Analysis of the High-Energy Starting Events in IceCube

Some more details on the analysis

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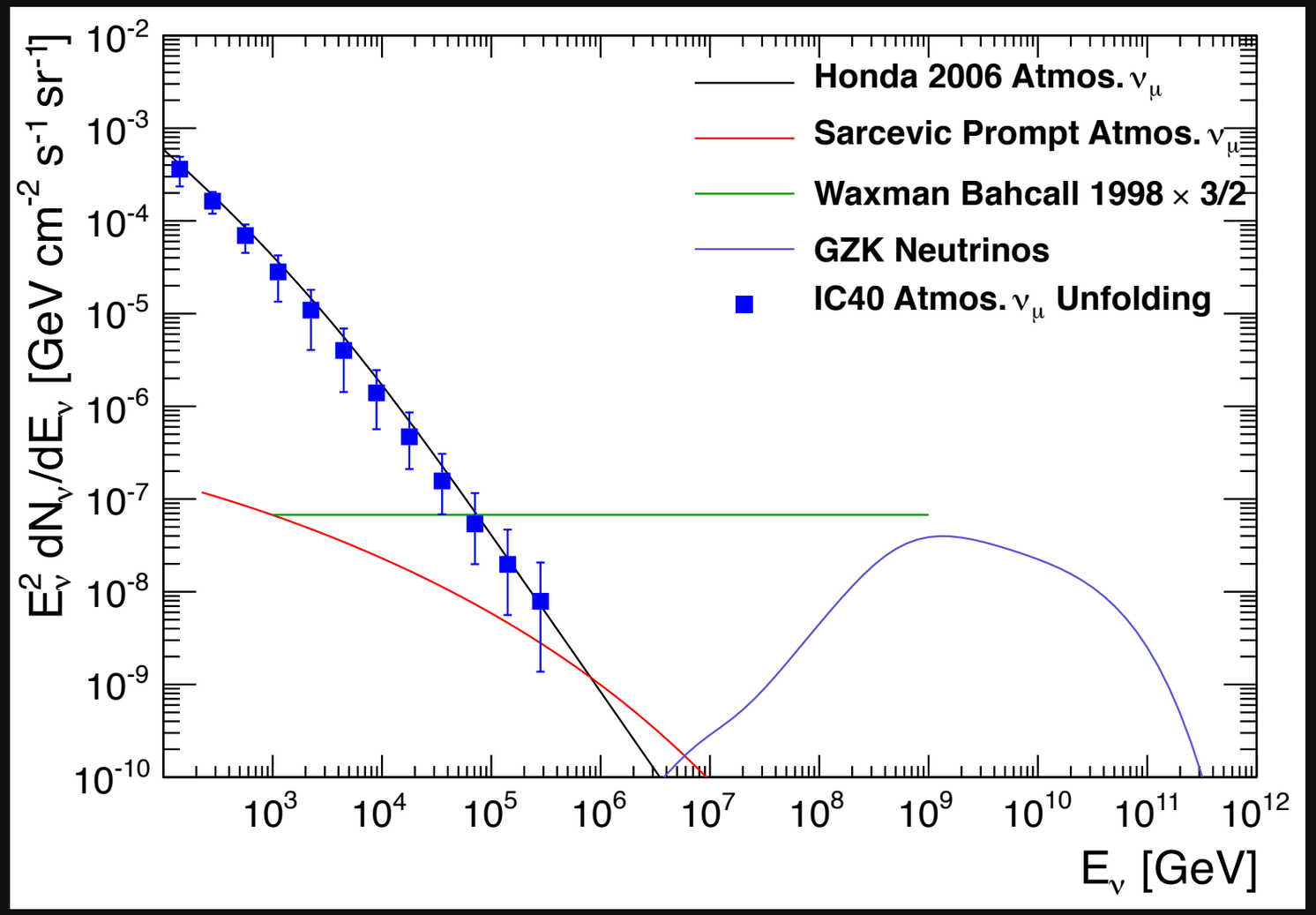
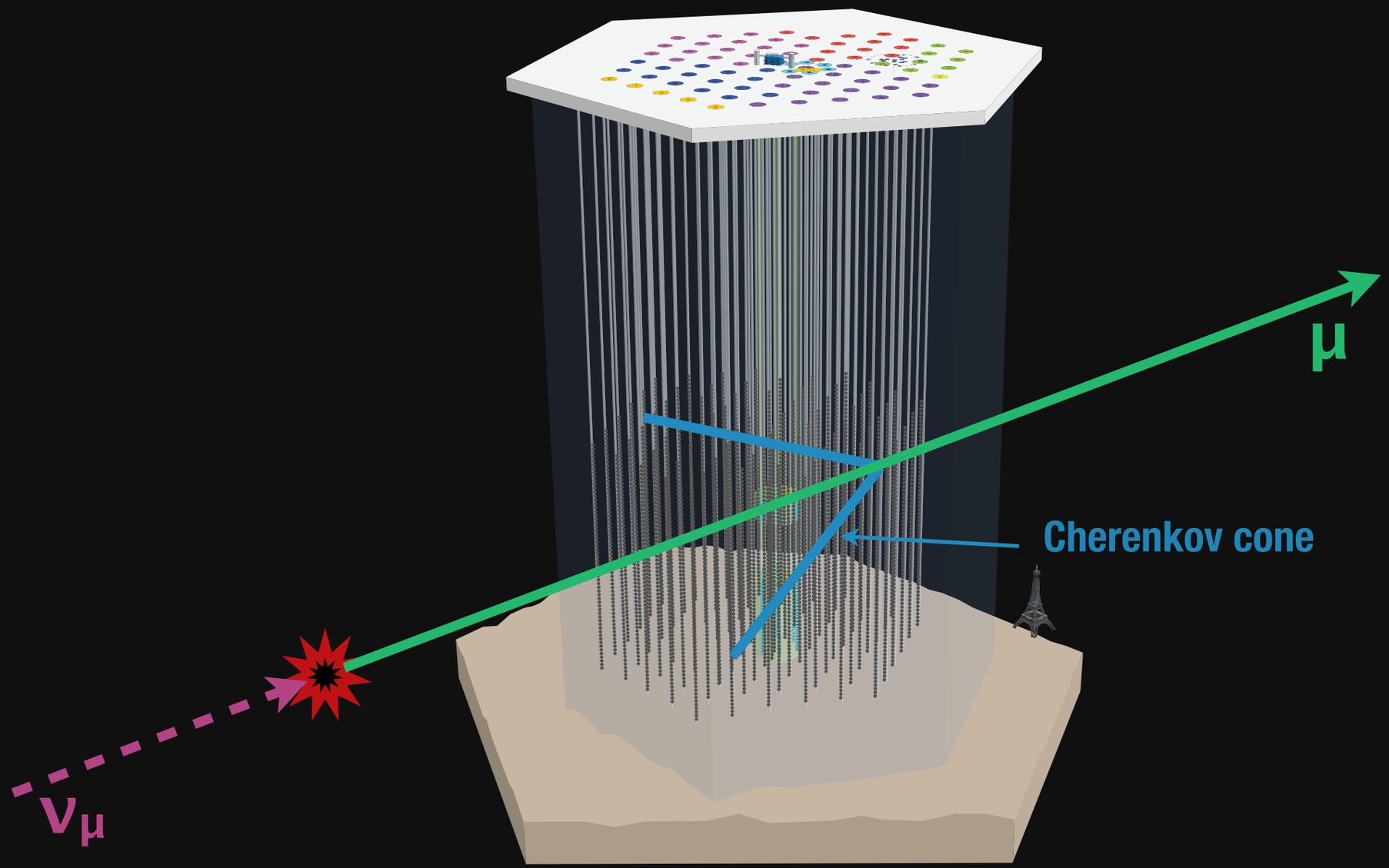
Interesting Neutrinos above 1 TeV

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



The IceCube Neutrino Observatory

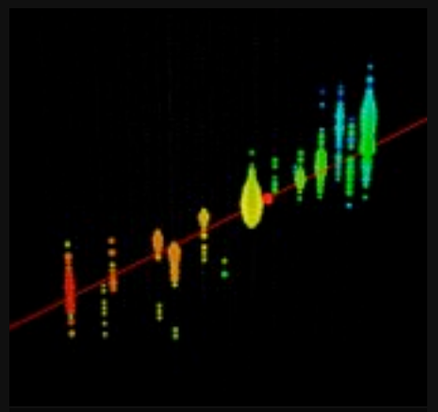
Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



Neutrino Event Signatures

Signatures of signal events

CC Muon Neutrino

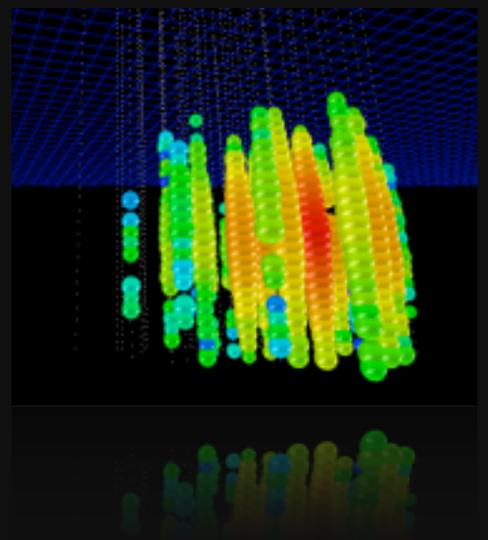


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / Electron Neutrino

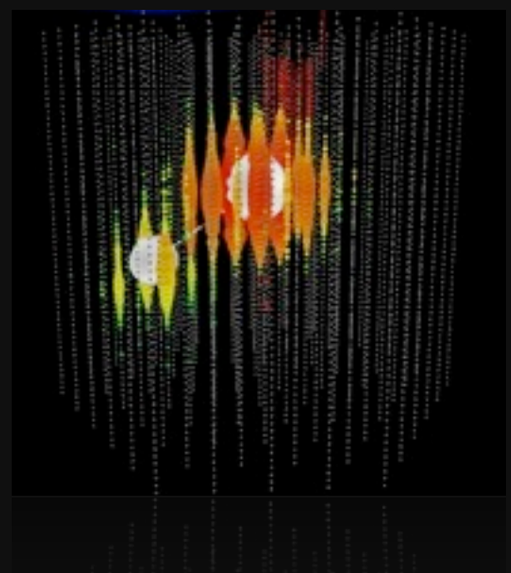


$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} \ + X$$
$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≈ 100 TeV)

CC Tau Neutrino



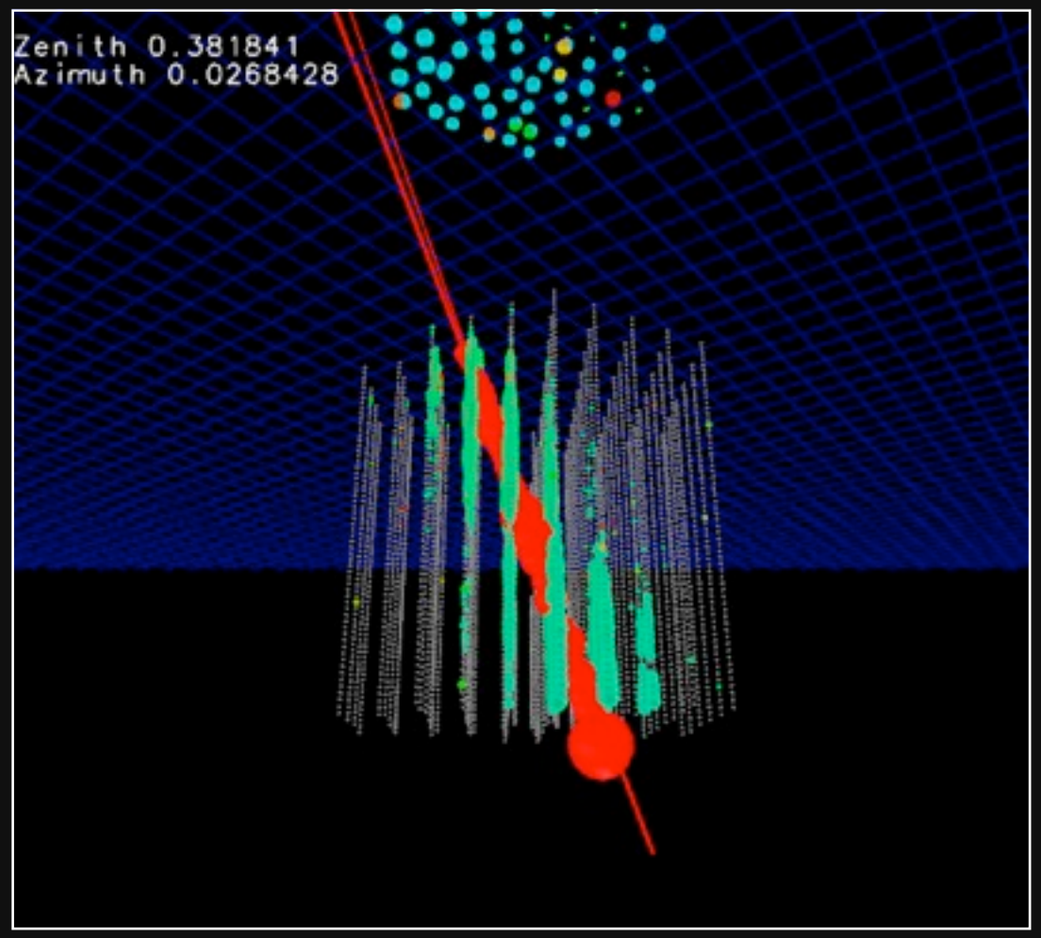
$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

(not observed yet)

