Tue Jan 3 03:34:01 2012

IceCube High Energy Neutrinos

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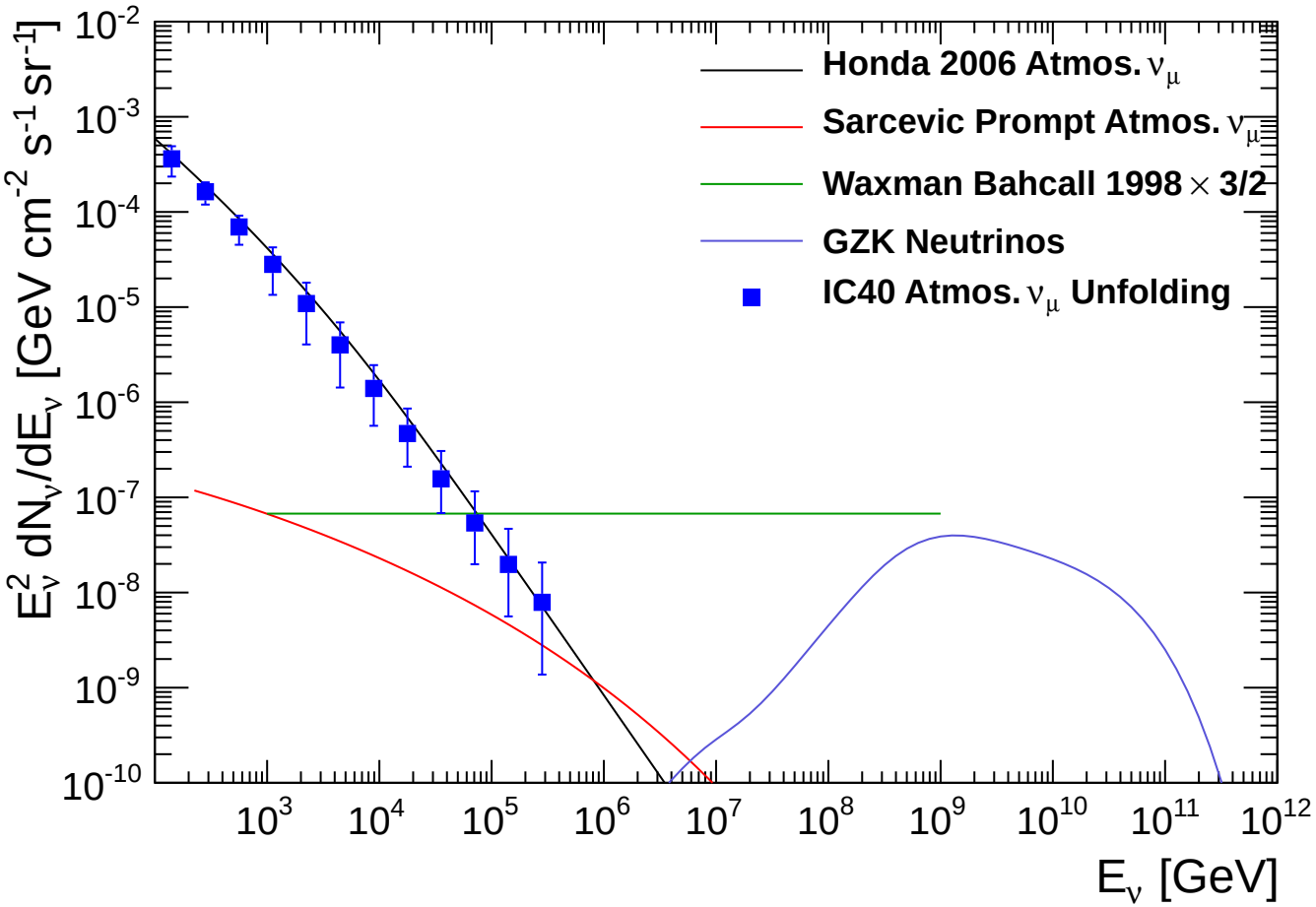
July 30, 2013

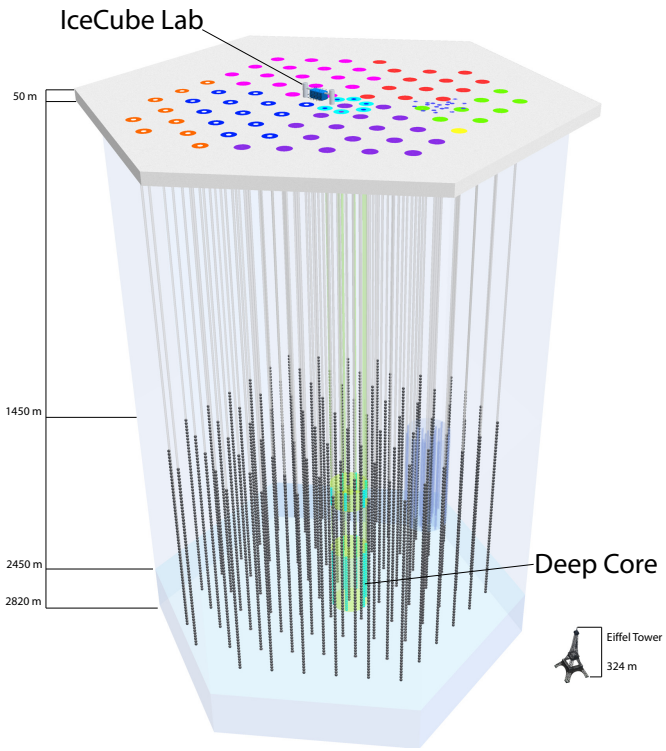
The Neutrino Landscape above 1 TeV

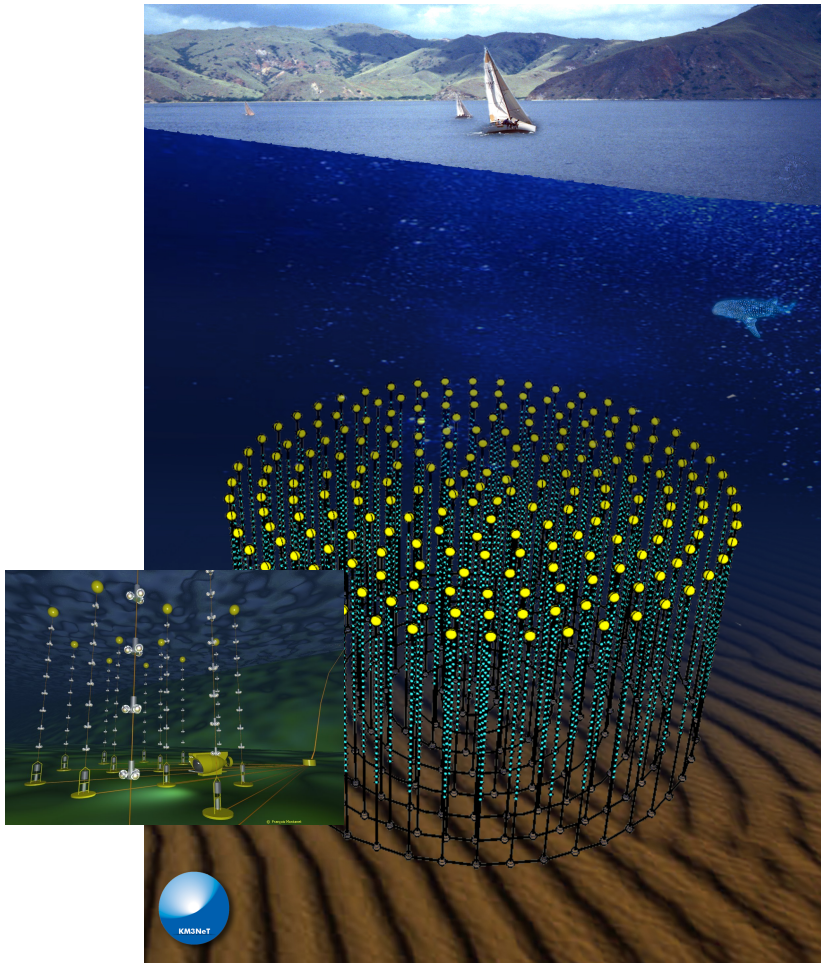


- π/K Atmospheric Neutrinos (dominant $<$ 100 TeV)
- Charm Atmospheric Neutrinos ("prompt", visible $\sim$ 100 TeV)
- Astrophysical Neutrinos (maybe dominant $>$ 100 TeV)
- Cosmogenic Neutrinos ($> 10^6$ TeV)

Gigaton Detectors To See High-Energy Component

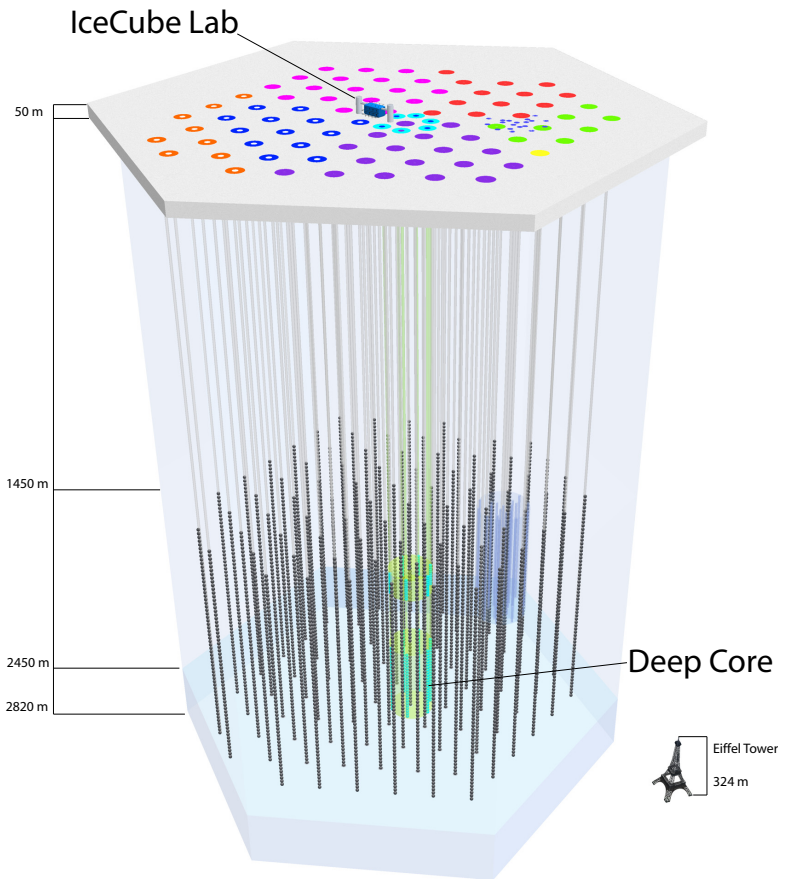
Need natural detectors: IceCube, KM3NET (future), ANTARES, Baikal





