Neutrino Astronomy and Fermi: The Past, The Present, and The Future

Drexel UNIVERSITY

11th International Fermi Symposium
Sept 9th, 2024

Naoko Kurahashi Neilson (Drexel University)

Associated with following Neutrino Telescopes but this talk is not on behalf of any!

ICECUBE P-ONE KM3NeT

THE PAST

The Birth of HE Neutrino Astronomy And A Decade of First Observations

A Decade of First Observations

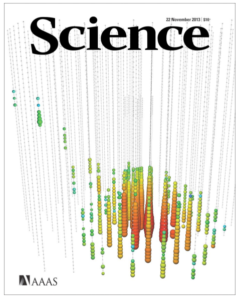
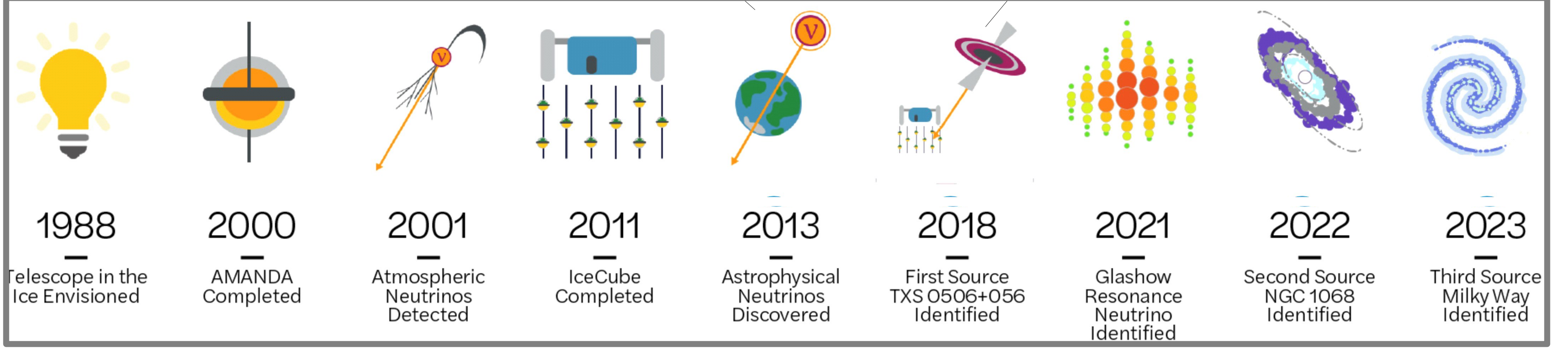


Image Credit: IceCube Collaboration



A Decade of First Observations

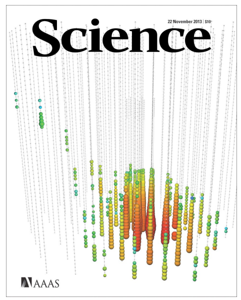
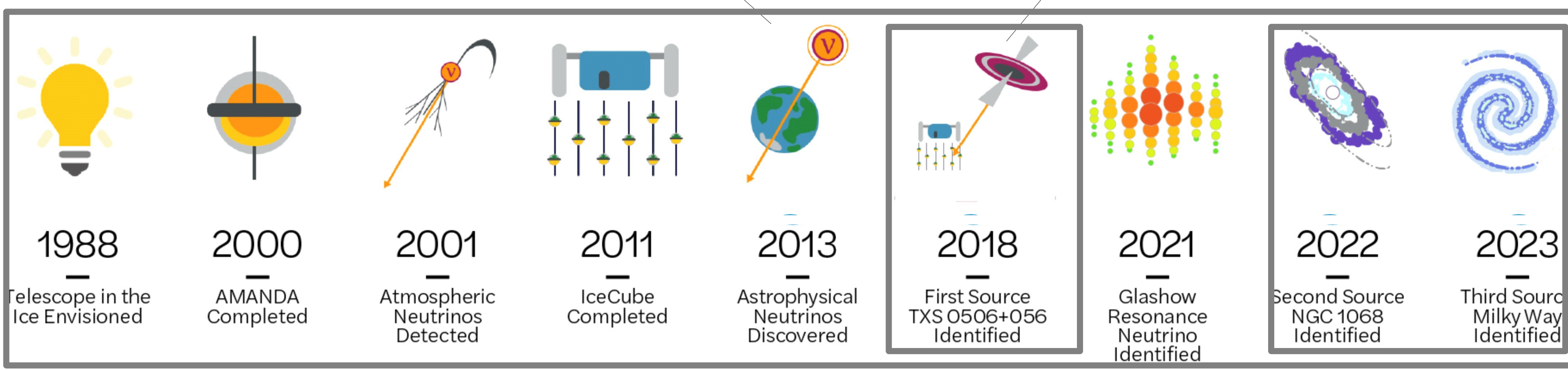
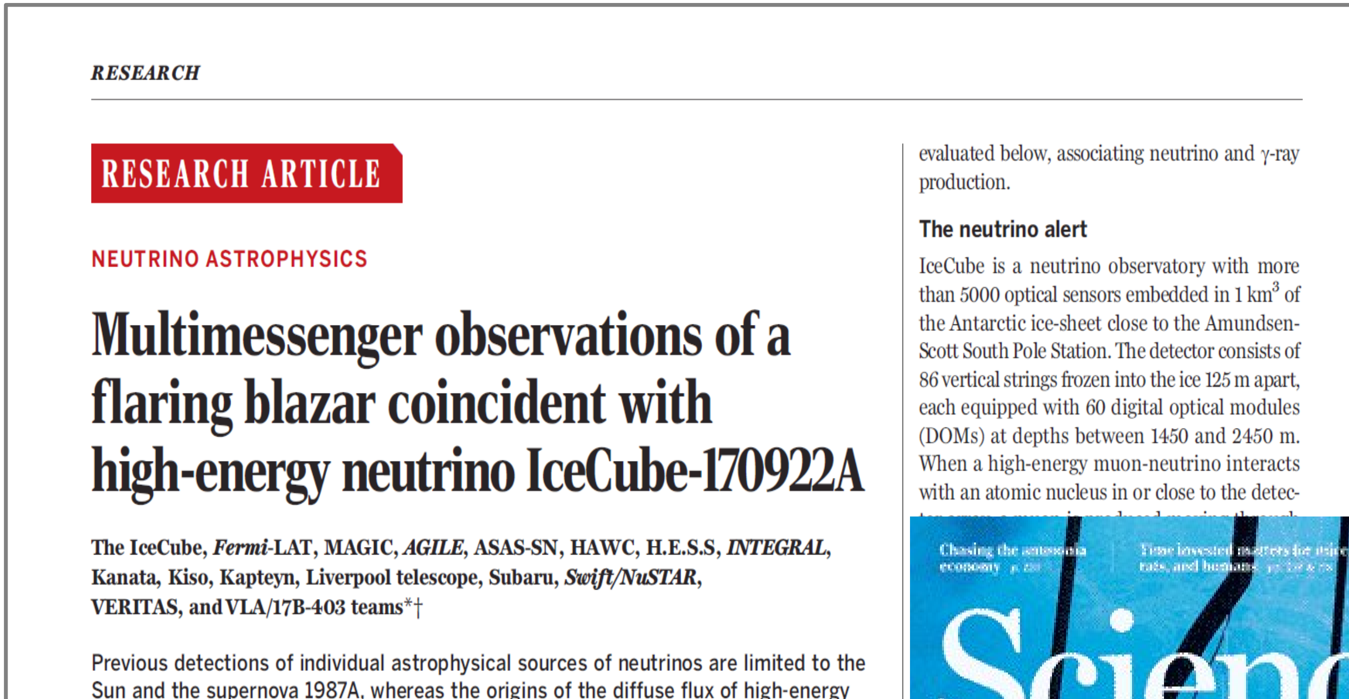


Image Credit: IceCube Collaboration



2018: Blazar TXS 0506+056



RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

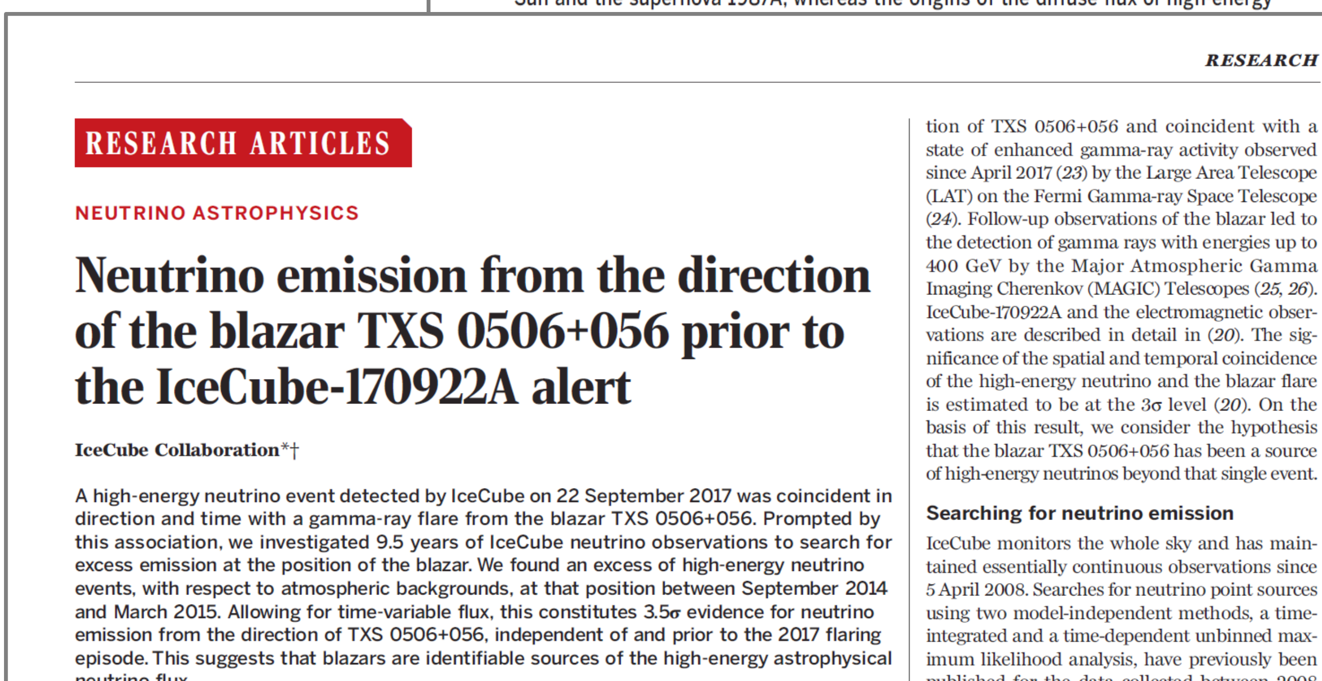
The IceCube, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

Previous detections of individual astrophysical sources of neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy

evaluated below, associating neutrino and γ-ray production.

