

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

SEARCH FOR NEUTRINOS FROM THE GALACTIC PLANE AND OTHER ASTROPHYSICAL EXTENDED SOURCES WITH ICECUBE



The IceCube Collaboration
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University of Wisconsin, Madison



ICECUBE

The detector, data, and event selection

The IceCube neutrino observatory instruments a cubic kilometer of ice at the South Pole using 86 strings of optical sensors. The detector was built over several years and took data while construction progressed until completion in 2011. The analysis presented here uses the combined 40-string and 59-string detector data taken from 2008 to 2010. Over 140,000 events were selected after cuts based on quality of the fitted track to neutrino-induced muon-like events, and estimated energy. At 10 TeV the median angular resolution of these events are $\sim 1^\circ$. In the northern sky, the atmospheric neutrino background dominates making the TeV-PeV region optimal for astrophysical source searches. In the opposite hemisphere, high energy atmospheric muons become the main background increasing the source sensitivity energy range to PeV-EeV. (For more on event selection and performance, see S. Odrowski's poster, abstract ID 134 and ArXiv:1111.2741v1). Two analysis results based on this data set are shown below.

Diffuse Neutrino Search from the Galactic Plane

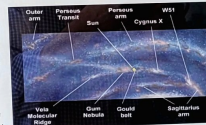
Motivation

Shown to the right is a sky map of gamma-rays observed by Fermi's Large Area Telescope (<http://heasarc.gsfc.nasa.gov/>). The two notable features seen are point sources and the diffuse haze from the galactic plane. Here we aim to detect the galactic haze in neutrinos.



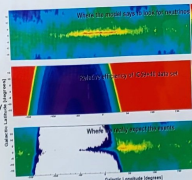
Deciding where to look

The expected flux of neutrinos along the galactic plane is not expected to be uniform. A spatial template to test must be chosen. The question is then whether neutrino production in the plane traces high-energy cosmic ray source location (as shown to the right), or the matter (gas) density



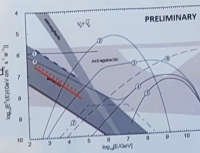
Testing the Fermi model

In this analysis, we chose the pion component of the Fermi diffuse galactic gamma-ray model (M. Ackermann *et al.* 2012 *ApJ* 750), which traces matter density. The model is shown in the top plot. IceCube's detector sensitivity is zenith angle dependent, and shown in galactic coordinates (middle). Convolving these, a map of expected neutrino arrival direction distribution is obtained (bottom).

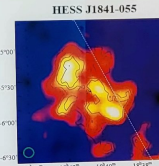


Results

An energy spectrum of $E^{2.7}$ is assumed following the gamma-ray measurement. A likelihood analysis is performed to see no evidence of signal. The 90% (red solid) and 99% (red dotted) upper limit of this signal hypothesis is plotted along with the model prediction (purple). Both are all-sky averages. The underlying plot is taken from Learned & Mannheim, *Annu. Rev. Nucl. Part. Sci.* 2000.



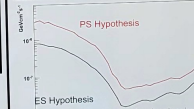
All-sky extended source search



Motivation

Shown to the left is an extended TeV gamma-ray source (Aharonian, *et al.* 2008 *A&A* 477). In order to look for extended sources (ES) of neutrinos, an all-sky likelihood search similar to an all-sky point source (PS) search (S. Odrowski's poster, abstract ID 134, ArXiv:1111.2741v1) is performed.

Discovery potential (for ES Flux of E^2)



Why a dedicated search?

The ES all-sky search replaces the 0° source extension hypothesis with up to a couple of degrees. The estimated flux needed for a 5-sigma discovery of a 3° extended source is compared for a point source and extended source analysis. It was also shown that overestimating the extension performs better than underestimating it.

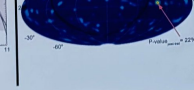
0° (PS)



1° (ES)



3° (ES)



Results

The sky maps plot the pre-trial p-value of a $0.5^\circ \times 0.5^\circ$ grid on the sky. The black solid line denotes the galactic plane. For the PS map, the hottest spot is (RA, deg) = (75.45, -18.5) with a post-trial p-value of 0.74, while for both the 1° and 3° maps, the hottest spot is (RA, deg) = (80.75, 4.25). For the 1° sky map, the hot spot post-trial p-value was 0.84, and 3° sky map, the hot spot corresponds to a post-trial p-value of 0.22.

First Galactic Plane analysis from IceCube (IC40+59)

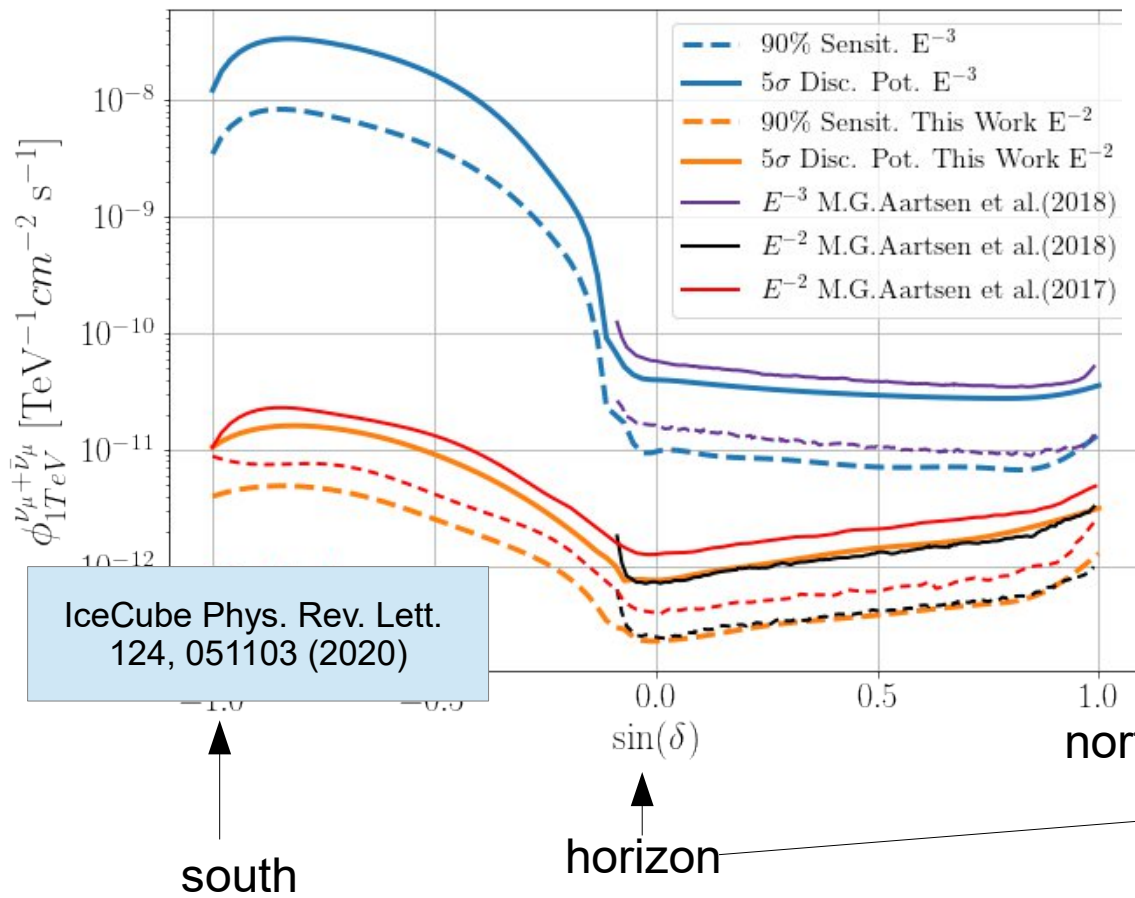
Discussion of "guaranteed neutrinos"

But the backgrounds!

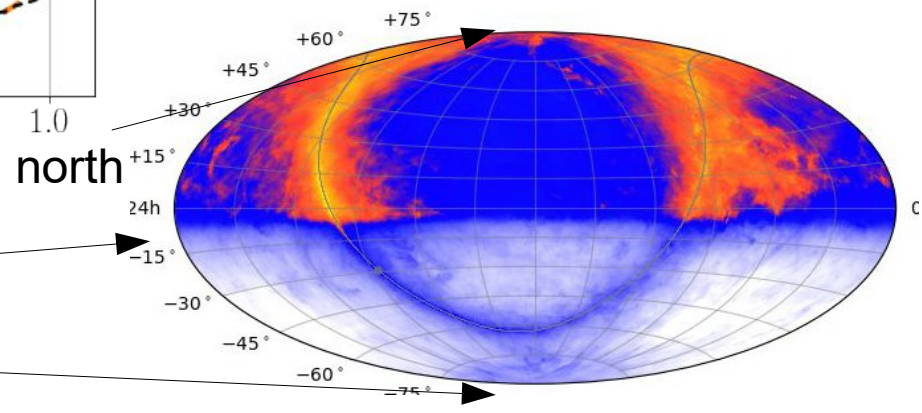
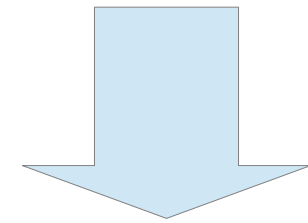
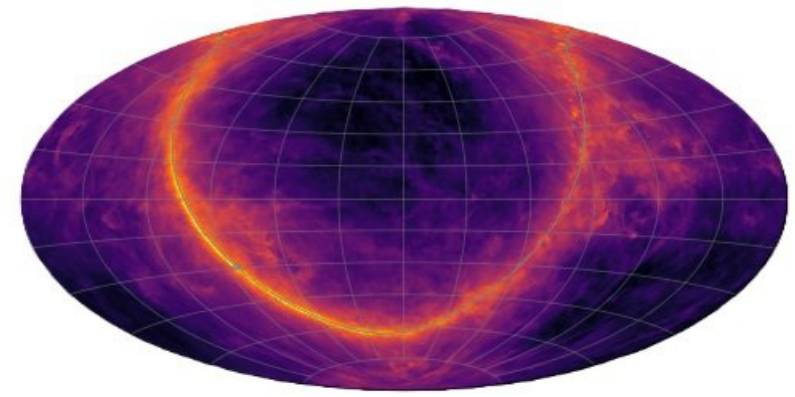
Photo: Jim Madsen