Backgrounds and Systematics

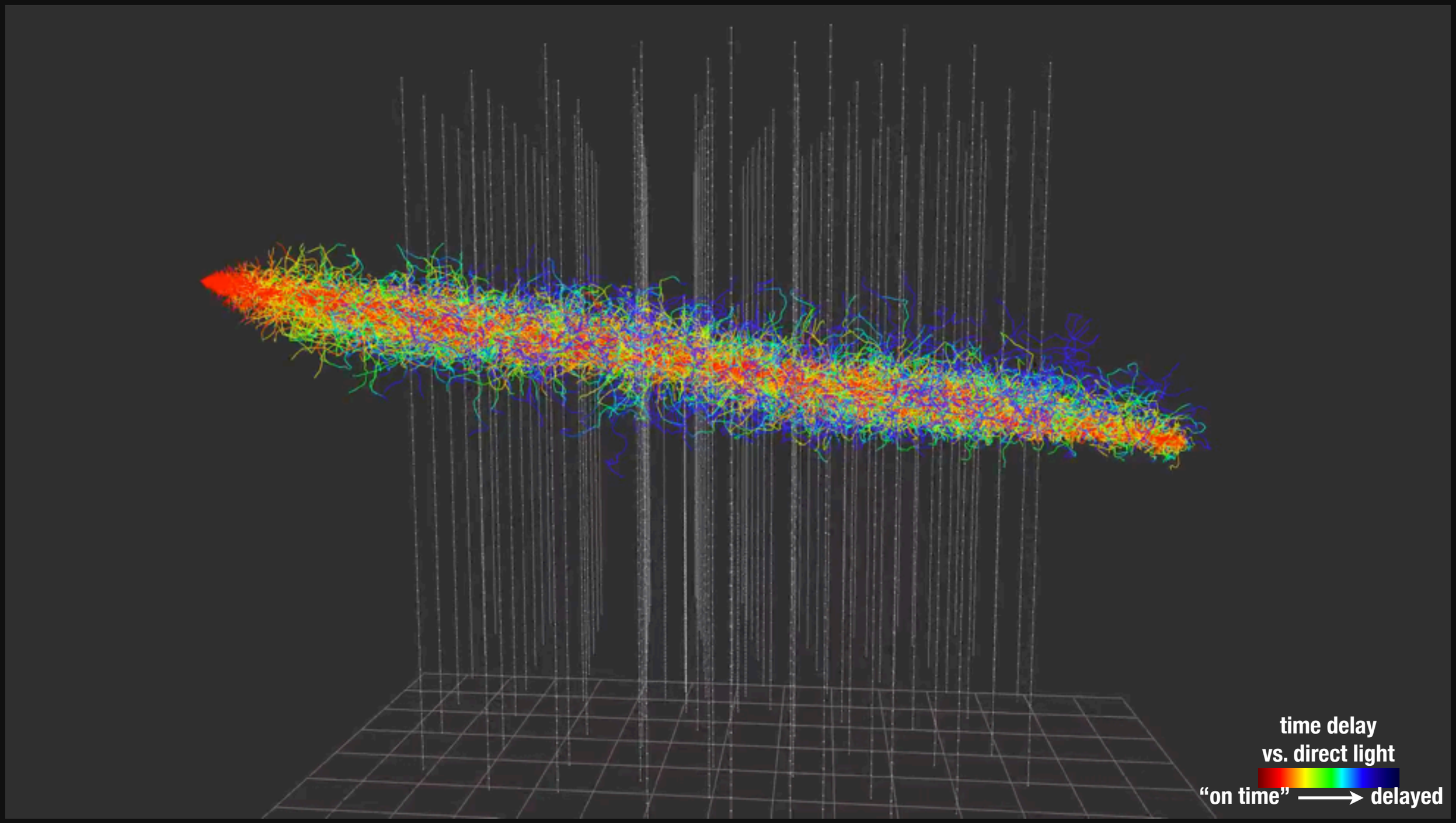
- **Backgrounds:**
  - Cosmic Ray Muons
  - Atmospheric Neutrinos
- **Largest Uncertainties:**
  - Optical Properties of Ice
  - Energy Scale Calibration
  - Neutral current / ν_e degeneracy



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

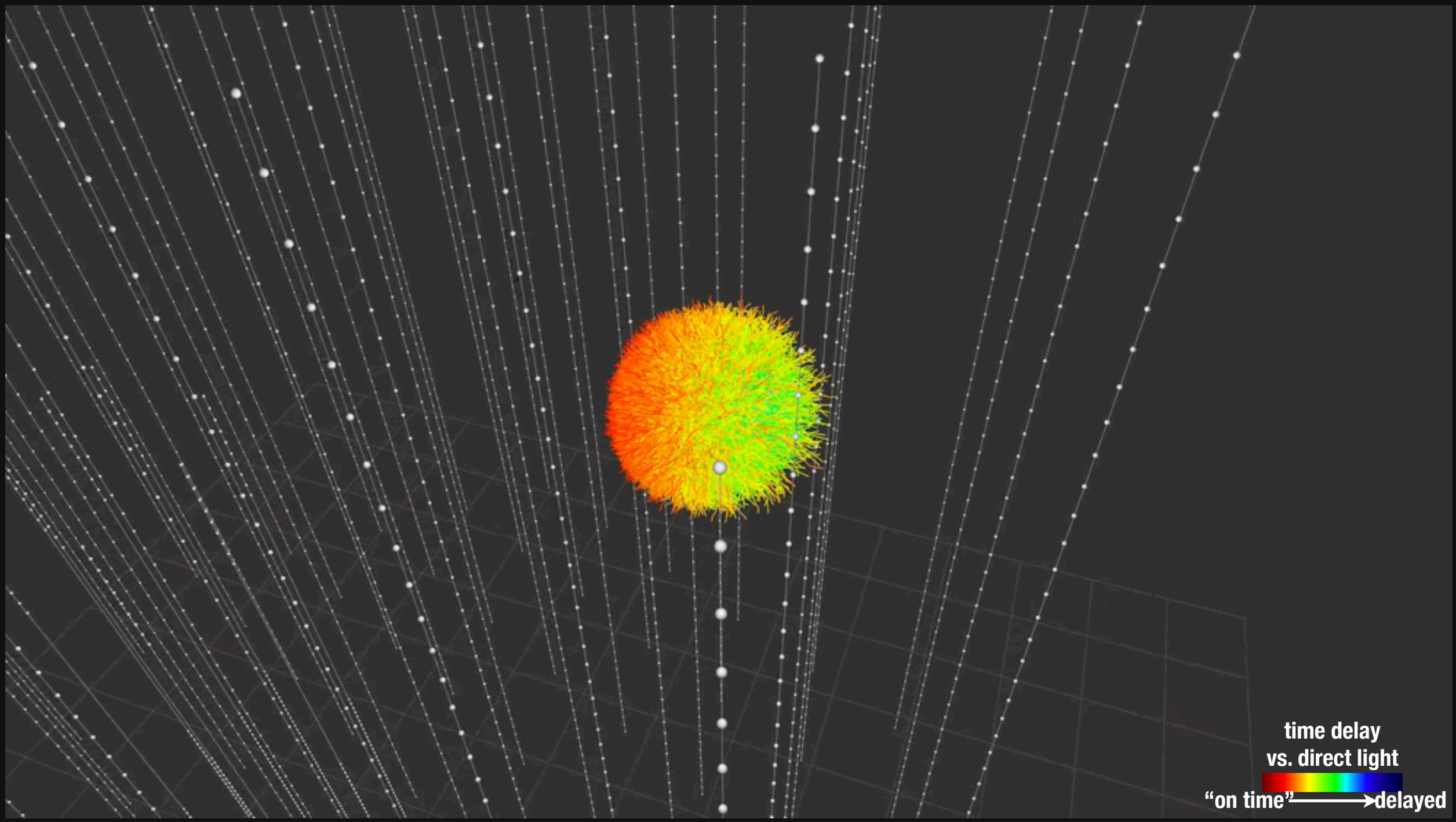
Muon Track in Ice

Light propagation is dominated by scattering



Shower in Ice

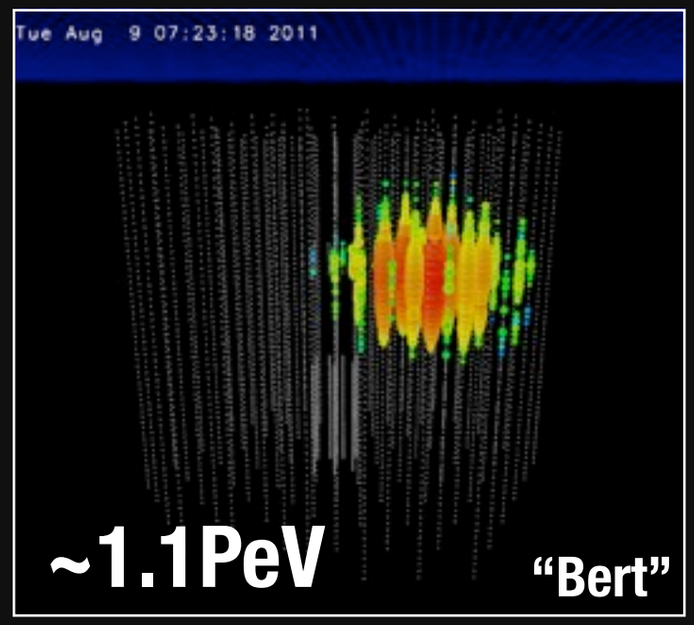
Shower directions reconstructed from timing profile

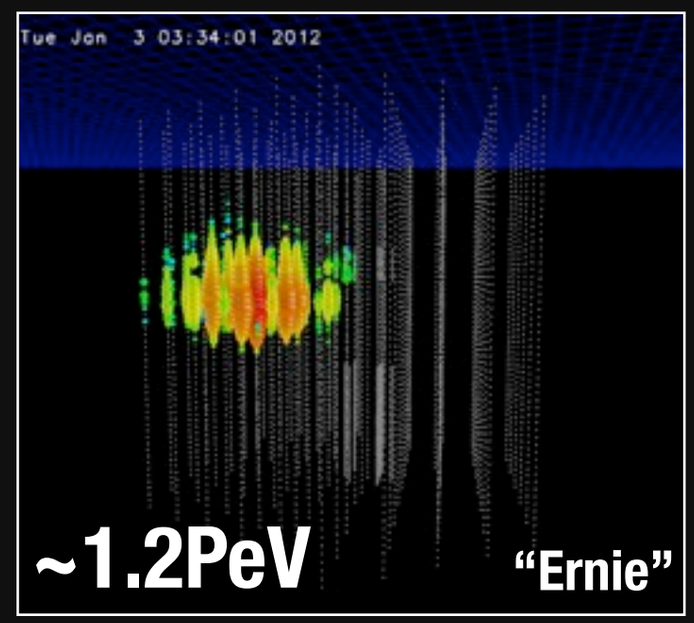


Results

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

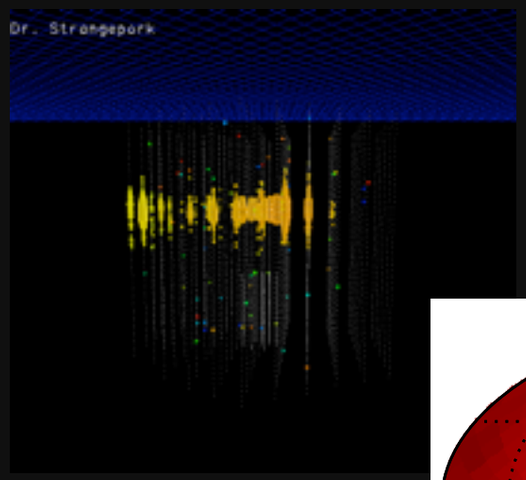
- **Two very interesting events in IceCube (between May 2010 and May 2012)**
  - shown at Neutrino ’12
  - 2.8σ excess over expected background in GZK analysis
  - paper submitted and on arXiv (arXiv:1304.5356)
- **There should be more**
  - GZK analysis is only sensitive to very specific event topologies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

