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Recent Highlights from IceCube

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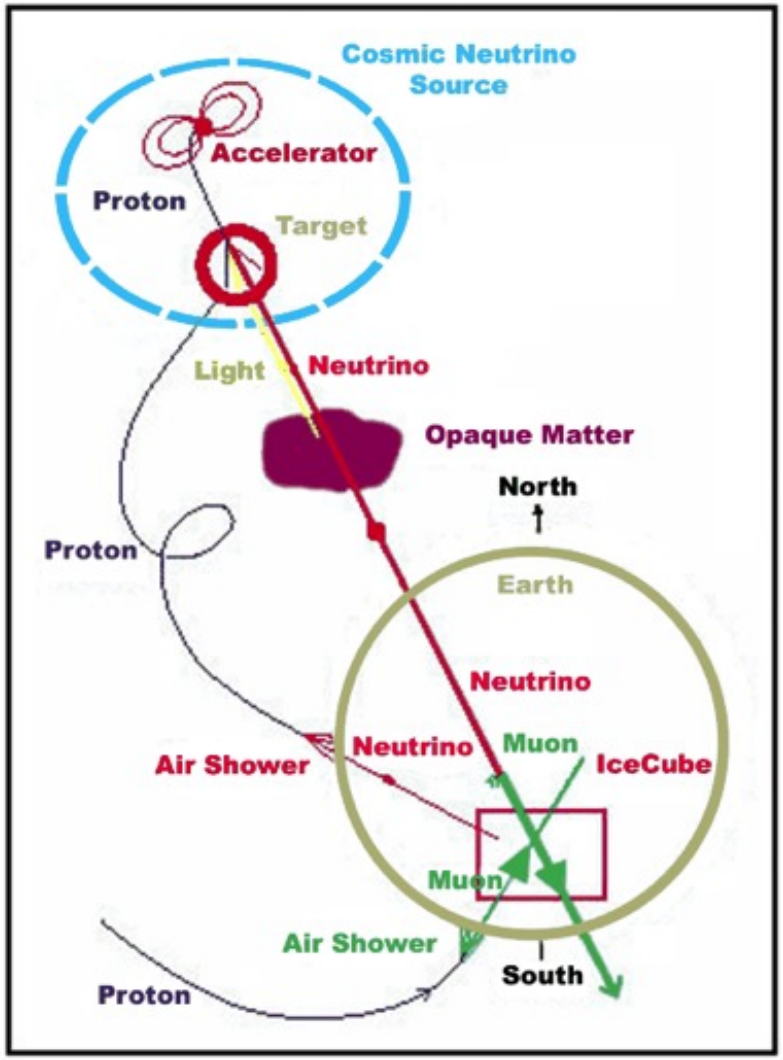
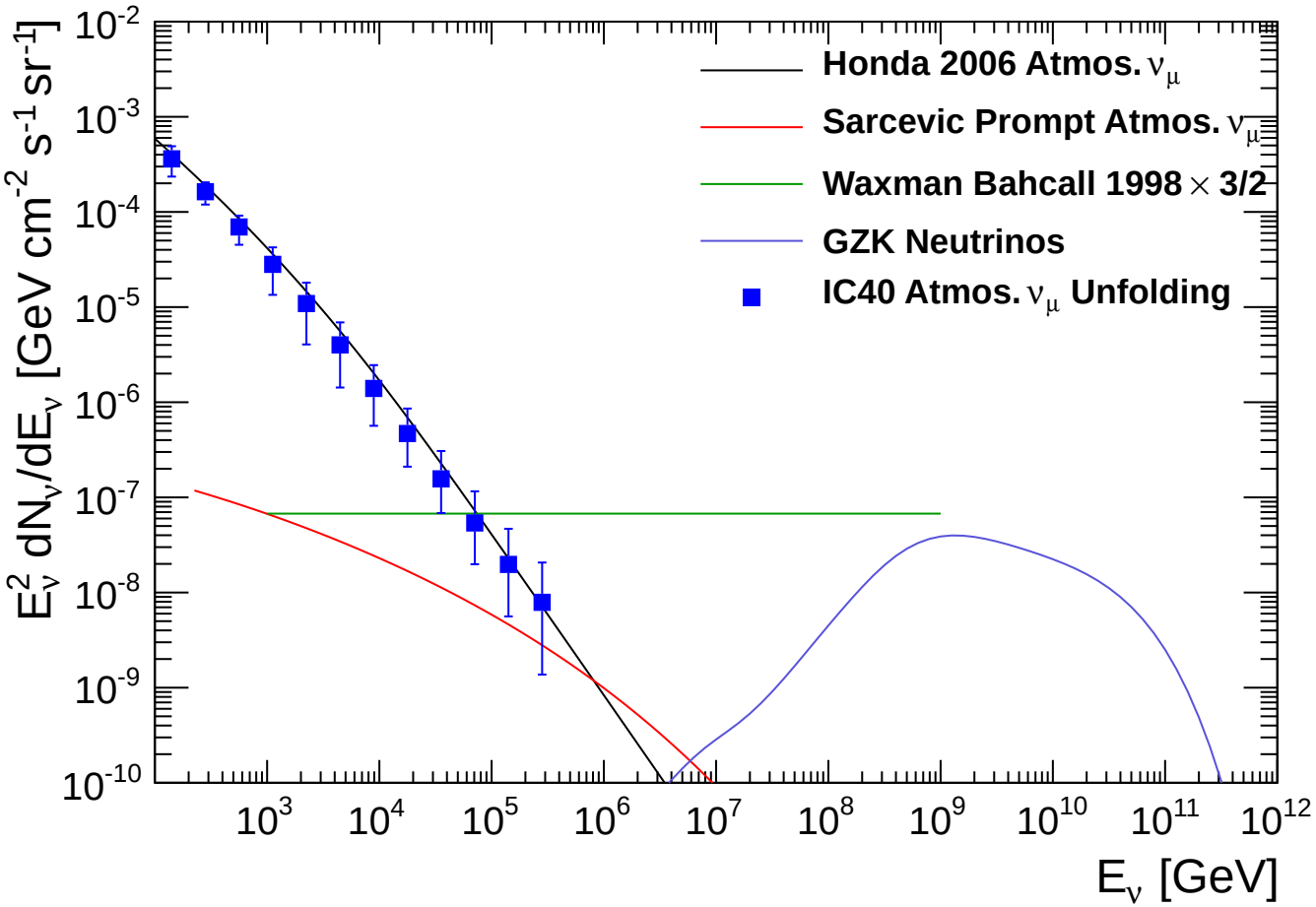
Why are TeV Neutrinos Interesting?

Neutrinos are ideal astrophysical messengers:

- Trace high-energy interactions
- Travel in straight lines
- Very difficult to absorb in flight
- Escape from dense environments
- Have lots of properties: energy, flavor, direction



A Neutrino Taxonomy at 100 GeV and Up



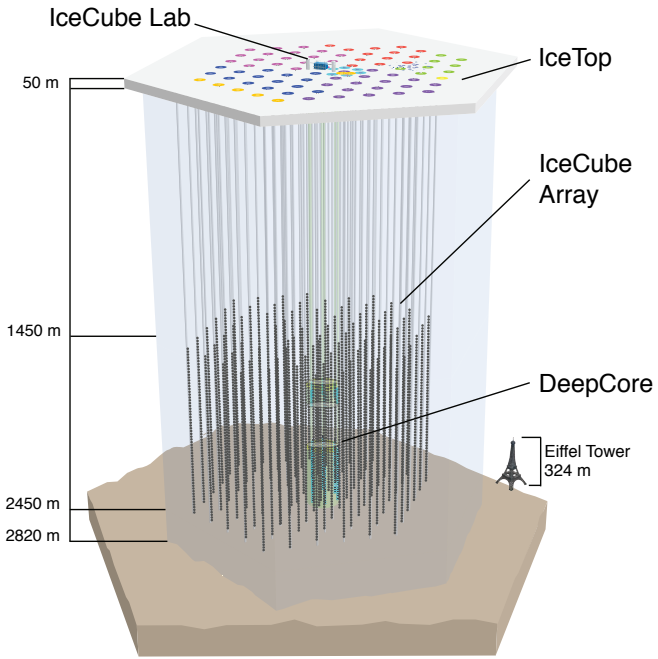
- π/K Atmospheric Neutrinos (dominant $<$ 100 TeV)
- Charm Atmospheric Neutrinos ("prompt", 300 TeV)
- Astrophysical Neutrinos (maybe dominant $>$ 100 TeV)
- Cosmogenic Neutrinos (10^6 TeV)

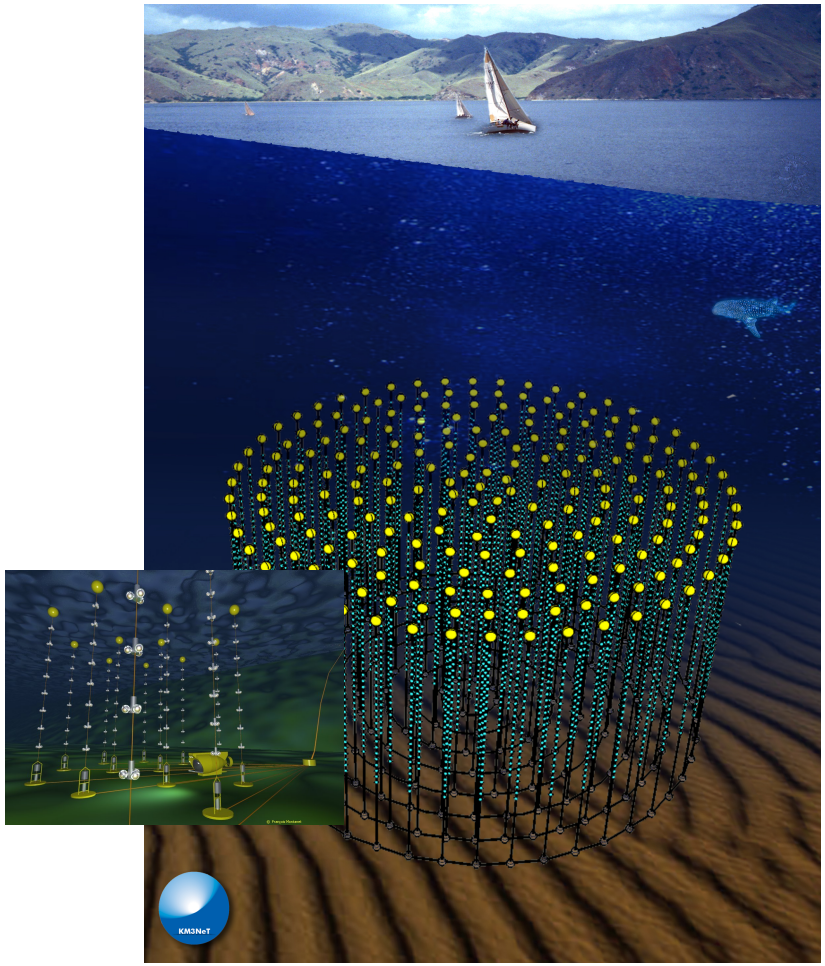
Challenges

- Neutrino cross-section is very small
- ...so are the fluxes
- Most astrophysical models predict on the order of 1 event/gigaton/year
- Discrimination against background (cosmic ray muons, atmospheric neutrinos from π, K decay)

Gigaton Detectors

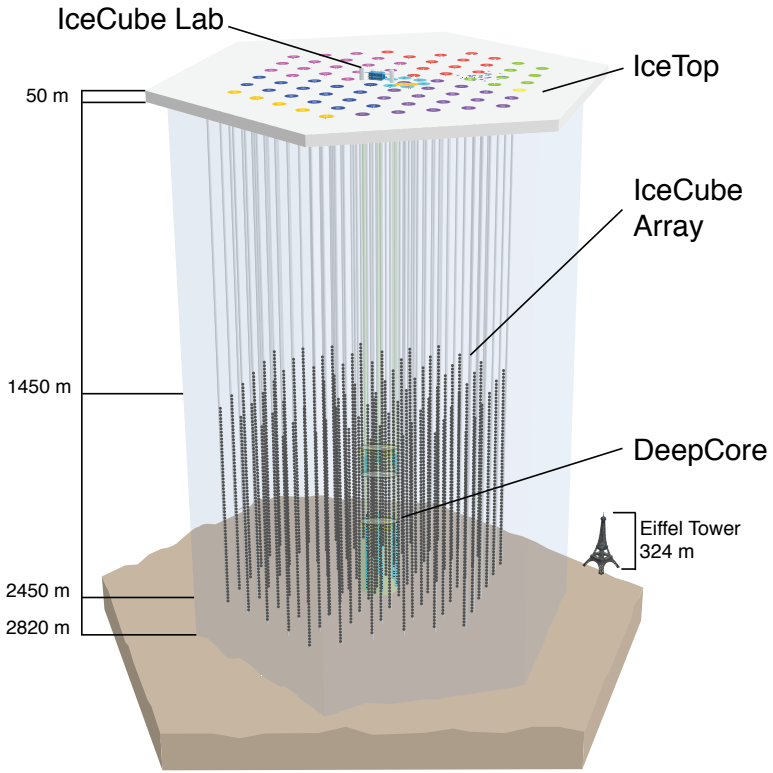
Need natural detectors: IceCube, KM3NET (future), ANTARES, Baikal





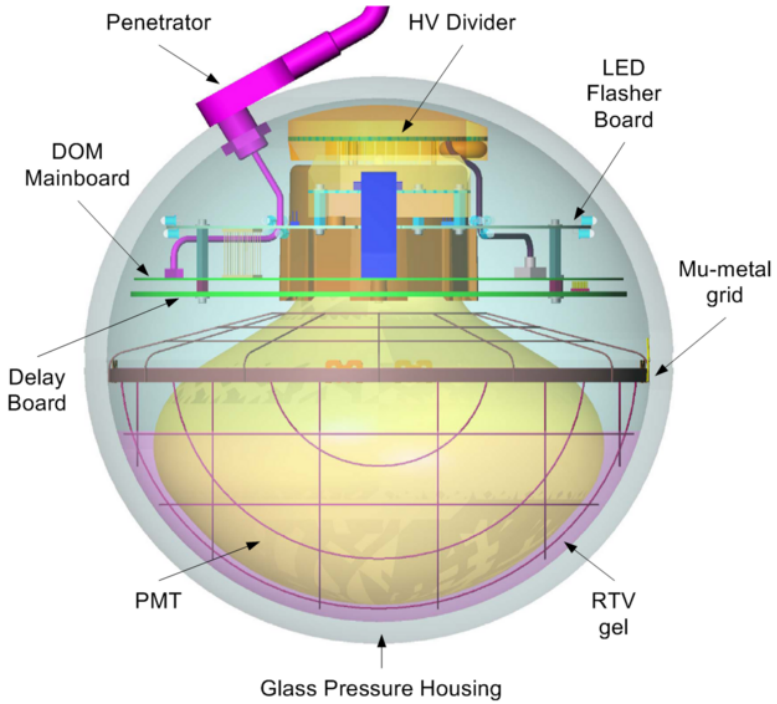
IceCube

- 5160 PMTs with waveform readout
- ns time resolution
- 1 km^3 volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 125 m string spacing
- DeepCore subarray lowers energy threshold to 10 GeV
- Due to increasing neutrino cross-section with E, larger energy range than most instruments



Digital Optical Modules

- 25 cm photomultiplier
- All-digitial readout: In-Situ Digitization
- Built-in calibration instruments
- Nanosecond global time resolution
- 300 MHz waveform digitization

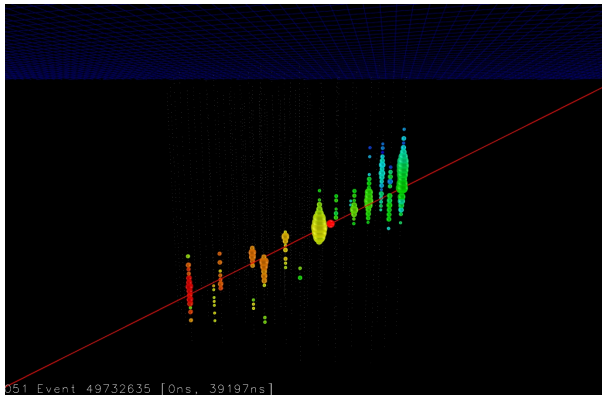


Event Signatures

Muon Neutrino CC (data)

< 1 degree angular resolution

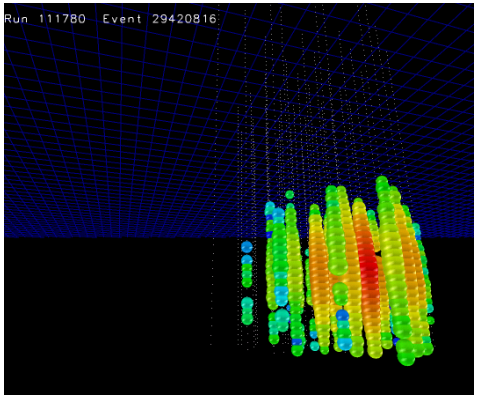
within a factor of 2 in muon energy



Neutral Current or Electron Neutrino (data)

