Recent results from gamma-ray observations

…. implications for Galactic cosmic rays ....

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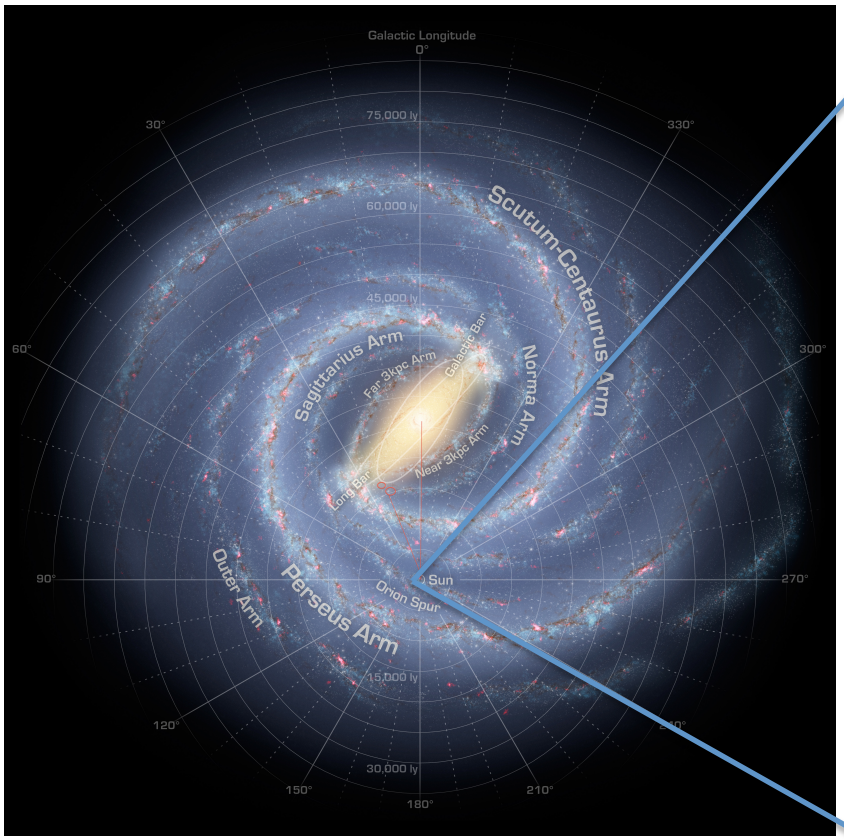
Introduction: direct measurements vs. gamma-ray probes of Galactic cosmic rays

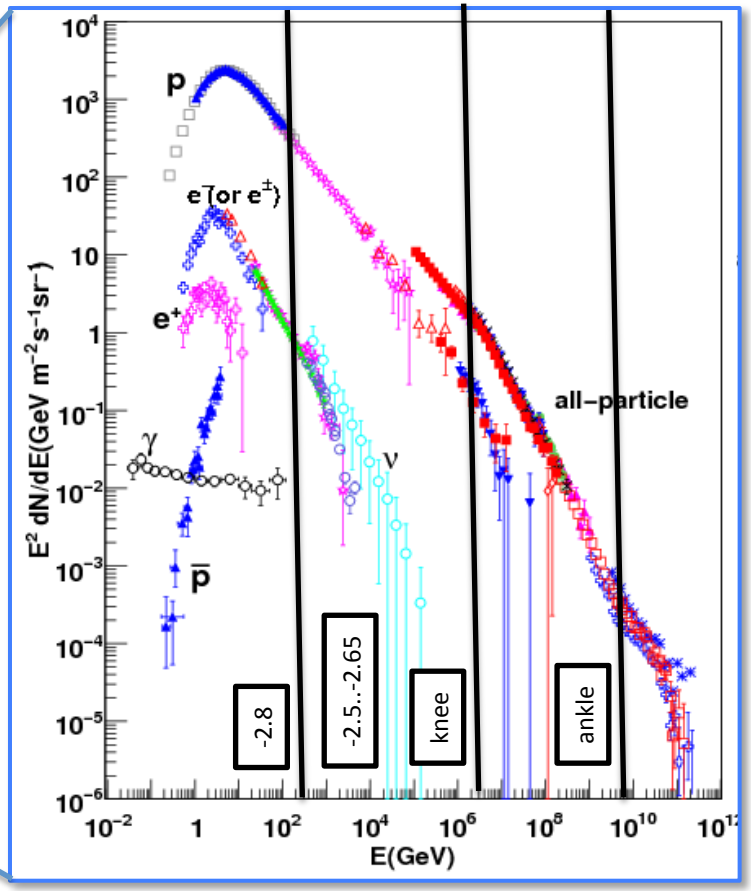
Gamma-ray results update:

- Pinpointing CR sources
- Diffuse emission on different distance scales
- What is the average CR spectrum in the Galaxy?

Summary

Single-point vs. distributed measurements of cosmic ray flux



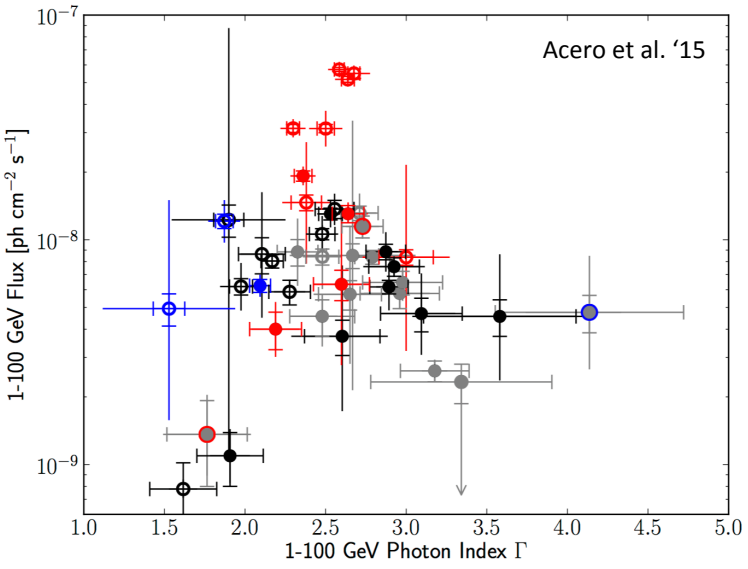


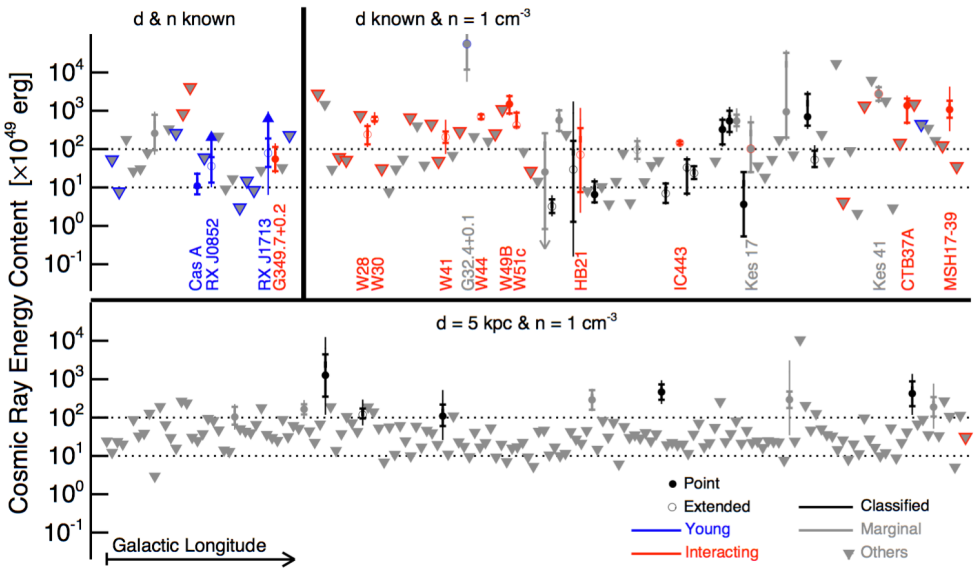
Local measurements of the properties of the cosmic ray (CR) flux provide single-point measurement, which are not necessarily representative of the entire CR population in the Galaxy.

γ-ray and neutrino observations are useful for pinpointing the Galactic CR sources and are also the only possibility for the measurement of the properties of the CR flux elsewhere in the Galaxy:

– if the slope $dN/dE \sim E^{-2.7} \sim E^{-(\Gamma+\delta)}$ characteristic for the Galactic CR population? What are the values of Γ and δ?
– do the breaks in the CR spectrum have “universal” nature, or they are occasional local effects?

Pinpointing CR sources



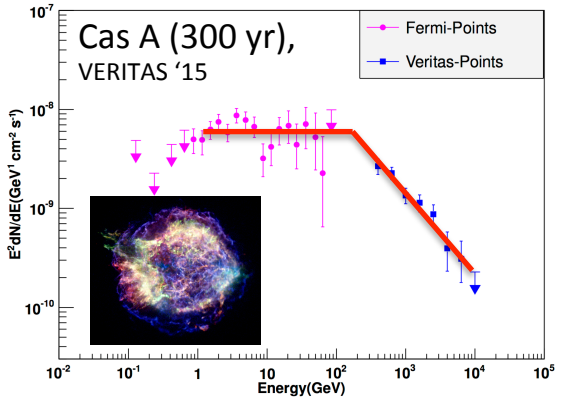


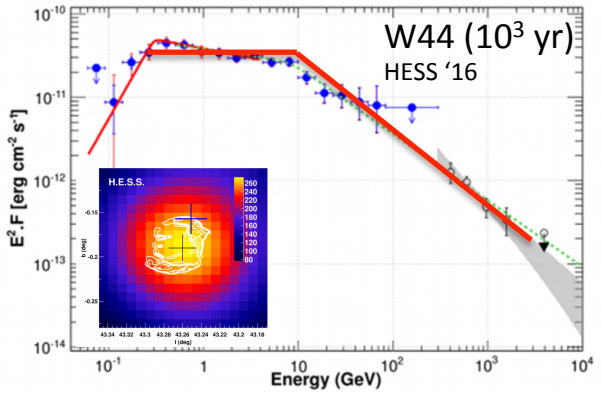
1st catalog of supernova remants detected by LAT.

