Recent Results from IceCube

Searches for high-energy neutrinos and future plans

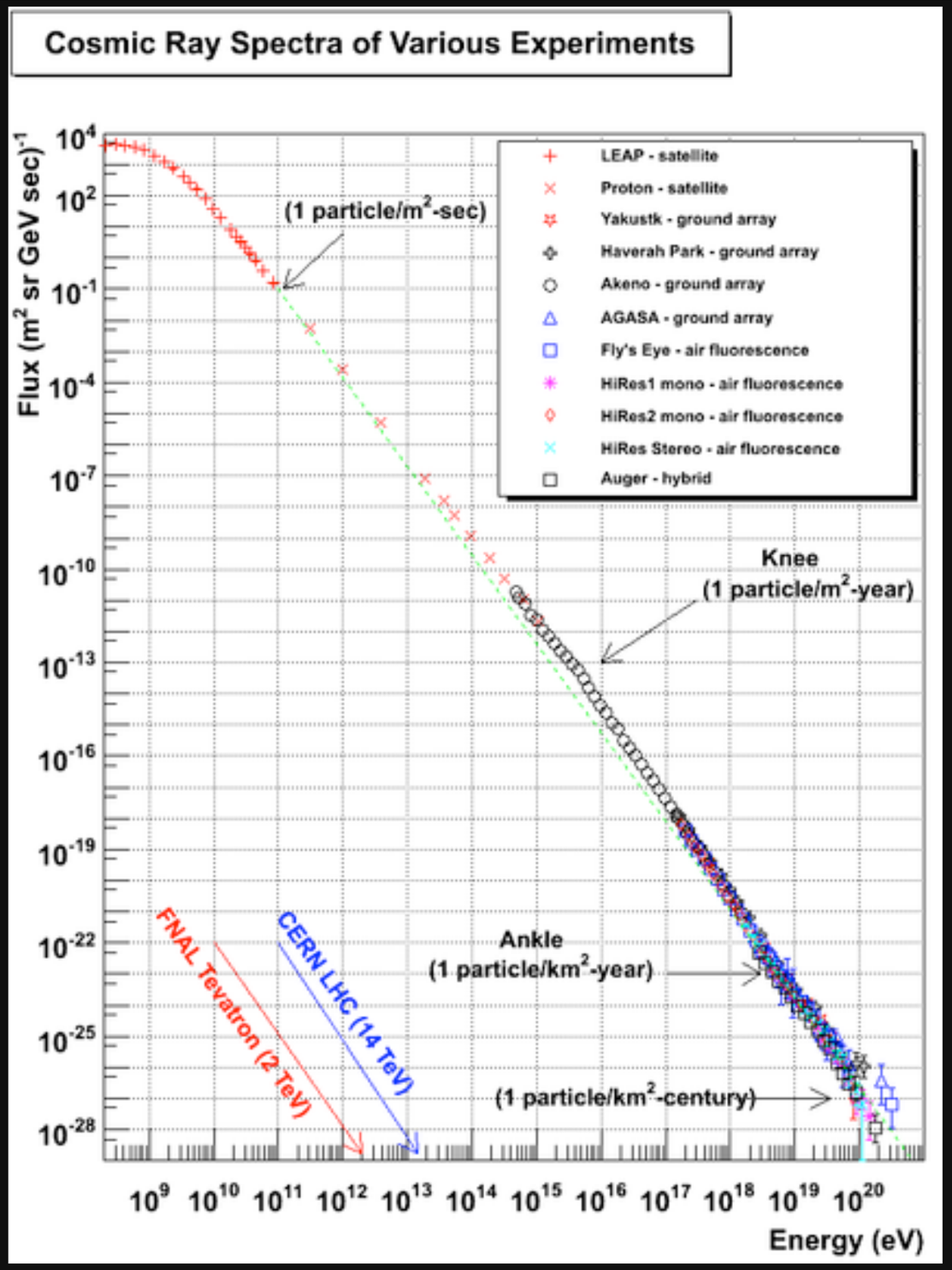
Claudio Kopper, University of Alberta

kopper@ualberta.ca

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…)

$$\mathrm{p} + \gamma \rightarrow \pi^0 + \mathrm{p}$$

or p, …

$$\hookrightarrow \gamma + \gamma + \mathrm{p}$$

$$\rightarrow \pi^+ + \mathrm{n}$$

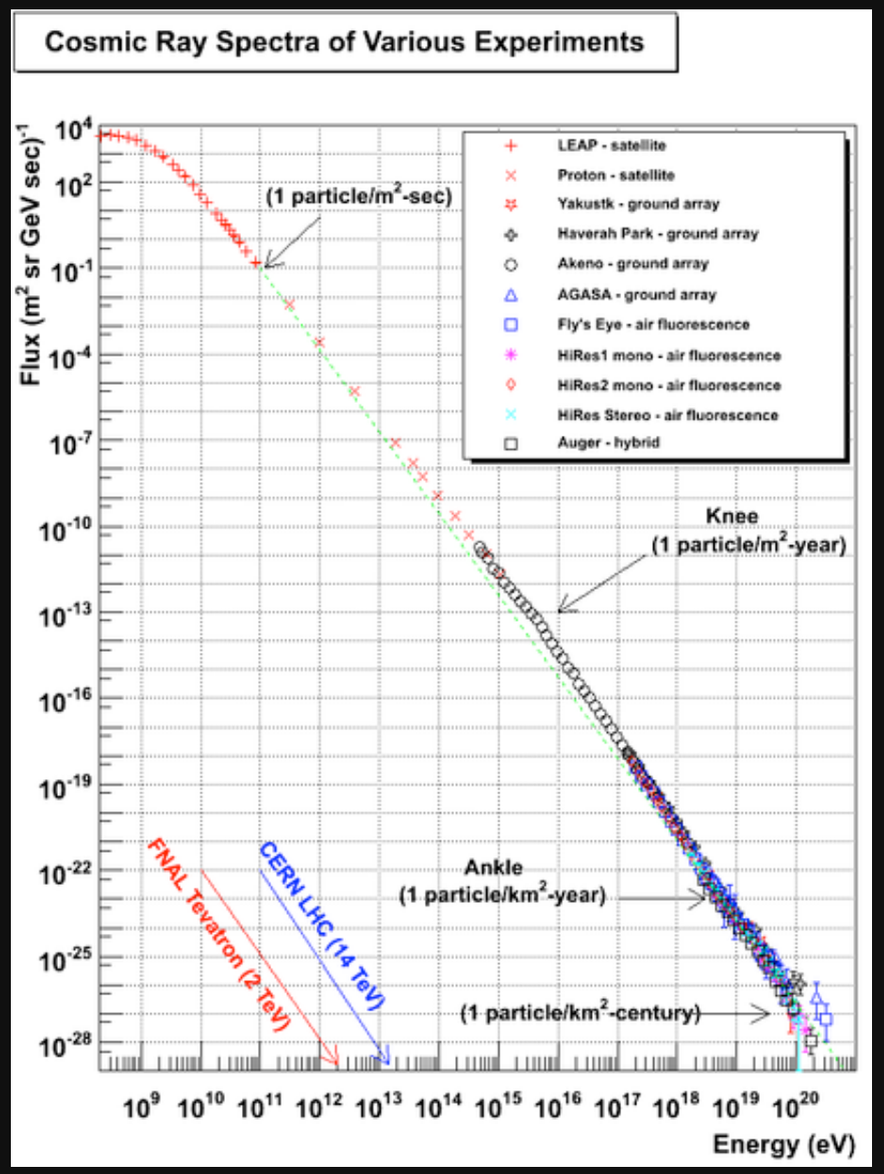
$$\hookrightarrow \mu^+ + \nu_\mu + \mathrm{n}$$

$$\hookrightarrow \mathrm{e}^+ + \nu_{\bar{\mu}} + \nu_\mathrm{e} + \nu_\mu + \mathrm{n}$$

TeV gamma rays

Cosmic rays?

TeV neutrinos

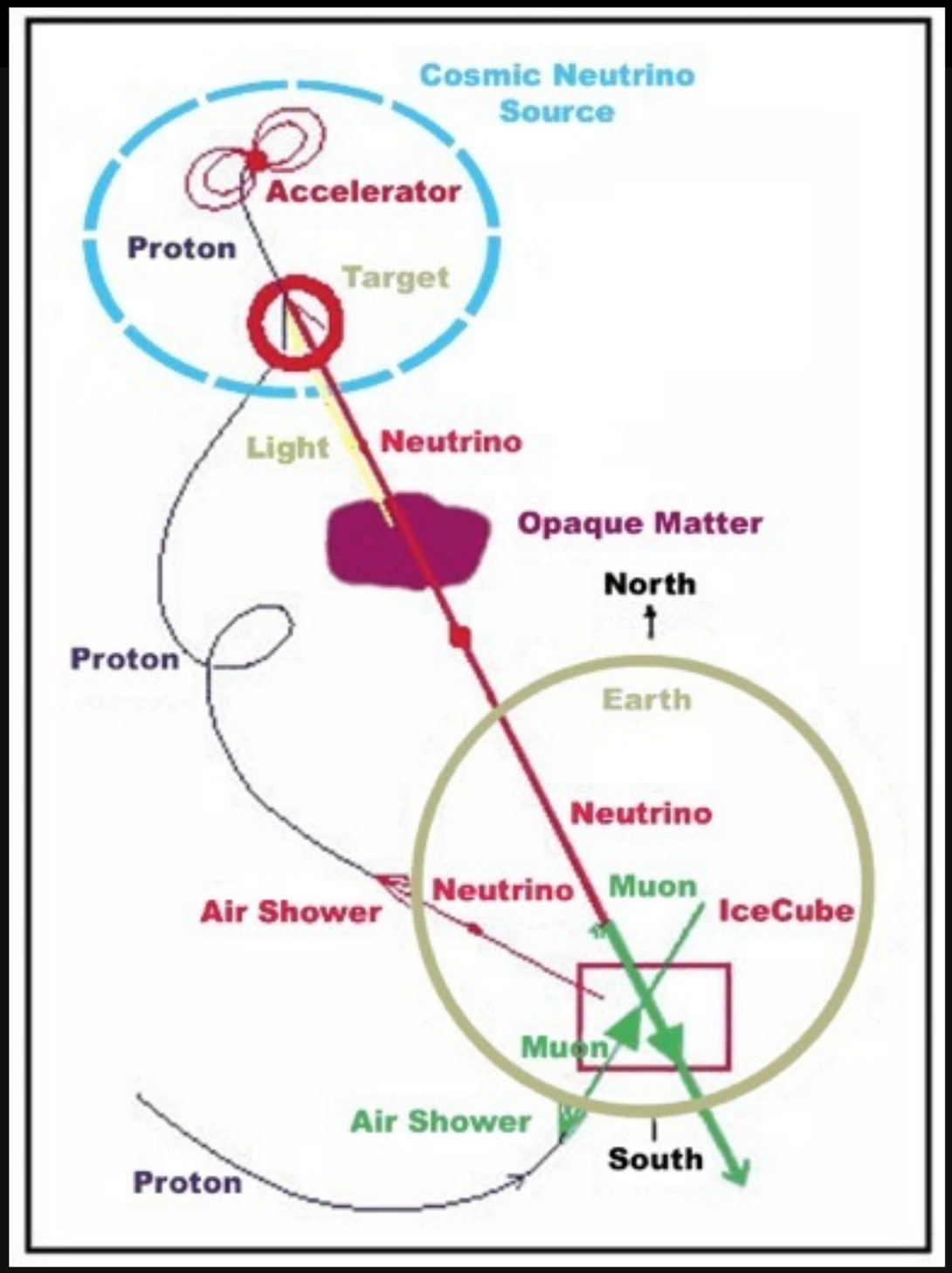


- **Neutrinos from cosmic ray interactions in:**
  - Atmosphere
  - Cosmic Microwave Background
  - Gamma Ray Bursts (Acceleration Sites)
  - Active Galactic Nuclei (Acceleration Sites)
  - ?

Why Neutrinos?

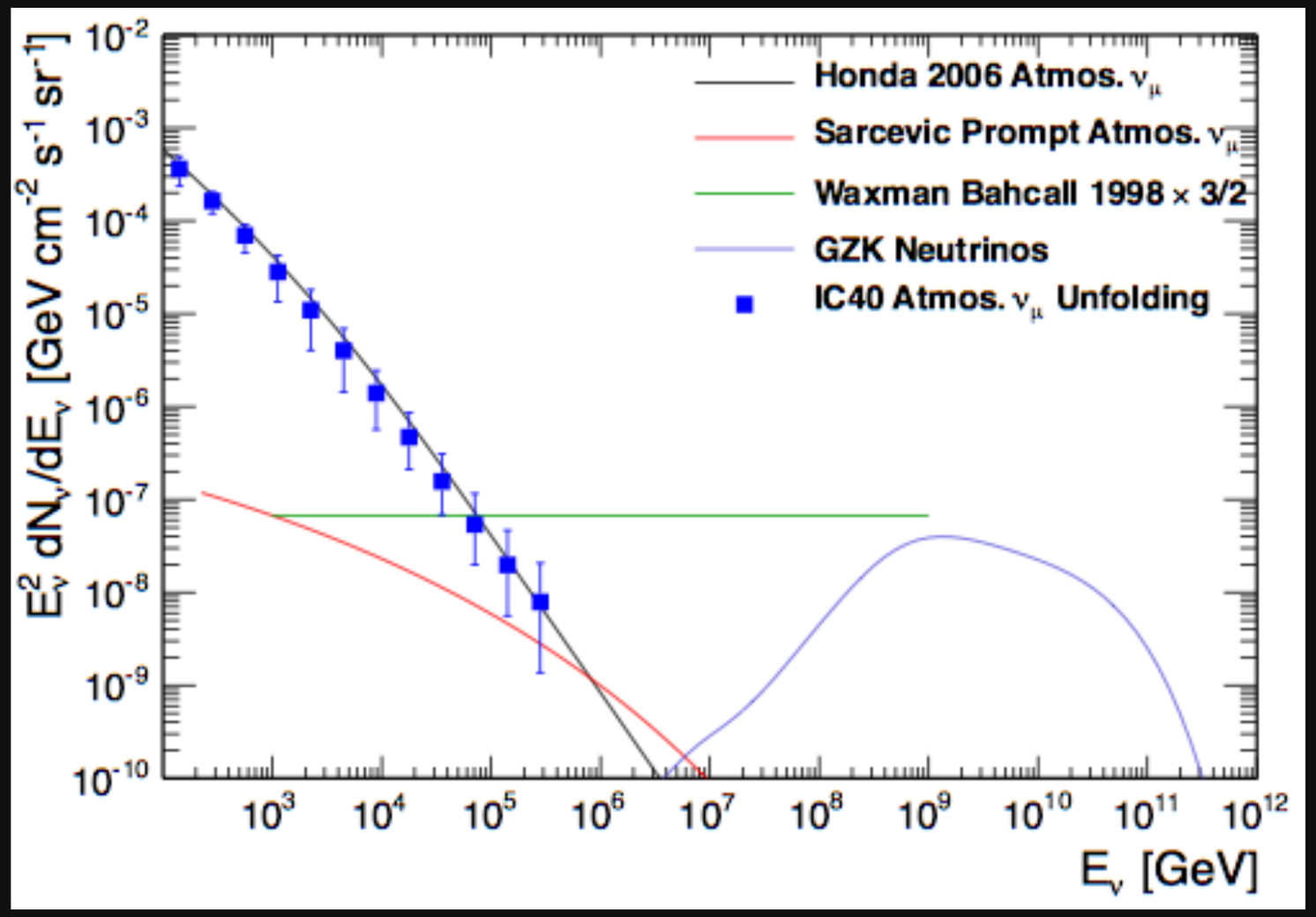
Neutrinos are ideal astrophysical messengers

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



Interesting Neutrinos above 1 TeV

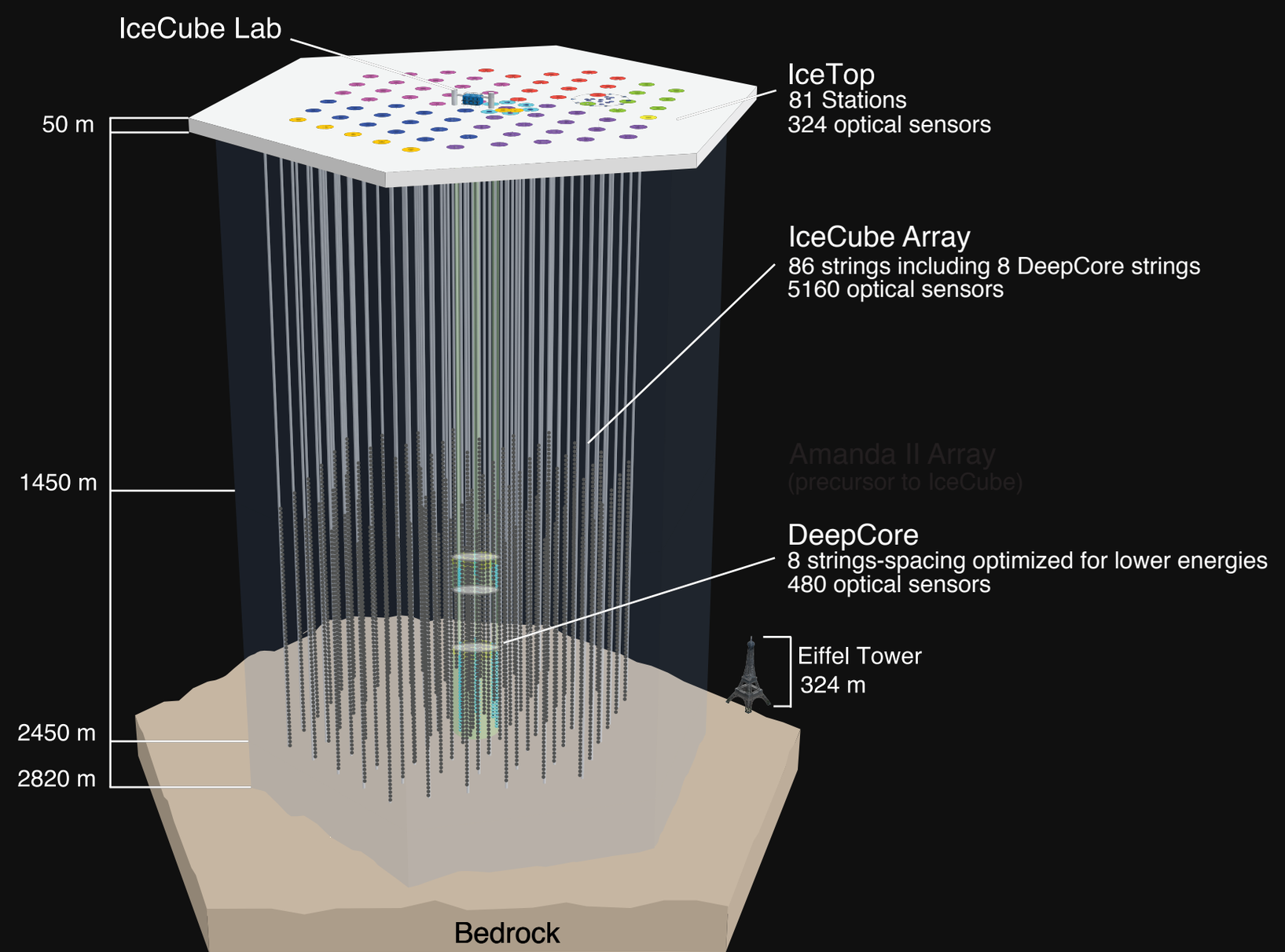
- **Atmospheric neutrinos (π/K)**
  - dominant < 100 TeV
- **Atmospheric neutrinos (charm)**
  - "prompt" ~ 100 TeV
- **Astrophysical neutrinos**
  - maybe dominant > 100 TeV
- **Cosmogenic neutrinos**
  - $>10^6$ TeV



The IceCube Neutrino Observatory

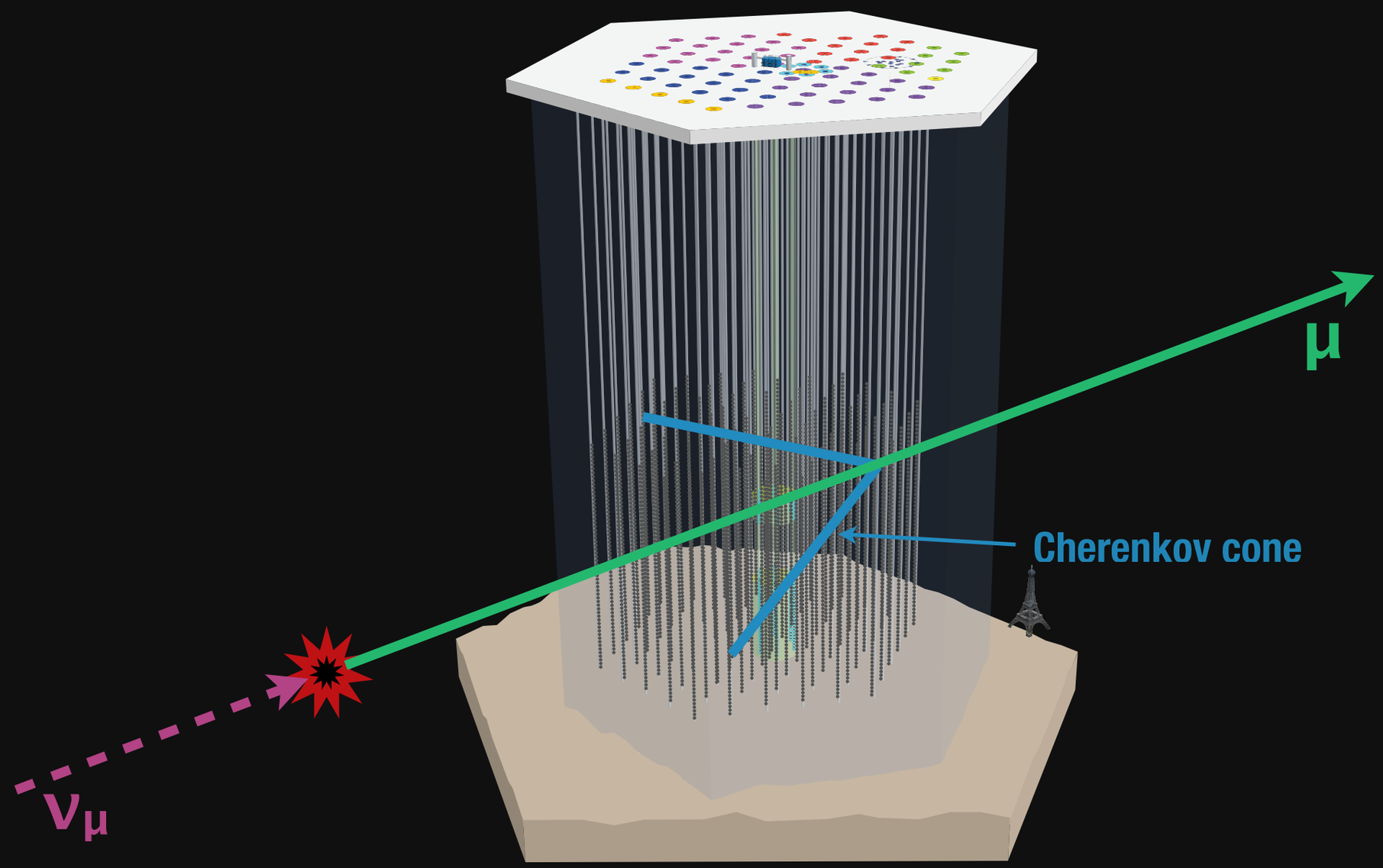
Deployed in the deep glacial ice at the South Pole

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



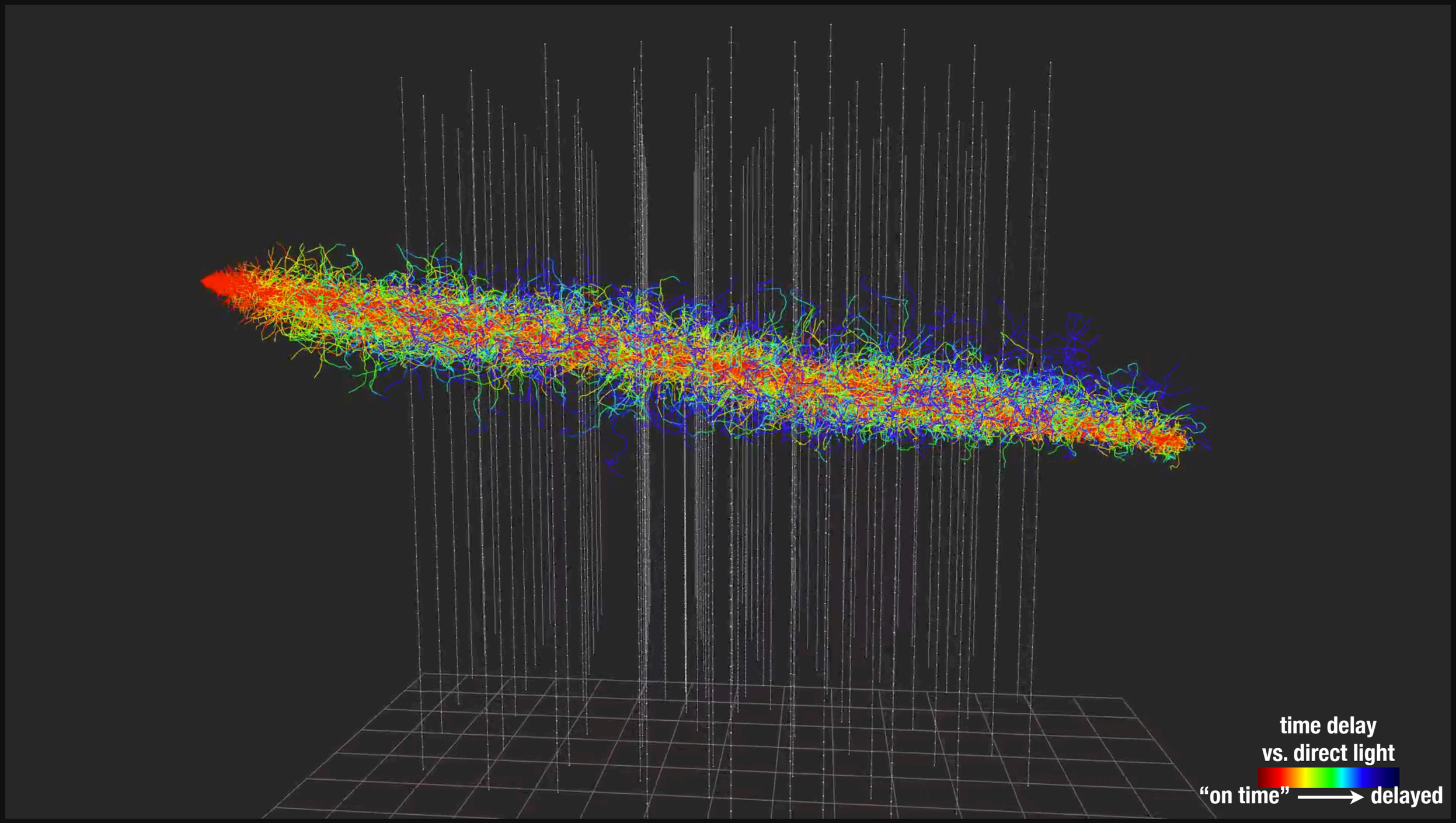
The IceCube Neutrino Observatory

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

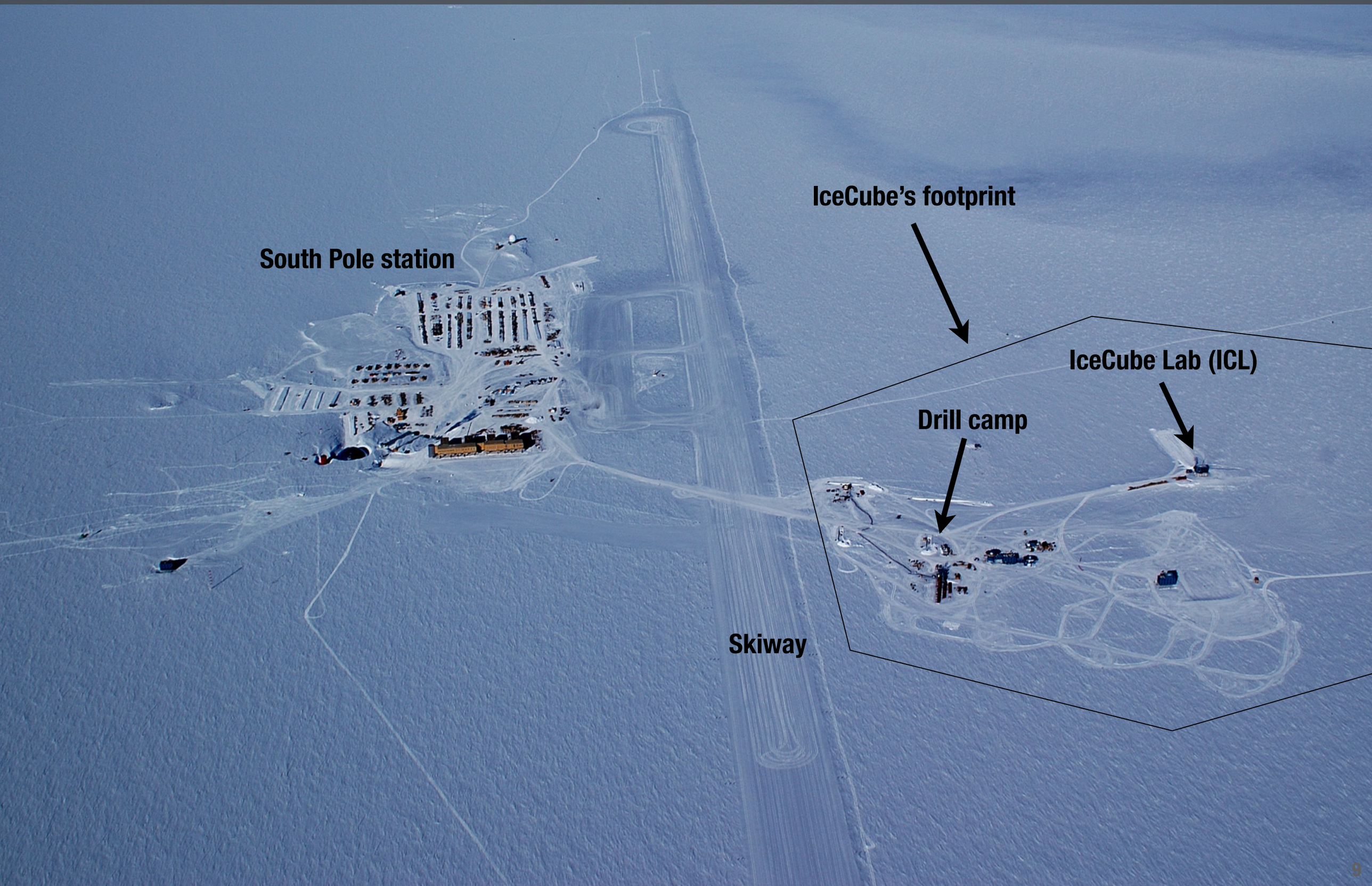


The IceCube Neutrino Observatory

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



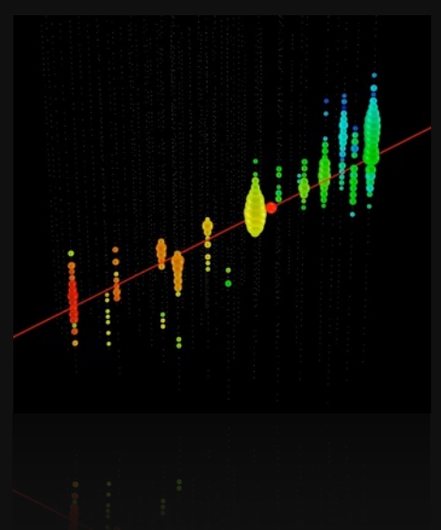
The IceCube Neutrino Observatory



Neutrino Event Signatures

Signatures of signal events

CC Muon Neutrino

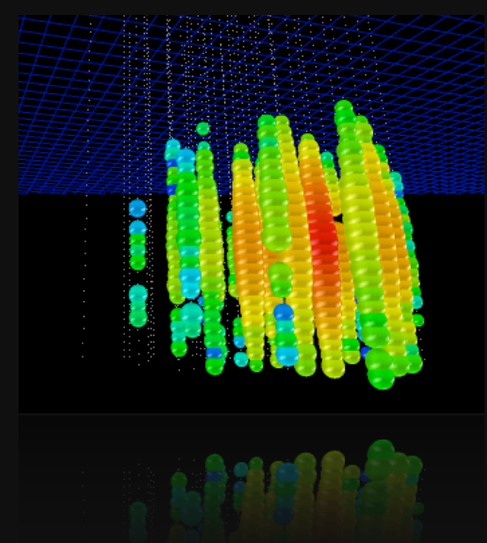


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

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

Neutral Current / Electron Neutrino



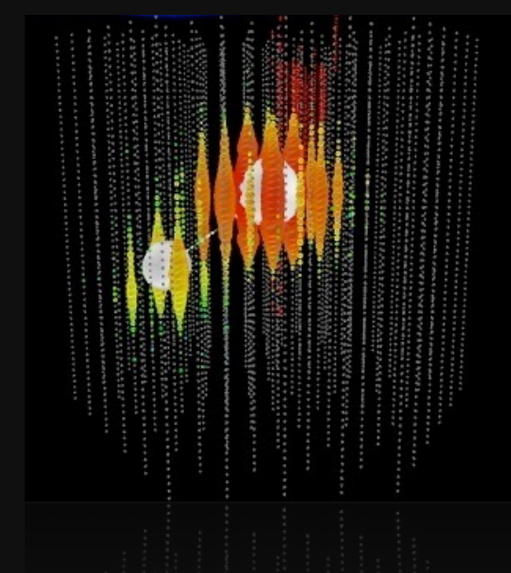
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} \ + X$$

