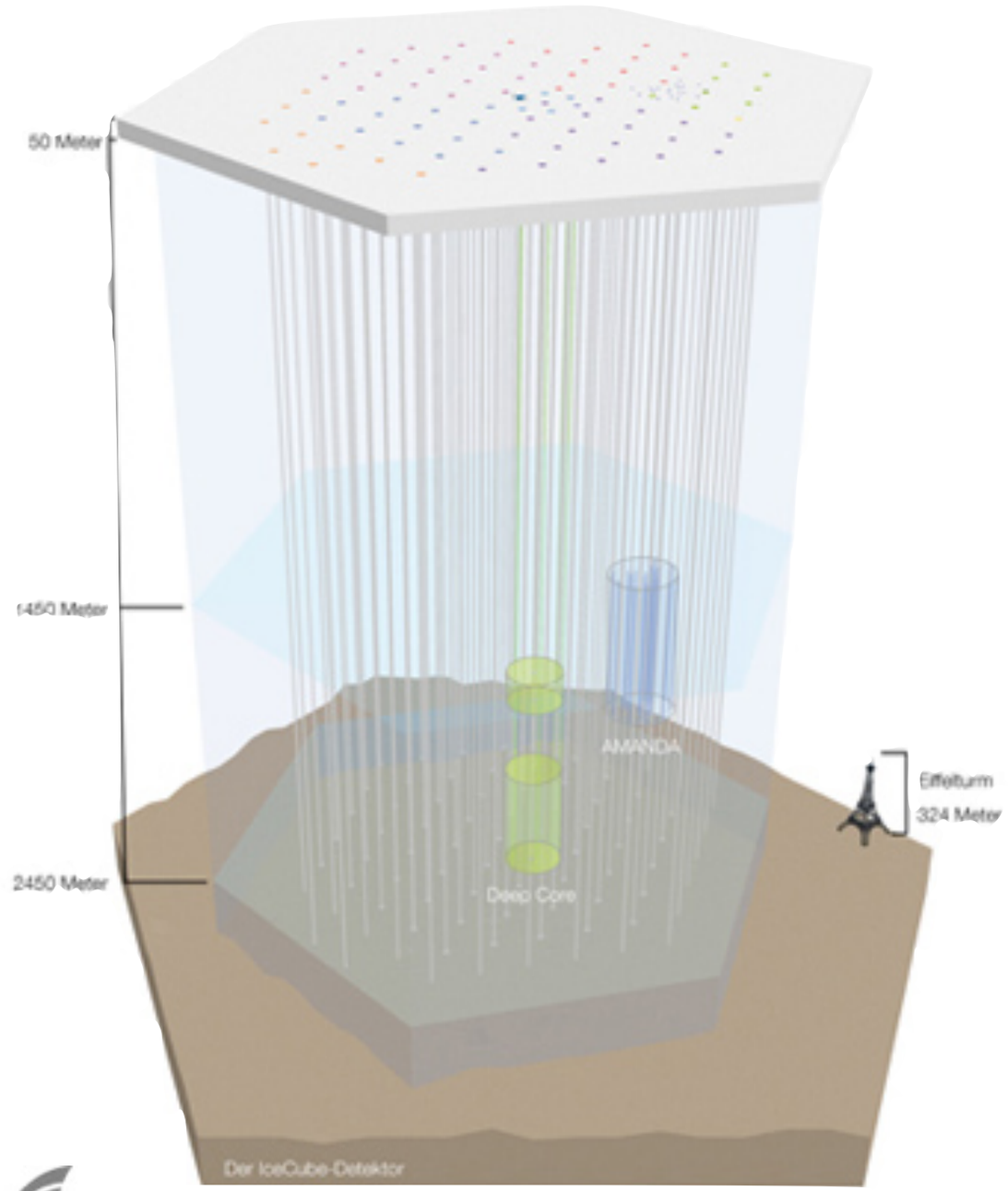
Recent results

from the IceCube neutrino observatory.



Markus Ackermann
on behalf of the IceCube collaboration

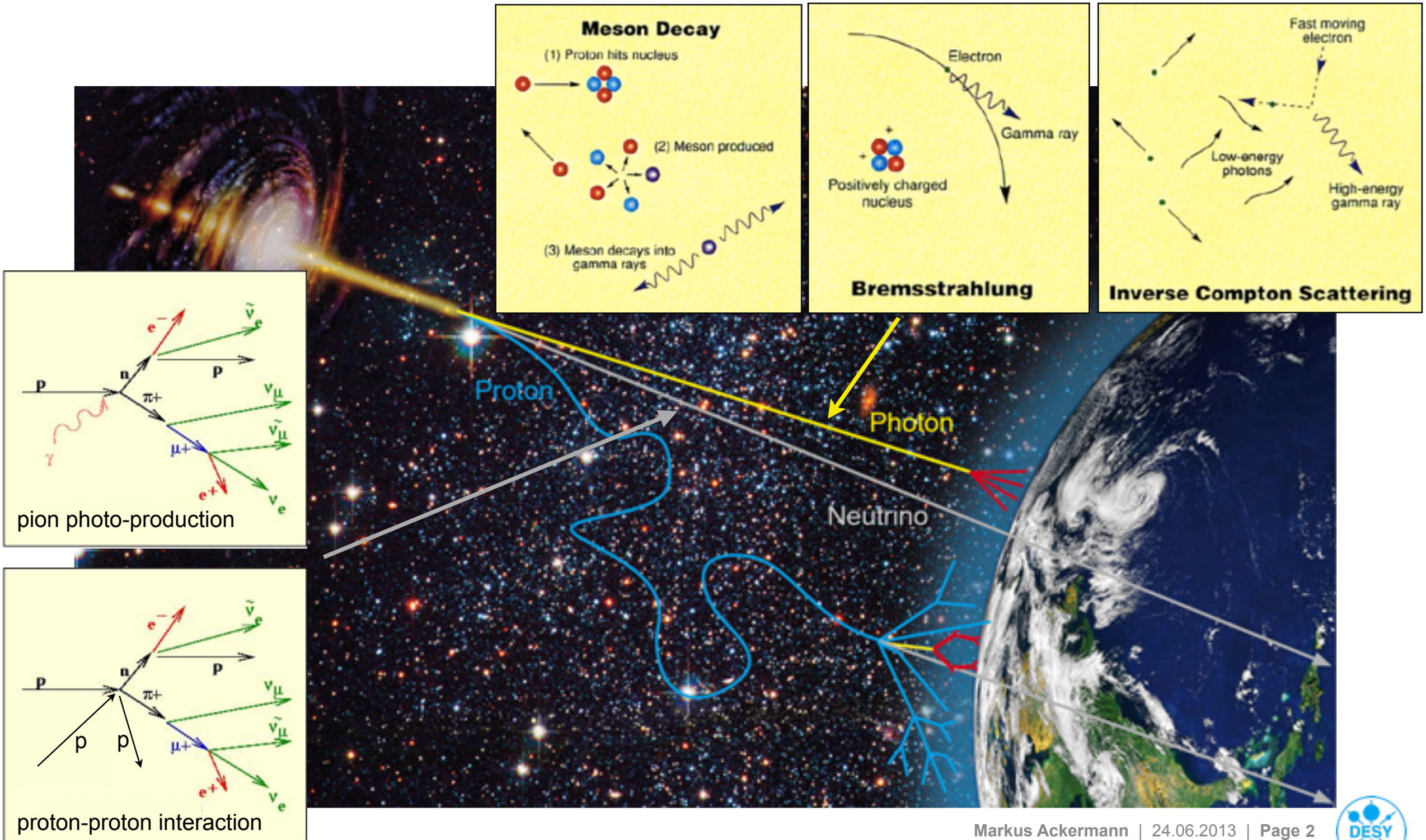
Seminar talk, LPNHE, Paris,
24.06.2013

HELMHOLTZ ASSOCIATION

DESY

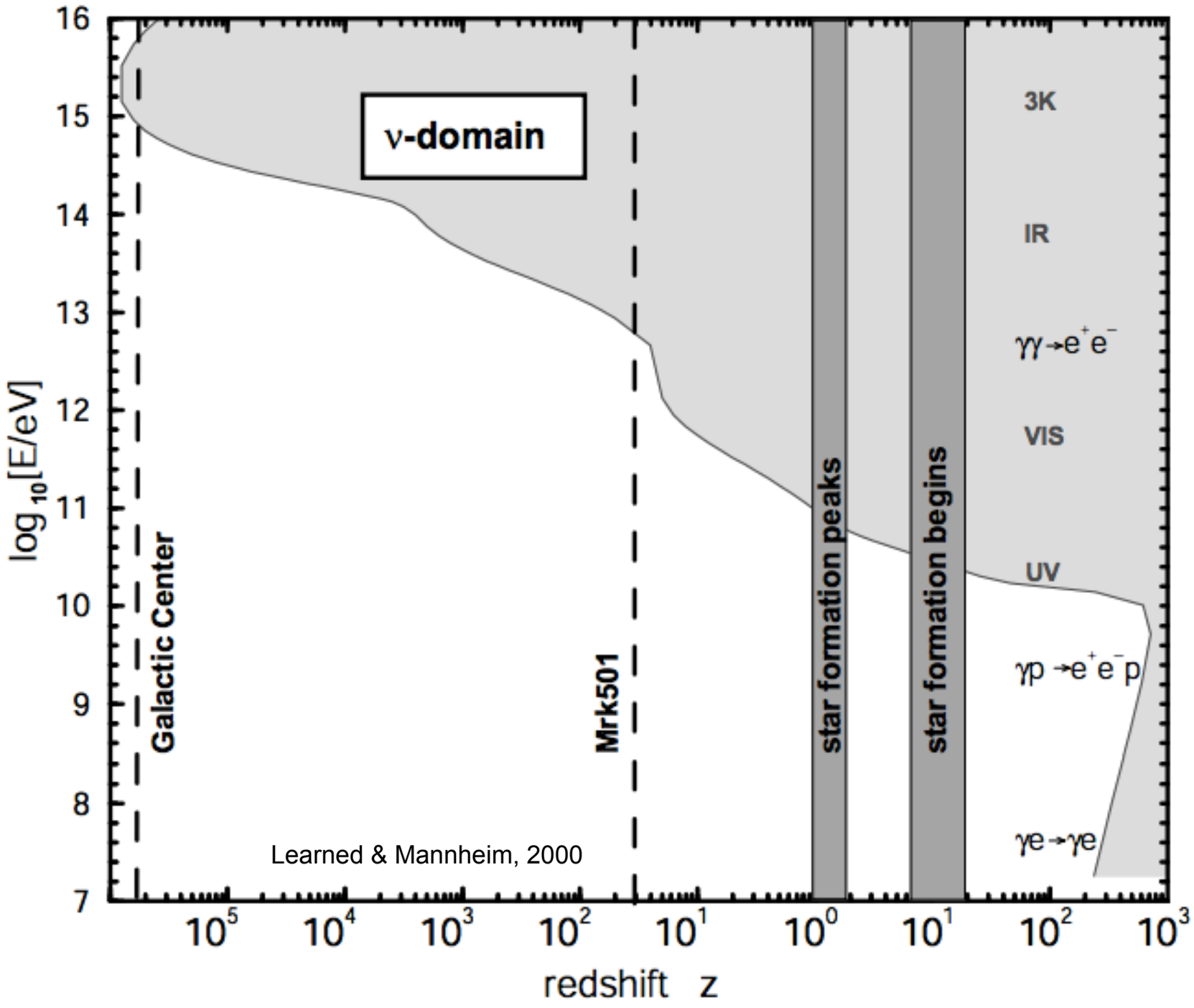
Gamma-ray and neutrino astrophysics.

> Gamma rays and neutrinos are complementary messengers to explore the high-energy universe.



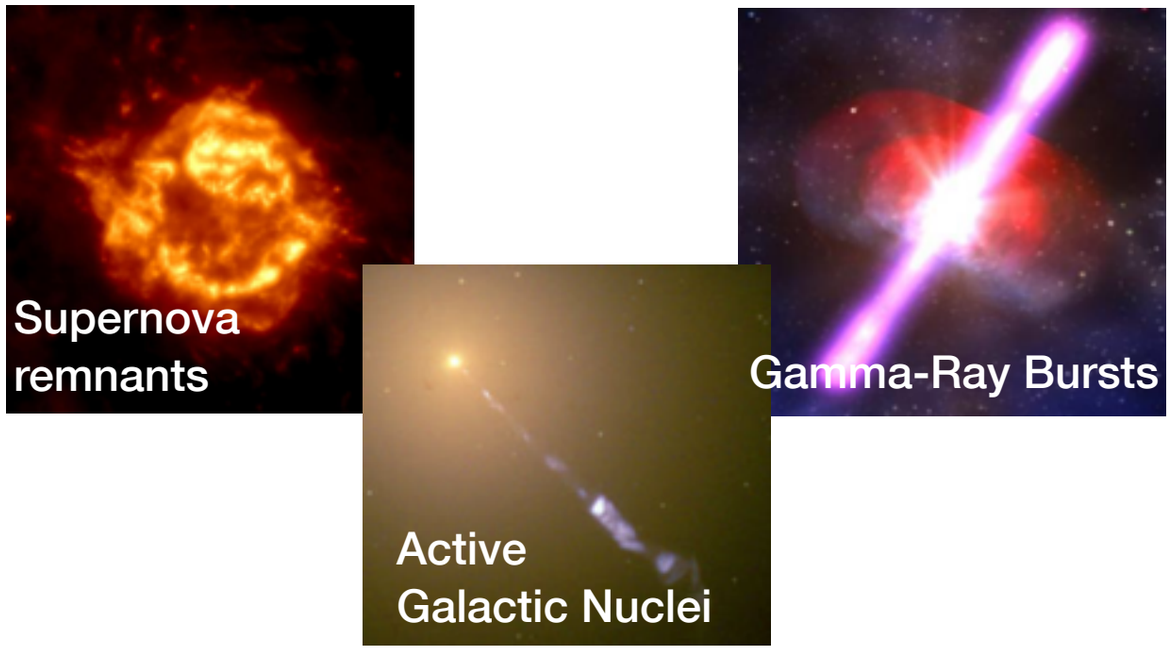
The gamma-ray and the neutrino domain.

- Above 100 GeV larger and larger fractions of the universe turn opaque for γ-rays.
- Only neutrino telescopes can do “PeV astronomy”.

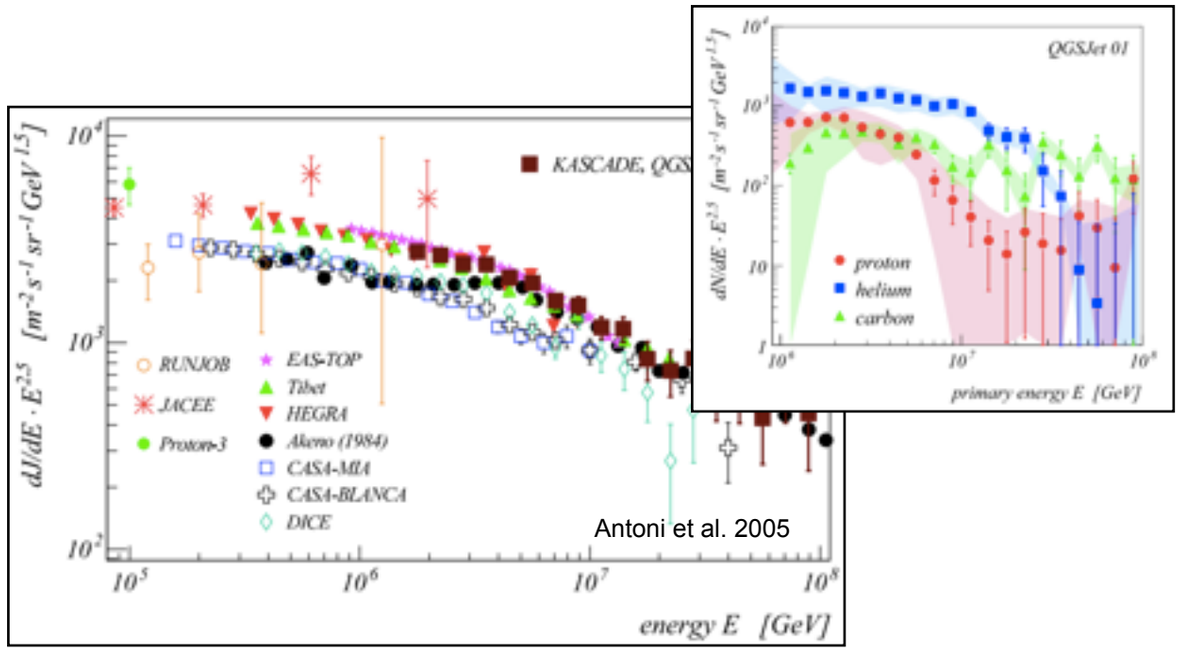


Learned & Mannheim, 2000

IceCube science.

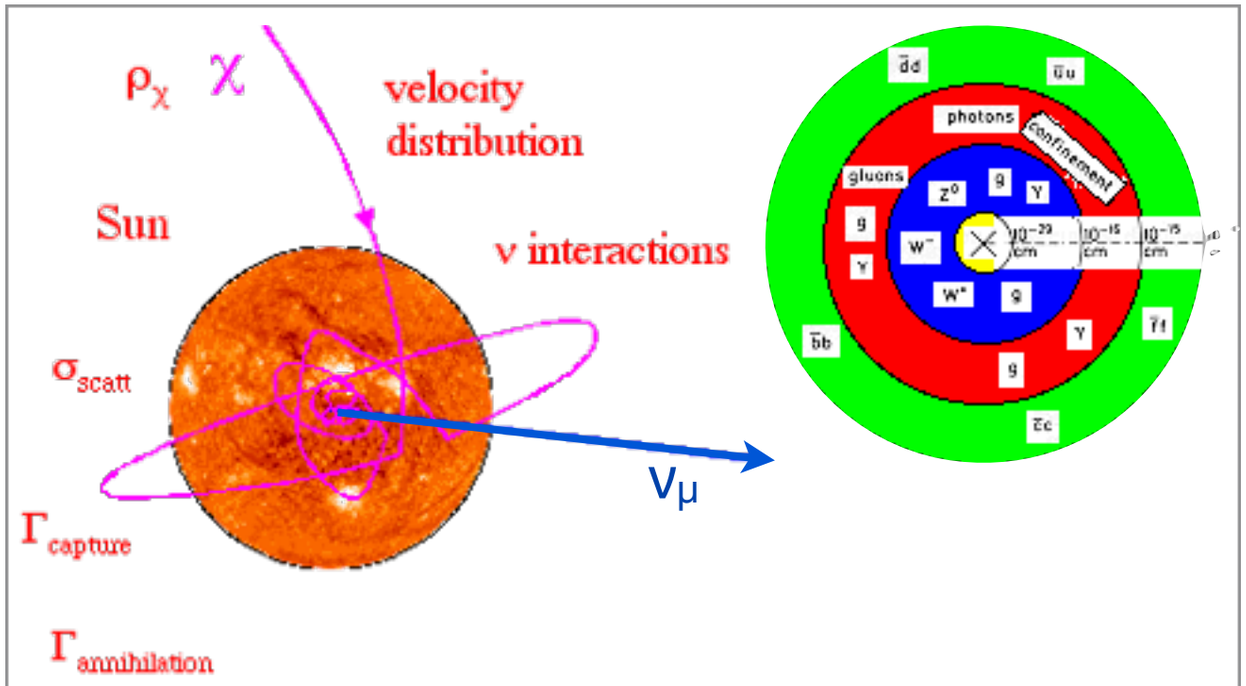


Neutrino astrophysics

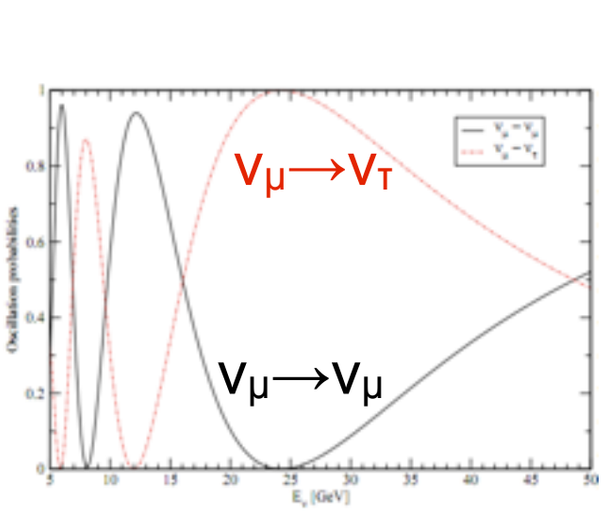


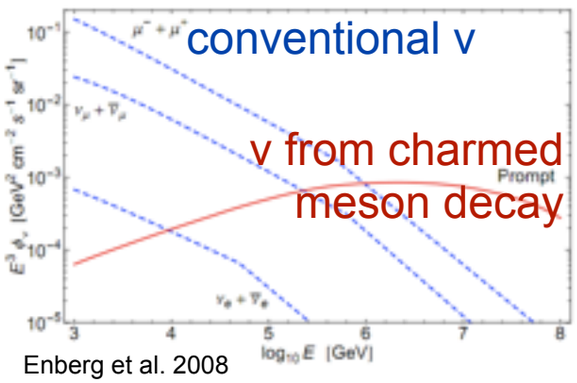
Antoni et al. 2005

Properties of cosmic rays



Dark matter & exotic particles





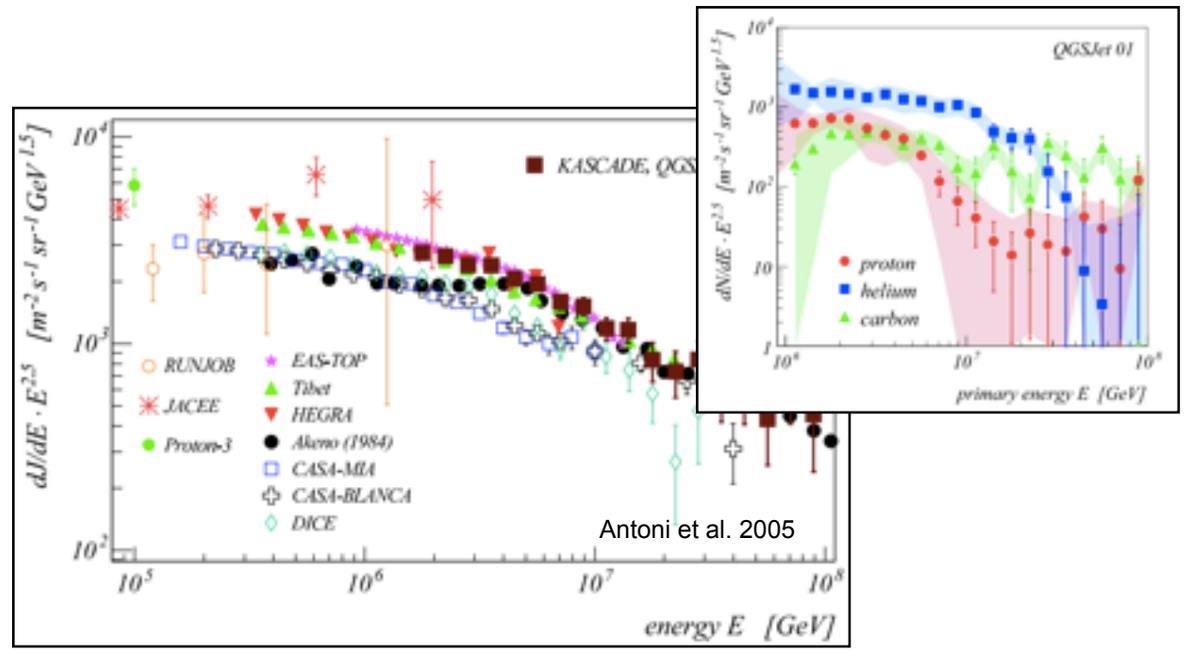
Enberg et al. 2008

Neutrino properties & particle physics

IceCube science.

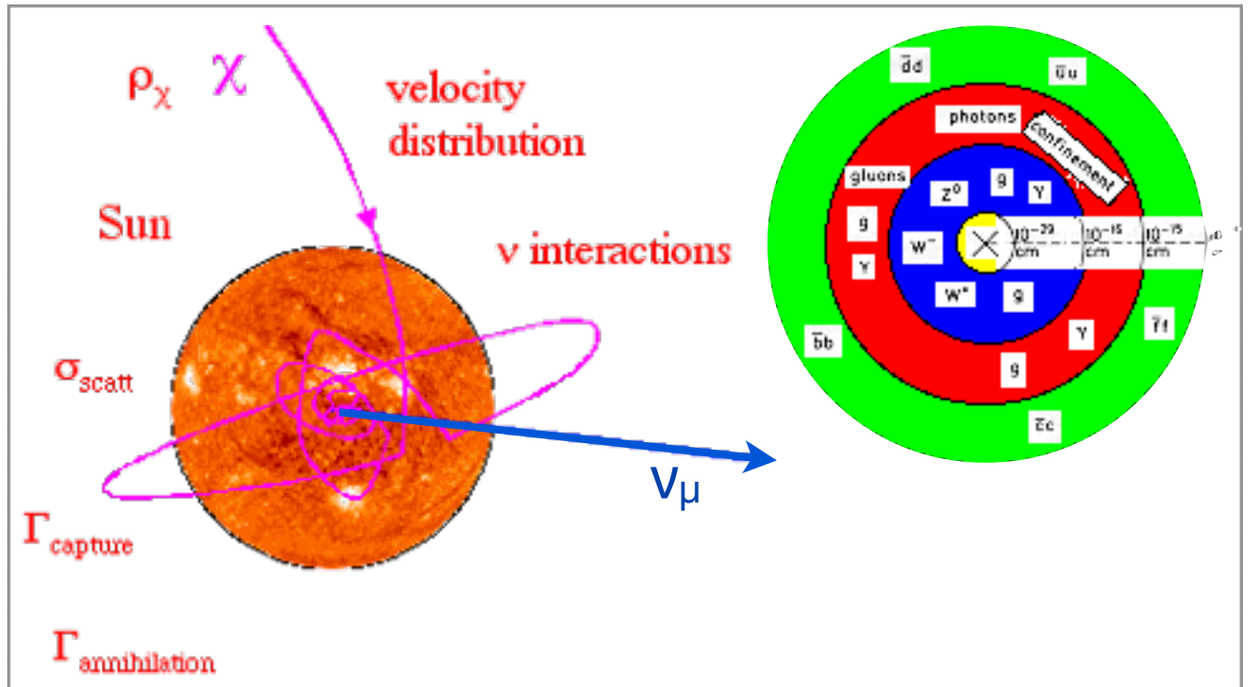
- Localized sources of neutrinos.
- Transients (GRBs, AGN flares, Supernovas).
- Diffuse astrophysical neutrinos.
- Cosmogenic neutrinos.

Neutrino astrophysics

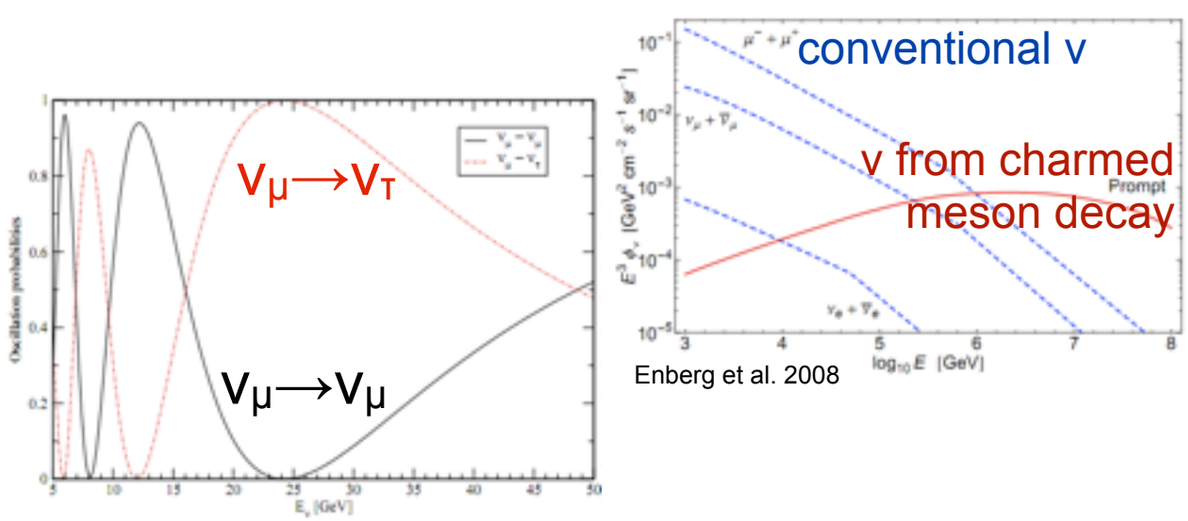


Antoni et al. 2005

Properties of cosmic rays



Dark matter & exotic particles



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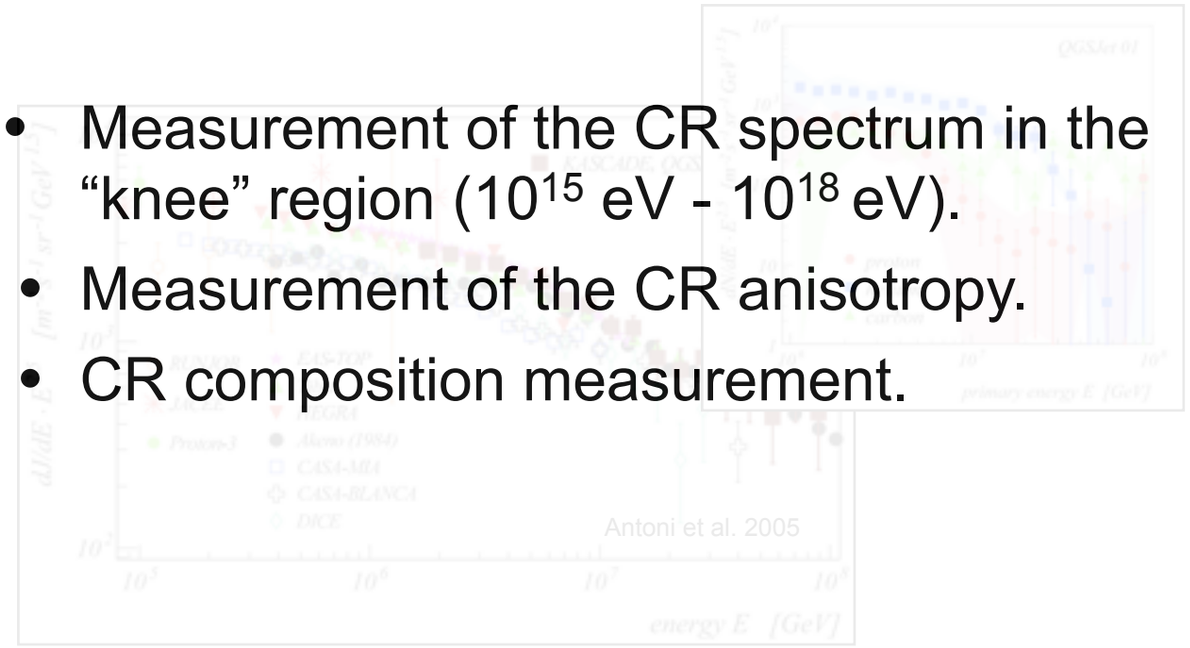
Supernova remnants

Gamma-Ray Bursts

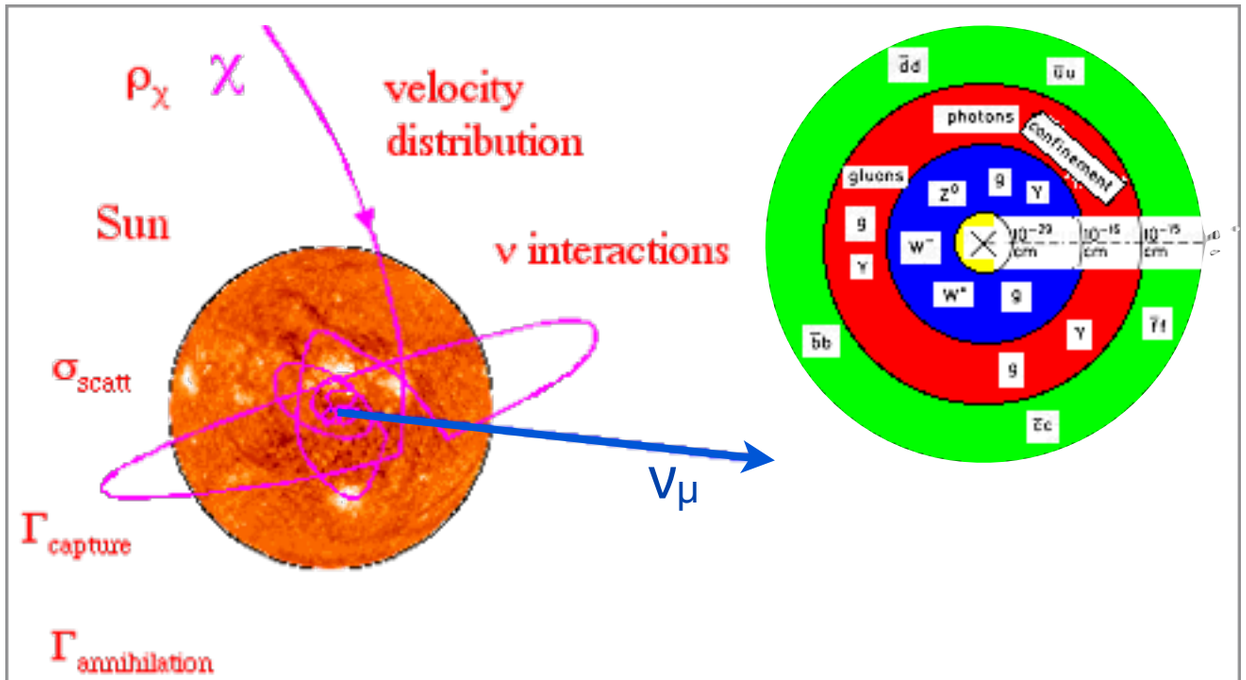
Active Galactic Nuclei

Neutrino astrophysics

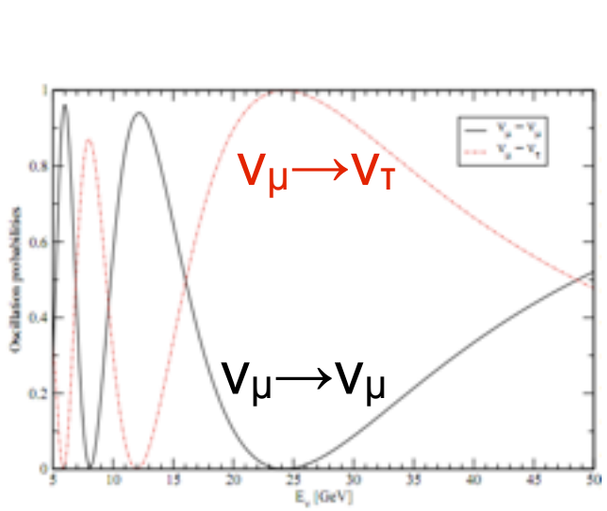
- Measurement of the CR spectrum in the “knee” region (10^{15} eV - 10^{18} eV).
- Measurement of the CR anisotropy.
- CR composition measurement.

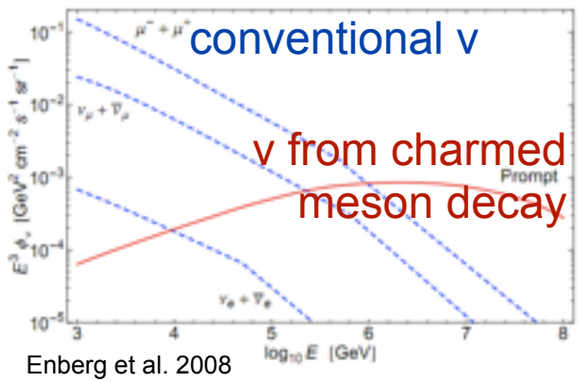


Properties of cosmic rays



Dark matter & exotic particles





Enberg et al. 2008

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Antoni et al. 2005

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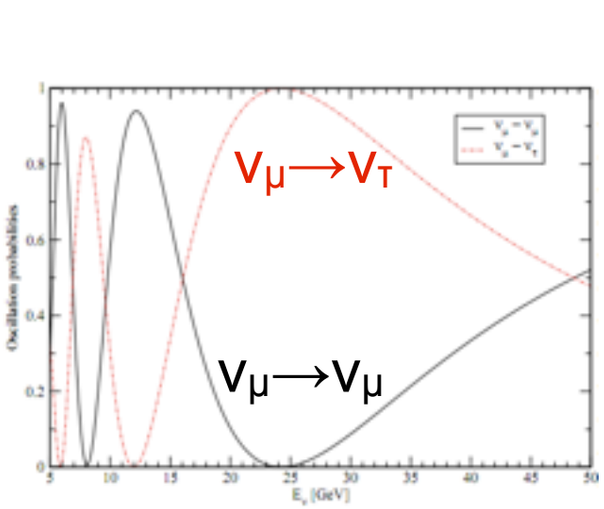
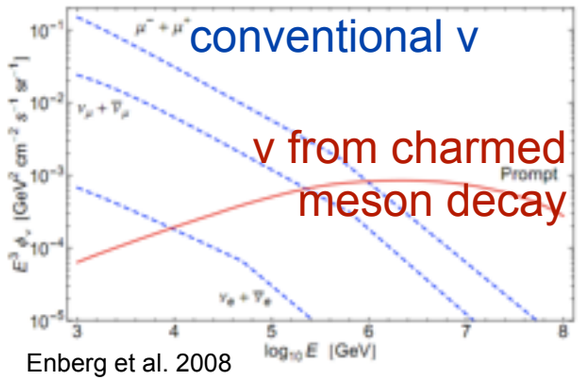
- Neutrinos from dark matter annihilation.
- Search for magnetic monopoles.
- Signatures of sterile neutrinos.

