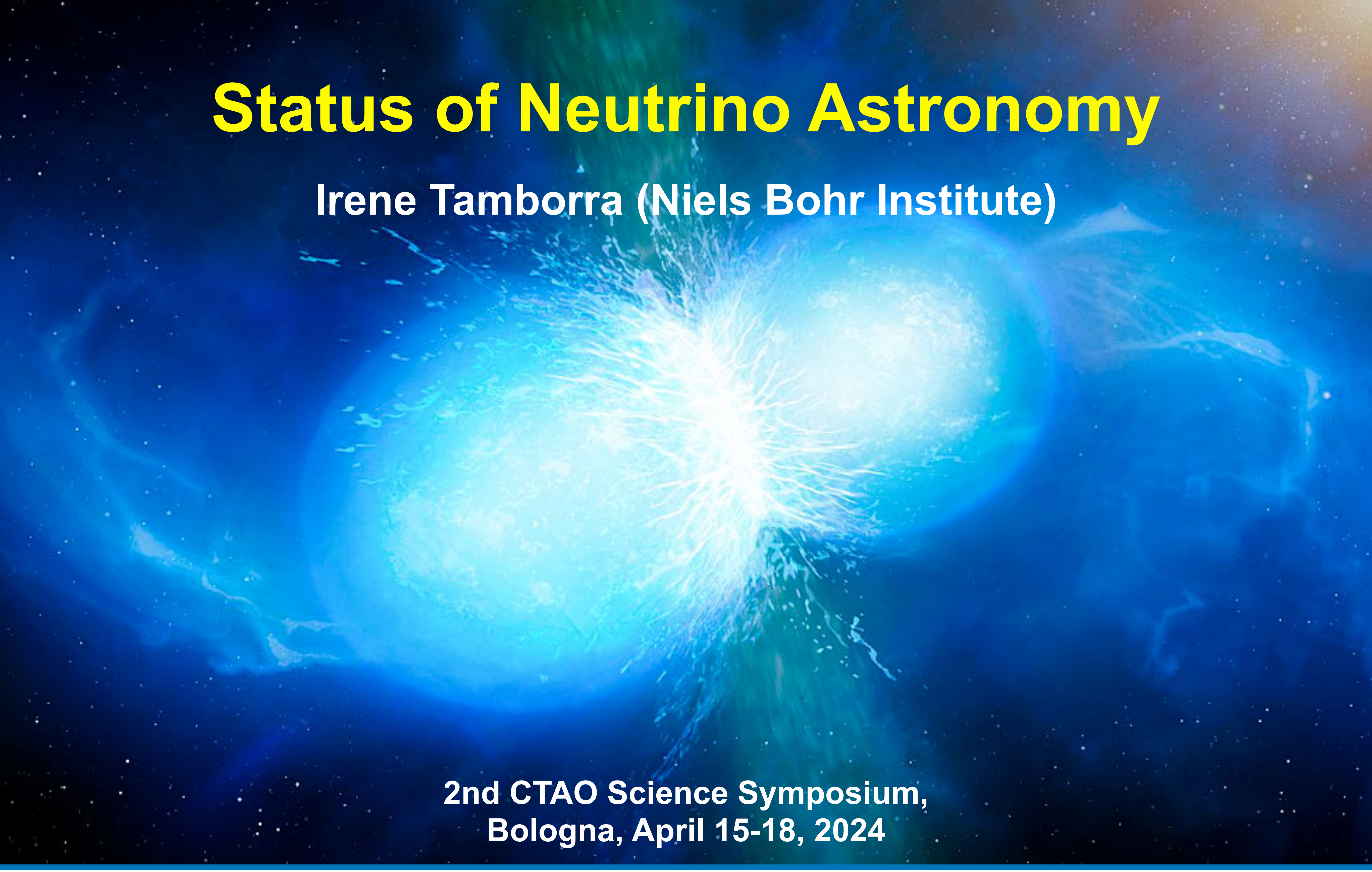
Status of Neutrino Astronomy

Irene Tamborra (Niels Bohr Institute)



2nd CTAO Science Symposium,
Bologna, April 15-18, 2024

VILLUM FONDEN
Sapere Aude
Funded by the European Union
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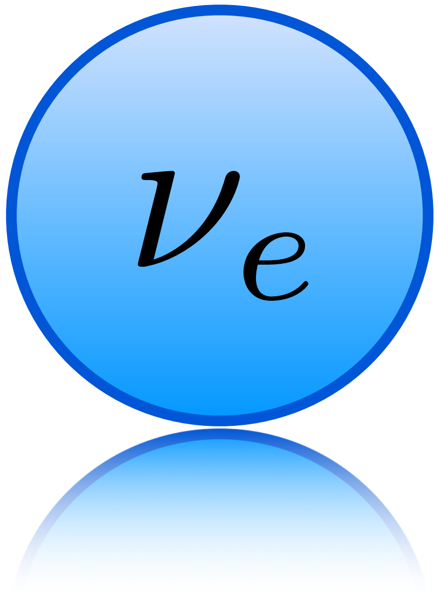
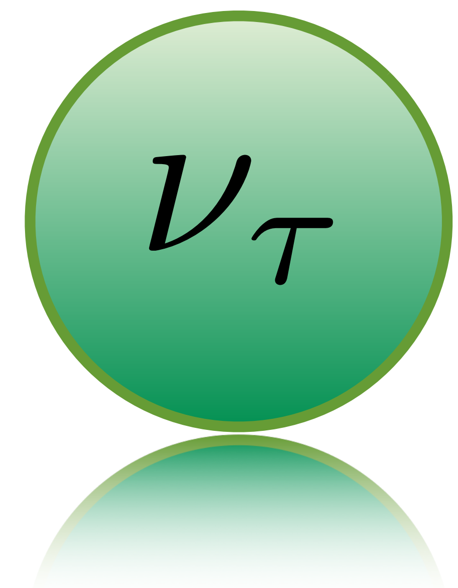
SFB 1258 Neutrinos Dark Matter Messengers

Neutrinos

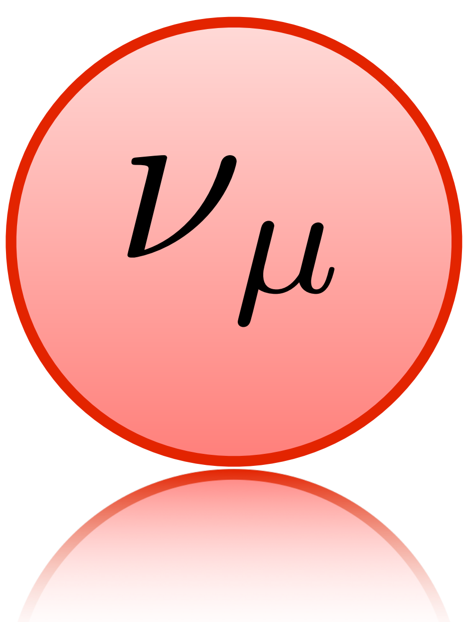


Ghostly

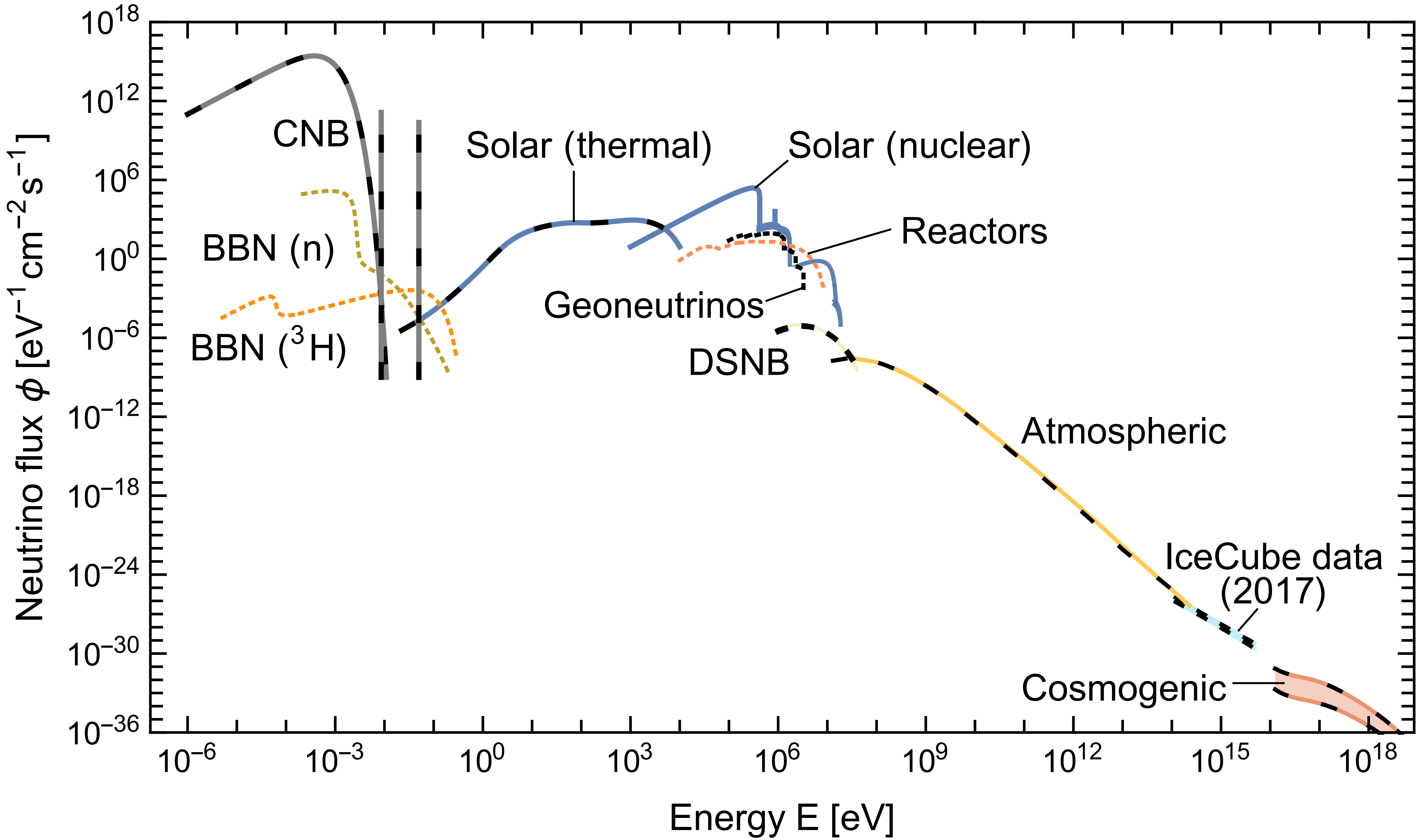
Abundant



Elusive



Grand Unified Neutrino Spectrum



Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020).

Neutrino Telescopes

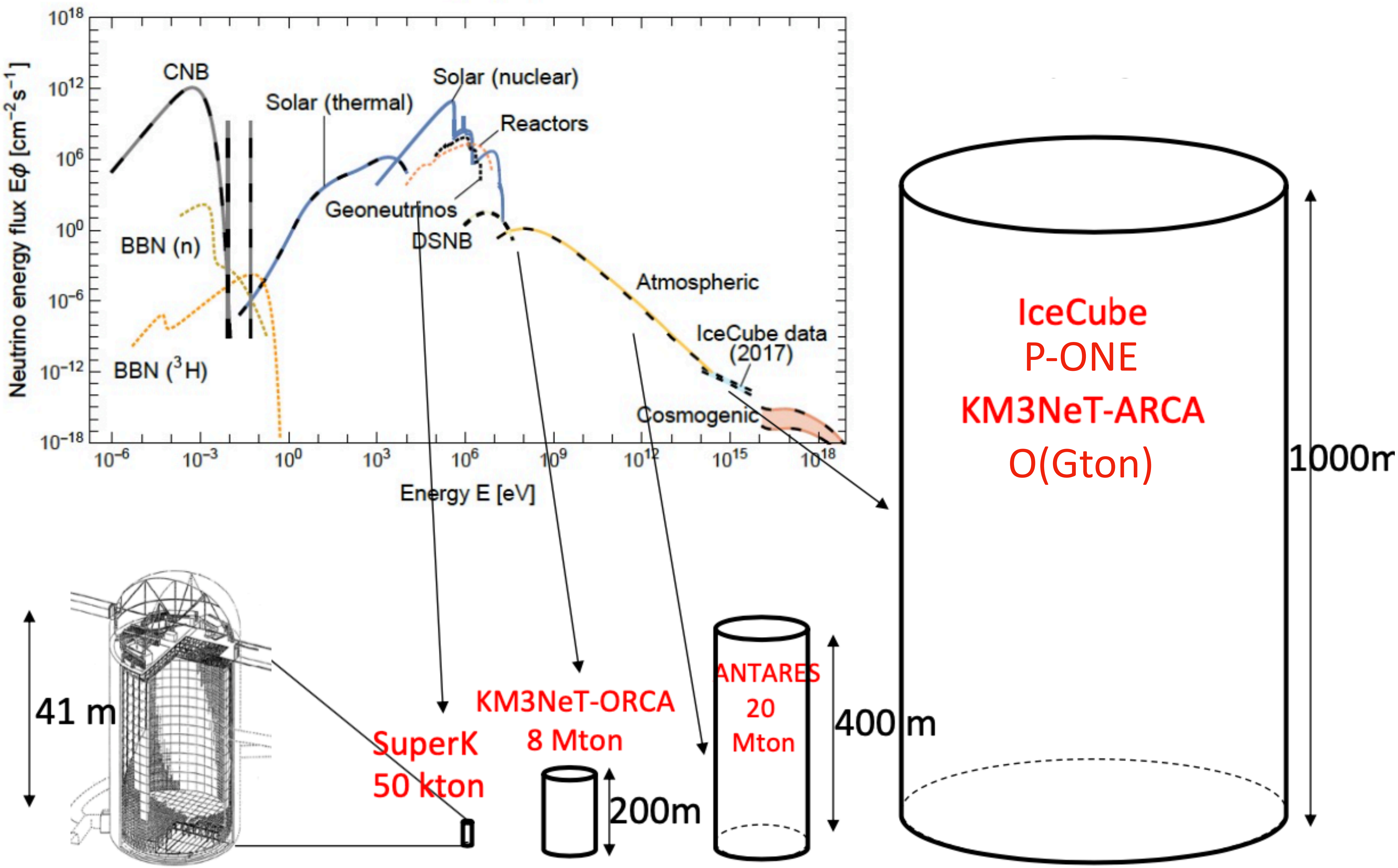
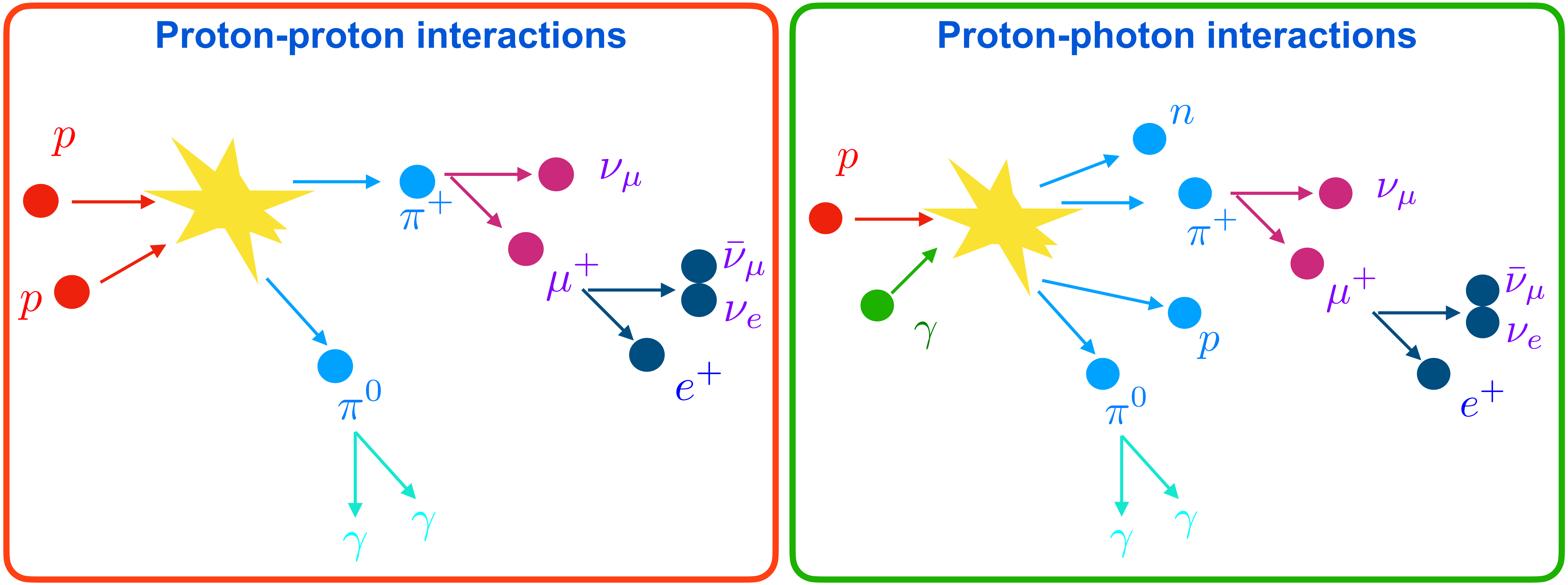


Image credit: adapted from P. Coyle.

Neutrino Gamma-Ray Connection



Electron and muon neutrinos are produced by charged pion decay.

Gamma-ray photons are produced by neutral pion decay.

Emerging Picture

It seems unlikely that the same source class(es) make(s) the bulk of the diffuse emission observed in gamma-rays and neutrinos.