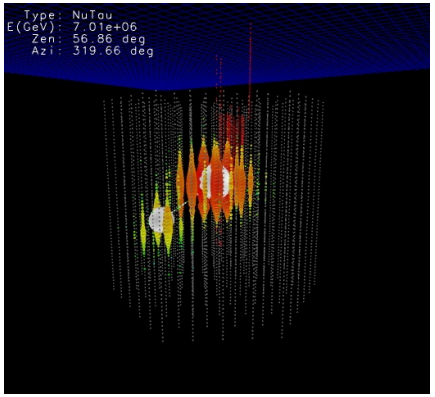
10 degree angular resolution (high energy)

$\sim 15\%$ deposited energy resolution



Tau Neutrino CC (simulation)

Not yet observed



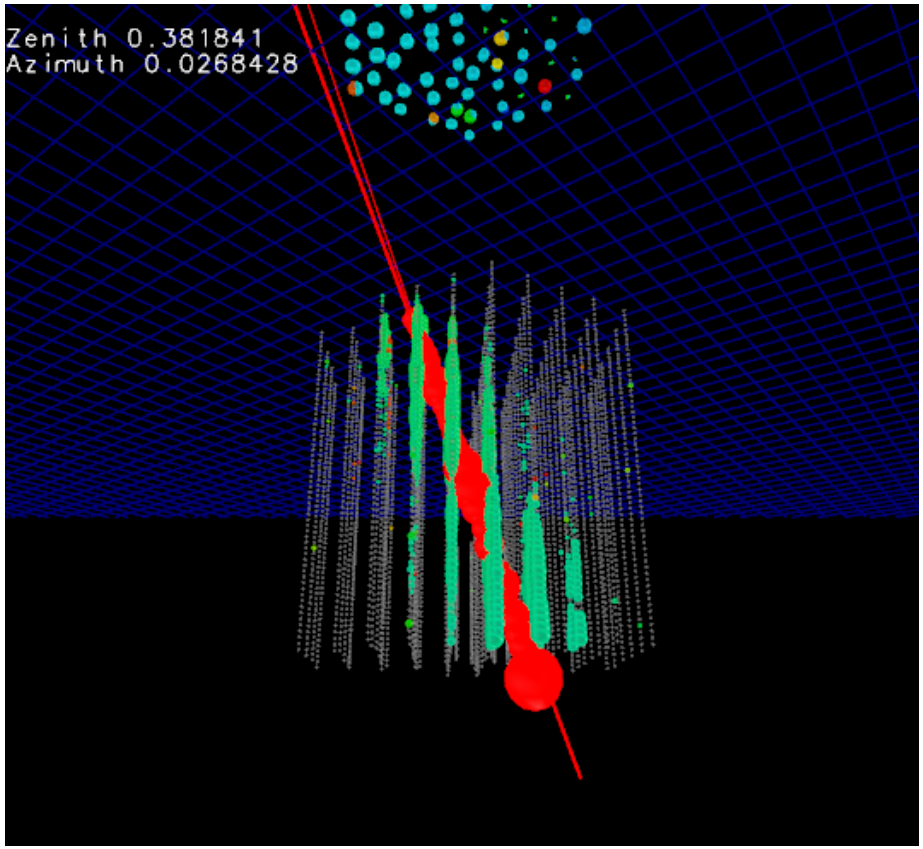
Challenges in Large-Volume Neutrino Detectors

Backgrounds:

- Cosmic Ray Muons (3000 Hz)
- Atmospheric Neutrinos (1 per 5 minutes)

Natural materials:

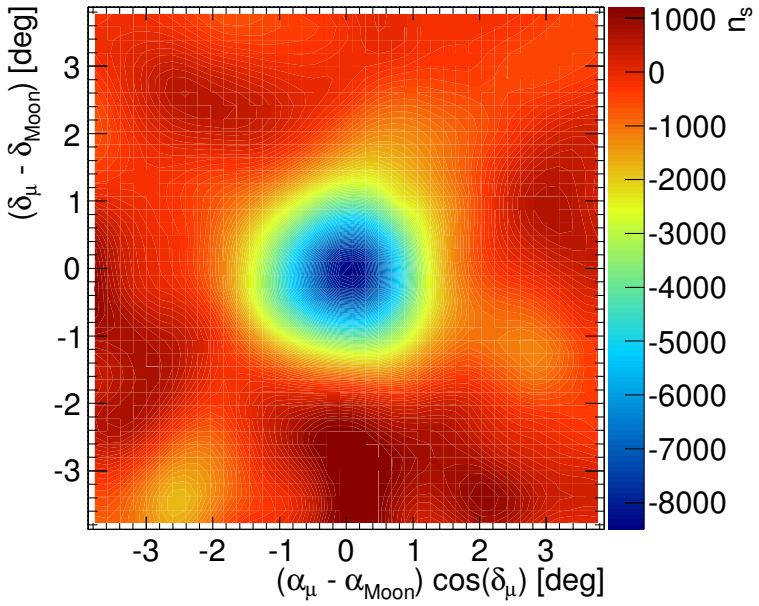
- Optical Properties of Ice measured In-Situ
- No Laboratory Calibration – must use cosmic rays



Calibration

Calibration Sources:

- LED Flashers on each DOM
- In-Ice Calibration Laser
- Cosmic Ray Energy Spectrum
- Moon Shadow
- Atmospheric Neutrino Energy Spectrum
- Minimum-Ionizing Muons

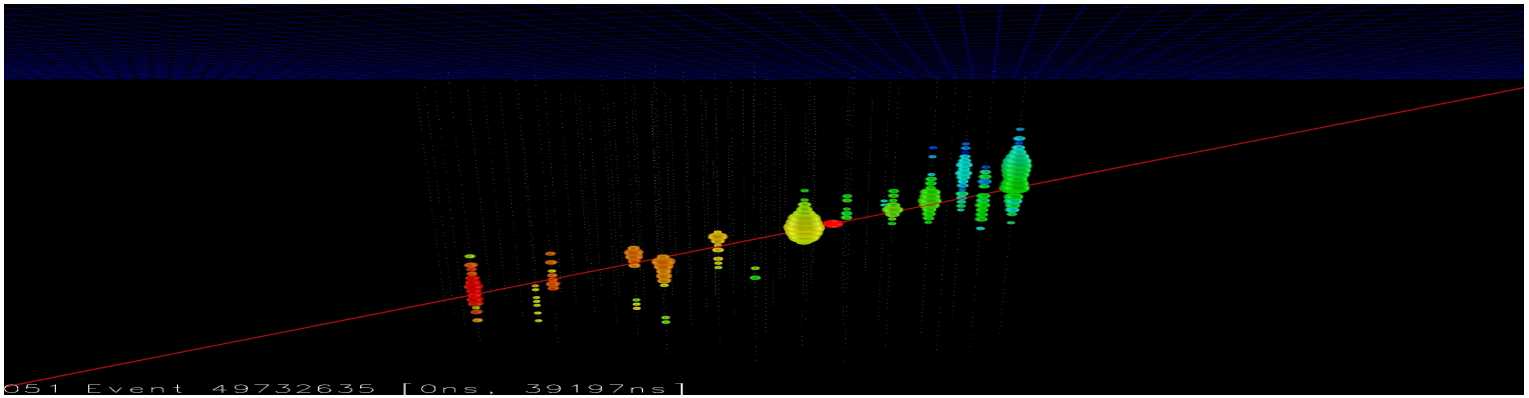


Moon Shadow in Cosmic Ray Muons in IceCube (59 strings)

Neutrino Identification

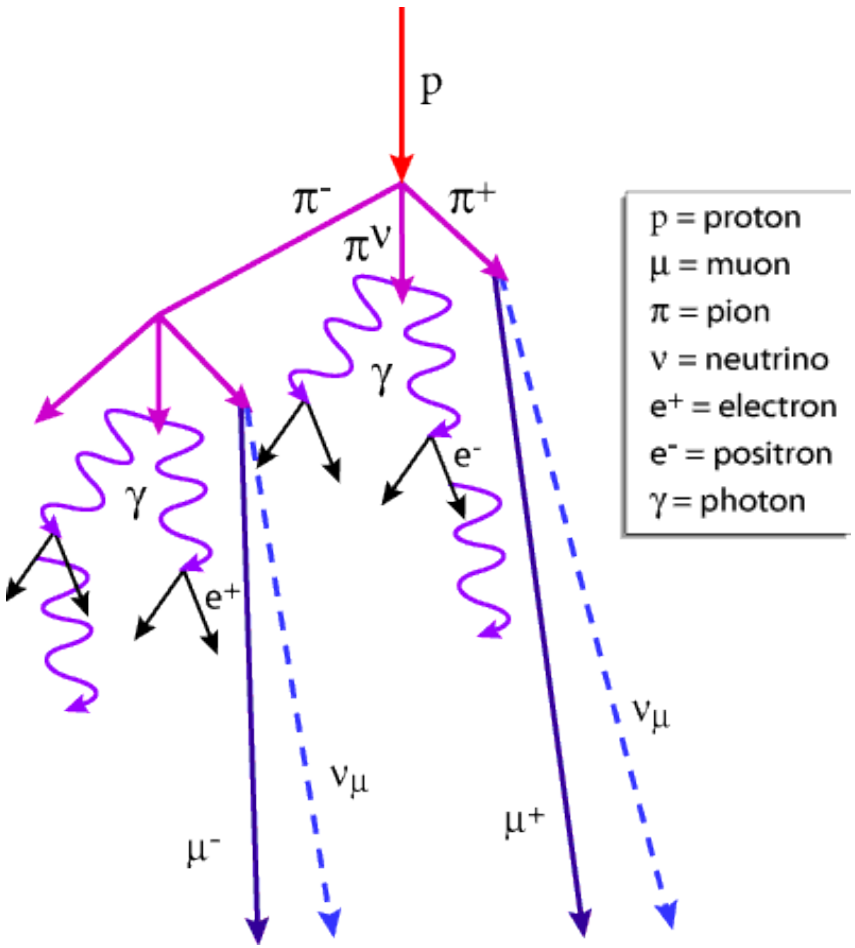
How to identify neutrinos?

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

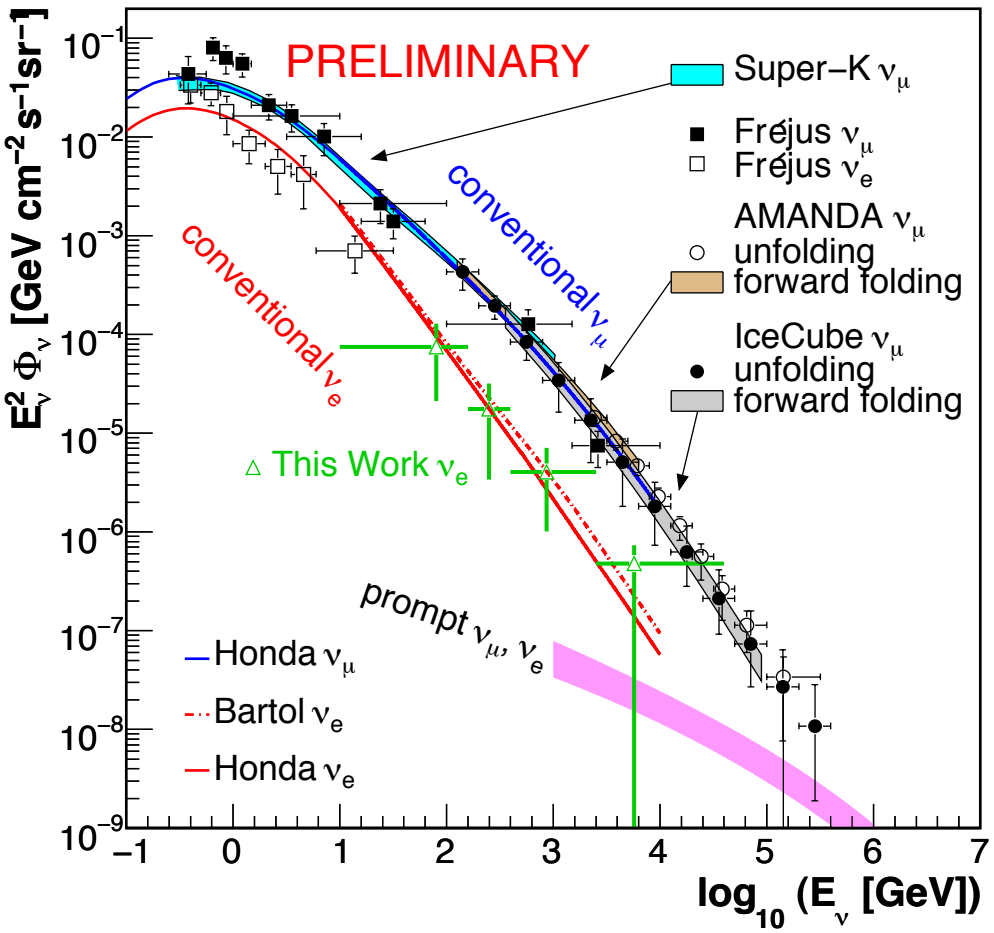


Atmsopheric Neutrinos

- Main Neutrino Source Visible to IceCube
- Produced in Cosmic Ray Interactions
- π^+/π^- and kaons produced in shower decay to neutrinos
- ν_μ dominated
- Unmeasured component at very high energies from charmed meson production
- Study air shower physics and neutrino oscillations



Atmospheric Neutrino Measurement

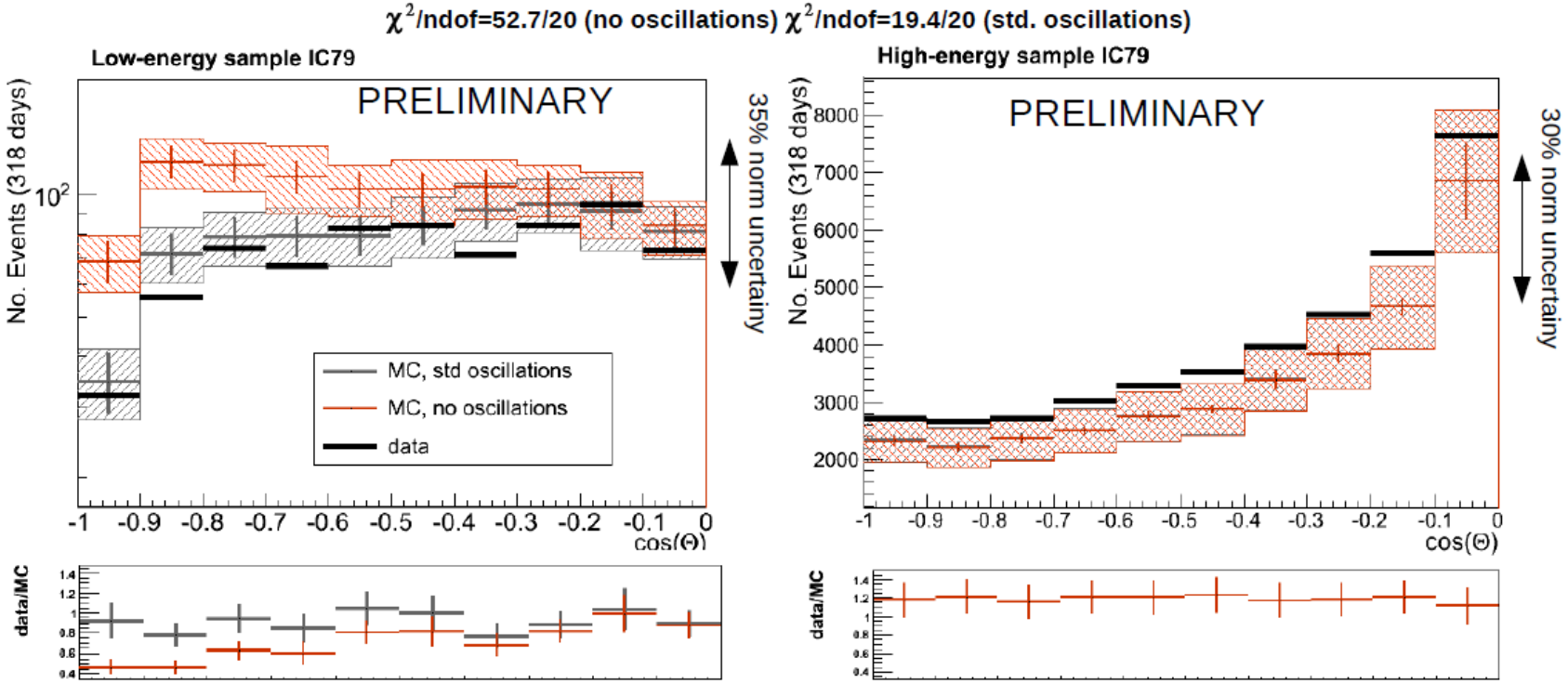


arXiv:1212.4760

- Largest-ever sample of atmospheric neutrinos: 100,000 events per year
- First measurement of atmospheric ν_e at TeV energies
- Approaching the ability to test prompt models

Neutrino Oscillations

Sensitive to Θ_{23} over long baselines from atmospheric neutrinos – zenith-dependent suppression of CC ν_μ as different chords of the Earth are traversed.