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

cascade (data)

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

CC Tau Neutrino



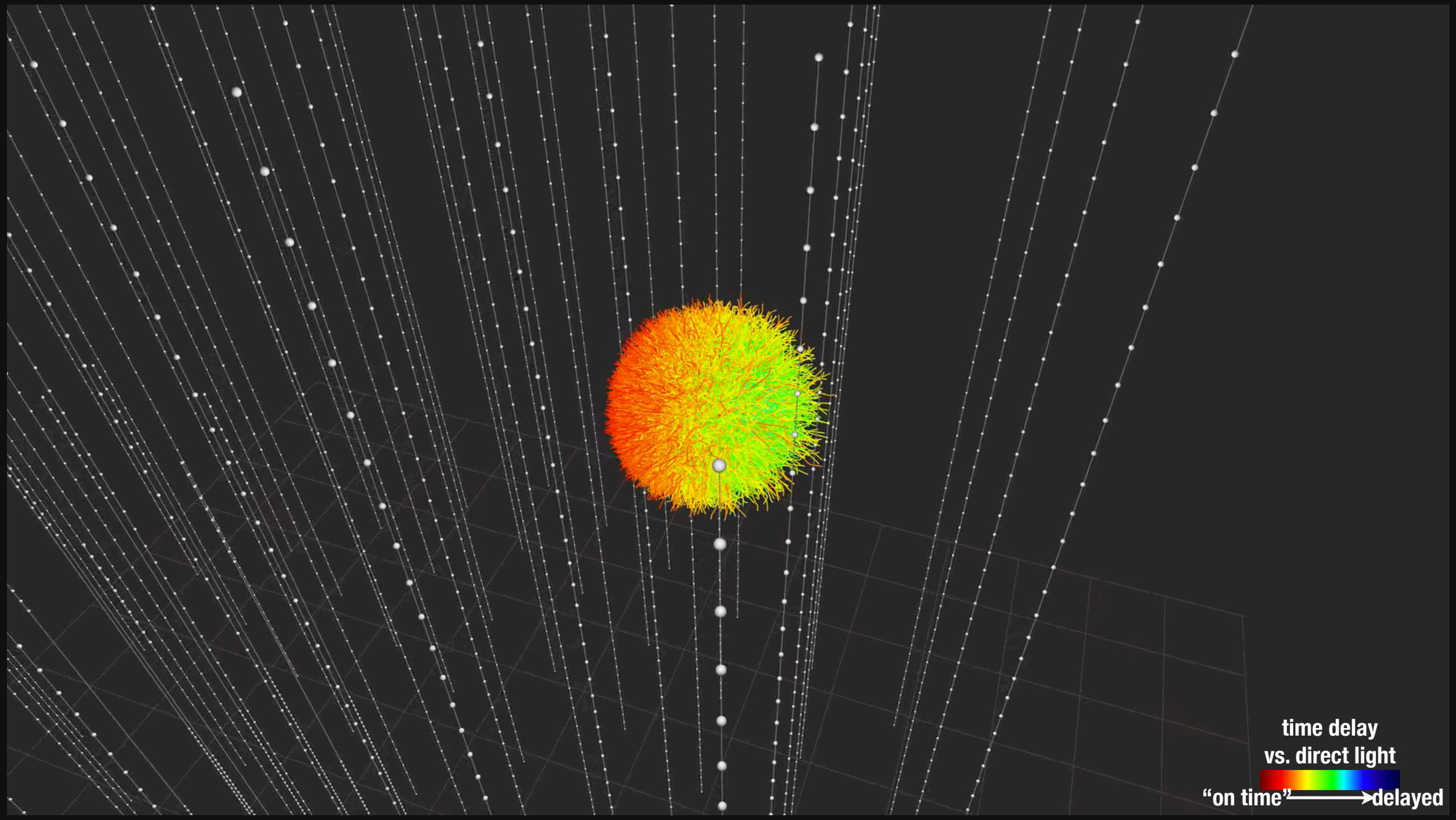
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" (≳10PeV) and other signatures (simulation)

(not observed yet)

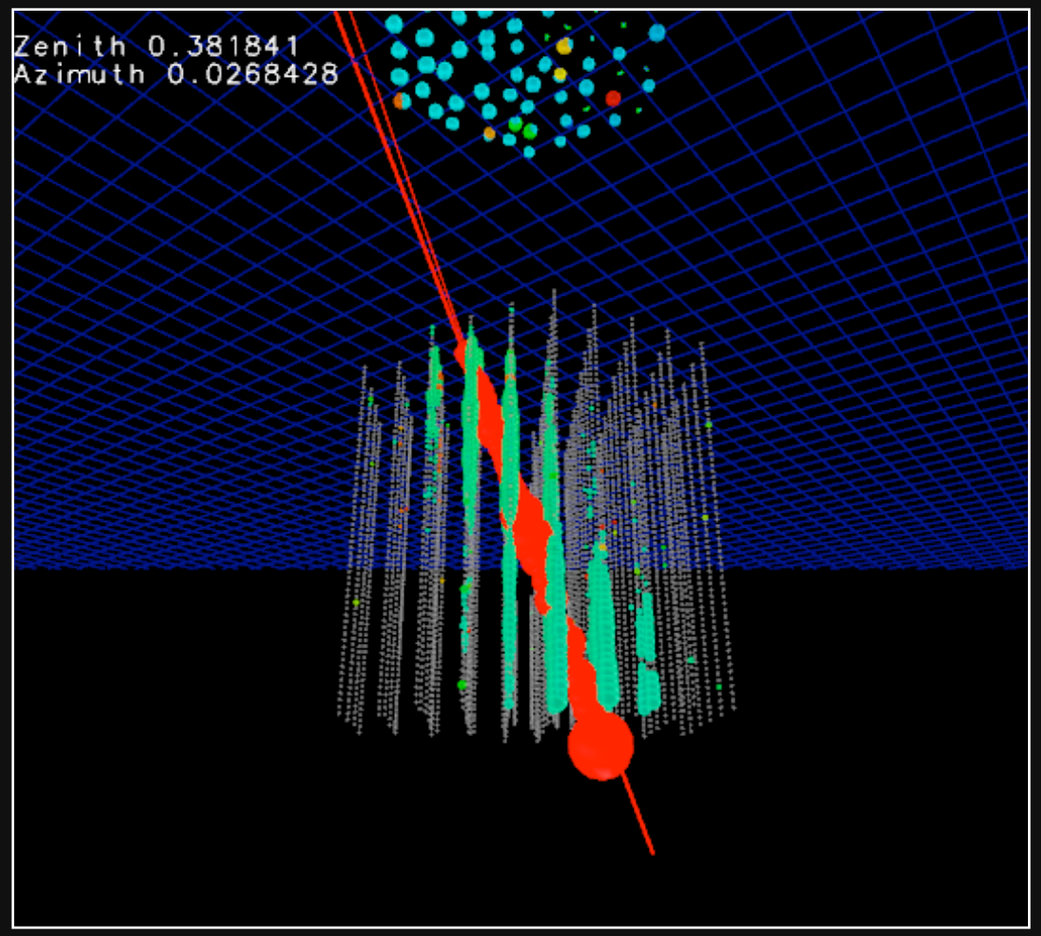
Directional Resolution for Showers

Shower directions reconstructed from timing profile



Backgrounds and Systematics

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

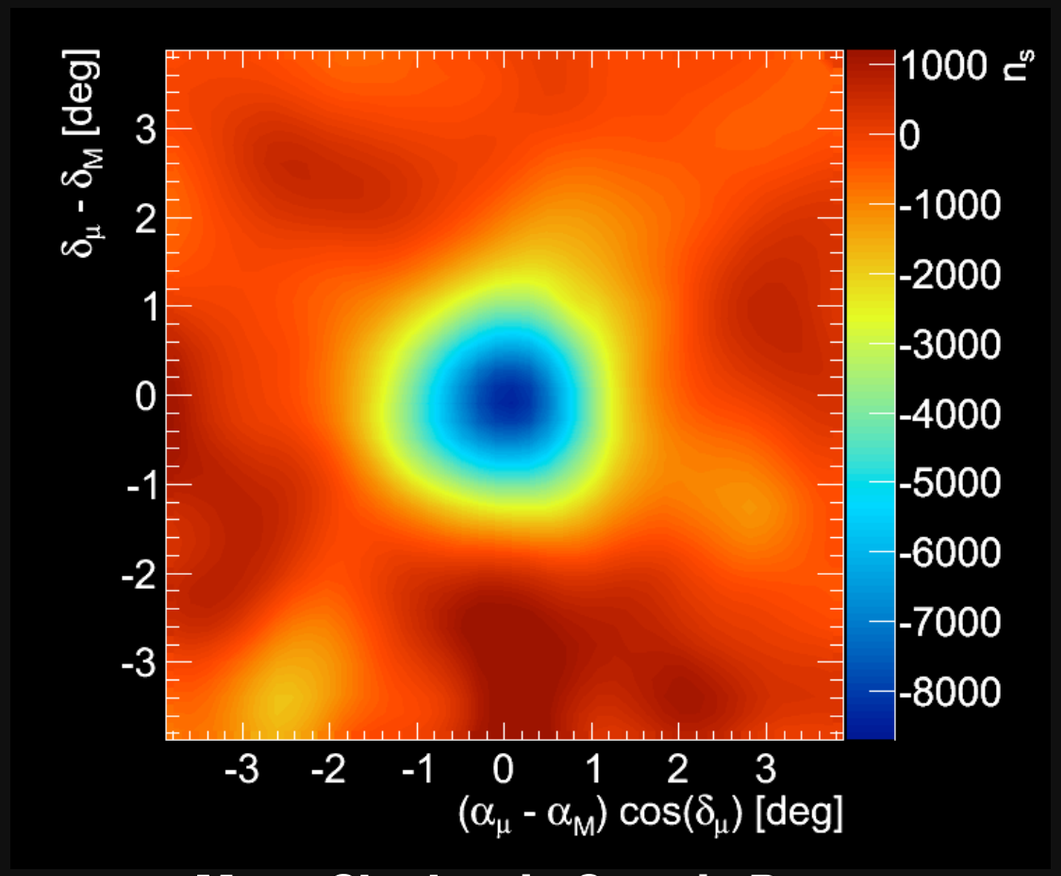


A bundle of muons from a CR interaction in the atmosphere (also observed in the "IceTop" surface array)

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
  - …

IceCube at CAP

- Francis Halzen: IceCube and the Discovery of High-Energy Cosmic Neutrinos (Plenary, Thursday, 11:45, CCIS L2-190)
- Tania Wood: Atmospheric Neutrino Measurement with IceCube Neutrino Observatory (this session)
- Benedikt Riedel: Long-Term Stability of Backgrounds in the IceCube Neutrino Observatory (this session)
- Sarah Nowicki: Direct reconstruction - a new event reconstruction algorithm for the IceCube Neutrino Observatory (this session)
- Ken Clark: Deep Core and PINGU - Studying Neutrinos in the Ice (T3-5, Tuesday 16:45, CAB 235)

The (Very) High-Energy Tail

Update of the high-energy astrophysical flux discovery analysis (now **4** years of data, up from 3 years in PRL 113, 101101)

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

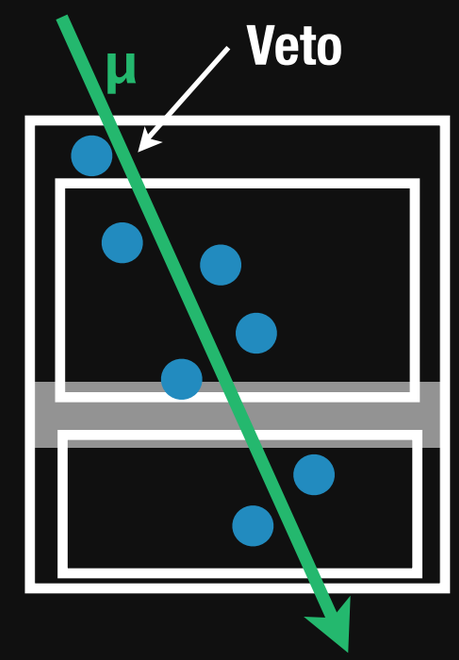
Background

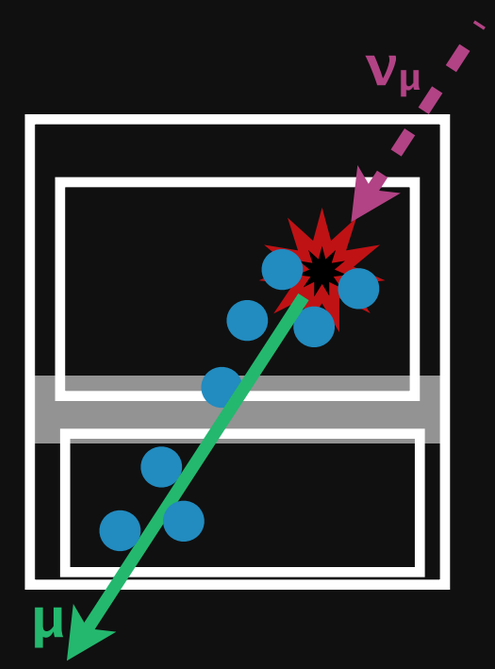
- Track-like events from Cosmic Ray muons and atmospheric ν_μ
- Soft spectrum ($E^{-3.7}$ - $E^{-2.7}$)
- Muons in the Southern Sky, neutrinos from the North

“Starting Event” Analysis

Specifically designed to find contained events.

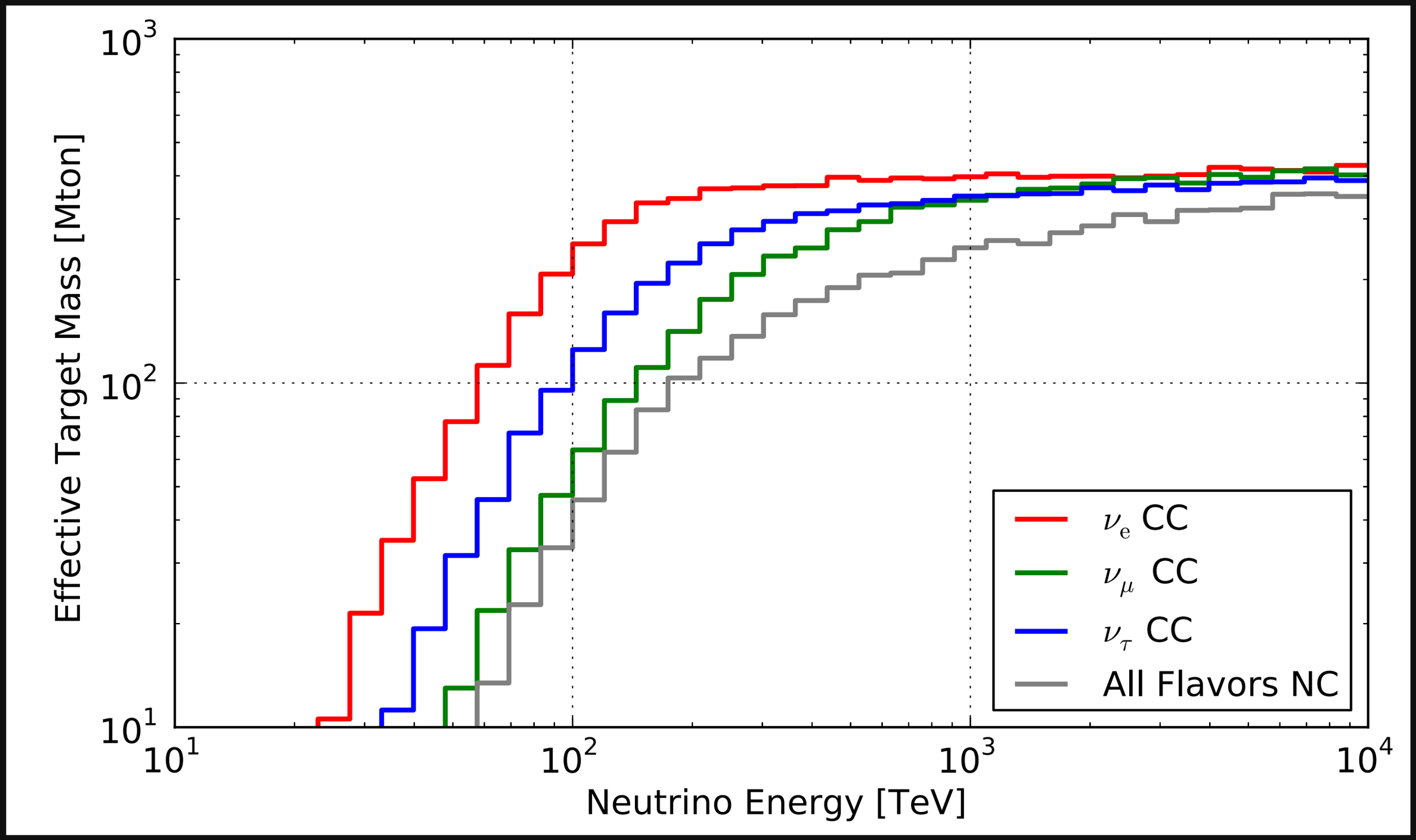
- Explicit contained search at high energies (cut: Q_{tot}>6000 p.e.)
- 400 Mton effective fiducial mass
- Use atmospheric muon veto
- Sensitive to all flavors in region above 60TeV deposited energy
- Estimate background from data





Effective Volume / Target Mass

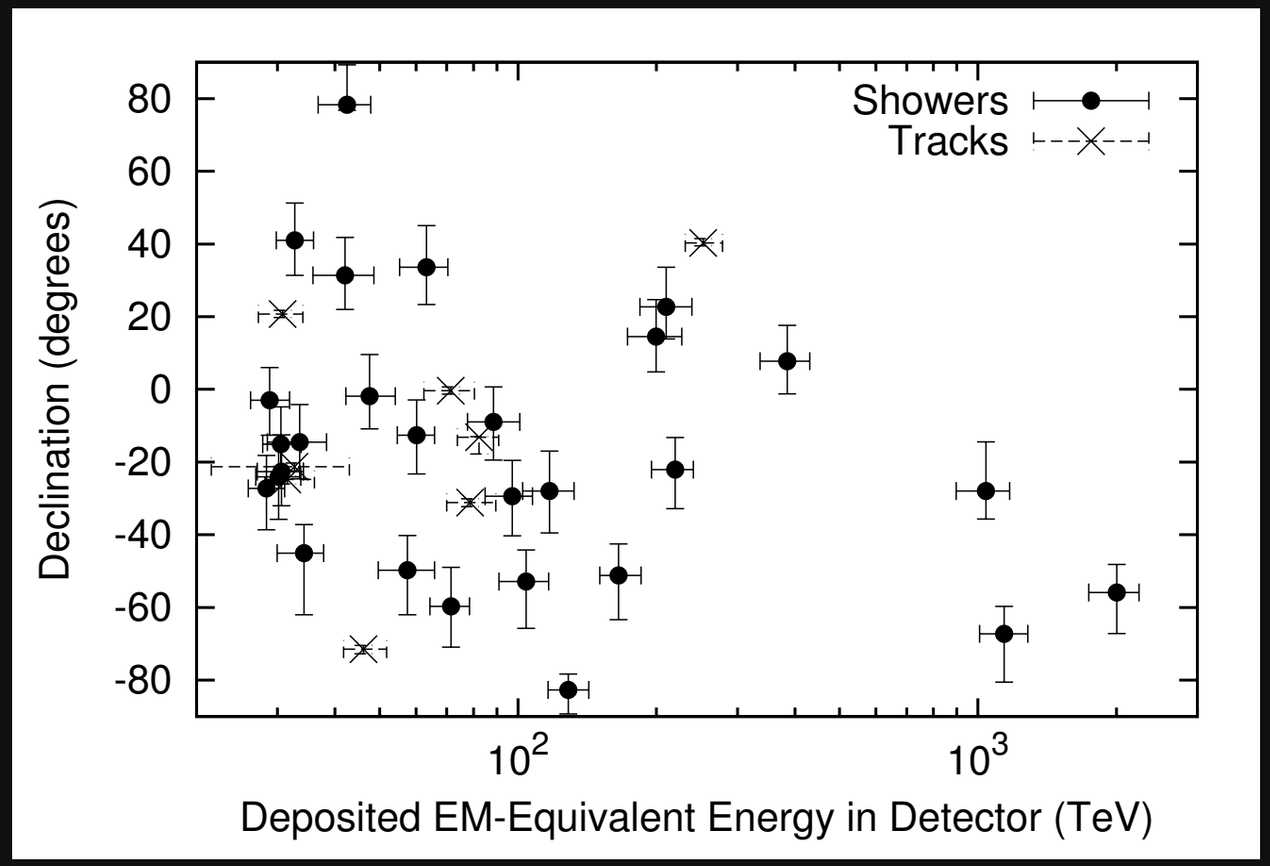
Fully efficient above 100 TeV for CC electron neutrinos
About 400 Mton effective target mass



What Did We Find?

37 events in **3 years** of IceCube data (PRL 113, 101101)
(988 days between 2010–2013)

- **36(+1) events observed!**
- **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

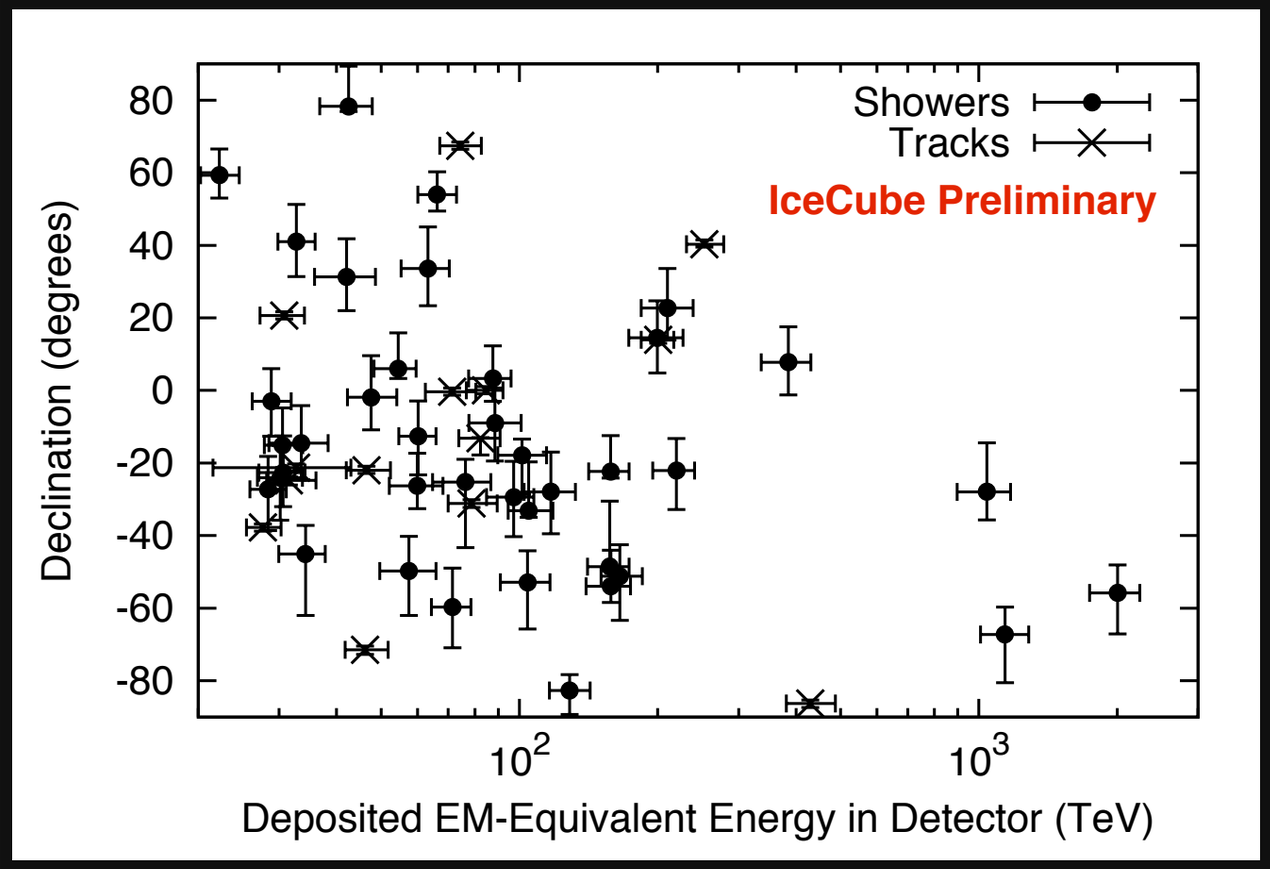


full likelihood fit of all components: 5.7σ for 36(+1) events

What Did We Find?