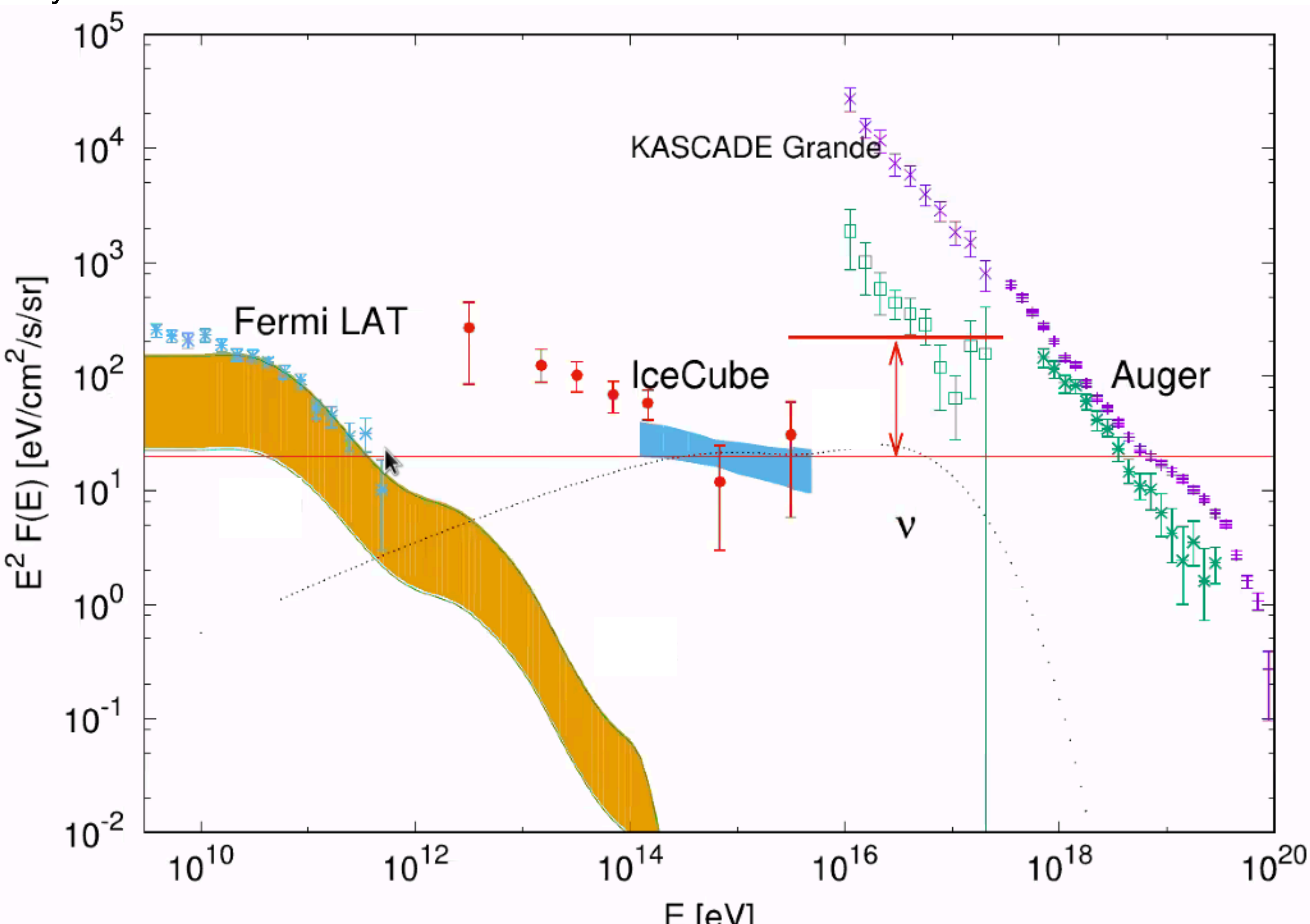
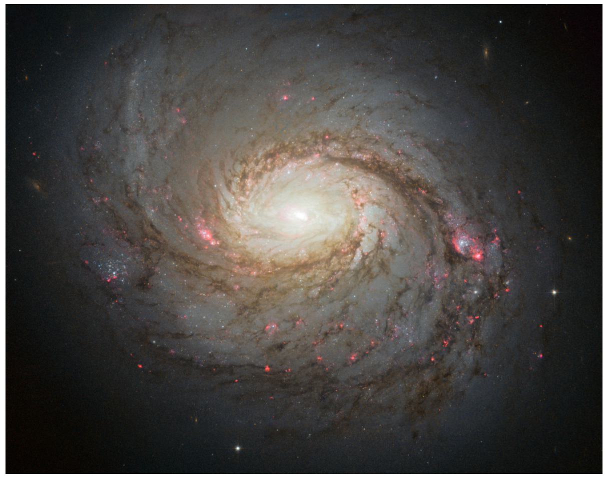
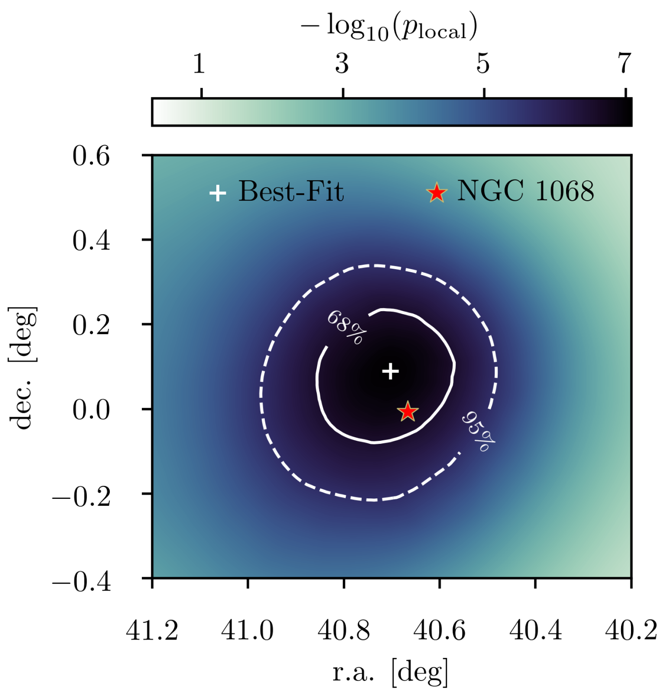


Image credit: Kowalski, PoS (ICRC 2021) 022.

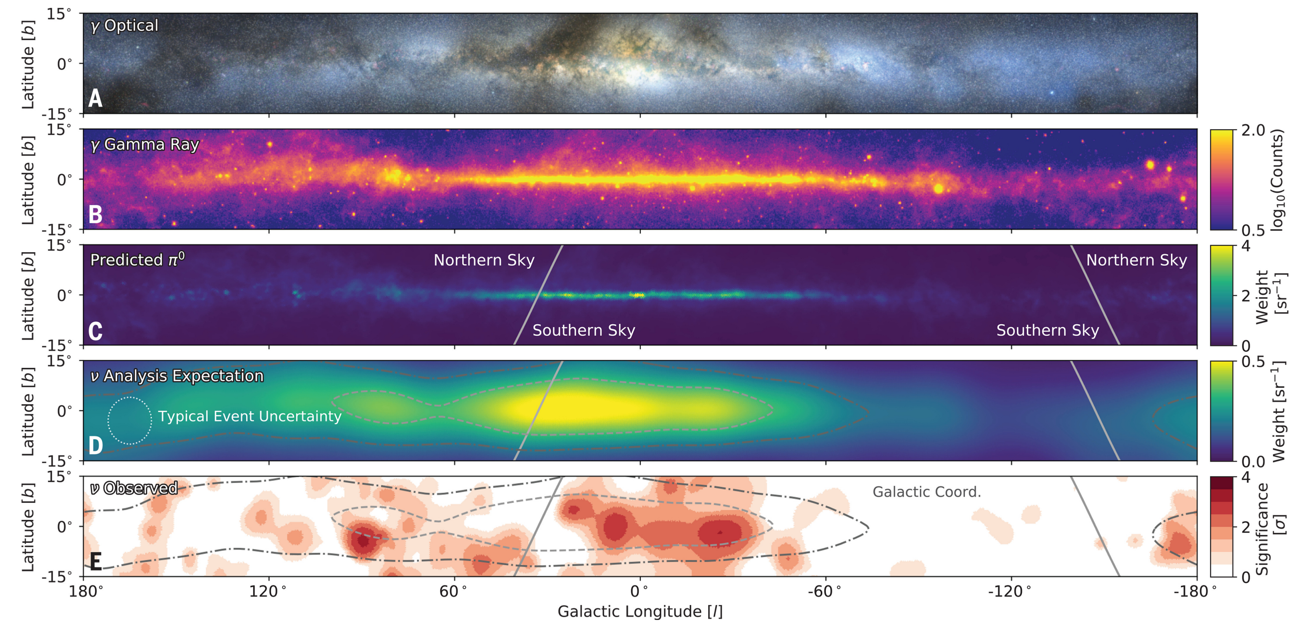
Neutrino-Electromagnetic Associations

Active Galaxies

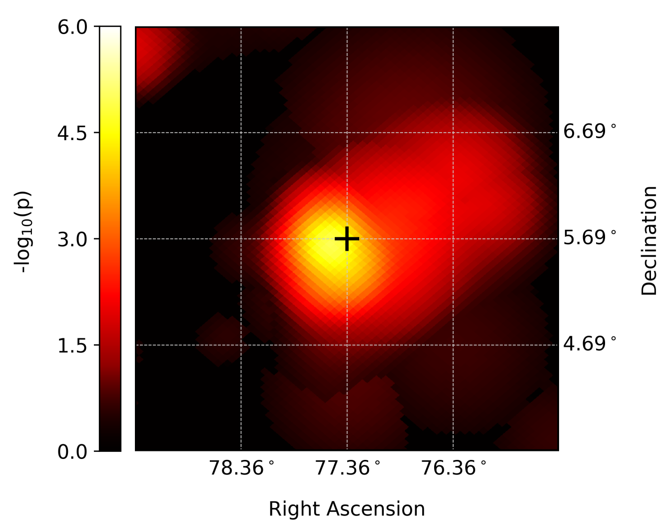




Our Galaxy



Blazars



Tidal Disruption Events/ Superluminous Supernovae?

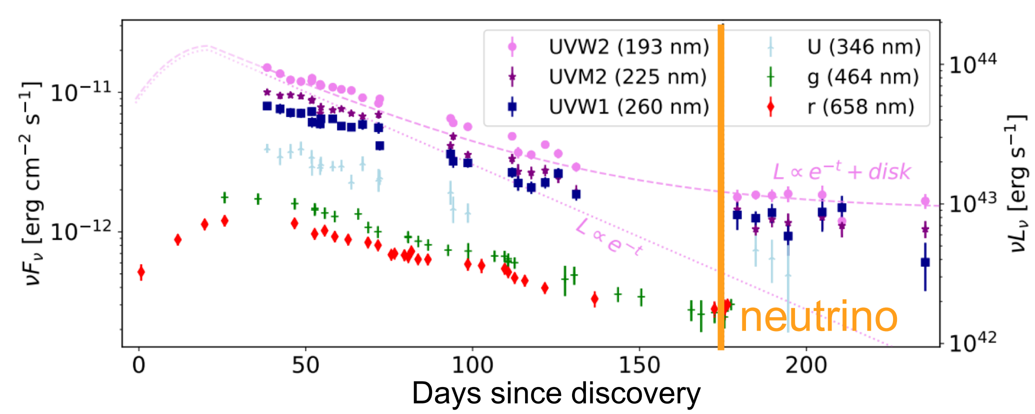
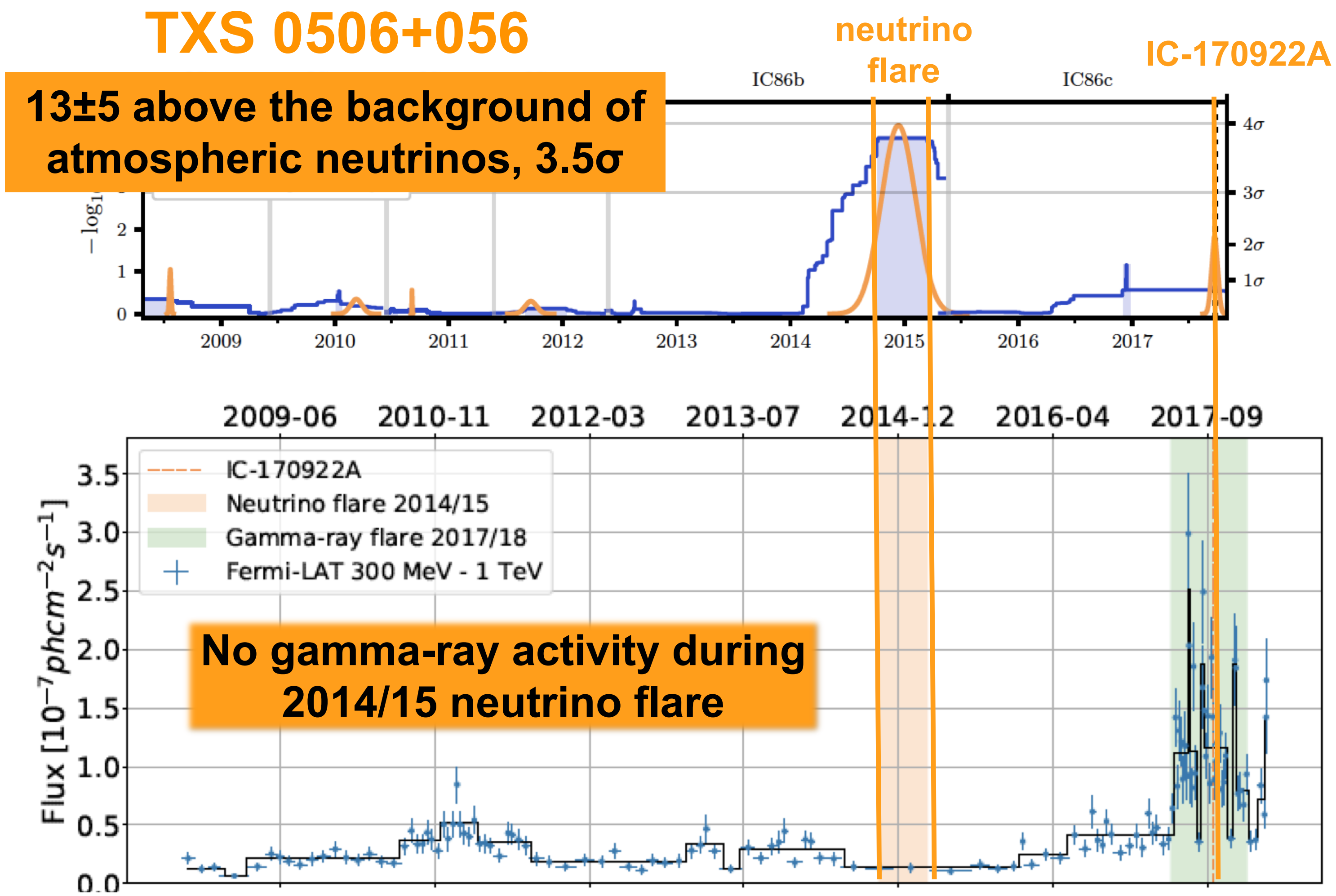


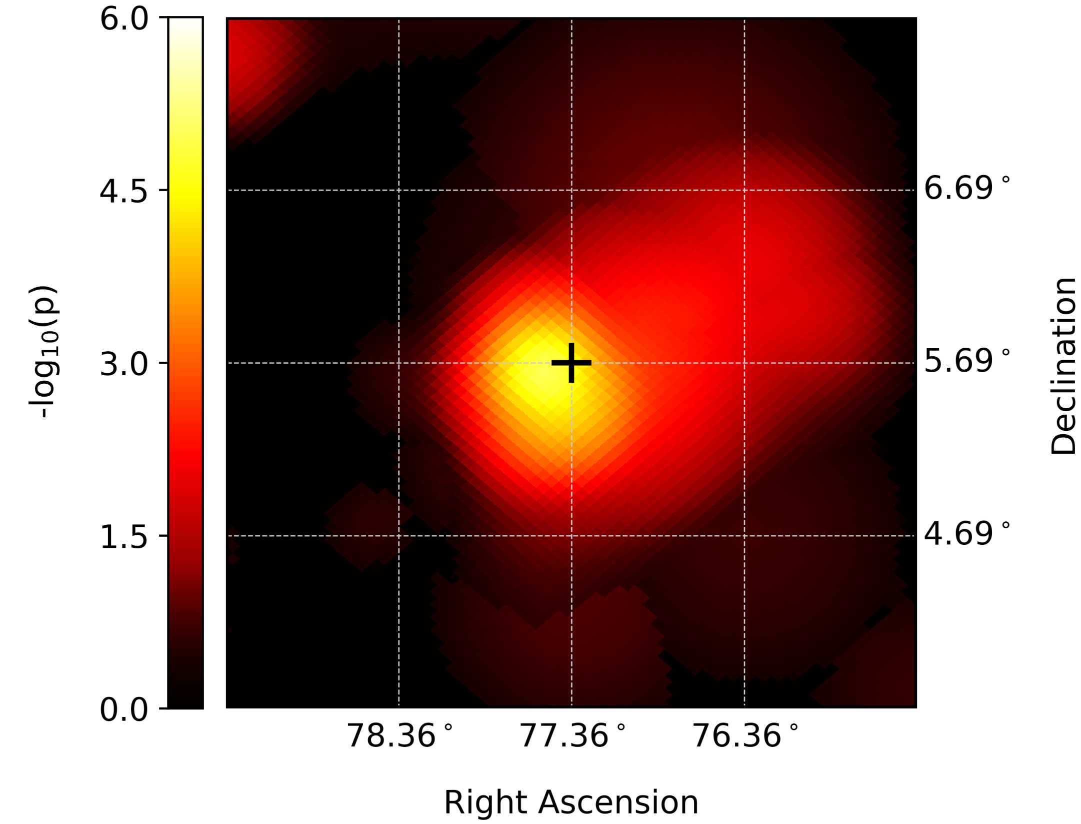
Image credits: IceCube Collaboration.

