IceCube and the future of Astroparticle Physics from the South Pole

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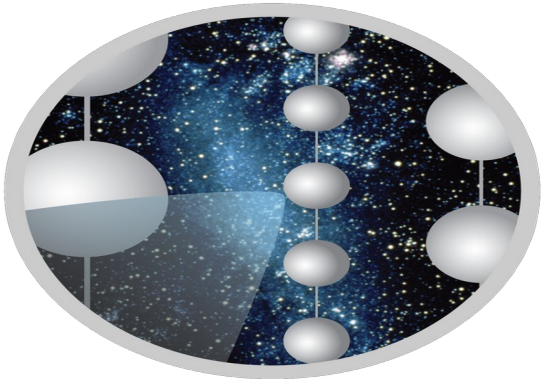
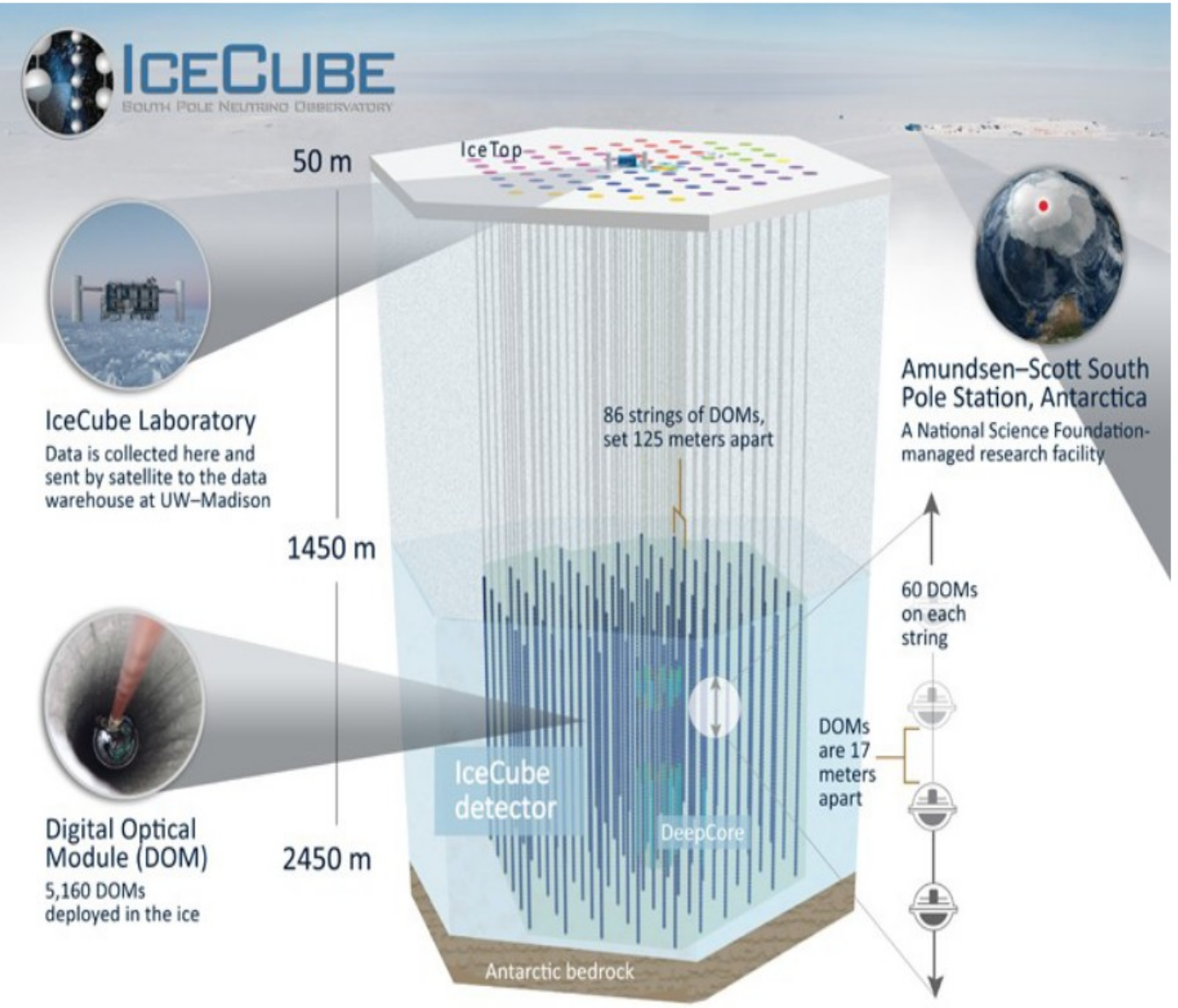
XXV DAE-BRNS High Energy Physics Symposium
December 12th – 16th, 2022

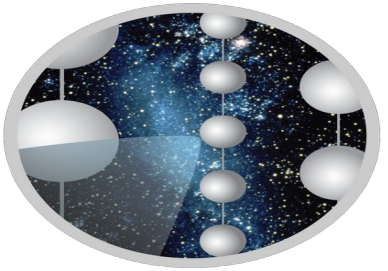


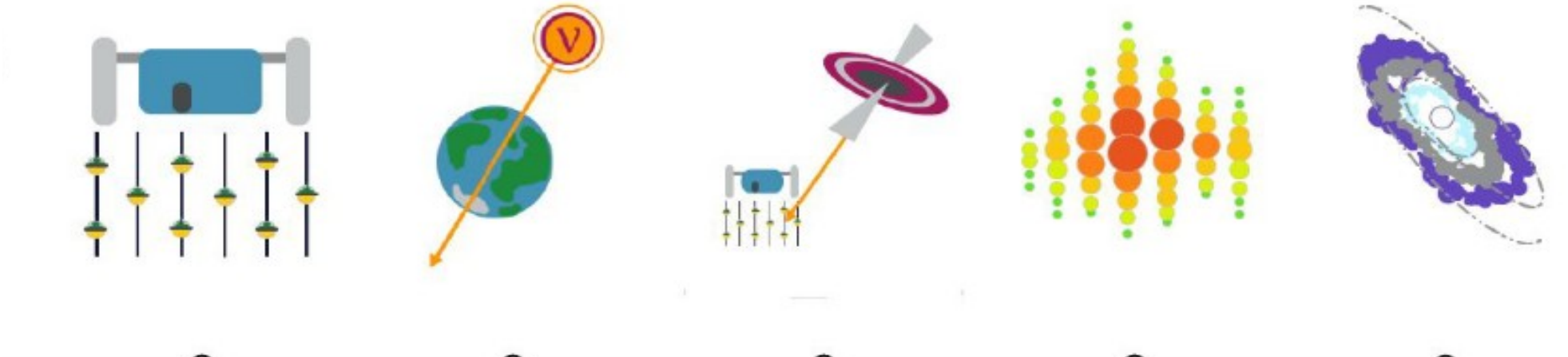
IceCube detector



- 1 km^3 volume
- 5160 PMTs
- 86 strings
- 17 m vertical spacing b/w DOMS
- 125 m horizontal string spacing
- Completed 2010
- Fully operational since 2011

History of neutrino astronomy in Antartica





2011
IceCube Completed

2013
Astrophysical Neutrinos Discovered

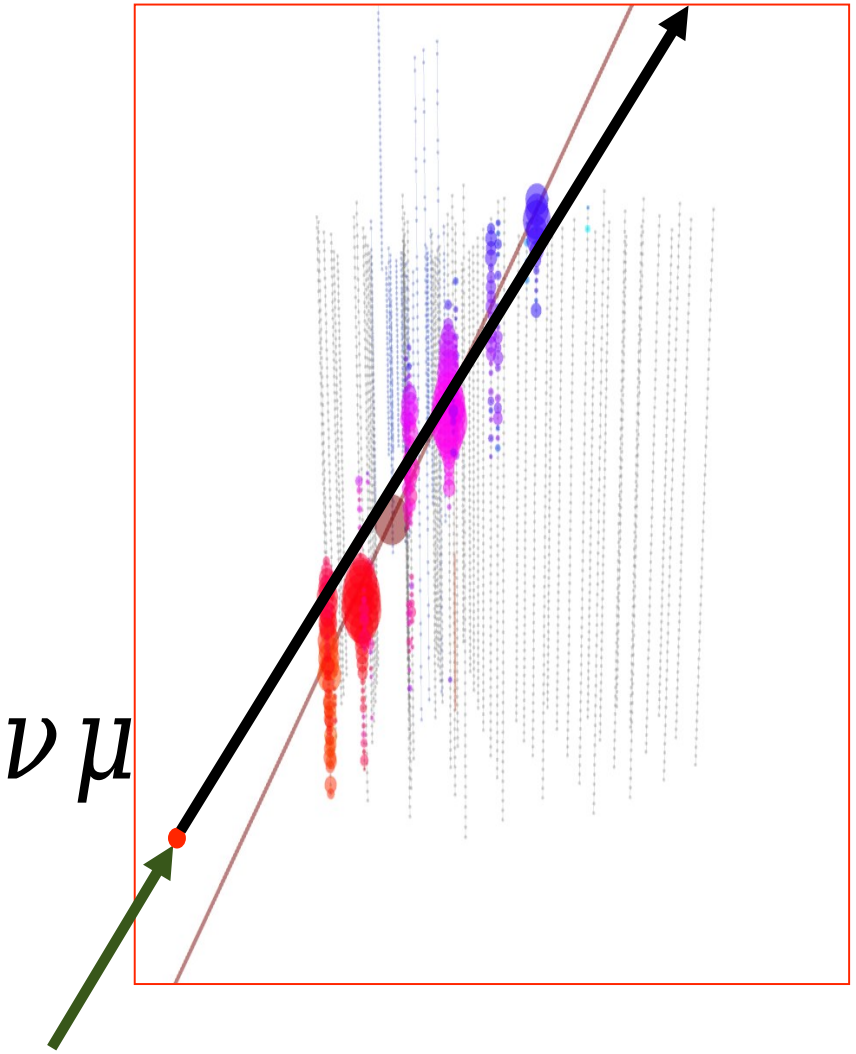
2018
First Source TXS 0506+056 Identified

