Neutrino Astronomy with IceCube

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for the IceCube Collaboration

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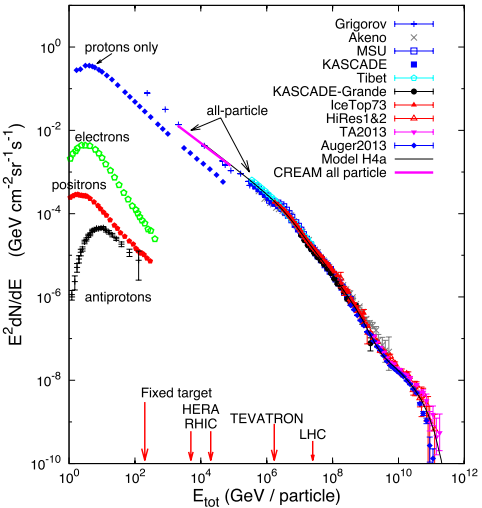
September 16, 2016

Cosmic Ray Astrophysics

Cosmic Rays

a century-old mystery



Lower energy cosmic rays: identified with solar and galactic (e.g. SN remnant) emission

Highest energy cosmic rays: sources **not yet identified**

Cosmic Rays

production and observation

Cosmic rays — p or heavier nuclei — are accelerated in violent astrophysical objects.

Then e.g.,

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \rightarrow p + 2\gamma & \text{(2/3 of all cases)} \\ n + \pi^+ \rightarrow n + e^+ + \nu_\mu + \nu_e + \bar{\nu}_\mu & \text{(1/3 of all cases)} \end{cases}$$

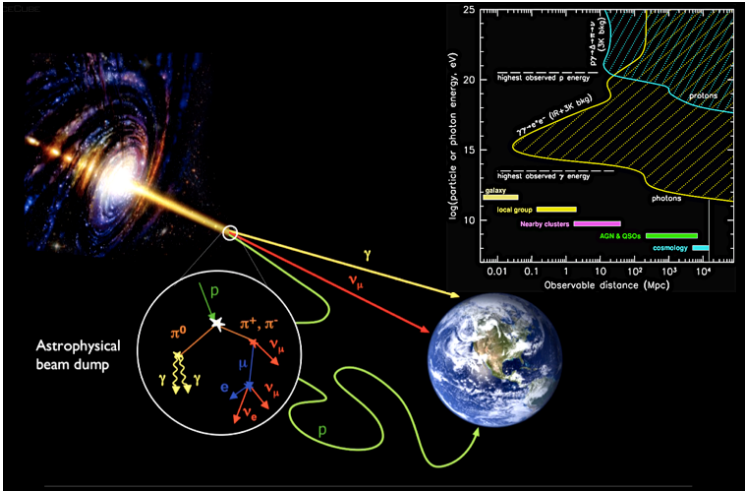
Photons attenuated by the CMB

Cosmic rays / charged particles travel in **curved paths** due to magnetic fields

Neutrinos travel long distances **largely unencumbered** by intervening matter

Cosmic Rays

propagation



The IceCube Neutrino Observatory

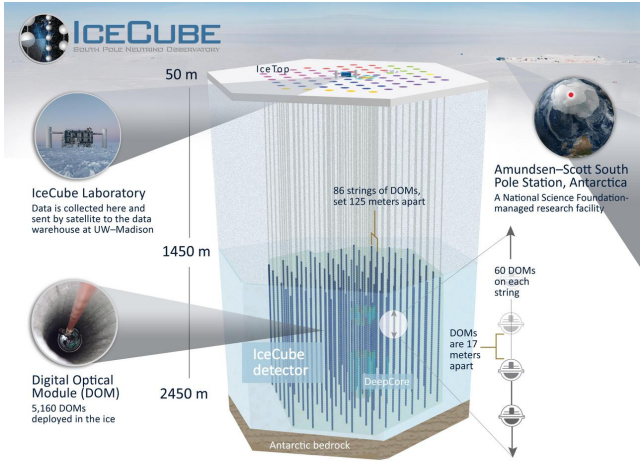
The IceCube Neutrino Observatory

1.5–2.5 km deep in the South Pole glacier

5160 PMTs arranged on **86** strings

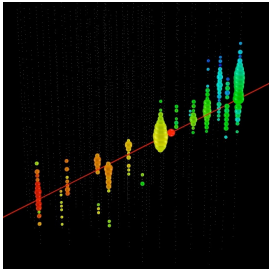
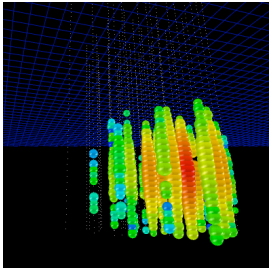
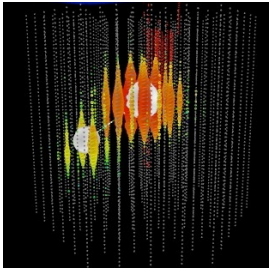
1 km^3 instrumented volume

