Astrophysical Neutrinos: IceCube highlights

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on behalf of the IceCube Collaboration

CRIS 2016

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

WIPAC
Wisconsin IceCube
Particle Astrophysics Center

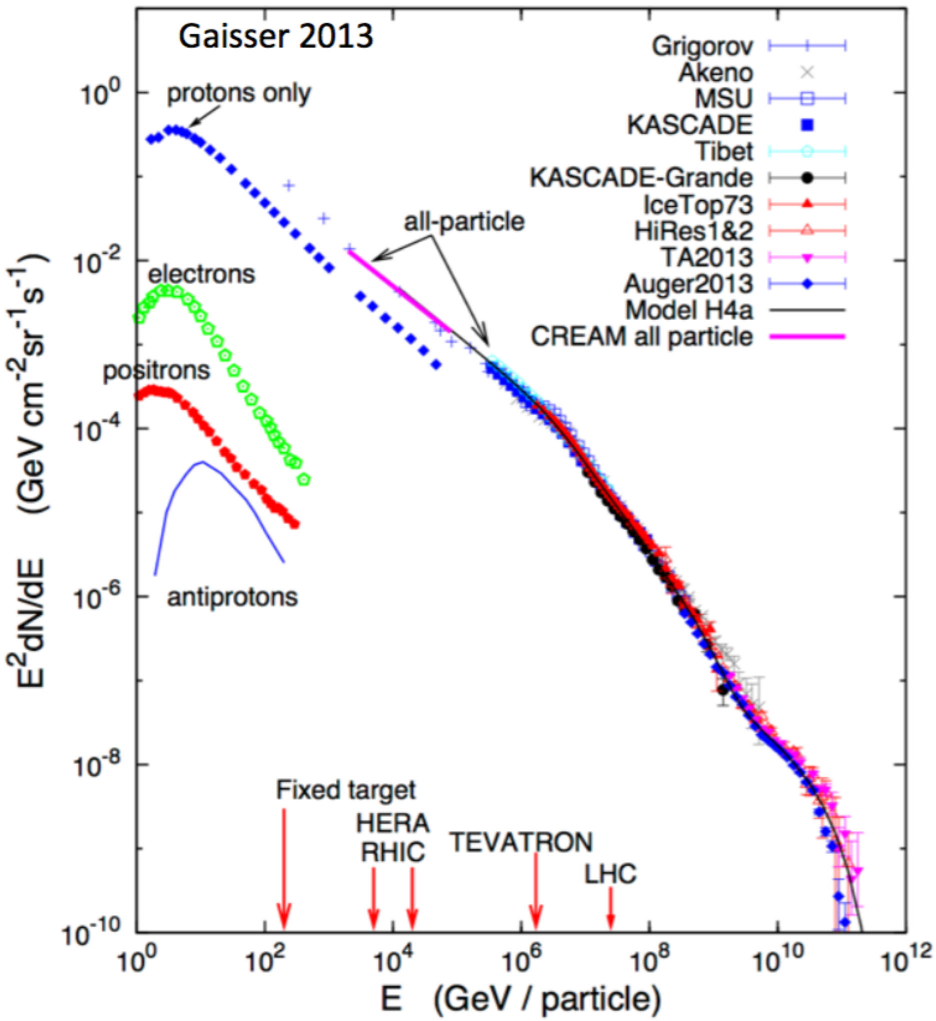
ICECUBE

1.

Cosmic rays and neutrinos

Multi-messenger astronomy

Cosmic rays spectrum



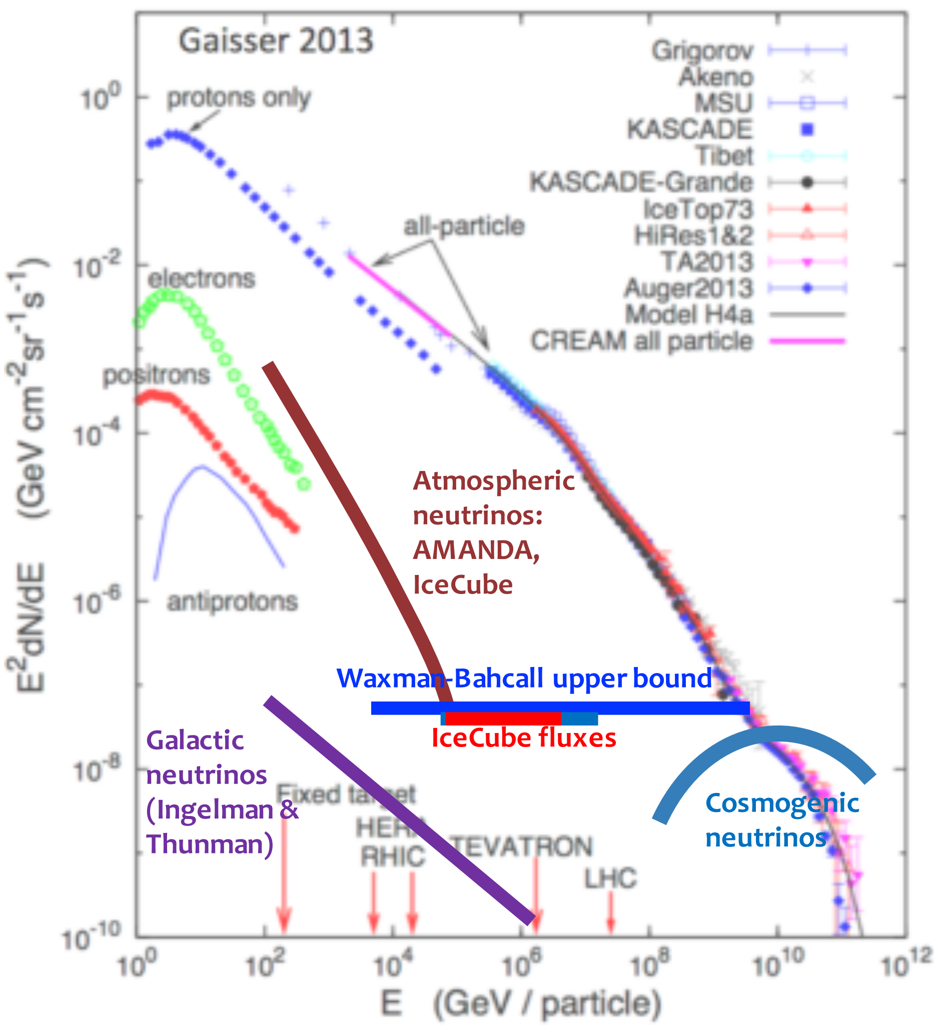
Can neutrinos reveal the origin of cosmic rays?

Neutrinos are produced in:

$p\,p \rightarrow NN + \pi^0, \pi^\pm \qquad p\,\gamma \rightarrow p\,\pi^0$
$\qquad\qquad\qquad\qquad\qquad\qquad n\,\pi^+$

$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

Neutrinos



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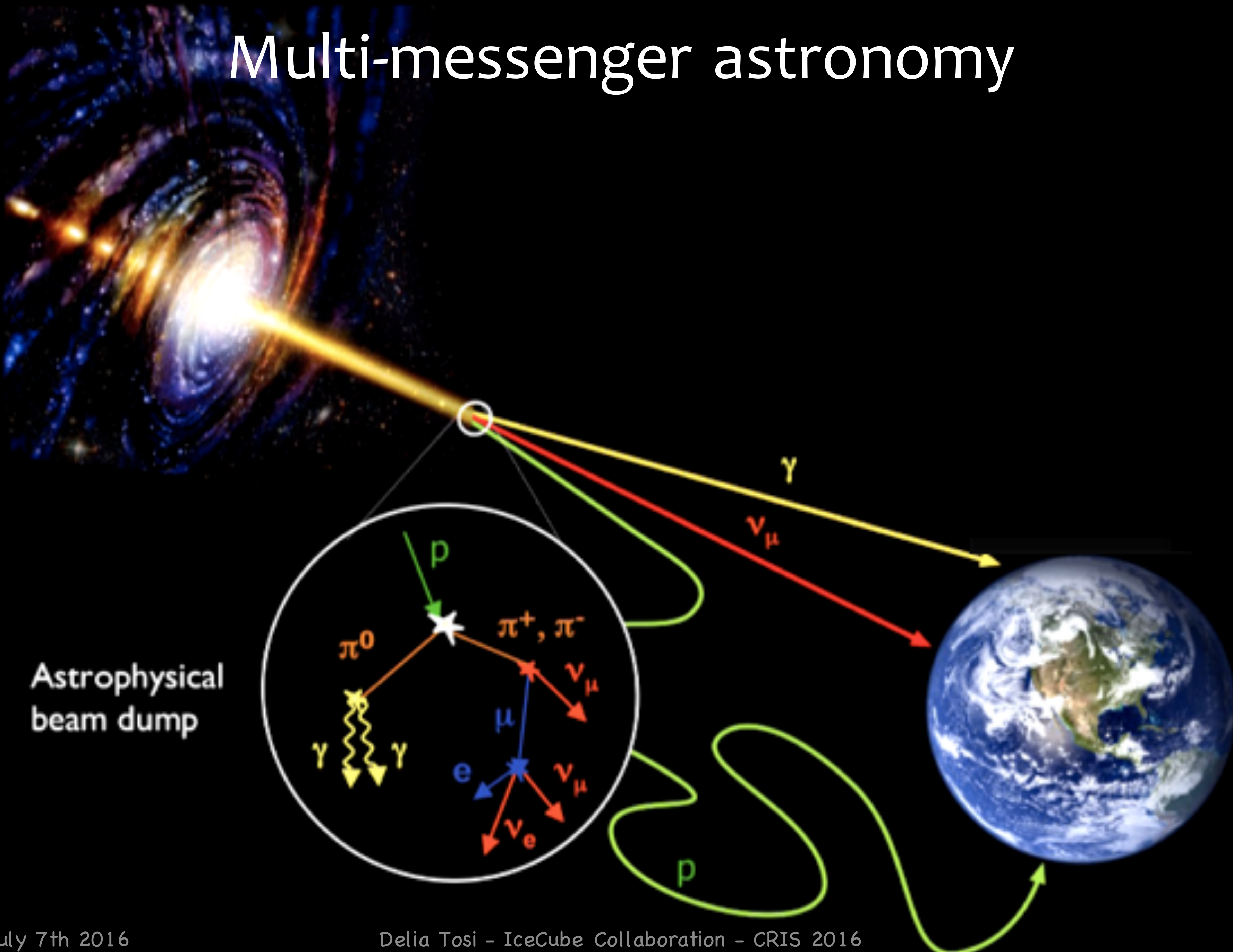
Known targets:

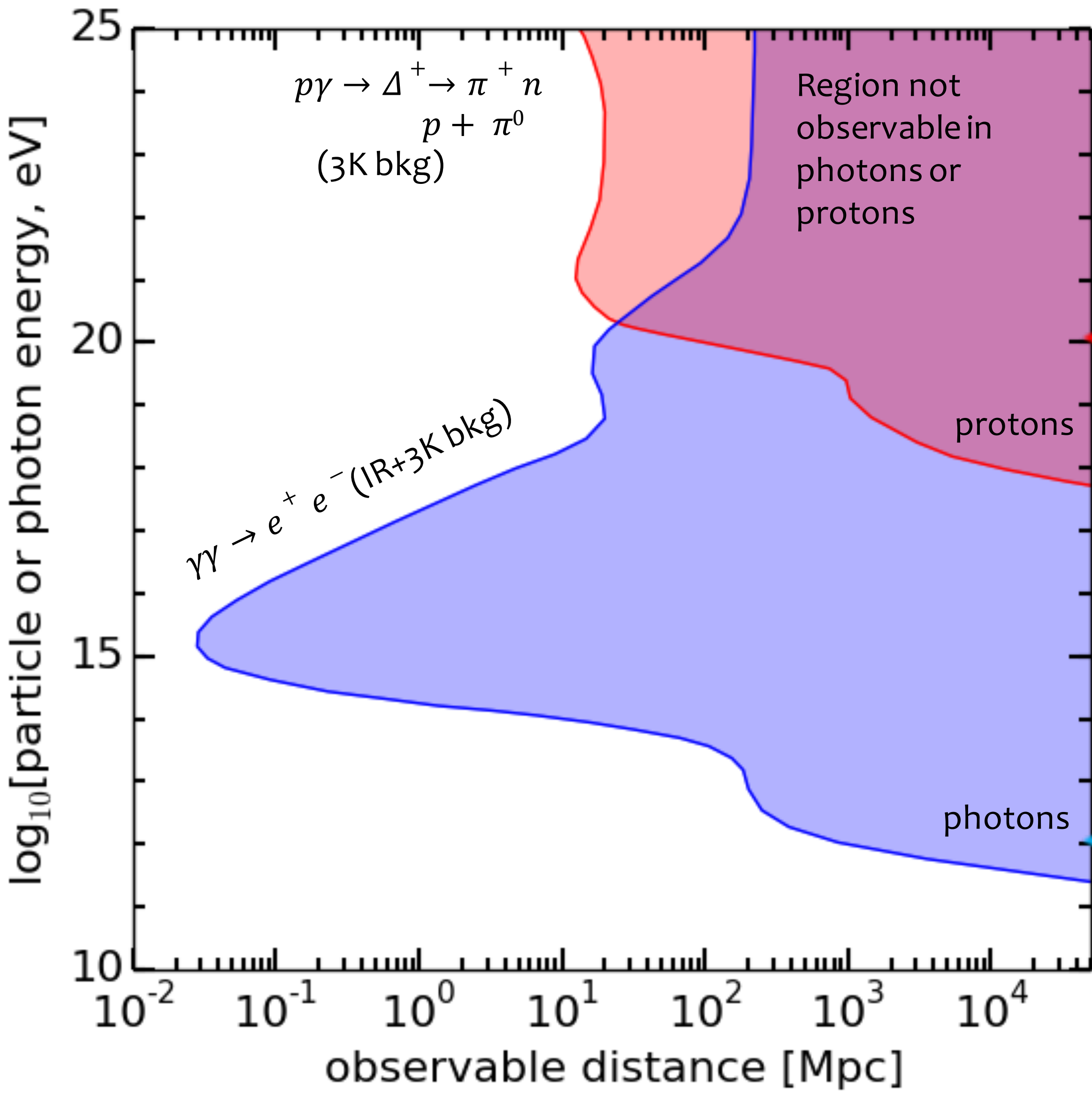
✓ Earth's atmosphere
→ atmospheric neutrinos (from π and K decay)

✘ Interstellar matter in Galactic plane
→ galactic neutrinos?

✘ Cosmic microwave background
→ cosmogenic neutrinos

Multi-messenger astronomy





Distant universe observable with neutrinos but not protons or gammas

100 EeV

1 TeV

2.