Blazars

Image credits: DESY Science Communication Lab

Fists Likely Neutrino-Source Association: Transient Source (2017)

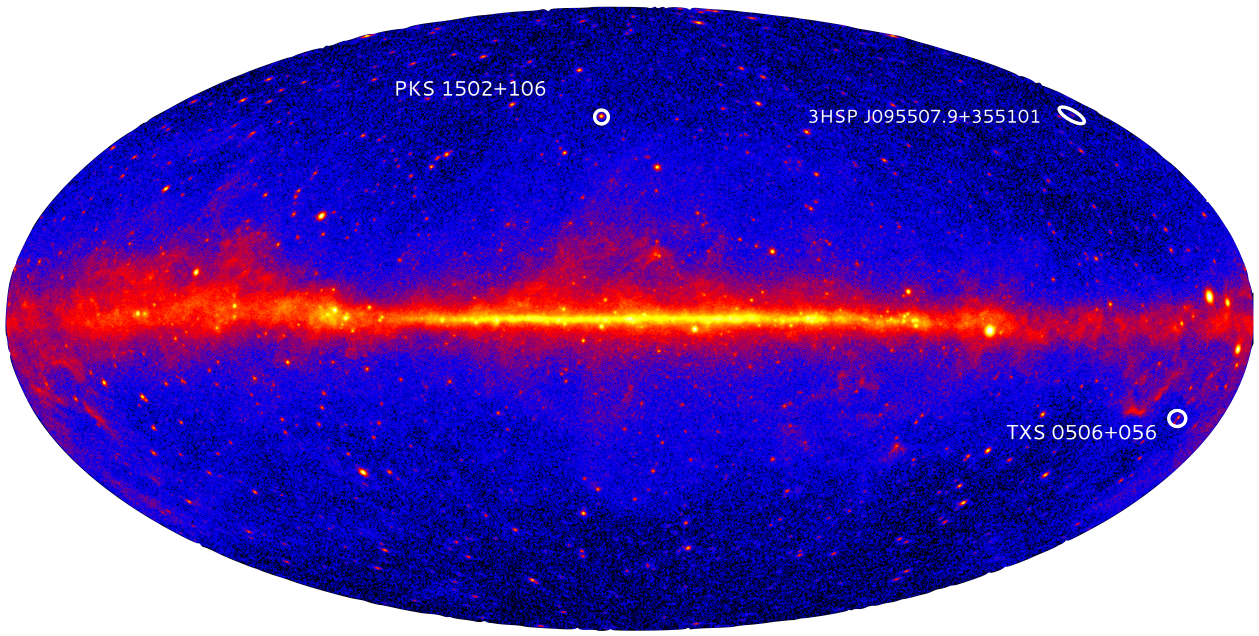


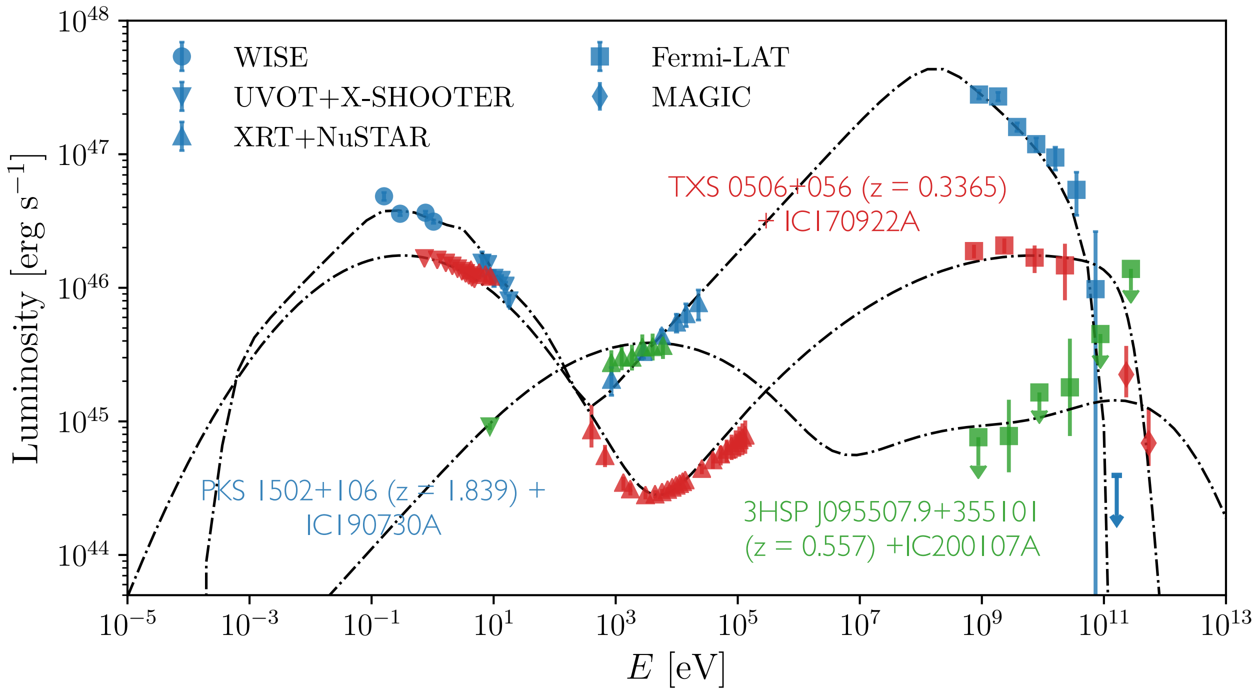


- Among 50 brightest blazars in 3LAC.
- Located ~4billion light years away.
- No clear correlation with events in time.

Figure credit: A. Franckowiak. IceCube Coll., Science 2018. Blaufuss (IceCube), GCN Circular 21916, Tanaka et al. (Fermi-LAT), AT 10791, Fox et al. (Swift and NuSTAR), AT 10845, Mirzoyan et al. (MAGIC), AT 10817, de Naurois et al. (HESS), AT 10787, Mukherjee et al. (VERITAS), AT 10833.

Neutrinos from Blazars/AGN





- No significant correlation among neutrino alerts (IceCat-1), Fermi-LAT 4LAC-DR2 catalog and Radio Fundamental Catalog. Less than 1% of all AGNs may be neutrino emitters.
- Extreme parameters required to explain neutrino events, atypical of blazar population.
- Multi-epoch source monitoring essential to understand observed emission. Need to move beyond one-zone models.
- New IceCube data sample of Northern Tracks leads to smaller normalization for neutrino flare from TXS 06056+056. Tension between neutrino and multi-wavelength electromagnetic data.

IceCube Coll., Astrophys. J. (2023). W. Luszczak PoS (ICRC2023) 1465. Garrappa et al., arXiv: 2401.06666.

Diffuse Neutrino Emission from Blazars

Blazars cannot explain the observed diffuse neutrino flux (despite blazars being dominant sources of the diffuse gamma-ray background above 10 GeV).

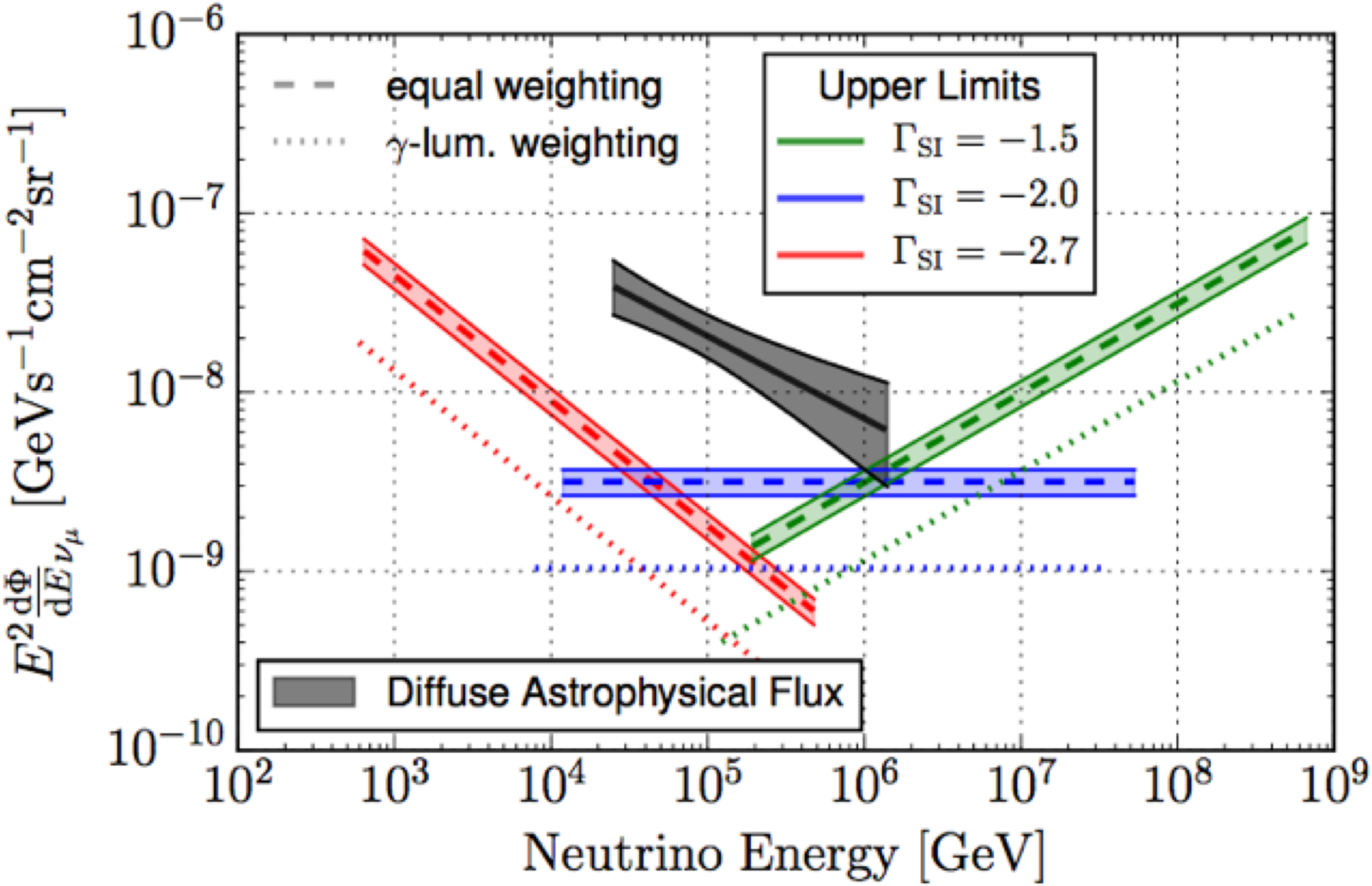
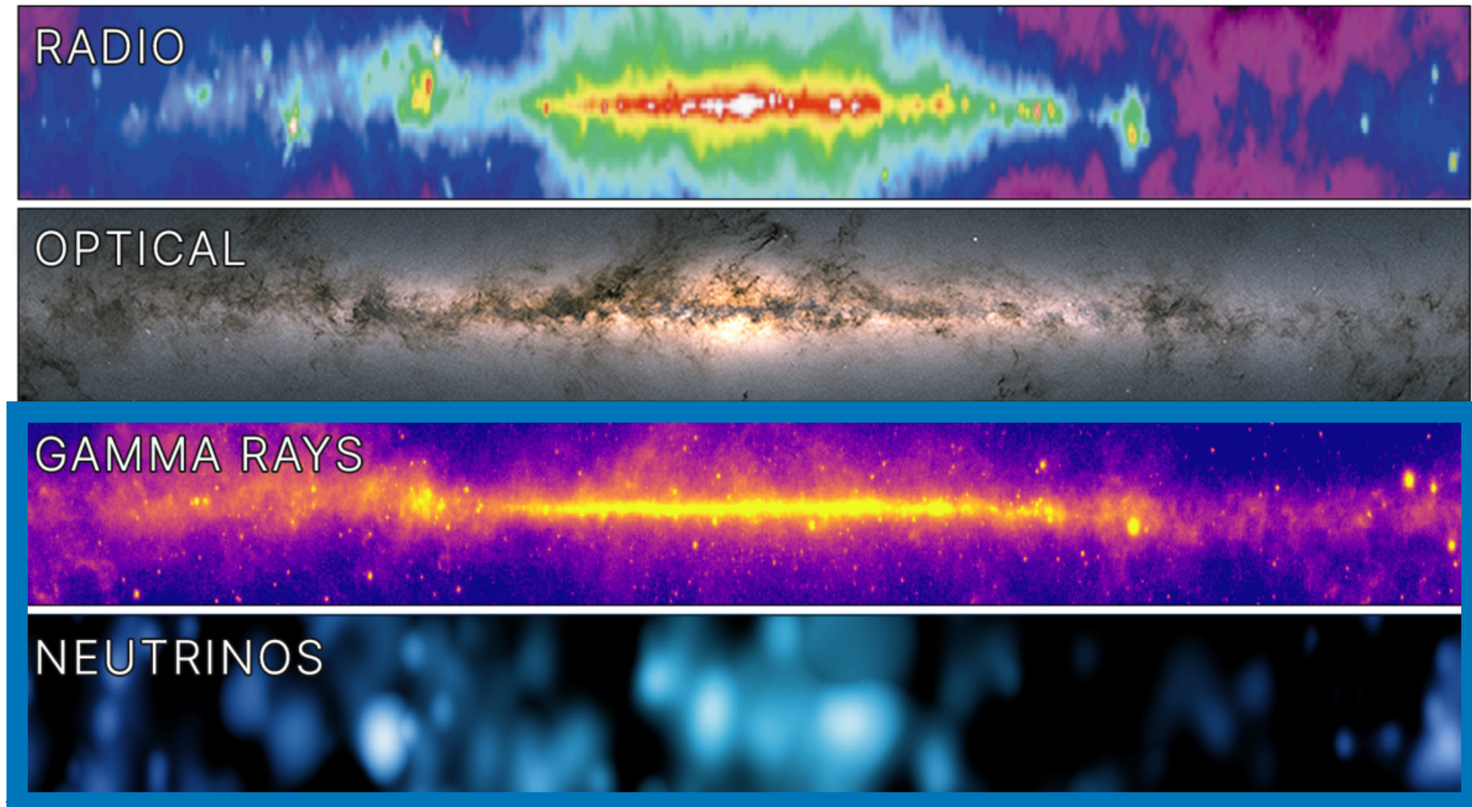


Figure credit: IceCube, Astrophys. J. (2017).

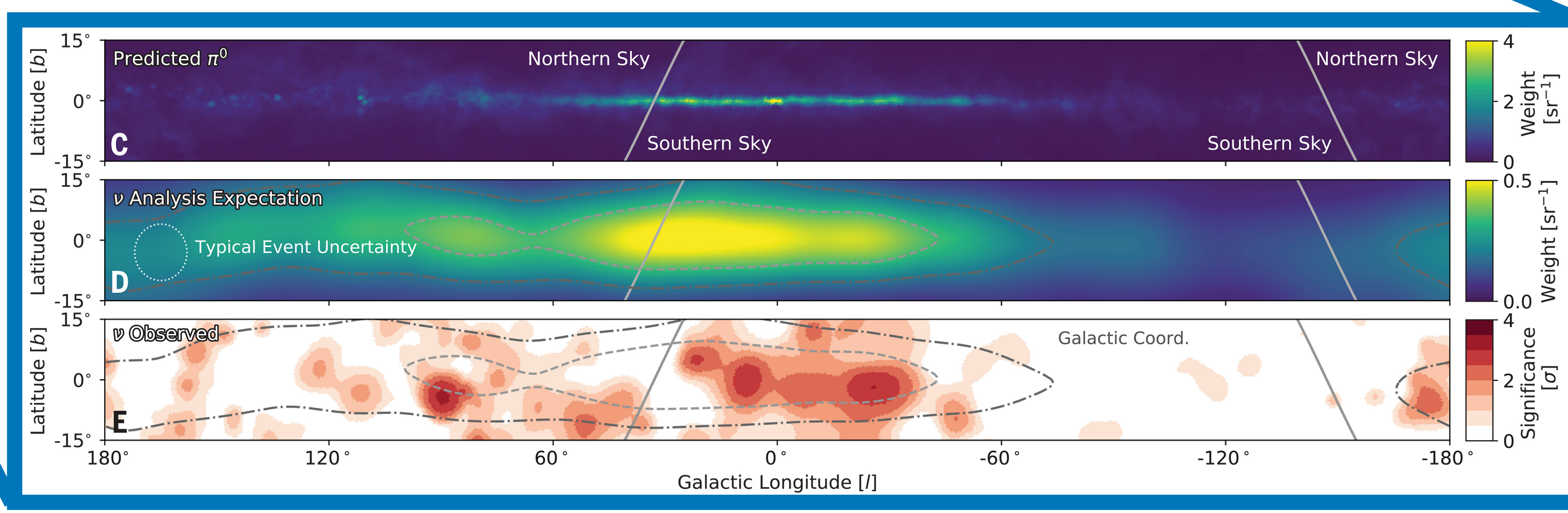
Our Galaxy

Image credits: IceCube Collaboration/Sciece Communication Lab for CRC 1491.

Multi-Messenger View of the Milky Way



Identification of neutrino emission from the Galactic plane at 4.5σ.

