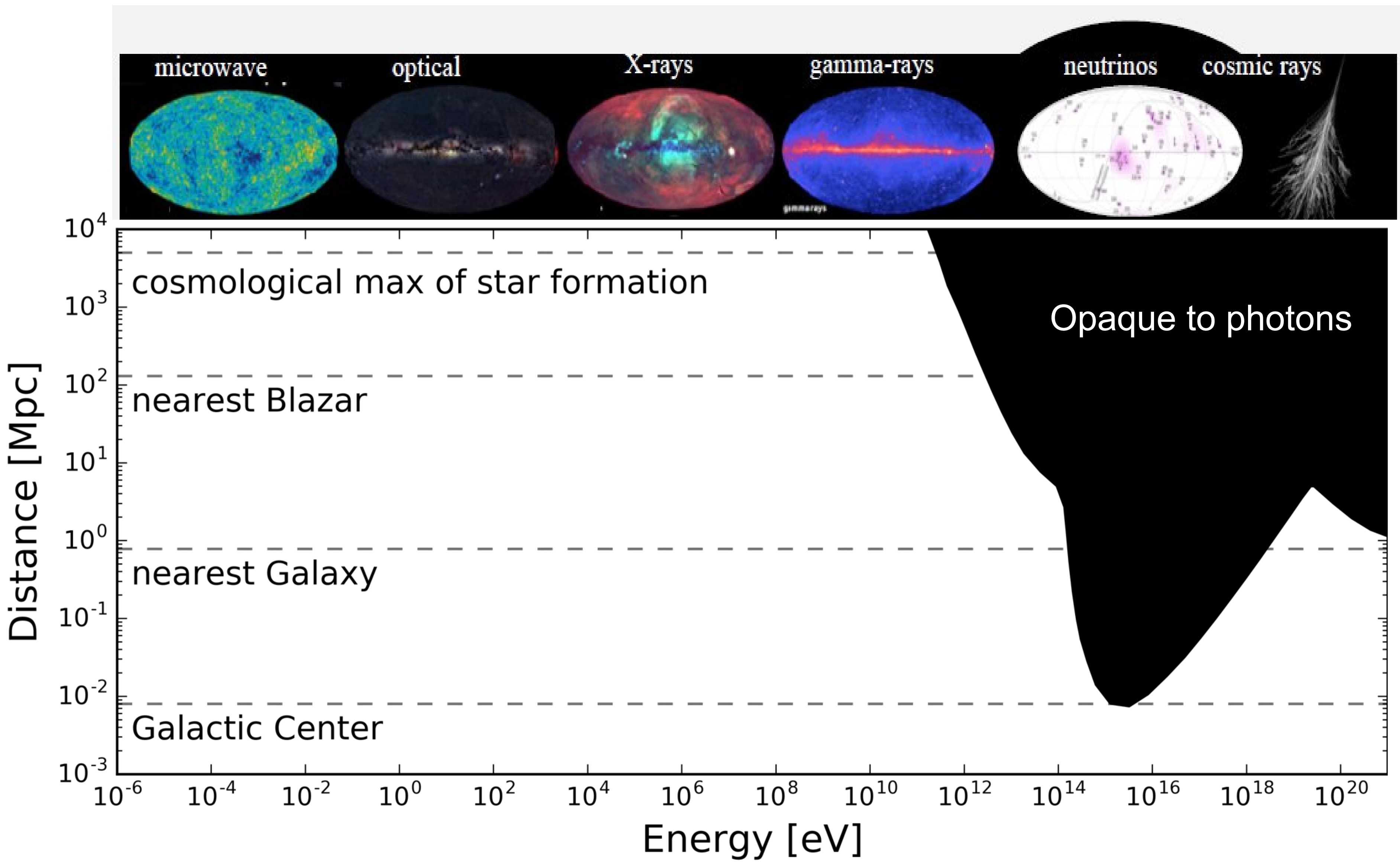
The High-Energy Invisible Universe

And the Evolution of Neutrino Telescopes

Naoko Kurahashi Neilson
(Drexel University)

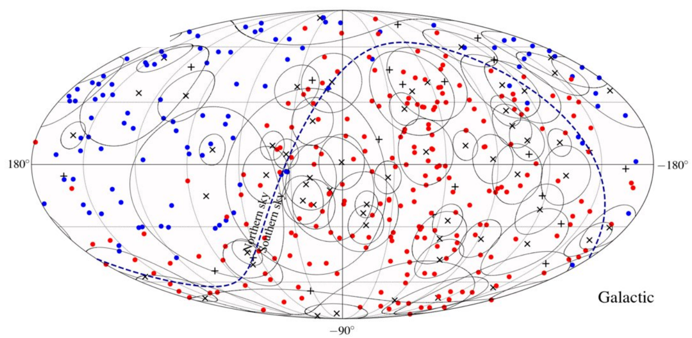
Yale Center for the Invisible Universe
May 30, 2025

Our Universe is “Invisible” at the Highest Energies



Localizing Sources with Cosmic Rays

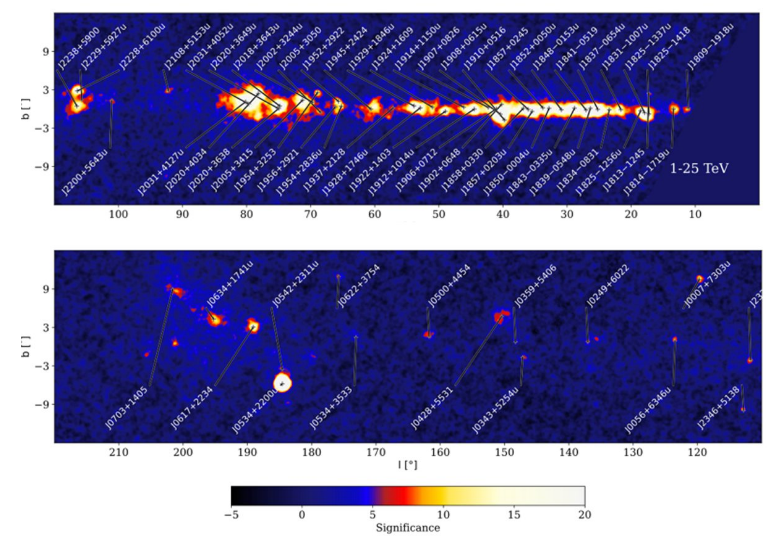
JCAP01(2016)037



- Composition-dependent distance of resolving power
- Nearby Sources?
- Attenuation creates neutrinos!

