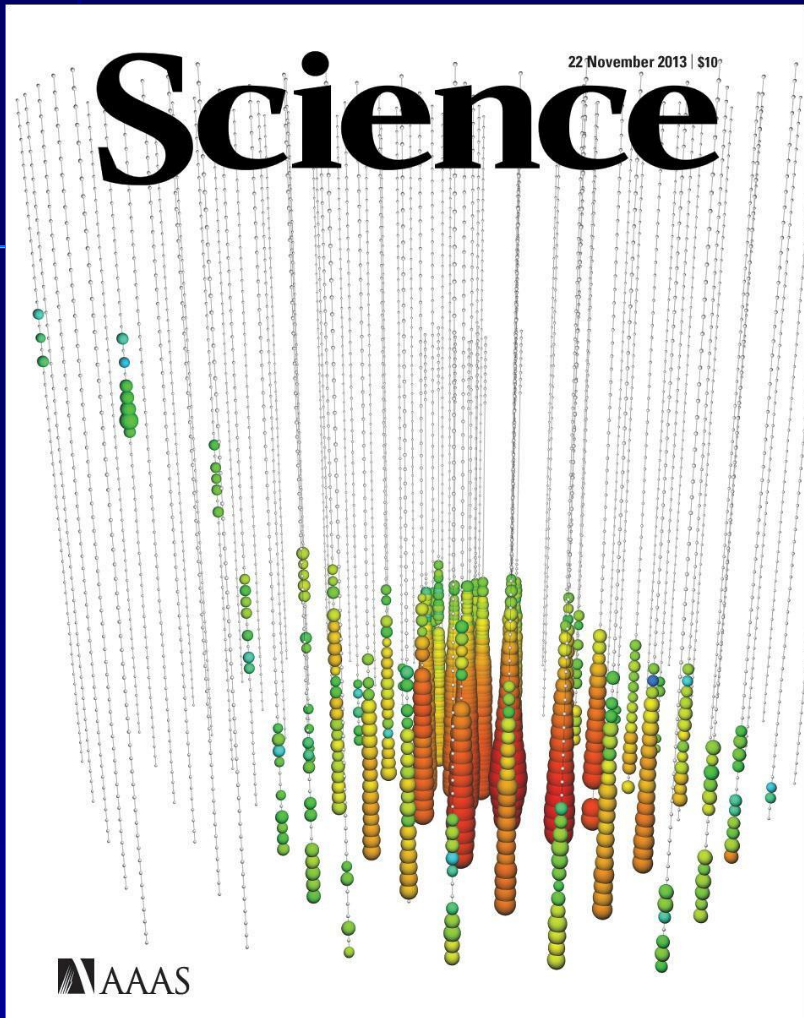
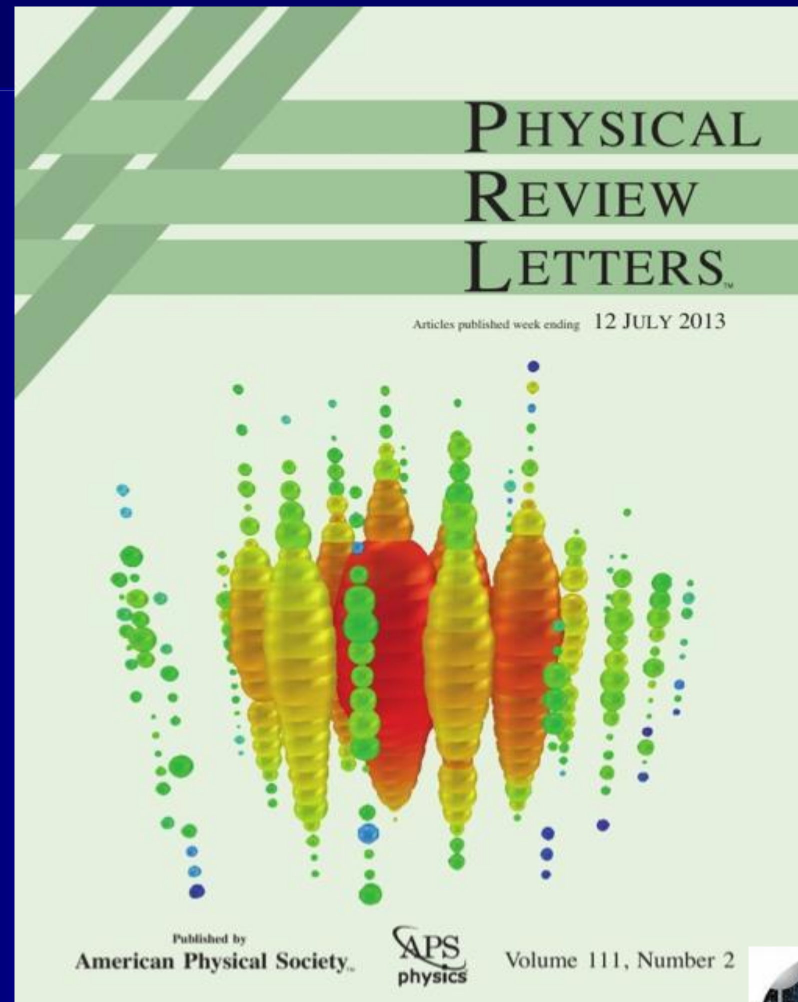
IceCube: Revealing a Neutrino Picture of the Cosmos

- **Introduction**
- **Detector Description**
- **Neutrino Window to the Cosmos**
- **Future Plans**
- **Conclusions**

Ali R. Fazely for the IceCube Collaboration.
icecube.wisc.edu
Miami Conference, December 14 -20, 2016


Science
22 November 2013 | $10
AAAS


PHYSICAL REVIEW LETTERS
Articles published week ending 12 JULY 2013
Published by
American Physical Society
APS physics
Volume 111, Number 2

What is IceCube?

- A gigaton neutrino detector funded through the National Science Foundation and EU funding agencies
- We are in our 13th project year and data taking with the full detector (86 strings) began in May 2011
- IceCube is the largest Neutrino Telescope in operation
- IceCube has opened up a neutrino window to the cosmos and has ushered in the dawn of Neutrino Astronomy. Science Cover Article November 22nd 2013, and PRL Cover, July 12, 2013.
- http://icecube.wisc.edu/

The IceCube Collaboration

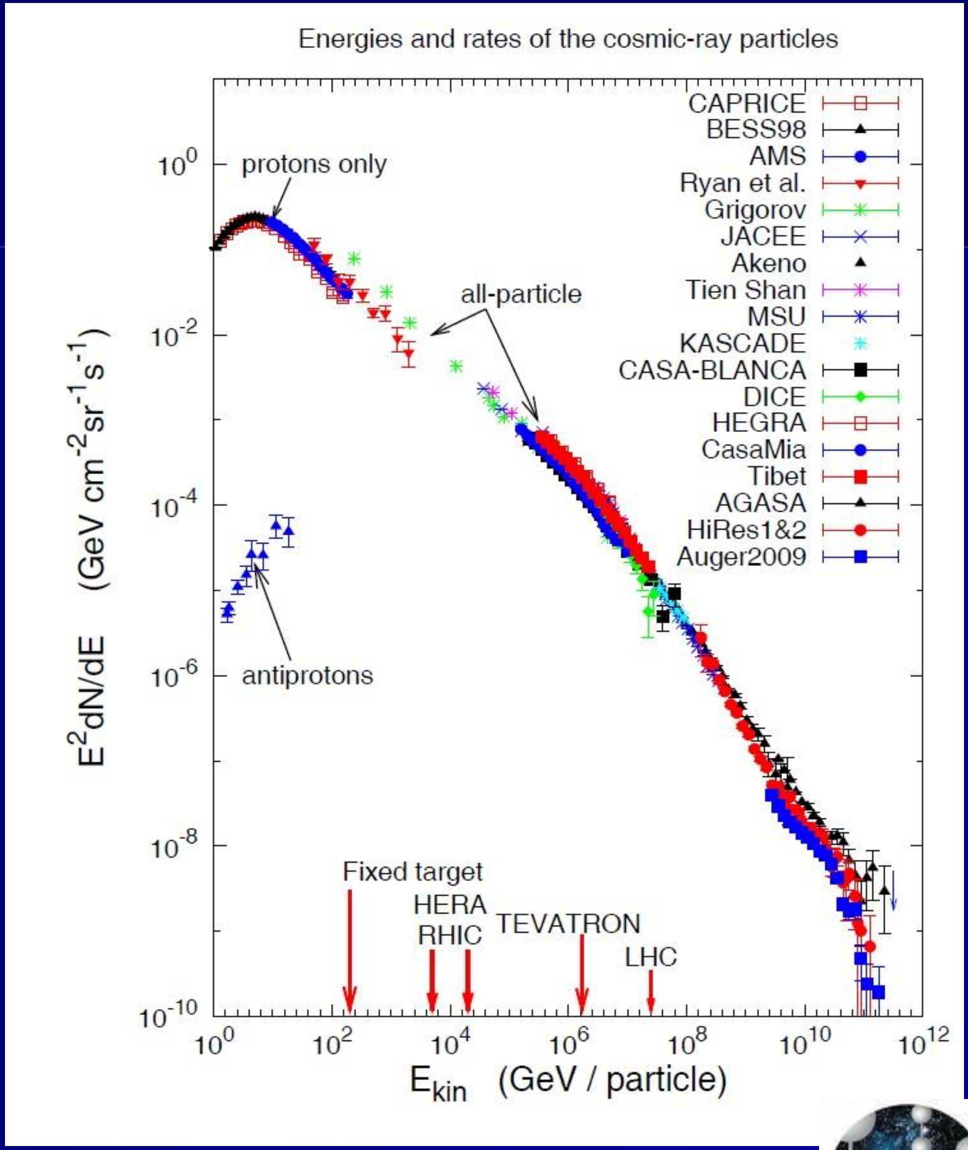
Funding Agencies

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)

Cosmic Rays: A century old puzzle

Balloon flights
1911-1913

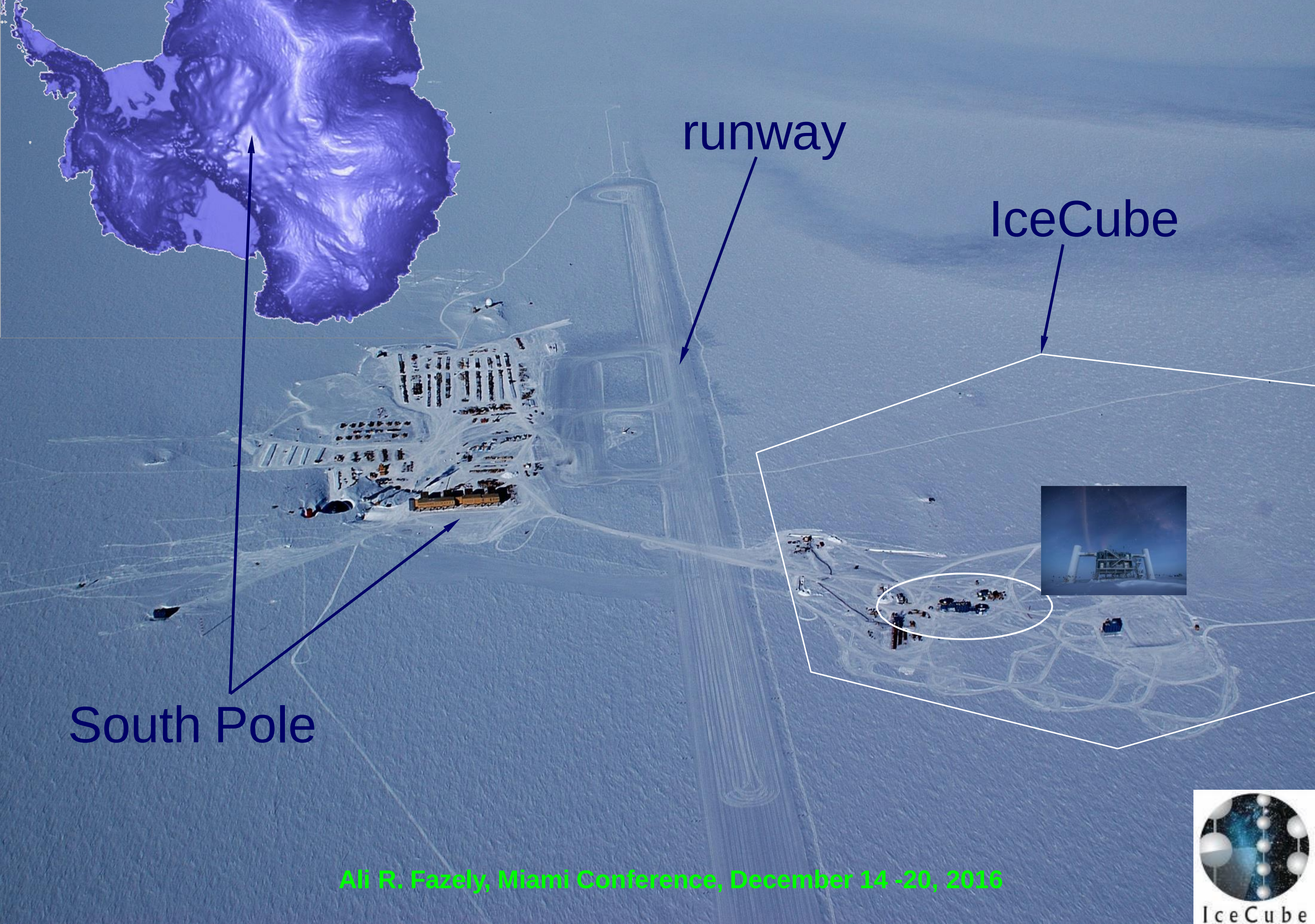
Victor Hess
Nobel Prize
1936



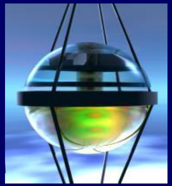
- Power law over many decades
- Origin Unknown