2021
Glashow Resonance Neutrino Identified

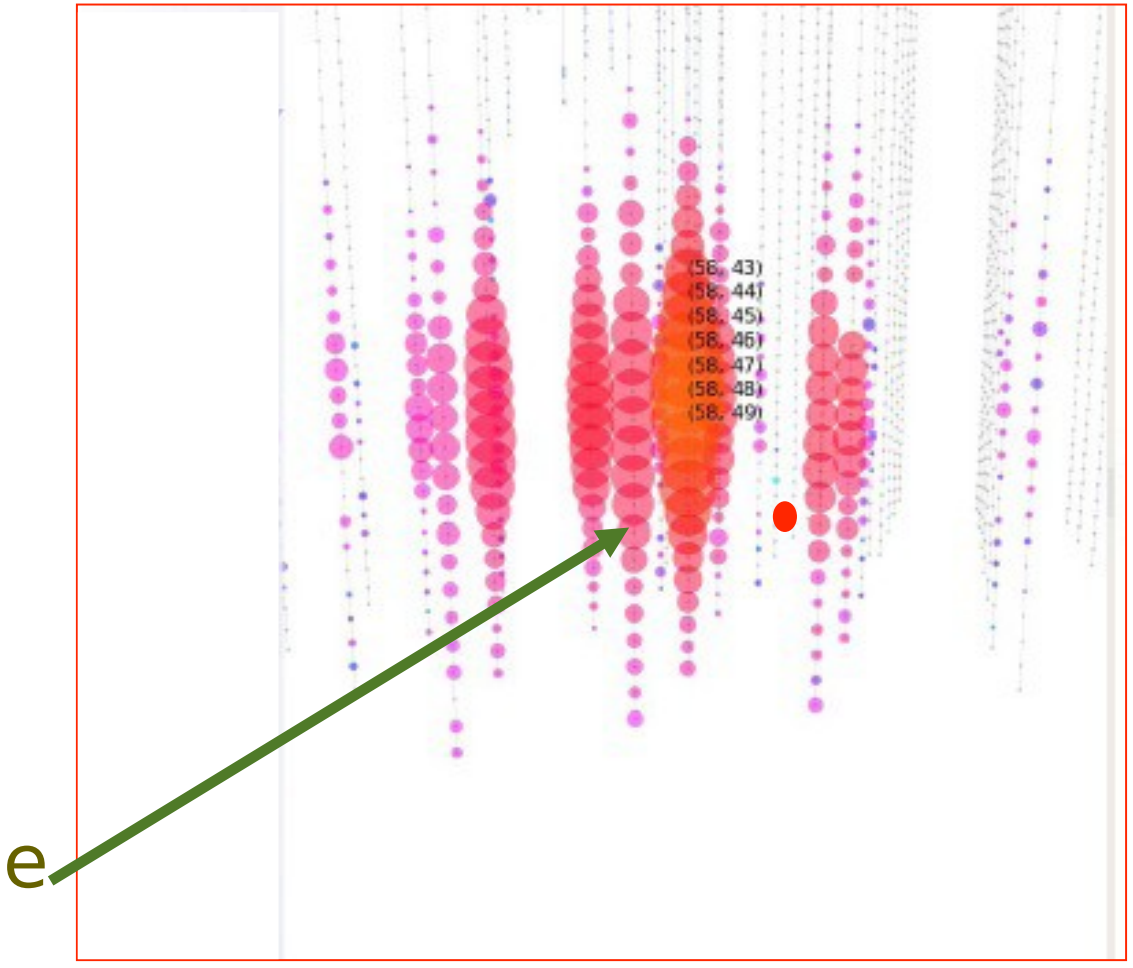
2022
Second Source NGC 1068 Identified

In-ice signatures

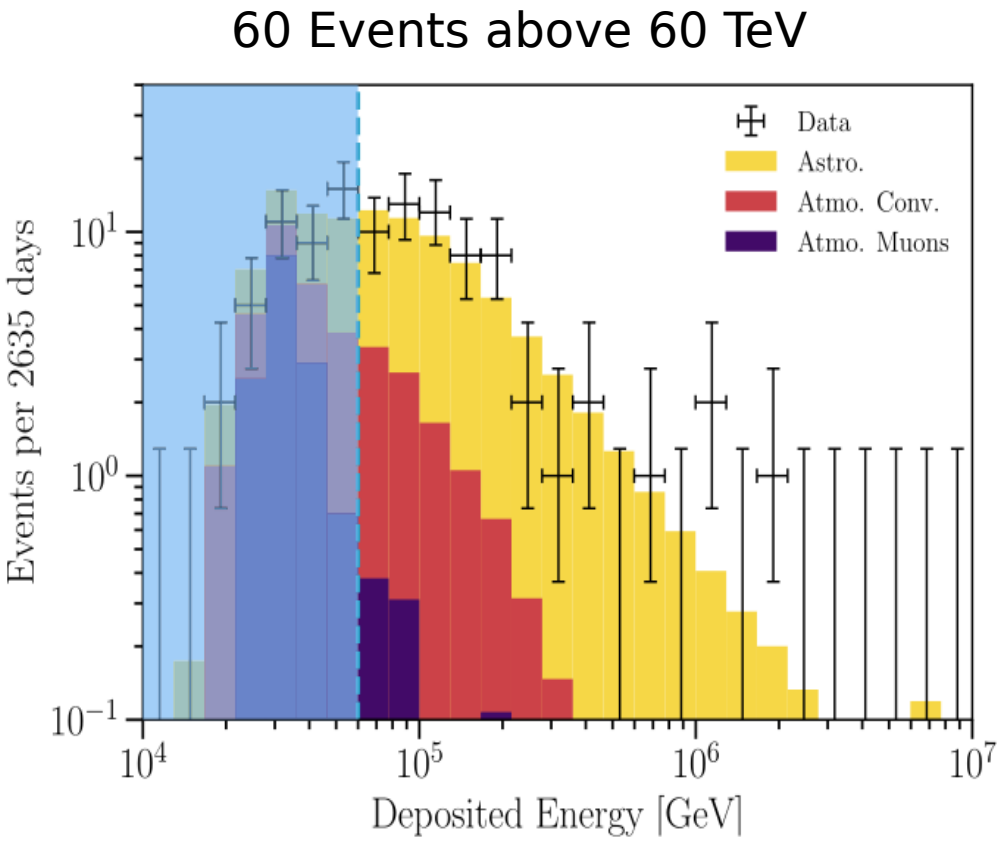
Muon tracks→ ν_μ (CC)

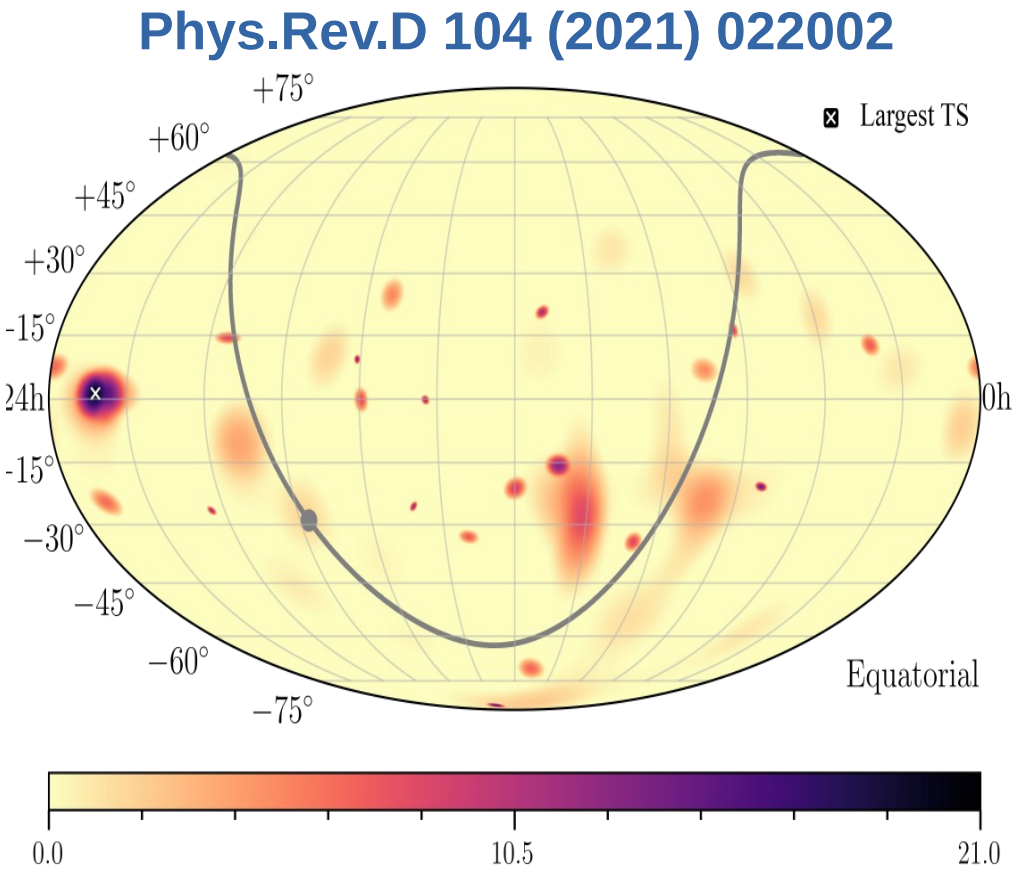


cascades → all flavors



The IceCube astrophysical flux (7.5 years of data)



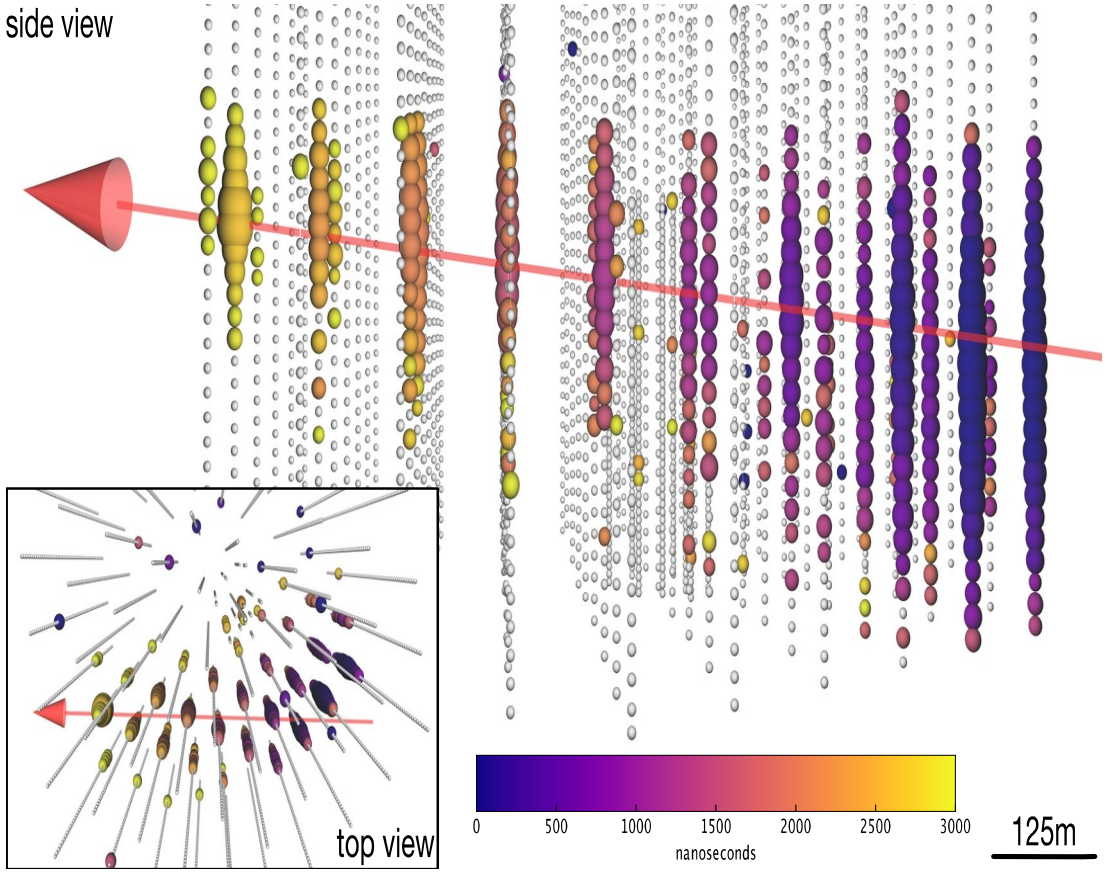


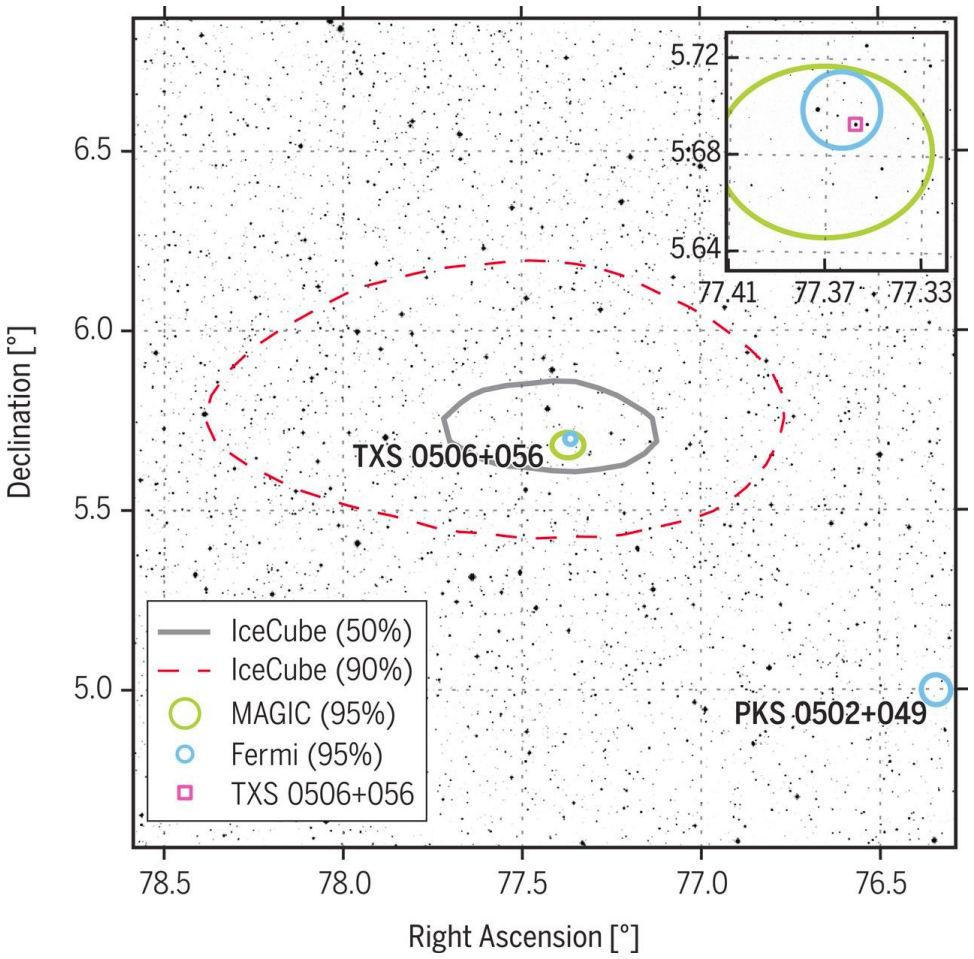
- **IceCube flux is mainly dominated by astrophysical neutrinos.**
- **The brightest point source is well separated from galactic plane.**

Multi-messenger alerts: TXS 0506+056

Science 361, eaat1378 (2018)