The neutrino alert

IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detec-



RESEARCH

RESEARCH ARTICLES

NEUTRINO ASTROPHYSICS

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

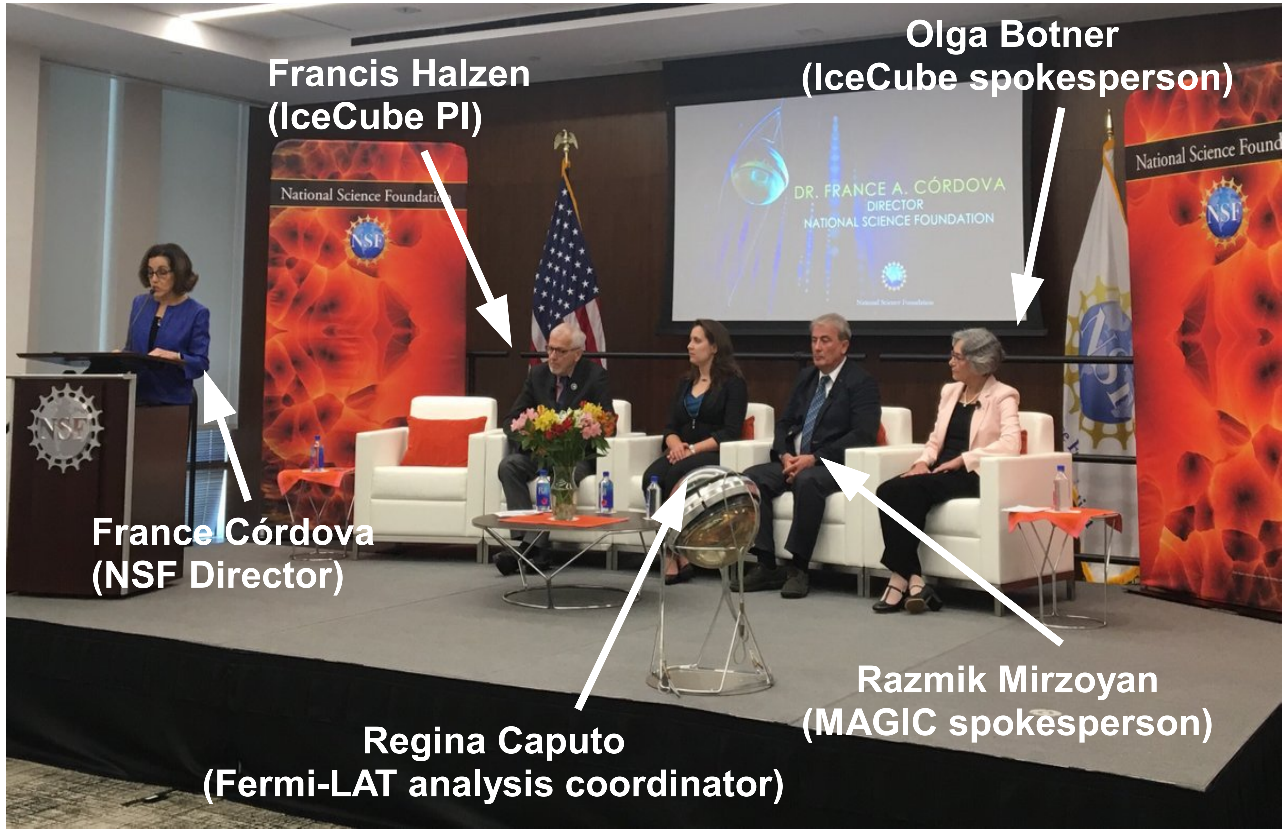
A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056. Prompted by this association, we investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of the blazar. We found an excess of high-energy neutrino events, with respect to atmospheric backgrounds, at that position between September 2014 and March 2015. Allowing for time-variable flux, this constitutes 3.5σ evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. This suggests that blazars are identifiable sources of the high-energy astrophysical

tion of TXS 0506+056 and coincident with a state of enhanced gamma-ray activity observed since April 2017 (*23*) by the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope (*24*). Follow-up observations of the blazar led to the detection of gamma rays with energies up to 400 GeV by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescopes (*25*, *26*). IceCube-170922A and the electromagnetic observations are described in detail in (*20*). The significance of the spatial and temporal coincidence of the high-energy neutrino and the blazar flare is estimated to be at the 3σ level (*20*). On the basis of this result, we consider the hypothesis that the blazar TXS 0506+056 has been a source of high-energy neutrinos beyond that single event.

Searching for neutrino emission

IceCube monitors the whole sky and has maintained essentially continuous observations since 5 April 2008. Searches for neutrino point sources using two model-independent methods, a time-integrated and a time-dependent unbinned maximum likelihood analysis, have previously been

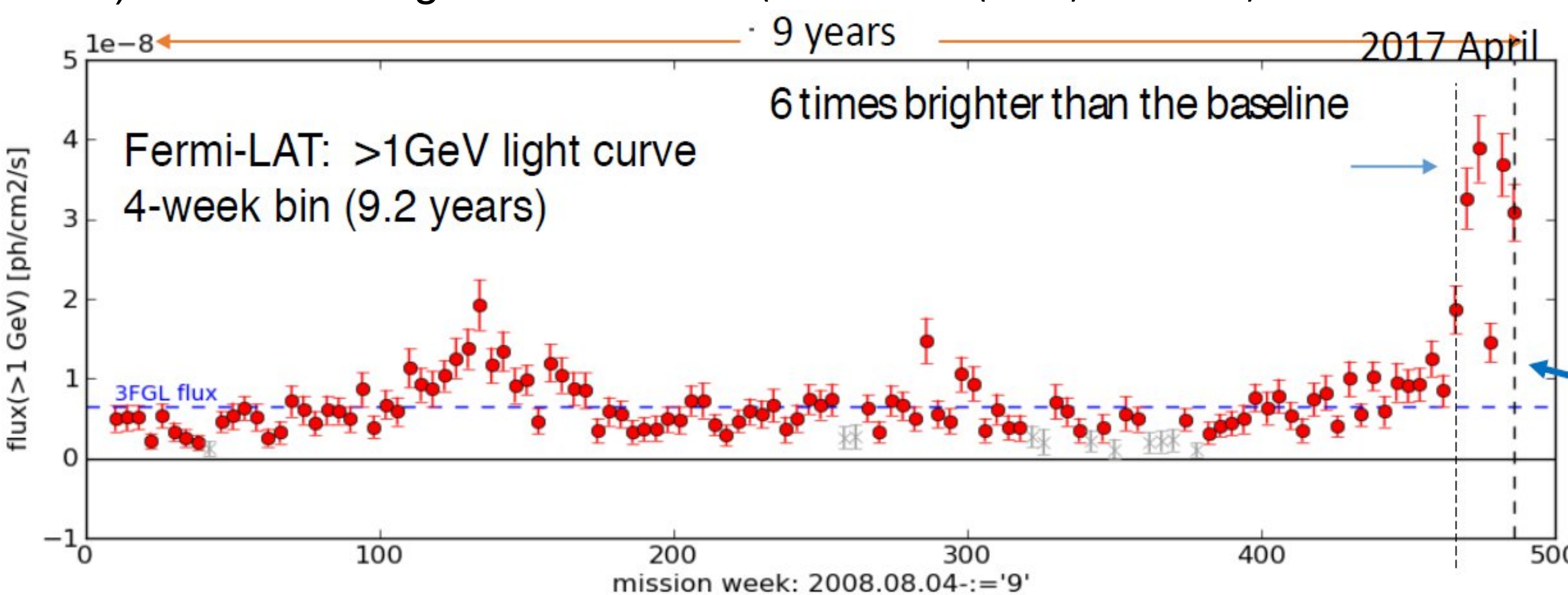
July 12, 2018, Press Conference at NSF



(We got dressed as professional as we could, and headed down to NSF HQ)

2018: Blazar TXS 0506+056

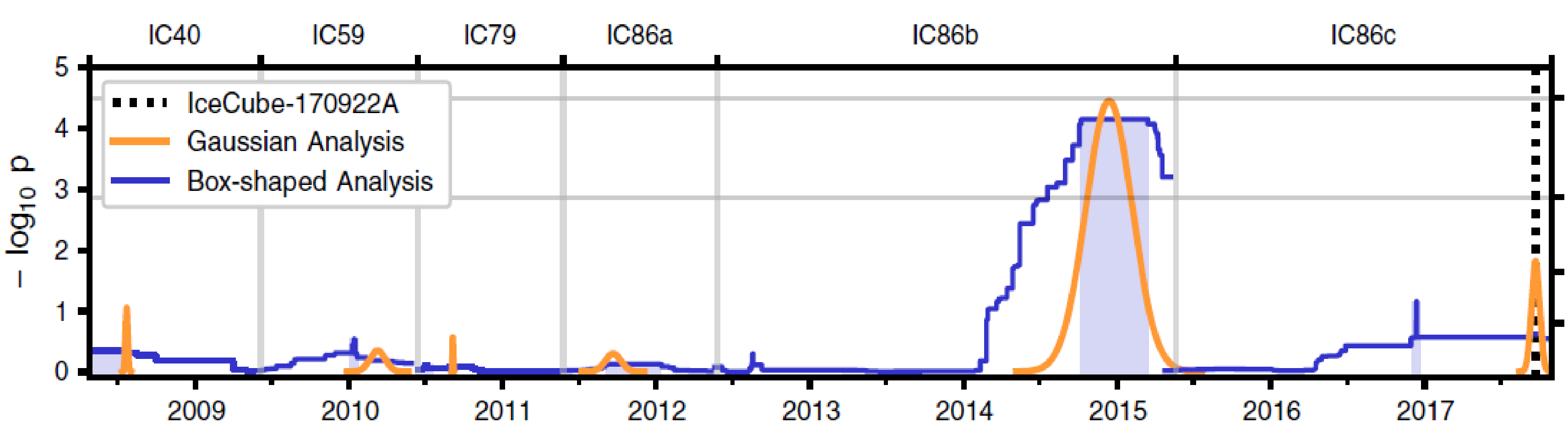
a) Multi-messenger Coincidence (Science 361 (2018) eaat1378)



p-value = 3σ

IceCube 170922A

b) Archival neutrino search (Science 361 (2018) 147-151)



p-value = 3.5σ

Why was Fermi important?

