The Present and Future of High-Energy Neutrino Astronomy

Neutrino 2024
June 19th, 2024

Naoko Kurahashi Neilson (Drexel University)

The Present: The Birth of HE Neutrino Astronomy

A Decade of First Observations

The Future: Towards Answers

A Decade To Establish the Field Firmly

The Present:
The Birth of HE Neutrino Astronomy
A Decade of First Observations

Neutrino Sources In The Sky

*salute to the “low-energy” neutrino astronomers with their sources: the sun and SN1987A

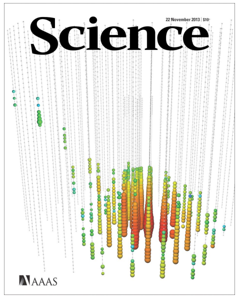
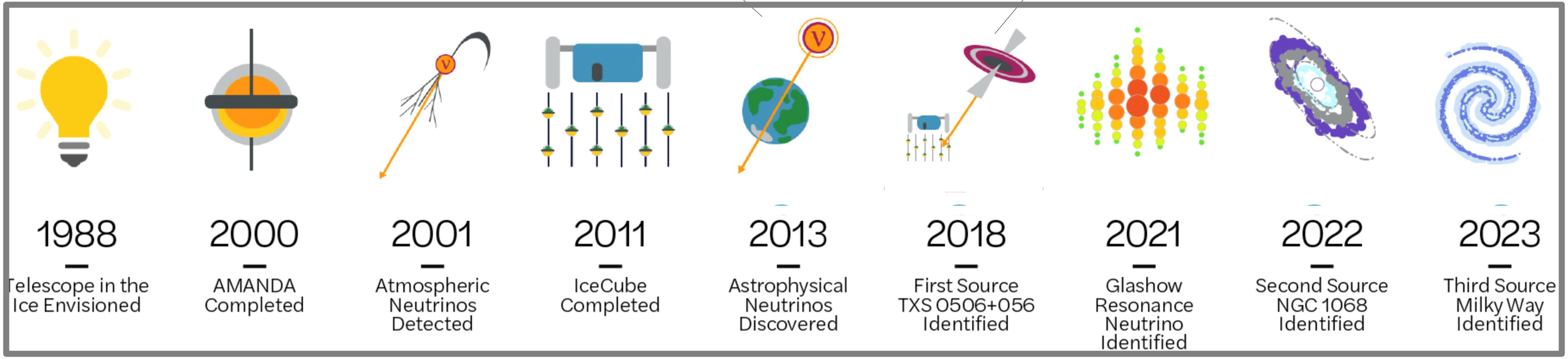


Image Credit: IceCube Collaboration



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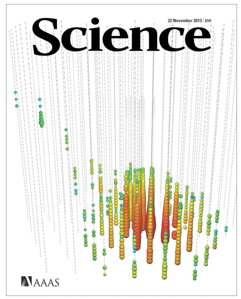

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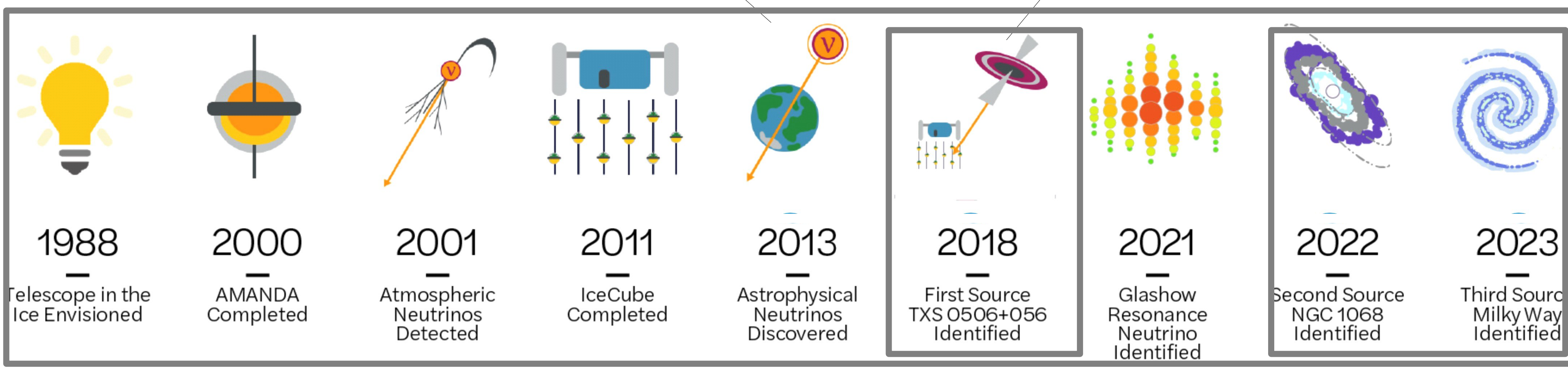

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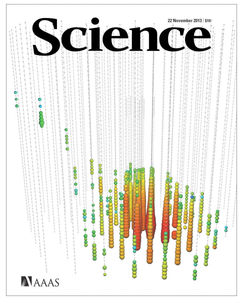
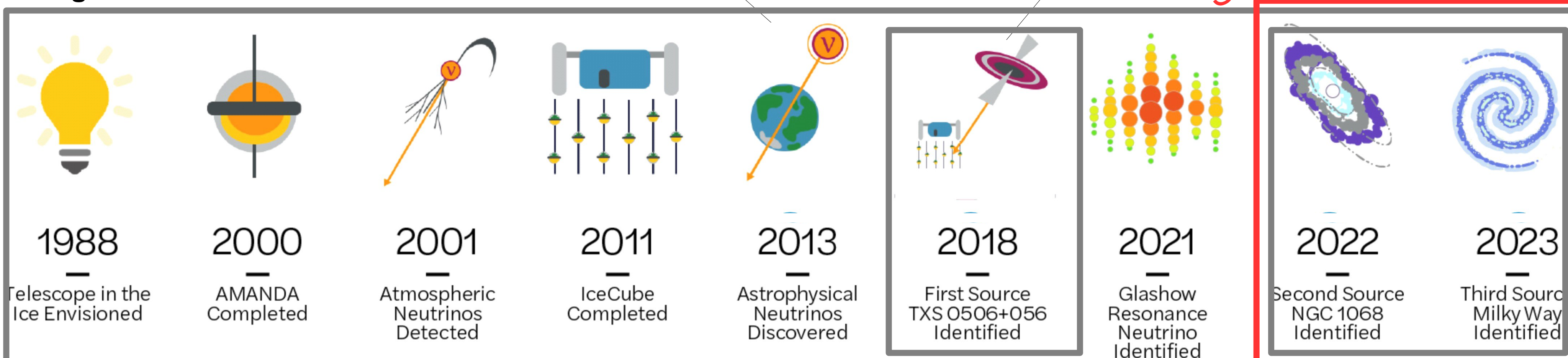


Since Neutrino2022!

Image Credit: IceCube Collaboration



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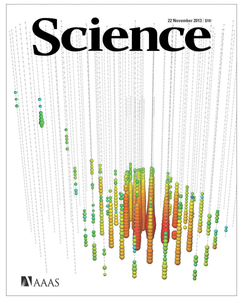

Since Neutrino2022!

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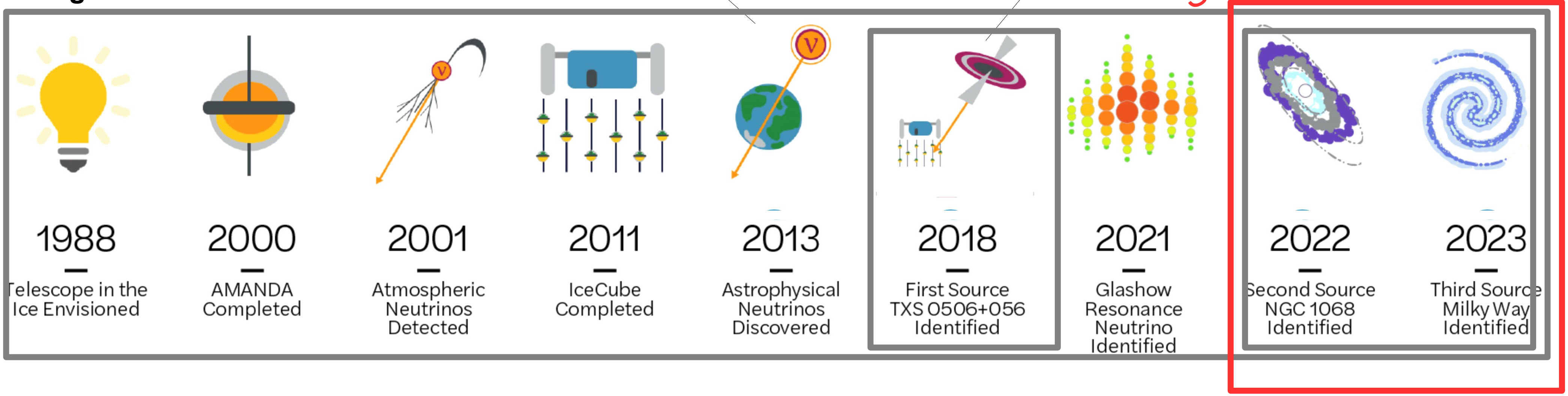


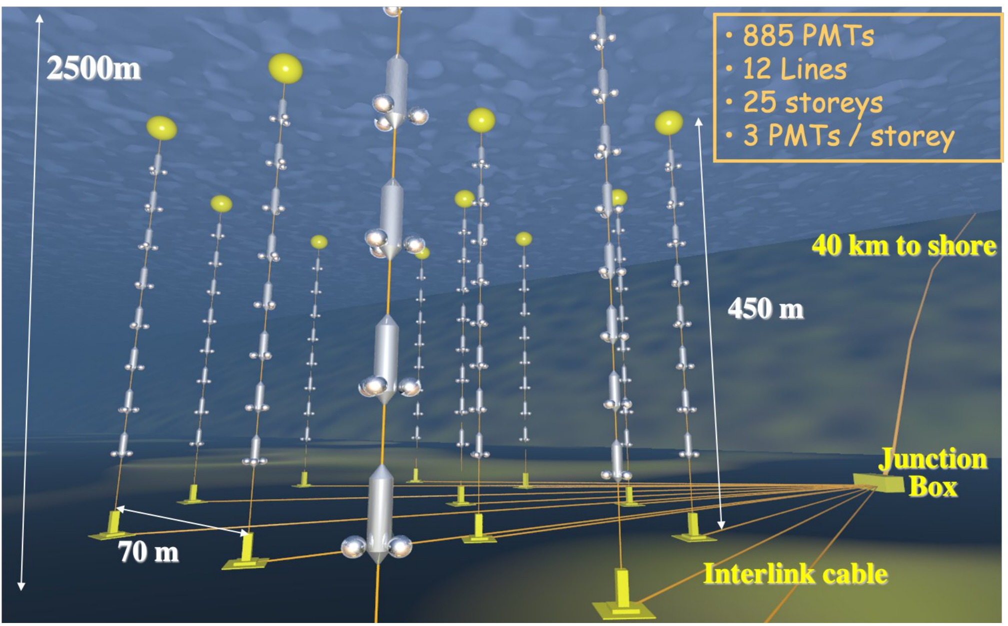
Birth of Neutrino Astronomy

- Why do these galaxies emit HE neutrinos?
- Why aren't they the same type?
- What other types emit HE neutrinos?
- Why not gamma-ray bursts?

Why did it take so long?