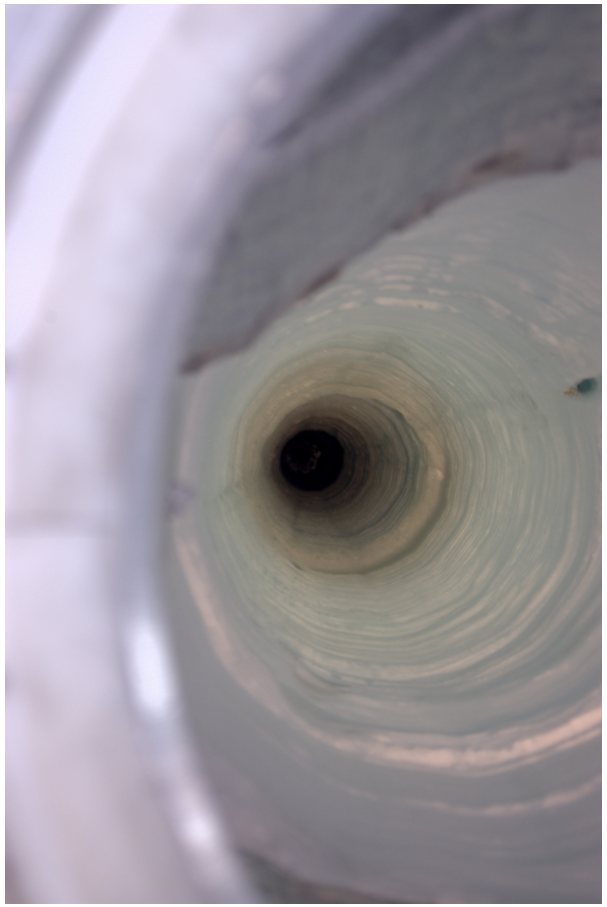
IceCube

- 5160 PMTs
- 1 km^3 volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 120 m string spacing
- Completed 2010



Physics Reach of IceCube

- Astrophysical ν
  - Understand Cosmic Ray Source Populations
  - Indirect Dark Matter Searches
  - Lorentz Invariance Violation
  - Direct Observation of ν_τ
- Atmospheric ν
  - Measurement of Atmospheric Neutrino Spectrum (100k events/year)
  - Measurement of θ_{23}
  - Cross-sections at ultra-high energies
  - Cosmic Ray Measurements

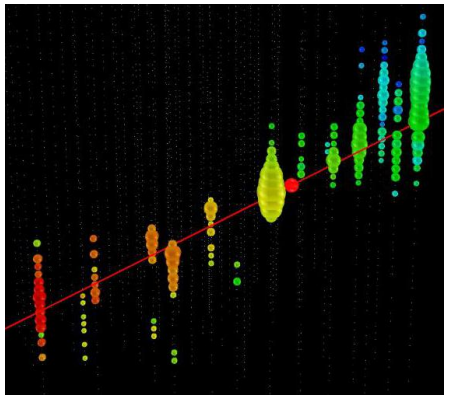


Event Signatures

Muon Neutrino CC (data)

< 1 degree angular resolution

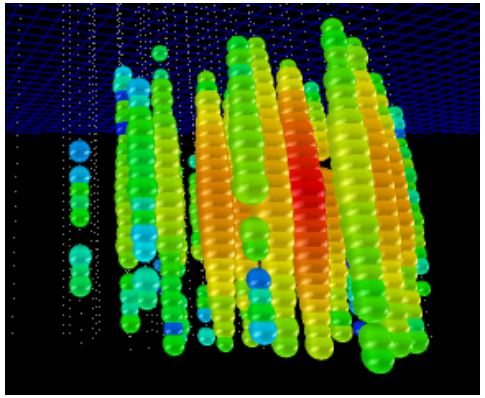
factor of 2 resolution of muon energy



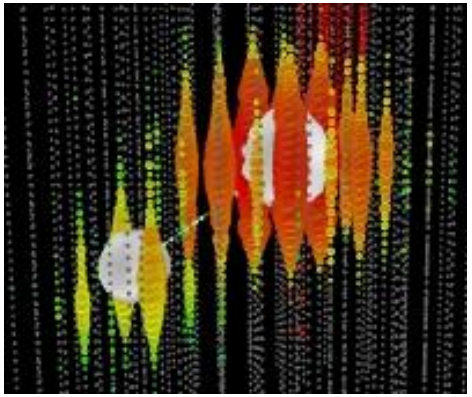
Neutral Current or Electron Neutrino (data)

10 degree angular resolution (high energy)

$\sim 15\%$ deposited energy resolution



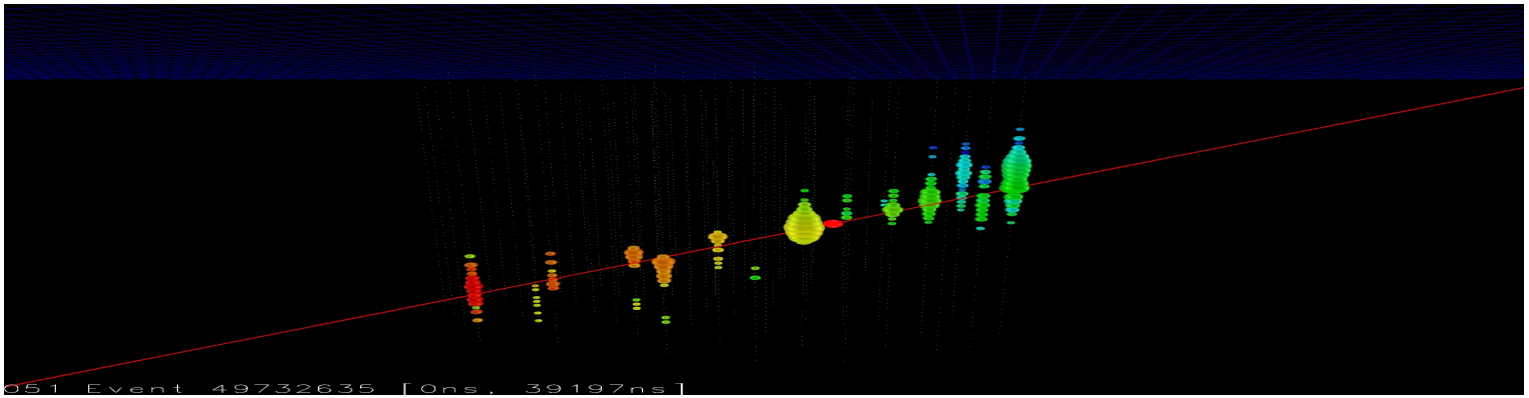
Tau Neutrino CC (simulation)



