Recent Results from IceCube

Evidence for High-Energy Extraterrestrial Neutrinos and More!

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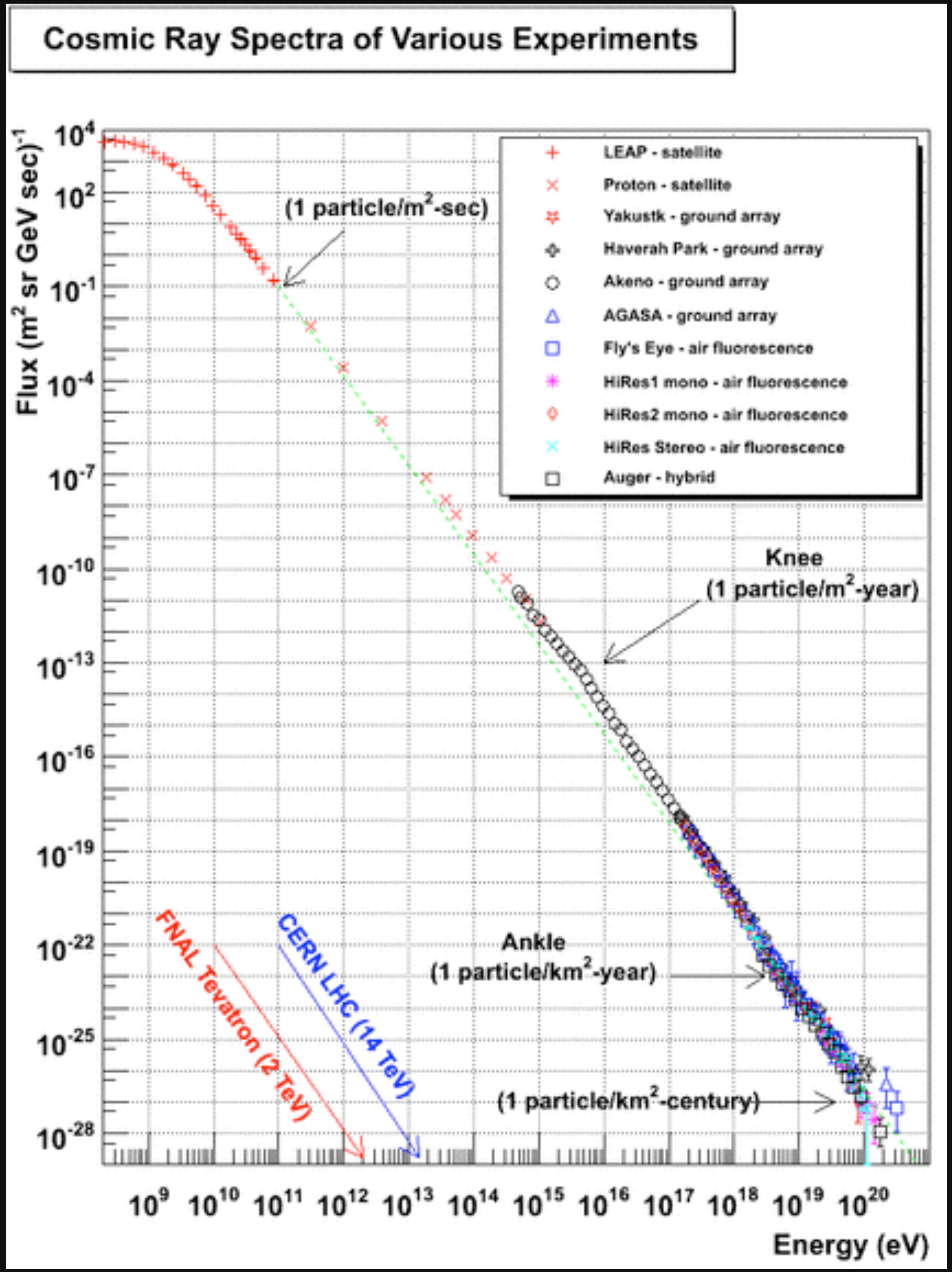
Cosmic Rays

Where (and how) are they accelerated?

- **Charged particles with energies up to 10^{21} eV (ZeV) (!)**
- **Their sources (especially at the highest energies) are still mostly unknown**



TeV Neutrinos

Observing astrophysical neutrinos allows conclusions about the acceleration mechanism of Cosmic Rays

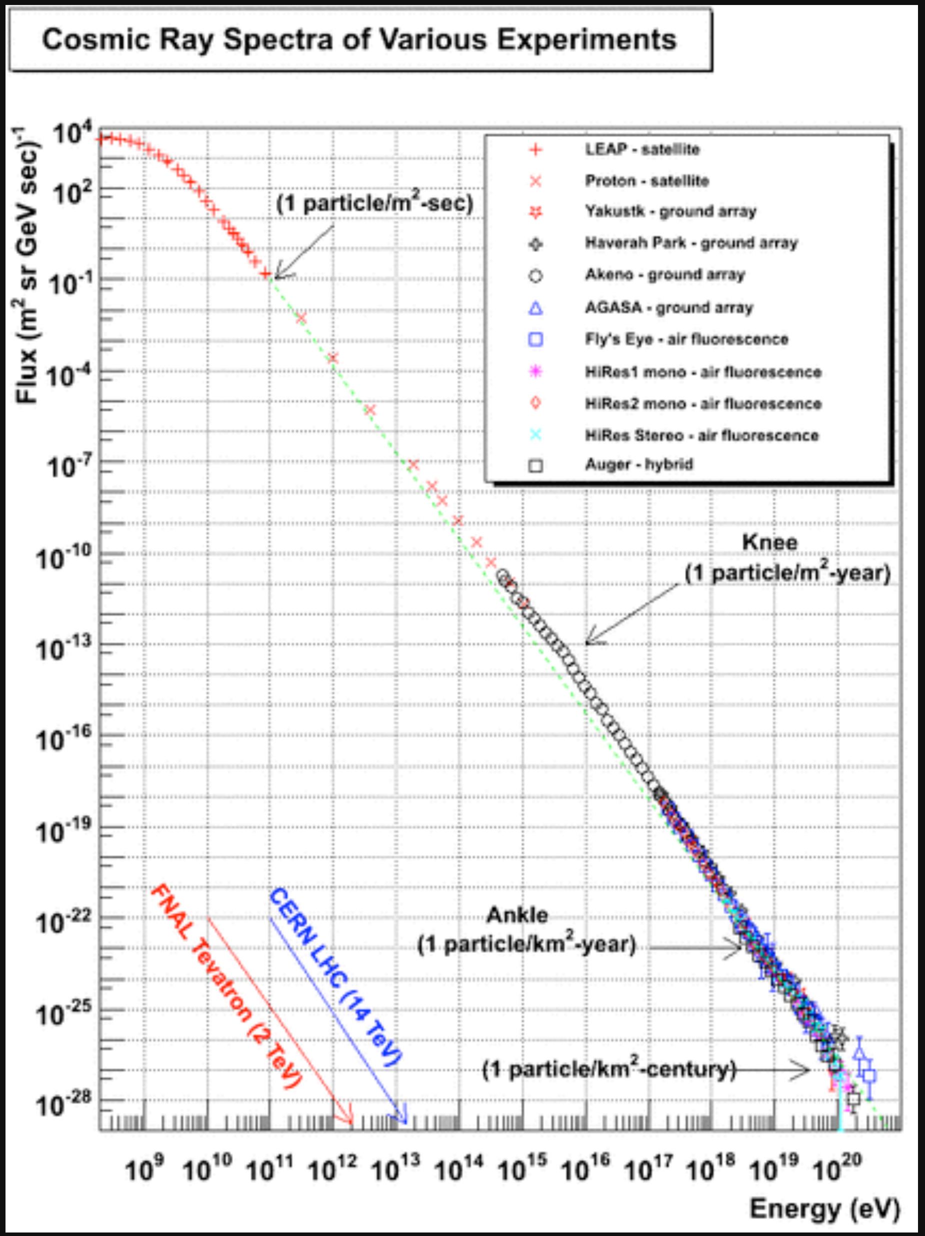
(can also be from leptonic processes…)

$$
\begin{aligned}
\mathrm{p} + \gamma \;&\rightarrow \pi^0 + \mathrm{p} \\
\text{or p, …} \qquad & \hookrightarrow \gamma + \gamma + \mathrm{p} \\
&\rightarrow \pi^+ + \mathrm{n} \\
& \hookrightarrow \mu^+ + \nu_\mu + \mathrm{n} \\
& \hookrightarrow \mathrm{e}^+ + \nu_{\bar{\mu}} + \nu_{\mathrm{e}} + \nu_\mu + \mathrm{n}
\end{aligned}
$$

TeV gamma rays

Cosmic rays?

TeV neutrinos

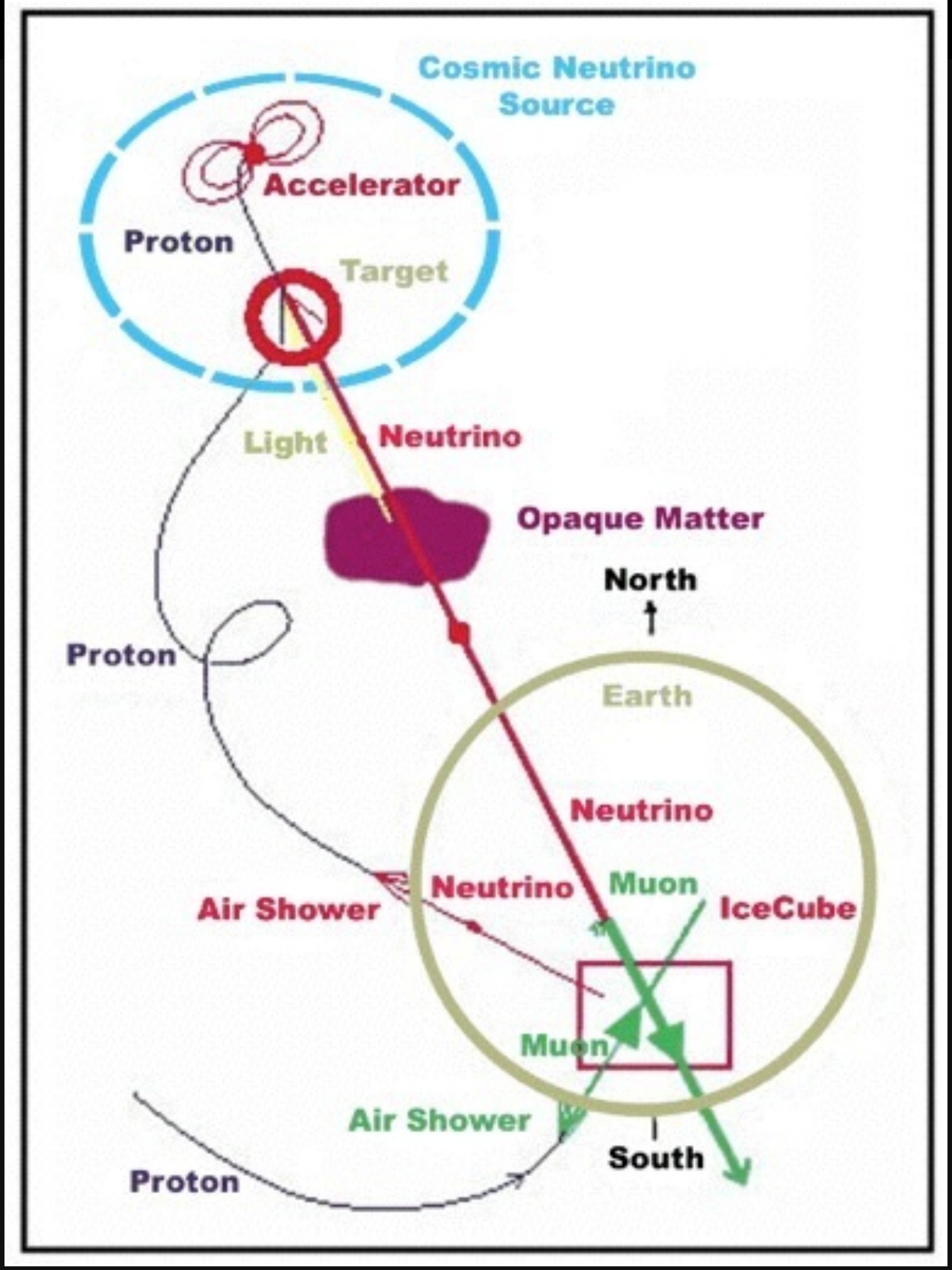


- **Neutrinos from cosmic ray interactions in:**
  - Atmosphere
  - Cosmic Microwave Background
  - Gamma Ray Bursts (Acceleration Sites)
  - Active Galactic Nuclei (Acceleration Sites)
  - ?

Why Neutrinos?

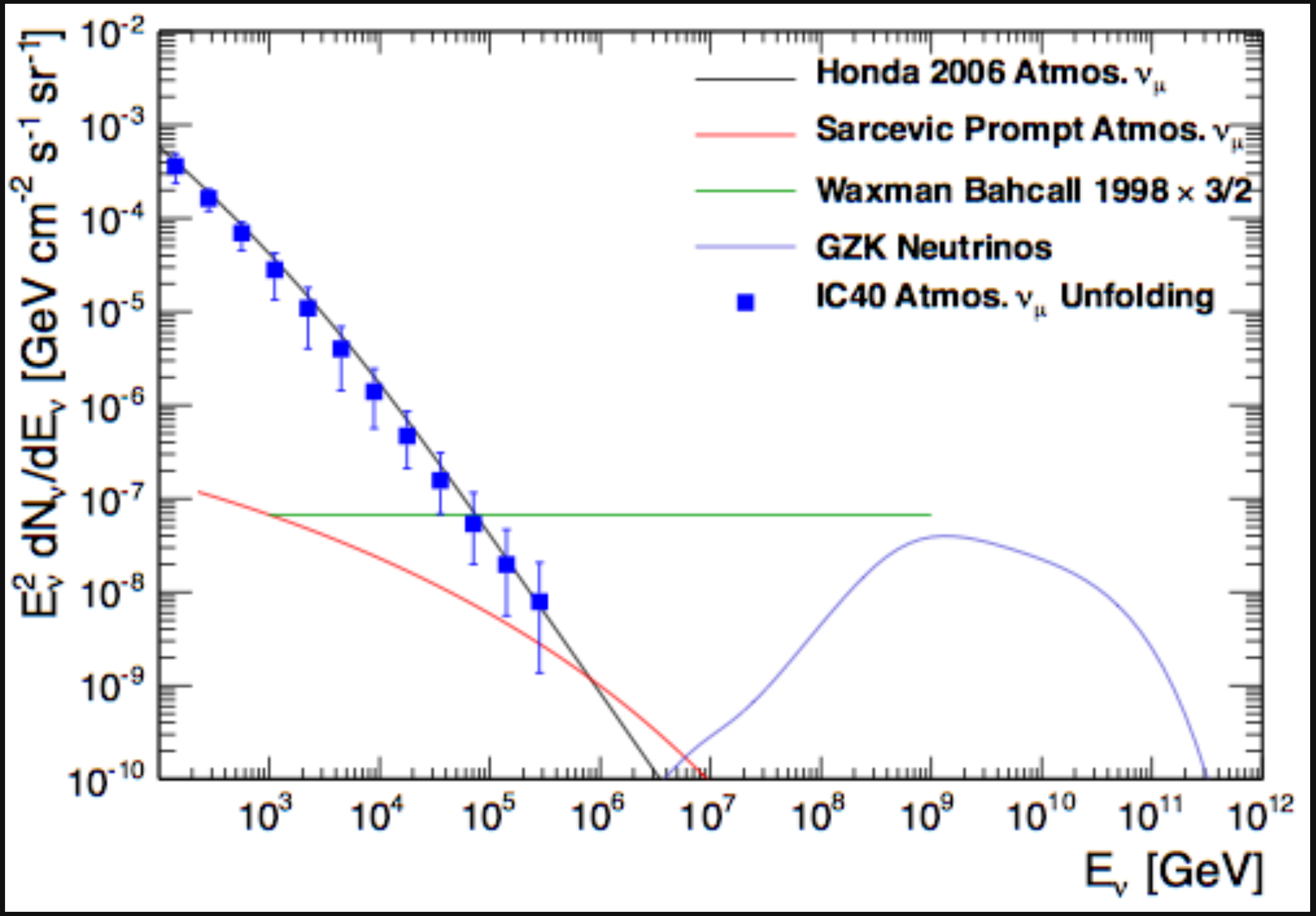
Neutrinos are ideal astrophysical messengers

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



Interesting Neutrinos above 1 TeV

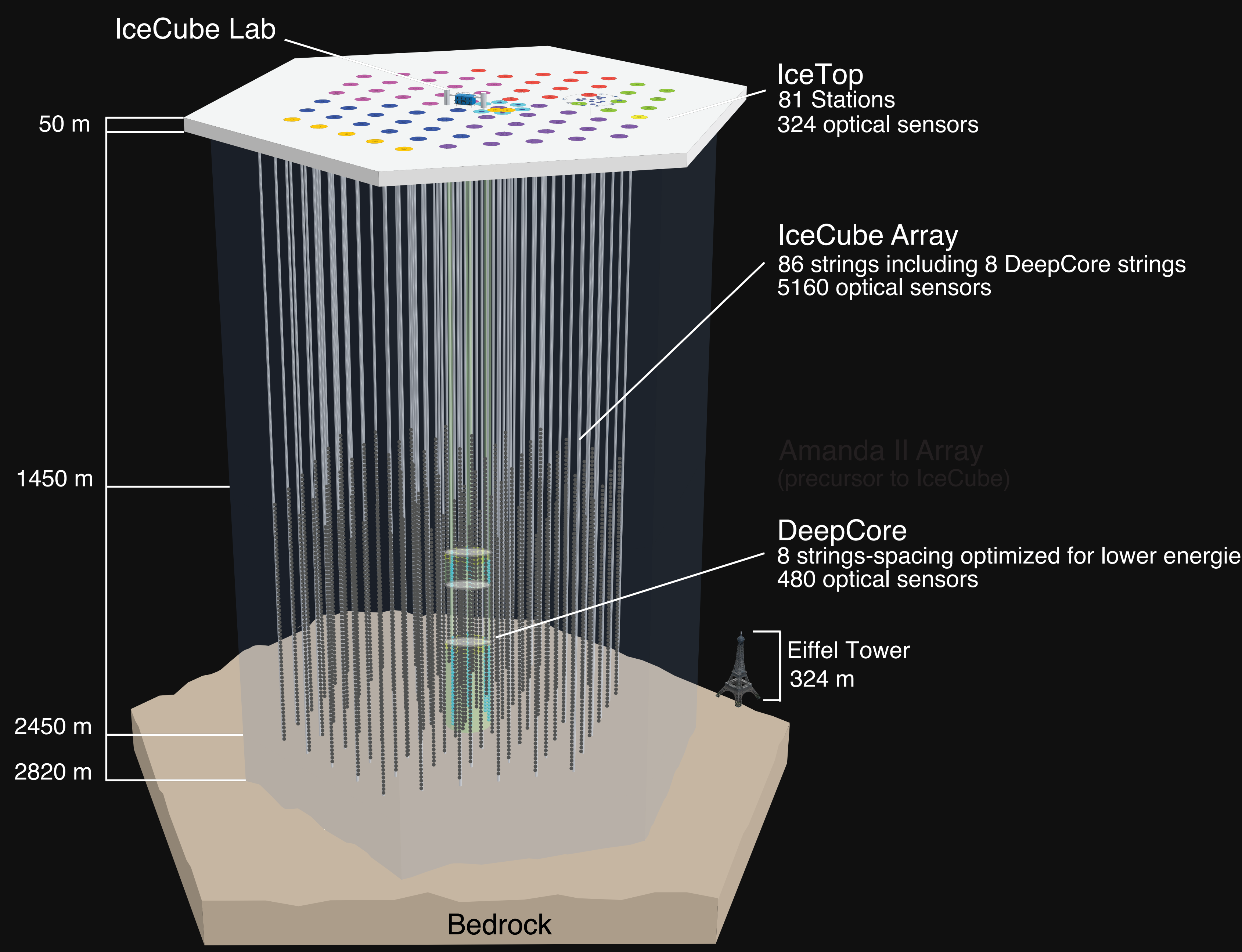
- **Atmospheric neutrinos (π/K)**
  - dominant < 100 TeV
- **Atmospheric neutrinos (charm)**
  - "prompt" ~ 100 TeV
- **Astrophysical neutrinos**
  - maybe dominant > 100 TeV
- **Cosmogenic neutrinos**
  - $>10^6$ TeV



The IceCube Neutrino Observatory

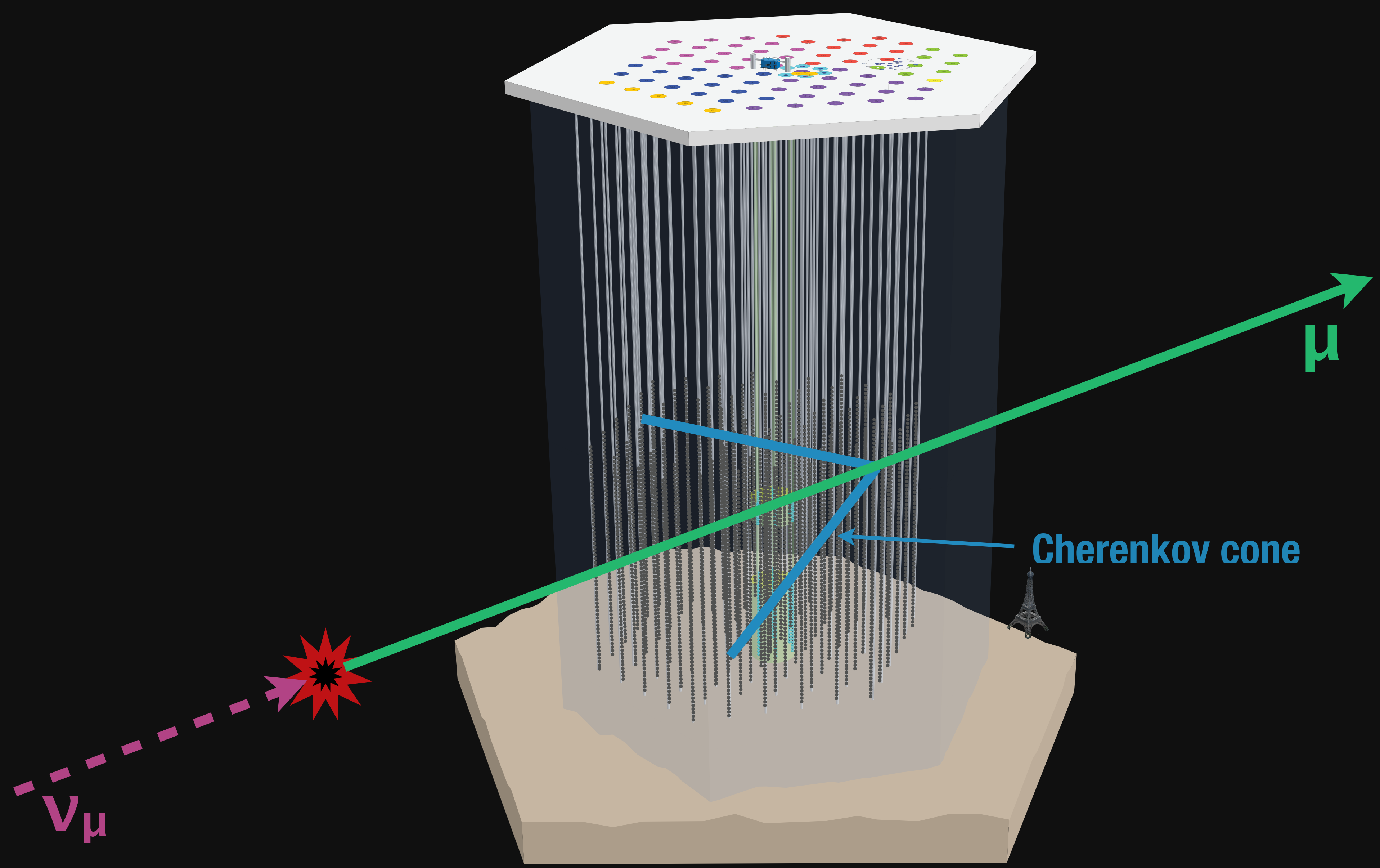
Deployed in the deep glacial ice at the South Pole

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



The IceCube Neutrino Observatory

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



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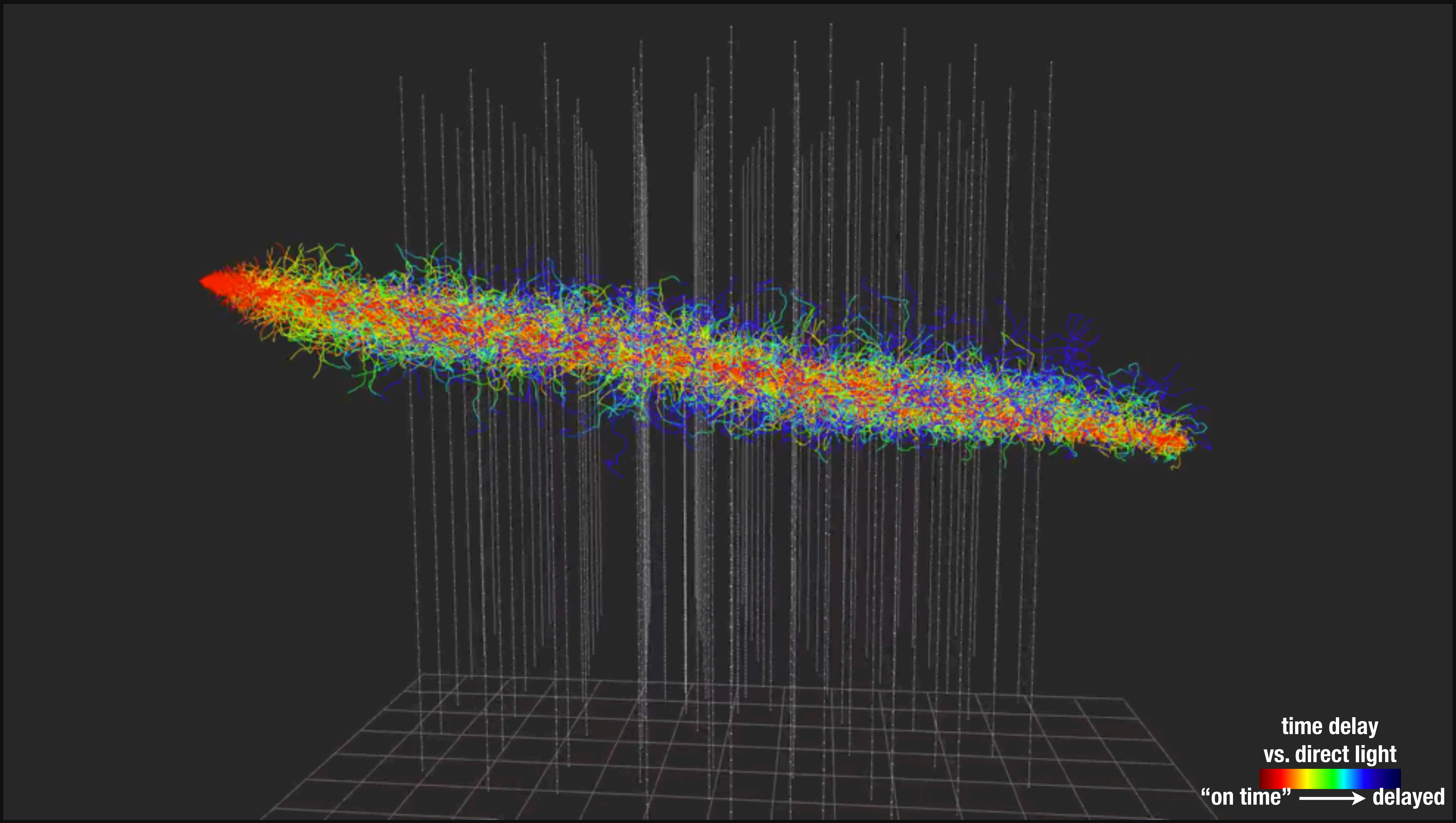

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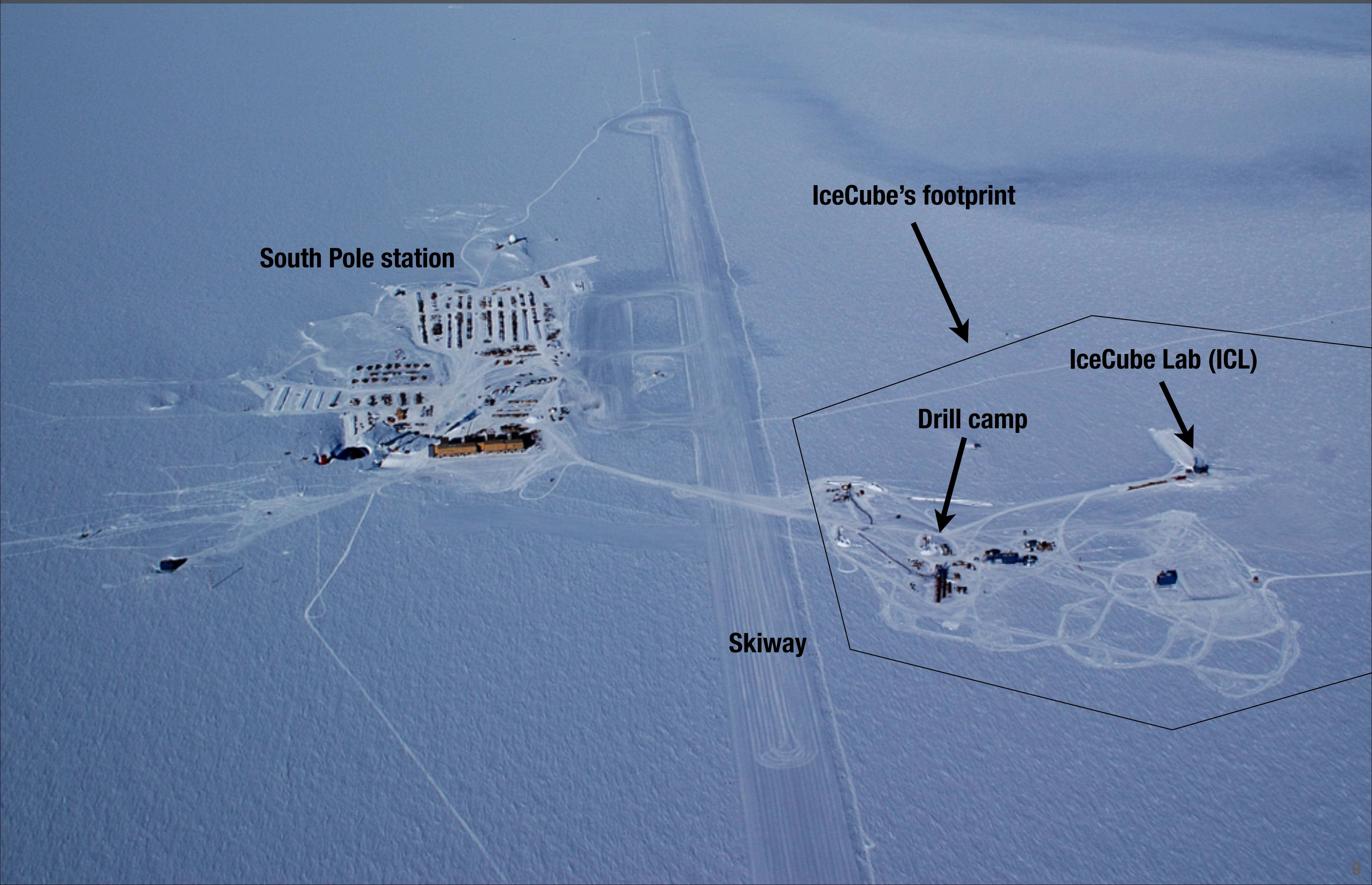
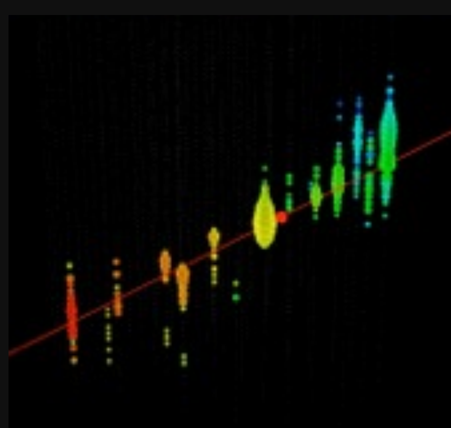


Neutrino Event Signatures

Signatures of signal events

CC Muon Neutrino

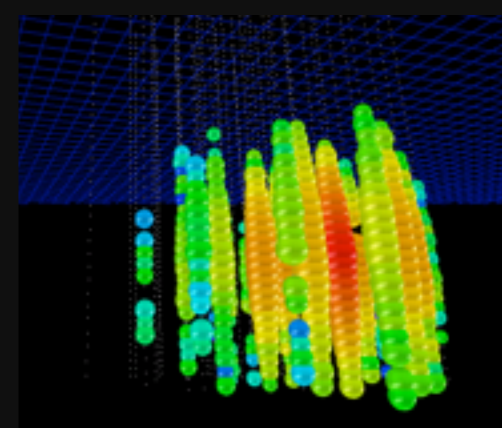


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1°$ angular resolution at high energies

Neutral Current / Electron Neutrino

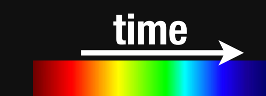


$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

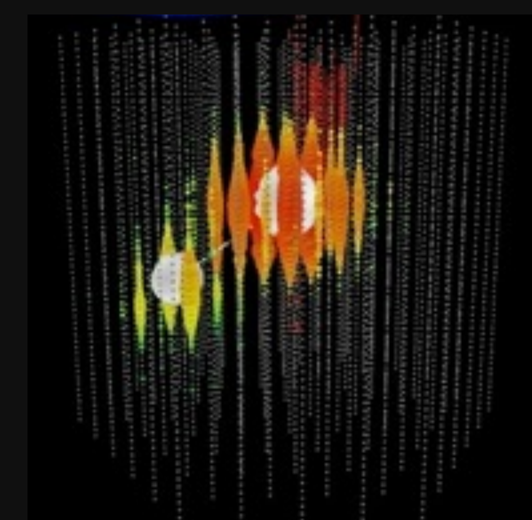
$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

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



CC Tau Neutrino



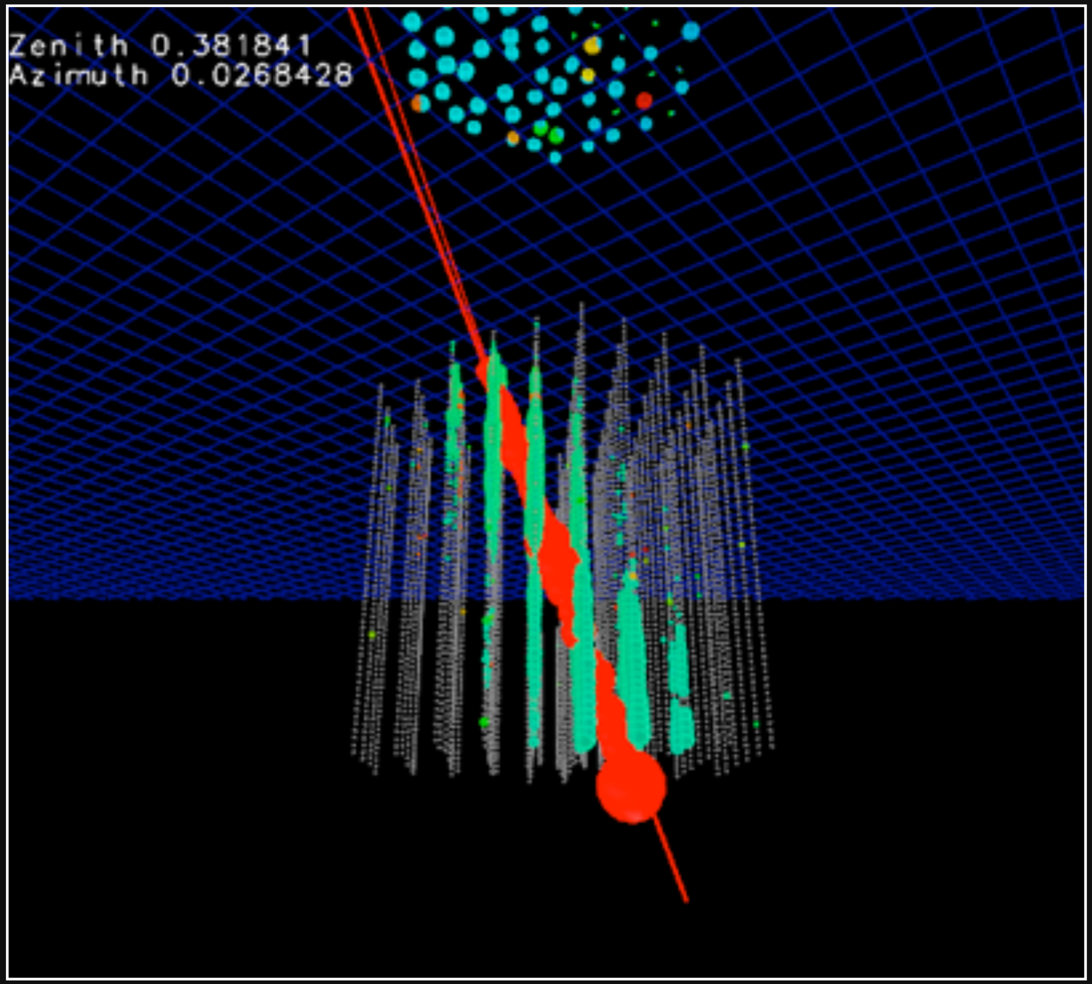
$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” ($\gtrsim$10PeV) 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

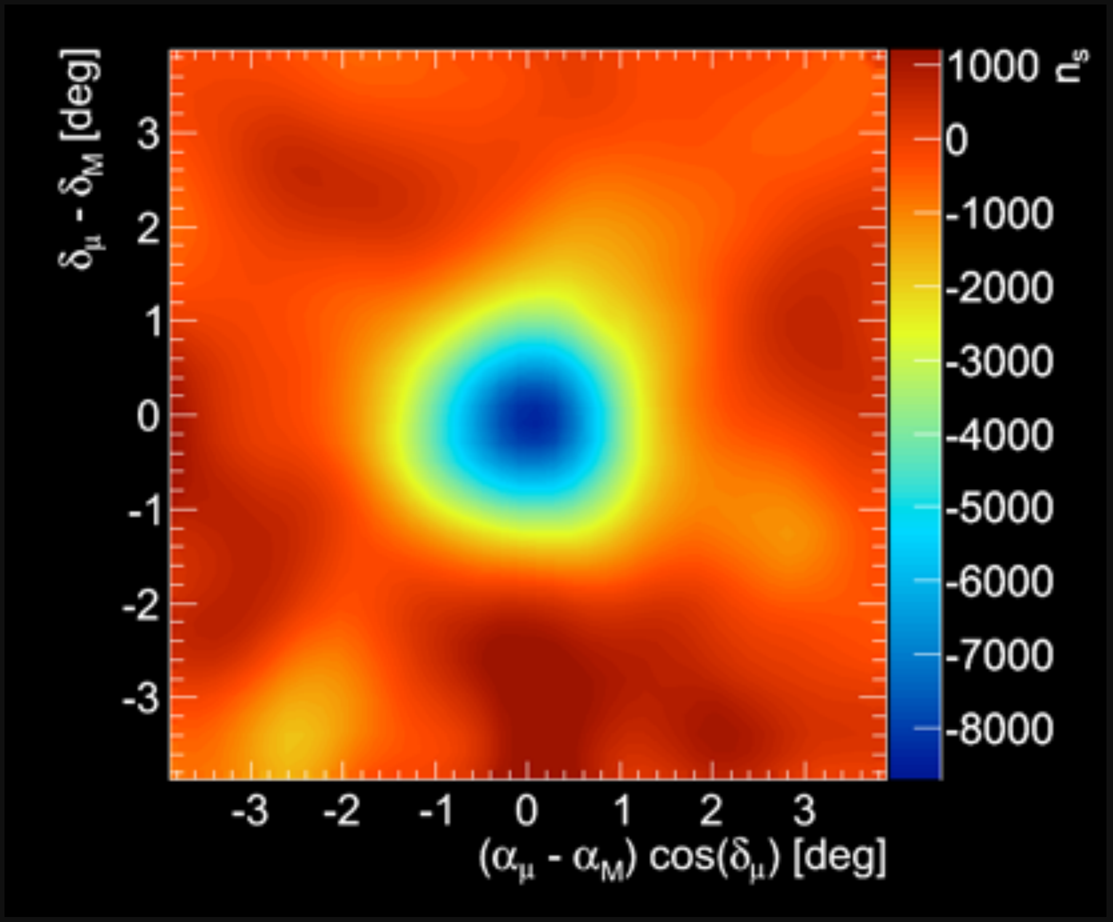


A bundle of muons from a CR interaction in the atmosphere (also observed in the "IceTop" surface array)

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)

Studying Neutrinos

Many possible analyses!

- **High-energy:**
  - Point-source searches looking for clustering in the sky
  - Diffuse fluxes above the atmospheric neutrino background
  - Gamma-ray bursts searches (models excluded by IceCube: Nature 484 (2012))
  - Ultra-high energy “GZK” neutrinos from proton interactions on the CMB
- **Low energy:**
  - Neutrino oscillations + more with PINGU upgrade!
- **Others:**
  - Dark Matter / WIMPs
  - …

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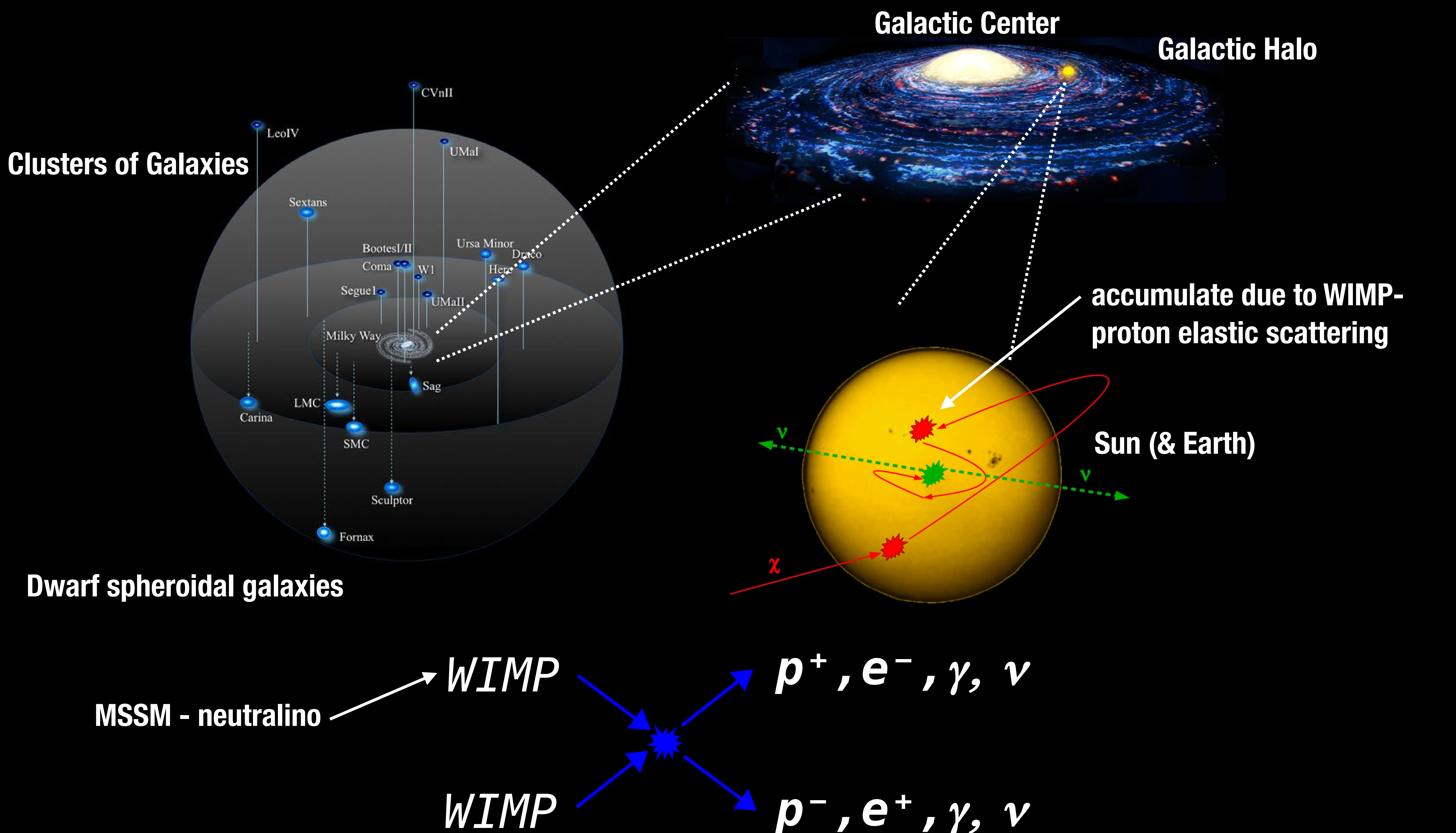
Indirect Dark Matter Searches

(High-Energy) Neutrino Signals from the Sun, the Galactic Center, Halo and more!

Indirect Dark Matter Searches

Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe



PRL 110 (2013) 131302

IceCube-79 Solar WIMP Search

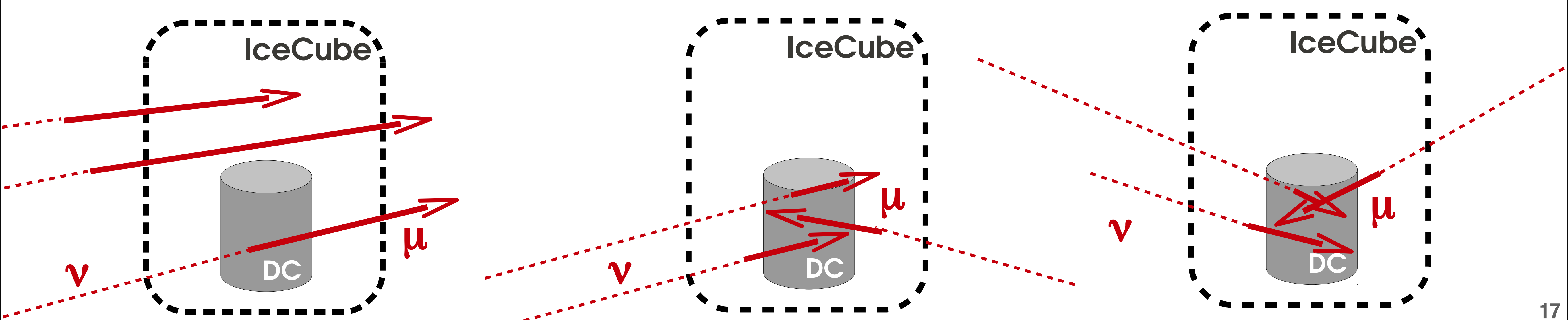
All-year search: three cuts to search for neutrinos above background from the Sun's direction, even when looking up in the Summer!