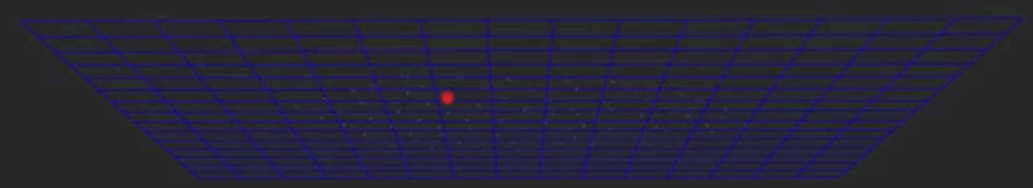
54 events in **4 years** of IceCube data
(1347 days between 2010–2014)

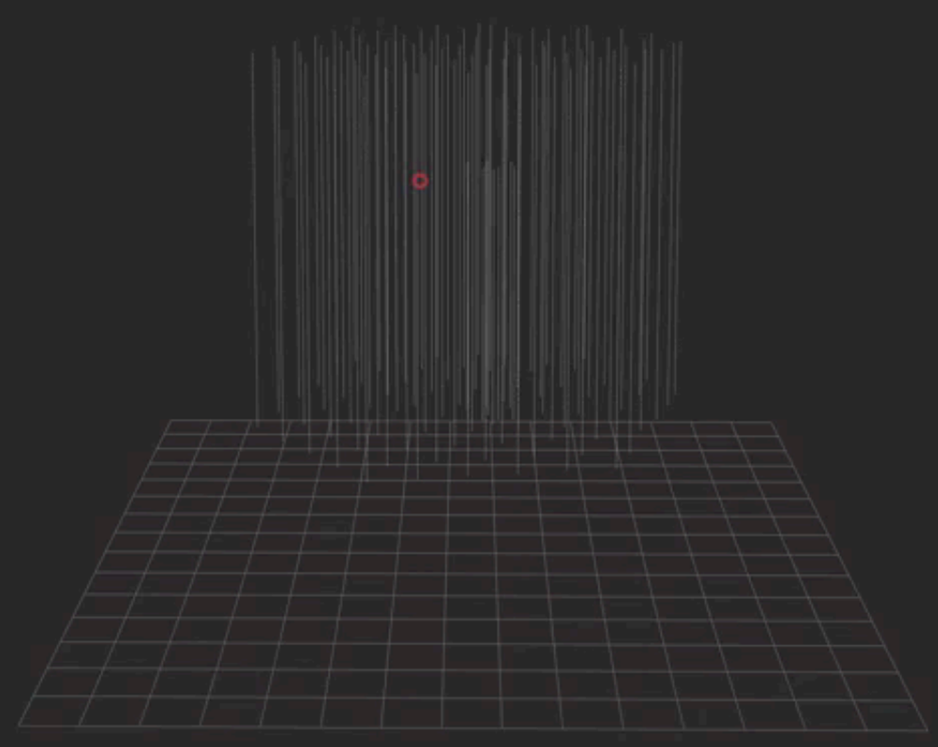
- **53(+1) events observed!**
- **Estimated background:**
  - $9.0^{+8.0}_{-2.2}$ atm. neutrinos
  - 12.6±5.1 atm. muons
- **One of them is an obvious (but expected) background**
  - coincident muons from two CR air showers



full likelihood fit of all components: 6.5σ for 53(+1) events

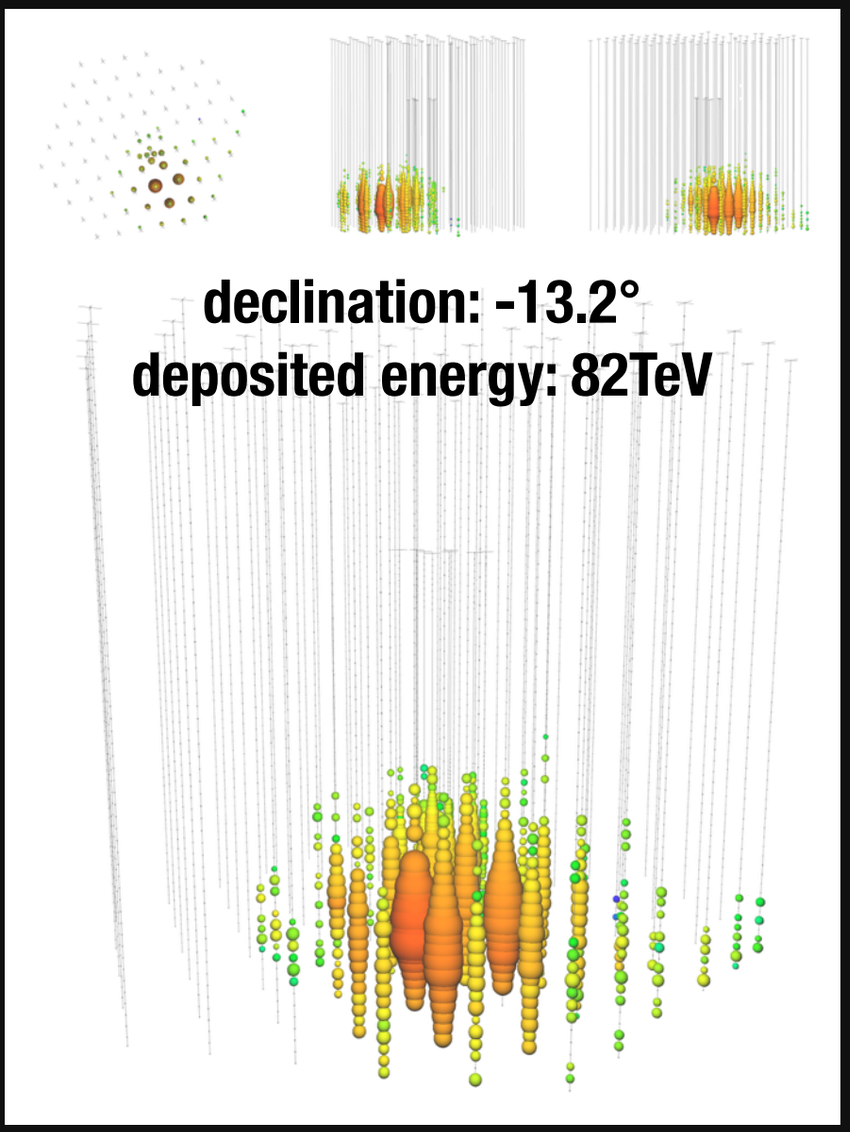
What Did We Find?

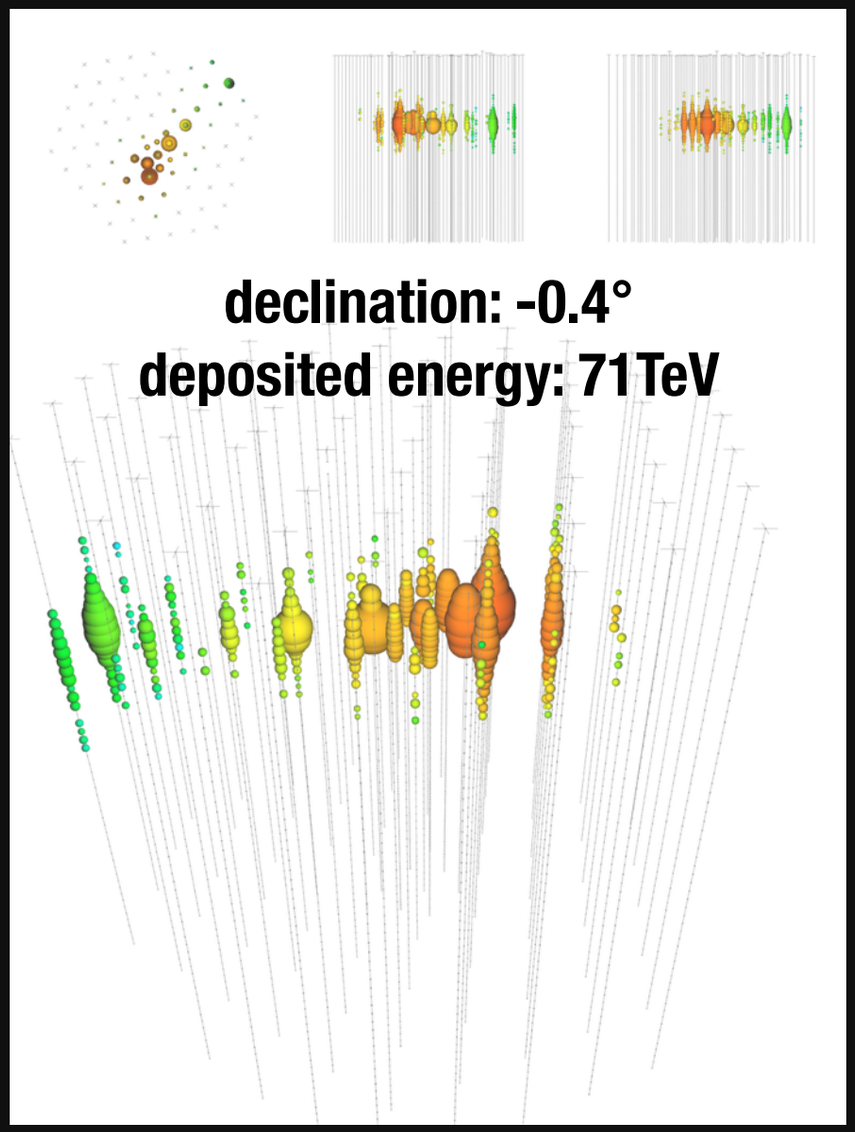


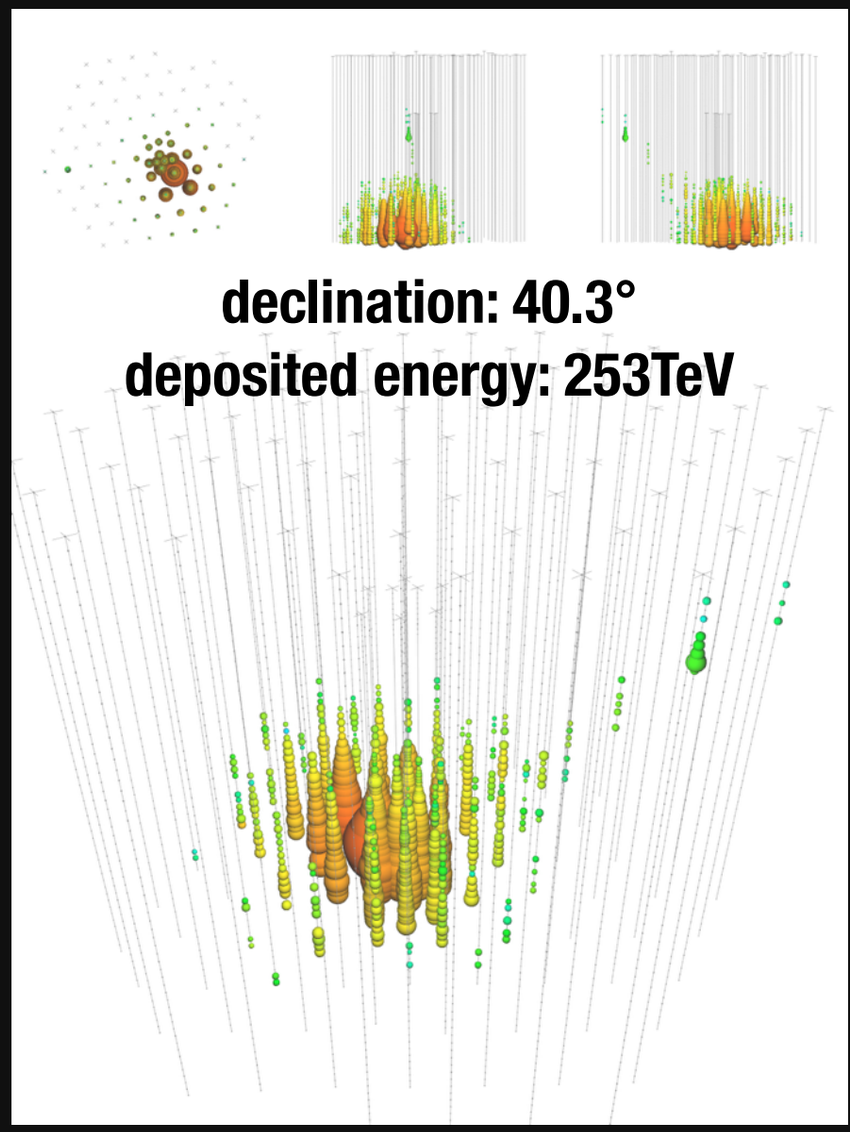


What Did We Find?

Some examples

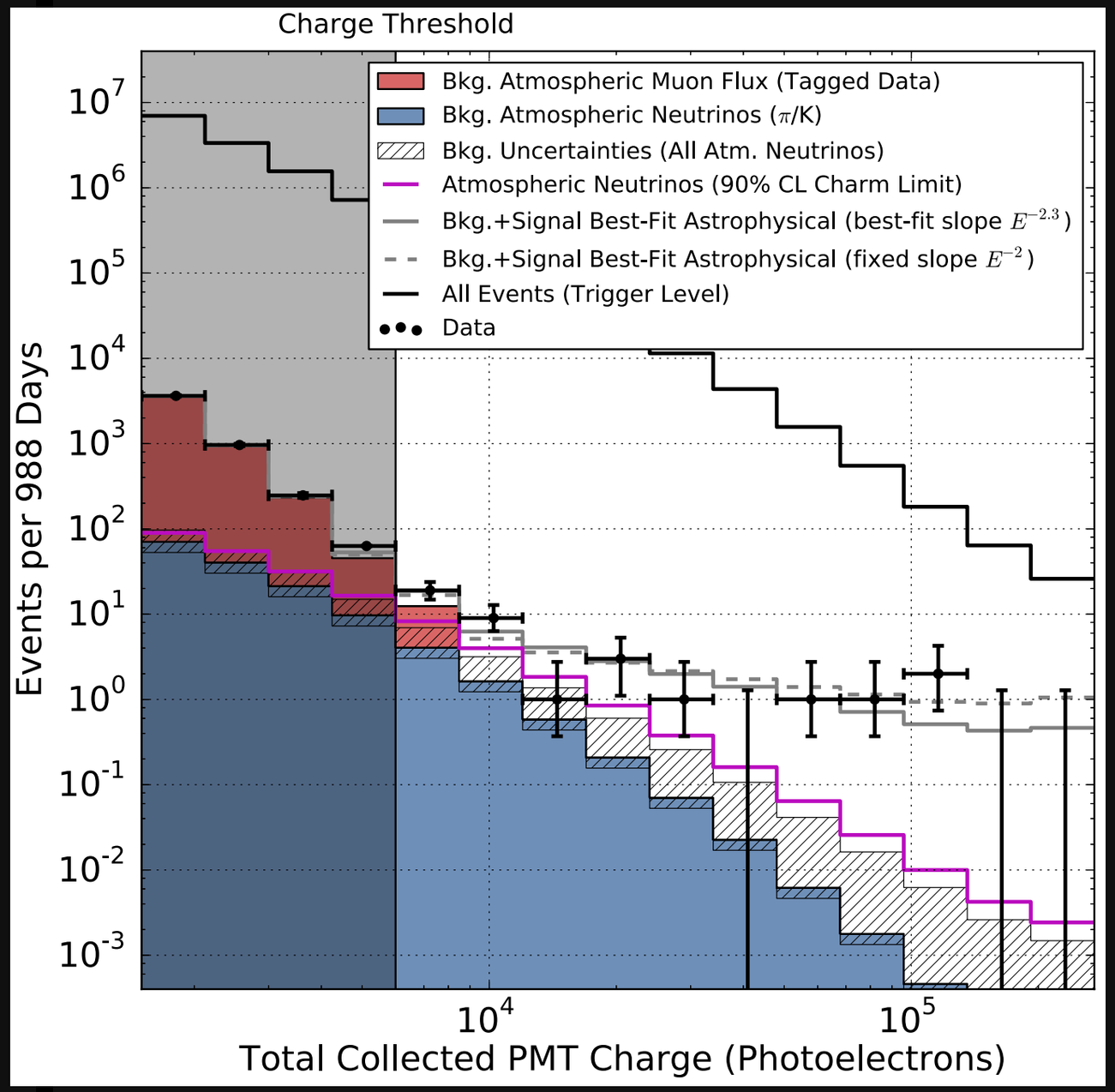






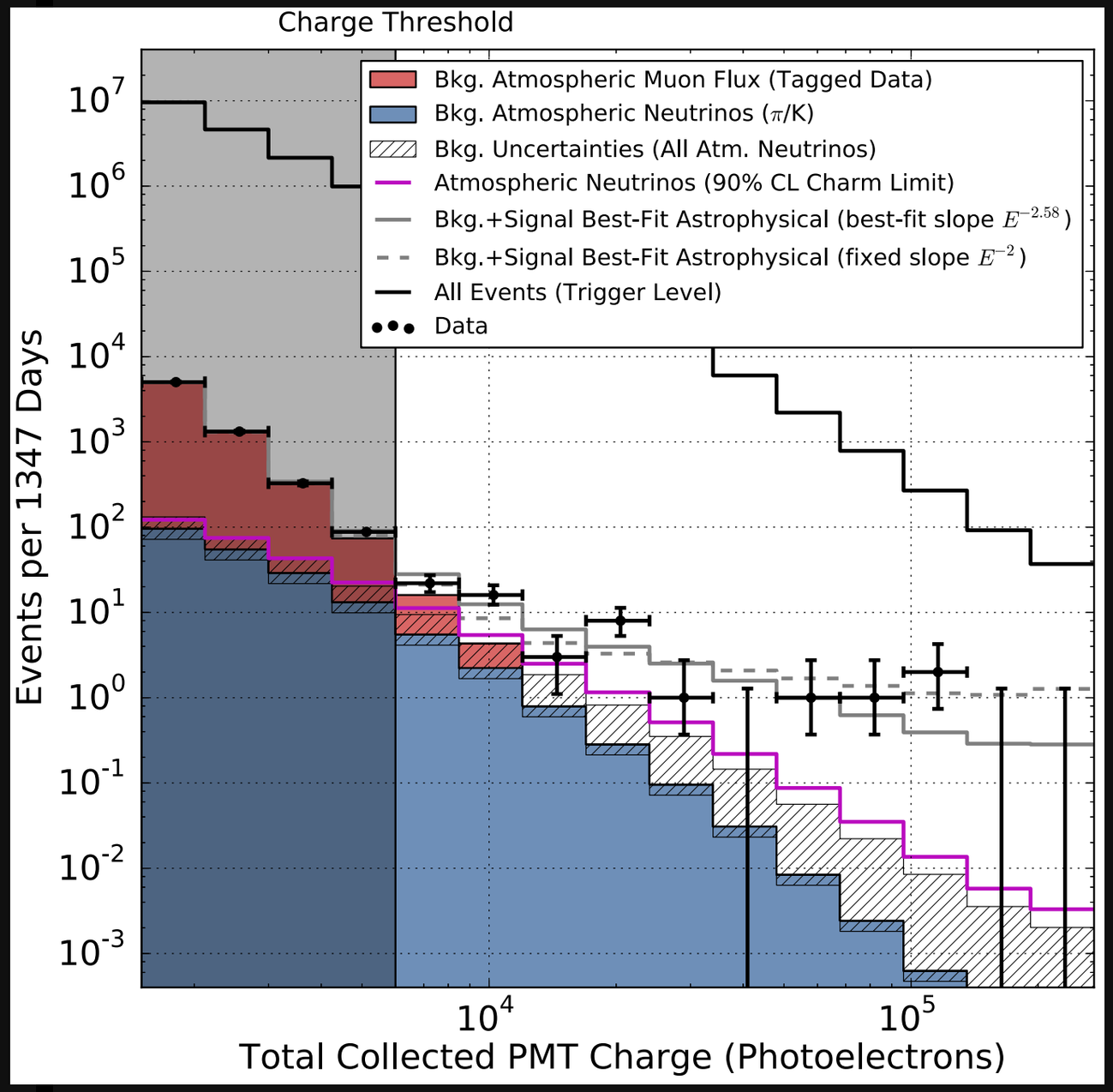
Charge Distribution

- 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)



Charge Distribution

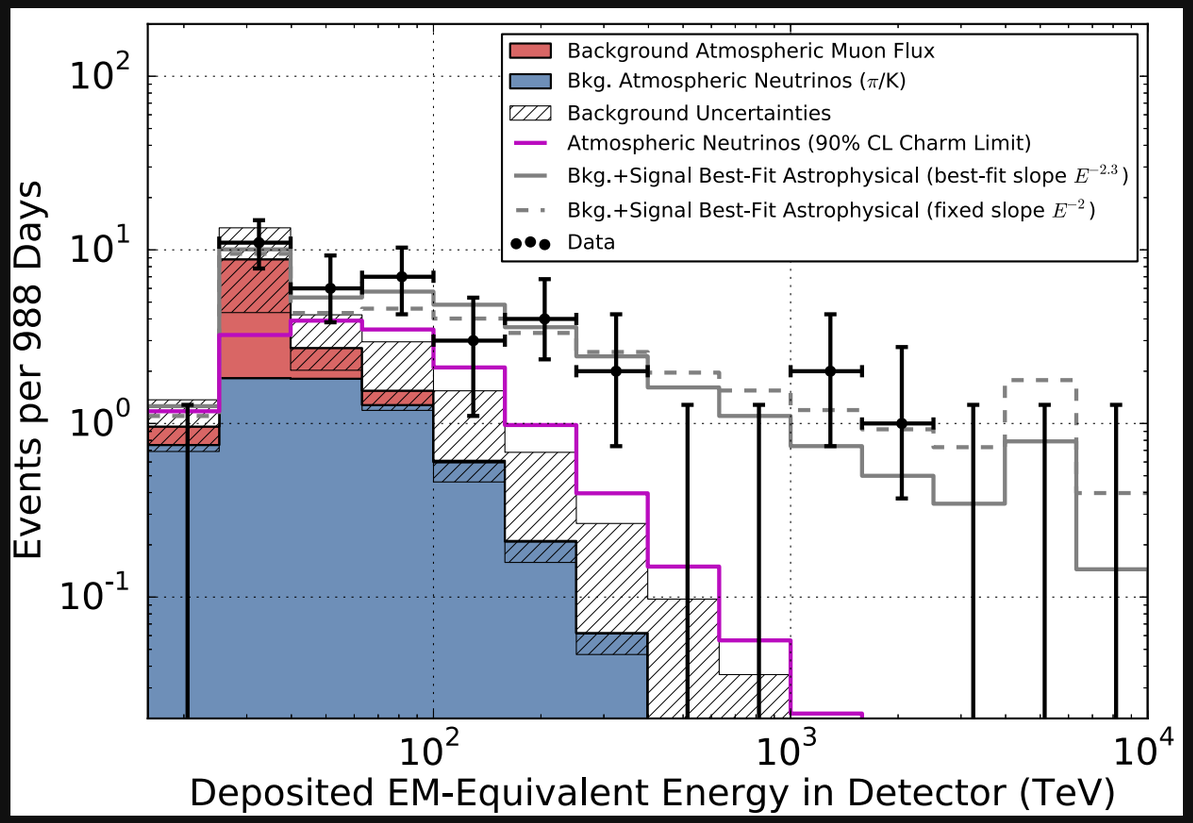
- Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold (Q_{tot}>6000)
- Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)



Energy Spectrum (3 years)

Compatible with benchmark E^{-2} astrophysical model

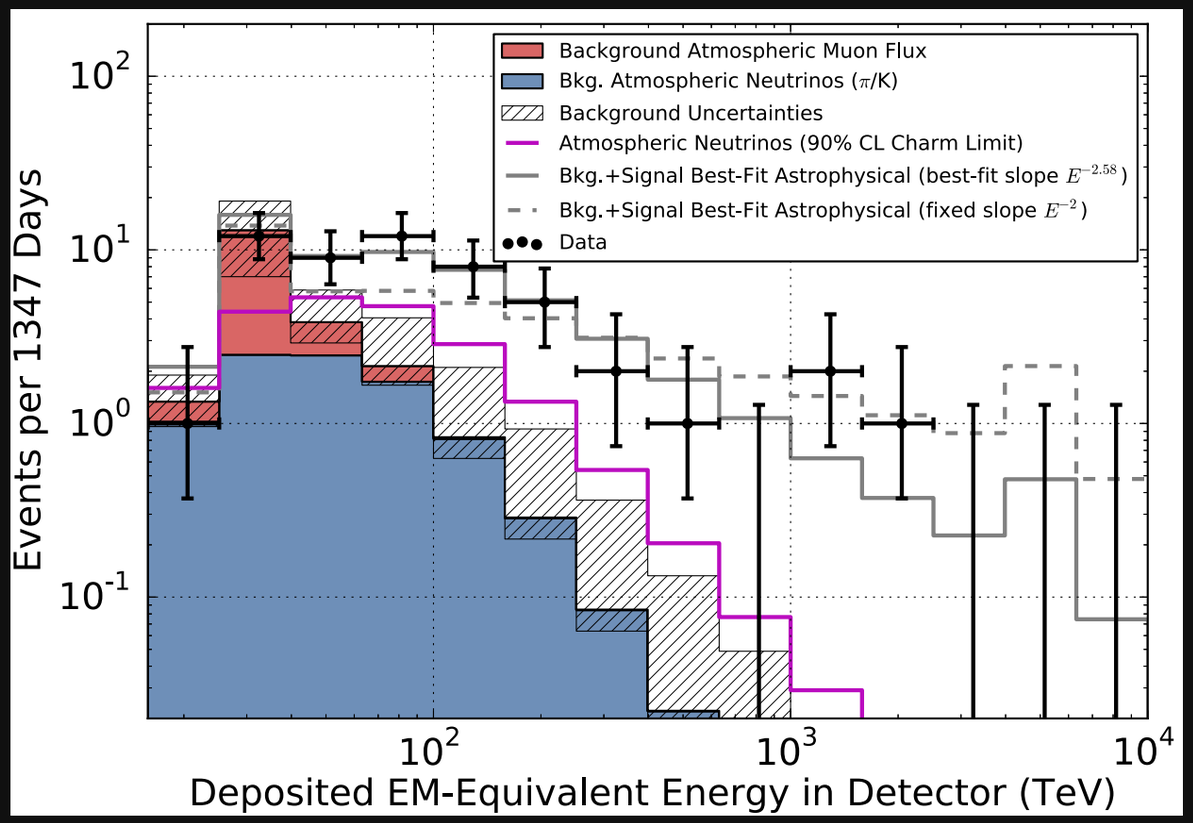
- Harder than any expected atmospheric background
- Merges well into background at low energies
- Potential cutoff at about 2-5 PeV (or softer spectrum)
- Best fit spectral index: $E^{-2.3}$



Energy Spectrum (4 years)

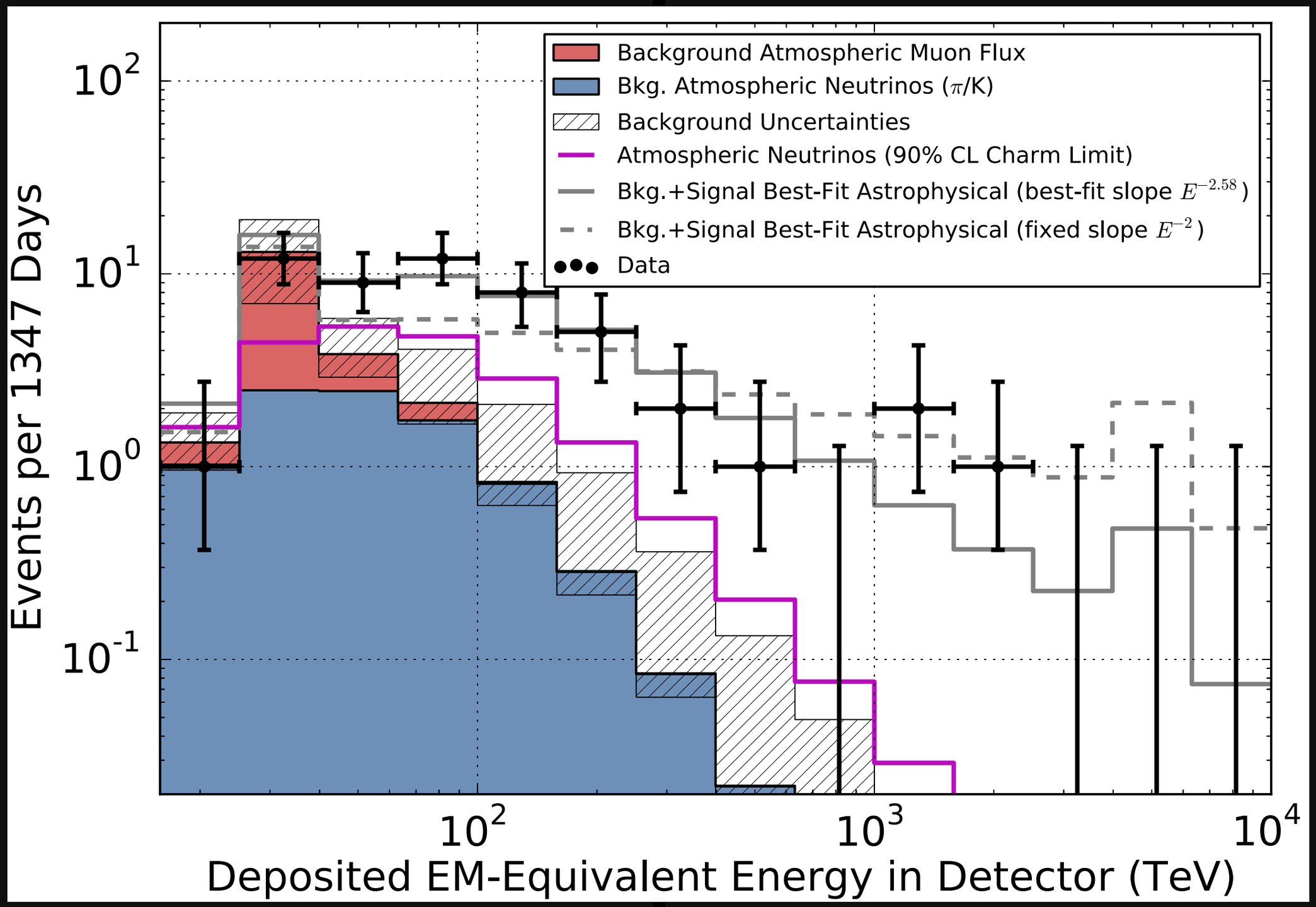
Somewhat compatible with benchmark E^{-2} astrophysical model or single power-law model, but looks like things are more complicated

- **Best fit assuming E^{-2} (per-flavor flux) (not a very good fit anymore):**
  - $0.84 \pm 0.3\ 10^{-8}\ E^{-2}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$
- **Best fit spectral index: $E^{-2.58}$**