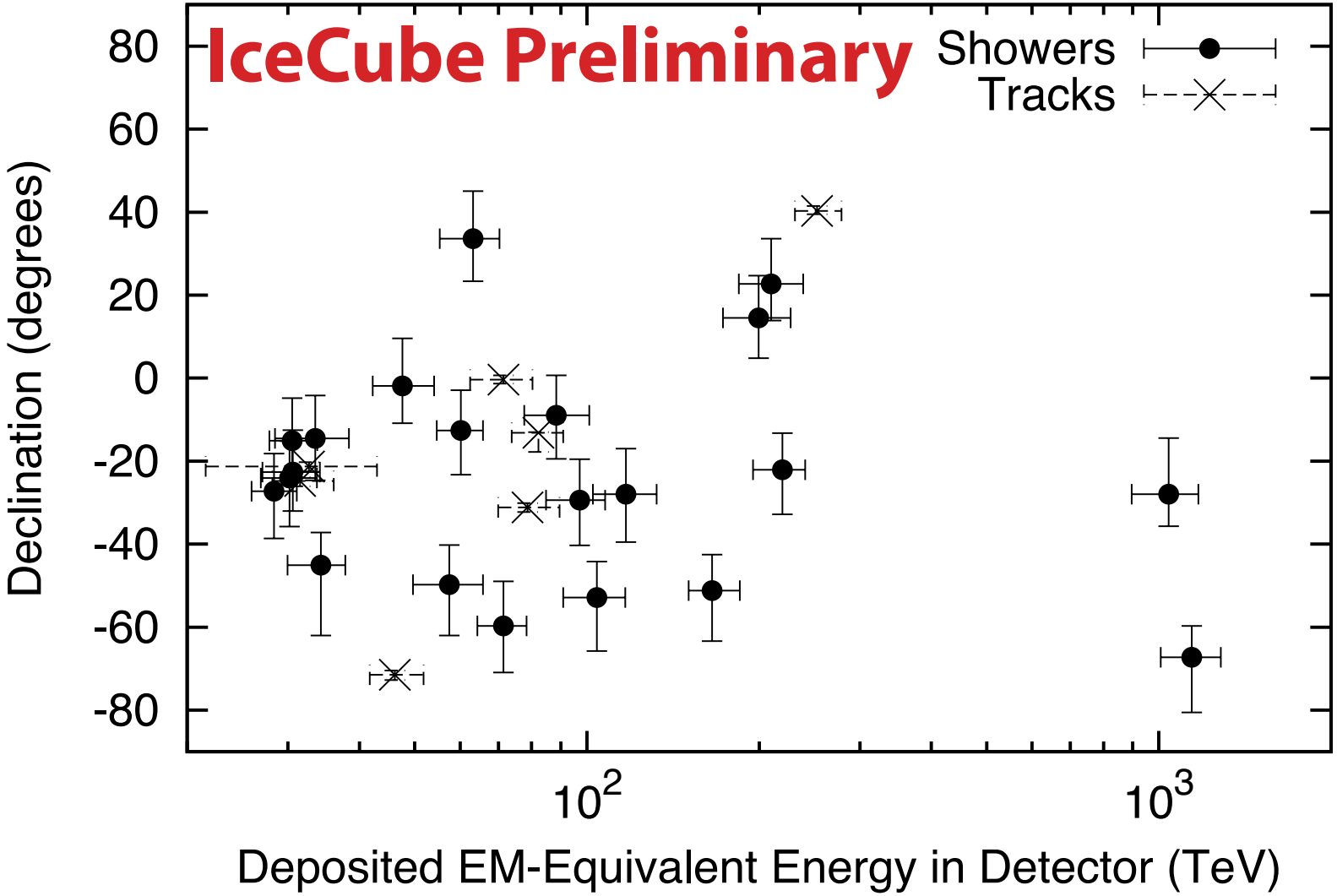
Neutrino Identification

How to identify neutrinos?

1. Upgoing muon tracks
   - Filter out CR muons with bulk of Earth
   - Unknown vertex – hard to measure energy
2. Contained vertex
   - Filter out CR muons using detector edge for anticoincidence
   - All charged particles seen
3. Excess over background
   - Works only for extremely bright/high energy sources



Results of Contained Vertex Event Search



28 events (7 with visible muons, 21 without) on background of $10.6^{+5.0}_{-3.6}$

Observables of Interest

Spectral slope Separate extraterrestrial fluxes from atmospheric, probe properties of accelerator

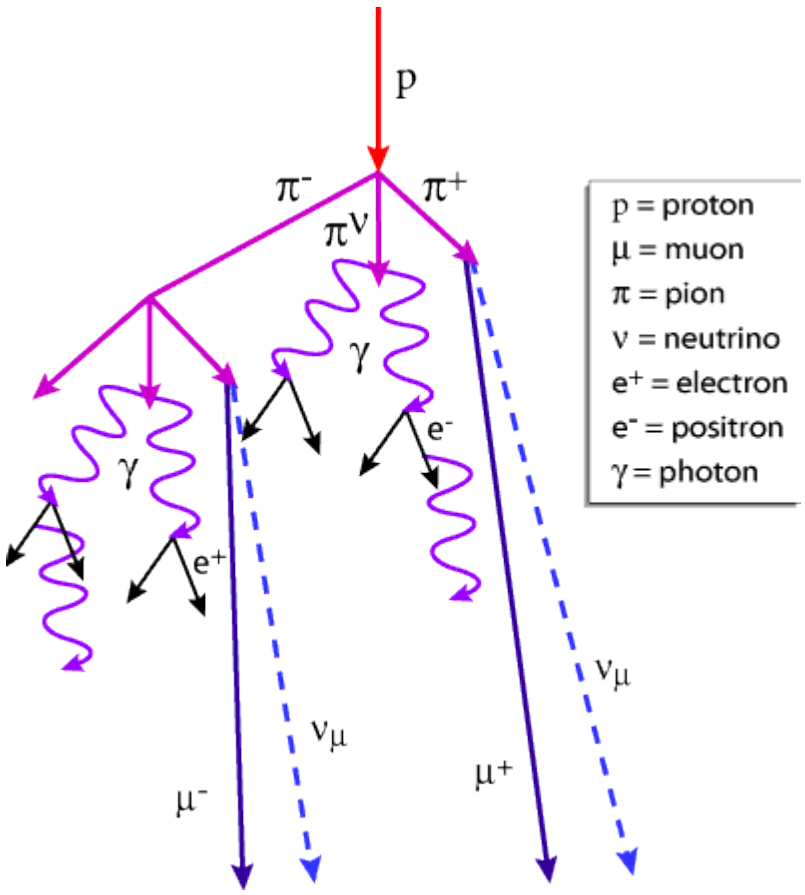
Spectral structure Cutoffs/slope changes may imply population changes

Flavor composition Discrimination against ν_μ dominated backgrounds, probes physics of production process

Zenith distribution Comparison to backgrounds, probes source locations

Vetoing Atmospheric Neutrinos: an Interesting Wrinkle

- Atmospheric neutrinos are made in air showers
- For downgoing neutrinos, the muons from the shower will likely not have ranged out when they arrive at IceCube
- Downgoing events that start in the detector are extremely unlikely to be atmospheric
- Note: optimal use requires *minimal* overburden to have the highest possible rate of cosmic ray muons



Schönert et al. arXiv:0812.4308

Signals and Backgrounds: Why This is Compelling

	Signal		Background		Data
✔	Cascade-dominated ($\sim 80\%$) from oscillations	✘	Track-like from CR muons and atmospheric ν_μ	•	21/28 are cascades
✔	High energy? Typically assume E^{-2}	✘	Soft spectrum ($E^{-3.7}$), $\lesssim 1$ event/year $>$ 100 TeV	•	Energies to above 1 PeV, 9 above 100 TeV
✔	Mostly (2/3) in southern sky from Earth absorption	✘	Muons in south, atmospheric neutrinos in north	•	24/28 from South, mostly cascades

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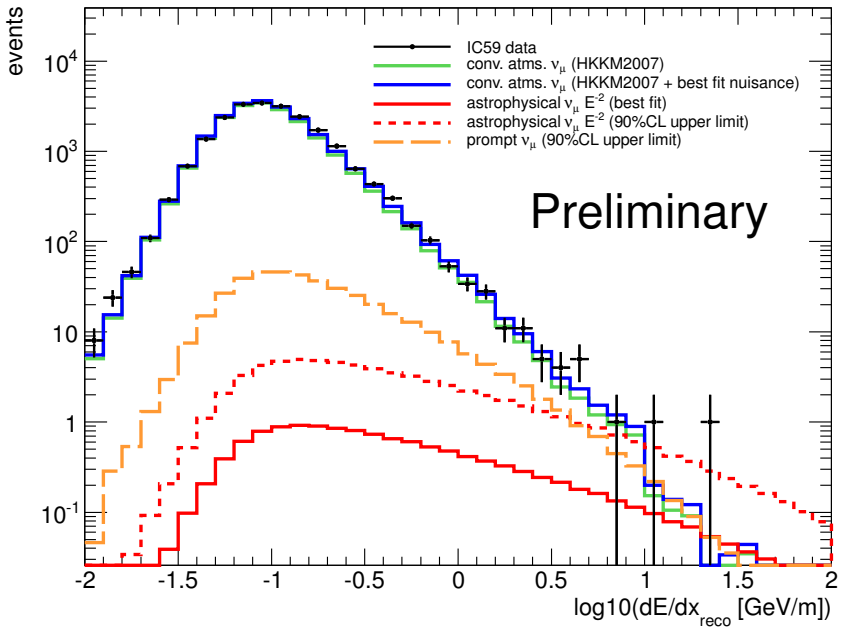
$\rightarrow 4\sigma$ evidence for astrophysical flux