- Ability to follow up on neutrino alerts and issue alert of simultaneous flaring with more precise location to others
- Over 9 years of LAT's continuous monitoring of TXS 0506+056 at constant intervals

A Decade of First Observations

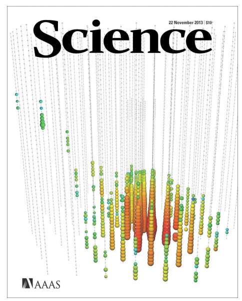
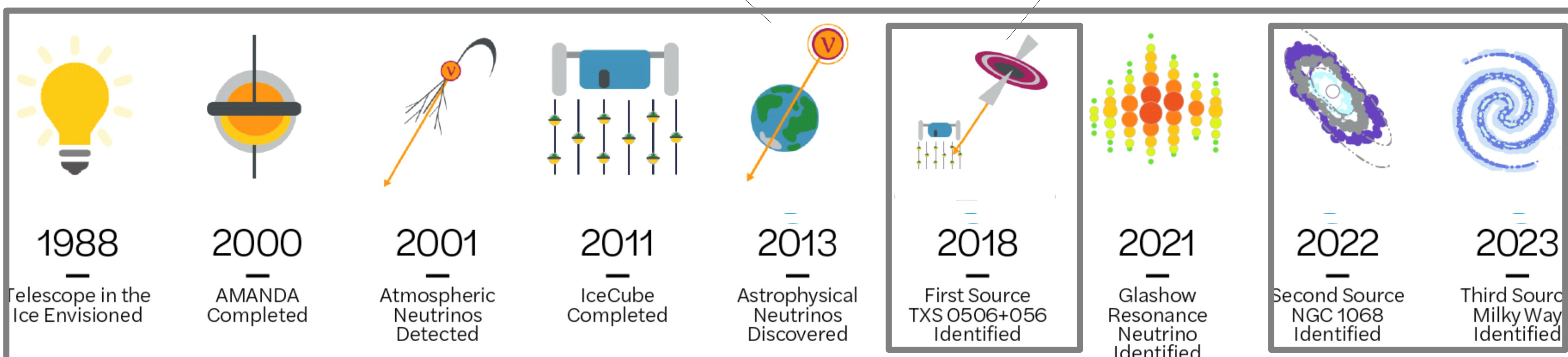


Image Credit: IceCube Collaboration



2022: NGC 1068

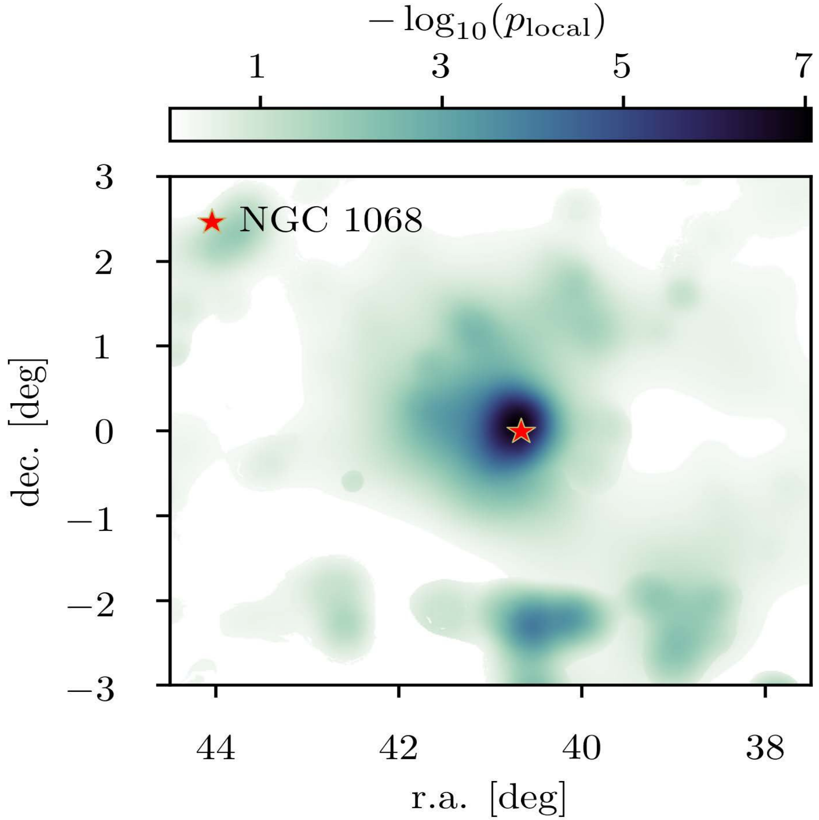
Why was Fermi important?

- Catalog search based on sources in 4FGL-DR2

- neutrino astronomy lives and dies by trials

- Updates to gamma-ray catalogs give neutrino searches new phase space

P-value = 0.001% (4.2 σ)



Science 378, 6619 (2022)

A Decade of First Observations

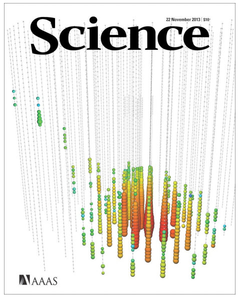
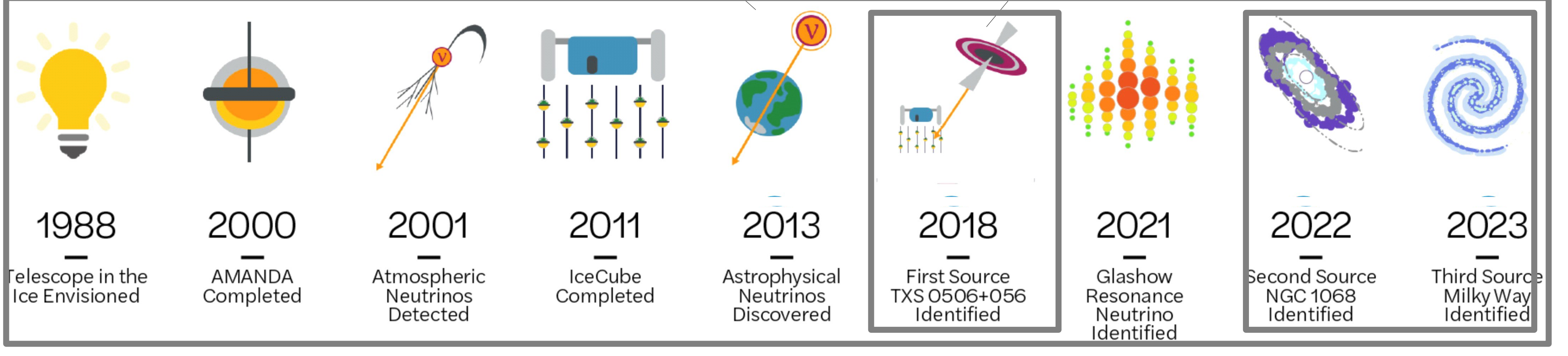
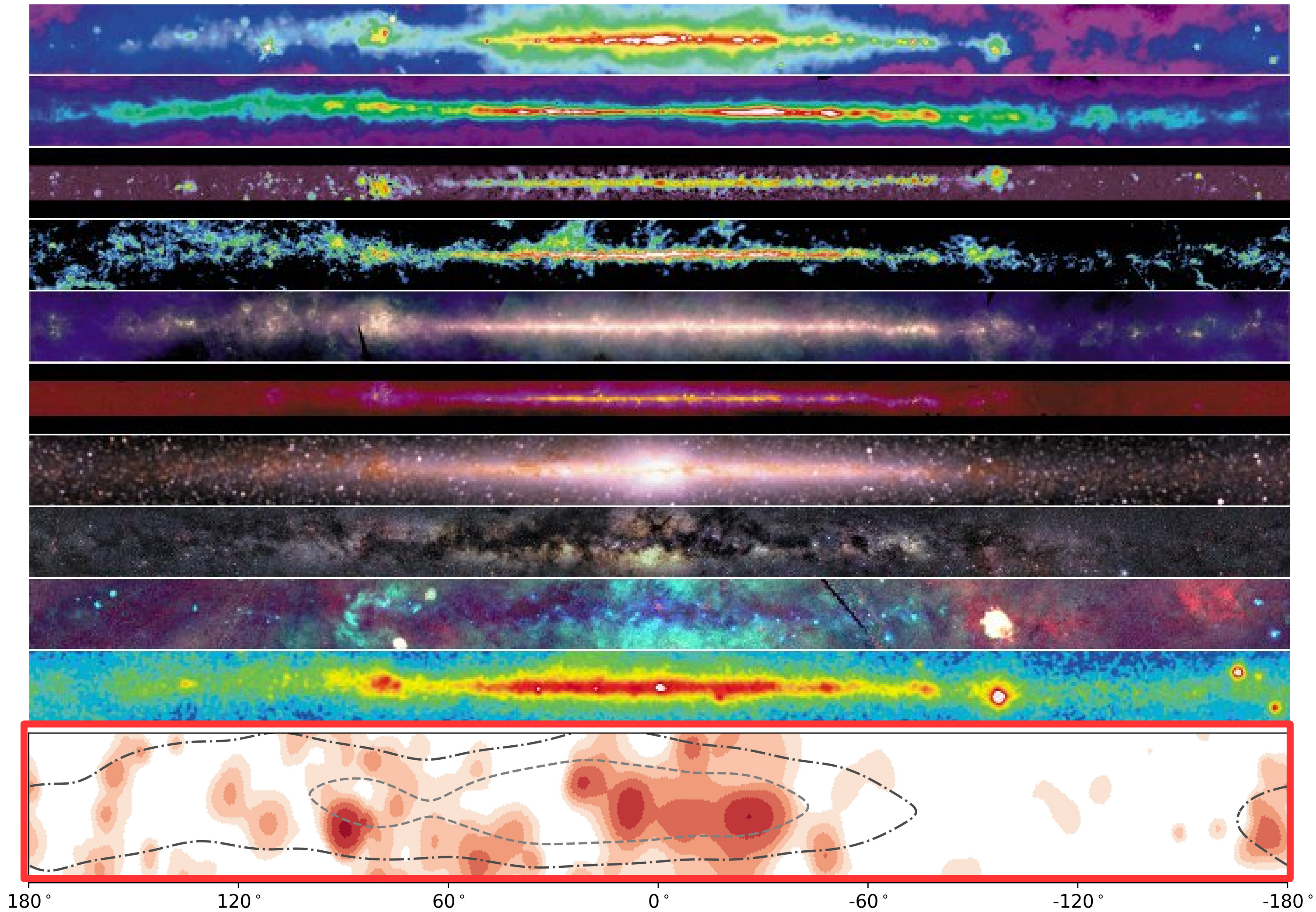


Image Credit: IceCube Collaboration



2023: Diffuse Galactic Plane



First time, a non-EM view of our Galaxy!

