Neutrino Astrophysics to Particle Physics with IceCube

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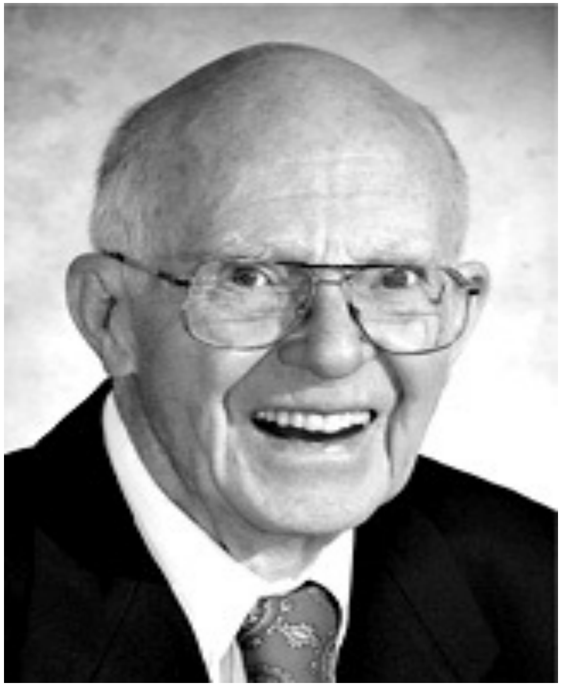
(For the IceCube Collaboration)

The Nobel Prize in Physics 2002



Raymod Davis Jr.

Detected Solar Neutrinos

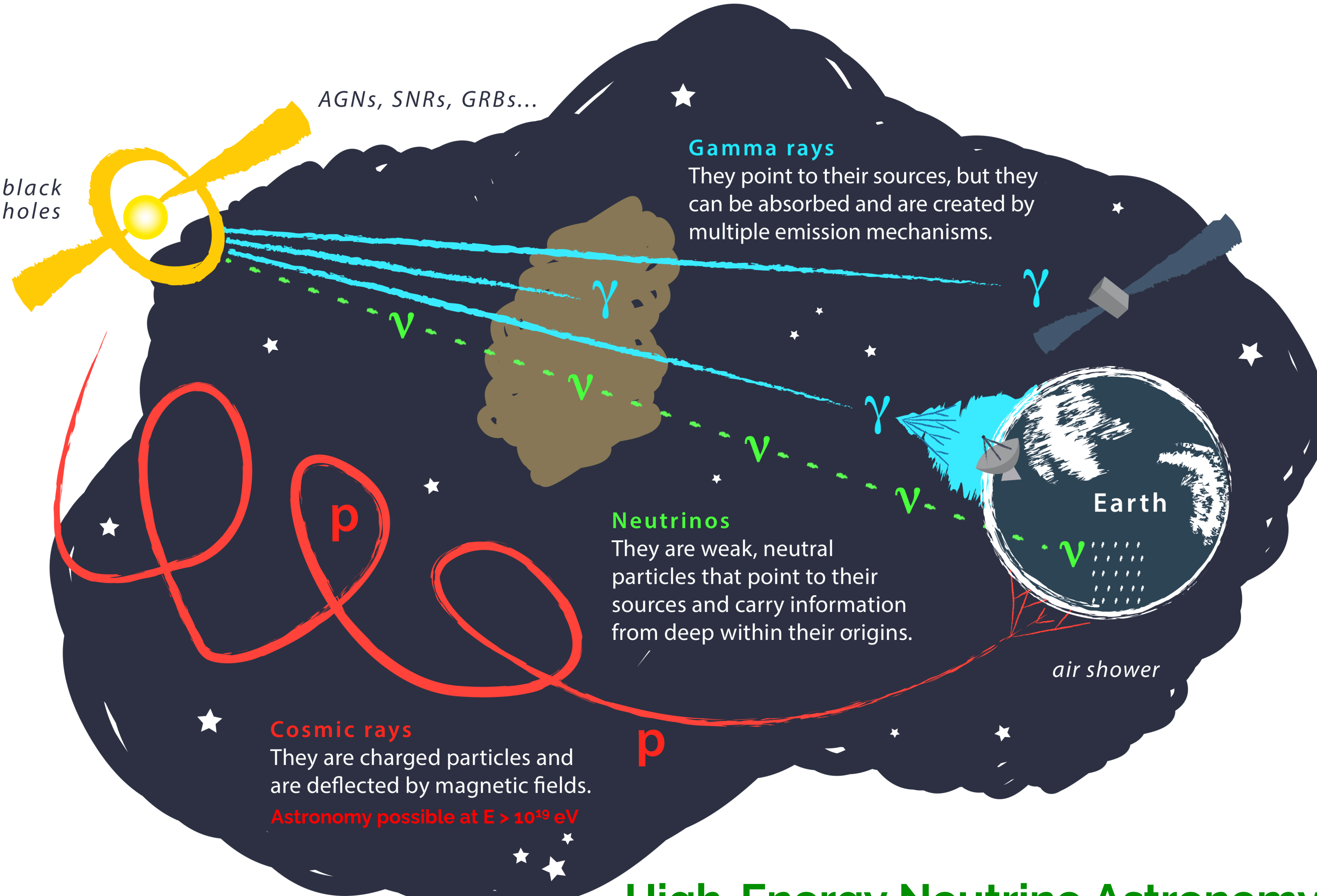
Masatoshi Koshiba

Detected Supernova Neutrinos

Detection of Cosmic Neutrinos ➔ A New Window on the Universe

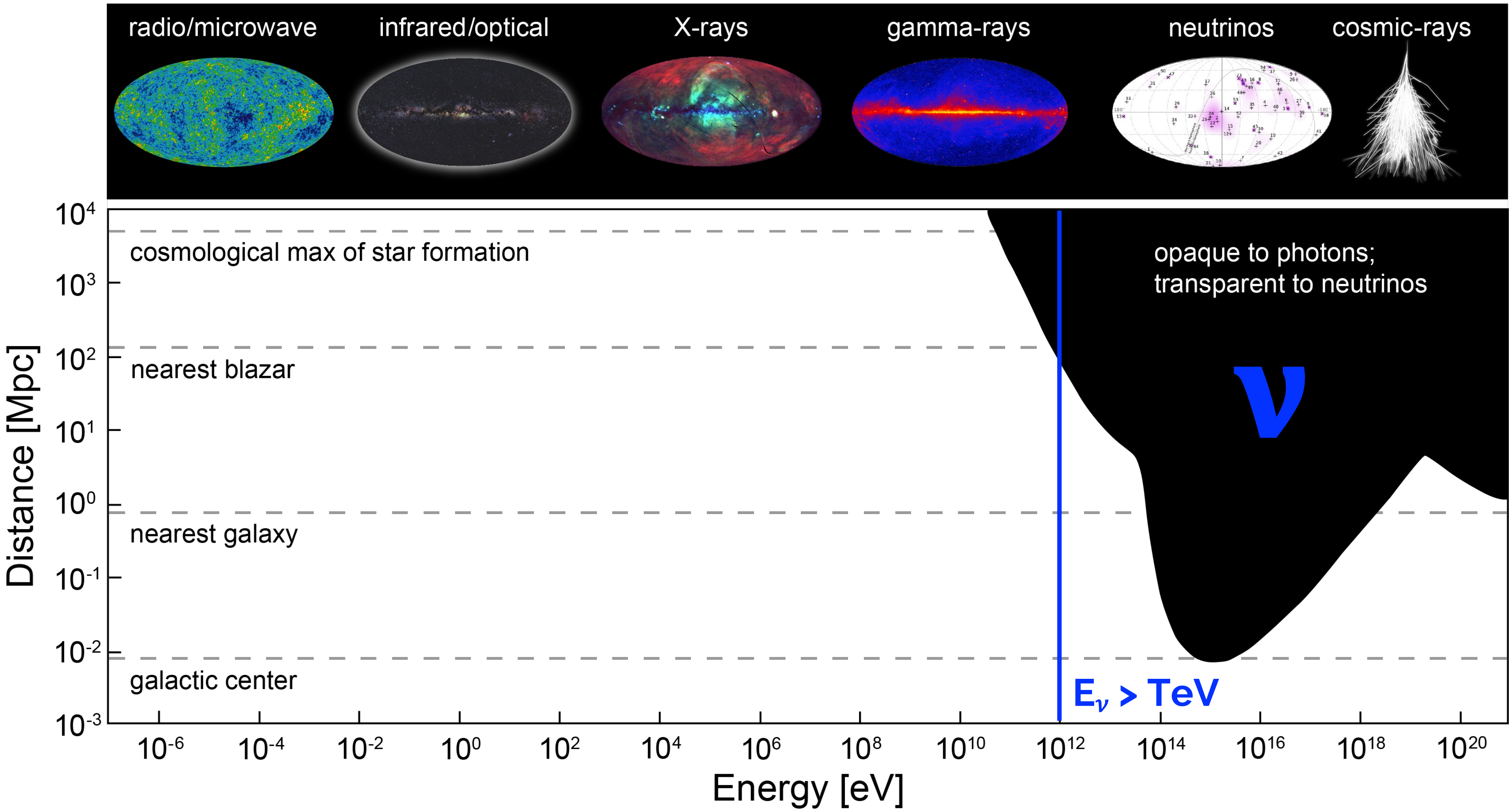
Era of Low-Energy Neutrino Astronomy began!

Detection of High-Energy Cosmic Neutrinos



High-Energy Neutrino Astronomy!

Highest Energy Radiation from Universe: Neutrinos & Cosmic Rays



Universe beyond our Galaxy is opaque to gamma rays

Neutrinos open a new window to observe the high-energy and distant Universe

For a recent review see: Arguelles, Halzen, Kurahashi, arXiv: 2405.17623 [hep-ex]

Accelerated cosmic ray beam (p) interact with gas (p) or radiation (γ).

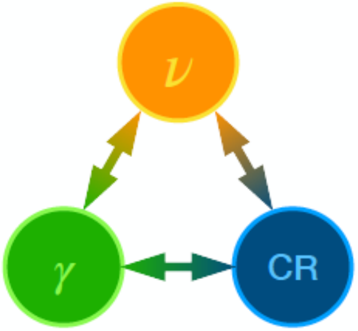
$$p + p \rightarrow n_\pi \left[\pi^0 + \pi^+ + \pi^-\right] + X$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 & (2/3) \\ n + \pi^+ & (1/3) \end{cases}$$

$$\begin{cases} \pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow \nu_\mu + \left(e^+ + \nu_e + \bar{\nu}_\mu\right) \\ \pi^- \rightarrow \bar{\nu}_\mu + \mu^- \rightarrow \bar{\nu}_\mu + \left(e^- + \bar{\nu}_e + \nu_\mu\right) \\ \pi^0 \rightarrow \gamma + \gamma \end{cases}$$

Neutrinos are "smoking gun" of cosmic ray accelerators

Correlated neutrinos~gamma rays~cosmic rays emission rate at source



$$\frac{1}{3}\sum_{\nu_\alpha} E_\nu^2 Q_{\nu_\alpha} \simeq \frac{K_\pi}{4} E_\gamma^2 Q_\gamma \simeq \frac{1}{4} f_\pi \frac{K_\pi}{1 + K_\pi} E_p^2 Q_p$$

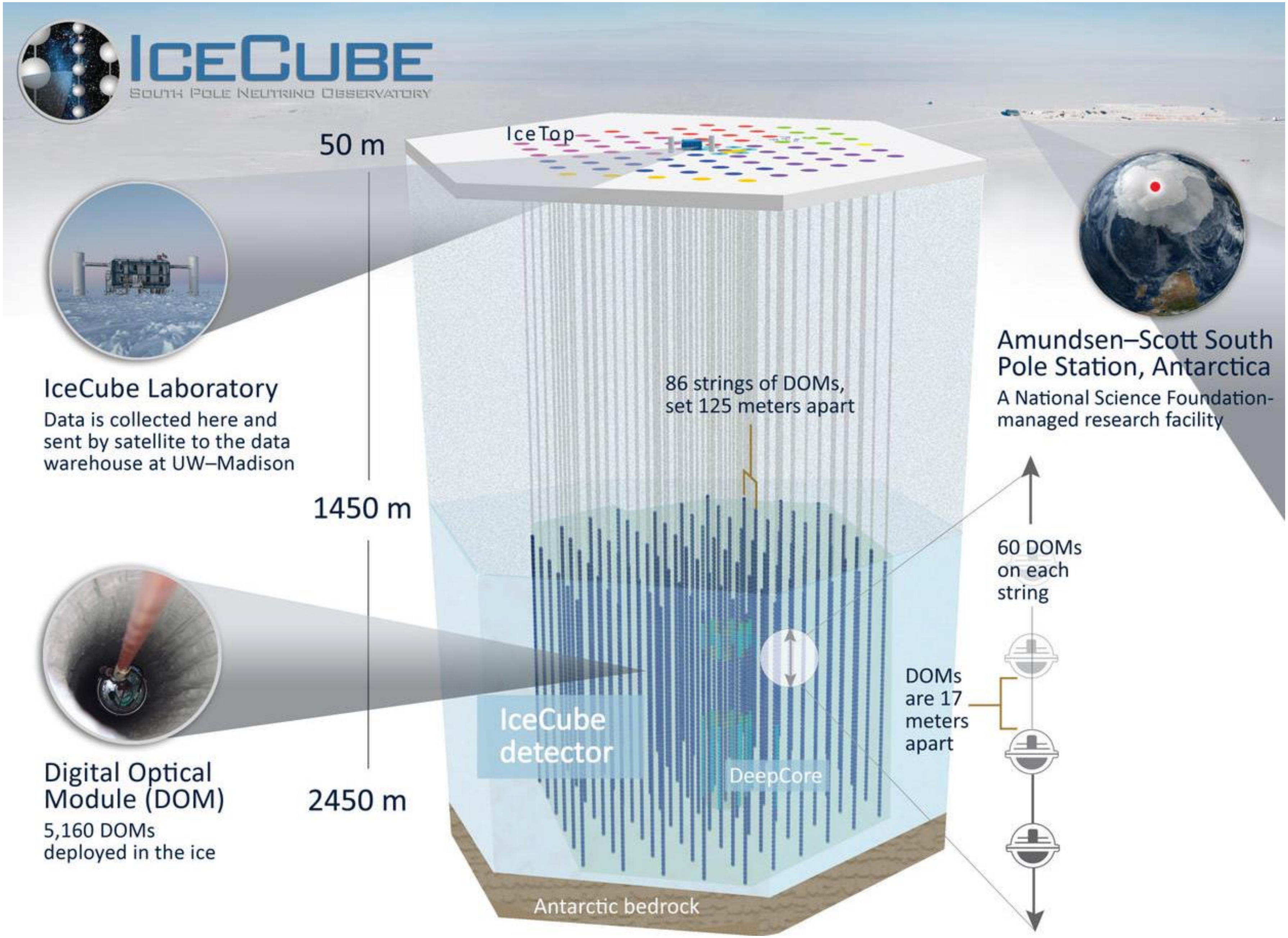
$$E_\nu \simeq \frac{1}{2} E_\gamma \simeq \frac{1}{20} E_p$$

One could use the CR flux to set a bound on the neutrino flux – Waxman-Bahcall bound for optically thin sources

