Galactic and Extragalactic Neutrino Factories

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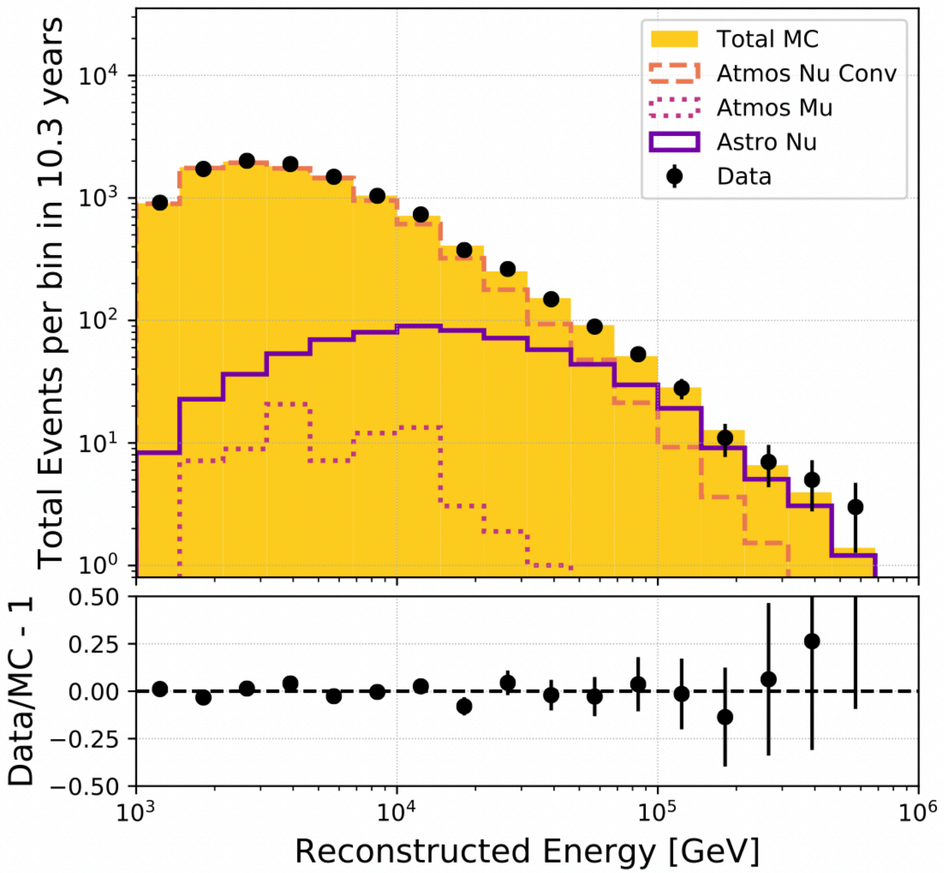
University of Wisconsin-Madison

TeVPA, Chicago, IL
August 28, 2024

(Surprising) Facts about Neutrino Sources

Diffuse neutrino flux with Starting Tracks

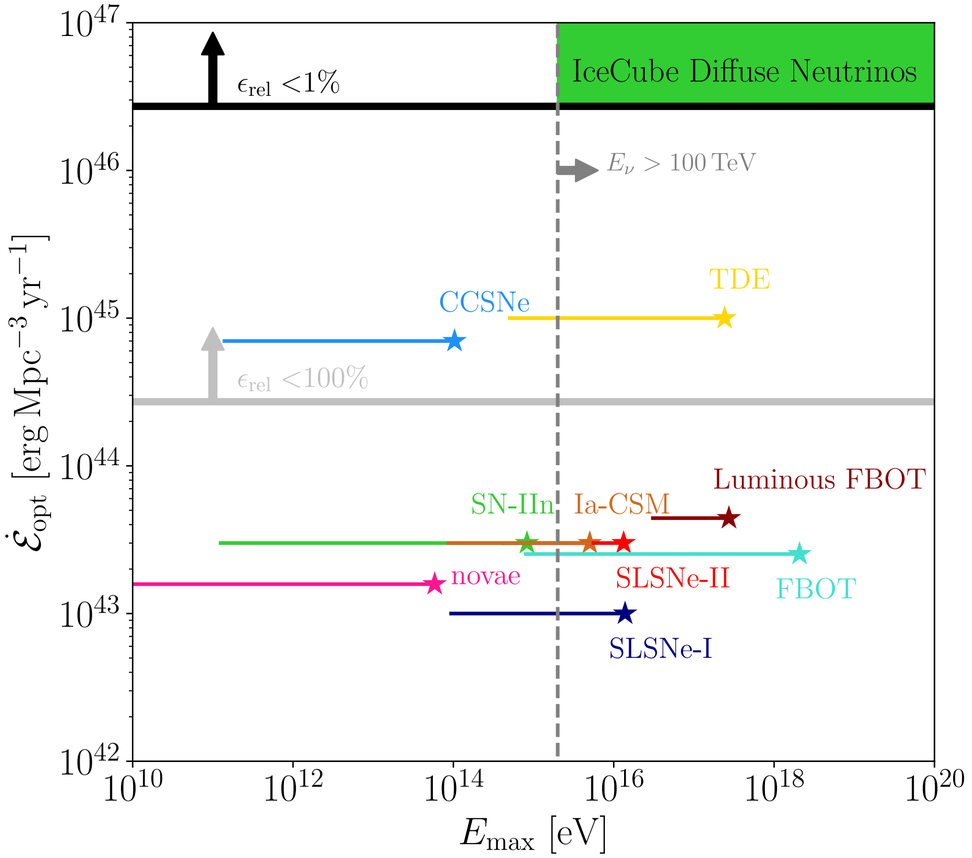


IceCube Coll., PRD (2024)

- **They exist!**

  A diffuse flux of astrophysical neutrinos is detected at TeV-PeV energies by IceCube.

