Recent IceCube Results on High Energy Neutrinos

Evidence for High-Energy Extraterrestrial Neutrinos

Claudio Kopper, UW Madison - for the IceCube Collaboration

ckopper@icecube.wisc.edu

TeV Neutrinos

Observing astrophysical neutrinos allows conclusions about the acceleration mechanism

$$
\begin{aligned}
p + \gamma \;(\text{or } p, \ldots) &\rightarrow \pi^0 + p \\
&\hookrightarrow \gamma + \gamma + p \\
&\rightarrow \pi^+ + n \\
&\hookrightarrow \mu^+ + \nu_\mu + n \\
&\hookrightarrow e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n
\end{aligned}
$$

TeV gamma rays ($\gamma + \gamma$)

Cosmic rays? (n)

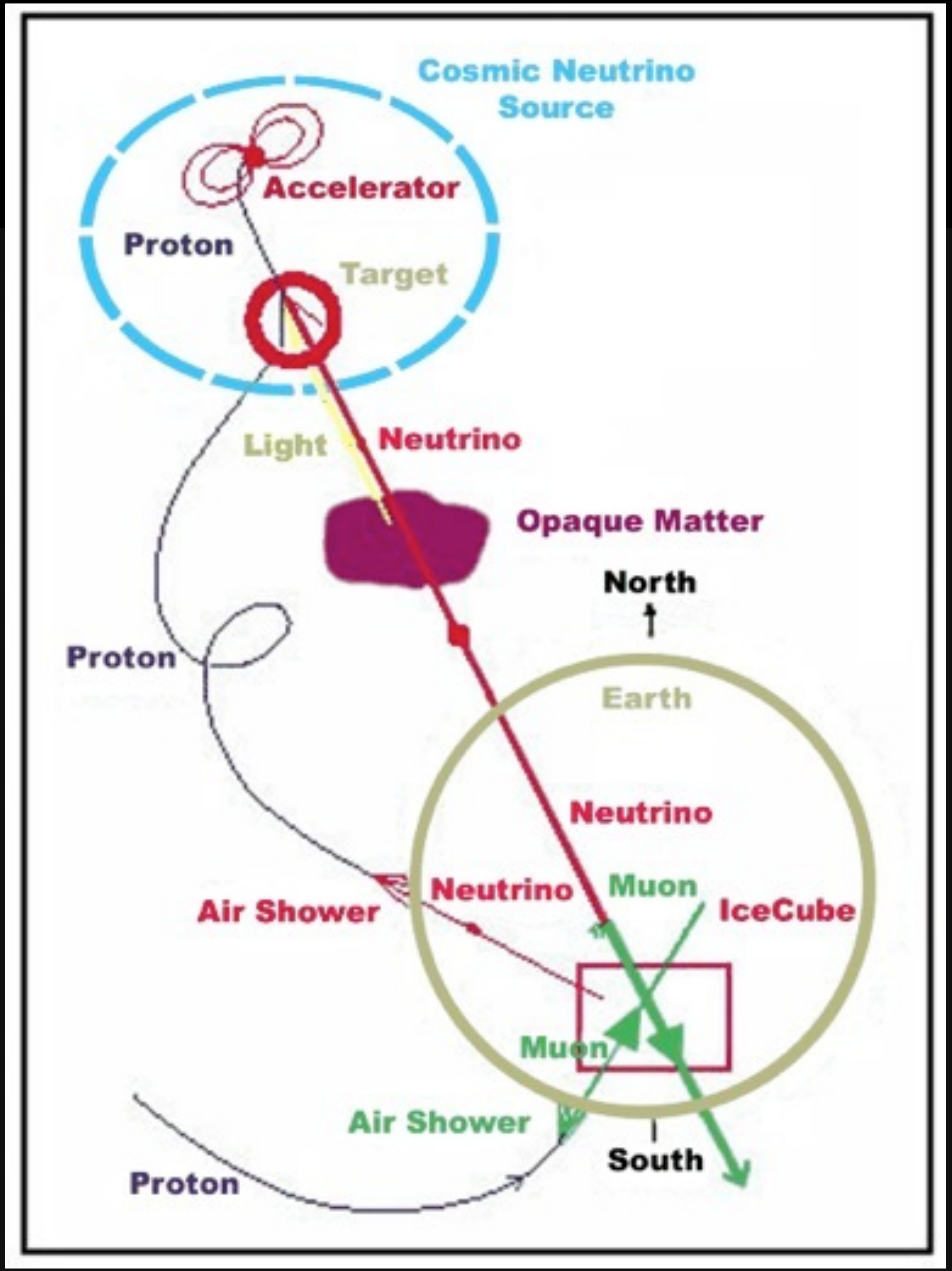
TeV neutrinos (ν_μ, $\nu_{\bar{\mu}} + \nu_e$)

- **Neutrinos from cosmic ray interactions in:**
  - Atmosphere
  - Cosmic Microwave Background
  - Gamma Ray Bursts (Acceleration Sites)
  - Active Galactic Nuclei (Acceleration Sites)
  - ?

Why Neutrinos?

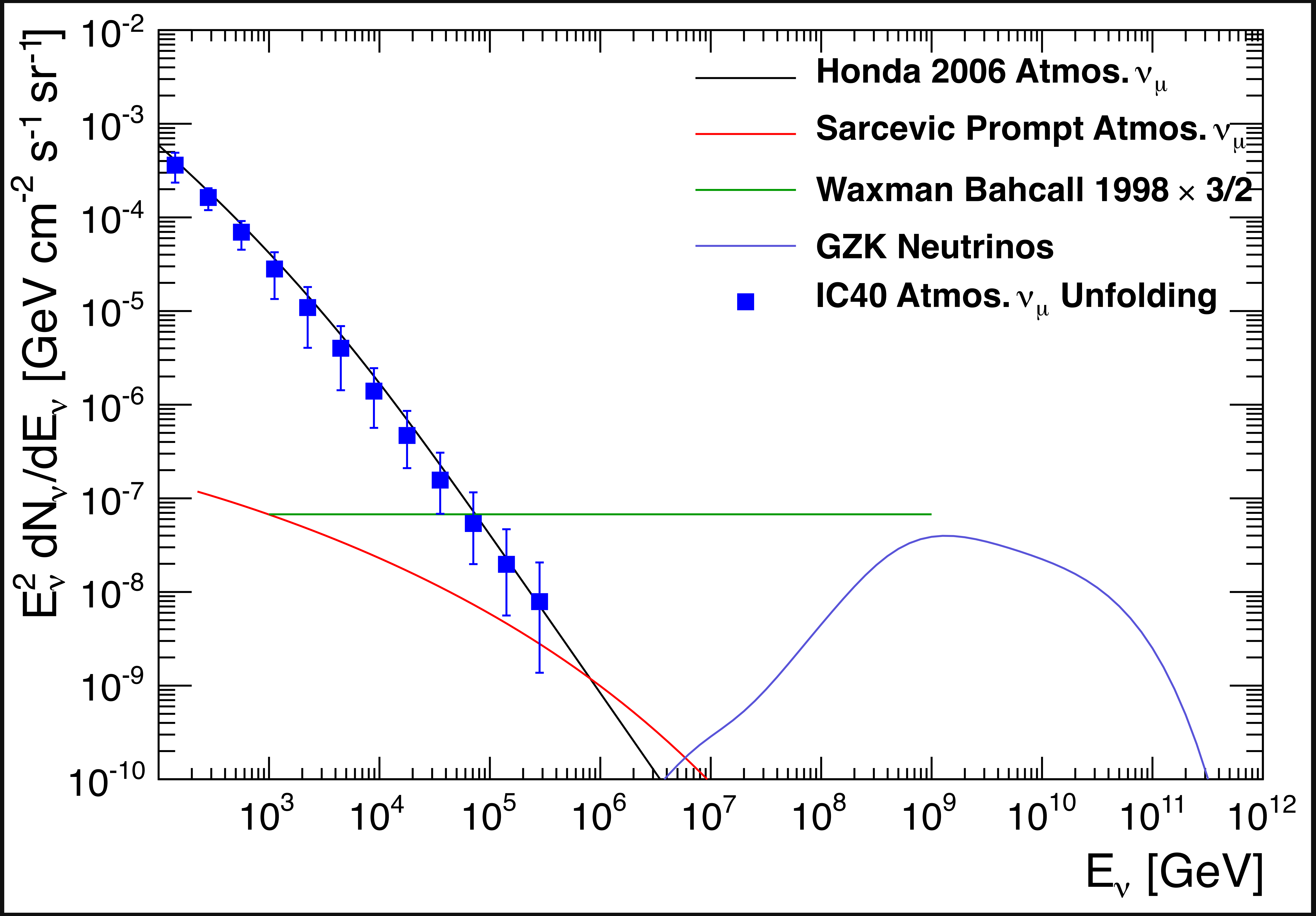
Neutrinos are ideal astrophysical messengers

- Travel in straight lines
- Very difficult to absorb in flight



Interesting Neutrinos above 1 TeV

- **Atmospheric neutrinos (π/K)**
  - dominant < 100 TeV
- **Atmospheric neutrinos (charm)**
  - "prompt" ~ 100 TeV
- **Astrophysical neutrinos**
  - maybe dominant > 100 TeV
- **Cosmogenic neutrinos**
  - $>10^6$ TeV

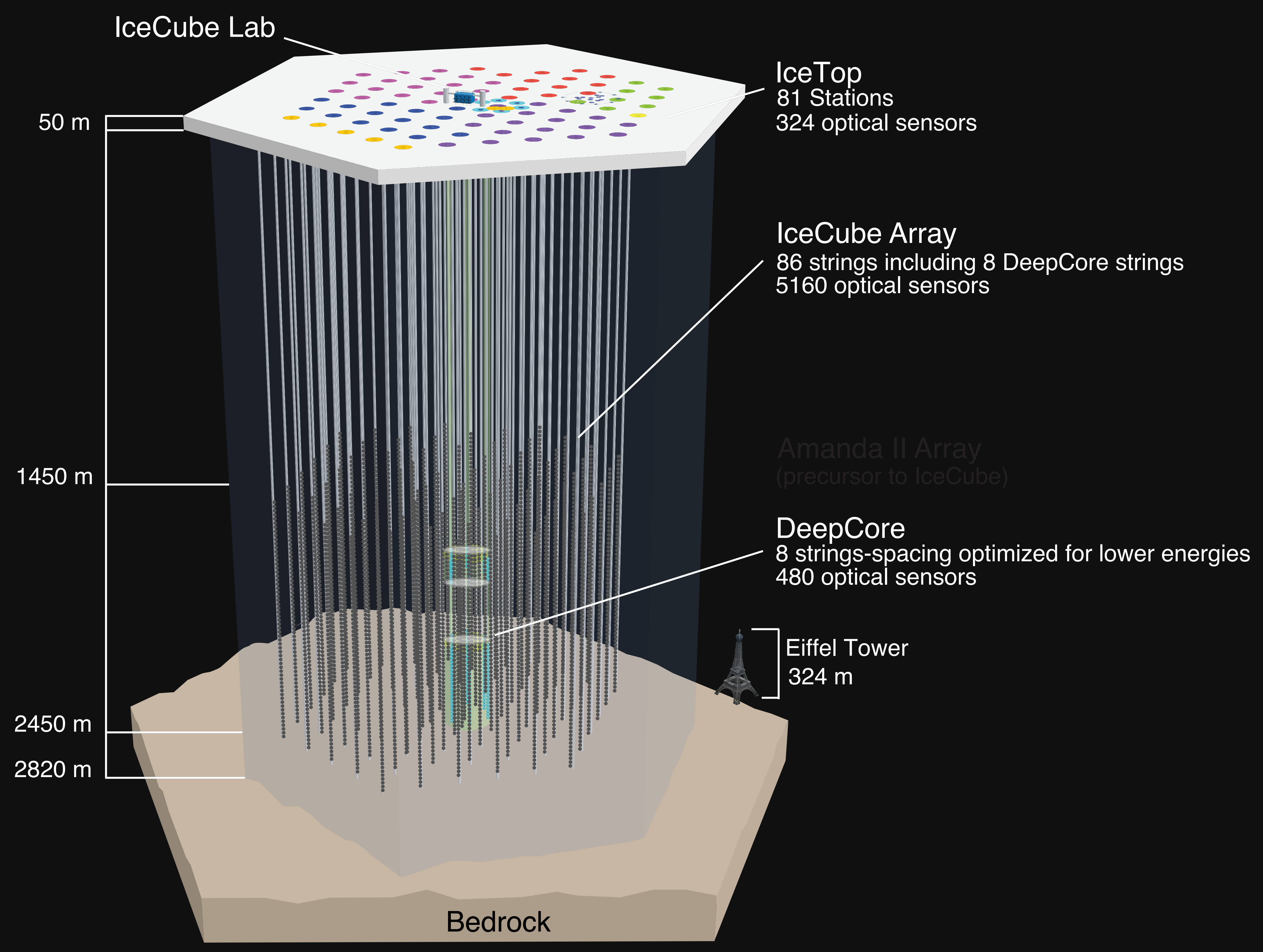


IceCube Preliminary

The IceCube Neutrino Observatory

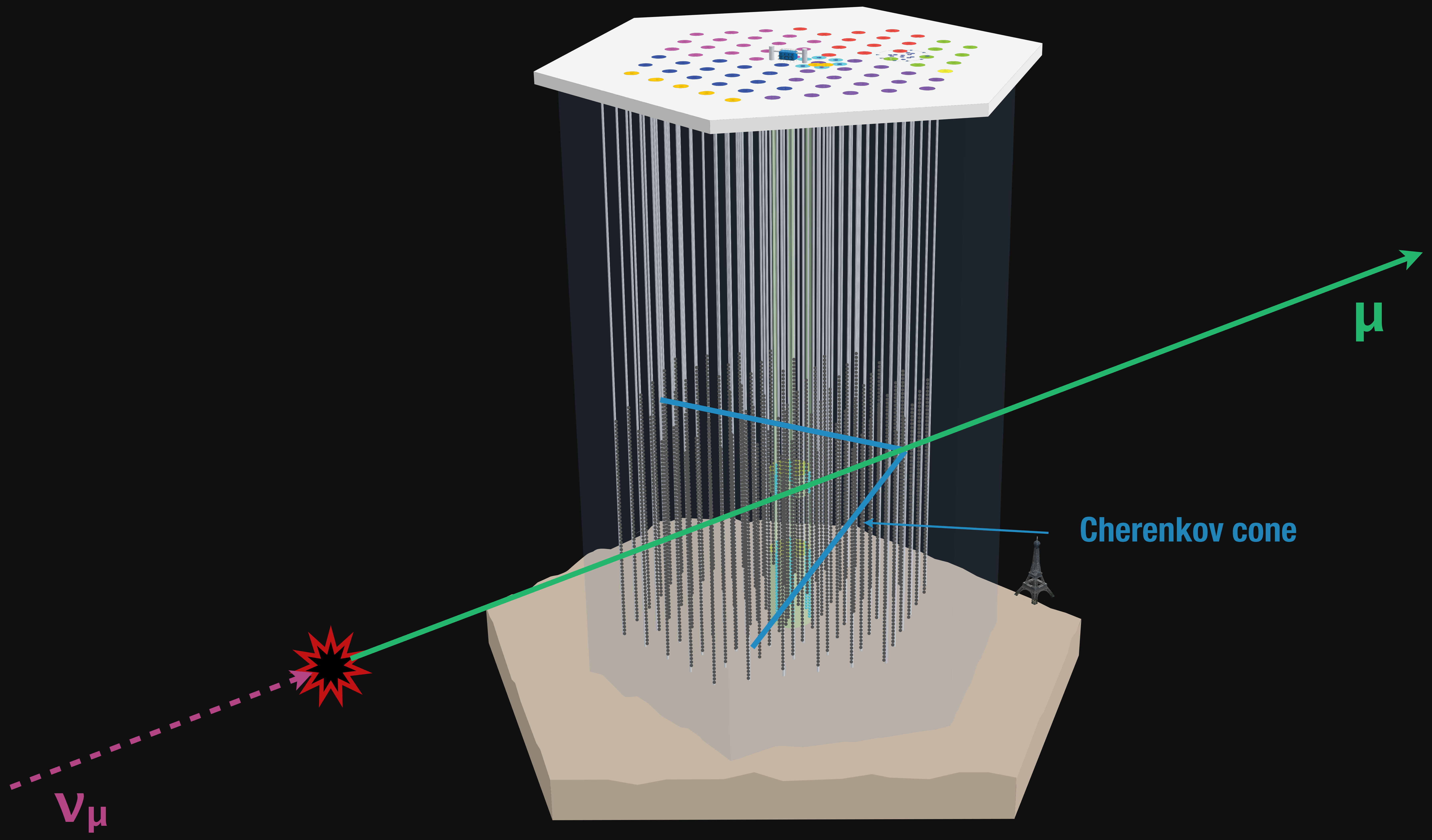
Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)

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



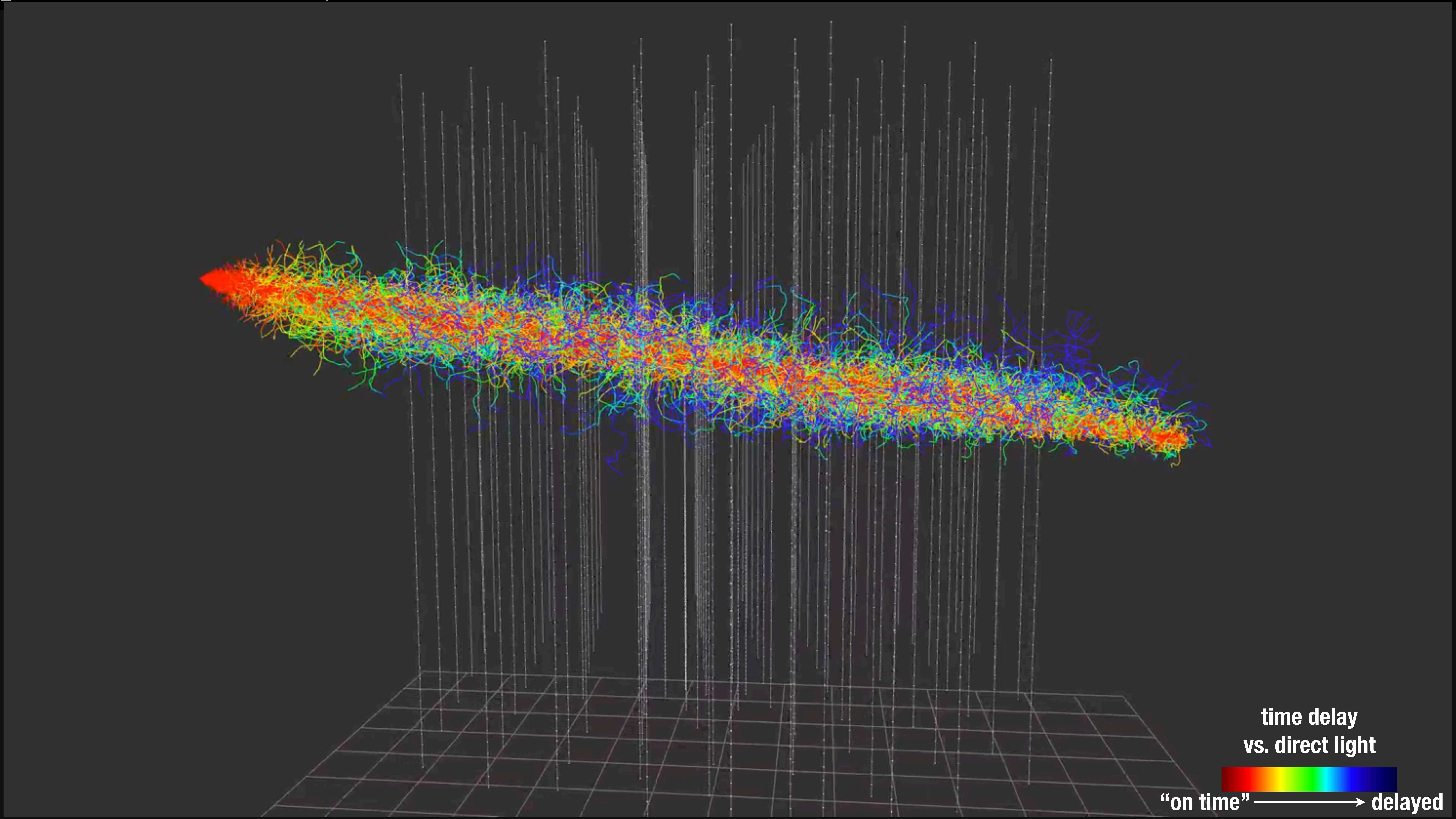
The IceCube Neutrino Observatory

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



The IceCube Neutrino Observatory

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)