IceCube

Amundsen-Scott South Pole Station



The IceCube Detector

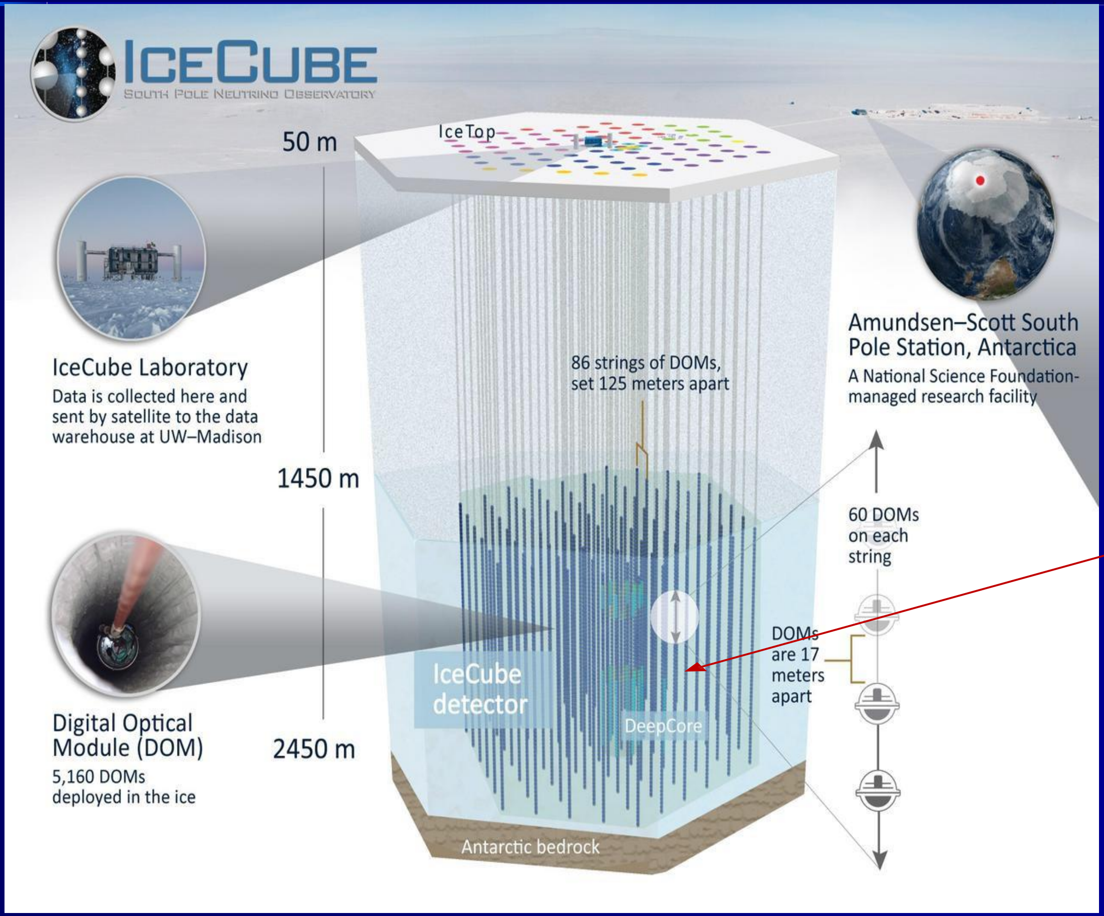


IceTop

Air shower detector threshold ~ 300 TeV

✓Completion: December 2010

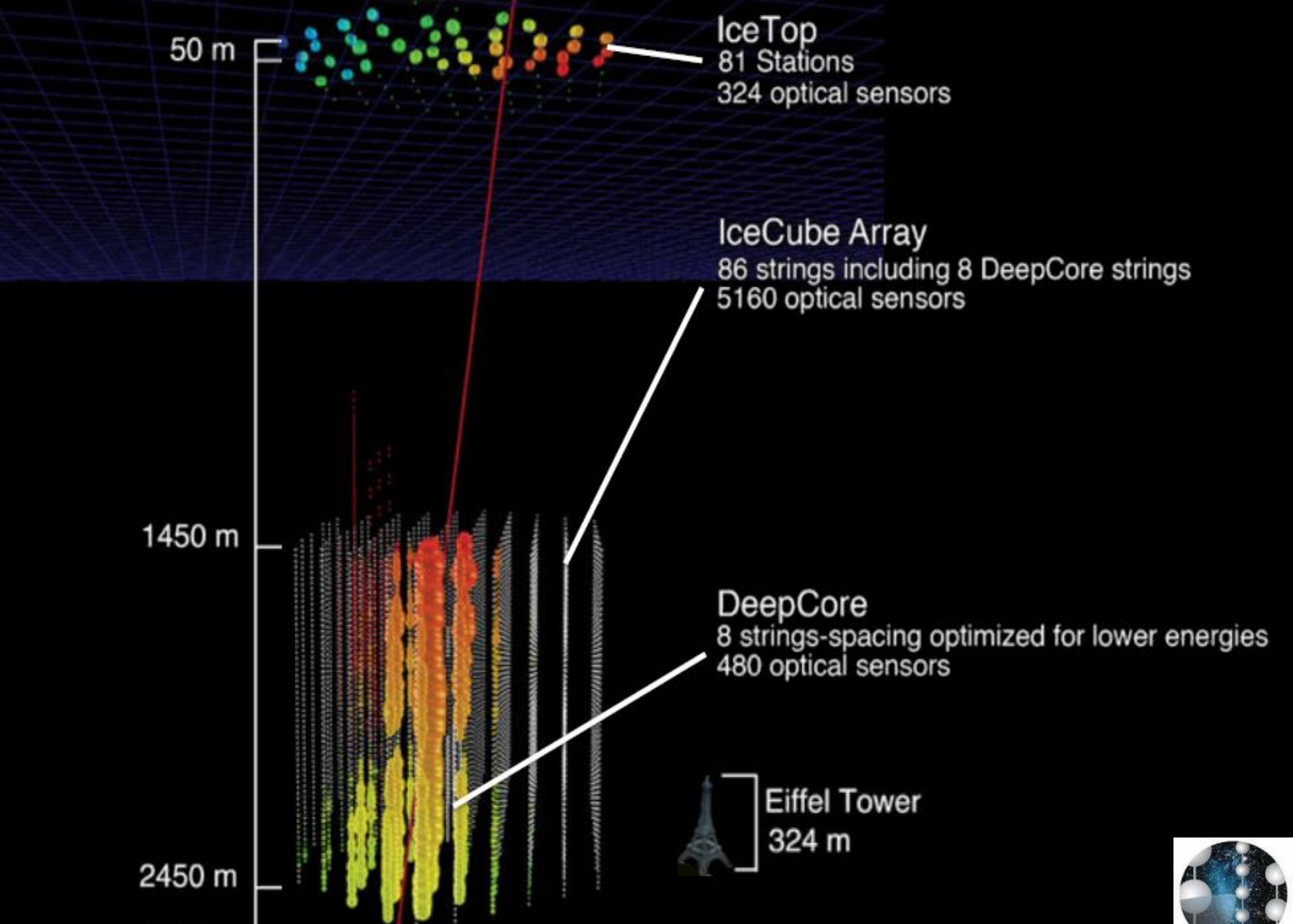
✓86 strings
✓2010: 79 Strings
✓2009: 59 Strings
✓2008: 40 Strings

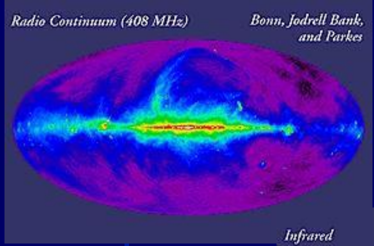


InIce

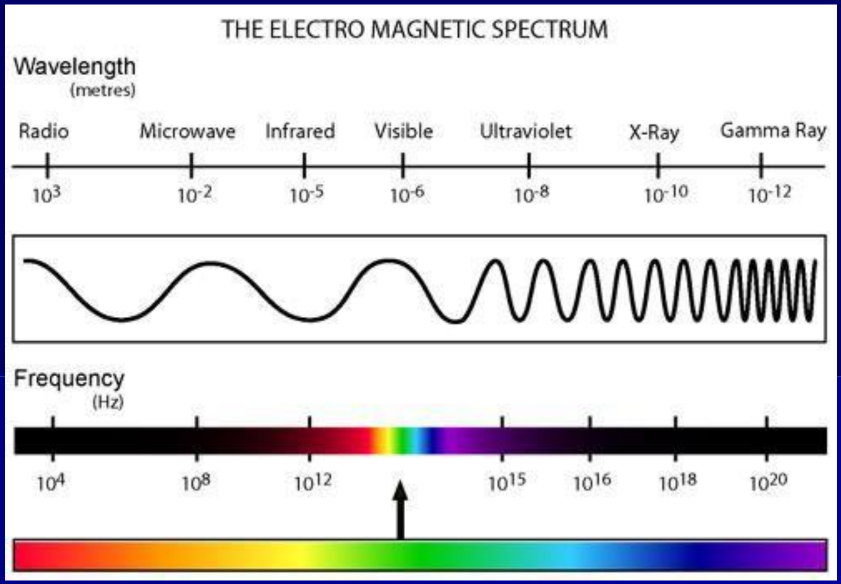
86 Strings, 60 Optical Modules per String

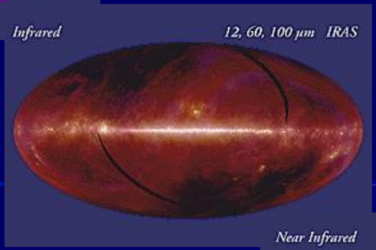
DeepCore

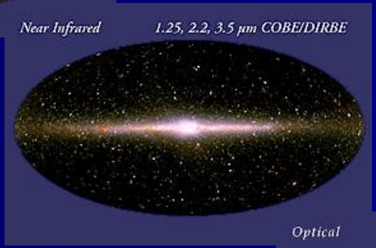

IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m

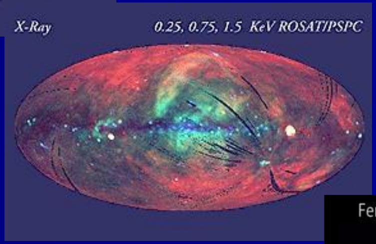


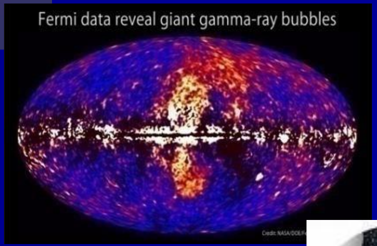
Observing the Universe





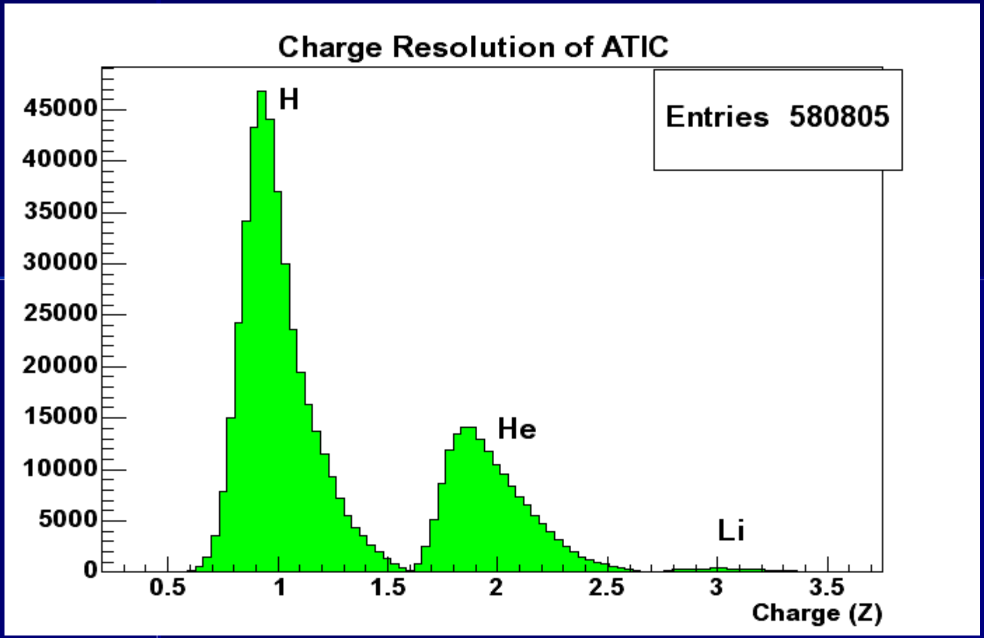


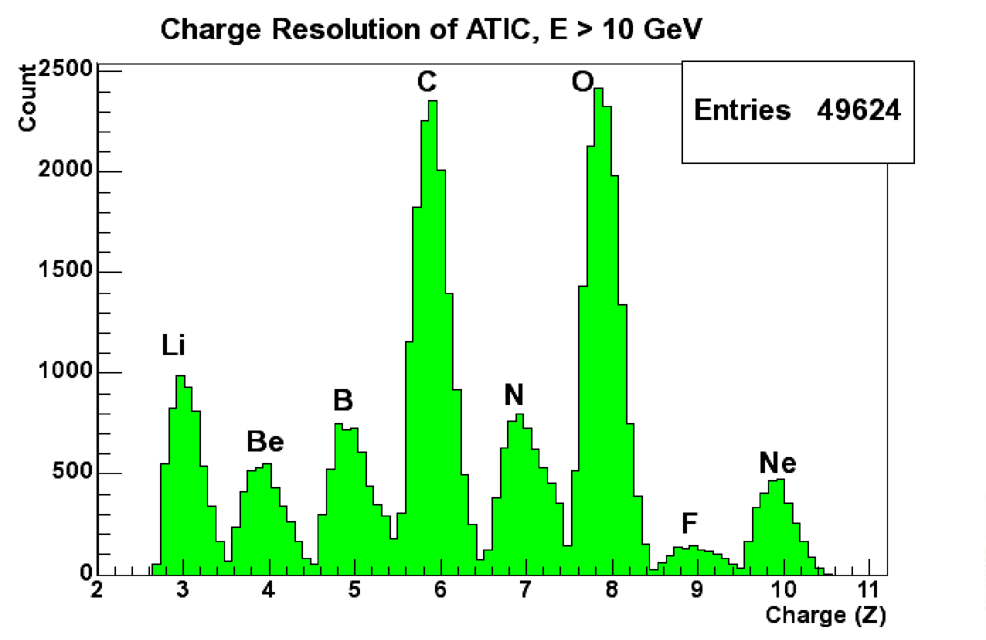




http://mwmw.gsfc.nasa.gov/mmw_allsky.html

Observing the Universe





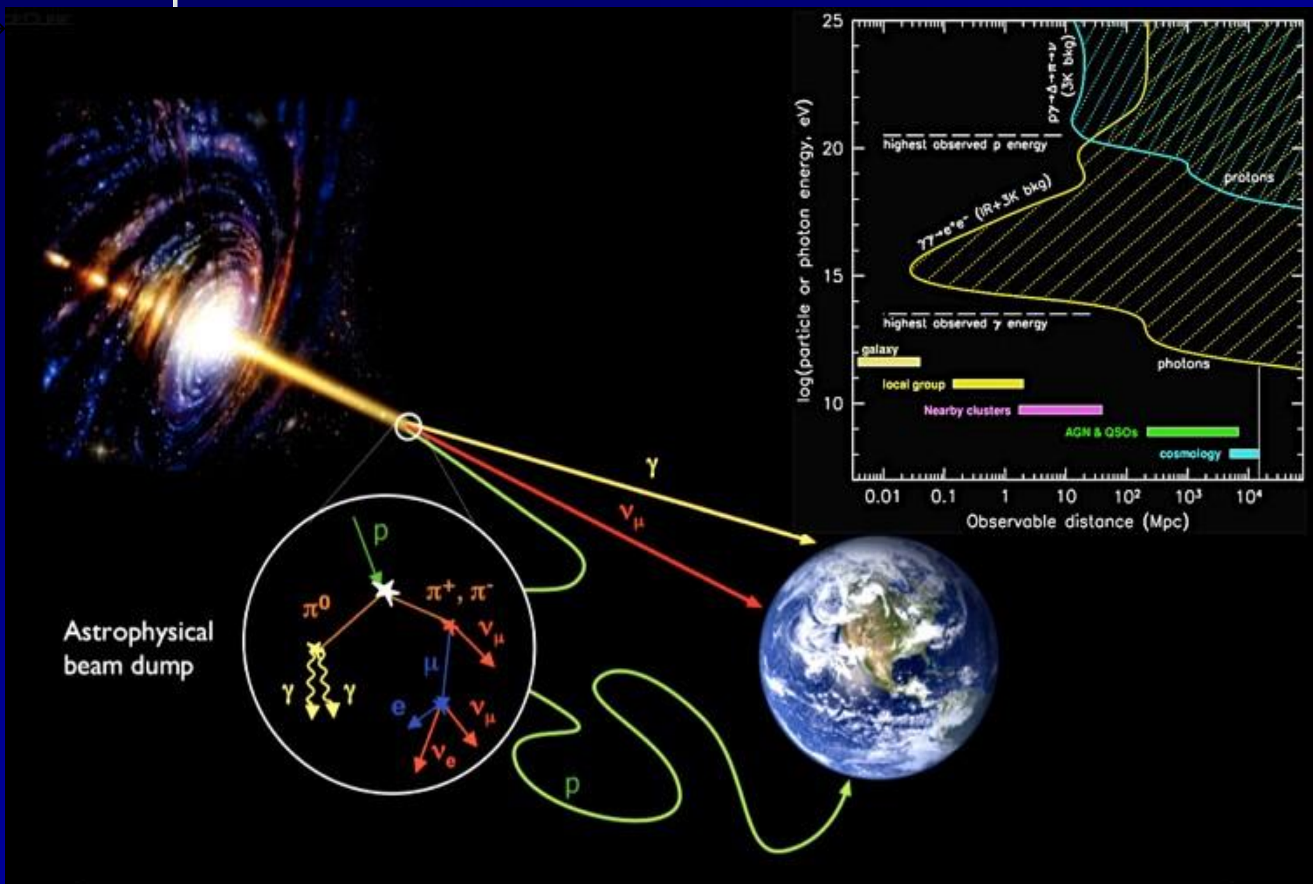
Nuclei are easy to detect with balloon and satellites. Lack directional information and limited to sub-PeV energies.

A.R. Fazely, et al.,
28^{th} International Cosmic Ray Conference, Tsukuba, Japan (2003)

Neutrinos as Cosmic Messengers

$$p + \gamma\,(CMB) \rightarrow \Delta^{+} \rightarrow n + \pi^{+} \rightarrow \nu_{\mu} + \mu^{+}$$

$$\hookrightarrow p + e^{-} + \nu_{e} \qquad \hookrightarrow \nu_{\mu} + \nu_{e} + e^{+}$$



p ***Protons:*** **deflected by magnetic fields.**

γ ***Photons:*** **easily absorbed by CMB backgrounds.**

ν ***Neutrinos:*** **not deflected by magnetic fields. Low interaction cross-section.**

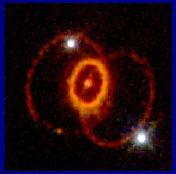
Slow History of Neutrinos!