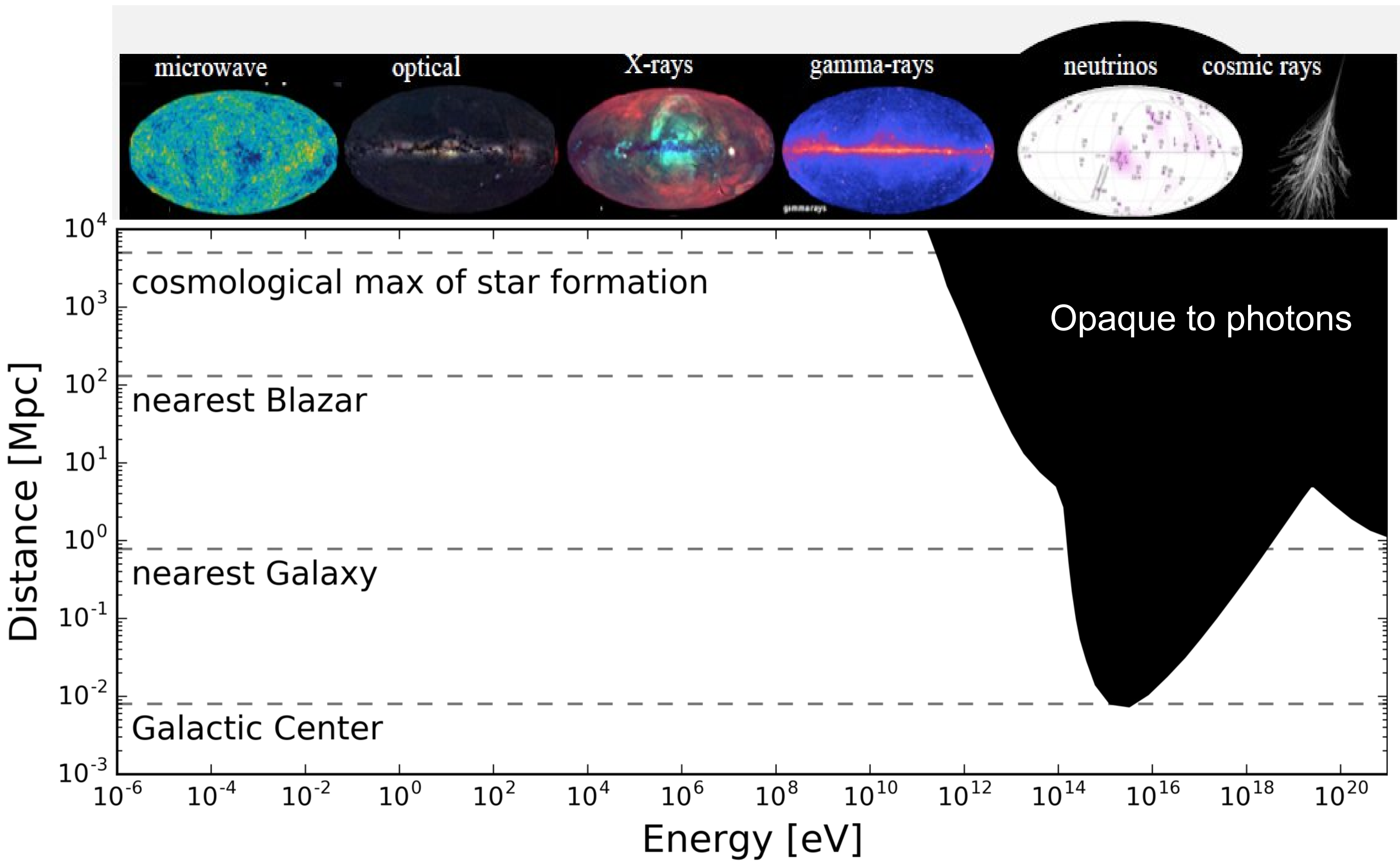
Nearby HE Gamma-Ray Sources

LHASSO Collaboration

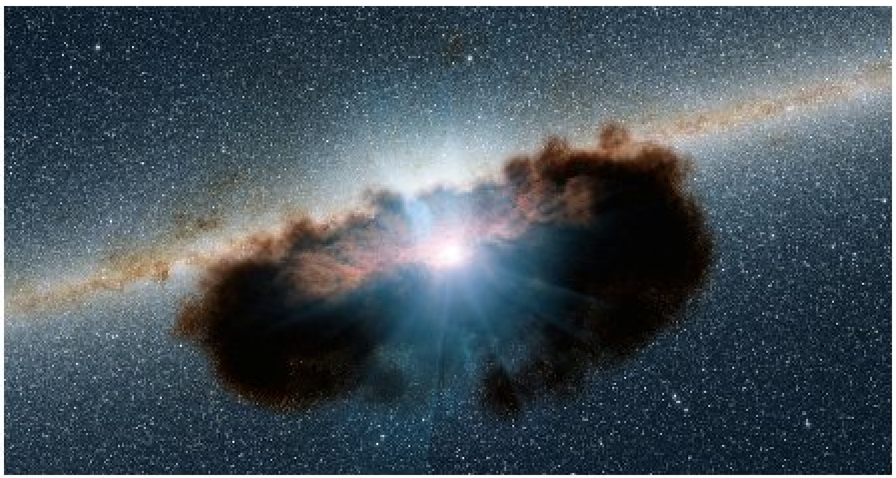


- Nearby Sources Observed (few dozen)
- Must be unobscured

Doesn't have to be intergalactic density



Obscured Sources

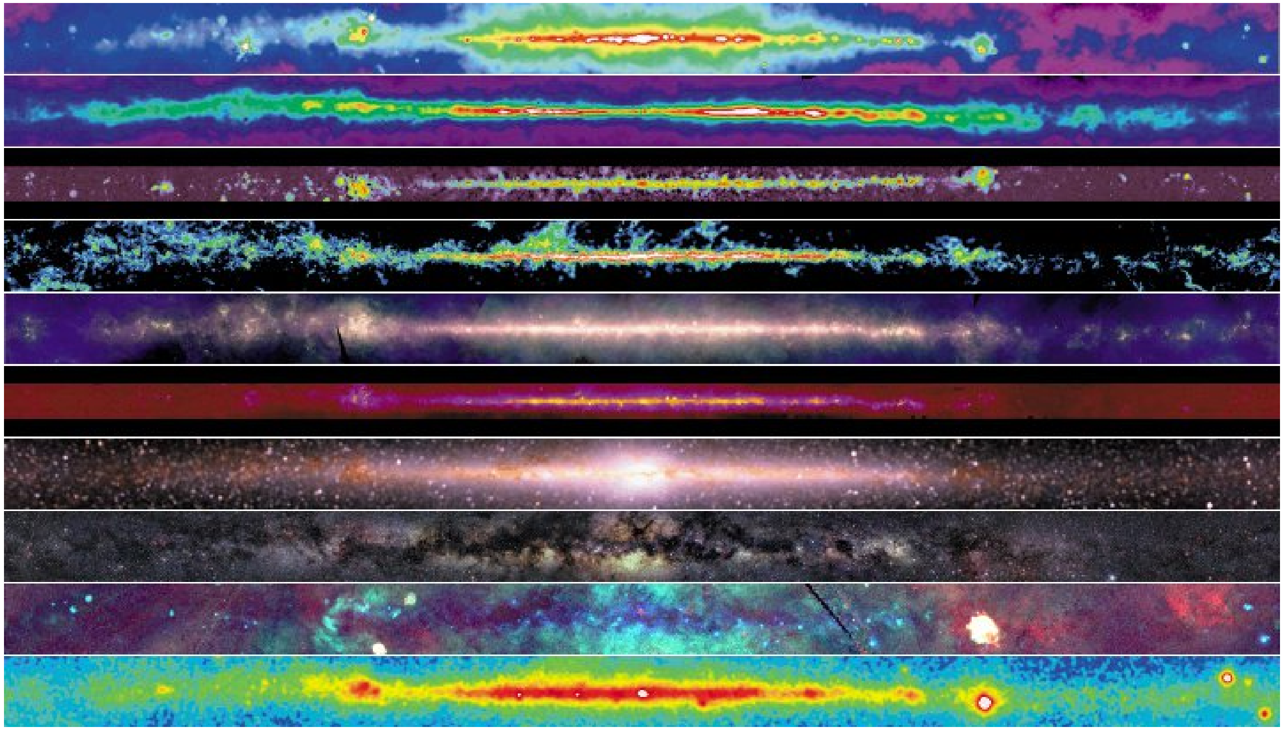


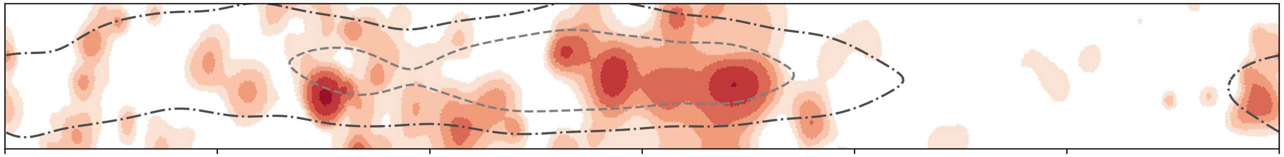
