IceCube capabilities to study neutrino emission from galactic and extragalactic sources

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INTERNATIONAL SYMPOSIUM ON MULTIPARTICLE DYNAMICS
8 - 12 September 2014 - Bologna, ITALY

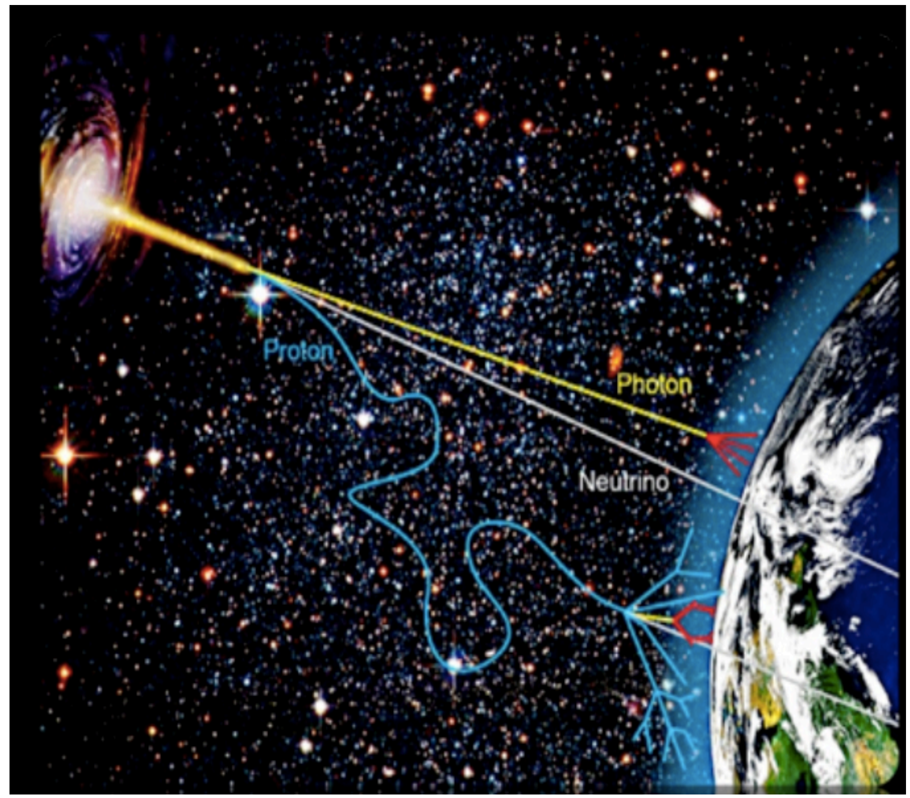
The IceCube Neutrino Observatory, located at the geographic South Pole, is the largest neutrino telescope in the world. IceCube is designed to detect high-energy neutrinos from galactic and extragalactic sources. The detector comprises a cubic kilometer of glacial ice instrumented with 86 vertical strings, each with 60 optical sensors, and a square kilometer array at the surface. IceCube sensors detect Cherenkov radiation from charged particles produced in all flavors of neutrino interactions in the ice. In this talk, recent results from searches for high-energy neutrinos will be presented, including the first detection of a diffuse flux of high-energy neutrinos of extraterrestrial origin.

Outline

- The IceCube detector
- High-Energy Extraterrestrial Neutrinos
  - First Observation of PeV-Energy Neutrinos
  - Follow-up on the detection of two PeV neutrino events
    - 28 events in two years of data (IC79 and IC86)
    - 37 events in three years of data
      - starting events used to reduce energy threshold and detect both tracks and showers from full sky

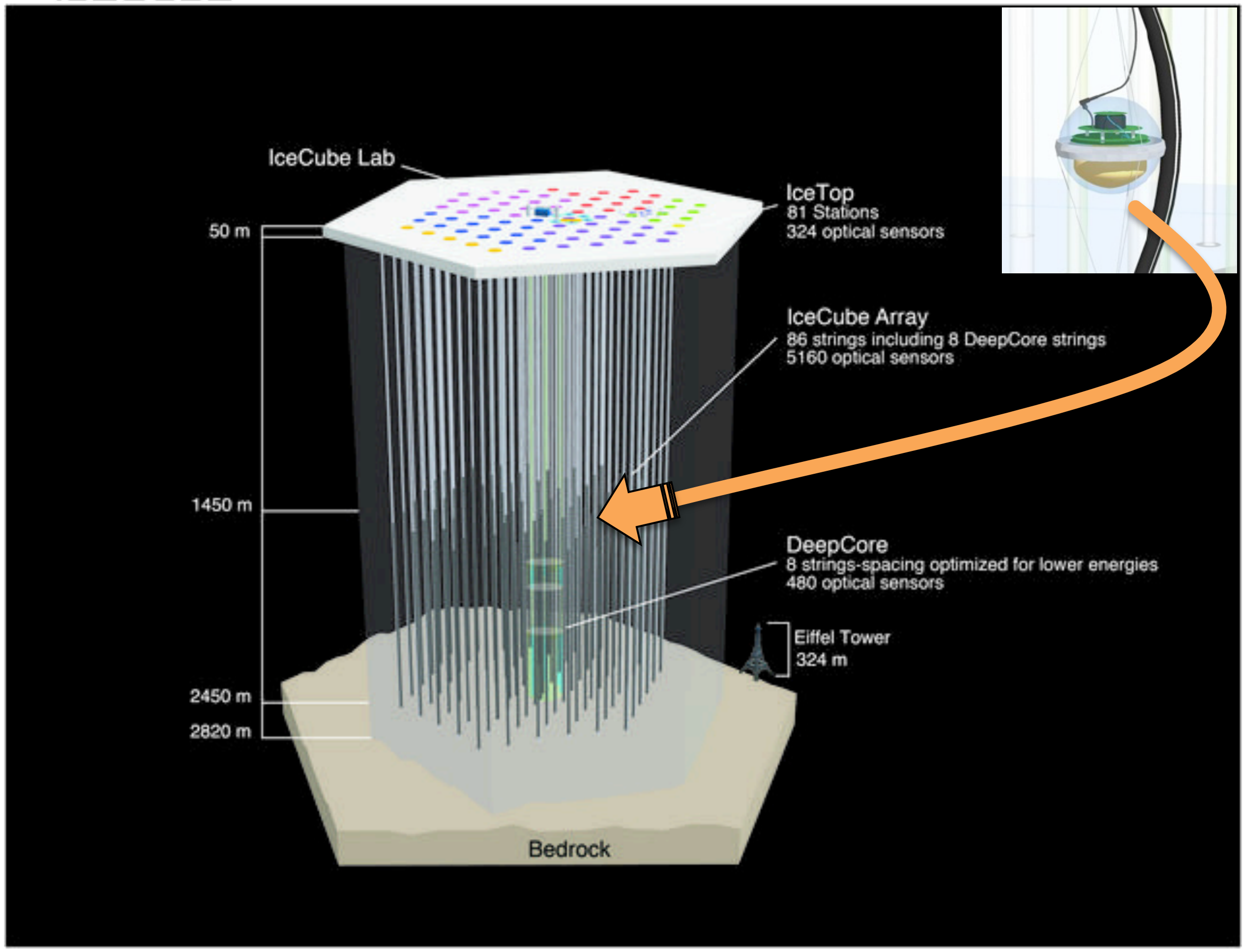
Neutrinos as the ideal astronomical messengers

- Neutrinos travel from the edge of the Universe
  - **with no deflection by magnetic fields**
  - **essentially without absorption**
- essentially no mass and no electric charge
  - similar to the photon **but interactions with matter are extremely weak**.



Direct information about cosmological objects of the high redshift universe like gamma-ray bursts and active galactic nuclei.

The IceCube neutrino observatory



86 strings with 60 Digital Optical Modules (DOMs)
(IceCube + DeepCore)

Optical sensor
10” photomultiplier (PMT)
+ in situ signal digitization
in pressure glass sphere

