Galactic neutrinos

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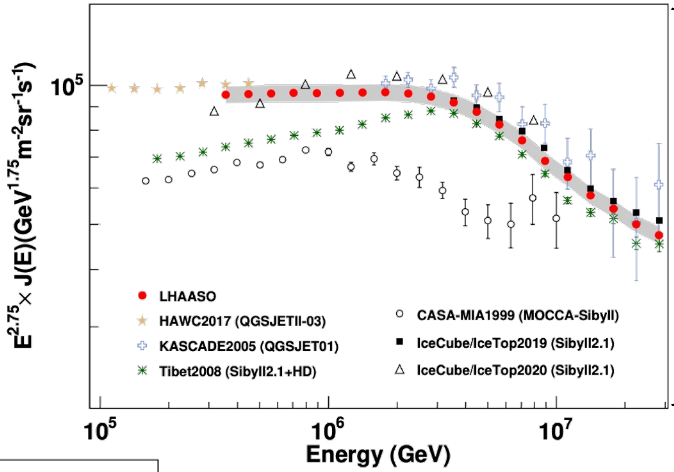
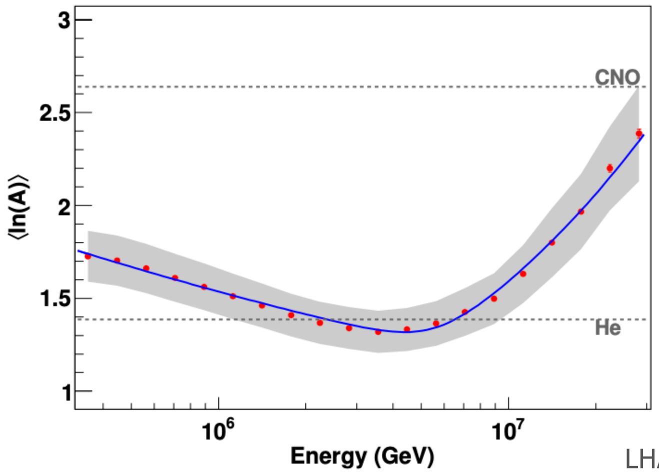
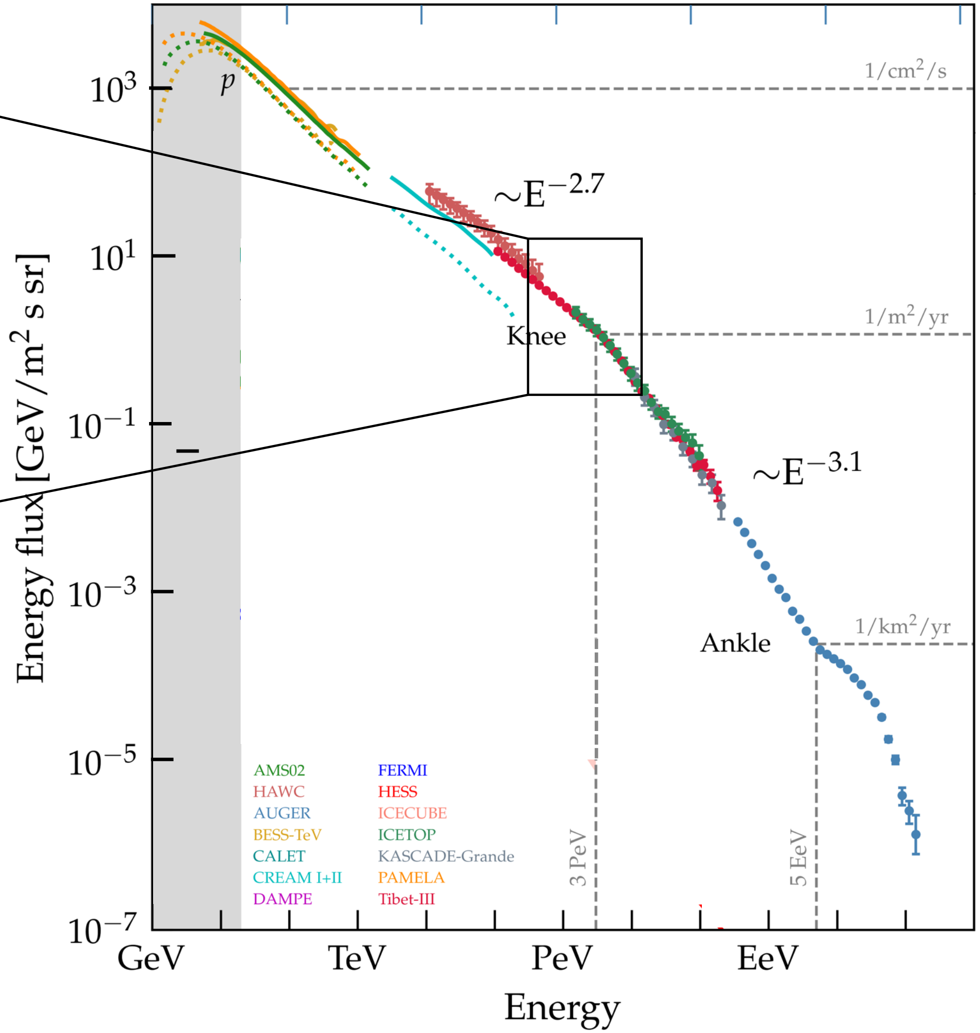
Galactic cosmic rays

- What is the average spectrum of cosmic rays in the Milky Way?
- Does it have a PeV "knee" feature?
- Is the knee at the same energy everywhere?
- What source class is responsible for the PeV cosmic rays?

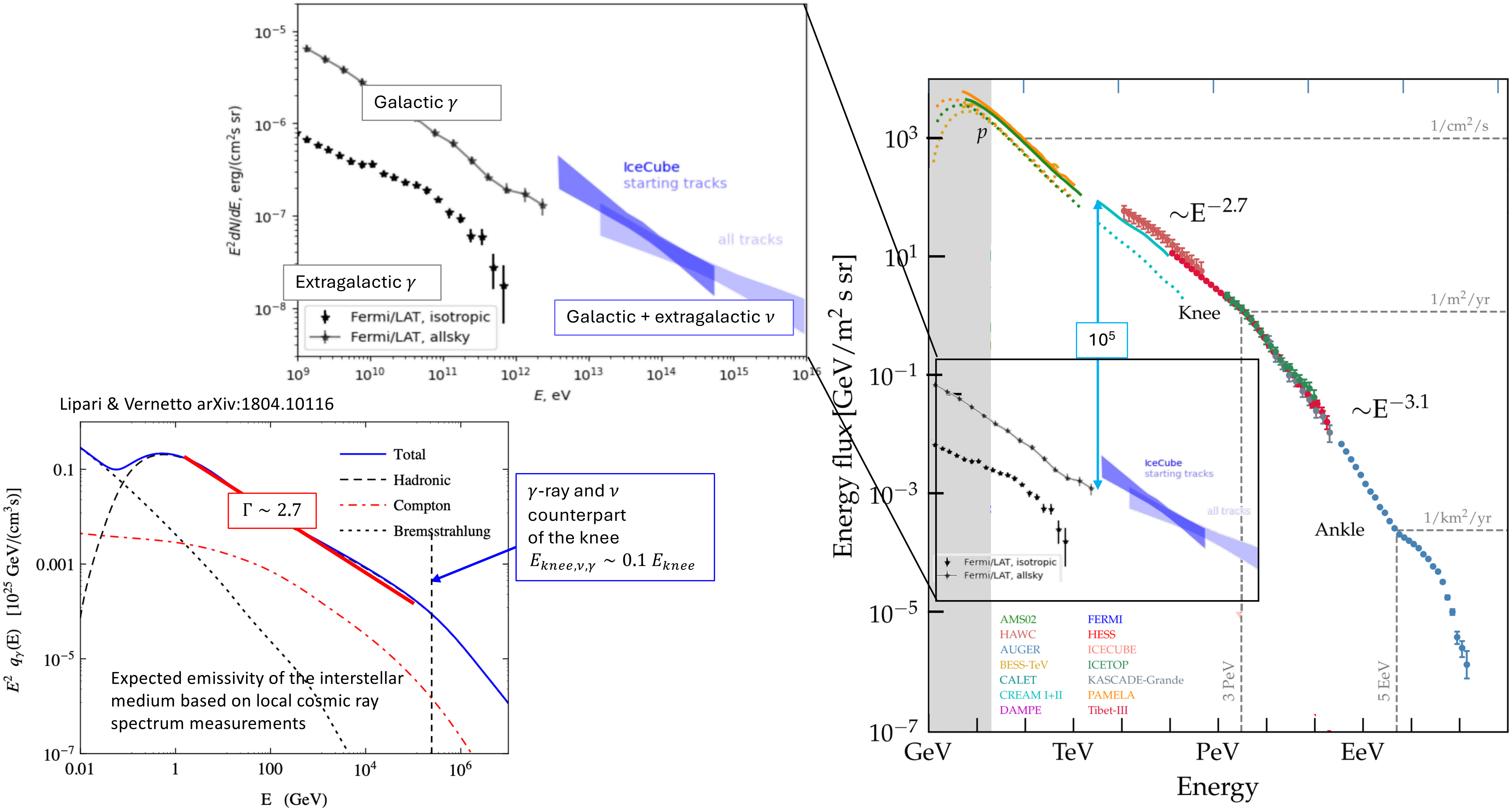






LHAASO Collab. arXiv:2403.10010

Galactic cosmic ray measurements with gamma-rays and neutrinos?