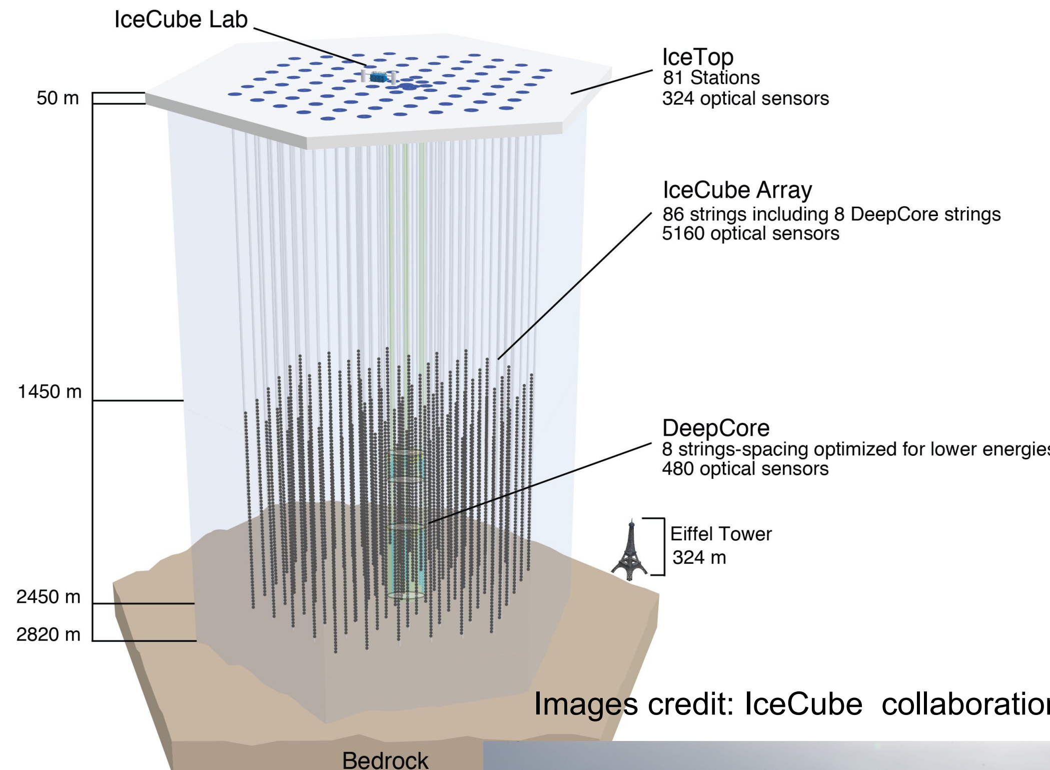
Why did it take so long?
The Size

ANTARES (2007-2022)

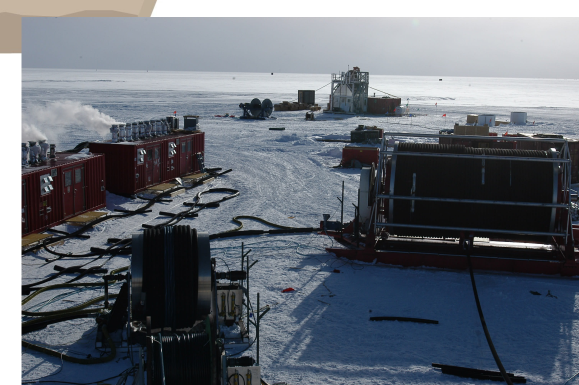


Images credit: ANTARES collaboration

IceCube (2011-)



Images credit: IceCube collaboration



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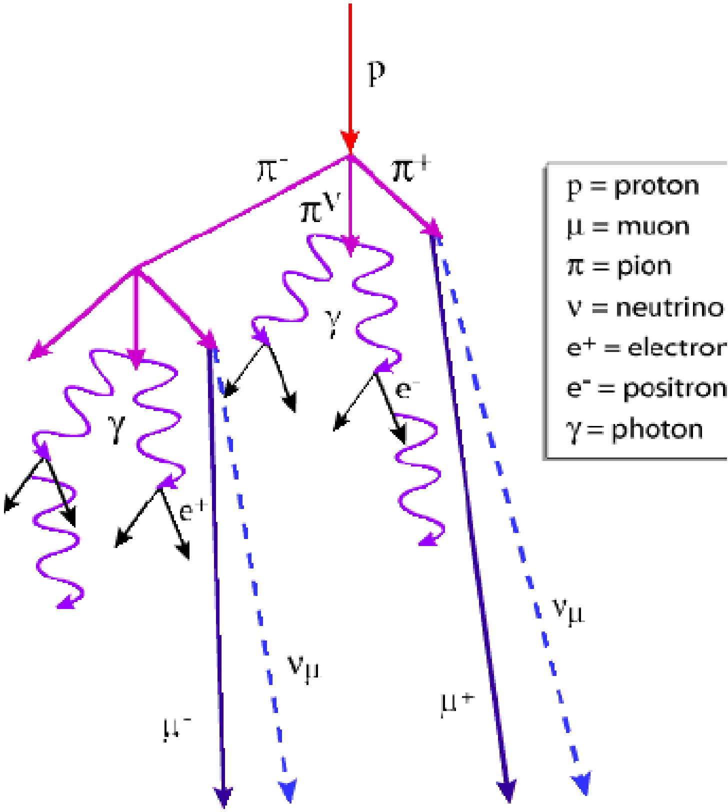
Why did it take so long? Backgrounds

Neutrino Telescopes must combat enormous background rates

- Atmospheric muons and neutrinos many orders higher rate
- No veto (~ish), no beam, source(s) unknown in location/time
- Overburden is what it is (~2.5km)

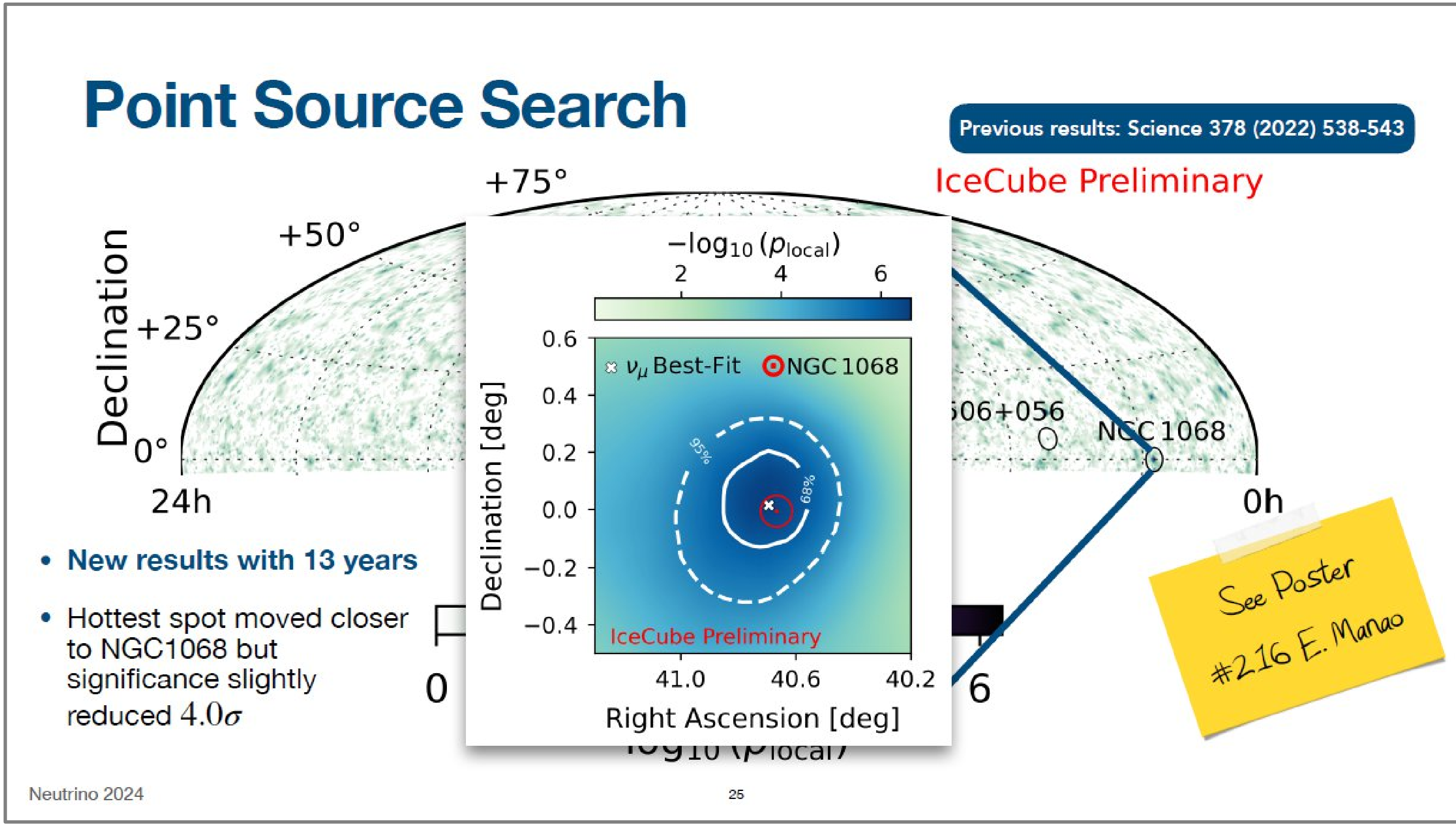
We had to wait for statistics and/or develop smarter ways to process the data!



Background Rates at IceCube Trigger:
Atmospheric Muons > 10^9 x signal rate
Atmospheric Neutrinos > 10^3 x signal rate