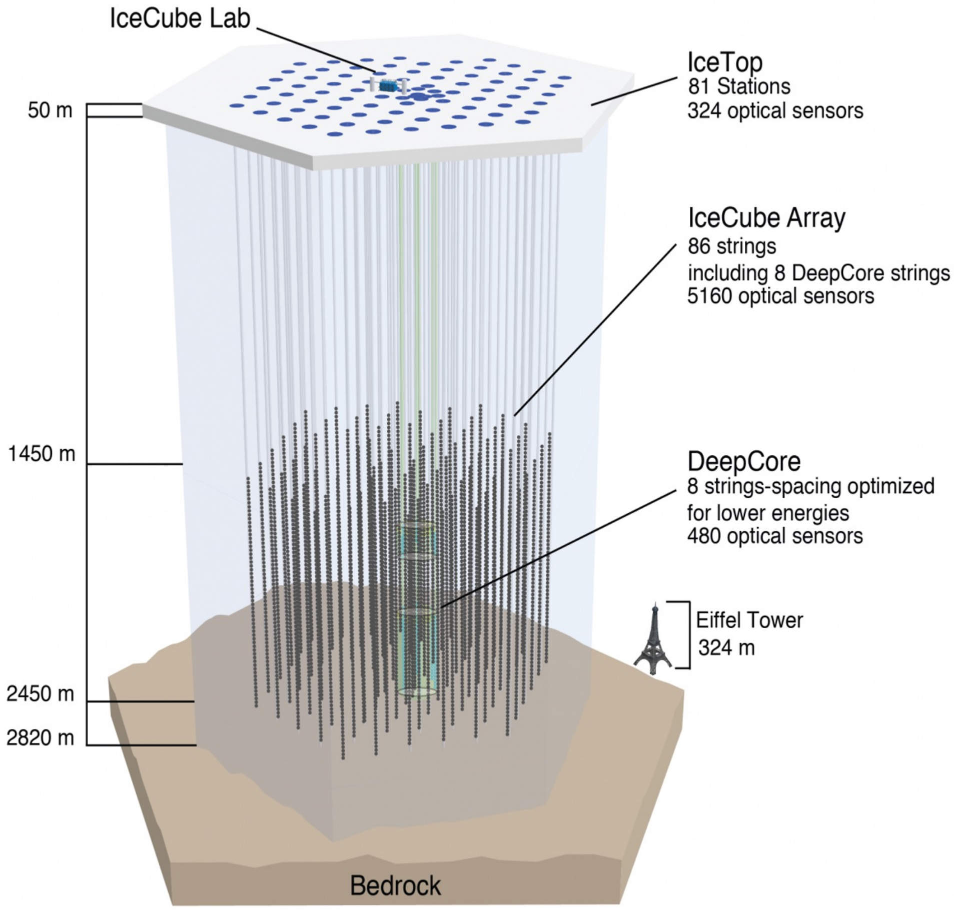
$$E_\nu^2 I_\nu(E_\nu) \sim 5 \times 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$ **Gigaton detector!**

Neutrinos open a new window to observe the high-energy and distant Universe

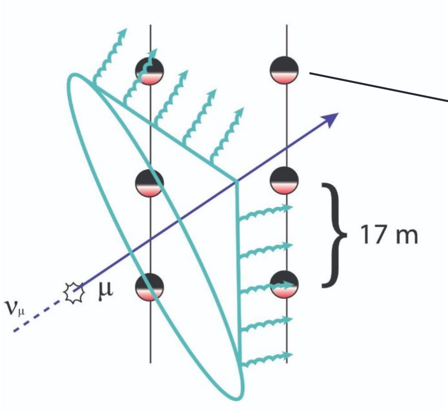
IceCube at South Pole



IceCube Neutrino Telescope



- 1 km³ ν detector deep under ice at South Pole
- 3 components: IceTop, IceCube, and DeepCore
- 5160 DOMs across 86 strings
- Optimized for TeV-PeV

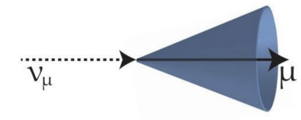


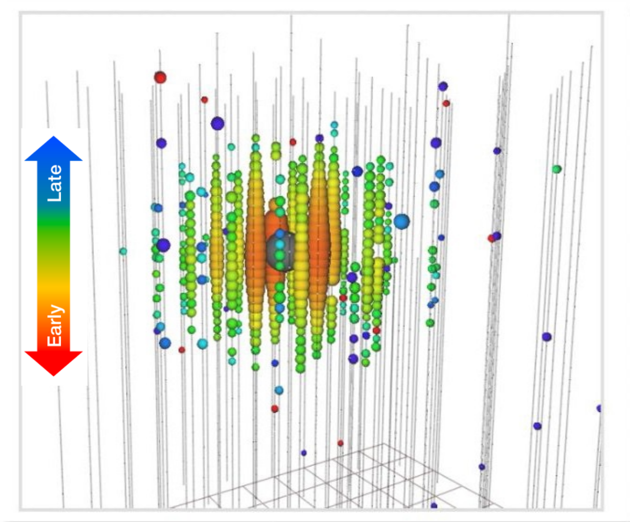
DOM

- Neutrino interacts with ice and produces charged lepton
- Lepton direction closely aligned with neutrino
- Charged leptons emit Cherenkov radiation, when they travel faster than light in a medium
- Radiation detected by DOM (Digital Optical Modules)

Event Signatures in IceCube

IceCube detects neutrinos by measuring the Cherenkov light emitted by charged secondary particles from neutrinos interacting with the ice and the Antarctic bedrock



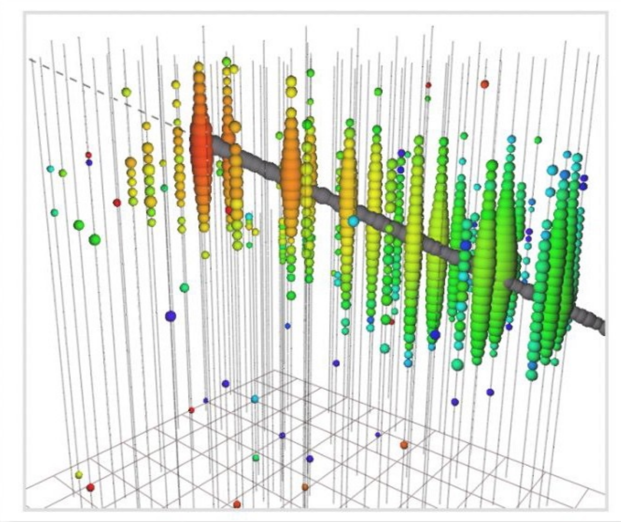


Cascade event

ν_e- CC (charged current) and all flavor NC (neutral current) interactions

↓

Good energy resolution ~ 15%
Poorer angular resolution ~ 10° (≳ 100 TeV)

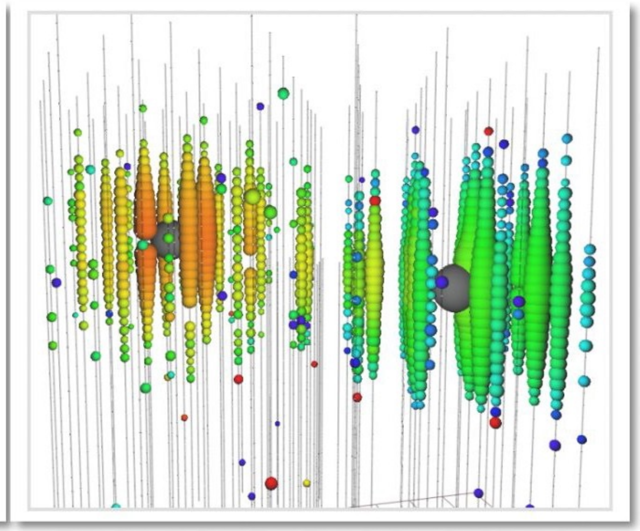


Track

ν_μ- CC and atmospheric muons

↓

Poorer energy resolution ~ factor of 2
Excellent angular resolution ~ 0.5°



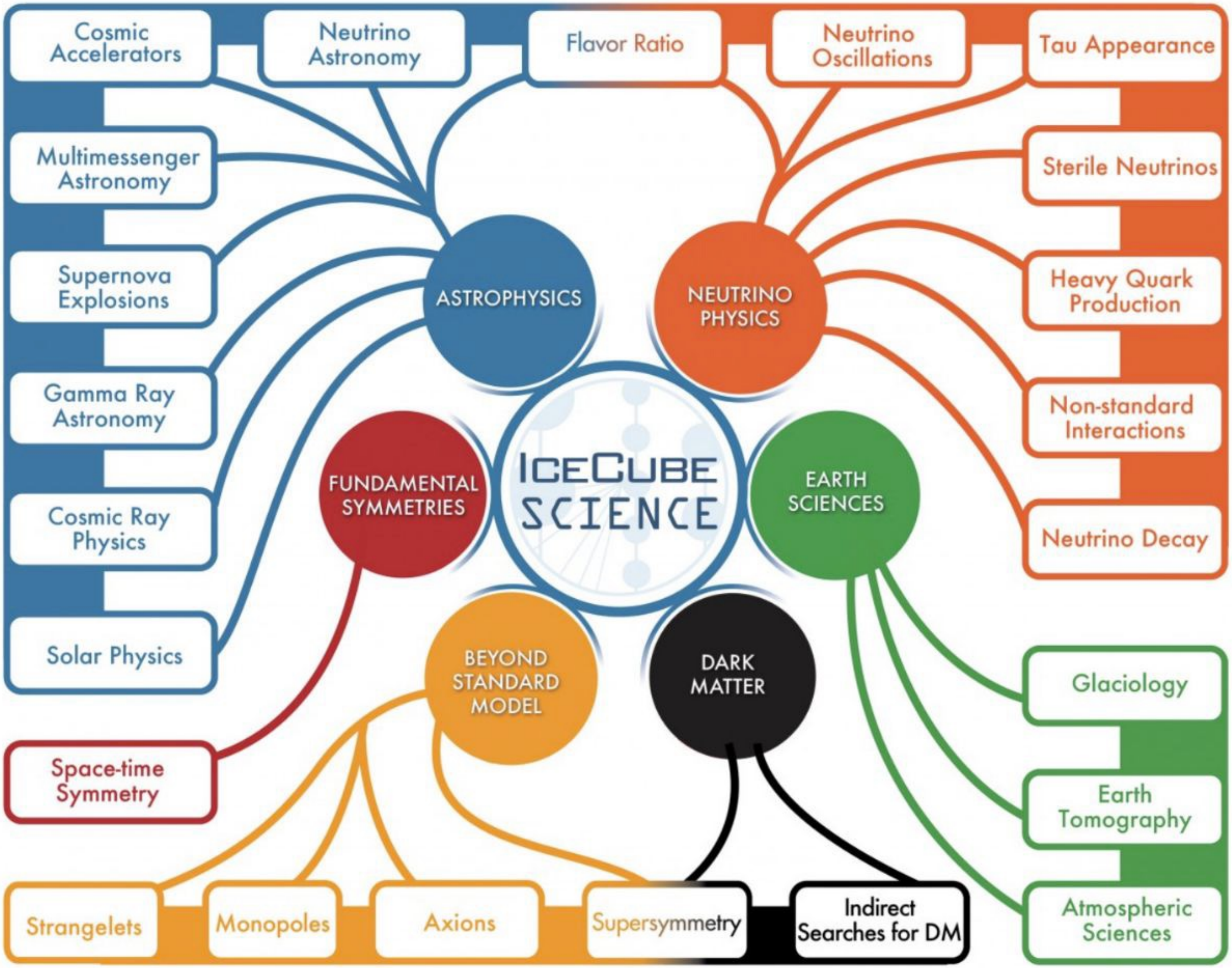
Double-Bang

ν_τ- CC interactions

↓

Distinctive double-cascade signatures in the full detector

IceCube Science – A Multidisciplinary Instrument



RESEARCH

RESEARCH ARTICLES

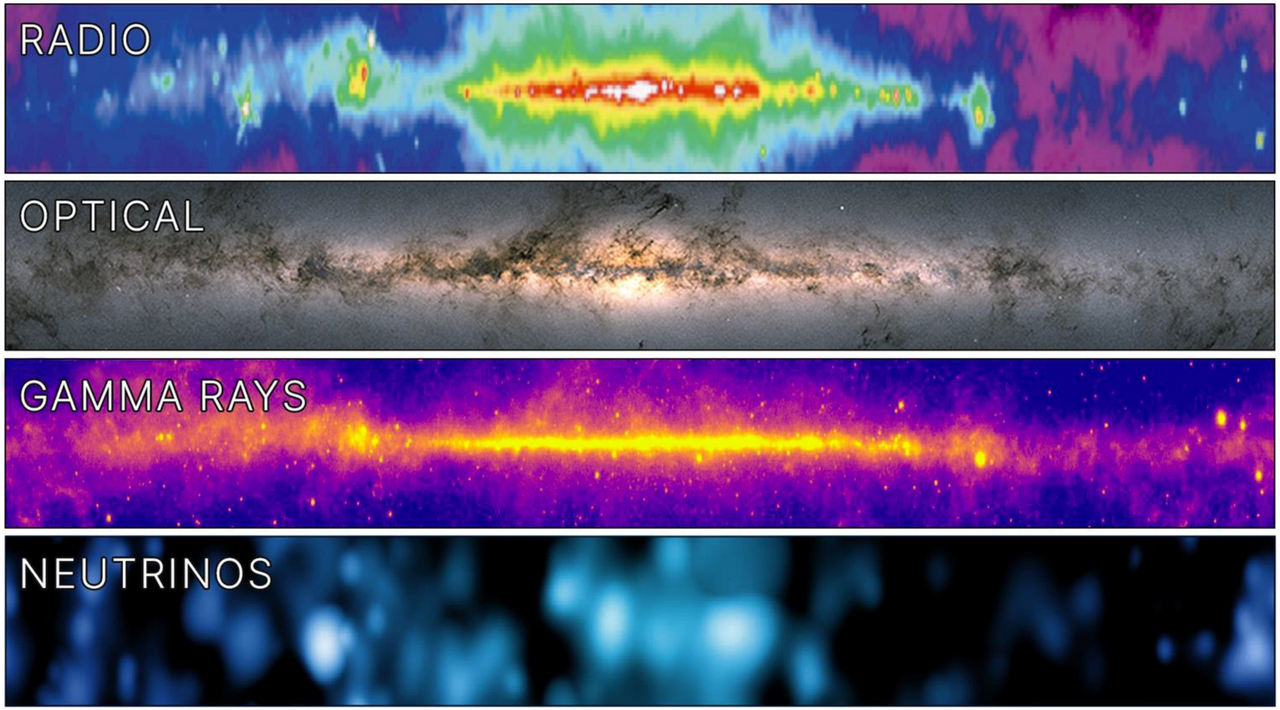
Science June 30, 2023

NEUTRINO ASTROPHYSICS

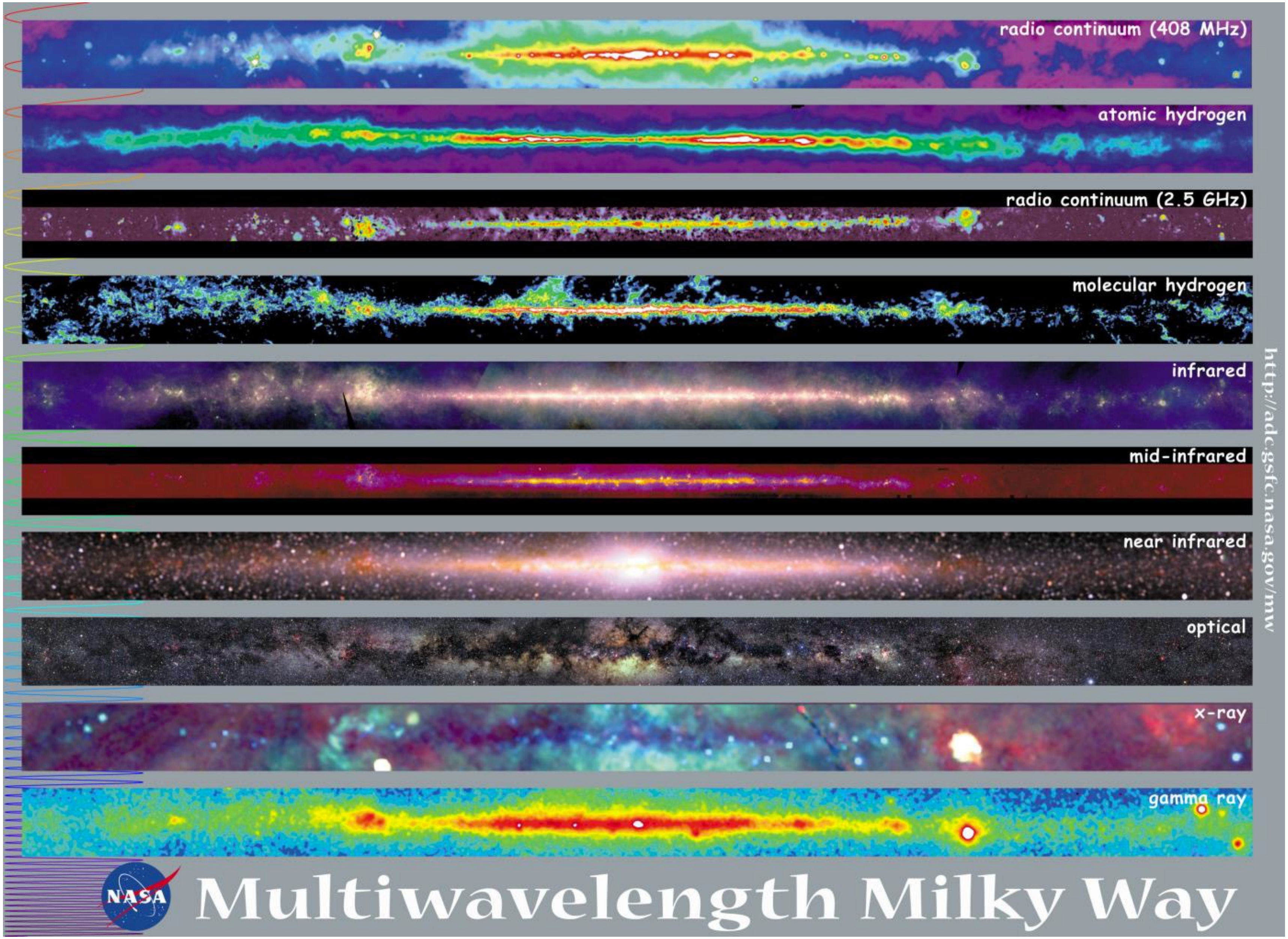
Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

