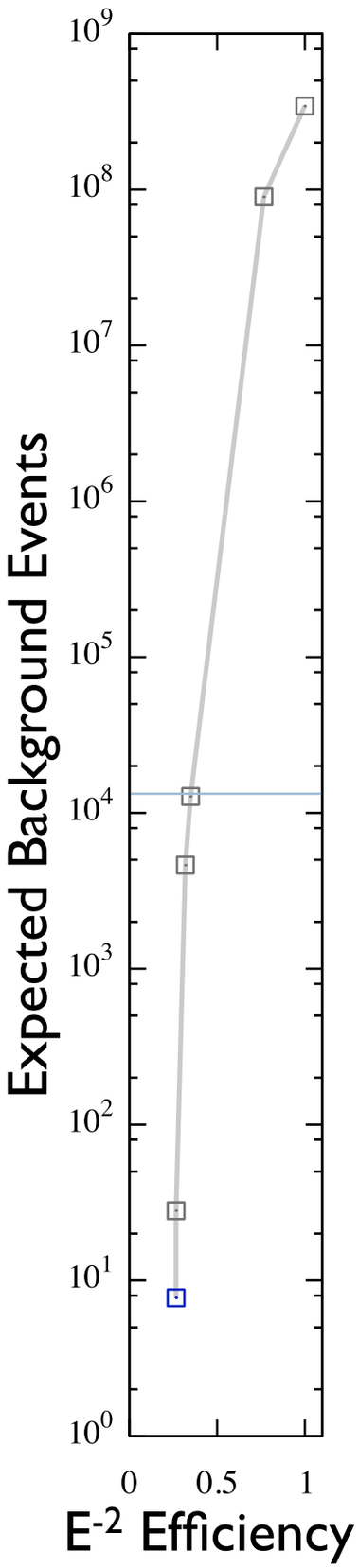
- Nothing prevents two events entering the detector at the same time—happens in ~10% of triggers
- Sometimes the relative timing of two showers is consistent with speed of light travel between them
- Cutting the event in half and doing two reconstructions is a simple, brute force way to solve this if nothing else worked