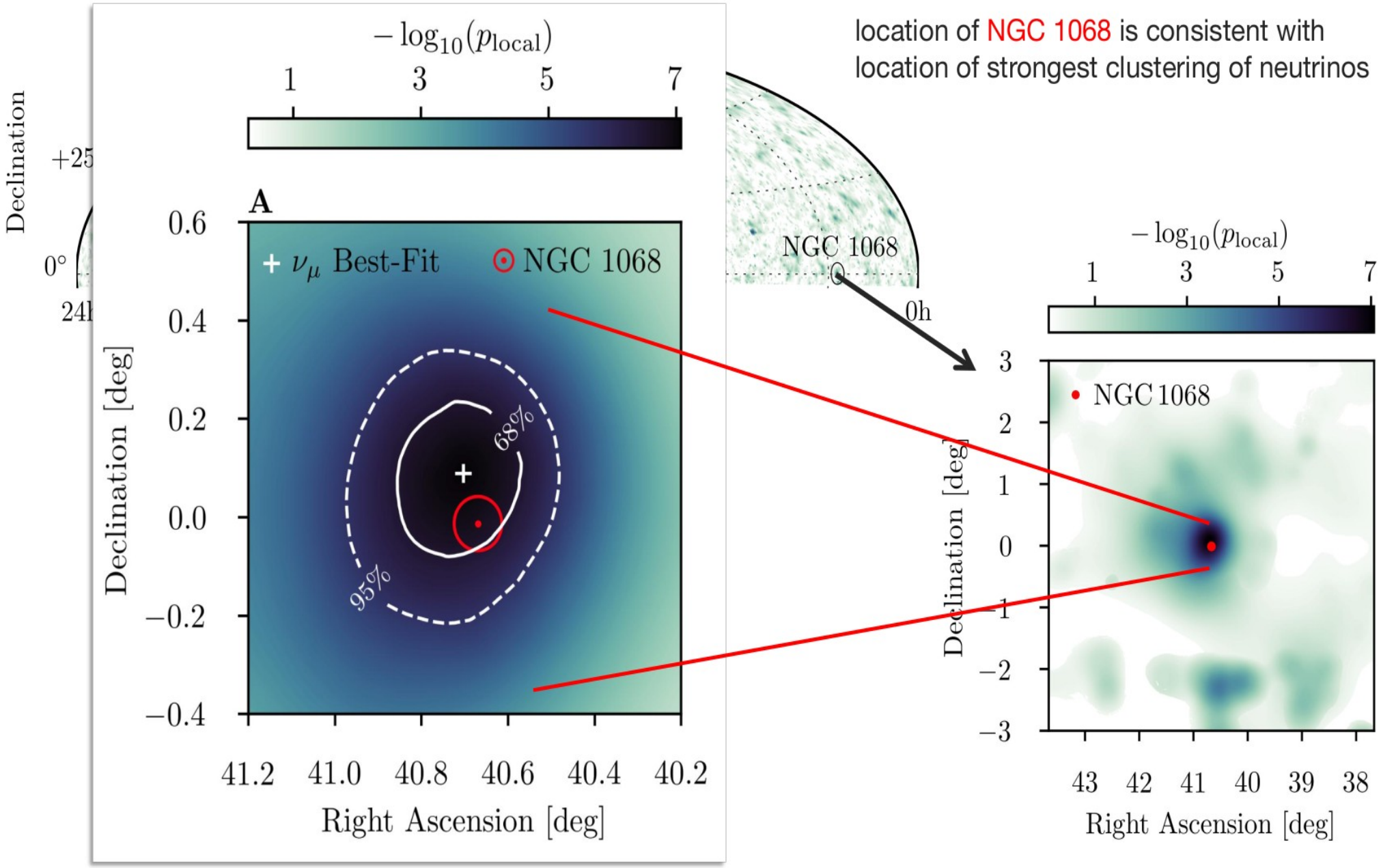
- **Positionally consistent with blazar TXS 0506+056**
- **~290 TeV estimated neutrino energy**





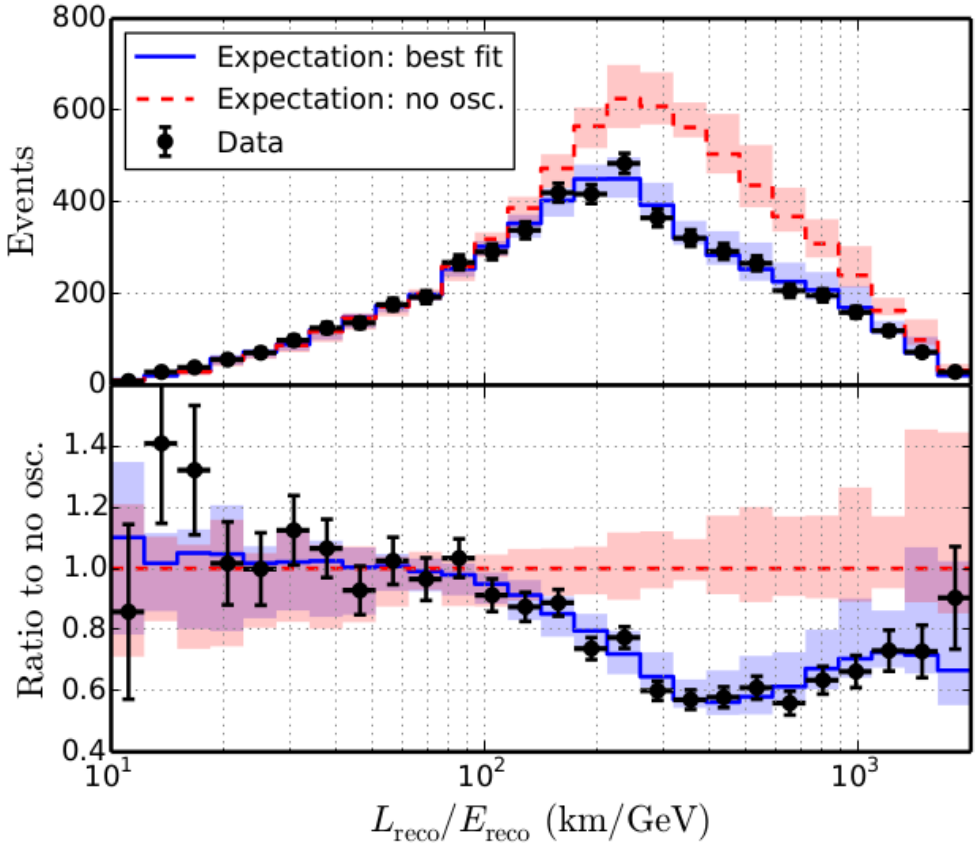
Recent NGC 1068

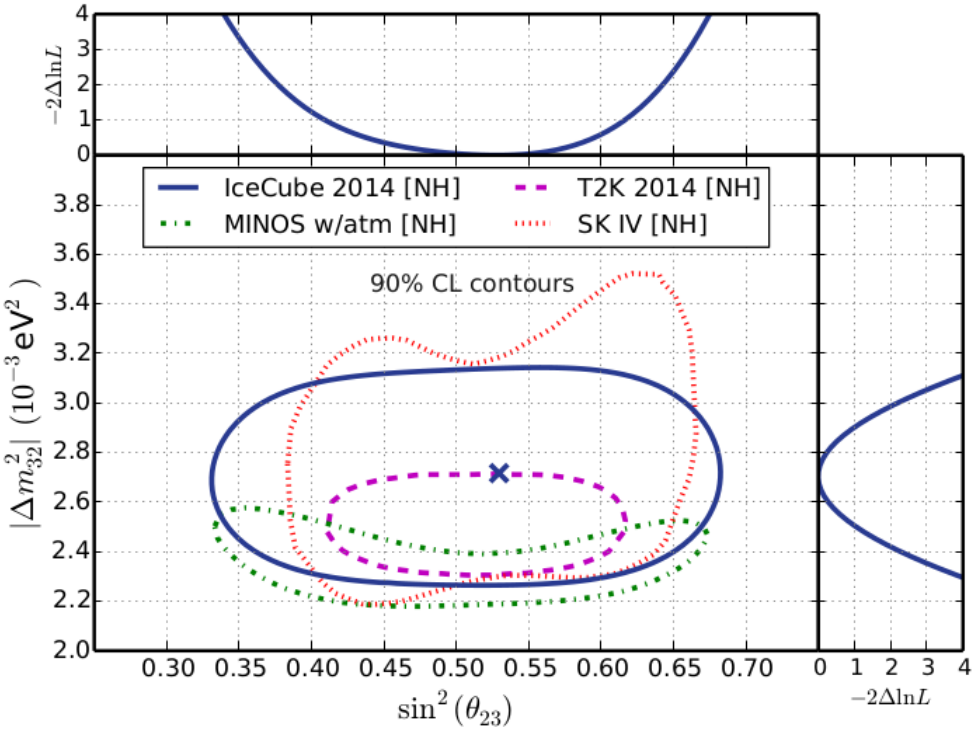
location of NGC 1068 is consistent with location of strongest clustering of neutrinos



Neutrino oscillations

Phys. Rev. D 91, 072004 (2015)





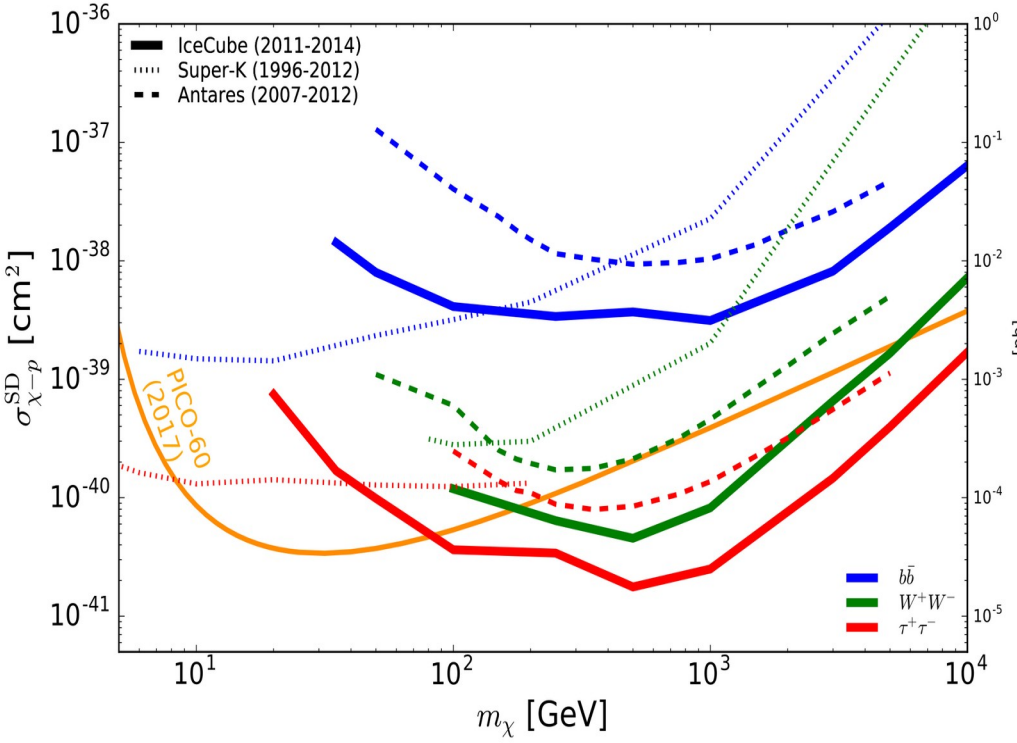
The transition probability between the two flavor eigen-states is given by:

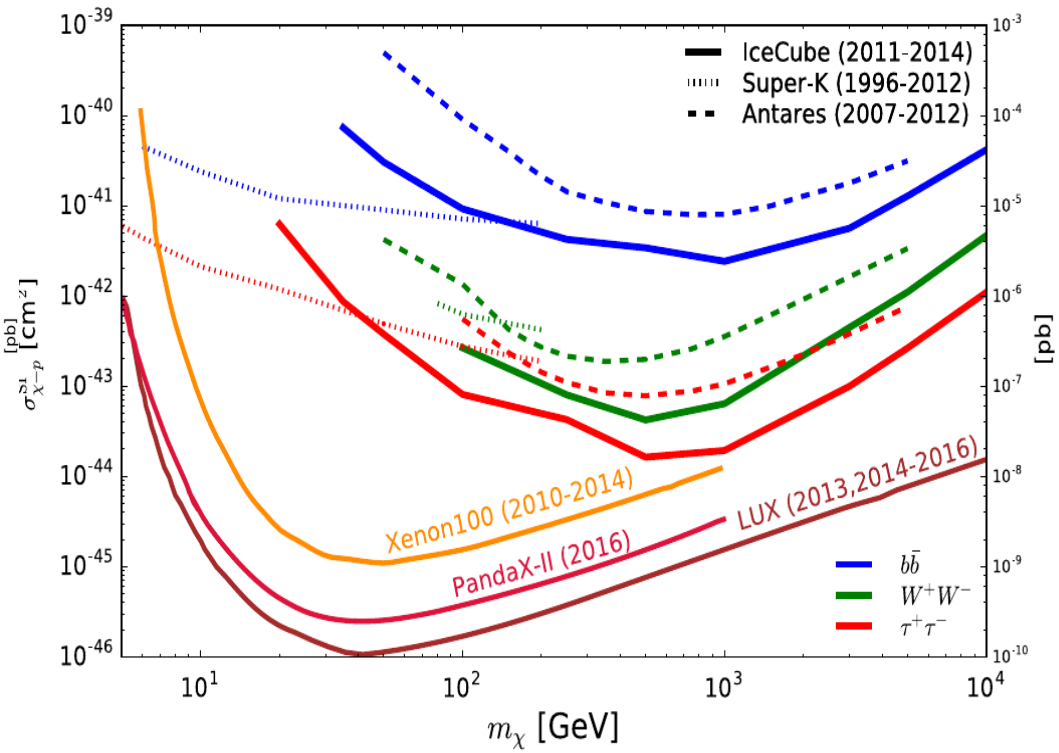
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\,\sin^2\left(\Delta m^2\,\frac{L}{4\,E_\nu}\right)$$