IceCube

How we detect neutrinos

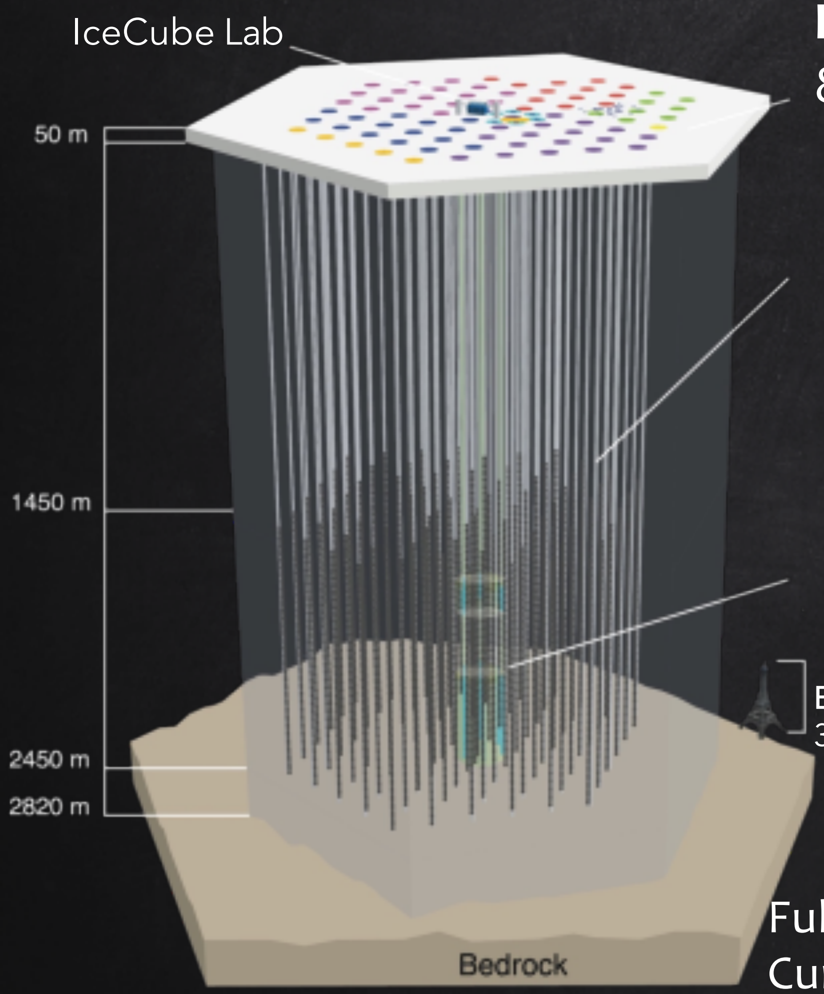
The IceCube Collaboration

311 people, 48 institutions, 12 country

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)
Japan Society for the Promotion of Science (JSPS)
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)

IceCube: detector



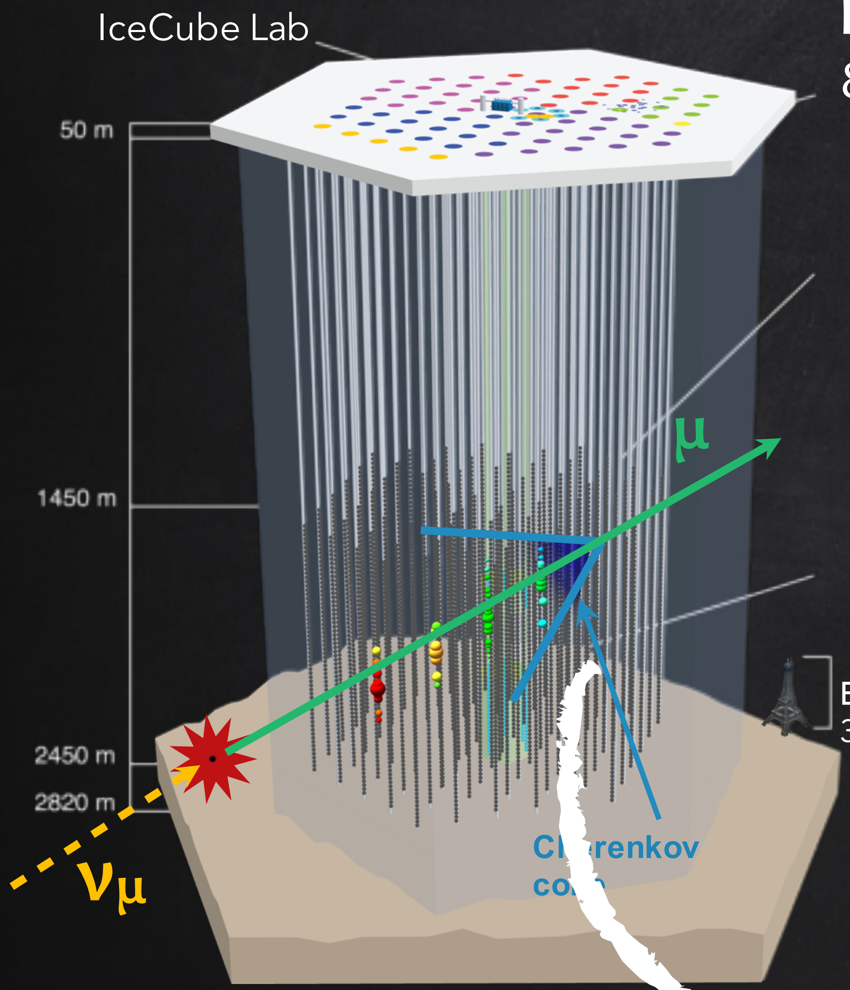
IceTop (CR physics)
81x2 tanks, 324 optical sensors

IceCube (completed in 2011)
86 strings (including DeepCore)
5160 optical sensors over 1 km^3 volume
17 m vertical spacing
125 m horizontal spacing

DeepCore (low energy)
8 strings, 480 optical sensors

Full detector data taking started in 2011
Current uptime > 99%
Clean uptime has increased since 2011 from 90 to > 98%

IceCube: detector



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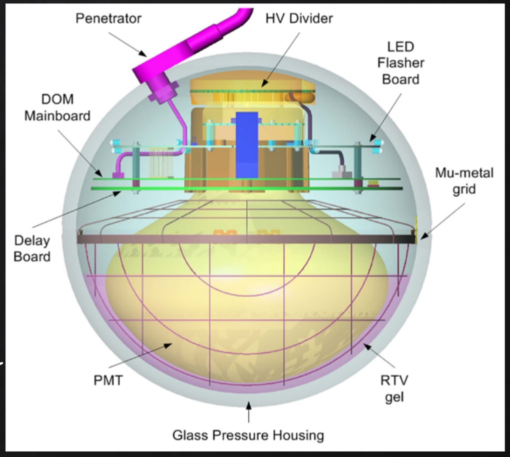
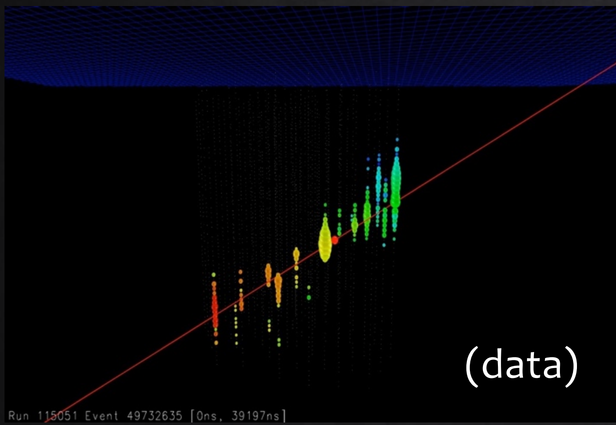


Event topologies in IceCube

tracks

CC (ν_μ)

$$\nu_\mu + N \rightarrow \mu + X$$



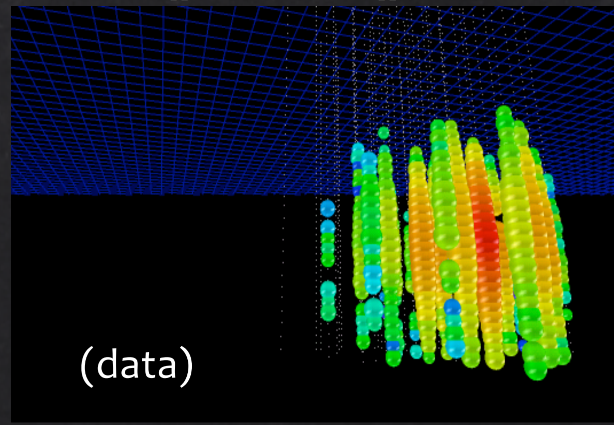
- ✓ Points back to source < 1° angular resolution at high energies
- ✗ Factor of ≈ 2 energy resolution

cascades

NC (ν_e, ν_μ, ν_τ) ∪ CC(ν_e)

$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

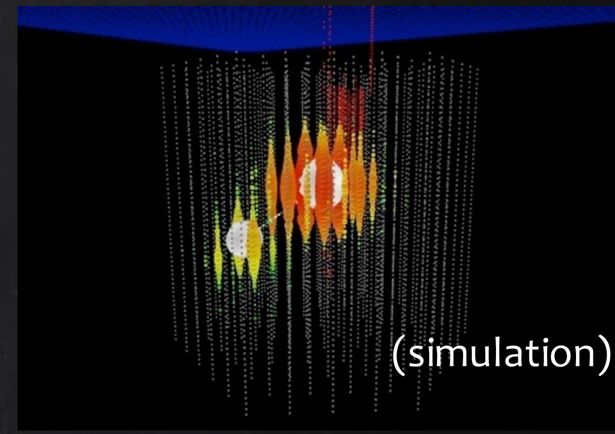


- ✓ Good deposited energy resolution (≈ ±15%)
- ✗ Poor angular resolution (≈ 10° angular resolution (energies ≳ 100 TeV)

double bang,

CC (ν_τ) , E_τ ≳10PeV

$$\nu_\tau + N \rightarrow \tau + X$$



- ✓ Good pointing
- ✓ Low background
- ✓ not observed yet
- ✓ Other ν_τ event topologies (lollipop, inverted lollipop, etc)

Overcoming the background

IceCube detects per year:

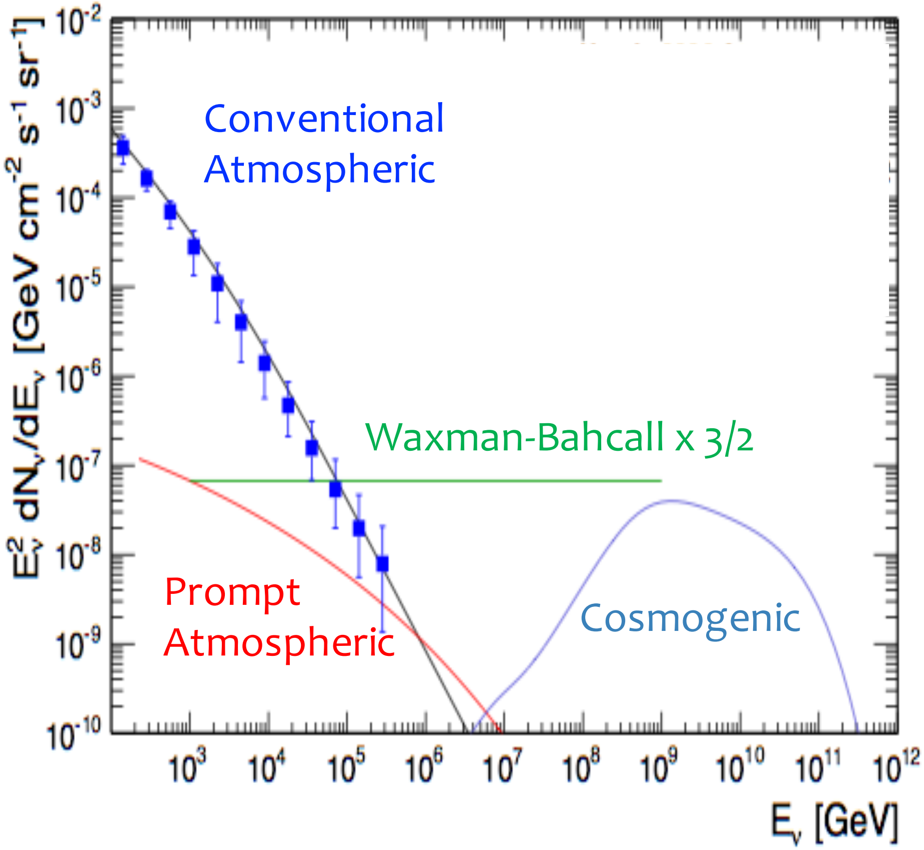
• atmospheric	μ	~7×10^{10}	~ 3000 per second,
• atmospheric	$\nu_\mu \rightarrow \mu$	$>8 \times 10^4$	~ 1 every 6 minutes
• cosmic*	$\nu_\mu \rightarrow \mu$	~10	< 1/month

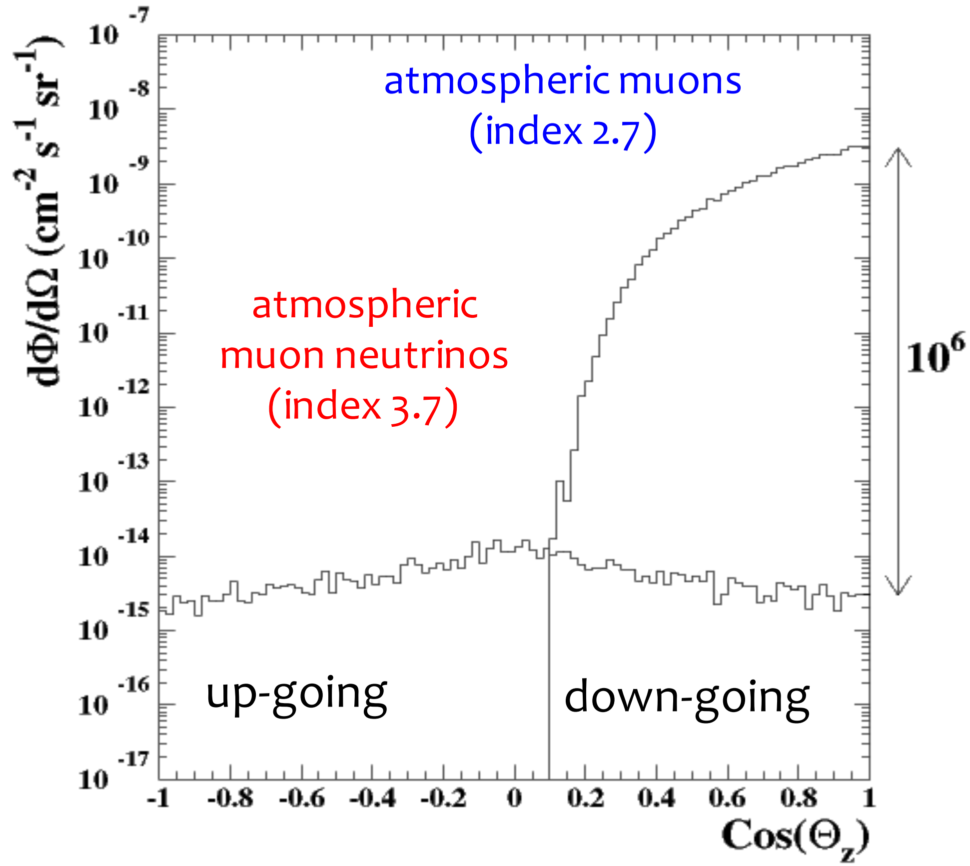
* starting in the detector, above 60 TeV

How to beat down the background?

Backgrounds

Background and signal differ in spectrum and angular distribution





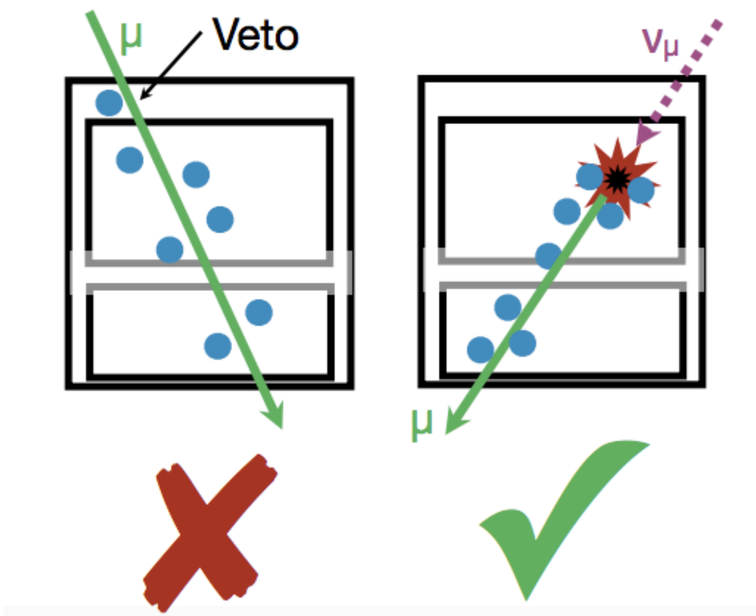
3.