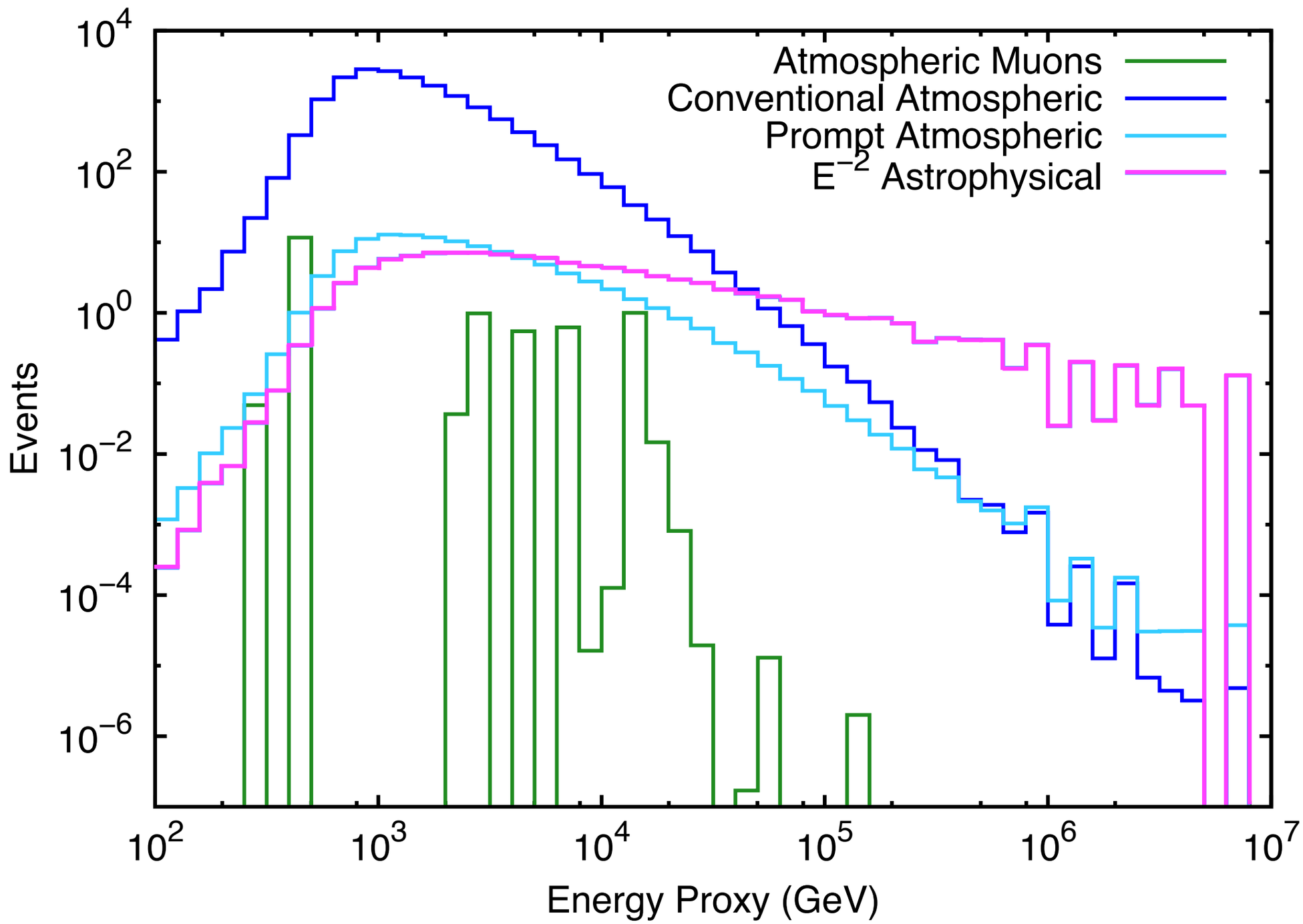
Final Selection





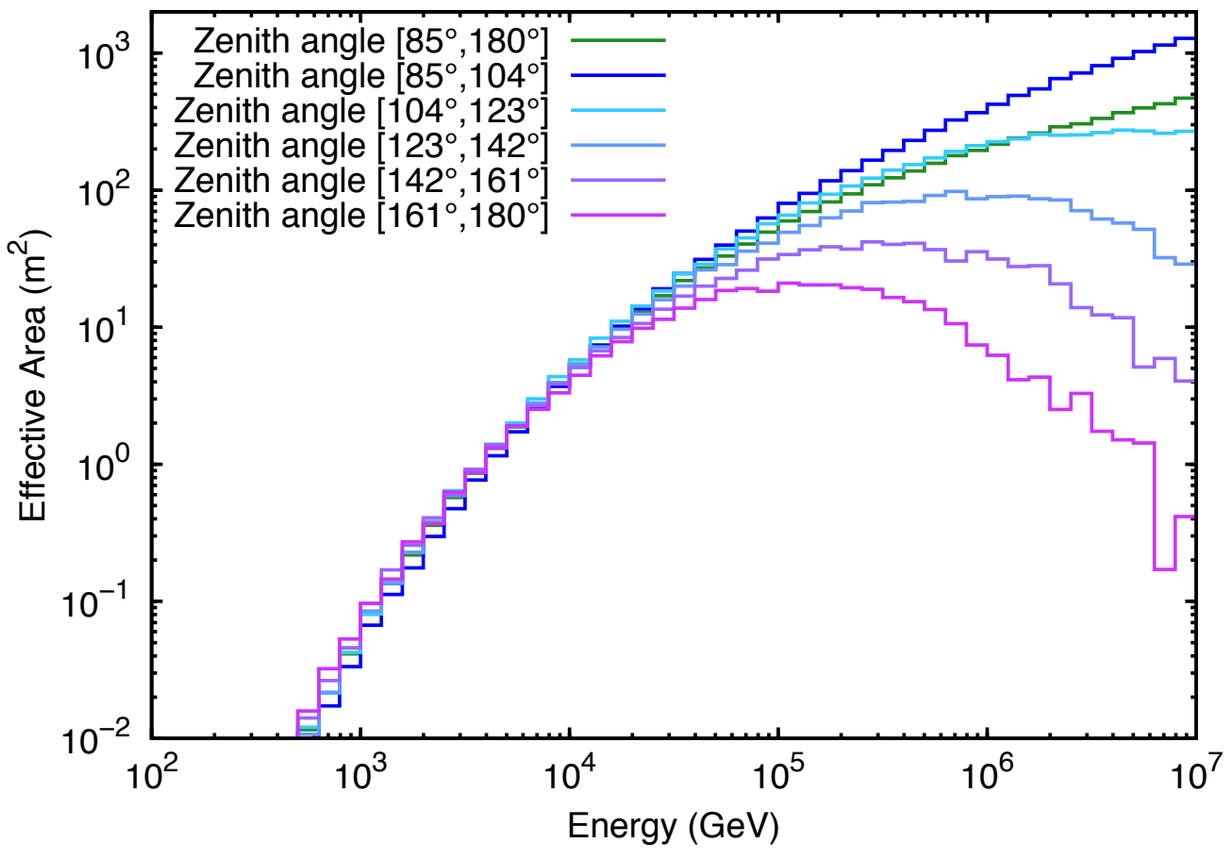
Final Selection



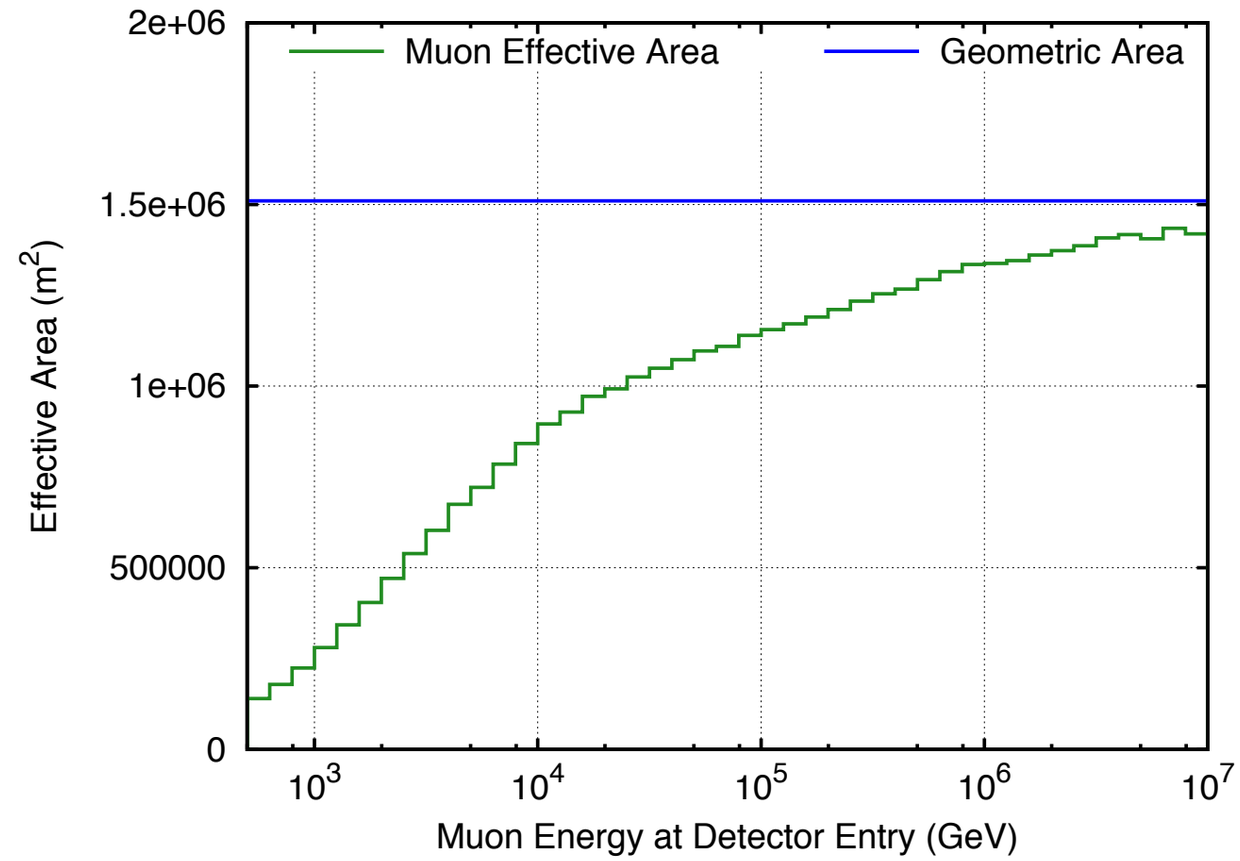


Effective Area

For Neutrinos



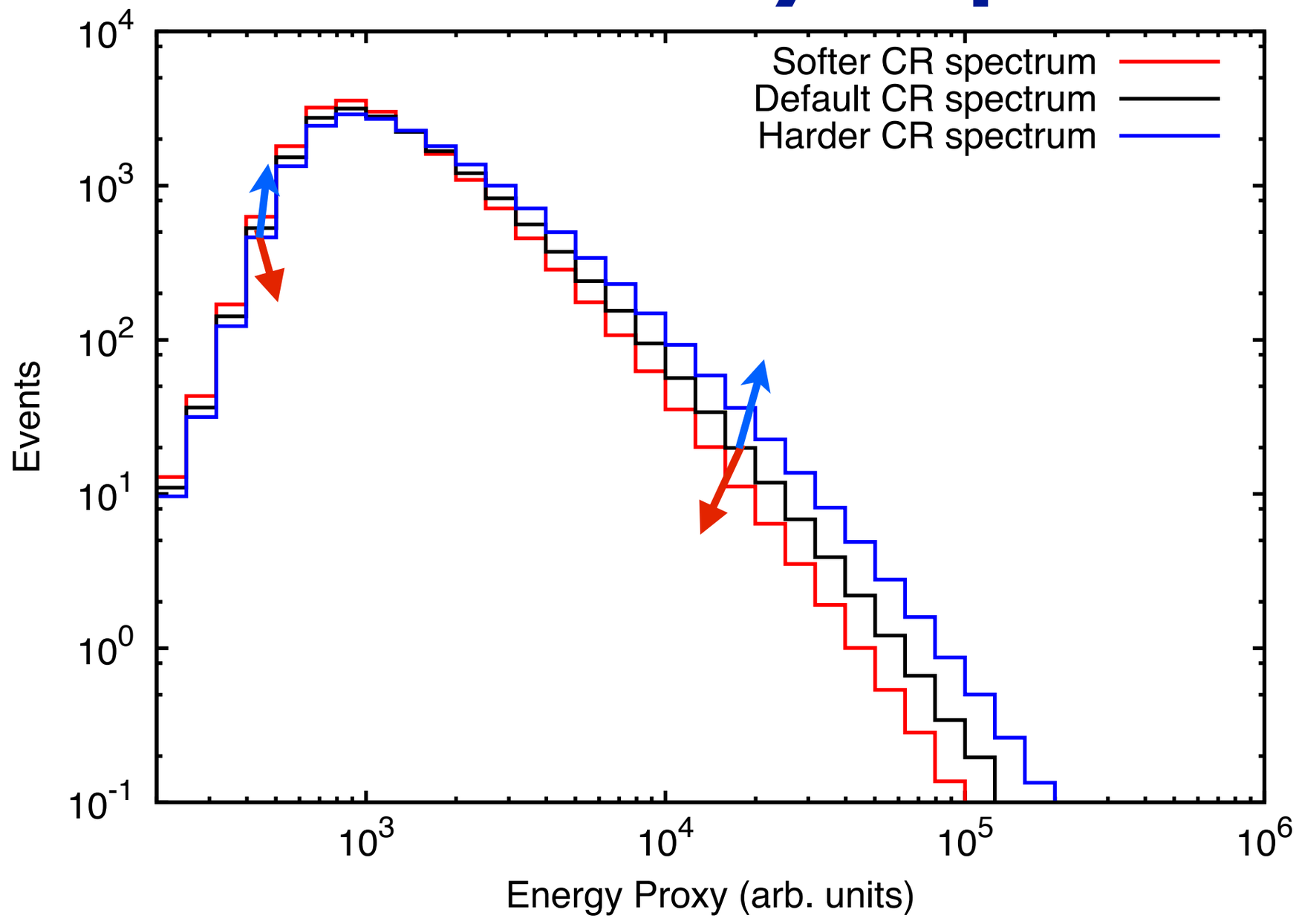
For Muons



- Area of ~60 m^2 for 100 TeV neutrinos
- Collect ~80% of muons which reach the detector with 100 TeV