(Surprising) Facts about Neutrino Sources

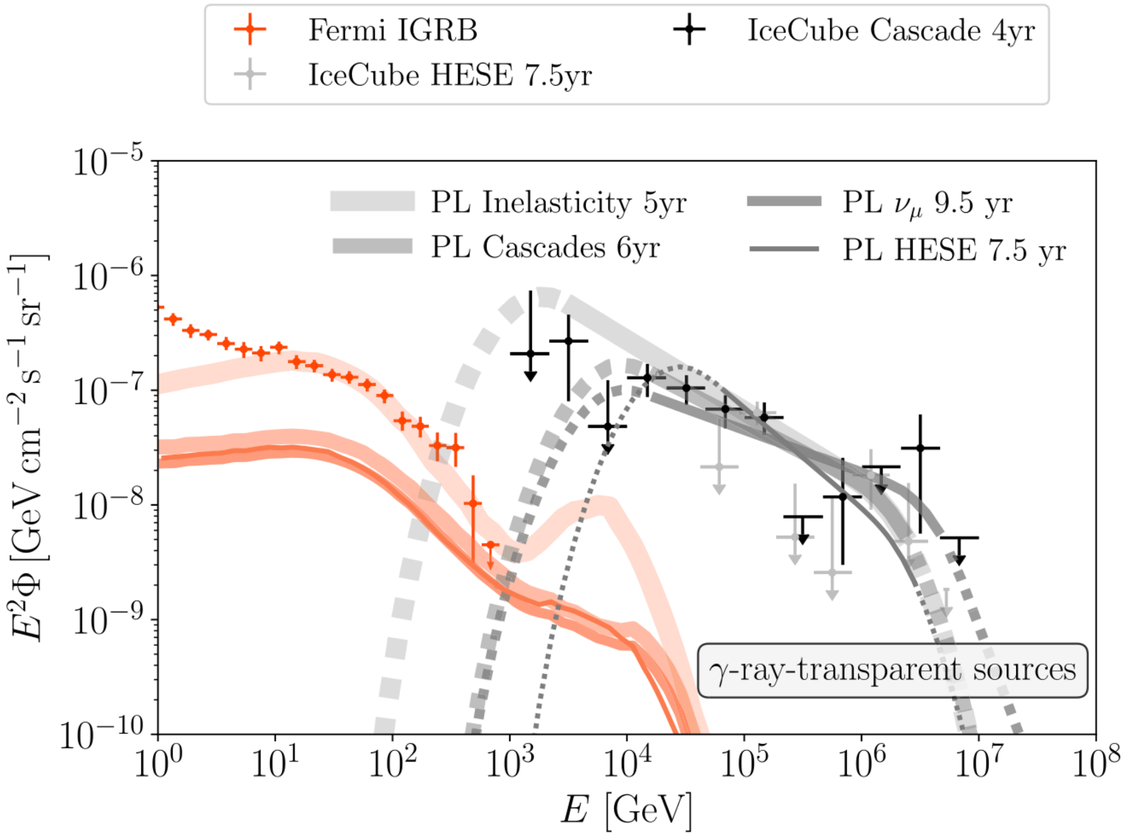


KF, Metzger, Vurm, Aydi, Chomiuk ApJ (2020)

- They exist!
- **There are a lot of them**

  Transients power by non-relativistic shocks can barely explain the diffuse neutrinos.

(Surprising) Facts about Neutrino Sources

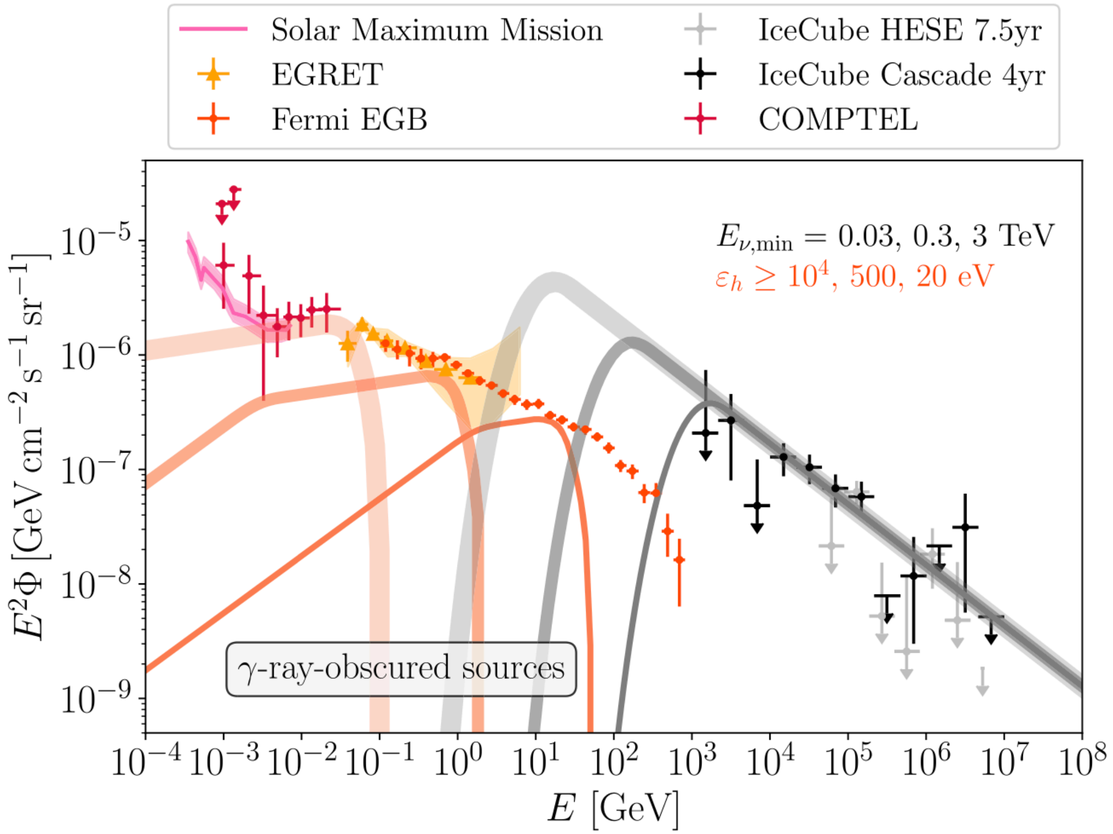


- They exist!
- There are a lot of them
- **They could be gamma-ray-opaque**

  Hints of gamma-ray obscuration suggested by **diffuse flux**

Murase, Guetta, Ahlers PRL (2016)
Capanema et al PRD (2020), JCAP (2021)
KF, Gallagher, Halzen, ApJ (2022)

(Surprising) Facts about Neutrino Sources



KF, Gallagher, Halzen, ApJ (2022)

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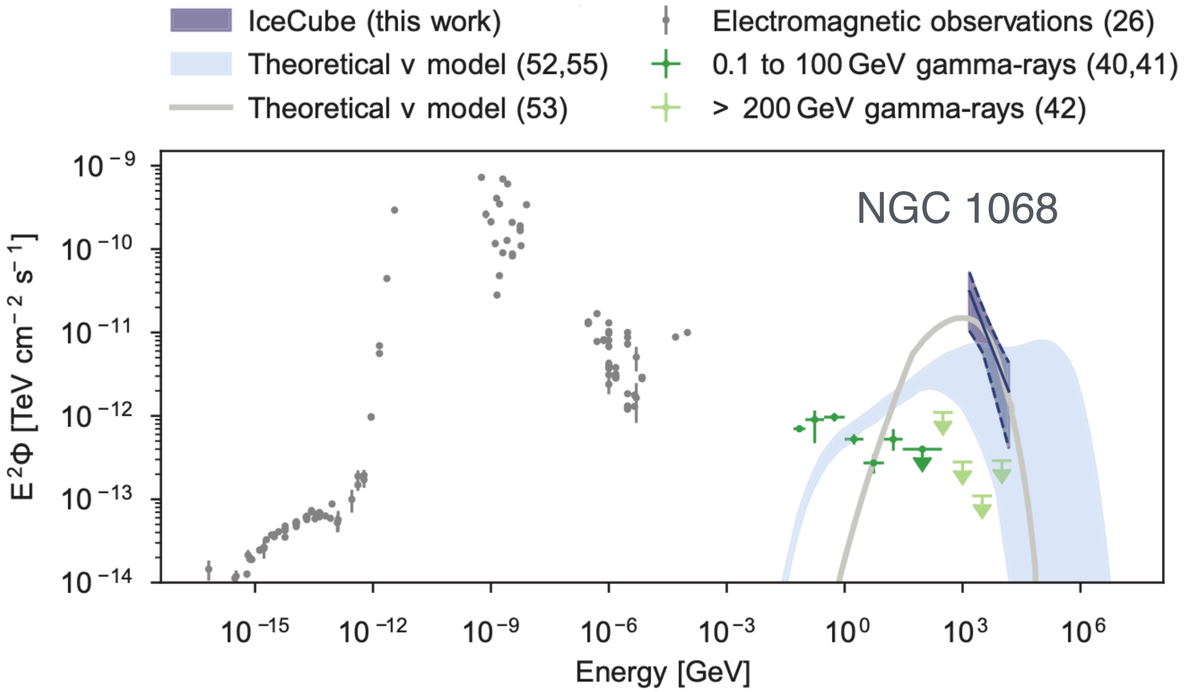
  Hints of gamma-ray obscuration suggested by diffuse flux. **Attenuated gamma rays may show up at lower energies.**