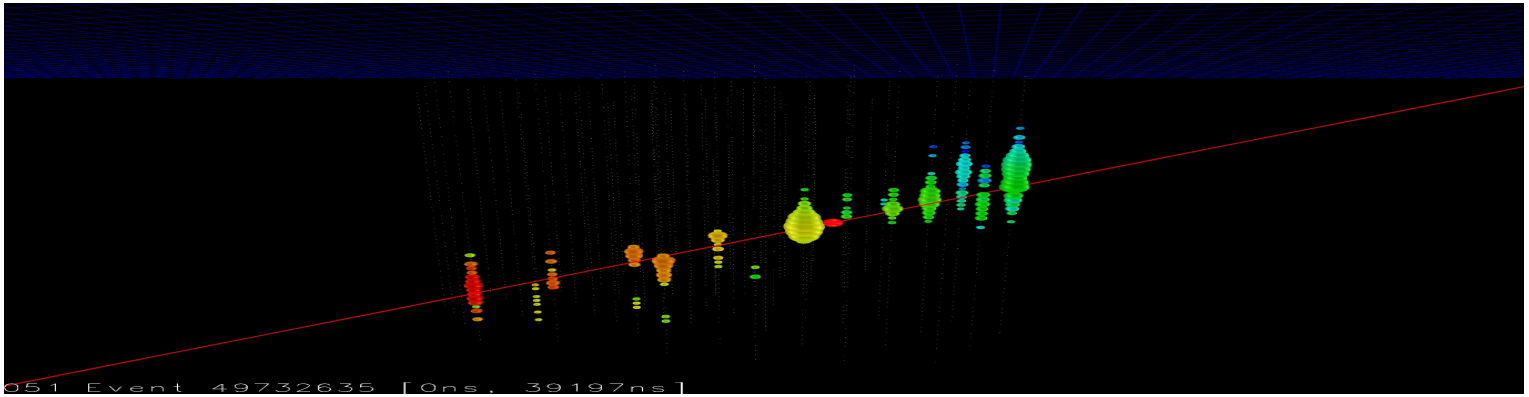


Extremely high statistics available with multi-megaton Deep Core subarray – first observation of neutrino oscillations in IceCube.

Beyond the Atmosphere

How to probe extraterrestrial fluxes?

1. Go to high energies
   - Atmospheric neutrino spectrum very steep
   - Above $\sim$ 100 TeV, atmospherics almost gone
2. Use southern hemisphere
   - Veto neutrinos with accompanying air showers
   - Veto ineffective below 10 TeV
3. Spatial anisotropy
   - Requires bright or small sources

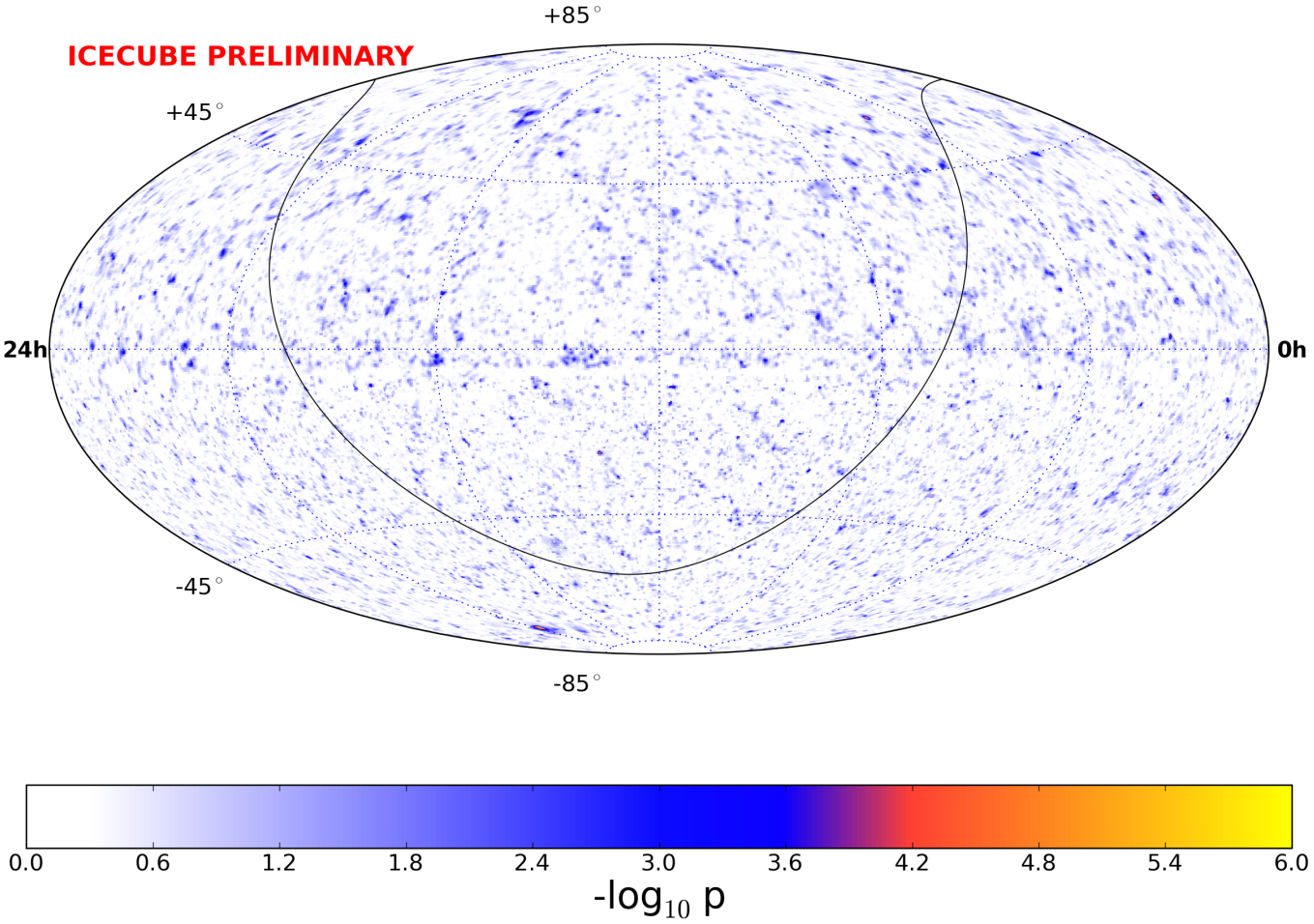


IceCube Astrophysical ν Searches

- High-Energy Point Sources
  - Main focus: cosmic ray accelerators (GRBs, AGN)
  - Primary energy range: > 10 TeV
  - Null results, now constraining models of cosmic ray acceleration
- WIMP Searches
  - WIMP annihilation signatures
  - Looks for point (e.g. Sun) or extended (e.g. Galactic Center) of neutrinos
  - Main goal of Deep Core subarray
  - Typical energy range: 20 GeV - 10 TeV (standard WIMPs)
  - Sensitive to very exotic high-mass particles as well
  - Increasingly strong limits
- Diffuse Neutrino Background
  - Sensitive above 100 TeV
  - More than 4σ evidence for high-energy flux

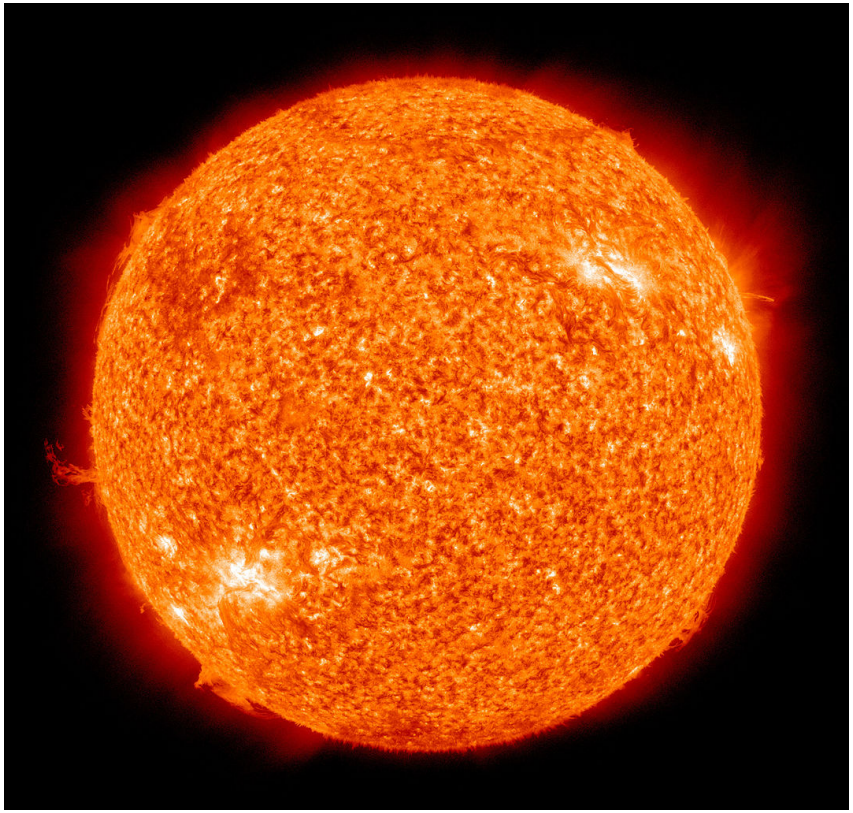
Steady Point Sources

Test theories of cosmic ray acceleration by searching for neutrinos produced in the same source: no sources identified



WIMP Searches

- Regions of high WIMP density (centers of massive objects)
- Search for neutrinos from WIMP annihilation
- Favorite targets: Sun, Earth, Galactic Center, Dwarfs
- Complementary to direct searches: fills out WIMP picture by testing other properties, and in multiple channels
- DM-Ice: direct detection coming too...

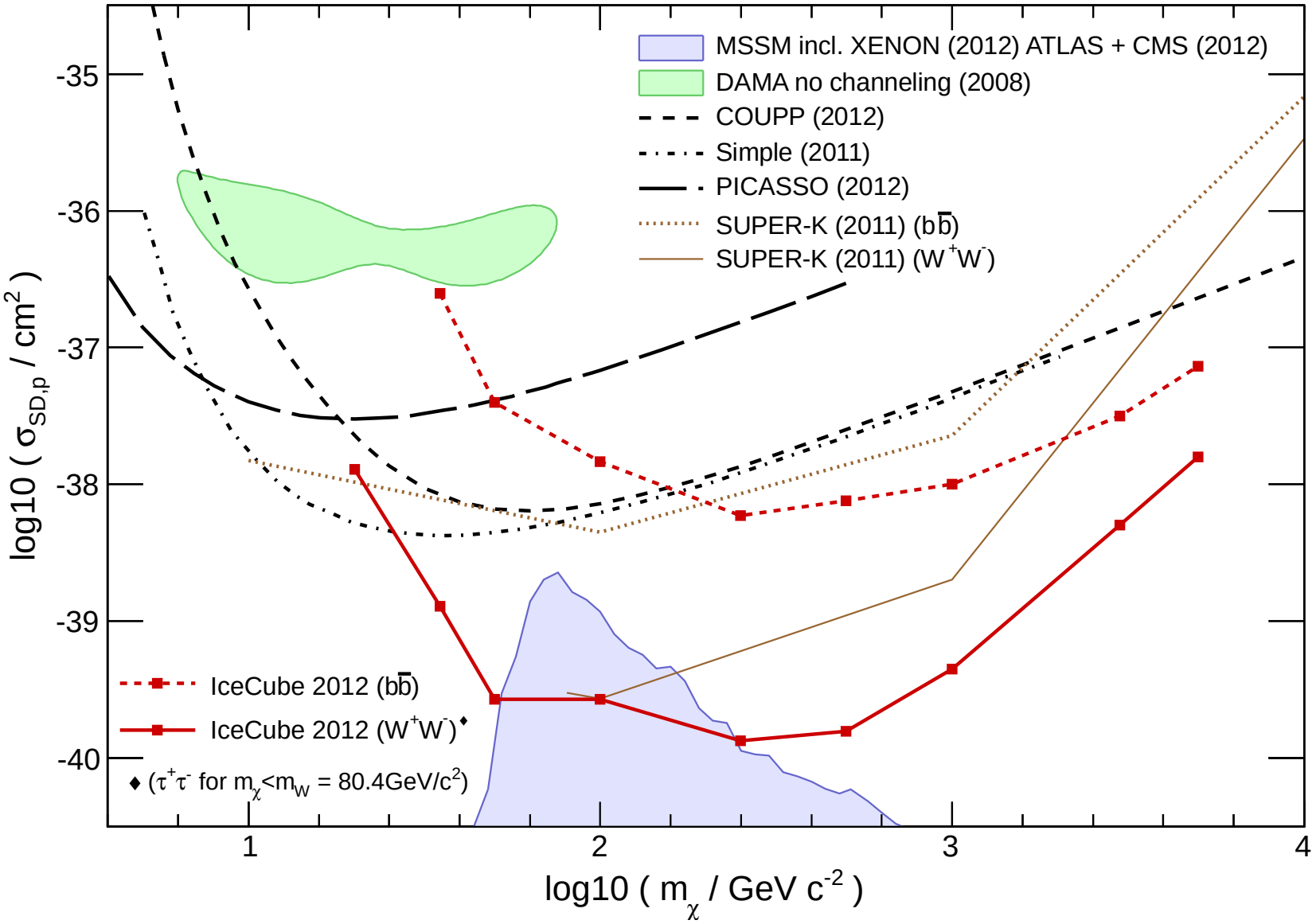


NASA

The Sun

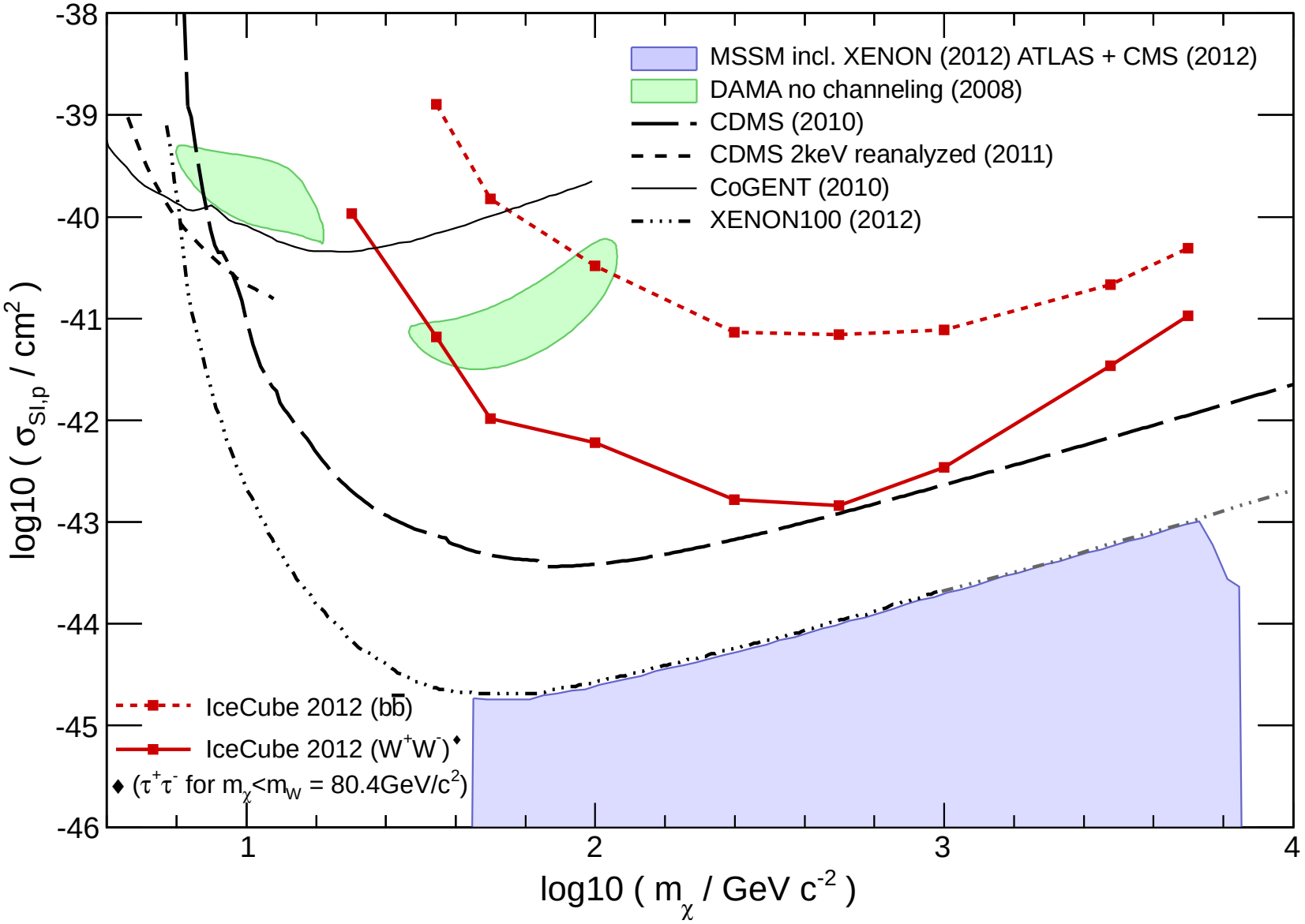
- WIMPs collect in gravitational potential wells
- Large and old enough assumed to be in capture/annihilation equilibrium
- Probes scattering cross-section through annihilation
- Neutrinos allow us to peer into the solar core
- No other source of high-energy neutrinos
- For $E_\nu \gtrsim 1$ TeV, neutrinos attenuated in stellar interior
- High sensitivity to spin-dependent cross sections due to proton target

