A search for extremely high energy neutrino flux with the 6 years of IceCube data

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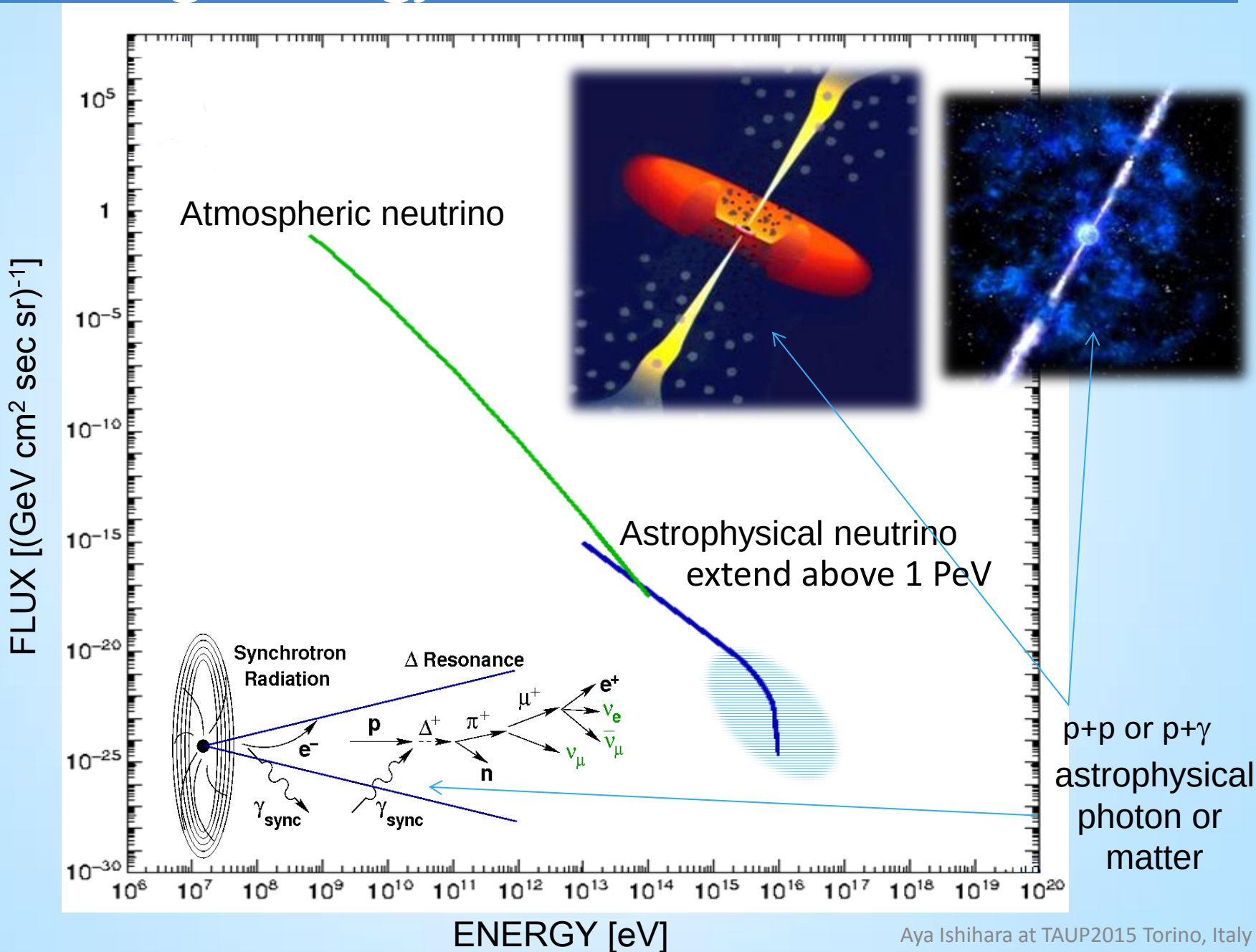
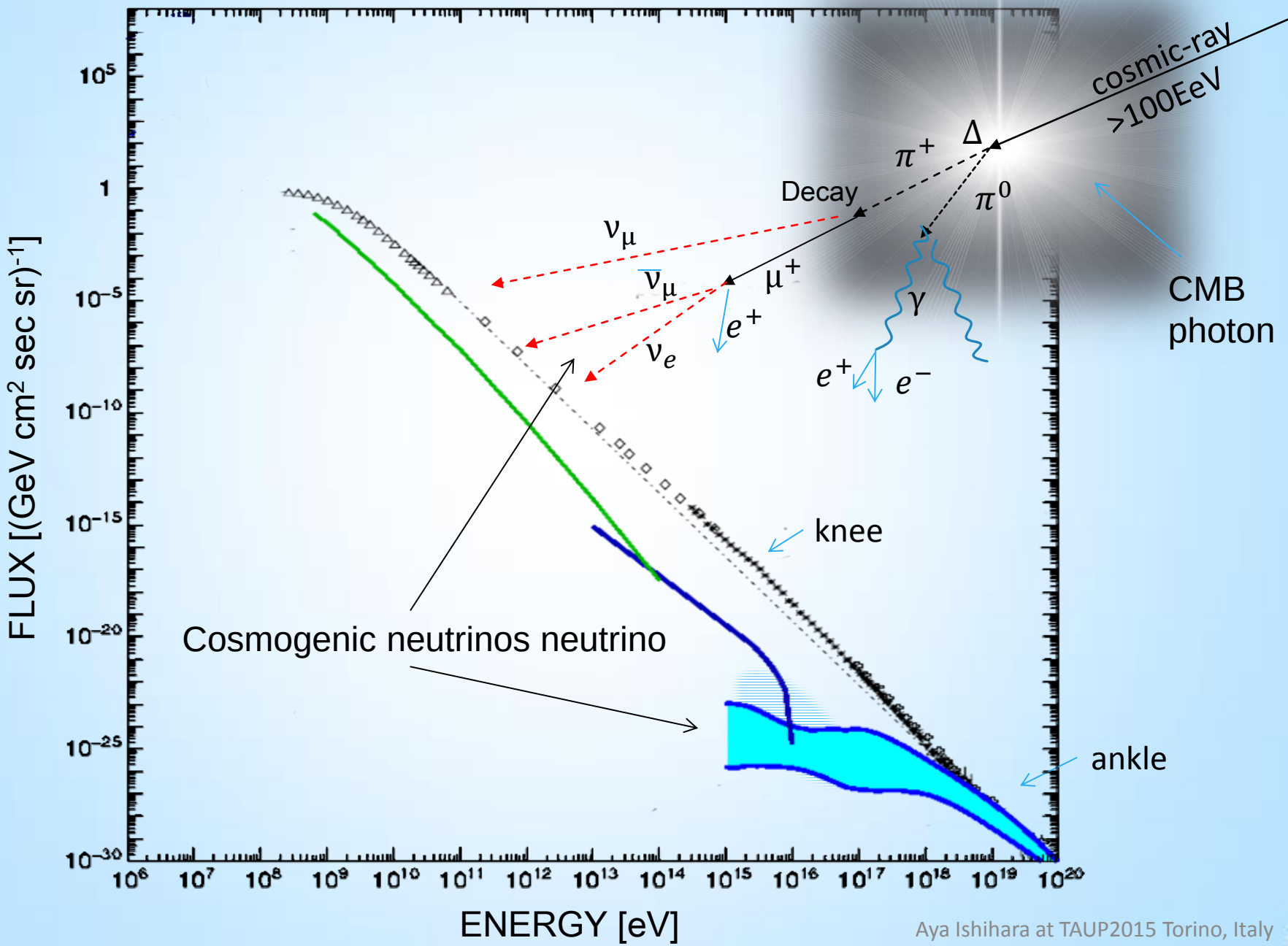
Ultra-high energy neutrinos in the Universe