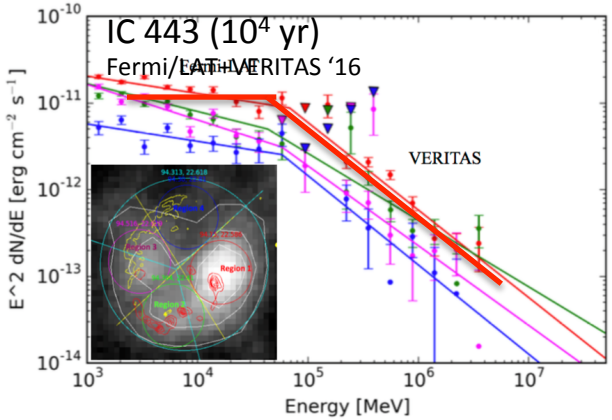
– 30 sources, 14 marginal associations (22% false associations possible), 245 non-detections.

– CR injection spectrum and overall power are difficult to measure because of uncertainties of the source environments (distance, ambient medium density), emission mechanisms (leptonic and hadronic)

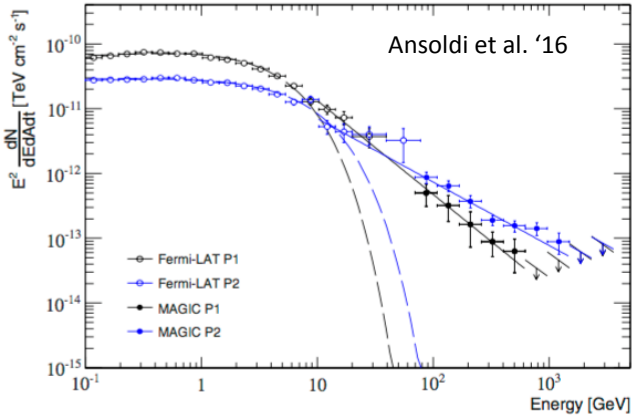
– escape of CRs from the sources.

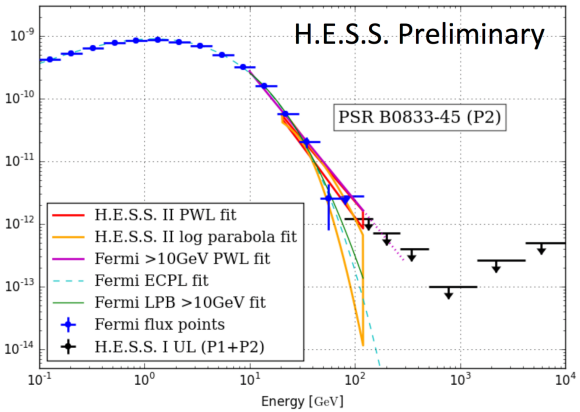






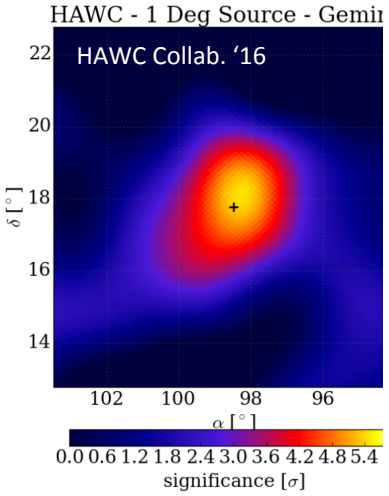
Pinpointing CR sources

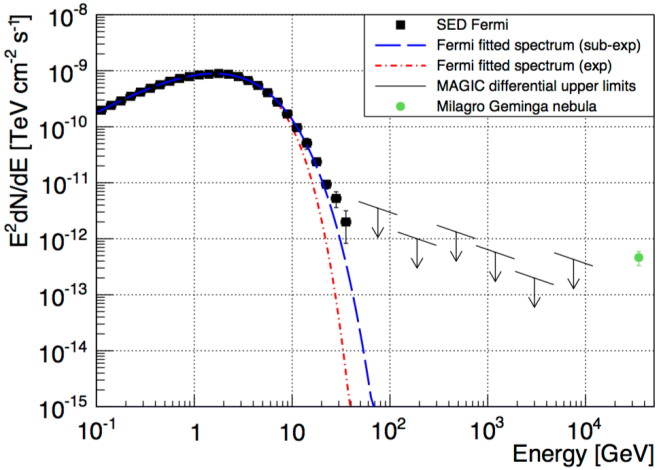


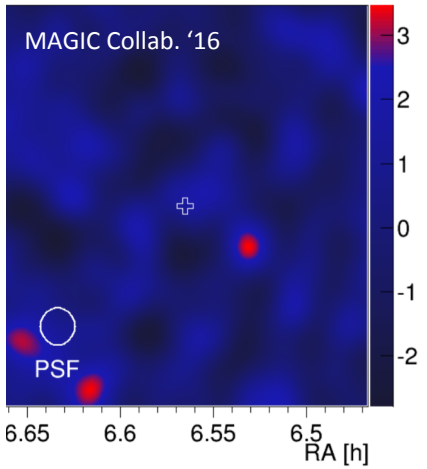


Pulsar wind nebulae from a dominant VHE gamma-ray source population in the Galaxy

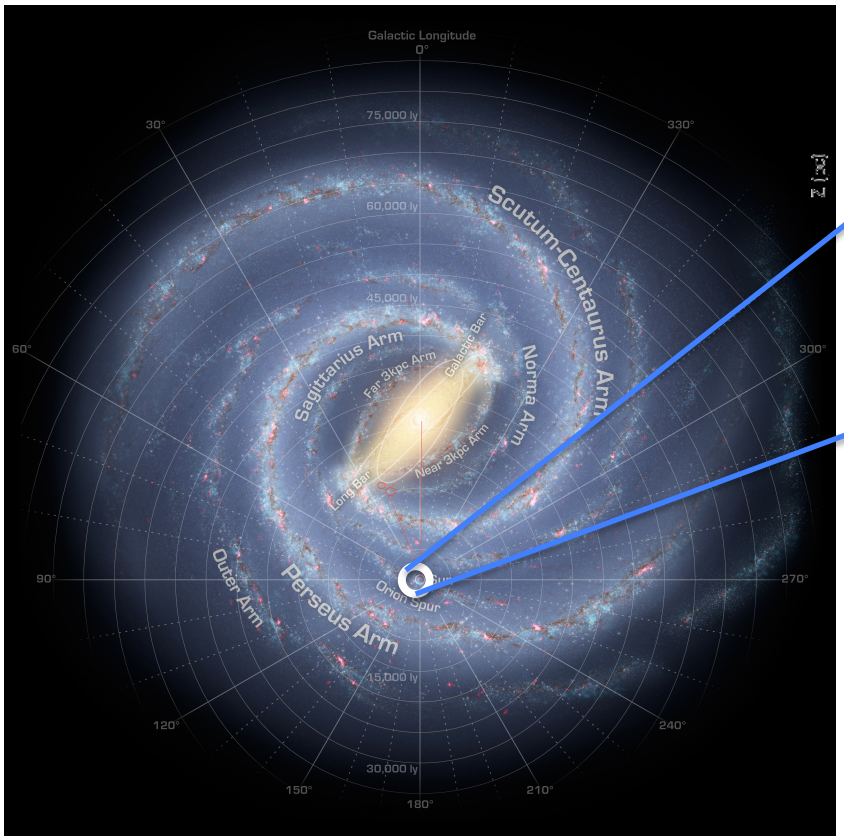
- acceleration up to PeV energy is observed in the Crab nebula
- pulsed emission from Crab and Vela pulsars are detected in the VHE band (up to TeV for Crab)
- recent controversy around (non)detection of the nebula of Geminga pulsar
- efficiency of proton acceleration in both pulsar magnetospheres and in the nebulae is not known.

