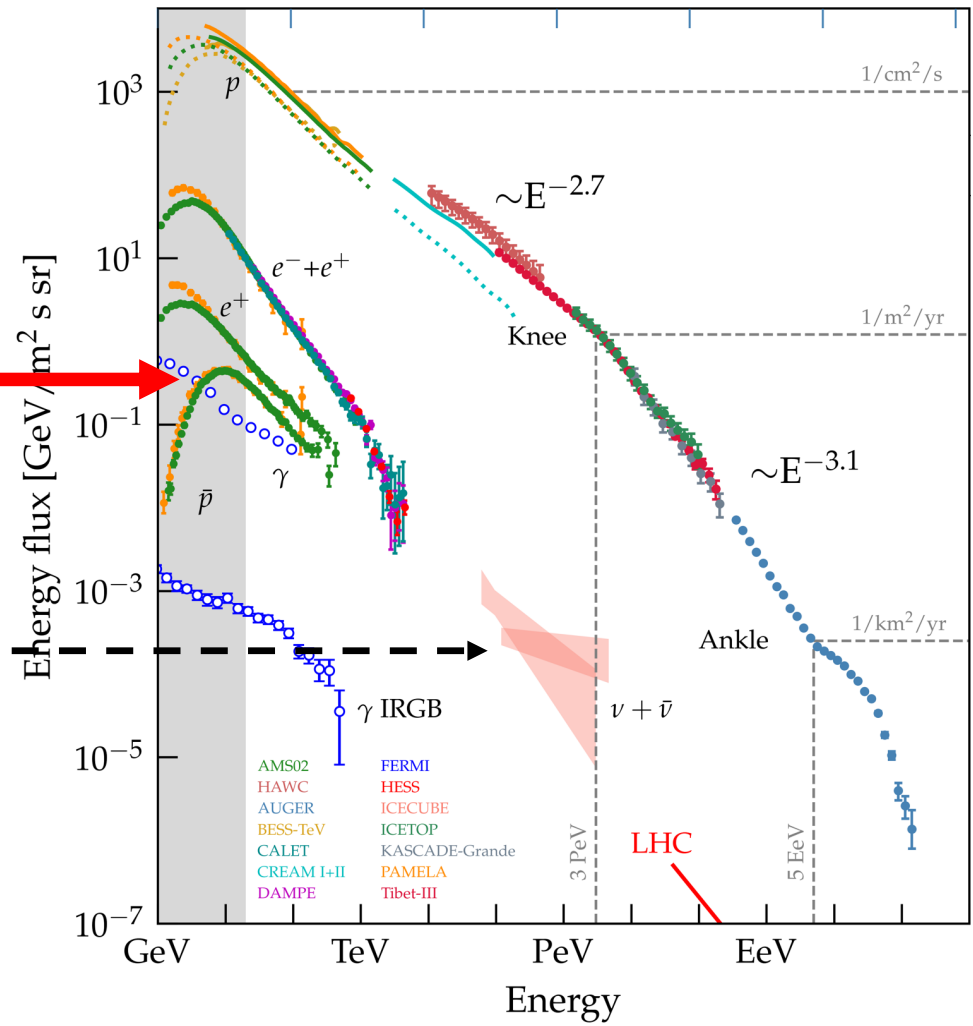


Diffuse gamma-ray emission

Andrii Neronov

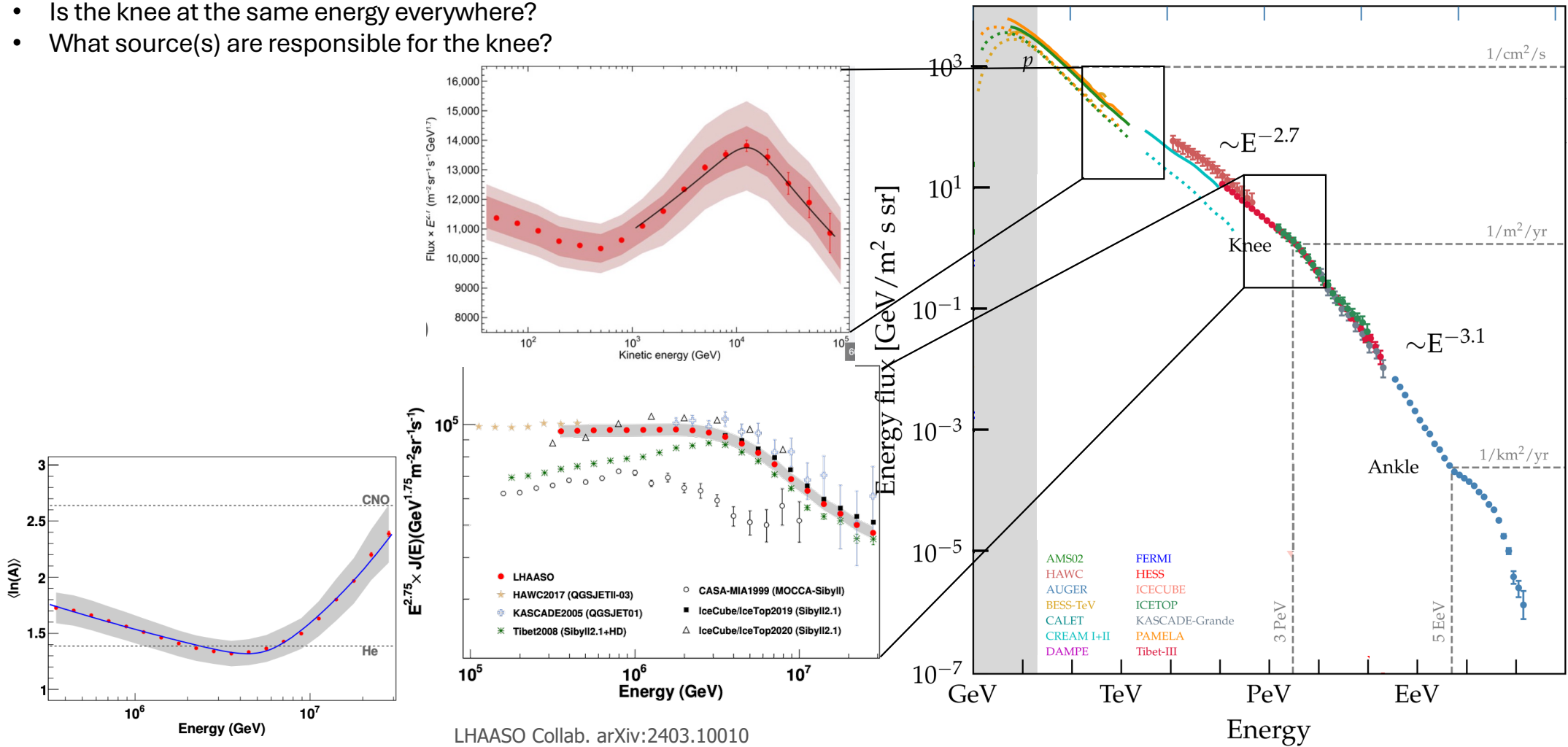
APC Paris & EPFL Lausanne

multi-messenger



Local Galactic cosmic rays

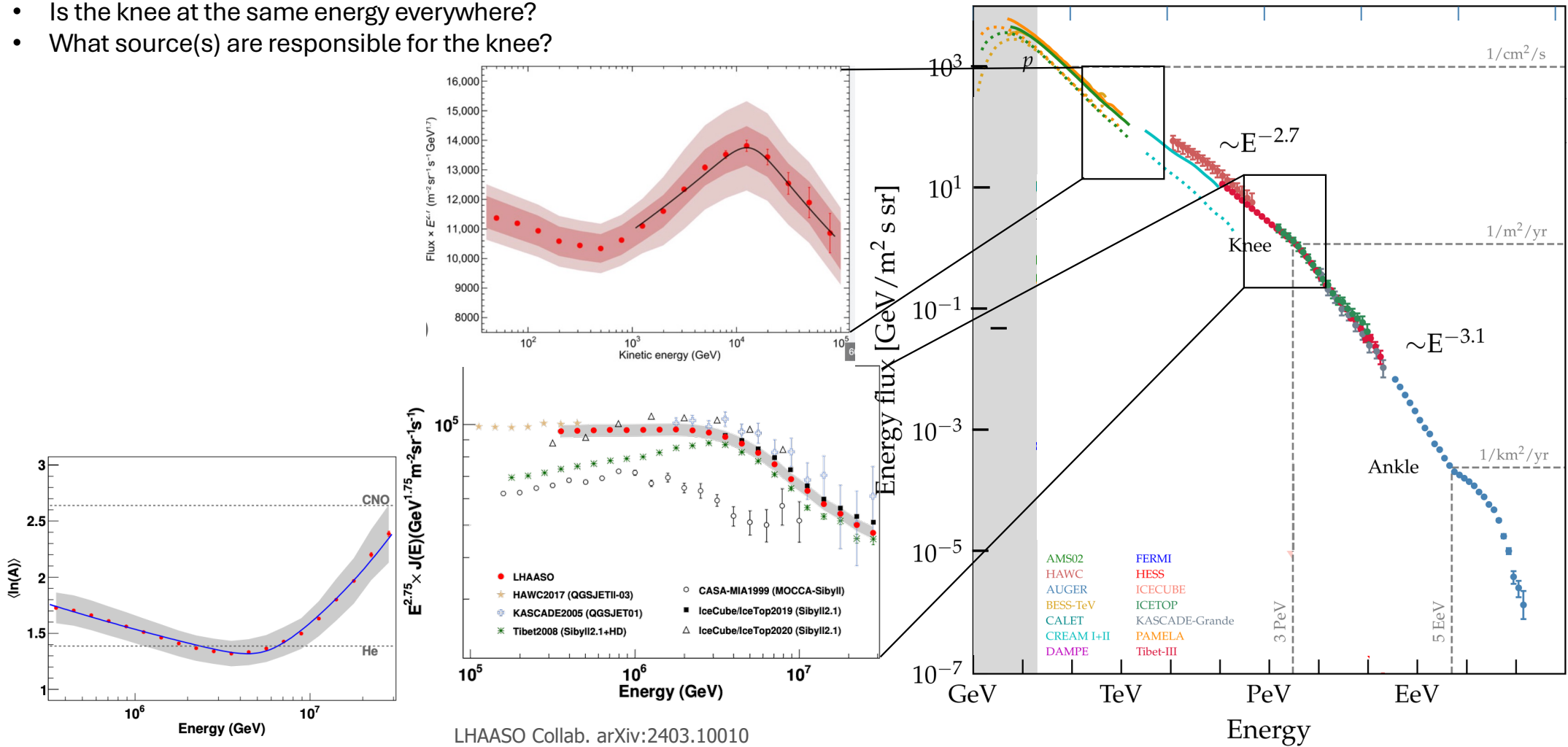
- What is the average spectrum of cosmic rays in the Milky Way?
- Does it have a PeV “knee” feature? Or the 10 TeV bump? Or 200 GeV hardening?
- Is the knee at the same energy everywhere?
- What source(s) are responsible for the knee?



LHAASO Collab. arXiv:2403.10010

Local Galactic cosmic rays

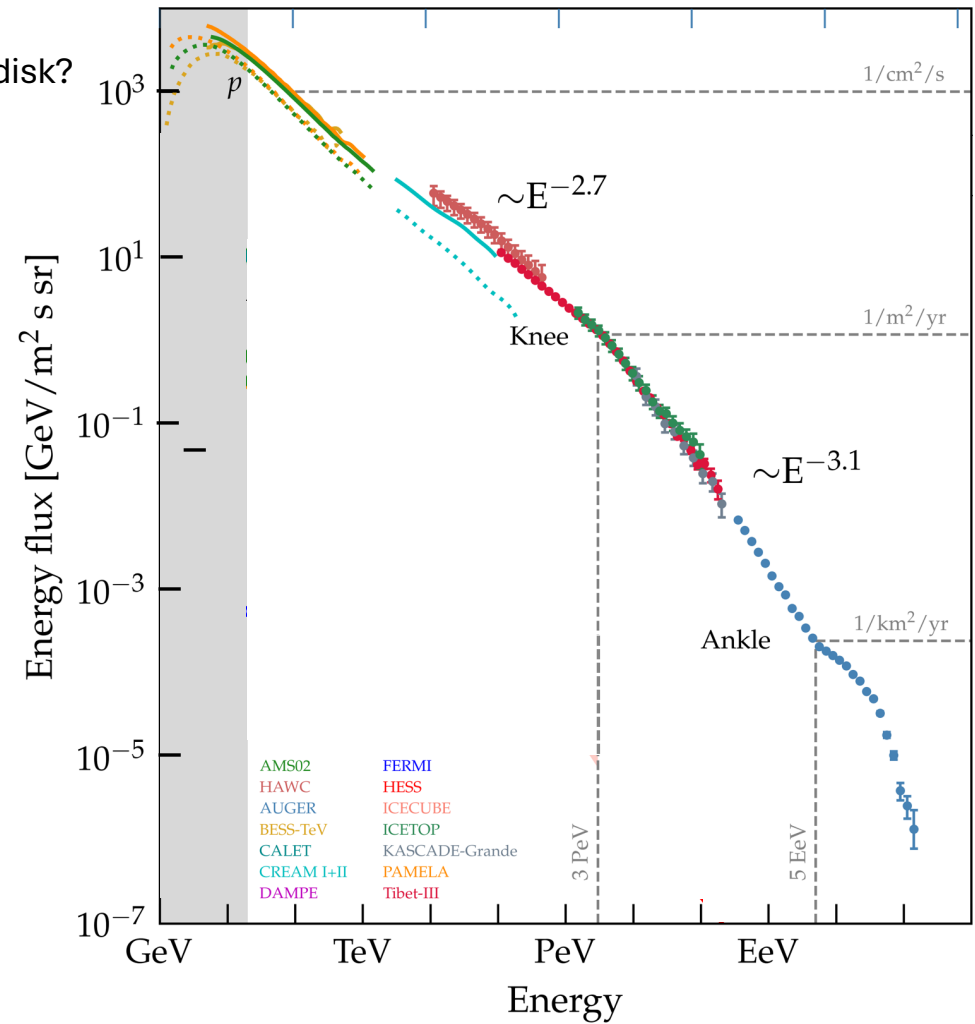
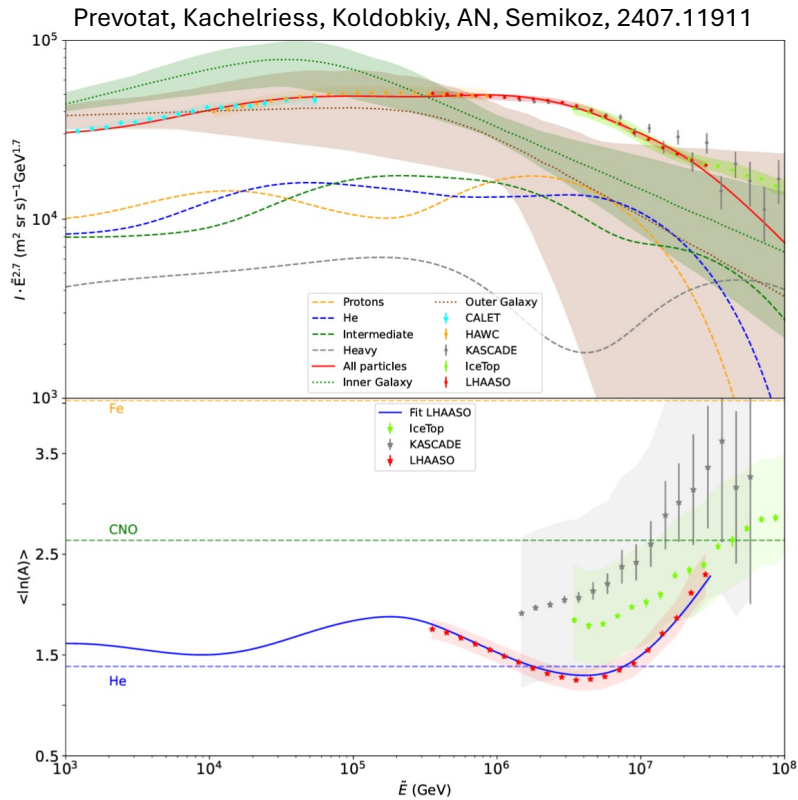
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LHAASO Collab. arXiv:2403.10010

Local Galactic cosmic rays modelling

- Multiple features have been identified in the high-precision measurements of the local cosmic ray spectrum with PAMELA, AMS-02, DAMPE, LHAASO.
- Are these features “universal”, i.e. present everywhere in the Milky Way disk?