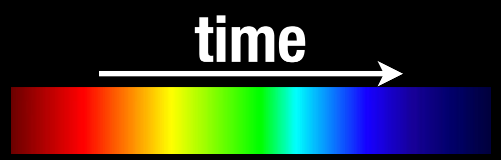


IceCube Preliminary

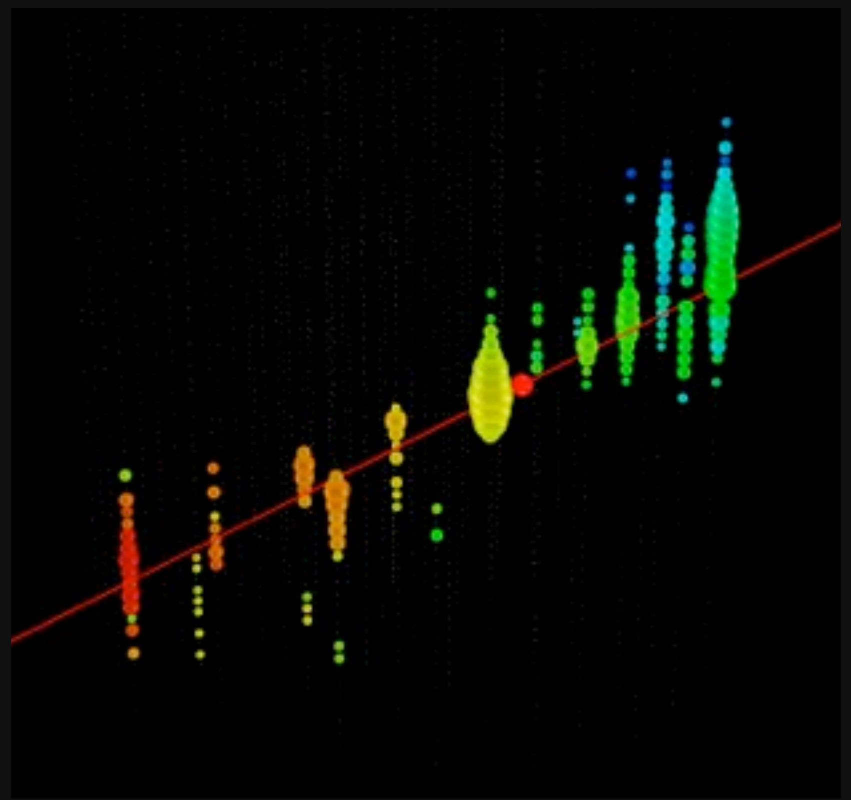
The IceCube Neutrino Observatory

Neutrino Event Signatures

Signatures of signal events



CC Muon Neutrino

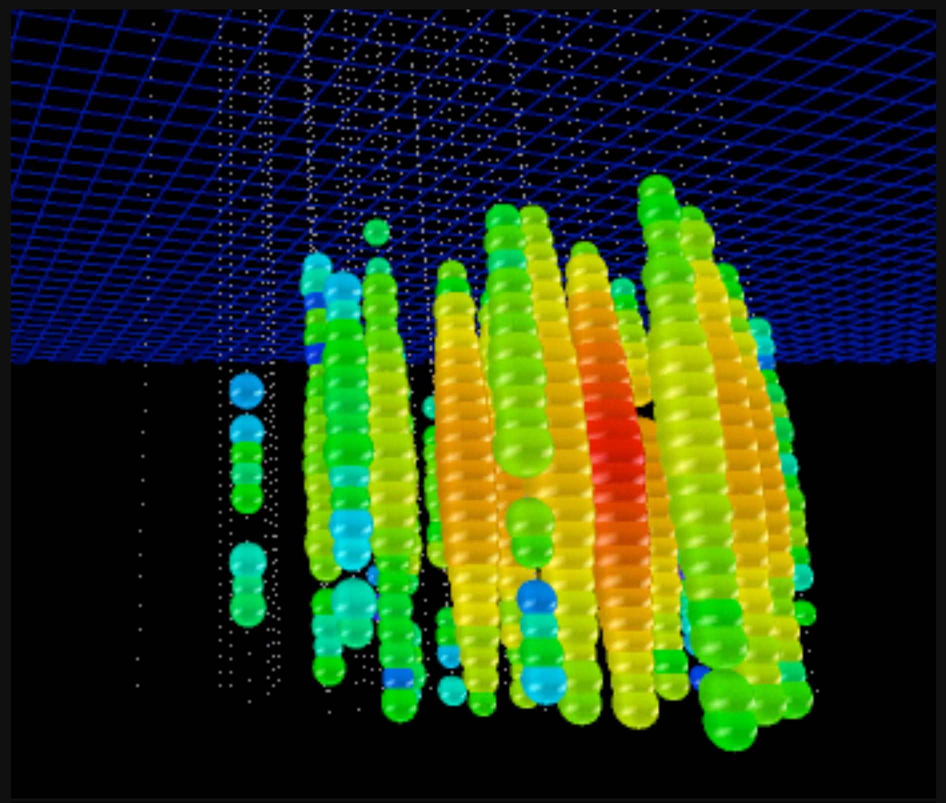


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

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

Neutral Current /Electron Neutrino



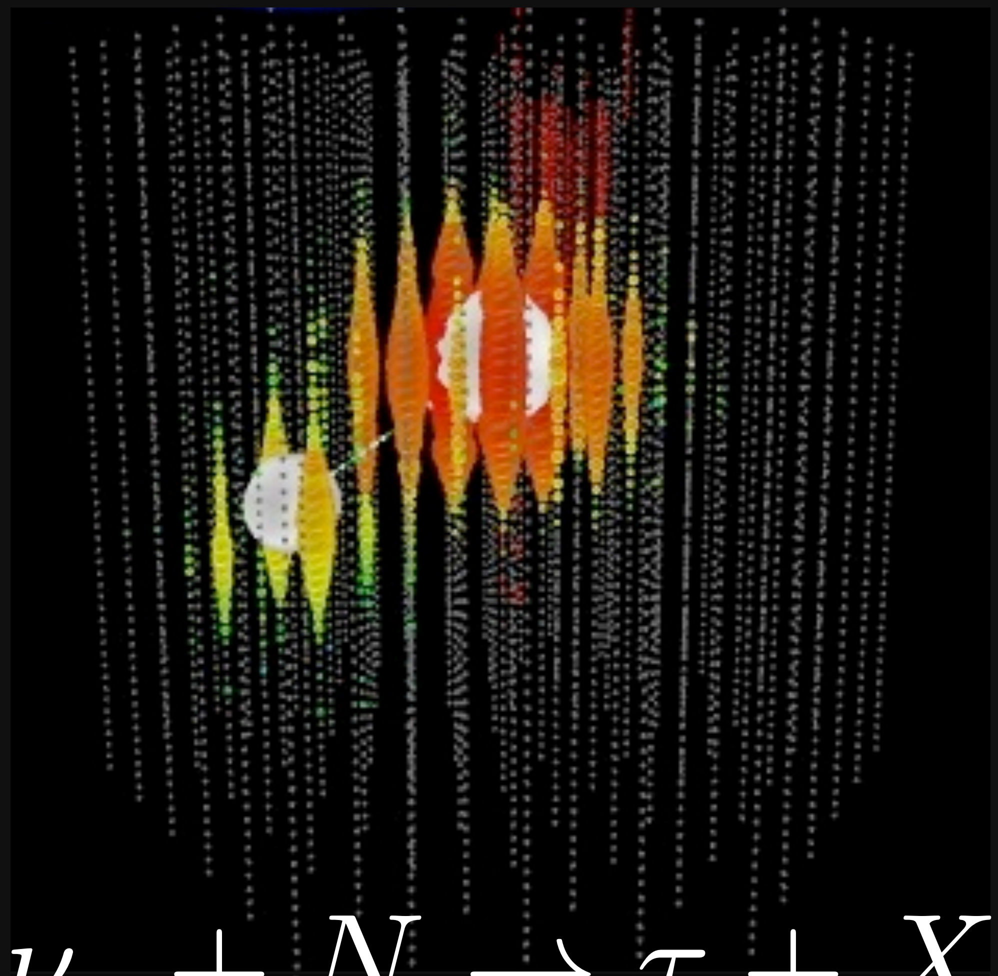
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

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

cascade (data)

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

CC Tau Neutrino



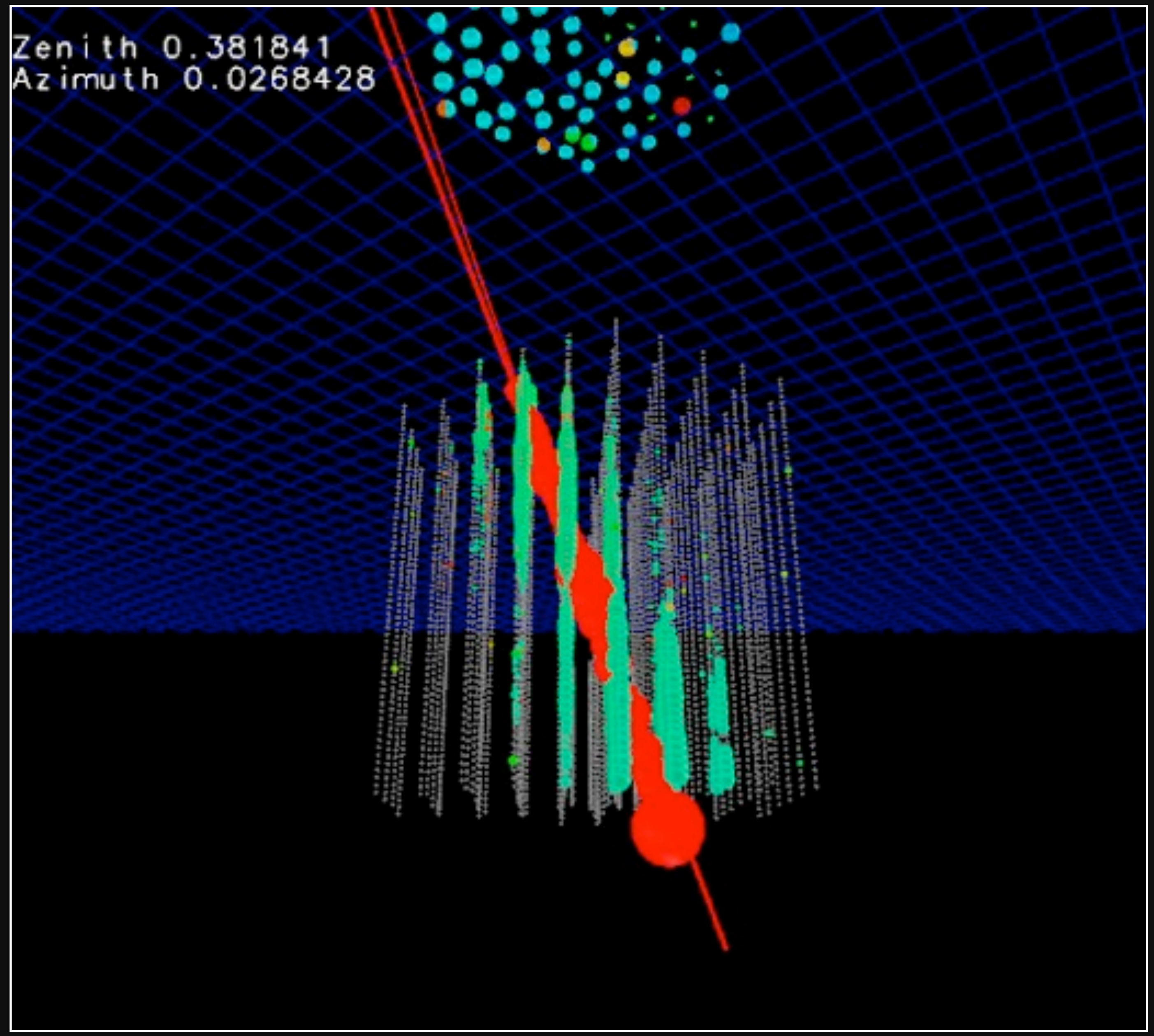
$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures
(simulation)

(not observed yet)

Backgrounds and Systematics

- **Backgrounds:**
  - Cosmic Ray Muons
  - Atmospheric Neutrinos
- **Largest Uncertainties:**
  - Optical Properties of Ice
  - Energy Scale Calibration
  - Neutral current / ν_e degeneracy

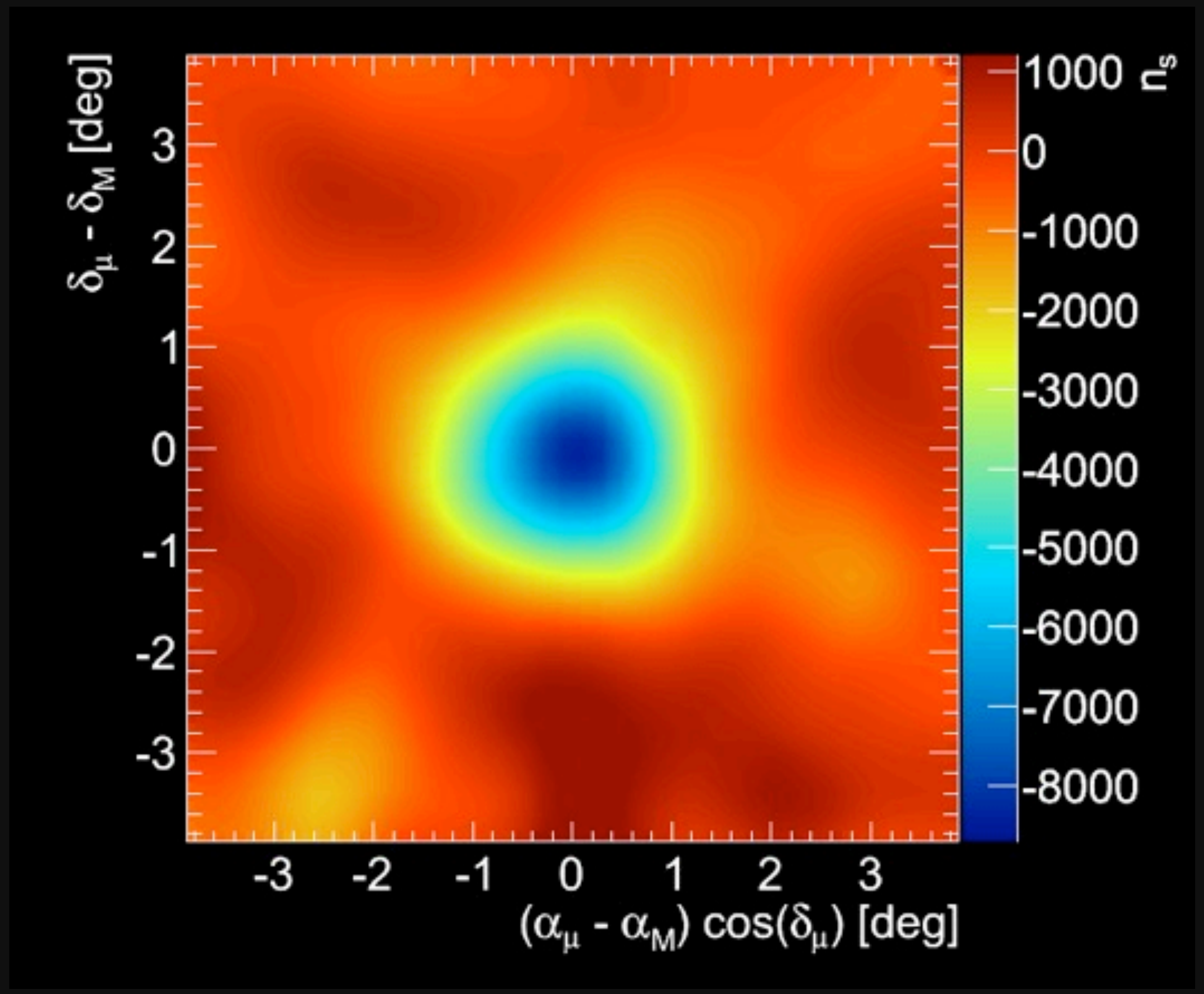


A bundle of muons from a CR interaction in the atmosphere
(also observed in the “IceTop” surface array)

Calibration

Various calibration devices/methods to control detector systematics

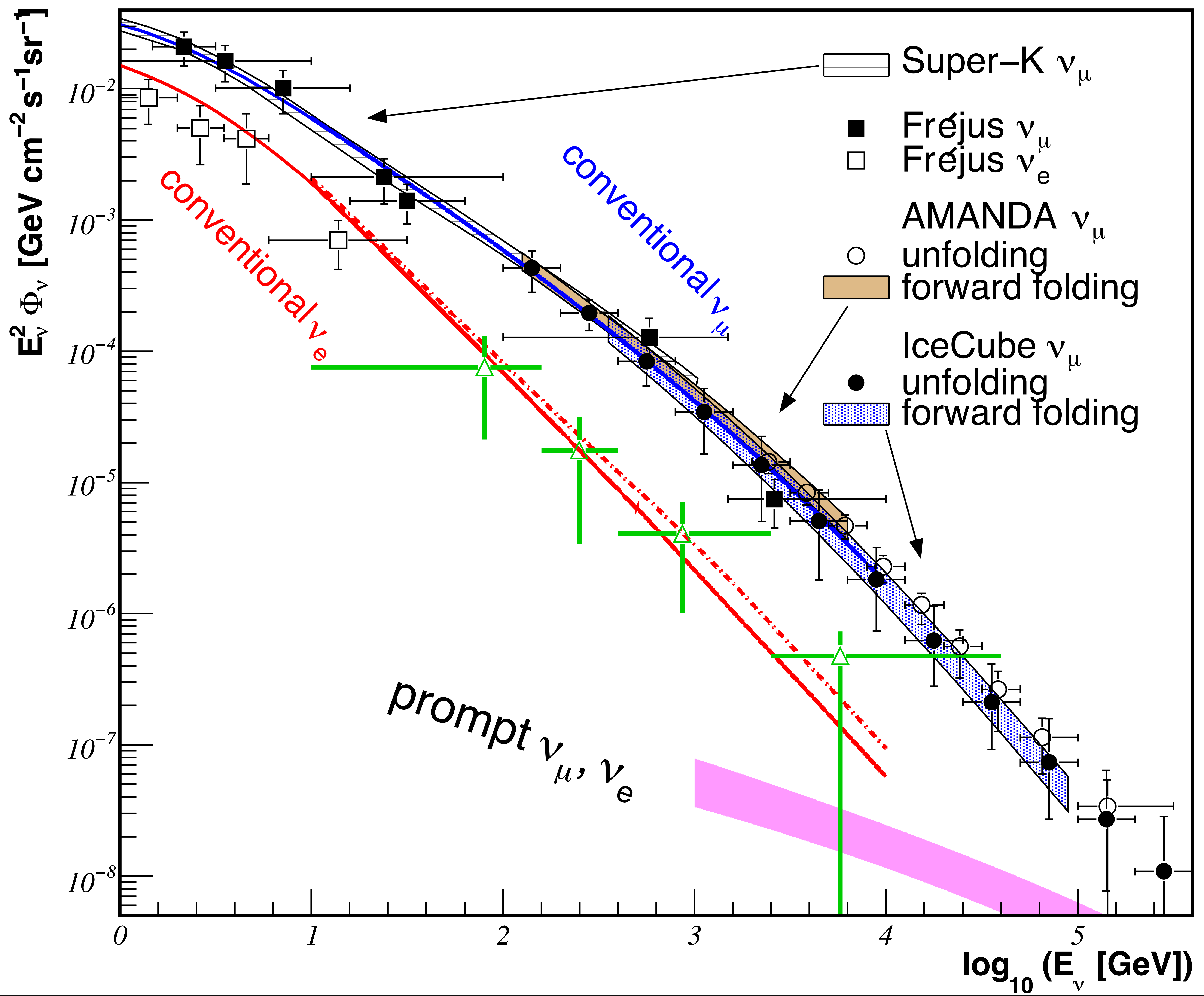
- LED flashers on each DOM
- In-ice calibration laser
- Cosmic ray energy spectrum
- Moon shadow
- Atmospheric Neutrino Energy Spectrum
- Minimum-ionizing muons



Moon Shadow in Cosmic Rays Muons in IceCube (59 strings)

Atmospheric Neutrino Spectrum

Measured with IceCube in ν_μ and ν_e



PRL 110 (2013) 151105

The High-Energy Tail

Searching for a signal above the atmospheric neutrino background

Signals and Backgrounds

Signal

- Dominated by showers (~80% per volume) from oscillations
- High energy (benchmark spectrum is typically E^{-2})
- Mostly in the Southern Sky due to absorption of high-energy neutrinos in the Earth

Background

- Track-like events from Cosmic Ray muons and atmospheric ν_μ
- Soft spectrum ($E^{-3.7}$ - $E^{-2.7}$)
- Muons in the Southern Sky, neutrinos in from the North

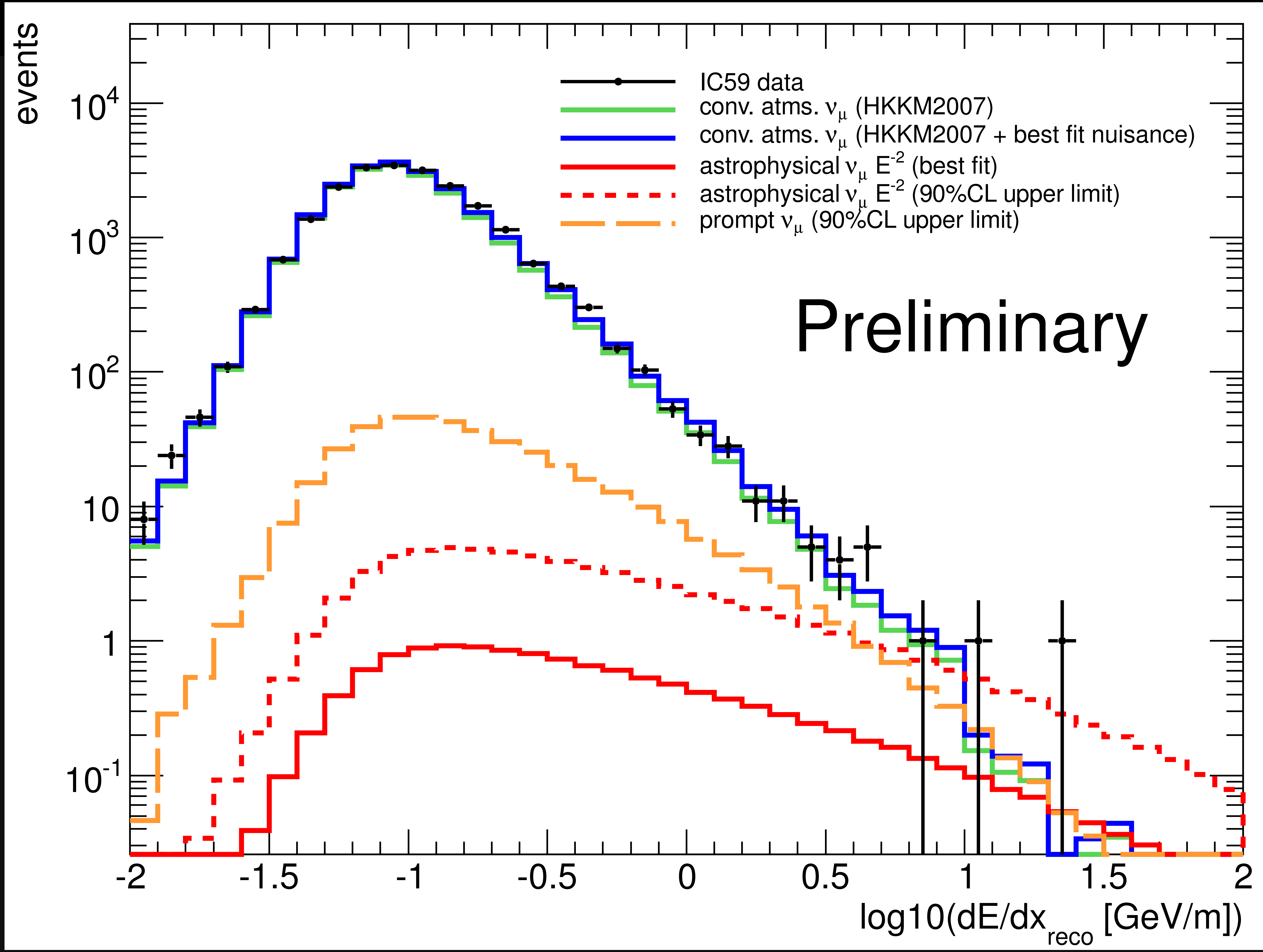
Observables

Different observables probe different properties

- **Spectral slope**
  - separate extraterrestrial flux from atmospheric, accelerator properties
- **Position of possible cutoff in energy**
  - accelerator properties, maybe different population of sources above/below CR knee?
- **Flavor composition**
  - physics of production process, discrimination against backgrounds
- **Zenith distribution**
  - comparison to backgrounds
- **Full arrival direction**
  - source locations once significant clustering is observed (skymap!)