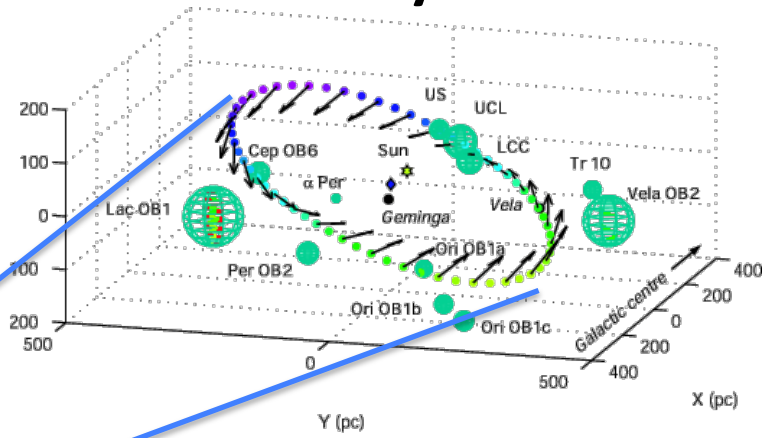


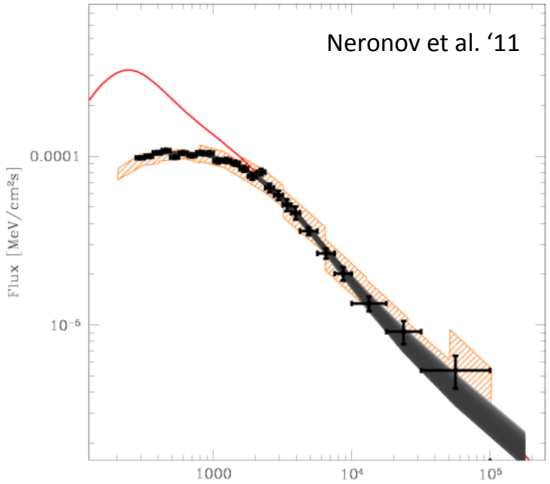




CR spectrum in the local Galaxy

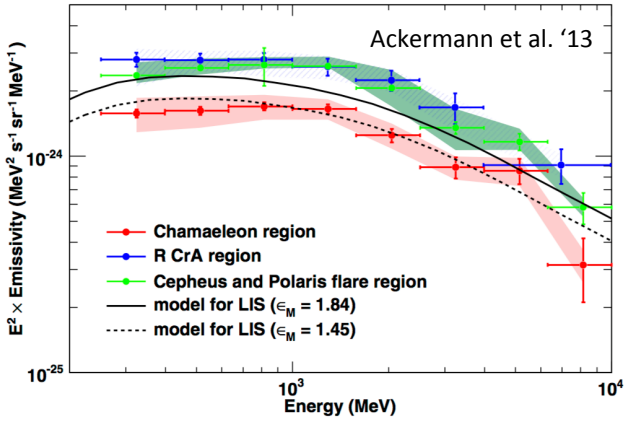




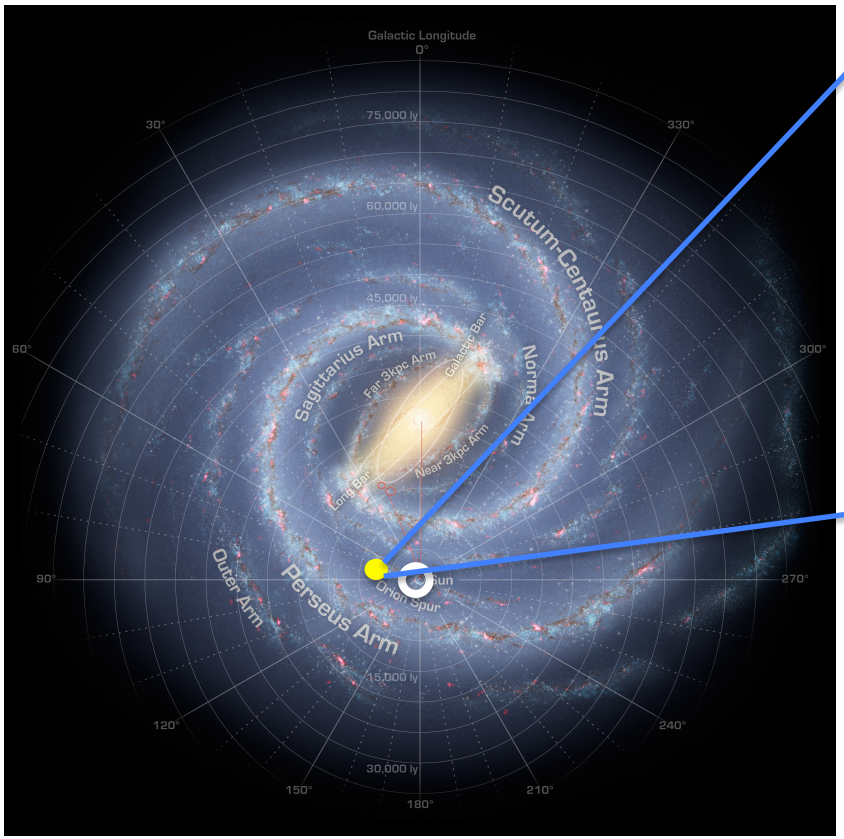


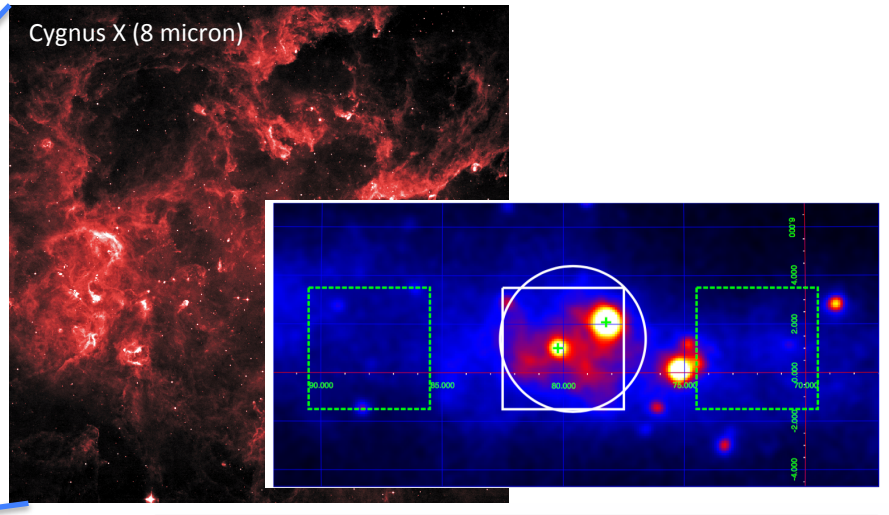
Molecular clouds in the local Galaxy form a ring-like structure, the Gould Belt of diameter ~ 1 kpc. Spectrum of gamma-ray emission from CR interactions in the clouds provides a measurement of the CR spectrum in the local Galaxy (free from the Solar modulation effect:

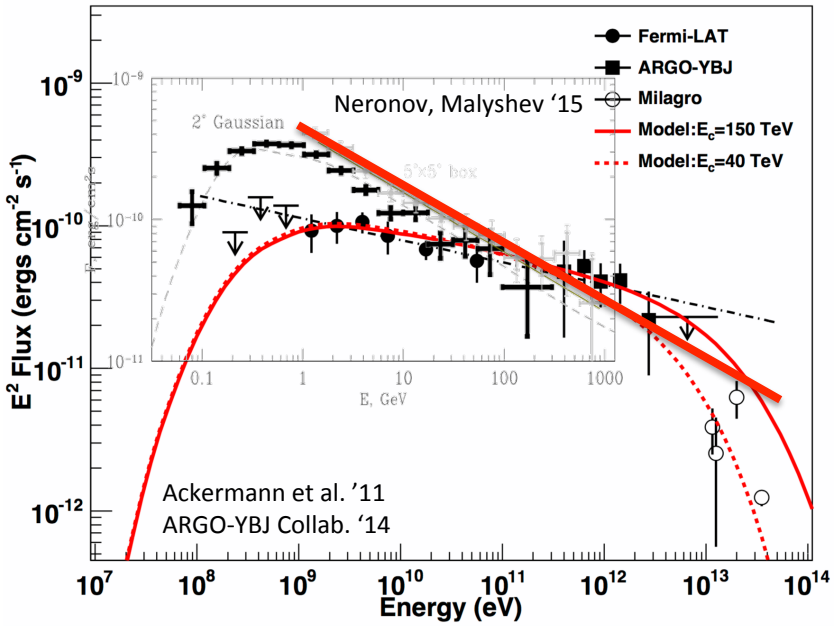
– CR spectrum in the local interstellar medium is soft ($\Gamma = 2.9 \pm 0.1$) in 10-100 GeV band … consistent with the locally measured one.



CR spectrum in a nearby star formation region





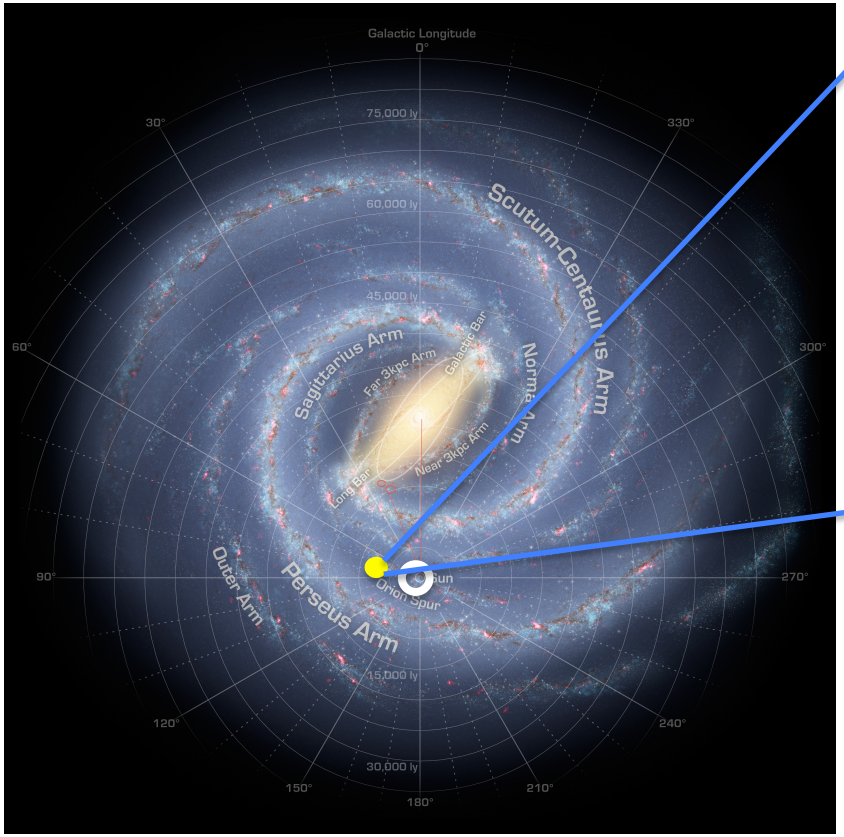


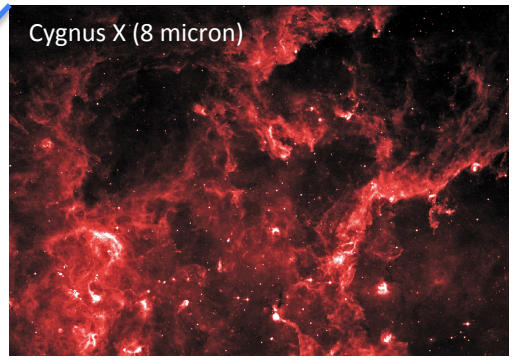
Recently started star formation activity did not leave time for CRs to diffuse out of the region. Spectral slope Γ=2.2 might be representative of the injection spectrum of CRs in the interstellar medium.

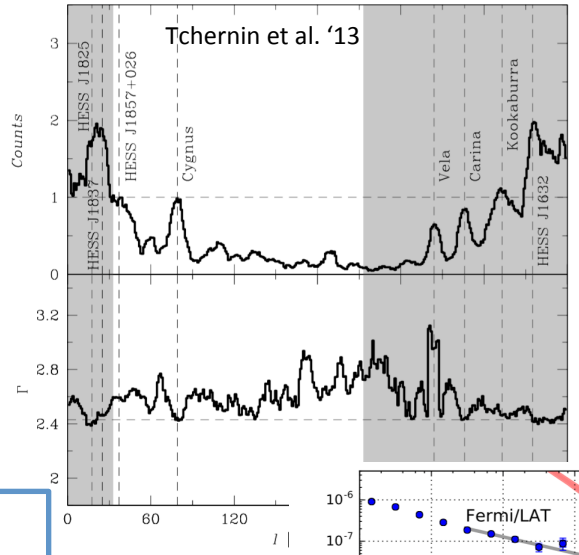
The slope measurement is very sensitive to the background modelling. Standard spectral extraction(s) yield softer spectrum, with the slope Γ=2.5.