Backgrounds In IceCube

Data from Fermi-LAT (2012) ApJ 750 3



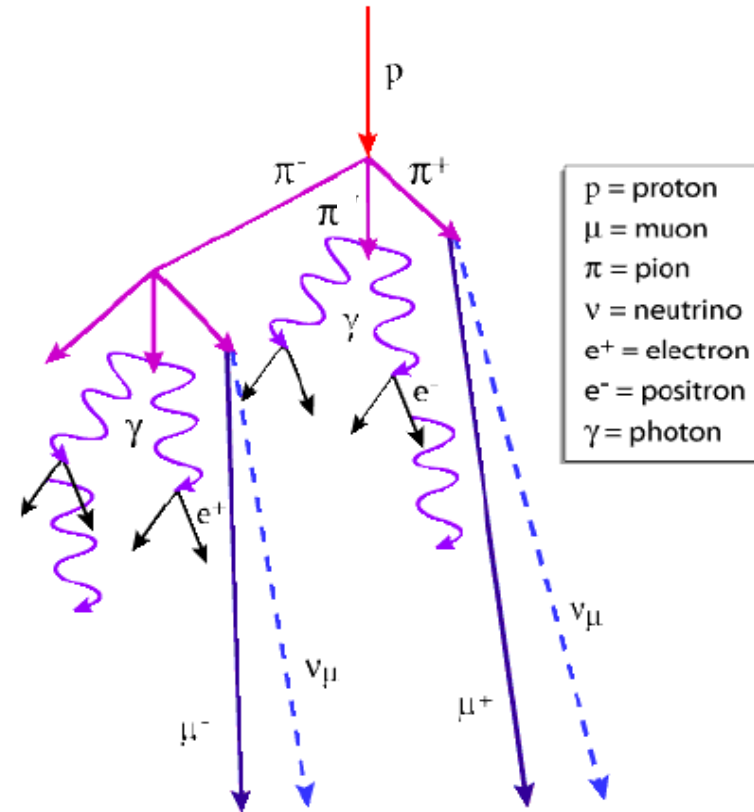
IceCube Phys. Rev. Lett.
124, 051103 (2020)



Background Domination

Backgrounds to first order are all **muons**

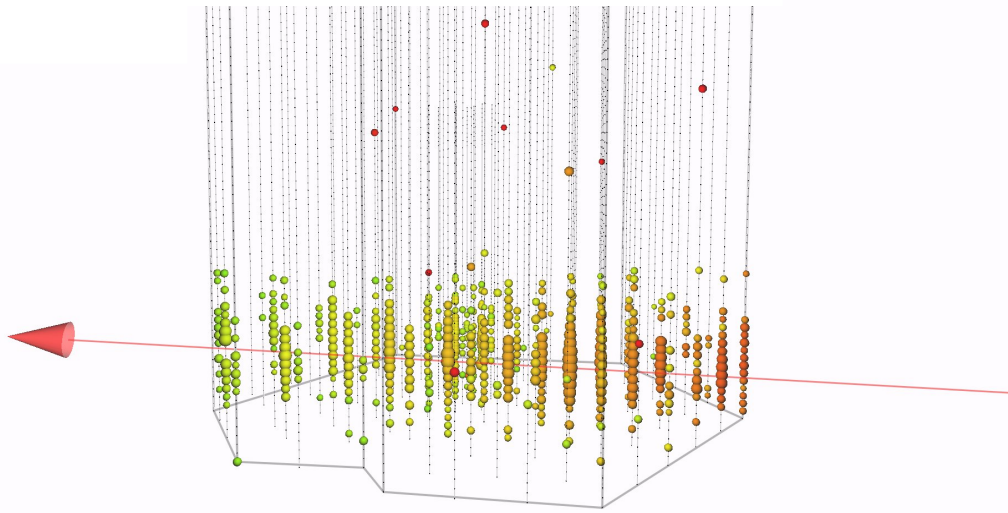
Muons make **tracks**, not cascades



Background Rates:

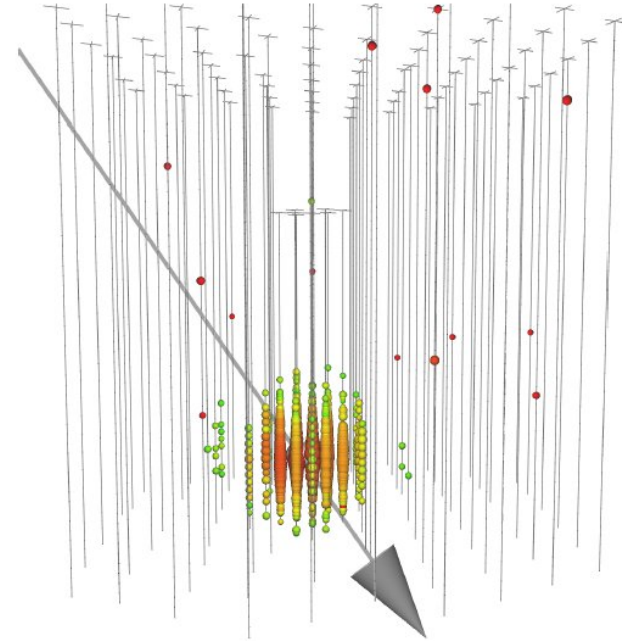
Atmospheric **Muons** > 10^9 x signal rate
Atmospheric Neutrinos > 10^3 x signal rate

Track Events



@ 100 TeV
Angular Resolution: $< 1^\circ$ 👍
Energy Resolution: \sim factor of 2 👎

Cascade Events



@ 100 TeV
Angular Resolution: $> 10^\circ$ 👎
Energy Resolution: 10% 👍

Why not search sources with cascade events?

Pros

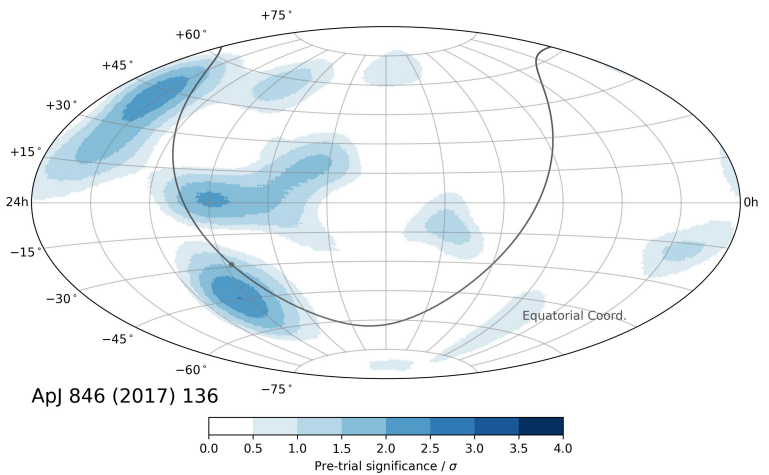
- Suppressed background
- Lower energy threshold
- Flavor ratio