Lipari & Vernetto arXiv:1804.10116

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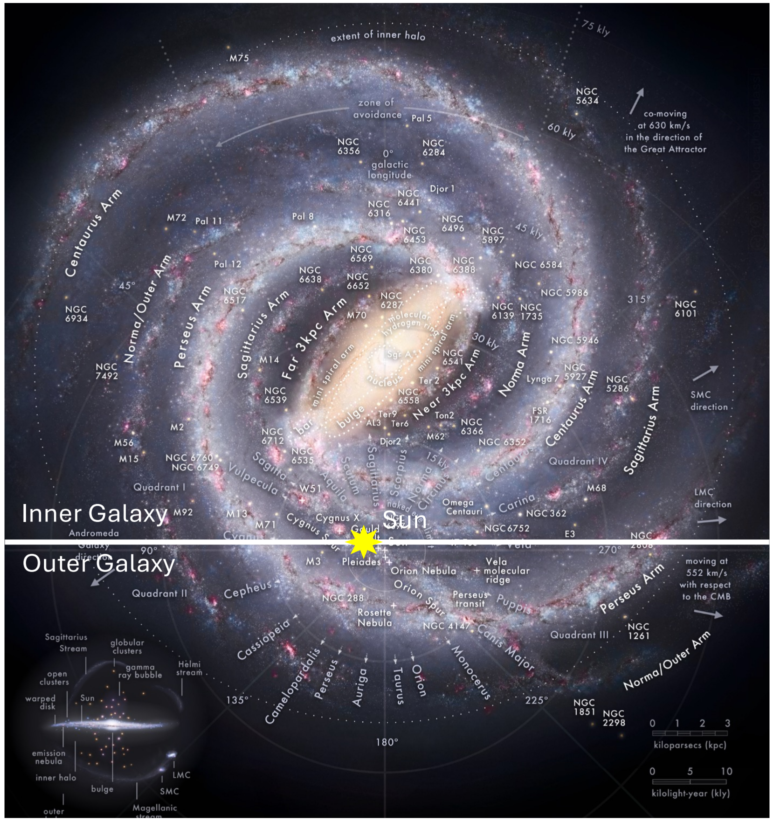
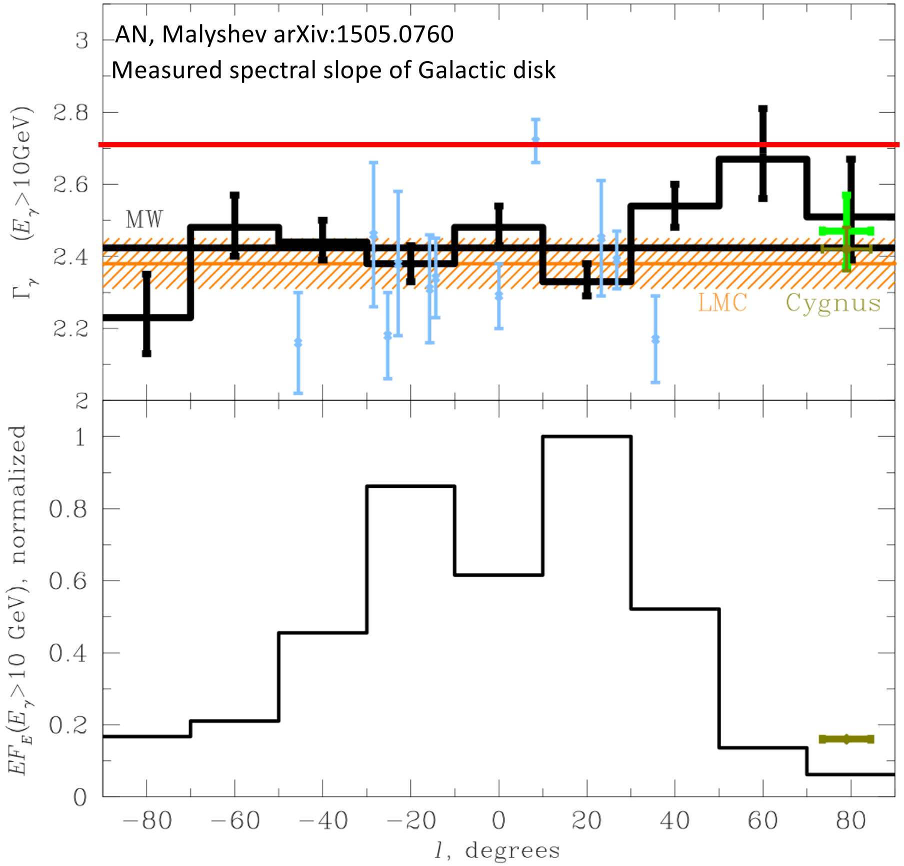
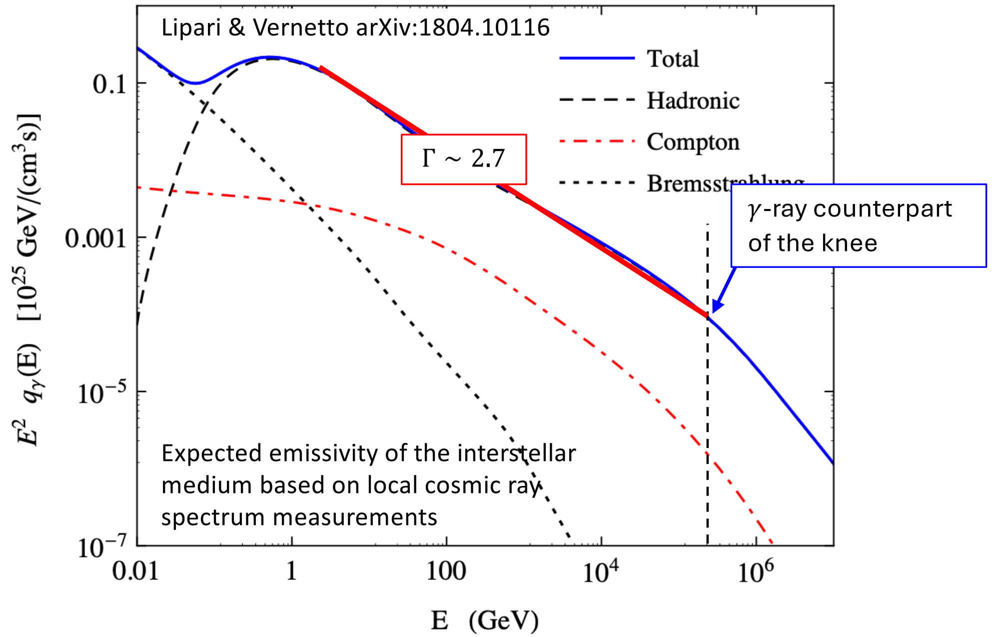




Slope of the gamma-ray spectrum in the inner part of the Milky Way (Galactic longitudes $|l| < 90°$) is $\Gamma \sim 2.4..2.5$

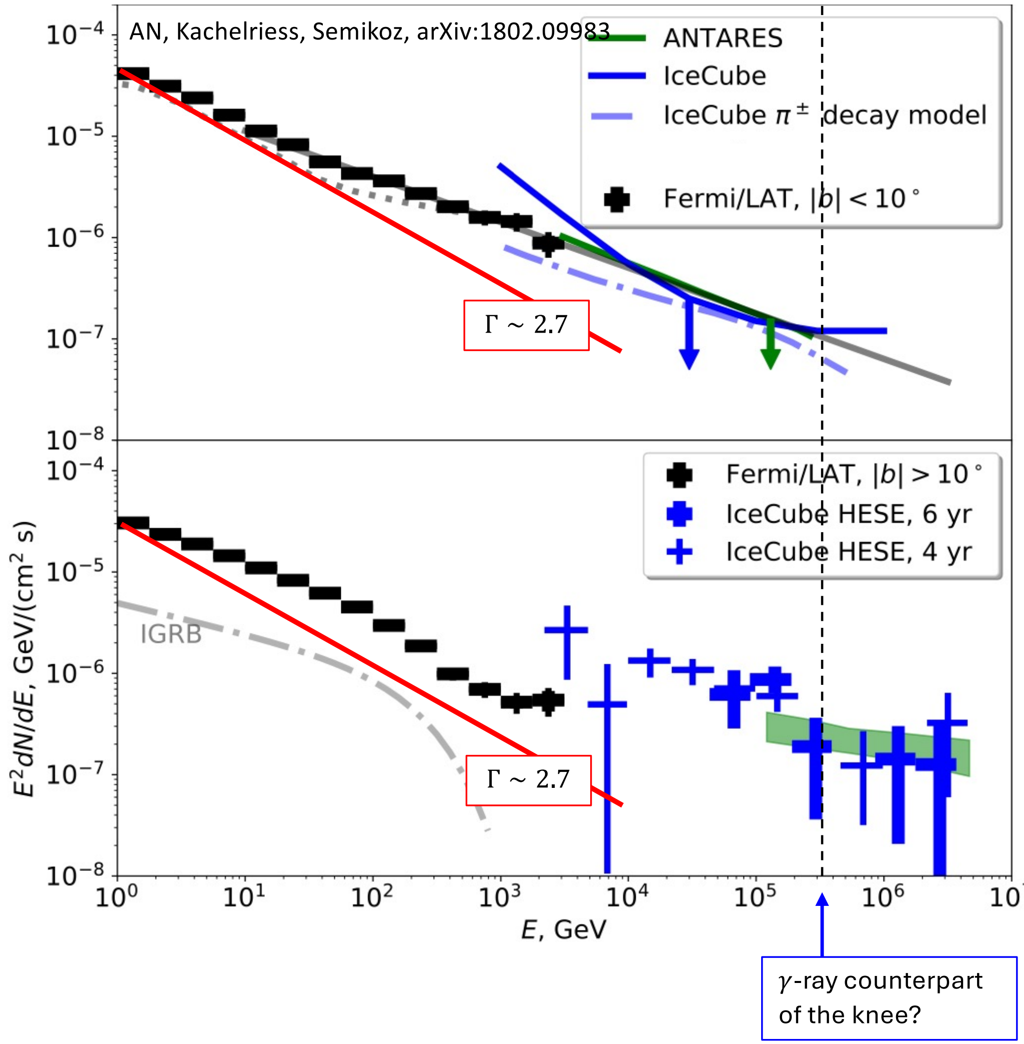
It is possible that the “average” slope of cosmic rays in the Galactic disk with $D \sim 8$ kpc distance is harder than the slope of the locally observed cosmic ray spectrum.

Galactic cosmic ray measurements with gamma-rays and neutrinos?



The expected level of diffuse Galactic neutrino emission is much below the level of the astrophysical neutrino flux if the $\Gamma \simeq 2.7$ is characteristic for the entire Galaxy. If the average cosmic ray spectrum is harder, Milky Way may provide a sizeable contribution to the astrophysical neutrino flux.

… and the neutrino counterpart of the knee is in the energy range of neutrino telescopes!



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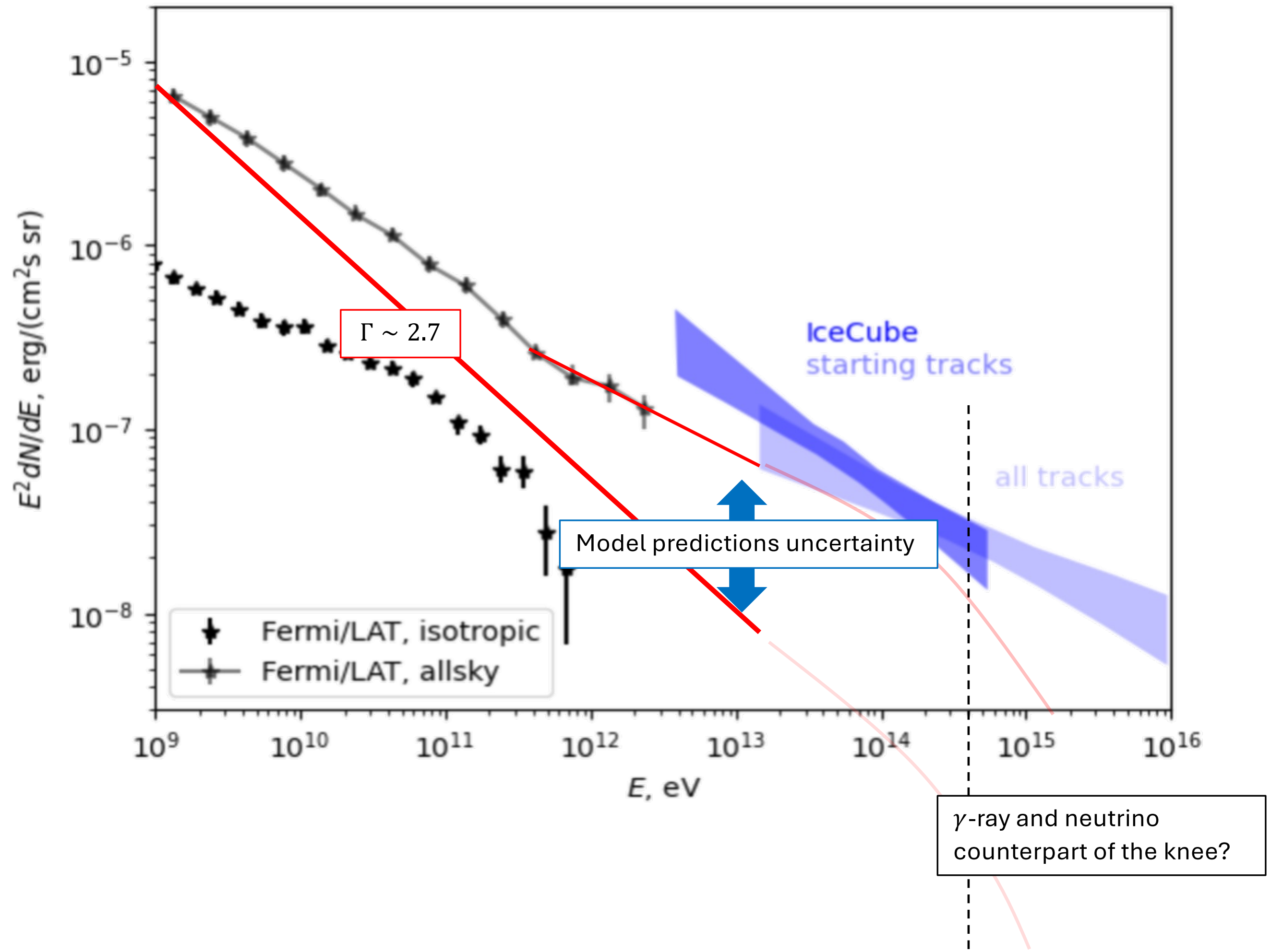


Isolated sources vs. diffuse emission

Cosmic rays diffuse through the interstellar medium, the (isotropic) diffusion coefficient estimate

$$D \sim 3\times10^{28}\left[\frac{E}{10\ \mathrm{GeV}}\right]^{\frac{1}{3}}\frac{\mathrm{cm}^2}{\mathrm{s}} \sim 3\times10^{30}\left[\frac{E}{10\ \mathrm{PeV}}\right]^{\frac{1}{3}}\frac{\mathrm{cm}^2}{\mathrm{s}}$$

The Milky Way gaseous disk with the density $n_d \sim 1\ \mathrm{cm}^{-3}$ has thickness $h_d \sim 150\ \mathrm{pc}$. Cosmic rays escaping from a source in the disk are confined in a “bubble” of the side r around the source as long as

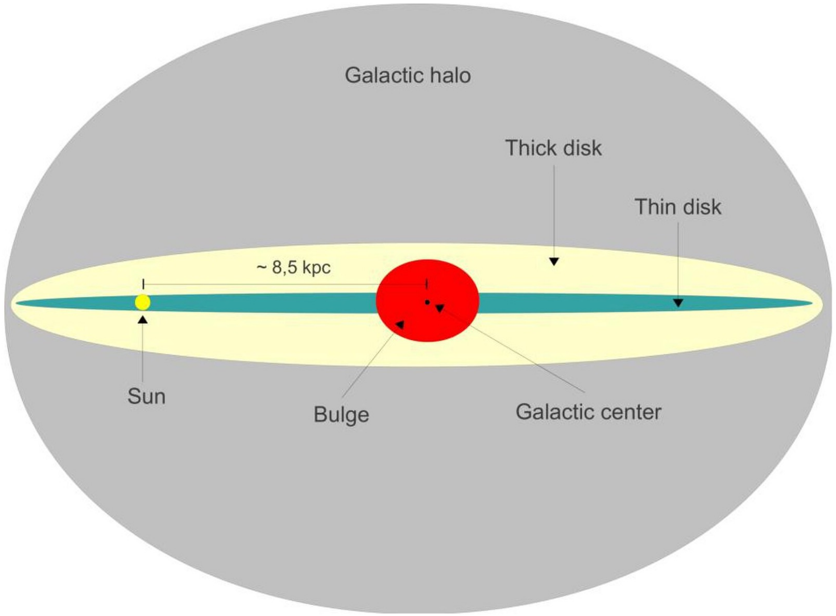
$$r \sim \sqrt{Dt} \simeq 100\left[\frac{t}{10^3\ \mathrm{yr}}\right]^{\frac{1}{2}}\left[\frac{E}{10\ \mathrm{PeV}}\right]^{\frac{1}{6}}\ \mathrm{pc} < h_d$$

Cosmic rays would still reside in a halo of the height H_h around the disk for longer time

$$t \sim \frac{H^2}{D} \simeq 10^5\left[\frac{E}{10\ \mathrm{PeV}}\right]^{-\frac{1}{3}}\left[\frac{H_h}{1\ \mathrm{kpc}}\right]^{2}\ \mathrm{yr}$$

Passage of the halo cosmic rays through the disk should form a diffuse glow of the disk.