1930 Pauli proposes Neutrinos

1956, Reines and Cowan discovery of neutrinos

1967, Davis Solar Neutrinos and their deficits

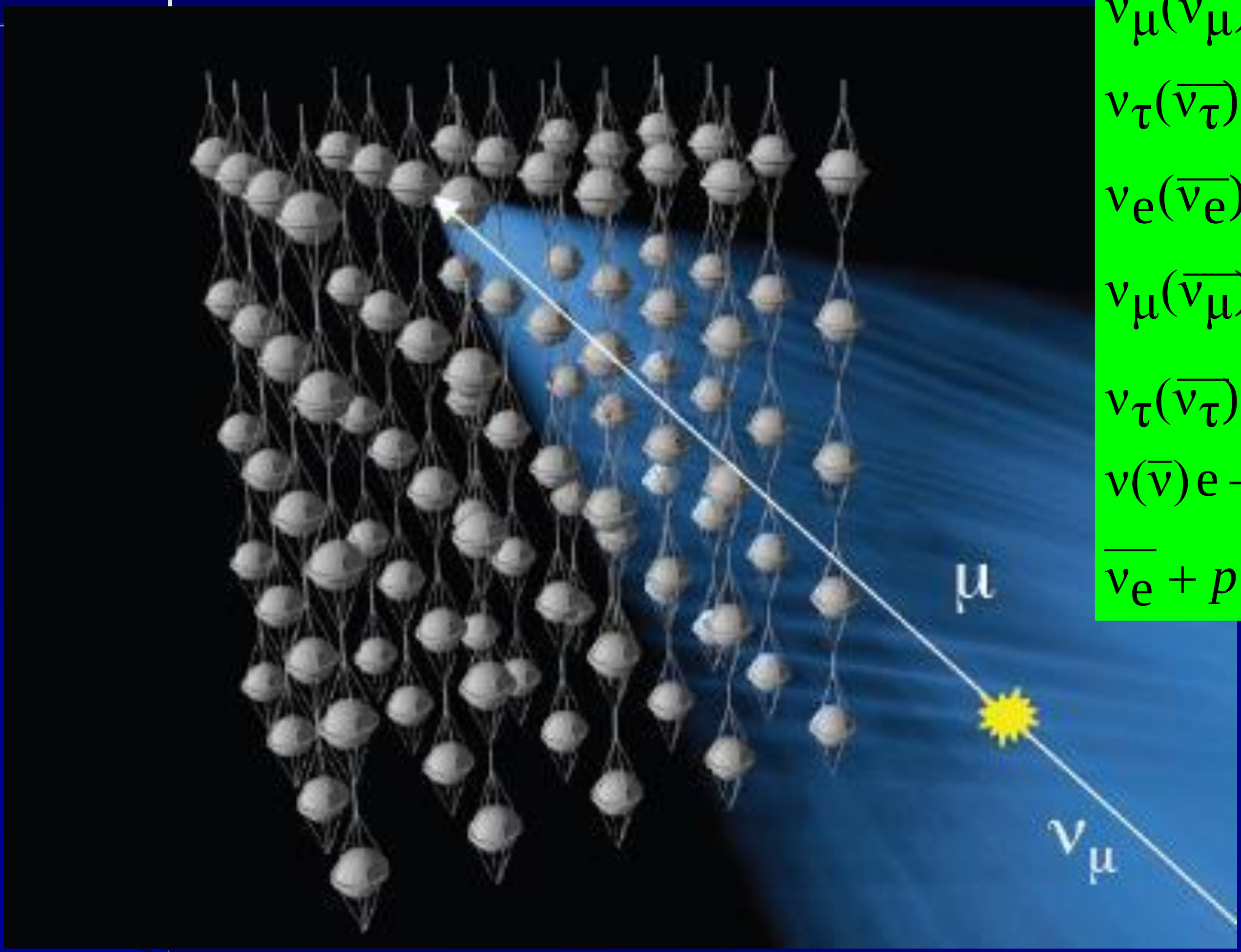
1987 Supernova IMB, Kamioka



1998 Neutrino Oscillations, Super-K

2013 Dawn of Neutrino Astronomy

Neutrino interactions



$$\nu_e(\overline{\nu_e}) + {}^{16}O \rightarrow e\,(e^+) + X \quad (CC)$$

$$\nu_\mu(\overline{\nu_\mu}) + {}^{16}O \rightarrow \mu(\mu^+) + X \quad (CC)$$

$$\nu_\tau(\overline{\nu_\tau}) + {}^{16}O \rightarrow \tau\,(\tau^+) + X \quad (CC)$$

$$\nu_e(\overline{\nu_e}) + {}^{16}O \rightarrow \nu_e(\overline{\nu_e}) + X \quad (NC)$$

$$\nu_\mu(\overline{\nu_\mu}) + {}^{16}O \rightarrow \nu_\mu(\overline{\nu_\mu}) + X \quad (NC)$$

$$\nu_\tau(\overline{\nu_\tau}) + {}^{16}O \rightarrow \nu_\tau(\overline{\nu_\tau}) + X \quad (NC)$$

$$\nu(\bar{\nu})\,e \rightarrow \nu(\bar{\nu})\,e(CC, NC)$$

$$\overline{\nu_e} + p \rightarrow e^+ + n, \; Supernova(CC)$$

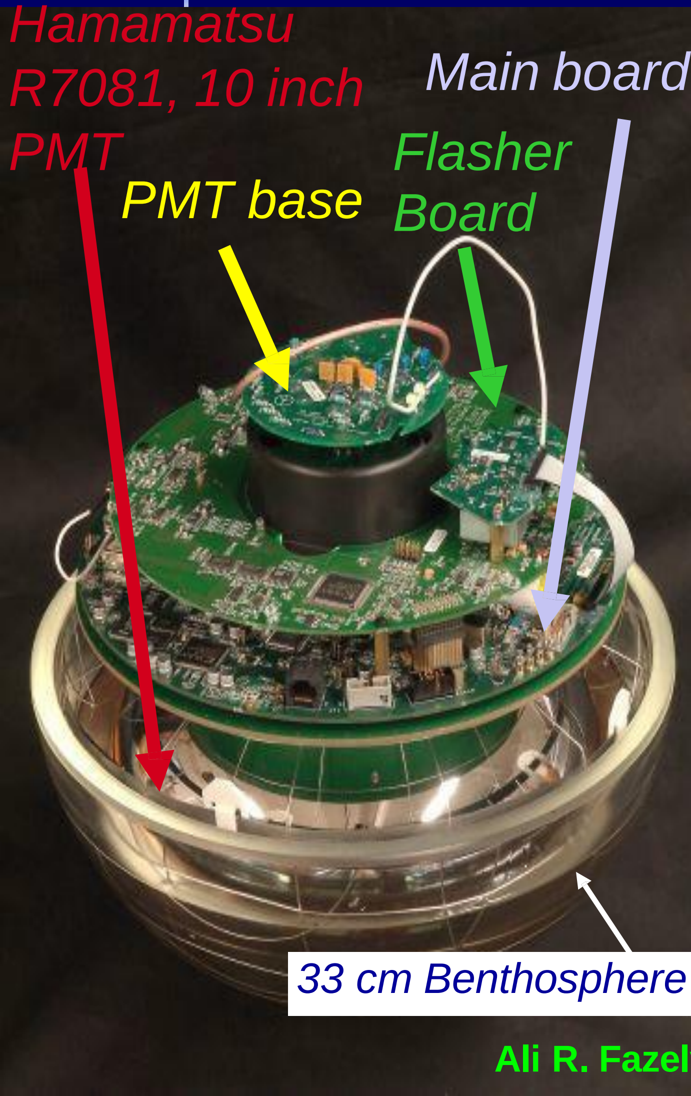
Digital Optical Module

IceCube

Sensing Neutrino Light

IceCube "Digital Optical Module" (DOM)

Power consumption: 3W

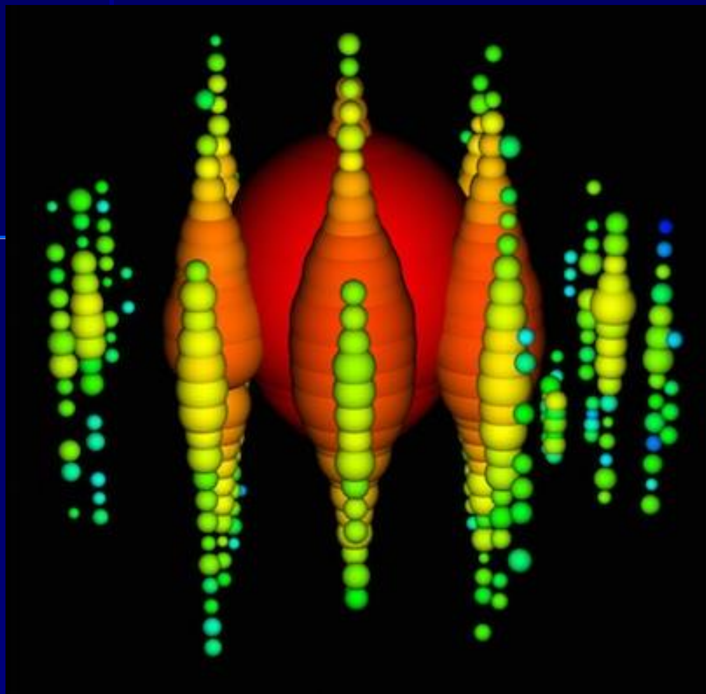


- Measure arrival time of every photon
- 2x 300MHz waveform digitizers
- 1x 40 MHz FADC digitizer
- Can trigger in coincidence w/ neighbor DOM
- Transmits data to surface on request
- Data sent over 3.3 km twisted pair copper cable
- Knows the time to within 3 nanoseconds to all other DOMs in the ice

Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized periodically to precision of O(2 nsec)

IceCube Construction

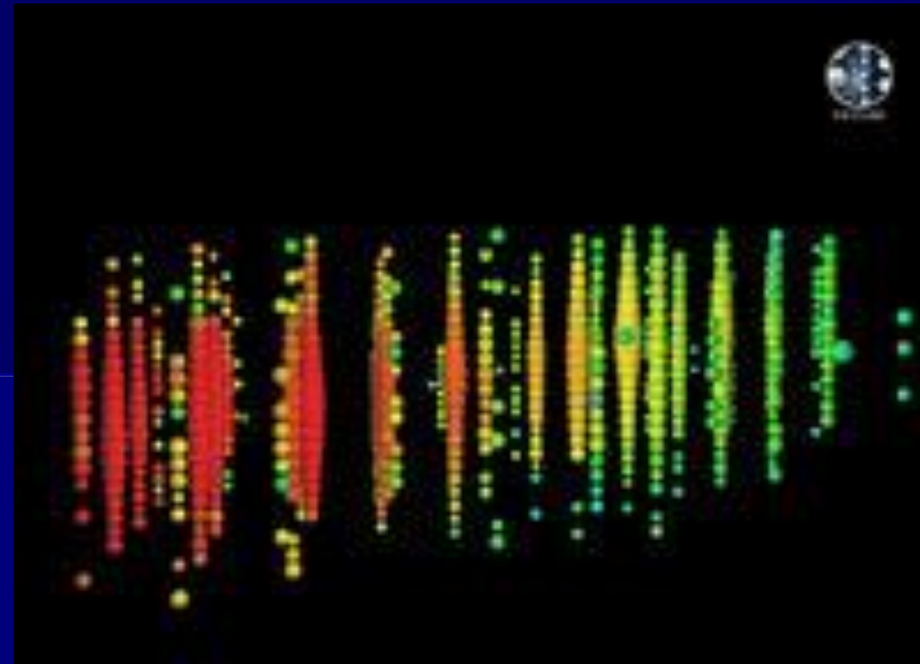
Event Topologies



ν_e data (Big Bird, 2.2 PeV)

Energy resolution ≈ 15% E(vis)

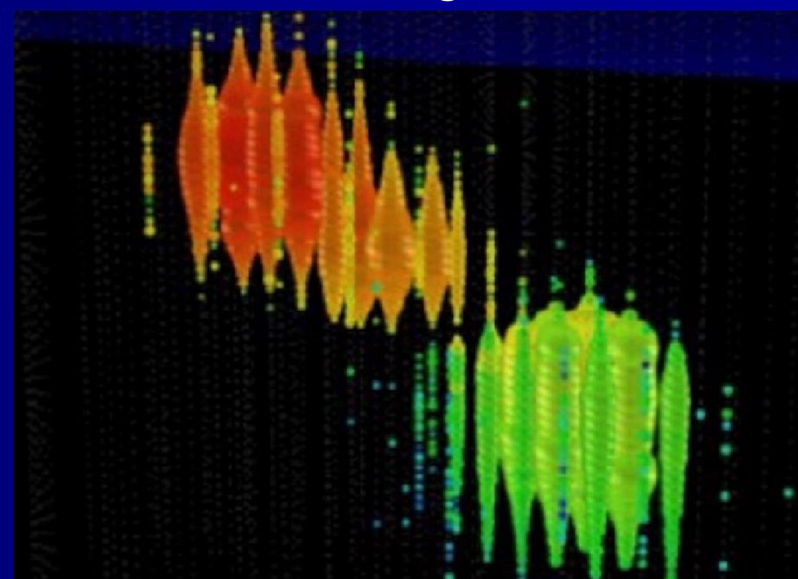
Angular resolution ≈ 10°



ν_μ data (466 TeV)

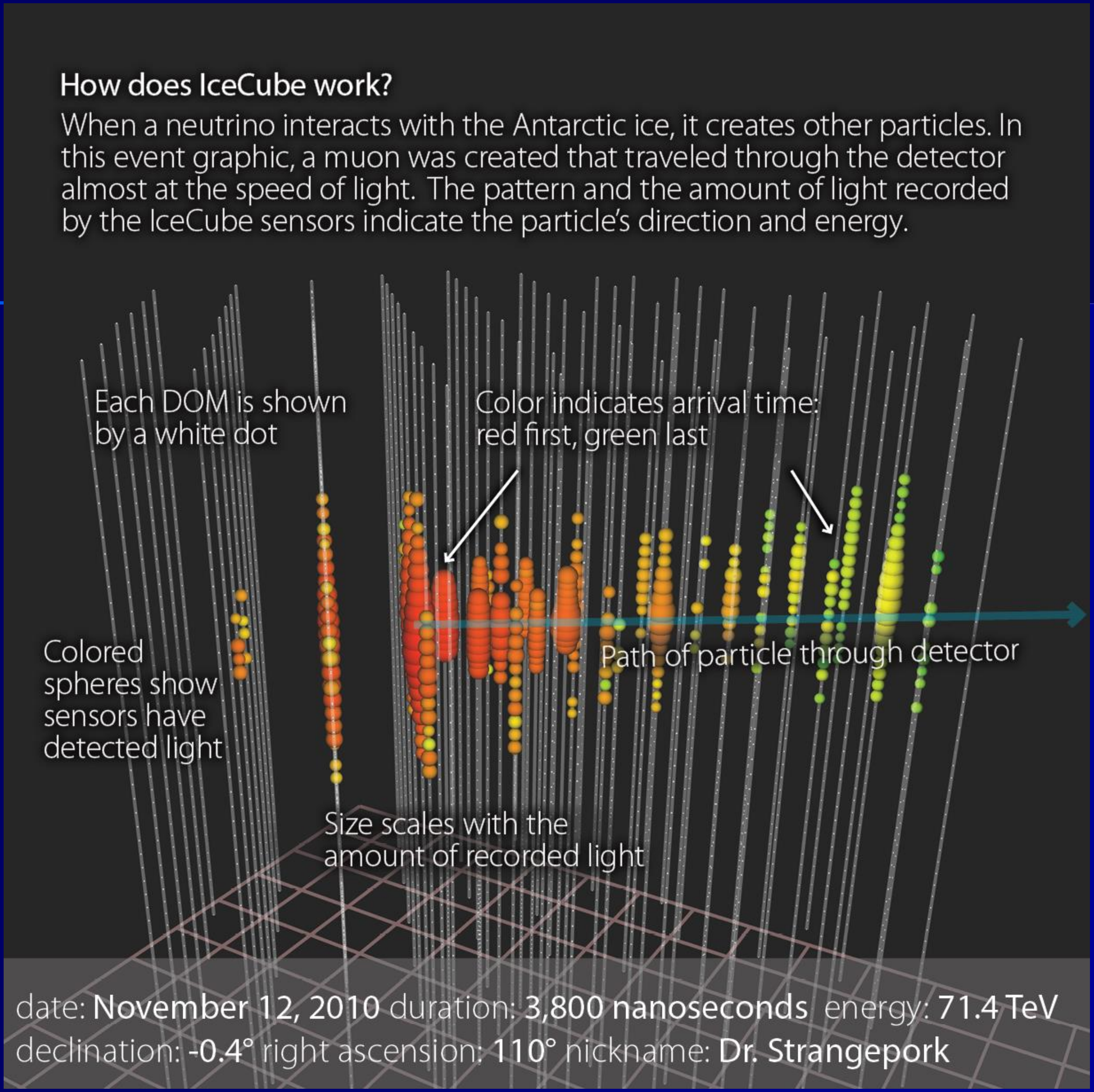
Energy resolution ≈ 2 x E(vis)

Angular resolution <1°

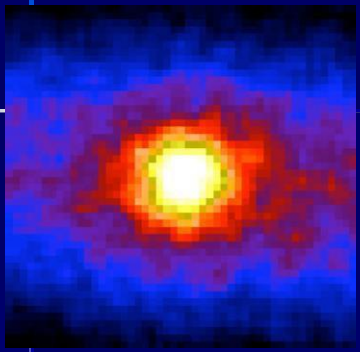


ν_τ simulation (16 PeV)

IceCube

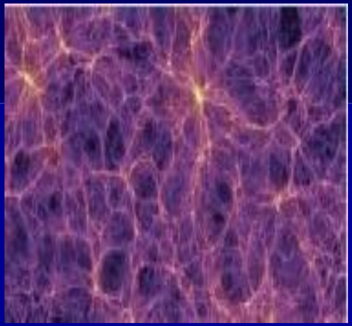

How does IceCube work?
When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle's direction and energy.
Each DOM is shown by a white dot
Color indicates arrival time: red first, green last
Colored spheres show sensors have detected light
Path of particle through detector
Size scales with the amount of recorded light
date: November 12, 2010 duration: 3,800 nanoseconds energy: 71.4 TeV
declination: -0.4° right ascension: 110° nickname: Dr. Strangepork

Possible ET Neutrino Sources

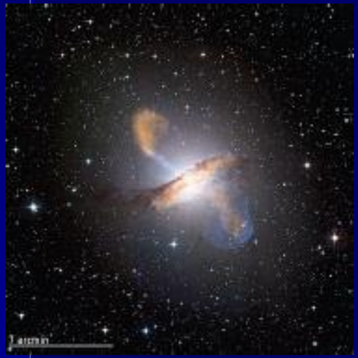


Solar Neutrinos

Supernova 1987A

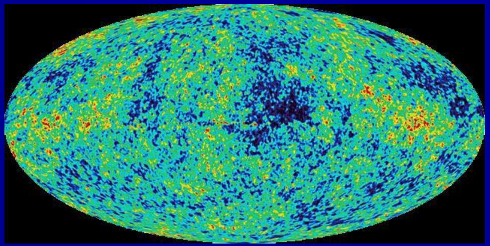


Dark Matter?