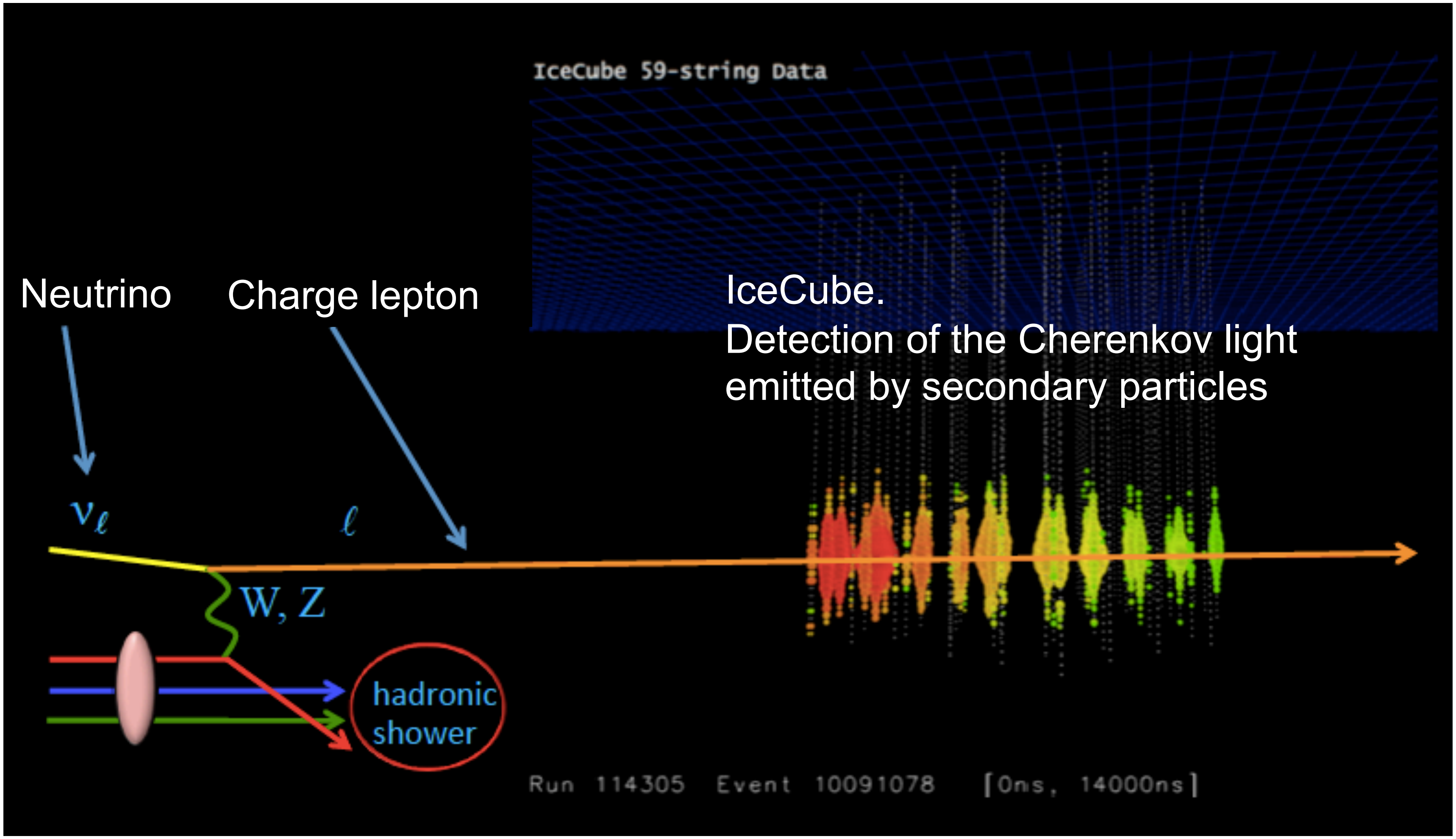
Deployed between 1450 and 2450 m depth

Instrumented volume: **1 km^3**

81 IceTop surface stations

Construction complete
December 2010
(data taking since 2005)

The IceCube neutrino observatory



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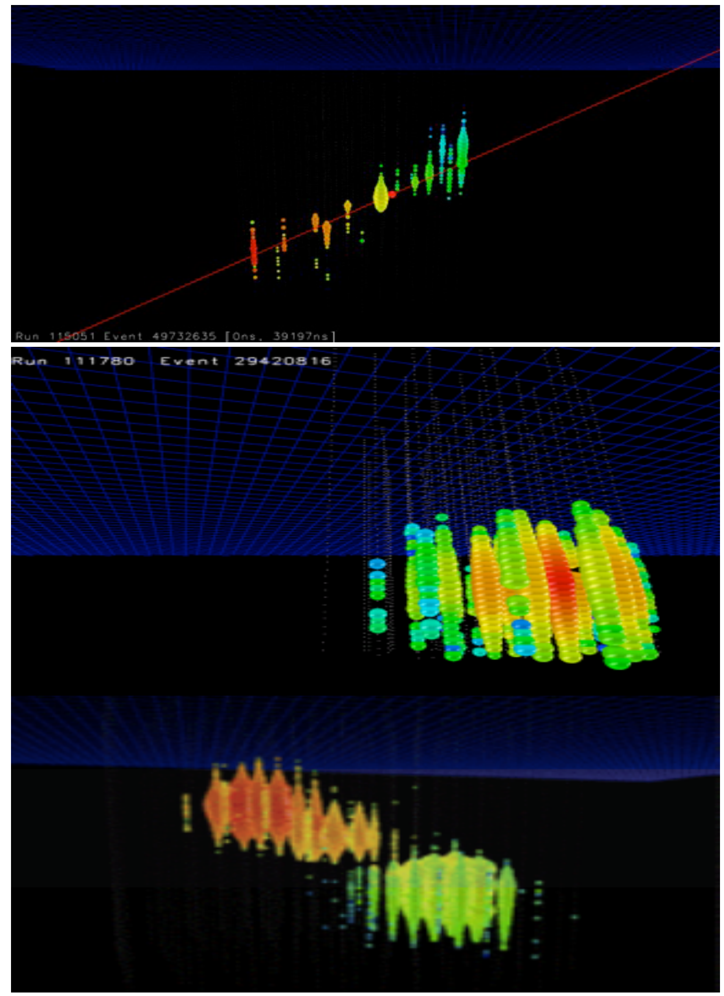
The IceCube neutrino observatory

ICECUBE

The light patterns reveal the type (flavor) of neutrino interaction and the energy and direction of the neutrino, making neutrino astronomy possible



Tracks (tracklike light pattern originating from neutrino-induced muons):

- Source - **ν_μ CC interactions**
- Good angular resolution (<1°)

Cascades (spherical light pattern produced by hadronic or electromagnetic particle showers)**:**

- Source - ν_e, ν_μ, ν_τ NC + ν_e CC interactions
- Good energy resolution (~10% at high energies), limited angular resolution (>10°)

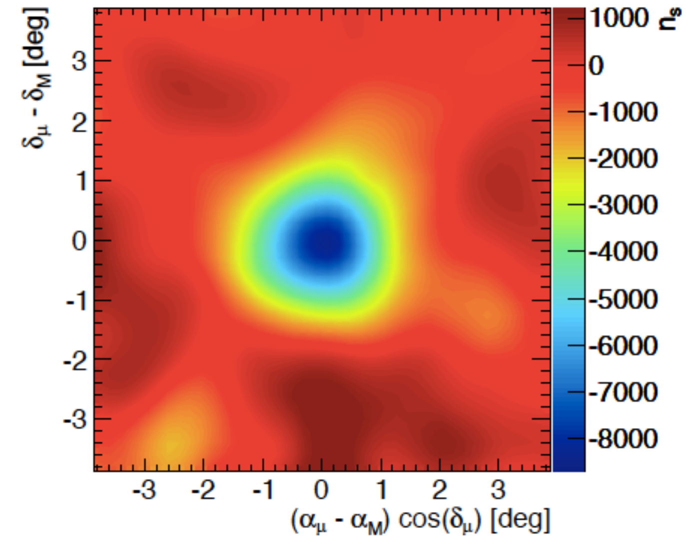
Composites (tracks + cascades)**:**

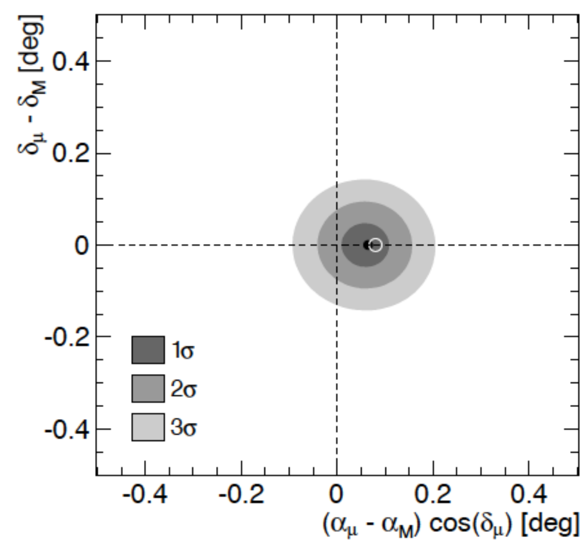
- Source - ν_μ CC (ν_τ CC) inside instrumented volume

IceCube
Detector performance

- The full detector (86 strings) collects data from 2010
- Over 98% of modules are operational
- Cosmic ray Moon shadow study as a verification of angular resolution and absolute pointing
  - shadow seen with 14σ
  - angular resolution 0.7°
  - systematic pointing error less than 0.1°

IC59 data





Phys. Rev. D89 (2014) 102004

First Observation of PeV-Energy Neutrinos

- Neutrino candidates are selected calorimetrically using the total **number** of observed **photoelectrons** in each **event** (**NPE**)

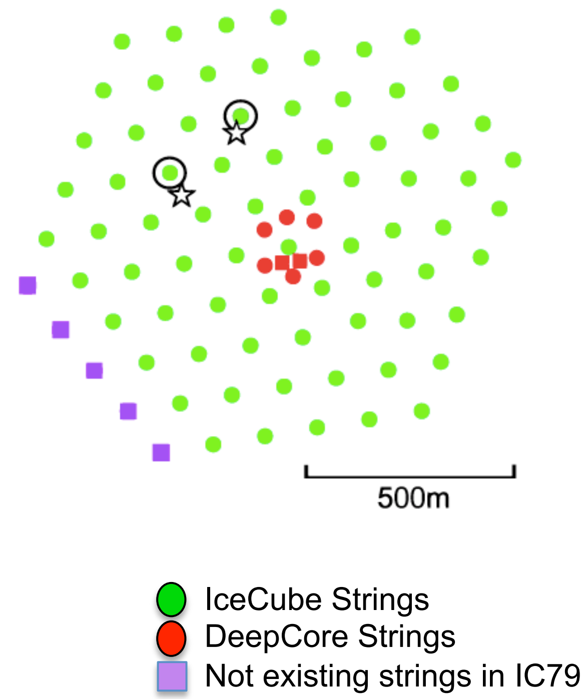
- The zenith angle distribution of atmospheric muons peaks in the downward-going direction and decreases towards the horizon
  - downward-going atmospheric muons are rejected by event reconstruction based on a track hypothesis in combination with a higher NPE selection in the downward-going region.