Dark matter & exotic particles





Enberg et al. 2008

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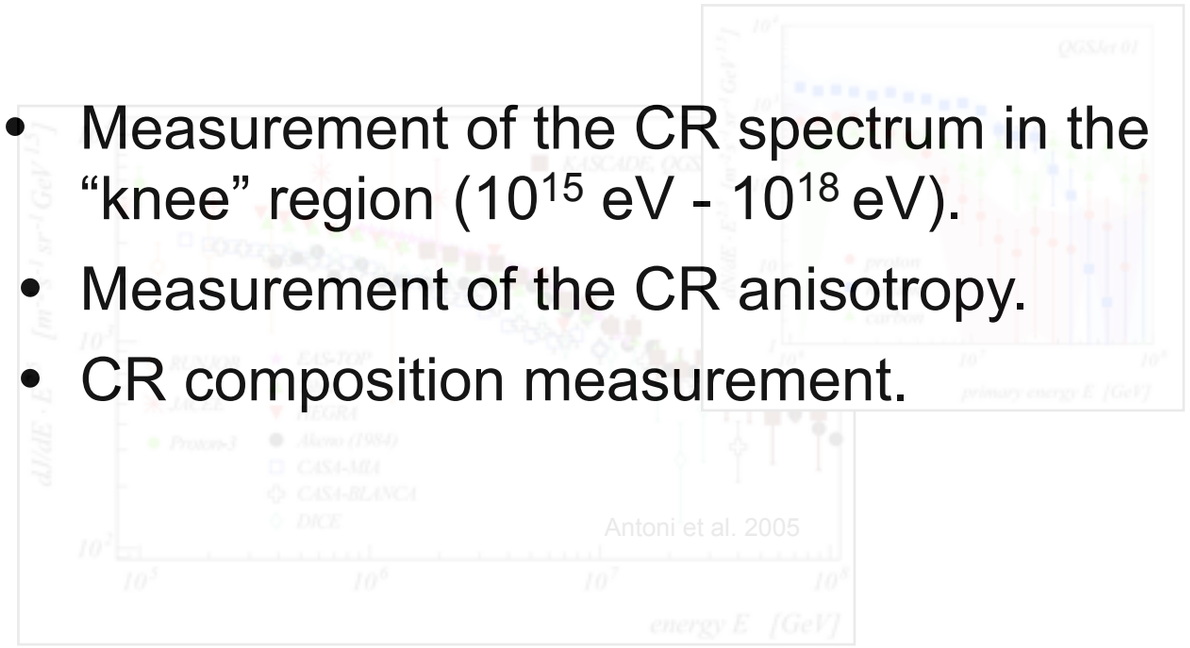

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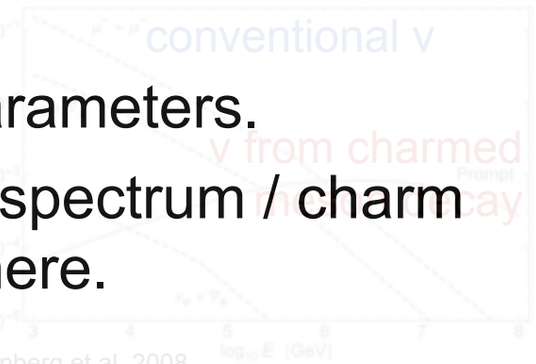
Dark matter & exotic particles

- Neutrino oscillation parameters.
- Atmospheric neutrino spectrum / charm production in atmosphere.
- ν_T - identification.



Neutrino properties
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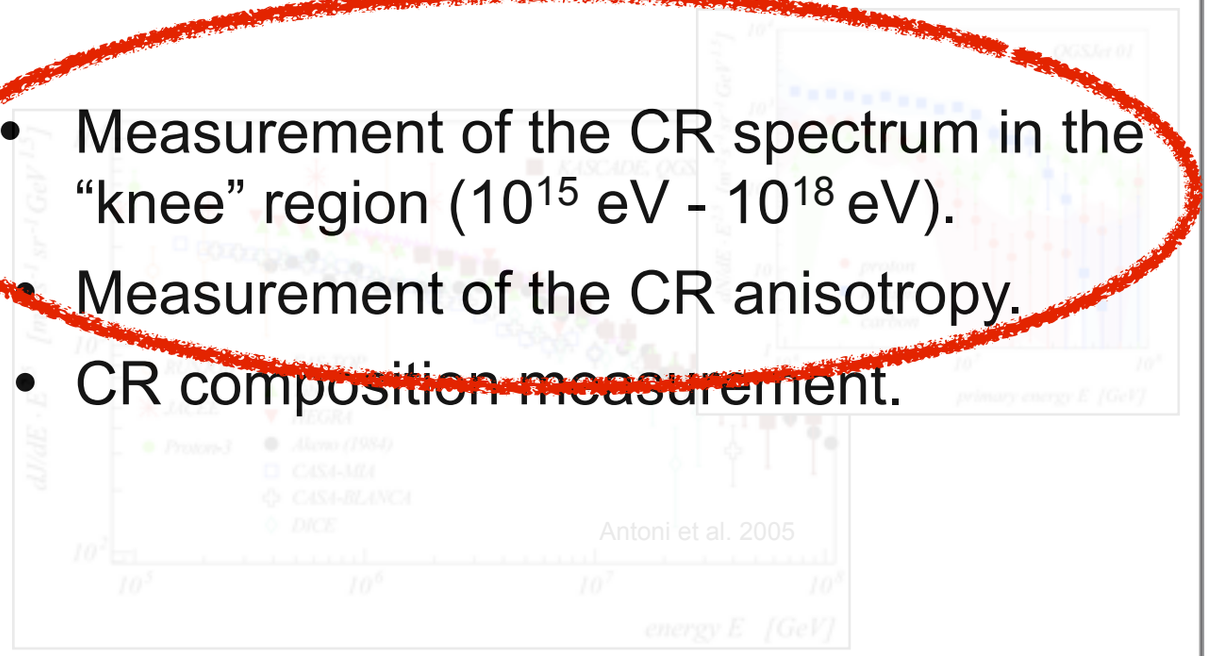

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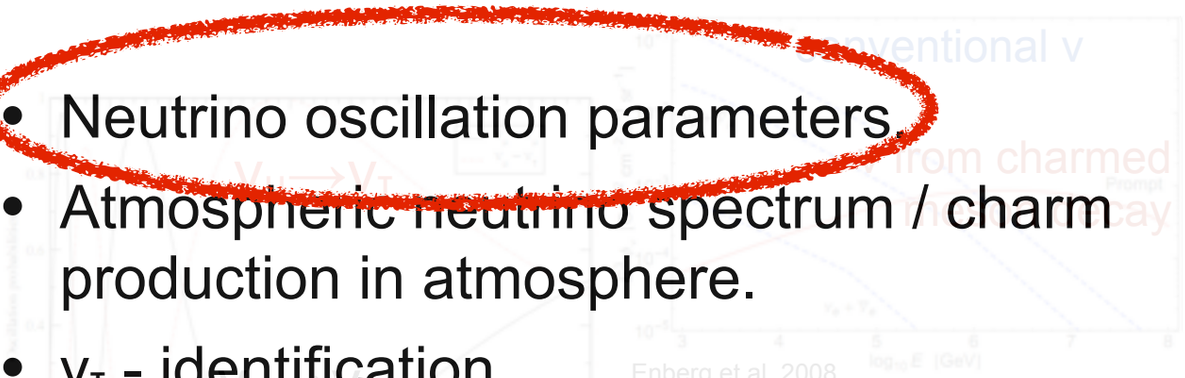
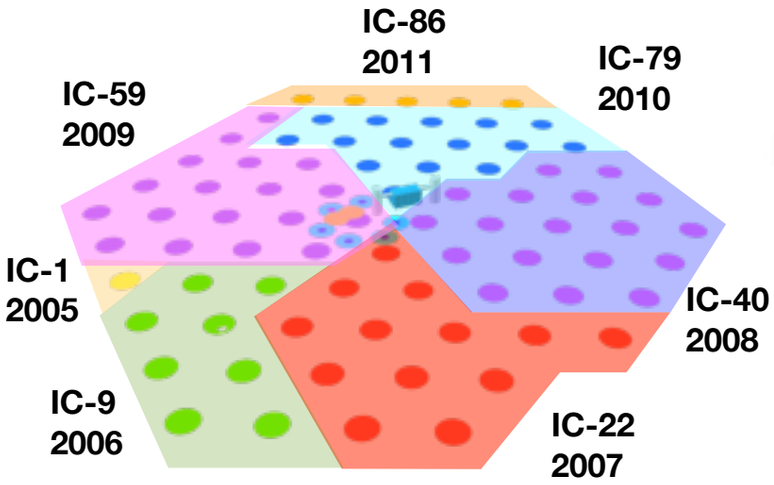
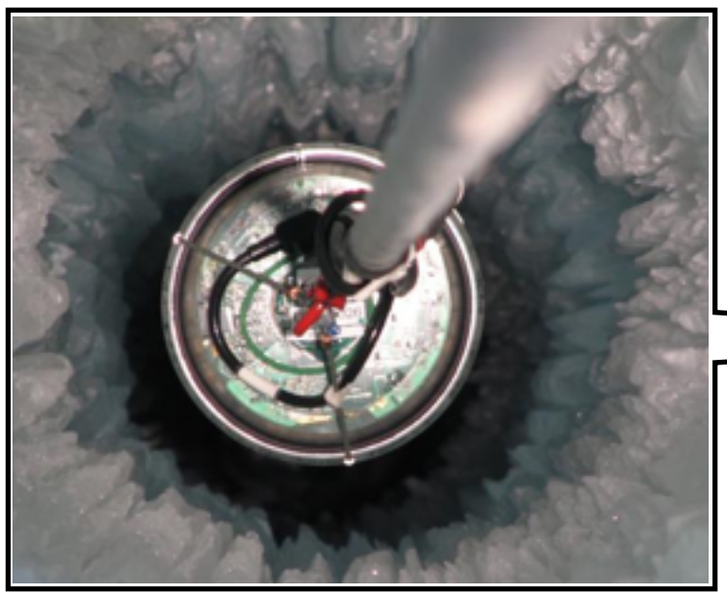
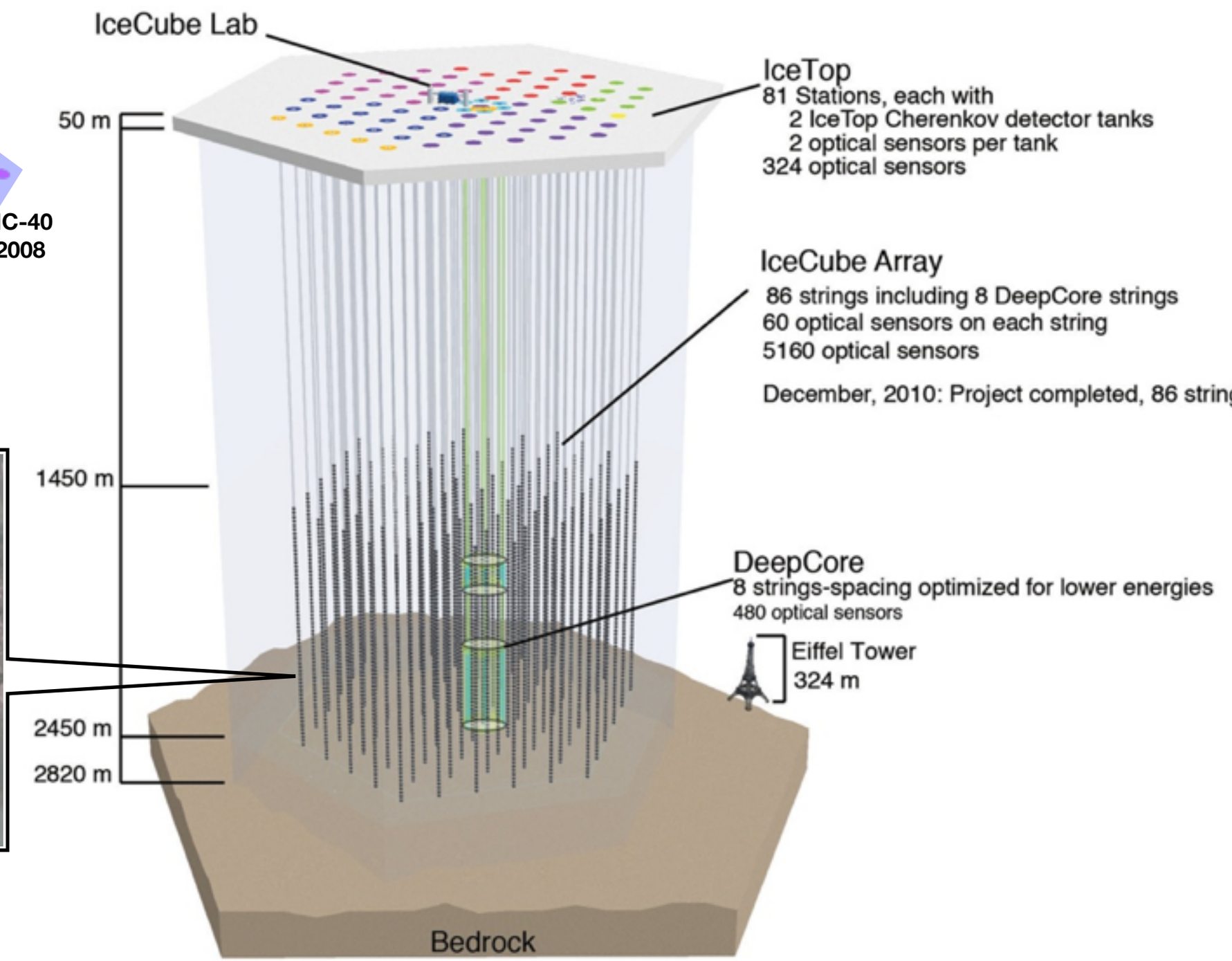


Neutrino properties & particle physics

The IceCube Neutrino Observatory.

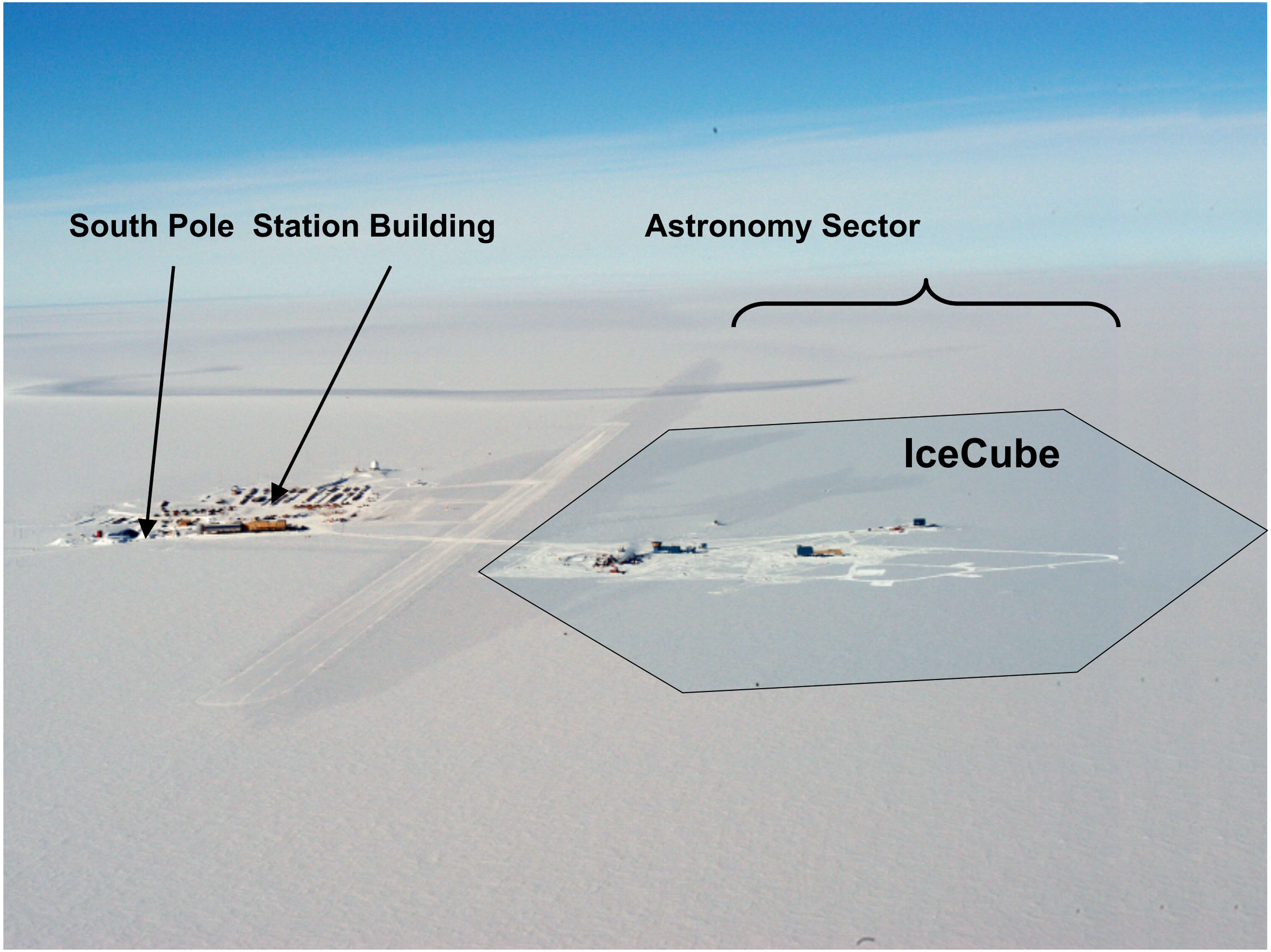






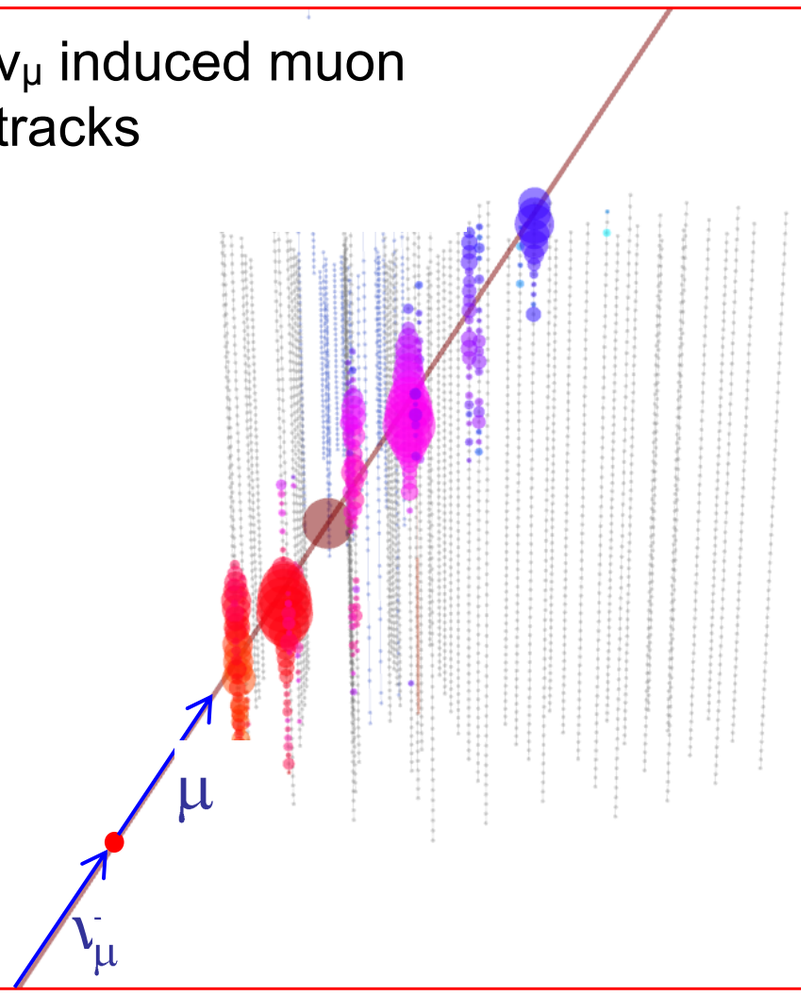
- Completed in December 2010 after 6 years of construction.
- Operational for science in different sub-detector configurations during construction phase (IC-22, IC-40, IC-59, IC-79)

IceCube @ South Pole.

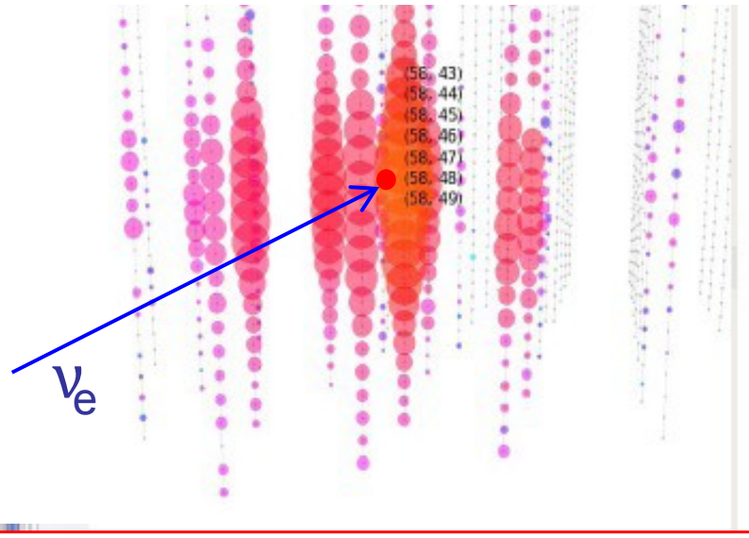


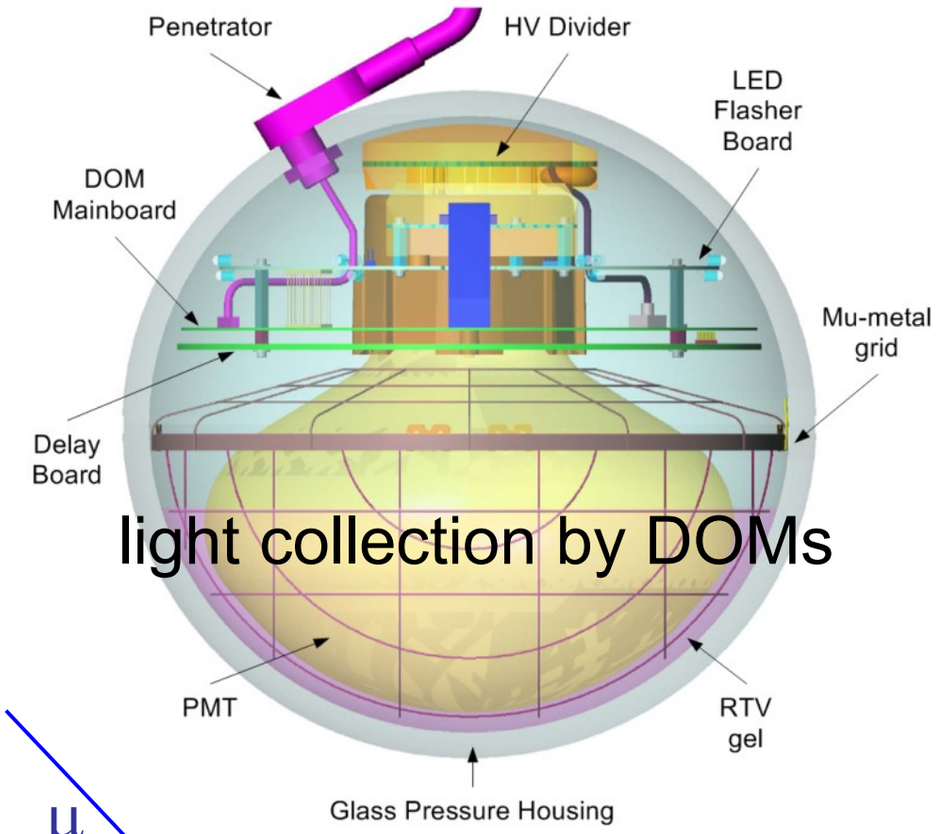
Particle signatures in IceCube.

ν_μ induced muon tracks



shower-type events from all ν flavors (“cascades”)



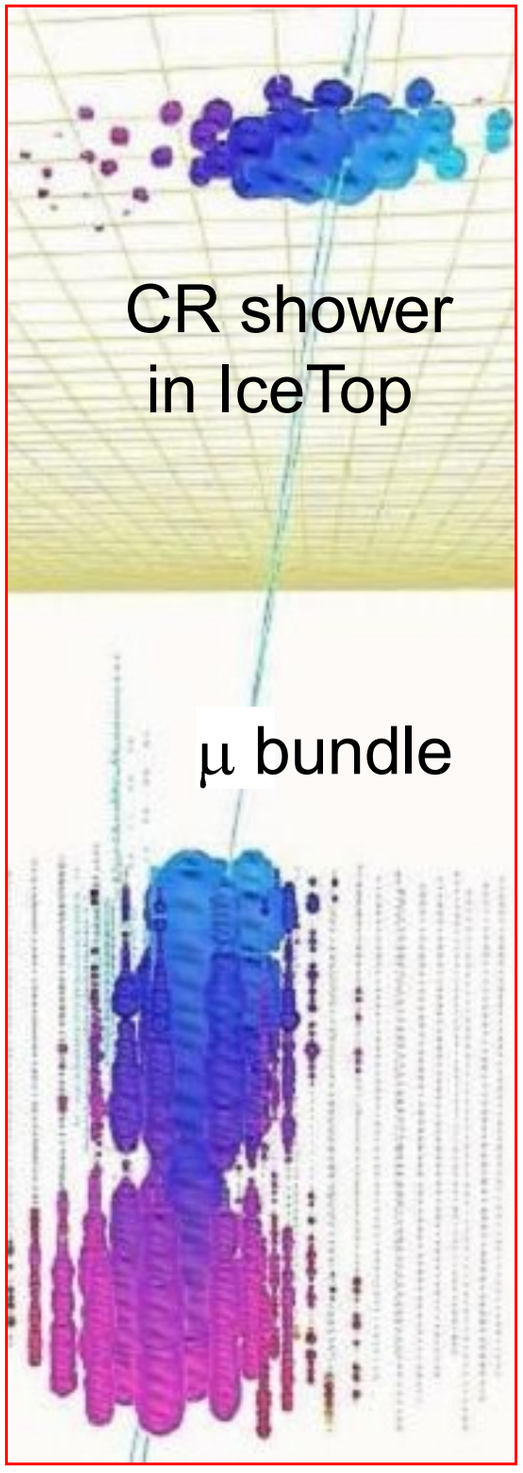


light collection by DOMs

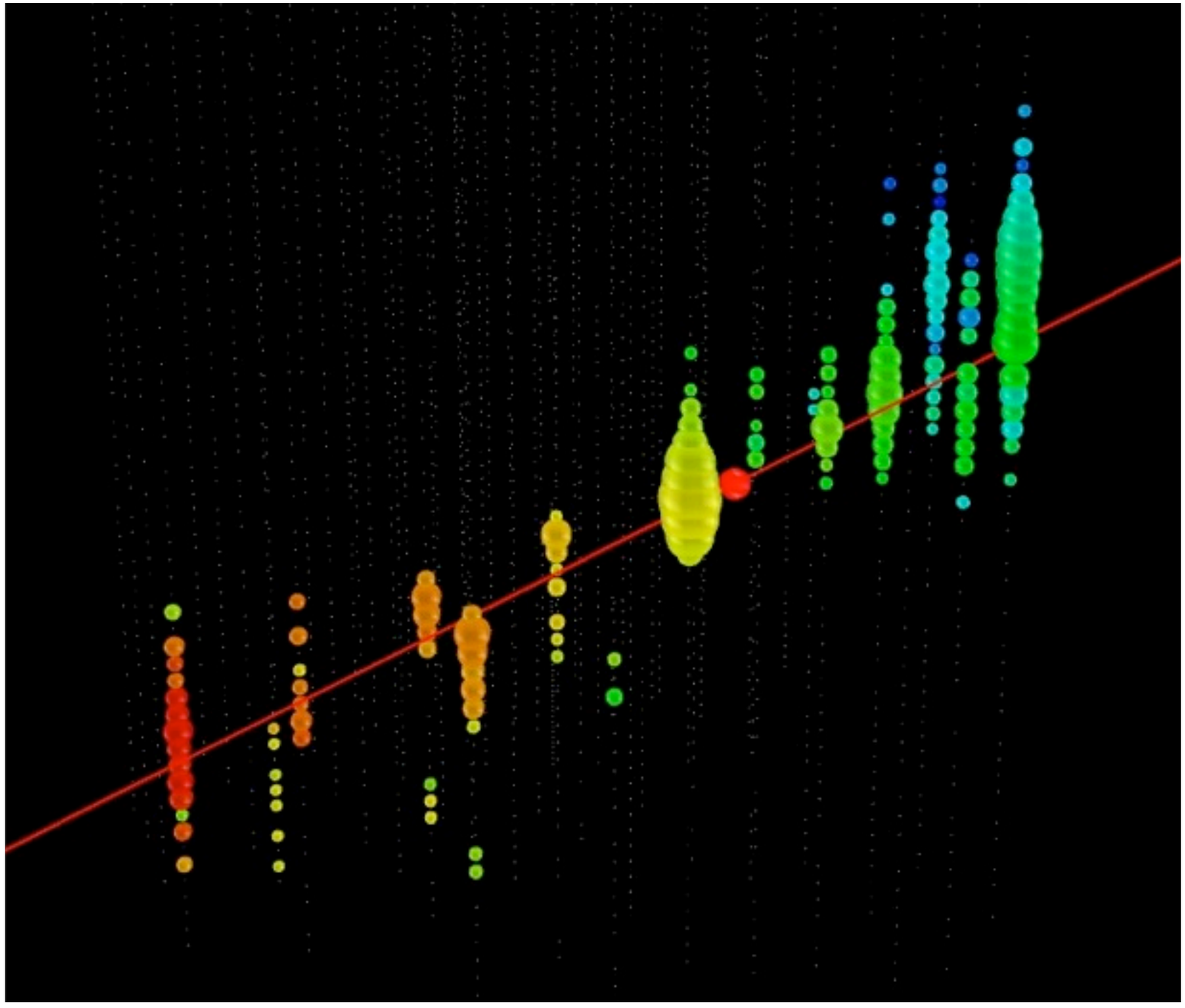
μ

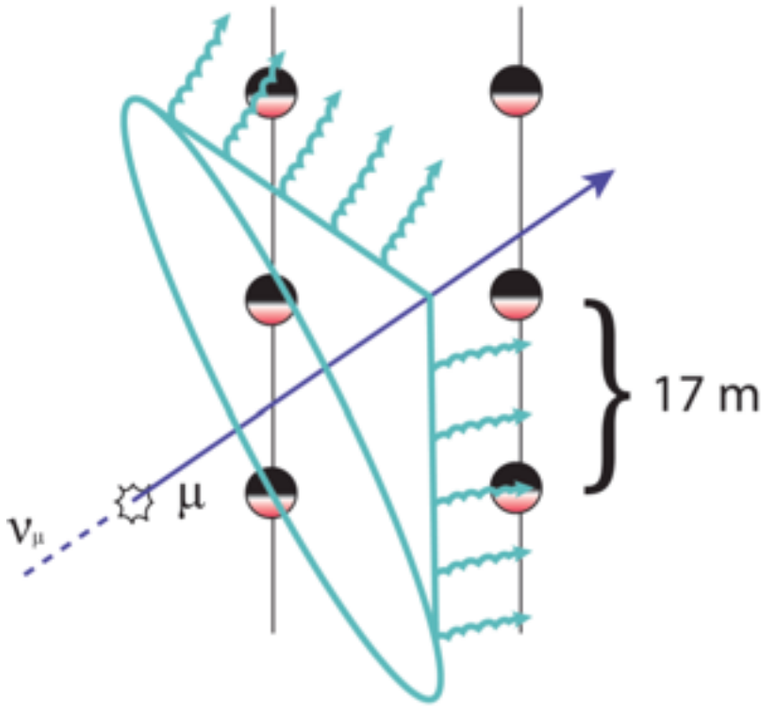
background & physics

CR shower muons



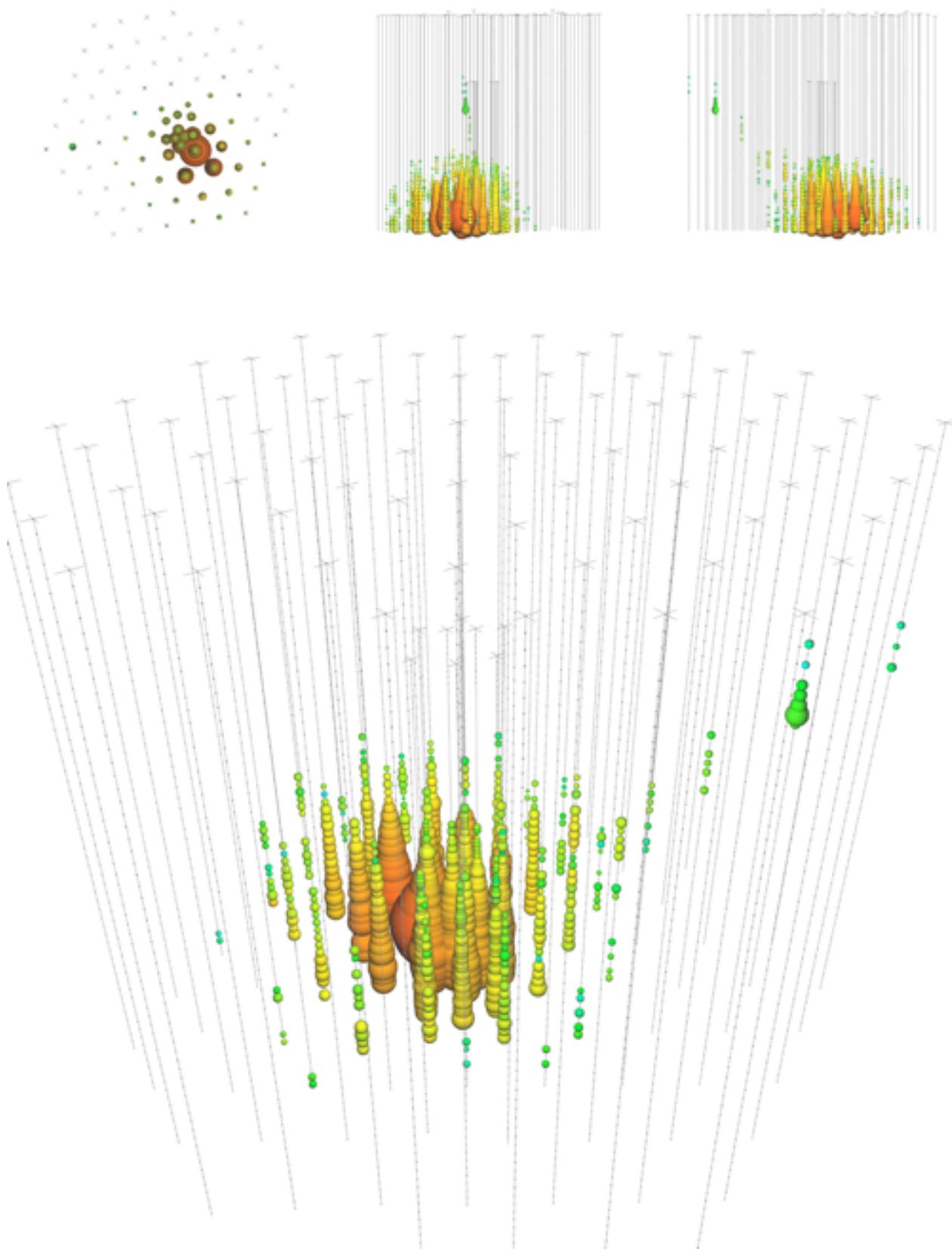
Neutrino induced muon tracks.

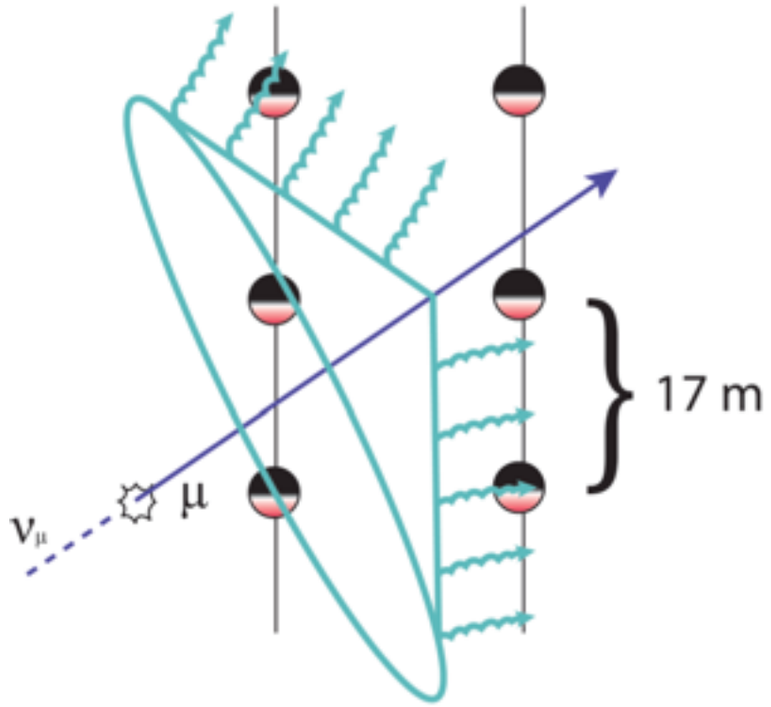




- **Only ν_μ CC** interactions
- Angular resolution: **< 1°**
- Energy measurement: **only dE/dx**
  - μ might have lost significant fraction of energy before entering the detector
- Effective volume **larger** than instrumented volume

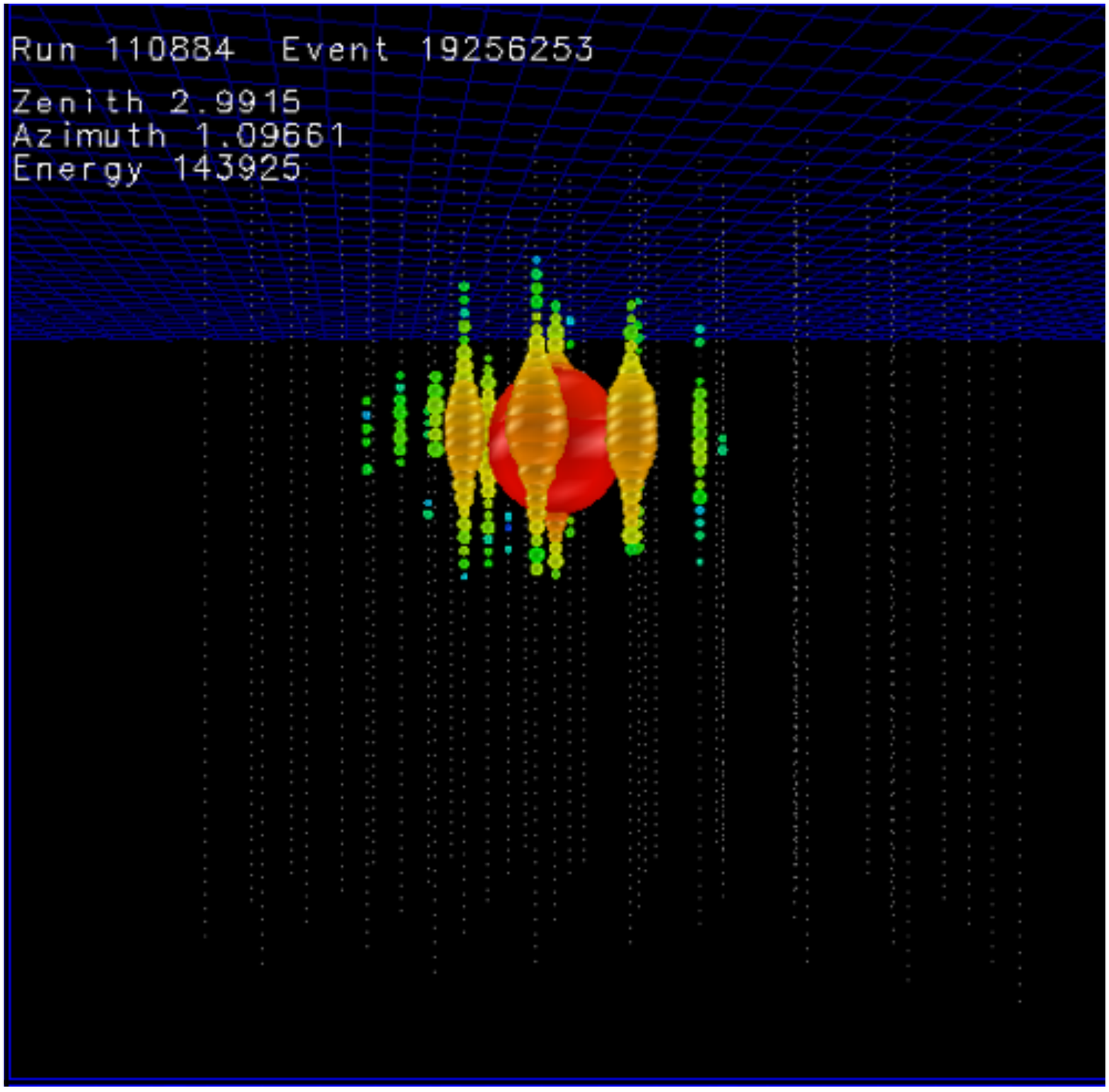
Semi-contained muon events.