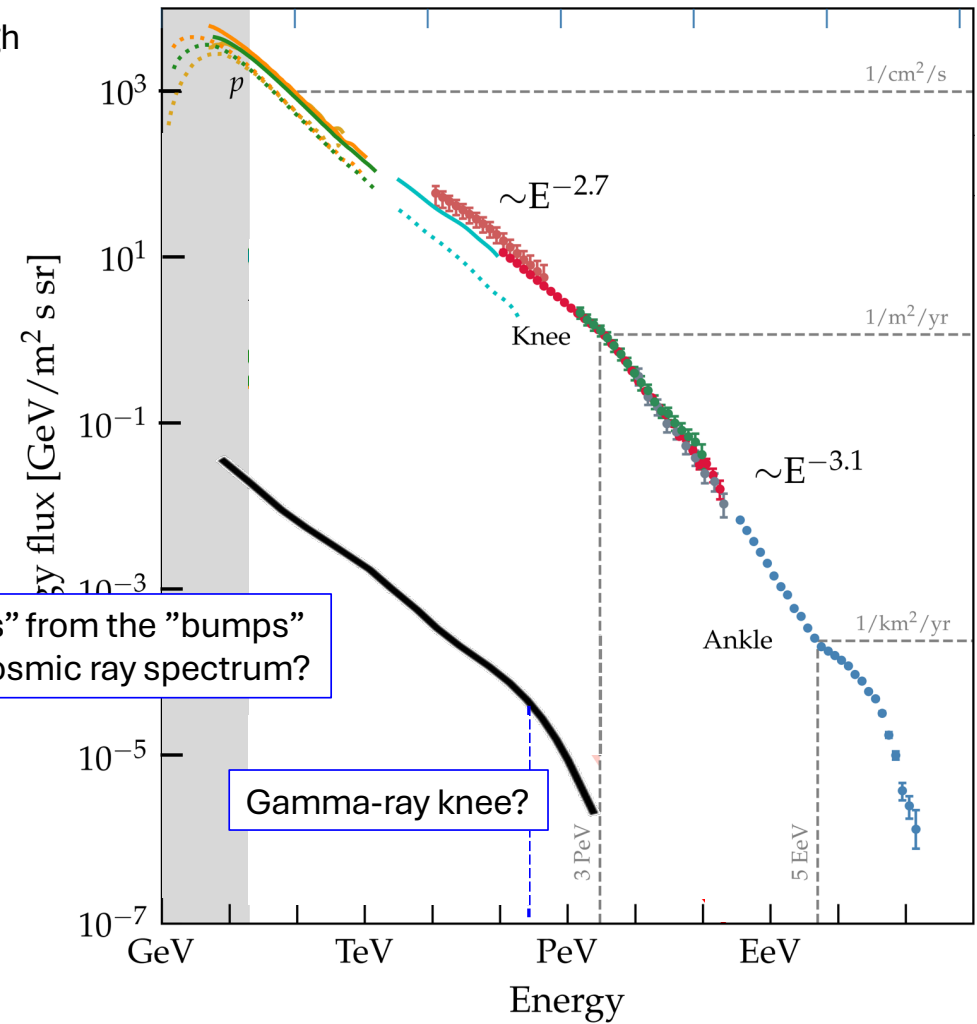
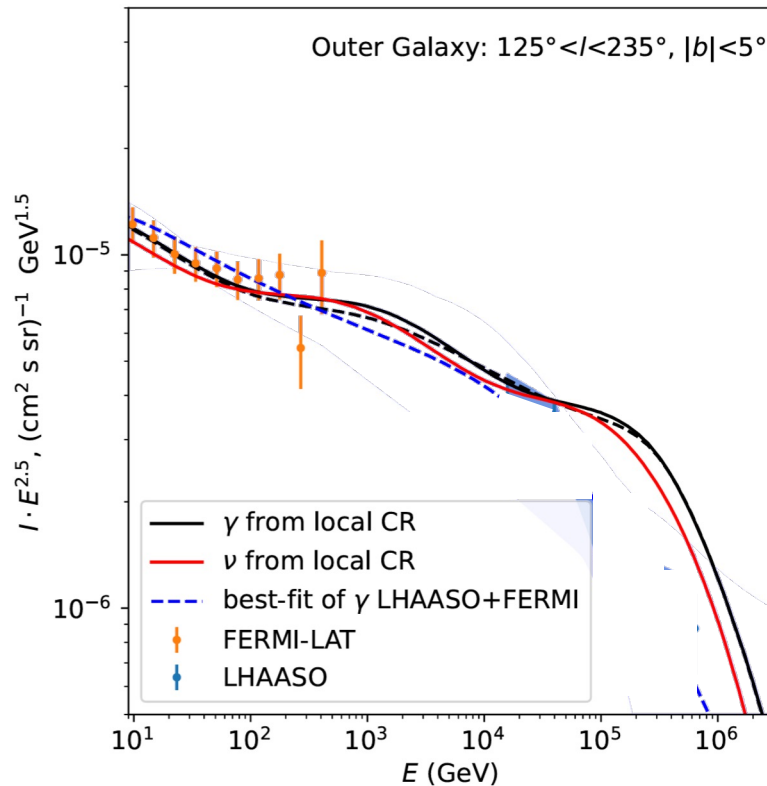


Testing cosmic ray models with gamma-ray data?

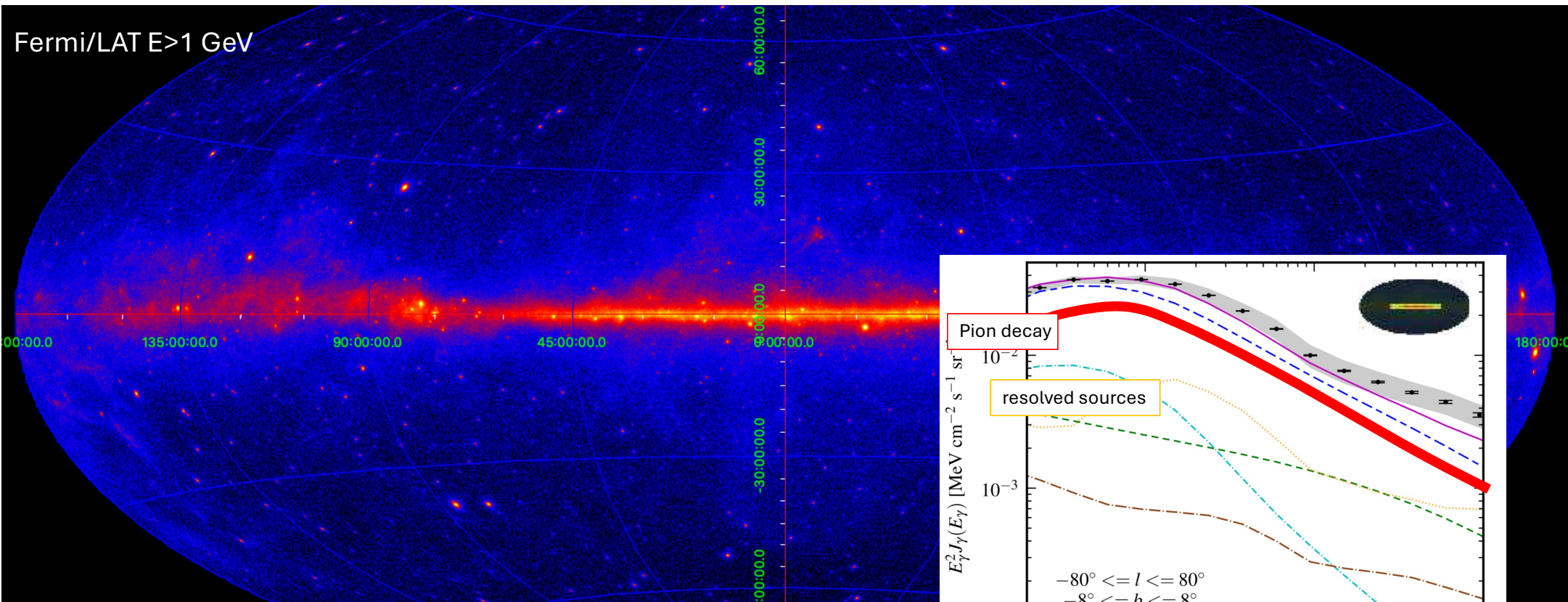
All these features should have counterparts in the spectrum of gamma-ray emission from cosmic ray interactions.

- Are these features detectable with newly available high sensitivity / high statistics gamma-ray observations up into PeV range?

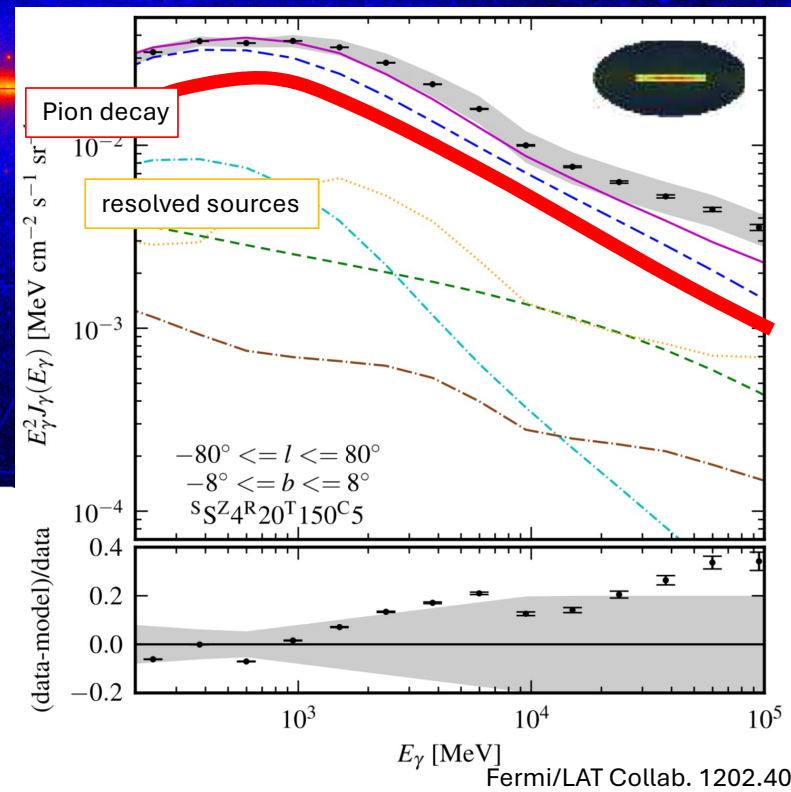
Prevotat, Kachelriess, Koldobkiy, AN, Semikoz, 2407.11911



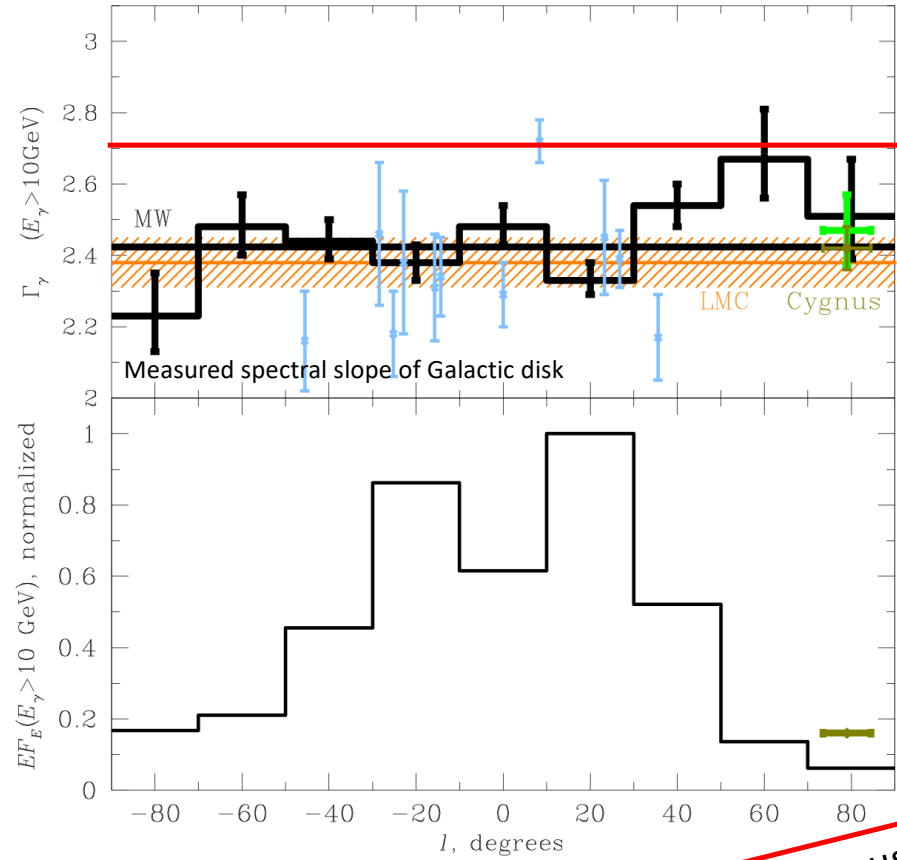
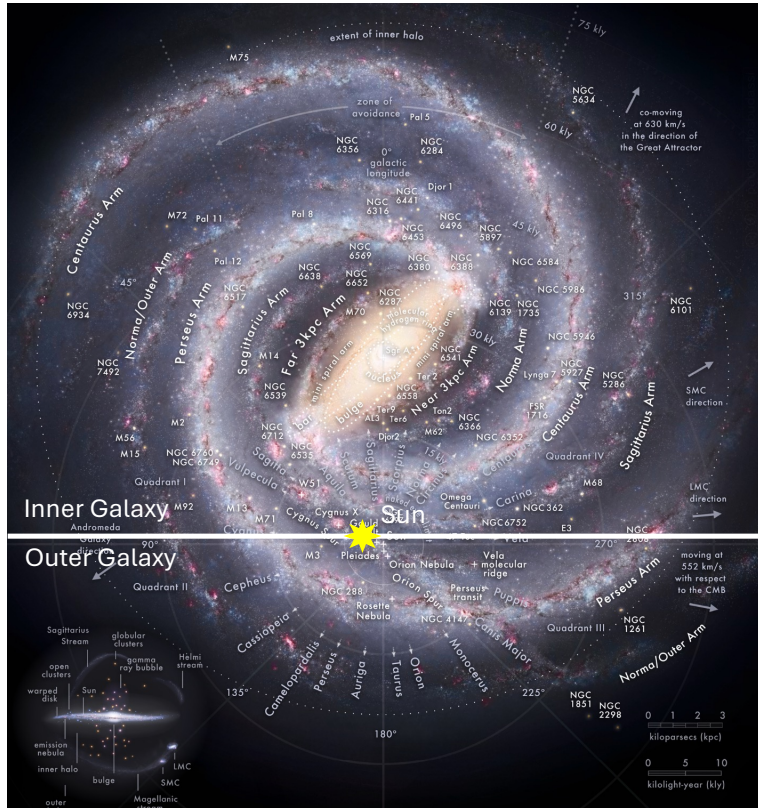
GeV gamma-rays from the Milky Way disk



High statistics measurements are available in the Fermi/LAT band since more than decade....