Hint in upgoing muons

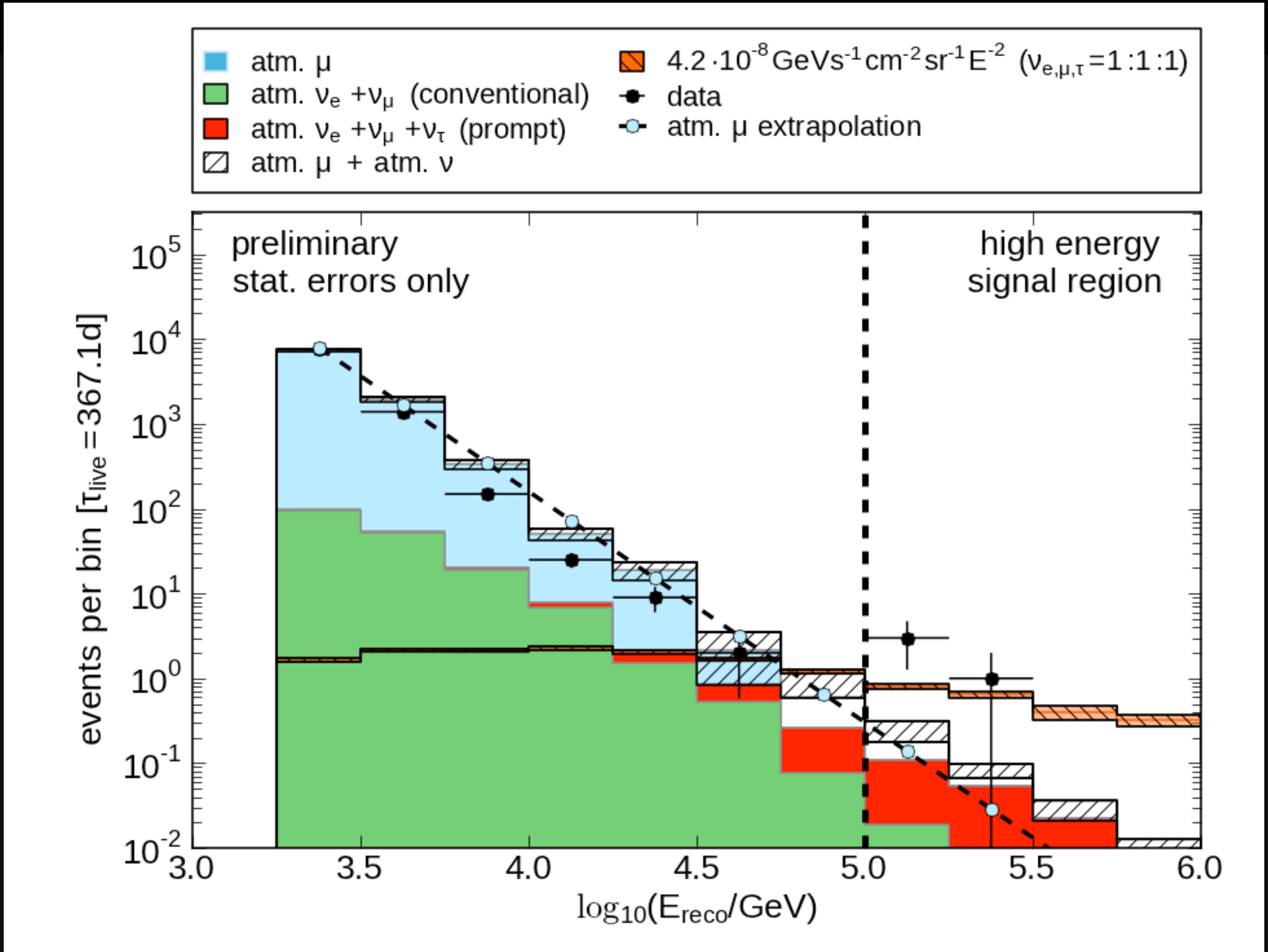
Study using the "IC59" partial detector during construction: 1.8σ



arXiv:1302.0127

Another Hint in Shower

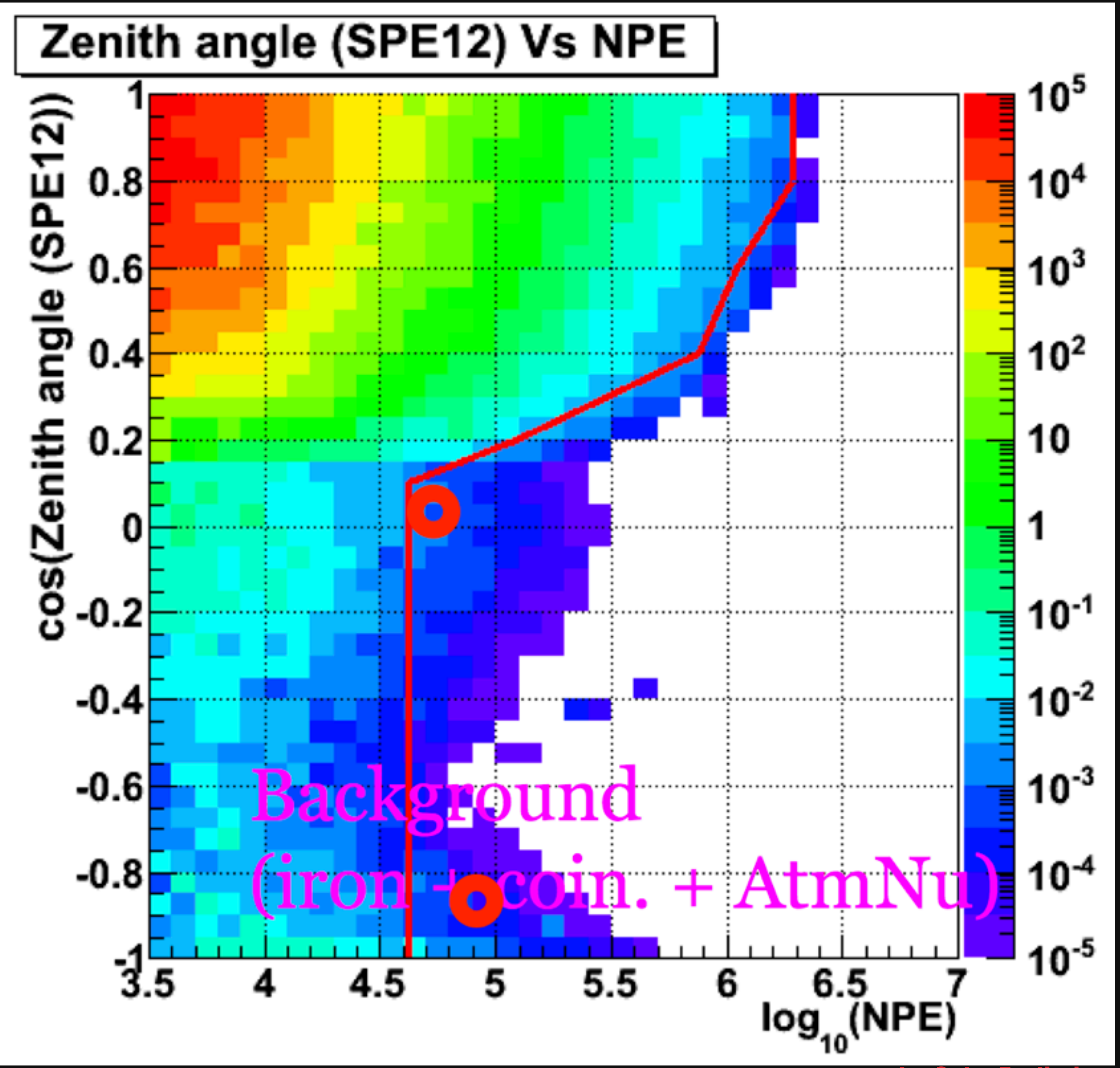
Study using the "IC40" partial detector during construction: 2.4σ



GZK Neutrino Analysis

Simple search to look for extremely high energies (10^9 GeV) neutrinos from proton interactions on the CMB

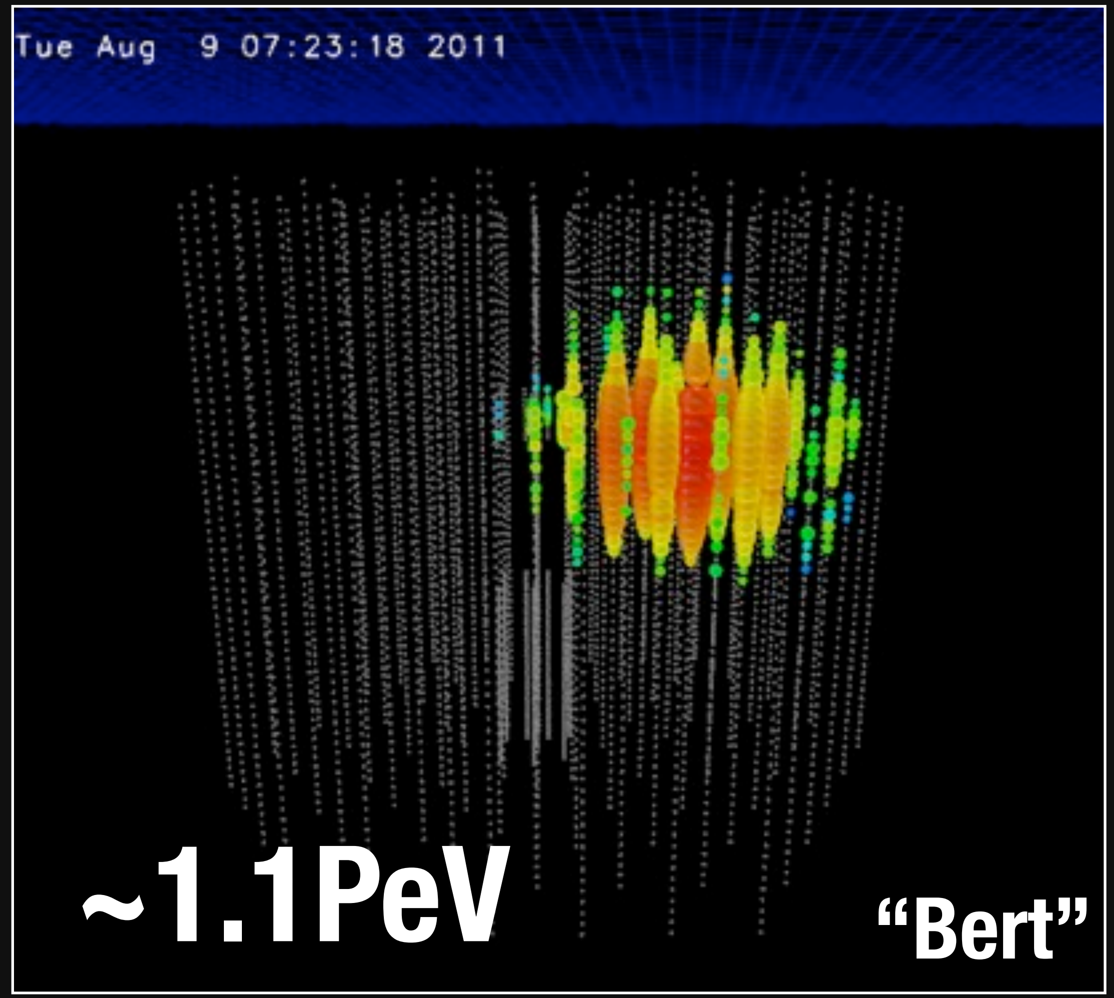
- **Upgoing muons**
  - Always neutrinos
  - Background: atm. neutrinos
  - High threshold (1 PeV)
- **Downgoing muons (VHE)**
  - Cosmic Ray muon background
  - Very high threshold (100 PeV)

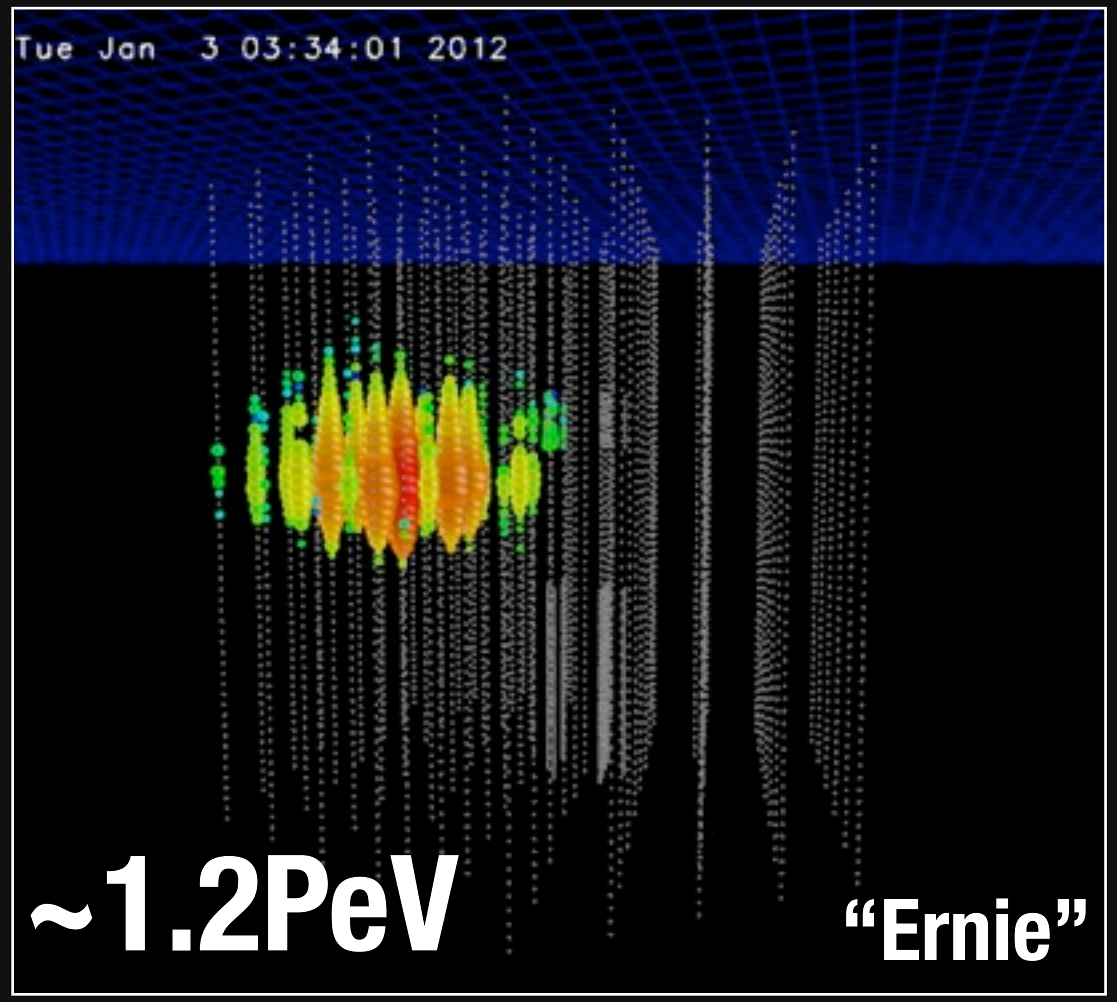


Results

Appearance of ~1 PeV cascades as an at-threshold background

- **Two very interesting events in IceCube (between May 2010 and May 2012)**
  - shown at Neutrino '12
  - 2.8σ excess over expected background in GZK analysis
  - paper submitted and on arXiv (arXiv:1304.5356)
- **There should be more**
  - GZK analysis is only sensitive to very specific event topologies at these energies



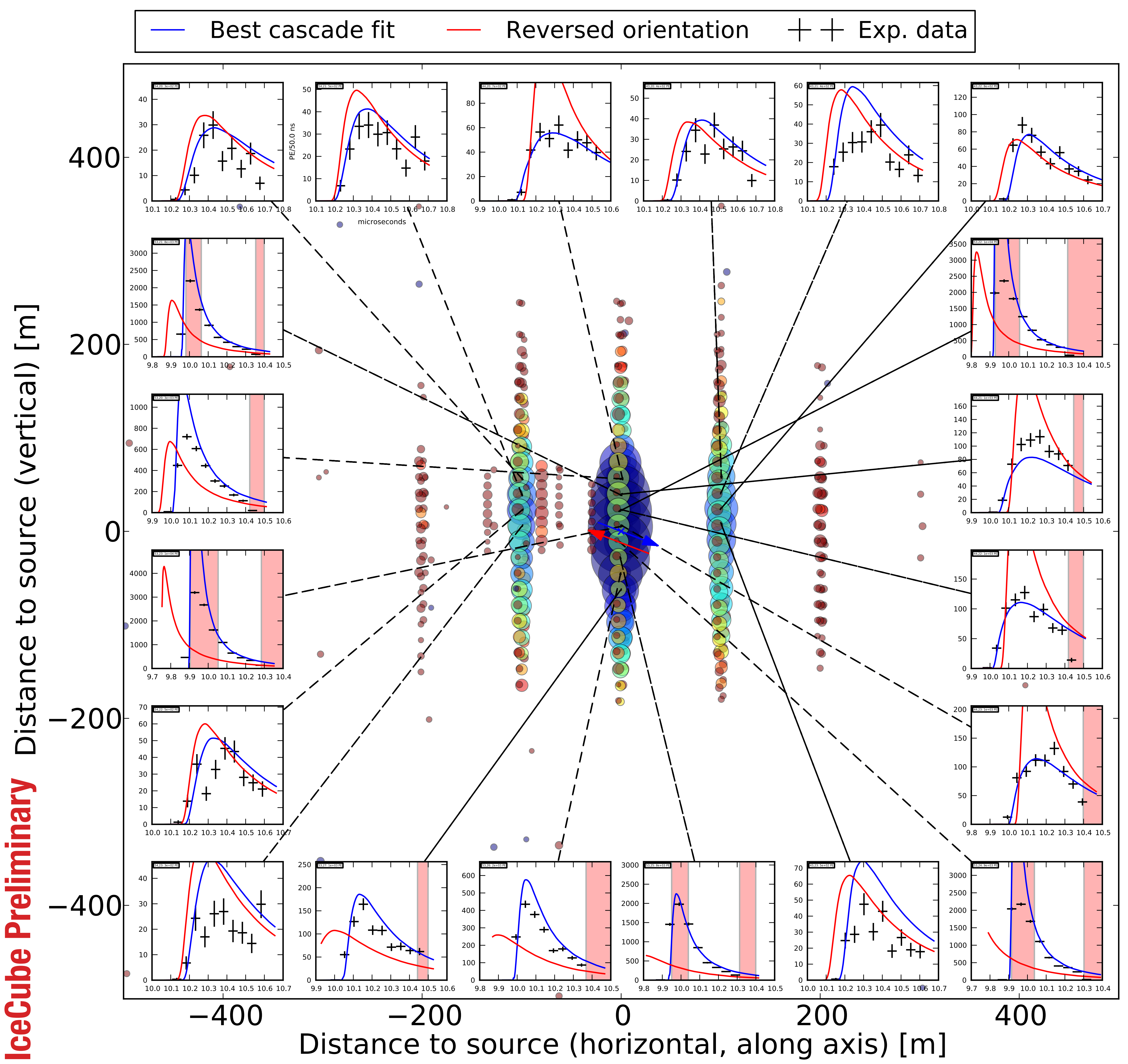


IceCube Preliminary

What are they?

