Galactic Neutrinos
- An Experimental Perspective -

Cosmic Rays and Neutrinos in
the Multi-Messenger Era

December 12th, 2024
APC Lab, Paris, France

Naoko Kurahashi Neilson (Drexel University)

First a Personal Story,
then IceCube,
then ANTARES KM3NeT Baikal GVD,
then the field,
then the future

First Galactic Plane analysis from IceCube (IC40+59)

Discussion of "guaranteed neutrinos"

But the backgrounds!

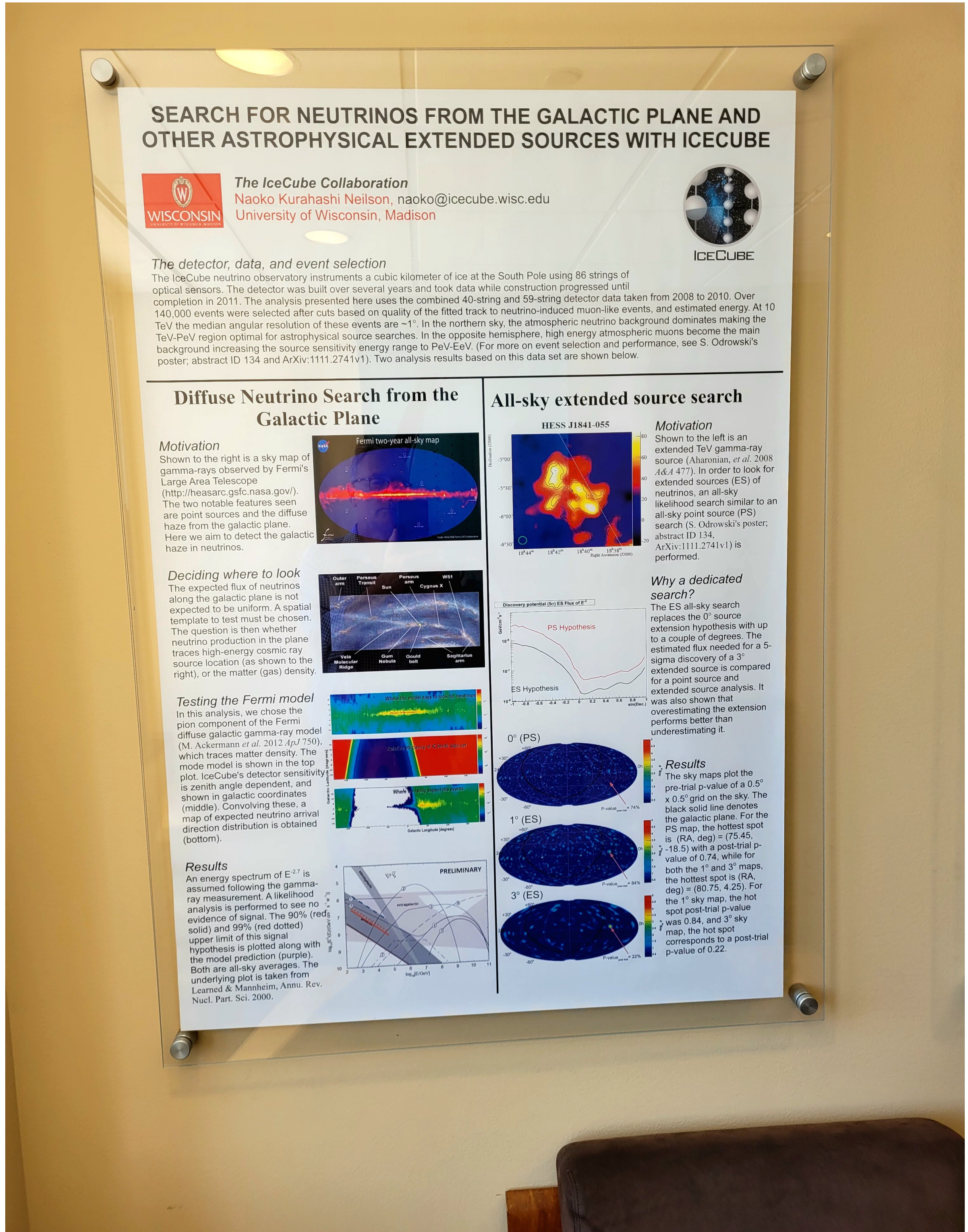
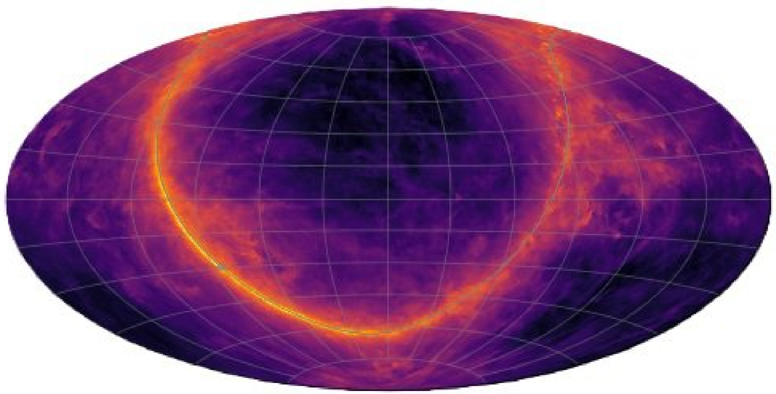
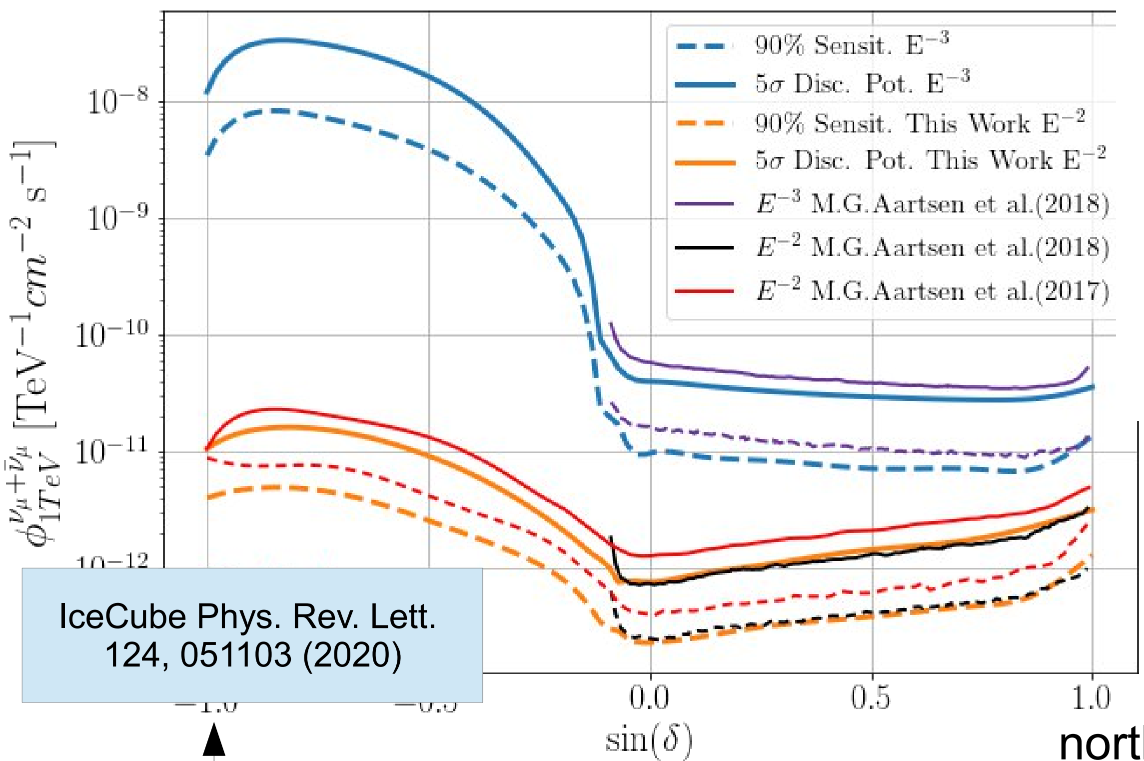


Photo:
Jim Madsen

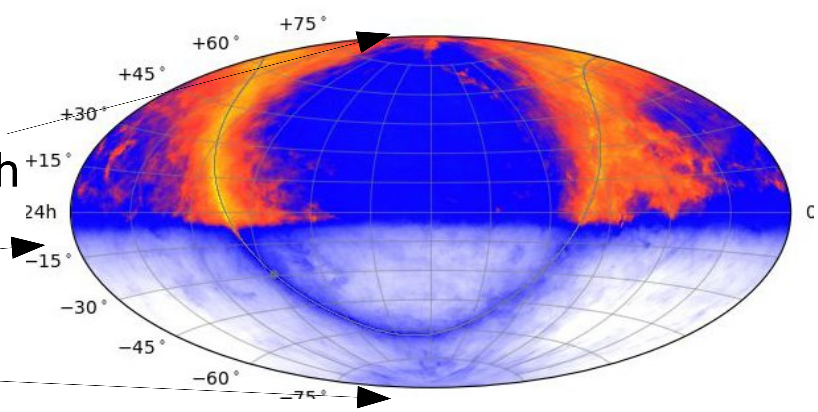
Backgrounds In IceCube

Data from Fermi-LAT (2012) ApJ 750 3





IceCube Phys. Rev. Lett. 124, 051103 (2020)

