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Results from the IceCube Neutrino Observatory

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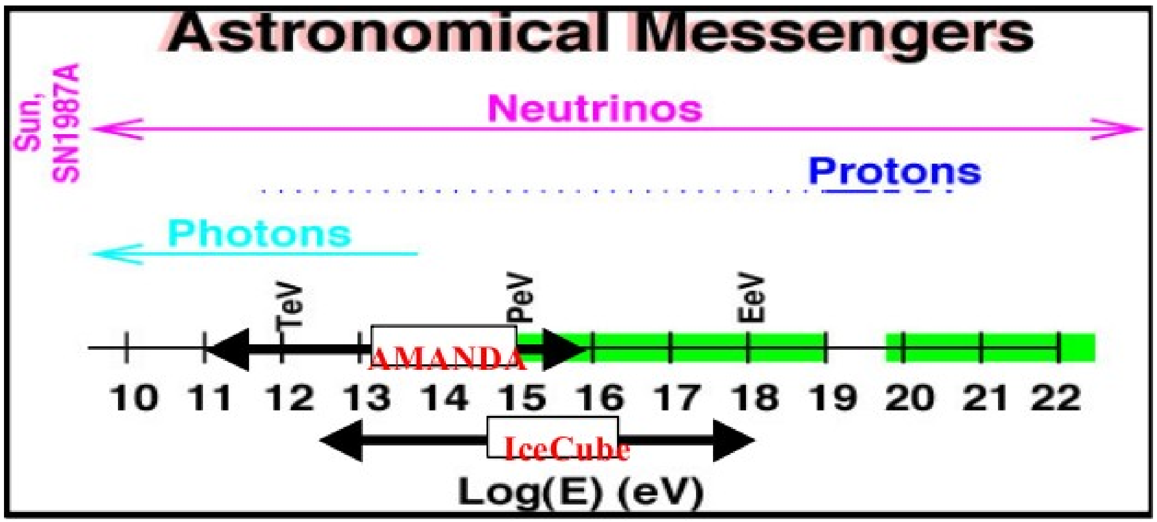
on behalf of the IceCube Collaboration

The IceCube Collaboration

International Funding Agencies

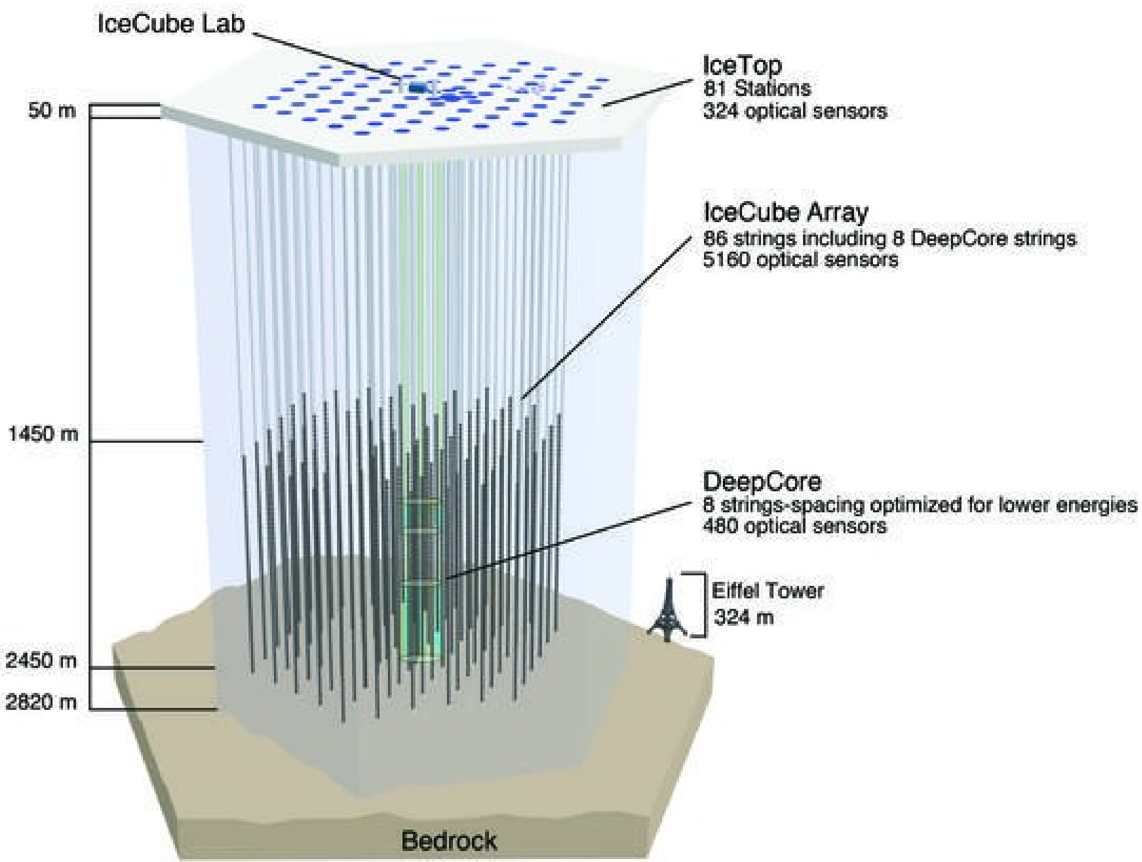
- Fonds de la Recherche Scientifique (FRS-FNRS)
- Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
- Federal Ministry of Education & Research (BMBF)
- German Research Foundation (DFG)
- Deutsches Elektronen-Synchrotron (DESY)
- Knut and Alice Wallenberg Foundation
- Swedish Polar Research Secretariat
- The Swedish Research Council (VR)
- University of Wisconsin Alumni Research Foundation (WARF)
- US National Science Foundation (NSF)

Astronomical messengers



- photons: absorbed at high energies
- protons: deflected below 10 EeV and attenuated above 50 EeV
- neutrinos: cover all energies
- neutrinos are hard to detect -> very large detector is needed ($\sim 1km^3$) IceCube detector

IceCube Detector



IceCube is a 1 km^3 neutrino telescope:

- 86 strings with 60 Digital Optical Modules (DOMs) per string
- DOMs located from 1450m to 2450m deep in Antarctic ice
- 81 strings have 2 IceTop surface tanks with 2 DOMs per tank

2006-2007 data set - IC9

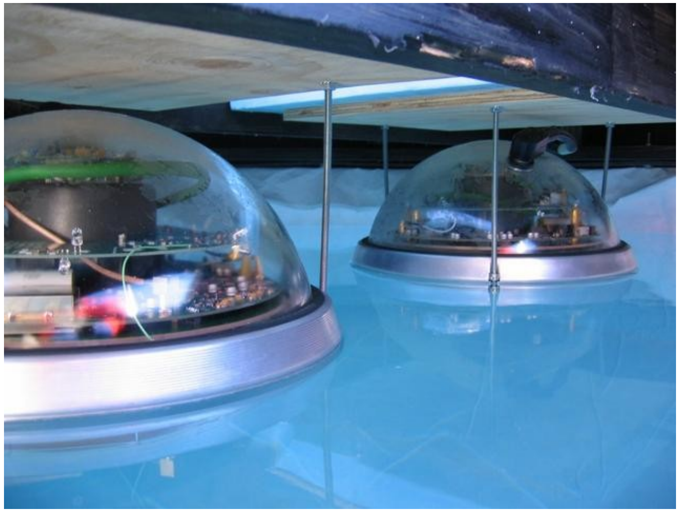
2007-2008 data set - IC22

2008-2009 data set - IC40

2009-2010 data set - IC59

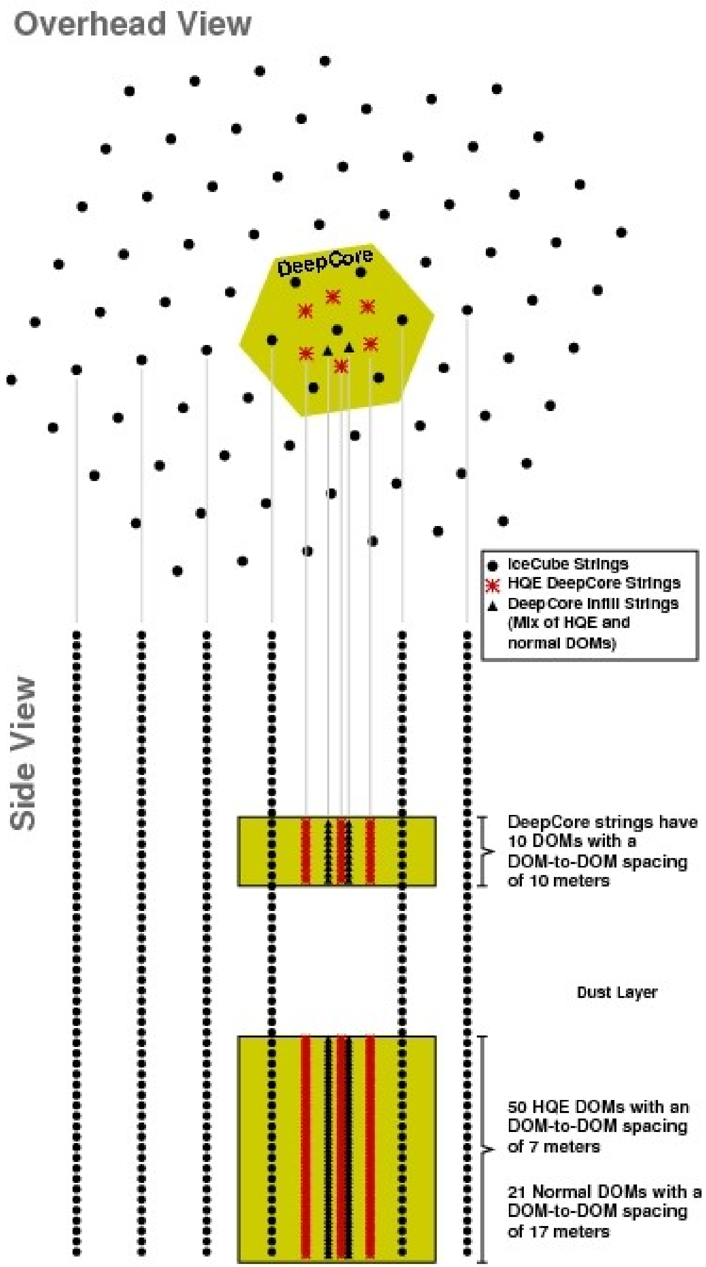
2010-2011 data set - IC79

2011-present data set – IC86 final configuration



IceTop tank

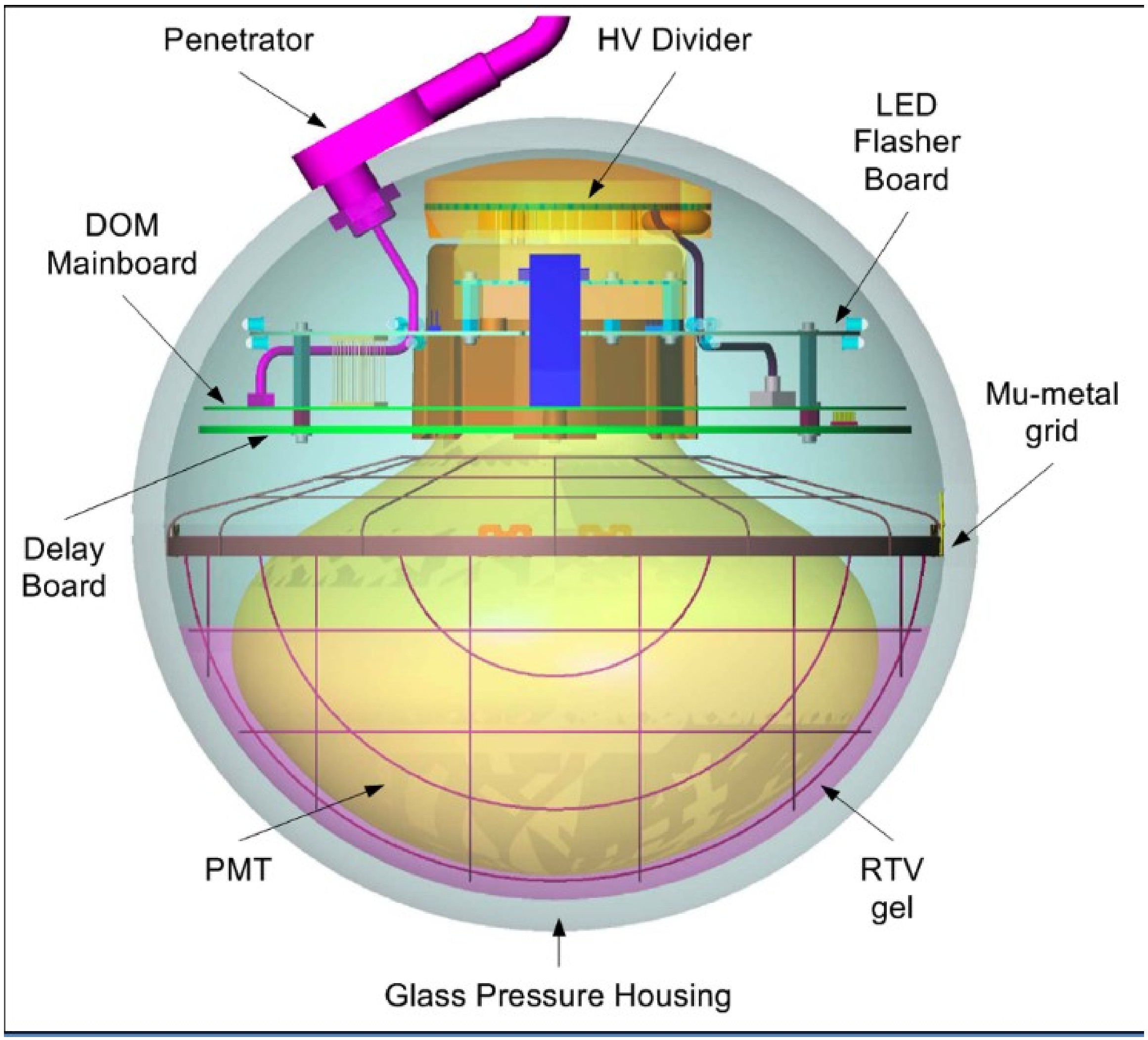
Deep Core



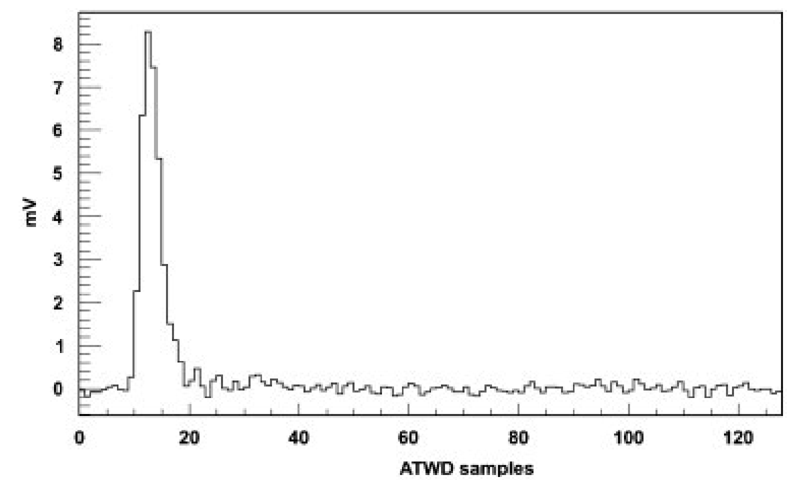
Deep Core is a low energy extension of IceCube

- 8 strings with high quantum efficiency DOMs
  - HQE DOMs are 35% more efficient
  - most HQE DOMs are located in the clearest ice
  - denser string-to-string and DOM-to-DOM spacing then standard IceCube strings
- ~25MT instrumental volume
- uses IceCube outer strings as a veto

Digital Optical Module (DOM)



- digitize PMT signal in ice
- contain flasher board with 12 LED's used for calibration