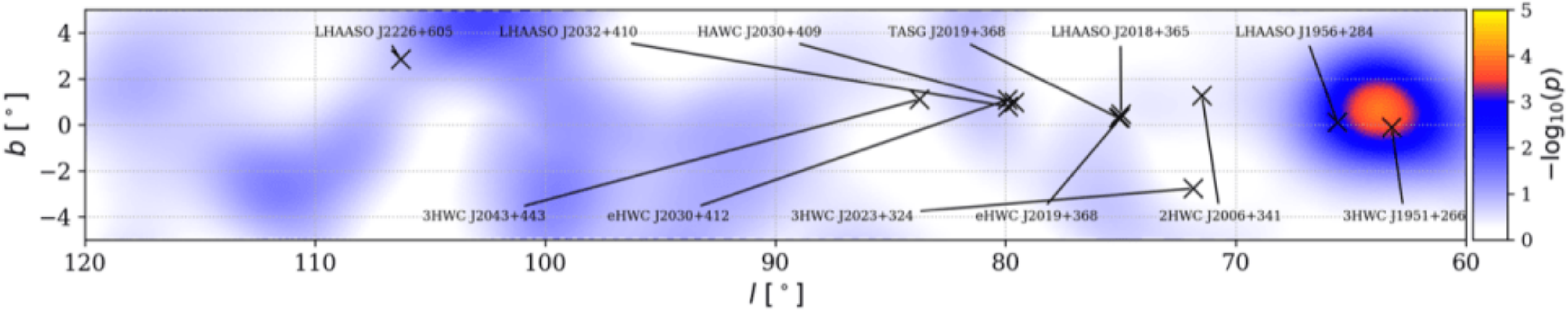


Signal consistent with diffuse emission from Galactic plane.
Population of unresolved point sources not excluded.

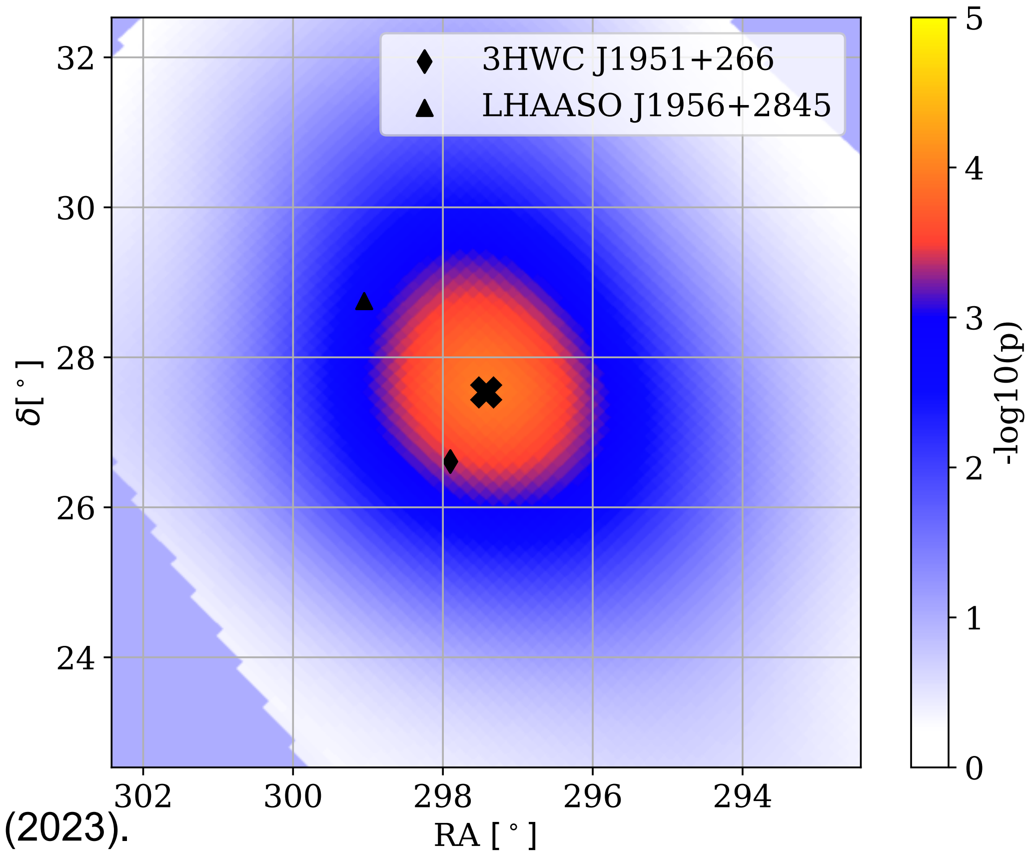
IceCube Collaboration, Science (2023).

Extended Sources in the Galactic Plane

Gamma-ray observations by HAWC and LHAASO show Galactic sources with spatially extended morphology and energy spectra beyond 100 TeV.



No evidence for time-integrated neutrino emission. Hotspot with unidentified TeV gamma-ray source (2.6σ). Constraints on hadronic emission in the Galaxy.



IceCube Collaboration, Astrophys. J. (2023).

Active Galaxies

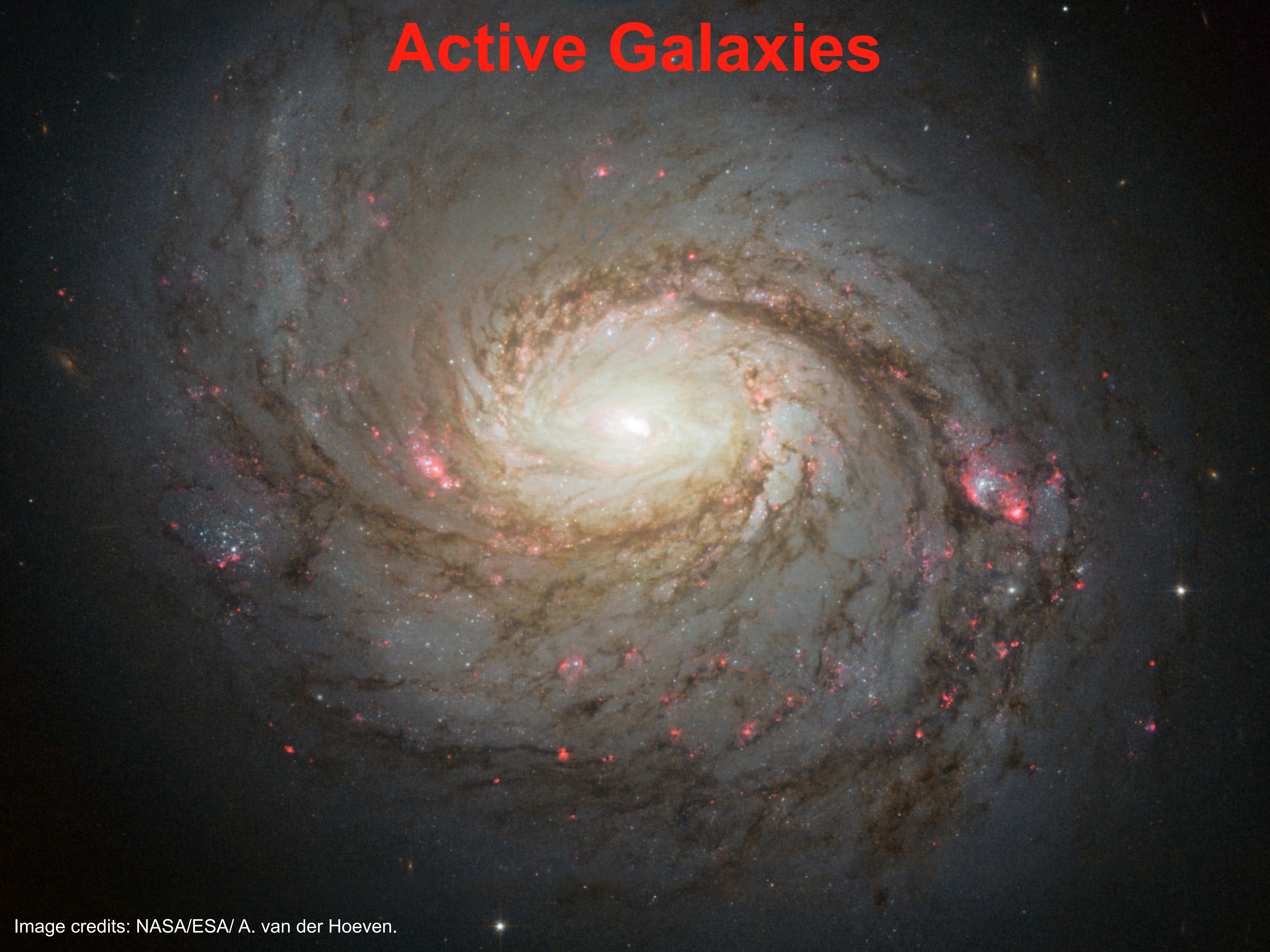
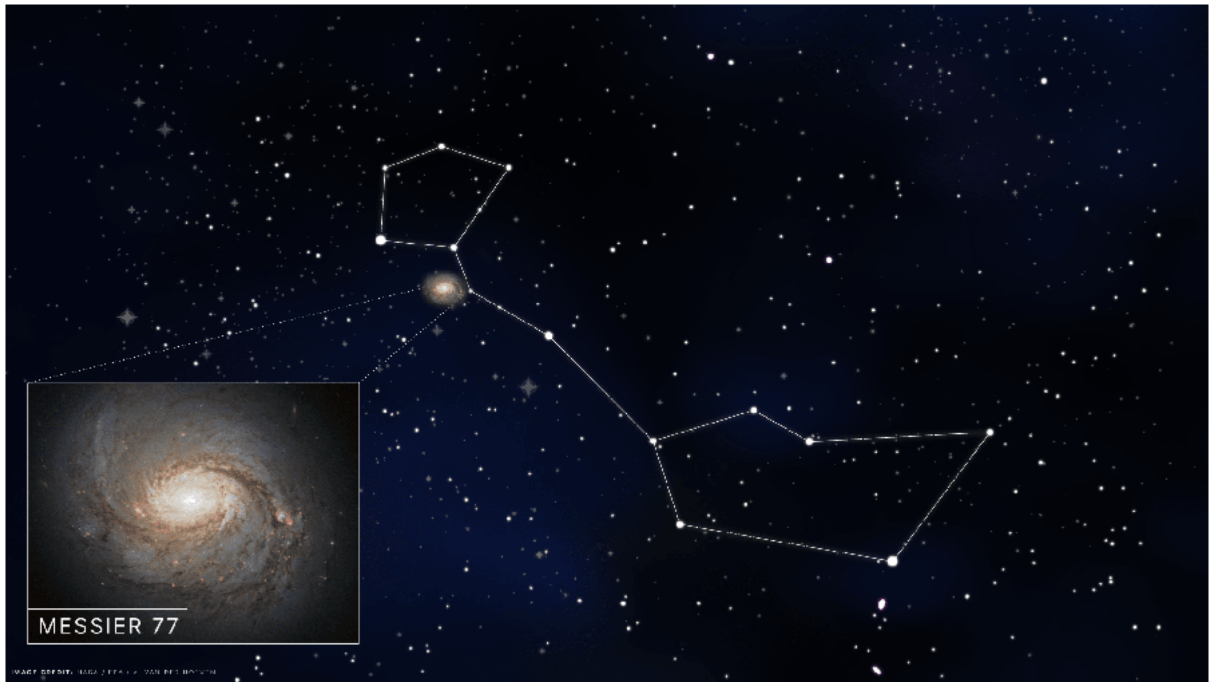
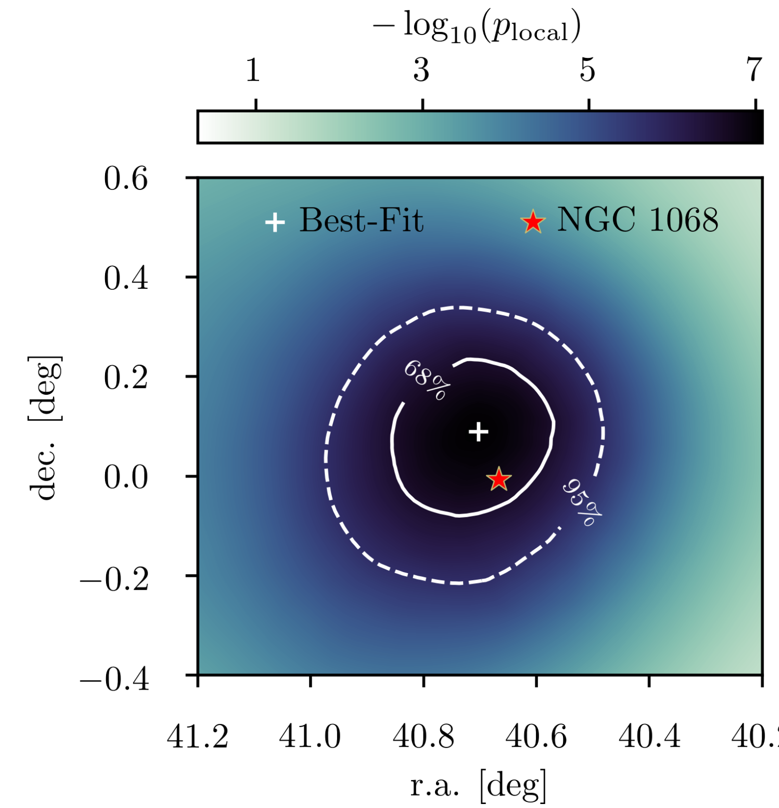


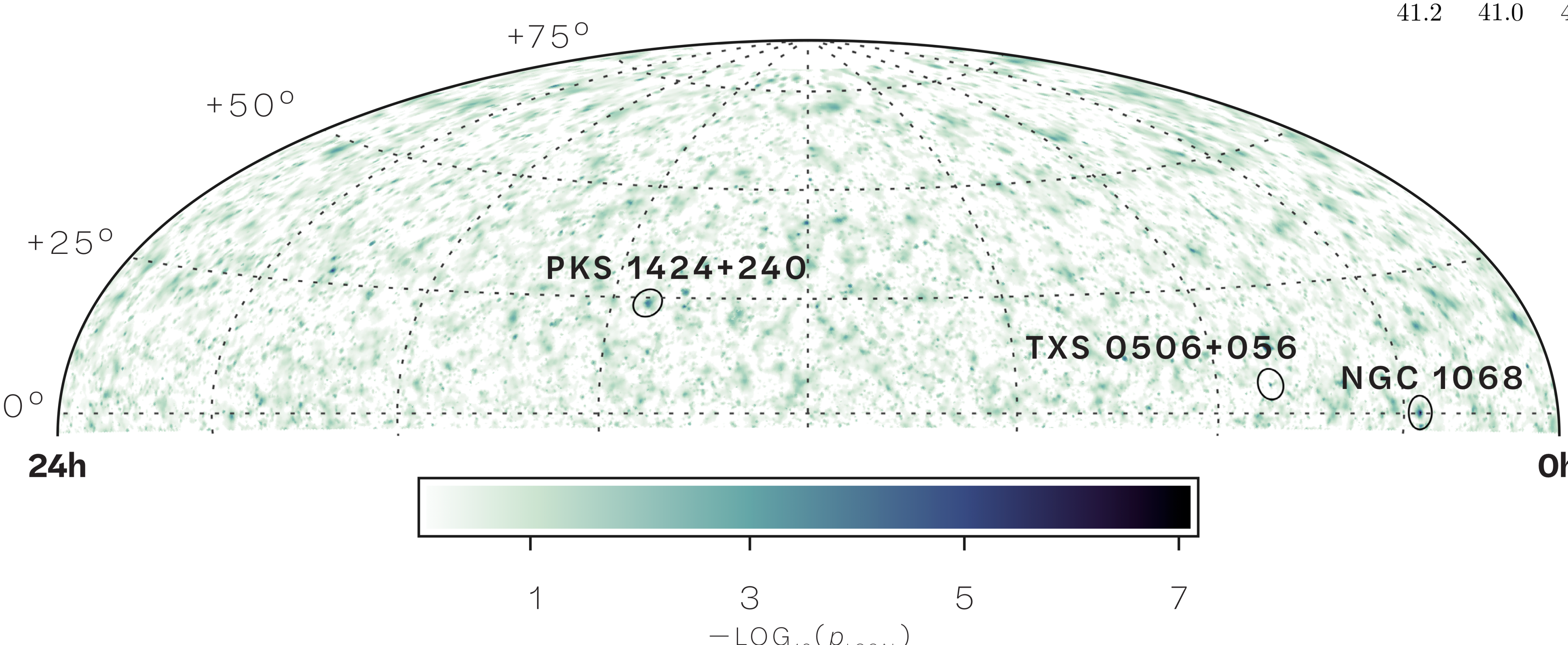
Image credits: NASA/ESA/ A. van der Hoeven.

