IceCube: Dawn of Multi-Messenger Astronomy

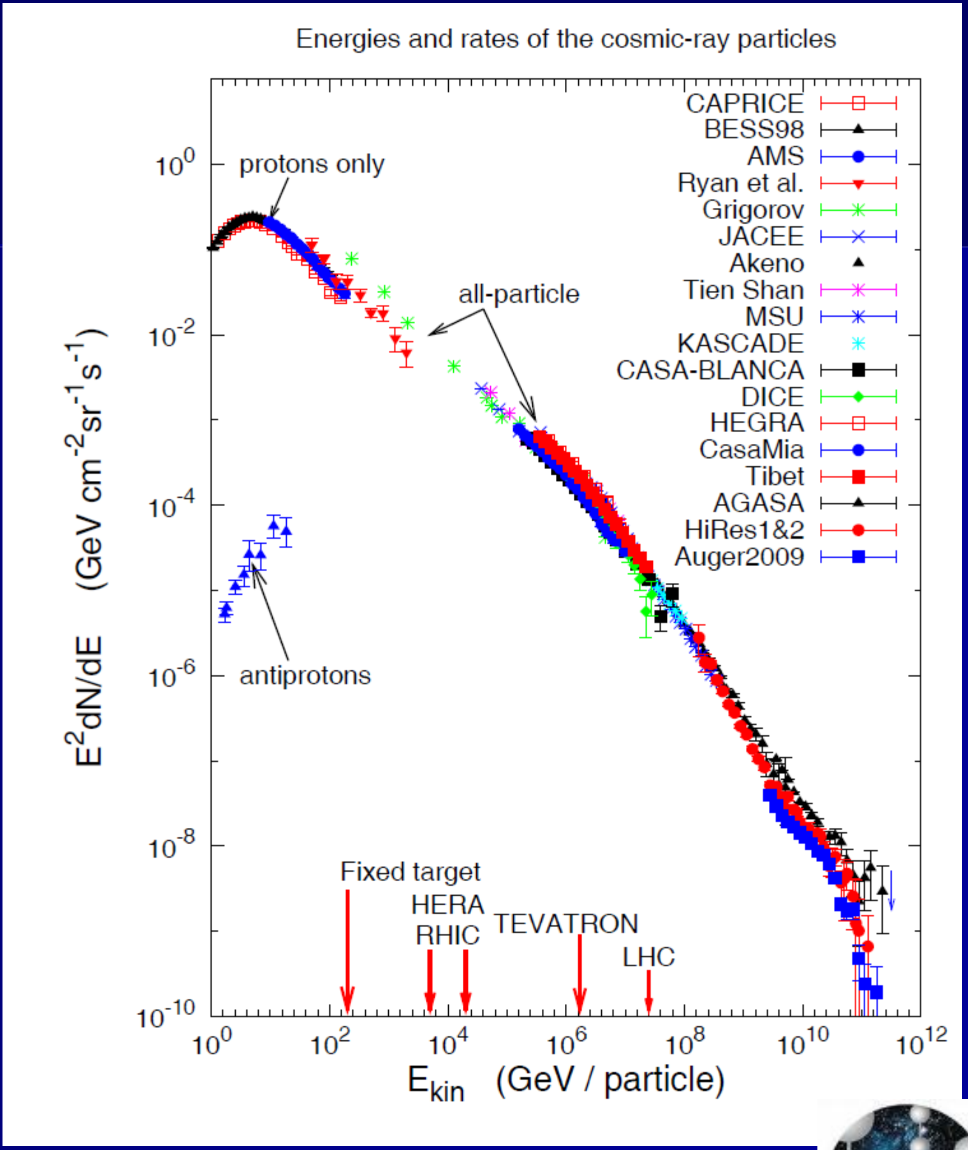
- Introduction
- Detector Description
- Multi-Messenger look at the Cosmos
- Updated Diffuse Astrophysical Neutrino Data
- Future Plans
- Conclusions

Ali R. Fazely, Southern University, for the
IceCube Collaboration. icecube.wisc.edu
Miami Conference, December 13 -19, 2018

Cosmic Rays: A century old puzzle

Balloon flights
1911-1913

Victor Hess
Nobel Prize
1936

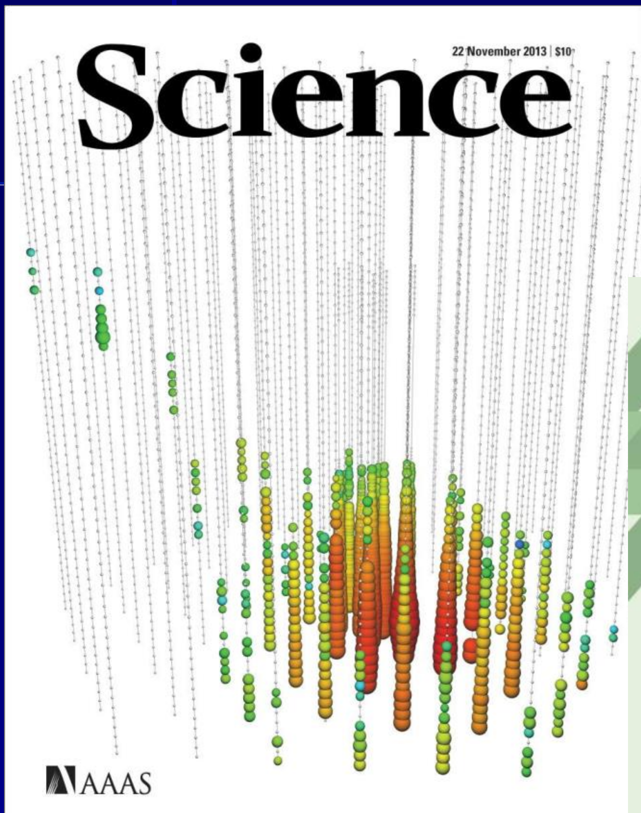


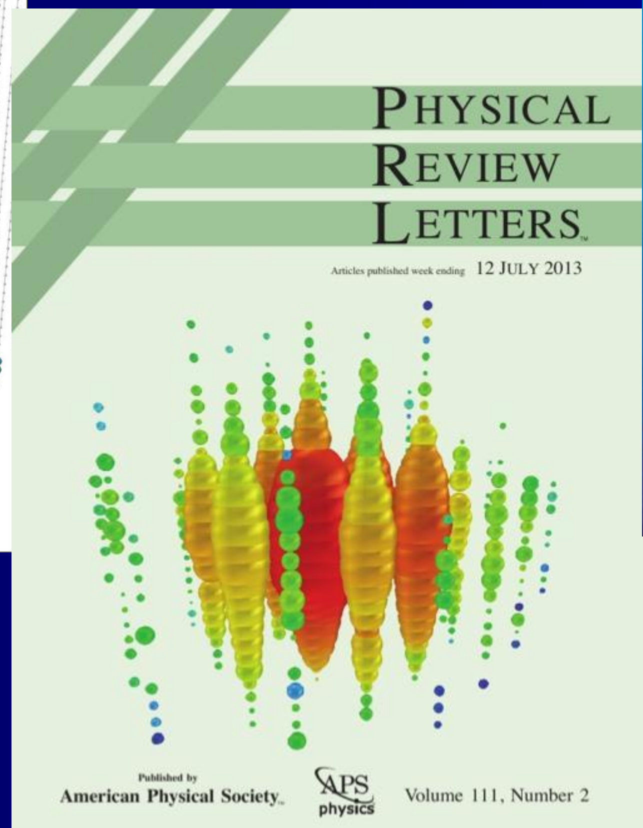
- Power law over many decades
- Origin Uncertain

IceCube

What is IceCube?

- A gigaton neutrino detector funded through the National Science Foundation and EU funding agencies
- We are in our 15th 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 and Multi-Messenger Astronomy.


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


Chasing the ammonia economy p. 120
Time invested matters for mice, rats, and humans pp. 124 & 178
Two spindles are better than one pp. 128 & 189
Science
$15
13 JULY 2018
sciencemag.org
AAAS
NEUTRINOS
FROM A BLAZAR
Multimessenger observations of an astrophysical neutrino source pp. 115, 146, & 147

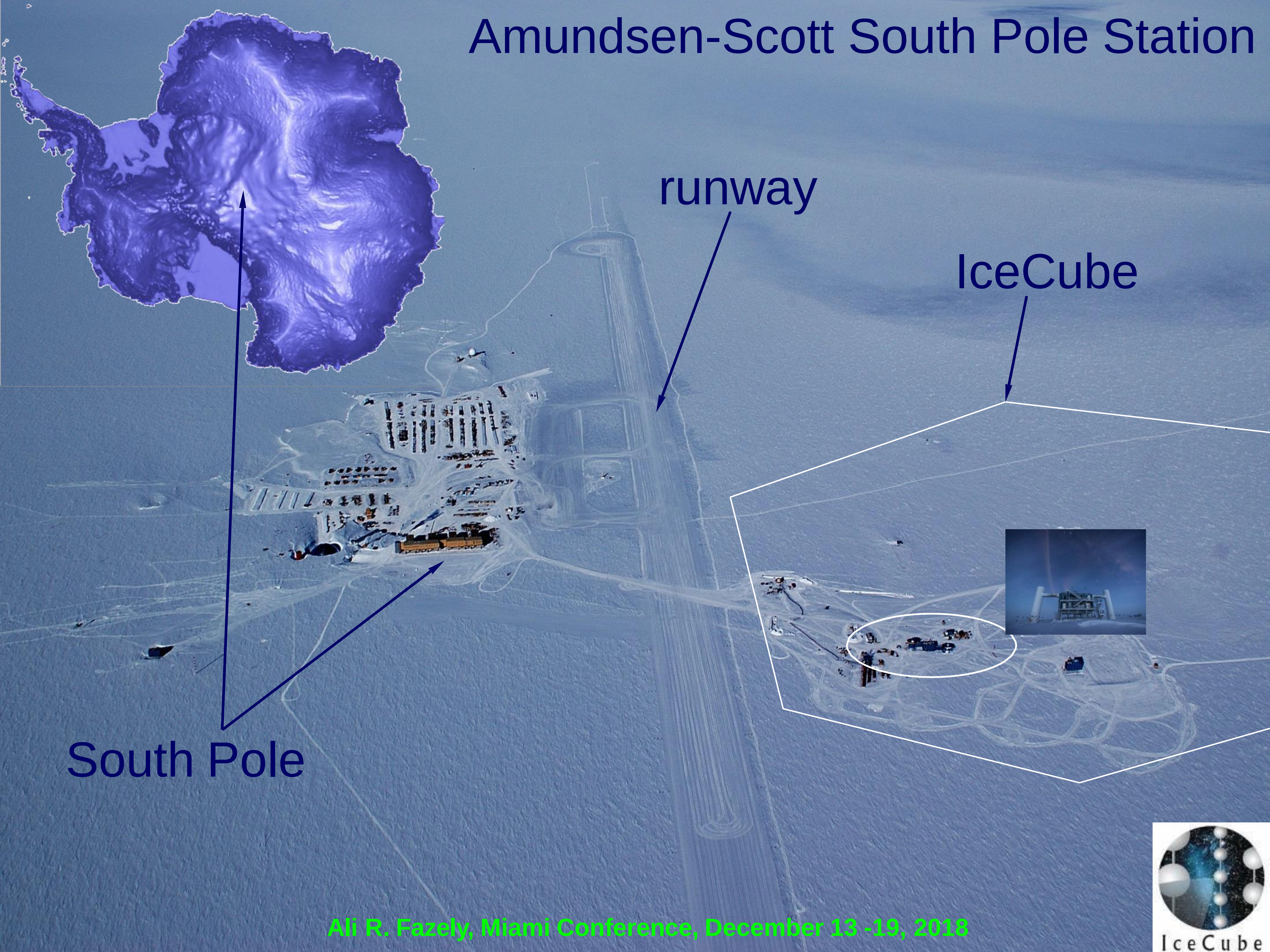
The IceCube Collaboration

Funding Agencies

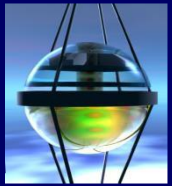
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube

Amundsen-Scott South Pole Station



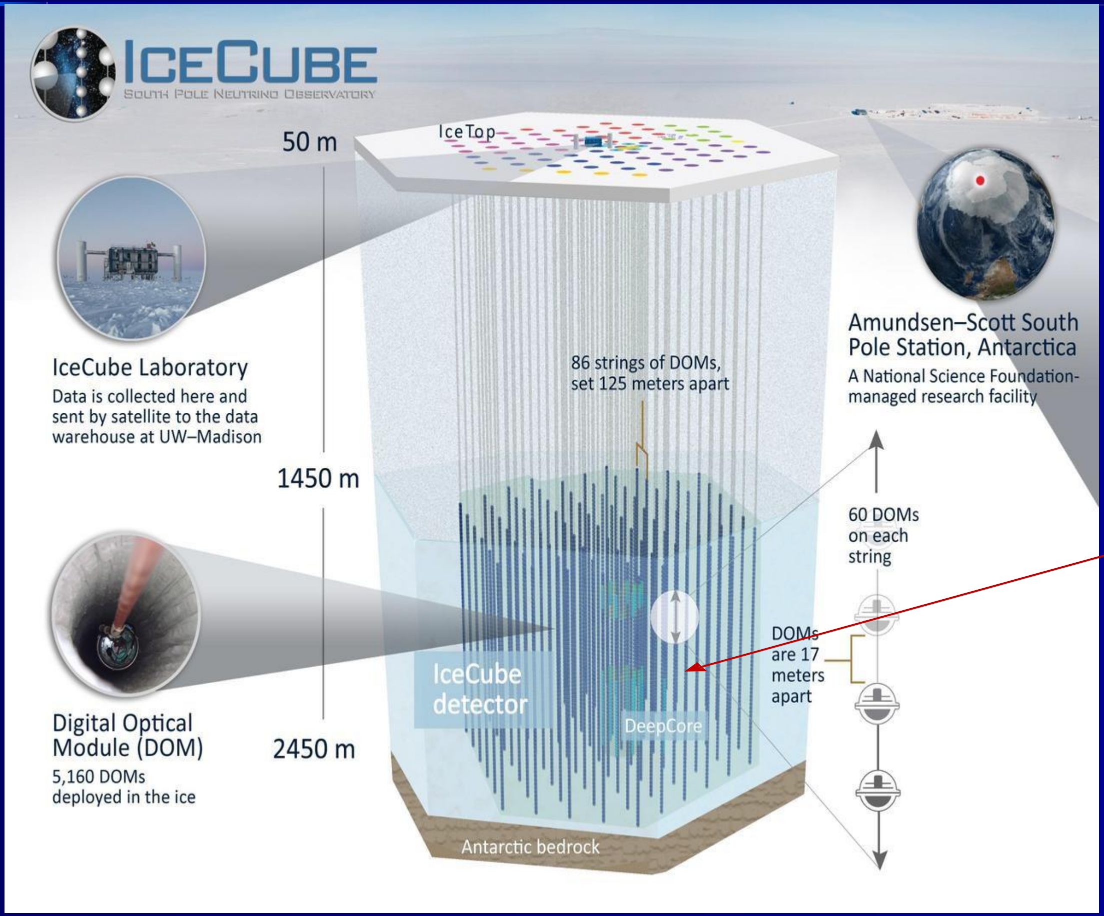
The IceCube Detector



IceTop

Air shower detector threshold ~ 300 TeV

✓Completion: December 2010



✓86 strings

✓2010: 79 Strings

✓2009: 59 Strings

✓2008: 40 Strings

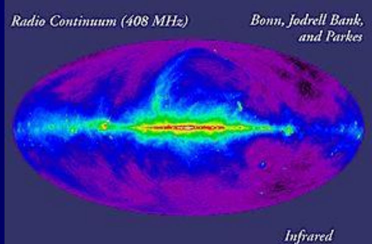
InIce

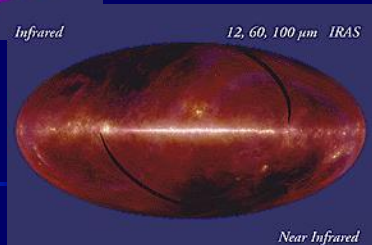
86 Strings, 60 Optical Modules per String

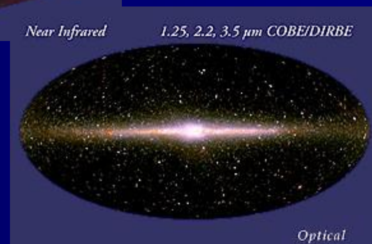
DeepCore

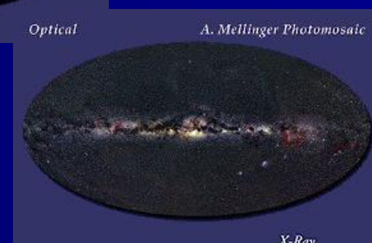
IceCube

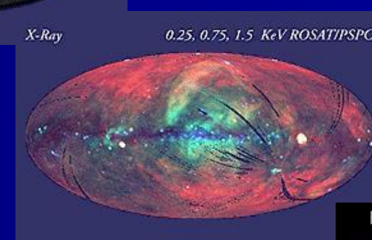
Observing the Universe

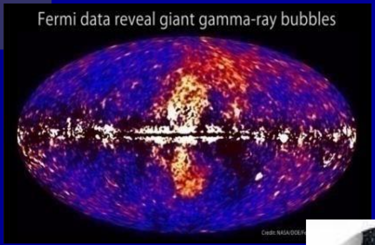


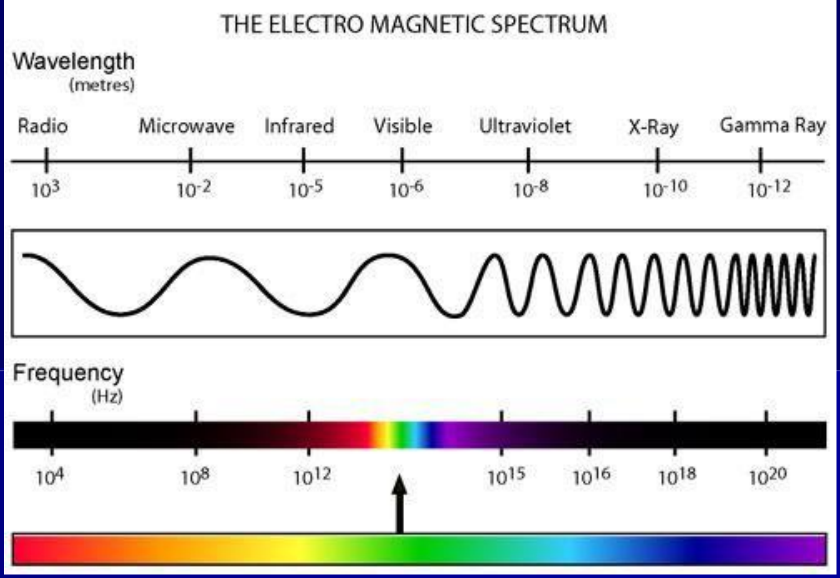








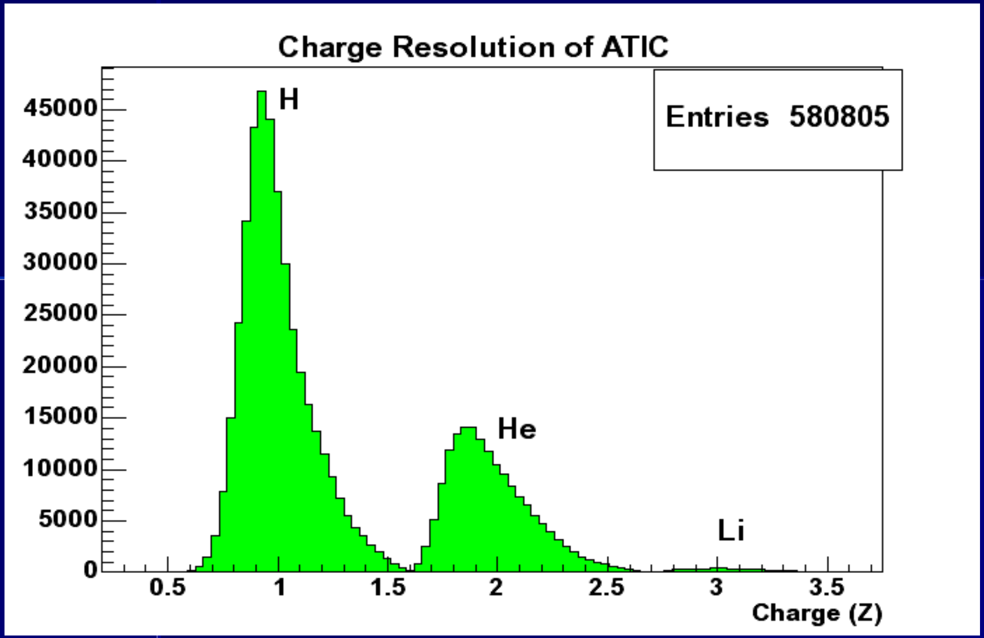




http://mwmw.gsfc.nasa.gov/mmw_allsky.html

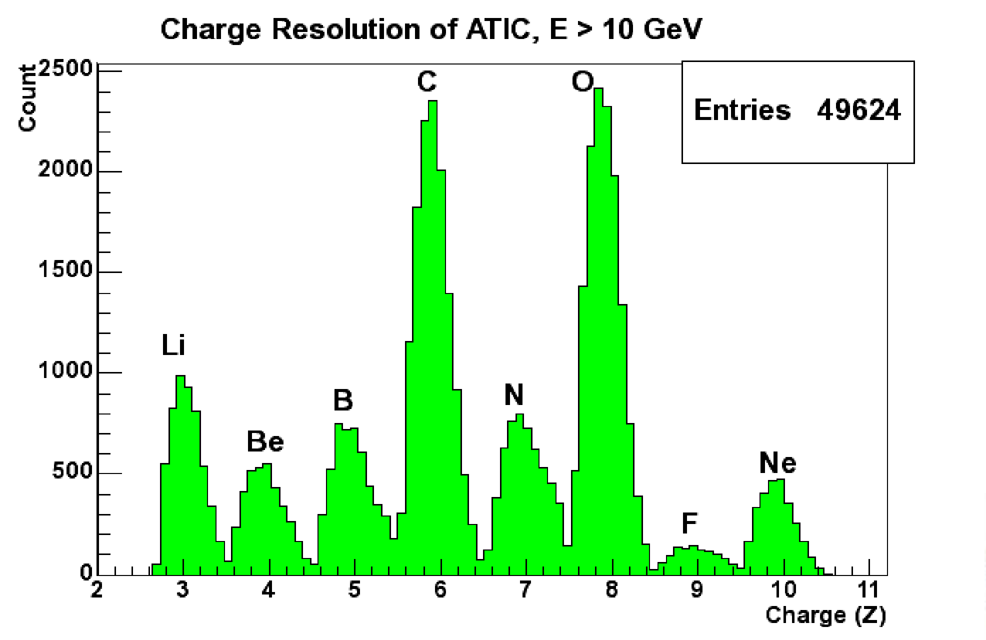
Ali R. Fazely, Miami Conference, December 13 -19, 2018

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.,
28th International Cosmic Ray Conference, Tsukuba, Japan (2003)

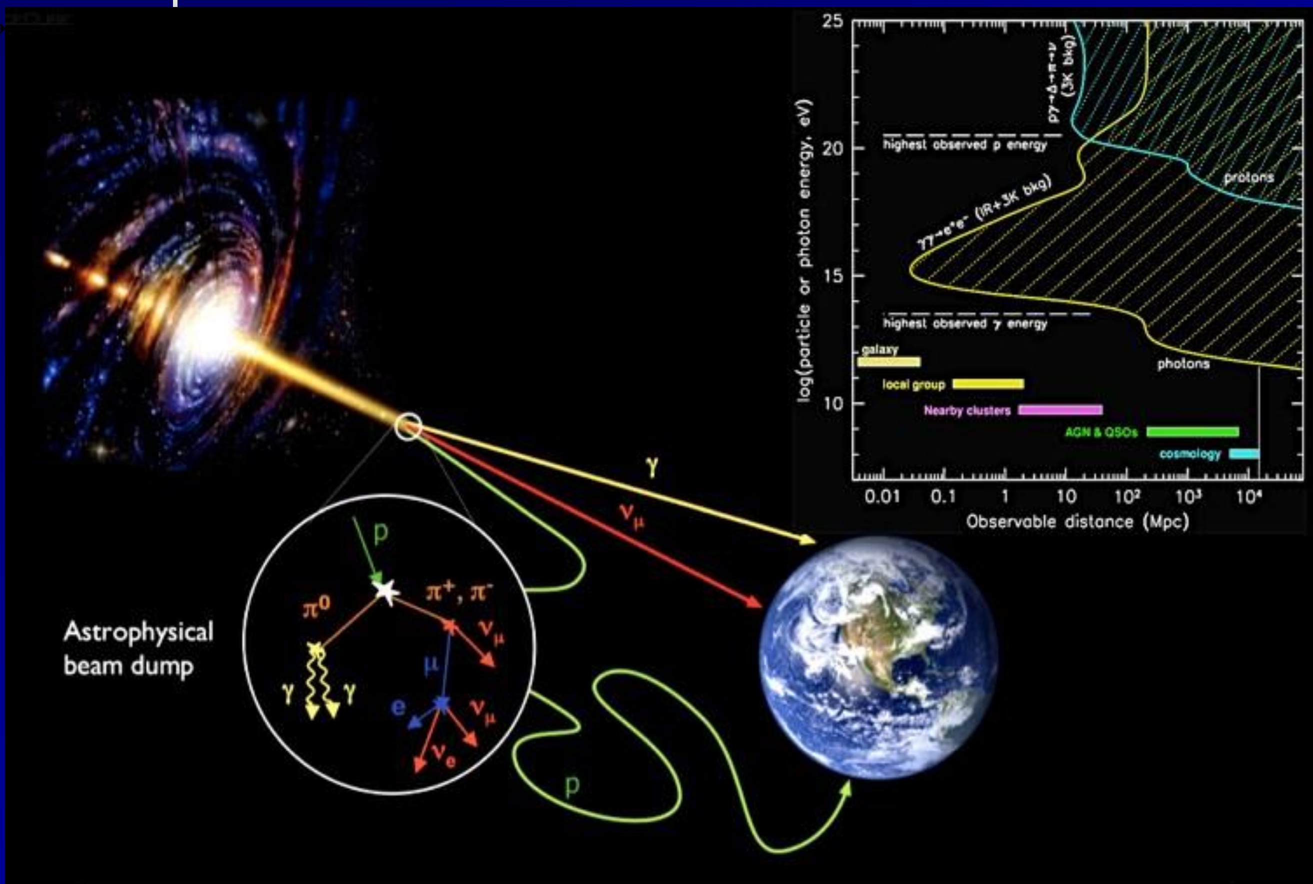


IceCube

Neutrinos as Cosmic Messengers

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

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



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

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

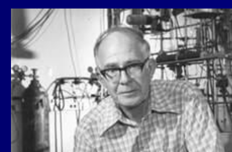
ν ***Neutrinos:*** **not deflected by magnetic fields. Low interaction cross-section.**

Slow History of Neutrinos!

