PeVatrons

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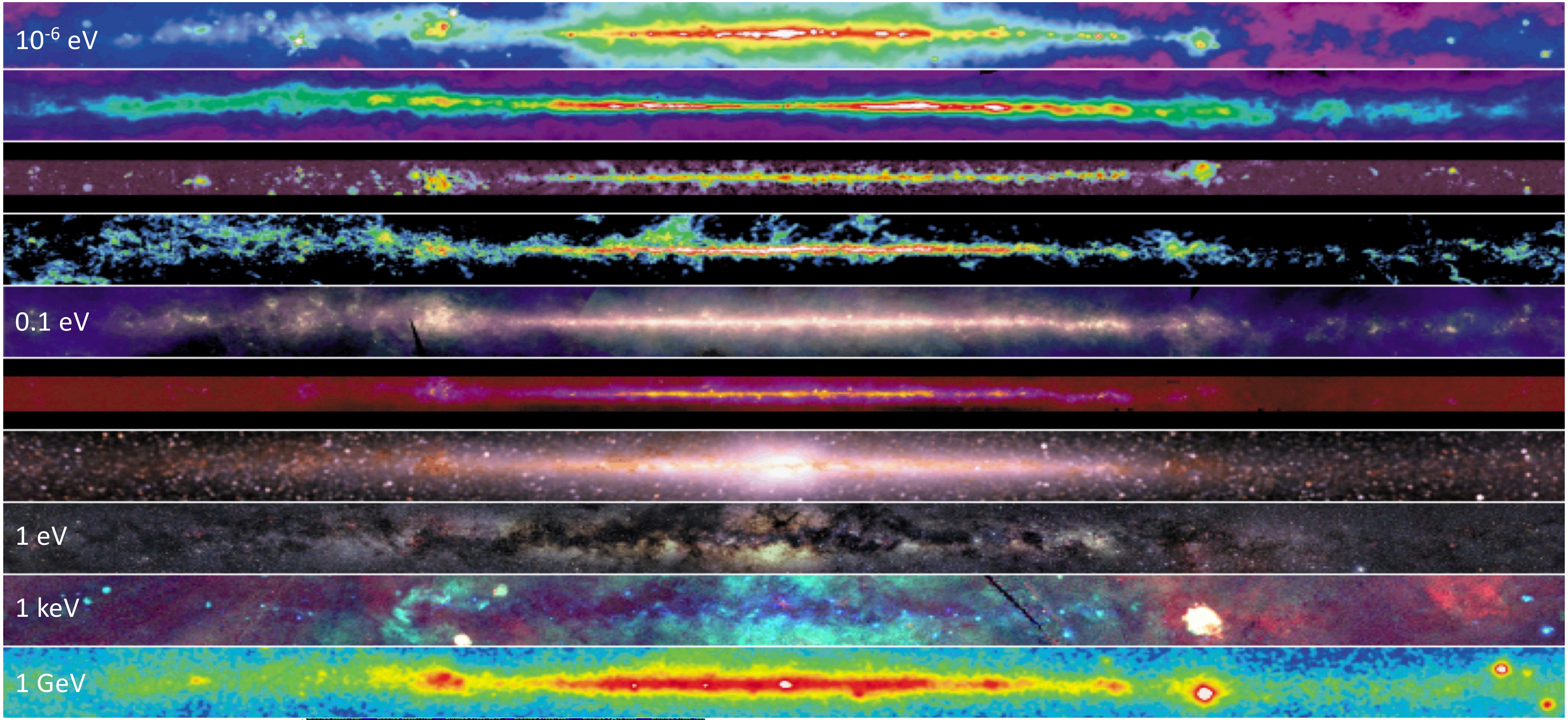
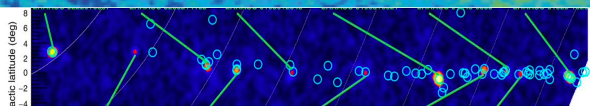
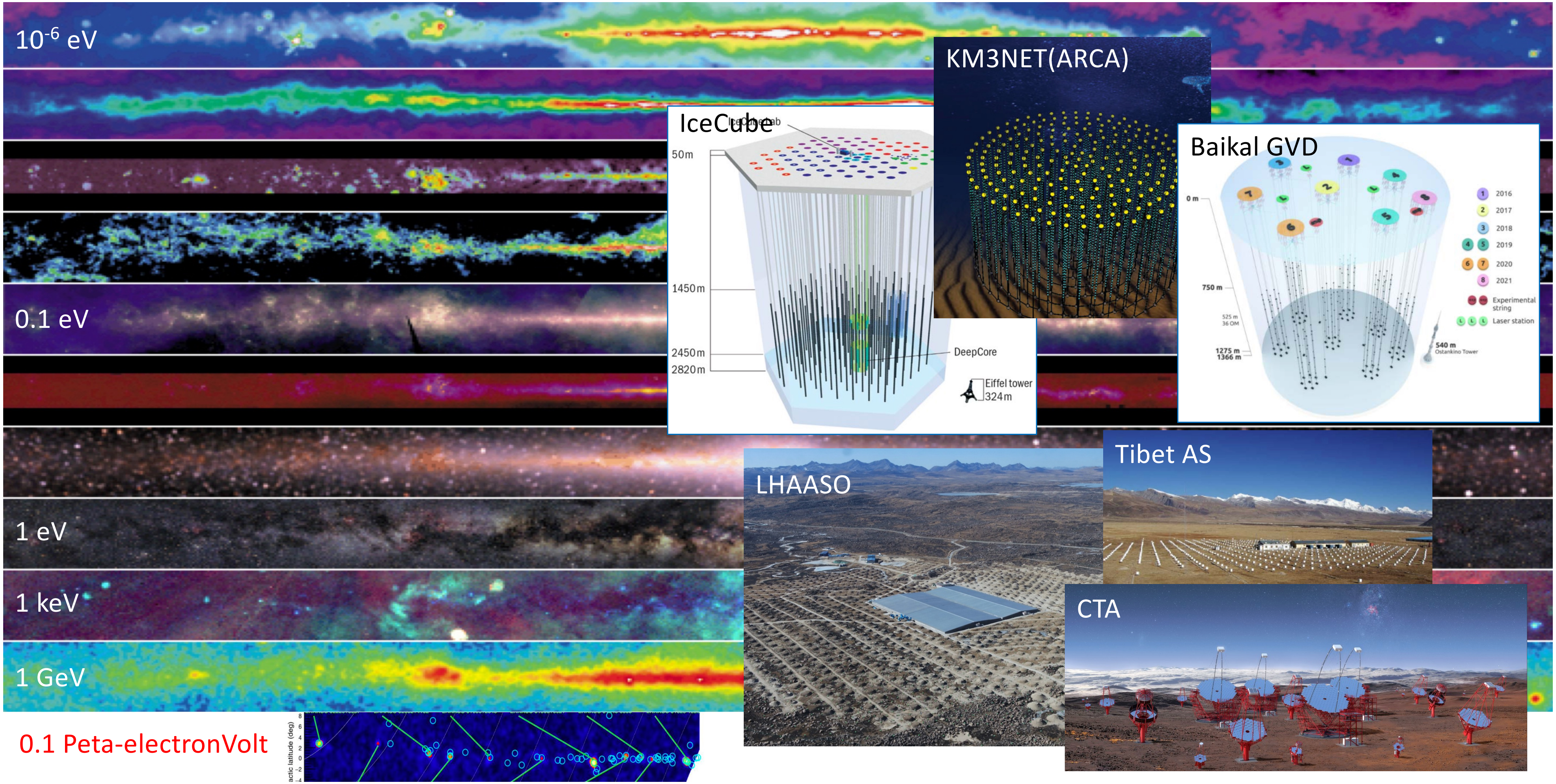