Neutrino-Source Association: Steady Source (2022)

NGC 1068

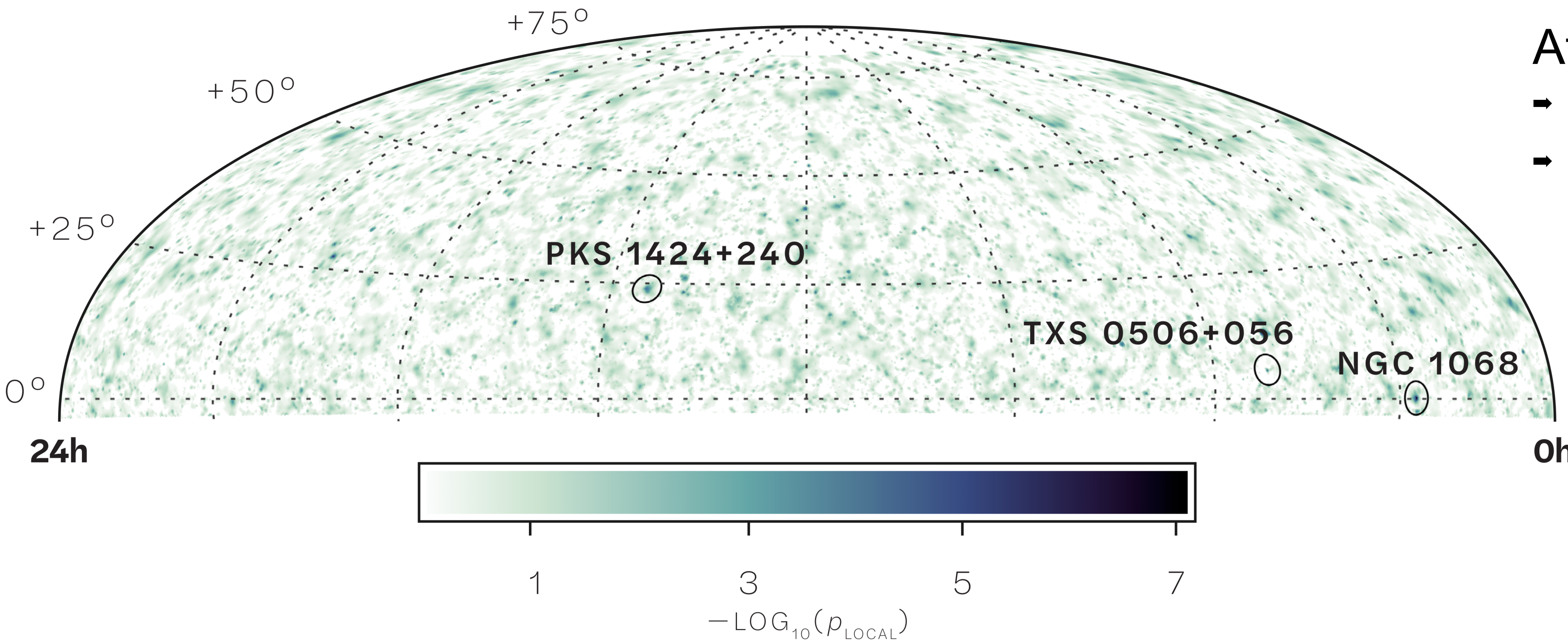






Abbasi et al., Science (2022). Photo Credit: Jack Pairin, IceCube/NSF.

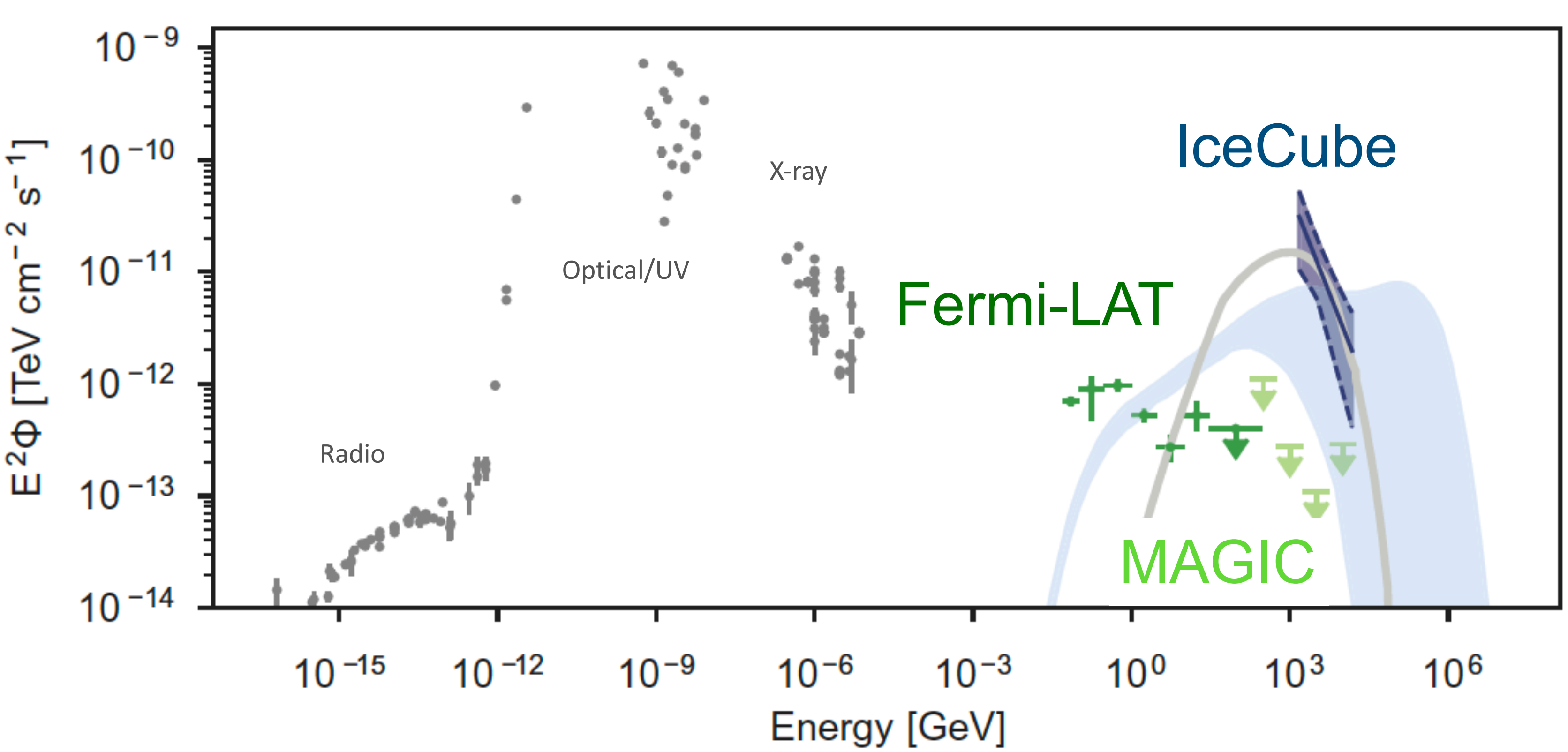
First Neutrino-Steady Source Association

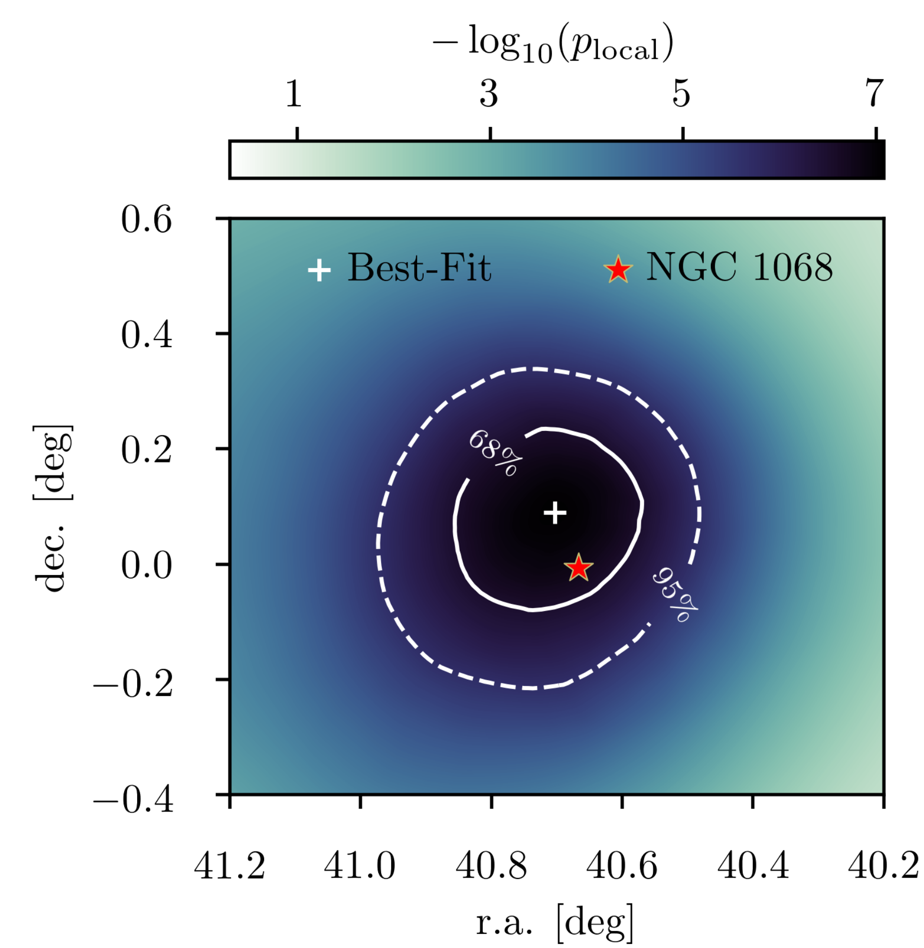


At the NGC1068 location:

- Astrophysical neutrino events = 79^{+22}_{-20}
- Spectral index = 3.2 ± 0.2

Smoking gun signature of hadronic particle acceleration. Significant gamma-ray absorption.



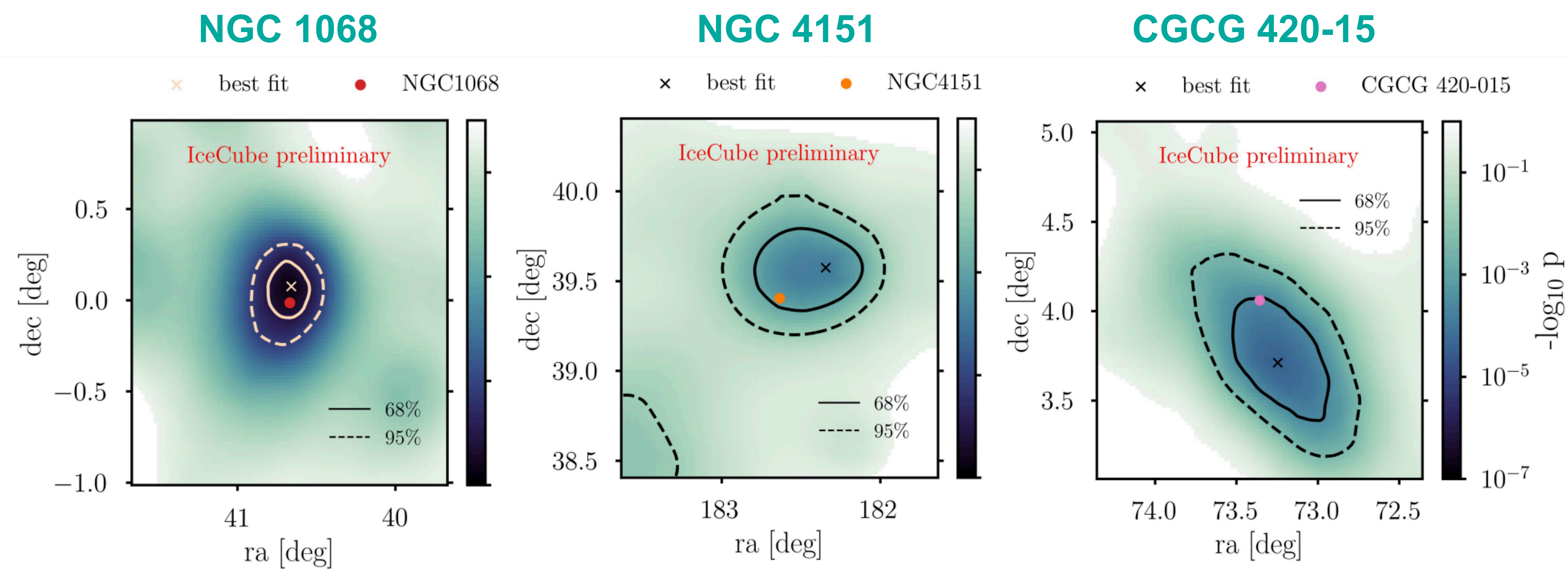


Abbasi et al., Science (2022). Figure credit: Jack Pairin, IceCube/NSF.

NGC 1068:
Neutrinos allow to explore the galaxy core.
Neutrinos carry information about the obscured supermassive black hole

Credit: NASA/JPL-Caltech

More X-Ray Bright Seyfert Galaxies?



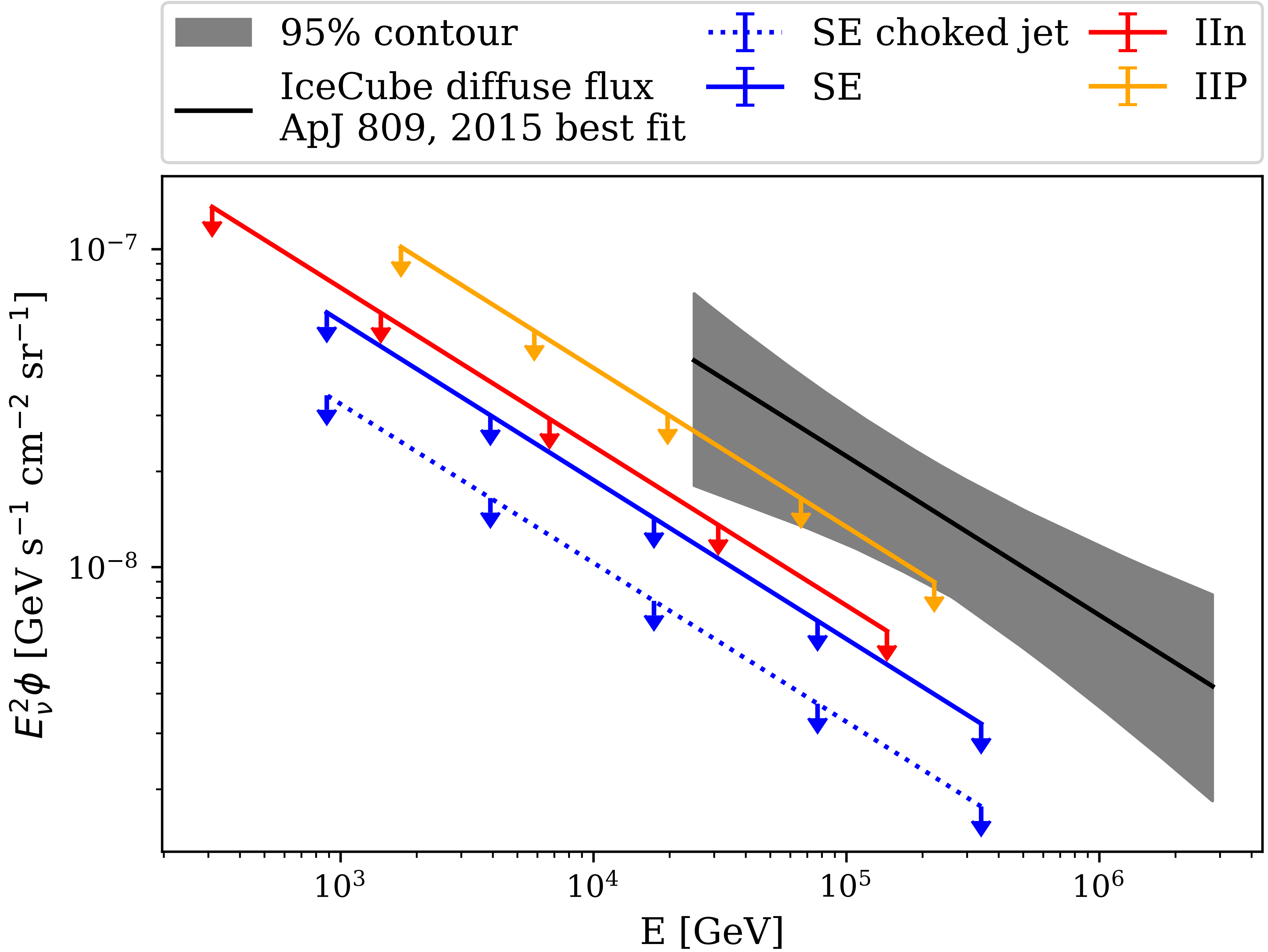
- Excess of neutrinos associated to NGC 4151 and CGCG 420-015 at 2.7σ in Northern sky.
- Similar analysis focusing on the Southern Sky in preparation.
- Emerging trend? Dominant high-energy neutrino sources might be gamma-ray dim.

T. Glauch et al., PoS(ICRC2023)1052

Supernovae

Image credits: ESA/Hubble & NASA.

Neutrinos from Supernovae

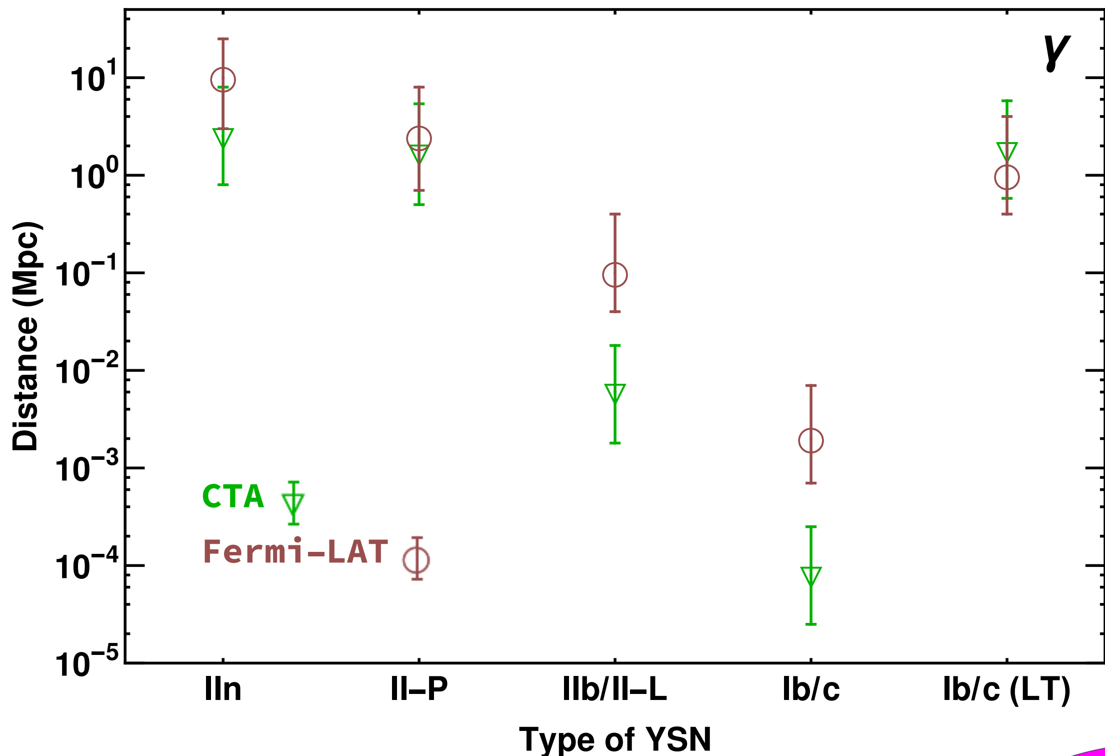


- No significant spatial or temporal correlation of high-energy neutrinos with supernovae found yet (upper limit on total energy emitted in neutrinos: 1.3×10^{49}erg for SNe IIn).
- SNe IIn (SNe IIP) do not contribute more than 33.9.6% (59.9%) to the diffuse neutrino flux observed by IceCube.