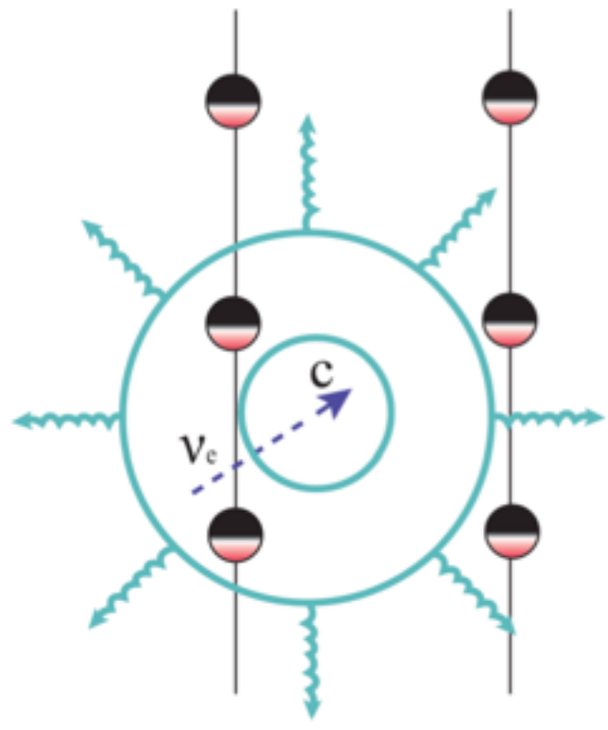


- **Only ν_μ CC** interactions
- Angular resolution: **< 1° - 10°**
- Energy measurement: **deposited energy** from hadronic shower **+ dE/dX** from muon
- Effective volume **smaller** than instrumented volume

Shower-type events.

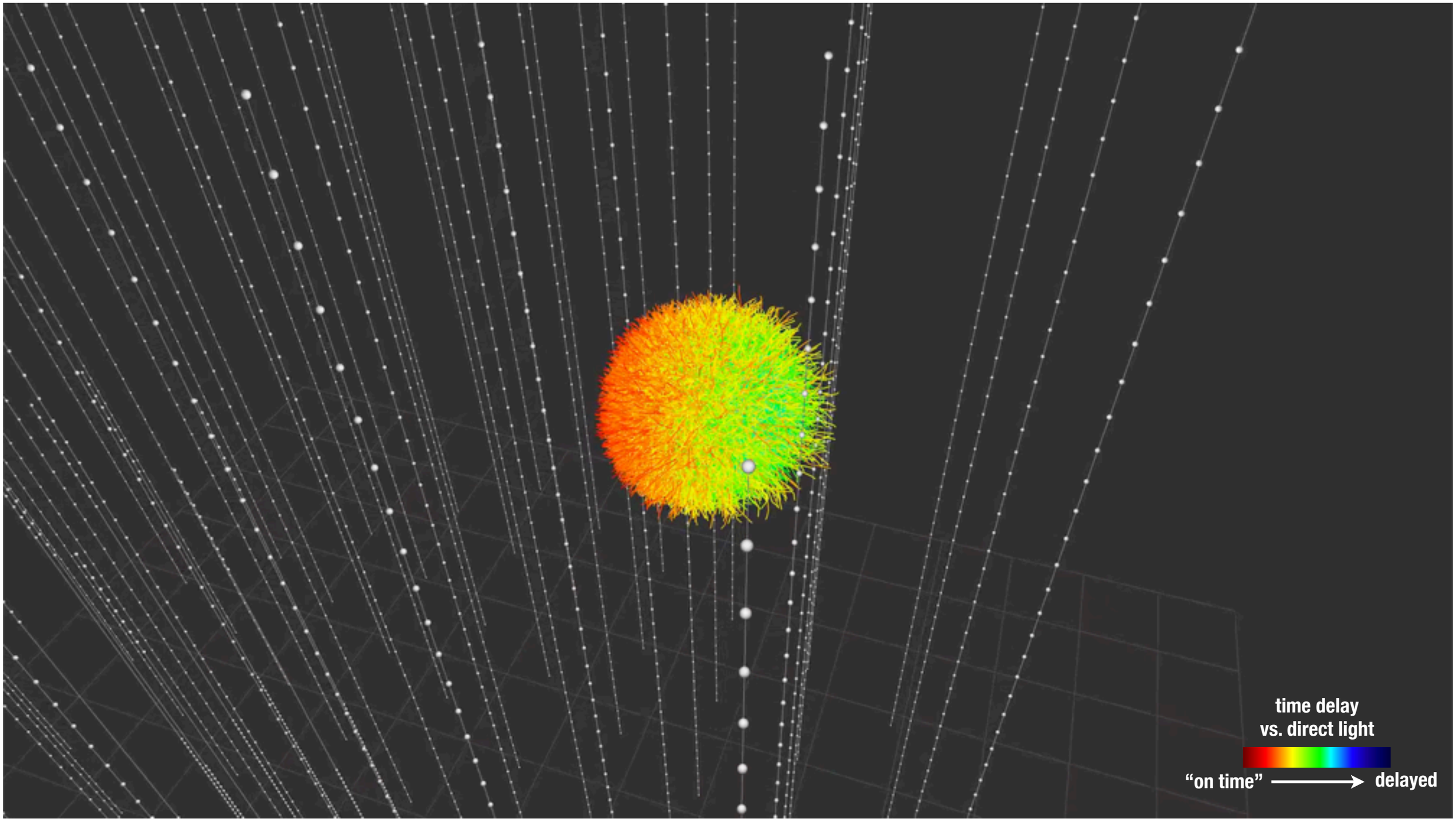


- > ν_e + ν_μ NC + ν_T interactions
- > Angular resolution: >~10˚
- > Energy resolution: 15%
- > Effective volume **smaller** than instrumented volume

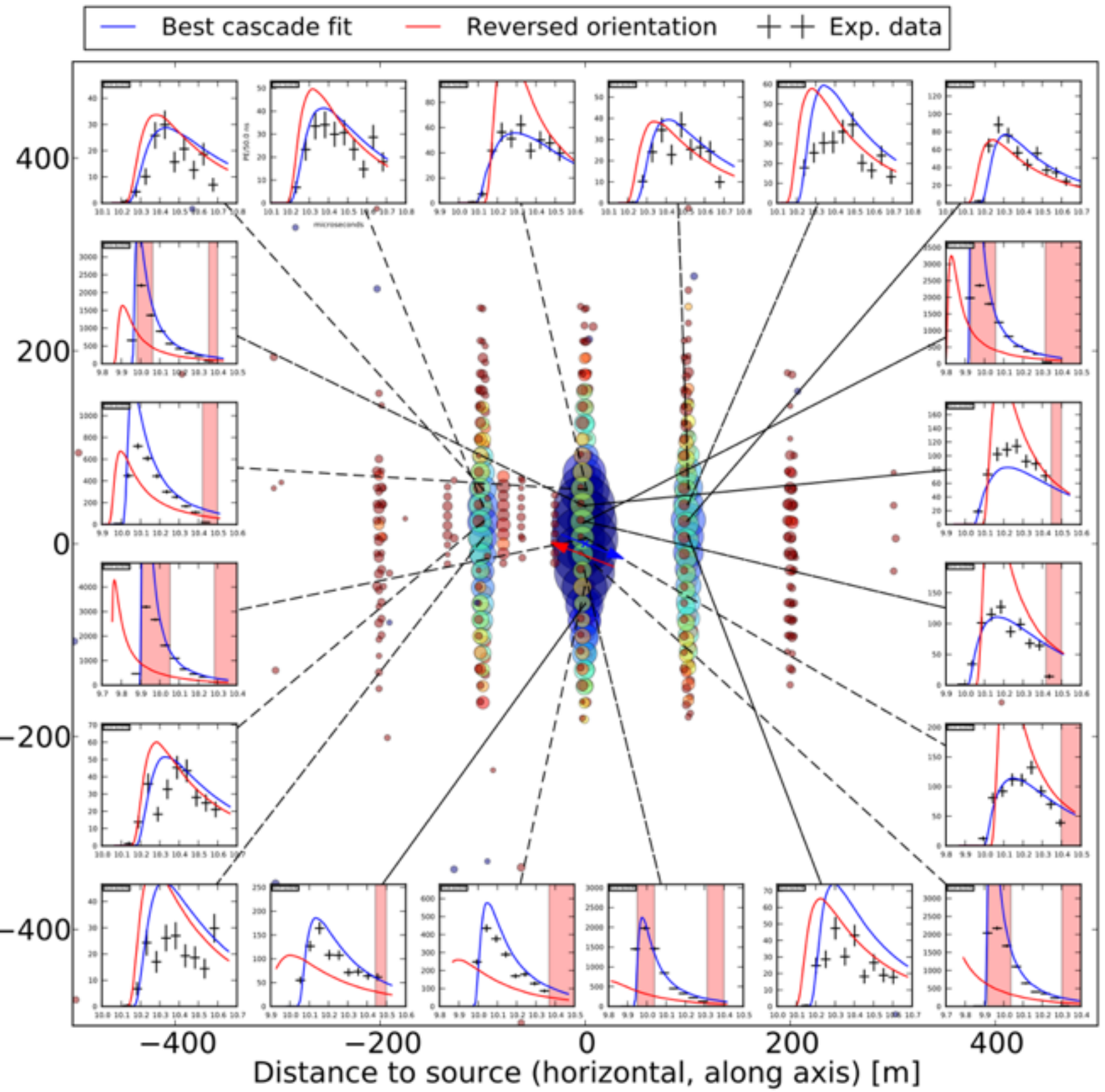


Reconstruction of shower-type events.

Reconstruction of shower-type events.



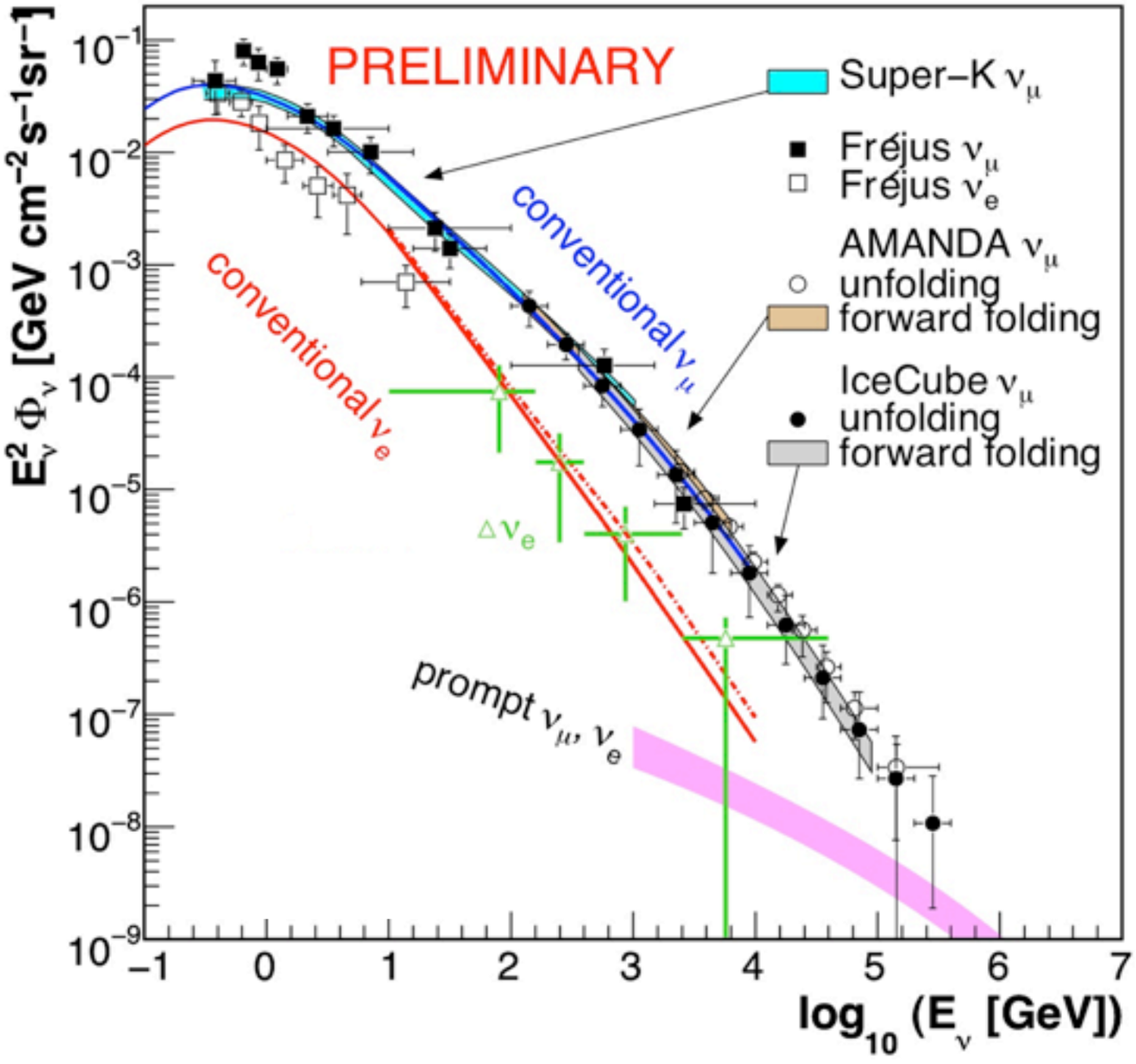
Angular & energy resolution for shower-type events.

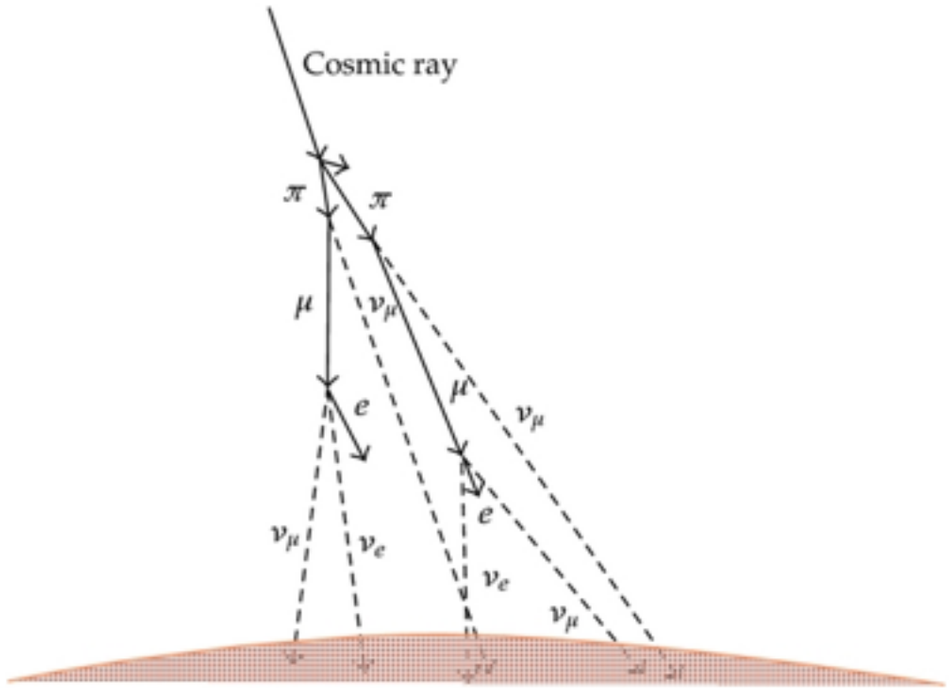


- Full likelihood reconstruction of observed waveforms.
- ~15% energy resolution.
- ≈ 10° angular resolution.
- Calibrated by artificial light sources and CR air shower muons.

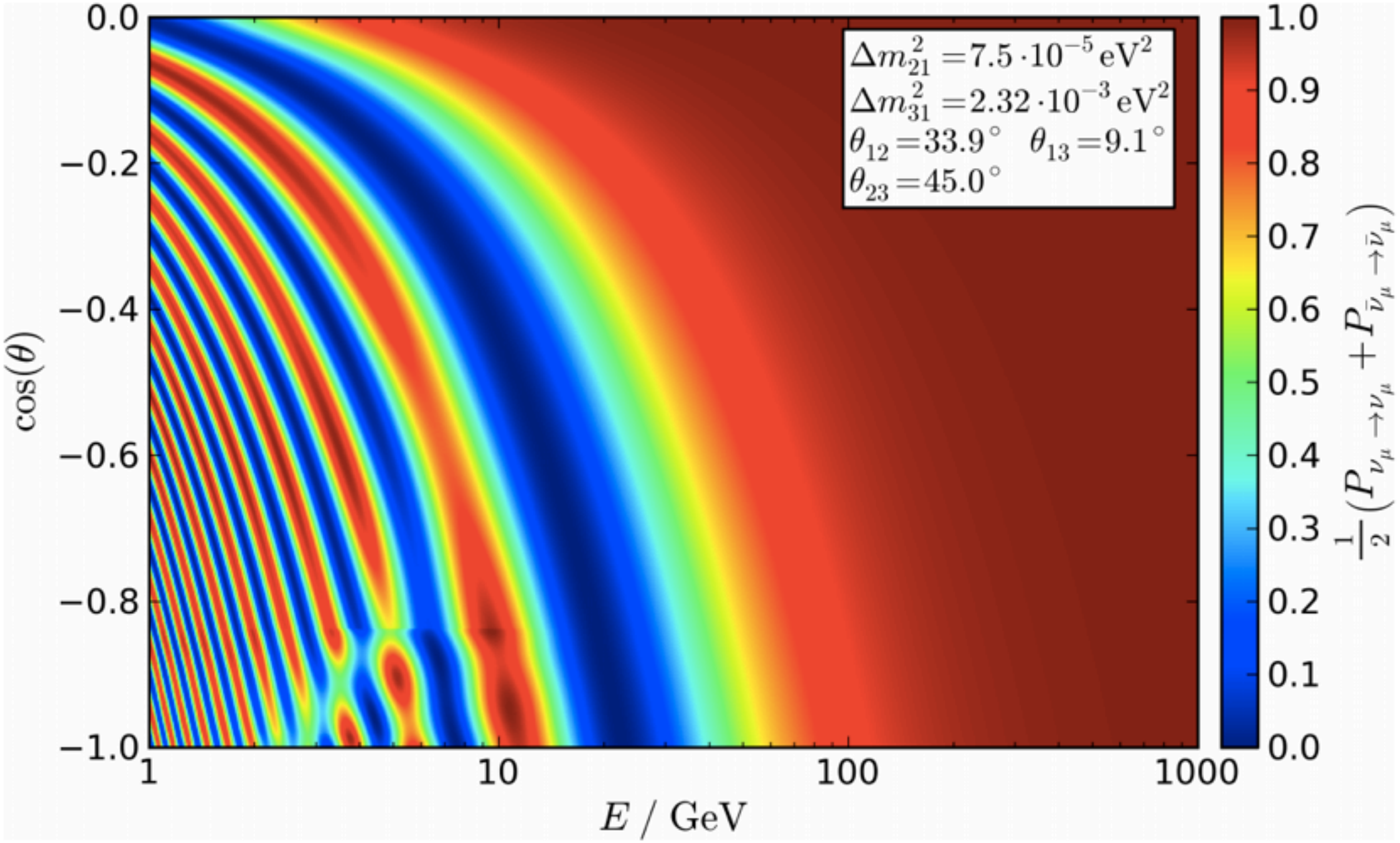
The atmospheric neutrino background.

- Most neutrinos detected in IceCube are of atmospheric origin.
- Atmospheric neutrinos are produced in CR air shower interactions.
- ν_e atmospheric neutrino flux ≪ ν_μ flux





Neutrino oscillations.

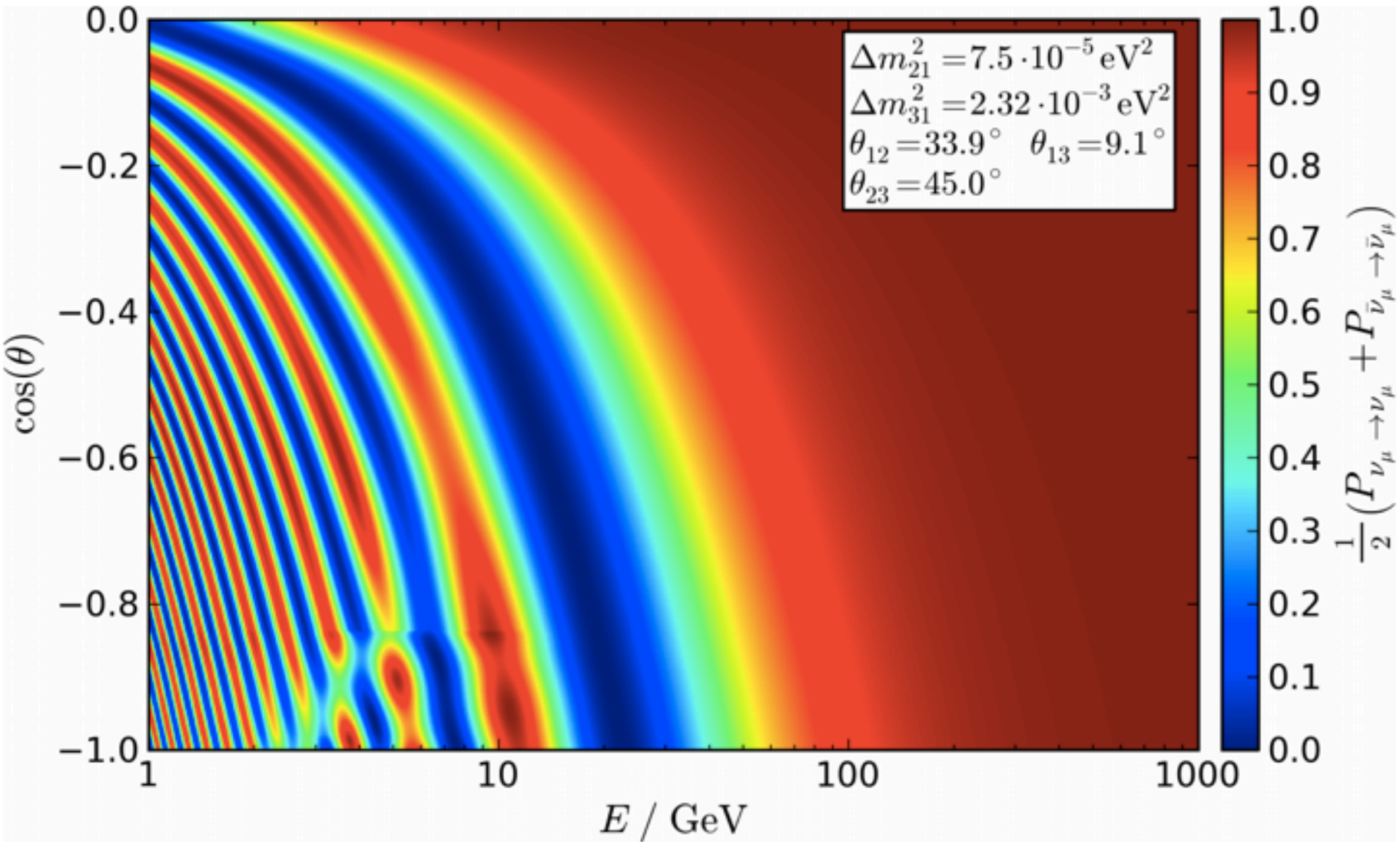


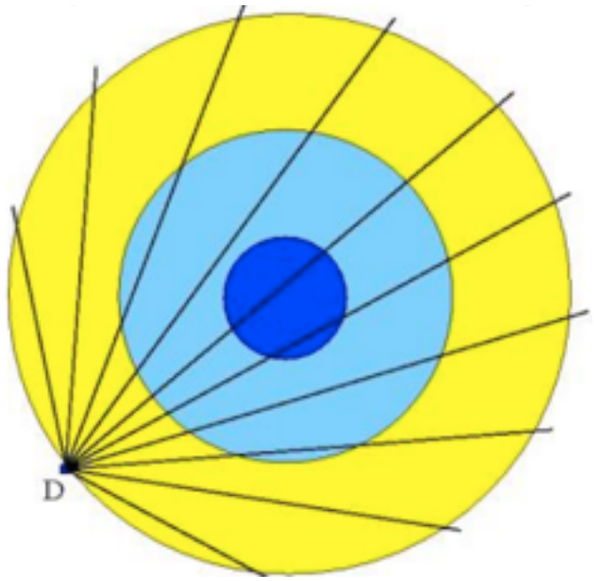
Neutrino oscillation parameters with IceCube.

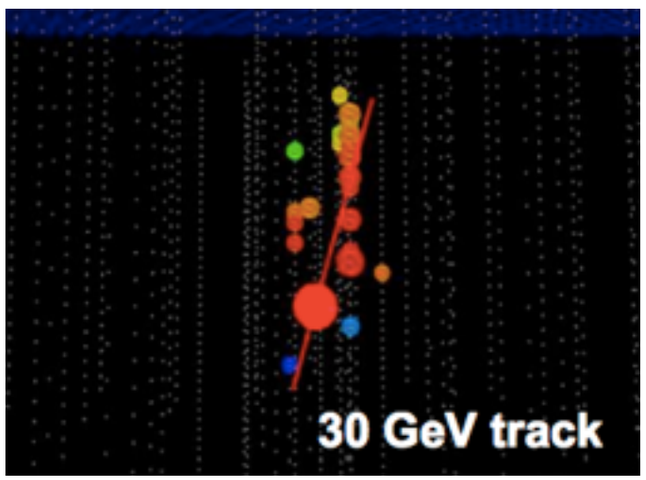
- Disappearance of atmospheric muon neutrinos due to flavor oscillations
- Maximum disappearance probability for vertical events around 25 GeV

- Disappearance probability (2-flavor formalism):

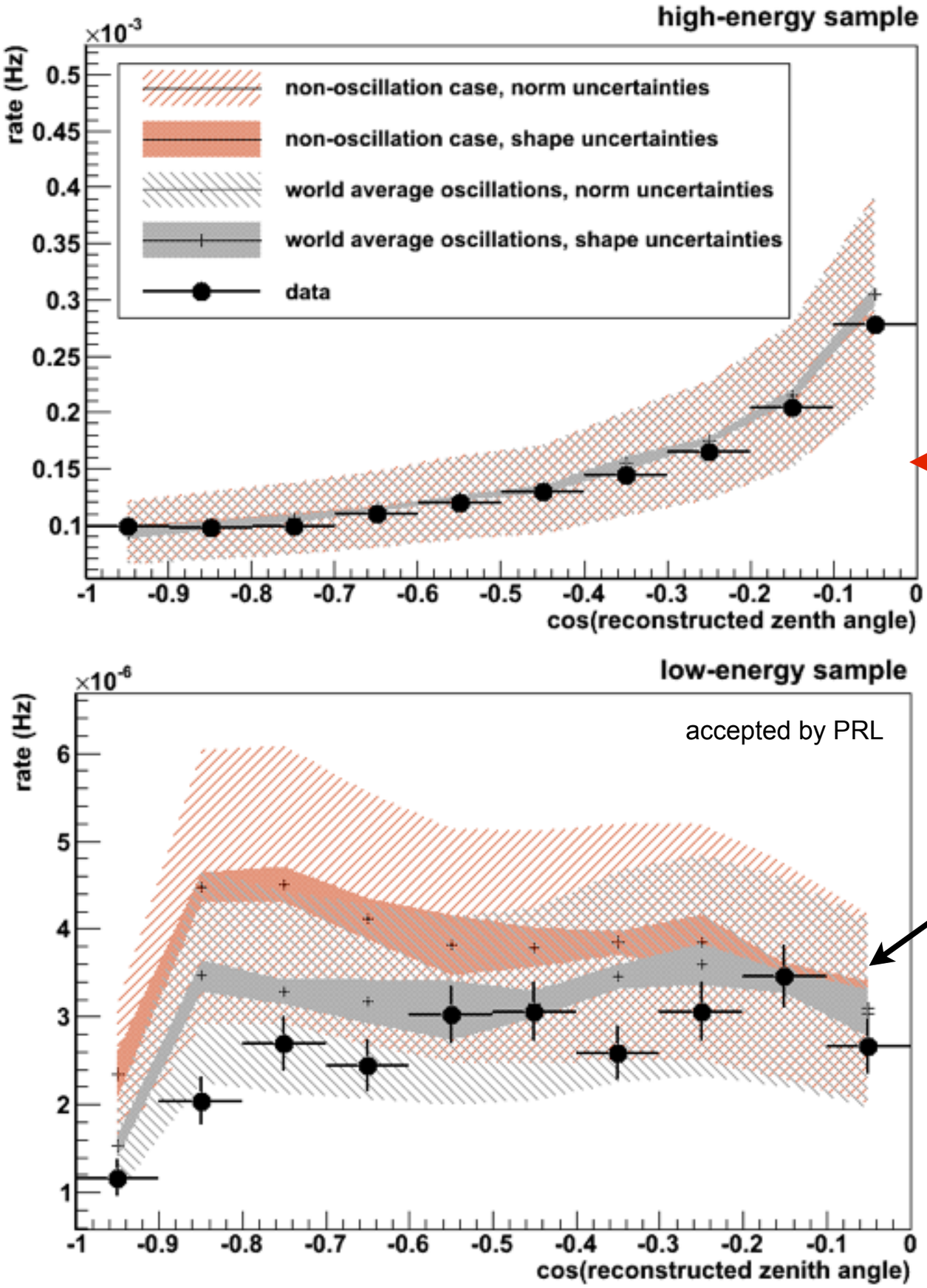
$$P\left(\nu_\mu \to \nu_\mu\right) = 1 - \sin^2\left(2\theta_{23}\right)\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right)$$





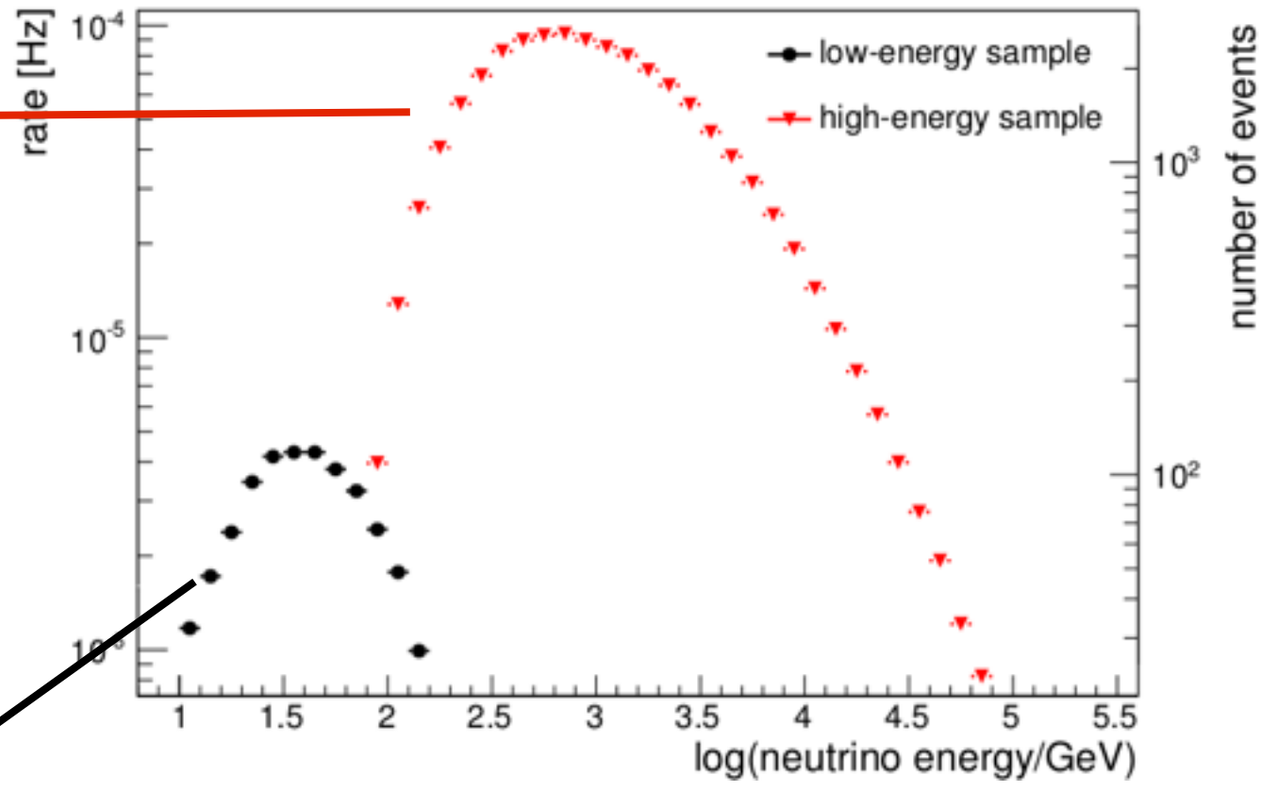


Neutrino oscillations with IceCube/DeepCore.



> First analysis of neutrino oscillation using standard IceCube reconstruction techniques.

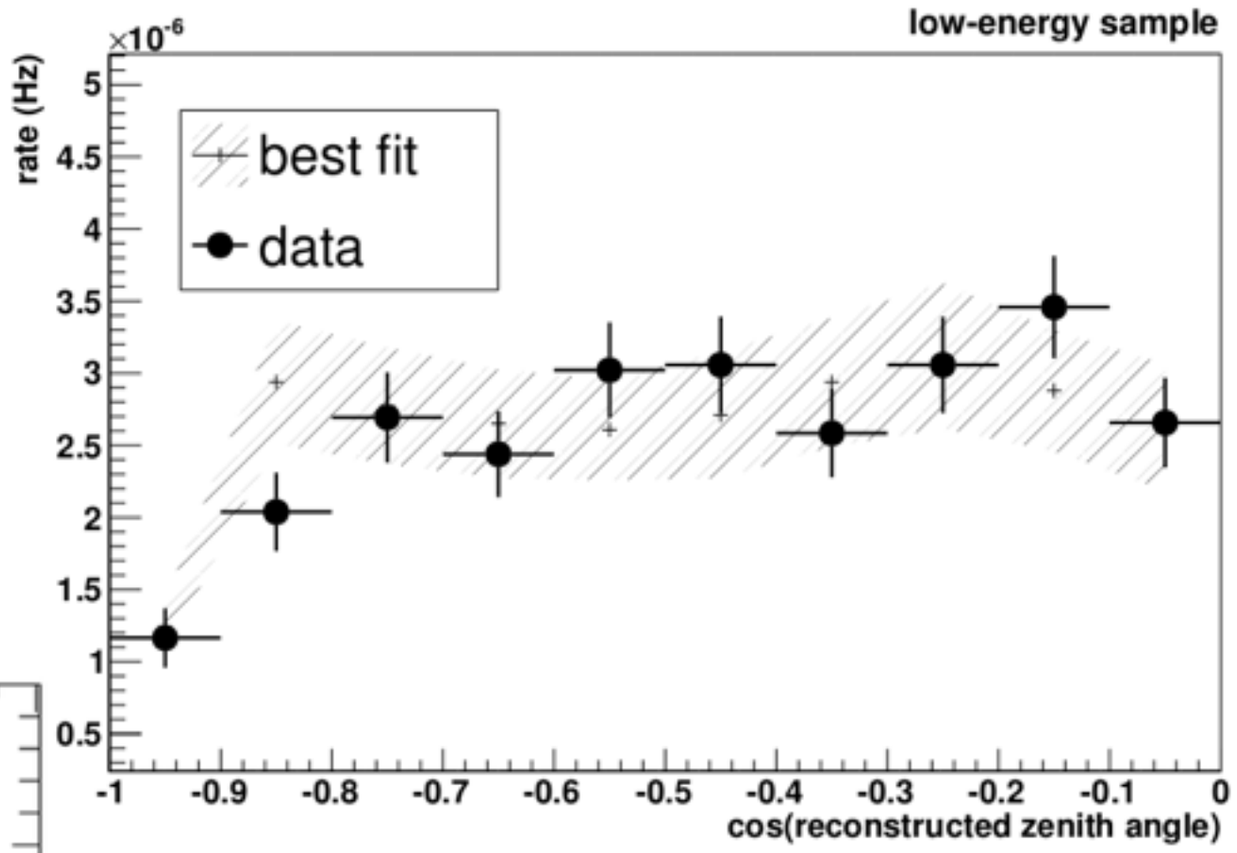
> IC-79 dataset (6 out of 8 DeepCore strings.