Spin-Dependent Results



arXiv:1212.4097, PRL 110

Spin-Independent Results



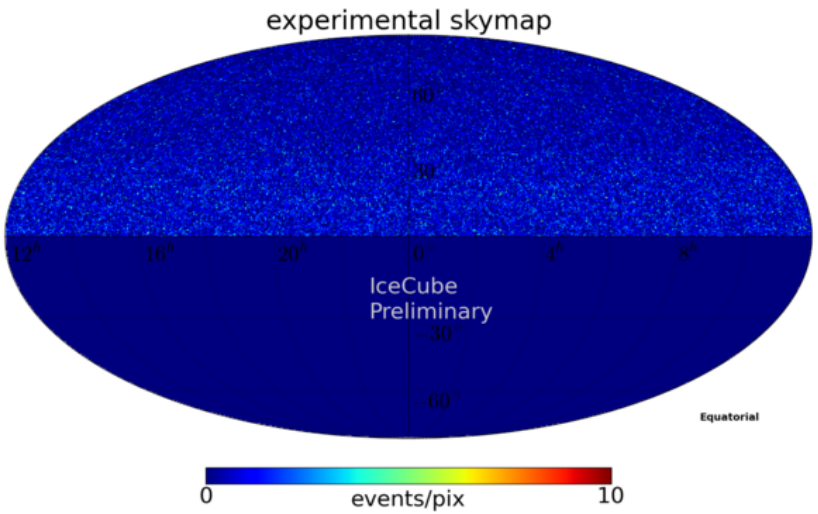
arXiv:1212.4097, PRL 110

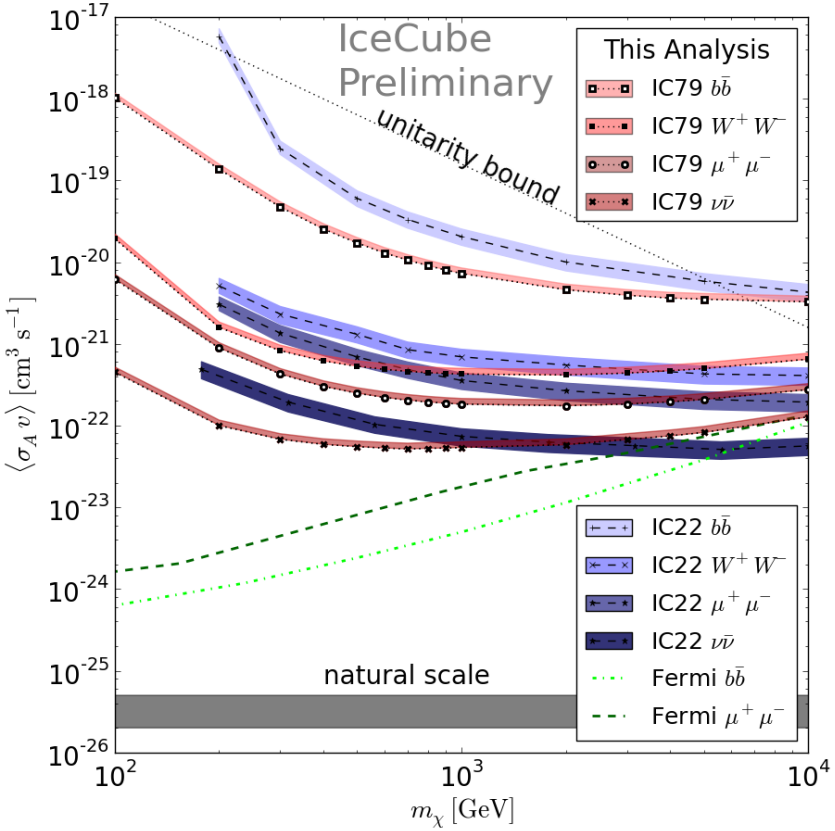
Galactic Sources

- Not in capture/annihilation equilibrium $\rightarrow$ probe self-annihilation only
- Test WIMP annihilation cross-section averaged over velocity distribution
- Tenuous enough that neutrinos are not absorbed in source: sensitivity to very high masses

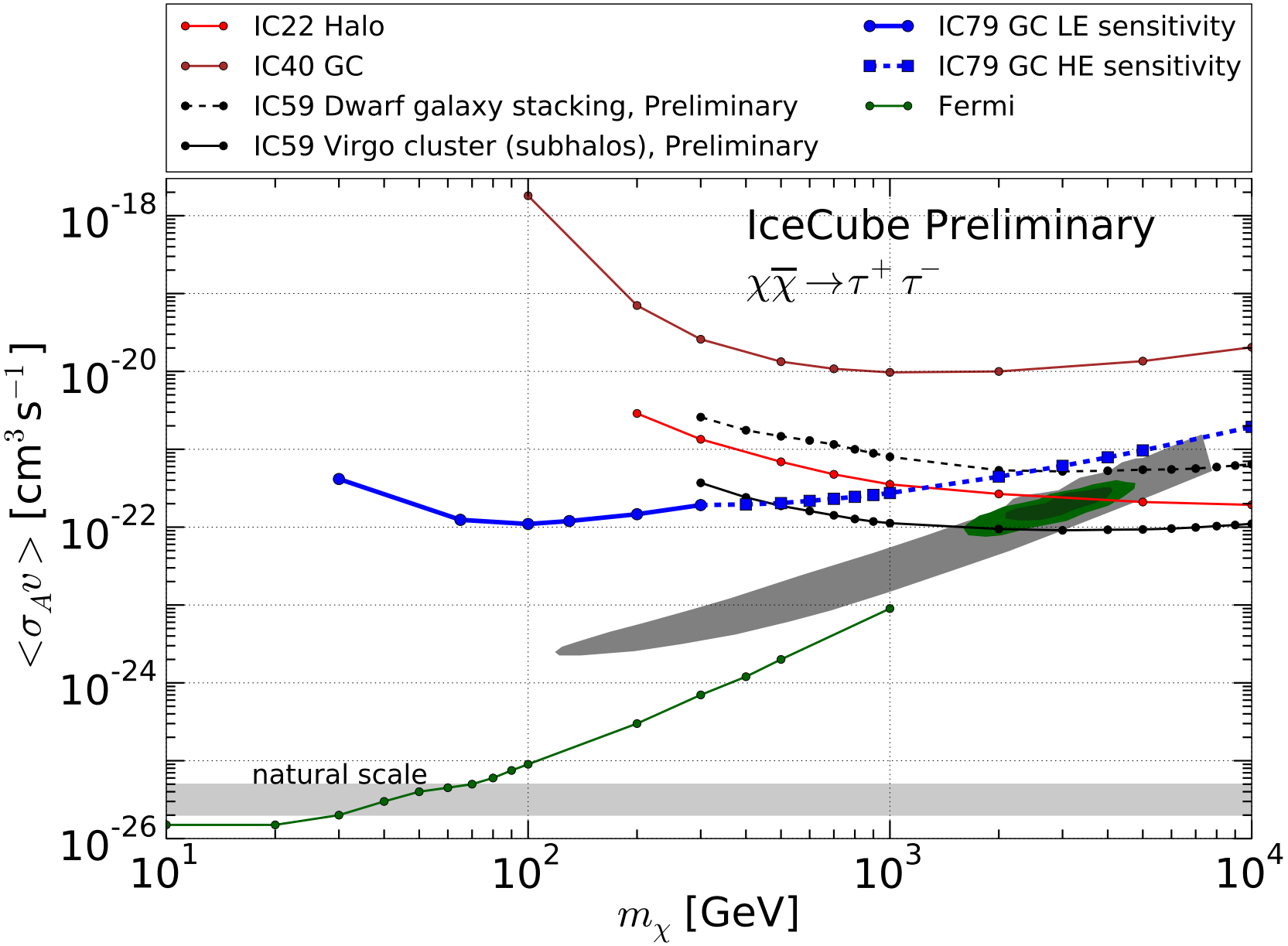
WIMP Halo Results

Look for large-scale anistropies around the galactic halo.





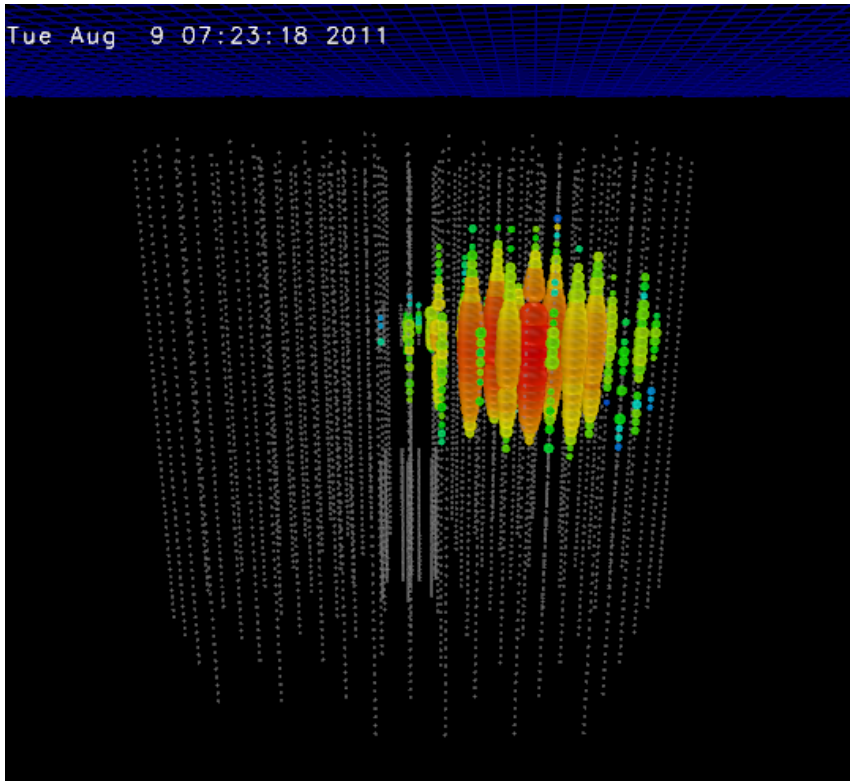
Galactic Center Search



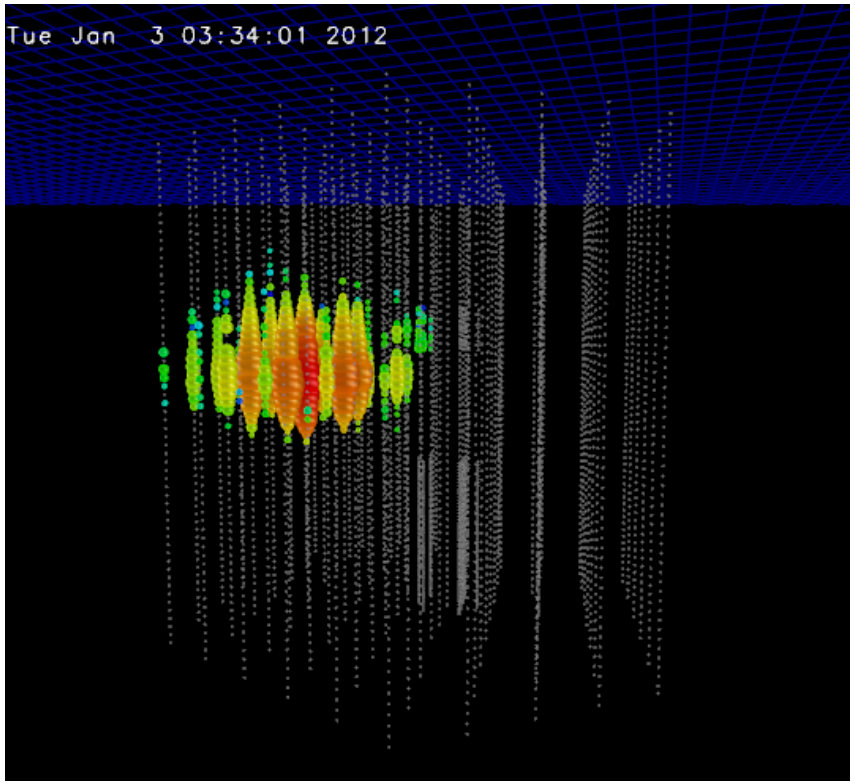
Diffuse Measurements

A mystery: PeV neutrinos

Appearance of ~ 1 PeV neutrinos at threshold in cosmogenic neutrino search – should be $\ll 1$ atmospheric neutrinos per year at these energies

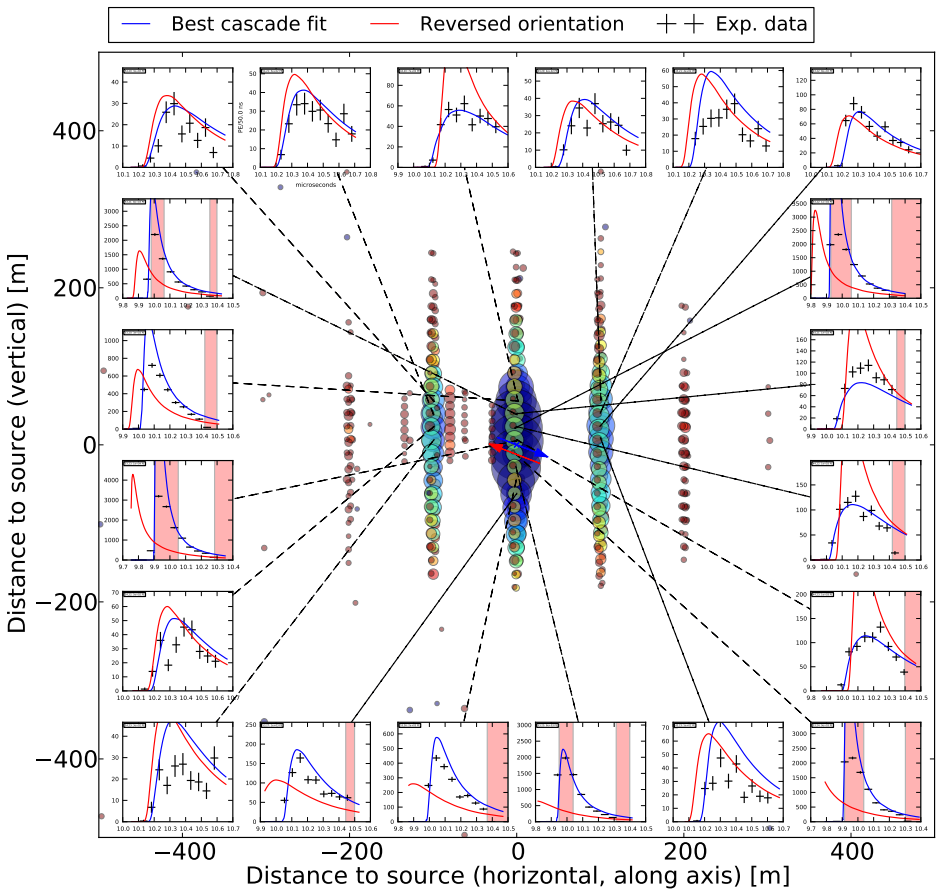


~ 1100 TeV



~ 1300 TeV

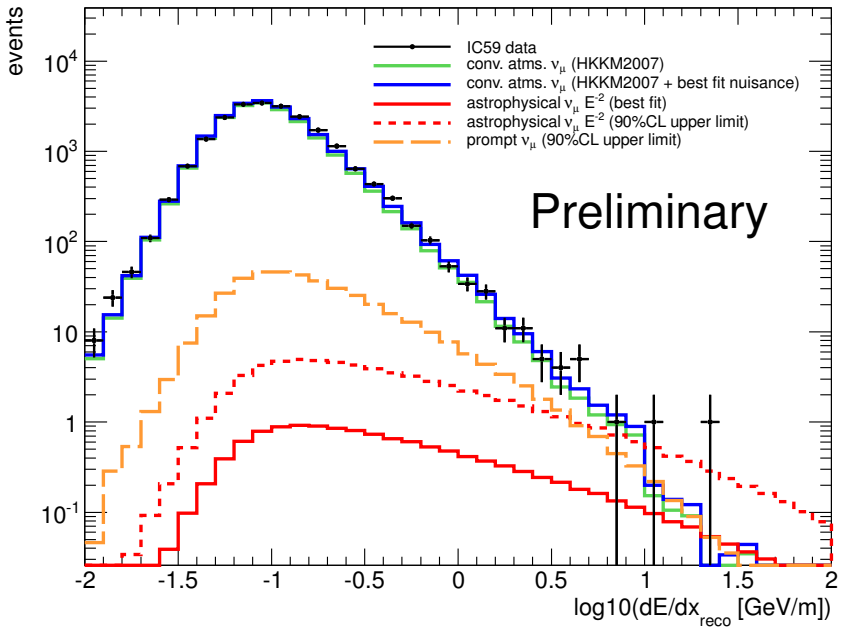
A closer look at a PeV shower



- Good absolute agreement with predictions for either ν_e or neutral-current
- Width of waveforms related to direction of Cherenkov cone
- Height proportional to energy
- Pointing established (blue arrow)
- Energy uncertainty of $^{+15\%}_{-13\%}$