Cons

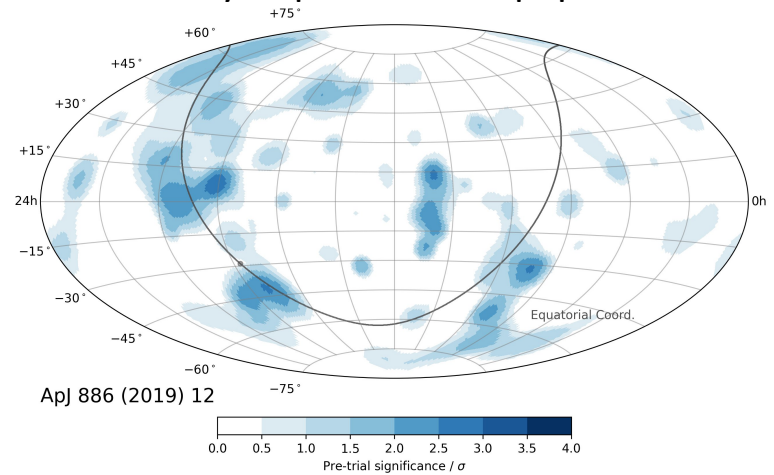
- Inferior pointing

Improving Astronomy with Cascade Events

Skymap from 2017 paper

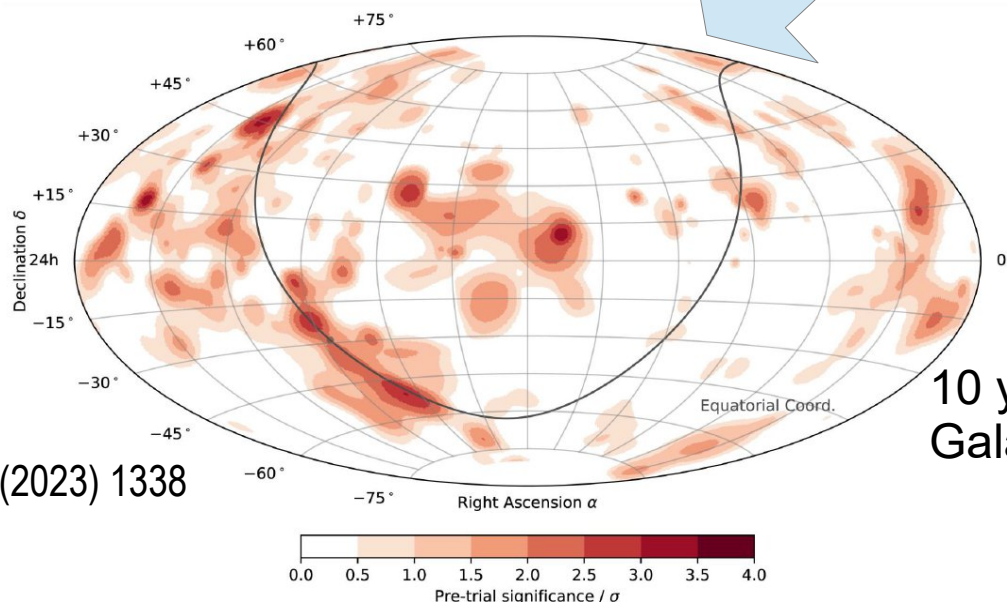


Skymap from 2019 paper



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

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

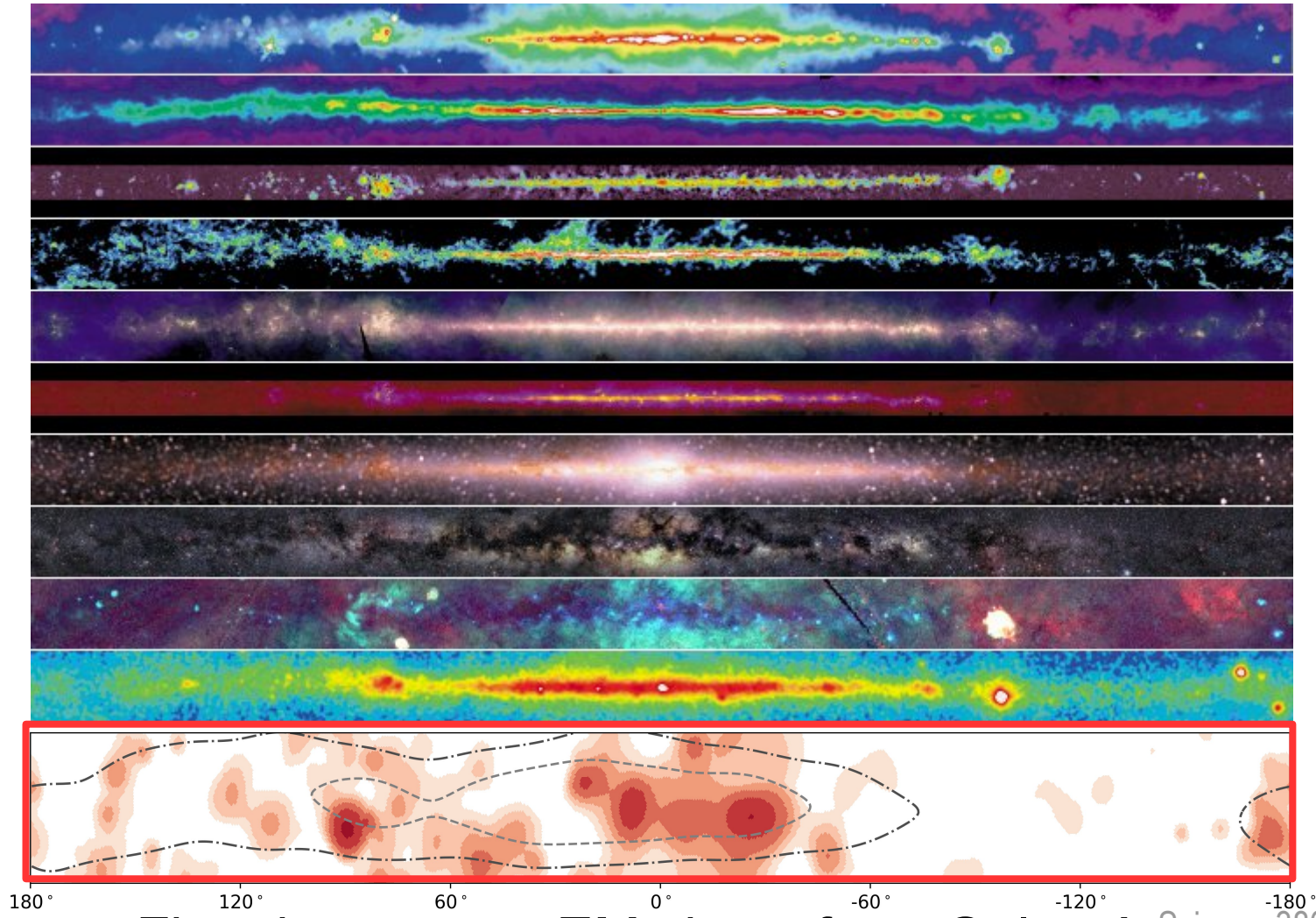


10 years of data
Galactic Plane p-value: 0.0004% (4.5σ)

The Milky Way

In Neutrinos!!!

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



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

Science 380 (2023) 1338

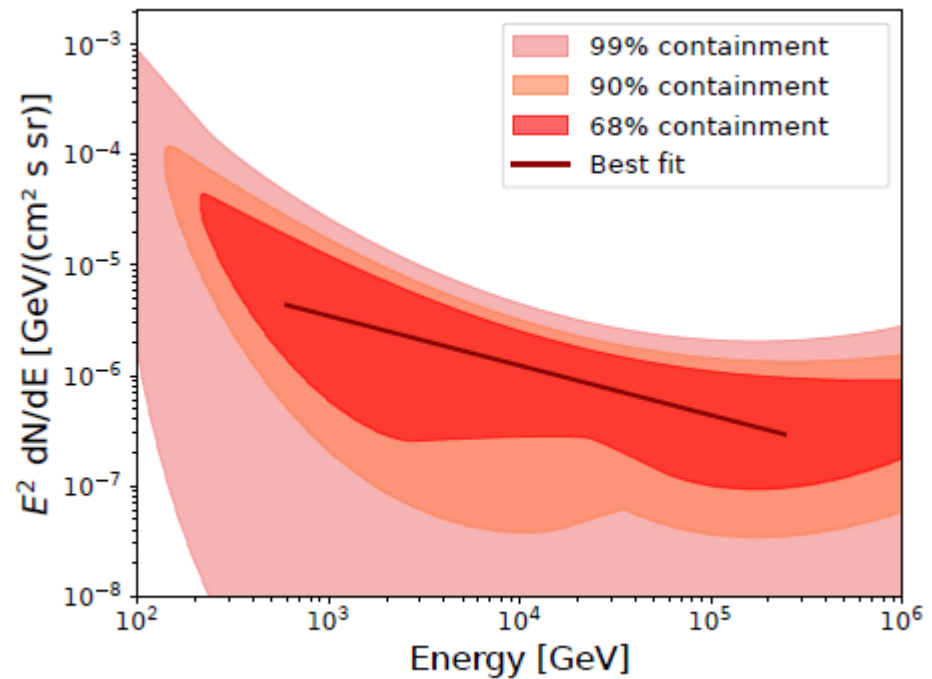
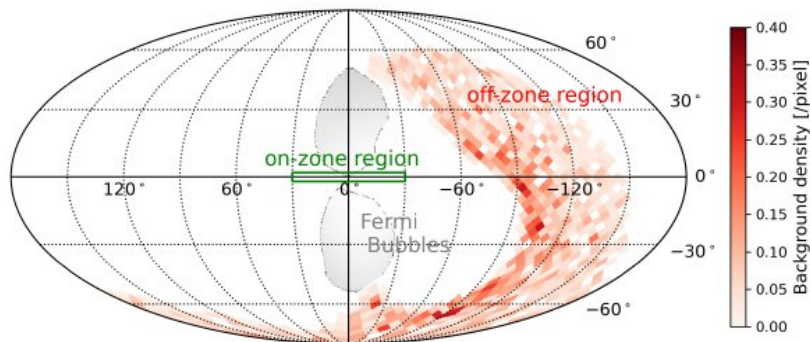
ANTARES Hints of Galactic Ridge

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

2.0σ ($\sim 4\%$) p-value

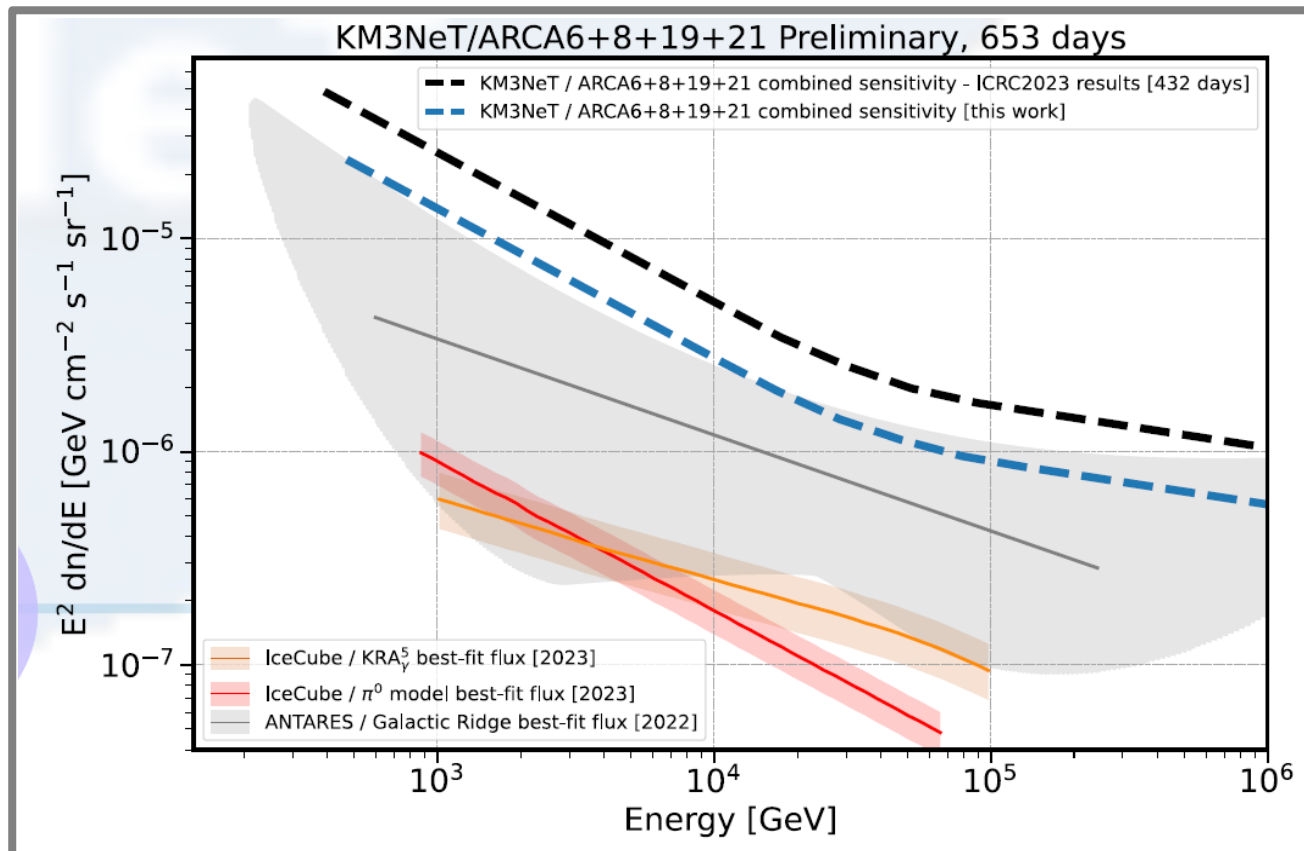
2.2σ ($\sim 2\%$) with Tracks Only

0.2σ ($\sim 44\%$) with Cascades Only



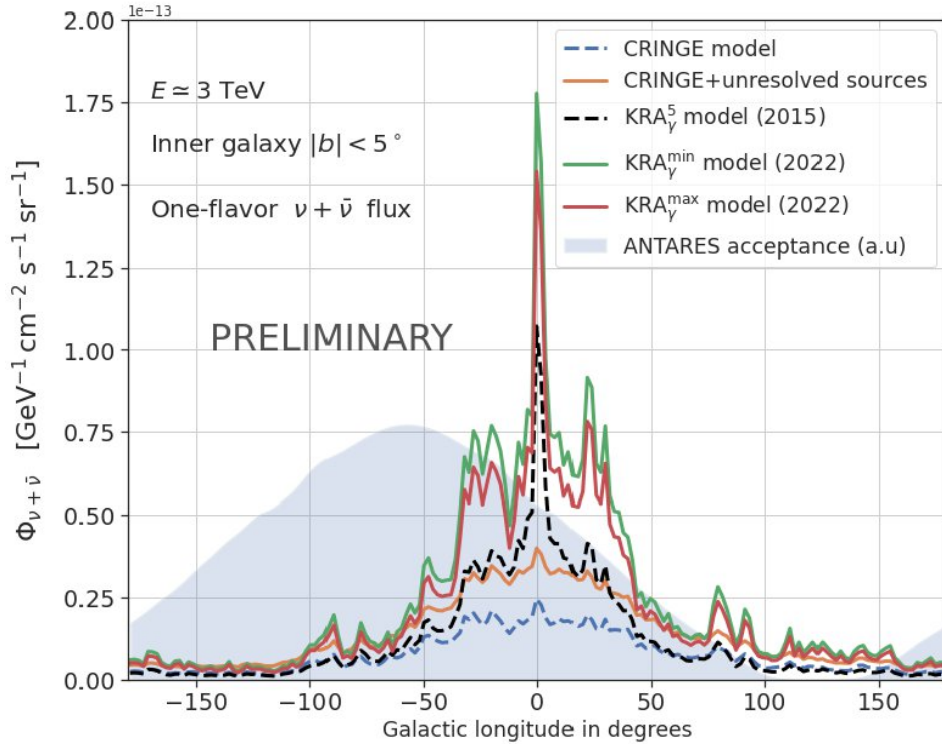
KM3NeT ARCA Catching Up

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



ANTARES Template Analysis

PoS ICRC2023 (2023) 1084



Model	r^{fit}	post-trial p-value
$\text{KRA}_\gamma^{\text{max}}$	$0.58^{+0.55}_{-0.48}$	$1.19 \cdot 10^{-1}$ (1.56σ)
$\text{KRA}_\gamma^{\text{min}}$	$0.59^{+0.57}_{-0.50}$	$1.30 \cdot 10^{-1}$ (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)