(Surprising) Facts about Neutrino Sources



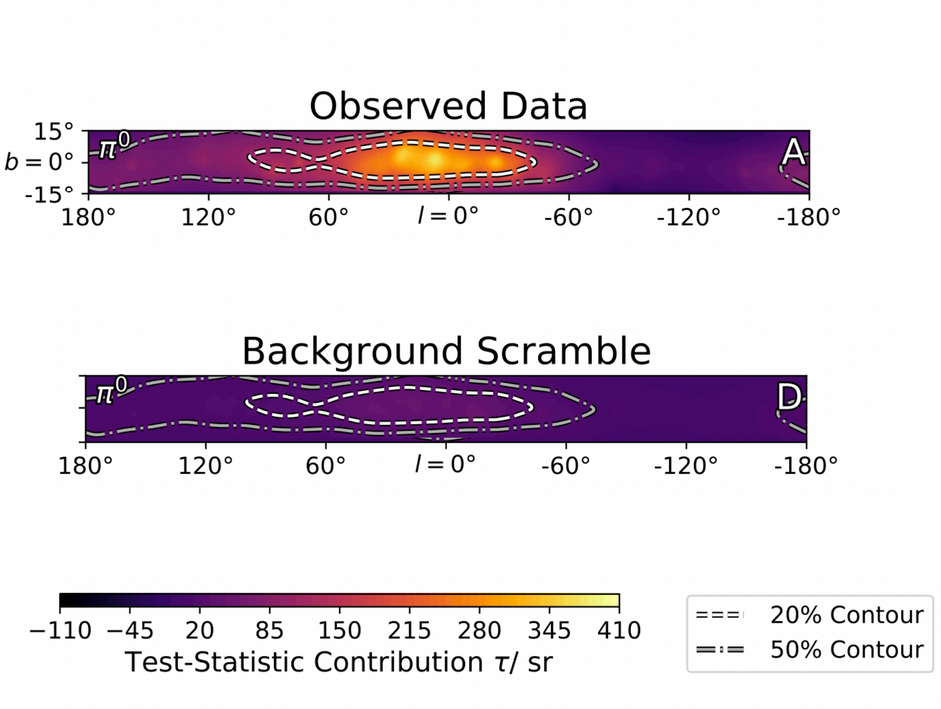
IceCube Collaboration, Science (2022)

IceCube Collaboration, 2406.06684, 2406.07601

- They exist!
- There are a lot of them
- **They could be gamma-ray-opaque**

  Hints of gamma-ray obscuration suggested by diffuse flux and **individual sources.**

(Surprising) Facts about Neutrino Sources



IceCube Collaboration, Science (2023)

- They exist!
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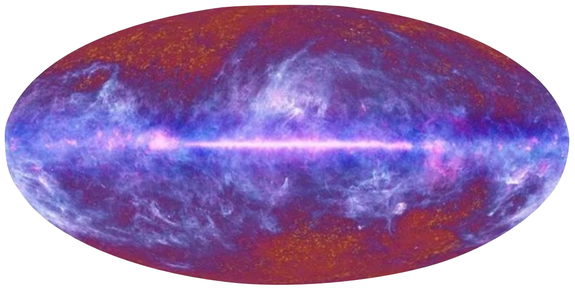
- **Some of them are Galactic**

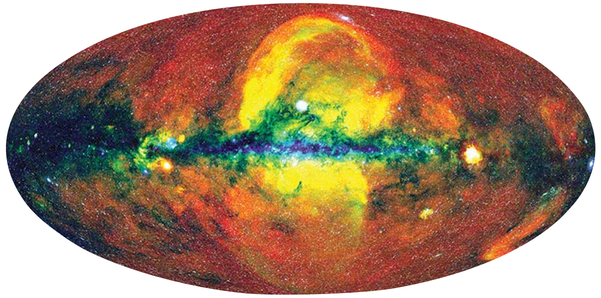
  Neutrino emission is observed from the Galactic plane

(Surprising) Facts about Neutrino Sources

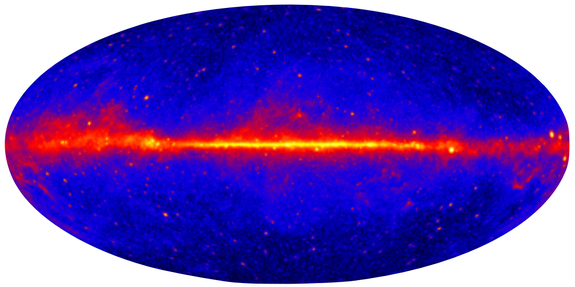
Planck 143 GHz



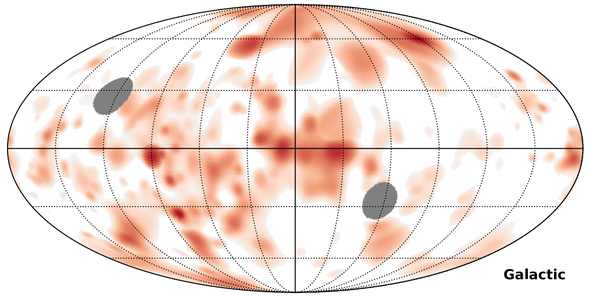
eROSITA 0.2-10 keV



Fermi-LAT 1-100 GeV



IceCube neutrinos



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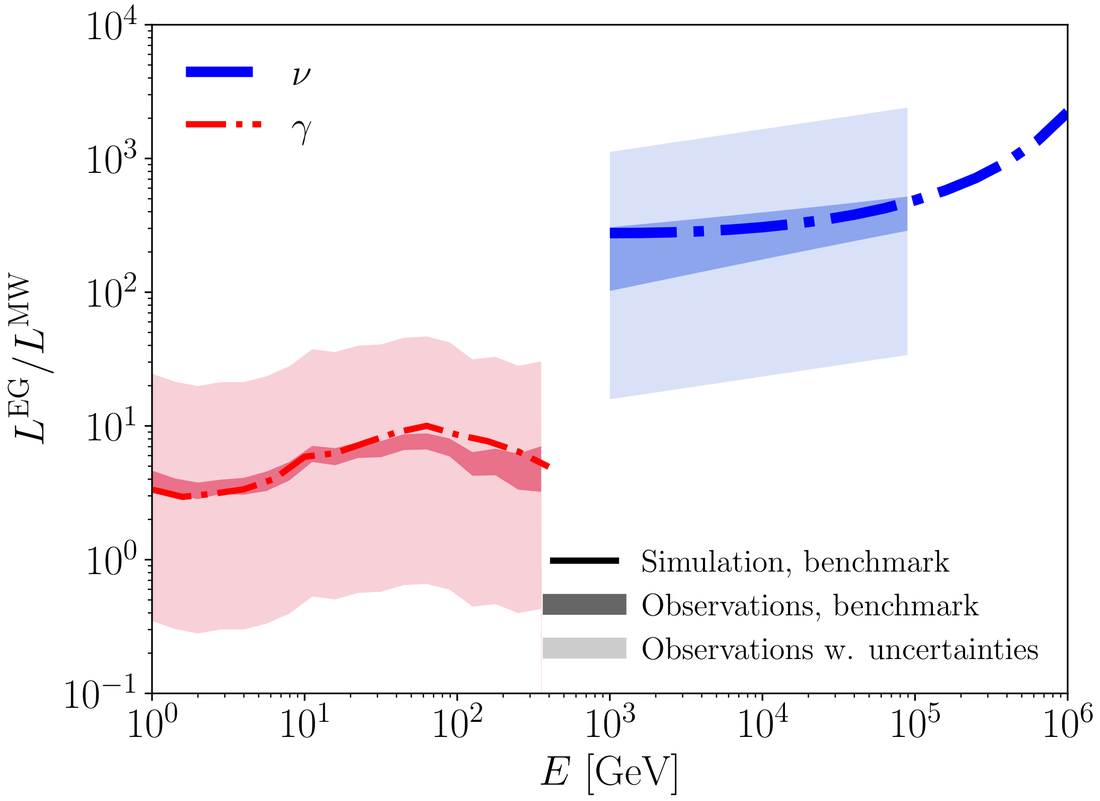
- **Extragalactic sources are more powerful**

(Surprising) Facts about Neutrino Sources



KF, Gallagher, Halzen, Nature Astronomy (2023)

- They exist!
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- **Extragalactic sources are more powerful**

  Our Galaxy has not hosted the type of sources that dominates the isotropic neutrino sky in the past few tens of kyrs.