Digitized PMT waveform

ICECUBE

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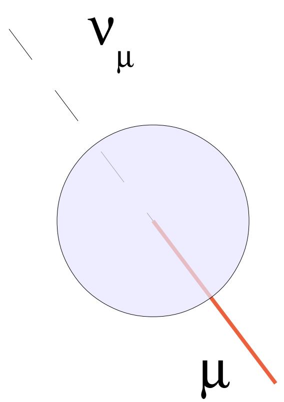
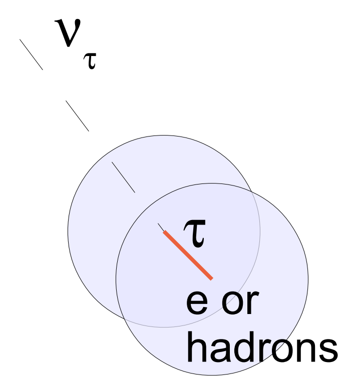
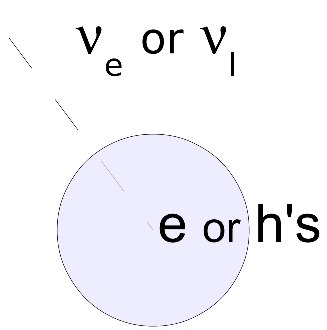
ν signals in IceCube



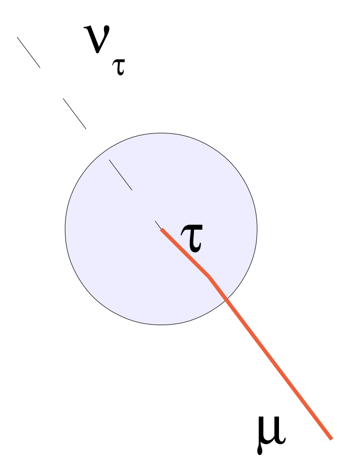
Cascade and track
(ν_μ CC interaction)



Two cascades and a track
(ν_τ CC interaction)

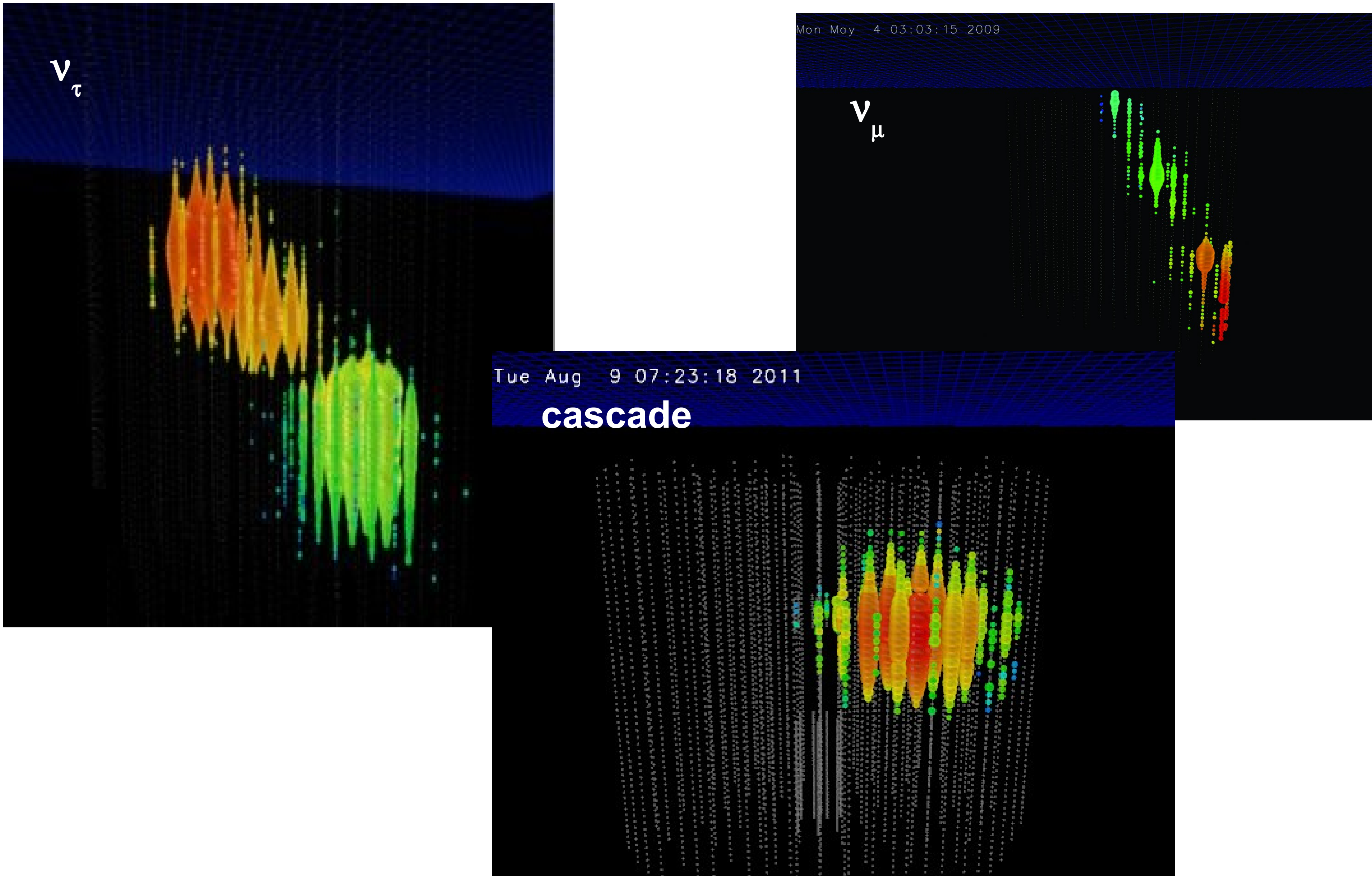


EM cascade
(ν_e CC interaction)
or hadron cascade
(NC interaction, all flavors)

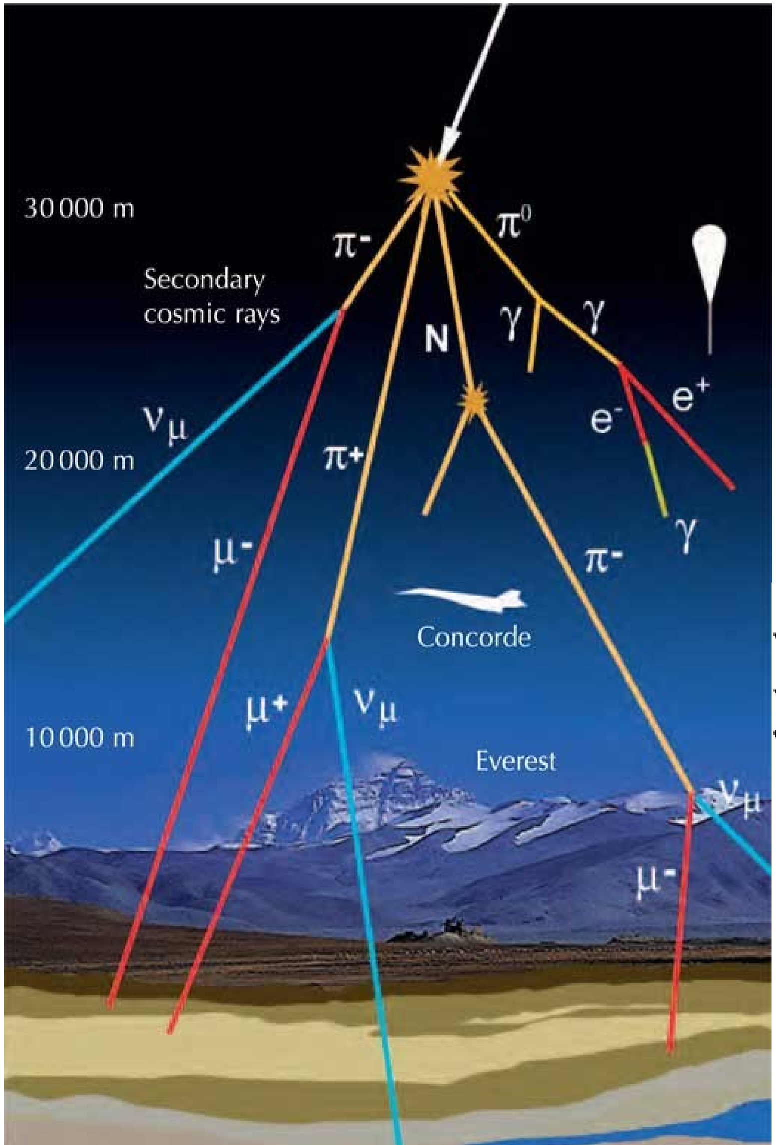


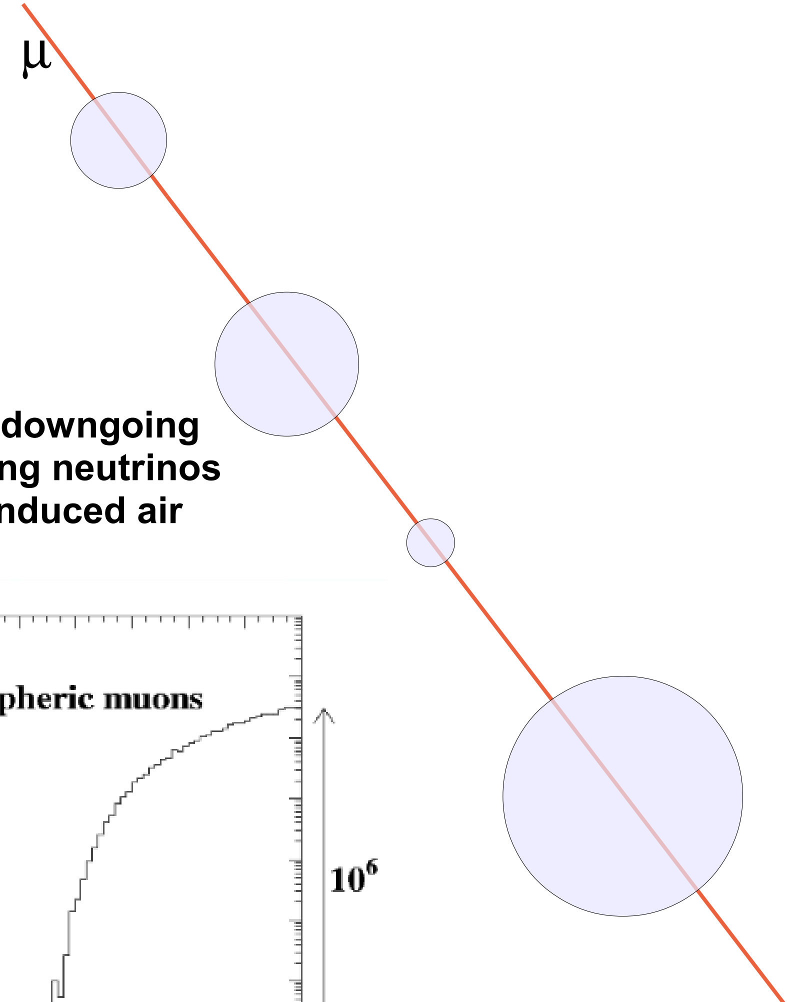
Cascade and track
(ν_τ CC interaction)

ν signals in IceCube

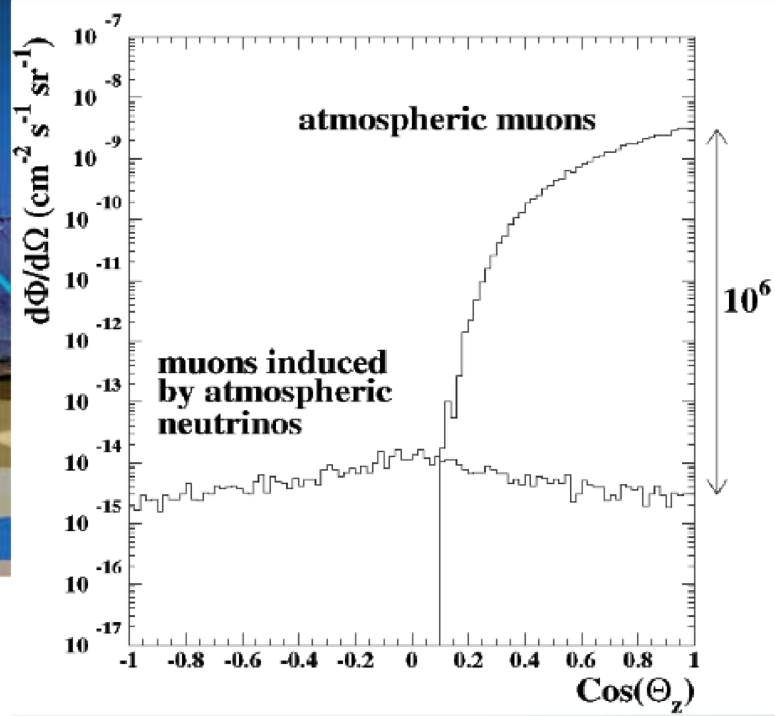


Background signals

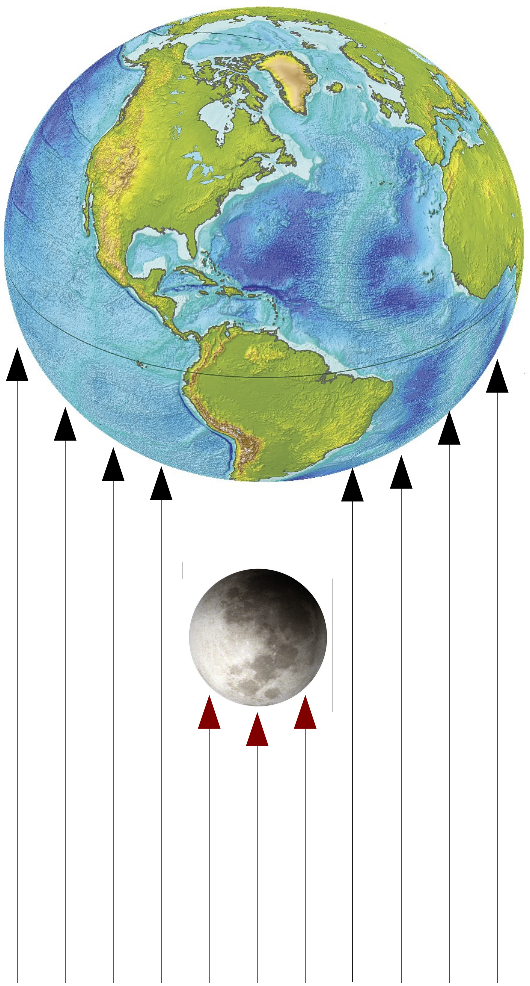


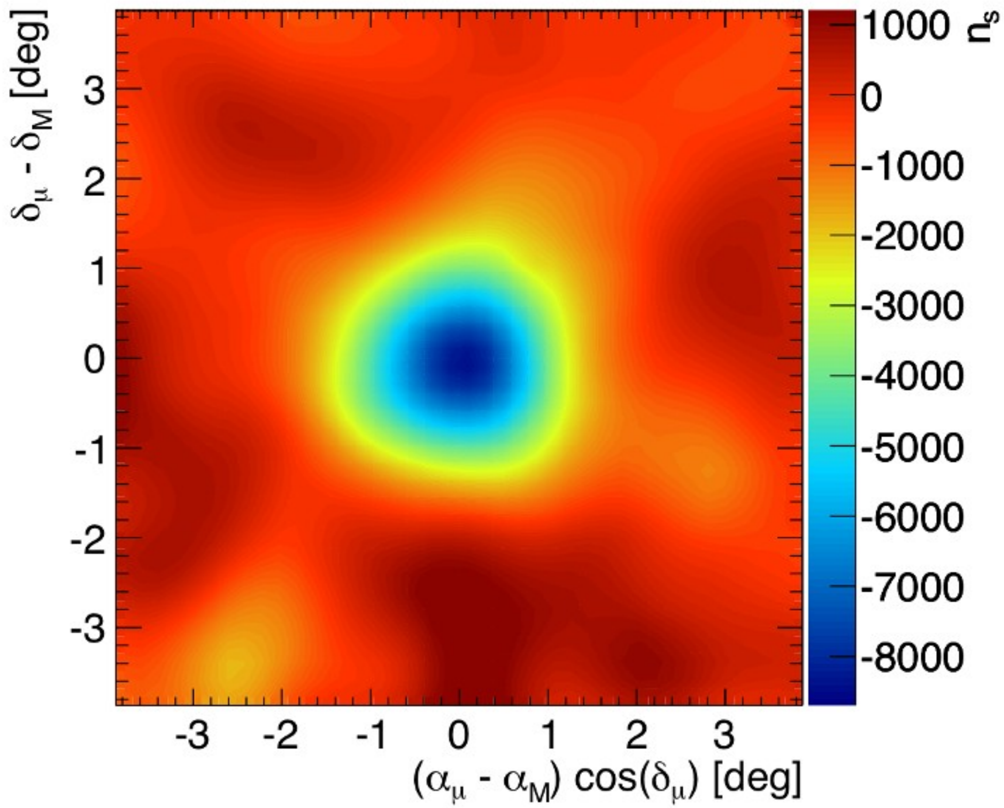


Backgrounds are downgoing muons and upgoing neutrinos from cosmic ray induced air showers



Moon shadow





- ➢ Use cosmic ray shadow of the Moon to demonstrate IceCube angular resolution and pointing
- ➢ Detected in IC40 (April 2008 – May 2009) and IC59 (May 2009 – May 2010)
- ➢ Significance of Moon shadow is > 10σ
- ➢ 1σ width of the Moon shadow is 0.7 degree

Astrophysical neutrinos

Possible astrophysical neutrino sources include:

- active galactic nuclei
- gamma ray bursts
- supernova remnants
- unknown sources?