Constructed **2005–2010**



Neutrino Detection

interactions and detector signatures

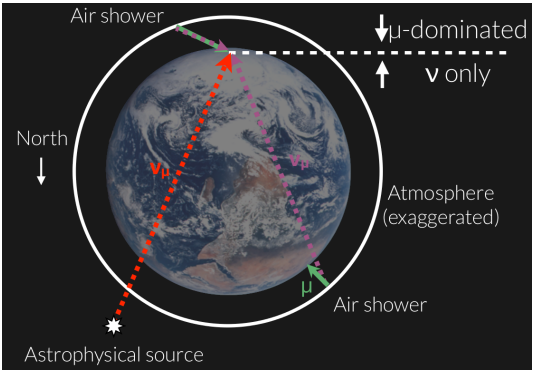
CC ν_μ	CC ν_e / NC ν_*	CC ν_τ
		
$\nu_\mu + N \to \mu + X$	$\nu_e + N \to e + X$ $\nu_* + N \to \nu_* + X$	$\nu_\tau \to \tau + X$
track	*cascade*	*cascade* (or *double-bang*)

Cosmic Ray Muon Background

two approaches to neutrino selection

Classic ν_μ strategy:

- Earth acts as neutrino filter
- Well-reconstructed up-going tracks must be neutrinos



→ North sky and ν_μ only

Cosmic Ray Muon Background

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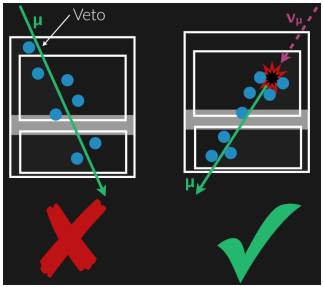
→ North sky and ν_μ only

Active veto to select starting events:

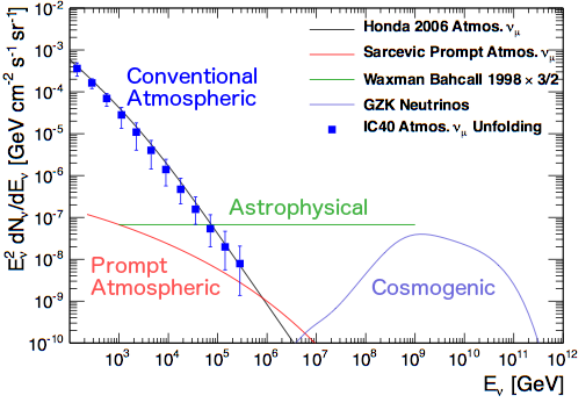


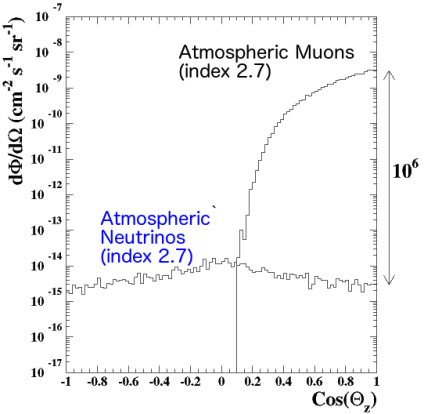
→ Reduced effective volume, but full sky and all flavor

Cosmic Ray Muon Background

muon and neutrino backgrounds

Background and signal differ in spectrum and angular distribution





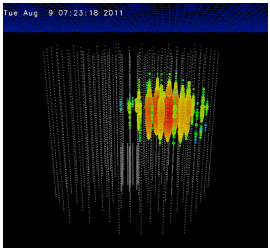
Astrophysical Neutrino Flux

Appearance of PeV neutrinos

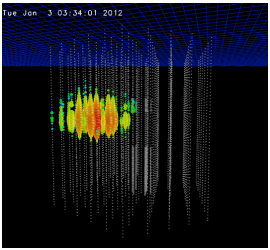
first hint of an astrophysical flux

Two PeV neutrinos found

2.8σ excess over background
[PRL 111, 021103 (2013)]



$\sim$ 1.0 PeV



$\sim$ 1.1 PeV

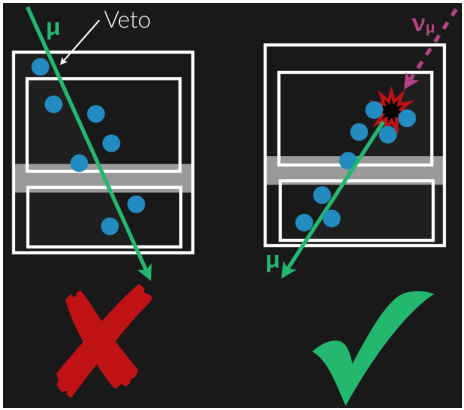
Veto methods were implemented to probe lower energies.