Supernovae happen 1-3 times per century in the Galaxy. If the diffusion coefficient is as in the estimate above, we expect to see only 10-30 confined cosmic ray bubbles around recent points of injection of PeV cosmic rays.



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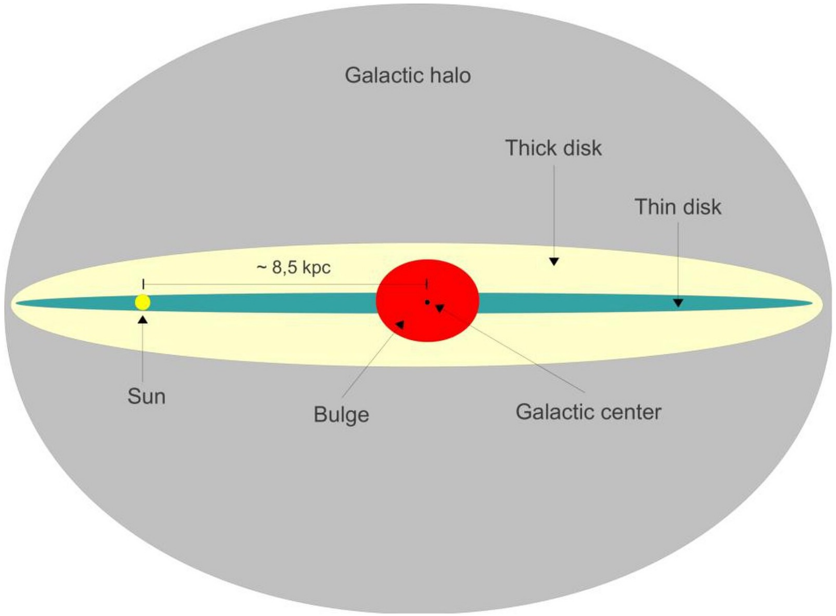
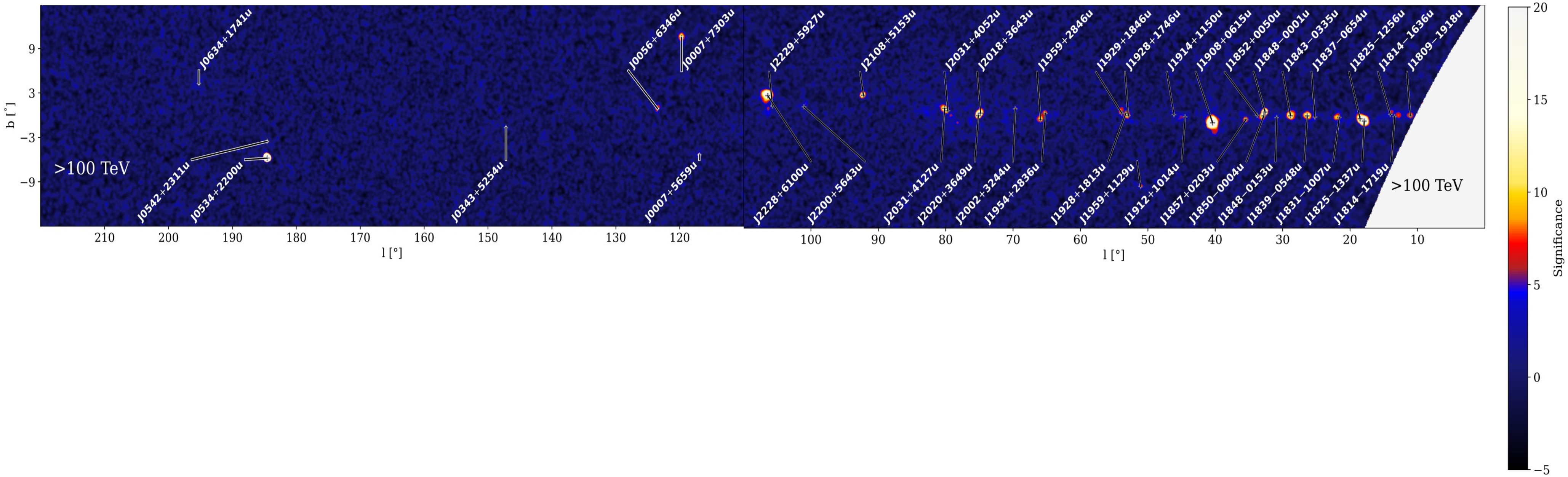


It is also possible that the diffusion coefficient in the disk is smaller, as indicated by the recent pulsar halo observations……

Gamma-ray sky at 100 TeV

LHAASO Collab. arXiv:2305.17030



43 sources at the energies $E > 100$ TeV in the first release of LHAASO catalogue. Some of these sources should be the confined PeV cosmic ray bubbles around recent injection points..... Large fraction of the sources is associated to pulsars, possibly tracing the recent points of injection of cosmic ray protons and nuclei ...... or electrons from pulsar winds?

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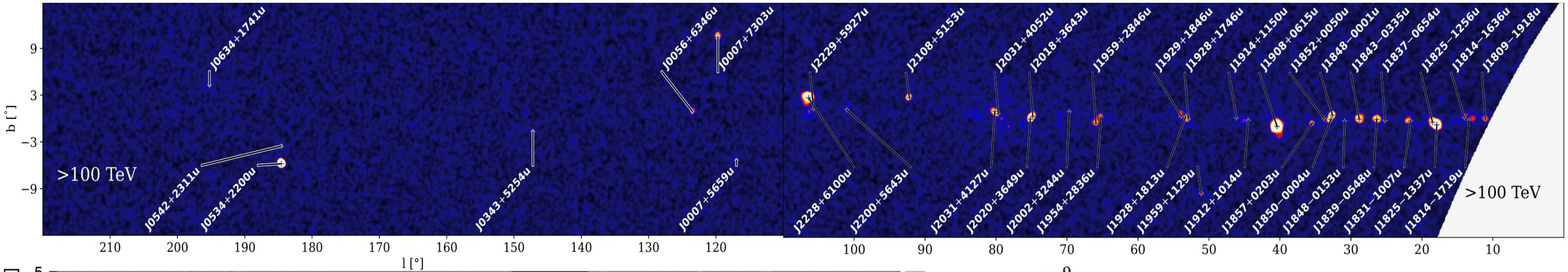