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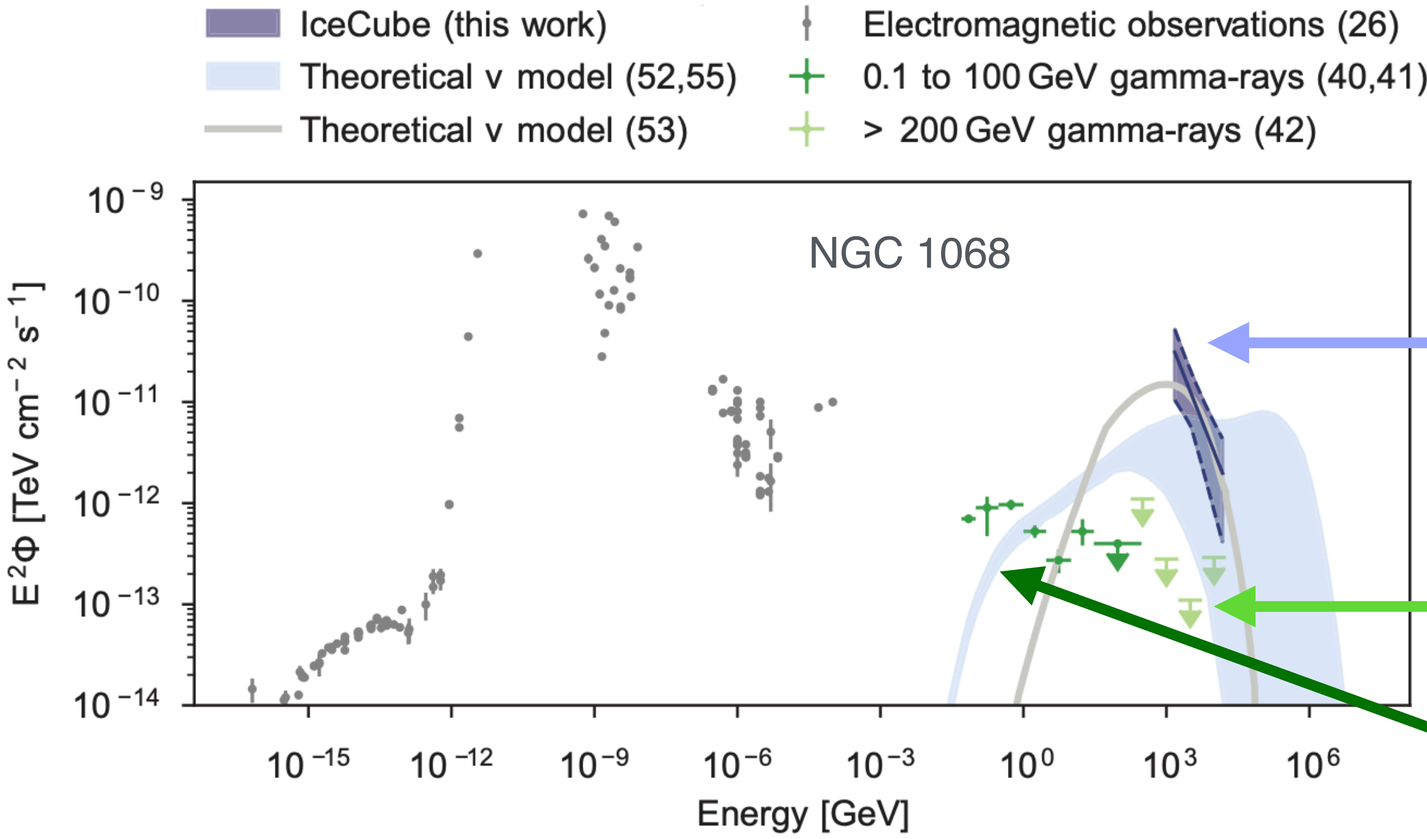
Gamma-ray-Opaque Neutrino Sources



Production of TeV ν needs pp interaction or $p\gamma$ interaction with ~10 keV X-ray.

Optical depth of IR/optical photons $\gtrsim 7$

Optical depth of X-rays $\gtrsim 4$

IceCube Collaboration, Science (2022)

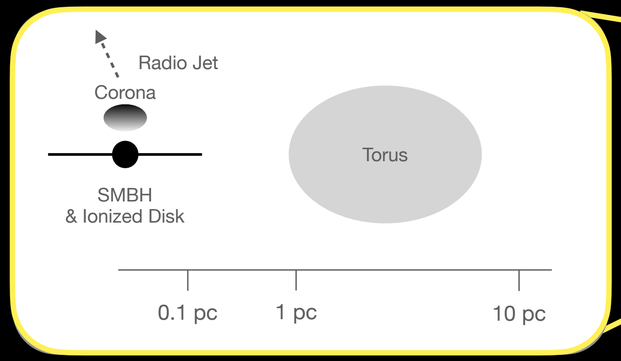
NGC 1068's Obscured Core

$$L_{\rm Edd} = 2.5 \times 10^{45}\,{\rm erg\,s^{-1}}$$

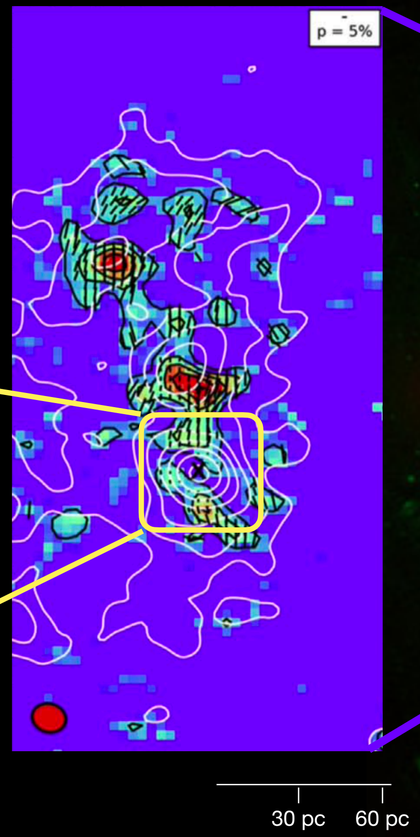
$$L_{\rm bol} = (0.4 - 4.7) \times 10^{45}\,{\rm erg\,s^{-1}}$$