High Energy Starting Events

results from four years of data

Search for **contained, very bright** events

Sensitive to all flavors above $\sim$ **60 TeV**



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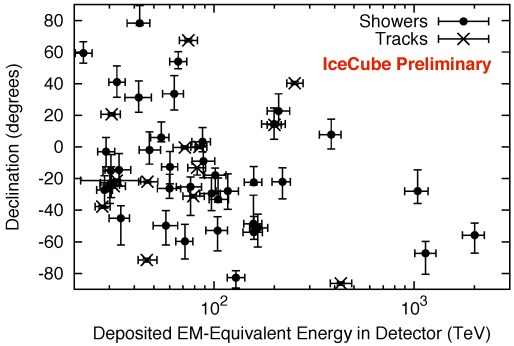

[ICRC2015 / PoS(ICRC2015)1081]

High Energy Starting Events

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Search for **contained, very bright** events

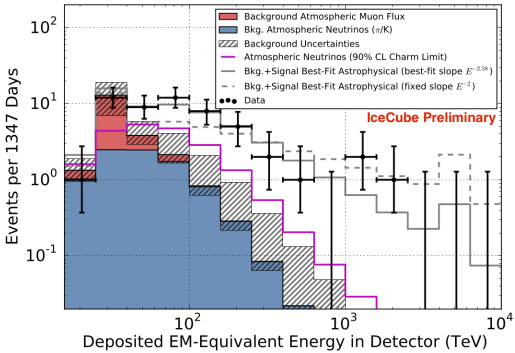
Sensitive to all flavors above $\sim$ **60 TeV**

53 events in four years

6.5σ above background from maximum likelihood forward-folding

Best fit spectrum:

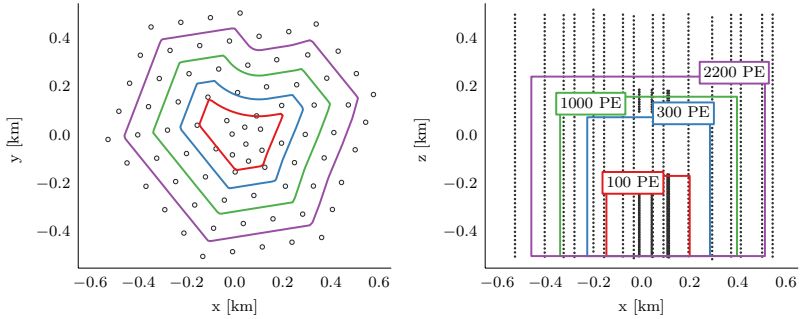
$$\Phi_\nu(E) = \Phi_0 \cdot (E/100\,\mathrm{TeV})^{-2.58\pm0.25}$$
$$\Phi_0 \simeq 2.2 \times 10^{-18}/\mathrm{GeV}/\mathrm{cm}^2/\mathrm{s}/\mathrm{sr}$$



[ICRC2015 / PoS(ICRC2015)1081]

Medium Energy Starting Events

probing lower energies with an adaptive veto



Active volume decreases with deposited energy — threshold reduced to $\sim 1\,\mathrm{TeV}$

Medium Energy Starting Events

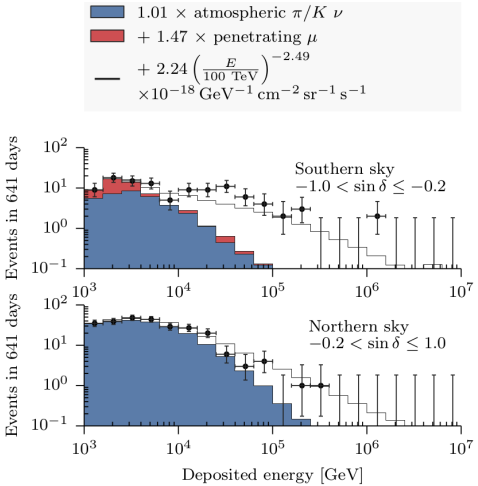
results from two years of data

Astrophysical excess down to $\sim$ **10 TeV**

Fit consistent with high energy search but errors are smaller

Model disagreement at 30 TeV **not significant** ($p = 5\%$)

[PRD 91, 022001 (2015)]



Astrophysical Muon Neutrinos

results from six years of data

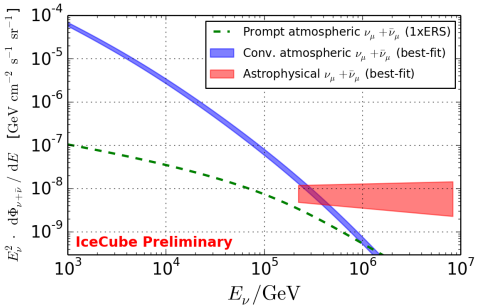
Accept incoming tracks → larger effective area

- Restricts search to **North sky ν_μ**
- Probes **higher energies**

Best fit spectrum:

$$\Phi_\nu(E) = \Phi_0 \cdot (E/100\,\mathrm{TeV})^{-2.08\pm0.13}$$

$$\Phi_0 = 0.82^{+0.30}_{-0.26} \times 10^{-18}/\mathrm{GeV}/\mathrm{cm}^2/\mathrm{s}/\mathrm{sr}$$