Production mechanism:

$p+p(\text{or } \gamma) \rightarrow \pi^0 \rightarrow \gamma$

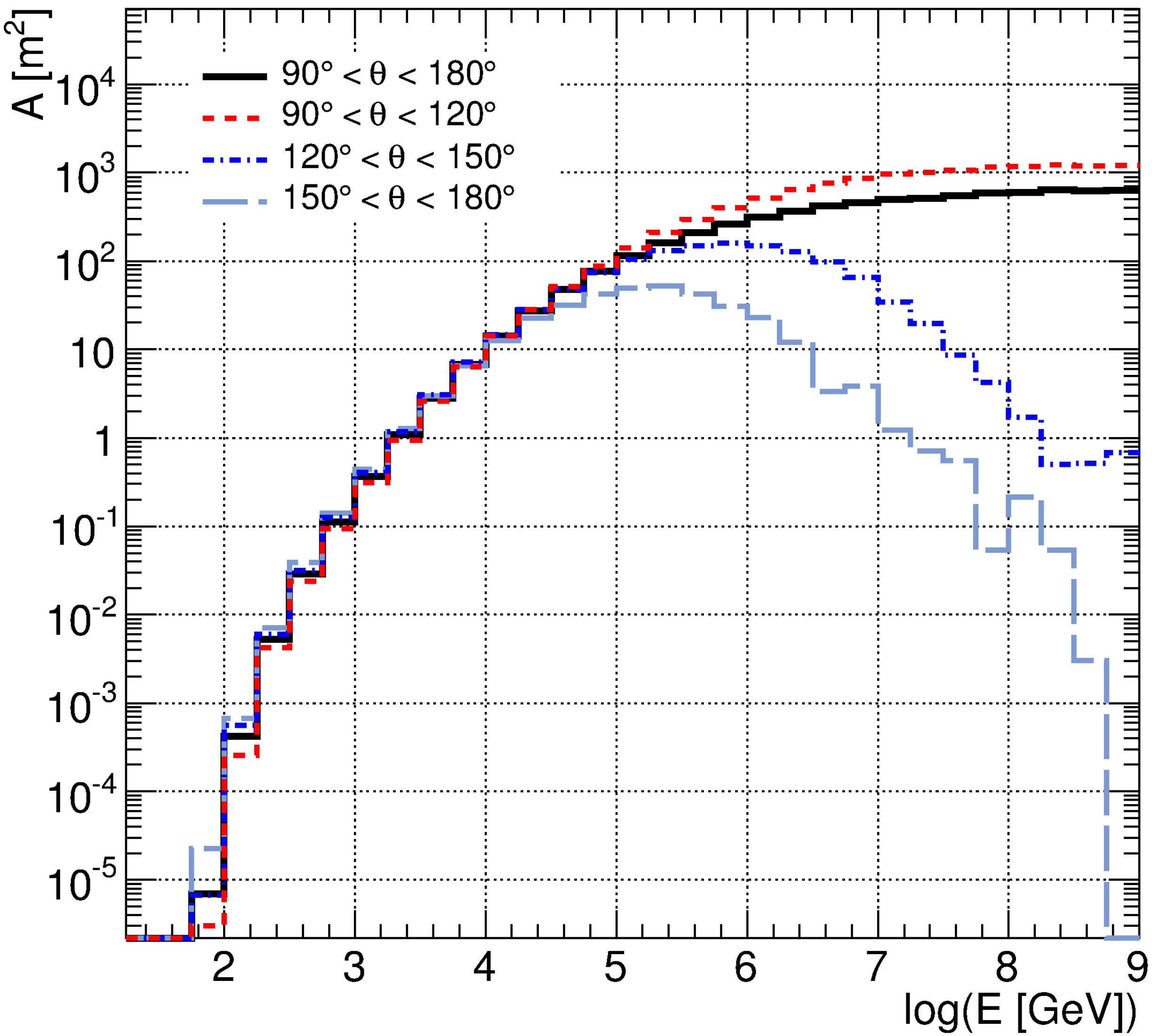
$\quad \hookrightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$

$\quad\quad \hookrightarrow e^{\pm} + \nu_{\mu} + \nu_{e}$

ν's initial flavor ratio is (1:2:0) $\rightarrow$ (1:1:1) ratio due to oscillation
There is a prediction of (1:1.8:1.8) flavor ratio at high energies

$dN/dE \sim E^{-2}$ - astrophysical neutrino spectrum

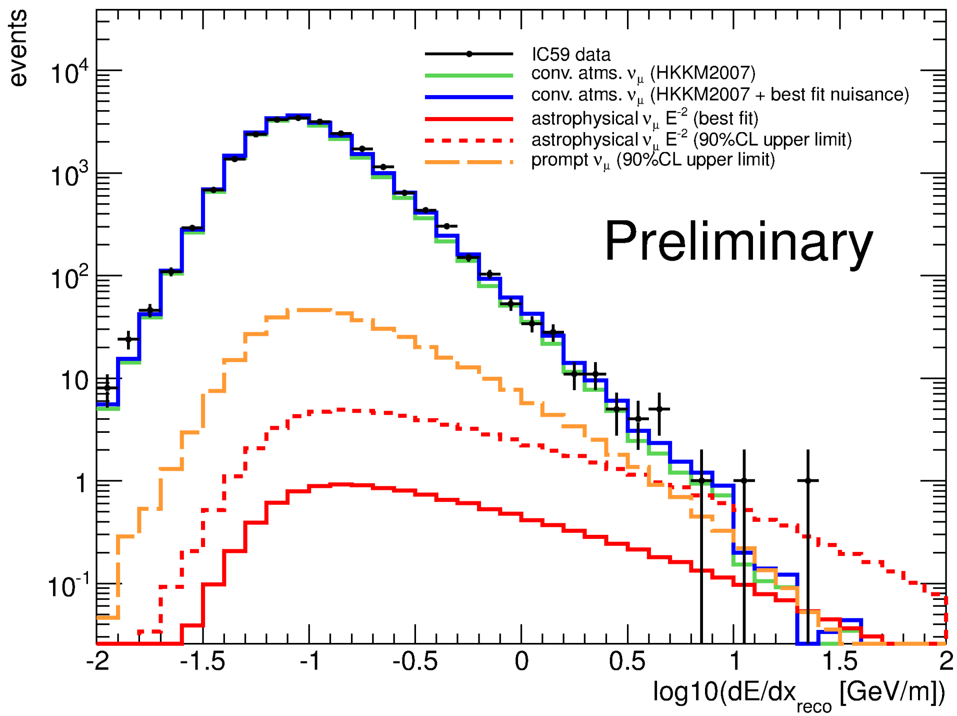
Diffuse muon neutrino search IC59



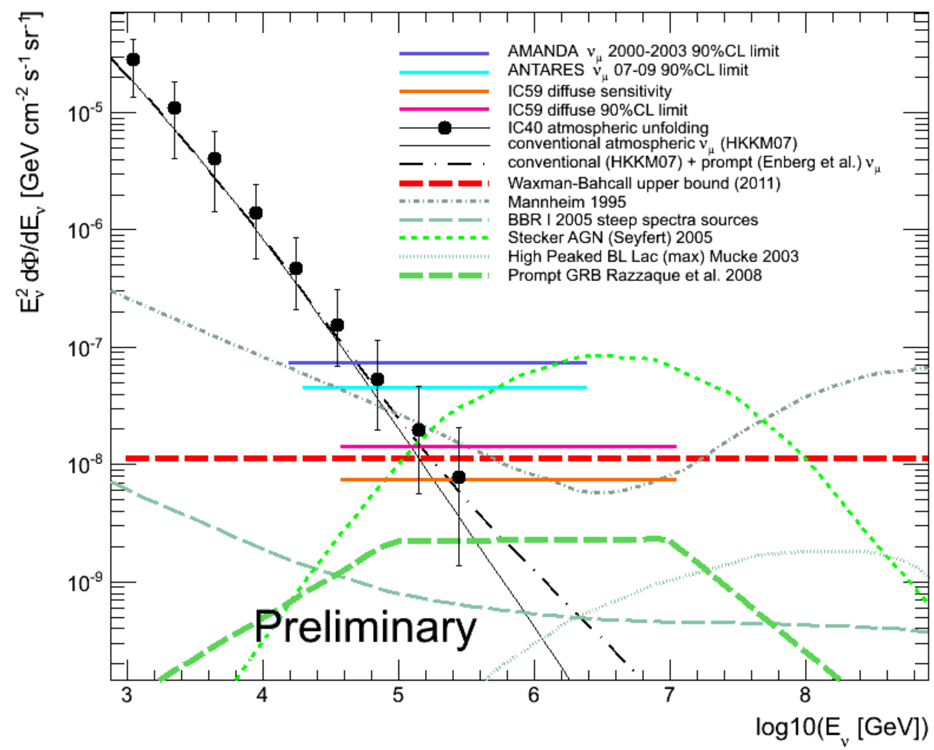
Neutrino effective area versus energy for different zenith angles

- Astrophysical neutrinos are expected to have E^{-2} spectrum, while atmospheric have softer $E^{-3.7}$ (conventional) or $E^{-2.7}$ (prompt) spectrum
- Looking for upward going tracks above atmospheric neutrino spectrum

Diffuse muon neutrino search IC59



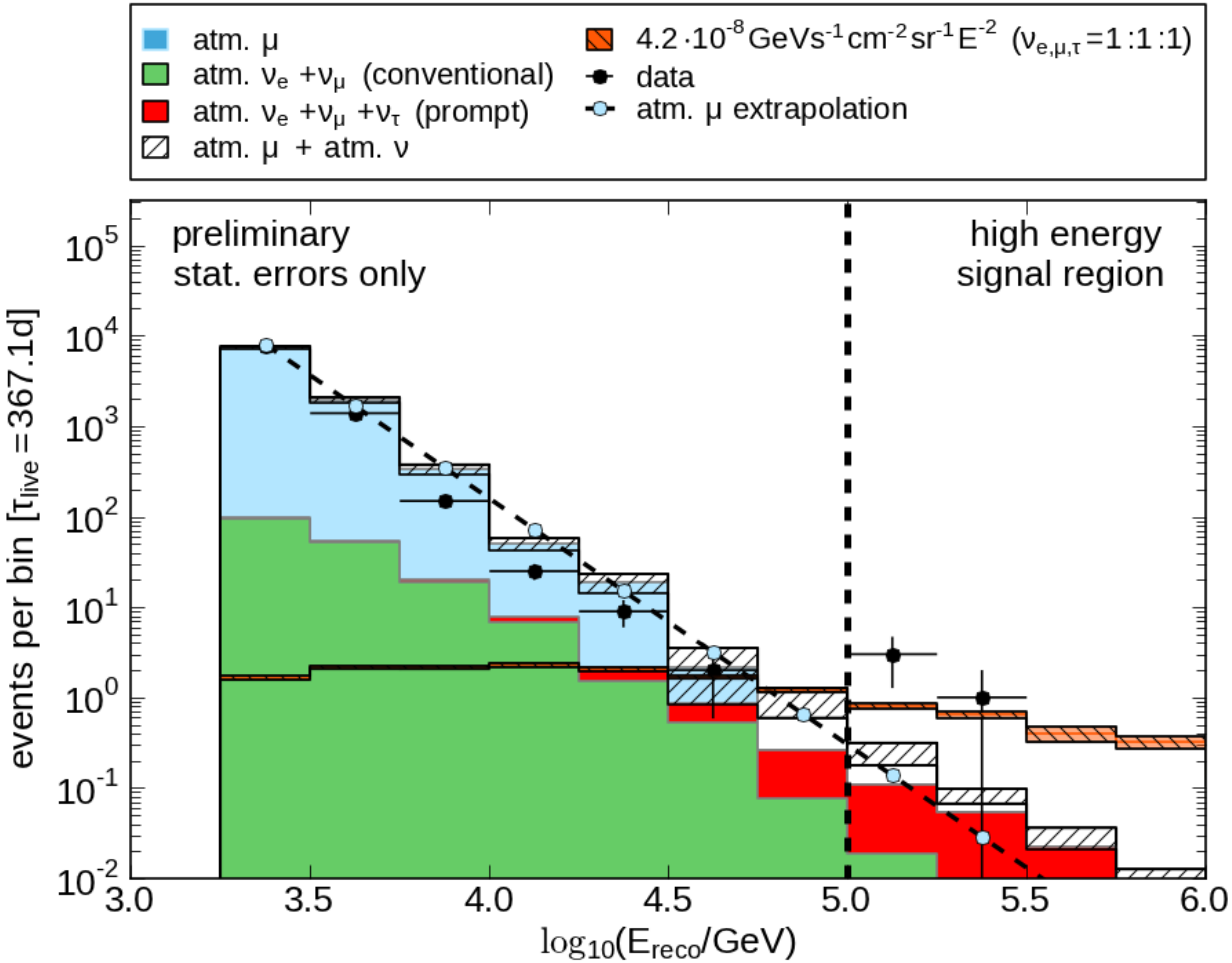
Event spectrum for muon neutrino



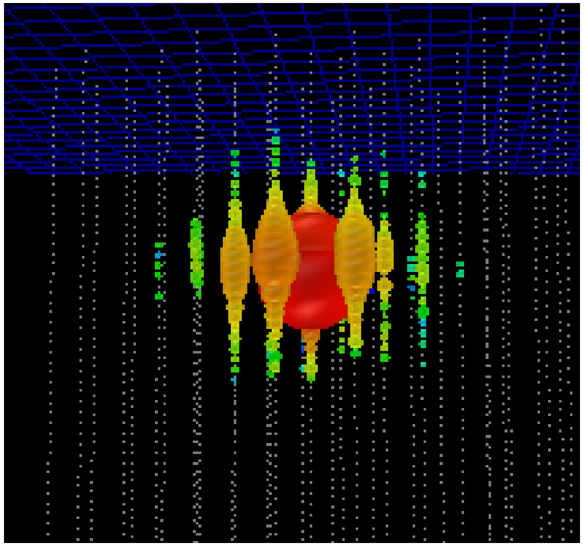
Final muon neutrino limit from IC59 analysis

Best fit astrophysical flux is not 0, but consistent with 0 at less than 2 σ

Diffuse cascade search in IC40



- The analysis uses 367.1 days of livetime (April 2008 to June 2009)
- Events must pass reconstructed energy threshold E_{reco}>100TeV
- Events must pass shape cuts (selecting spherical events)
- Incident muons are vetoed
- Events with early hits are rejected
- 3 events were found with 2.4σ excess over atmospheric muons and neutrinos



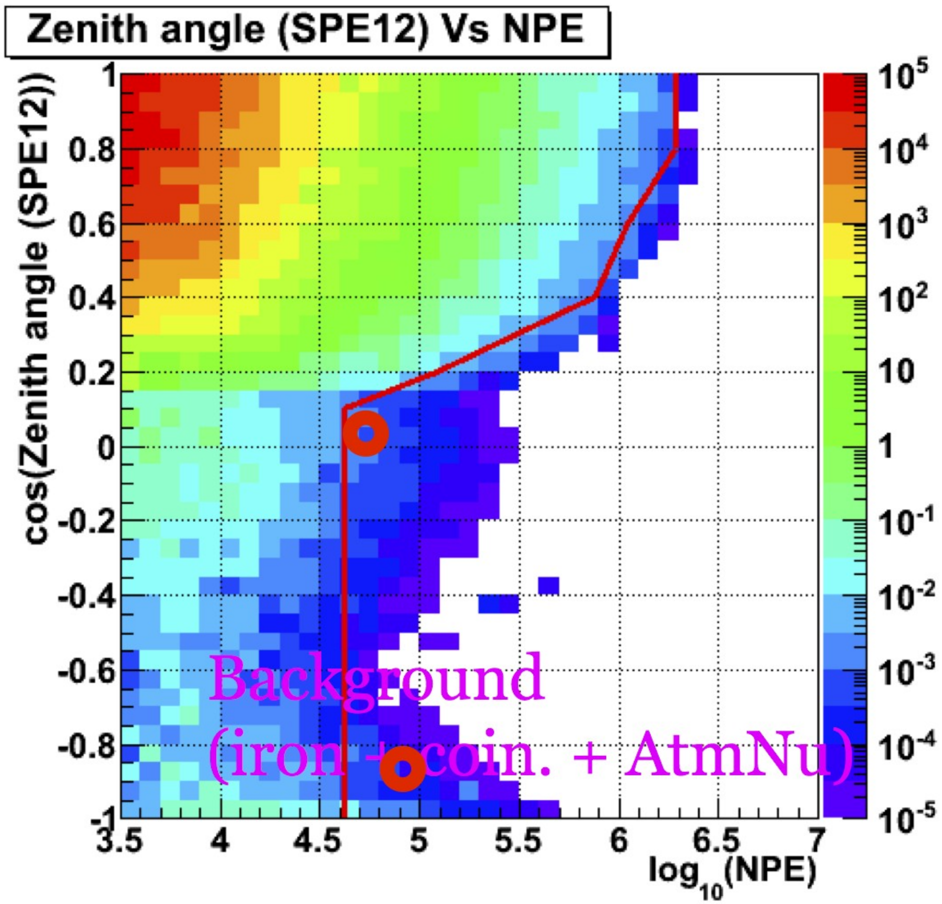
Ultra high energy neutrinos in IC79 and IC86