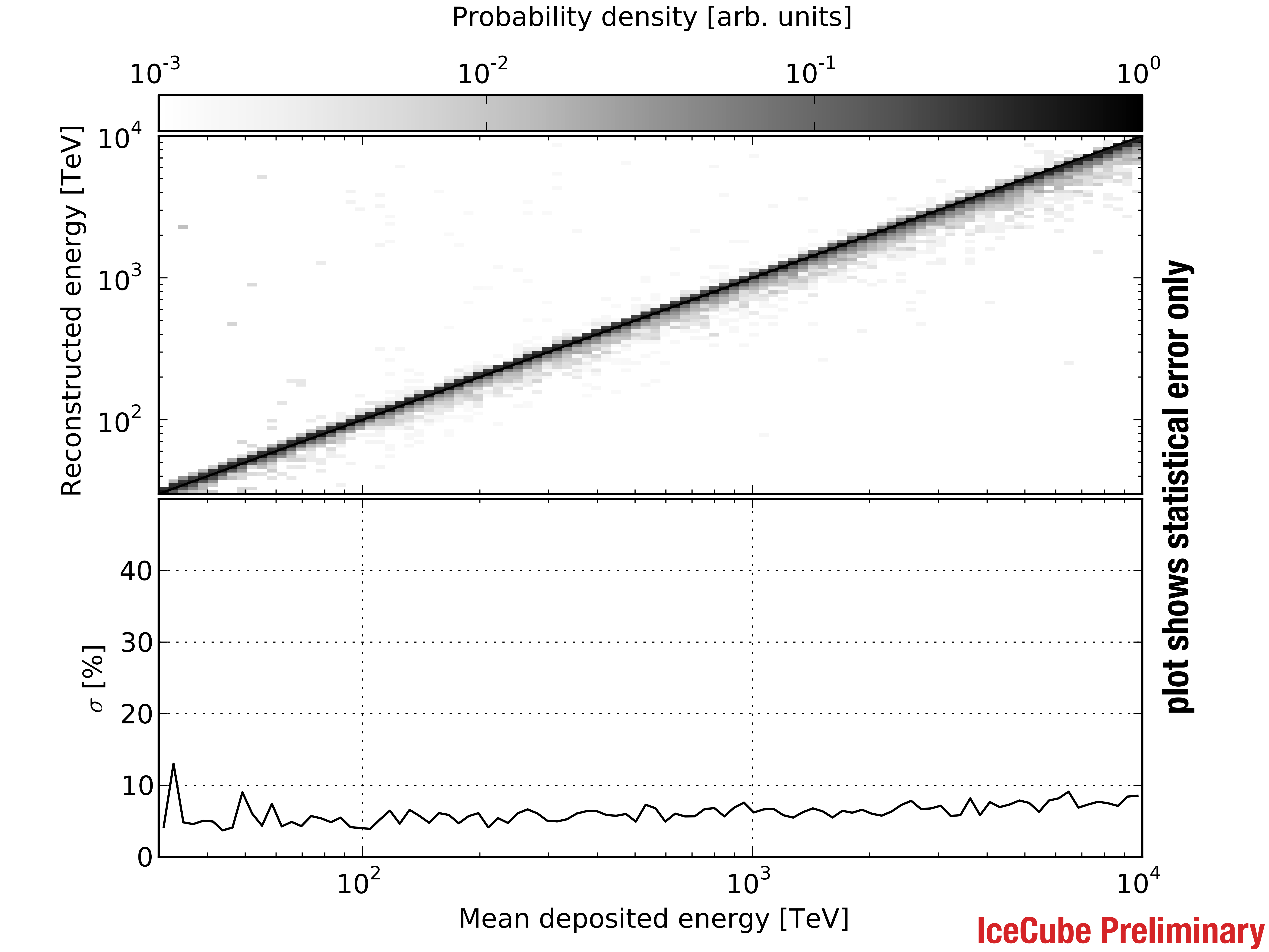
Studying individual events in IceCube

What are they?



Energy Reconstruction of EM showers

for analysis selection



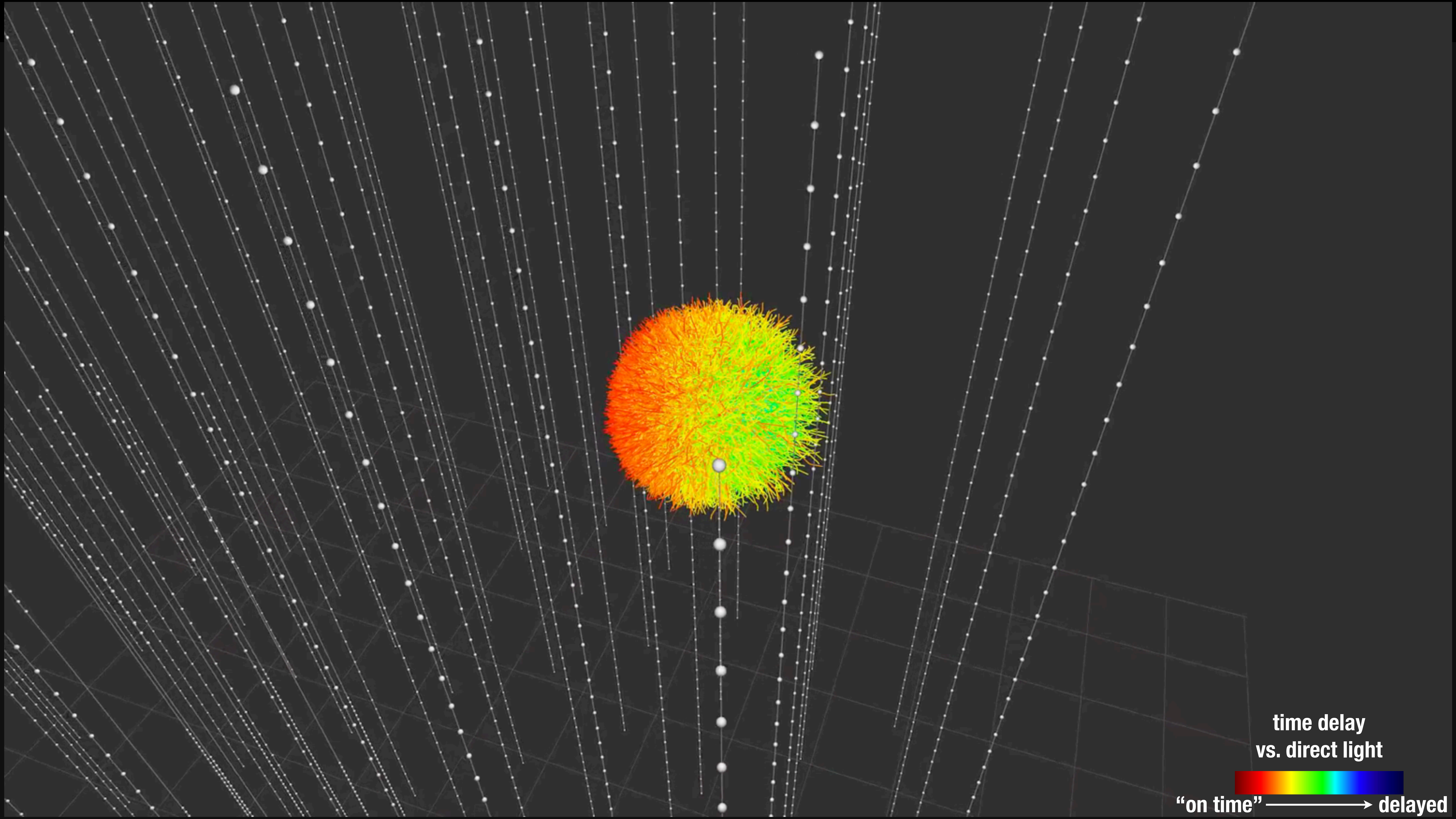
plot shows statistical error only

Systematics in Energy Reconstruction

- **Energy scale: better than ≈ 10%**
  - From minimum ionizing muons: ±5%
  - Scales very well to higher energies over orders of magnitude (measured with in-ice calibration laser)
- **Modeling of photon transport in ice**
  - Measured with in-ice calibration LEDs and other devices (dust logger, ...)
- **Statistical error at 1 PeV is negligibly small**

Directional Resolution for Showers

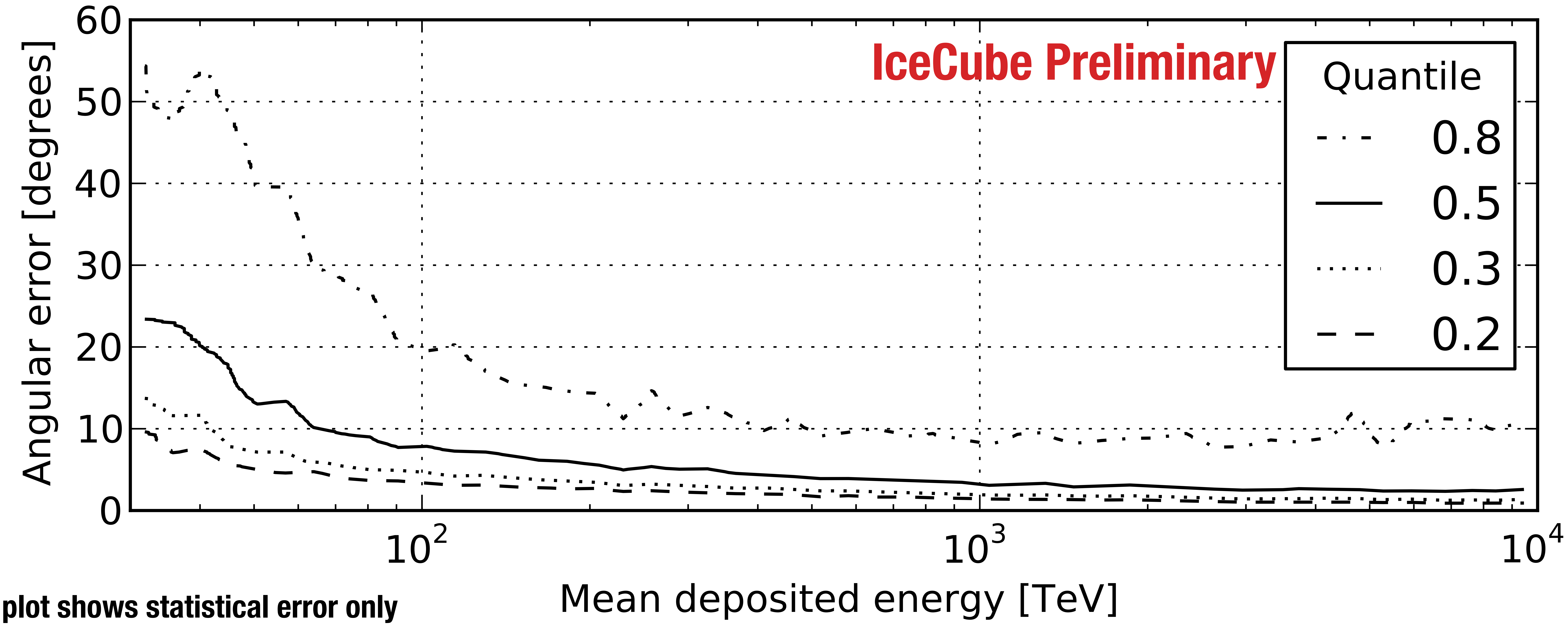
Shower directions reconstructed from timing profile



IceCube Preliminary

Directional Resolution for Showers

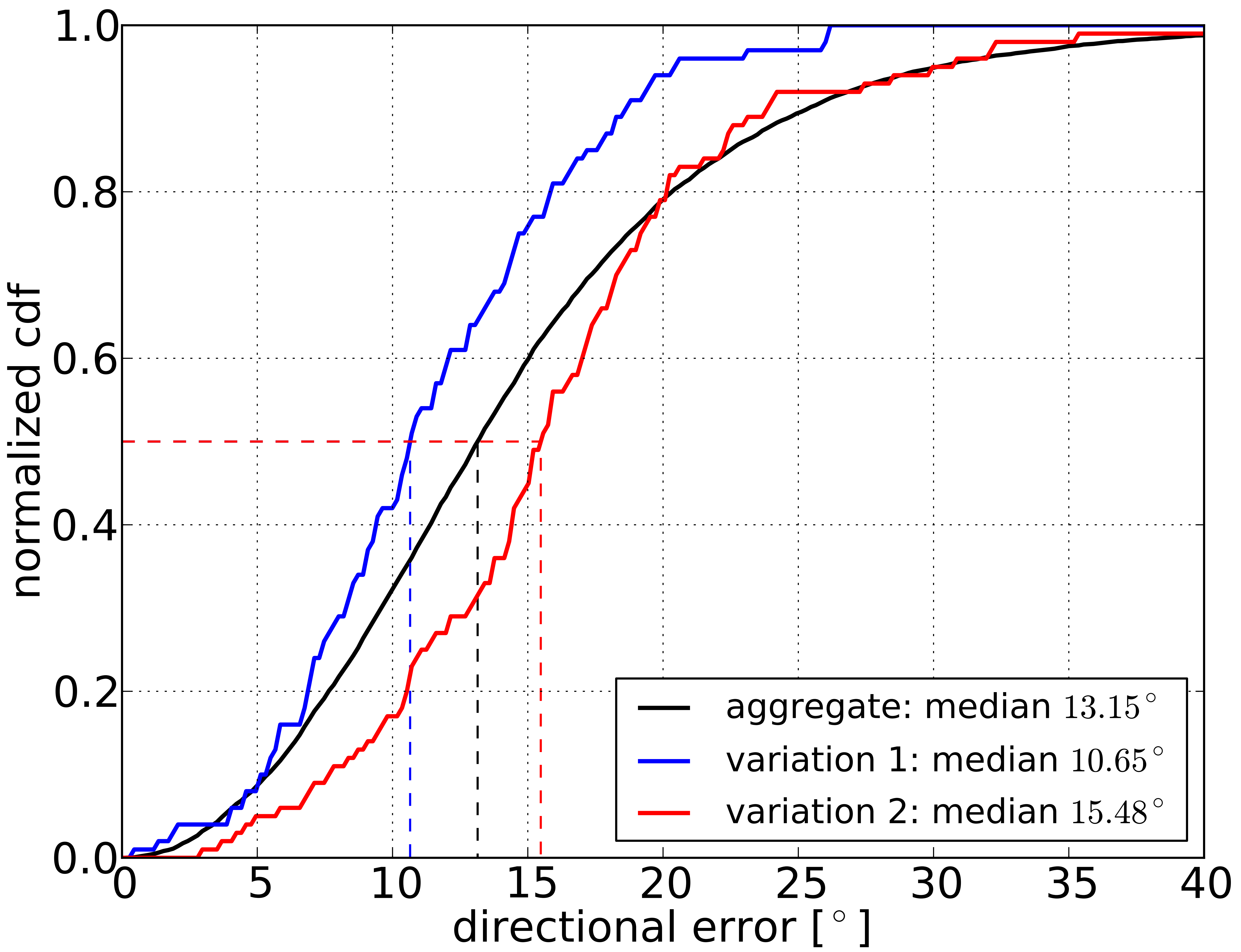
Statistical uncertainties in angular reconstruction for showers is small.
Dominated by ice systematics!



plot shows statistical error only

Directional Resolution for Showers

- **Angular error distributions on the order of 10°-15° depending on the ice model assumption**
  - two ice examples are shown
  - aggregate resolution in black



resolution for an individual example event from re-simulation

IceCube Preliminary

Things We Know

- At least two PeV neutrinos in a 2-year dataset
- Events are downgoing
- Seems not to be GZK (too low in energy)
- Higher than expected for atmospheric background
- Spectrum seems not to extend to much higher energies
  - unbroken E^{-2} would have made 8-9 more above 1 PeV

Things We Wanted to Learn

- Isolated events or tail of spectrum?
- Spectral slope/cutoff
- Flavor composition
- Where do they come from?
- Astrophysical or air shower physics (e.g. charm)?
- Need more statistics to answer all of these!

High-Energy Contained Vertex Search

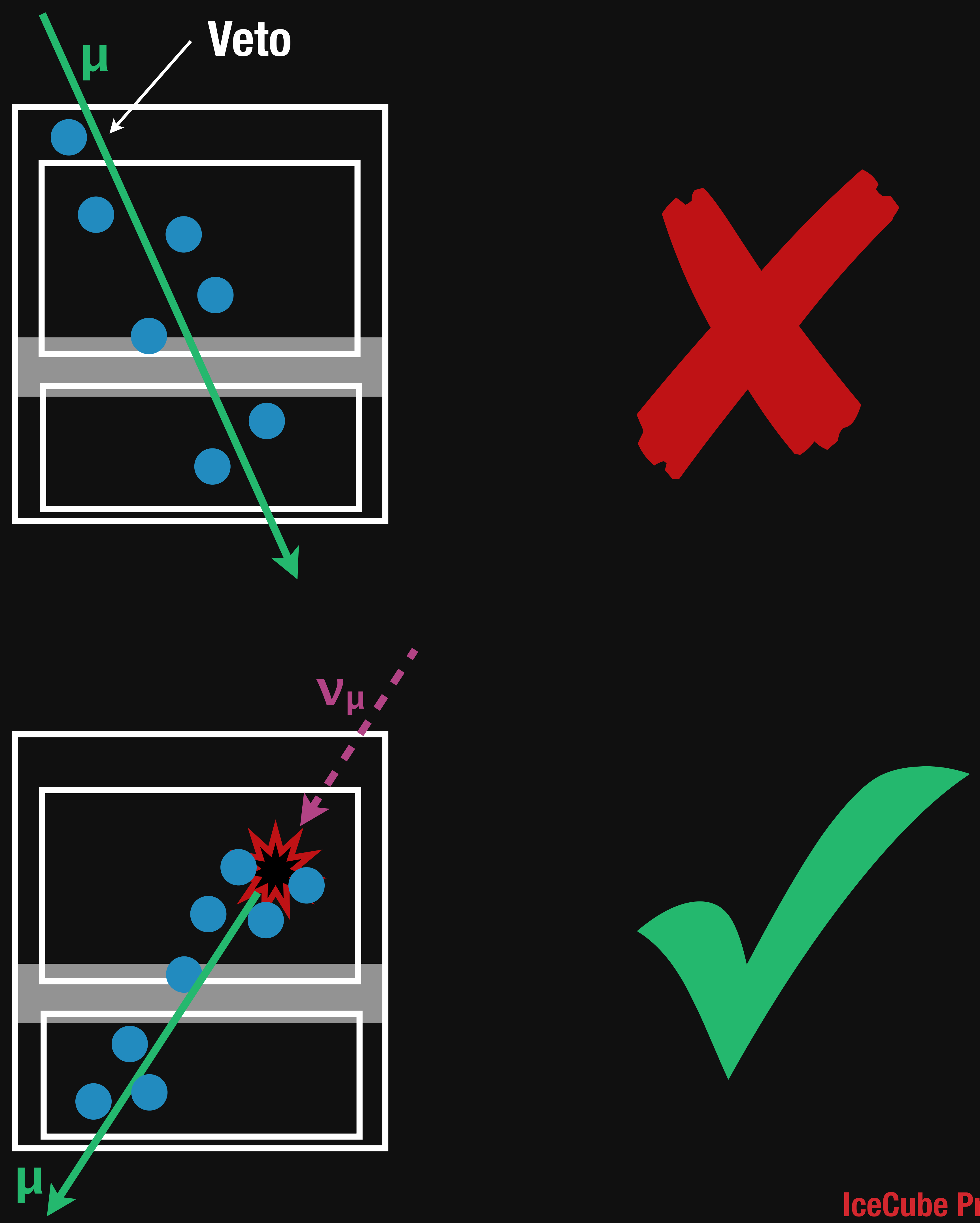
How we found more...

Follow-up Analysis

Specifically designed to find these contained events

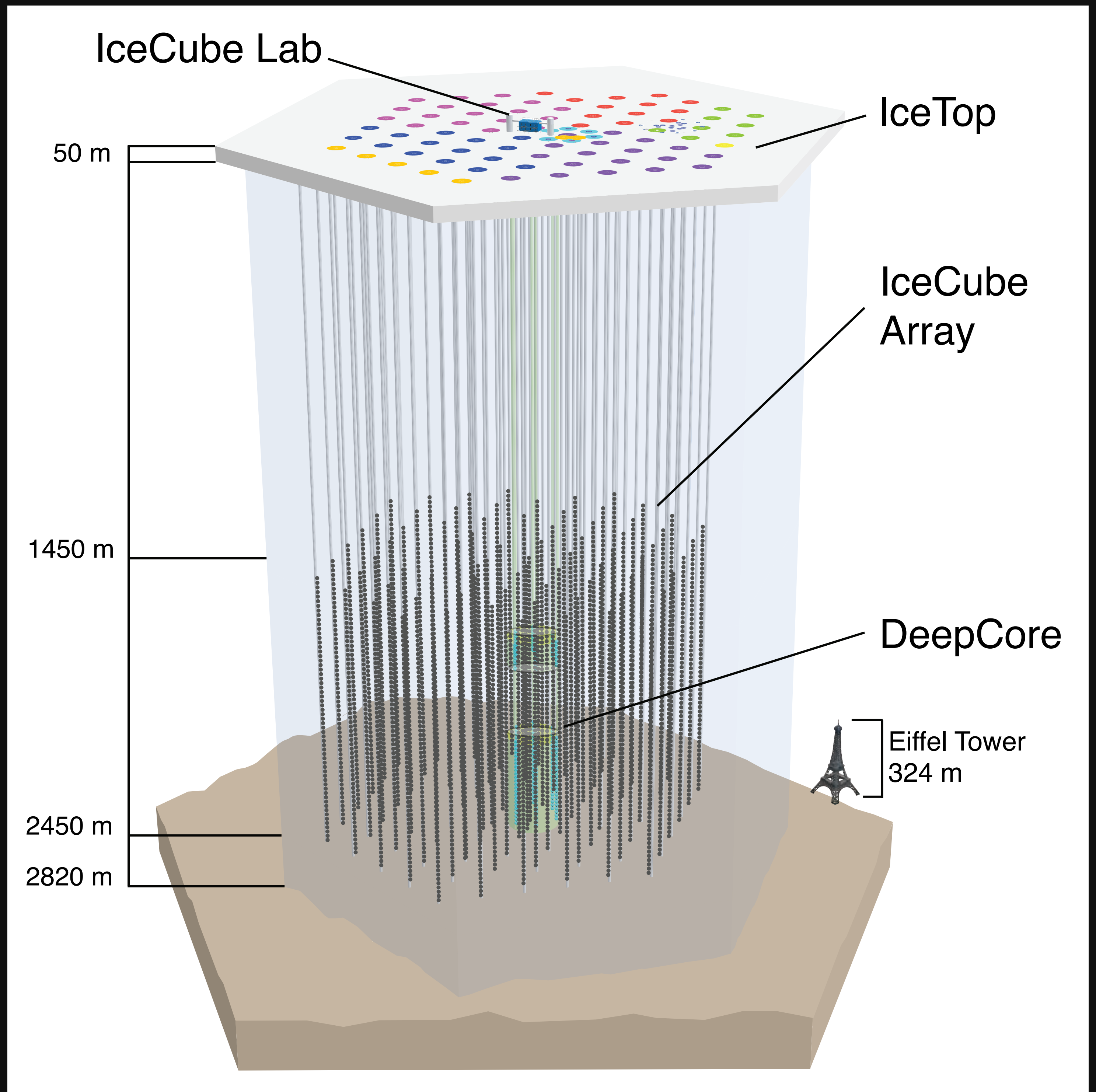
Analysis of dataset taken from May 2010 to May 2012 (662 days of livetime)