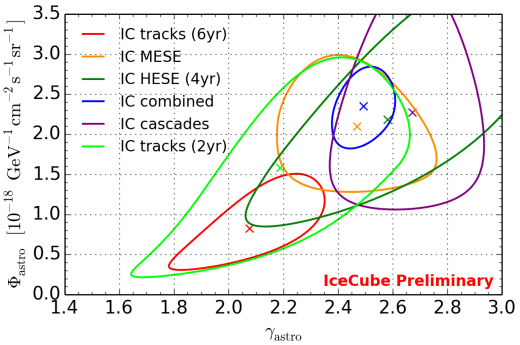
[ICRC2015 / PoS(ICRC2015)1079]

Astrophysical Flavor Ratio

constraining source emission with an IceCube global fit

Astrophysical spectrum measured by several analyses

- Some are partially correlated
- Global fit benefits from best statistics
- Tension may come from different energy ranges of the analysis



[ApJ 809, 98 (2015)]

Astrophysical Flavor Ratio

constraining source emission with an IceCube global fit

Astrophysical spectrum measured by several analyses

- Some are partially correlated
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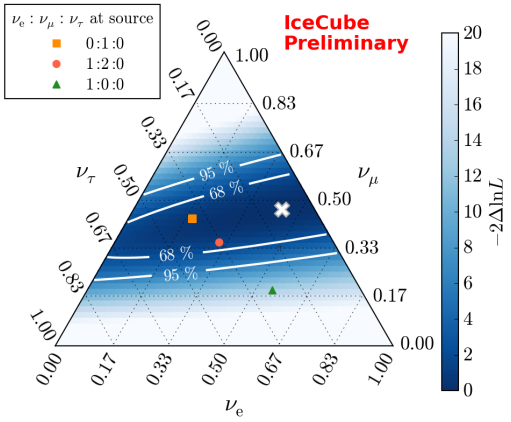
Some sensitivity to $\nu_e : \nu_\mu : \nu_\tau$ ratio at source

- n-decay dominance excluded at 3.6σ



[ApJ 809, 98 (2015)]

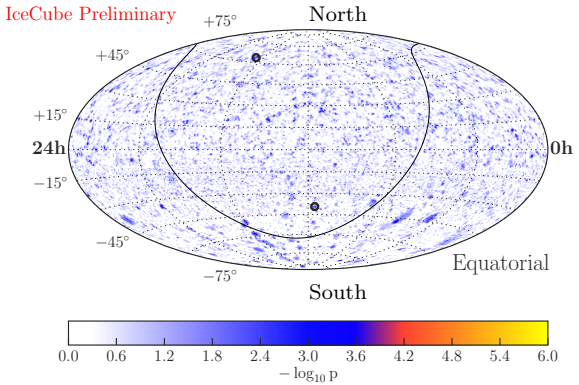
Searching for Sources

Point Source Analysis

search for clustering with 6 years of muon tracks

Standard skymap dominated by **atm. ν** in the North and **atm. μ** in the South

- North: $p = 44\%$
- South: $p = 39\%$



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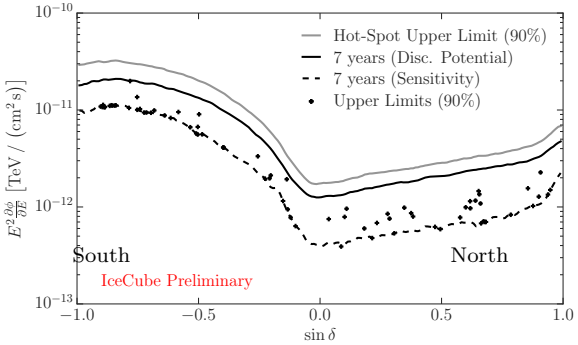
- North: $p = 44\%$
- South: $p = 39\%$

Excess of hot spots?

- North: $p = 42\%$
- South: $p = 39\%$
- Galactic Plane $\pm 15^\circ$: $p = 57\%$



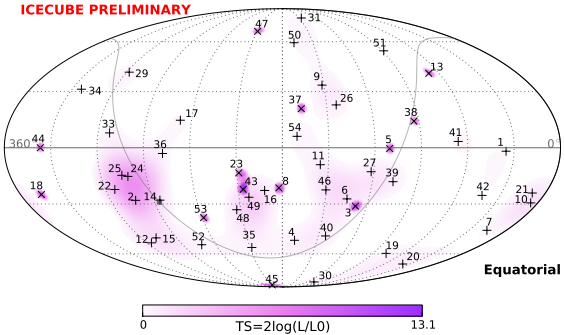
[ICRC2015 / PoS(ICRC2015)1047 (6 year results)]

Starting Event Source Analyses

searches for clustering of starting events

Starting events $\gtrsim 60\,\text{TeV}$ (4yr)