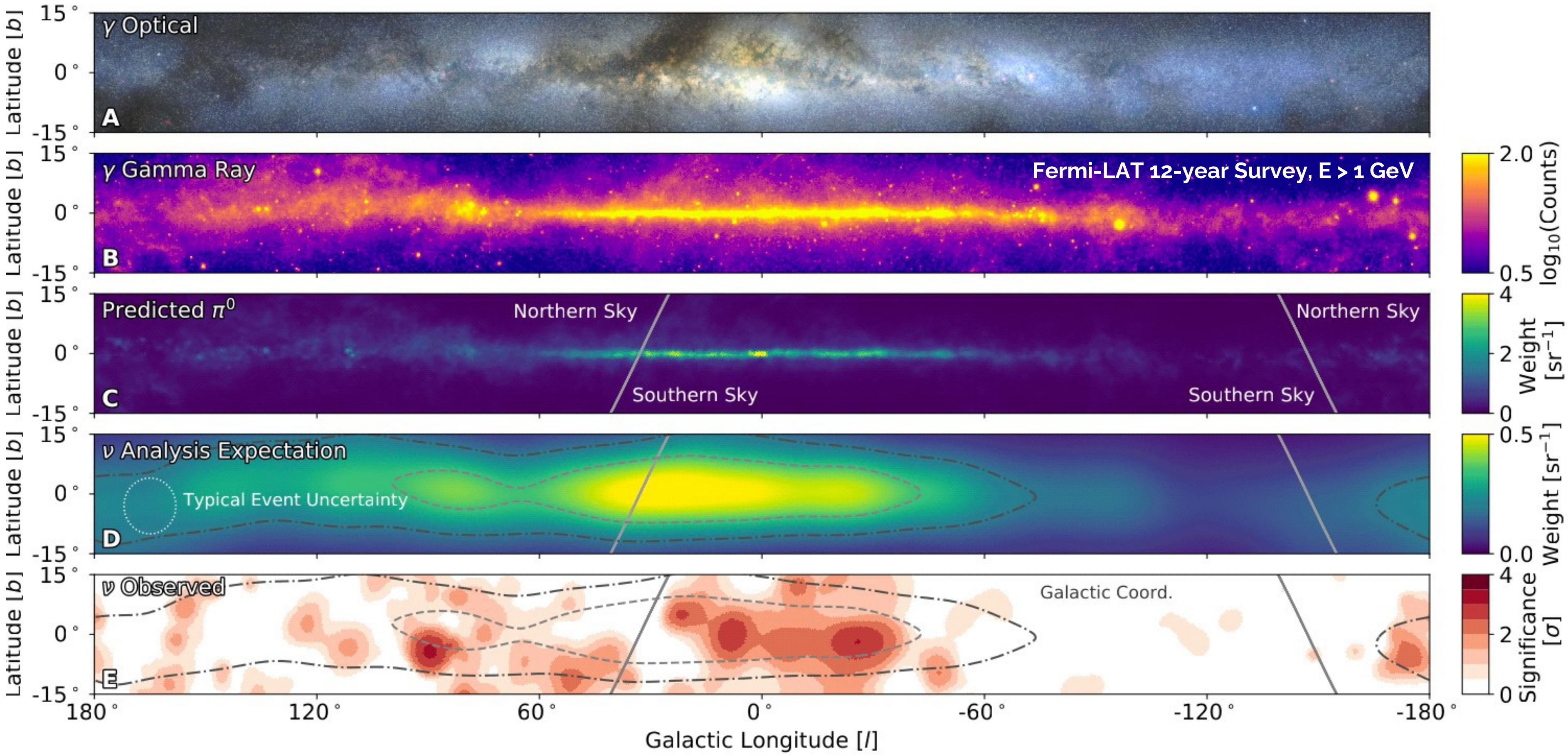
DOI: 10.1126/science.adc9818



The Multiwavelength Milky Way

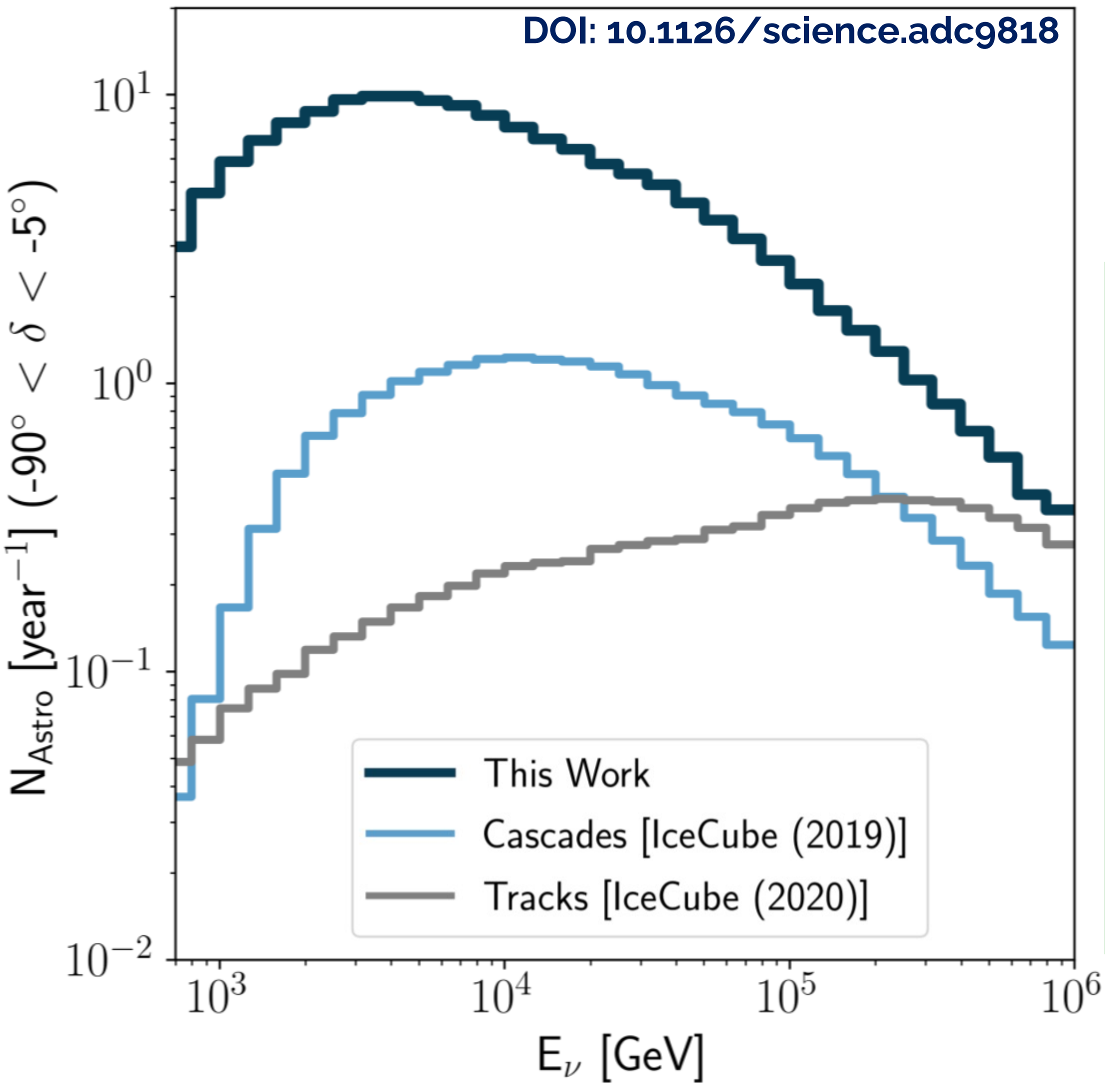


± 10° in latitude, from radio to gamma ray



First Observation of the Diffuse Galactic Plane in Neutrinos!

Important Breakthrough in Selection of Astrophysical Neutrinos



Event rates in the past

- Atmospheric muons: ~ 2700 per second
- Atmospheric neutrinos: ~ 1 per hour
- Astrophysical neutrinos: ~ 1 per day

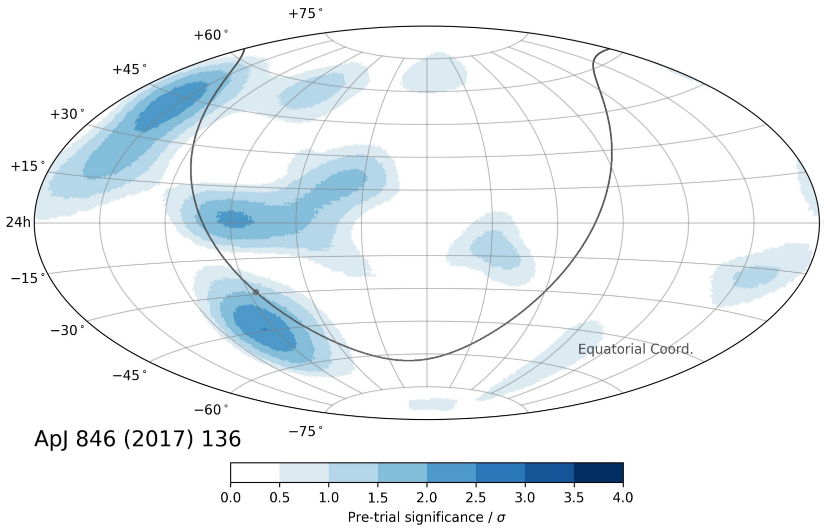
Event selection at present

- Employs series of convolutional neural networks (CNNs) & boosted decision trees
- Improved reconstruction resolution over entire energy range
- Huge improvement in cascade events
- 30 times as many events as precursor analysis
- Background reduced by almost 8 orders of magnitude (~ 2700/s to ~ 17/day)
- Analysis sensitivity improved by a factor of 3

Equivalent to savings of 75 years of detector lifetime > $500 million

Improved Astronomy due to Cascade Events

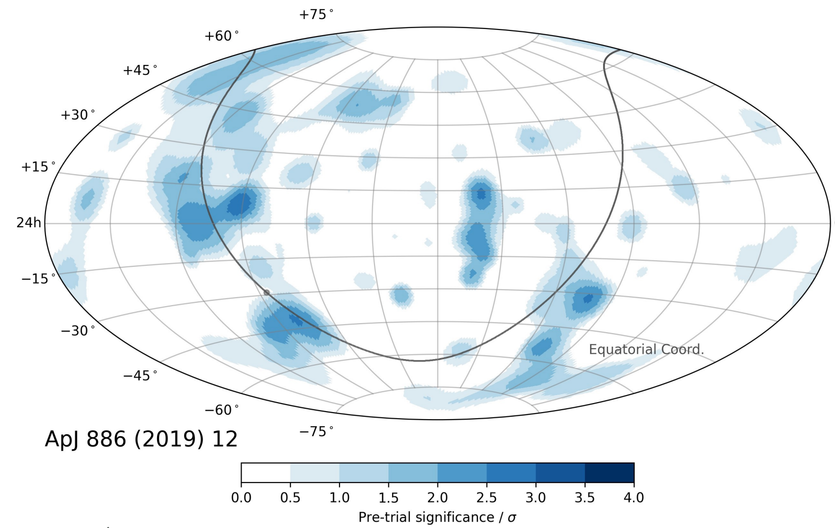
Skymap from 2017 paper



ApJ 846 (2017) 136

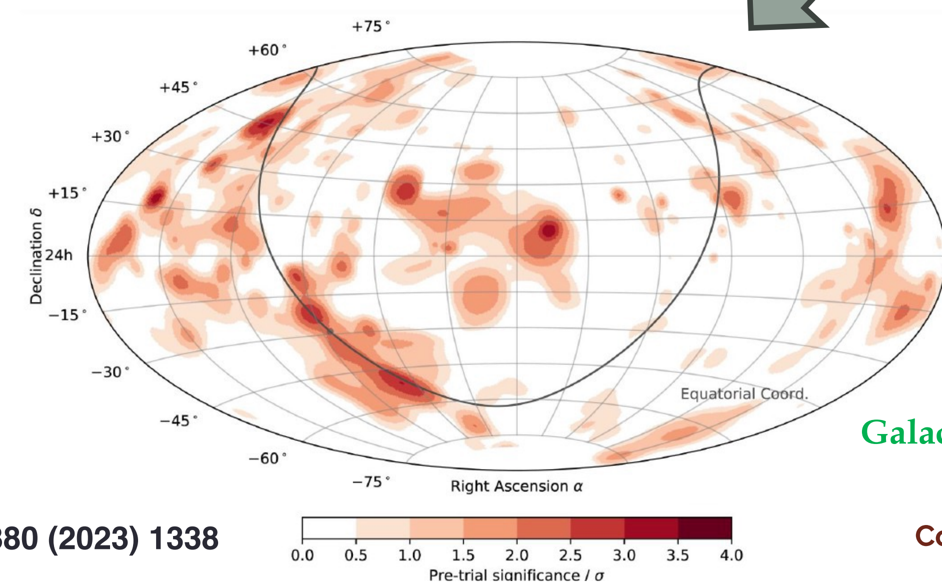
2 years of data
Galactic Plane p-value: 65%

Skymap from 2019 paper



ApJ 886 (2019) 12

7 years of data
Galactic Plane p-value: 2.1% (2σ)



10 years of data
Galactic Plane p-value: 0.0004% (4.5σ)

Science 380 (2023) 1338

Courtesy Naoko Kurahashi Neilson (ICRC 2023)

Take Home Message

+ Strong evidence for neutrino emission from the Galactic plane

- Background-only hypothesis rejected at 4.5σ
- Emission from Galactic plane may explain up to ~ 10% of astrophysical flux observed by IceCube
- Independent hints in IceCube track channels (~ 2.7σ) and in ANTARES (~ 2σ)

+ Observation enabled by new tools based on Deep Learning

- 30 times as many events than precursor selection
- Improved reconstruction resolution by up to 50%
- Analysis sensitivity improved by a factor of 3

+ This result leads to many new questions:

- Pure diffuse emission, or point sources in there too? Emission from the Sgr A*? What is the energy spectrum? Comparison with multiwavelength emissions…Origin of CRs? Galactic structure?......

+ Hope:

- Ongoing studies, future upgrades, and comb. w/ other ν detectors may help to address these issues

We have arrived in the era of high-energy neutrino astronomy!