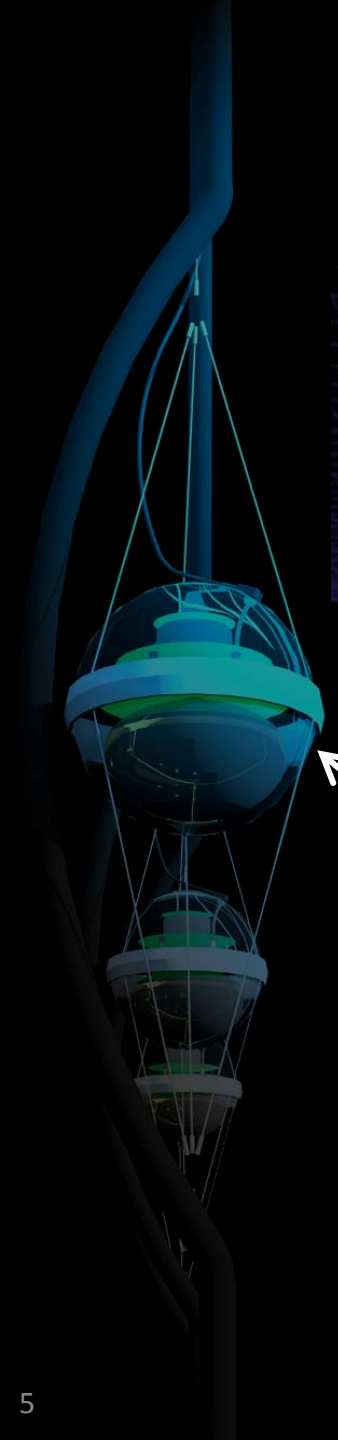
Extremely-high energy neutrinos in the Universe