- $p = 58\%$



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Starting events $\gtrsim 60$ TeV (4yr)

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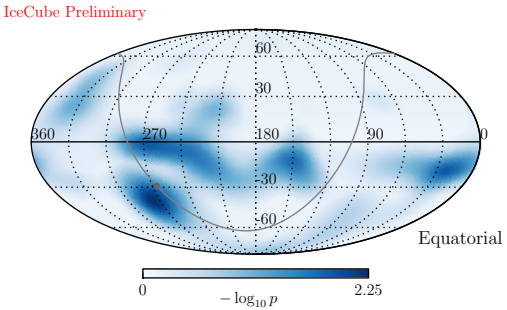
Contained cascades $\gtrsim 1$ TeV (2yr)

- $p = 52\%$



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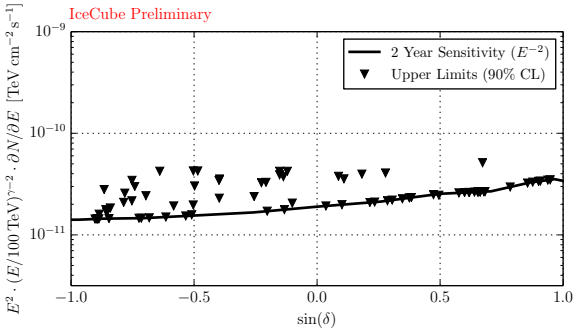
Strong cascade sensitivity in South



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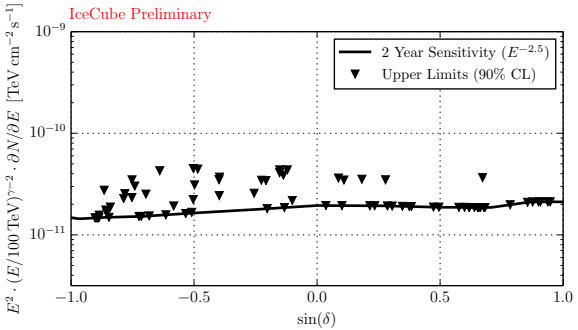
Strong cascade sensitivity in South

- Even for softer spectra or extended sources

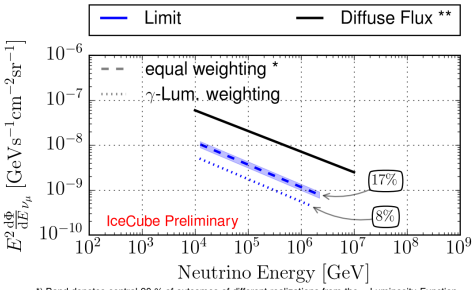


Multimessenger Astronomy

follow-up by IceCube

Fermi-LAT blazar stacking analysis:
862 blazars observed over **3 years**

- Flux-weighted: $p = 36\%$
- Unweighted: $p = 6\%$



*) Band denotes central 90 % of outcomes of different realizations from the γ-Luminosity Function. This limit also holds for all (quasi-)isotropic subpopulations, independent of their gamma emission.

**) 1-flavor diffuse fit result [arxiv:1410.1749]

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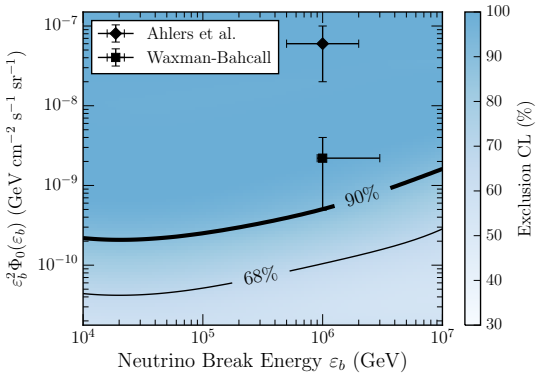
GRB stacking analysis:
506 observed in tracks, **807** in cascades

- $p = 32\%$



[accepted by ApJ]

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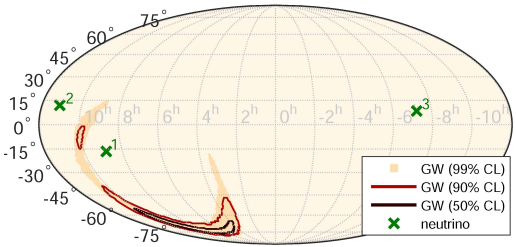
LIGO **GW150914**

- 3 off-source, low-energy ν within $\pm 500\,\mathrm{s}$



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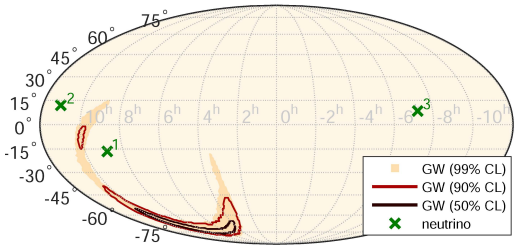


Rapid follow-up under development!