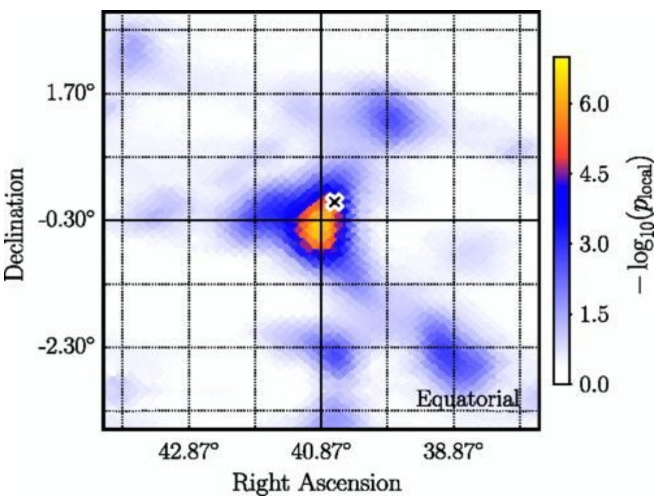
The First Steady Neutrino Source: NGC 1068

AGN promising candidate for neutrino source since 1970s

IceCube identified neutrino emission from NGC 1068, a Type II Seyfert galaxy, at 4.2σ in 2022 ⇒ very close, z = 0.004 (14 Mpc)

Soft best-fit spectrum power-law with spectral index $\gamma = 3.2 \pm 0.2$

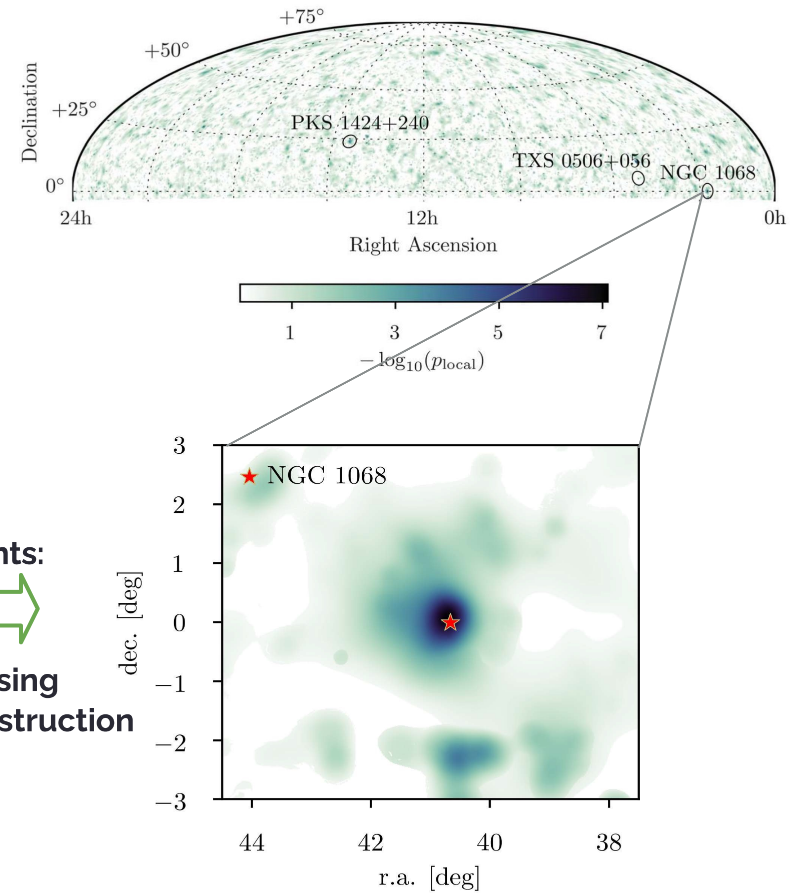
p-value: 0.2% (2.9σ)



IceCube, PRL 124, 051103 (2020)

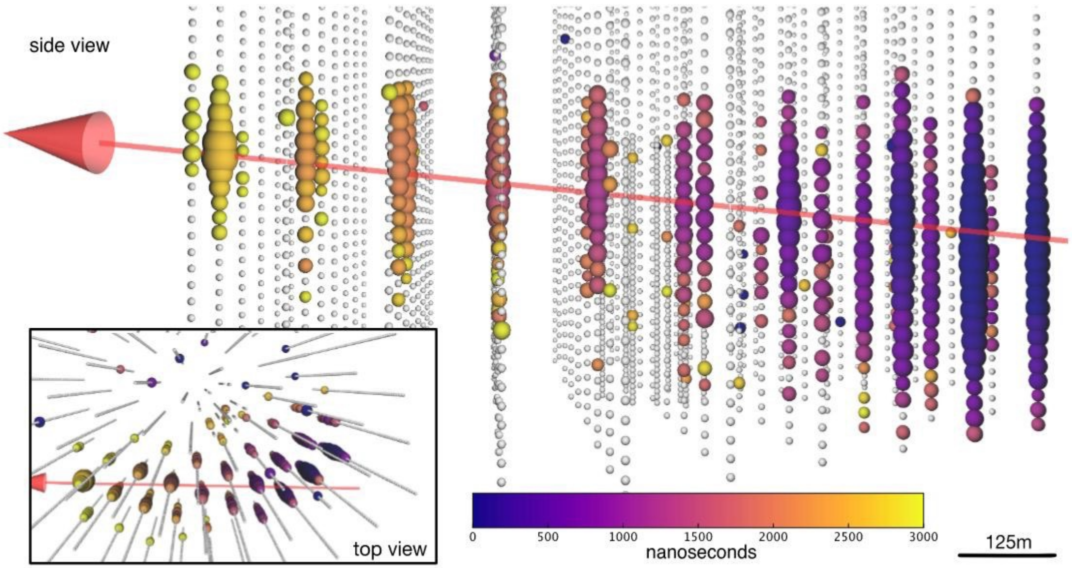
Analysis improvements:

- **Improved data processing**
- **Improved event reconstruction**

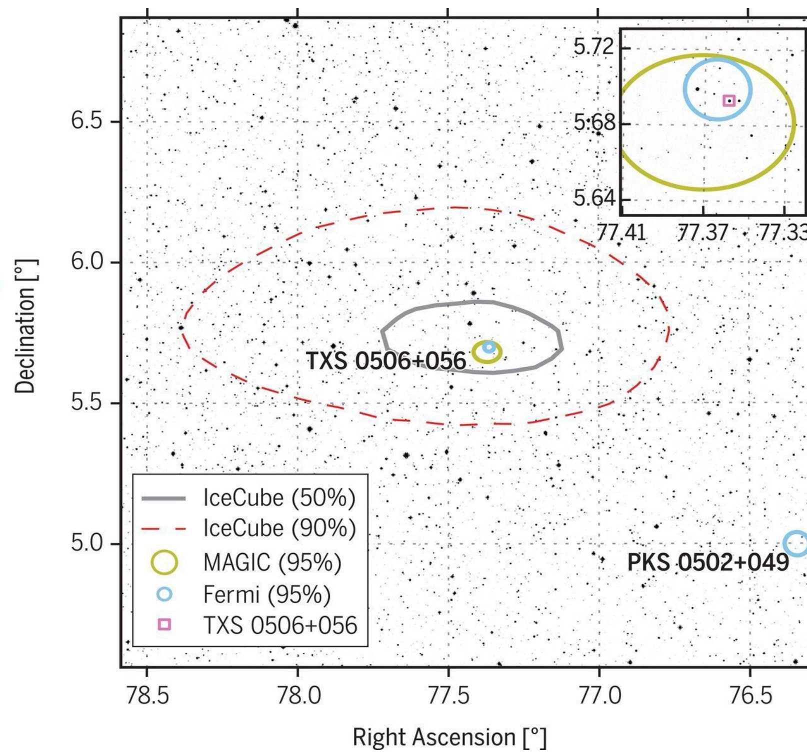


p-value: 0.001% (4.2σ)

Multimessenger observations of a flaring blazar



IceCube-170922A 290 TeV neutrino
coincident with the TXS0506+056 blazar

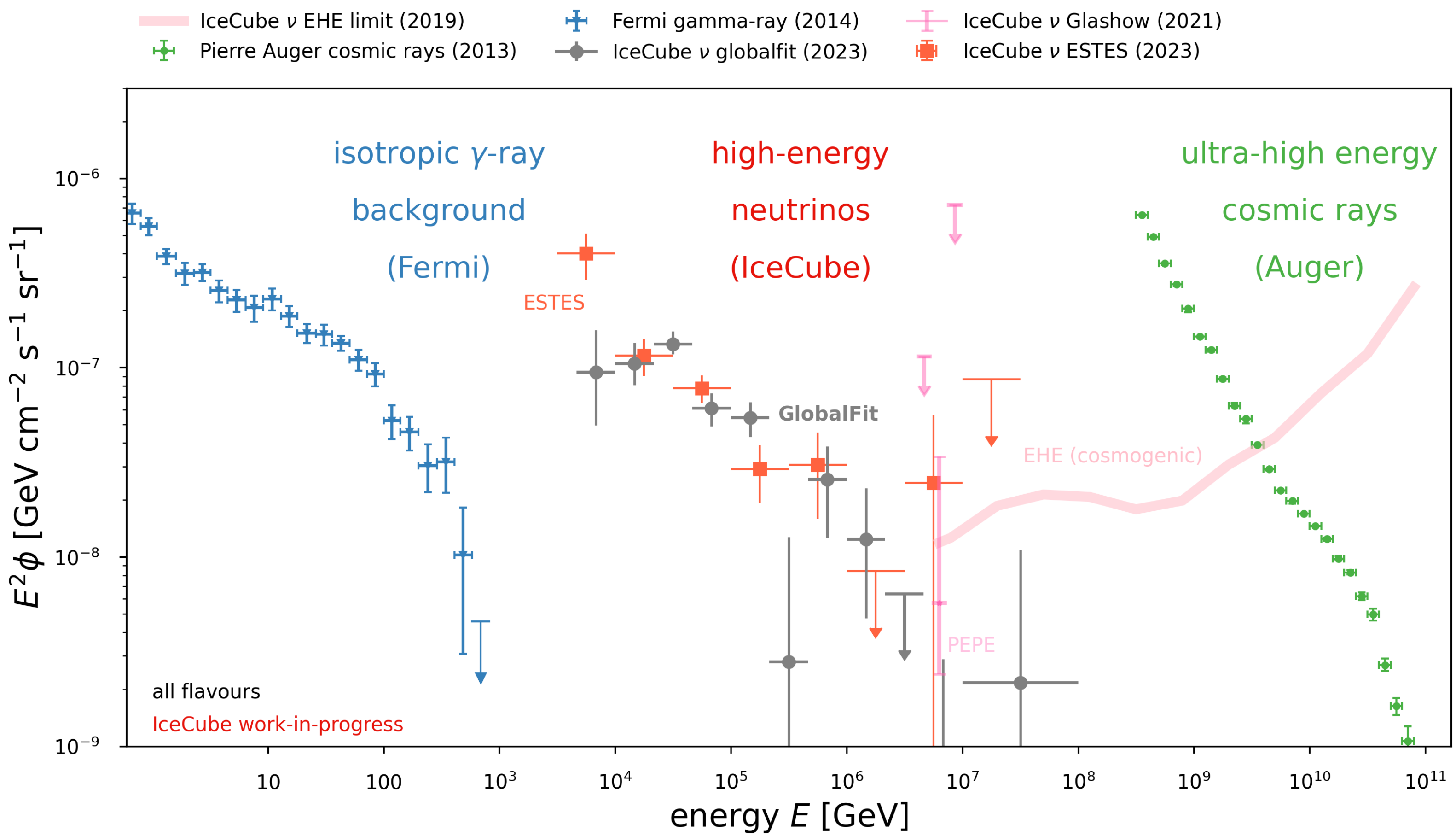


Science 36, eaat1378 (2018)

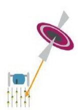
Following an alert sent by IceCube on 23.09.2017, Fermi-LAT & MAGIC detected γ-flaring activity and very-high-energy γ rays, respectively, in the direction of blazar TXS 0506-056

IceCube investigated models associating neutrino & γ-ray production & find that correlation of the neutrino with the flare of TXS 0506+056 is statistically significant at 3σ

Astrophysical Neutrinos: Extragalactic Diffuse Flux



So far IceCube has identified three neutrino sources, but there are many open questions:

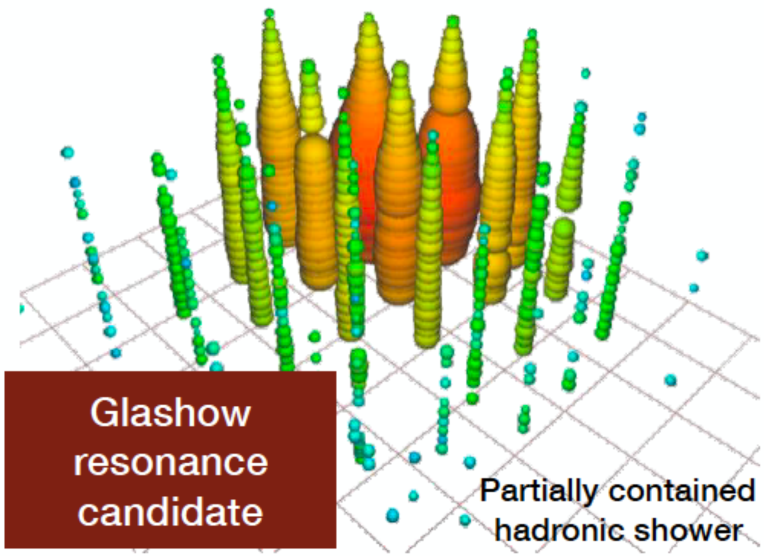
1. **TXS 0506+056 blazar** 
2. **NGC 1068 AGN** 
3. **Galactic Plane** 

The majority of the astrophysical flux that IceCube sees comes from a diffuse component that remains to be fully understood, as it differs depending on the chosen event sample, sky coverage, energy range

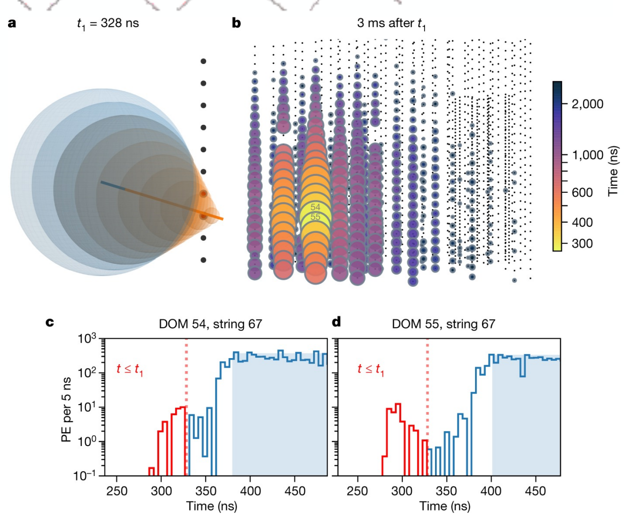
Break from a single power-law?