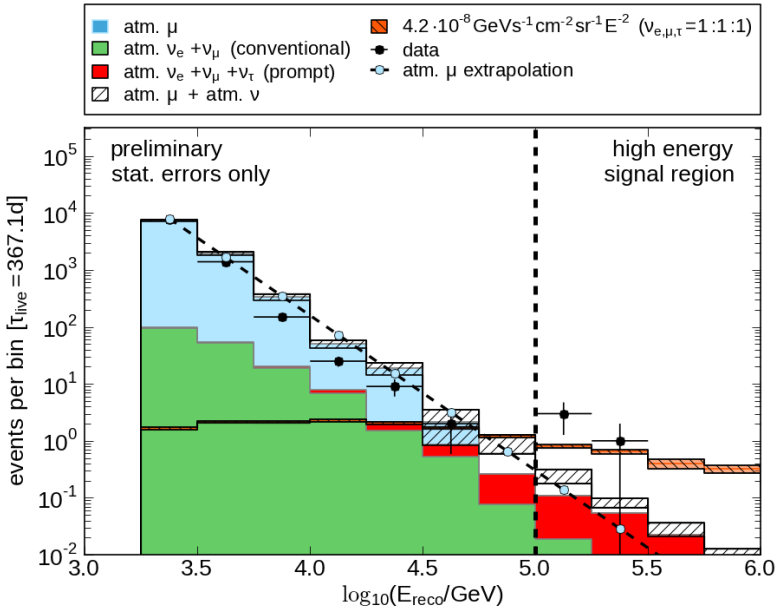
Hints in other channels

IC59 Northern ν_μ arXiv:1302.0127



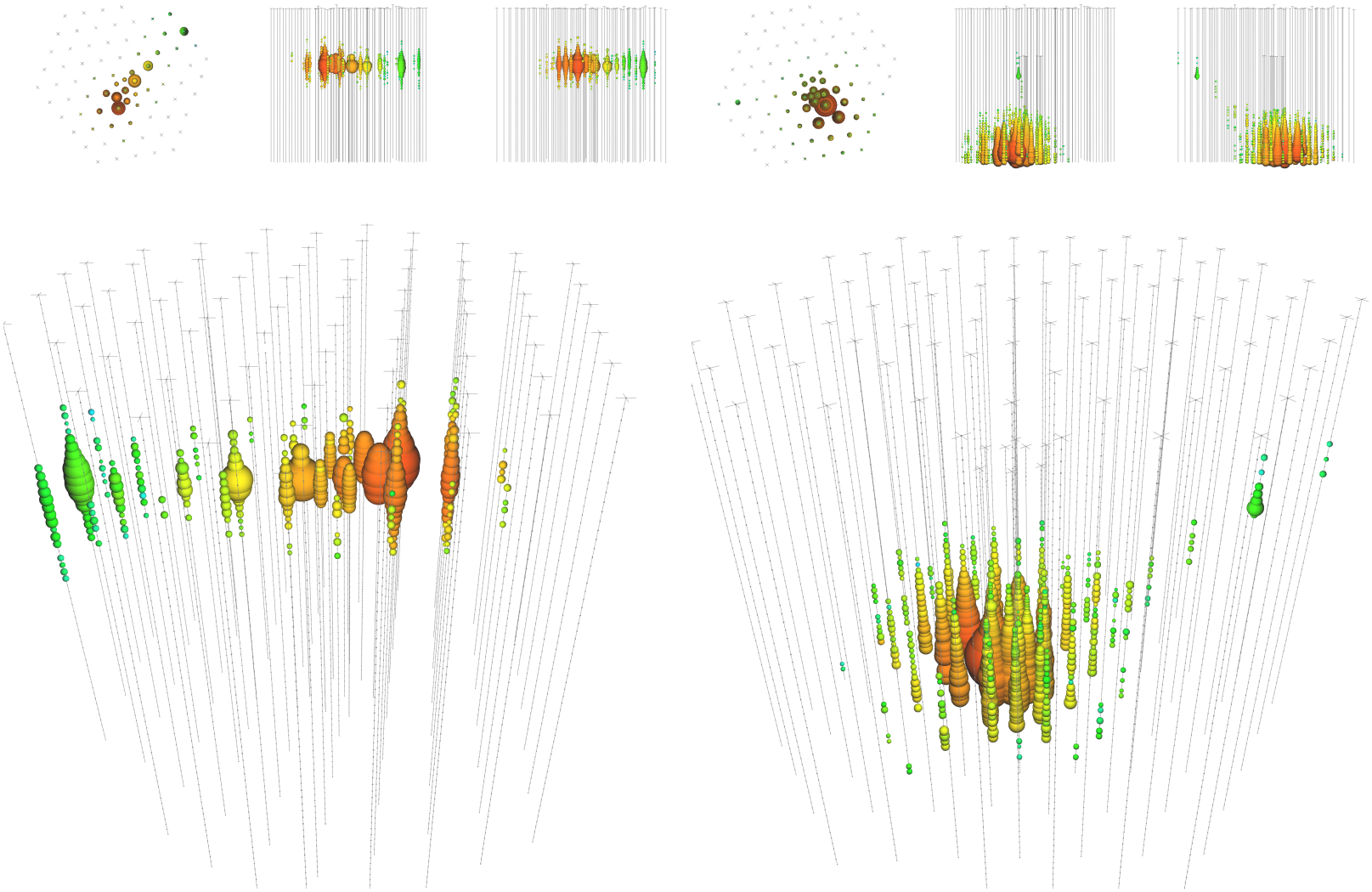
2009, 1.8σ

IC40 Cascades



2008, 2.4σ

Some interesting events

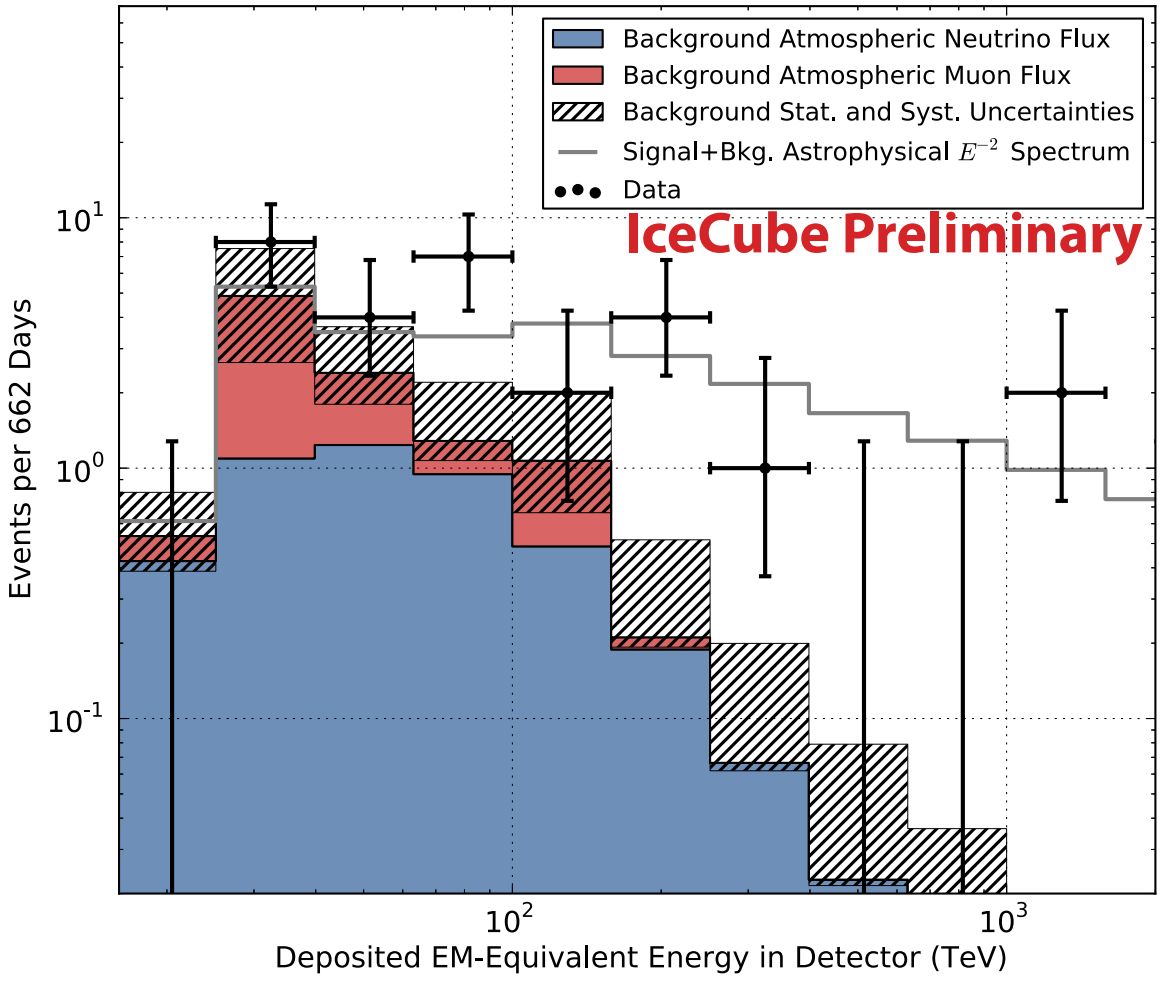


74.1 TeV, -0.4°

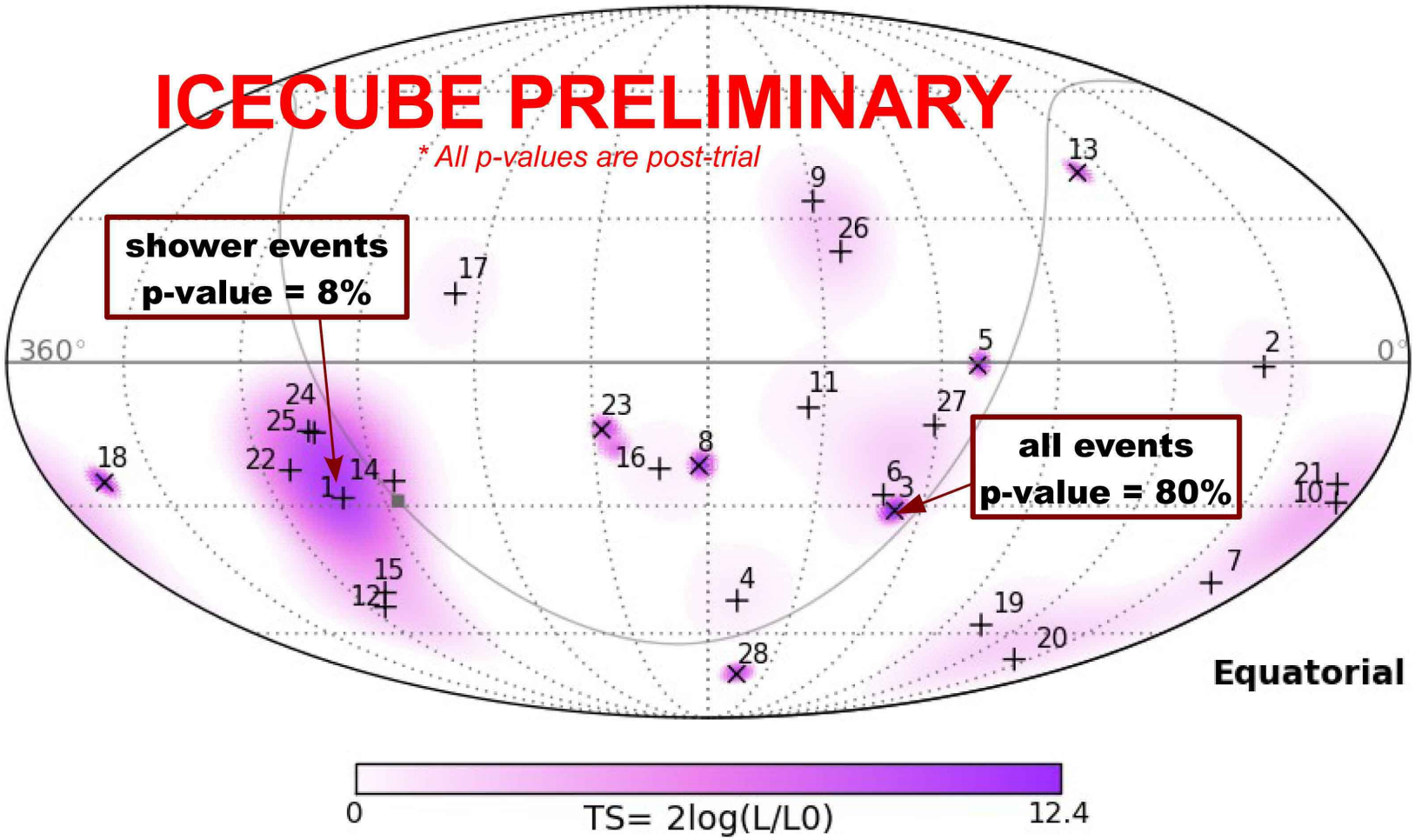
252.7 TeV, $+40^\circ$

Energy Spectrum

- Harder than any expected atmospheric background
- Merges well into expected backgrounds at low energies
- Potential cutoff around 2 PeV if E^{-2}
- Too few events to measure spectrum well