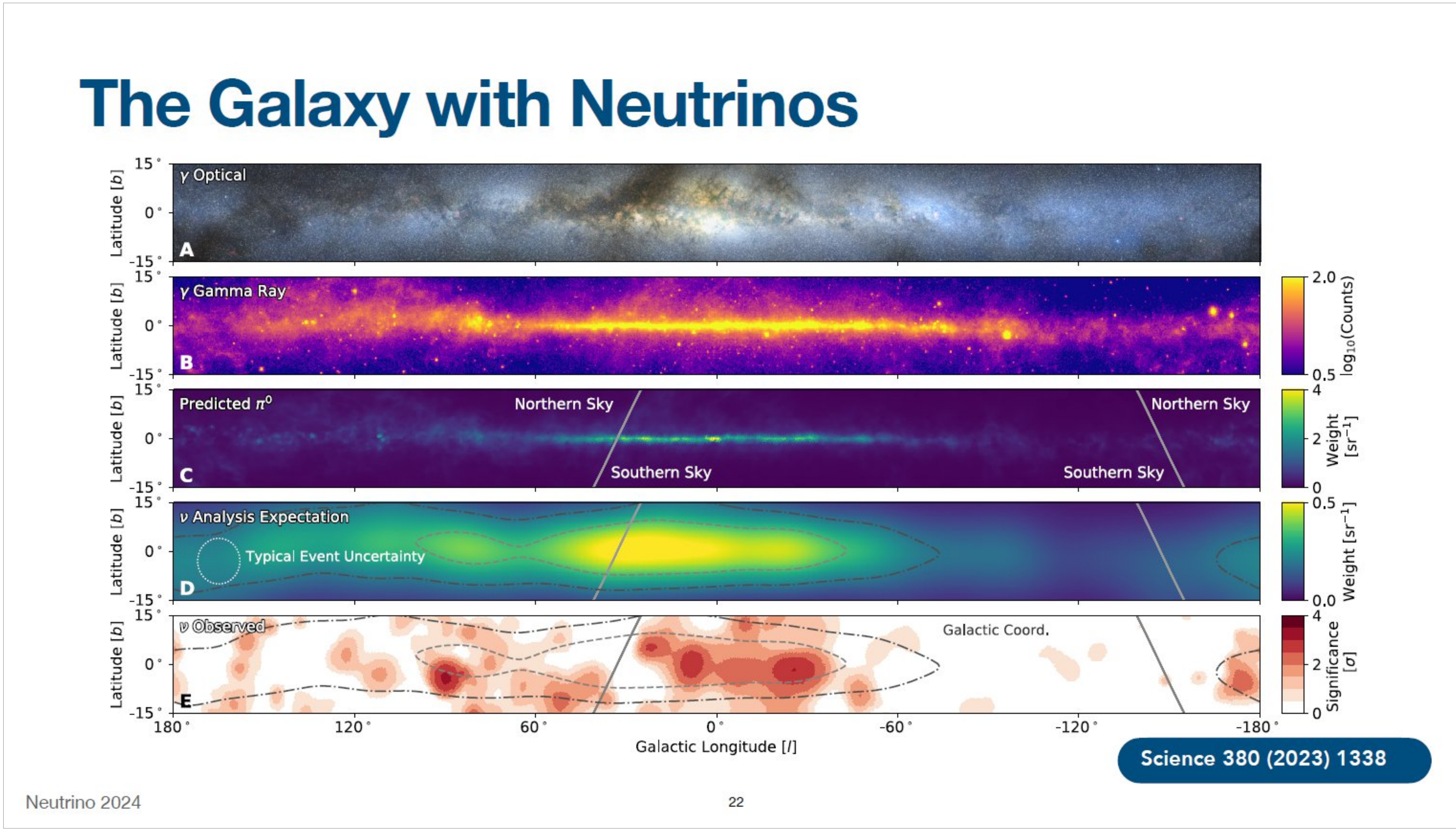
Recent News!

Recent News



Slide from J. Aguillar (IceCube)

Recent News



Slide from J. Aguillar (IceCube)

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.

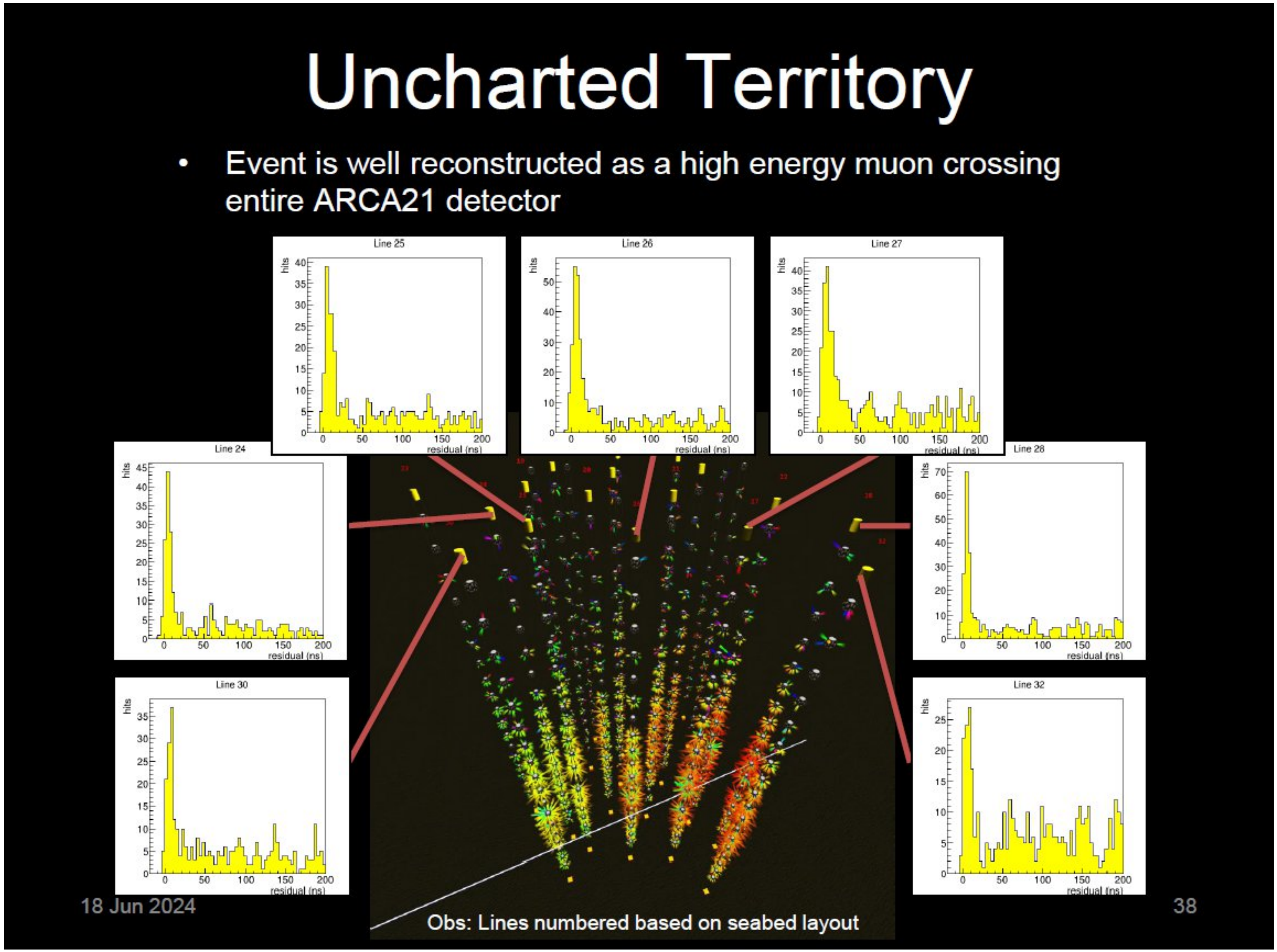
The Milky Way emits radiation across the electromagnetic spectrum, from radio waves to gamma rays. Observations at different wavelengths provide insight into the structure of the Galaxy and have iden-

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

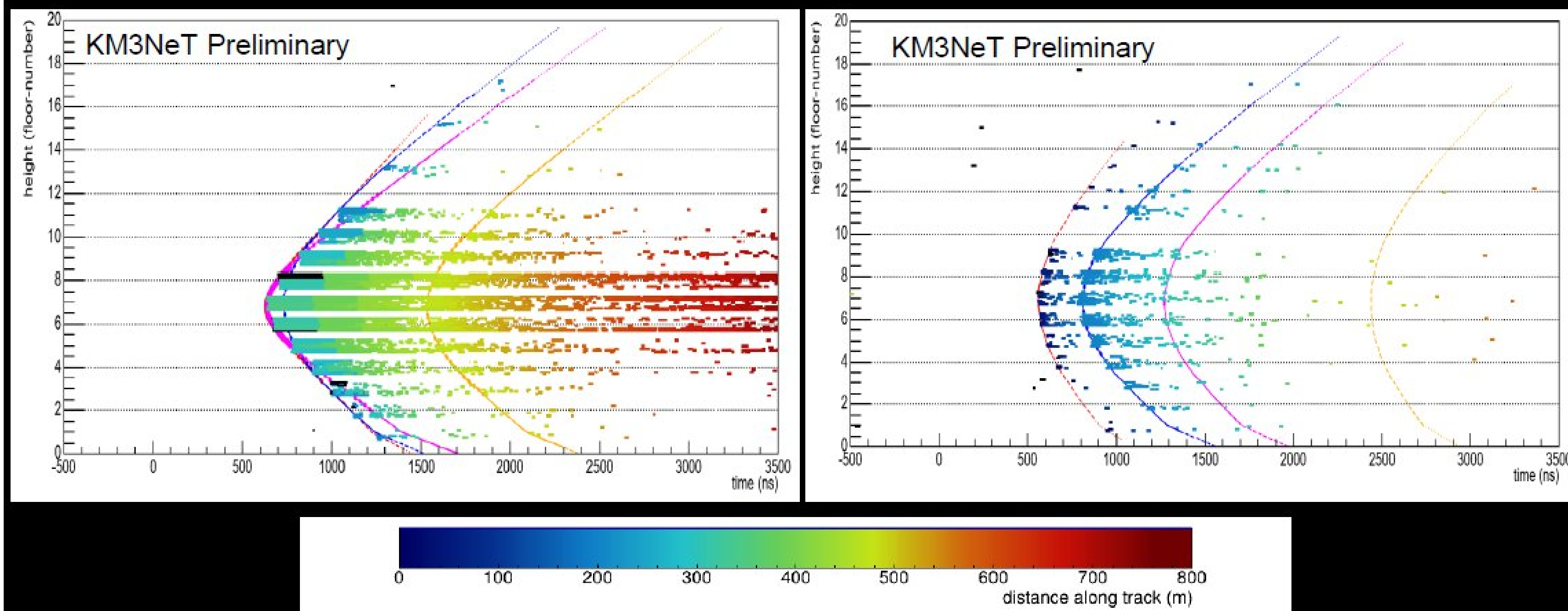
Recent News



Slide from J. Coelho (KM3NeT)

Uncharted Territory

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons
- Space-time distribution of light consistent with shower hypothesis associated with these energy depositions
- Low scattering is key to observing this richness of detail



18 Jun 2024

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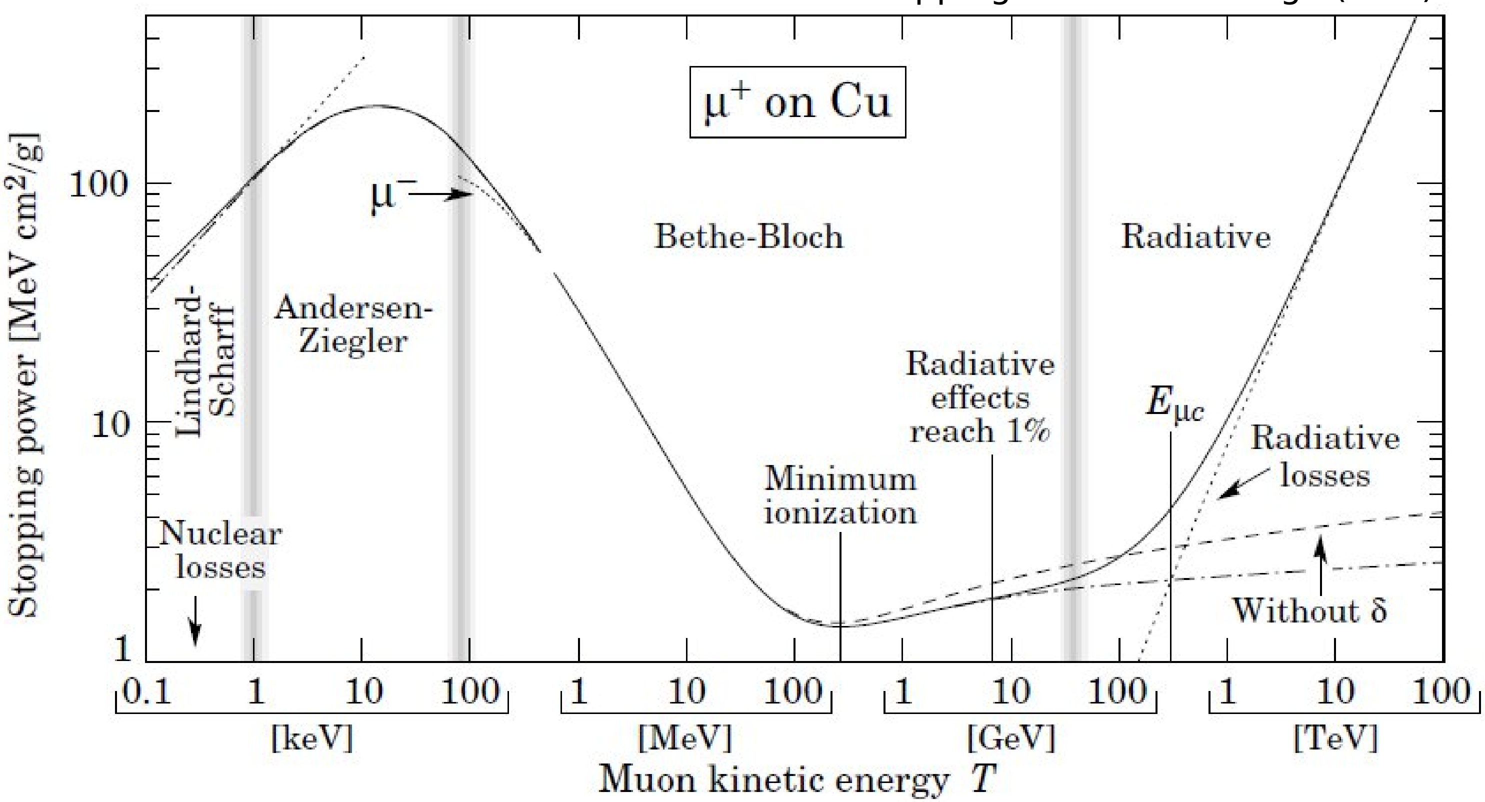
Slide from J. Coelho (KM3NeT)