PRL 111, 021103 (2013)

First Observation of PeV-Energy Neutrinos

PRL 111, 021103 (2013)

- Data collected between **May 2010 and May 2012,**
  - effective live time of **615.9 days** (excluding 54.2 days used for the optimization of the analysis)
    - **IC79** (DOMs on 79 strings) - **285.8** days live time (33.4 days excluded)
    - **IC86** (the first year data taking with the full 86-string) - **330.1** days live time (20.8 days excluded)



First Observation of PeV-Energy Neutrinos

PRL 111, 021103 (2013)

- Blind analysis was performed (using ~10% of data)
- Selection
- **Stage one filter**:
  - Events are triggered when **eight or more DOMs record signals in local coincidences** (nearest or next-to nearest DOM on the same string triggers within ±1 μs)
  - NPE >1000
- **Cleaning**:
  - Two stage cleaning based on the spatial separation and the time interval between hits is applied
  - DeepCore data are not used to maintain uniformity across the detector volume
- **Additional cuts**:
  - Downward-going atmospheric muon rejection:
    - events with at least 300 hits and NPE >= 3200 are selected
    - for selected events the directions are reconstructed with a track hypothesis and harder NPE cut is applied

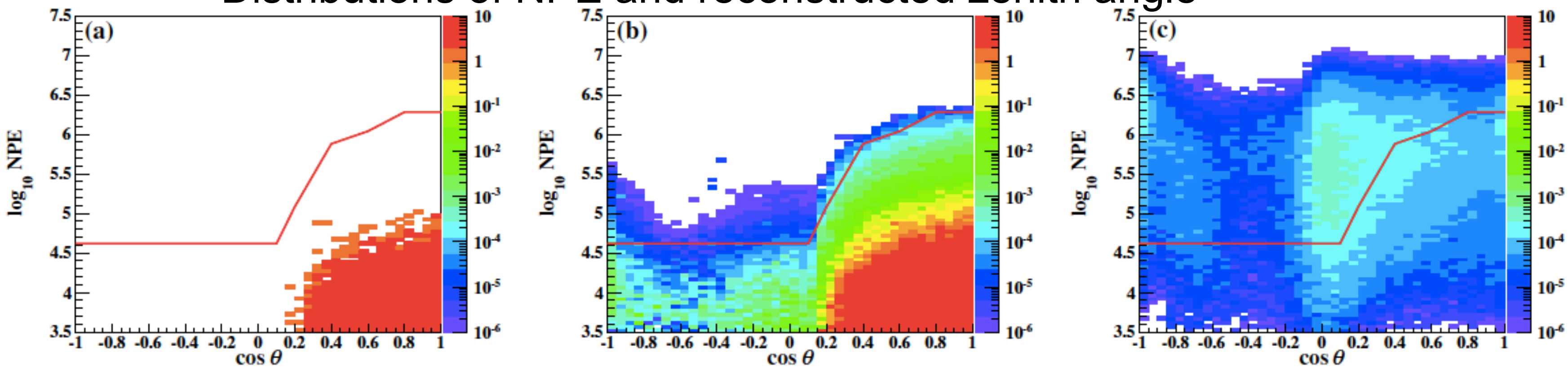
Extremely High Energy filter data

First Observation of PeV-Energy Neutrinos

- Additional cuts

PRL 111, 021103 (2013)

Distributions of NPE and reconstructed zenith angle



the IC79 experimental test sample　　total background　　cosmogenic signal neutrino

IC79

- a log-likelihood fit is performed and an event selection based on a fit quality parameter is applied
  - to remove events which contain muons from independent air showers.

IC86

regression technique is used to remove hits that have a timing significantly different from what is expected from the bulk of the photons from a muon track

First Observation of PeV-Energy Neutrinos

PRL 111, 021103 (2013)

- The expected number of **background events** in the final sample for the 615.9 day live time from atmospheric muons is
  - **0.038 ± 0.004 stat + 0.021- 0.038 syst**
- and from neutrinos from decays of pions and kaons is
  - **0.012 ± 0.001 stat + 0.010 – 0.007 syst**

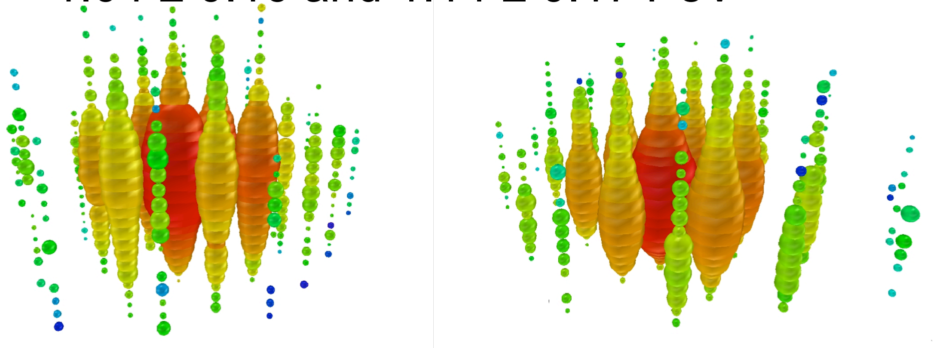
- Adding prompt atmospheric neutrinos from charm production by cosmic rays + improved cosmic ray spectrum modeling (Phys. Rev. D 78, 043005, 2008)

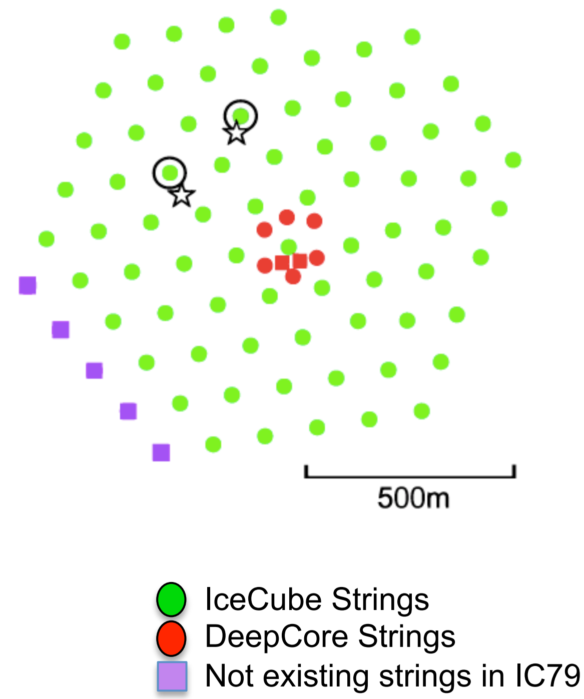
  the total number of background events is:
  - **0.082 ± 0.004 stat + 0.041 – 0.057 syst**

  - The main systematic uncertainties are from the measurement of NPE and from uncertainties in the cosmic ray flux.

Two PeV events detected in two years of data

1.04 ± 0.16 and 1.14 ± 0.17 PeV **PRL 111, 021103 (2013)**



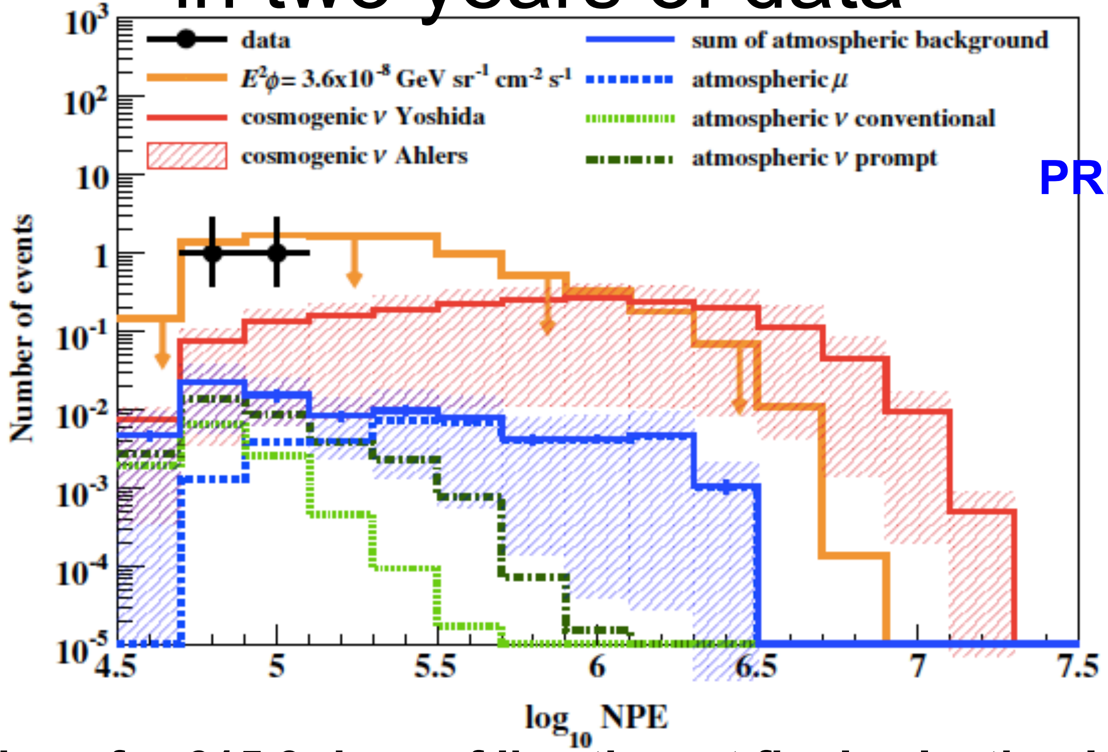


- **One year with 79 strings + one year with 86 strings**
- Analysis optimized for extremely high energy (GZK) neutrinos
- Each event has a lower limit on neutrino energy equal to at least 1 PeV

- First hint of astrophysical neutrinos
  - atmospheric events unlikely to produce that many events at that energy):

    2.8 σ significance

Two PeV events detected in two years of data



PRL 111, 021103 (2013)

NPE distributions for 615.9 days of live time at final selection level

•black points – experimental data (data errors – 68% confidence interval (Phys. Rev. D 57, 3873, 1998))

•**solid blue line –** sum of the atmospheric muon (dashed blue), conventional atmospheric Neutrino (dotted light green) and the baseline prompt atmospheric neutrino (dotted-dashed green) background.