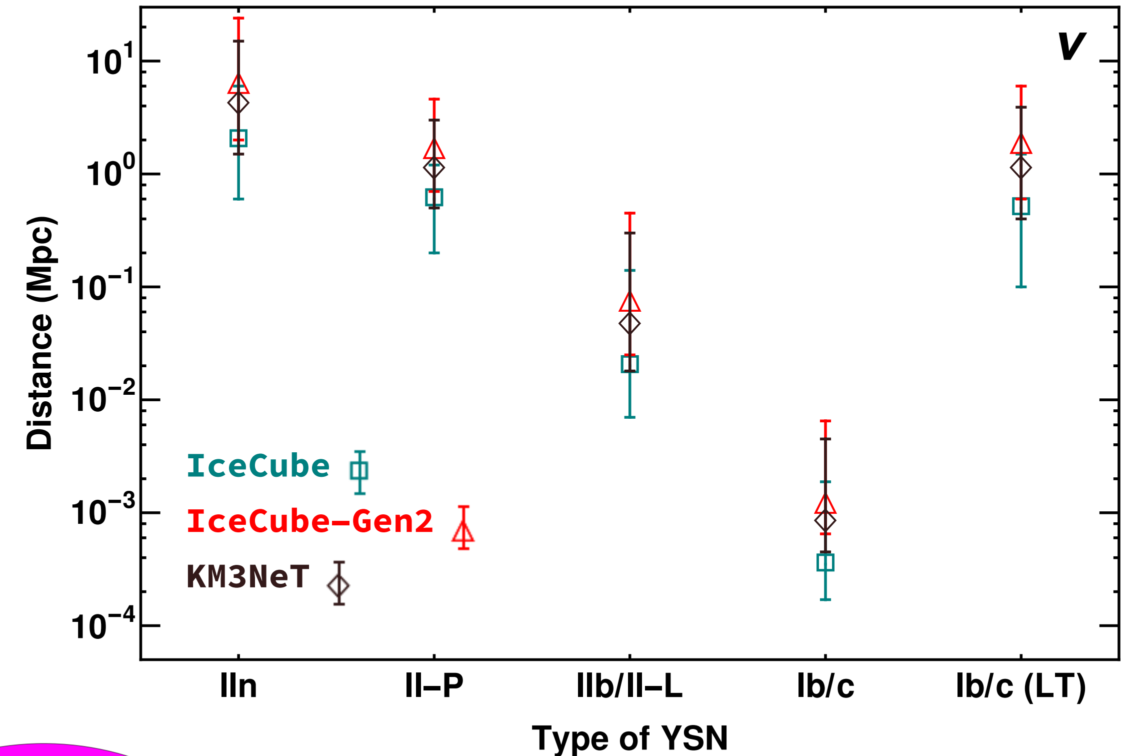
IceCube Coll., Astrophys. J. Lett. (2023).

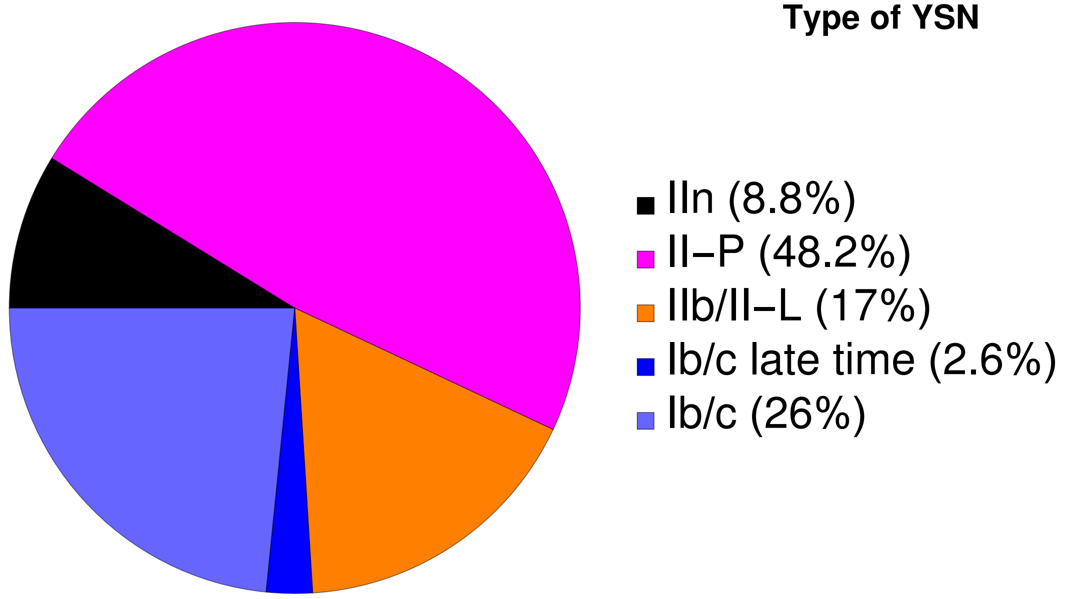
Gamma-Ray and Neutrino Joint Detections

Gamma-rays



Neutrinos

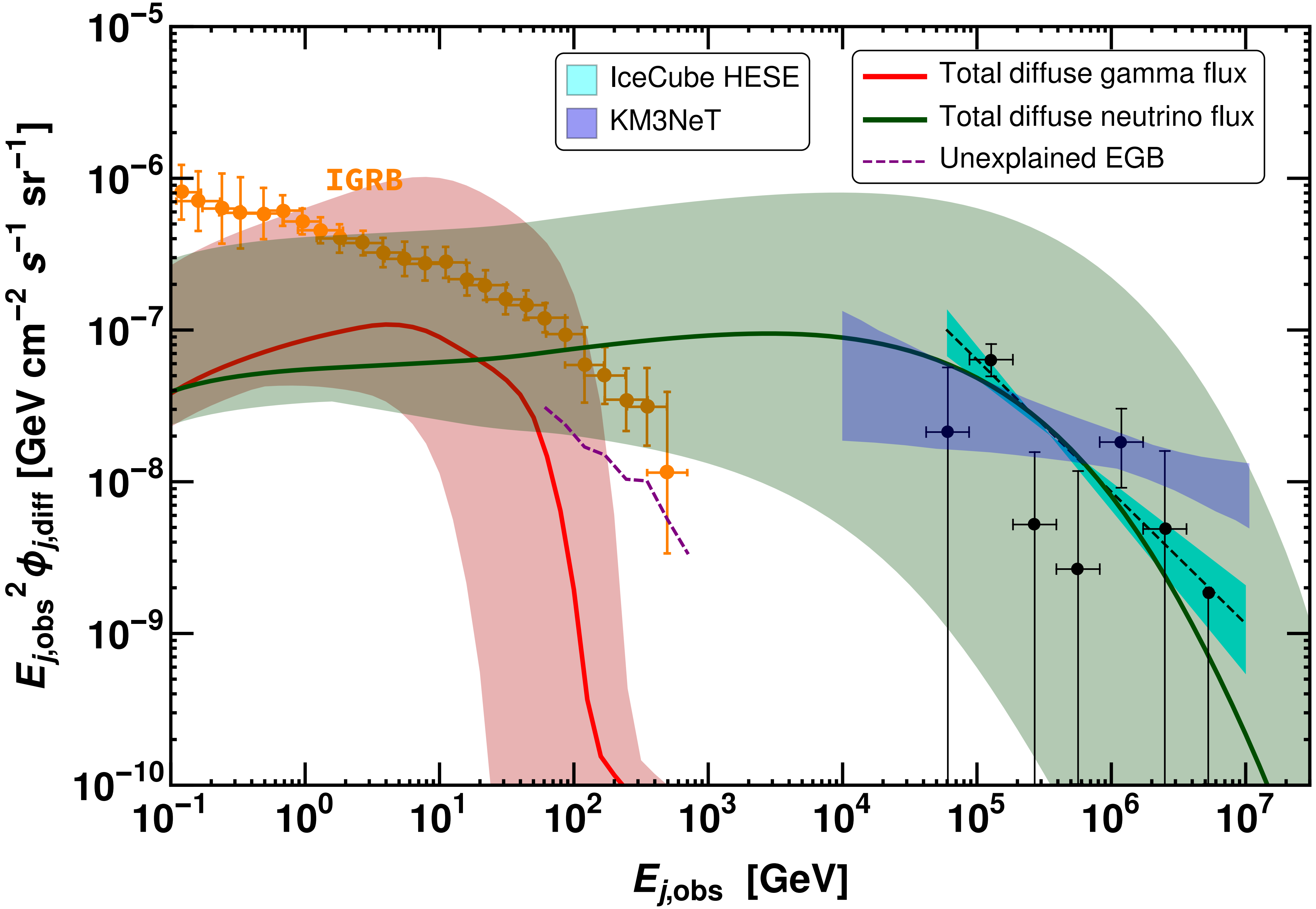




- SNe of Type IIn and II-P detectable in gamma-rays and neutrinos in the local universe.
- Gamma-rays and neutrinos can probe the structure of circumstellar medium and test of particle acceleration.

Sarmah, Chackaborty, Tamborra, Auchettl, JCAP (2022). Pitik, Tamborra, Angus, Auchettl, ApJ (2022). Pitik, Tamborra, Lincetto, Franckowiack, MNRAS (2023). Kheirandish & Murase, Astrophys. J. Lett. (2023). Murase, arXiv: 2312.17239. IceCube Coll., Astrophys. J. Lett. (2023).

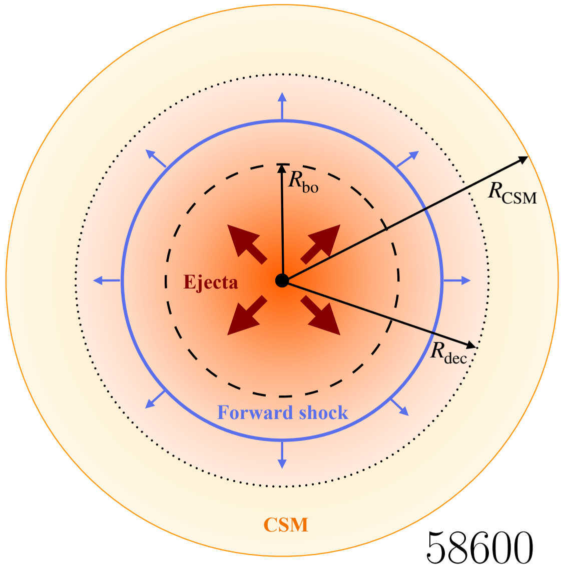
Gamma-Ray and Neutrino Diffuse Emission

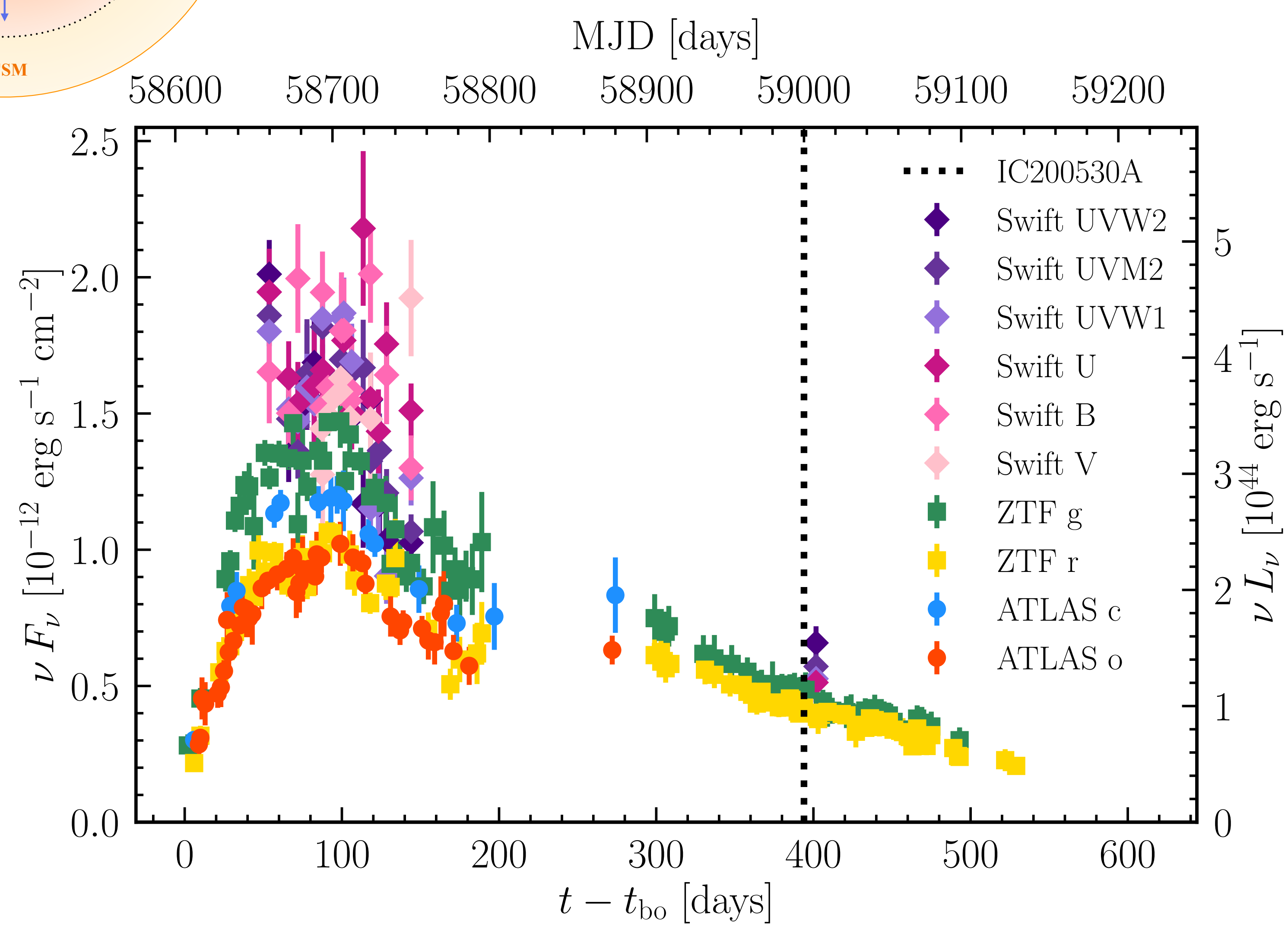


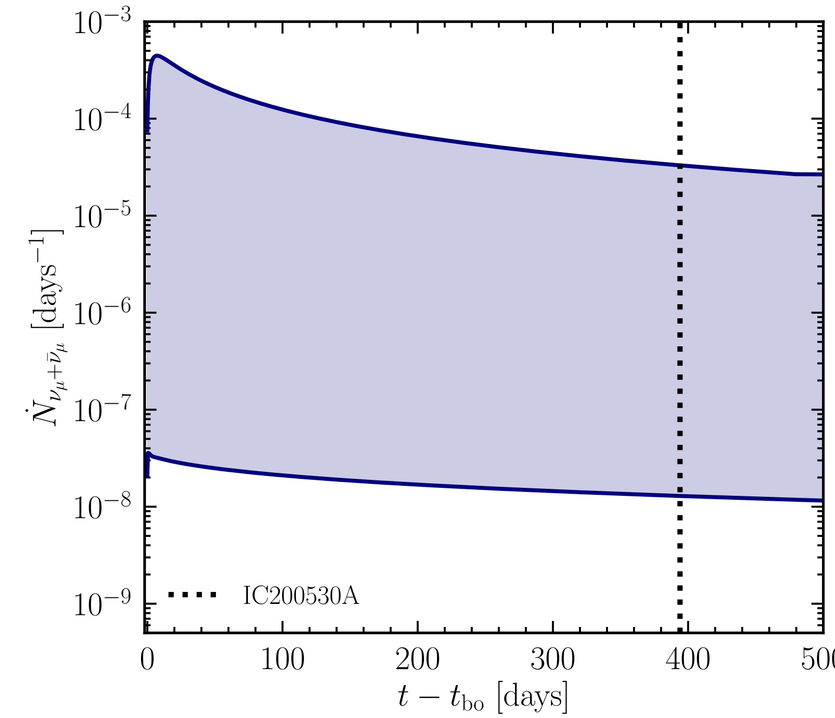
Supernovae may explain the low-energy excess observed in the diffuse background of high-energy neutrinos, without overshooting the gamma-ray diffuse background (no need to invoke hidden cosmic ray accelerators?).