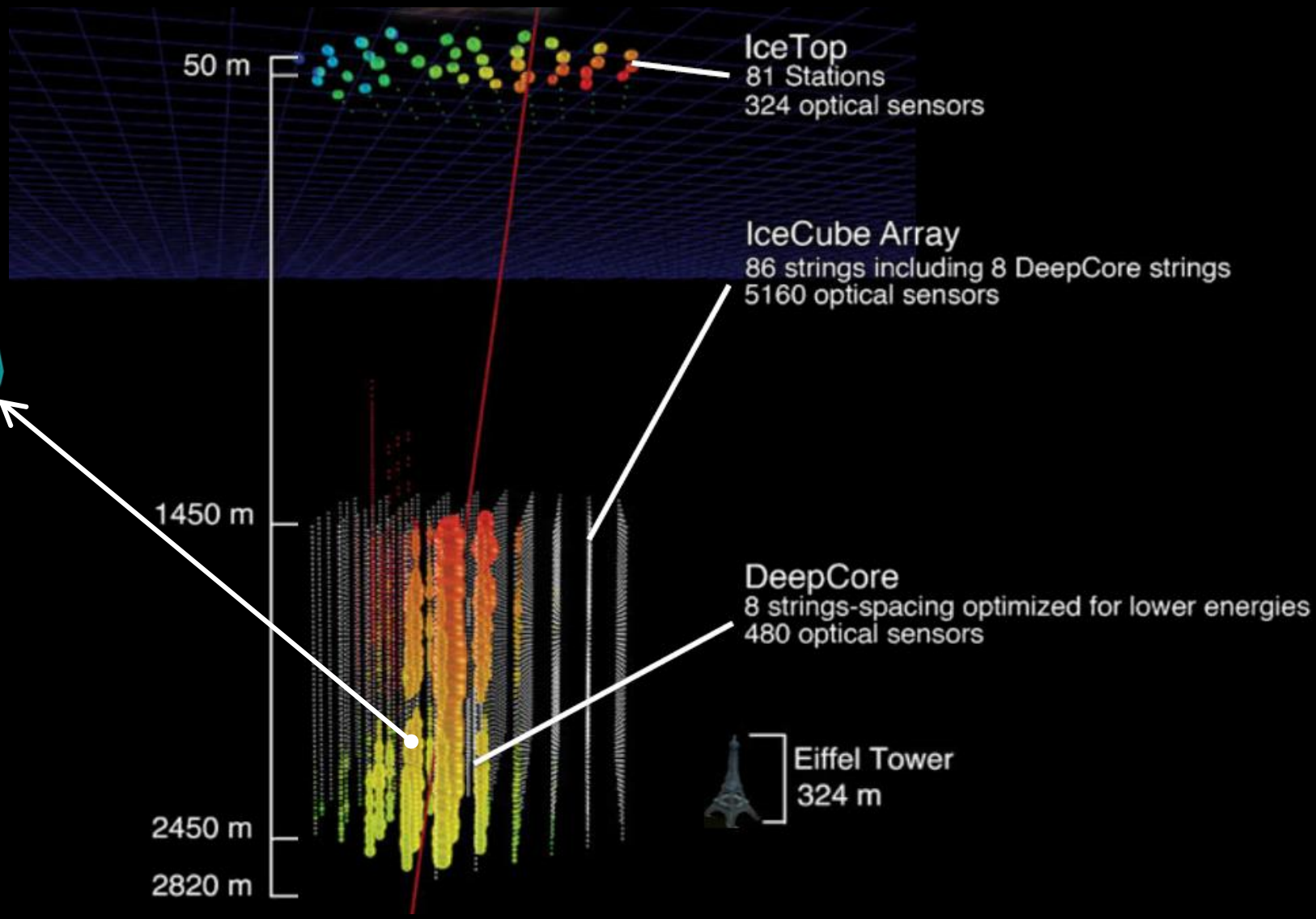


Cosmic neutrino flux above a few PeV

- Unattenuated neutrinos over cosmological distances
- PeV to EeV sky with charge neutral particle
- Neutrinos associated with UHE cosmic-ray production and gamma-rays
- Above GZK cutoff energies, UHE cosmic-ray compositions…

The IceCube Detector





The IceCube Collaboration

http://icecube.wisc.edu

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
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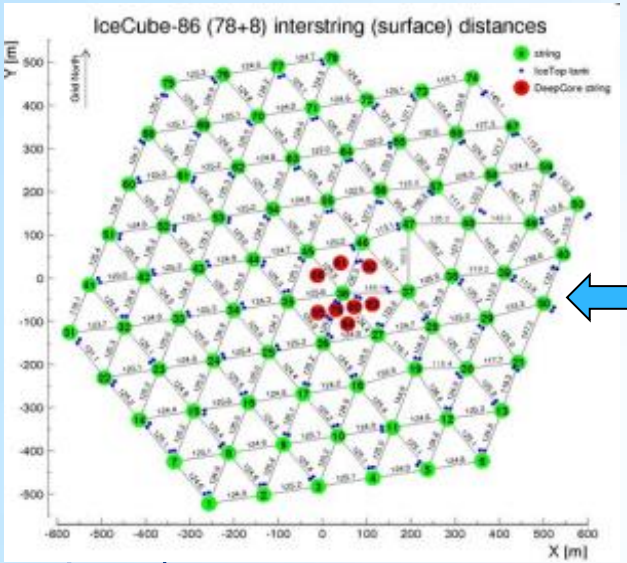
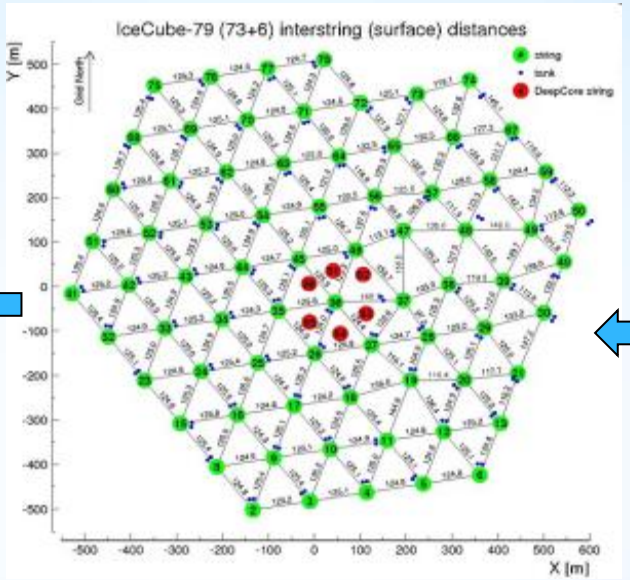
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

The IceCube Construction and Runs

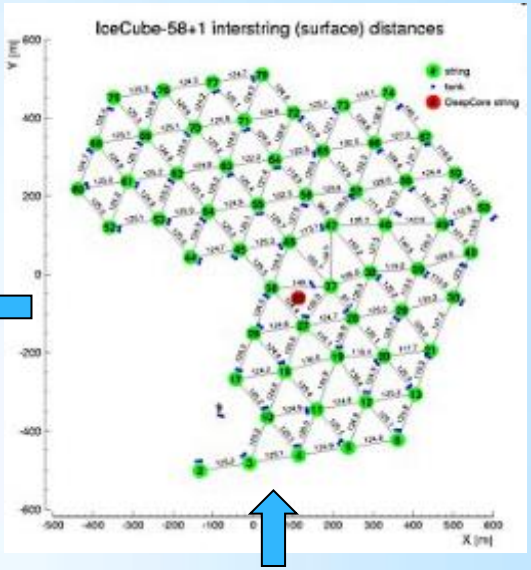
IC86 = full IceCube (2011~)



IC79 (2010-2011)



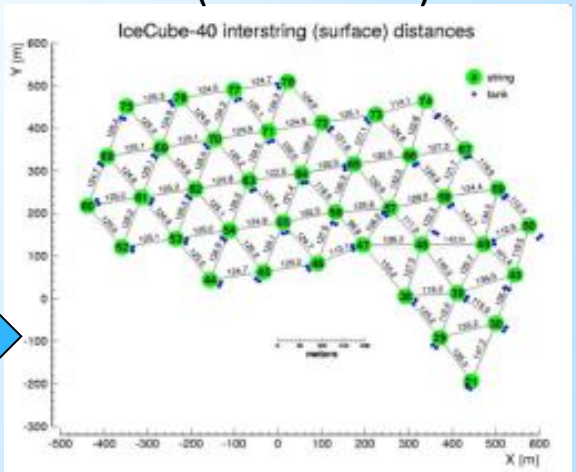
IC59 (2009-2010)



Stable full operation since May 2011 - Now taking 5th year physics run with the full IceCube configuration

This work analyze data from IC40 to 3rd year IC86 run (total ~6 year)

IC40 (2008-2009)