Active Galactic Nuclei

Gamma Ray Bursts

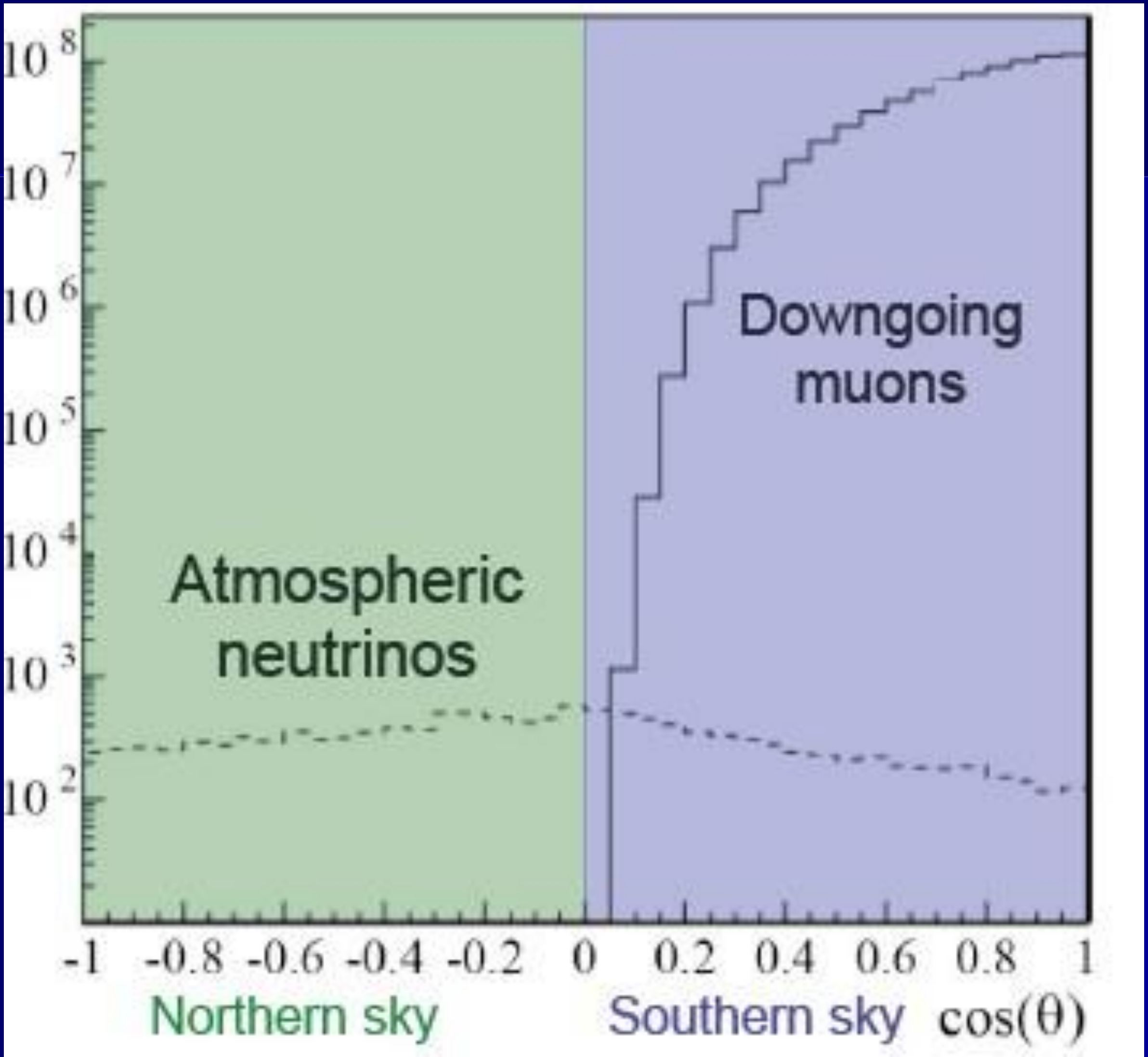


Cosmogenic Neutrinos

Backgrounds

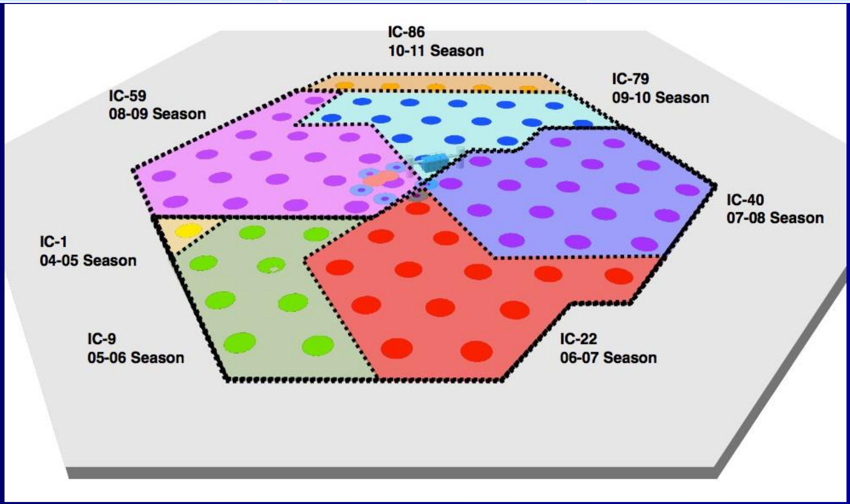
The majority of triggers in IceCube are from atmospheric muons

We record over 6×10^9 muons and 74,000 atmospheric muon neutrinos per year.



IceCube History and Rates

Configuration	Date	Livetime	μ-rate (Hz)	ν-rate/day
AMANDA(19)	2000-06	3.8 years	100	5
IC9	2006	137 days	80	1.7
IC22	2007	275 days	600	28
IC40	2008-09	376 days	1100	38
IC59	2009-10	348 days	1900	125
IC79-DC6	2010-11	1.0 year	2250	170
IC86-DC8	5/2011-present		2700	190



Atmospheric Neutrinos

•Main Background to Astrophysical Search

•Created by high energy cosmic rays colliding w

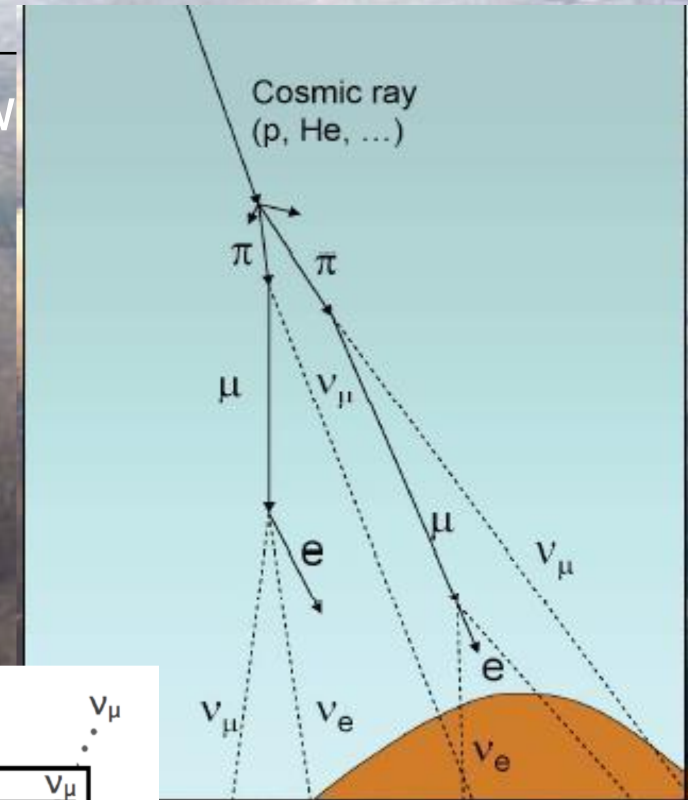
O and N in the Earth's atmosphere

•Conventional (Pions & Kaons) vs. Prompt

(Charmed Mesons)

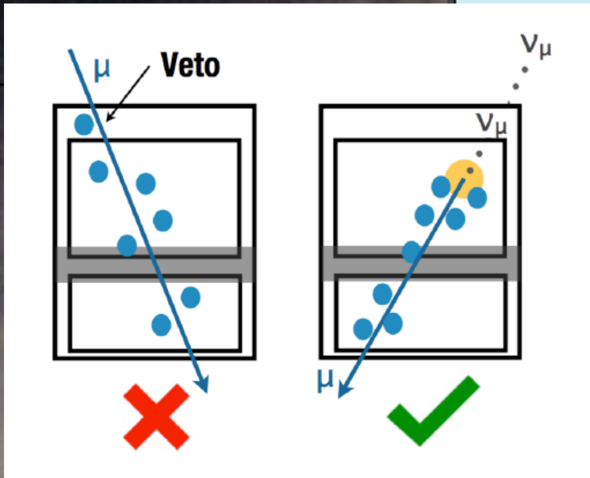
•Conventional ~ $E^{-3.7}$ Spectrum

•Prompt ~ $E^{-2.7}$ Spectrum



$$p + \mathrm{O}N \rightarrow \pi^+, K^+, D^+, \text{etc.}$$

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

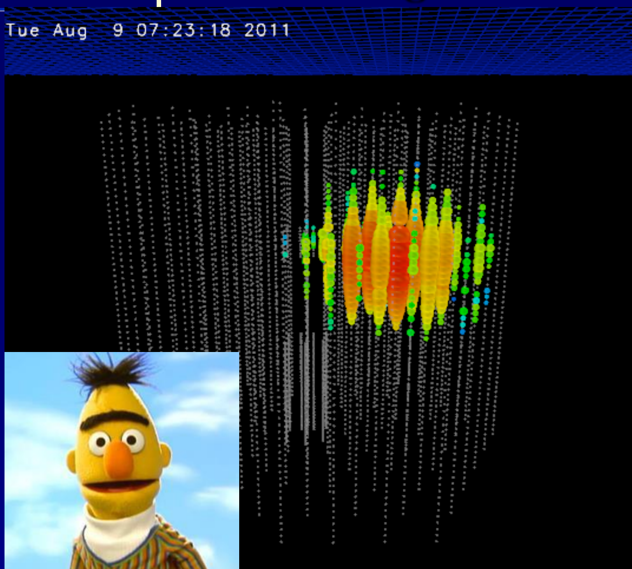


Observation of Highest Energy Neutrinos Dubbed "Bert, Ernie & Big Bird".

(PRL 111 021103 2013)

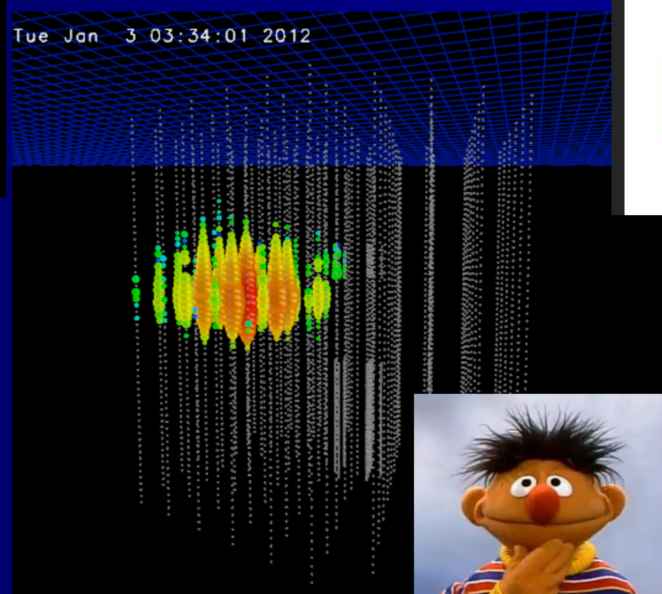
$\nu_e CC$ on nuclei or electrons or ν_x NC on nuclei and electrons

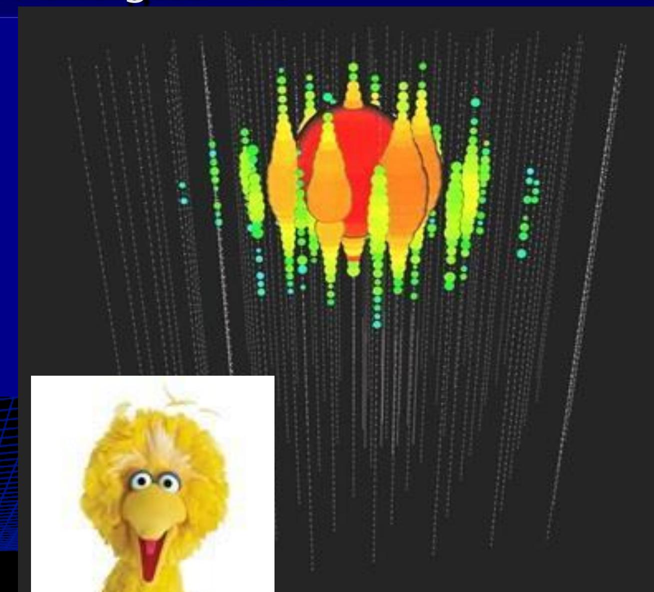
Angular resolution on cascade events at these energies ~10°



Aug., 9th, 2011
Run 118545
-Event 63733662
NPE: 7.0 x 10^4
NDOM: 354
1.04±0.16 PeV

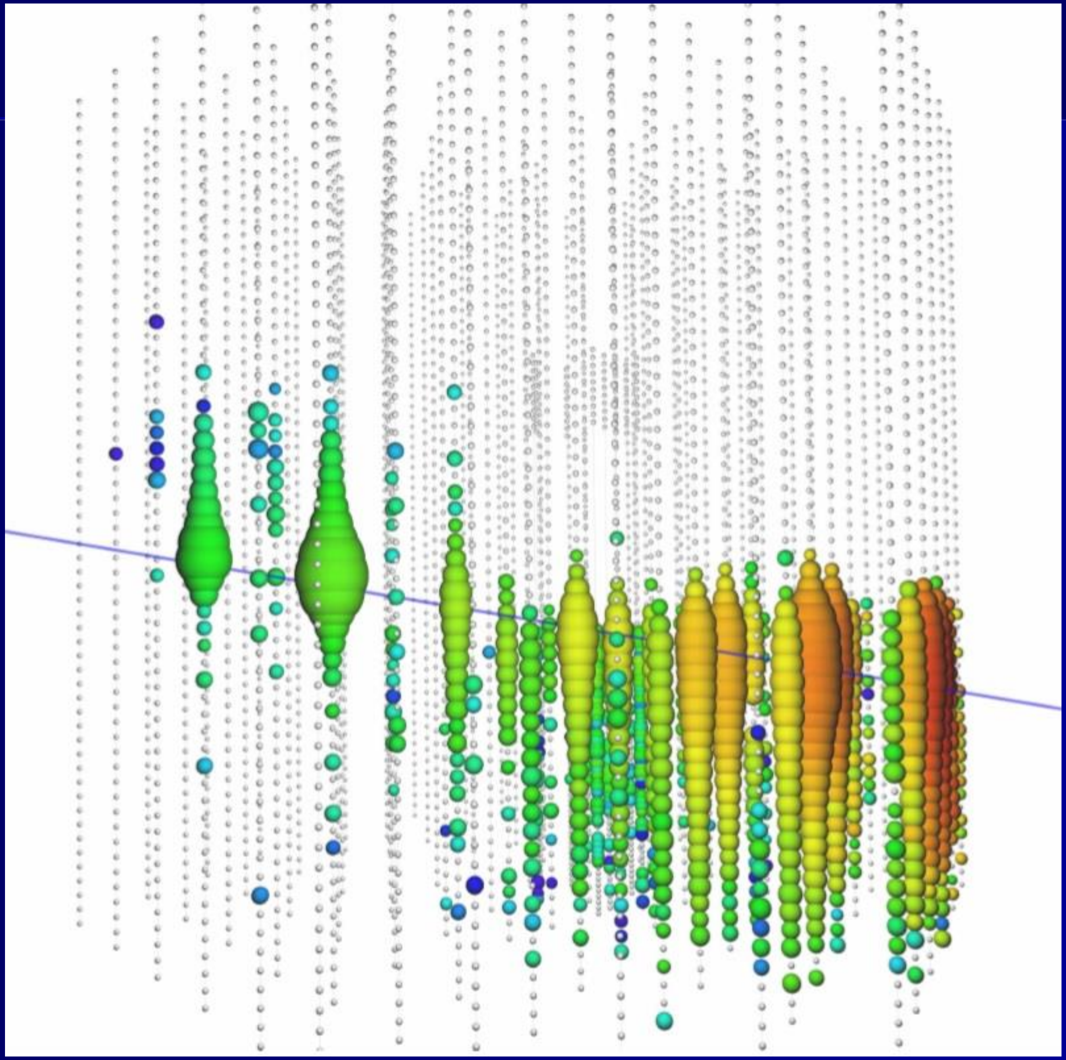
Jan, 3rd, 2012
Run 119316
-Event 36556705
NPE: 9.6 x 10^4
NDOM: 312
1.14±0.17 PeV





Dec, 4th, 2012
2.2± PeV

Observation of Highest Energy Neutrinos
2.6 ± 0.3 PeV, observed June 11, 2014
(ICRC 2015, July 30 to August 6, 2015, The Hague, The Netherlands.)