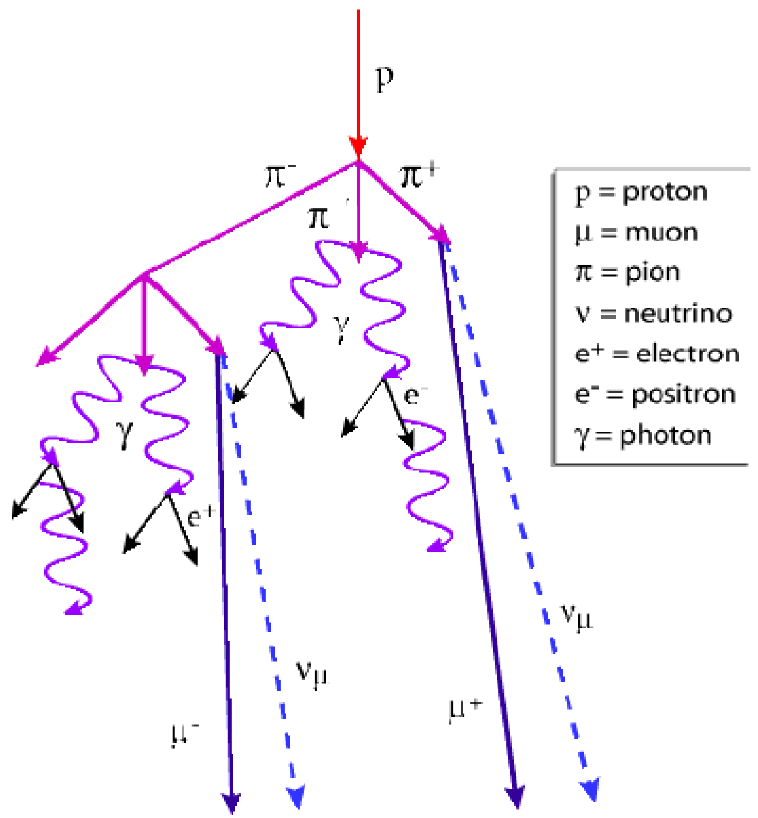


north

south

horizon

Background Domination



Backgrounds to first order are all muons

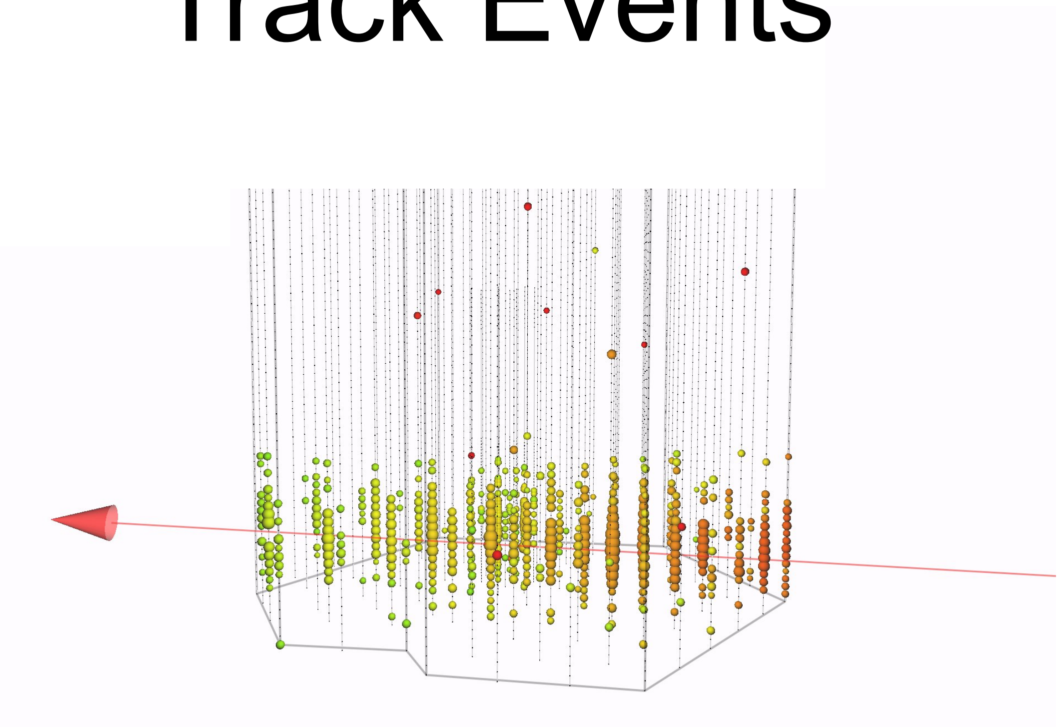
Muons make tracks, not cascades

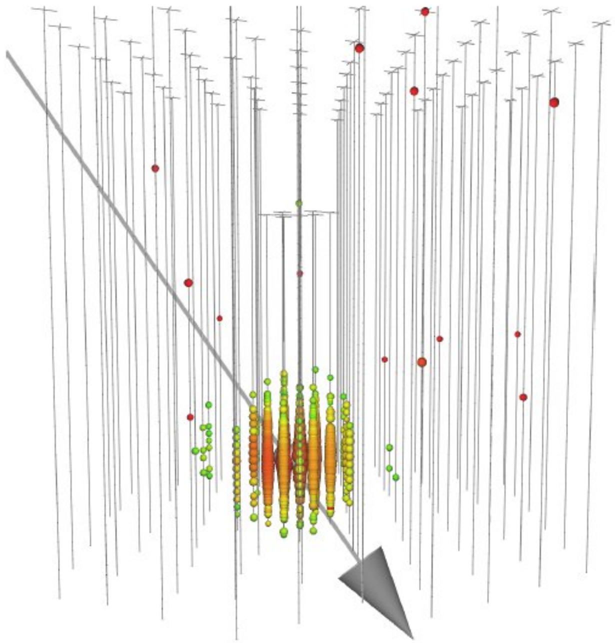
Background Rates:

Atmospheric Muons > 10^9 x signal rate
Atmospheric Neutrinos > 10^3 x signal rate

Track Events

Cascade Events





@ 100 TeV
Angular Resolution: < 1°
Energy Resolution: ~ factor of 2

@ 100 TeV
Angular Resolution: > 10°
Energy Resolution: 10%

Phys. Rev. Lett. 124, 051103 (2020)

Why not search sources with cascade events?

Pros

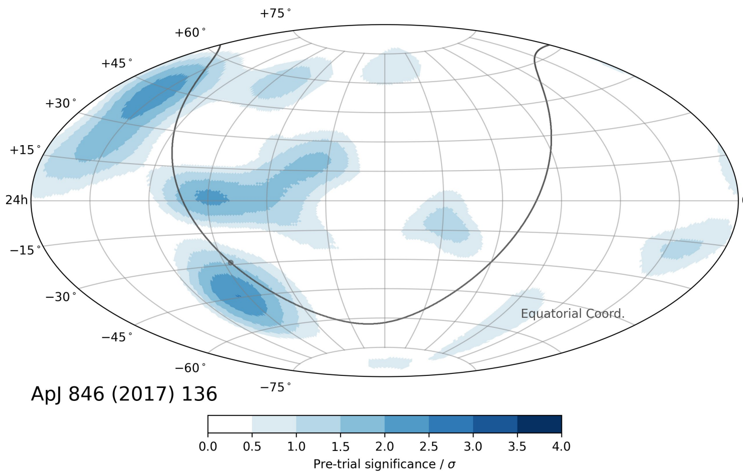
- Suppressed background
- Lower energy threshold
- Flavor ratio

Cons

- Inferior pointing

Improving Astronomy with Cascade Events

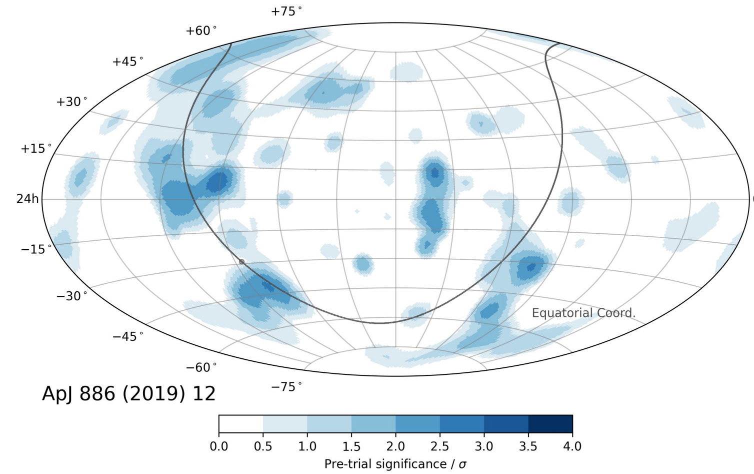
Skymap from 2017 paper



ApJ 846 (2017) 136

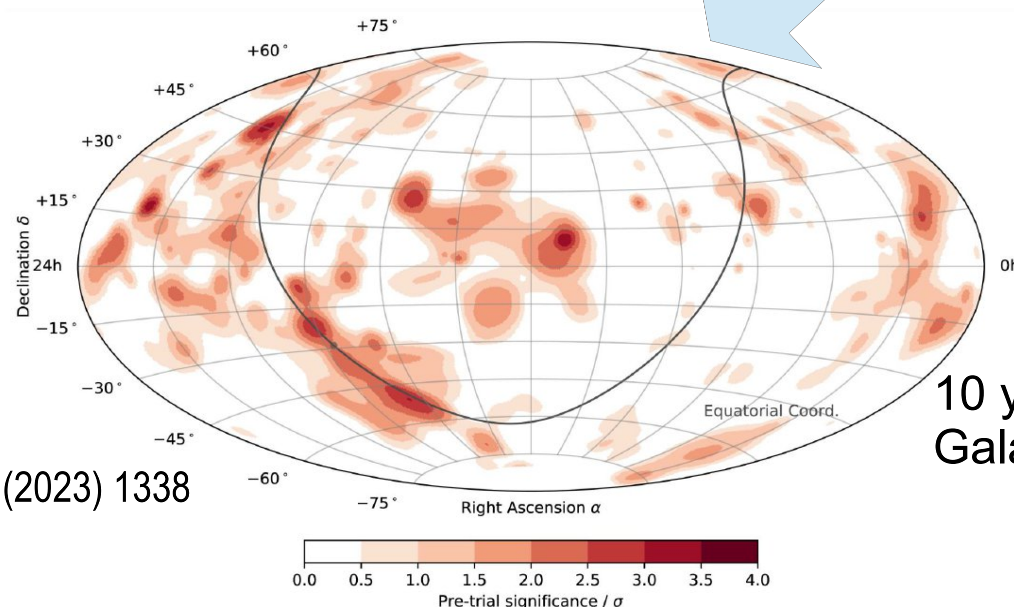
2 years of data
Galactic Plane p-value: 65%

Skymap from 2019 paper



ApJ 886 (2019) 12

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



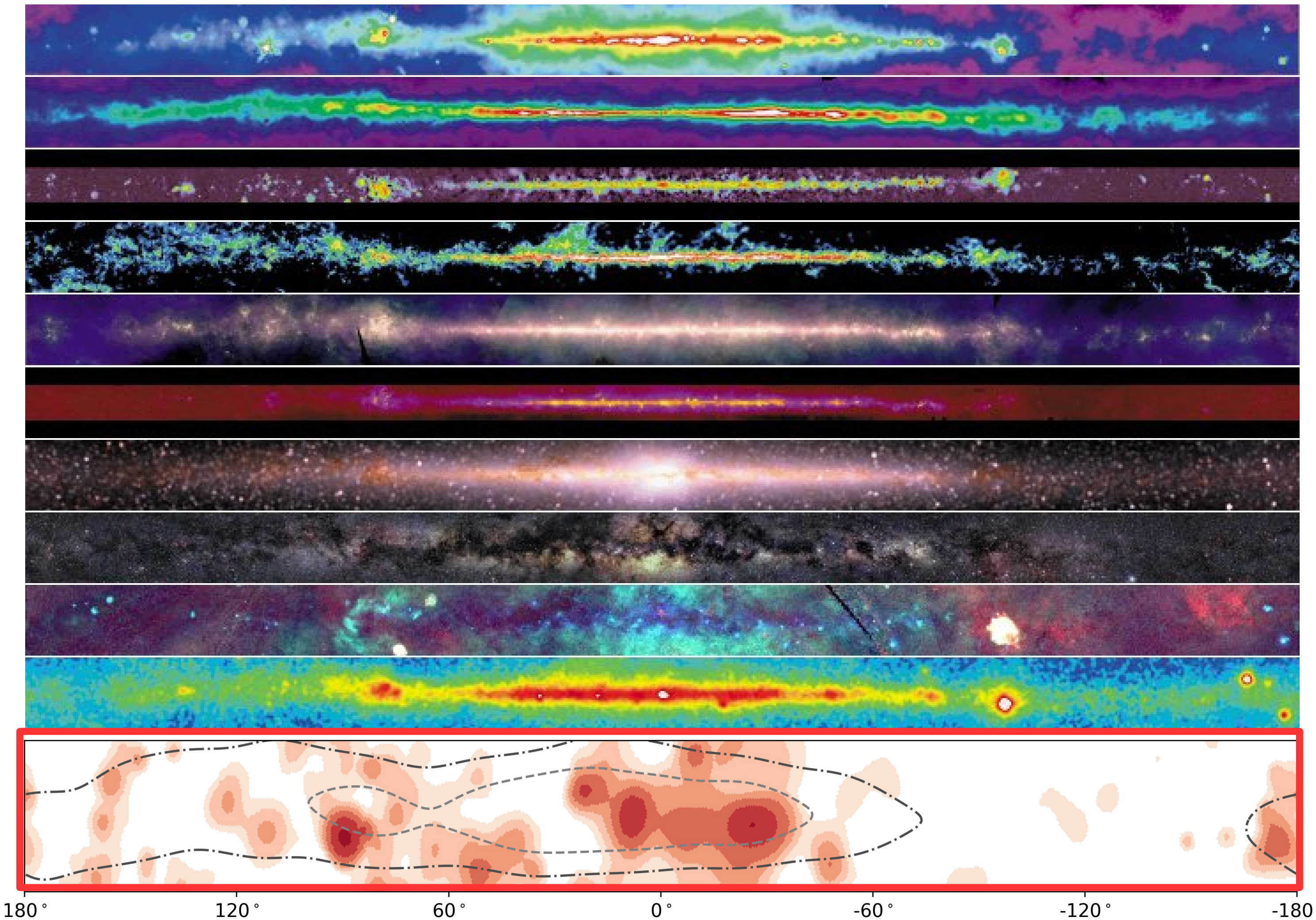
Science 380 (2023) 1338

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

The Milky Way

In Neutrinos!!!