0.1 Peta-electronVolt



Motivations: new window for astronomical observations

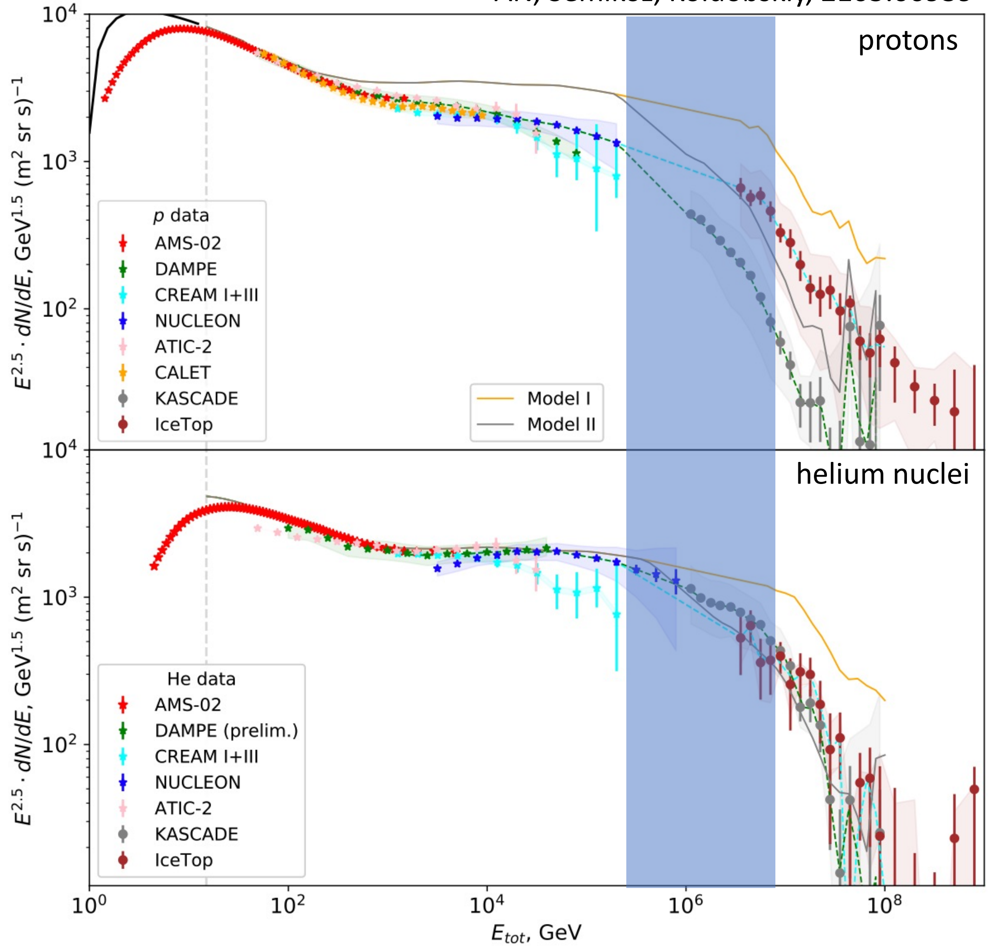


Motivations: the knee of the cosmic ray spectrum

Cosmic ray spectrum measured at the Earth location has a “knee” feature at PeV energy. The nature of this feature is not understood:

- Is it a “universal” feature of the cosmic ray spectrum everywhere in the Galaxy or it is a local feature of the spectrum in the solar neighbourhood?
- Does it reveal the high-energy end of Galactic cosmic ray spectrum?
- Or is it showing a change of regime of propagation of cosmic rays through interstellar medium?
- Or may be it is an “feature” on top of otherwise powerlaw average spectrum, produced by cosmic ray flux from a nearby source?

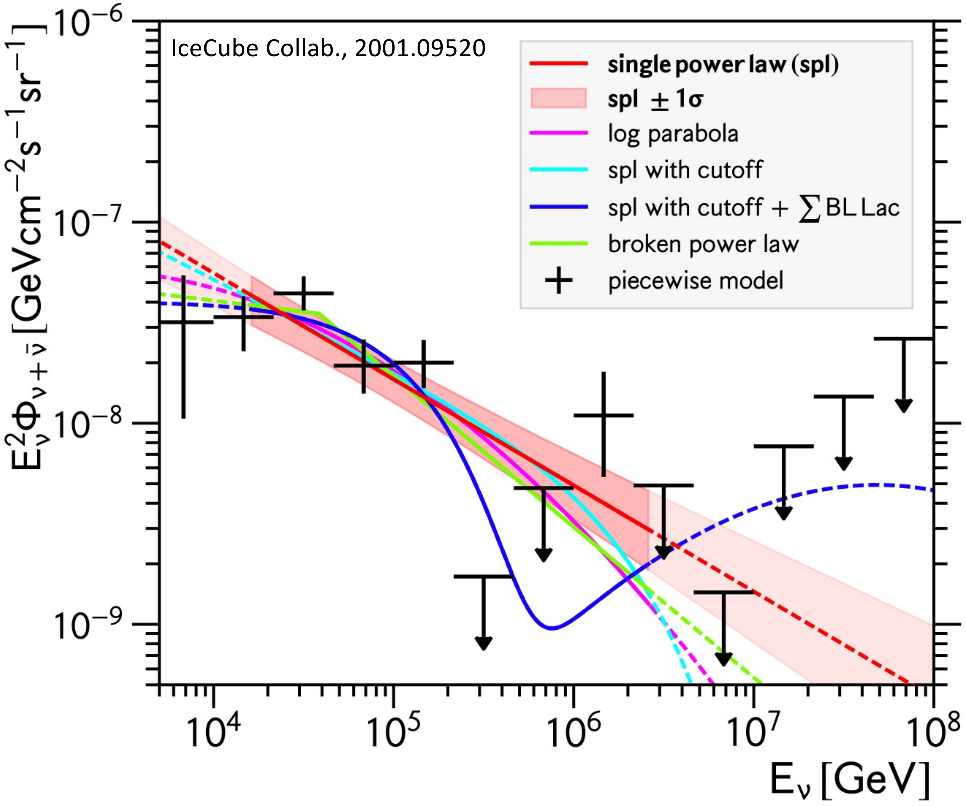
AN, Semikoz, Koldobskiy, 2105.00959



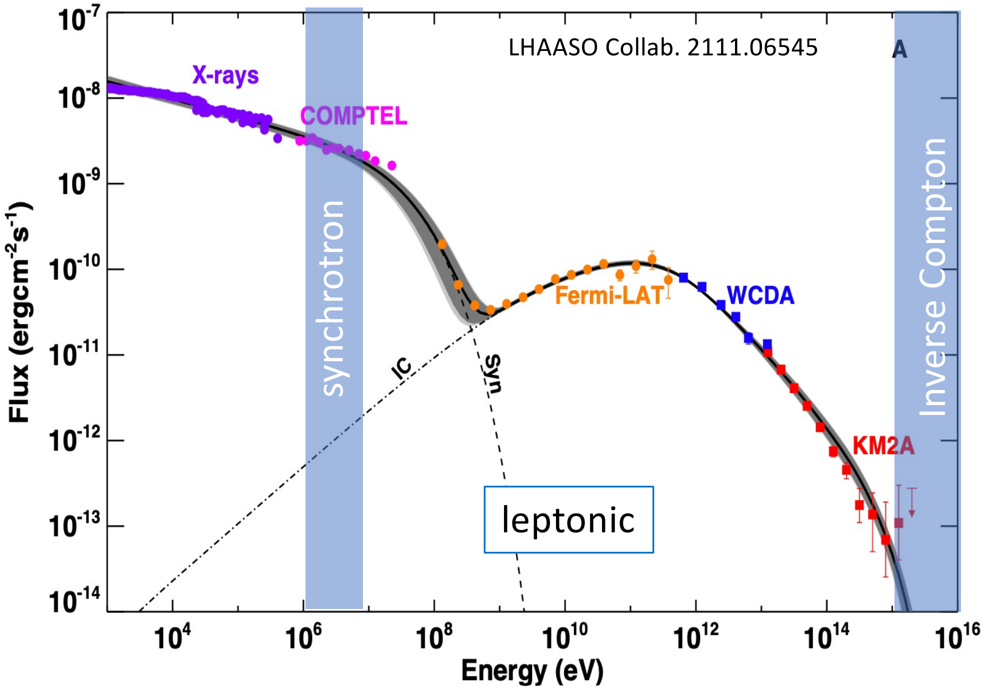
Motivations: the astrophysical neutrino signal