Ali R. Fazely, Miami Conference, December 14 -20, 2016

IceCube

Backgrounds for "Bert & Ernie"

Background Source	Contribution Level (~ 616 days)
Atmospheric Muons	0.038 ± 0.004
Neutrinos from pion and Kaon Decay	0.012 ± 0.001
Prompt Neutrinos from Charm Production *	0.033 ± 0.001
Total	0.082 ± 0.001

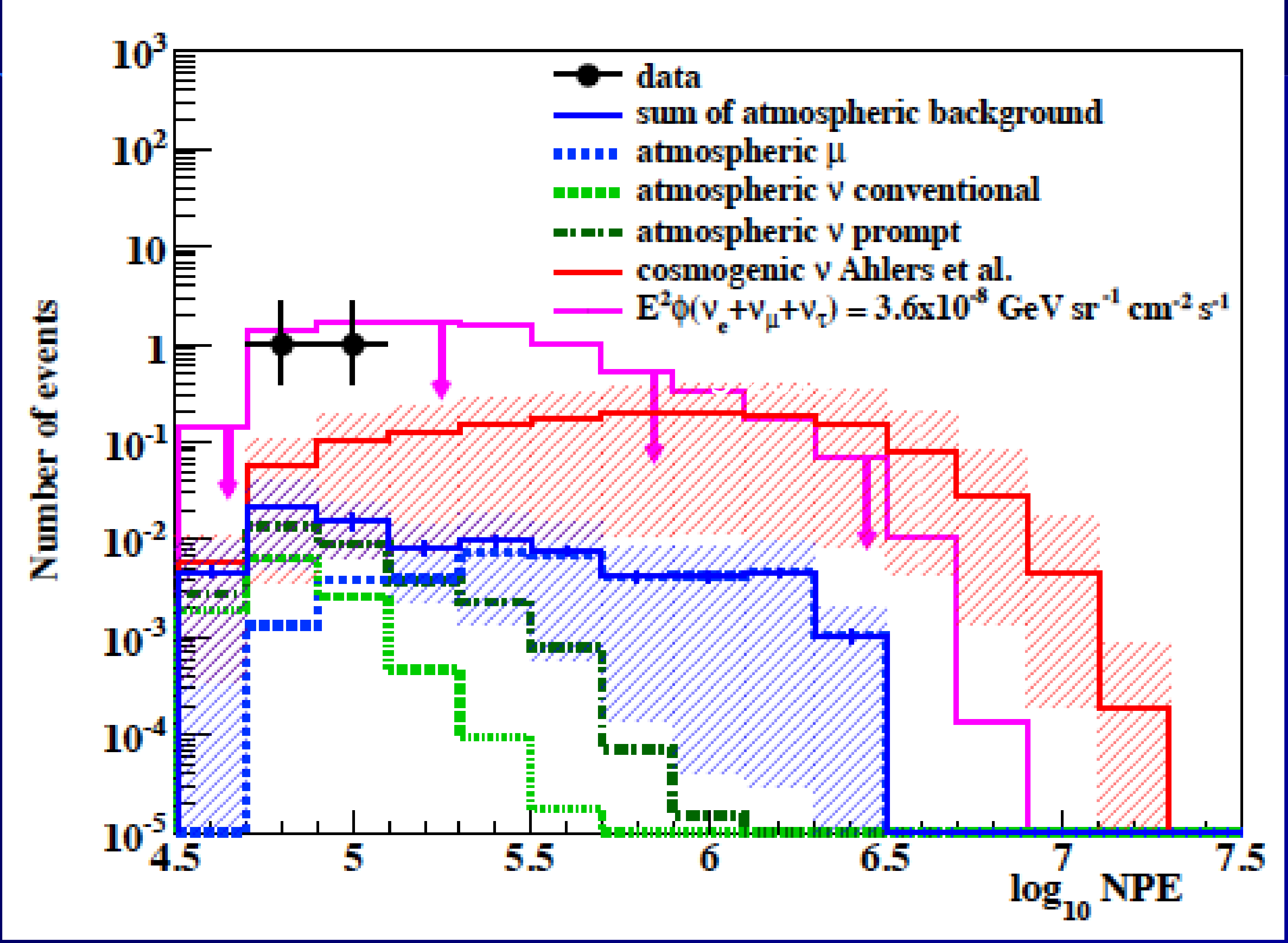
* R. Enberg, et al., PRD078 043005 (2008)

Significance = 2.8σ

IceCube

NPE Distributions

(PRL 111 021103 2013)



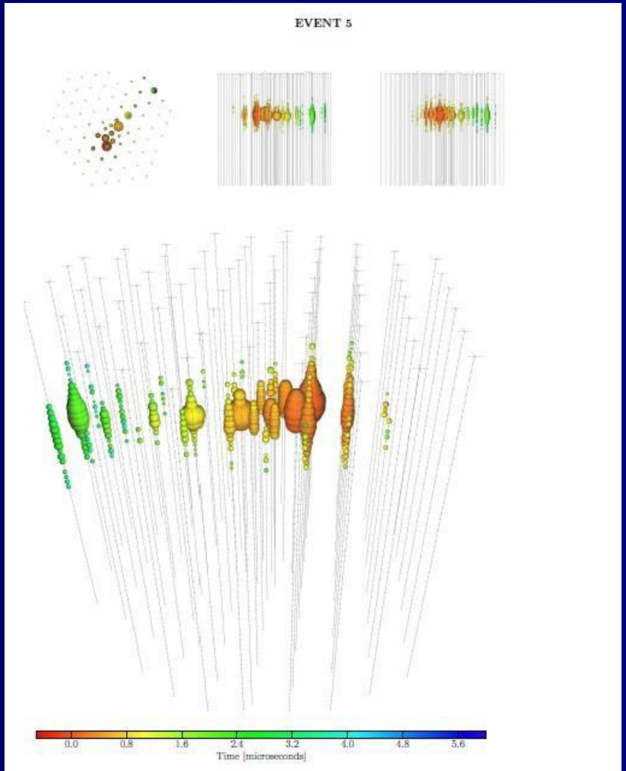
IceCube

Results

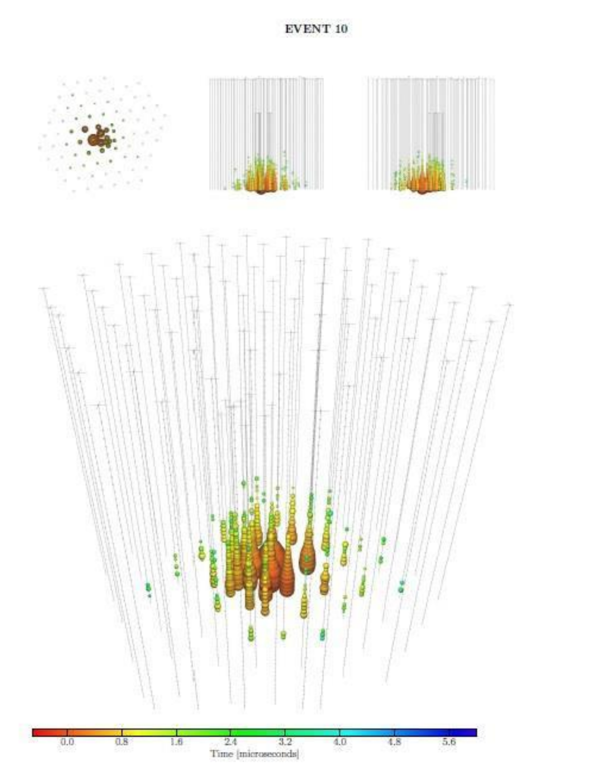
IceCube: Science 22 Vol. 342 no. 6161 (2013), Phys. Rev. Lett.113 (2014) 101101

Physics Cuts

1) PMT charge, Q > 6000 p.e., contained events within detector fiducial volume
2) Accept both tracks and cascades
3) Veto background atmospheric μ and neutrinos
4) 60 TeV < Edep < 3 PeV



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$71.4^{+9.0}_{-9.0}$	55512.5516214	−0.4	110.6	$\lesssim 1.2$	Track



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$97.2^{+10.4}_{-12.4}$	55695.2730442	−29.4	5.0	8.1	Shower

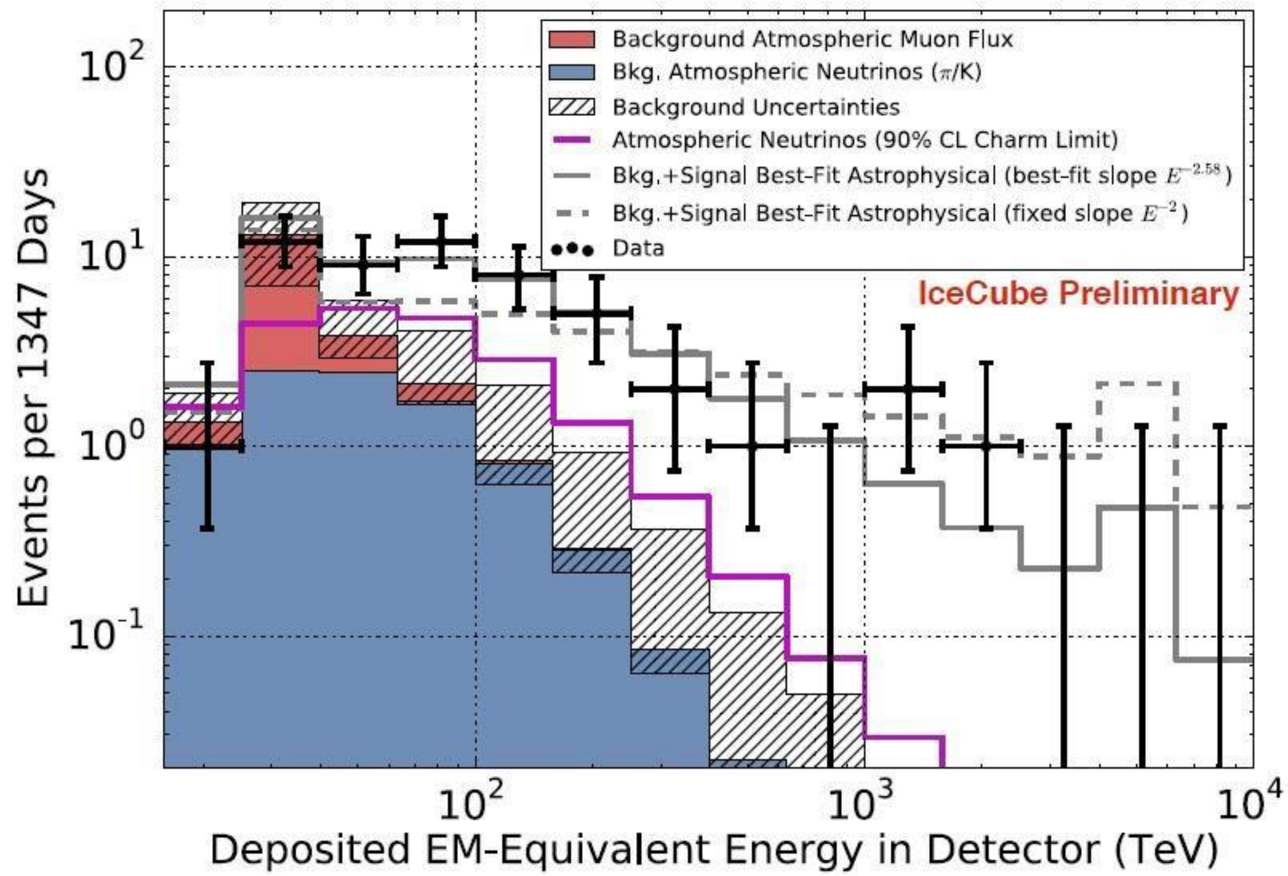
IceCube

High-Energy Extraterrestrial Neutrinos in the IceCube Detector

54 events, (15 tracked, 39 cascades) observed.

Backgrounds are disfavored at a Significance of 7σ

ICRC 2015, 4 years of data
arxiv.org/pdf/1510.05223v2



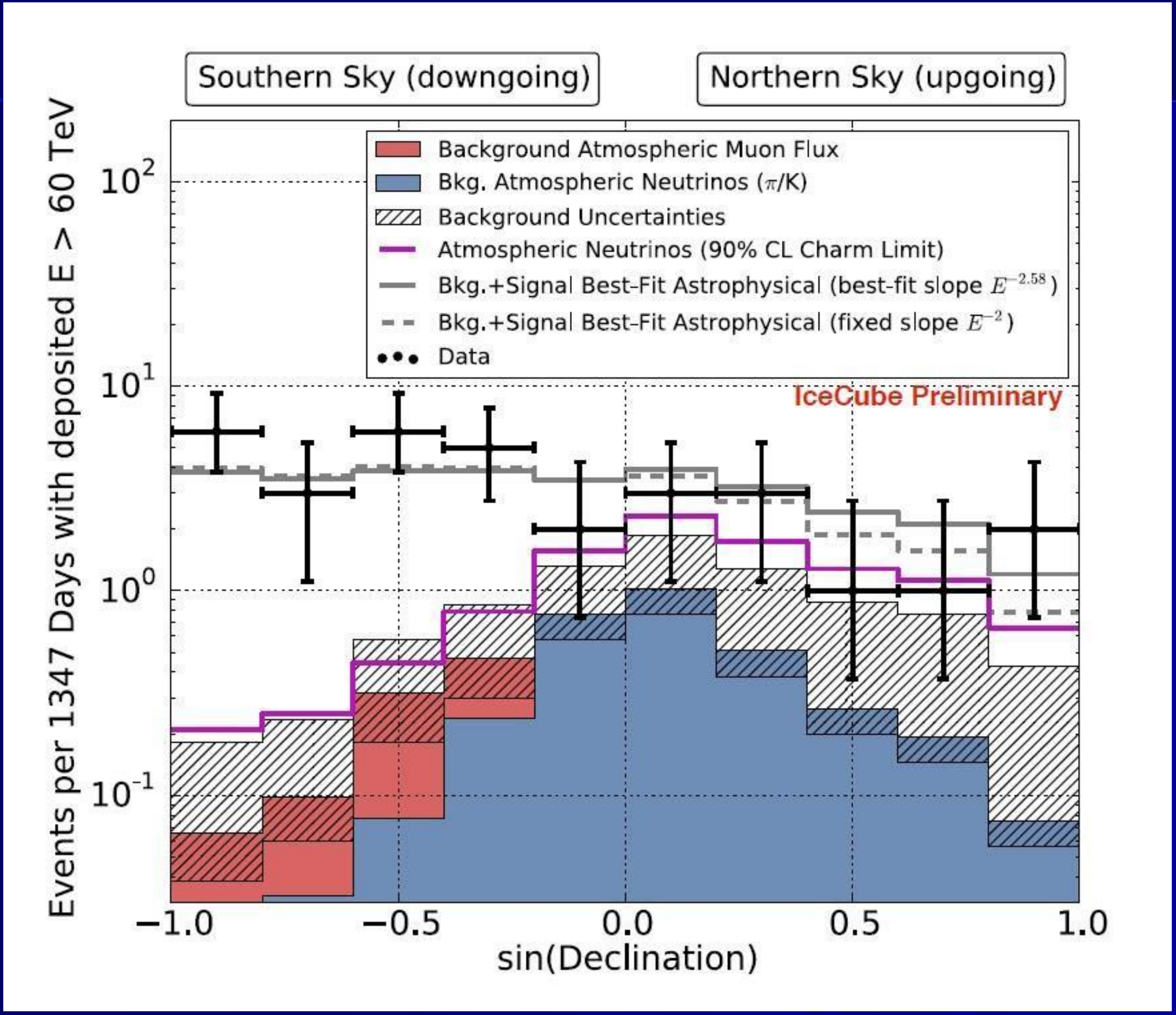
$$E^2\Phi(E) = 0.84 \pm 0.3 \times 10^{-8} \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