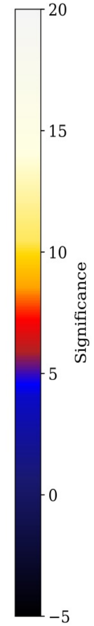

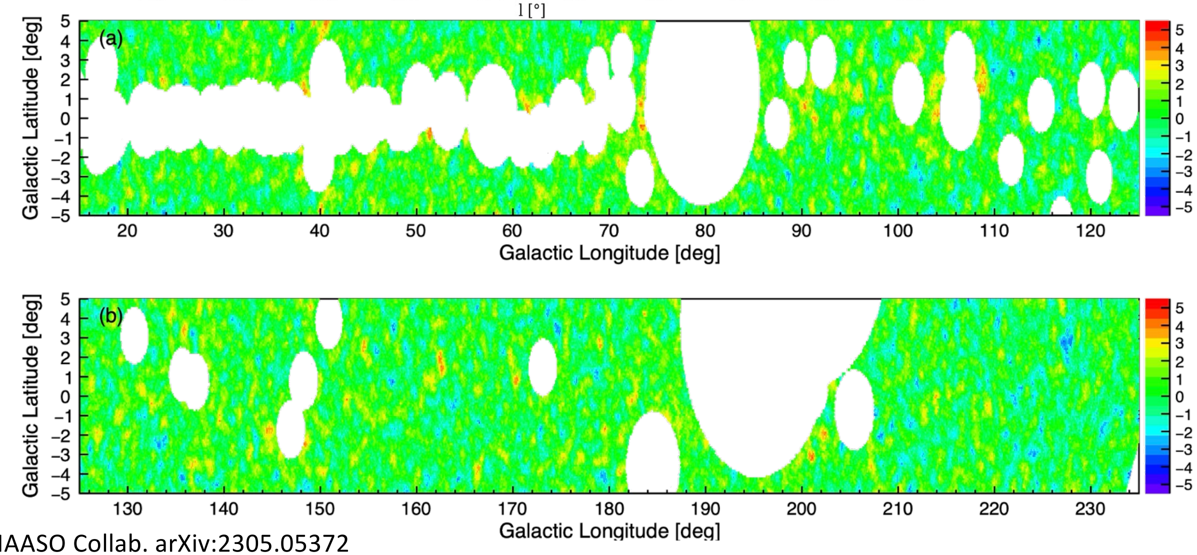

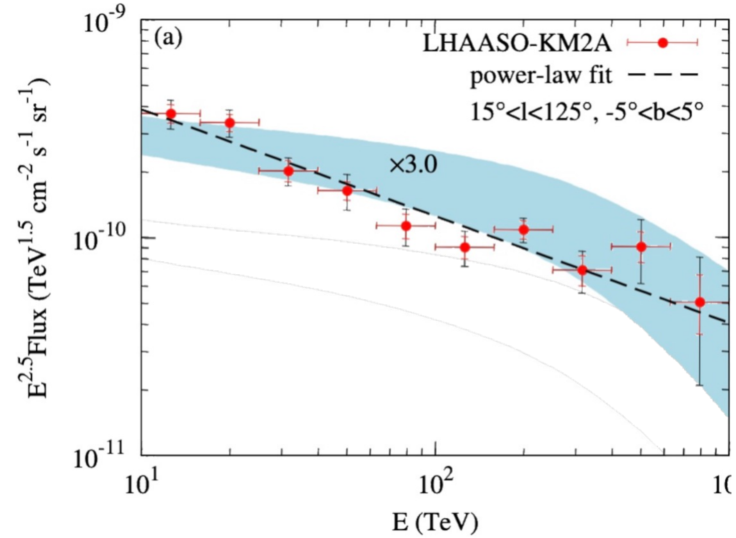

LHAASO Collab. arXiv:2305.05372

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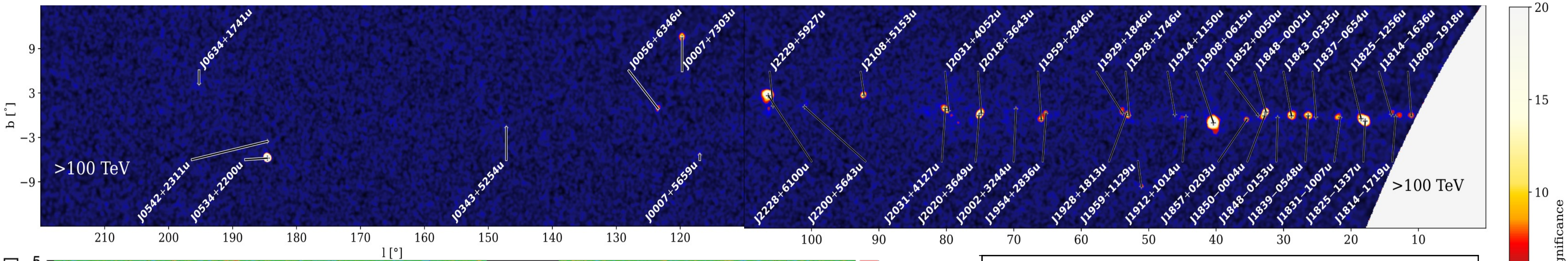
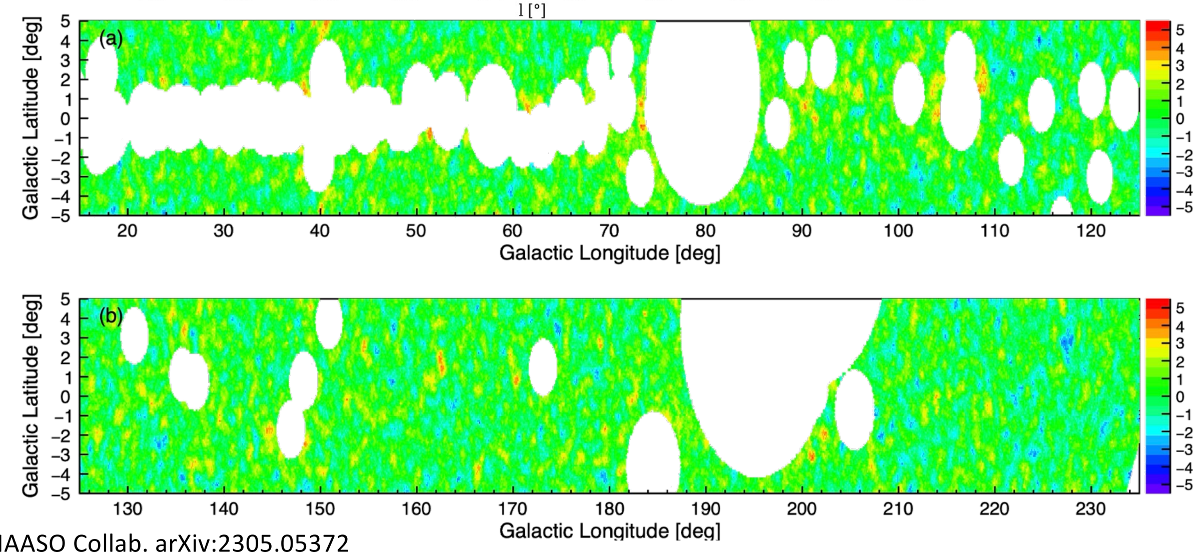
Gamma-ray sky at 100 TeV

LHAASO Collab. arXiv:2305.17030





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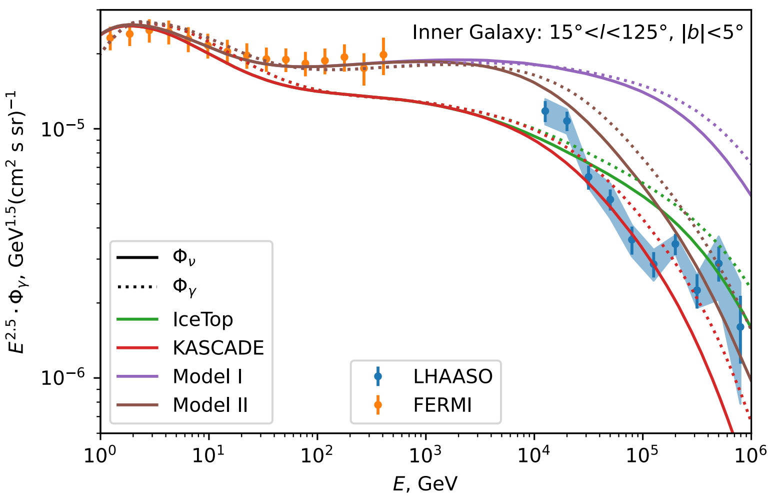

Koldobskiy et al. ICRC2023, https://pos.sissa.it/444/813/

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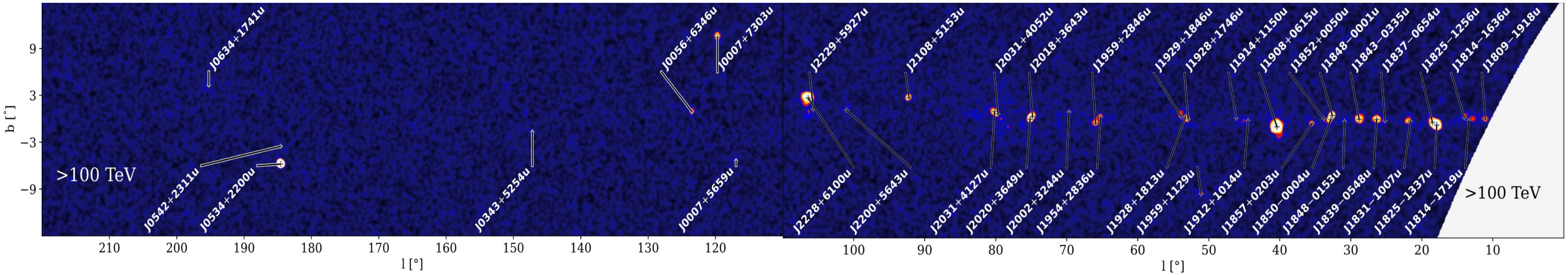
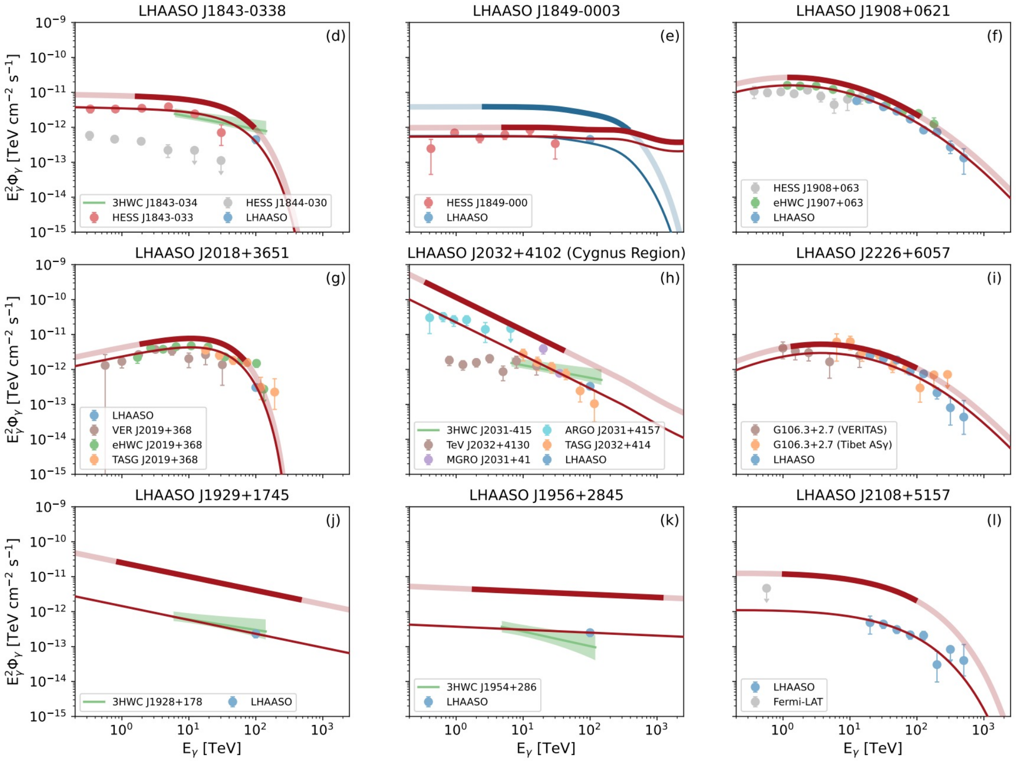
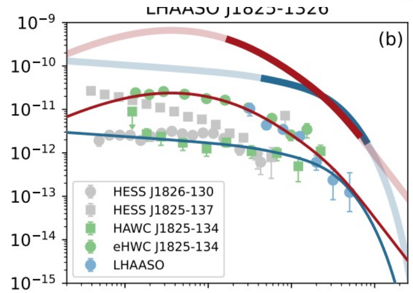
The diffuse flux is higher than expected in a model of a “universal” cosmic ray population with identical spectrum all across the Galaxy. This is consistent with harder average spectrum of Galactic cosmic ray population, ... or with a new unresolved source population (pulsar halos?)

Neutrino counterparts of the 100 TeV gamma-ray sources?

LHAASO Collab. arXiv:2305.17030







Huang, Li, arXiv:2112.14062

Decade-long exposure of IceCube in the track channel is not sufficient for detection of even the brightest HAWC / LHAASO Galactic gamma-ray source(s).......

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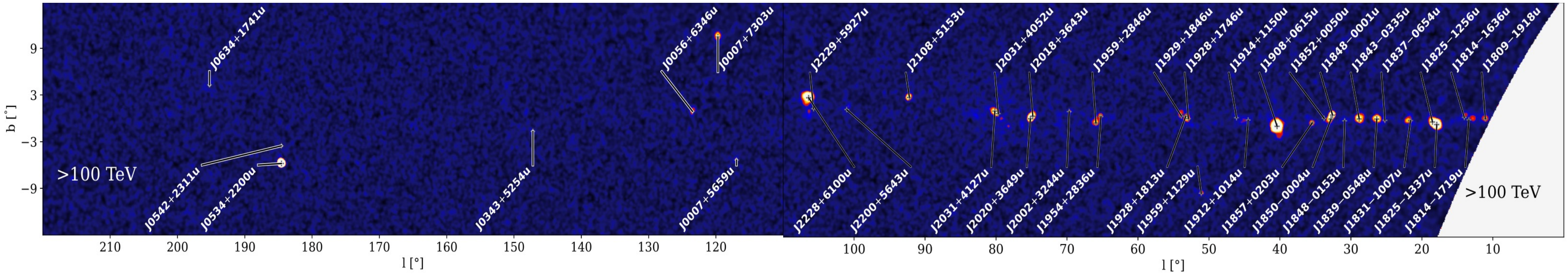
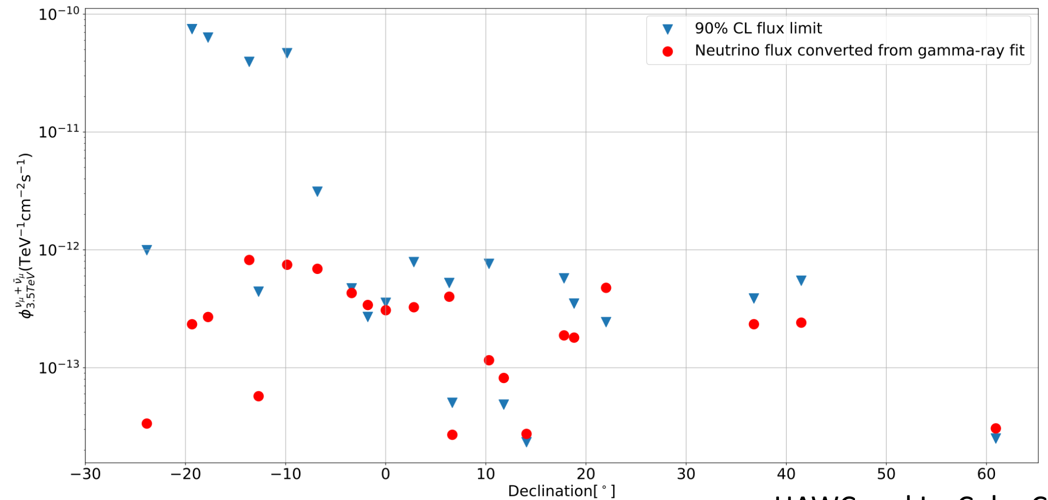




Decade-long exposure of IceCube in the track channel is not sufficient for detection of even the brightest HAWC / LHAASO Galactic gamma-ray source(s).......