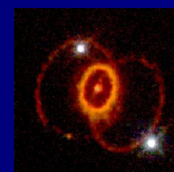
1930 Pauli proposes Neutrinos

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

IceCube

2018 Dawn of Multi-Messenger Astronomy

IceCube

IceCube

Neutrino interactions

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

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

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

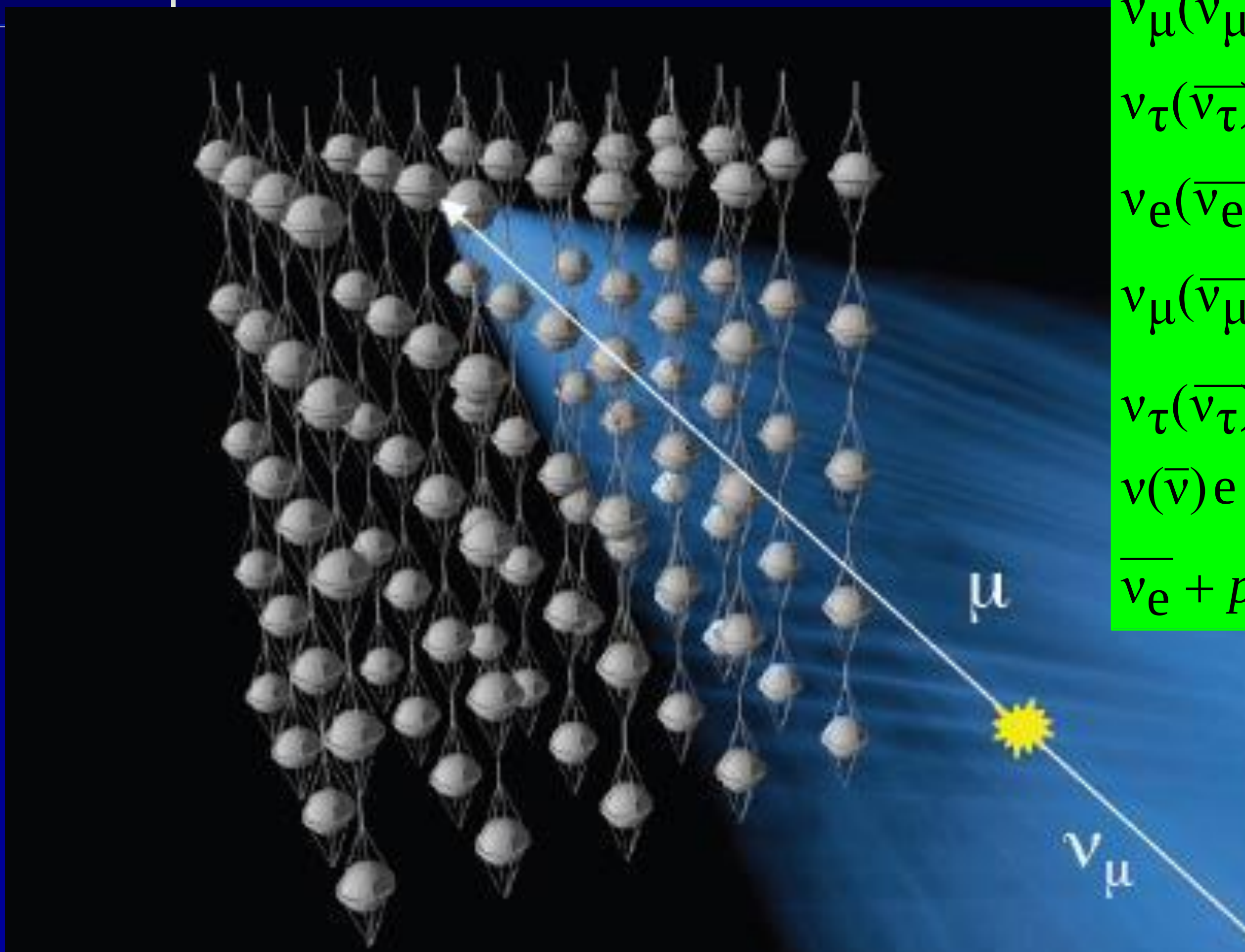
$$\nu_e(\overline{\nu_e}) + {}^{16}O \rightarrow \nu_e(\overline{\nu_e}) + X \quad (NC)$$

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

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

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

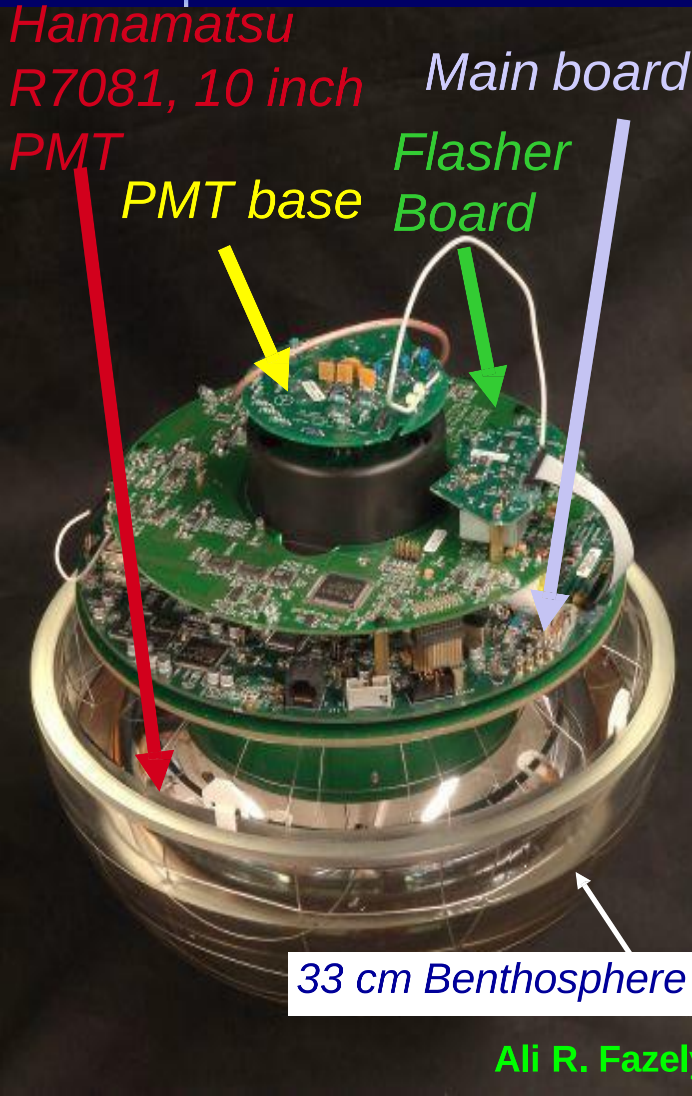
$$\overline{\nu_e} + p \rightarrow e^+ + n, \textit{Supernova}(CC)$$



Sensing Neutrino Light

IceCube "Digital Optical Module" (DOM)

Power consumption: 3W

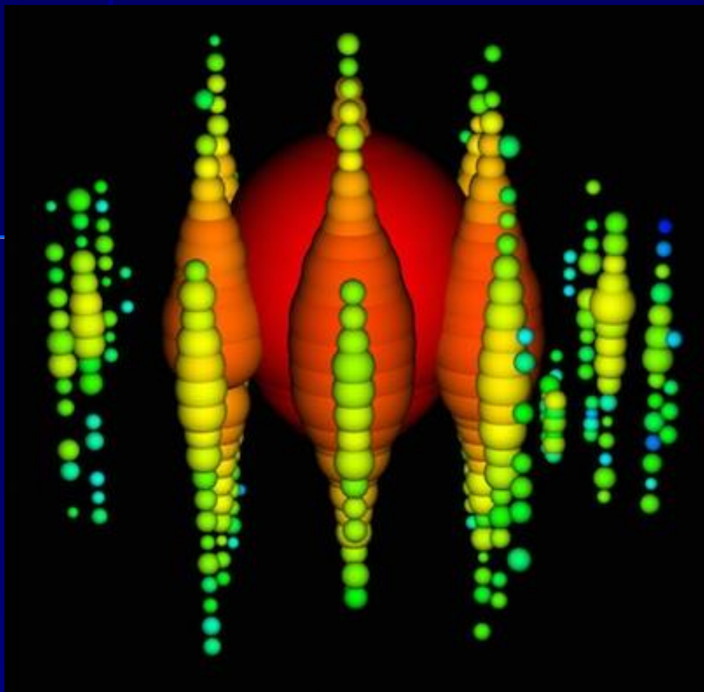


- Measure arrival time of every photon
- 2x 300MHz waveform digitizers
- 1x 40 MHz FADC digitizer
- Can trigger in coincidence w/ neighbor DOM
- Transmits data to surface on request
- Data sent over 3.3 km twisted pair copper cable
- Knows the time to within 3 nanoseconds to all other DOMs in the ice

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

IceCube Construction

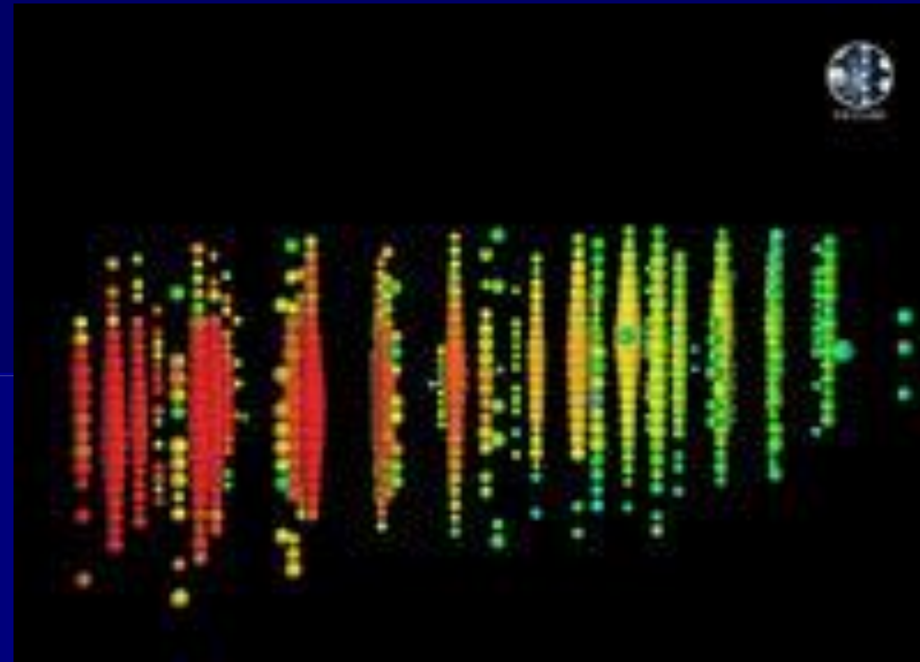
Event Topologies



ν_e data (Big Bird, 2.2 PeV)

Energy resolution ≈ 15% E(vis)