Bethe-Bloch Reminder

Muon Stopping Power and Range (PDG)



Radiative loss regime – stochastic energy loss

The Future: Towards Answers
A Decade To Establish the Field Firmly

Multi-Wavelength Astronomy

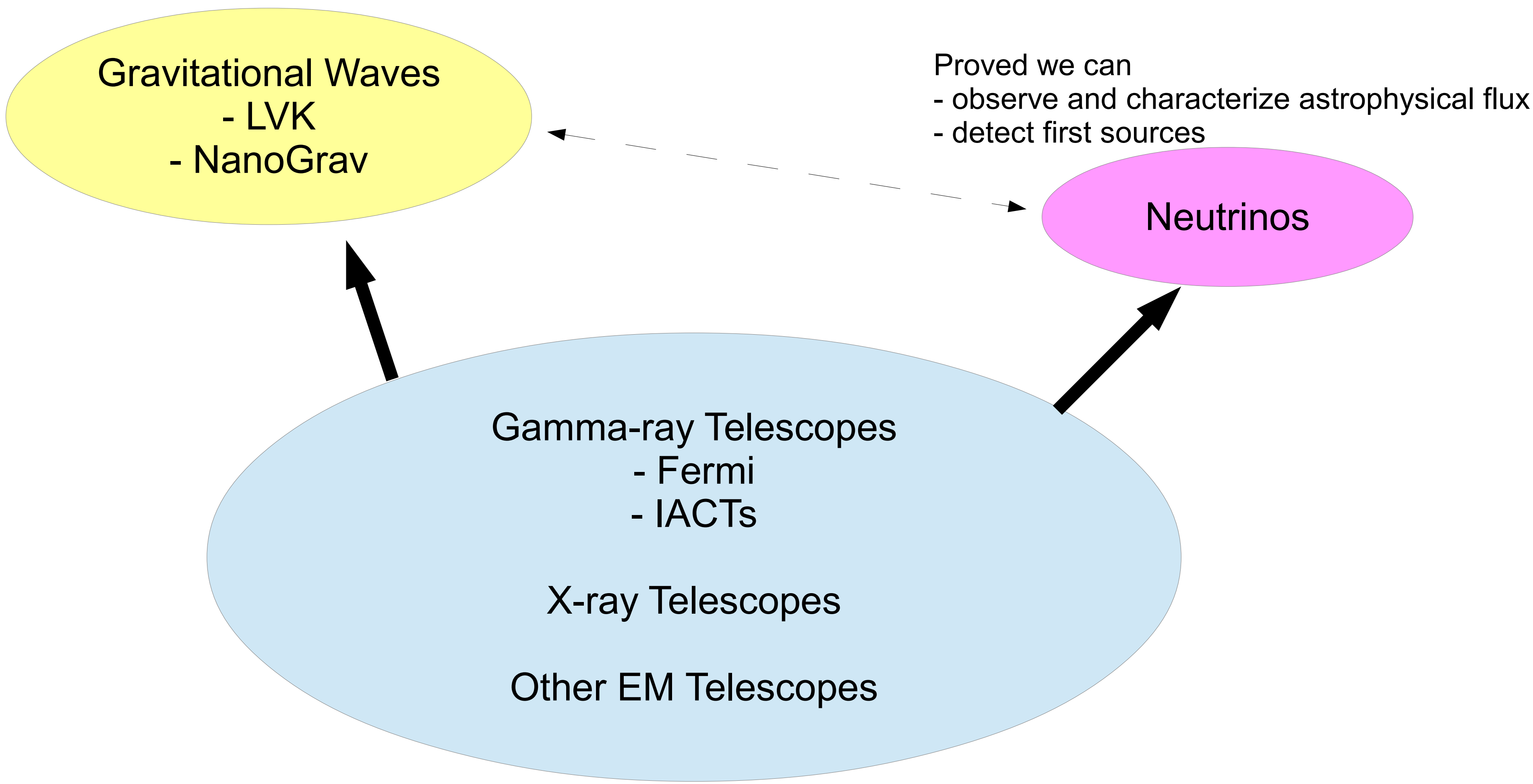
Gamma-ray Telescopes
- Fermi
- IACTs

X-ray Telescopes

Other EM Telescopes

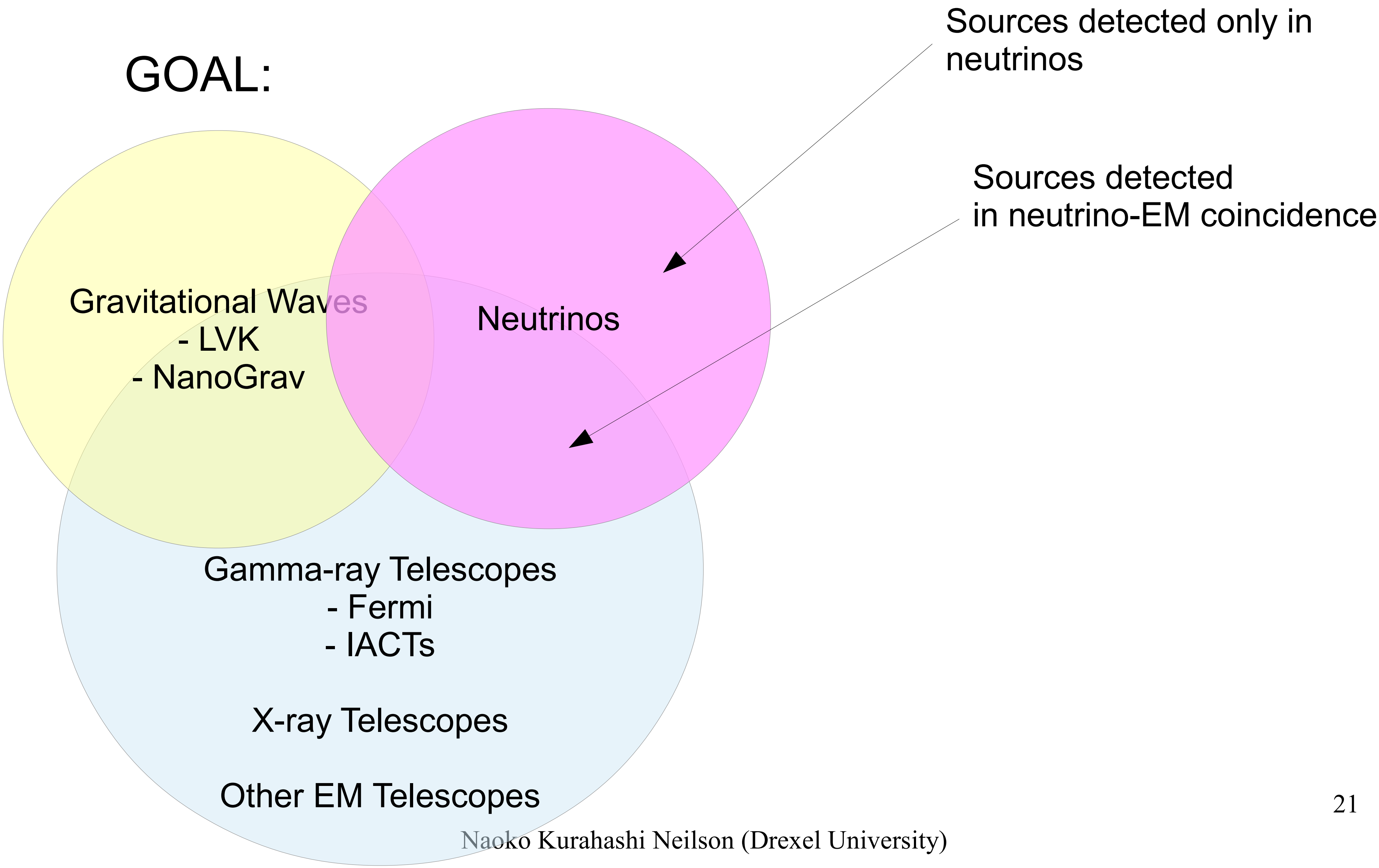
Multi-Wavelength Astronomy

Multi-Messenger Astronomy



Future Multi-Messenger Astronomy

GOAL:



Future Multi-Messenger Astronomy

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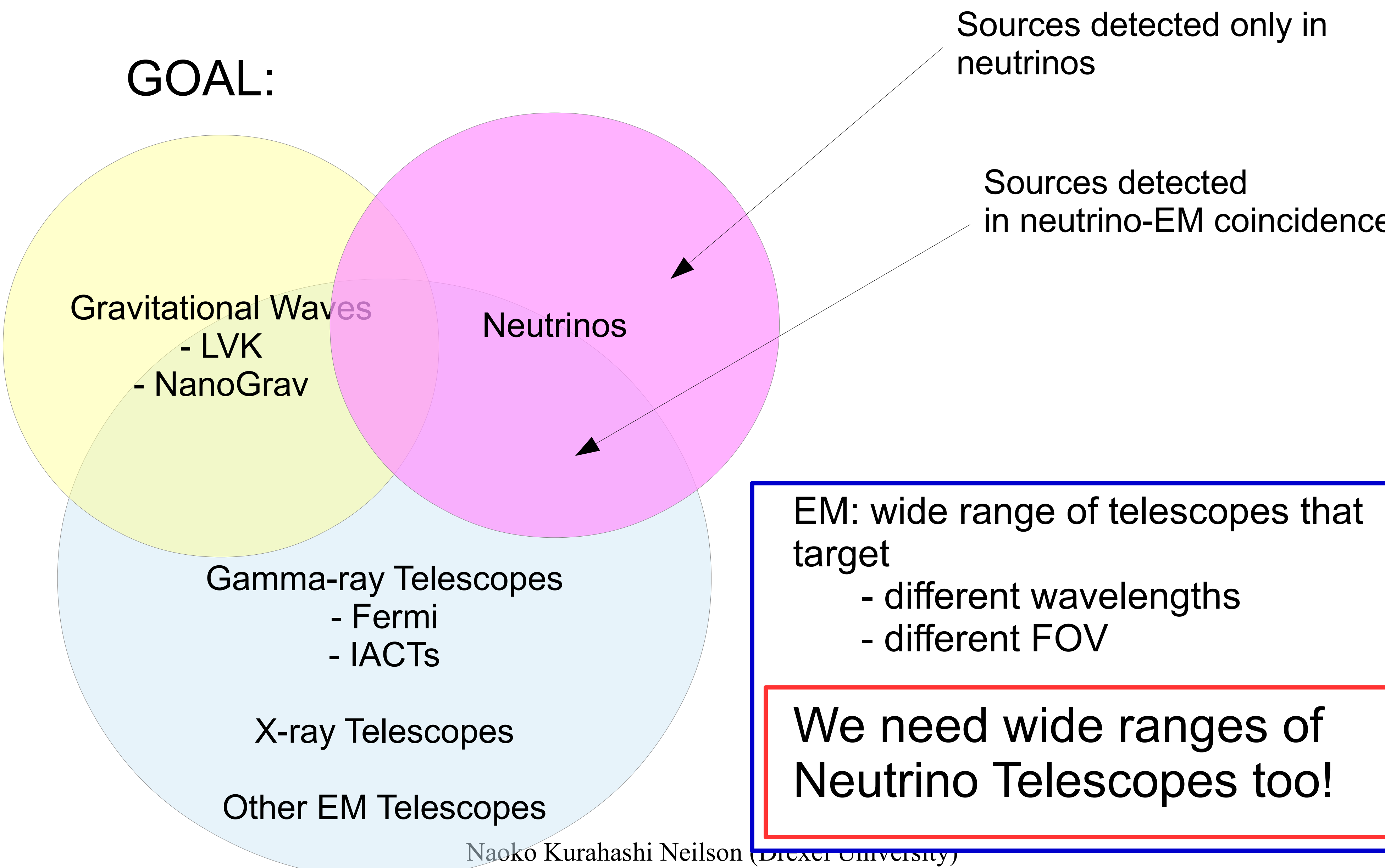

EM: wide range of telescopes that target
- different wavelengths
- different FOV

We need wide ranges of Neutrino Telescopes too!

3 Priorities to Achieve this Goal

- More Neutrino Telescopes
- Complementary Location
- Complementary Technology

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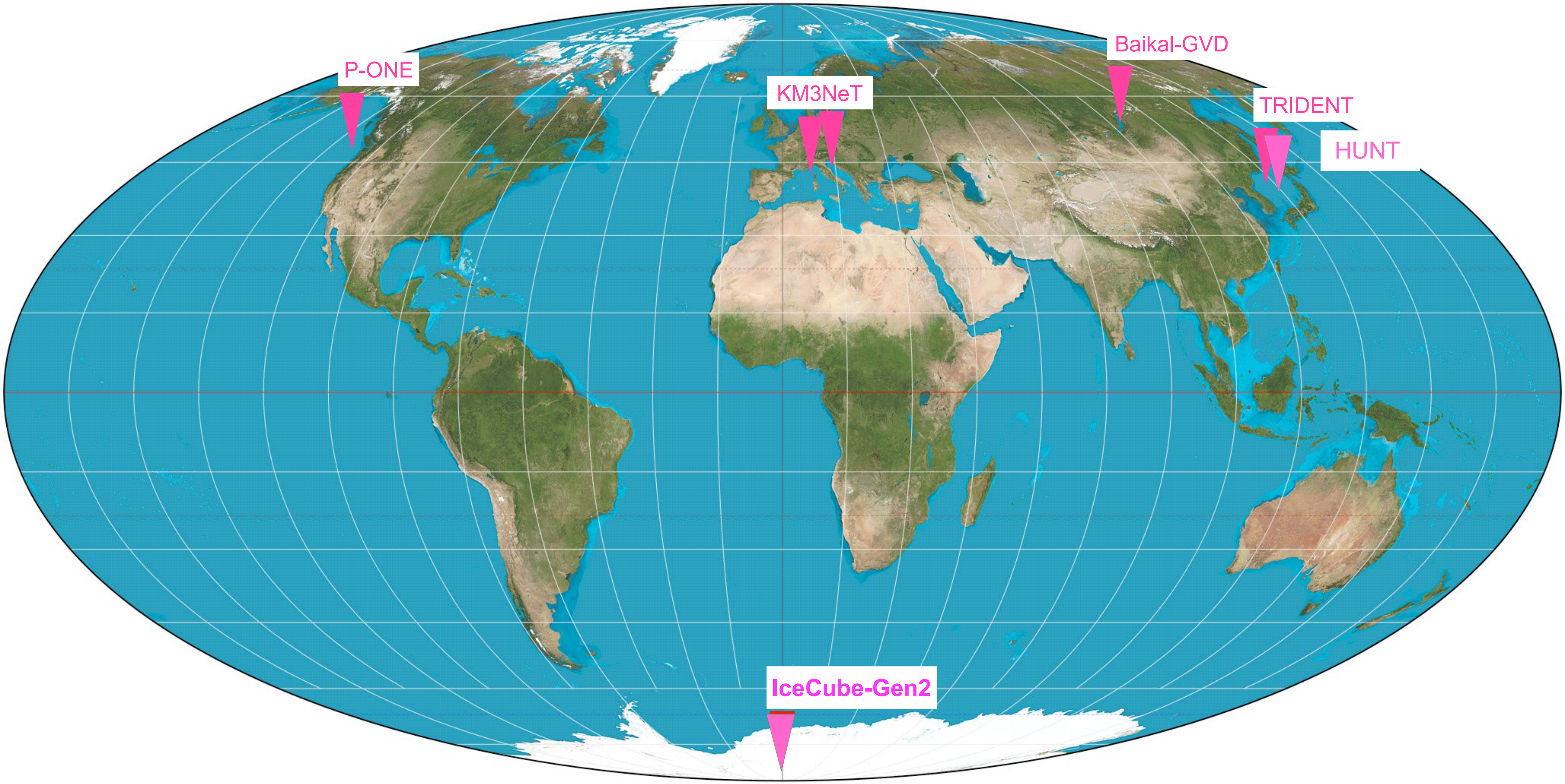
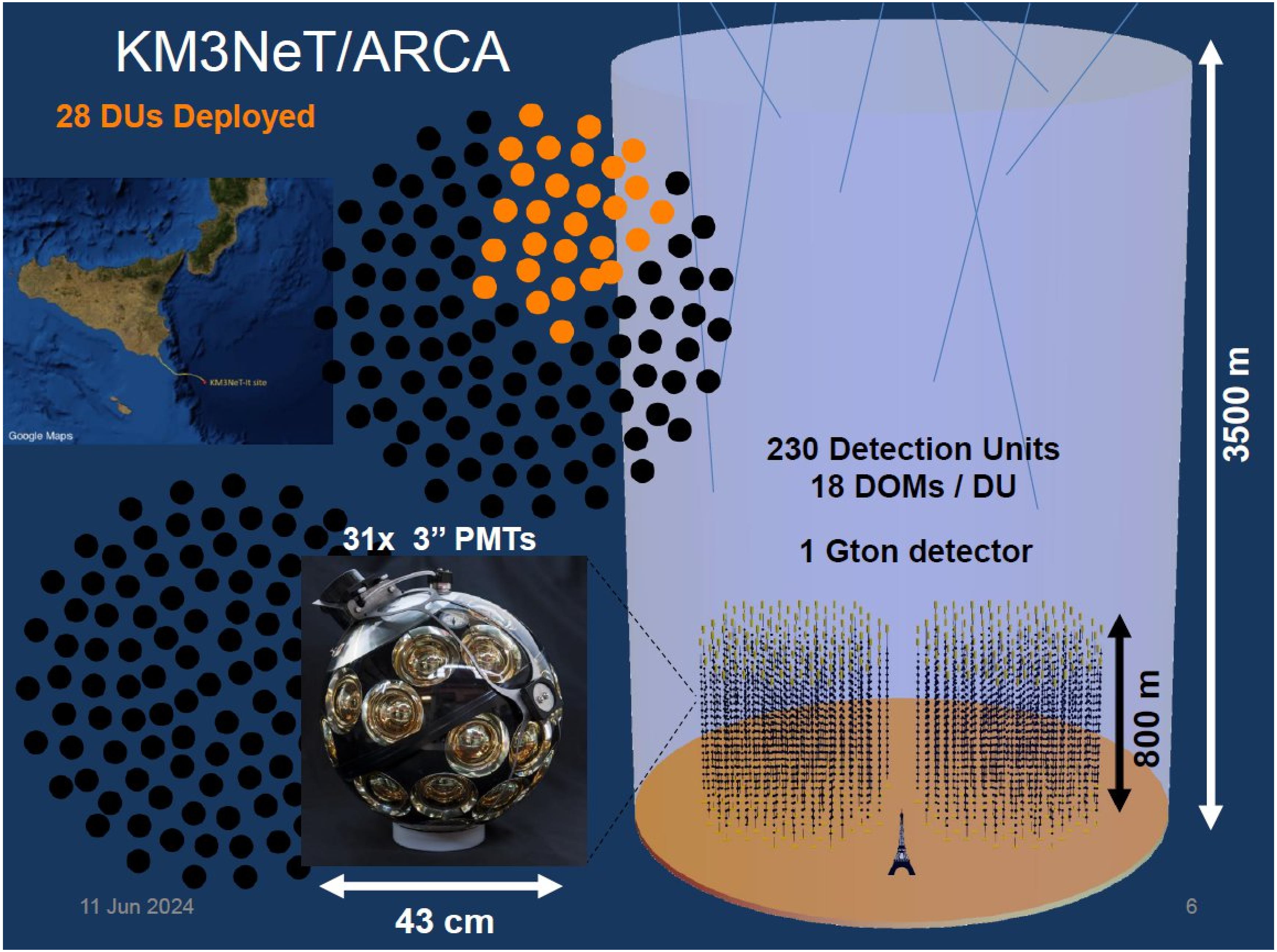
Priority: Complementary Locations

