The Present and Future of Neutrino Astronomy

Matariki Edition

Img: Māpua School

ICECUBE P-ONE KM3NeT

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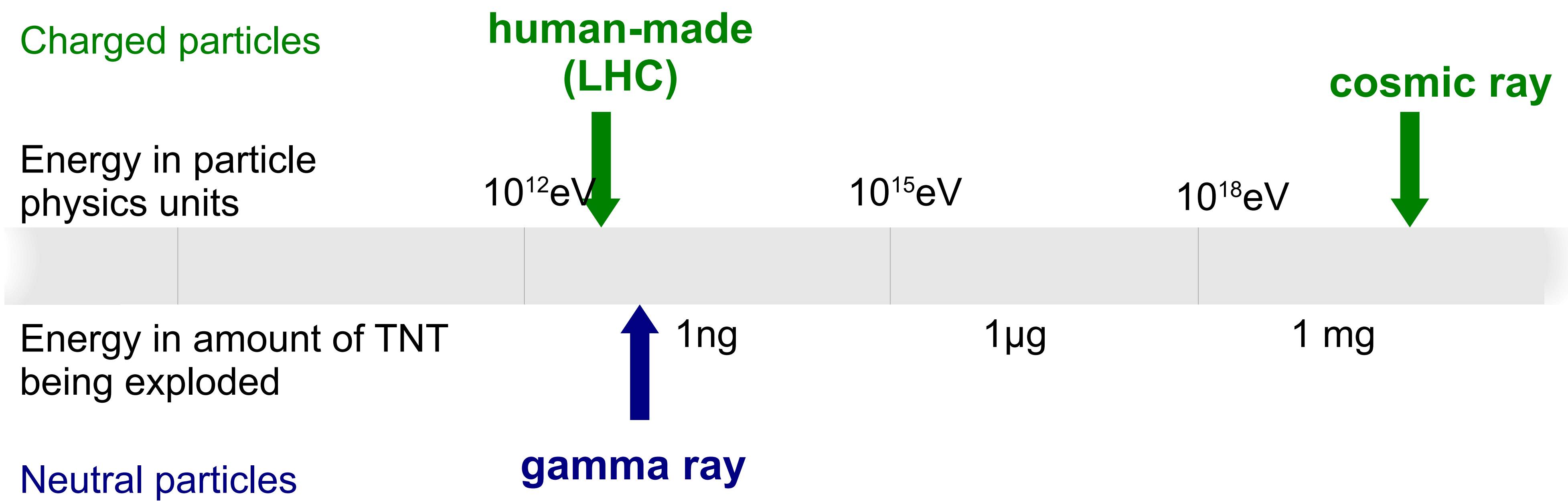
Drexel University, Philadelphia, USA

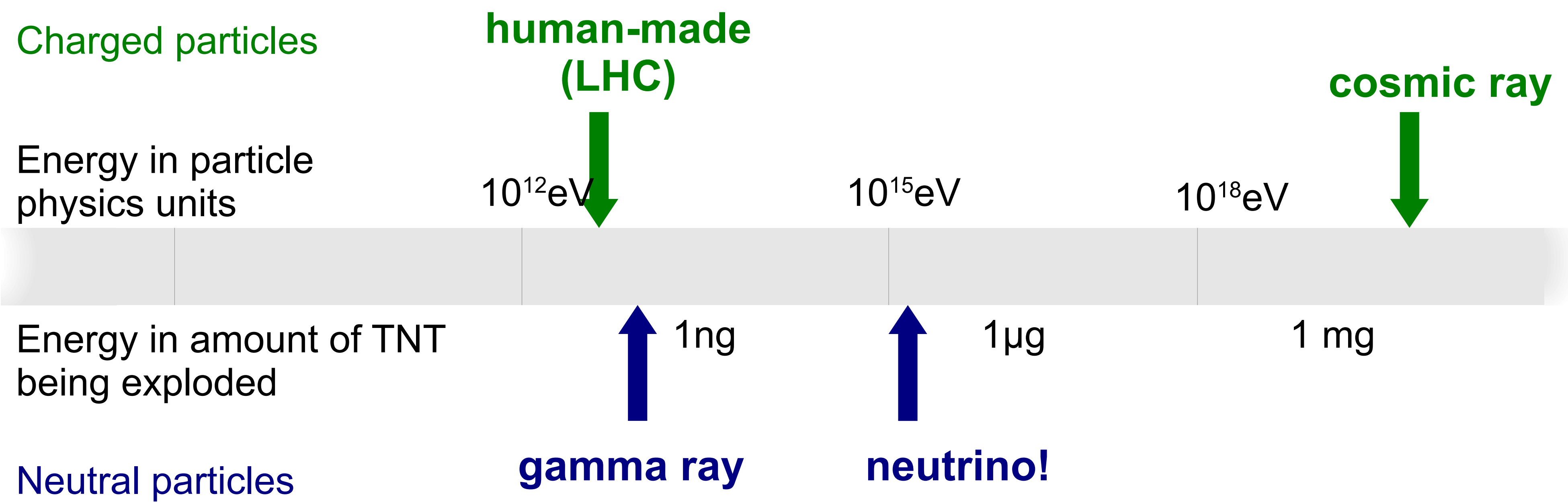
CosPA2026
July 9th, 2026

Drexel UNIVERSITY

Highest energy particles observed (in 2013)

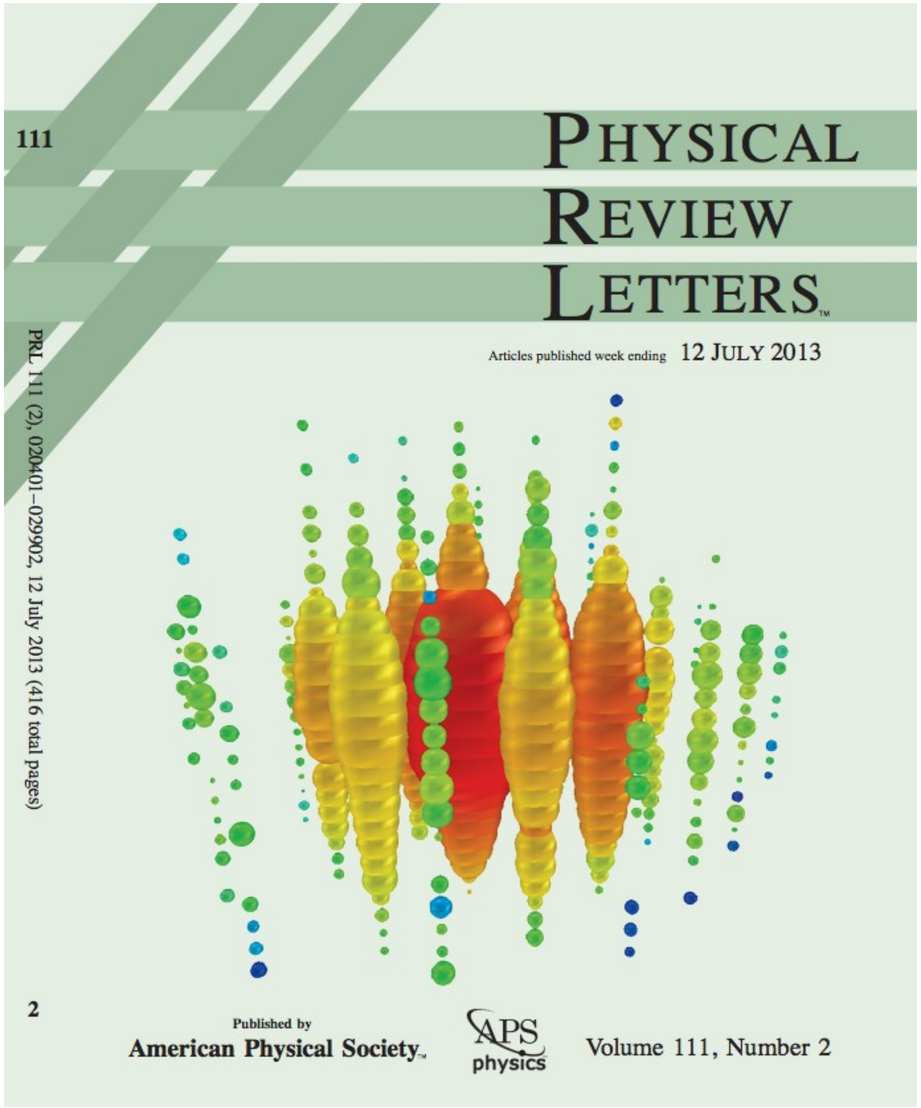


Highest energy particles observed (in 2013)

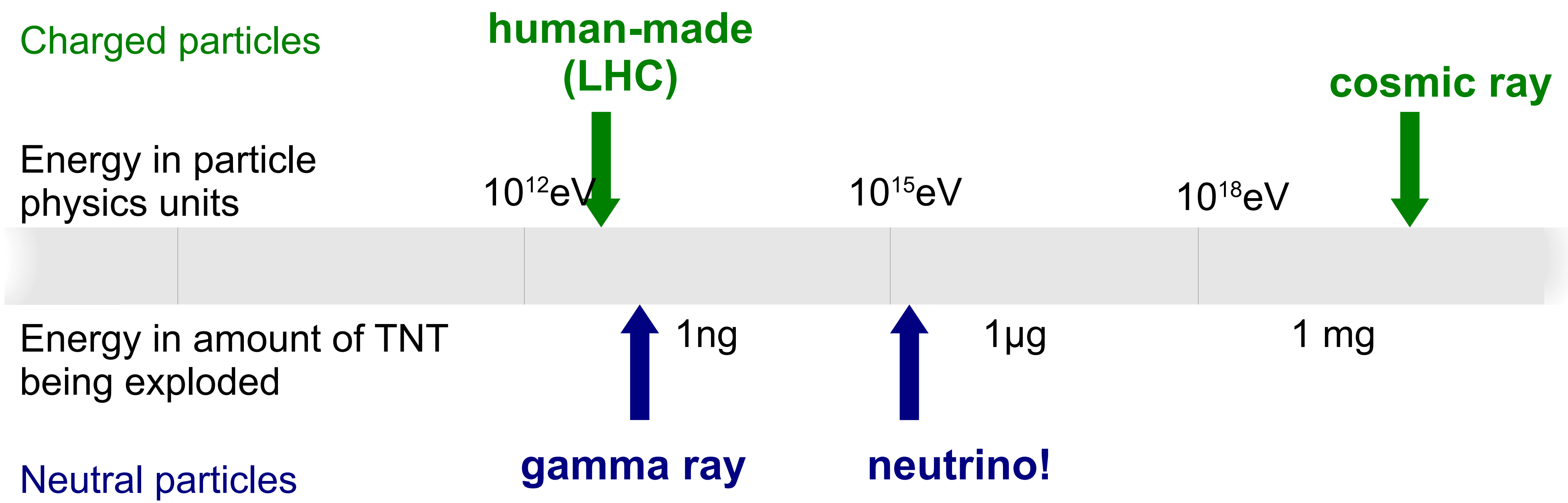


In 2013, IceCube discovered the then highest energy neutral particle.

Here it is!


111
PHYSICAL
REVIEW
LETTERS
Articles published week ending 12 JULY 2013
PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)
2
Published by
American Physical Society
APS physics
Volume 111, Number 2

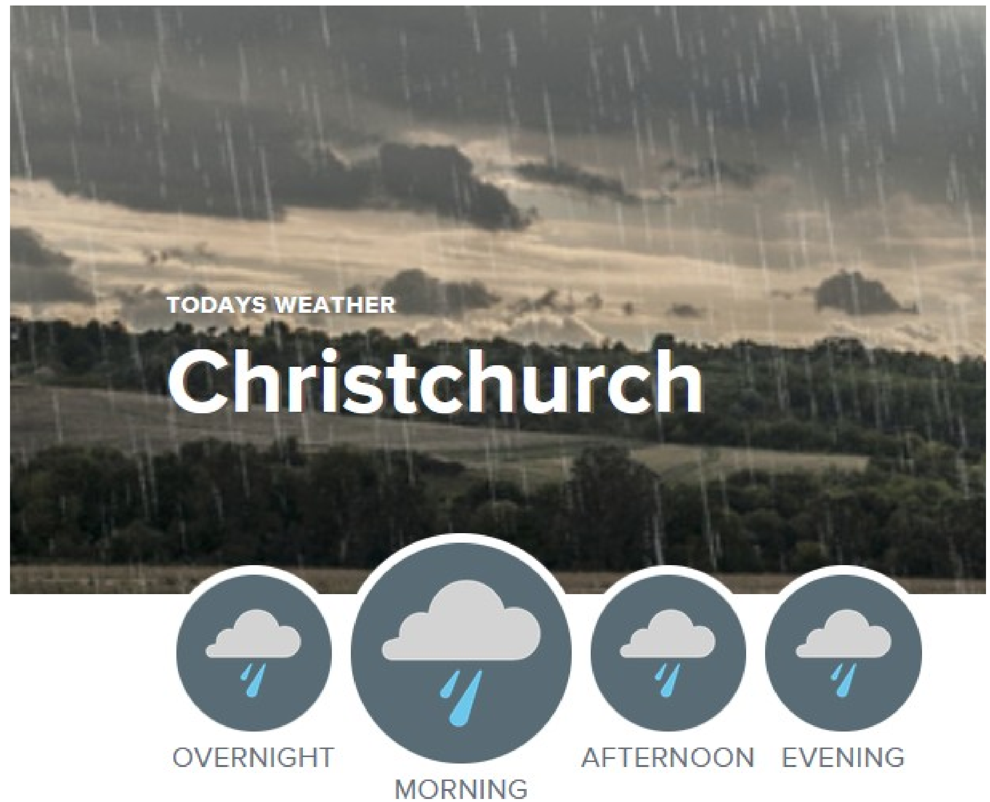
Highest energy particles observed (in 2013)



- how is it so high energy?
- how was it created?
- what created it?

Stars in Christchurch…?