- **Northern Hemisphere: (winter - looking down)**
  - look for incoming and starting (contained) events
- **Southern Hemisphere: (summer - looking up)**
  - look for events starting deep in the detector to reduce downgoing background
- **317 days of livetime, down to neutrino energies of ~10GeV!**

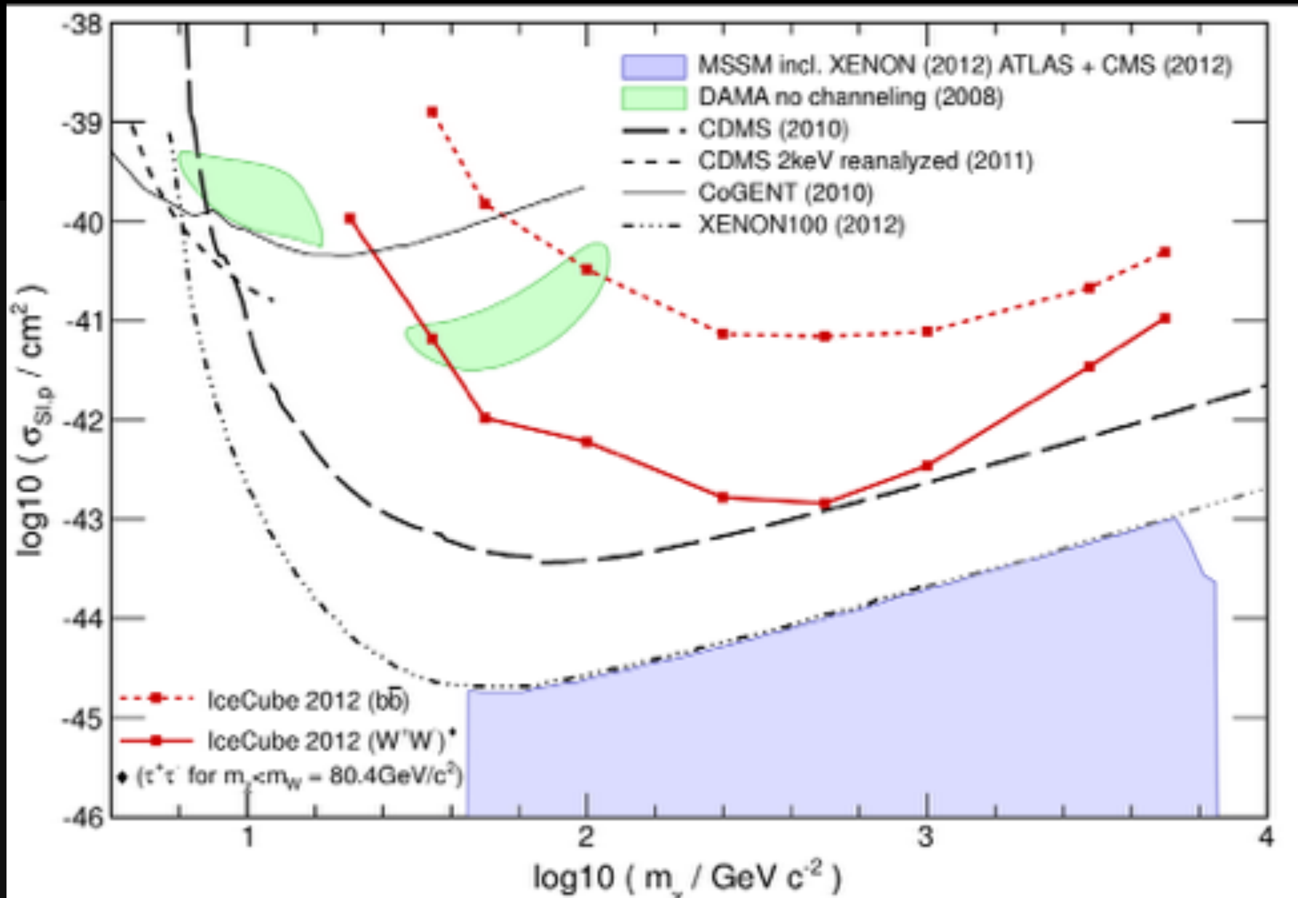
- *Up-going* 1
- No containment

- *Up-going* 2
- strong containment

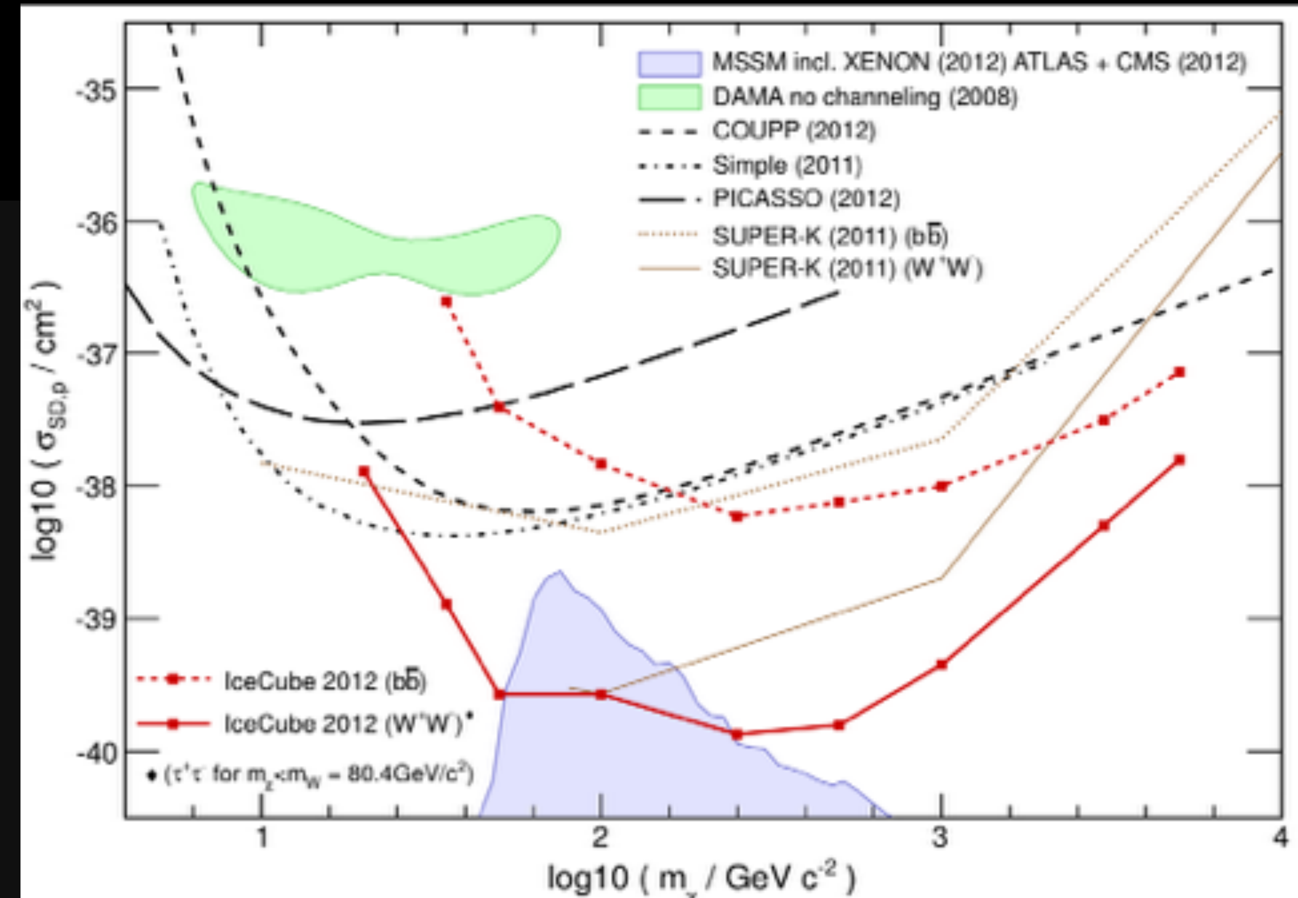
- *Down-going* 3
- strong containment



IceCube-79 Solar WIMP Search



90% CL χ-p cross-section (spin-independent)

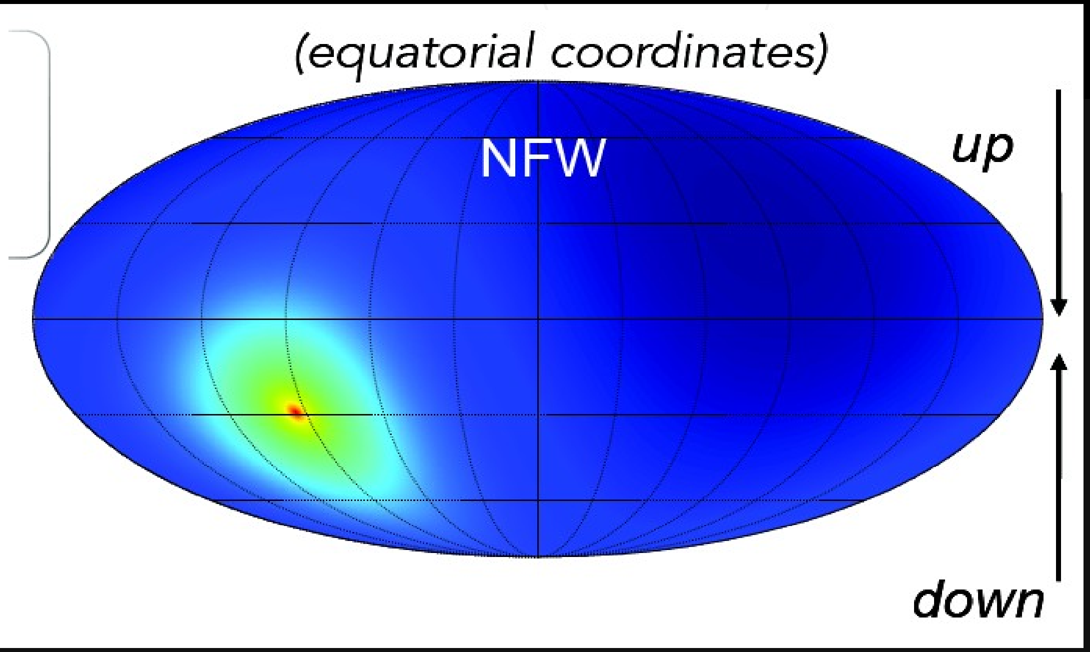


90% CL χ-p cross-section (spin-dependent)

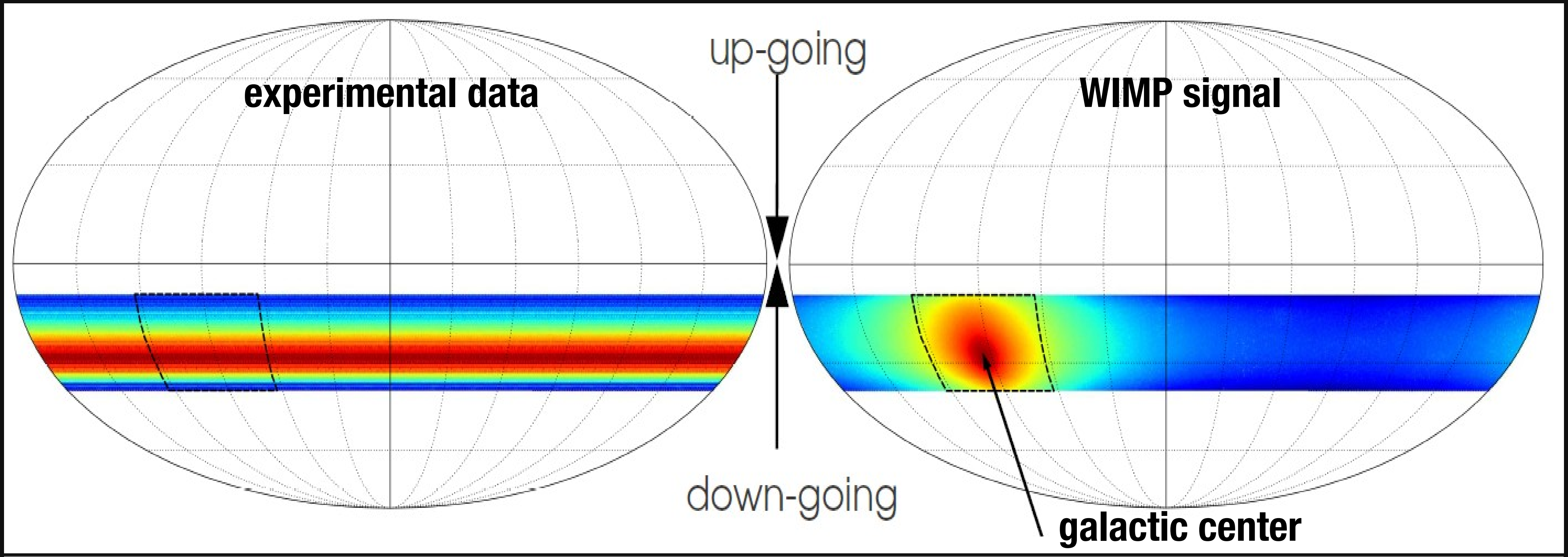
- **Complementary to direct detection search efforts**
  - fills out WIMP picture by testing other properties
- **Most stringent SD cross-section limit for most models**

Galactic Center Dark Matter Search

IceCube-79 string configuration



- **Two different analyses:**
    - DeepCore and DeepCore+IceCube
- **lower the energy threshold to ~10 GeV**
- **Improved muon veto**
- **Use scrambled data for background estimation**



Various Potential Dark Matter Signals

Various analyses looking at different source distributions

- **Galactic Halo:**
  - IC22 PRD 8 (2011) 022004
  - IC79 in preparation
- **Galactic Center:**
  - IC79 in preparation
- **Dwarf spheroids:**
  - IC59 PRD 88 (2013) 122001
- **Clusters of galaxies:**
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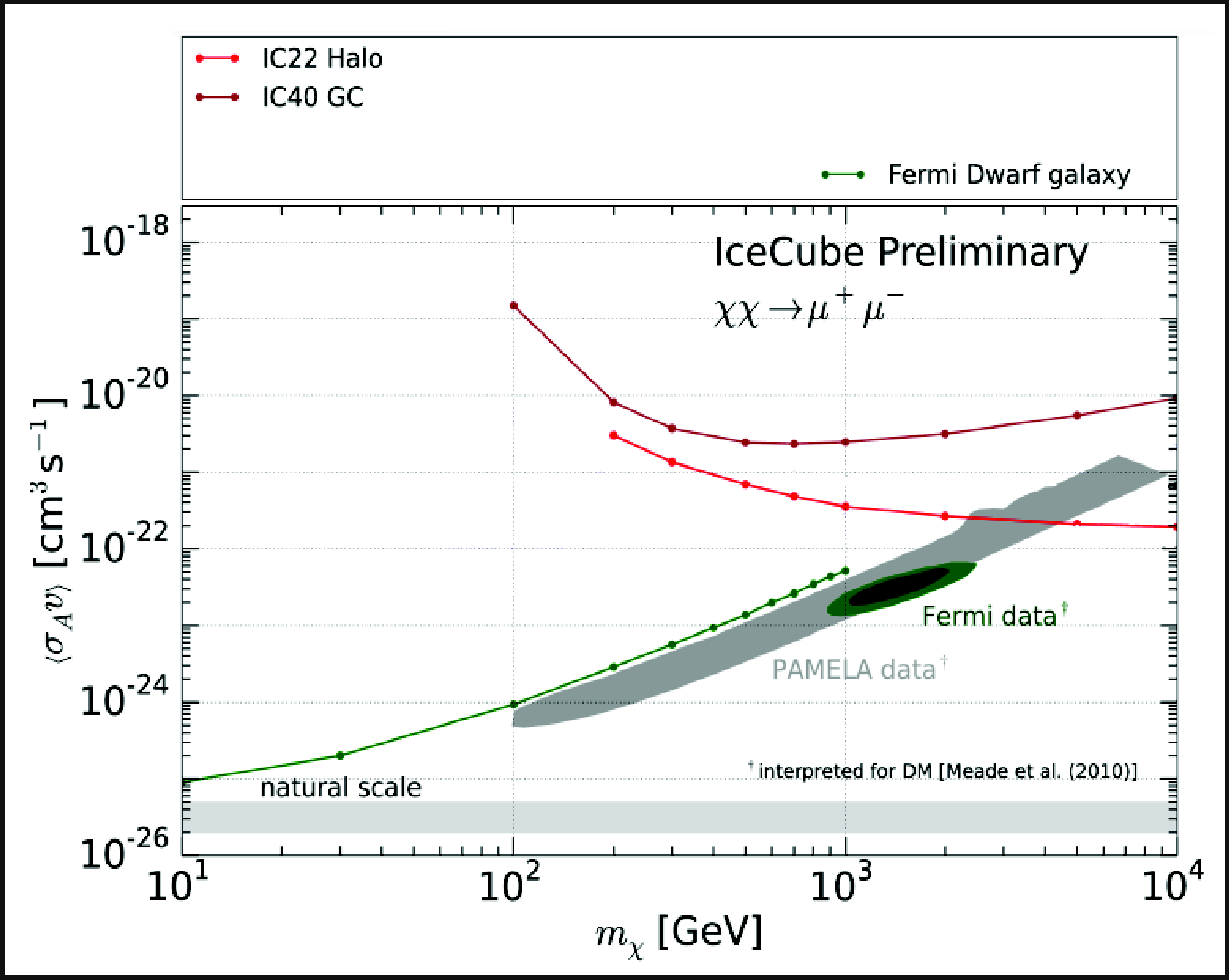

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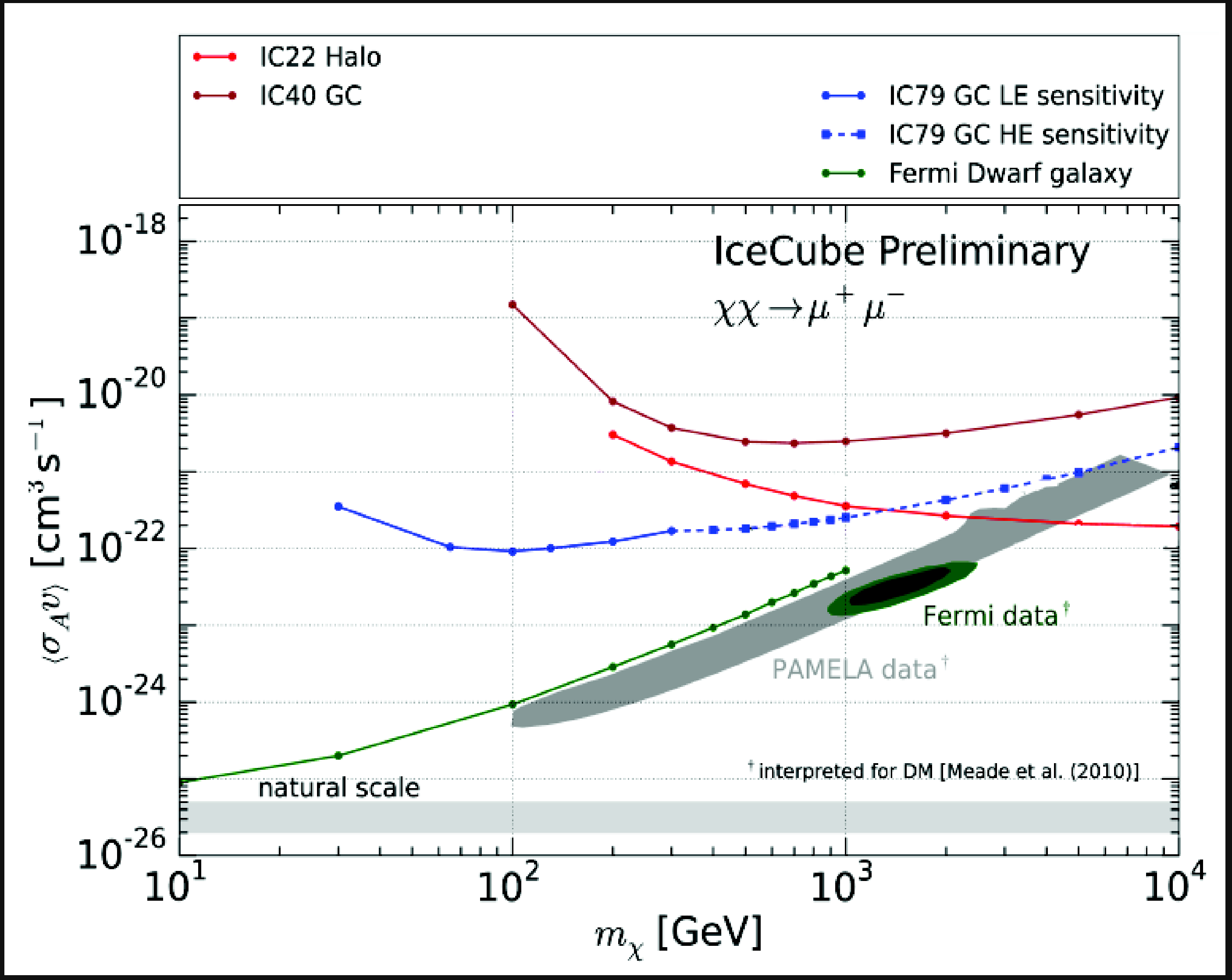

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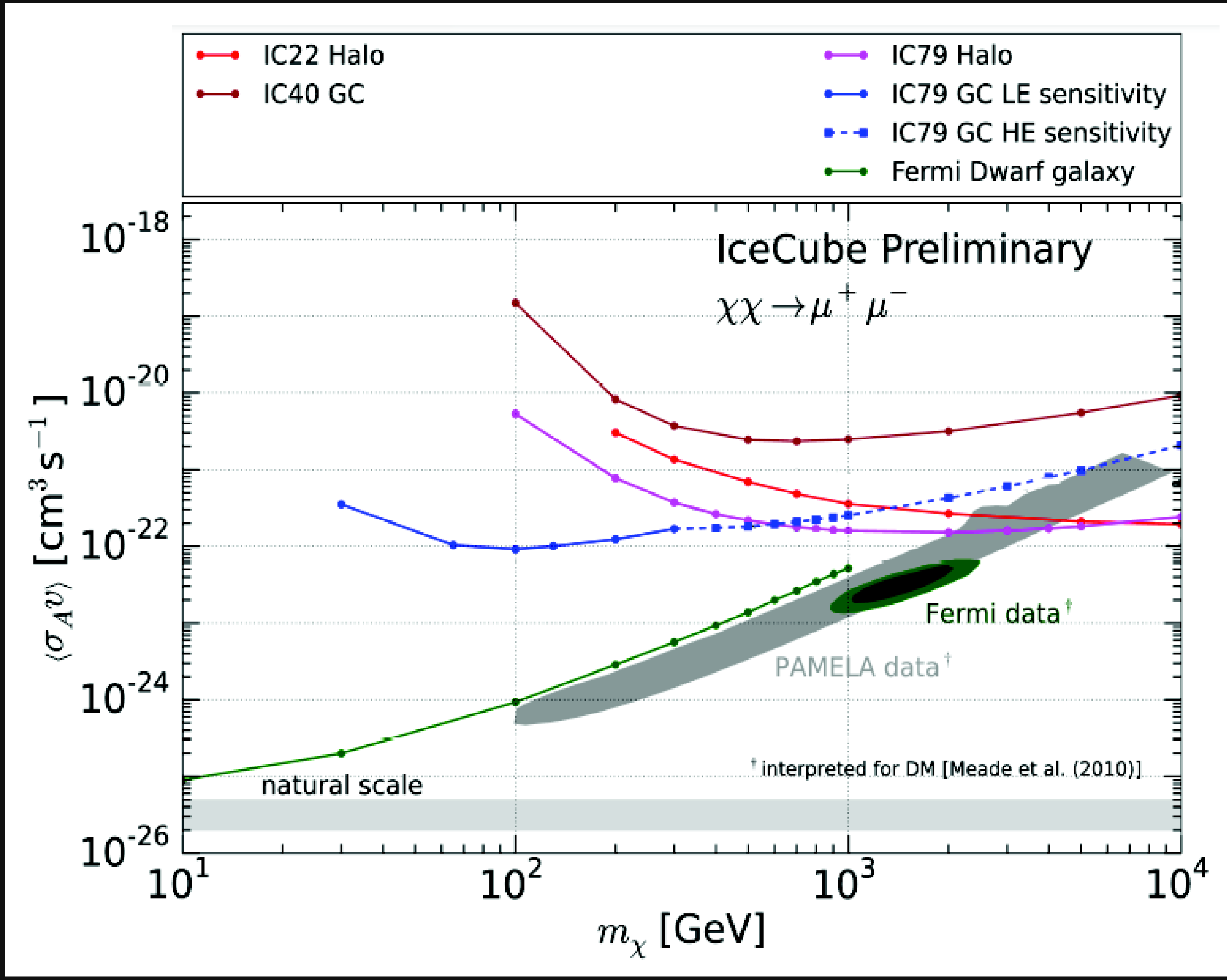

Various Potential Dark Matter Signals

Various analyses looking at different source distributions

- **Galactic Halo:**
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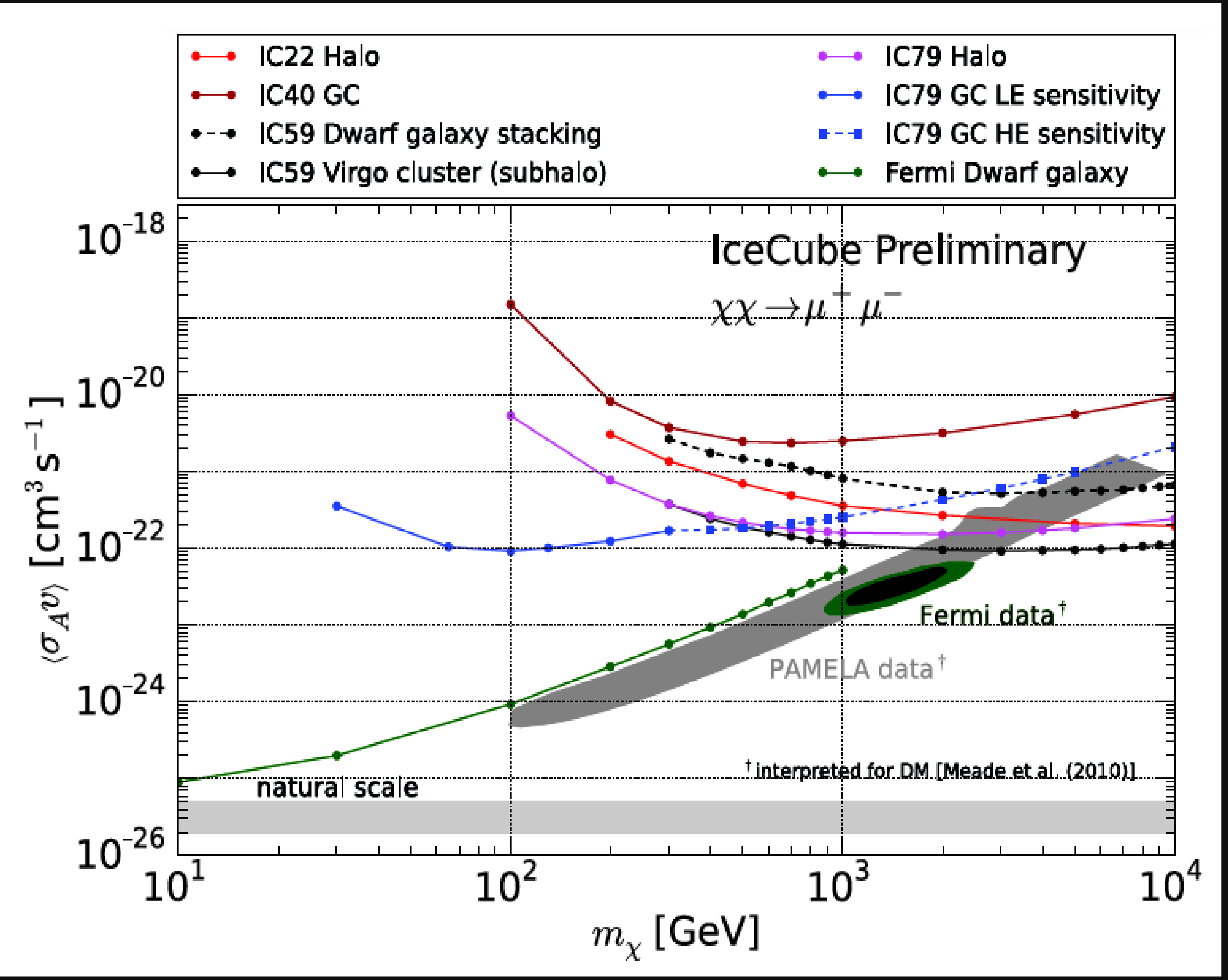
  - IC79 in preparation
- **Galactic Center:**
  - IC79 in preparation
- **Dwarf spheroids:** high mass/light ratio
  - IC59 PRD 88 (2013) 122001
- **Clusters of galaxies:**
  - IC59 PRD 88 (2013) 122001



The (Very) 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

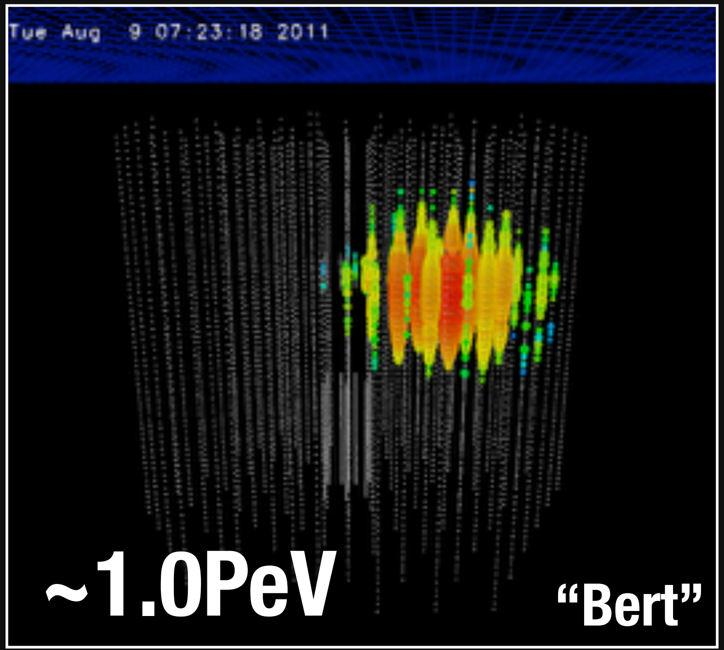
Background

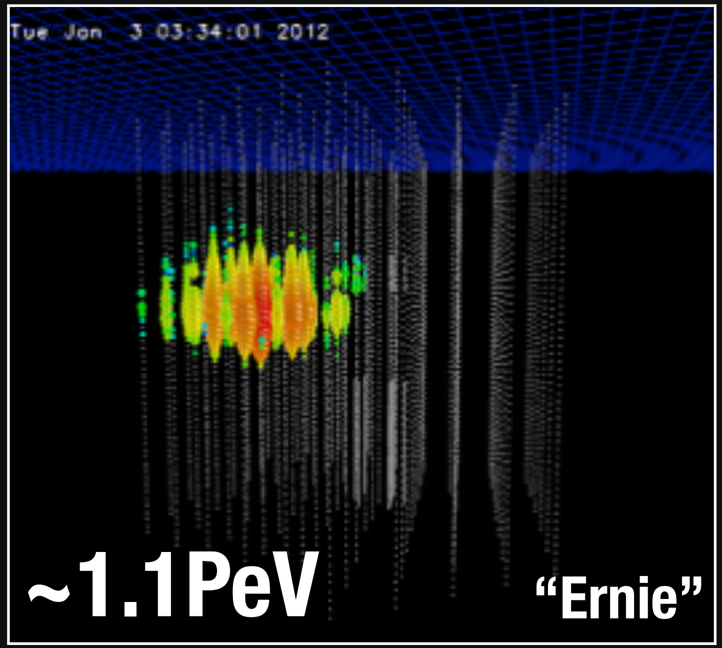
- Track-like events from Cosmic Ray muons and atmospheric ν_μ
- Soft spectrum ($E^{-3.7}$ - $E^{-2.7}$)
- Muons in the Southern Sky, neutrinos from the North

Results

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

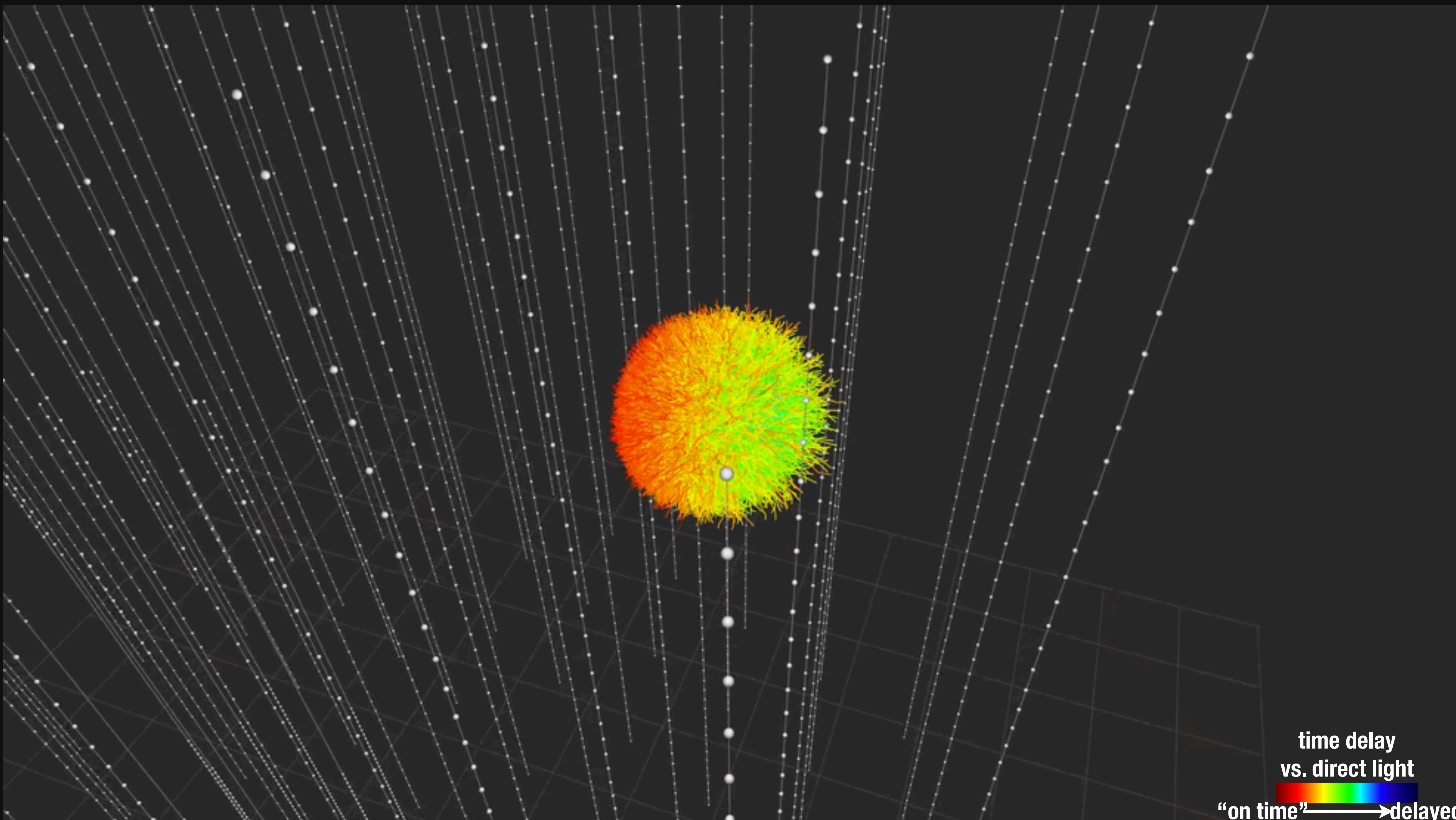
- **Two very interesting events in IceCube (between May 2010 and May 2012)**
  - shown at Neutrino '12
  - 2.8σ excess over expected background in GZK analysis
  - (PRL 111, 021103 (2013))
- **There should be more**
  - GZK analysis is only sensitive to very specific event topologies at these energies





Directional Resolution for Showers

Shower directions reconstructed from timing profile



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
    - (in tension with unbroken E^{-2})

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!

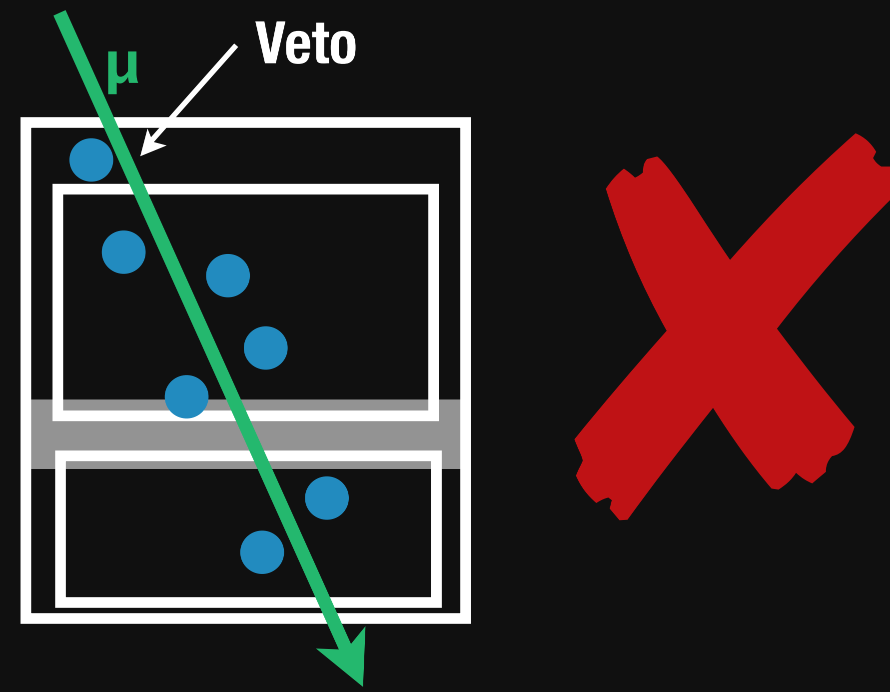
High-Energy Contained Vertex Search

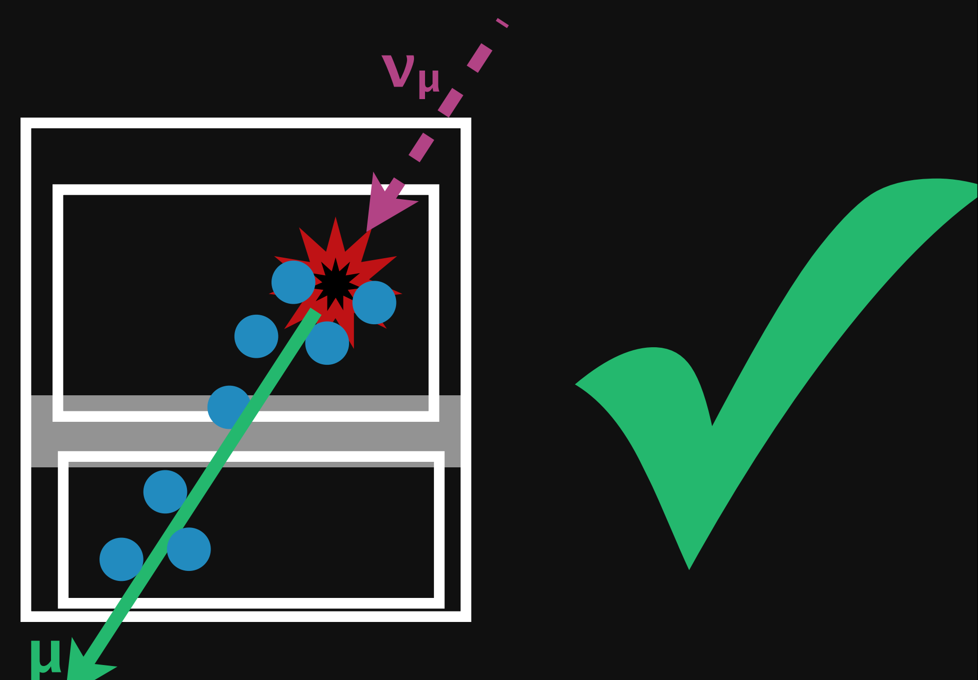
How we found more...

Follow-up Analysis

Specifically designed to find these contained events.