BAT AGN Spectroscopic Survey

Sometimes (often?) the most energetic particle production sites have the most density of “stuff” around them

Maybe even in our own Galaxy?

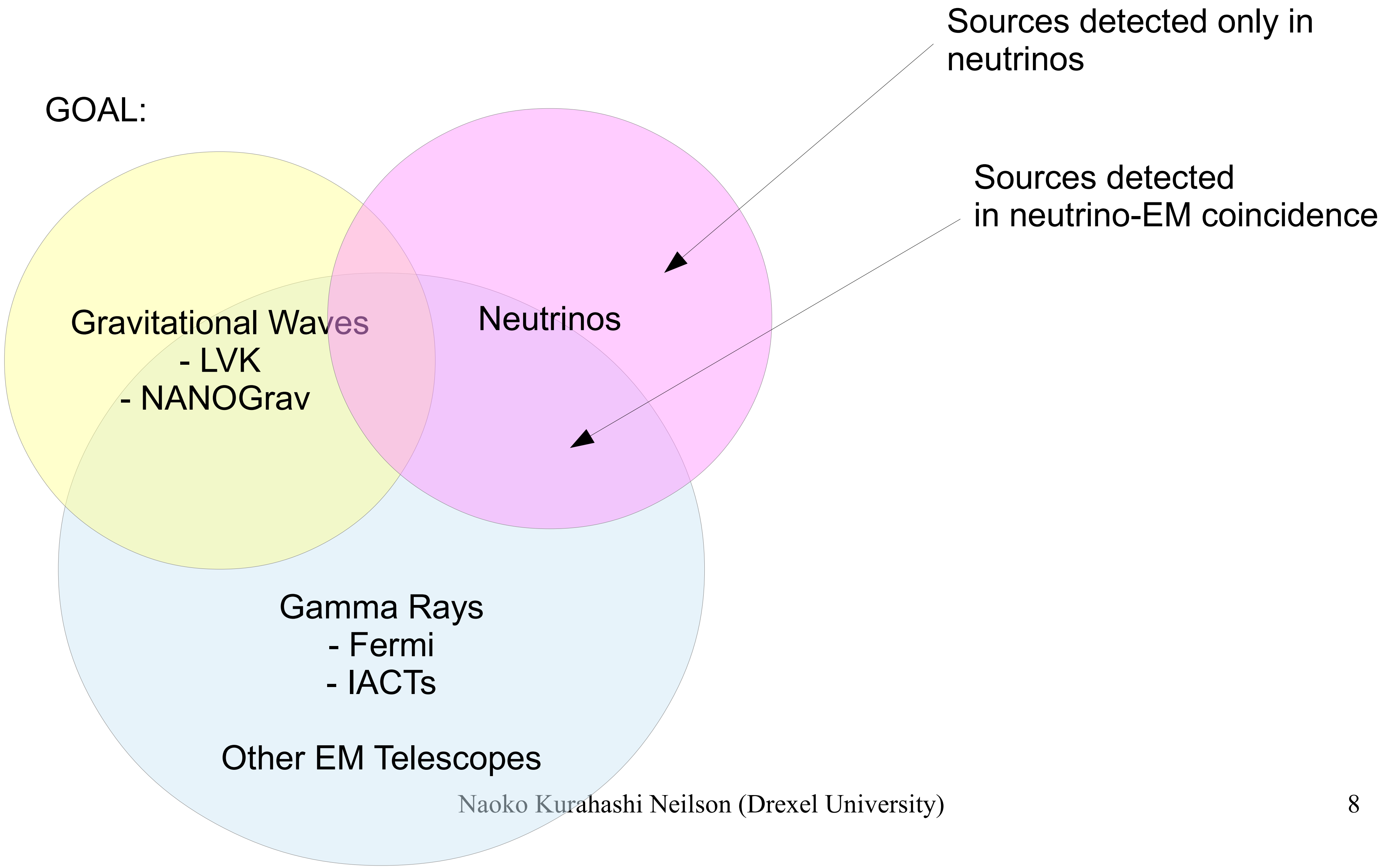
https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html





There must be more high-energy astronomical objects out there observable with neutrinos