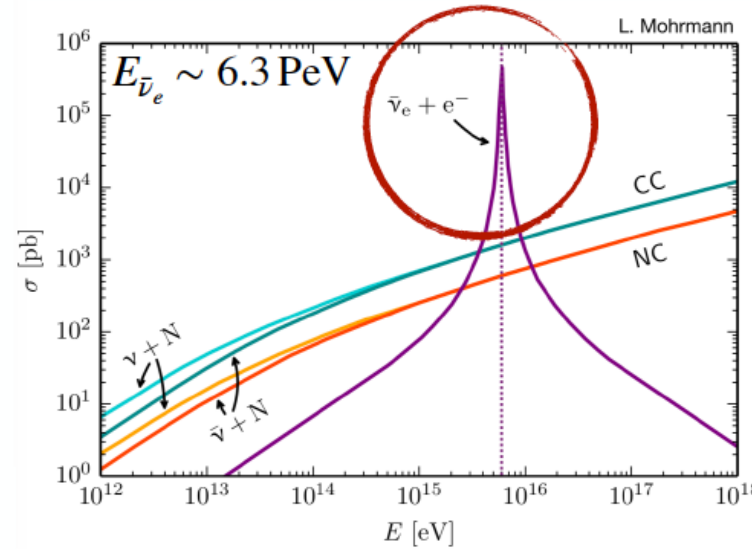
Glashow Resonance: A prediction, 60 years later observed

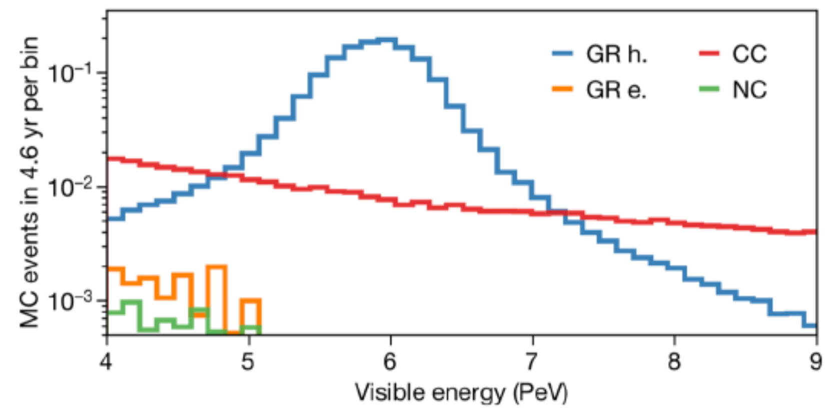
- Resonant interaction $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$
- Disentangle antineutrinos from the total neutrino flux.

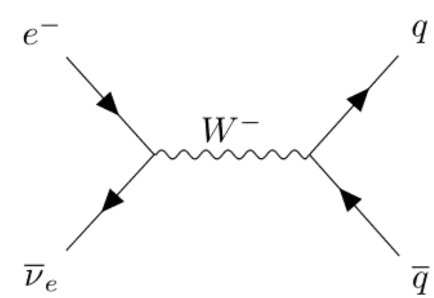


IceCube Nature 591 (2021) 7849









pion production

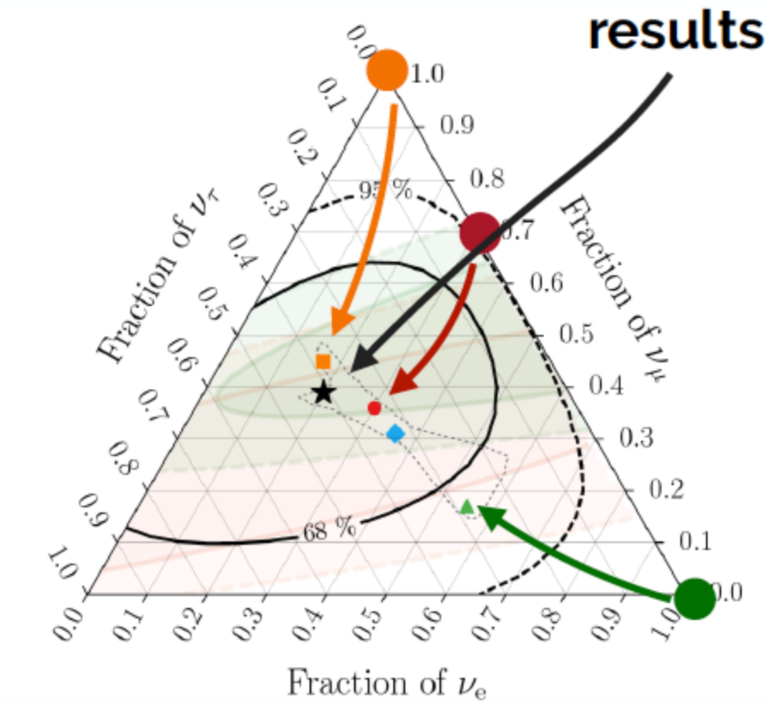
$$\pi^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu$$
$$\downarrow$$
$$e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu \qquad \textbf{(1:2:0)}$$

neutron decay

$$n \to p + e^- + \overline{\nu}_e \qquad \textbf{(1:0:0)}$$

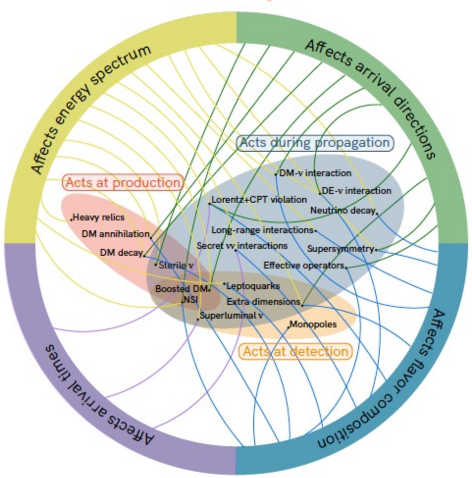
muon dumped

$$\pi^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu \qquad \textbf{(0:1:0)}$$



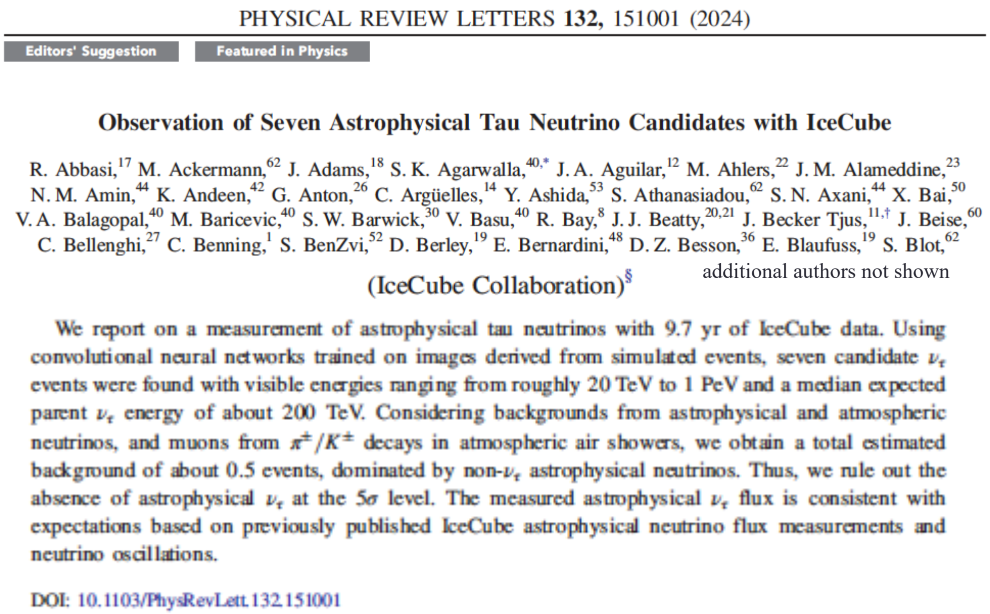
Eur. Phys. J. C 82, 1031 (2022)

Courtesy J. A. Aguilar



An important tool to search for the BSM physics in IceCube

Seven Astrophysical Tau Neutrino Candidates


PHYSICAL REVIEW LETTERS **132**, 151001 (2024)

Editors' Suggestion Featured in Physics

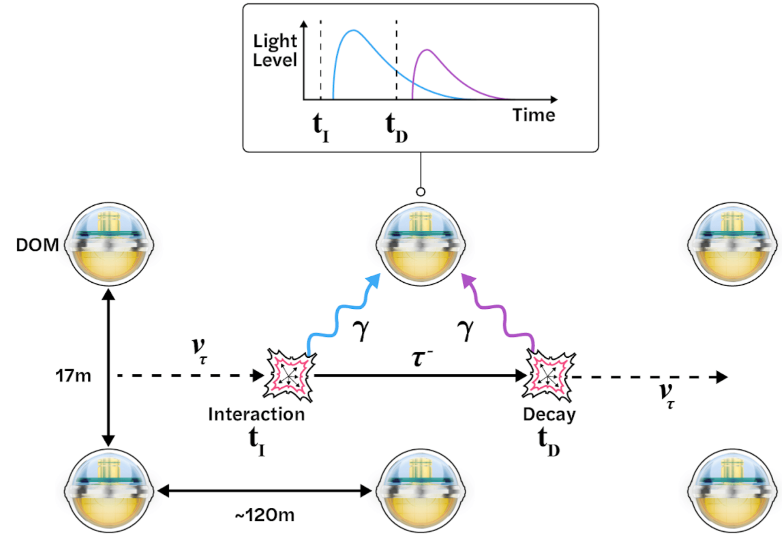
Observation of Seven Astrophysical Tau Neutrino Candidates with IceCube

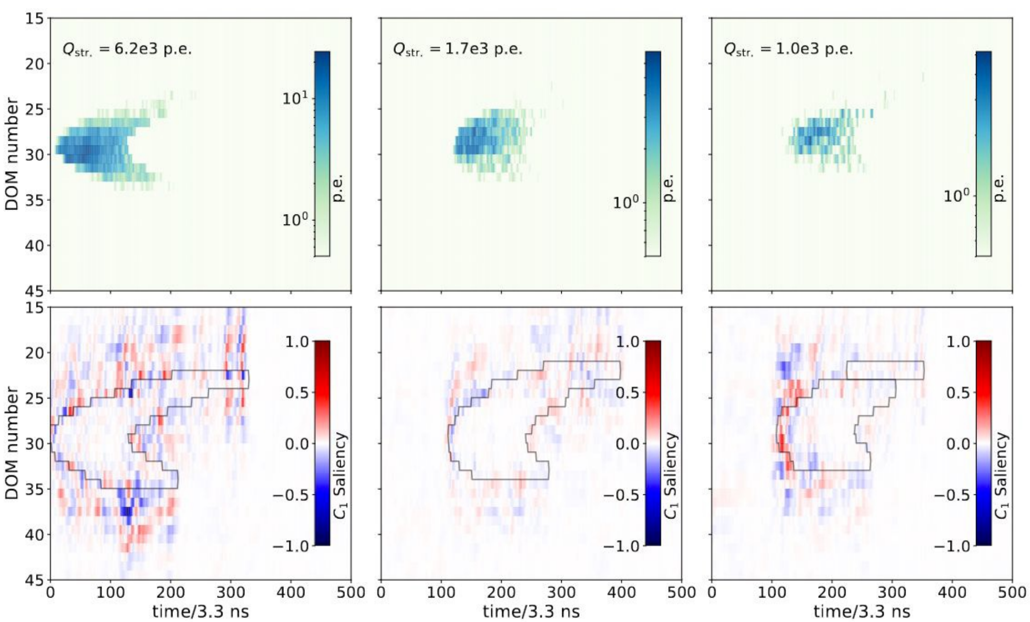
R. Abbasi,[17] M. Ackermann,[62] J. Adams,[18] S. K. Agarwalla,[40,*] J. A. Aguilar,[12] M. Ahlers,[22] J. M. Alameddine,[23] N. M. Amin,[44] K. Andeen,[42] G. Anton,[26] C. Argüelles,[14] Y. Ashida,[53] S. Athanasiadou,[62] S. N. Axani,[44] X. Bai,[50] V. A. Balagopal,[40] M. Baricevic,[40] S. W. Barwick,[30] V. Basu,[40] R. Bay,[8] J. J. Beatty,[20,21] J. Becker Tjus,[11,†] J. Beise,[60] C. Bellenghi,[27] C. Benning,[1] S. BenZvi,[52] D. Berley,[19] E. Bernardini,[48] D. Z. Besson,[36] E. Blaufuss,[19] S. Blot,[62] additional authors not shown

(IceCube Collaboration)[§]

We report on a measurement of astrophysical tau neutrinos with 9.7 yr of IceCube data. Using convolutional neural networks trained on images derived from simulated events, seven candidate ν_τ events were found with visible energies ranging from roughly 20 TeV to 1 PeV and a median expected parent ν_τ energy of about 200 TeV. Considering backgrounds from astrophysical and atmospheric neutrinos, and muons from $\pi^\pm/K^\pm$ decays in atmospheric air showers, we obtain a total estimated background of about 0.5 events, dominated by non-ν_τ astrophysical neutrinos. Thus, we rule out the absence of astrophysical ν_τ at the 5σ level. The measured astrophysical ν_τ flux is consistent with expectations based on previously published IceCube astrophysical neutrino flux measurements and neutrino oscillations.

DOI: 10.1103/PhysRevLett.132.151001





Detection of astrophysical ν_τ require shower-like bright events (double cascades)

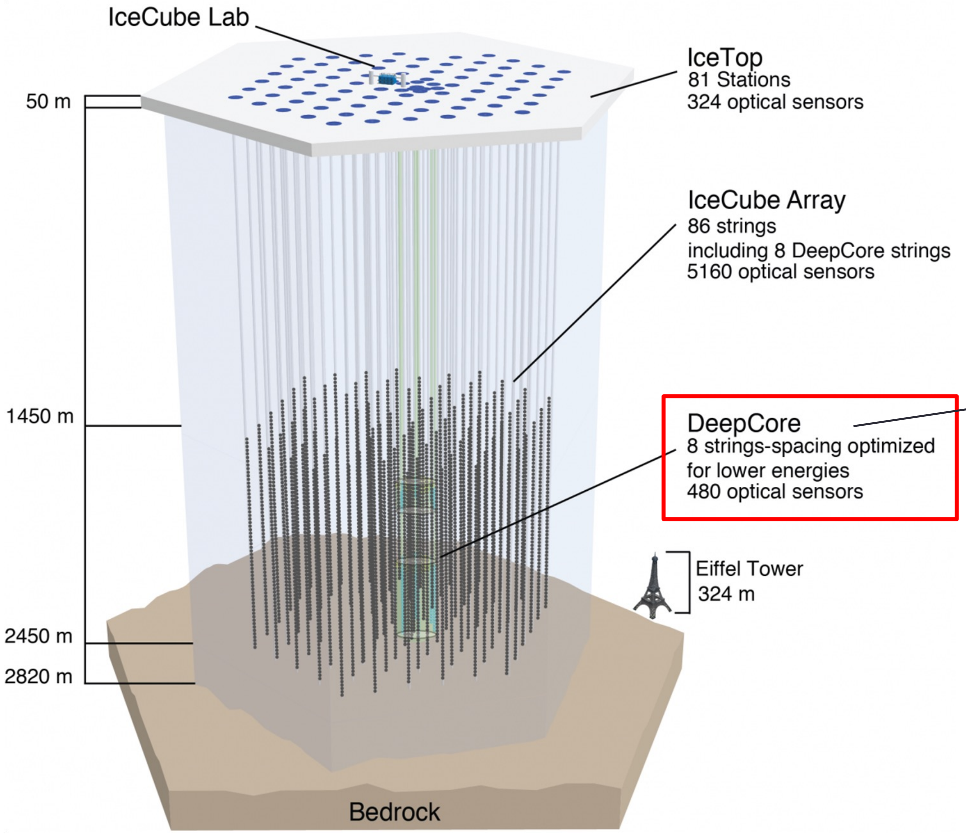
Study images of 3 brightest neighbouring strings

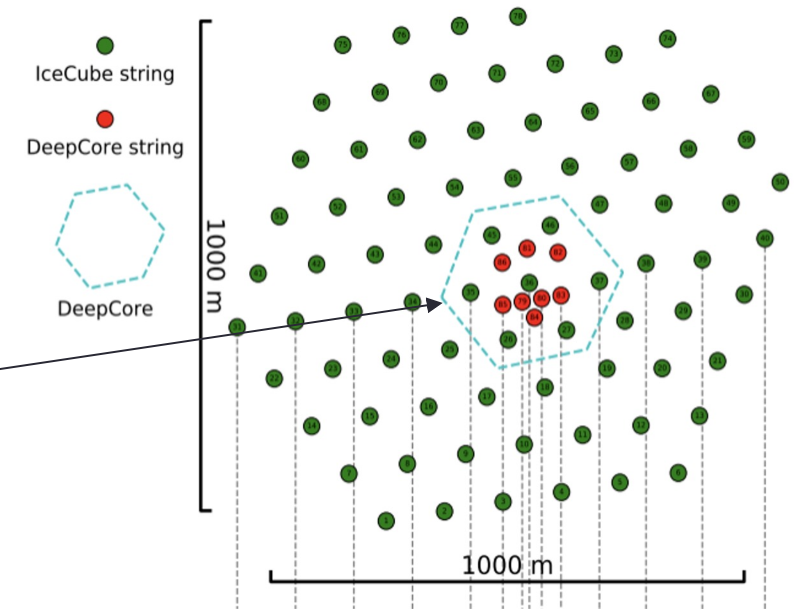
Train 3 CNNs to distinguish astrophysical ν_τ from possible backgrounds