Baikal-GVD

ArXiv:2411.05608 (2024)

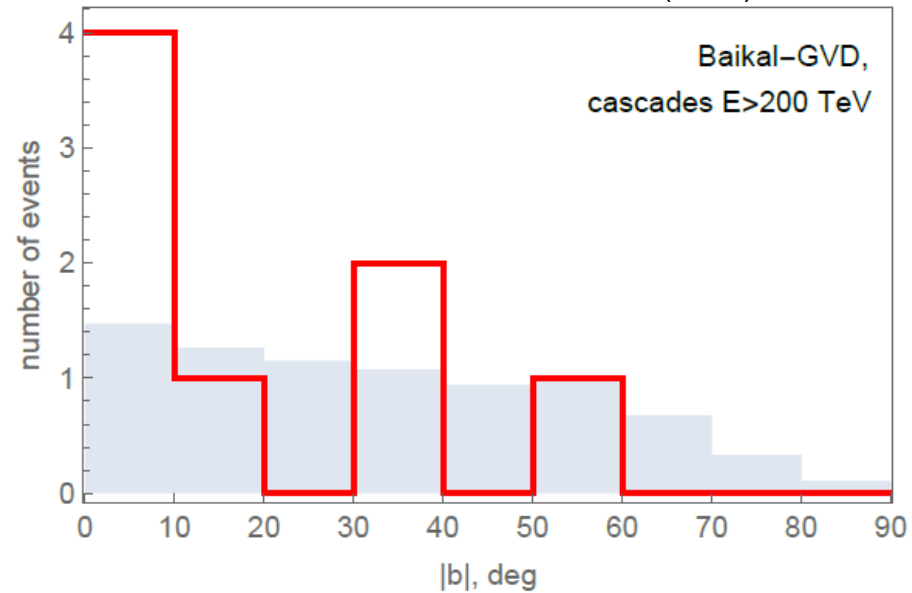
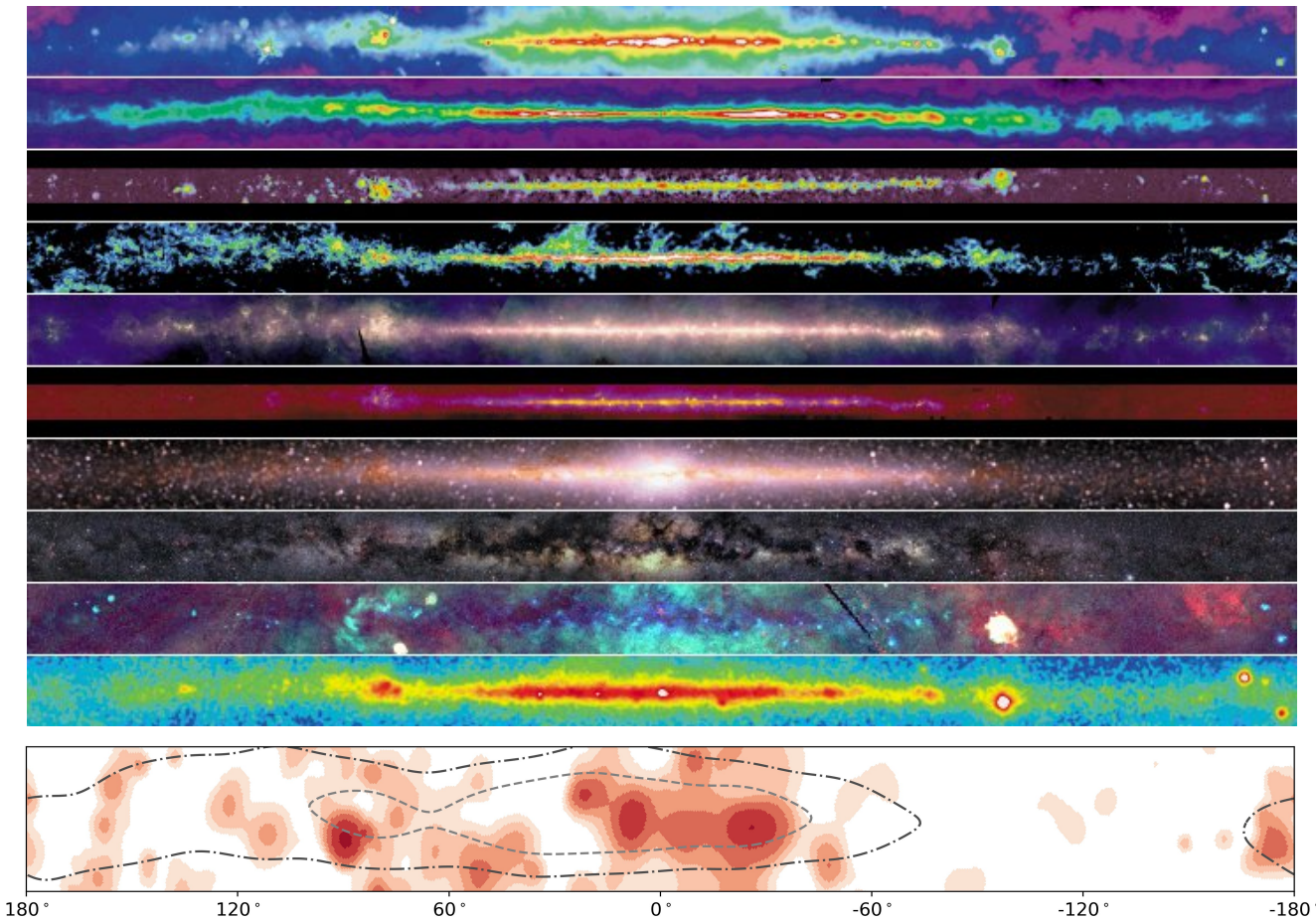


Figure 2. Observed (red line) and expected (shaded histogram) distribution of $|b|$ for Baikal-GVD cascades with $E \geq 200$ TeV.

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

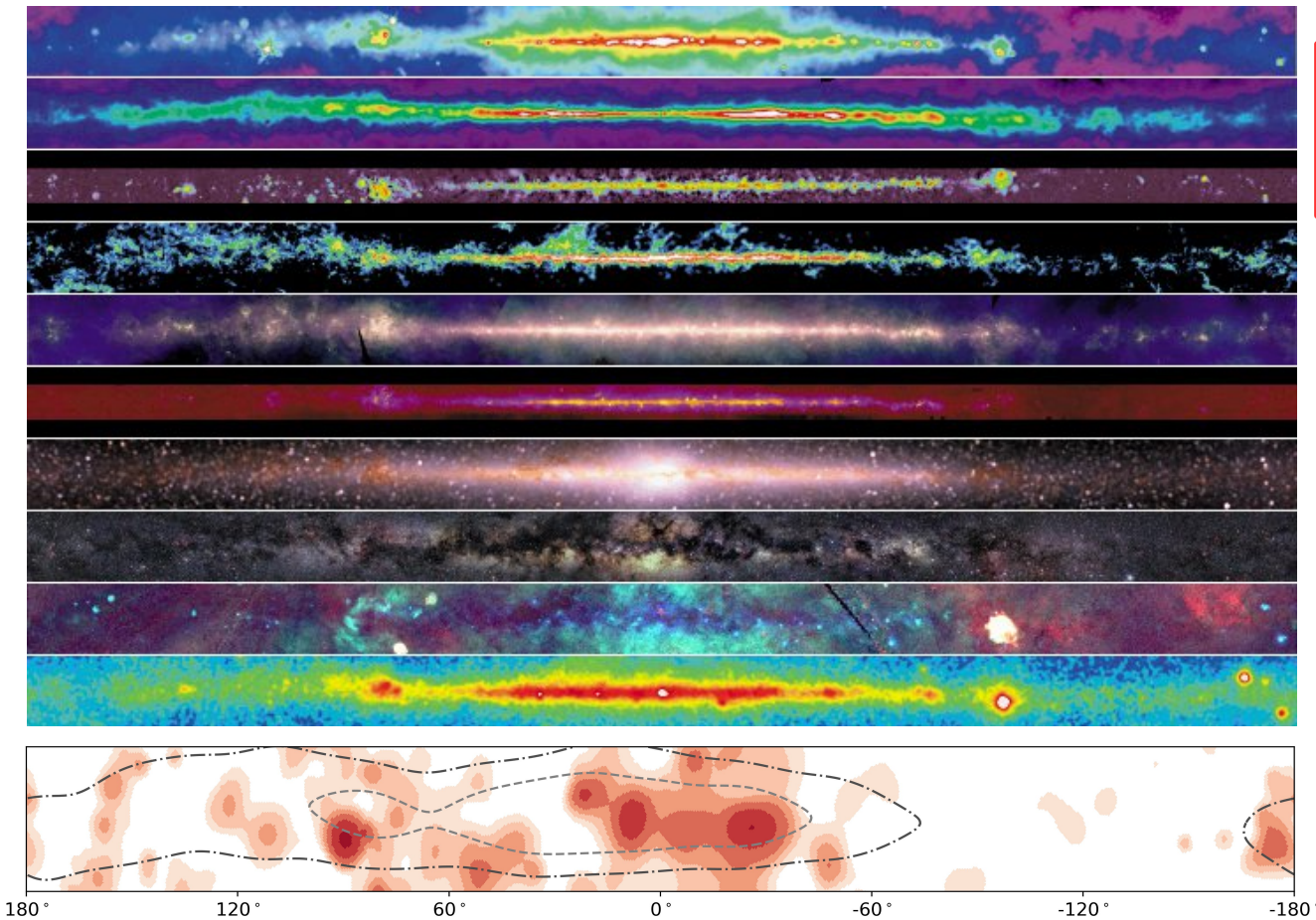


- Are there point sources mixed in with diffuse emission?
- Which ones? How much?
- Energy spectrum?
- Template discrimination?
- How does it compare to multi-wavelength emissions?

Science 380 (2023) 1338

Now that we see it, the questions...