(Optical HE) Neutrino Telescopes





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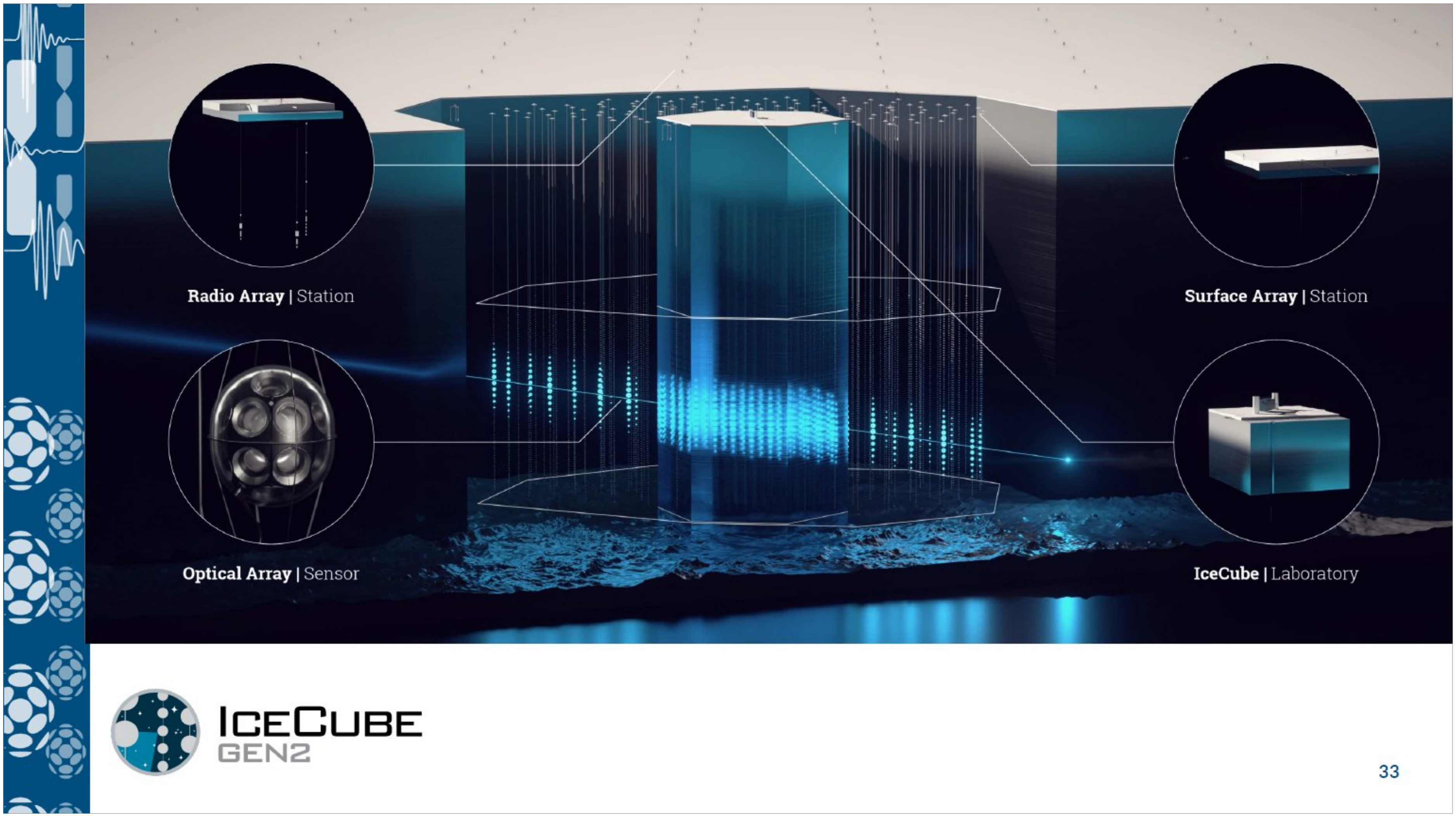
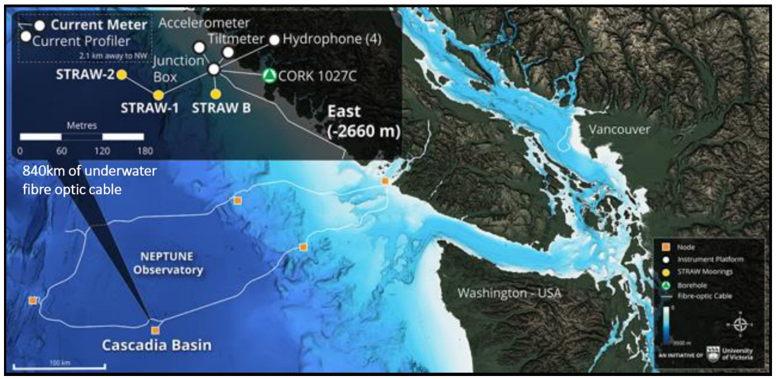


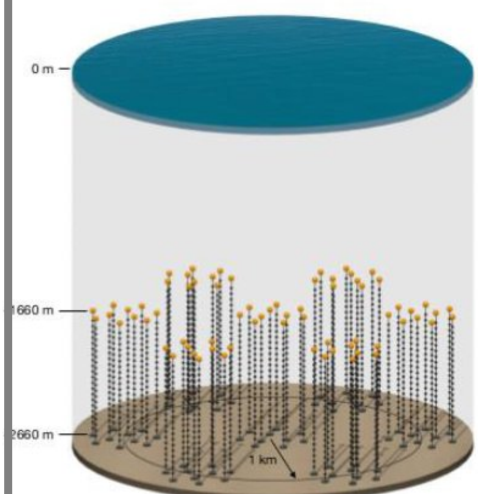
Slide from J. Aguillar (IceCube)