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



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

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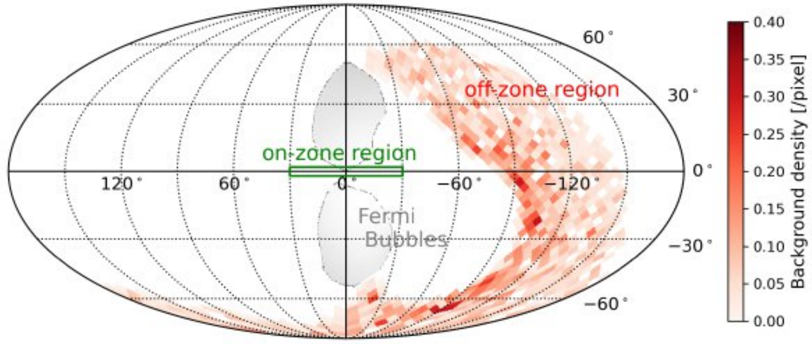
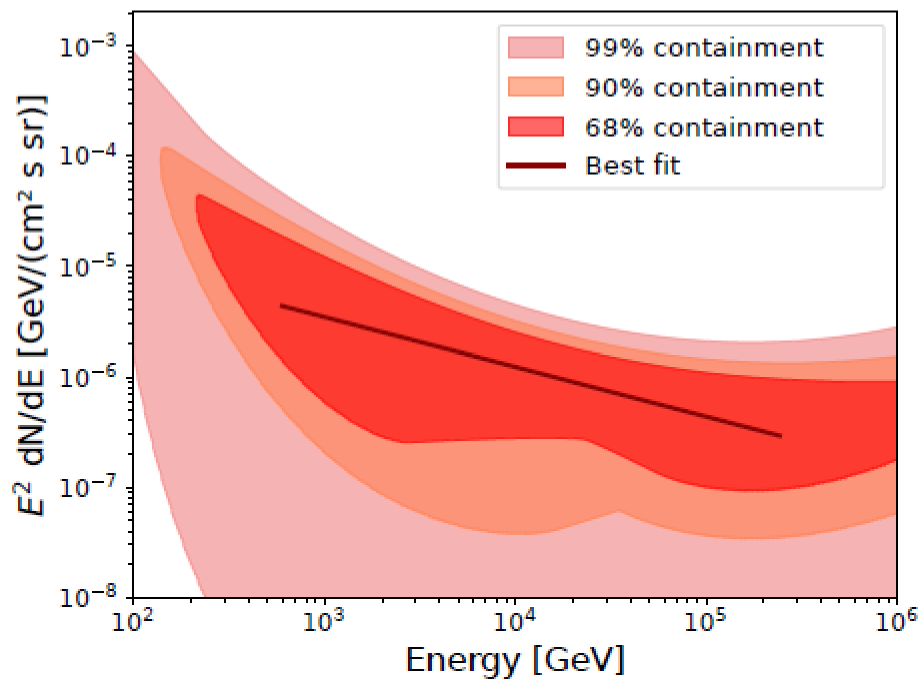
ANTARES Hints of Galactic Ridge

ANTARES Collaboration, Phys. Lett. B, 841 (2023)

2.0σ (~ 4%) p-value

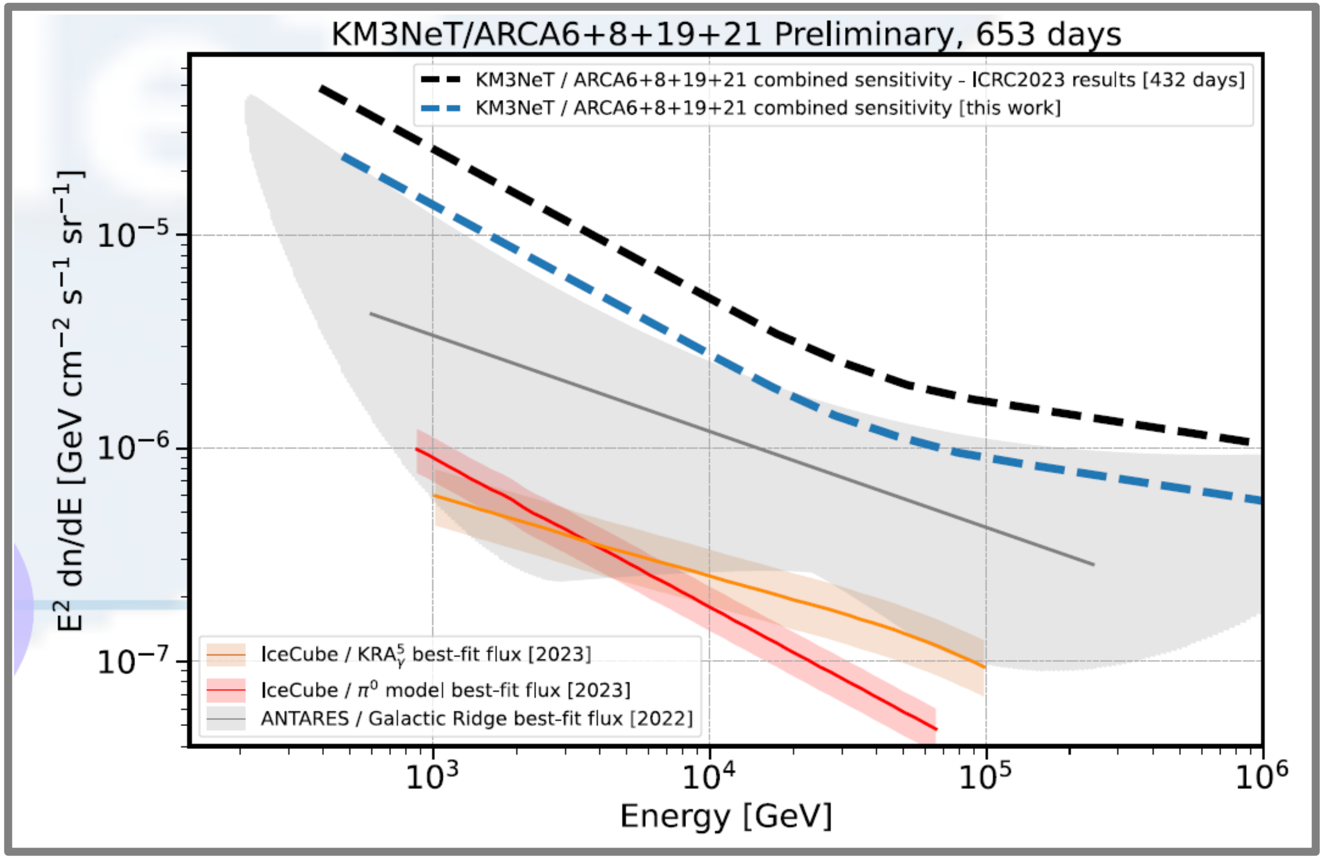
2.2σ (~ 2%) with Tracks Only
0.2σ (~ 44%) with Cascades Only



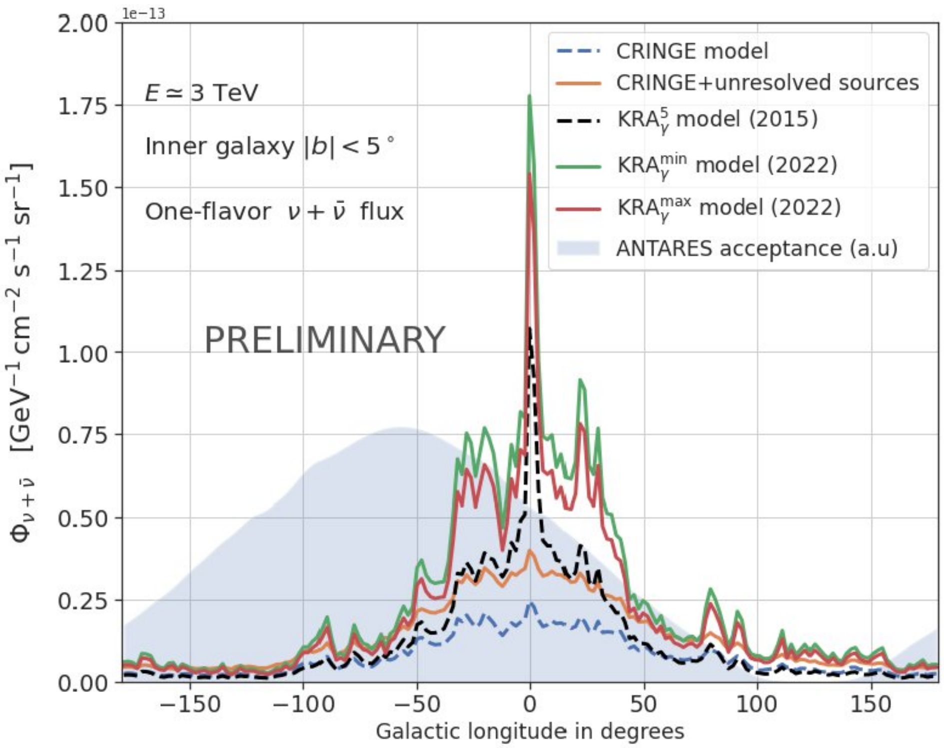


KM3NeT ARCA Catching Up

L.A. Fusco, V. Tsourapis, F. Filippini, E. Drakopoulou, C. Markou, A. Sinopoulou, E. Tzamariudaki on behalf of the KM3NeT collaboration (Neutirno 2024)



ANTARES Template Analysis



PoS ICRC2023 (2023) 1084

Model	r^{fit}	post-trial p-value
KRA_γ^{max}	$0.58^{+0.55}_{-0.48}$	$1.19 \cdot 10^{-1}$ (1.56σ)
KRA_γ^{min}	$0.59^{+0.57}_{-0.50}$	$1.30 \cdot 10^{-1}$ (1.51σ)
KRA_γ^{5}	$0.93^{+0.81}_{-0.70}$	$8.92 \cdot 10^{-2}$ (1.70σ)
CRINGE+Unresolved	$1.08^{+1.18}_{-1.07}$	$1.79 \cdot 10^{-1}$ (1.34σ)
CRINGE	$1.58^{+2.46}_{-1.58}$	$2.74 \cdot 10^{-1}$ (1.09σ)

N

Baikal-GVD

ArXiv:2411.05608 (2024)

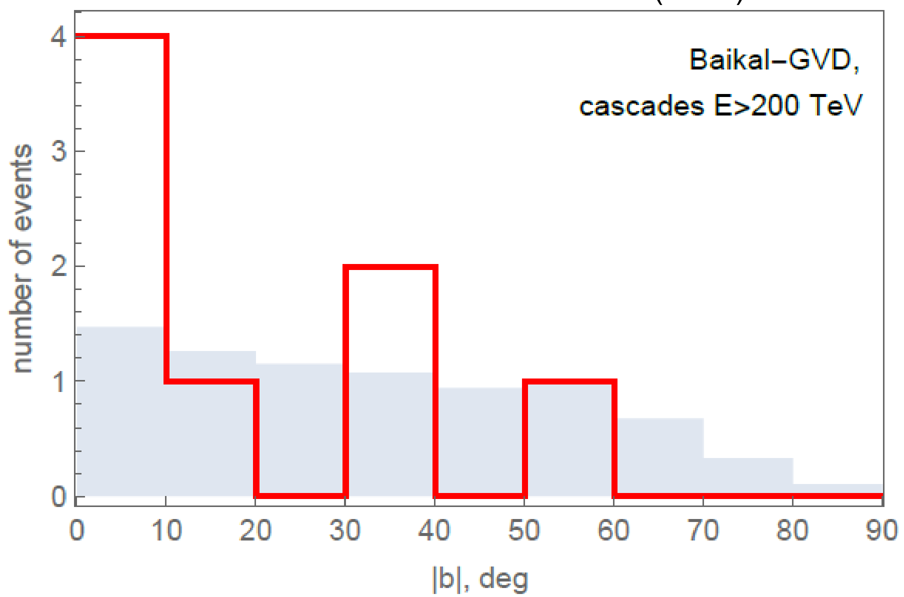
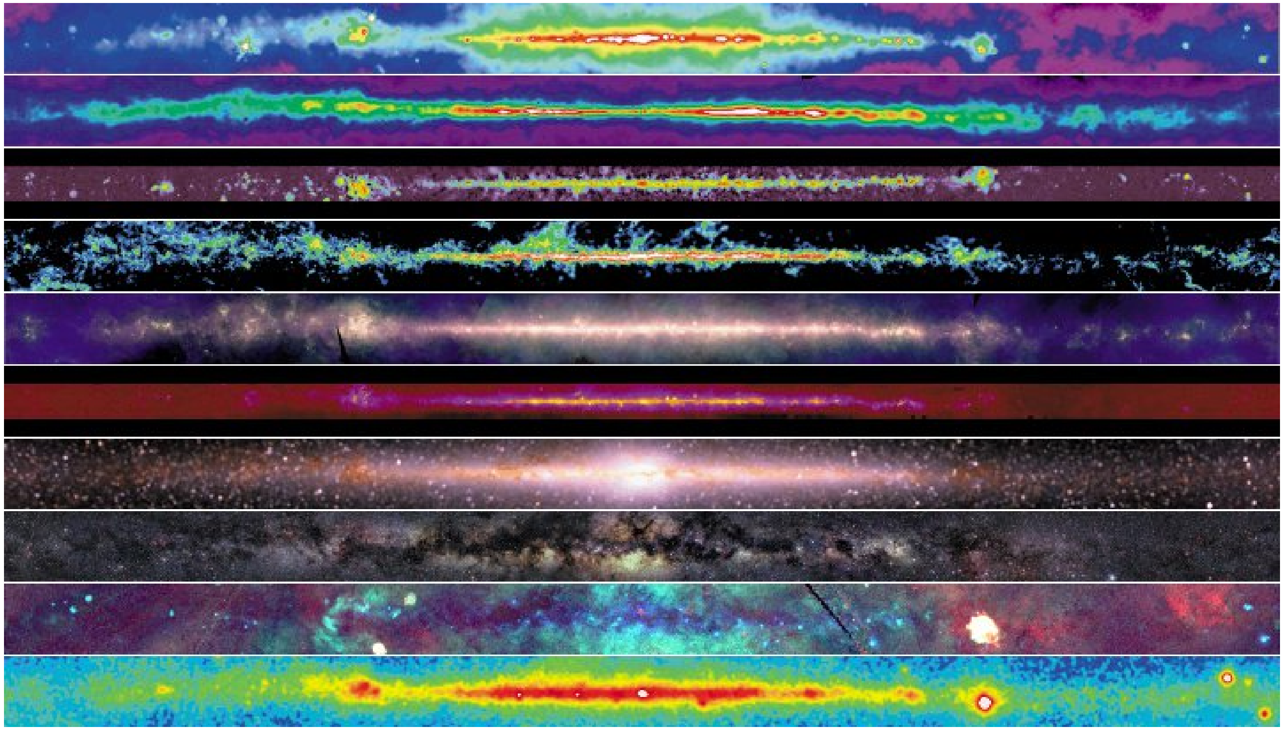