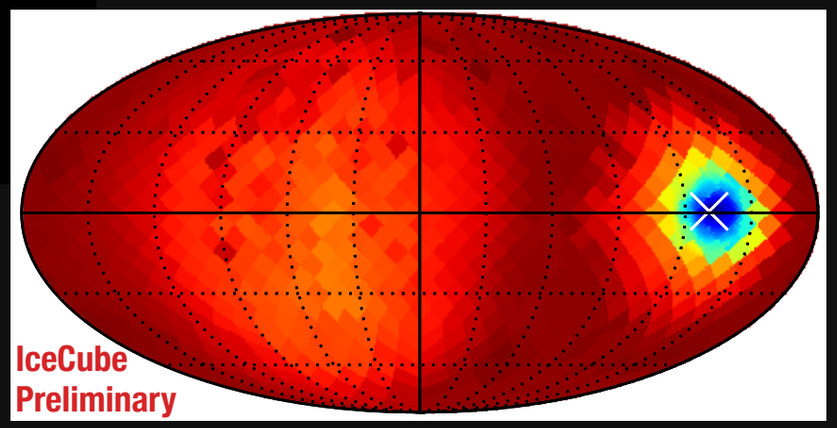


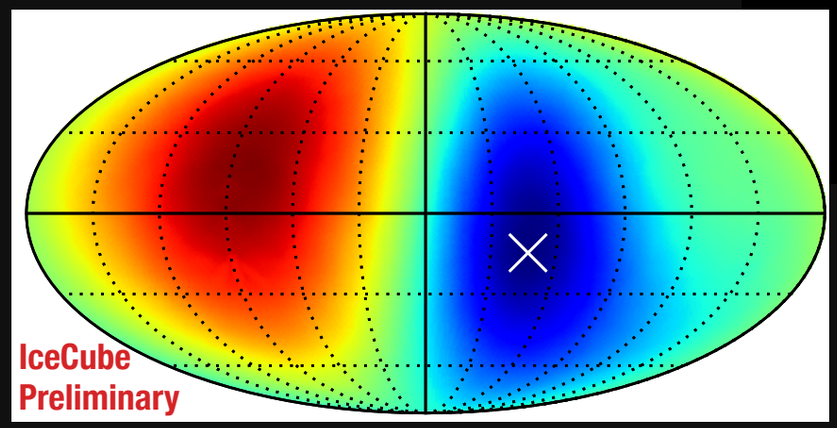


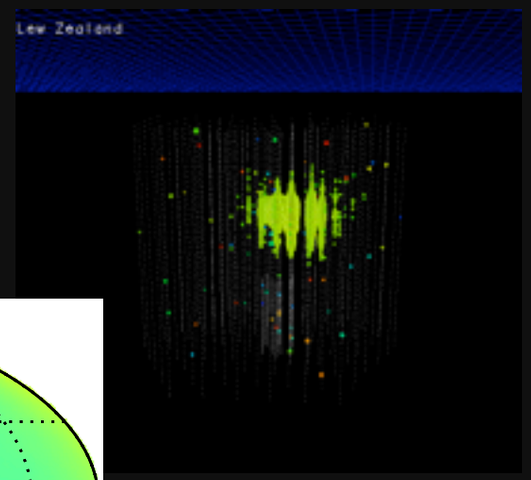
Event Reconstruction

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



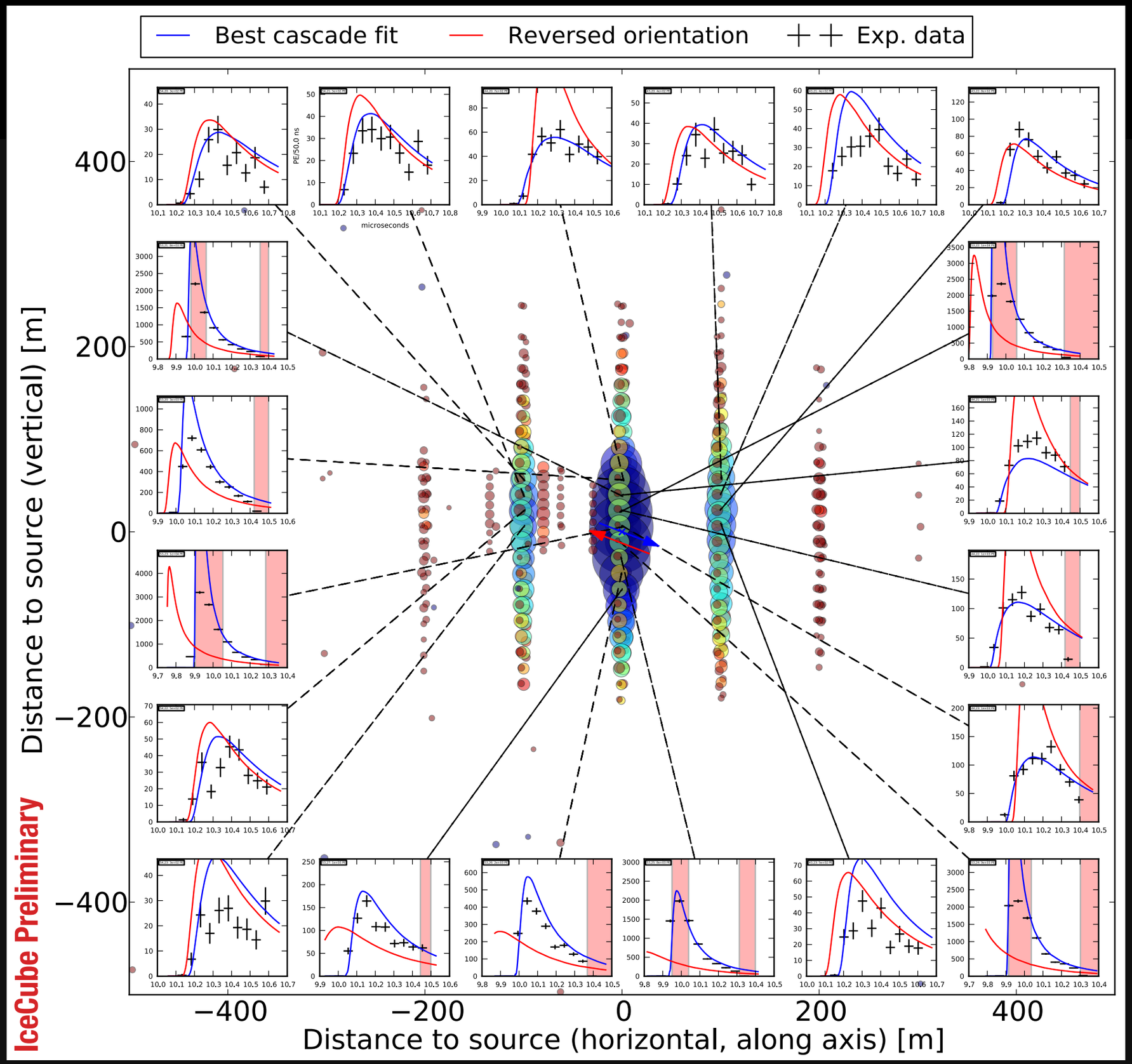






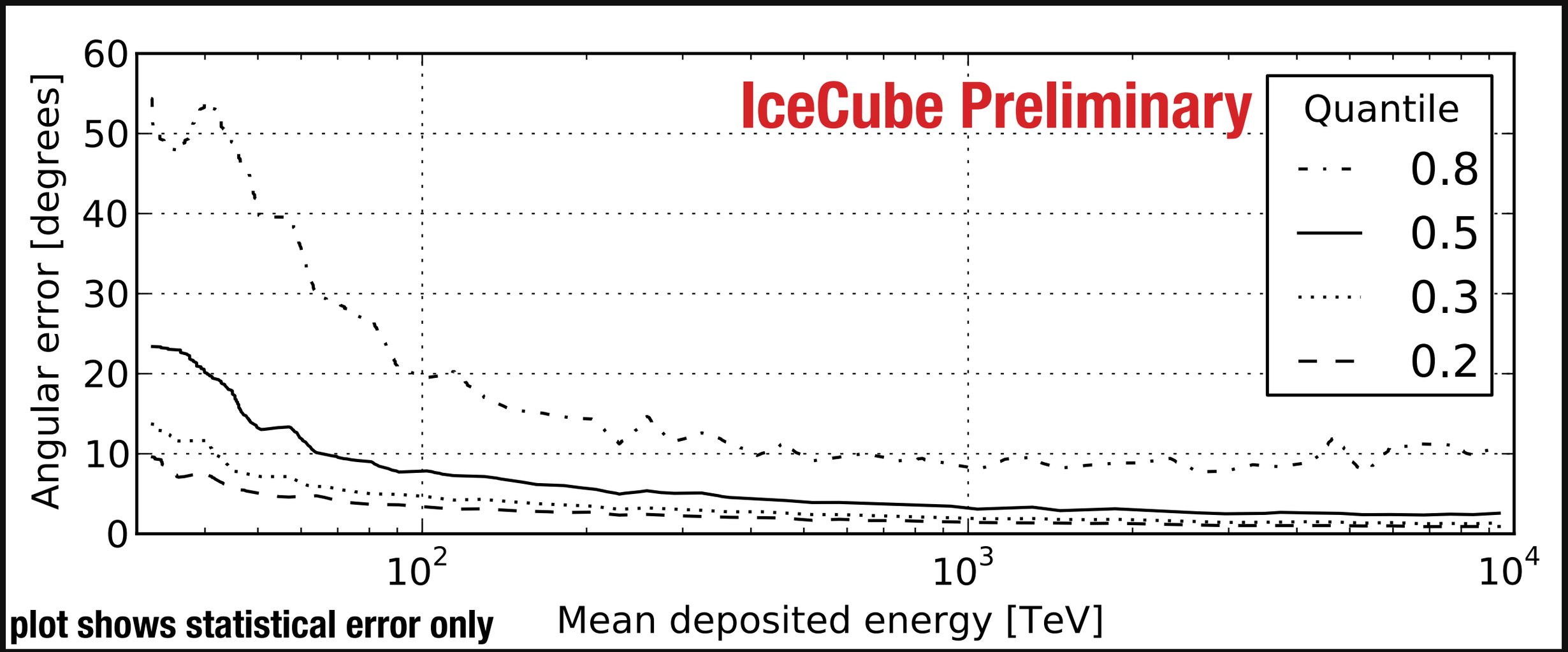
- Fits for deposited energy along a “track” in each skymap direction based on hit pattern using a detailed model of the glacial ice optical properties
- Result: direction with uncertainty and estimate for deposited energy

Event Reconstruction



Directional Resolution for Showers

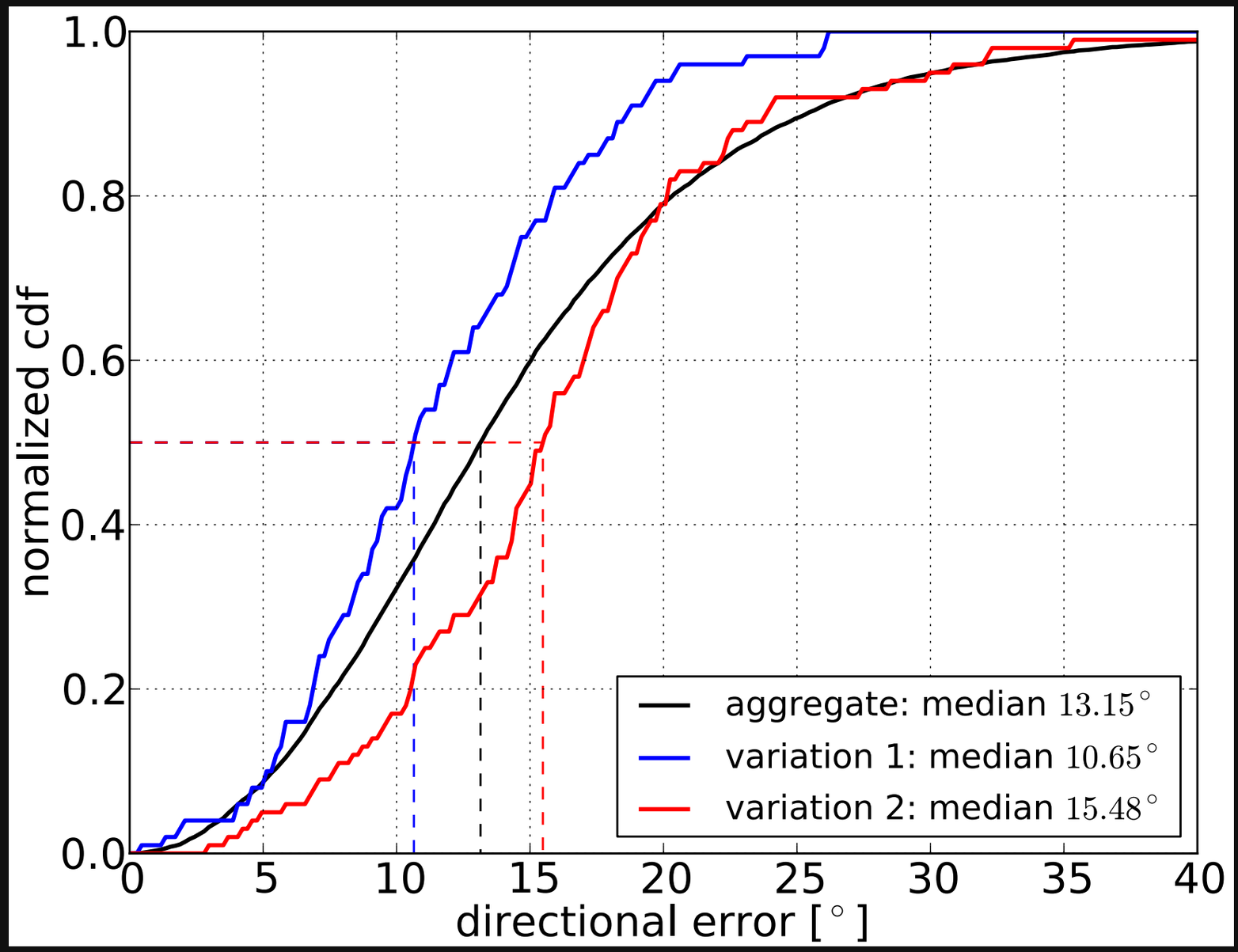
Statistical uncertainties in angular reconstruction for showers is small. Dominated by ice systematics!