- Note that the muon from a 100 TeV neutrino might be arbitrarily low energy by the time it reaches the detector

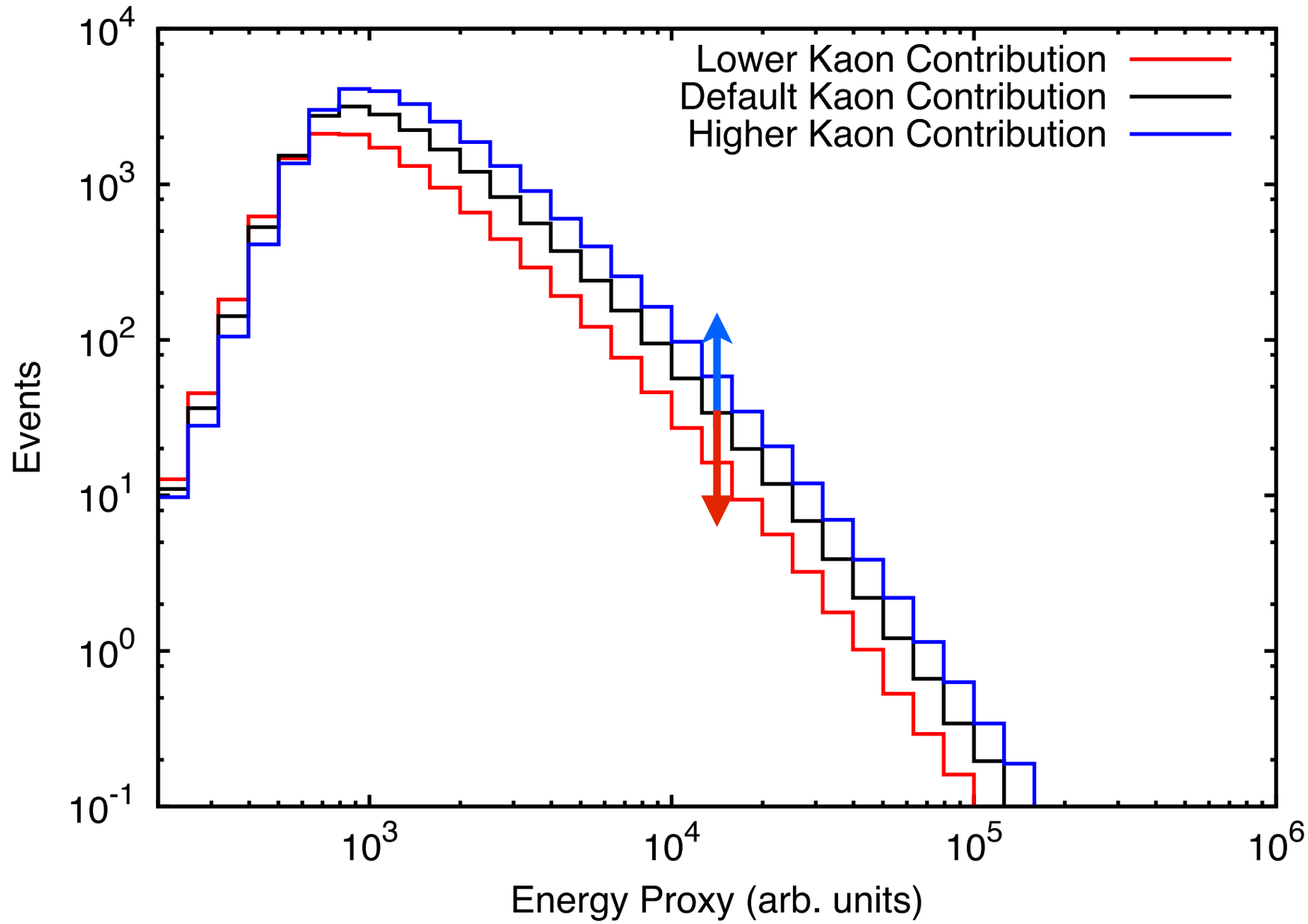
Systematics

The Cosmic Ray Spectrum



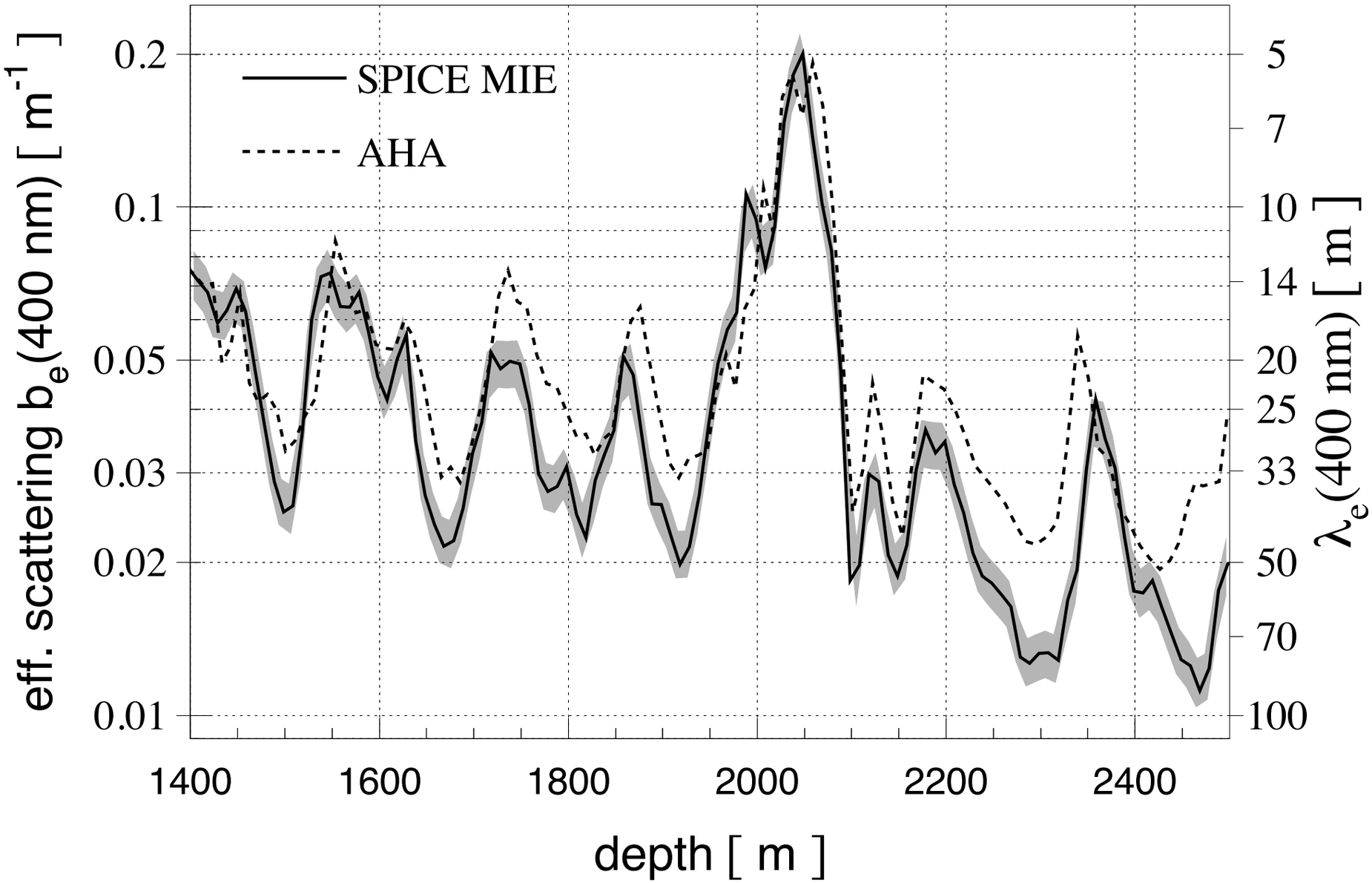
- Want to absorb as many systematic effect as possible into the likelihood fit
- Uncertainty in the slope of the cosmic ray spectrum goes directly into the slope of the atmospheric neutrino spectra