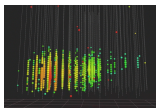
- GRBs and other flaring objects
- "What did IceCube see?"

Multimessenger Astronomy

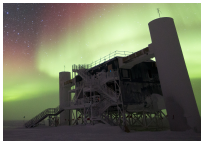
follow-up of IceCube events

Neutrino selection in **real-time** at South Pole

IceCube ν



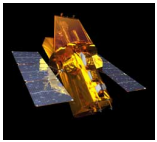
Real-time Processing



Iridium Data Transfer to "The North"

Gamma (e.g. Veritas)

X-ray (e.g. Swift-XRT)



Optical (e.g. PTF)

Multimessenger Astronomy

follow-up of IceCube events

Neutrino selection in **real-time** at South Pole

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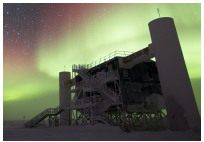

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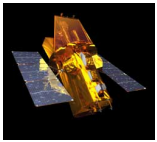
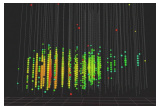


IceCube ν



- "Multiplet" follow-up online since 2008
- "Singlet" follow-up starting this year!

http://gcn.gsfc.nasa.gov/notices_amon/67093193_127853.amon

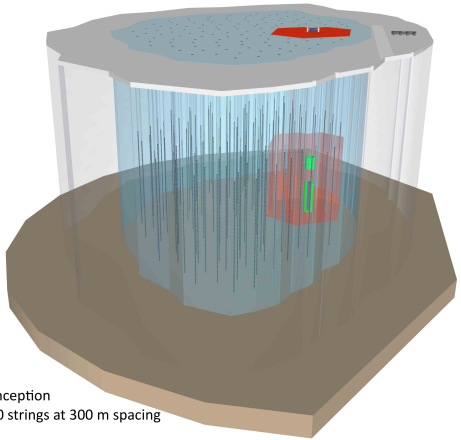
Optical (e.g. PTF)

Proposed Detector Extensions

IceCube-Gen2 / PINGU

extending the energy reach of IceCube

Gen2 would instrument $\sim$ **10 km^3**



Artist conception
Here: 120 strings at 300 m spacing

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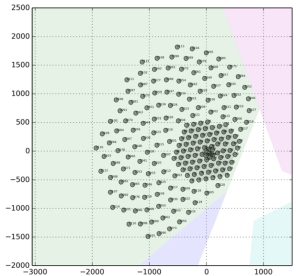
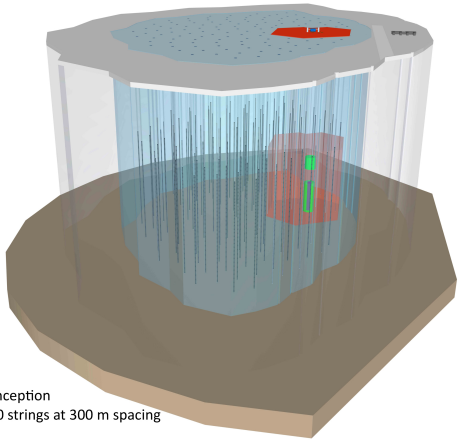
Layout optimization still in progress





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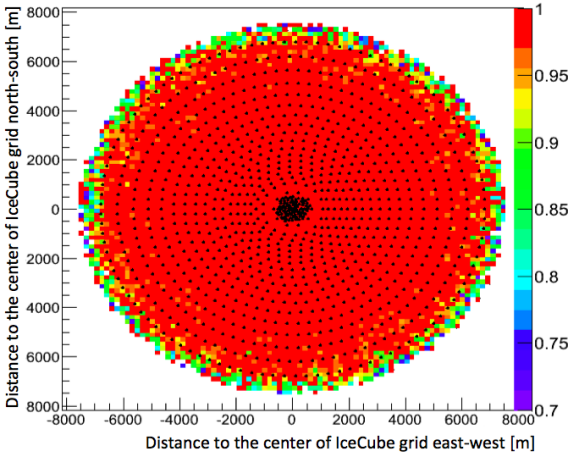
Surface veto could dramatically improve sensitivity to **Southern sources**



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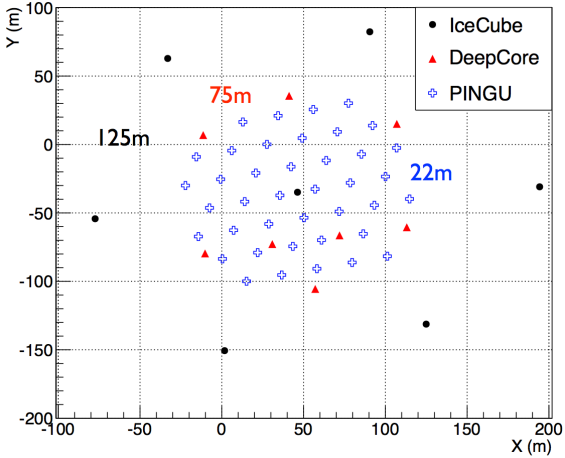
PINGU low-energy infill array would allow studies of **fundamental physics**



Summary and Outlook

the dawn of neutrino astronomy

IceCube has discovered and begun to characterize an astrophysical neutrino flux in the TeV to PeV region.