The New York Times

Neutrinos Build a Ghostly Map of the Milky Way

Astronomers for the first time detected neutrinos that originated within our local galaxy using a new technique.

Share full article

RESEARCH

RESEARCH ARTICLES

NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

The origin of high-energy cosmic rays, atomic nuclei that continuously impact Earth's atmosphere, is unknown. Because of deflection by interstellar magnetic fields, cosmic rays produced within the Milky Way arrive at Earth from random directions. However, cosmic rays interact with matter near their sources and during propagation, which produces high-energy neutrinos. We searched for neutrino emission using machine learning techniques applied to 10 years of data from the IceCube Neutrino Observatory. By comparing diffuse emission models to a background-only hypothesis, we identified neutrino emission from the Galactic plane at the 4.5σ level of significance. The signal is consistent with diffuse emission of neutrinos from the Milky Way but could also arise from a population of unresolved point sources.

The Milky Way emits radiation across the electromagnetic spectrum, from radio waves to gamma rays. Observations at different wavelengths provide insight into the structure of the Galaxy and have iden- energy gamma-ray point sources (also visible in Fig. 1B), several classes of which are potential cosmic-ray accelerators and therefore possible neutrino sources (*6*–*10*). This makes the Galactic plane an expected location of

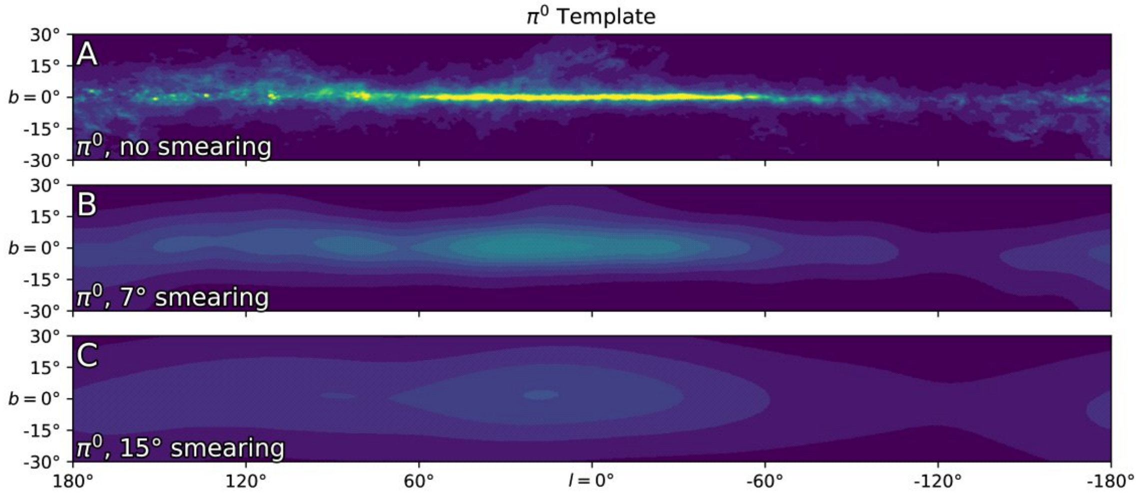
neutrino (ν_τ) with nuclei, as well as scattering interactions of all three neutrino flavors [ν_e, muon neutrino (ν_μ), and ν_τ] on nuclei. Because the charged particles in cascade events travel only a few meters, these energy depositions appear almost point-like to IceCube's 125-m (horizontal) and 7- to 17-m (vertical) instrument spacing. This results in larger directional uncertainties than tracks. Tracks are elongated energy depositions (often several kilometers long), which arise predominantly from muons generated in cosmic-ray particle interactions in the atmosphere or muons produced by interactions of ν_μ with nuclei. The energy deposited by cascades is often contained within the instrumented volume (unlike tracks), which provides a more complete measure of the neutrino energy (*19*).

Searches for astrophysical neutrino sources are affected by an overwhelming background of muons and neutrinos produced by cosmic-ray interactions with Earth's atmosphere. Atmospheric muons dominate this background; IceCube records about 100 million muons for every observed astrophysical neutrino. Whereas muons from the Southern Hemisphere (above IceCube) can penetrate several kilometers deep

Why was Fermi important?

Fermi-LAT π0 Model

Ackermann, M., Ajello, M., Atwood, W. B., et al. ApJ (2012) 750



Spatial template, energy profile, all based on Fermi-LAT model

↓

An observation-based model gives neutrino telescopes the cleanest test therefore limiting trials of models to be tested

A Decade of First Observations

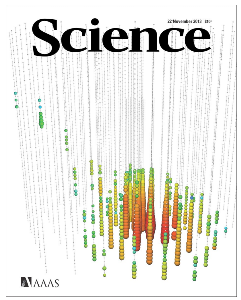
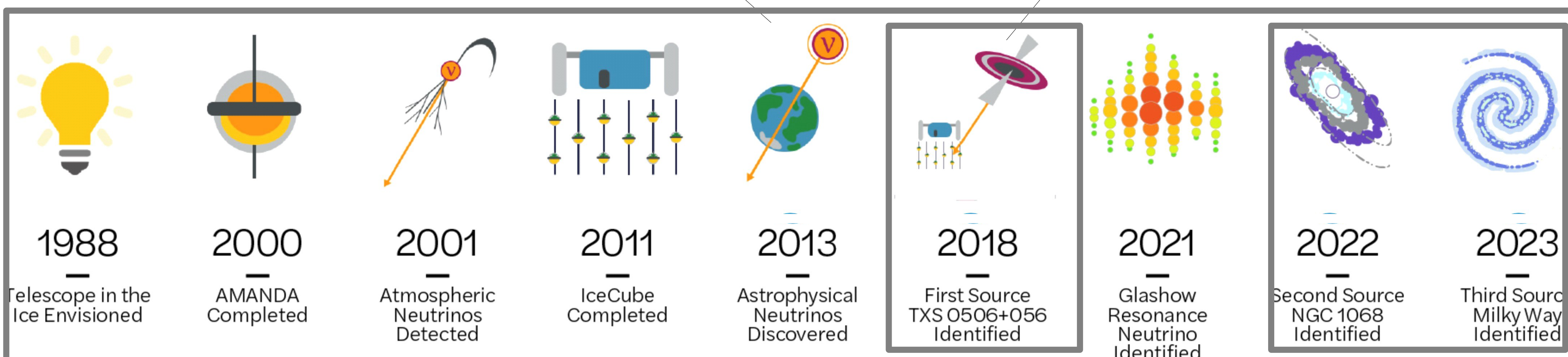


Image Credit: IceCube Collaboration



Notice no Gamma-Ray Bursts!

THE PRESENT

Fermi Tethers Neutrino Astronomy to Astronomy

IceCube publications from the neutrino sources working group, 2024-2022

All-Sky Search for Transient Astrophysical Neutrino Emission with 10 Years of IceCube Cascade Events, IceCube Collaboration, Astrophysical Journal 967 (2024) 481

Search for 10-1,000 GeV Neutrinos from Gamma-Ray Bursts with IceCube IceCube Collaboration,Astrophysical Journal 964 (2024) 126

Search for Continuous and Transient Neutrino Emission Associated with IceCube's Highest-Energy Tracks: An 11-Year Analysis, IceCube Collaboration, Astrophysical Journal 964 (2024) 40

A Search for IceCube sub-TeV Neutrinos Correlated with Gravitational-Wave Events Detected By LIGO/Virgo, IceCube Collaboration, The Astrophysical Journal 959 (2023)

Search for Extended Sources of Neutrino Emission in the Galactic Plane with IceCube, IceCube Collaboration, Astrophysical Journal 956 (2023) 20

Search for Correlations of High-Energy Neutrinos Detected in IceCube with Radio-Bright AGN and Gamma-Ray Emission from Blazars, IceCube Collaboration, Astrophysical Journal 954 (2023) 75

Search for sub-TeV Neutrino Emission from Novae with IceCube-DeepCore IceCube Collaboration, Astrophysical Journal 953 (2023) 160

Constraints on Populations of Neutrino Sources from Searches in the Directions of IceCube Neutrino Alerts, IceCube Collaborations, The Astrophysical Journal 951 (2023) 45

Observation of high-energy neutrinos from the Galactic plane IceCube Collaboration, Science 380, 6652 (2023)

Constraining High-Energy Neutrino Emission from Supernovae with IceCube, IceCube Collaboration, Astrophysical Journal Letters 949 (2023)

A Search for Coincident Neutrino Emission from Fast Radio Bursts with Seven Years of IceCube Cascade Events, IceCube Collaboration, Astrophysical Journal 946 (2023) 80

Limits on Neutrino Emission from GRB 221009A from MeV to PeV using the IceCube Neutrino Observatory, IceCube Collaboration, The Astrophysical Journal Letters 946 (2023) L26

Searches for Neutrinos from Large High Altitude Air Shower Observatory Ultra-High-Energy γ-ray Sources Using the IceCube Neutrino Observatory, IceCube Collaboration, Astrophysical Journal Letters 945 (2023) L8

IceCube Search for Neutrinos Coincident with Gravitational Wave Events from LIGO/Virgo Run O3, IceCube Collaborations, Astrophysical Journal 944 (2023) 80

Searches for Neutrinos from Gamma-Ray Bursts Using the IceCube Neutrino Observatory, IceCube Collaborations, Astrophysical Journal 939 (2022)

Evidence for Neutrino Emission from the Nearby Active Galaxy NGC 1068, IceCube Collaboration, Science 378 (2022) 538-543

Searching for High-Energy Neutrino Emission from Galaxy Clusters with IceCube, IceCube Collaborations, Astrophysical Journal Letters 938 (2022) L11