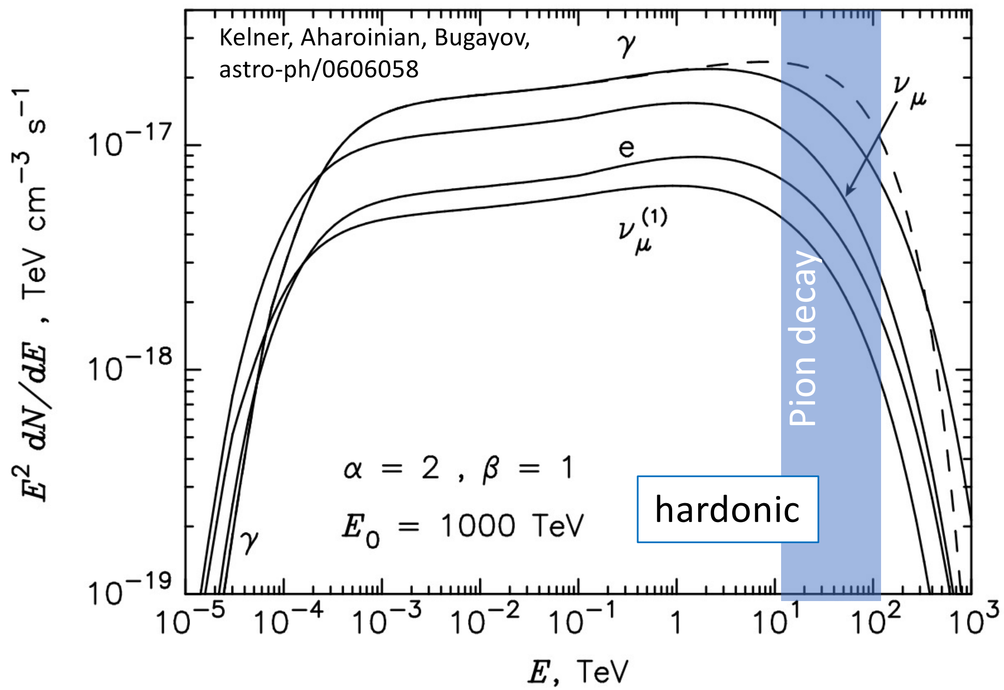
Astrophysical neutrino signal in the PeV energy range is produced by sources accelerating particles to multi-PeV energies. These sources are uncertain:

- Are the sources extragalactic or part of the flux comes from sources in the Milky Way?
- Is the flux superposition of emission from large number of unresolved isolated source or there is a truly diffuse component?
- What is the mechanism of production of neutrinos: pp or $p\gamma$?
- What sources in the Galaxy are responsible for the production of cosmic ray flux at the knee?



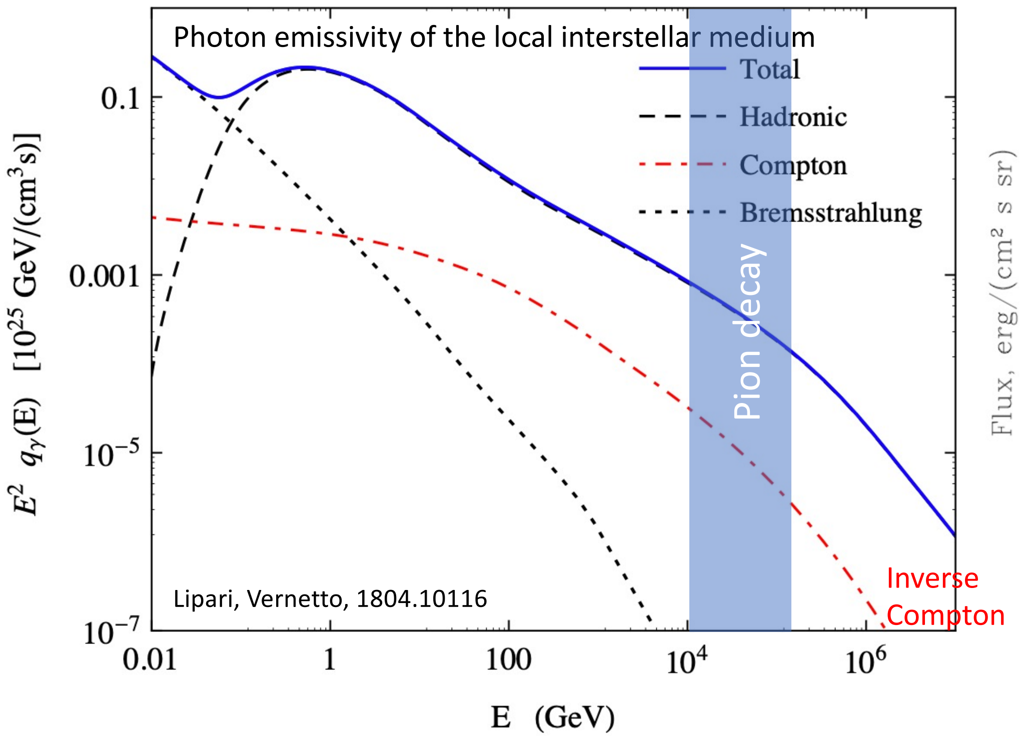
Neutrinos and gamma-rays from PeV electrons and protons/nuclei

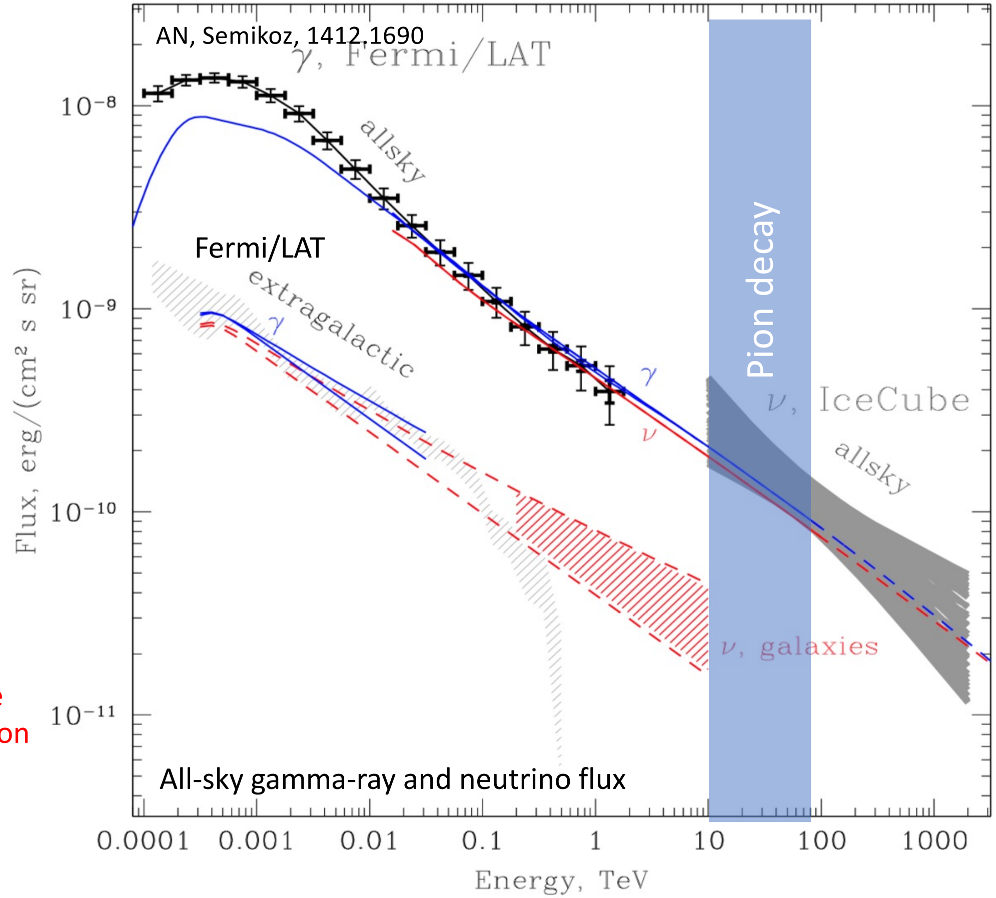




- Inverse Compton emission from PeV electrons scattering CMB, infrared and visible light is emitted at PeV energy $E_{IC} \sim E_e$.
- Synchrotron emission from PeV electrons in magnetic field 0.1 mG (Crab nebula) is emitted at $E_s \simeq 5 \left[\frac{B}{10^{-4}\ \mathrm{G}}\right] \left[\frac{E_e}{1\ \mathrm{PeV}}\right]^2$ MeV
- Pion decay gamma-rays and neutrinos from PeV protons are emitted in the 10-100 TeV energy range, $E_{\nu,\gamma} \sim 0.01..0.1\ E_p$.