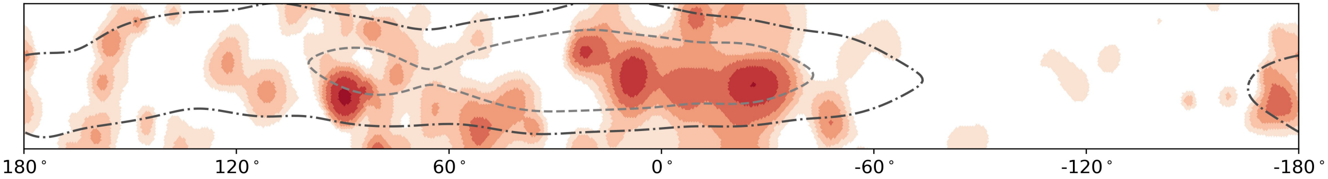
Figure 2. Observed (red line) and expected (shaded histogram) distribution of $|b|$ for Baikal-GVD cascades with $E \geq 200$ TeV.

Excess of HE cascade events at low Galactic latitudes
2.5σ (1.4%) p-value with no trials

Now that we see it, the questions...

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





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- Are there point sources mixed in with diffuse emission?
- Which ones? How much?
- Energy spectrum?
- Template discrimination?
- How does it compare to multi-wavelength emissions?

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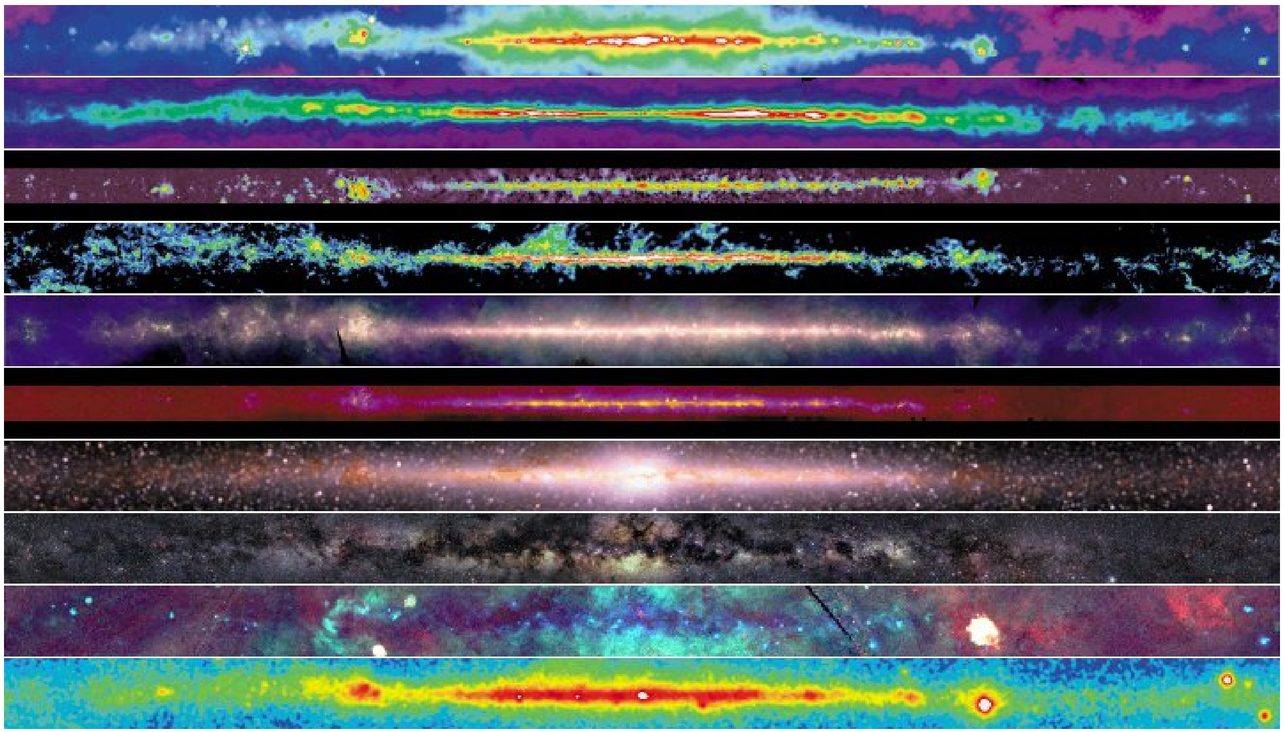

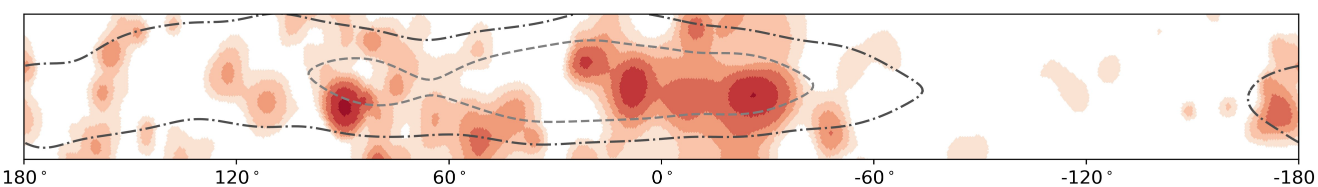

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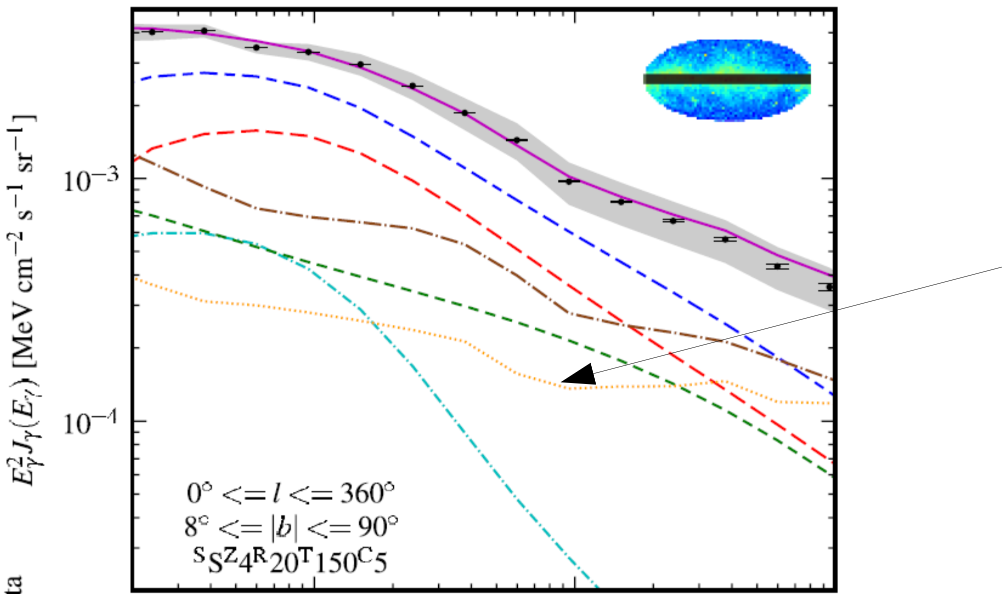
Diffuse Flux vs Resolved Sources

Nothing new (gamma rays for example)



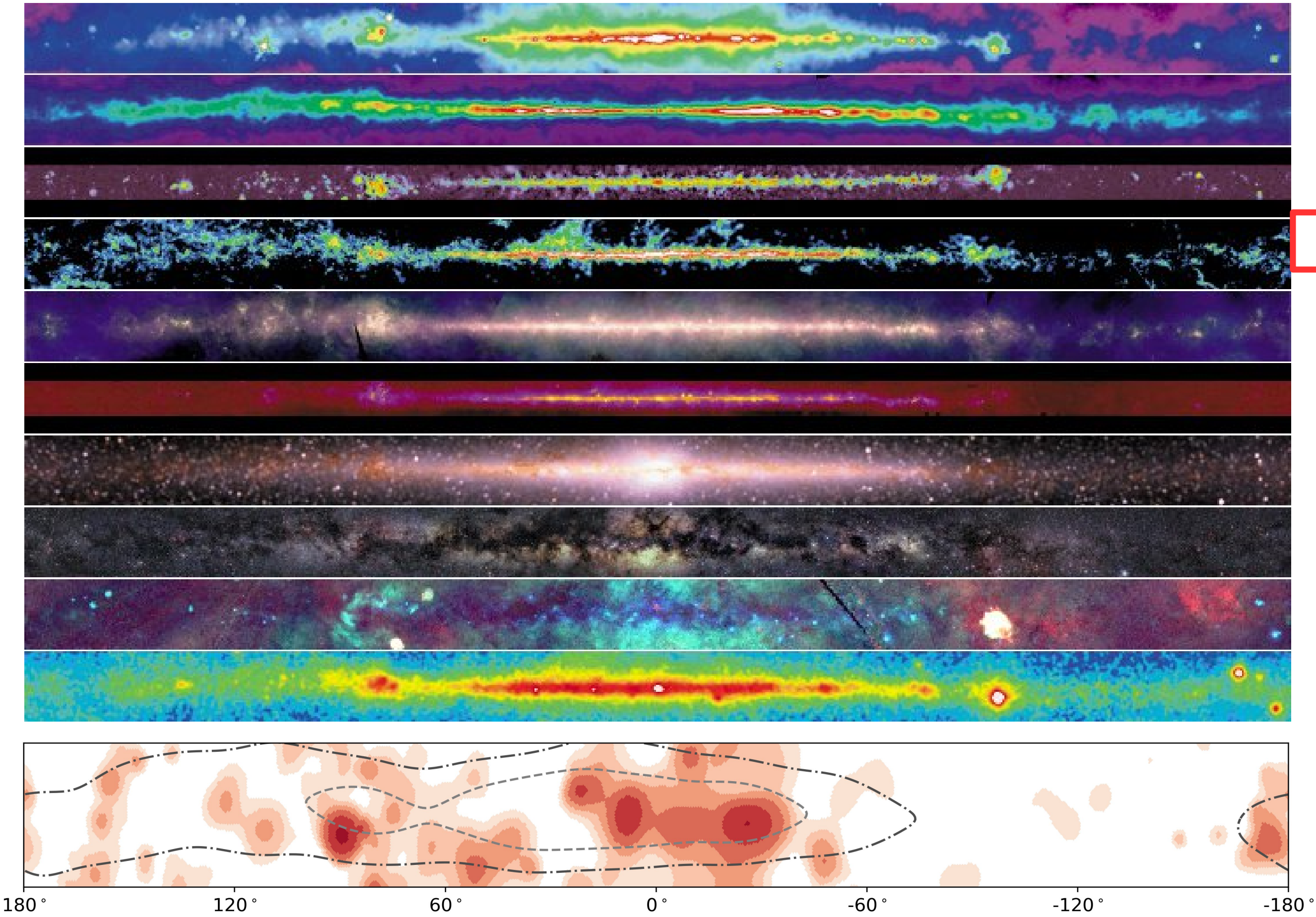
Fermi-LAT (2012) ApJ 750 3

… but we have no known Galactic neutrino sources so everything is unresolved sources

Naoko Kurahashi Neilson, (Drexel University)

Now that we see it, the questions...

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



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These are not individual energy bins!

A model fit → only normalization allowed to float!