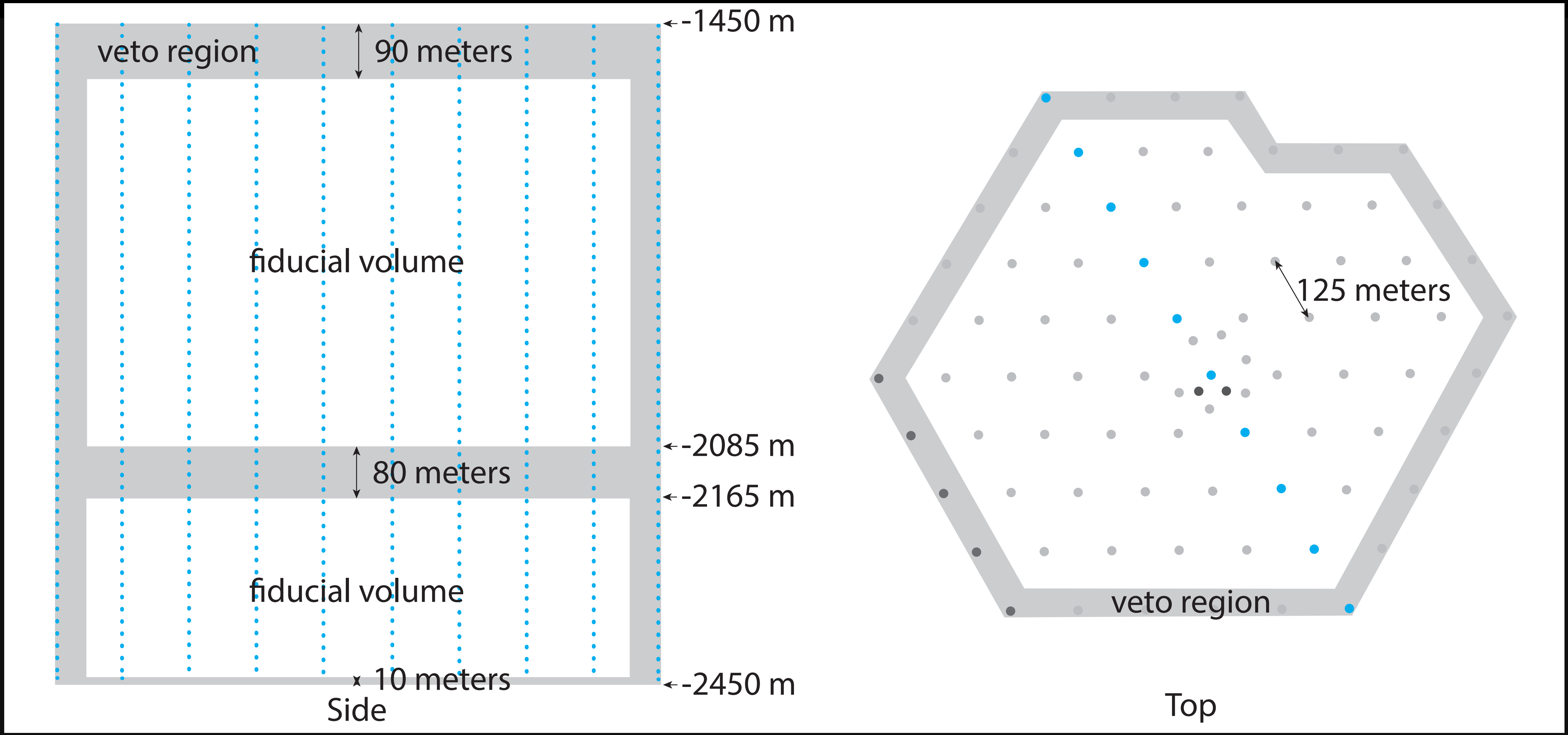
- Explicit contained search at high energies (cut: Q_{tot}>6000 p.e.)
- 400 Mton effective fiducial mass
- Use atmospheric muon veto
- Sensitive to all flavors in region above 60TeV deposited energy
- Three times as sensitive at 1 PeV
- Estimate background from data





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)**

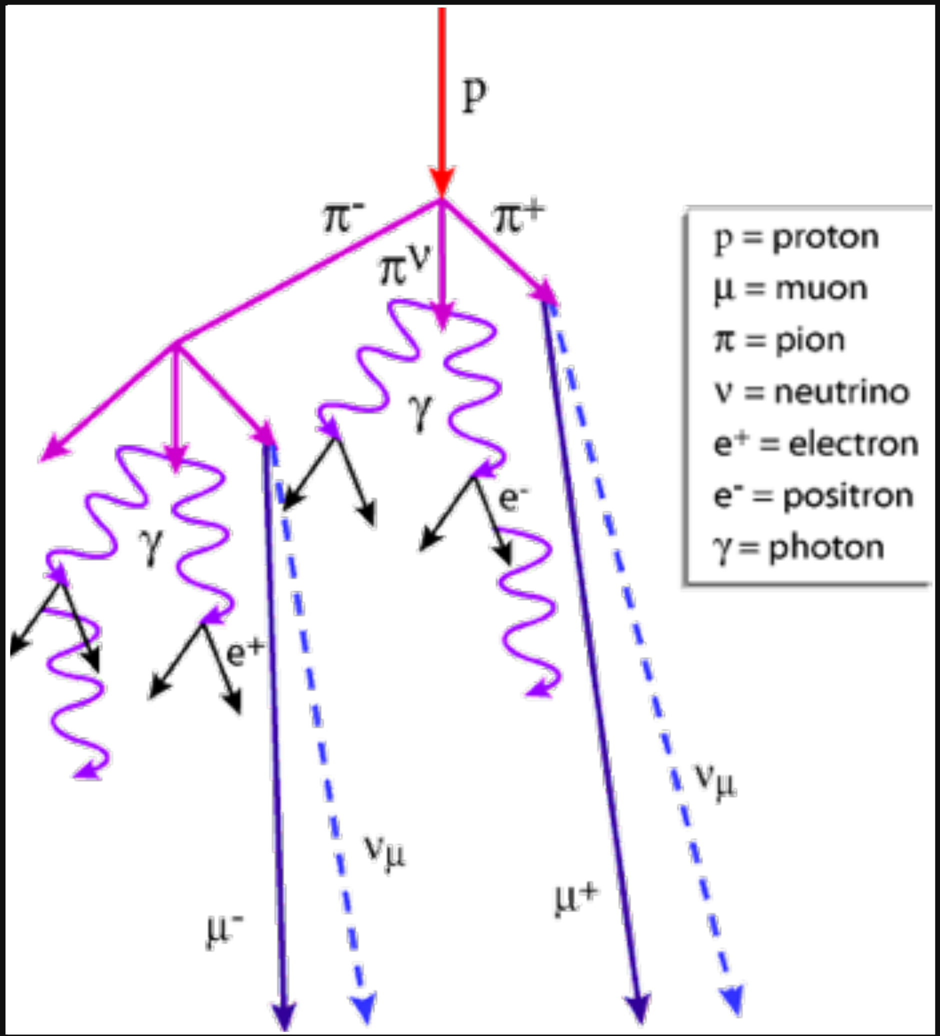
Background 2 - Atmospheric Neutrinos

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 (prompt neutrinos): 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**
- **High-energy downgoing events that start in the detector are extremely unlikely to be atmospheric**

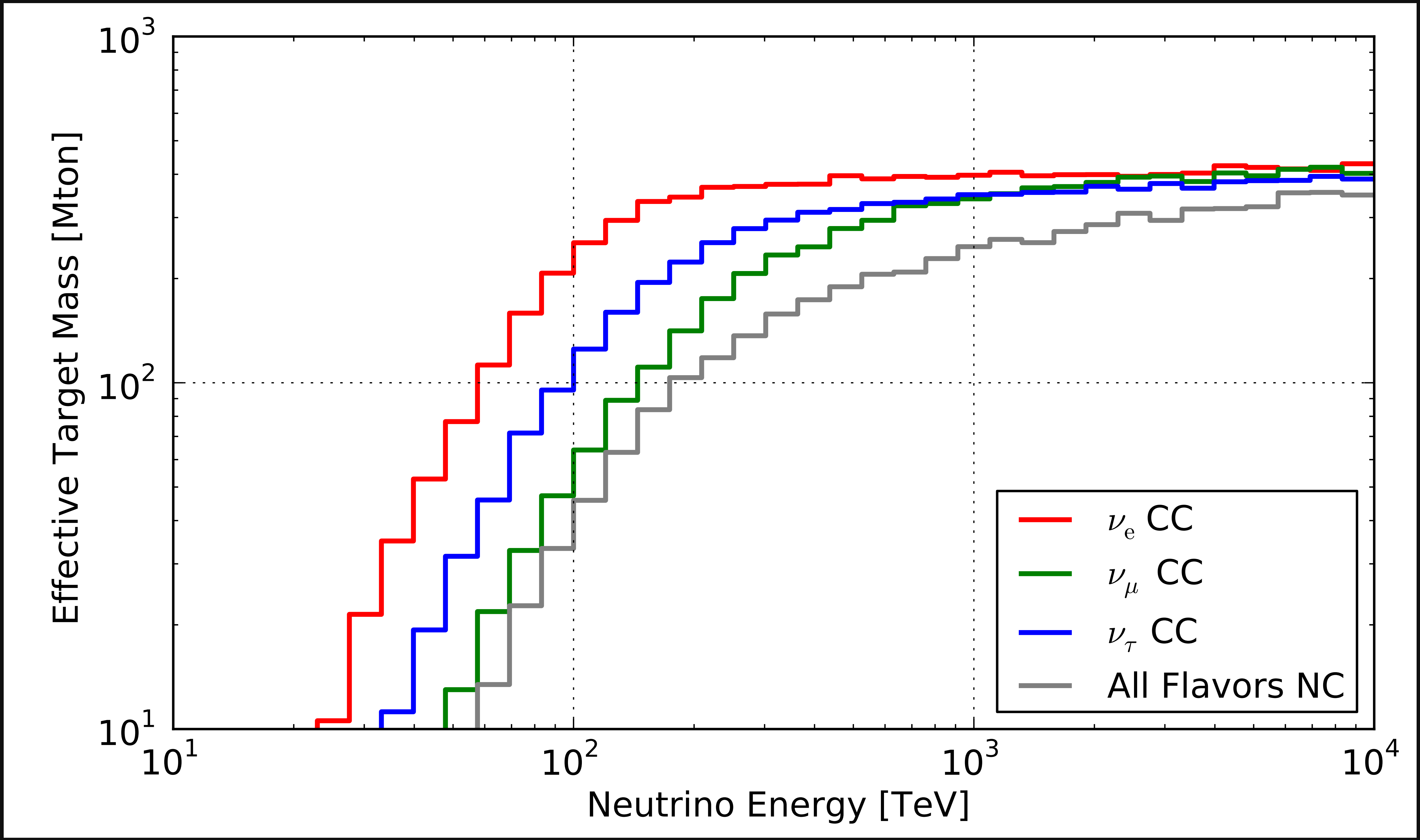


Schönert et al., arXiv:0812.4308

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

Effective Volume / Target Mass

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



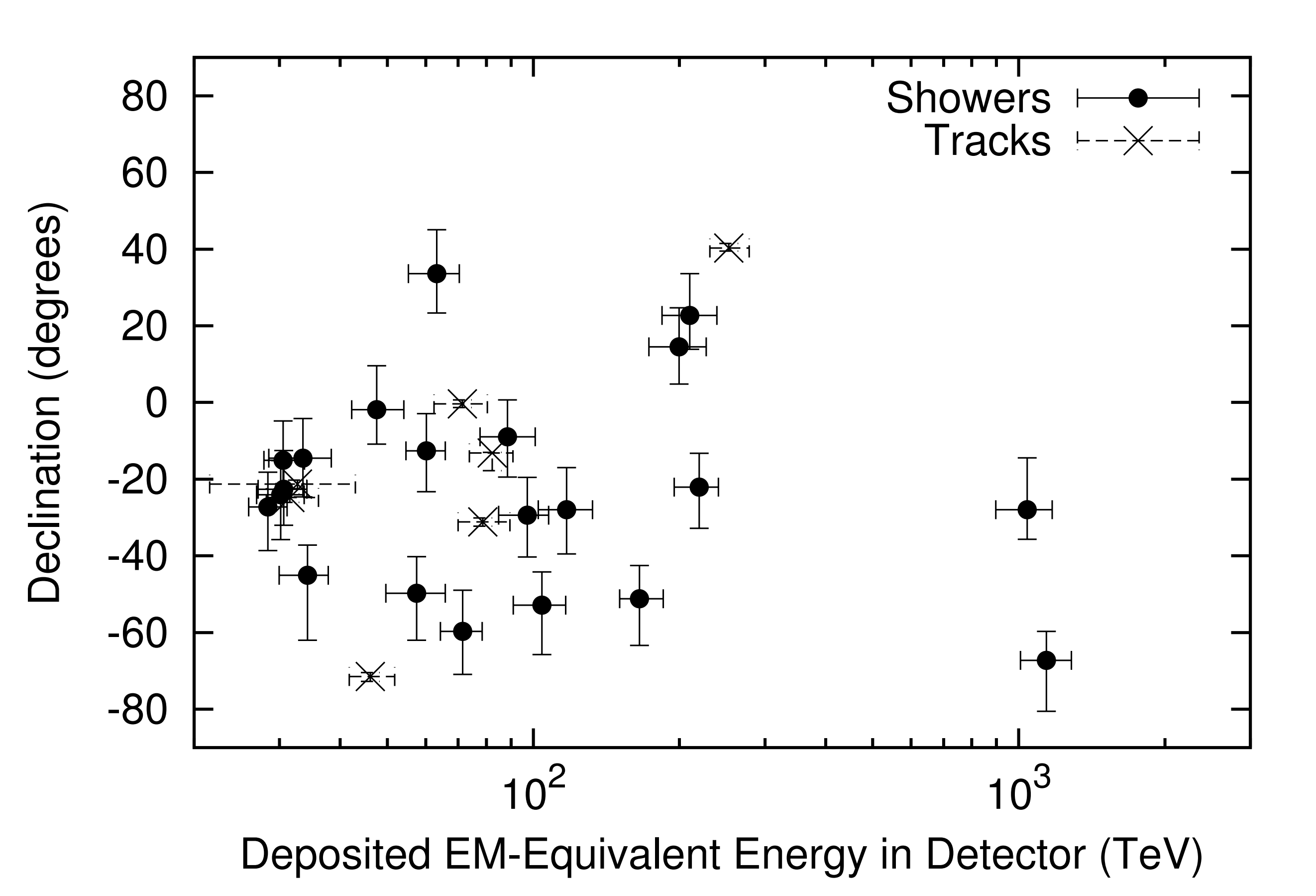
What Did We Find?

26 more events!

What Did We Find?

28 events in **2 years** of IceCube data
(662 days between 2010–2012)

- **28 events observed!**
  - 26 new events in addition to the two 1 PeV events!
- **Estimated background:**
  - $4.6^{+3.7}_{-1.2}$ atm. neutrinos
  - 6.0 ± 3.4 atm. muons



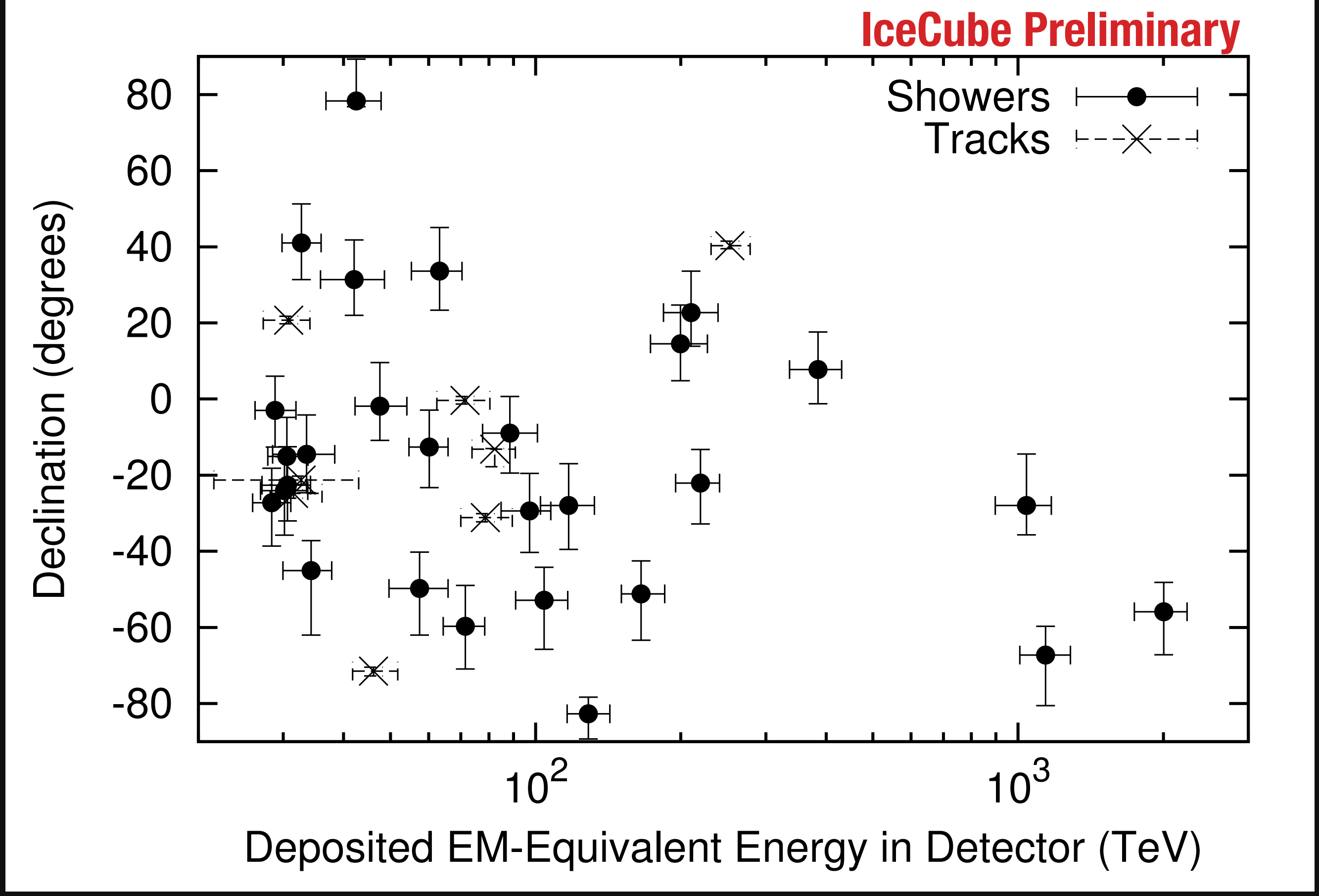
significance w.r.t. reference bkg. model:
3.3σ for 26 events
combining with 2.8σ from GZK result:
4.1σ for 26+2 events
full likelihood fit of all components:
4.1σ for 28 events

What Did We Find?

37 events in **3 years** of IceCube data
(988 days between 2010–2013)

Preliminary

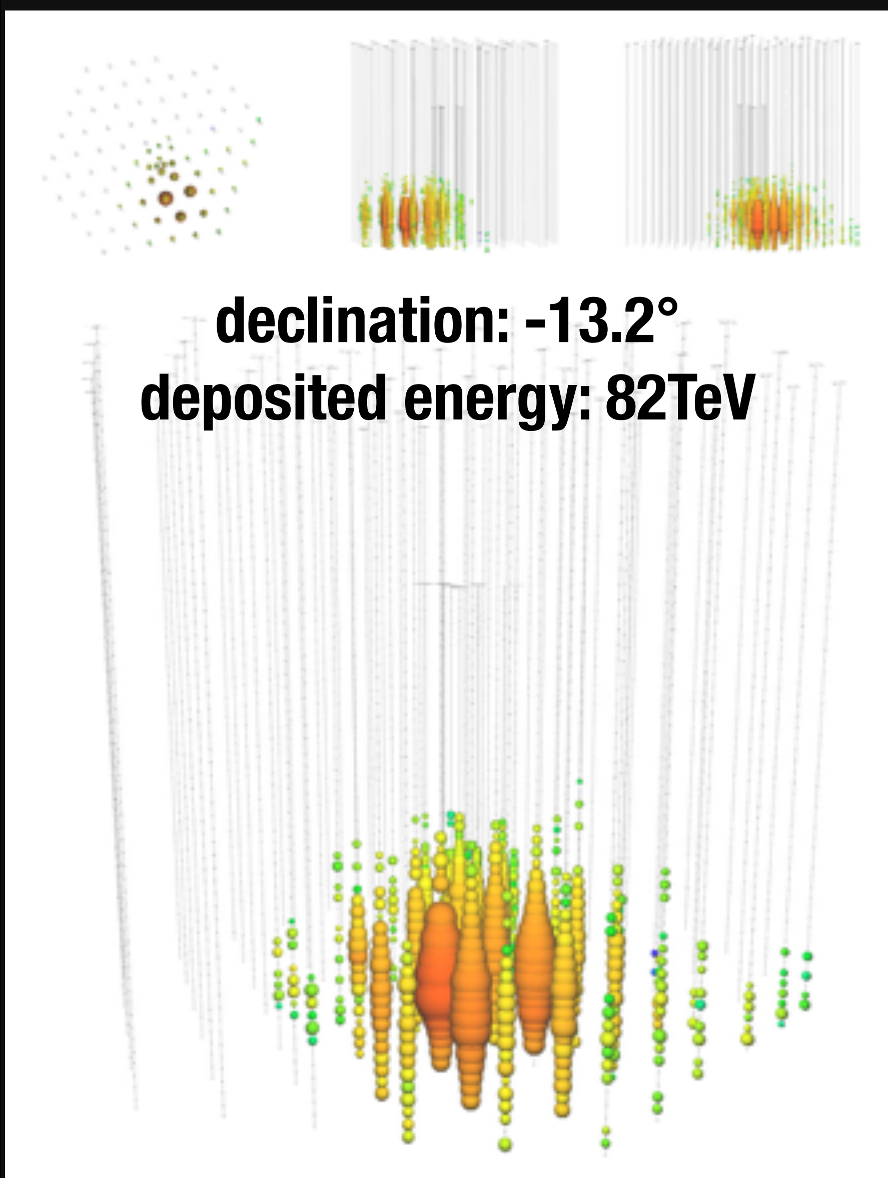
- **37 events observed!**
  - 35 new events in addition to the two 1 PeV events!
- **Estimated background:**
  - $6.6^{+5.9}_{-1.6}$ atm. neutrinos
  - 8.4 ± 4.2 atm. muons
- **One of them is an obvious (but expected) background**
  - coincident muons from two CR air showers

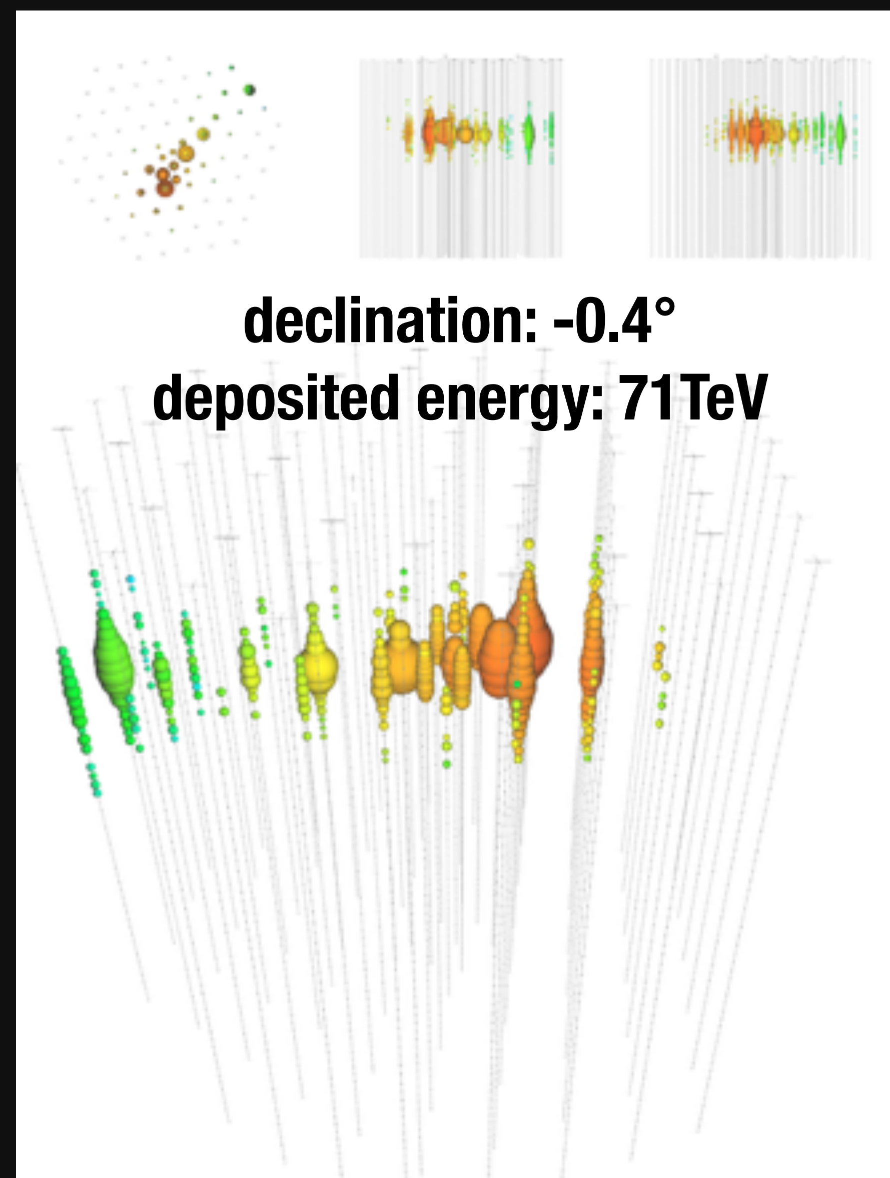


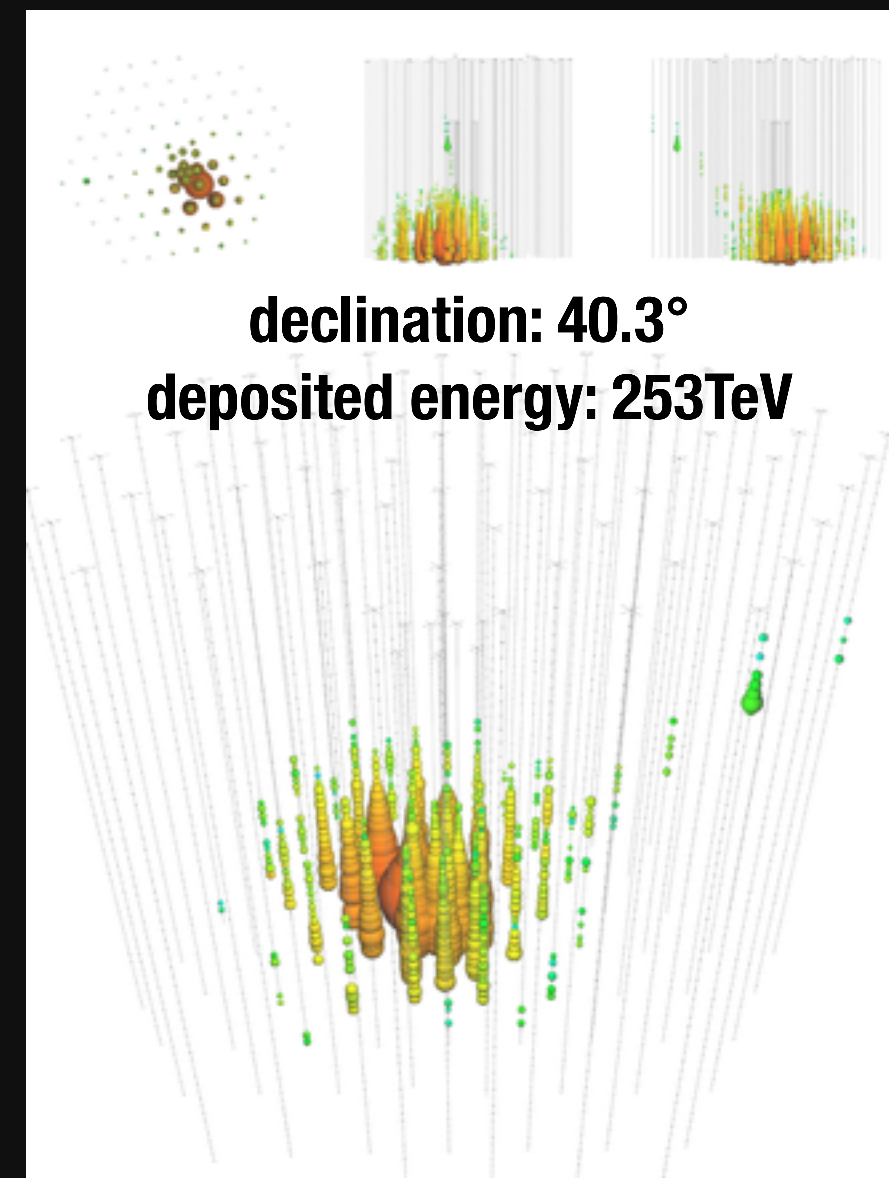
combining with 2.8σ from GZK result:
4.8σ for 35+2 events
full likelihood fit of all components:
5.7σ for 36(+1) events

What Did We Find?

Some examples

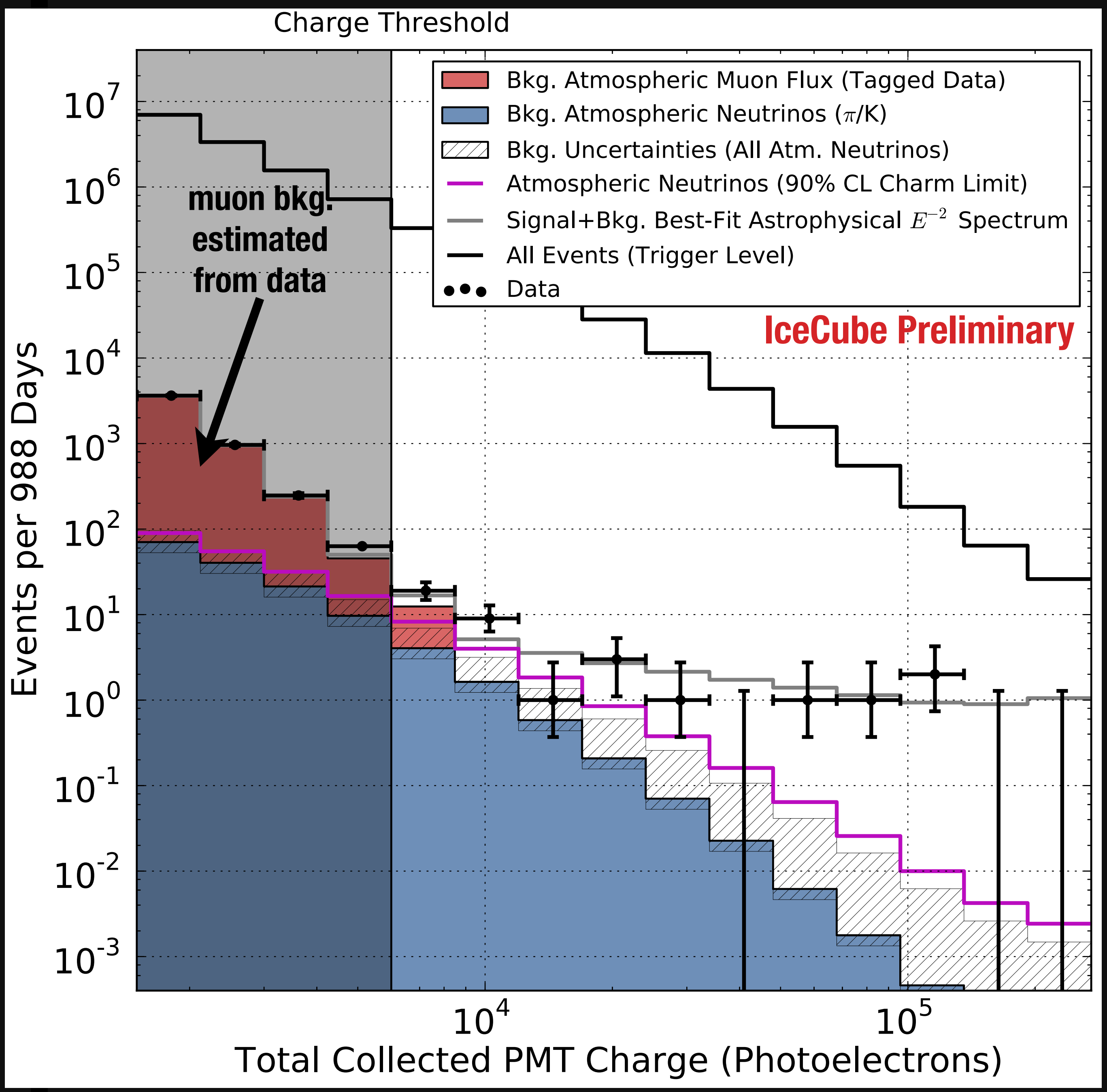






Charge Distribution

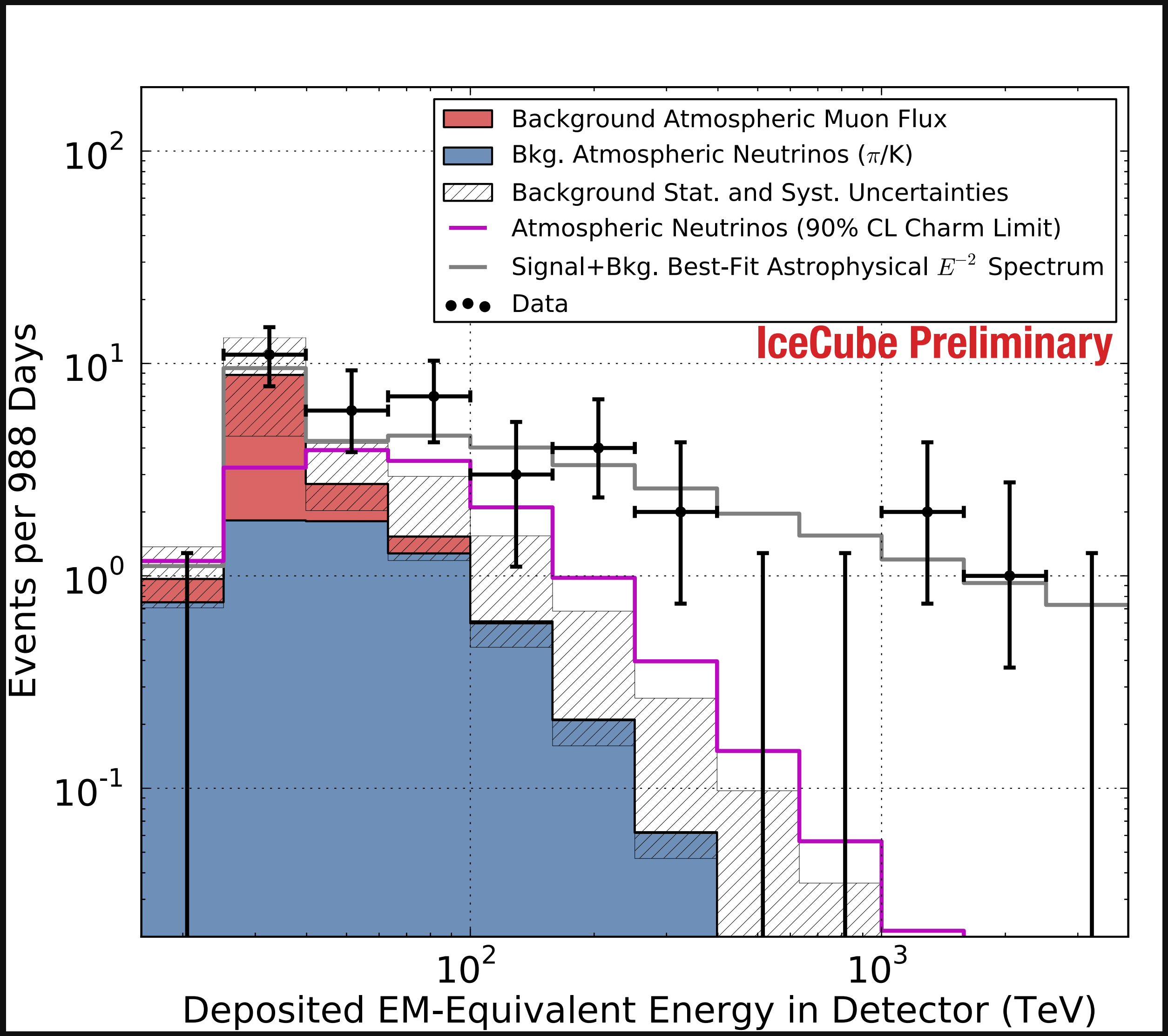
- Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold ($Q_{tot}>6000$)
- Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)



Energy Spectrum

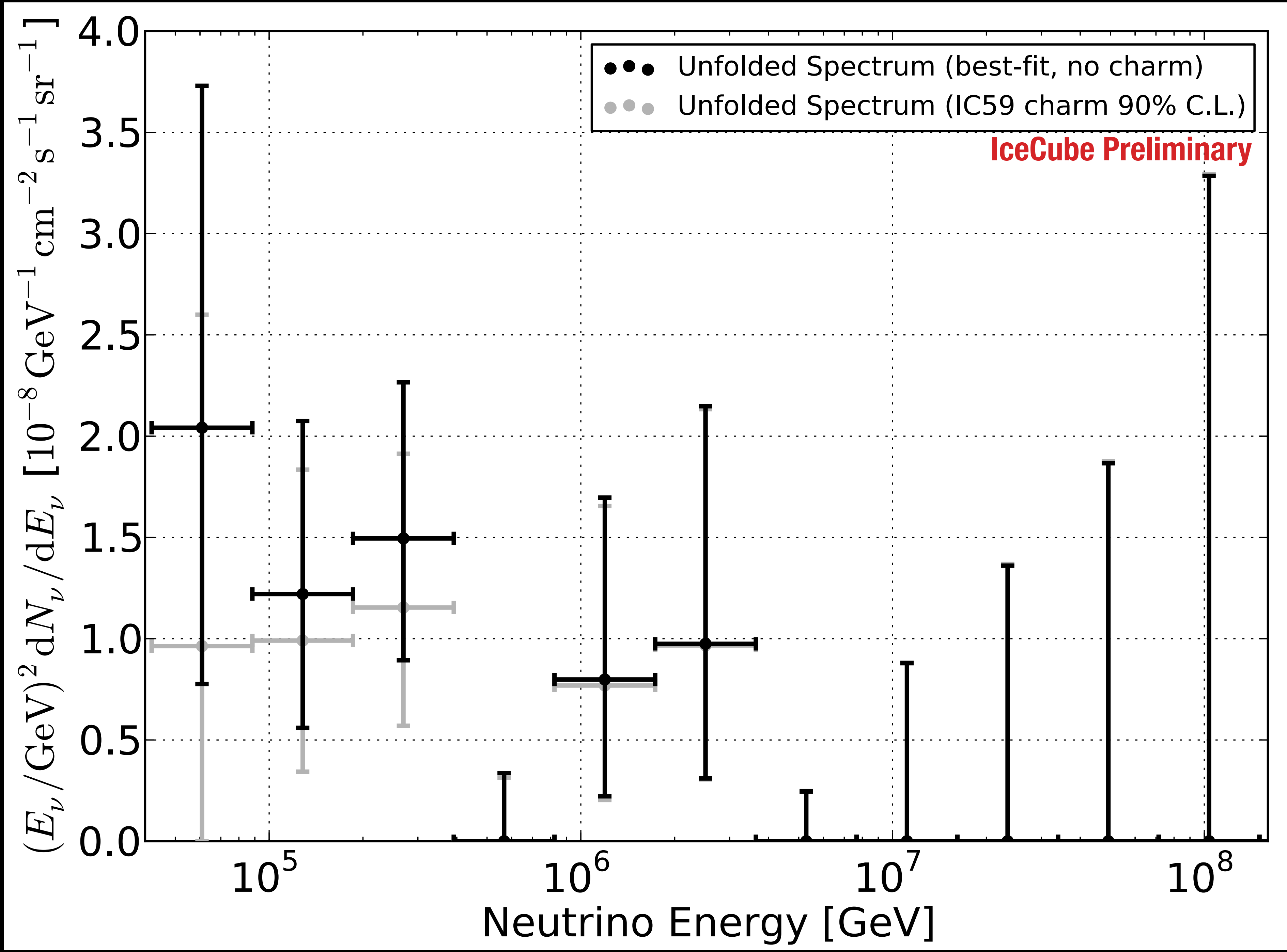
Compatible with benchmark E^{-2} astrophysical model

- Harder than any expected atmospheric background
- Merges well into background at low energies
- Potential cutoff at about 2-5 PeV (or softer spectrum)
- Best fit (per-flavor flux):
  - $0.95 \pm 0.3\ 10^{-8}\ E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$



Unfolding to Neutrino Energy

An attempt to plot the spectrum: unfolded to true neutrino energy, simultaneously fitting for backgrounds

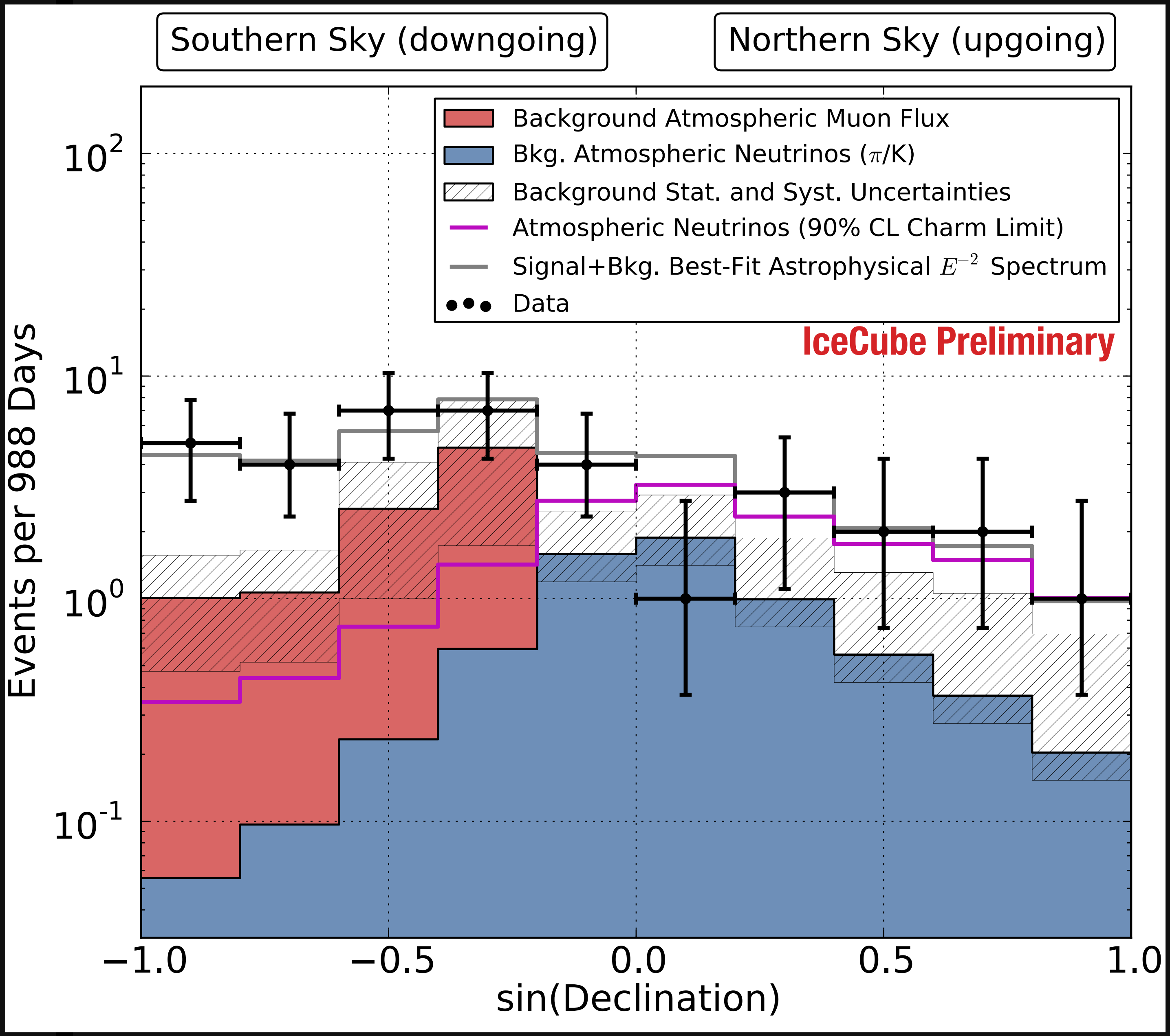


assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino

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



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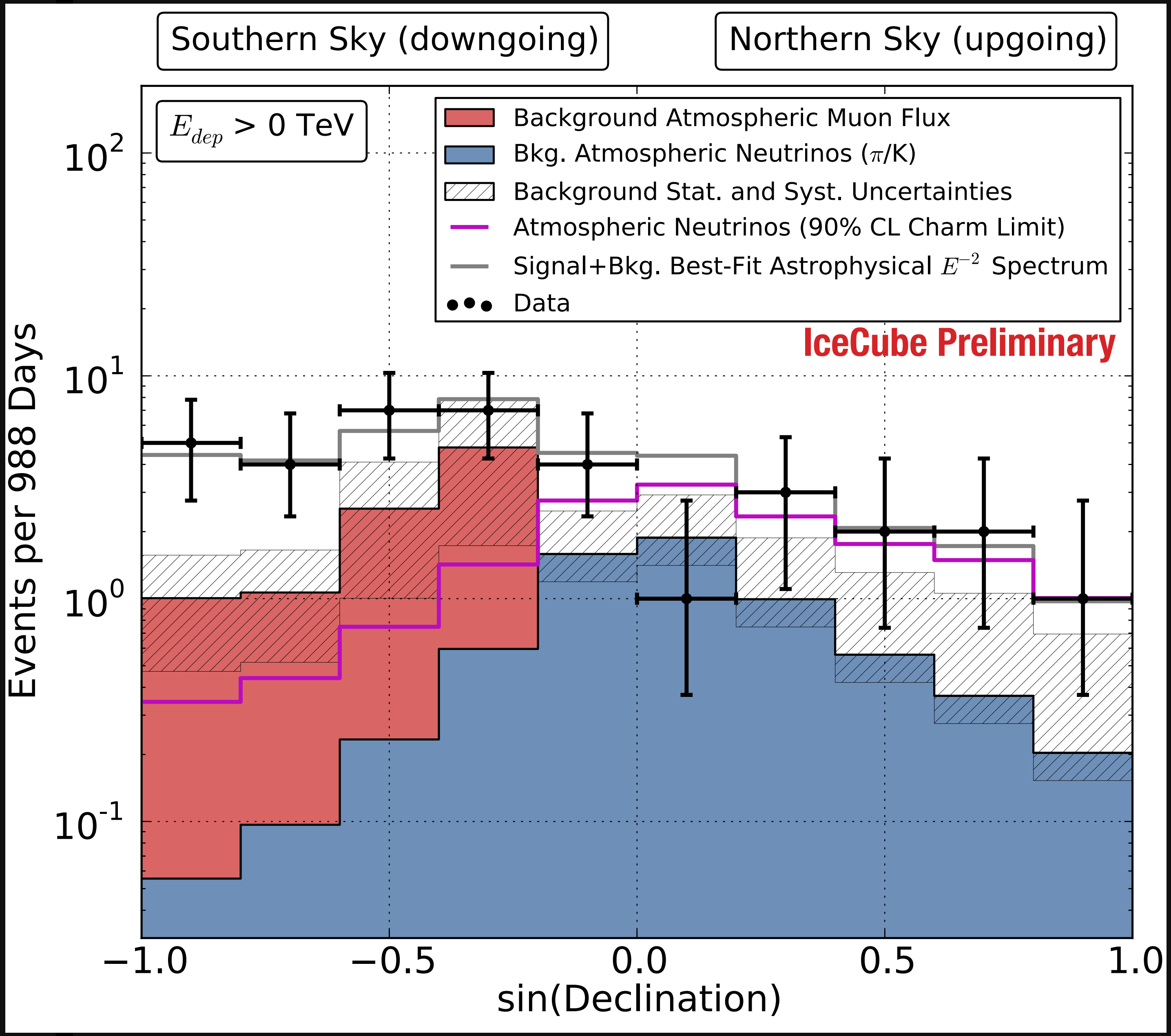

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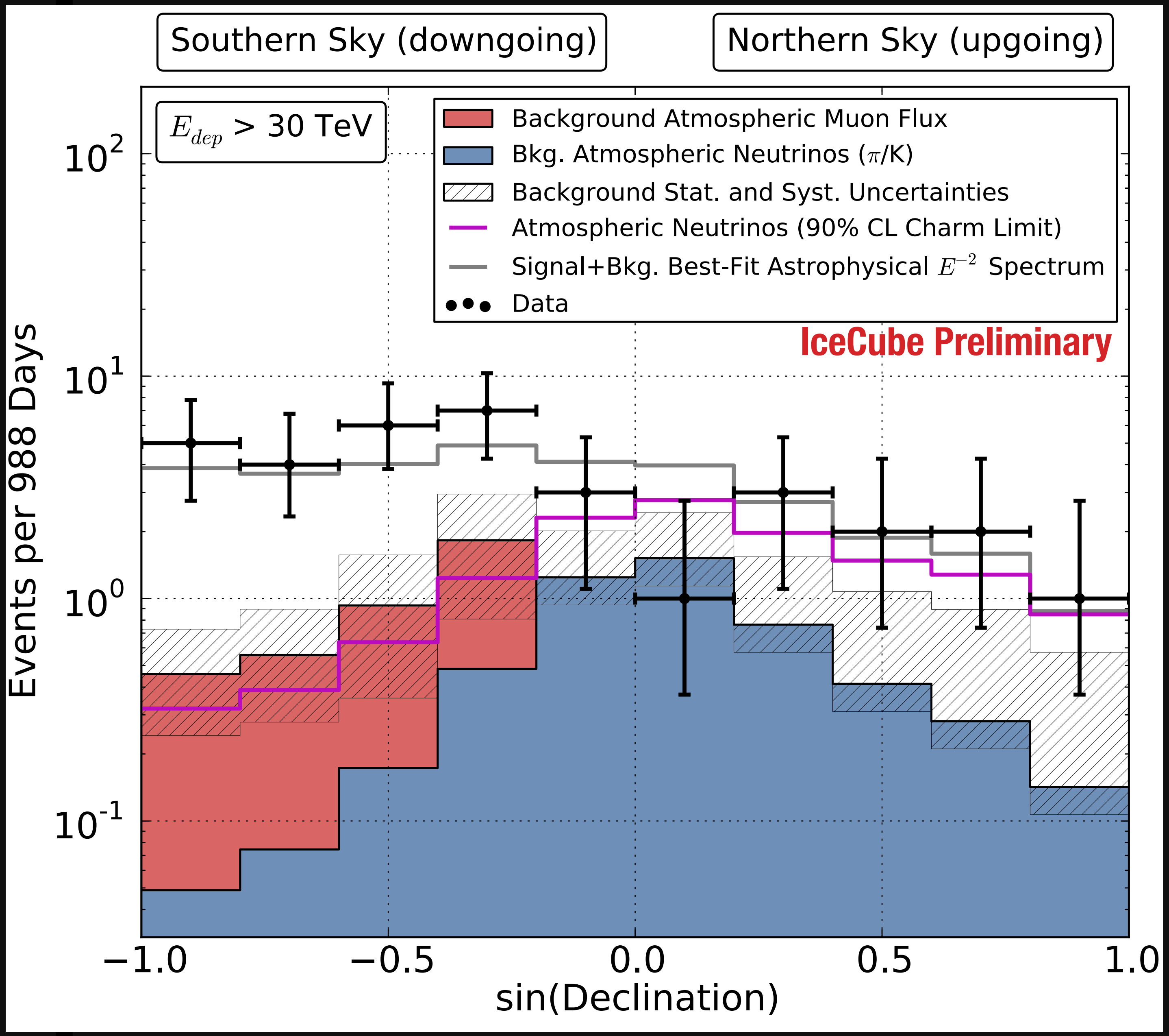