The astrophysical flux

Discovery and evidence

High Energy Starting Events

- Interactions inside the detector are more likely to be due to neutrinos, as opposed to penetrating muons
- Effective selection of all flavors neutrinos above 60 TeV



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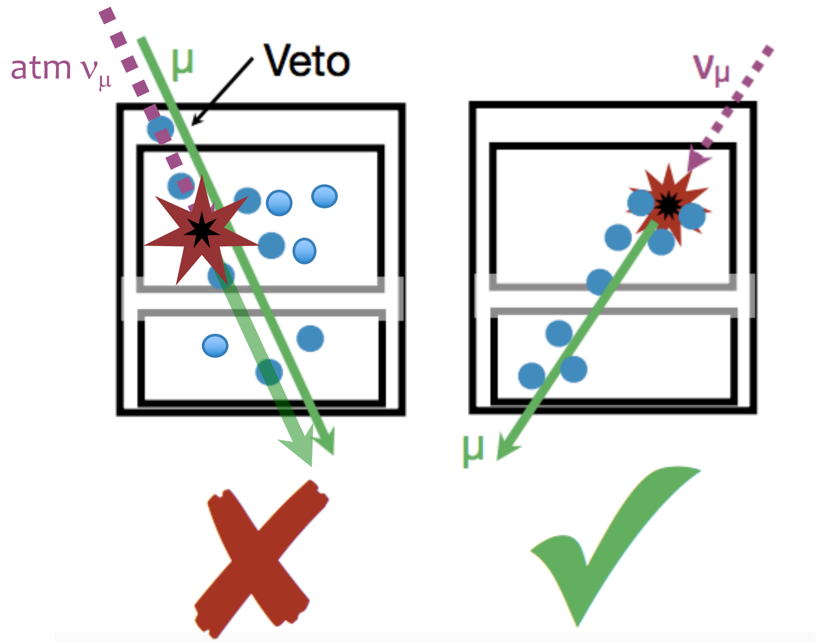

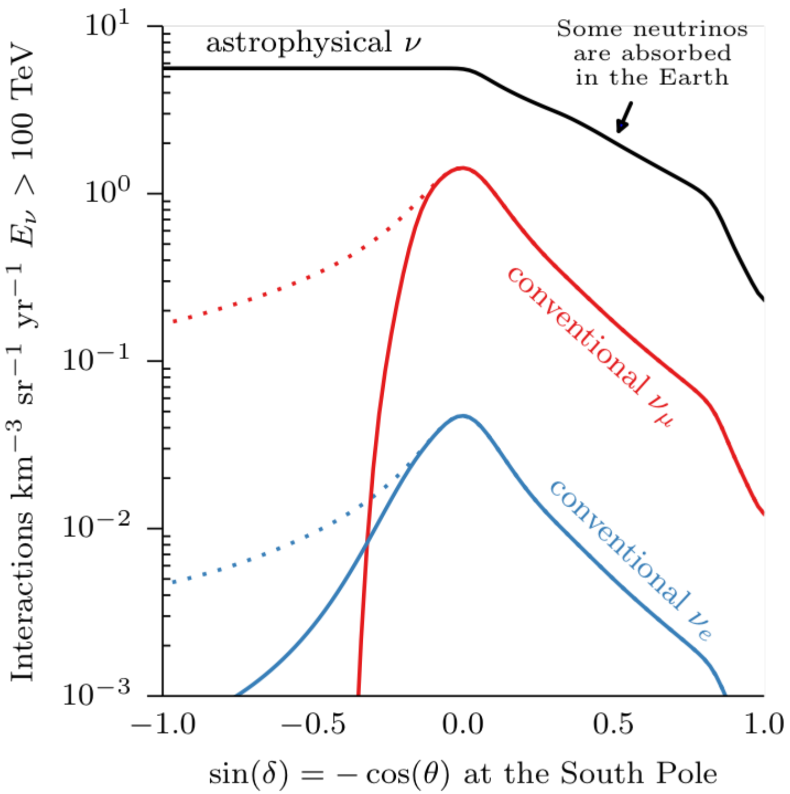

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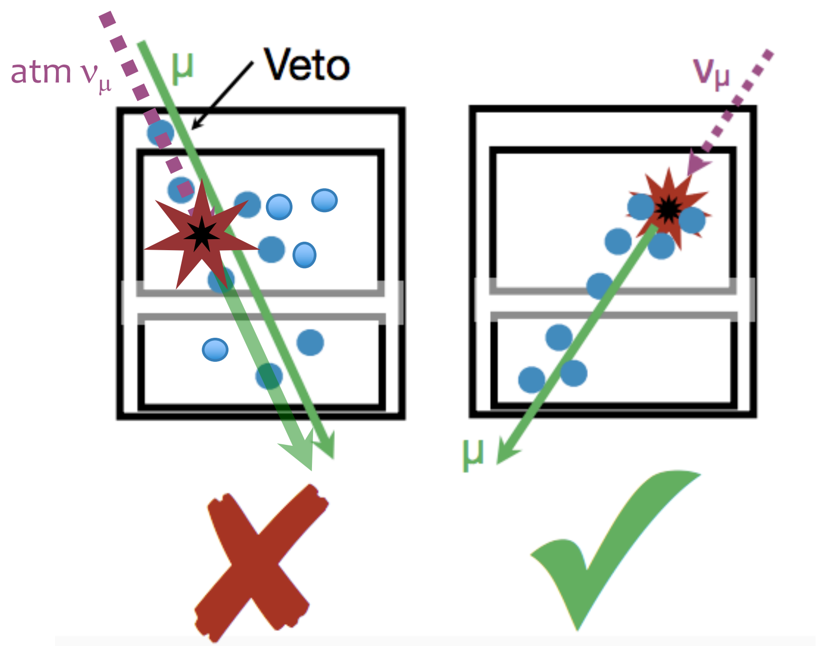
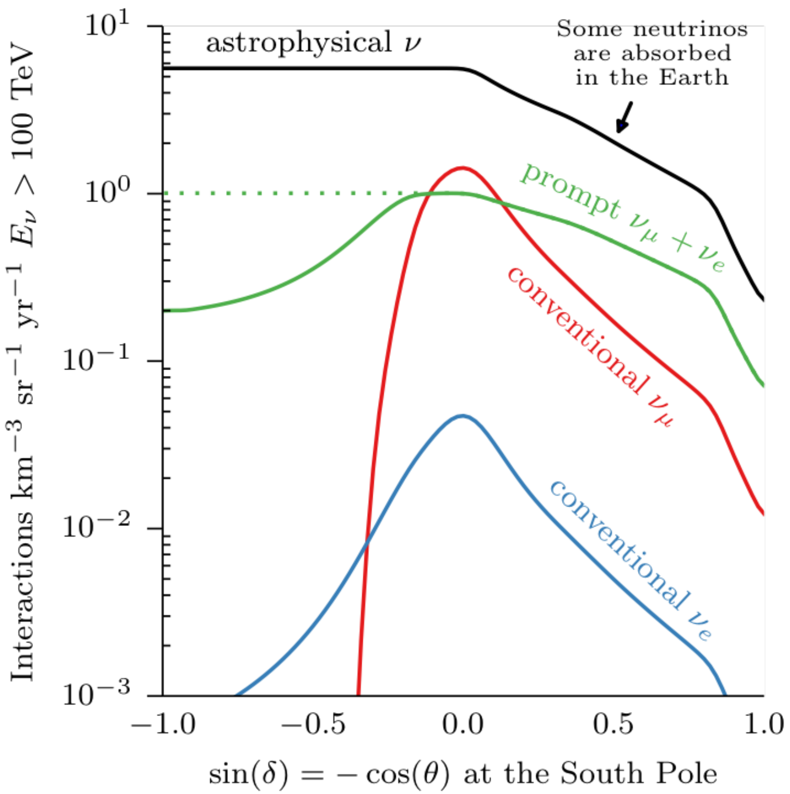
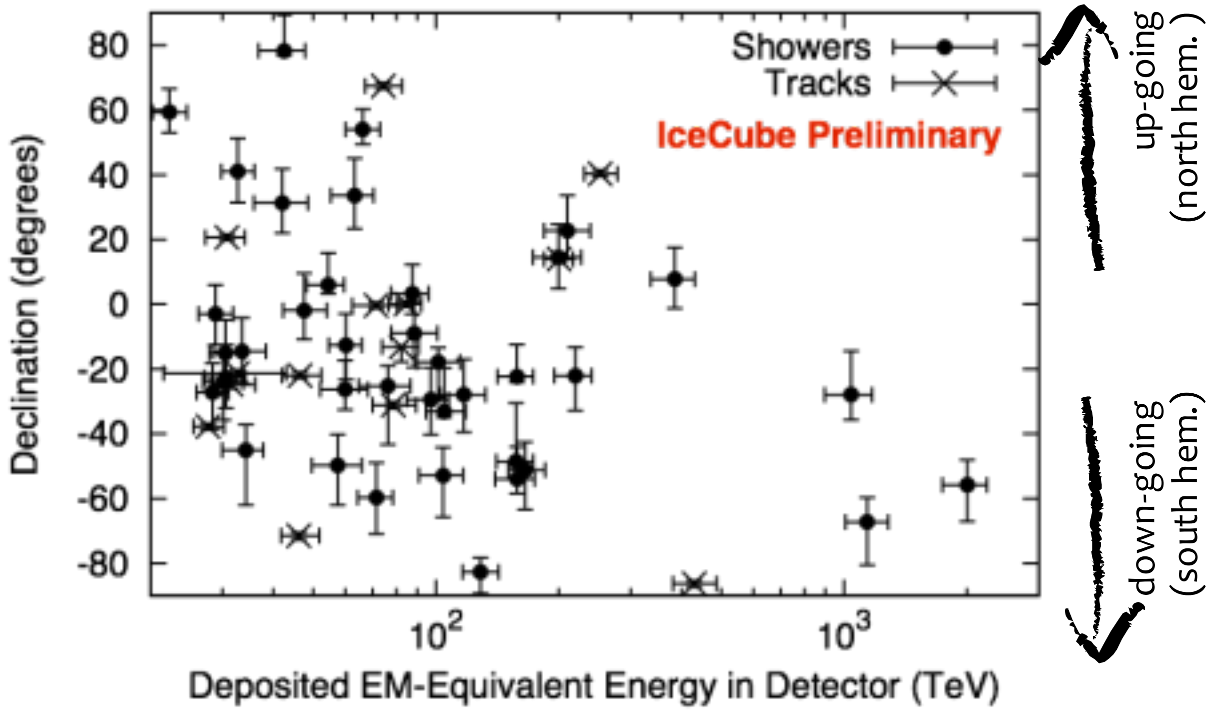




Starting event search results (updated to 4 years)

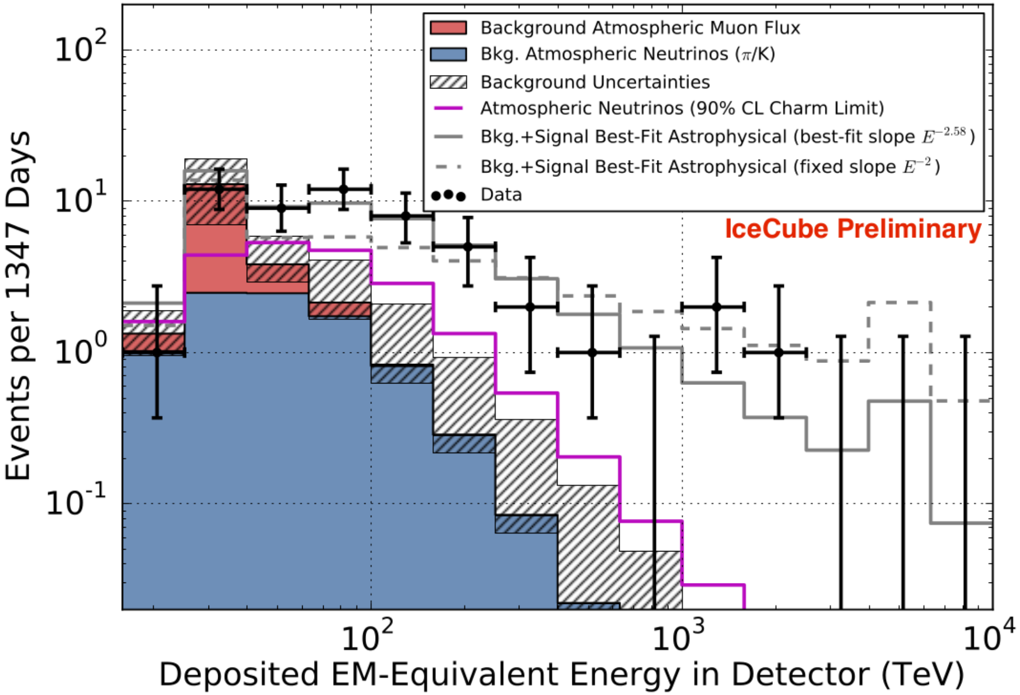
- **53(+1)** events observed over 4 yrs (one background event removed)

- Estimated background:
  - $9.0^{+8.0}_{-2.2}$ atm. ν
  - 12.6±5.1 atm. μ
- Astrophysical events purity increases with energy
- At high energy, up-going neutrinos are absorbed by Earth.

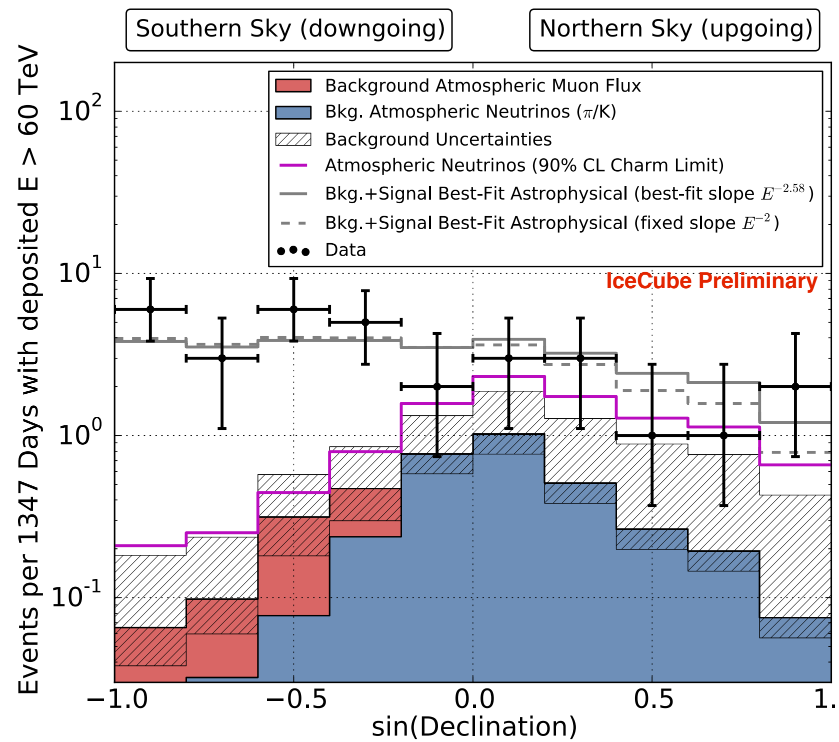


Significance: 6.5σ for 53(+1) events
ICRC2015 / PoS(ICRC2015)1081

Energy Spectrum



Atmospheric neutrinos removed more efficiently in the southern hemisphere due to rejection of accompanying muons

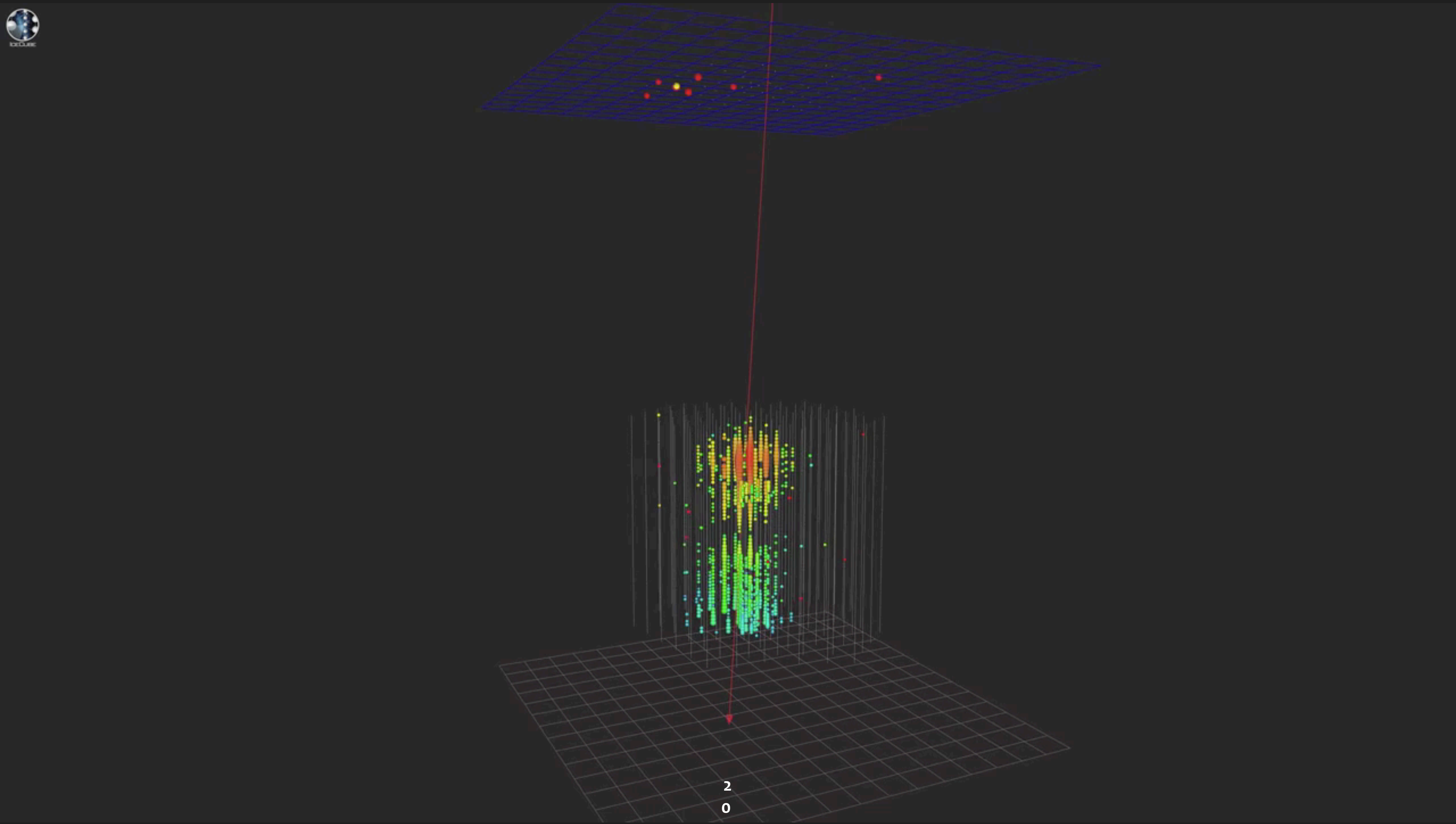


Best fit spectrum:

$$\Phi_\nu(E) = \Phi_0 \cdot (E / 100\ \text{TeV})^{-2.58\pm0.25}$$

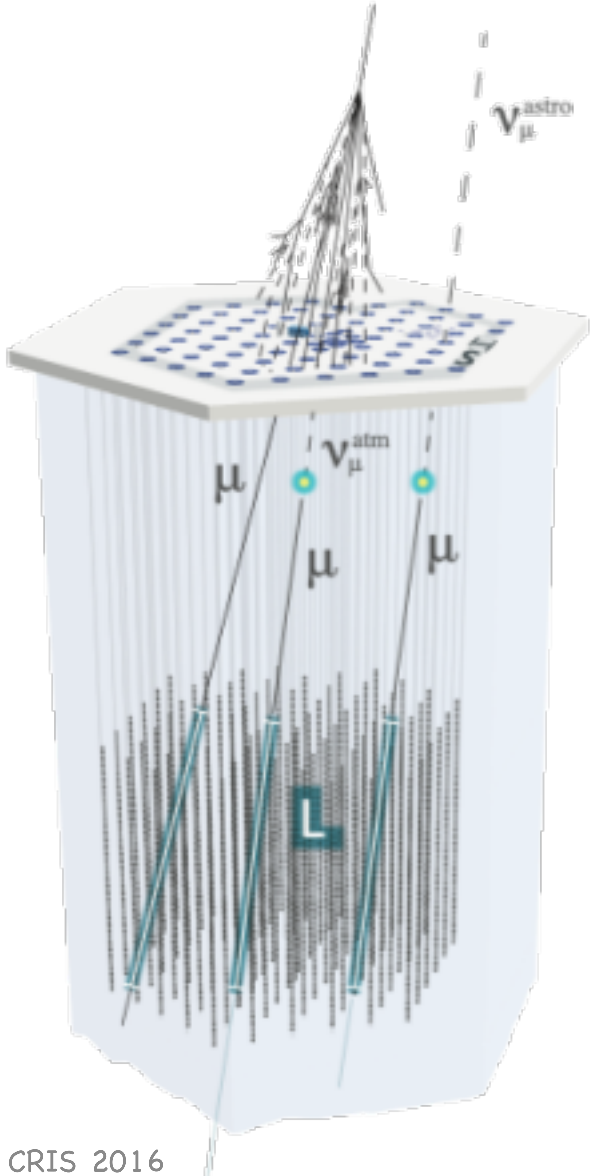
$$\Phi_0 \simeq 2.2 \times 10^{-18} / \text{GeV} / \text{cm}^2 / \text{s} / \text{sr}$$

ICRC 2015
1510.05223



Veto efficiency in the southern hemisphere

- At increasing energies up-going neutrinos are absorbed by the earth, so being able to detect down-going neutrinos becomes more important
- Previous event starts in the detector, but what about the volume above?
- Using a surface veto increases the effective volume of the detector up to surface
- Veto efficiency (and coverage) under study now with IceTop (mostly interesting for a future extended surface veto array)



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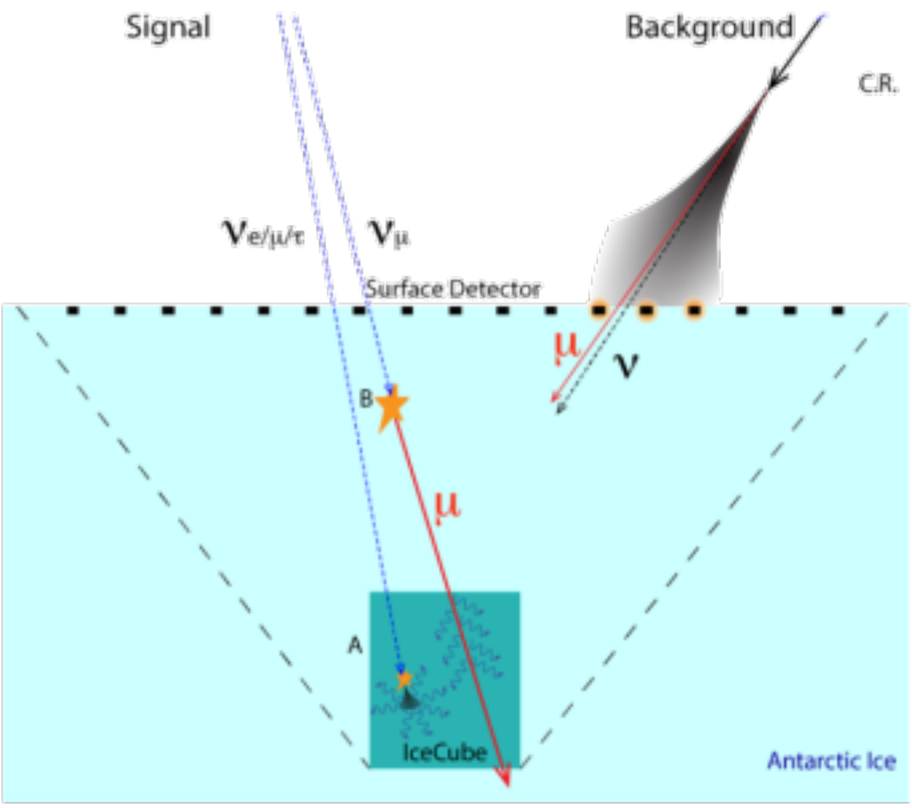
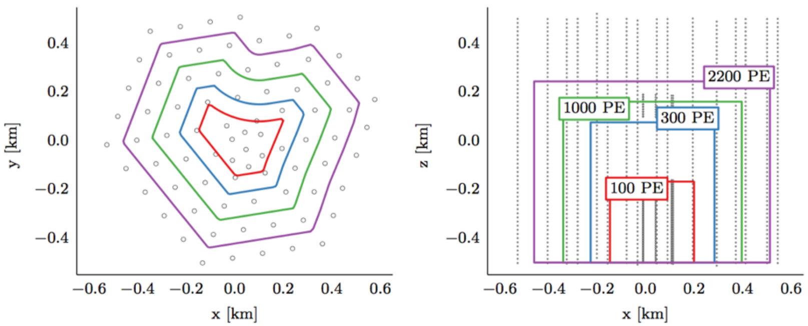
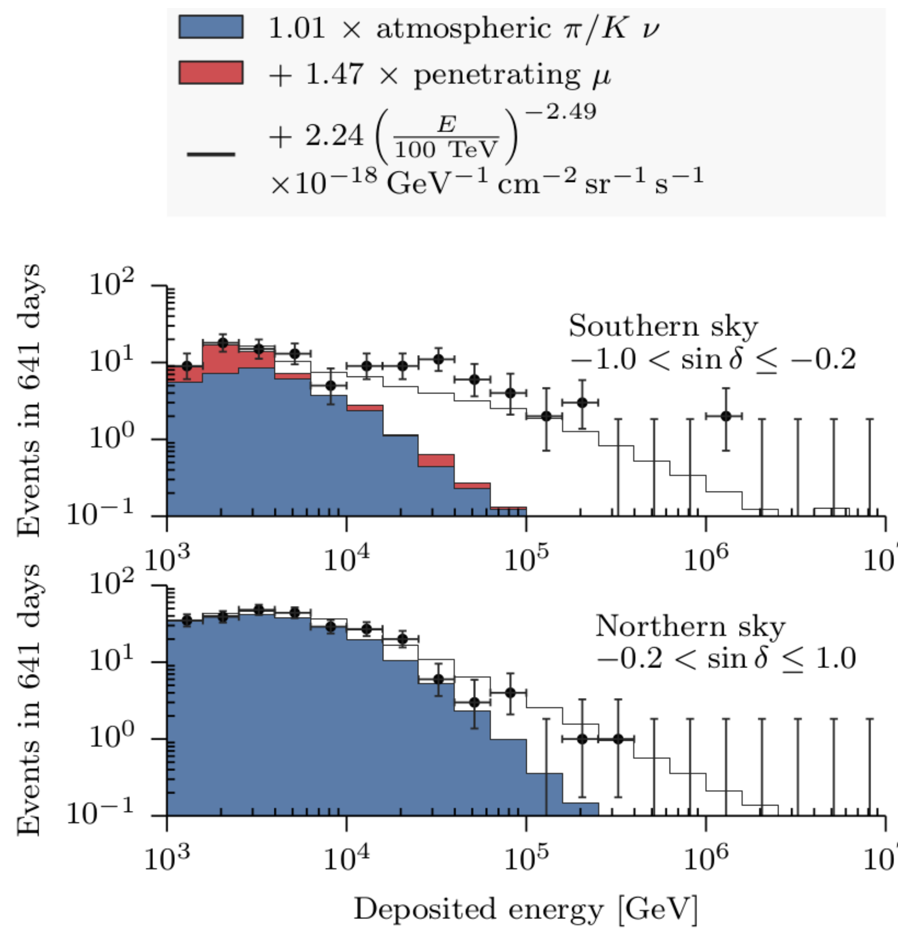


Medium energy starting events

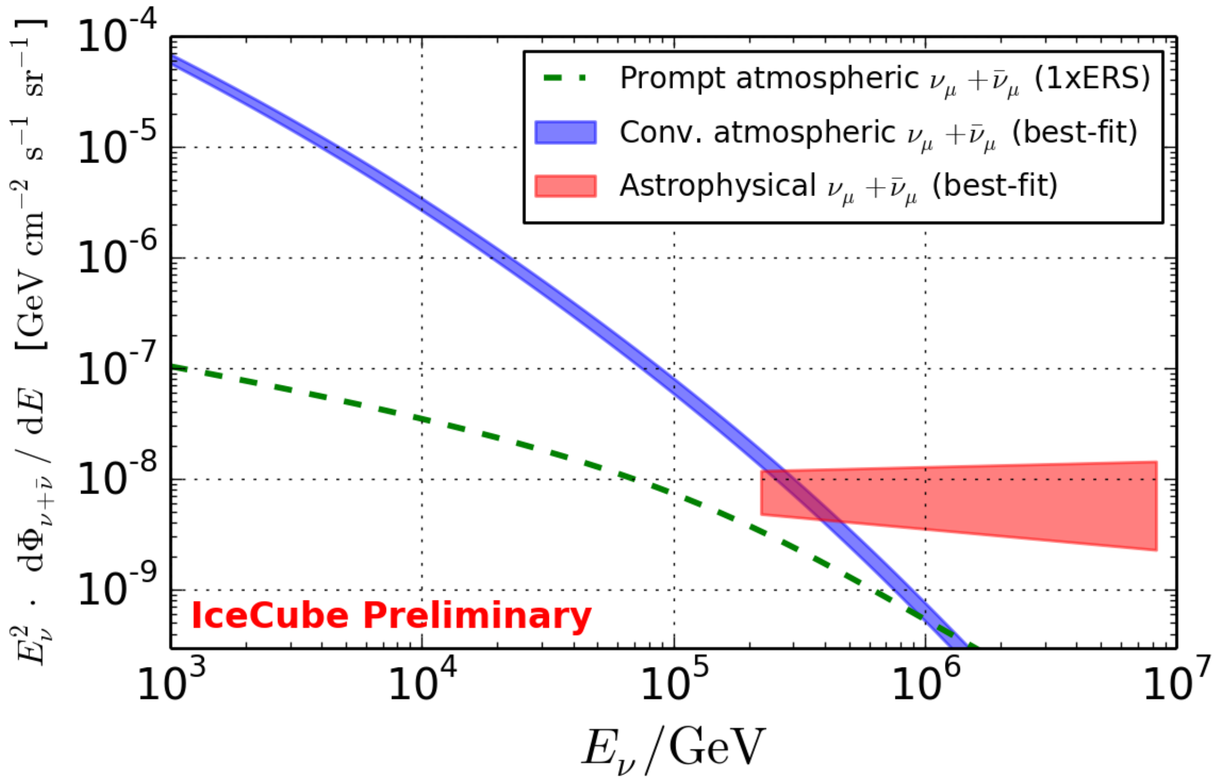


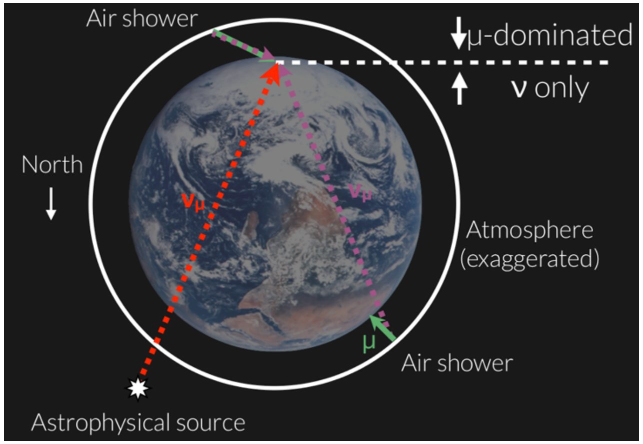
- Veto layer thickness depends on energy
- Threshold decreases from 60 TeV to 1 TeV (deposited energy)
- 106 events >10 TeV in 2 yrs
- No charm indication, model dependent upper limit at ~1.5 x ERS (2008) prediction



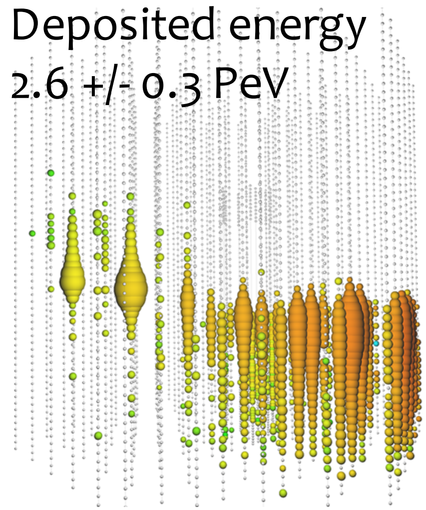
Best-fit spectral index: 2.5 ± 0.12

Northern (up-going) muon neutrinos, 6 yrs of data, 09-15



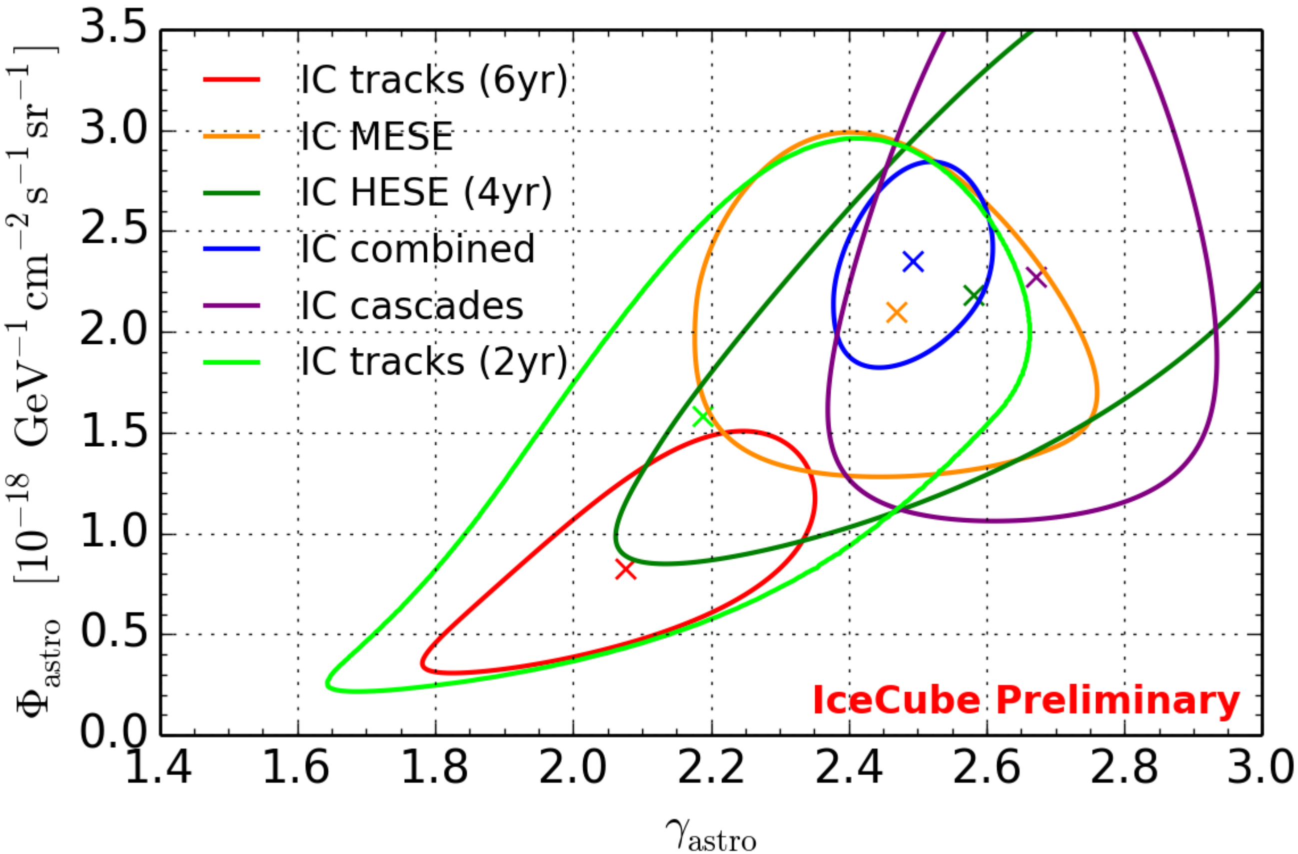


- Highest energy neutrino observed so far found in this search
- Deposited energy 2.6 +/- 0.3 PeV