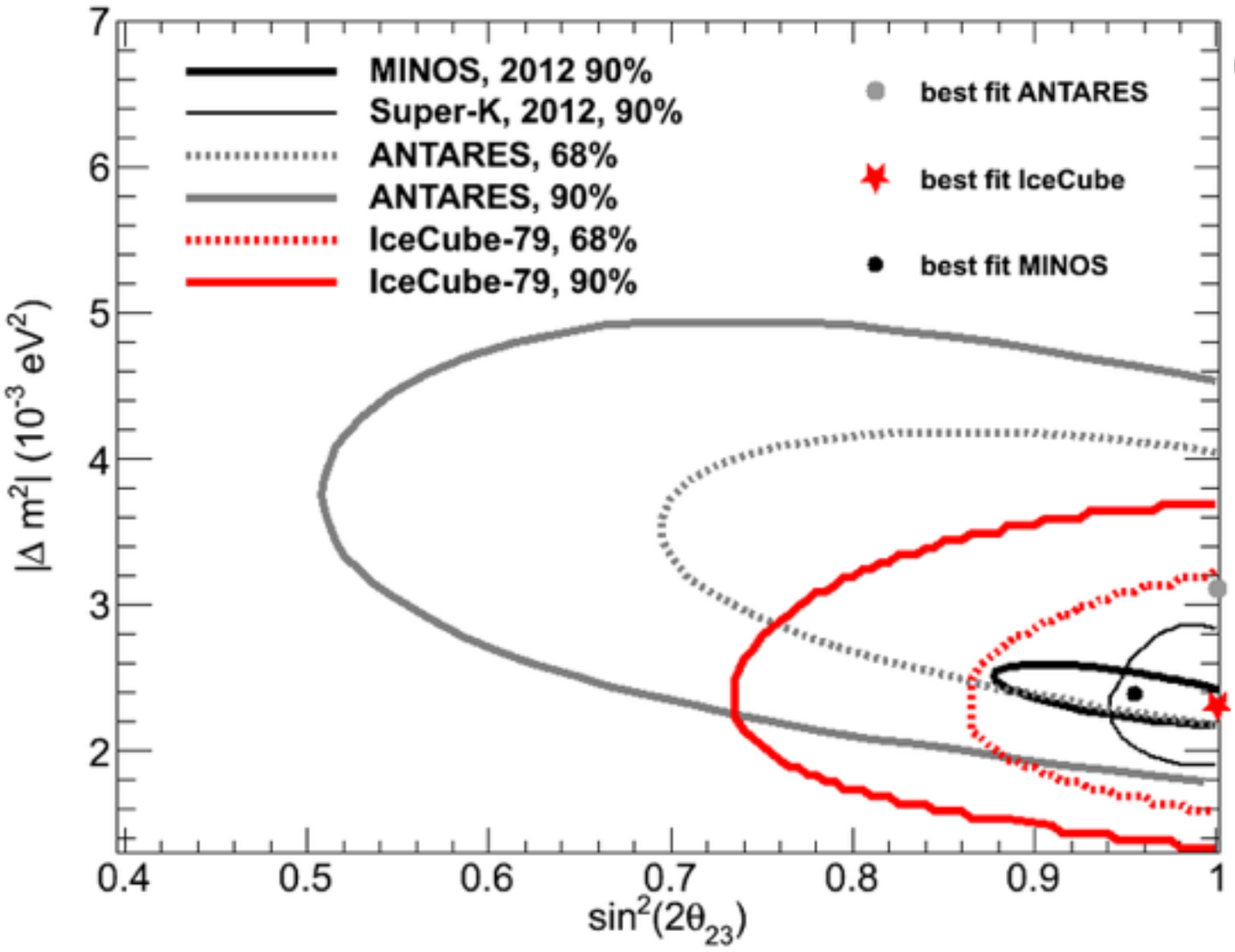


> Combined fit of a low-energy and a high-energy event sample to constrain systematic uncertainties.

Neutrino oscillations with IceCube/DeepCore.

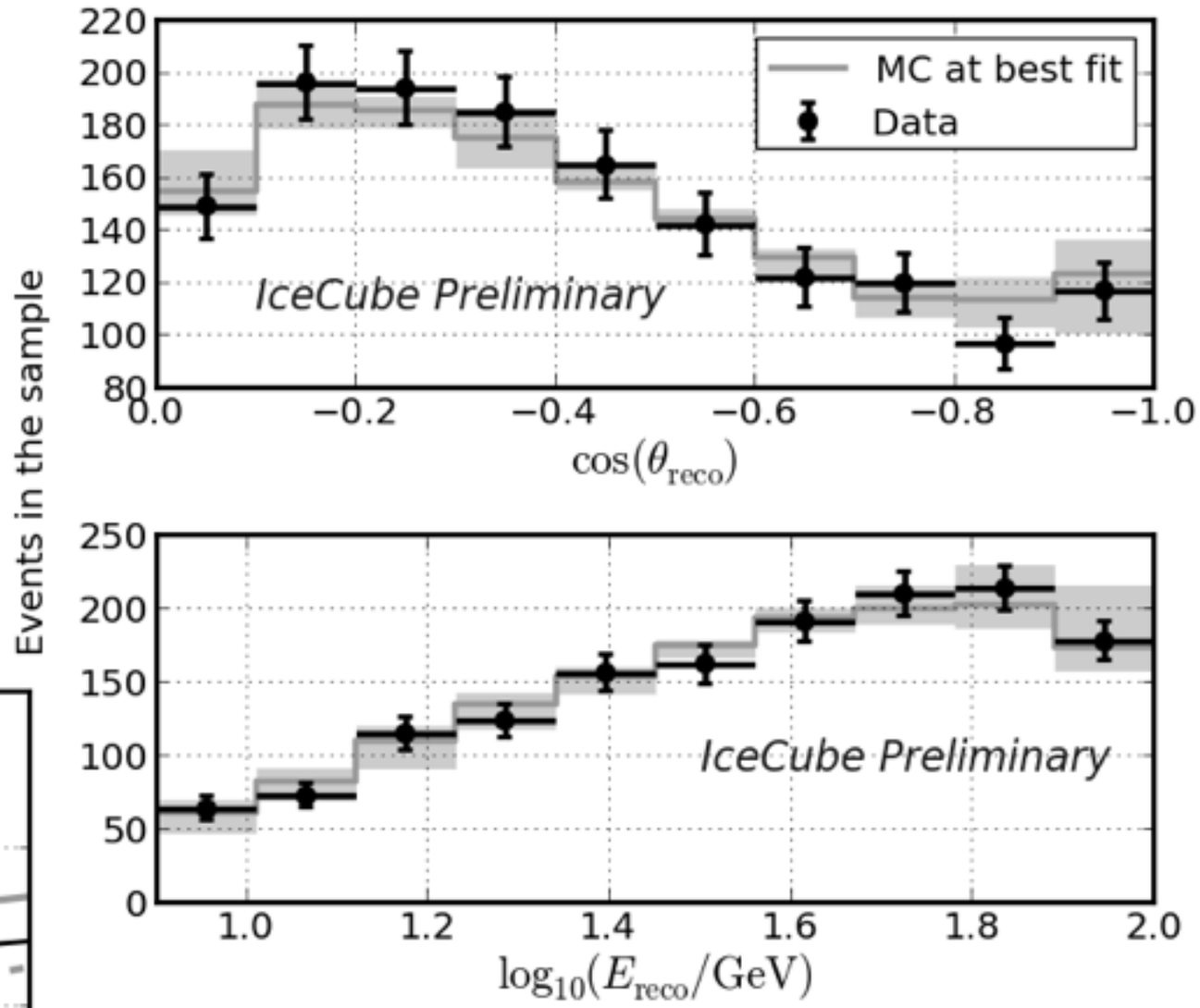
- No-oscillation scenario excluded at > 5σ level
- Constraints on the oscillation parameters in agreement with world average.

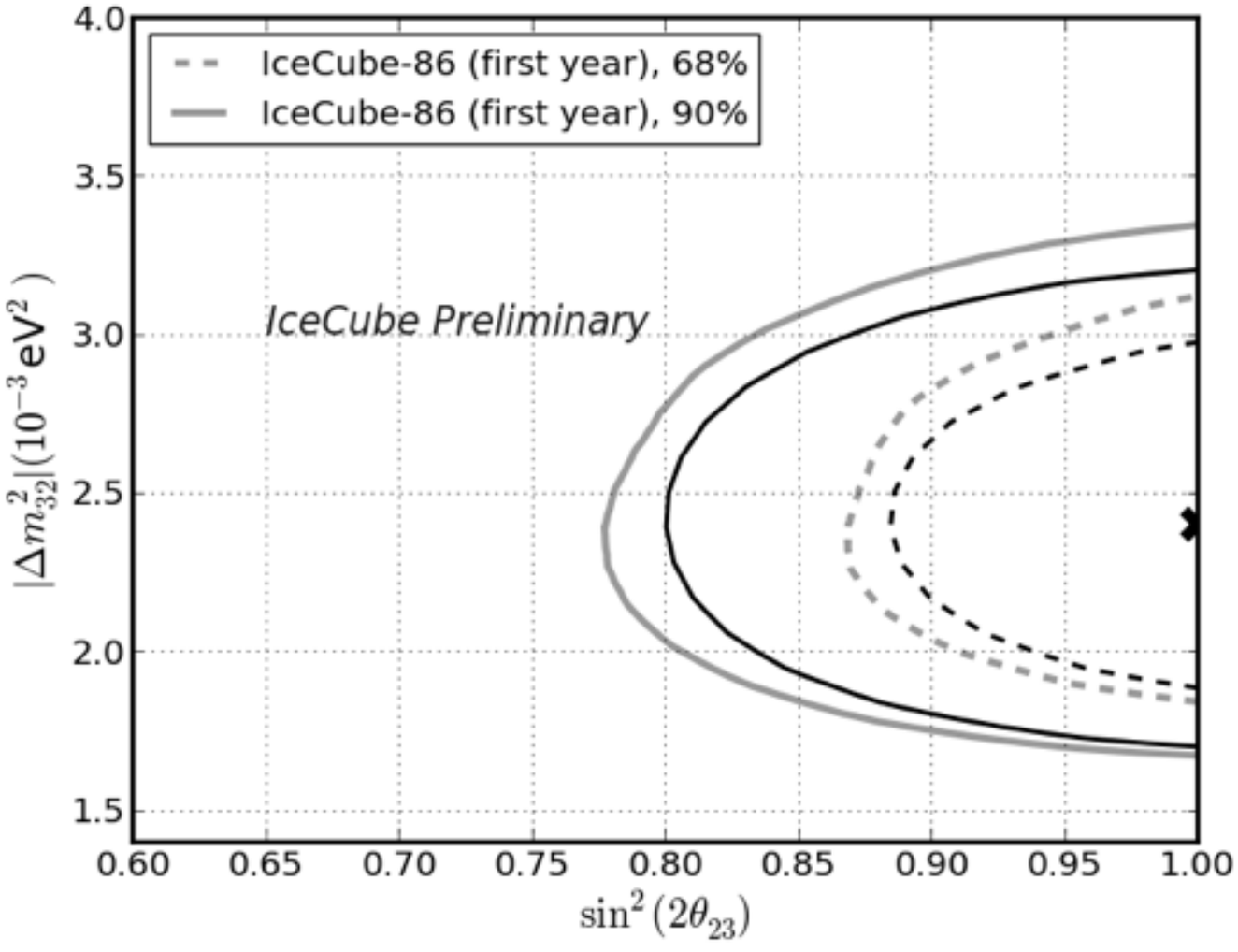




Neutrino oscillations with IceCube/DeepCore.

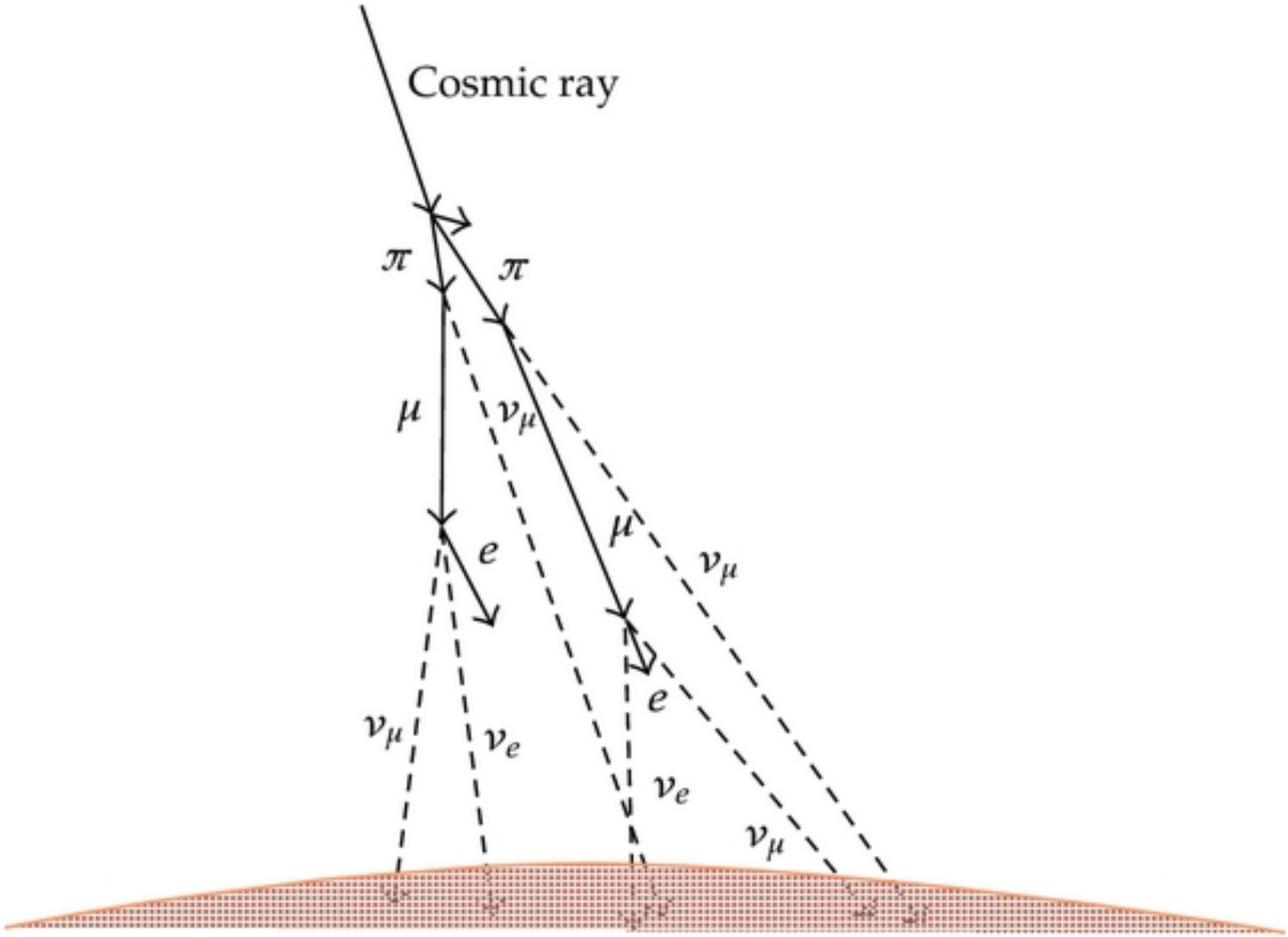
- Dedicated reconstruction algorithm for low-energy events.
- 2-d likelihood fit of reconstructed energy and zenith angle to determine oscillation parameters.
- First year of IC-86 dataset (2 additional DeepCore strings)

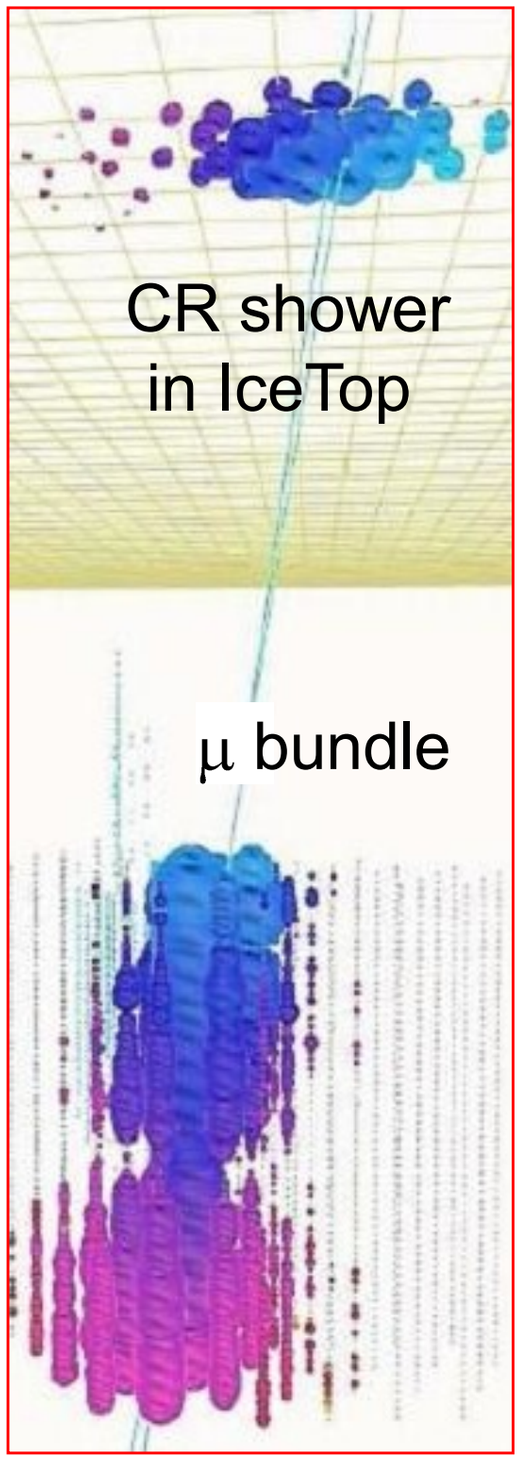




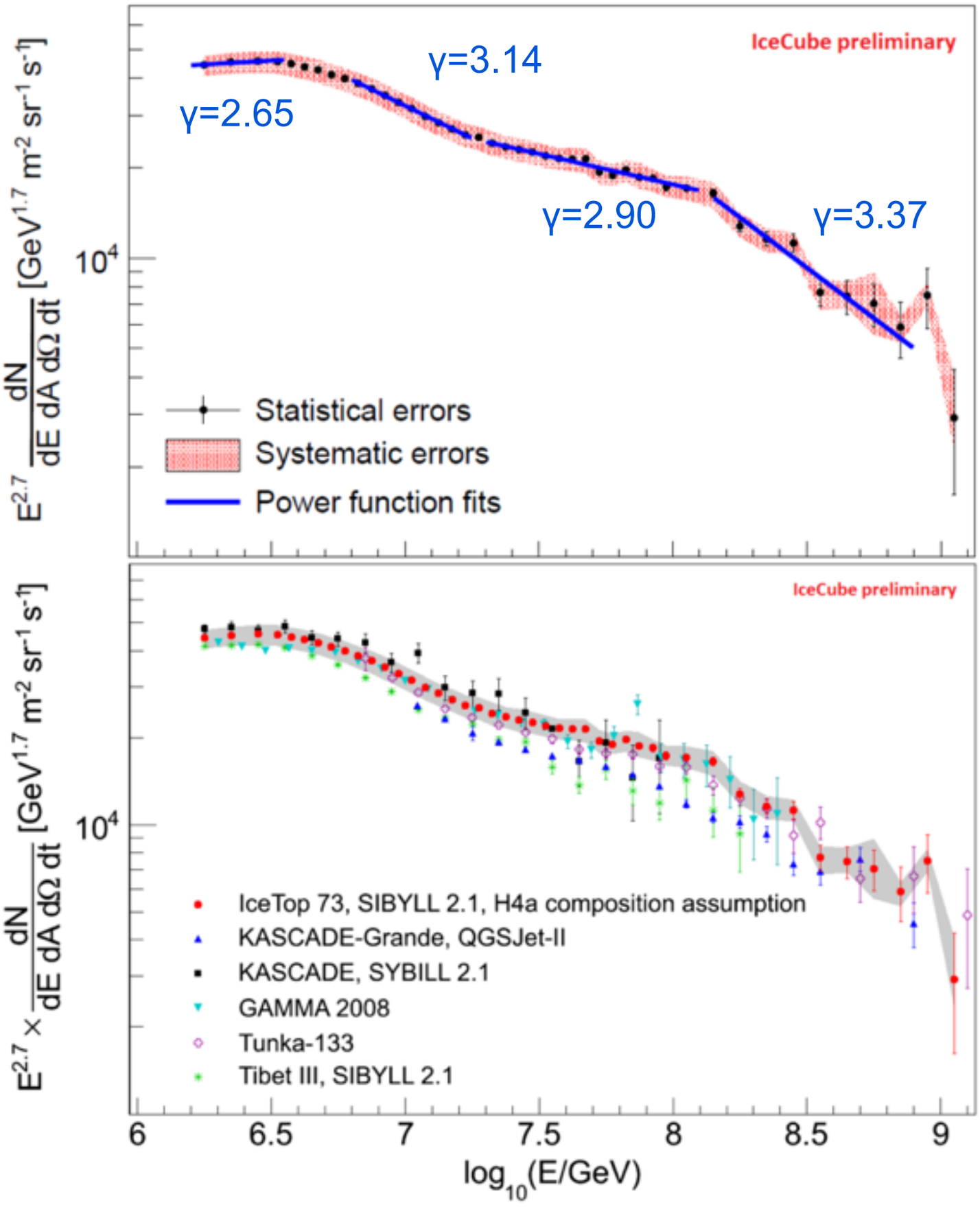
- Tighter constraints on oscillation parameters, to be updated with a larger dataset.

The spectrum and anisotropy of cosmic rays.



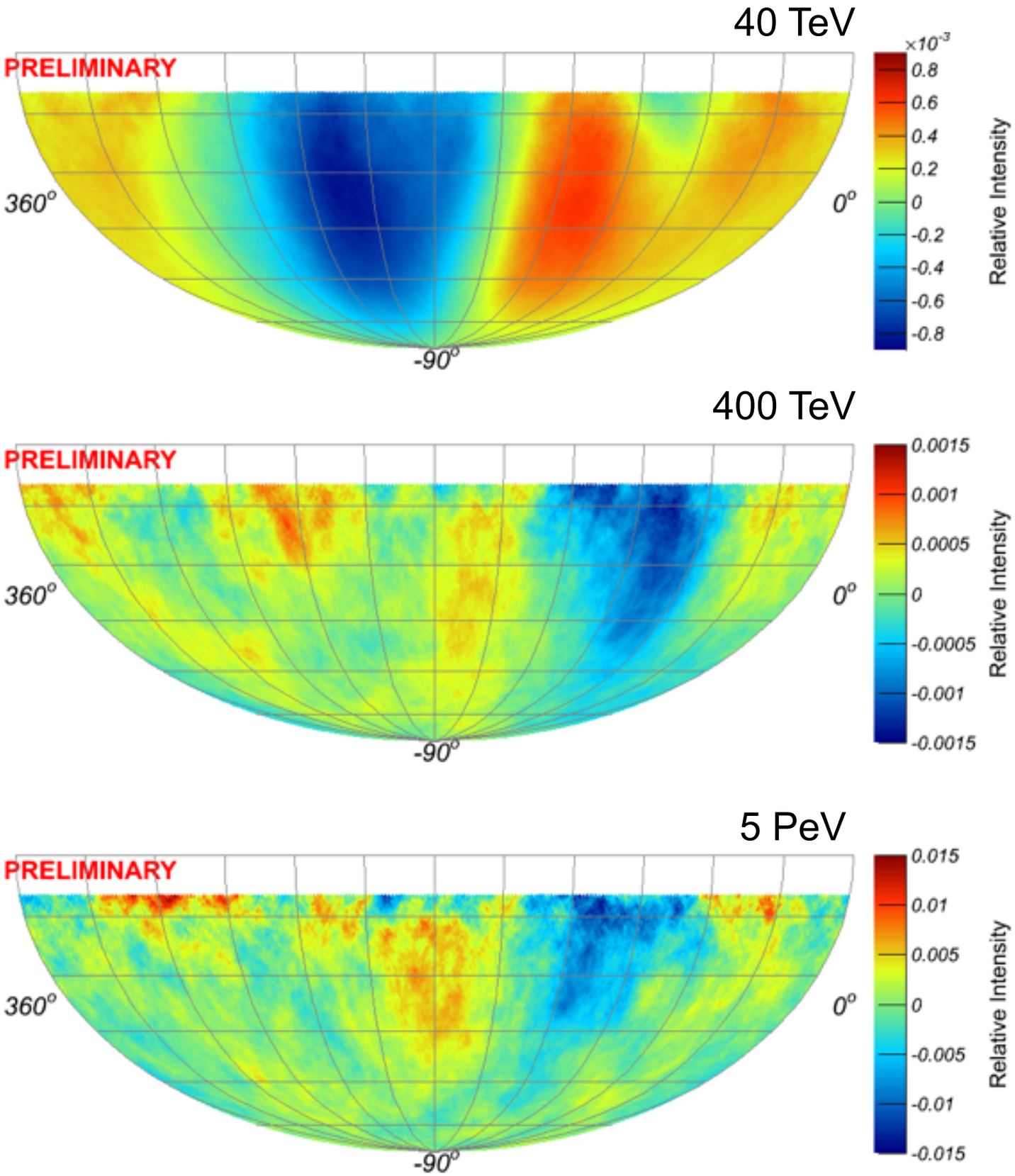


The CR spectrum measured with IceCube.

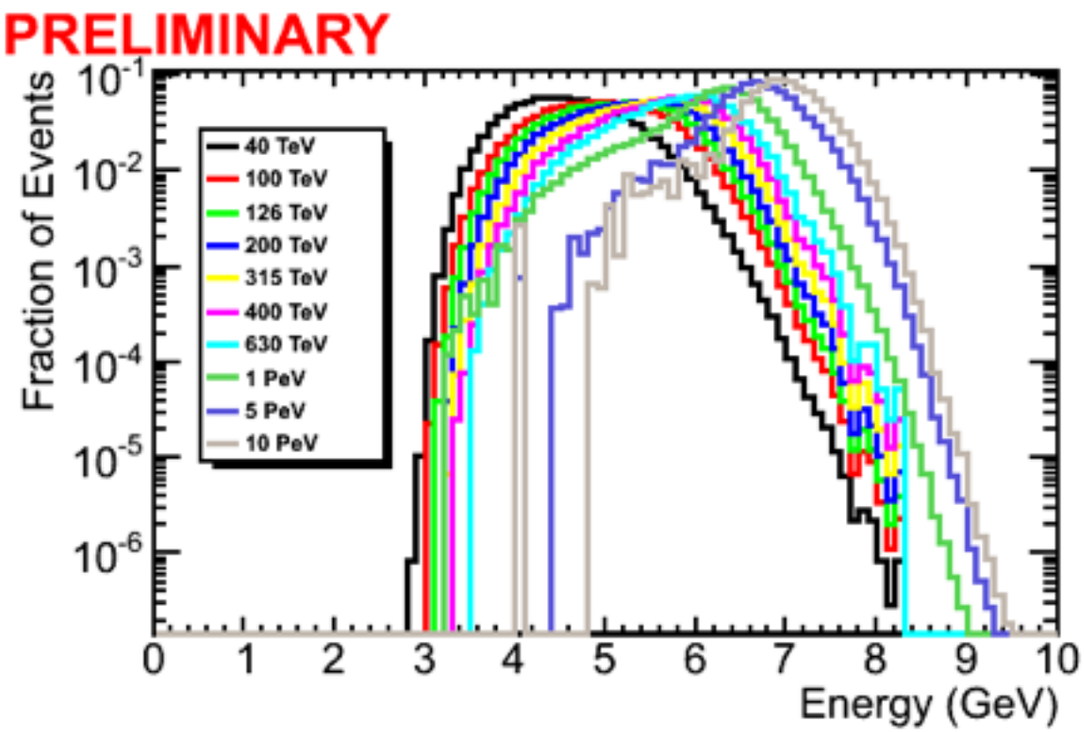


- Spectrum of CR between 1 PeV and 1 EeV measured with high precision with 73 IceTop station.
- Clear evidence for several changes in the spectral index in this range.
- Improved systematics than in previous years, new underlying composition model.
- Combined spectrum/ composition study using IceTop and IceCube data together on same data set soon.

The anisotropy of the cosmic rays.

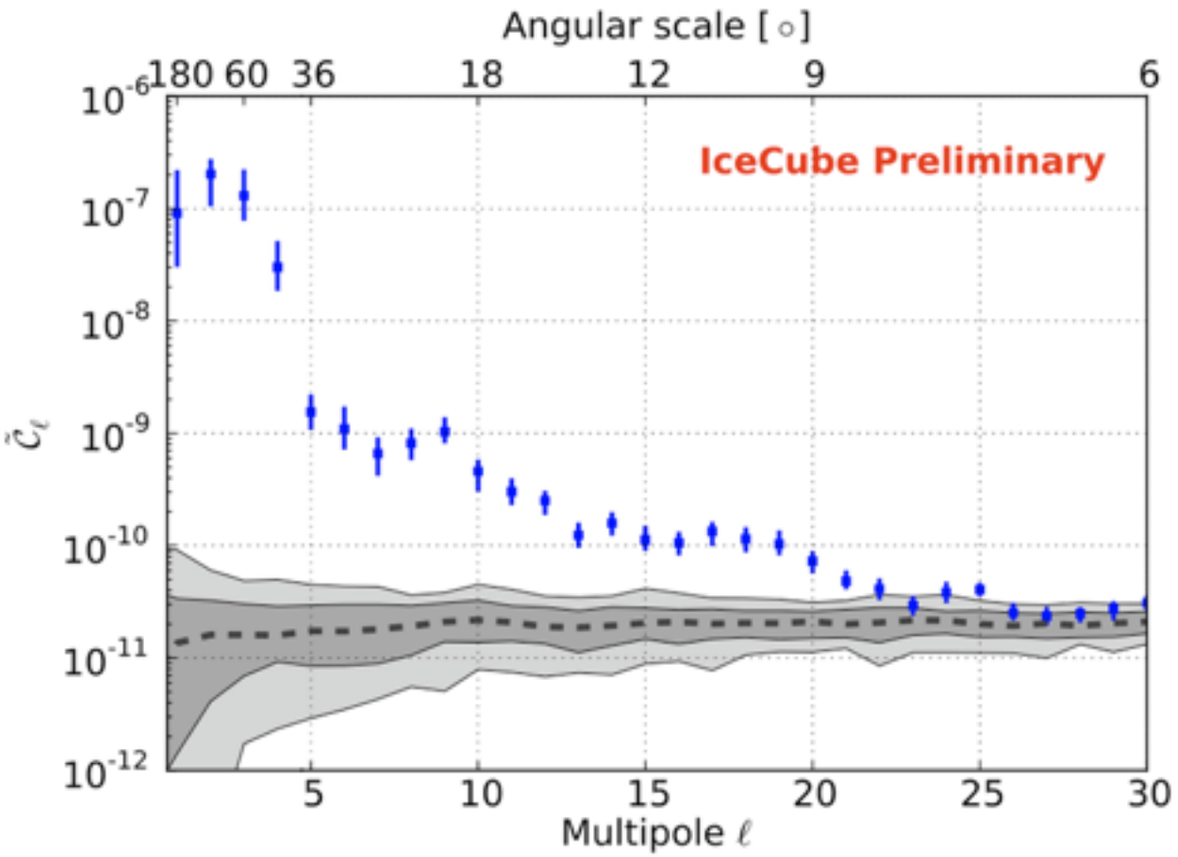


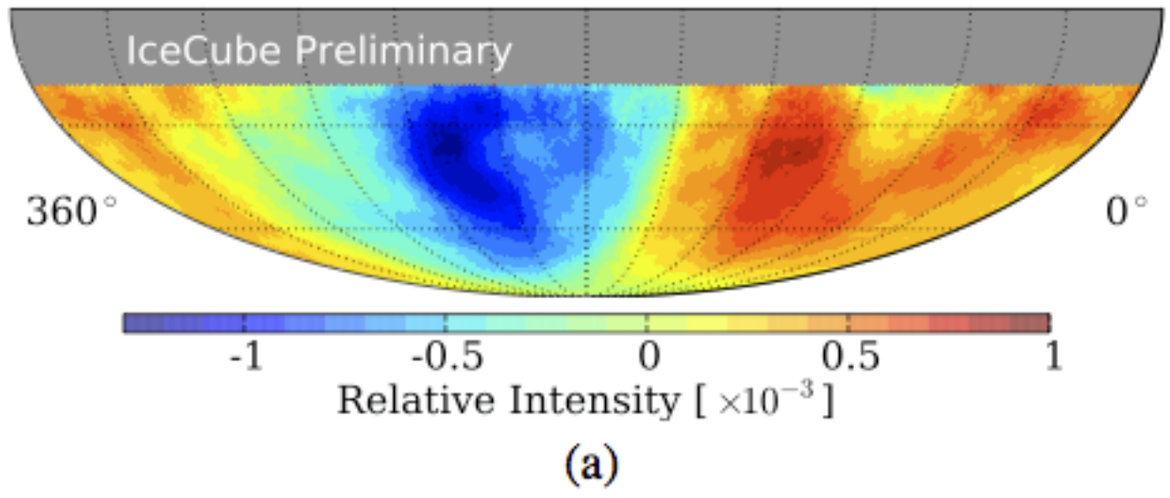
- First measurement on the anisotropy on the southern hemisphere.
- Measured between 20 TeV and 10 PeV with 4 years of IceCube data.



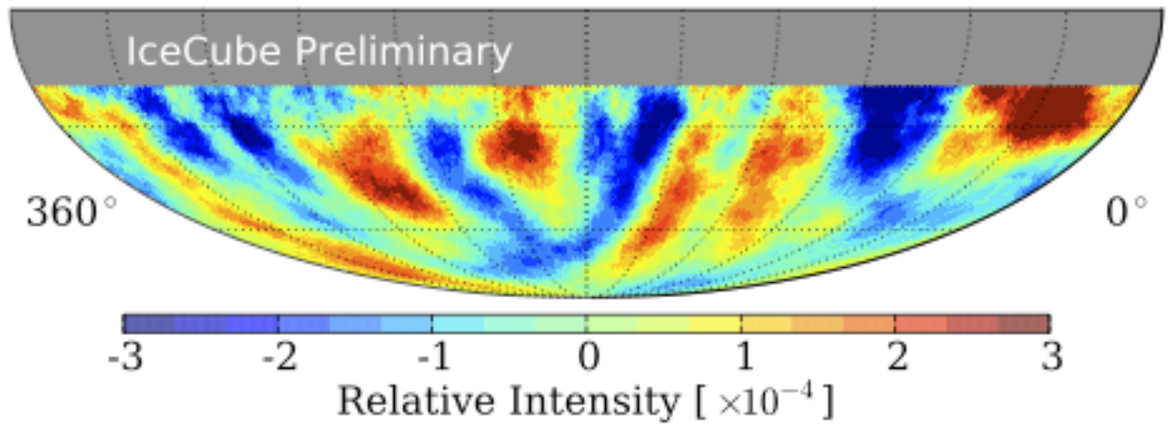
- Amplitude increases with energy, phase shifts.
- Origin still unclear.

Small scale anisotropy.

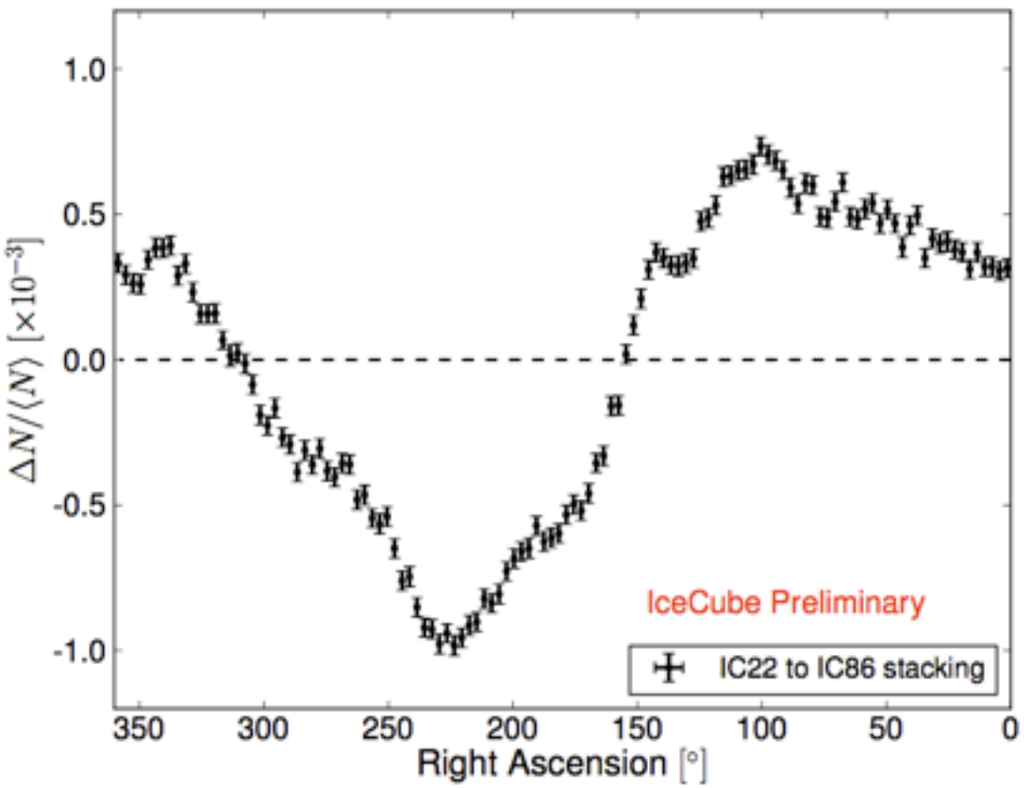




(a)

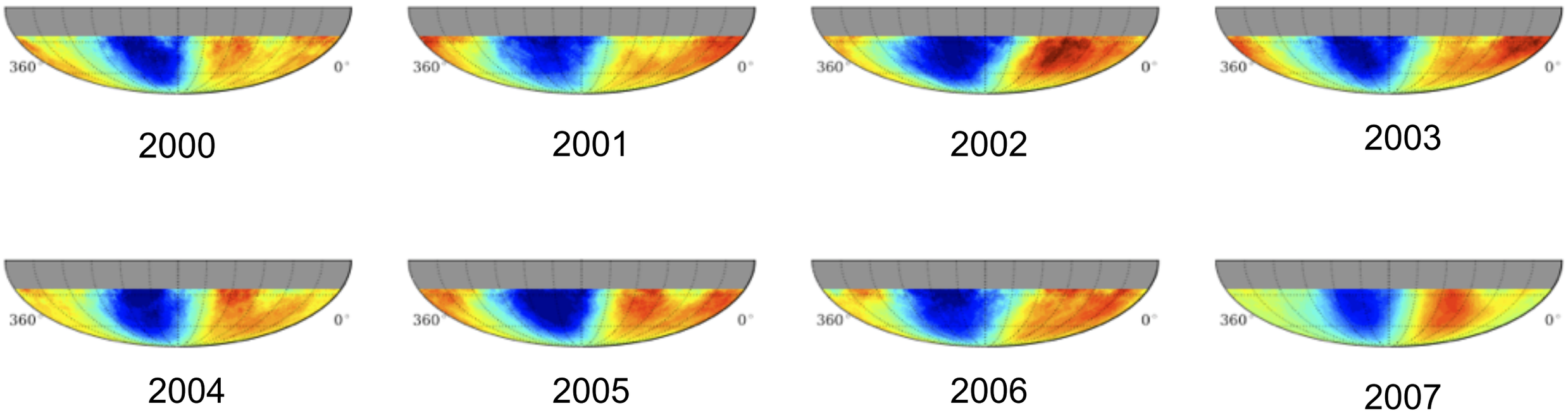


(c)



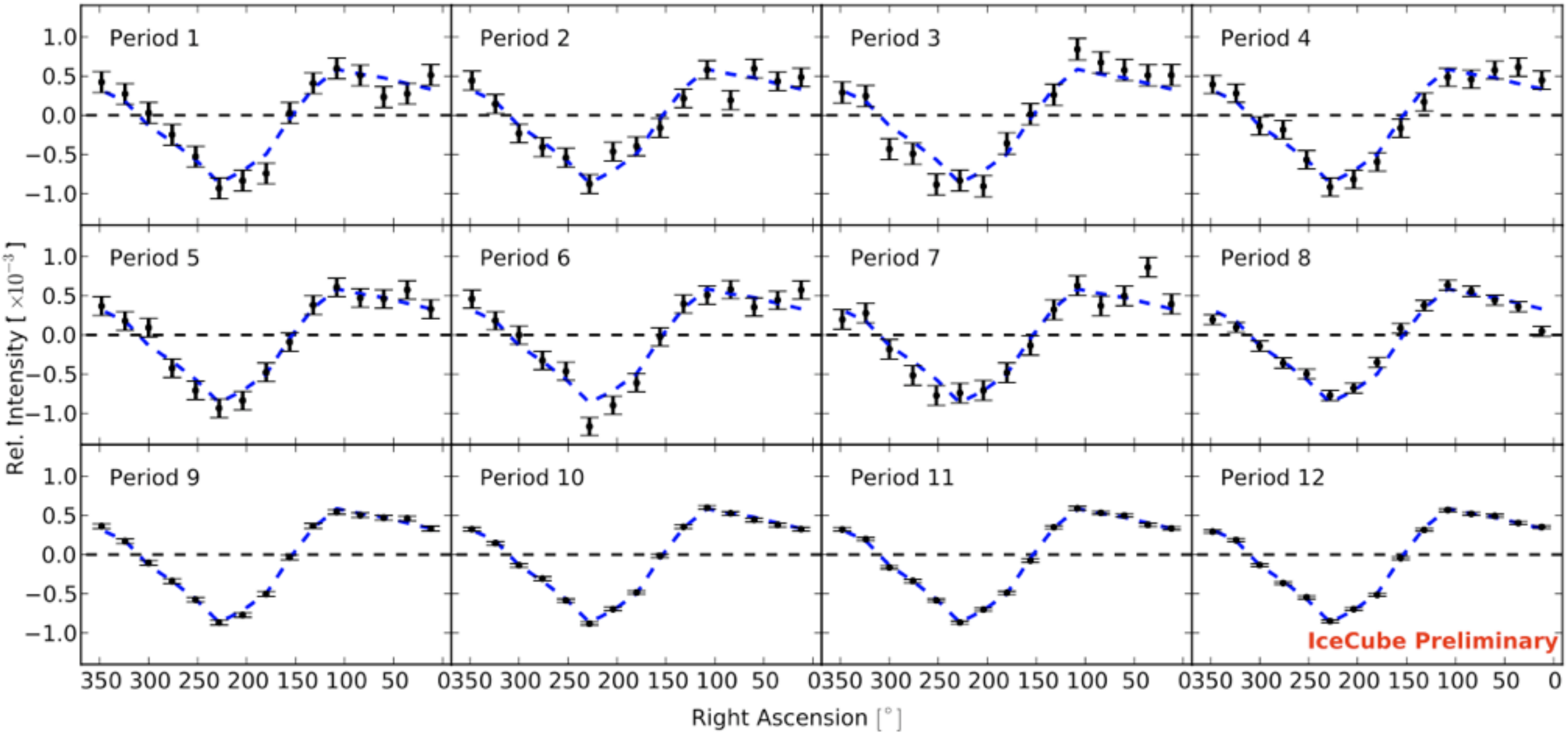
- Significant structures persist after dipole and quadrupole subtraction.
- Detection of anisotropy on angular scales < 10 deg.