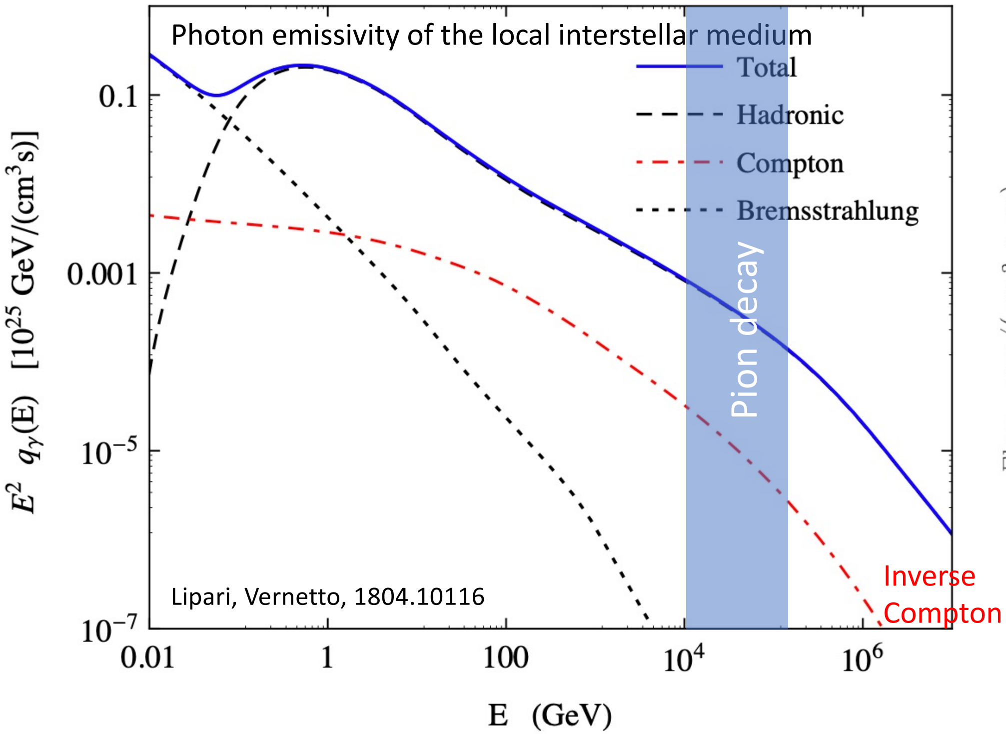
Collective gamma-ray and neutrino flux from Galactic PeVatrons

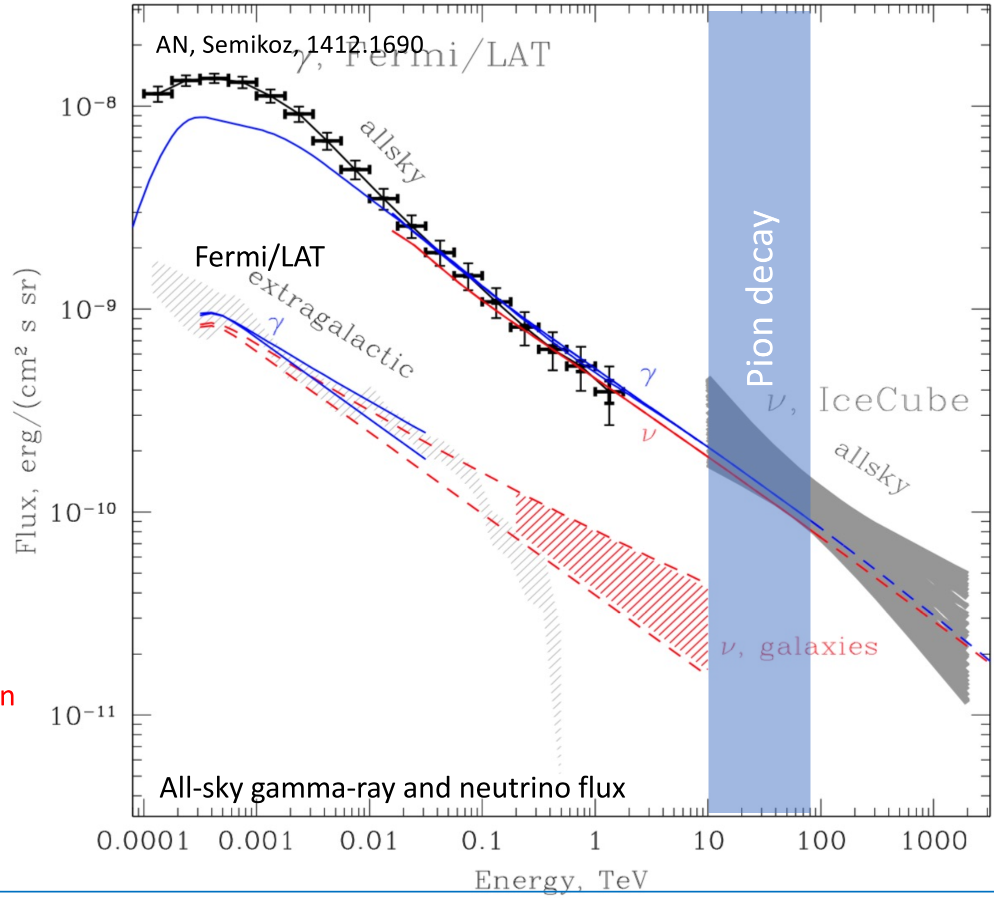




– The strongest detectable signal on the sky is perhaps collective emission from all PeV cosmic rays in the interstellar medium.

Collective gamma-ray and neutrino flux from Galactic PeVatrons





Observations in 10 TeV-1 PeV gamma-ray and neutrino channel can be used to

- measure average spectrum of cosmic rays: is its slope equal to the locally measured (around $\frac{dN}{dE} \sim E^{-2.7}$)?
- find out if the ”knee” is local or general feature of cosmic ray spectrum across the Galaxy?
- see how do PeV cosmic rays propagate through the interstellar medium: isotropic / anisotropic diffusion, free streaming?