Goal of Multi-Messenger Astronomy

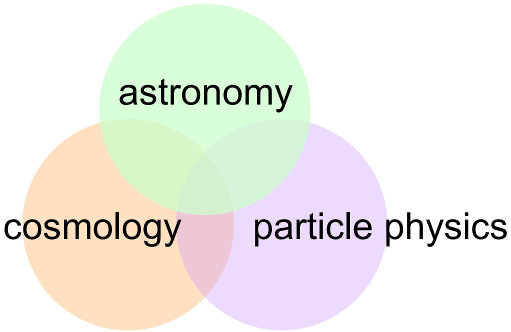


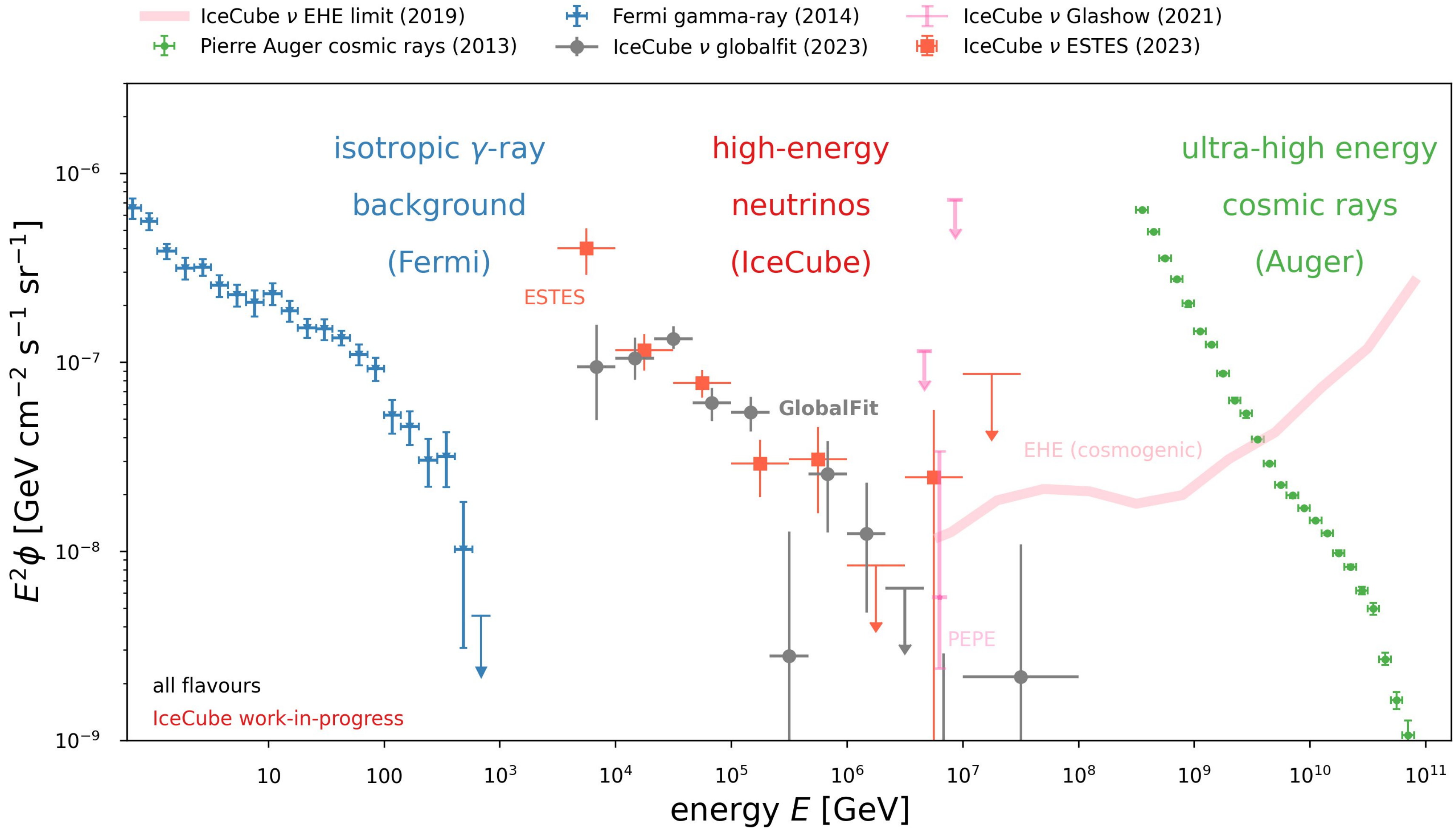
What do we gain? = What questions can we answer?

- What is making UHECR?
- Are there HE astronomical objects that only neutrinos can trace?
- What is the gamma-ray-neutrino relationship?
- How are neutrinos accelerated to TeV/PeVs?
    - AGN Core vs Jet?
    - Which source types? What makes some sources “special” within their types?
    - GRB has no neutrinos?

- Mass Hierarchy
- Cross section measurements beyond accelerator energies
    - Which QCD model correctly predicts muon multiplicity?
- Oscillation measurements at long and extreme baselines
    - BSM effects of flavor oscillation (quasi-Dirac, decoherence)
    - Monopoles
    - Sterile neutrino signatures

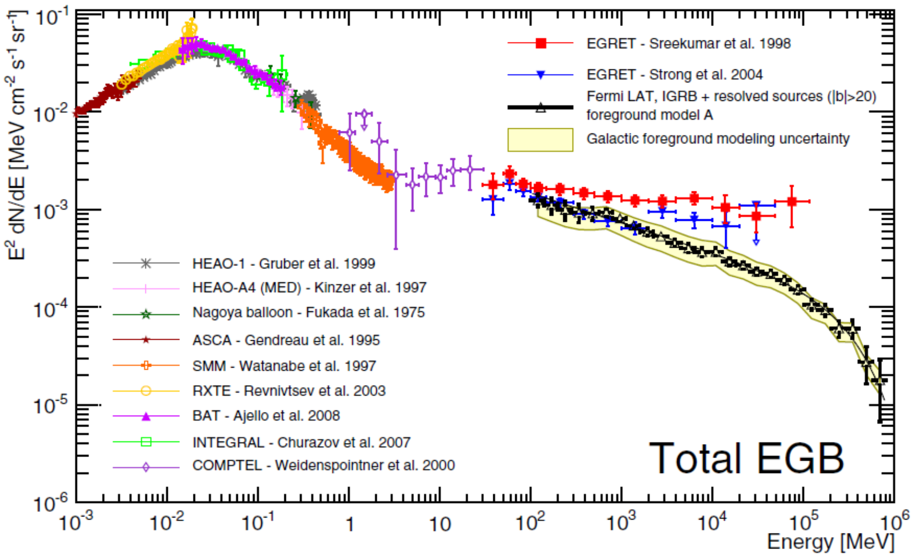
- DM signatures via HE neutrinos
- Primordial neutrinos?

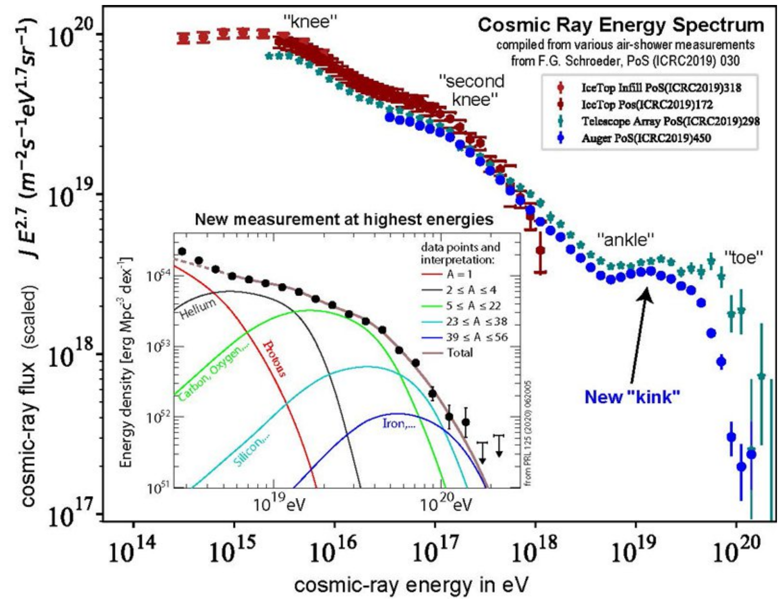



IceCube ν EHE limit (2019)
Pierre Auger cosmic rays (2013)
Fermi gamma-ray (2014)
IceCube ν globalfit (2023)
IceCube ν Glashow (2021)
IceCube ν ESTES (2023)
isotropic γ-ray background (Fermi)
high-energy neutrinos (IceCube)
ultra-high energy cosmic rays (Auger)
ESTES
GlobalFit
EHE (cosmogenic)
PEPE
all flavours
IceCube work-in-progress
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
energy E [GeV]