Meson Production



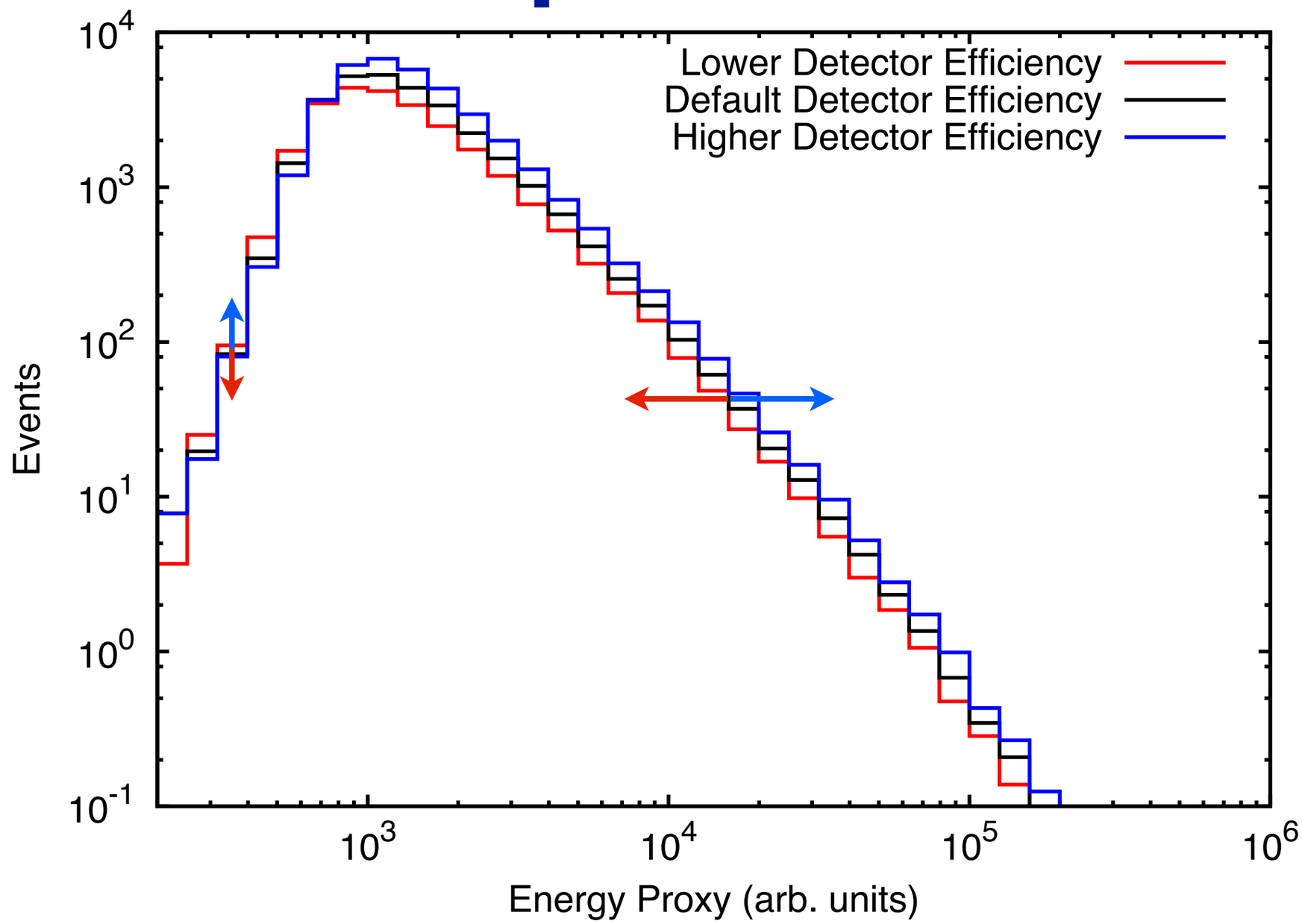
- Atmospheric neutrinos are produced mainly by the decays of light mesons —mostly kaons at >~TeV energies
- Relative production rates are not well measured

Ice Modeling



- Optical properties of the ice must be fit from calibration data
- The whole model has far too many models to fit in the neutrino analysis, can only repeat the fit using discrete model variations

Detector Optical Sensitivity

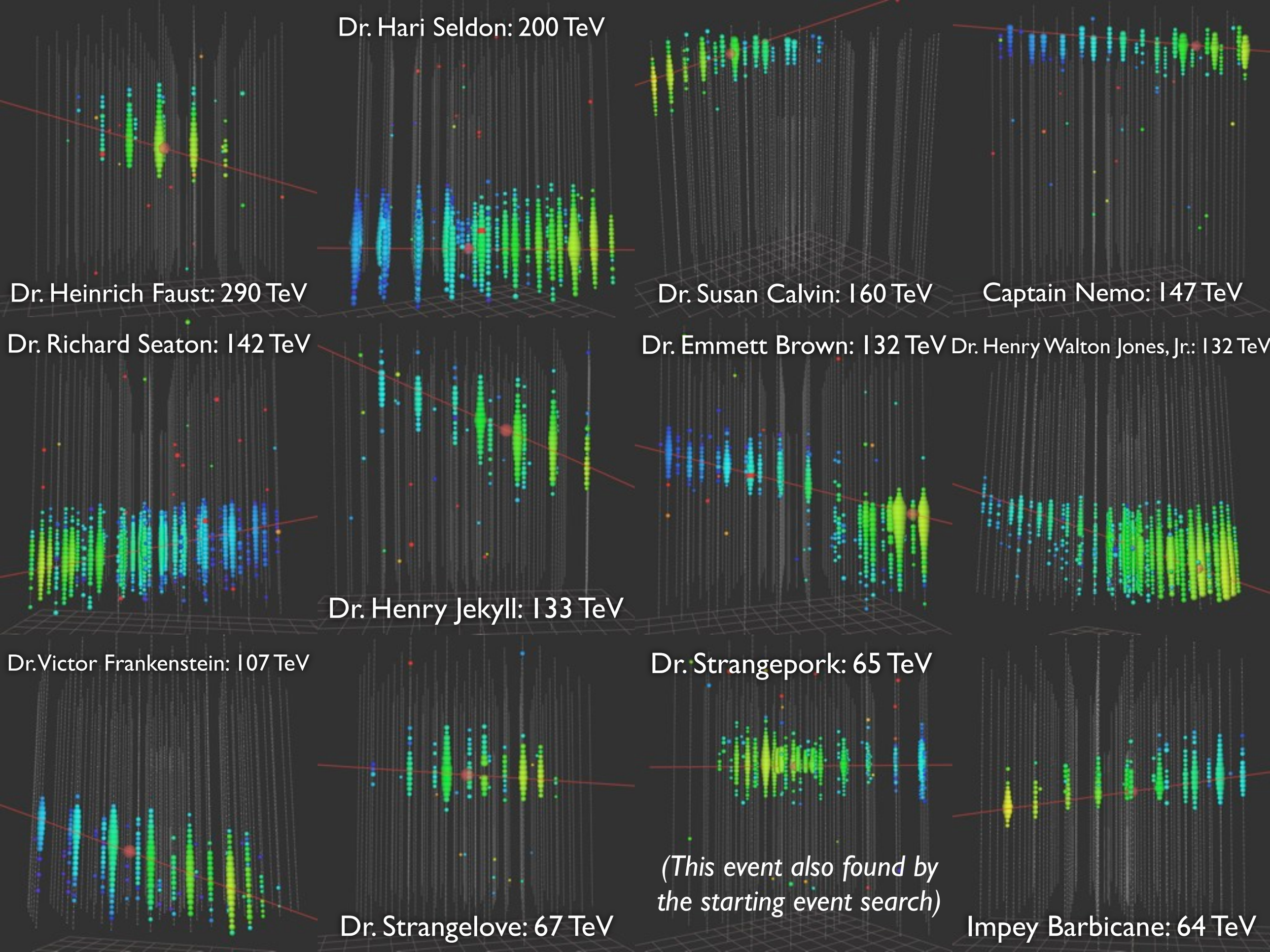


- At high energies an incorrect understanding of detector sensitivity shifts measured energies
- At low energies threshold effects due to photon quantization take over

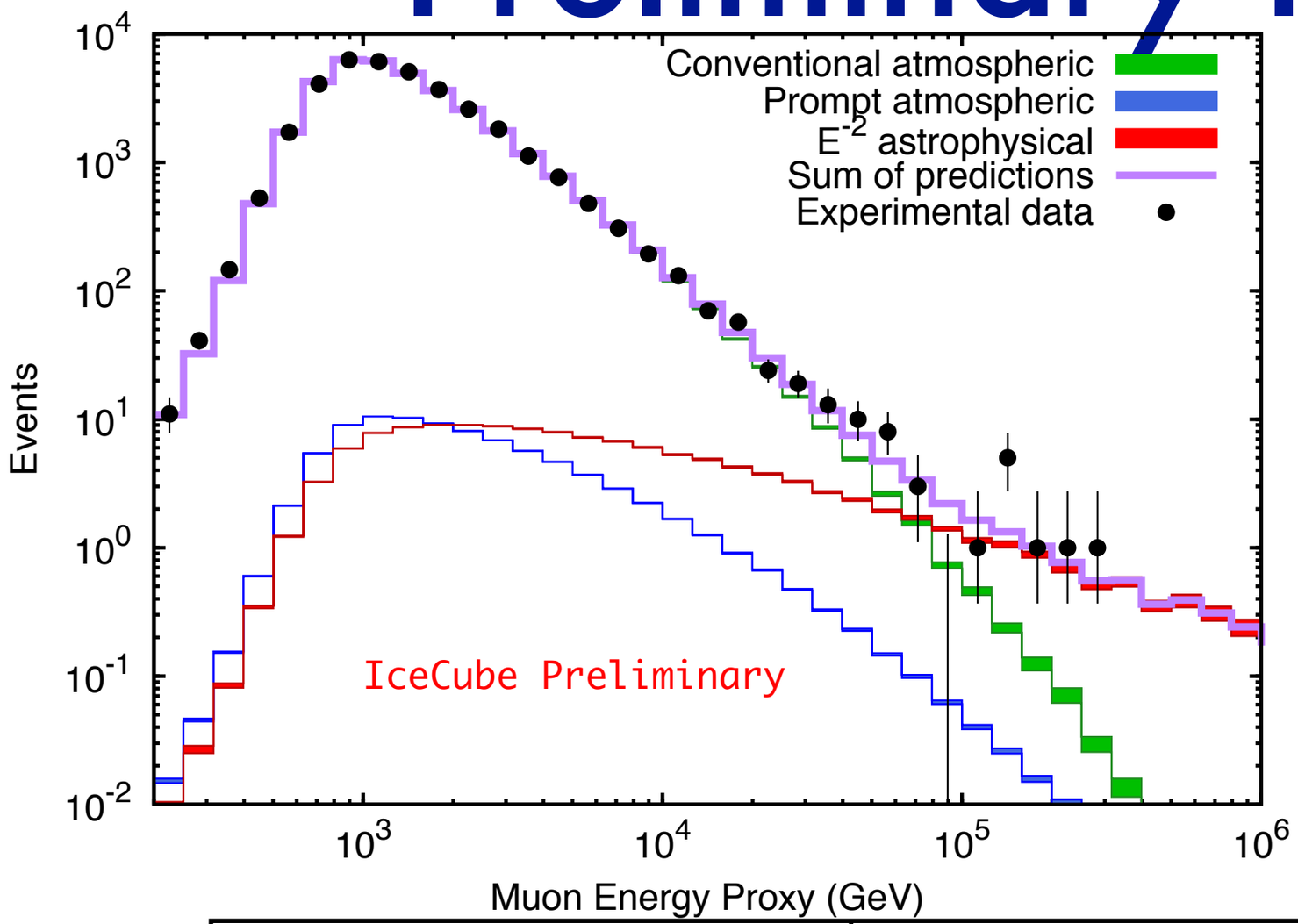
Systematic Effects

Type	Effect	Handling
Input Fluxes	CR normalization	Included in likelihood
	CR slope	Included in likelihood
	CR knee	Repeat fit with different knee models
	Pion/Kaon behavior	Included in likelihood
	Tau neutrinos	Included in likelihood
Particle Interaction	Neutrino cross sections	Repeat fit after reweighting neutrino simulation to match simulation with newer cross sections
Cherenkov Light Propagation	Bulk ice modeling	~Included in likelihood
	Hole ice	Repeat fit on data simulated without hole ice
	Ice anisotropy	Repeat fit on data simulated with simulated anisotropy
Detector Hardware	DOM efficiency	Included in likelihood