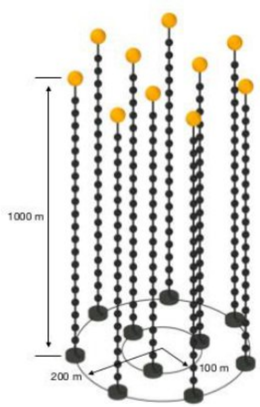
New Hemisphere New Comers

P-ONE
Pacific Ocean Neutrino Explorer

Leverage existing facilities







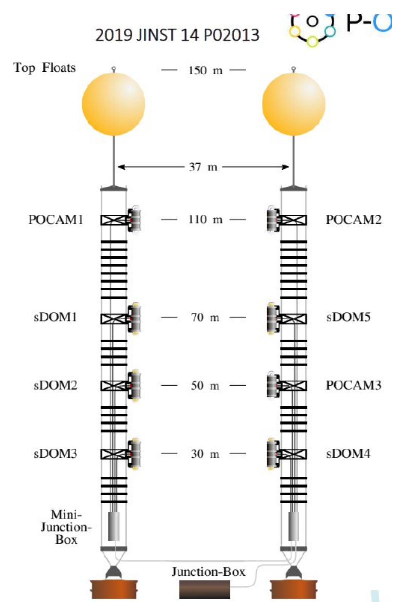
Images: courtesy P-ONE collaboration

Huge telescopes in the South China Sea

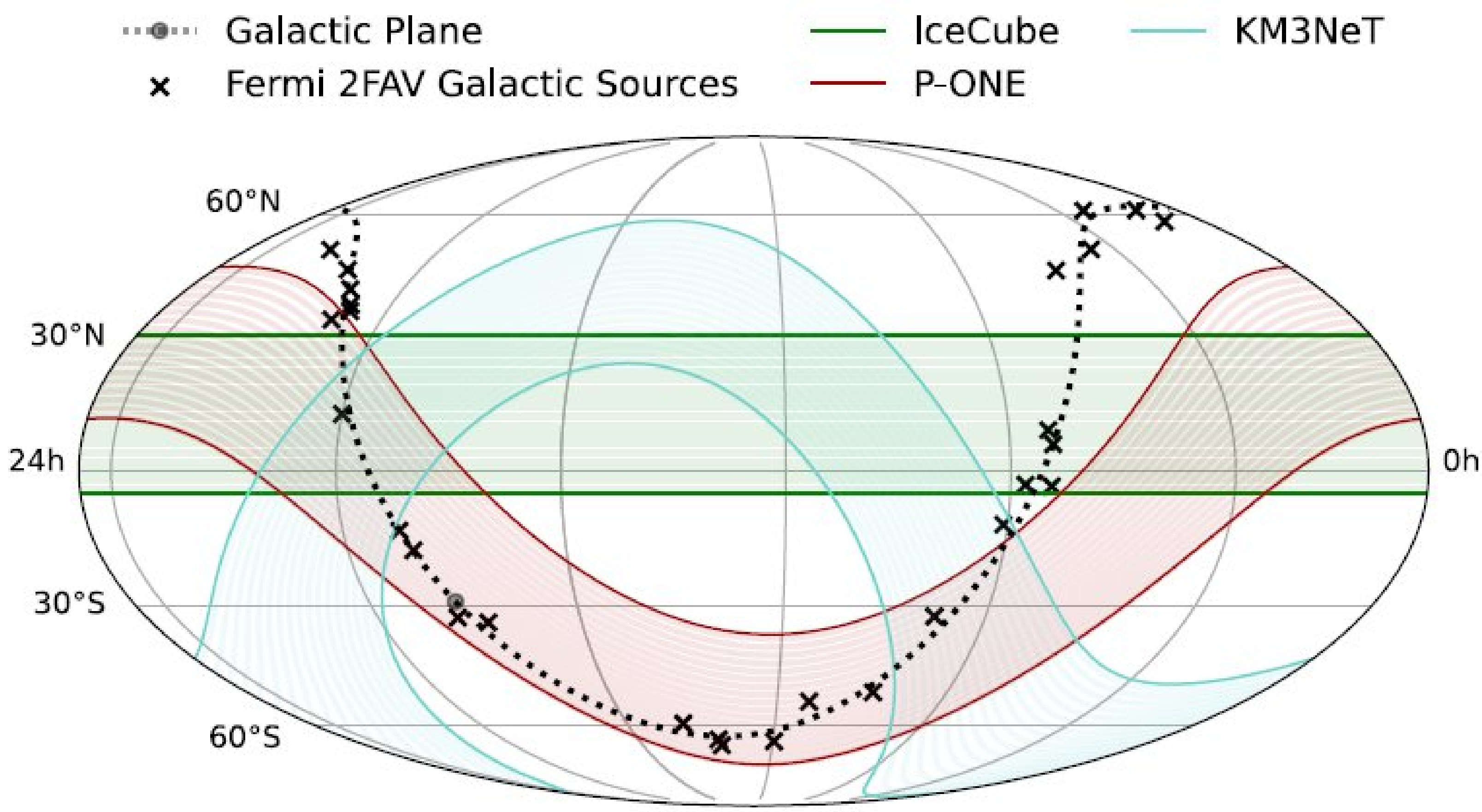
TRIDENT 海铃计划

HUNT

Pathfinder strings deployed and recovered



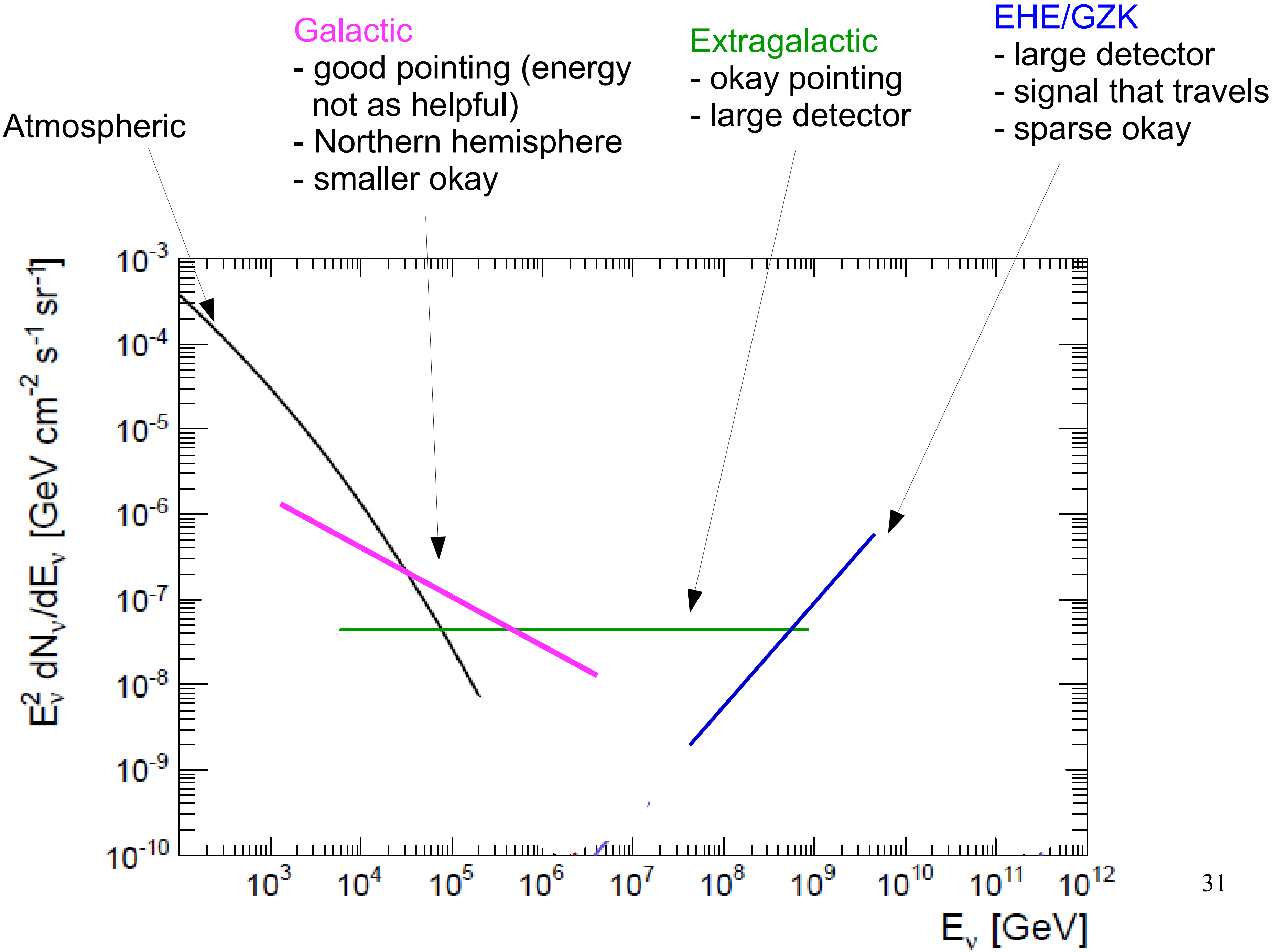
Complementary Peak Sensitivity → Important for Transients



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

Priority: Complementary Technology

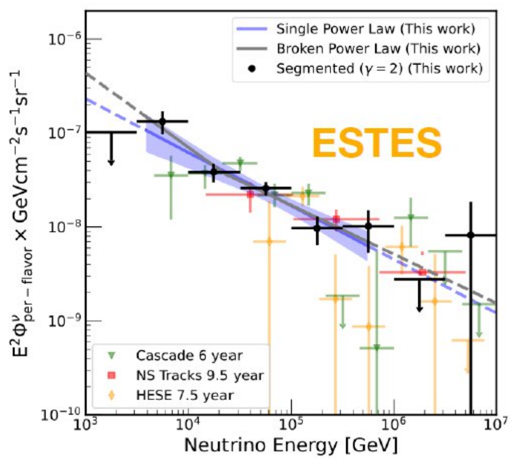
Diverse Neutrino Astronomy Targets

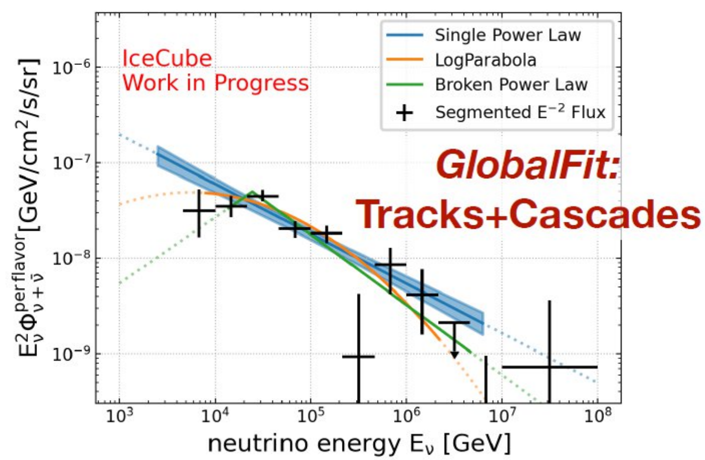


Beyond the Simple Power Law

Segmented E^{-2} flux

IceCube Collaboration, arXiv:2402.18026





PoS(ICRC2023)1064

The observed spectrum is consistent with single power-law but favors more complex shapes

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Slide from J. Aguillar (IceCube)

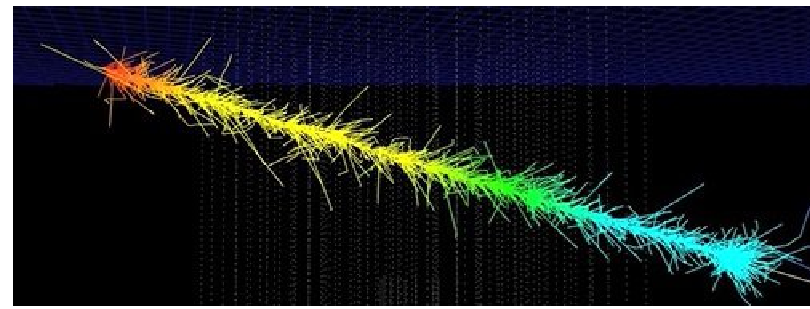
Diverse Neutrino Astronomy Targets

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

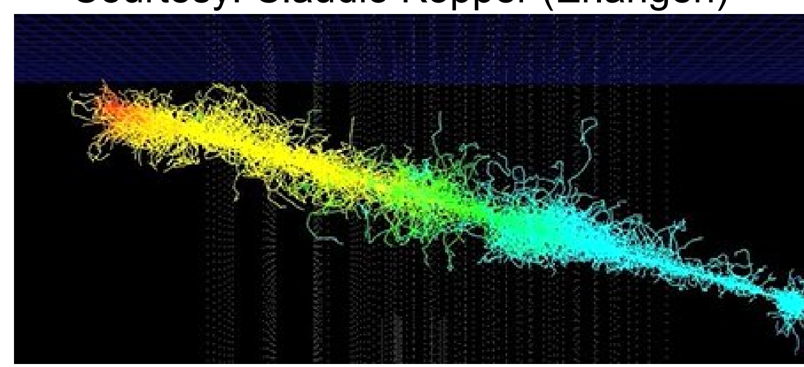
Extragalactic
- good pointing
- large detector

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

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

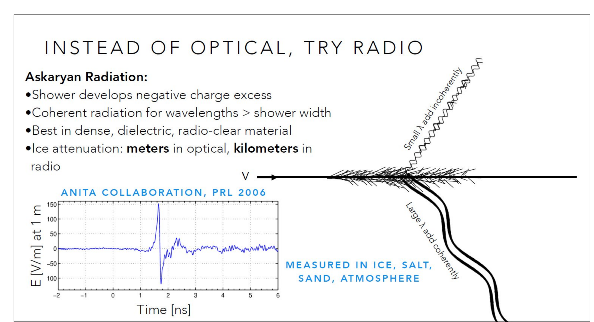


Courtesy: Claudio Kopper (Erlangen)



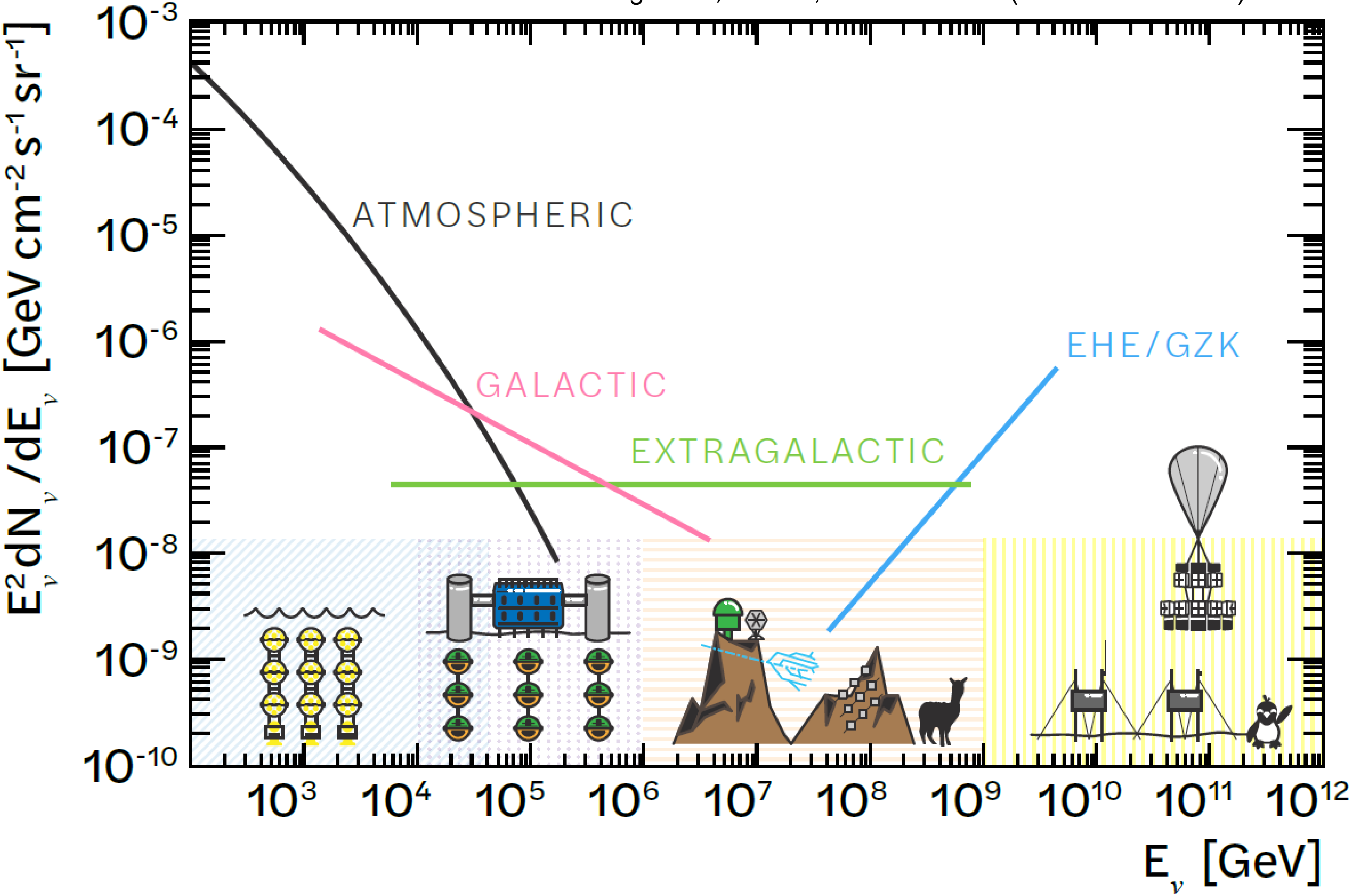
Ice Cherekov
- Scattering ✗ → Harder to point
- Absorption ✓ → Easier to make large detector

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



See talk by K. Hughes

Argüelles, Halzen, and Kurahashi (arXiv:2405.17623)