Preliminary fit:
$\Phi(E_\nu) = 0.82^{+0.30}_{-0.26}\ 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}sr^{-1}s^{-1}}\ (E_\nu/100\mathrm{TeV})^{-(2.08\pm0.13)}$
prompt fits to 0, upper limit details under study
PoS(ICRC2015)1079

Combined fit from all analyses



PoS(ICRC2015)1066 (combined fit, all-flavor)

PoS(ICRC2015)1081 (all-flavor, starting, 4 yrs)

PRL 115, 081102 (2015) (ν_μ, Northern Sky, 2 yrs)

PoS(ICRC2015)1109 (cascades, 2 yrs, >10 TeV)

PRD 91, 022001 (2015) (all-flavor, starting, >1 TeV)

6-year tracks (PoS(ICRC2015)1079, ν_μ, Northern Sky)

Global fit

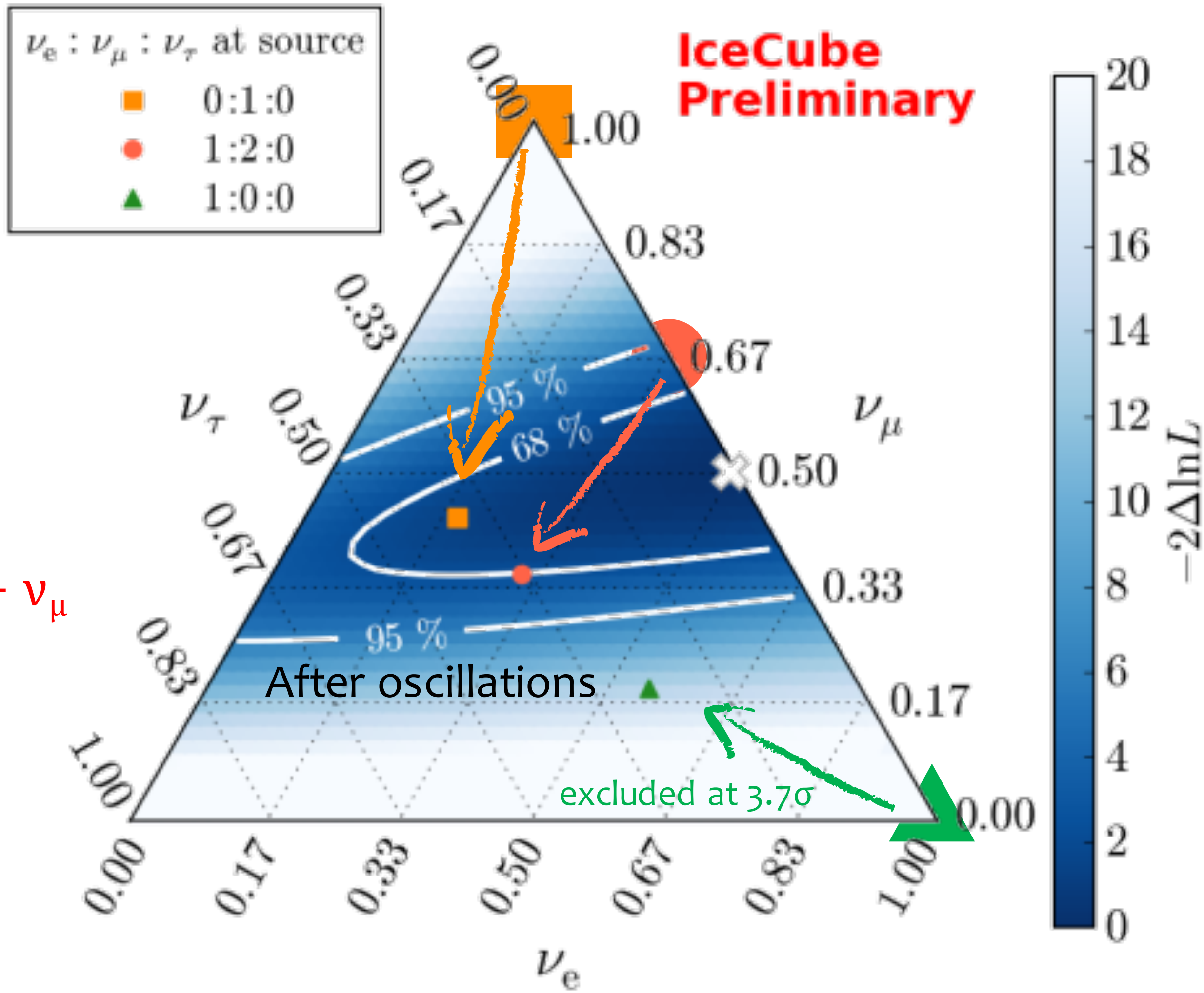
90% C.L. contours of various IceCube analyses - **single unbroken power-law** fits

Datasets are not independent

Flavor fit (6 years of data)

Scenarios:
Muon damped
Pion decay
Neutron decay

$\pi^+ \rightarrow \mu^+ + \nu_\mu$
$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$
$n^0 \rightarrow p + e^- + \bar{\nu}_e$



ApJ 809, 98 (2015)/
PoS(ICRC2015)1066

flavor components are free to float, but assumed to follow the same energy spectrum (spectral index and cut-off energy are free to float)

Tau neutrino search

PRD 93, 022001 (2016)

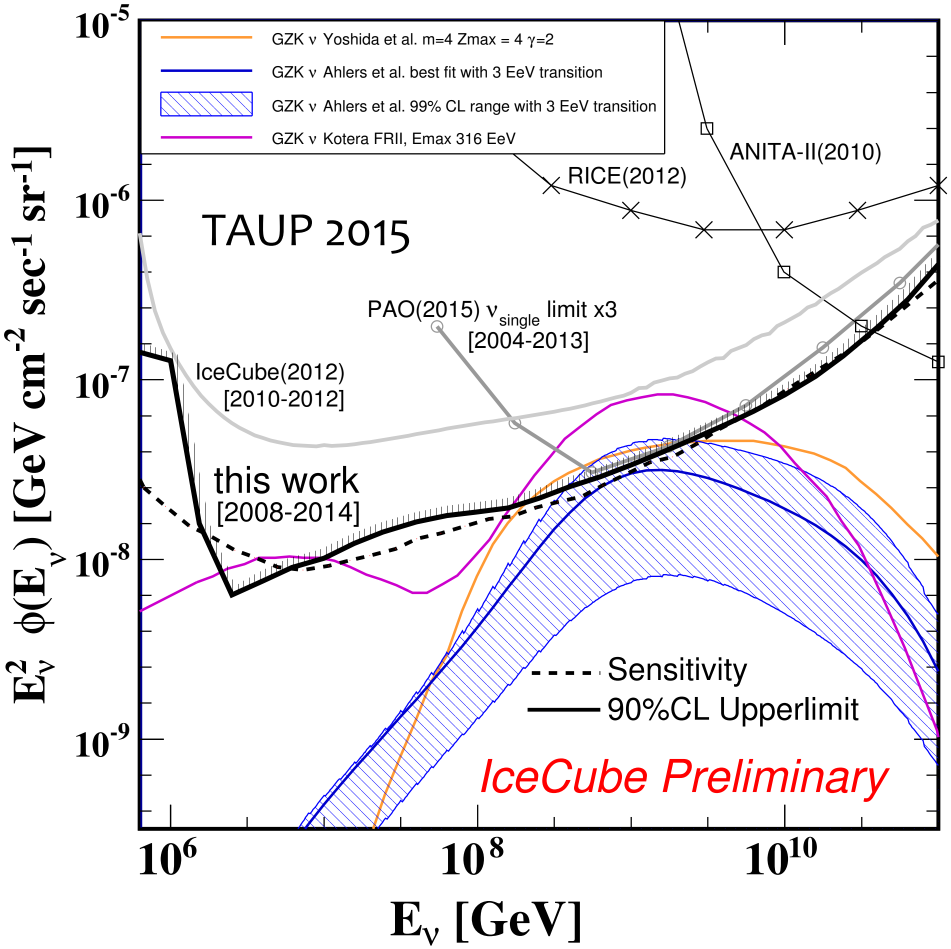
TABLE I. Predicted event rates from all sources at the final cut level. Errors are statistical only.

Data samples	Events in 914.1 days (final cut)
Astrophysical ν_τ CC	$(5.4 \pm 0.1) \times 10^{-1}$
Astrophysical ν_μ CC	$(1.8 \pm 0.1) \times 10^{-1}$
Astrophysical ν_e	$(6.0 \pm 1.7) \times 10^{-2}$
Atmospheric ν	$(3.2 \pm 1.4) \times 10^{-2}$
Atmospheric muons	$(7.5 \pm 5.8) \times 10^{-2}$

0.54 cosmic tau neutrinos expected in 3 years of data, none observed

2.5 orders of magnitude lower energy than previous (Pierre Auger) tau neutrino searches

Search for cosmogenic neutrinos



Non-detection in 6 years of data (including 3 years of IC86)

Beginning to disfavor proton UHECR models in favor of heavier composition

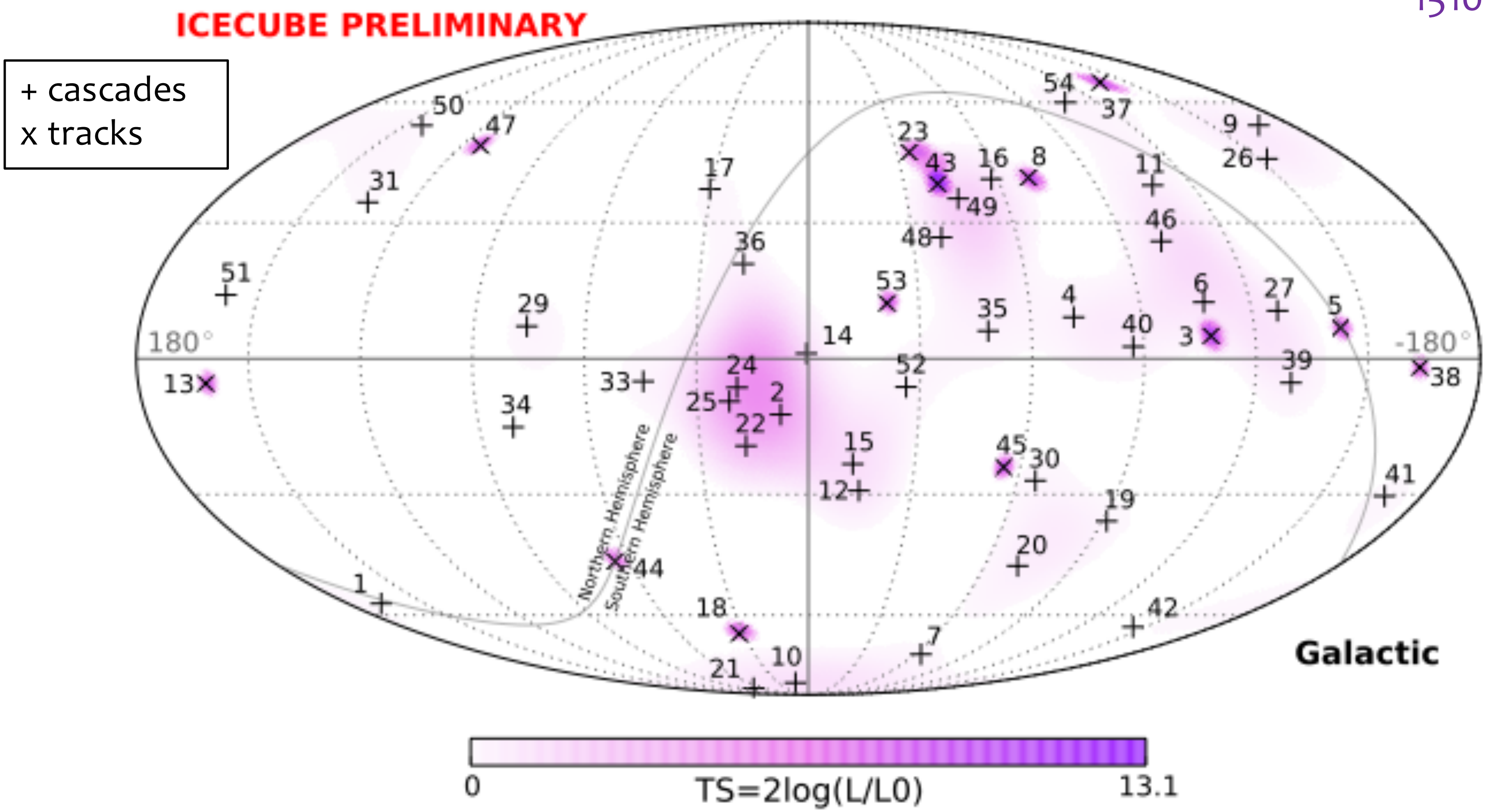
4.

Are there sources?