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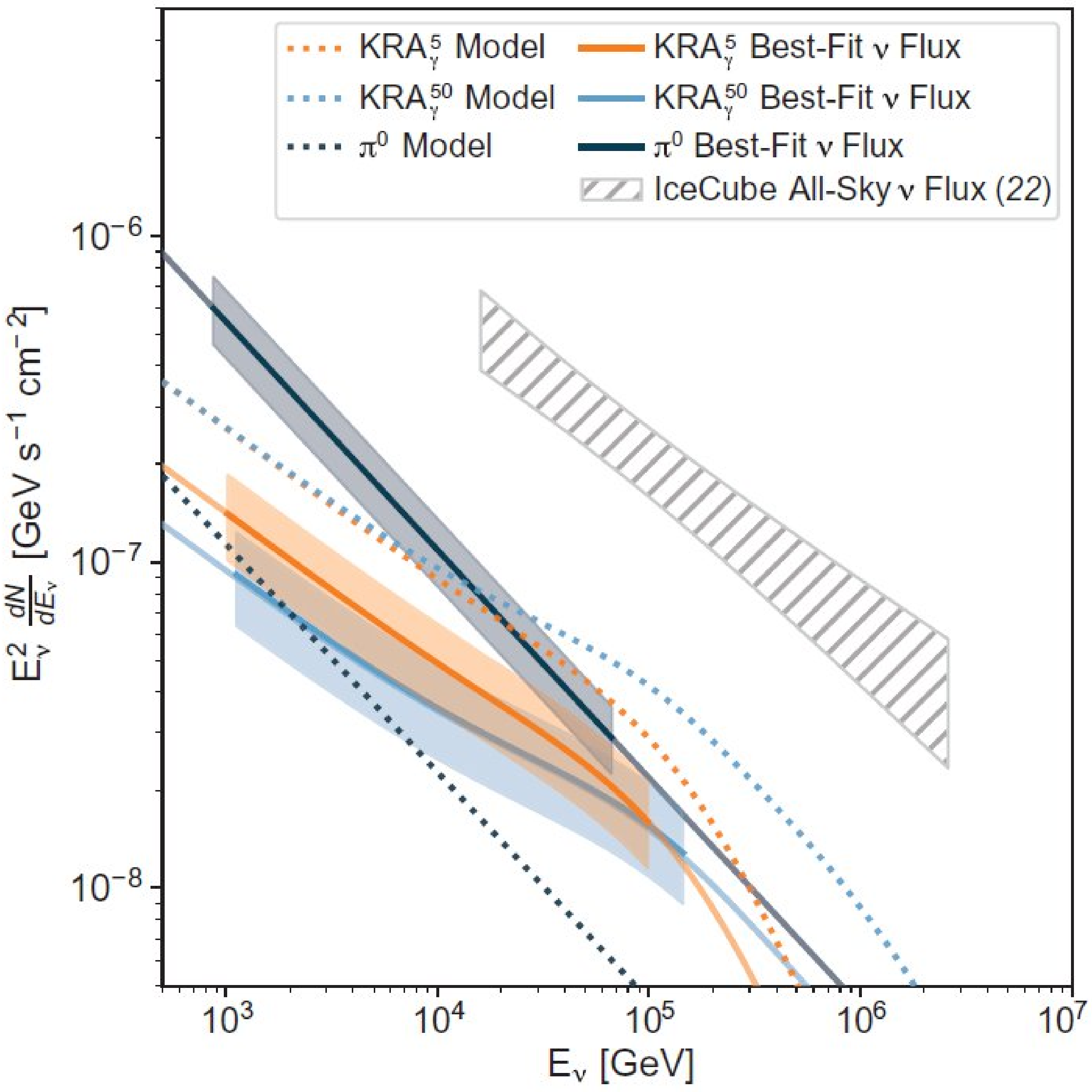

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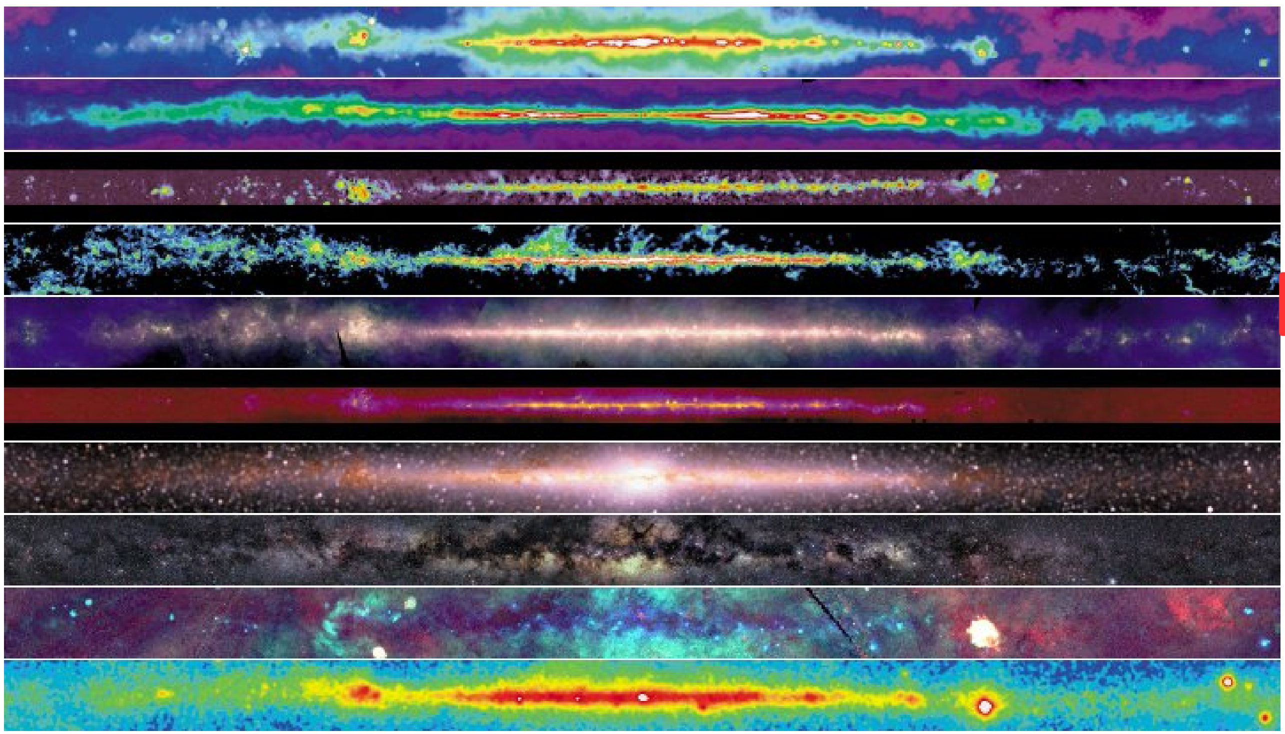

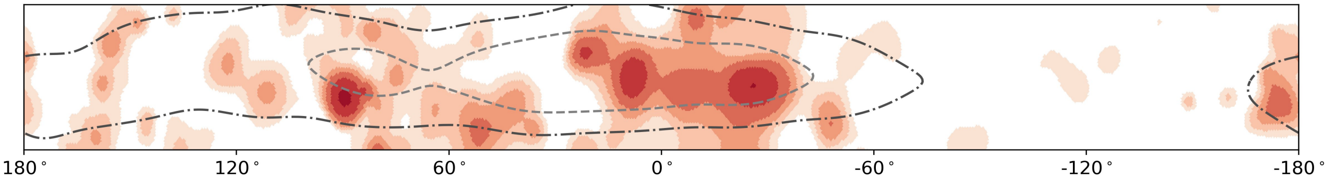

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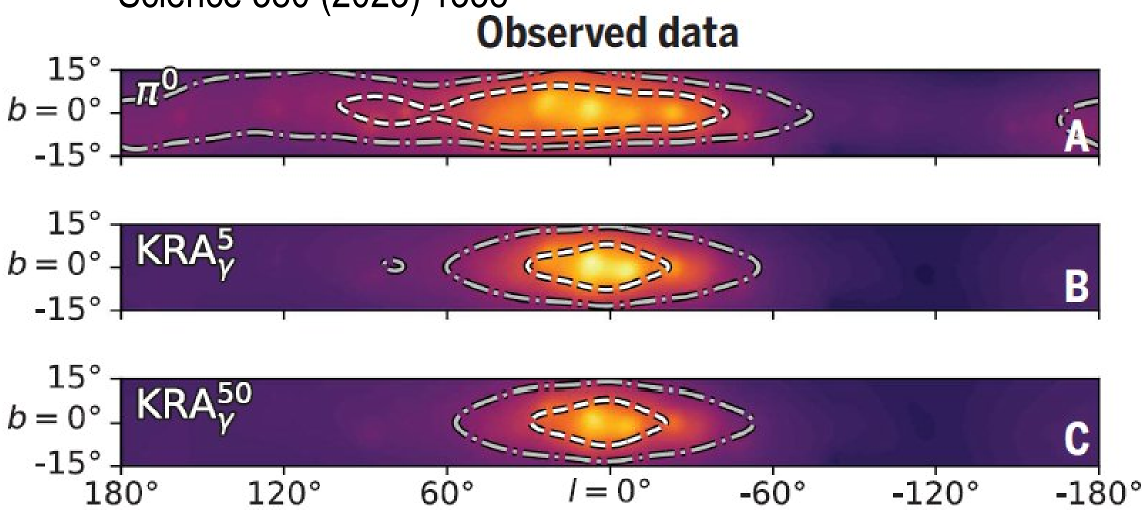
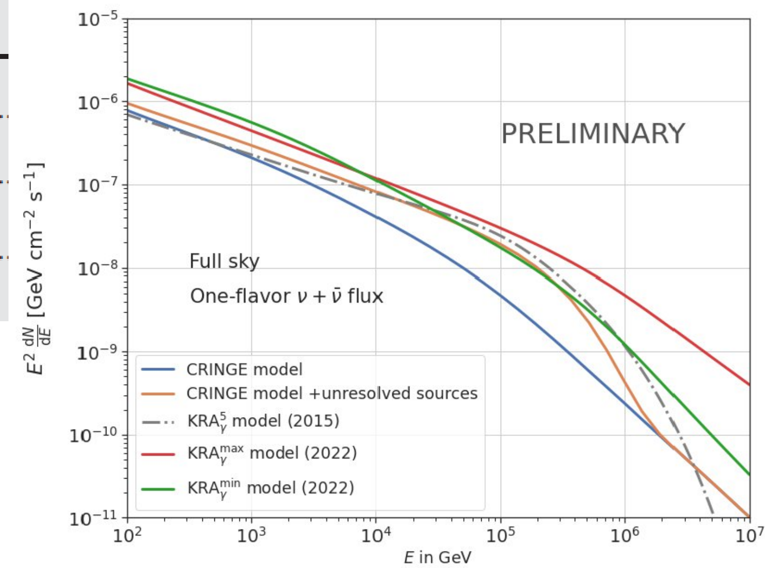


	Flux sensitivity Φ	*P* value
	Diffuse Galactic plane analysis	
π^0	5.98	1.26×10^{-6} (4.71σ)
KRA$_\gamma^5$	0.16 × MF	6.13×10^{-6} (4.37σ)
KRA$_\gamma^{50}$	0.11 × MF	3.72×10^{-5} (3.96σ)

PoS ICRC2023 (2023) 1084



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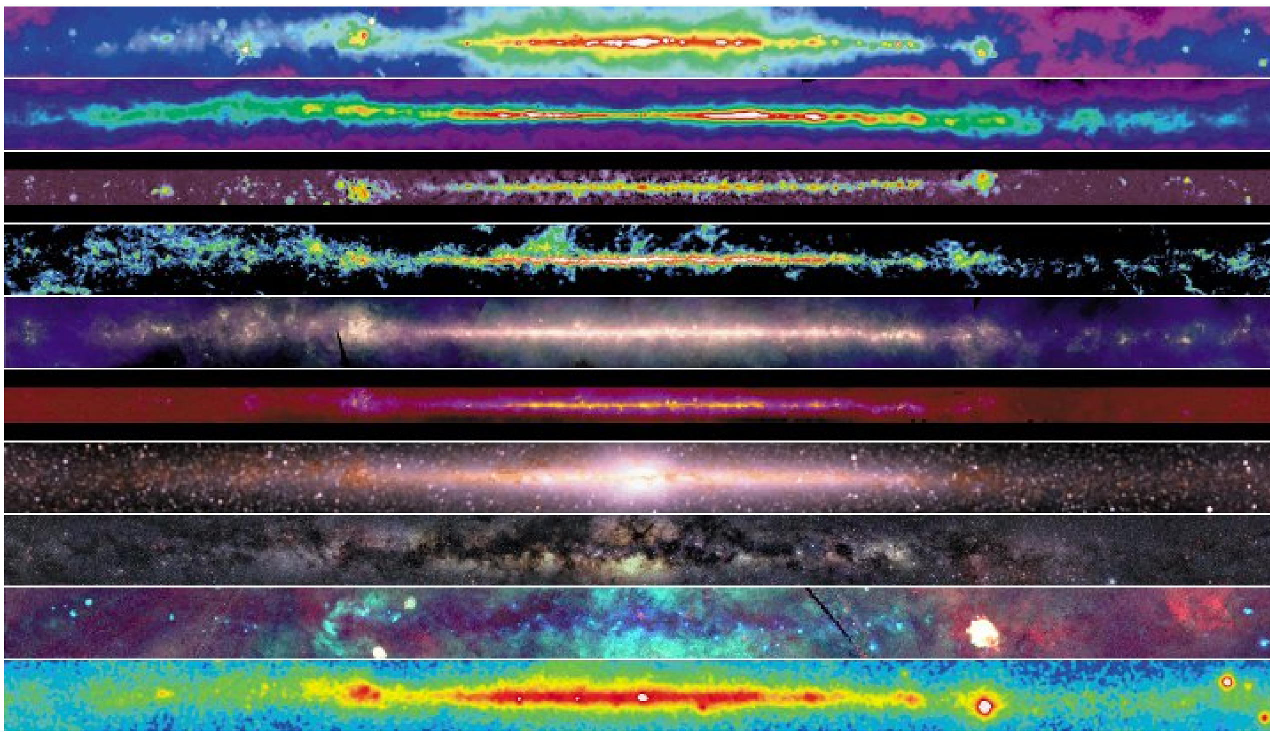