Search for Astrophysical Neutrinos from 1FLE Blazars with IceCube IceCube Collaborations, The Astrophysical Journal 938 (2022) 38;

Search for Spatial Correlations of Neutrinos with UHE Cosmic Rays, ANTARES, IceCube, Auger, and Telescope Array Collaborations, The Astrophysical Journal 934 (2022) 164

Search for Neutrino Emission from Cores of Active Galactic Nuclei IceCube Collaborations, Physical Review D106 (2022) 022005

Search for High-Energy Neutrinos from Ultraluminous Infrared Galaxies with IceCube, IceCube Collaboration, Astrophysical Journal 926 (2022) 59, 11 ;

IceCube publications from neutrino sources working group, 2024-2022

All-Sky Search for Transient Astrophysical Neutrino Emission with 10 Years of IceCube Cascade Events, IceCube Collaboration, Astrophysical Journal 967 (2024) 481

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A Search for IceCube sub-TeV Neutrinos Correlated with Gravitational-Wave Events Detected By LIGO/Virgo, IceCube Collaboration, The Astrophysical Journal 959 (2023)

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Search for Astrophysical Neutrinos from 1FLE Blazars with IceCube IceCube Collaborations, The Astrophysical Journal 938 (2022) 38

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Search for Neutrino Emission from Cores of Active Galactic Nuclei IceCube Collaborations, Physical Review D106 (2022) 022005

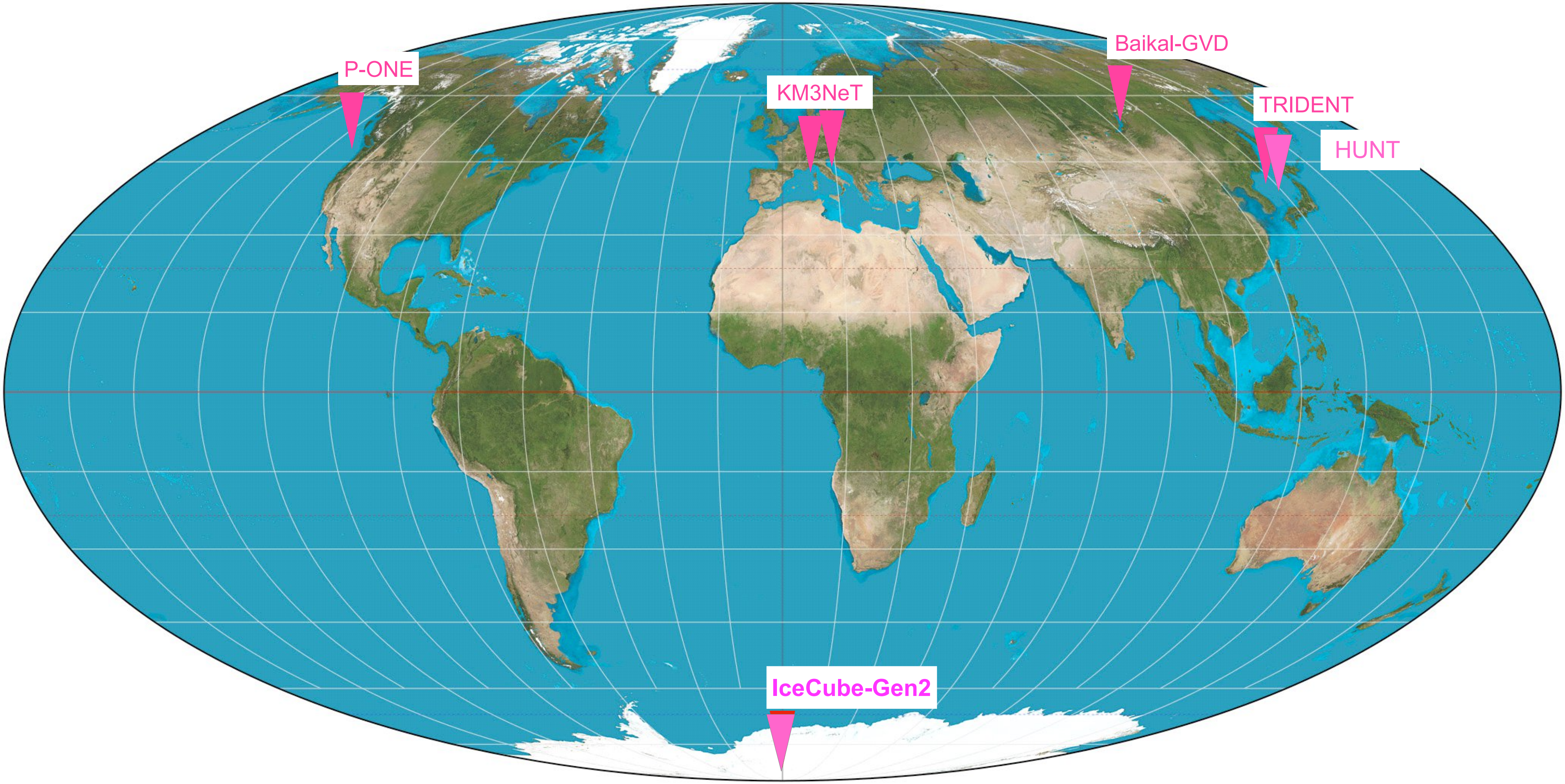
Search for High-Energy Neutrinos from Ultraluminous Infrared Galaxies with IceCube, IceCube Collaboration, Astrophysical Journal 926 (2022) 59, 11 ;

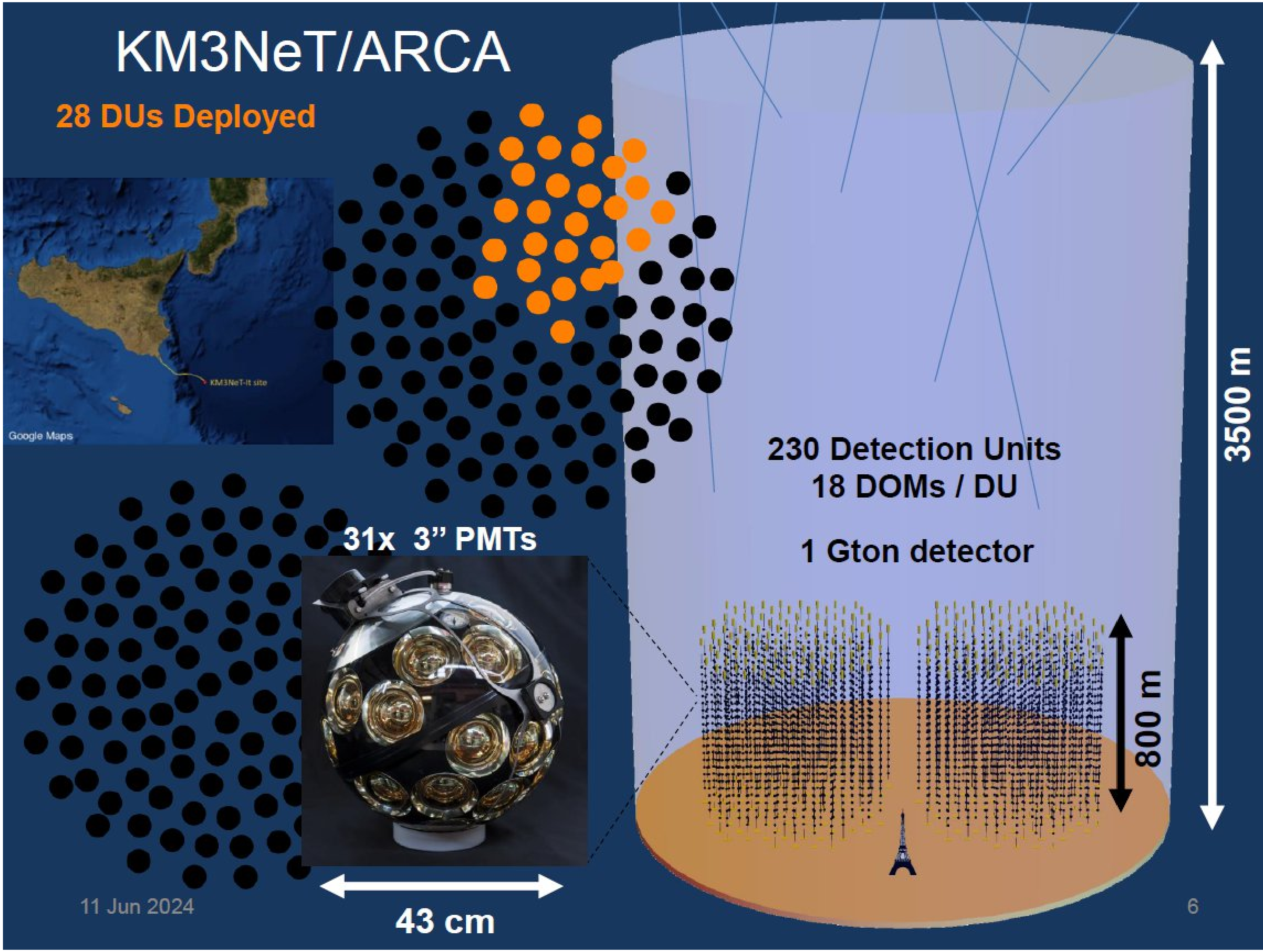
https://icecube.wisc.edu/science/publications/

THE FUTURE

More Neutrino Telescopes
Galactic Neutrino Astronomy
Need for Gamma Ray Partners

Planned Future Neutrino Telescopes





Slide from J. Coelho (KM3NeT)