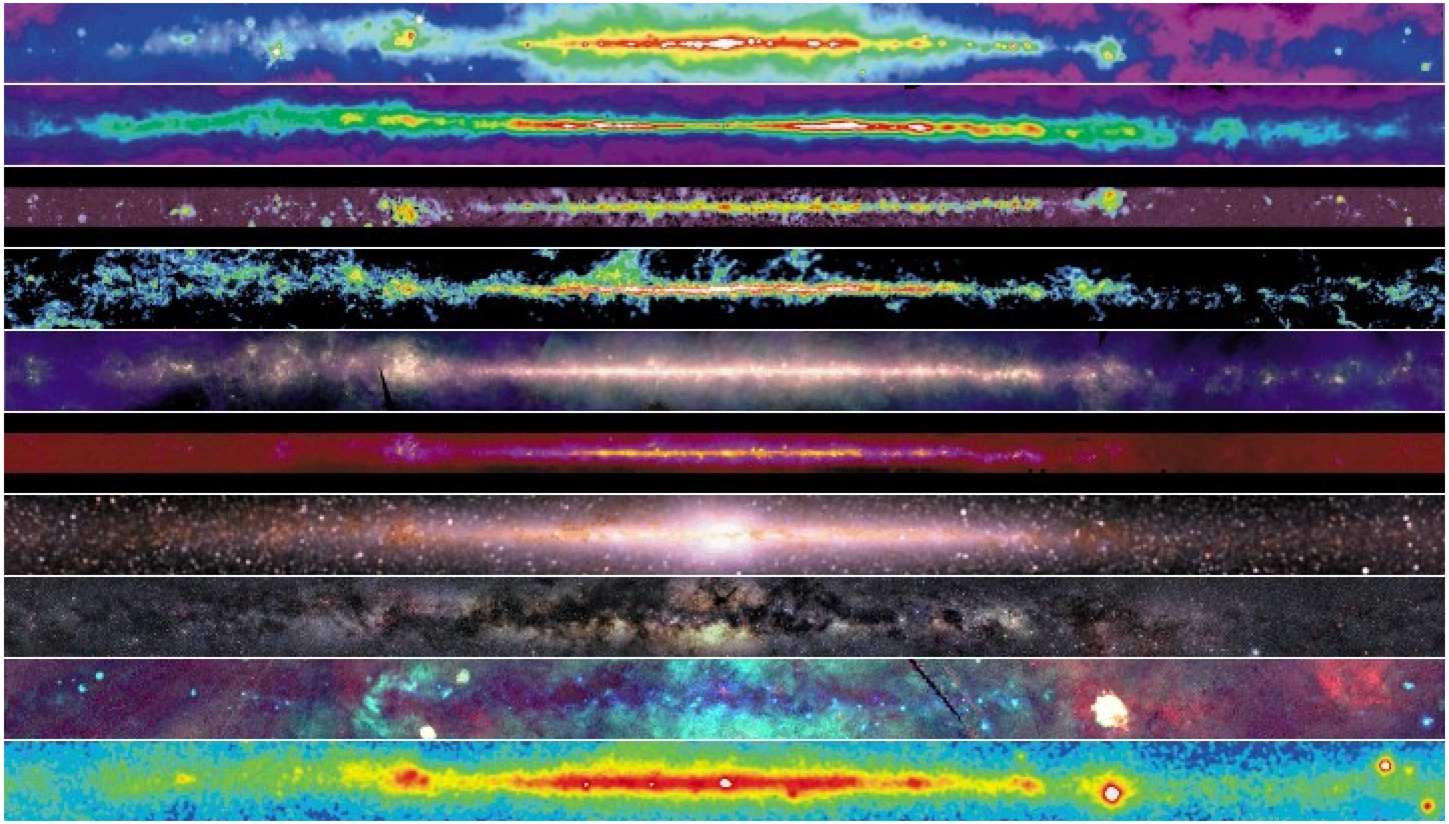
Website: Canterbury Weather Updates




img credit: Yuya Makino/NSF

The Milky Way

Iconic image of the multiwavelength Milky Way
(+/- 10^o in latitude, from radio to gamma ray)

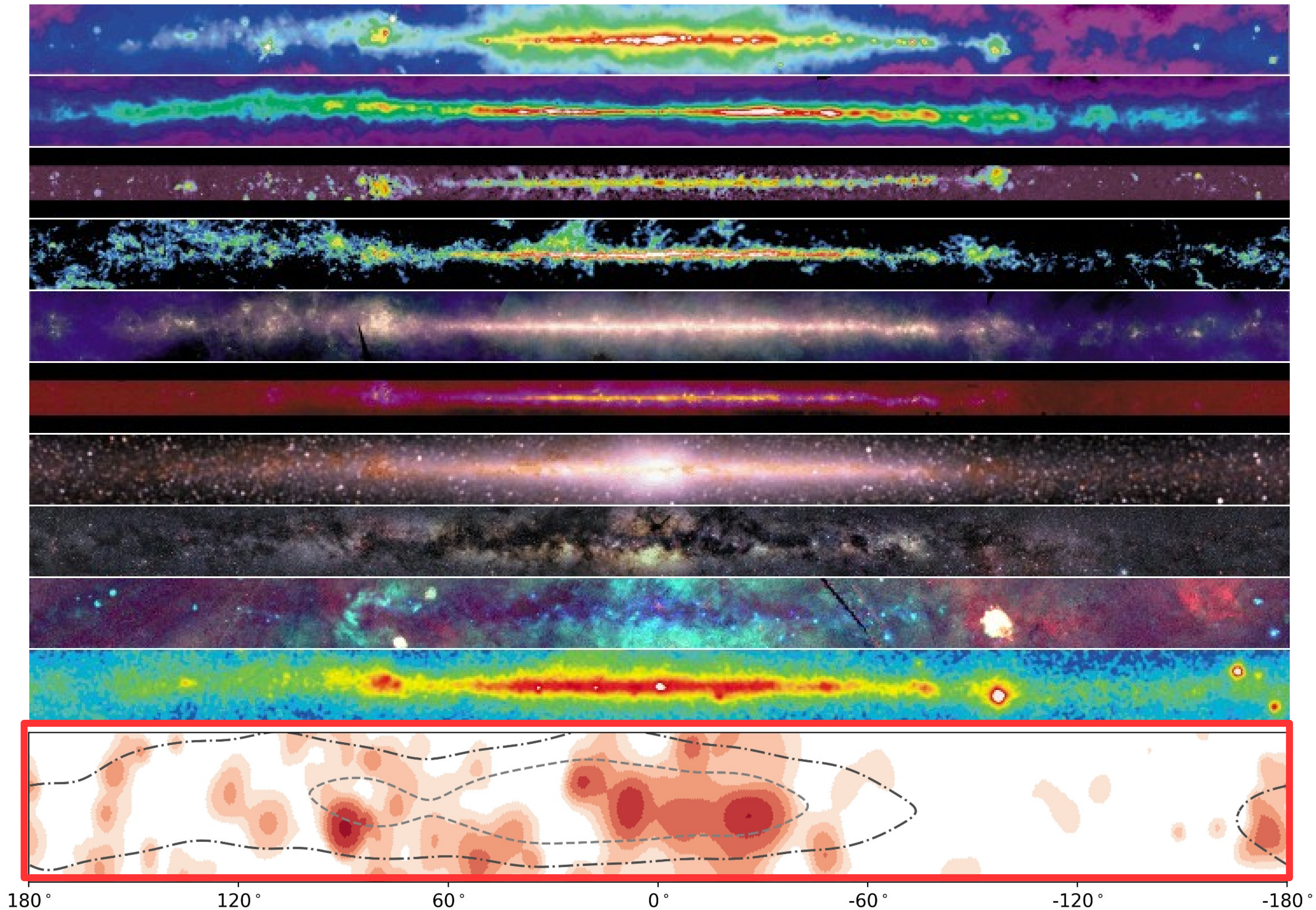


https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html


Periodic Table of Elements
Galactic Longitude
Galactic Latitude
atomic hydrogen
molecular hydrogen
infrared
near infrared
optical
x-ray
gamma ray
CAS A
CYGNUS LOOP
SAGITTARIUS SPIRAL ARM TANGENT
KEPLER'S SNR
NORMA SPIRAL ARM TANGENT
COALSACK
CARINA NEBULA
VELA
PUPPIS A
MON OB2
IC 443
CRAB
GALACTIC BULGE
GEMINGA
GEM OB1
Angular Resolution
Frequency Range
Multiwavelength Milky Way
NASA

The Milky Way

In Neutrinos!!!



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

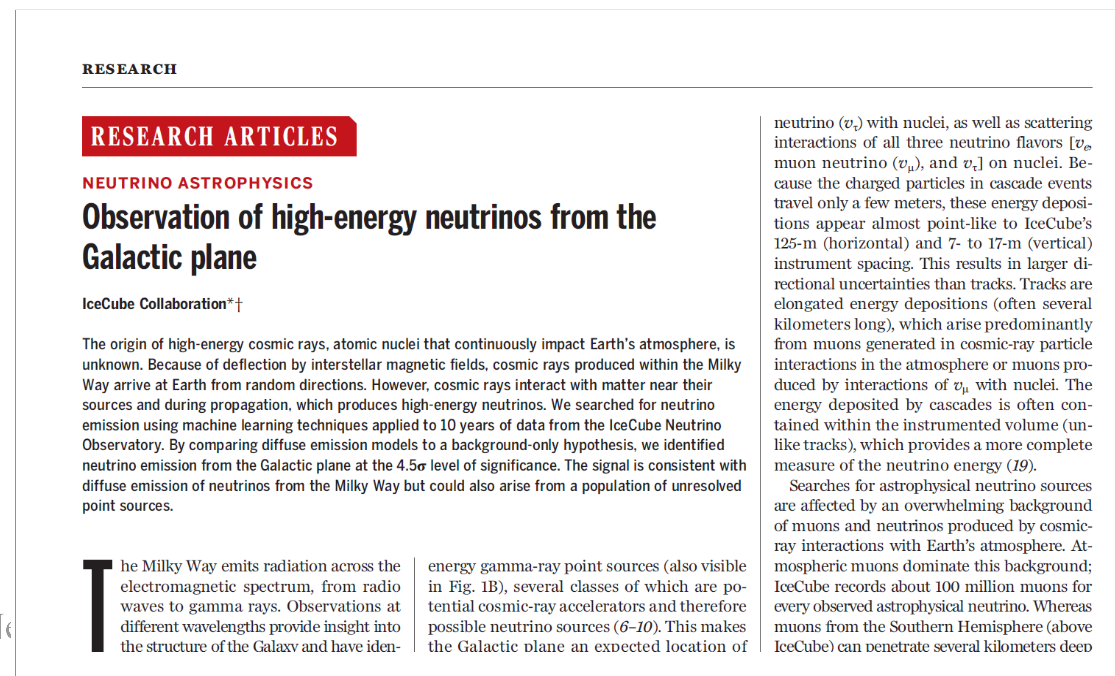
Science 380 (2023) 1338


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-

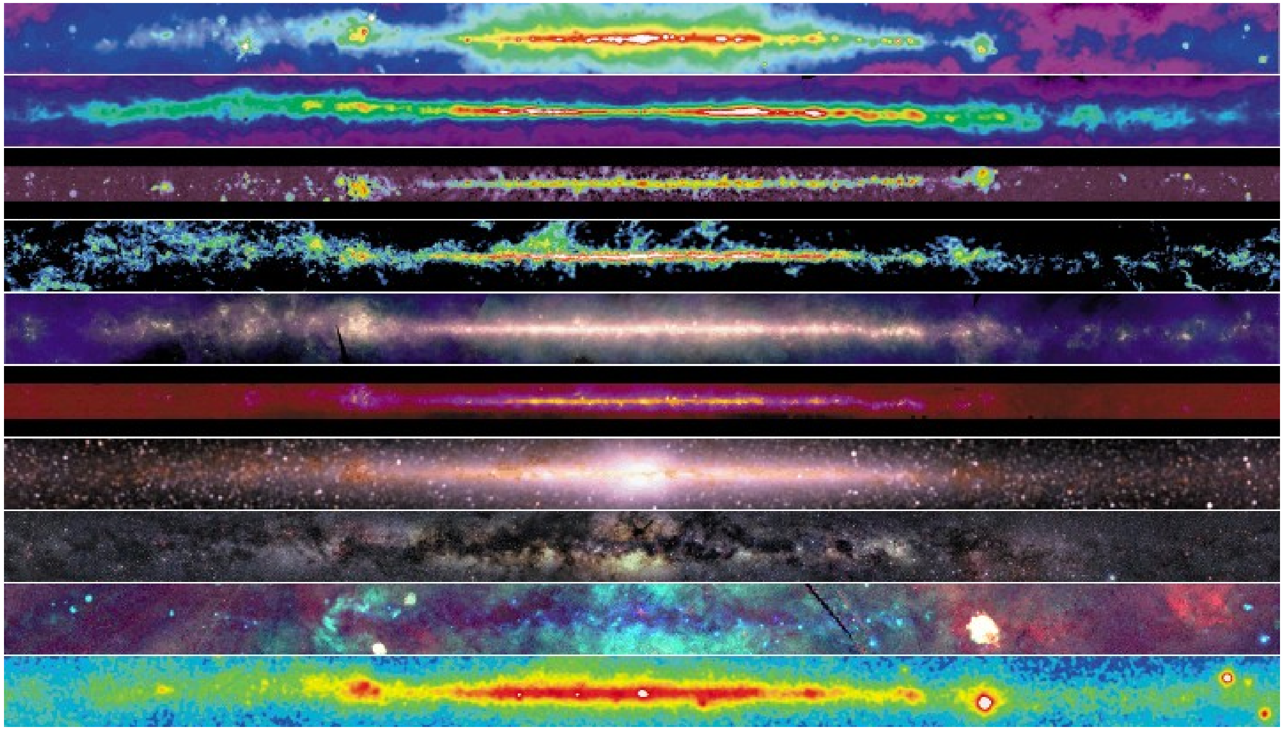
energy gamma-ray point sources (also visible in Fig. 1B), several classes of which are potential cosmic-ray accelerators and therefore possible neutrino sources (*6–10*). This makes the Galactic plane an expected location of

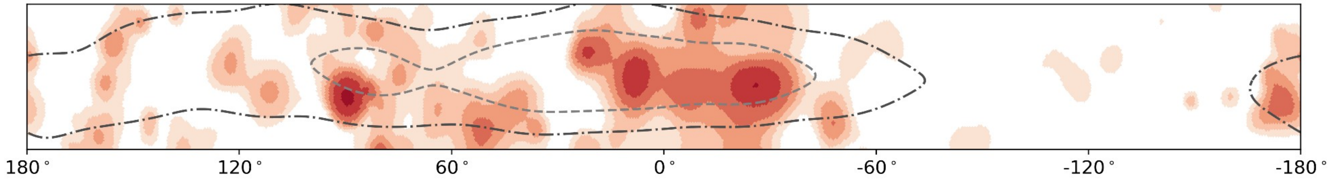
neutrino (v_τ) with nuclei, as well as scattering interactions of all three neutrino flavors [v_e, muon neutrino (v_μ), and v_τ] on nuclei. Because the charged particles in cascade events travel only a few meters, these energy depositions appear almost point-like to IceCube's 125-m (horizontal) and 7- 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 v_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

Now that we see it, the questions...

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





- Are there point sources mixed in with diffuse emission?
- Which ones? How much?
- Energy spectrum?
- Spatial feature?

- How does it compare to multi-wavelength emissions?