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

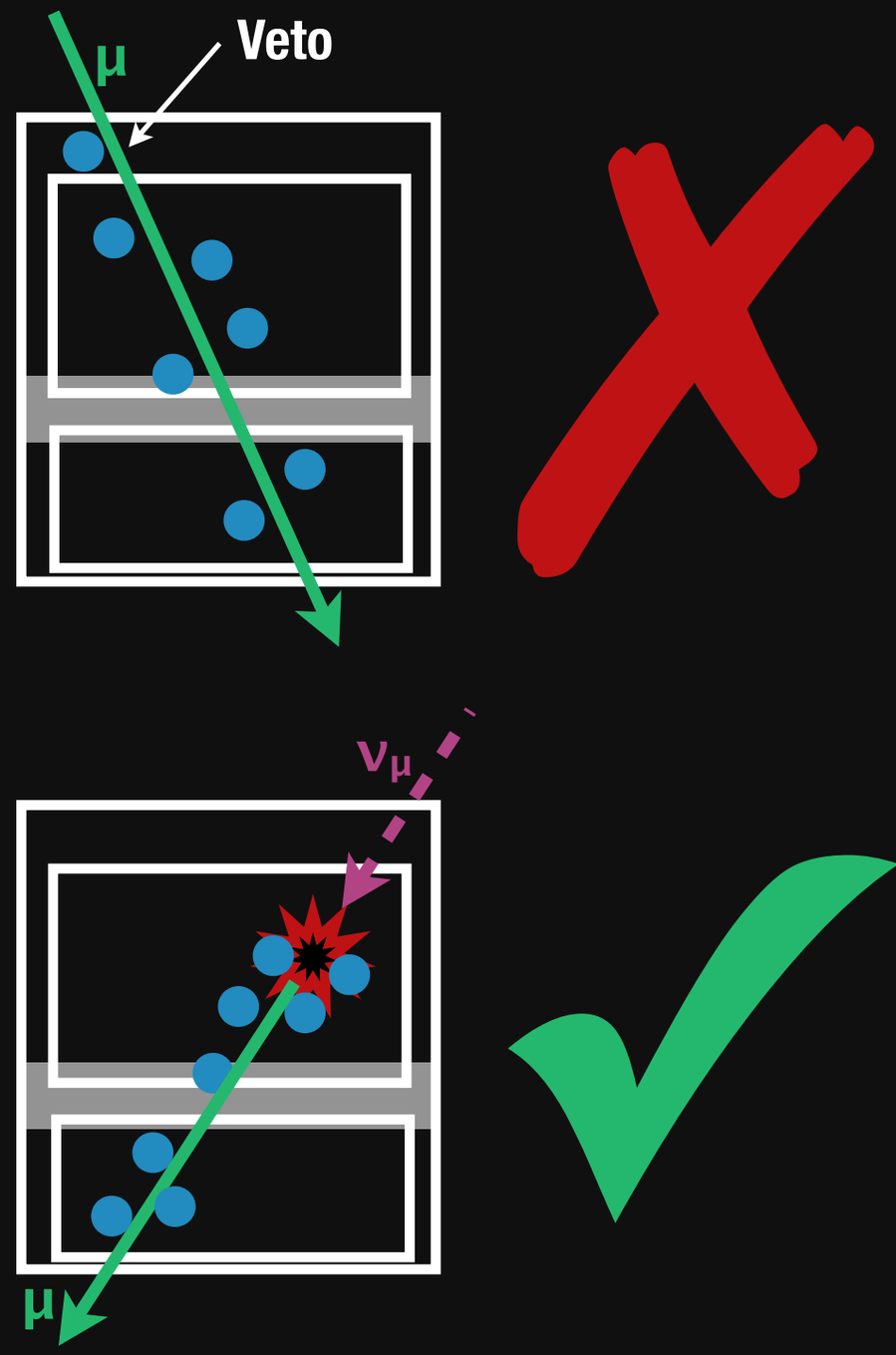


resolution for an individual example event from re-simulation

Contained Event Analysis

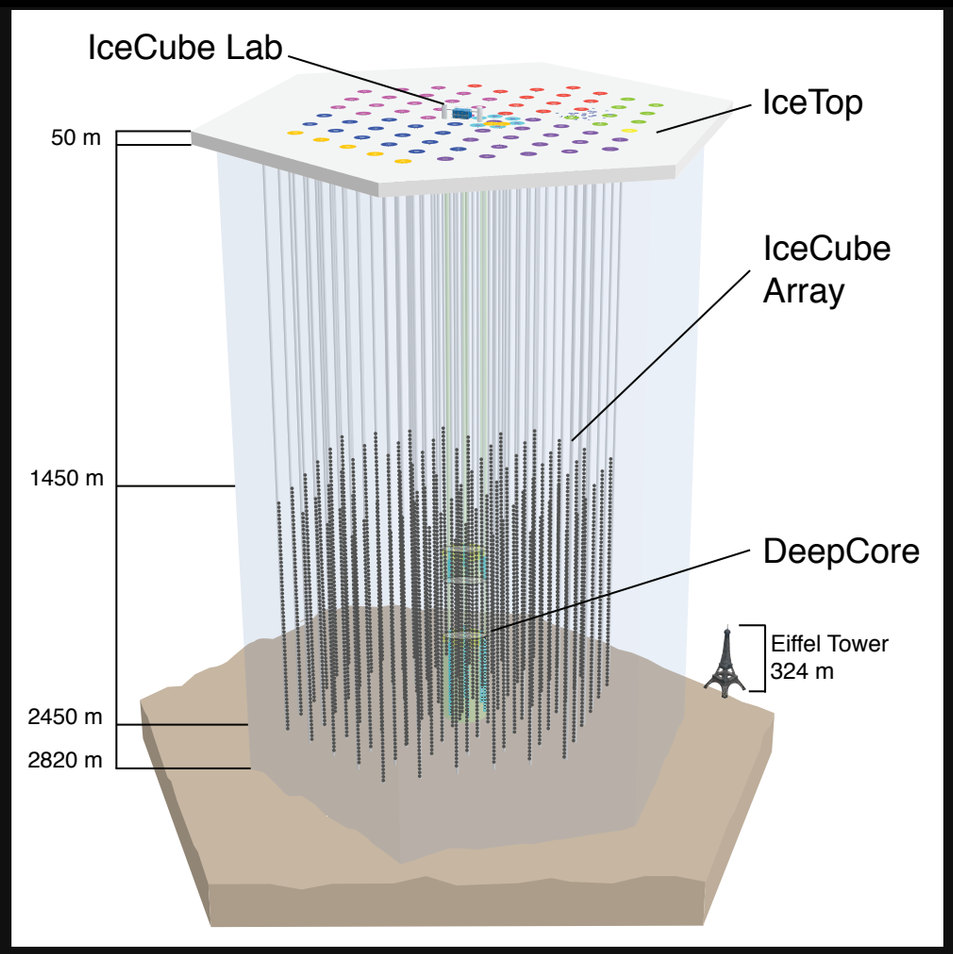
Specifically designed to find these contained events. Analysis of dataset taken from May 2010 to May 2012 (662 days of livetime)

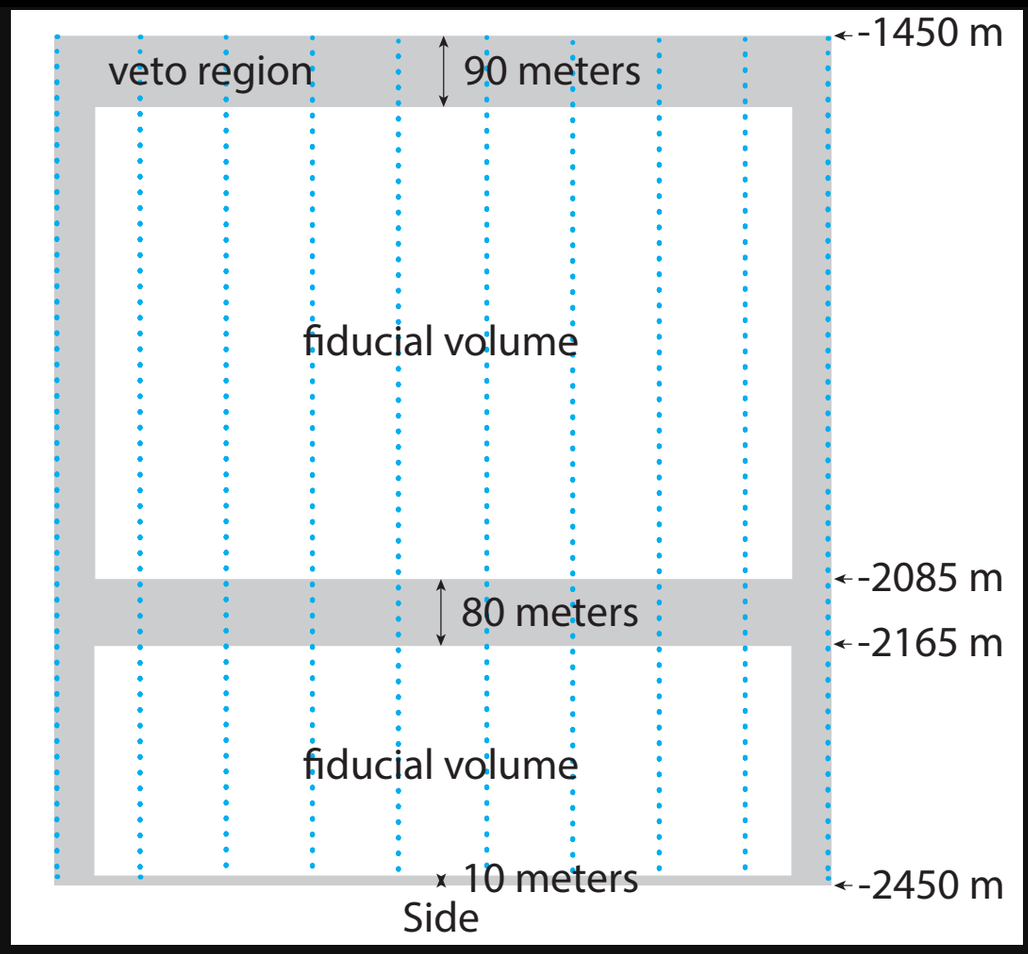
- **Explicit contained search at high energies (cut: Q_{tot}>6000)**
- **400 Mton effective fiducial mass**
- **Use atmospheric muon veto**
- **Sensitive to all flavors in region above 60TeV**
- **Three times as sensitive at 1 PeV**
- **Estimate background from data**



Background 1 - Atmospheric Muons

Mostly incoming atmospheric muons sneaking in through the main dust layer





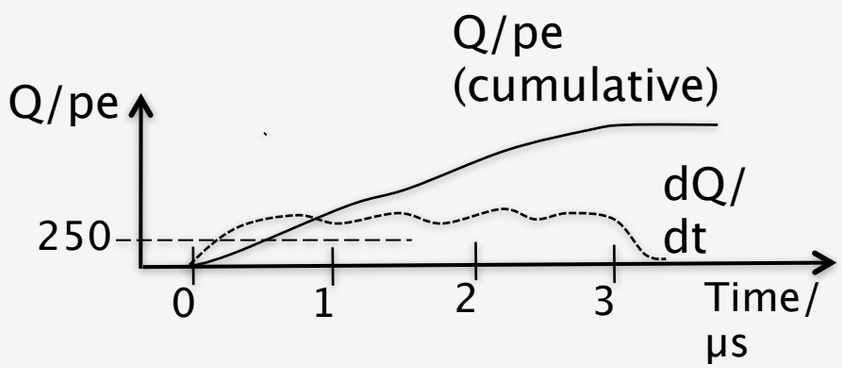
- Reject incoming muons when “early charge” in veto region
- Control sample available: tag muons with part of the detector - known bkg.
- 6±3.4 muons per 2 years (662 days)

Background 1 - Atmospheric Muons

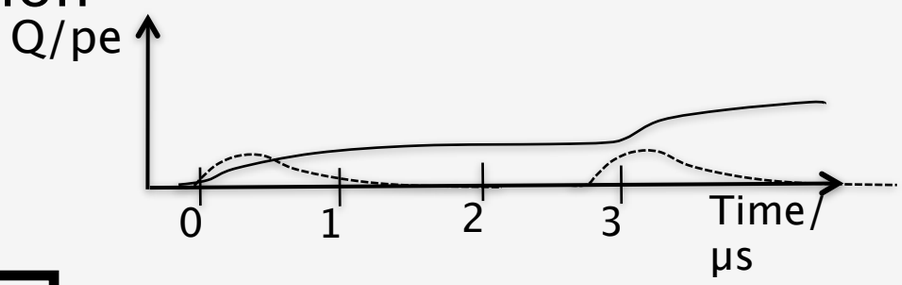
What's "early charge"?