Study of the time dependence of the CR anisotropy.



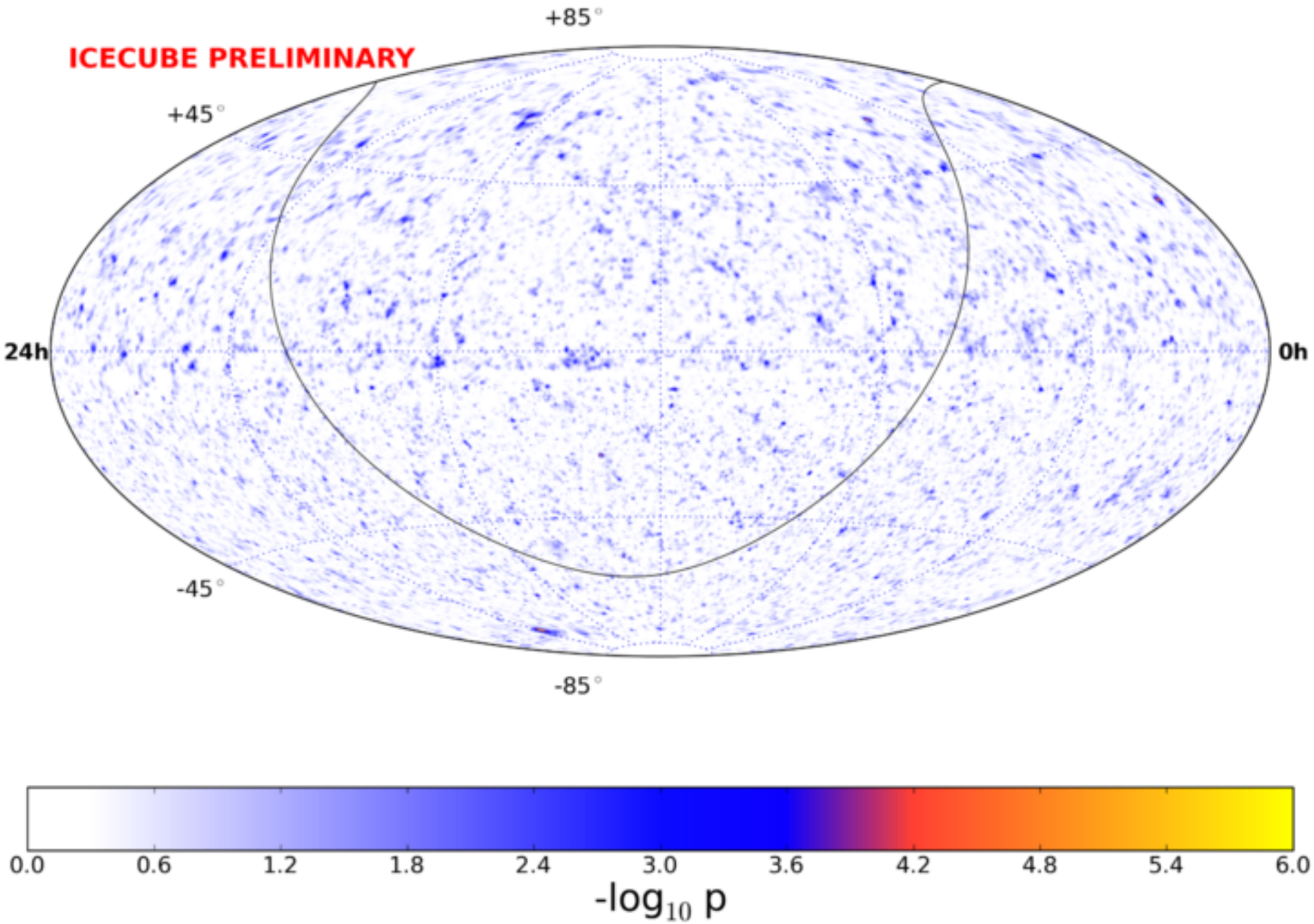
- 12 years of data from AMANDA and IceCube from 2000 - 2012.
- Good χ^2 for all years except 2008 (IC-22) with respect to average.
- No visible time dependence of the anisotropy amplitude/phase.

Study of the time dependence of the CR anisotropy.



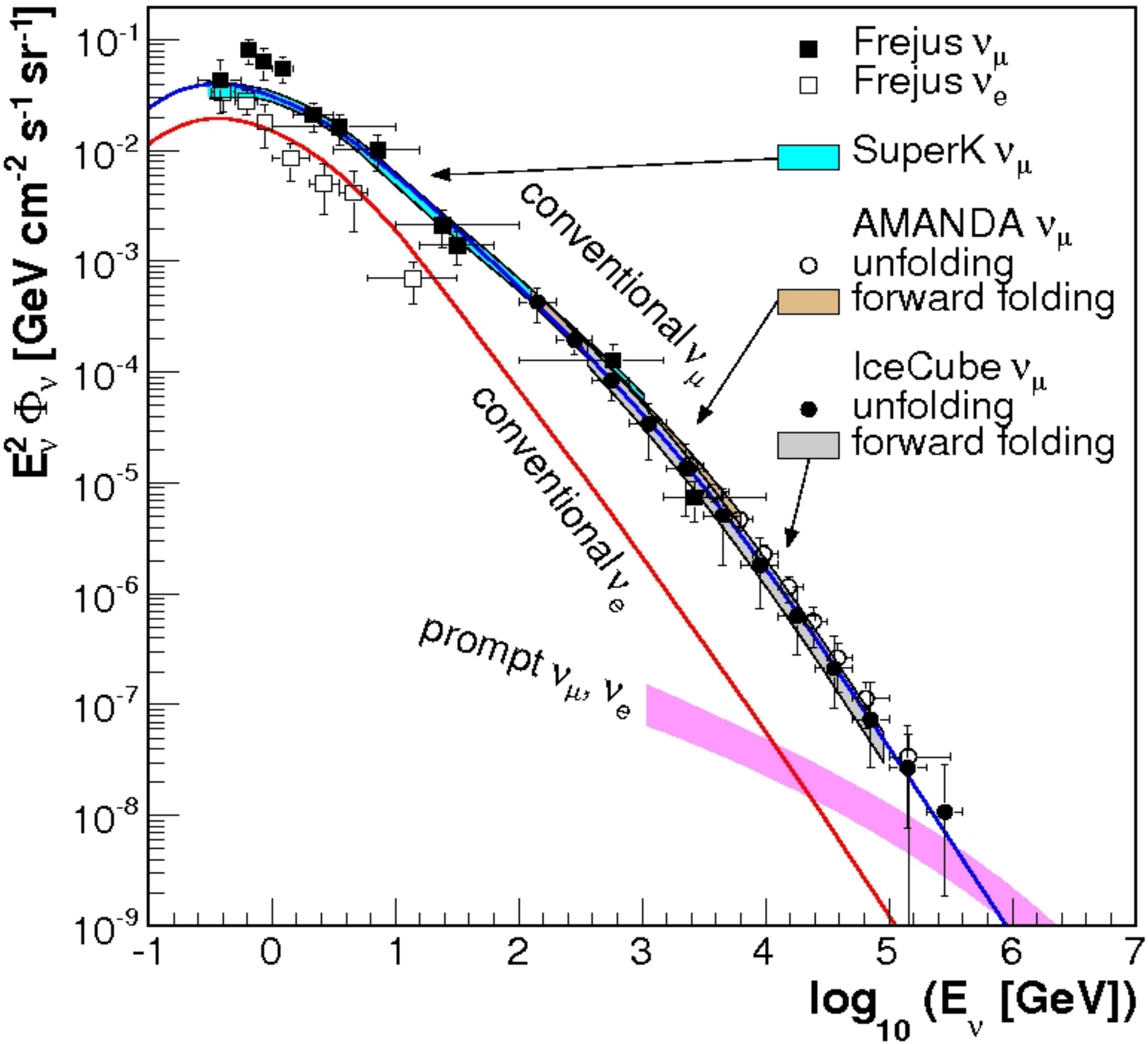
- 12 years of data from AMANDA and IceCube from 2000 - 2012.
- Good χ^2 for all years except 2008 (IC-22) with respect to average.
- No visible time dependence of the anisotropy amplitude/phase.

Search for a diffuse flux of astrophysical neutrinos.



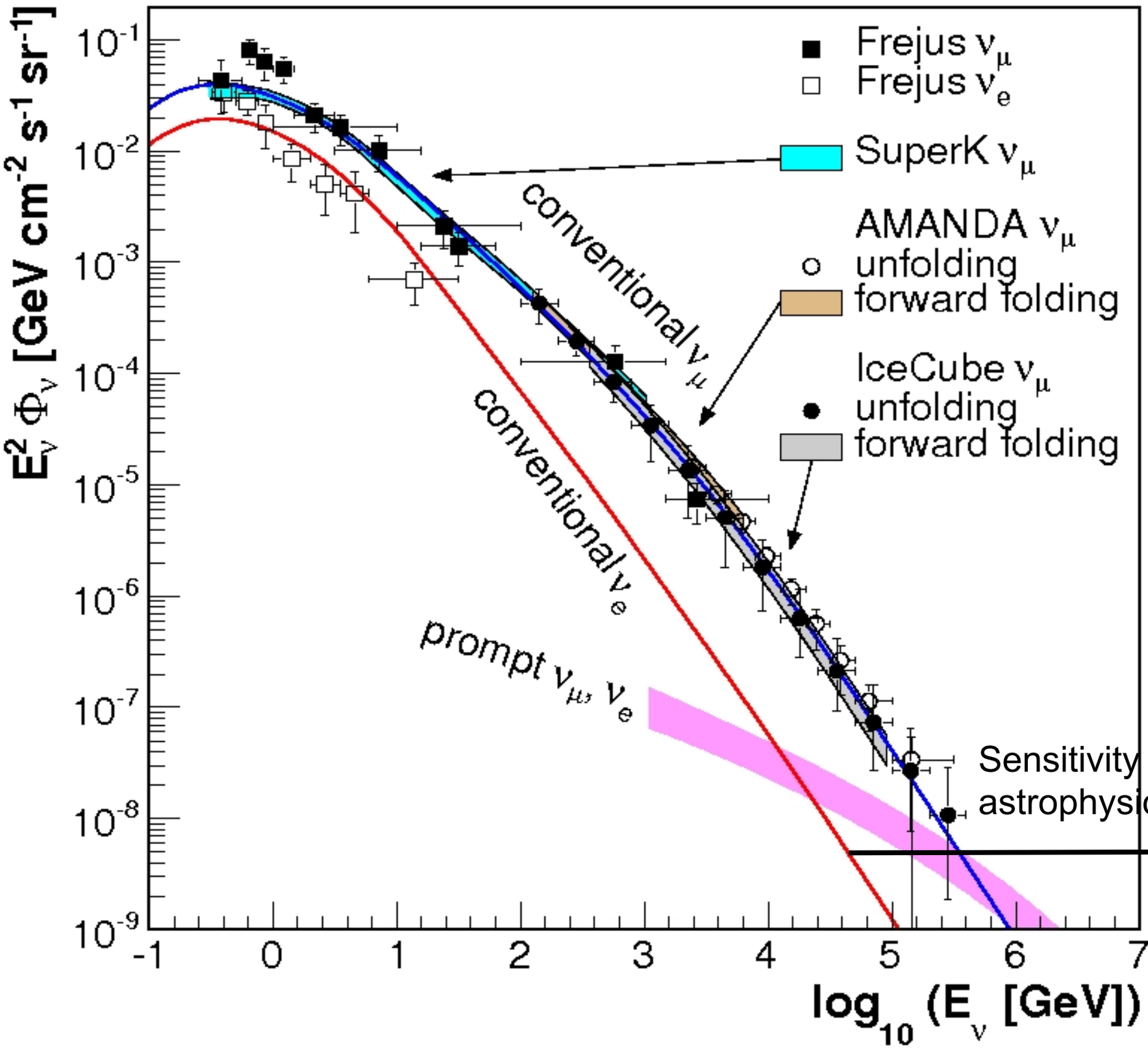
- No individual neutrino sources detected so far (2008-2012 data).
- Universe is transparent for neutrinos → many faint sources can add up to a detectable diffuse neutrino flux.

Search for diffuse astrophysical neutrinos.



- Diffuse signal arises from the sum of all astrophysical neutrino sources.
- Atmospheric neutrino background limits sensitivity at energies below tens of TeV.

Search for diffuse astrophysical neutrinos.



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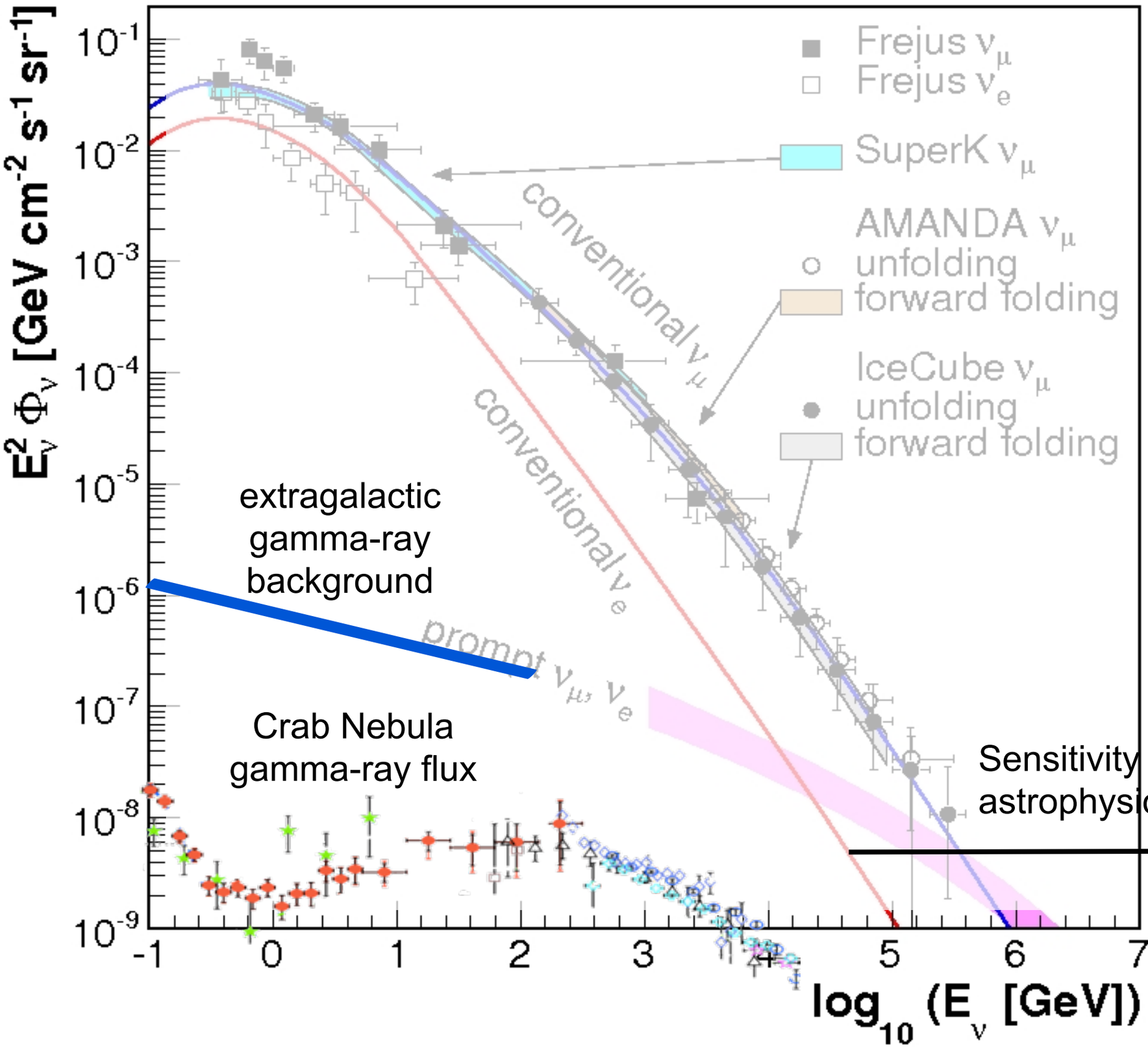
Sensitivity level of IceCube for a diffuse astrophysical neutrino signal

Search for diffuse astrophysical neutrinos.



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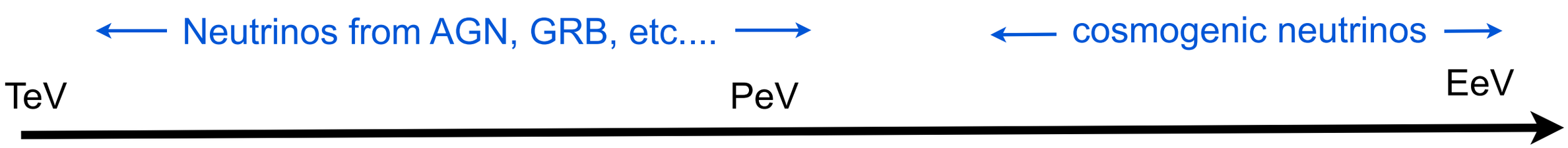
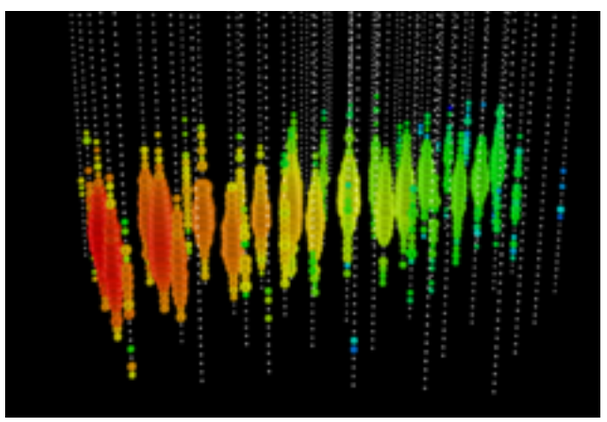
Search for diffuse astrophysical neutrinos



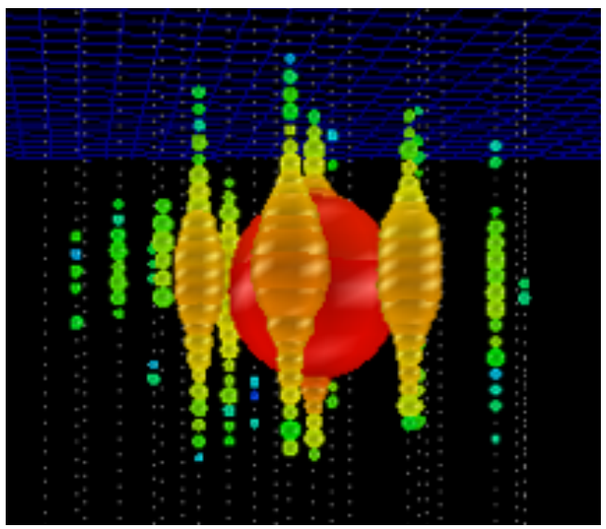
> Search for a high-energy tail of the diffuse ν_μ spectrum.

- Analyze the dE/dX spectrum of a clean ν_μ sample.



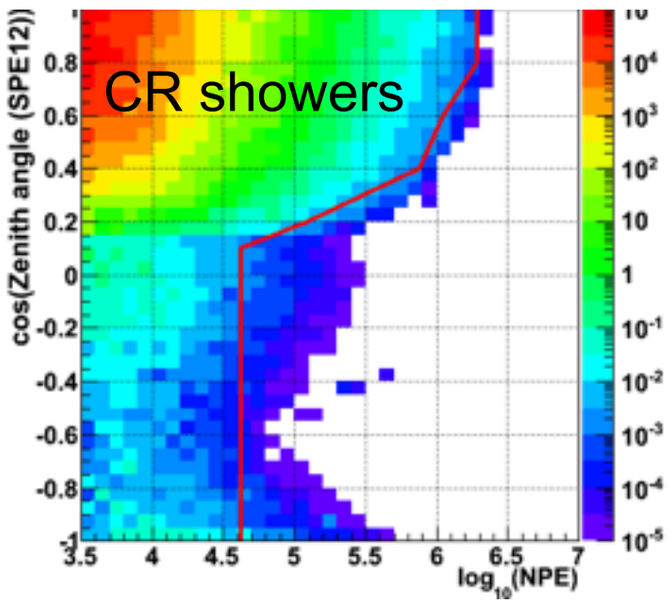
> Search for contained shower-type events

- Isolate shower-type events and analyze energy spectrum



> Search for bright events.

- Reject bright muon bundles from CR showers, keep everything else.



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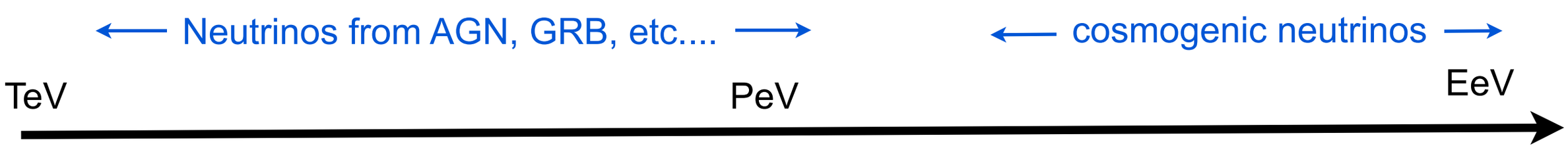

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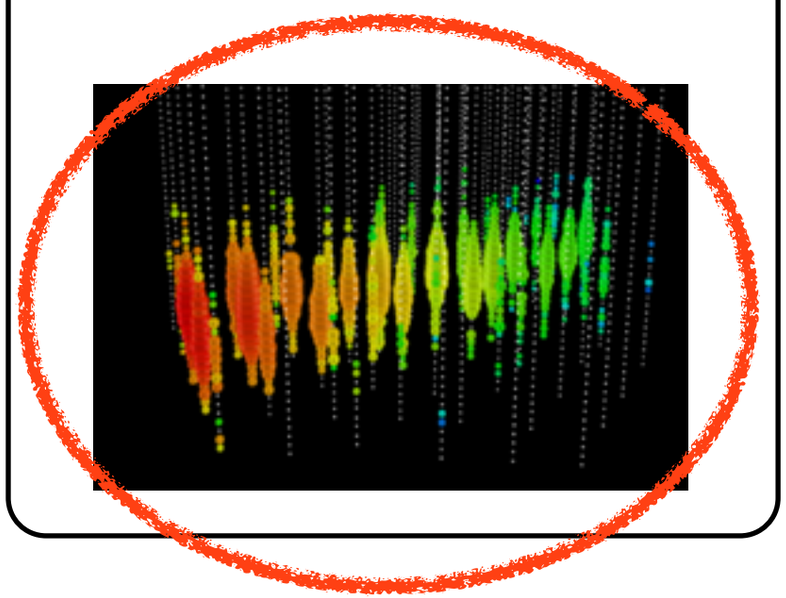

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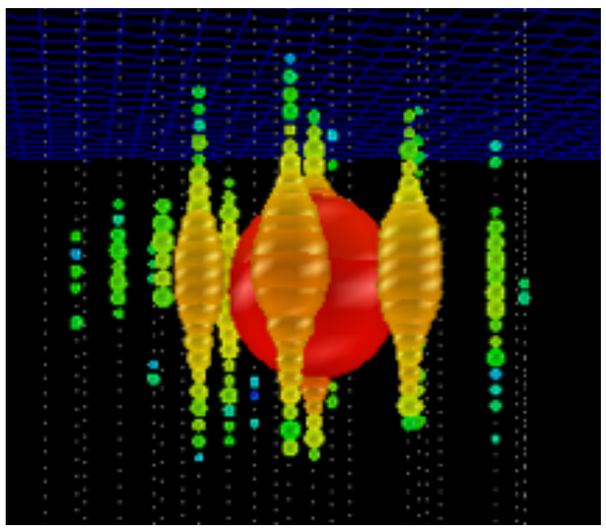

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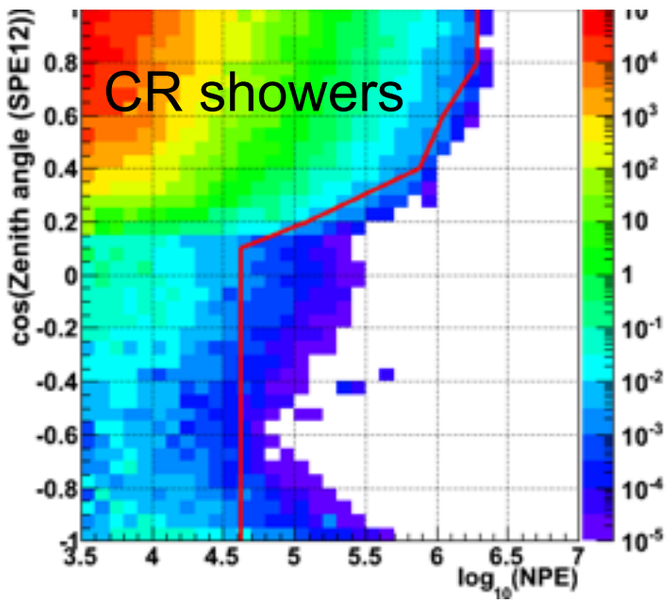
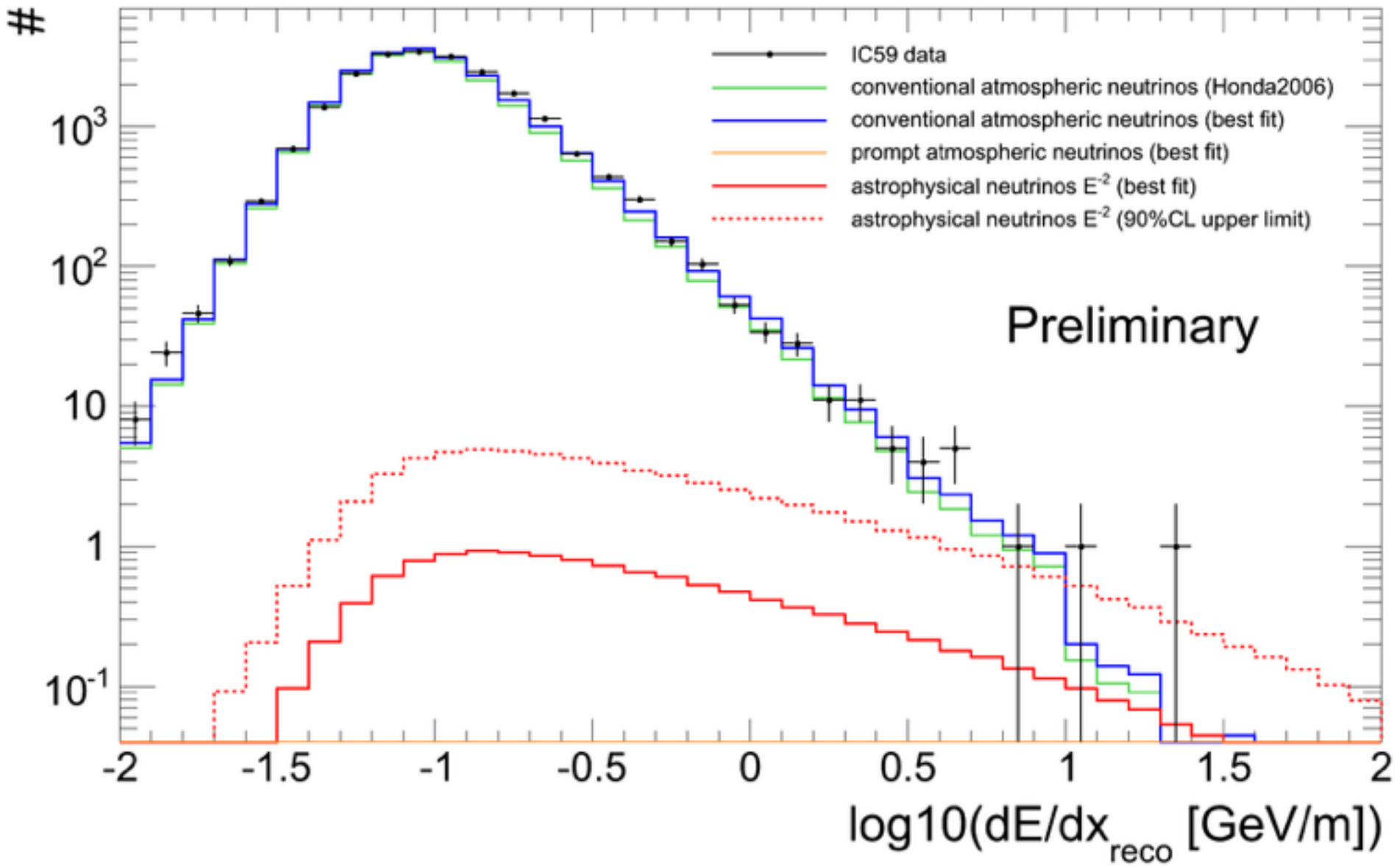
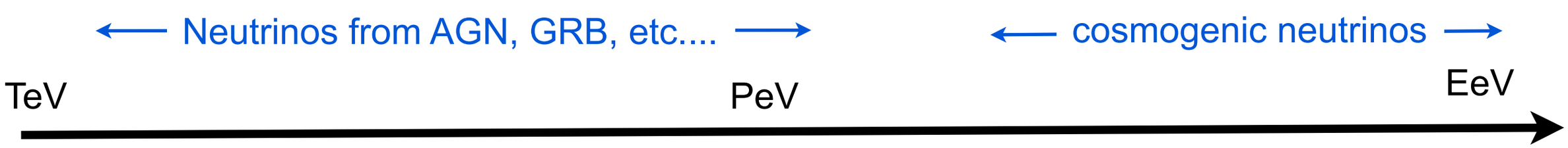


Search for an high-energy tail in the ν_μ dE/dx spectrum.



- Data from 2009 analyzed (IC-59)
- Good agreement with atmospheric neutrino spectrum.
- Slight excess found at high energies (significance: 1.8σ)

Search for diffuse astrophysical neutrinos.



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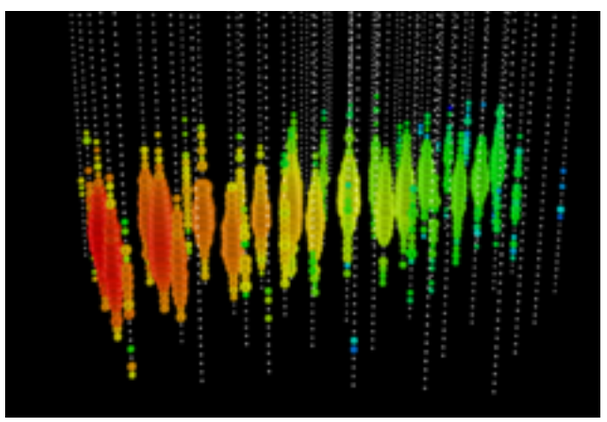

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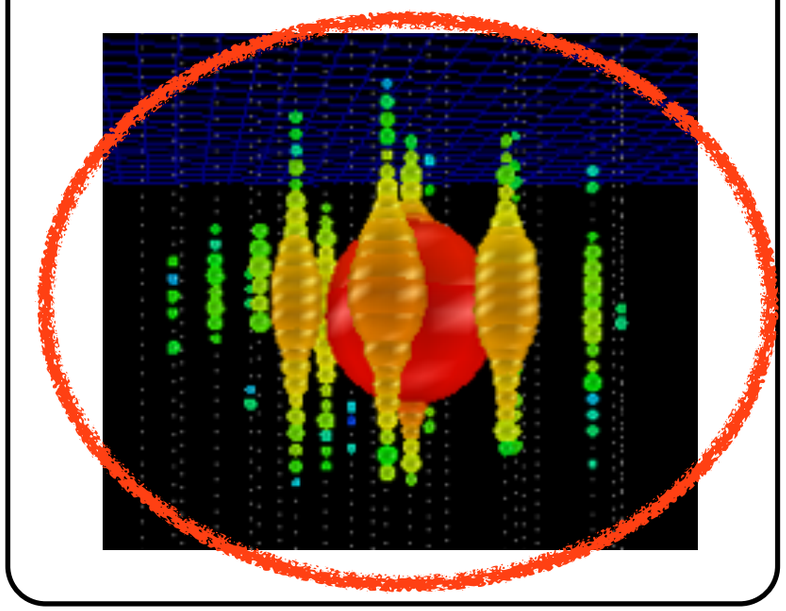