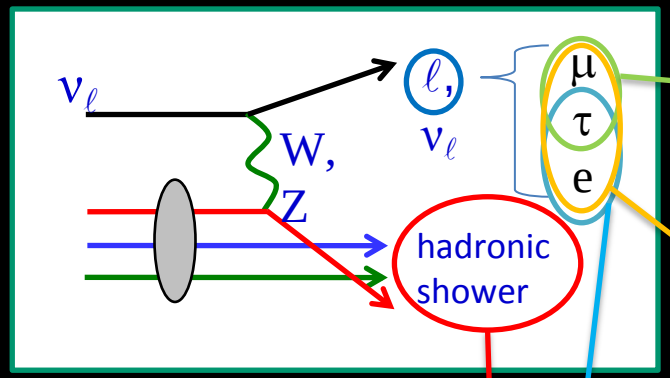


IC22 (2007-2008)

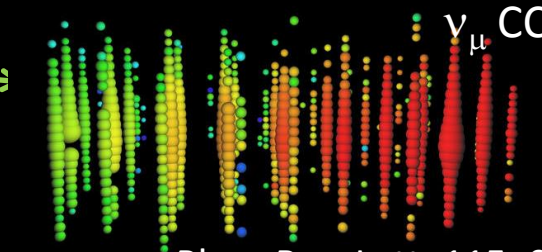
IC9 (2006-2007)

IC1(2005-2006)

IceCube channels



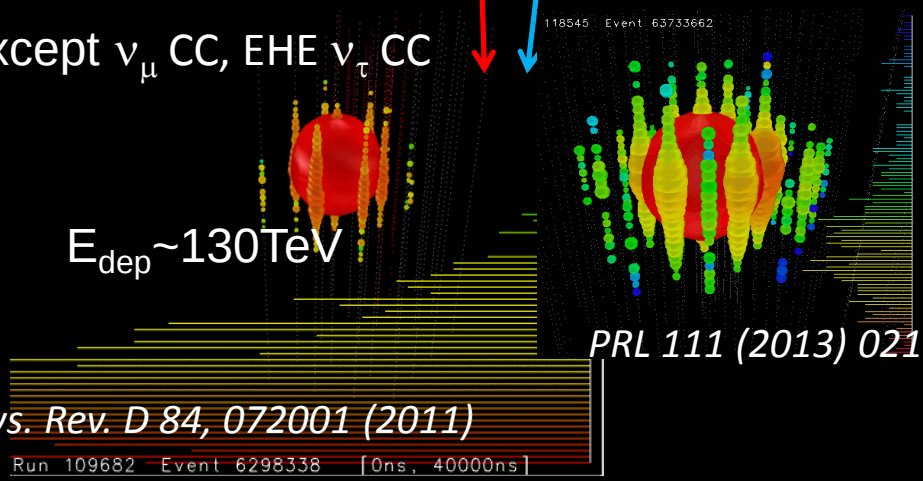
~880TeV upward through-going muon track event



Phys. Rev. Lett. 115, 081102

Cascade-like events

All except ν_μ CC, EHE ν_τ CC

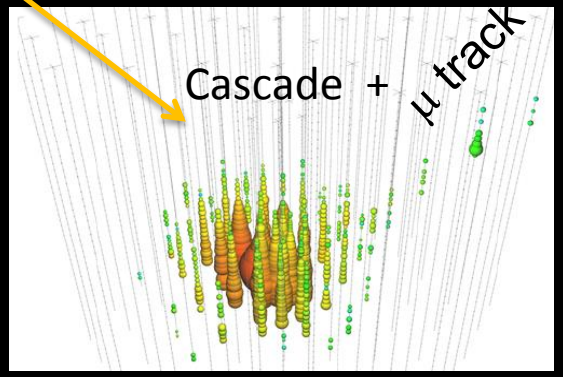


E_{dep}~130TeV

PRL 111 (2013) 021103

Phys. Rev. D 84, 072001 (2011)

Starting events
sensitive to all flavor CC/NC



Science 22 Vol. 342 (2013)
PRL 113, 101101 (2014)

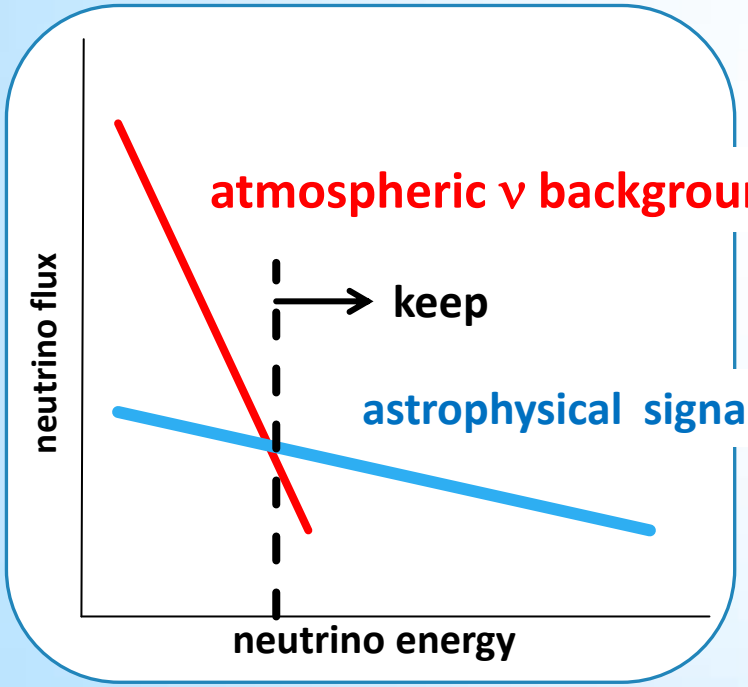
EHE neutrino search with IceCube

Reducing ***atmospheric neutrino*** background by placing threshold on energy proxy (NPE)

+

atmospheric muon background is reduced by well reconstructed downward-going tracks