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

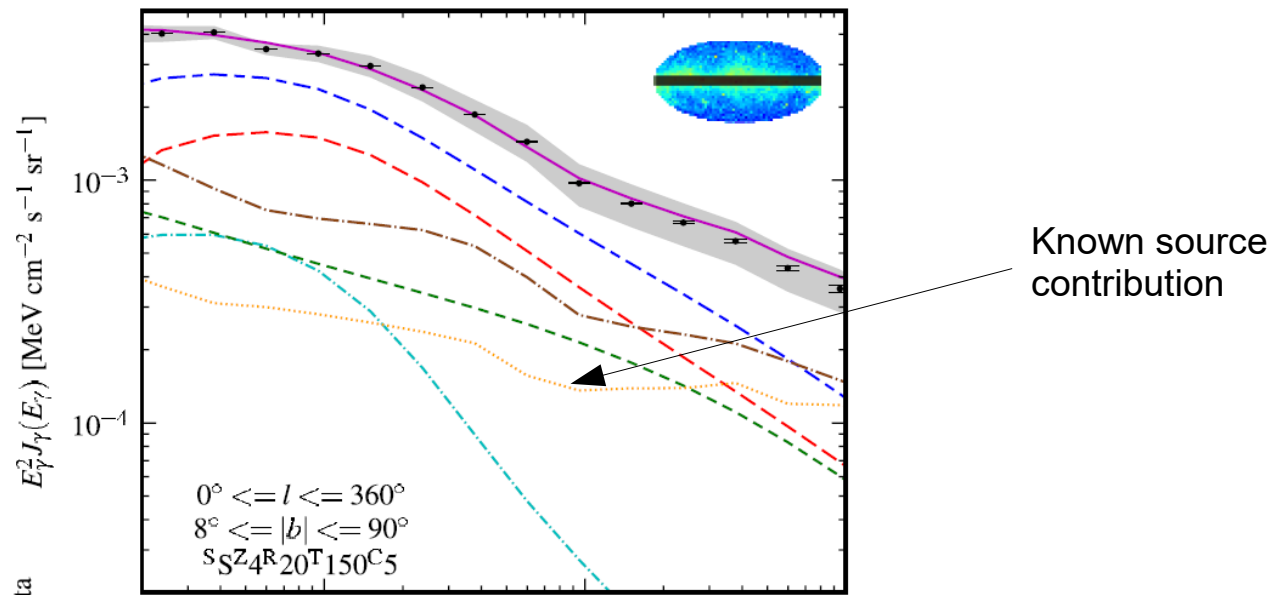


- Are there point sources mixed in with diffuse emission?
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- Energy spectrum?
- Template discrimination?
- How does it compare to multi-wavelength emissions?

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Diffuse Flux vs Resolved Sources

Nothing new (gamma rays for example)

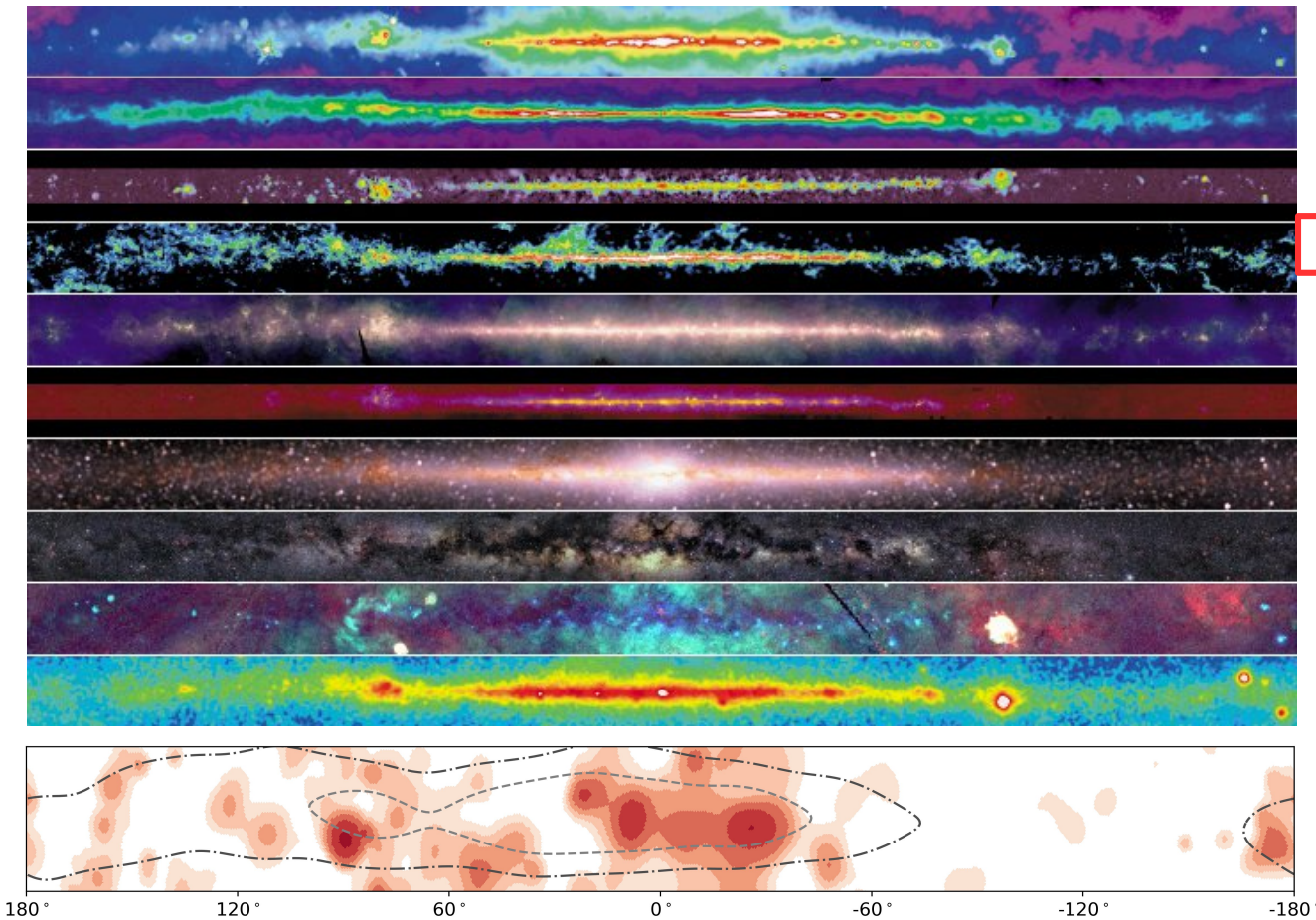


Fermi-LAT (2012) ApJ 750 3

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

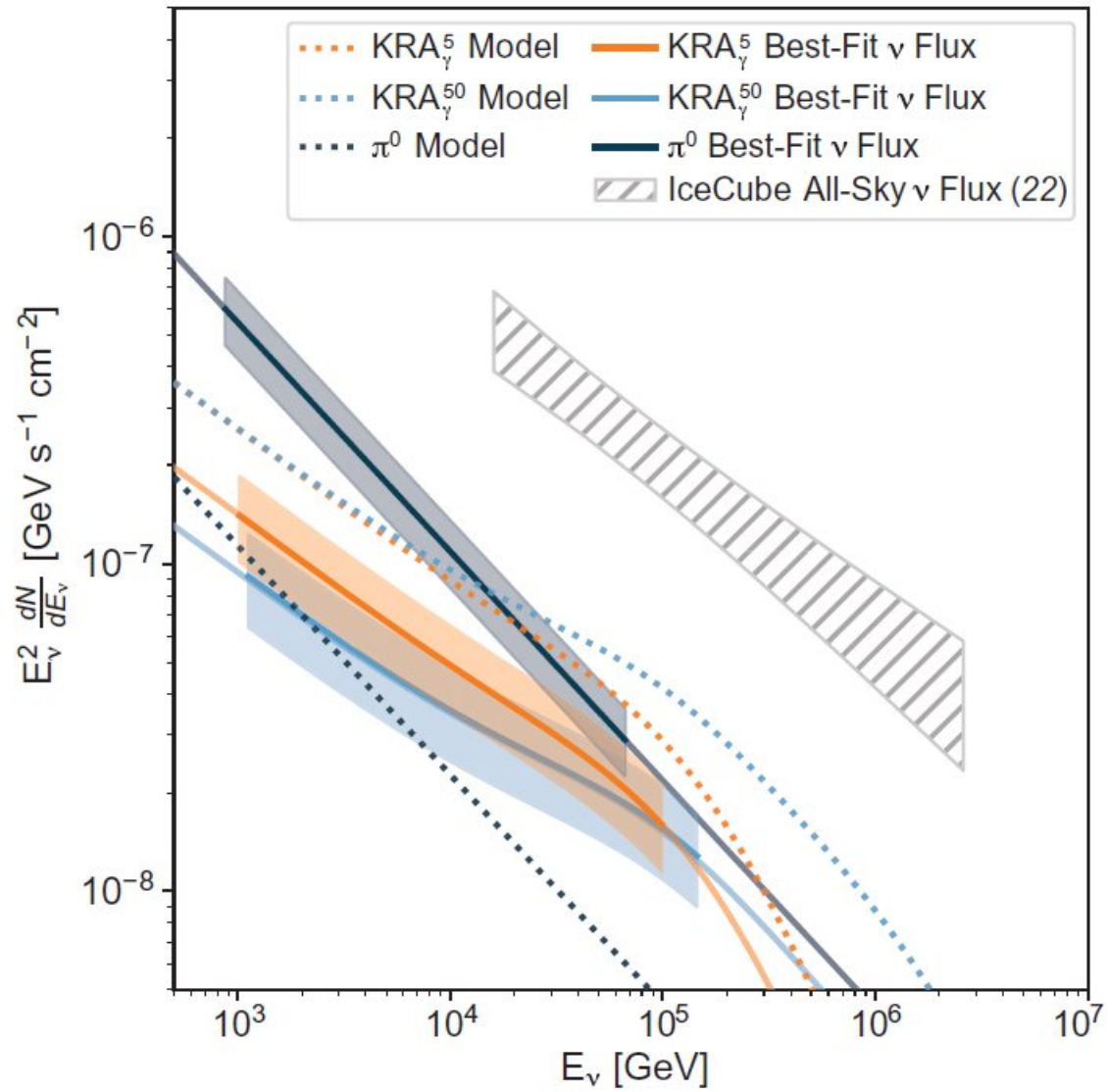
Now that we see it, the questions...