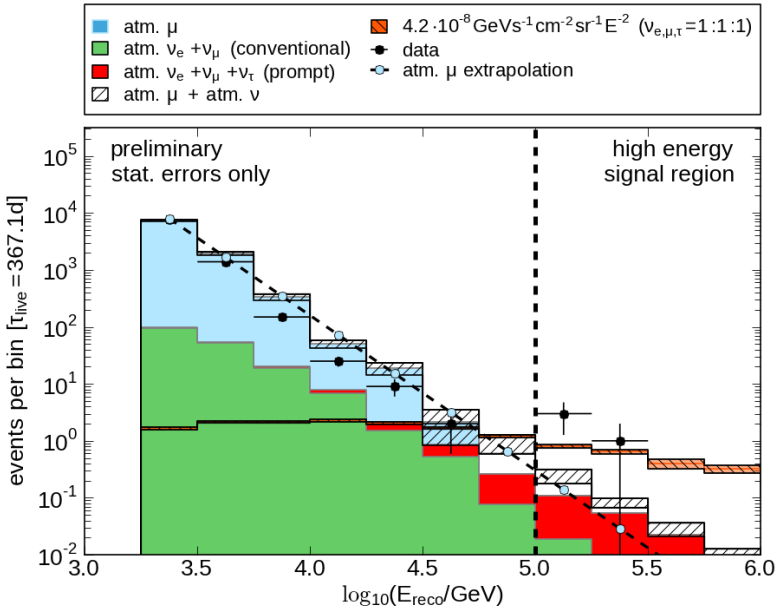
Hints in other channels

IC59 Northern ν_μ arXiv:1302.0127



2009, 1.8σ

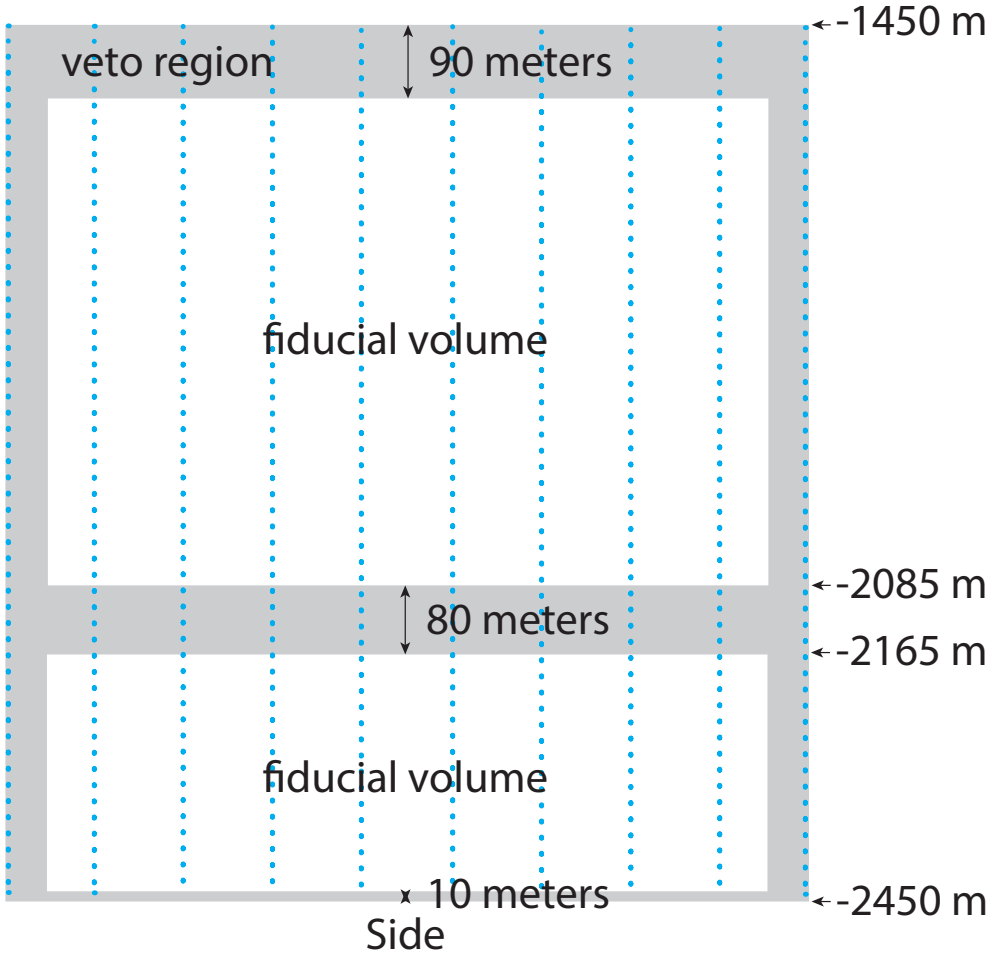
IC40 Cascades



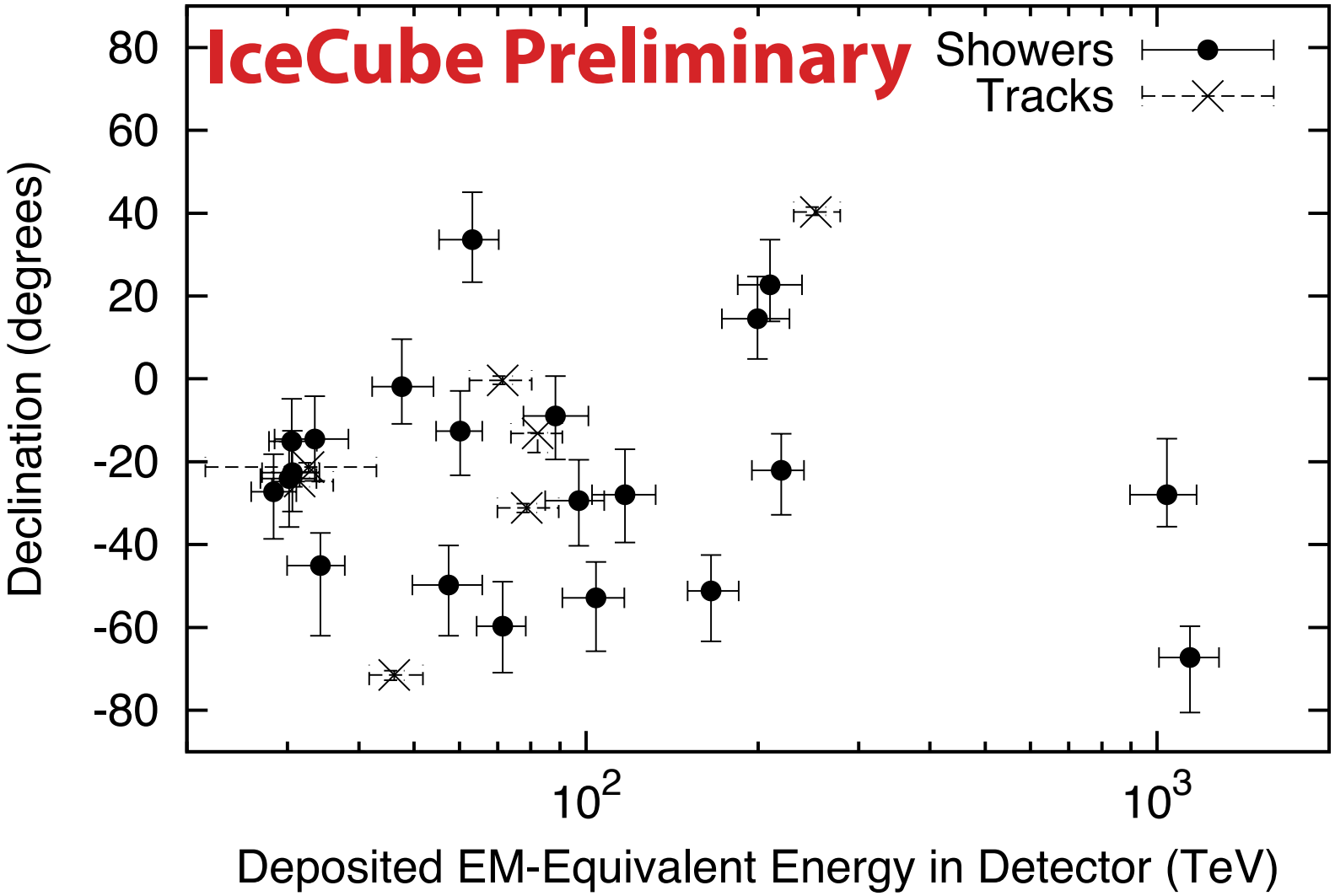
2008, 2.4σ

Follow-up Event Selection For Contained Events

- Define a fiducial volume and a veto region
- Make sure first hits are not on boundary
- Go to high energy (> 6000 PE) to make sure significant numbers of photons expected on boundary
- Topology/direction independent sample
- Becomes efficient at $\sim 50 - 100$ TeV



Results of 2-year Contained Vertex Event Search (2010-2012)



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

Observables of Interest

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

Spectral structure Cutoffs/slope changes may imply population changes

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

Zenith distribution Comparison to backgrounds, probes source locations

Signals and Backgrounds: Why This is Compelling

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

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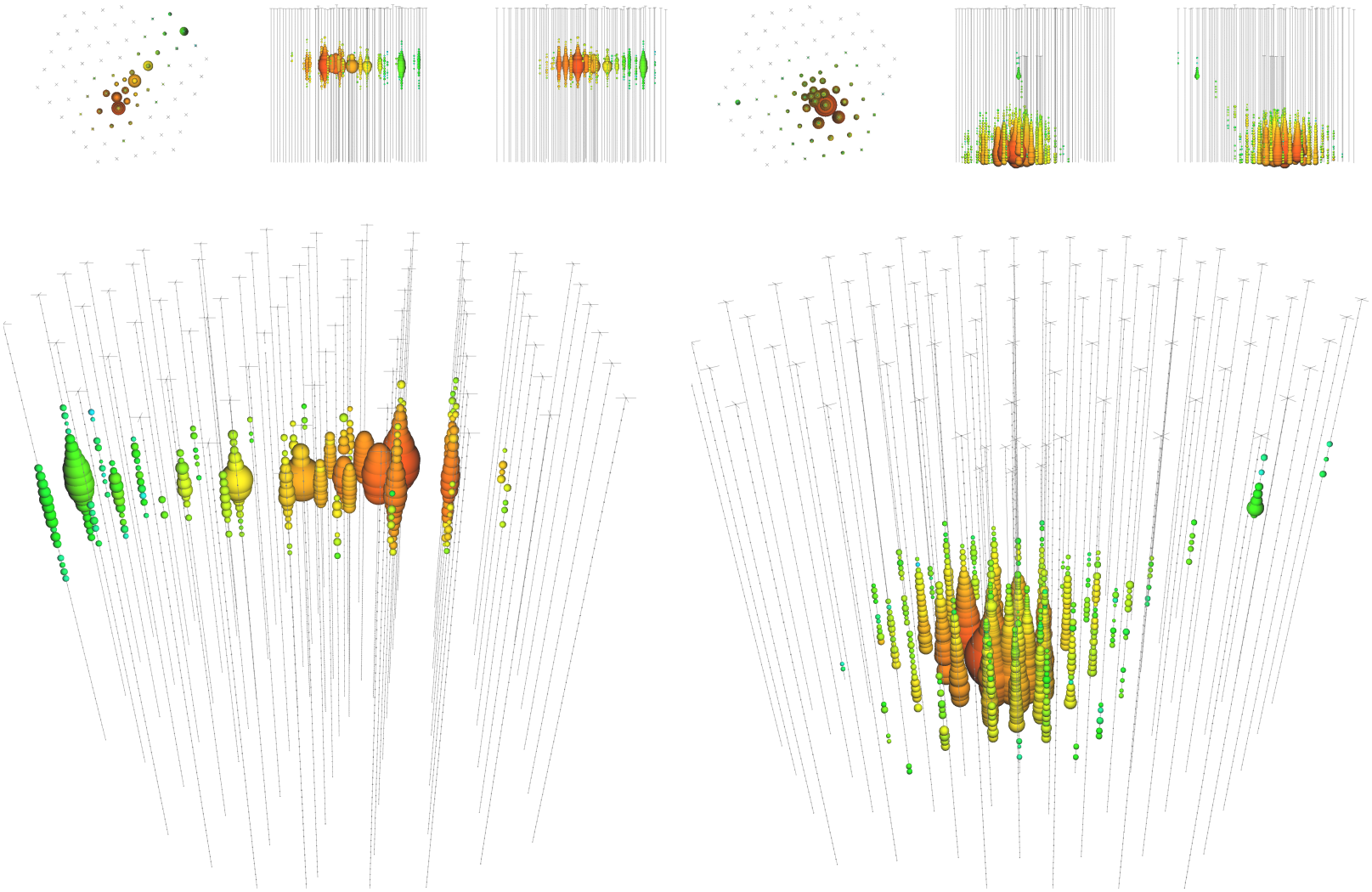
$\rightarrow 4\sigma$ evidence for astrophysical flux