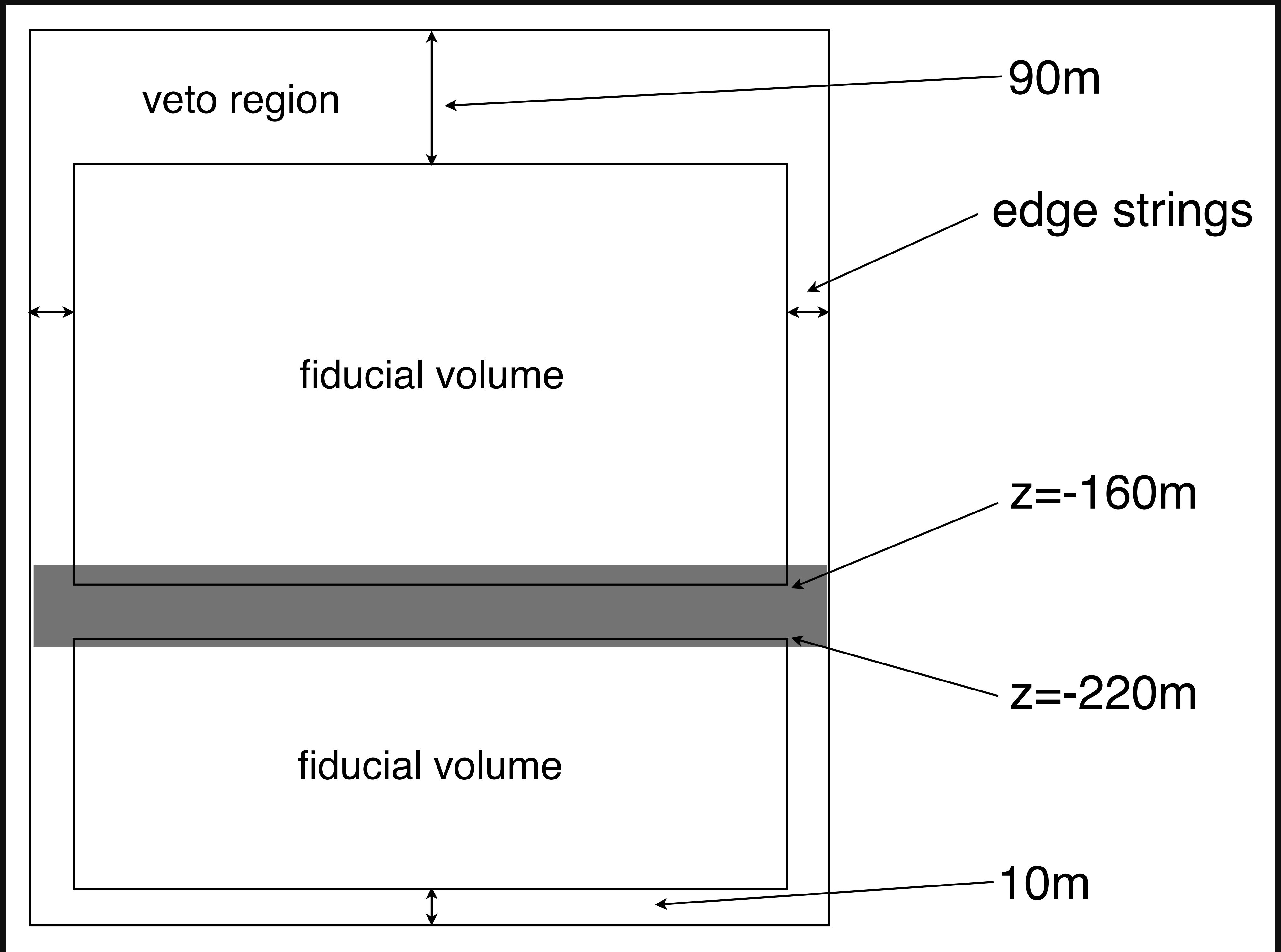
- **Explicit contained search at high energies (cut: Q_{tot}>6000)**
- **400 Mton effective fiducial mass**
- **Use atmospheric muon veto**
- **Sensitive to all flavors in region above 60TeV**
- **Three times as sensitive at 1 PeV**
- **Estimate background from data**



Background 1 - Atmospheric Muons

Mostly incoming atmospheric muons sneaking in through the main dust layer



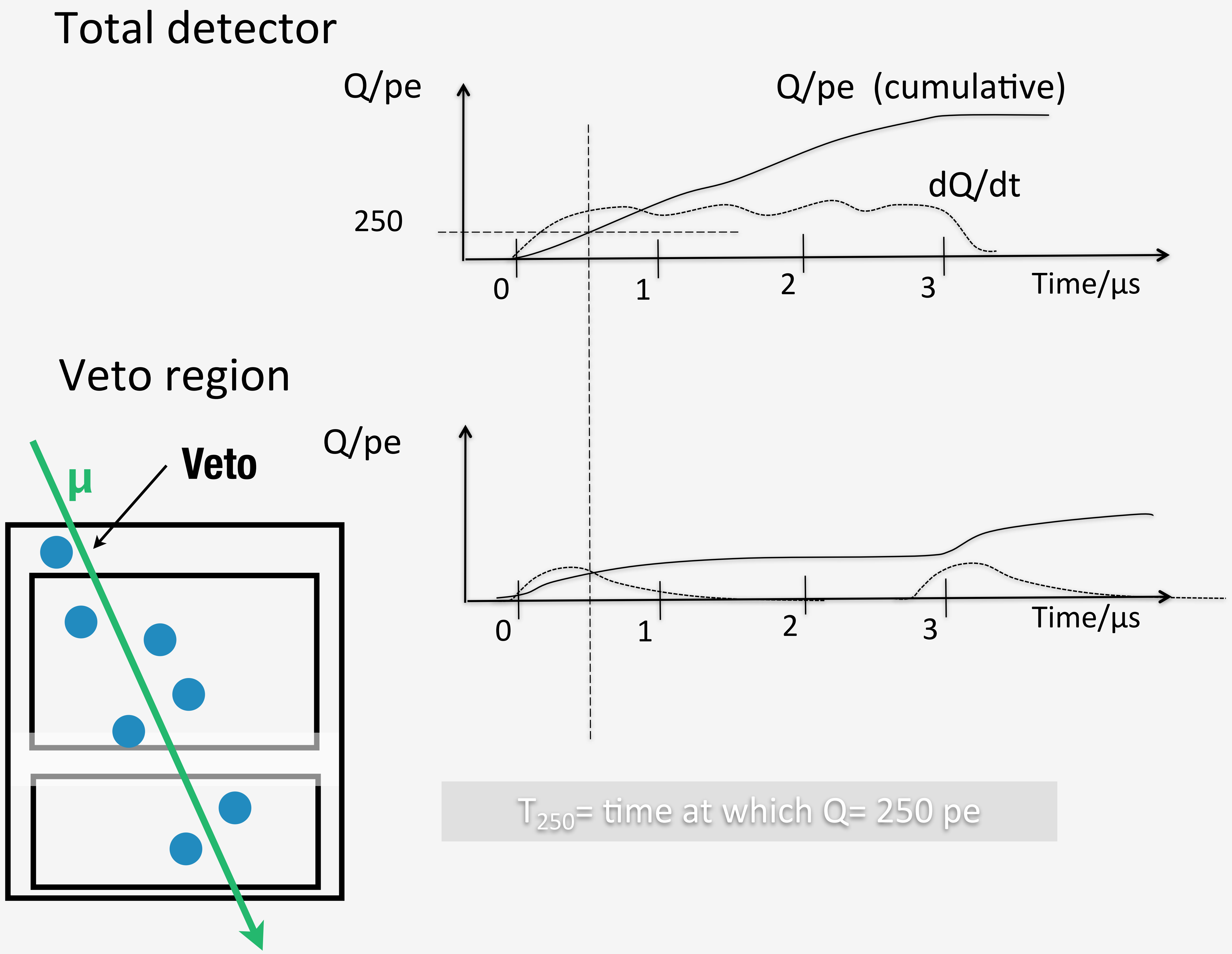


- Reject incoming muons when "early charge" in veto region
- Control sample available: tag muons with part of the detector - known bkg.
- 6±3.4 muons per 2 years (662 days)

Background 1 - Atmospheric Muons

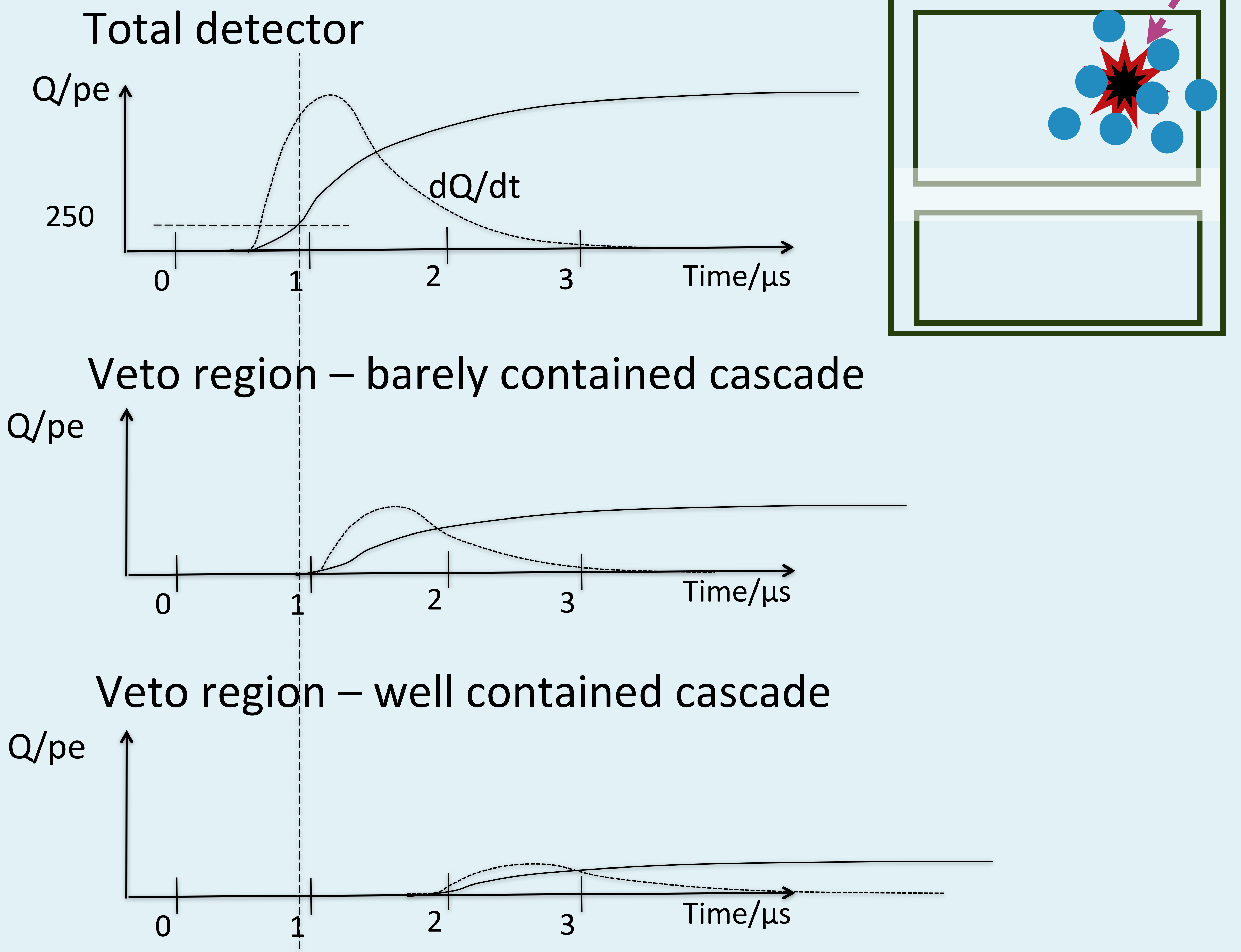
What's "early charge"?

Throughgoing muon



T_{250}= time at which Q= 250 pe

Contained cascade



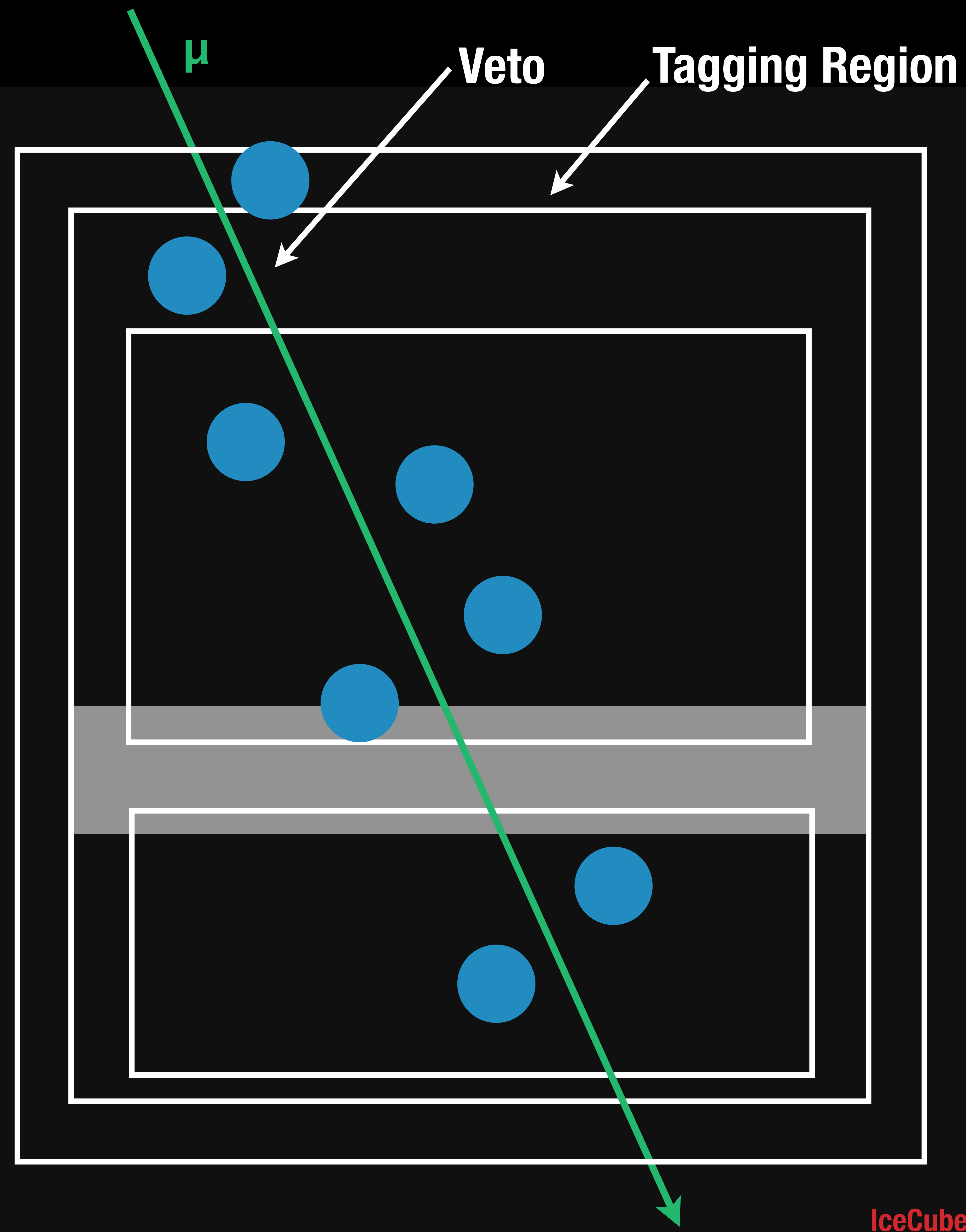
T_{250}= time at which Q= 250 pe

IceCube Preliminary

Estimating Muon Background From Data

Use known background from atmospheric muons tagged in an outer layer to estimate the veto efficiency

- Add one layer of DOMs on the outside to tag known background events
  - Then use these events to evaluate the veto efficiency
- Avoids systematics from simulation assumptions/models!
- Can be validated at charges below our cut (6000 p.e.) where background dominates



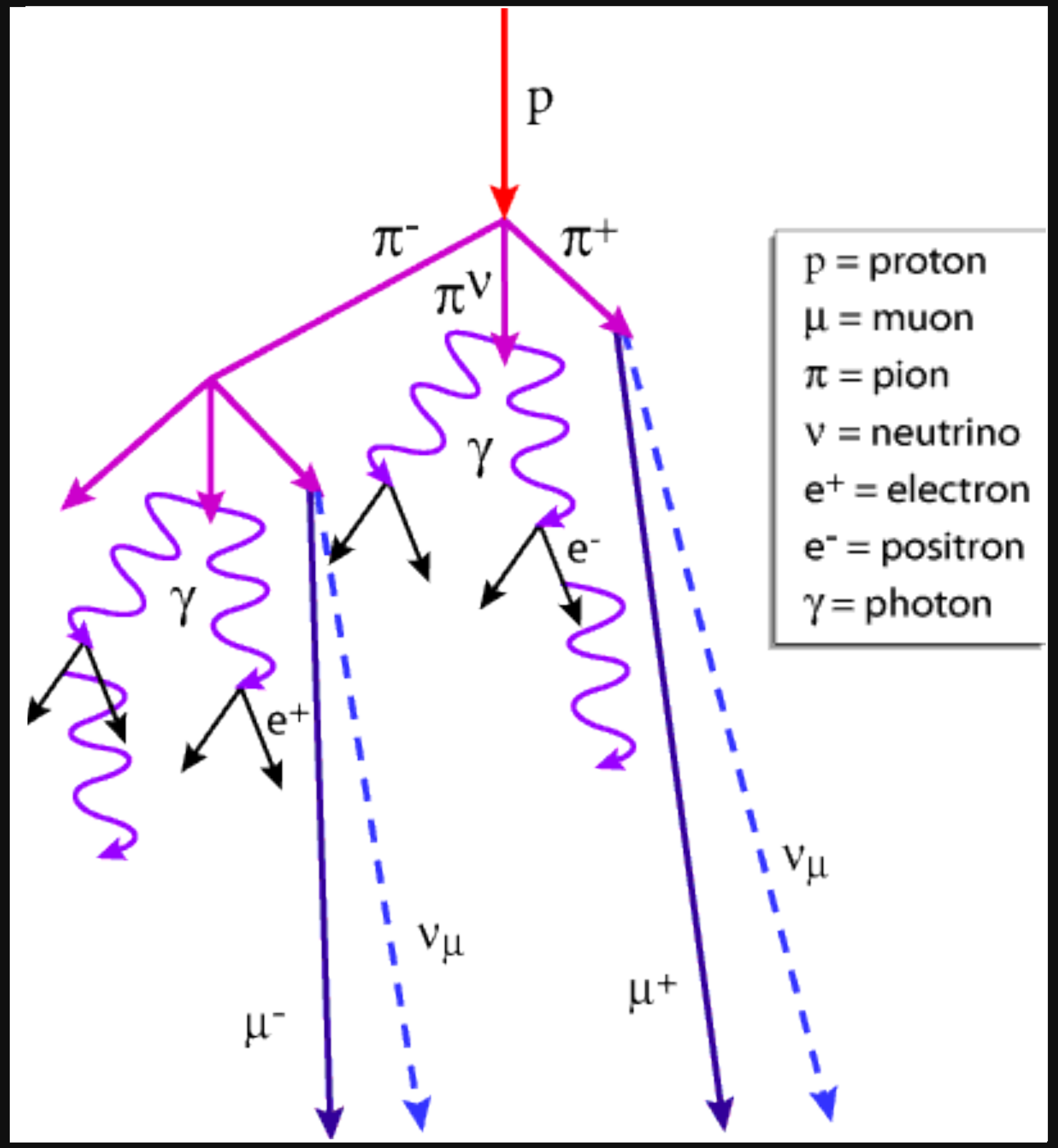
Background 2 - Atmospheric Neutrinos

Very low at PeV energies

- Typically separated by energy
- Very low at PeV energies (order of 0.1 events/year)
- Large uncertainties in spectrum at high energies
- $4.6^{+3.7}_{-1.2}$ events in two years (662 days)
- Rate accounts for events vetoed by accompanying muon from the same air shower in the Southern Sky
- Baseline model: Enberg et al. (updated with cosmic-ray Knee model)

Vetoing Atmospheric Neutrinos

- Atmospheric neutrinos are made in air showers
- For downgoing neutrinos, the muons will likely not have ranged out at IceCube
- Downgoing events that start in the detector are extremely unlikely to be atmospheric

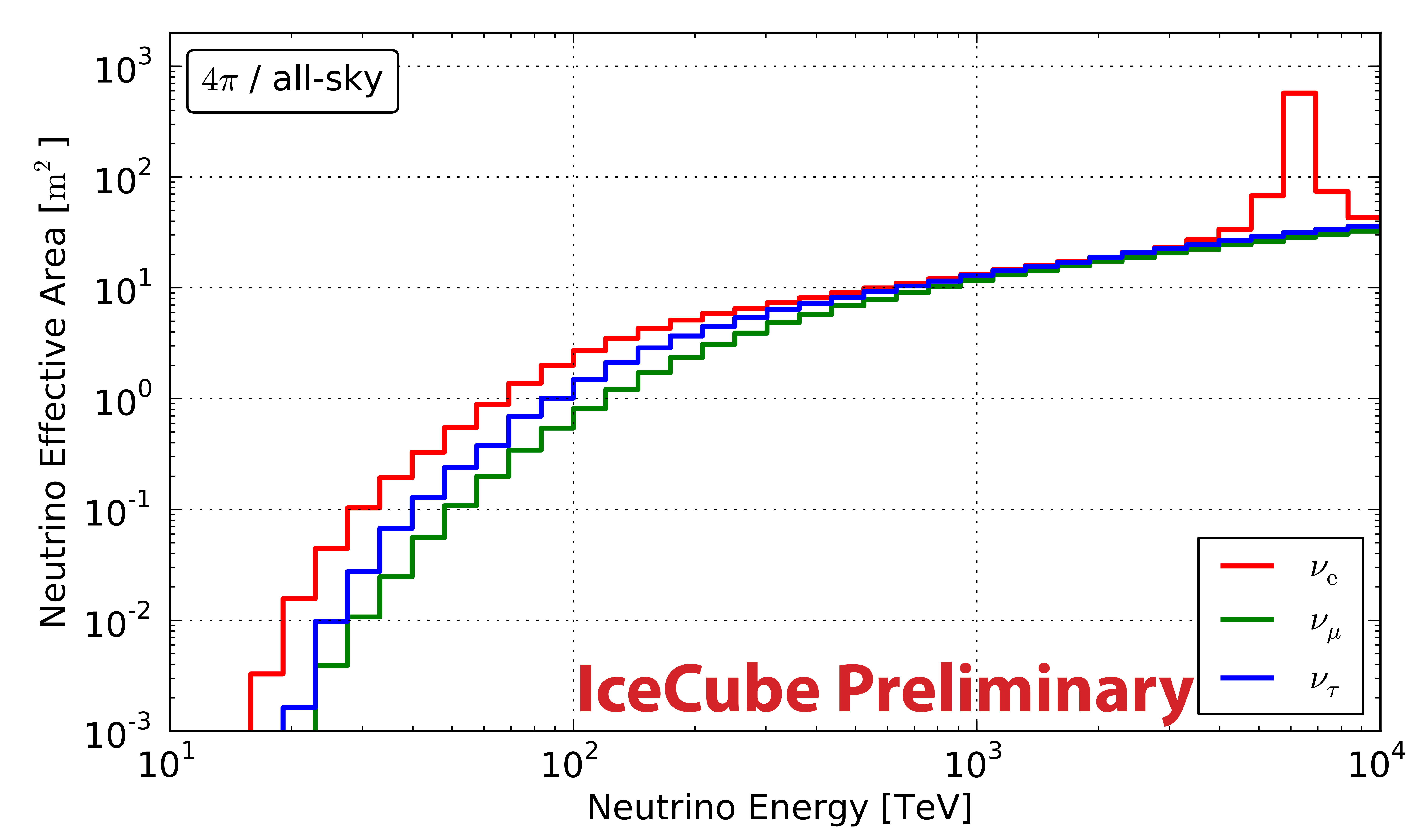


Schönert et al., arXiv:0812.4308

- Note: optimal use requires *minimal* overburden to have the highest possible rate of cosmic ray muons!