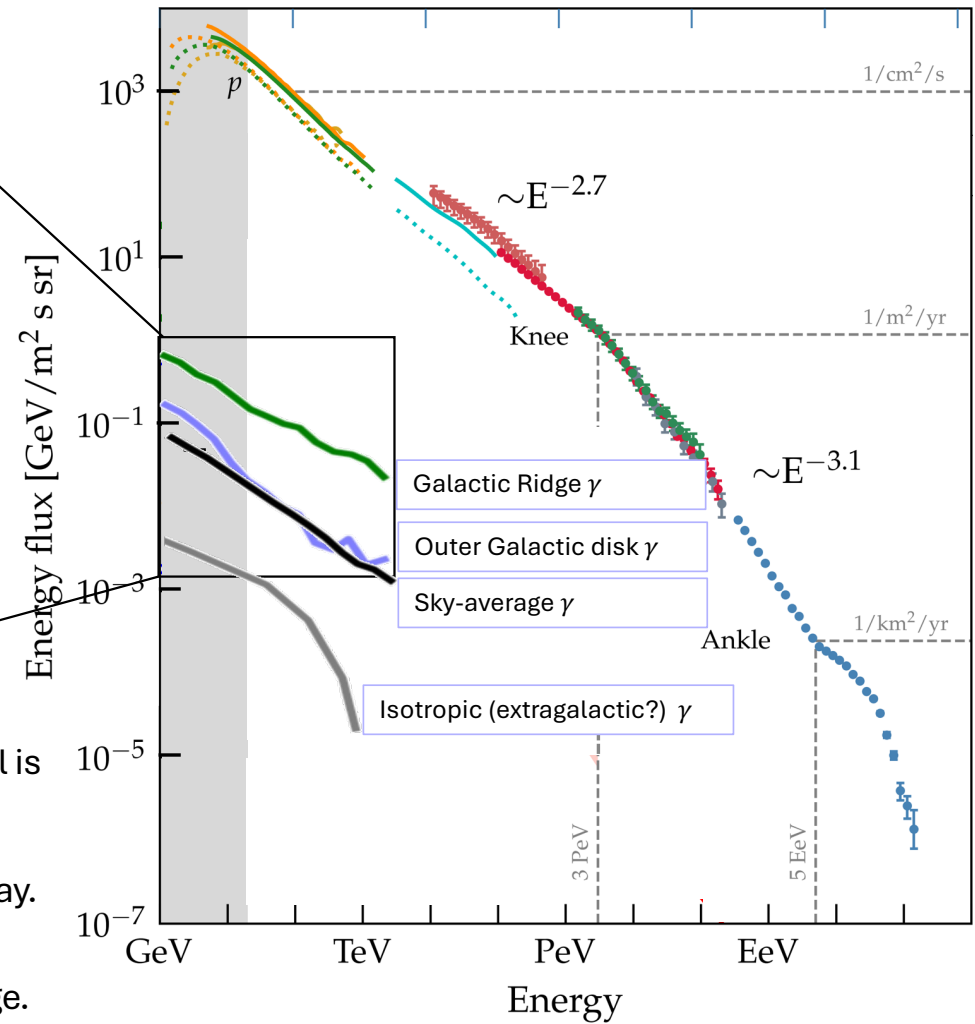
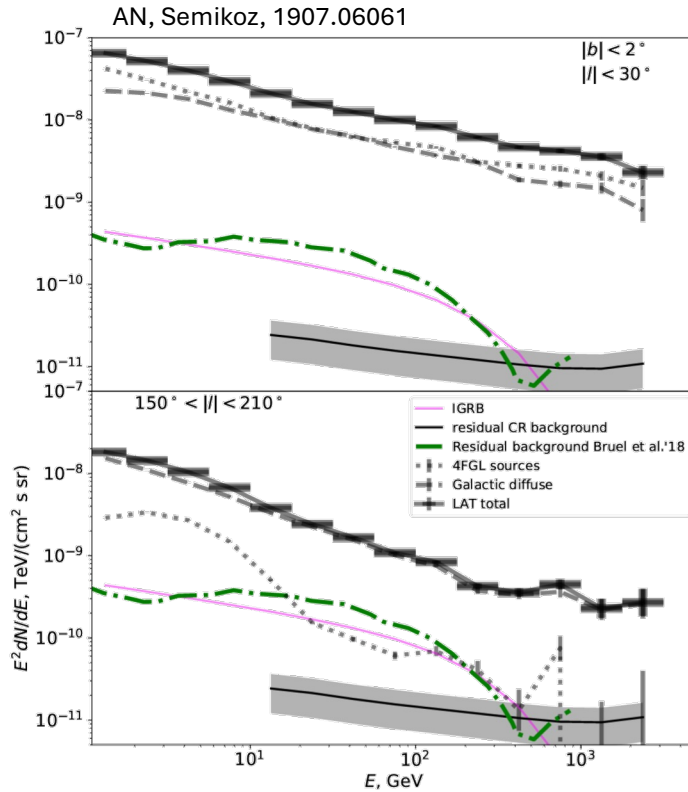
GeV gamma-rays from the Milky Way disk



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

Does this measurement invalidate models that assume “universal” cosmic ray spectrum across the entire Milky Way? Is local (our outer Galaxy) cosmic ray spectrum different from the inner Galaxy (or average?) Galactic cosmic ray spectrum?

TeV gamma-rays from the Milky Way disk

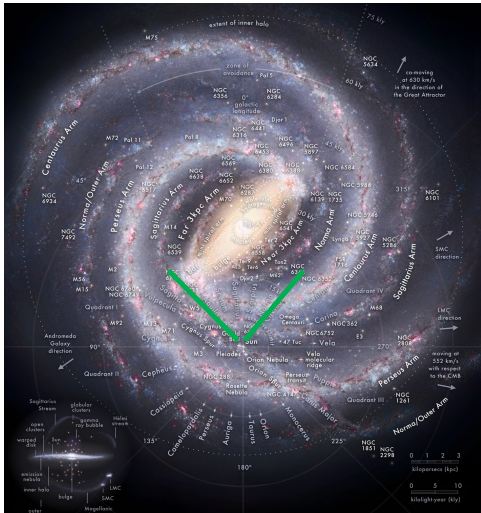
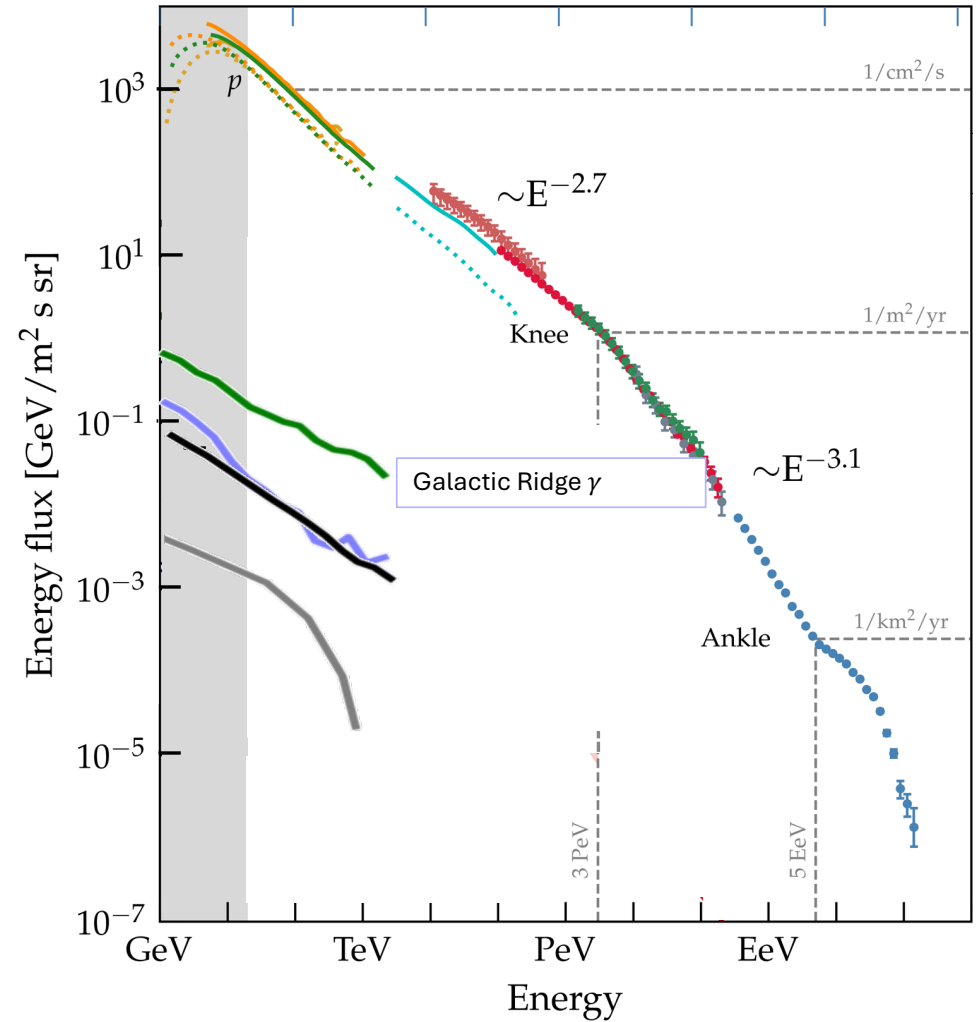
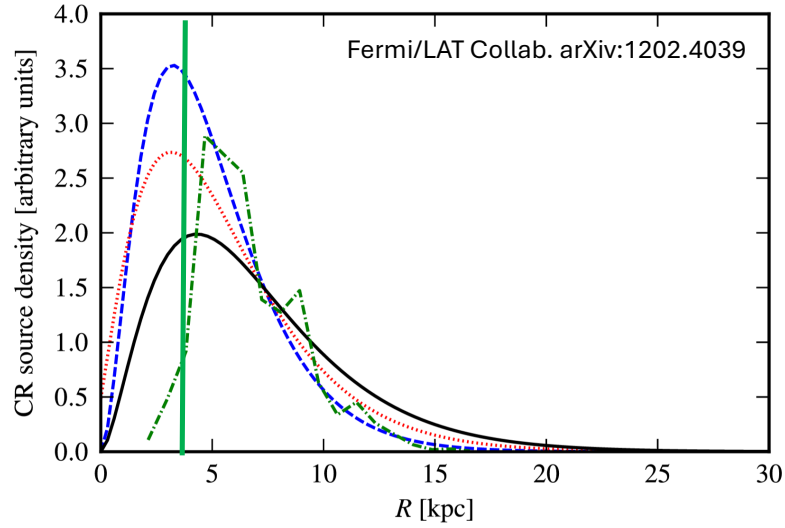


Fermi/LAT runs out of statistics toward TeV, but still, the Galactic disk signal is detected with high significance....

TeV gamma-ray all-sky flux is also dominated by emission from the Milky Way. The brightest part of the sky in the inner Galaxy is Galactic Ridge, $|l| < 30^\circ$.

Spectrum of gamma-ray emission from the Ridge is hard, up to the TeV range.

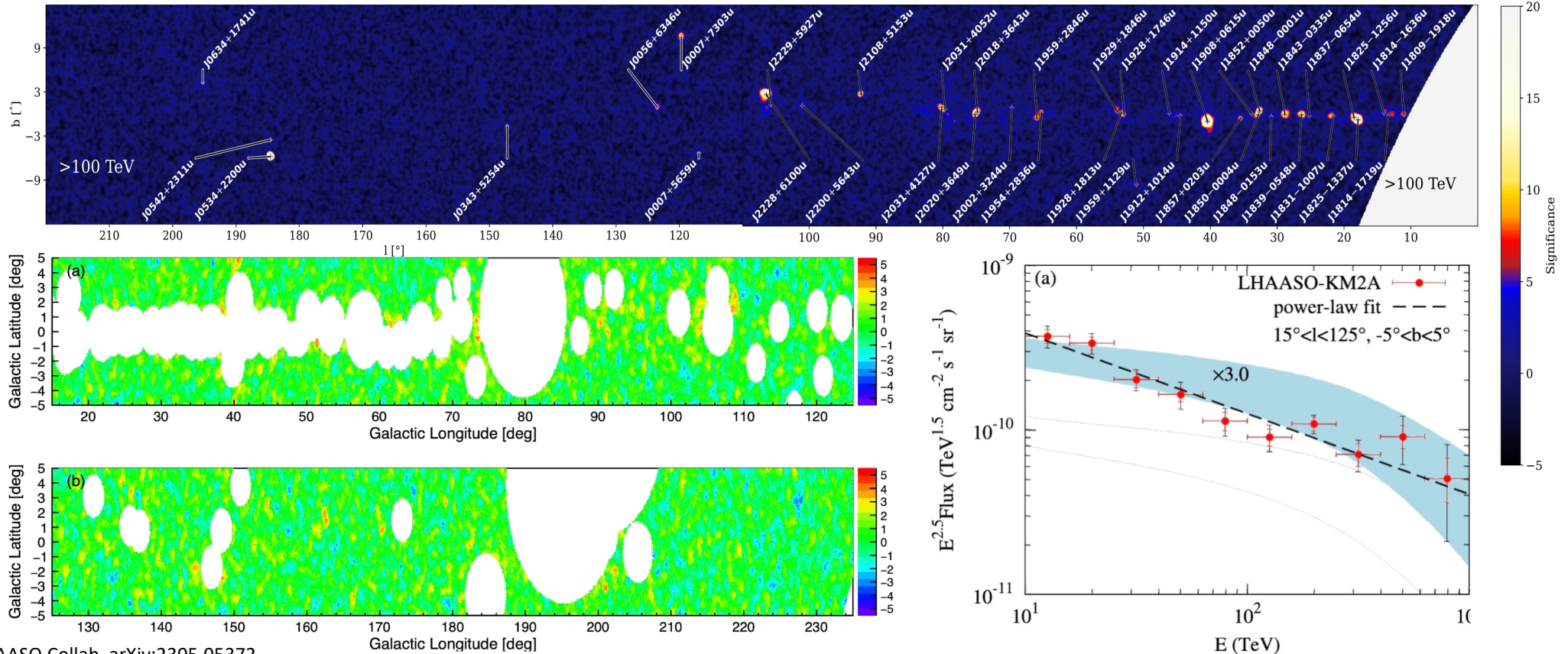
TeV gamma-rays from the Milky Way disk



The Galactic Ridge traces the peak of the star formation rate in the Milky Way at ~ 4 kpc radius from the Galactic Center.