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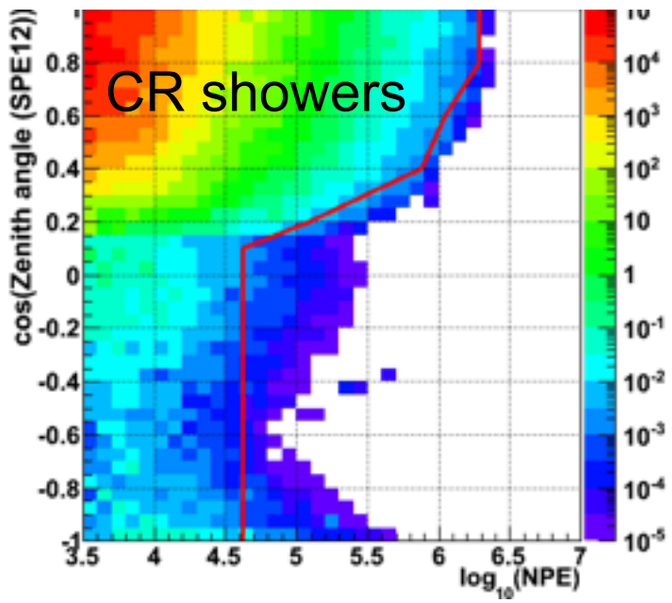
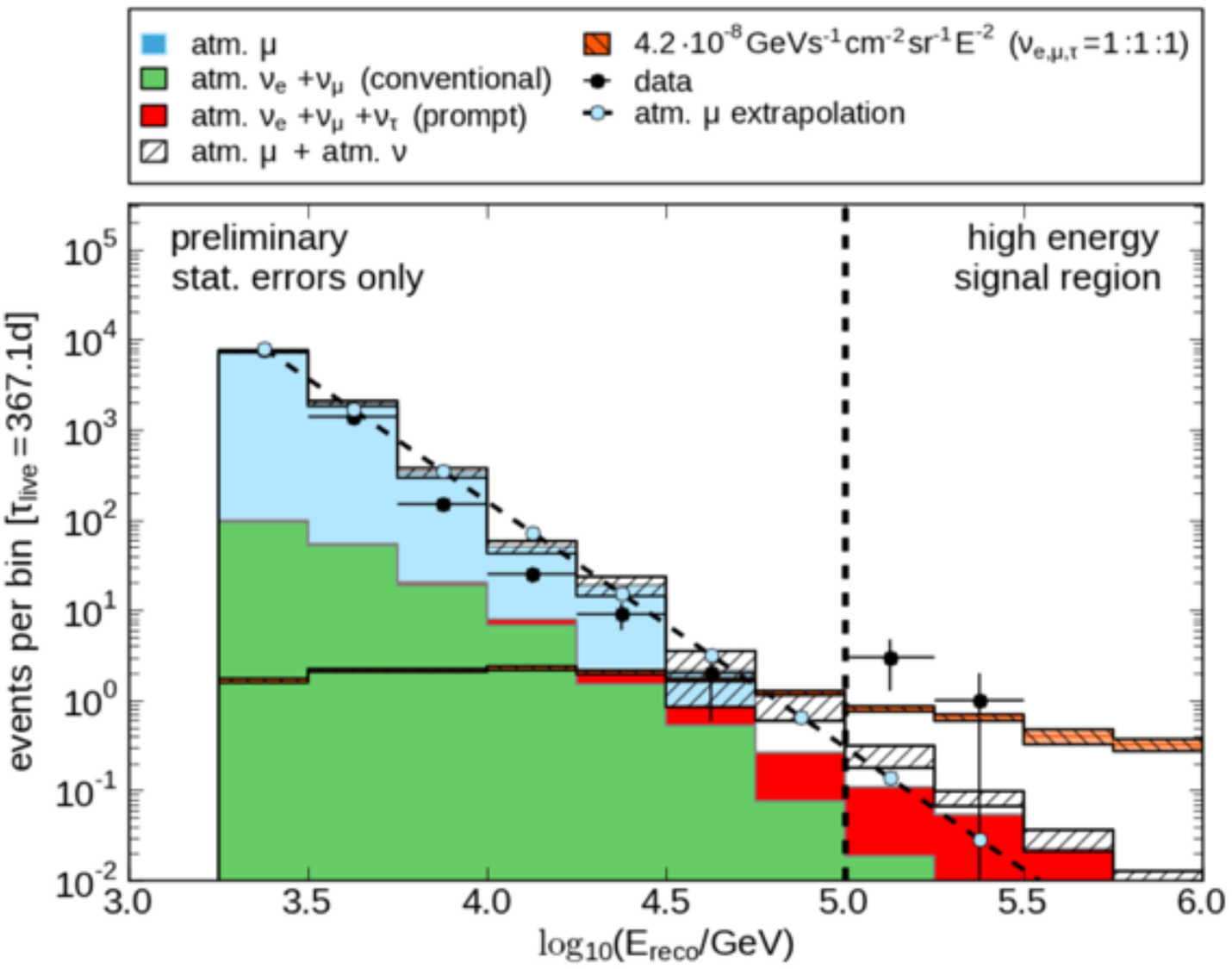
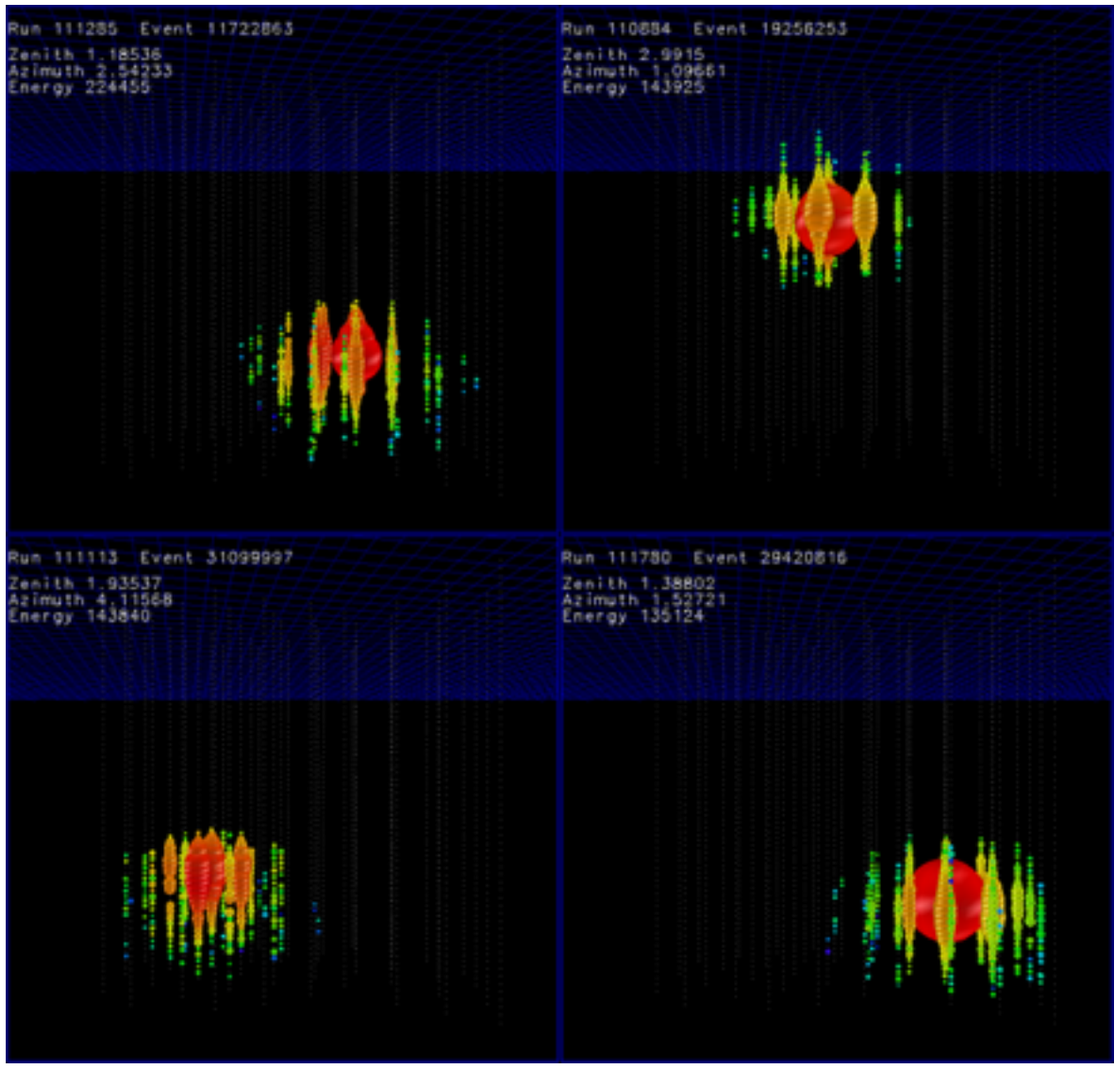


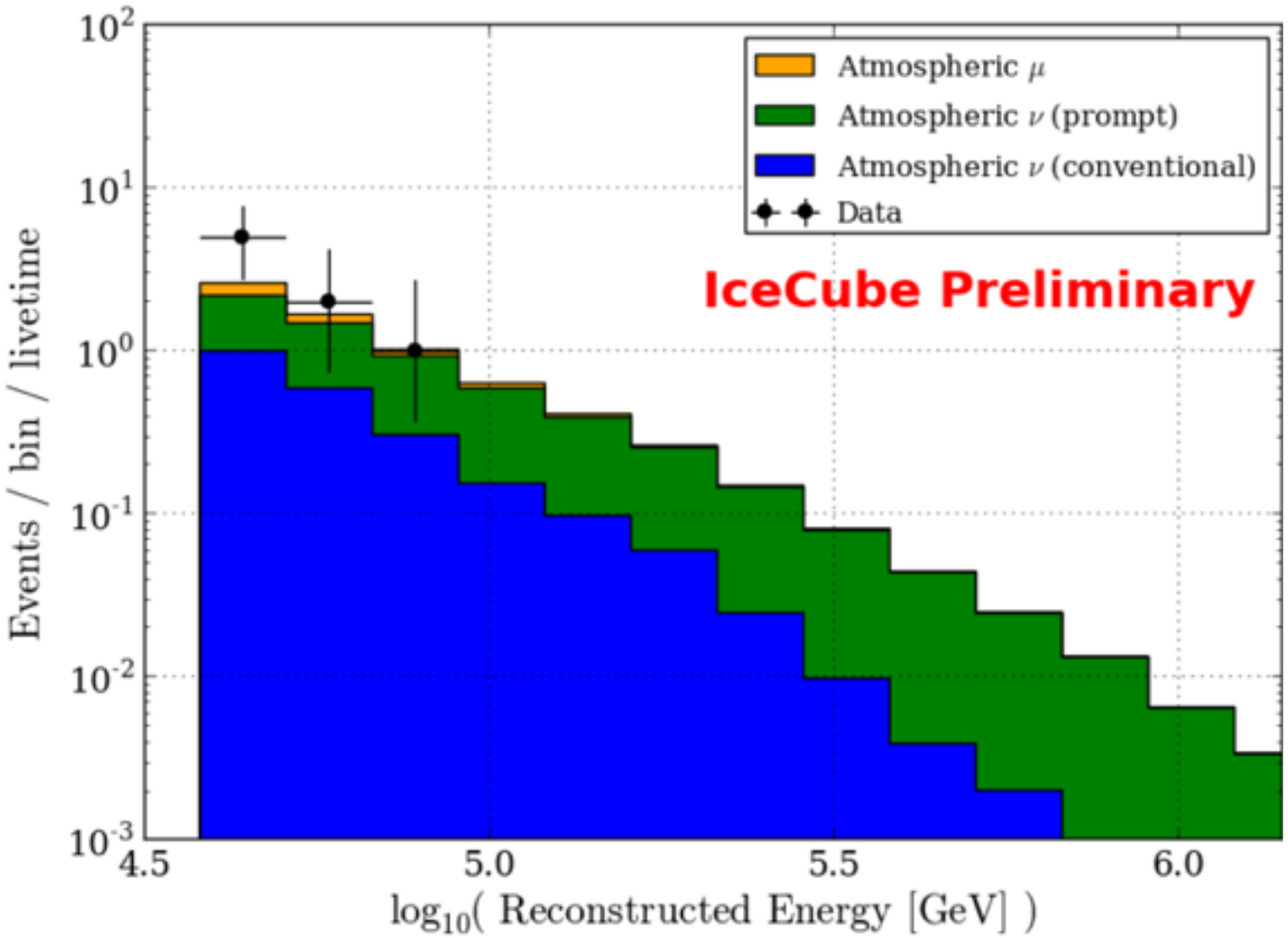
Search for contained events with 2008 (IC-40) data.

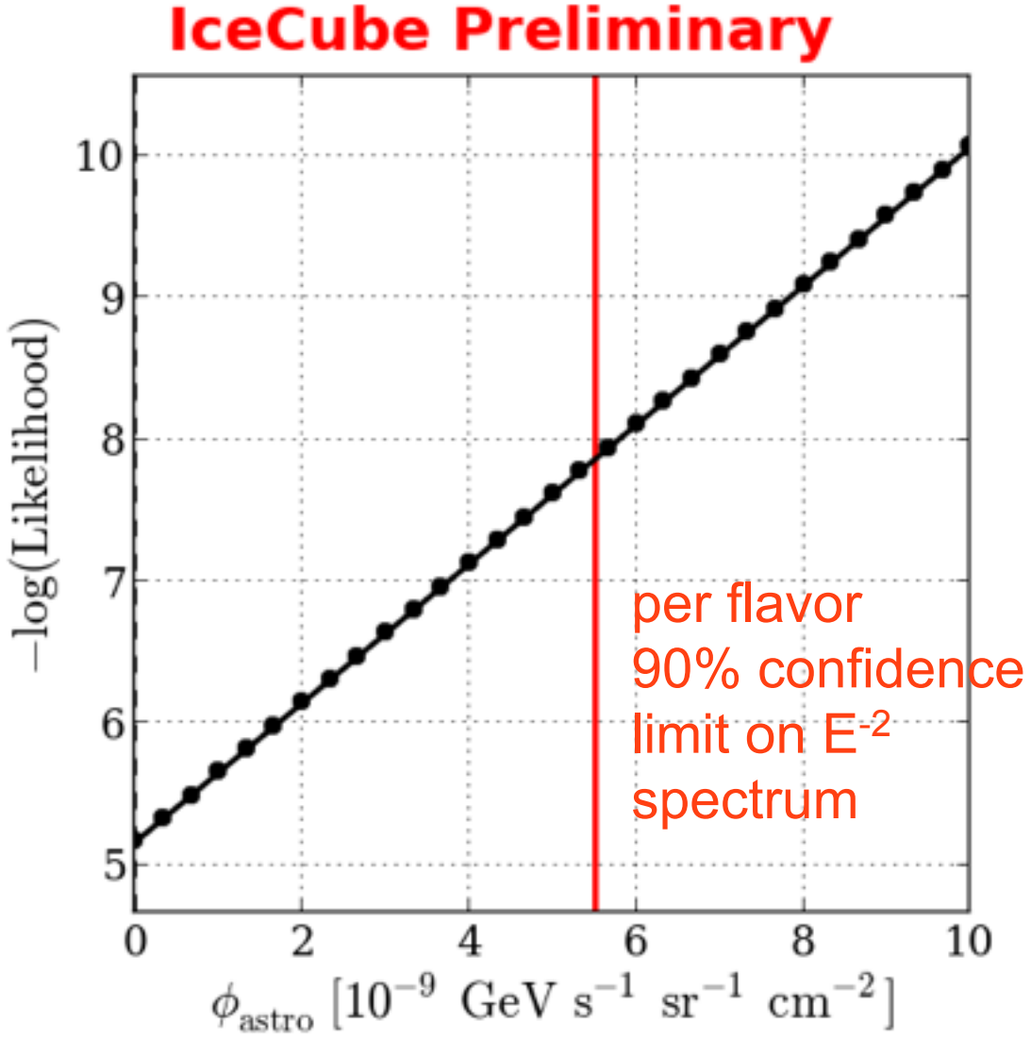




- 4 events observed above 100 TeV in 2008 data sample.
- Highest energy: ~ 220 TeV
- 2.4σ fluctuation over background (not including syst. uncertainties).

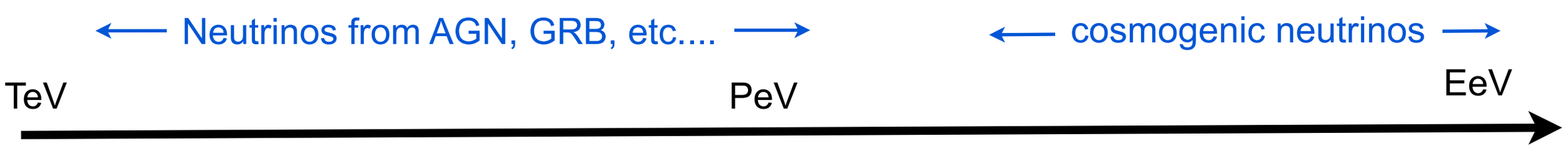
Search for contained events with 2009 (IC-59) data.





- 8 events above ~ 40 TeV in similar analysis of IC-59 data.
- No events above 100 TeV.
- Compatible with expectations from atmospheric background.
- Maximum Likelihood fit of spectrum prefers no astrophysical contribution.

Search for diffuse astrophysical neutrinos.



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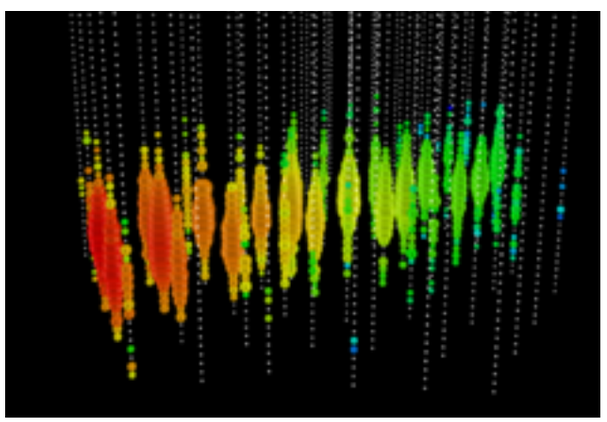

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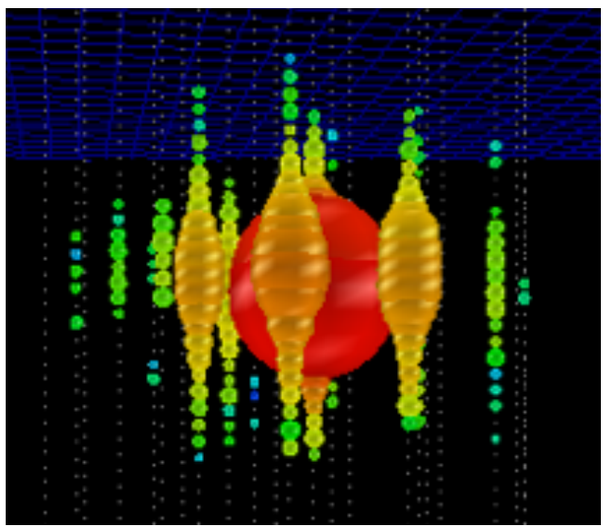

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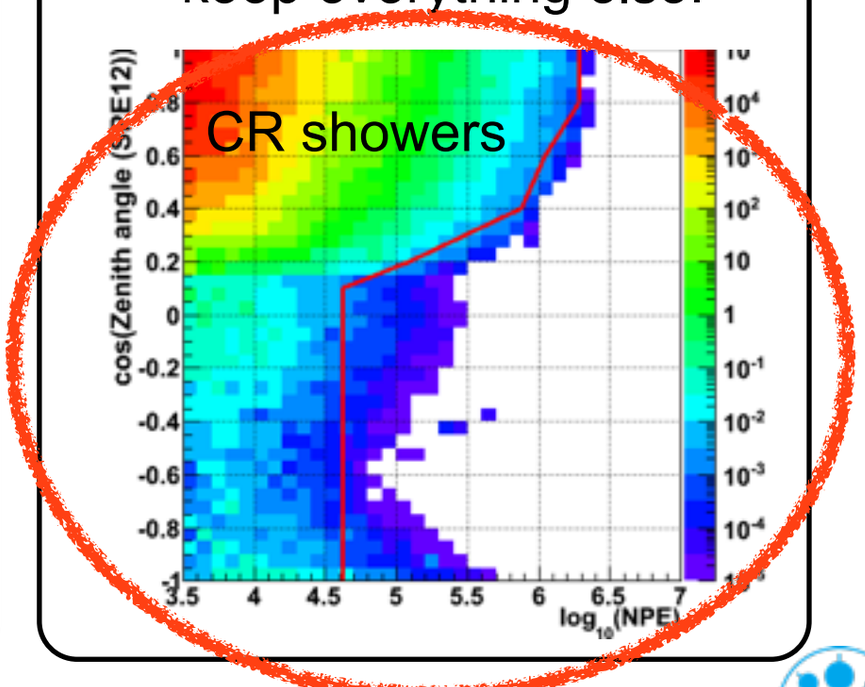
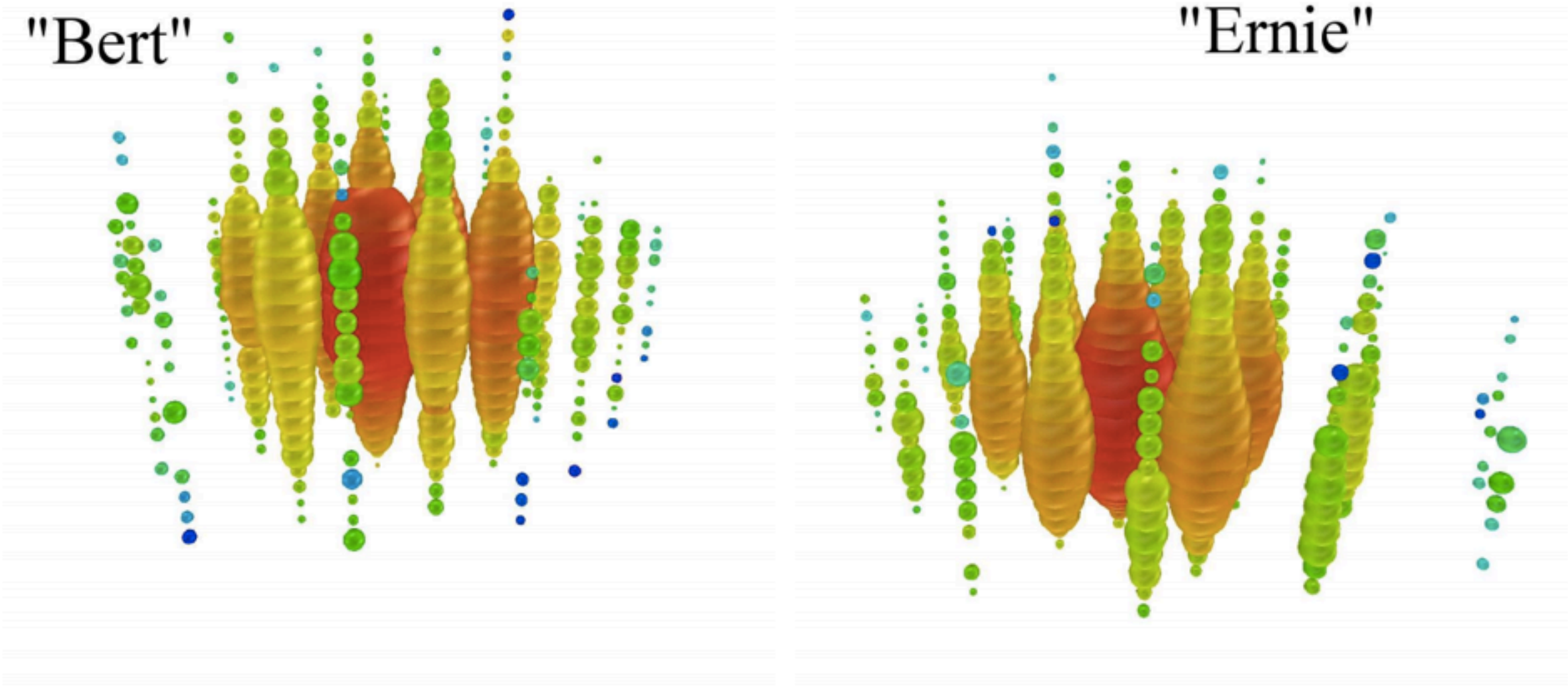
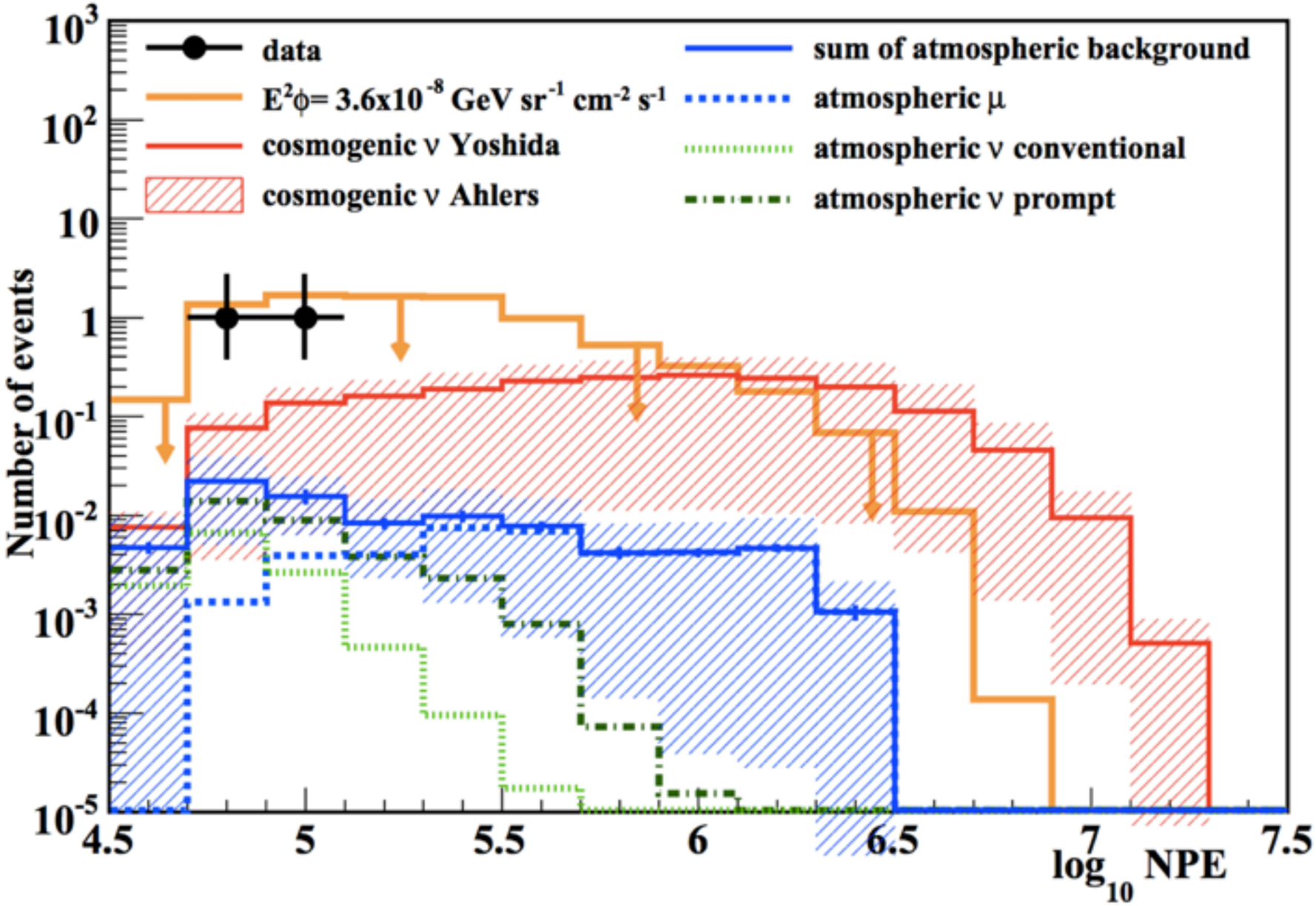


Search for cosmogenic neutrinos with 2010-2012 data.



- Two shower type events found in 616 days of IceCube observations.
- Deposited energies: 0.97 ± 0.15 PeV (Bert), 1.12 ± 0.17 PeV (Ernie).
- Neutrino energies could be higher, if neutral current interaction.

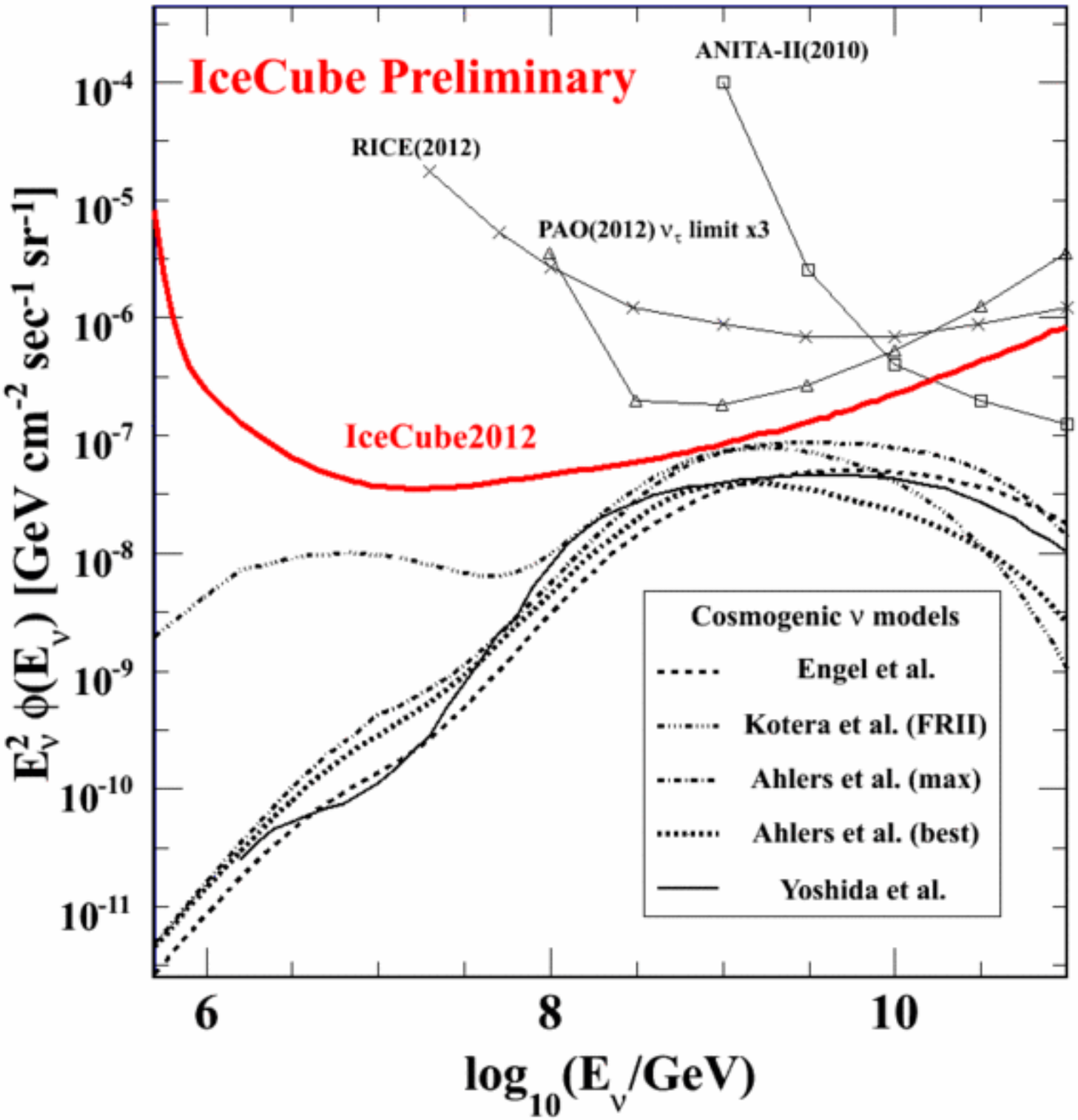
Search for cosmogenic neutrinos with 2010-2012 data.



- Search targeted for multi-PeV to EeV events expected from cosmogenic neutrinos.
- PeV events found at the brightness threshold for this analysis.
- 2.8σ above expectations from atmospheric background.

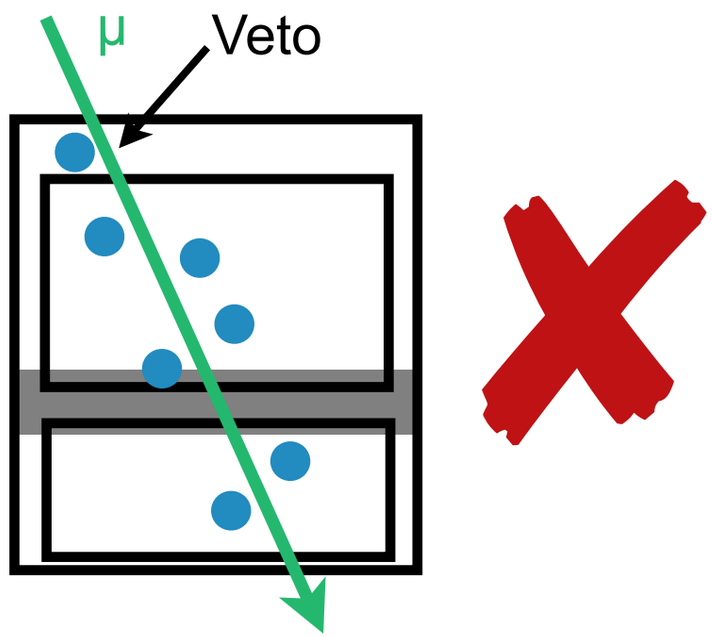
Flux upper limits on the cosmogenic neutrino flux.

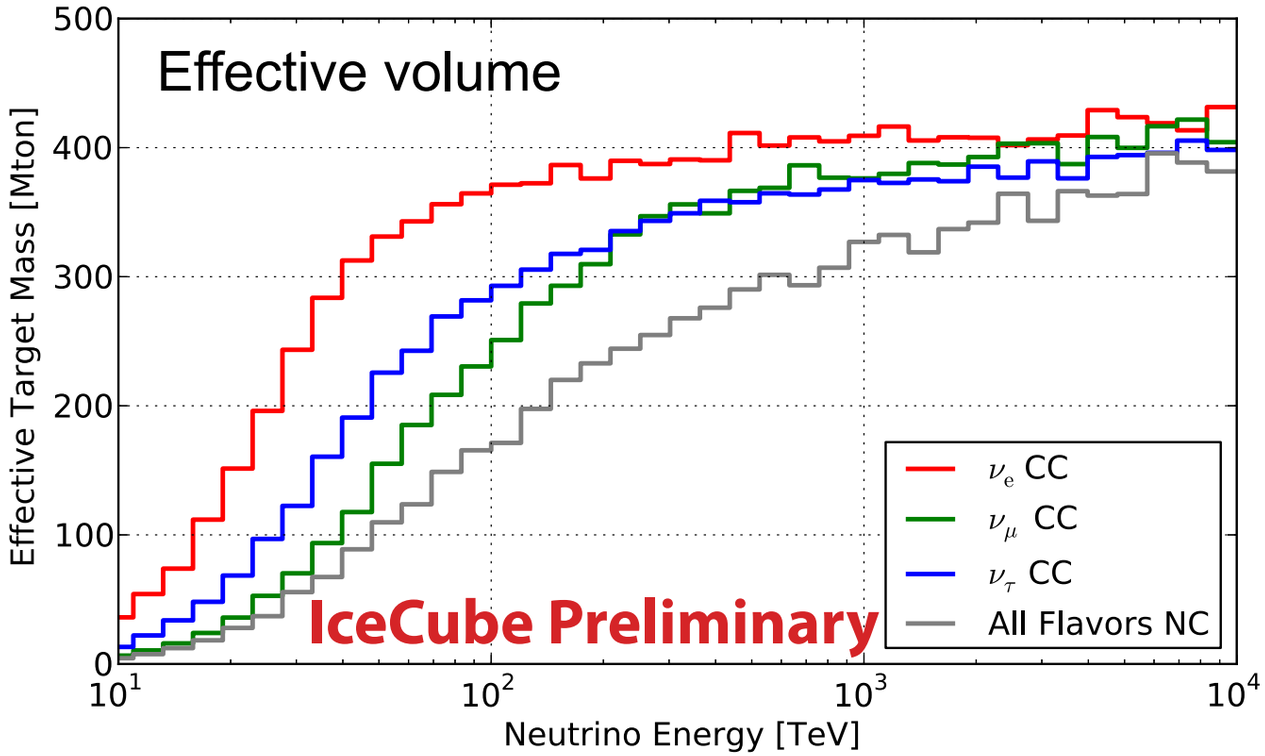
- Cosmogenic neutrinos: Interactions of UHECRs with the intergalactic photon fields.
- Higher energy neutrinos expected ⟶ PeV events likely not cosmogenic.
- Differential limits on cosmogenic neutrino flux

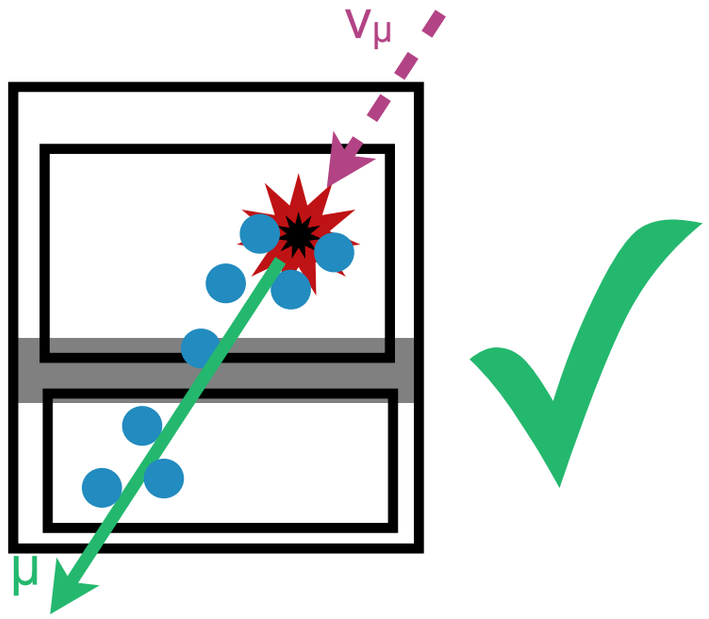


Search for contained and semi-contained events.