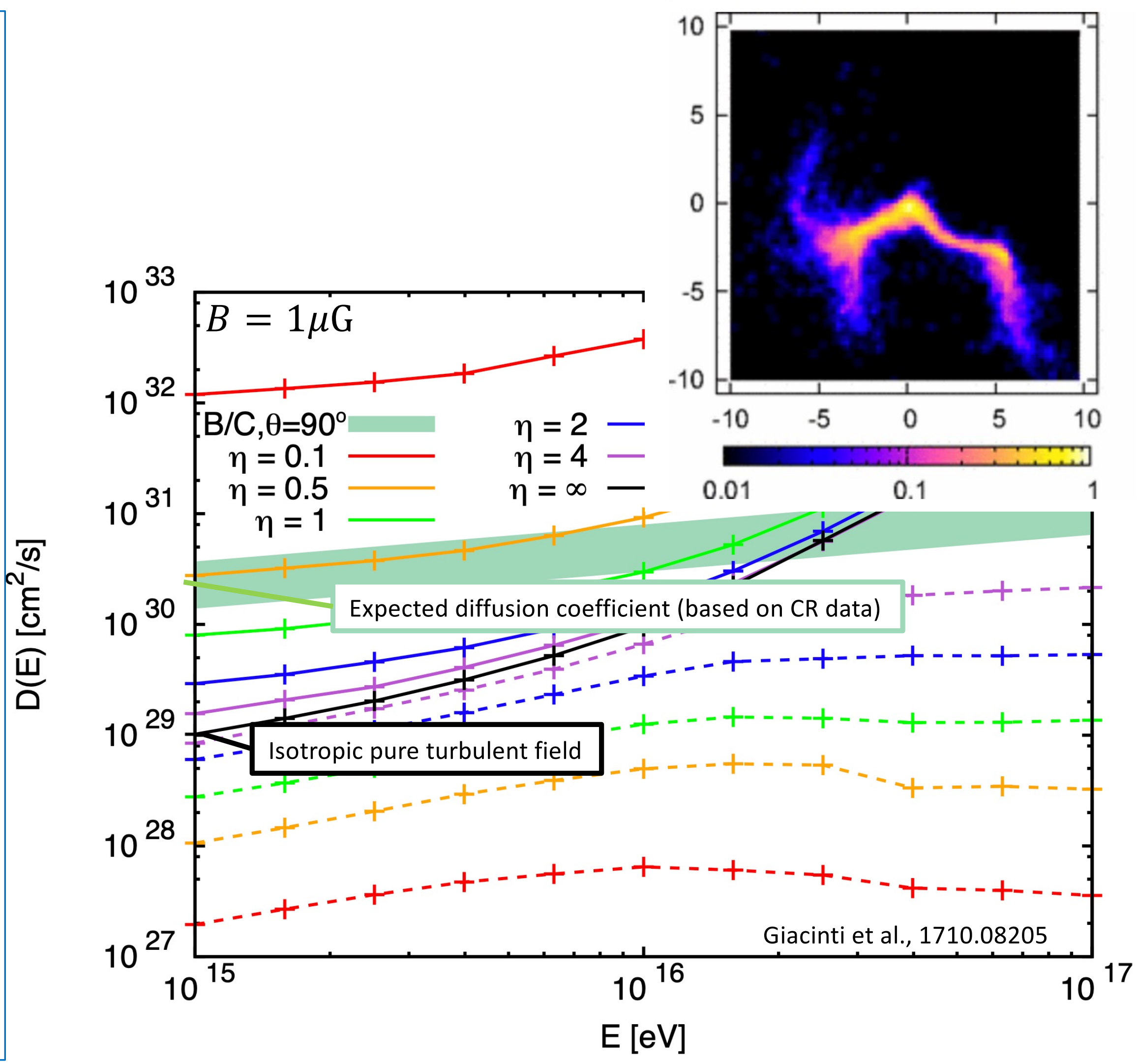
How do PeV particles move through interstellar medium?

PeV particles are perhaps the particles saturating the "Hillas bound": $E \leq ZeBR$. They escape from sources on the "light-crossing" time scale of $t \sim R/c$ if they don't loose energy on this time scale (electrons probably do).

Fast-escaping PeV protons and nuclei (that form the bulk of cosmic rays) can mostly be seen when they diffuse through the interstellar medium.

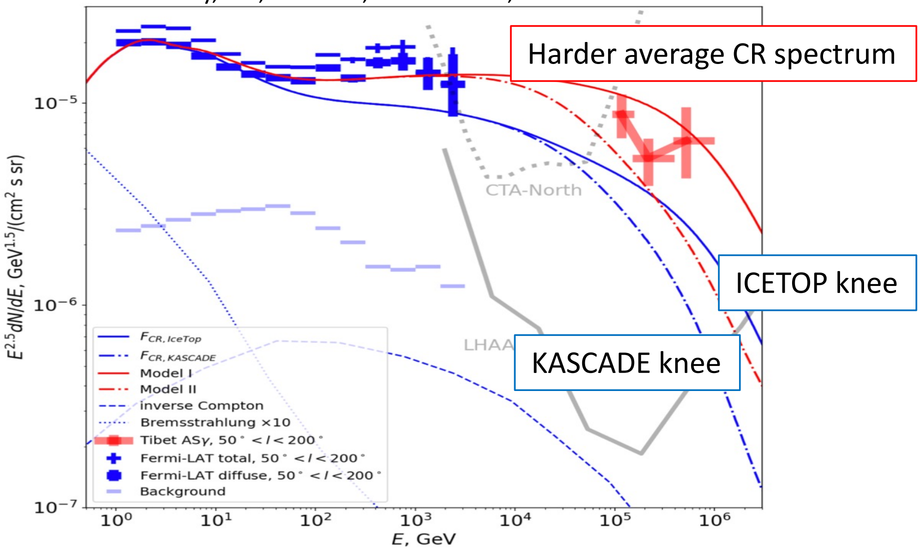
Modelling of PeV proton propagation though the interstellar magnetic field shows that the diffusion is strongly anisotropic $D_{||} \gg D_{\perp}$. Emission from particles spreading from injection points should be seen as "filaments" with width/length determined by the ratio $D_{\perp}/D_{||}$.

PeV particles escape fast from the Galaxy and only a small amount of sources contributes to the overall diffuse and isolated source fluxes. This opens a possibility to observe the details of the filamentary spread on source-by-source basis (?)

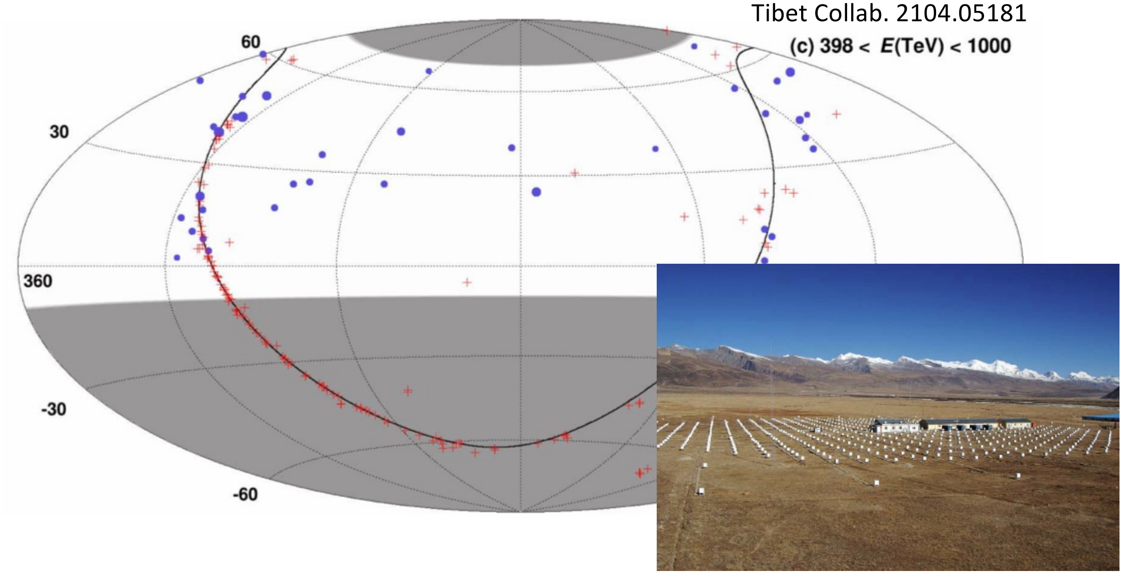


PeV diffuse flux observations by Tibet AS

Koldobskiy, AN, Semikoz, 2105.00959,



Tibet Collab. 2104.05181



Tibet AS collaboration has reported detection of diffuse emission in the energy range up to 1 PeV (overlapping with that of IceCube neutrino signal) from parts of the Galactic Plane.

- This is the first measurement relevant for clarification of the nature of the knee of cosmic ray spectrum for a study of (anisotropic) diffusion of PeV particles.
- Signal statistics is still too low for constraining the spectrum of cosmic rays in different parts of Galactic disk or for observing filamentary diffusion of cosmic rays.
- Isolated source and diffuse flux contributions are added together.