TeV-PeV gamma-rays from the Milky Way disk

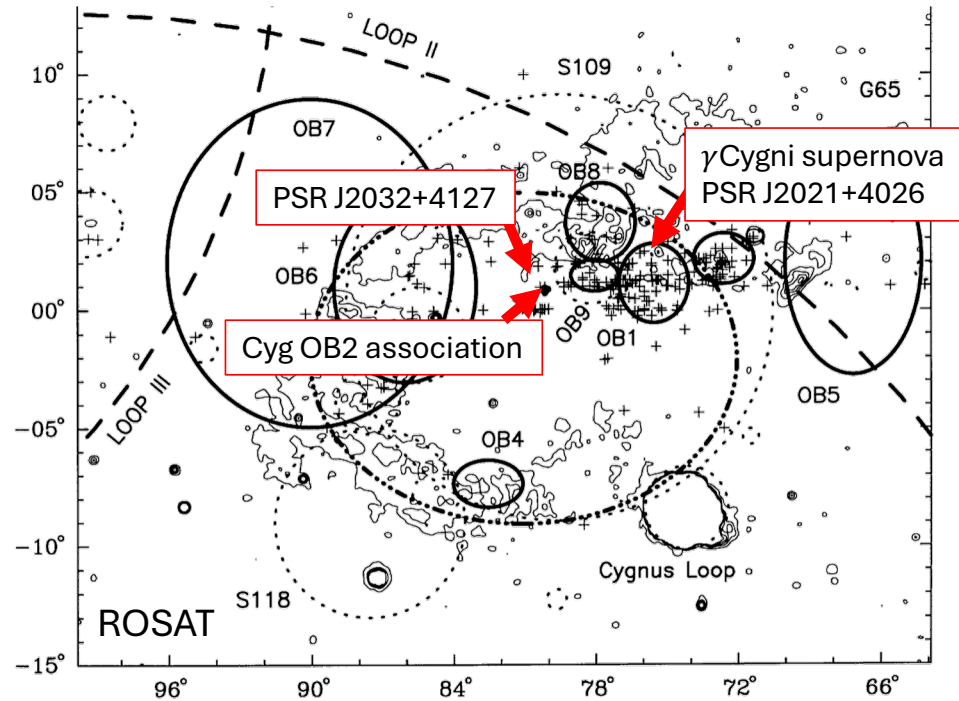
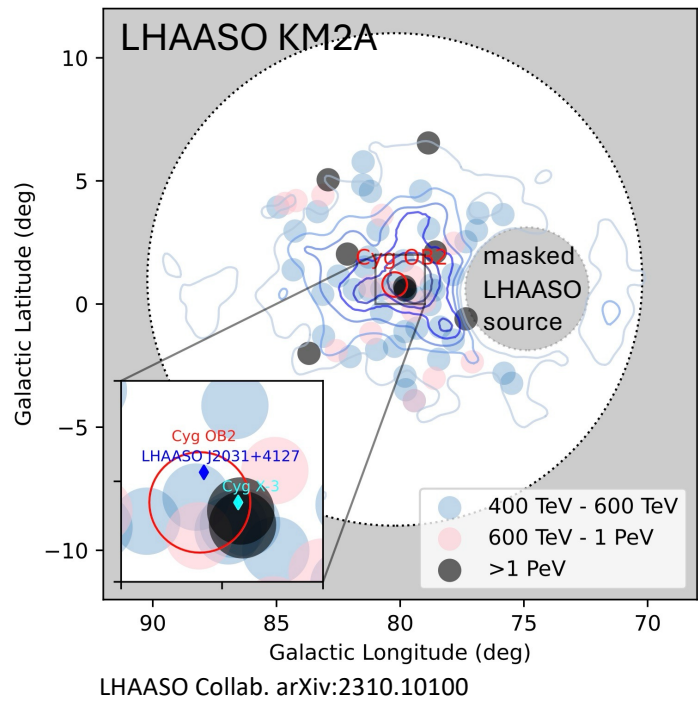
LHAASO Collab. arXiv:2305.17030



LHAASO Collab. arXiv:2305.05372

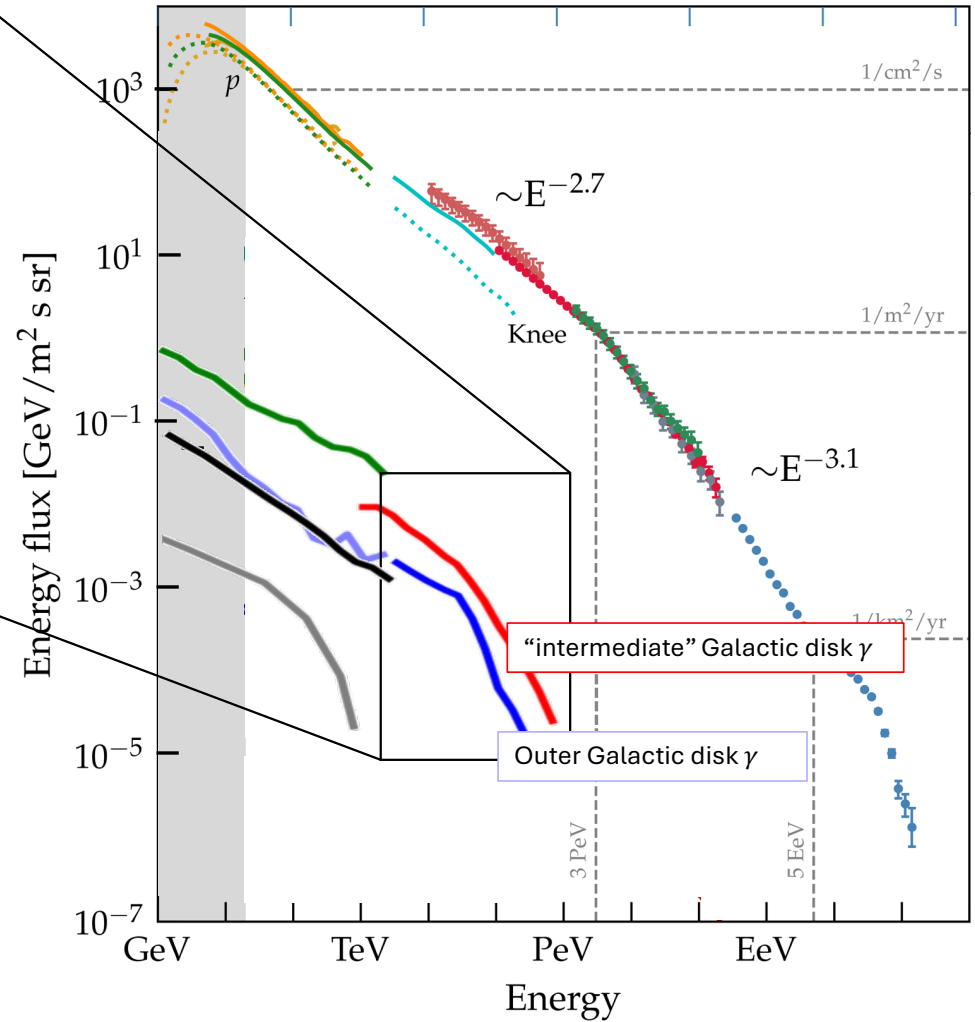
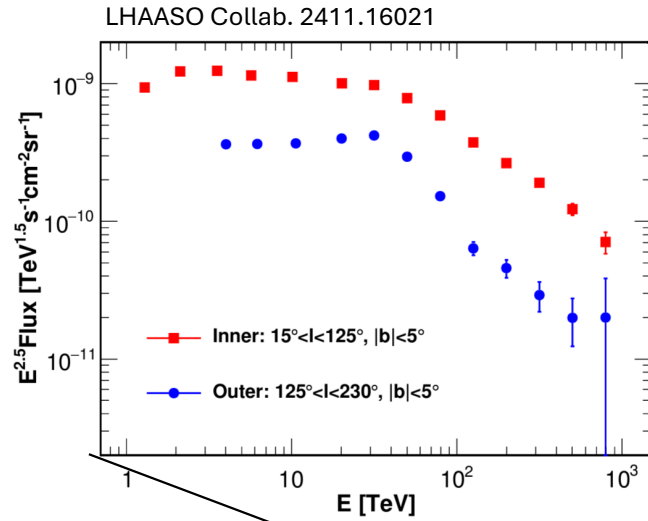
LHAASO provides measurements of the spectrum of diffuse emission from the Milky Way disk up to PeV energy range. The diffuse flux is higher than expected in a model of a “universal” cosmic ray population with identical spectrum all across the Galaxy.

Multi-PeV gamma-rays from the Milky Way



LHAASO runs out of statistics in the PeV energy range, only brightest sources on the sky are detectable.

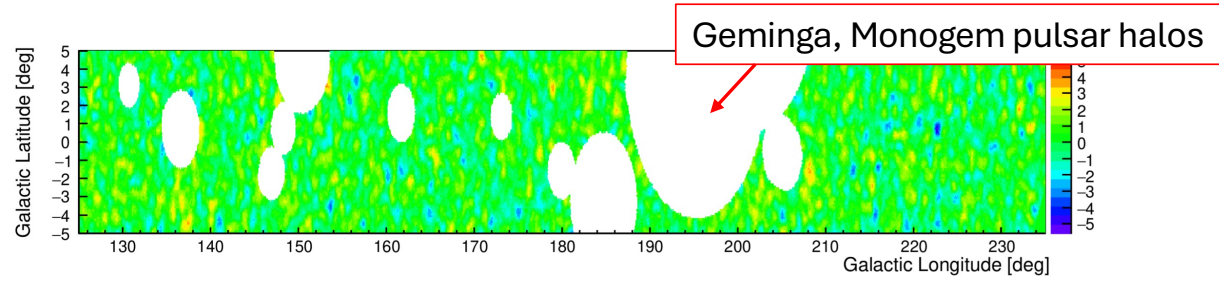
Overall gamma-ray flux: total flux measurements



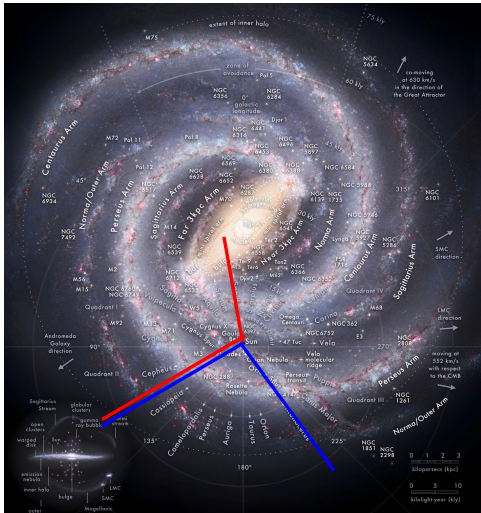
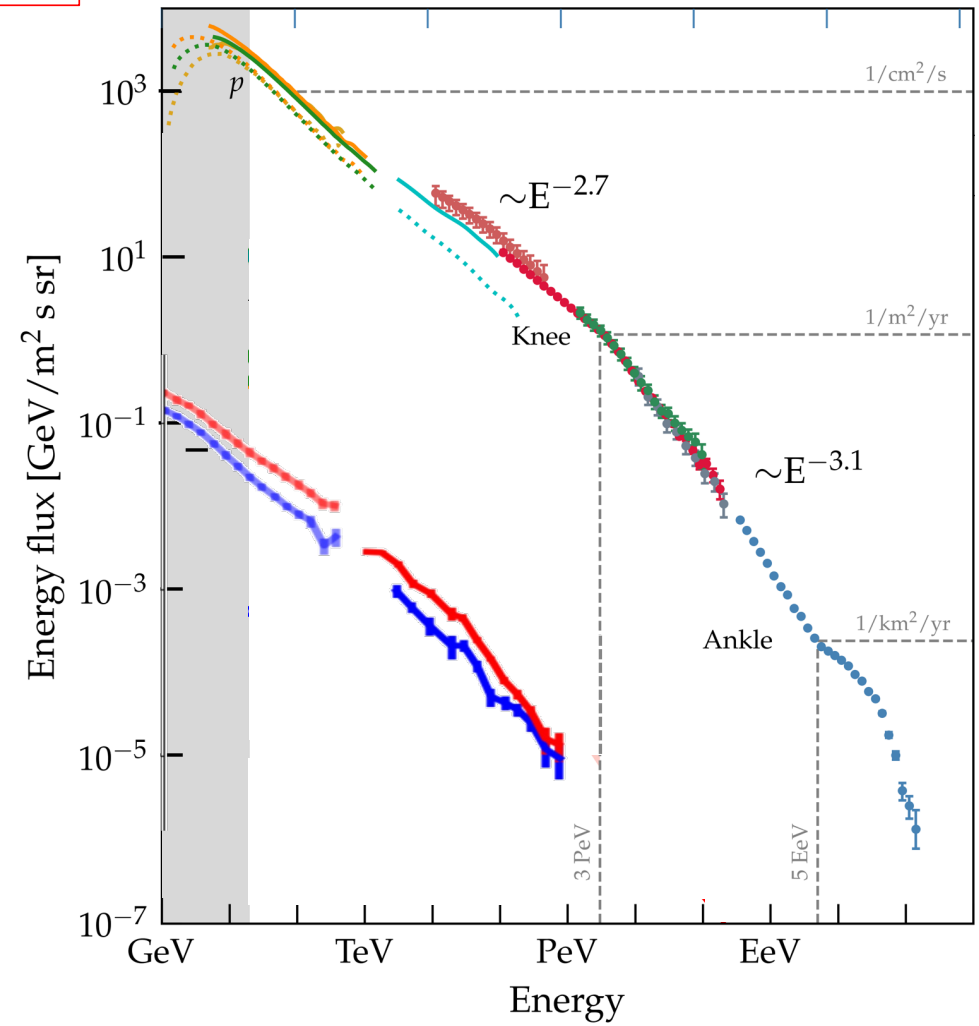
a sharp feature in the total flux spectrum of the outer Galaxy:

Specific source / source class / cosmic rays in the Perseus arm?

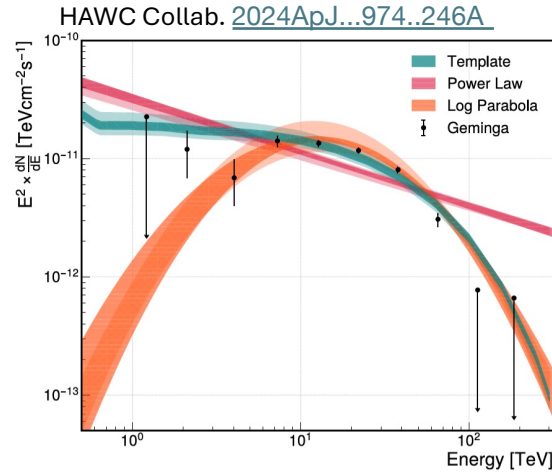
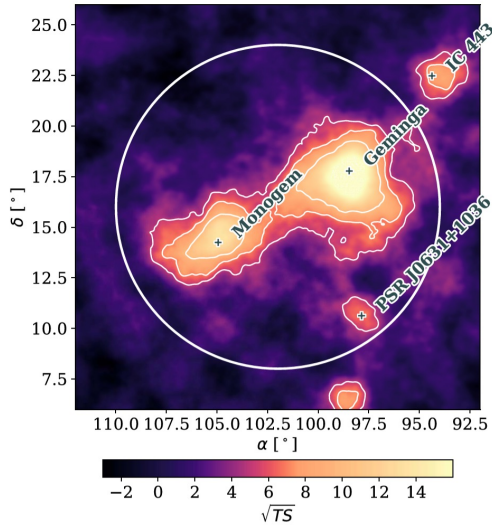
Total flux vs. resolved sources