- **90% CL contours for the oscillation parameters, obtained from IceCube data is compatible with results from other experiments.**

Dark matter

Eur. Phys. J. C (2017) 77:146





- **For spin dependent scattering, IceCube has better limits as compared to direct detection experiment.**
- **Direct detection experiments have more stringent constraints for Spin Independent scattering.**

Galactic neutrino flux @ 7 years of IceCube data

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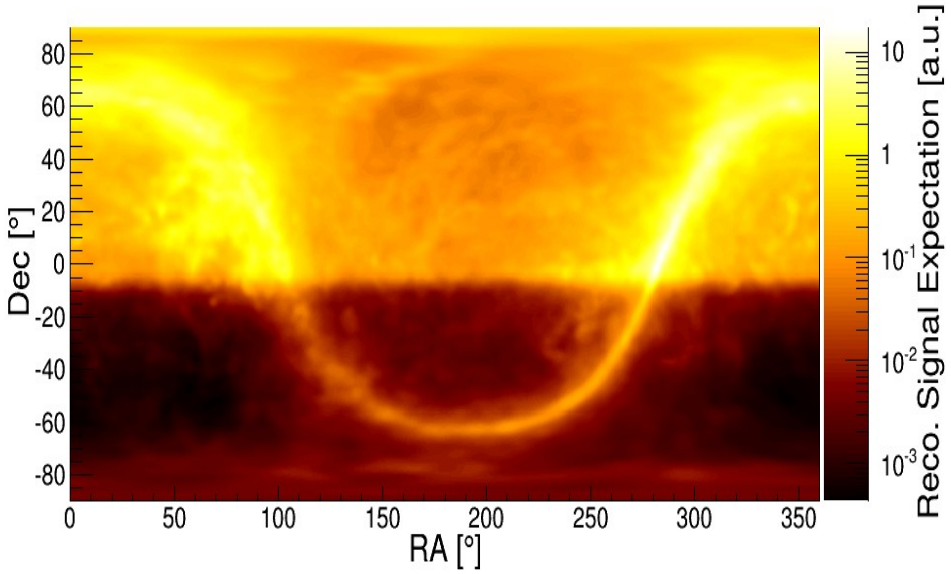
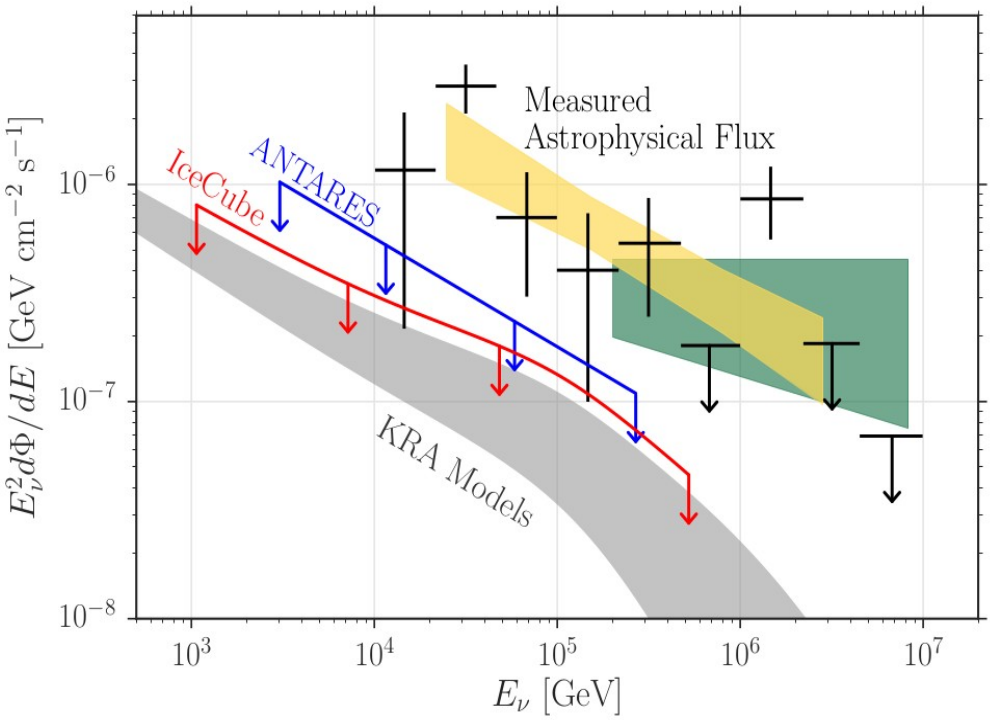
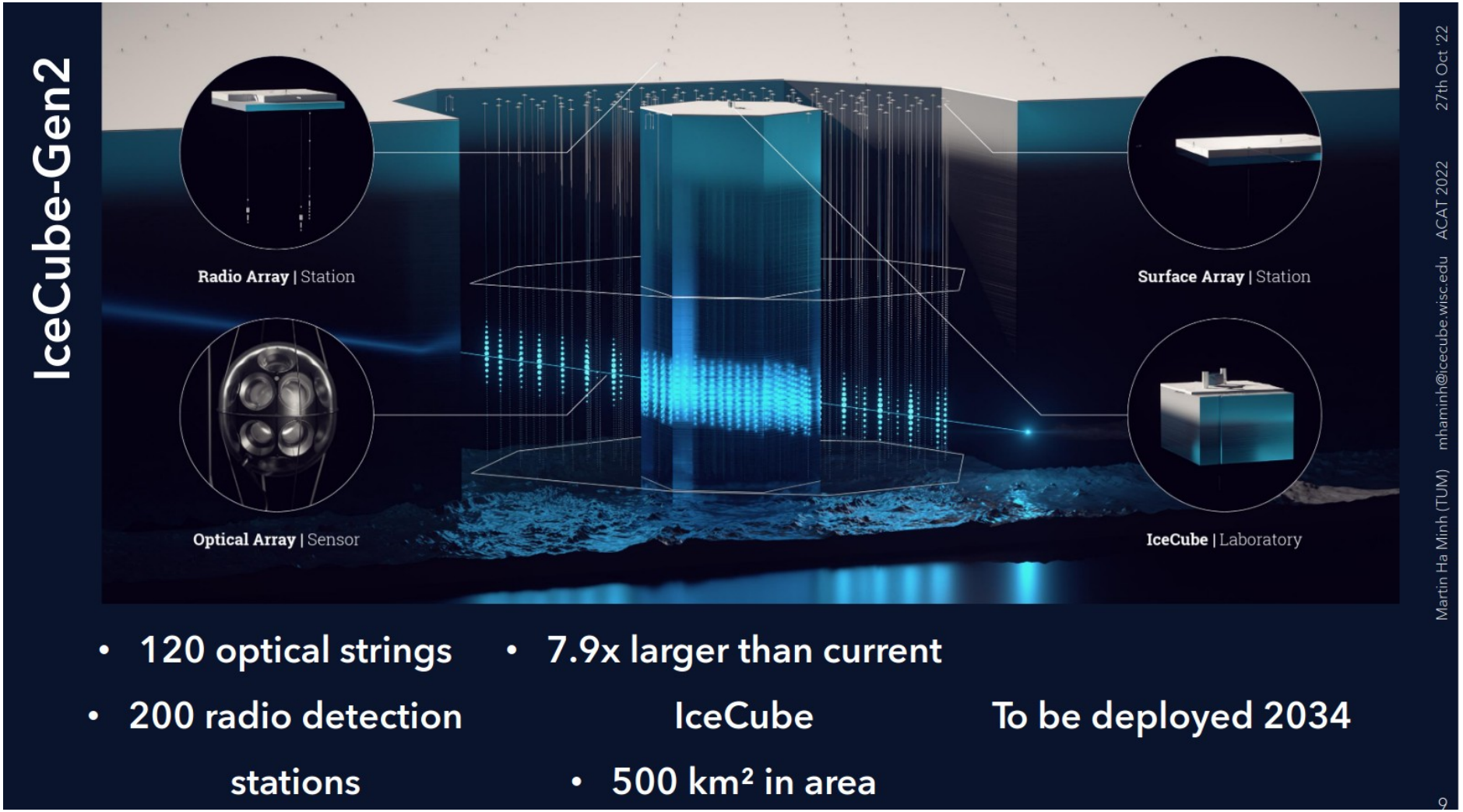




- **Distribution of neutrino events fitted to ps template while using Fermi decay model.**

- **Fluxes are integrated over full sky, with upper limits at 90% confidence level.**
- **Gray band : predictions of KRA models.**
- **Red → IceCube 7 year data upper limit.**
- **Green band → only using northern sky muon data**