Clustering in time or space
Overlap with other classes of sources

Starting events: no clustering

ICRC 2015
1510.05223

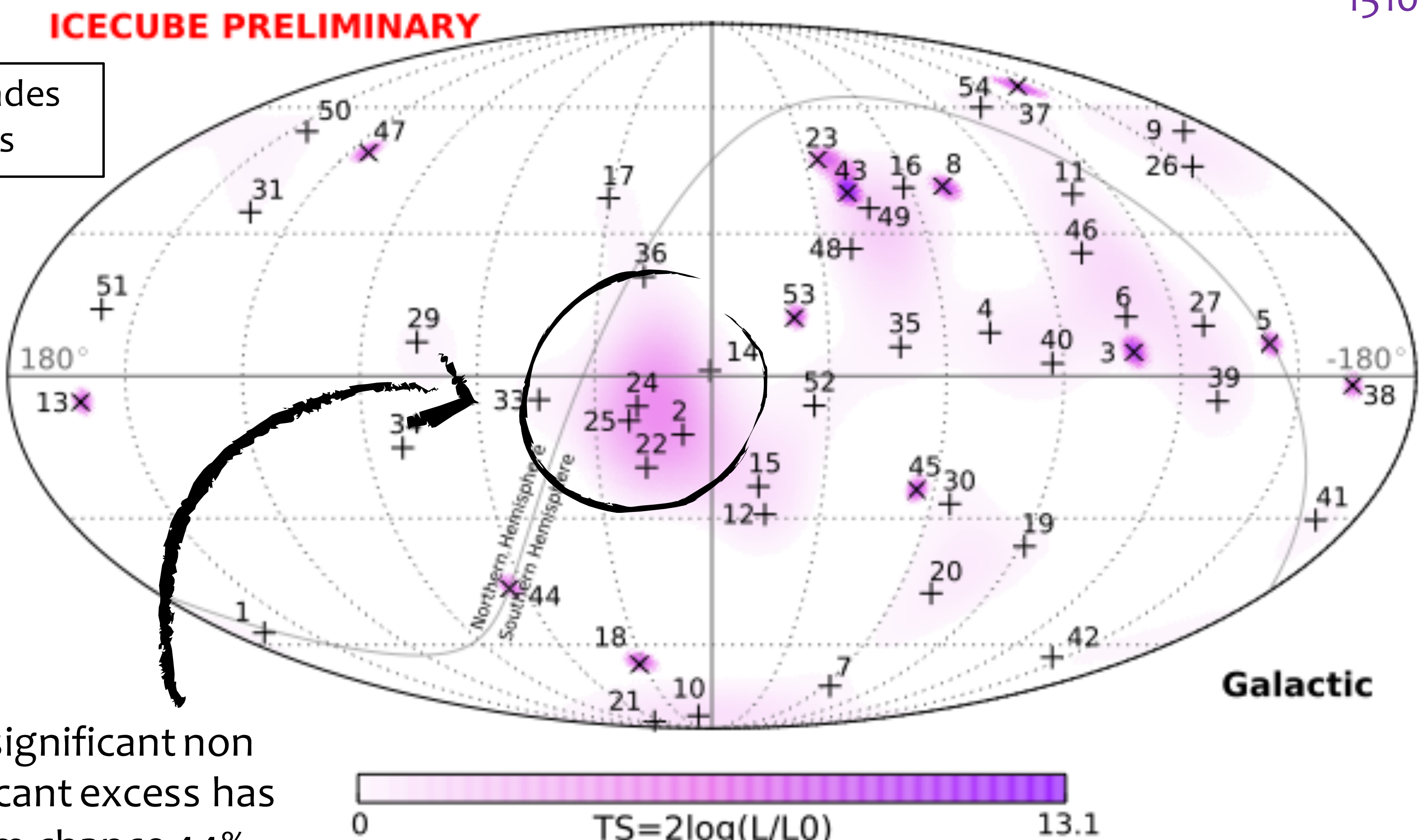


Post trial p-values

Starting events: no clustering

ICRC 2015
1510.05223

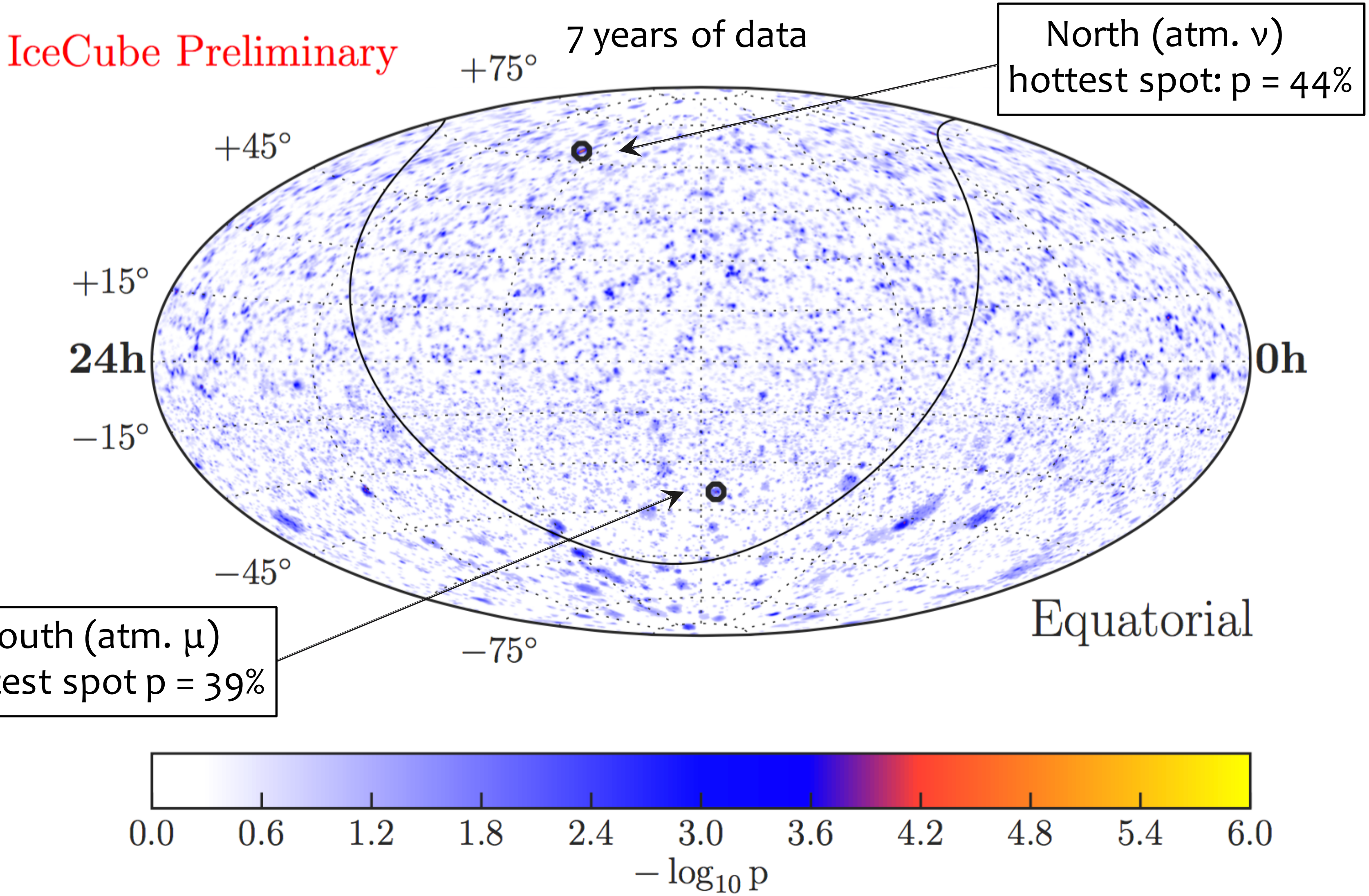
+ cascades
x tracks



Most significant non significant excess has random chance 44%

Post trial p-values

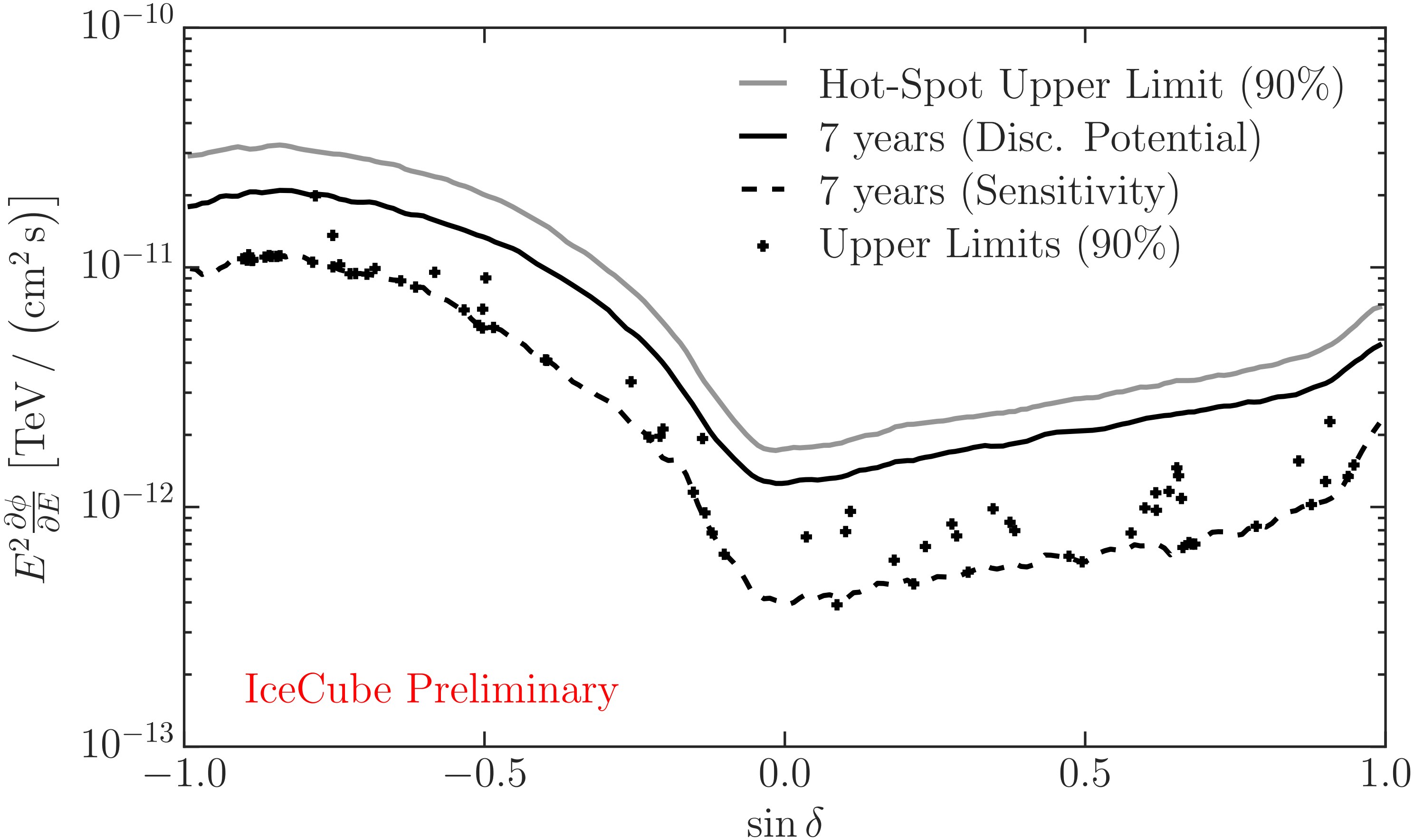
Standard point sources search, time integrated (ν_μ)



No significant excess of hotspots in either hemisphere or in the galactic plane (+/- 15°)

Upper limits on point sources over 4π sky

Assumes unbroken E^{-2} spectrum



Southern hemisphere

Northern hemisphere

Other sources searches

✘ Fermi-LAT blazar stacking analysis: 862 blazars (3 yrs)

- <30% contribution to neutrino flux

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

- <1% contribution to neutrino flux

✘ LIGO GW150914

- 3 off-source, low-evergy ν within ±500 s

✘ Several other searches from members of the collaboration or outside the collaboration, but no convincing result yet.

✘ Follow up programs for interesting IceCube events in place and developing further (recently added high energy starting event singlet added to GCN public alerts)

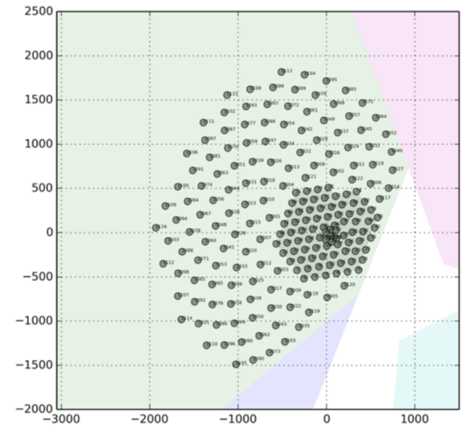
5.

Proposed detector extensions

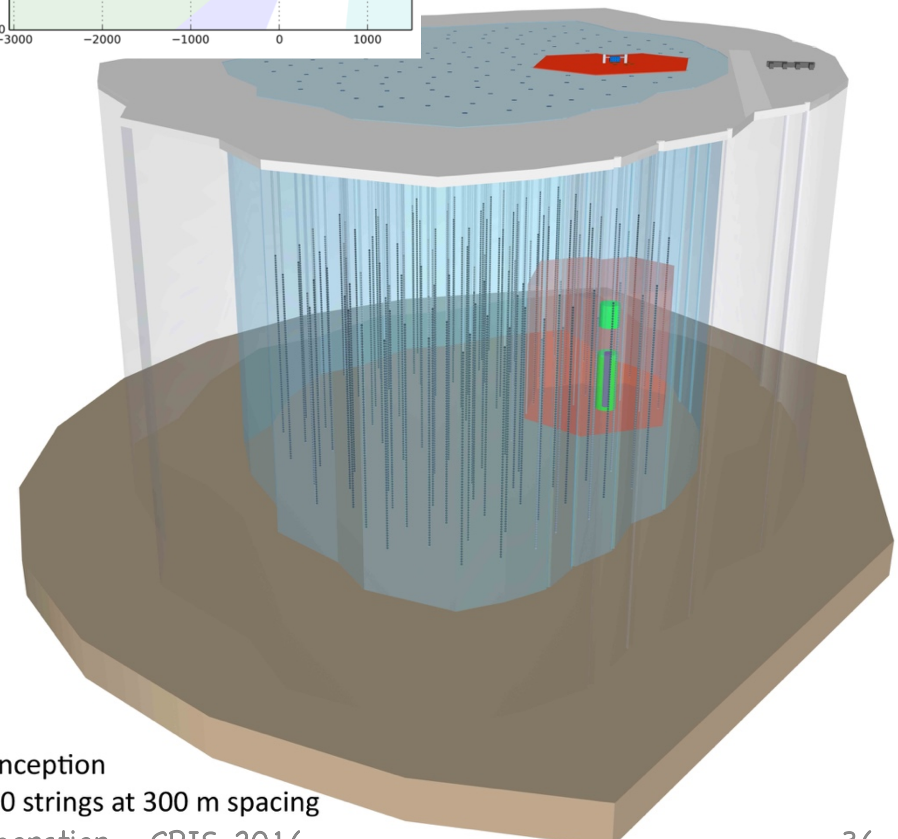
IceCube Gen2

Proposed extension (geometry still under study) includes:

- low energy infill (PINGU)
- 10 km^3 instrumented volume
- surface array for veto and CR physics
  - RD for new sensor types and new technology undergoing