$$L_{2-10\,{\rm keV}} = 10^{43-44}\,{\rm erg\,s^{-1}}$$

$$L_{\nu} = 2.9 \times 10^{42}\,{\rm erg\,s^{-1}}$$



Sketch of the inner 10 pc

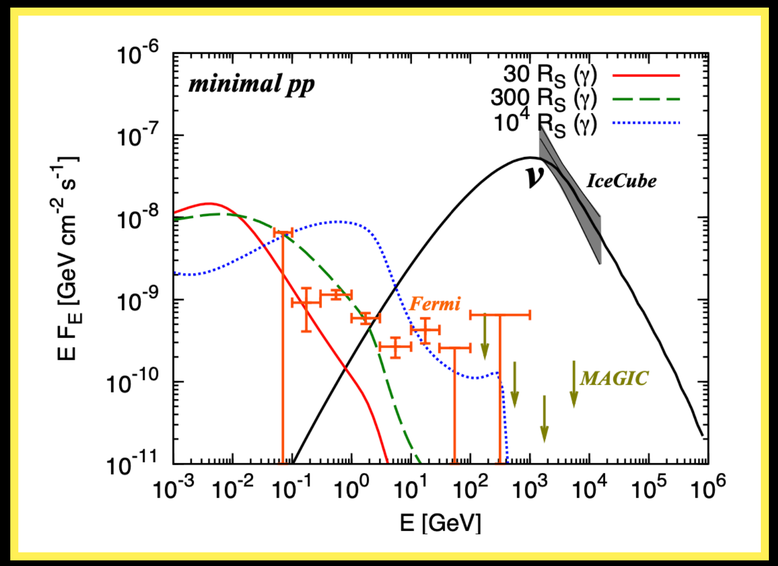


ALMA polarized flux
Lopez-Rodriquez et al ApJ (2020)

Radio: blue
Optical: green
X-ray: red
Image Credit: Chandra

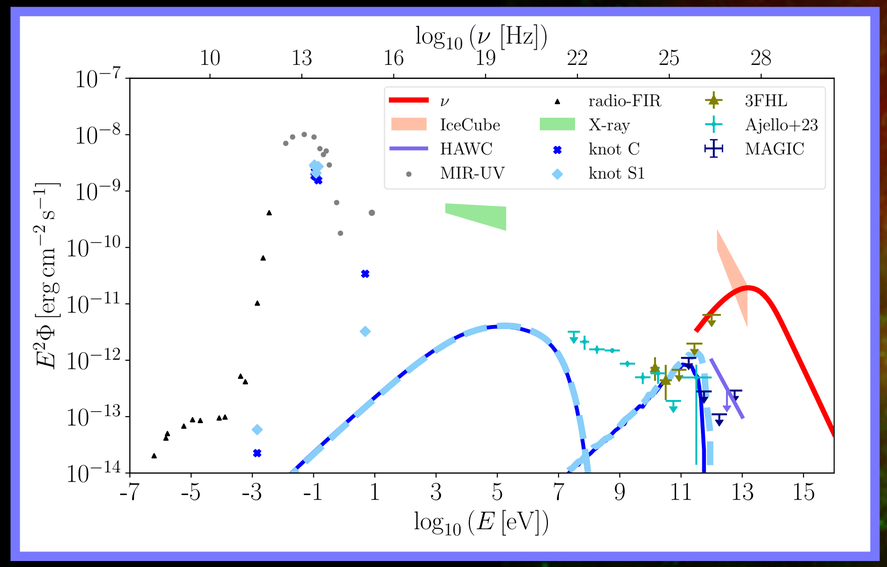
NGC 1068's Obscured Core

Corona

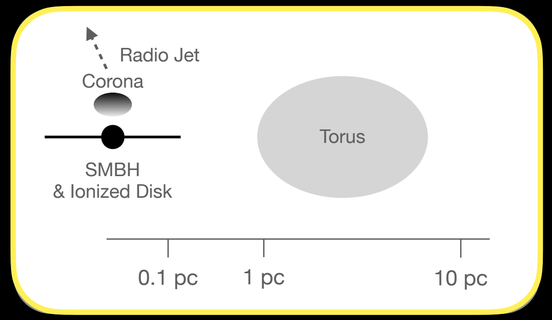


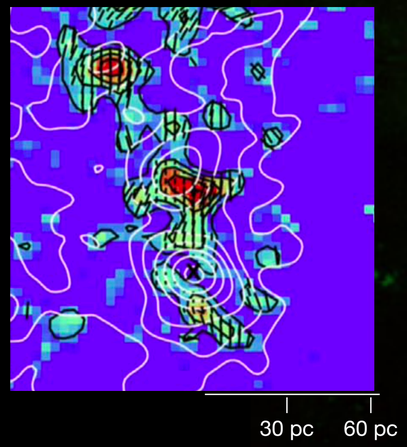
Murase, Kimura, Meszaros PRL (2020)

Jet-molecular cloud interaction



KF, Rodriguez, Halzen, Gallagher ApJ (2023)





- Neutrino production site has to be **compact**, have **intense radiation field** and **efficient particle acceleration**
- Neutrinos could provide information from sites that are challenging for astronomy.

See also:

Inoue, Khangulyan, Doi ApJL (2020), Galaxies (2021), Kheirandish, Murase, Kimura ApJ (2021), Eichmann et al ApJ (2022), Murase ApJL (2022), Inoue et al (2022), Hooper & Plant PRL (2023), Fiorillo et al ApJL (2024), Mbarek et al PRD (2024), Yasuda et al (2024) and others