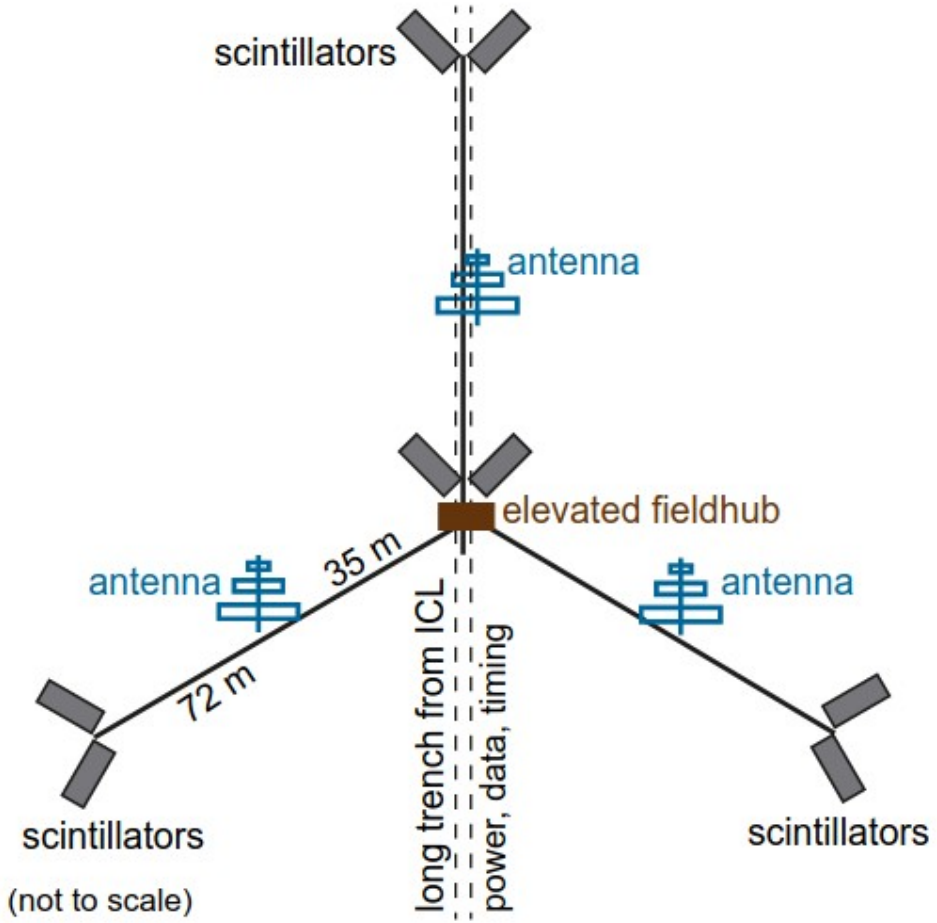
IceCube Gen-2

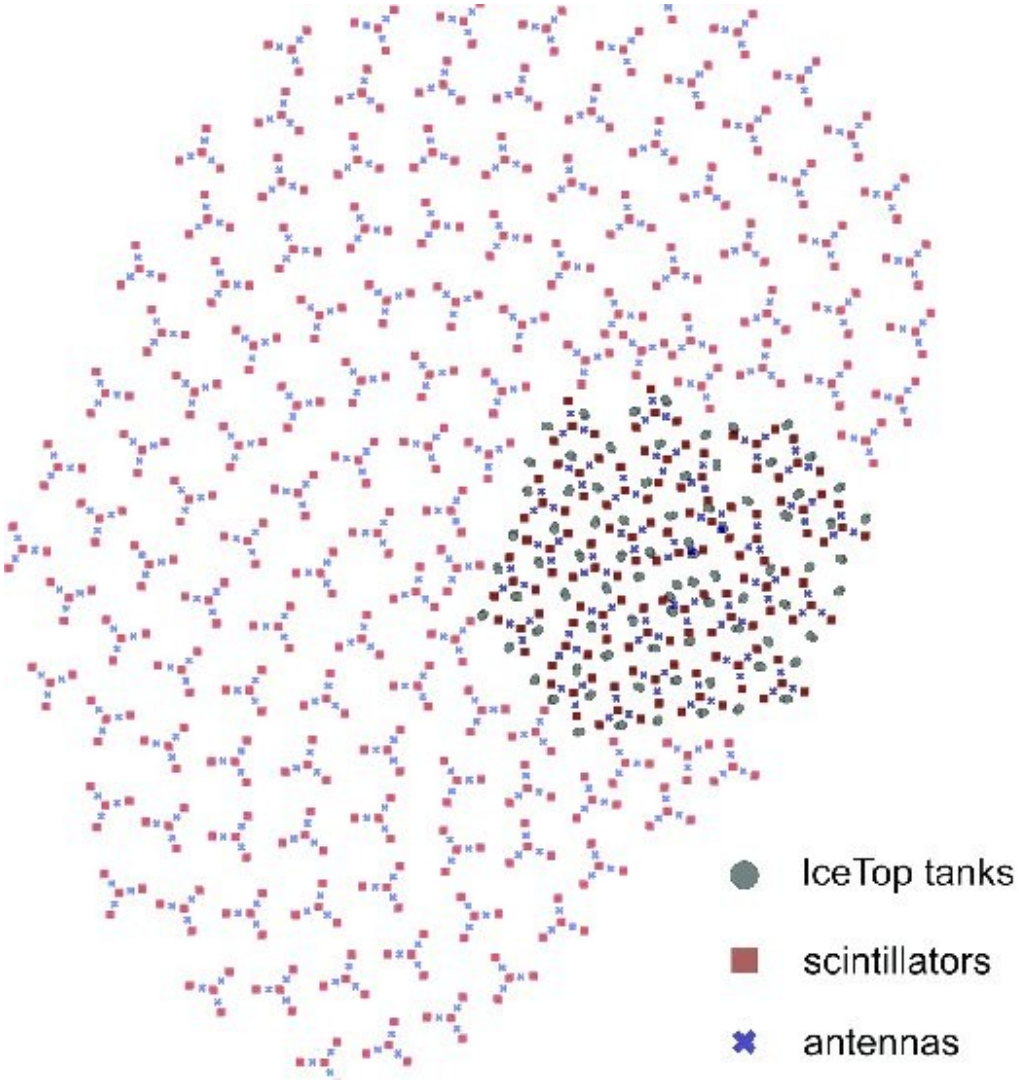


Physics motivation:

- **Resolve the high-energy neutrino sky from TeV to EeV energies**
- **Investigate cosmic particle acceleration through multi-messenger observations**
- **Reveal the sources and propagation of the highest energy particles in the universe**
- **Probe fundamental physics with high-energy neutrinos**

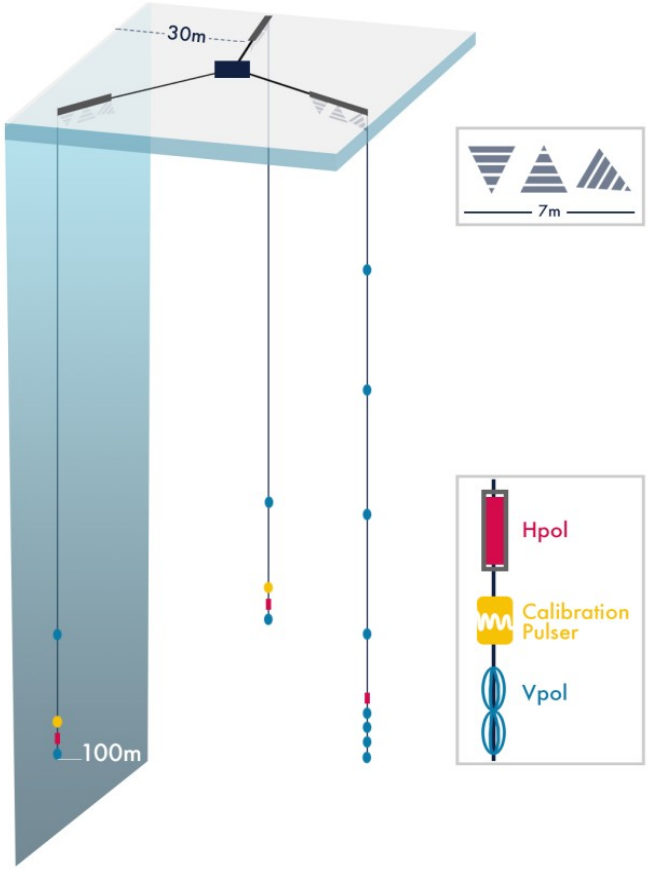
Gen-2 surface array





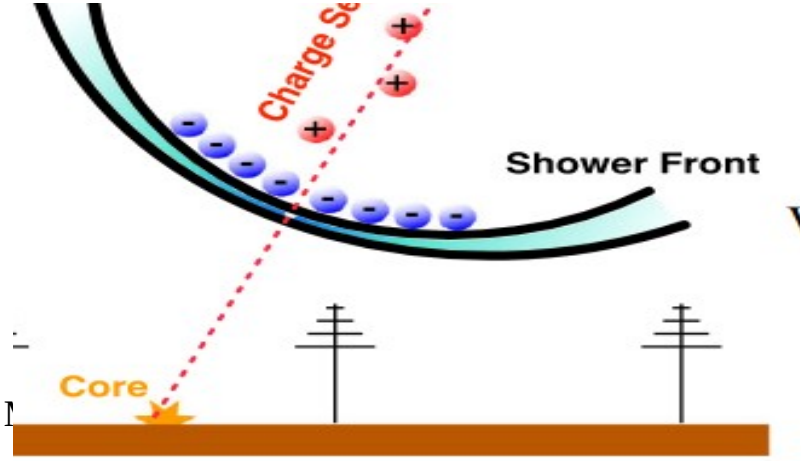
- **Total 120 hybrid stations**
- **Each station consists of 8 scintillators and 3 radio antennas.**

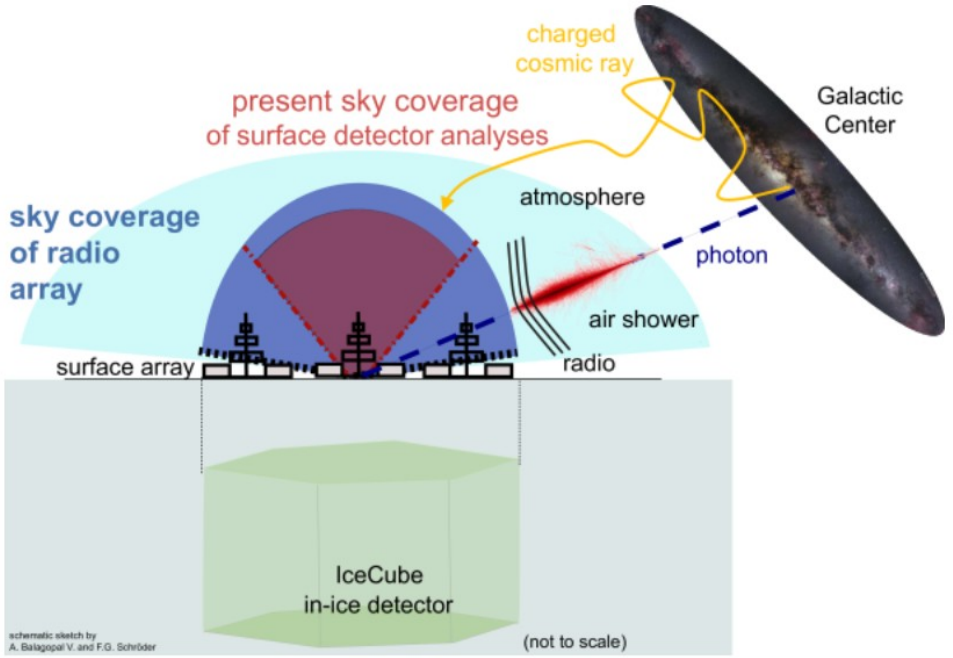
Gen-2 radio array



- **Total 200 hybrid radio stations, made up of shallow and deeper antennas.**

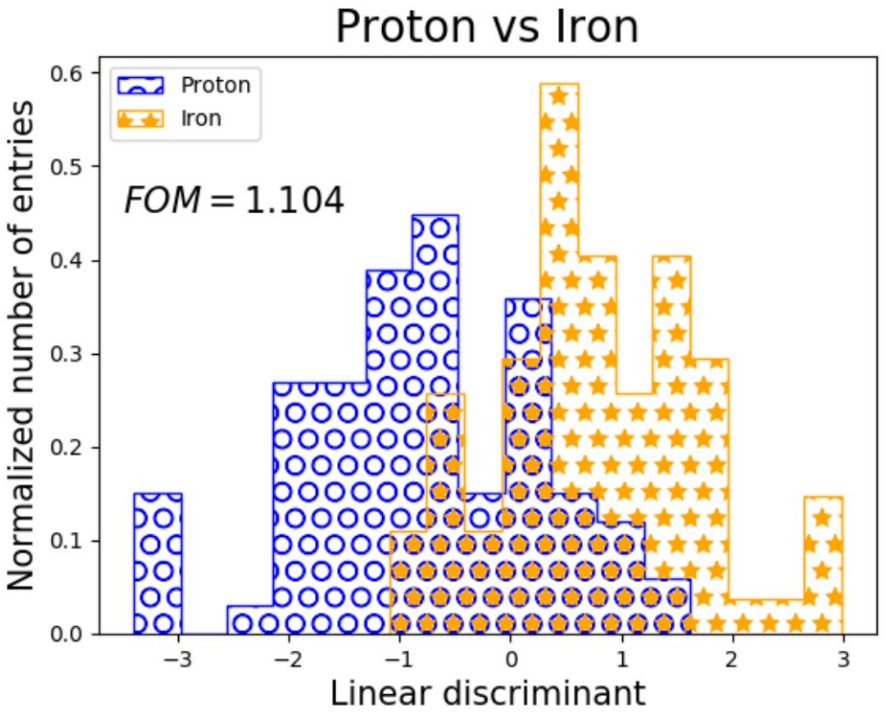
Askaryan effect: **The electromagnetic component of the shower evolves over time as additional electrons are up-scattered from the ice, leading to a relativistically moving negative charge excess in the shower front and a charge separation along the shower axis. A dipole is formed that changes as the shower develops and thereby emits radiation.**



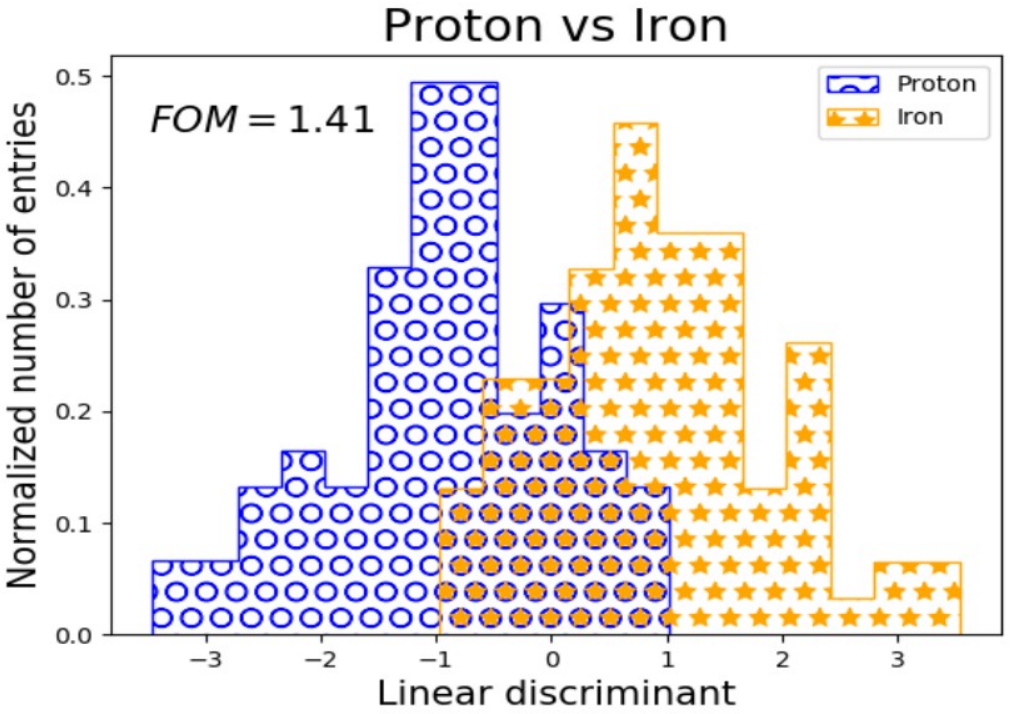


Composition sensitivity studies for IceCube Gen-2

Case 1: surface array only



Case 2: surface array + InIce



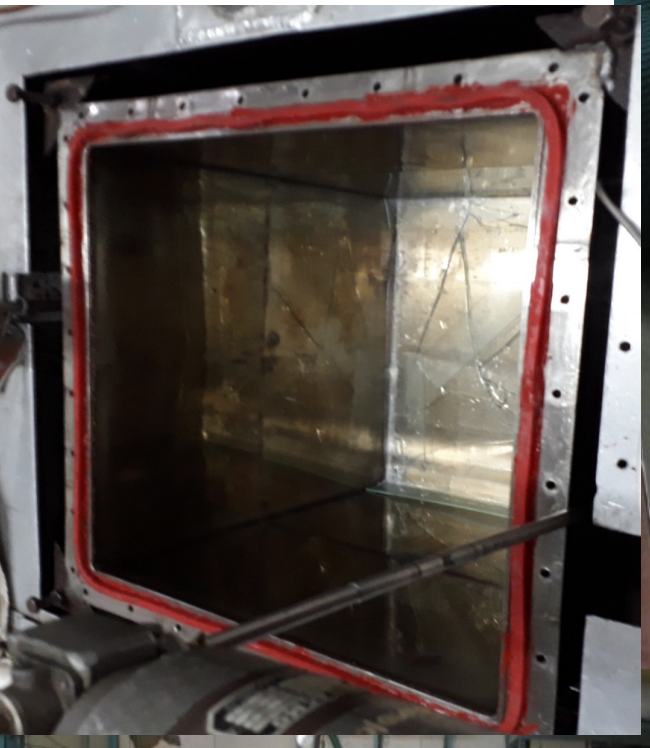
$$FOM = \frac{|\mu_p - \mu_i|}{\sqrt{\sigma_p^2 + \sigma_i^2}}$$