Background sources:

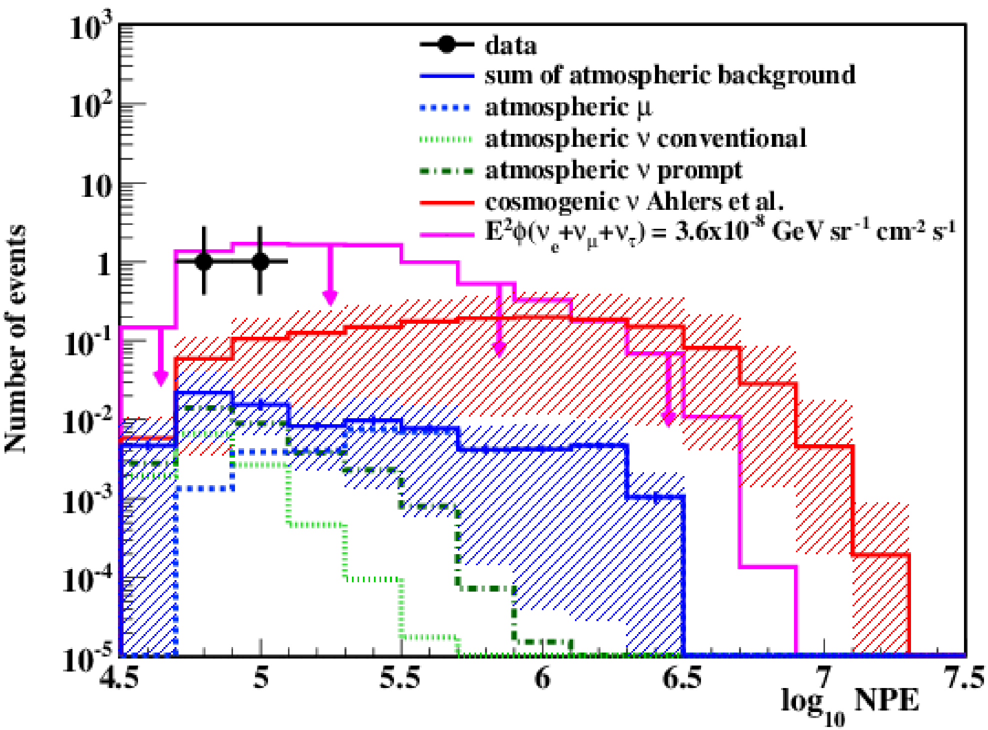
- Neutrinos generated in atmospheric showers
- Highest energy down going muons

Selection criteria:

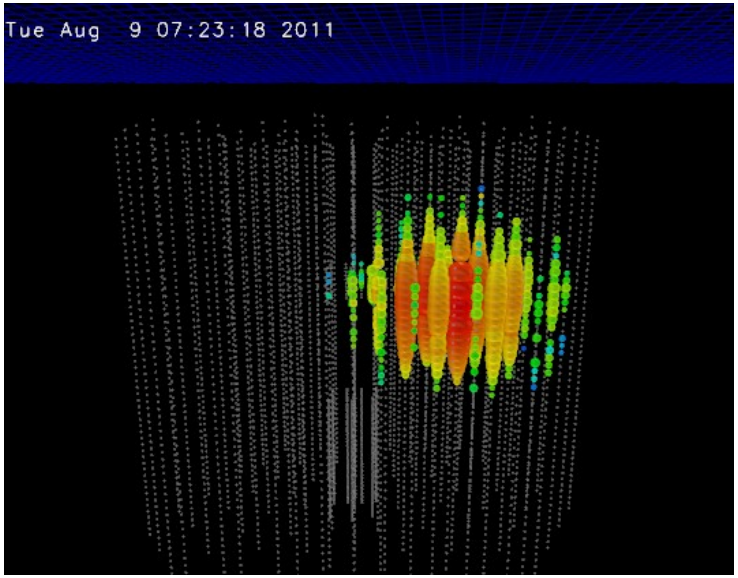
- High number of photo electrons (PE)
- Vertex inside the IceCube volume
- Zenith angle cut (atmospheric muon and neutrino backgrounds have a stronger zenith angle dependence than signal)



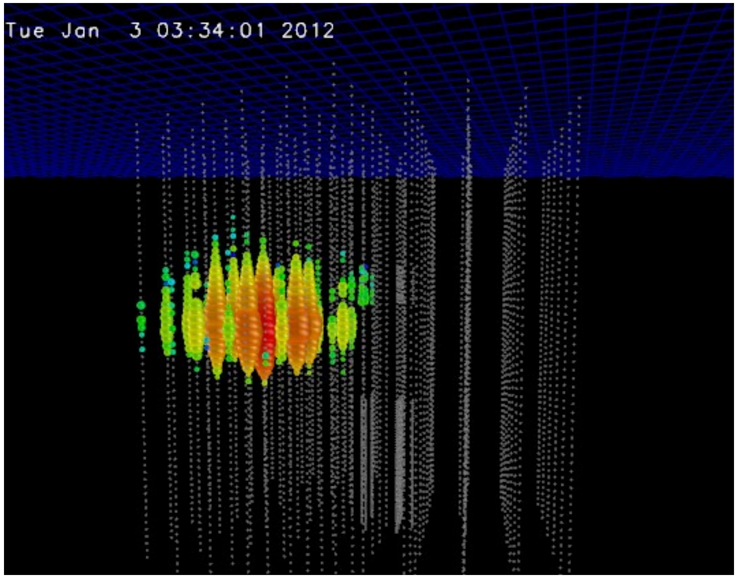
Ultra high energy neutrinos in IC79 and IC86



Bert
~1050 TeV



Ernie
~1150TeV



Two events with visible energy of ~1 PeV found after 615.9 days

2.8σ significance with respect to expected atmospheric background

Highest energy neutrino events ever observed

High energy contained vertex search in IC79 and IC86

Analysis first presented at IPA 2013, Madison

Event selection:

Event charge is at least 6000 PE

Out of first 250 PEs no more then 3 PE in the veto region

662 days of livetime from May 2010 to May 2012

Sensitive to all neutrino flavors

Muon background:

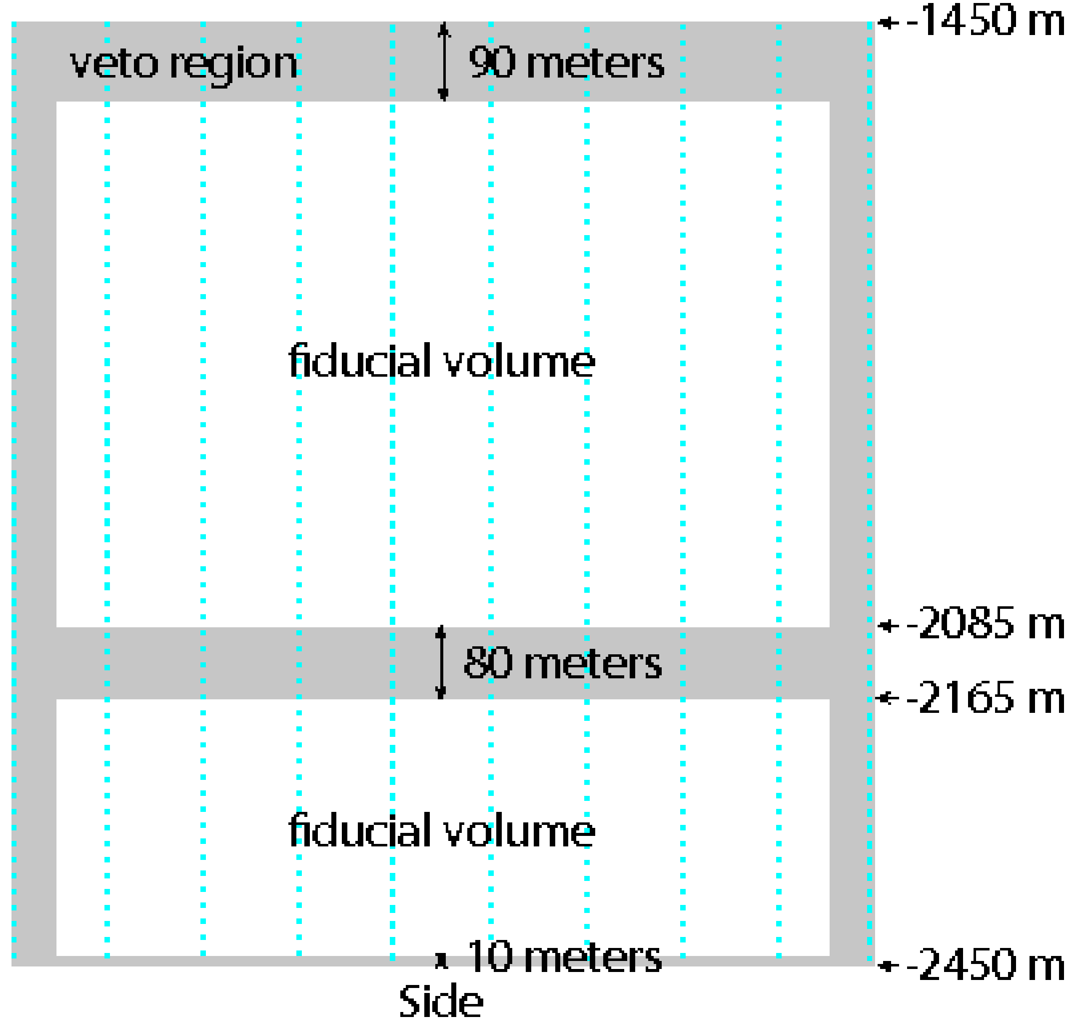
Muons can rarely penetrate veto region

6 muons per two years

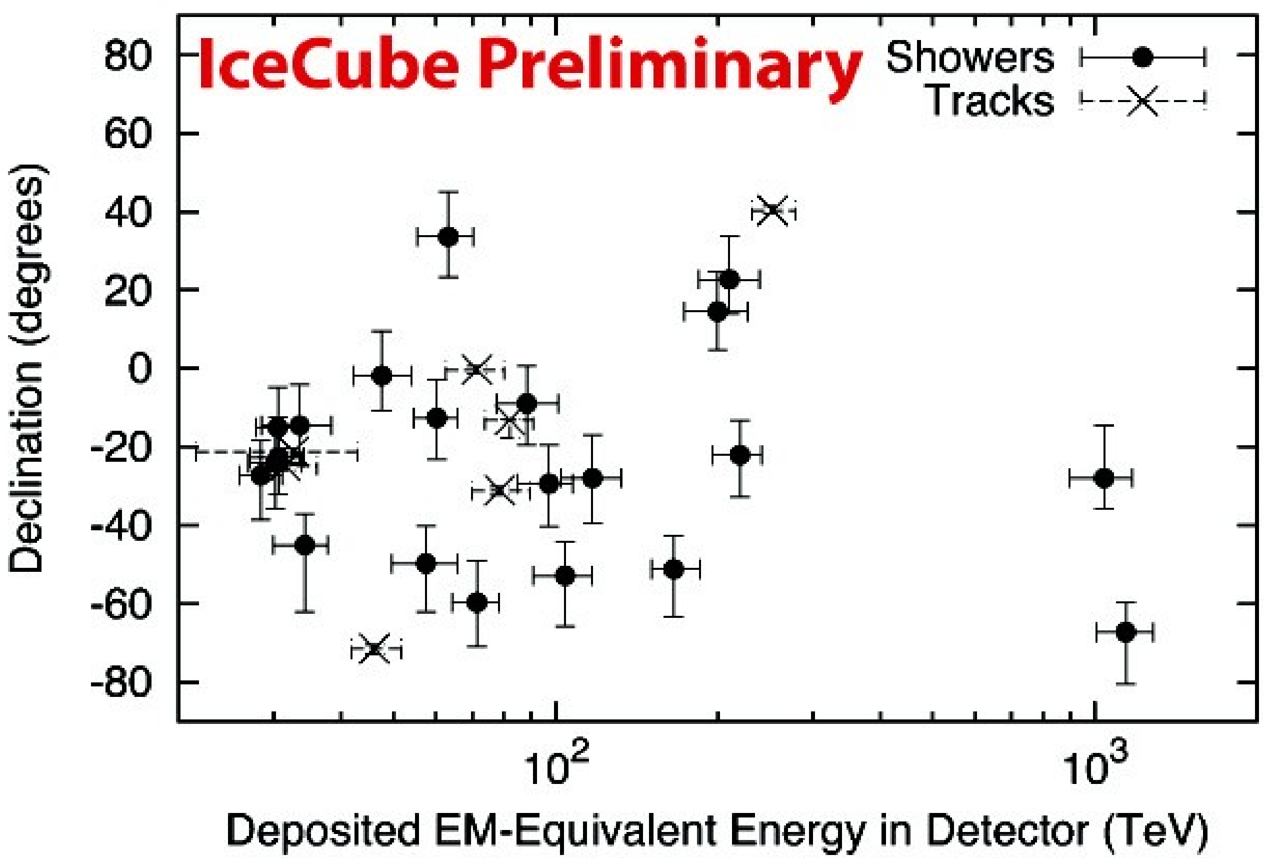
Atmospheric ν background:

Estimated using atmospheric neutrino measurements and CORSIKA simulation

4.6 conventional and 1.5 prompt neutrino events per two years



Results of contained event search



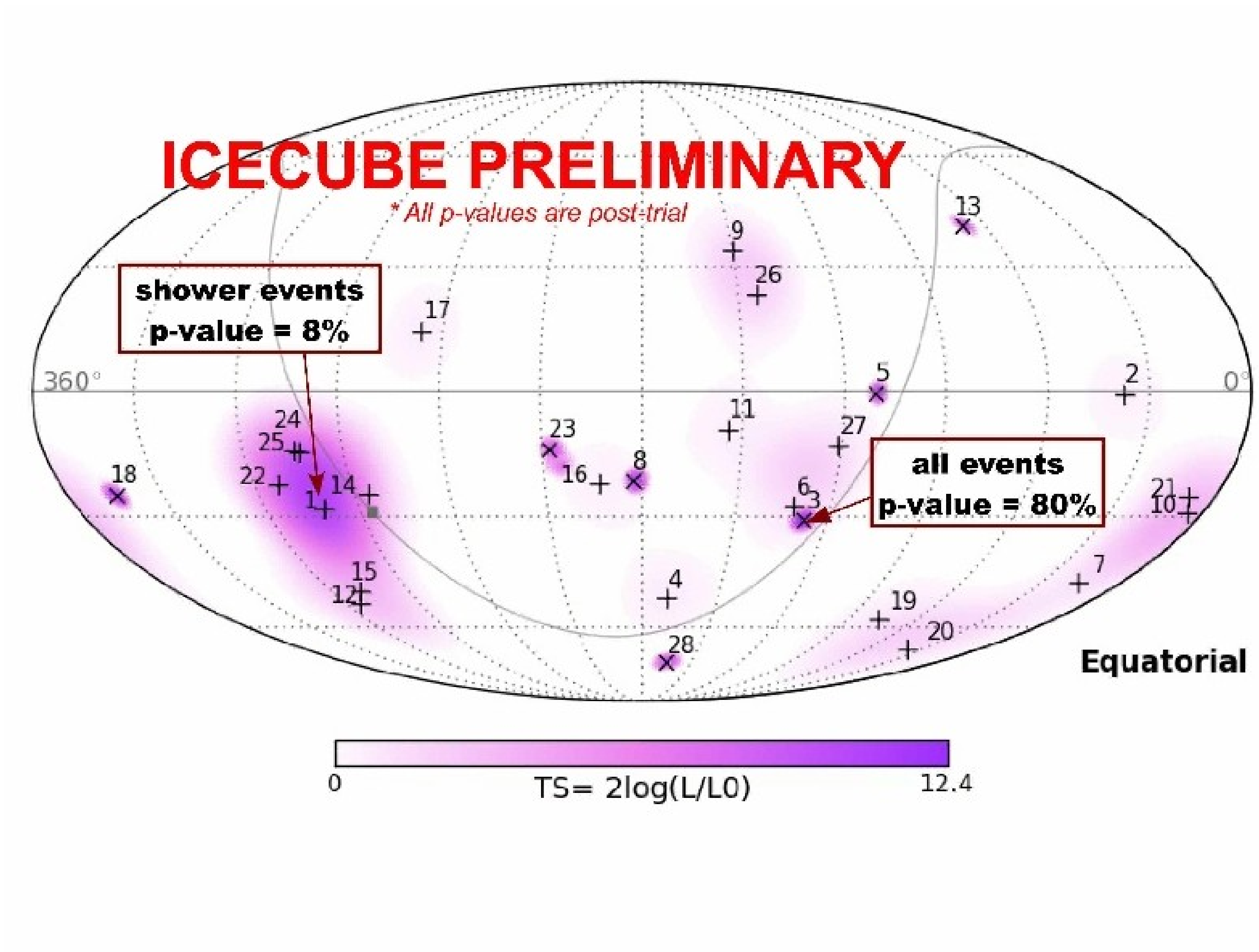
662 days data sample gives 28 events between 30 and 1200 TeV