LHAASO Collab. 2411.16021



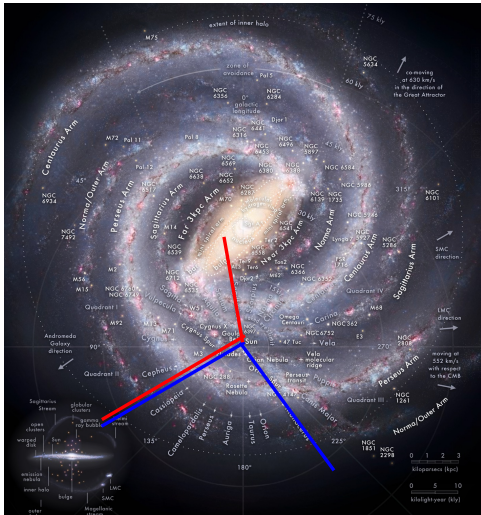
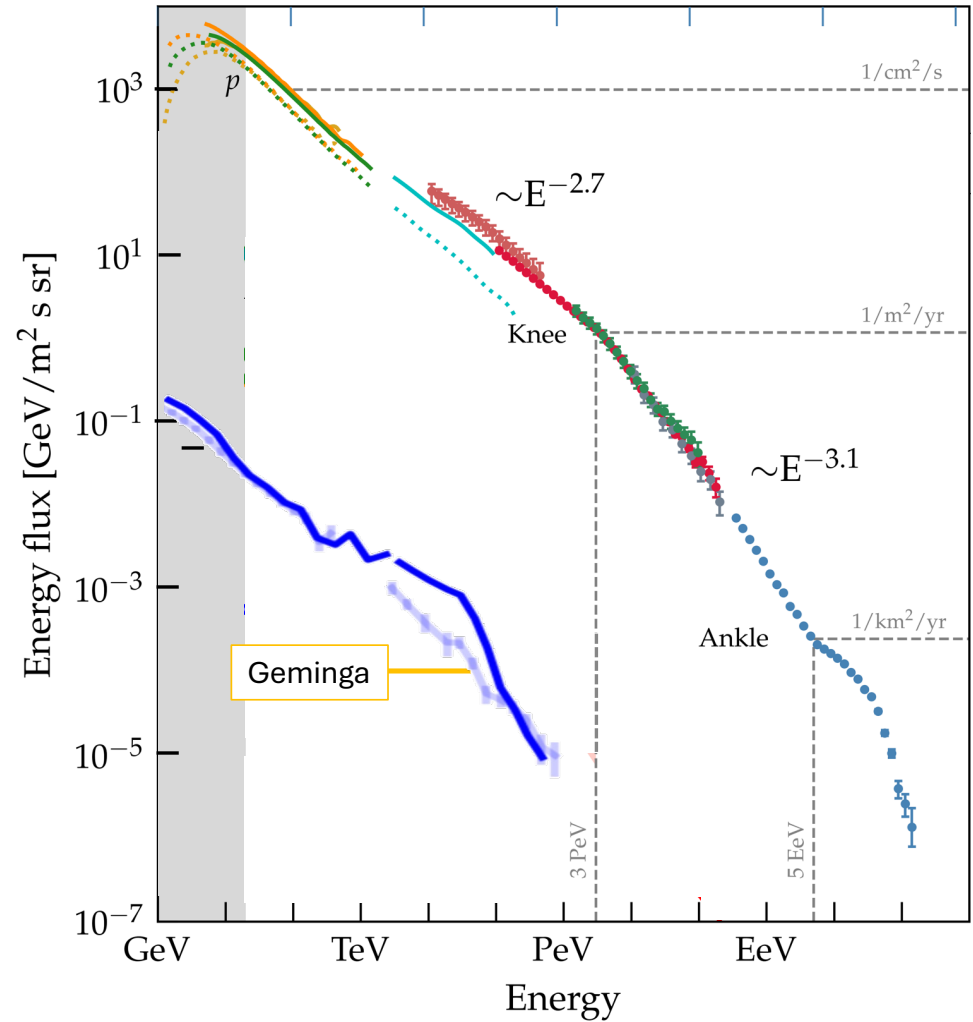
Total flux vs. resolved sources → diffuse flux vs. unresolved sources



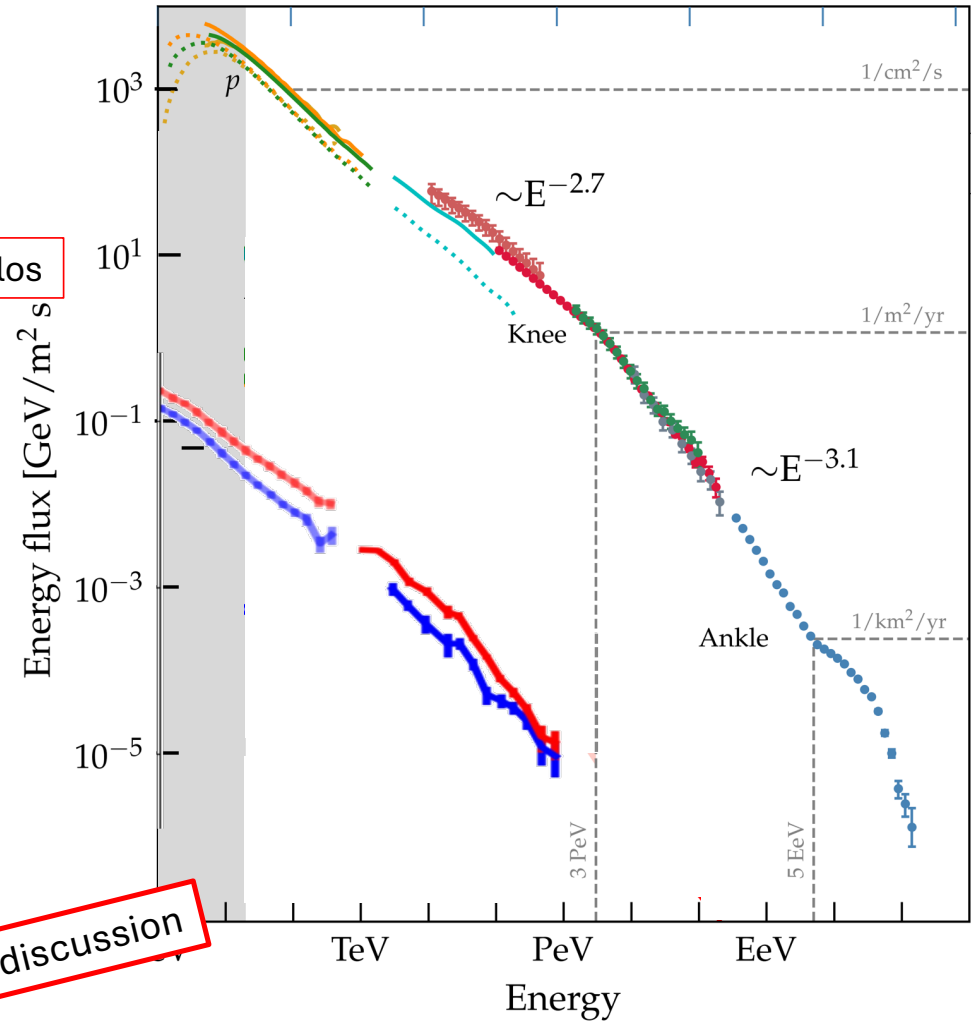
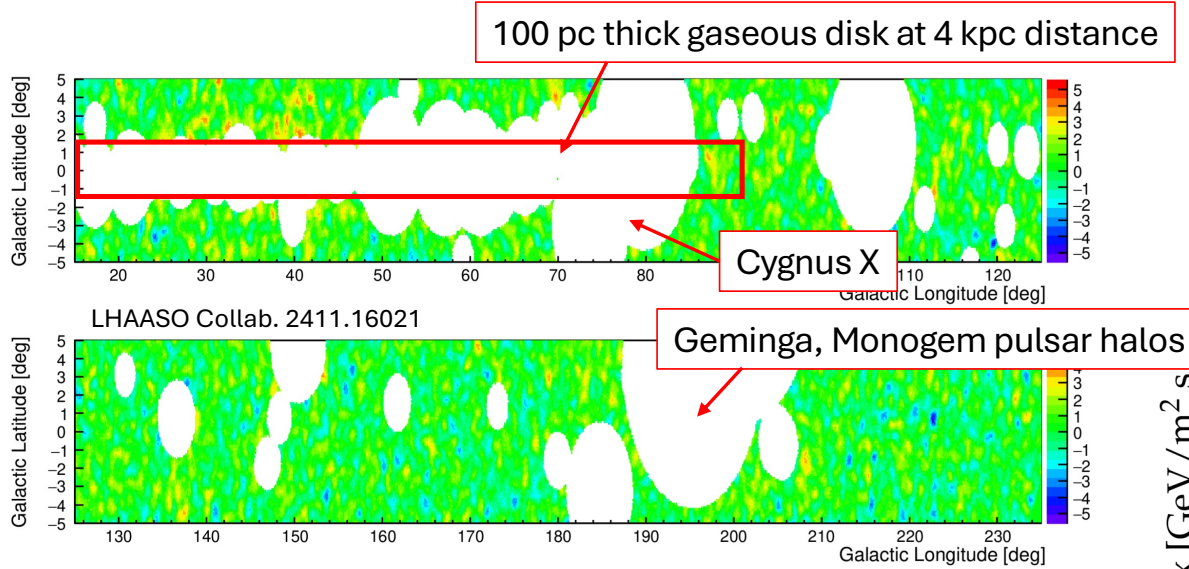
Features in the total spectrum of the outer Galaxy are from brightest pulsar halos.....

Unresolved sources may produce features in the diffuse emission spectrum, unrelated to the features from the cosmic ray interactions.

... for discussion



Diffuse flux: inner vs. outer Galaxy



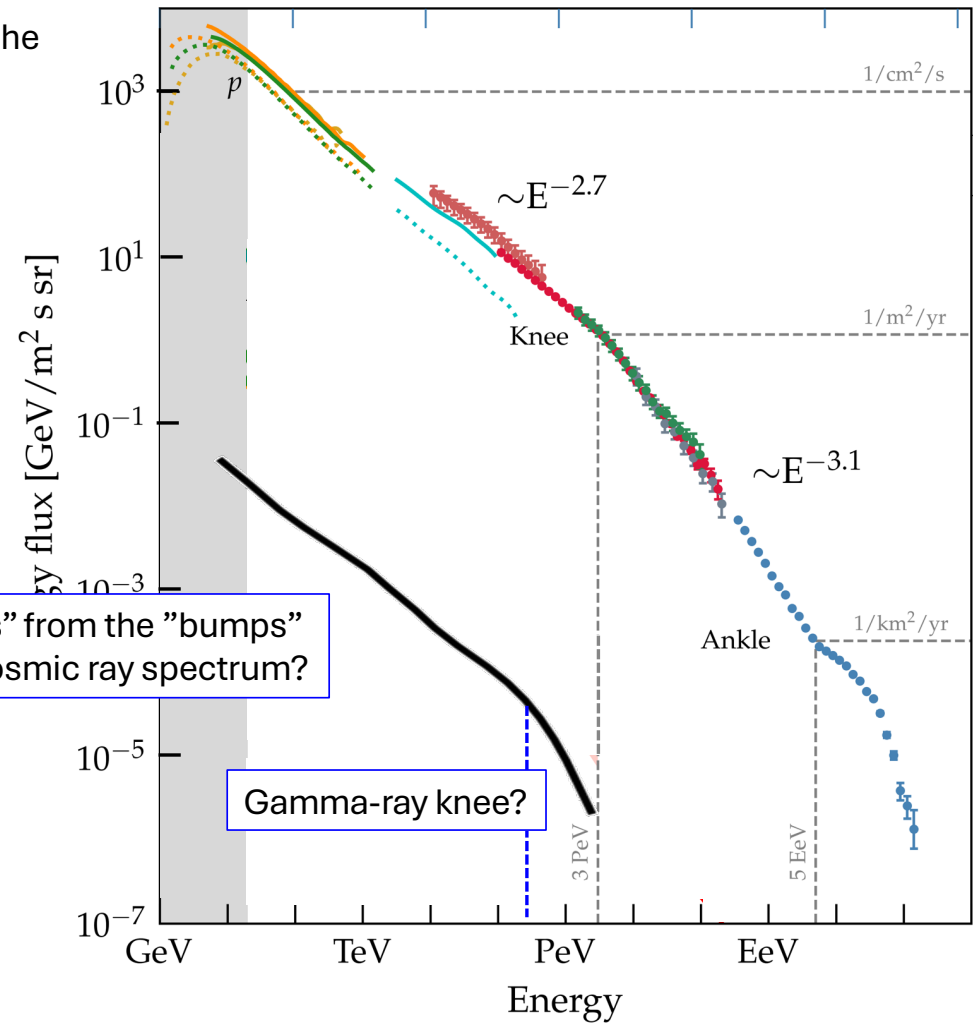
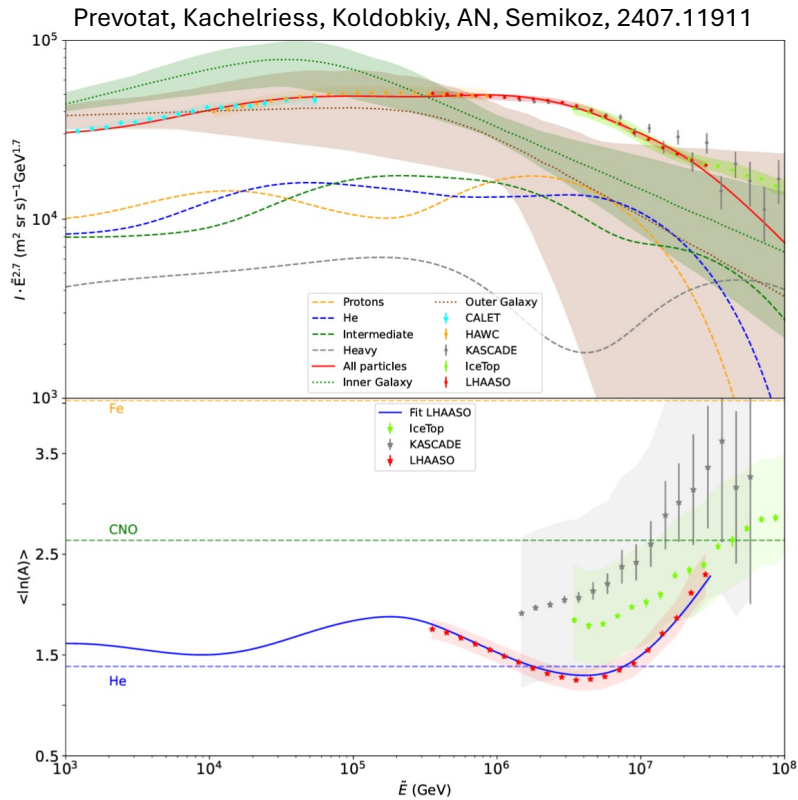
Strategy of “masking” resolved sources in LHAASO removes diffuse emission from the inner Galactic Disk (where Fermi/LAT measurements hint for a possibly harder cosmic ray spectrum).

LHAASO measurements rather probe the cosmic ray spectrum in the local Galaxy.