Γ=2.2 ; δ=0.5?

CR spectrum in a nearby star formation region



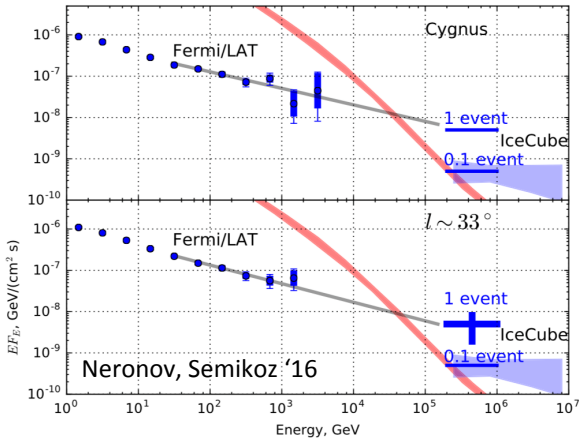




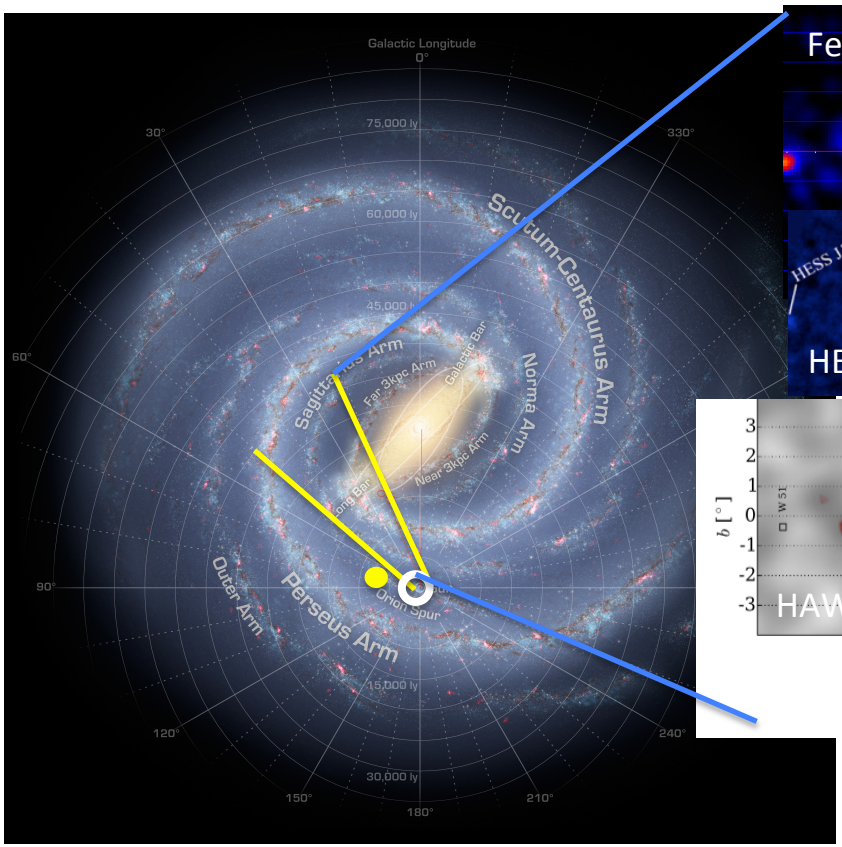
Cygnus X region is the brightest (or second-brightest) Galactic extended source in the Northern hemisphere, should be detectable by IceCube in the through-going muon detection mode on decade time scale.

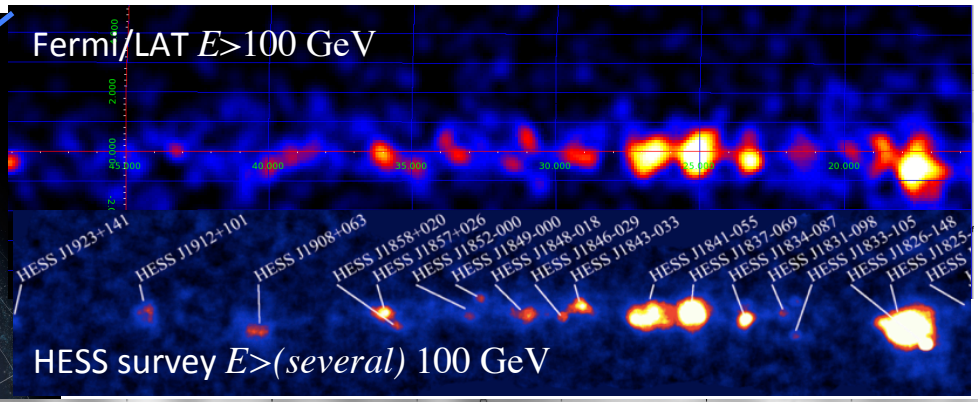
– independent verification of the hard slope of the CR spectrum is possible.

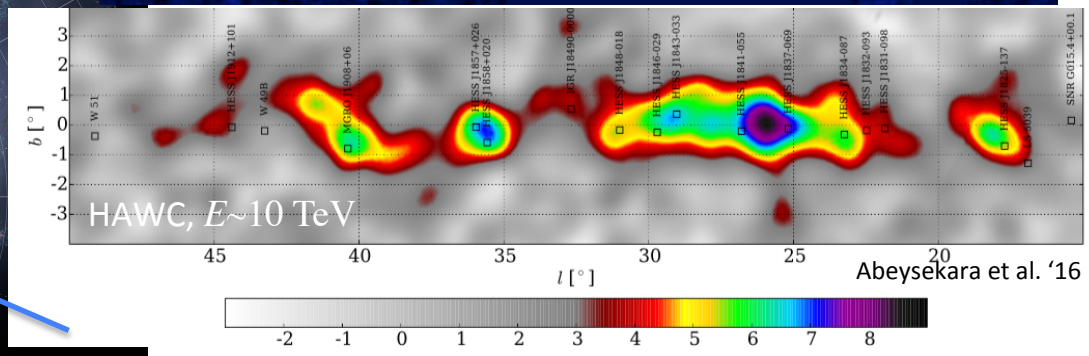
– published IceCube data set has exposure above 200 GeV which should have given 1 neutrino event from Cygnus.



CR spectrum in distant regions of Galactic Plane



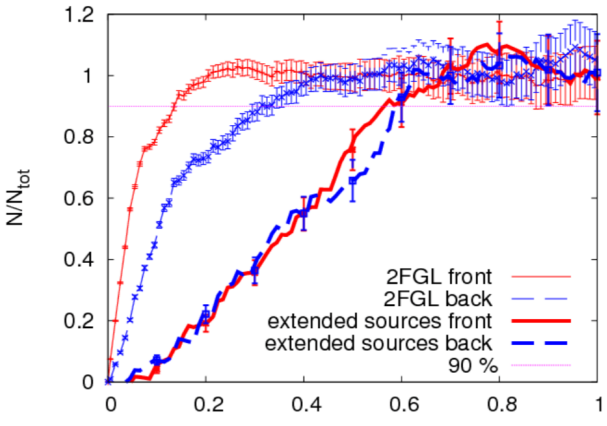




Abeysekara et al. '16

Galactic Plane surveys with Fermi/LAT, HESS, HAWC reveal a set of sources, not obviously identified with supernova remnants or pulsar wind nebulae

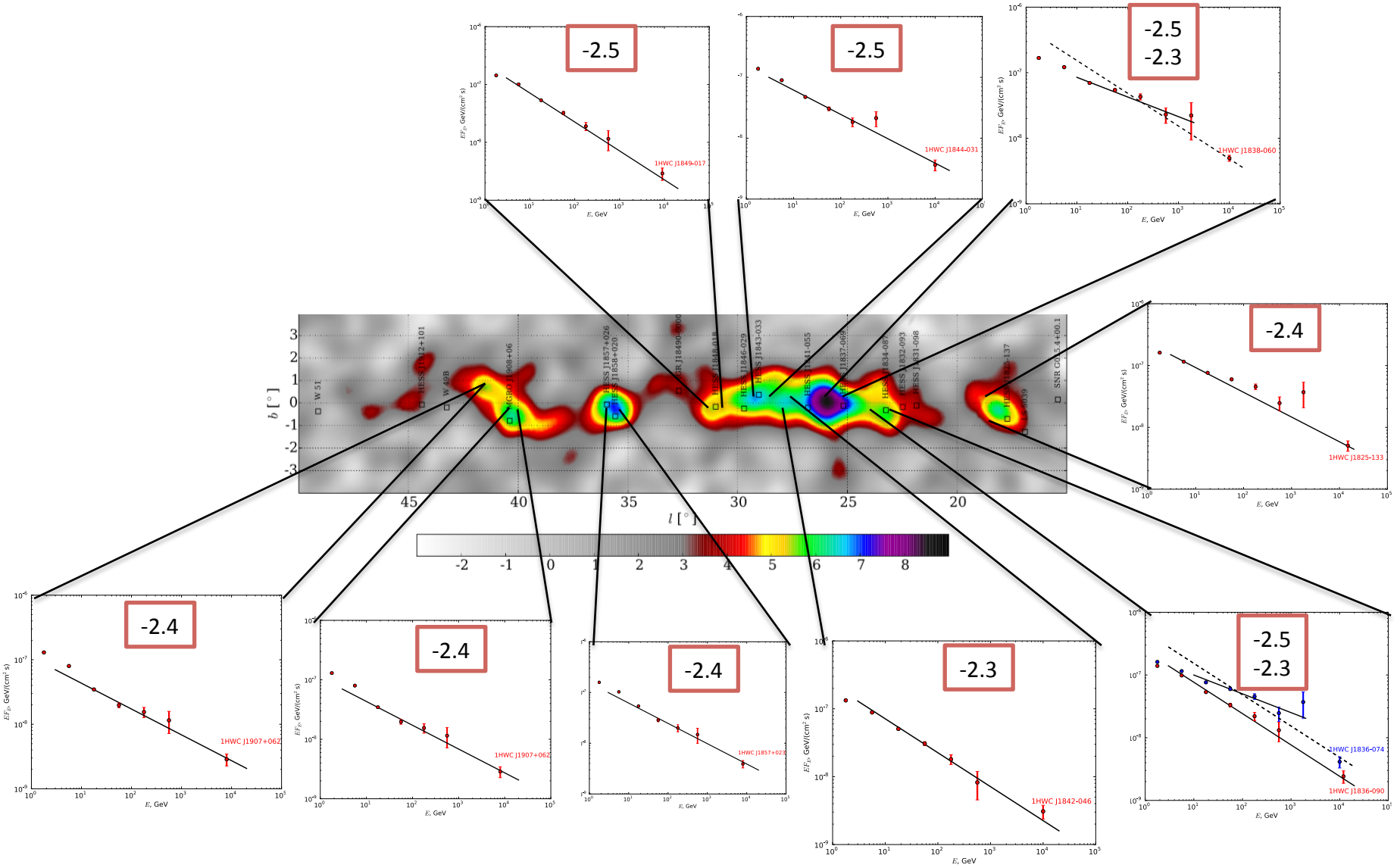
– large number of sources have degree-scale extensions, which corresponds to ~100 pc at ~4 kpc distance. Typical size of an OB association like Cygnus OB2 (too large for an isolated SNR or PWN).