21 are shower like and 7 have tracks in them

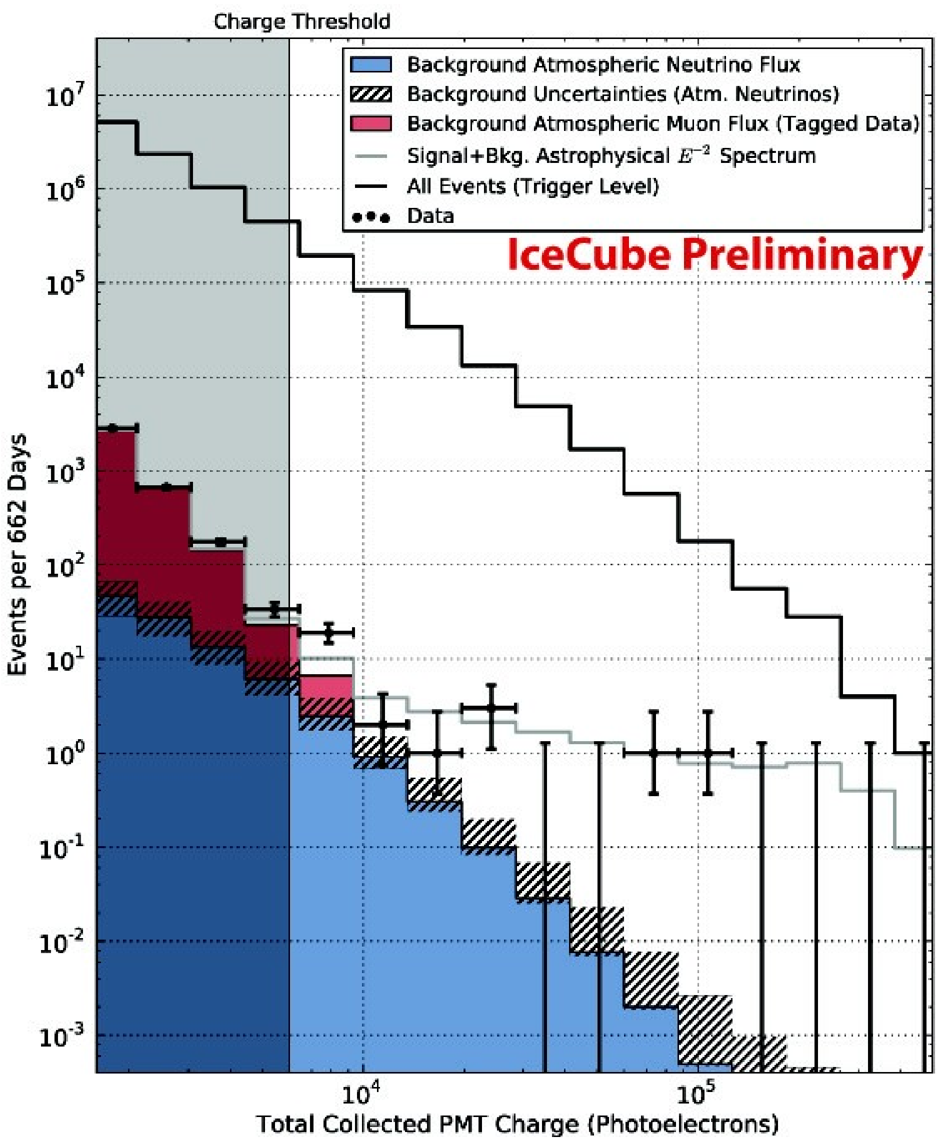
Expected background is 12.1±3.4 events

Estimated significance for the data set is 4.1σ relative to atmospheric neutrino spectrum

Sky map for contained event search

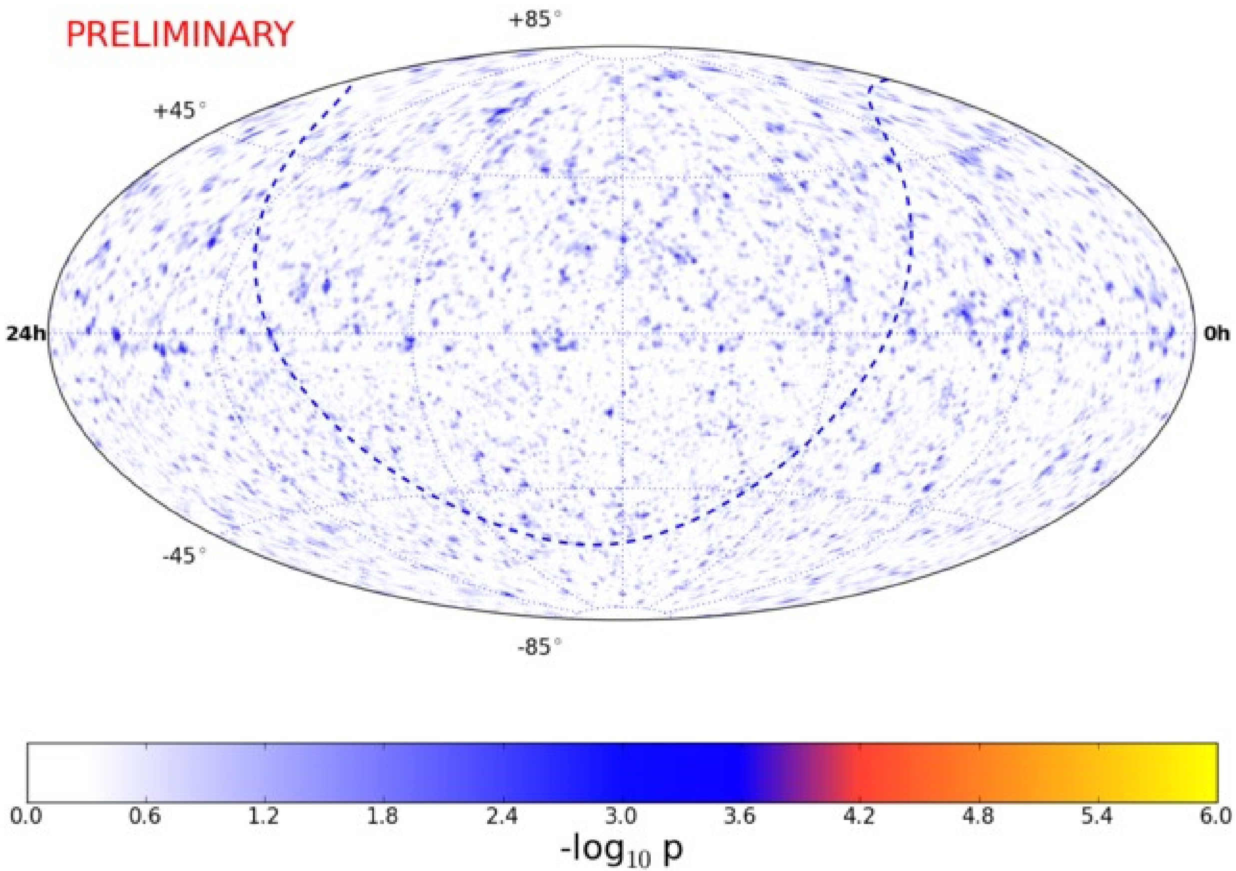


Results of contained event search



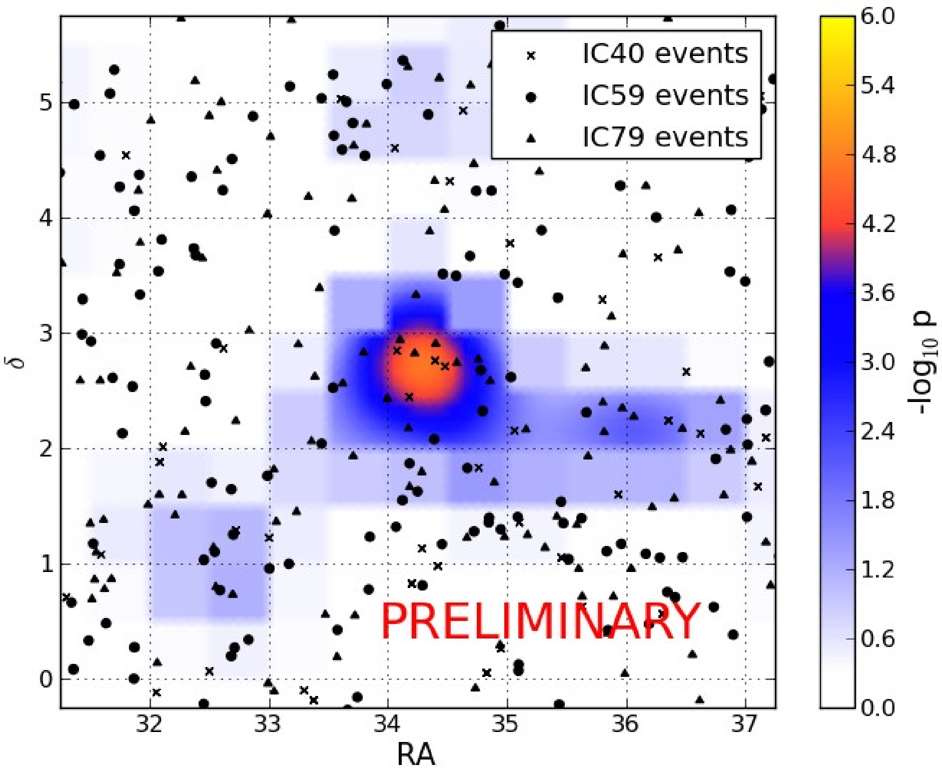
- Events are consistent with neutrinos
- No significant clustering
- Flavor distribution is consistent with astrophysical (1:1:1)
- Compatible with isotropic flux

Point source search in IC40+IC59+IC79

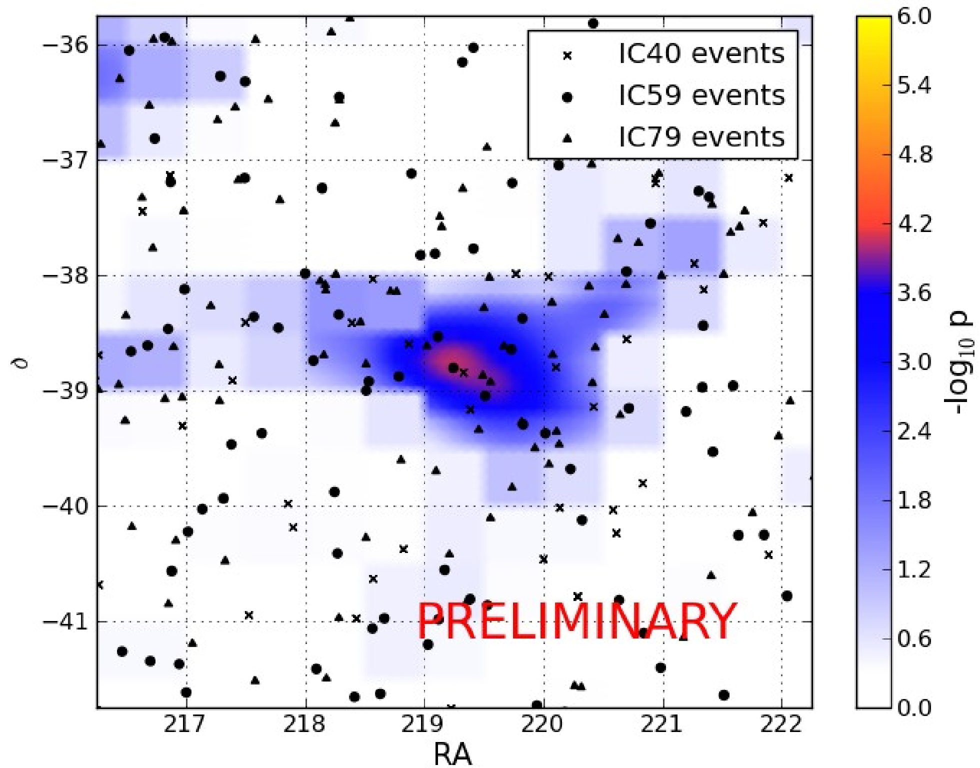


- Search for statistically significant clustering of events on the sky
- Muon neutrinos from northern hemisphere and high energy muons from southern hemisphere
- No statistically significant point sources found