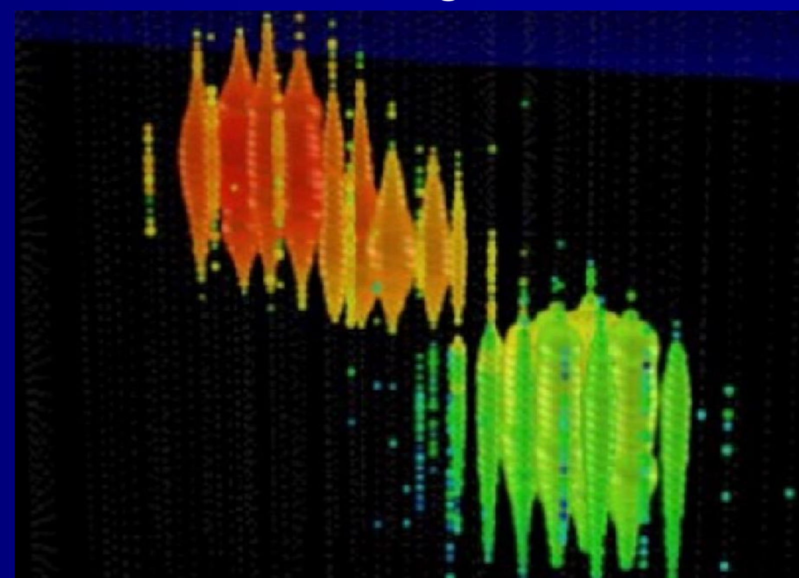
Angular resolution ≈ 10°



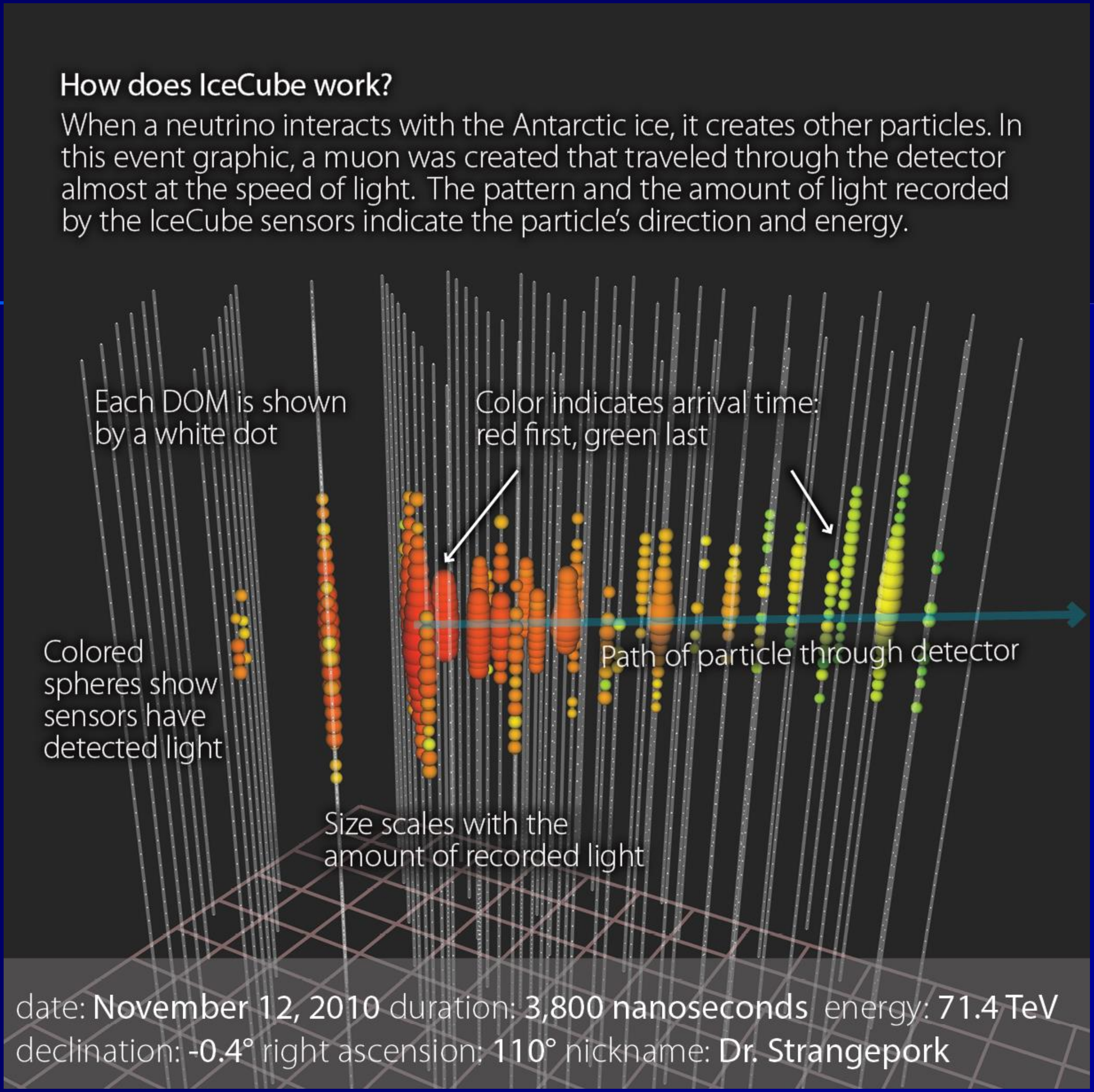
ν_μ data (466 TeV)

Energy resolution ≈ 2 x E(vis)

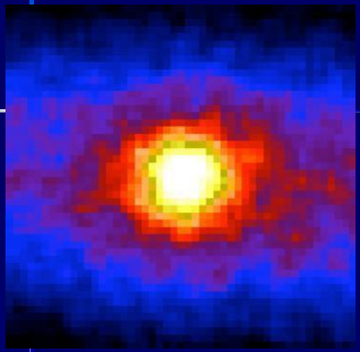
Angular resolution <1°



ν_τ simulation (16 PeV)

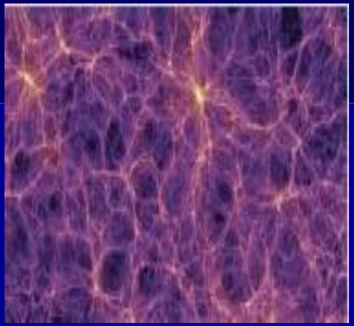

How does IceCube work?
When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle's direction 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

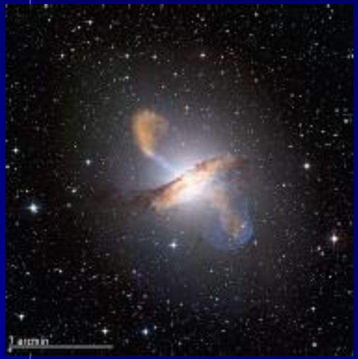


Solar Neutrinos

Supernova 1987A

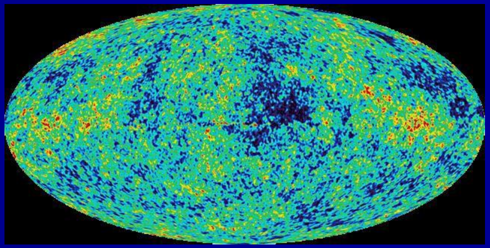


Dark Matter?



Active Galactic Nuclei
Blazars

Gamma Ray Bursts



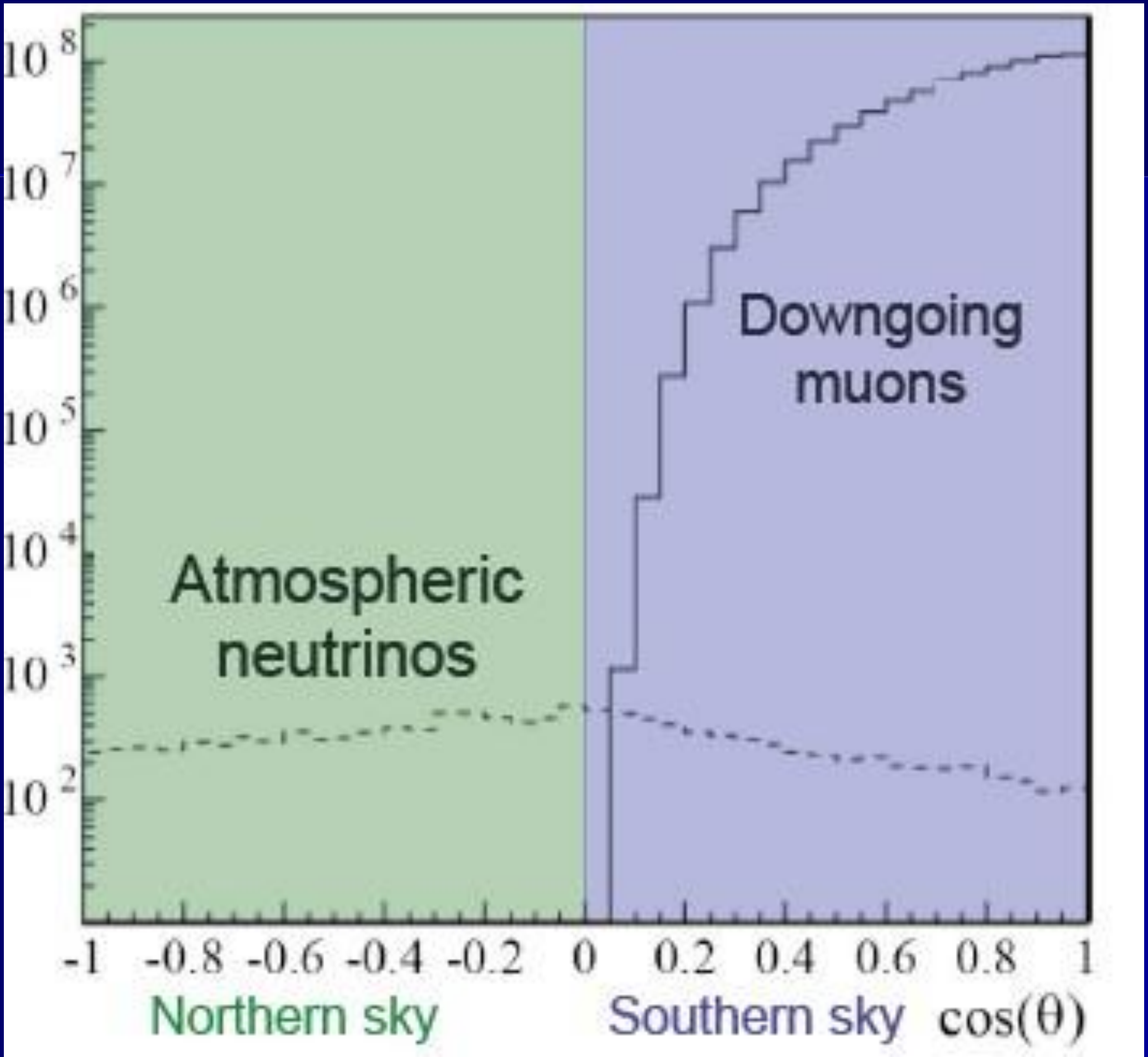
Cosmogenic Neutrinos

IceCube

Backgrounds

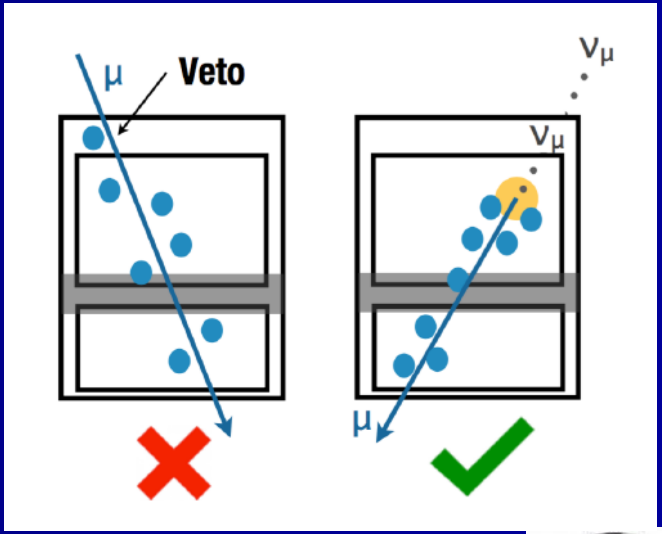
The majority of triggers in IceCube are from atmospheric muons

We record over 6 x10^9 muons and 74,000 atmospheric muon neutrinos per year.