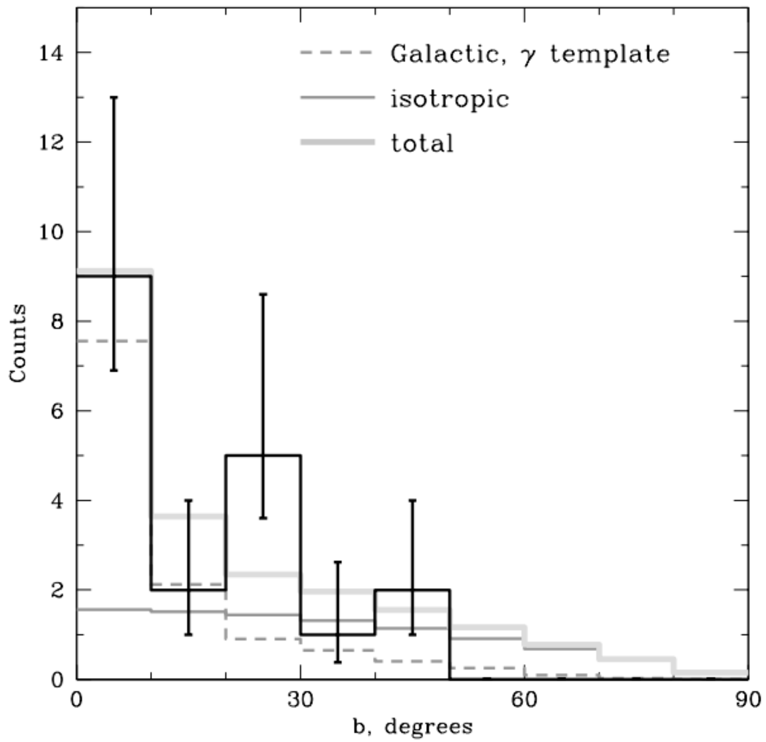
... although for several sources the neutrino flux upper limit is below the measured γ-ray flux, confirming the ”leptonic” origin of the source flux

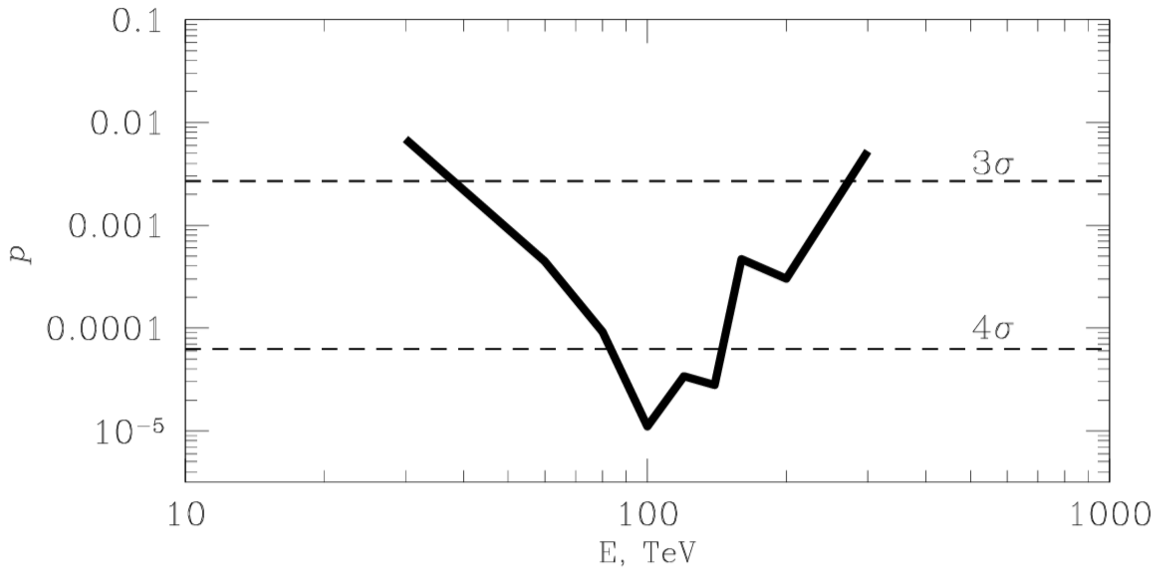
HAWC and IceCube Collab. arXiv: 2405.03817

Name	α	β	Neutrino 90% CL flux limit [TeV^{-1}cm^{-2}s^{-1}]	p-value	Hadronic fraction limit	
3HWC J1847-017	-2.66	0.09	2.70×10^{-13}	1	0.79	
3HWC J1914+118	-2.69	0	4.87×10^{-14}	1	0.59	
3HWC J1922+140	-2.77	0	2.33×10^{-14}	1	0.85	Star forming region, W51
3HWC J0534+220	-2.82	0.12	2.44×10^{-13}	0.36	0.51	PWN Crab
3HWC J2227+610	-2.42	0	2.51×10^{-14}	1	0.82	Composite SNR/PWN? G106.3+2.7

Overall (isolated sources + diffuse) neutrino signal from the Milky Way

AN, Semikoz, arXiv:1509.03522

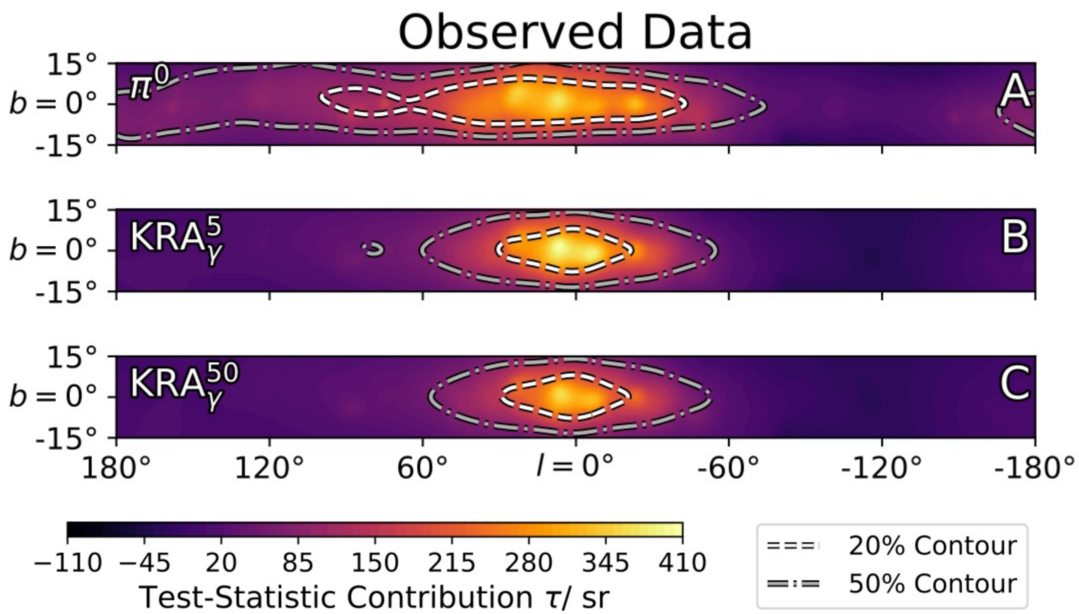


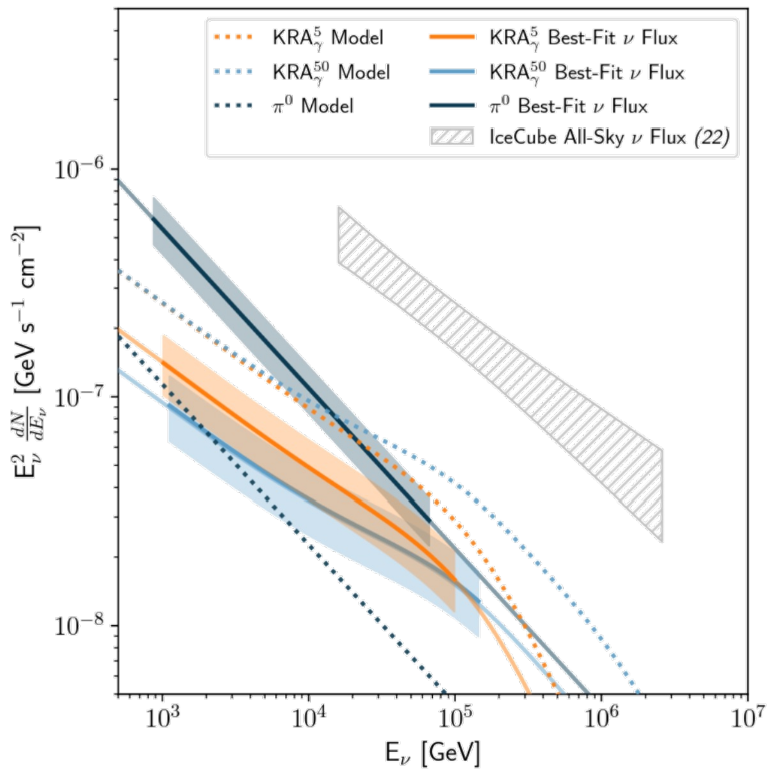


Event distribution in the cascade channel revealed a mild anisotropy toward the Galactic Plane, in $10° - 30°$ angle (comparable to the angular resolution of the cascades), with pre-trial probability $p \sim 10^{-5}$. Account of the trial factor on the angular and energy cut gives post-trial probability close to 3σ level. Up to 50% of the overall neutrino flux can be Galactic

Diffuse neutrino signal from the Milky Way

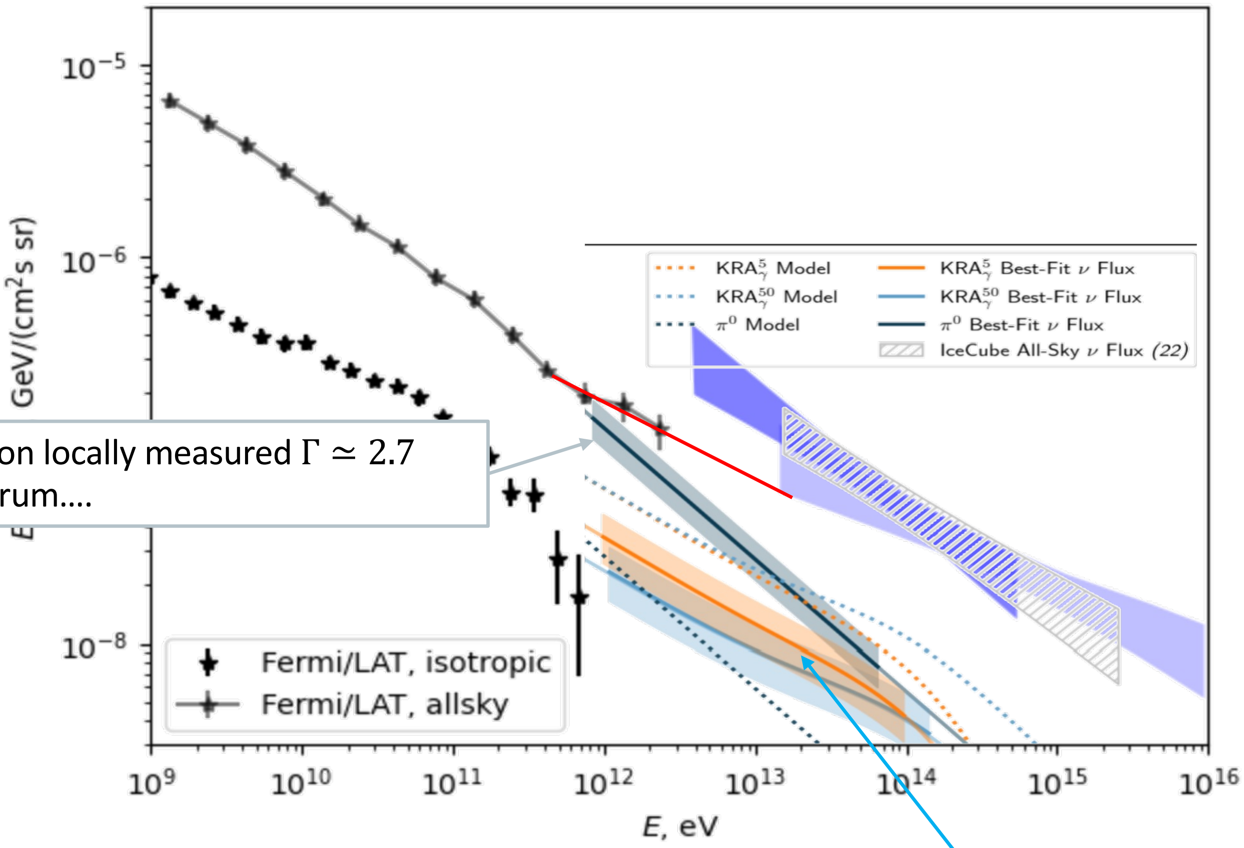
IceCube Collab. arXiv:2307.04427





IceCube collaboration has performed a likelihood fit of the all-sky data based on a theoretical template (consistent with Fermi gamma-ray diffuse emission data). This analysis finds 4.5σ excess toward the Galactic template flux.

Diffuse neutrino signal from the Milky Way



Template based on locally measured $\Gamma \simeq 2.7$ cosmic ray spectrum….

Template tuned to reproduce the $\Gamma \simeq 2.5$ slope of gamma-ray emission from the Galactic disk….