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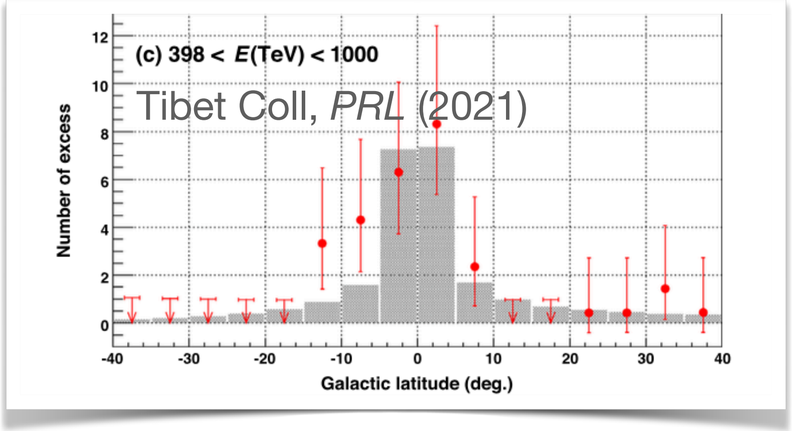
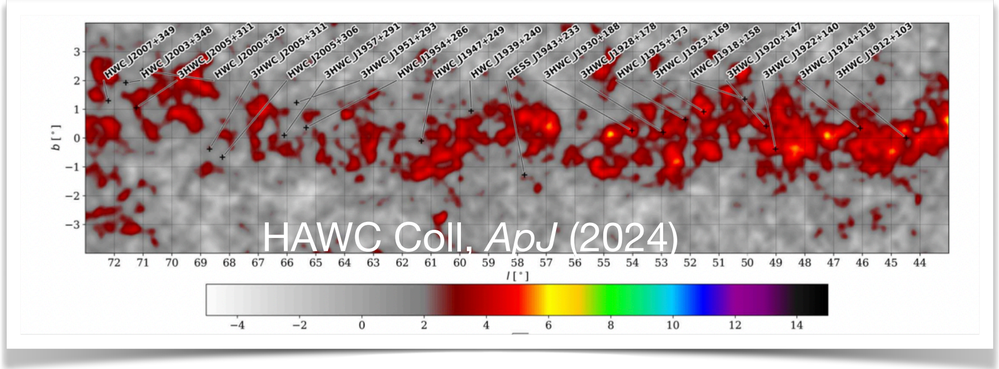
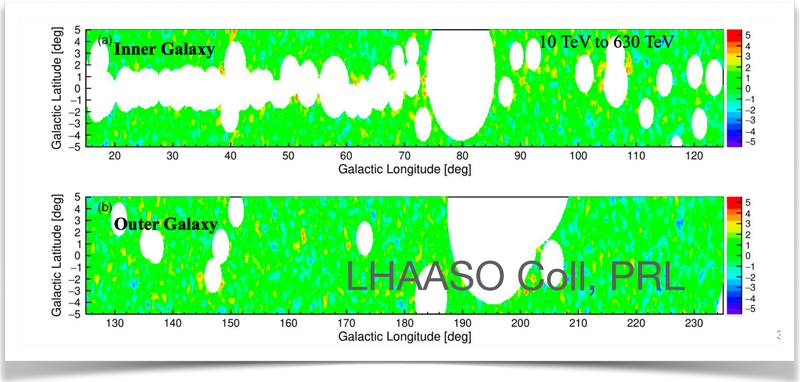
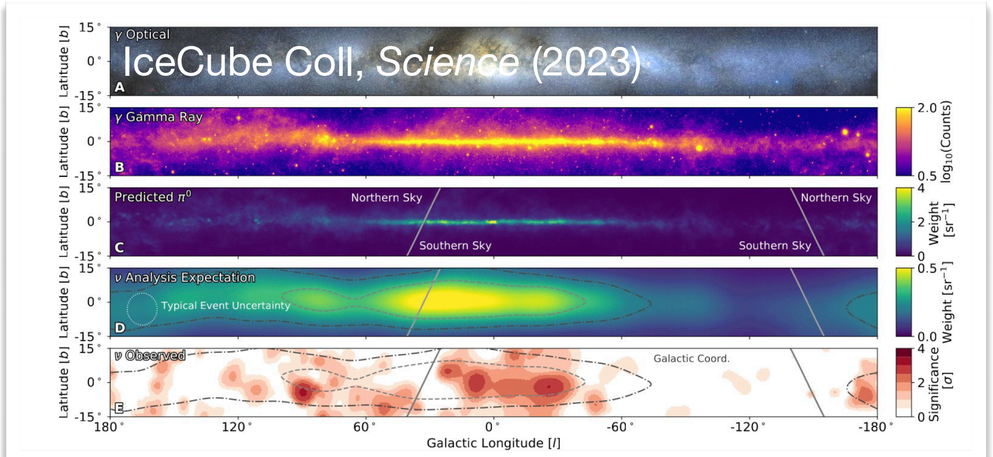
- Some of them are Galactic
- Extragalactic sources are more powerful

TeV to PeV multi-messenger emission by the Galactic Plane







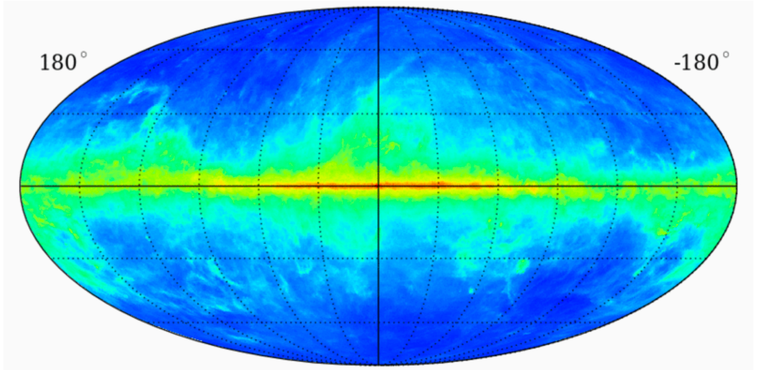


What do we learn about the **Galactic diffuse emission**?