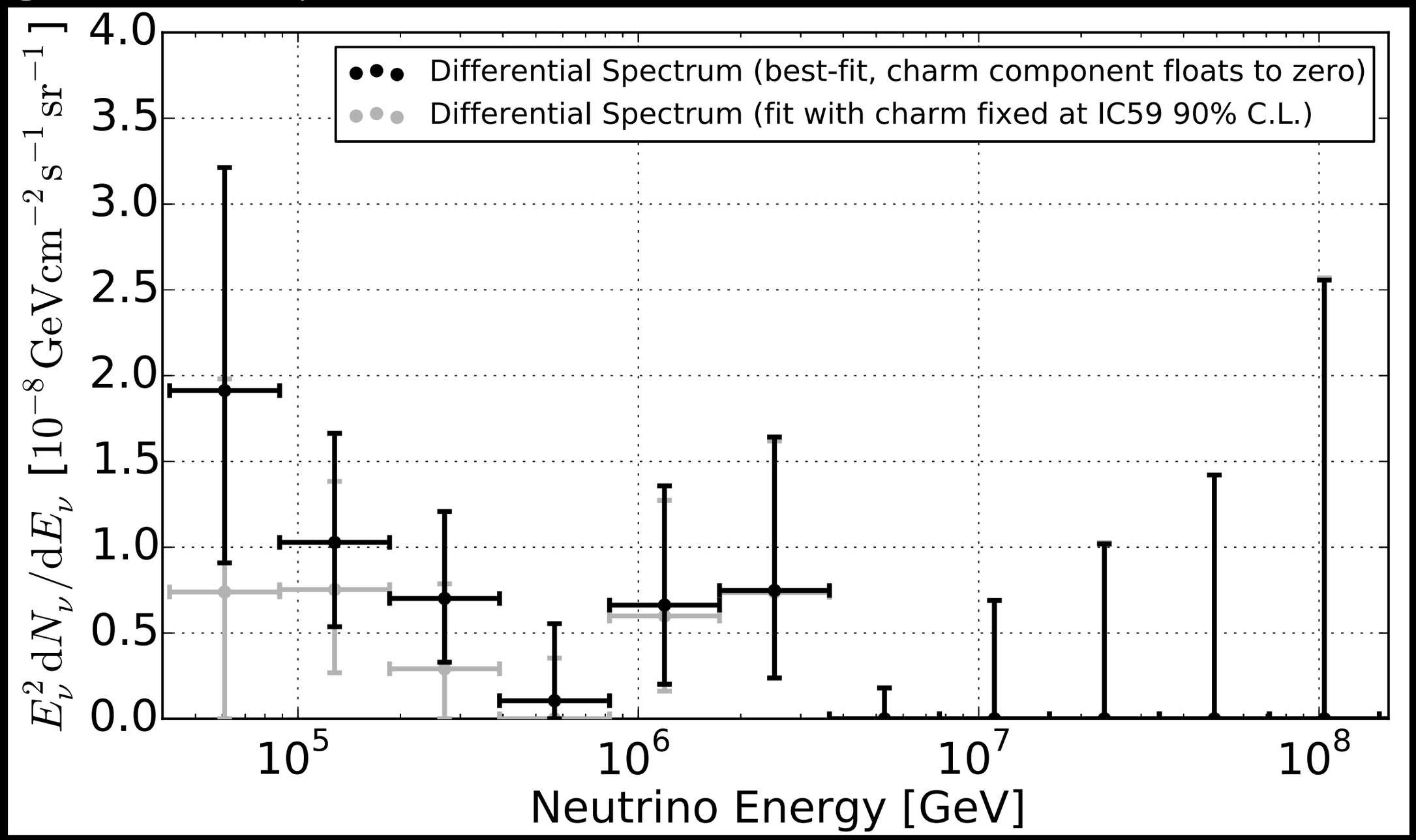
Energy Spectrum

Compatible with benchmark E^{-2} astrophysical model



Unfolding to Neutrino Energy

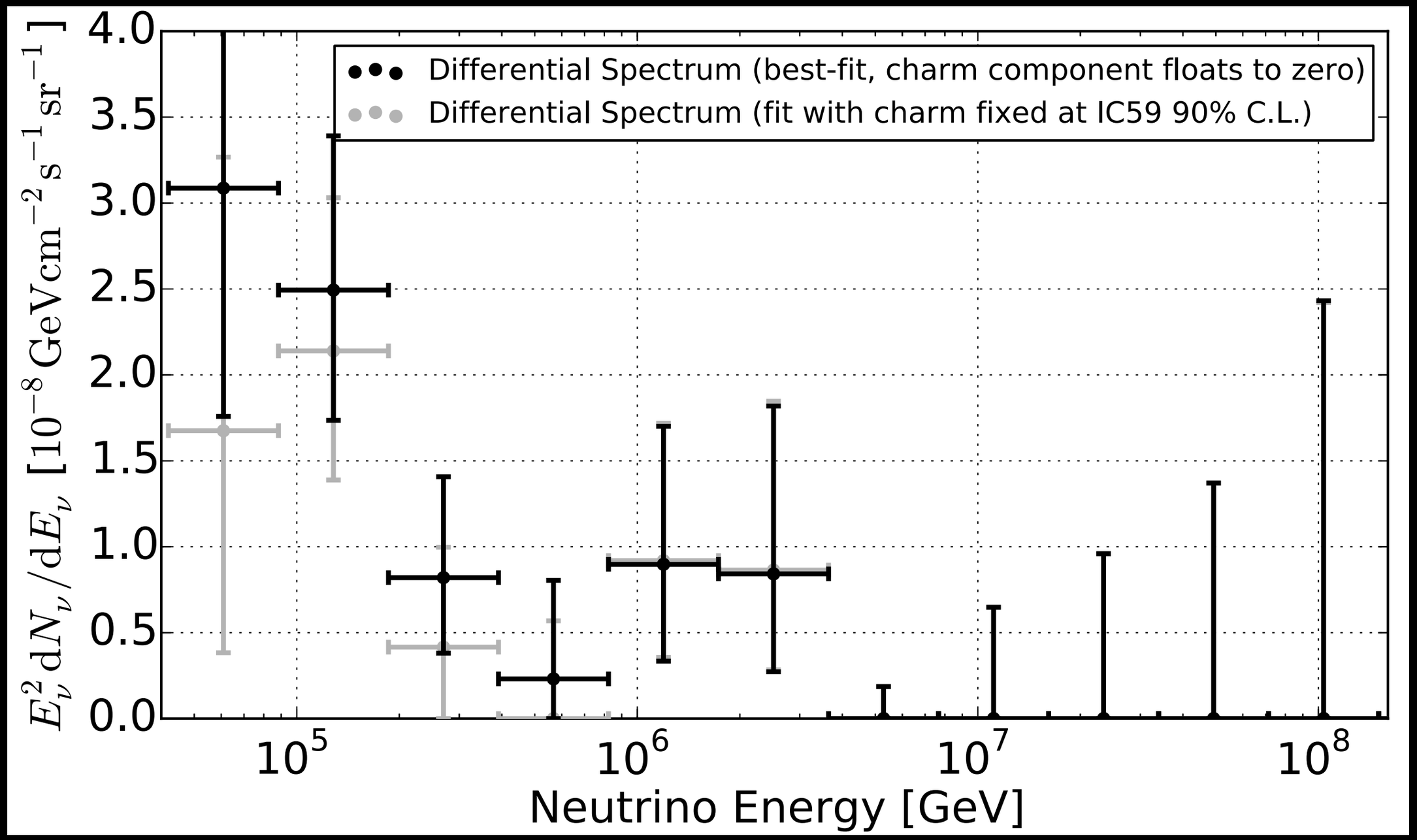
Unfolded to true neutrino energy, simultaneously fitting for backgrounds - updated from PRL plot version with priors for backgrounds - 3 years



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

Unfolding to Neutrino Energy

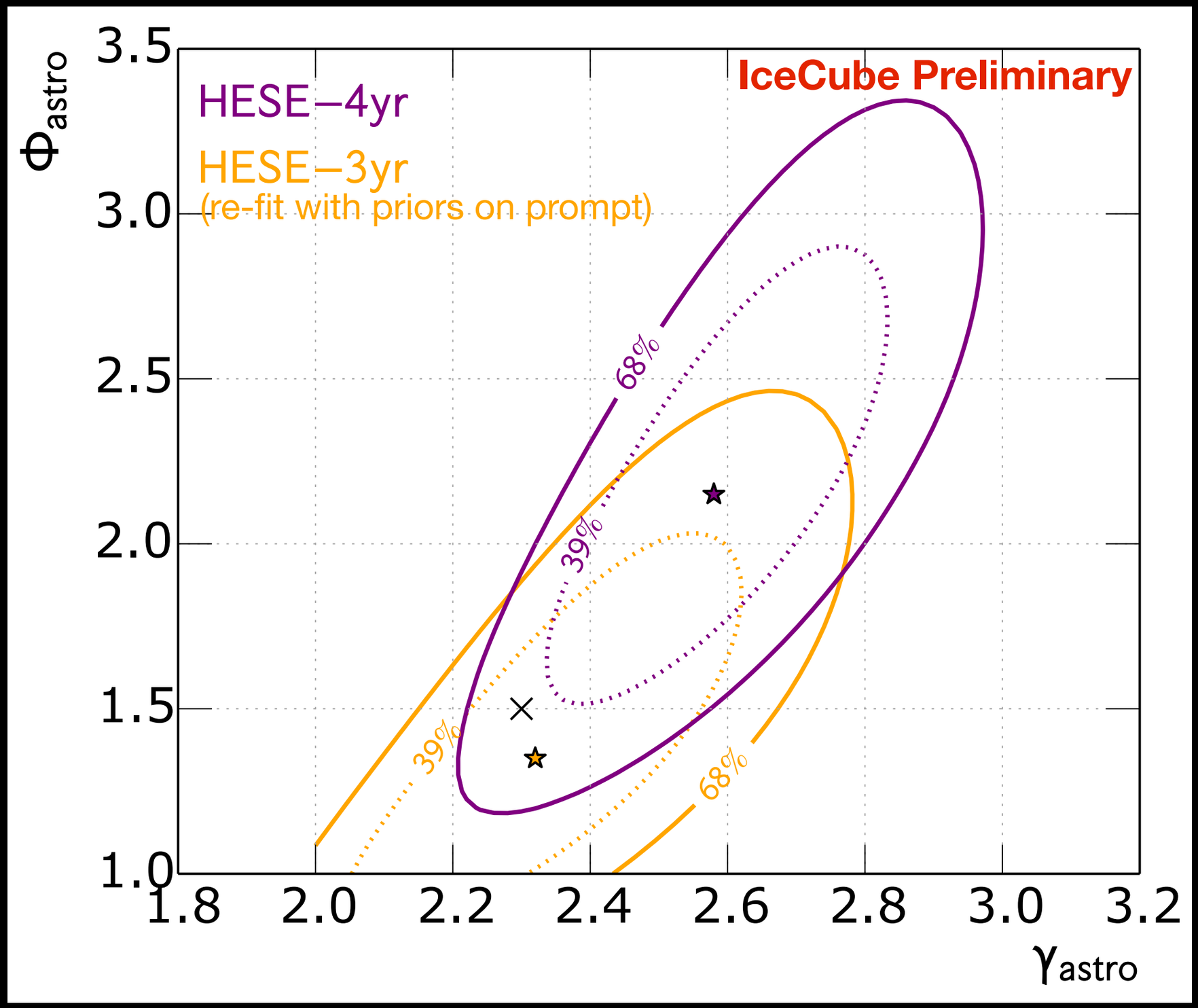
4 years - mostly new events at lower energies, not so many more at the PeV-level - still compatible within errors



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

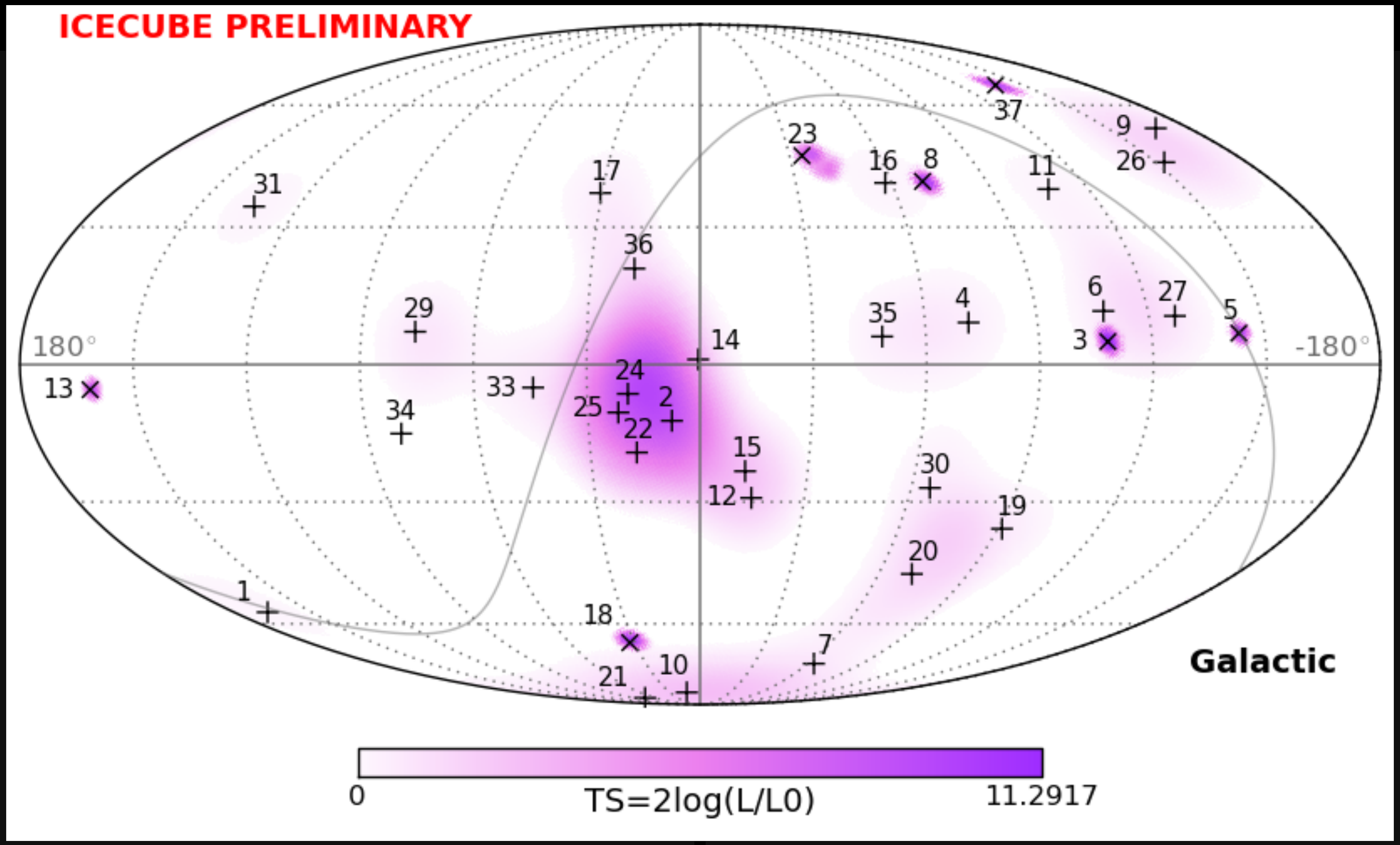
Spectral Fit

Normalization vs. spectral index contour plot
Note: 3-year data re-fit since PRL with priors for backgrounds



Skymap / Clustering

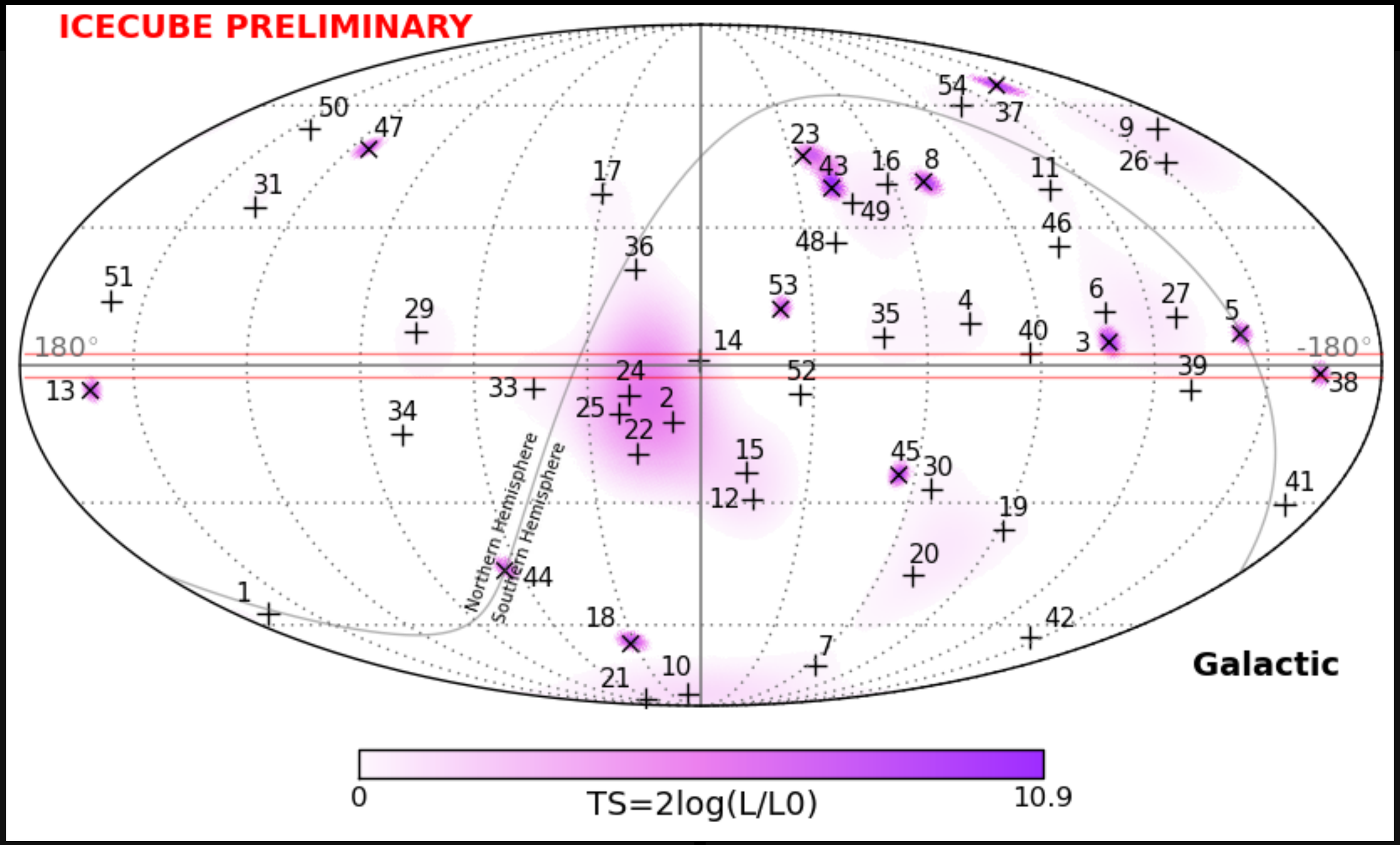
No significant clustering observed (three years)



(all p-values are post-trial)

Skymap / Clustering

No significant clustering observed (four years)



(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: 18% (not significant)
- Other searches (multi-cluster, galactic plane, time clustering, GRB correlations) not significant either

Improved Veto Techniques

(arXiv:1410.1749 - only 2 years of data so far - more data being added right now)

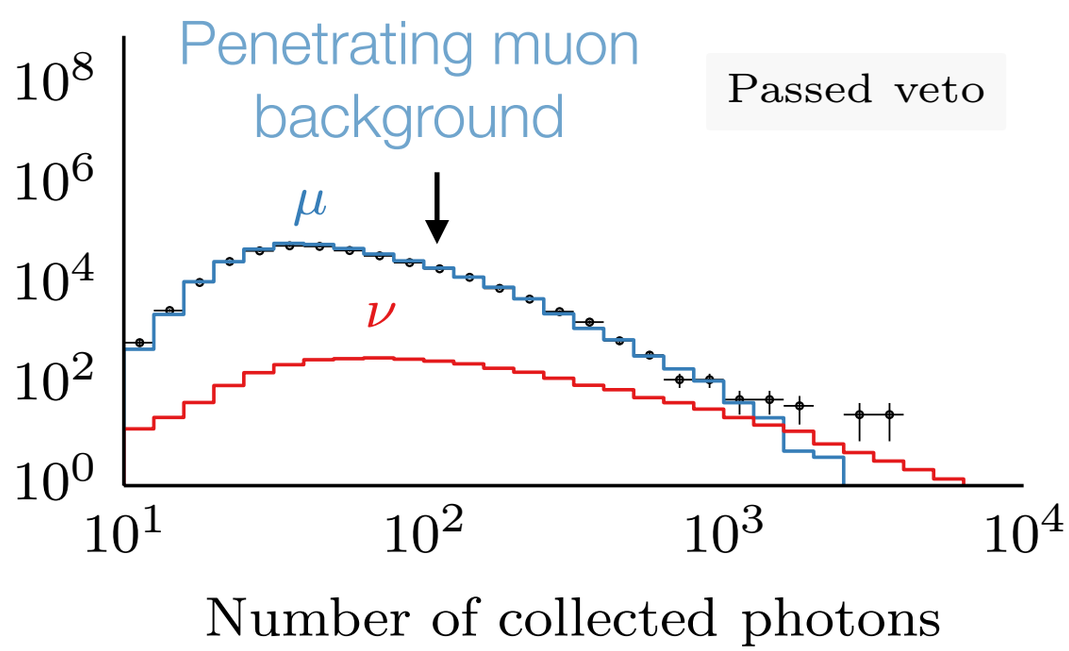
- **What happens to the astrophysical flux below 60 TeV?**
- **How large is the neutrino flux from atmospheric charm?**
- **-> Need to observe lower-energy neutrinos, especially from the southern sky.**

Improved Veto Techniques

What happens to the astrophysical flux below 60 TeV?

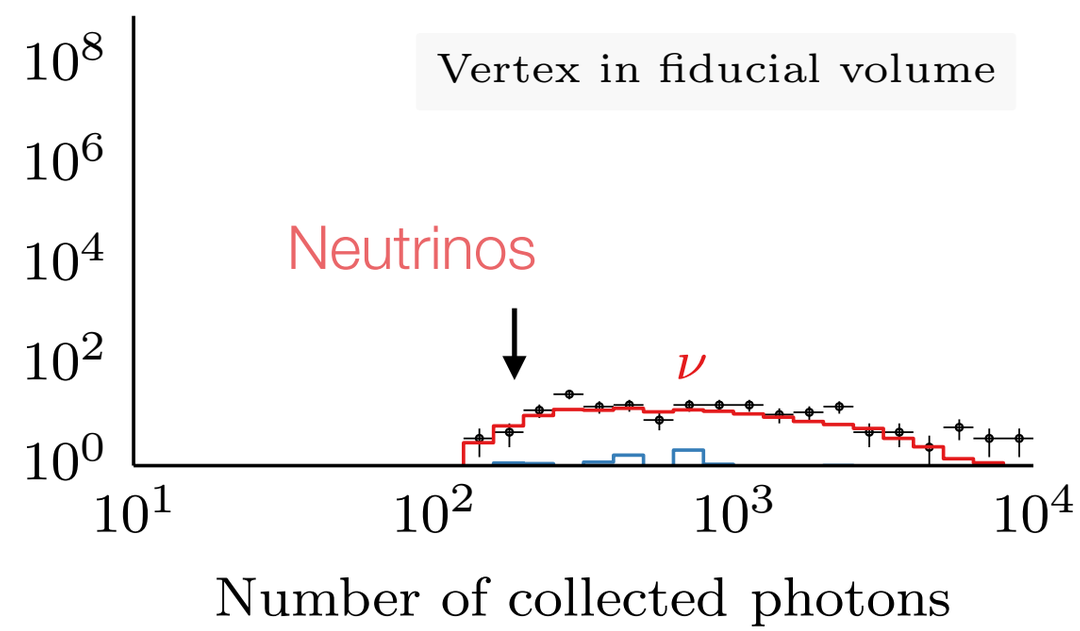
Outer-layer veto

Neutrino-dominated for E_{dep} > 60 TeV

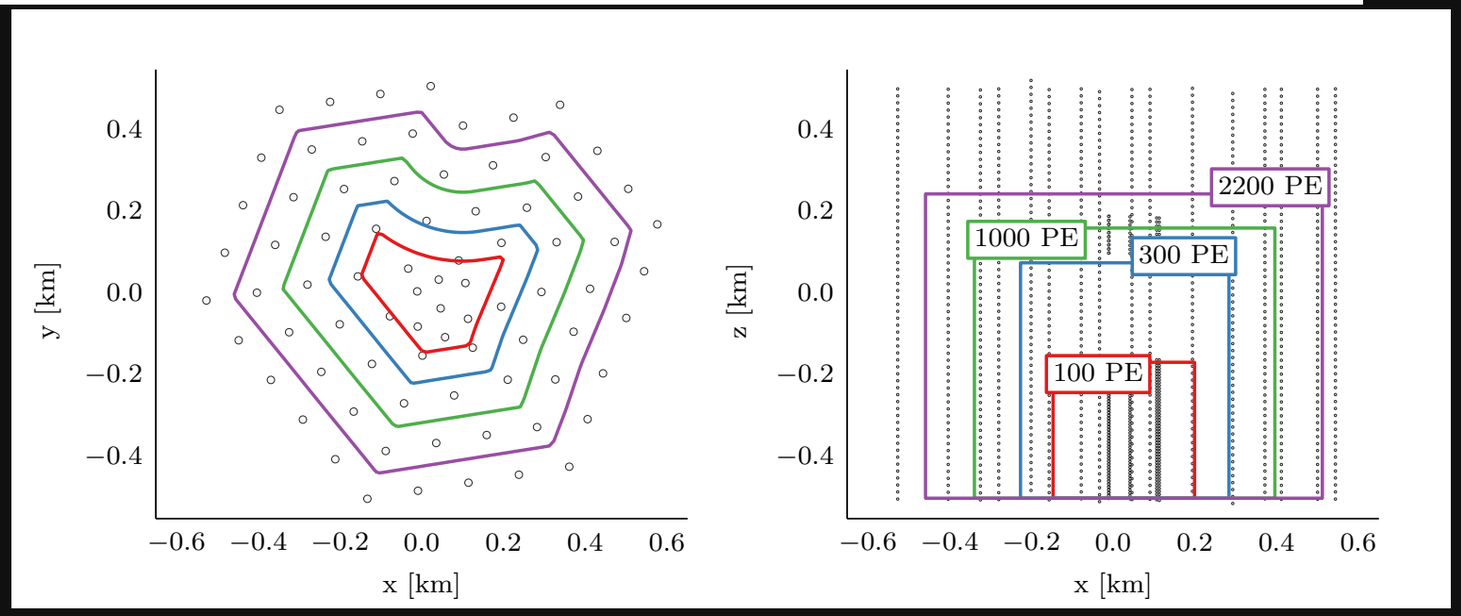


Energy-dependent veto

Neutrino-dominated for E_{dep} > 1 TeV



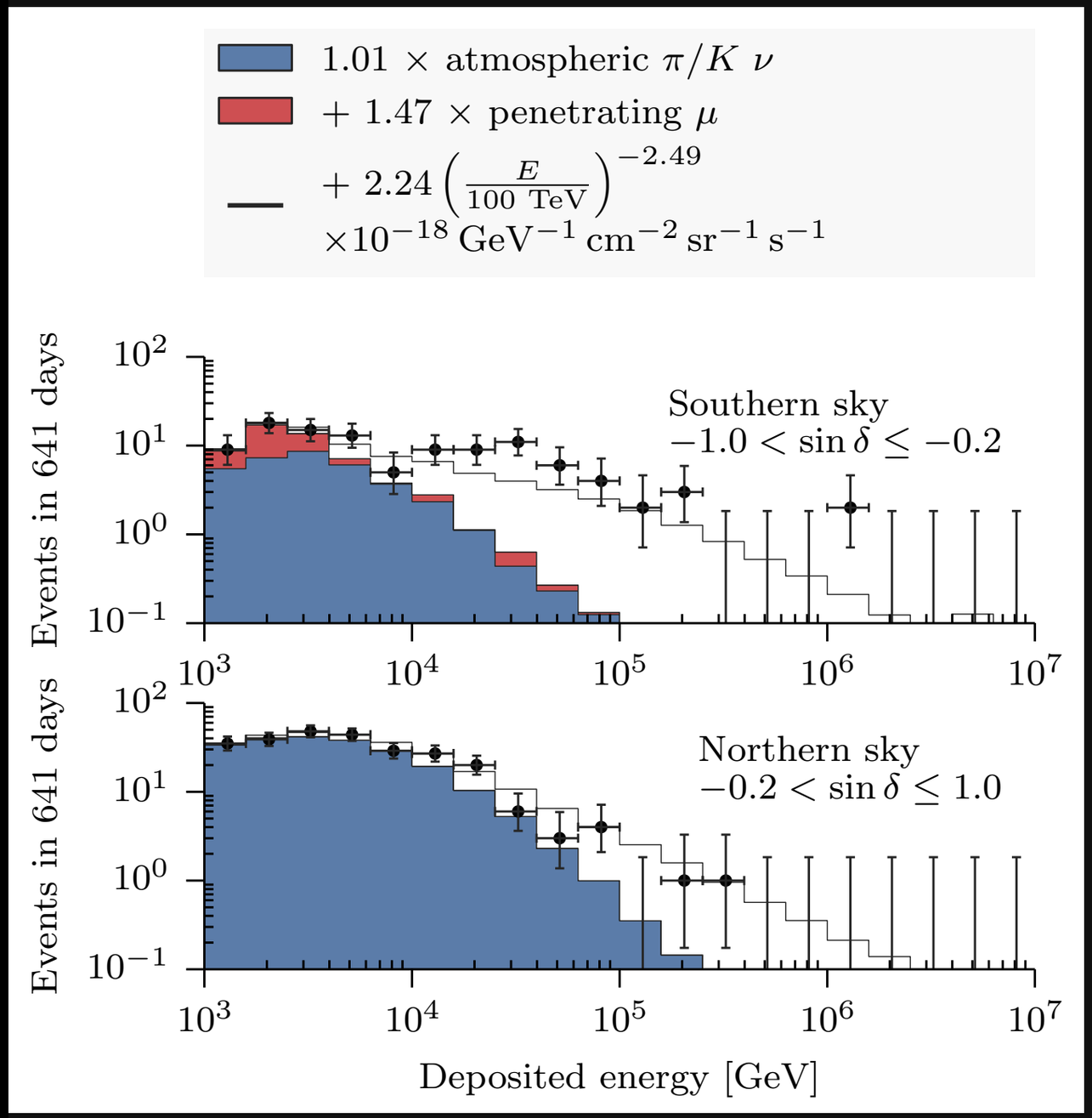
Thicker veto at low energies suppresses penetrating muons without sacrificing high-energy neutrino acceptance



Results

283 cascade and 105 track events in 2 years of data

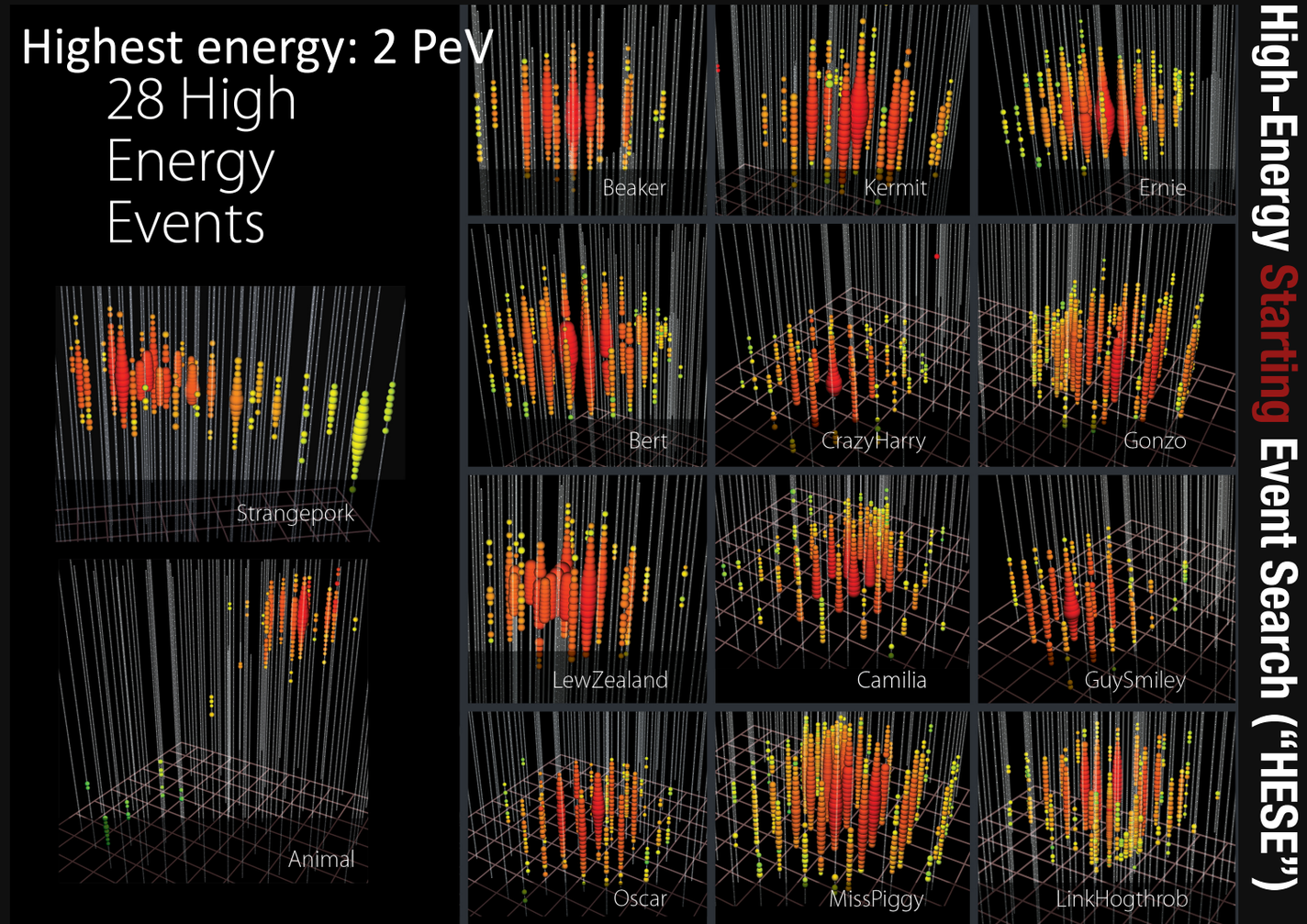
- 106 > 10 TeV, 9 > 100 TeV (7 of those already in high-energy starting event sample)
- Conventional atmospheric neutrino flux observed at expected level with starting events
- Astrophysical excess continues down to 10 TeV in the southern sky
- Deviation from model at 30 TeV (statistical fluctuation)
- Model-dependent upper limit on flux from charmed meson decay: 1.4 x ERS prediction



Other Channels?