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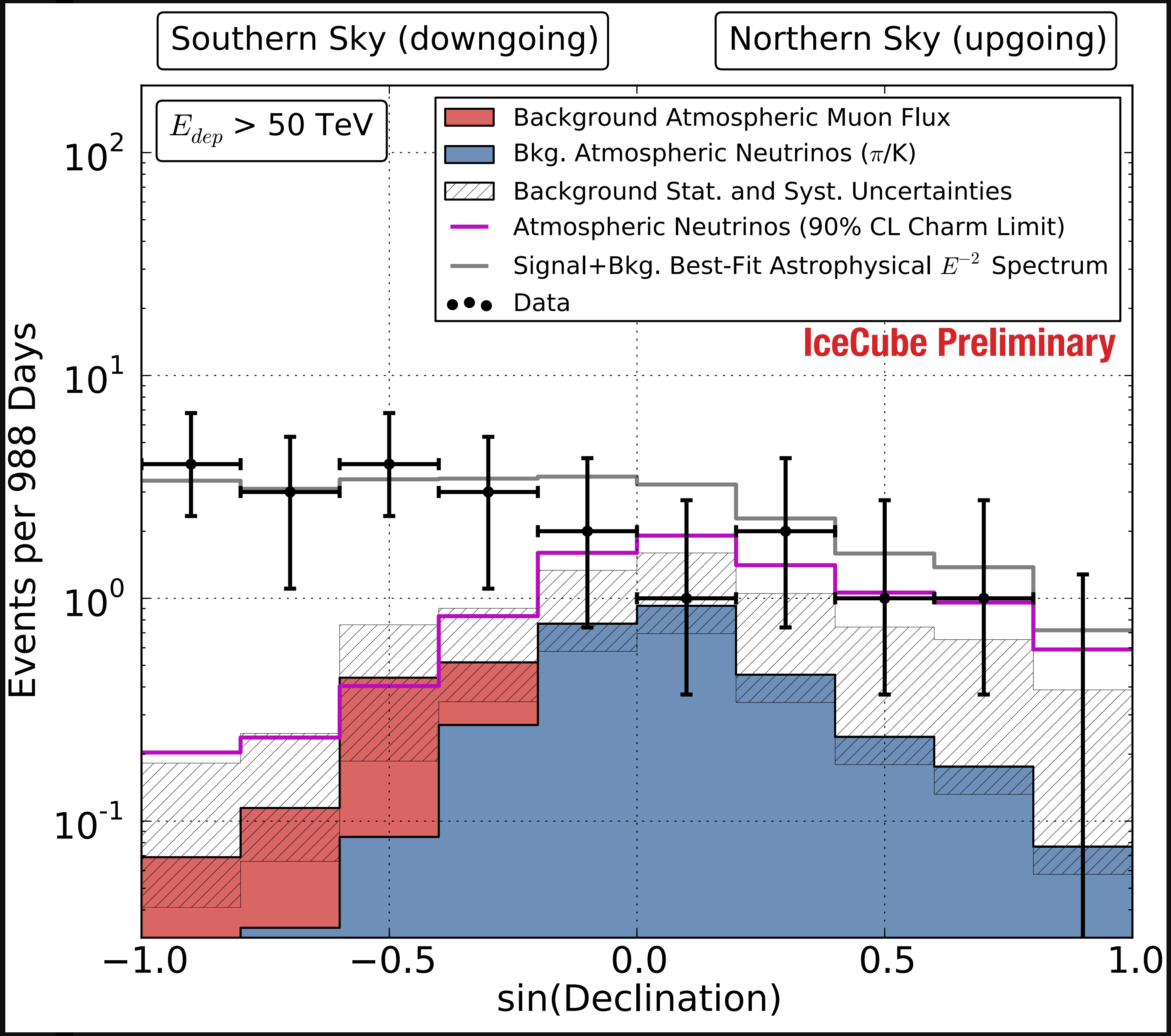

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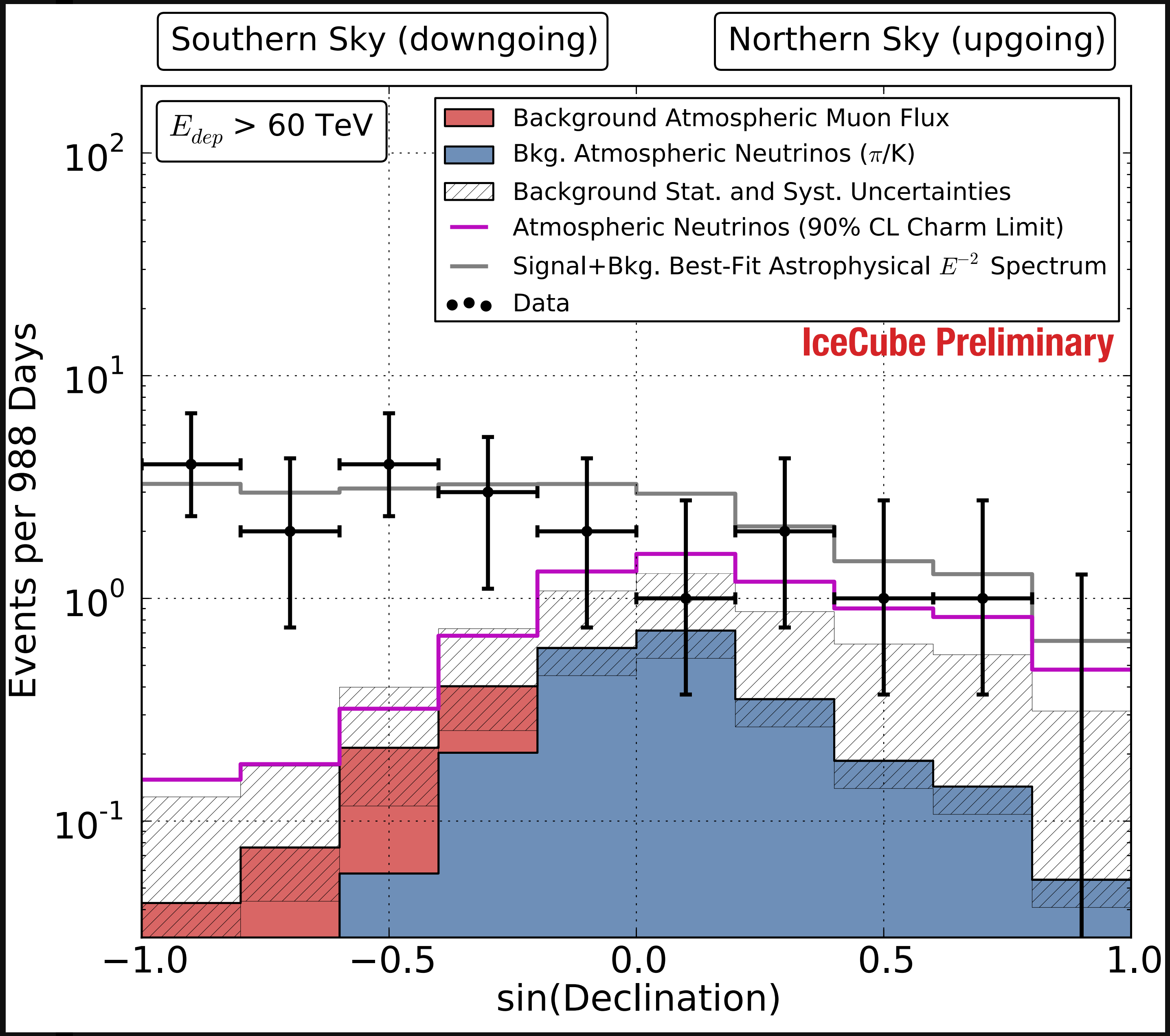

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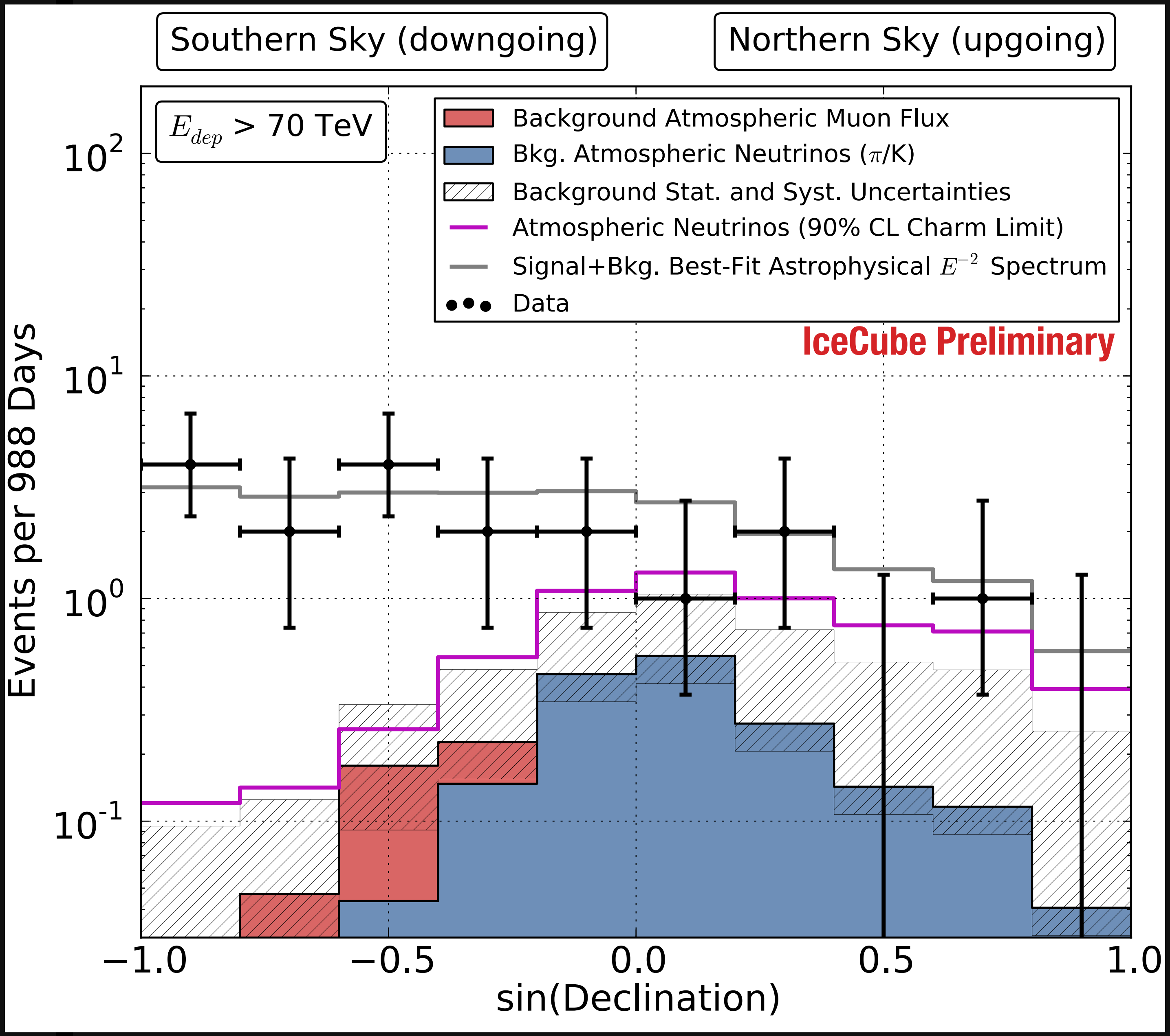

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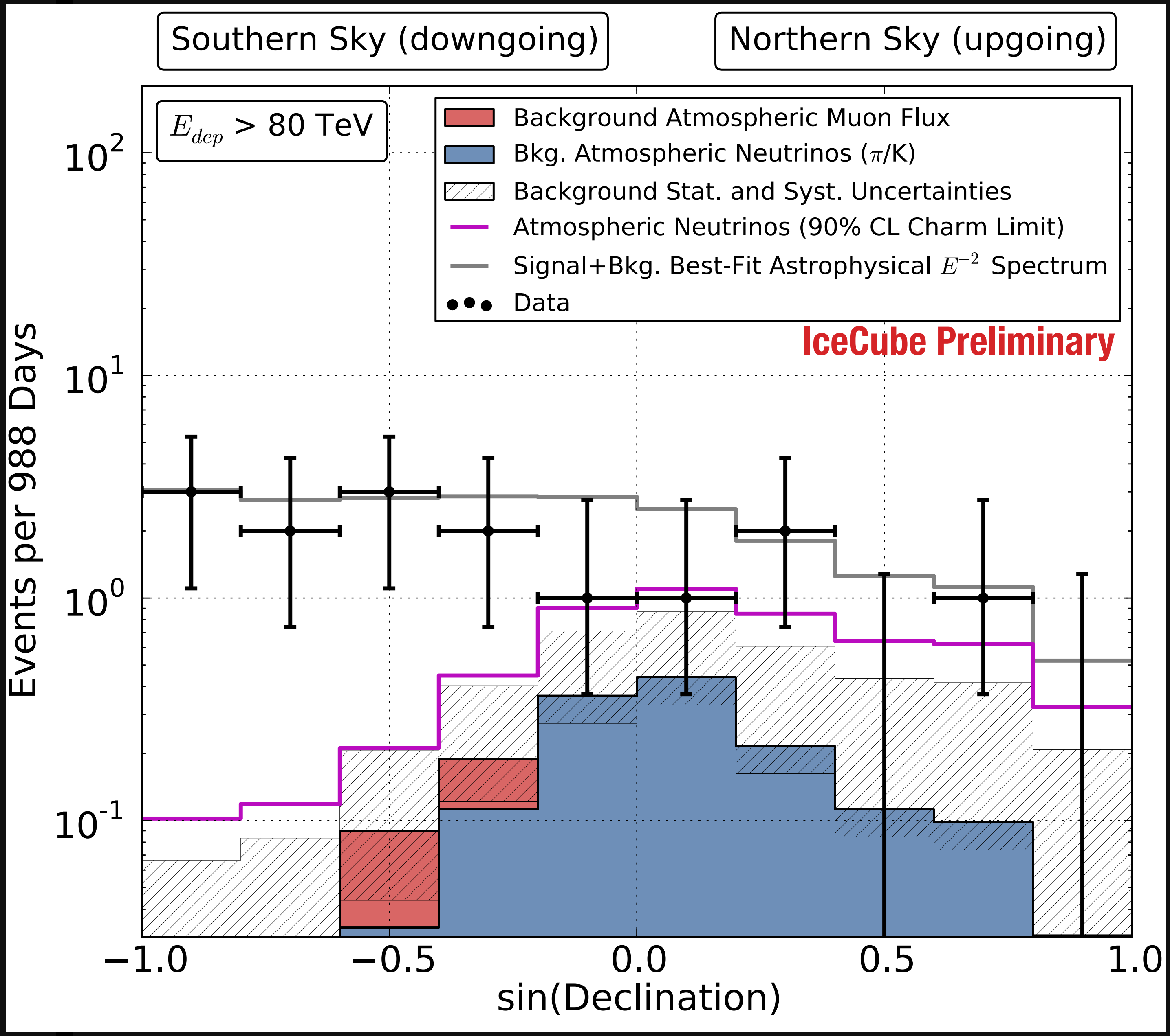

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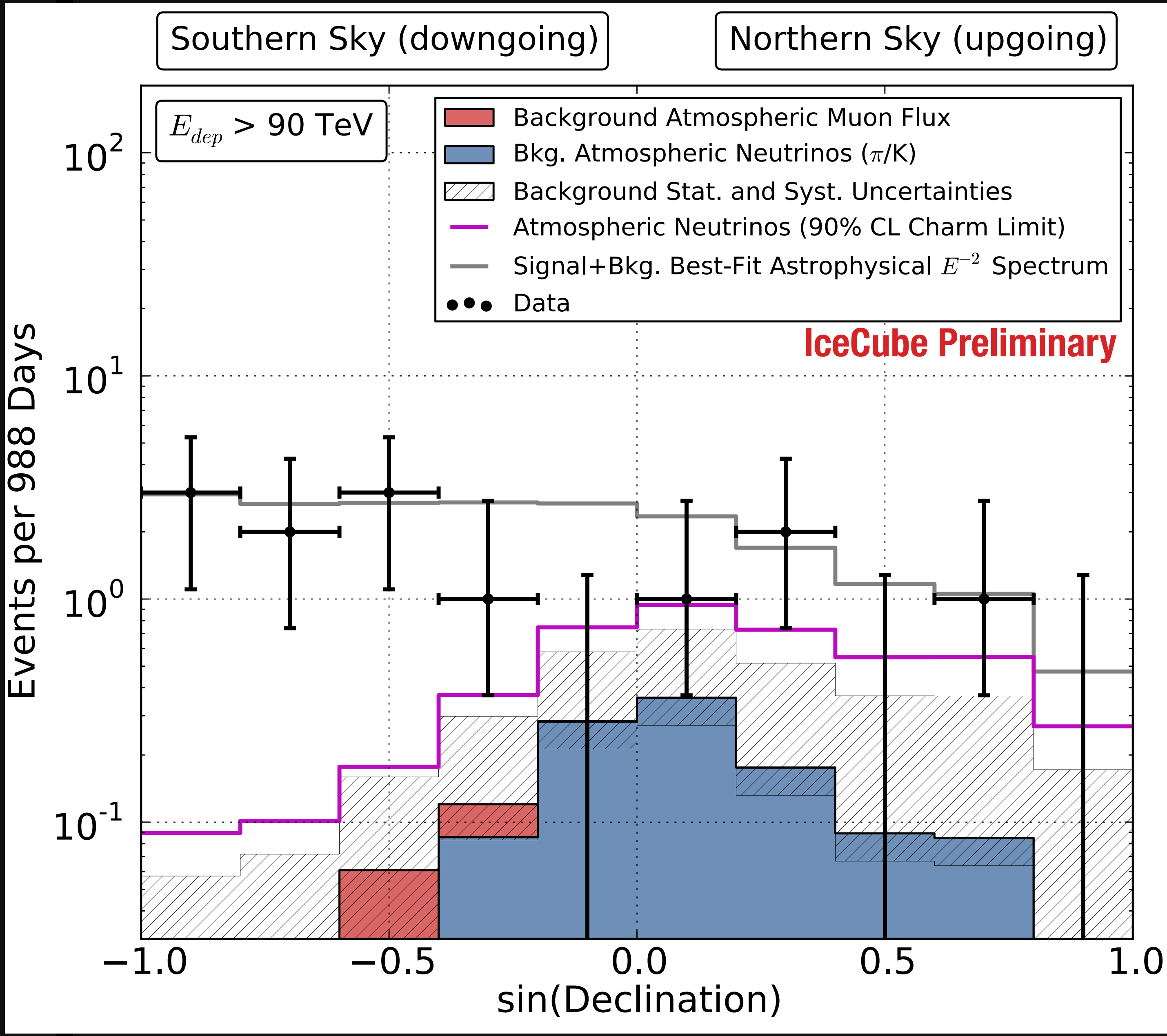

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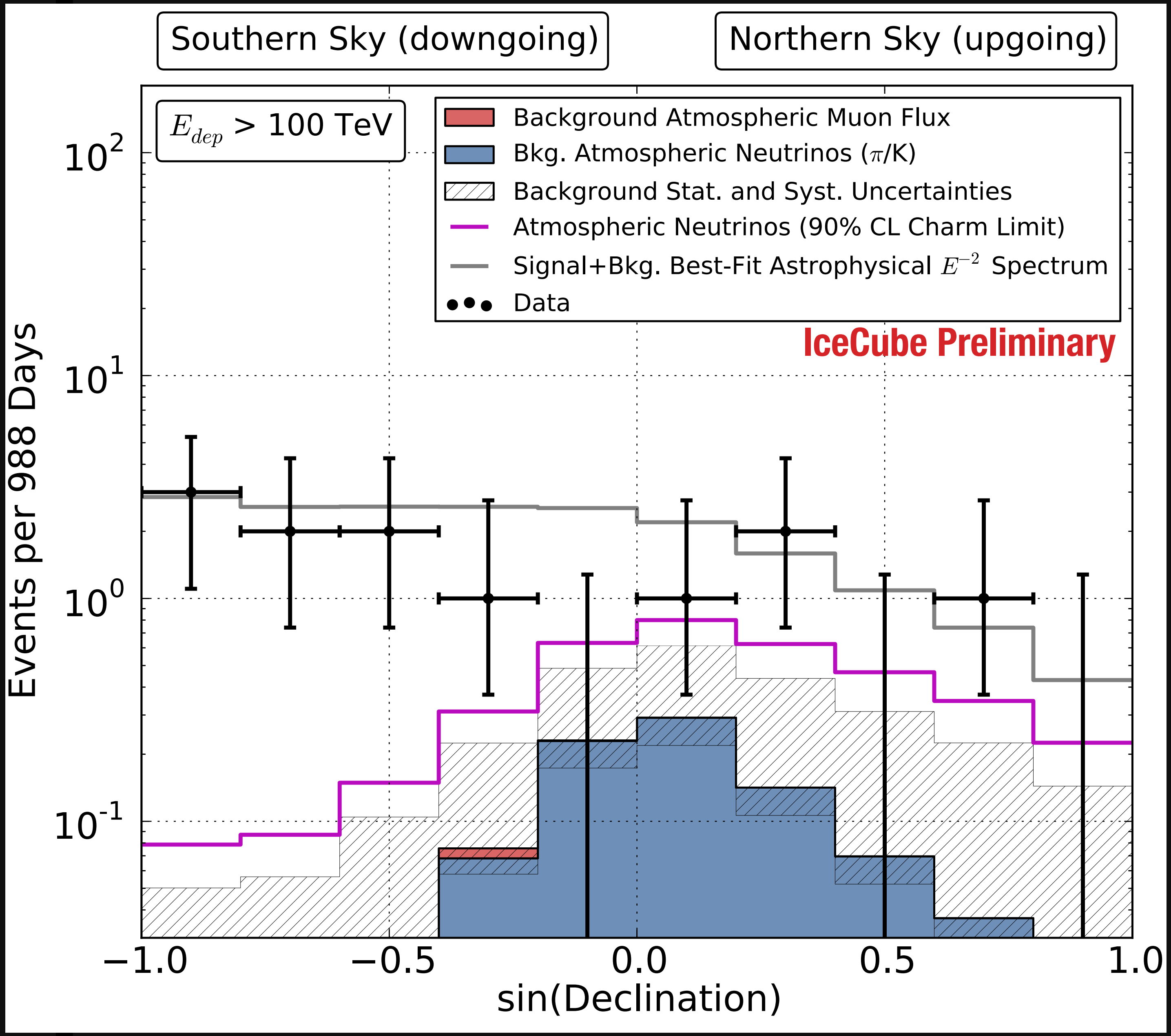

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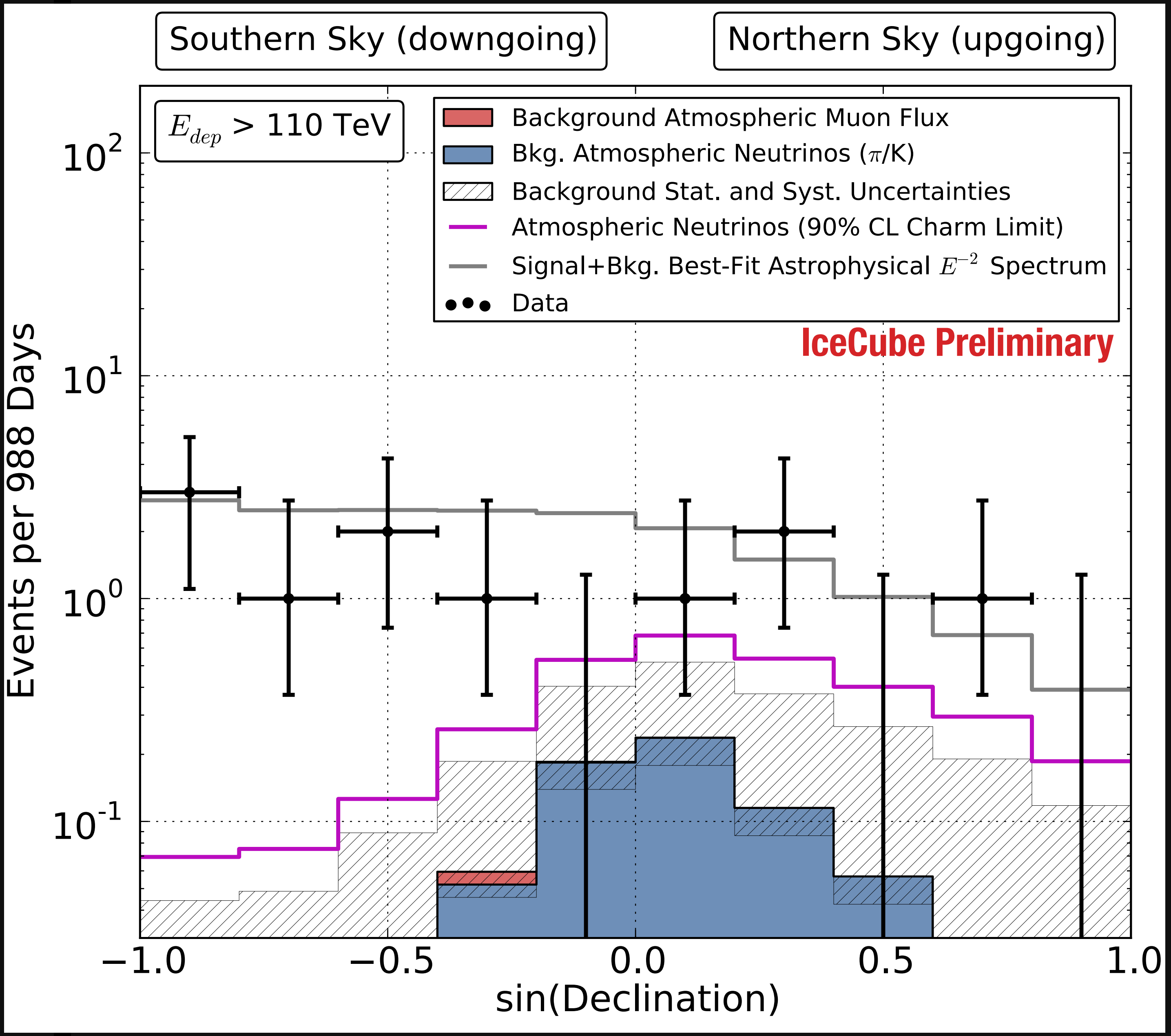

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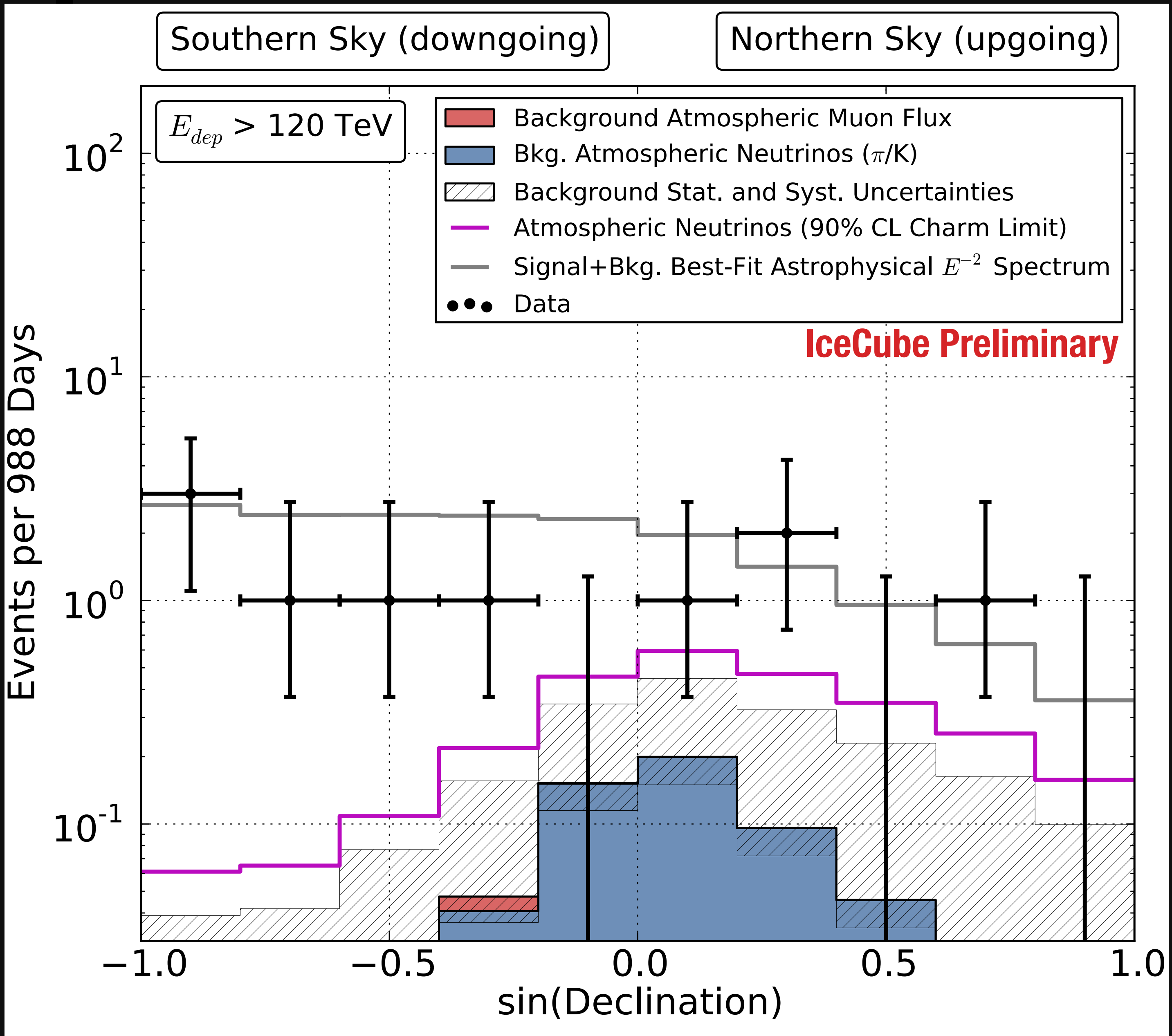

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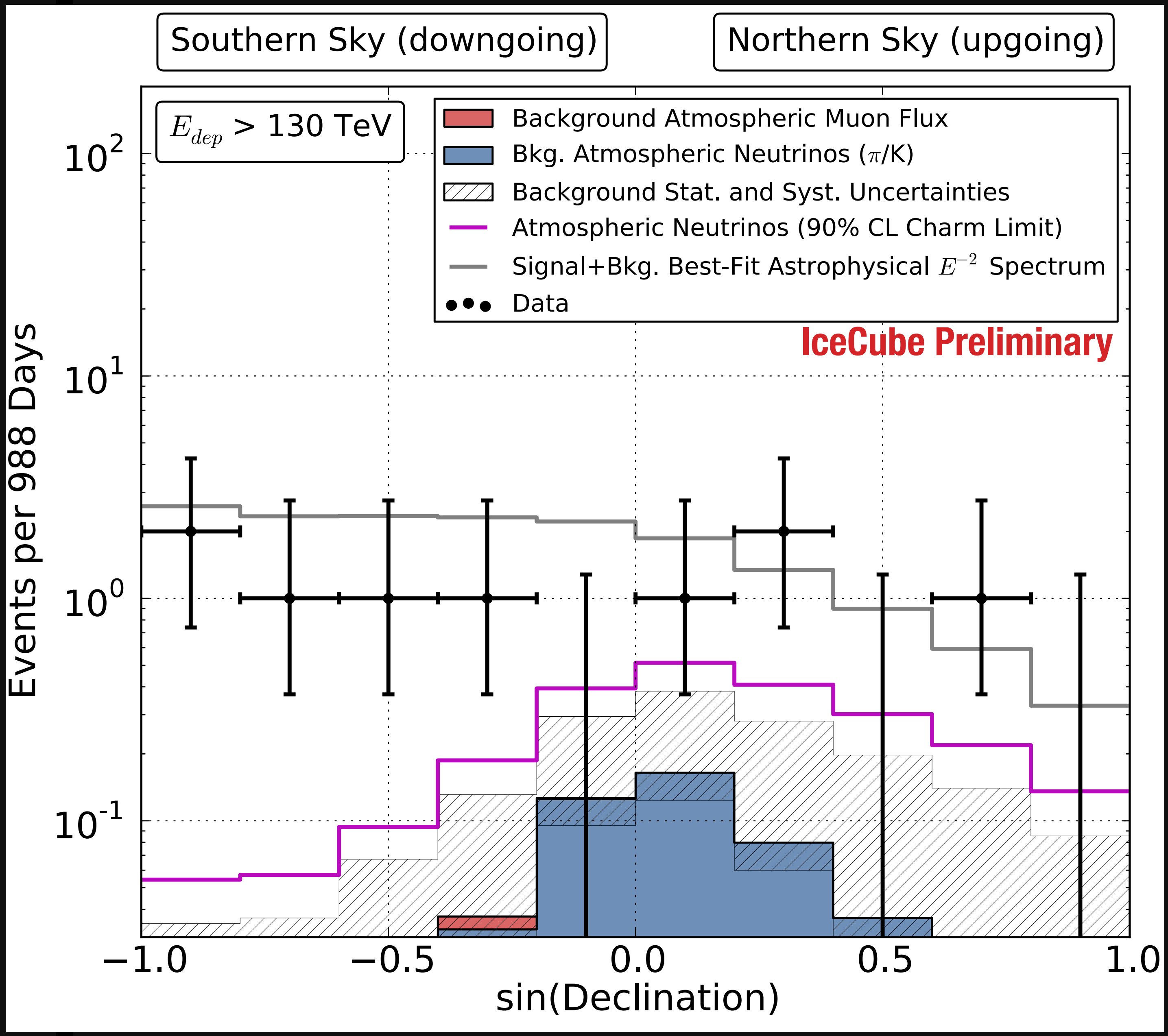

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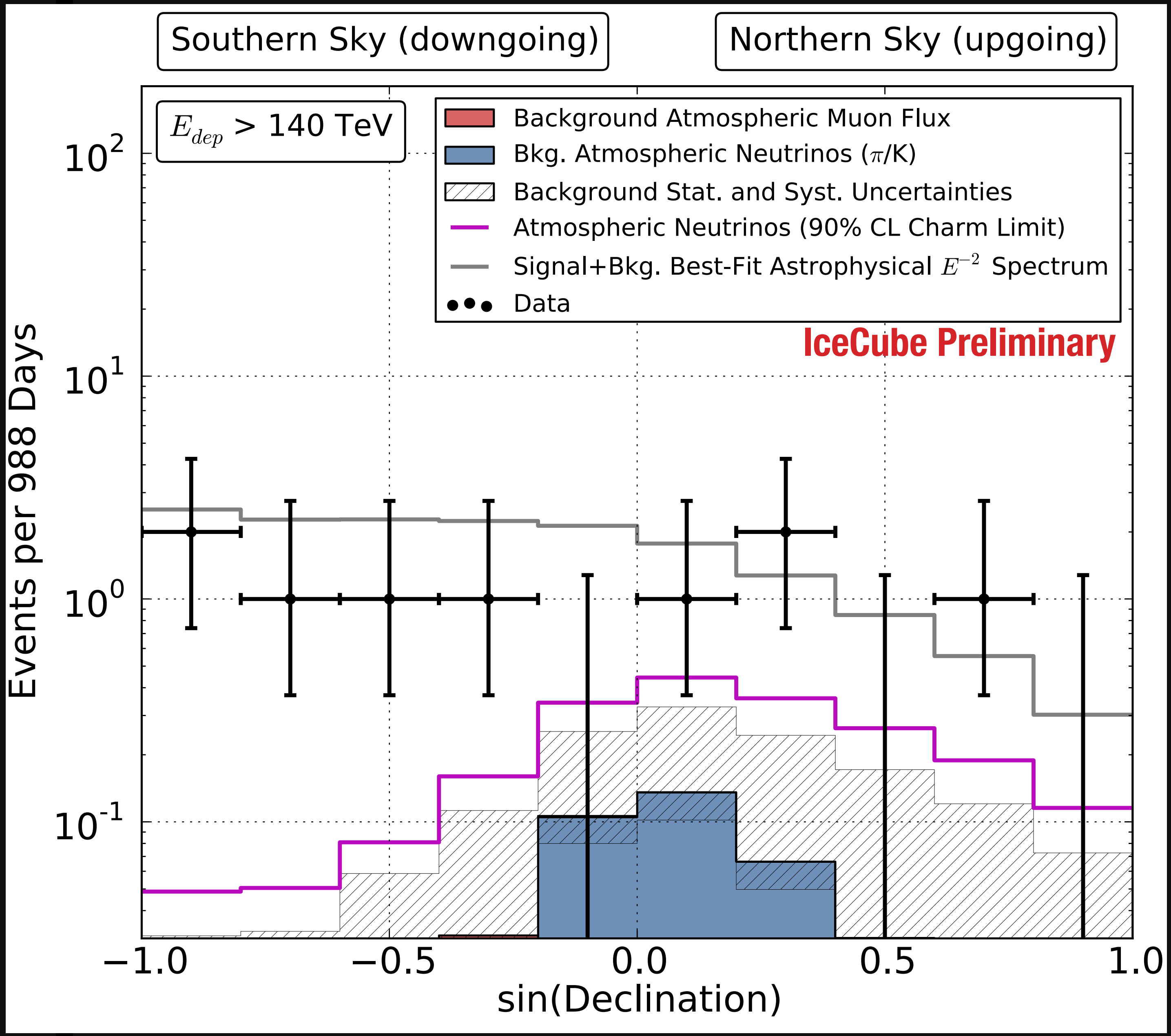

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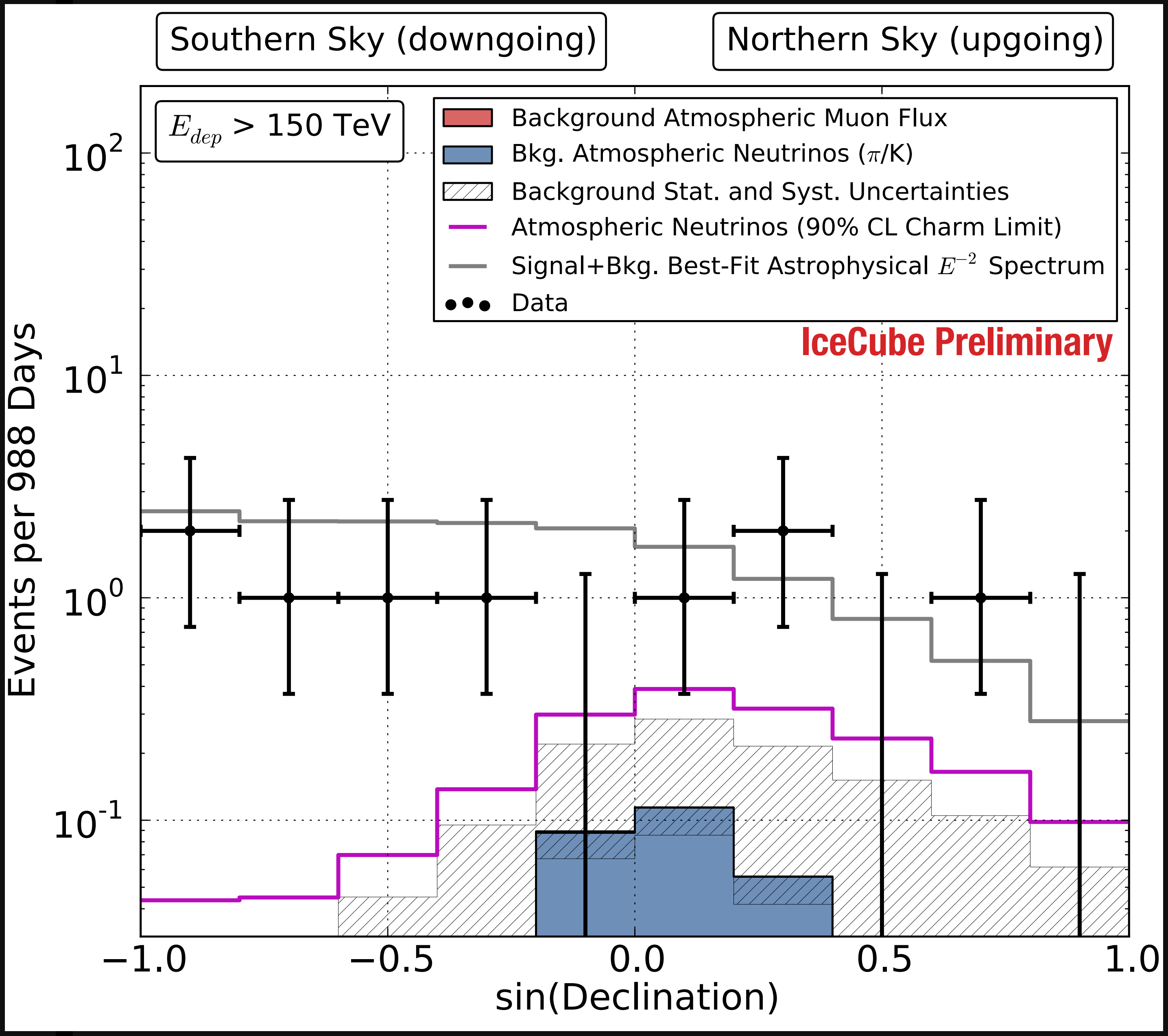

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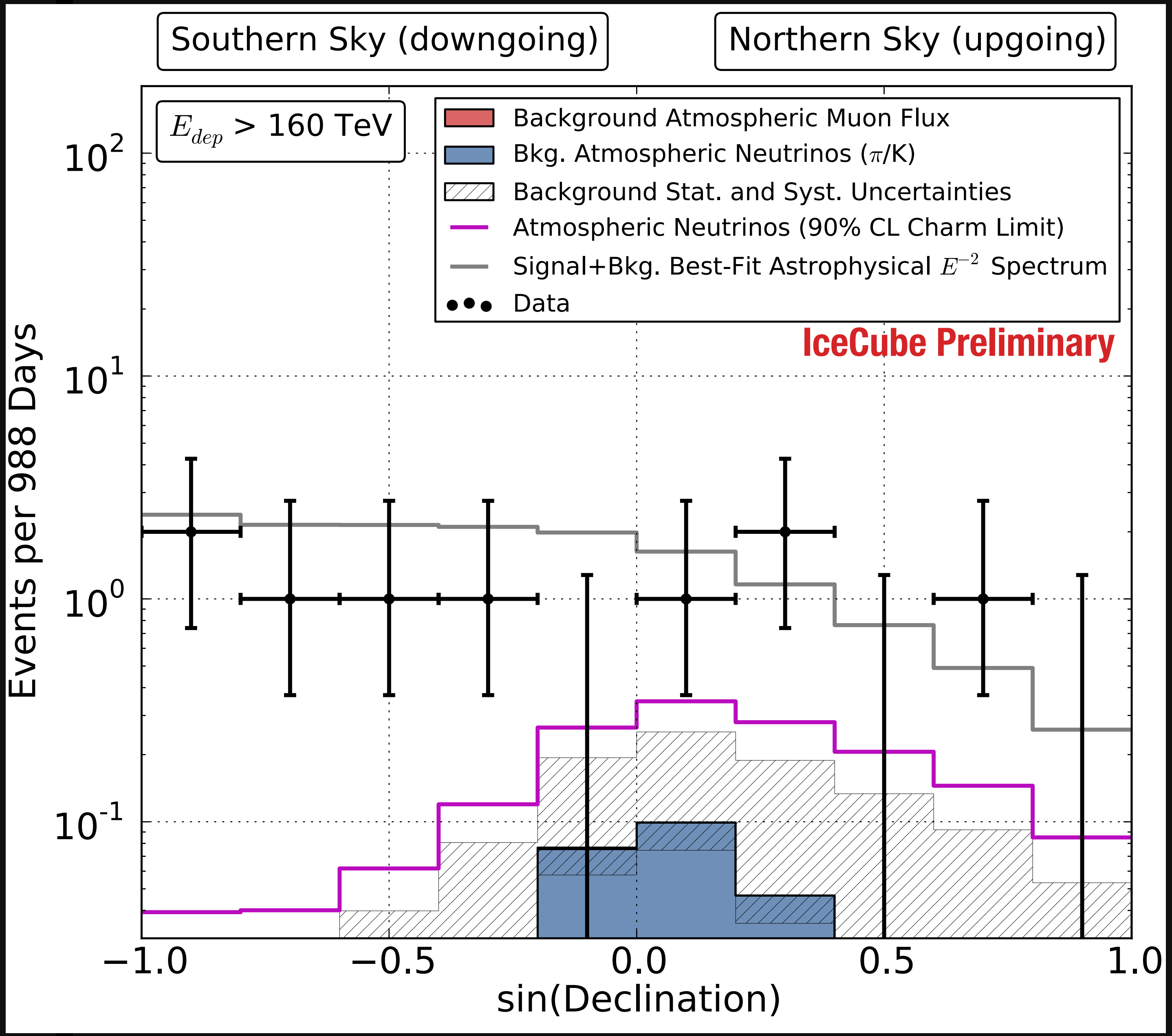