Galactic Diffuse Emission

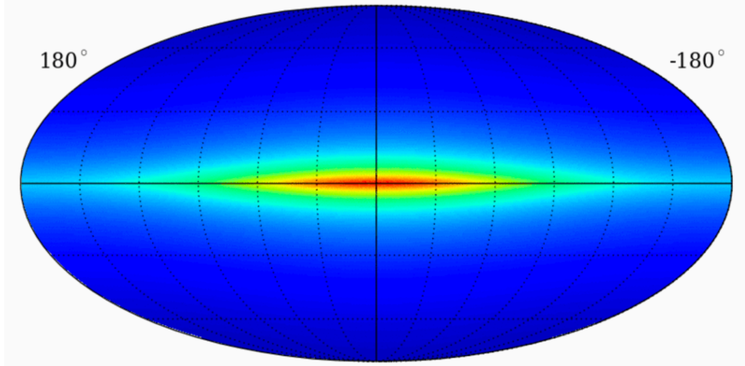
ν and γ

Pion Decay

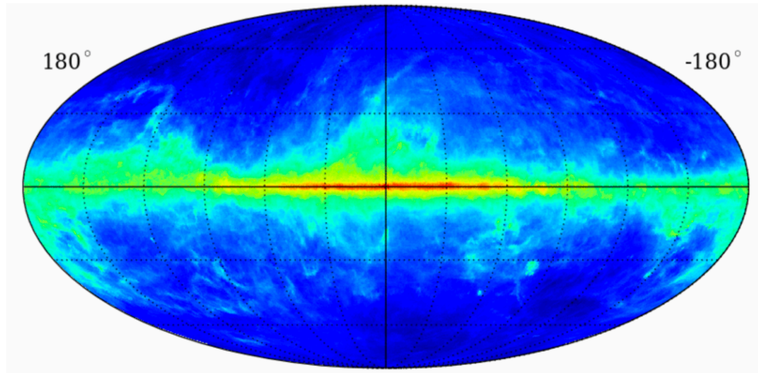


γ only

Inverse Compton

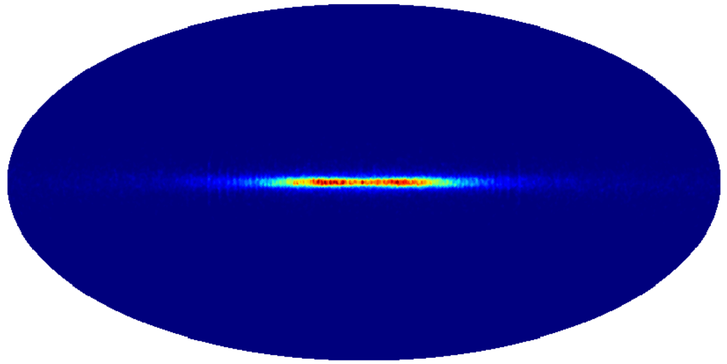


Bremsstrahlung



ν and/or γ

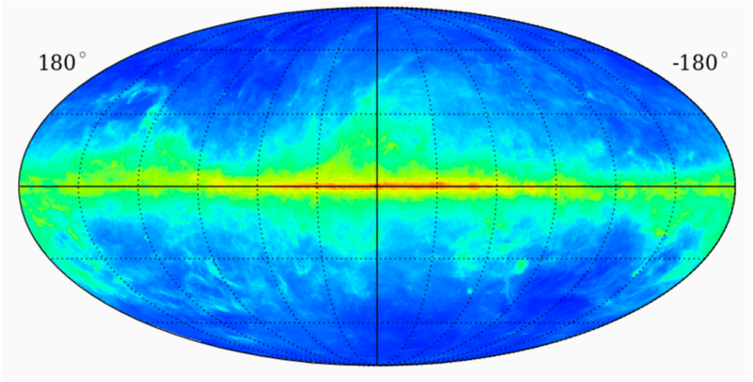
Unresolved Sources

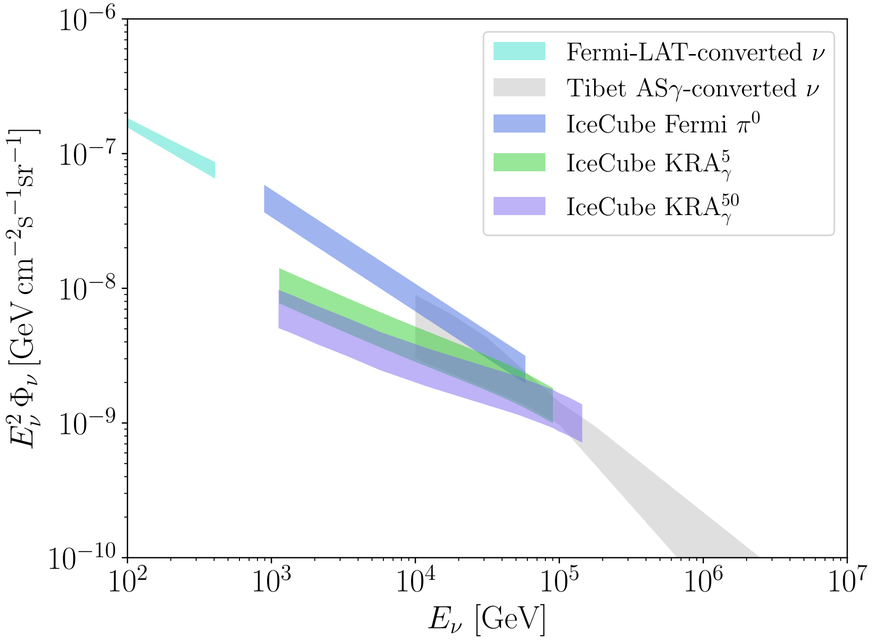


Galactic Diffuse Emission: Pion Decay by the Cosmic-ray Sea

ν and γ

Pion Decay





Fraction of hadronic contribution to the Galactic diffuse emission **depends on model at 1-10 TeV**; likely **significant above tens of TeV**

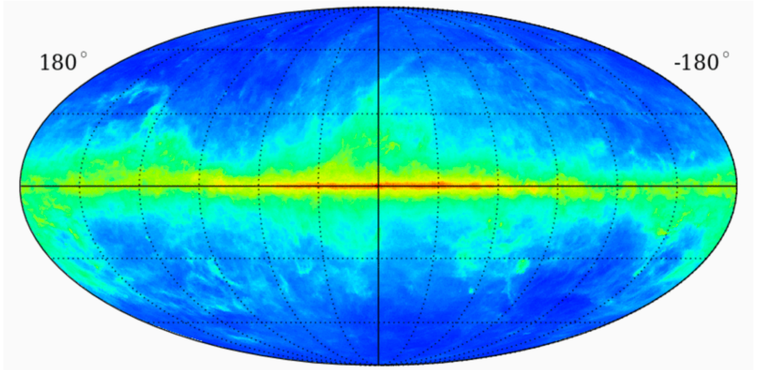
KF, Gallager, Halzen, Nature Astronomy (2023)

See also:
Fermi π^0: Fermi-LAT Coll., ApJ (2012)
KRA: Gaggero et al ApJL (2015)
CRINGE model: Schwefer et al ApJ (2023)

Galactic Diffuse Emission

ν and γ

Pion Decay



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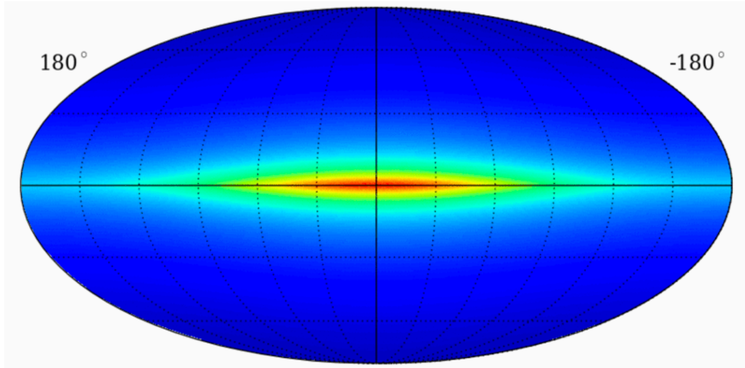

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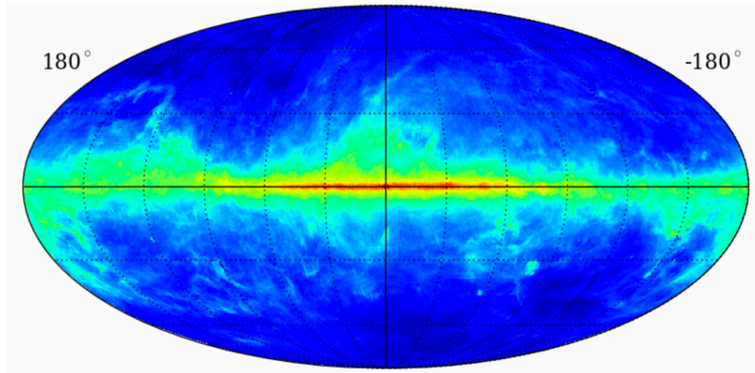
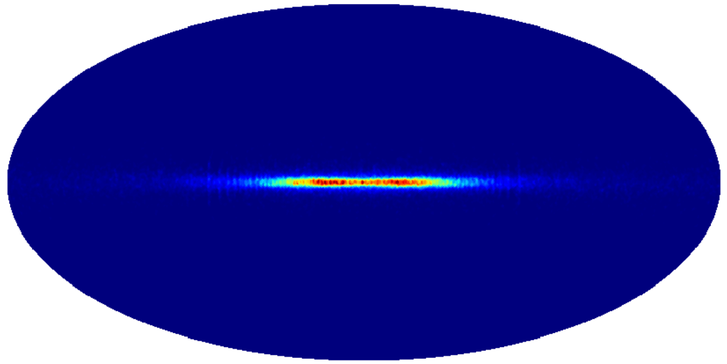
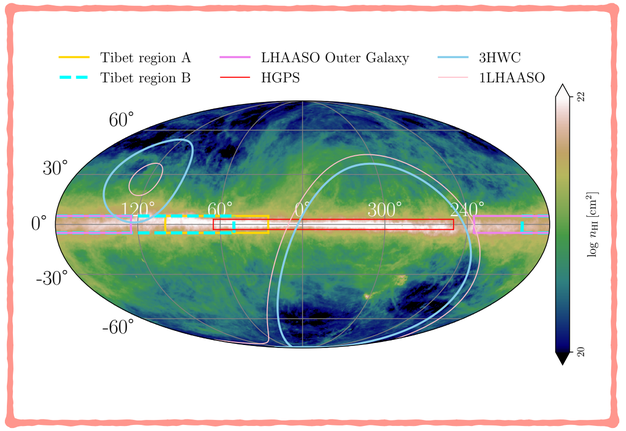