Most of the "starting" sample consists of showers, with a high acceptance in the southern sky

- **Deposited (i.e. measured) energies closely related to neutrino energies**
  - **Great for discovering a signal**

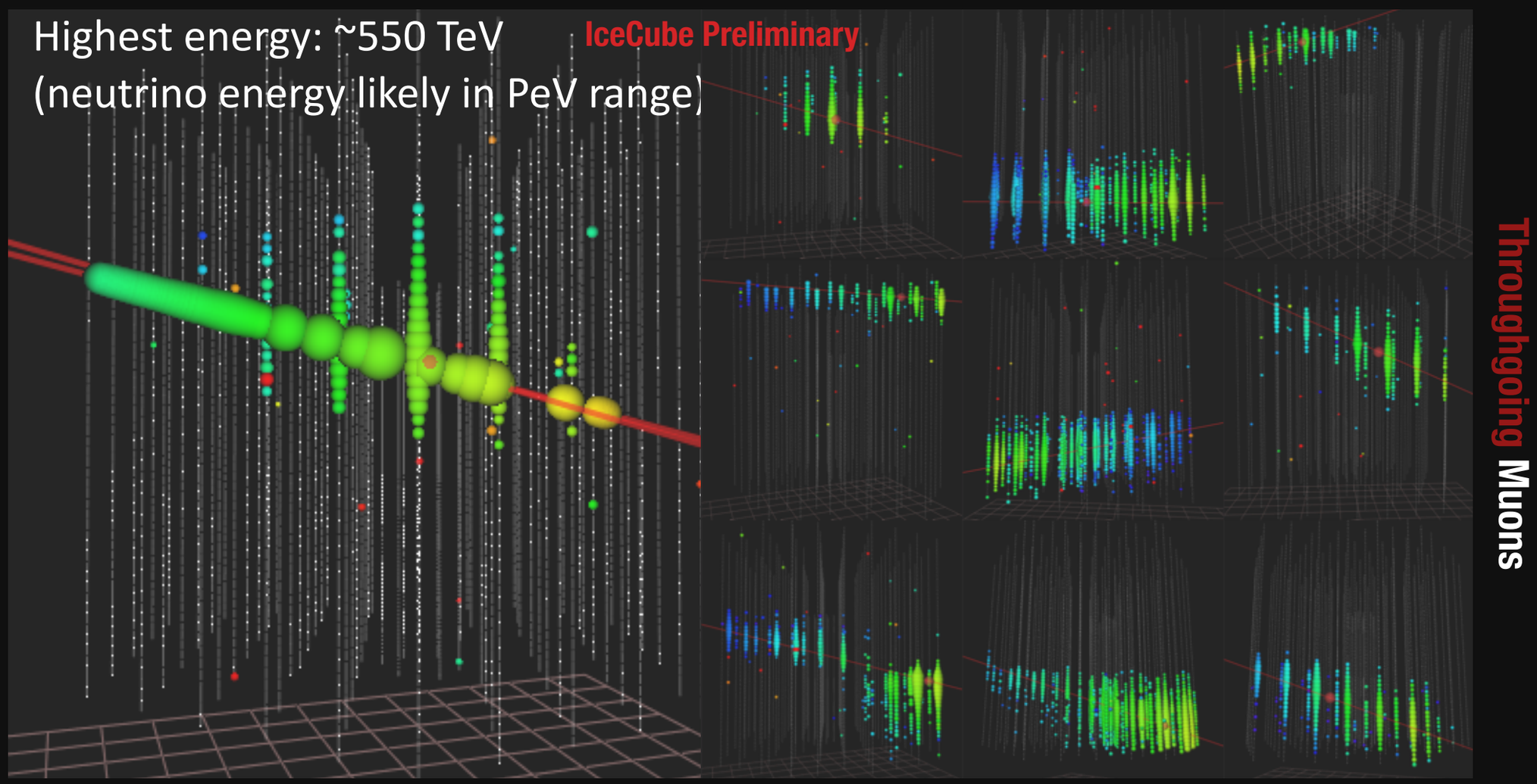


High-Energy Starting Event Search ("HESE")

Other Channels?

We have now seen a similar flux in the muon channel - at 3.7σ
Publication under review

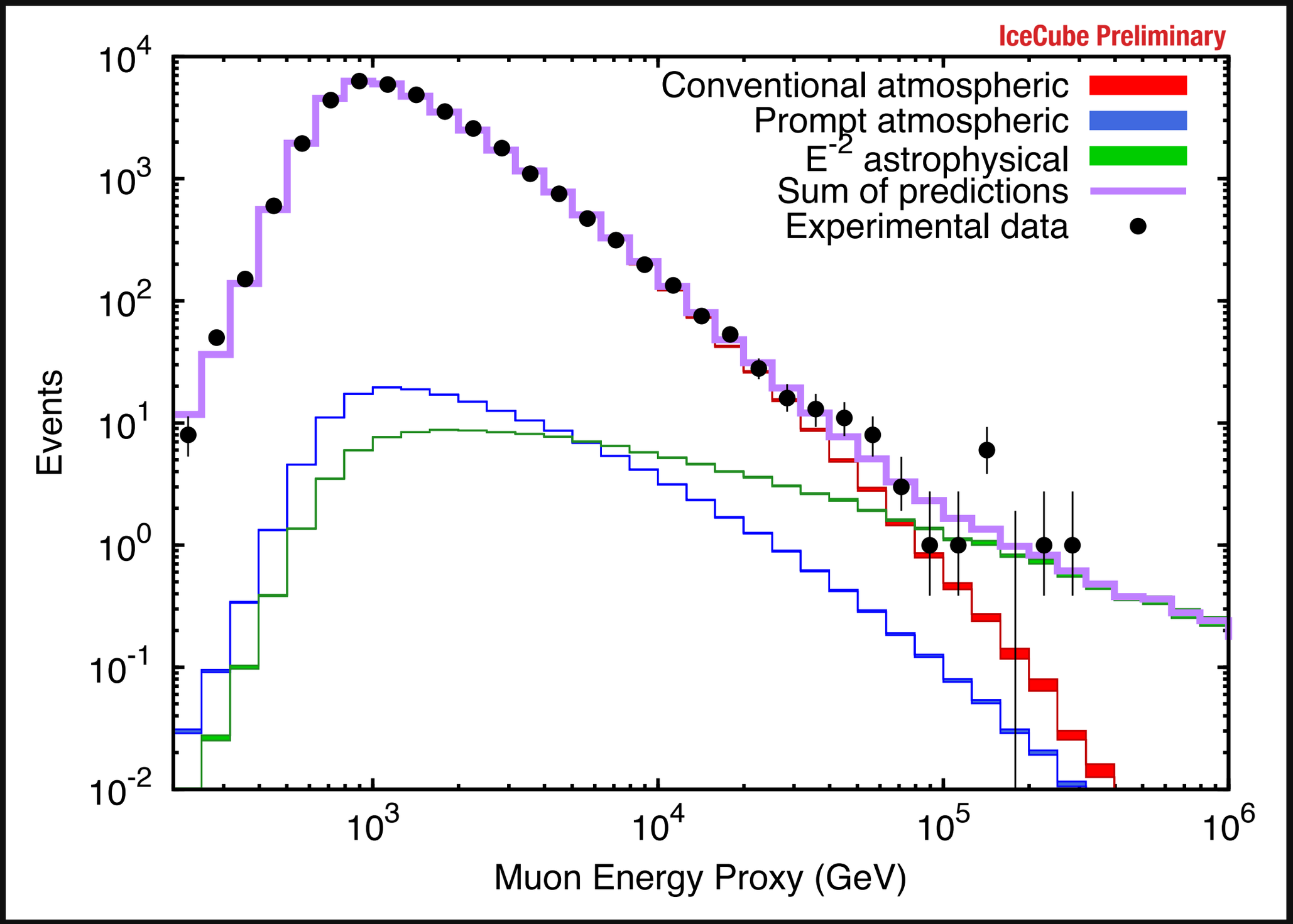
- **Similar flux in more “traditional” muon channel, accepting incoming muons, looking below the horizon (northern sky)**



Upgoing Muons - Spectral Components

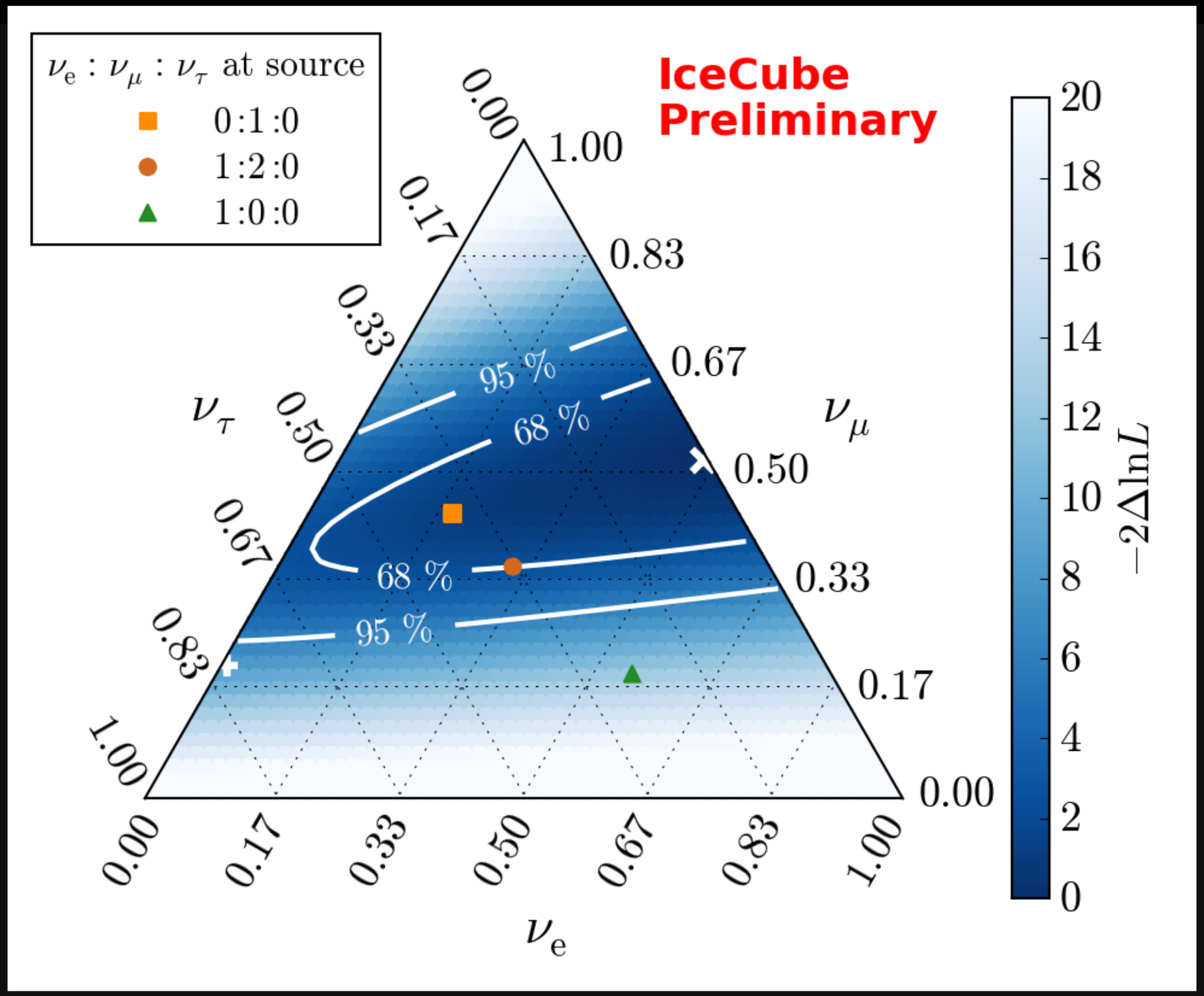
Two years of data - for E^{-2} spectral assumption - best fit is $E^{-2.2}$

Normalization for E^{-2}: $0.99^{+0.4}_{-0.3}\ 10^{-8}\ E^{-2}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$



Global Fit (of several IceCube analyses)

Publication under review - interesting results such as flavour ratio



The Future

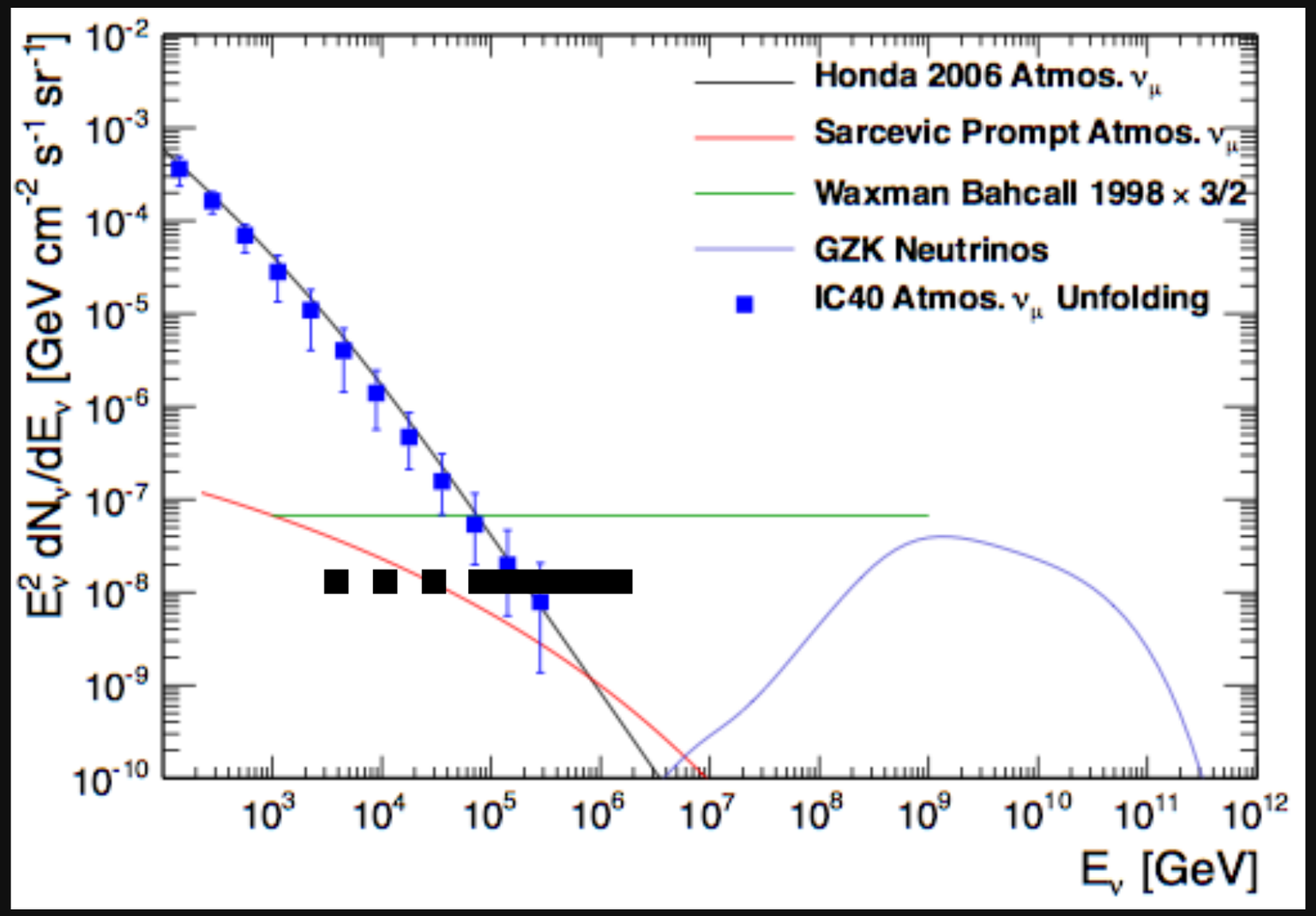
At the highest energies: “neutrino = extraterrestrial source”

- **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)

Note

For pointing searches we can tolerate more background!

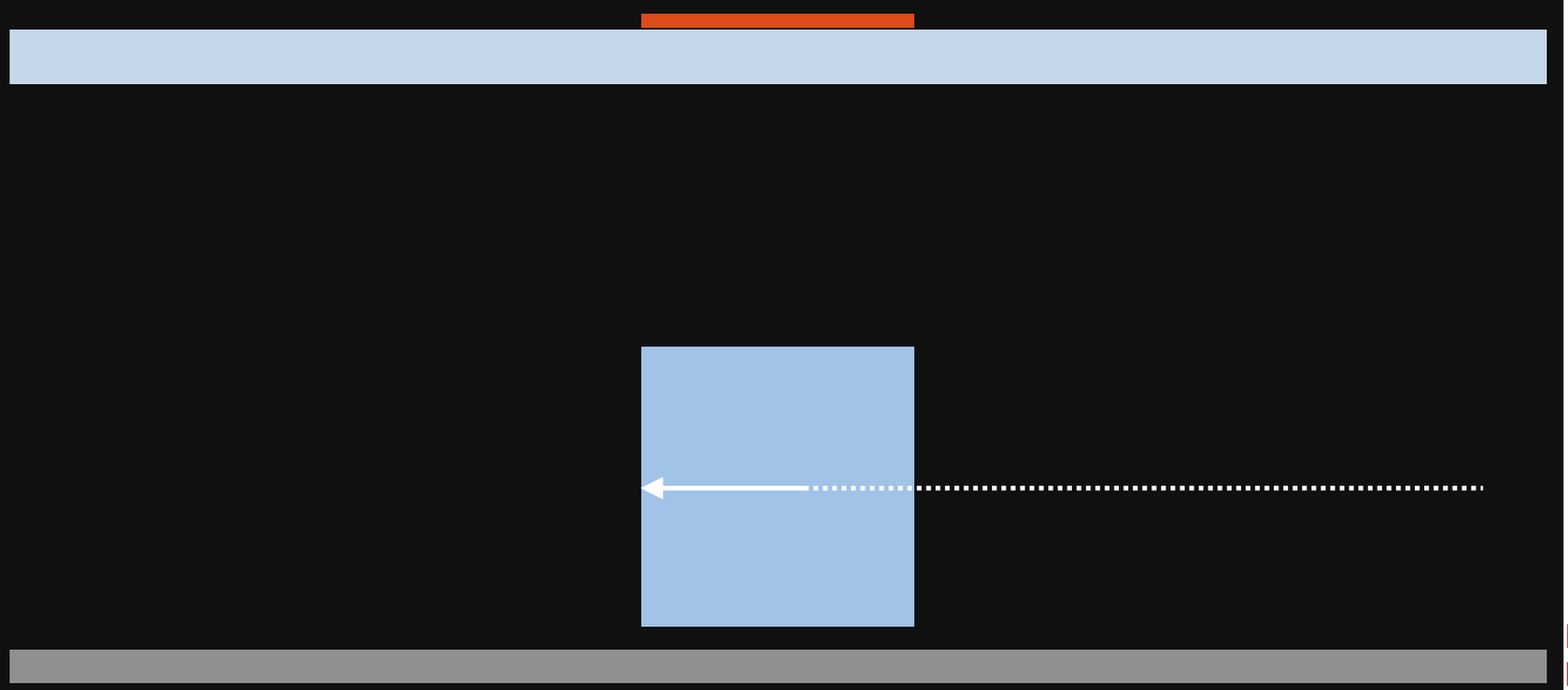
- **"Starting Event" analysis provides a sample with very low background (from atm. neutrinos and muons)**
- **HE flux likely continues down to lower energies, hidden in the atm. background**
- **Pointing searches can tolerate a bit more background!**