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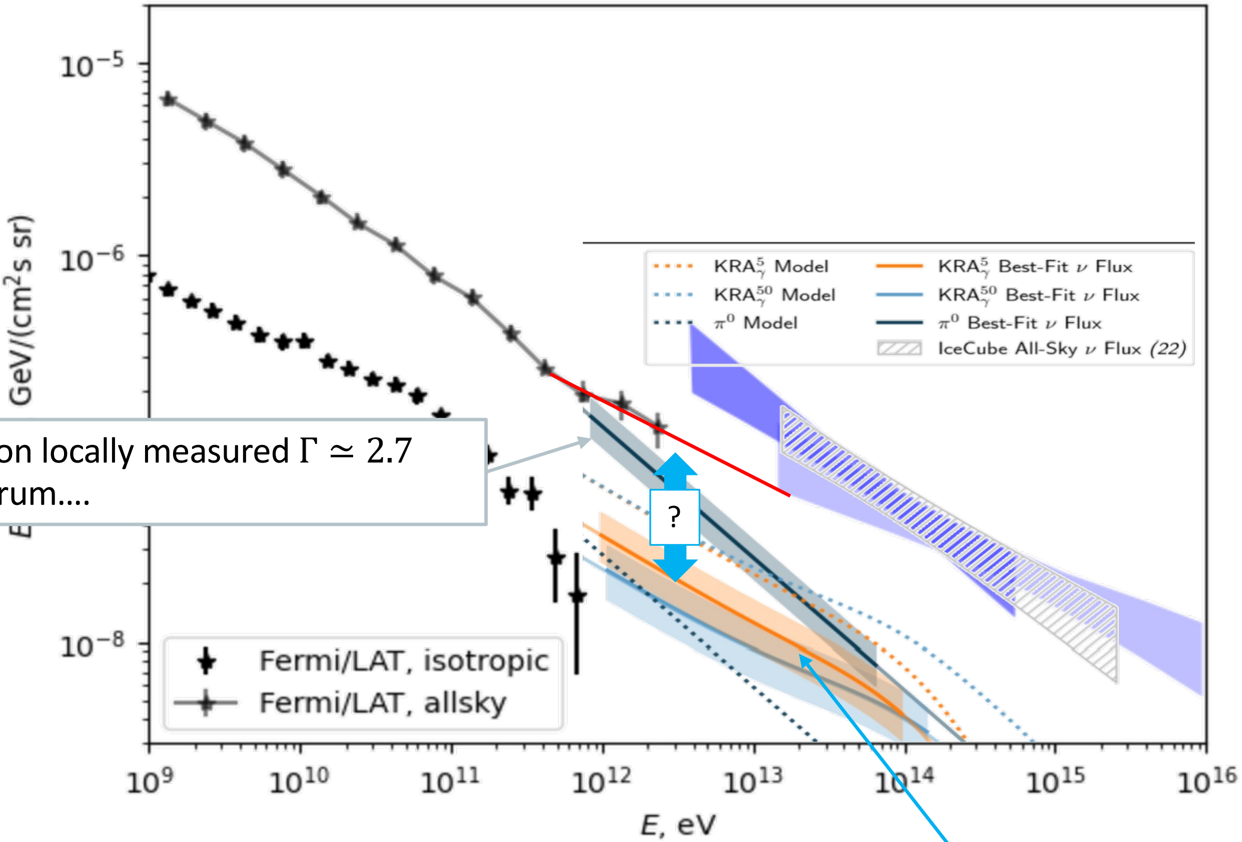

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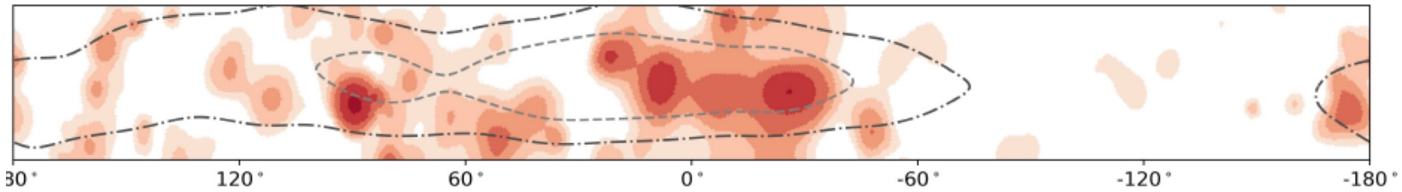
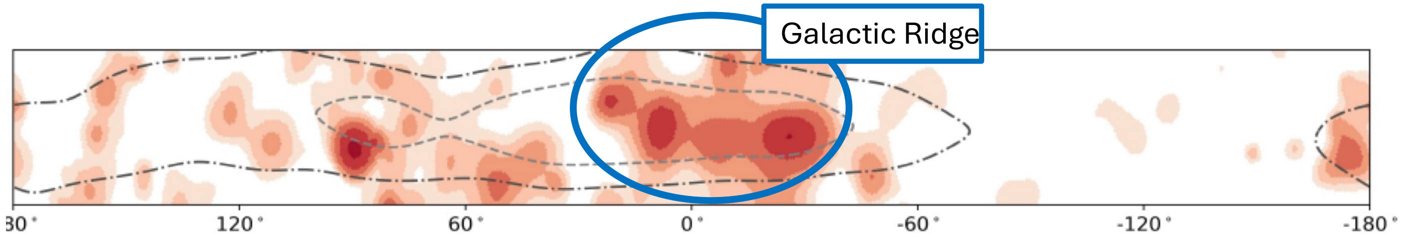
All-sky vs. selected sky regions Galactic neutrino signal



IceCube Collab. arXiv:2307.04427

Alternative approach explored in arXiv:2307.04427: instead of template fitting, search for point-like sources. No single significant excess detected, but known remarkable sites in the Galactic disk are visible on the excess map.

Neutrino signal from the Galactic Ridge



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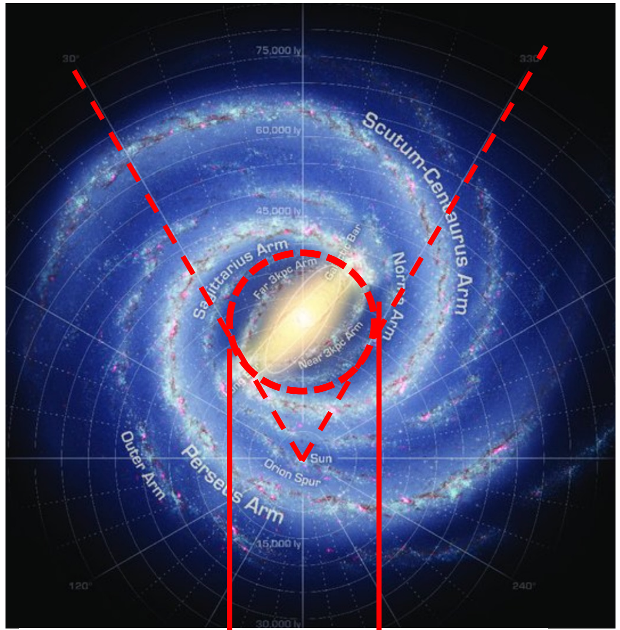
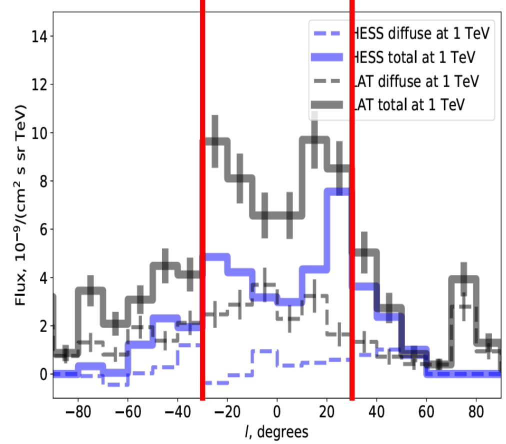


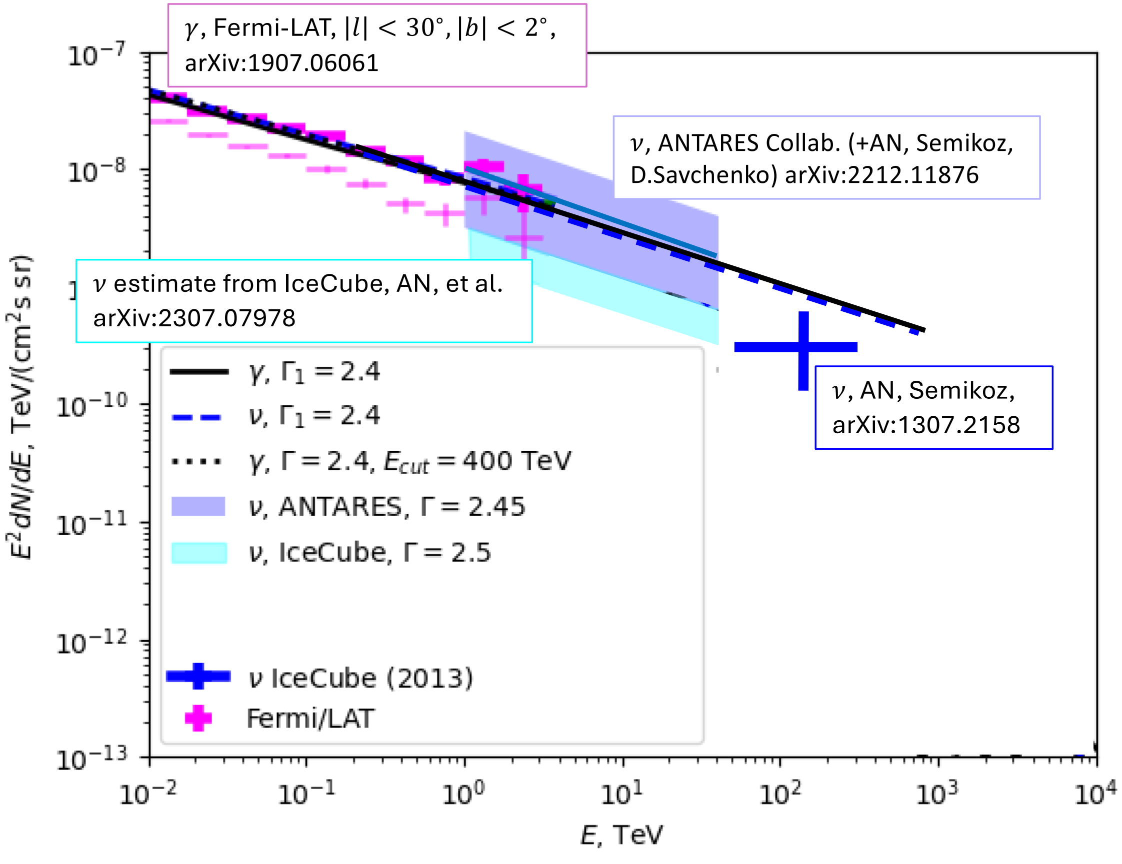


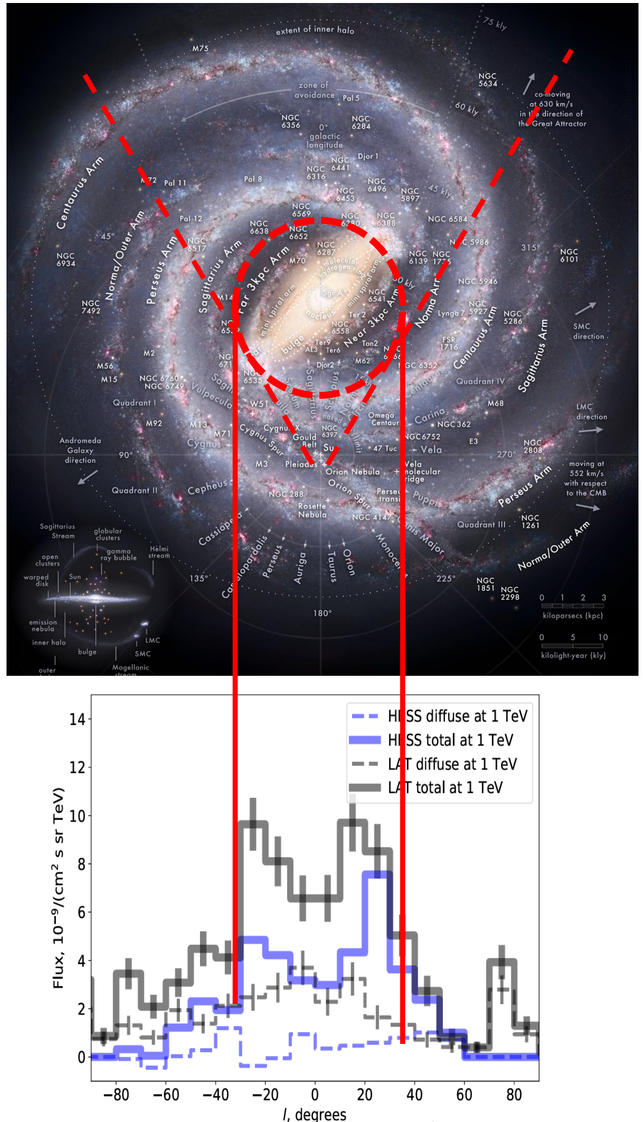
AN, Semikoz, arXiv:1907.06061

Star formation rate in the Milky Way peaks at ~ 4 kpc radius ring. This ring is seen at $|l| < 30°$ "Galactic Ridge" from the Earth. Brightest part of the Galactic diffuse emission, hard spectrum ($\Gamma \simeq 2.5$).