Real-time follow-up campaigns have been in place through agreements with other observatories: optical, X-ray, gamma-ray, gravitational wave

Now beginning to release public alerts (starting events, high energy events, doublets) to broader community in real time for follow-up

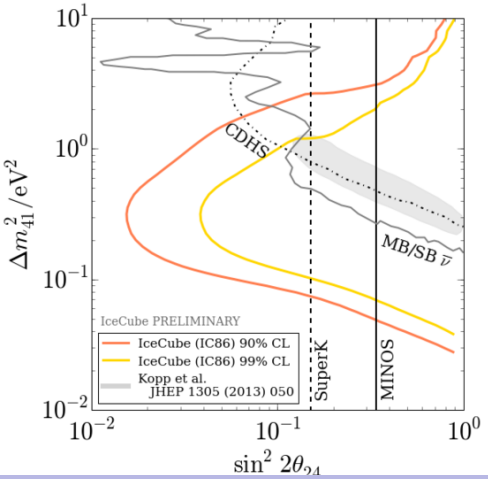
IceCube upgrade under development: high energy extension, surface veto array, PINGU

Backup Slides

Sterile Neutrino Search

- We unblinded one year of data which had $\sim$ 20,000 neutrino events.
- Distributions compatible with the no sterile hypothesis
- IceCube result is competitive with other limits and the World best at $\sim 0.1 - 1.0\, eV^2$.

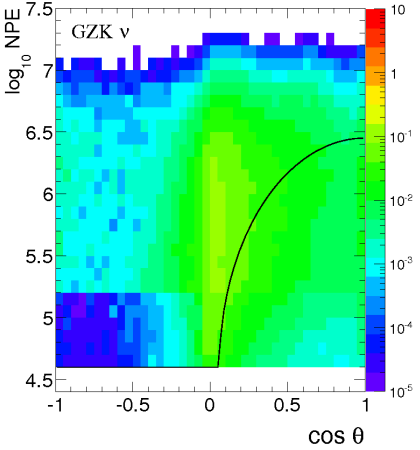
See arXiv:1605.01990 for more details



UHE Neutrino Search

search for cosmogenic neutrinos with maximal UHE acceptance

UHE neutrinos distributed more broadly throughout sky than atmospheric backgrounds



[ICRC2015 / PoS(ICRC2015)1064 (6 year results)]

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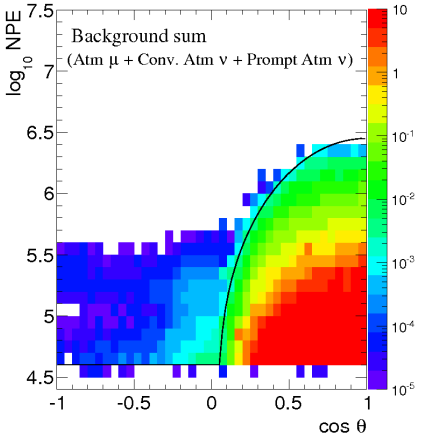
Good signal acceptance / background rejection possible with simple charge $\times$ zenith cut



[ICRC2015 / PoS(ICRC2015)1064
(6 year results)]

UHE Neutrino Search

search for cosmogenic neutrinos with maximal UHE acceptance

UHE neutrinos distributed more broadly throughout sky than atmospheric backgrounds

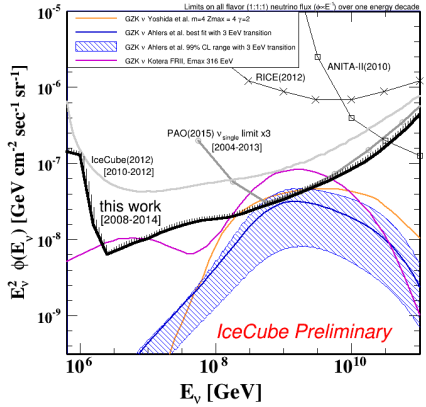
Good signal acceptance / background rejection possible with simple charge $\times$ zenith cut

No significant signal observed

Flux limits calculated in decades in energy

- Beginning to constrain cosmogenic ν scenarios

[ICRC2015 / PoS(ICRC2015)1064
(6 year results)]