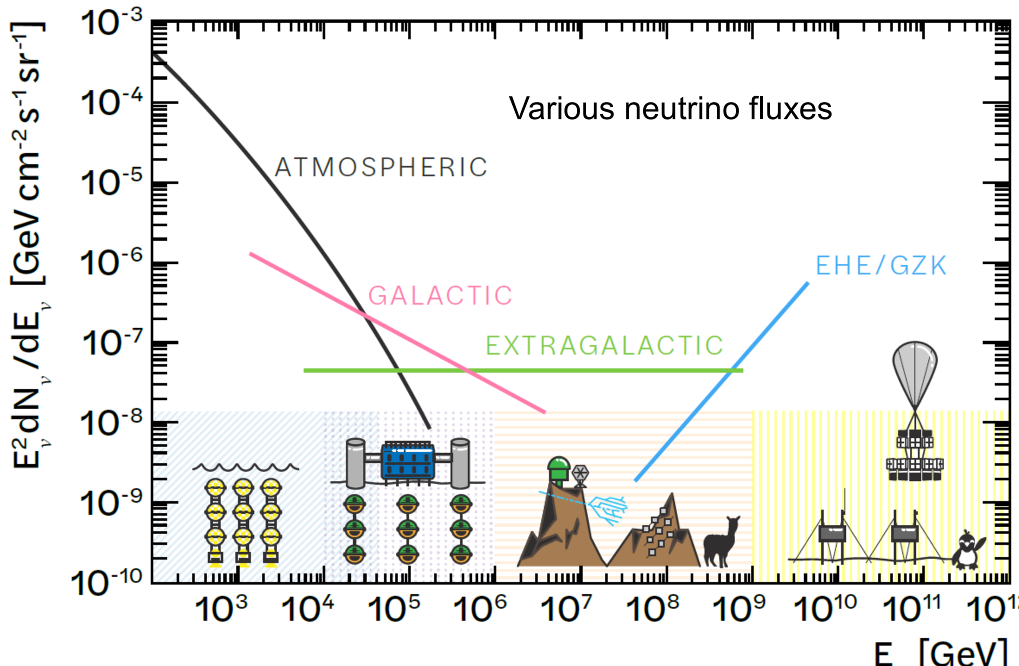
High Energy Fluxes Are Small

M. Ackermann et al 2015 ApJ 799 86



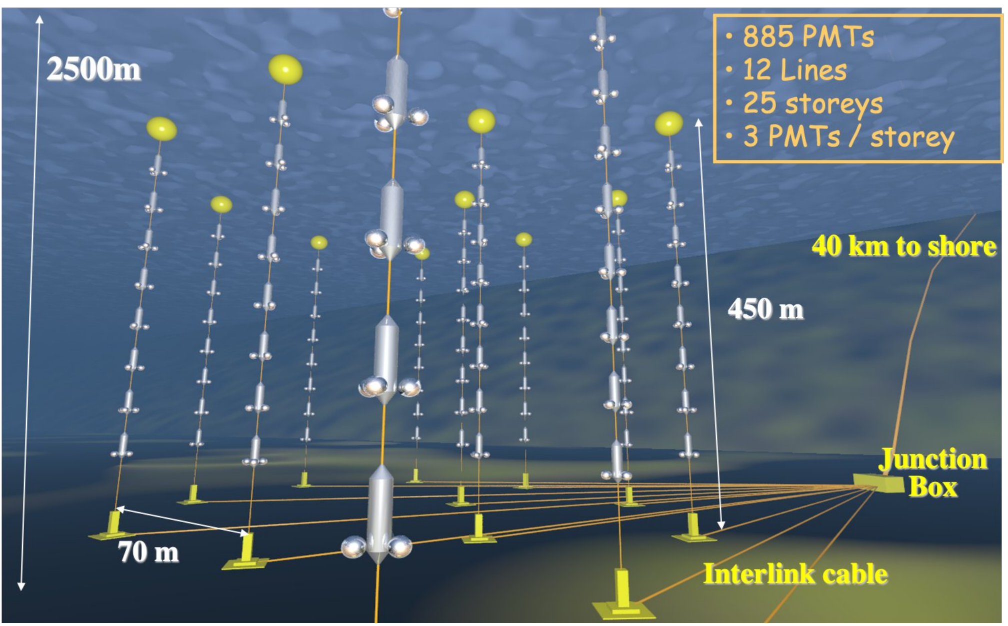


Arguelles, Halzen, Kurahashi, PRX (2025)



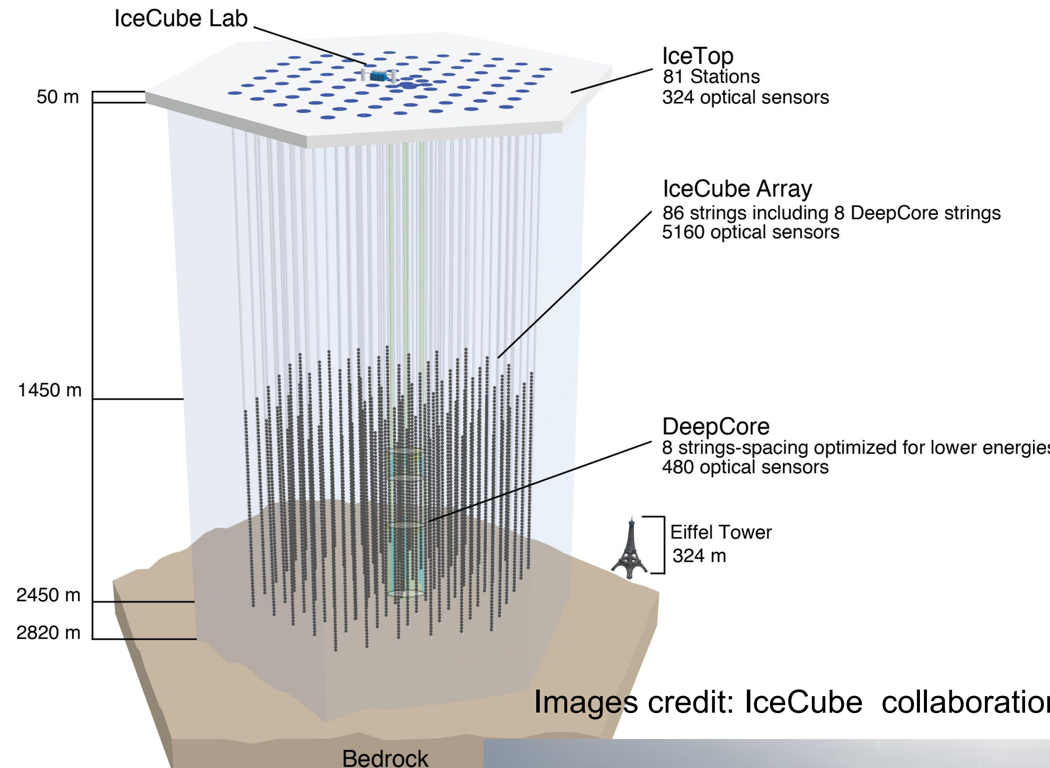
Need Large Detectors

ANTARES (2007-2022)