HE Neutrino Sources In The Sky

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

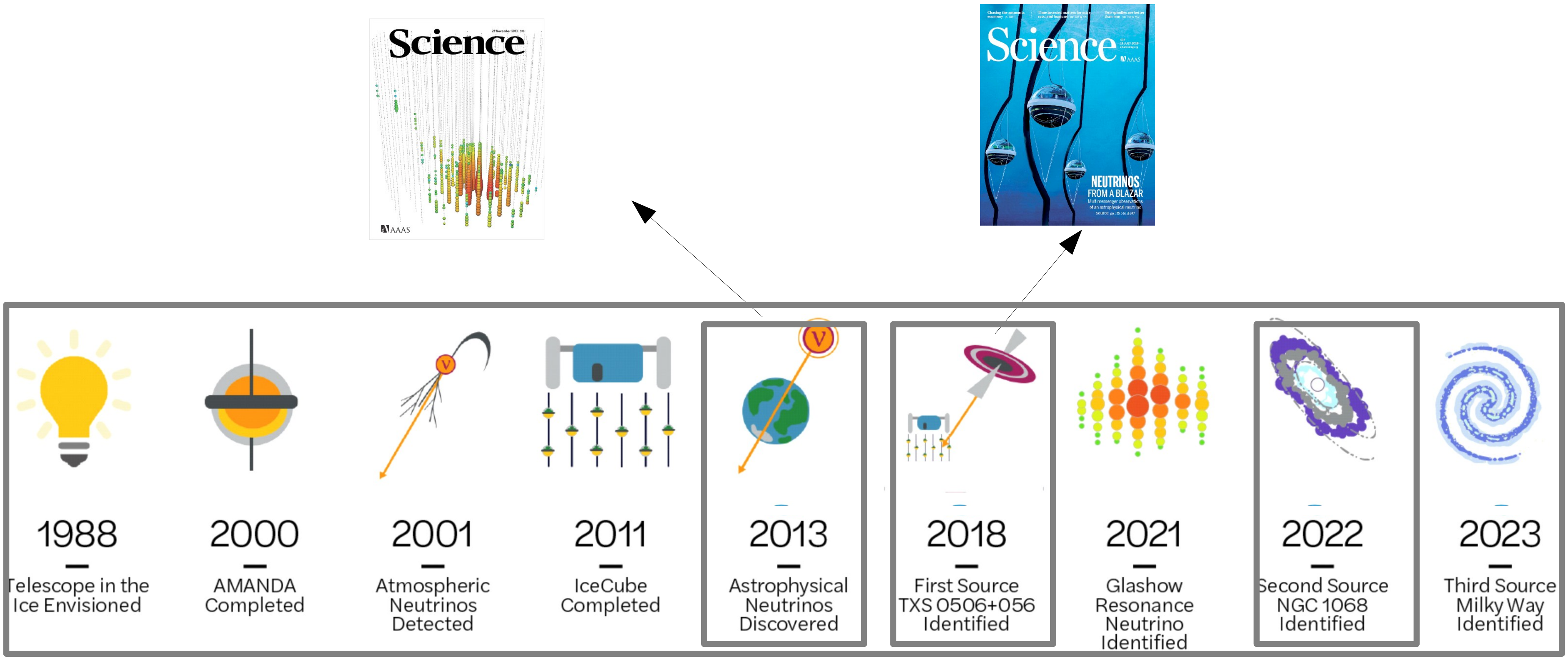
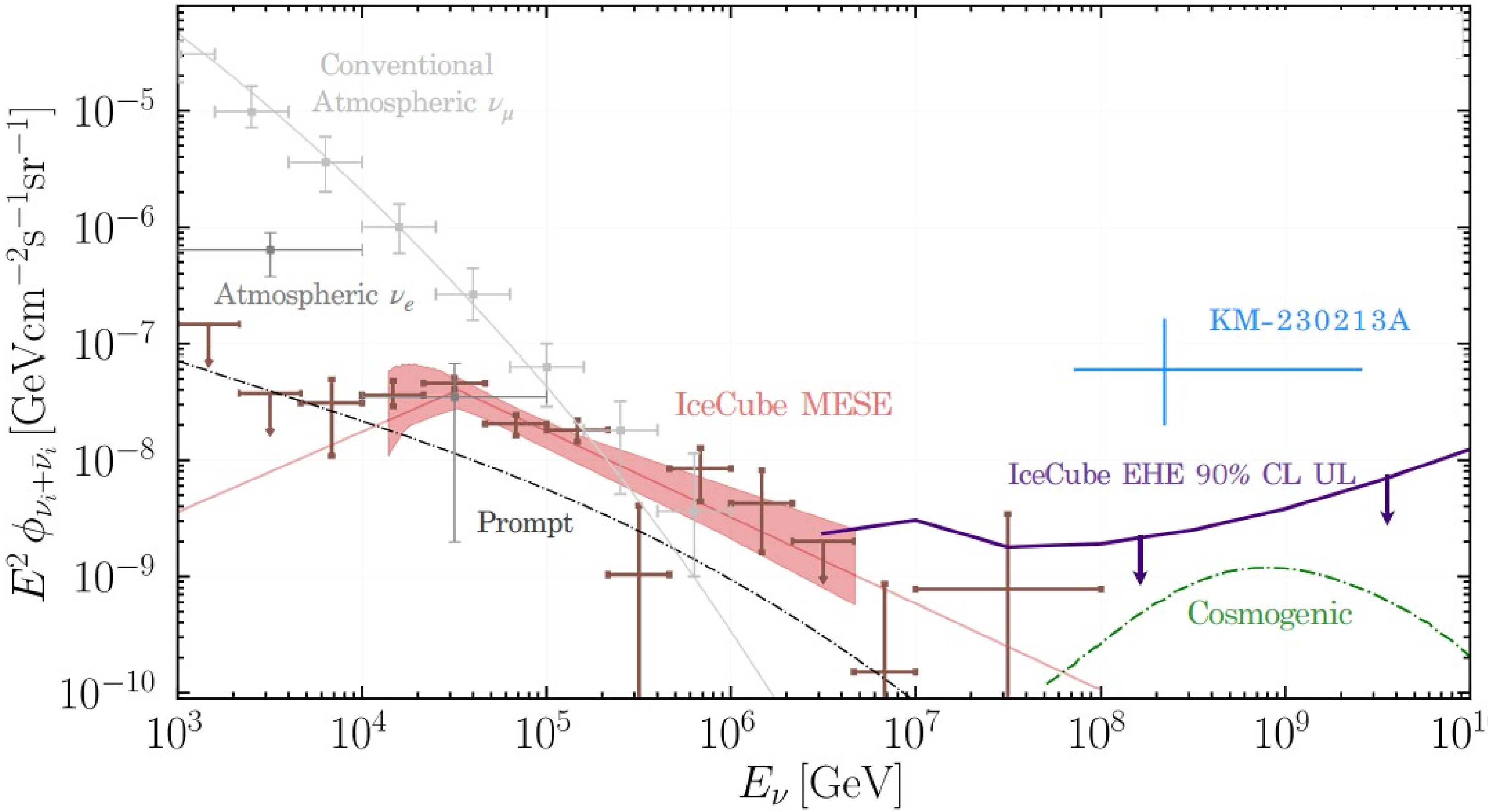


Image Credit: IceCube Collaboration

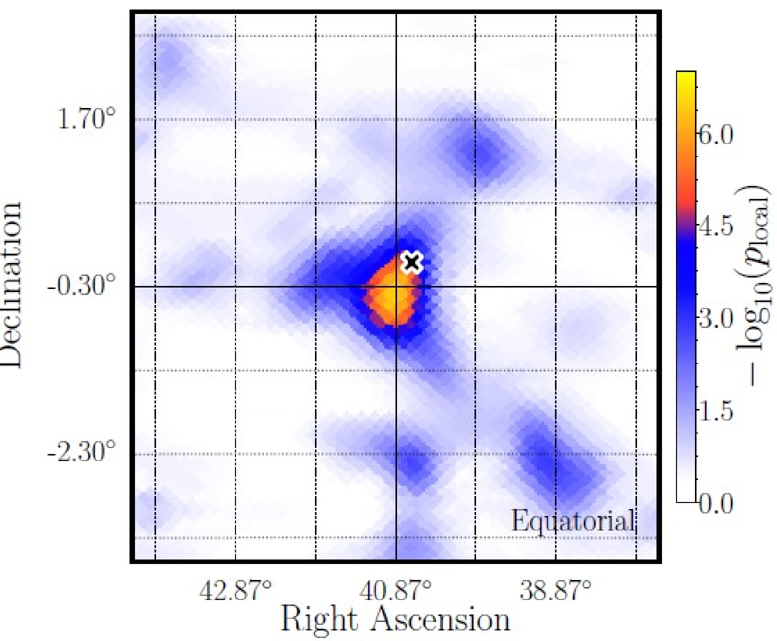
Extragalactic Diffuse Neutrinos



NGC 1068

- Starburst Galaxy
- Seyfert II
- 14 Mpc

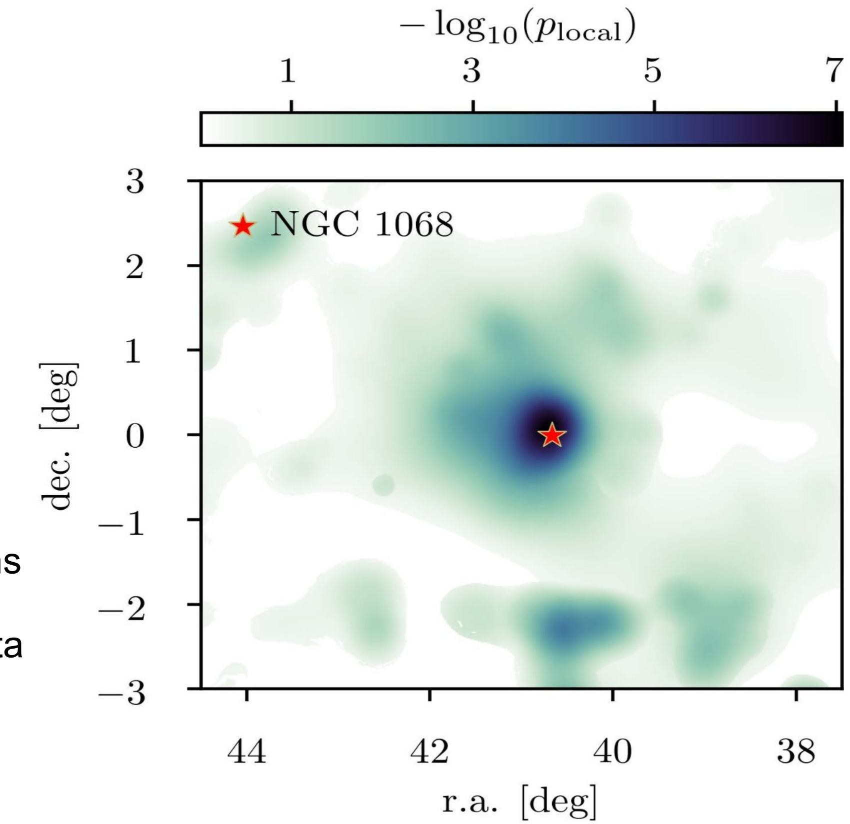
p-value = 0.2% (2.9 σ)



PRL 124, 051103 (2020)

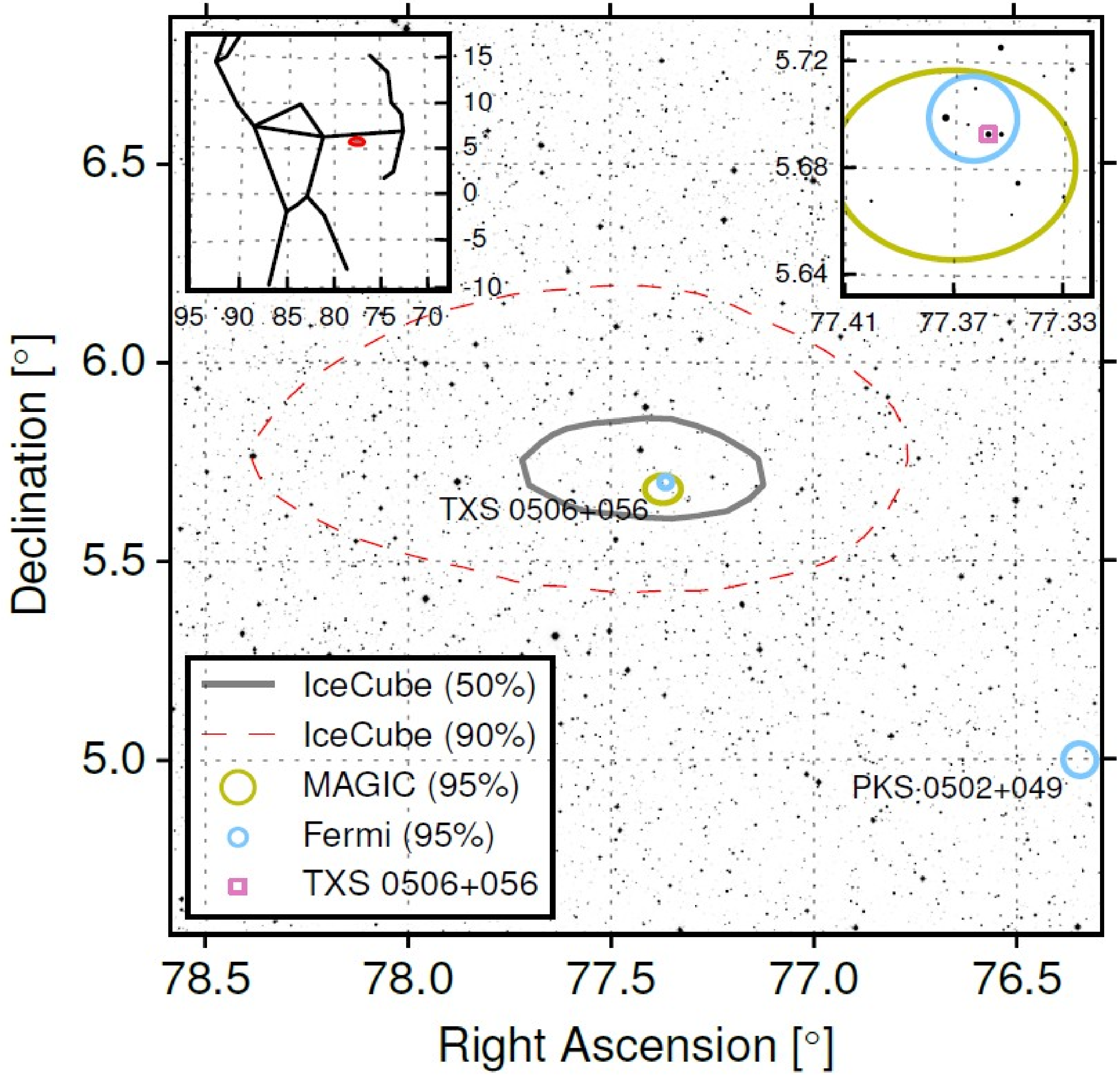
Low Level Data quality improvements (pass 2)
+
Improved reconstructions
+
Additional 2 years of data