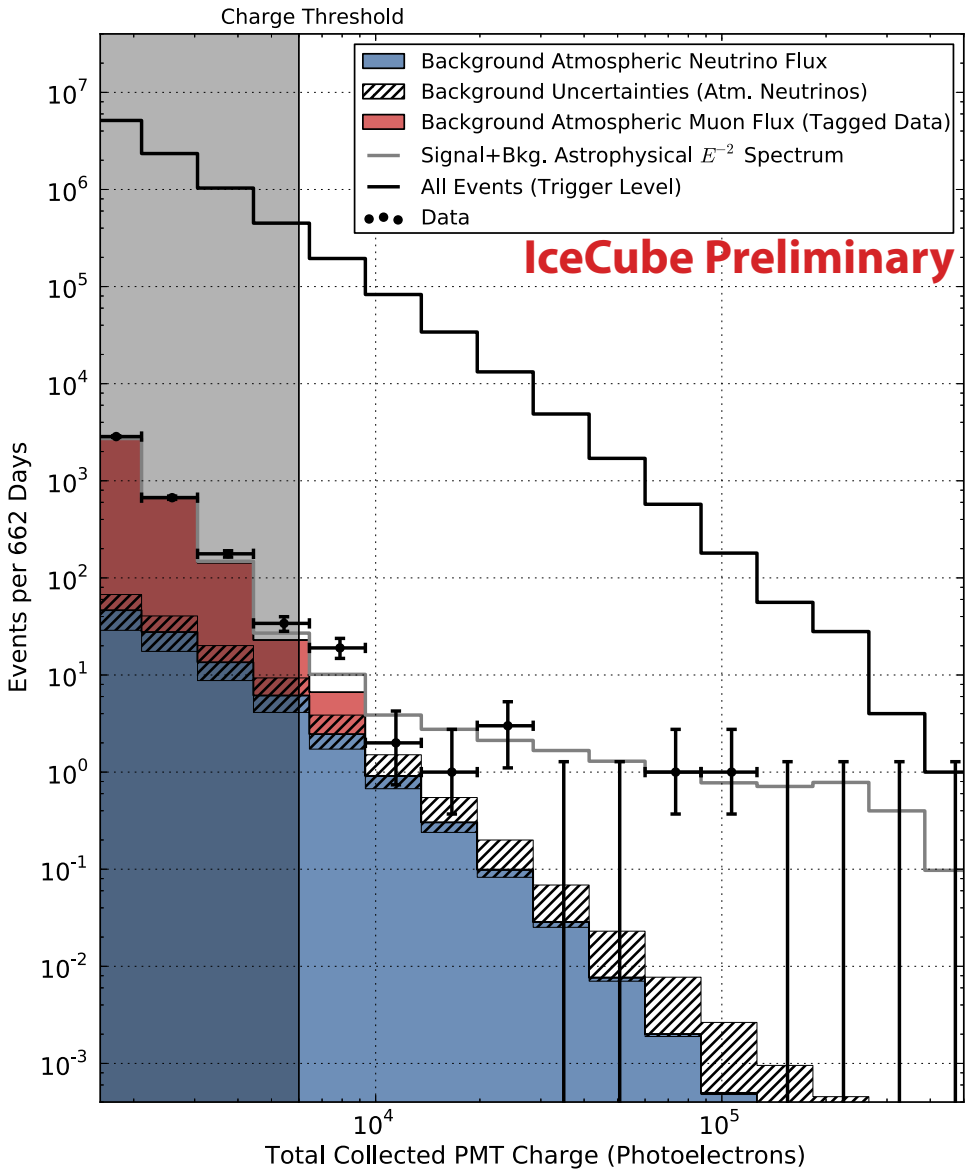
Skymap: Compatible with Isotropy



Too few events to evaluate isotropy or identify sources

Summary

- Energy spectrum seems hard
- Flavor distribution consistent with 1:1:1
- Angular distribution makes atmospheric explanation hard: where are the air showers?
- Matches expectations for astrophysical flux
- Still no evidence for clustering
- Does not continue at E^{-2} past a few PeV
- Hard to characterize without more statistics



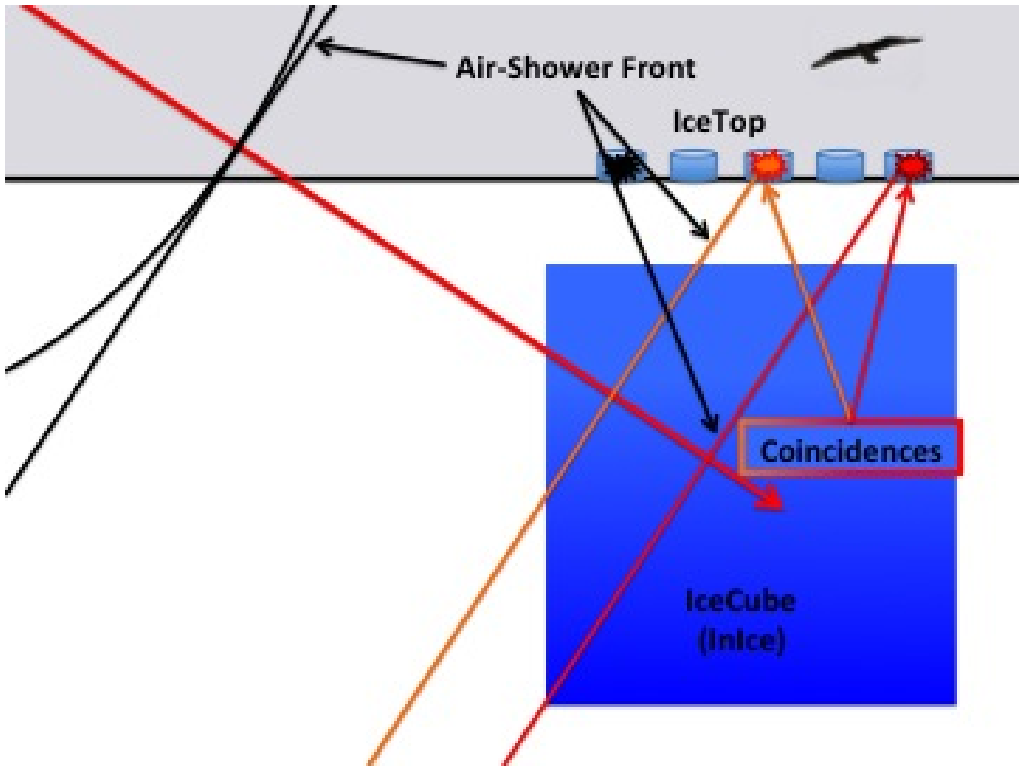
Parameters of the Future

- Atmospheric neutrino veto is a very powerful concept
- Dominant observable channel for astrophysical diffuse flux is 100 TeV - 1 PeV cascade events
- If an astrophysical flux, $\mathcal{O}(20)$ events per year per fiducial gigaton
- Analysis now gives $\mathcal{O}(100)$ events in IceCube in 10 years
- Angular resolution for cascades limited by modelling of light transport and sparse instrumentation
- Need $\mathcal{O}(10)$ events from a source to identify
- Flavor composition probes particle and astrophysics