•red line represents the cosmogenic neutrino model

•orange line represents an E^2 power-law flux

Evidence for Extraterrestrial Neutrinos in two years of data

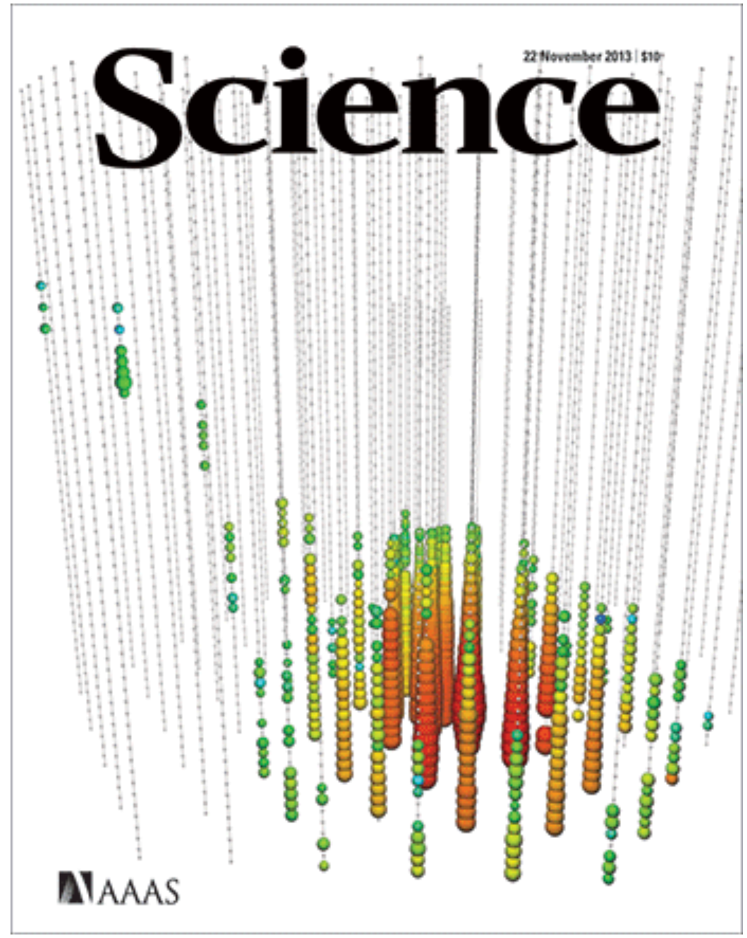
- Follow-up analysis

IC79+IC86 analysis of "Starting Events" (2010-2012, 662 days) to search for all-flavor neutrinos (starting tracks + contained cascades)

Improved sensitivity
Extended energy coverage down to ~30 TeV

- **26 additional events (28 total)**

- Inconsistent with purely atmospheric origin at **4.1 σ significance**



Science 342, 1242856 (2013) DOI: 10.1126/science.1232856

Evidence for Extraterrestrial Neutrinos in three years of data

- **Accepted by Phys. Rev. Lett.**
  - **arXiv:1405.5303**

- IC79 and IC86 (2010-2013, 988 days)

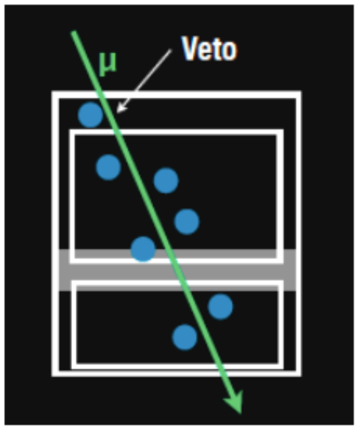
- **Observed 37 events** (HESE III sample)

  (28 cascade-like, 9 track-like) in 30 TeV < Ev < 3 PeV

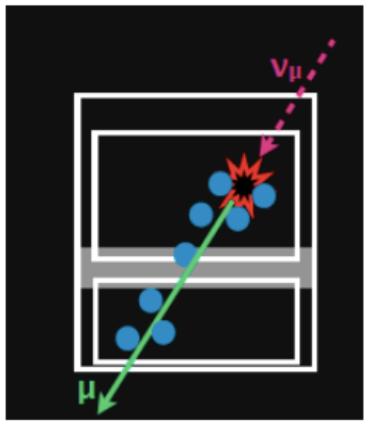
HESE III- High Energy Starting Events in three years of data

Evidence for Extraterrestrial Neutrinos in three years of data

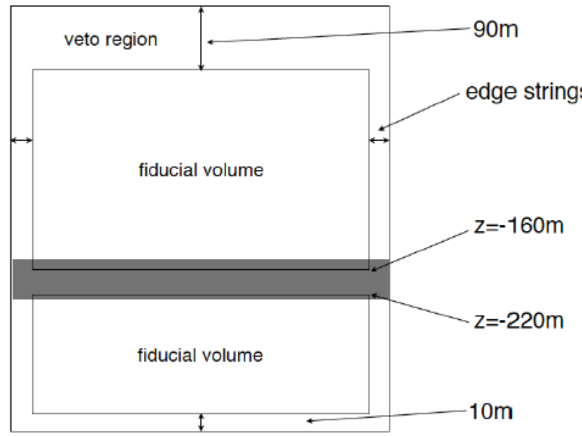
- High charge events with vertices contained in the detector



Reject



Accept



Reject incoming muons when *"early charge"* in veto region

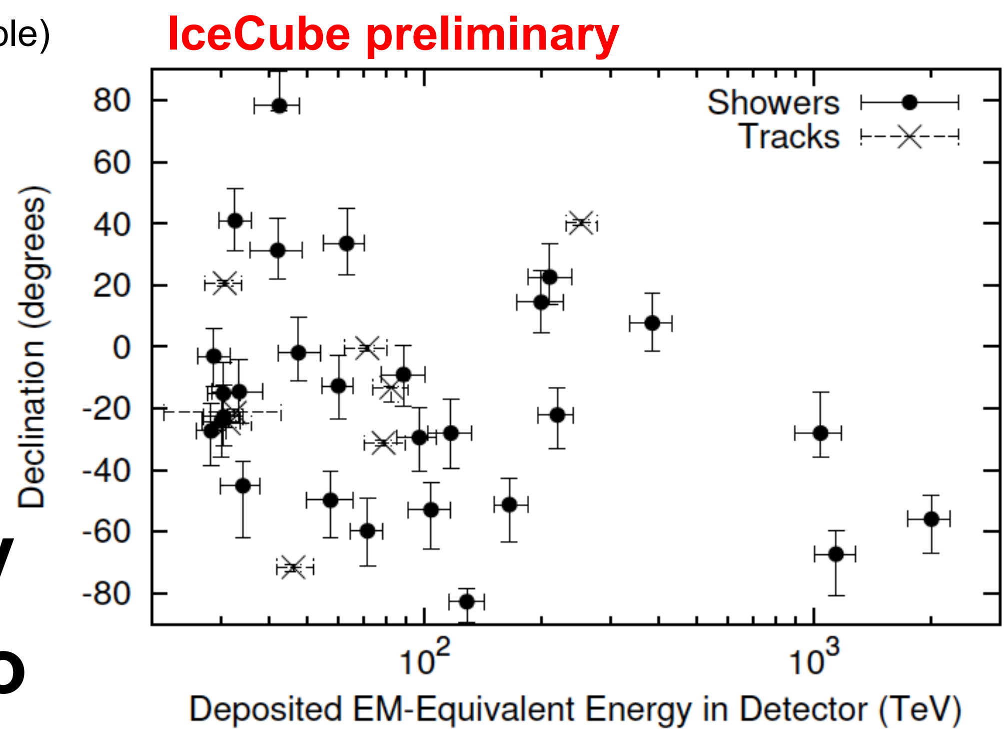
Selection criteria:
Qtot > 6000 pe and early charge relatively high
Well contained vertices
No flavor tagging
Veto is used to reject (and estimate remaining) background

Background:
Atmospheric muons (tagged muons)
Atmospheric neutrinos

Evidence for Extraterrestrial Neutrinos in three years of data

- 37 events total (HESE III sample)
  - Estimated background
    - 8.4 ± 4.2 atm. muons
    - 6.6 +5.9 -1.6 atm. neutrinos