P-value = 0.001% (4.2 σ)



Science 378, 6619 (2022)

TXS0506+056



15
10
5
0
-5
-10
95 90 85 80 75 70
5.72
5.68
5.64
77.41 77.37 77.33
TXS 0506+056
PKS 0502+049
IceCube (50%)
IceCube (90%)
MAGIC (95%)
Fermi (95%)
TXS 0506+056
6.5
6.0
5.5
5.0
Declination [°]
78.5 78.0 77.5 77.0 76.5
Right Ascension [°]

Neutrino Sources In The Sky

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

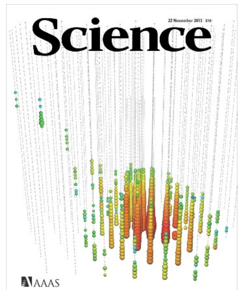
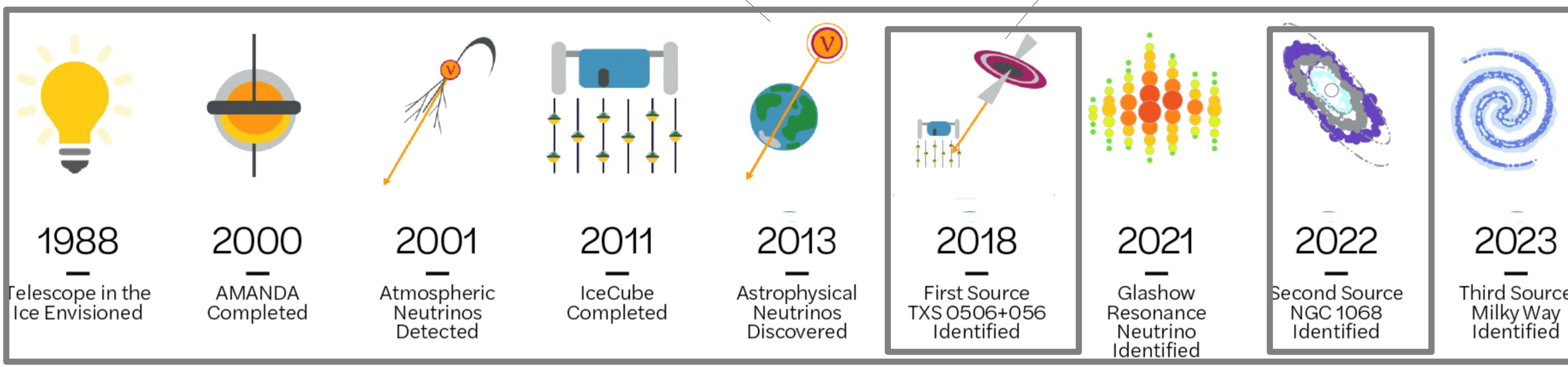


Image Credit: IceCube Collaboration



Why don’t we see more HE neutrino emitting sources?

- What other types emit HE neutrinos?
- Why not gamma-ray bursts?

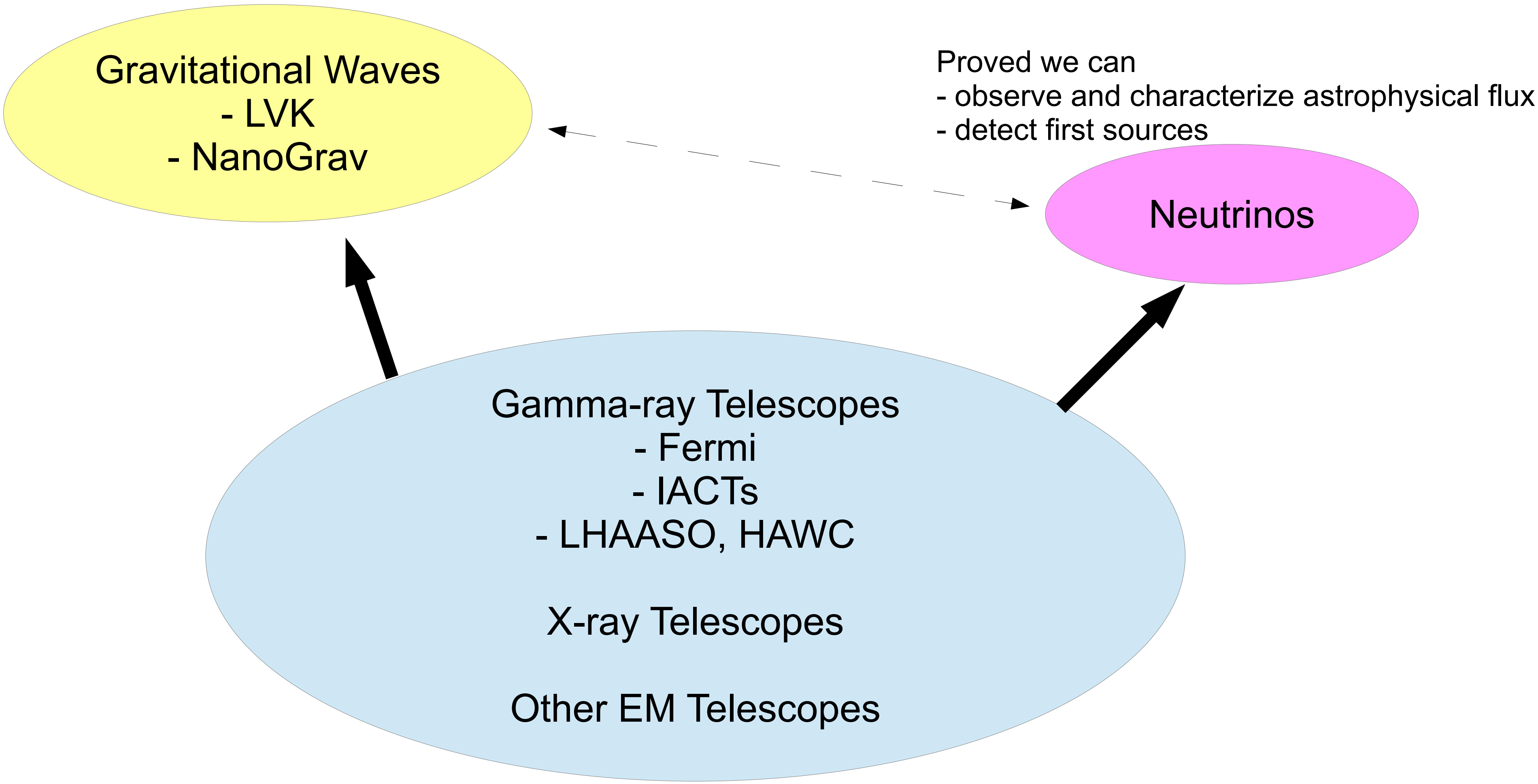
We don't know what source population makes the neutrinos flux

		Upper limit in diffuse flux	notes
2LAC Blazars	All blazars	~ 7%	862 sources, E-2.5
	FSRQs	~5%	310 sources, E-2.5
	LSPs BL Lacs	~5%	68 sources, E-2.5
	ISP/HSP	~6%	301 sources, E-2.5
3FHL Blazars	All blazars	~17%	745 northern sources, E-2
	HSP BL Lacs	~15%	356 northern sources, E-2
	LSP/ISP BL Lacs	~12%	212 north sky sources, E-2
	FSRQs	~17 %	101 north sky sources, E-2
Nearby Starburst Galaxies		~ 8%	127 sources, E-2
Galactic Sources	Young SNR	~ 5%	30 sources no PWN or MC, E-2
	Young PWN	~ 3%	10 sources with no MC, E-2
GRBs		~1%	506 bursts, E-2 to -2.7

ApJ vol. 835 (2017), Astrophys.J. 796:10 (2014), ApJ, 805, L5 (2015), PoS-ICRC2019-916

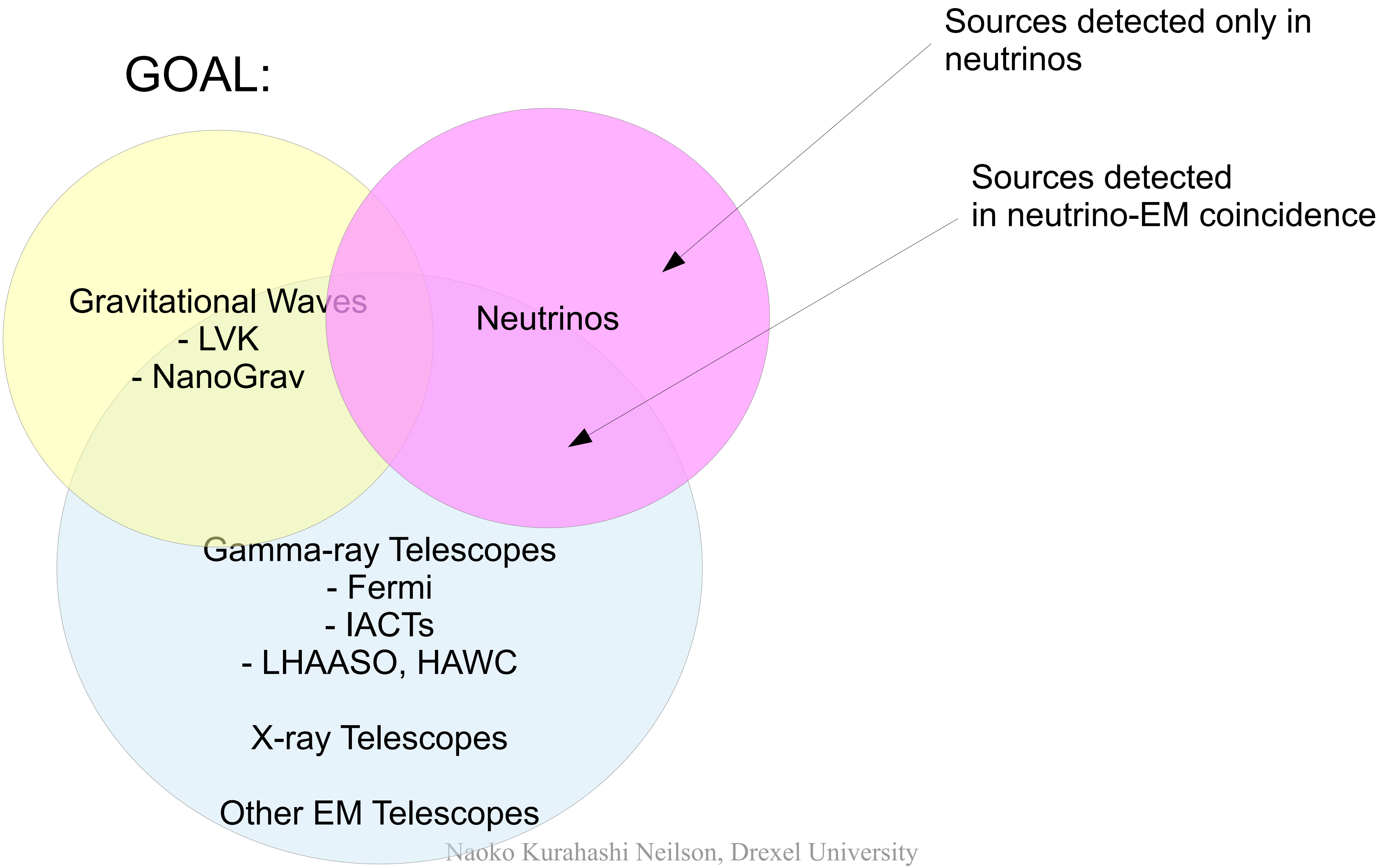
Multi-Wavelength Astronomy

Multi-Messenger Astronomy



Future Multi-Messenger Astronomy

GOAL:

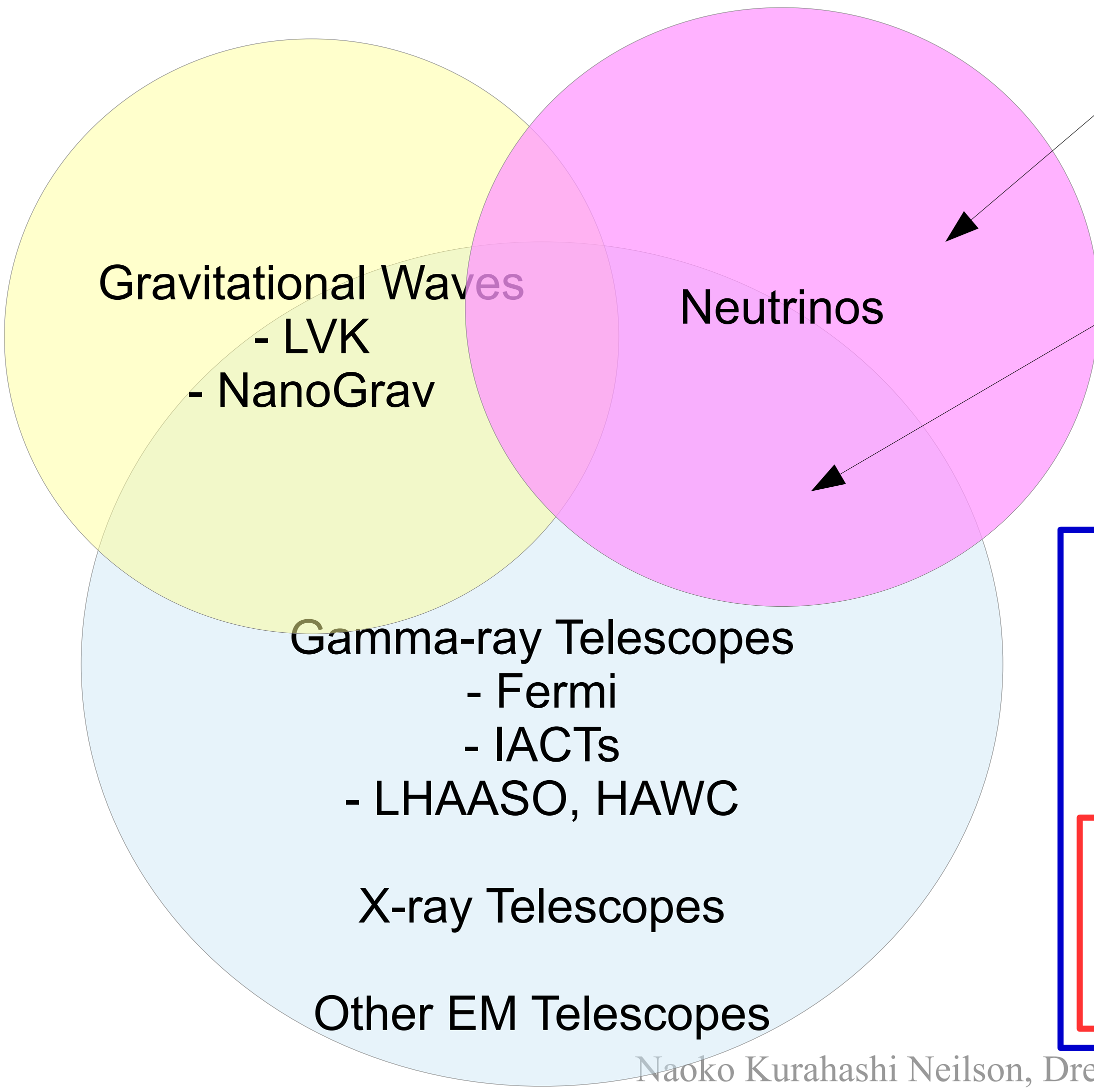


Future Multi-Messenger Astronomy

GOAL:

Sources detected only in neutrinos

Sources detected in neutrino-EM coincidence



EM: wide range of telescopes that target

- different wavelengths
- different FOV

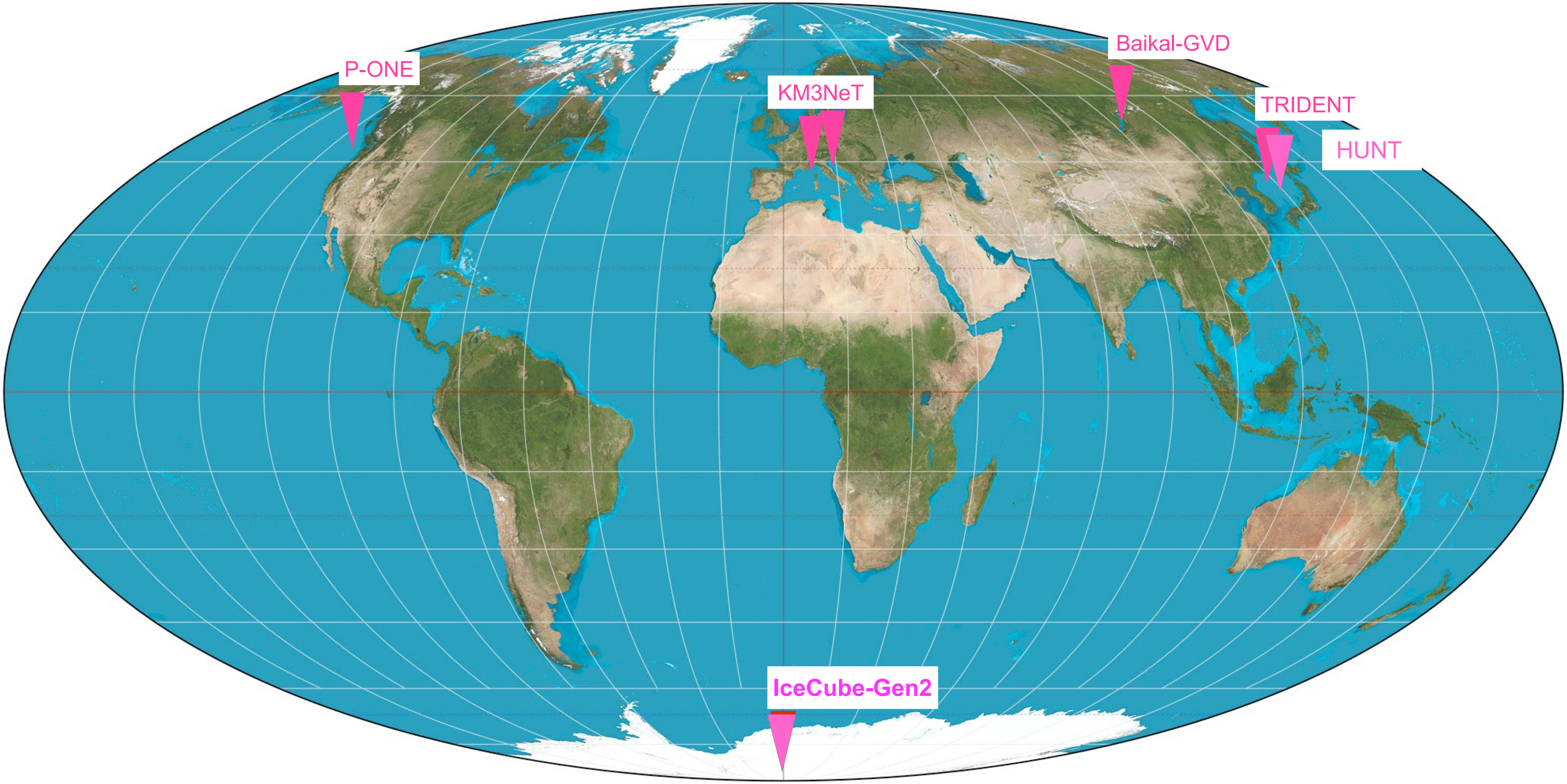
We need wide ranges of Neutrino Telescopes too!

3 Priorities to Achieve this Goal

- More Neutrino Telescopes
- Complementary Location
- Complementary Technology

Priority: Complementary Locations

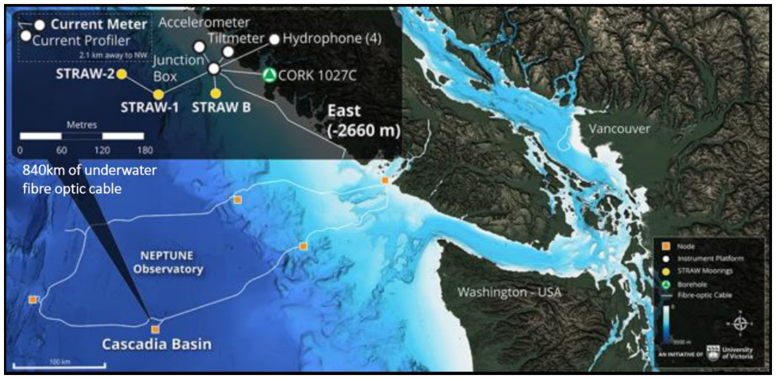
(Optical HE) Neutrino Telescopes

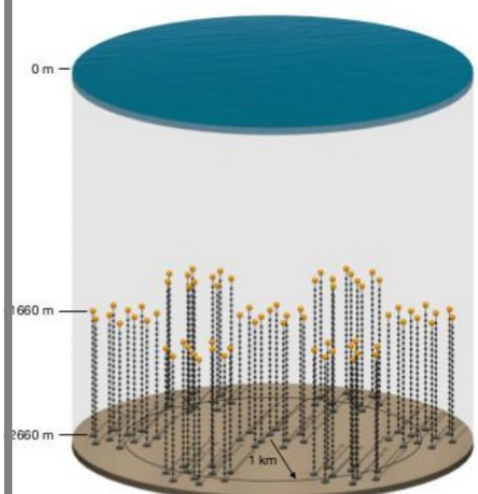


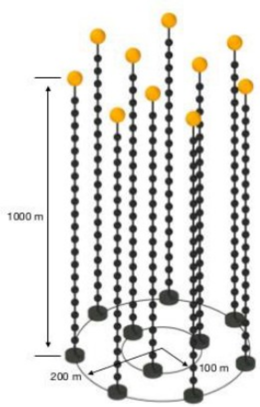
New Hemisphere New Comers

P-ONE
Pacific Ocean Neutrino Explorer

Leverage existing facilities





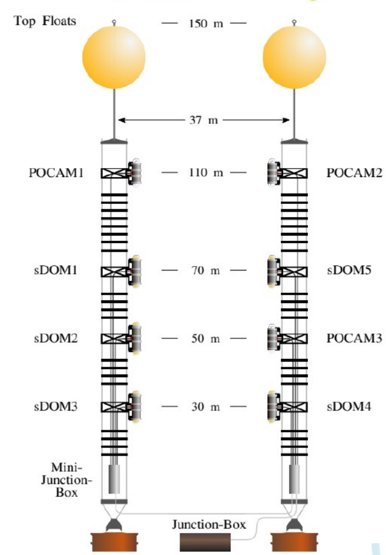


Images: courtesy P-ONE collaboration

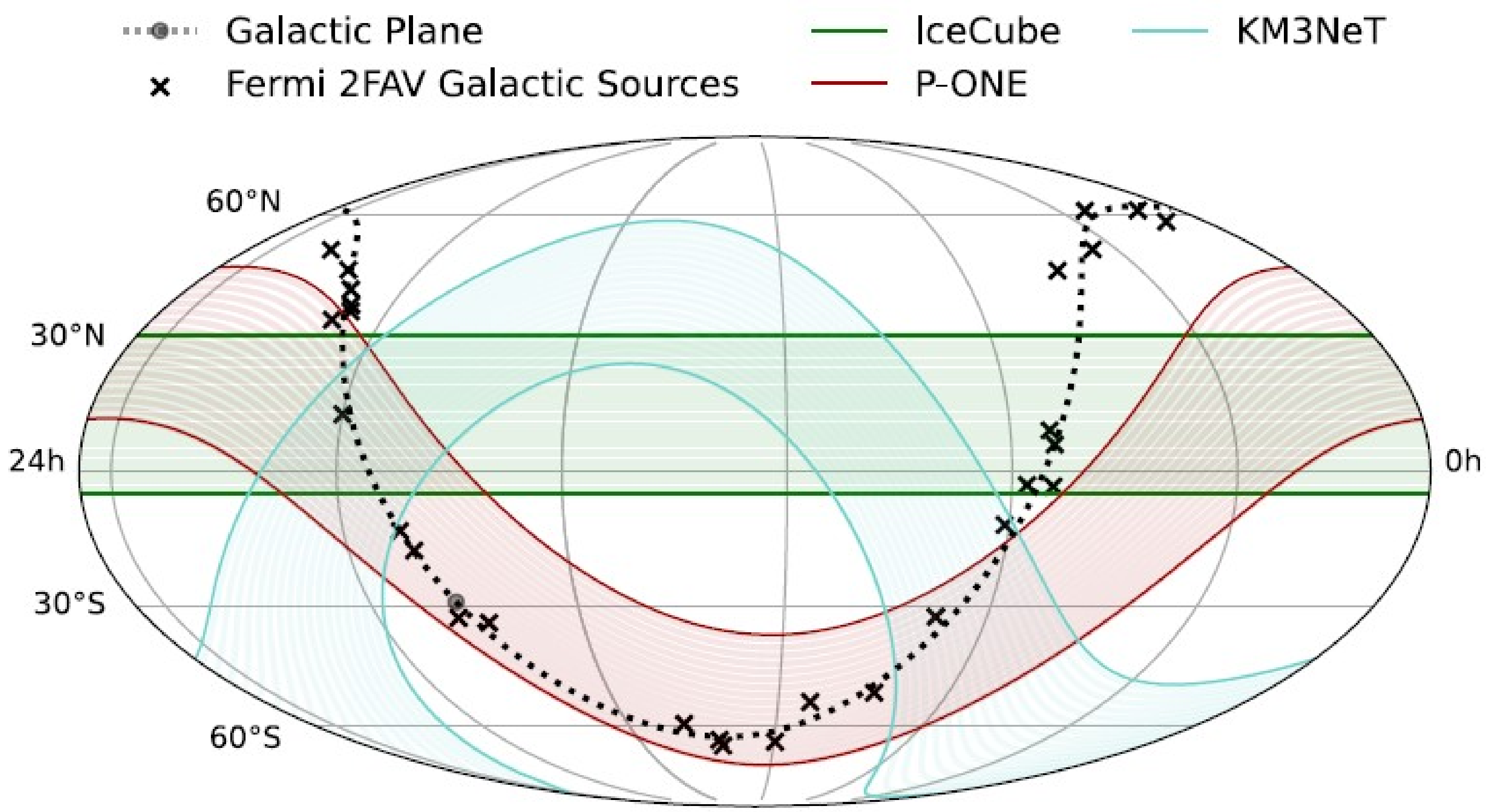
Huge telescopes in the South China Sea

Pathfinder strings deployed and recovered

2019 JINST 14 P02013



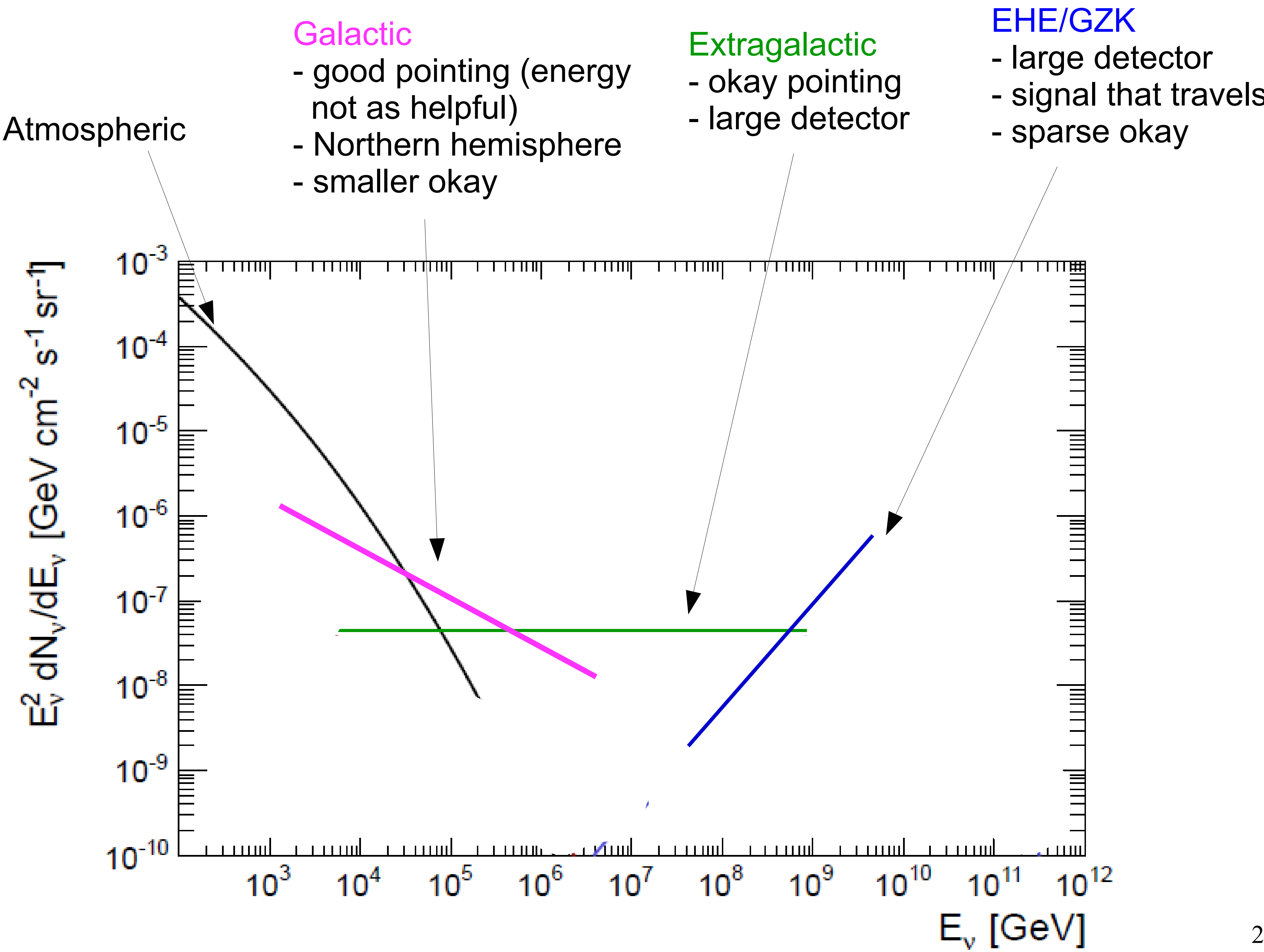
Complementary Peak Sensitivity
→ Important for Transients