IceCube

Results, Declination

ICRC 2015, 4 years of data

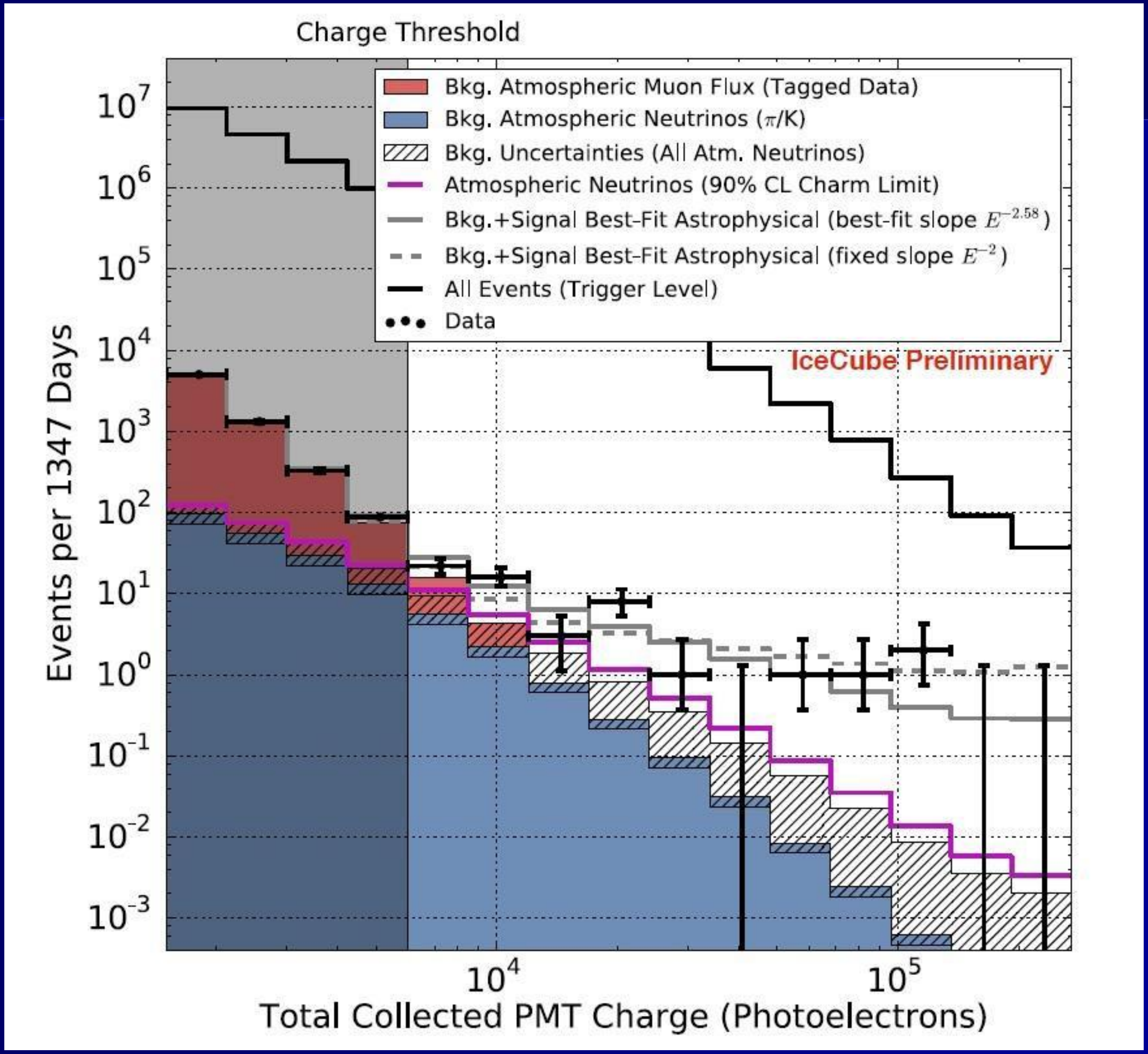
arxiv.org/pdf/1510.05223v2



Results, PMT Charge

ICRC 2015, 4 years of data

arxiv.org/pdf/1510.05223v2

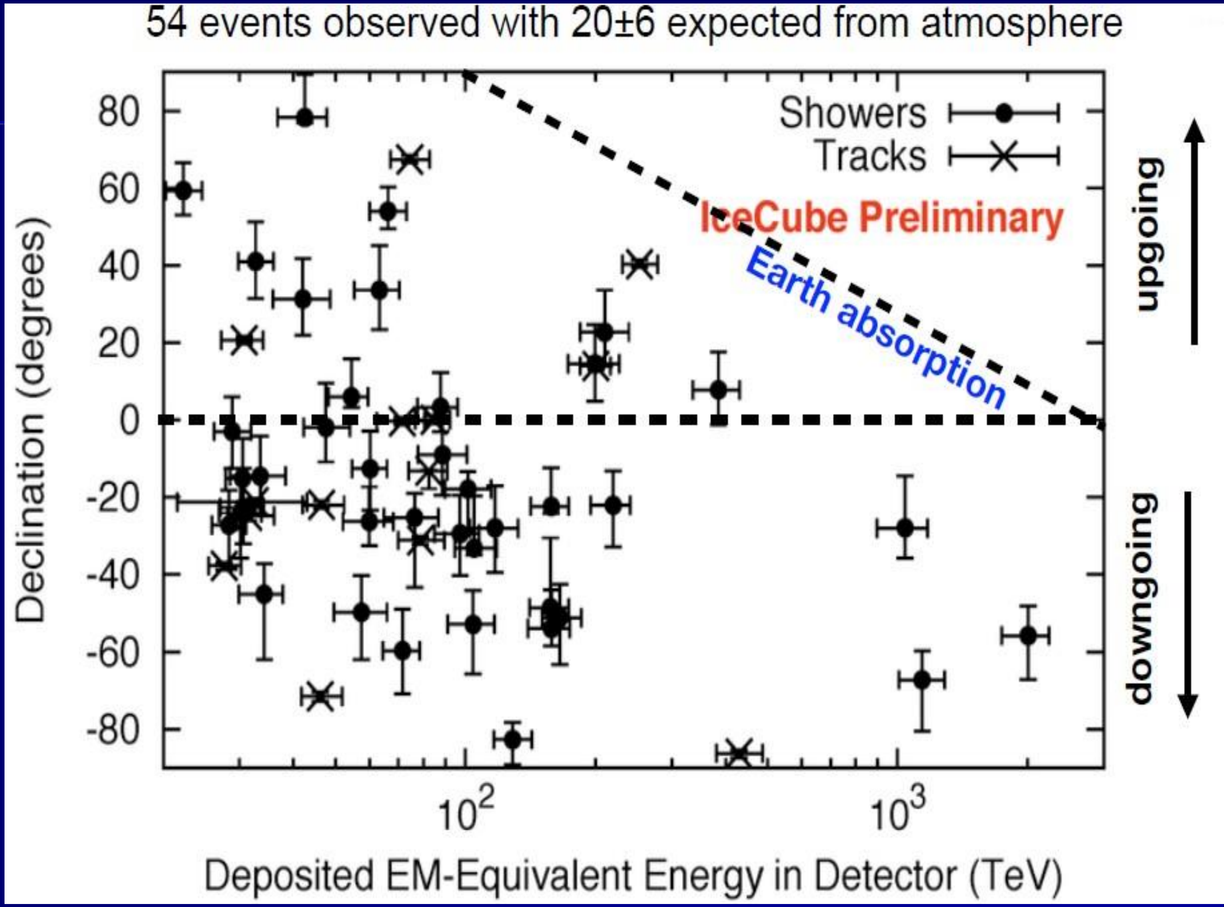


Declination vs. deposited energy

ICRC 2015, 4 years of data
arxiv.org/pdf/1510.05223v2

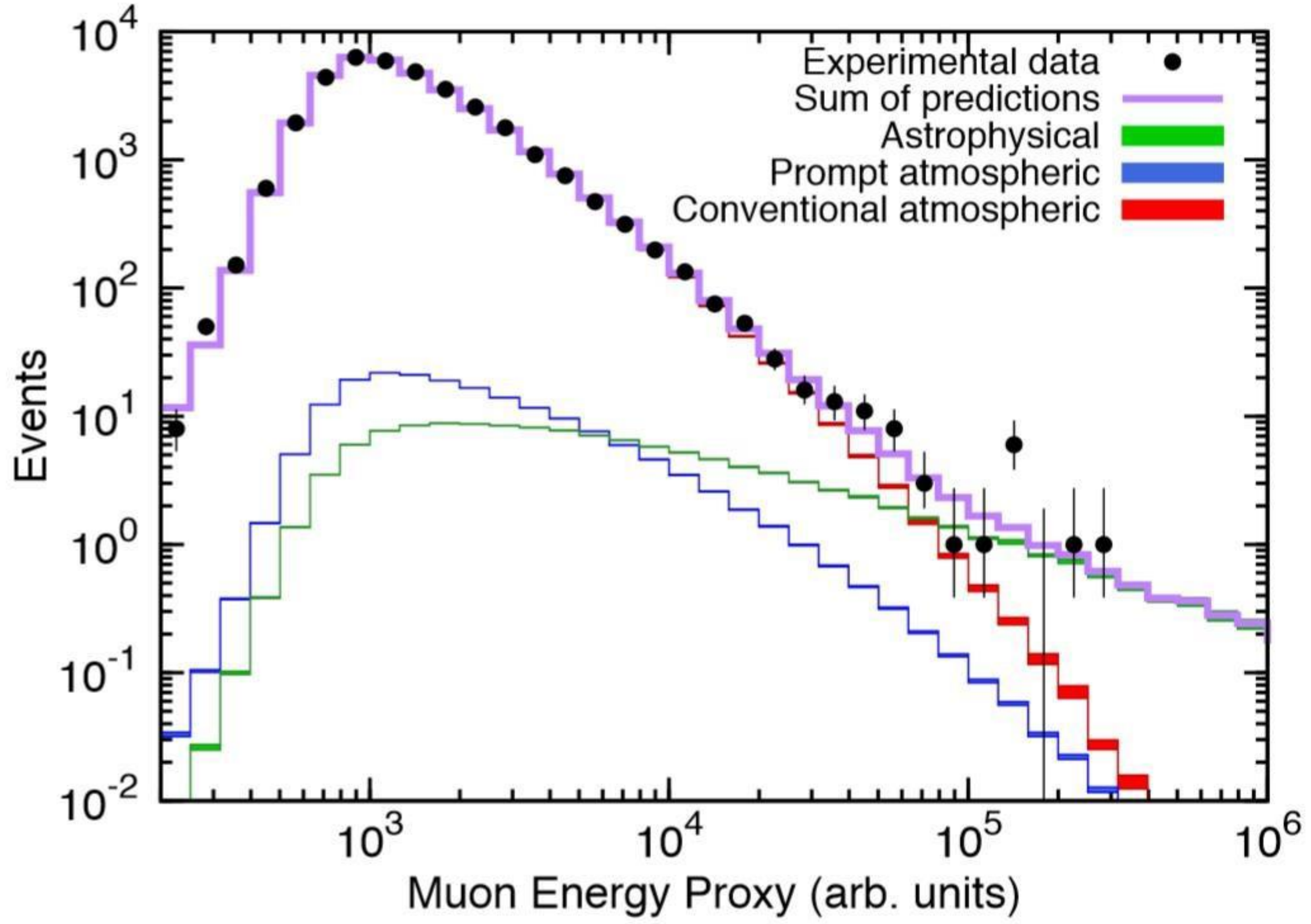
A few observations.

- Signal contains 41 cascades and 13 tracks
- Atmospheric neutrinos: track/cascade = 2
- Most events originate from southern sky because most HE neutrinos from northern sky are absorbed by the Earth
- Excess from the southern sky is not due to atmospheric ν_μ because they are reduced in the south by μ rejection



IceCube

Astrophysical Muon Neutrinos Northern Sky



The distribution of reconstructed muon energy proxy for events sample, compared to the expected distributions for an E^{-2} flux. Significance = 3.7σ

330 TeV<E<1.4 PeV

PRL 115, 081102 (2015)

$$\Phi(E_\nu) = 9.9^{+3.9}_{-3.4} \times 10^{-19}\, \mathrm{GeV}^{-1}\, \mathrm{cm}^{-2}\, \mathrm{sr}^{-1}\, \mathrm{s}^{-1} \left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-2}$$

Likelihood Search for a Point Source
- Test Statistic (TS) Calculation -

Maximize the likelihood L at every point in the sky x

Total # of events = 28

# of events from source Varied to maximize L

$$L(x) = \prod_{i}^{n_{tot}} \left[\frac{n_s}{n_{tot}} \times S_i(x) + \frac{n_{tot} - n_s}{n_{tot}} \times B_i(x) \right]$$

Reconstruction map value at position x from event i

Uniform value for each event at every position

** Events' energies not used in the likelihood*

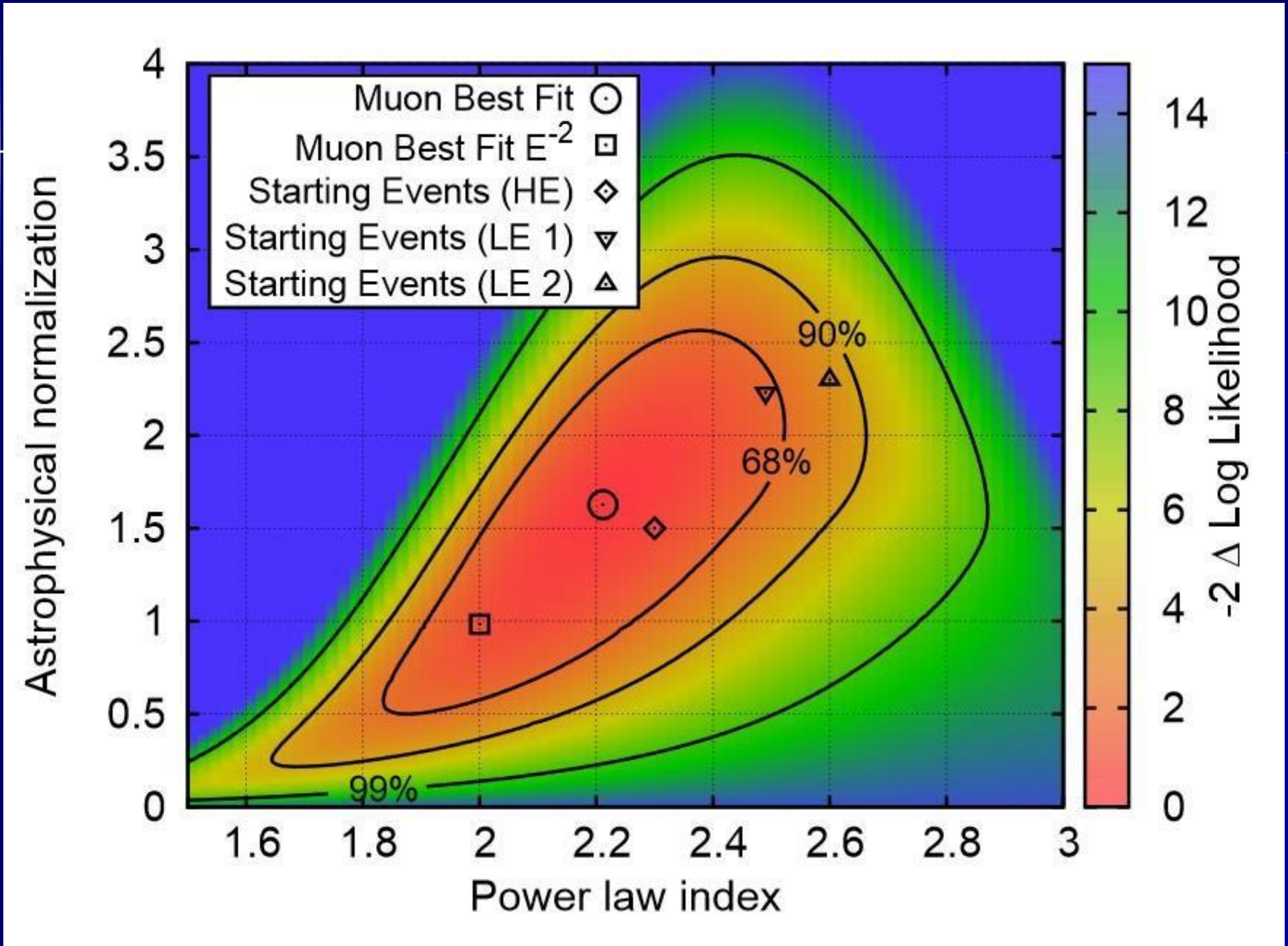
TS is calculated for every point in the sky x