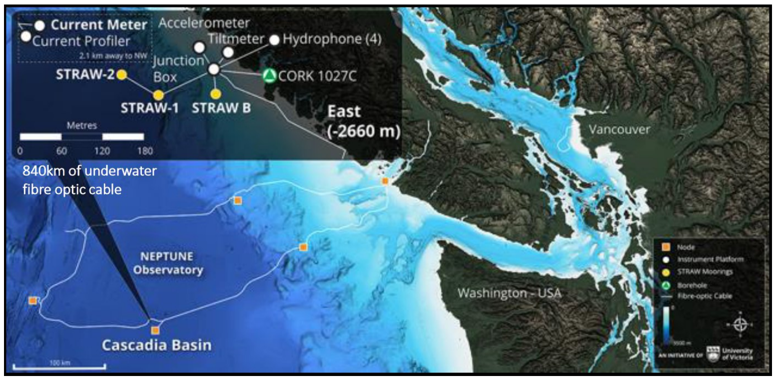
New Hemisphere New Comers

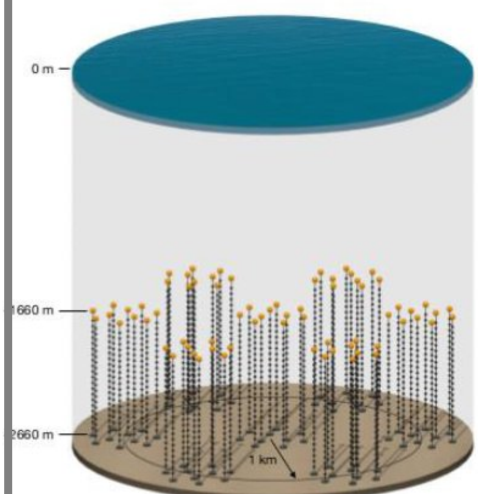
P-ONE

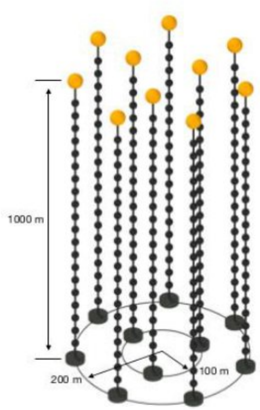
Pacific Ocean Neutrino Explorer

Leverage existing facilities

OCEAN NETWORKS CANADA







Images: courtesy P-ONE collaboration

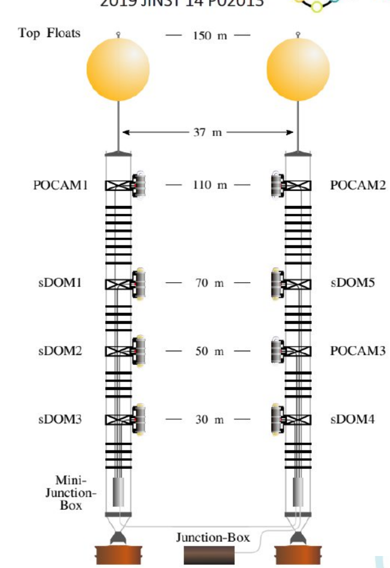
Huge telescopes in the South China Sea

TRIDENT 海铃计划

HUNT

Pathfinder strings deployed and recovered

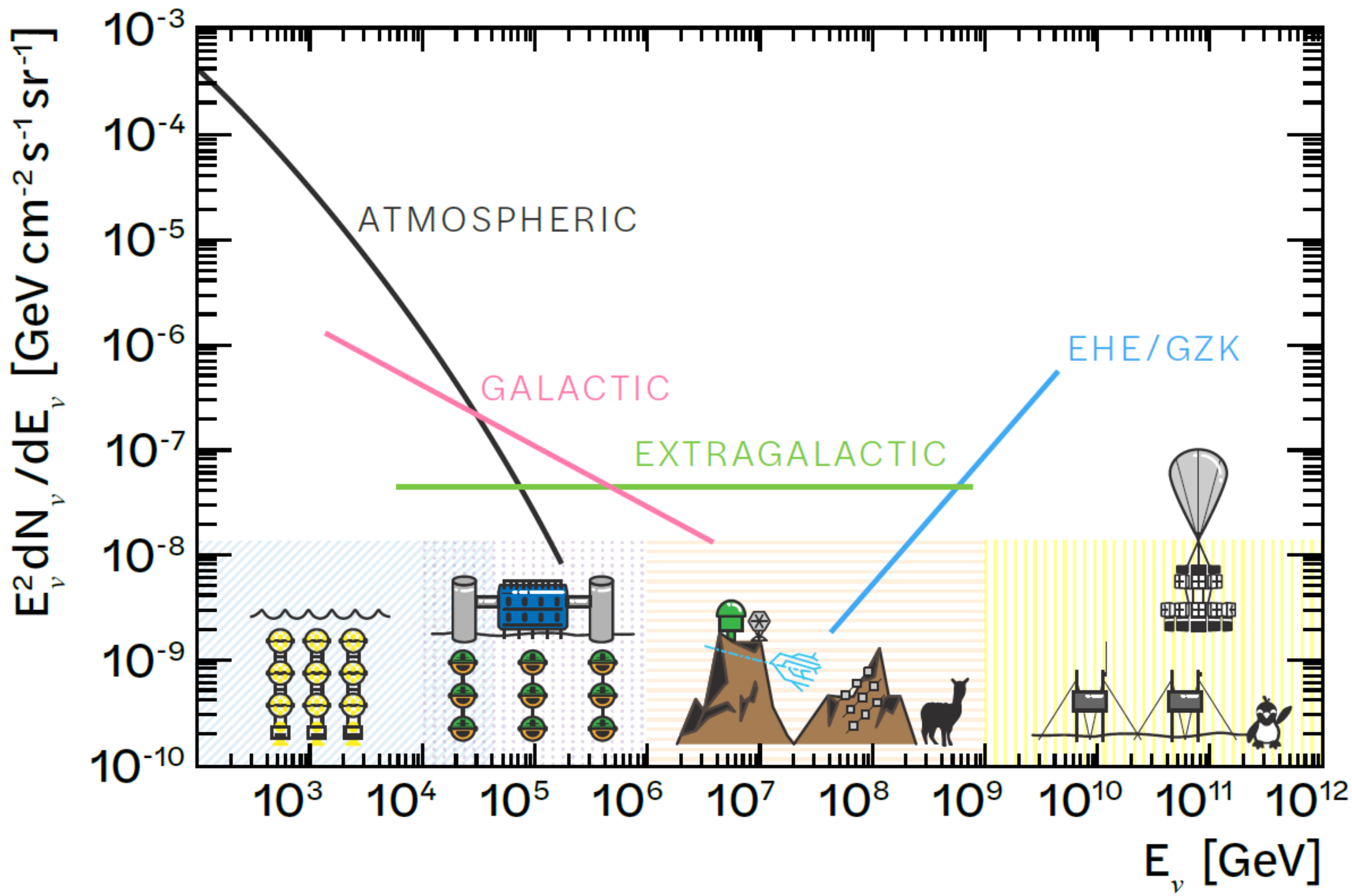
2019 JINST 14 P02013



Water-based Neutrino Telescopes → Lower Energy Sensitivity

Northern Hemisphere Neutrino Telescopes → Southern Sky Sensitivity

Argüelles, Halzen, and Kurahashi (arXiv:2405.17623)



Conclusions

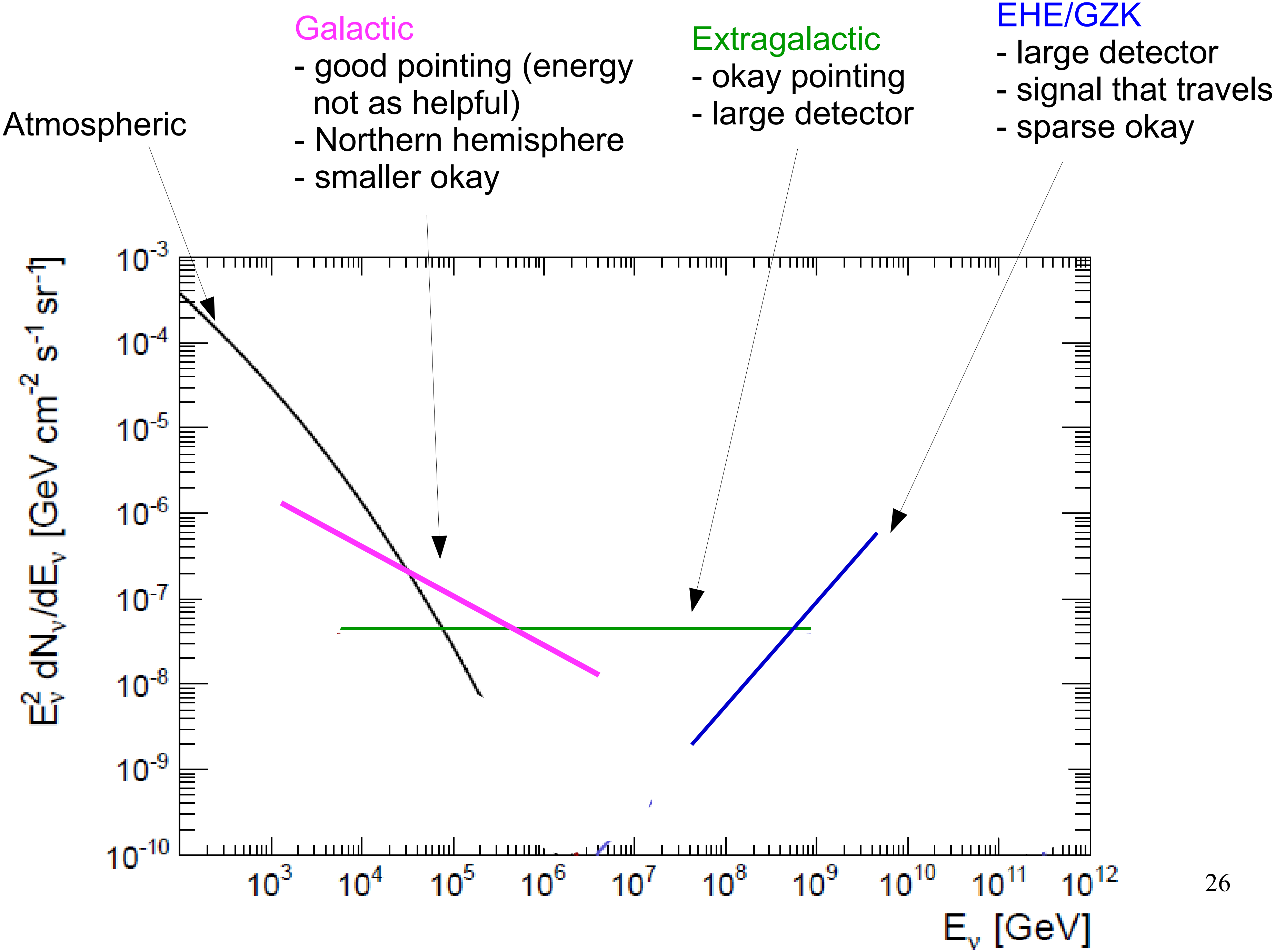
- HE Neutrino Astronomy has enjoyed a decade of initial success with Fermi playing a critical role
- A maturing field is emerging with differently optimized telescopes, many of which are water-based northern hemisphere detectors → Galactic Neutrino Astronomy
- IceCube's success based on decade+ overlapping operational period with Fermi. **Will future Neutrino Telescopes have a gamma-ray partner?**

What neutrino astronomy needs

- Survey Telescope with wide FOV to match all-sky nature of neutrino telescopes
- Ability to follow up neutrino alerts with large angular error
- Coverage of MeV to TeV energy
- Galactic understanding?