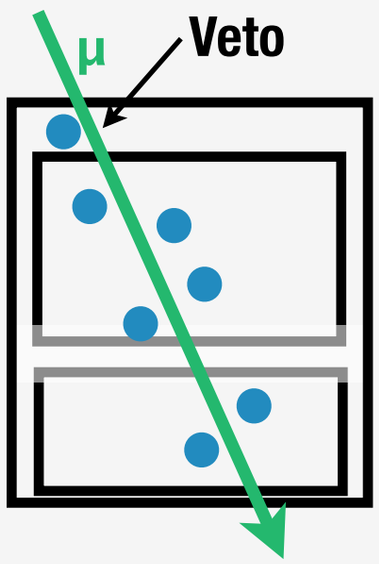
Throughgoing muon

Total detector



Veto region

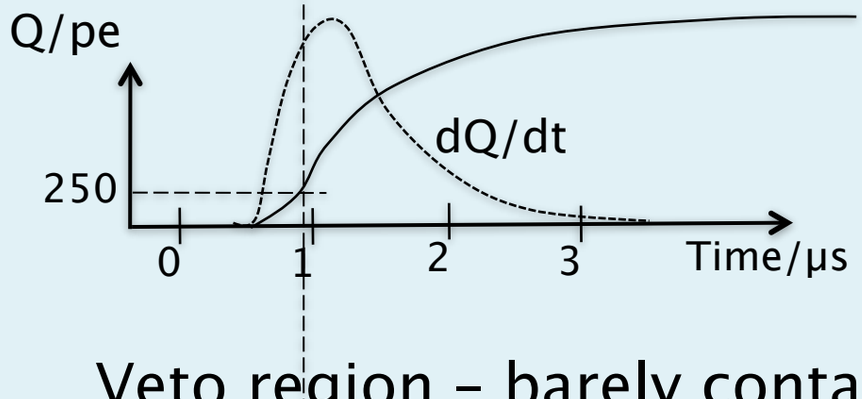


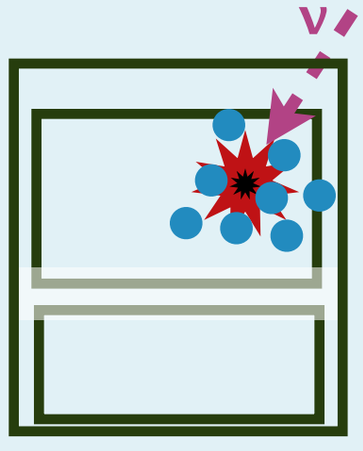


T_{250}= time at which Q= 250 pe

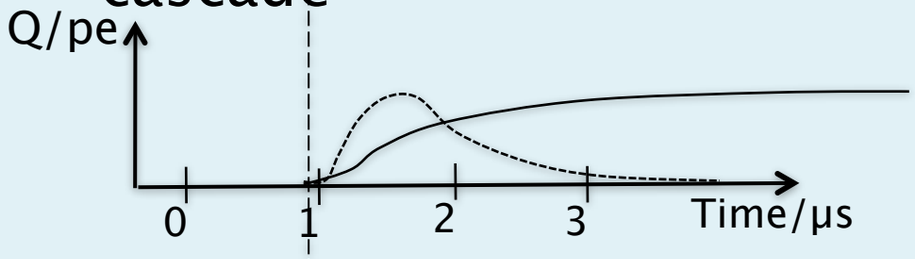
Contained cascade

Total detector

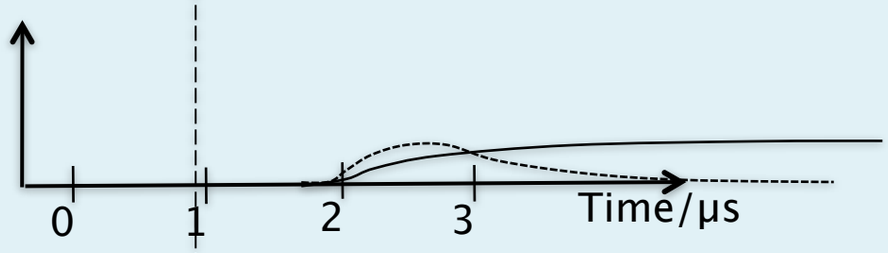




Veto region – barely contained cascade



Veto region – well contained cascade

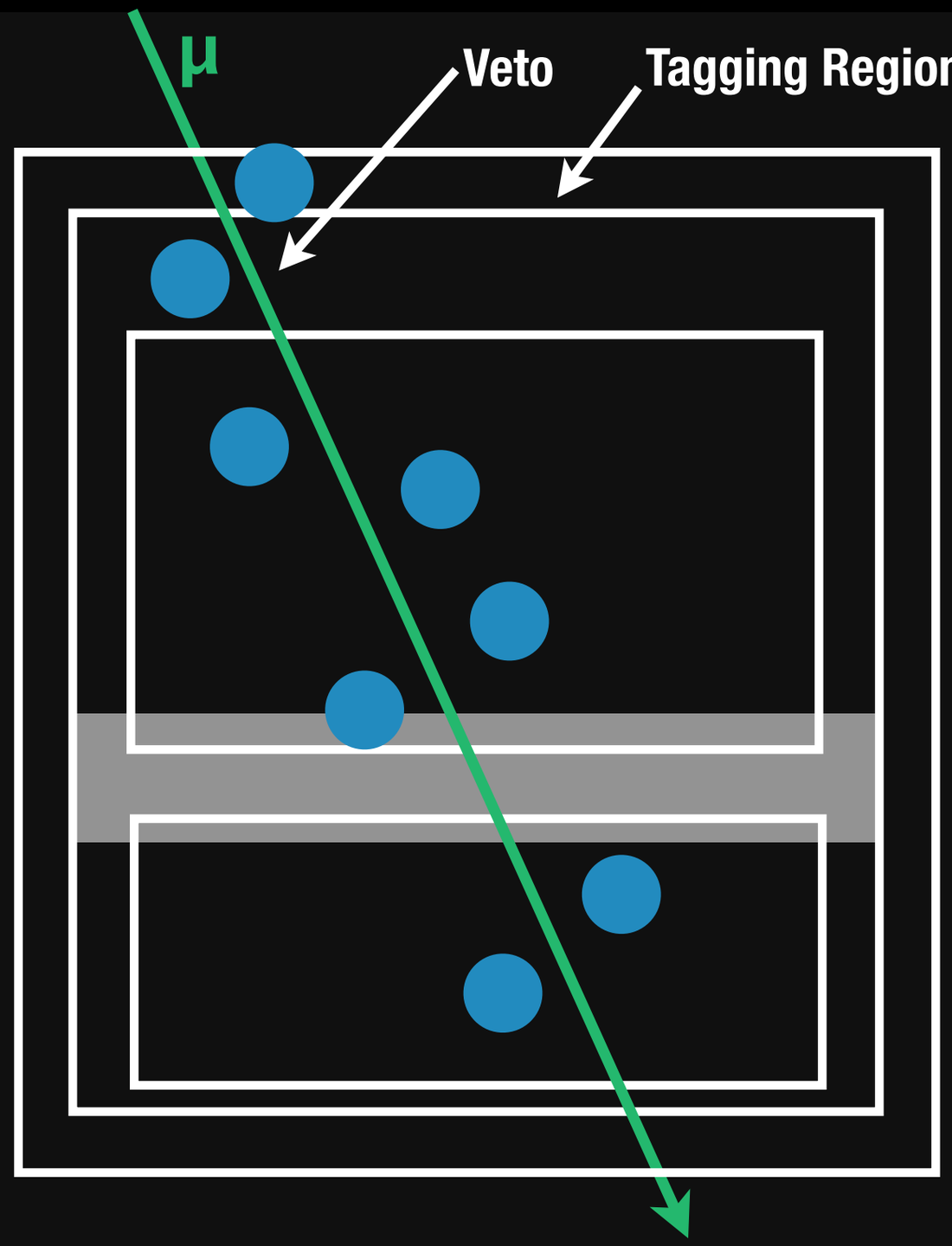


T_{250}= time at which Q= 250 pe

Estimating Muon Background From Data

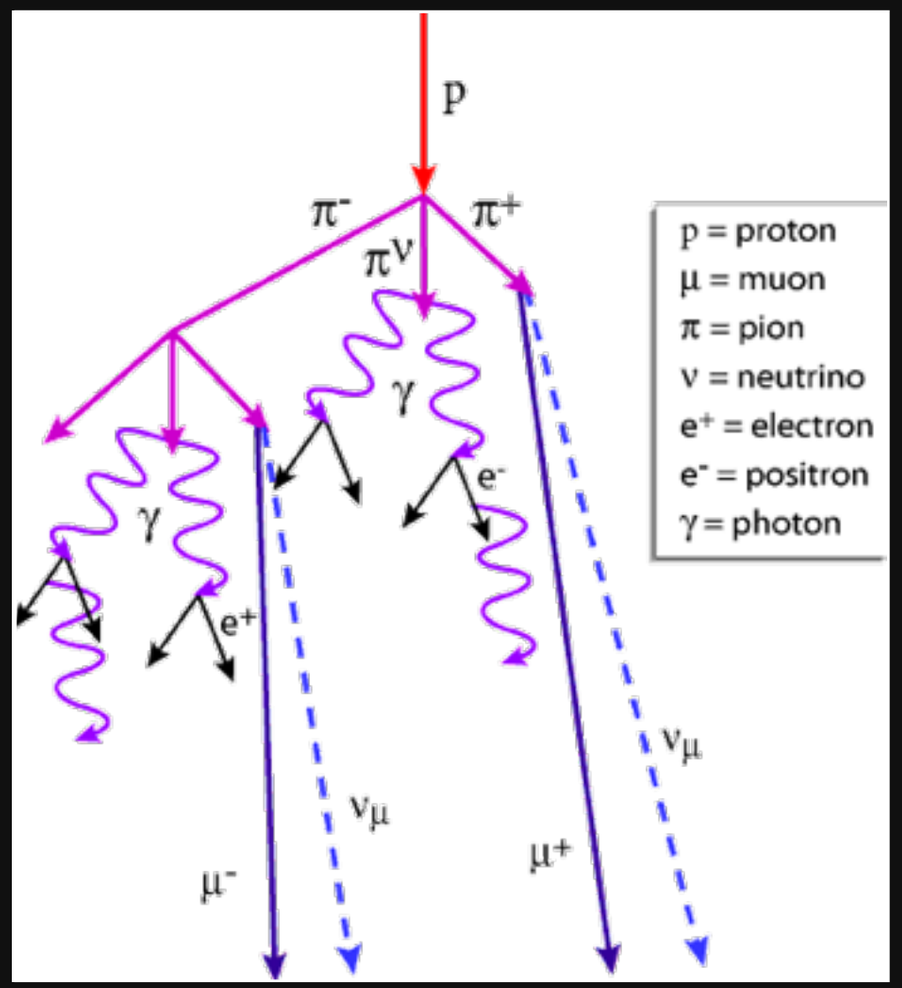
Use known background from atmospheric muons tagged in an outer layer to estimate the veto efficiency

- **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 a cut (6000 p.e.) where background dominates**



Vetoing Atmospheric Neutrinos

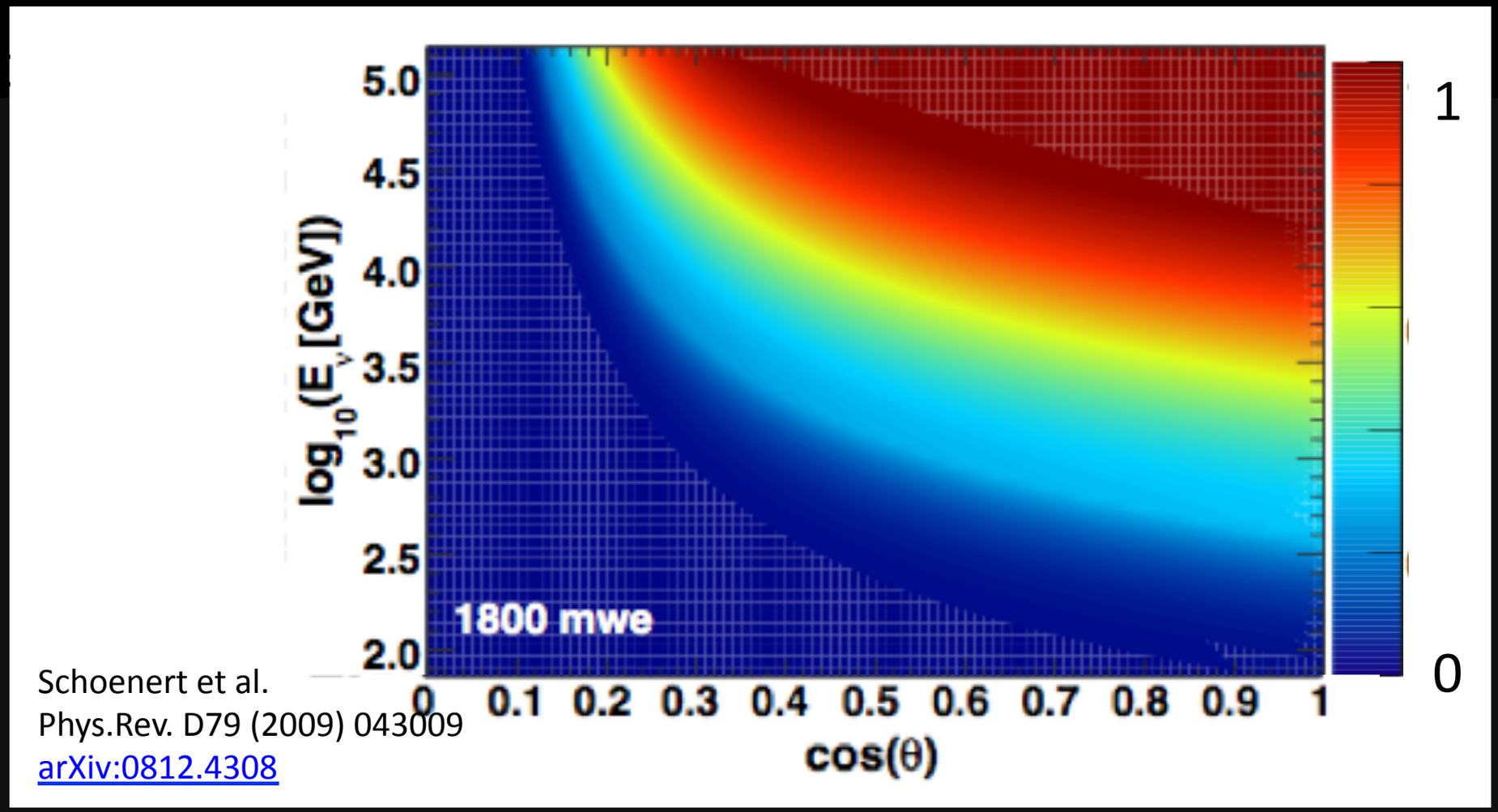
- Atmospheric neutrinos are made in air showers
- For downgoing neutrinos, the muons will likely not have ranged out at IceCube
- Downgoing events that start in the detector are extremely unlikely to be atmospheric



Schönert et al., arXiv:0812.4308

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

Vetoing Atmospheric Neutrinos

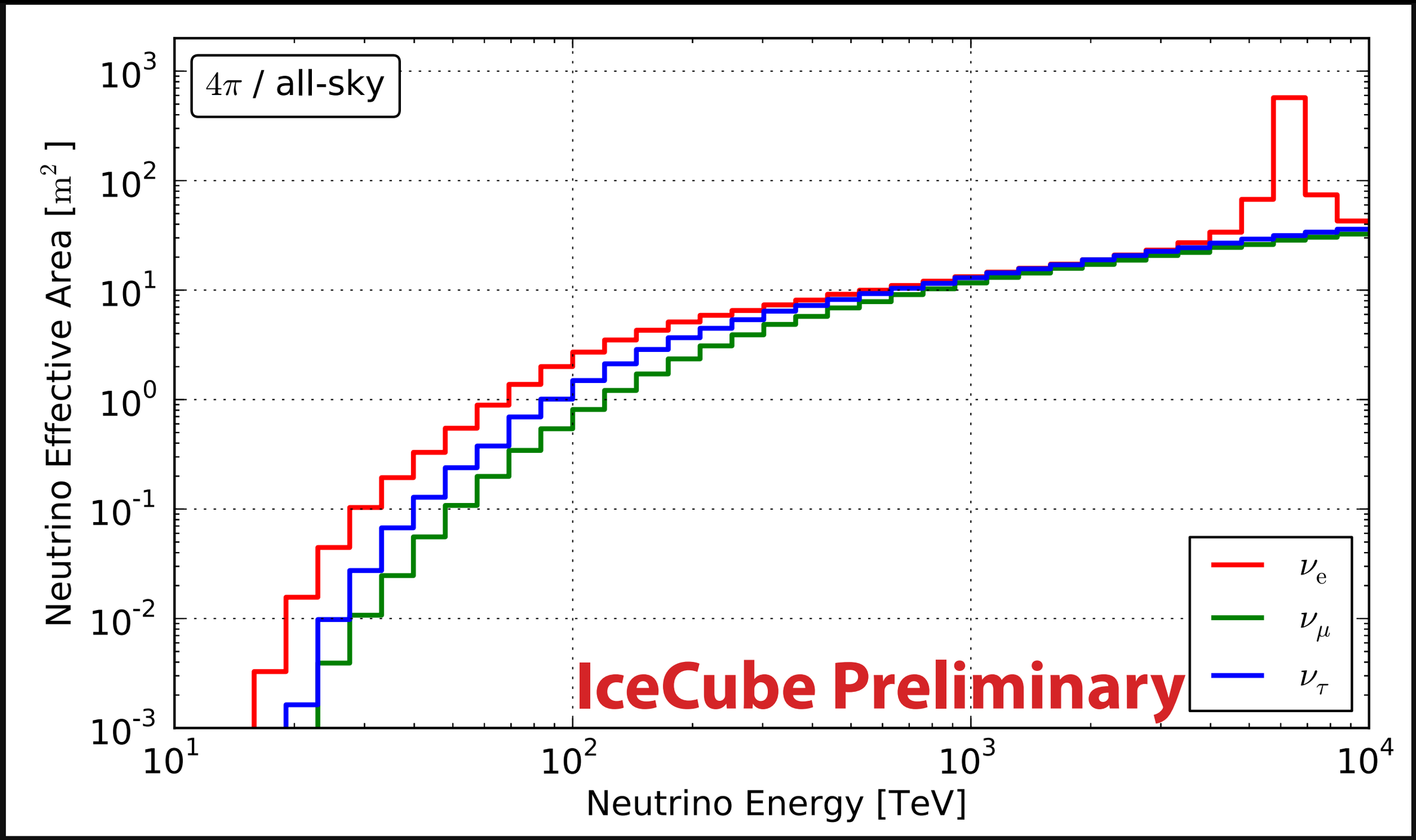


Schoenert et al.
Phys.Rev. D79 (2009) 043009
arXiv:0812.4308

- conservative assumption: always allow a 10% chance in calculations that event will not be vetoed