= **what not rejected is EHE signal candidate of different event properties**



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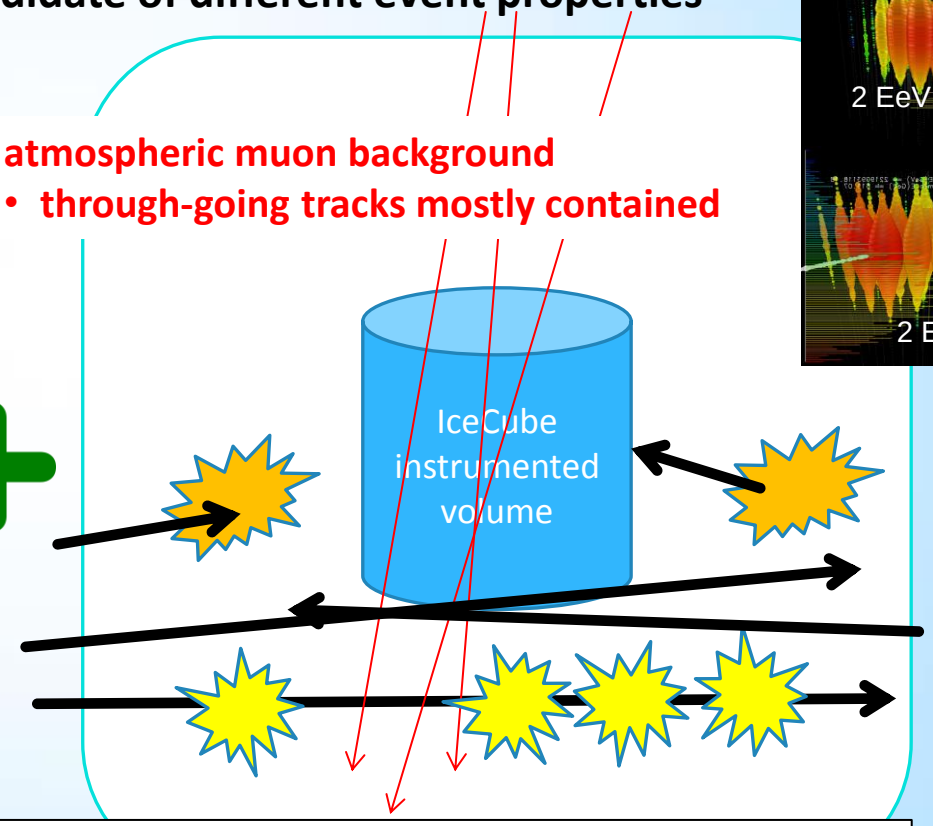
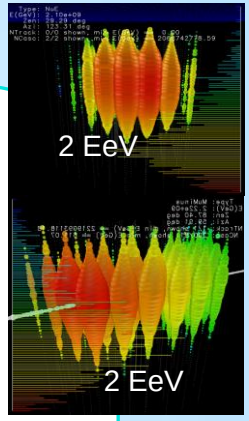


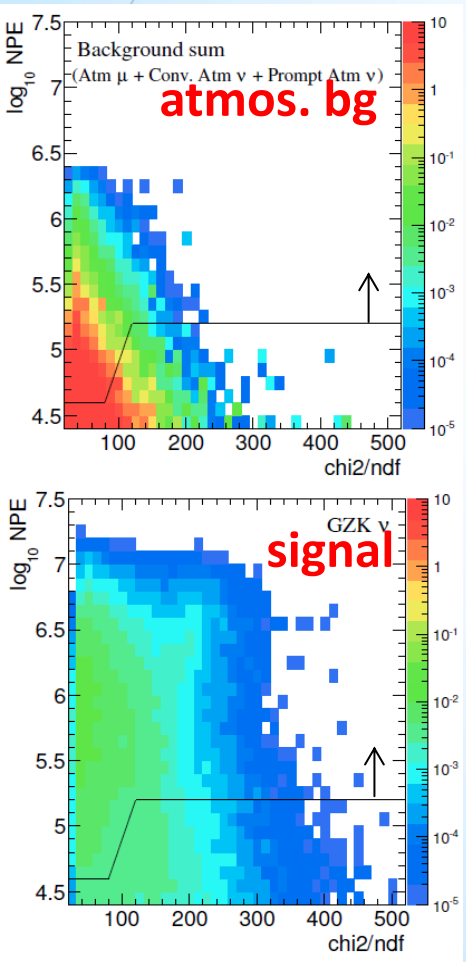


EHE signals are very bright/energetic

- **mostly uncontained through-going and cascade events**
- **topological features change with energies**

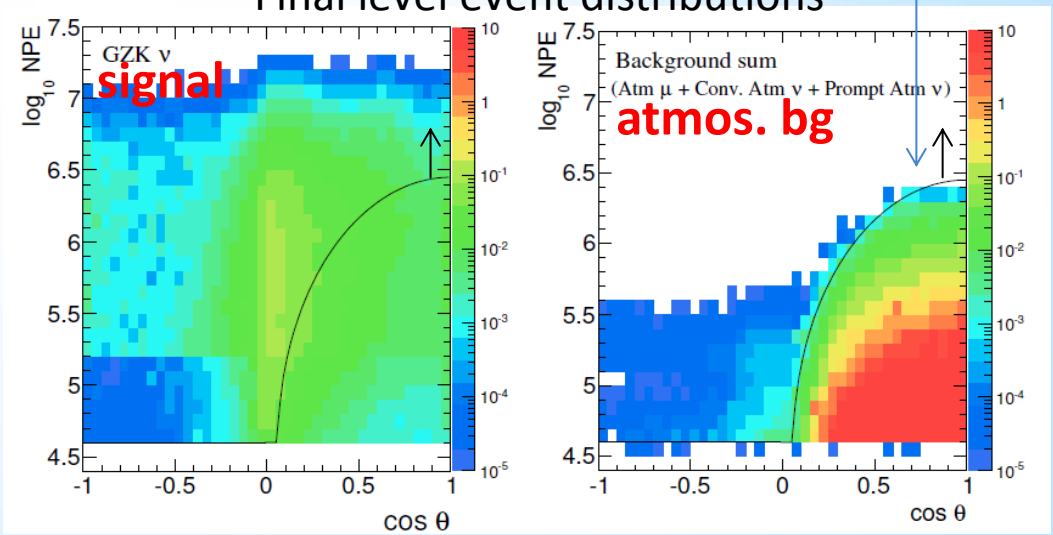
Event selection

- Events are from April 2008 to May 2014 (Effective livetime of 2014 days = 5 years and 189days)
  1. Events above the threshold NPE lines are kept
  2. Higher NPE threshold for downward-going track