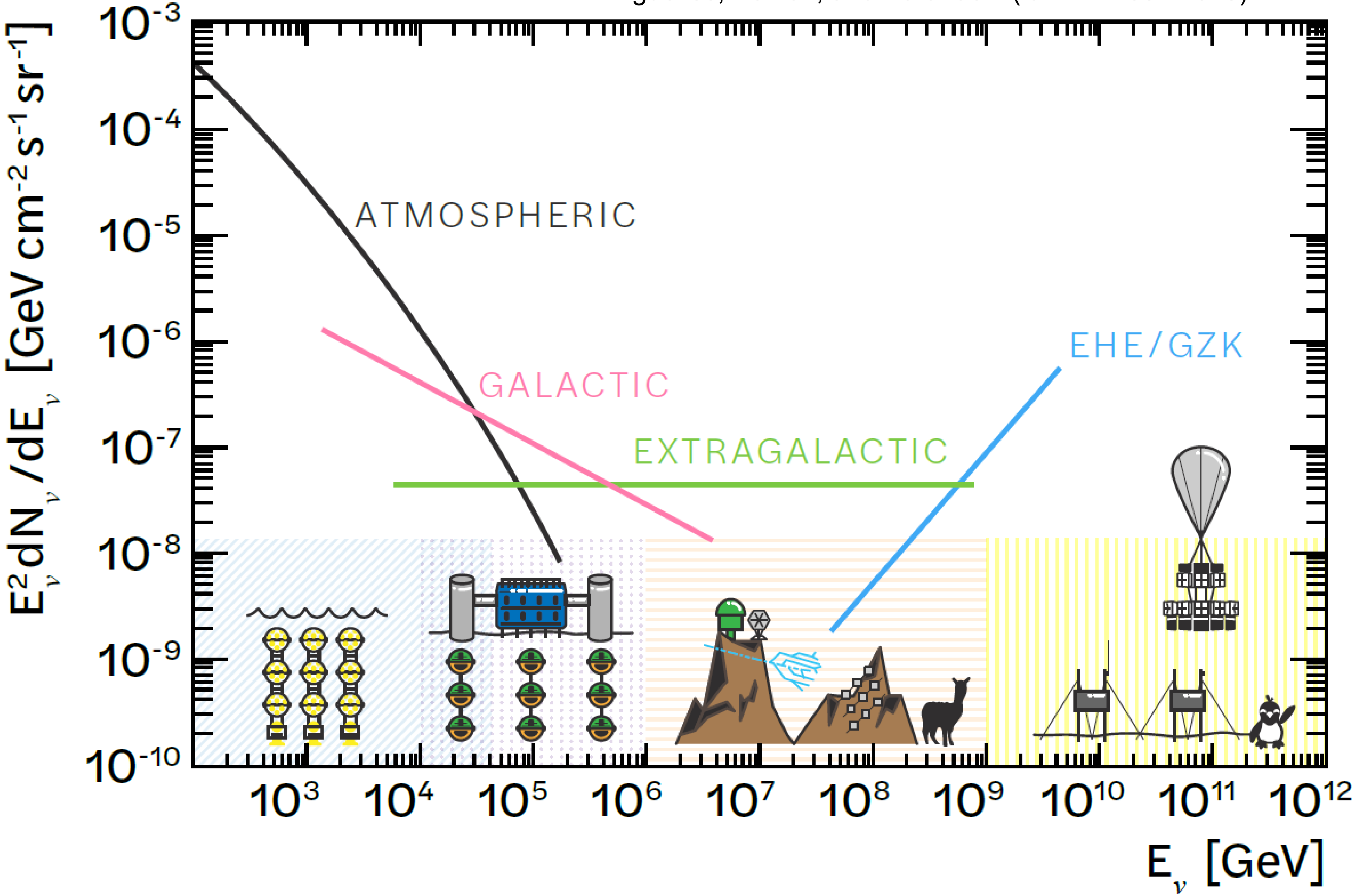
Courtesy: P-ONE, L. Schumacher (Erlangen), S. Sclafani (Univ of Maryland)

Priority: Complementary Technology

Diverse Neutrino Astronomy Targets



Argüelles, Halzen, and Kurahashi (arXiv:2405.17623)

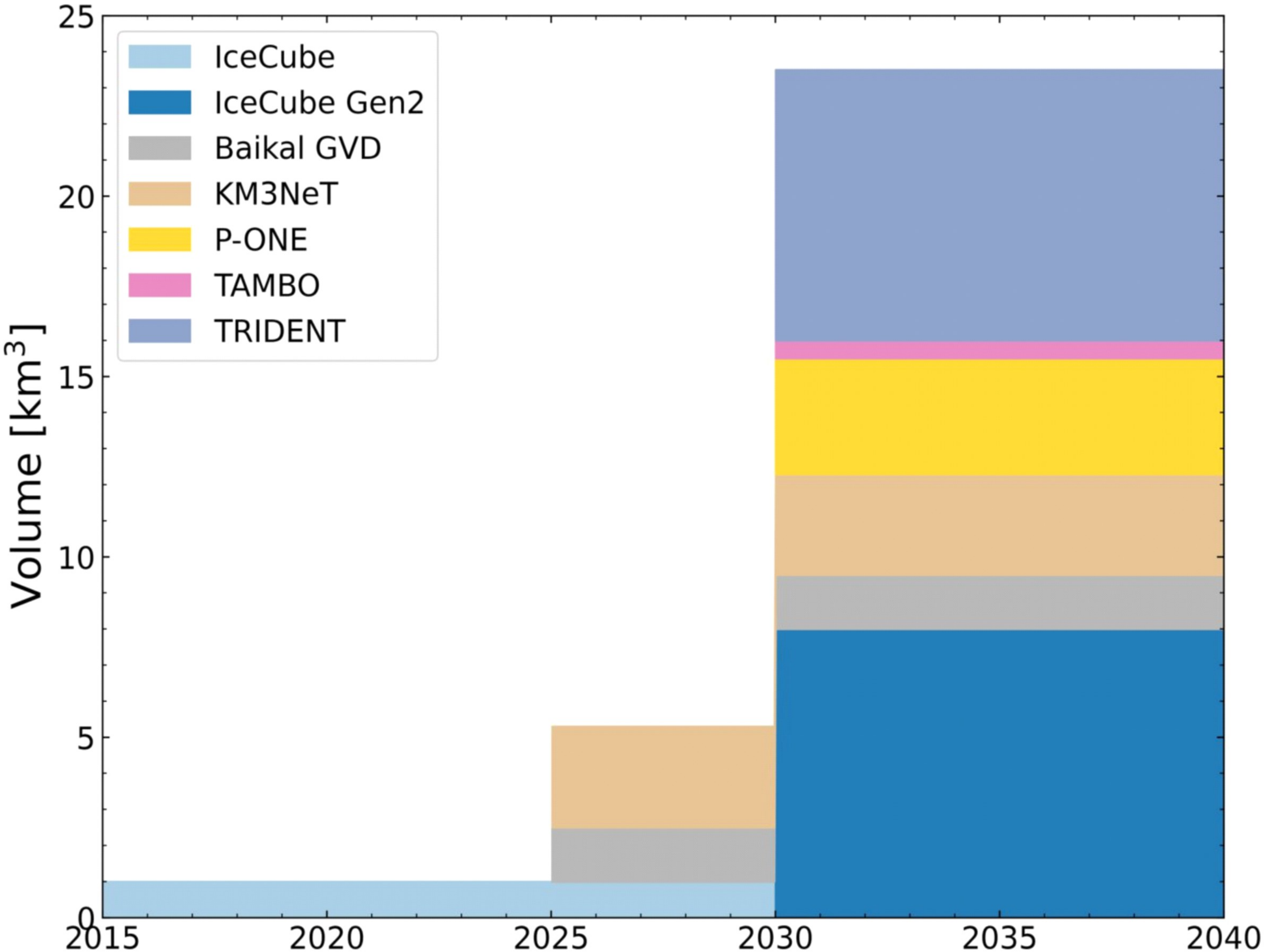


Diverging Optimizations
→ Good Sign of a Maturing Field

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

Expanding Volume of Neutrino Telescopes



Courtesy: Q. Liu (Queens) ICRC2023

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

Naoko Observing Stars and Galaxies (2012) South Pole

Conclusions

Present Neutrino Astronomy

- The Universe emits high-energy neutrinos
- So does our Galaxy

Future Neutrino Astronomy

- Needs to become a strong partner in multi-messenger astronomy
- Need for more neutrino telescopes to identify more sources

Backup Slides

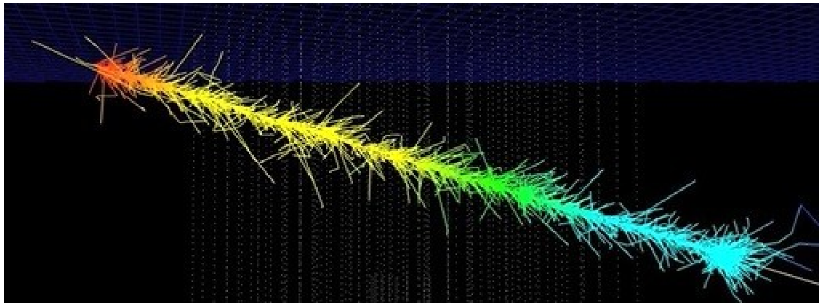
Diverse Neutrino Astronomy Targets

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

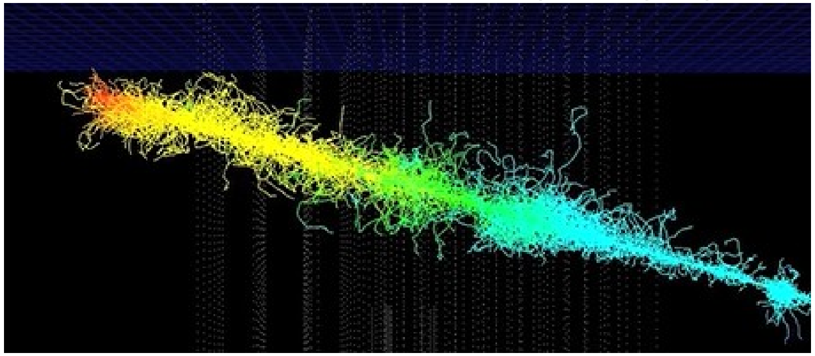
Extragalactic
- good pointing
- large detector

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

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

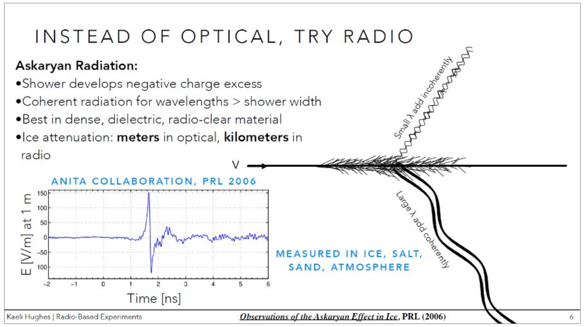


Courtesy: Claudio Kopper (Erlangen)



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

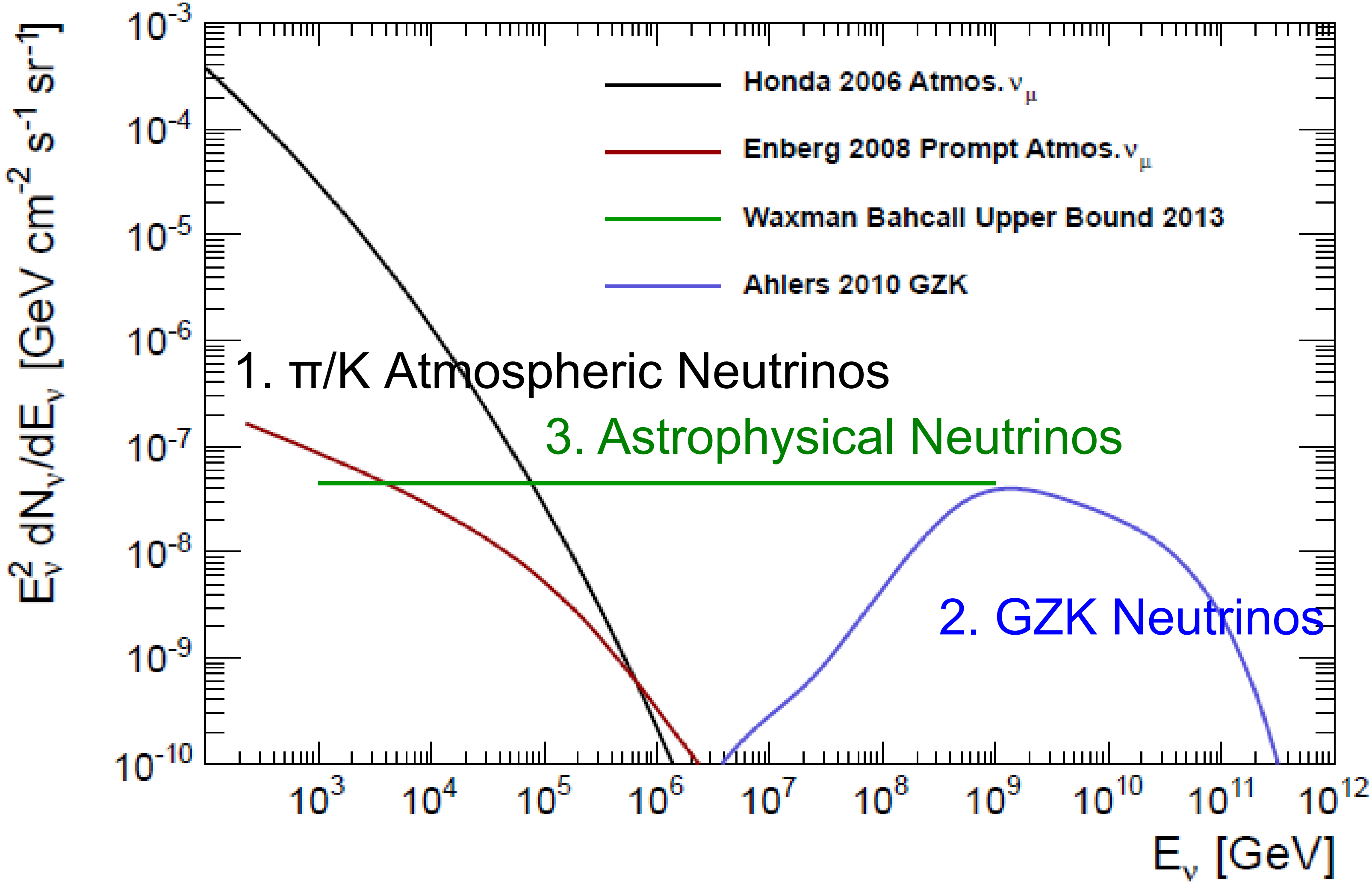
Radio
- Absorption ✓✓ → Can make detector very large
- Energy threshold very high