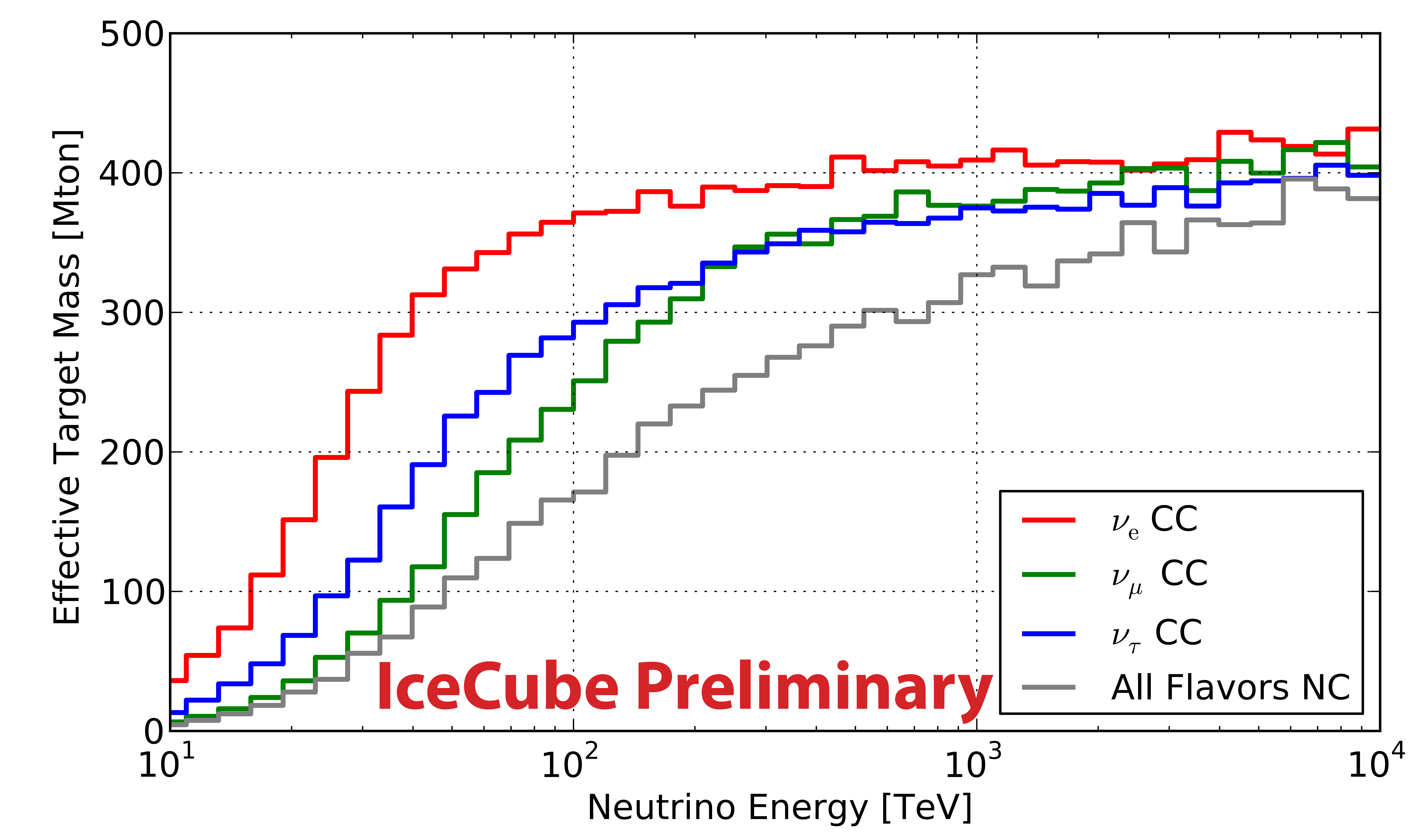
Effective Area

Differences at low energies between the flavors due to leaving events at constant charge threshold



Effective Volume / Target Mass

Fully efficient above 100 TeV for CC electron neutrinos
About 400 Mton effective target mass



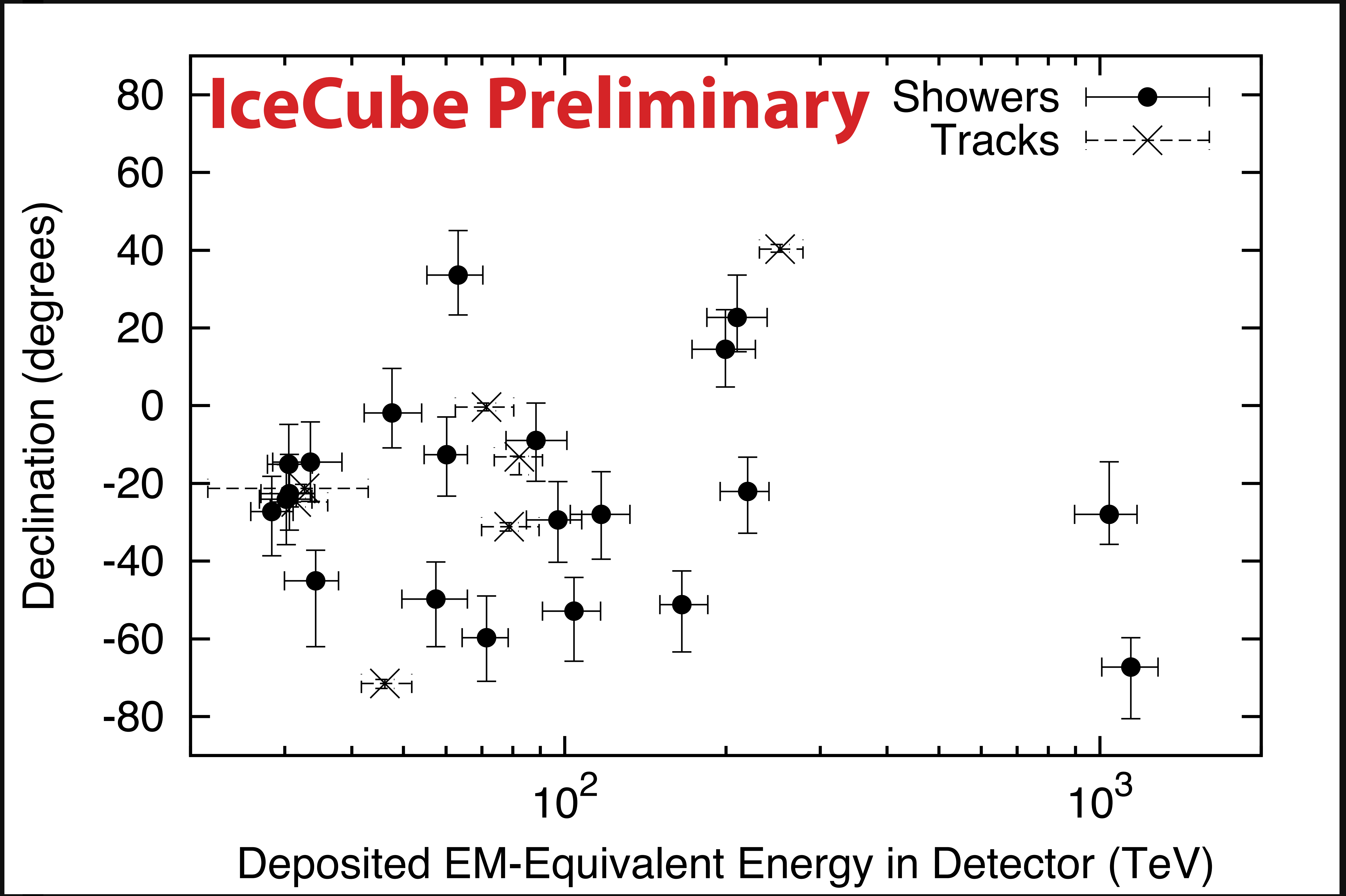
What Did We Find?

26 more events!

What Did We Find?

26 more events in the 2 years of IceCube data (2010/2011 season: "IC79"&"IC86")

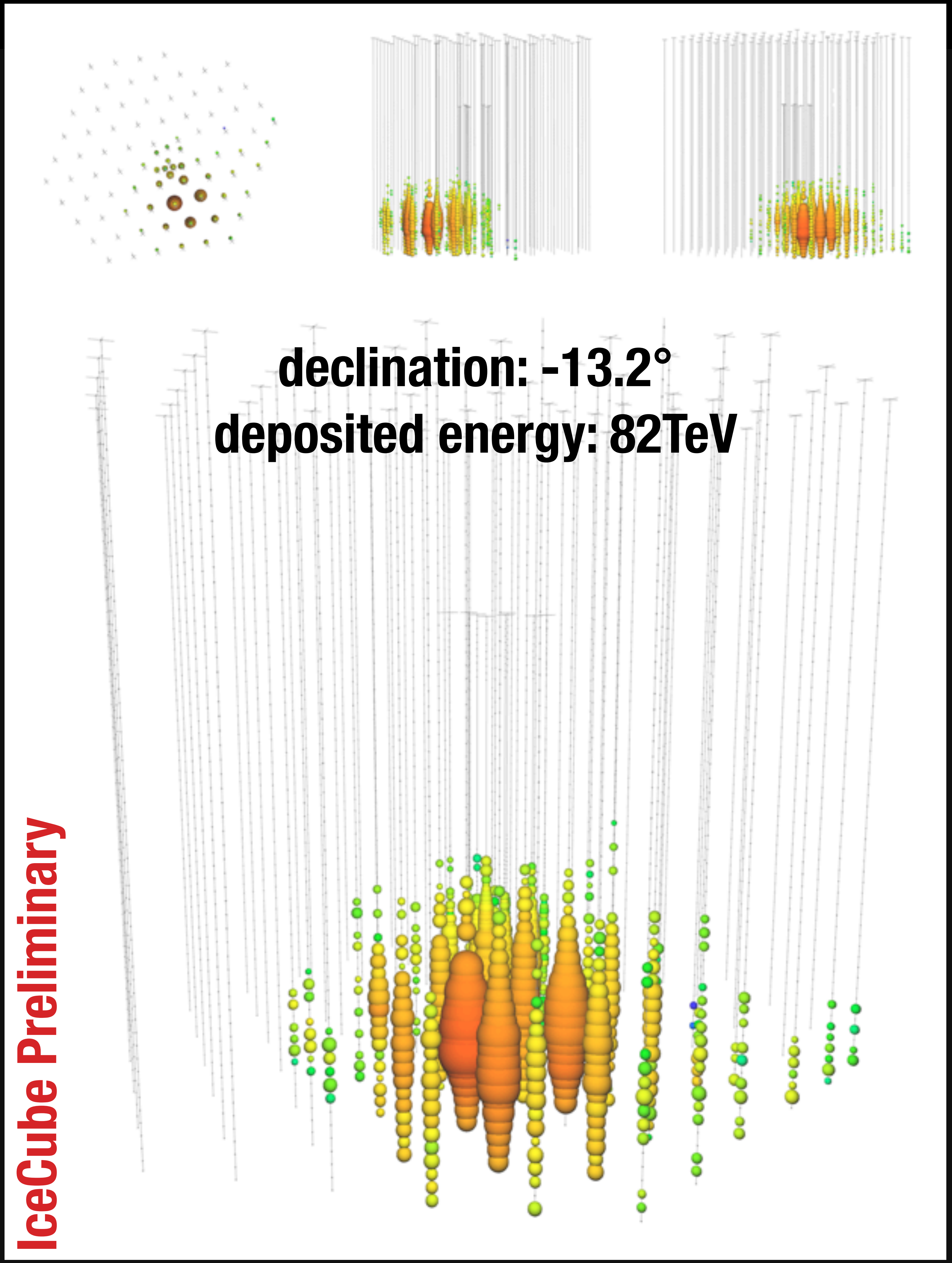
- **28 events observed!**
  - 26 new events in addition to the two 1 PeV events!
- **Track events (x) can have much higher neutrino energies than deposited energies**
  - also true on a smaller scale for shower events for all signatures except charged-current ν_e
- **Background: $10.6^{+5.0}_{-3.6}$**
  - (or 12.1±3.4 for reference neutrino background model)

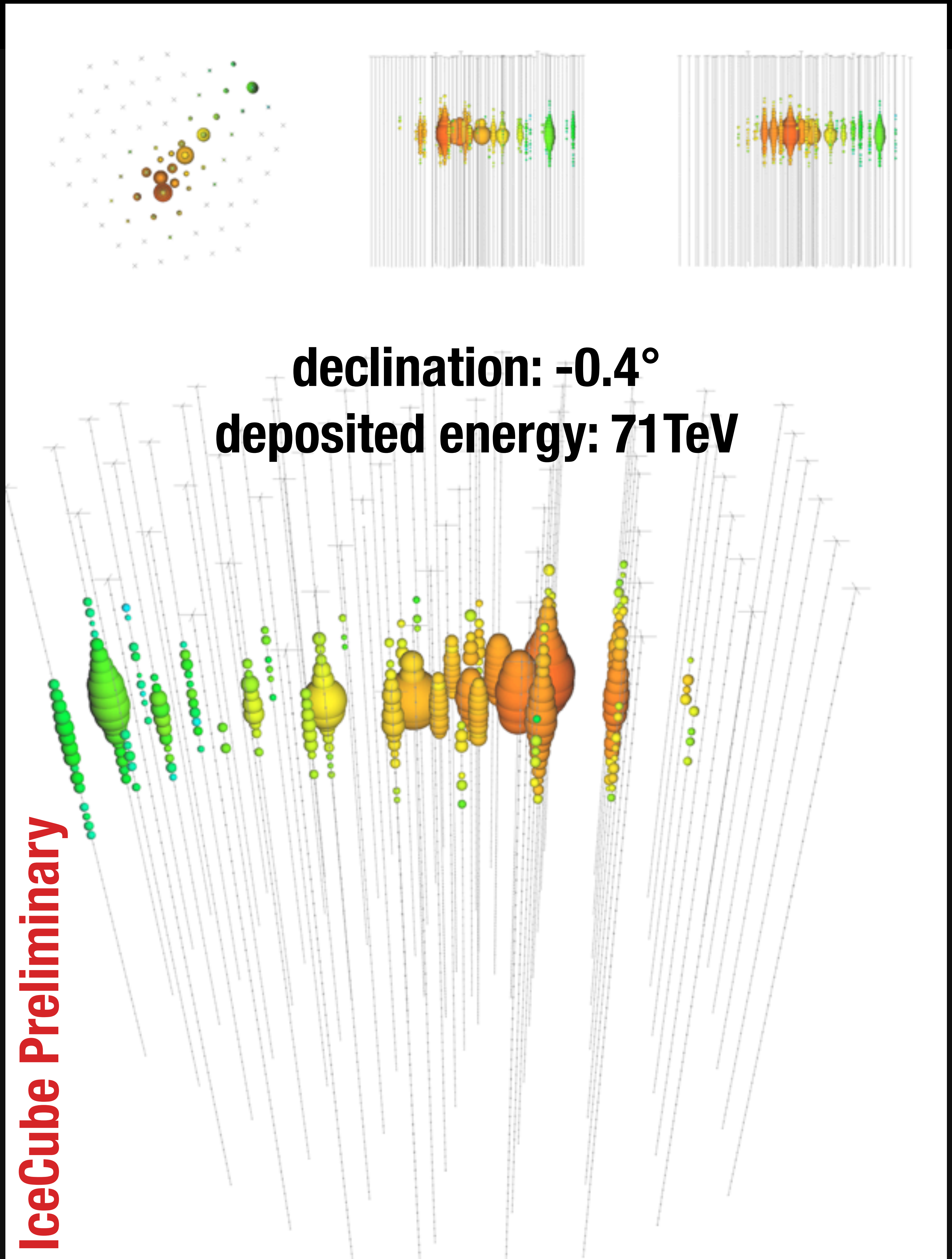


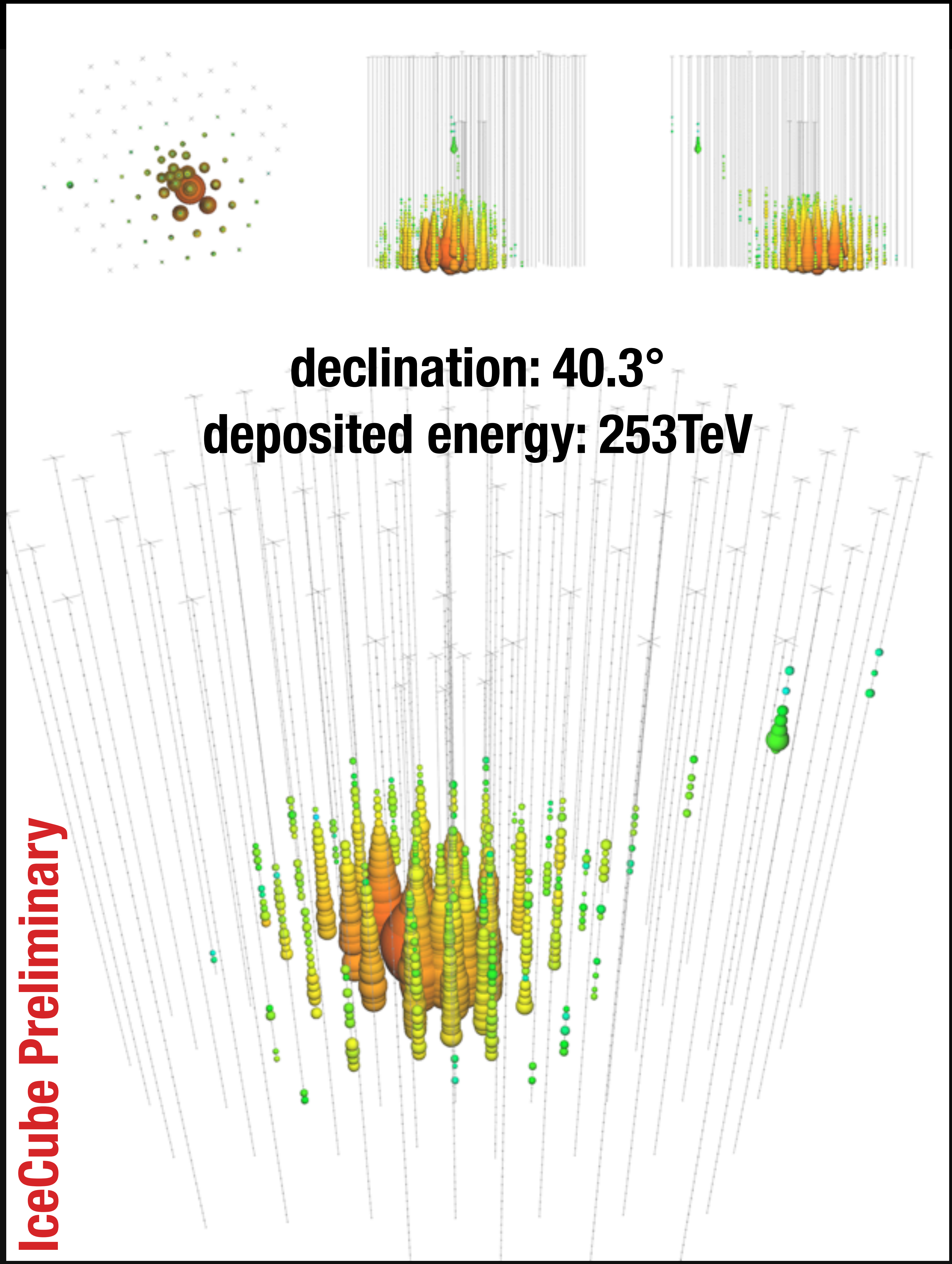
(preliminary significance w.r.t. reference bkg. model: 3.3σ for 26 events; 4.1σ for 28 events)

What Did We Find?