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?
- Template discrimination?
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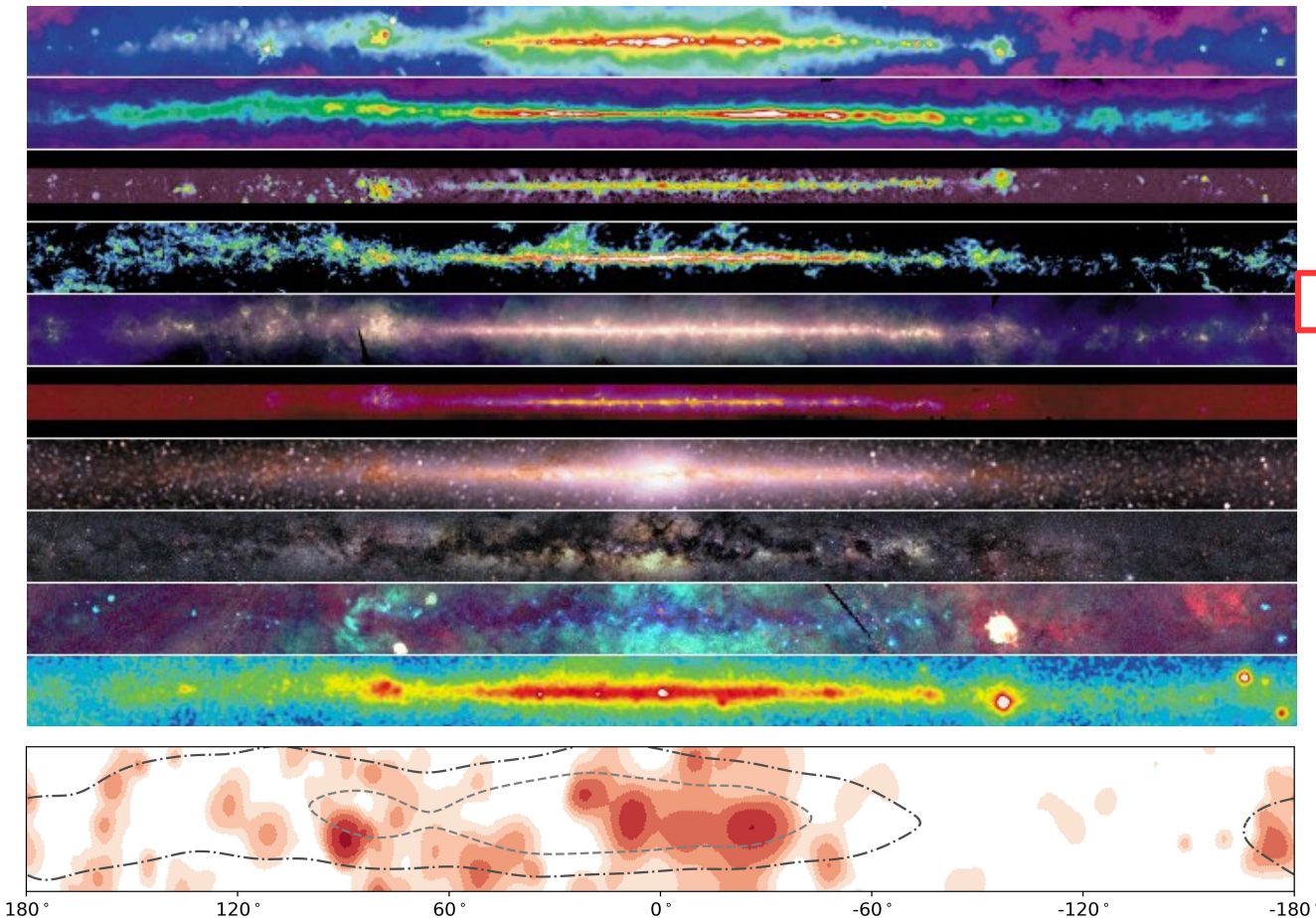


These are not individual energy bins!

A model fit \rightarrow only normalization allowed to float!

Now that we see it, the questions...

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

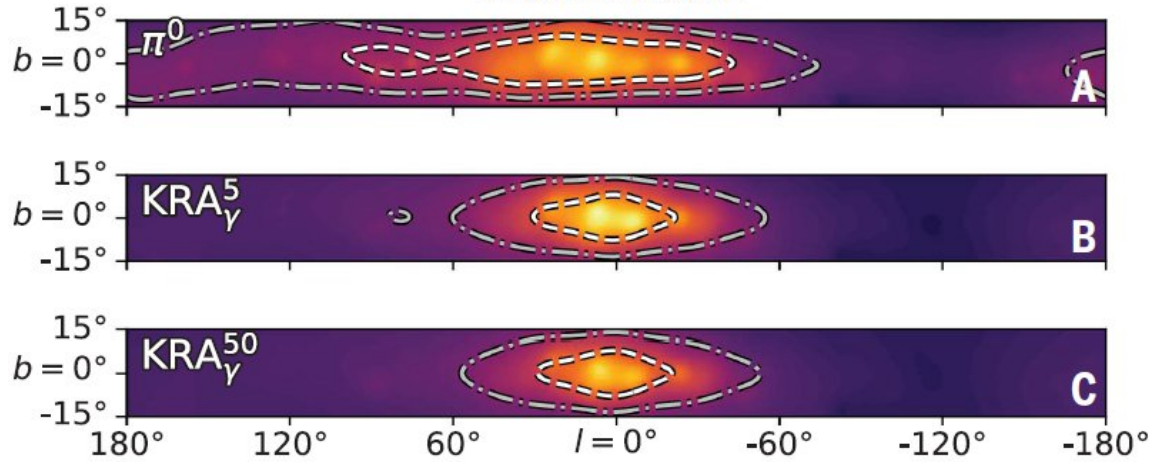


- Are there point sources mixed in with diffuse emission?
- Which ones? How much?
- Energy spectrum?
- **Template discrimination?**
- How does it compare to multi-wavelength emissions?

Science 380 (2023) 1338

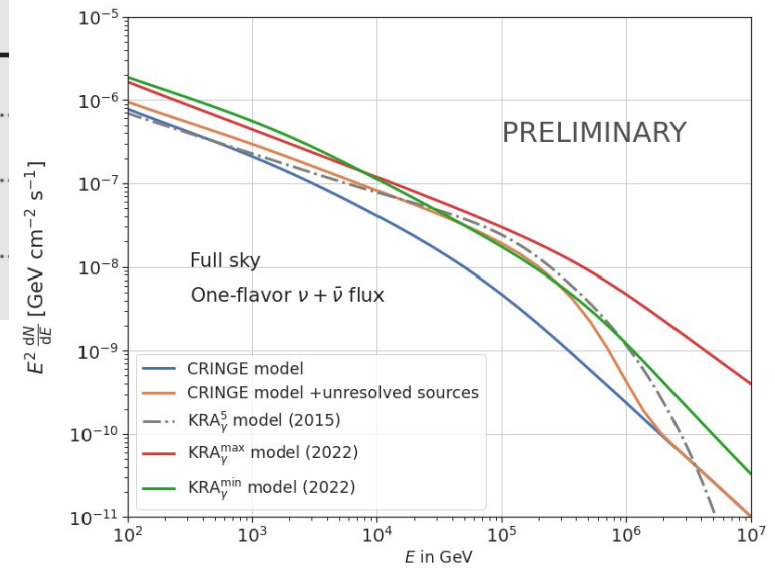
Science 380 (2023) 1338

Observed data



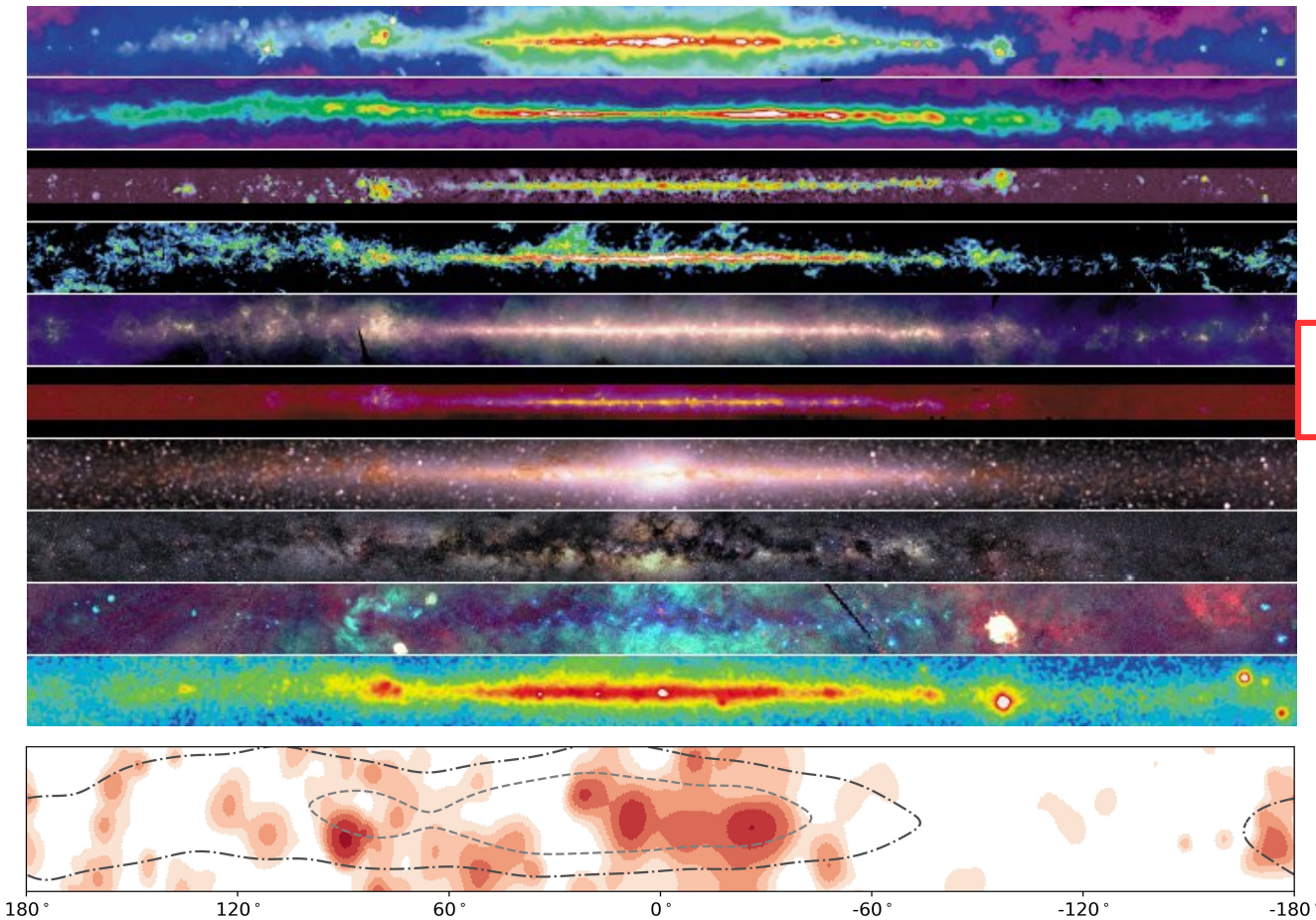
	Flux sensitivity Φ	P value
<i>Diffuse Galactic plane analysis</i>		
π^0	5.98	1.26×10^{-6} (4.71σ)
KRA_γ^5	$0.16 \times \text{MF}$	6.13×10^{-6} (4.37σ)
KRA_γ^{50}	$0.11 \times \text{MF}$	3.72×10^{-5} (3.96σ)

PoS ICRC2023 (2023) 1084



Now that we see it, the questions...