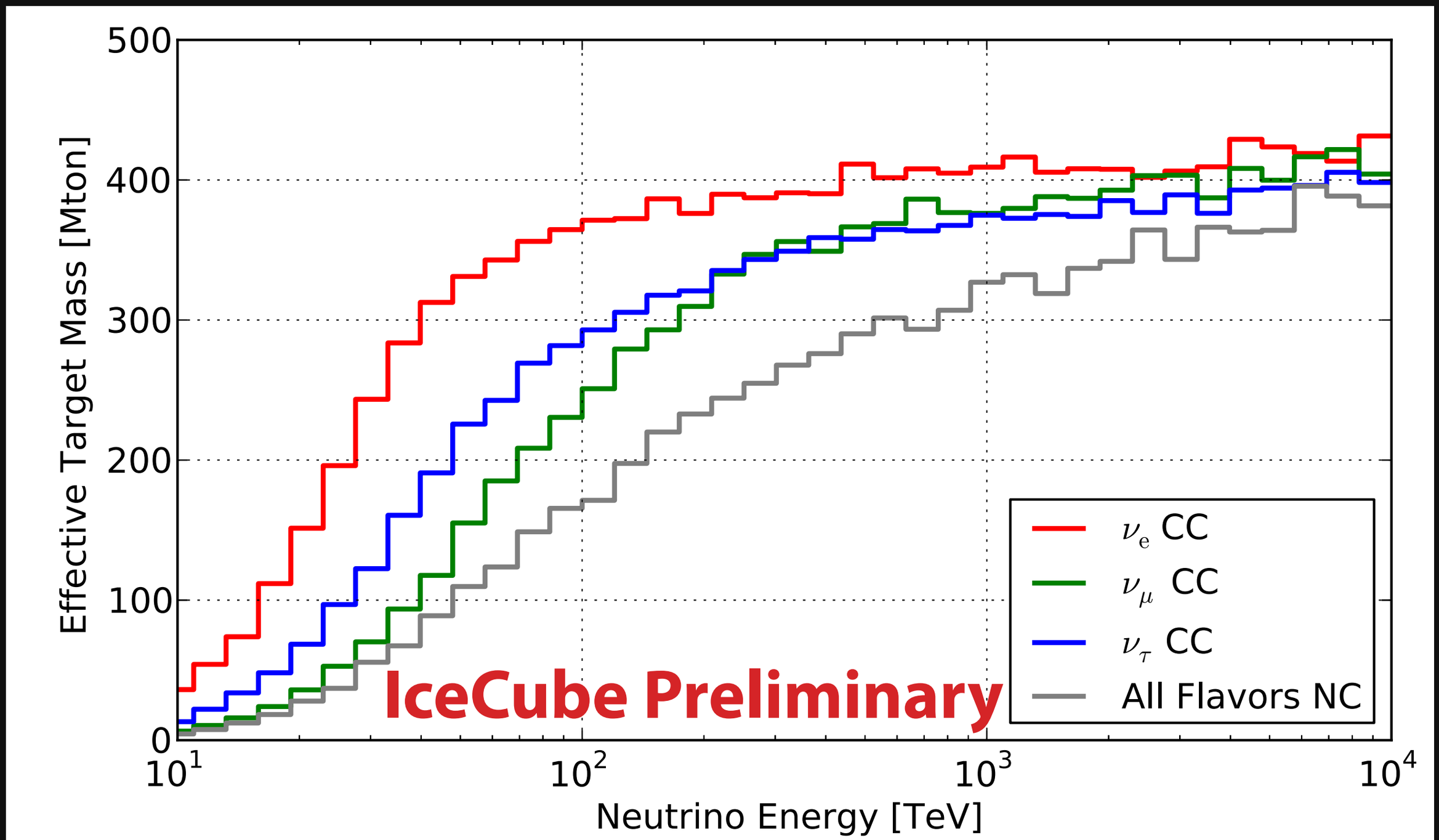
Effective Area

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



Effective Volume / Target Mass

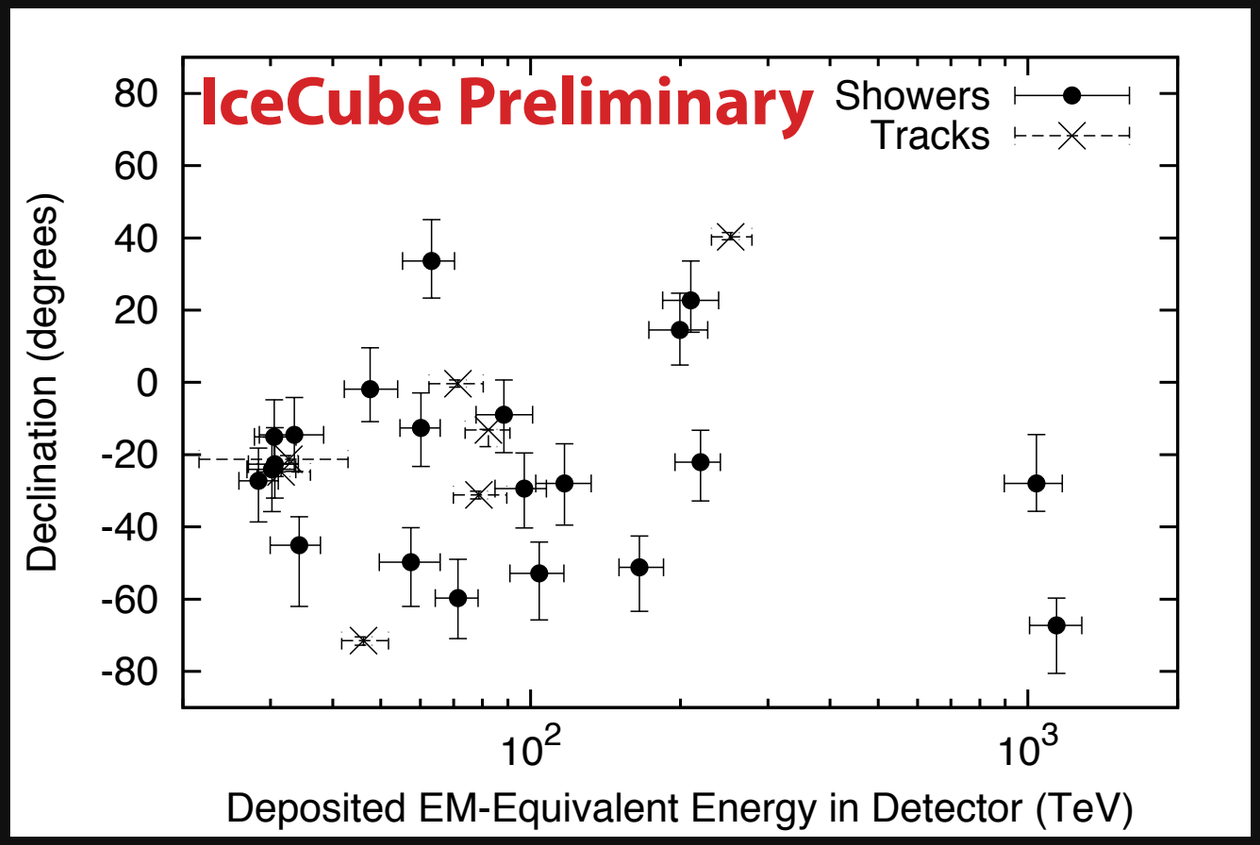
Fully efficient above 100 TeV for CC electron neutrinos
About 400 Mton effective target mass



What Did We Find?

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

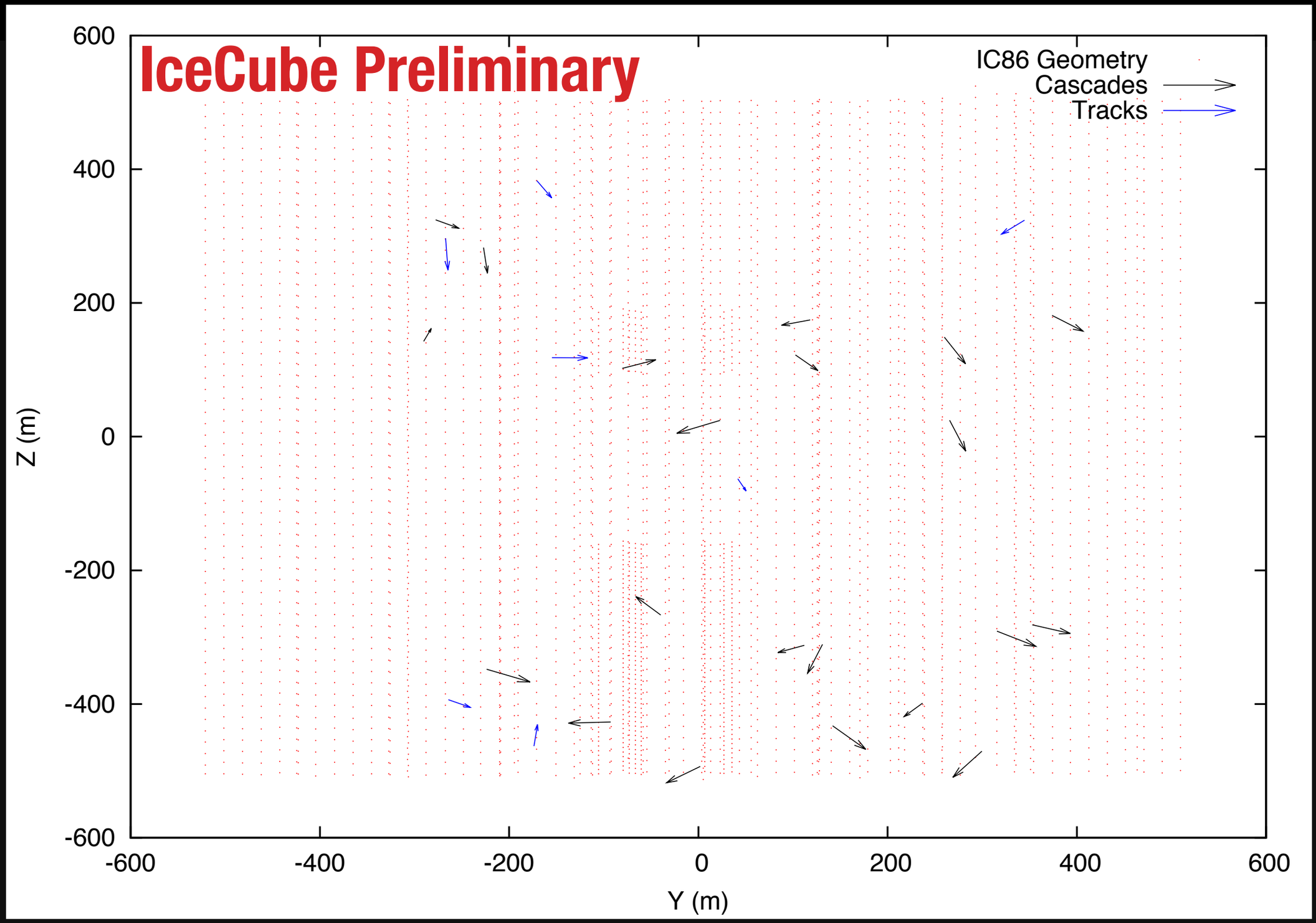
- **28 events observed!**
  - 26 new events in addition to the two 1 PeV events!
- **Track events (x) can have much higher neutrino energies than deposited energies**
  - also true on a smaller scale for shower events for all signatures except charged-current ν_e
- **Background: $10.6^{+5.0}_{-3.6}$**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



(preliminary significance w.r.t. reference bkg. model: 3.3σ for 26 events; 4σ for 28 events)