Some examples

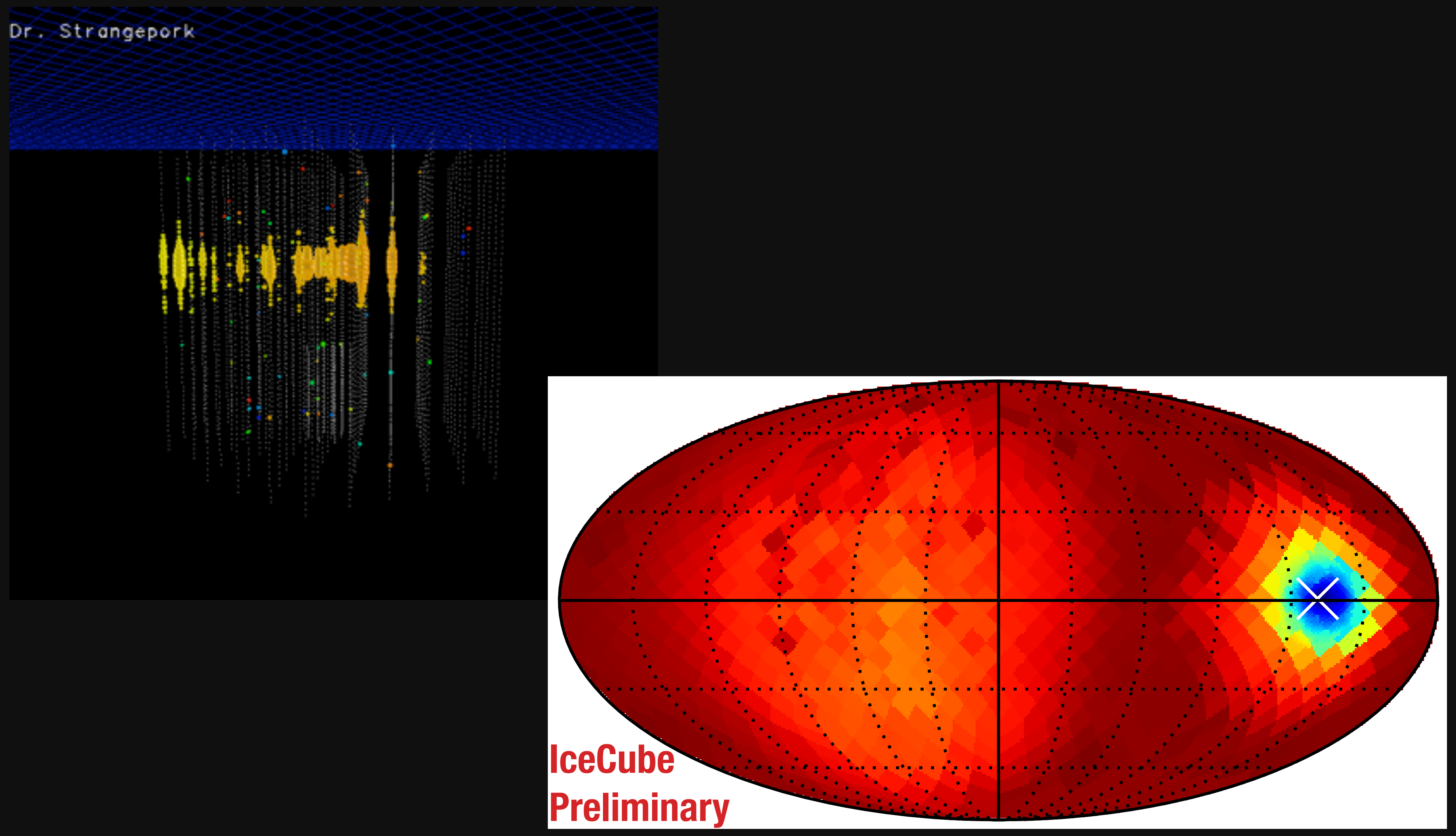


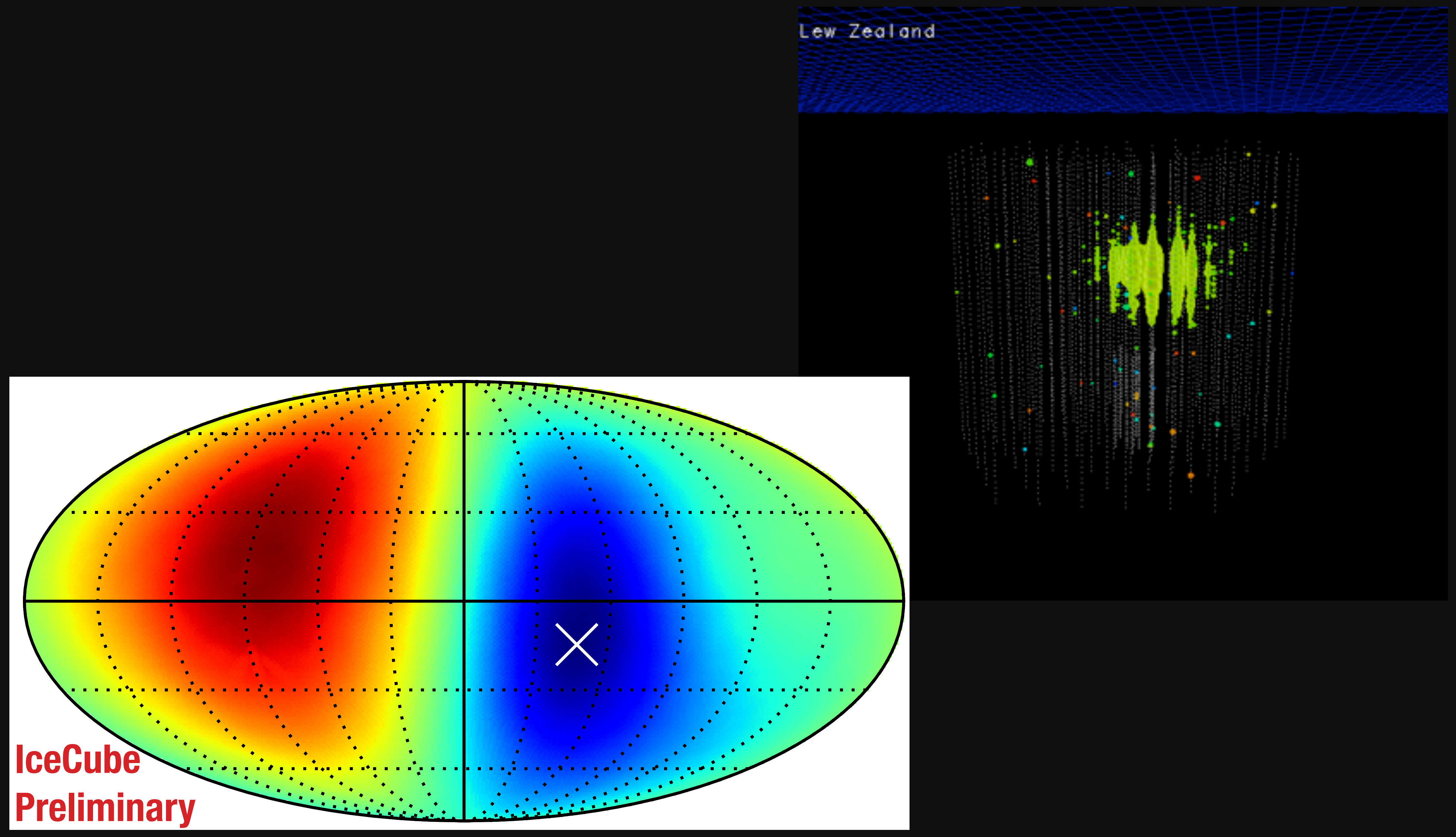




Event Reconstruction

Generic full-sky likelihood scan for each event (works with shower and track signatures)

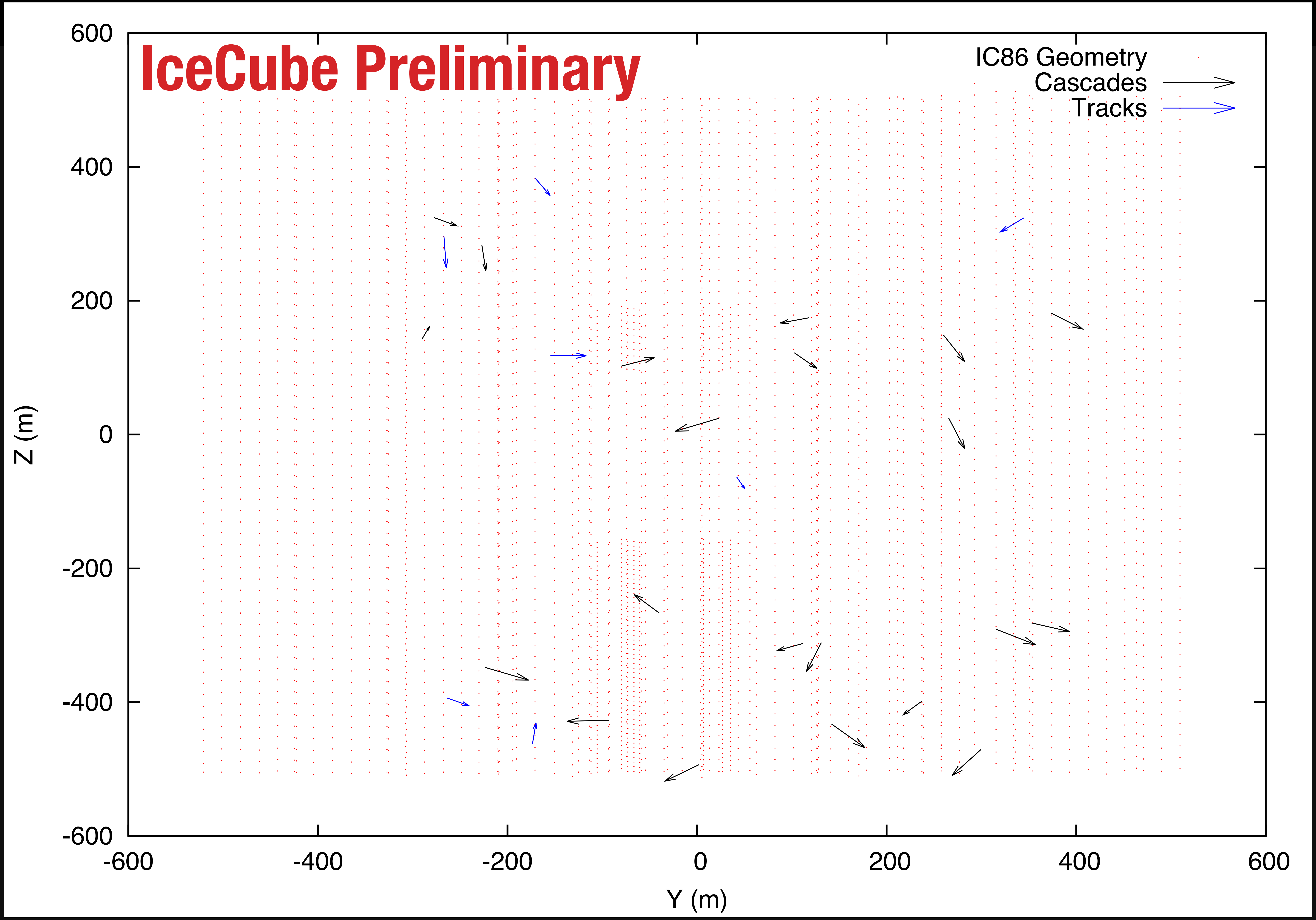




- Fits for deposited energy along a “track” in each skymap direction based on hit pattern using a detailed model of the glacial ice optical properties
- Result: direction with uncertainty and estimate for deposited energy

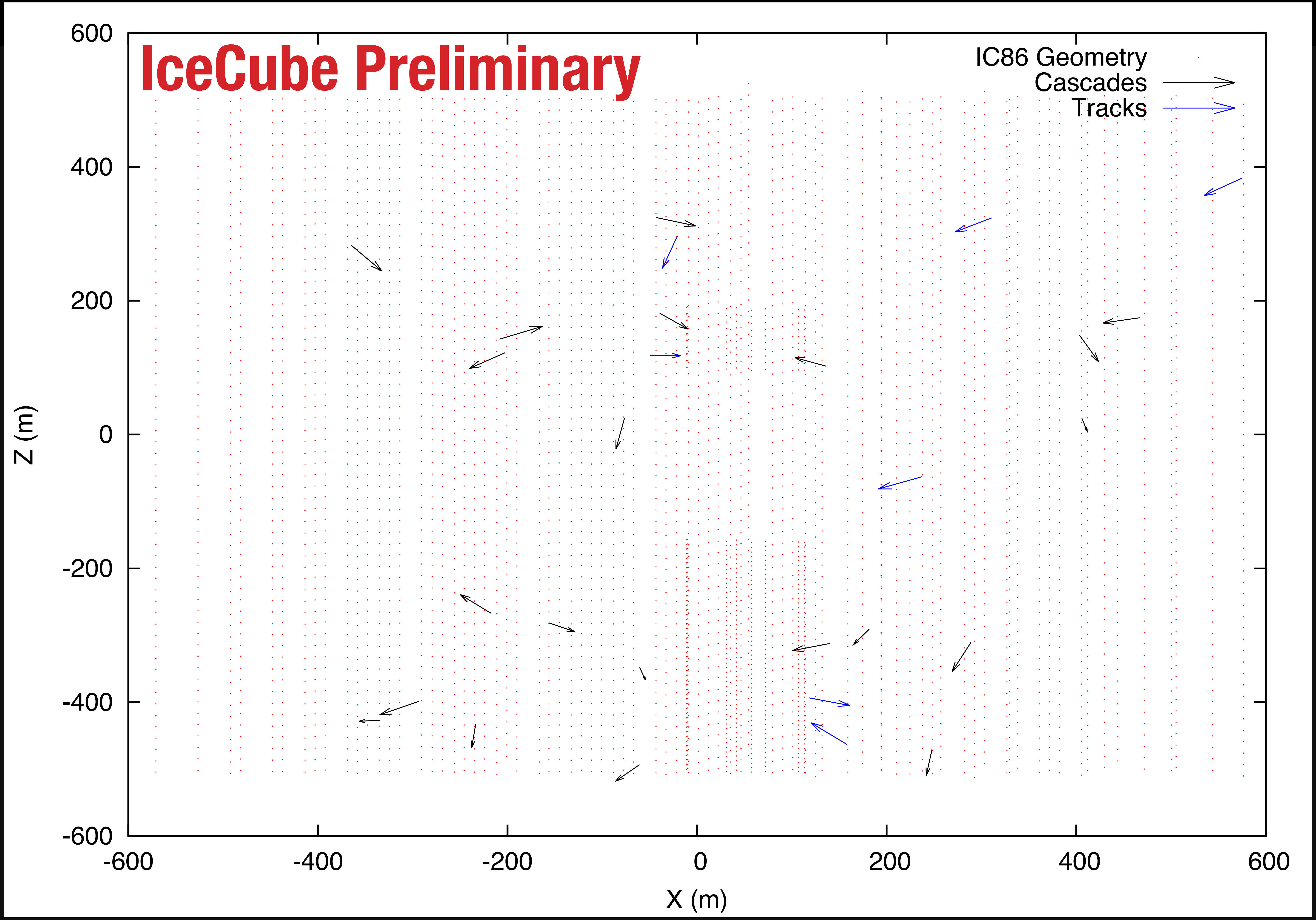
Event Distribution in Detector

Uniform in fiducial volume



Event Distribution in Detector

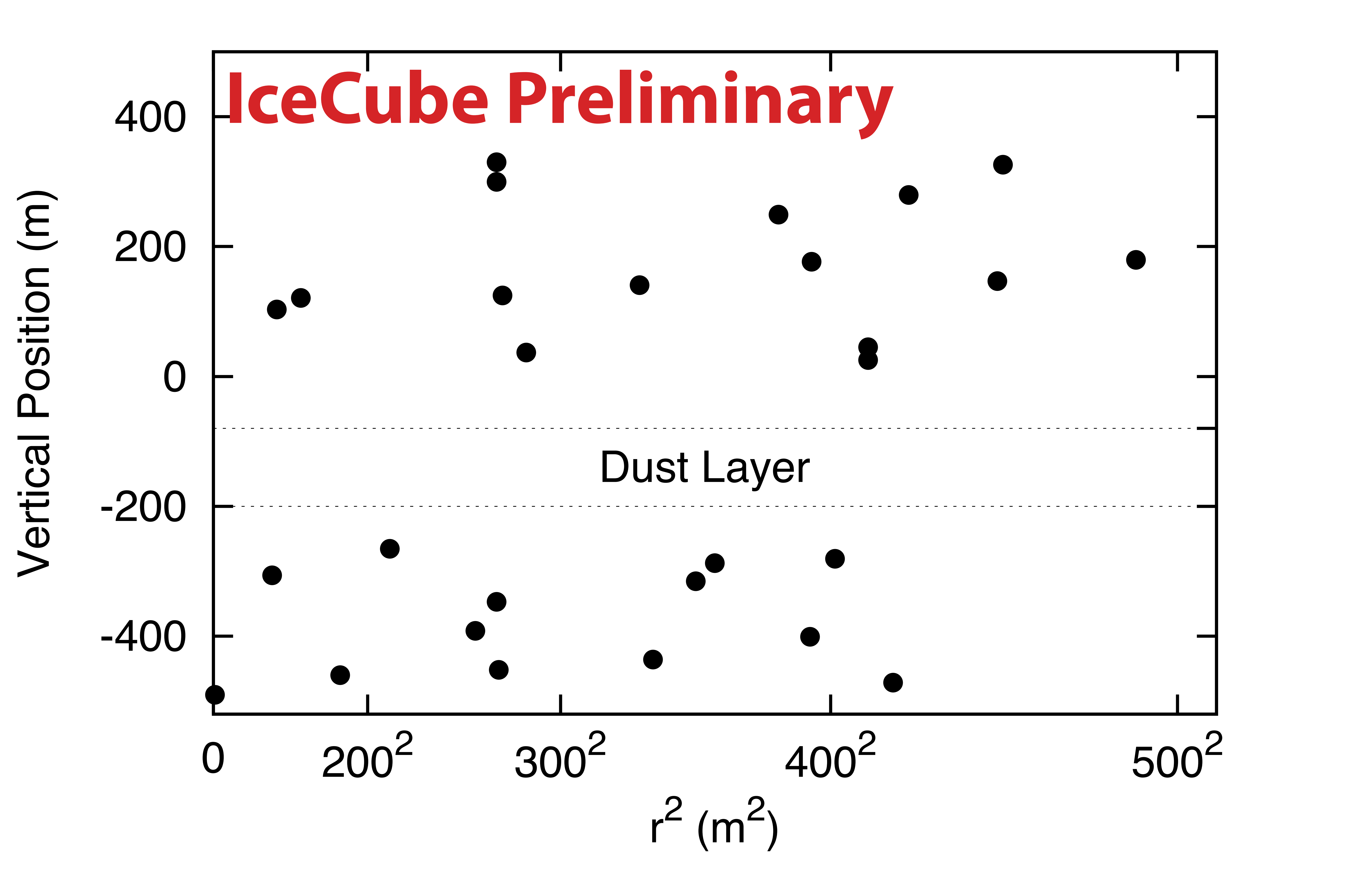
Uniform in fiducial volume



Event Distribution in Detector

Uniform in fiducial volume

- Backgrounds from atm. muons would pile up preferentially at the detector boundary
- No such effect is observed!