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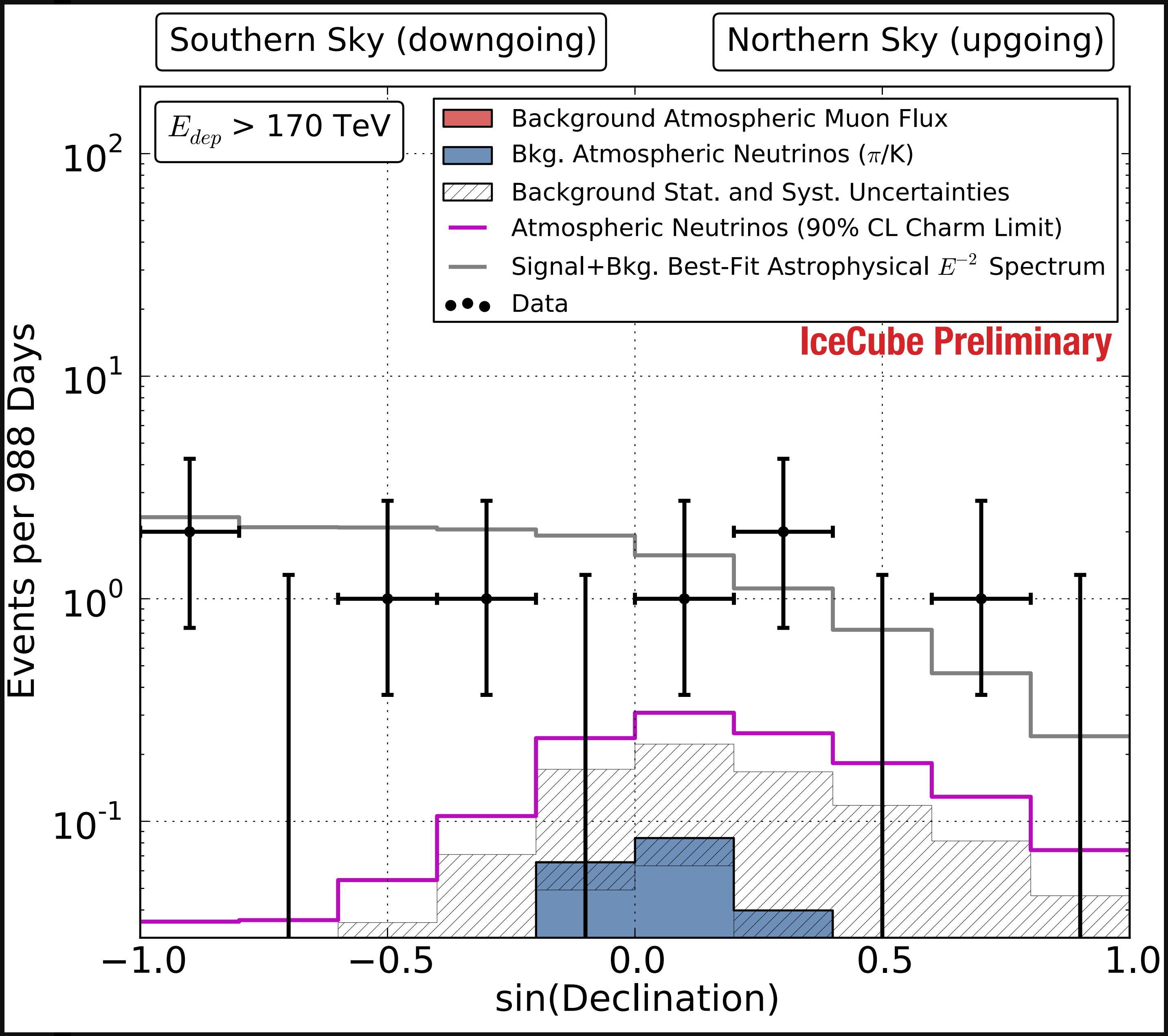

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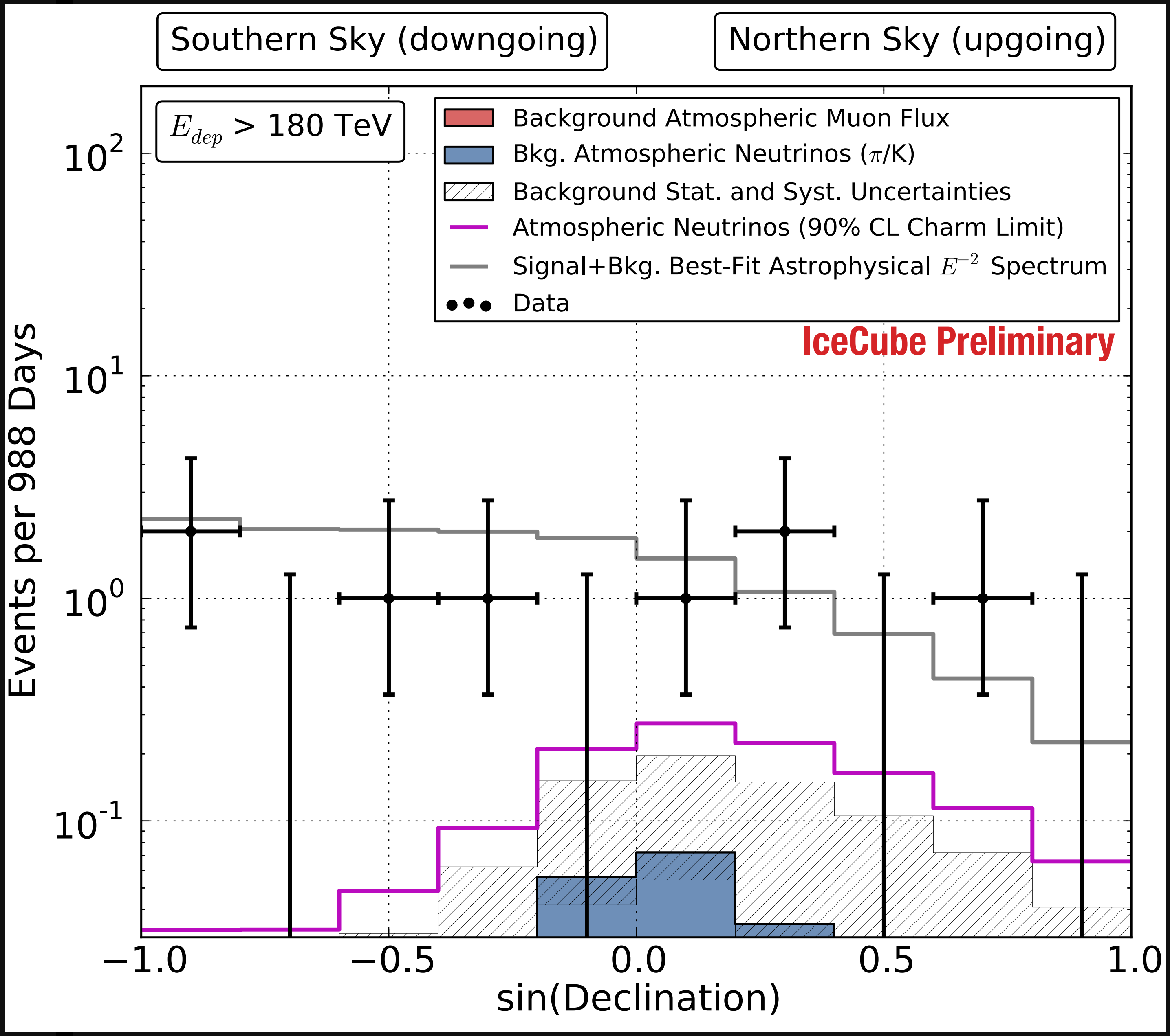

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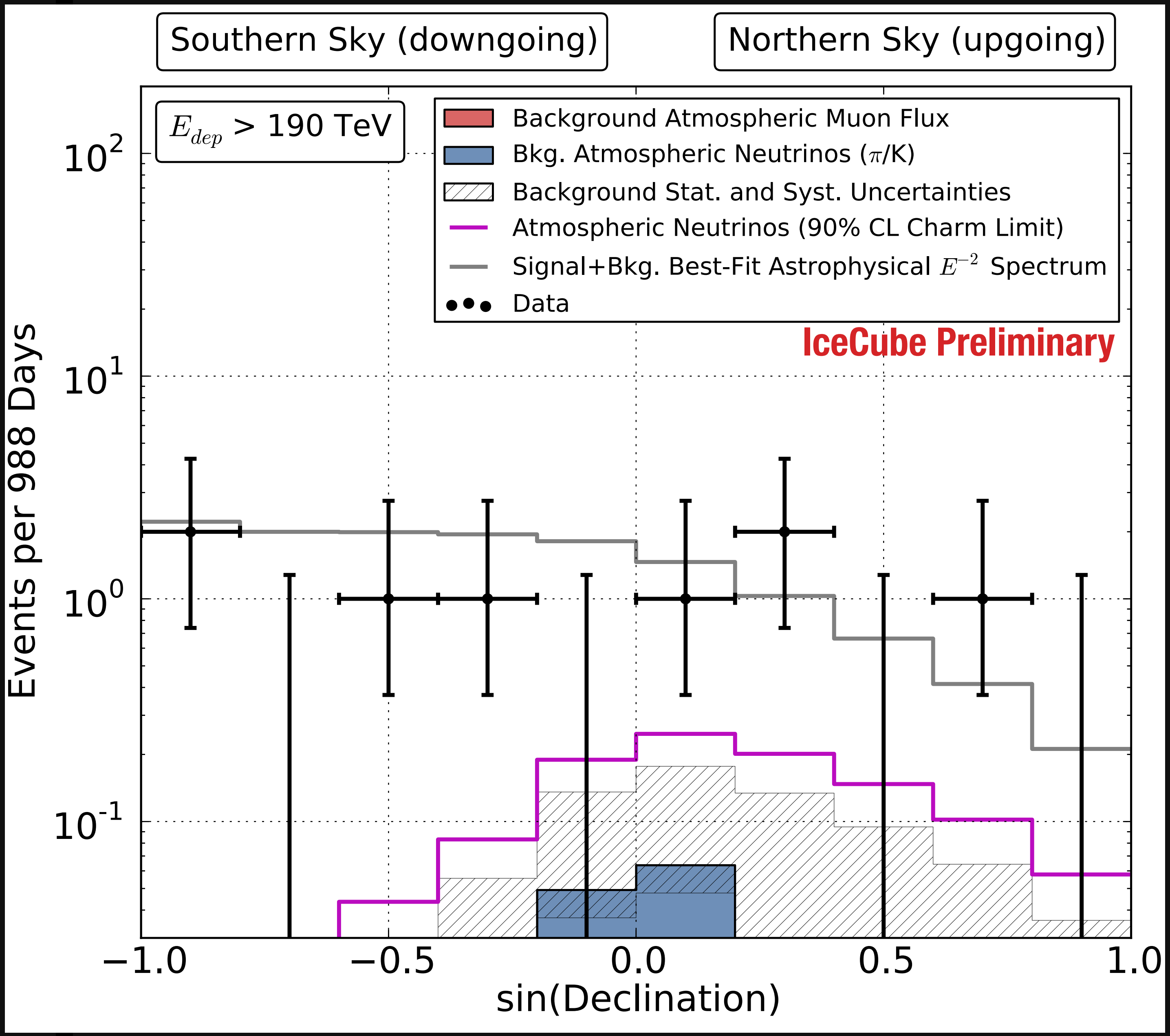

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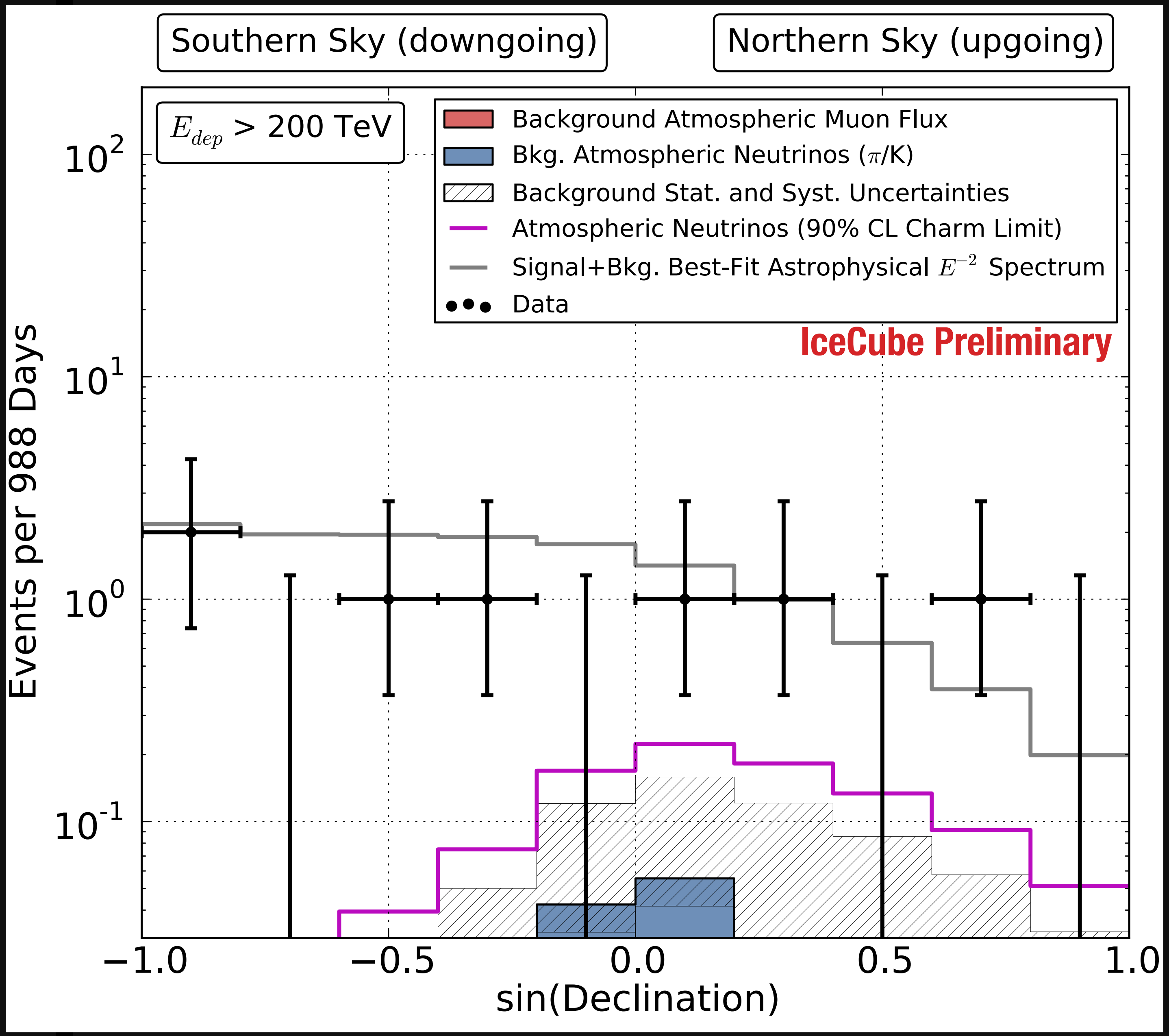

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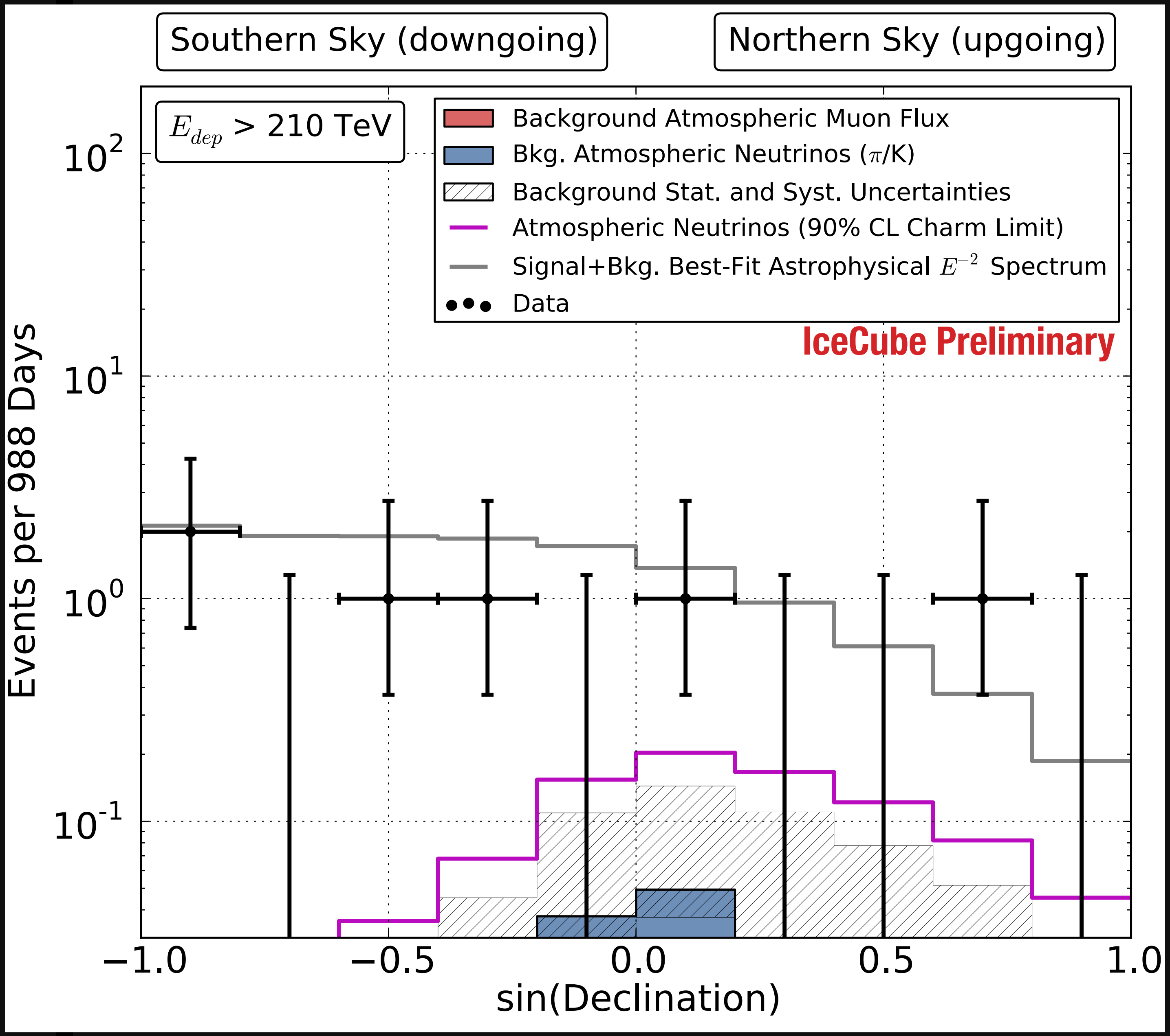

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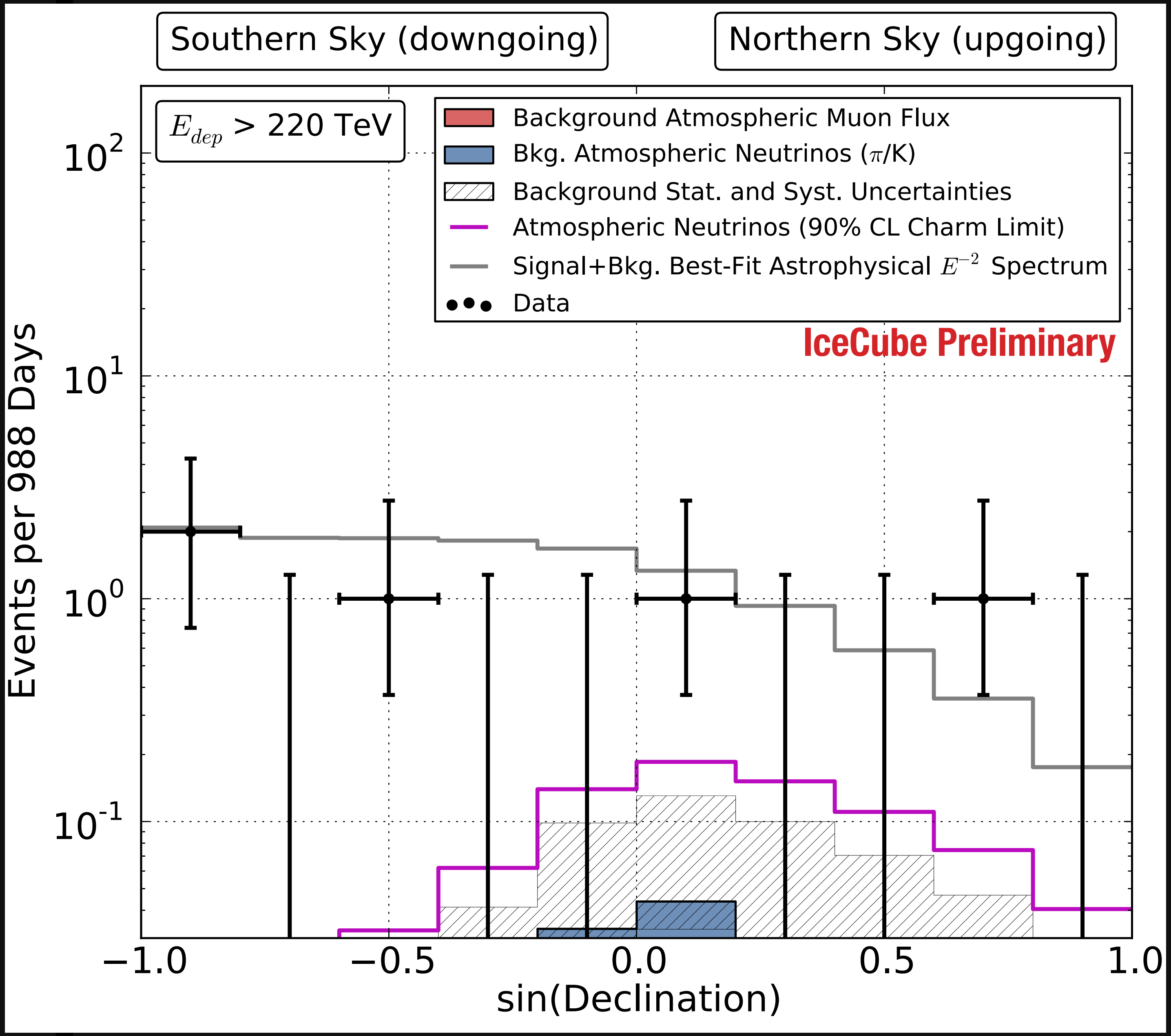

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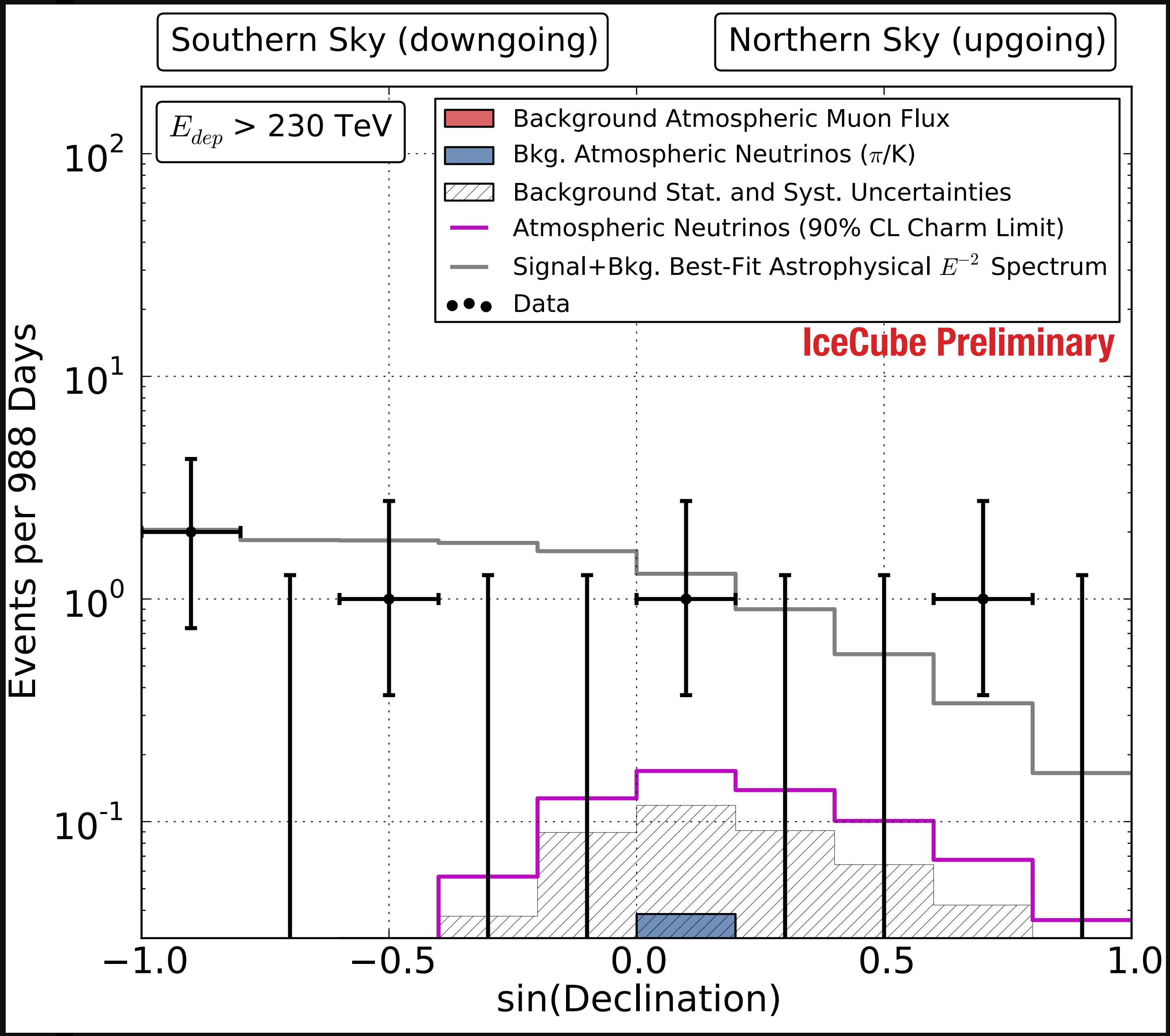

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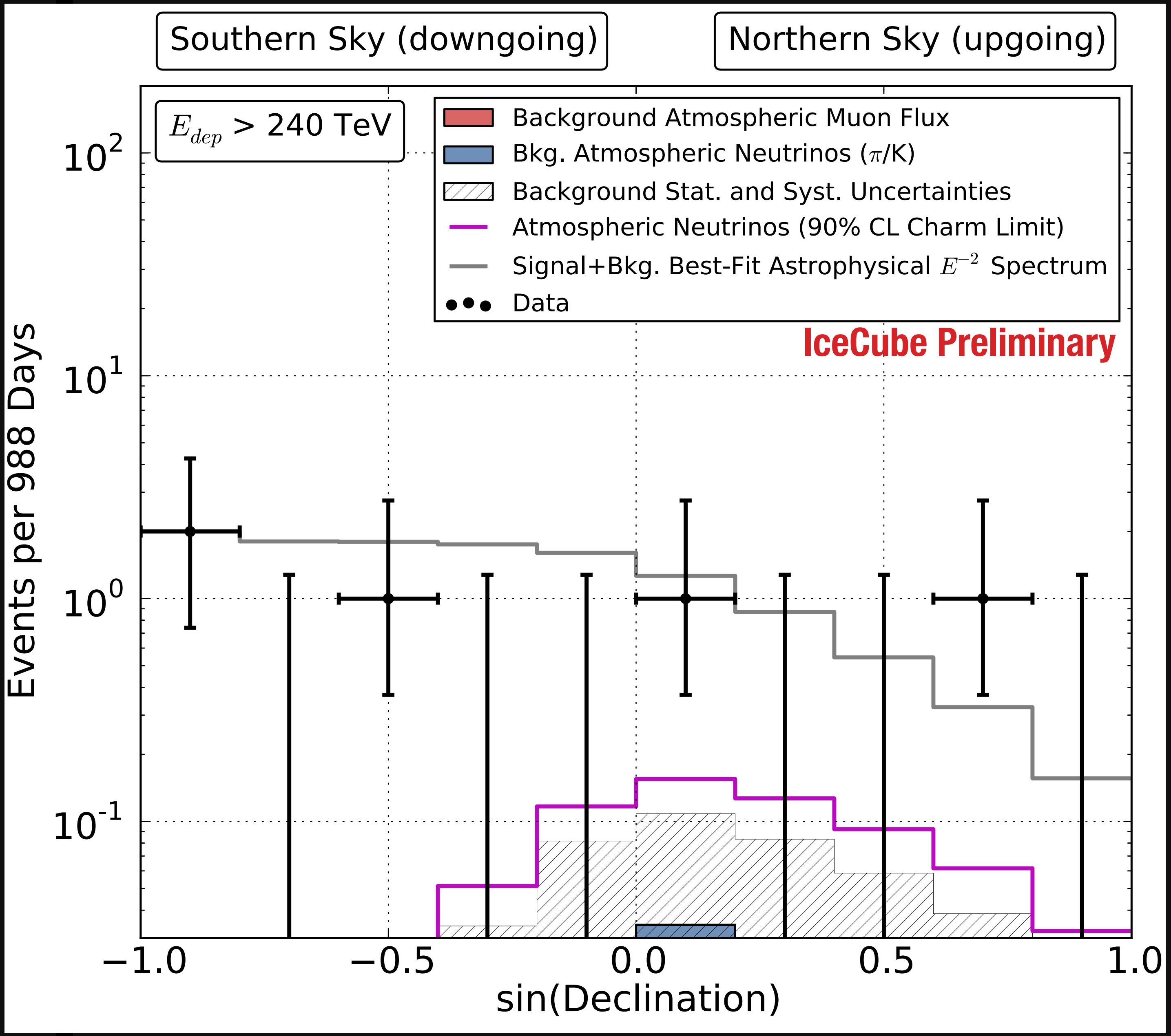

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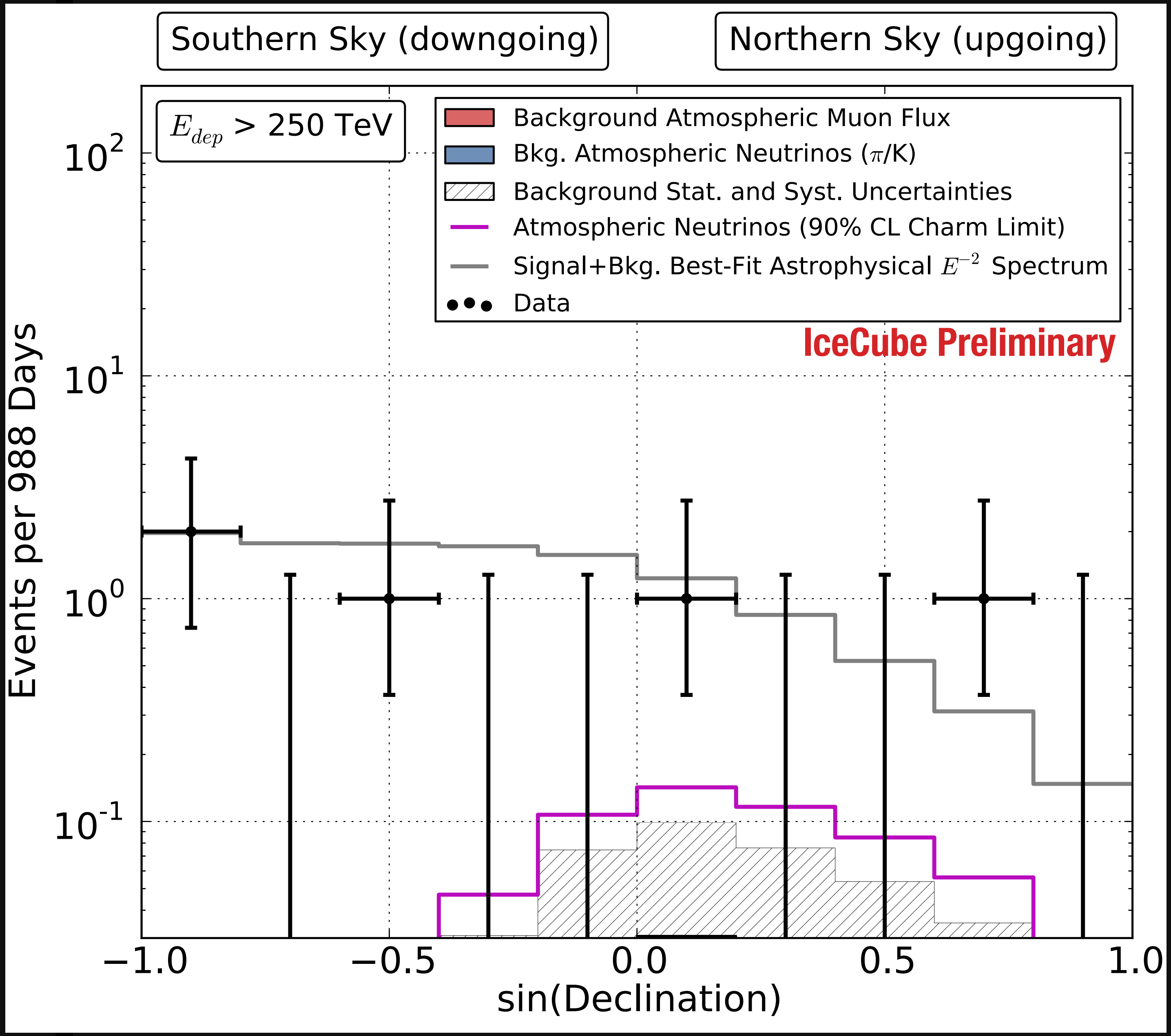

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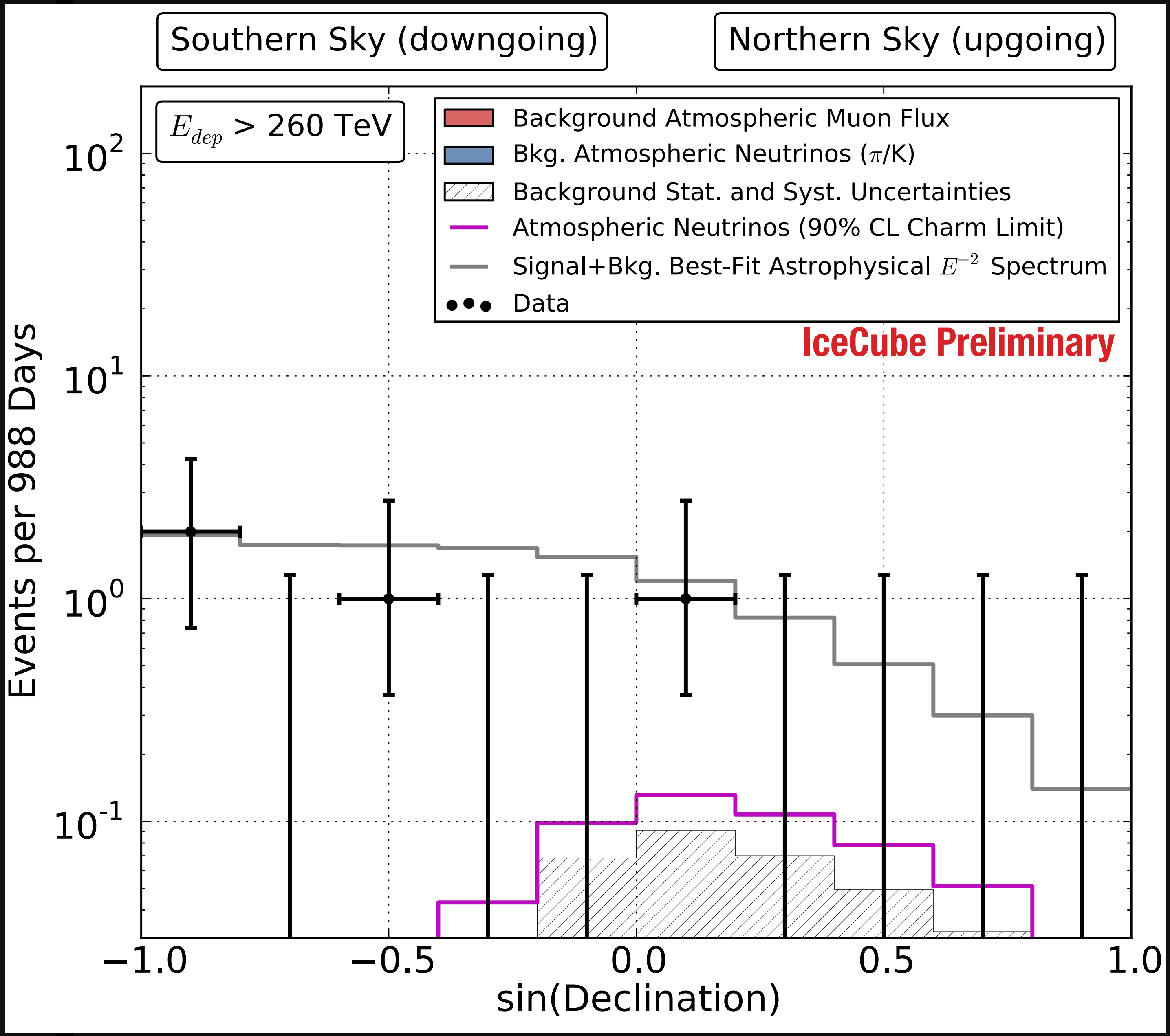

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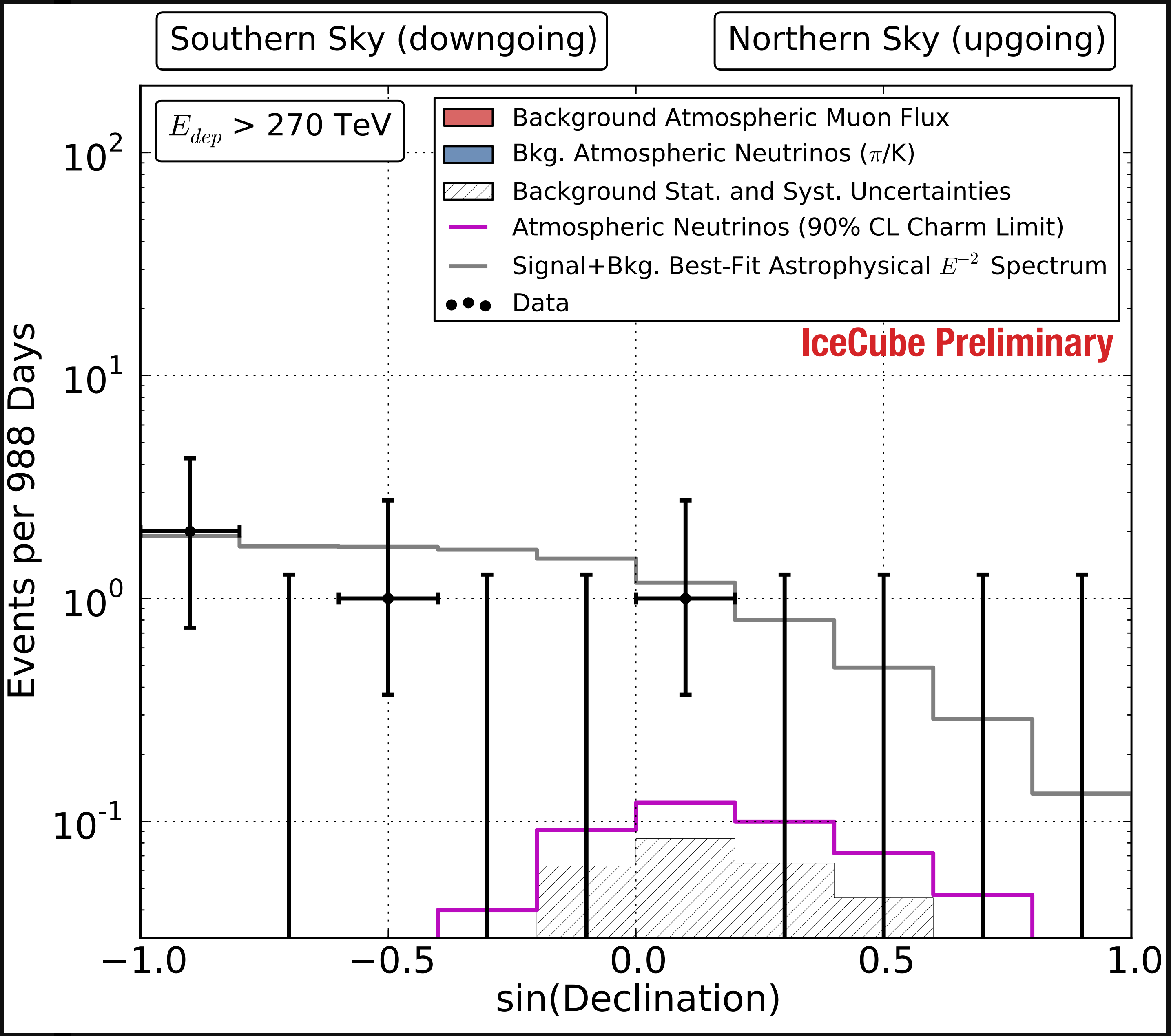

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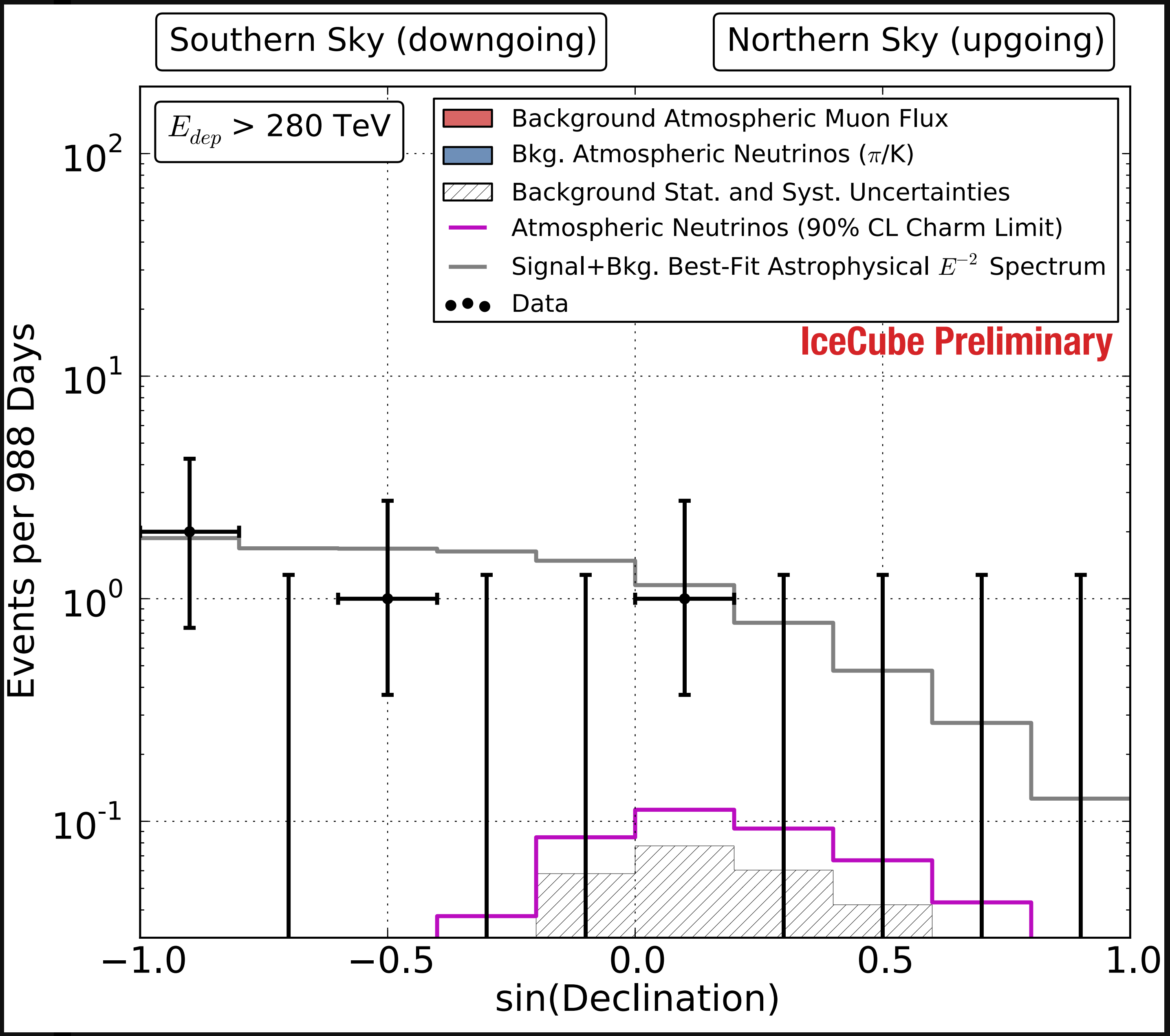

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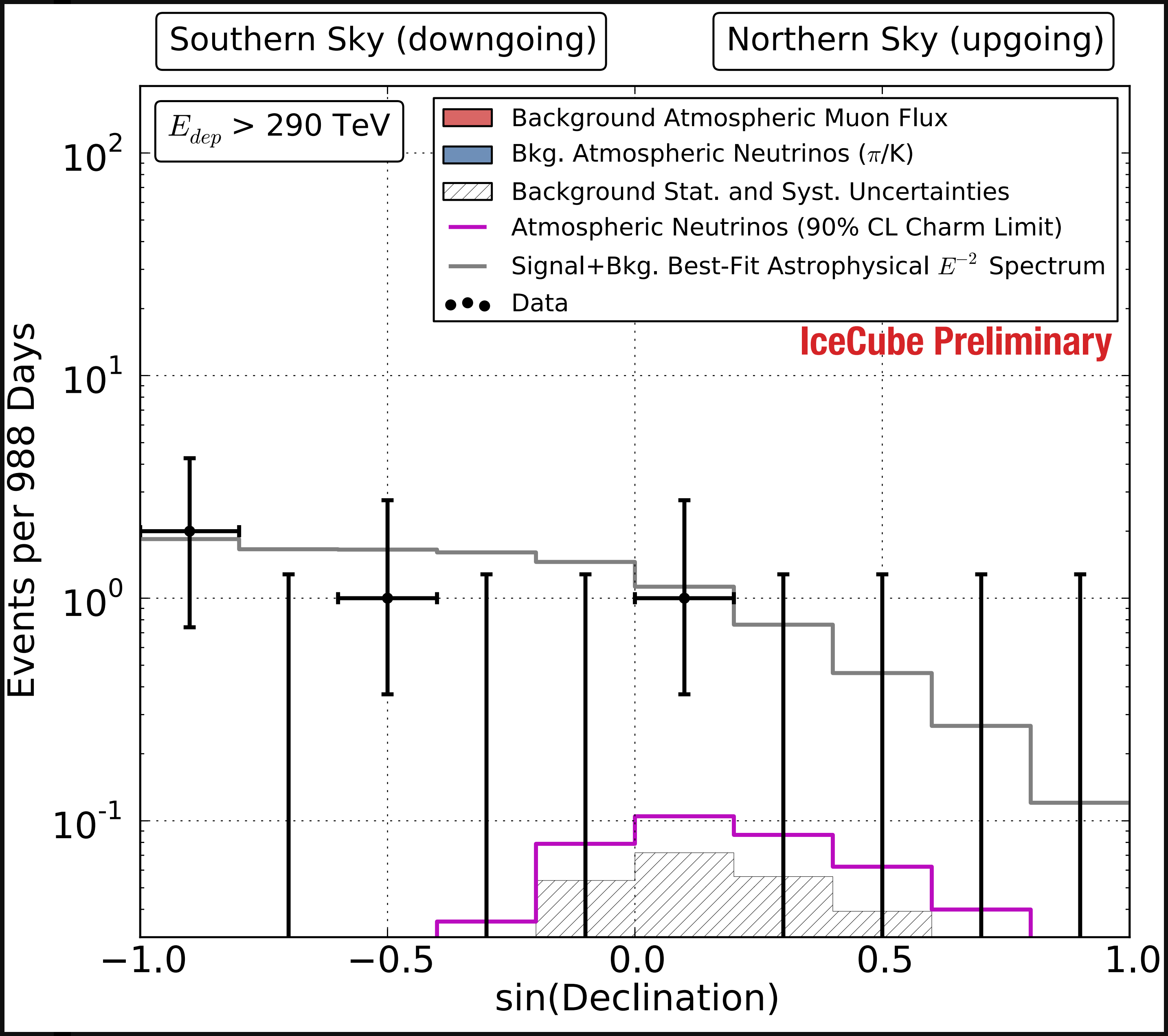