Point source search in IC40+IC59+IC79

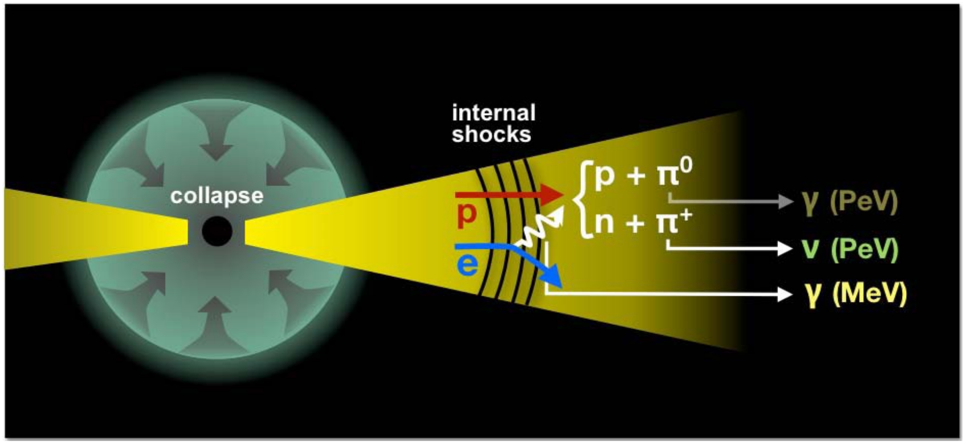


Most significant spot in northern hemisphere

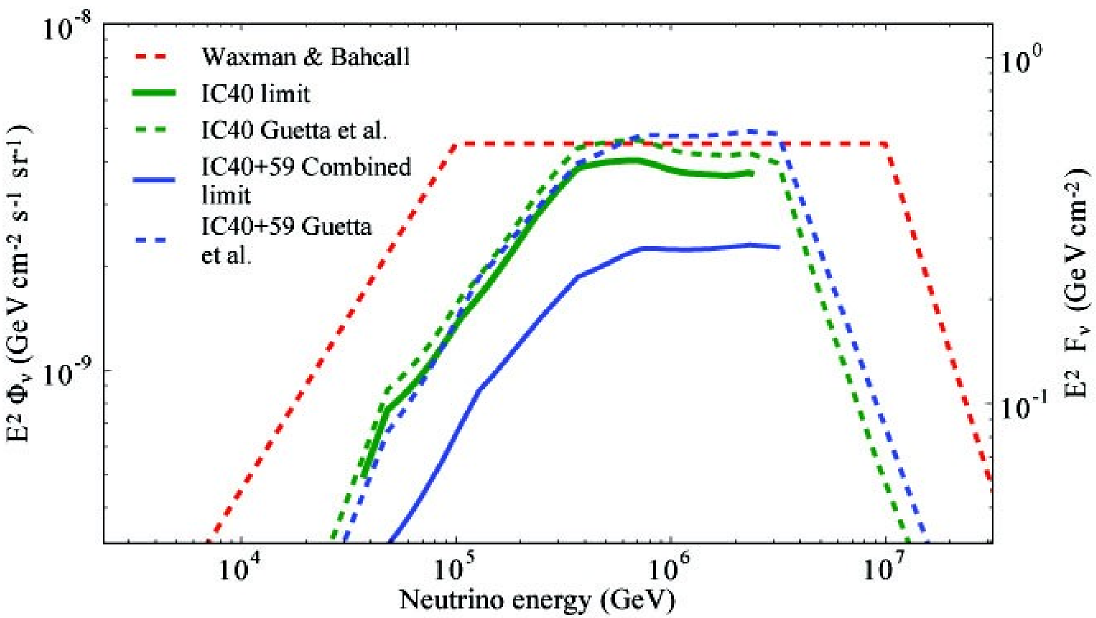


Most significant spot in southern hemisphere

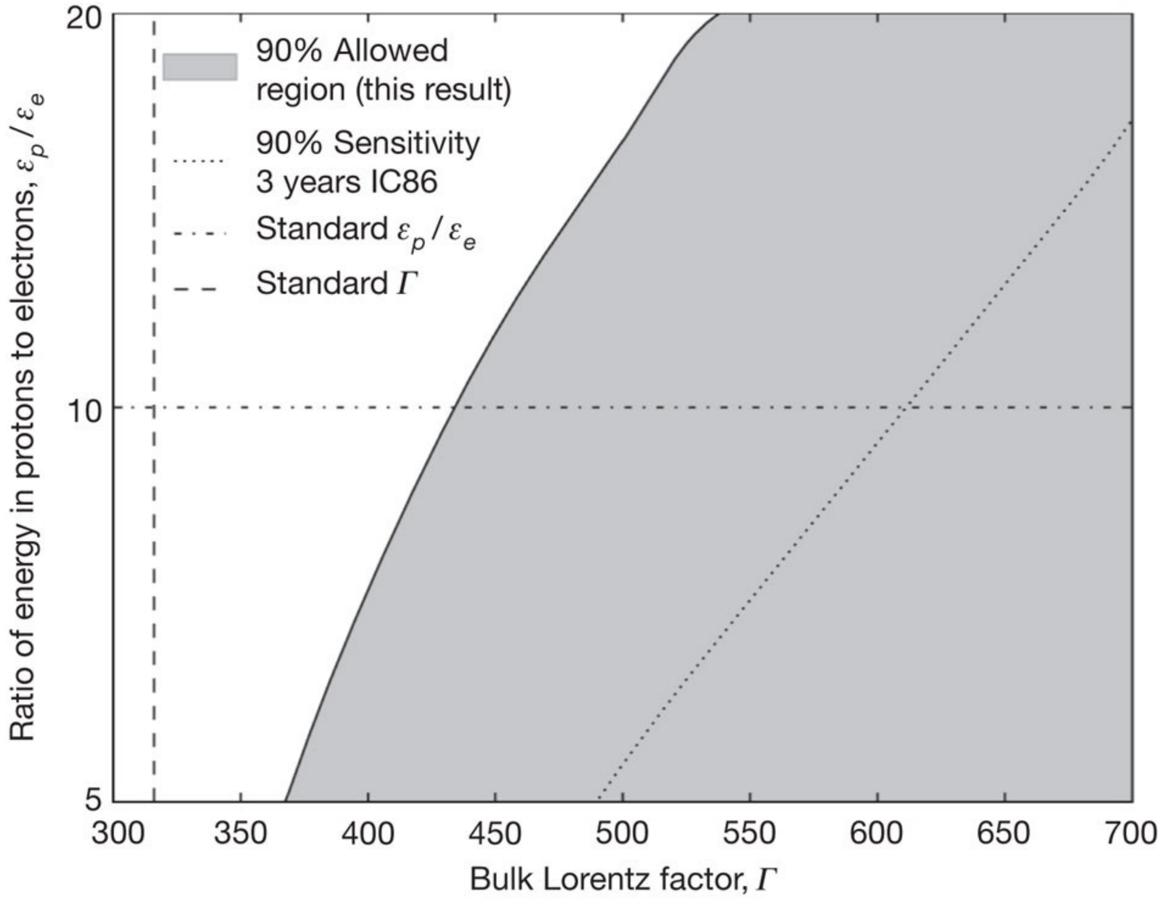
Gamma Ray Burst with IC40 and IC59



- GRB models predict neutrino fluxes detectable by IceCube
- Search for muon neutrinos coincident with time and position of GRB
- Use northern sky GRBs to reduce atmospheric muon background
- Data collected in IC40 and IC59 configurations from April 2008 to May 2010.
- 117 IC40 GRBs + 98 IC59 GRBs in northern sky
- No muon neutrino events were found within time window of 0.1-100 s and within 10 degrees of the GRB direction
- 5.2 events expected based on GRB based spectra



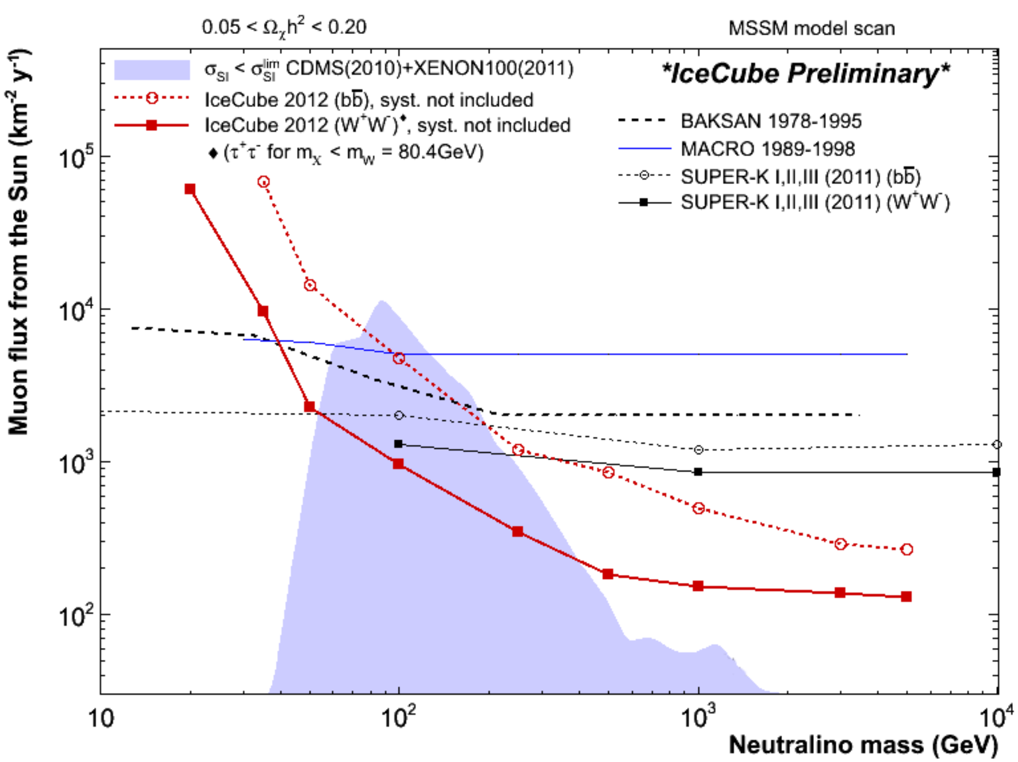
Constrains on GRB fireball parameters



Places a stringent constraint on GRBs as a source of high energy cosmic rays

Indirect dark matter search in IC79

- WIMPs (Weakly Interacting Massive Particles) are one of the popular Dark Matter candidates
- WIMPs might be captured in massive celestial bodies, like the Sun
- Captured WIMPs produce neutrinos in self annihilation



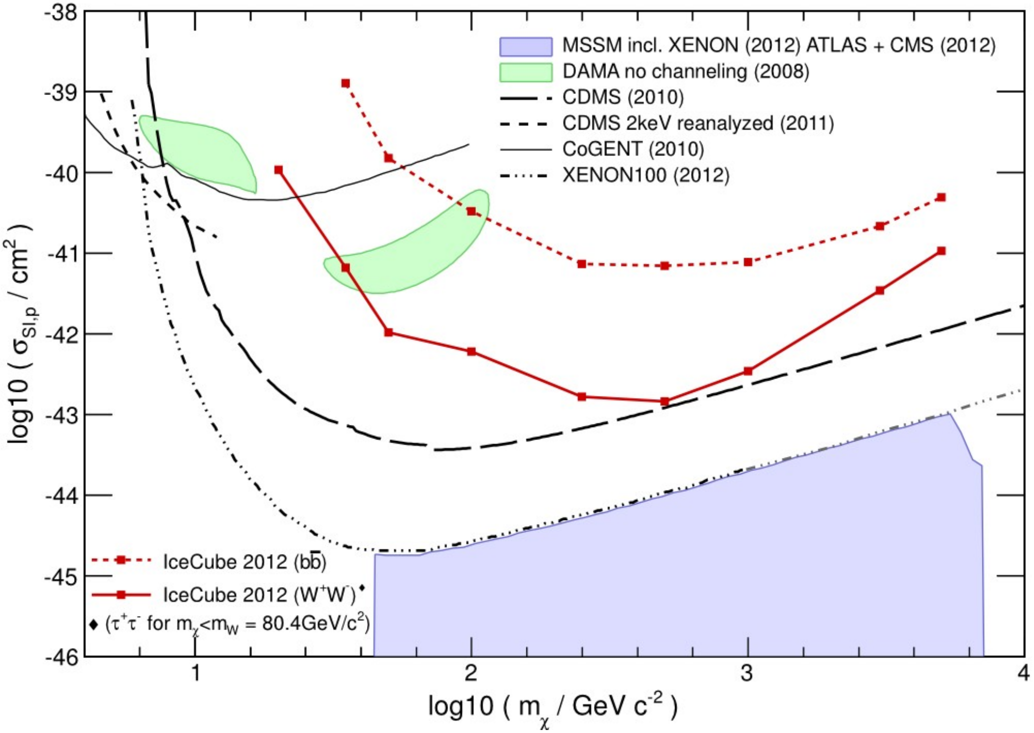
Limits on muon flux from the Sun

Search for muon neutrinos from the direction of the Sun

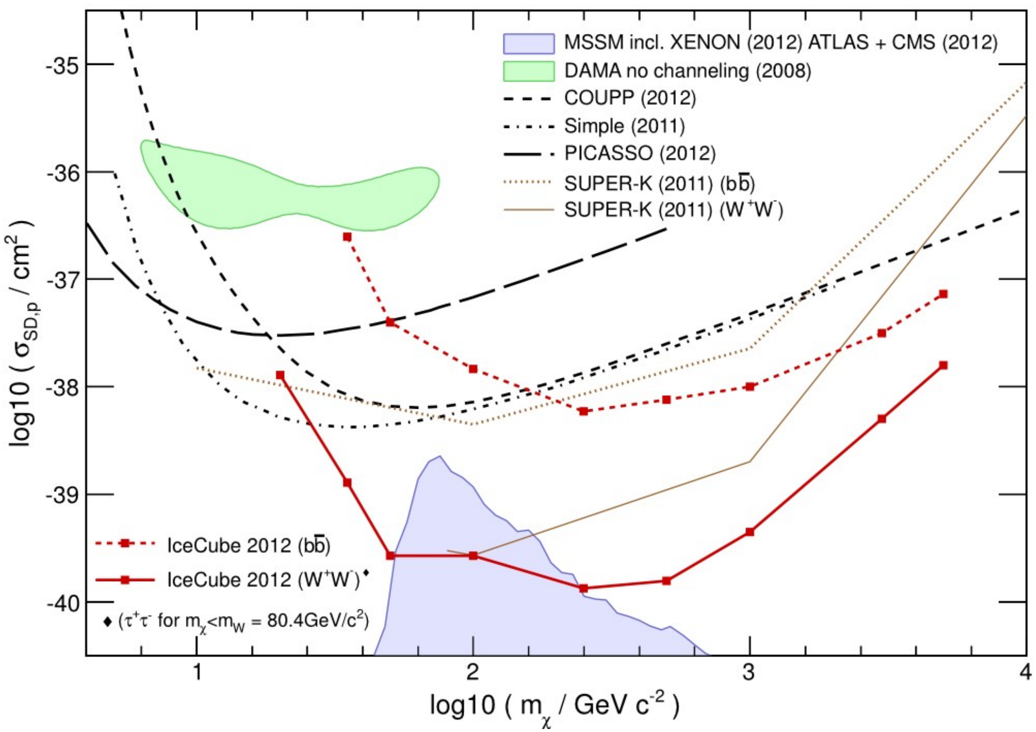
317 days in IC79 (June 2010 to May 2011)