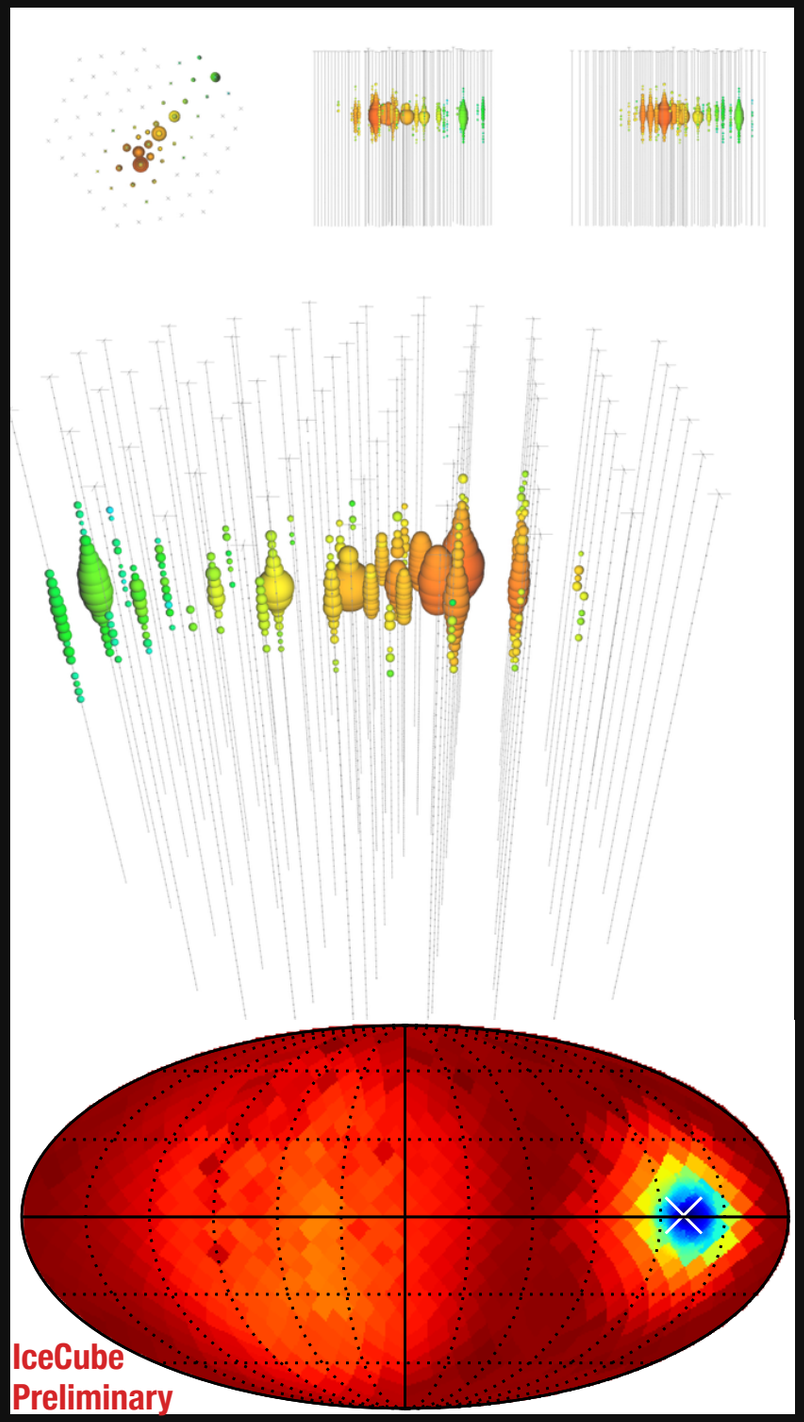


The Future

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

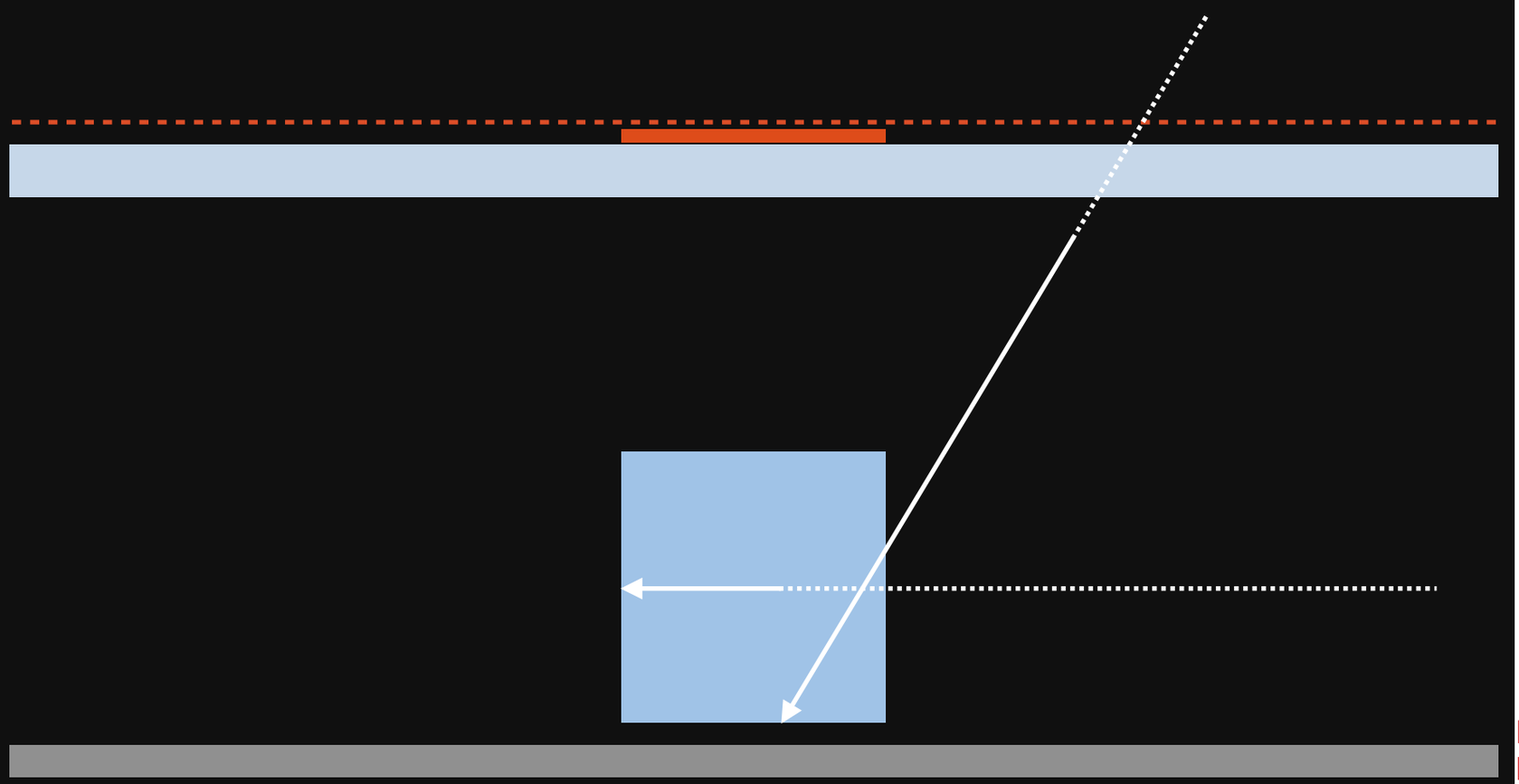


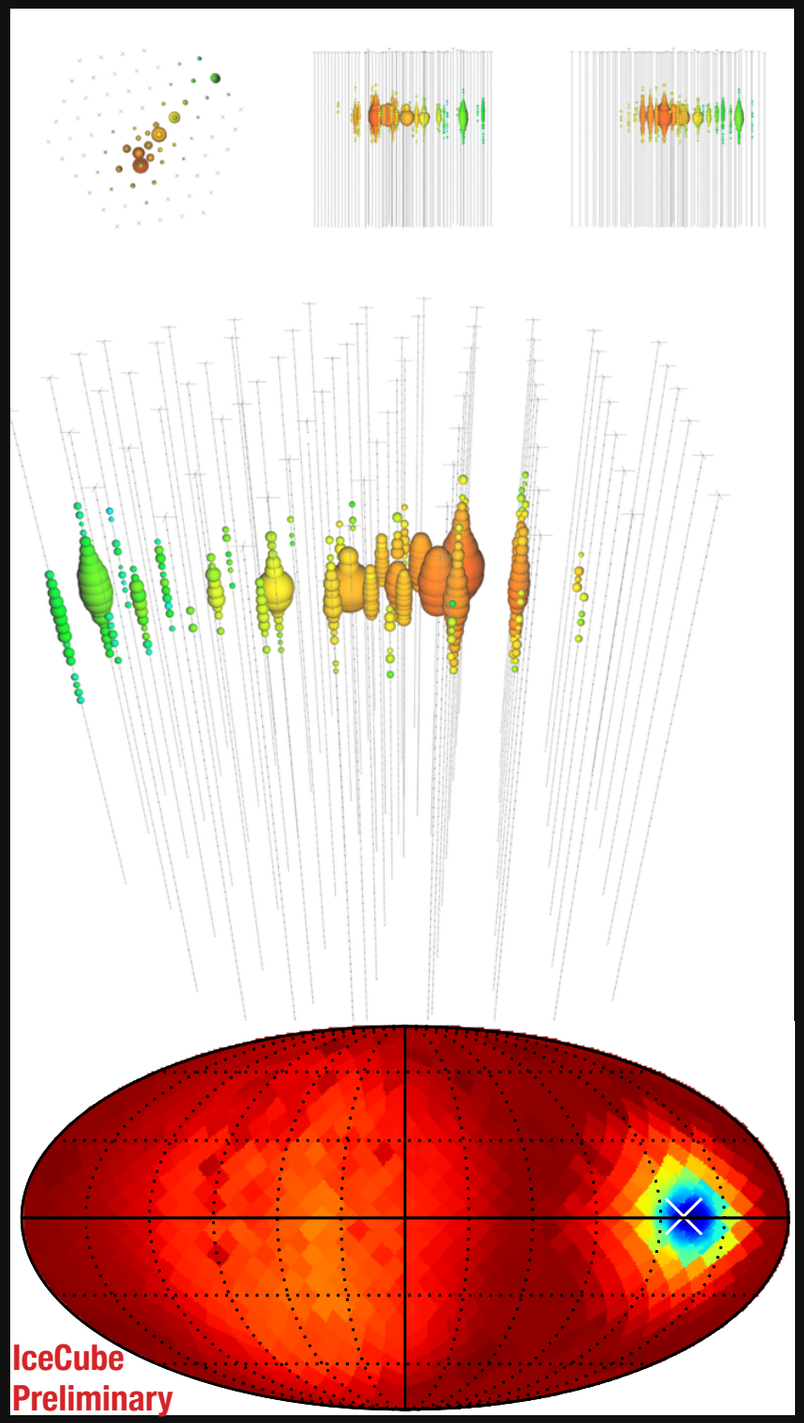


The Future

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

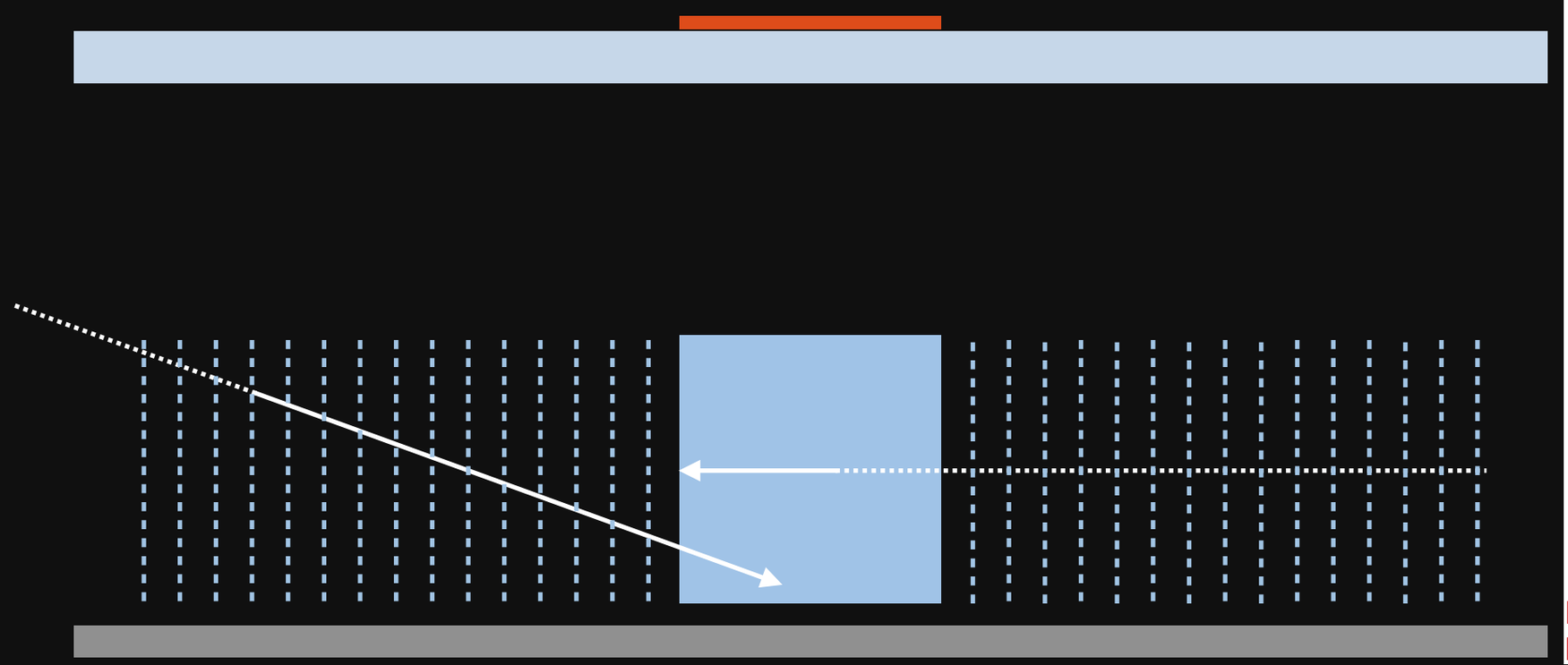


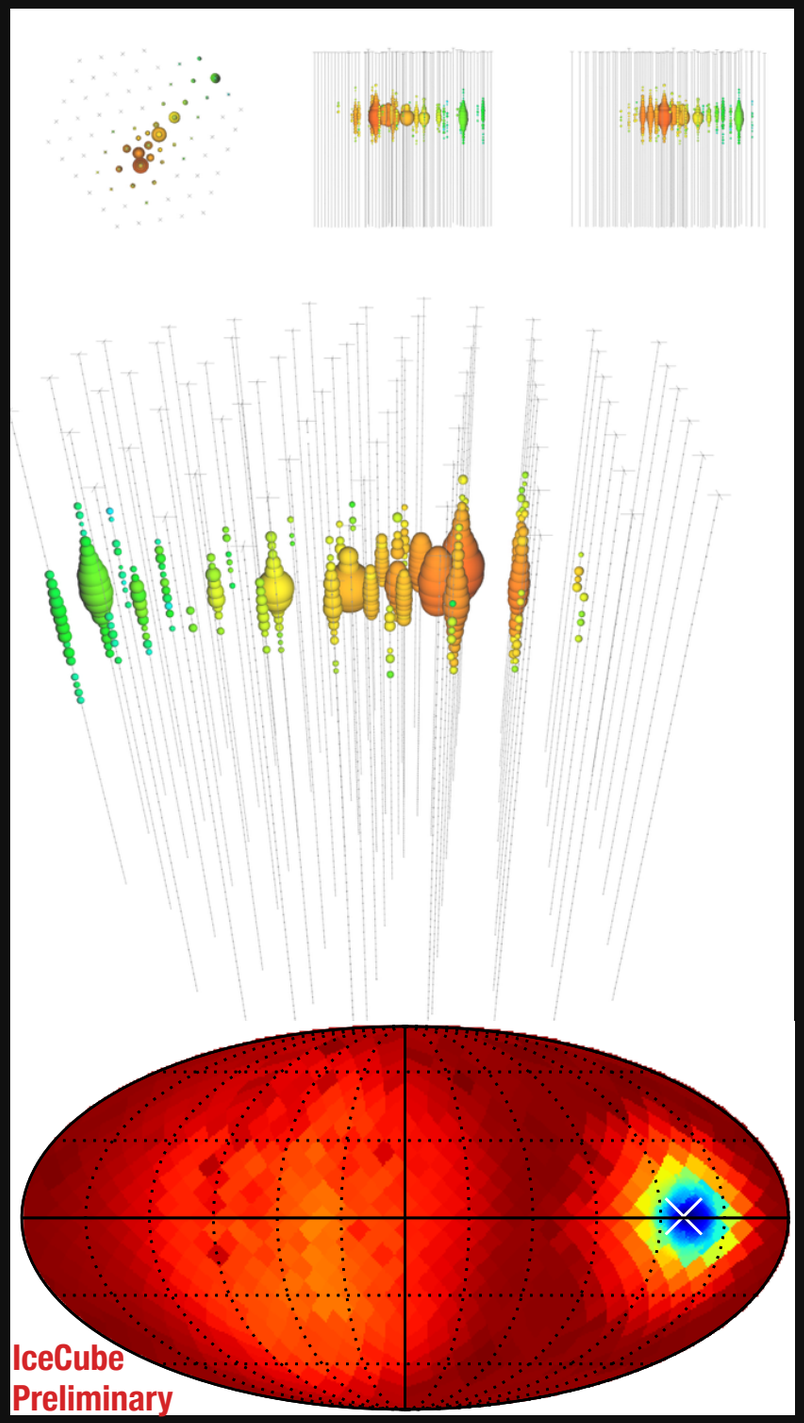


The Future

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

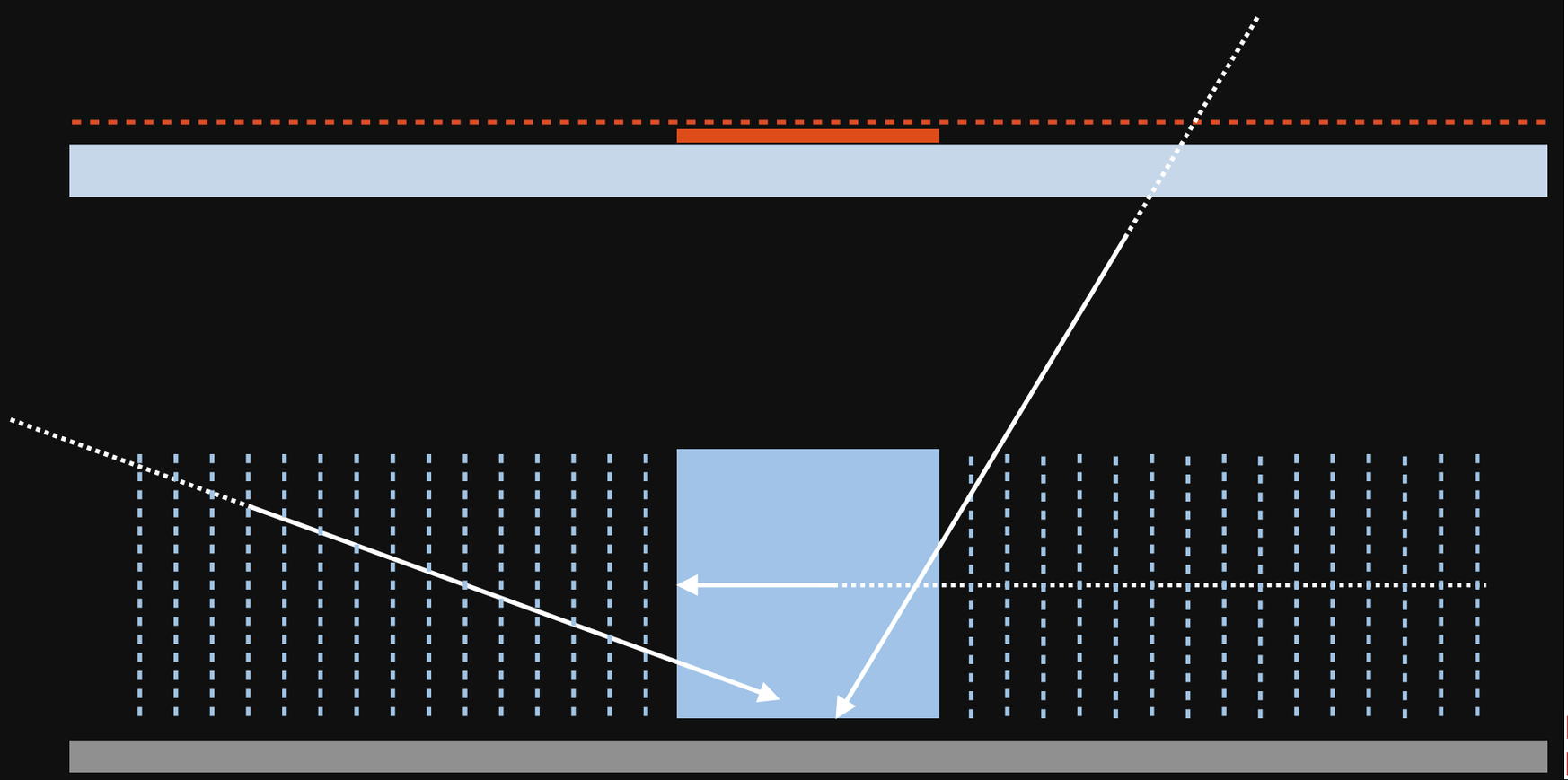


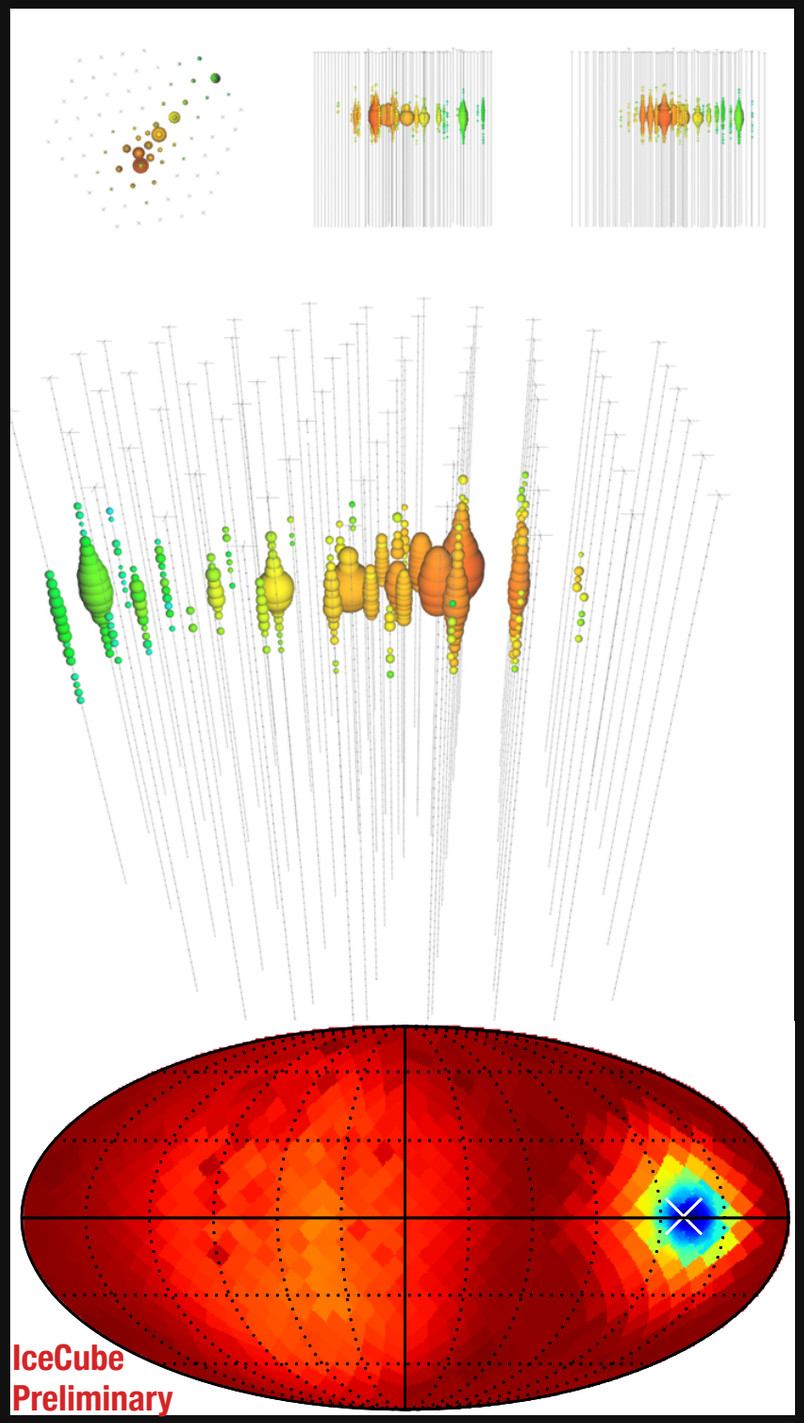


The Future

How do we get more tracks?

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



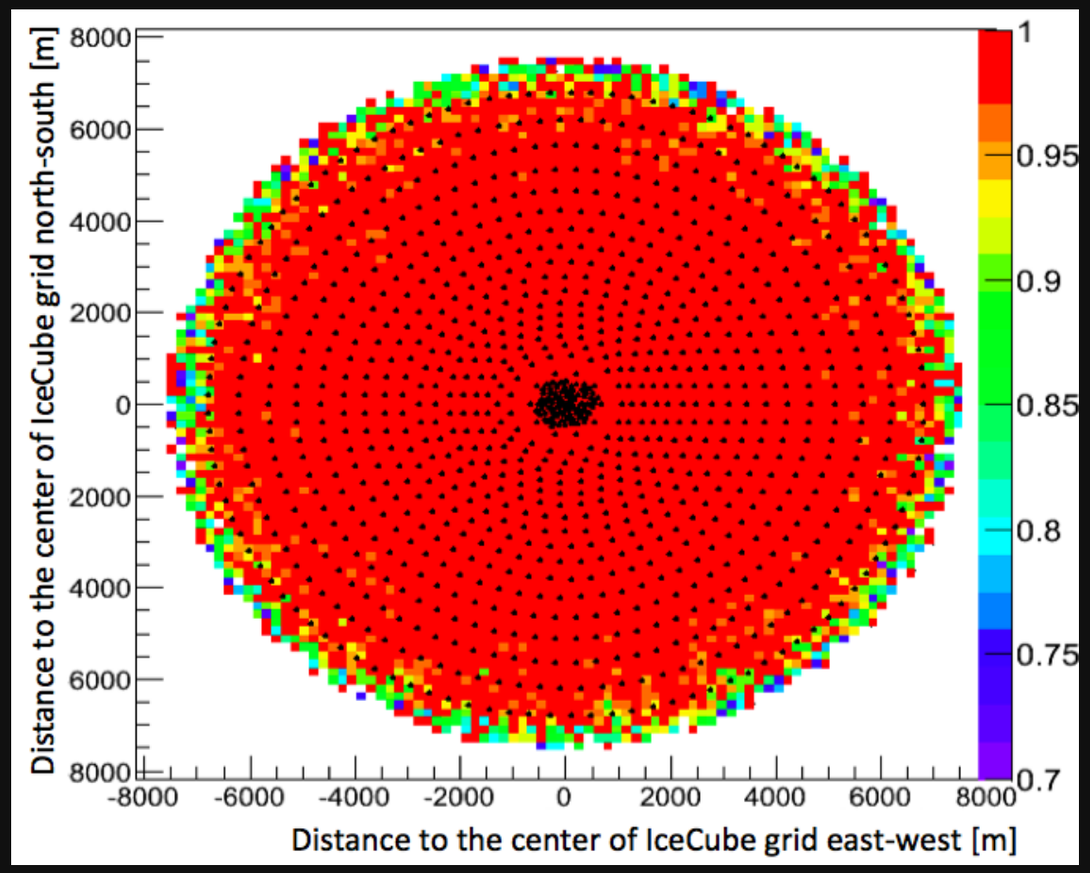


all results/designs shown are preliminary

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!**

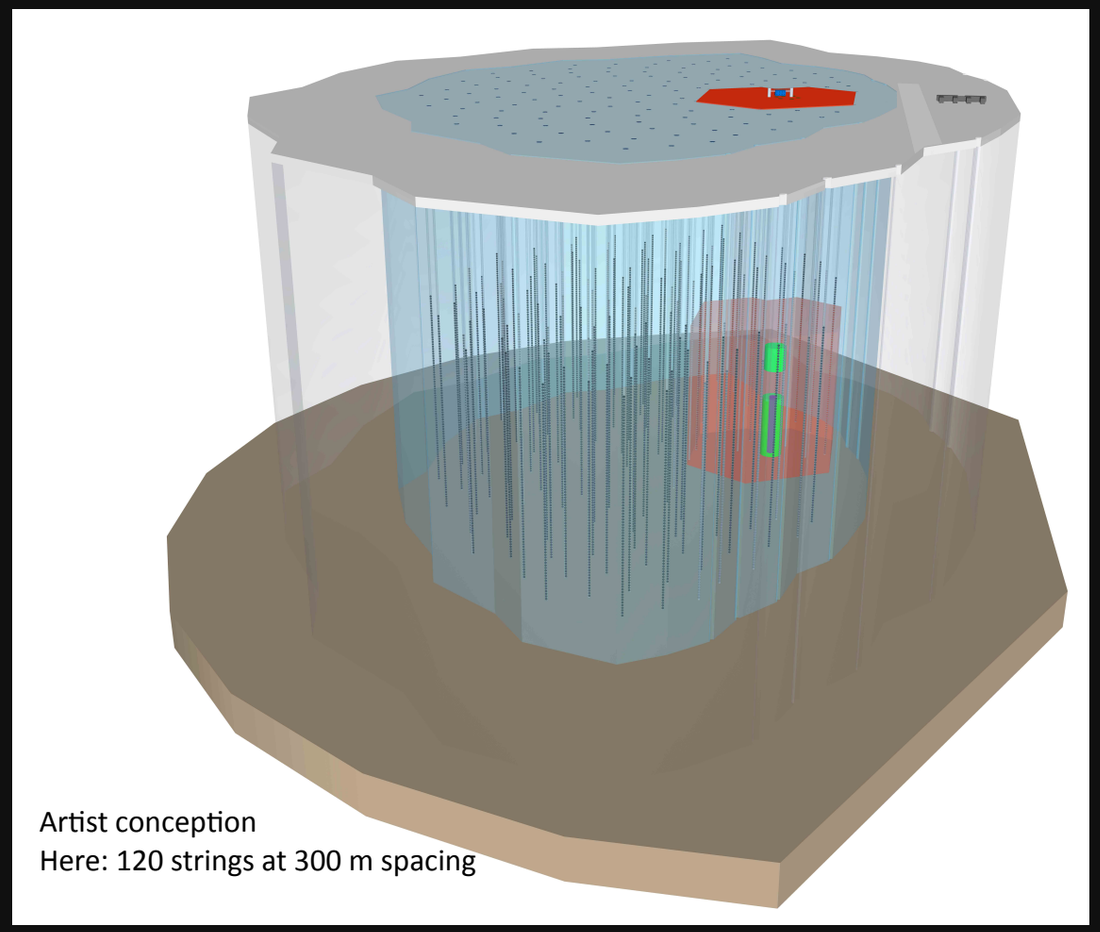


all results/designs shown are preliminary

The Future

An upgraded IceCube detector for high energies

- Current threshold at about 1TeV
- Can afford a slightly higher threshold of ~30 TeV



assuming ~100 new strings

The Future

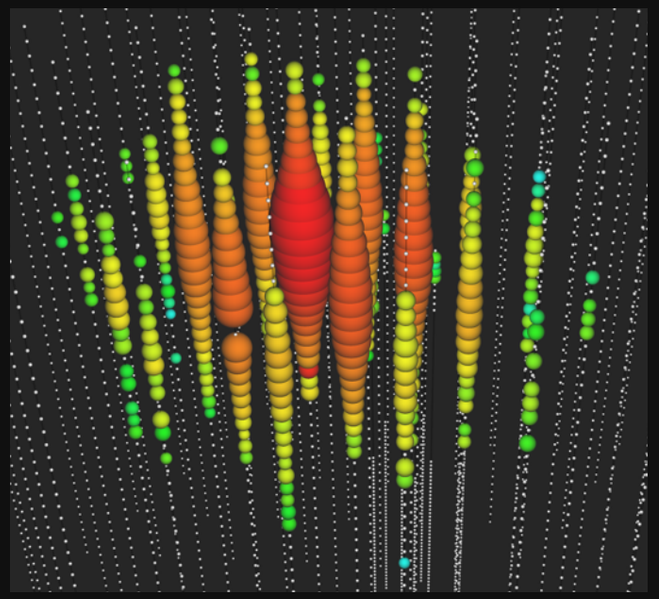
An upgraded IceCube detector for high energies - in addition to low energies (PINGU!)

- “Next generation” detector upgrade, extending the energy range
- PINGU
  - O(40) densely packed strings
  - Neutrino mass hierarchy, neutrino physics, dark matter,…
- “High-Energy Upgrade” (to be named)
  - O(100) strings, 5-10 km^3
  - Identify astrophysical sources of neutrinos (and cosmic rays!), neutrino and particle physics
- Surface component: veto downgoing background, CR physics,…

Conclusions

Stay tuned!

- 53(+1) events with energies above ≈ 50 TeV found in three years of IceCube data
- We see this in other channels (incoming muons) and down to energies of 10 TeV now!
- Statistics are steadily increasing, we are now working on characterizing the flux better and better
- We are planning future upgrades to measure this even better and look for the sources of these neutrinos

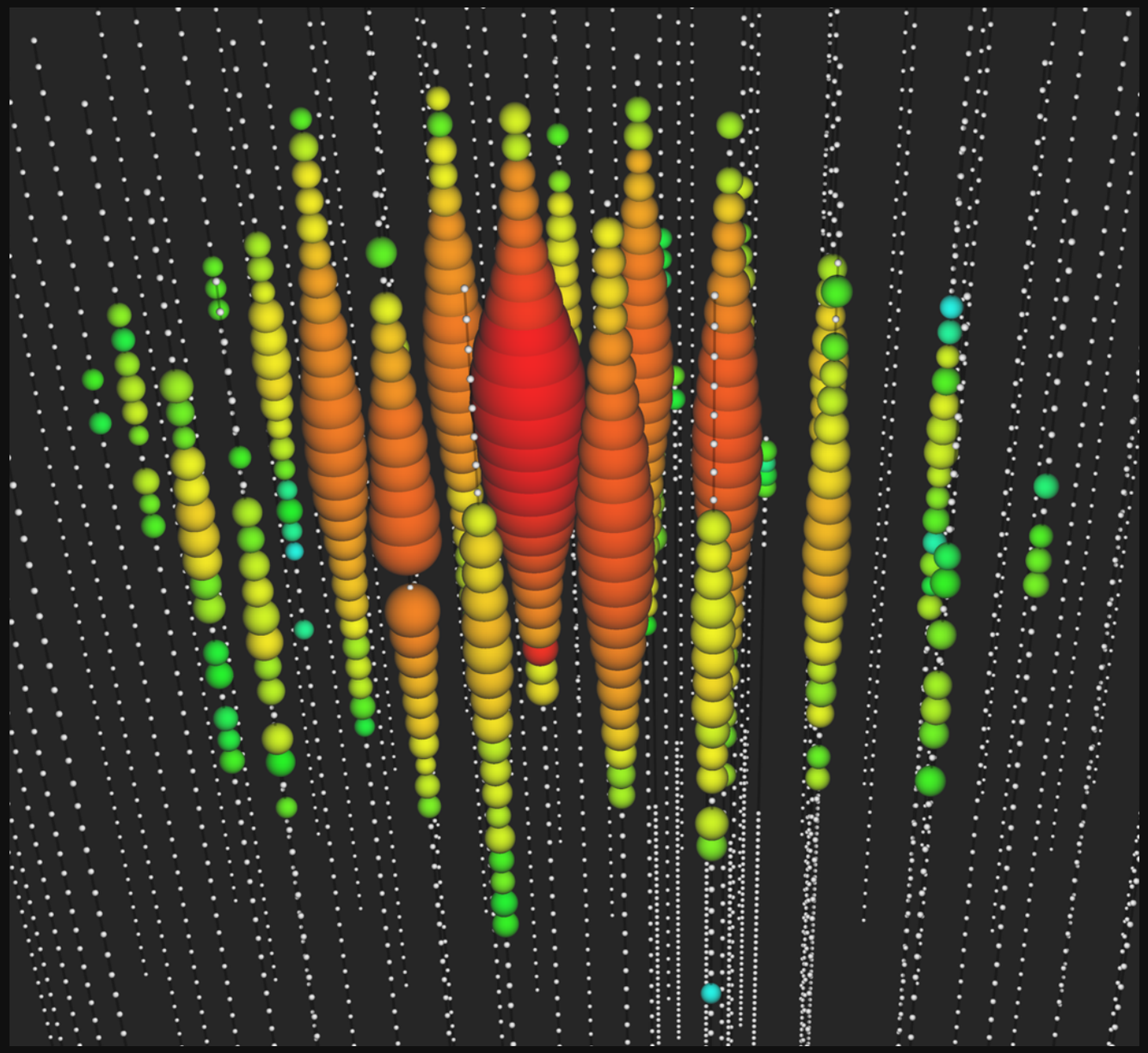


The IceCube Collaboration

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)

Thank you!