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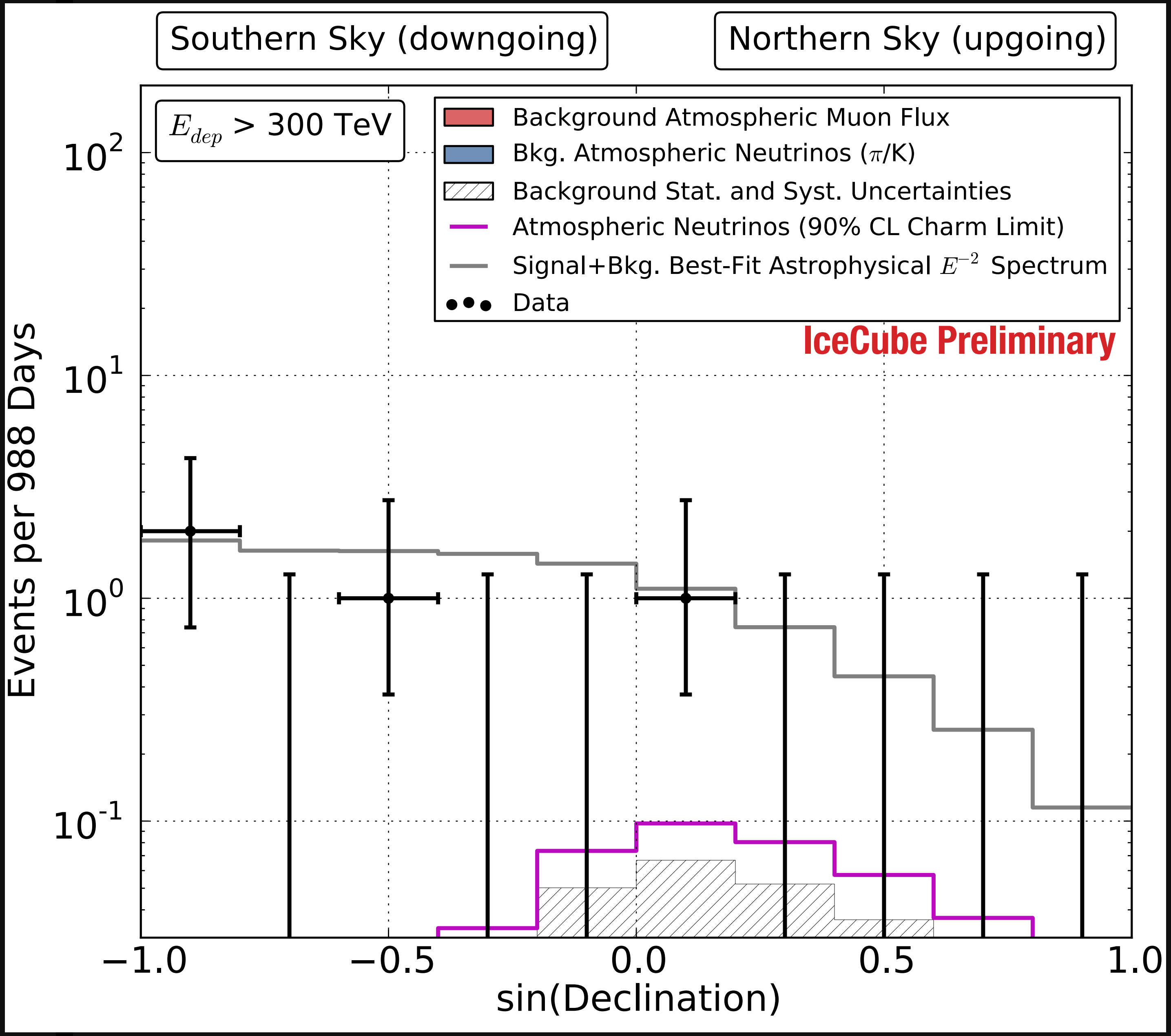
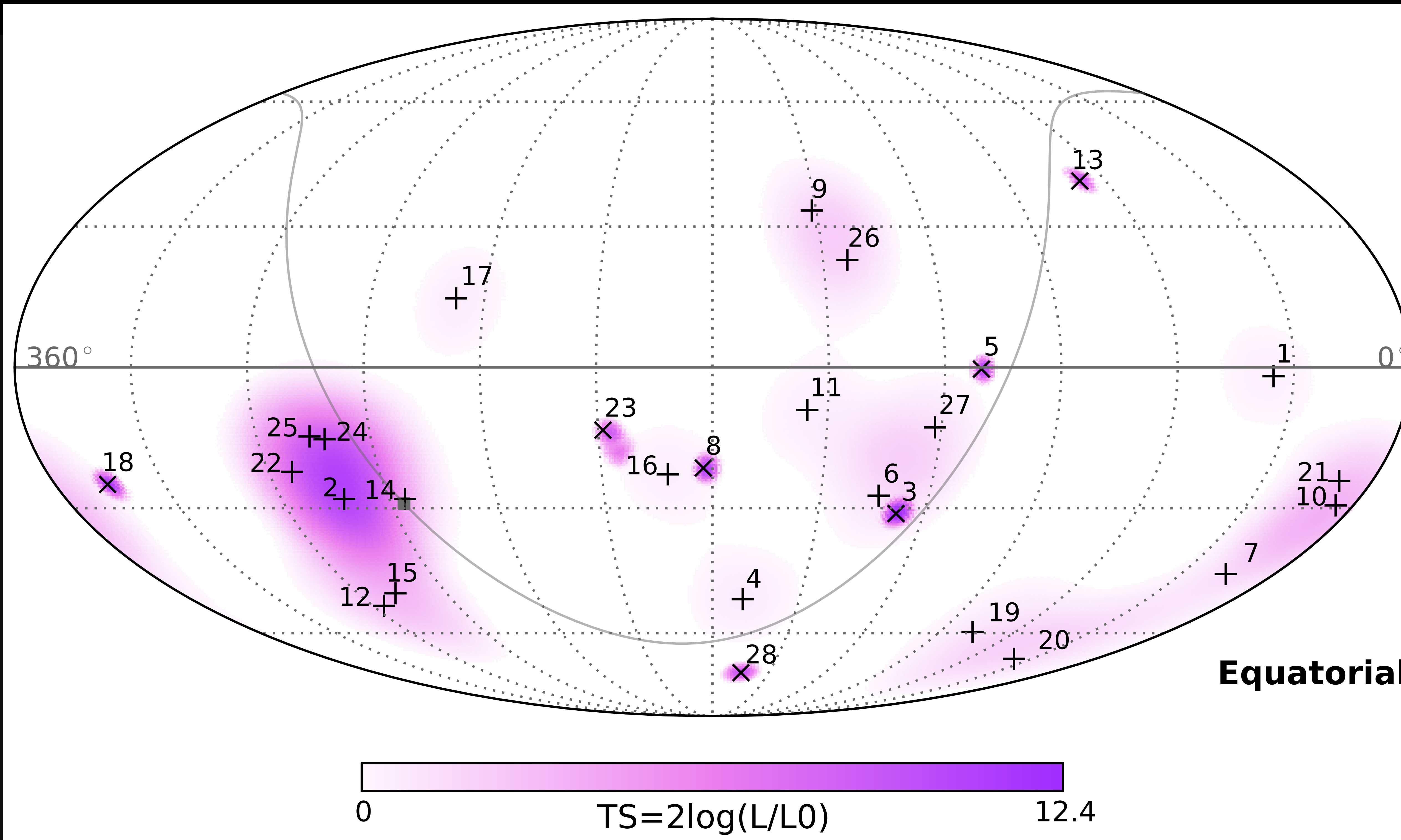


Skymap / Clustering

No significant clustering observed (first two years)



(all p-values are post-trial)

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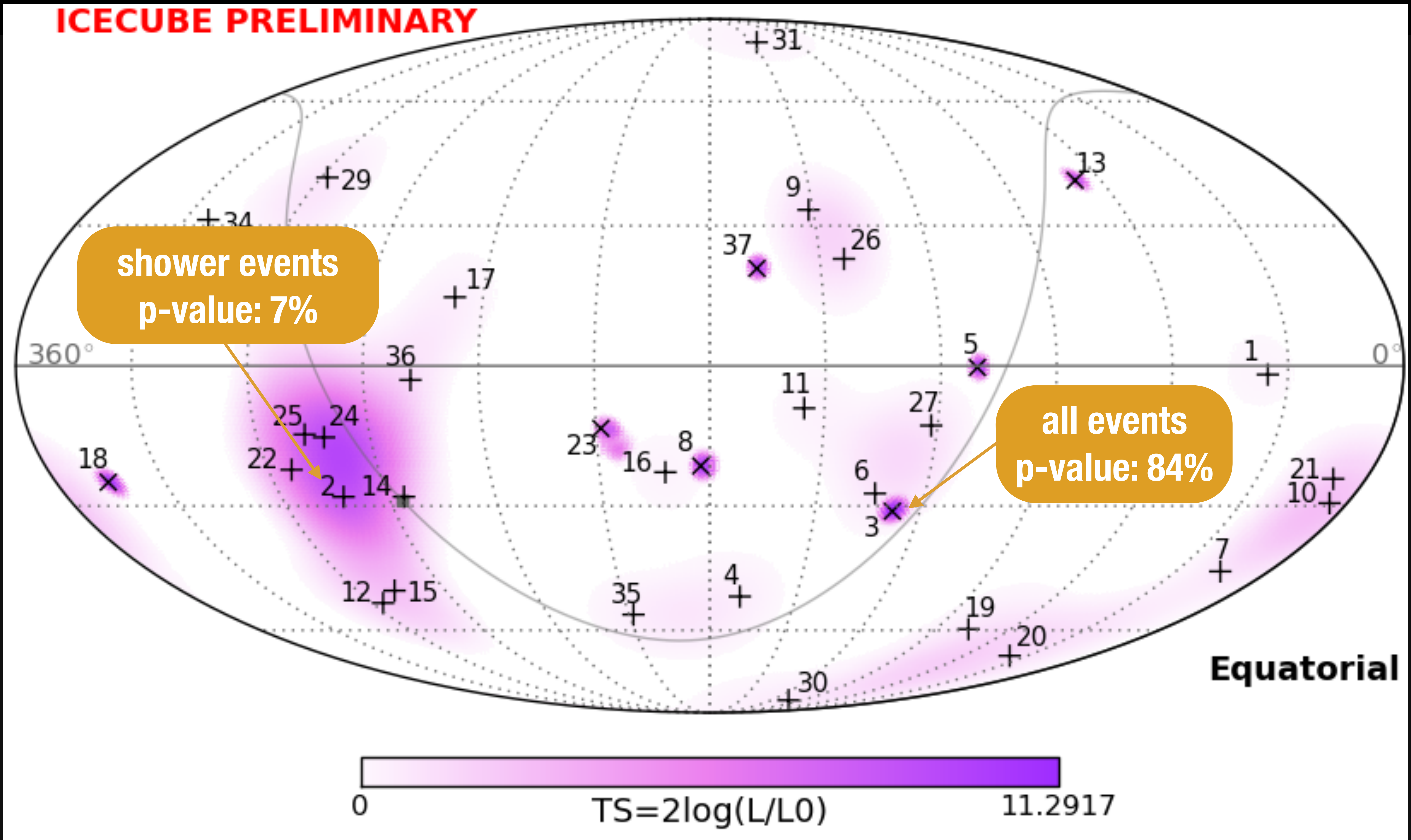

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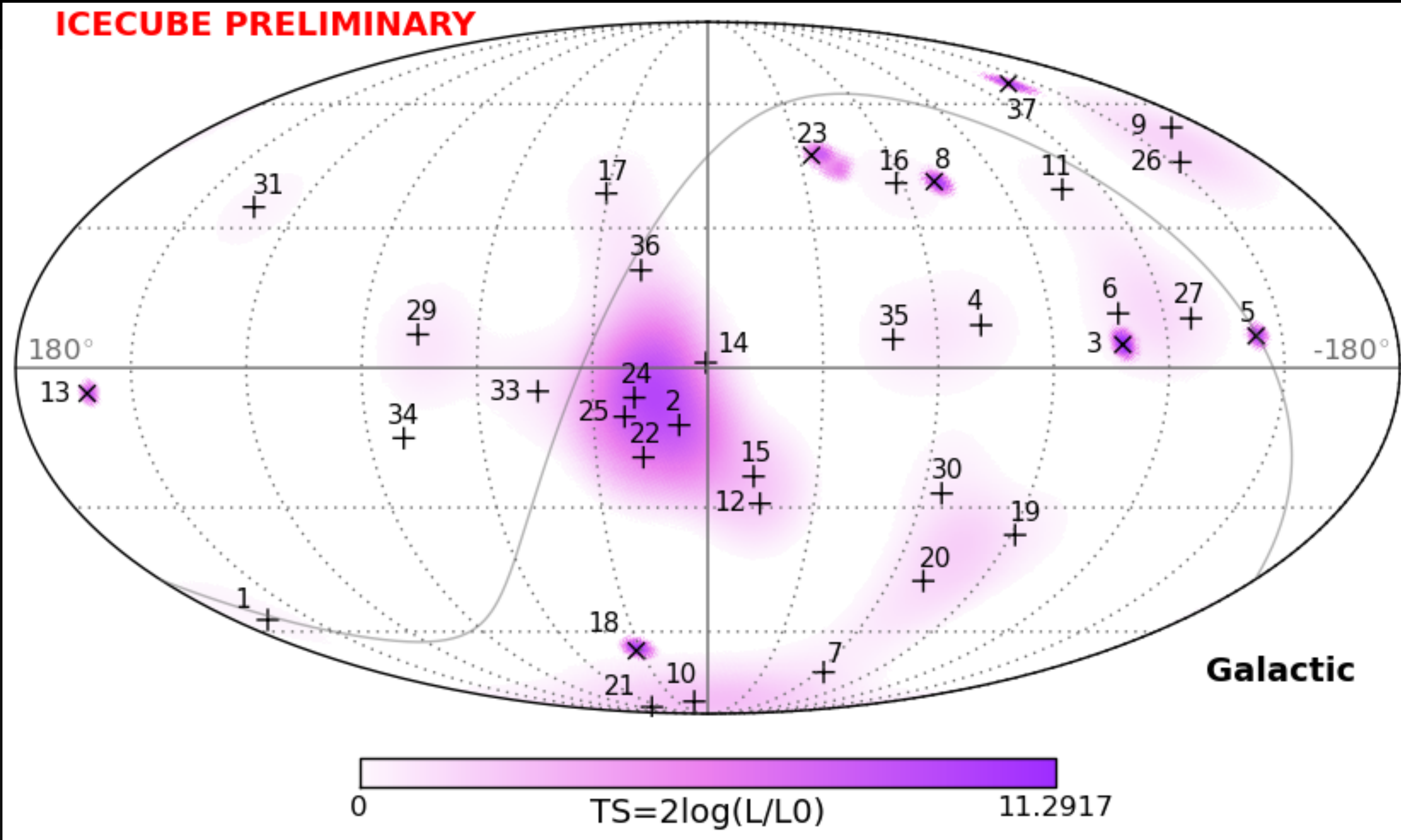


(all p-values are post-trial)

Skymap / Clustering

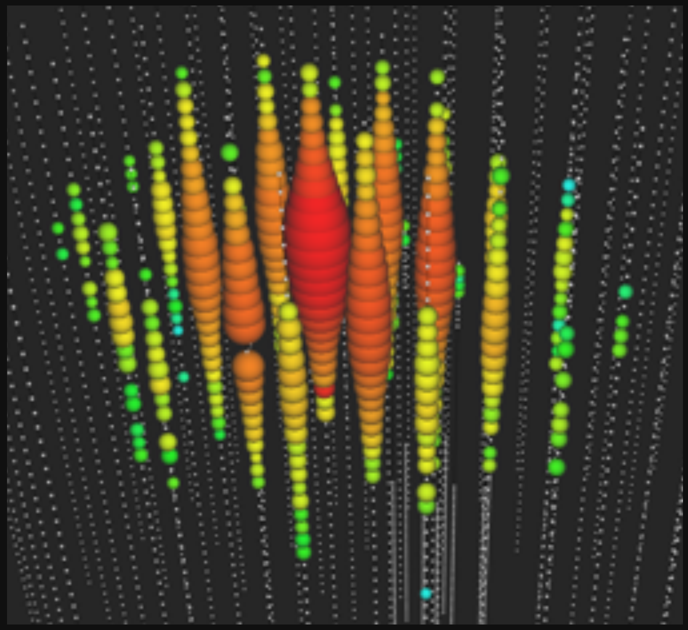
No significant clustering observed

- Analyzed with a variant of the standard PS method (w/o energy) (i.e. scrambling in RA)
- Most significant excess close to (but not at!) the Galactic Center
- Significance: 7% (not significant)
- Other searches (multi-cluster, galactic plane, time clustering, GRB correlations) not significant either

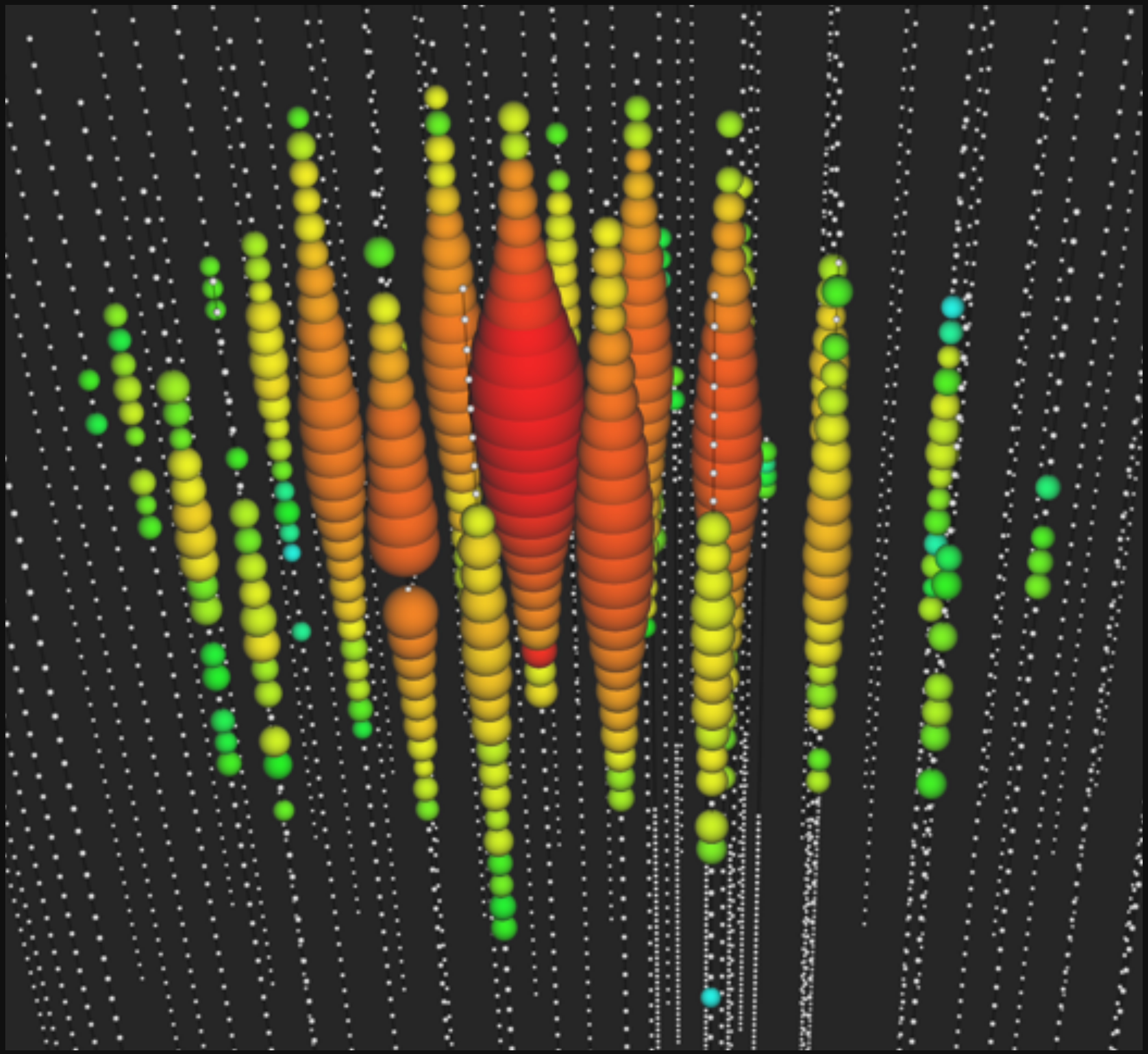
Conclusions

Stay tuned!

- ~~28~~ 36(+1) events with energies above ≈ 50 TeV found in ~~two~~ three years of IceCube data
- Increasing evidence for high-energy component beyond the atmospheric spectrum
- Original 2-year sample inconsistent at 4.1σ with standard background assumptions
- Less clear what it is - compatible with astrophysical explanations
- (Even) more data coming soon!



Thank you!



2 PeV event - “Big Bird”

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)

Backup

The Future

What can we do?

The Future

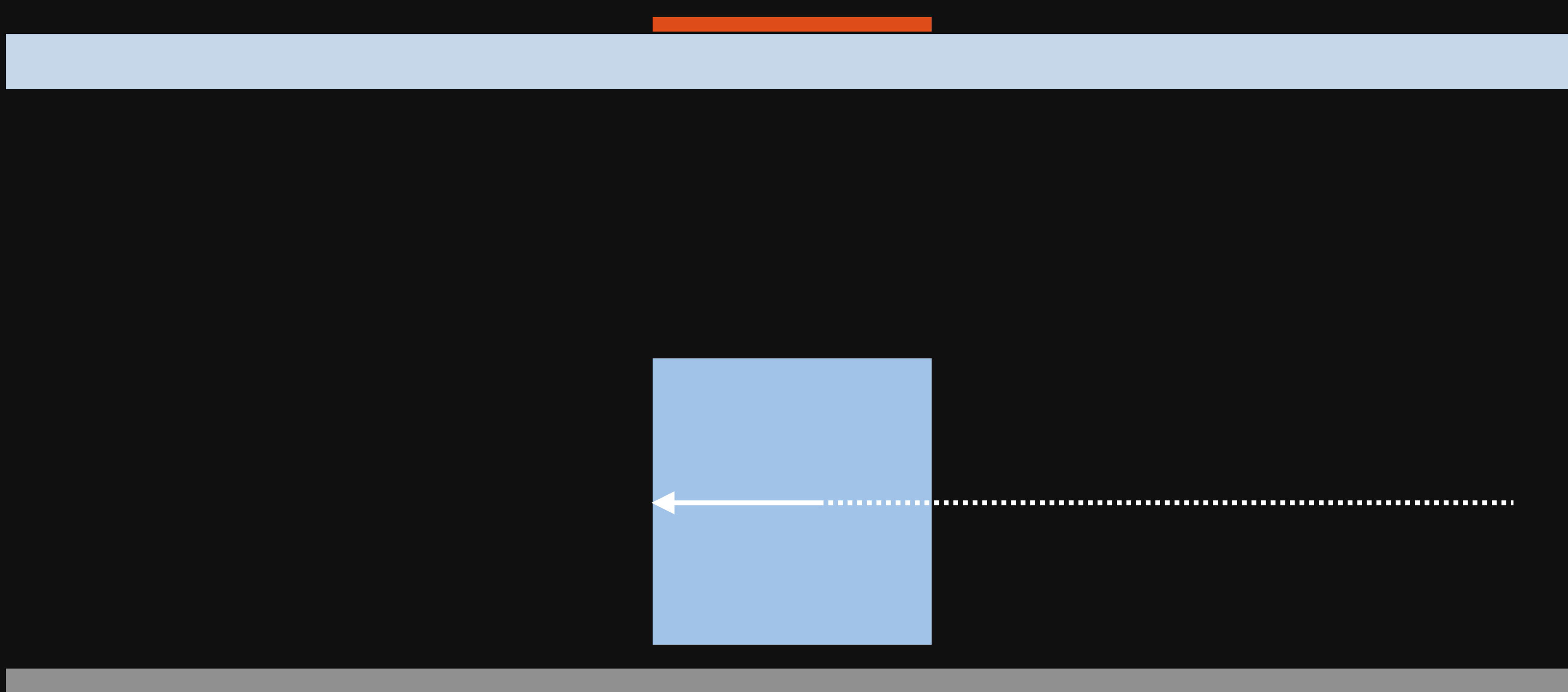
At the highest energies: "neutrino = extraterrestrial source"

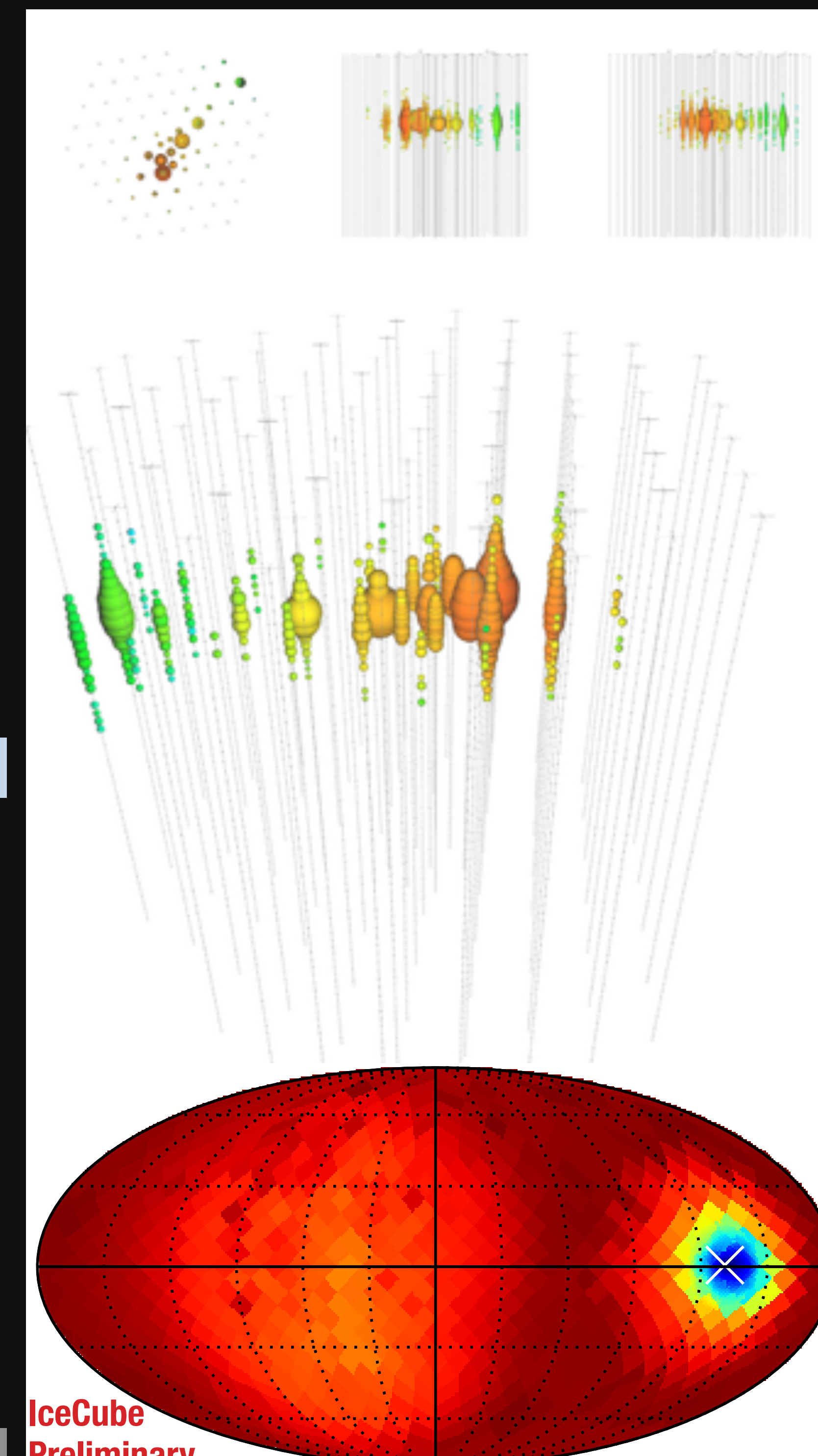
- **Lots of cascades, only a few tracks**
  - cascades are limited by angular resolution O(10deg), dominated by ice systematics
  - great for measuring a diffuse flux, not so great for astronomy
- **We need more tracks!**
  - (and of course we need to continue improving our systematics on the ice for cascades)

The Future

At the highest energies: “neutrino = extraterrestrial source”

- **We have a few nice starting tracks!**
  - e.g. “event #5” - starts three layers of strings inside the detector

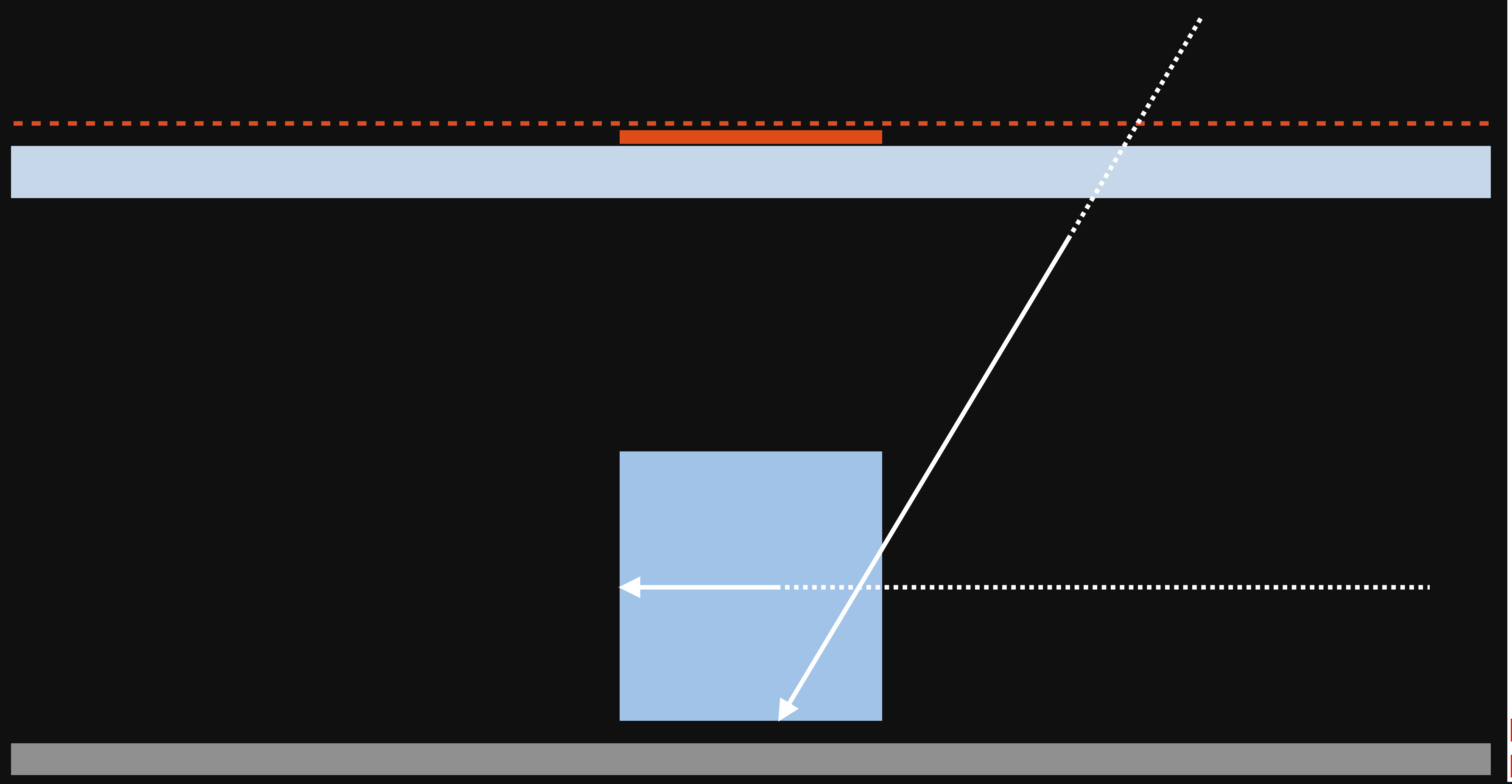


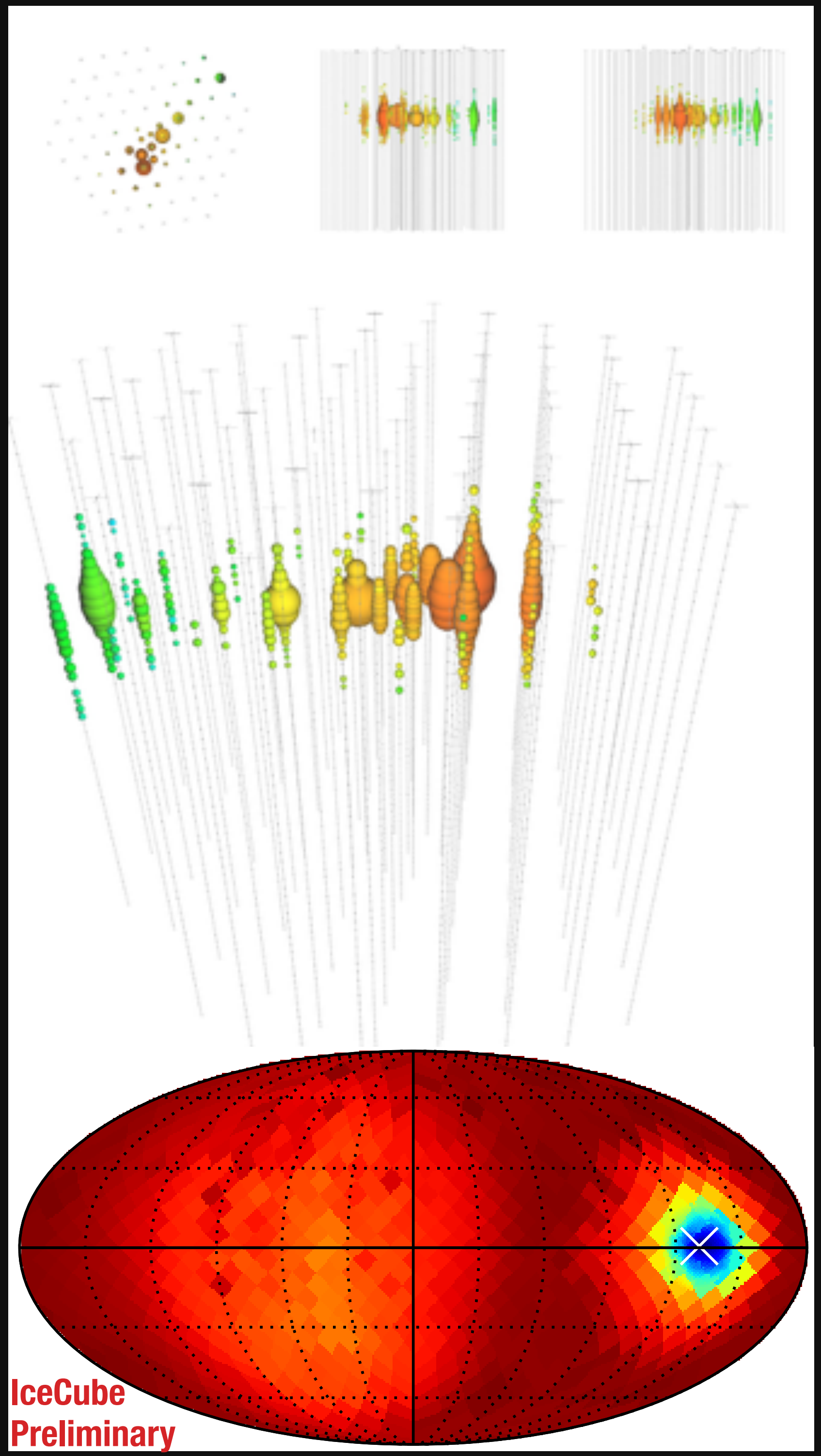


The Future

How do we get more tracks?

- **Add a large surface array, extending several km - can act as a CR veto**
  - enlarged volume for “starting” tracks

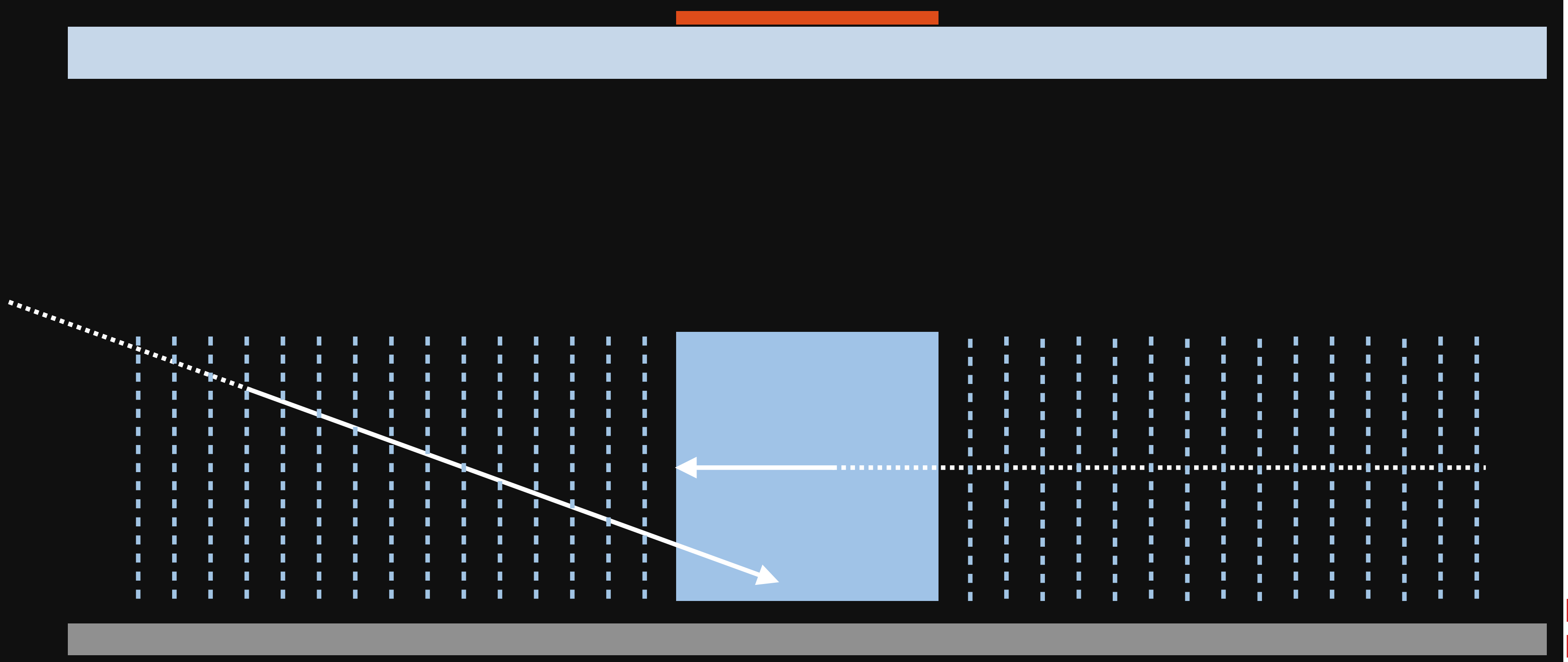


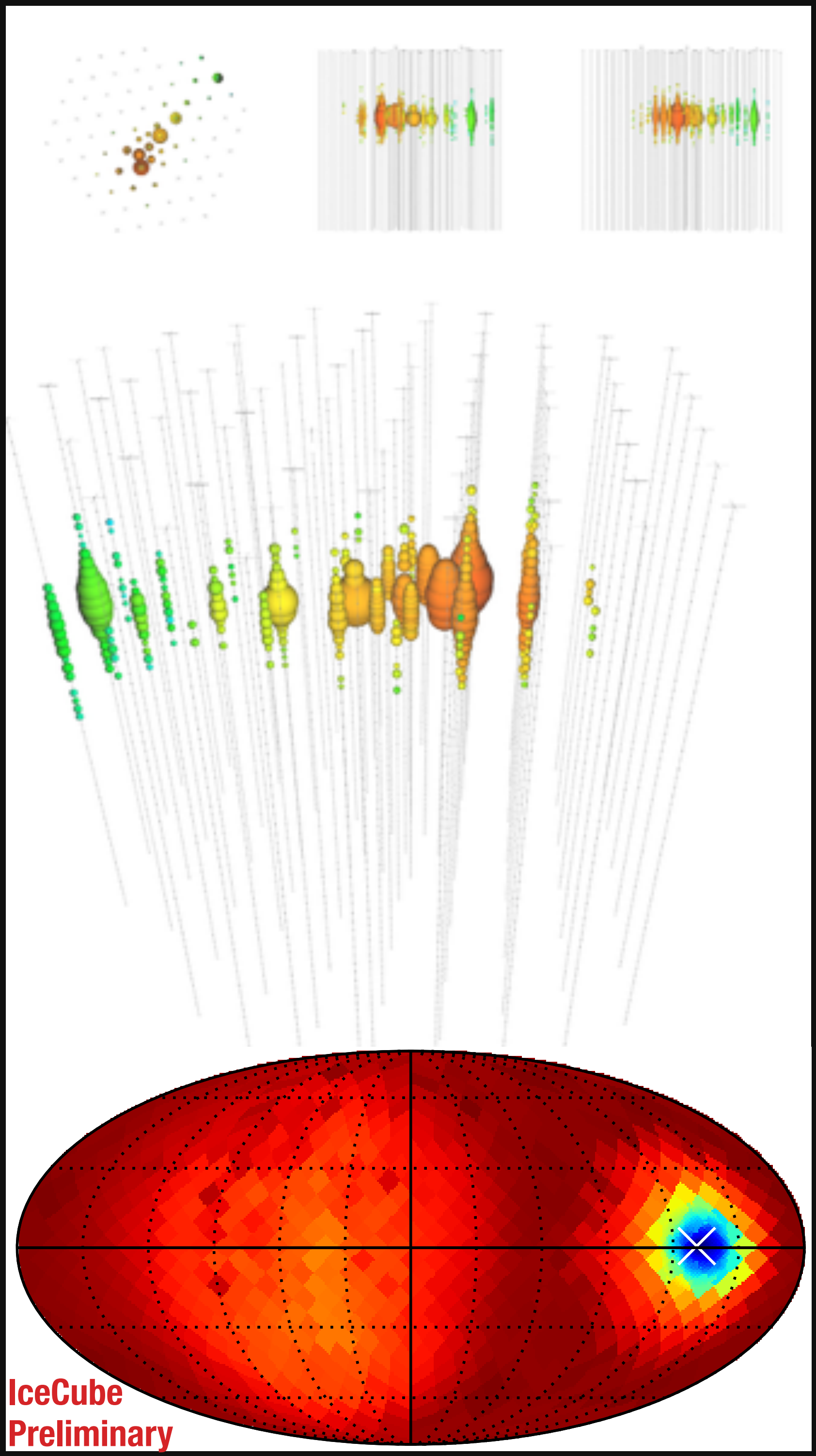


The Future

How do we get more tracks?