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



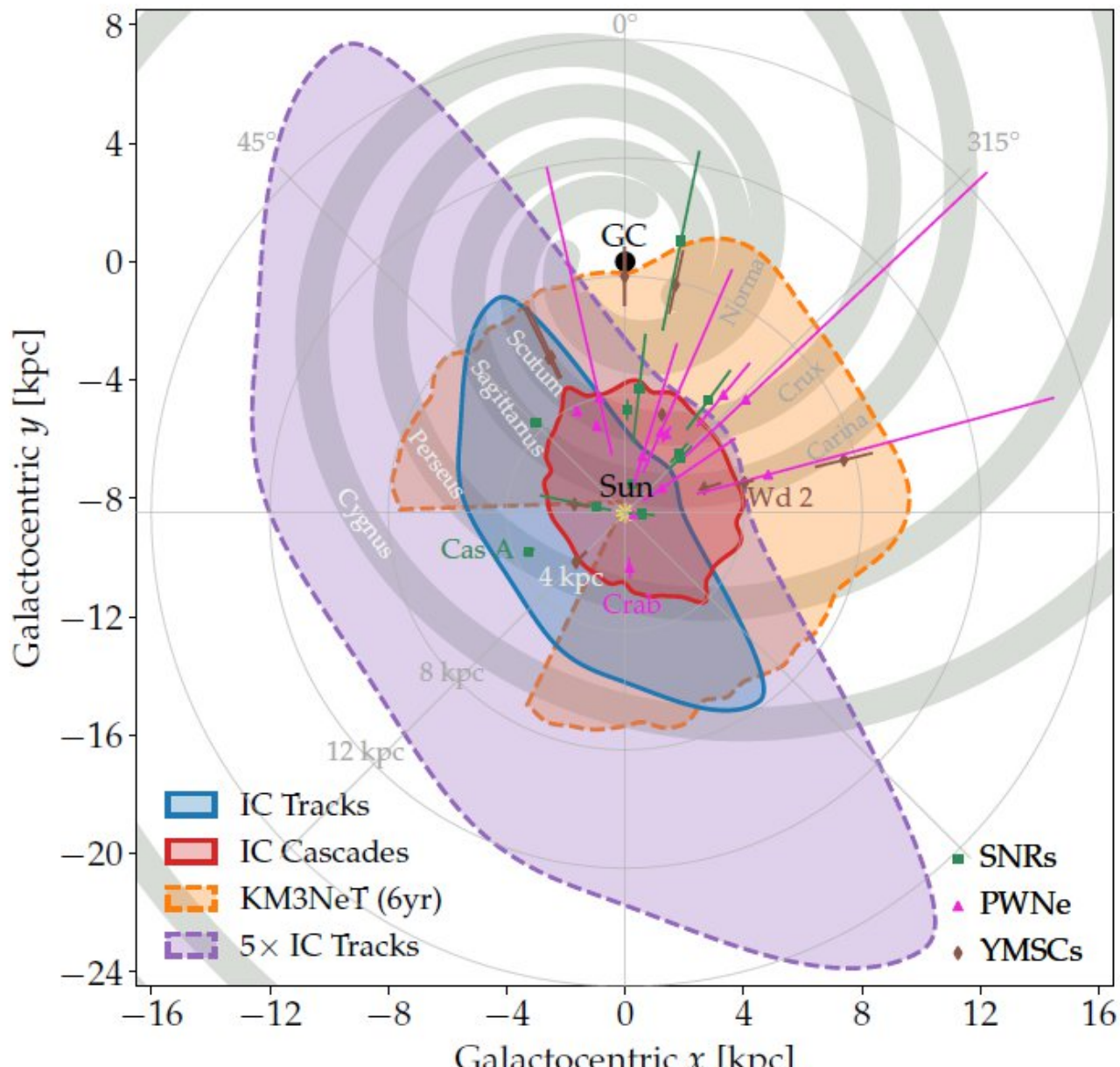
- Are there point sources mixed in with diffuse emission?
- Which ones? How much?
- Energy spectrum?
- Template discrimination?
- How does it compare to multi-wavelength emissions?

Science 380 (2023) 1338

Future of Galactic Neutrino Observations

Galactic Neutrino Astronomy Reach

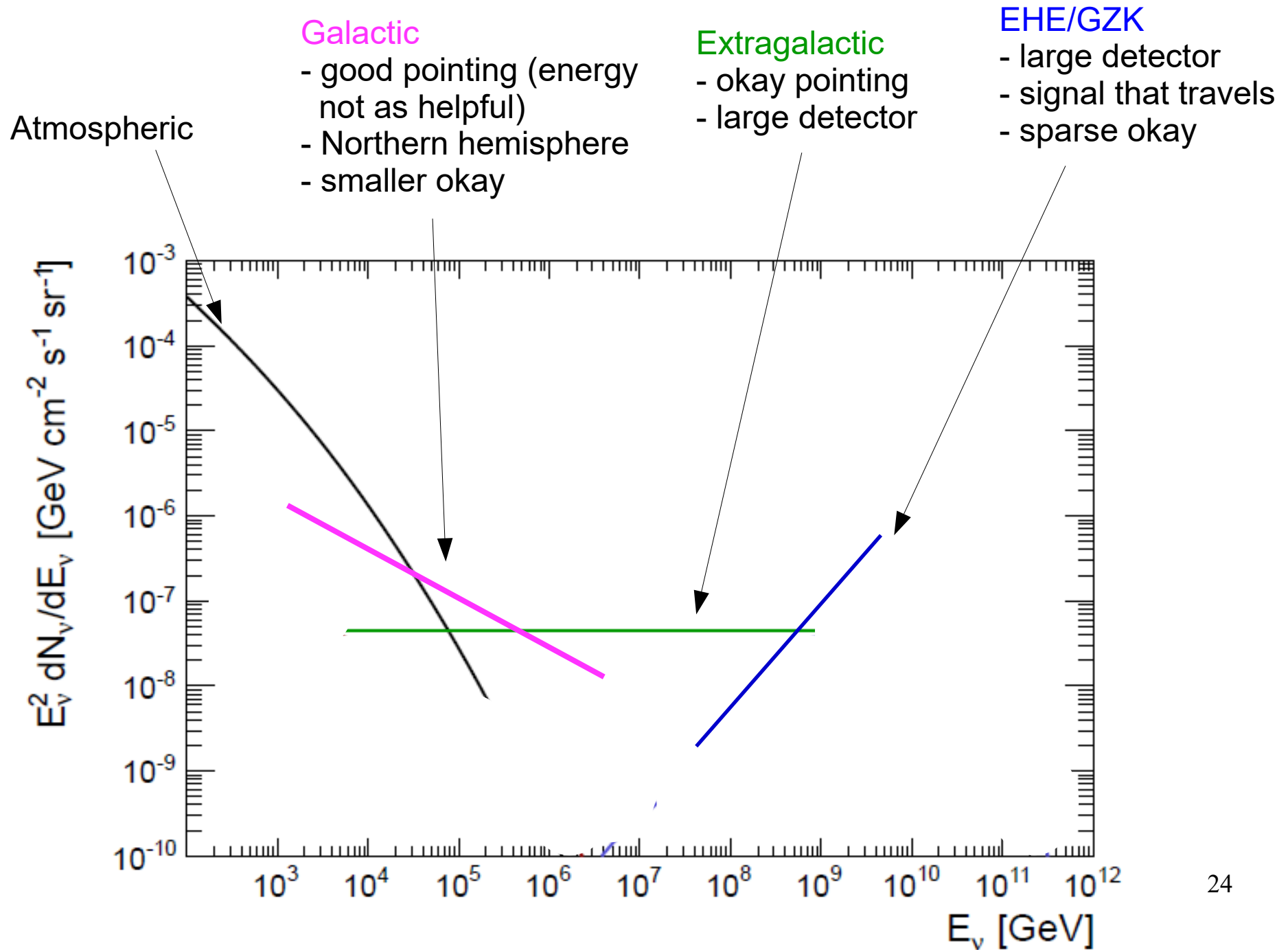
Discovery horizon for $L_{100\text{TeV}} = 10^{34}$ erg/s ($\Phi \propto E^{-2}$)



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

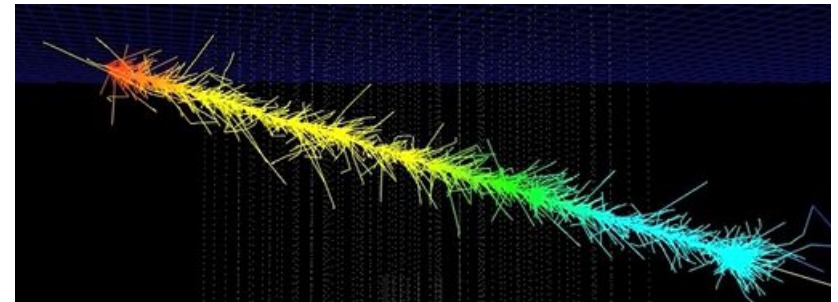
- good pointing
- large detector

EHE/GZK

- large detector
- signal that travels
- sparse okay

Water Cherenkov

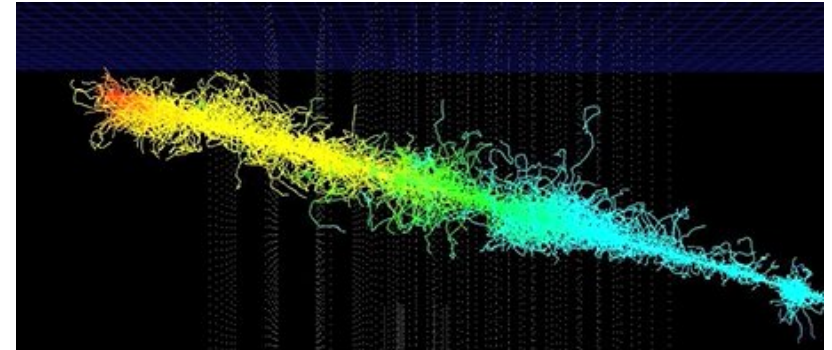
- Scattering ✓ → Good Pointing
- Absorption ✗ → Harder to make large detector



Courtesy: Claudio Kopper (Erlangen)