2 PeV event - “Big Bird”

Backup

Indirect Dark Matter Searches

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

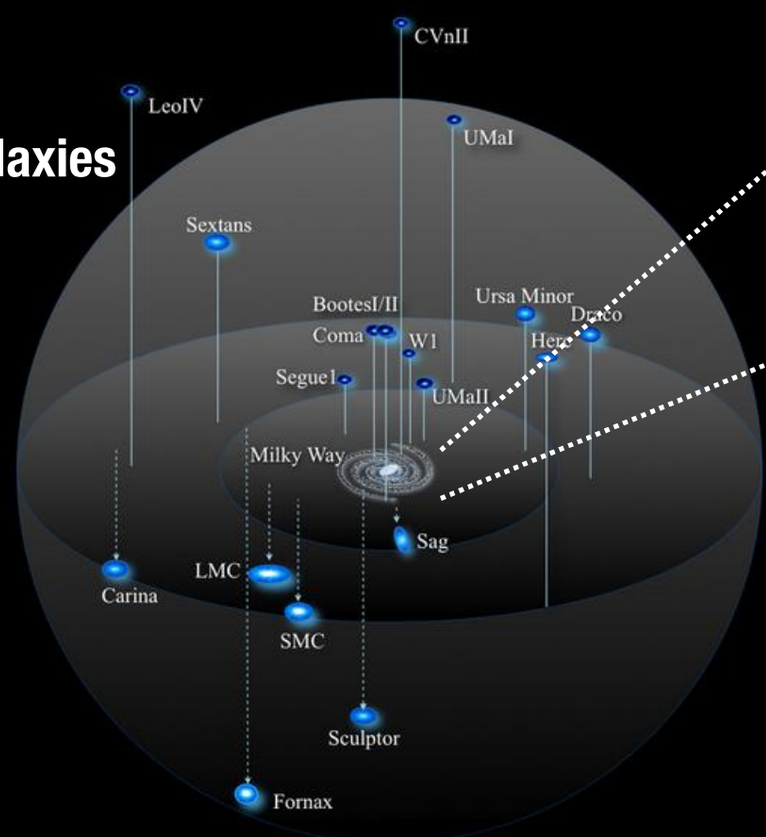
Indirect Dark Matter Searches

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

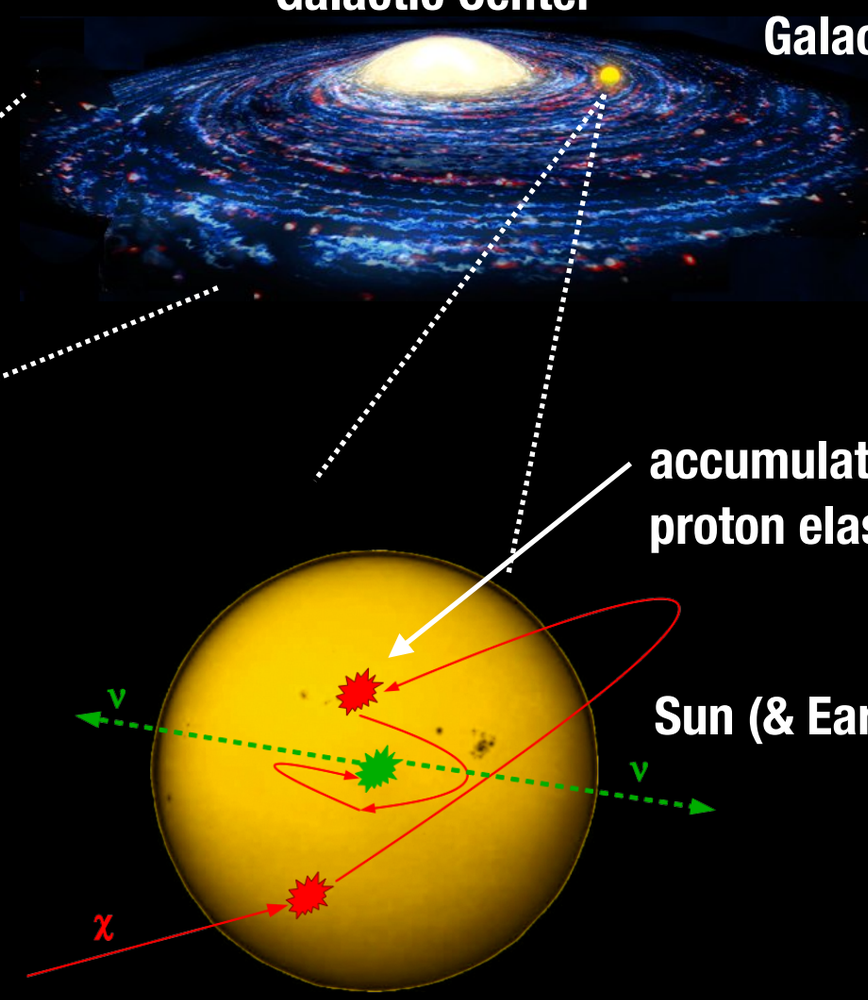
Galactic Center

Galactic Halo

Clusters of Galaxies



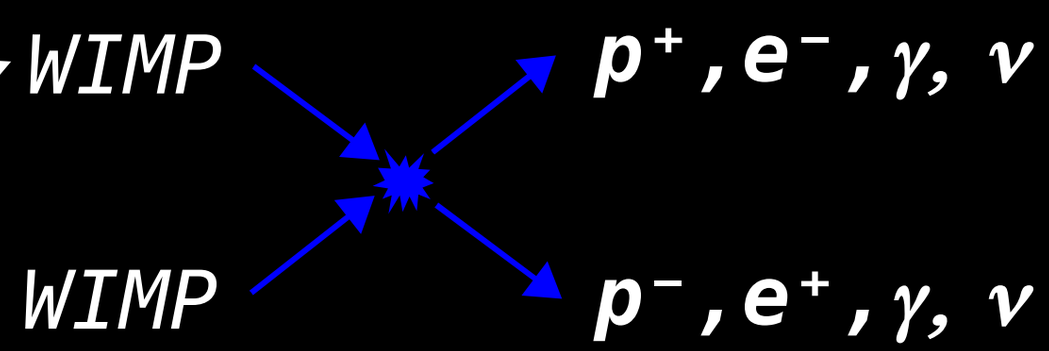
Dwarf spheroidal galaxies



accumulate due to WIMP-proton elastic scattering

Sun (& Earth)

MSSM - neutralino



PRL 110 (2013) 131302

IceCube-79 Solar WIMP Search

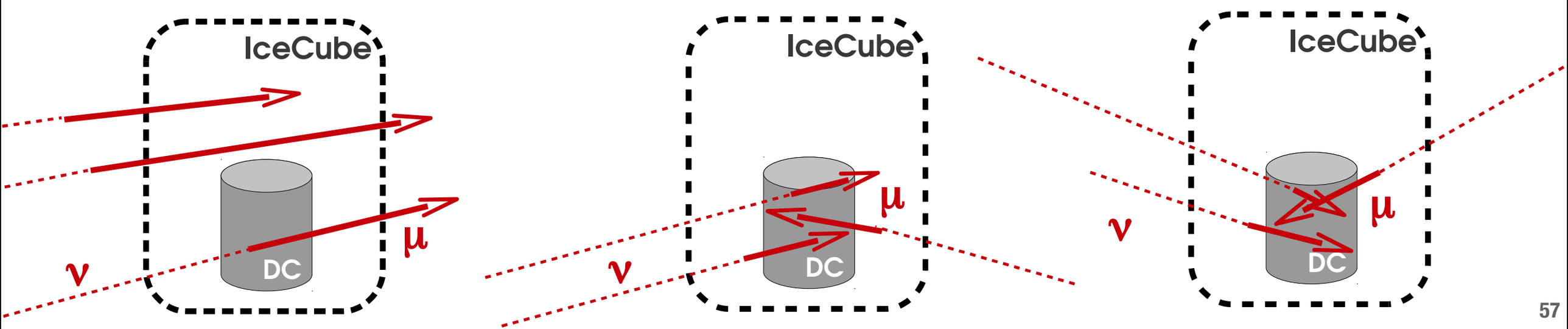
All-year search: three cuts to search for neutrinos above background from the Sun's direction, even when looking up in the Summer!

- **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!**

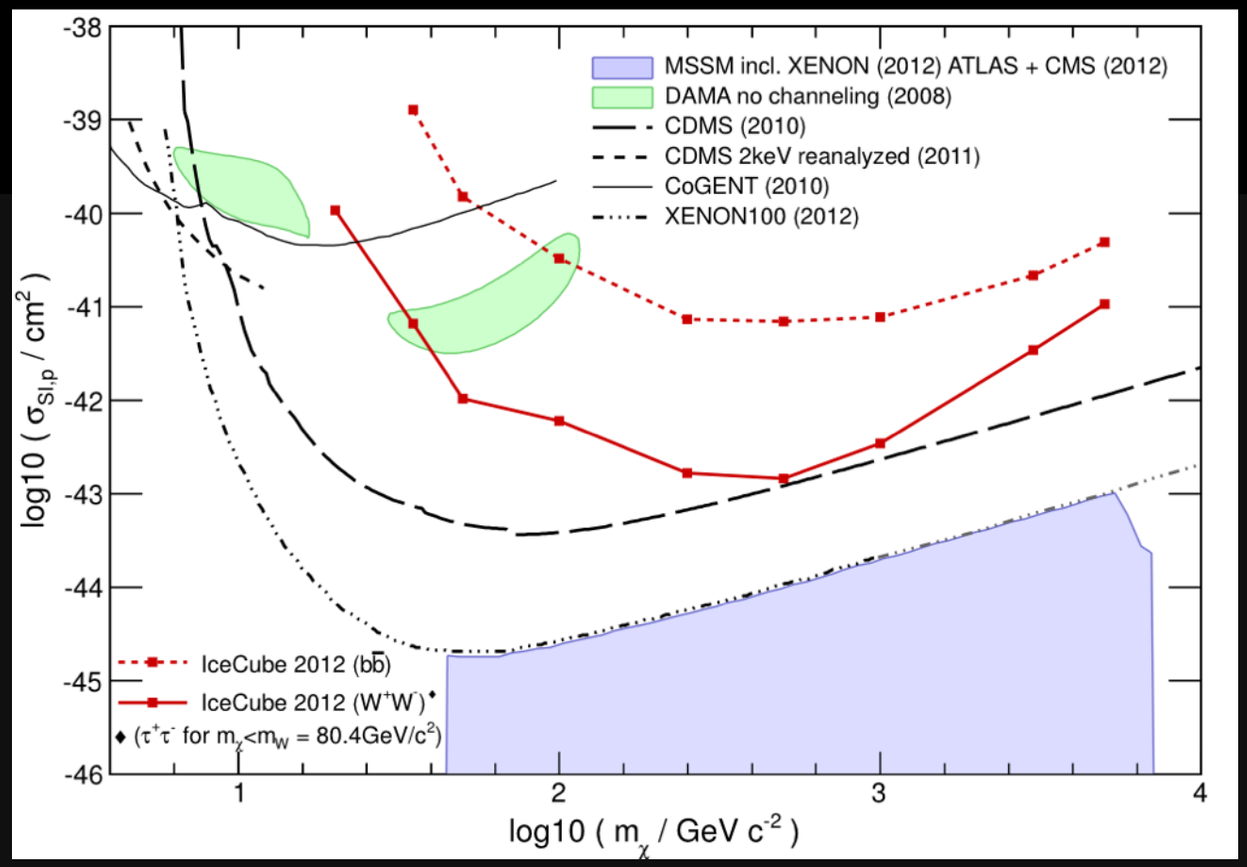
- *Up-going* 1
- No containment

- *Up-going* 2
- strong containment

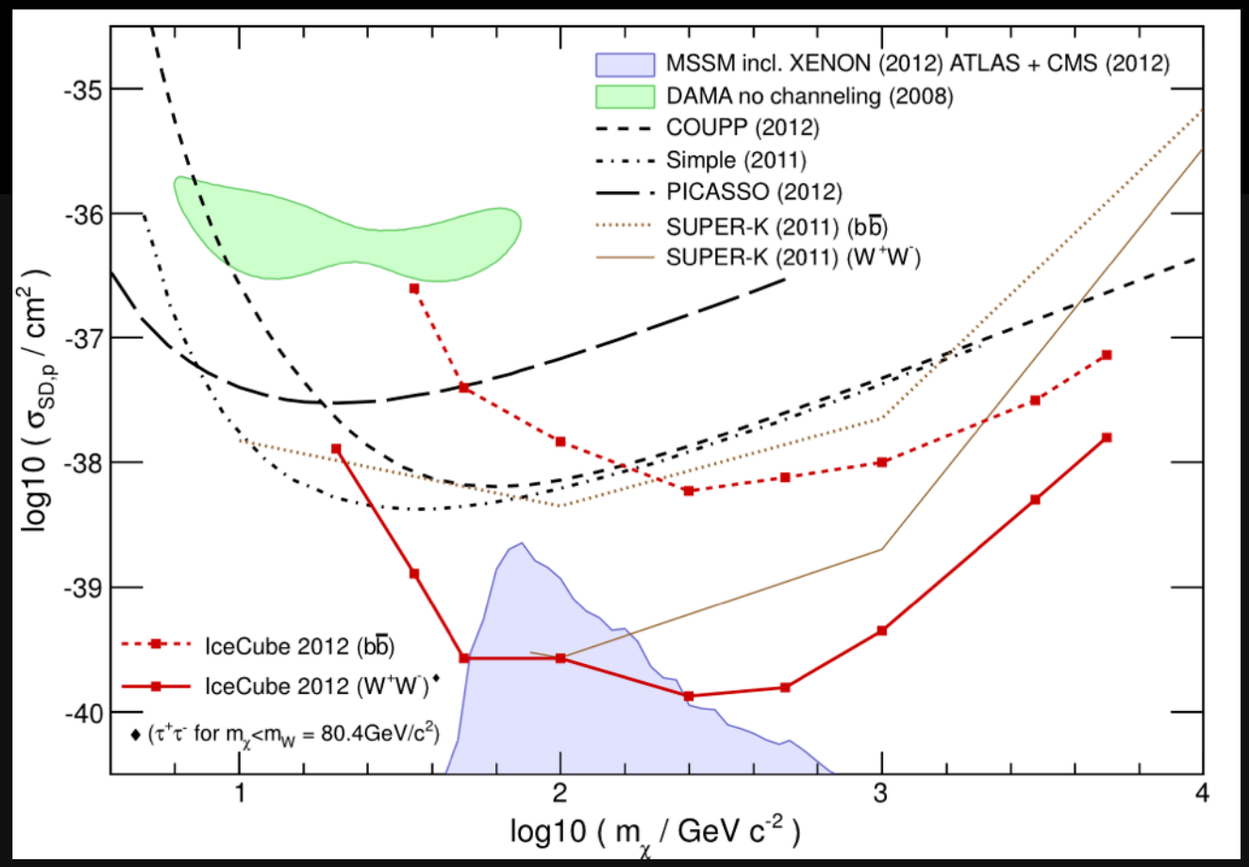
- *Down-going* 3
- strong containment



IceCube-79 Solar WIMP Search



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

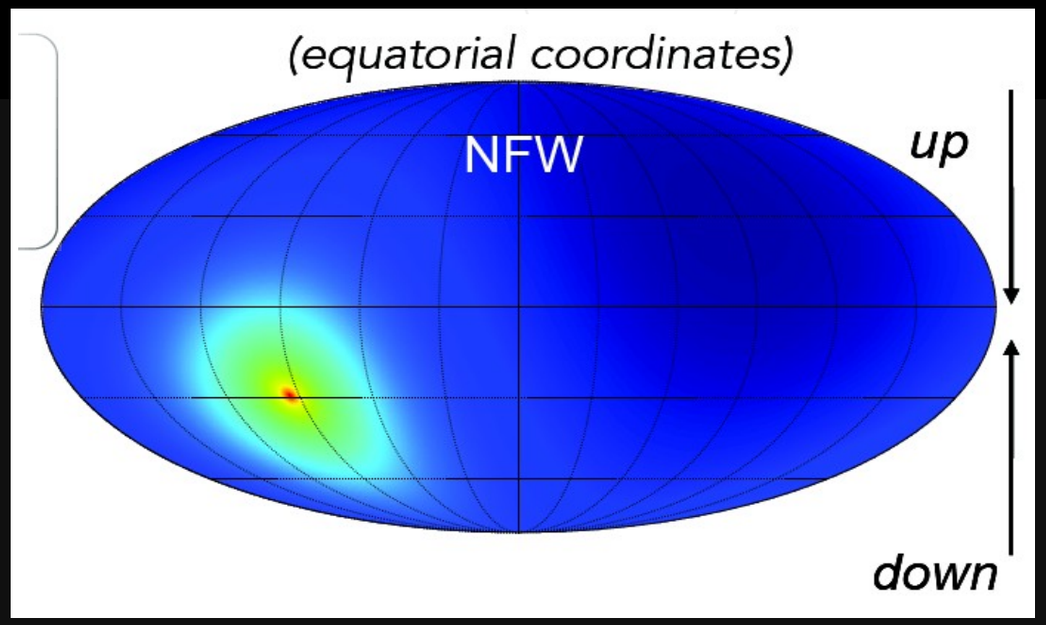


90% CL χ-p cross-section (spin-dependent)

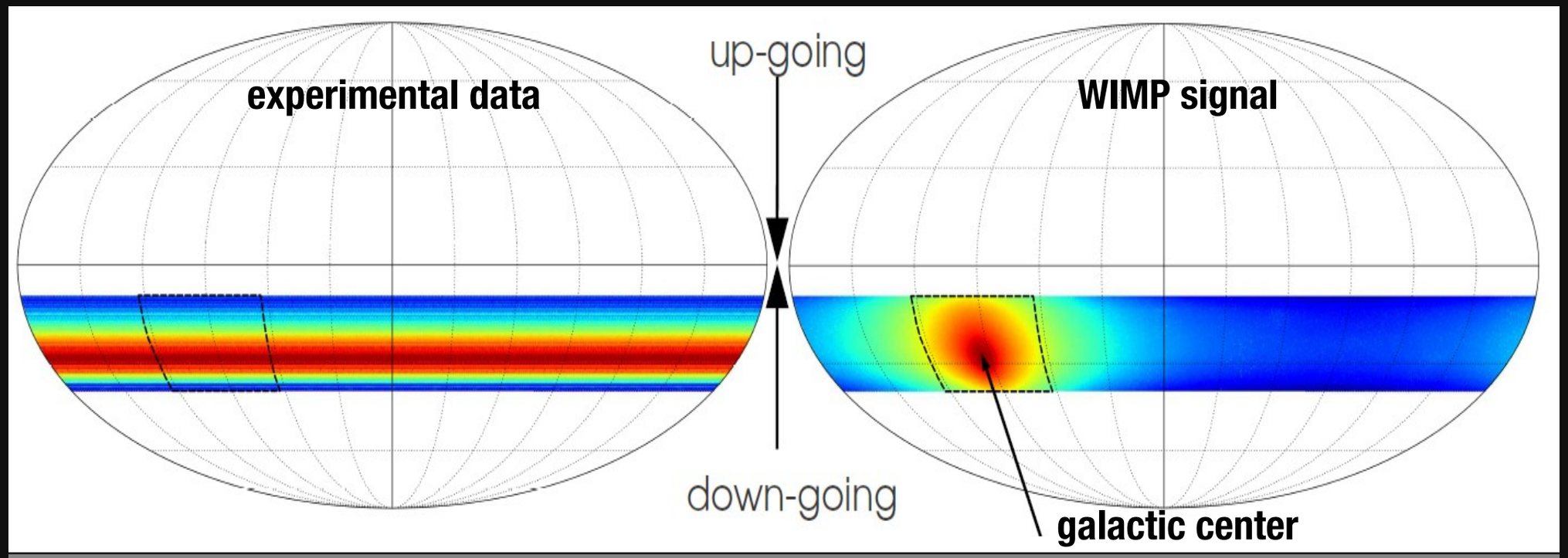
- **Complementary to direct detection search efforts**
  - fills out WIMP picture by testing other properties
- **Most stringent SD cross-section limit for most models**

Galactic Center Dark Matter Search

IceCube-79 string configuration



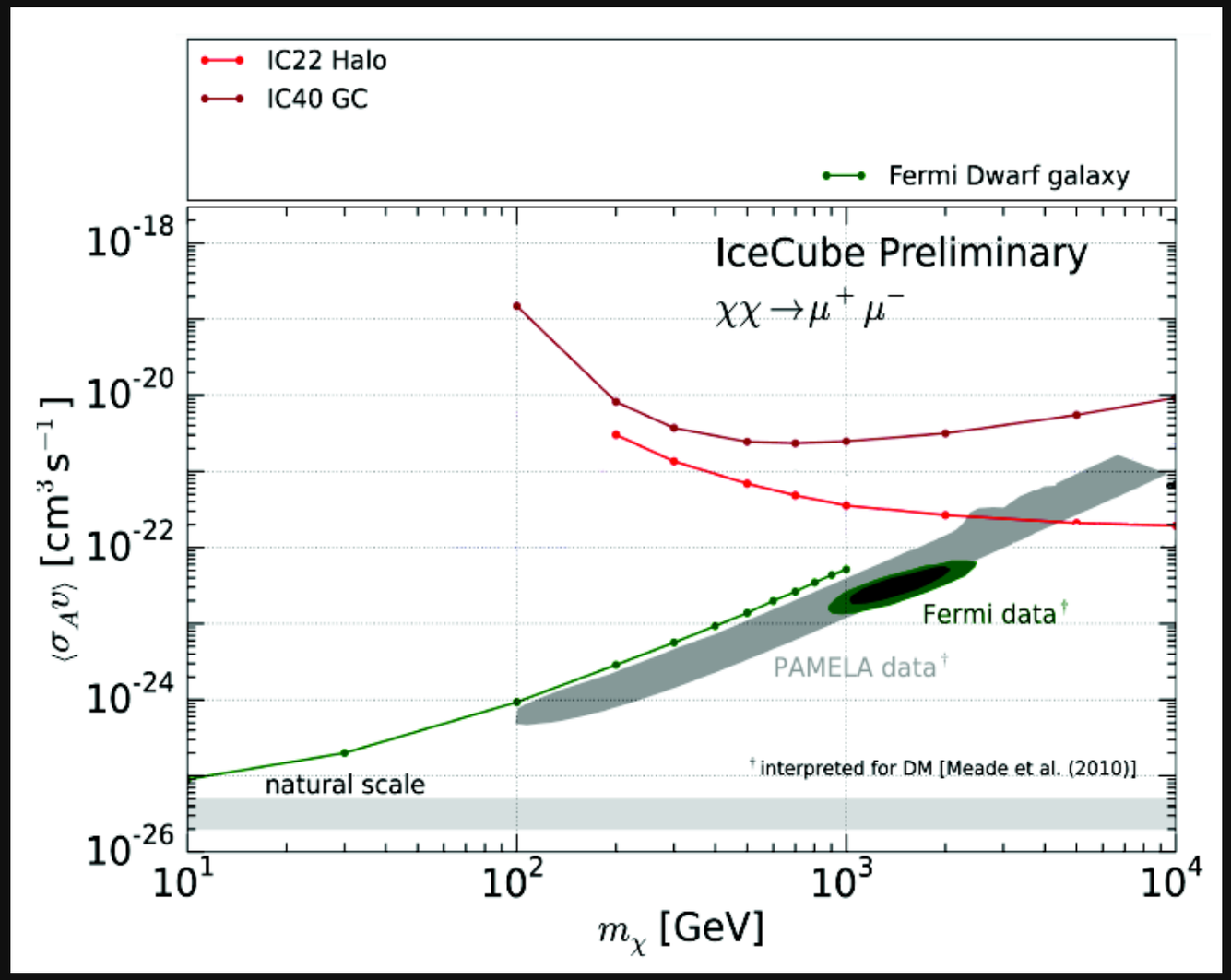
- **Two different analyses:**
  - DeepCore and DeepCore+IceCube
- **lower the energy threshold to ~10 GeV**
- **Improved muon veto**
- **Use scrambled data for background estimation**



Various Potential Dark Matter Signals

Various analyses looking at different source distributions

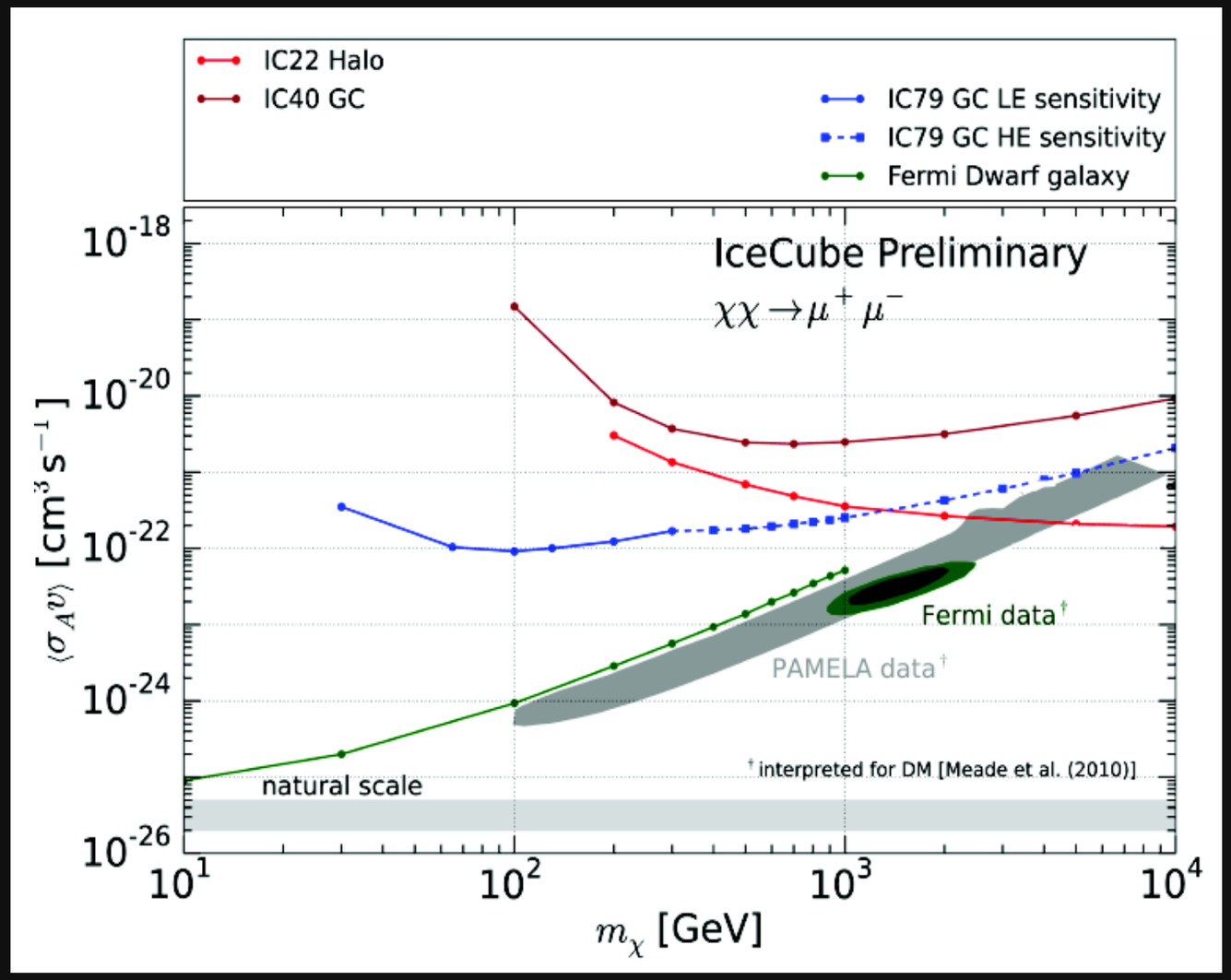
- **Galactic Halo:**
  - IC22 PRD 8 (2011) 022004
  - IC79 in preparation
- **Galactic Center:**
  - IC79 in preparation
- **Dwarf spheroids:**
  - IC59 PRD 88 (2013) 122001
- **Clusters of galaxies:**
  - IC59 PRD 88 (2013) 122001