Some interesting events

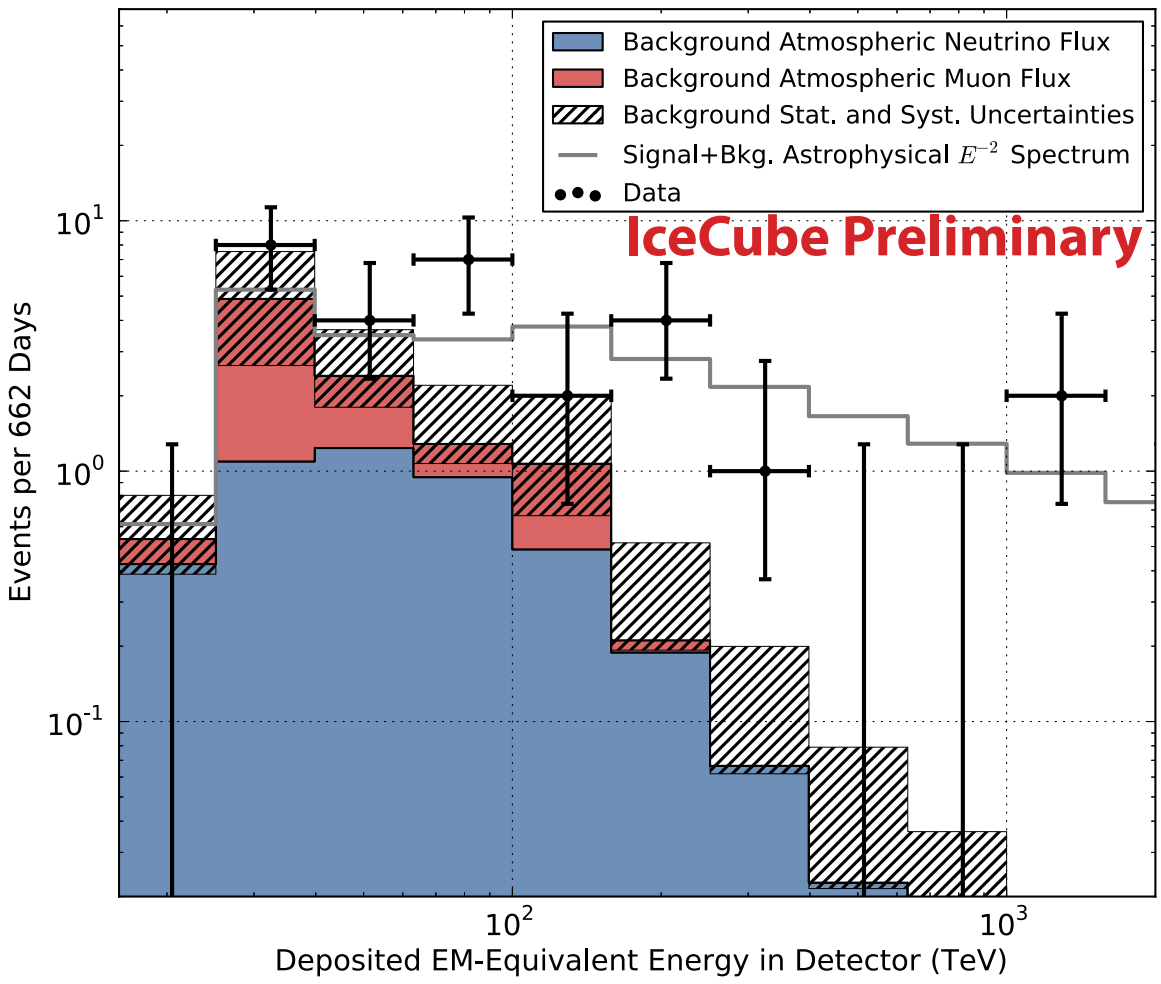


74.1 TeV, -0.4°

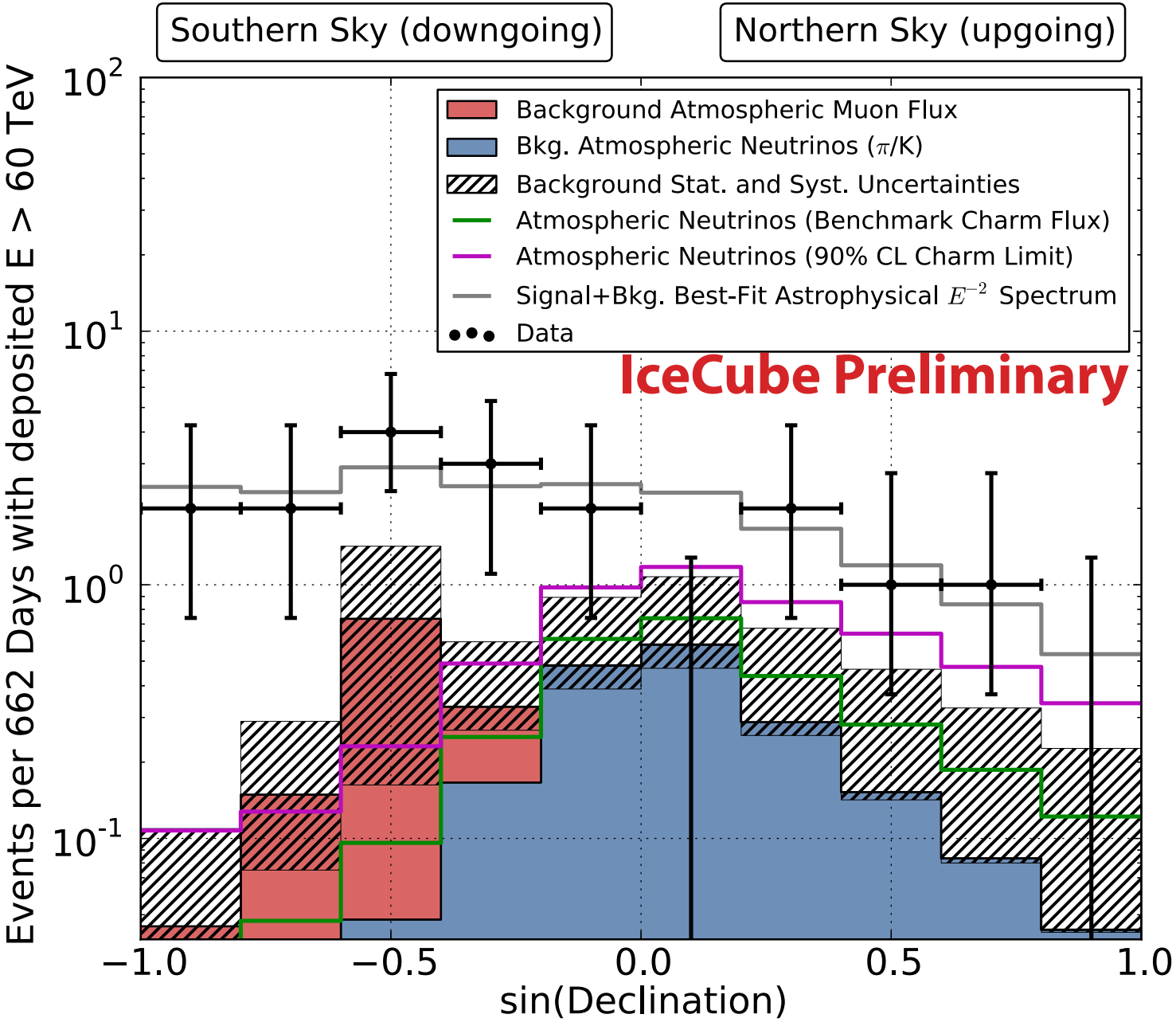
252.7 TeV, $+40^\circ$

Energy Spectrum

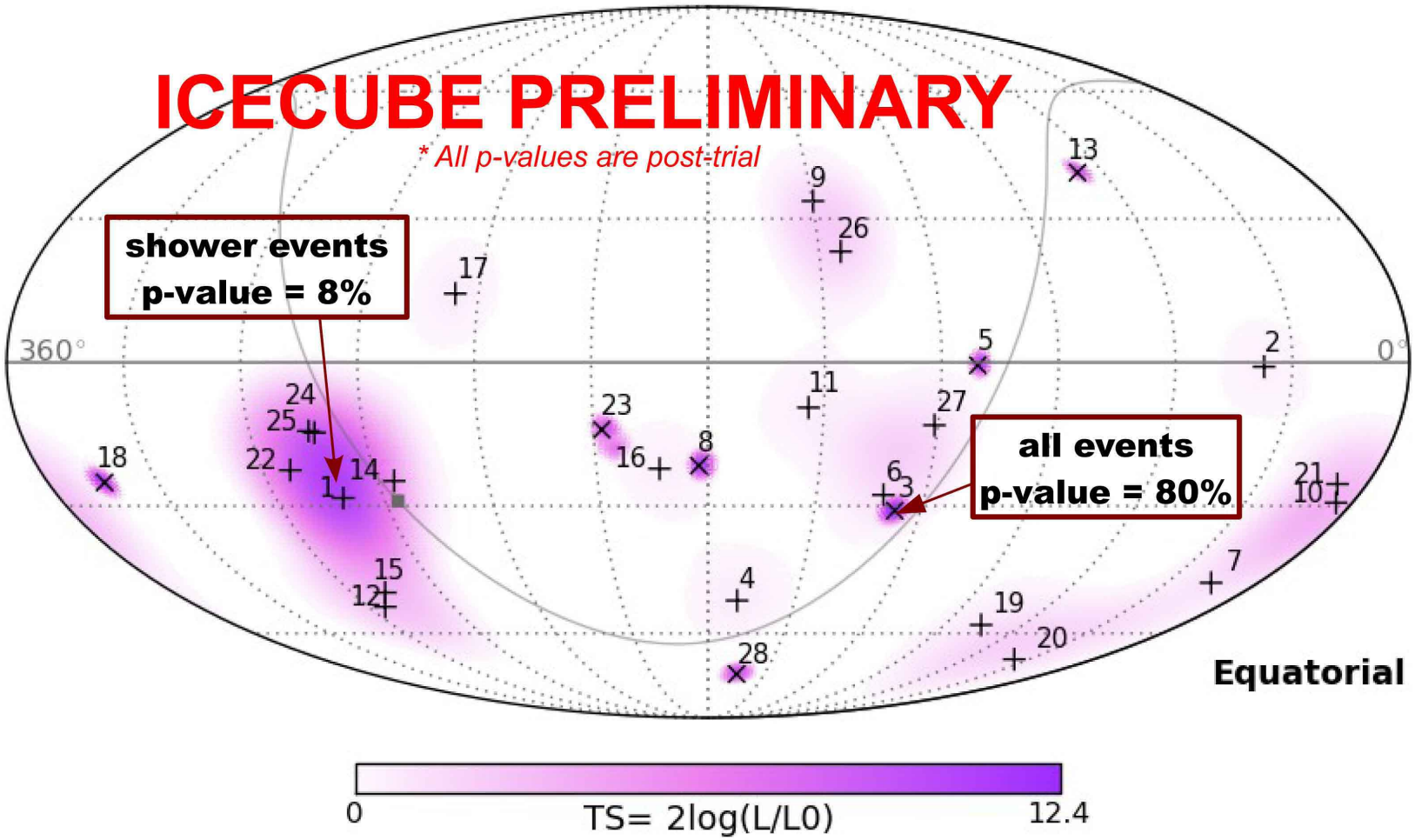
- Harder than any expected atmospheric background
- Merges well into expected backgrounds at low energies
- Potential cutoff around 2 PeV if E^{-2}
- Too few events to measure spectrum well



Zenith Distribution (> 60 TeV dep)



Skymap: Compatible with Isotropy



Too few events to evaluate isotropy or identify sources

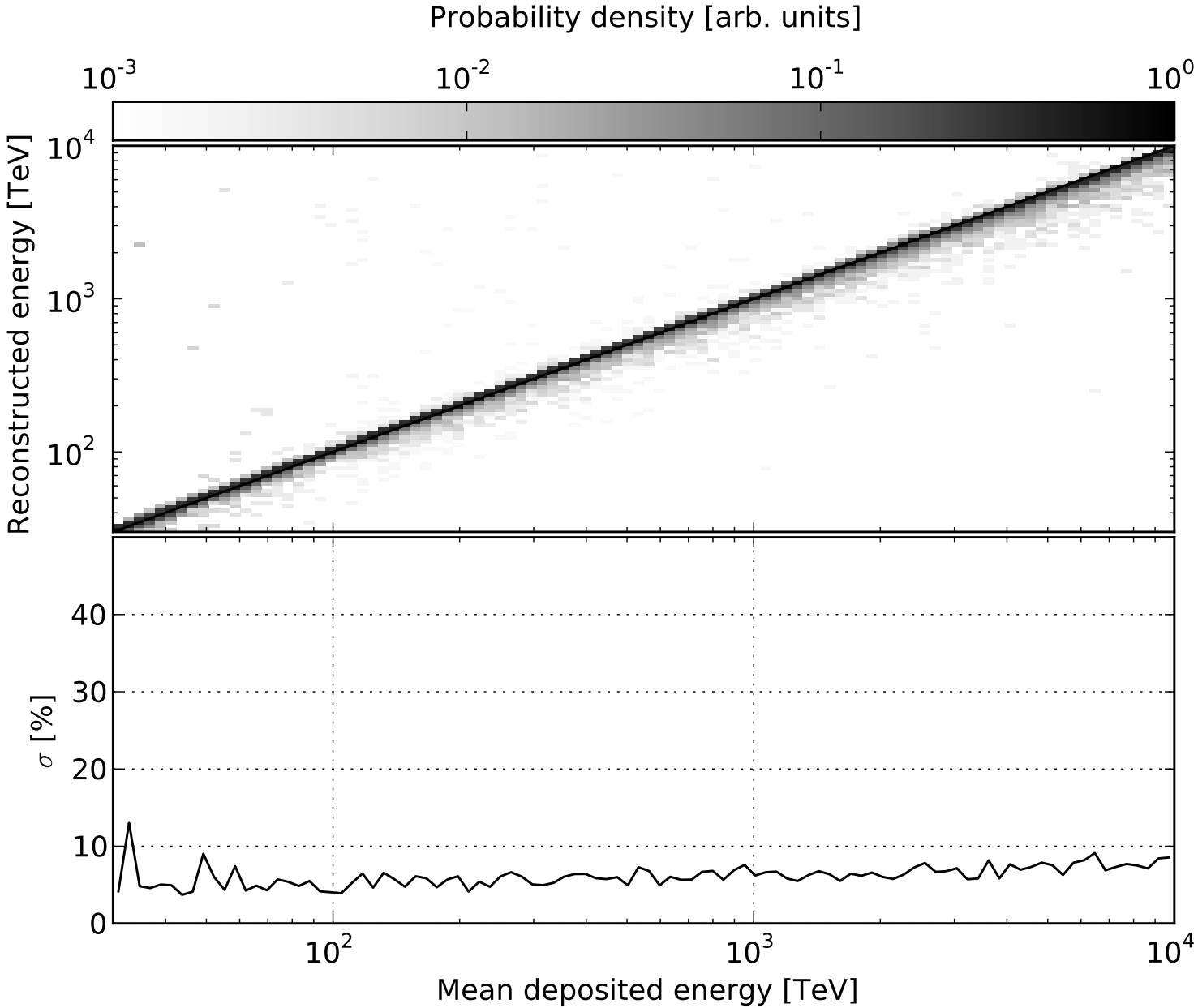
Next Steps

- Rich program of neutrino measurements in place
- New channels (southern hemisphere, ν_e, low energies) opening
- Strong complementarity of WIMP observations with direct and gamma-ray measurements
- IceCube probing interesting regions of parameter space on many topics
- First apparent astrophysical neutrinos at high energies seen and of unknown origin
- Hopefully, more to come