Where i = Fe, O, He

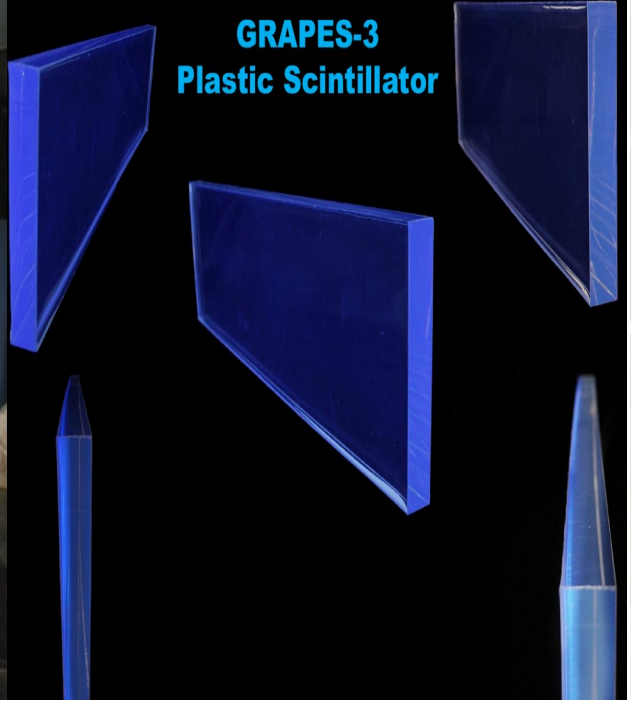
Primaries	Case 1	Case 2
Proton vs Iron	1.104	1.41
Proton vs Oxygen	0.89	0.991
Proton vs Helium	0.29	0.442

Possibilities of Indian contribution @ hardware aspects

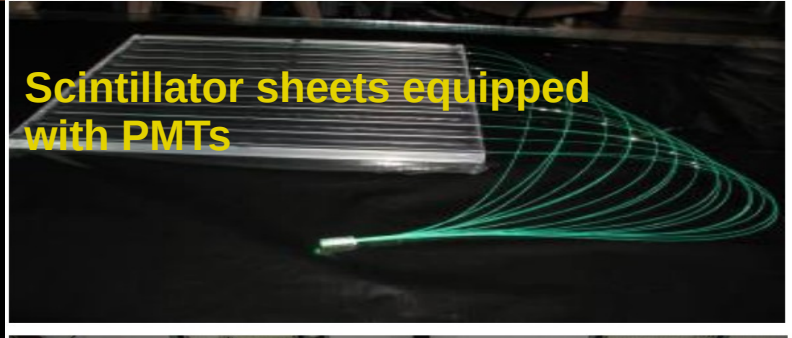
Cast for scintillator sheet fabrication, with silicon oil bath



Uniform distribution of grains in trays



Scintillator sheets equipped with PMTs



Summary

- **The astrophysical neutrino flux measurements are done using the IceCube data, followed by discovery of two extra-galactic neutrino sources: TXS 0506+056 and NGC 1068, which contribute ~ 1% of extragalactic neutrino flux.**
- **IceCube data measurements on neutrino oscillations is compatible with results from other experiments.**
- **IceCube has the world-best limits for the spin dependent scattering cross-sections for dark matter.**
- **IceCube upper limits for galactic neutrino flux is at 90% confidence level.**
- **Deployment of radio array during IceCube Gen-2 will increase the sky coverage.**
- **Simulation studies for IceCube Gen-2 confirms that it will enhance the composition sensitivity studies.**
- **Indian institutes are fully capable to make hardware contribution towards IceCube Gen-2.**


BACKUP

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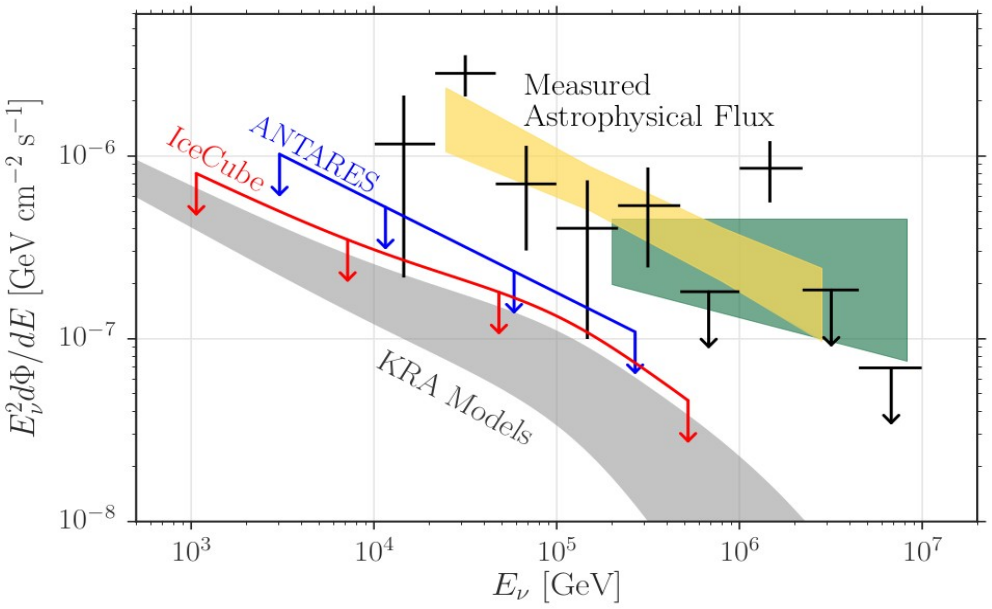
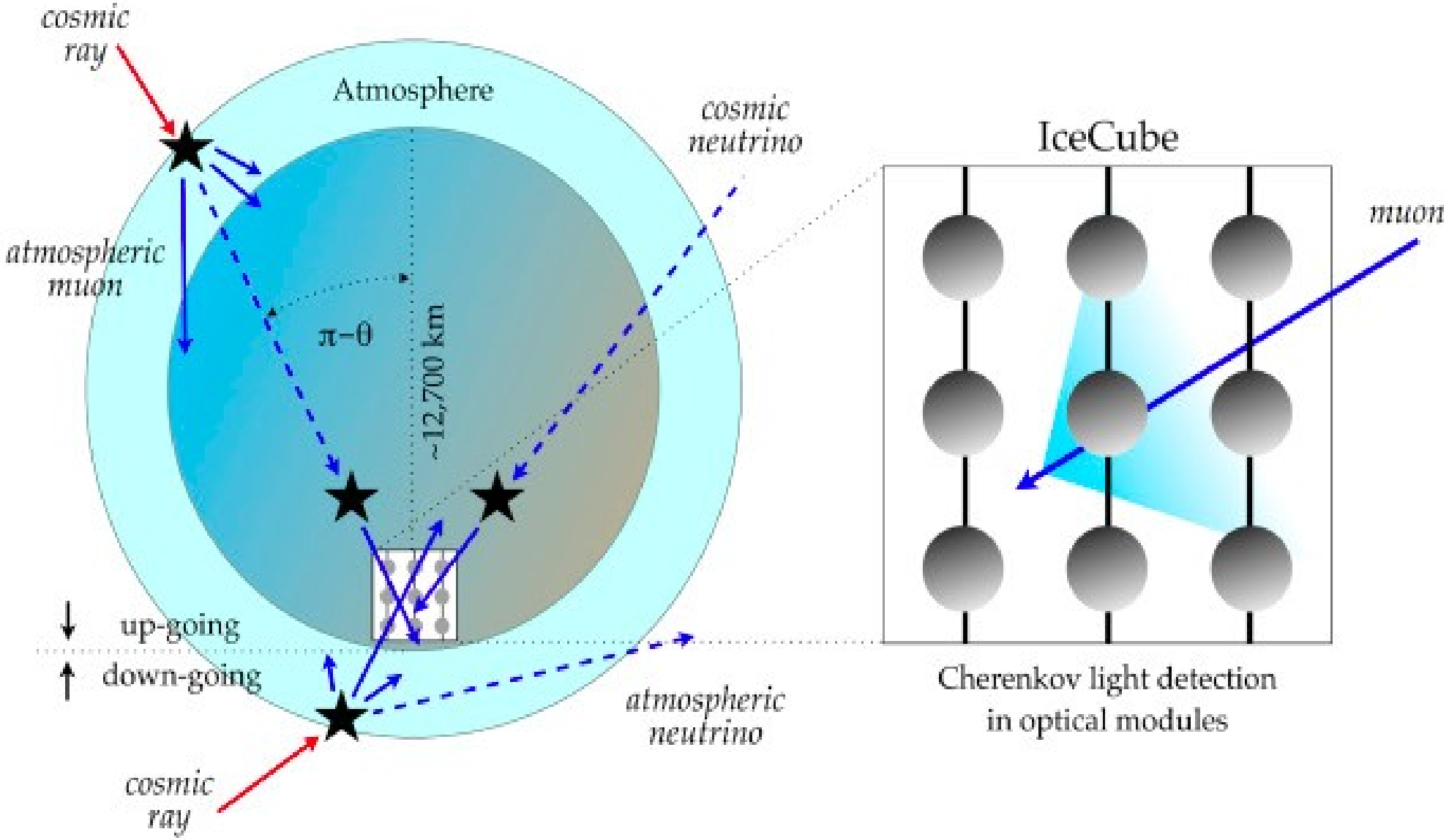
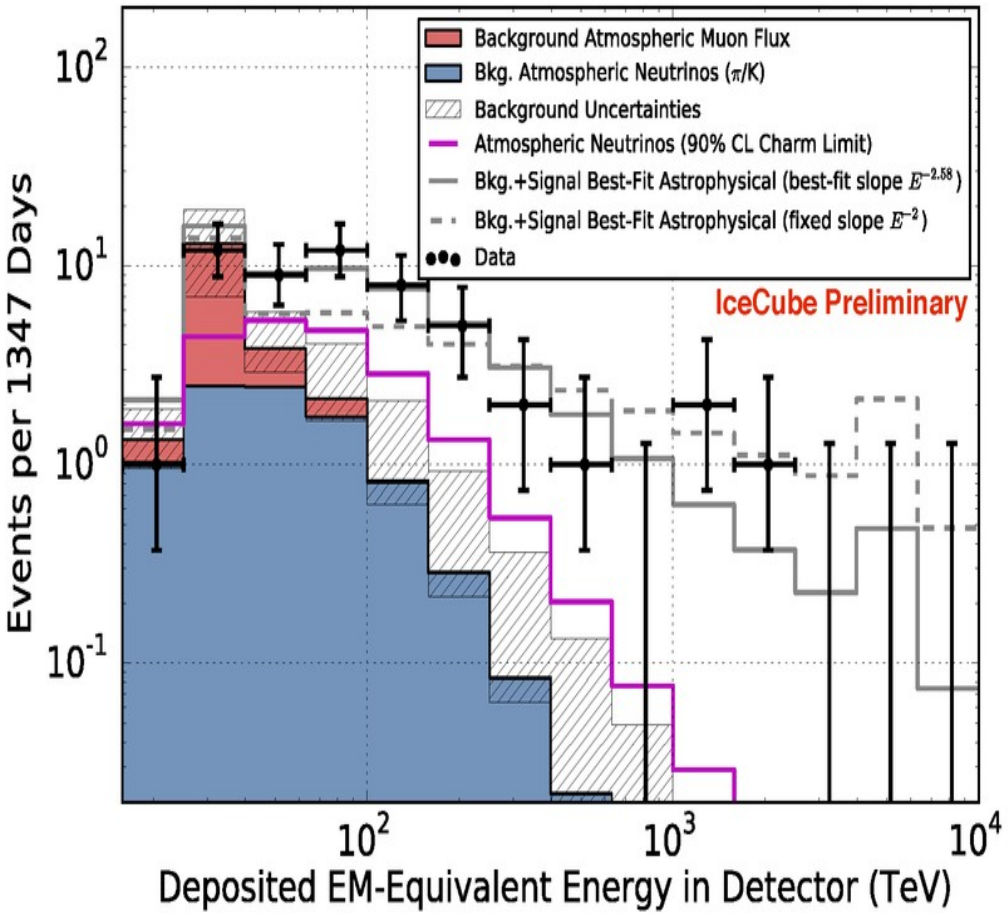