Systematic Studies and Cross-Checks

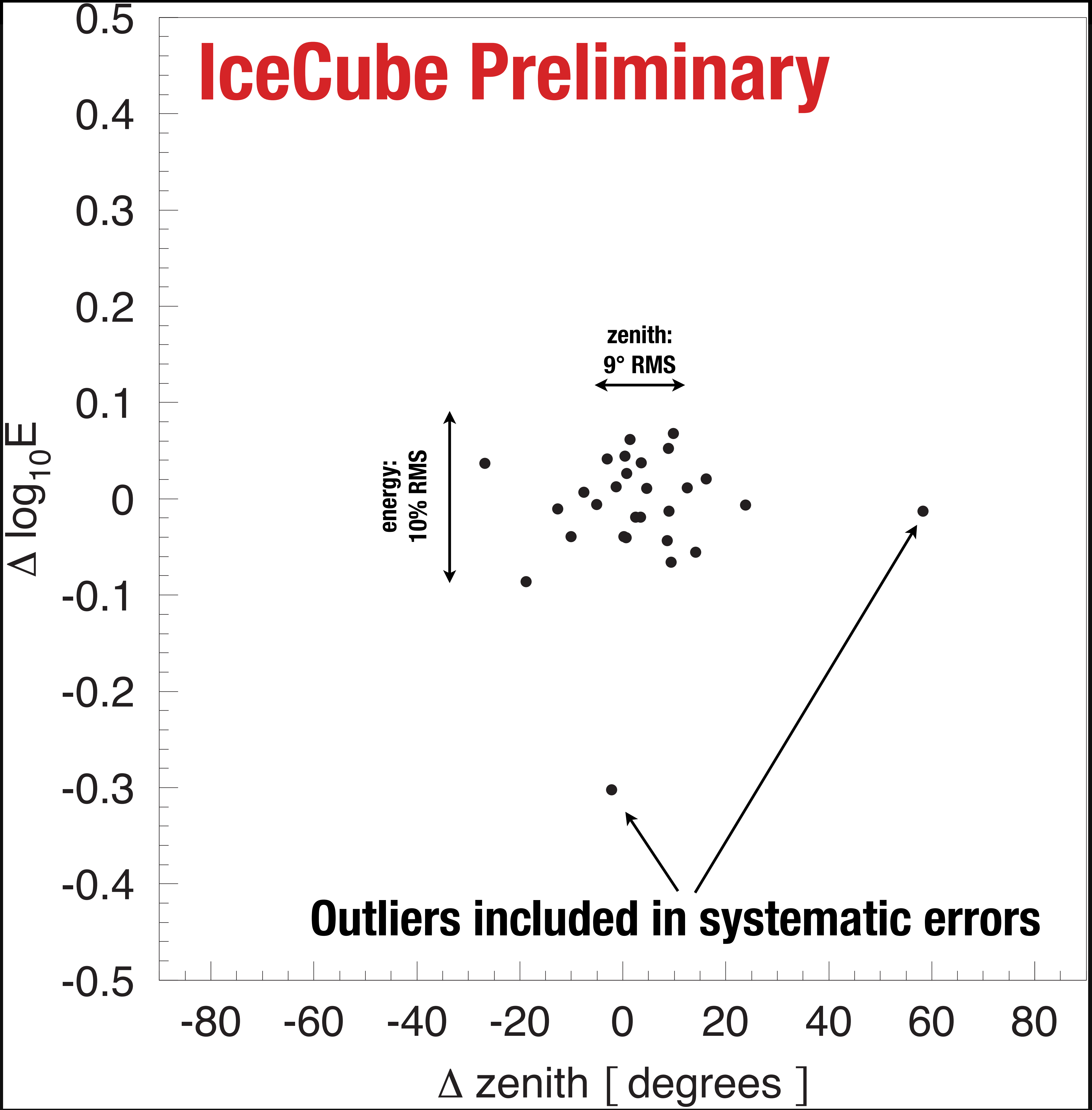
- **Systematics were checked using an extensive per-event re-simulation**
  - varied the ice model and energy scale within uncertainties for each iteration and repeated analysis
- **Different fit methods applied to the events show consistent results**

- **Tracks:**
  - good angular resolution (<1deg)
  - inherently worse resolution on energy due to leaving muon
- **Showers:**
  - larger uncertainties on angle (about 10°-15°)
  - good resolution on deposited energy (might not be total energy for NC and ν_τ)

Systematic Studies and Cross-Checks

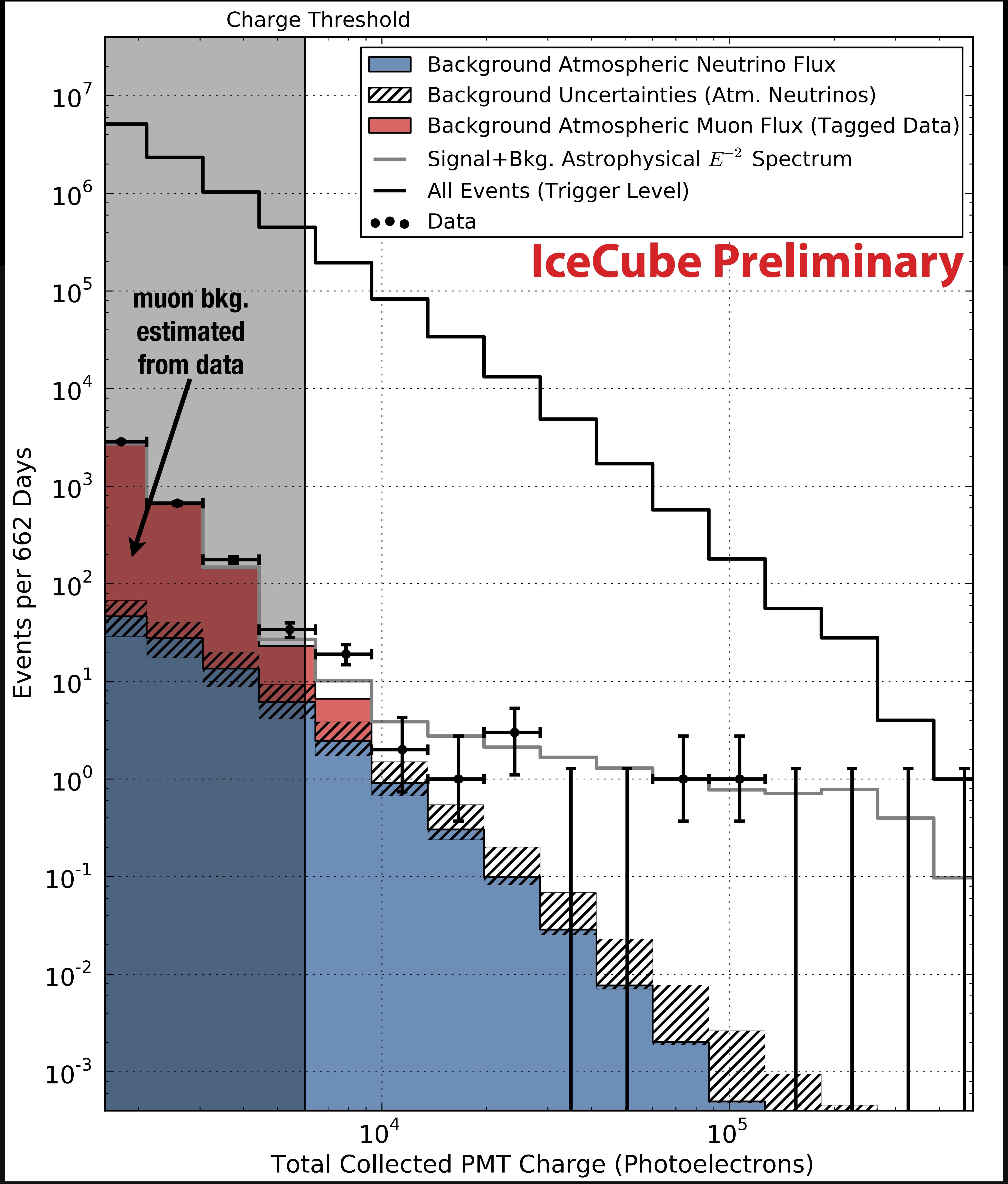
Cross-check with a fit method based on direct re-simulation of events

- **Second fit method based on continuous re-simulation of events**
  - Can include ice systematics like directional anisotropy in the scattering angle distribution and tilted dust layers directly in the fit!
  - Very slow, works for shower-like events
- **Shown: comparison with other method**
- **Within these known bounds: all results are compatible to within 10%**



Charge Distribution

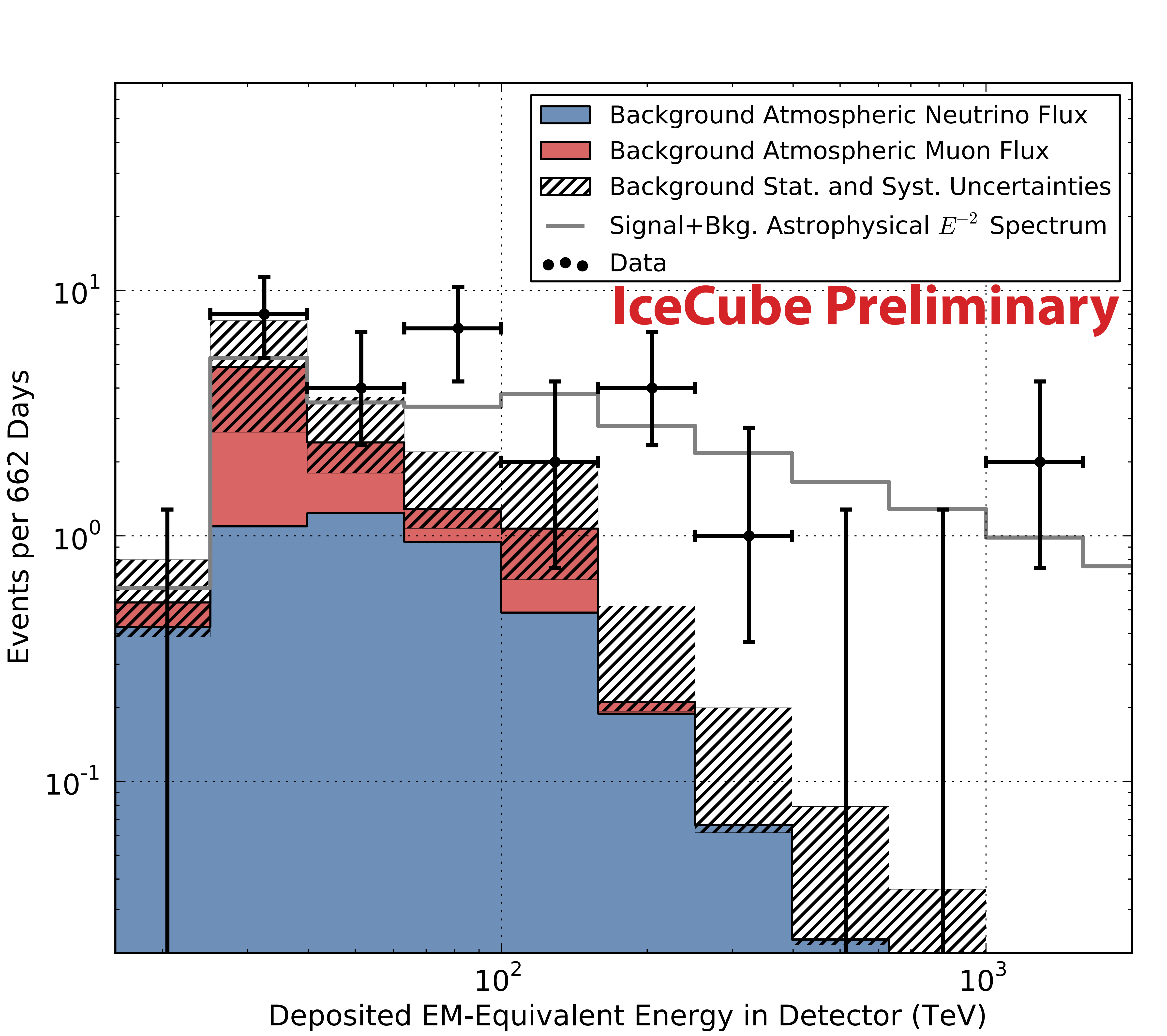
- Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold (Q_{tot}>6000)
- Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)



Energy Spectrum

Compatible with benchmark E^{-2} astrophysical model

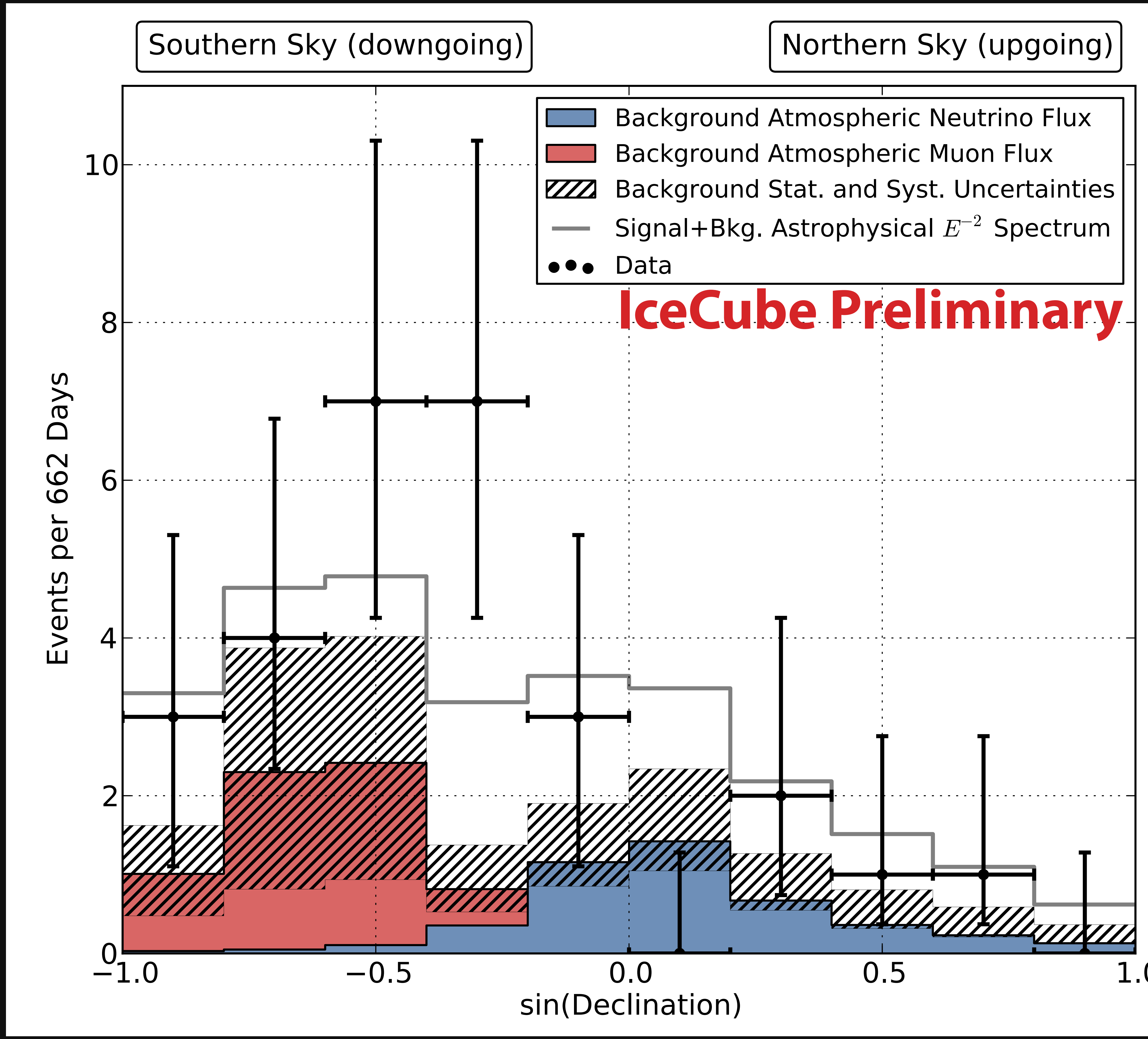
- **Harder than any expected atmospheric background**
- **Merges well into background at low energies**
- **Potential cutoff at about 2-5 PeV**
  - at $1.6^{+1.5}_{-0.4}$ PeV when fitting a hard cutoff



Declination Distribution

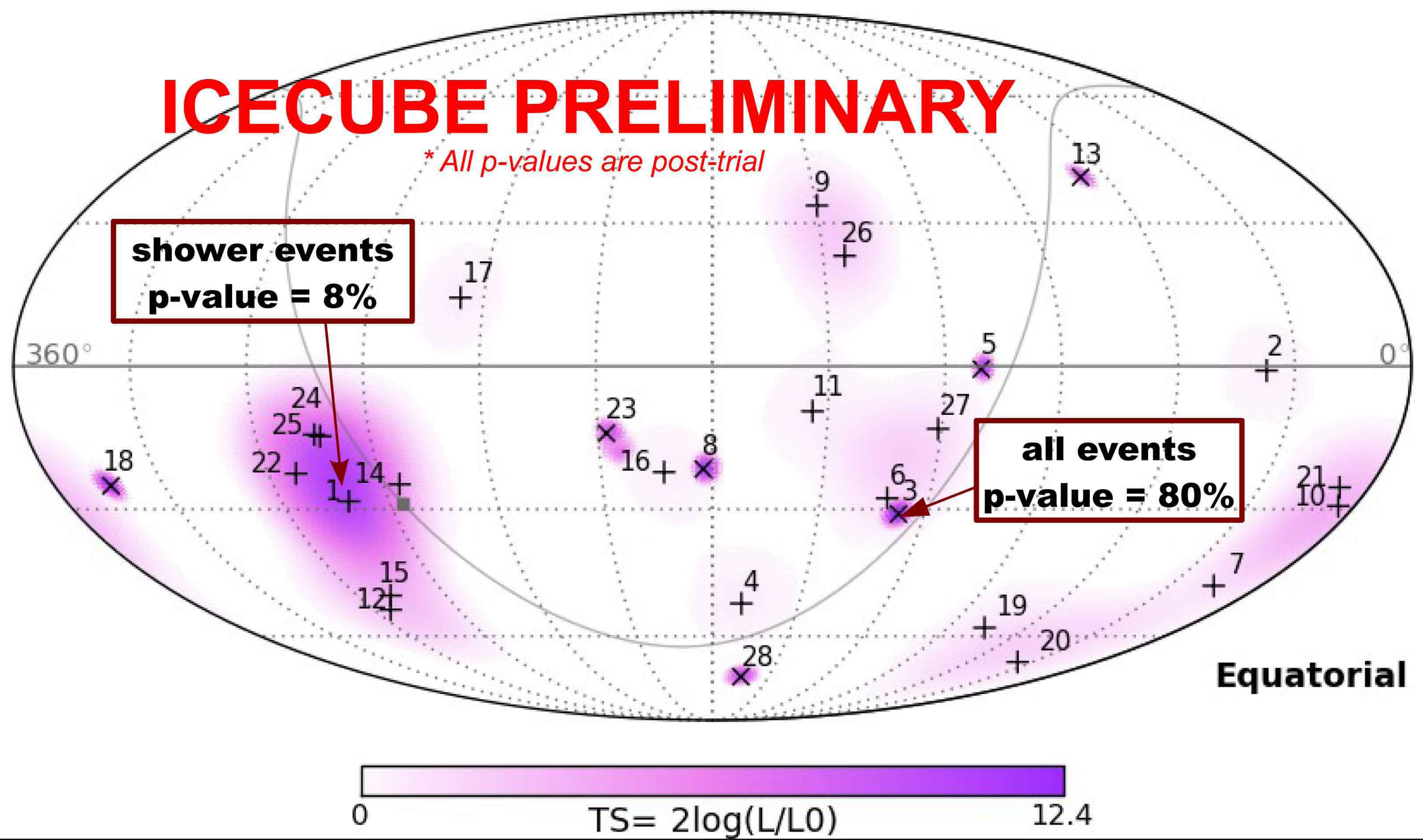
Or: "Zenith Distribution" because we are at the South Pole

- Compatible with isotropic flux
- Events absorbed in Earth from Northern Hemisphere
- Minor excess in south compared to isotropic, but not significant



Skymap / Clustering

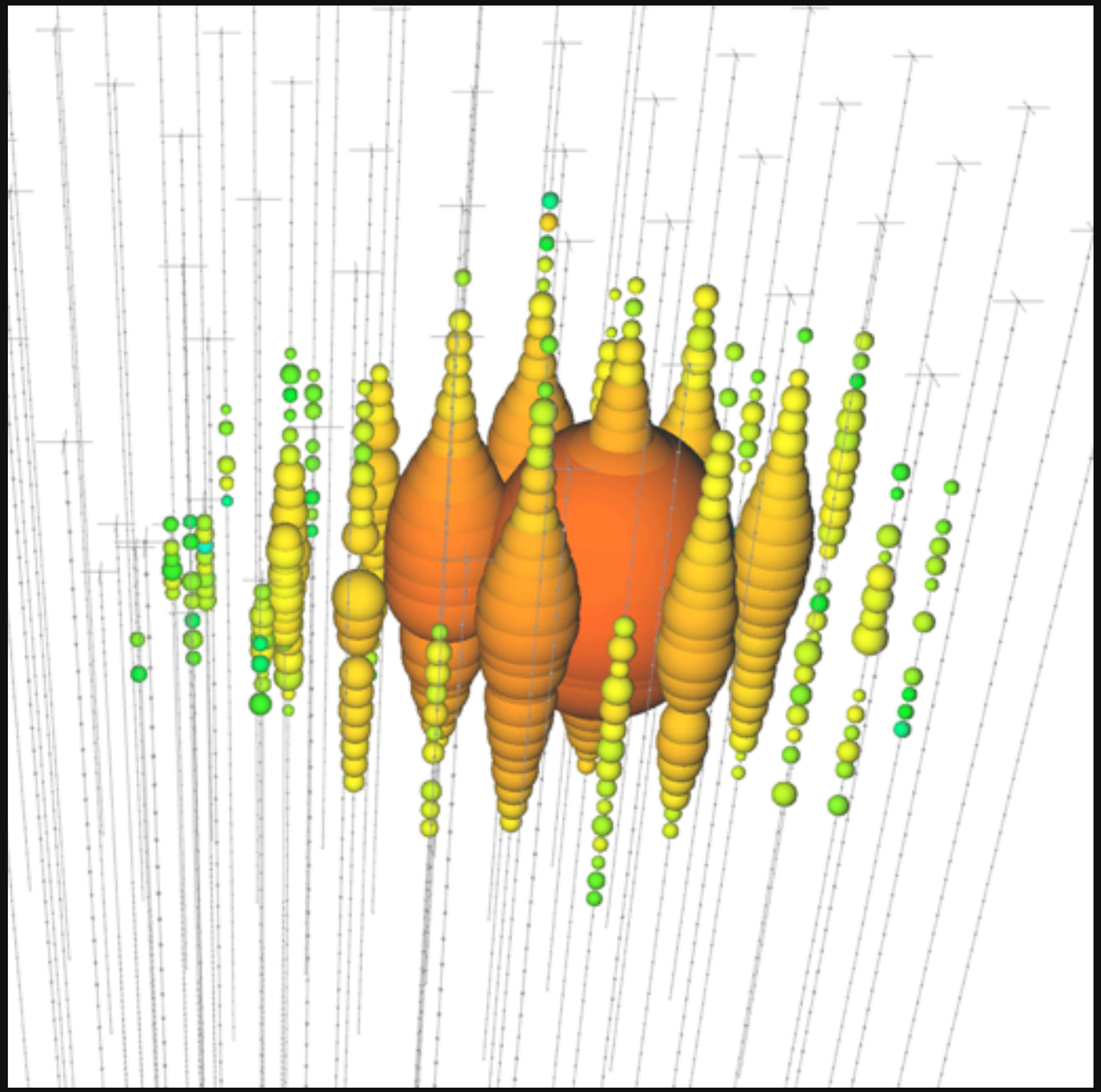
No significant clustering observed



Conclusions

Stay tuned!

- 28 events with energies above ≈ 50 TeV found in two years of IceCube data (2010 & 2011)
- Increasing evidence for high-energy component beyond the atmospheric spectrum
- Inconsistent at 4.1σ with standard background assumptions
- Less clear what it is - compatible with astrophysical explanations
- Publication coming soon - more data coming soon!



The IceCube Collaboration includes about 250 researchers from 39 institutions around the world. Prof. Francis Halzen, University of Wisconsin – Madison is the principal investigator and Prof. Olga Botner from Uppsala University serves as the collaboration spokesperson.

IceCube Neutrino Observatory

Built under a National Science Foundation (NSF) Major Research and Facilities Construction grant with contributions from national funding agencies and private foundations in Germany, Sweden, Japan, and Belgium.

Operated with support from the NSF Office of Polar Programs and funding agencies in Germany, Sweden, Belgium, UK, Switzerland, Japan, Canada, New Zealand and Australia.