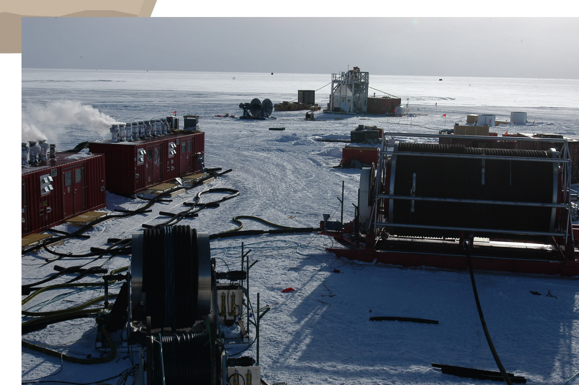


Images credit: ANTARES collaboration

IceCube (2011-)



Images credit: IceCube collaboration

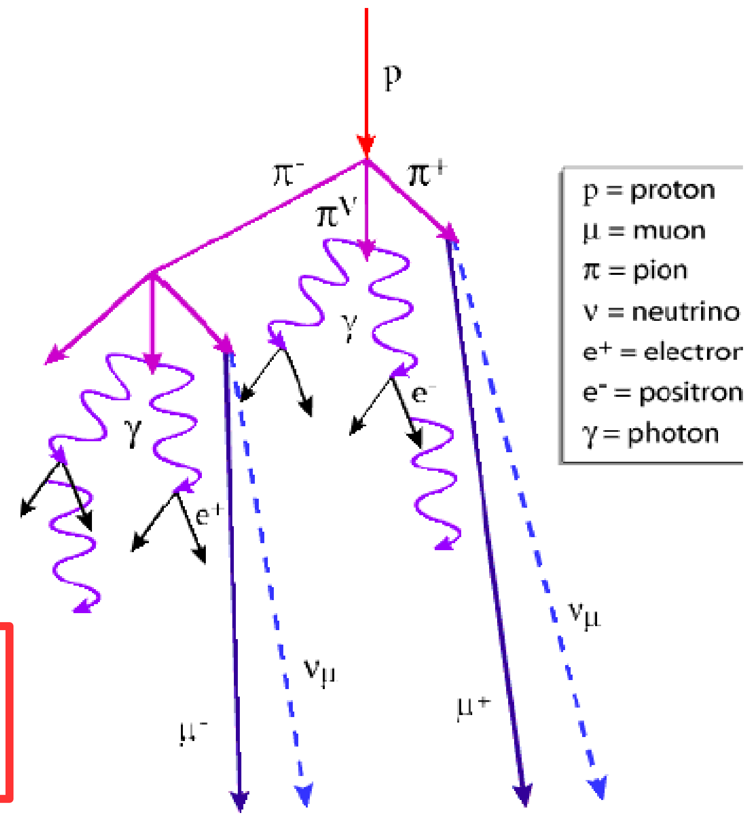


Naoko Kurahashi Neilson (Drexel University)

Need To Overcome Background

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

Successful Decade!

Science

Current Issue First release papers Archive About Submit manu

HOME > SCIENCE > VOL. 361, NO. 6398 > MULTIMESSENGER OBSERVATIONS OF A FLARING BLAZAR COINCIDENT WITH HIGH-ENERGY NEUTRINO...

RESEARCH ARTICLE

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

THE ICECUBE COLLABORATION, FERMI-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, KANATA, [...], A...

& Affiliations

SCIENCE • 13 Jul 2018 • Vol 361, Issue 6398 • DOI: 10.1126/science.aat1378

Neutrino emission from a flaring blazar

Neutrinos interact only very weakly with matter, but giant de
ceeded in detecting small numbers of astrophysical neutrinos
background, only two individual sources have been identified
nearby supernova in 1987. A multiteam collaboration detecte

Science

Current Issue First release papers Archive About Submit ma

HOME > SCIENCE > VOL. 378, NO. 6619 > EVIDENCE FOR NEUTRINO EMISSION FROM THE NEARBY ACTIVE GALAXY NGC 1068

RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

ICECUBE COLLABORATION, R. ABBASI, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, J. M. ALAMEDDINE, C. ALISPACH, [...], AND P. ZHELNIN

+376 authors Authors Info & Affiliations

SCIENCE • 3 Nov 2022 • Vol 378, Issue 6619 • pp. 538-543 • DOI: 10.1126/science.abg3395

Nearby active galaxy emits neutr

Observations have shown a diffuse backgroun
known to be of extragalactic origin. However, i
vidual sources that contribute to this backgrou
alyzed the arrival directions of astrophysical n
sources (see the Perspective by Murase). They

Naoko Kurahashi N

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*).