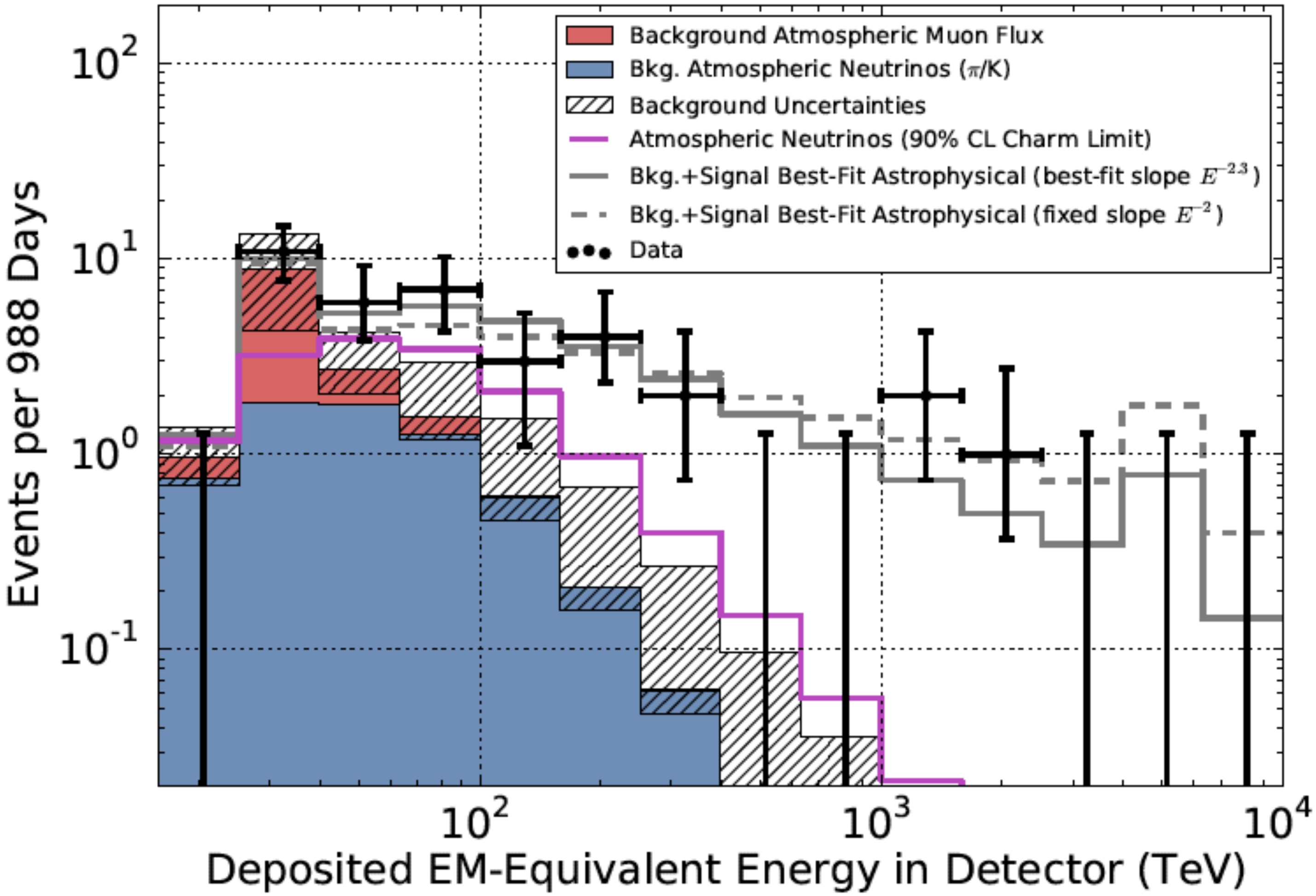
- **5.7σ rejection of only atmospheric neutrino flux**



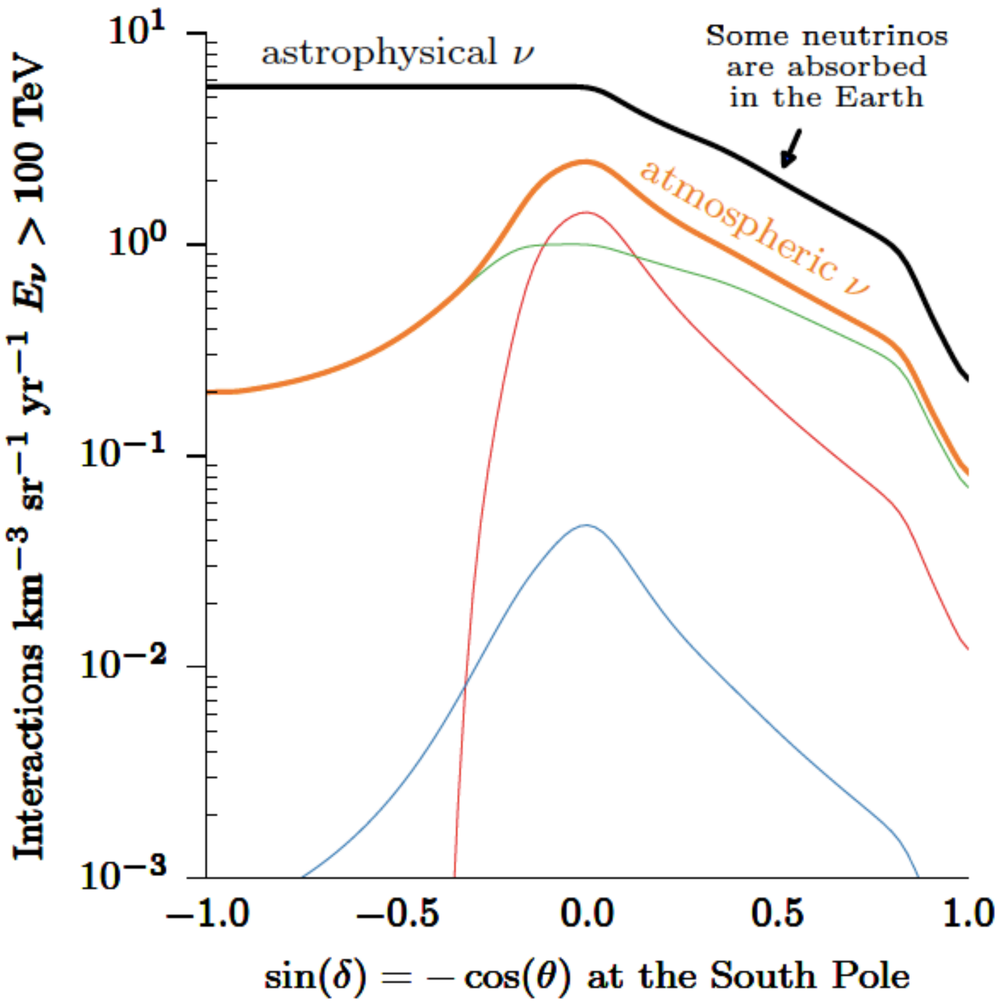
HESE III- High Energy Starting Events in three years of data

Evidence for Extraterrestrial Neutrinos in three years of data

IceCube preliminary



Expected distribution of events in declination

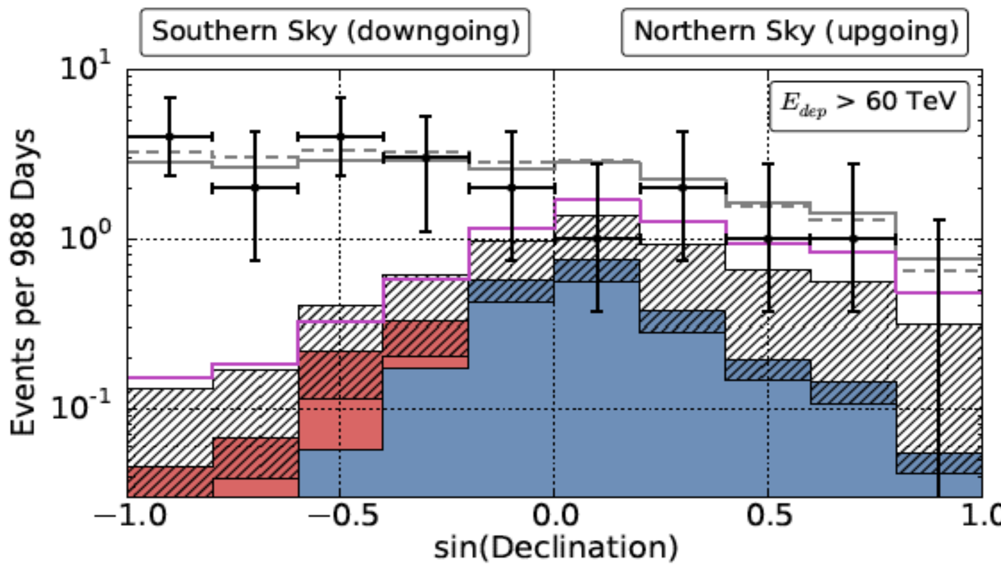


The zenith distributions of high-energy astrophysical (black) and atmospheric neutrinos (orange) are essentially different

Diagram borrowed from Jakob van Santen (ISVHECRI 2014), CERN

Evidence for Extraterrestrial Neutrinos in three years of data

- Expected and observed distribution of events in declination for various cuts in deposited energy



E_{dep} > 60 TeV

IceCube preliminary

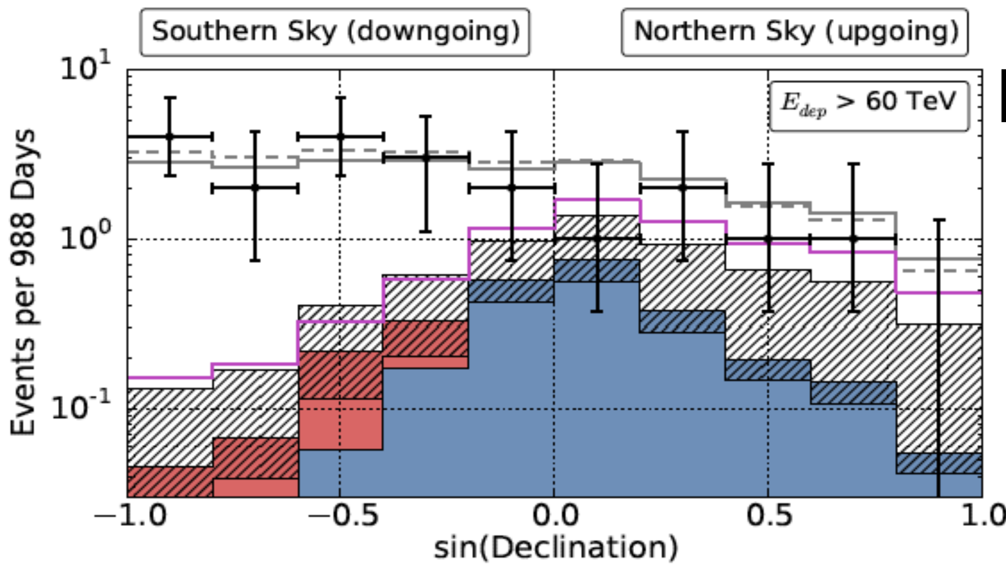
Best fit per-flavor astrophysical flux $(\nu + \bar{\nu})$ in [60 TeV, 3 PeV] energy range

is $E^2\phi(E) = 0.95 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$

Background only hypothesis disfavored at 5.7σ

Evidence for Extraterrestrial Neutrinos in three years of data

- Expected and observed distribution of events in declination for various cuts in deposited energy