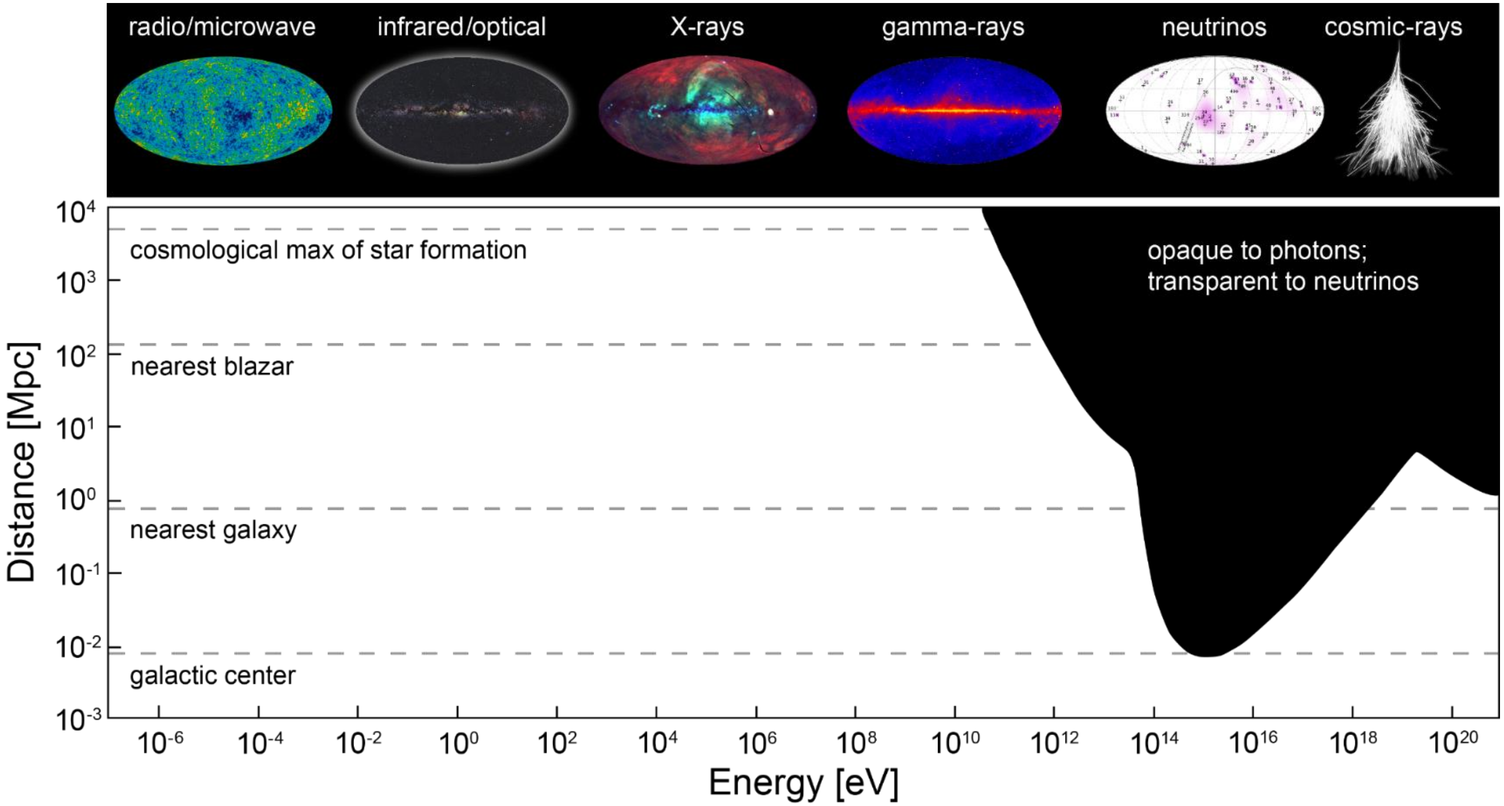


Atmospheric Neutrinos

- Main Background to Astrophysical Search
- Created by high energy cosmic rays colliding with O and N in the atmosphere
- Conventional (Pions & Kaons) vs. Prompt (Charmed Mesons)
- Conventional ~ $E^{-3.7}$ Spectrum
- Prompt ~ $E^{-2.7}$ Spectrum



Multi-messenger Astronomy
A new approach to observing the universe



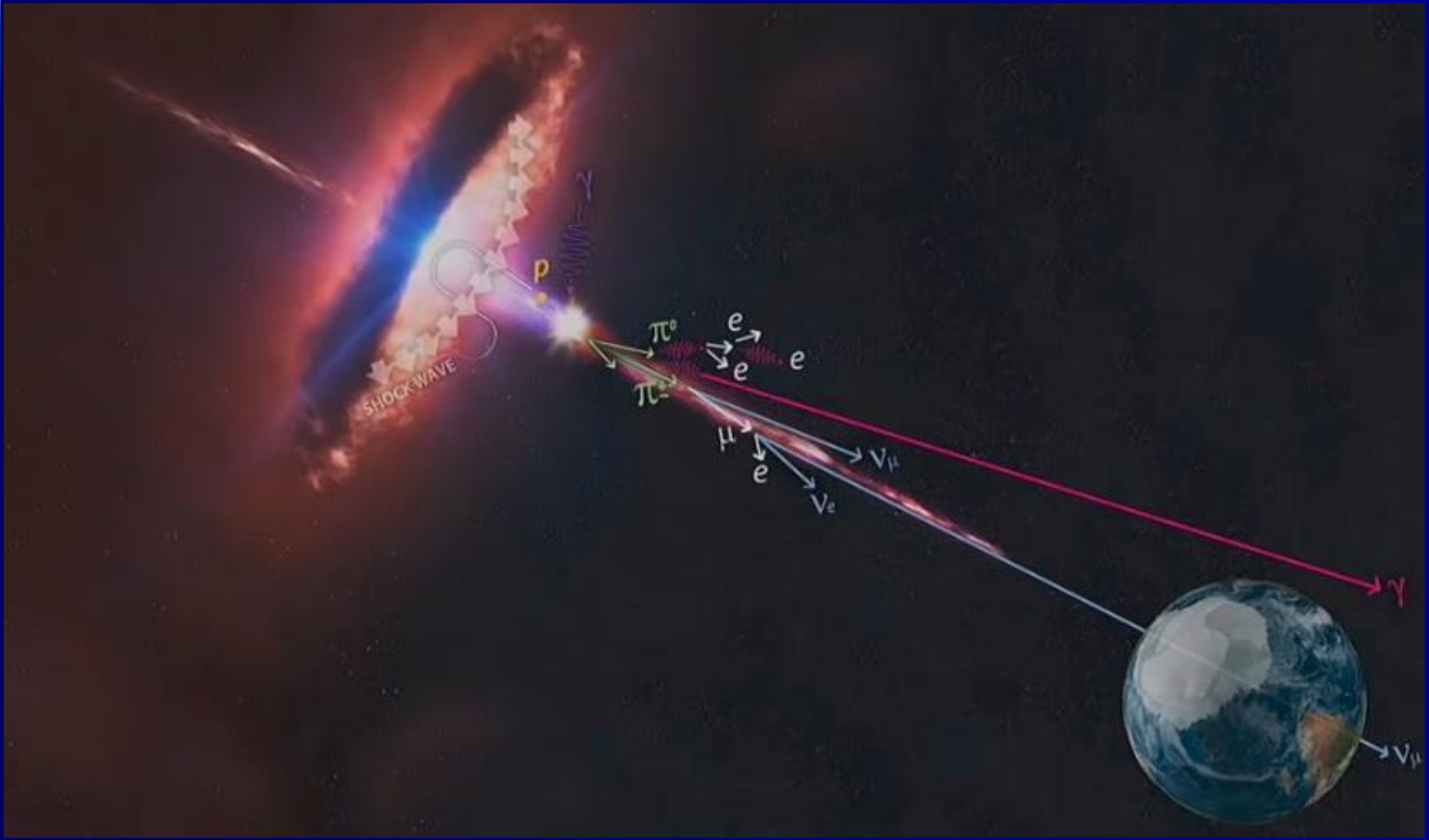
Multi-messenger Astronomy

A new approach to observing the universe

Blazar TXS 0506+056

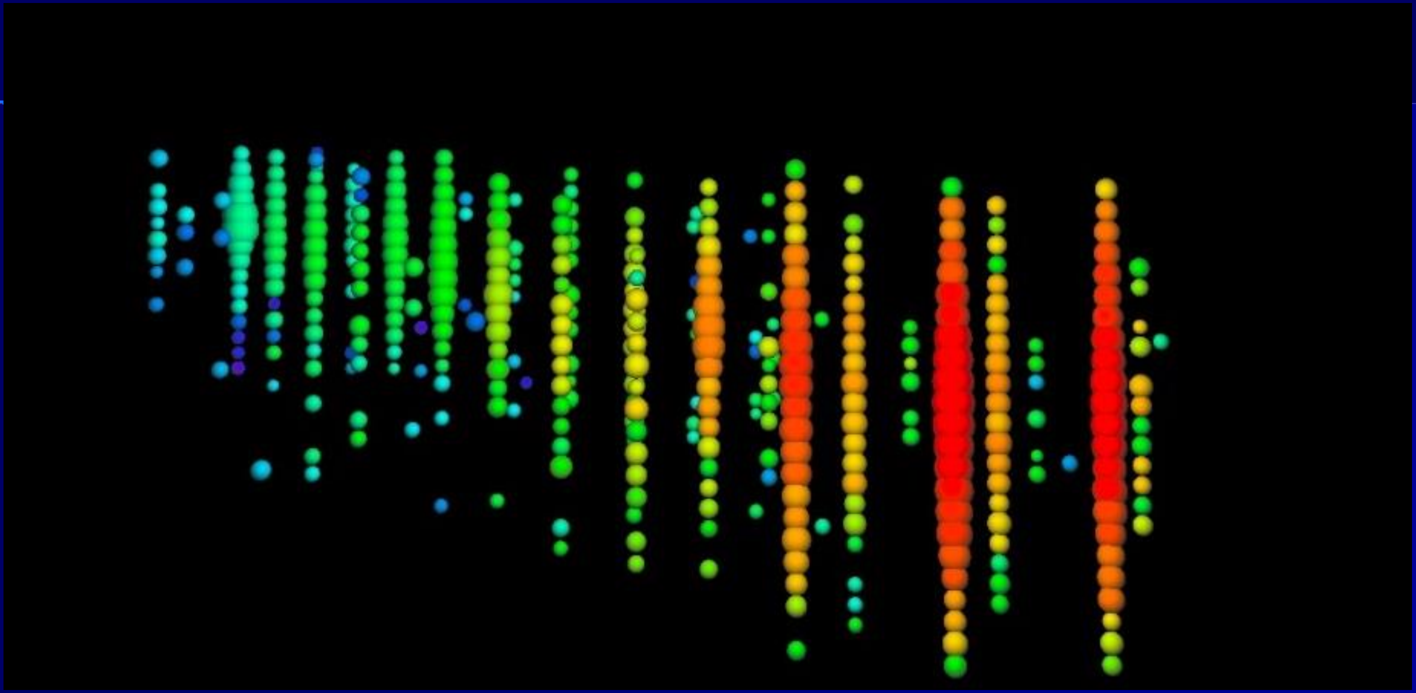
Distance: 1.75 Mparsec, 5.7 Billion l.y.

Jets are pointing directly toward Earth.



Multi-messenger Astronomy

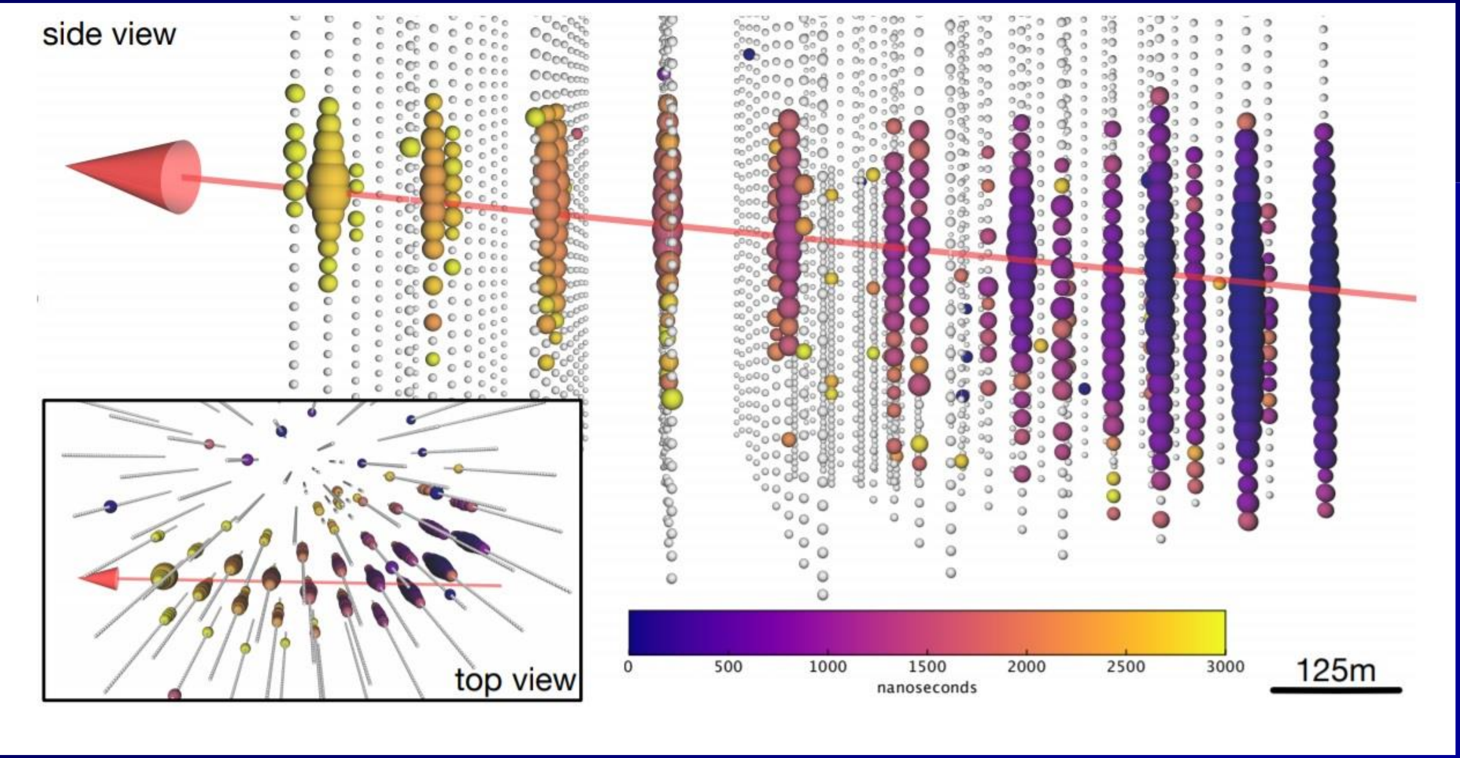
A new approach to observing the universe