- **Add more strings, with wider spacing**
    - enlarges volume for starting tracks (and "ordinary" tracks)
    - long lever arm ➔ better resolution

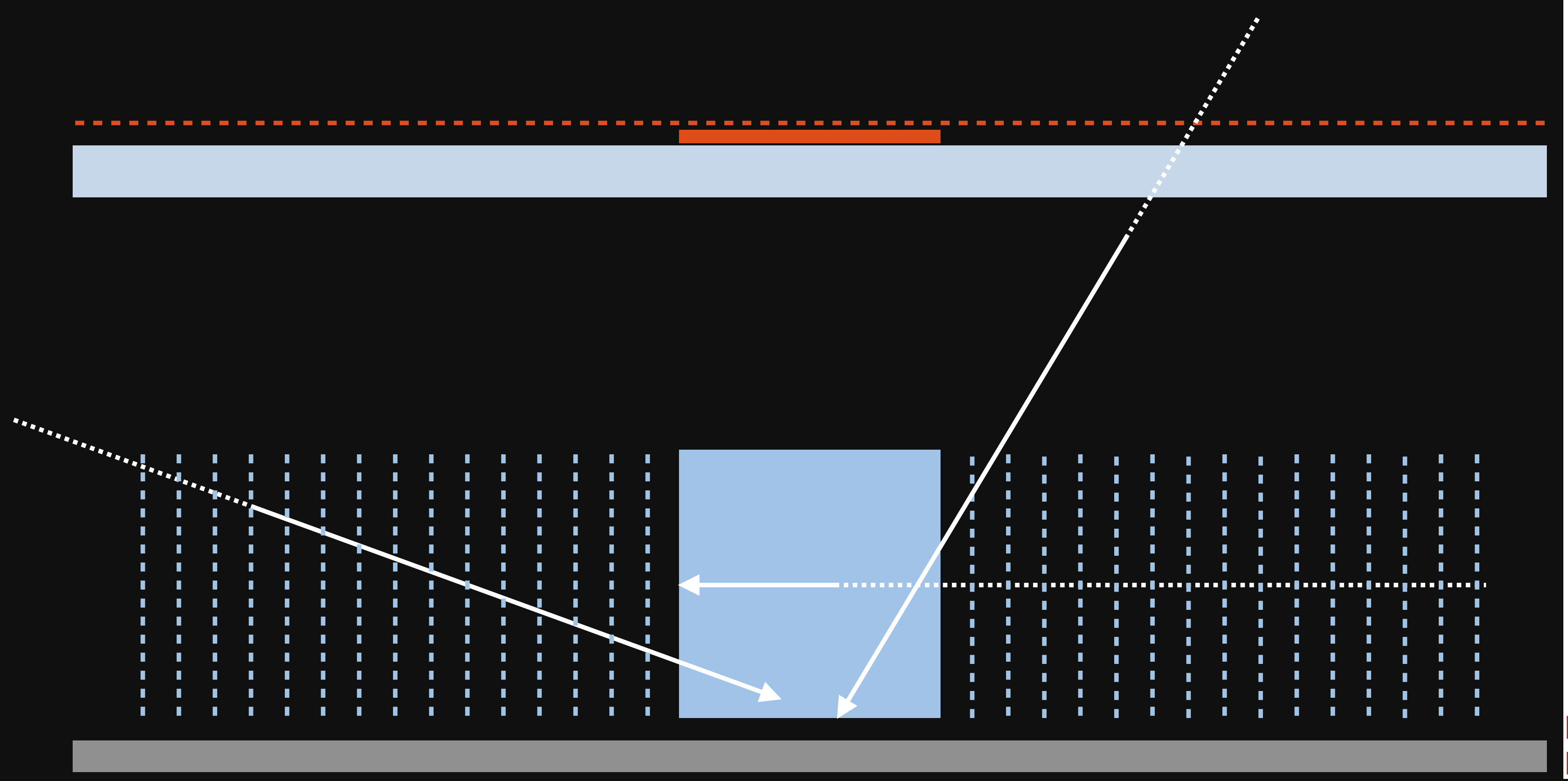


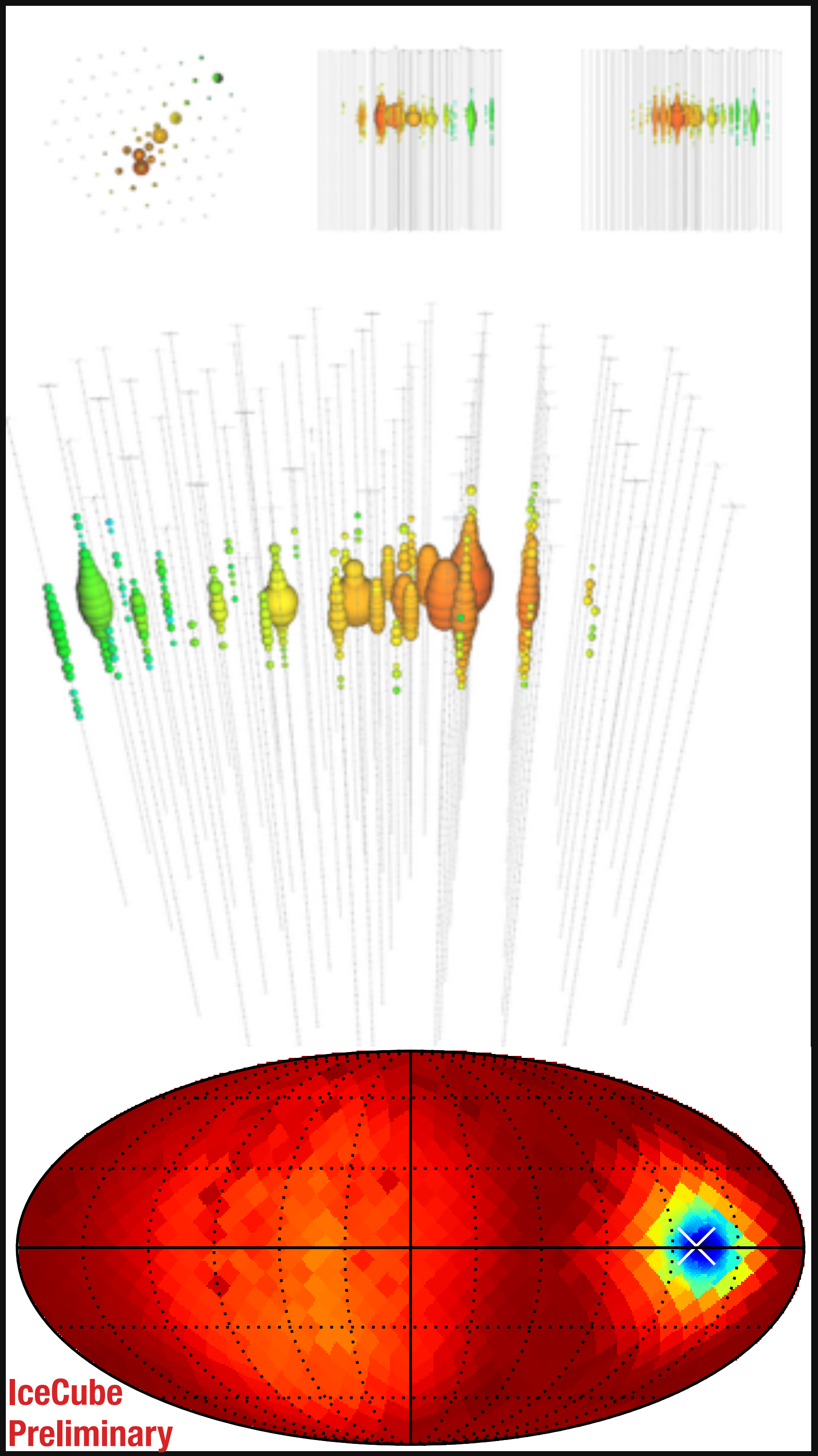


The Future

How do we get more tracks?

- **Or, of course, both!**

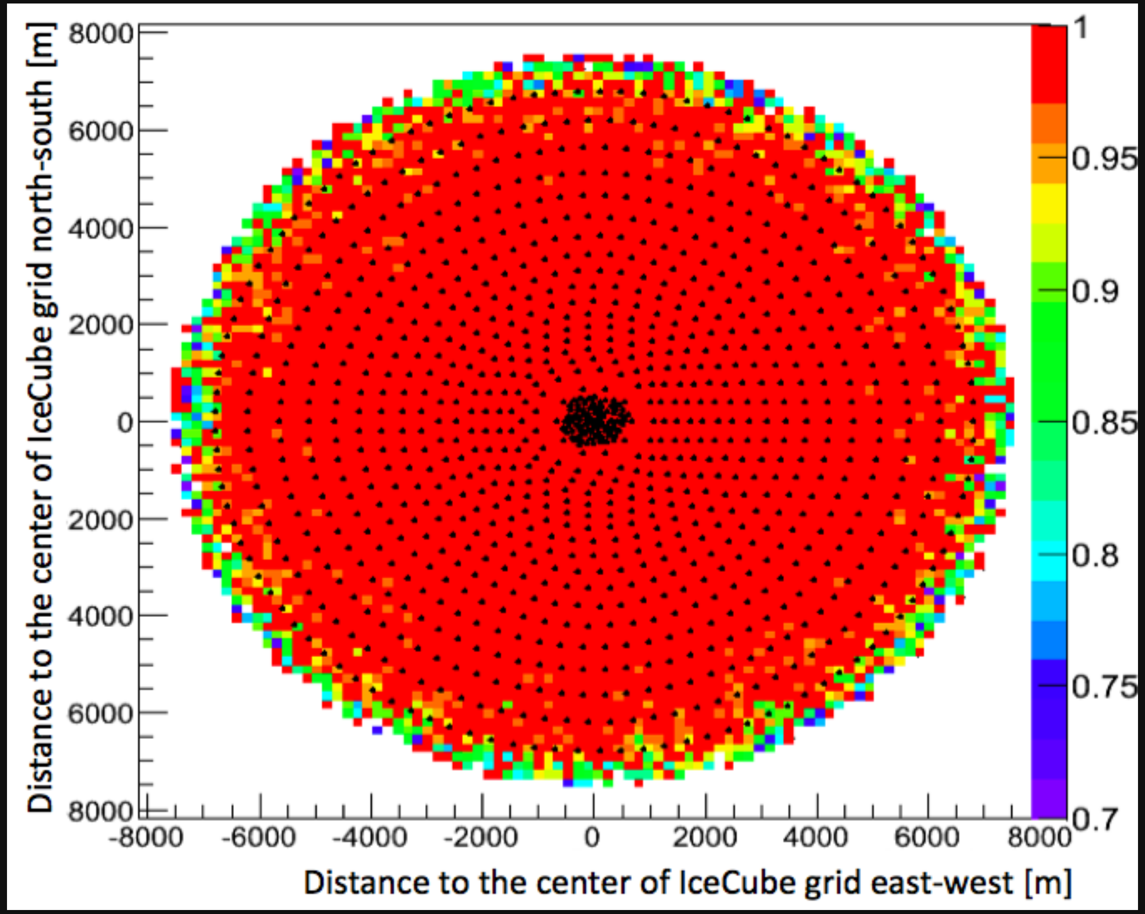




The Future

R&D for a surface array

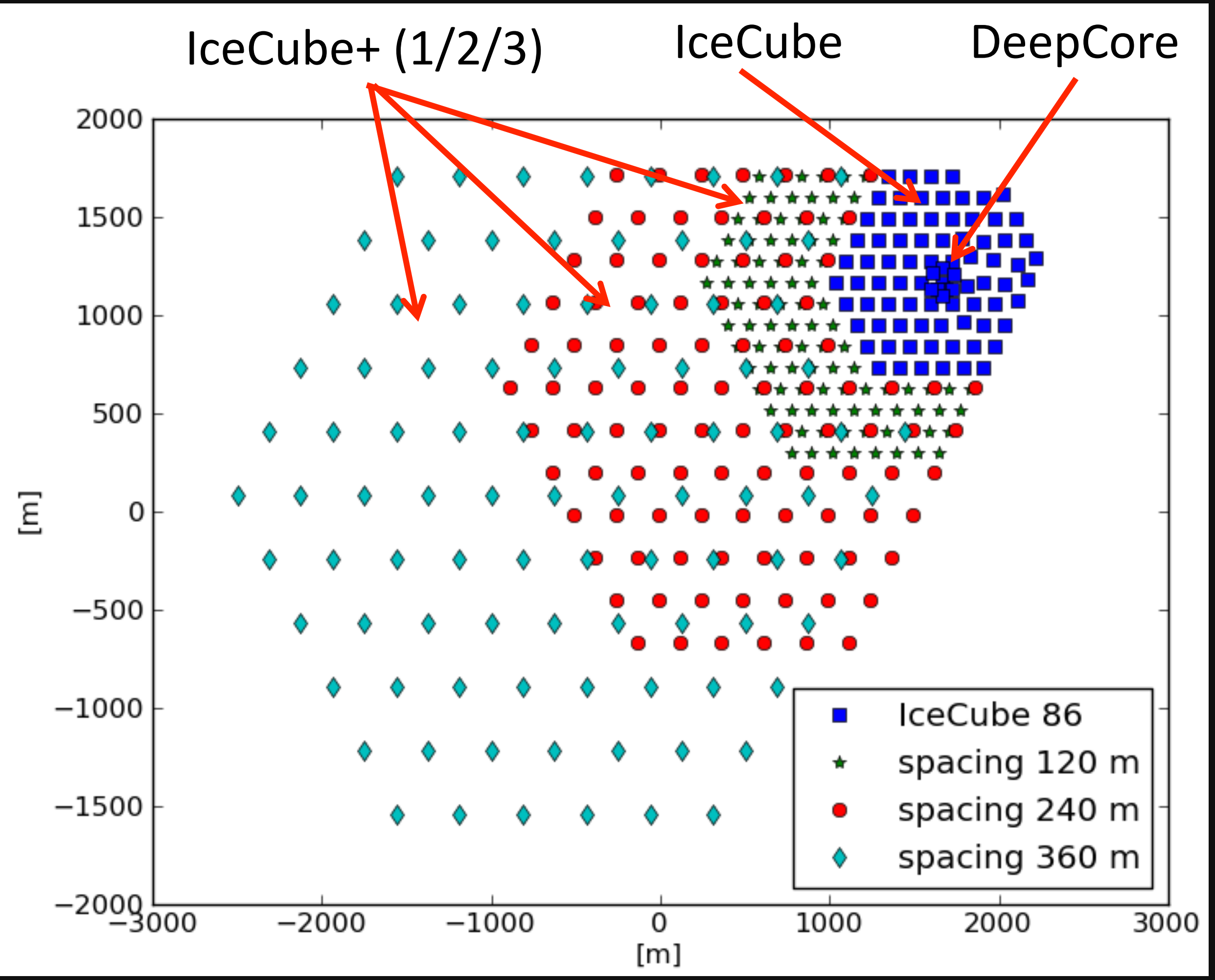
- **Similar to the current "IceTop" surface array**
  - using simplified versions of the current IceTop tanks
- **R&D is underway!**



The Future

An upgraded IceCube detector for high energies

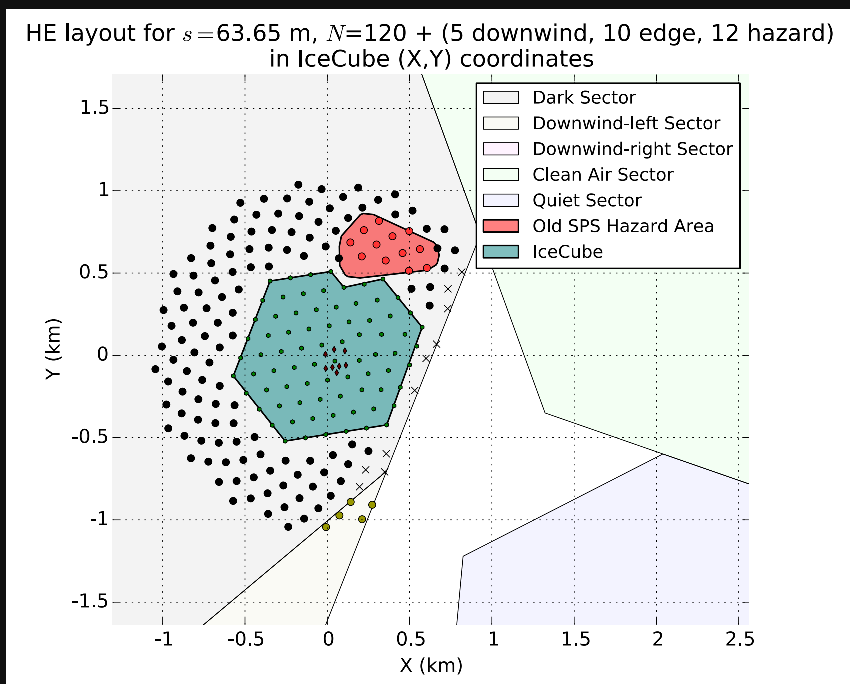
- **Current threshold at about 1TeV**
- **Can afford a slightly higher threshold of O(10 TeV)**
  - ➡ larger string-to-string spacing:
    - IceCube: 1 km^2
    - +HEX 120m: 2.3 km^2
    - +HEX 240m: 6.3 km^2
    - +HEX 360m: 12.6 km^2
- **Initial simulations are running!**

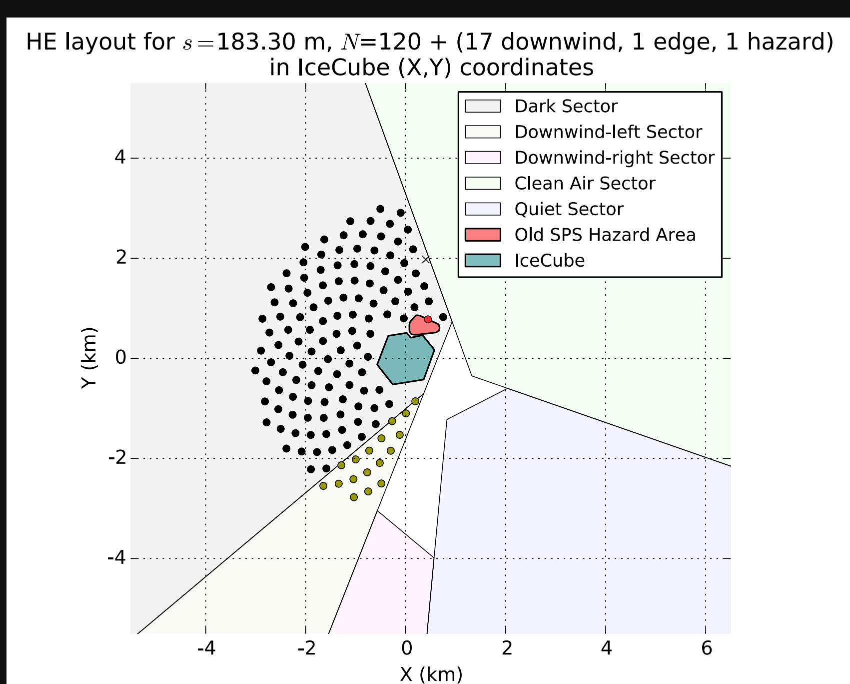


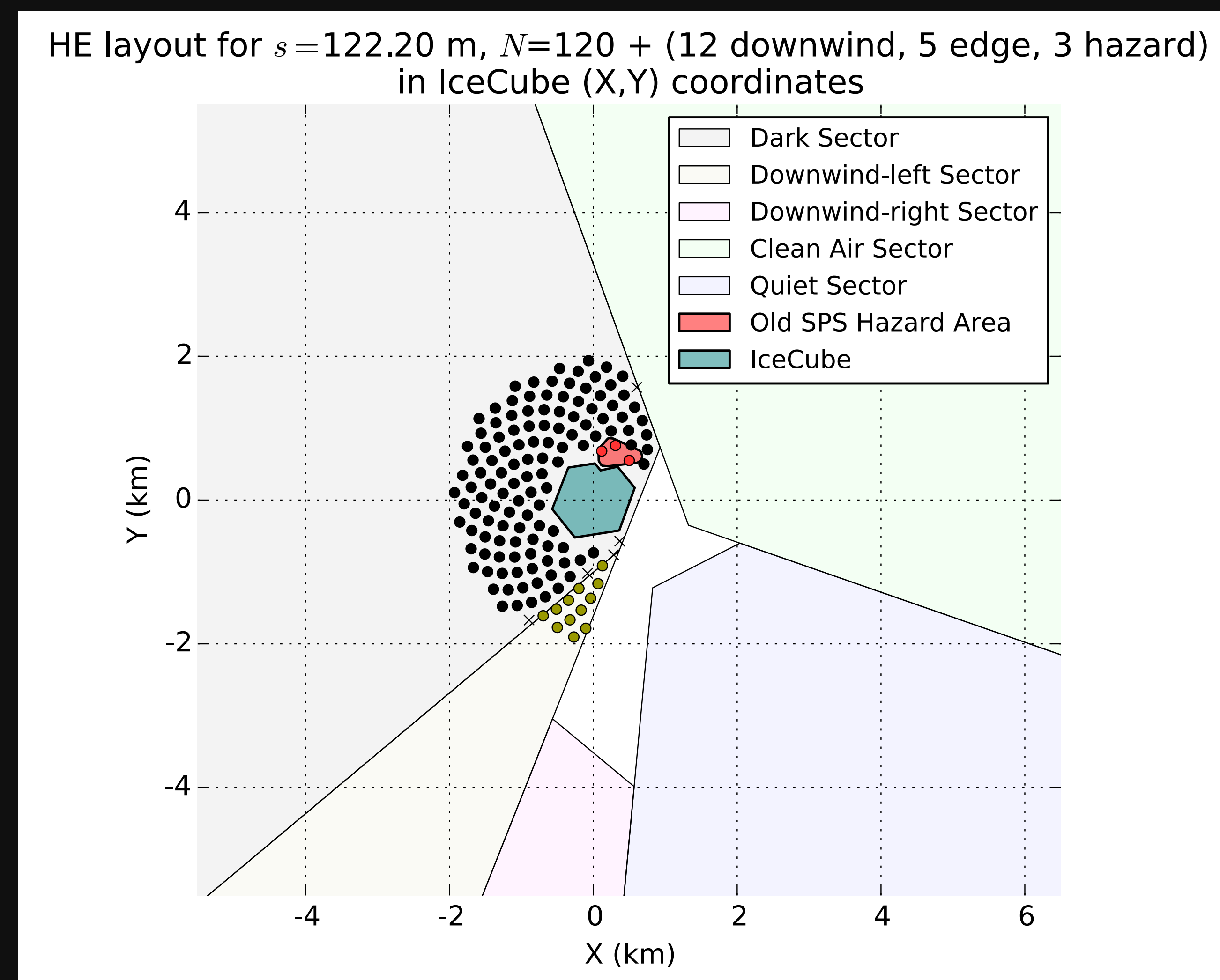
assuming ~100 new strings

The Future

Some of the things we are thinking about…

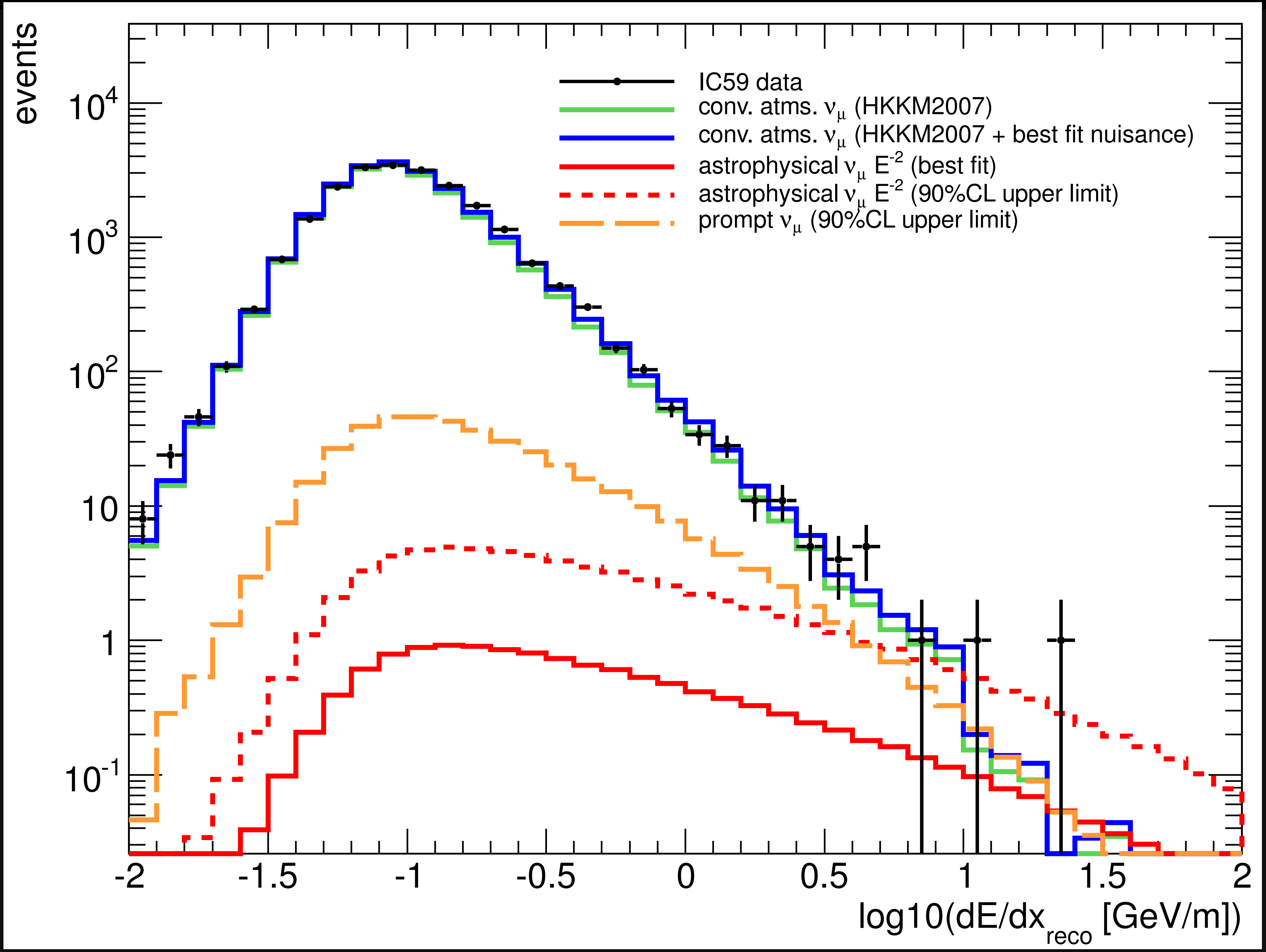






Hint in Upgoing Muons

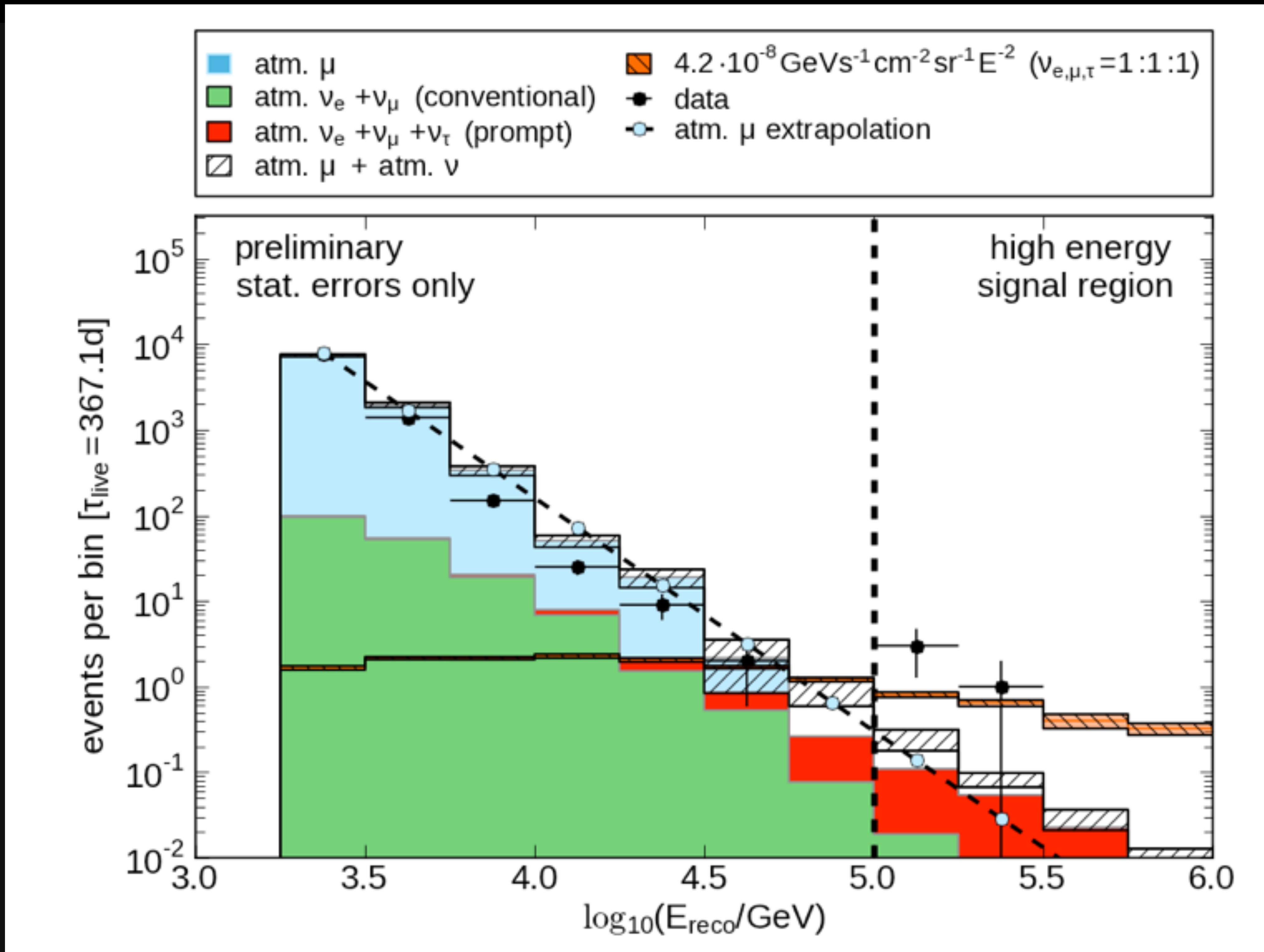
Study using the "IC59" partial detector during construction: 1.8σ



arXiv:1302.0127

Another Hint in Showers

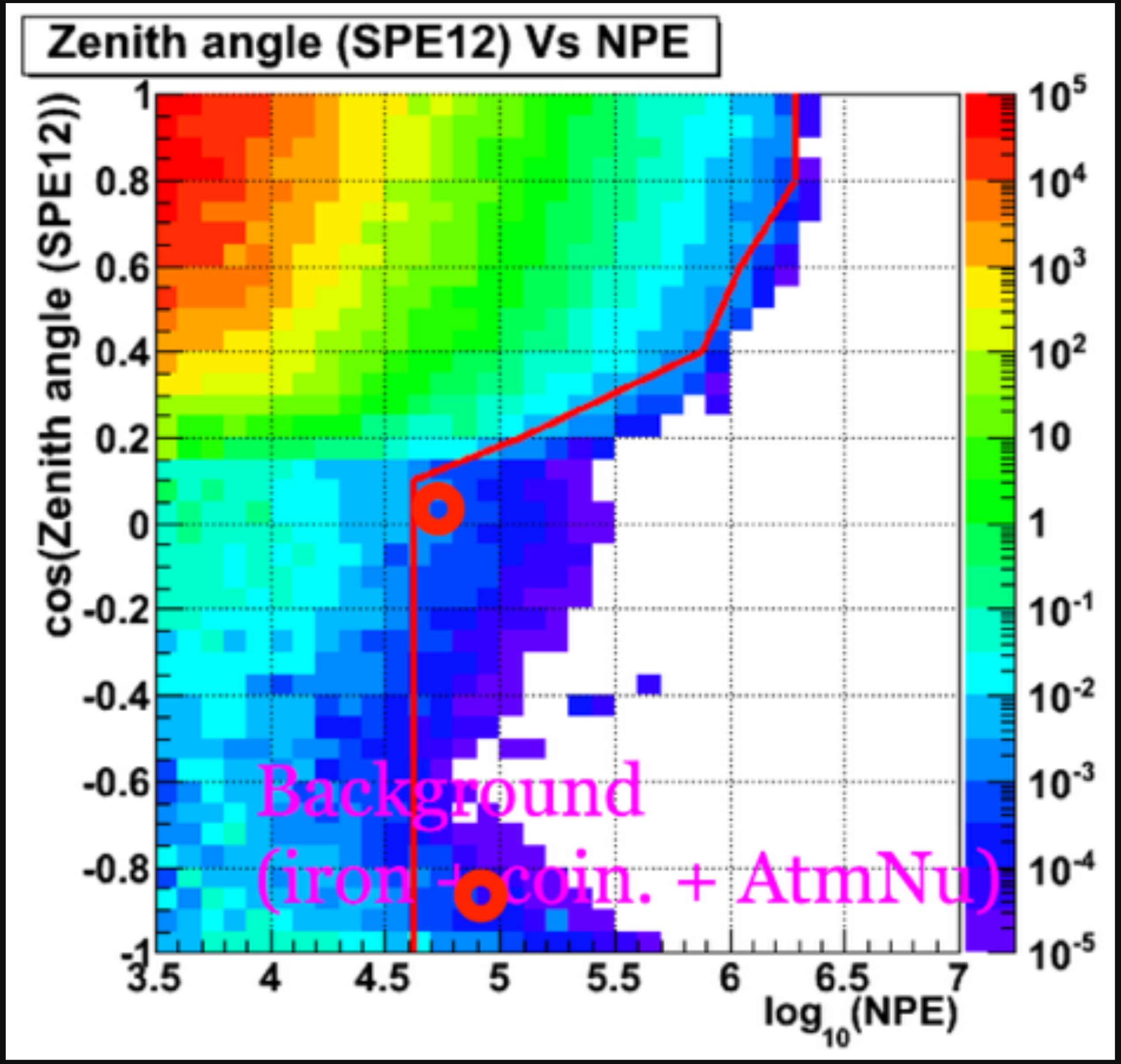
Study using the “IC40” partial detector during construction: 2.4σ



GZK Neutrino Analysis

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

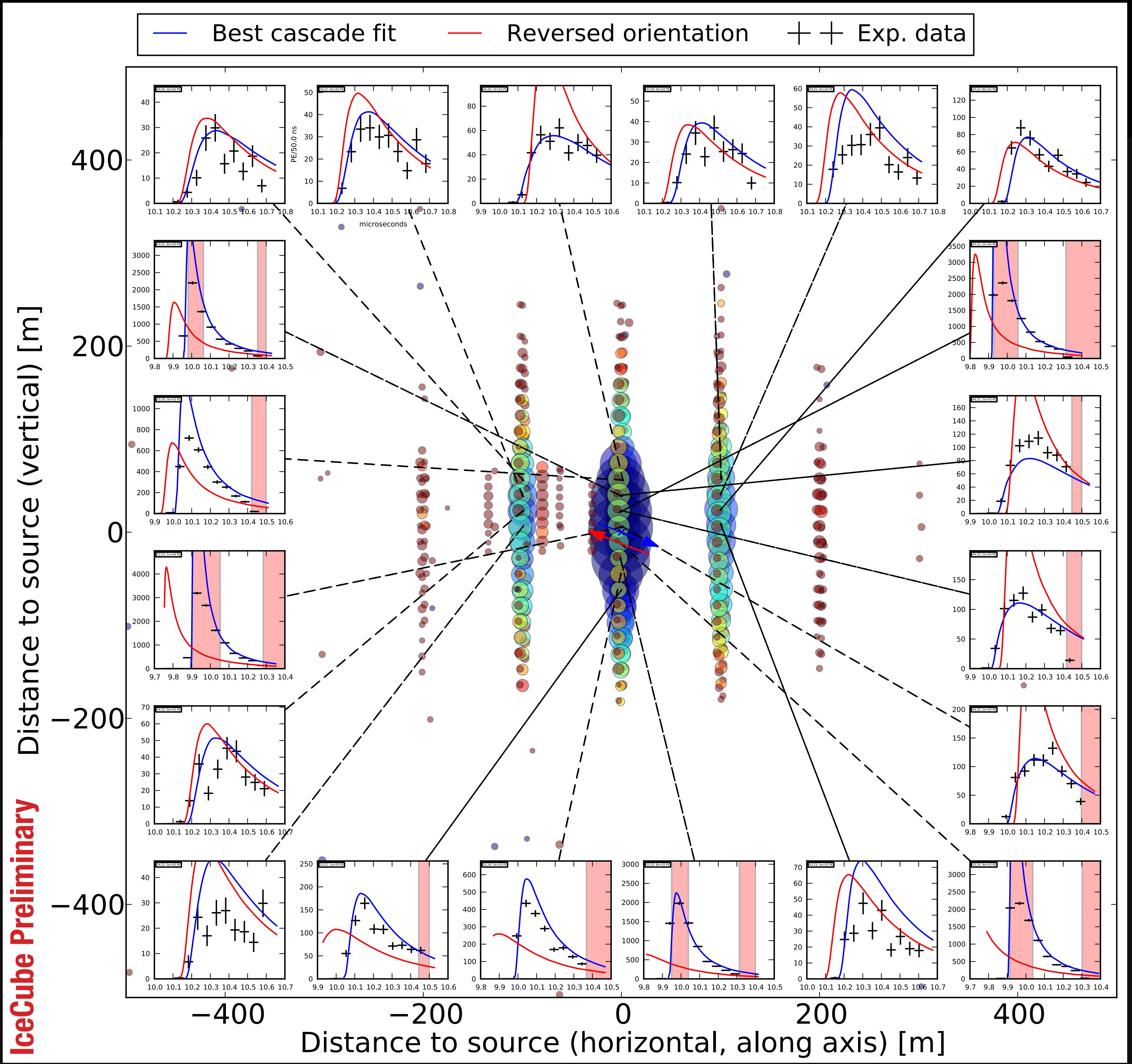
- **Upgoing muons**
  - Always neutrinos
  - Background: atm. neutrinos
  - High threshold (1 PeV)
- **Downgoing muons (VHE)**
  - Cosmic Ray muon background
  - Very high threshold (100 PeV)



What are they?

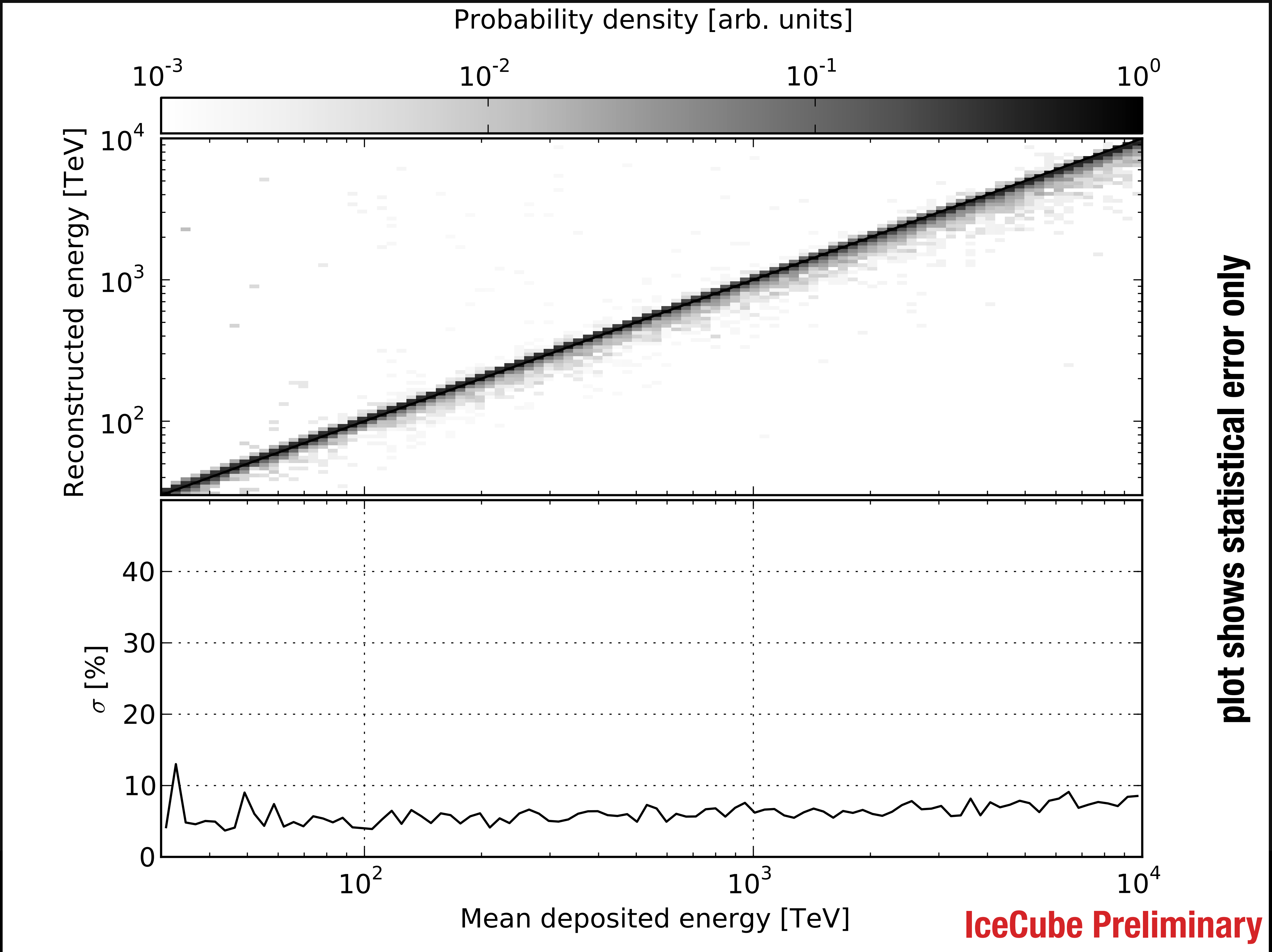
Studying individual events in IceCube

What are they?



Energy Reconstruction of EM showers

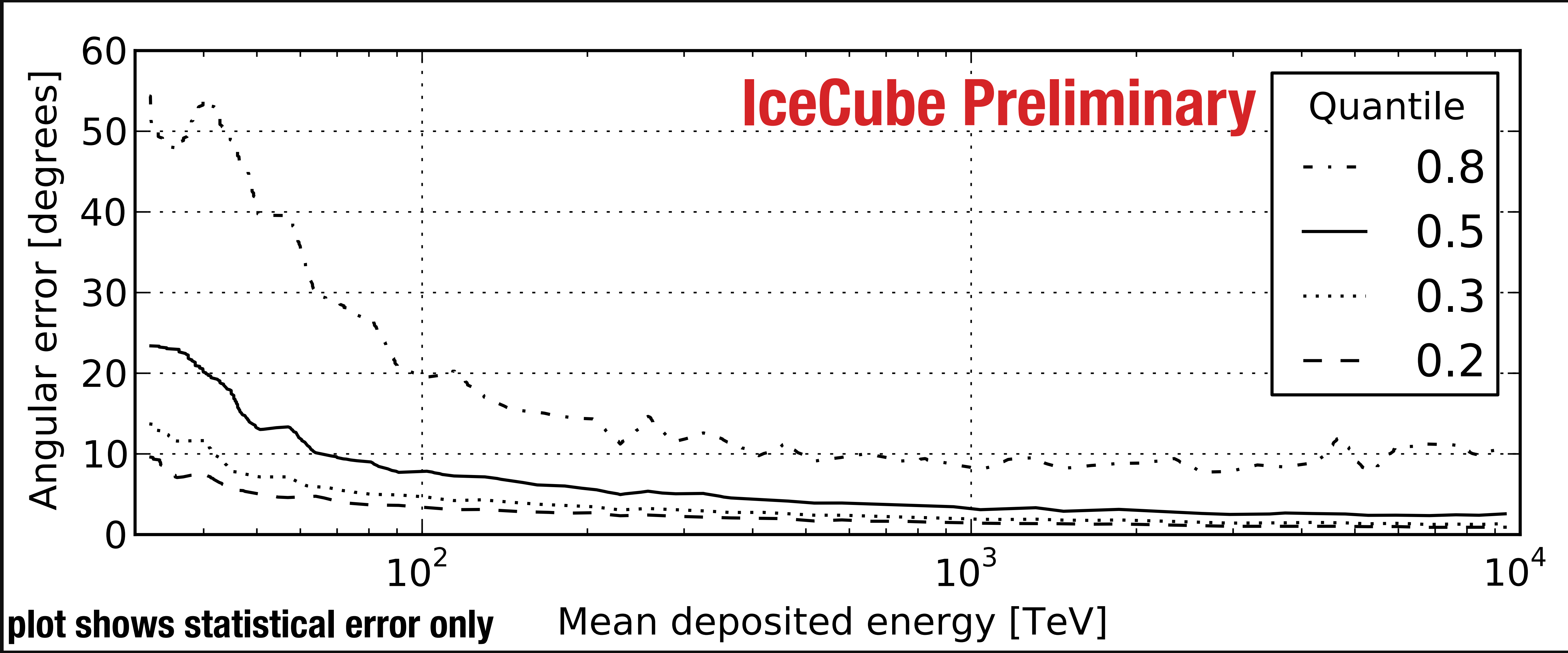
for analysis selection



plot shows statistical error only

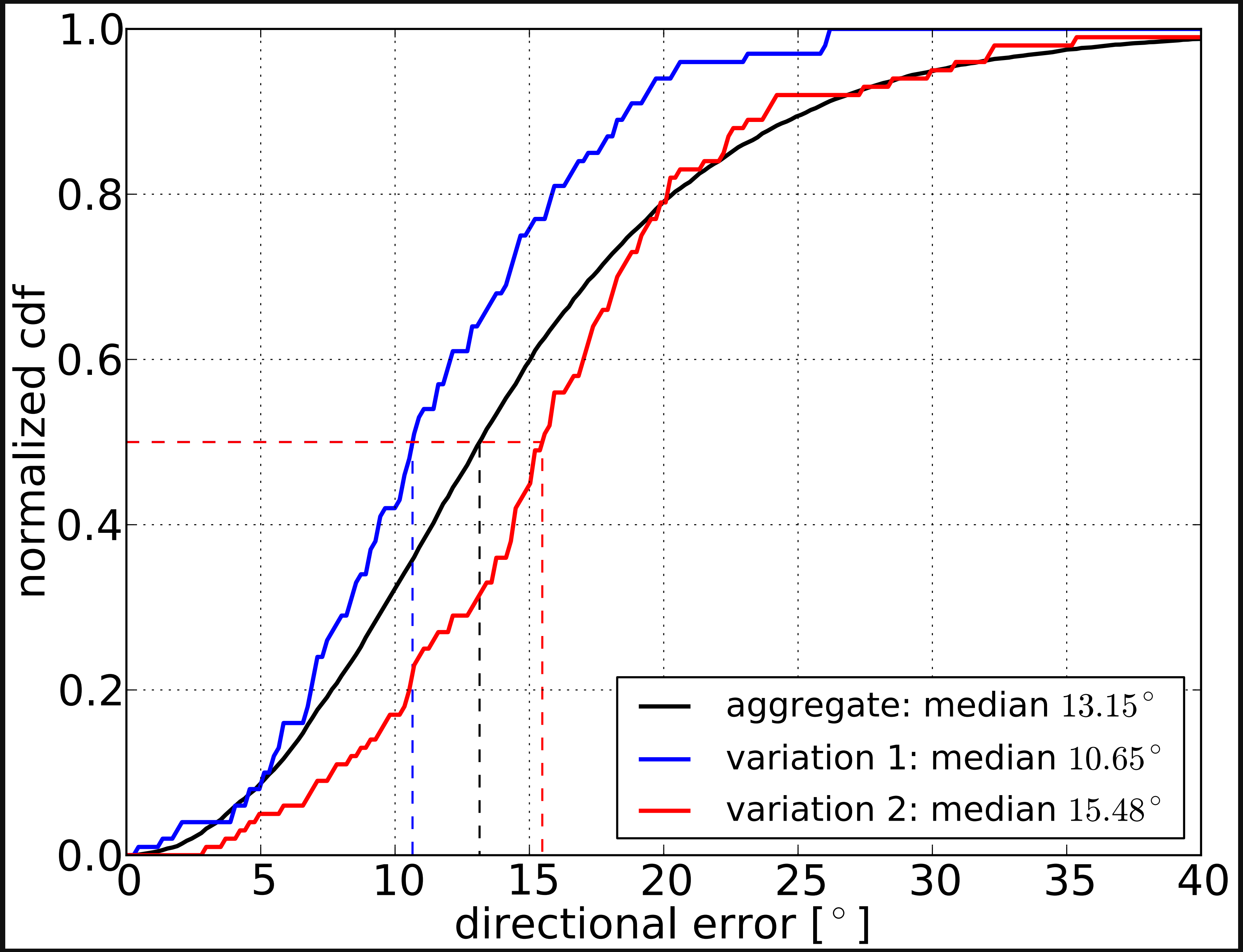
Directional Resolution for Showers

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



Directional Resolution for Showers

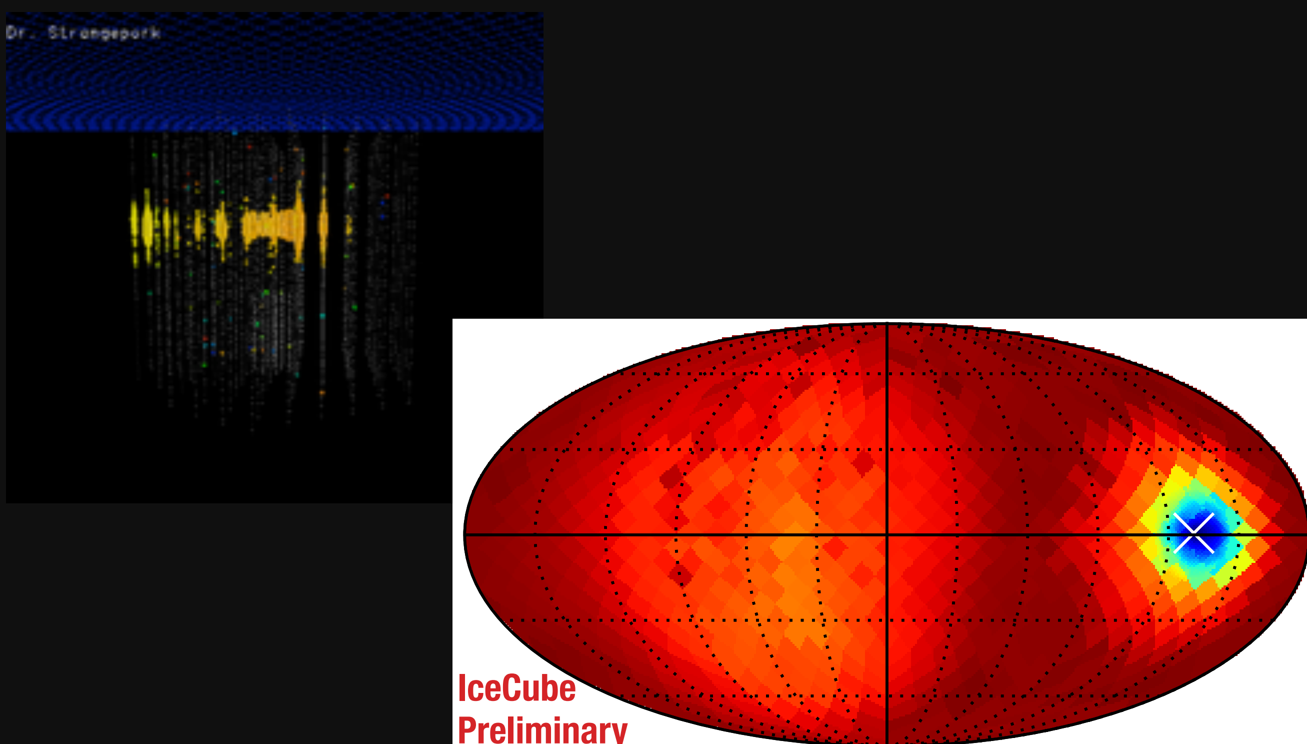
- **Angular error distributions on the order of 10°-15° depending on the ice model assumption**
  - two ice examples are shown
  - aggregate resolution in black