Results


Dr. Hari Seldon: 200 TeV
Dr. Heinrich Faust: 290 TeV
Dr. Susan Calvin: 160 TeV
Captain Nemo: 147 TeV
Dr. Richard Seaton: 142 TeV
Dr. Emmett Brown: 132 TeV
Dr. Henry Walton Jones, Jr.: 132 TeV
Dr. Henry Jekyll: 133 TeV
Dr. Victor Frankenstein: 107 TeV
Dr. Strangepork: 65 TeV
(This event also found by the starting event search)
Dr. Strangelove: 67 TeV
Impey Barbicane: 64 TeV

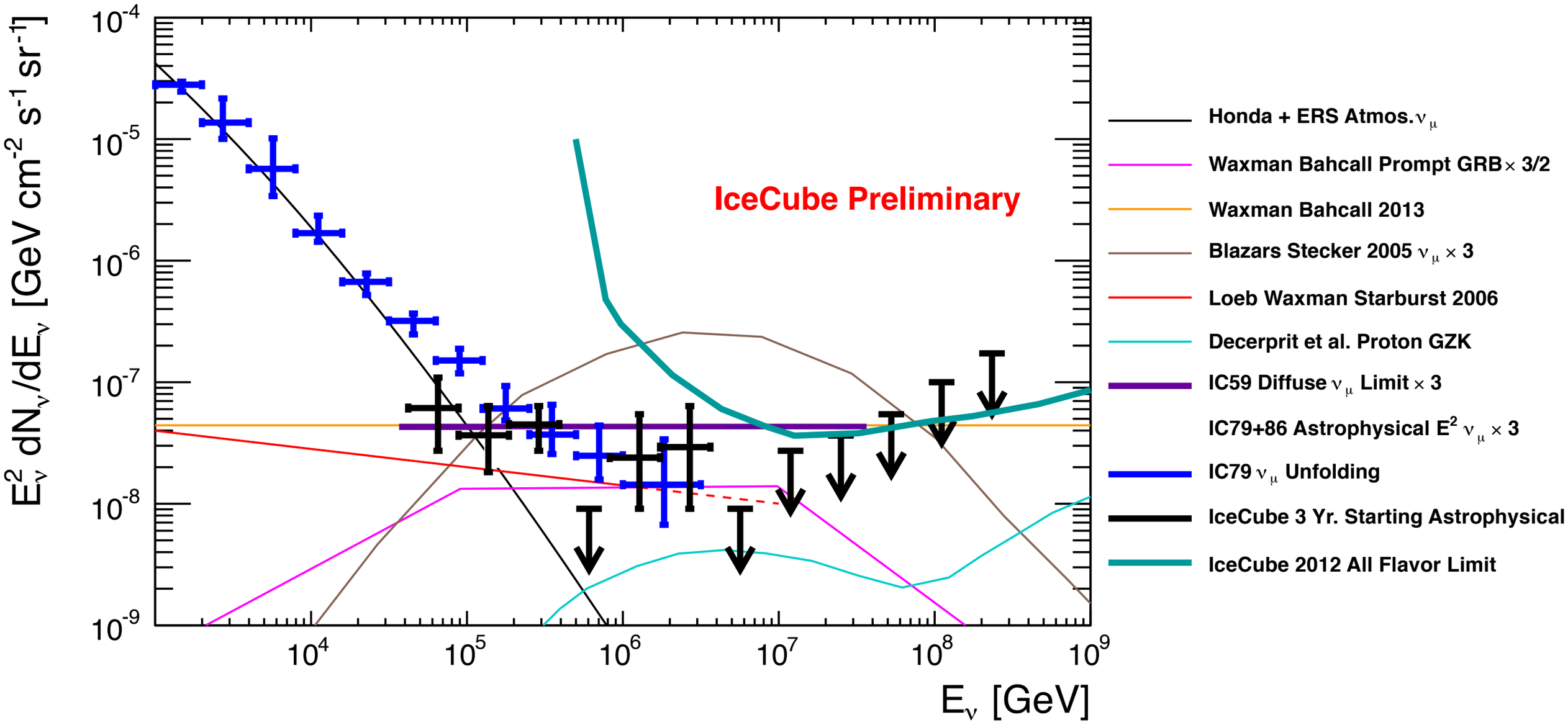
Preliminary Results



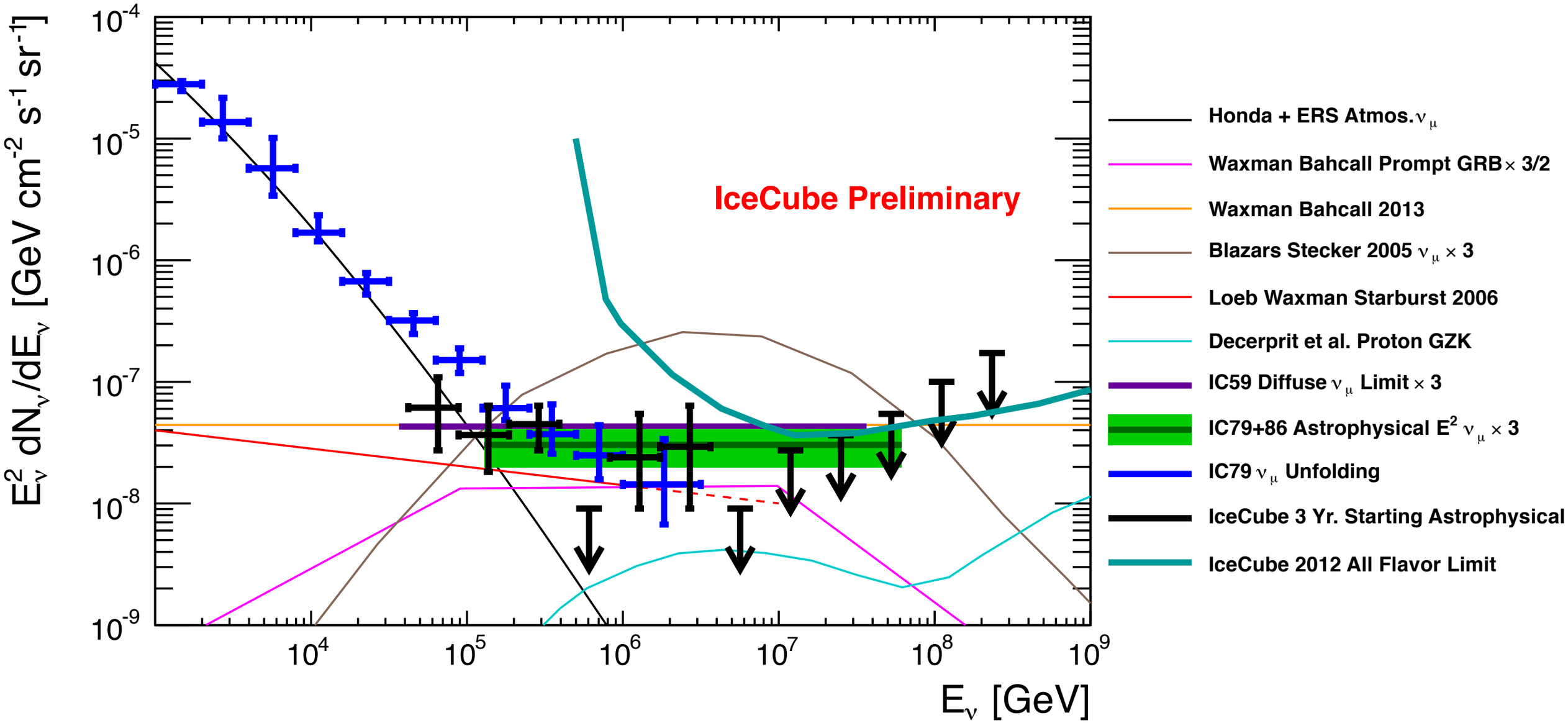
- The best-fit astrophysical flux is 1.01×10^{-8} GeV^{-1} cm^{-2} s^{-1} sr^{-1}
- The atmospheric-only hypothesis is disfavored at 3.9σ.

Conventional Normalization	0.94 [0.90,0.99] times the Honda 2006 flux
Prompt Normalization	0.45 [0,1.91] times the ERS prompt flux
Astrophysical Normalization	1.01×10^{-8} [.69,1.37] GeV^{-1} cm^{-2} s^{-1} sr^{-1}
CR Slope Change	-0.027 [-0.037,-0.016]
DOM efficiency	+18.6% [18.1,19.2]
Relative Kaon Contribution	1.15 [1.09,1.20] times the Honda model