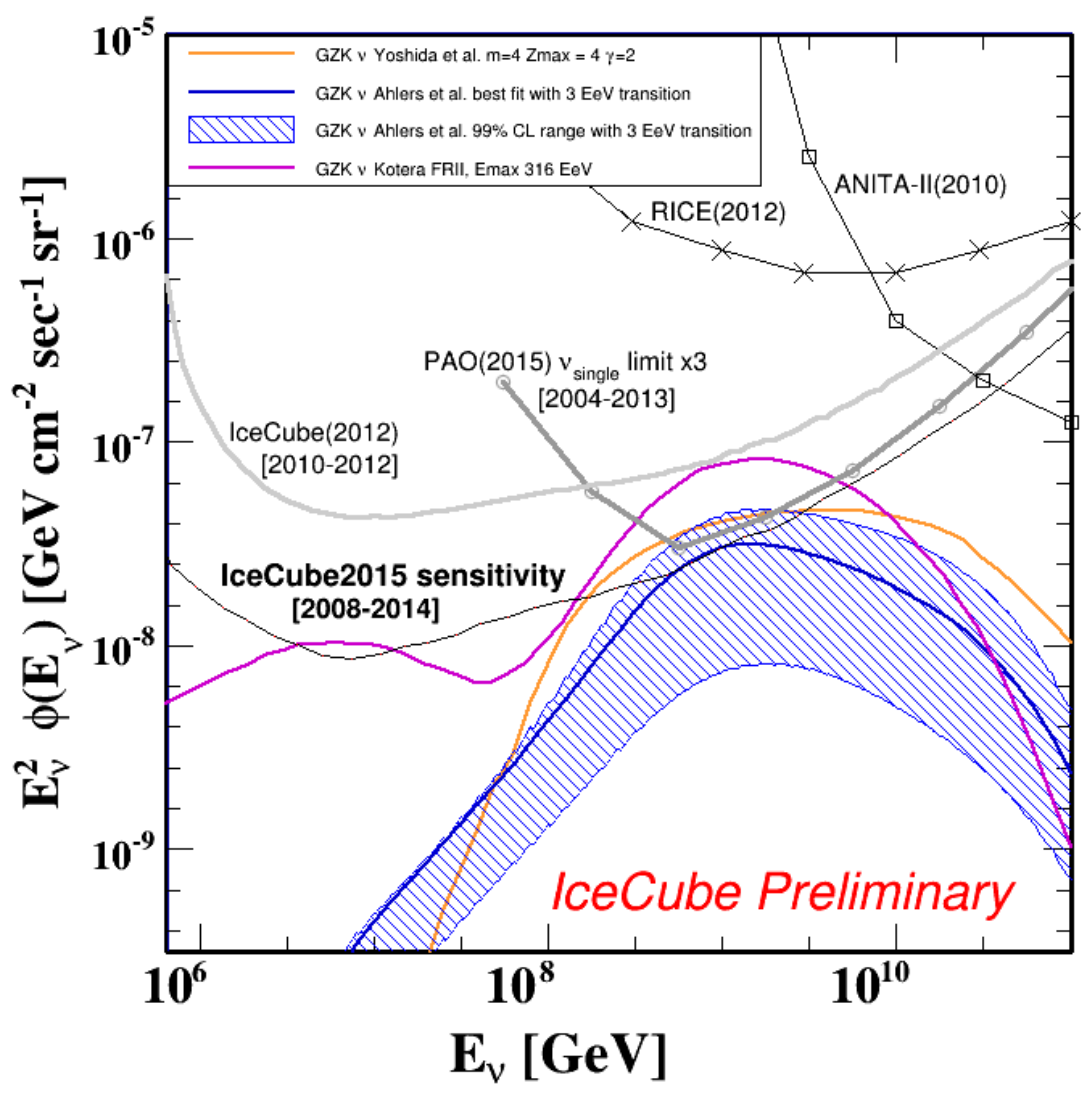


Tighter cut for downward-going track like events

Final level event distributions

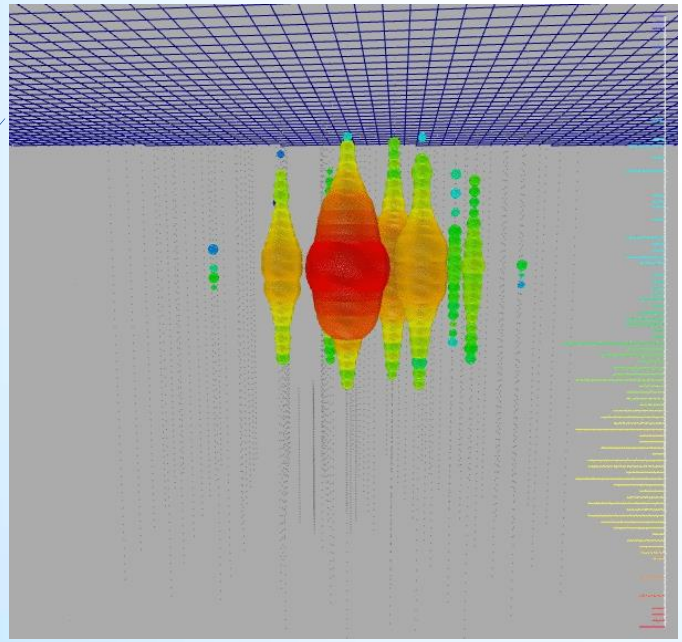


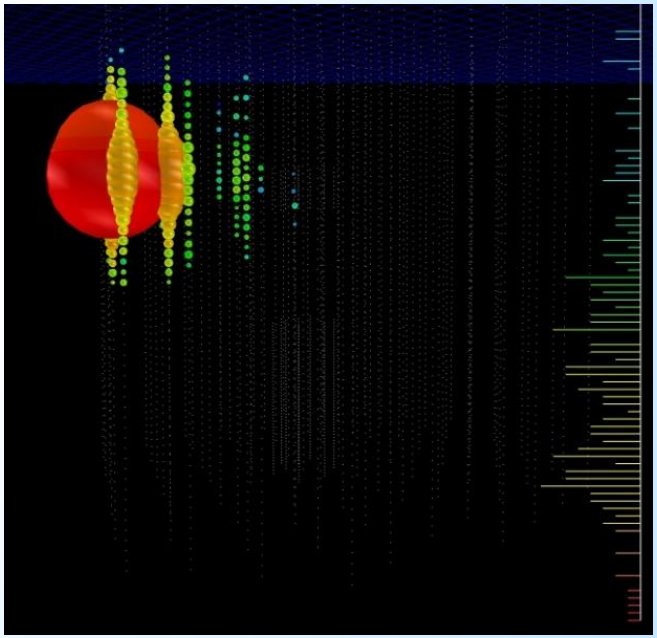
Sensitivity



Observation

- One partially contained upward-going cascade observed in Nov 16, 2012 data
  - Preliminary estimate of energy deposit: 770 TeV (NPE=74300)
  - Vertex position close to the outer most layer of optical sensors