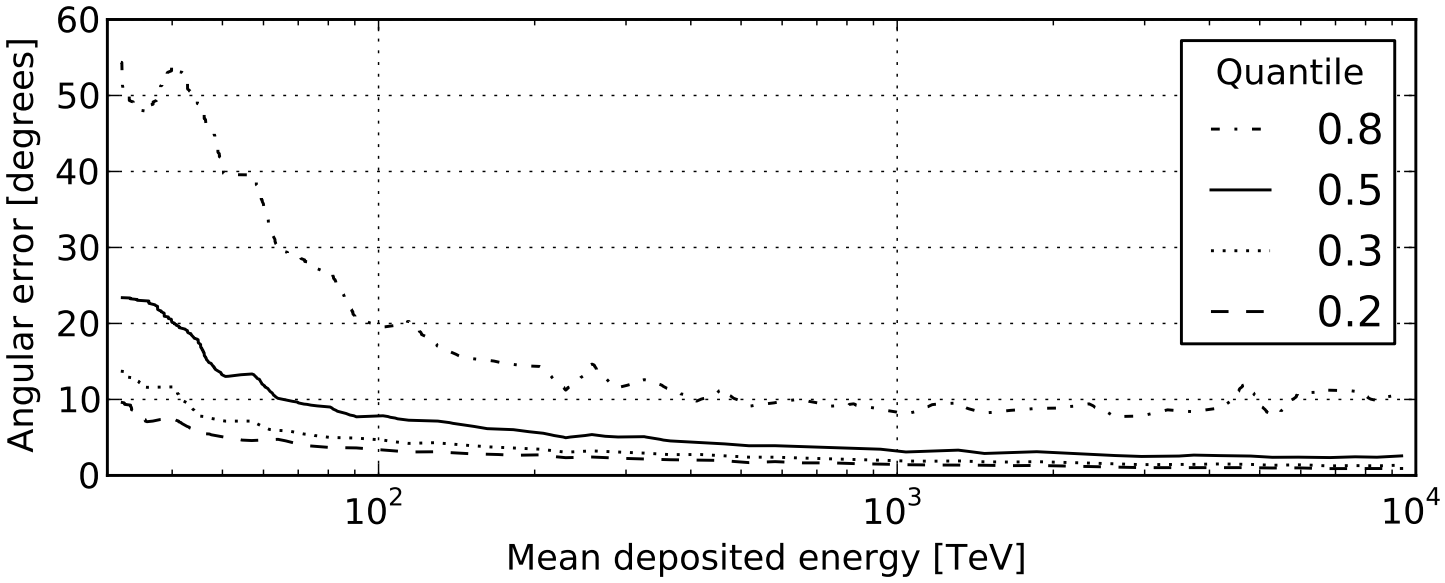
The Beginning

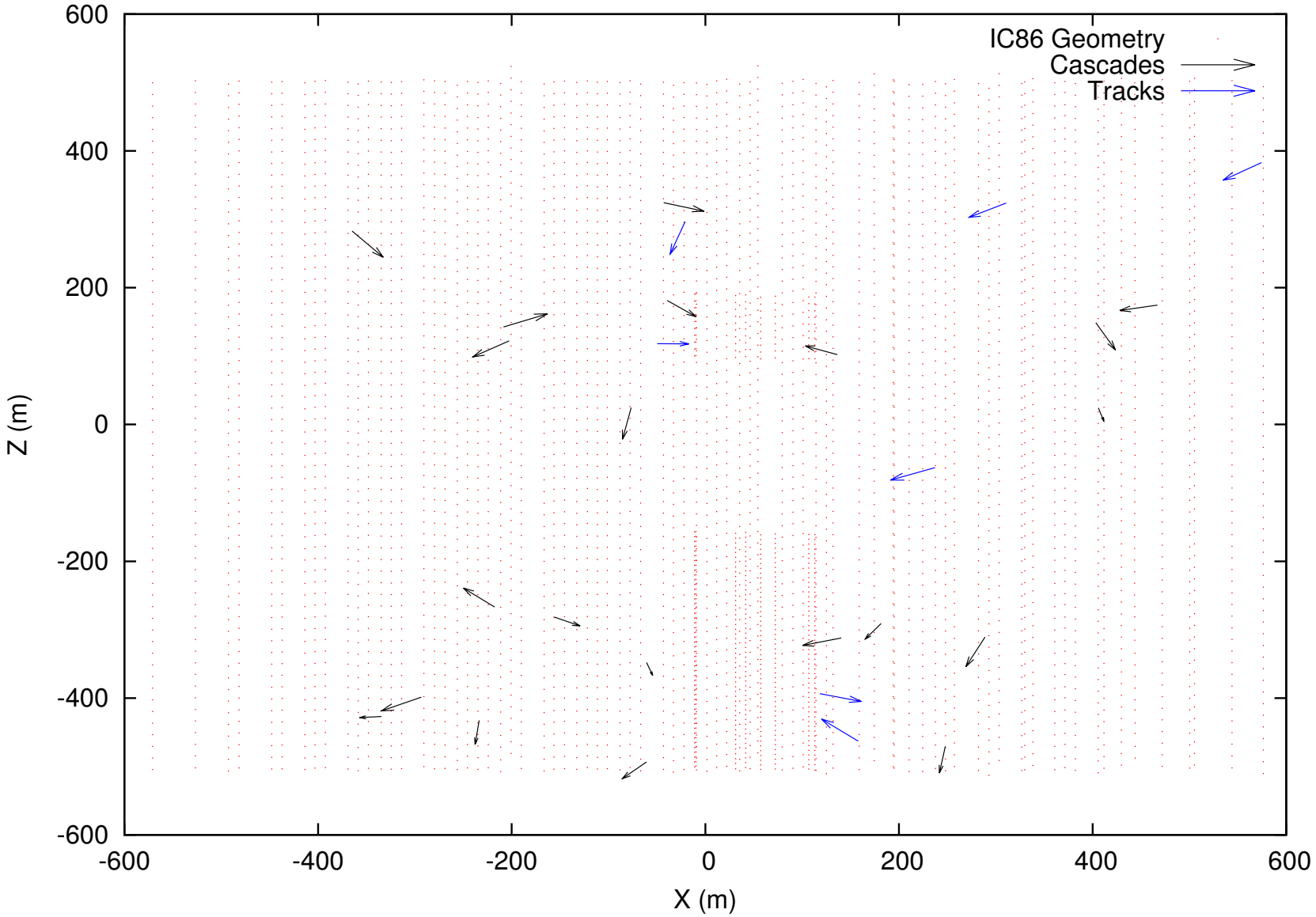
Backup

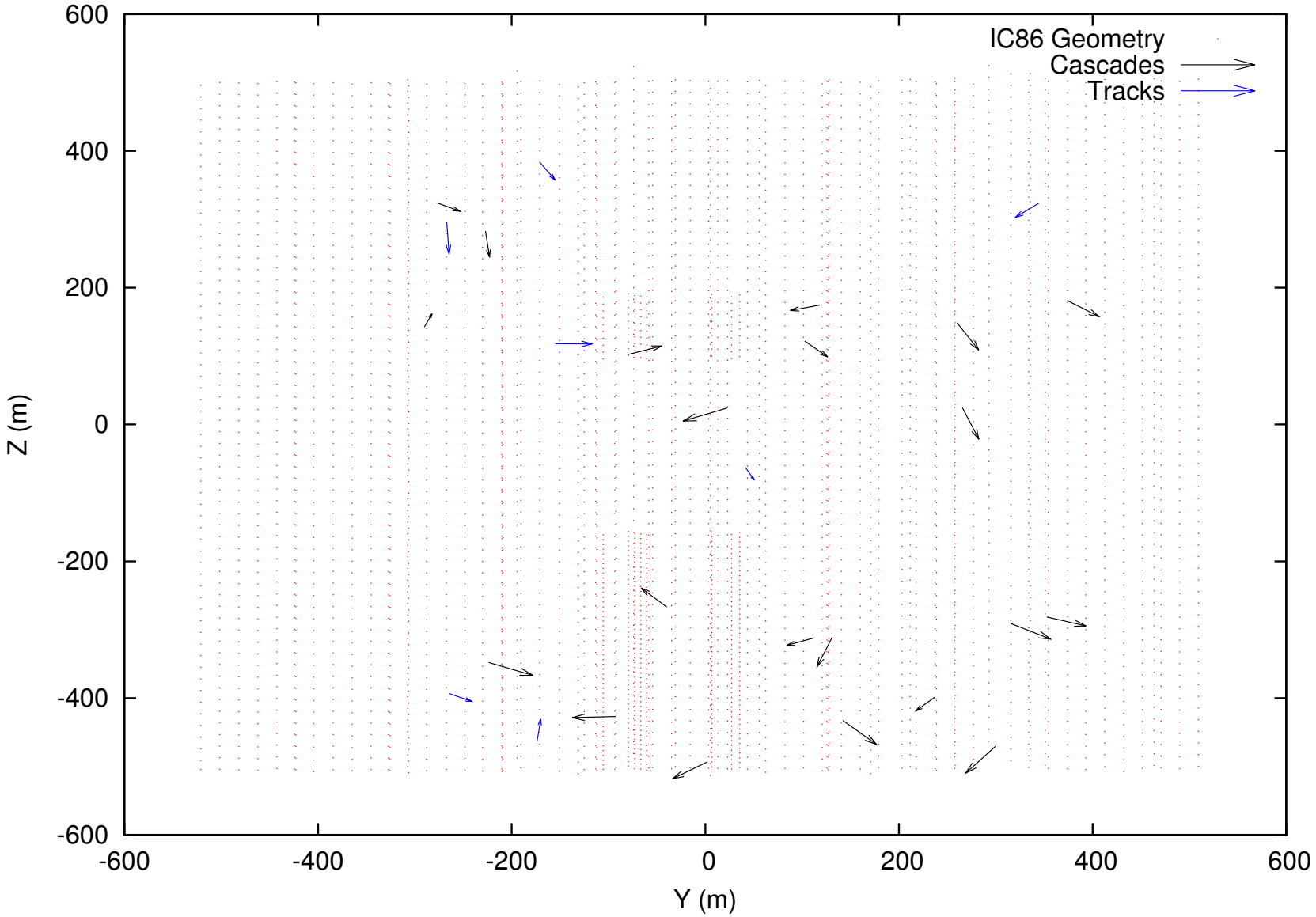
Shower Energy Resolution

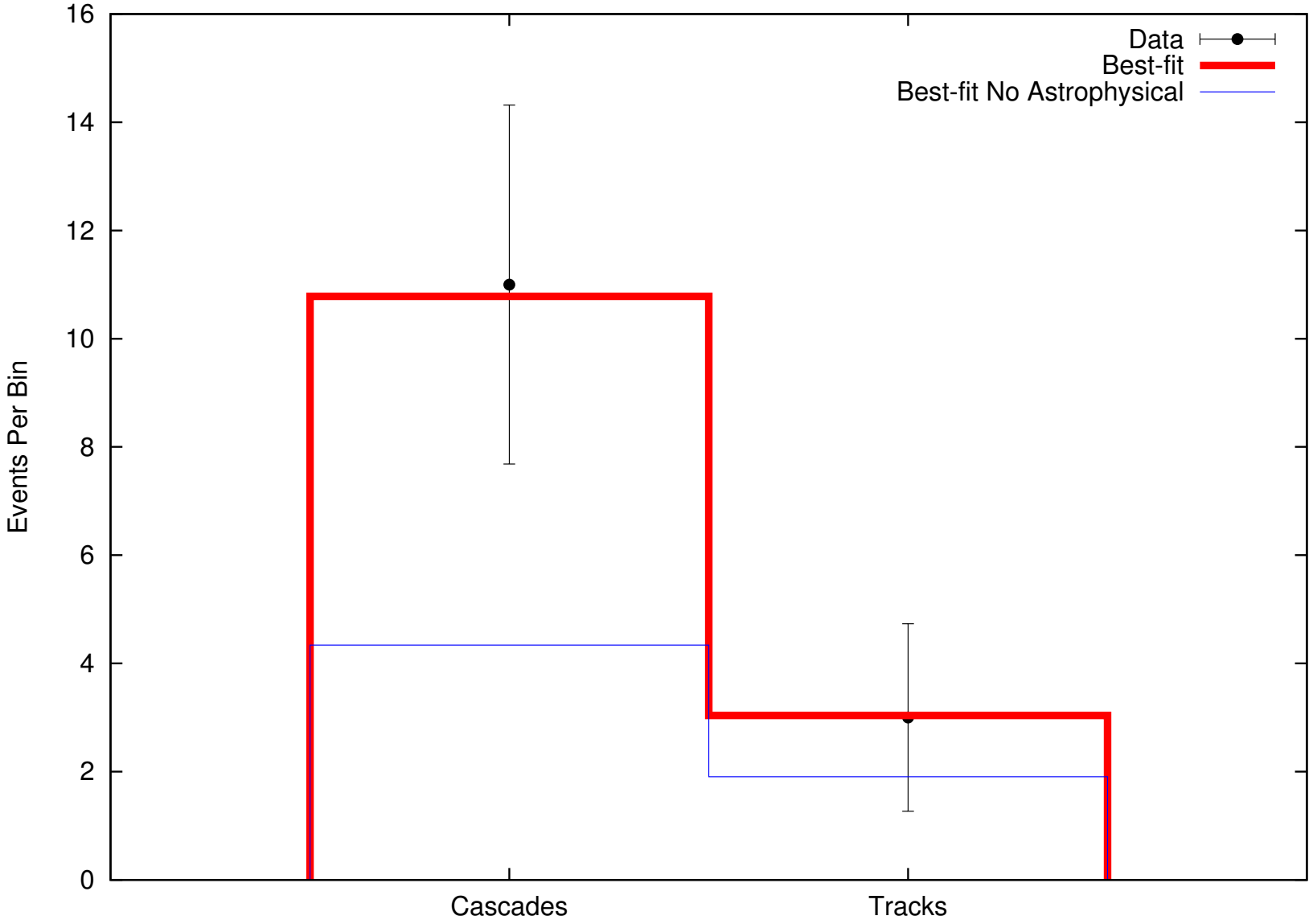


Shower Angular Resolution

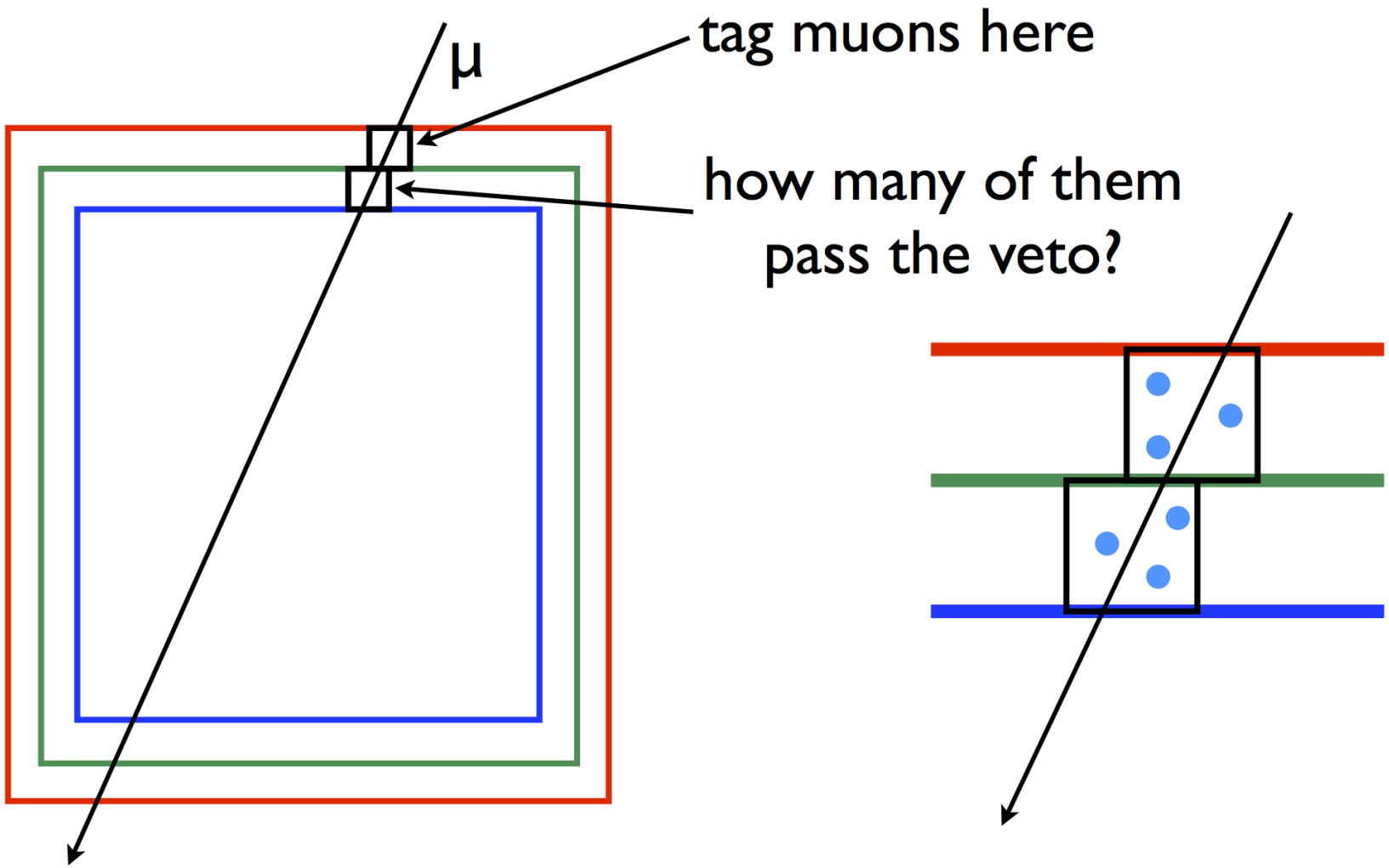



IC86 Geometry
Cascades
Tracks
600
400
200
0
-200
-400
-600
Z (m)
-600
-400
-200
0
200
400
600
X (m)


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


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

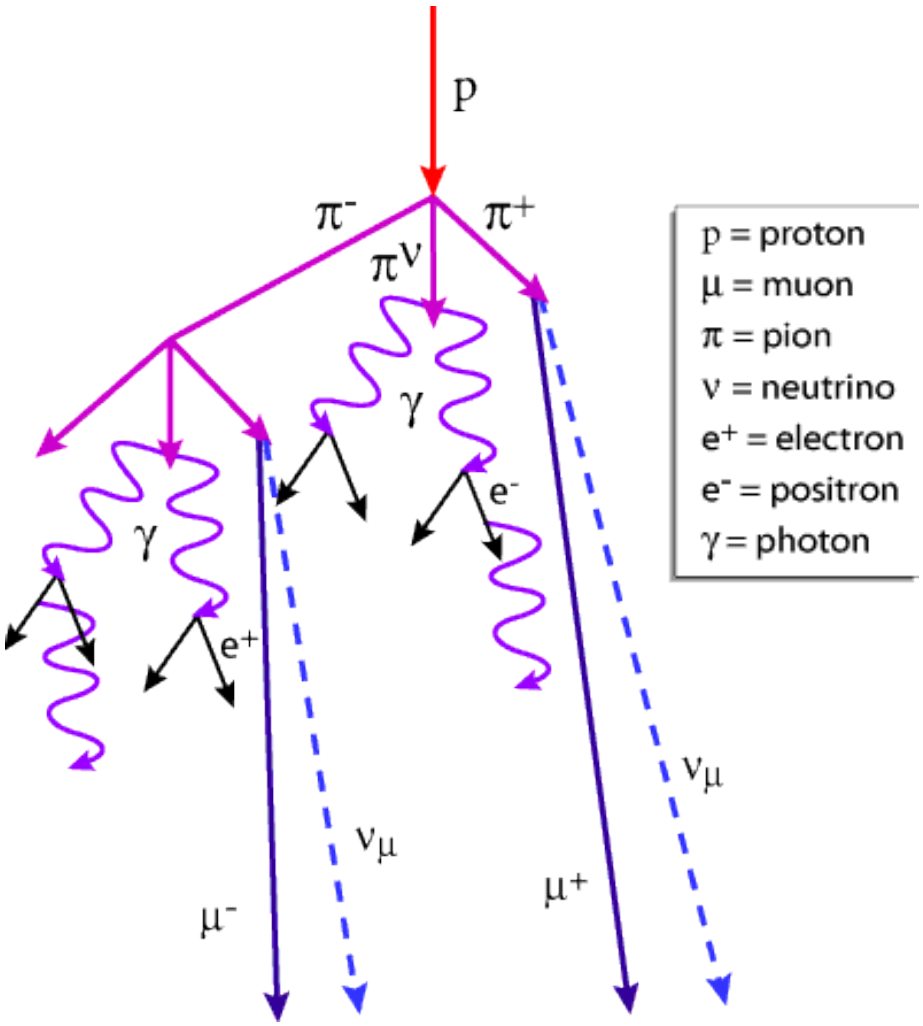
Background 1: Muon Background



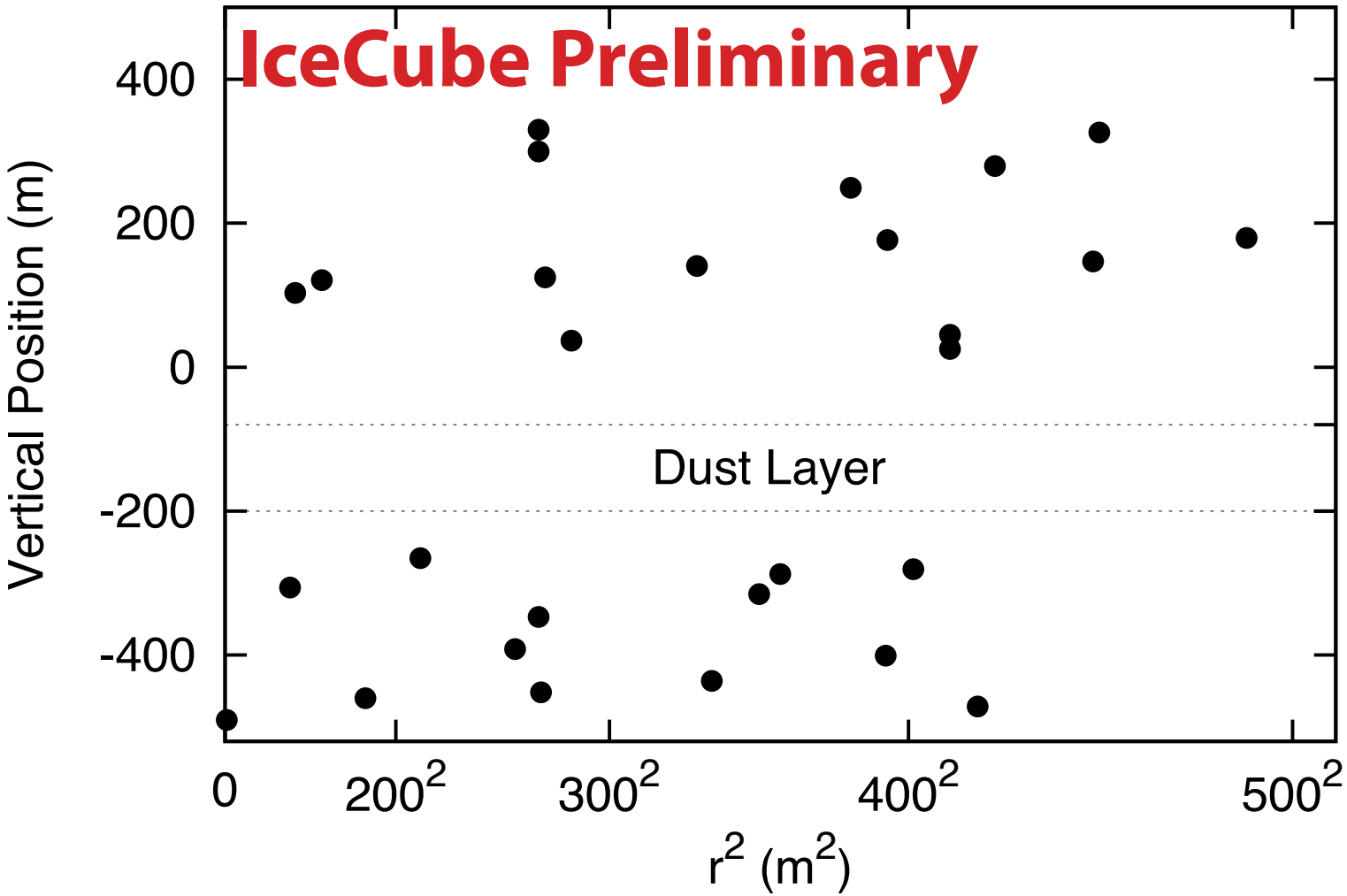
- Estimate Muon Background from Data
- Use outer tagging layer, see how many miss
- 3 ± 1.5 background events per year