Context

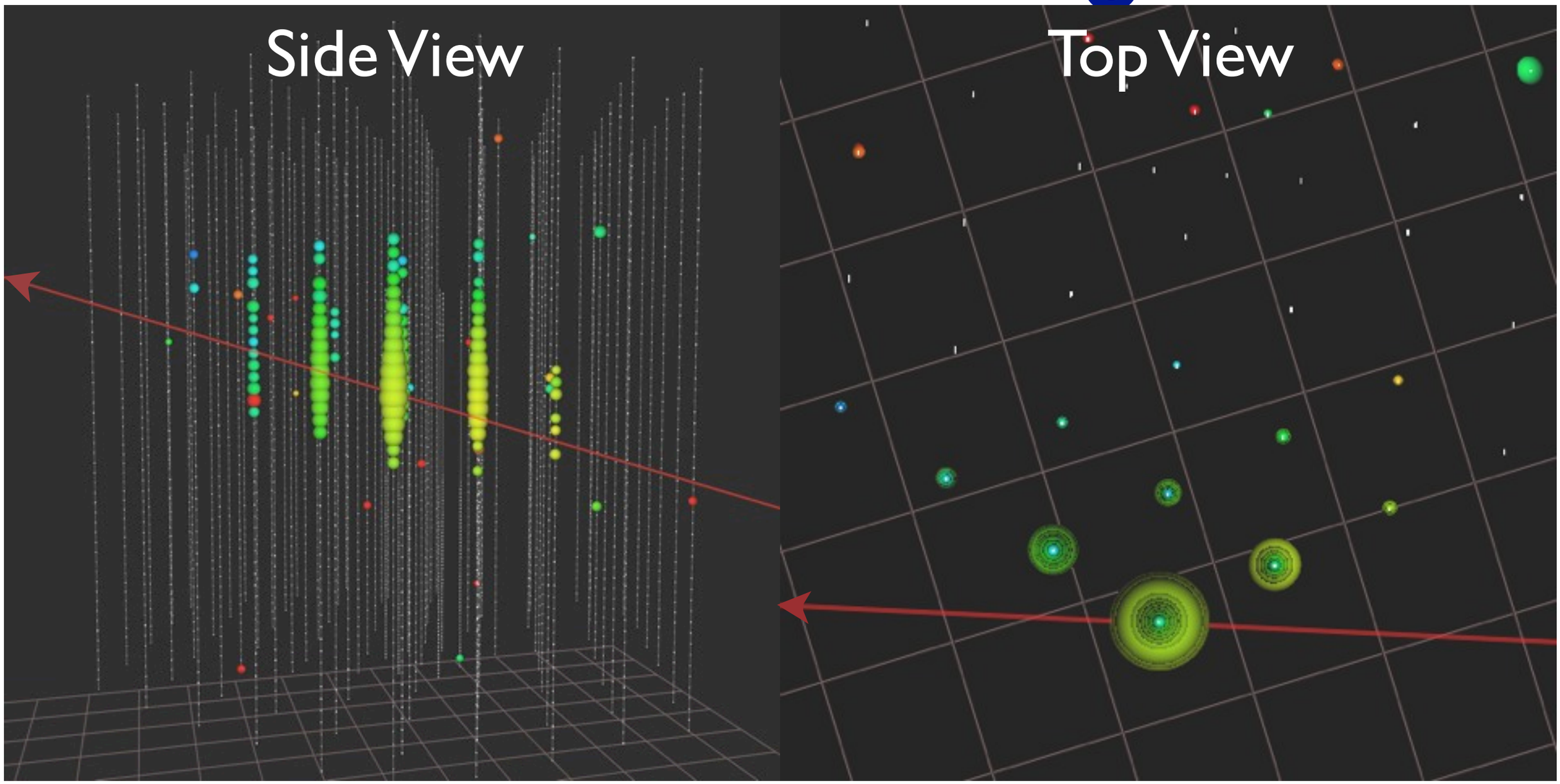

IceCube Preliminary
$E_\nu^2\, dN_\nu/dE_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]
Honda + ERS Atmos. ν_μ
Waxman Bahcall Prompt GRB × 3/2
Waxman Bahcall 2013
Blazars Stecker 2005 ν_μ × 3
Loeb Waxman Starburst 2006
Decerprit et al. Proton GZK
IC59 Diffuse ν_μ Limit × 3
IC79+86 Astrophysical E^2 ν_μ × 3
IC79 ν_μ Unfolding
IceCube 3 Yr. Starting Astrophysical
IceCube 2012 All Flavor Limit

Context



The flux observed by this analysis is compatible with the starting event result, although it is a (nearly) disjoint data sample

A close look at a single event

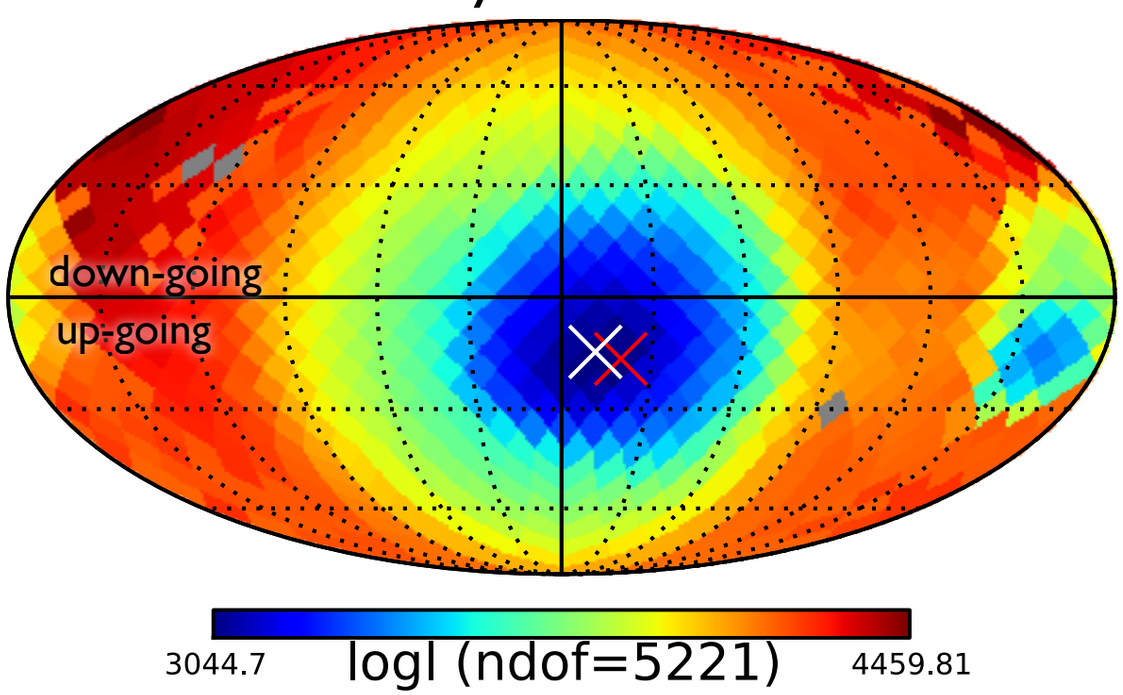


- Event reconstructed as a '~300 TeV' muon with a zenith angle of 106°
- By eye, this isn't very certain
- How do we know that this is an up-going signal track, not a down-going background track?

Can we do a more detailed reconstruction?

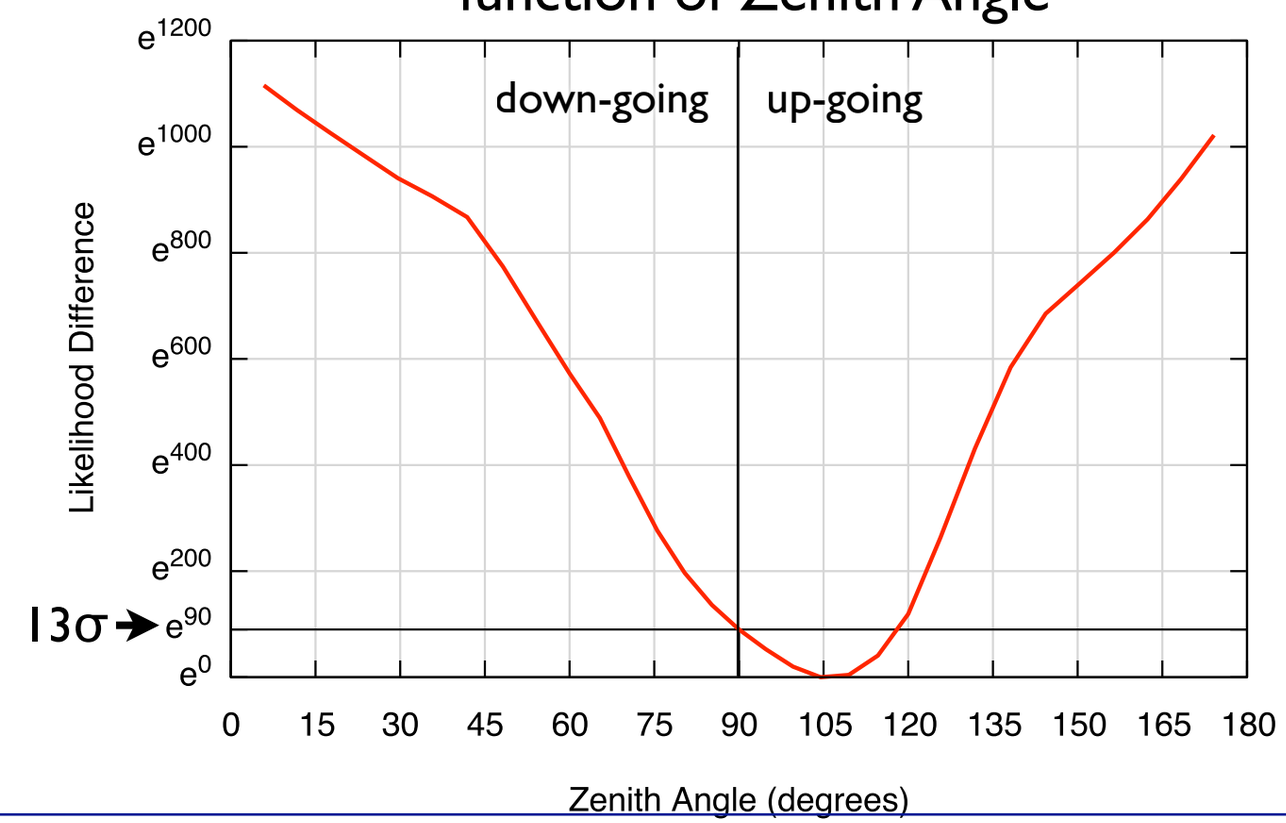
- For each a grid of possible directions, unfold the energy losses required to produce the observed light pattern
- Comparing the resulting likelihoods, we see that all down-going solutions are strongly disfavored (at least 13σ)

Whole-sky Likelihood Scan



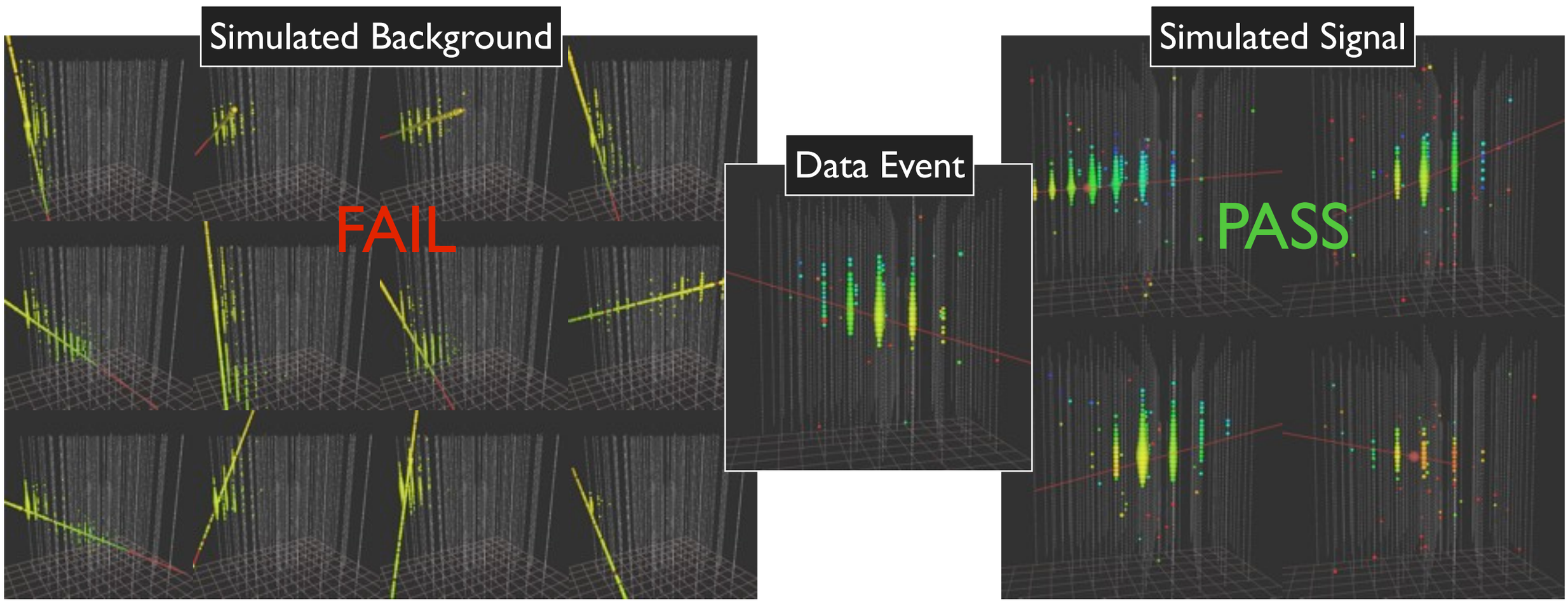
White X: Best scan result
Red X: Simple result