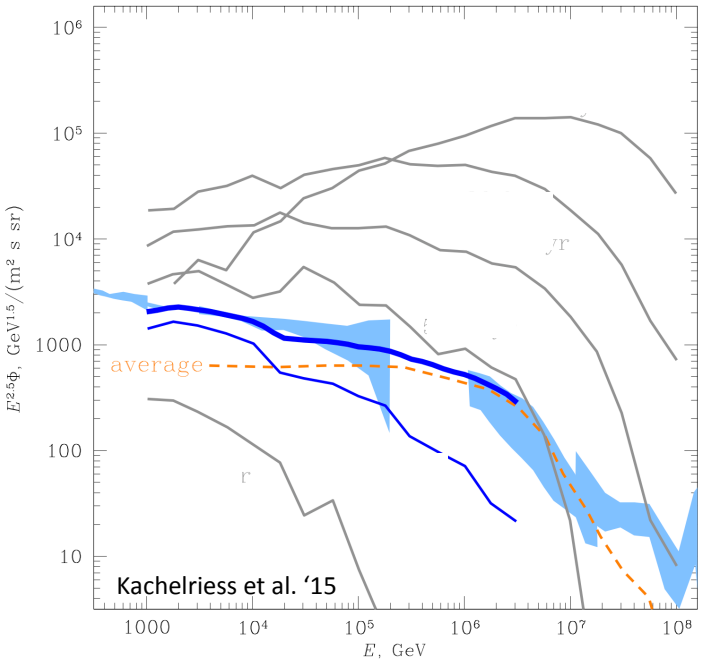
Neronov, Semikoz et al. '12

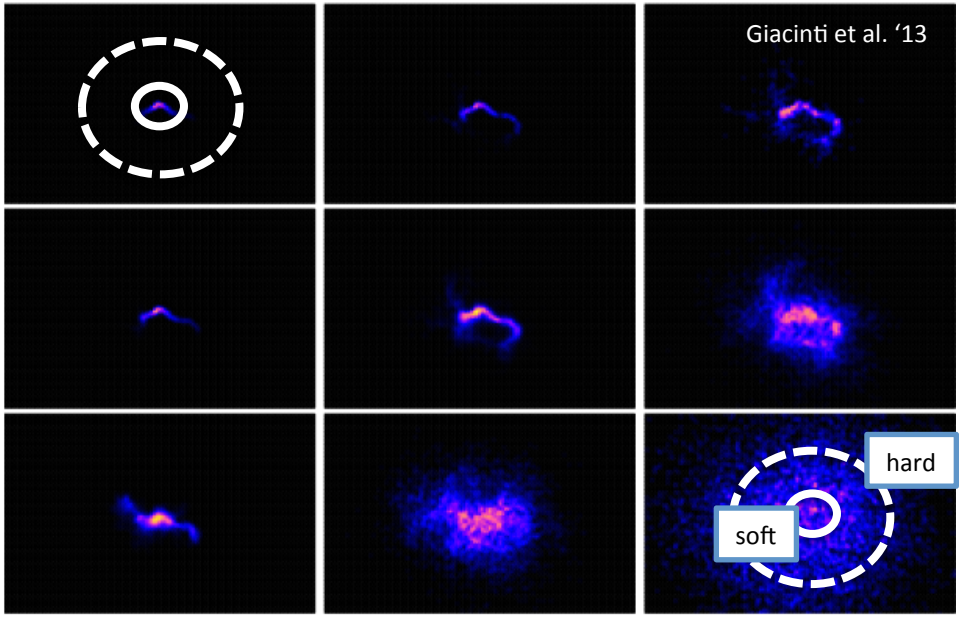
CR spectrum in distant regions of Galactic Plane

Fermi/LAT + HAWC spectra of HAWC sources have the slopes 2.3 to 2.5.



CR spectrum in distant regions of Galactic Plane

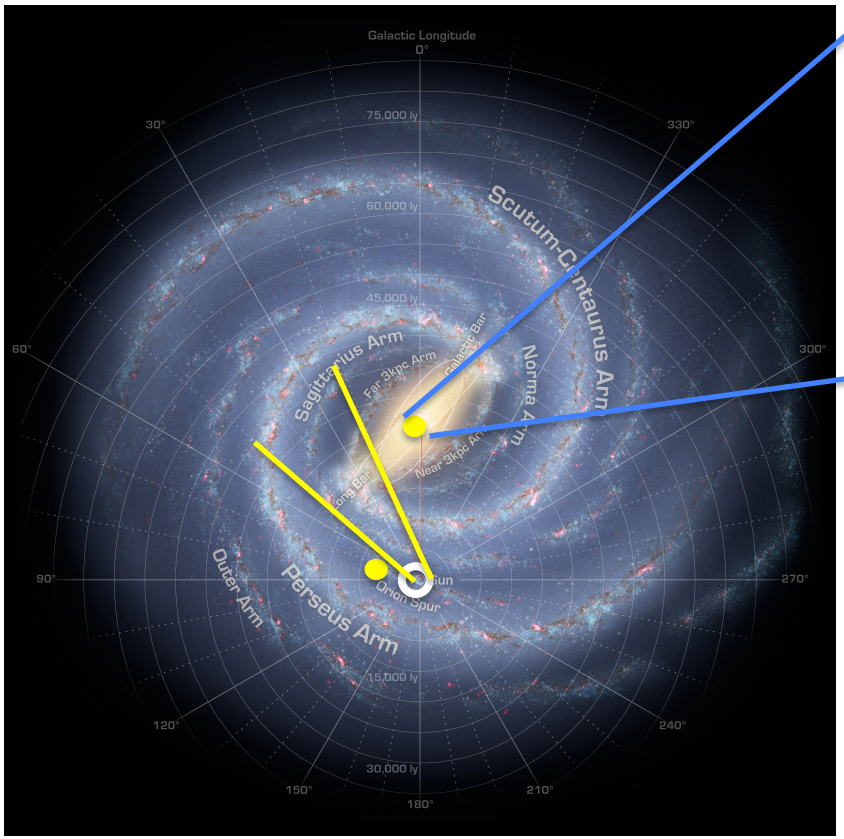


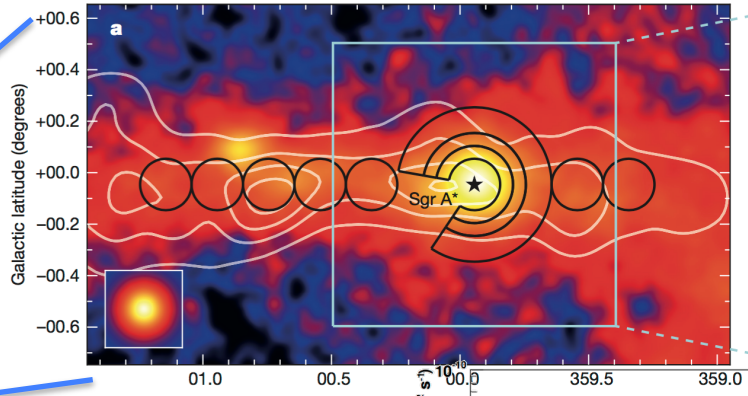


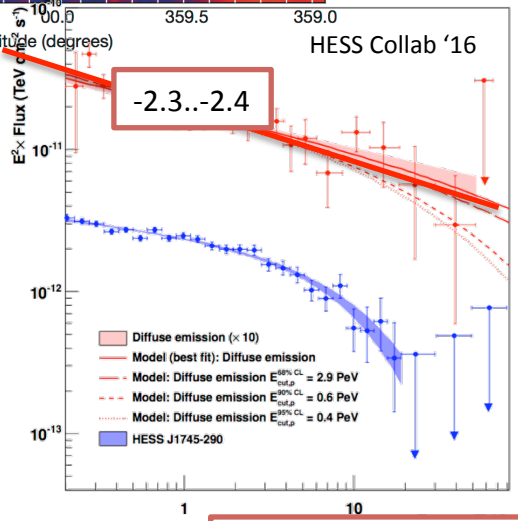
Extended Galactic sources might also trace the spread of cosmic rays from individual SNR, PWNe or star forming regions.

– in this case the measured spectral slope is strongly dependent on position in the source, or on the fraction of the source from which the flux is collected.