More at VLVnT, Aug 5-7, Stockholm

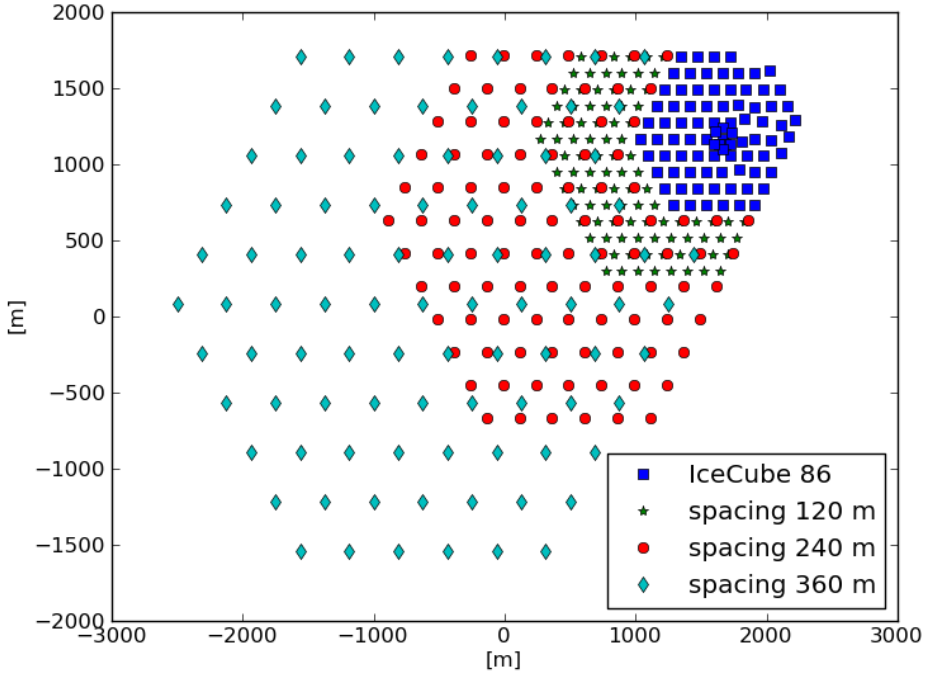
Surface Air Shower Veto Extension

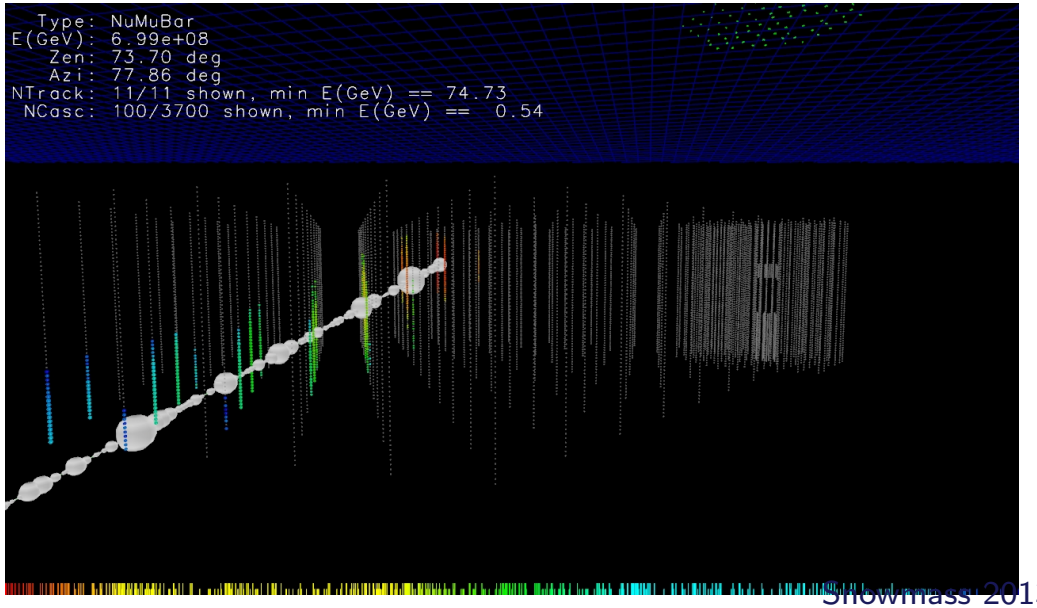
- Use surface veto to reject cosmic ray background
- Lowers energy threshold for southern uncontained muons from several PeV to 100 TeV
- May gain a factor of 3-5 in southern ν_μ
- Improving ν_μ improves point source sensitivity
- Low cost



IceCube++: toward 10 km^3

- How do you get an order of magnitude in volume?
- Current IceCube string spacing optimized for 10-30 TeV
- What if we optimize for 1 PeV?
- 2.3 km^3, 5.3 km^3, and 12.6 km^3 options at right
- Understanding background rejection of wide spacing in progress

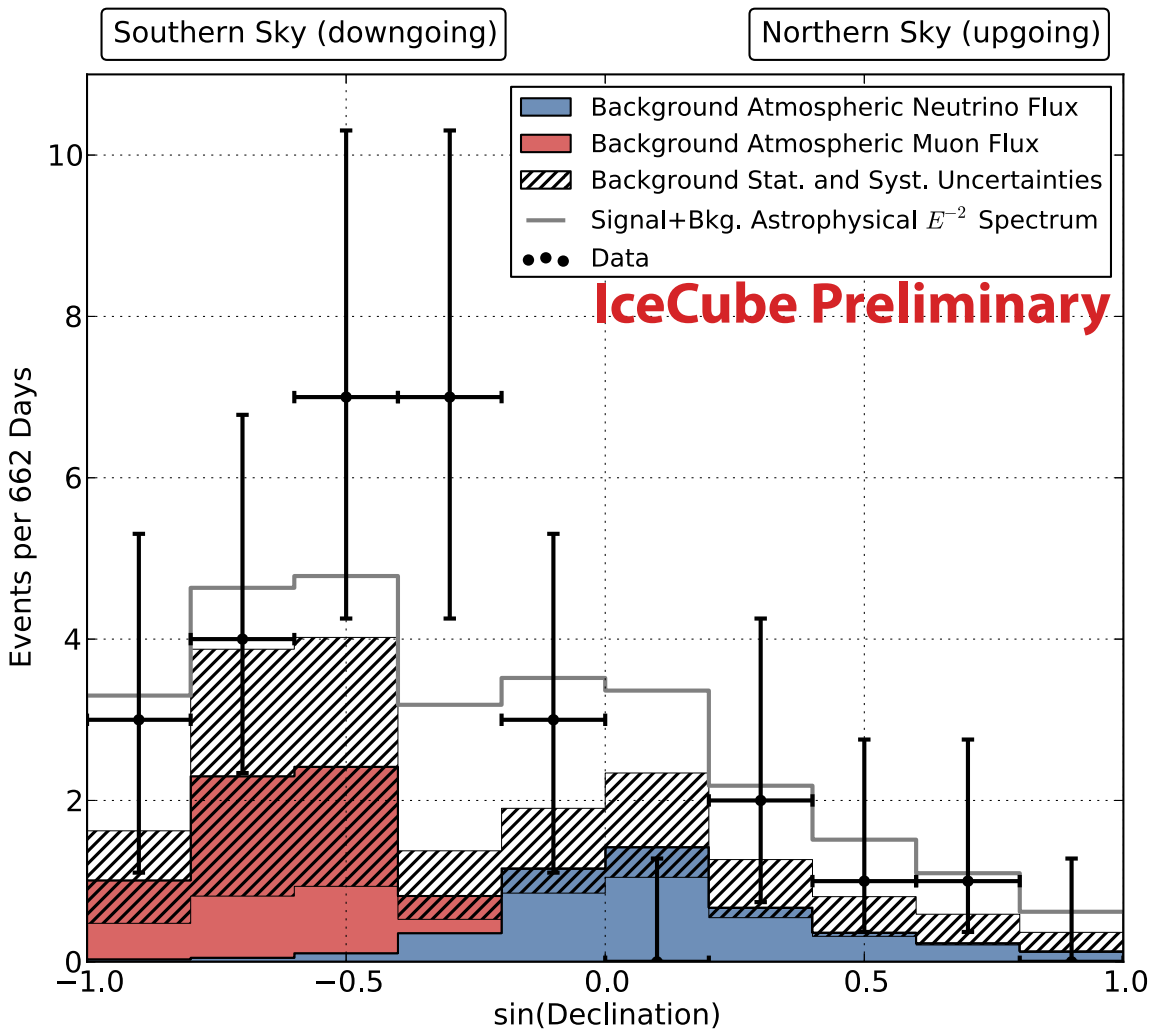




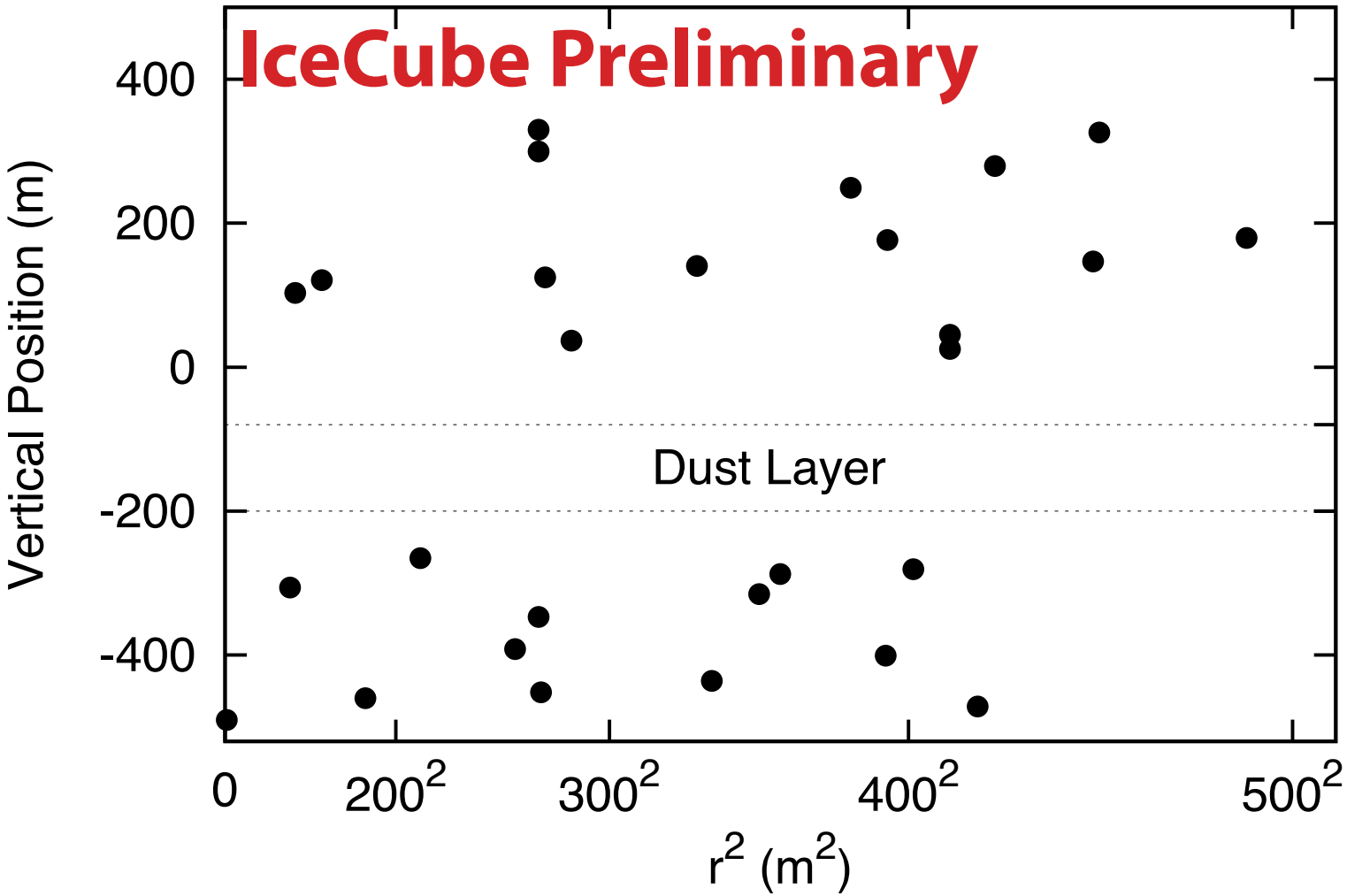
Backup

Zenith Distribution

- Compatible with Isotropic Flux
- Events from North absorbed in Earth
- Minor excess in south compared to isotropic, but not significant