7 astrophysical ν_τ candidates identified with CNN using 9.7 years of IceCube data – some events show clear double-pulse waveforms

We rule out the absence of astrophysical ν_τ at 5.1 σ

DeepCore Detector



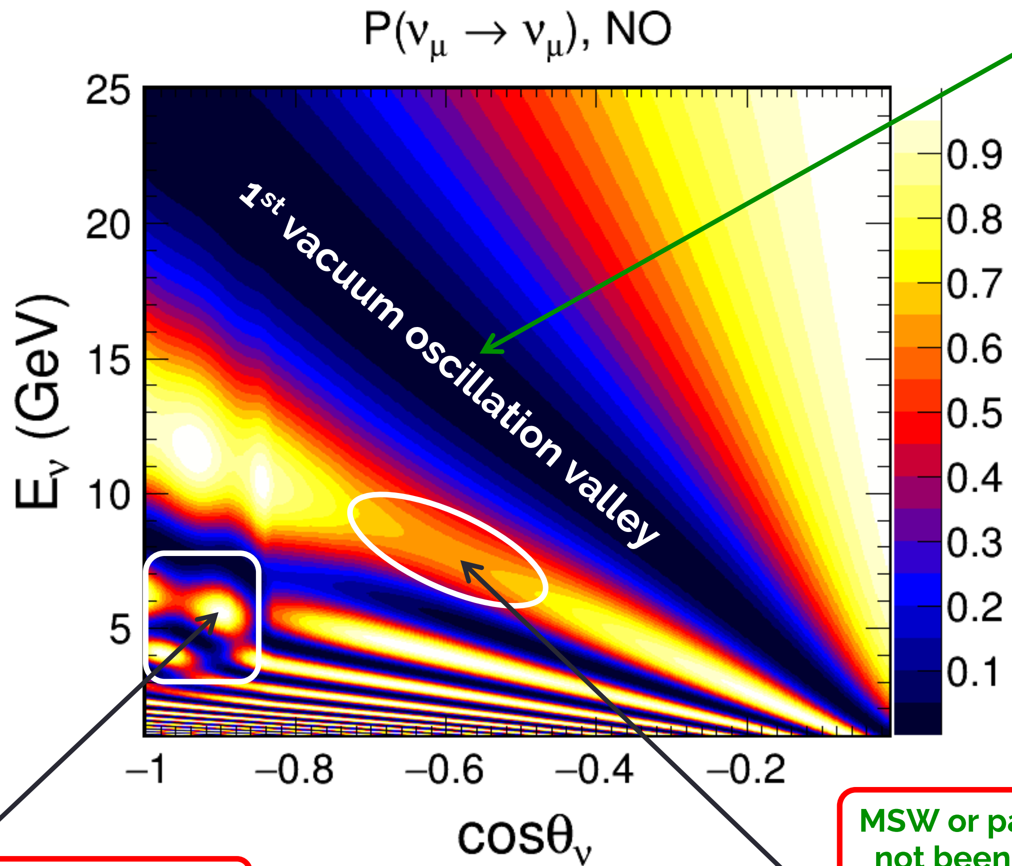


DeepCore

- 8 dedicated strings with denser spacing
- 40–70 m horizontally & 7 m vertically
- Optimized for GeV scale neutrinos
- Uses IceCube as VETO
- Fiducial volume ~ 10 Mton

The design and performance of IceCube DeepCore (2012): Astroparticle Physics, 35(10), 615-624 (2012)

Oscillograms for Muon Neutrino Survival Channel



Provides information on atmospheric neutrino oscillation parameters

MSW or parametric resonances have not been observed yet inside Earth!

Parametric resonance region

$\cos\theta_\nu < -0.8$
3 GeV $< E_\nu < 6$ GeV
reducing threshold helps

Useful to probe Earth's matter effect

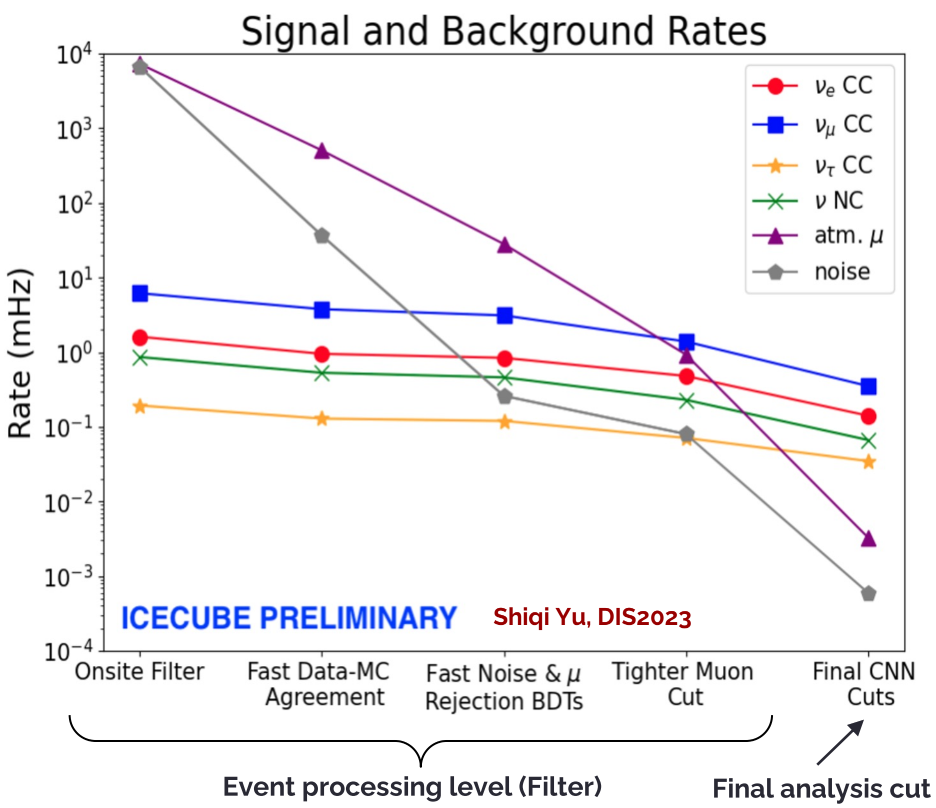
MSW resonance region

$-0.8 < \cos\theta_\nu < -0.5$
6 GeV $< E_\nu < 10$ GeV

Kumar, Khatun, Agarwalla, Dighe, EPJC 81 (2021) 2, 190

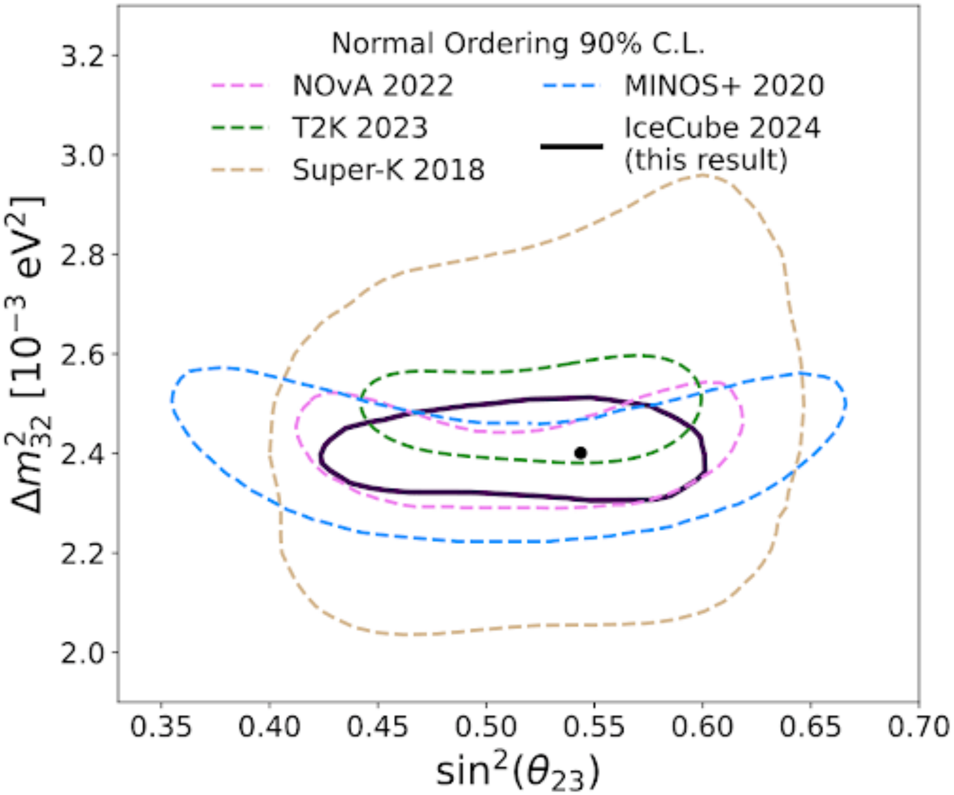
Simulated Neutrino Events

- Convolutional Neural Network (CNN) based reconstruction
- Monte Carlo (MC) simulation with 9.3 years of exposure (2012 - 2021)
- Huge statistics (~192k events)
- Neutrinos comprise 99.5% of sample
- High statistics in ν_μ CC channel
- Filters are applied to eliminate primary backgrounds: noise and atm. muon contamination (~0.5%)

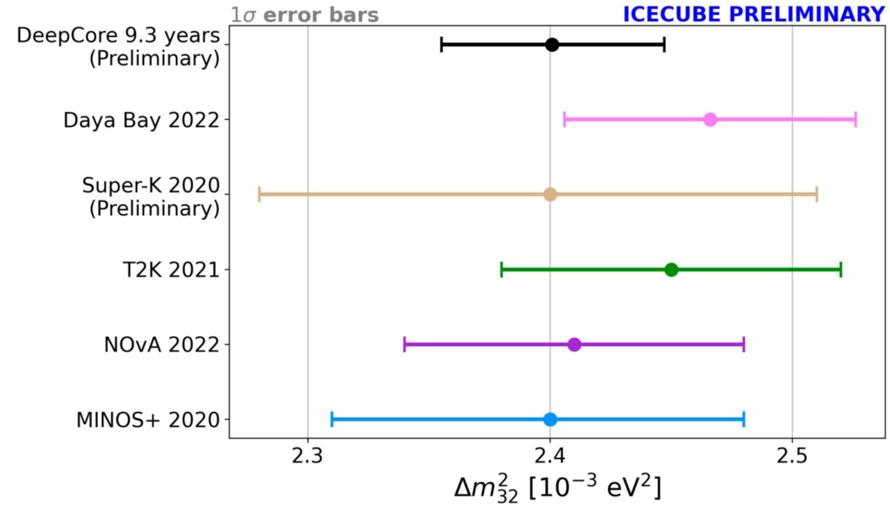


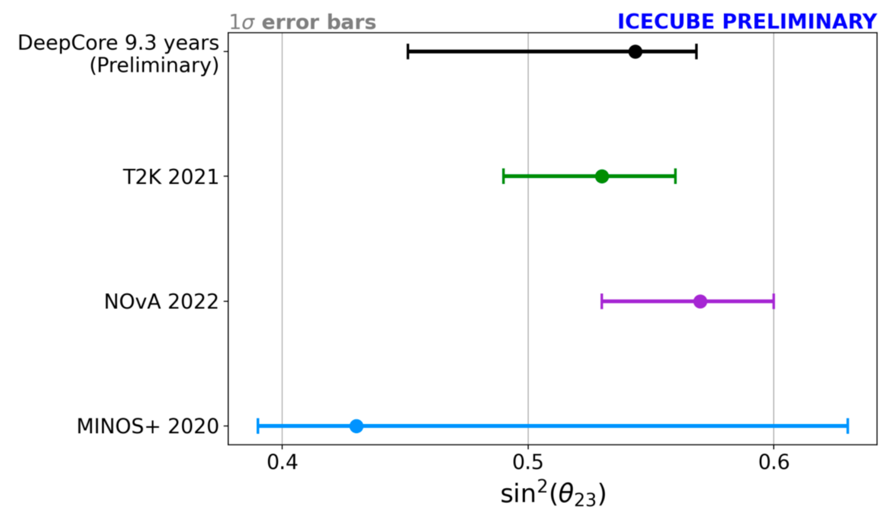
Selection	Expected MC Events (9.3 yr)	% of Sample
$\nu_e + \bar{\nu}_e$ CC	48616	25.2
$\nu_\mu + \bar{\nu}_\mu$ CC	110656	57.5
$\nu_\tau + \bar{\nu}_\tau$ CC	10938	5.7
$\nu_{\text{all}} + \bar{\nu}_{\text{all}}$ NC	21412	11.1
μ_{atm}	973	0.5
All MC	192597	–

Latest Oscillation Results from DeepCore



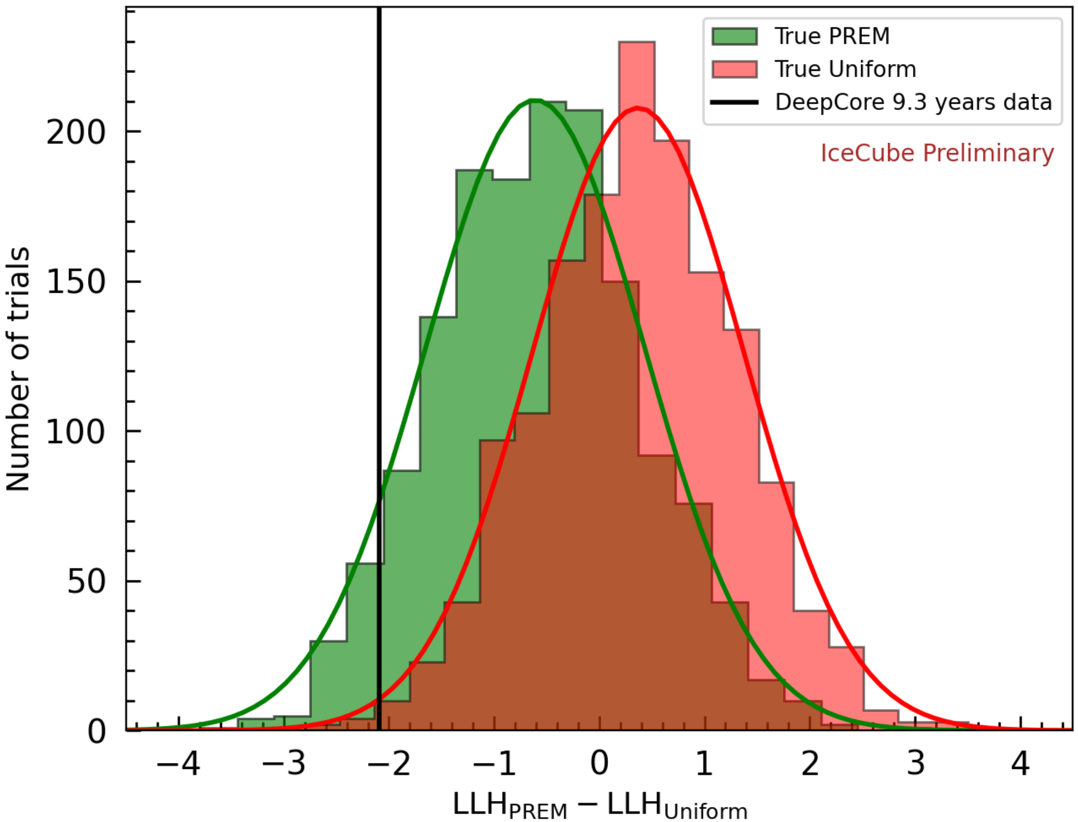
arXiv:2405.02163





ICRC2023 arXiv:2307.15855

- These new result are compatible & complementary with the existing measurements
  - High-precision measurement on Δm^2_{32}
- Comparatively high-energy sample (5 – 100 GeV) and different systematic uncertainties
  - Strong validation of the standard 3-flavor oscillation