E_{dep} > 60 TeV

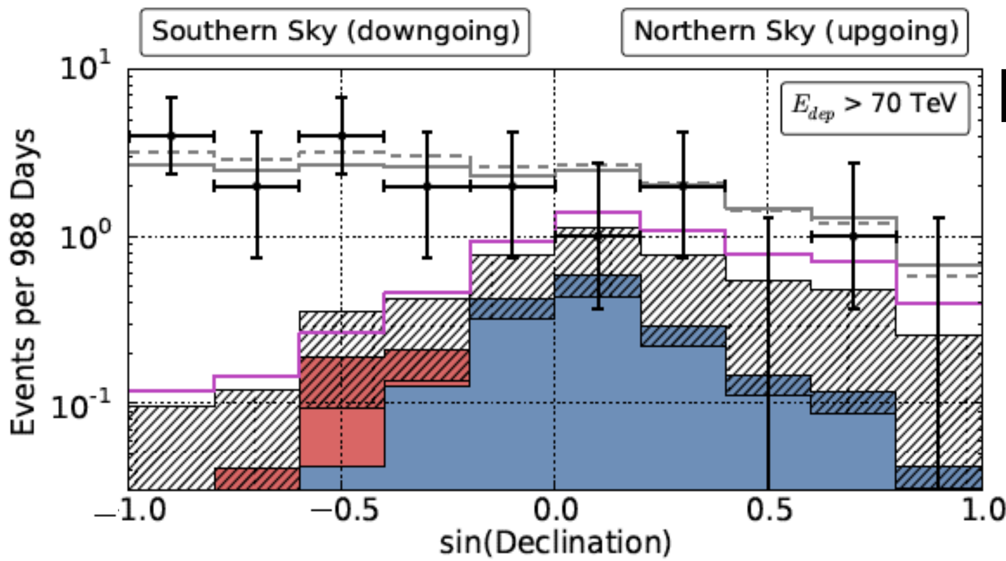
IceCube preliminary

atm. ν self-veto (arXiv 0812.4308)
Atmospheric neutrinos are vetoed by accompanying muons, astrophysical neutrinos are not

earth absorption
neutrino interaction cross-section increases with energy

Evidence for Extraterrestrial Neutrinos in three years of data

- Expected and observed distribution of events in declination for various cuts in deposited energy



E_{dep} > 70 TeV

IceCube preliminary

Evidence for Extraterrestrial Neutrinos in three years of data

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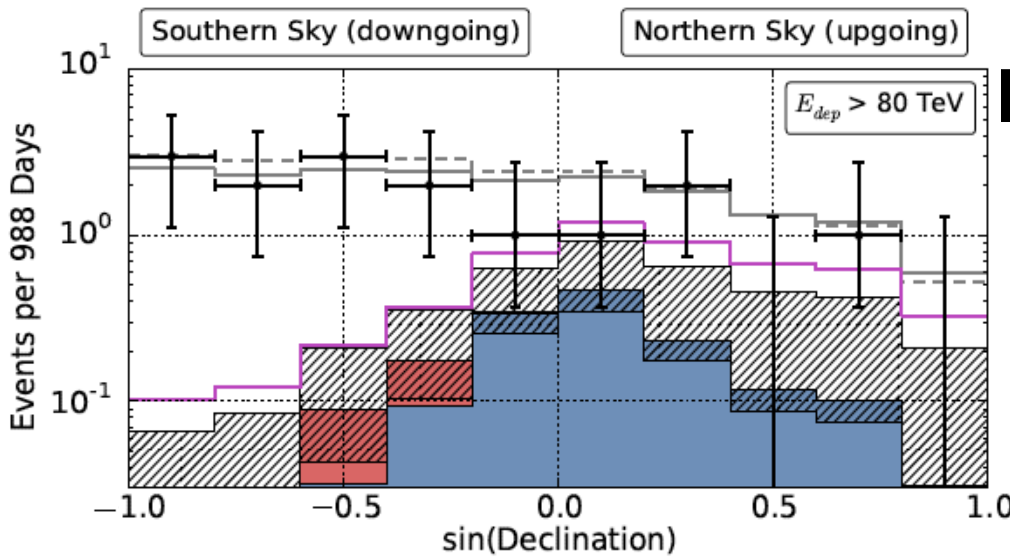

E_{dep} > 80 TeV

IceCube preliminary

Evidence for Extraterrestrial Neutrinos in three years of data

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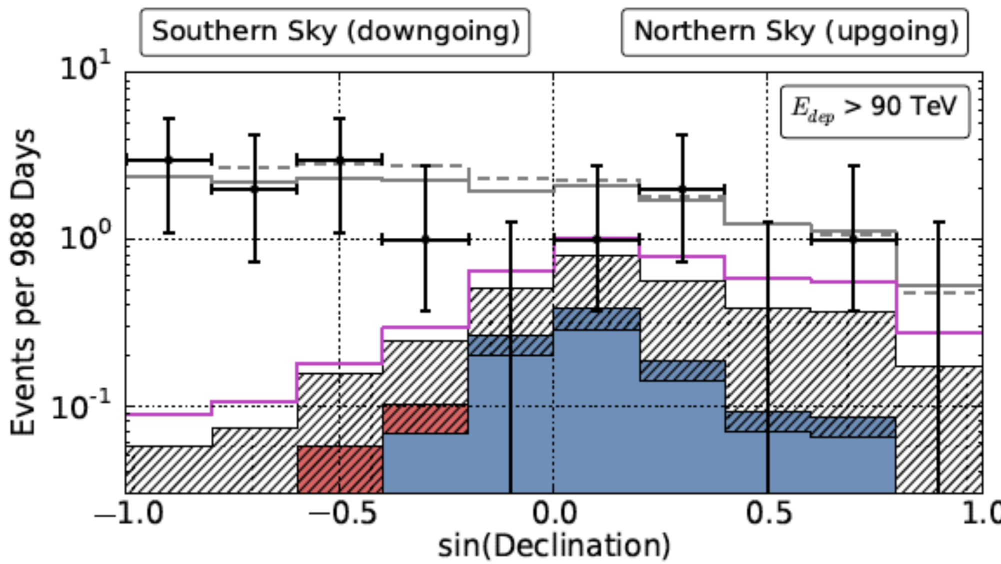

E_{dep} > 90 TeV

IceCube preliminary

Evidence for Extraterrestrial Neutrinos in three years of data

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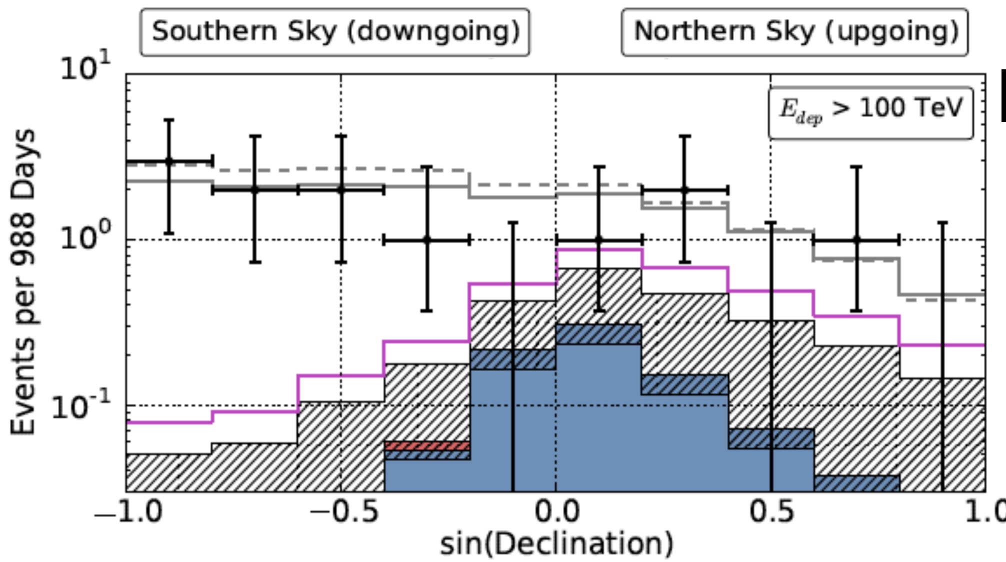