- Designed to find contained events below the energy threshold of the “Bert-and-Ernie” analysis
  - same dataset
  - 662 days of livetime
- Use outer IceCube layers as incoming track veto
  - Additional atmospheric muon veto
  - Sensitive to all flavors in region above ~ 60TeV
  - Muon background can be estimated from data



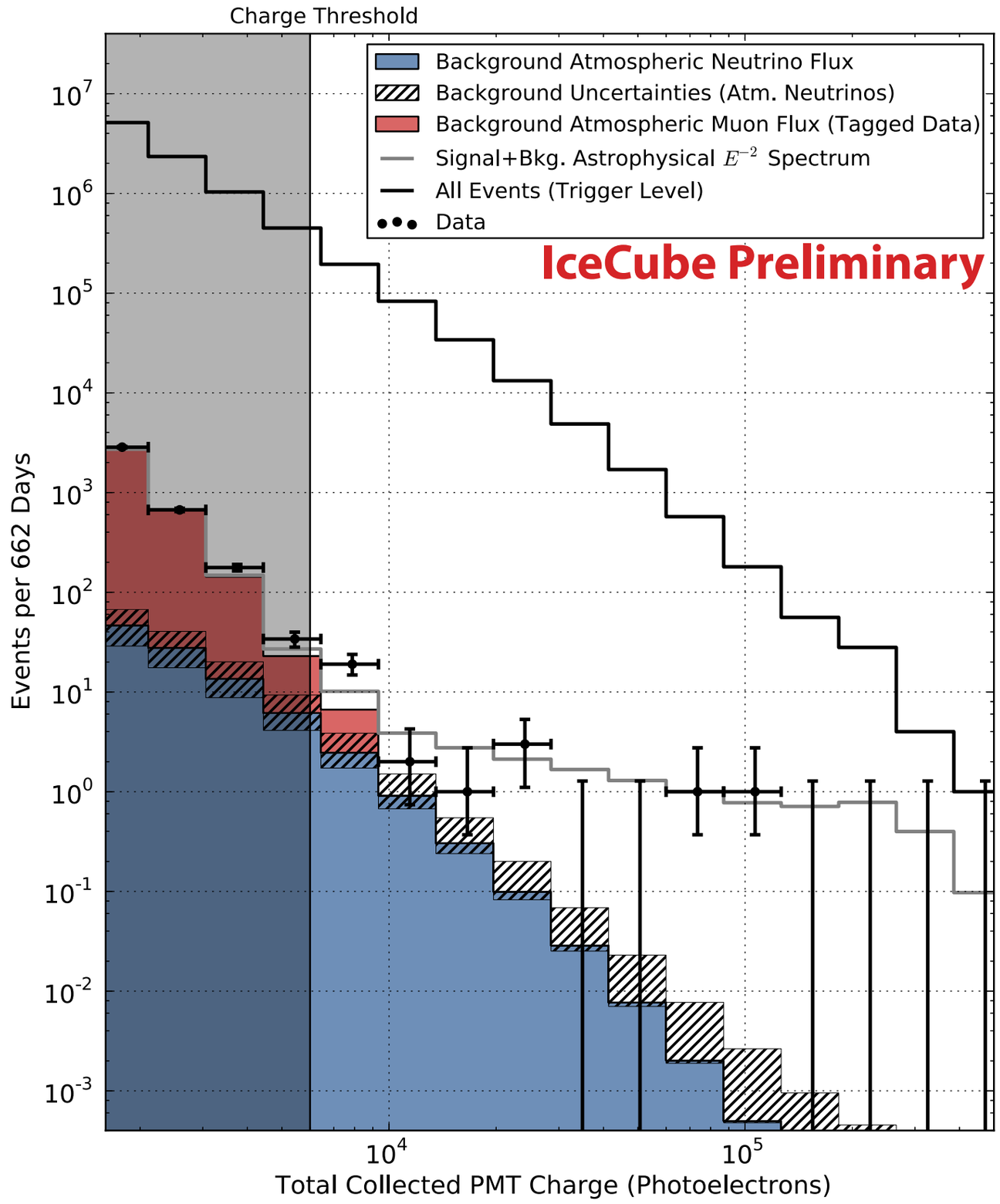




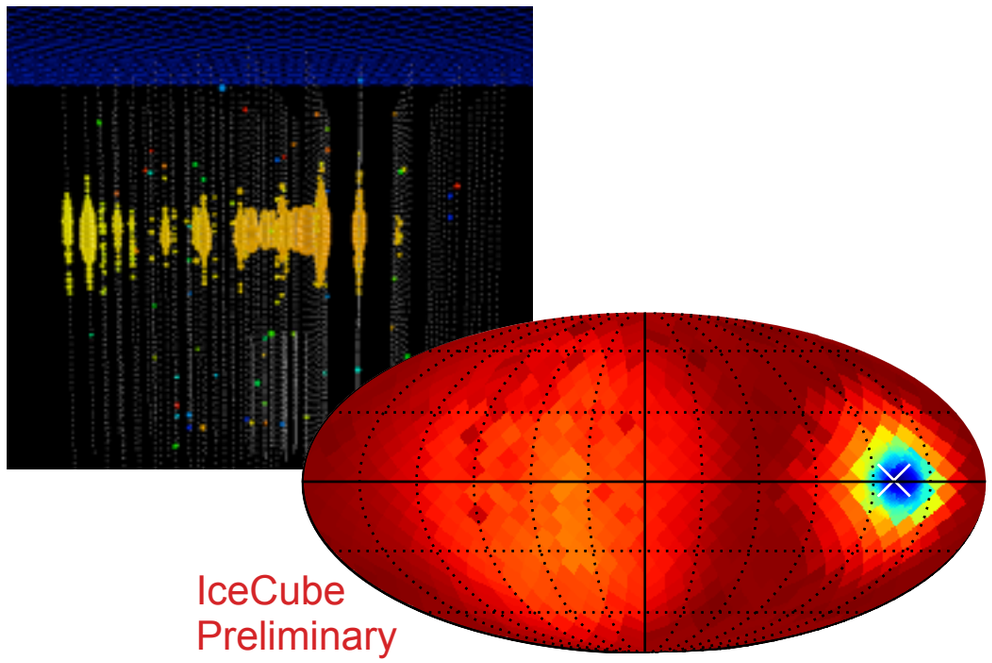
Search for contained and semi-contained events

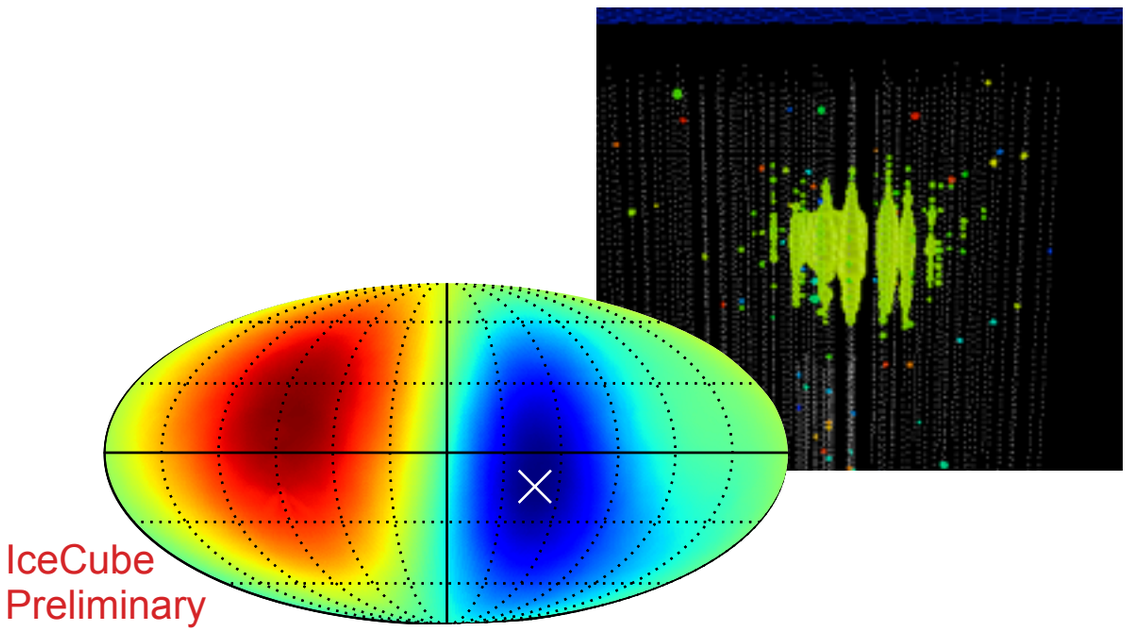
- 28 events observed including Ernie and Bert (7 with visible muons, 21 without)
- Expected background 12.1±3.4 (1.5 from charm)
- Muon contamination estimated from data
- Significance calculation
  - previous analysis (Ernie & Bert) → 2.8σ
  - follow-up analysis (26 events, without Ernie & Bert) → 3.3σ

Combined 4.1σ



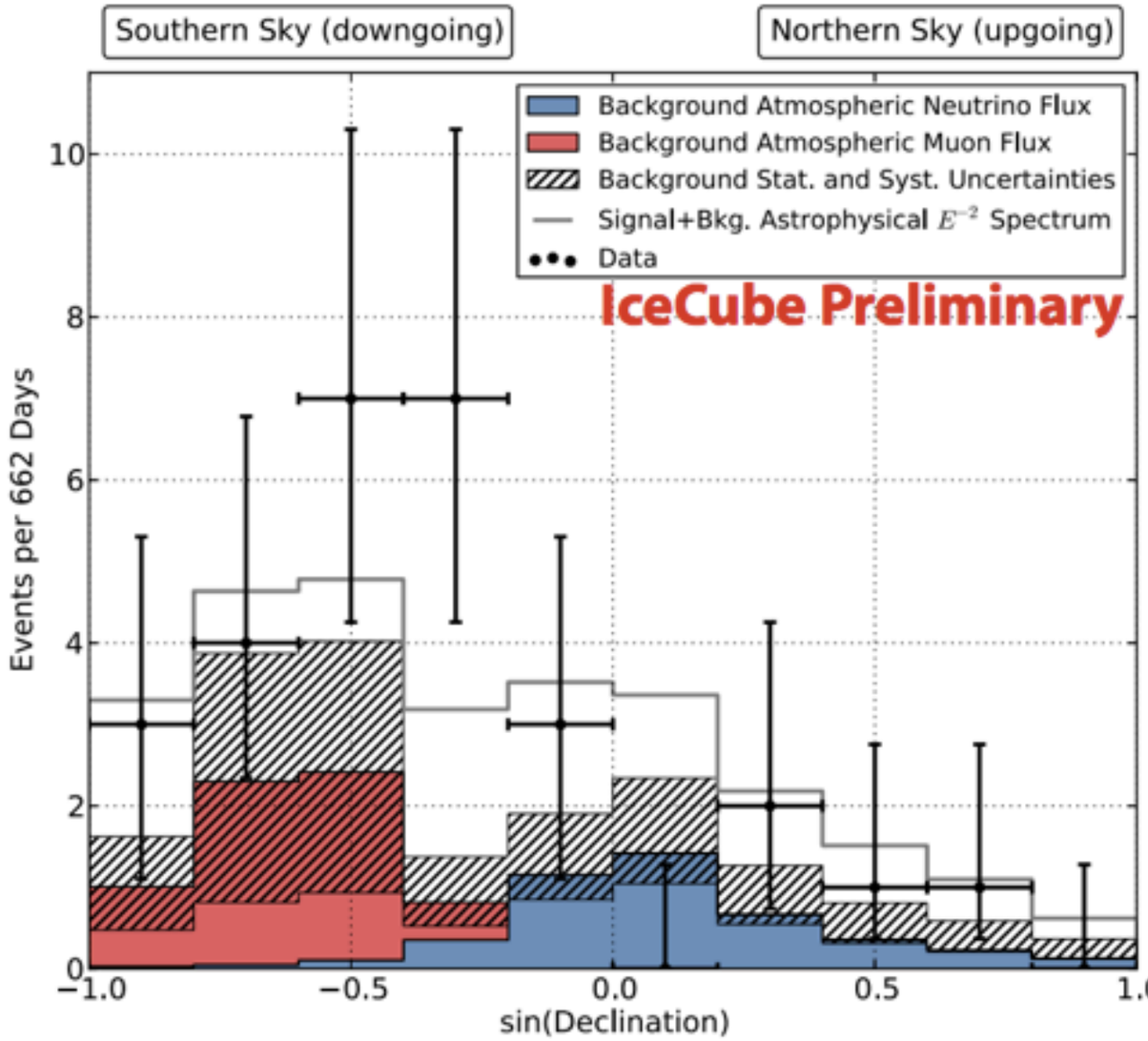
Event reconstruction.

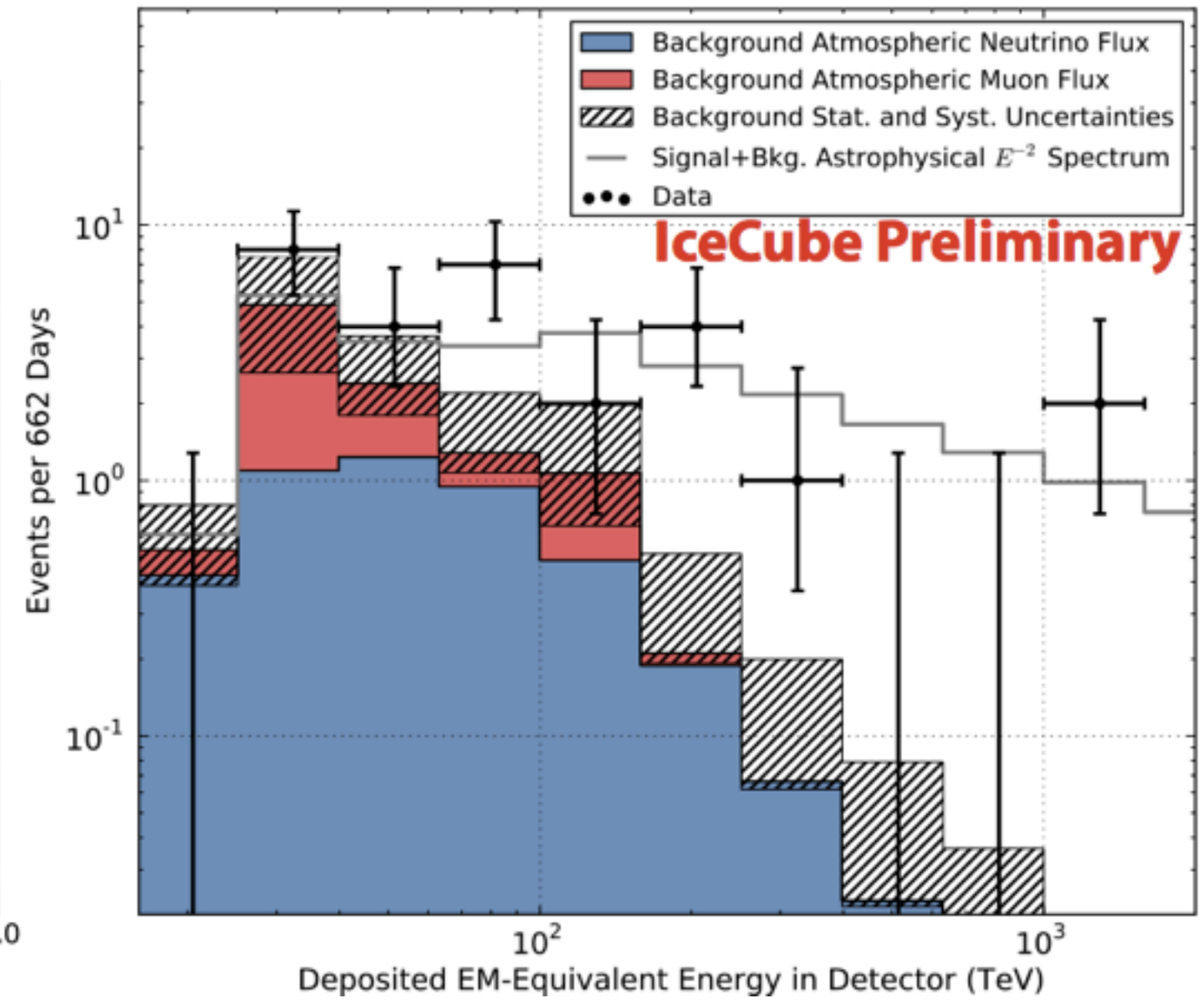




- Generic full-sky likelihood scan for each event
- Fits of energy depositions along a “track” in each direction based on hit pattern
  - using a detailed model of the glacial ice optical properties
- Results: Vertex, direction, deposited energy (incl. uncertainties)
- For NC events, tracks: deposited energy ≠ neutrino energy

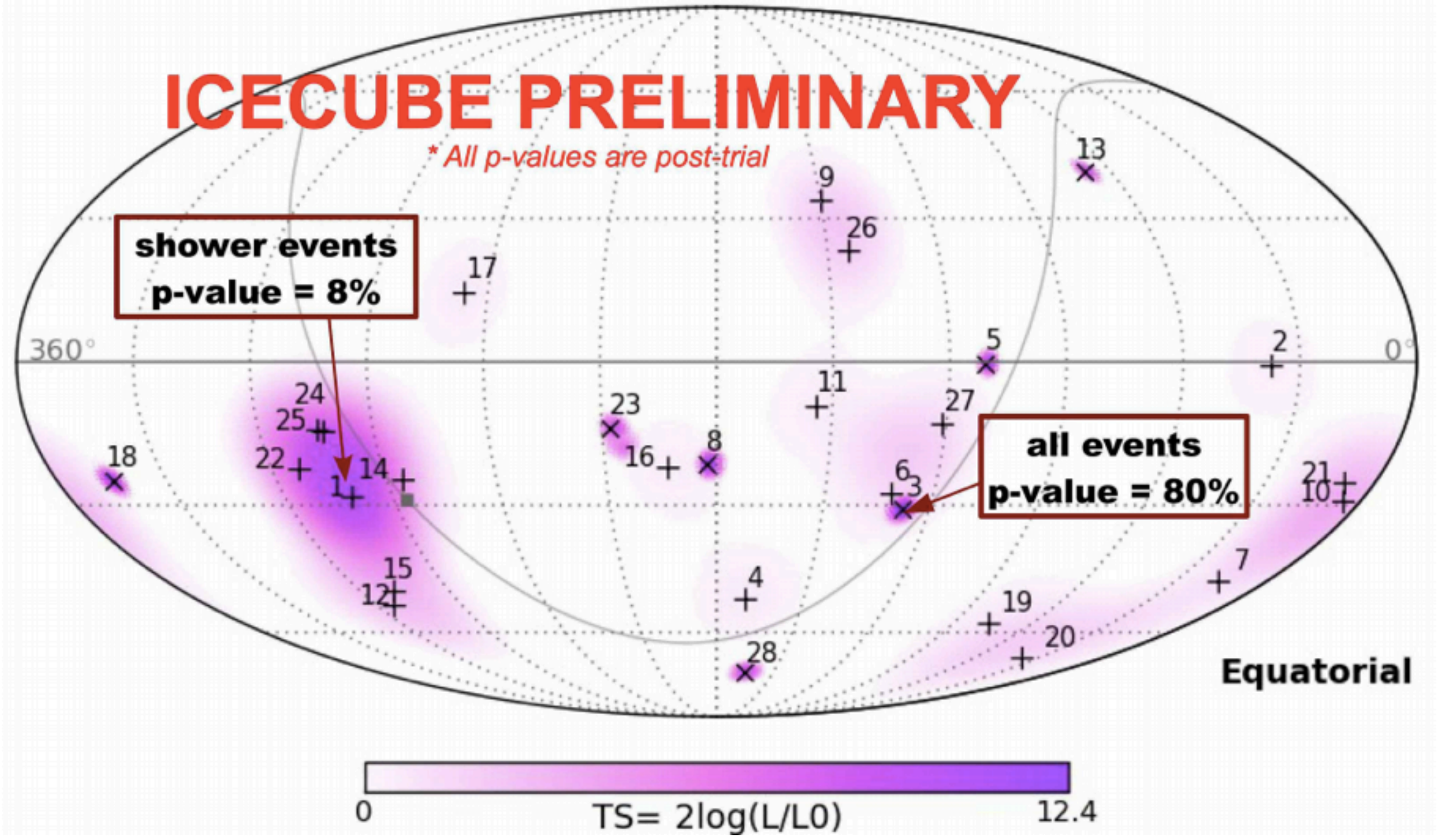
Contained and semi-contained events.





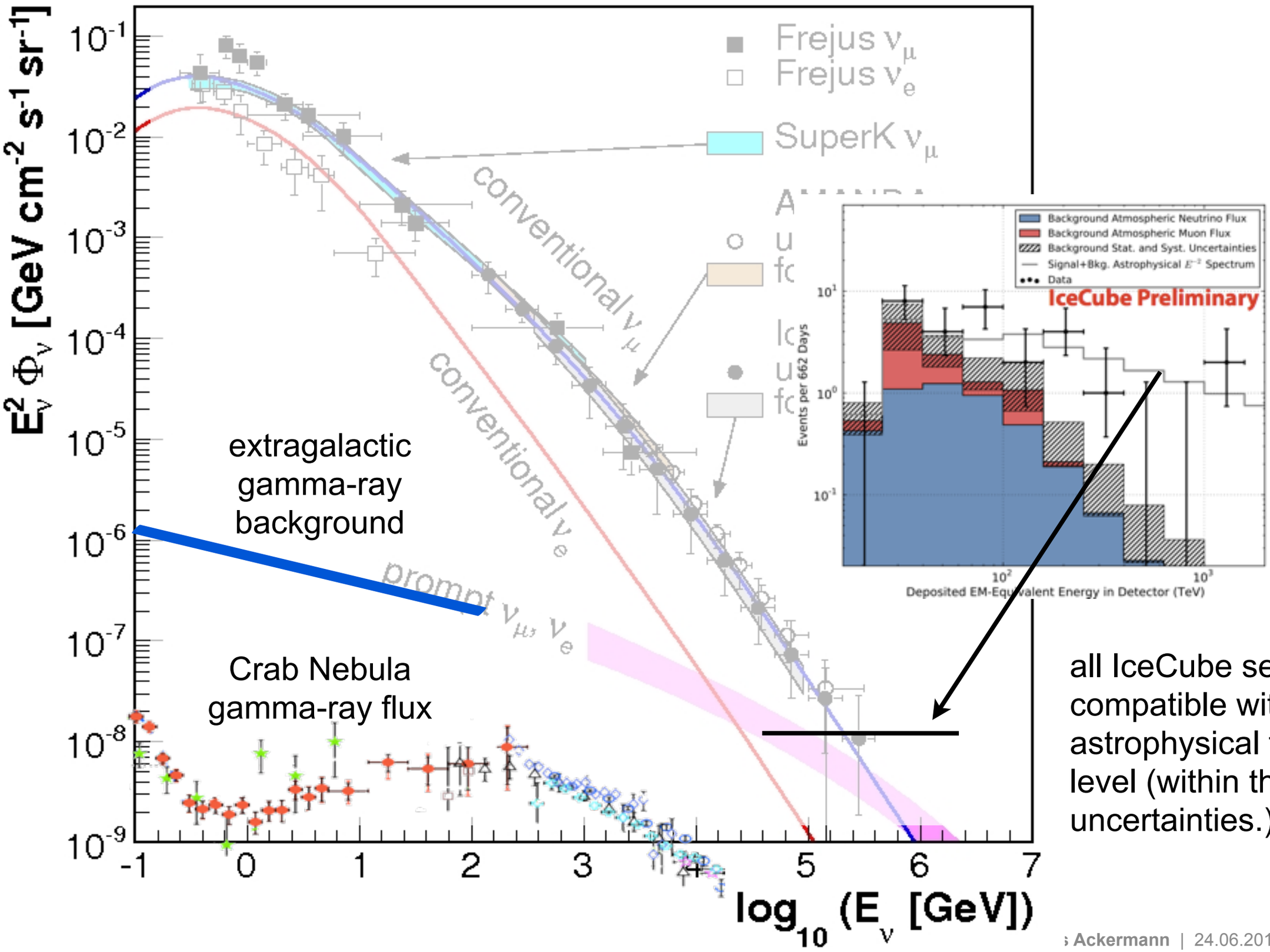
- Energy spectrum harder than expected from atmospheric neutrinos
- Zenith distribution biased towards Southern hemisphere in contrast to expectations from atmospheric neutrinos.
- Possible cutoff ~ 2PeV (no events seen at higher energies)

Distribution of high-energy neutrinos on the sky.



- Event distribution compatible with expectations from background + isotropic astrophysical flux.
- More data needed to distinguish different hypotheses of astrophysical origin.

Evidence for an astrophysical diffuse neutrino flux.



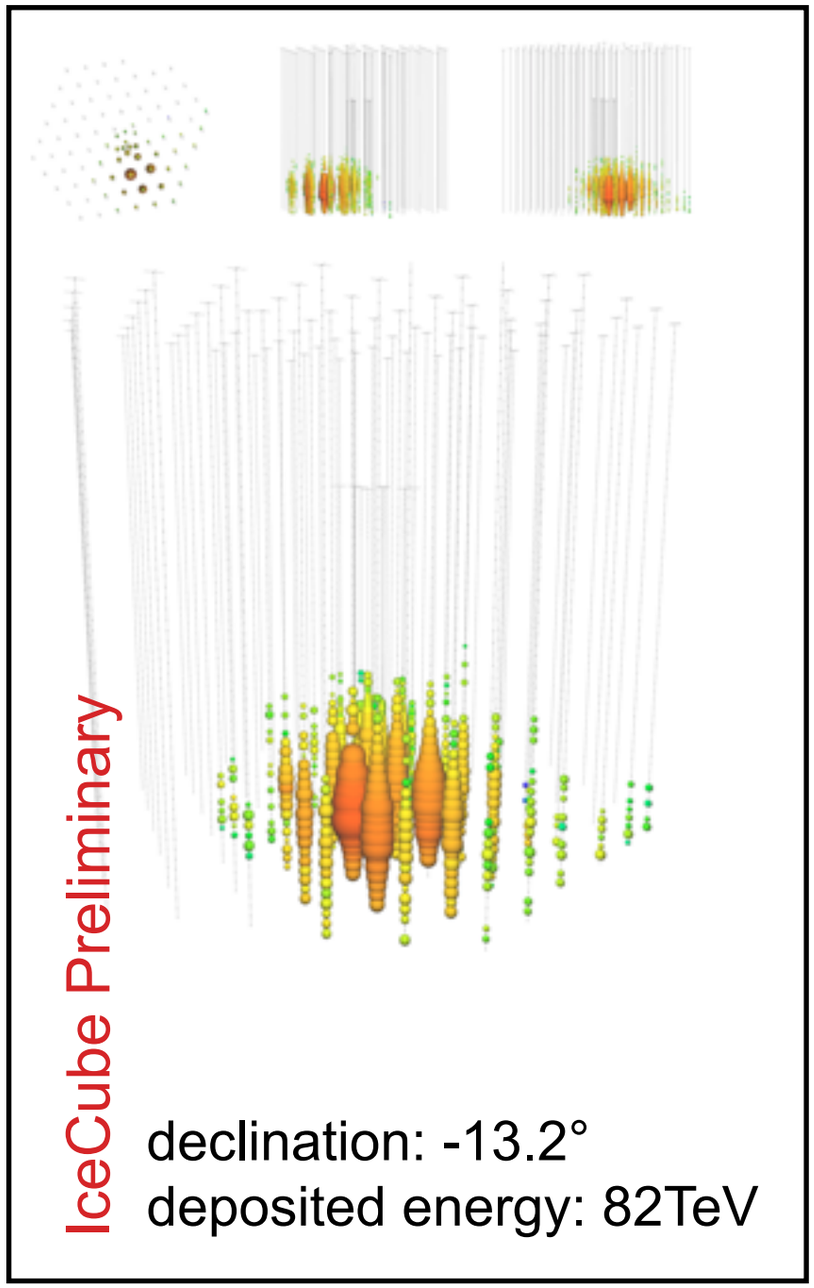
all IceCube searches are compatible with an astrophysical flux on this level (within their uncertainties.)

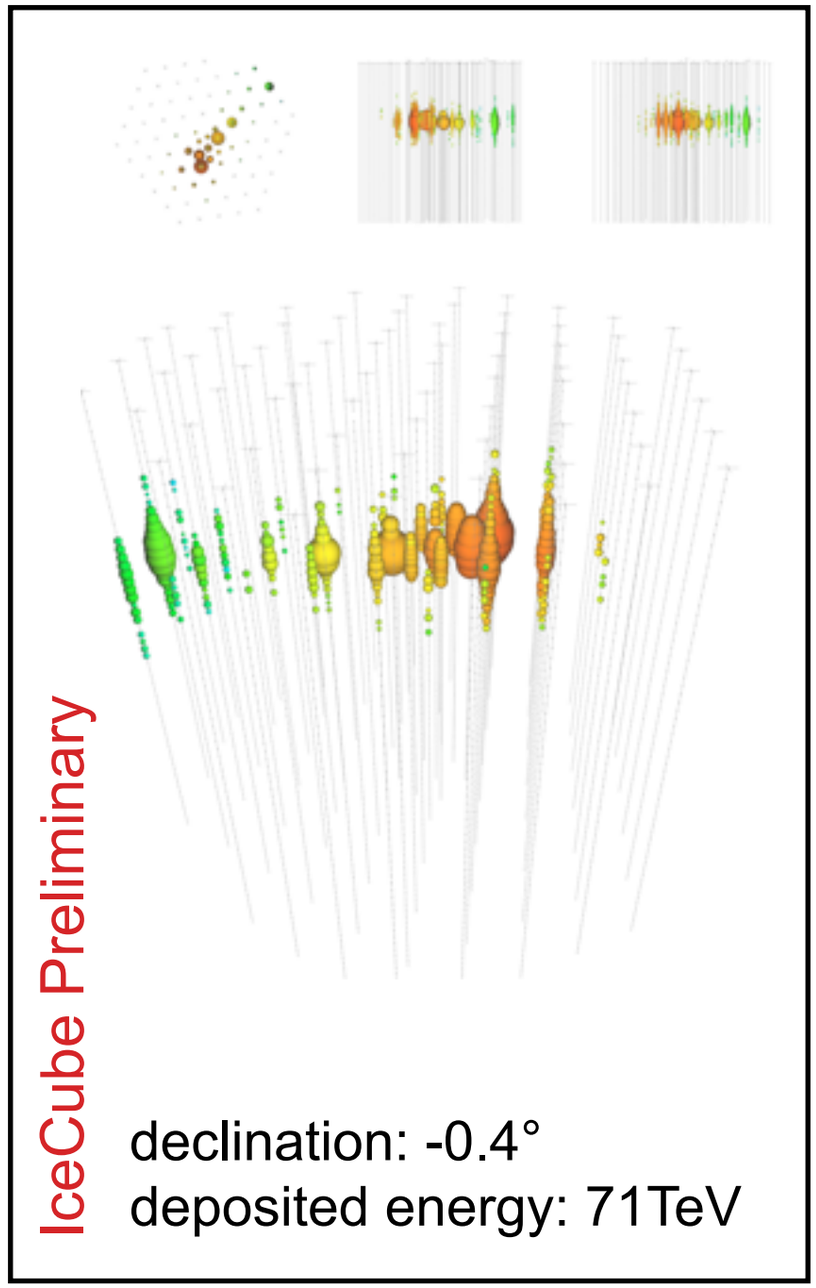
Summary.

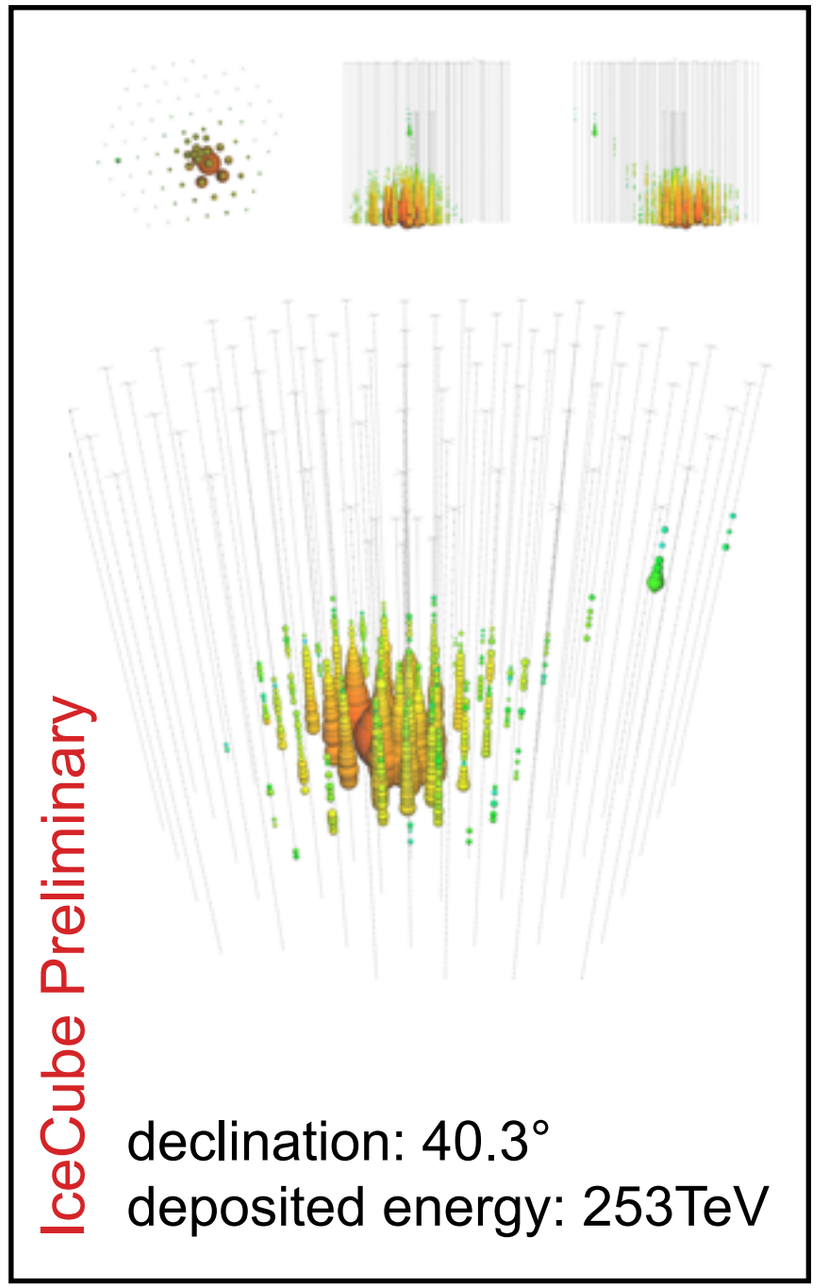
- After 6 years of construction the full IceCube detector is operating smoothly since 2011.
- Many exciting results and measurements in the last couple of years.
- First measurement of neutrino oscillations via ν_μ disappearance above 10 GeV.
- High-precision measurements of the CR spectrum and anisotropy with IceTop and IceCube detectors.
- Analysis of 2 years of full IceCube data results in a 4.1σ excess over atmospheric background expectations. Additional low-significance excesses found in construction phase data
- No clear statement on origin or distribution of the events possible at the moment. Excess compatible with an isotropic flux of astrophysical neutrinos.
- We are looking into a bright future....

Backup

Some interesting events.

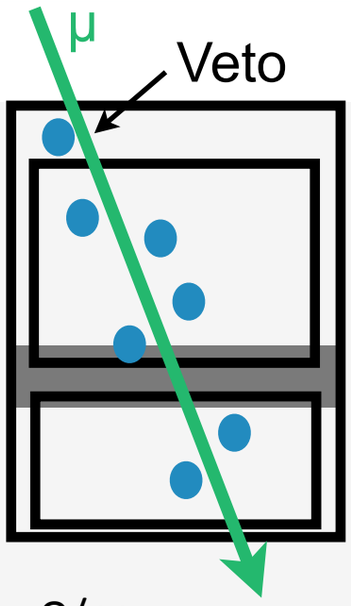






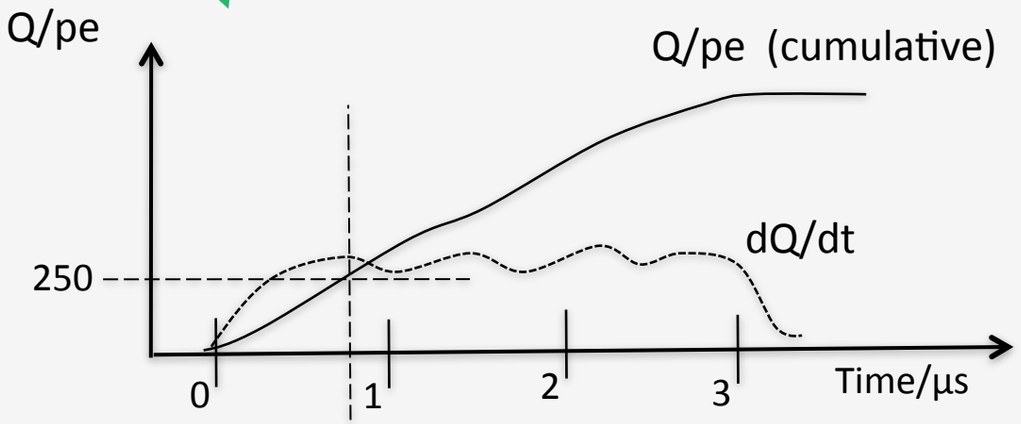
- events with clear signatures of out-going muon tracks

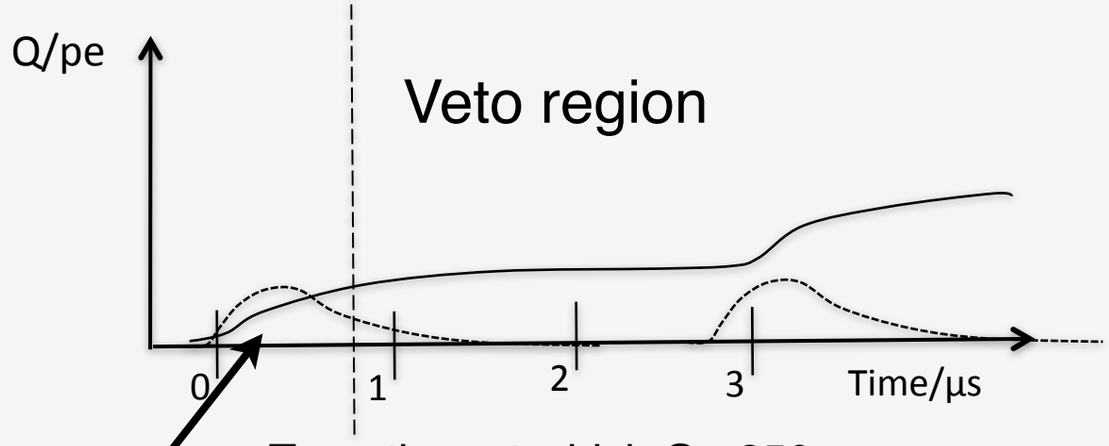
Atmospheric muon veto.