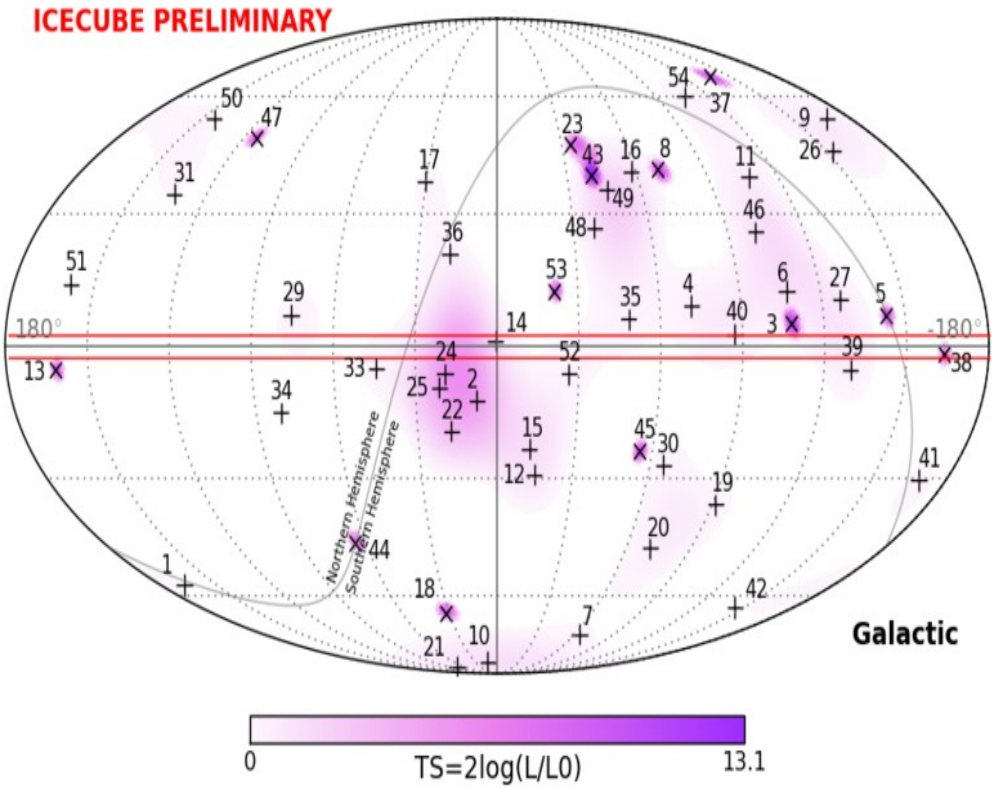
Fluxes are integrated over full sky, with upper limits at 90% confidence level.
Gray band : predictions of KRA models.
Red → IceCube 7 year data upper limit.
Green band → only using northern sky muon data
Yellow band → power law unfolding of the IceCube data.
Black points → differential unfolding of the IceCube data.

$$\mathrm{TS} = -2\ln[\mathcal{L}(n_s = 0)/\mathcal{L}(\hat{n}_s)]$$


cosmic ray
Atmosphere
cosmic neutrino
IceCube
muon
atmospheric muon
π−θ
~12,700 km
up-going
down-going
atmospheric neutrino
cosmic ray
Cherenkov light detection in optical modules

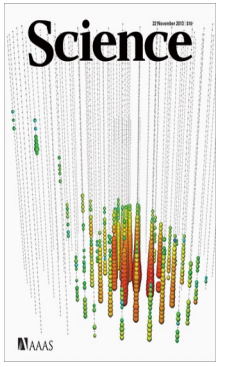
The IceCube astrophysical flux



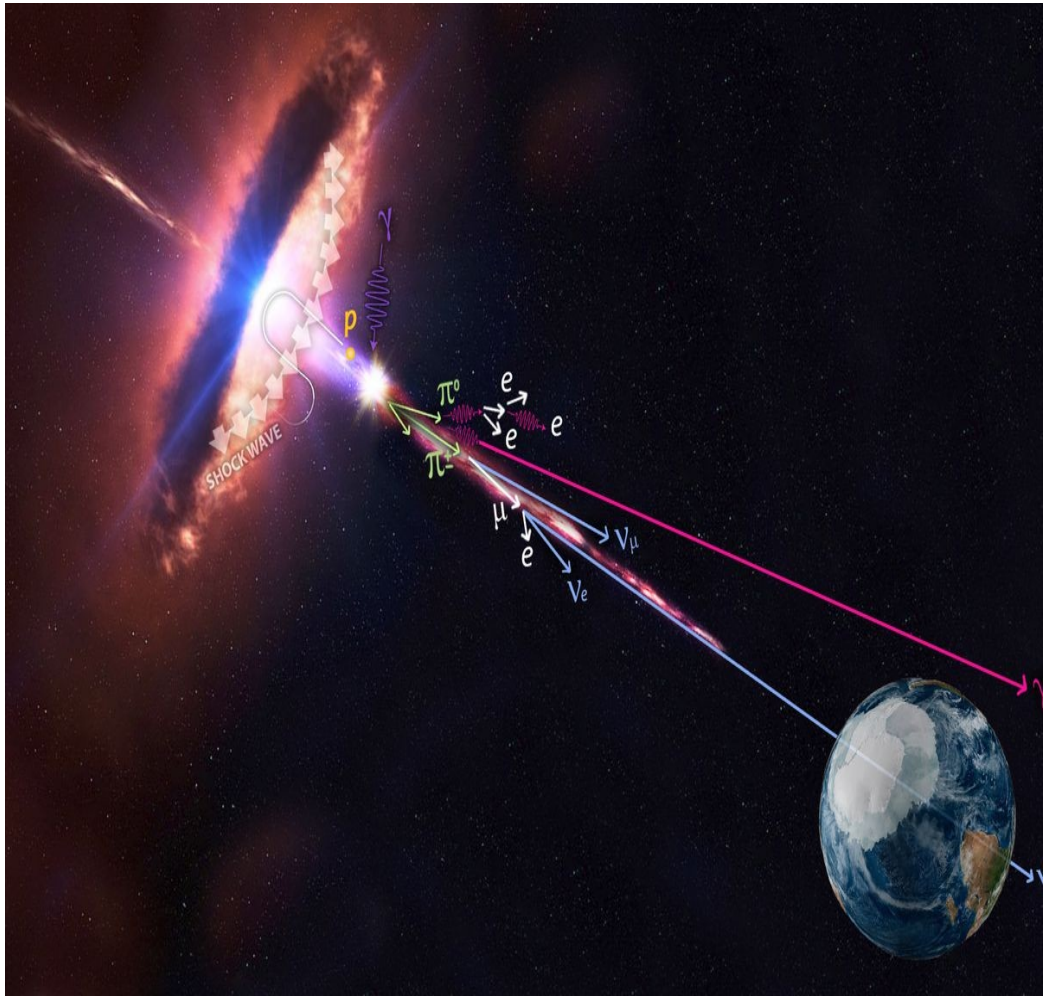


54 events seen on an expected background of 12.6 5.1 and

No statistically significant clustering



Multi-messenger source: TXS 0506+056

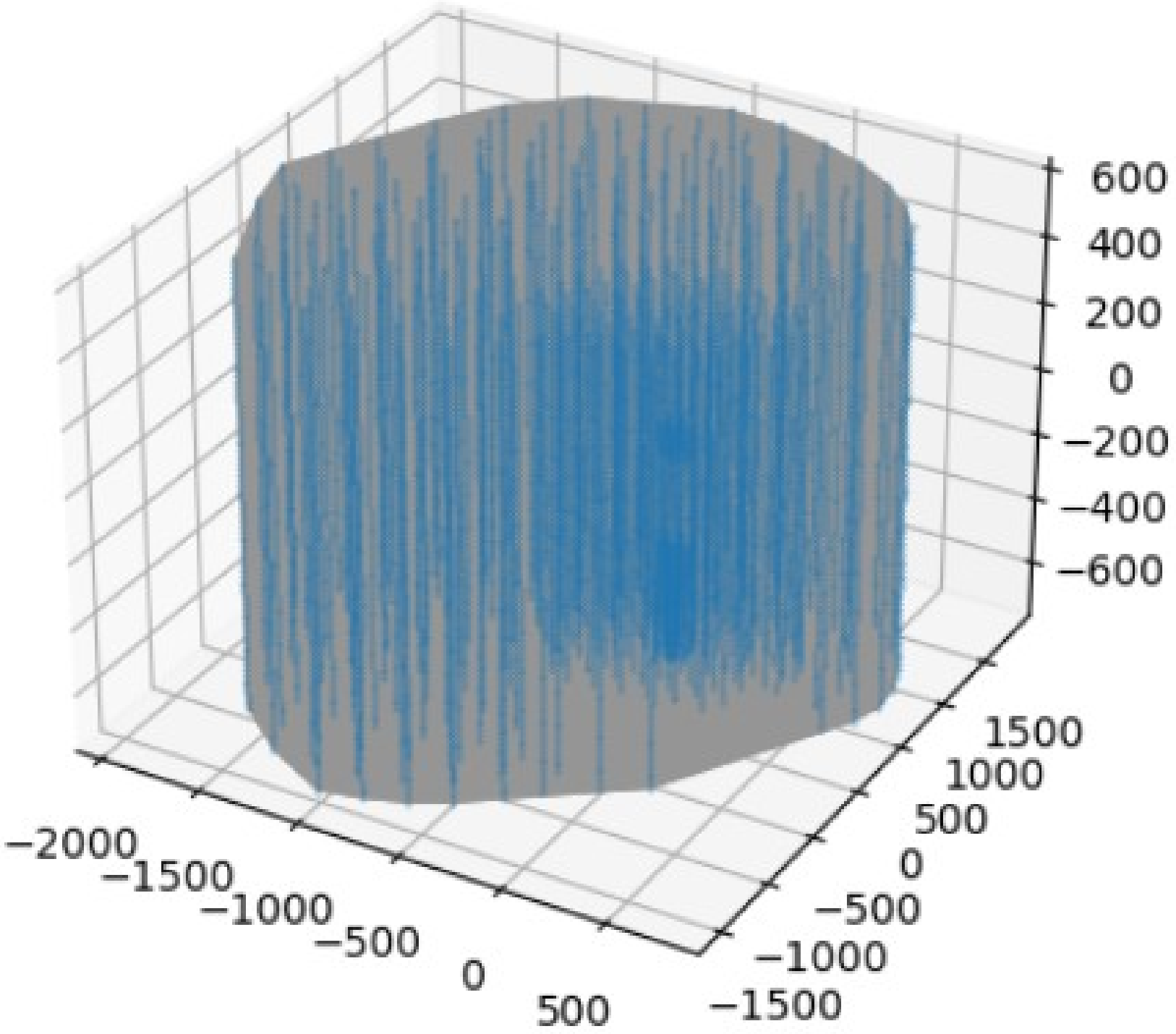


Two analyses provide evidence that TXS 0506+056 is the first of the long-sought sources of astrophysical neutrinos.

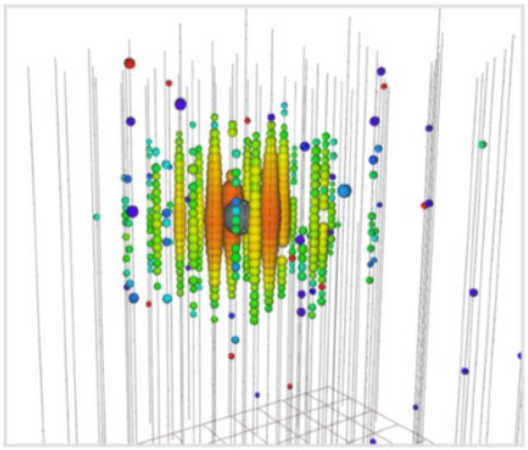
When both results are considered together, this provides evidence that blazars, especially TXS 0506+056, is a site of high-energy cosmic ray acceleration, and blazars are a potential source of a sizable fraction of the IceCube diffuse neutrino flux.