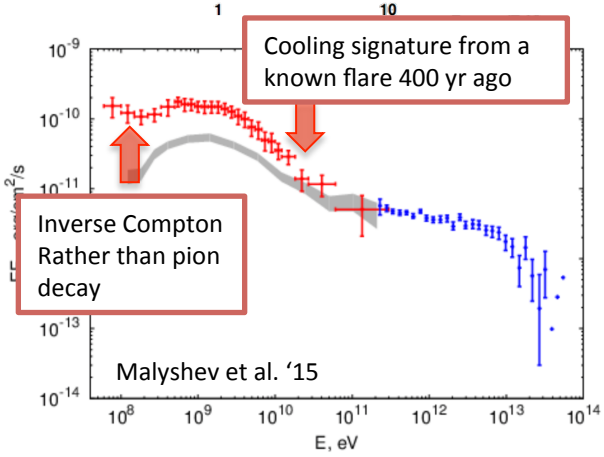
The Galactic Centre Pevatron







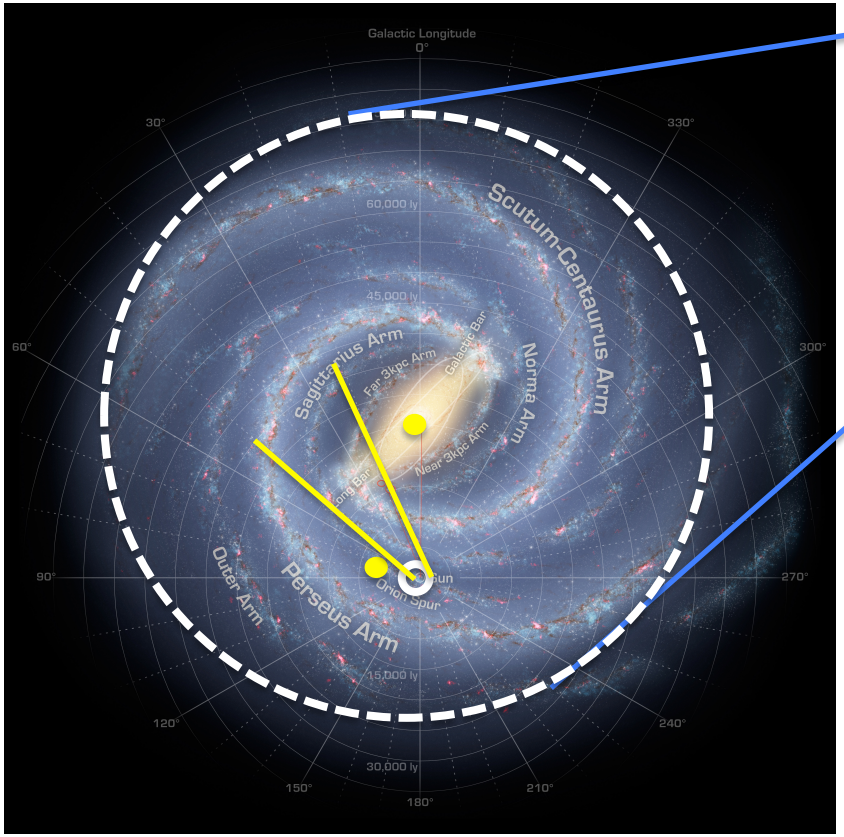
Γ=? ; δ=?

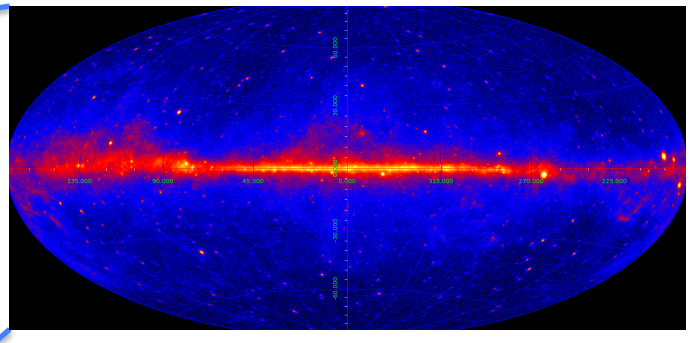


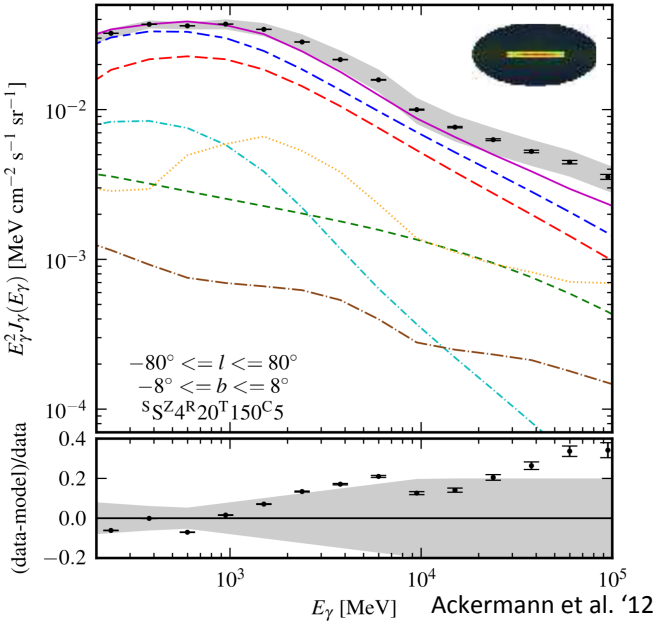
Spread of CRs around an isolated source is explicitly observed near the Galactic Centre source, with the spectrum extending to tens-of-TeV.

- The 2.3.. 2.4 slope of the spectrum of the extended source is determined by the diffusion of CRs through the interstellar medium.
- CR injection spectrum of the source is not directly measurable because of strong leptonic component and influence of time variability of injection rate on the spectrum.
- In leptonic scenario, the injection spectrum of electrons is close to Γ=2.

CR spectrum in the Galactic Disk







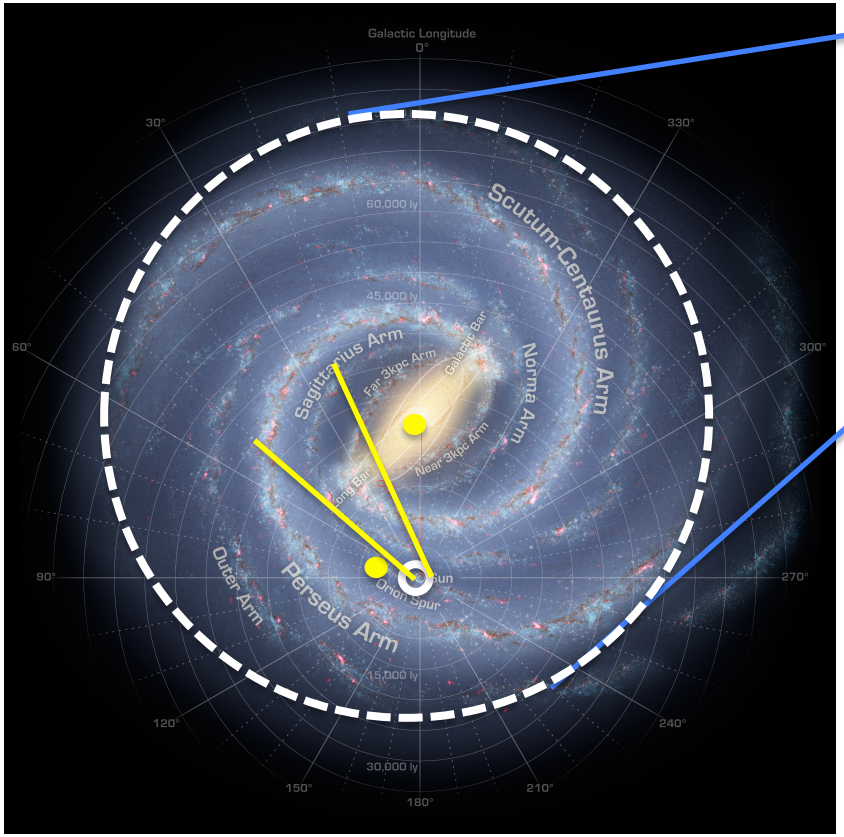
Ackermann et al. '12

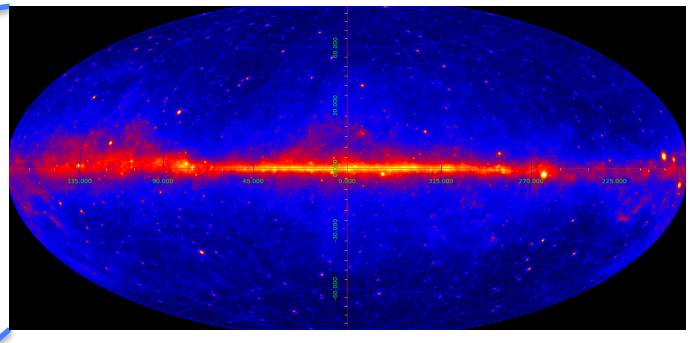
Modeling of overall diffuse emission could provide "typical" slope of the CR spectrum in the Galaxy.

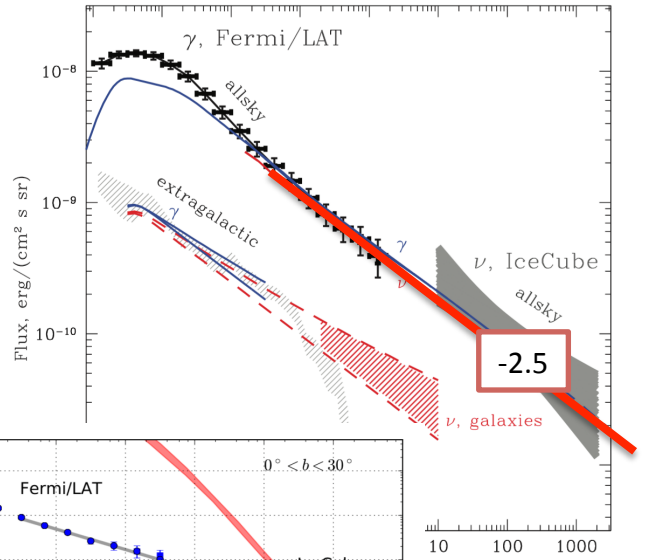
– phenomenological model with many parameters

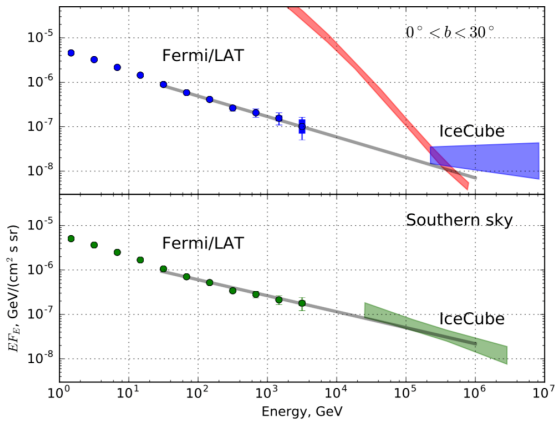
– the data were judged to be consistent with the model assuming a universal CR slope 2.7