P-value:

- **True PREM**:

94% (No. of trials right to the data line: 1406)

- **True Uniform**:

0.46% (No. of trials left to the data line: 7)

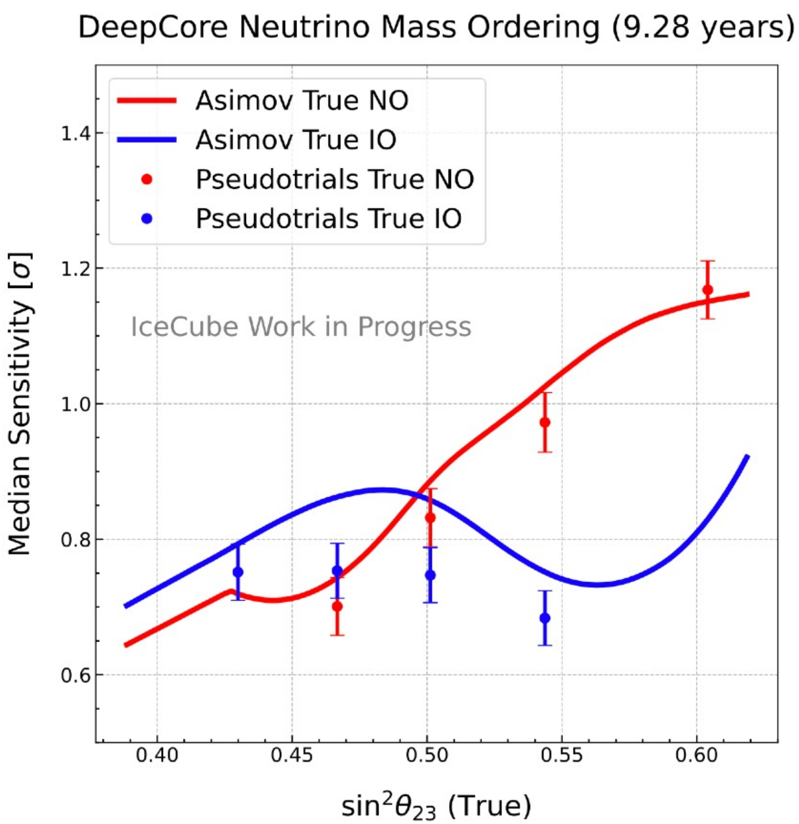
- **CLs** = (0.0046)/(1-0.94) = **7.6%**
- **CL to reject uniform hypothesis 92.4%**

$$\text{significane}\,(\eta_\sigma) = \sqrt{2}\,\text{erfc}^{-1}(2 \times CL_s)$$

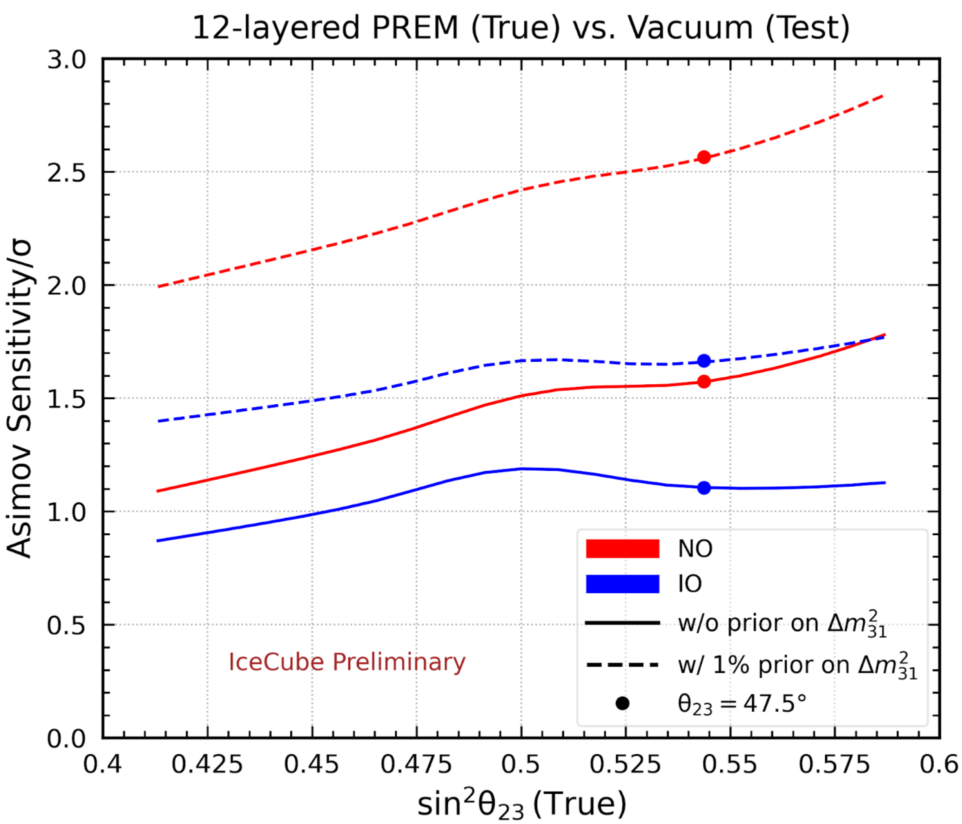
Significance to rule out homogeneous Earth is ~ 1.4σ

Talk by Krishnamoorthi J in this conference

Sensitivity towards Neutrino Mass Ordering and Earth's Matter Effect

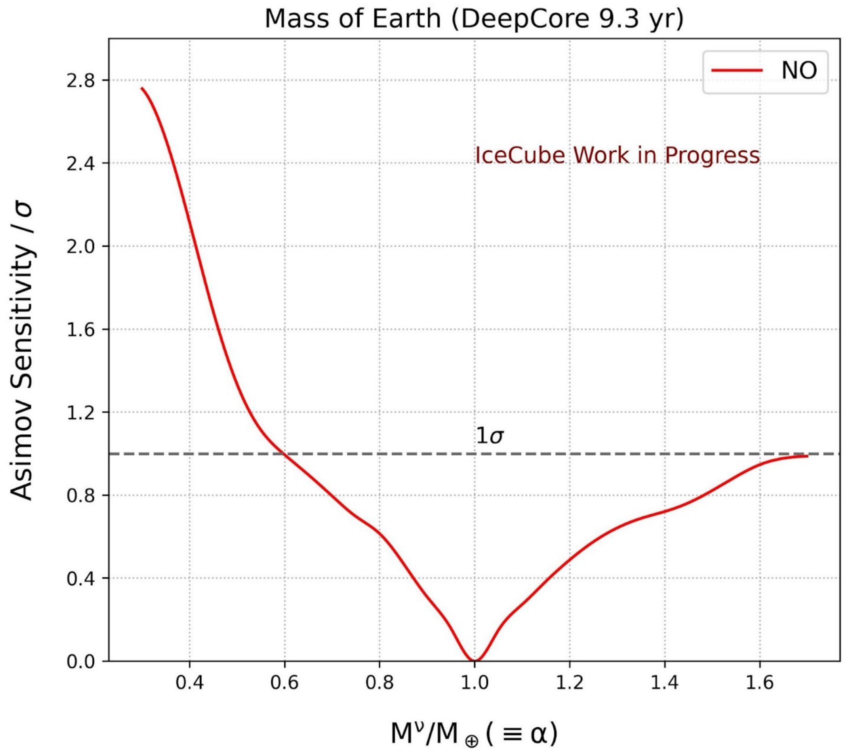


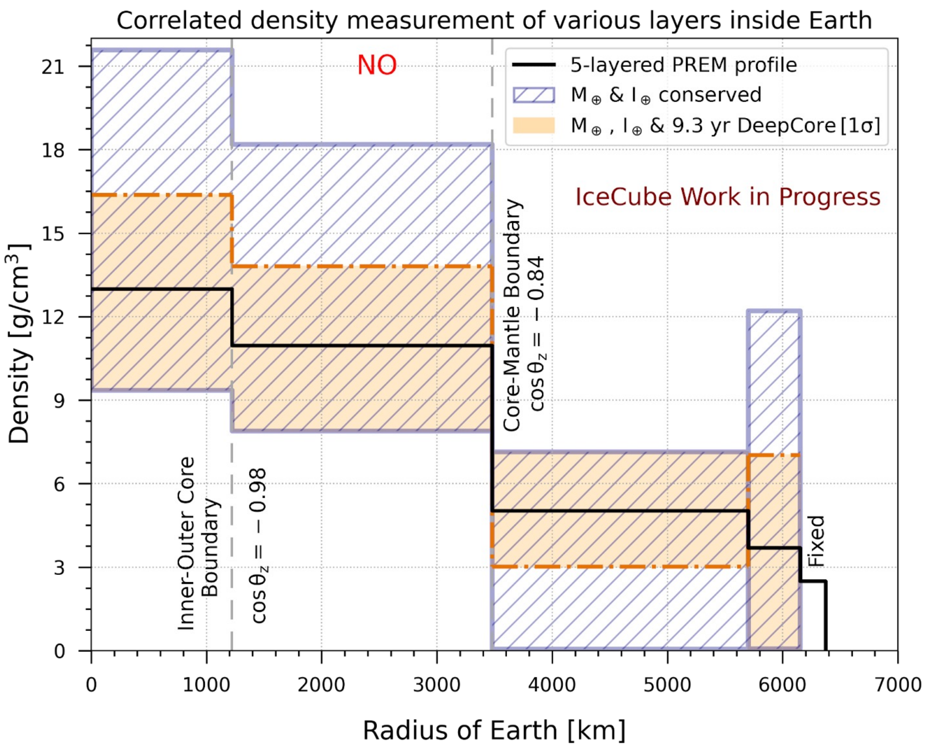
See talks given in NuFact 2023 and NuTel 2023



Talk by Anuj Kumar Upadhyay in this conference

Correlated Density Measurement of Various Layers inside Earth

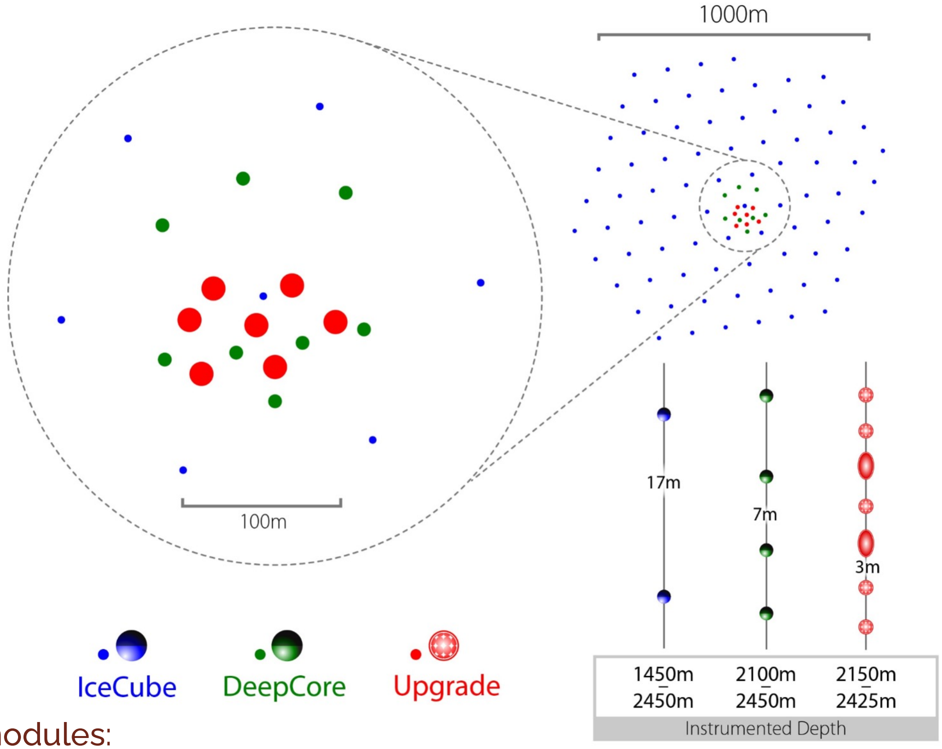


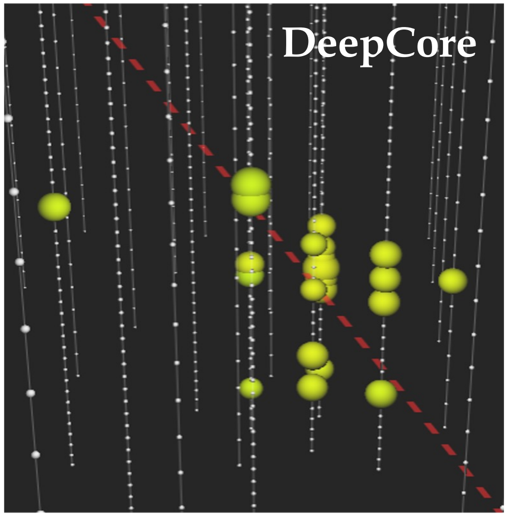


Talk by Sharmistha Chattopadhyay in this conference

A New Extension of DeepCore: IceCube Upgrade

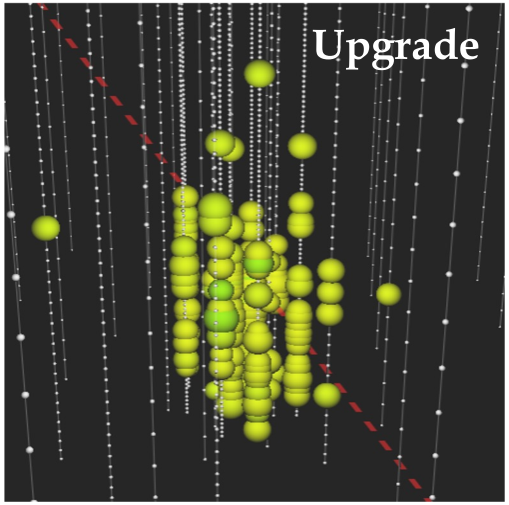
- **2 Mton of dense instrumentation for low-energy measurements**
- **7 new strings in the center region of detector: energy threshold ~ 1 GeV**
- **Higher event rate: 4 x DeepCore**
- **To be deployed in the Antarctic summer of 2025/26**

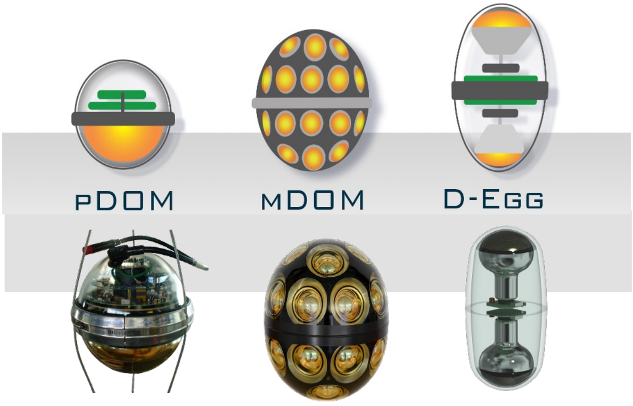




30 GeV Neutrino

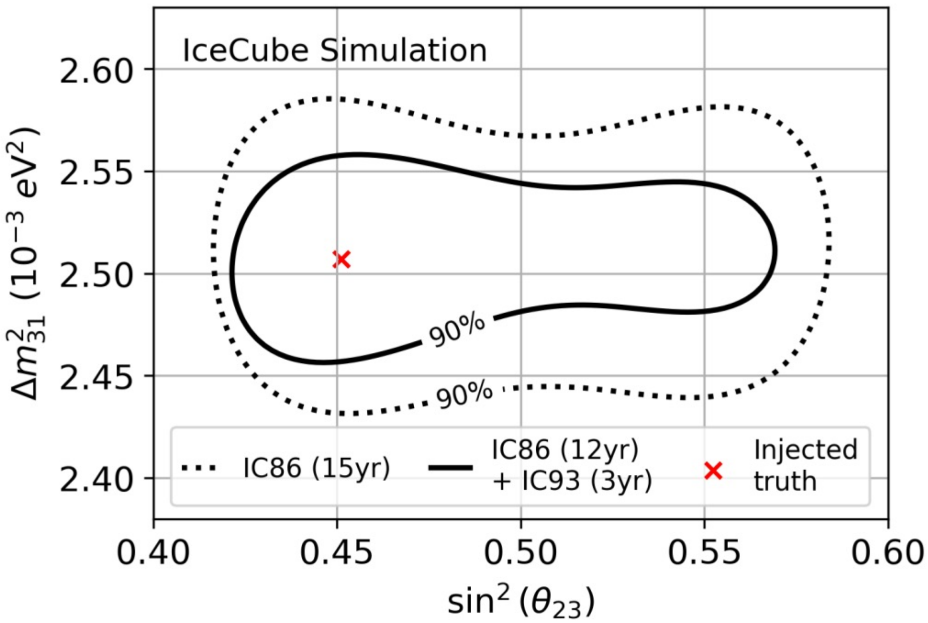
Spacing between new modules:
20 m horizontally & 3 m vertically