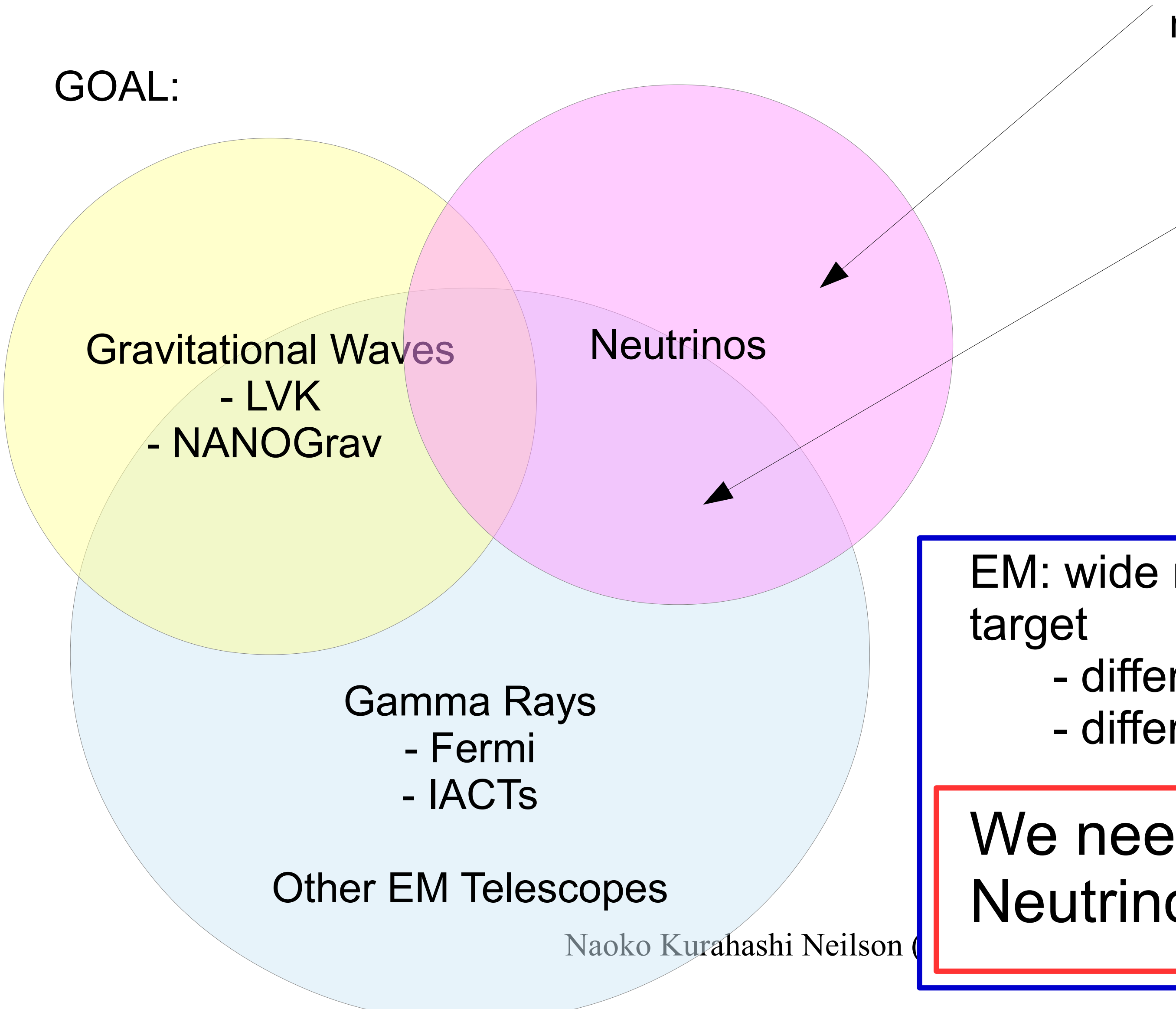
Searches for astrophysical neutrino sources are affected by an overwhelming background of muons and neutrinos produced by cosmic-ray interactions with Earth's atmosphere. Atmospheric muons dominate this background; IceCube records about 100 million muons for every observed astrophysical neutrino. Whereas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

Goal of Multi-Messenger Astronomy

GOAL:

Sources detected only in
neutrinos

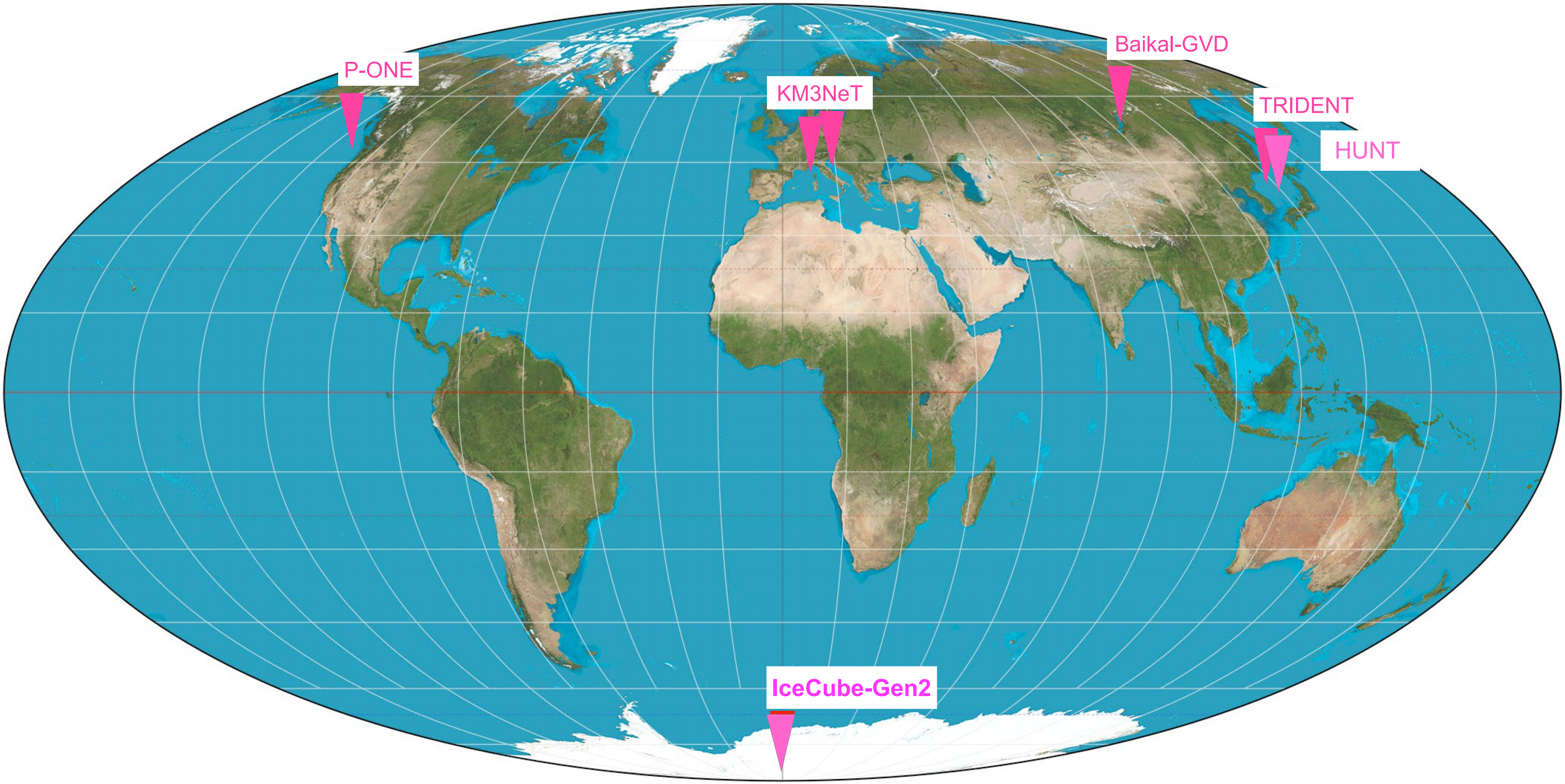
Sources detected
in neutrino-EM coincidence



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

We need wide ranges of Neutrino Telescopes too!