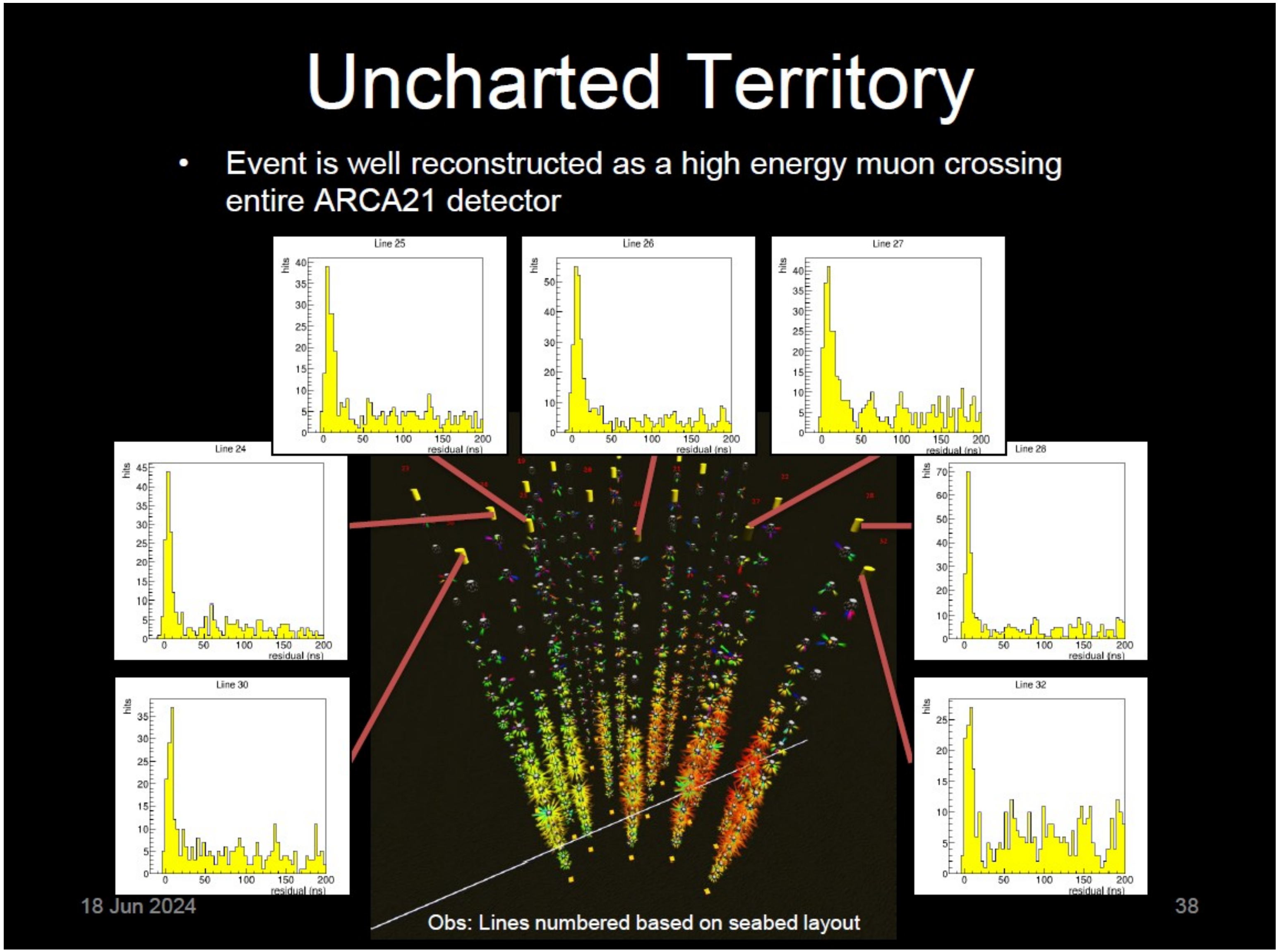
See talk by K. Hughes

AGN Unification

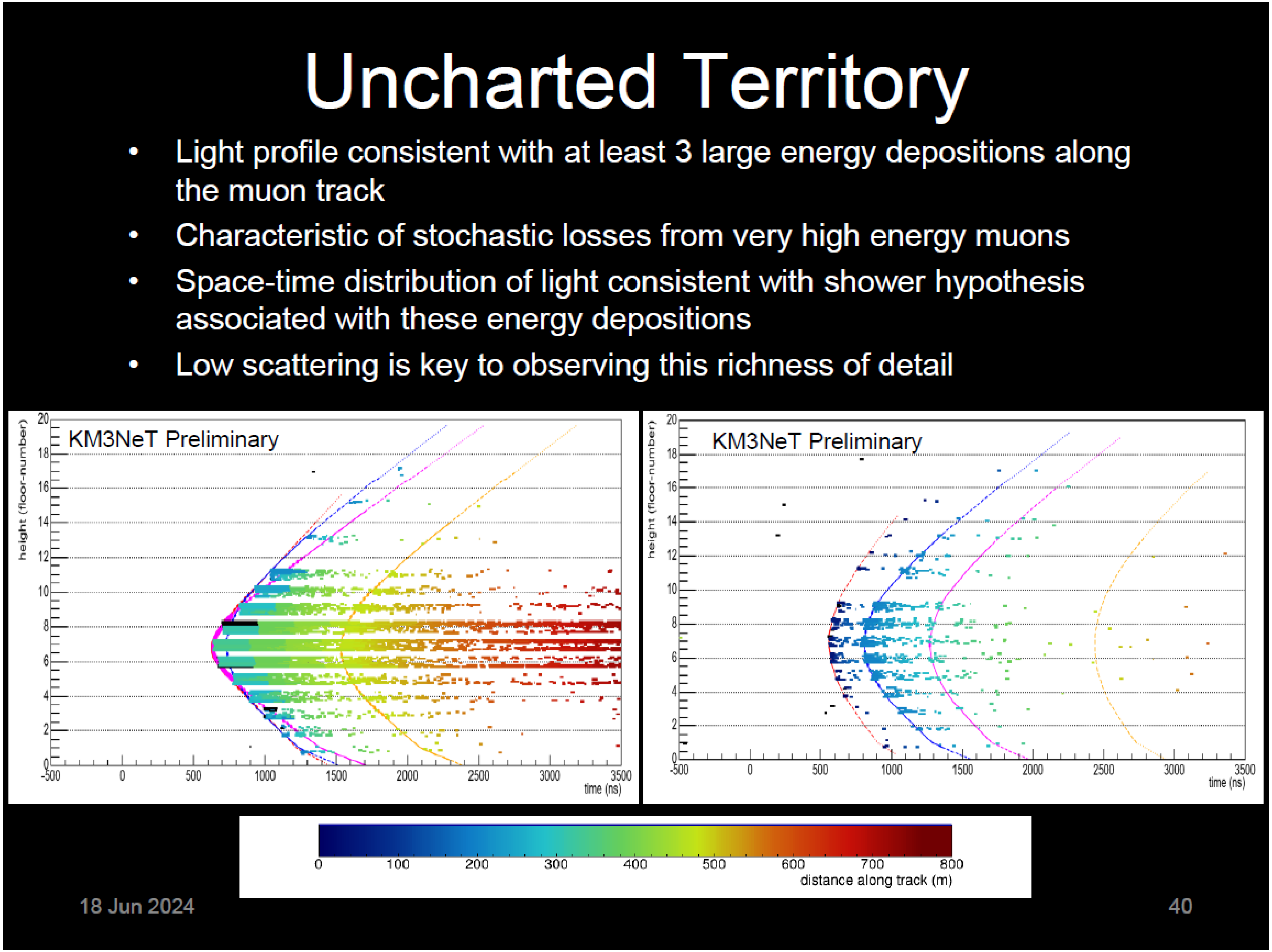
The Predicted Neutrino Spectrum



Recent News



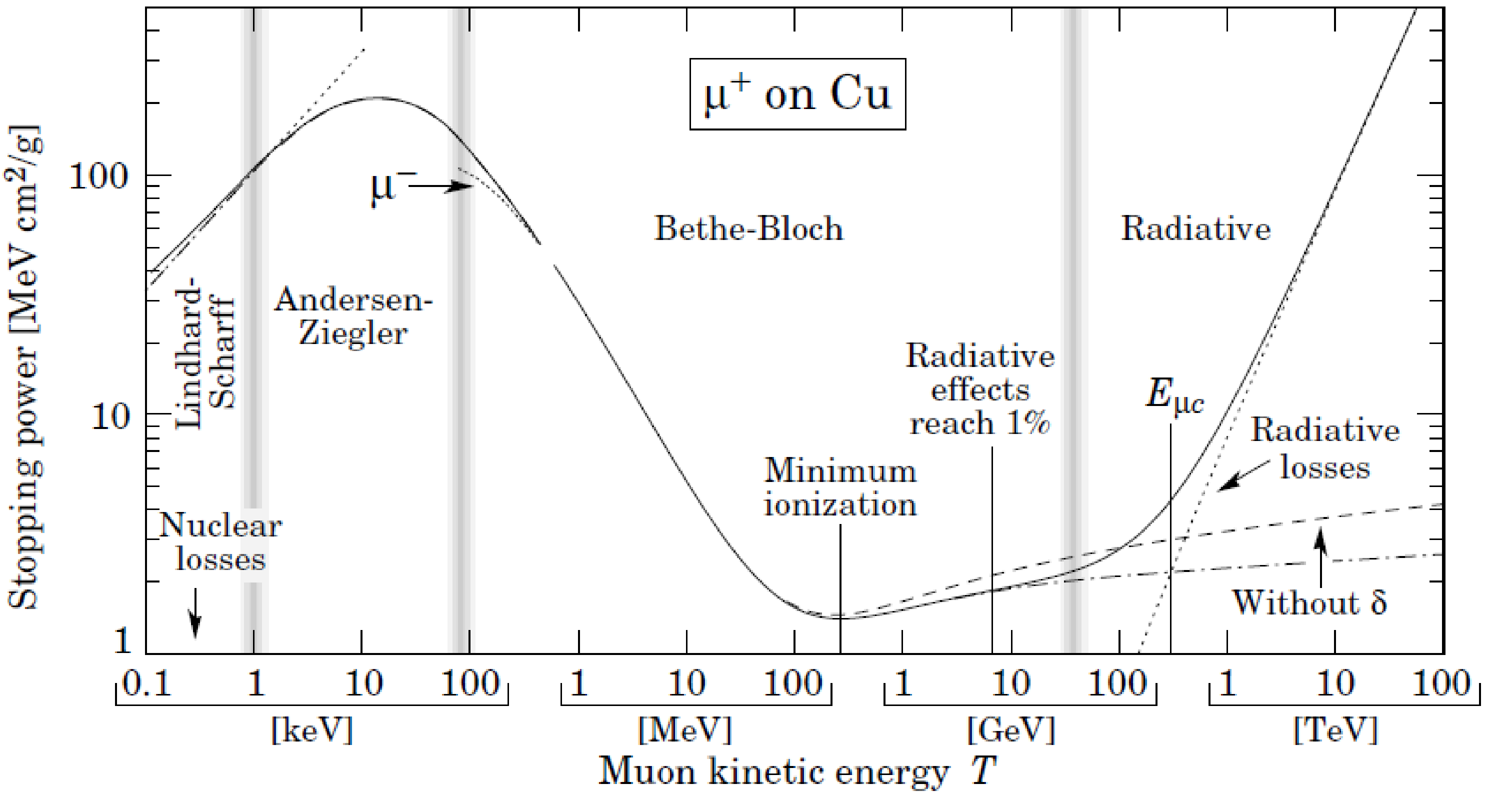
Slide from J. Coelho (KM3NeT)



Slide from J. Coelho (KM3NeT)