This event display, from the high-energy muon neutrino detected by IceCube on Sept. 22, 2017, shows a muon, created by the interaction of a muon neutrino with the IceCube.
Event Number: **IceCube-170922A, E = 290 TeV**

Multi-messenger Astronomy

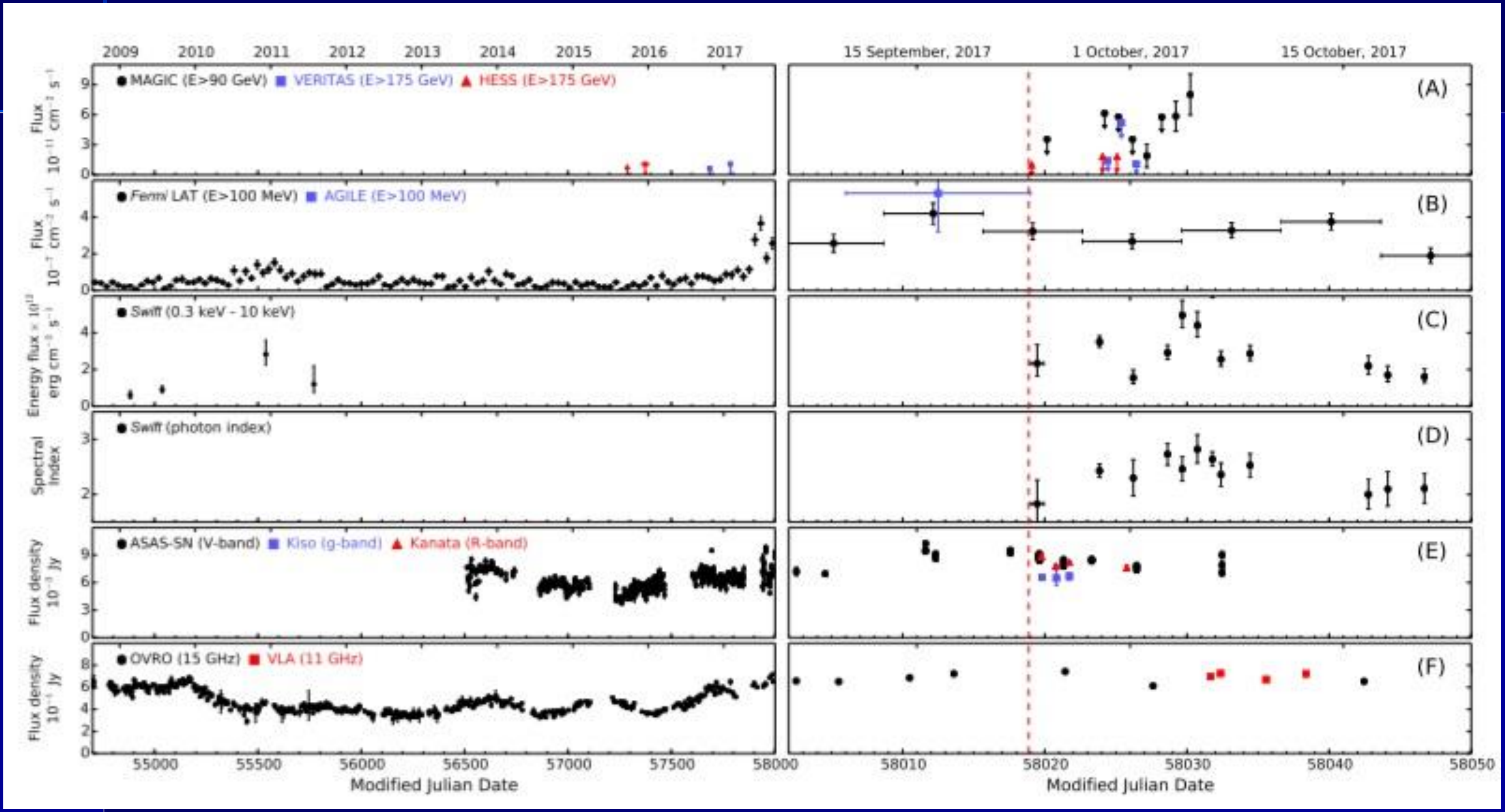
A new approach to observing the universe



- The observed DOM time shows dark blues for earliest hits and yellow for latest.
- The total time the event took to cross the detector is ~3 μs.
- The size of a colored sphere is proportional to the logarithm of the amount of light observed by the DOM. The total charge recorded is ~5800 photoelectrons.
- The best-fitting track direction is shown as an arrow, consistent with a zenith angle 5.7 +0.50 −0.30 degrees below the horizon.

Multi-messenger Astronomy

A new approach to observing the universe



Multi-messenger Astronomy

A new approach to observing the universe

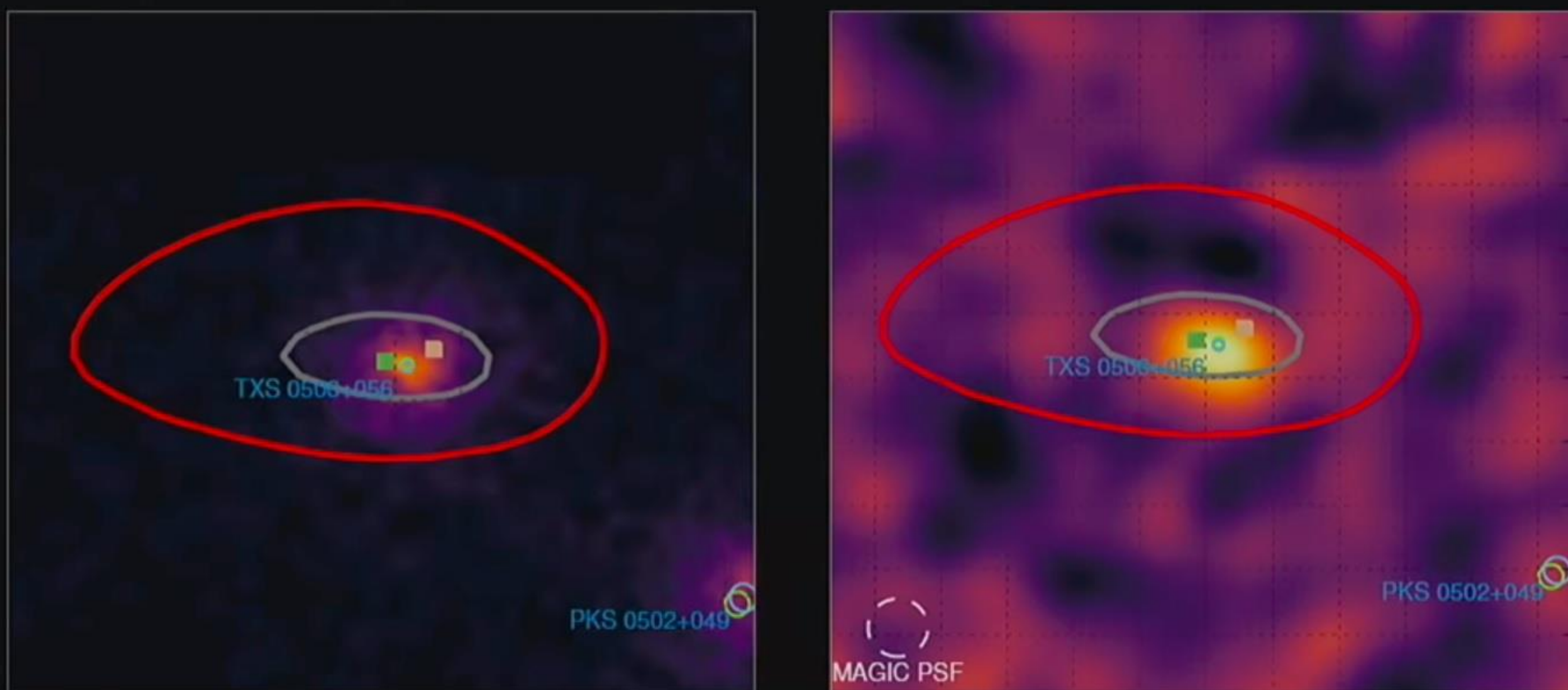
Timeline for Multi-messenger EM events Following IceCube Trigger by Blazar TXS 0506+056

Multi-messenger Astronomy

A new approach to observing the universe

Neutrino points within 0.06º of a known Fermi blazar

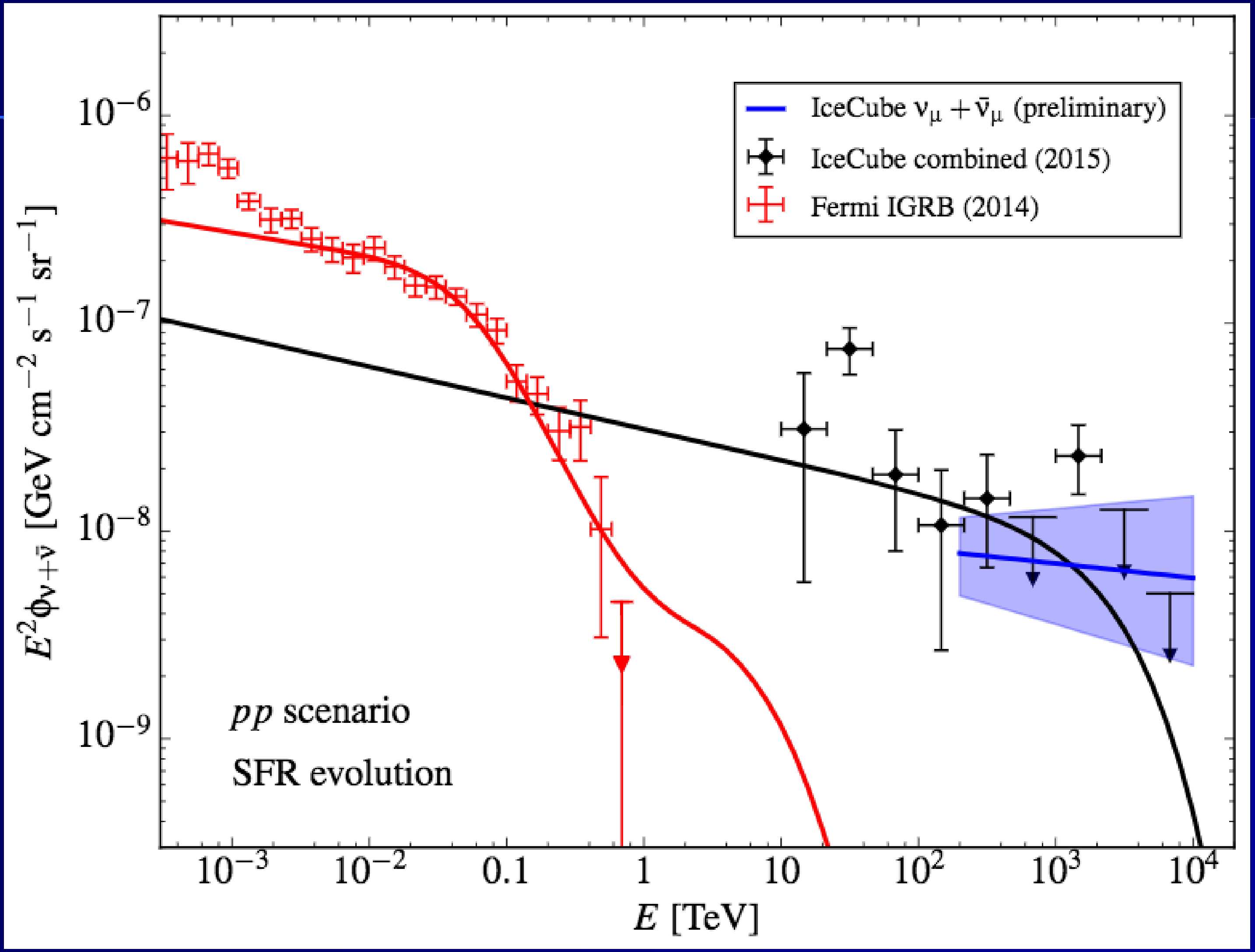
MAGIC detects emission of >100 GeV gammas



Science 361, eaat1378 (2018)
Science 361, 146 (2018)