Many question still remain:

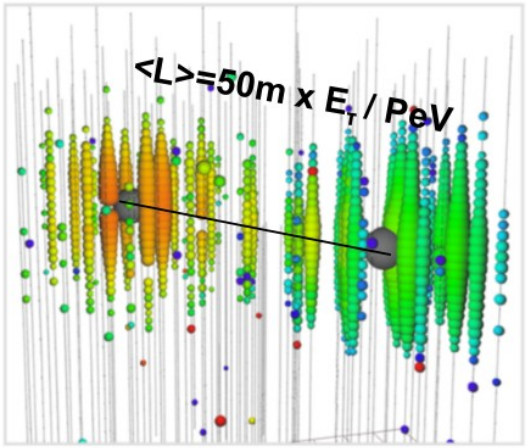
- Why TXS 0506+056?
  - A distant (4 Bly) and very luminous blazar • Why not closer blazars?
- What other objects are out there like TXS 0506+056?
  - Ongoing investigations with partners to resolve
  - Continued alerts


600
400
200
0
−200
−400
−600
1500
1000
500
0
−500
−1000
−1500
−2000
−1500
−1000
−500
0
500

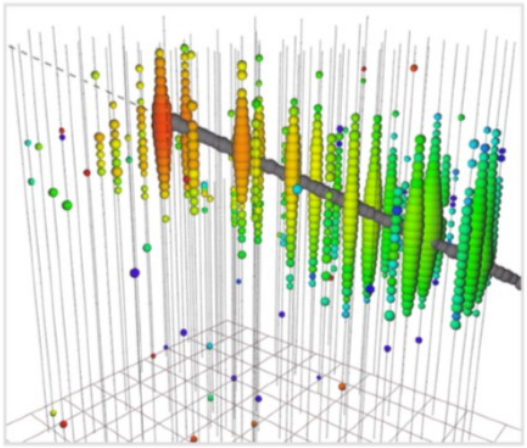
Neutrino Signatures in IceCube



Electron neutrinos:
isolated cascades



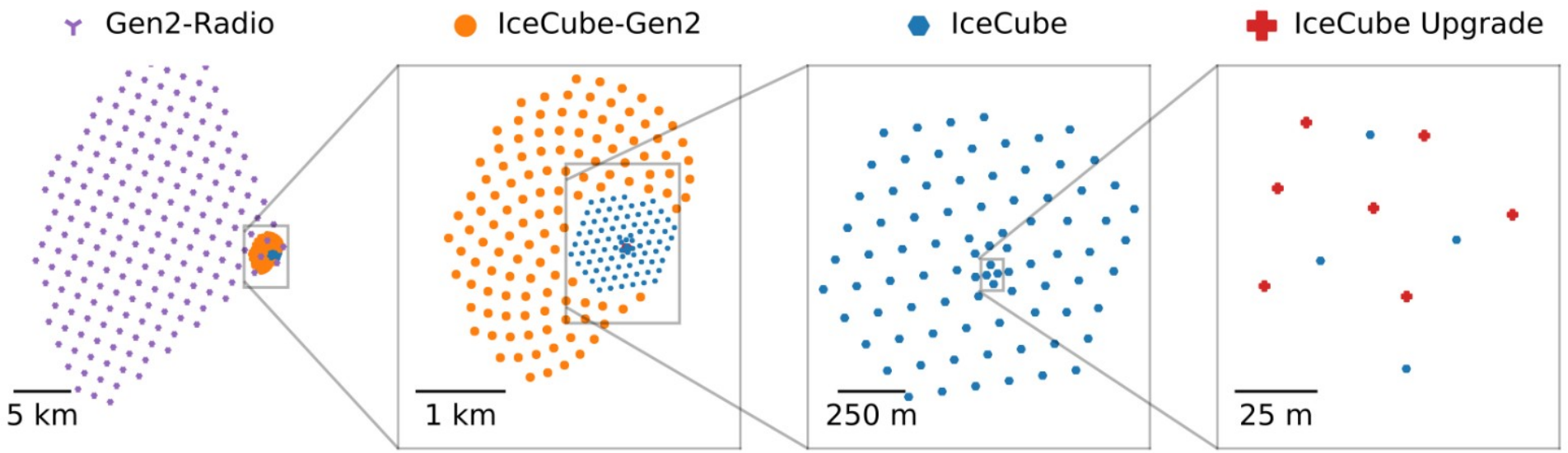
Tau neutrinos:
“double bang”



Muon neutrinos:
track-like events

The IceCube Gen2 facility at the South Pole

Wide-band observatory: Optimizing scales for leading sensitivity from 10^9 to 10^{20} eV



IceCube-Gen2 planed construction: 2024-2032 | **completed in 2010** | **under construction**

Gen2 white paper: 2008.04323

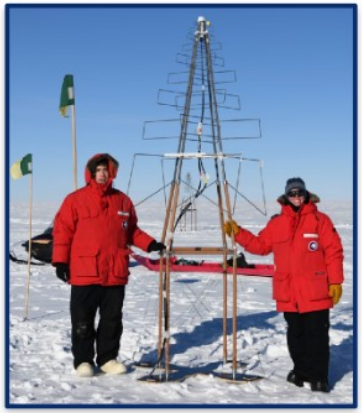
Developments towards IceCube-Gen2

Building on experience and new technology

IceCube Installation

Operating sensors in the ice since 2006, with no evidence for aging

New surface technology

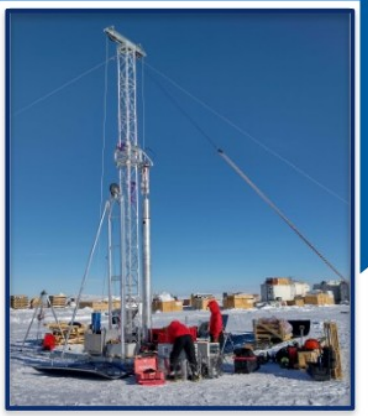


Scintillator / radio station deployed at South Pole (2019) (PoS ID 314)

IceCube Upgrade / Gen2 Phase 1

Deployment of next generation sensors (see next slide)

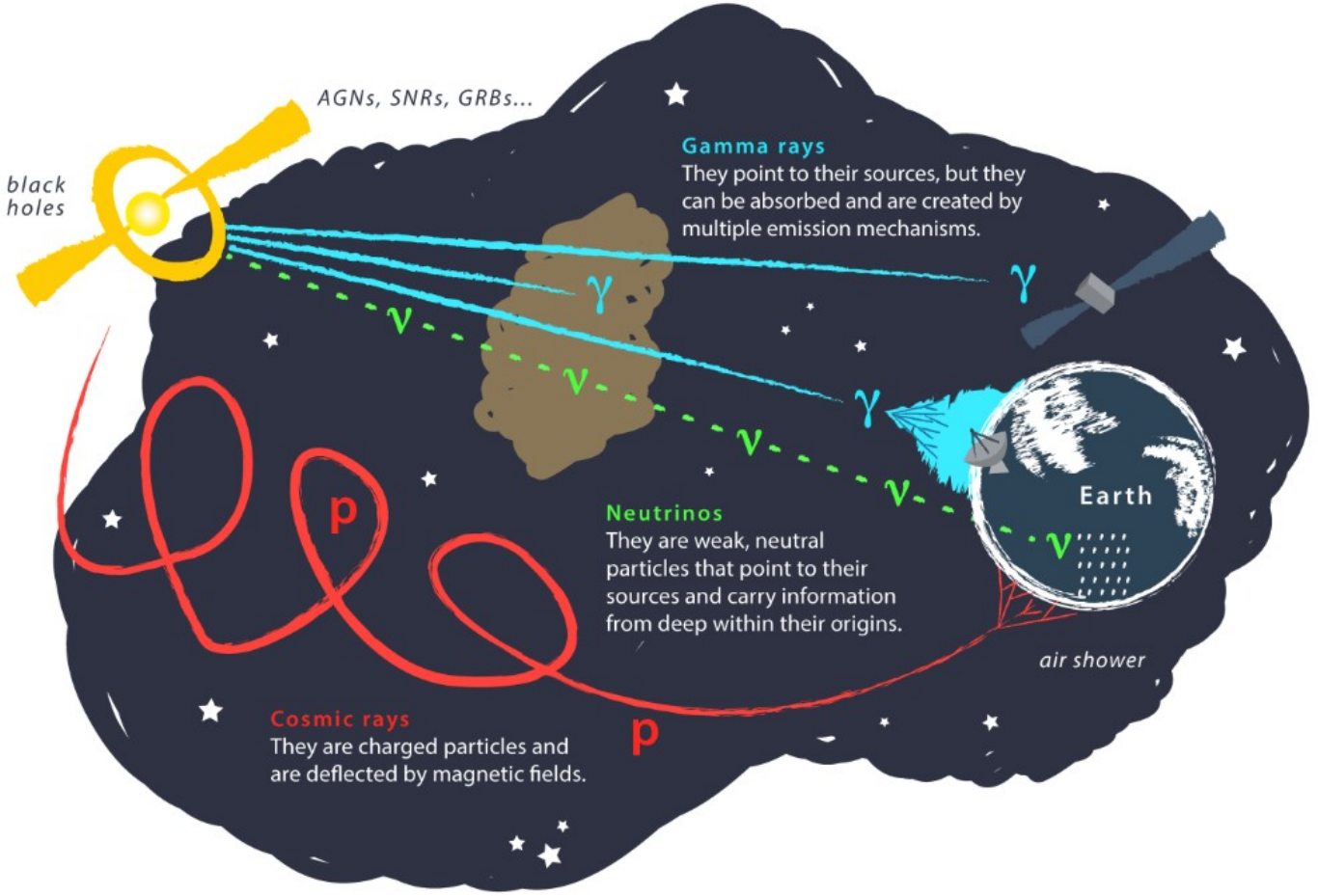
Radio-Tests in Greenland



Radio technology deployed in Greenland (2021, see S. Wissel et al., PoS ID 001)

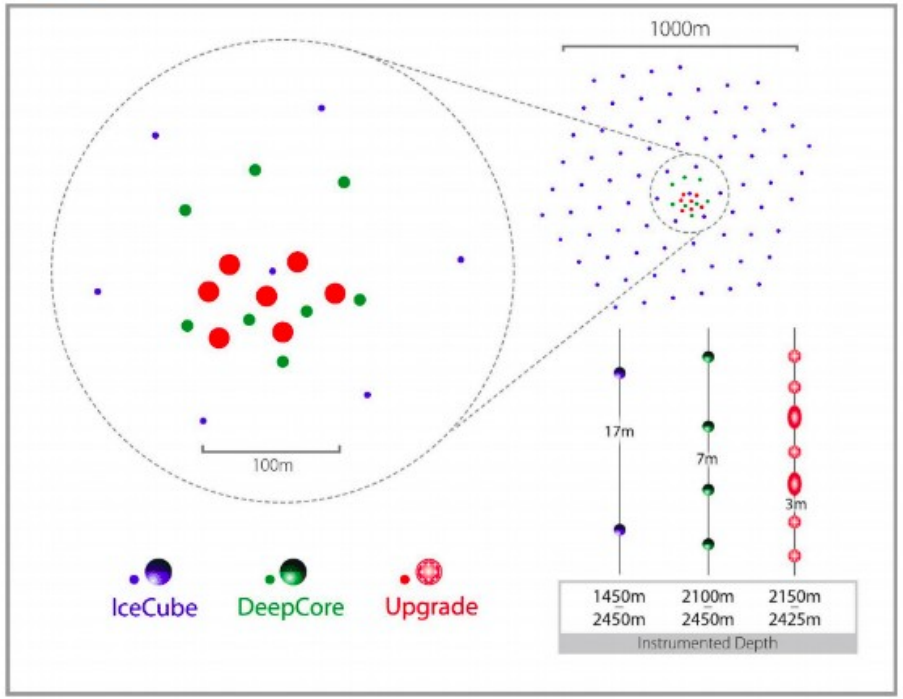
IceCube GEN2

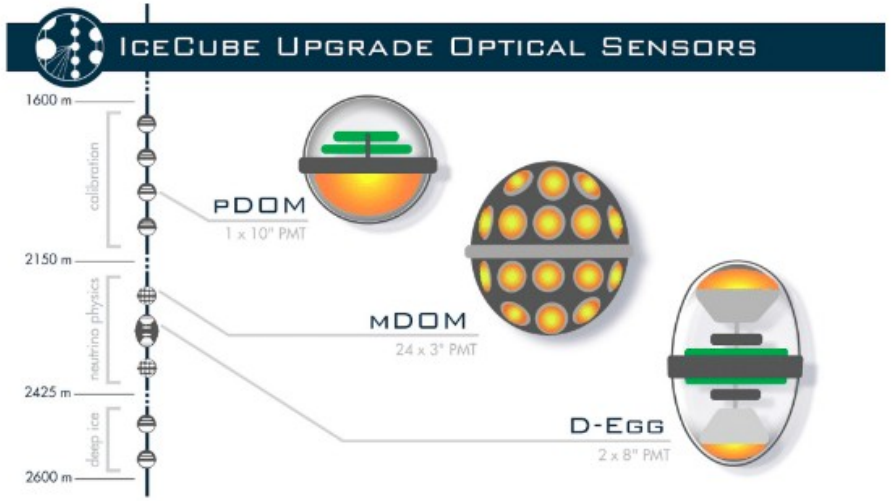
Neutrino Production



The Future: Lower Energies

IceCube Upgrade





- Seven new in-filled strings
- Better efficiency and reconstruction at low energies
- Delayed due to Covid-19: deployment in 2025/26 season.

Sensor	mDOM	D-Egg
Number of PMTs	24	2
PMT diameter [inch]	3.15	8
PMT QE type	Normal QE	High QE
Module diameter [cm]	36	30
Module height [cm]	41.1	53.4
Effective photon detection area ($\lambda = 400$nm) [cm^2]	108	94