Backups?

Diverse Neutrino Astronomy Targets



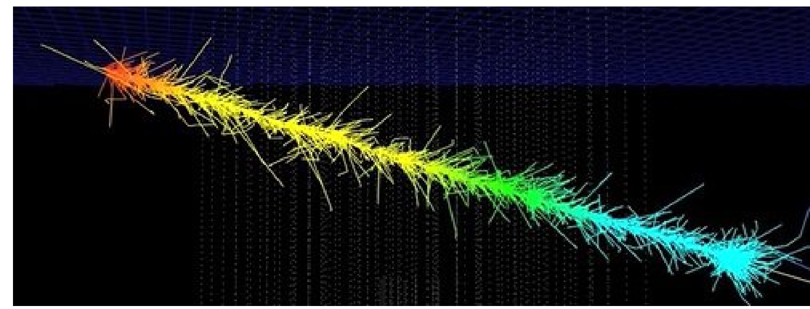
Diverse Neutrino Astronomy Targets

Galactic
- good pointing (energy not as helpful)
- Northern hemisphere
- smaller okay

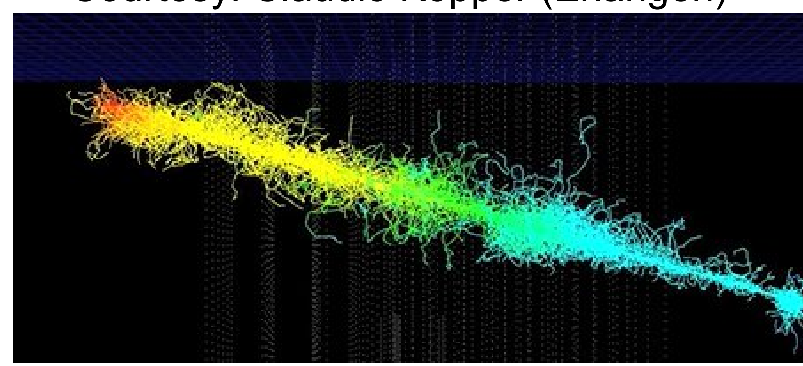
Extragalactic
- good pointing
- large detector

EHE/GZK
- large detector
- signal that travels
- sparse okay

Water Cherenkov
- Scattering ✓→ Good Pointing
- Absorption ✗→ Harder to make large detector

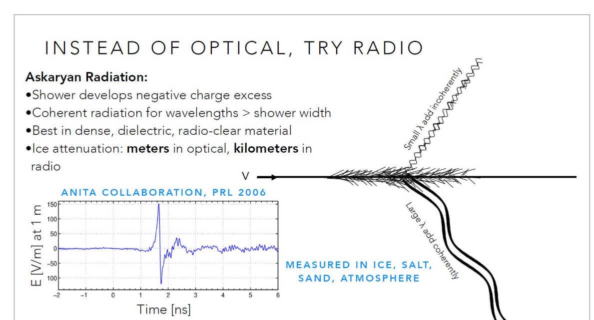


Courtesy: Claudio Kopper (Erlangen)



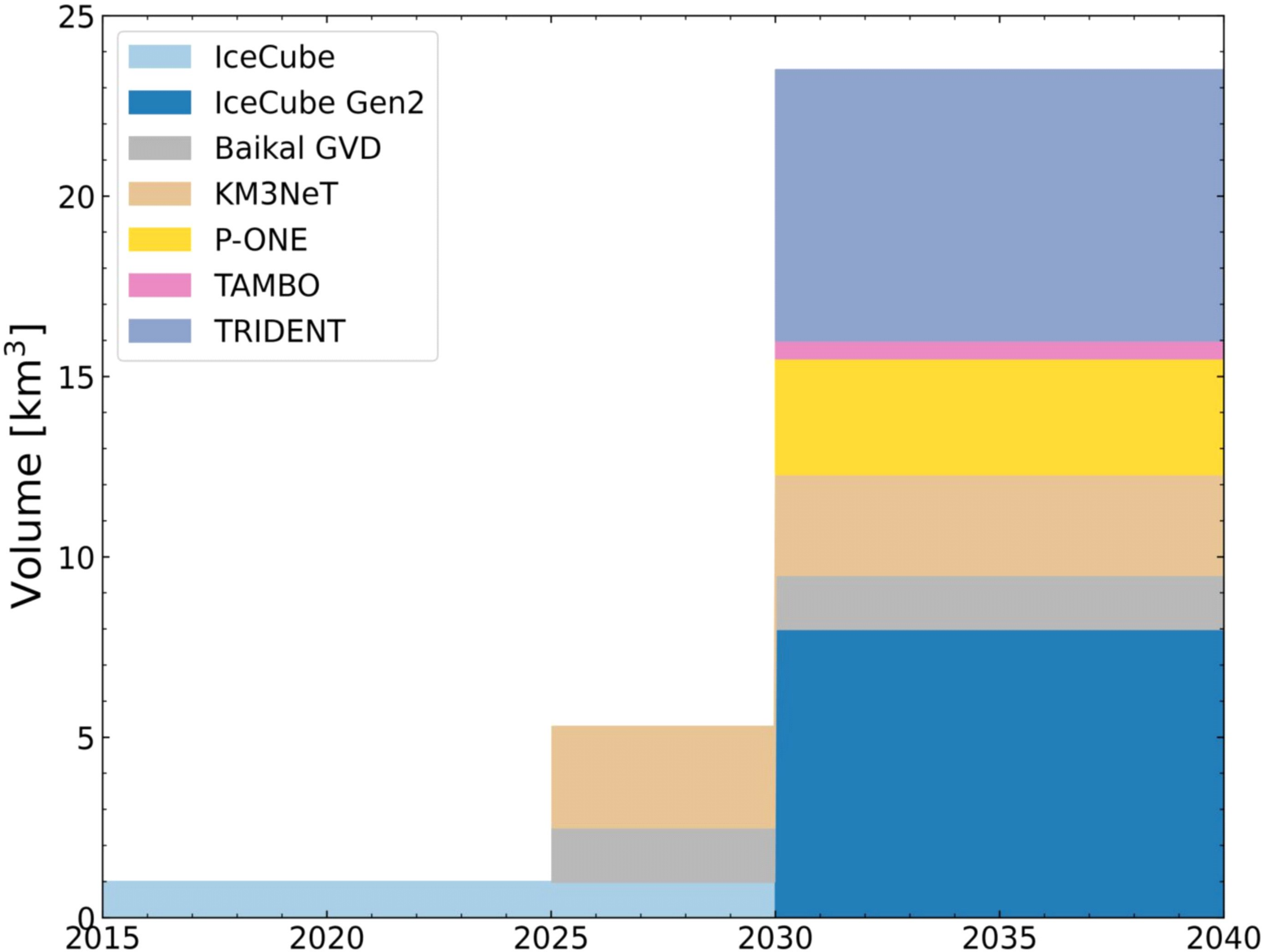
Ice Cherekov
- Scattering ✗→ Harder to point
- Absorption ✓→ Easier to make large detector

Radio
- Absorption ✓✓ → Can make detector very large
- Energy threshold very high