Energy resolution
~15% contained cascades
~30% partially contained cascades

The binned Poisson LLH analysis

Ex.) BG only hypothesis

$$L_0 = \prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}})$$

$$L_1 = \prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \lambda^{\max} \mu_{jk}^{\mathrm{GZK}})$$

The likelihood ratio

$$\Lambda \equiv \frac{L_1}{L_0} = \frac{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \lambda^{\max} \mu_{jk}^{\mathrm{GZK}})}{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}})}$$

The log-likelihood ratio

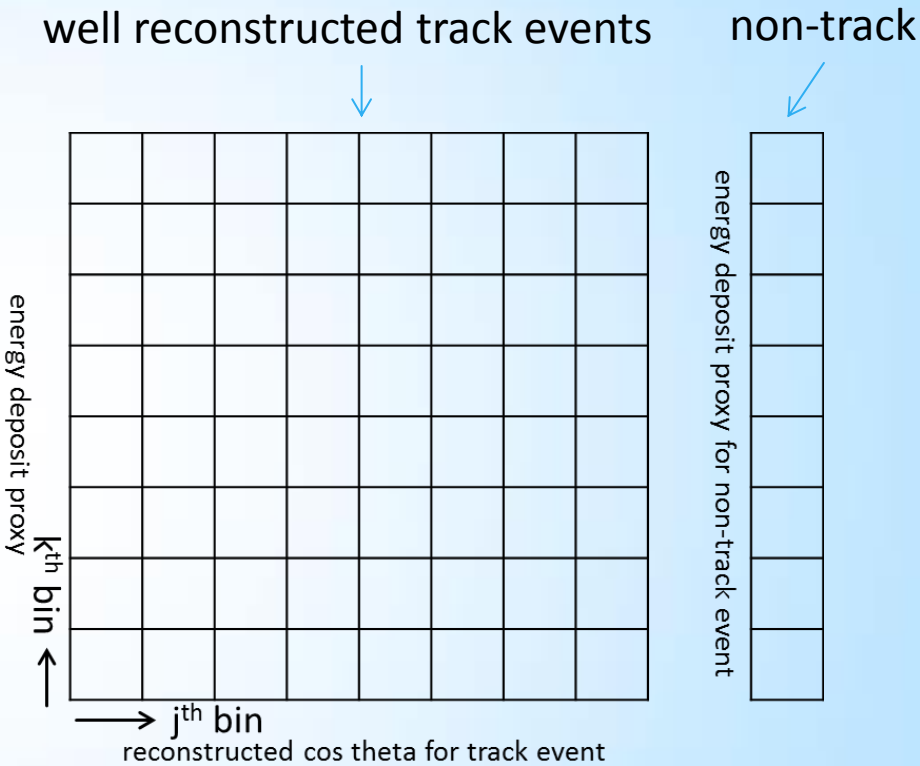
$$x^2 \equiv \ln \Lambda$$

is the test statistic

P-value

Estimated by replica experiments

$$p = Pr(x^2 > x^2_{\mathrm{obs}}).$$



Results

Is the observed event explained by background?

Background only hypothesis test p-value: 0.7%

Hypothesis of observed event being of atmospheric origin rejected at 99.3%CL

Is the observed event astro or cosmogenic origin?

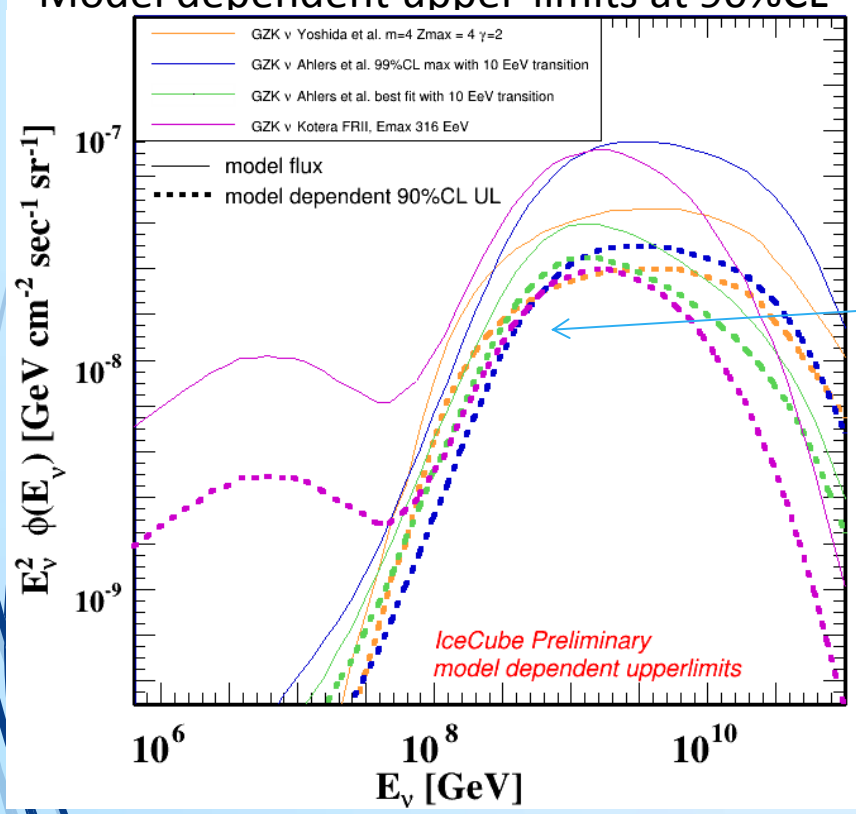
Observation is inconsistent with GZK hypothesis with p-value of 0.8%	**E^{-2} signal model is compatible with p-value of 90%**