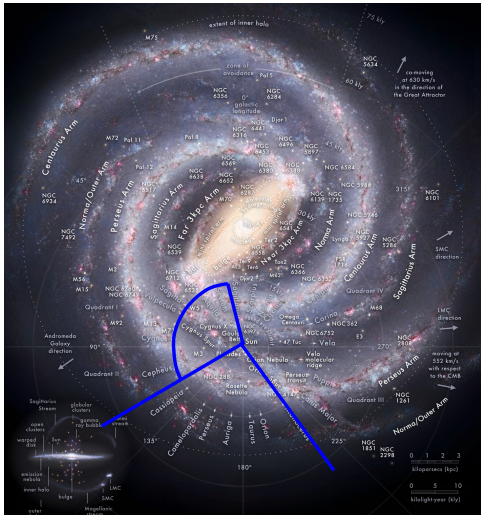
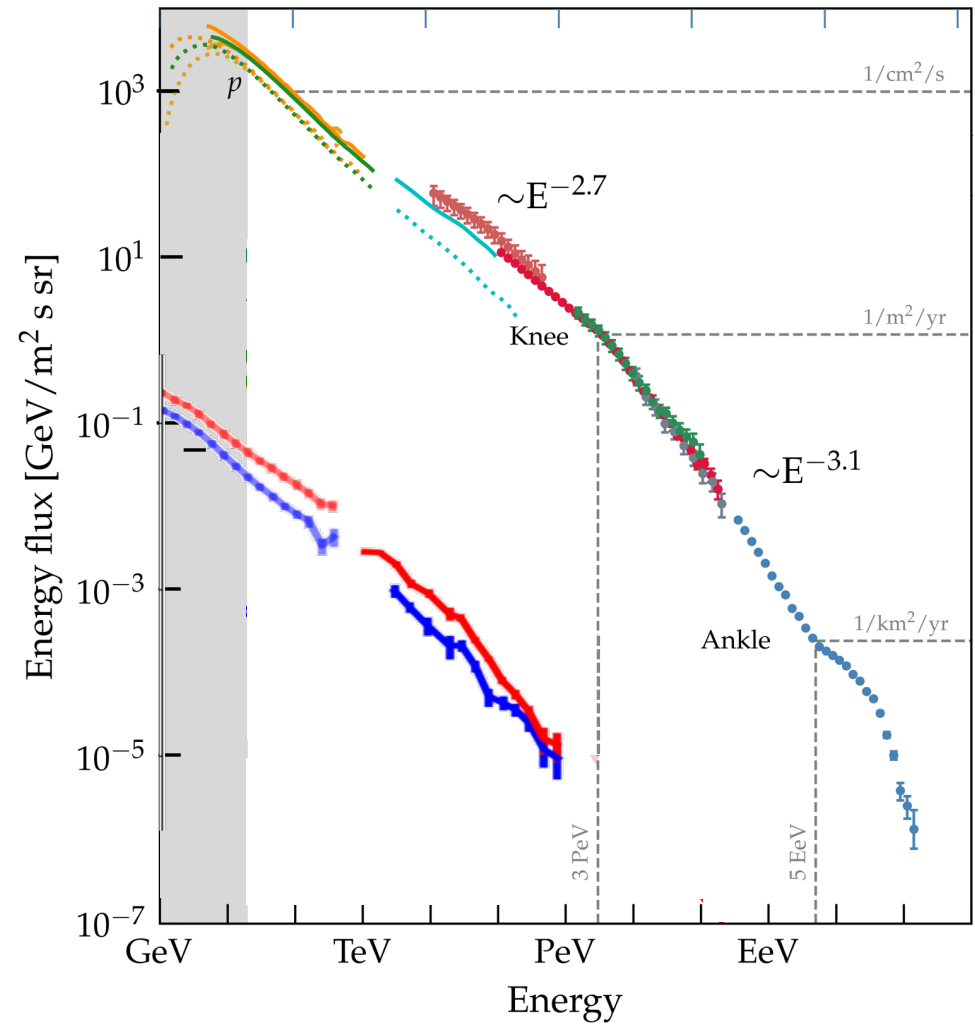
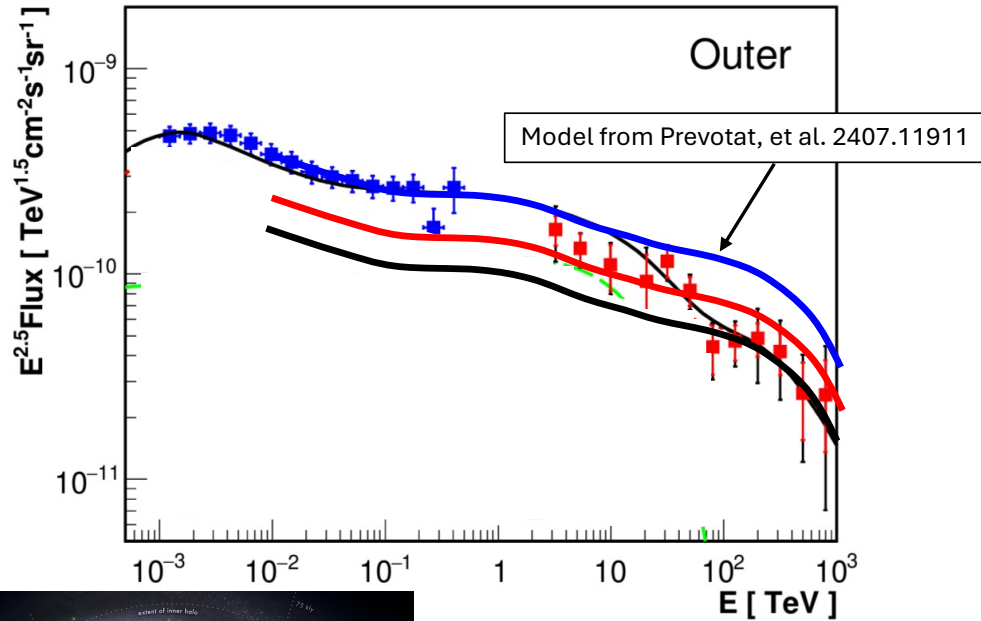
... for discussion

Testing cosmic ray models with gamma-ray data?

- The features of the cosmic ray spectrum should have counterparts in the spectrum of gamma-ray emission from the Milky Way disk.
- Precision of measurements of gamma-ray flux becomes sufficient for the search of such features.



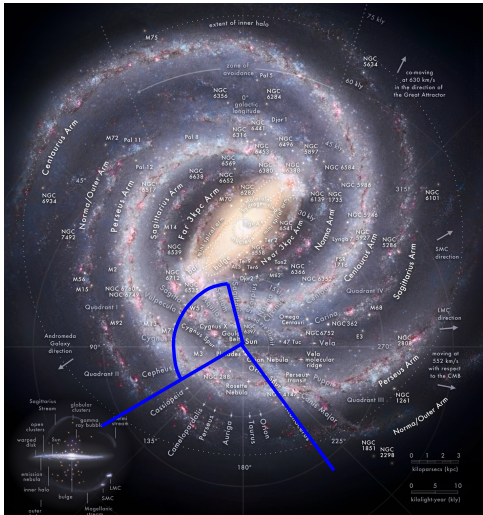
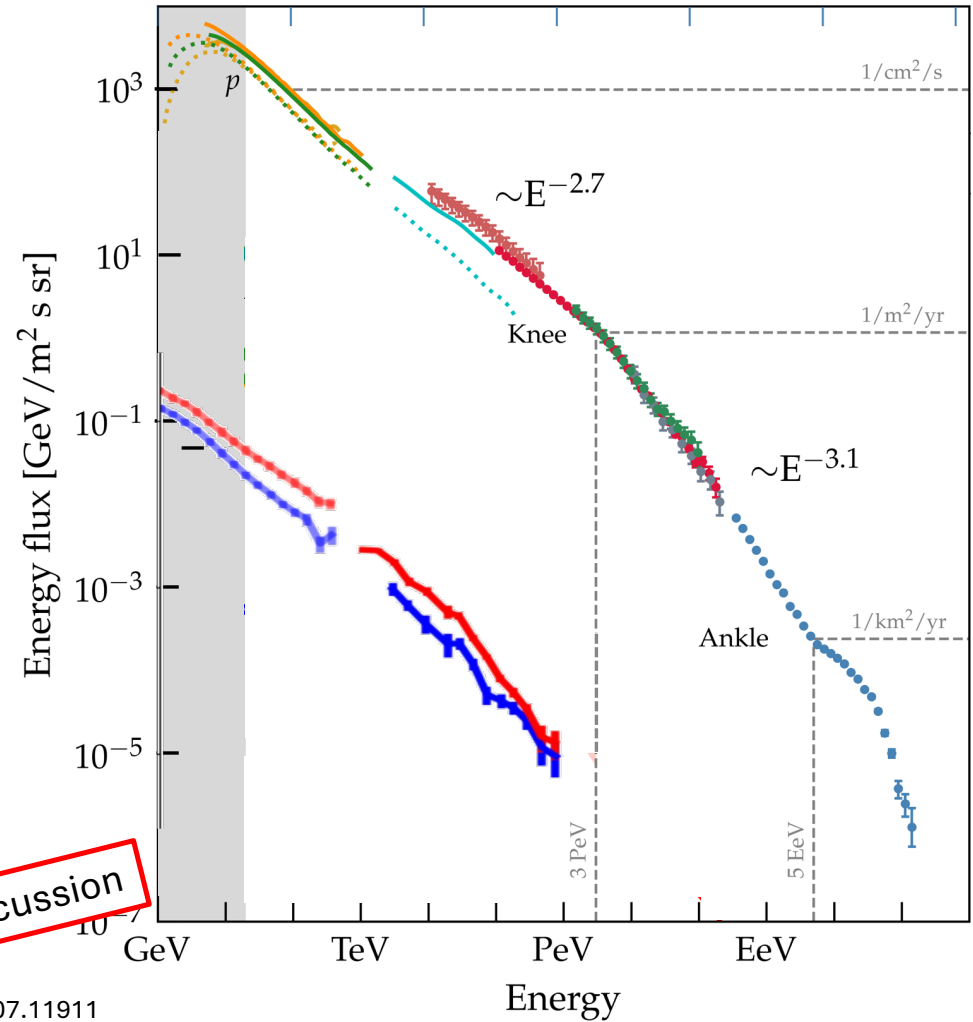
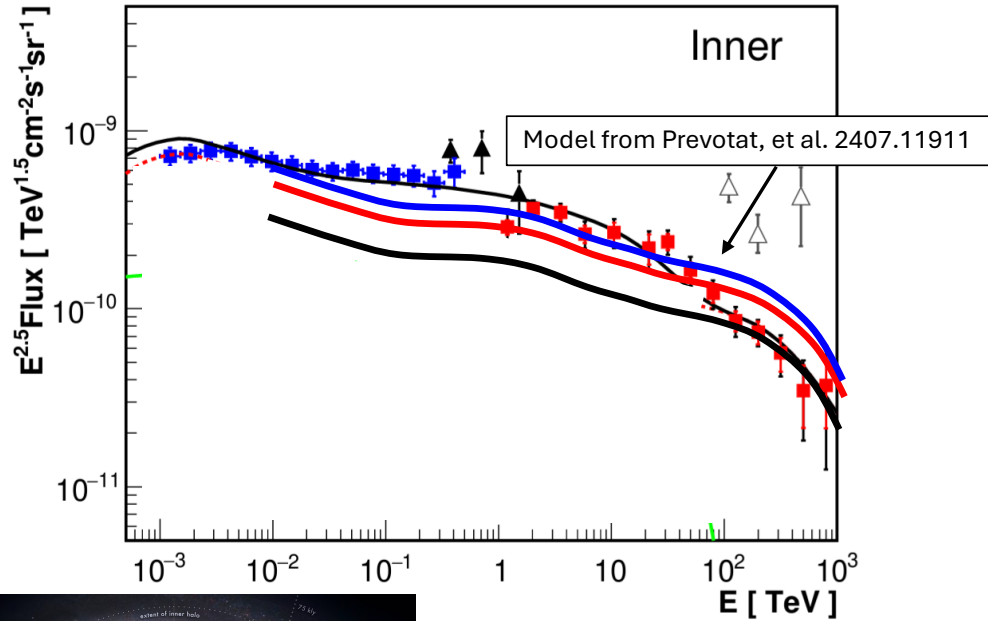
Where is the gamma-ray counterpart of the knee?



Gamma-ray counterpart of the “knee” of the local cosmic ray spectrum is not (yet?) seen in LHAASO + Fermi/LAT diffuse spectrum.

The knee energy may be position-dependent in the Galactic disk.

Where is the gamma-ray counterpart of the knee?



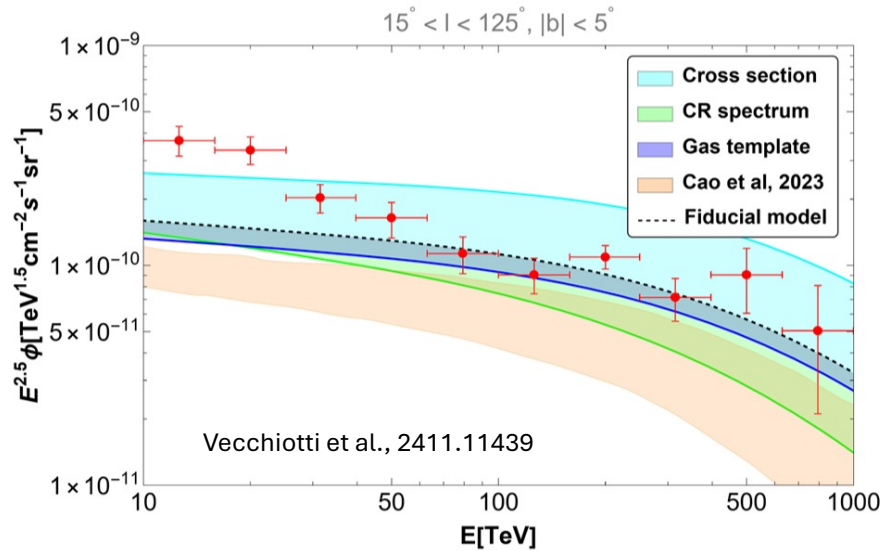
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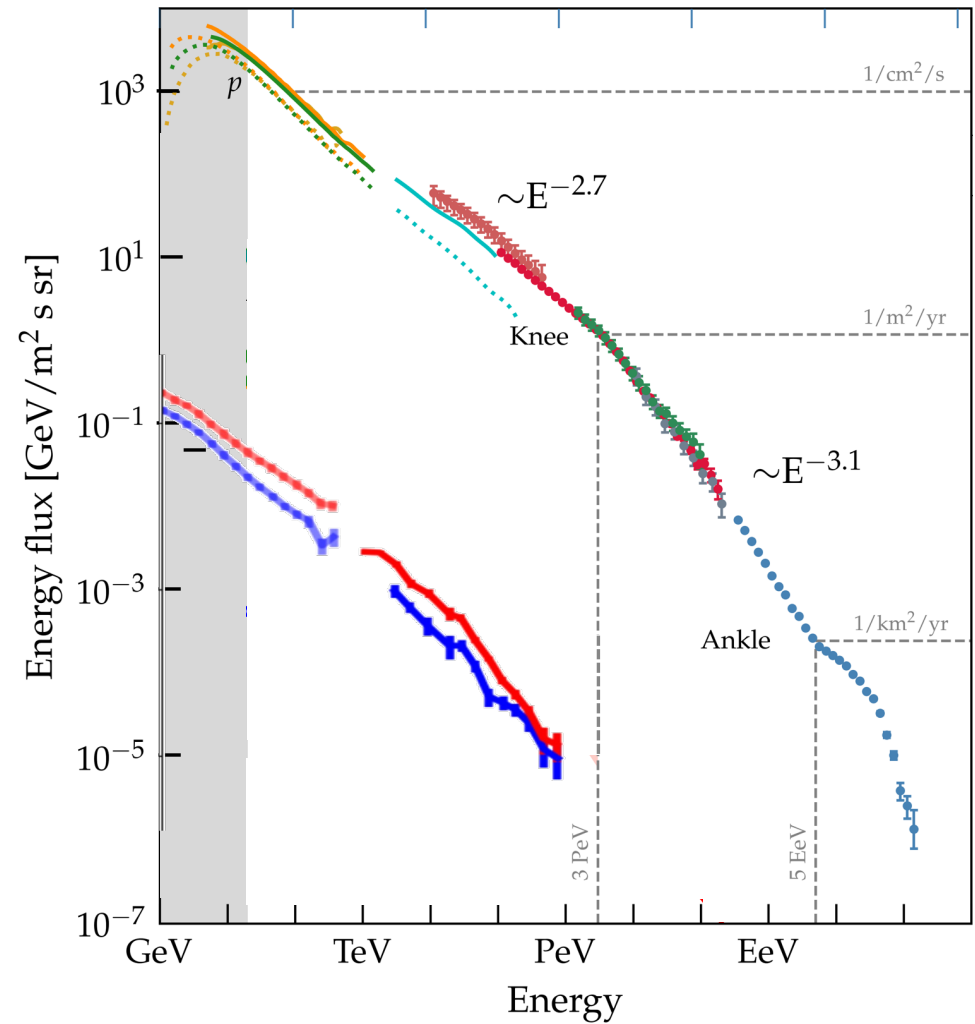
Prevoat, Kachelriess, Koldobkiy, AN, Semikoz, 2407.11911

Where is the gamma-ray counterpart of the knee?