CR spectrum in the Galactic Disk









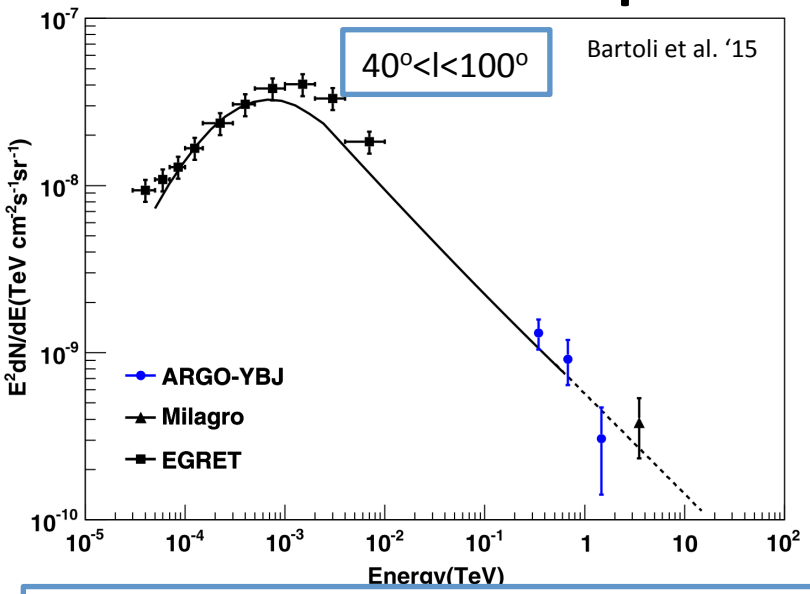
Neronov et al. '14

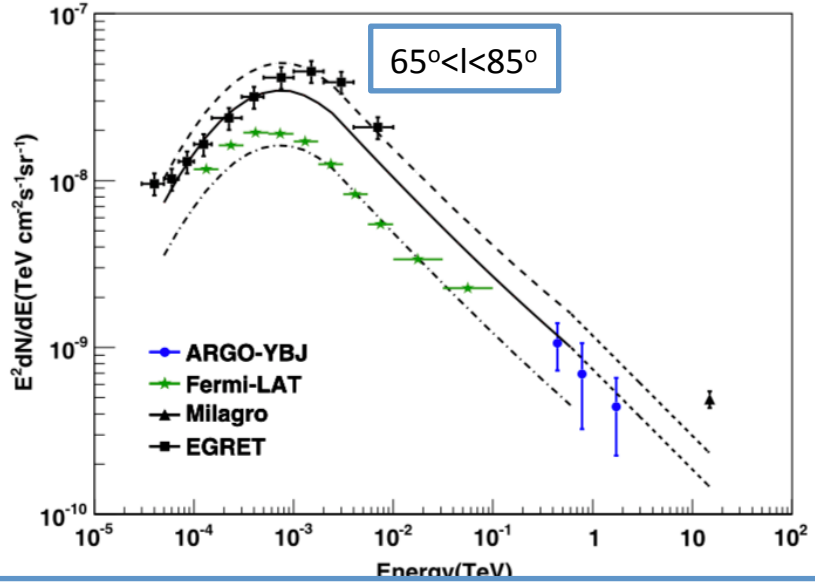
Neronov, Semikoz '16

Modeling of overall diffuse emission could provide "typical" slope of the CR spectrum in the Galaxy.

- phenomenological model with many parameters
- the data were judged to be consistent with the model assuming a universal CR slope 2.7
- however, the all-sky spectrum has the slope 2.5 above 10 GeV
- slope and normalization of the all-sky spectrum are consistent with those of astrophysical neutrinos.

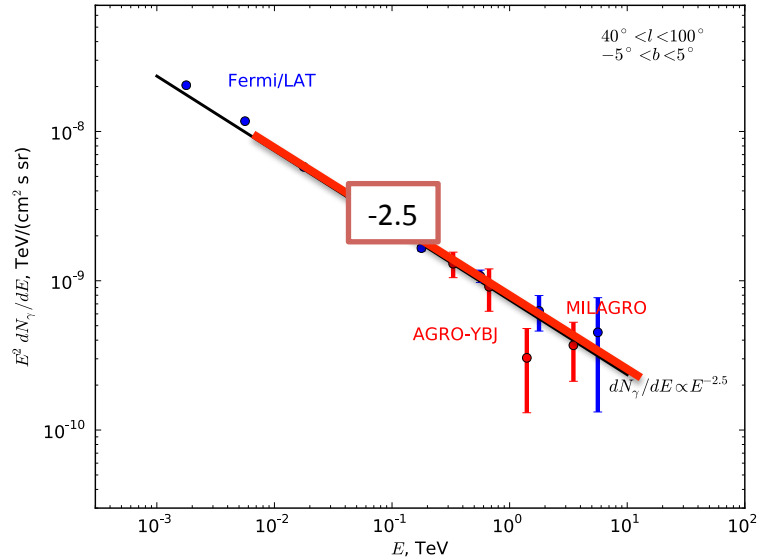
CR spectrum in the Galactic Disk

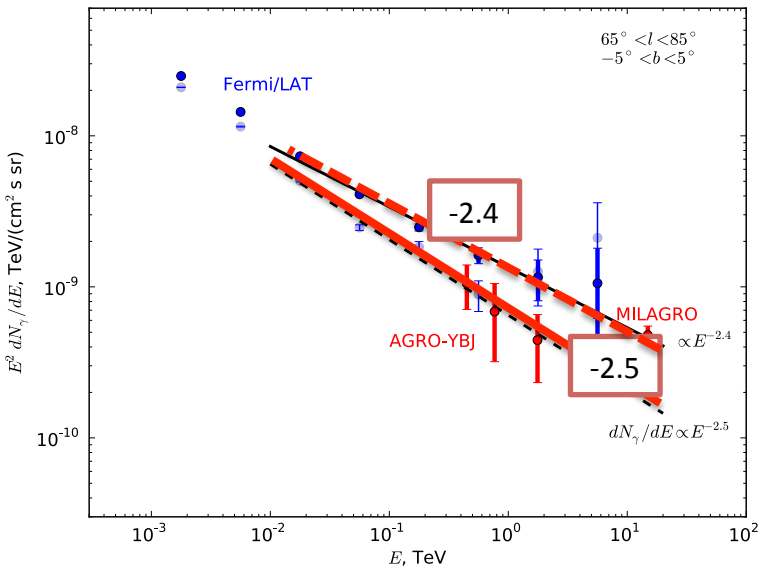




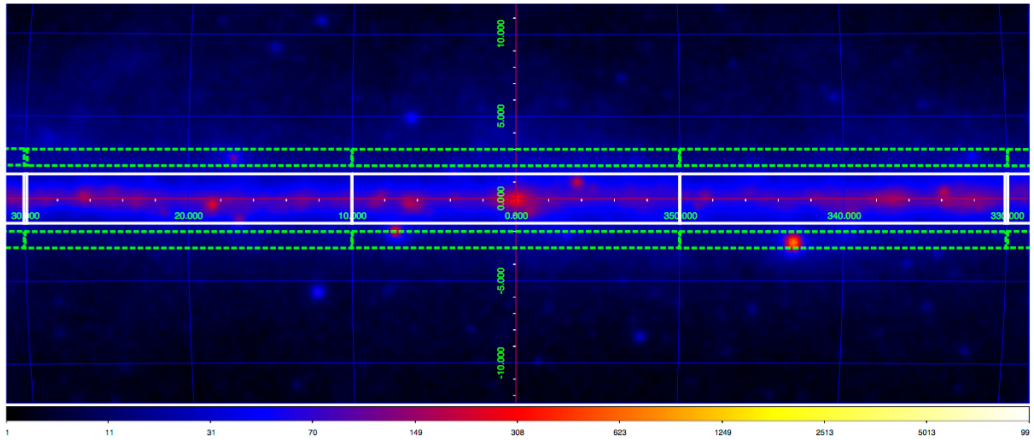
ARGO-YBJ has reported slopes of diffuse emission spectra consistent with locally observed CR slope.

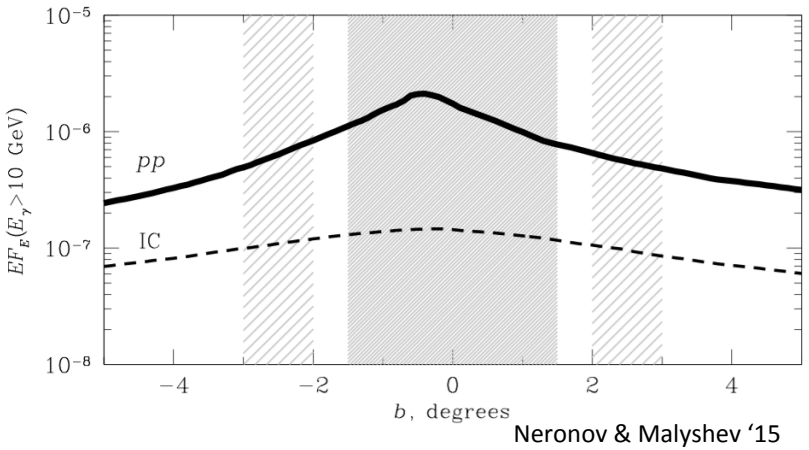
– properly combined with Fermi data the spectral slopes appear to be ~2.5.