Best Likelihoods as a function of Zenith Angle

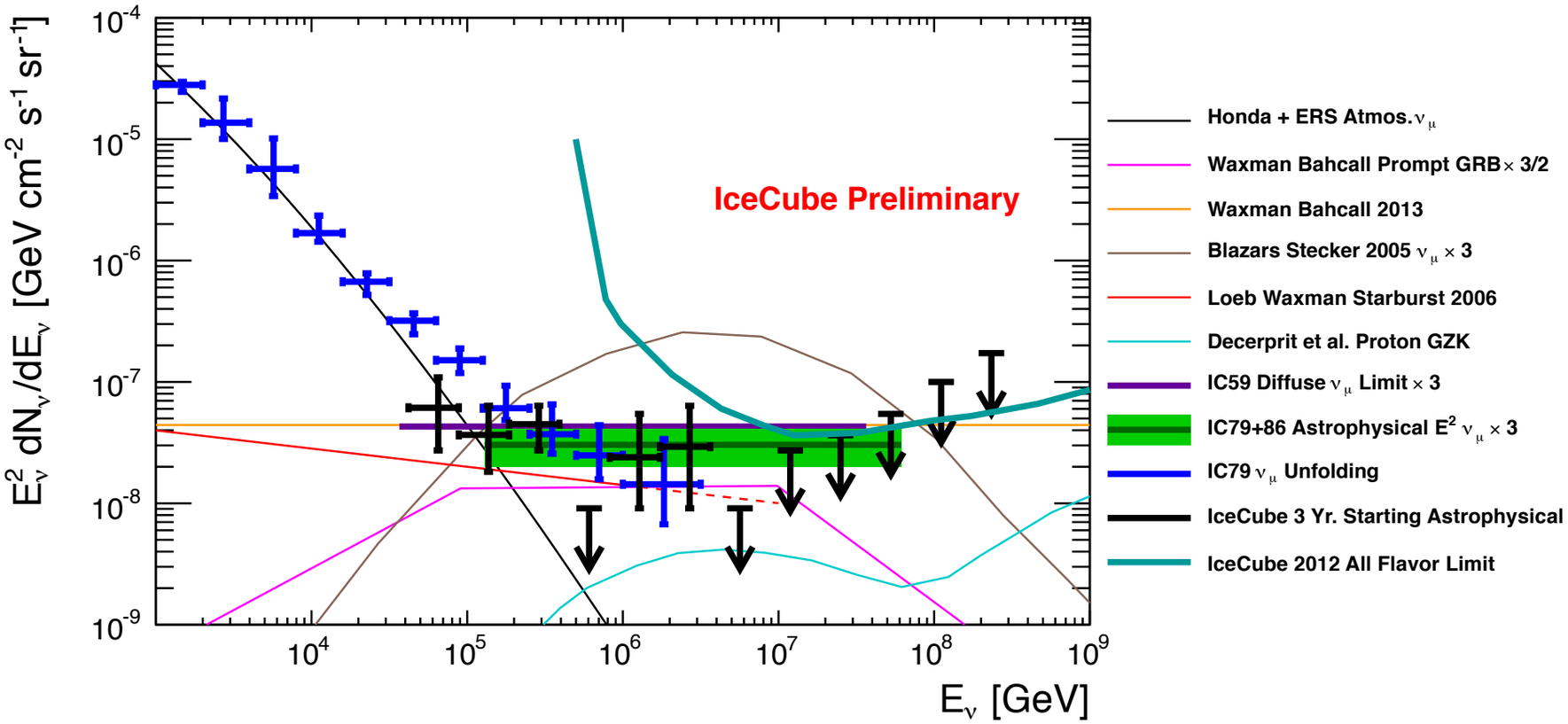


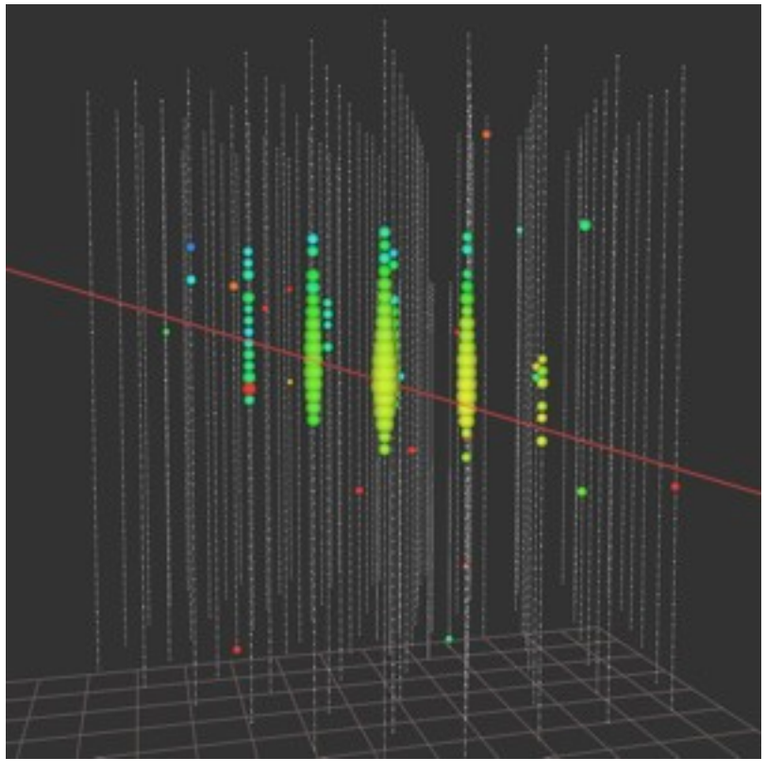
Can we simulate a similar event?

- In >100 years equivalent of simulated background, no events with similar geometries pass the selection criteria
- A simulation of signal events produces a number of successes



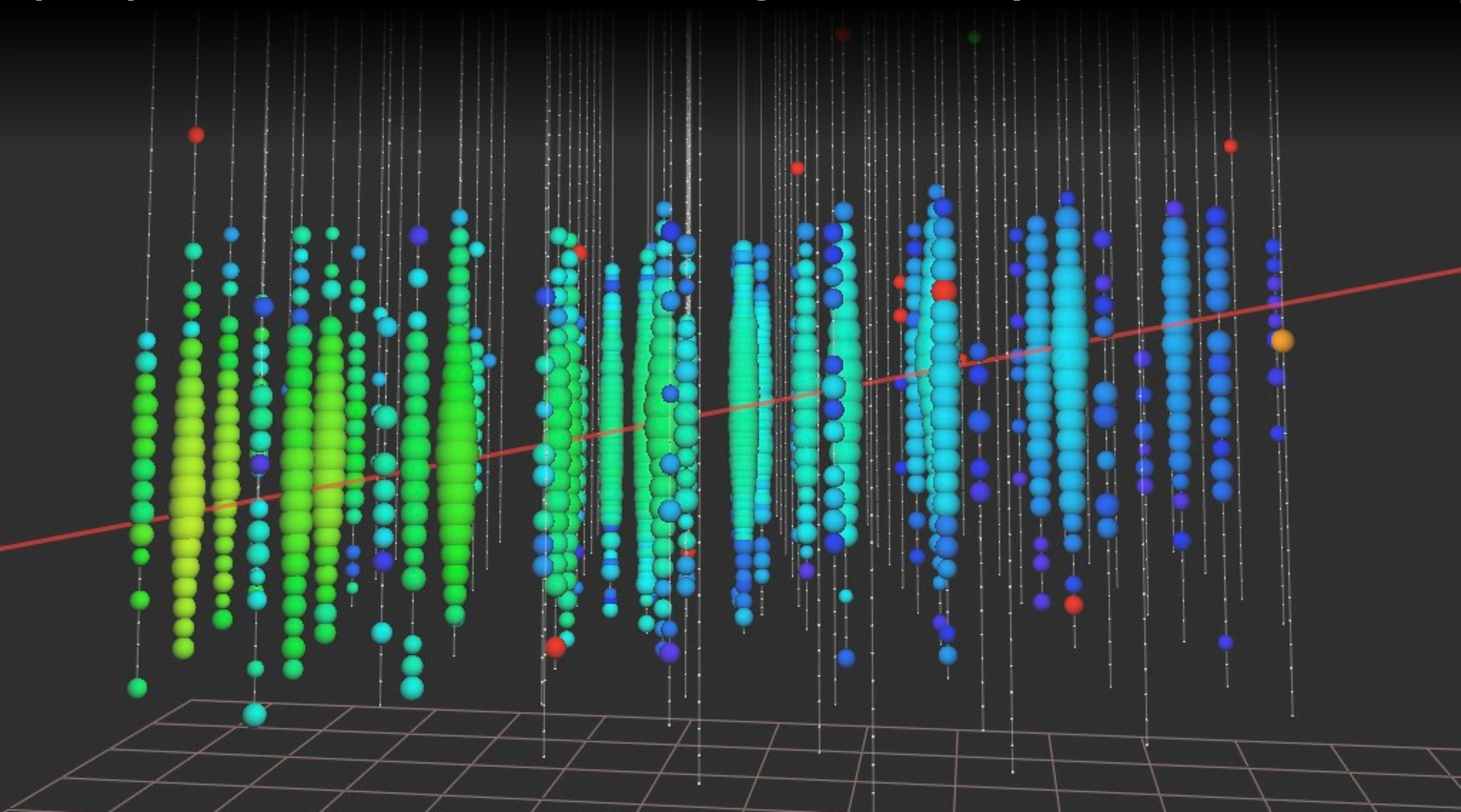
Conclusions



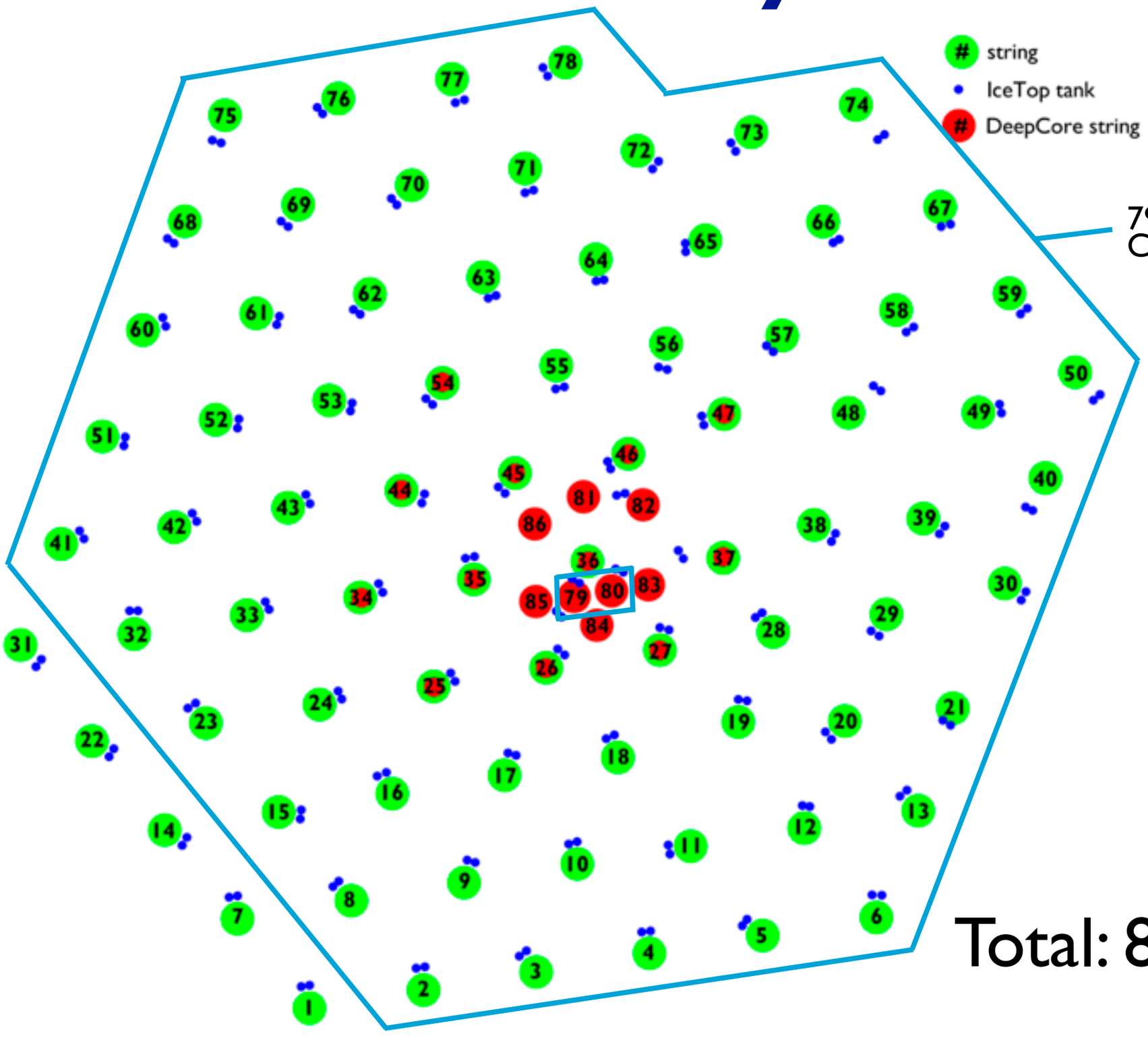


- Analyses of different detection channels in IceCube point to the same astrophysical neutrino flux (~10^{-8} GeV^{-1} cm^{-2} s^{-1} sr^{-1})
- For (neutrino induced) muon events IceCube can not only make use of events which interact far from the detector, but also some events which never properly enter the detector