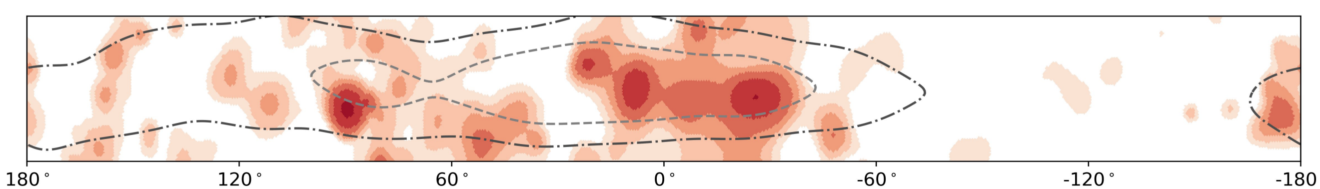

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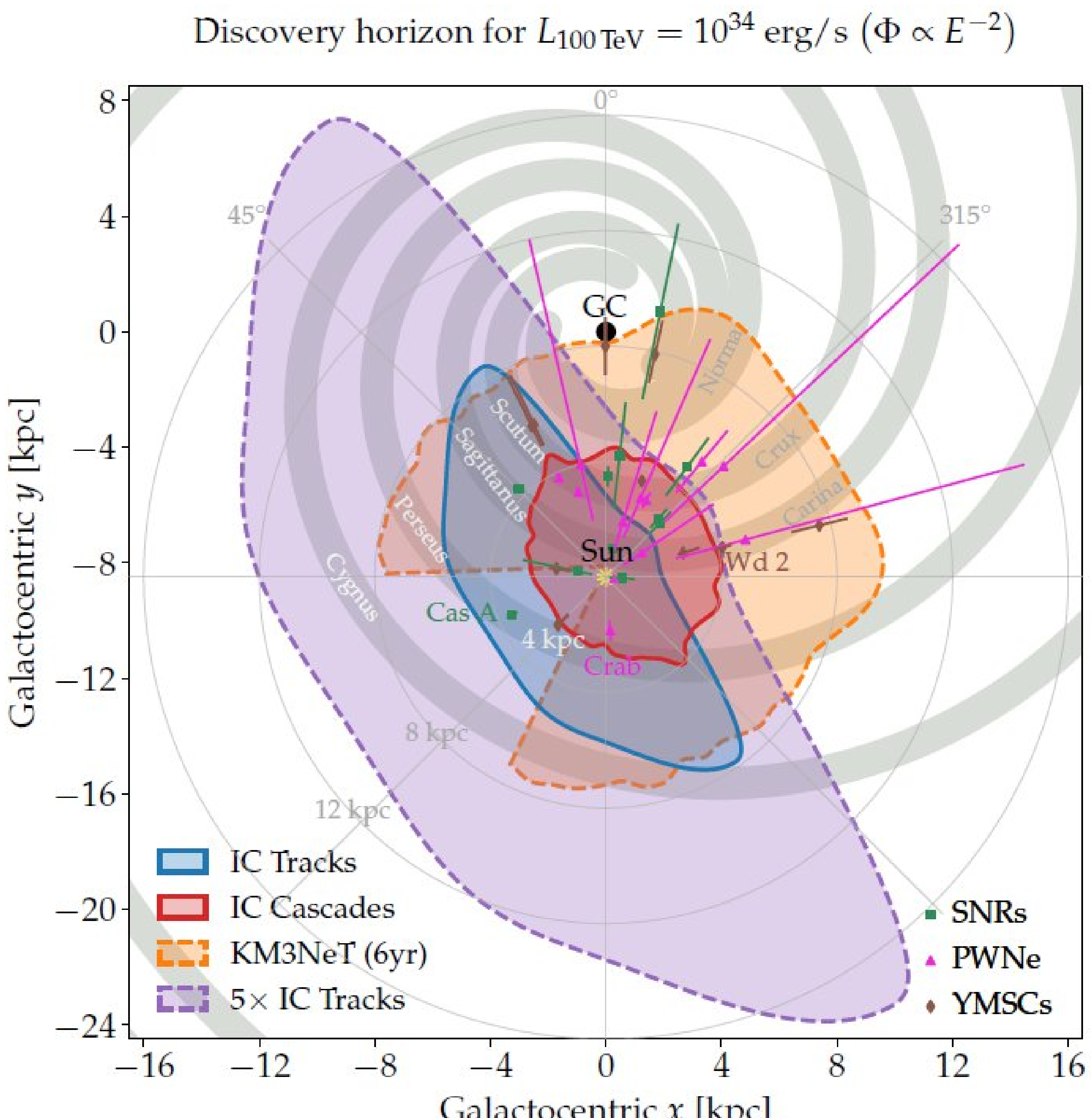
Future of Galactic Neutrino Observations

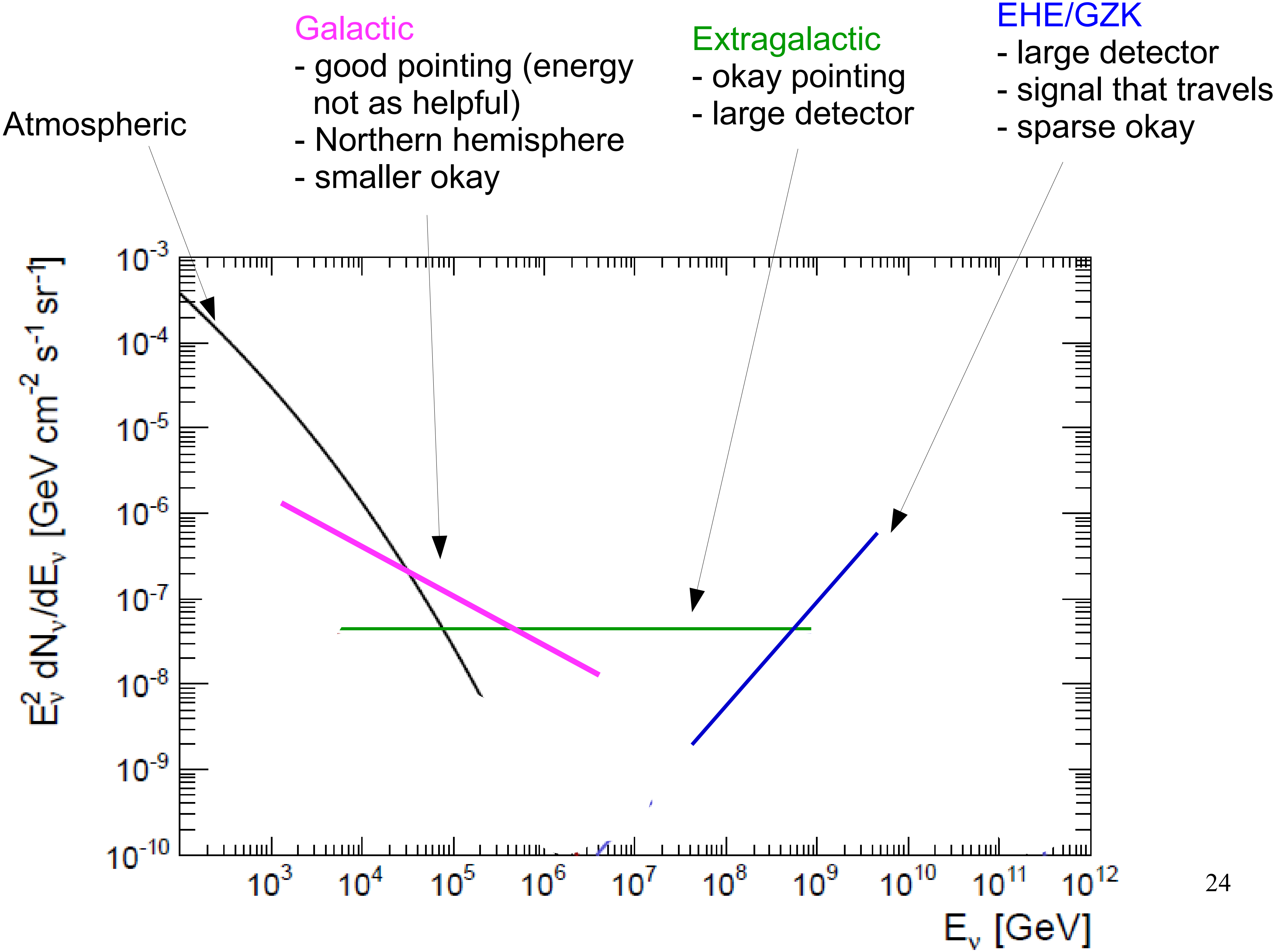
Galactic Neutrino Astronomy Reach



Phys. Rev. D 109, 043007 (2024)

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

Diverse Neutrino Astronomy Targets



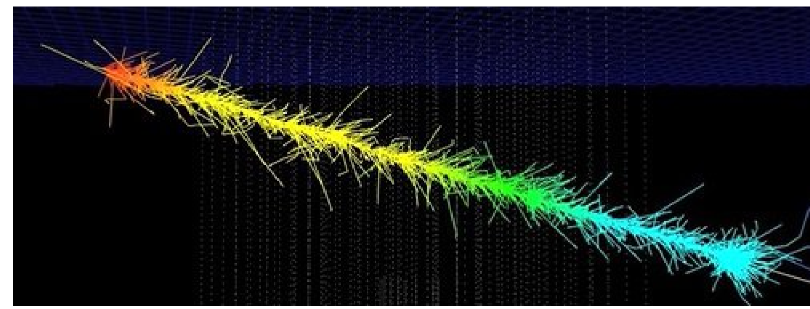
Diverse Neutrino Astronomy Targets

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

Extragalactic
- good pointing
- large detector

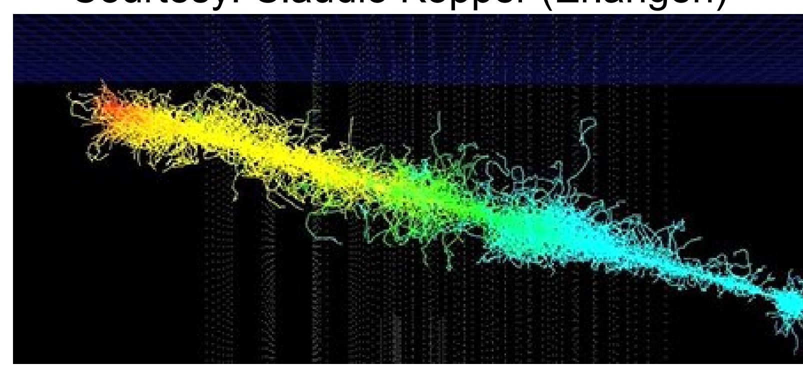
EHE/GZK
- large detector
- signal that travels
- sparse okay

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

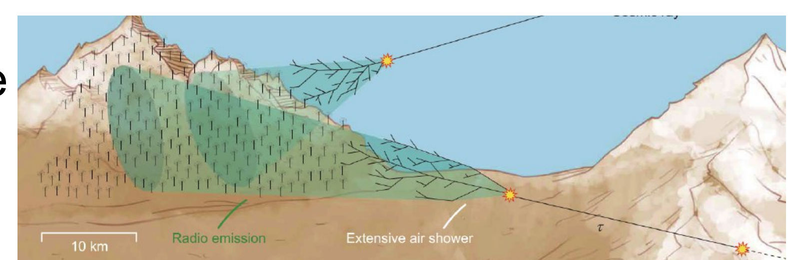


Courtesy: Claudio Kopper (Erlangen)