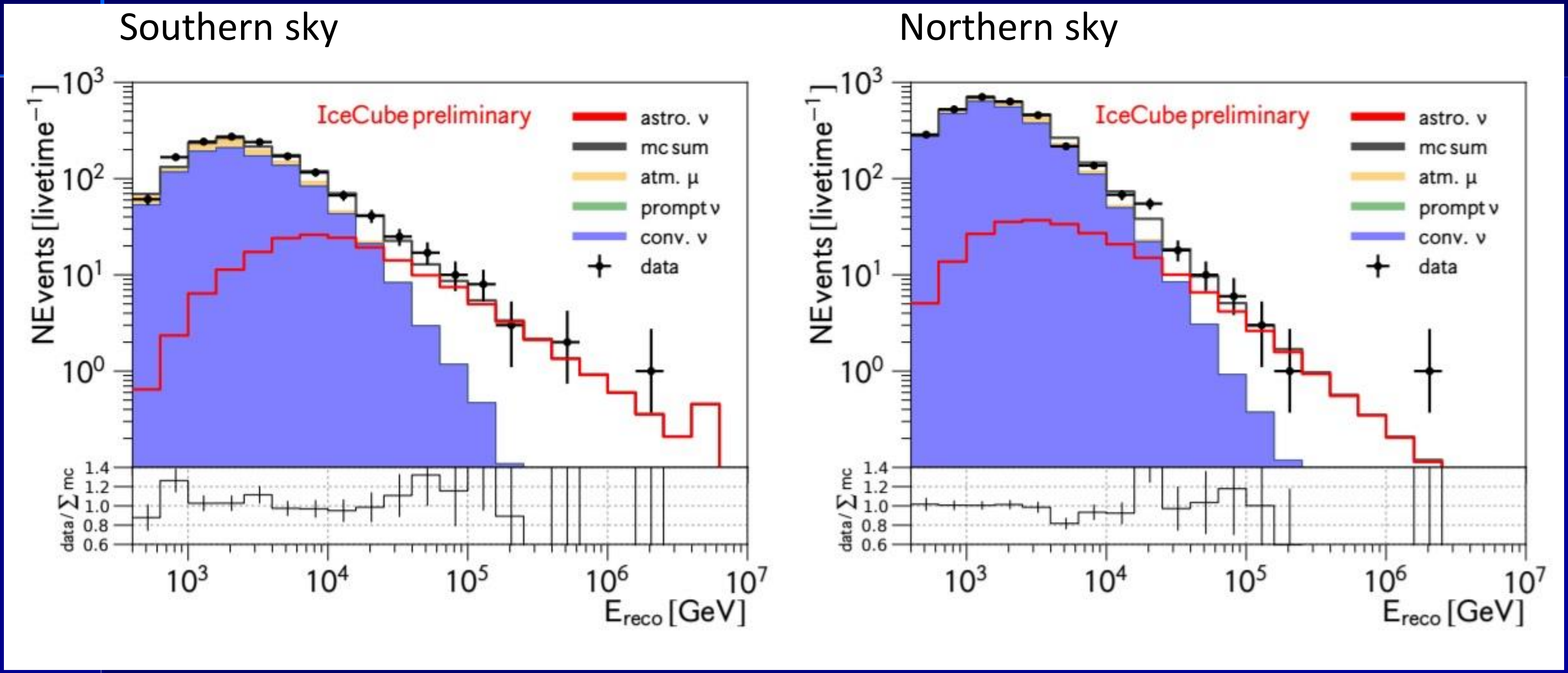
IceCube

Neutrino diffuse flux



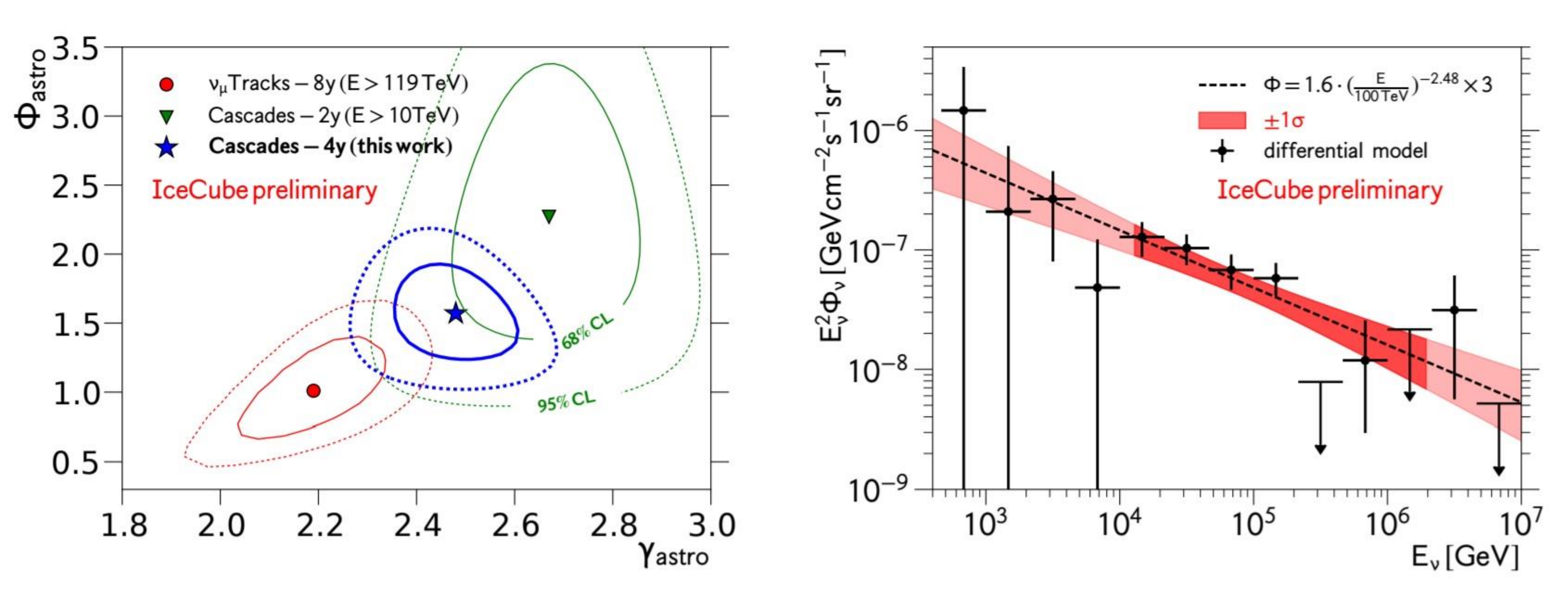
Neutrino diffuse flux

Cascade events (2012-15)



$\Phi = \Phi_0 \, E^{-\gamma}$, $\gamma = 2.48 \pm 0.08$

Neutrino diffuse flux

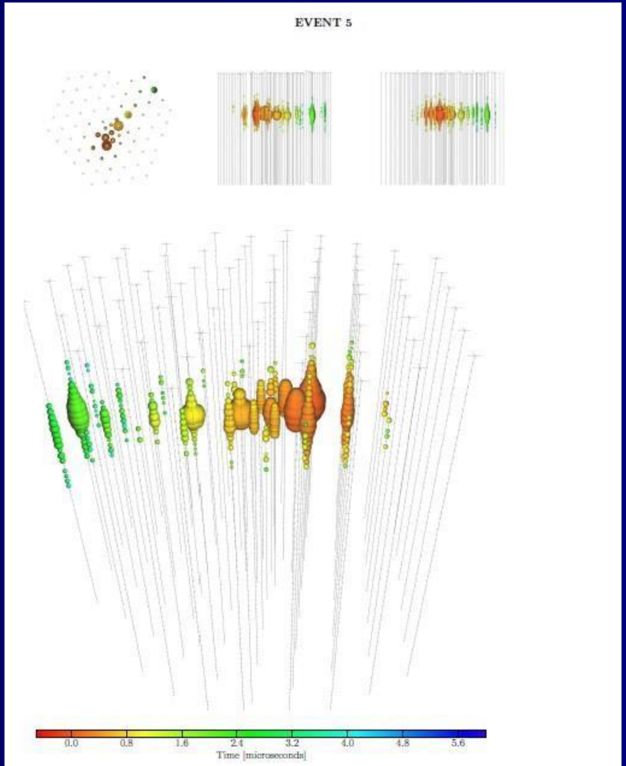


Neutrino diffuse flux

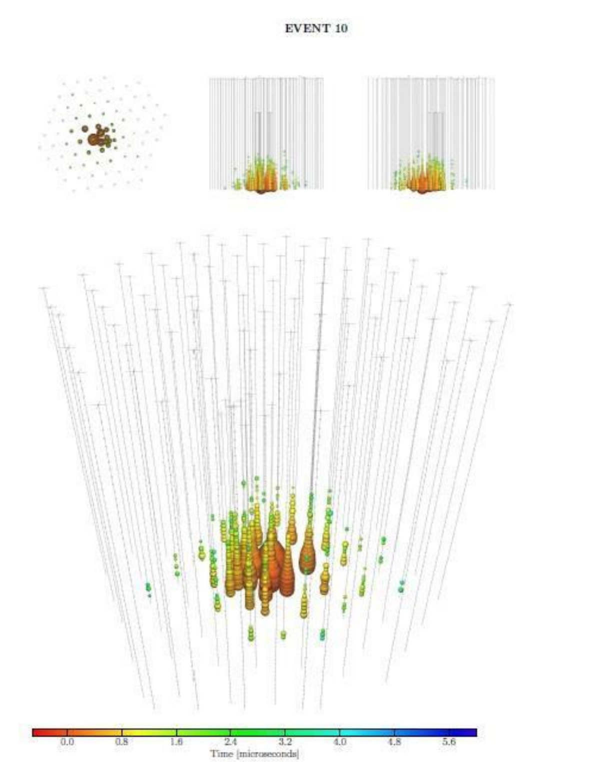
IceCube: Science 22 Vol. 342 no. 6161 (2013), Phys. Rev. Lett.113 (2014) 101101