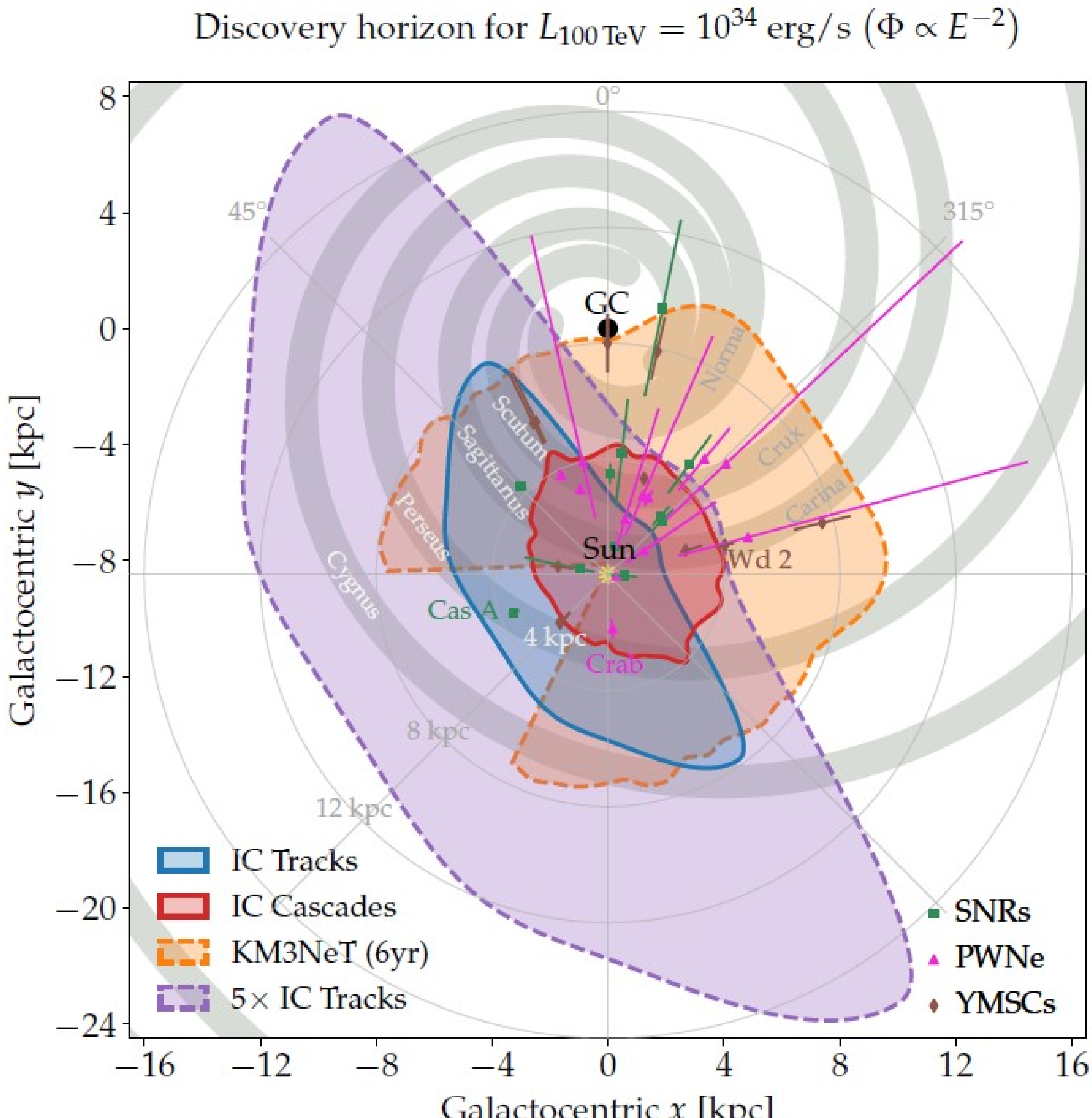
Bethe-Bloch Reminder

Muon Stopping Power and Range (PDG)



Radiative loss regime – stochastic energy loss

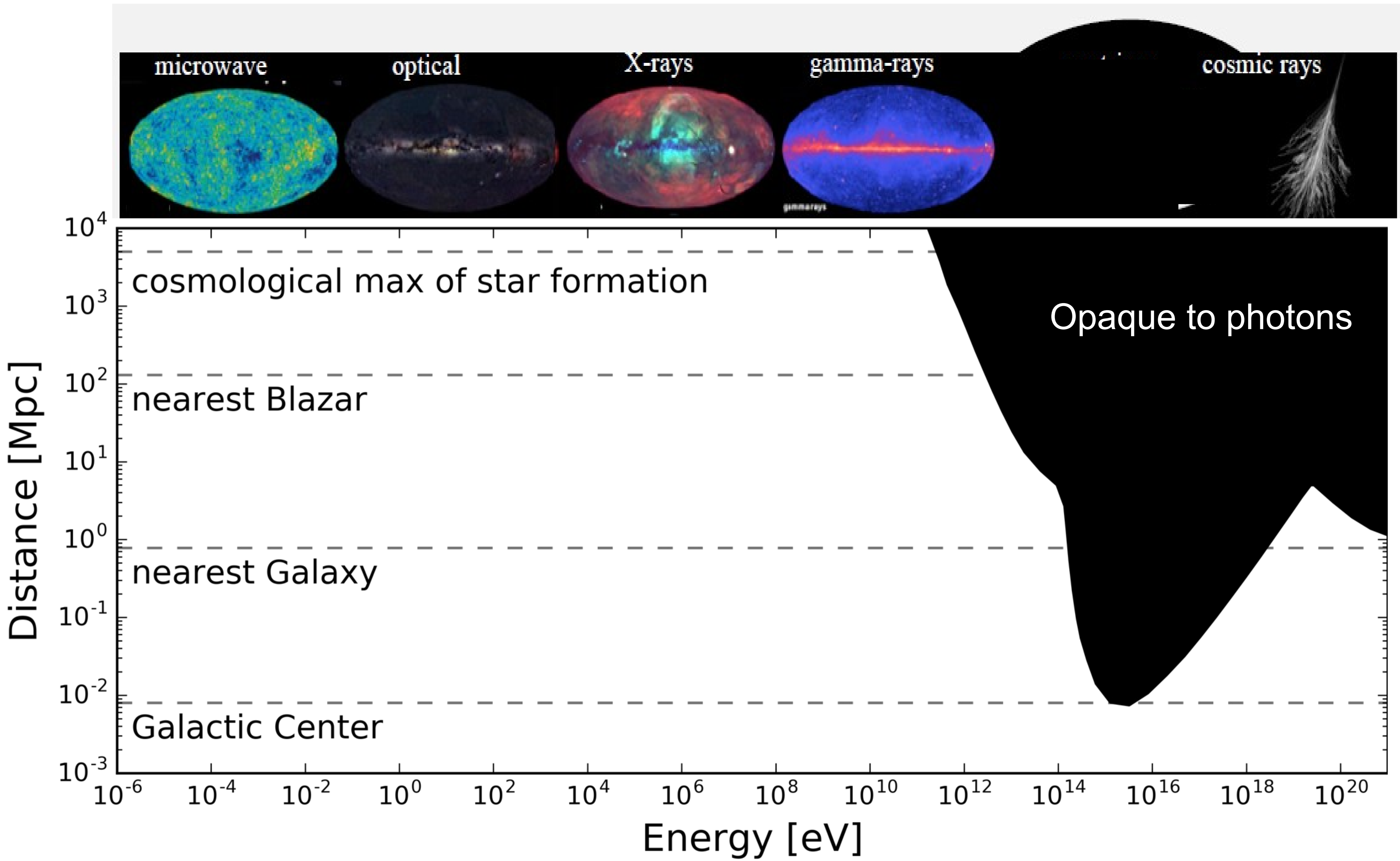
Galactic Neutrino Astronomy Needs



Phys. Rev. D 109, 043007 (2024)

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

High-Energy Astronomy – Cosmic Rays, γ rays, and neutrinos



Naoko Kurahashi Neilson, Drexel University

IceCube is a data-analysis driven experiment

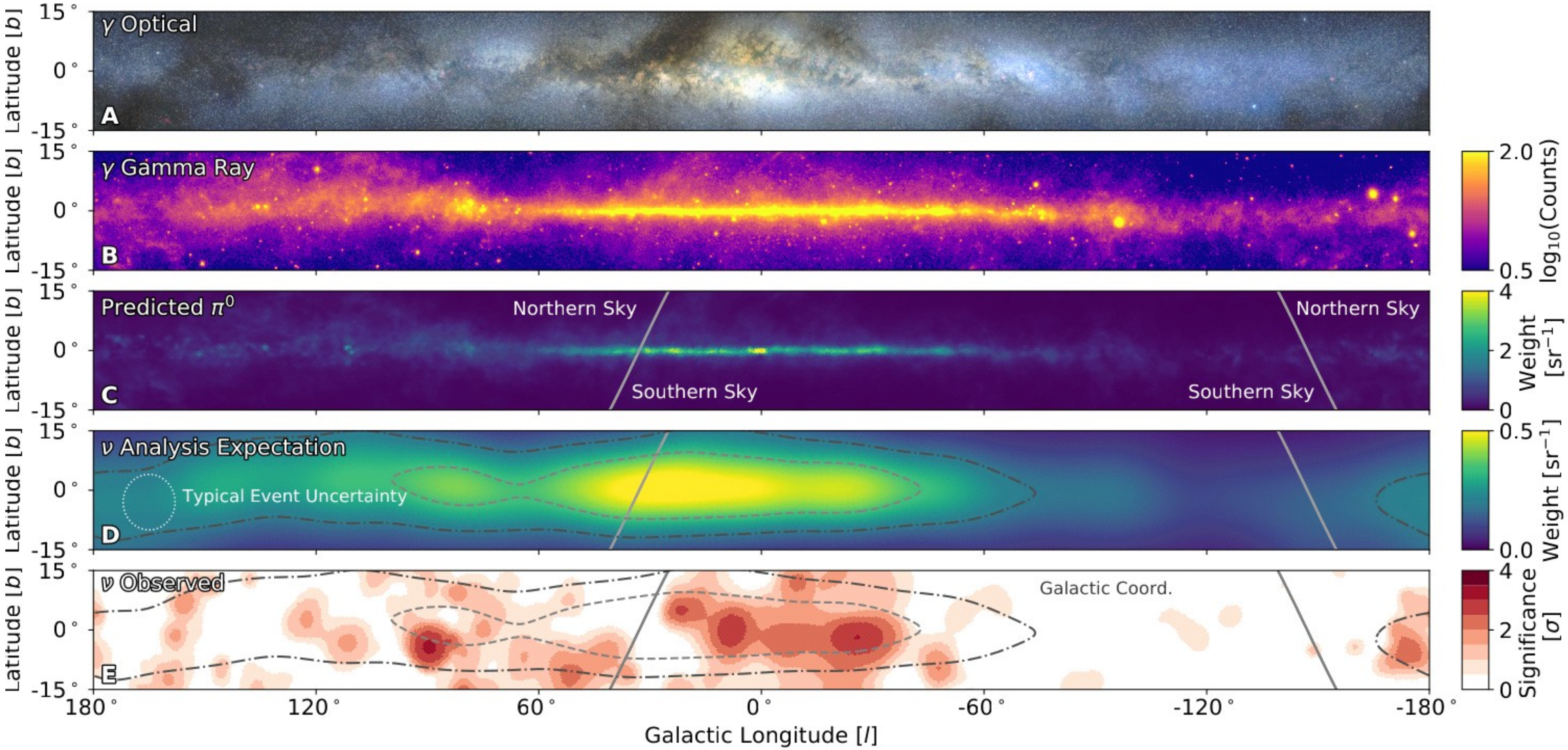
Event Rates:
For every 1 Astrophysical Neutrino,
~10^9 Atmospheric Muons → ~100% Tracks
~10^3 Atmospheric Neutrinos → ~95% Tracks

IceCube Analyses
- need to win the fight against background!
- need to win against trials!*

*word of caution: you can see anything you want to see in IceCube data if you're not careful about trials

2023 Result!

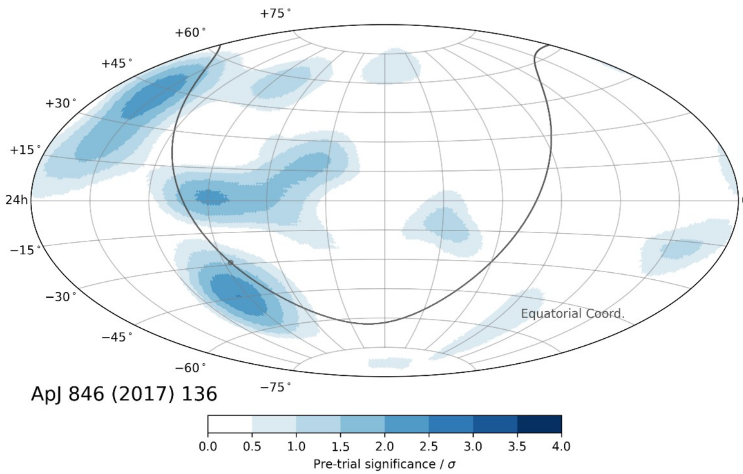
4.5σ
(0.00038%)



Science 380 (2023) 1338

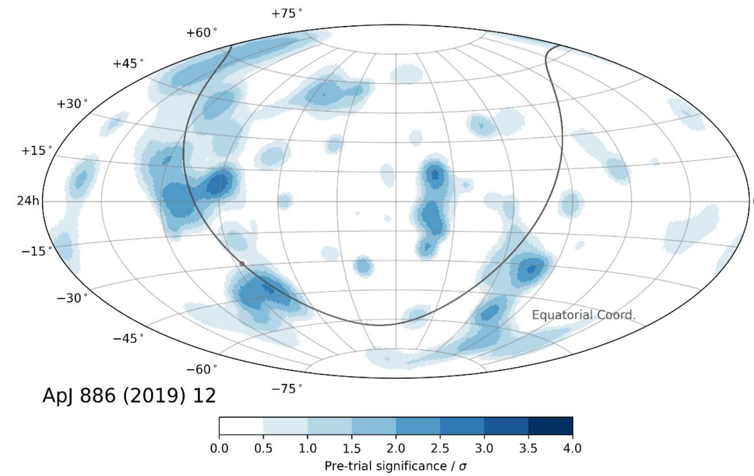
Improving Astronomy with Cascade Events

Skymap from 2017 paper



ApJ 846 (2017) 136

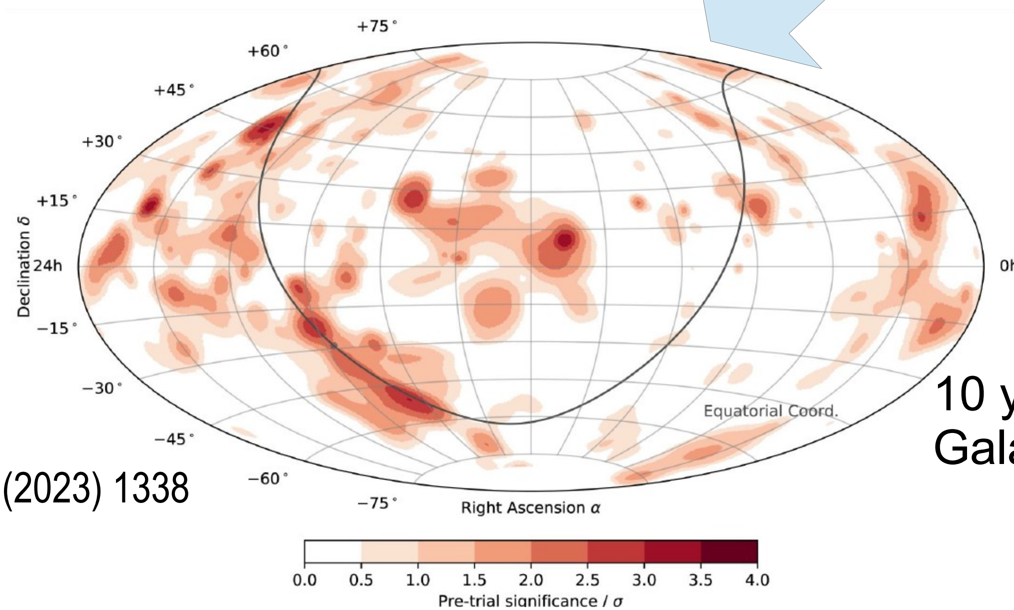
Skymap from 2019 paper



ApJ 886 (2019) 12

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

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



Science 380 (2023) 1338

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