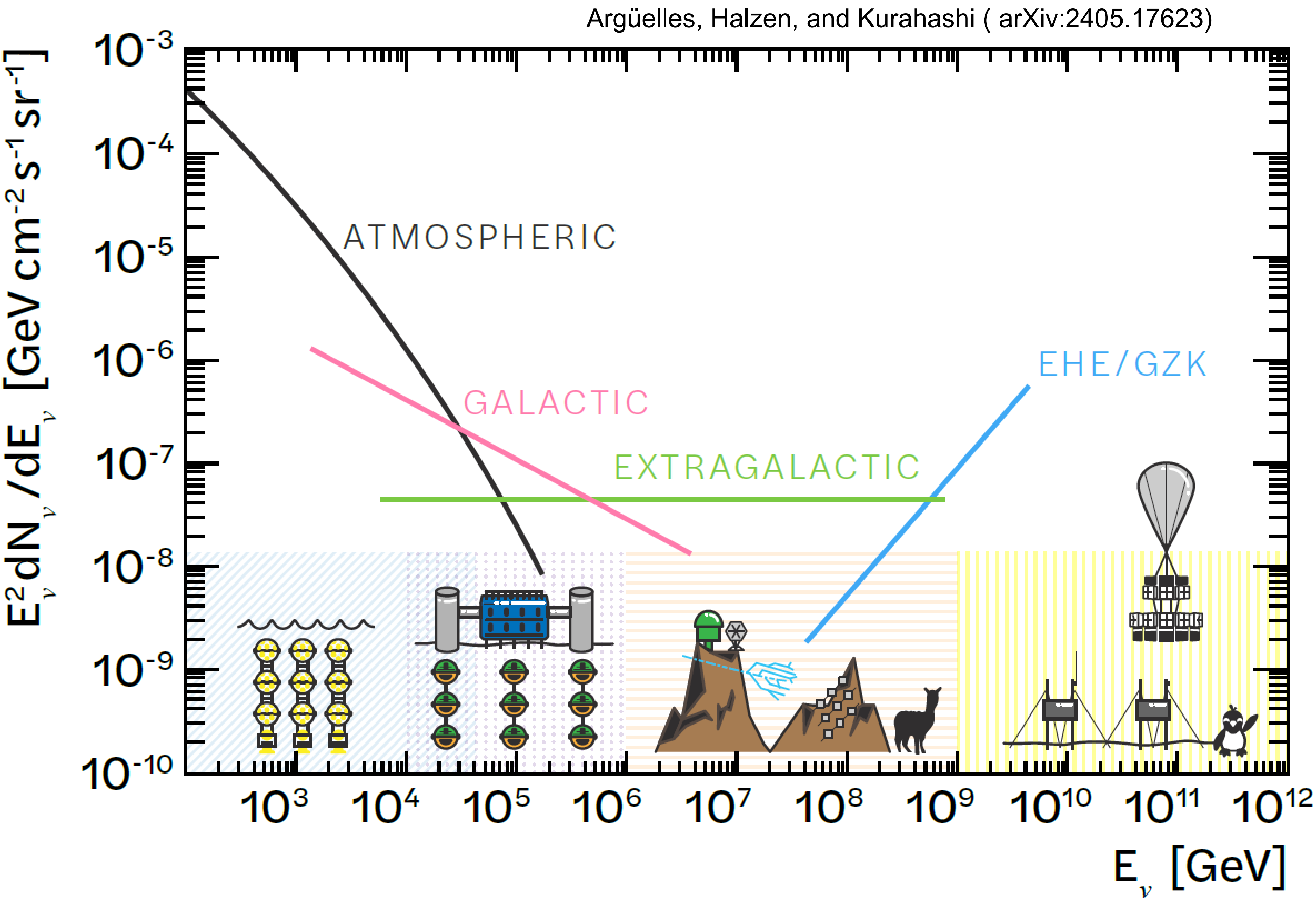
Ice Cherekov
- Scattering ✗ → Harder to point
- Absorption ✓ → Easier to make large detector



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



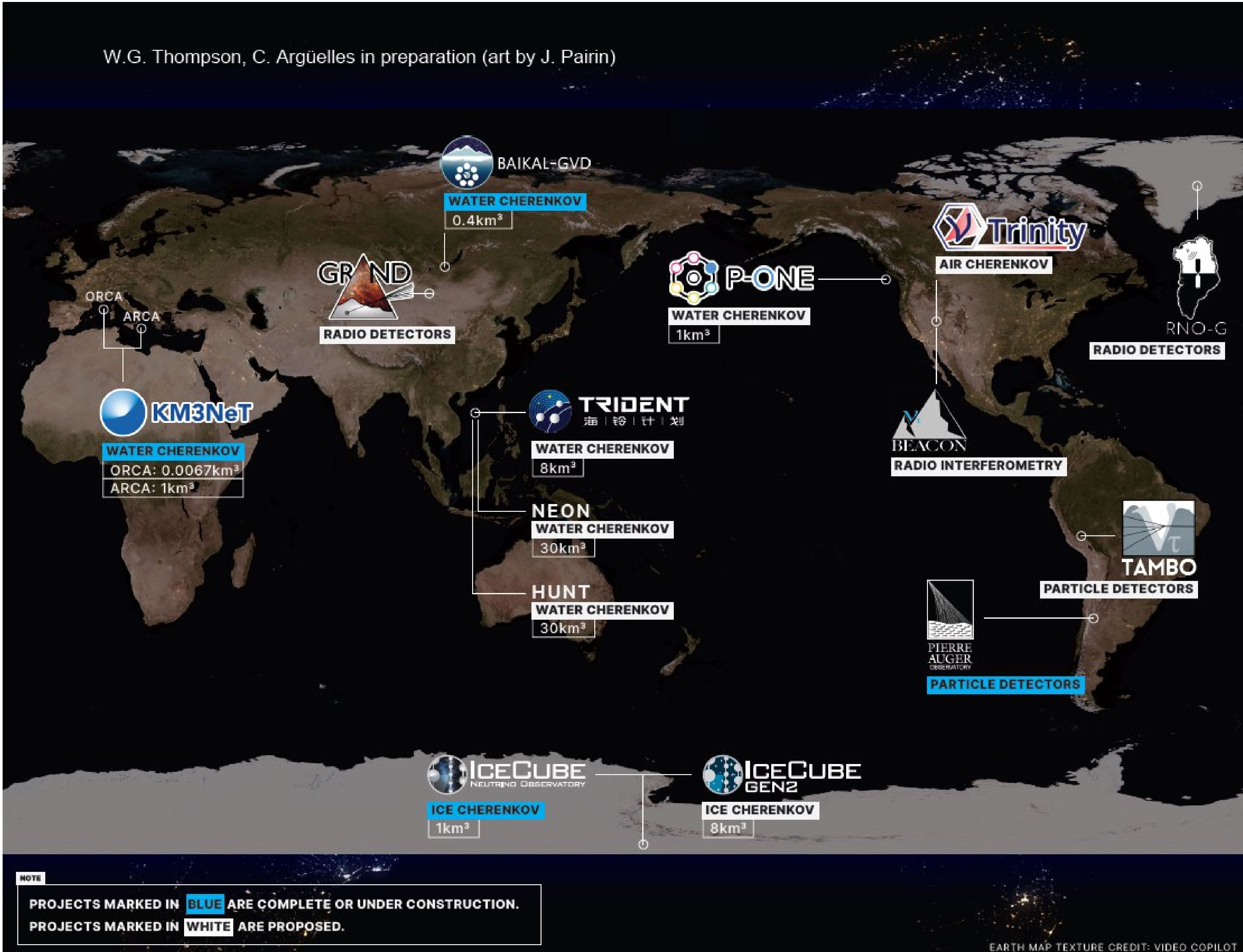
Courtesy: GRAND Collaboration

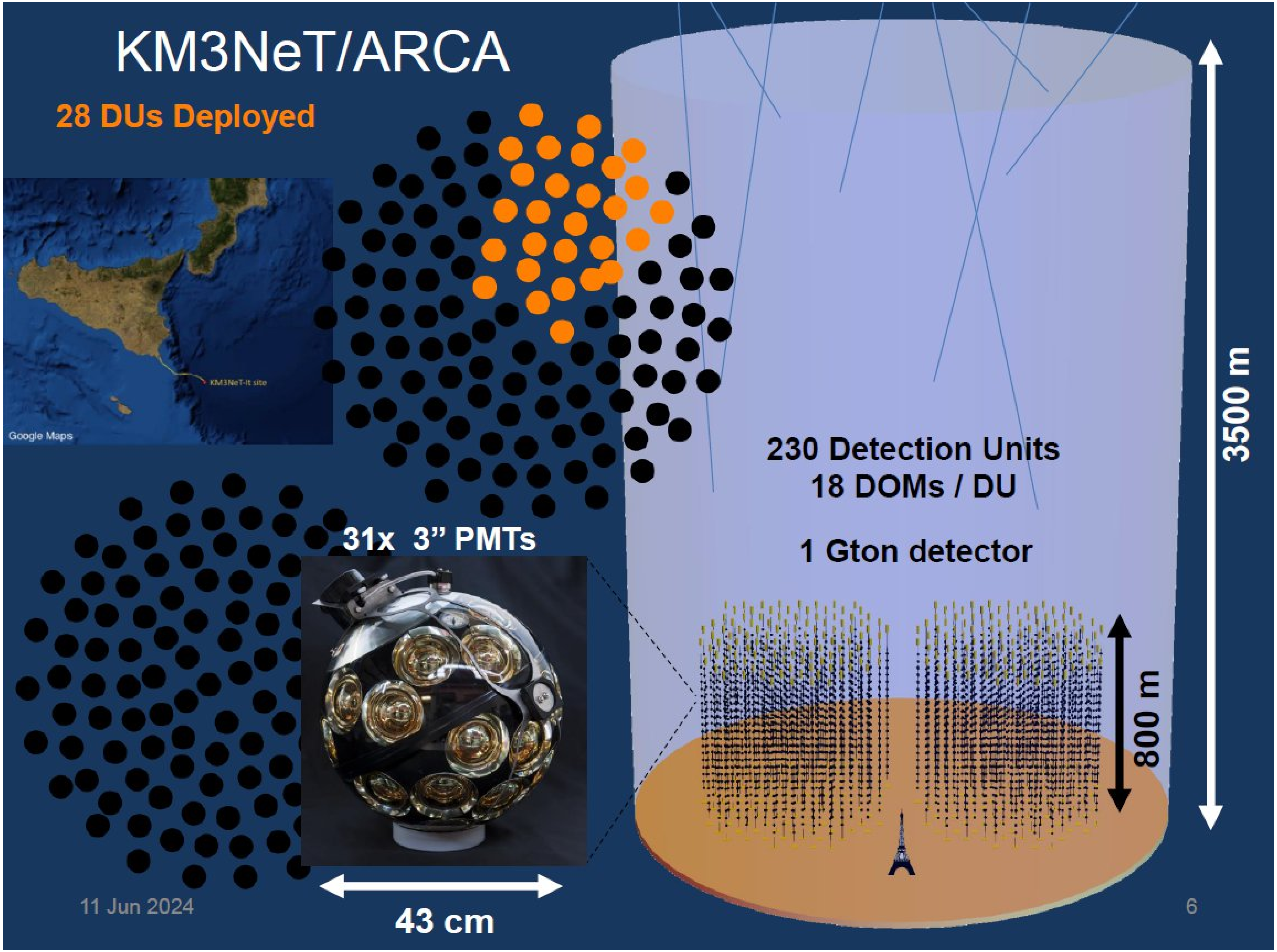

Argüelles, Halzen, and Kurahashi (arXiv:2405.17623)
ATMOSPHERIC
GALACTIC
EXTRAGALACTIC
EHE/GZK
$E_\nu^2 dN_\nu/dE_\nu$ [GeV cm^{-2}s^{-1}sr^{-1}]
E_ν [GeV]
10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10}
10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}

Diverging Optimizations
→ Good Sign of a Maturing Field

Large Scale Water Cherenkov Detectors Needed!

* Caveat: Specialized data sets for IceCube (e.g. PoS ICRC20231051) can do better and more are coming!