Neutrino signal from the Galactic Ridge

ANTARES telescope has reported an estimate of the Ridge flux based on ($< 3\sigma$) excess seen with "aperture photometry". Flux consistent with extrapolation of Fermi/LAT spectrum.





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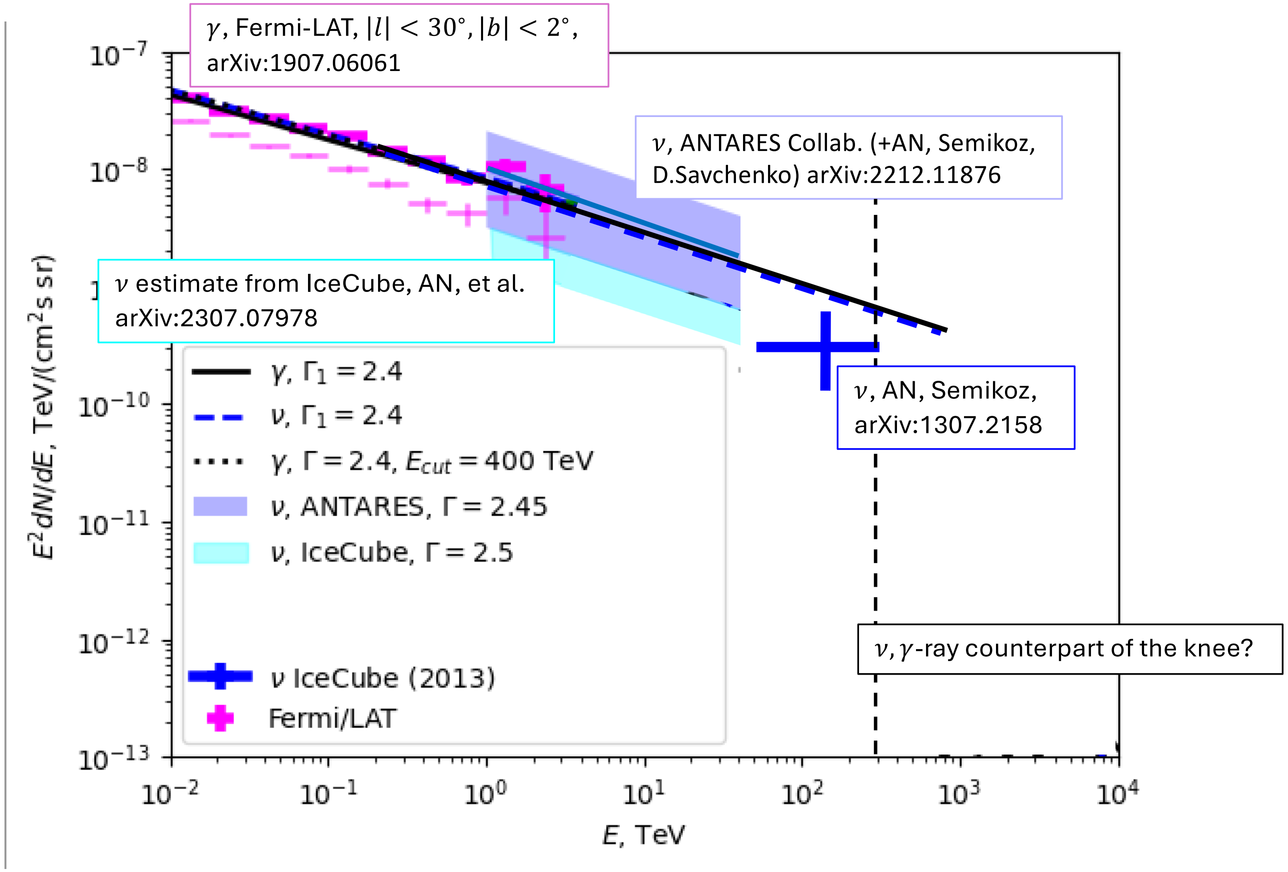
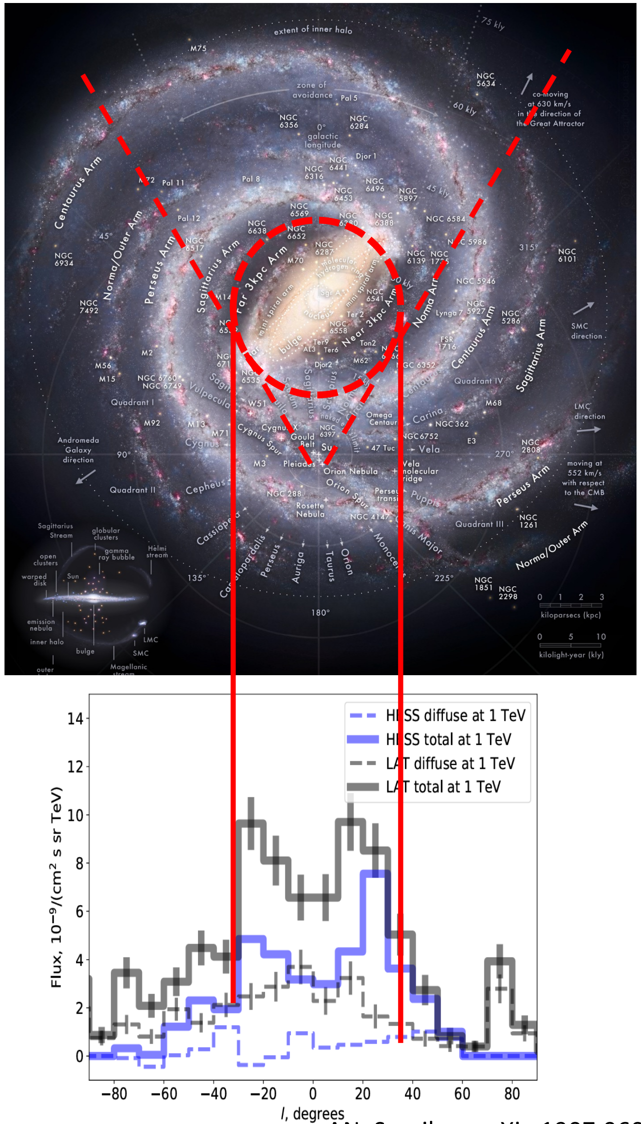
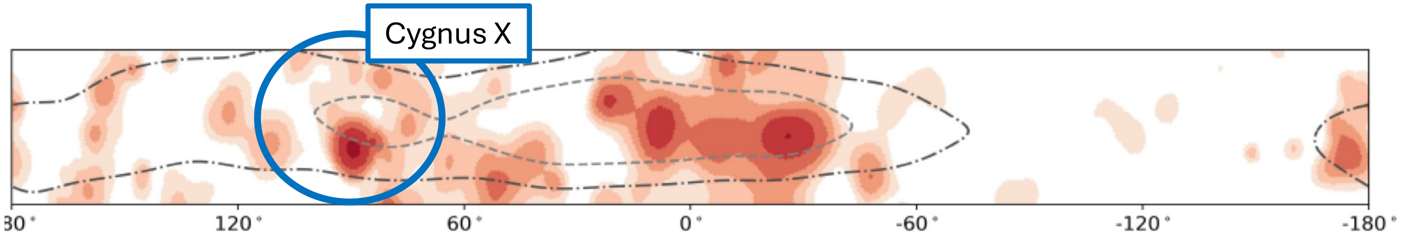




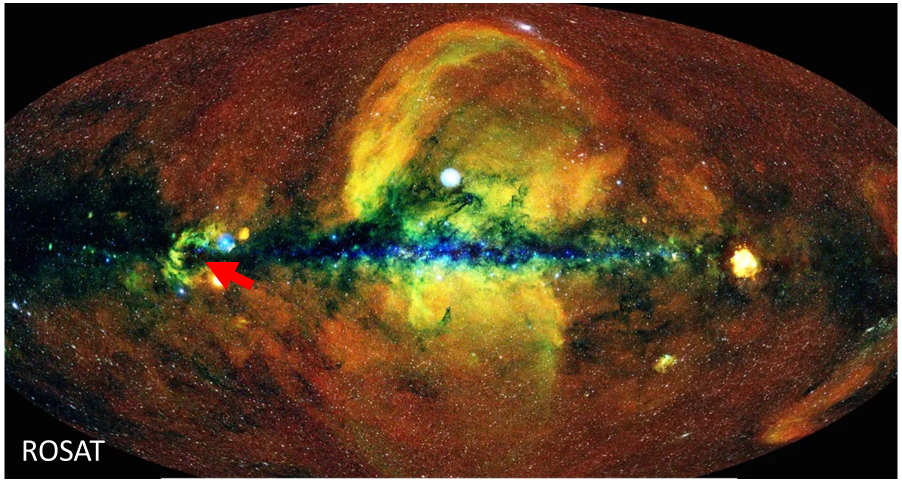
AN, Semikoz, arXiv:1907.06061

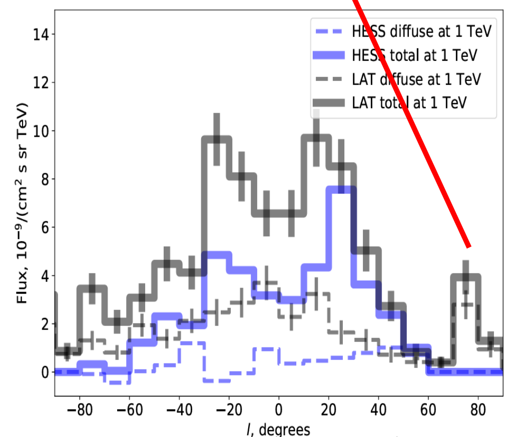
Neutrino signal from Cygnus X



IceCube Collab. arXiv:2307.04427

Direction toward Cygnus X is along the local Galactic arm. Cygnus X is the nearest active star forming region in this to the Solar system.