ν and/or γ

Unresolved Sources

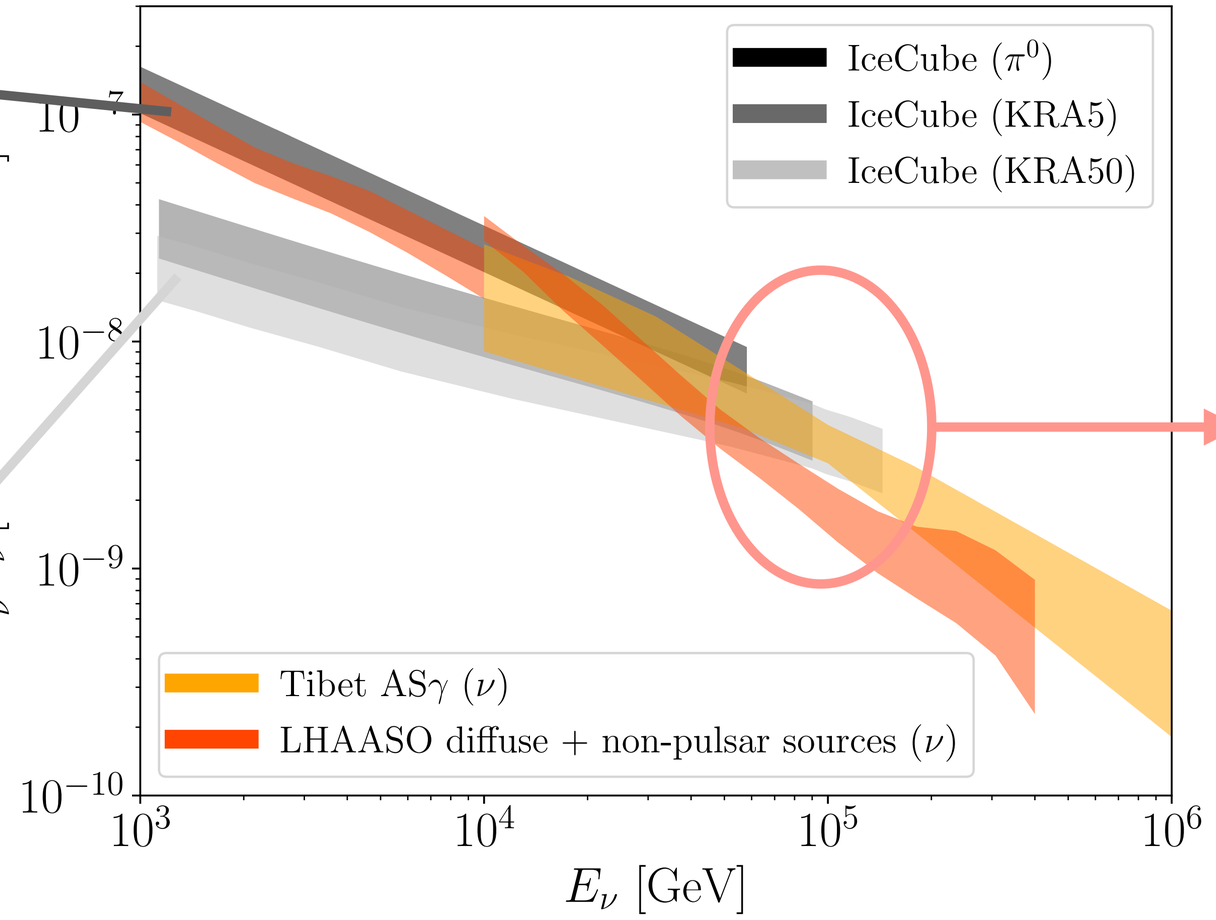


Galactic Diffuse Emission: Source Contribution



Partial contribution by unresolved hadronic sources such as star-formation regions and molecular clouds

(Neronov+2023, Abhijit+2024)



Hadronic diffuse emission or/and a population of **γ-ray opaque neutrino emitters**

Room left for **leptonic emitters** such as TeV halos

(Dekker+2024, Kai+2024, Kaci+2024)

KF & Murase ApJL (2023)

See also analysis of Vecchiotti+2023, Silvia+2024

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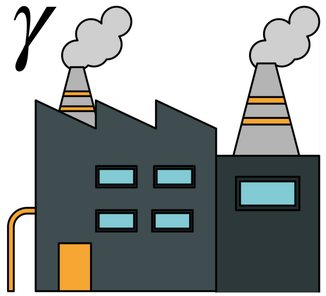

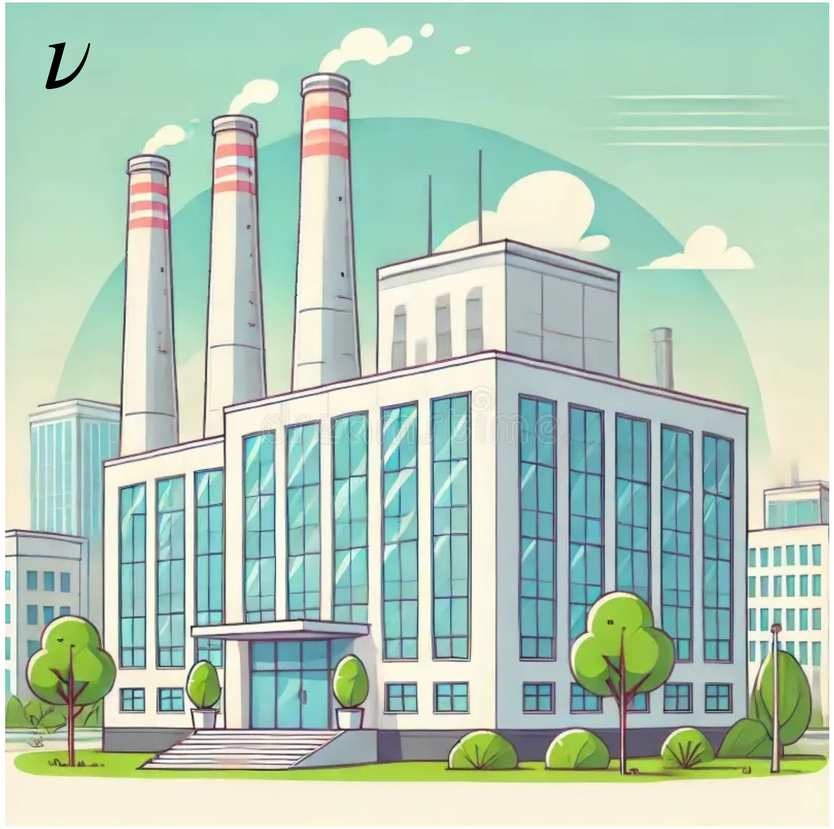

Nature of the bulk of the neutrino sources are yet to be revealed!

https://events.icecube.wisc.edu/event/183/overview

SuGAR MADISON 2024

SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

OCTOBER 14-17

Science Goals

The symposium aims to investigate the long-standing mystery surrounding the origin of cosmic rays within our galaxy. This event will bring together renowned experts to discuss both experimental and theoretical aspects of cosmic ray physics, with a particular emphasis on galactic sources.

Despite ongoing research, the question of where cosmic rays originate within the Milky Way remains unanswered. The symposium will host a number of invited speakers who are experts in various aspects of galactic multi-messenger astrophysics.

Furthermore, two dedicated discussion panels will provide opportunities for open discussion. One panel will delve into the current status and challenges of multi-messenger observations and theoretical modeling. The other will address the future of observations and instrumentation required to make a breakthrough in our understanding of the galactic origin of cosmic rays.

Scientific Organizing Committee

- Pasquale Blasi (GSSI, L'Aquila, Italy)
- Damiano Caprioli (University of Chicago, U.S.A.)
- Ke Fang (University of Wisconsin–Madison, U.S.A.)
- Francis Halzen (University of Wisconsin–Madison, U.S.A.)
- Szabolcs Marka (Columbia University, U.S.A.)
- Simona Toscano (Université Libre de Bruxelles, Belgium)