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

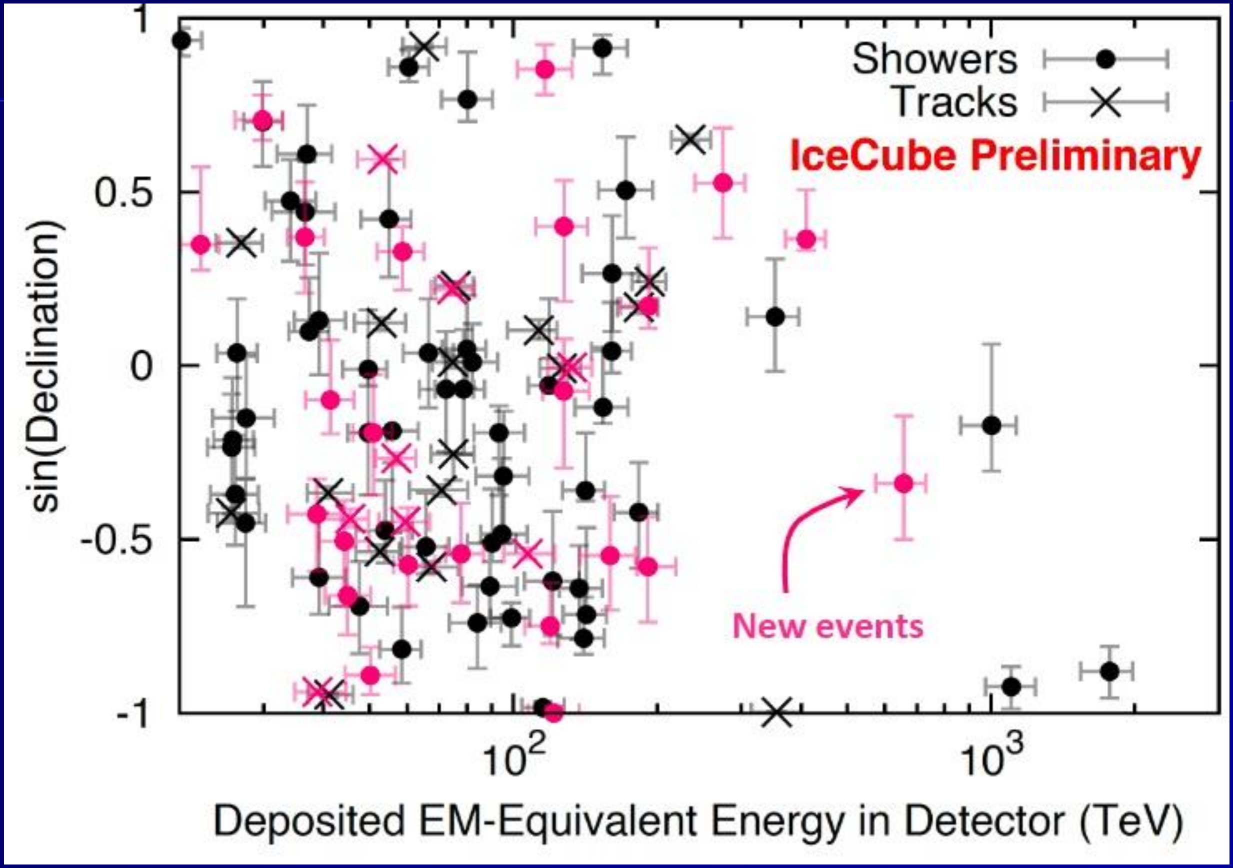
IceCube

Declination vs. deposited energy

Neutrino2018, 7.5 years of data

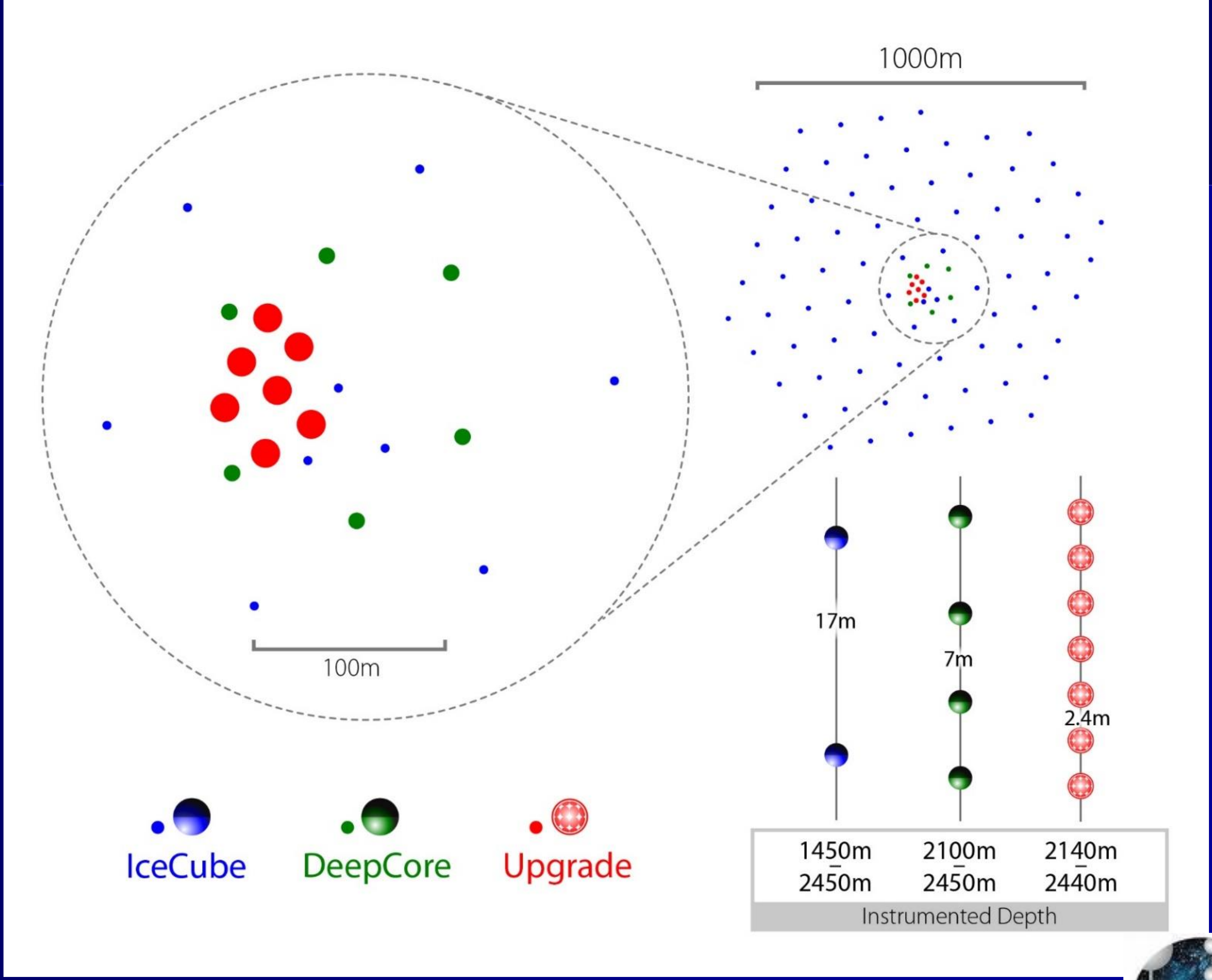
A few observations.

- Signal contains 60 events above 60 TeV
- 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



Future Plans, IceCube-Gen2

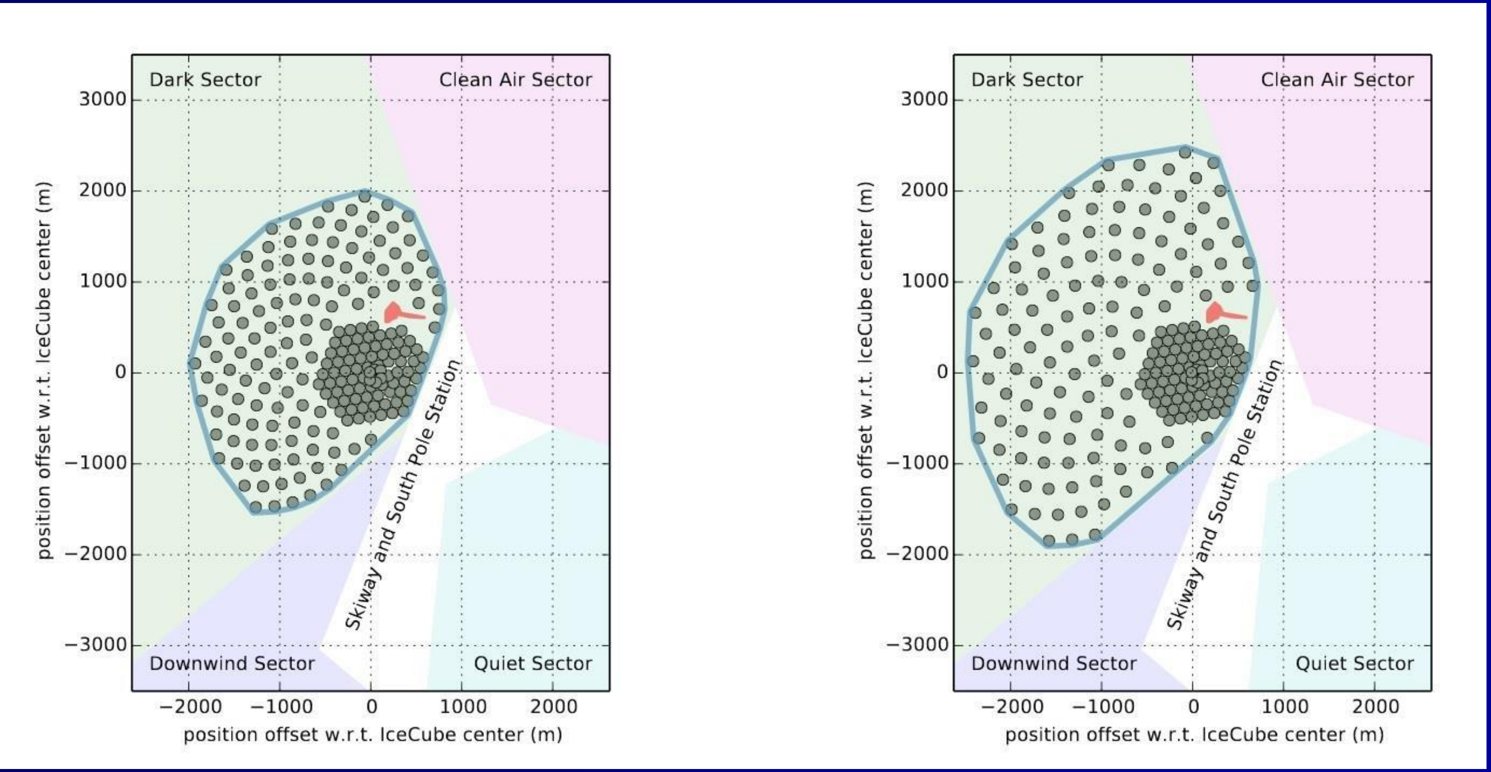
- Designed for GeV Neutrinos
- Tau Neutrino Appearance
- Dark matter searches
- 125 DOM/string
- 2 m DOM spacing
- 20 m string spacing
- Deployment 22-23
- Funding outlook: positive



Future Plans, IceCube-Gen2

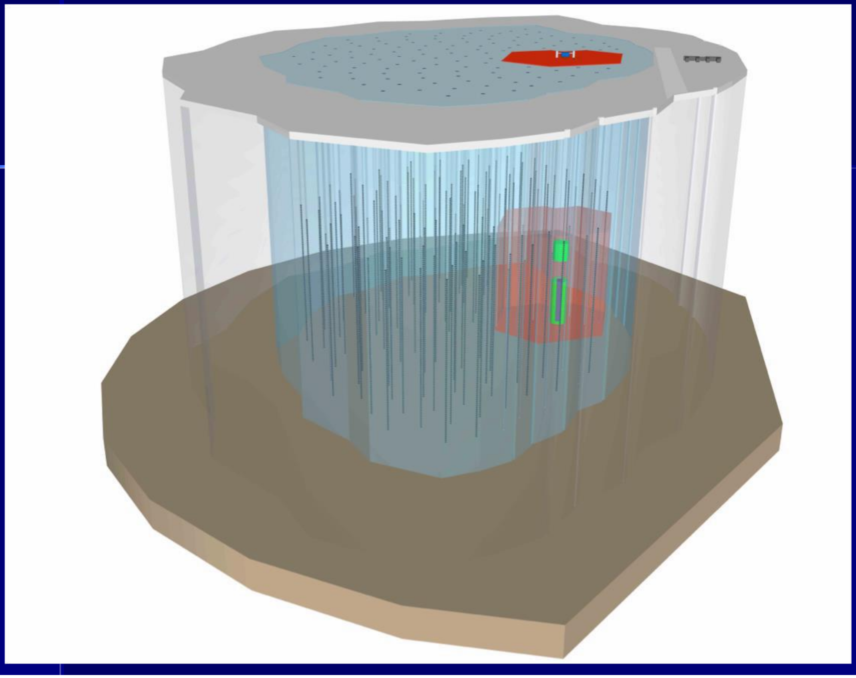
Larger IceCubes, up to more than an order of magnitude in mass/volume. Much higher statistics in the PeV region, much higher energy neutrino acceptance, a deeper view of the cosmos and source ID of high energy neutrino production.

240 m Spacing

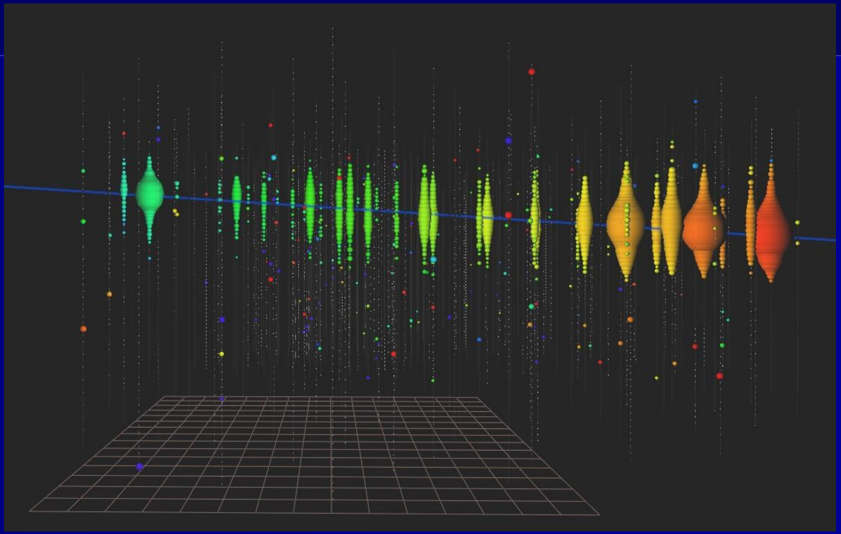


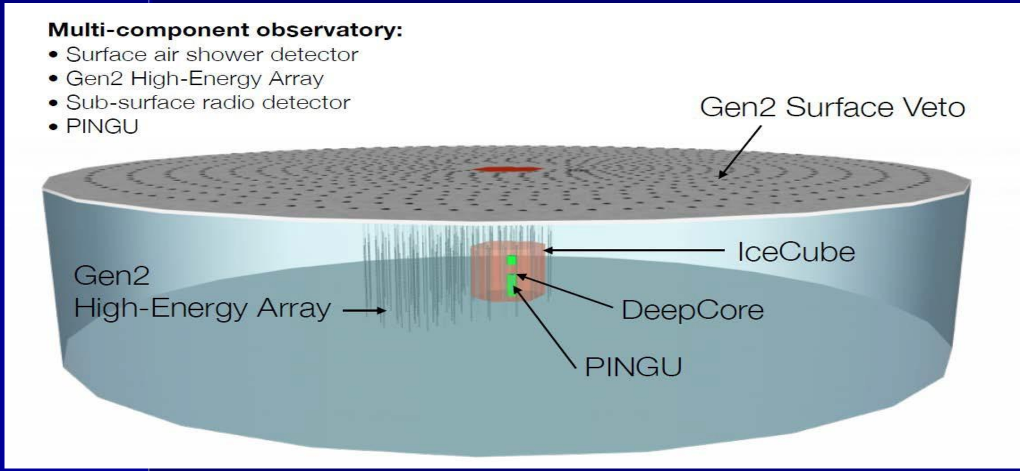
300 m spacing

Future Plans, IceCube-Gen2



A simulated 60-PeV horizontal muon





Completion date 2032!

Conclusions and Outlook

- IceCube has answered the century old question about the origin of the high energy cosmic rays.
- Real-time coincidence measurements are now possible with other detectors, such as optical, X-ray, gamma-ray in the form a Multi-Messenger approach to astronomy.
- IceCube has observed, High Energy Astrophysical Neutrinos and has opened the era of neutrino astronomy.
- Future plans: IceCube Extensions for Higher Energies and dense array for Neutrino Mass Hierarchy, Dark matter, Tau neutrino appearance … …