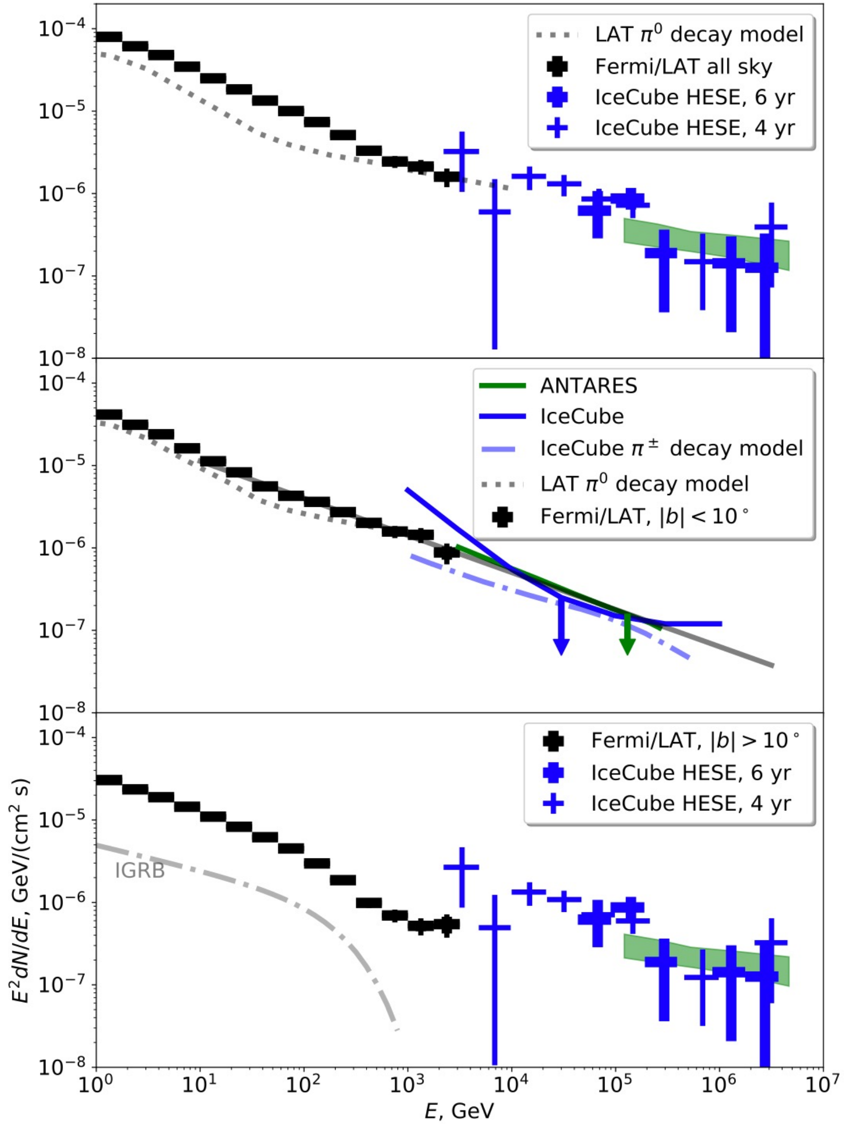
Diffuse neutrino flux from the Galaxy?

Diffuse emission from the Galaxy can be detected in neutrnios.

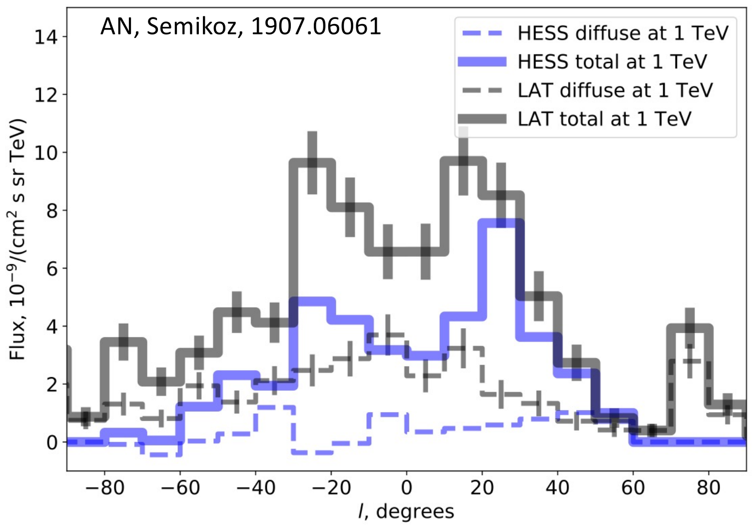
“Cascade” detection channel provides the best possibility: it has good energy resolution and lower background.

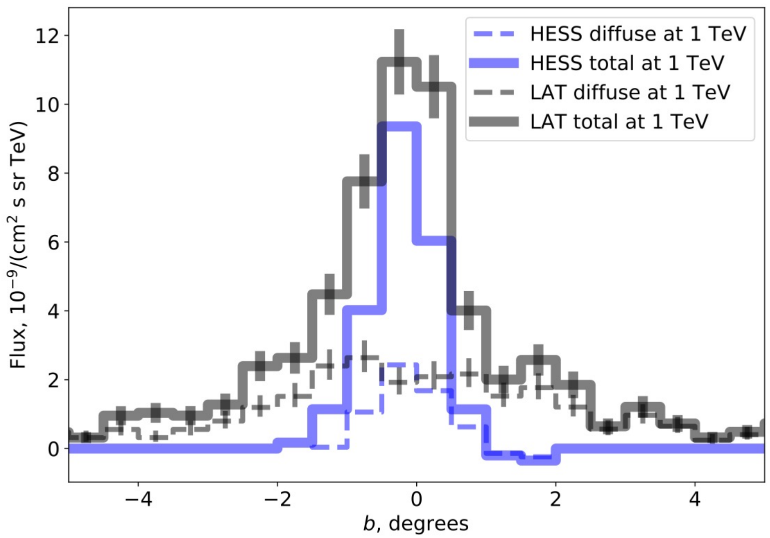
Start of operations of Km3NET and Baikal GVD will provide an improvement of the ”cascade” signal channel technique with good energy and angular resolution (~5 degrees), possibly enabling mapping of the galactic diffuse neutrino flux in 10-100 TeV band.

CTA can extend the measurements of diffuse emission into E>10 TeV range overlapping with the energy ranges of “cascade” signal of neutrino telescopes and in this way help to pinpoint the Galactic part of the signal.



Challenges for 10 TeV diffuse flux study with CTA





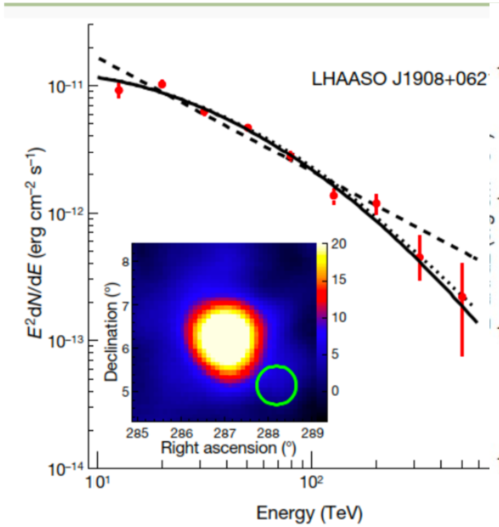
Compared to Fermi/LAT, Cherenkov telescopes

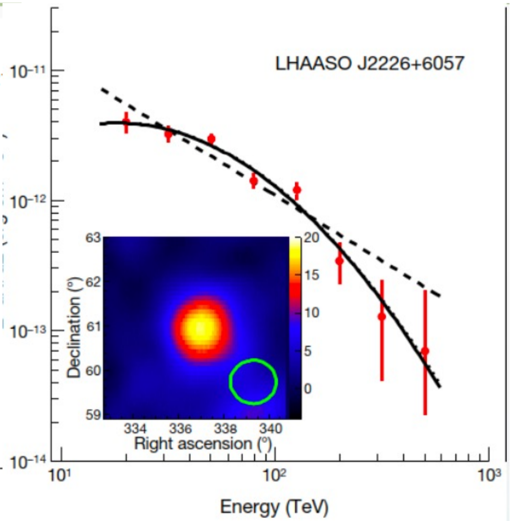
- have relatively narrow field of view
- detect diffuse flux on top of strong residual cosmic ray background.