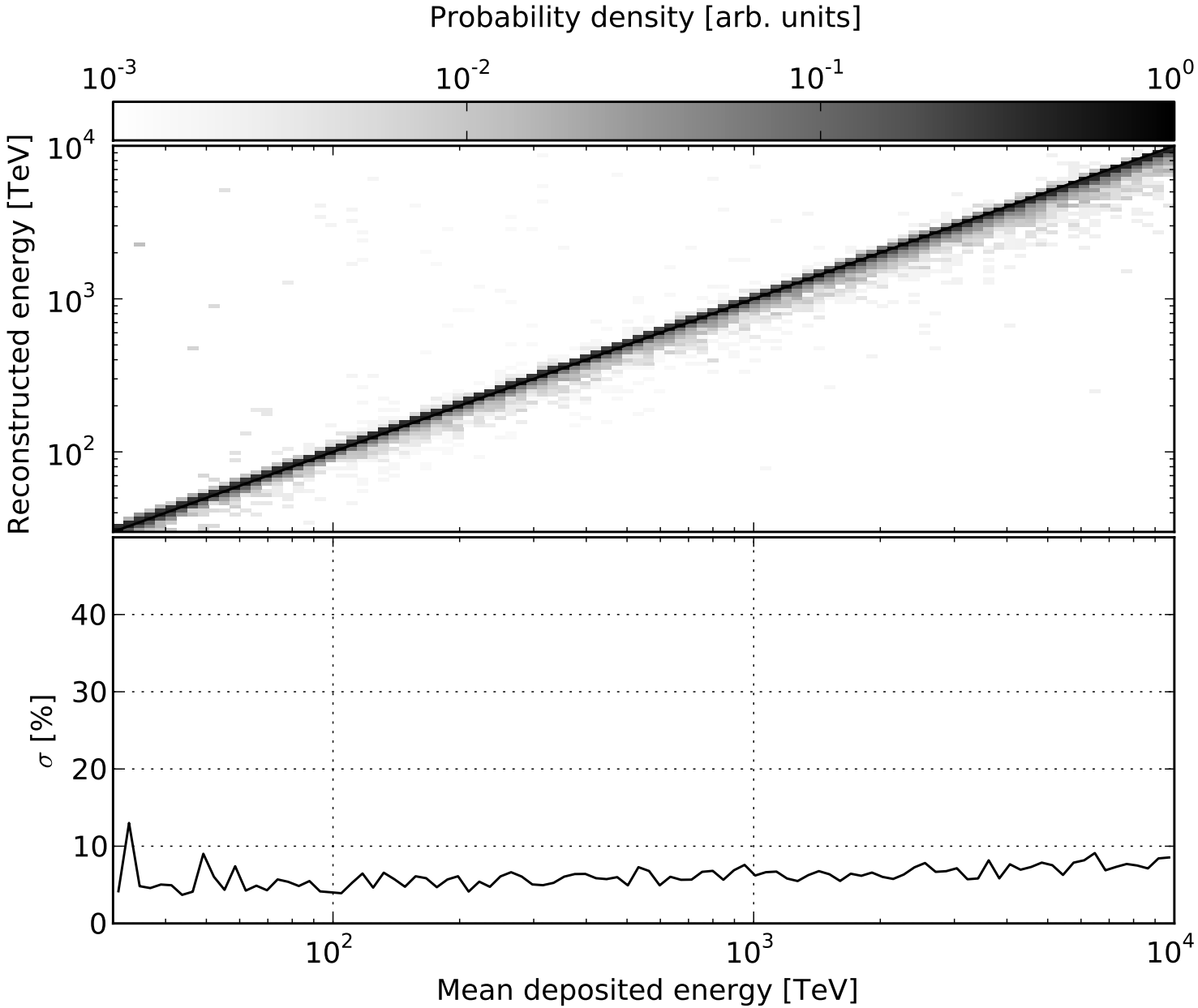


Event Distribution in Detector

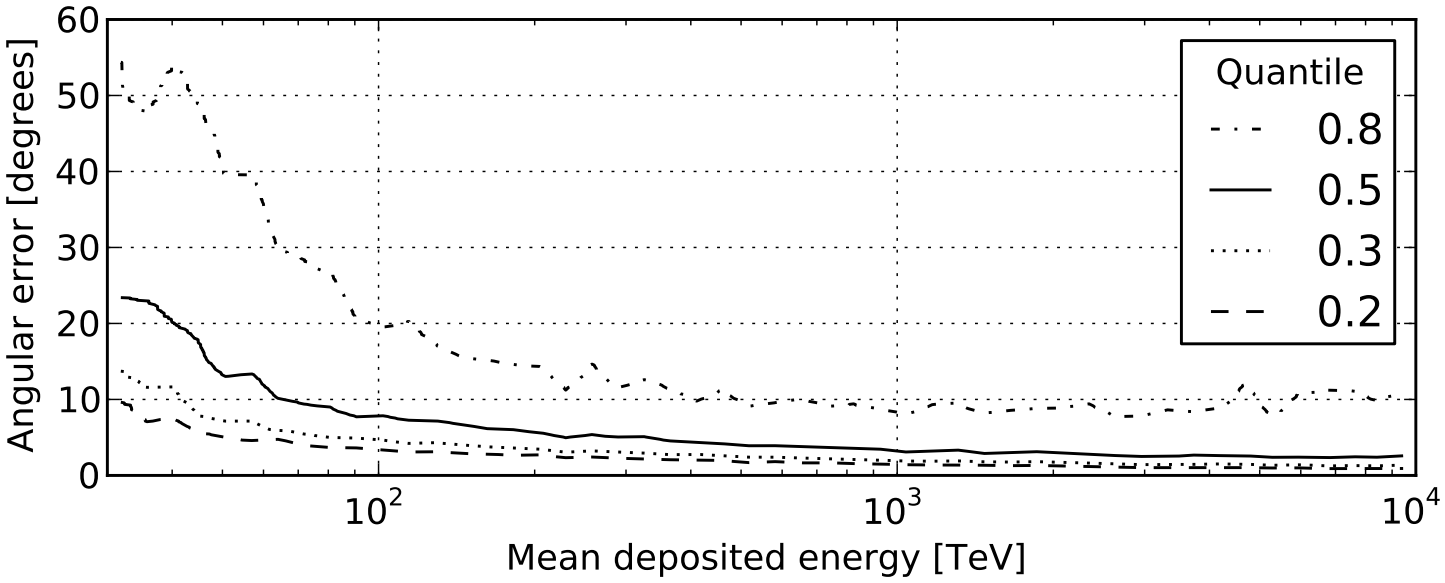


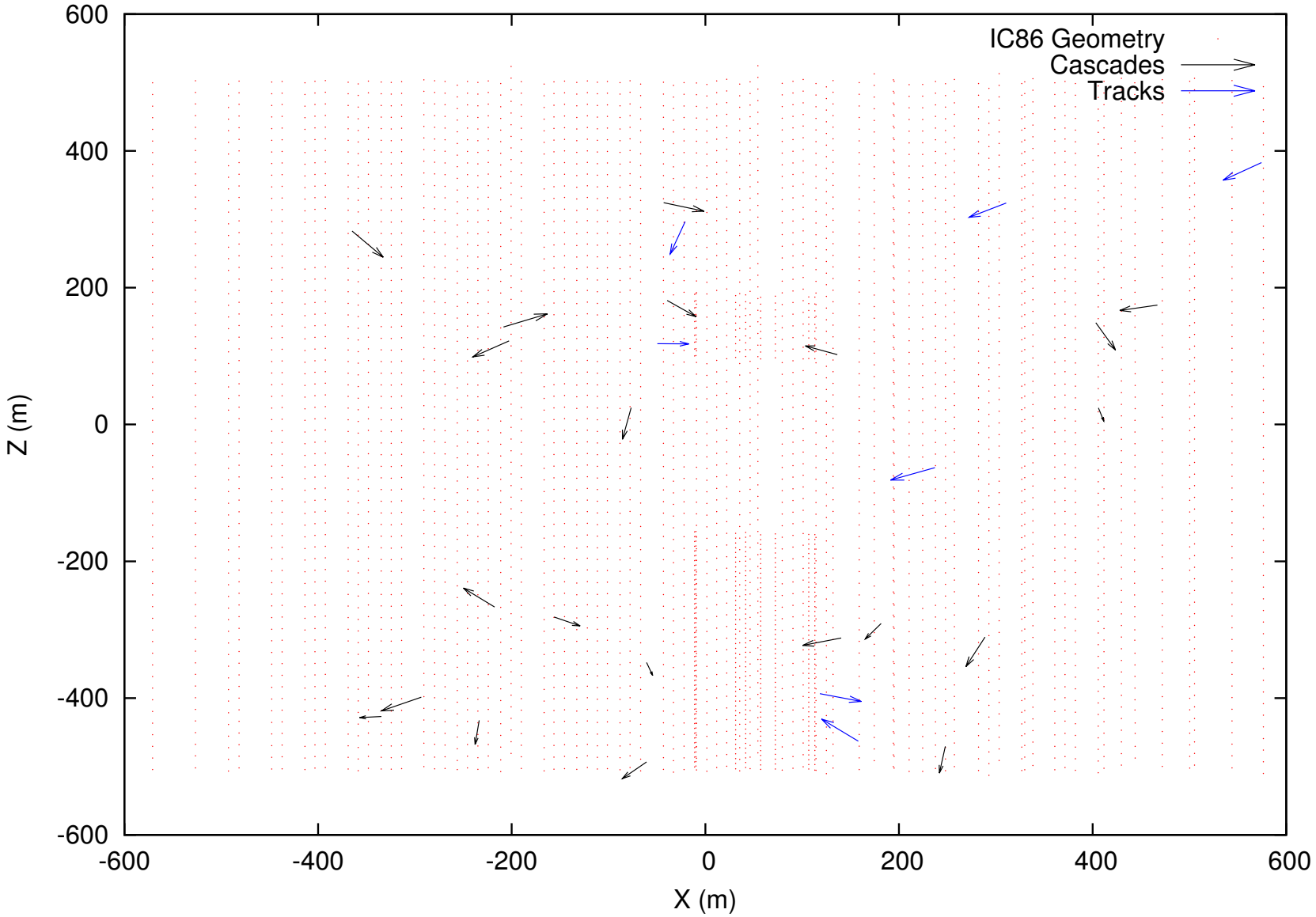
Uniform in fiducial volume

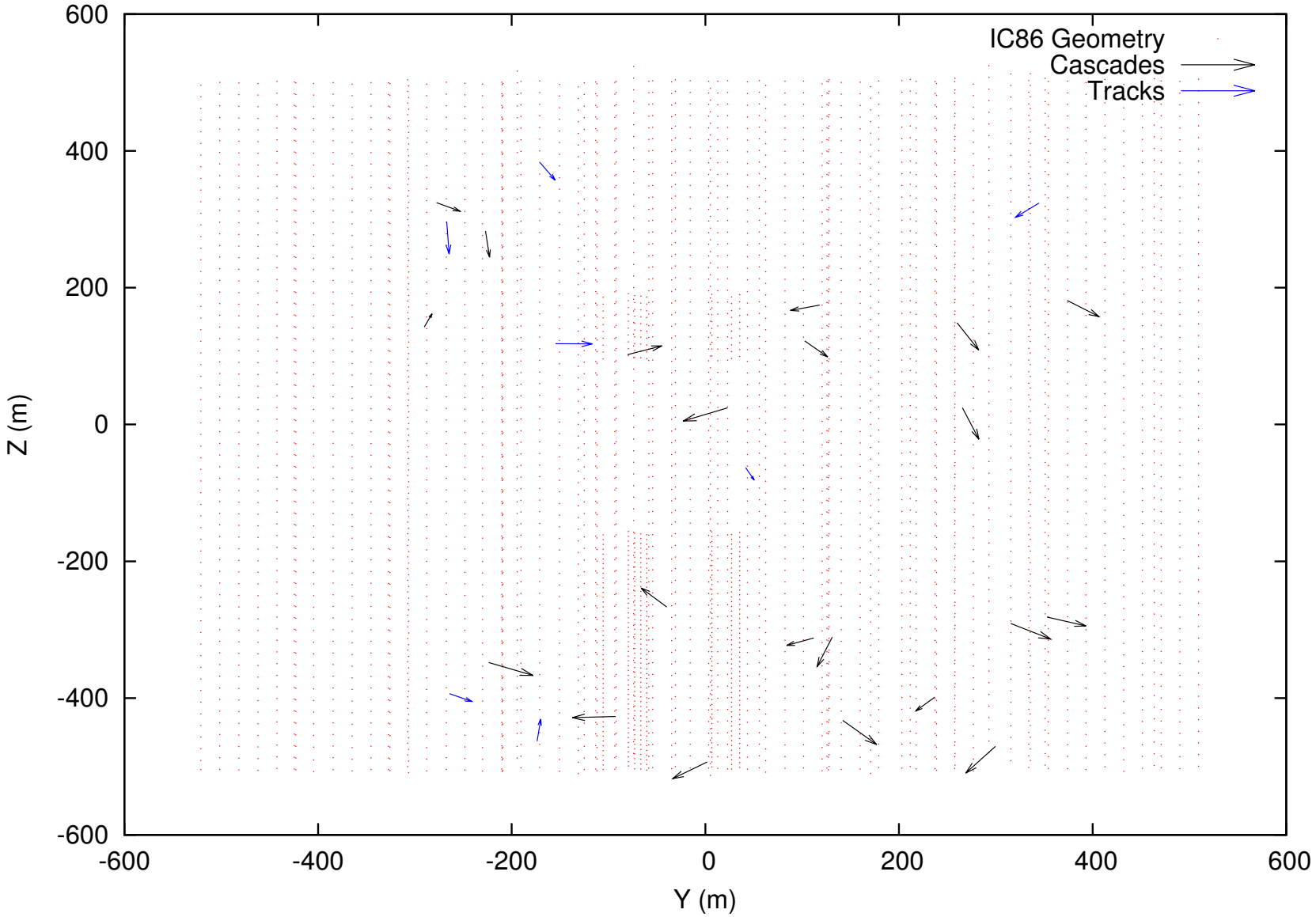
Shower Energy Resolution



Shower Angular Resolution




IC86 Geometry
Cascades
Tracks
600
400
200
0