$$TS(x) = 2 \times \log\left(L(x) / L_0(x) \right)$$

where $L_0 = L(x, n_s = 0)$

IceCube

Astrophysical Muon Neutrinos

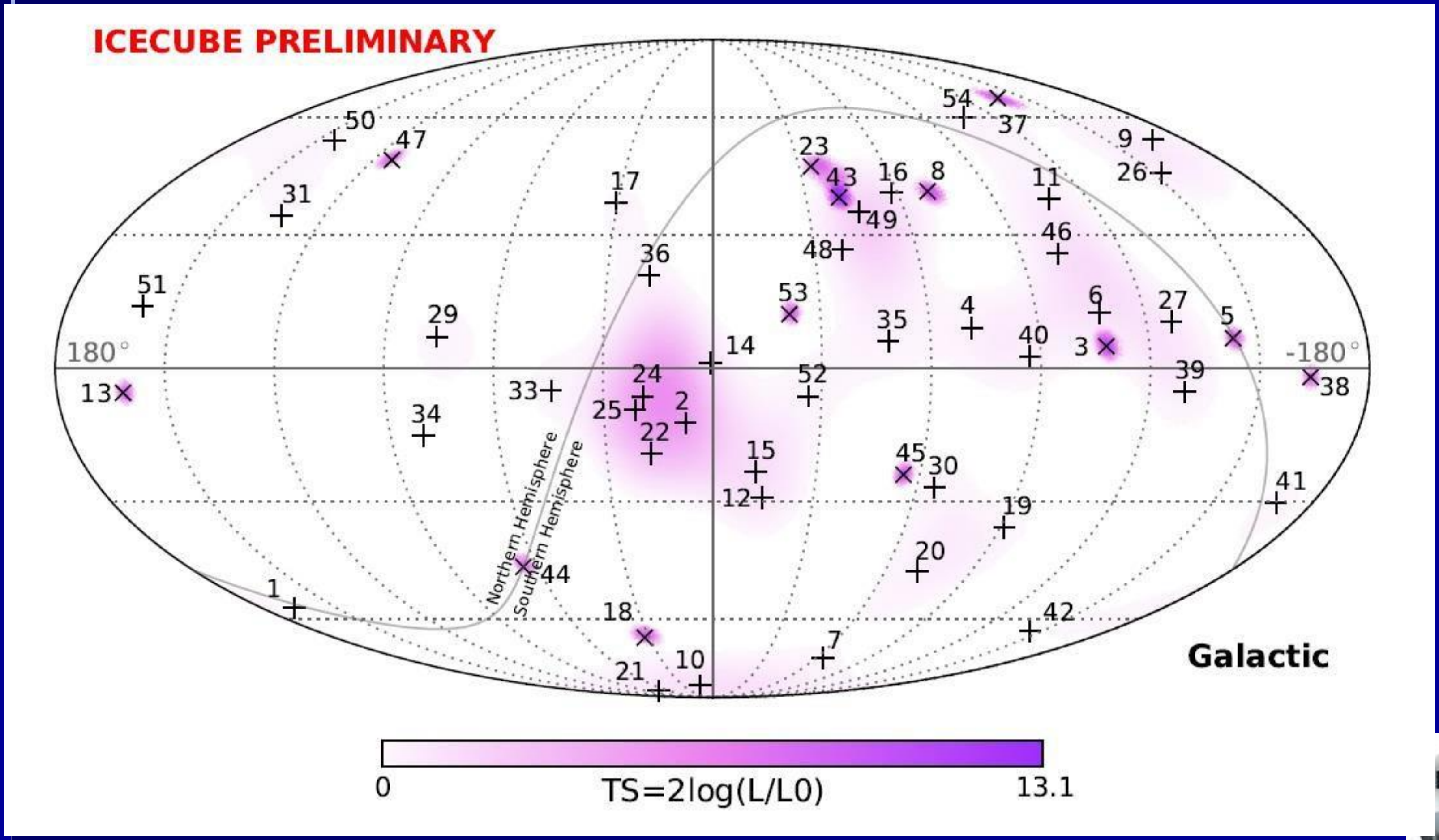


Point Source Analysis

Test null hypothesis vs. most likely
L0: null hypothesis
L: maximized likelihood

x: tracked events
+: cascade events

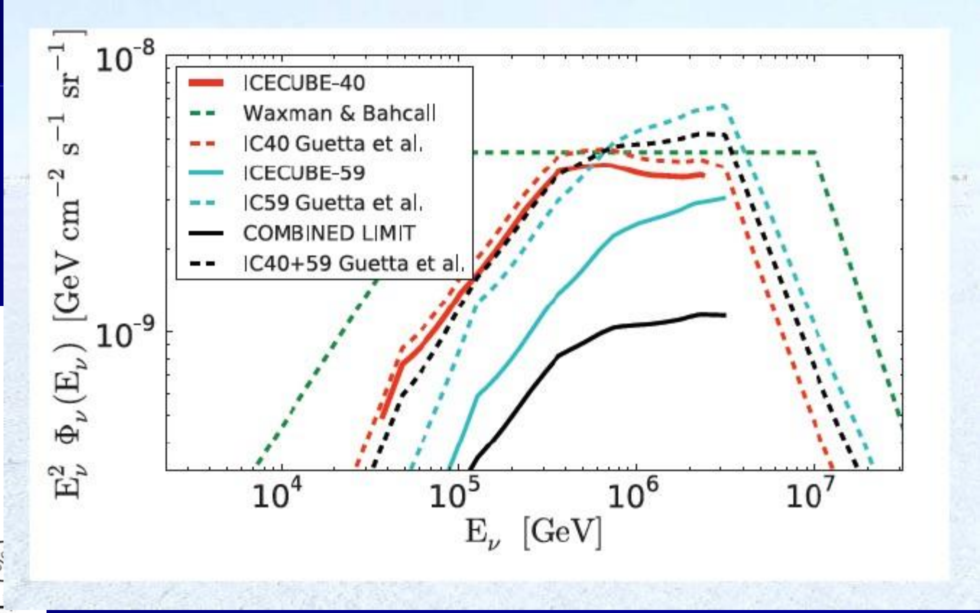
No significant clustering
Cascade events p-value = 18%

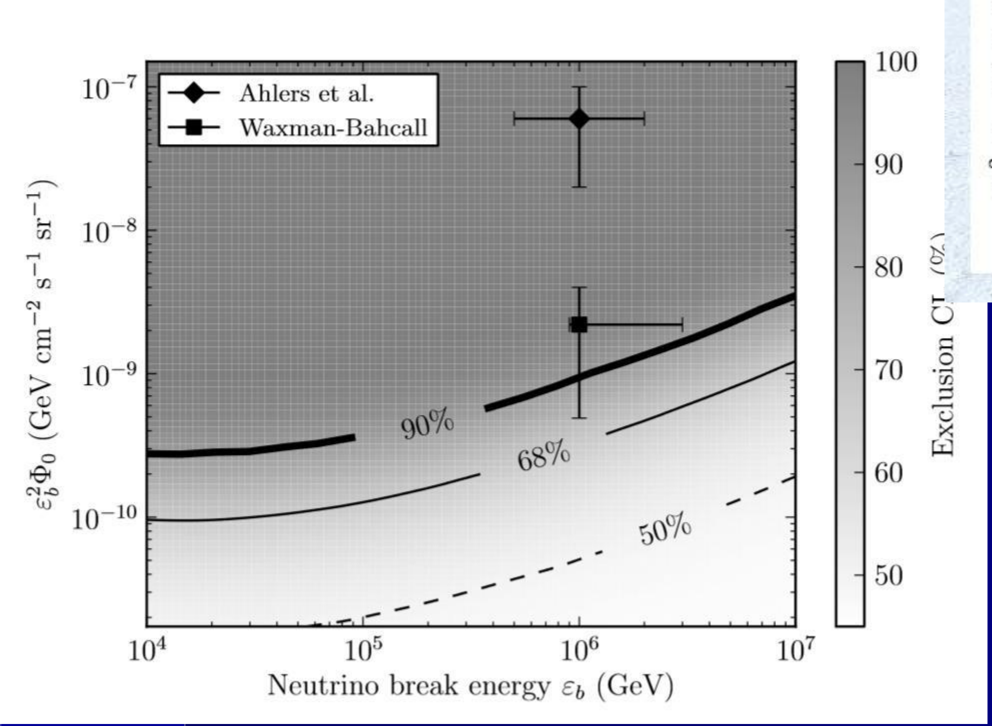


Point Source Analysis

IC40 data **2008-2012** (508 GRBs in northern sky). **No coincidence found. Note, analysis has very low background because both direction and timing coincidence are applied.**

APJ, Letter 805 1 , 2015
4 years of data, we found 1 neutrino event correlated with A GRB with p = 0.46

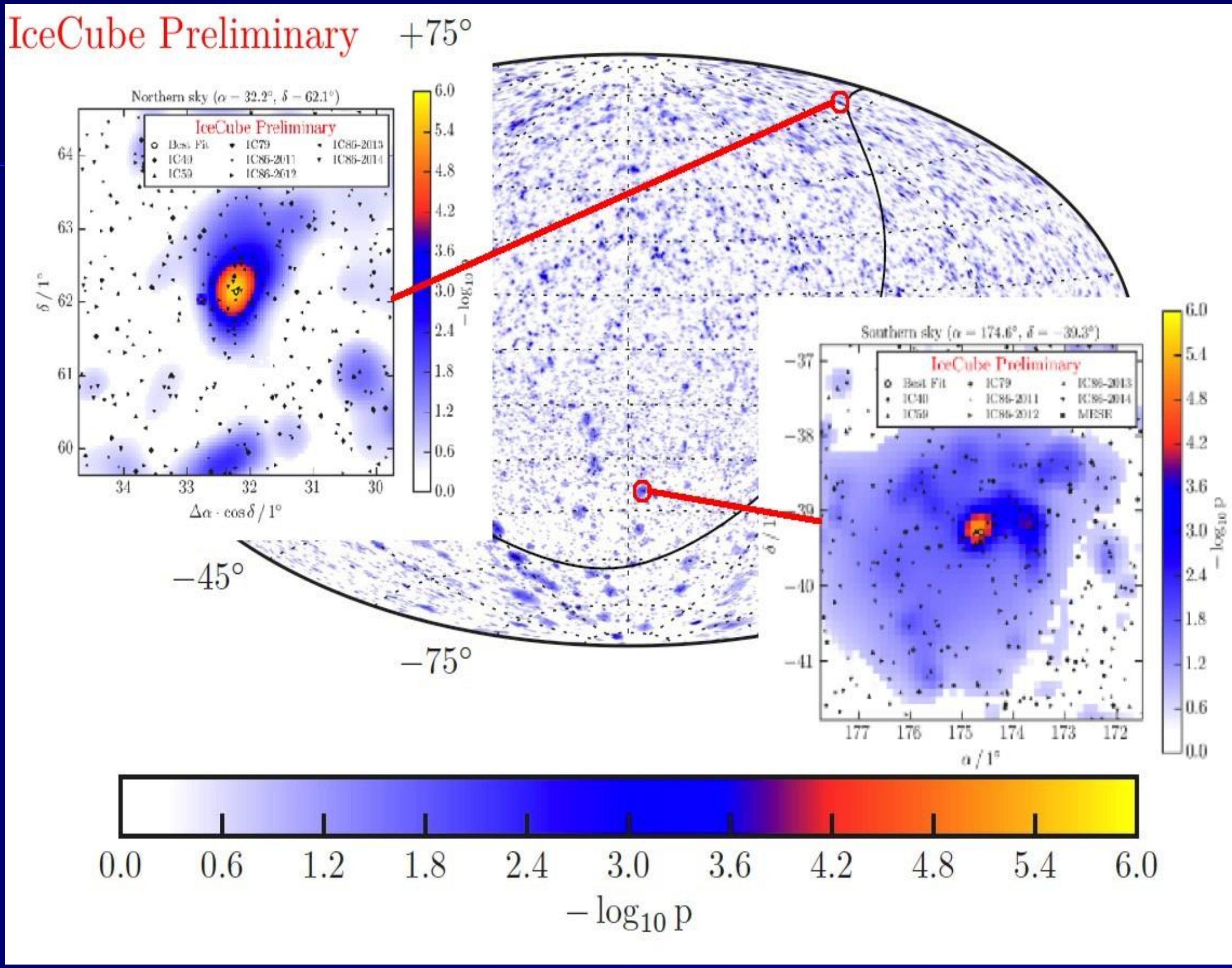




Point Source Analysis

6 years of muon data.
p (North Sky)= 0.29
P (Southern Sky = 0.17

Overwhelmingly dominated by atmospheric neutrinos

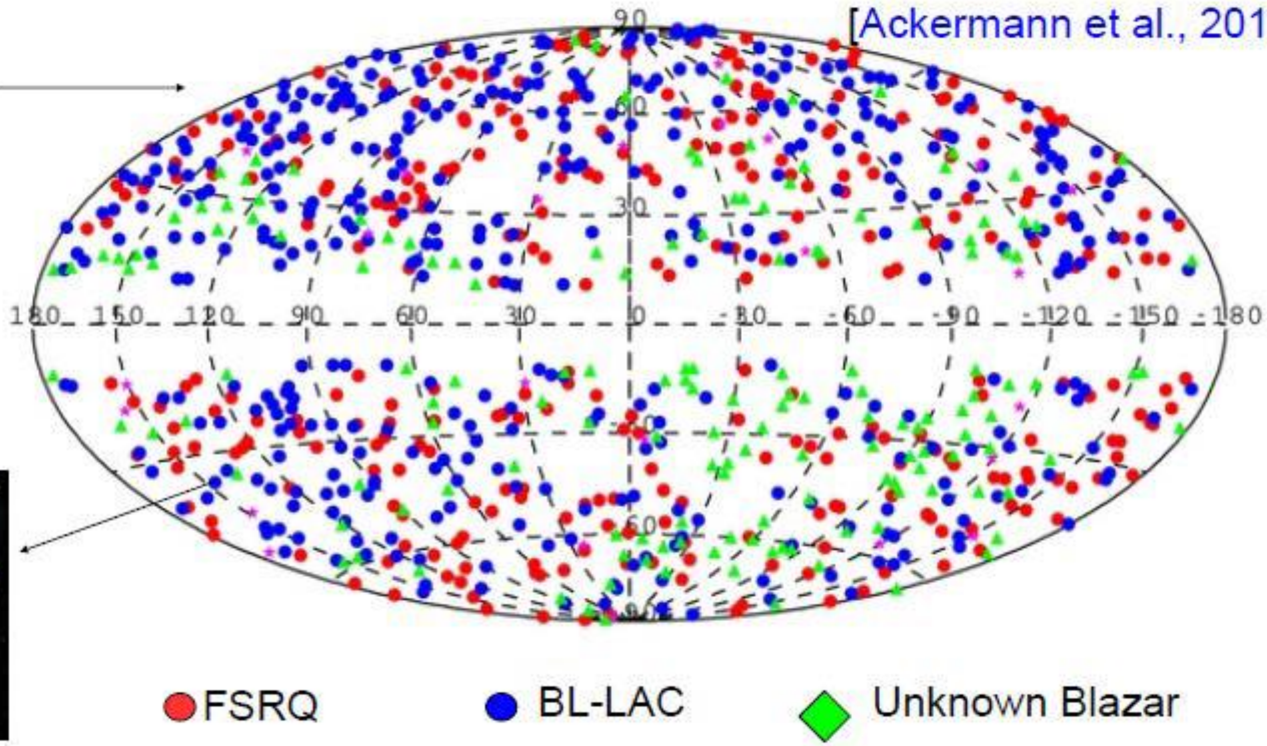


Search for neutrinos from Fermi-LAT blazars

Total sources: ~ 900

FERMI-LAT AGN SKYMAP (|b| > 10)

[Ackermann et al., 2011]