Various Potential Dark Matter Signals

Various analyses looking at different source distributions

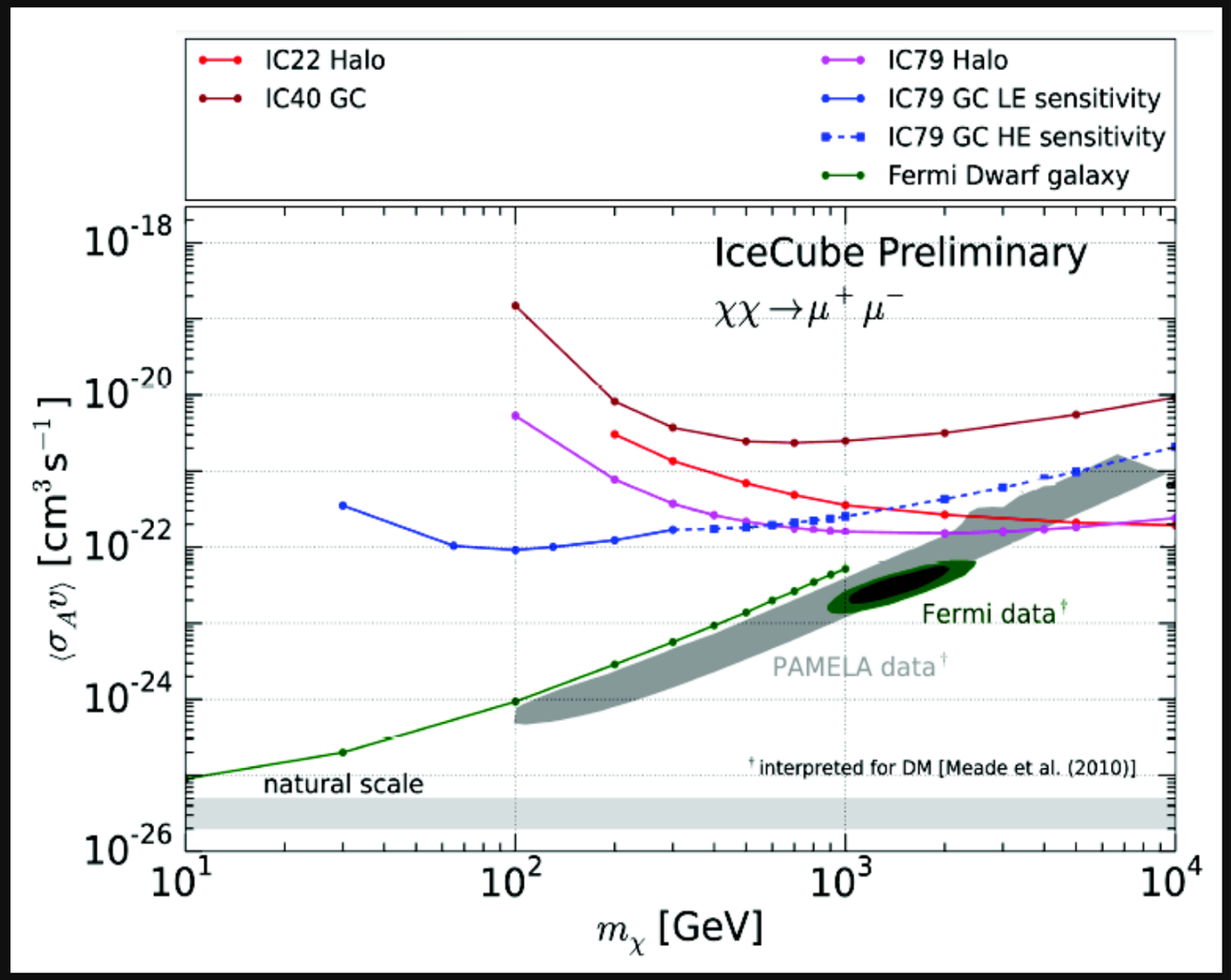
- **Galactic Halo:**
  - IC22 PRD 8 (2011) 022004
  - IC79 in preparation
- **Galactic Center:**
  - IC79 in preparation
- **Dwarf spheroids:**
  - IC59 PRD 88 (2013) 122001
- **Clusters of galaxies:**
  - IC59 PRD 88 (2013) 122001



Various Potential Dark Matter Signals

Various analyses looking at different source distributions

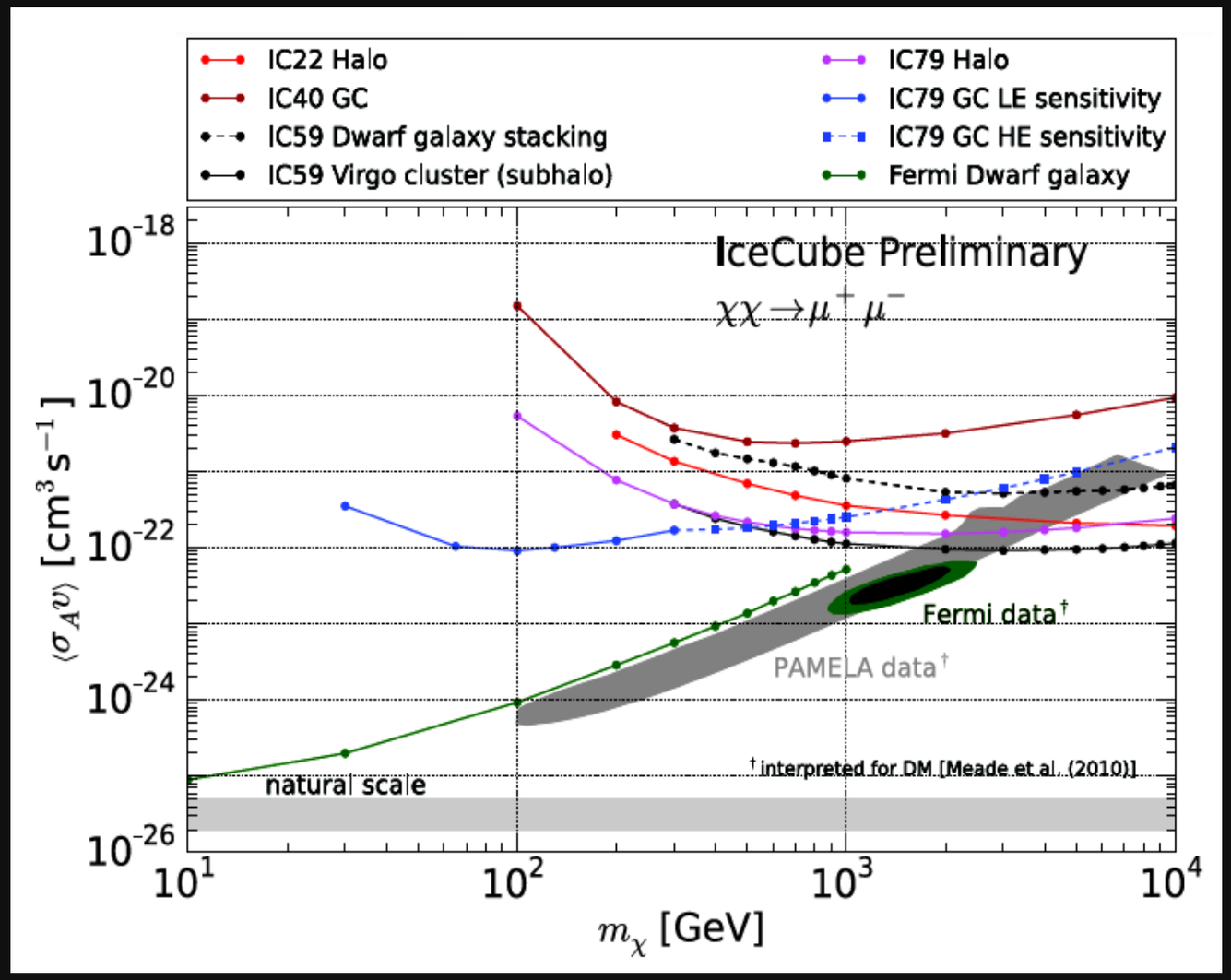
- **Galactic Halo:**
  - IC22 PRD 8 (2011) 022004
  - IC79 in preparation
- **Galactic Center:**
  - IC79 in preparation
- **Dwarf spheroids:**
  - IC59 PRD 88 (2013) 122001
- **Clusters of galaxies:**
  - IC59 PRD 88 (2013) 122001



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:** high mass/light ratio
  - IC59 PRD 88 (2013) 122001
- **Clusters of galaxies:**
  - IC59 PRD 88 (2013) 122001

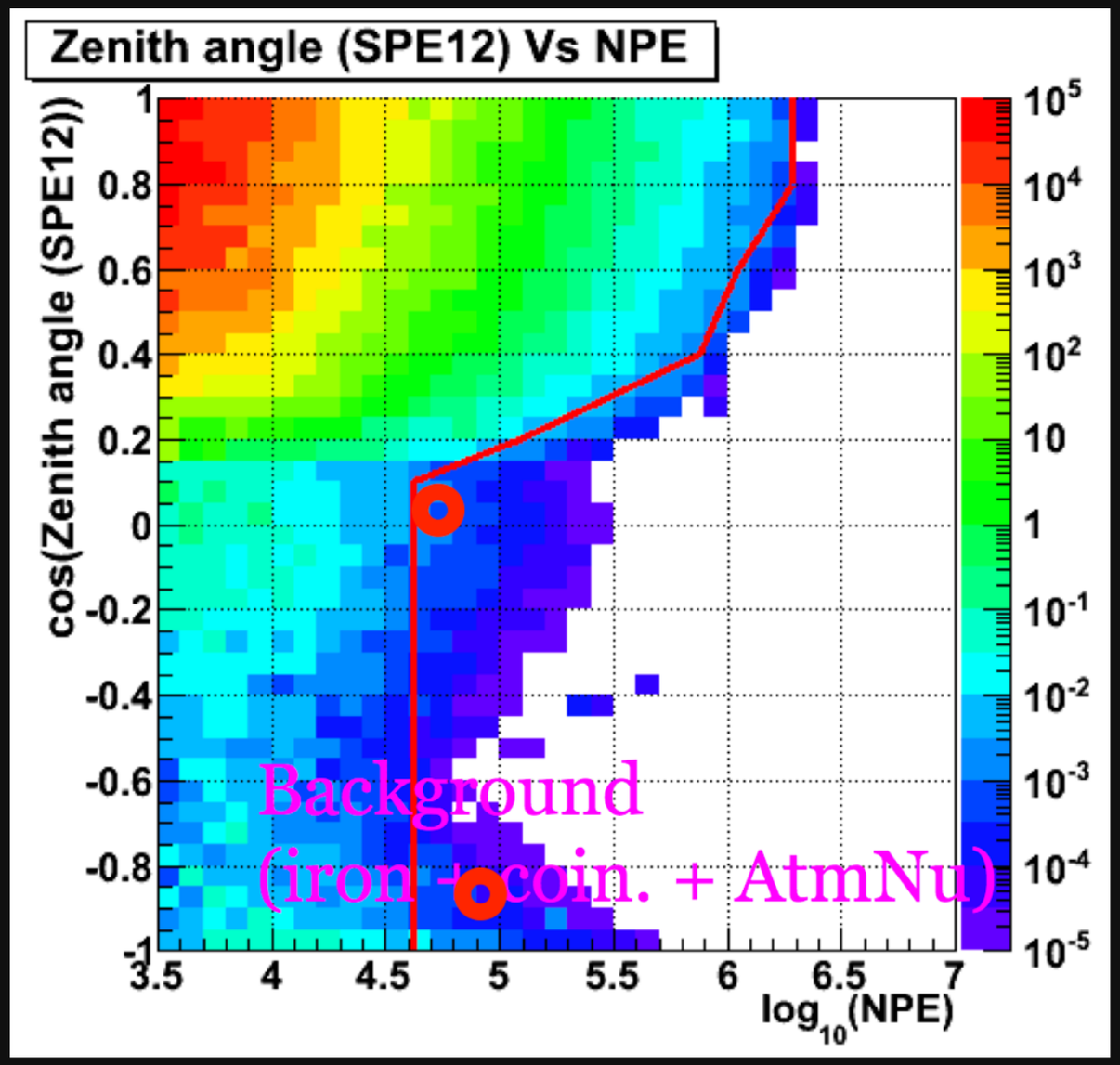


High-Energy Analysis Details

GZK Neutrino Analysis

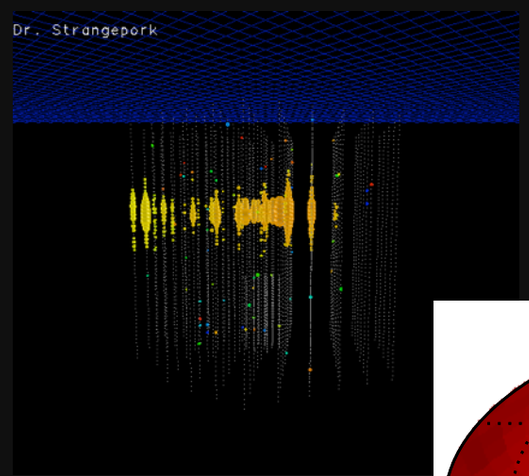
Simple search to look for extremely high energies (10^9 GeV) neutrinos from proton interactions on the CMB

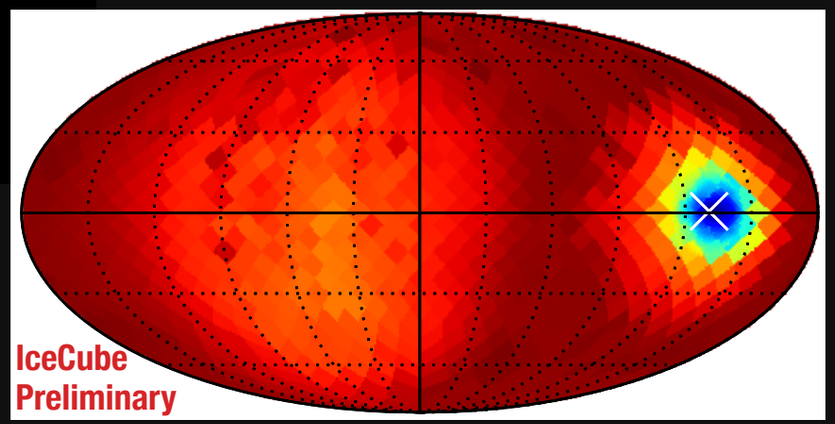
- **Upgoing muons**
  - Always neutrinos
  - Background: atm. neutrinos
  - High threshold (1 PeV)
- **Downgoing muons (VHE)**
  - Cosmic Ray muon background
  - Very high threshold (100 PeV)



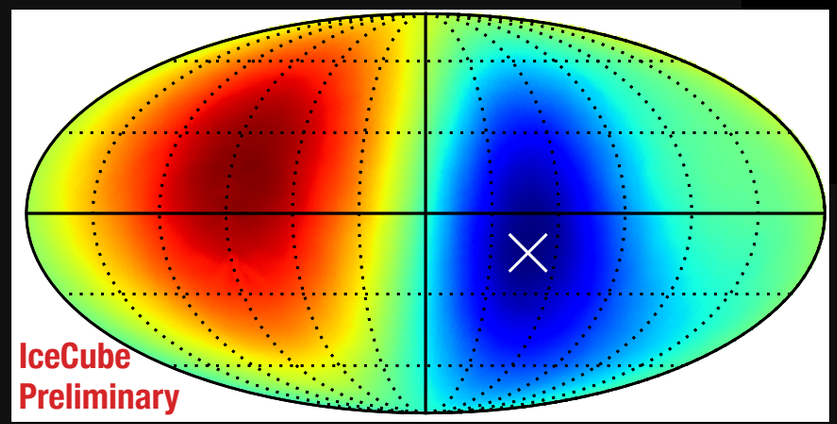
Event Reconstruction

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

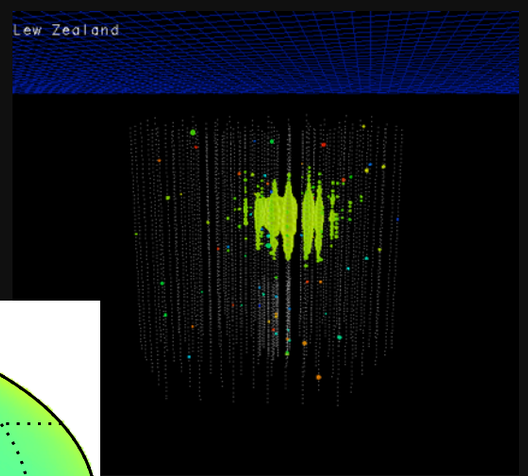




track



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

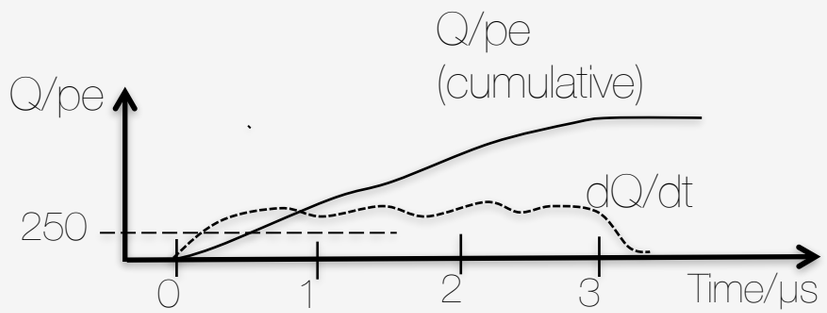
- **Energy scale: better than ≈ 10%**
  - From minimum ionizing muons: ±5%
  - Scales very well to higher energies over orders of magnitude (measured with in-ice calibration laser)
- **Modeling of photon transport in ice**
  - Measured with in-ice calibration LEDs and other devices (dust logger, ...)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

Background 1 - Atmospheric Muons

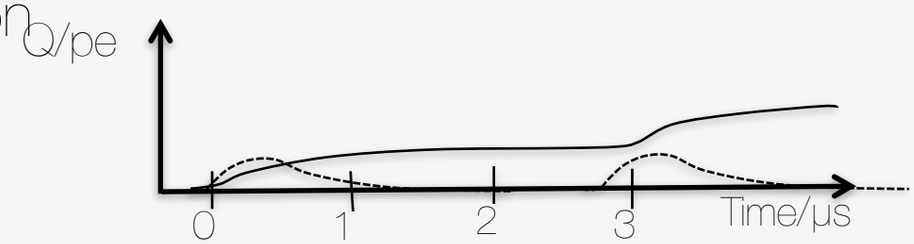
What's "early charge"?

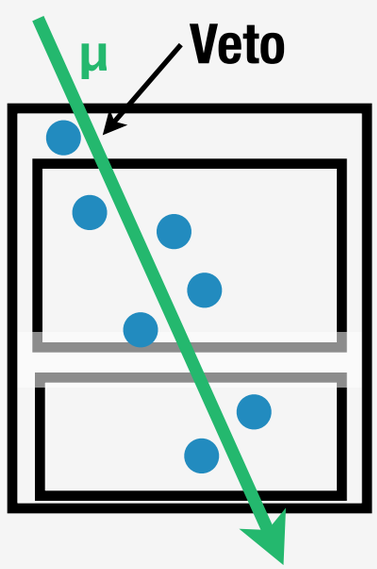
Throughgoing muon

Total detector



Veto region

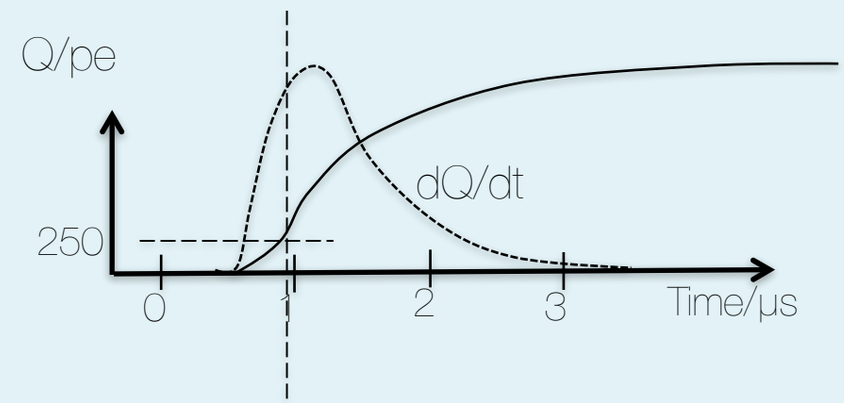


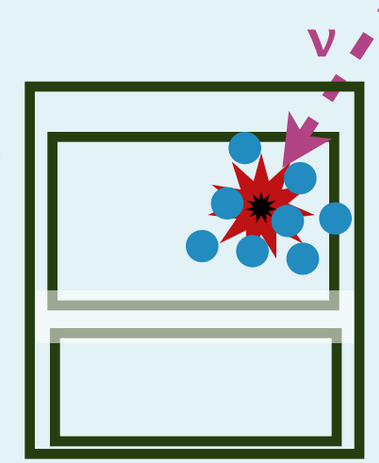


T_{250}= time at which Q= 250 pe

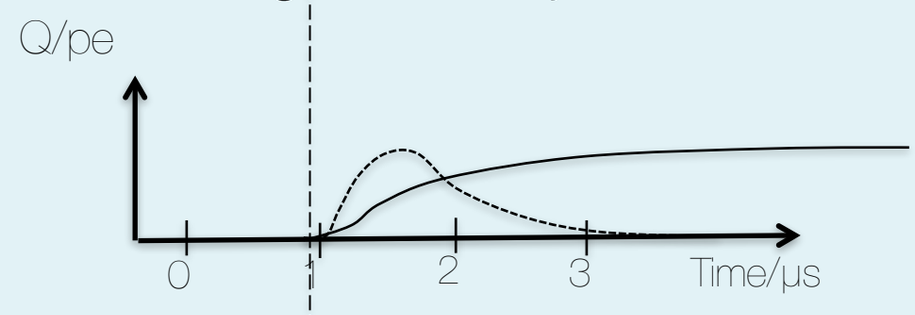
Contained cascade

Total detector

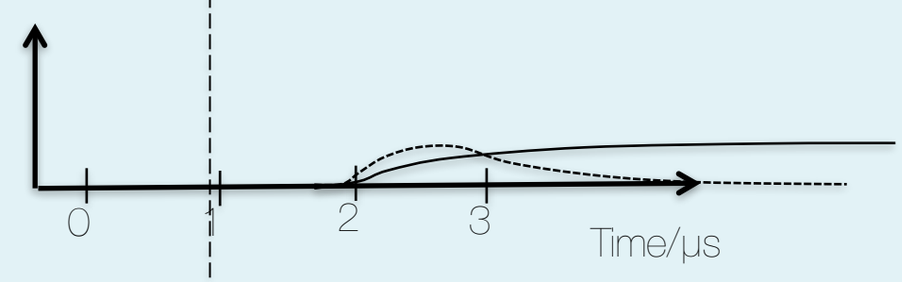




Veto region – barely contained cascade



Veto region – well contained cascade

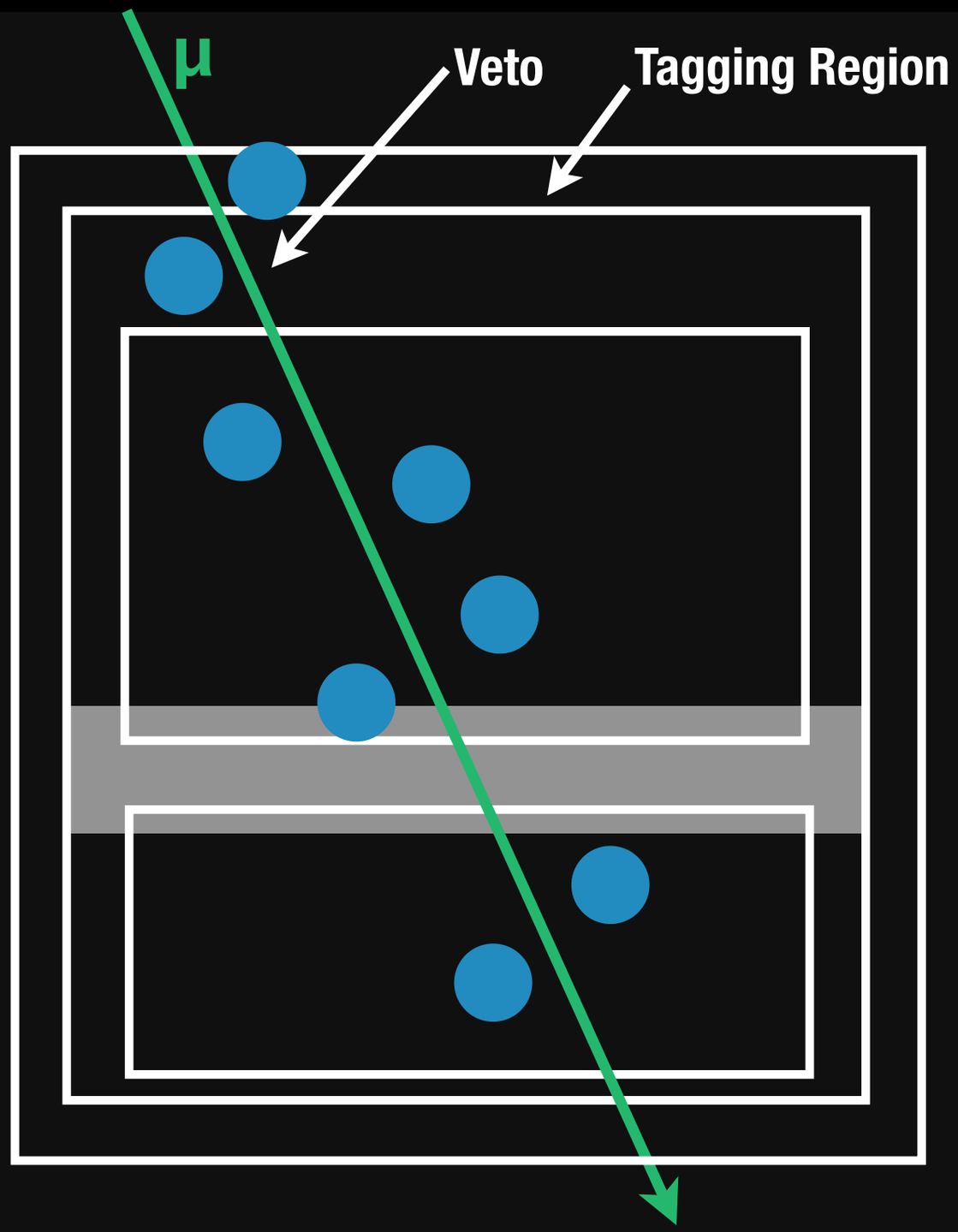


T_{250}= time at which Q= 250 pe

Estimating Muon Background From Data

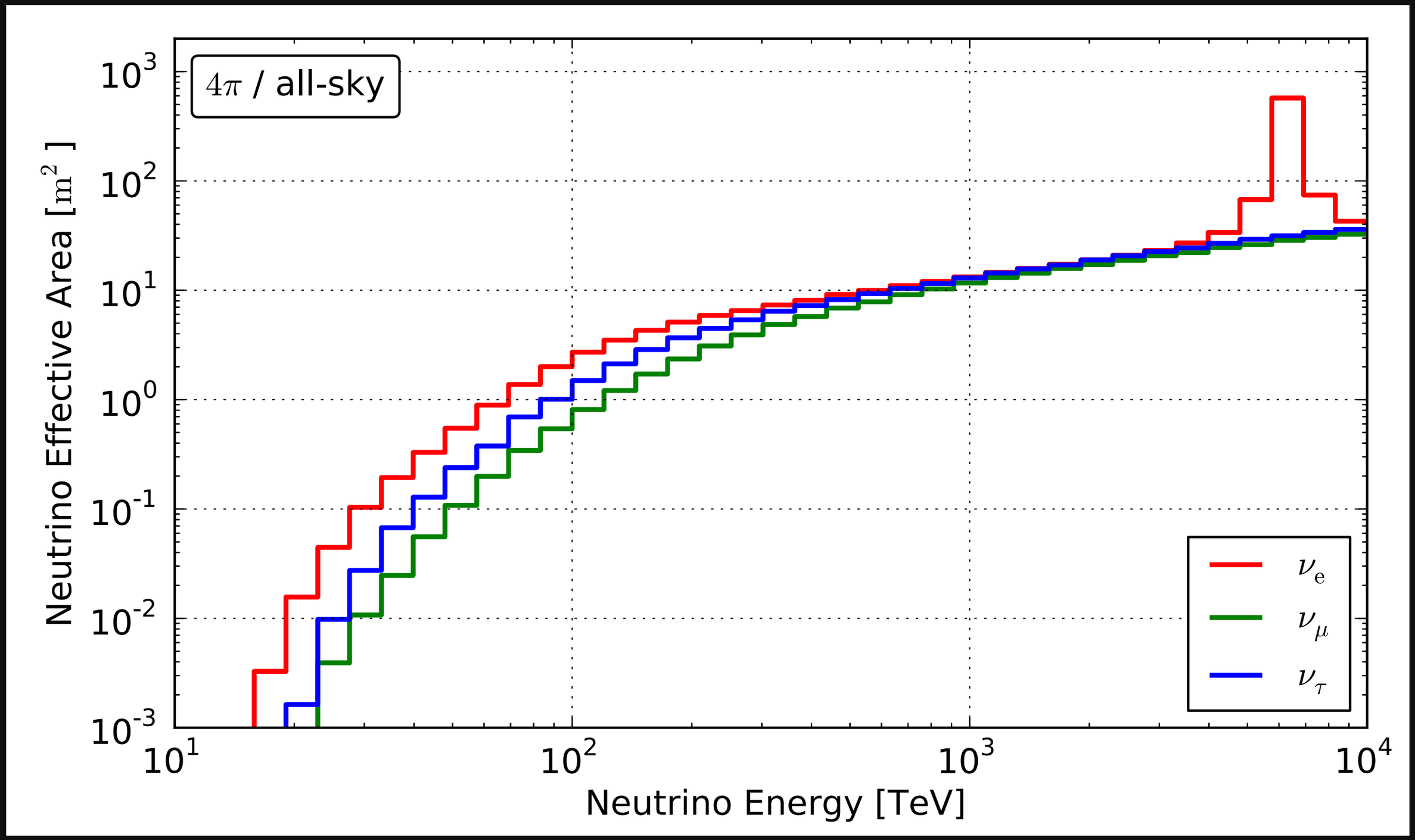
Use known background from atmospheric muons tagged in an outer layer to estimate the veto efficiency

- **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



Atmospheric Neutrino Spectrum

Measured with IceCube in ν_μ and ν_e