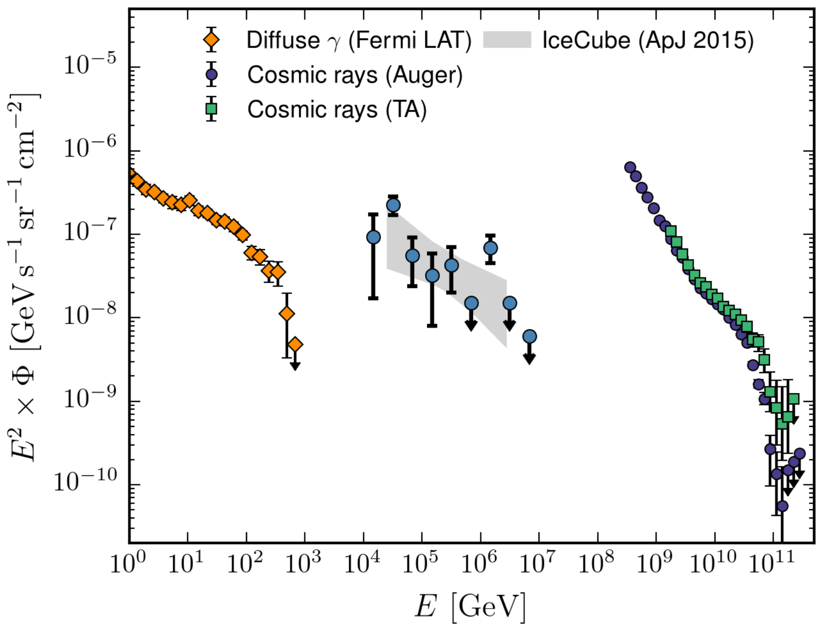


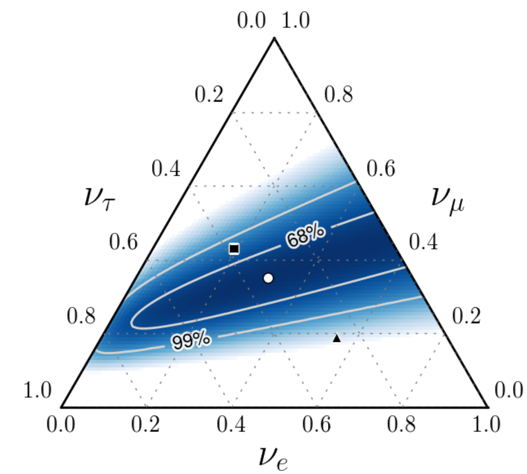
Example Sunflower geometry



Artist conception
Here: 120 strings at 300 m spacing

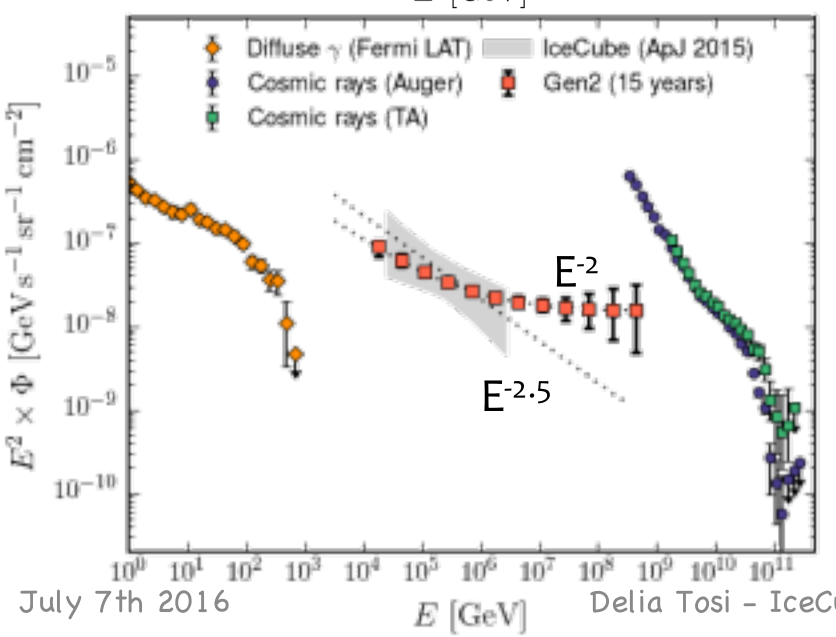
Examples of physics reach of Gen2

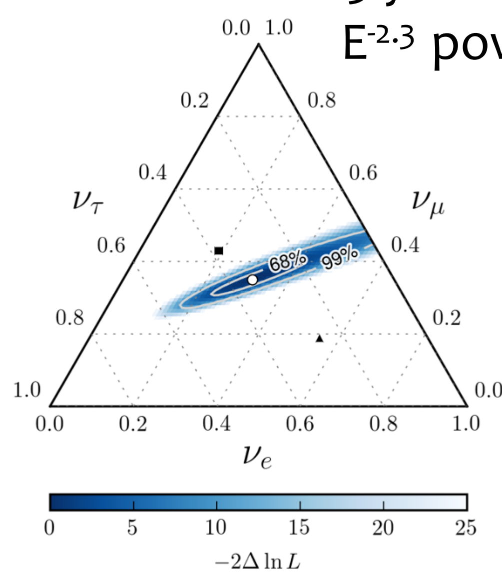




15 years of Gen2

$E^{-2.3}$ power law





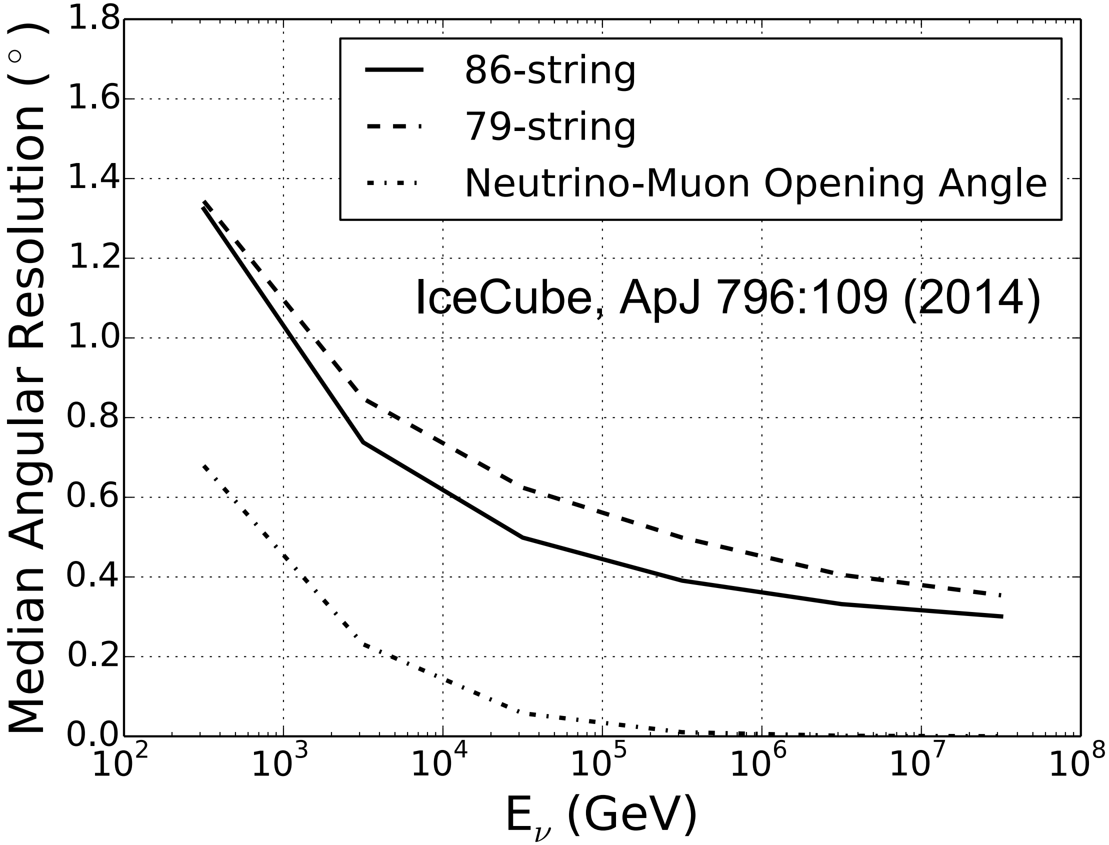
Conclusions

- A diffuse astrophysical neutrino flux (TeV to PeV)
- No point/discrete sources have been found yet
- Multi-messenger studies provide constraints on source classes
- More sophisticated techniques are under development now to increase sensitivity to astrophysical neutrinos
- 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

6.

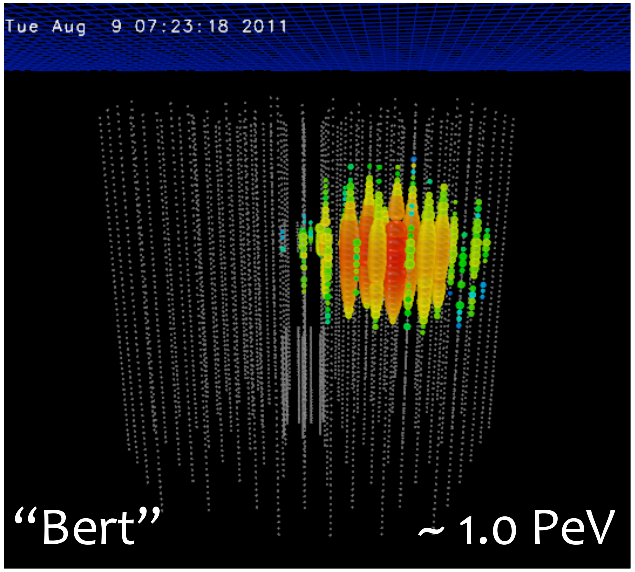
Backup slides

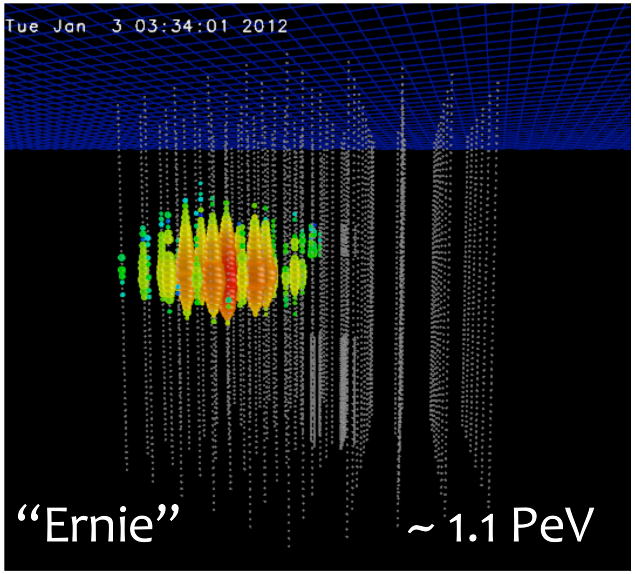
Muon neutrino angular resolution



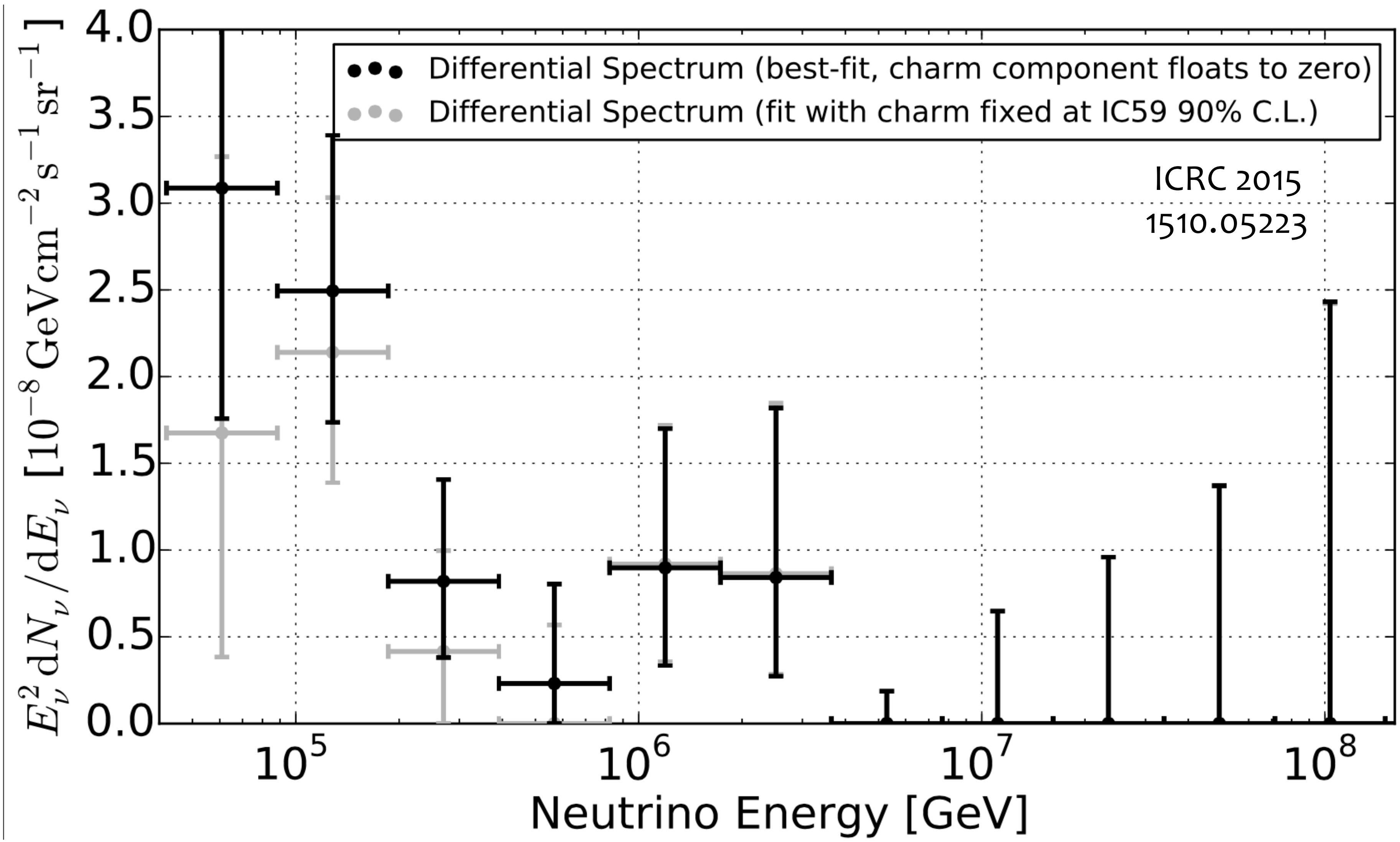
The discovery of the astrophysical flux

- Two high energy neutrinos first discovered during a search for the Cosmogenic neutrino flux over two years of data
- 2.8σ excess over background [PRL 111, 021103 (2013)]
- Methods were designed to lower the energy threshold

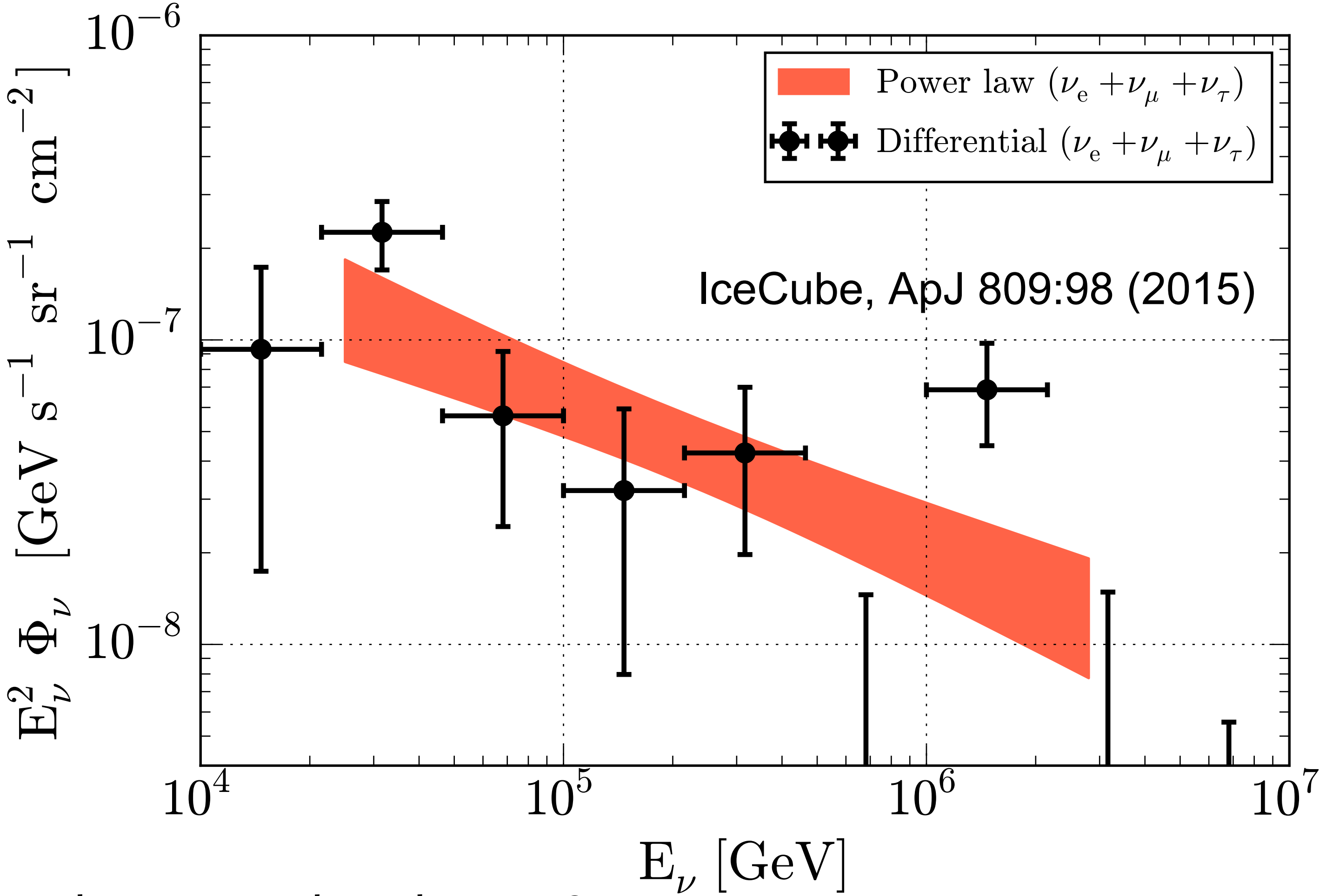




Starting event energy spectrum unfolded to neutrino energy



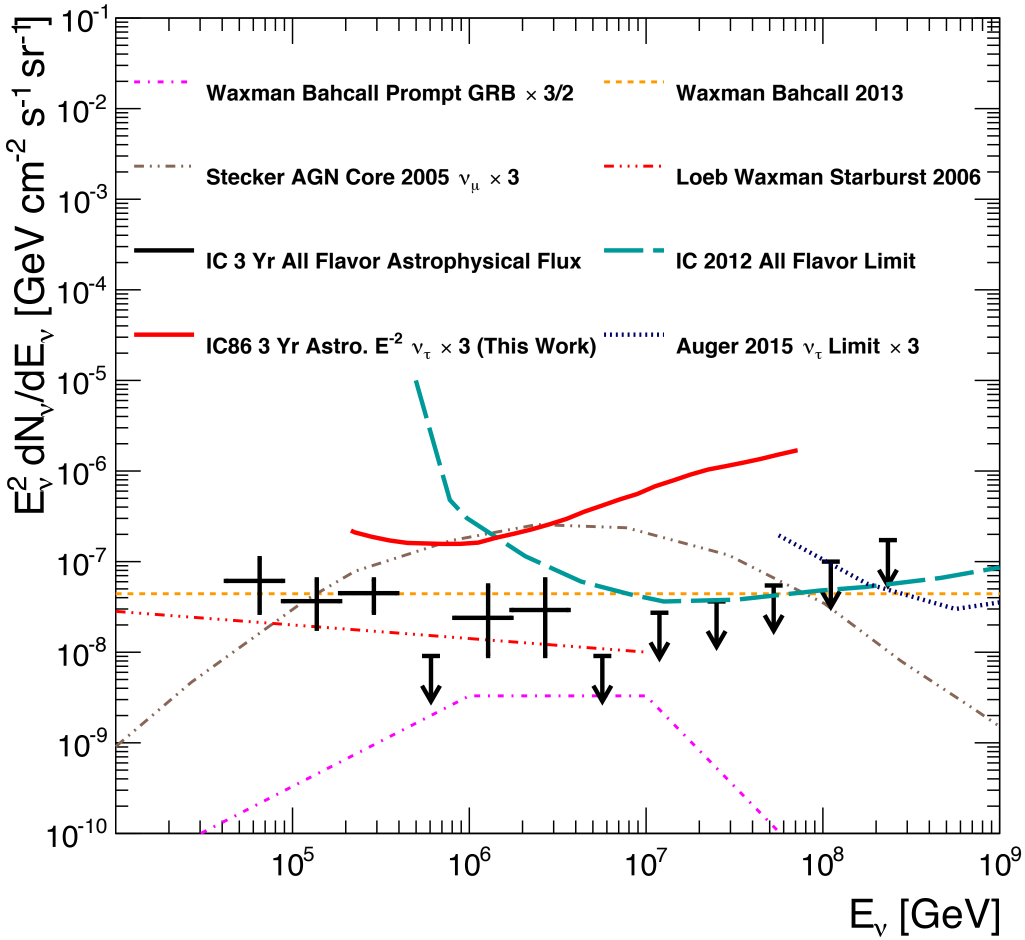
Global fit of multiple IceCube channels and data sets