E_{dep} > 100 TeV

IceCube preliminary

Evidence for Extraterrestrial Neutrinos in three years of data

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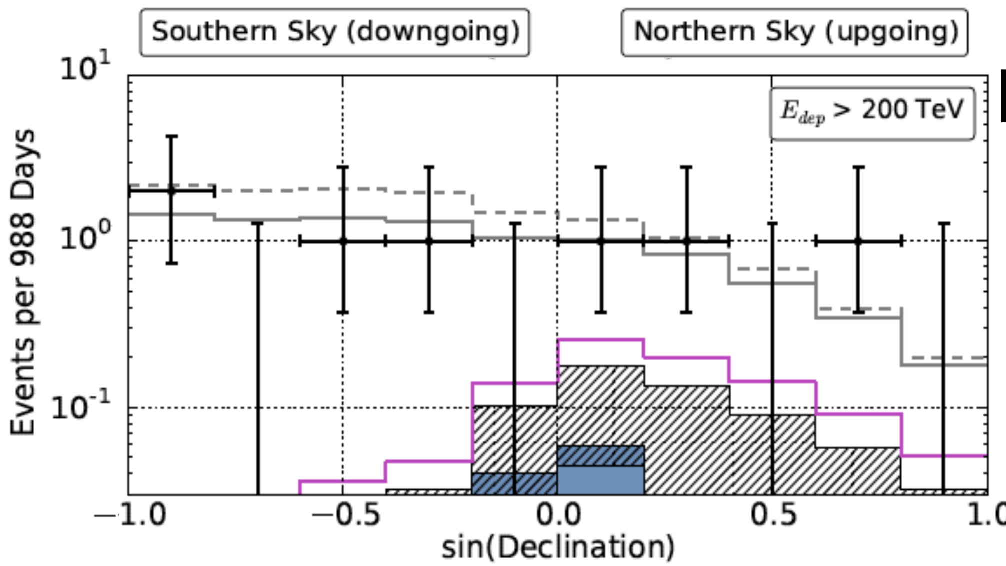
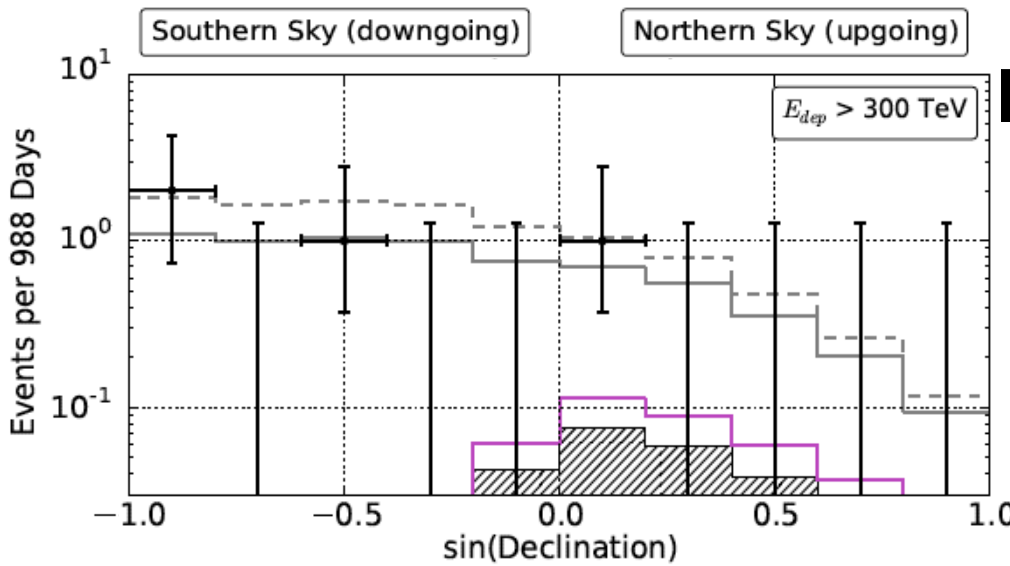


E_{dep} > 200 TeV

IceCube preliminary

Evidence for Extraterrestrial Neutrinos in three years of data

- Expected and observed distribution of events in declination for various cuts in deposited energy



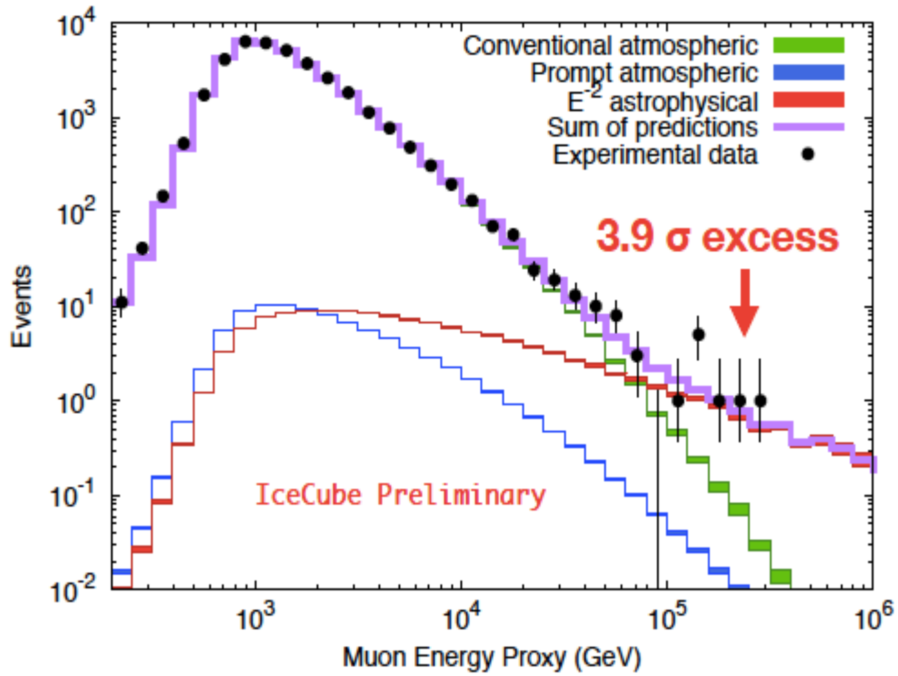
E_{dep} > 200 TeV

IceCube preliminary

HESE III sample is dominated by cascades from the Southern Sky (downgoing)
What about the Northern Sky and track like events (ν_μ) ?

Excess in incoming muons from the Northern Sky

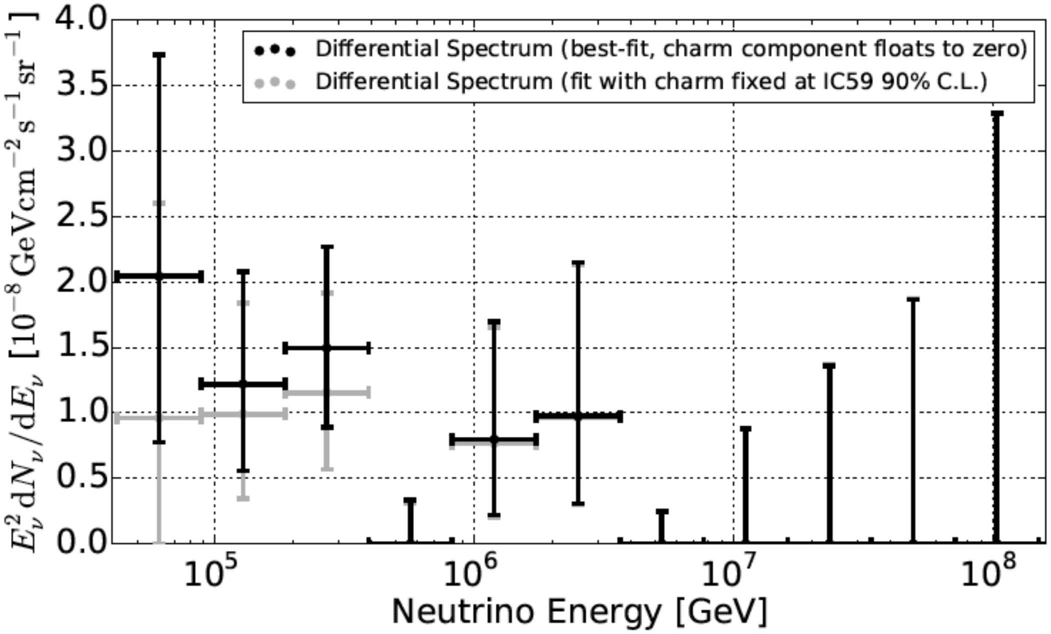
Data IC79 + IC86 (2010 – 2012)



Preliminary

$$E_\nu^2 \Phi_\nu = \begin{cases} 0.95 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}} & \text{High-energy starting events} \\ 1.01 \pm 0.35 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}} & \text{Upgoing } \nu_\mu \end{cases}$$