-200
-400
-600
Z (m)
-600
-400
-200
0
200
400
600
X (m)


IC86 Geometry
Cascades
Tracks
600
400
200
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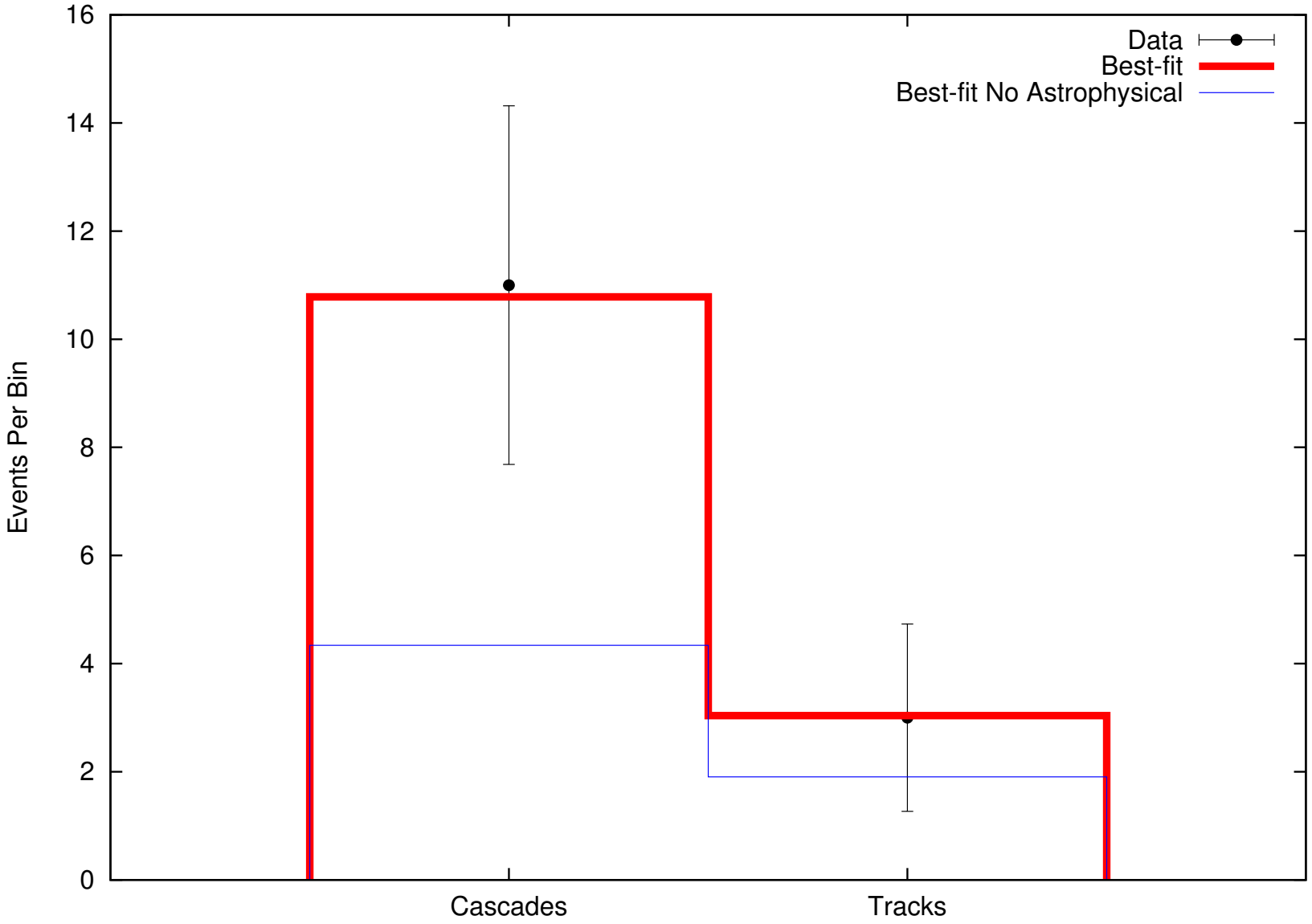
Z (m)
-600
-400
-200
0
200
400
600
Y (m)


Data
Best-fit
Best-fit No Astrophysical
Events Per Bin
0
2
4
6
8
10
12
14
16
Cascades
Tracks