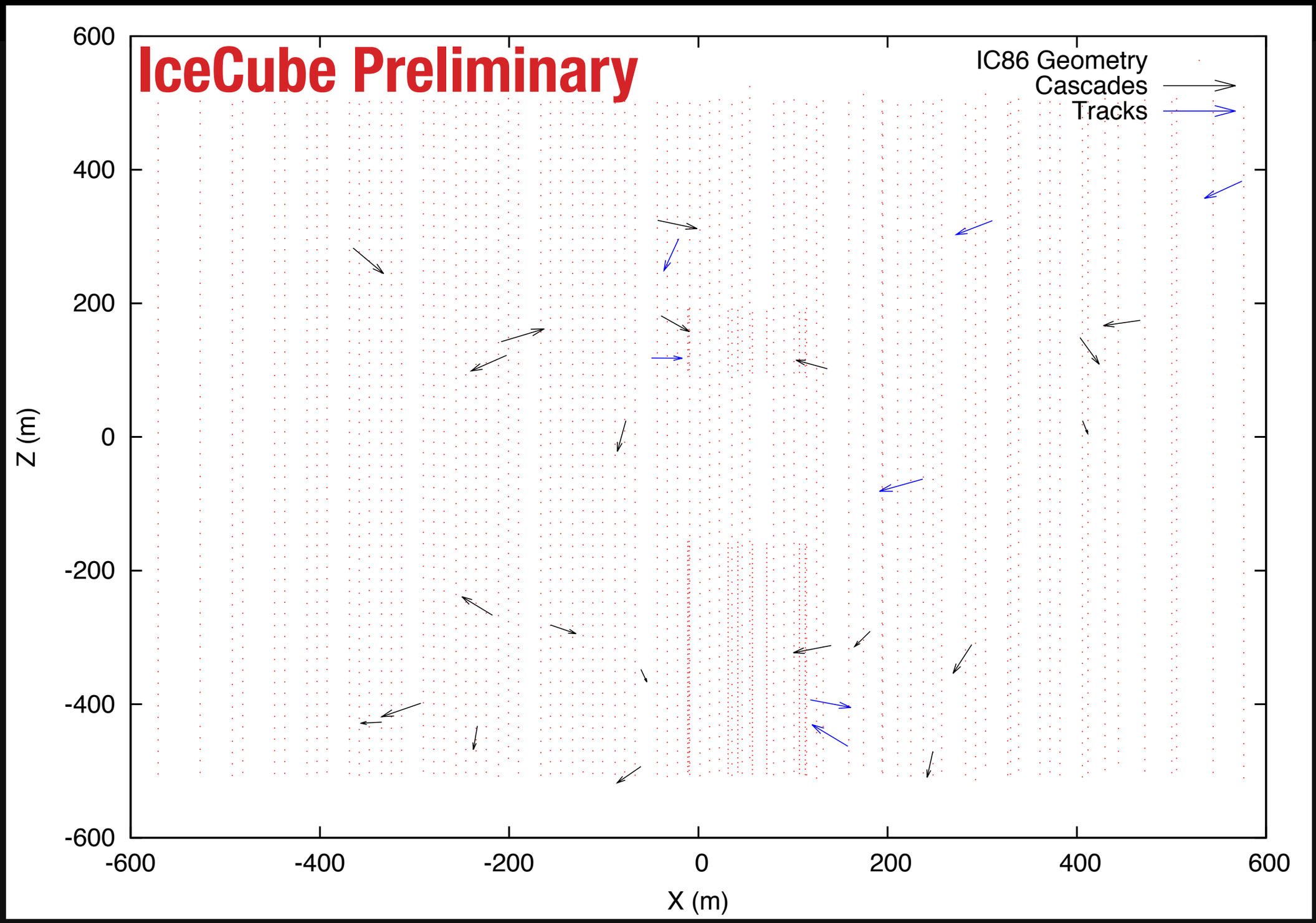
Event Distribution in Detector

Uniform in fiducial volume



Event Distribution in Detector

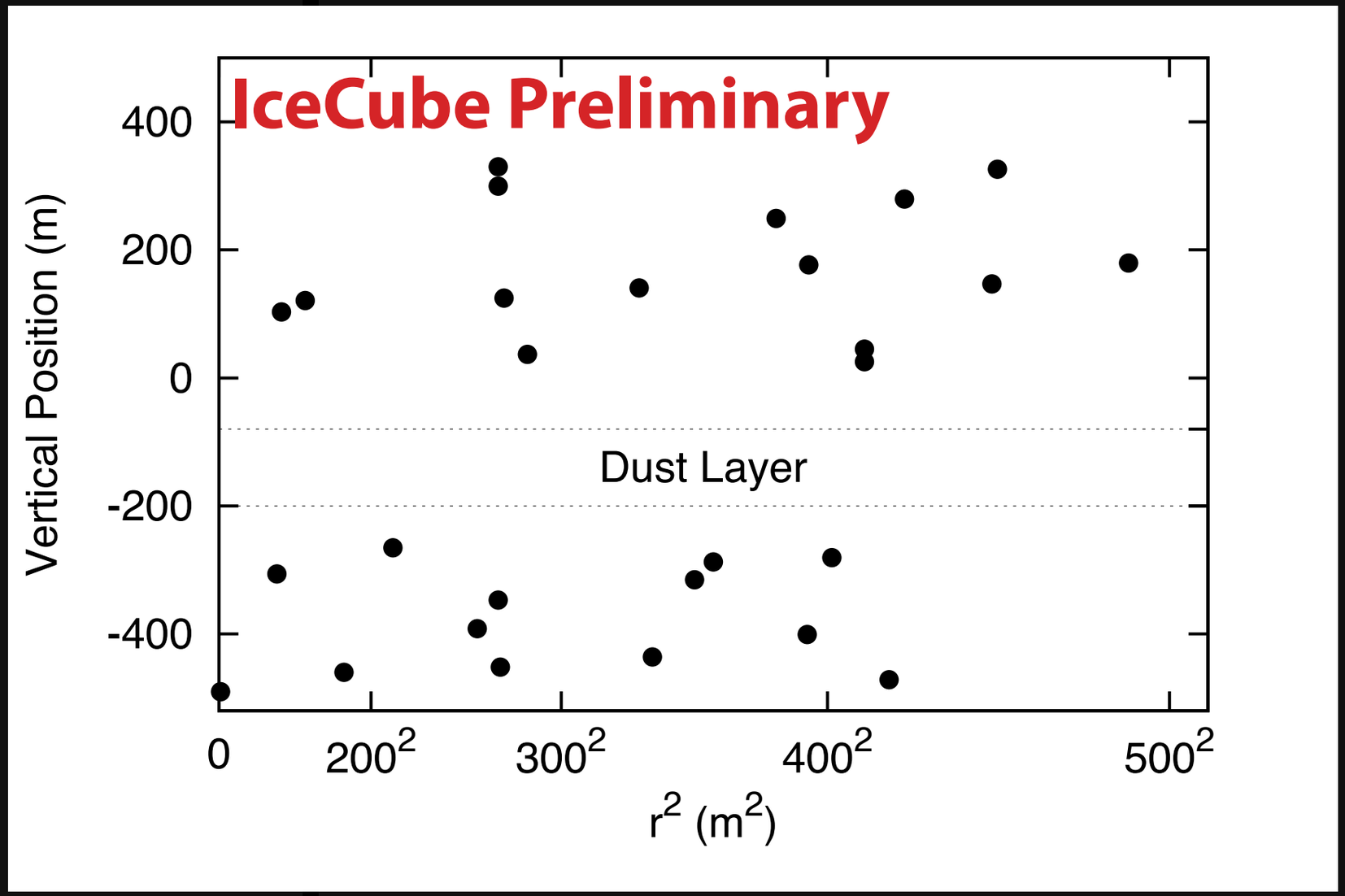
Uniform in fiducial volume



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

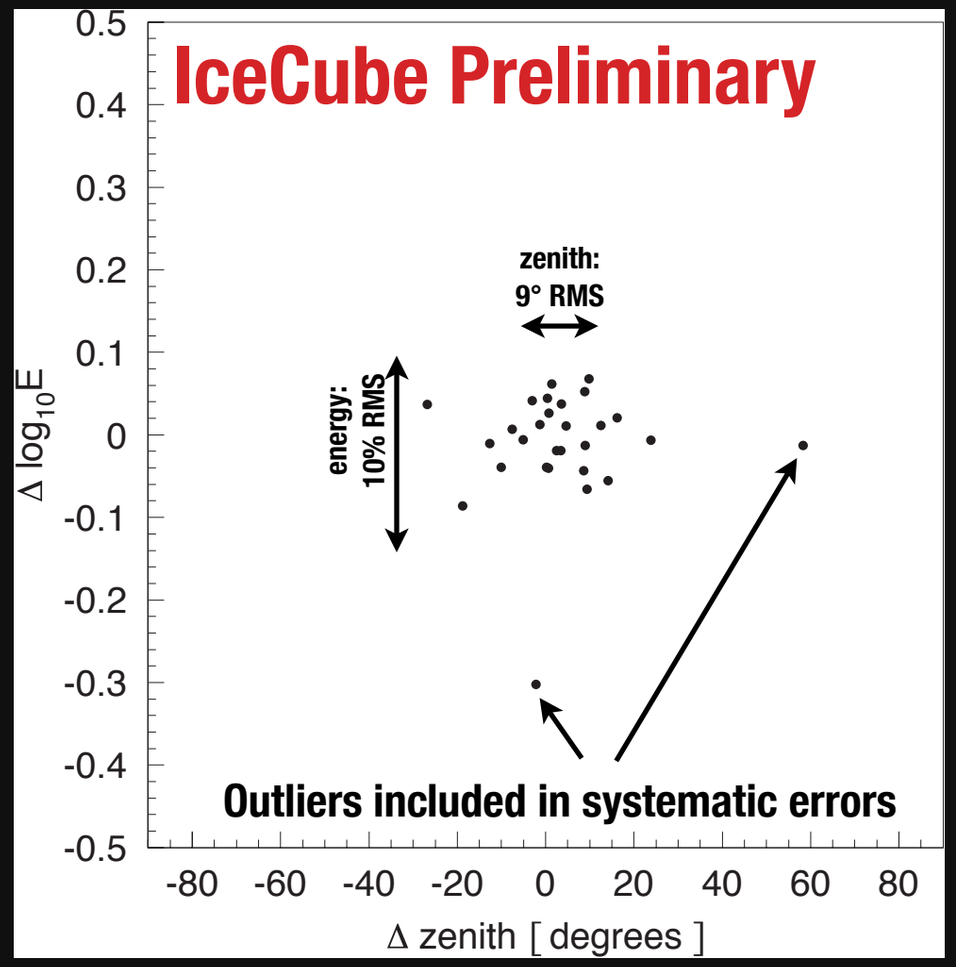
- **Systematics were checked using an extensive per-event re-simulation**
  - varied the ice model and energy scale within uncertainties for each iteration and repeated analysis
- **Different fit methods applied to the events show consistent results**

- **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

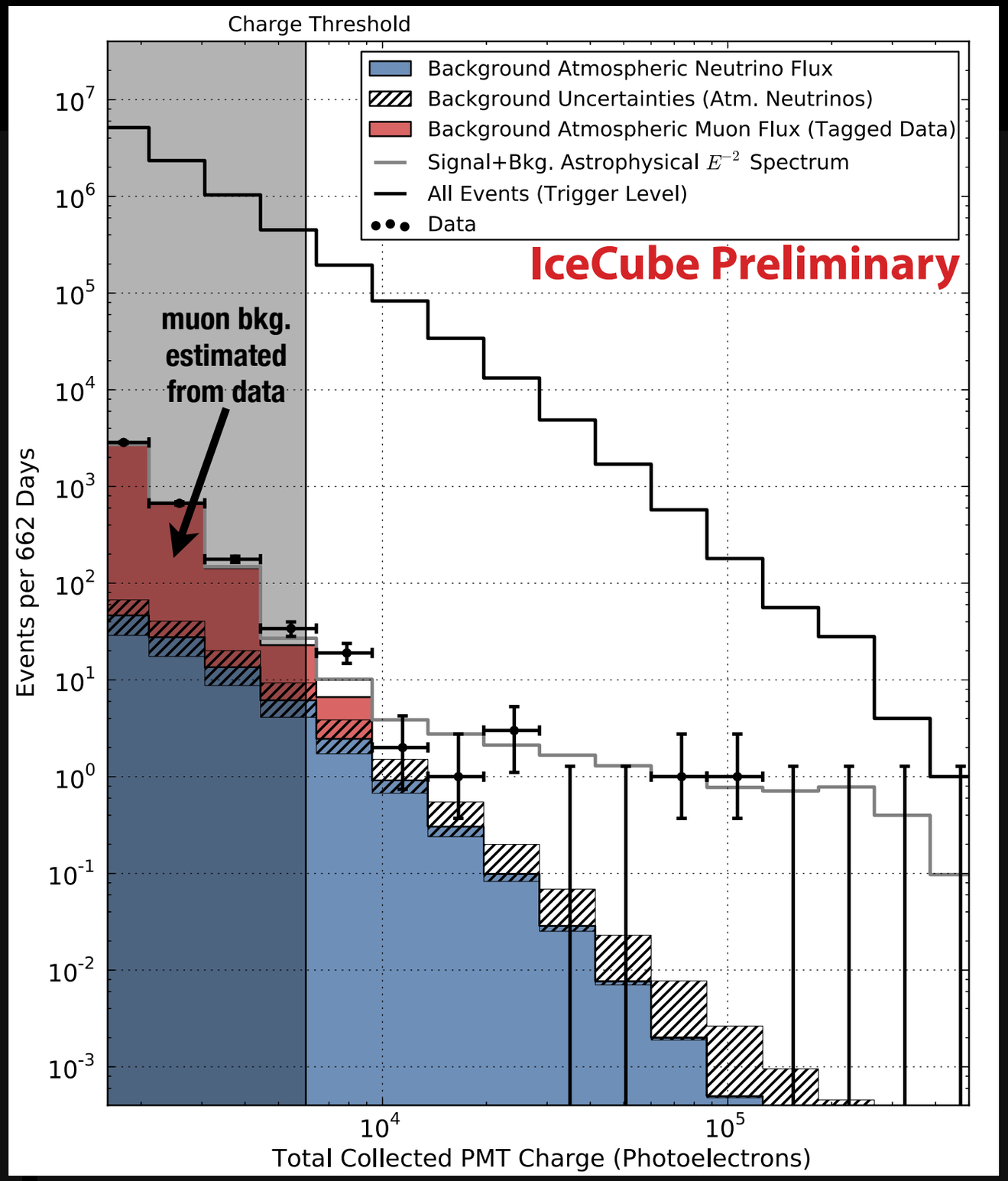
Cross-check with a fit method based on direct re-simulation of events

- **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 with Muon Bkg.