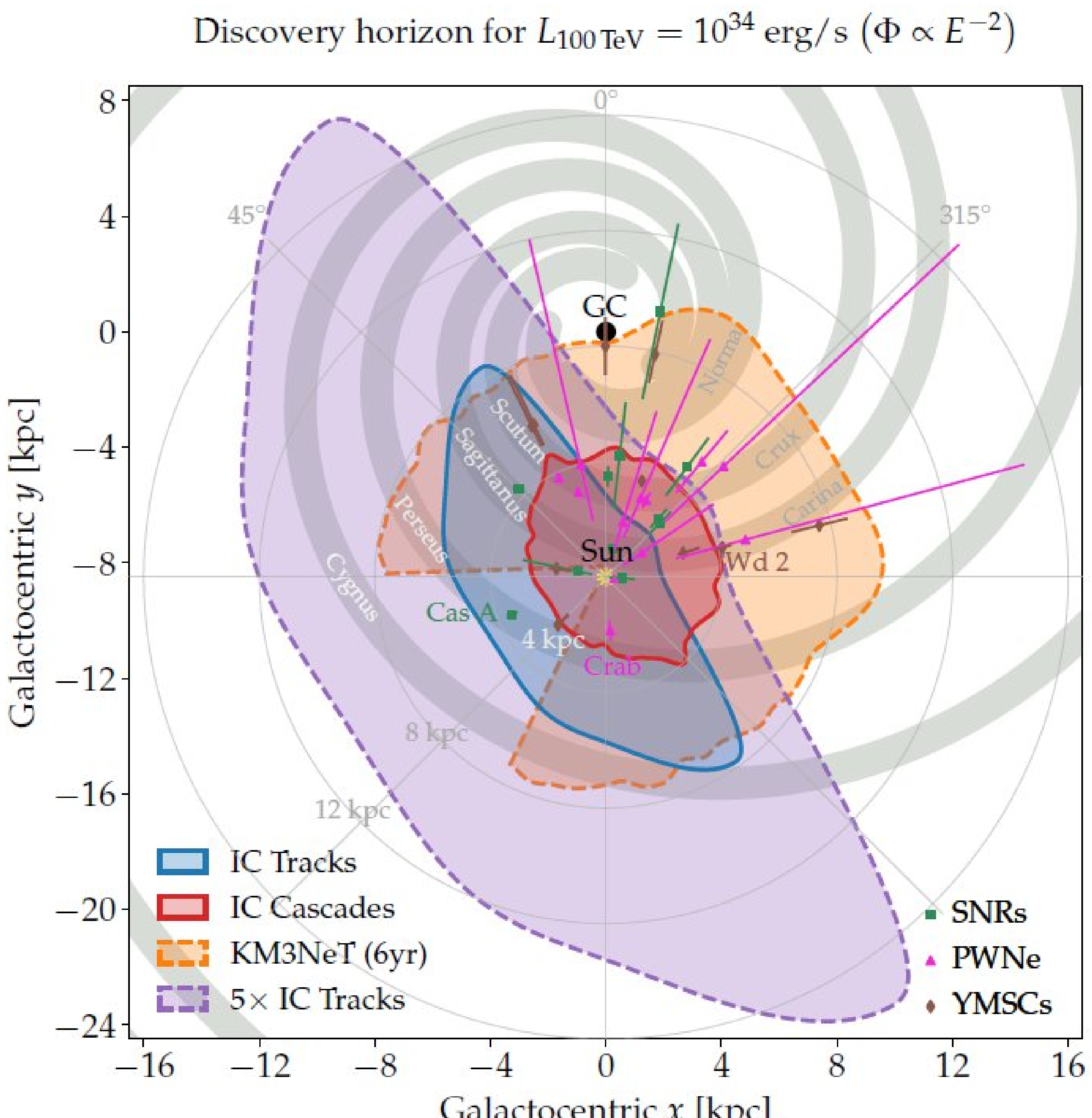
See talk by K. Hughes

Expanding Volume of Neutrino Telescopes



Courtesy: Q. Liu (Queens) ICRC2023

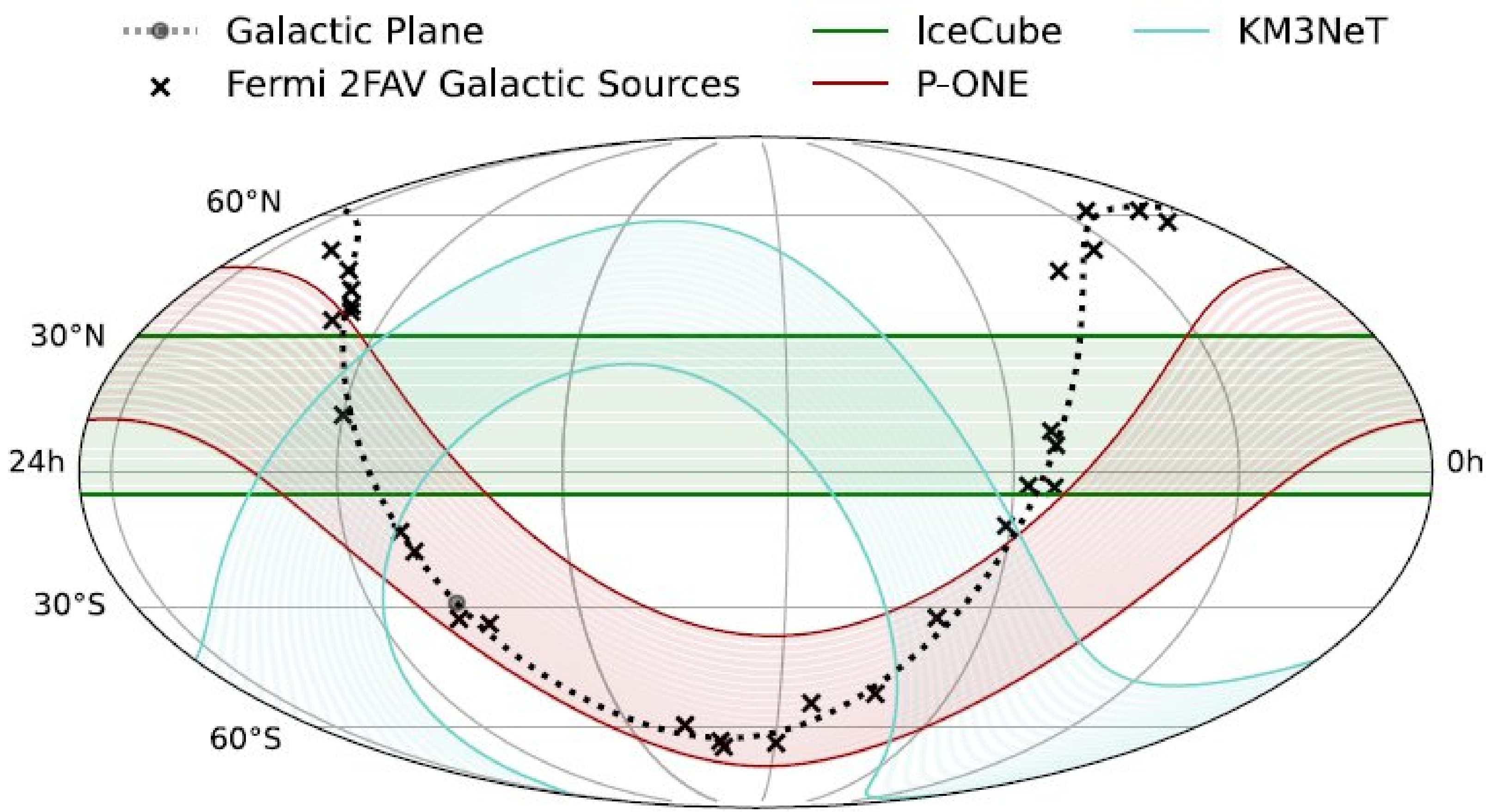
Galactic Neutrino Astronomy Needs



Phys. Rev. D 109, 043007 (2024)

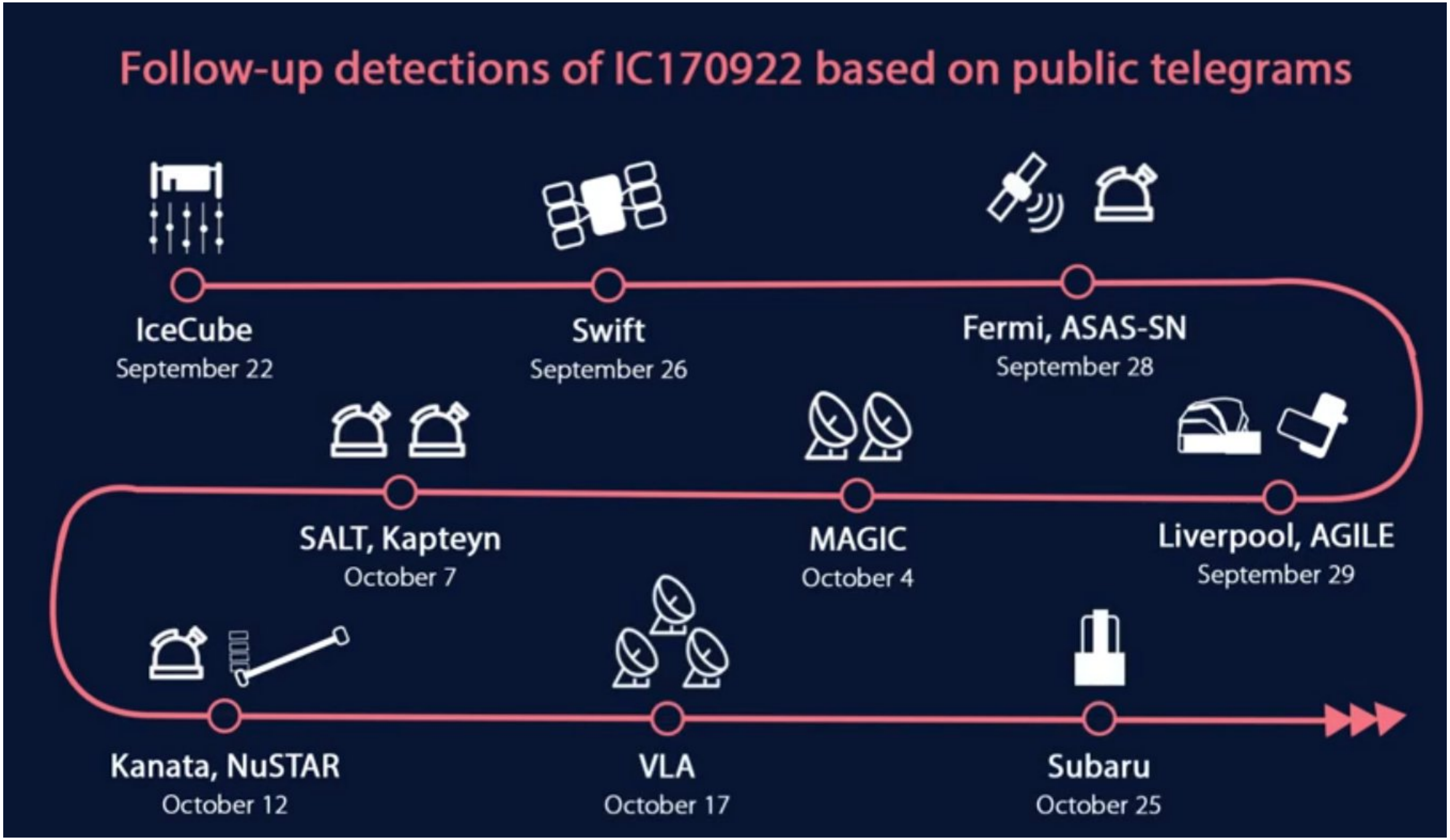
A. Ambrosone, K. M. Groth, E. Peretti, and M. Ahlers

Complementary Peak Sensitivity → Important for Transients



Courtesy: P-ONE, L. Schumacher (Erlangen), S. Sclafani (Univ of Maryland)

IC170922 Alert → TXS 0506+056 Coincident Observation



IceCube publications from point source working group, 2018-2020

IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-wave Transient Catalog
Astrophys.J.Lett. 898 (2020) 1, L10, Astrophys.J. 898 (2020) 1, L10

IceCube Search for High-Energy Neutrino Emission from TeV Pulsar Wind Nebulae.
Astrophys.J. 898 (2020) 2, 117

ANTARES and IceCube Combined Search for Neutrino Point-like and Extended Sources in the Southern Sky
Astrophys.J. 892 (2020), 92

A search for IceCube events in the direction of ANITA neutrino candidates
Astrophys. J., 892 (2020), 1

Constraints on neutrino emission from nearby galaxies using the 2MASS redshift survey and IceCube
JCAP 07 (2020), 042

Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data
Phys.Rev.Lett. 124 (2020) 5, 051103

A Search for Neutrino Point-source Populations in 7 yr of IceCube Data with Neutrino-count Statistics
Astrophys.J. 893 (2020) 2, 102

A Search for MeV to TeV Neutrinos from Fast Radio Bursts with IceCube
Astrophys.J. 890 (2020) 2, 111

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