Results consistent with atmospheric background, no excess seen from the Sun

Indirect dark matter search in IC79

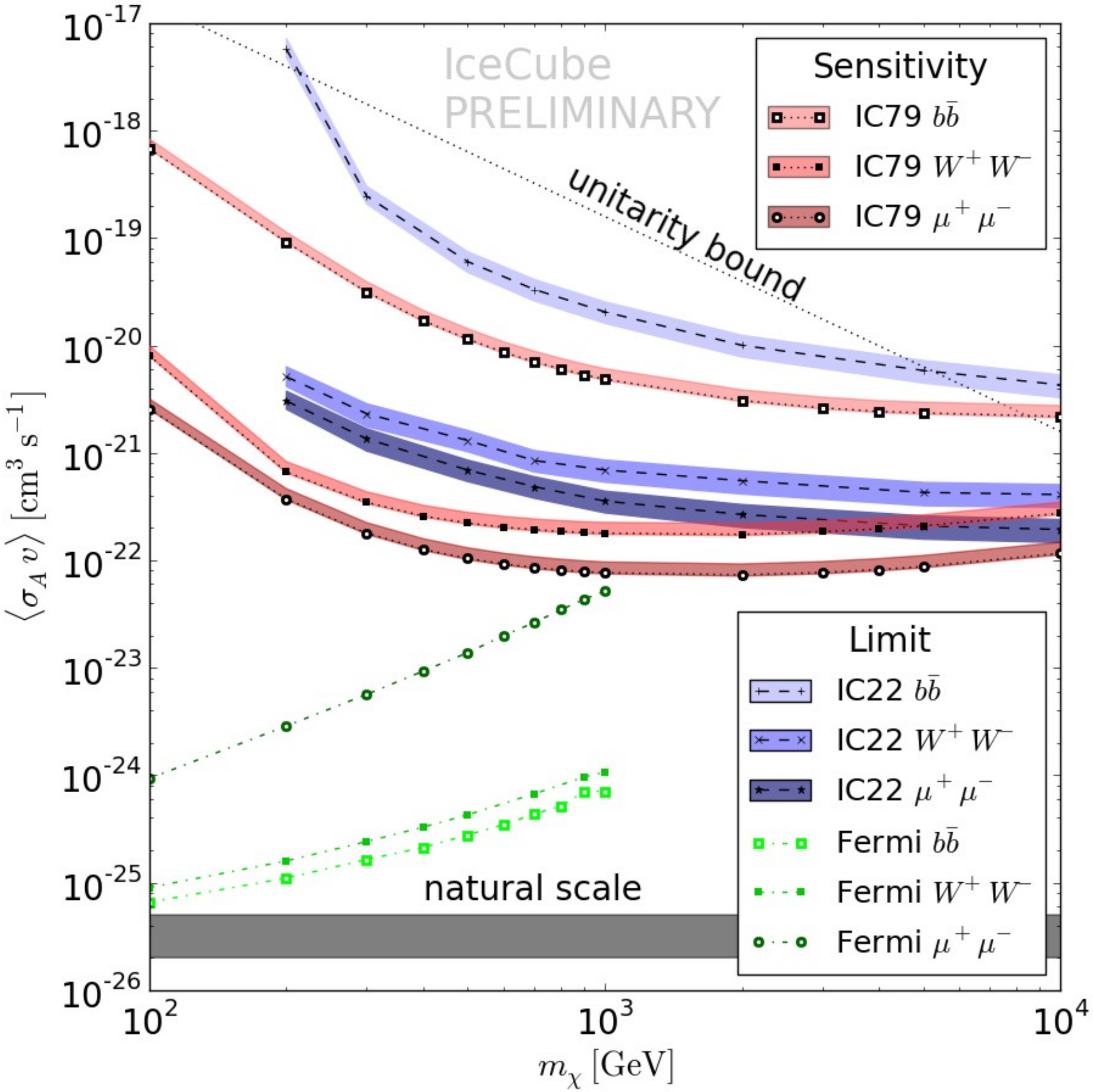


Spin-independent cross section limits



Spin-dependent cross section limits

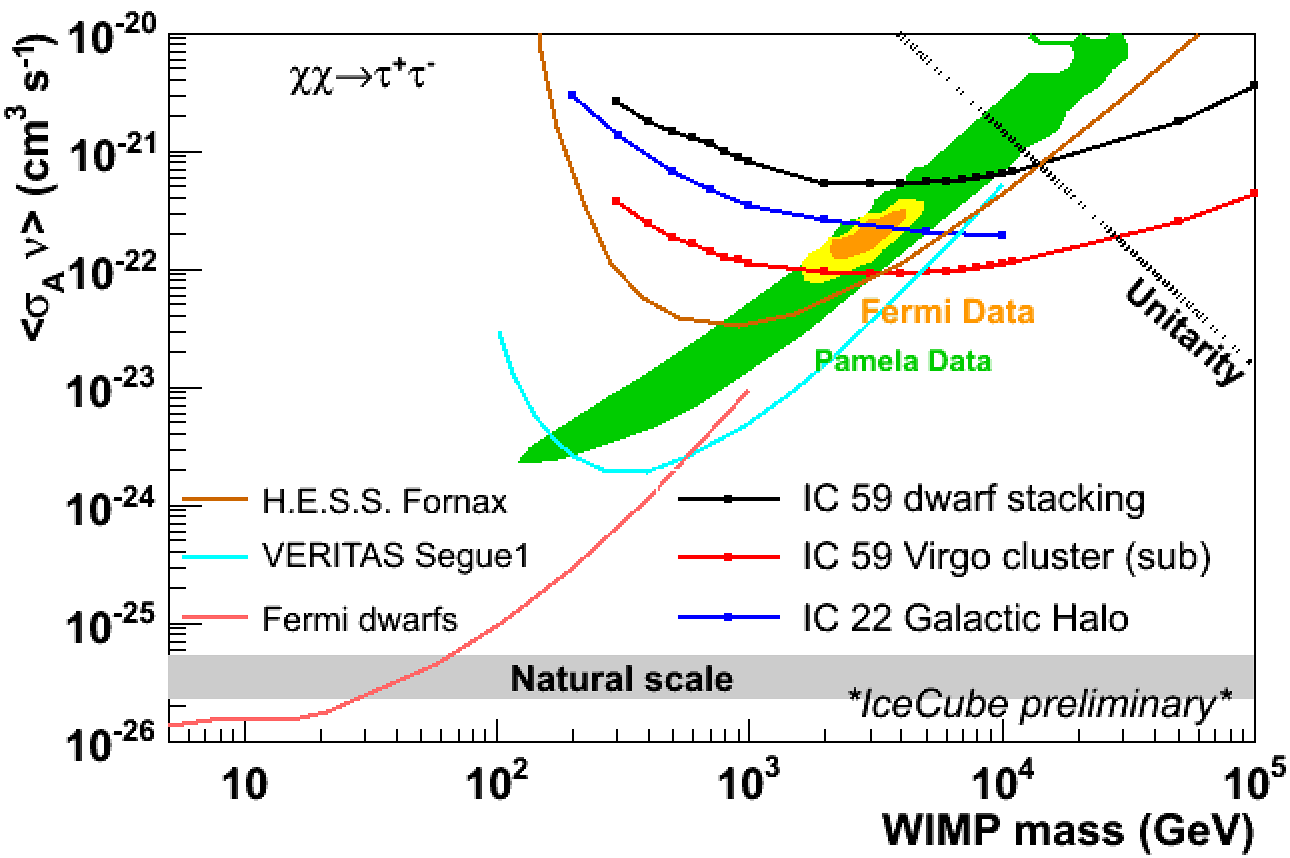
Indirect dark matter search in IC79



Limit on WIMP annihilation cross section

- Search for dark matter annihilation in galactic halo
- search for anisotropy in neutrino flux caused by WIMP annihilation in Galactic Halo: flux in the direction of the galactic center should be larger than in the direction of the anti-center
- No significant anisotropy observed

Indirect dark matter search in IC59 Dwarf galaxies and galaxy clusters



IC79 DC cascades

Study of atmospheric neutrino induced cascades in Deep Core

Signal:

Cascades are produced by CC ν_e events and NC events all flavors (atmospheric cascades)

Data:

281 day of IceCube data collected from June 2010 to May 2011

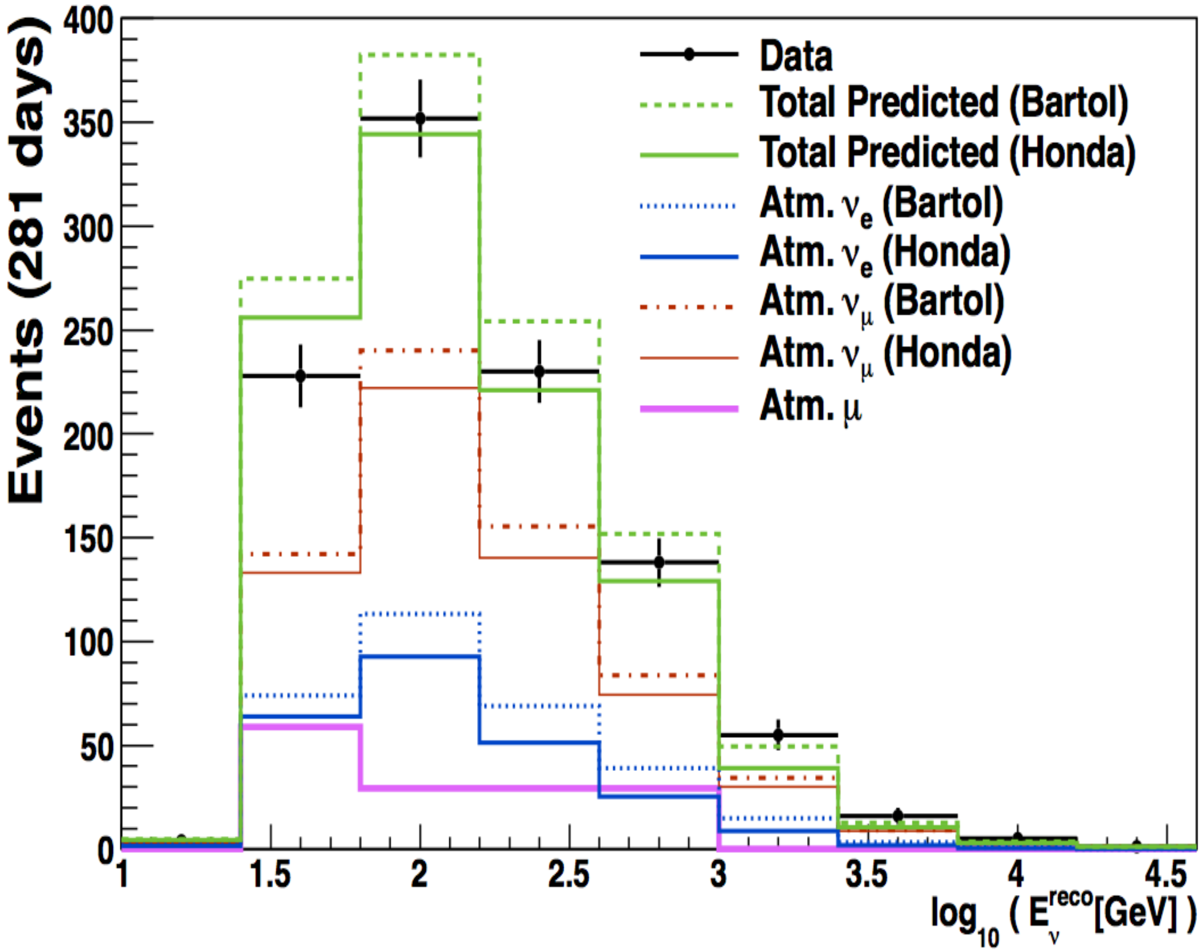
Backgrounds:

Atmospheric muon events

Use IceCube as a veto

CC ν_μ tracks misreconstructed as cascades

IC79 DC cascades



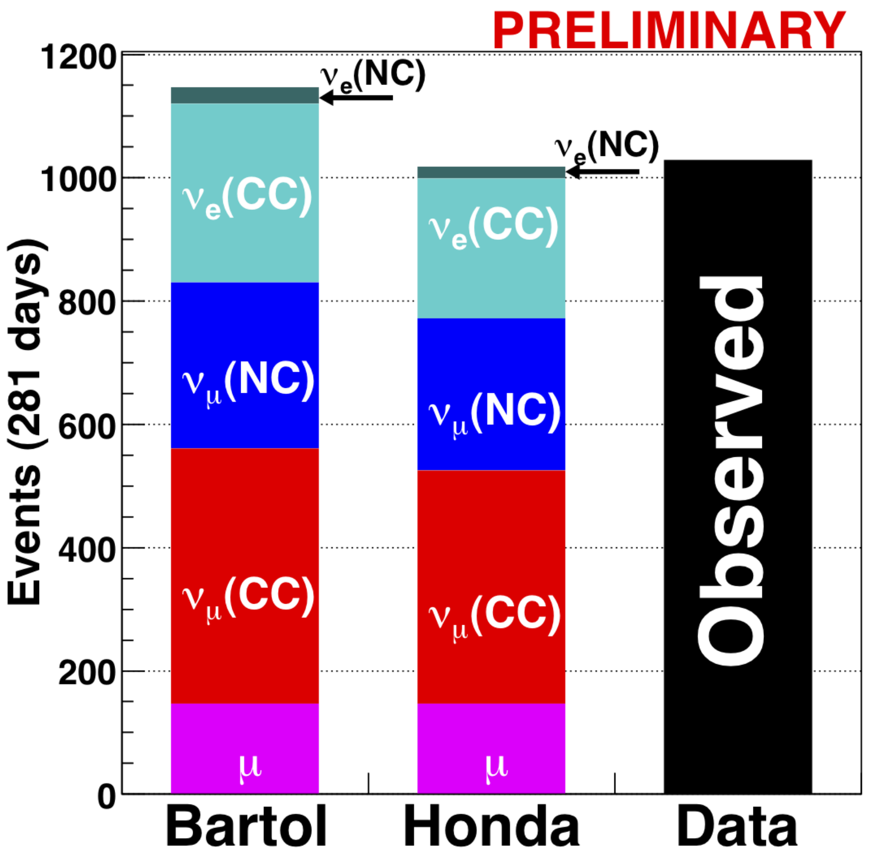
The event rate as function of reconstructed cascade energy.

Due to relatively high energy neutrino oscillation has a very small effect on these results (1.8% for ν_μ 0.1 % for ν_e)

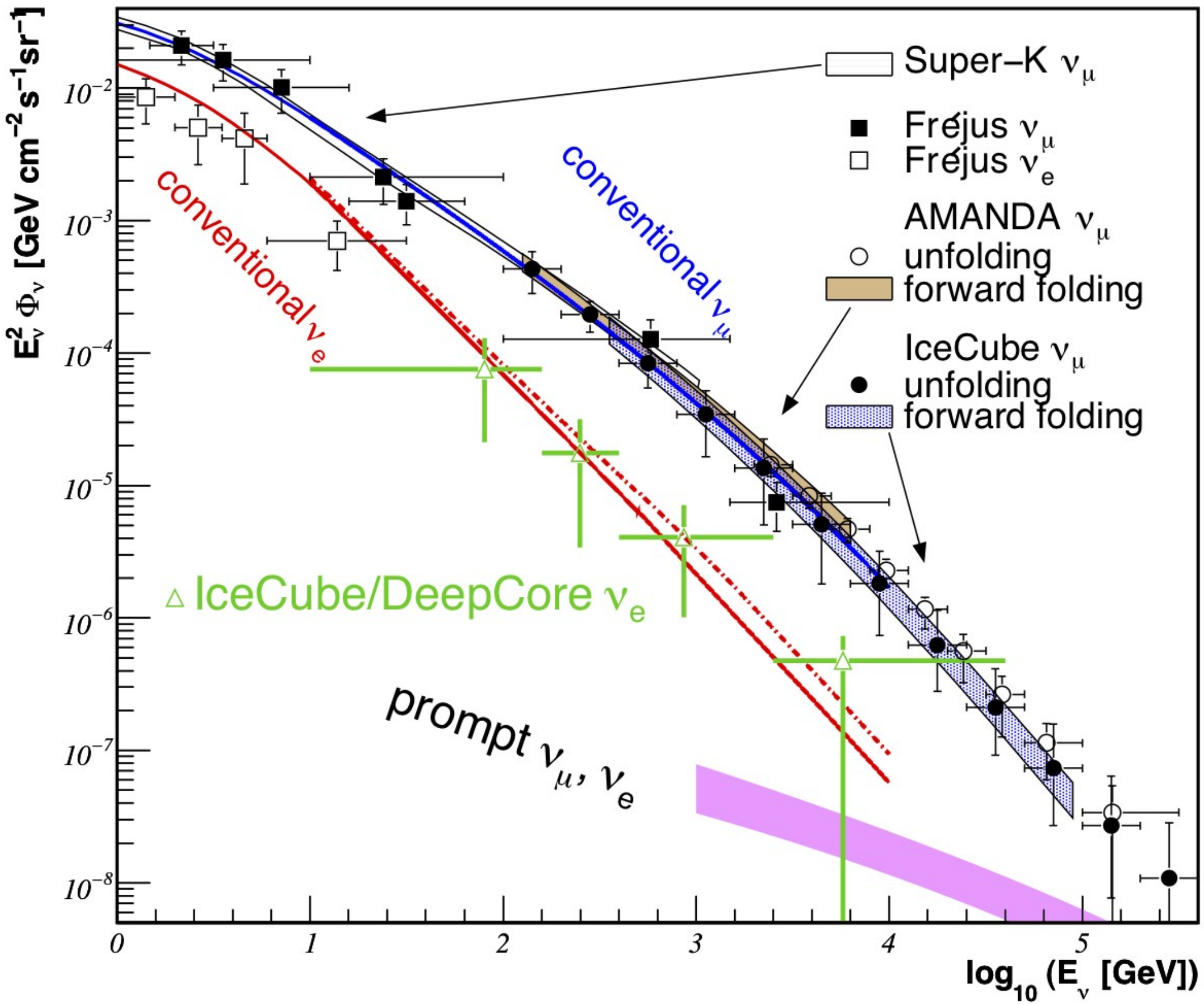
IC79 DC cascades

Type	Signal			Background		MC	N^{obs}
	ν_eNC	ν_eCC	ν_μNC	ν_μCC	atm. μ	Sum	
Bartol	26	290	267	403	147	1134	-
Honda	19	227	245	368	147	1007	-
Average	23	259	256	385	147	1070	-
Data	-	-	-	-	-	-	1029

Number of events that passed final cuts observed in 281 days. Neutrino simulations have statistical uncertainties less than 2%, while muon MC have uncertainty 45%.