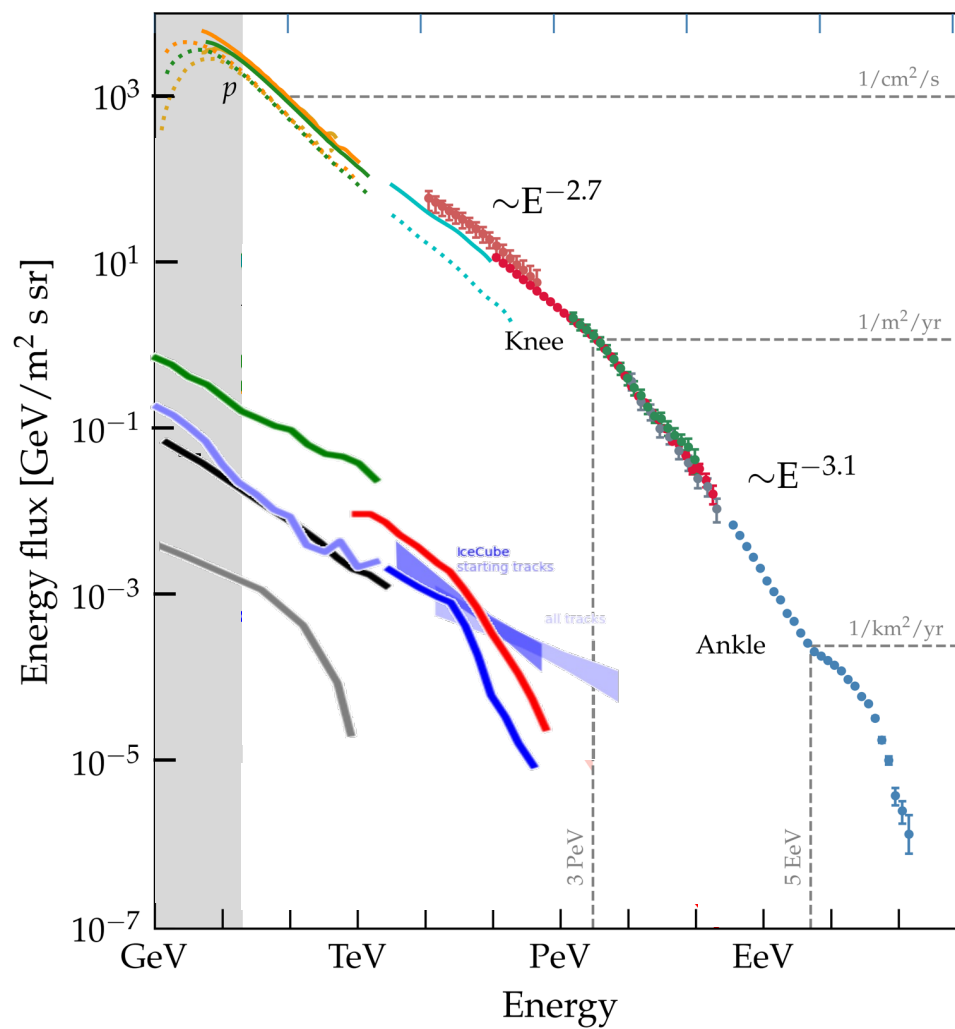
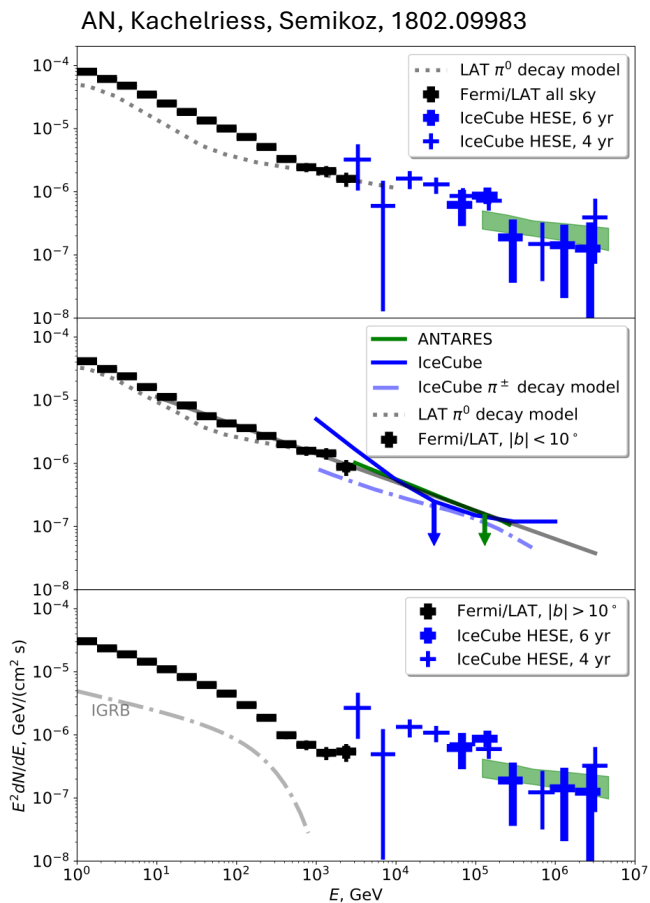


Caveat: systematic uncertainties of calculation of diffuse flux from the cosmic ray data are large.

... for discussion

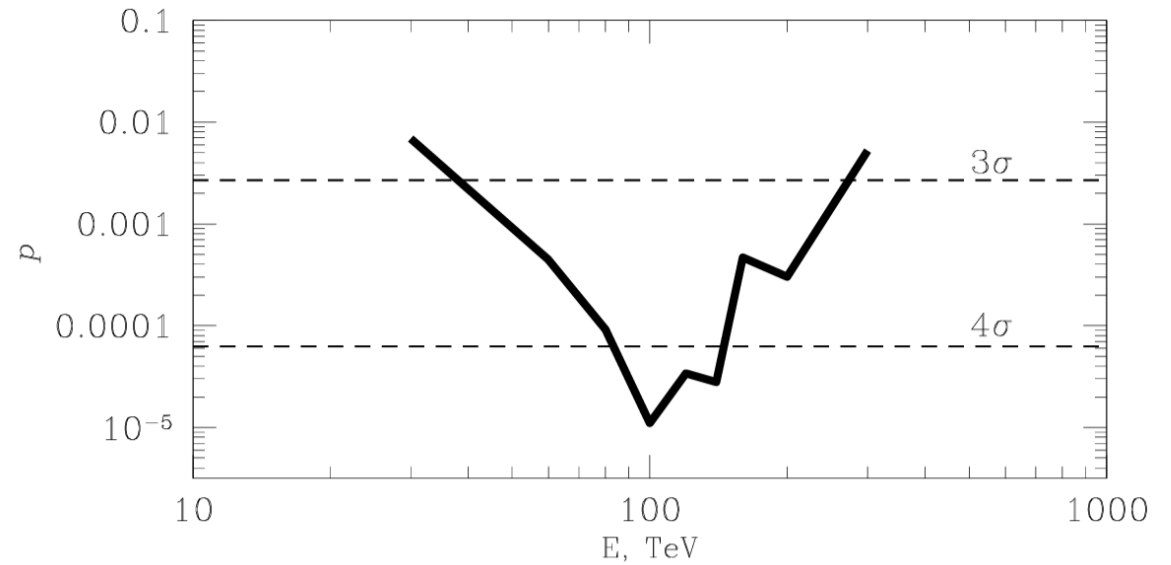
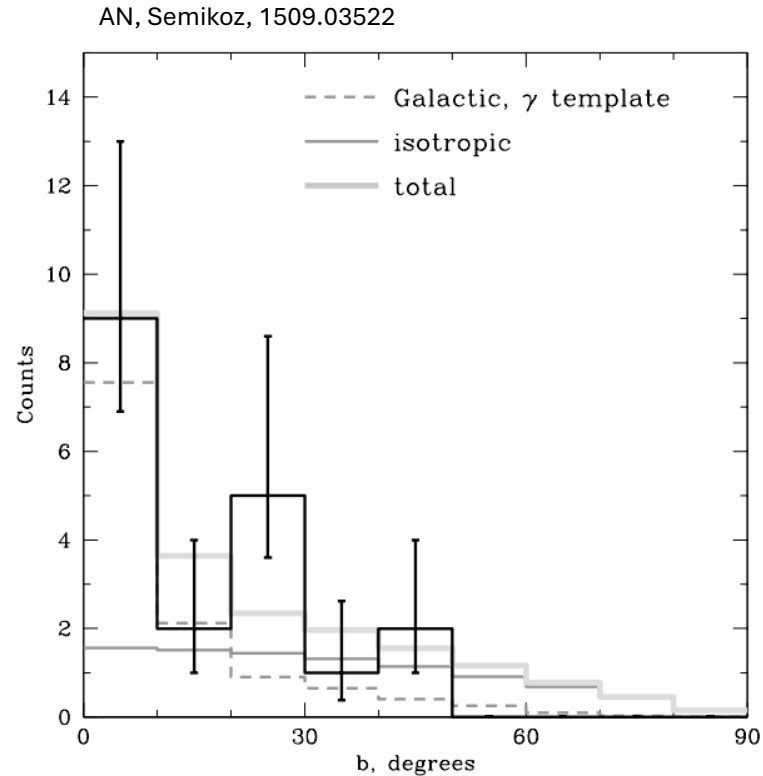


Neutrino counterpart of Galactic gamma-ray flux?



Both cosmic ray interactions in the interstellar medium and resolved sources may produce neutrinos together with gamma-rays.

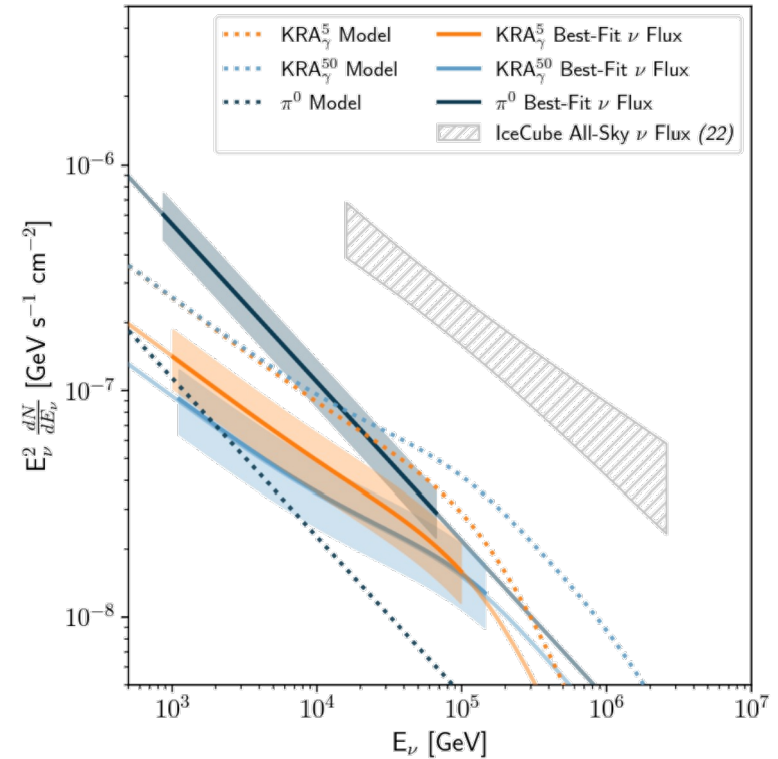
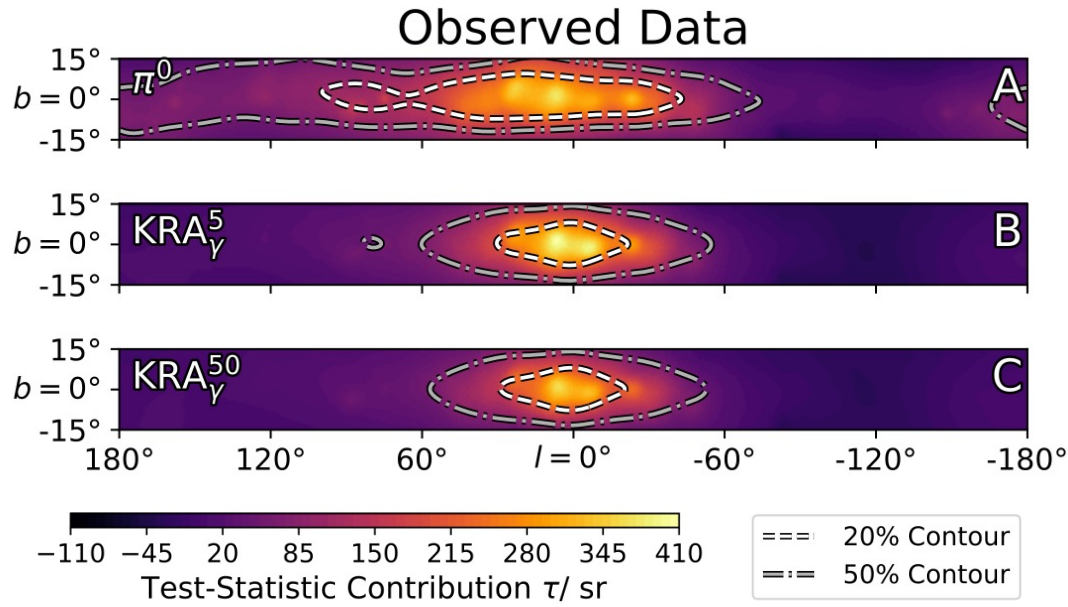
Neutrino counterpart of Galactic gamma-ray flux?