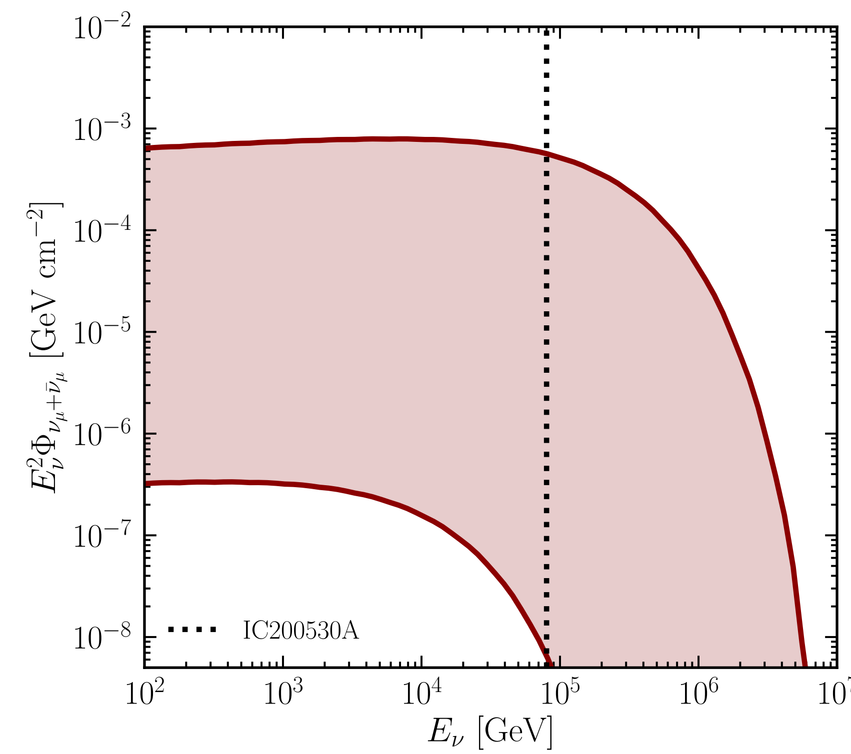
Sarmah, Chackraborty, Tamborra, Auchettl, JCAP (2022). Brose, Sushch, Mackey, MNRAS (2022).

AT 2019fdr: Source Misidentification





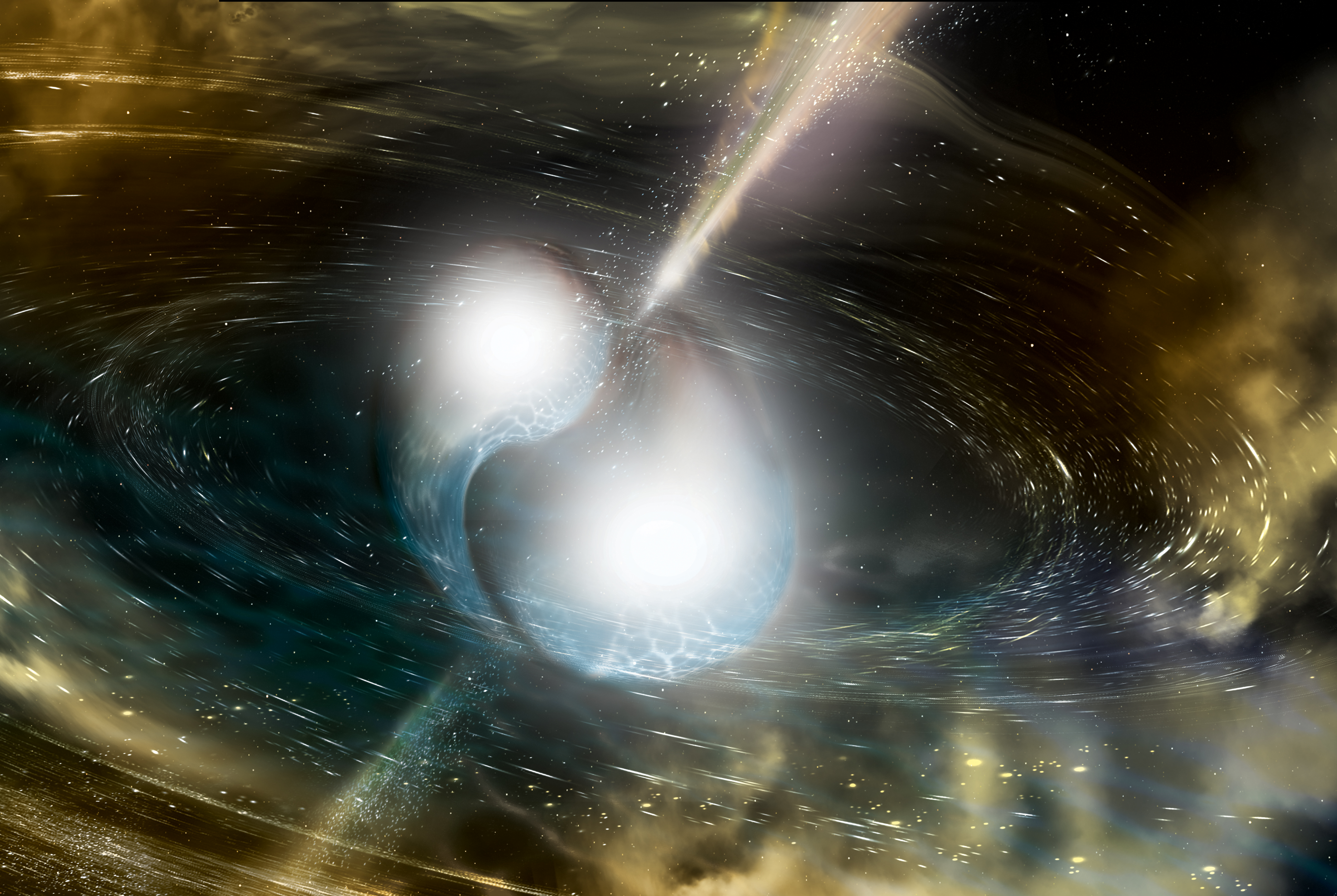




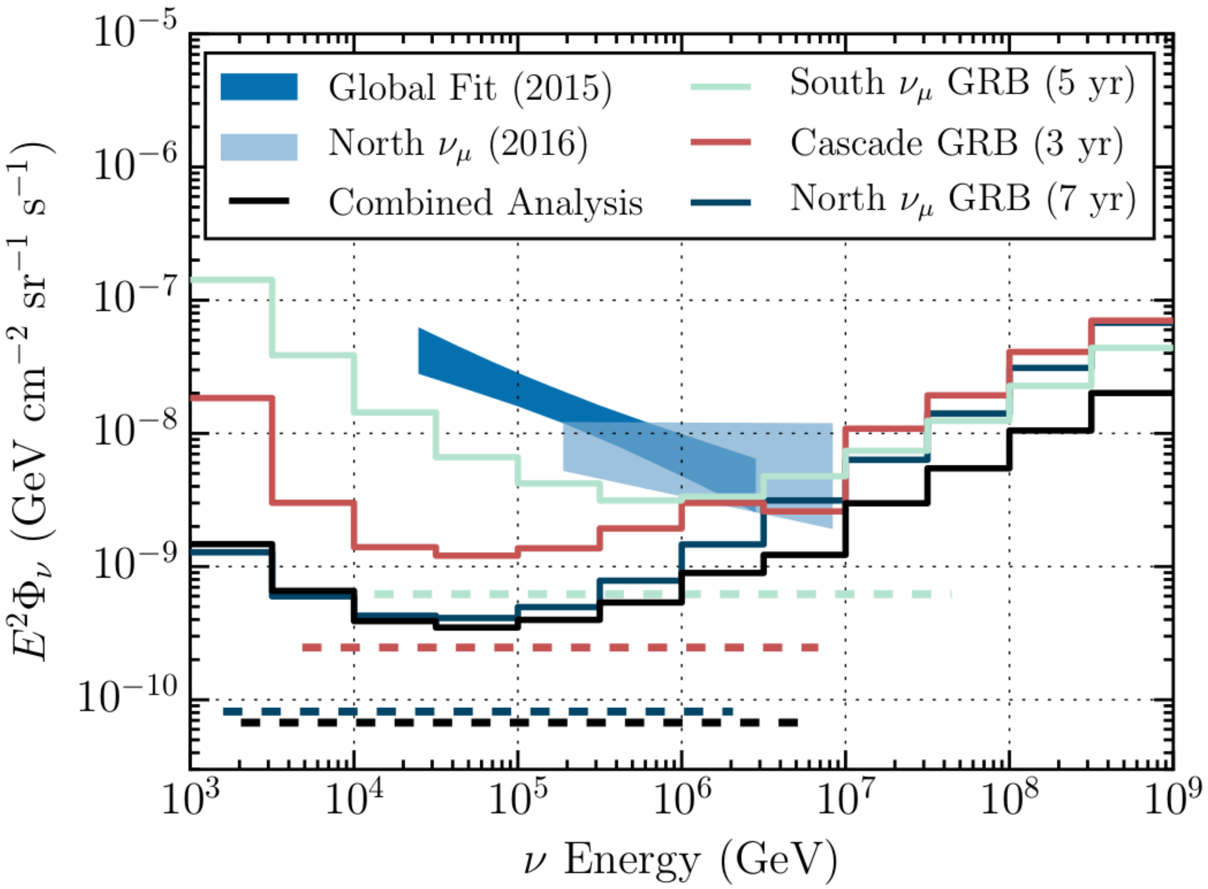
- Is AT2019fdr a tidal disruption event or a superluminous supernova?
- Hydrogen-rich superluminous supernova scenario compatible with IC200530A.

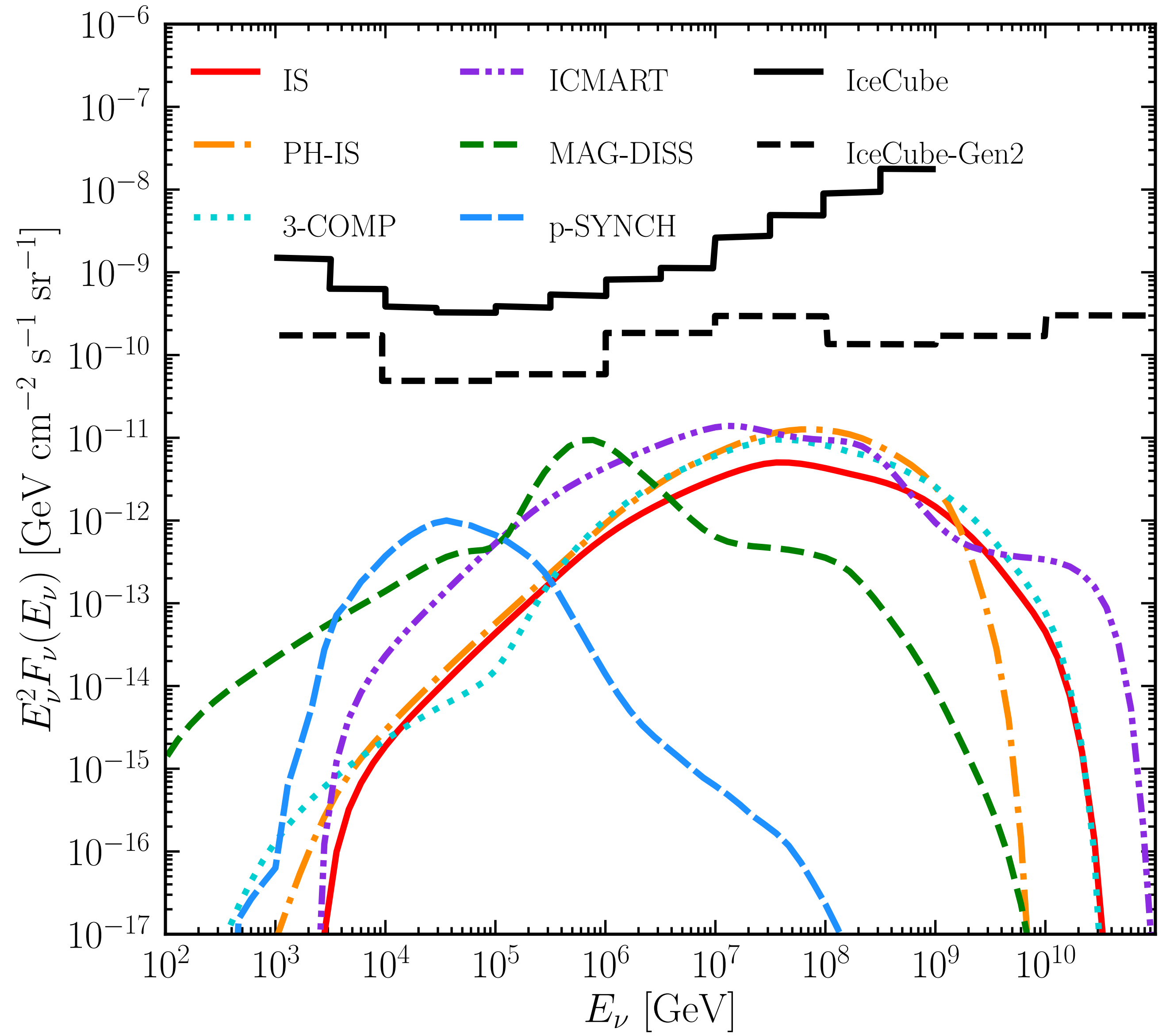
Pitik, Tamborra, Angus, Auchettl, ApJ (2022). Reusch et al., PRL (2022). van Velzen et al., arXiv: 2111.09391.

Gamma-Ray Bursts



High Energy Emission from Gamma-Ray Bursts

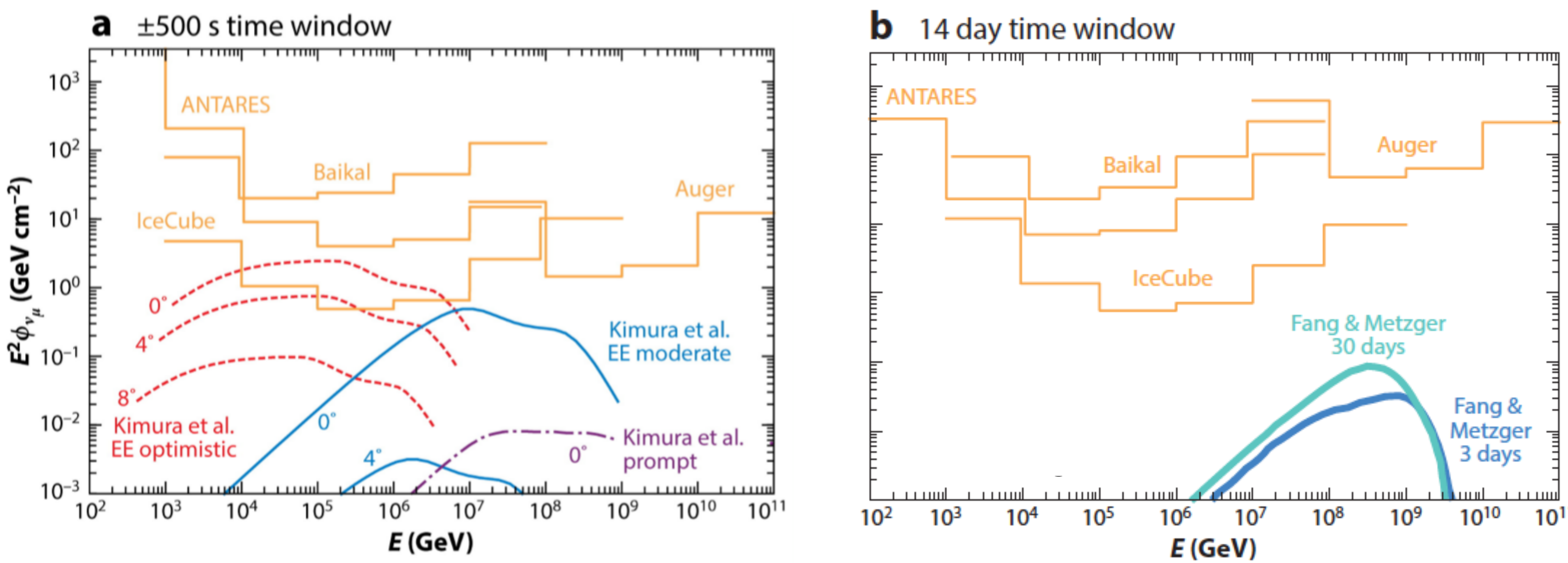




- No successful detection of high energy neutrinos from long GRBs (<1% to diffuse emission).
- Neutrino emission strongly depends on GRB emission mechanism.

ANTARES Coll., MNRAS (2020). IceCube Coll., ApJ (2017). Pitik, Tamborra, Petropoulou, JCAP (2021). Rudolph et al., MNRAS (2022), ApJ (2020).

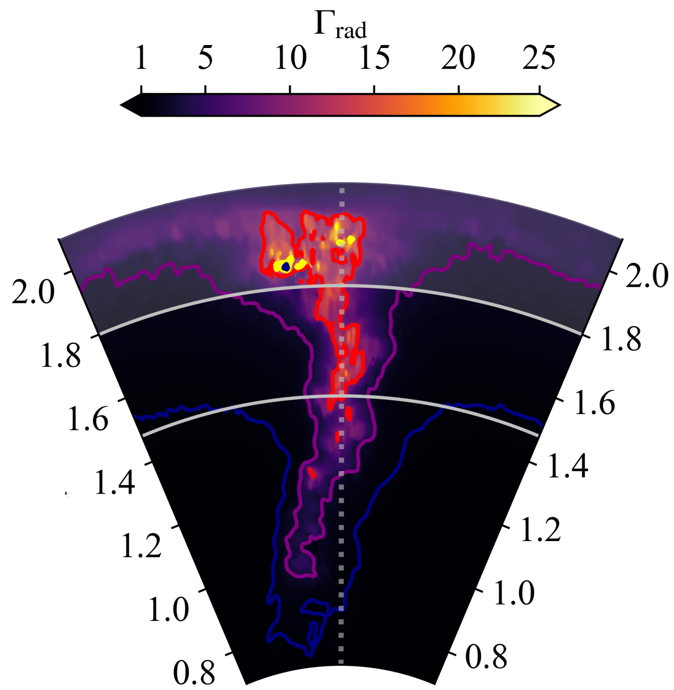
High Energy Neutrinos from GRB 170817A?