CR spectrum in the Galactic Disk



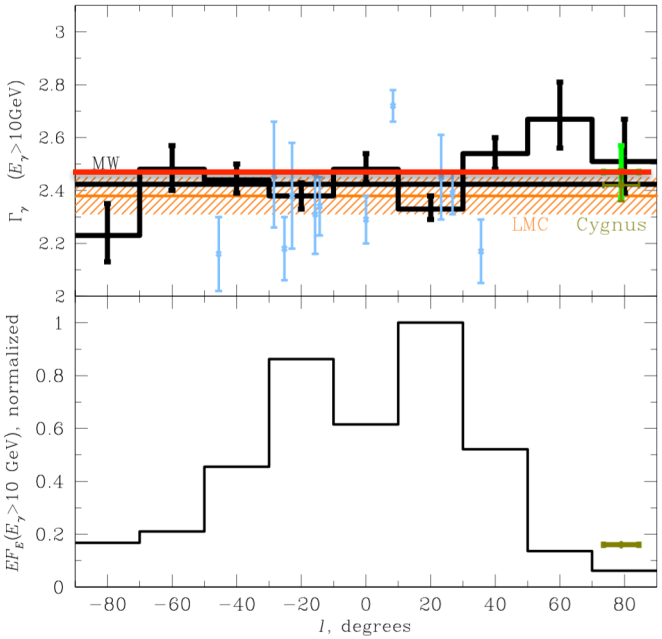


Neronov & Malyshev '15

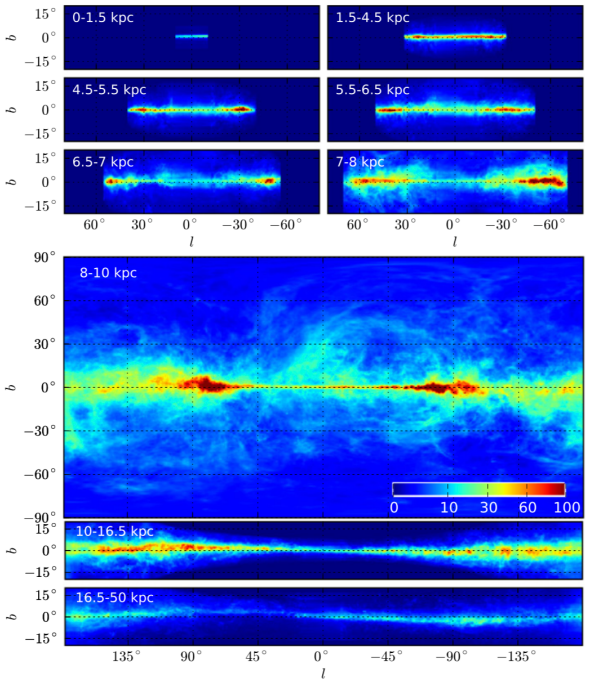
Pion decay and inverse Compton components could be separated by extracting the spectrum from a narrow strip along the Galactic Plane in which the pion decay flux peaks.

This approach provides a measurement of the slope of the CR spectrum in the inner Galaxy ($-90^o<l<90^o$)

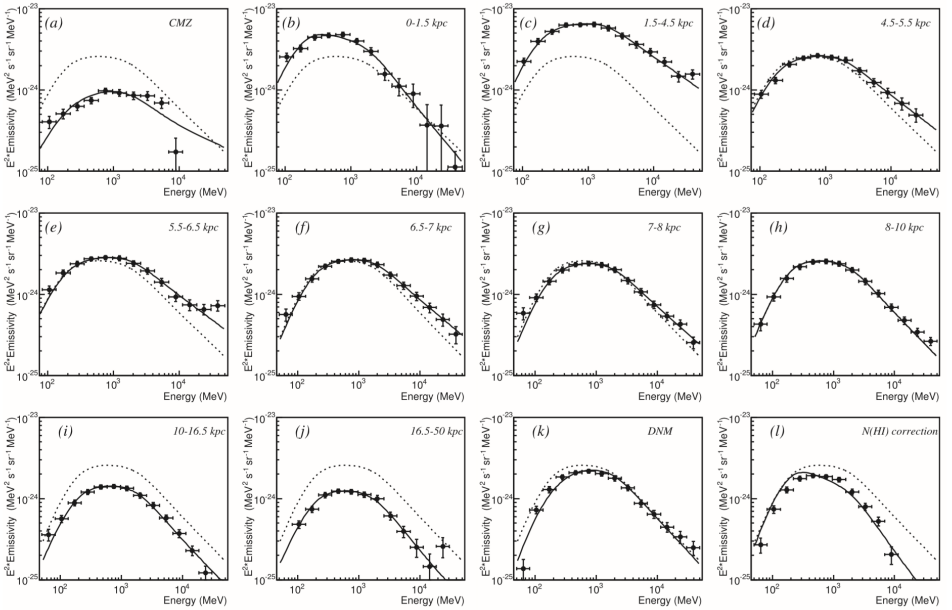
– the average slope is ~ -2.5.



Average CR spectrum in the Galaxy



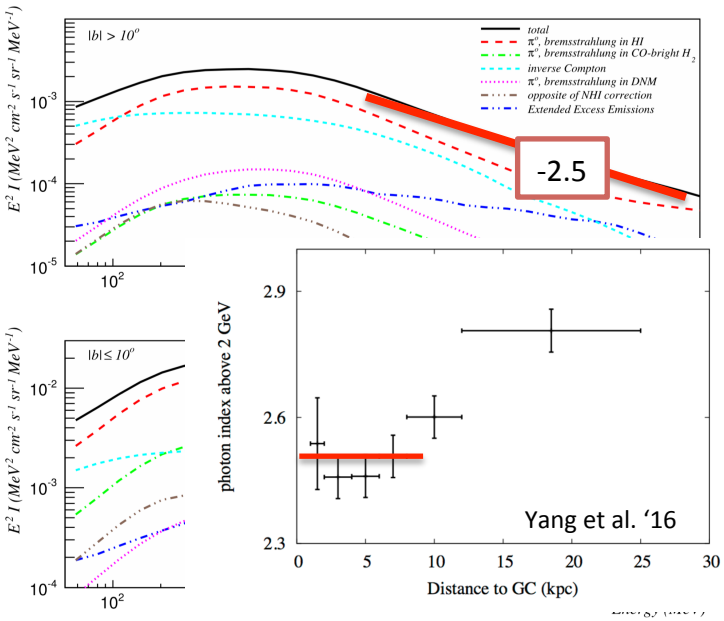
Acero et al. '16



New analysis of diffuse emission by Fermi Collaboration has introduced Galactocentric-distance-dependent pion decay emission templates.

– average slope of the CR spectrum appears variable with distance from the Galactic Centre. It is typically harder within the Solar distance, compared to the locally observed slope.

– pion decay spectrum slope above ~10 GeV is found to be consistent with ~2.5.



Γ=? ; δ=?

$-(\Gamma+\delta)=2.5$

Hard / variable CR spectrum in the Galaxy?

Average spectrum of CRs in the inner galaxy appears harder (slope -2.5) than the CR spectrum in the local interstellar medium.

Consistent with injection spectrum with the slope $\Gamma \sim 2.1 \,..\, 2.2$ (Cygnus cocoon) and diffusion through turbulent magnetic field with Kolmogorov spectrum ($\delta \sim 1/3$).

Softer spectrum in the local Galaxy could be due to the variable star formation:

- CR spectrum is harder than average in regions with growing star formation rate
- CR spectrum is softer than average in regions with decreasing star formation rate.

Neronov et al. '11

An alternative possibility is that δ depends on the distance to the Galactic Centre

- $\delta(R)=A+B*R$ provides satisfactory description of diffuse emission data
- possible physical model is spatial variability of the properties of turbulent magnetic field component properties (strength, correlation length, spectrum).
- … related to the spatial variability of the star formation rate.

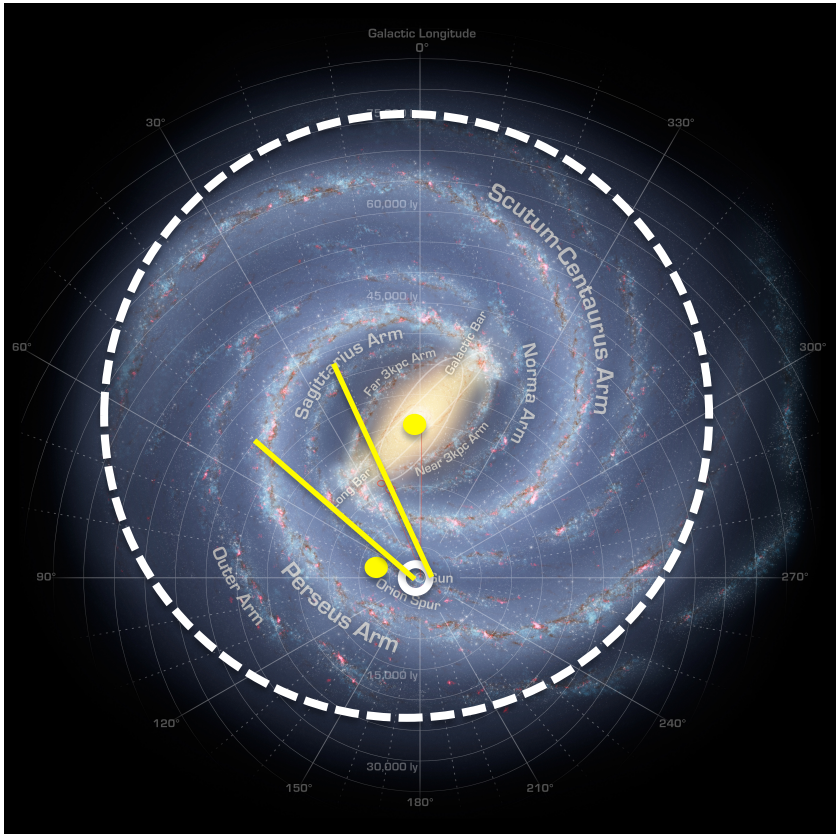
Gaggero et al. '15

Still another possibility is spatially / temporarily variable energy-dependent balance between CR advection and diffusion through self-generated turbulence.

Recchia et al. '16

…

Summary



γ-ray observations are useful for pinpointing the Galactic CR sources and are also the only possibility for the measurement of the properties of the CR flux elsewhere in the Galaxy:

– if the slope $dN/dE \sim E^{-2.7} \sim E^{-(\Gamma+\delta)}$ characteristic for the Galactic CR population?

No.

– What are the values of Γ and δ?

$\Gamma+\delta \sim 2.5$

(inner Galaxy, within Solar circle)

(above ~100 GeV [10 GeV gamma-ray energy])

– do the breaks in the CR spectrum have "universal" nature, or they are occasional local effects?

???

Hard / variable Galactic CR spectrum result could be verified in a straightforward way via detection of Galactic component of astrophysical neutrino signal.

Fermi bubbles