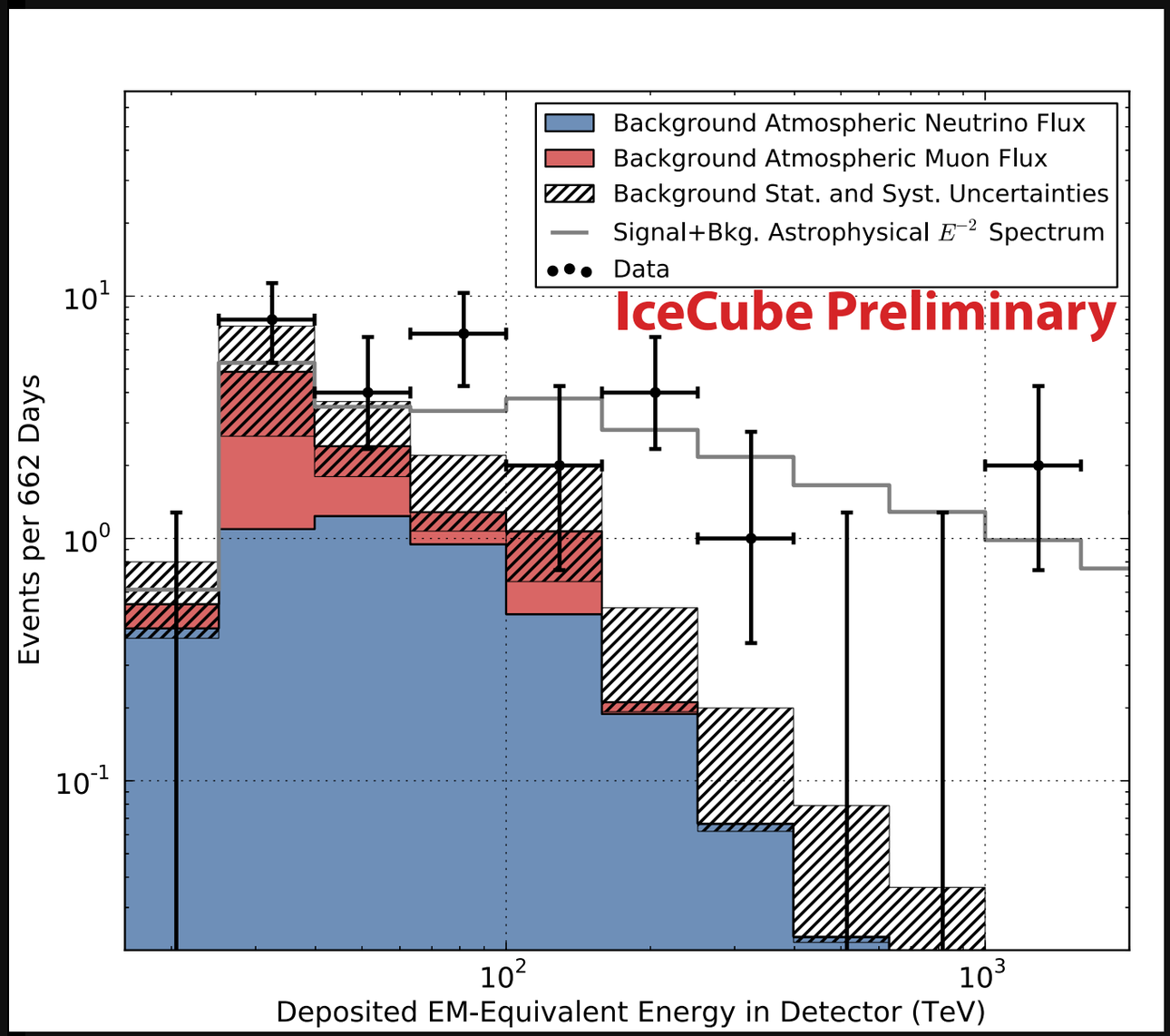
- Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold (Q_{tot}>6000)
- Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)



Energy Spectrum

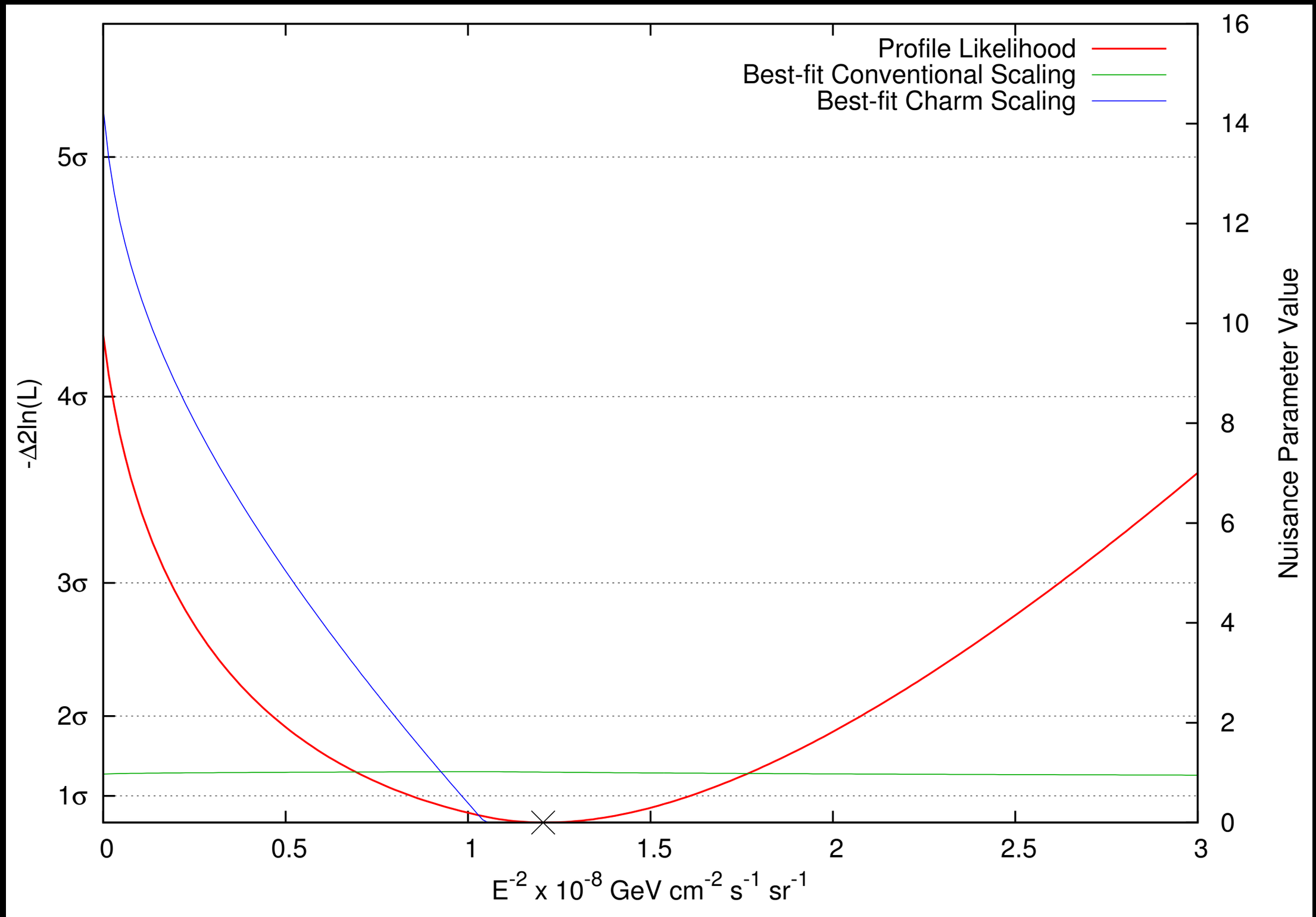
Compatible with benchmark E^{-2} astrophysical model

- **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
- **Best fit (assuming 1:1:1):**
  - $1.2 \pm 0.4\ 10^{-8}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$



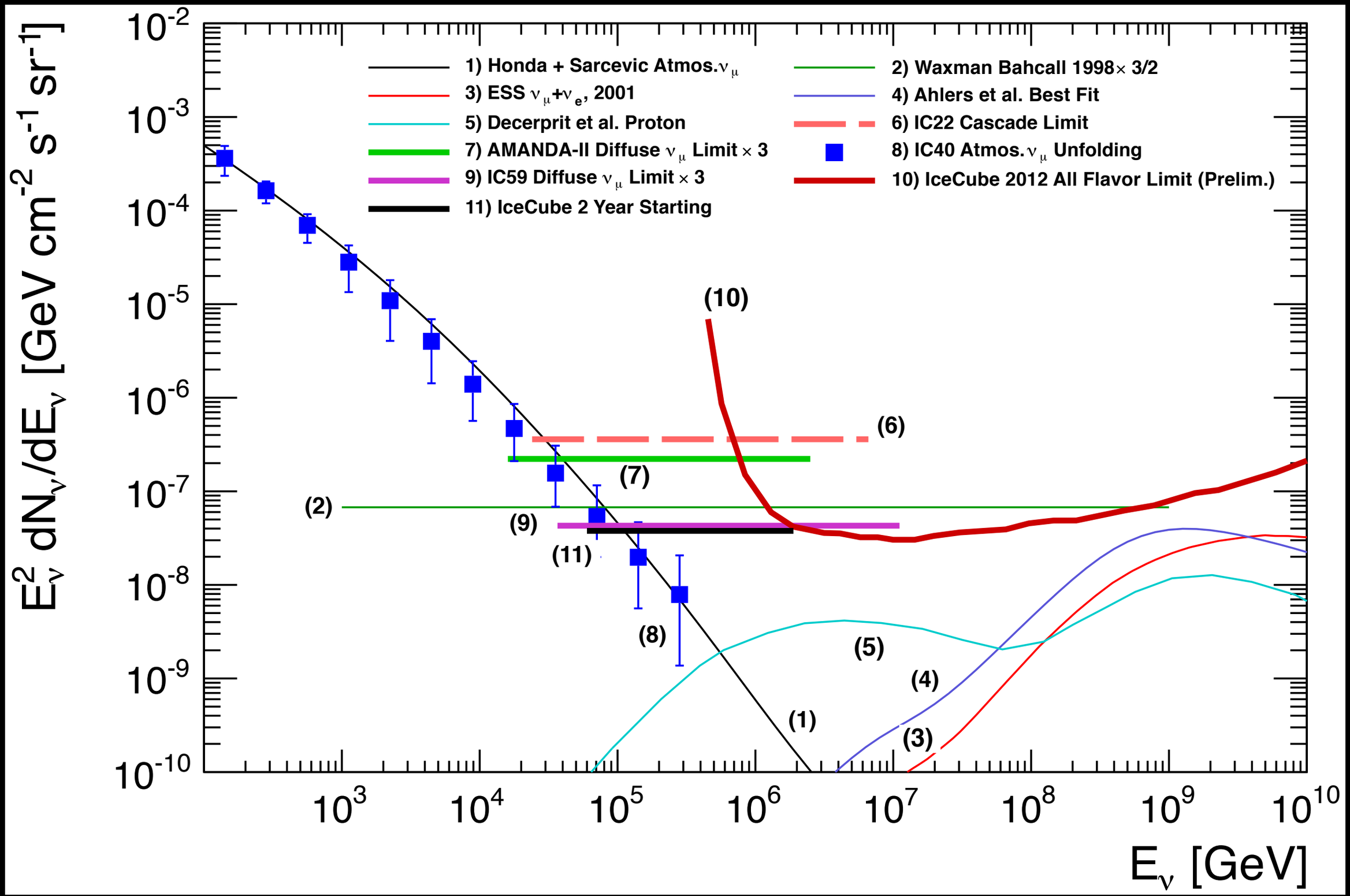
Global fit using 28 events

No prior on charm, E^{-2} fit between 60 TeV < E < 2 PeV



Fluxes and Limits

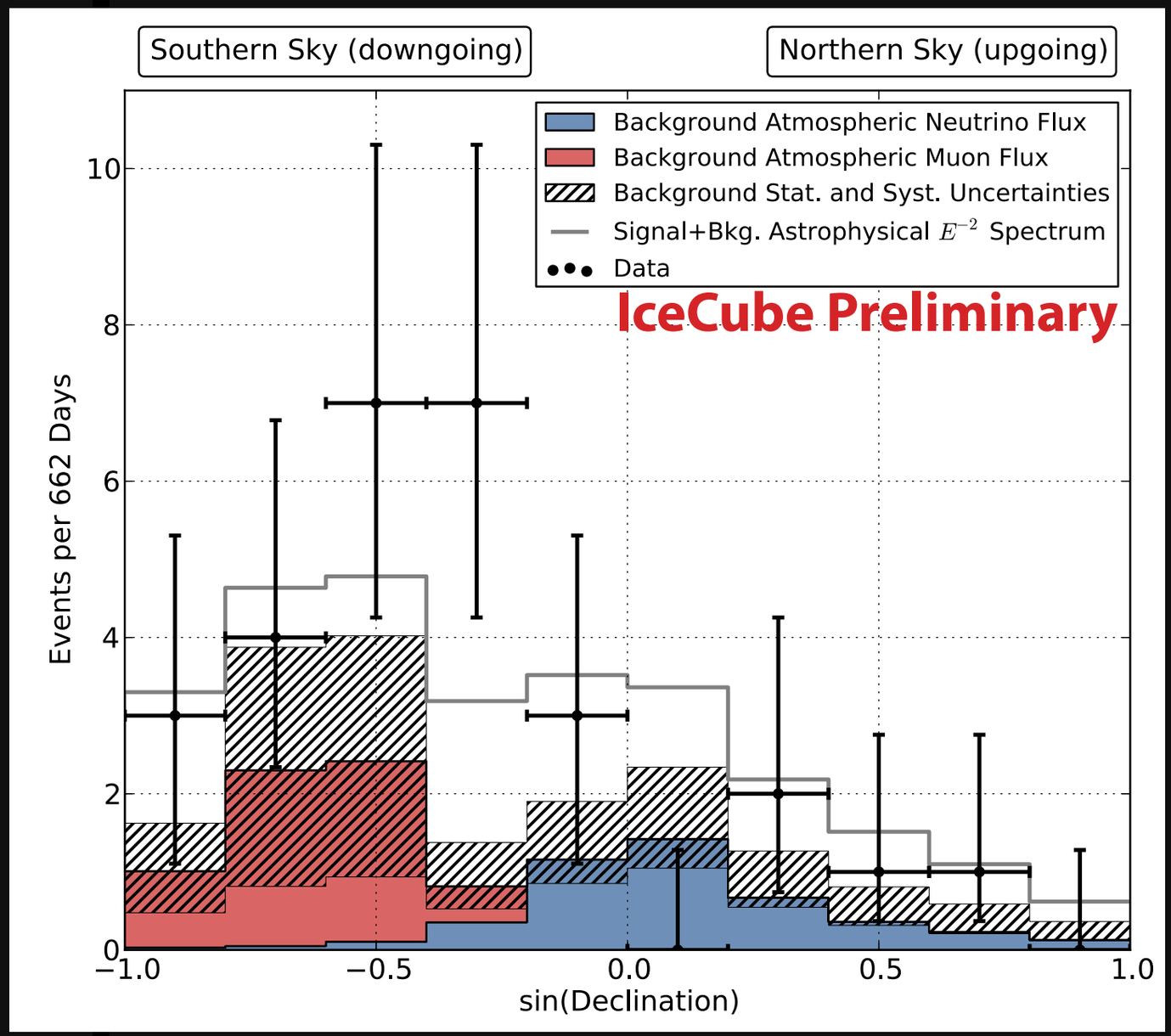
Fluxes normalized to 3 flavors except atm. neutrinos



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**



The Future

- **Improvements of the method, like:**
  - dynamic veto "thickness" as a function of charge
  - enhancements of the detector (top veto, additional strings, ...)??
- **Take more data with IceCube!**
  - one more year of data is being analyzed
- **Publication coming very soon!**