Through-going muon

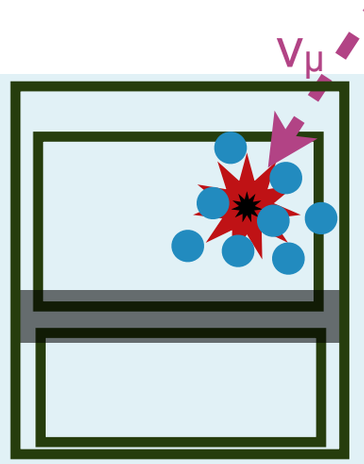
Total detector



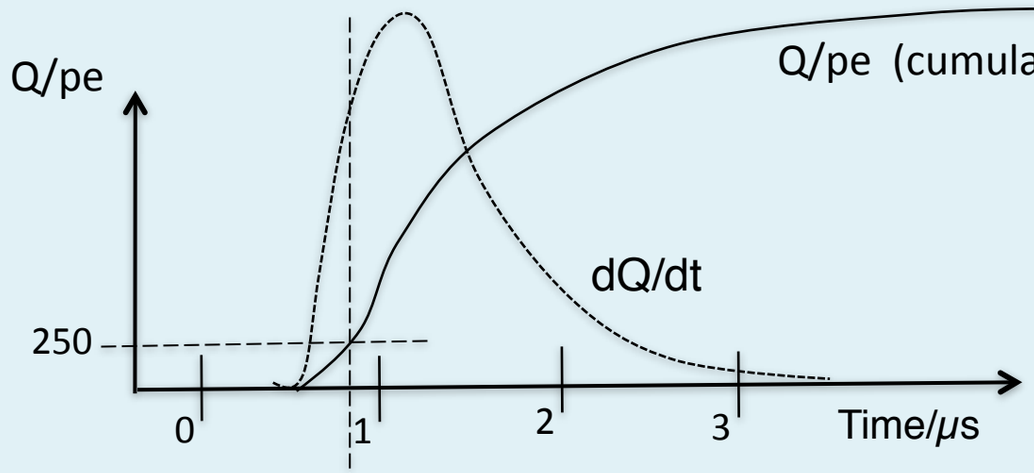


T_{250}= time at which Q= 250 pe

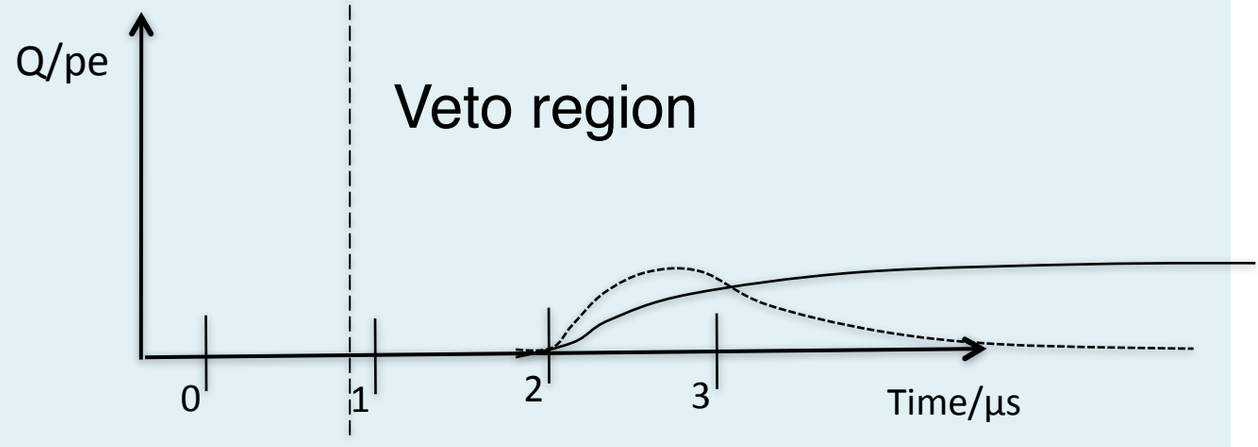
Contained cascade



Total detector



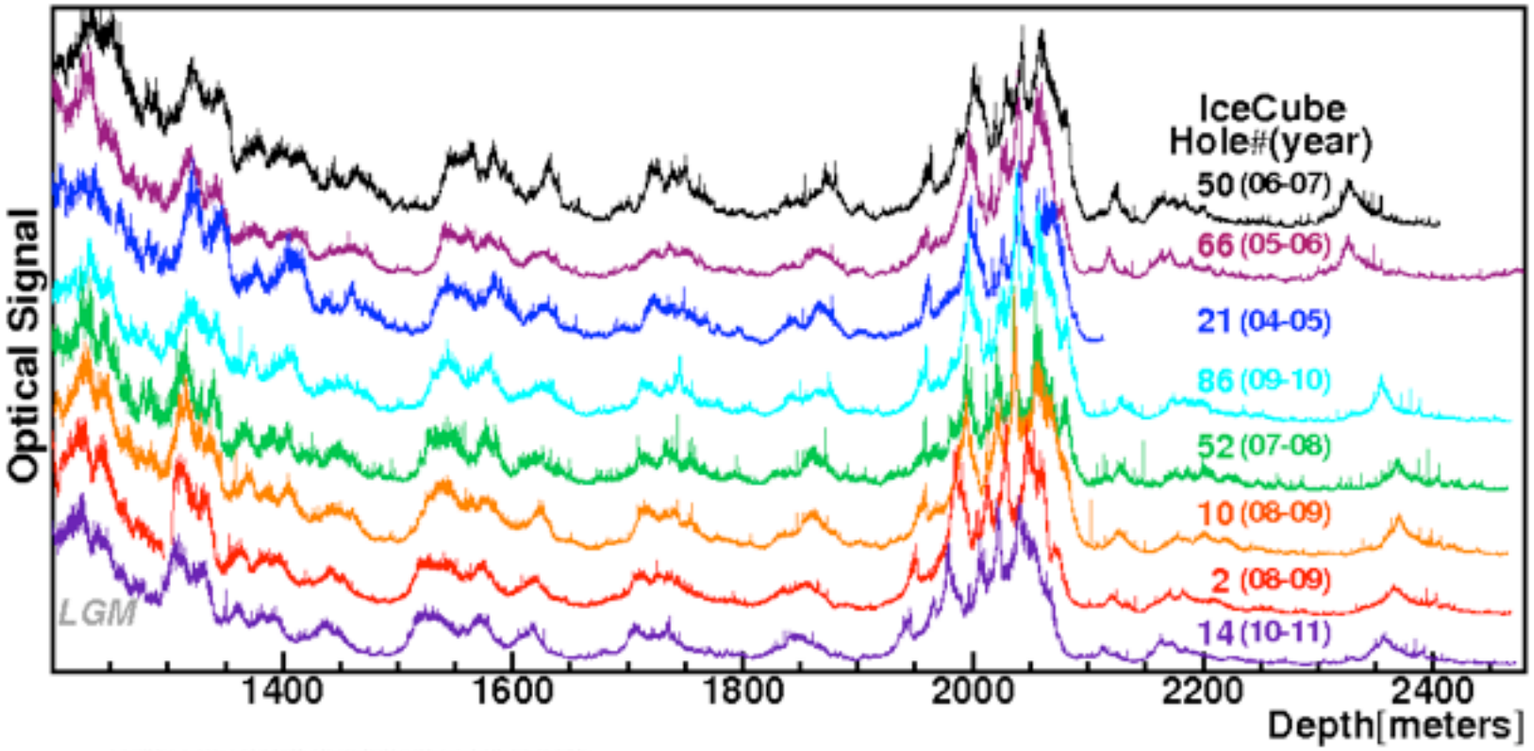
IceCube Preliminary



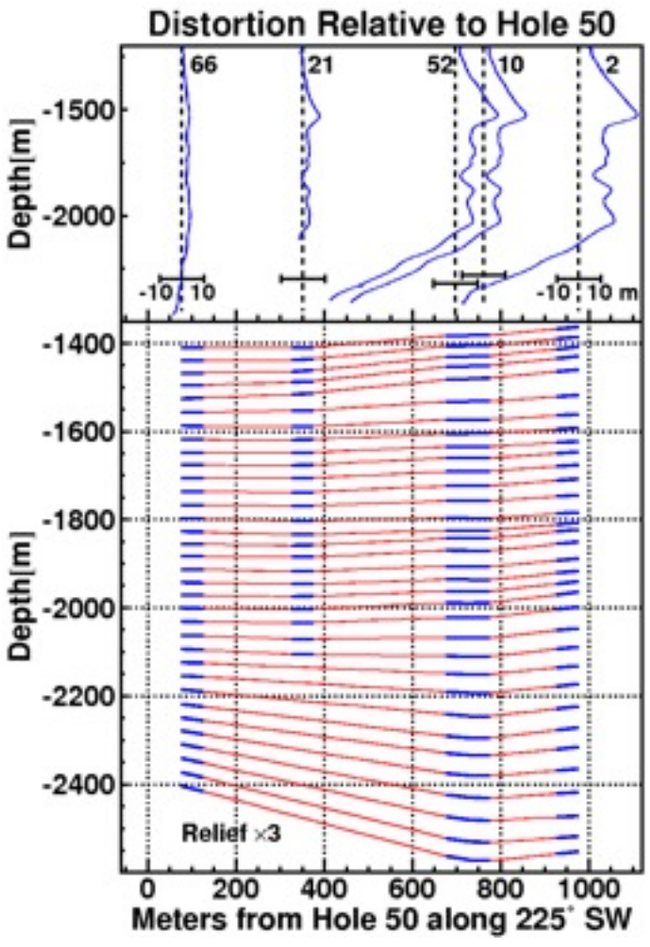
T_{250}= time at which Q= 250 pe

reject event if more than 3 pe (pe = photo-electron)

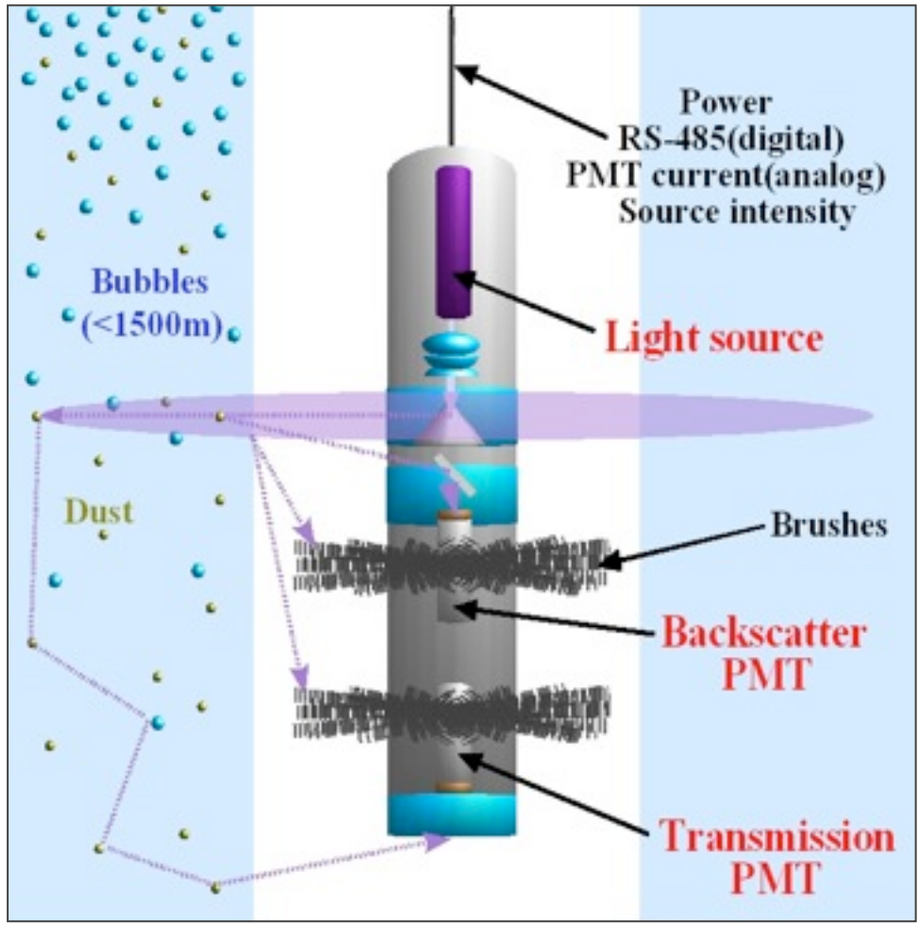
Optical properties of the South Pole Ice sheet.



- Measured during the deployment of IceCube by dedicated device: (“DustLogger”)
- In-situ measurements by artificial light sources.

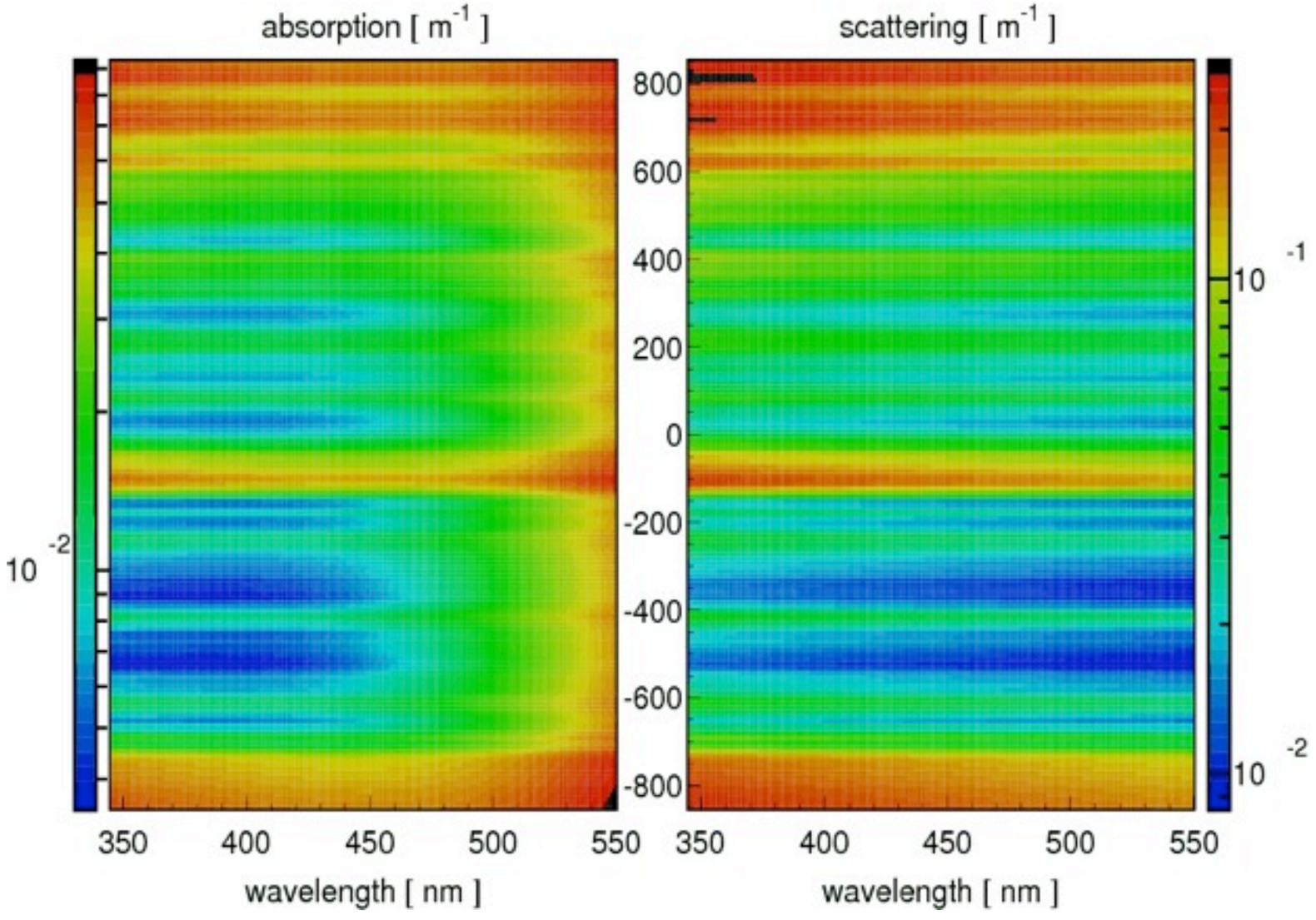


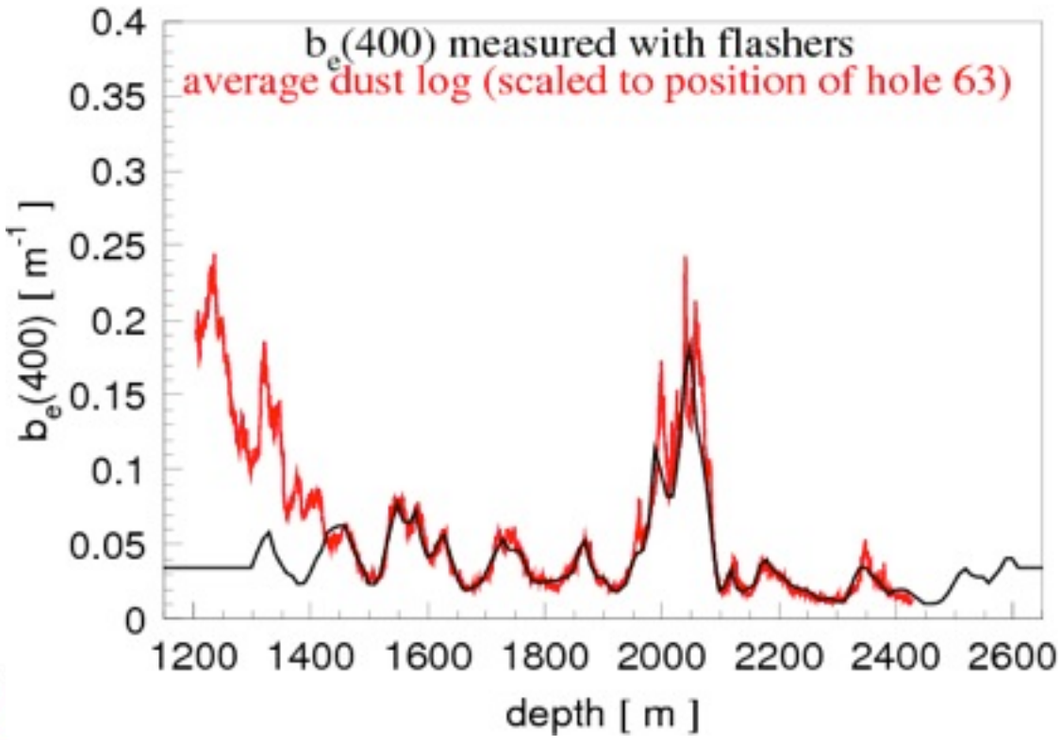
- Absorption and scattering of light in dust grains.
- Very inhomogenous due to deposits from the atmosphere over hundreds of millennia.

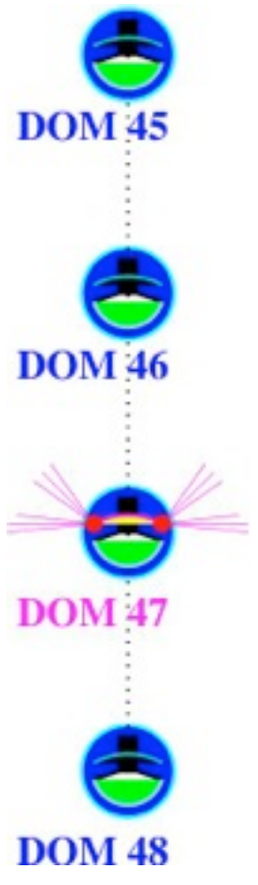


Optical properties of the antarctic ice sheet.

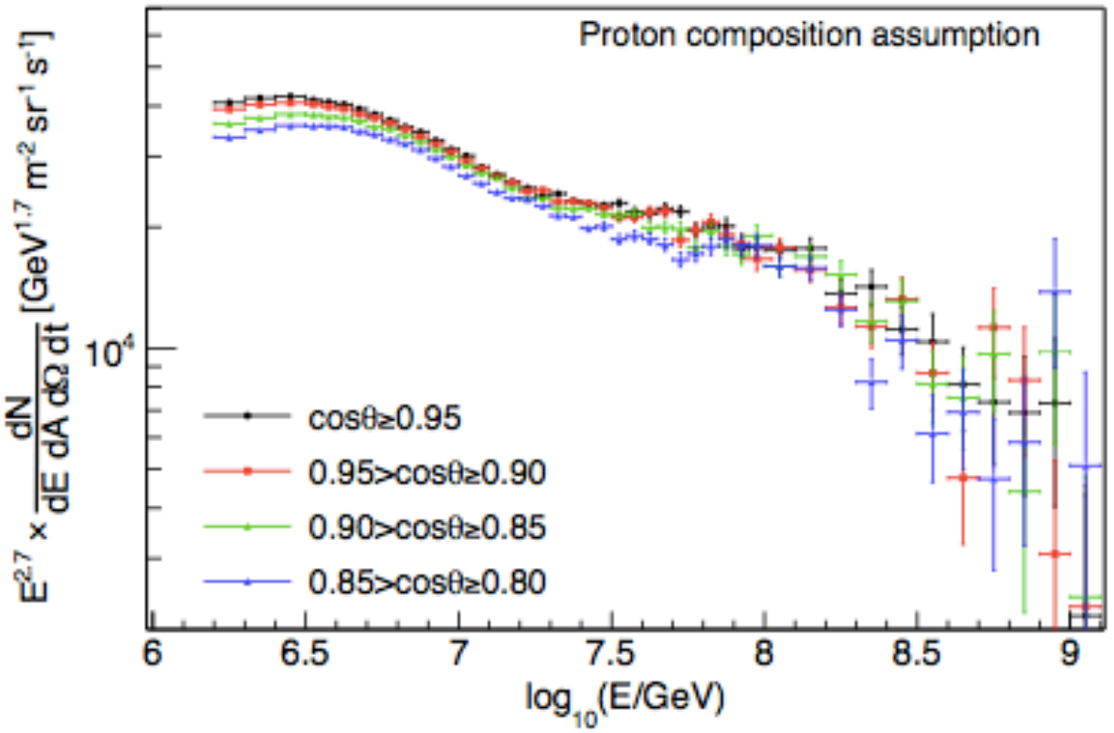
- Complex model of the optical properties necessary for simulation and reconstruction.
- For simulation: Massive parallel computing on GPU clusters used to trace the path of photons in the inhomogenous ice.



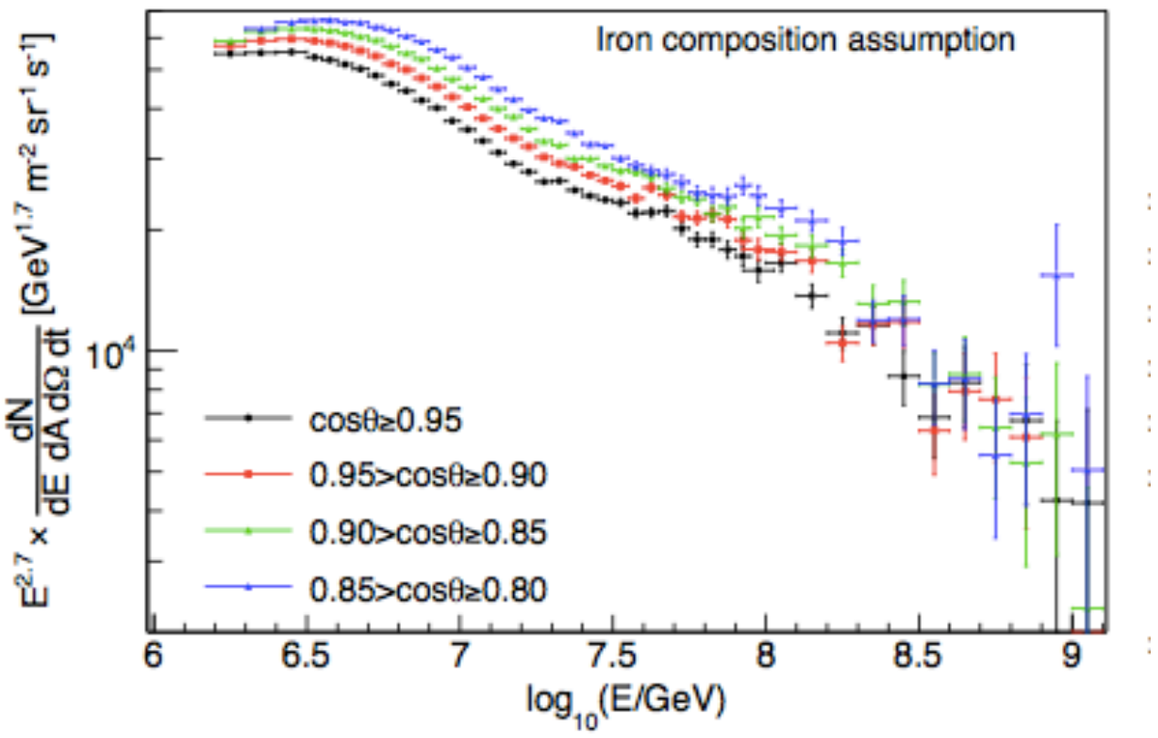




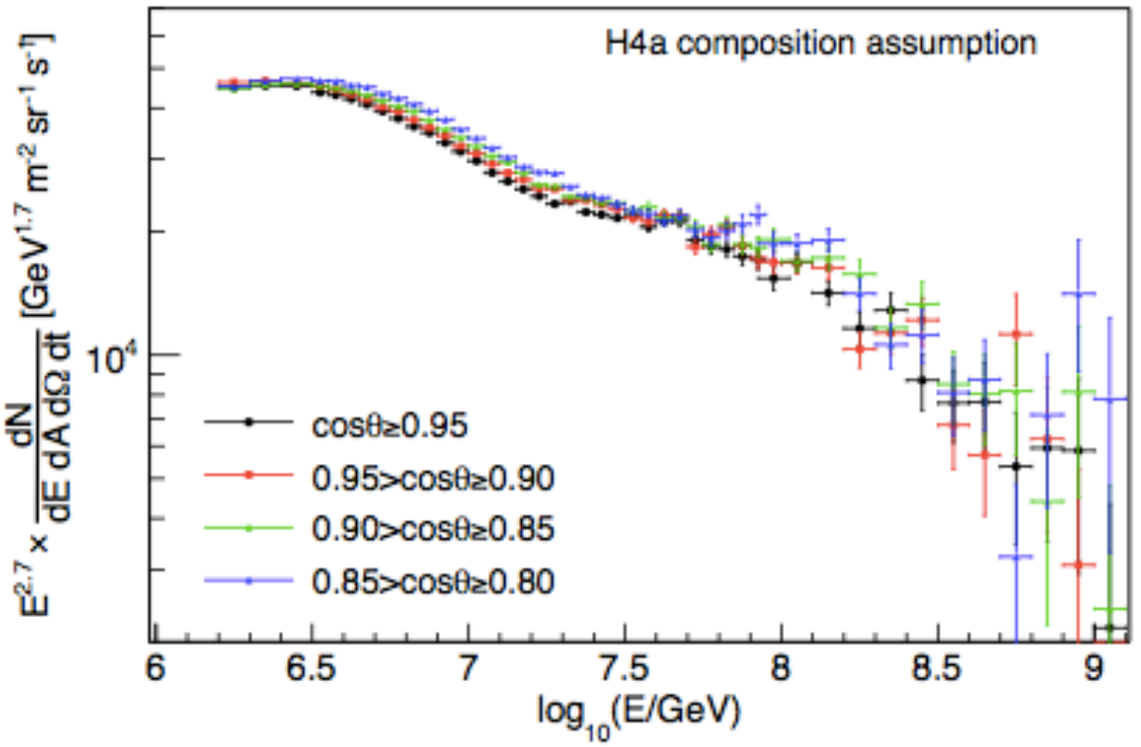
Effects of composition on CR spectrum.



(a)Proton.



(b)Iron.

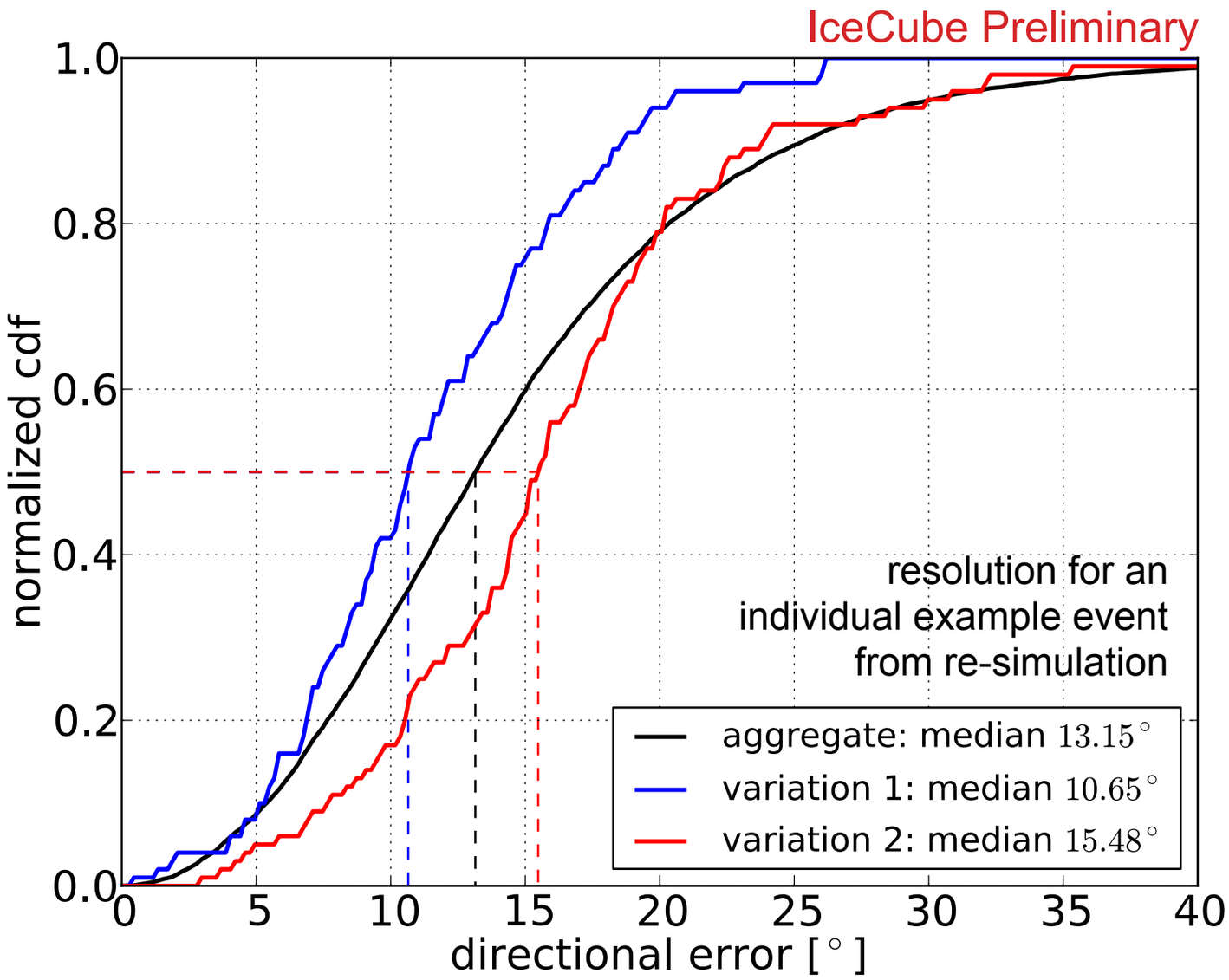


(c)H4a.

Showers: directional reconstruction.

Angular error distributions on the order of 10°-15° depending on ice model assumption

- Two ice examples are shown
- Average resolution in black



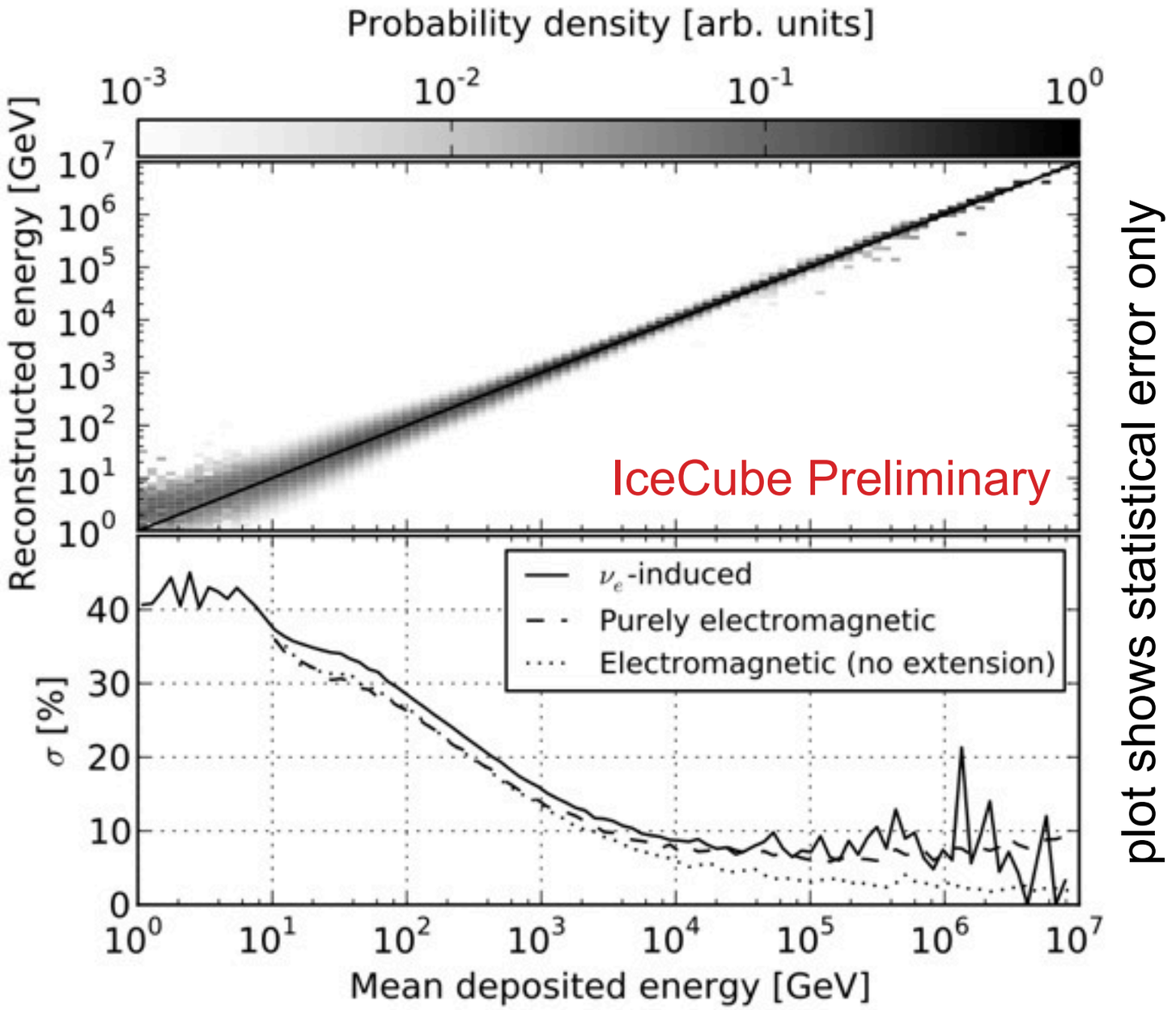
Showers: energy reconstruction

Energy calibration

- LED flashers
- In-ice calibration laser
- Atmospheric neutrino energy spectrum
- Minimum-ionizing muons

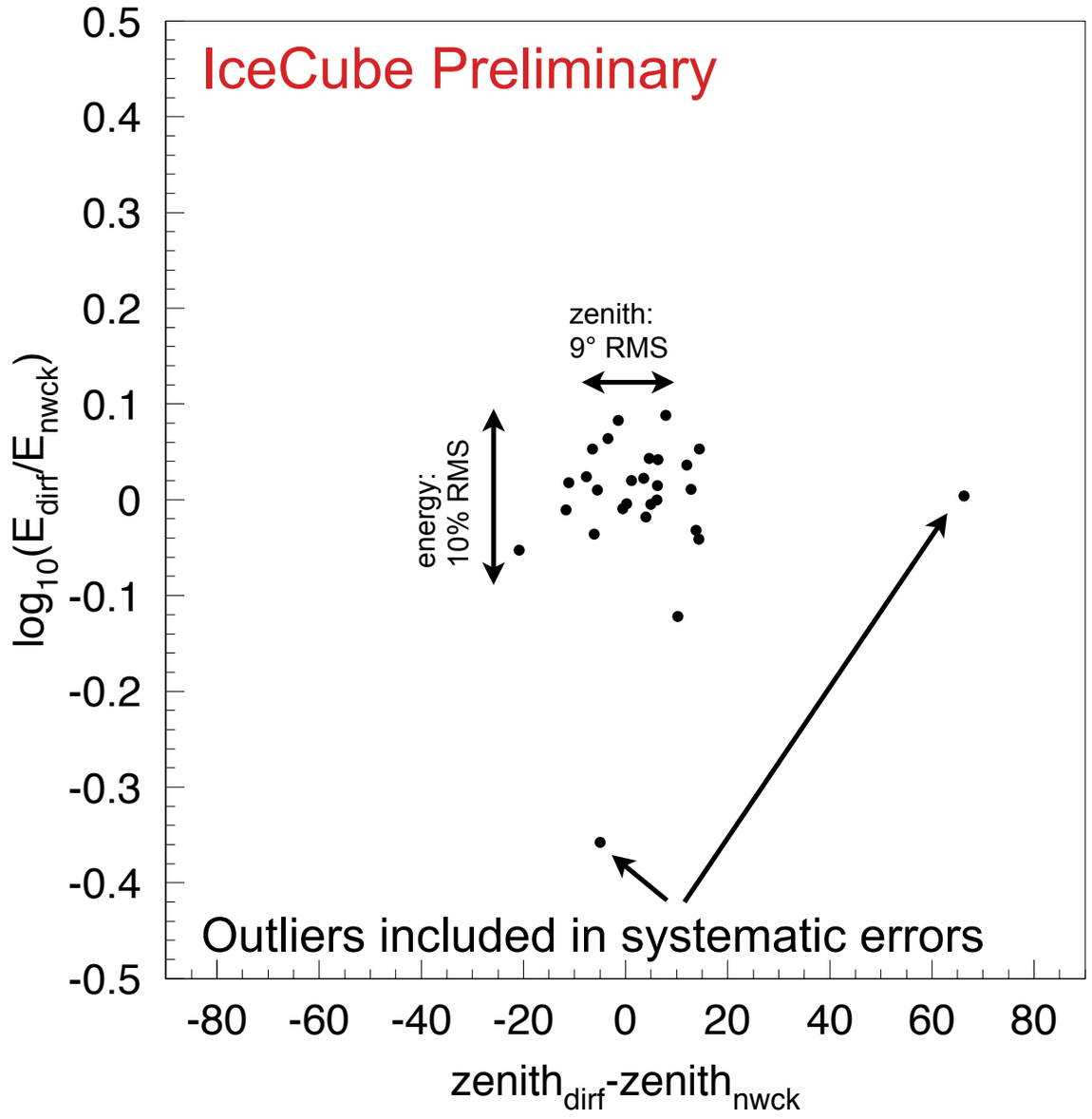
Results

- Energy resolution < 10% above 10 TeV
- Systematics limited ≳ 10 TeV



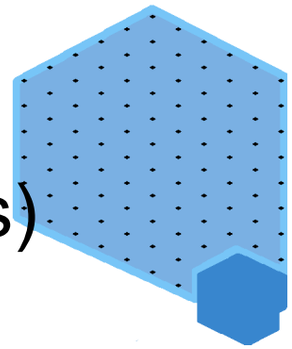
Systematic checks.

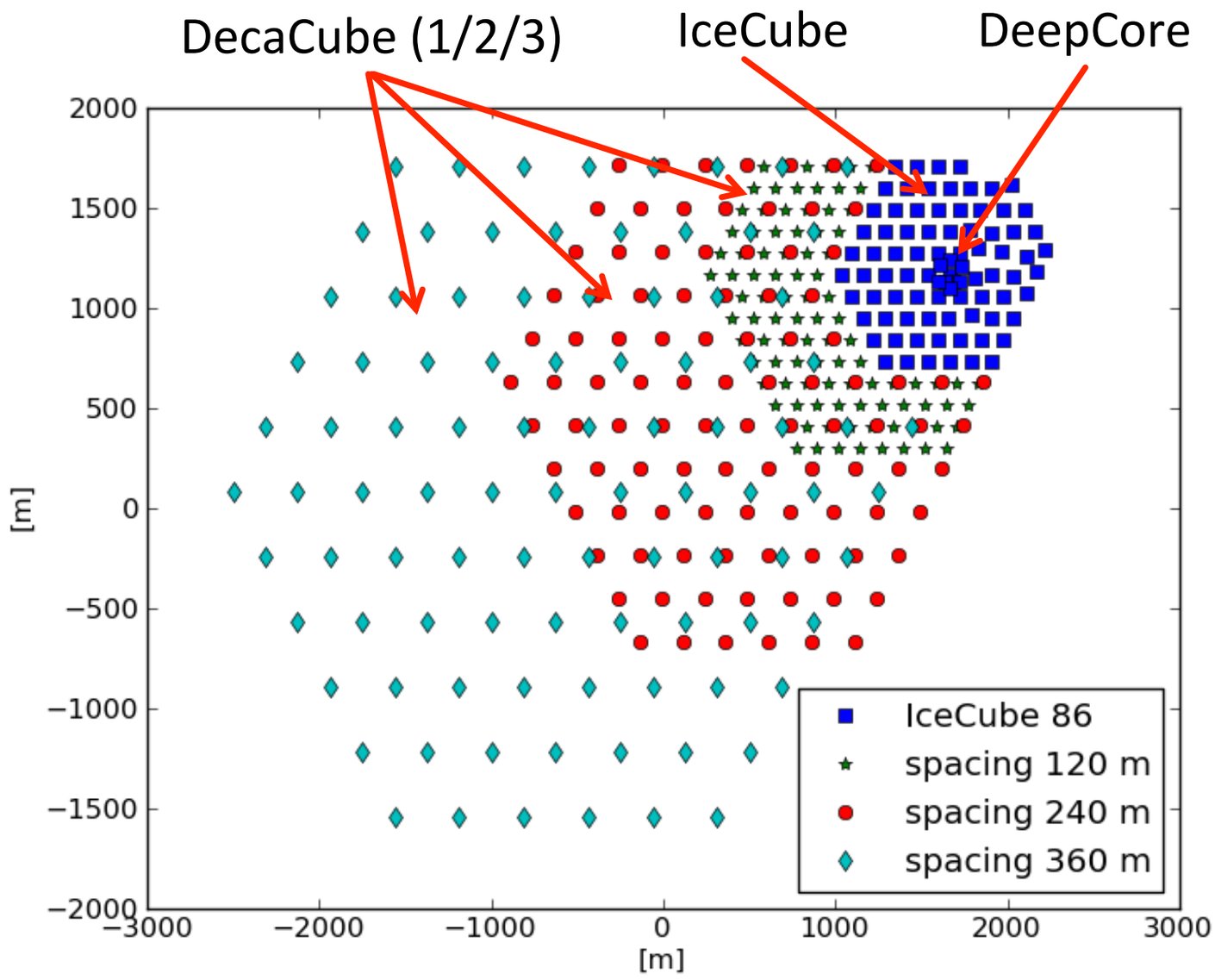
- Second fit method based on continuous re-simulation of events
  - can include ice systematics like directional anisotropy in the scattering angle distribution and tilted dust layers directly in the fit!
  - very slow, works for shower-like events
- Shown: comparison with other method
- Within these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



Click to add title.

increase in threshold not important
(in the region where atmospheric background dominates)





Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3