Global Neutrino Telescopes

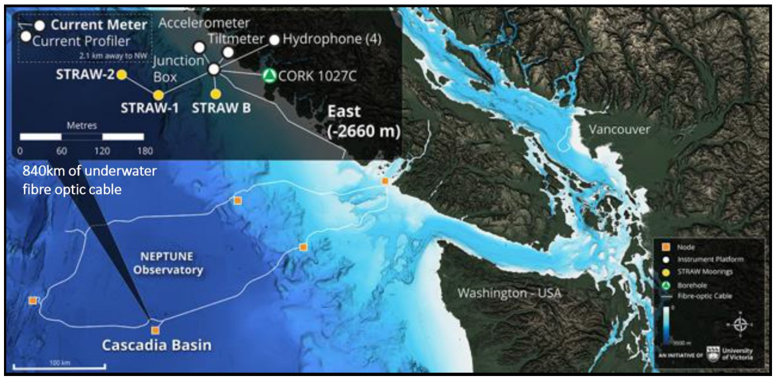


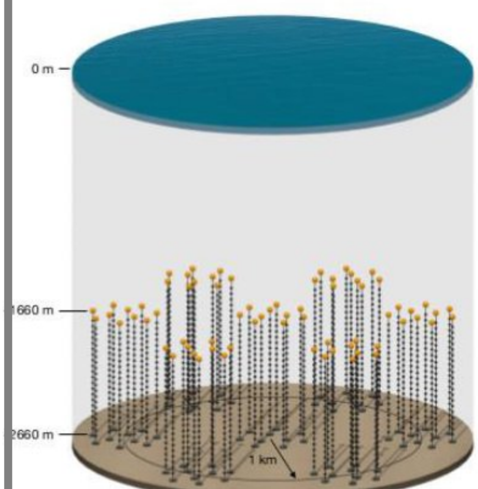
New Hemisphere New Comers

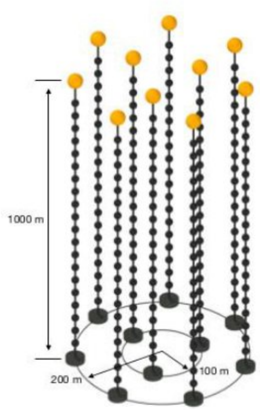
P-ONE

Pacific Ocean Neutrino Explorer

Leverage existing facilities





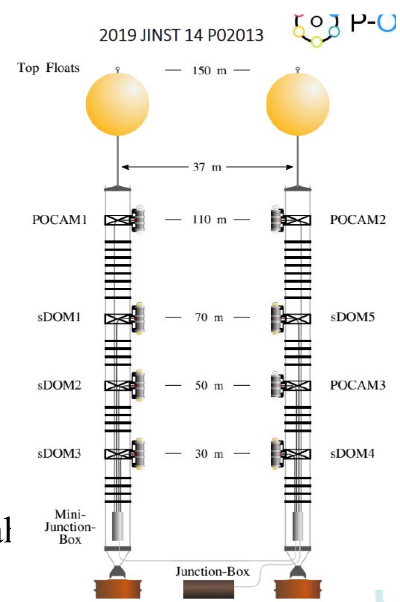


Huge telescopes in the South China Sea

TRIDENT 海铃计划

HUNT

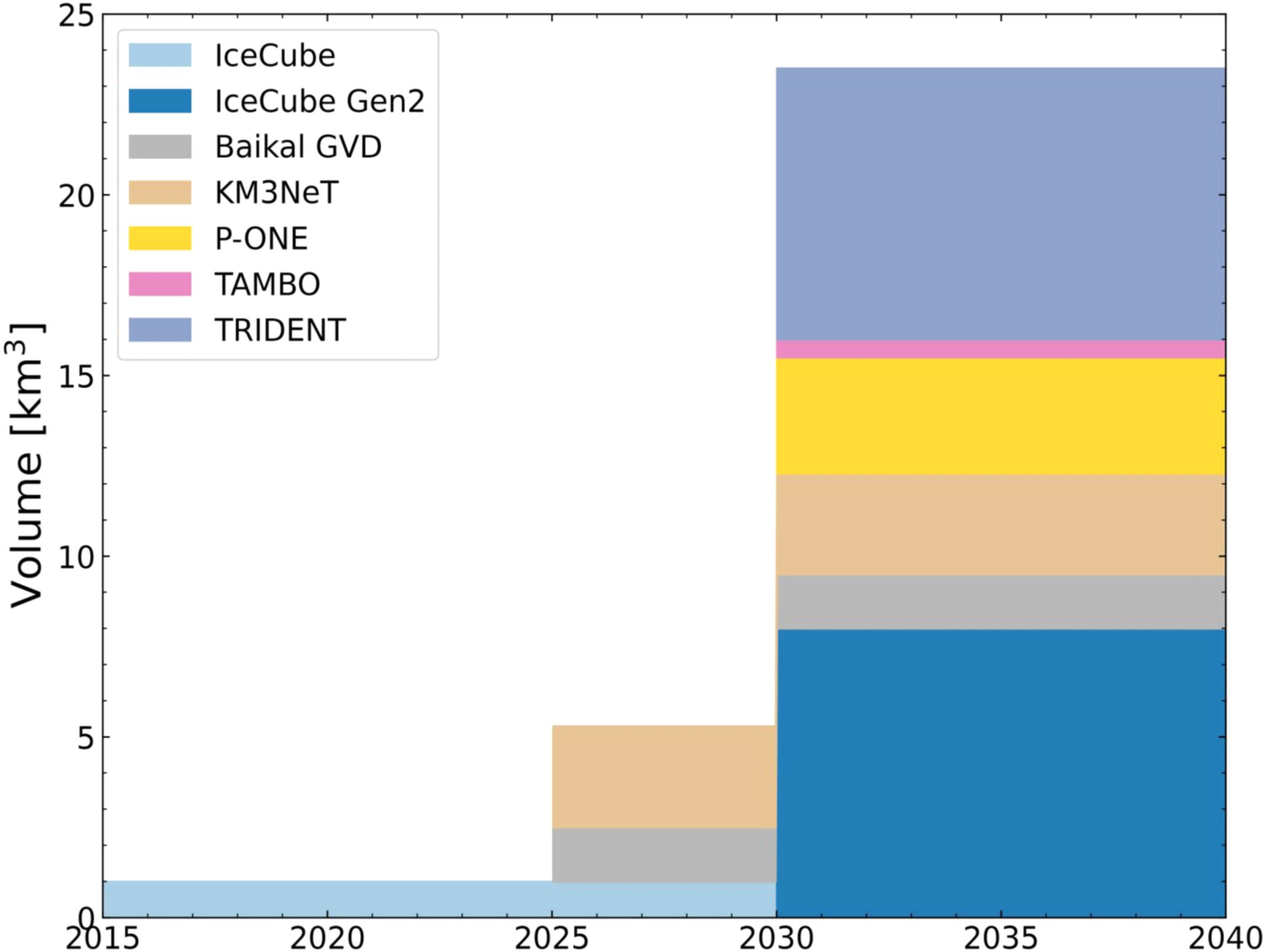
Pathfinder strings deployed and recovered



Images: courtesy P-ONE collaboration

Naoko Kural rsity)

Expanding Volume of Neutrino Telescopes



Courtesy: Q. Liu (Queens) ICRC2023

Women Observing Stars (1936) Ota Chou
National Museum of Modern Art, Tokyo

Conclusions

There are so many questions in the HE invisible Universe

Neutrino telescopes can provide answers in the next decade

Naoko Observing Stars and Galaxies (2012) South Pole