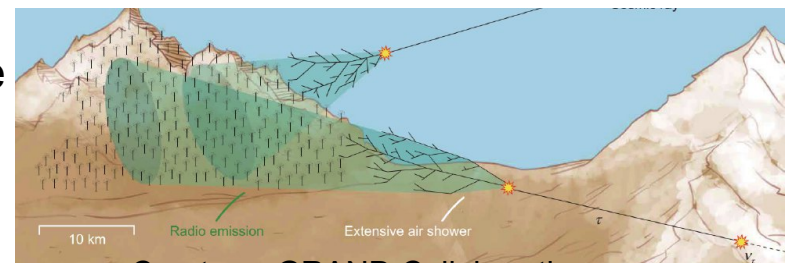
Ice Cherenkov

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

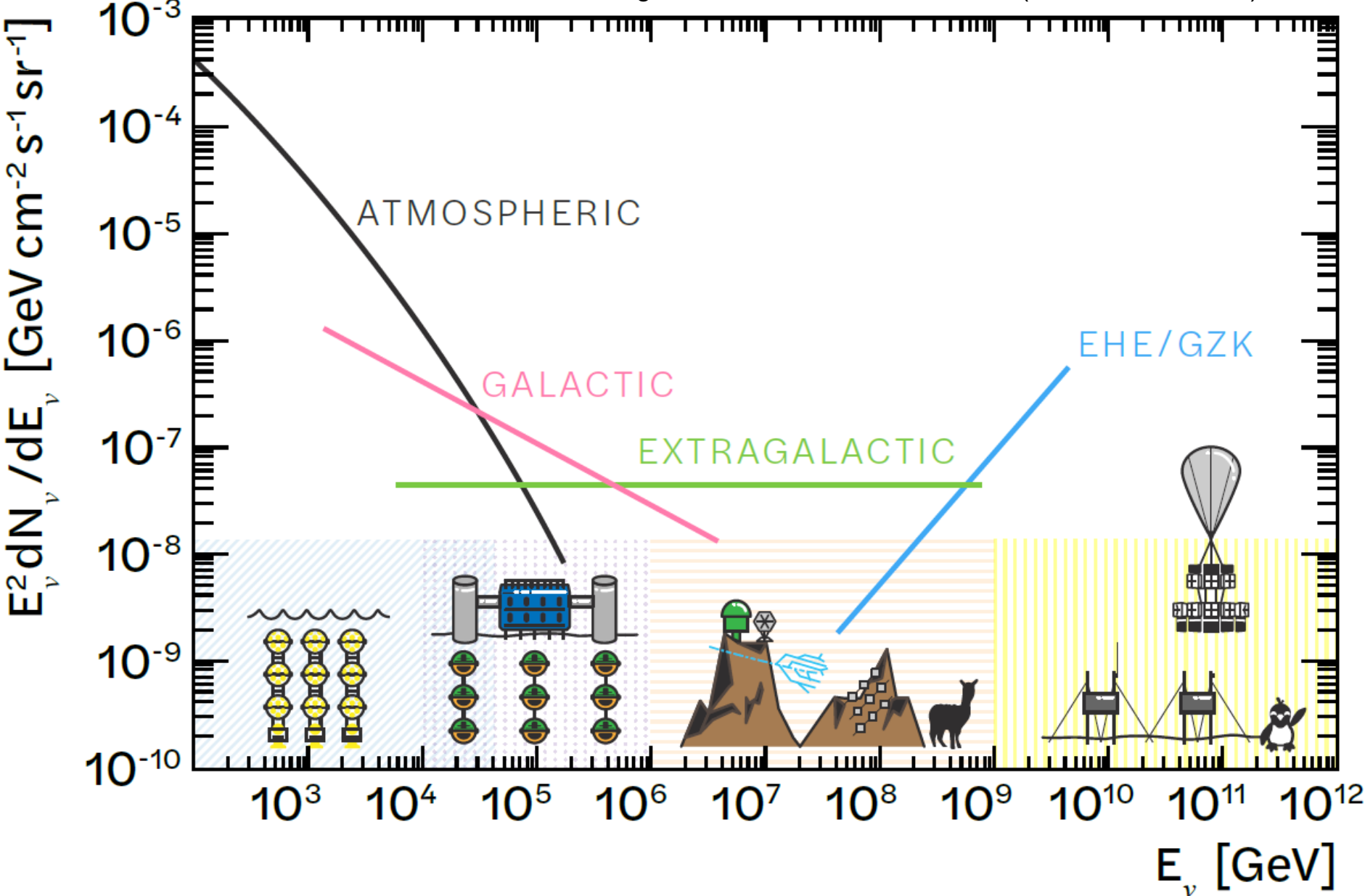


Radio

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



Courtesy: GRAND Collaboration



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)



NOTE
PROJECTS MARKED IN **BLUE** ARE COMPLETE OR UNDER CONSTRUCTION.
PROJECTS MARKED IN **WHITE** ARE PROPOSED.

KM3NeT/ARCA

28 DUs Deployed



31x 3" PMTs



43 cm

11 Jun 2024

230 Detection Units
18 DOMs / DU

1 Gton detector

800 m

3500 m

6

Slide from J. Coelho (Neutrino2024)

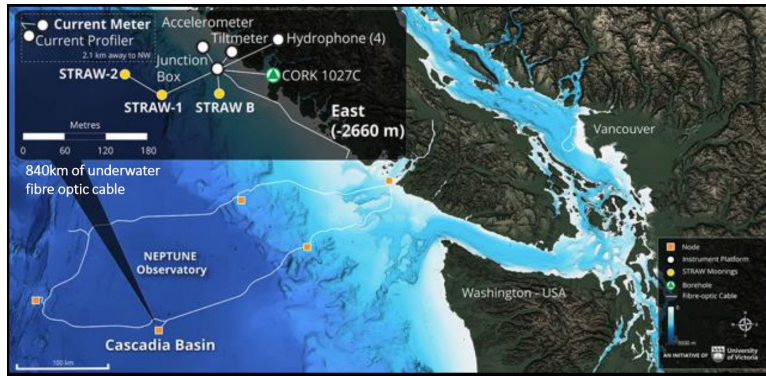
New Hemisphere New Comers



P-ONE

Pacific Ocean Neutrino Explorer

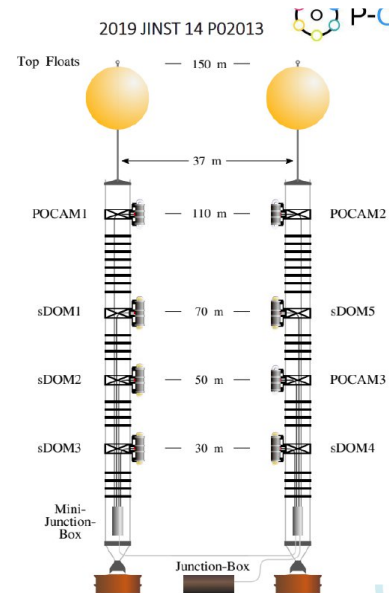
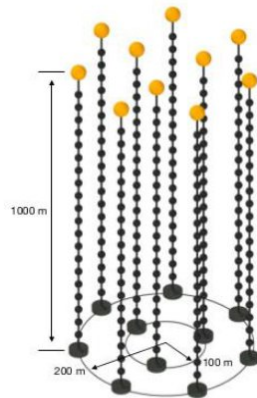
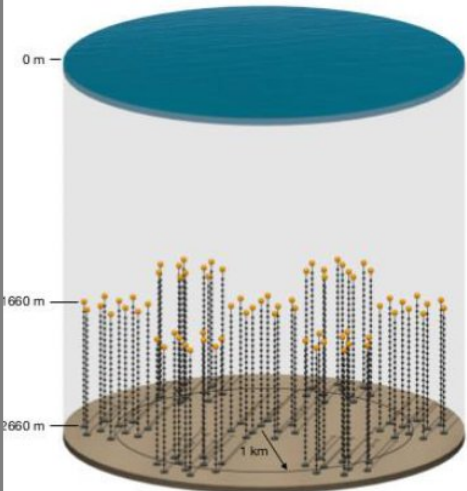
Leverage existing facilities



Huge telescopes in the South China Sea

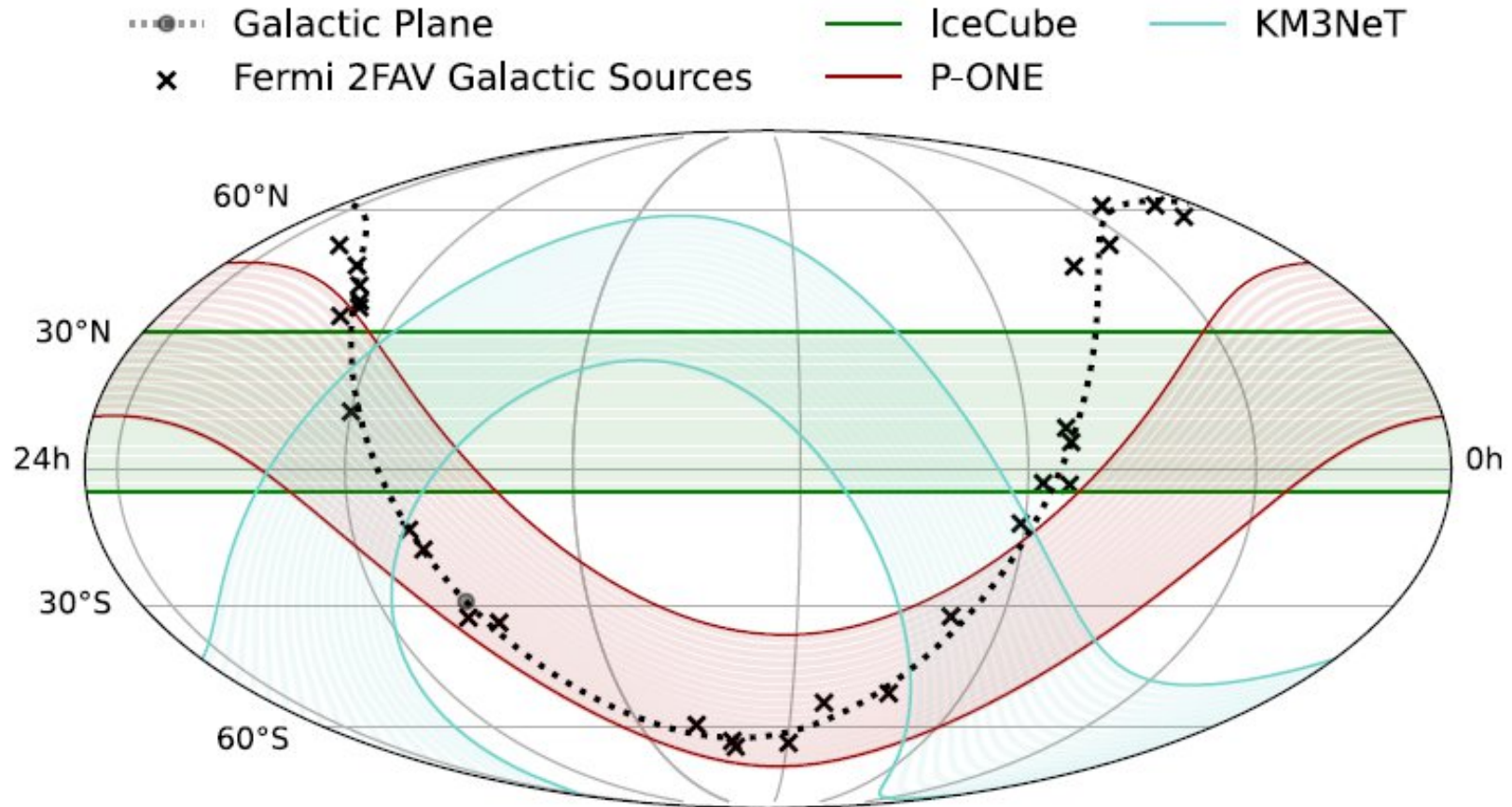


Pathfinder strings deployed and recovered



Images: courtesy P-ONE collaboration

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 (ν_e) 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_e 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