Background 2: Atmospheric Neutrinos

- π/K rate well constrained: 2.3 ± 0.6 events per year
- Charm rate not well constrained: upper limit (1σ) of 1.7 events per year
- Total: $2.3^{+1.9}_{-0.6}$ events per year

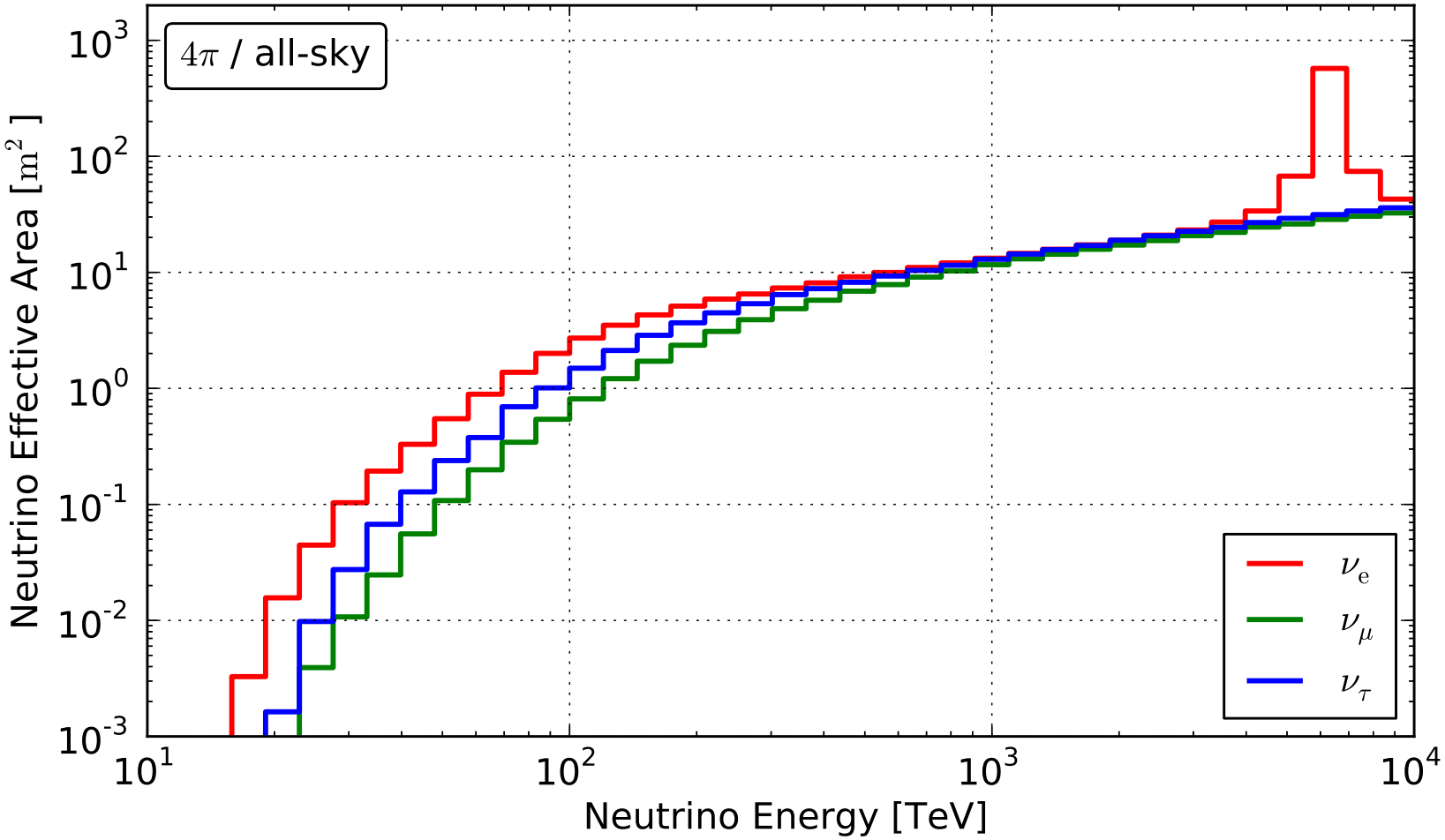


Event Distribution in Detector

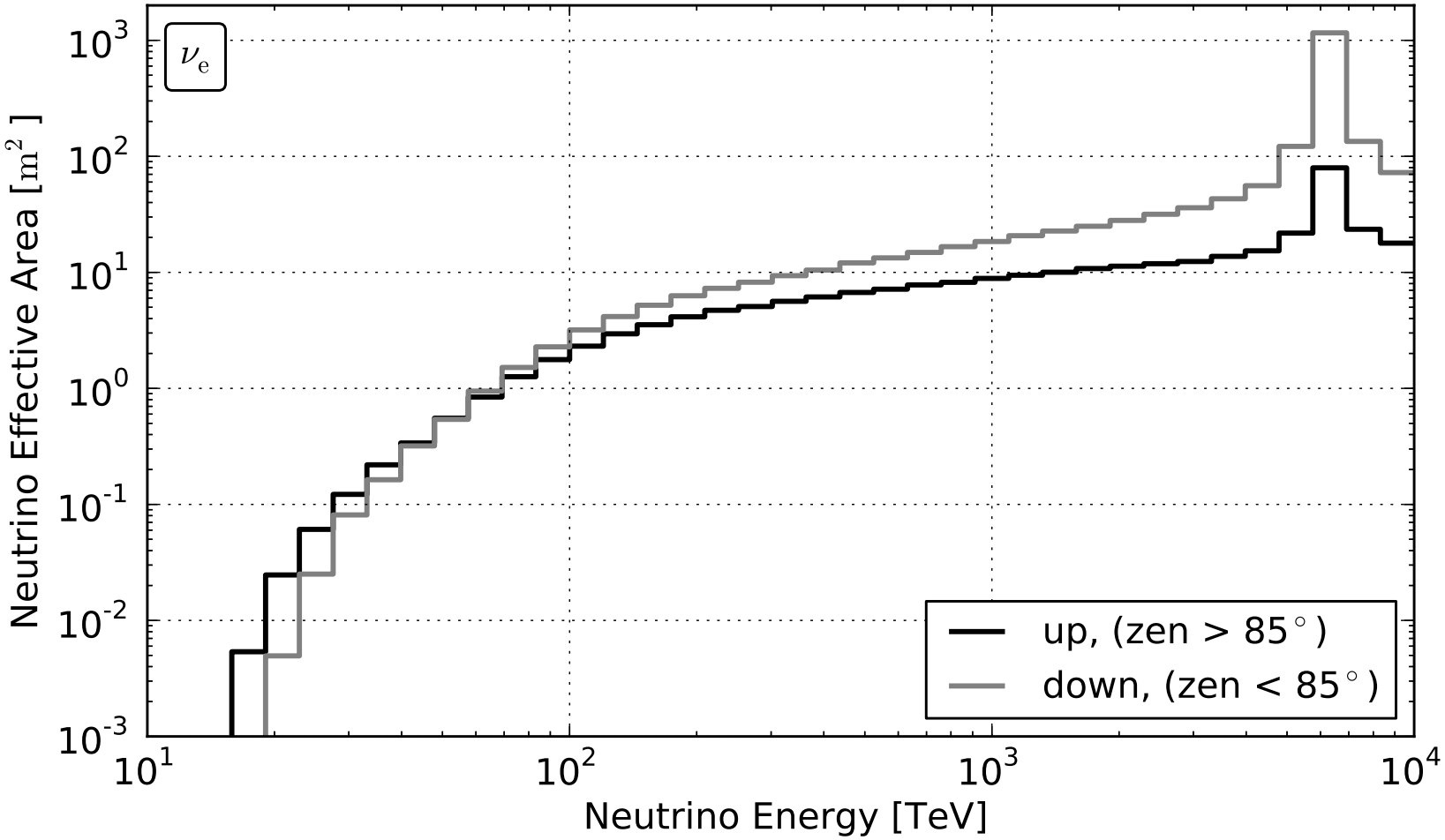


Uniform in fiducial volume

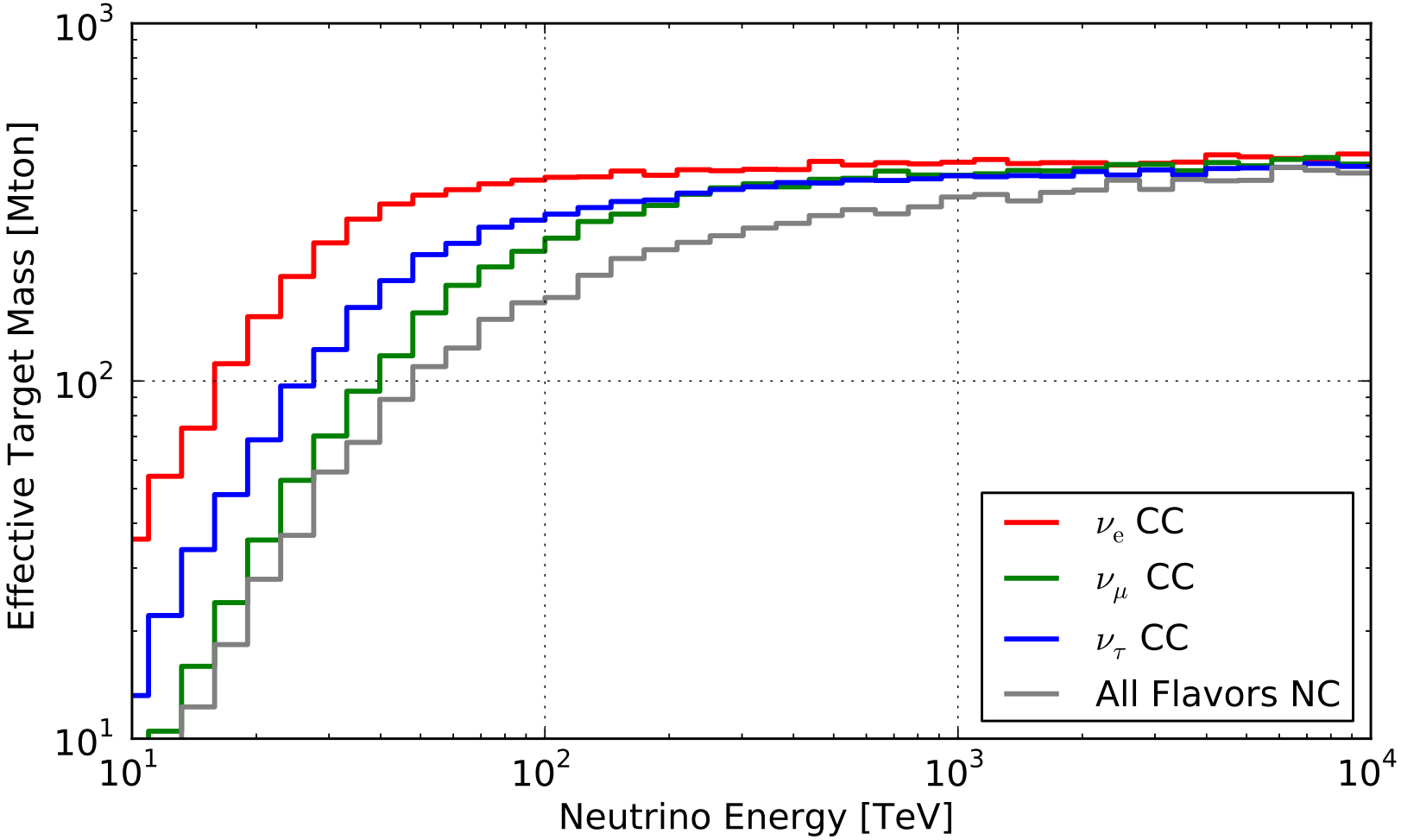
Effective Area 1



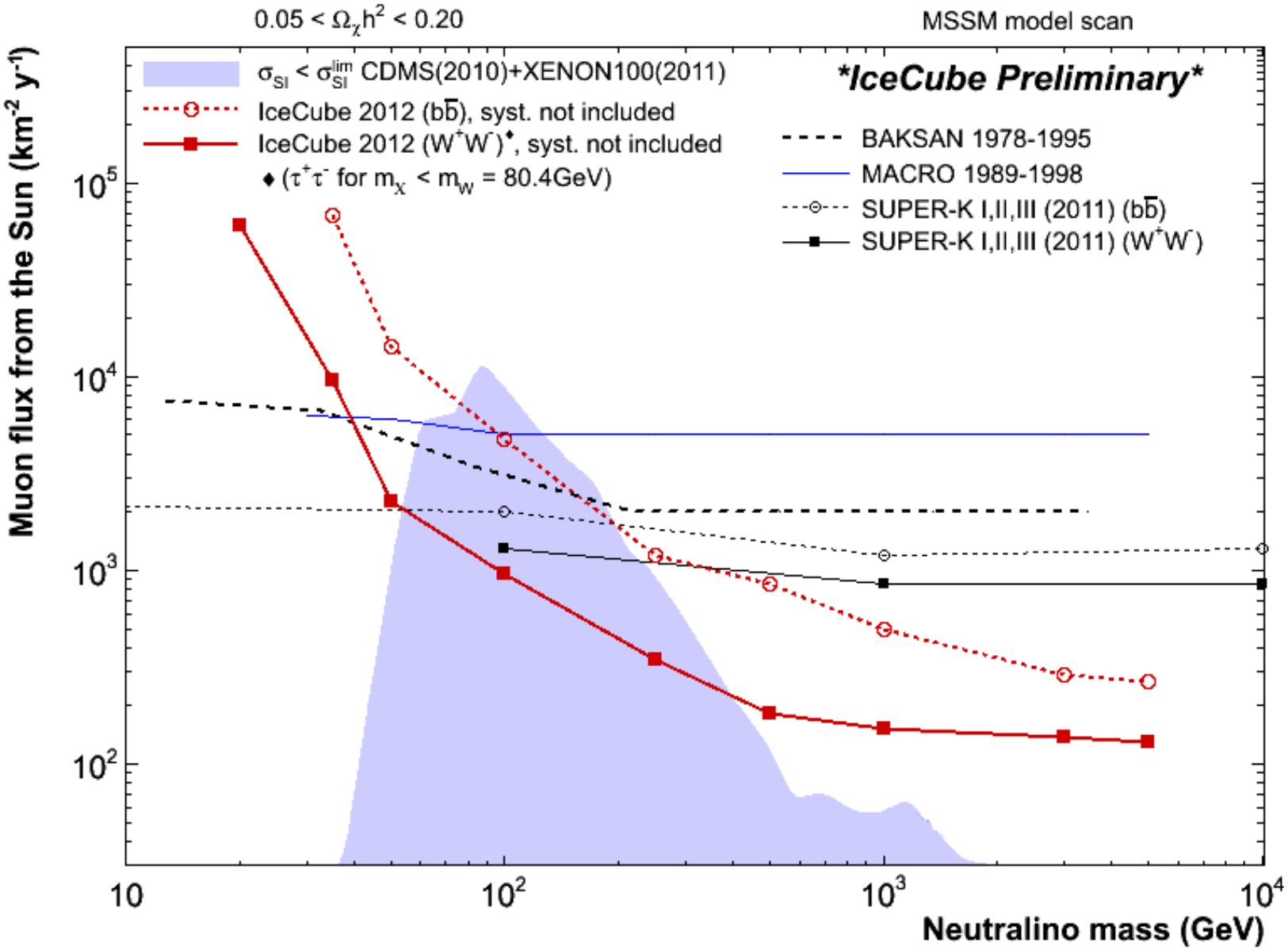
Effective Area 2



Effective Volume



Muon Flux From Sun



Charge Distribution