IC79 electron neutrino spectrum



First measurement of atmospheric electron neutrino flux above 80 GeV

Neutrino oscillation

$$P(\nu_\mu \rightarrow \nu_\tau) = 1 - \sin^2(2\theta_{23}) \sin^2(1.27\Delta m_{23}^2 L/E)$$

θ_{23} is the mixing angle between the two neutrino mass eigenstates,

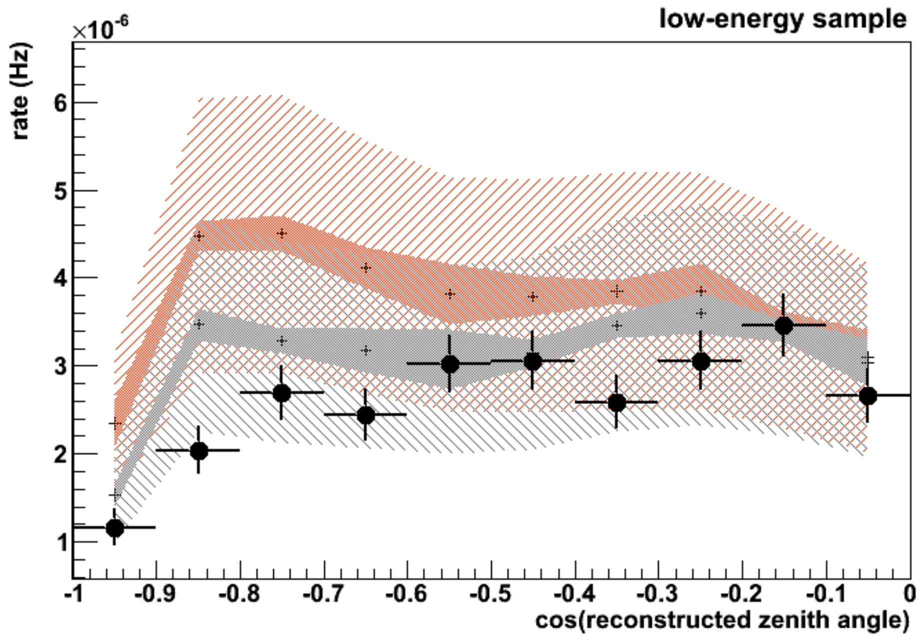
Δm_{23}^2 is the difference of the square of their masses in eV^2

L is the distance traveled in kilometers

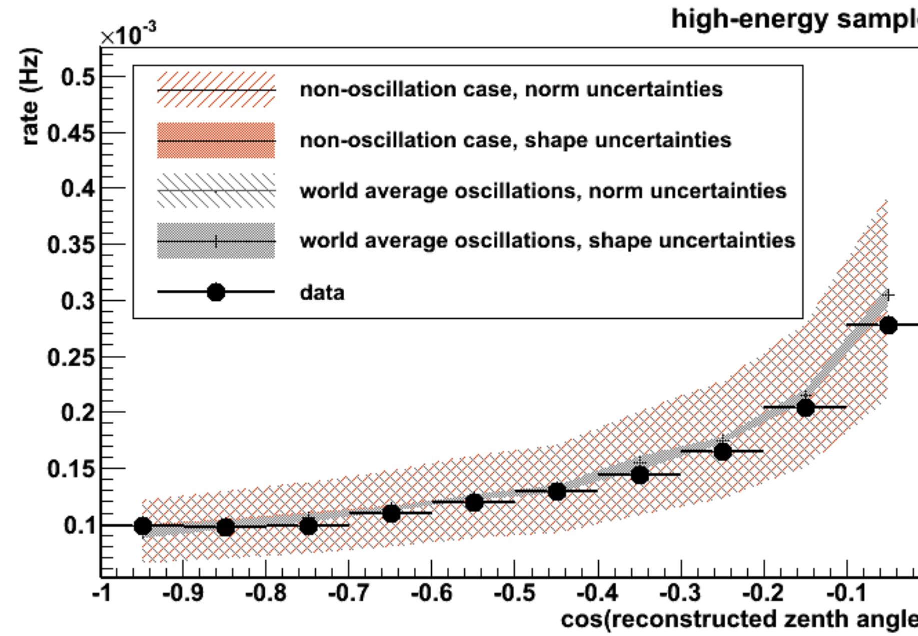
E the neutrino energy in GeV

- Muon neutrino disappearance in atmospheric neutrinos
- ν_e, $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$ are produced
- Main source of background is atmospheric muons – very high rate
- Background is rejected by applying muon veto
- Search for atmospheric neutrino oscillation in IC79 data from May 2010 to May 2011 (318.9 days livetime)

IC79 muon neutrino disappearance



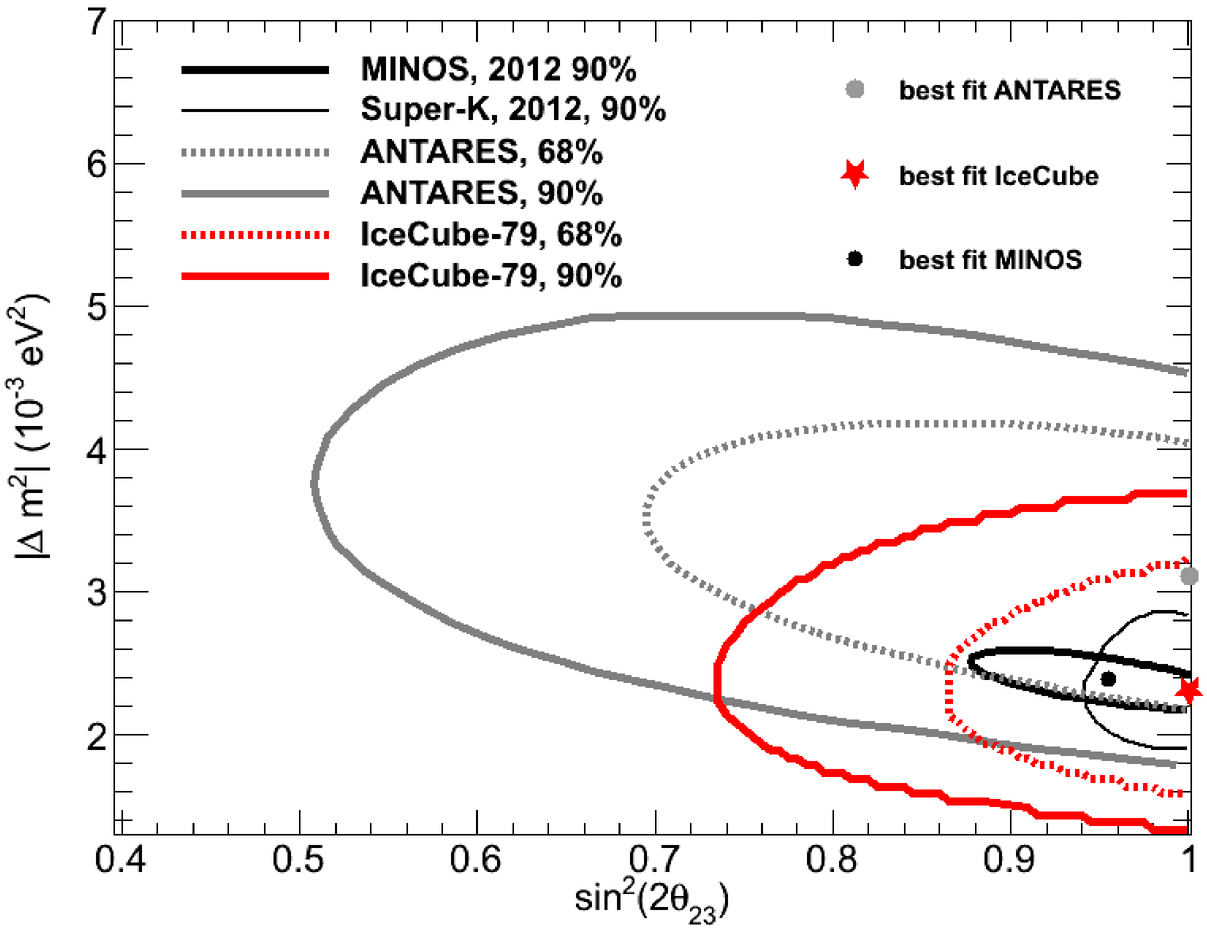
Low energy sample 20 GeV<E<100 GeV



High energy sample E>100 GeV

Data and Monte Carlo for oscillation and non-oscillation hypothesis
Oscillation hypothesis assumed that $\sin^2\Theta_{23} = 0.995$ and $\Delta m^2_{23} = 2.39$ 10-3 eV^2
Non-oscillation hypothesis rejected with 5.6σ significance

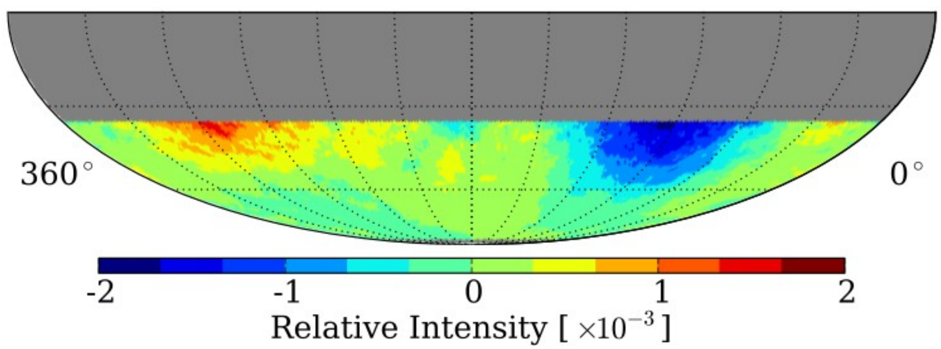
IC79 Muon neutrino disappearance



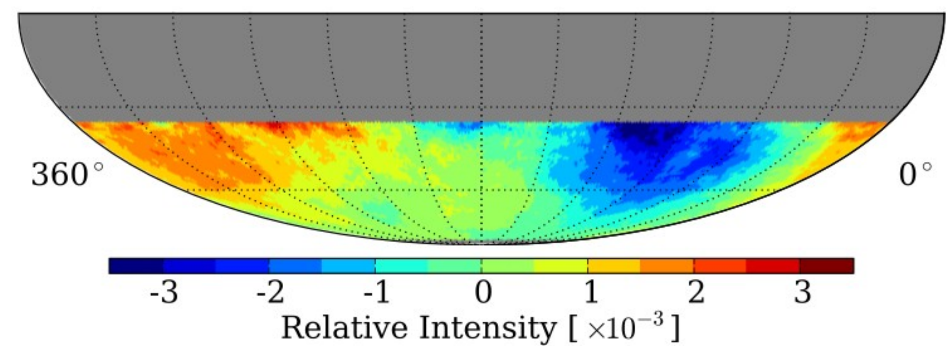
Significance contours for this atmospheric neutrino oscillation analysis, compared with the results of ANTARES, MINOS and SuperKamiokande

Cosmic ray anisotropy in IceTop

IceTop is sensitive to cosmic rays between 100 TeV and 1EeV
Search for anisotropy in the southern hemisphere cosmic ray sky



Sky map of relative intensity for cosmic rays of median energy 400 TeV, May 2010 to May 2011 (73 IceTop tanks)



Sky map of relative intensity for cosmic rays of median energy 2 PeV, May 2010 to May 2011 (73 IceTop tanks)

Anisotropy observed up to PeV energies

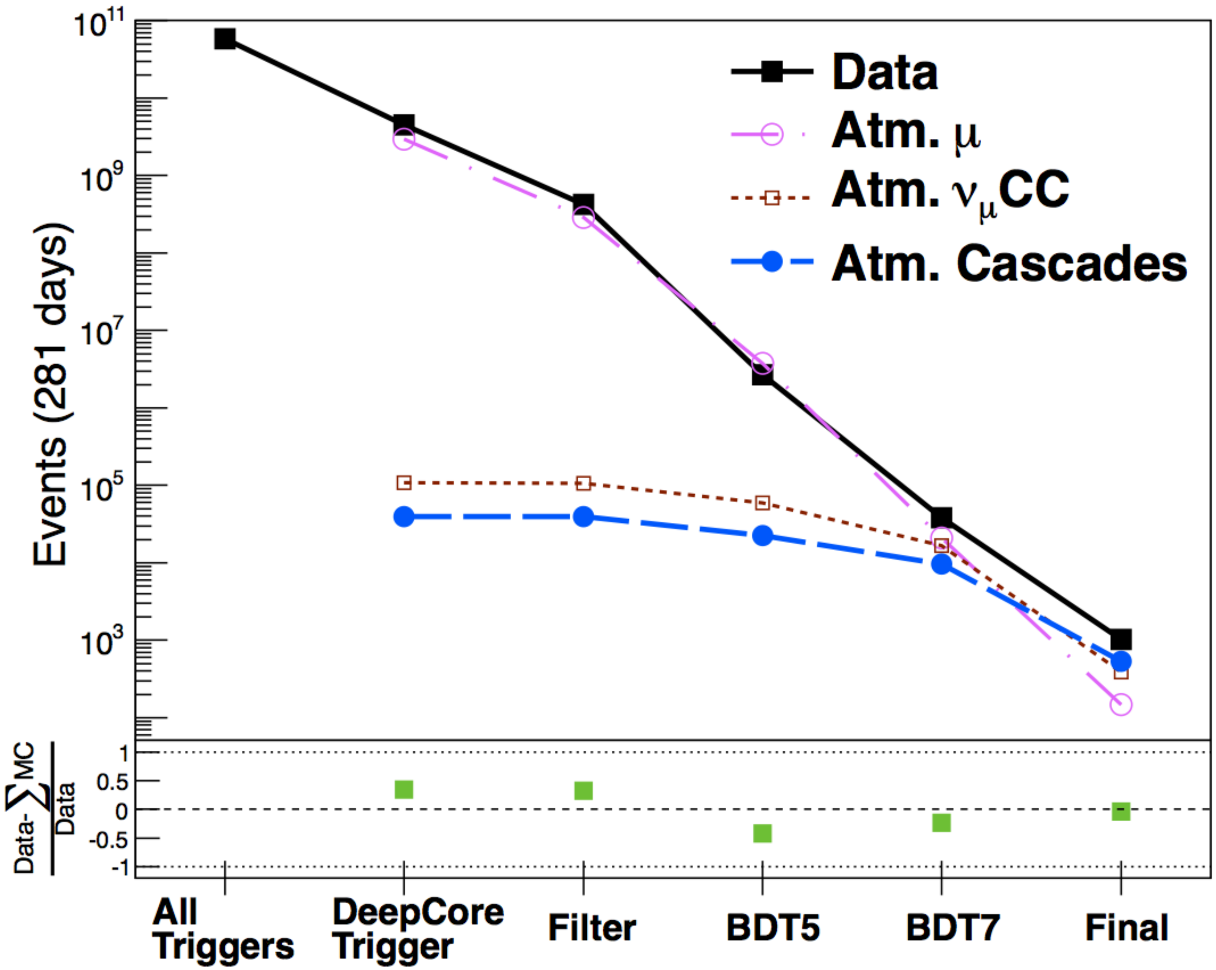
Using IC59 data cosmic ray anisotropy observed in the range 20-400 TeV

Summary

- IceCube has been taking data in final configuration since 2011
- IceCube has seen highest energy neutrino events ever observed
- Contained event search in IceCube may see the first hint of diffuse astrophysical neutrino flux
- IceCube DeepCore has observed electron neutrino cascades and atmospheric muon neutrino disappearance

Back Up slides

IC79 DC cascades



Deep Core Trigger: we have an event in Deep Core

Filter: this event is not muon going through IceCube

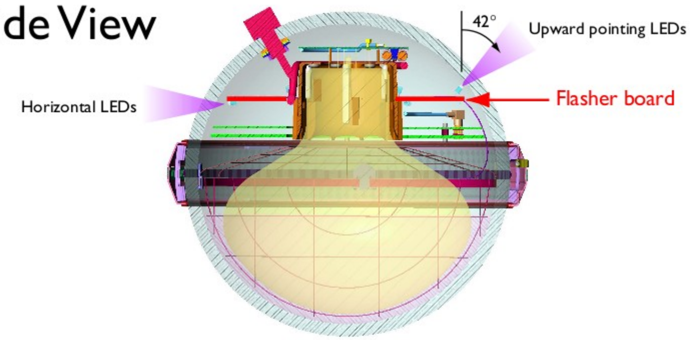
BDT5: 5 variables describing event topology are used in Boosted Decision Tree (BDT) algorithm.

BDT7: events are reconstructed assuming originated from muon and neutrino cascade; these reconstructions provide 7 variables for the second BDT cut.

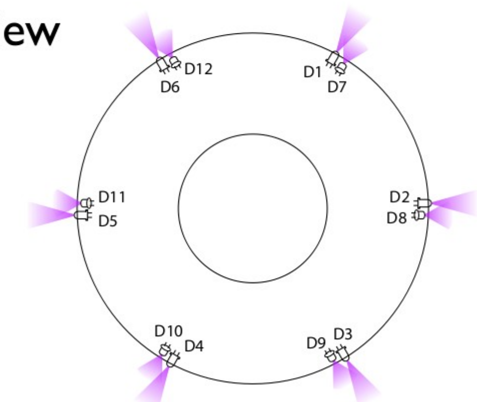
Final: mostly neutrino events, but many come from CC ν_μ interactions, not from ν_e or NC ν_μ. Final cut separate ν_μ background

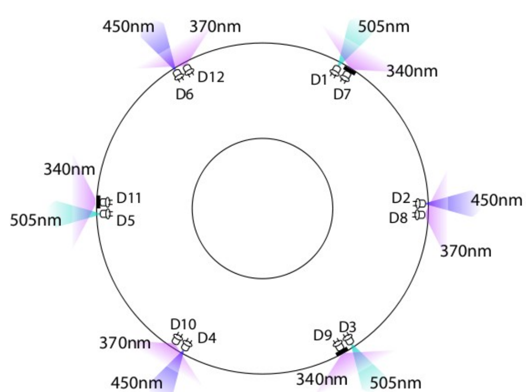
Flasher board

Side View



Top View





- contain 12 405 nm LED's
- 6 horizontal and 6 tilted at ~40 degrees upward
- LED's can be flashed separately with different brightness
- each LED produces a pulse from 5-65 ns
- 16+1 boards have LED's with different wavelength (cDOMs), all horizontal

Plots from Chris Wendt's talk