- The observed 770TeV event is not likely to be atmospheric background, nor cosmogenic neutrino event…
- Consistent with another HE neutrino event following power-law ν flux

Model dependent test and upperlimits

Model hypothesis tests including the 1 event observation			*90%CL
Models	**event rates /livetime**	**p-values**	**Model dependent UL***
Ahlers Fermi max fit (10EeV transition)	8.6 events	0.05%	0.35 times model flux
Ahlers Fermi best fit (10EeV transition)	4.2 events	3%	0.7 times model flux
Kotera FRII dip model	11.7 events	0.002%	0.3 times model flux
Kotera SFR dip model	2.8 events	16.6%	1.2 times model flux

Model dependent upper-limits at 90%CL



Different cosmogenic model dependent limits give similar UL in the energy region between 10^8GeV and 10^9GeV

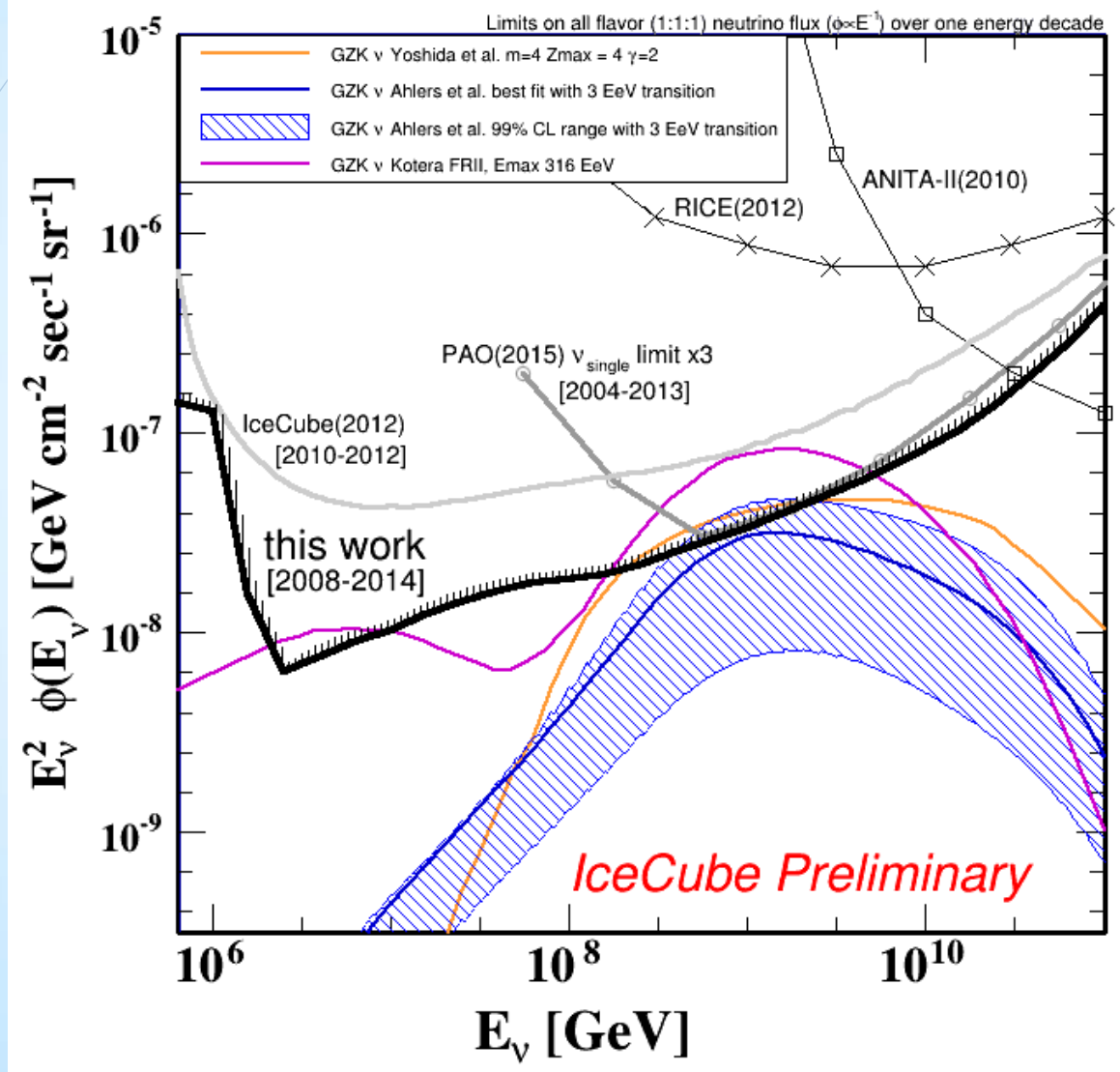
This implies, despite the differences in spectral shape, models with

$$E\frac{d\phi^{GZK}}{dE} < 10^{-16.5}[cm^{-2}sec^{-1}str^{-1}]$$

(10^8GeV - 10^9GeV)

are currently only allowed at 90%CL

Quasi-differential Upperlimits



Summary and prospects

- Neutrinos above PeV energies are searched by IceCube 6 year sample from April 2008 to May 2014
- One partially contained 770TeV cascade event is observed
- The event is most consistent with a E-2 astrophysical neutrino, not from GZK mechanism
- Tight constraints on several cosmogenic neutrino models are placed
- The analysis will include an additional year sample taken by May 2015 soon

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Ahlers Fermi best fit (10EeV transition)	4.2 events	3%	0.7 times model flux
Ahlers Fermi max fit (3EeV transition)	5.1 events	1.5%	0.59 times model flux
Ahlers Fermi best fit (1EeV transition)	2.3 events	21%	1.33 times model flux
Kotera FRII dip model	11.7 events	0.002%	0.3 times model flux
Kotera SFR dip model	2.8 events	16.6%	1.2 times model flux
Yoshida (4,4)	5.6 events	1%	0.54 times model flux