Event distribution in the cascade channel revealed a mild anisotropy toward the Galactic Plane, in $10^\circ - 30^\circ$ 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

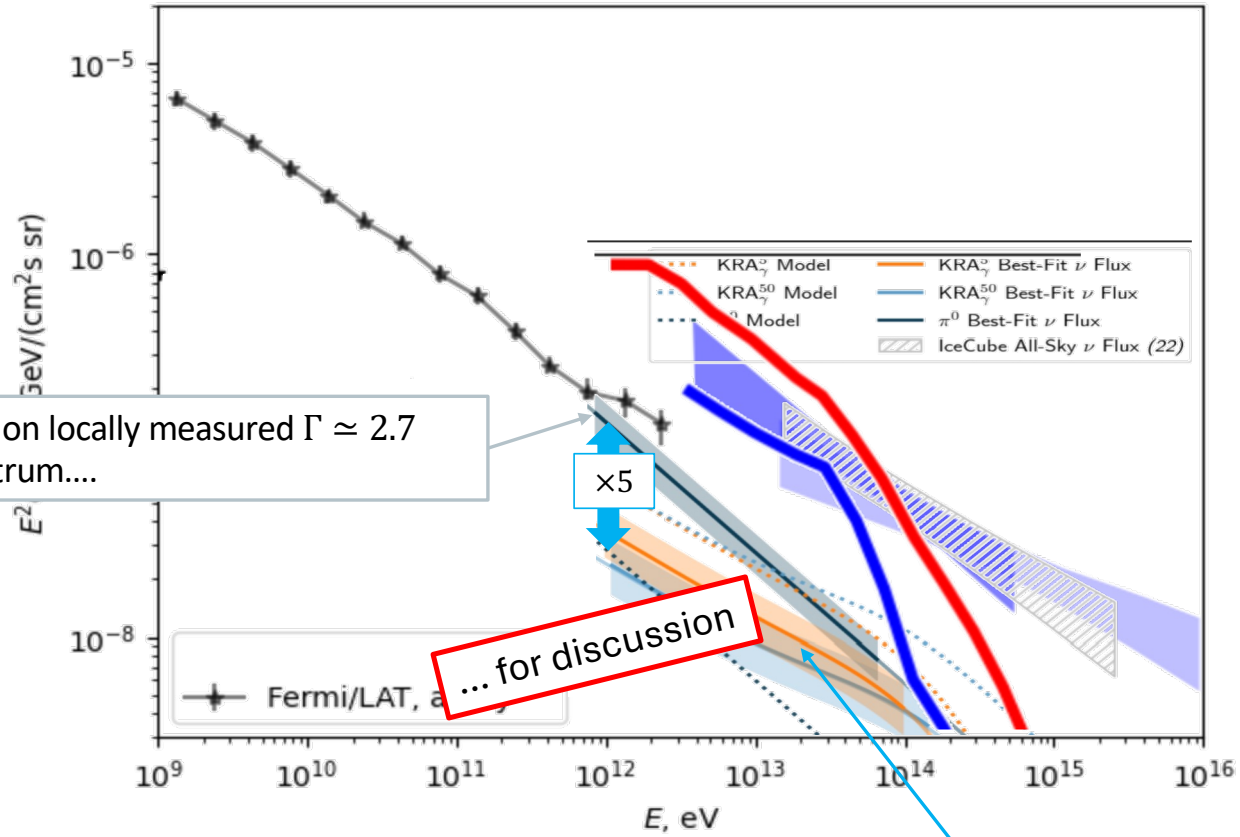
Diffuse neutrino signal from the Milky Way

IceCube Collab. 2307.04427



IceCube collaboration has performed a search for diffuse neutrino flux 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



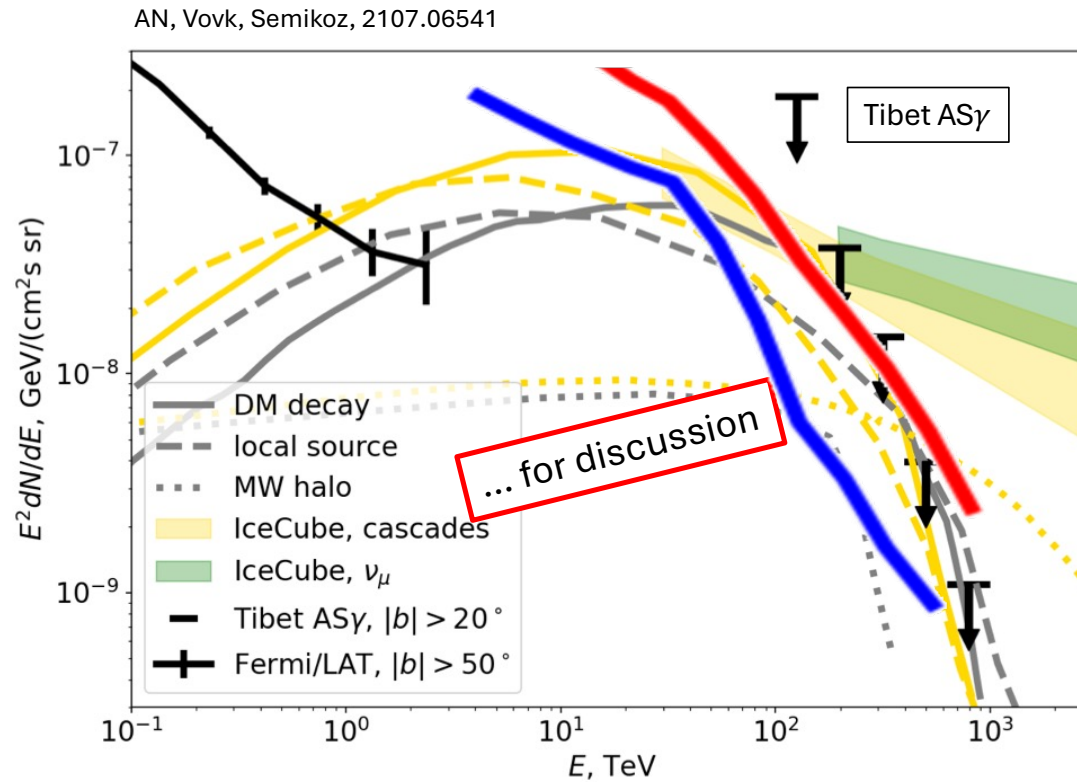
Template based on locally measured $\Gamma \approx 2.7$ cosmic ray spectrum....

x5

... for discussion

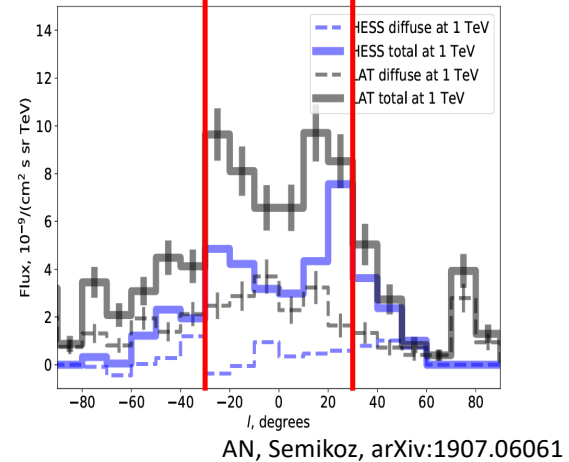
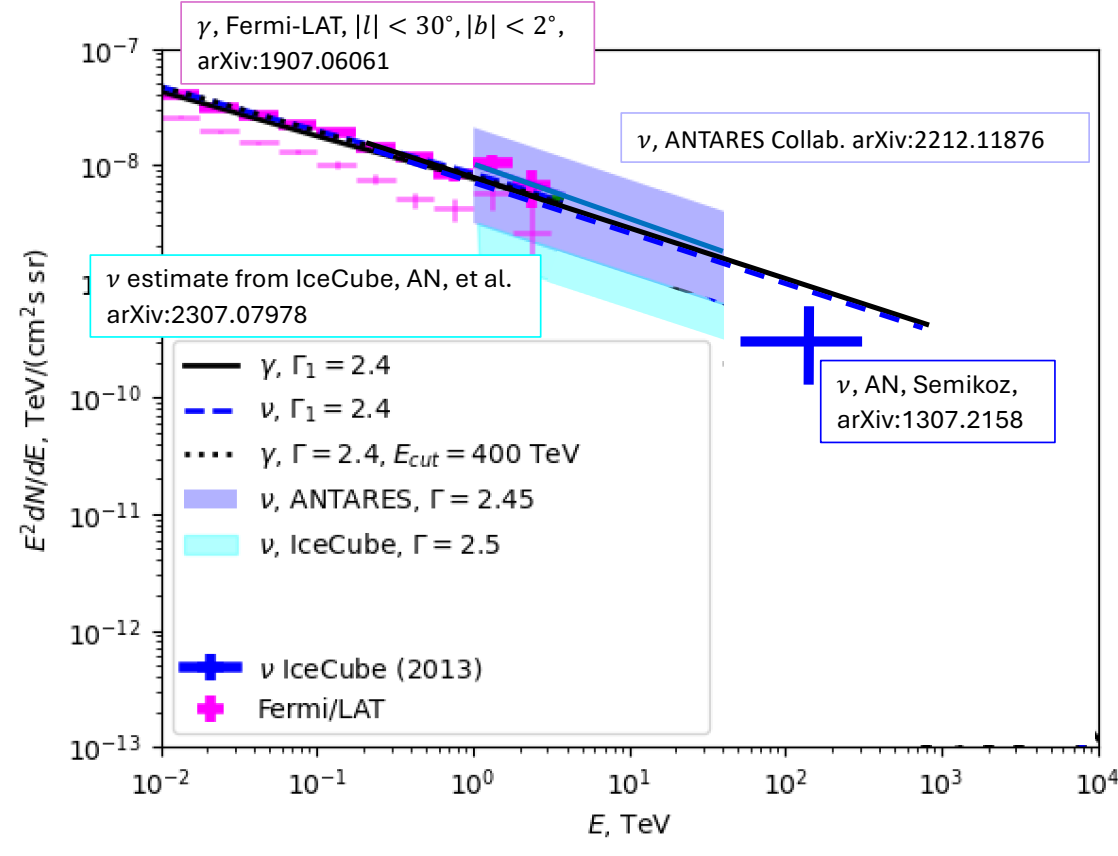
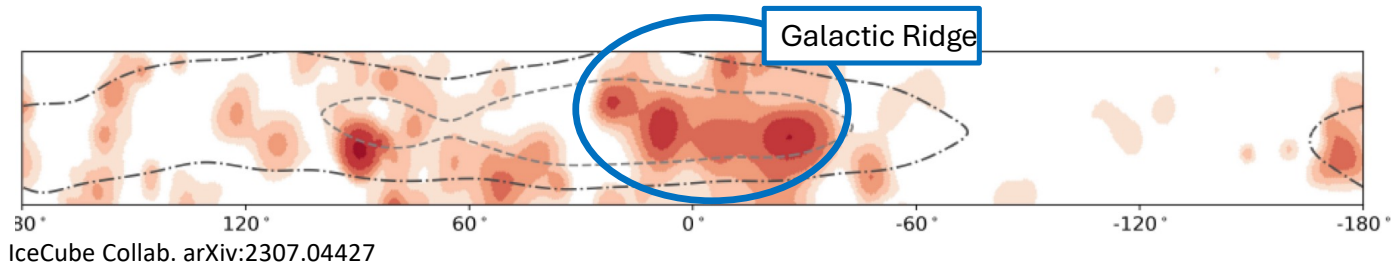
Template tuned to reproduce the $\Gamma \approx 2.5$ slope of gamma-ray emission from the Galactic disk....

Nearly isotropic Galactic gamma-ray and neutrino signal?

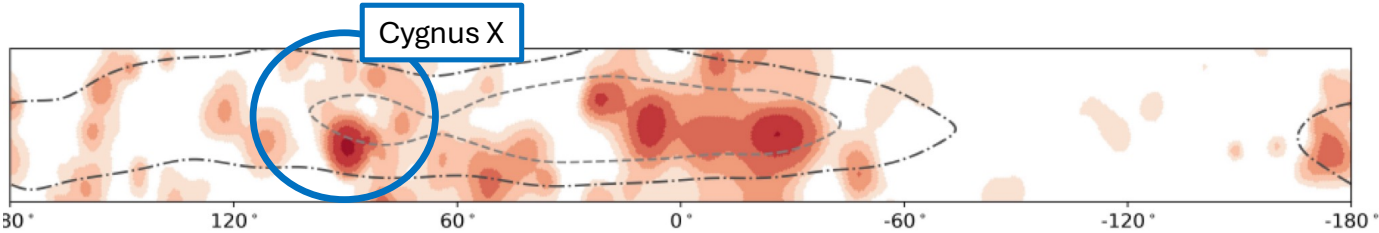


LHAASO measurements do not constrain signal that may be distributed over large part of the sky (nearly isotropic, e.g. large scale halo around Milky Way, or signal from a very nearby local source). Tightest constraint on isotropic flux at PeV is from Tibet ASy.

Hard cosmic ray spectrum (or resolved hadronic sources) in the Galactic Ridge?

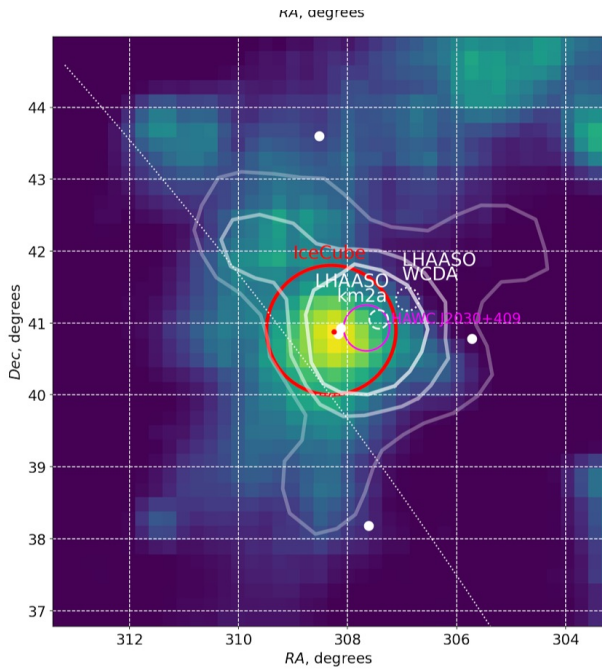


Hadronic gamma-ray + neutrino flux from Cygnus Cocoon?

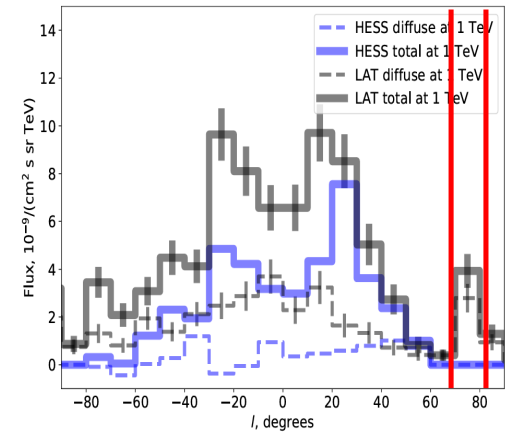
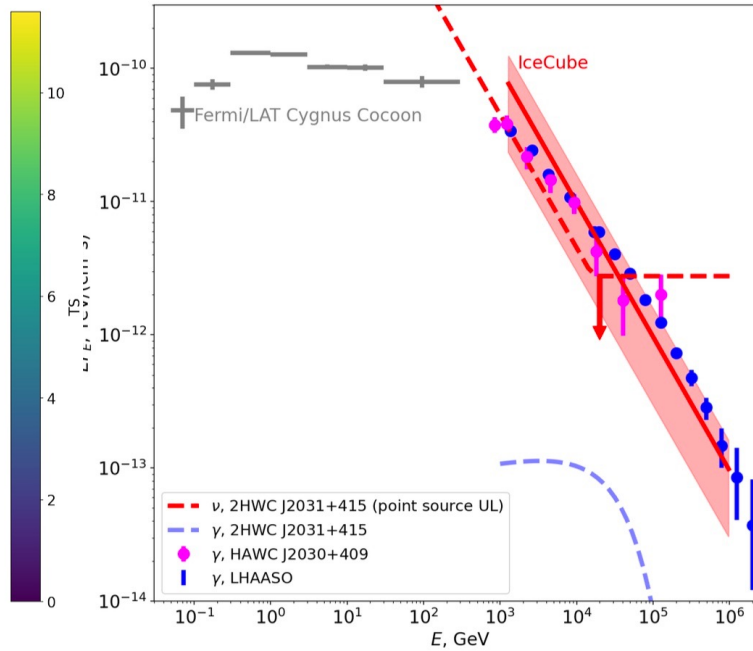


IceCube Collab. arXiv:2307.04427

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.



AN, Semikoz, Savchenko, 2311.13711



AN, Semikoz, arXiv:1907.06061

Summary

High-quality gamma-ray data up to PeV and complementary neutrino data start to provide a possibility to answer the questions

- 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(s) are responsible for the knee?