- Showers and tracks, 2008-2013
- Fit well by unbroken power law with index 2.50 ± 0.09
- E^{-2} disfavored at 3.8 sigma

Tau neutrino upper limit from three years of 86-string data

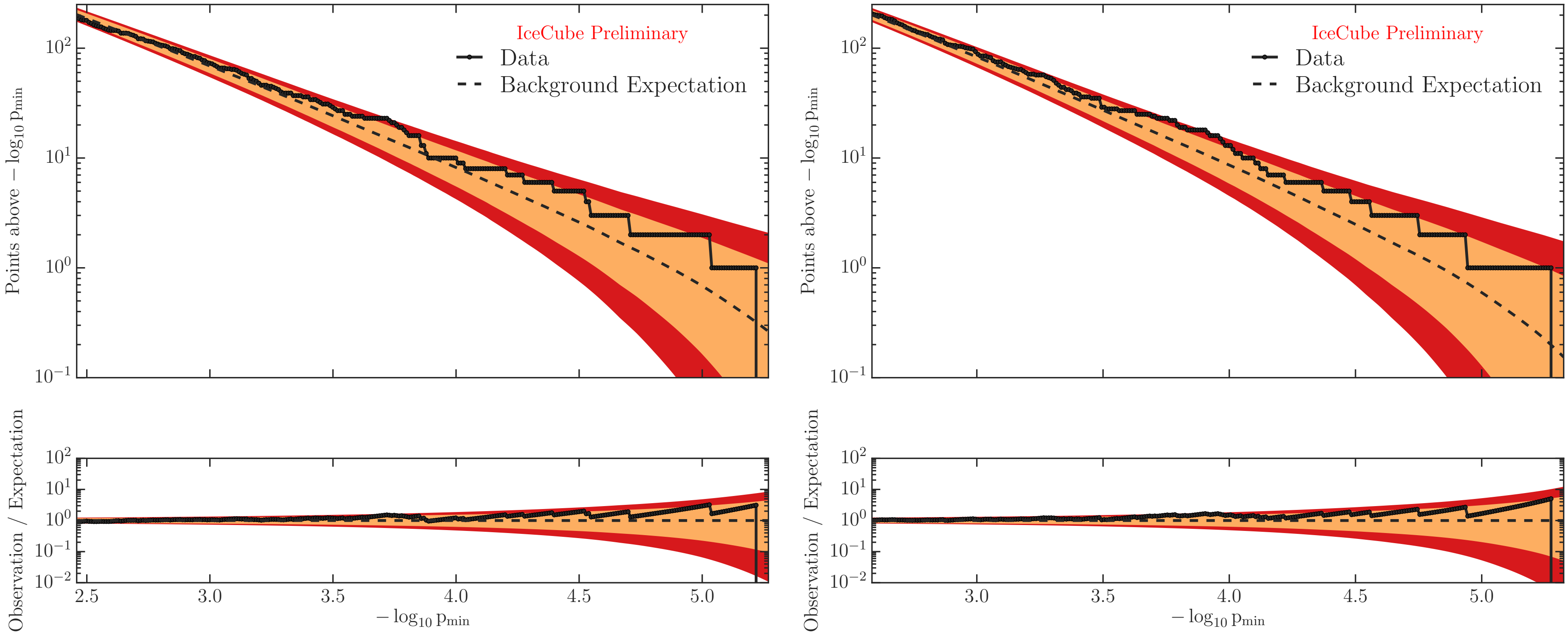
PRD 93, 022001 (2016)



Reached 2.5 orders of magnitude lower energy than previous (Pierre Auger) tau neutrino searches

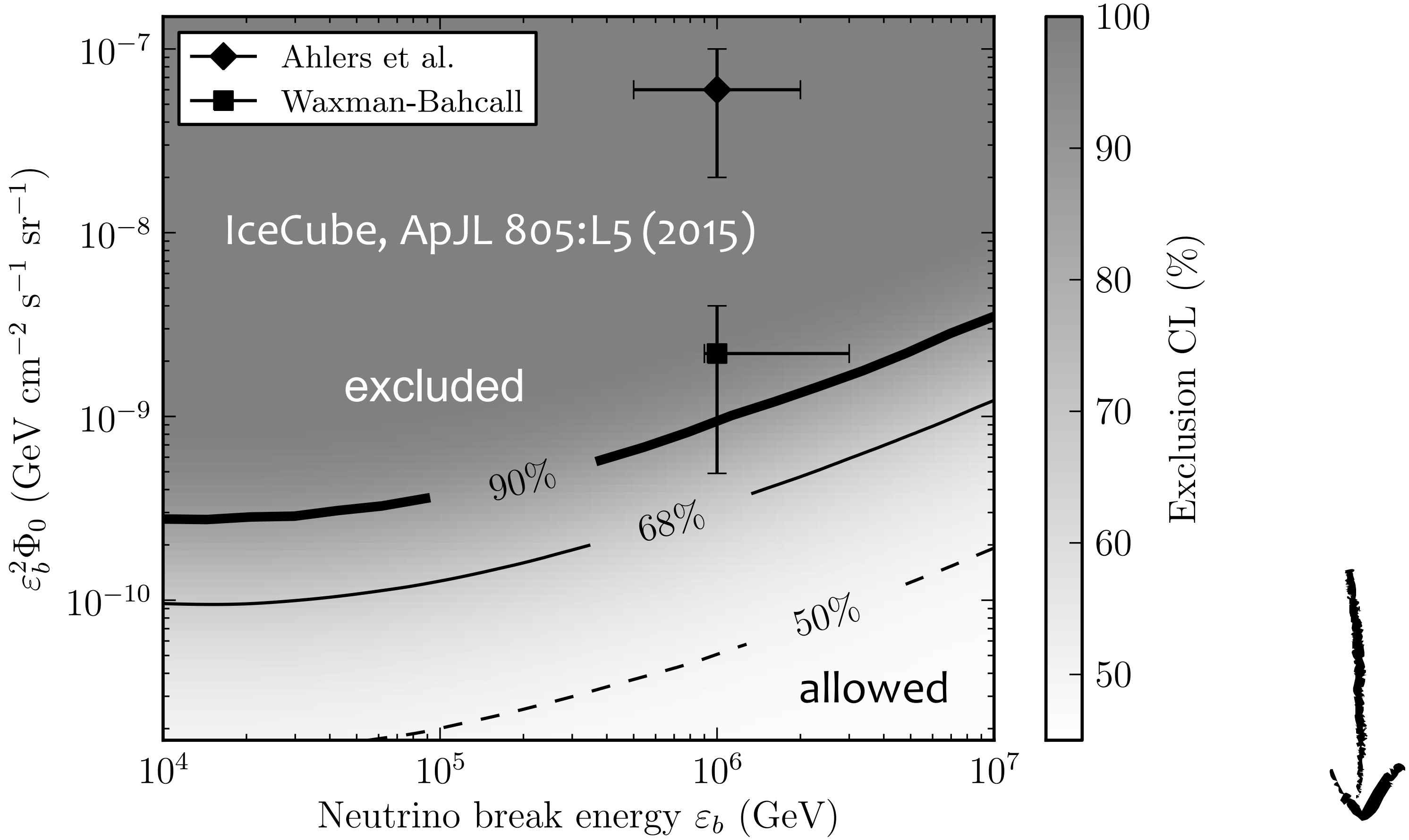
No excess of hotspots

North: p = 42% South: p = 39%



Also, nothing in the Galactic plane (+/- 15°): p = 57%

The neutrinos are not produced by GRBs



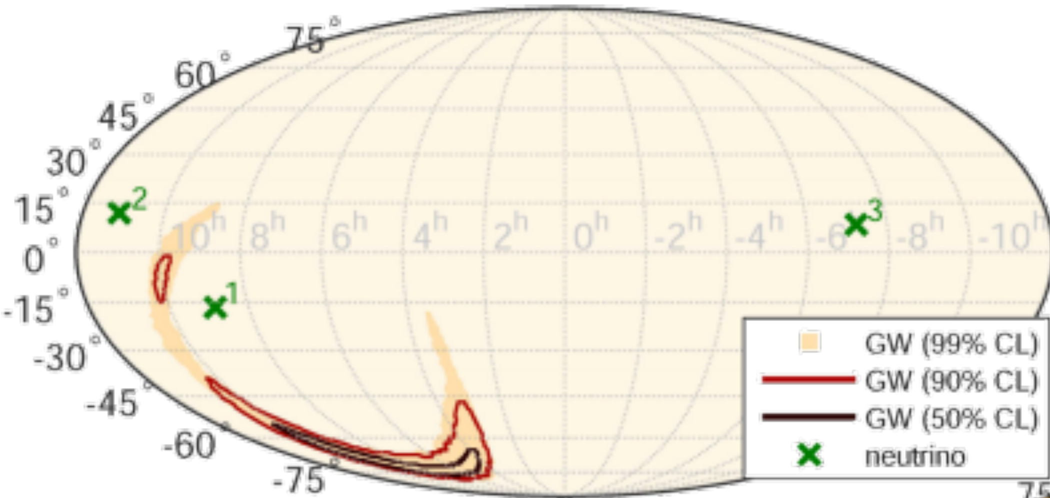
Four years of data (40, 59, 79, 86 strings) and 506 bursts (Swift, Fermi)

One low-significance event detected

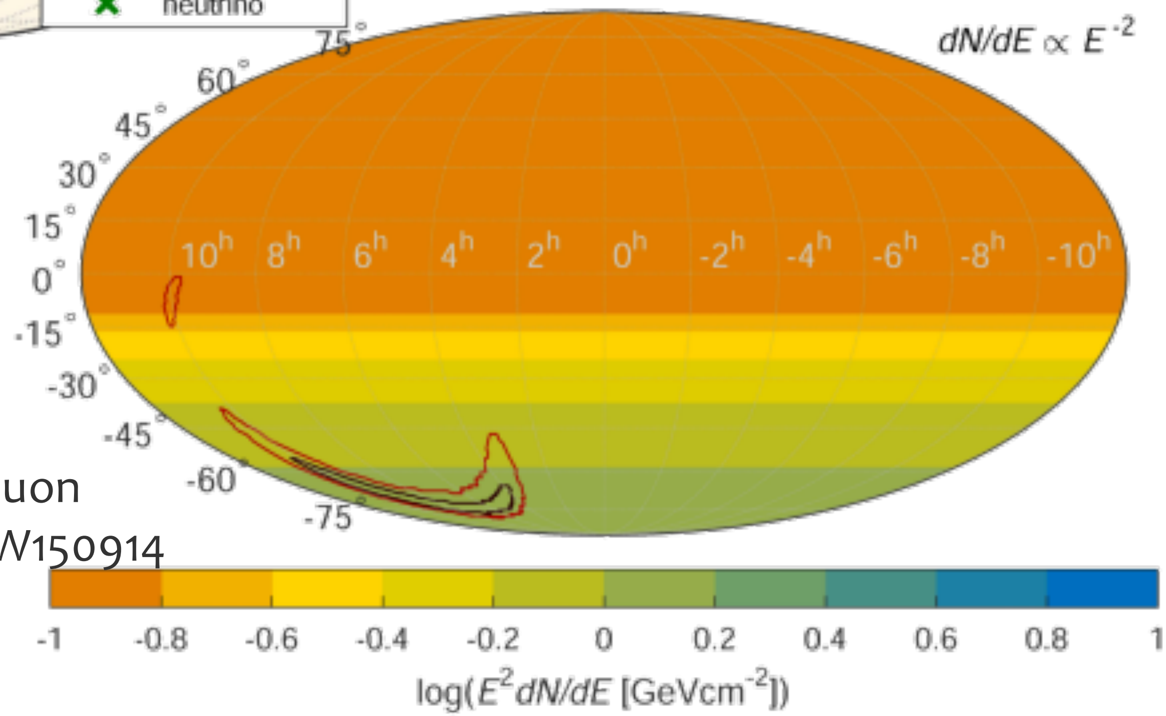
<1% of astrophysical neutrino signal produced by GRBs

This rules out GRBs as predominant source of UHECR

And no correlation with Gravitational Waves



Neutrino candidates within +/- 500s of GW150914



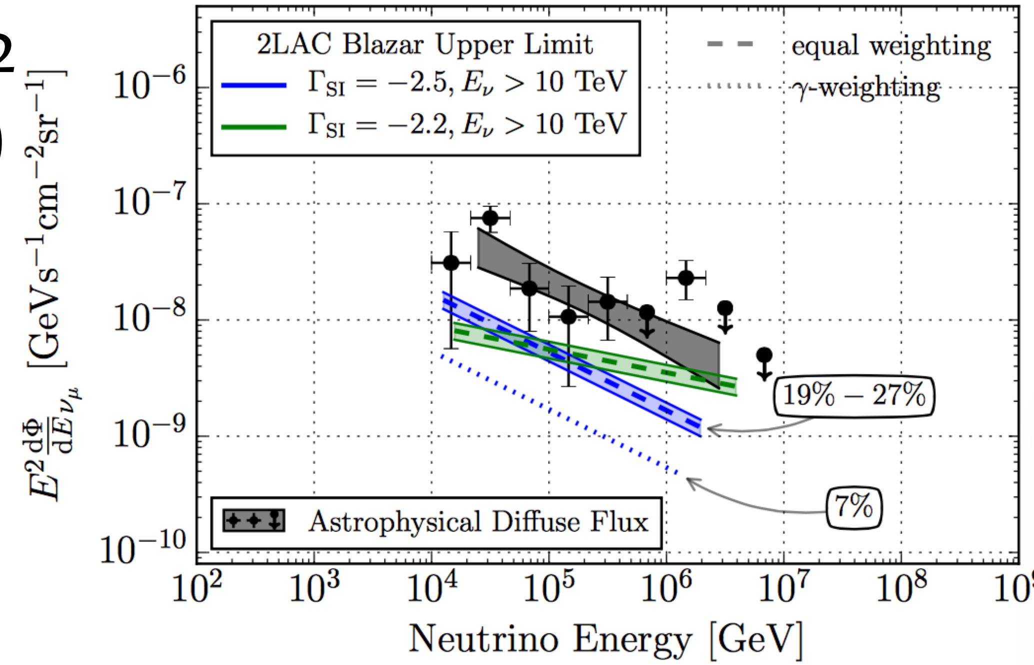
Upper limit on the high-energy muon neutrino spectral fluence from GW150914 as a function of source direction.

Search for correlation between IceCube neutrinos and GeV blazars

Fermi 2LAC sample of 862 objects (3 yrs of IceCube)

Contribution of 2LAC blazars to neutrino signal at most:

- 27% if equal weighting among blazars
- 17% if neutrino flux proportional to gamma flux



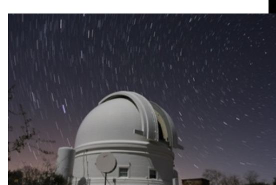
IceCube, submitted

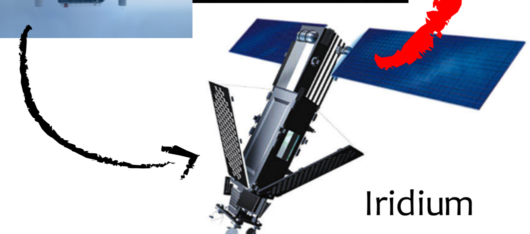
Follow ups and real time alerts

Gamma (e.g.: Veritas HESS, Magic)

X-ray (e.g.: SWIFT)

Optical (e.g: PTF)





Iridium satellites

- ✓ Multiplet alert active since 2008
- ✓ Singlet starting event track alert started in April http://gcn.gsfc.nasa.gov/doc/Public_Doc_AMON_IceCube_GCN_Alerts_v2.pdf
- ✓ public GCN alerts for high energy events