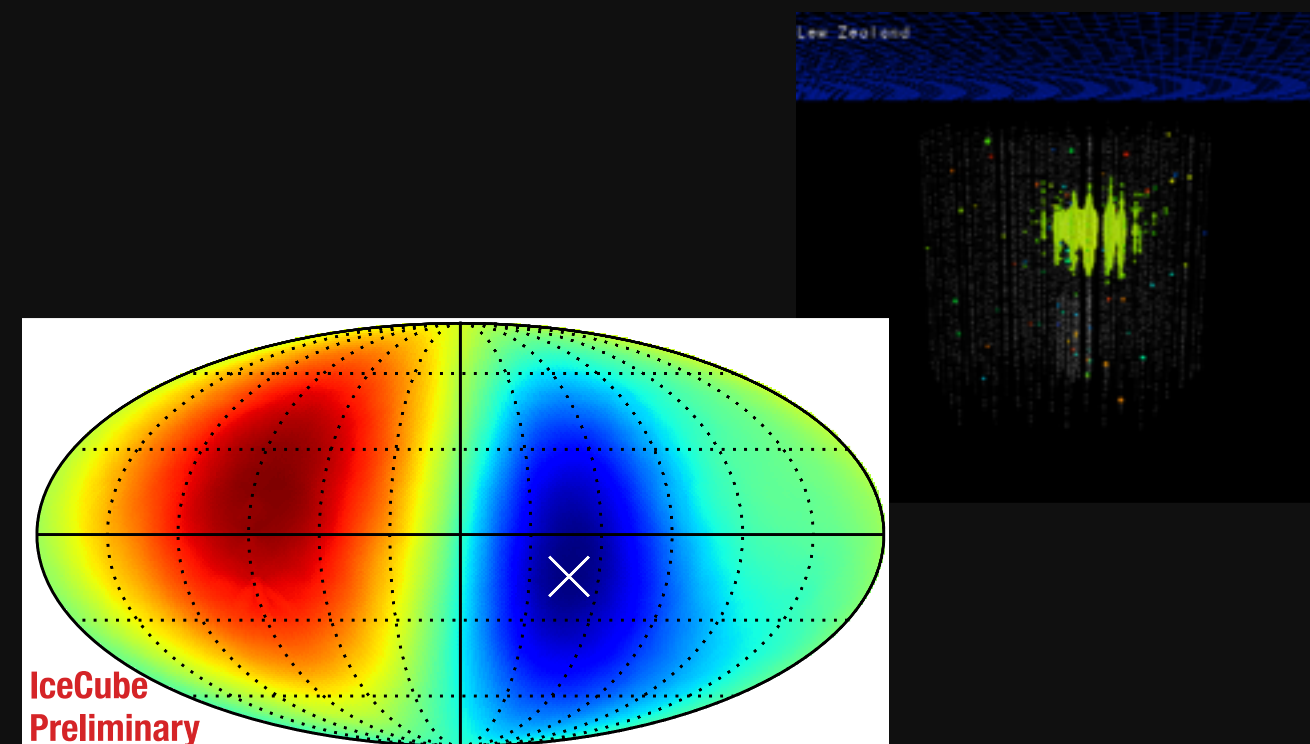
resolution for an individual example event from re-simulation

Event Reconstruction

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



track



shower

- 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

Systematics in Energy Reconstruction

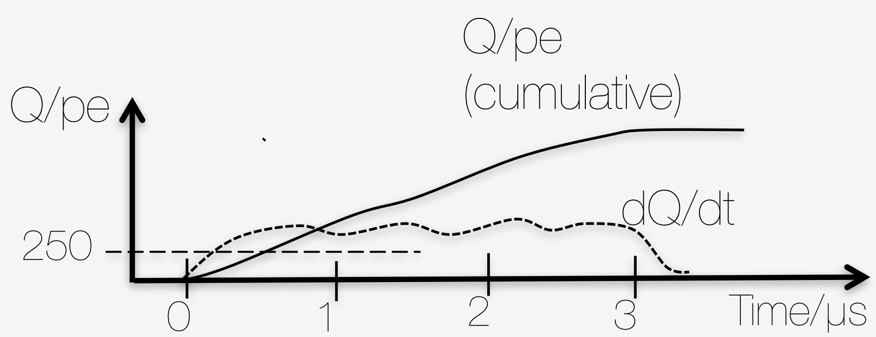
- **Energy scale: better than ≈ 10%**
  - From minimum ionizing muons: ±5%
  - Scales very well to higher energies over orders of magnitude (measured with in-ice calibration laser)
- **Modeling of photon transport in ice**
  - Measured with in-ice calibration LEDs and other devices (dust logger, ...)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

Background 1 - Atmospheric Muons

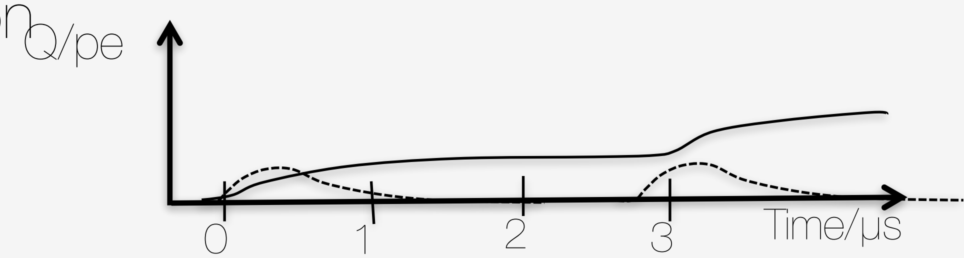
What's "early charge"?

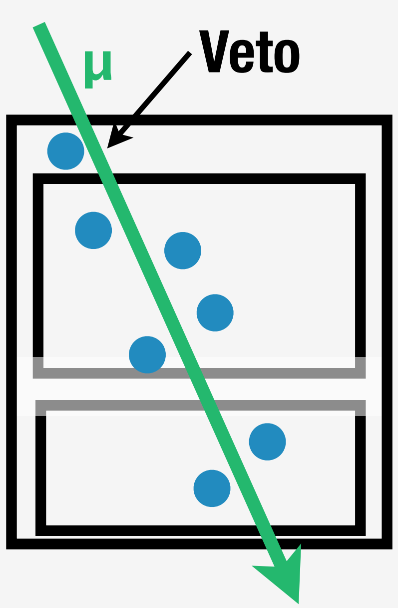
Throughgoing muon

Total detector



Veto region

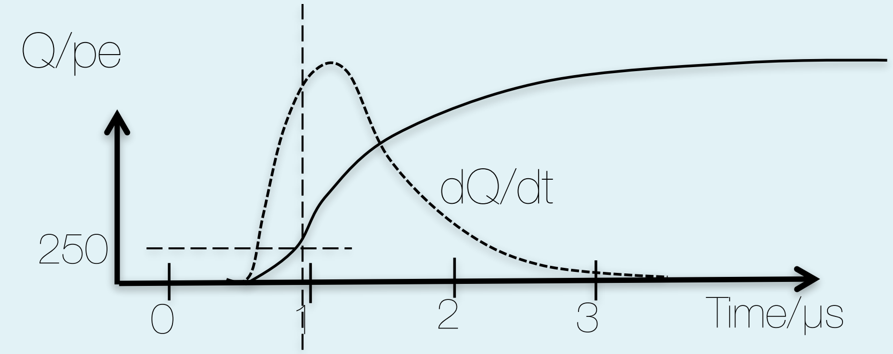


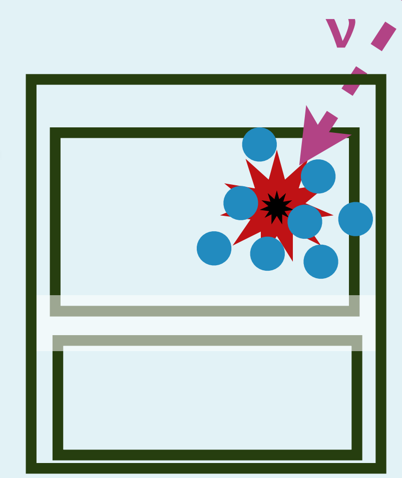


T_{250}= time at which Q= 250 pe

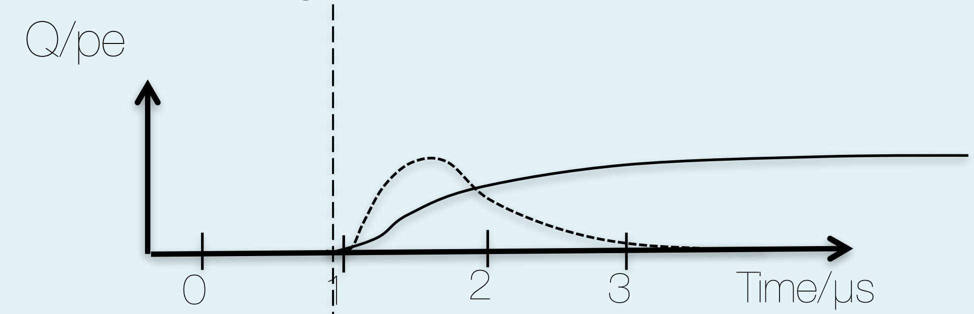
Contained cascade

Total detector

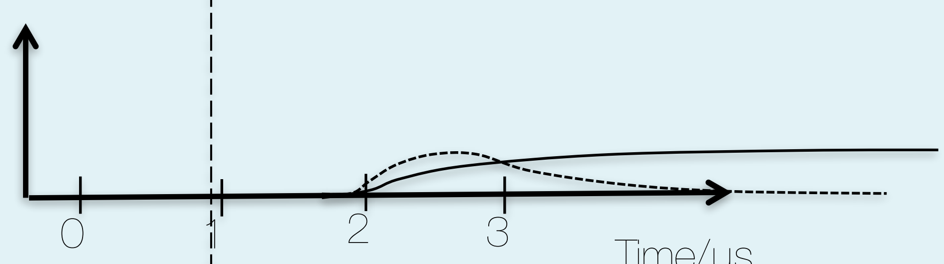




Veto region – barely contained cascade



Veto region – well contained cascade

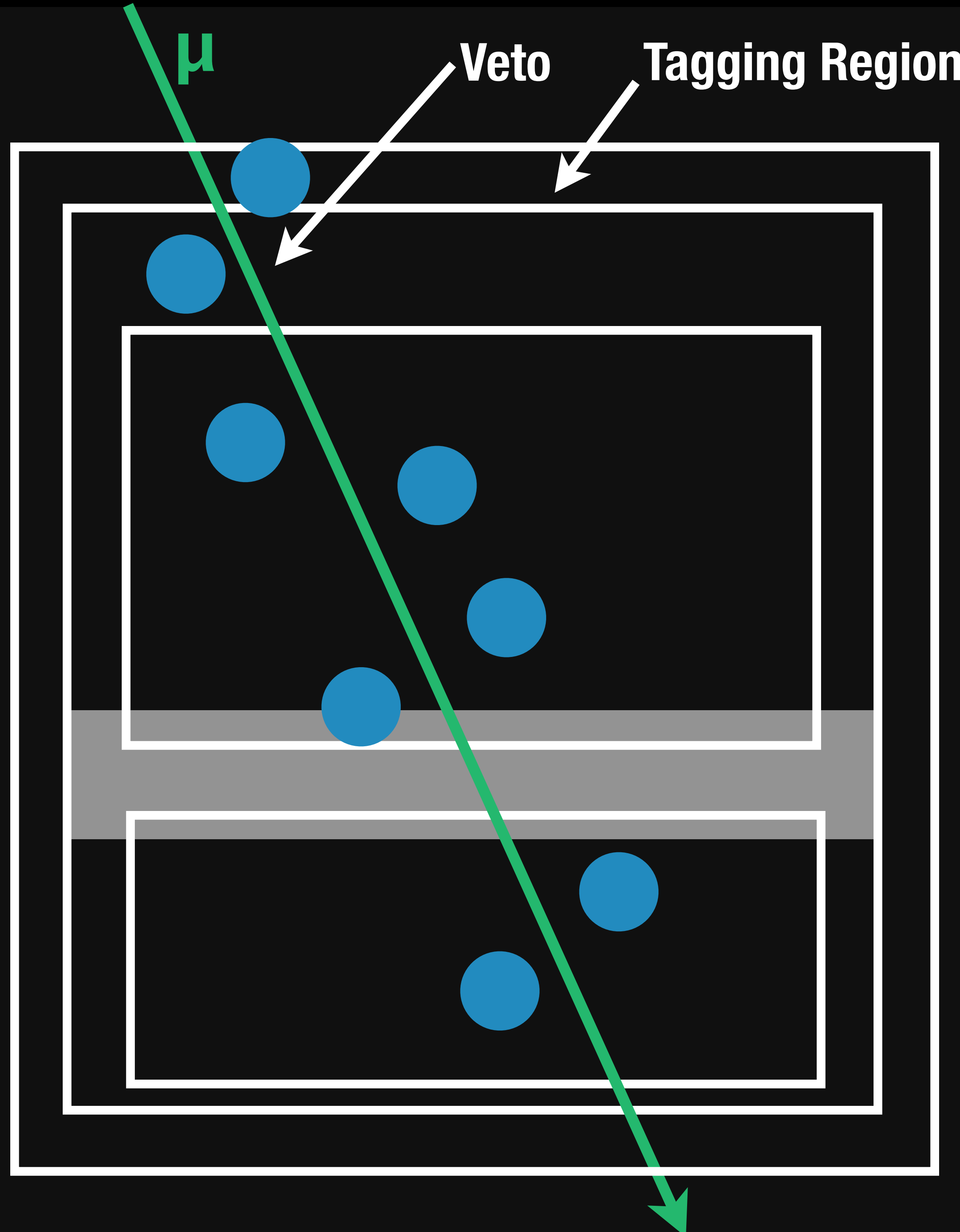


T_{250}= time at which Q= 250 pe

Estimating Muon Background From Data

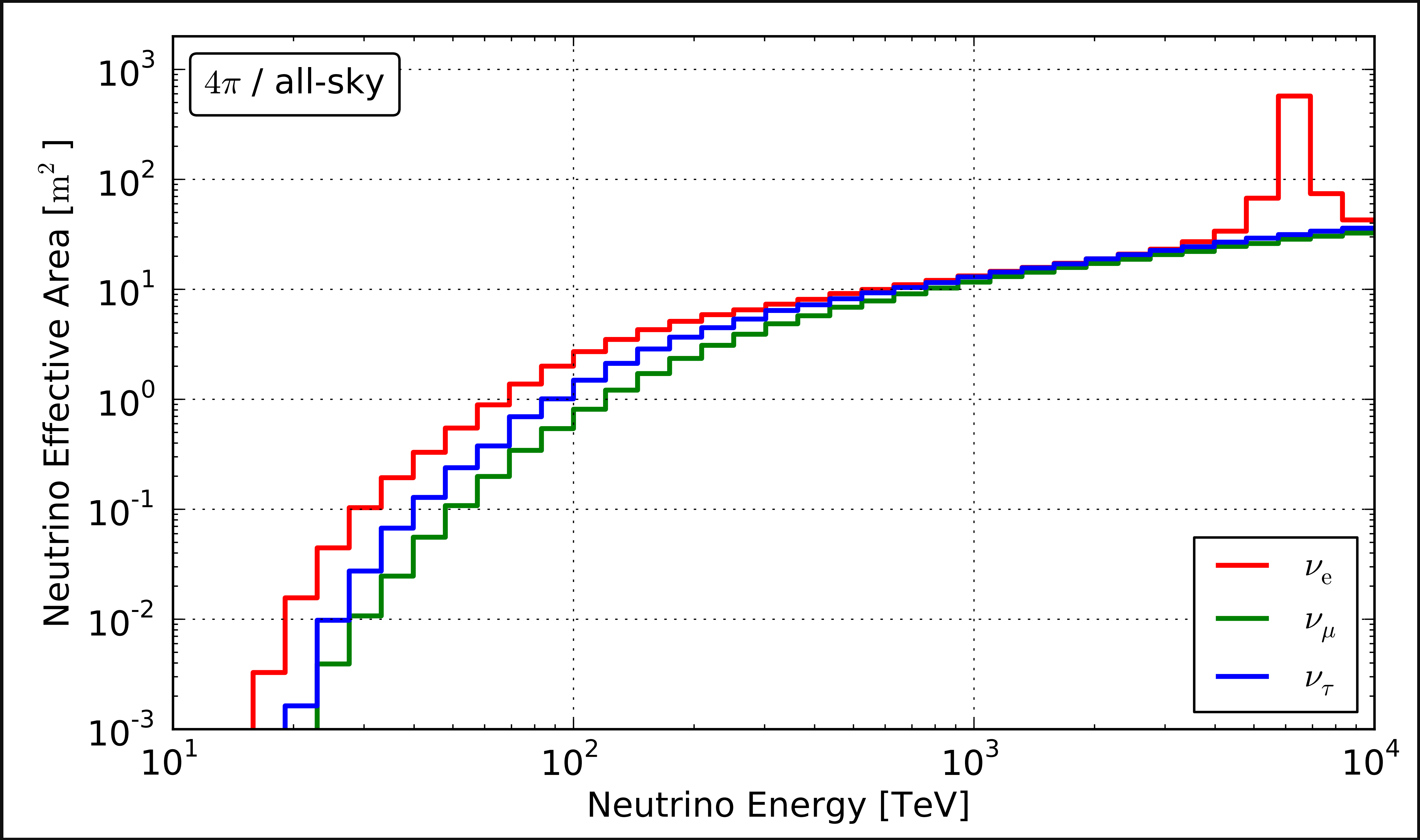
Use known background from atmospheric muons tagged in an outer layer to estimate the veto efficiency

- 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 our cut (6000 p.e.) where background dominates



Effective Area

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



Systematic Studies and Cross-Checks

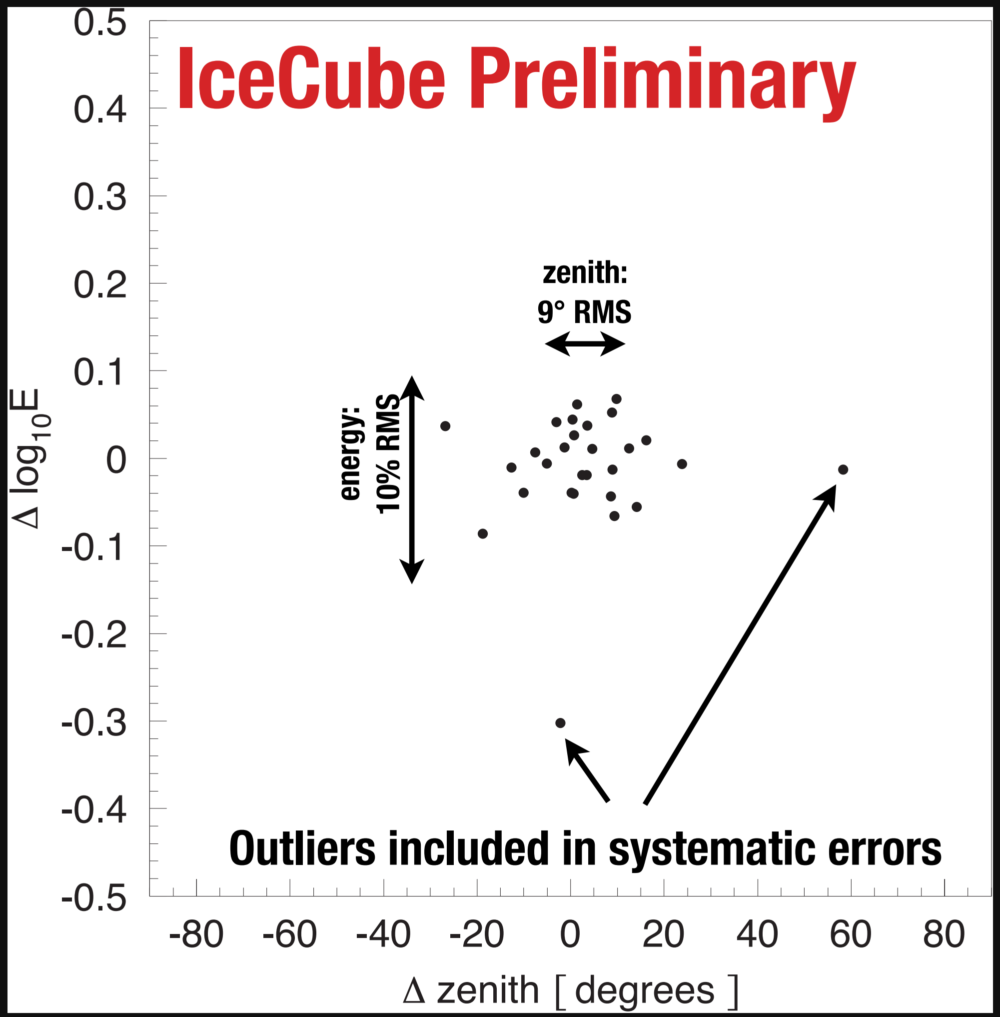
- **Systematics were checked using an extensive per-event re-simulation**
  - varied the ice model and energy scale within uncertainties for each iteration and repeated analysis
- **Different fit methods applied to the events show consistent results**

- **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

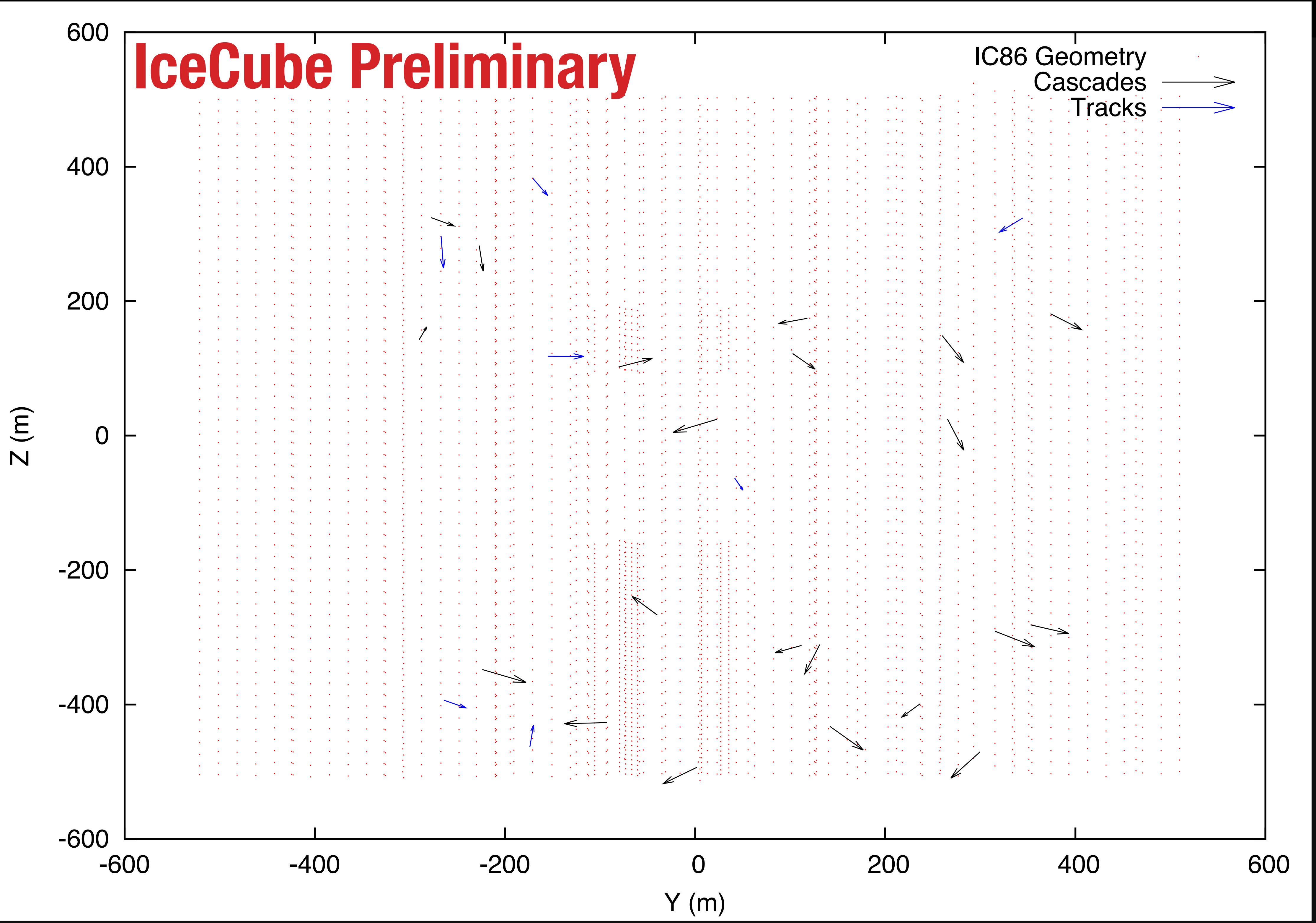
Cross-check with a fit method based on direct re-simulation of events

- **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%**



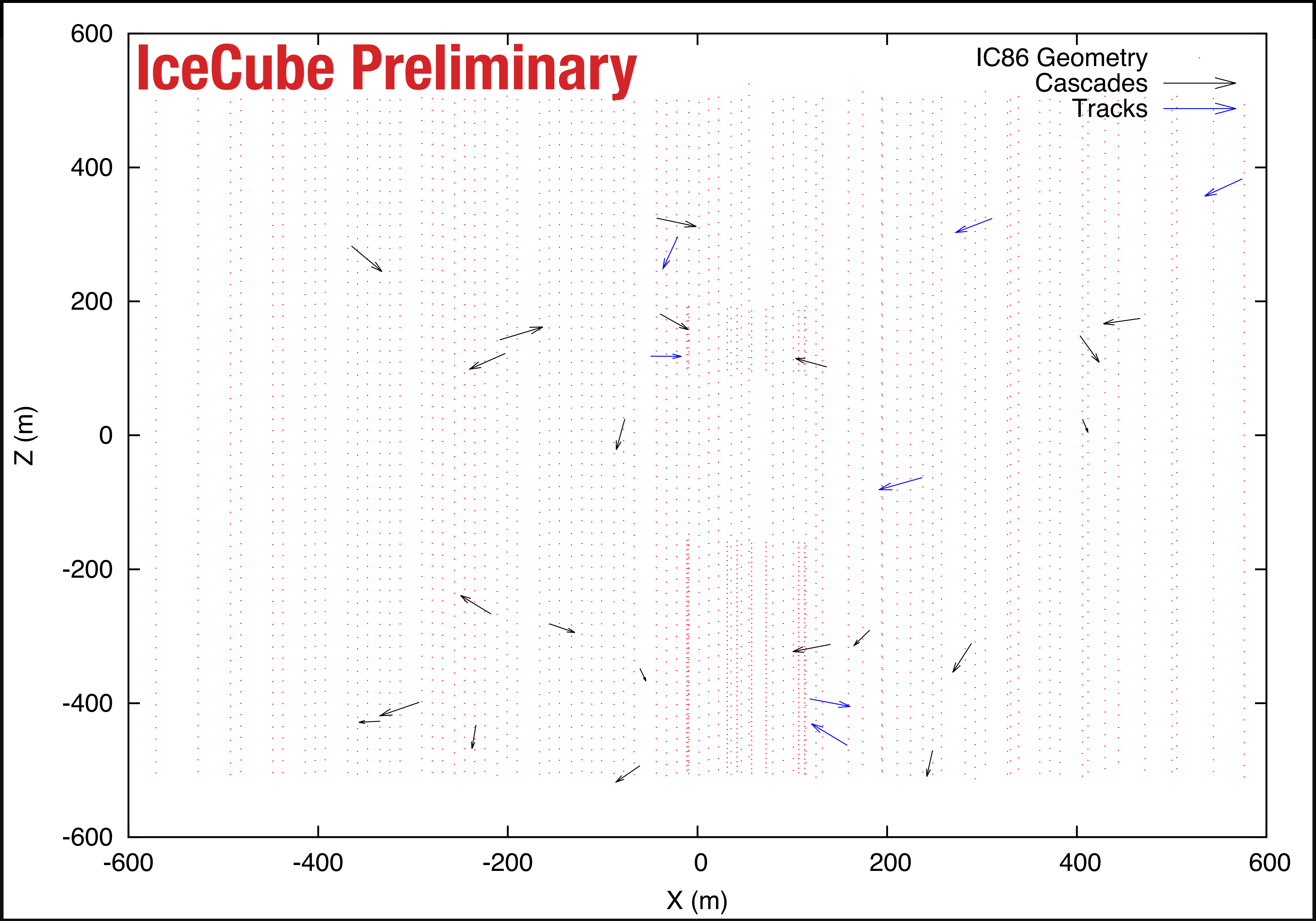
Event Distribution in Detector

Uniform in fiducial volume



Event Distribution in Detector

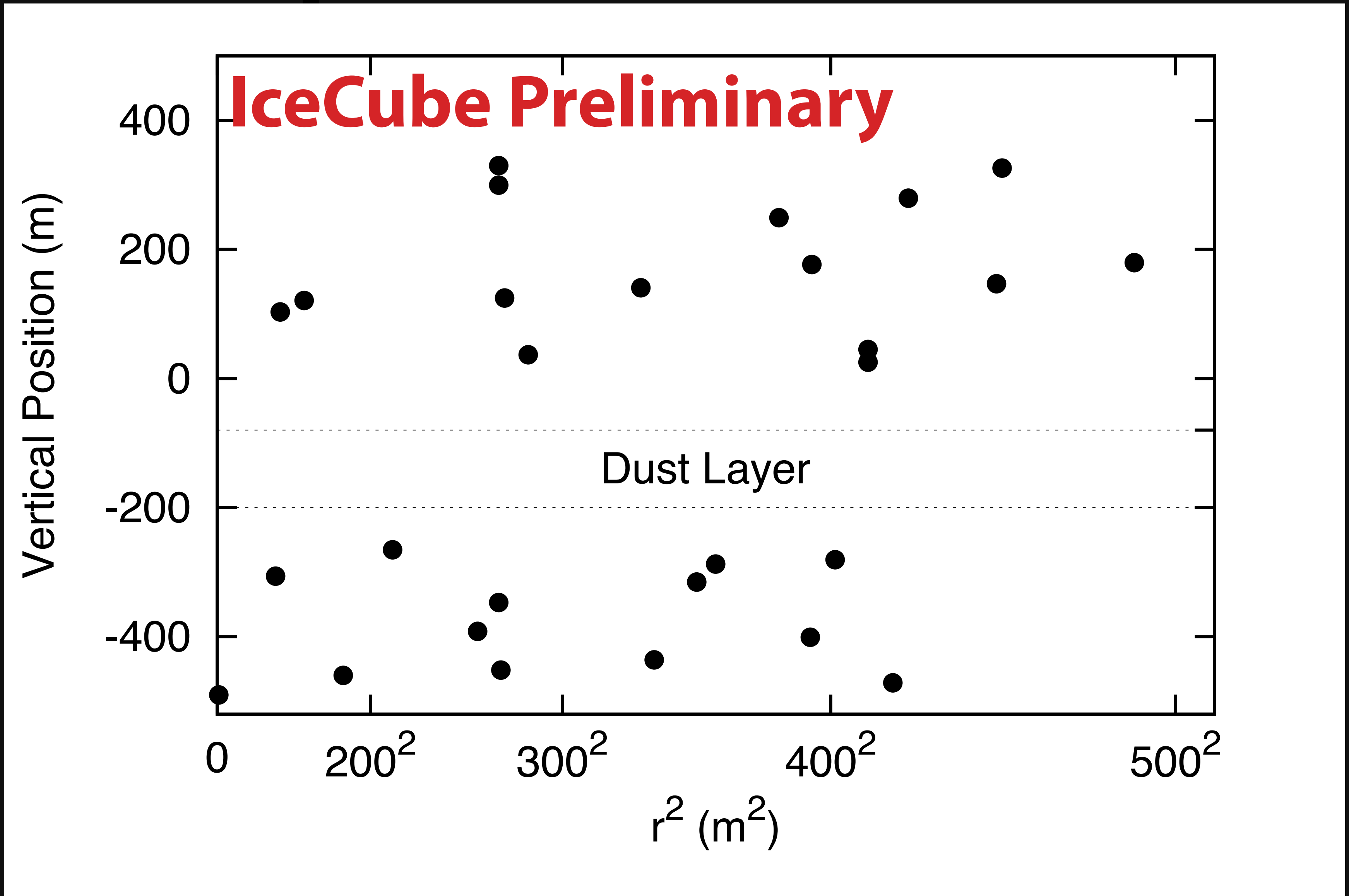
Uniform in fiducial volume



Event Distribution in Detector

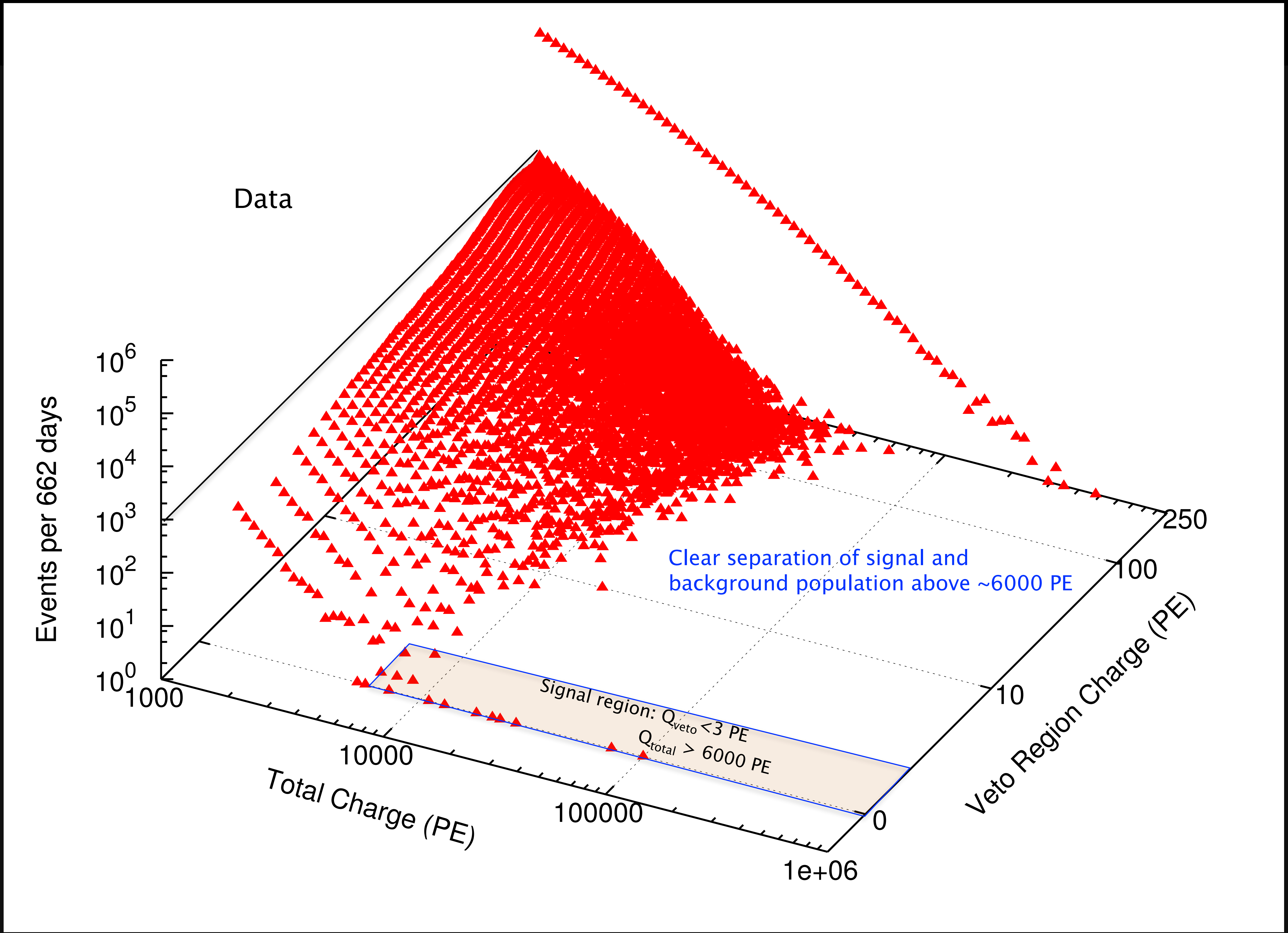
Uniform in fiducial volume

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



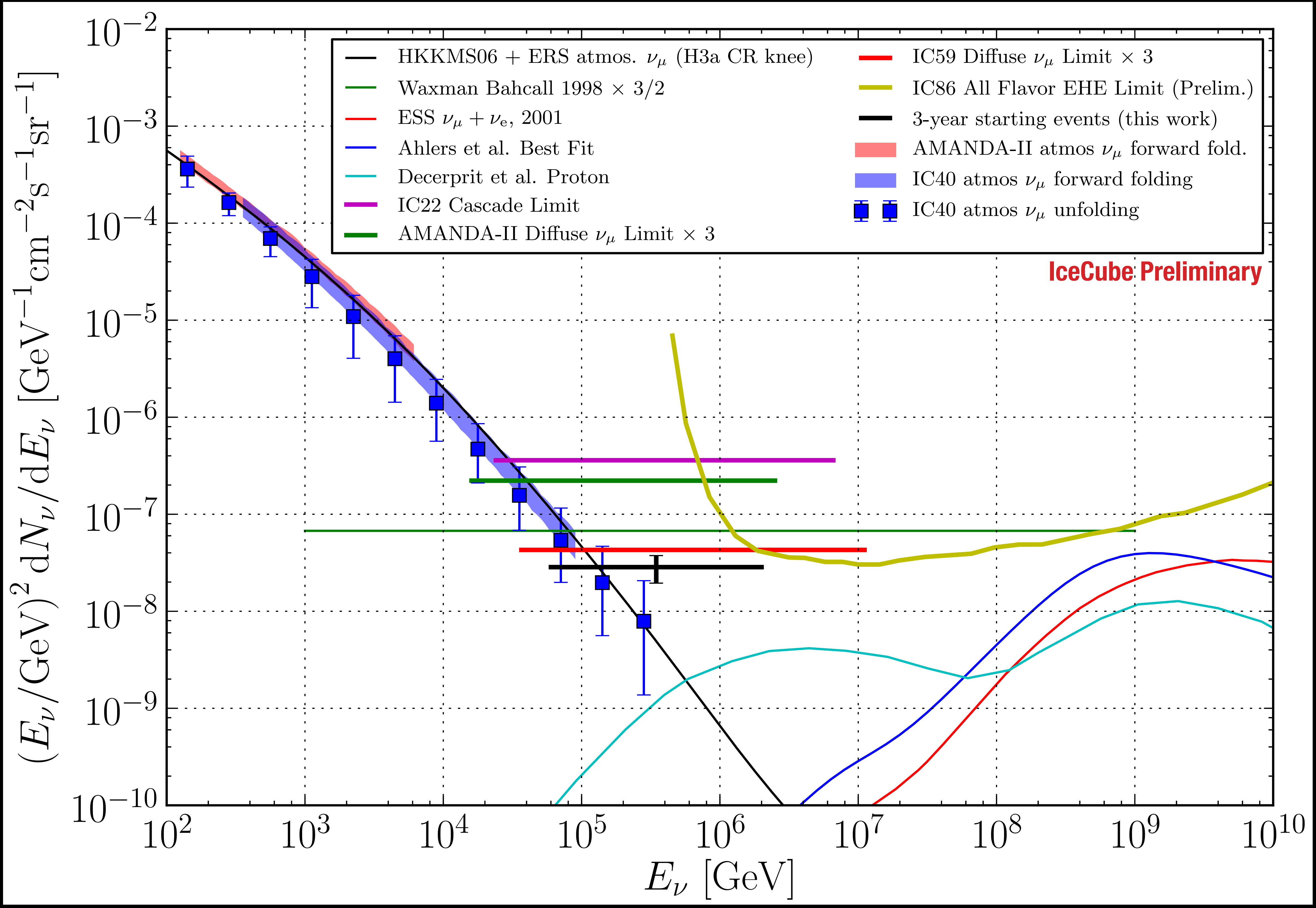
Events Selection

Charge in veto region vs. total charge



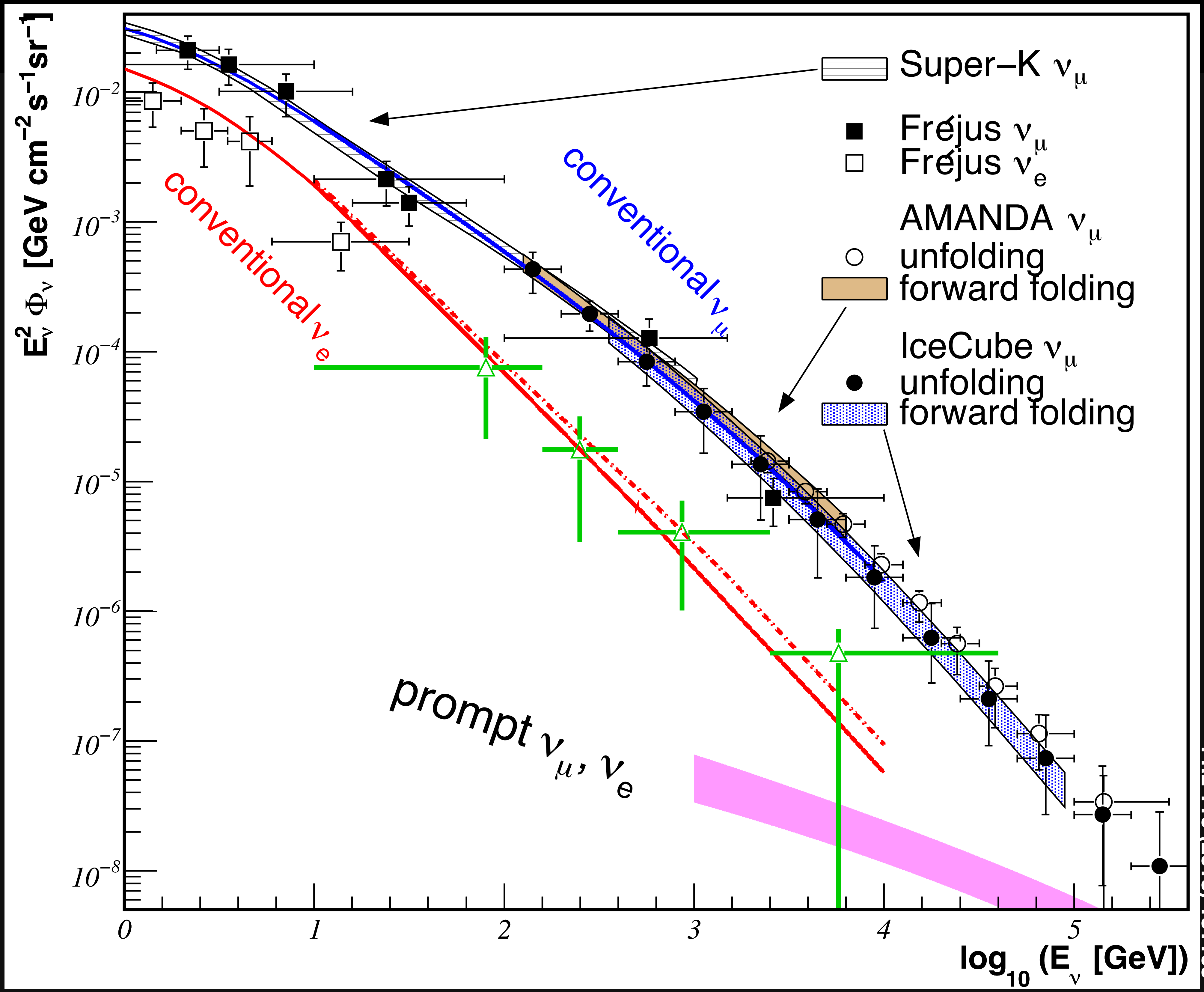
Fluxes and Limits

Fluxes normalized to 3 flavors (1:1:1) except atm. neutrinos



Atmospheric Neutrino Spectrum

Measured with IceCube in ν_μ and ν_e



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