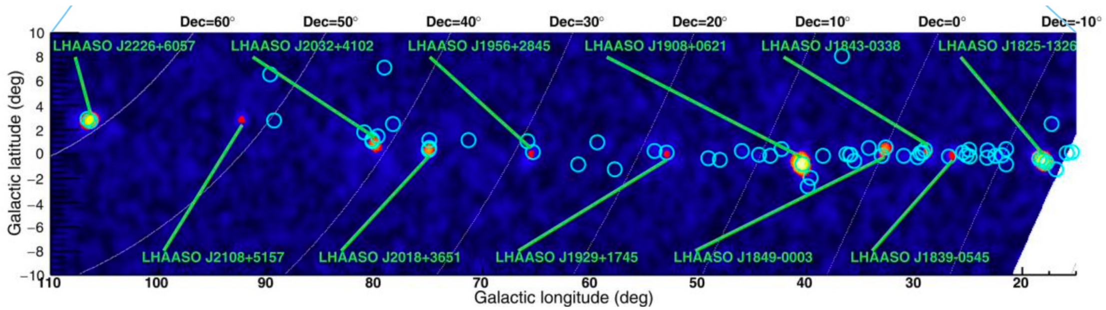
Precision of measurement of diffuse emission with CTA will be strongly limited by precision of estimate of the residual cosmic ray background and on the large angular scale diffuse background model (from LHAASO?).

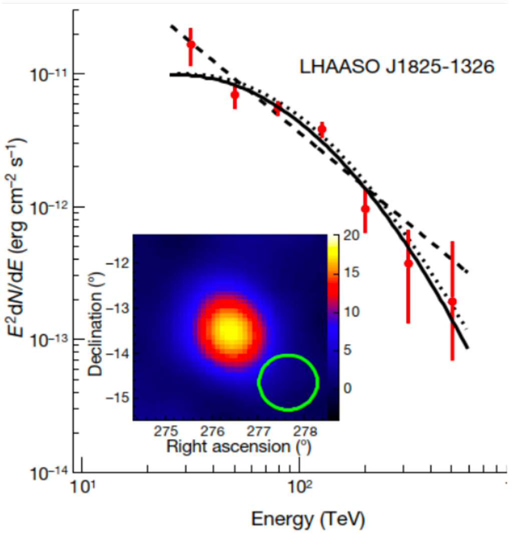
Figure above illustrates the problem: HESS was able to only derive a lower bound on diffuse flux from the innermost part of the Galactic disk (blue dashed lines).

Diffuse flux vs. resolved sources









LHAASO has reported detection of first γ-ray sources in 0.1-1 PeV energy range, with spectra extending into PeV range without cutoffs.

Most of the sources are extended. This possibly starts to reveal the process of escape of high-energy particles from the "PeVatron" acceleration sites into interstellar medium.

Deeper exposure will presumably start to reveal how extended emission around sources gradually "dissolves" into the diffuse flux. This will allow to understand the relation between "isolated sources" and "diffuse emission". They would need to be studied simultaneously.

LHAASO Collab. https://doi.org/10.1038/s41586-021-03498-z

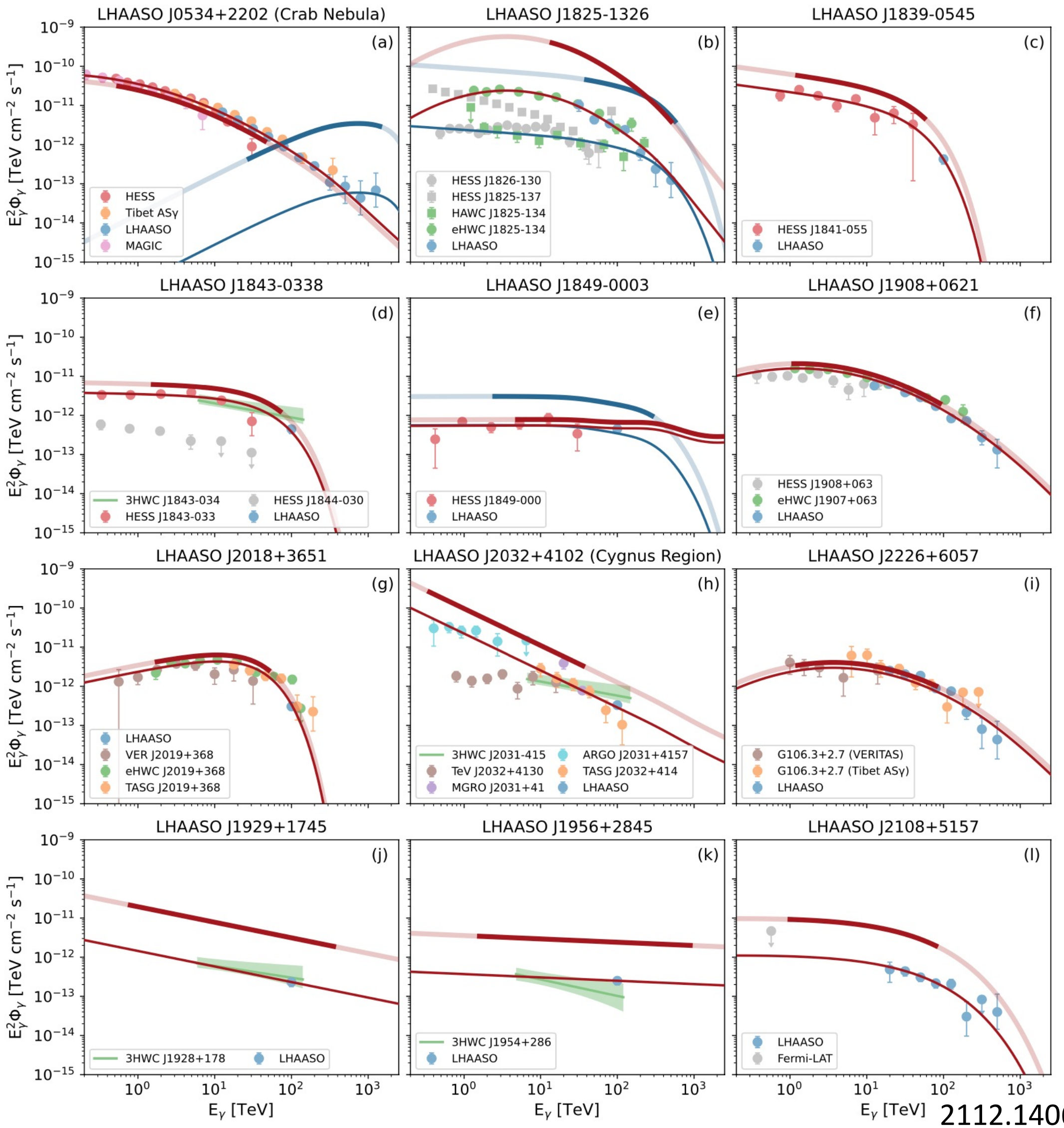
AN, Semikoz 2001.11881

Hadronic vs. leptonic components of the spectra

The emission from Galactic PeVatrons may be dominated by electrons that readily loose energy before escaping from the acceleration sites (contrary to protons).

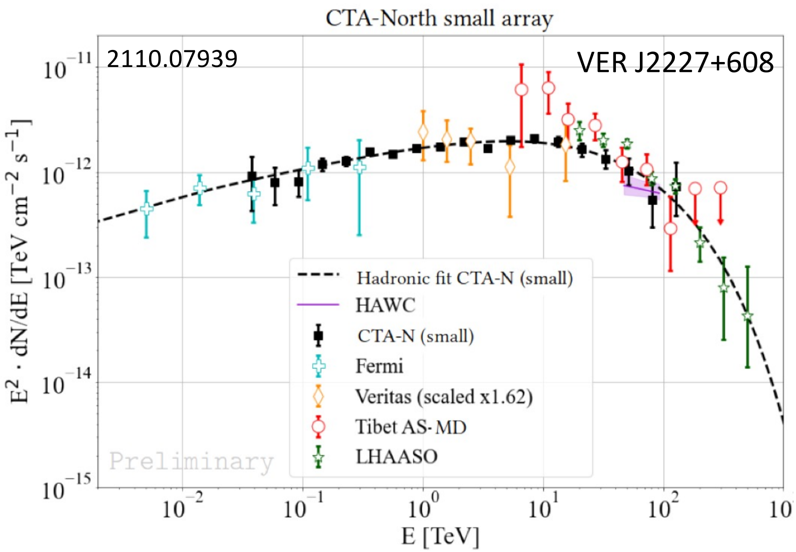
Proton component of the isolated source flux can be spotted based on neutrino detection.