W.G. Thompson, C. Argüelles in preparation (art by J. Pairin)
BAIKAL-GVD
WATER CHERENKOV
0.4km³
GRAND
RADIO DETECTORS
ORCA
ARCA
KM3NeT
WATER CHERENKOV
ORCA: 0.0067km³
ARCA: 1km³
P-ONE
WATER CHERENKOV
1km³
Trinity
AIR CHERENKOV
RNO-G
RADIO DETECTORS
TRIDENT
海 | 铃 | 计 | 划
WATER CHERENKOV
8km³
BEACON
RADIO INTERFEROMETRY
NEON
WATER CHERENKOV
30km³
HUNT
WATER CHERENKOV
30km³
TAMBO
PARTICLE DETECTORS
PIERRE AUGER OBSERVATORY
PARTICLE DETECTORS
ICECUBE
NEUTRINO OBSERVATORY
ICE CHERENKOV
1km³
ICECUBE GEN2
ICE CHERENKOV
8km³
NOTE
PROJECTS MARKED IN BLUE ARE COMPLETE OR UNDER CONSTRUCTION.
PROJECTS MARKED IN WHITE ARE PROPOSED.
EARTH MAP TEXTURE CREDIT: VIDEO COPILOT



Slide from J. Coelho (Neutrino2024)

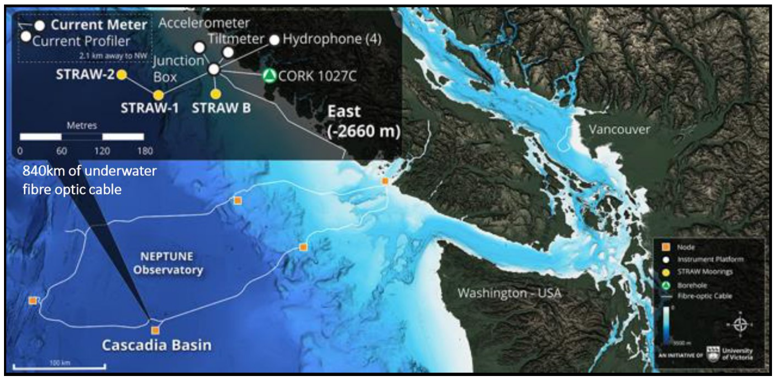
New Hemisphere New Comers

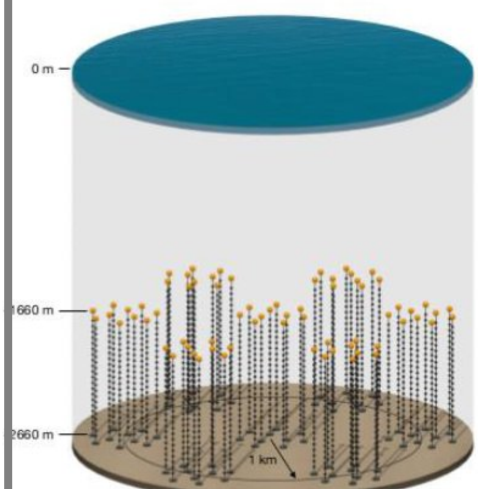
P-ONE

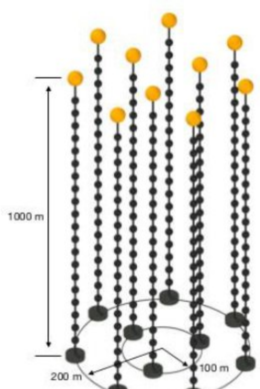
Pacific Ocean Neutrino Explorer

Leverage existing facilities

OCEAN NETWORKS CANADA







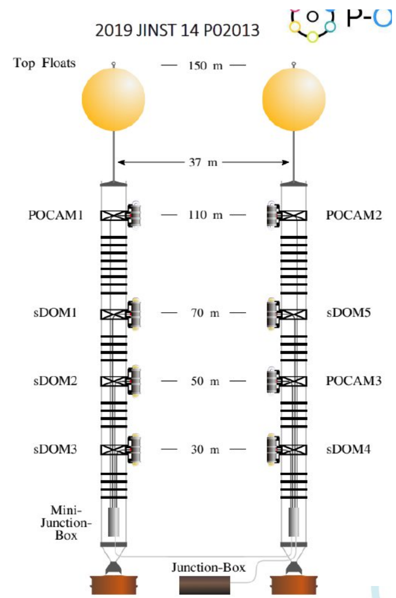
Images: courtesy P-ONE collaboration

Huge telescopes in the South China Sea

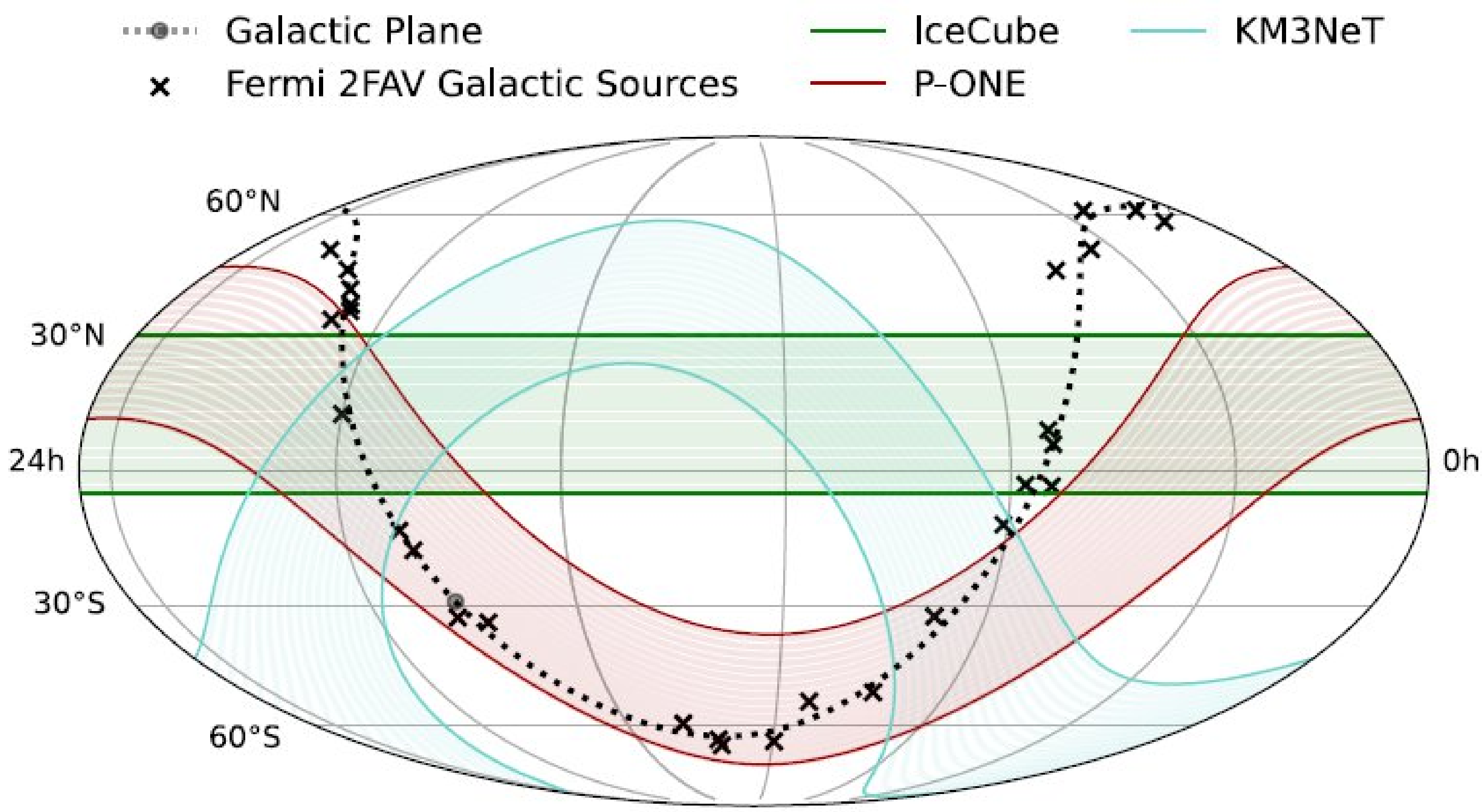
TRIDENT
海 | 铃 | 计 | 划

HUNT

Pathfinder strings deployed and recovered



Complementary Peak Sensitivity → Important for Galactic Transients



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

Conclusions

- ~2023 Start of High-Energy Galactic Neutrino Astronomy
- Raises lots of questions, not enough data (above background) to answer
- IceCube can add some answers
- Ultimately, answering them needs large scale water Cherenkov neutrino telescopes

Experimental wish list:

- **Keep IceCube Running**
- **Complete KM3NeT/ARCA**
- **Complementary Pacific Telescopes**

Backups

AGN Unification

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

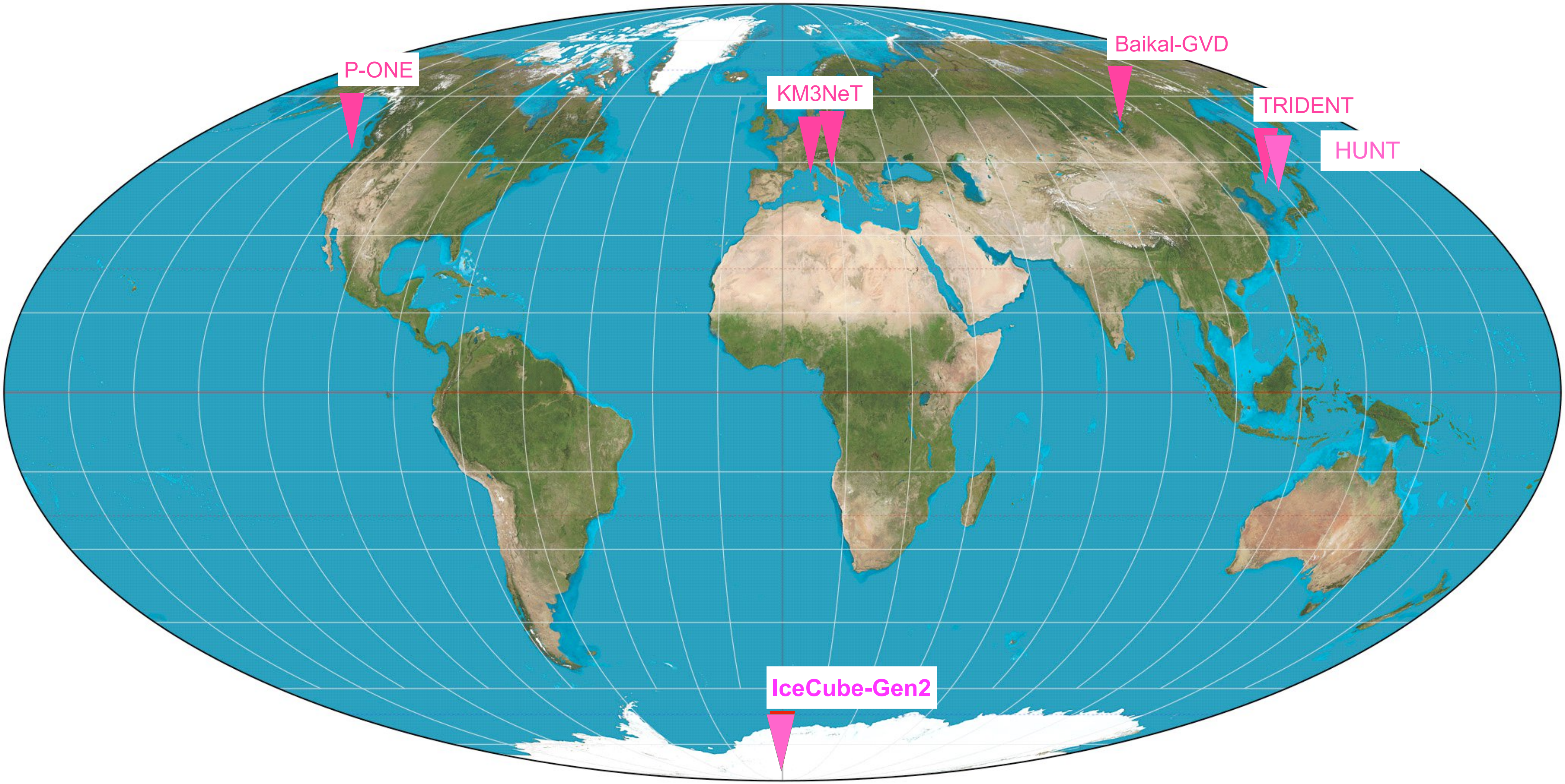
neutrino (v_τ) with nuclei, as well as scattering interactions of all three neutrino flavors [v_e, muon neutrino (v_μ), and v_τ] on nuclei. Because the charged particles in cascade events travel only a few meters, these energy depositions appear almost point-like to IceCube's 125-m (horizontal) and 7-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

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

(Optical HE) Neutrino Telescopes



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