One big open question: If a number of these events are astrophysical, what sources do they come from? Unfortunately, this analysis can't give the answer, but many people in IceCube are thinking about ways that we could!

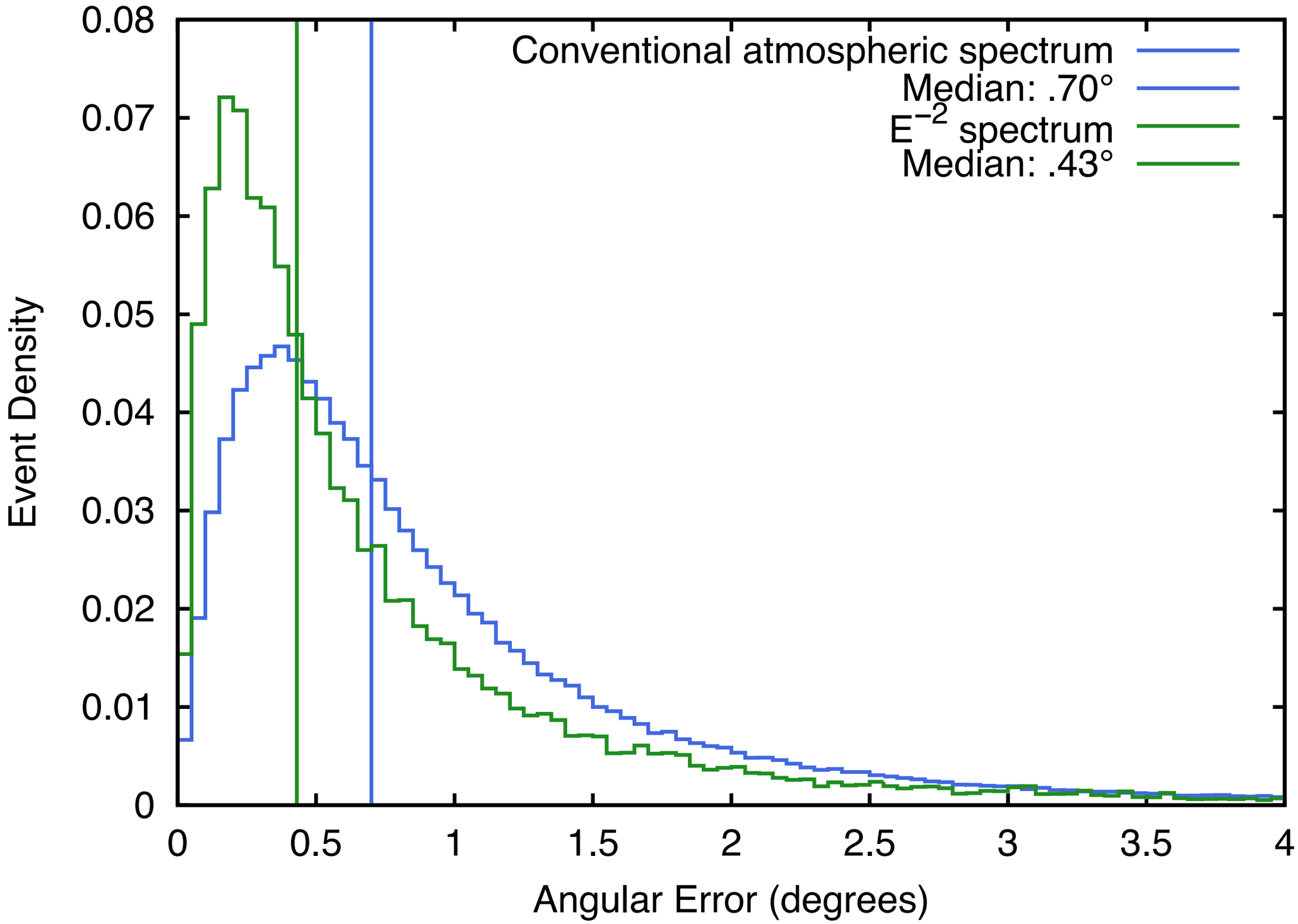


Detector Layout

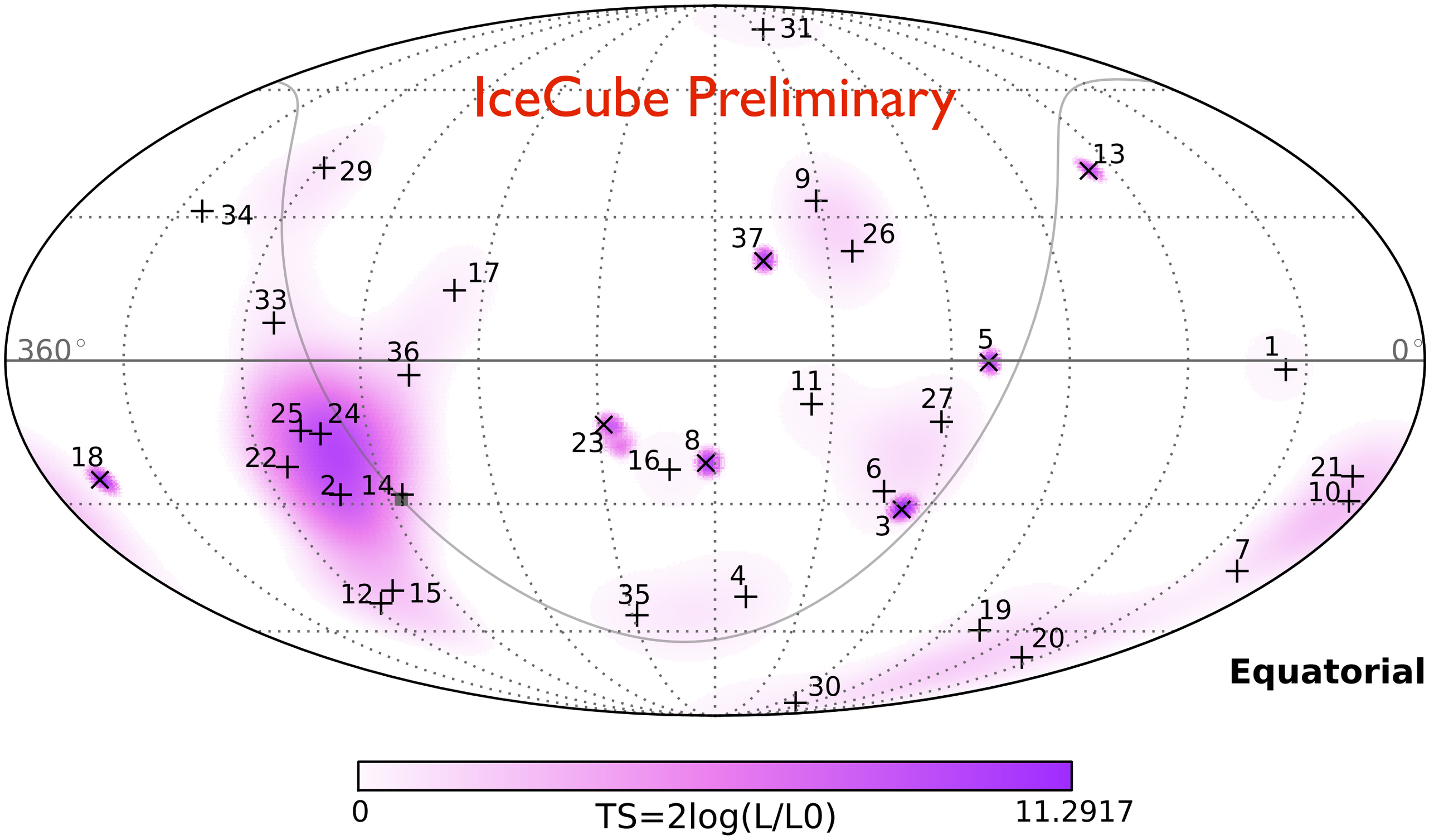


Total: 86 Strings

Angular Resolution

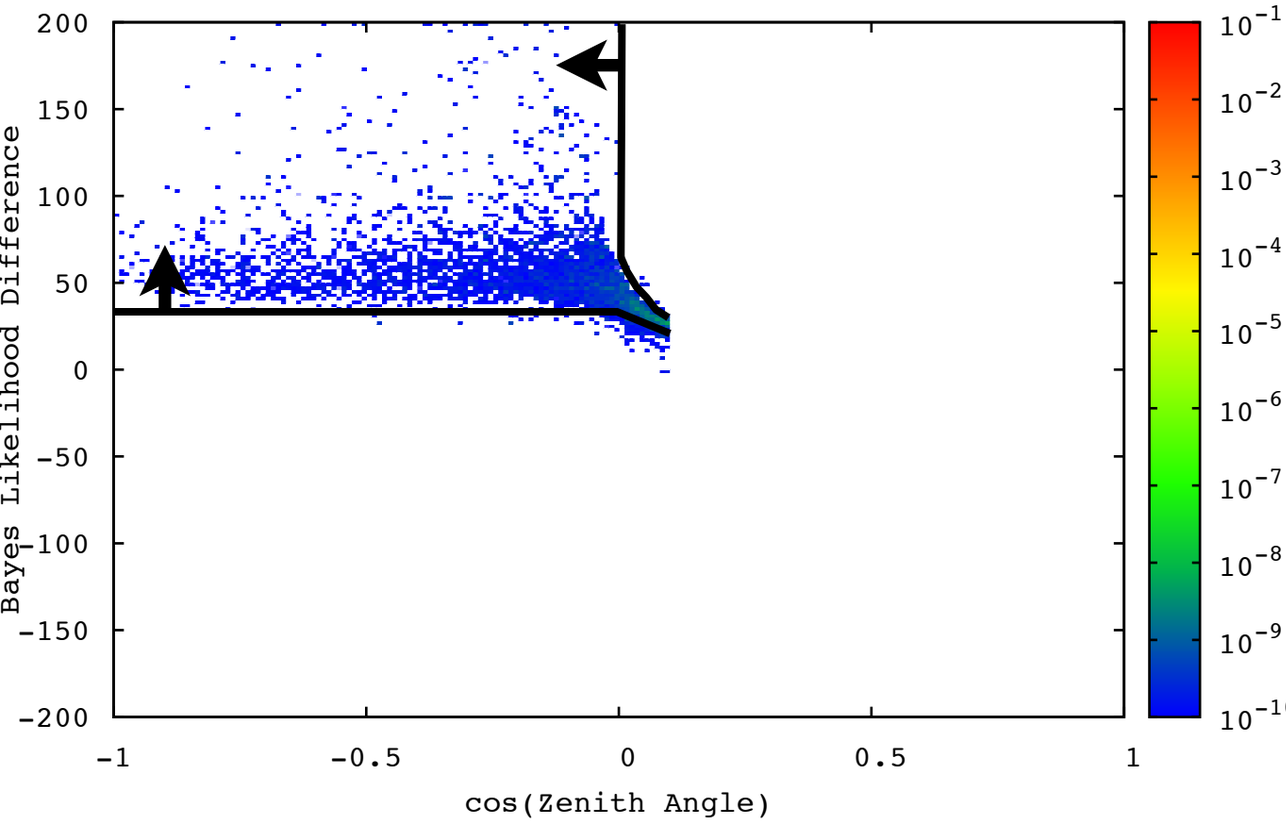


Starting Events—3 Years

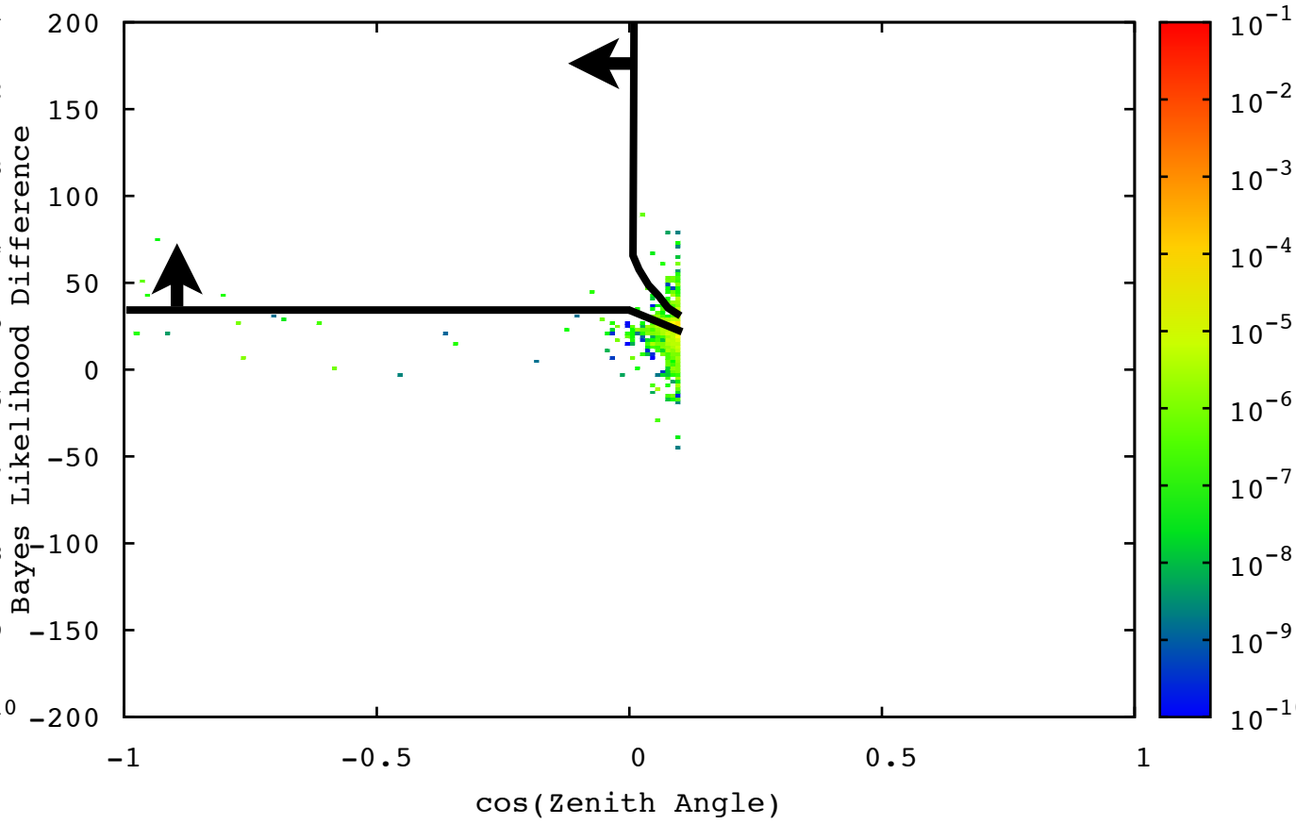


Bayesian Reconstruction Cut

E^{-2} Neutrinos



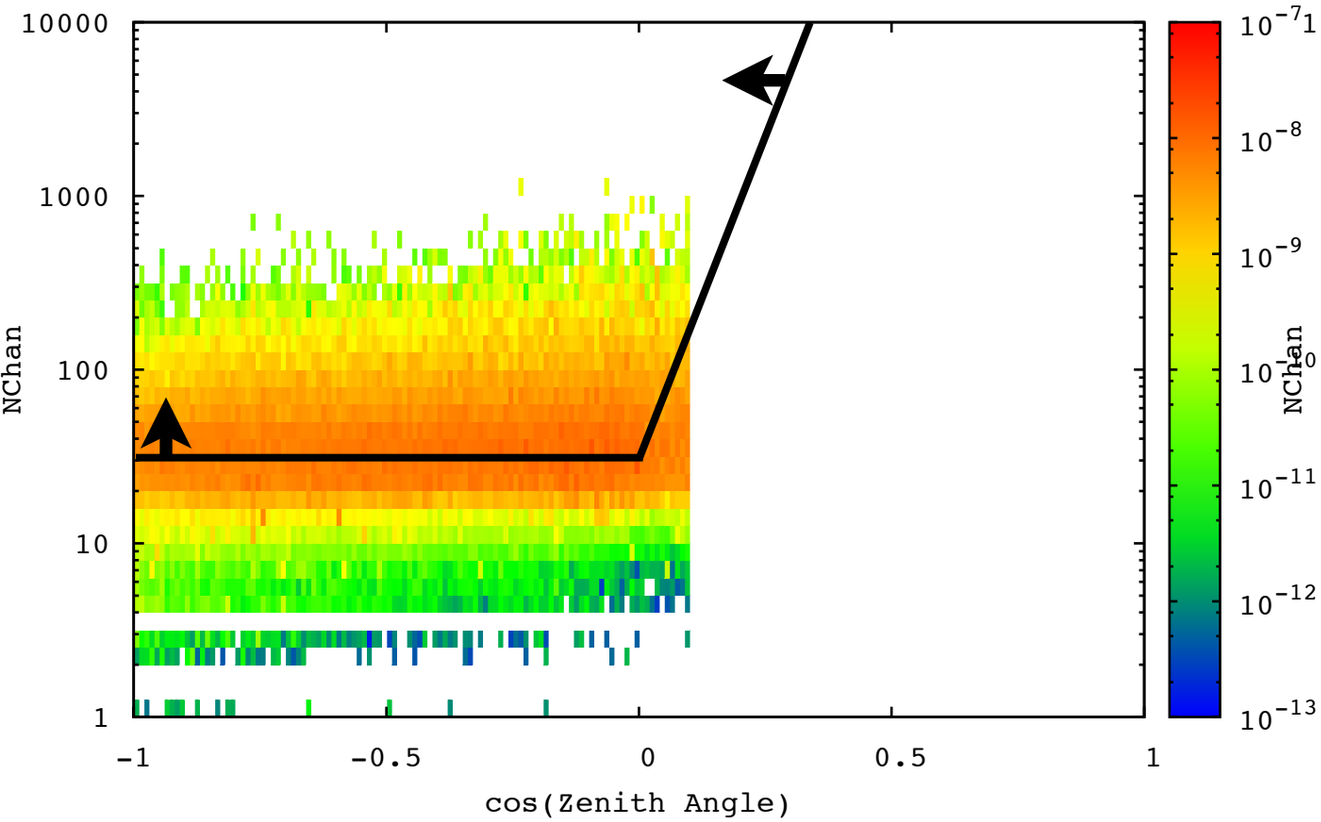
Simulated Airshowers



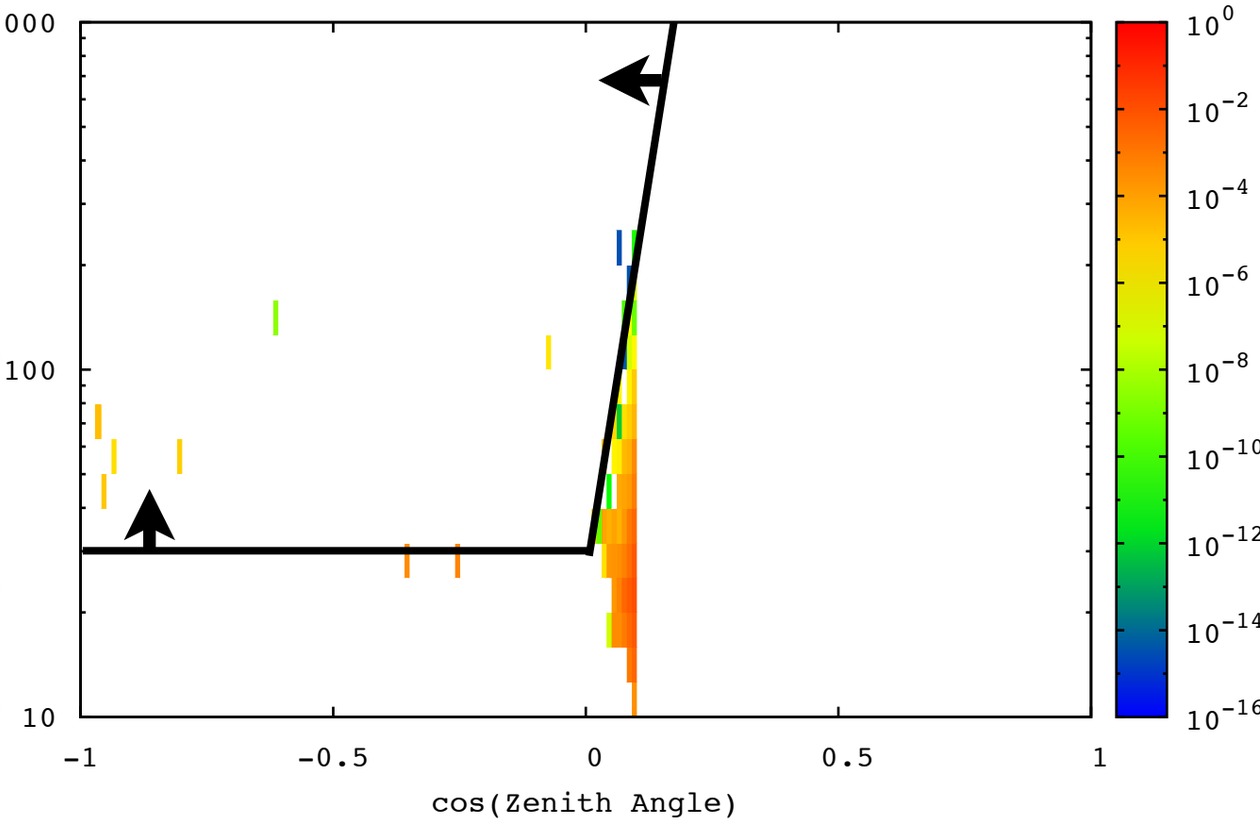
- Another way to check for a successful reconstruction is to compare the standard reconstruction to a constrained reconstruction which uses a prior based on the expected airshower distribution

Filter by Energy and Overburden

E^{-2} Neutrinos



Simulated Airshowers



- Most of the remaining background events near the horizon are low energy muon bundles which are close to ranging out
- Number of triggered detector channels is a simple energy measure
- The target signal spectrum is harder, so dim, low energy events can be cut