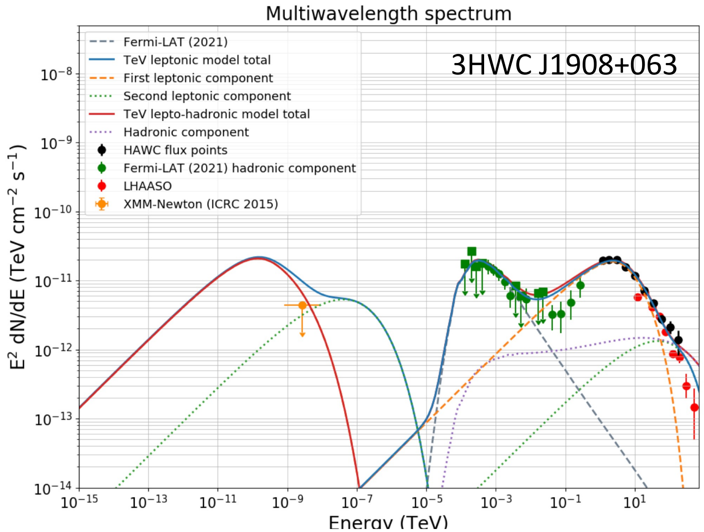
However, detection in neutrino channel is also difficult, because the sensitivity of IceCube (10 year exposure) is not sufficient for detection of signals from isolated sources even from the brightest LHAASO sources.

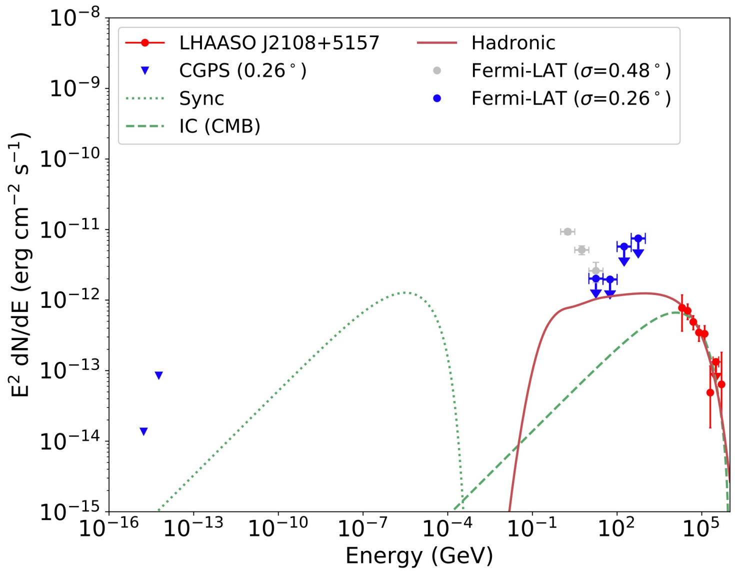


2112.14062

Wide energy coverage of CTA to separate hadronic and leptonic components





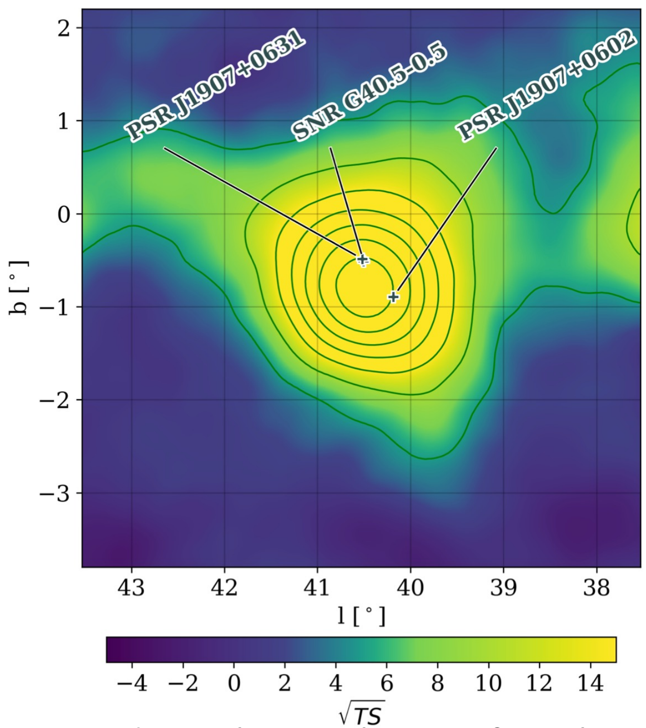


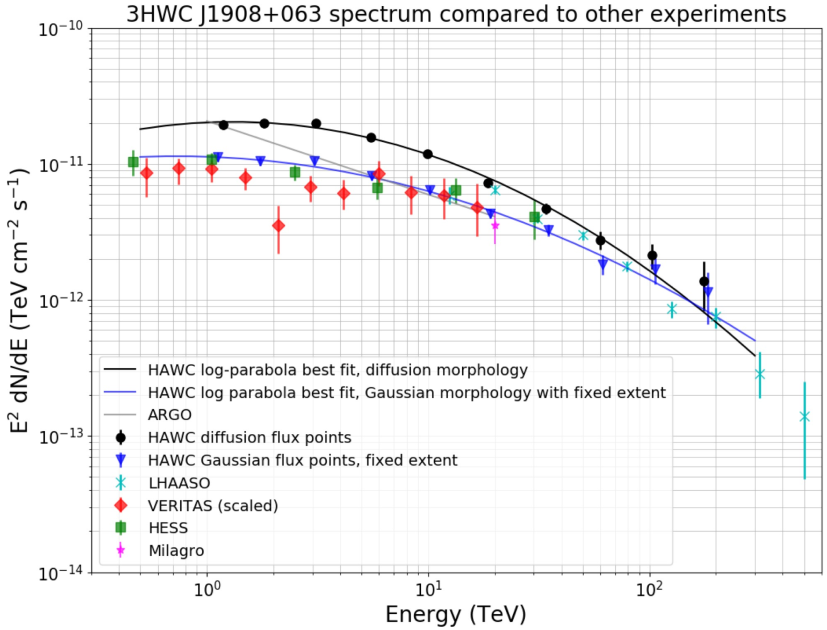
In the absence (scarcity) of neutrino flux measurements, the only possibility to separate leptonic and hadronic components will be through spectral-spatial modelling of the gamma-ray signal.

CTA will provide an advantage of broad energy coverage important for reliable model fitting without cross-calibration factors between different instruments.

High angular resolution of CTA for improved understanding of source morphology

HAWC Collab. 2112.00674





Limited angular resolution of air shower arrays (HAWC, LHAASO) limits the possibilities for source morphology stuydy. . Uncertainties of the source morphology limit the precision of spectral modelling (as shown on example of 3HWC J1908+063): factor of 2 difference of flux estimates for the “gaussian” and “isotropic diffusion” spatial models in the right panel.

Better angular resolution of CTA will help to reveal the details of escape of PeV particles into interstellar medium and improve spatial modelling for LHAASO/HAWC measurements. LHAASO/HAWC

Summary

Gamma-ray and neutrino observations are starting to explore new PeV astronomical observational window.

An immediate use for the observational data in this new observational window is to probe the physics of PeV cosmic rays and the origin of the astrophysical neutrino signal:

– test the nature of the ”knee” of cosmic ray spectrum
– find if the slope of the cosmic ray spectrum varies across the galaxy
– test the mechanism of propagation of cosmic rays through interstellar medium
– understand if there is a part of the astrophysical neutrino signal comes from the Galaxy

First gamma-ray data at E>100 TeV from HAWC, Tibet-AS, LHAASO reveal

– diffuse emission from interstellar medium
– isolated sources mostly extended

Quality of the data is not (yet) sufficient for understanding if

– the source emission is of “leptonic” or “hadronic” origin
– the details of extended source morphologies

CTA data will be complementary to the LHAASO and neutrino telescopes data:

– wide energy coverage with good energy resolution: improved spectral modelling (leptonic vs. hadronic)
– high angular resolution: improve modelling of details of source morphologies, extended source -> diffuse emission transition.