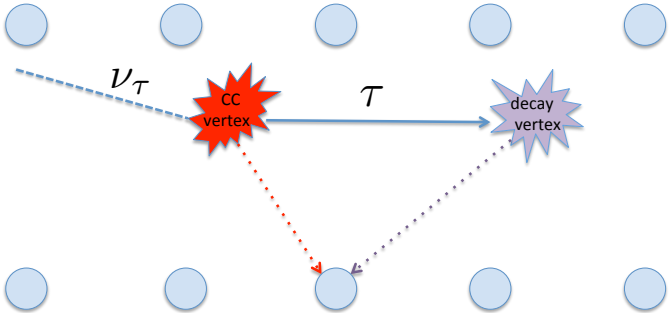


Tau Neutrino Search

resolving ν_τ products using per-PMT data

$\gtrsim 80\%$ of ν_τ produce two showers

IceCube cannot resolve two cascades except at UHE



[PRD 93, 022001 (2016)]

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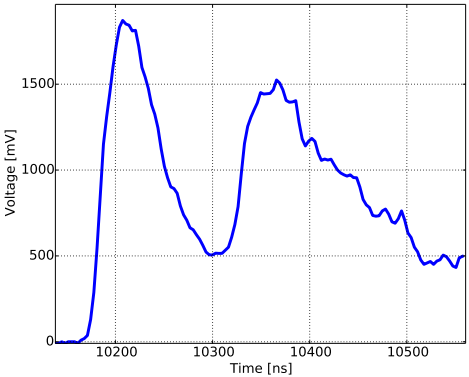
Instead, search for double pulses in individual PMT waveforms



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Tau Neutrino Search

resolving ν_τ products using per-PMT data

$\gtrsim 80\%$ of ν_τ produce two showers

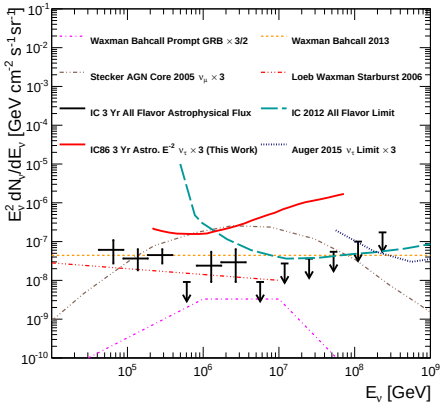
IceCube cannot resolve two cascades except at UHE

Instead, search for double pulses in individual PMT waveforms

No evidence yet for ν_τ in IceCube

- Flux upper limits set

[PRD 93, 022001 (2016)]

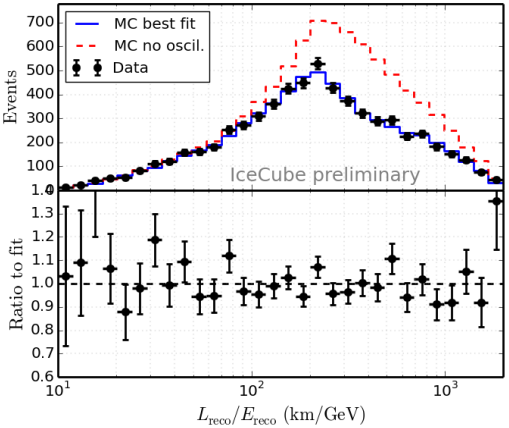


Neutrino Oscillations

measuring atmospheric ν_μ disappearance

Can use deposited energy and path length through Earth to constrain neutrino oscillations

Best measurement so far is for ν_μ disappearance



Neutrino Oscillations

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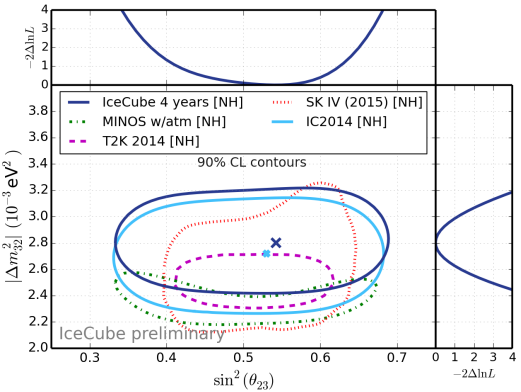
$\sin^2(\theta_{23})$ vs. $|\Delta m^2_{32}|$ fit consistent with other experiments

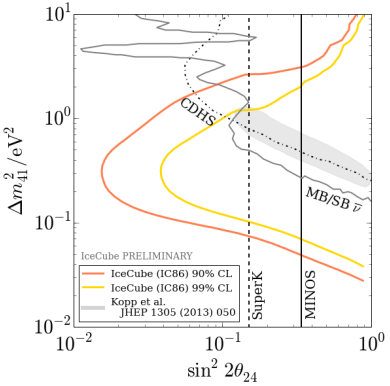


Sterile Neutrino Search

constraining oscillations to and from sterile neutrinos

Similar to standard oscillation search, but with a 3+1 neutrino flavor model

No evidence found — upper limits disfavor hints of sterile neutrinos from other experiments



Magnetic Monopole Search

search for bright signals from magnetic monopoles

Magnetic monopoles would produce bright tracks relative to muon tracks

Separate analyses search for monopoles above and below Cherenkov threshold

No evidence found — flux limits set as a function of $\beta = v/c$

[EPJ C76 (2016) 133]