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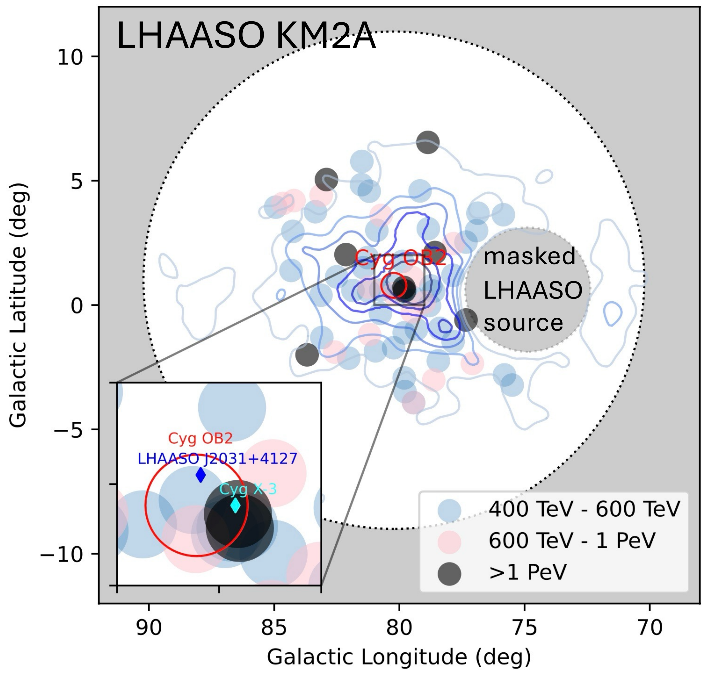
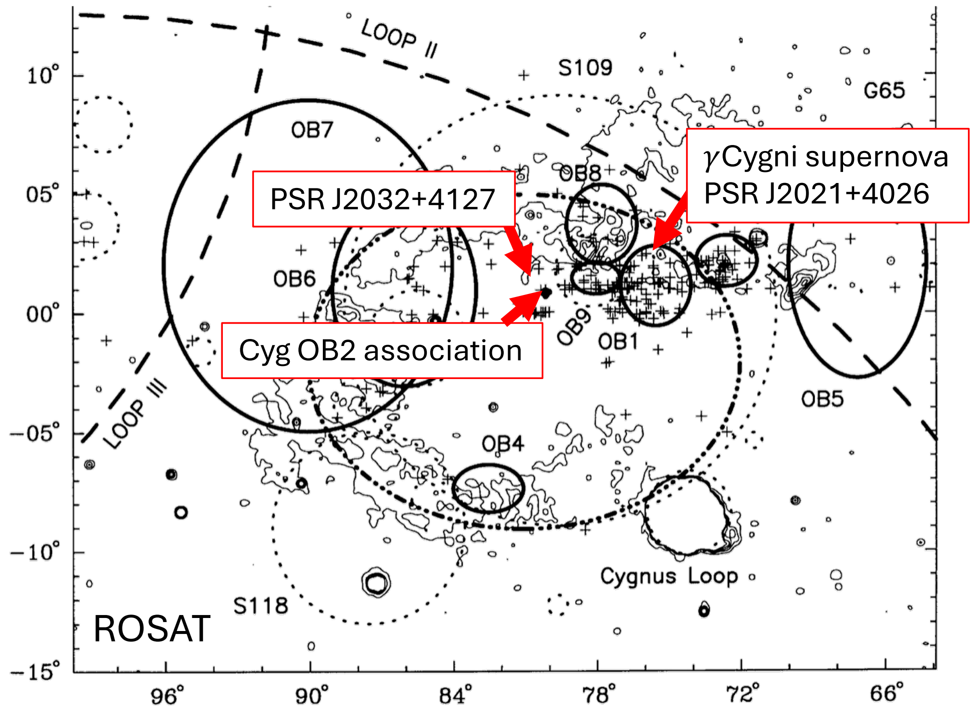
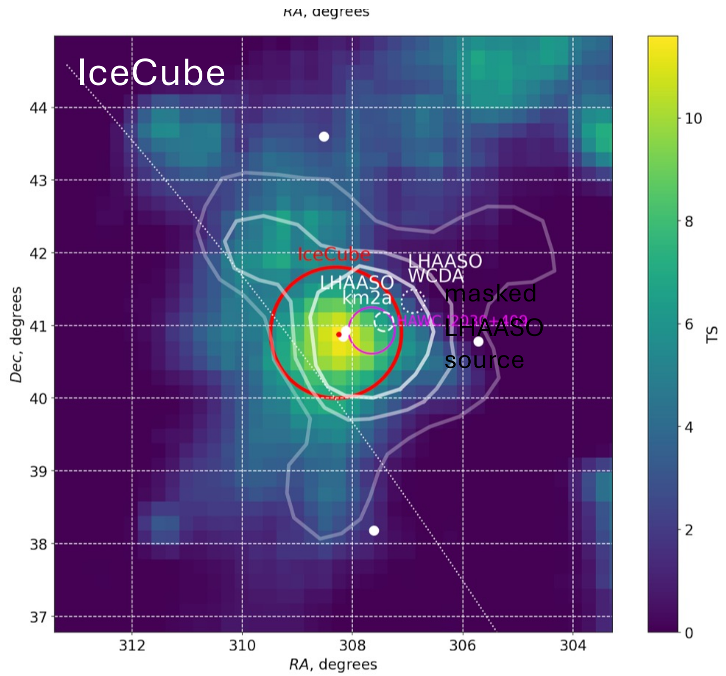


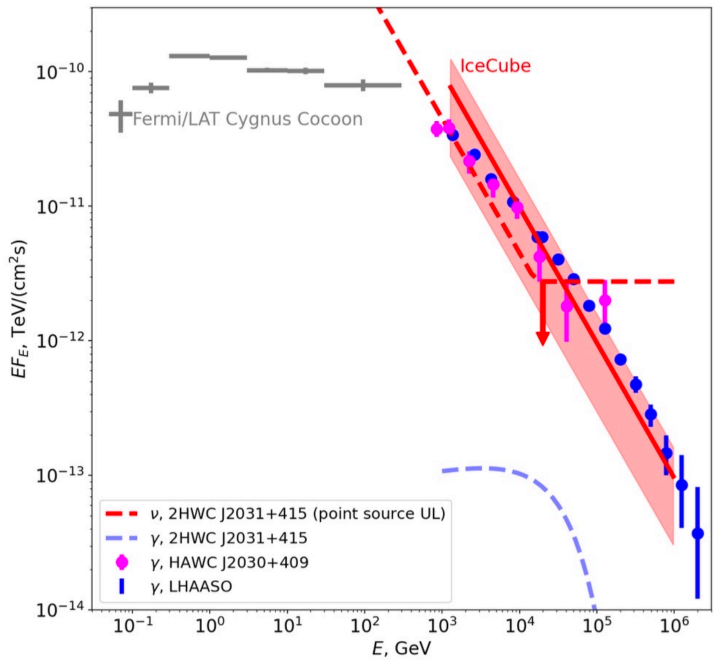
LHAASO Collab. arXiv:2310.10100



Fermi/LAT, HAWC, LHAASO observe a very extended source with morphology close to that of the Cygnus Cocoon detected by Fermi/LAT, (approximated by a $\sim 2^\circ$ Gaussian) and visible across a 10° scale region. Centroid of the Gaussian is close to the position(s) of Cyg OB2 association, but the centroid position depends on assumptions about source geometry and may be energy-dependent (does not give a clear association with possible the source of high-energy particles).

Neutrino signal from Cygnus region





Gamma-ray telescopes, including Fermi/LAT and LHAASO, cannot constrain the origin of the gamma-rays. IceCube neutrino telescope observes an excess of events from the extended source positionally coincident with the LHAASO source and with flux compatible with that measured by LHAASO. This is expected for a source powered by proton / nuclei interactions. The source is perhaps “hadronic”.

Neronov, Semikoz, Savchenko, arXiv:2311.13711

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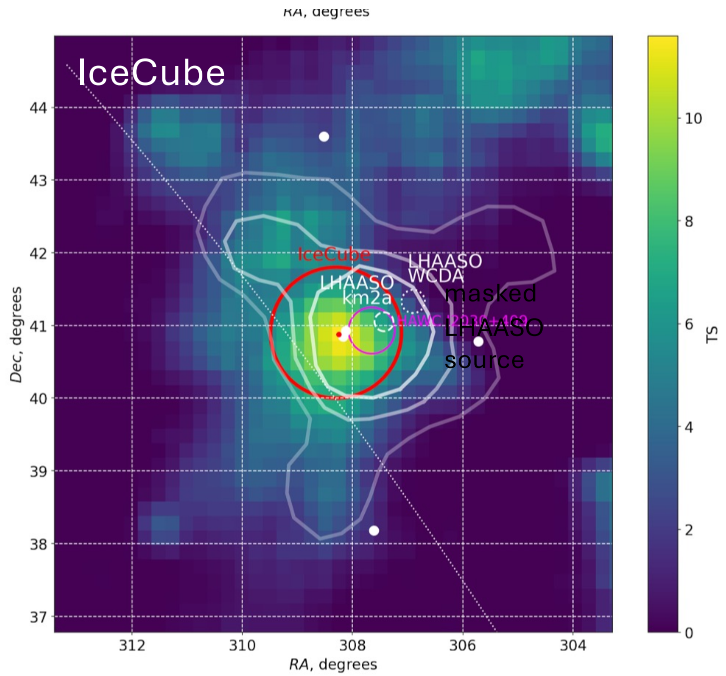
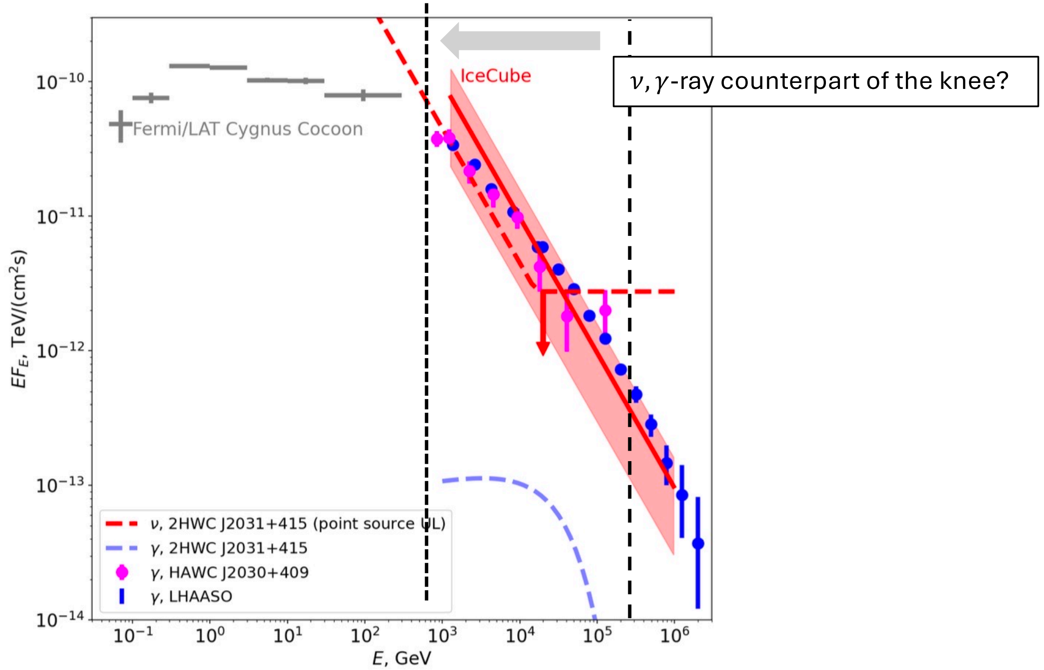
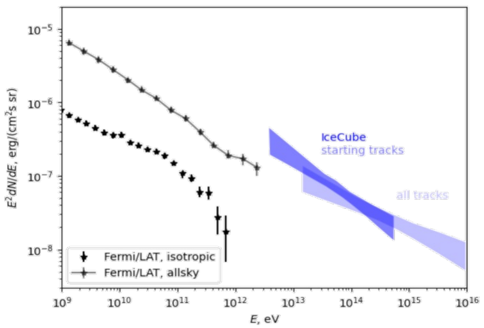
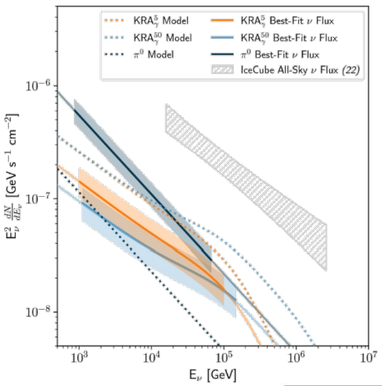


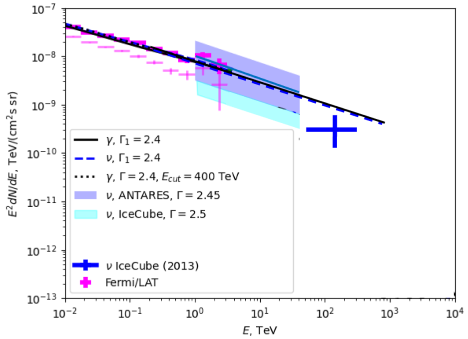


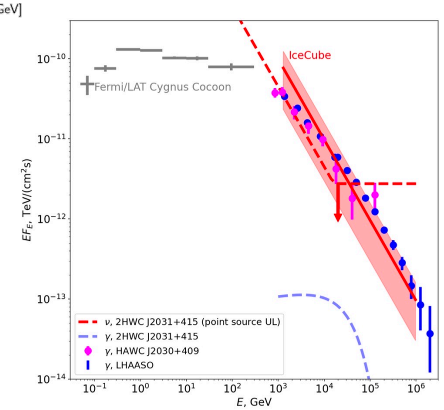
Gamma-ray telescopes, including Fermi/LAT and LHAASO, cannot constrain the origin of the gamma-rays. IceCube neutrino telescope observes an excess of events from the extended source positionally coincident with the LHAASO source and with flux compatible with that measured by LHAASO. This is expected for a source powered by proton / nuclei interactions. The source is perhaps "hadronic".

Neronov, Semikoz, Savchenko, arXiv:2311.13711









Summary

Neutrino and gamma-ray observations in 100 TeV band can provide useful information on variations of the spectral slope and existence of the knee feature of Galactic cosmic ray population.

Gamma-ray observations alone cannot isolate the emission component produced by interactions of cosmic ray protons and nuclei.

Sensitivity of neutrino telescopes starts to be sufficient for detection of the overall neutrino flux from

– the entire Milky Way
– the Galactic Ridge
– Cygnus X region