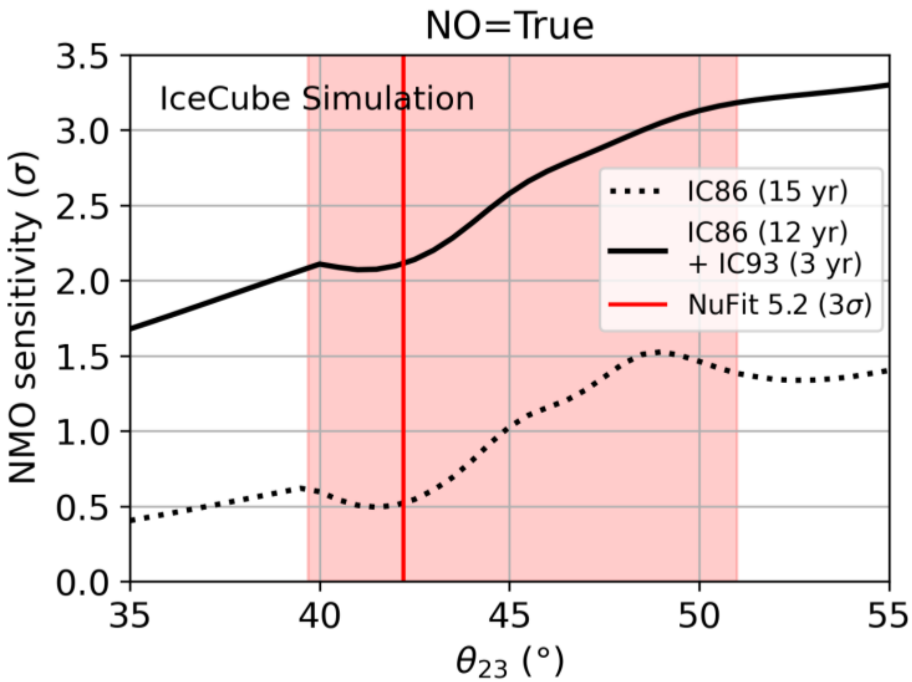




2 new types of optical modules w/ multi-PMT configurations

ICRC2019 arXiv:1908.09441 ICRC2023 arXiv:2307.15295

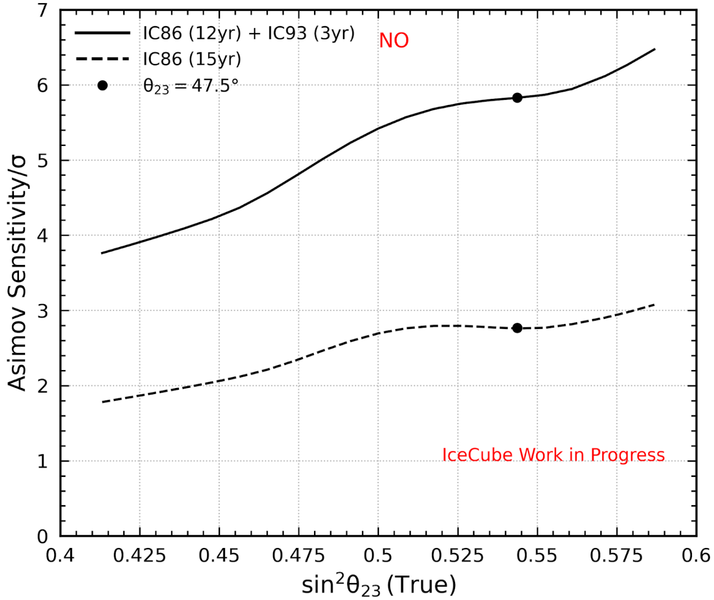




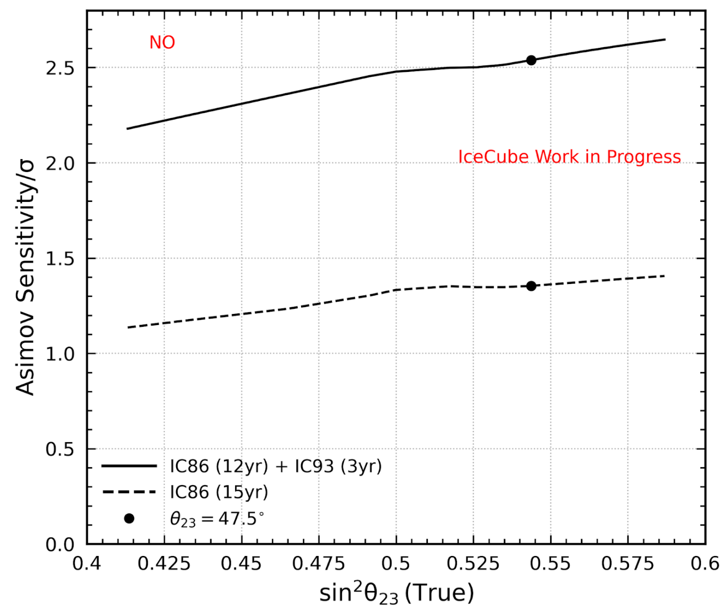
ICRC2023 arXiv:2307.15295

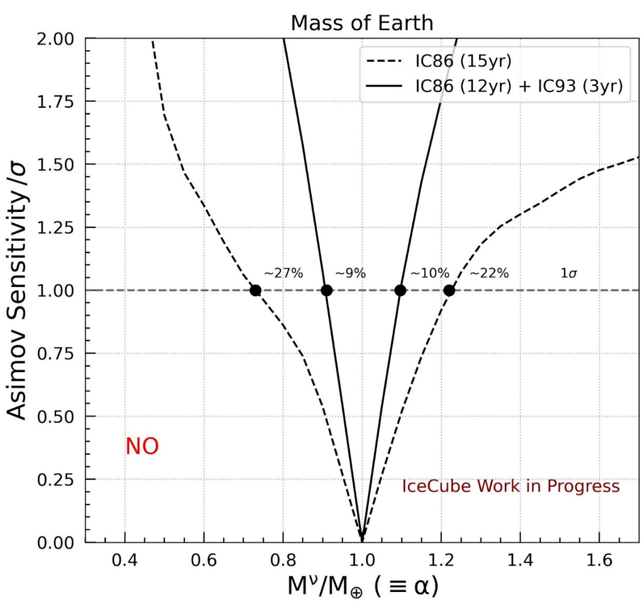
- **90% confidence level after 3 years with the new strings assuming NuFit 5.2 best-fit values**
- **With the new strings, IceCube's sensitivity to Δm^2_{31} and θ_{23} increases by about 20 to 30%**
- **4 times enhancement in the sensitivity to neutrino mass ordering**

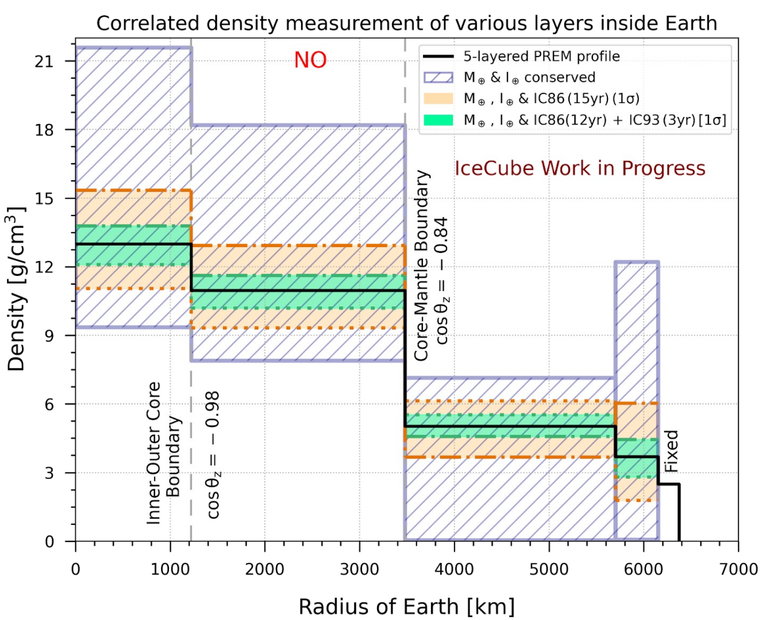
Upgrade sensitivity to reject vacuum hypothesis



Upgrade sensitivity to reject homogeneous Earth

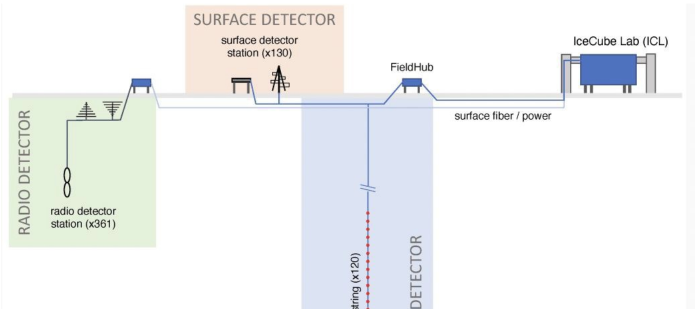


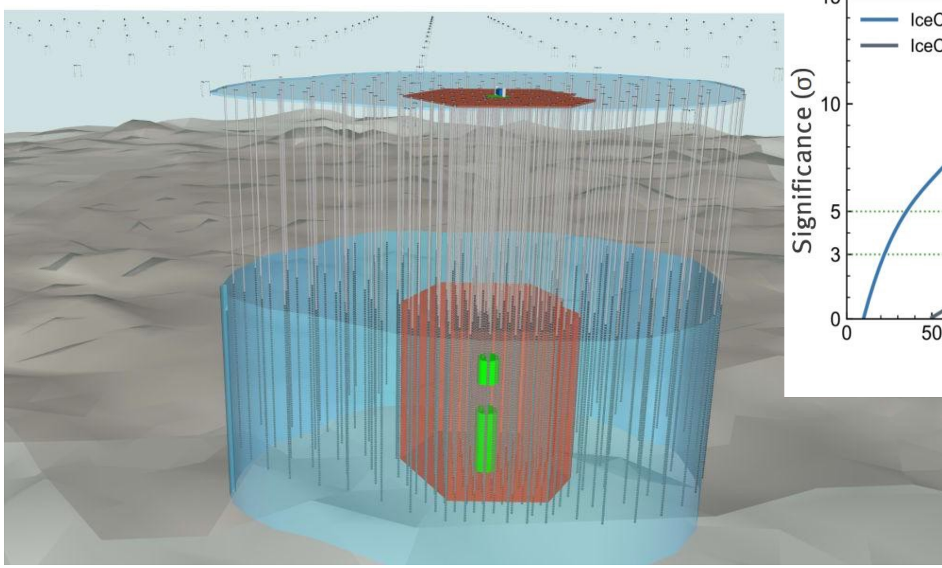


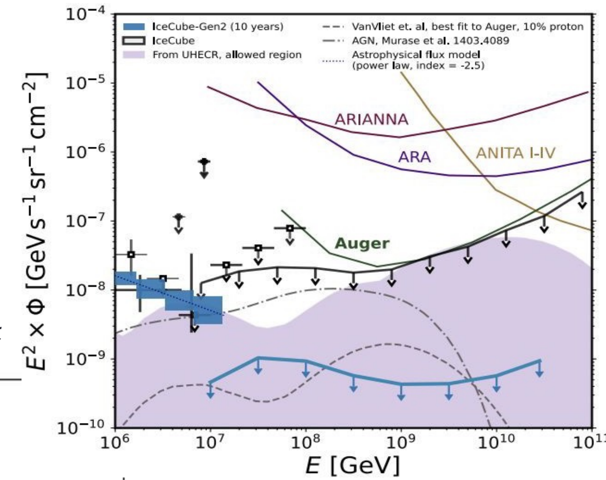


IceCube-Gen2: A Massive Telescope

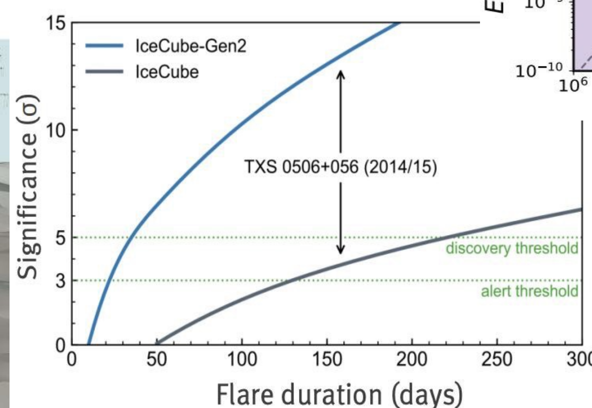
From IceCube-Gen2 Collaboration (2023): IceCube-Gen2 Technical Design: The IceCube-Gen2 Neutrino Observatory
https://icecube-gen2.wisc.edu/science/publications/TDR



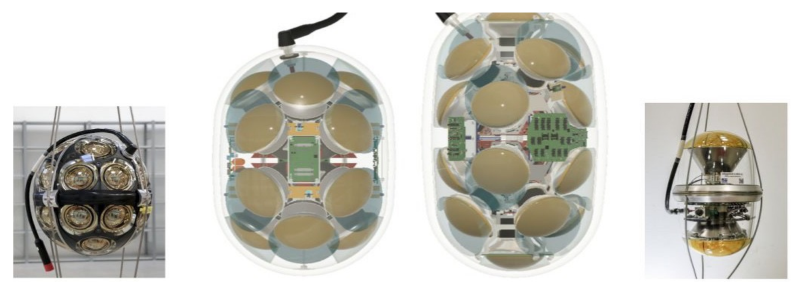




Improved sensitivity plot



IceCube-Gen2 is the proposed extension of IceCube detector: increase the instrumented volume from 1 km3 to ~ 8 km^3, 9600 additional modules, extend to higher energy (10^{18} eV) with radio and surface array, and new detector design



Proposed detector designs based on mDOM and D-Egg from the Upgrade

Concluding Remarks

- Over the past decade, the IceCube Neutrino Observatory has opened up a new window onto the extreme and hidden universe. It has detected high-energy neutrinos of astrophysical origin and successfully identified the first sources.

- The DeepCore array in the central region of IceCube has enabled the detection and reconstruction of atmospheric neutrinos with energies as low as a few GeV, providing high-precision measurements of oscillation parameters and first glimpse of Earth matter effects.

- IceCube Upgrade - a new low-energy extension of DeepCore with novel sensors will address several open questions in three-flavour neutrino oscillation paradigm and significantly improve the detector calibration, resulting in better particle identification, angular, and energy resolution.

- The proposed IceCube-Gen2 will substantially increase the detection rate of astrophysical neutrinos with highest energies to better understand their possible sources and source populations.

Thank you!