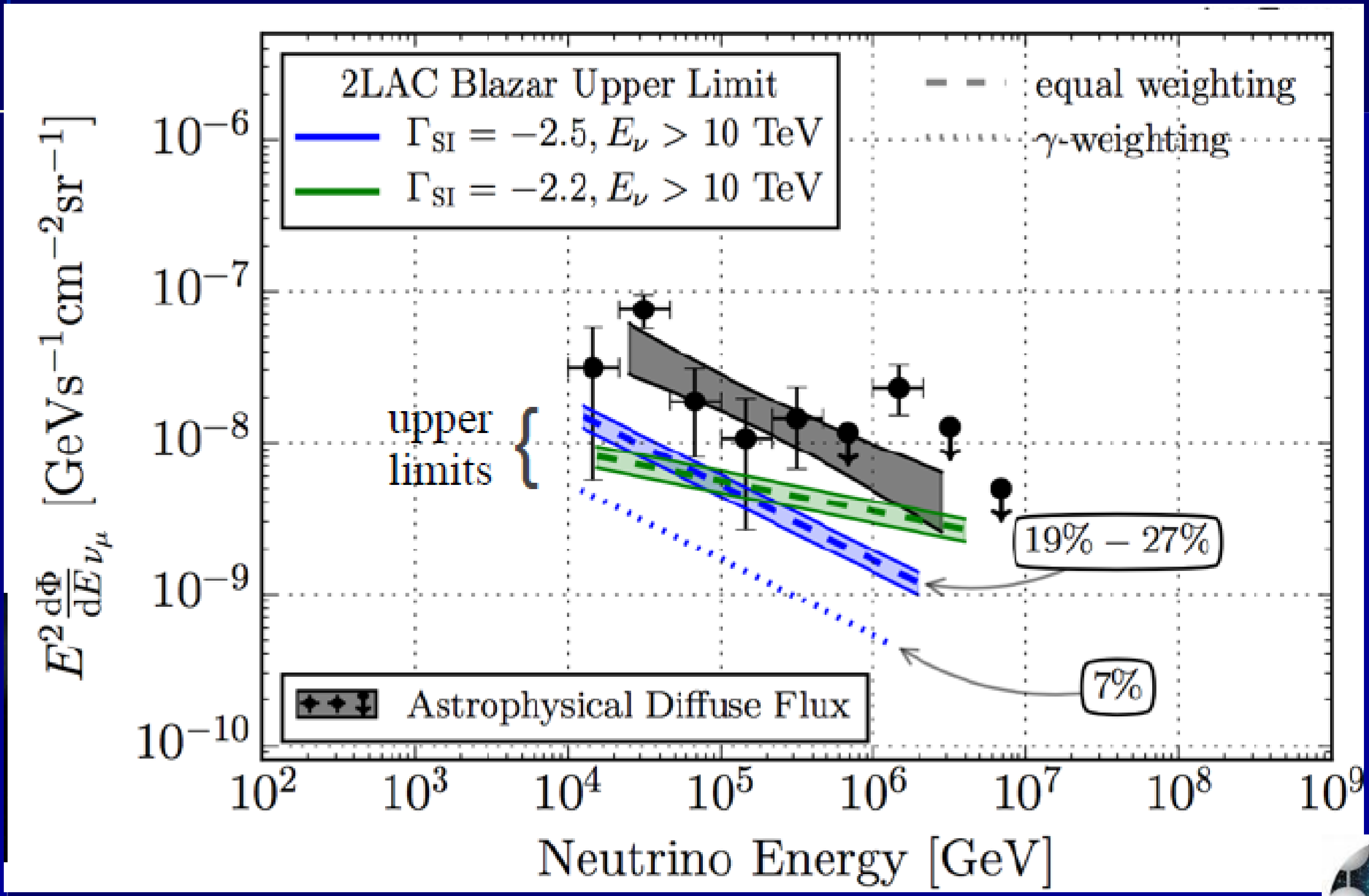


FSRQ: flat-spectrum radio quasars; BL-LAC: BL-**Lacertae**

IceCube

Search for neutrinos from Fermi-LAT blazars

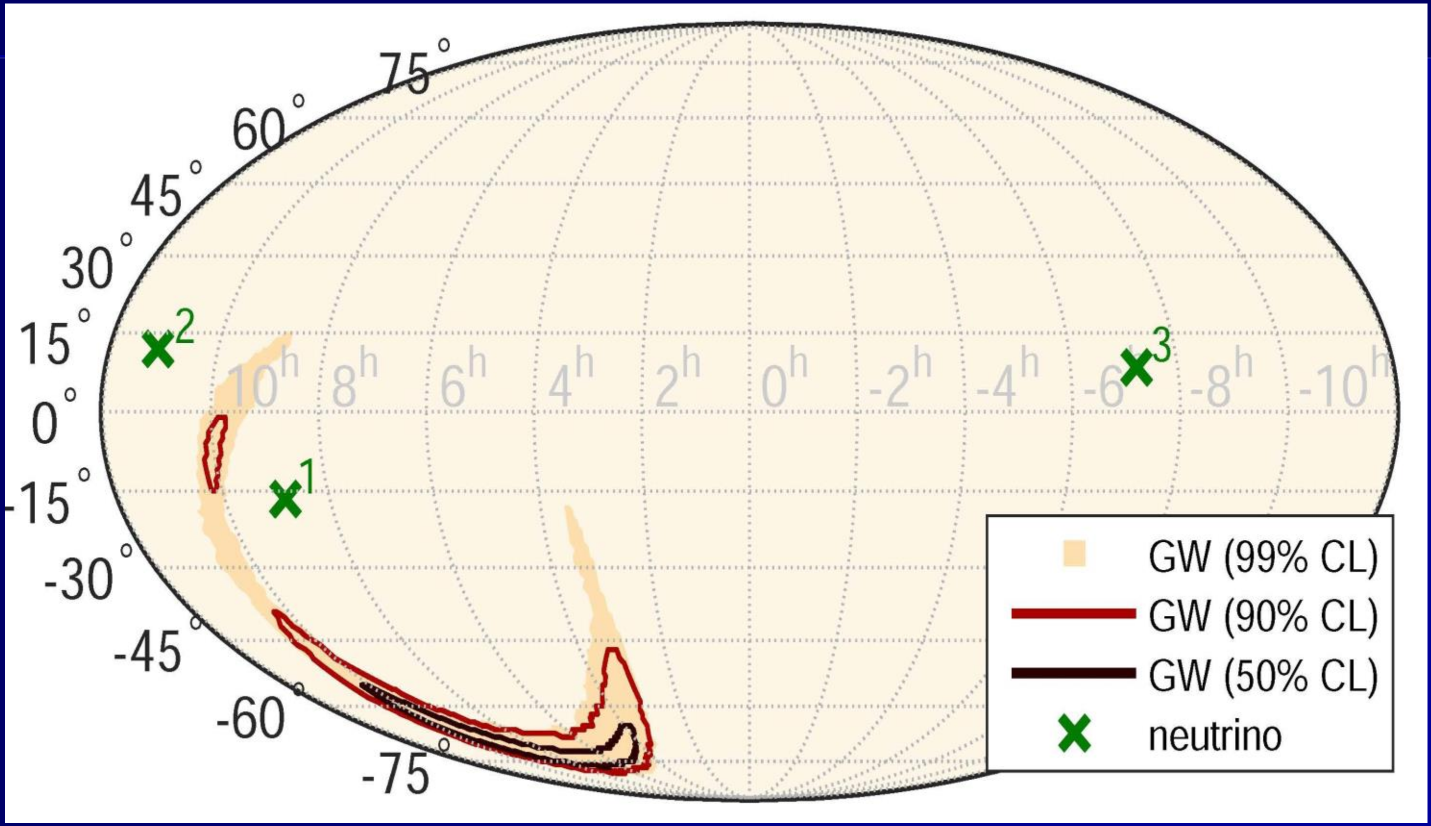
IceCube Collaboration: arXiv:1611.03874



Search for neutrinos in coincidence with LIGO

GW150914

3 Muon neutrinos
($\Delta t = \pm 500\ s$)
With energies
175, 1.22, 0.33 TeV.
No coincidence was
found. With LIGO.



E_ν (total) = 5.4 x 10^{51} – 1.3 x 10^{54} erg
E (gravity) $\backsimeq$ 5.4 x 10^{54} erg

Search for neutrinos from Fermi-LAT blazars

IceCube Collaboration: arXiv:1611.03874

Nine from ten integral tests show over- fluctuations, but none of them are significant. The largest over fluctuation, a 6% p-value, is observed for all 862 2LAC blazars combined using the model independent equal-weighting scheme. The differential test for all 2LAC blazars using equal source weighting (gamma and neutrio) reveals that the excess appears in the 5-10 TeV region with a local p-value of 2.6 σ.

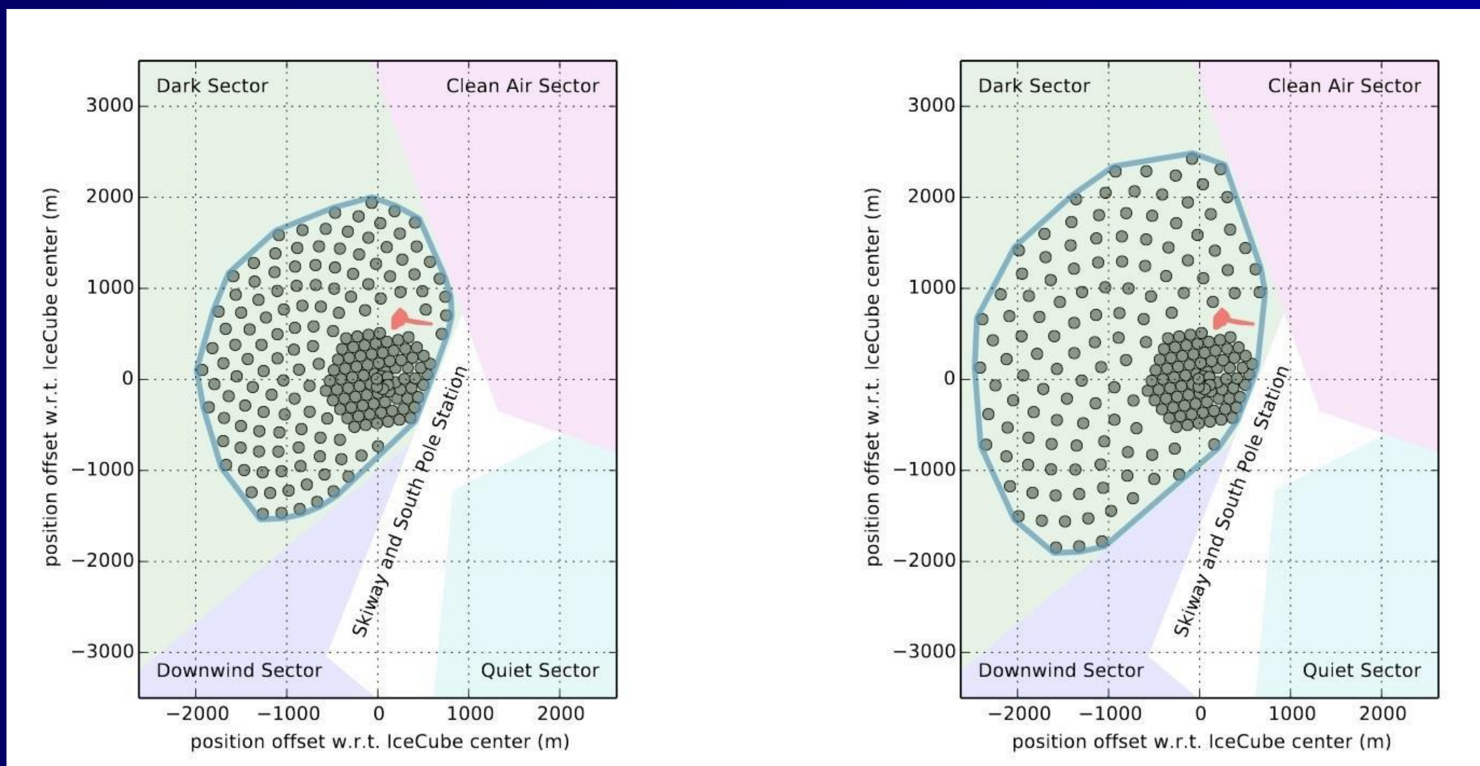
No correction for testing multiple hypotheses is applied, since even without a trial correction this excess cannot be considered significant.

Future Plans, IceCube-Gen2

Larger IceCubes, up to more than an order of magnitude in mass/volume. Much higher statistics in the PeV region, much higher energy neutrino acceptance, a deeper view of the cosmos and source ID of high energy neutrino production.

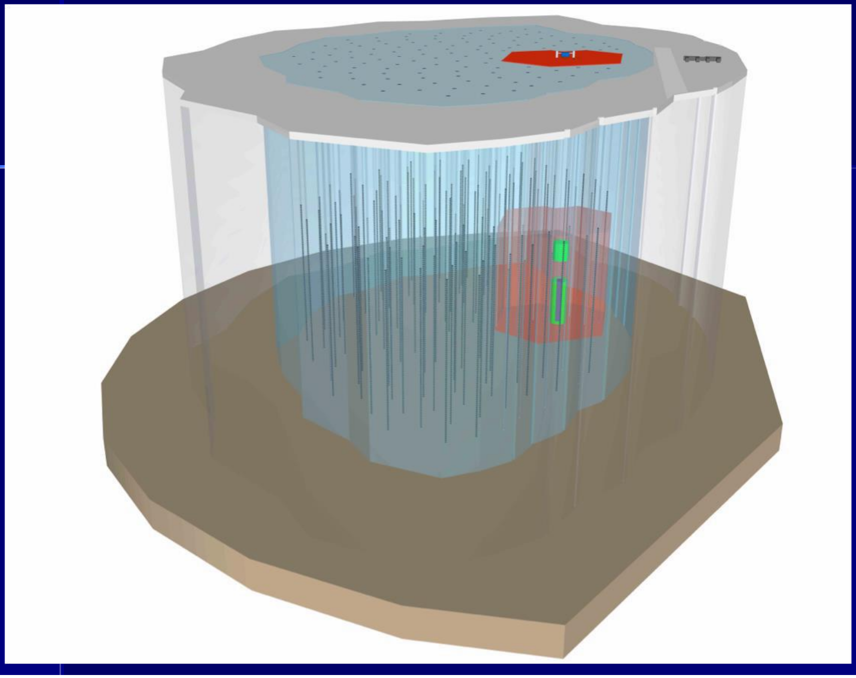
PINGU, acronym for Precision IceCube Next Generation Upgrade, is a proposed dense array and has physics goals such as precision measurements of neutrino oscillations (mass hierarchy, ...) and other physics such as test of low mass dark matter models. arXiv:1412.5106

240 m Spacing

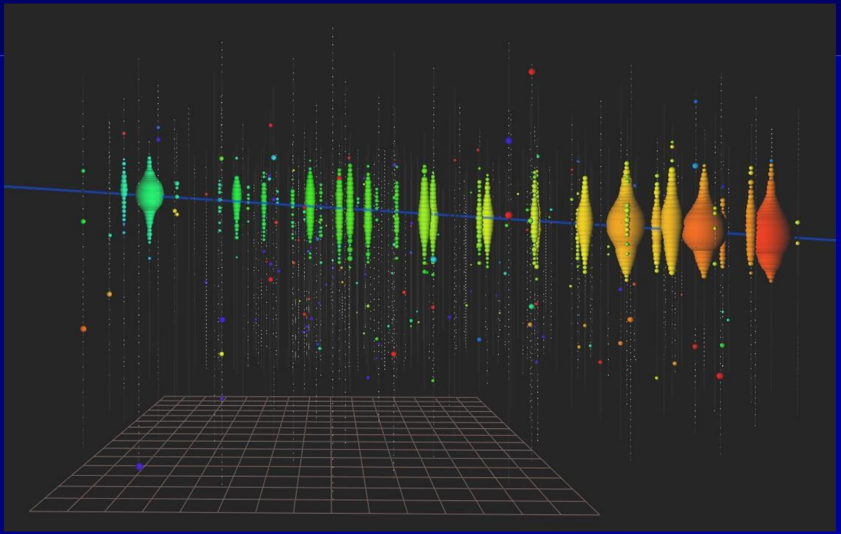


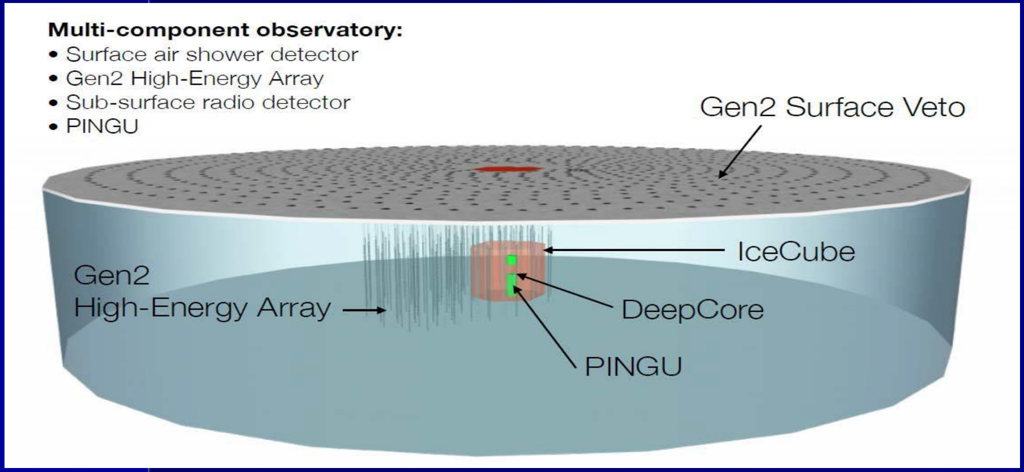
300 m spacing

Future Plans, IceCube-Gen2



A simulated 60-PeV horizontal muon





Completion date 2032!

Conclusions and Outlook

- IceCube has observed High Energy Astrophysical Neutrinos and has achieved its main goal of opening the era of neutrino astronomy.
- Further question: what is the origin of the high energy neutrinos?
- Real-time coincidence measurements are now possible with other detectors, such as optical, X-ray, gamma-ray and gravitational waves
- Future plans: IceCube Extensions for Higher Energies and PINGU dense array for Neutrino Mass Hierarchy ... ...