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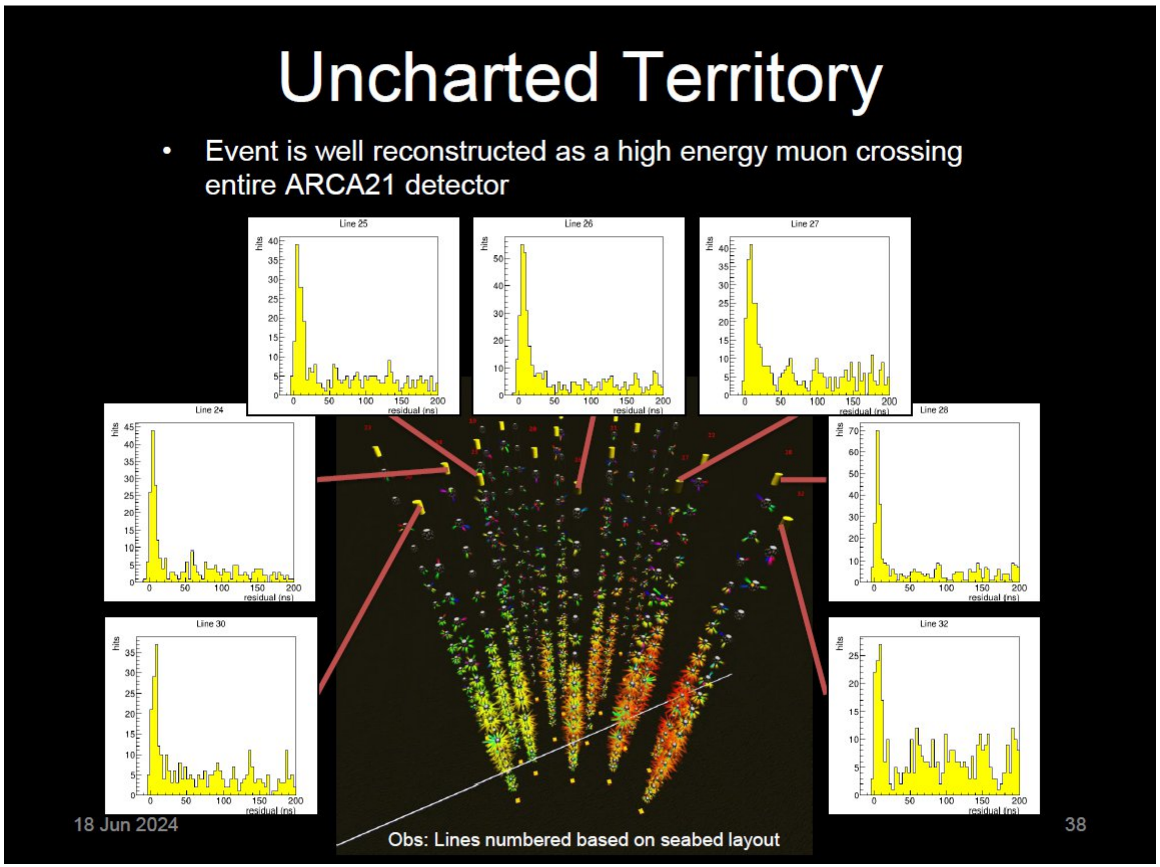
Diverging Optimizations → Good Sign of a Maturing Field

Priority: Instrumented Volume

- Fundamental challenge for all neutrino telescopes is the high background rate
- We need statistics! More neutrinos above background!
- More PMTs, more photo-cathode coverage around the world → more data → more signal collected



VHE neutrino events are rare

Yet this was seen in ARCA21
(9% completed ARCA!)

Globally dispersed detector important

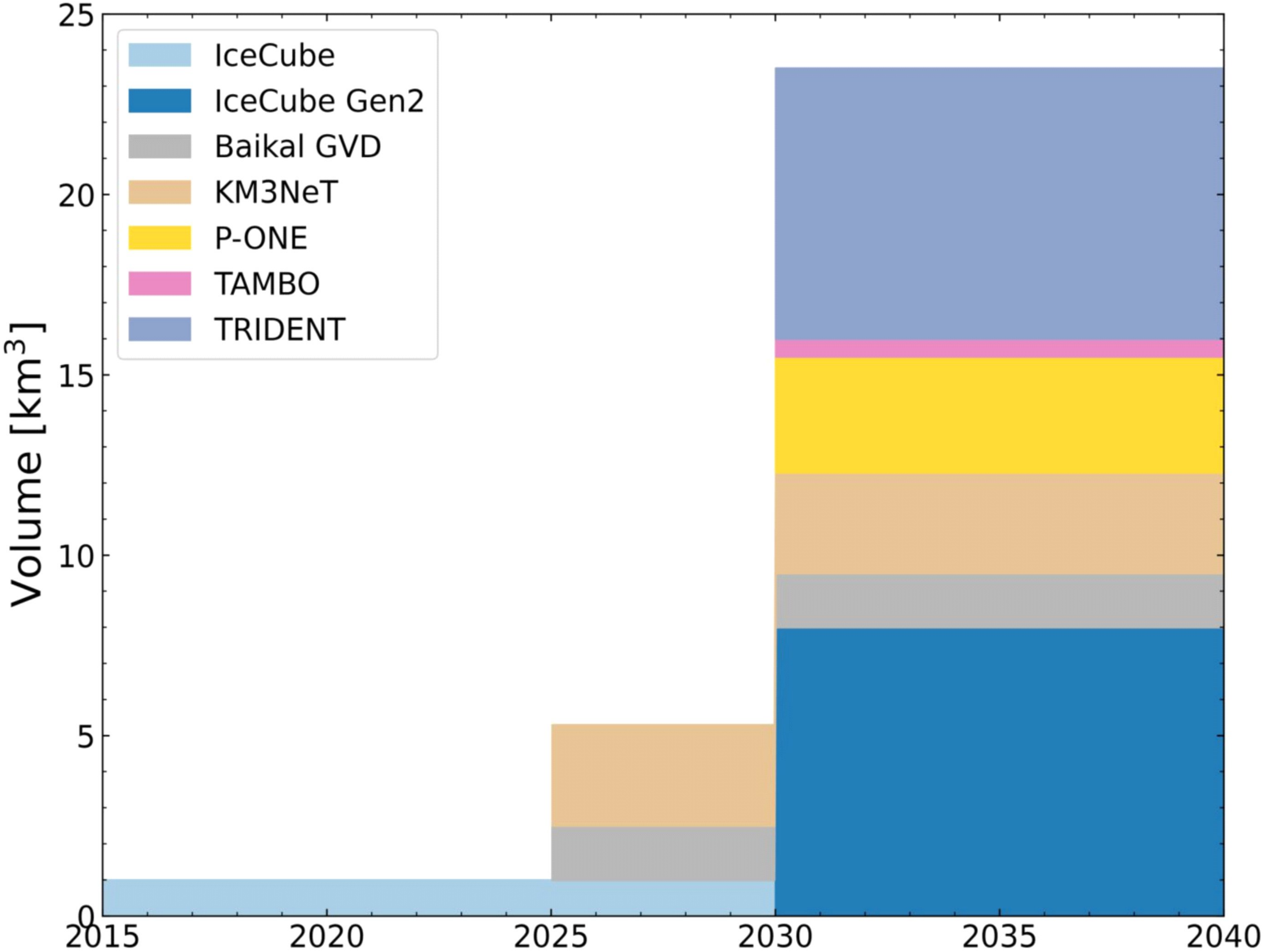
Conclusions

- HE Neutrino Astronomy has enjoyed a decade of initial success
- A maturing field is emerging
- Next Goal: Differently optimized telescopes, in different parts of the world, using different approaches, making simultaneous observations of sources, combining data, and making discoveries

What needs to happen in the next decade to achieve this:

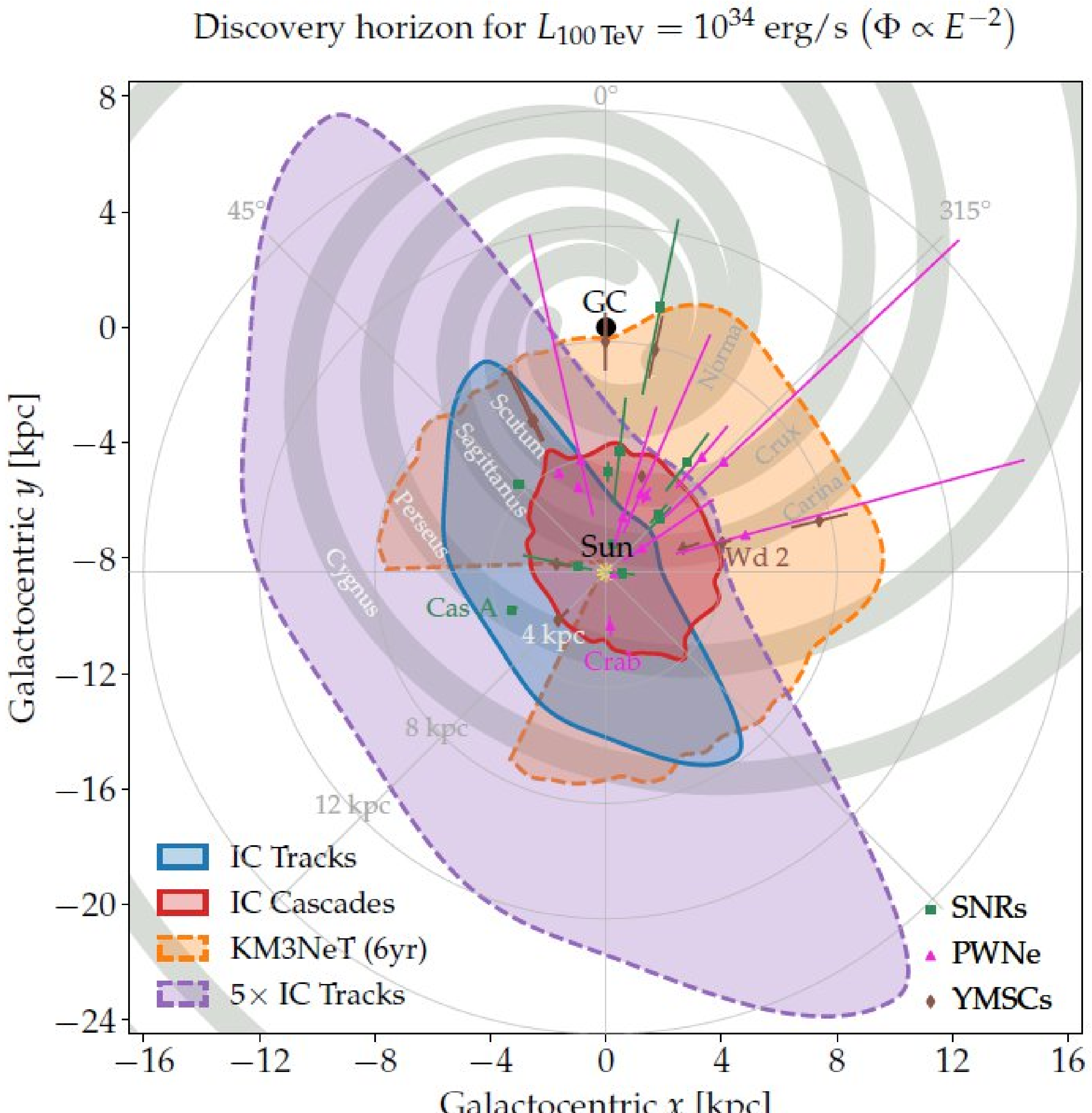
- **Keep IceCube Running**
- **Complete KM3NeT**
- **P-ONE as First Pacific Telescope**
- **Towards IceCube-Gen2**
- **Extend to the Highest Energy with Skimming Taus/Radio Detectors**

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