Evidence for Extraterrestrial Neutrinos in three years of data



IceCube preliminary

assumptions:
a 1:1:1 favor ratio and isotropy

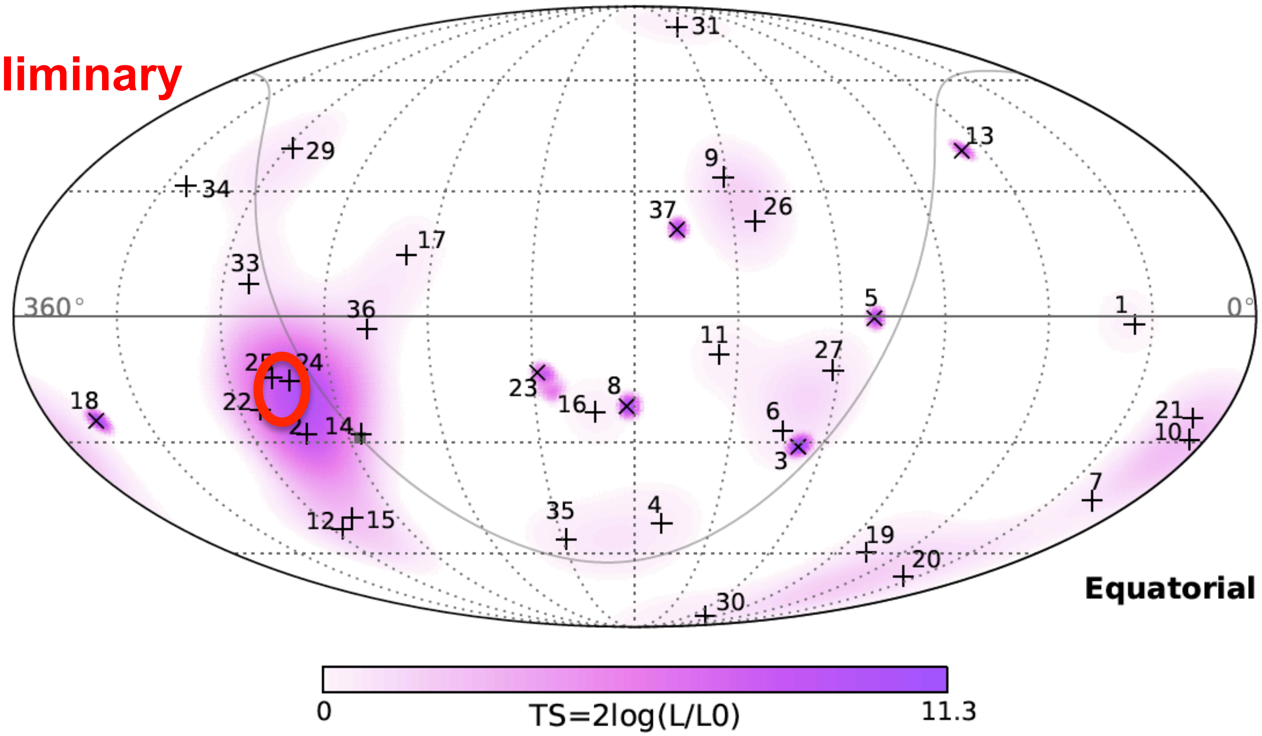
reconstructed spectrum is compatible with E^{-2}

an unbroken E^{-2} flux at our best-fit level predicts 3.1 additional events above 2 PeV (not seen) → either a softer spectrum (-2.3 ± 0.3) or a cut off at high energies

Sky map
HESE-III

ICECUBE

IceCube preliminary



No evidence of (significant) spatial clustering

most significant cluster happens by chance 7.2% of the time

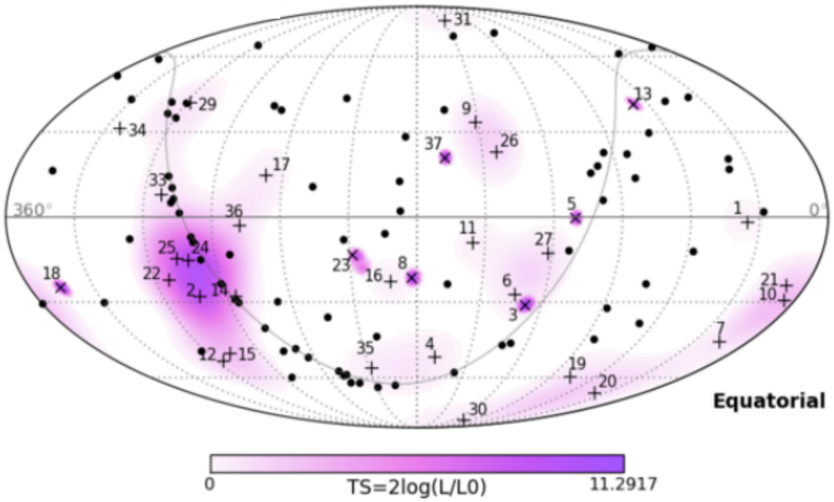
HESE III- High Energy Starting Events in three years of data

Sky map HESE-III

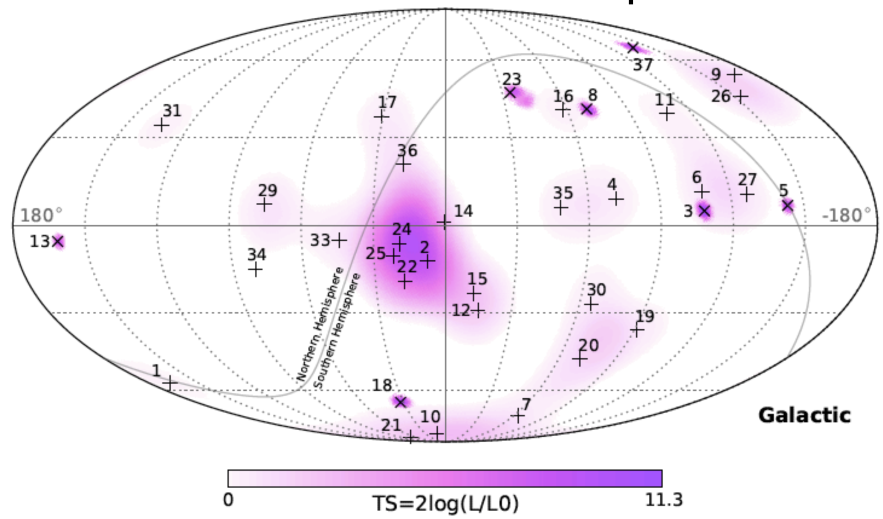
ICECUBE

IceCube preliminary

Correlation with potential sources?



Correlation with Galactic plane?



There is still no evidence for point sources of high-energy neutrinos

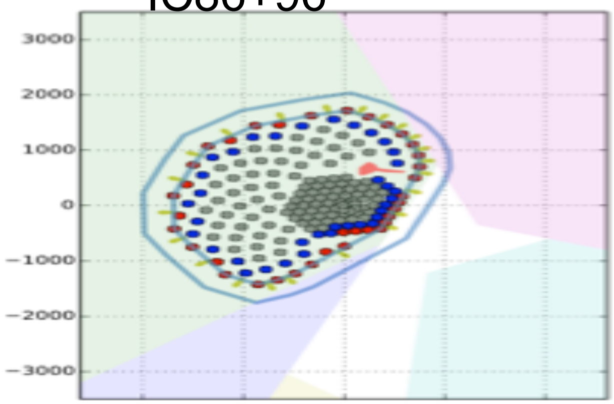
HESE III- High Energy Starting Events in three years of data

Outline

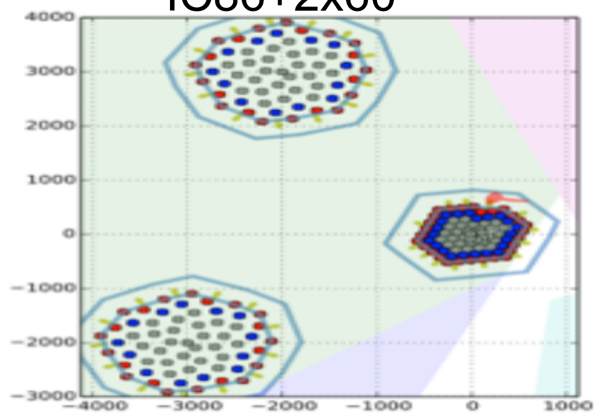
- **IceCube detector**
  - Data taking with full detector
  - Improvement in analysis techniques
- **Extraterrestrial Neutrinos**
  - First observation of astrophysical high energy (PeV) neutrinos
    - no evidence for point sources
  - Diffuse flux (IC79 + IC86)
    - $E_\nu^2 \Phi_\nu = \begin{cases} 0.95 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}} & \text{High-energy starting events} \\ 1.01 \pm 0.35 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}} & \text{Upgoing } \nu_\mu \end{cases}$
- **Atmospheric neutrinos**
  - 100000's v on disks
- Proposal for a next generation **High Energy Extension (HEX)** detector
- Proposal for low-energy **PINGU infill extension**
  - Letter of intent on the archive (arXiv:1401.2046)

HEX
Next generation IceCube

strings:
IC86+96



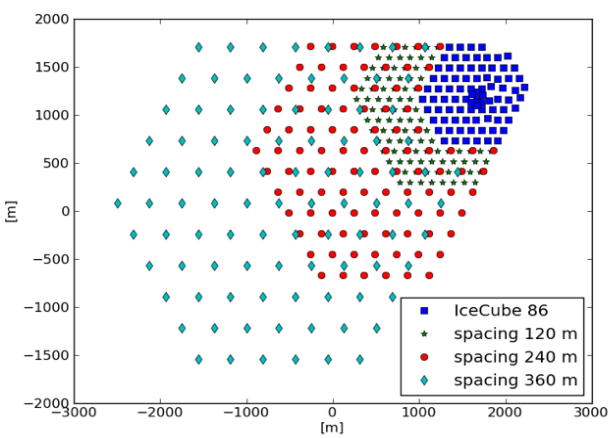
strings:
IC86+2x60



String spacing: ~240m

~ 200 PeV
Cascade events/10 years

~ 500 – 1000 **vμ**
above
100 TeV (μ energy)



IC86+98 Spacing 120m → 2.3 km^3
IC86+99 Spacing 240m → 6.3 km^3
IC86+95 Spacing 360m → 12.6 km^3

geometry not optimum

Conclusions

- IceCube has an ability to perform precise neutrino astronomy
- **Diffuse astrophysical flux of neutrinos has been observed**
  - reconstructed spectrum is compatible with E^{-2}
  - there is still no evidence for point sources of high-energy neutrinos
- Exciting time for the neutrino telescopes!

physicsworld
BREAKTHROUGH OF THE YEAR 2013