- No neutrinos detected from prompt short GRB phase yet.
- Neutrinos from long-lived ms magnetar and internal shock propagating in kilonova ejecta.
- Favorable detection opportunities with multi-messenger triggers.

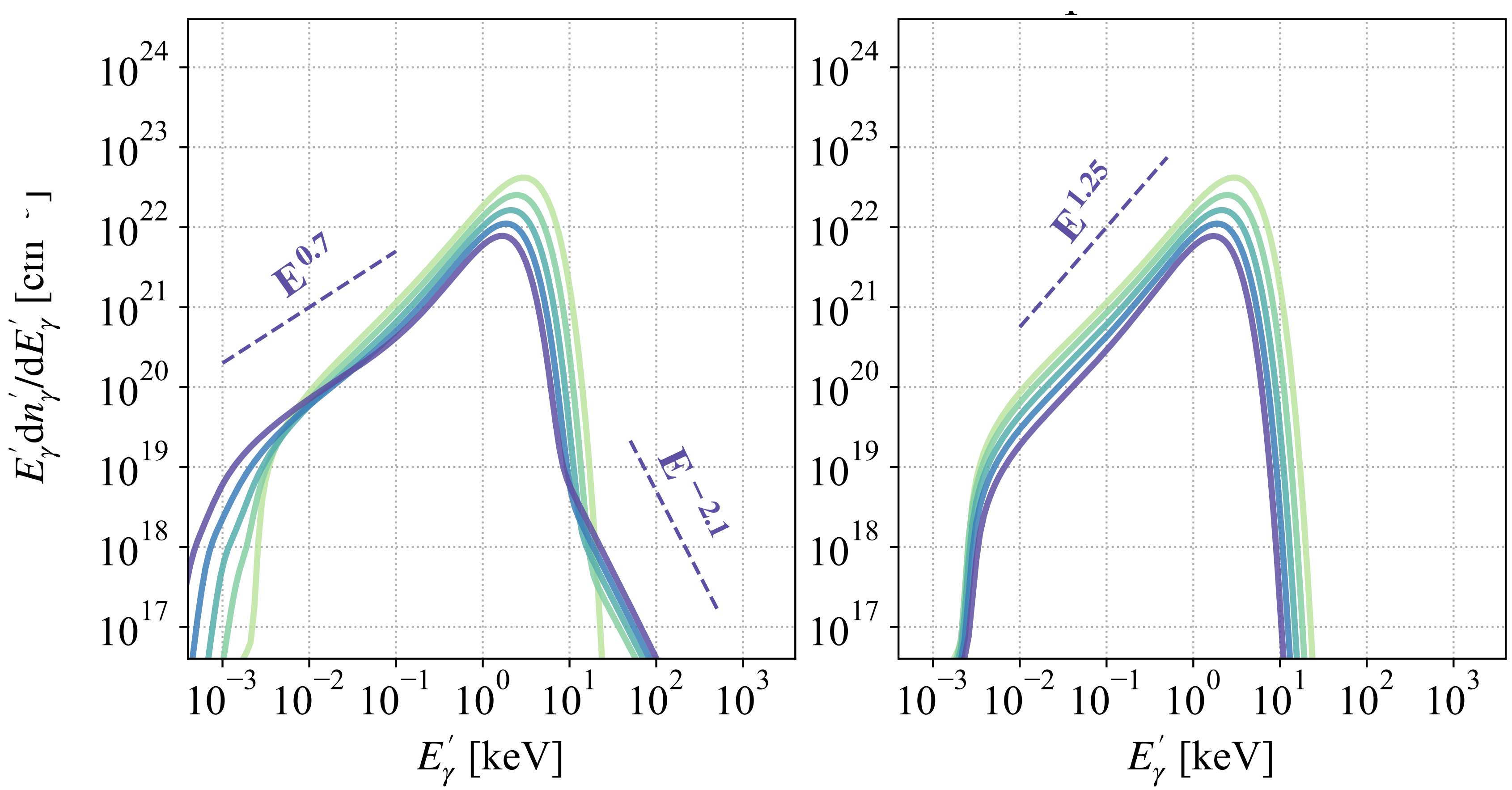
Figure credit: Christian Spiering. Murase& Bartos, Ann. Rev. (2019). Fang & Metzger, ApJ (2017). Kimura et al., PRD (2018). Biehl et al., MNRAS (2018). Kyutoku, Kashiyama, PRD (2018). Tamborra, Ando, JCAP (2015). Gottlieb, Globus, ApJL (2021).

On the Origin of the Photon Distribution



Leptonic + hadronic processes (our work)

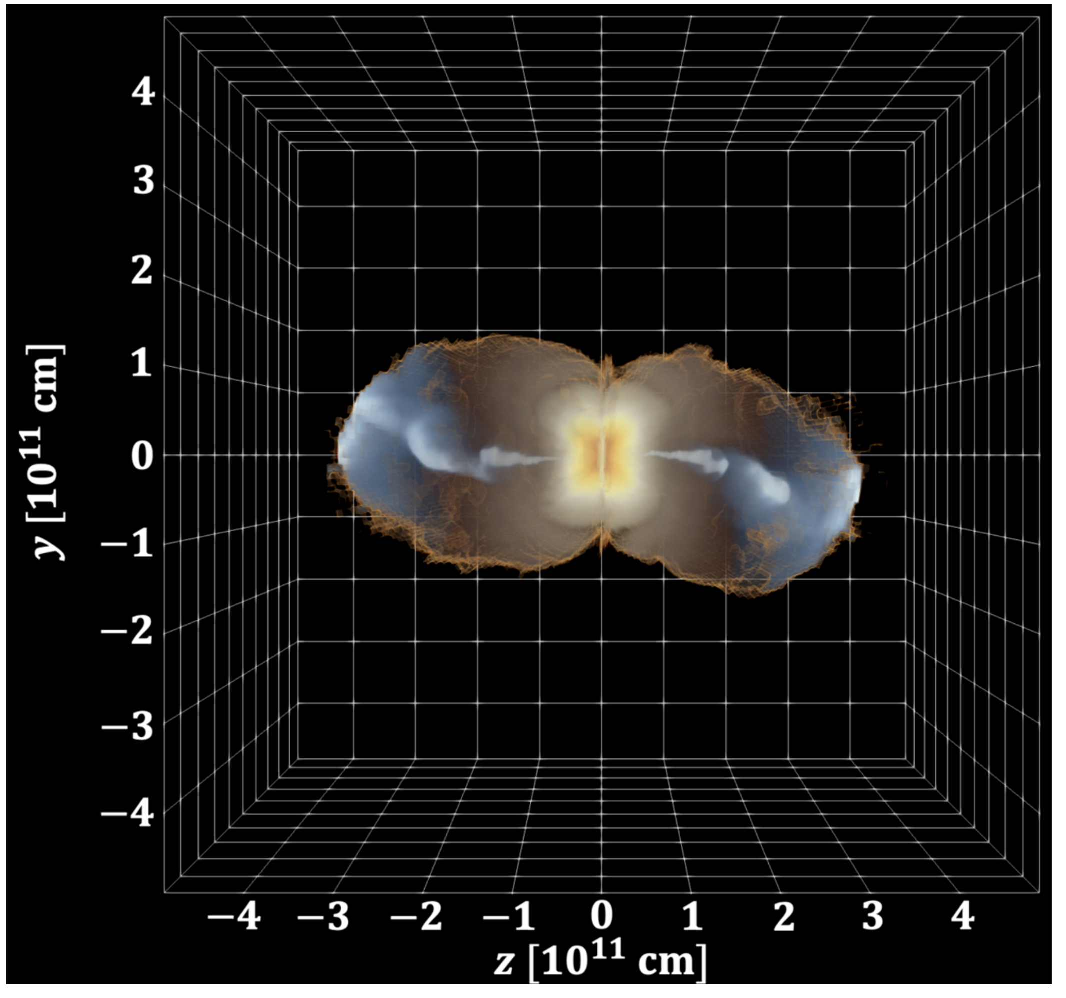
Leptonic processes only (usually considered)

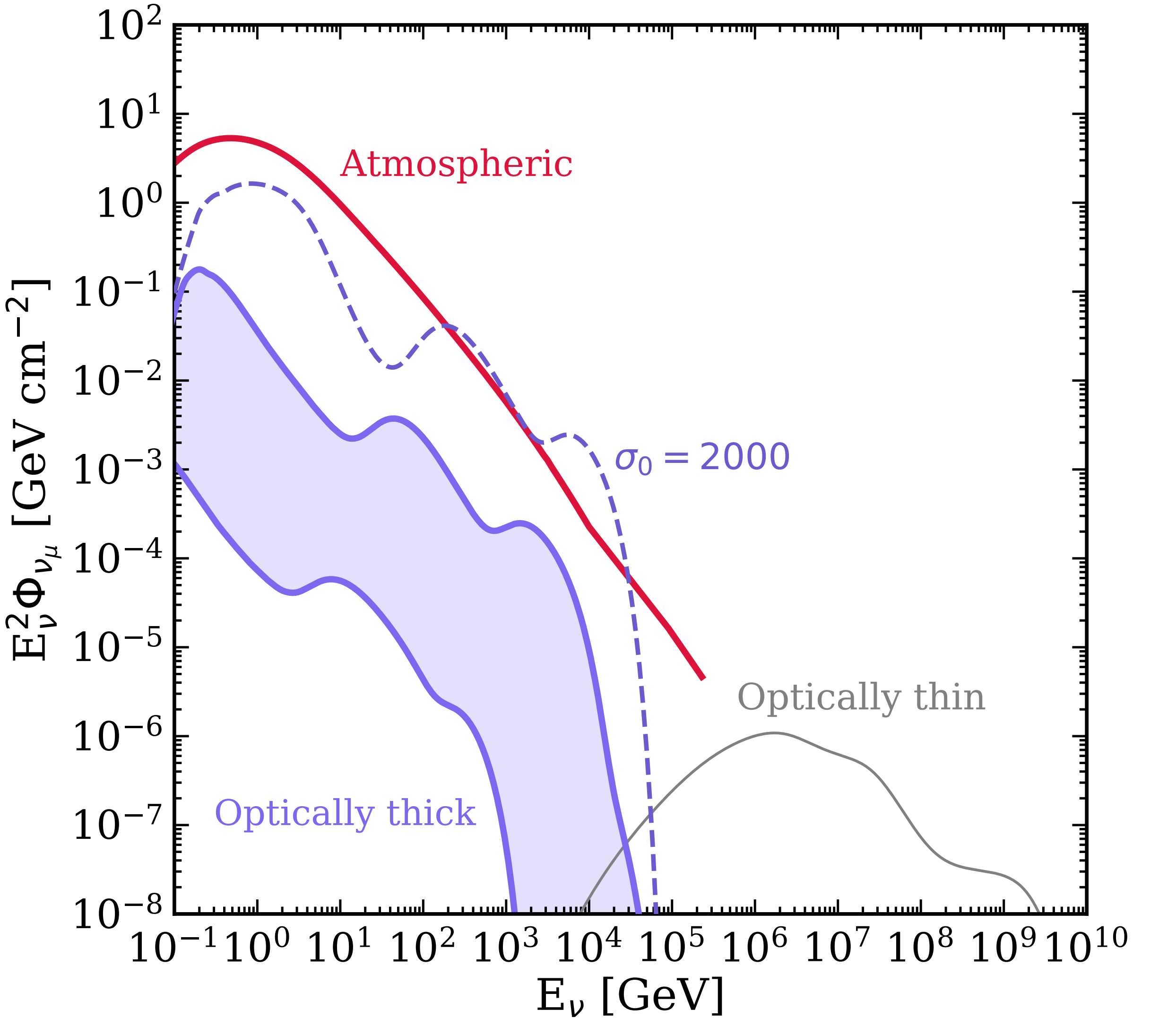


- Origin of observed Band-like photon spectrum in short GRBs is poorly understood.
- Bulk of non-thermal photon spectrum can stem from hadronic processes below the photosphere (usually just invoked for neutrino production).

Rudolph, Tamborra, Gottlieb, Astrophys. J. Lett. (2024).

On the Origin of the Neutrino Distribution



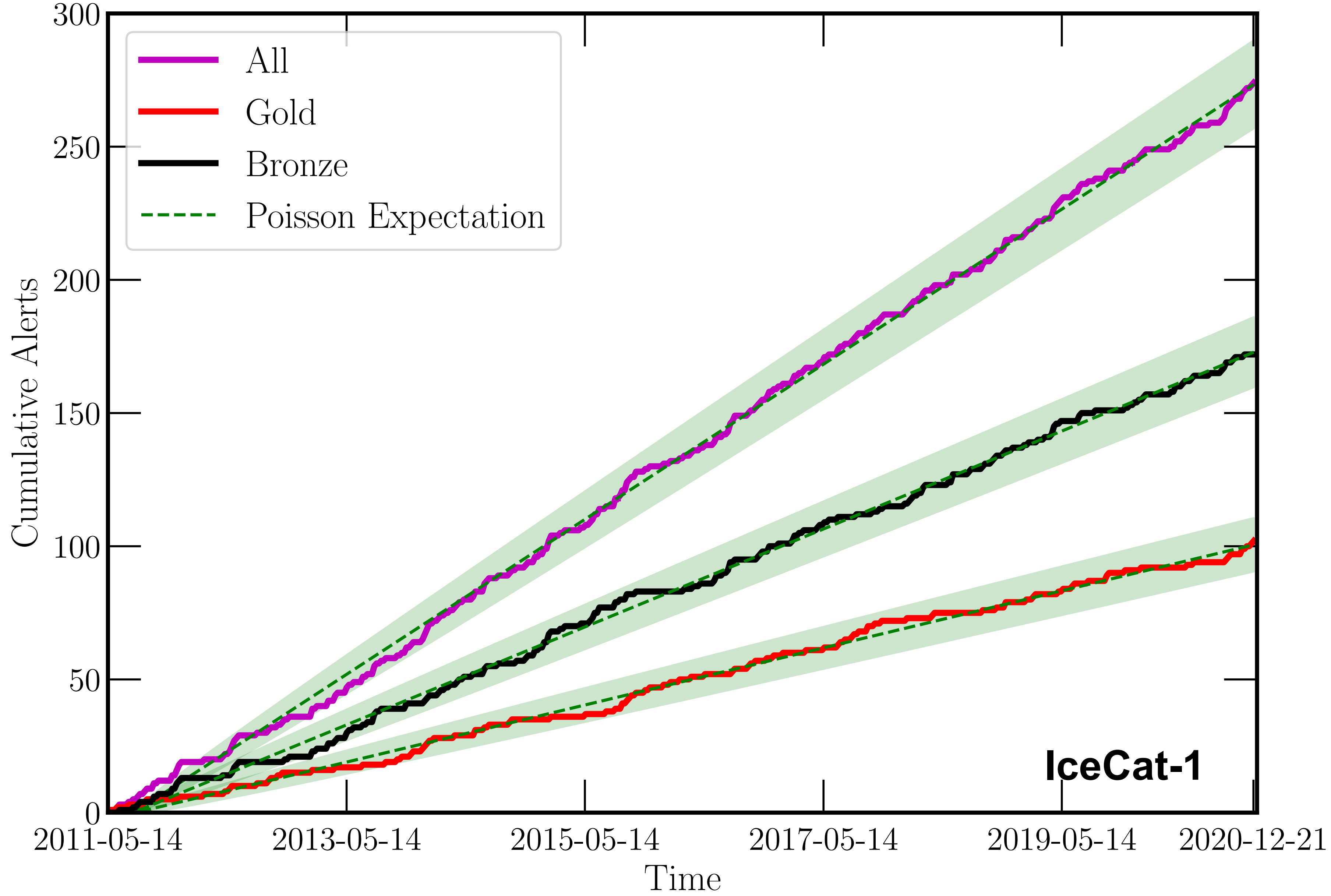


- State-of-the-art collapsar jet simulations predict neutrino signal different than expected.
- Subphotospheric neutrinos have lower energies than previously expected; detection possible with IceCube DeepCore.

Guarini, Tamborra, Gottlieb, PRD (2023). Rudolph, Tamborra, Gottlieb, Astrophys.J. Lett. (2024). IceCube Coll., Astrophys. J. (2024).

Follow-Up Programs

Optimizing Follow-Up Programs



- Stacking neutrino searches based on “standard candles” are not optimal.
- Essential to combine X-ray/radio and UVOIR observations to aid neutrino searches.
- Neutrino bright sources may not be gamma-ray bright.

Figure credits: IceCube Collaboration, Astrophys. J. Suppl. (2023).

Pitik, Tamborra, Lincetto, Franckowiack, MNRAS (2023). Guarini, Tamborra, Margutti, Ramirez-Ruiz, PRD (2023).

Conclusions

- Fantastic progress in multi-messenger searches of astrophysical sources.

- Origin of diffuse emission of high-energy neutrinos is still mysterious, but number of likely neutrino-electromagnetic associations is increasing.

- Robust 1:1 neutrino-gamma-ray connection is not so obvious as previously expected.

- We need to optimize multi-messenger follow-up programs for growing number of high-energy neutrino alerts.

- Interpretation of multi-messenger data requires a major step forward in source modeling.

Very exciting times ahead!!

Thank you!