INVESTIGATING COSMIC RAY DISTRIBUTION AND PROPAGATIONS USING GAMMA-RAY ASTRONOMY

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In collaborations with Bing Liu, Guangxing Li, Xiaona Sun, Felix Aharonian et.al

outline

1. The Galactic diffuse gamma-ray emission and distribution of CRs

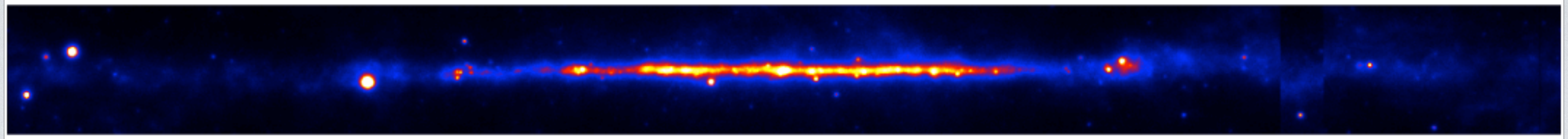
2. effective confinement of CRs near accelerators

3. small scale inhomogeneity

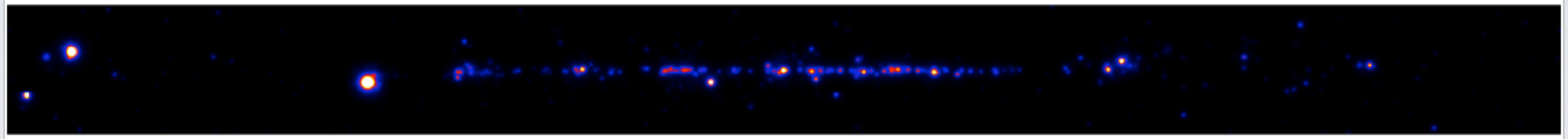
DIFFUSE GAMMA

DIFFUSE GAMMA-RAY EMISSIONS

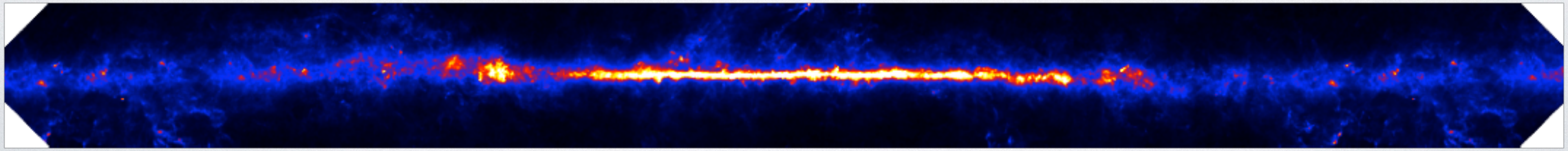
Gamma-ray counts map



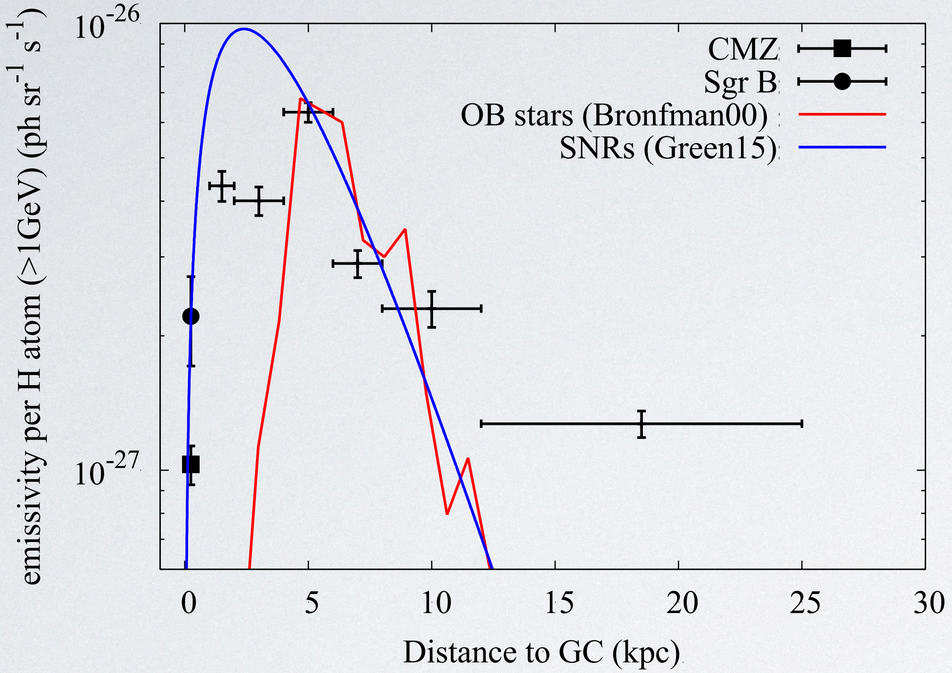
Point source contribution

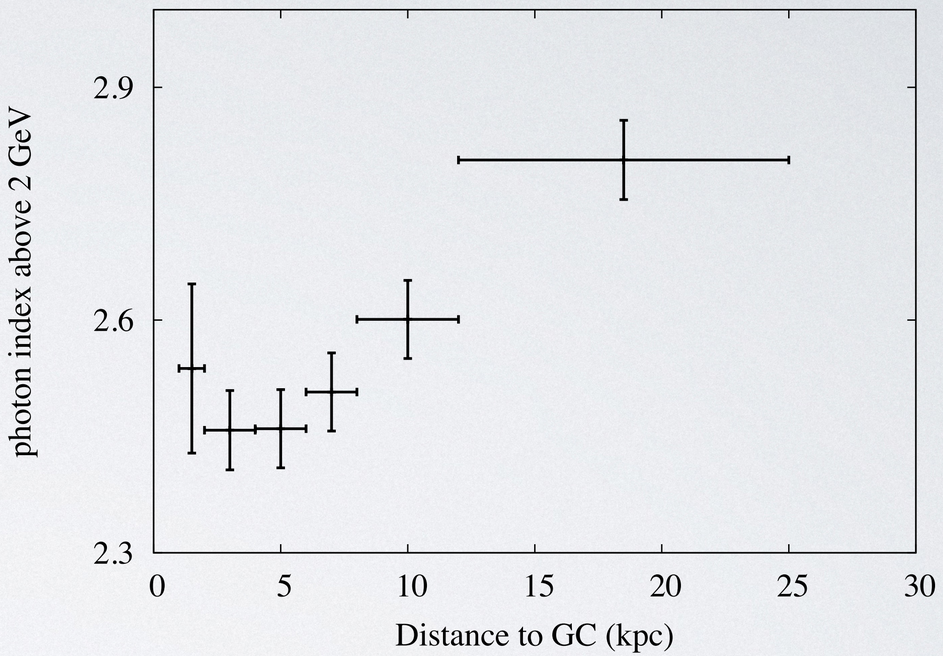


Dust opacity map (gas column)



CR RADIAL DISTRIBUTIONS IN THE MILKY WAY



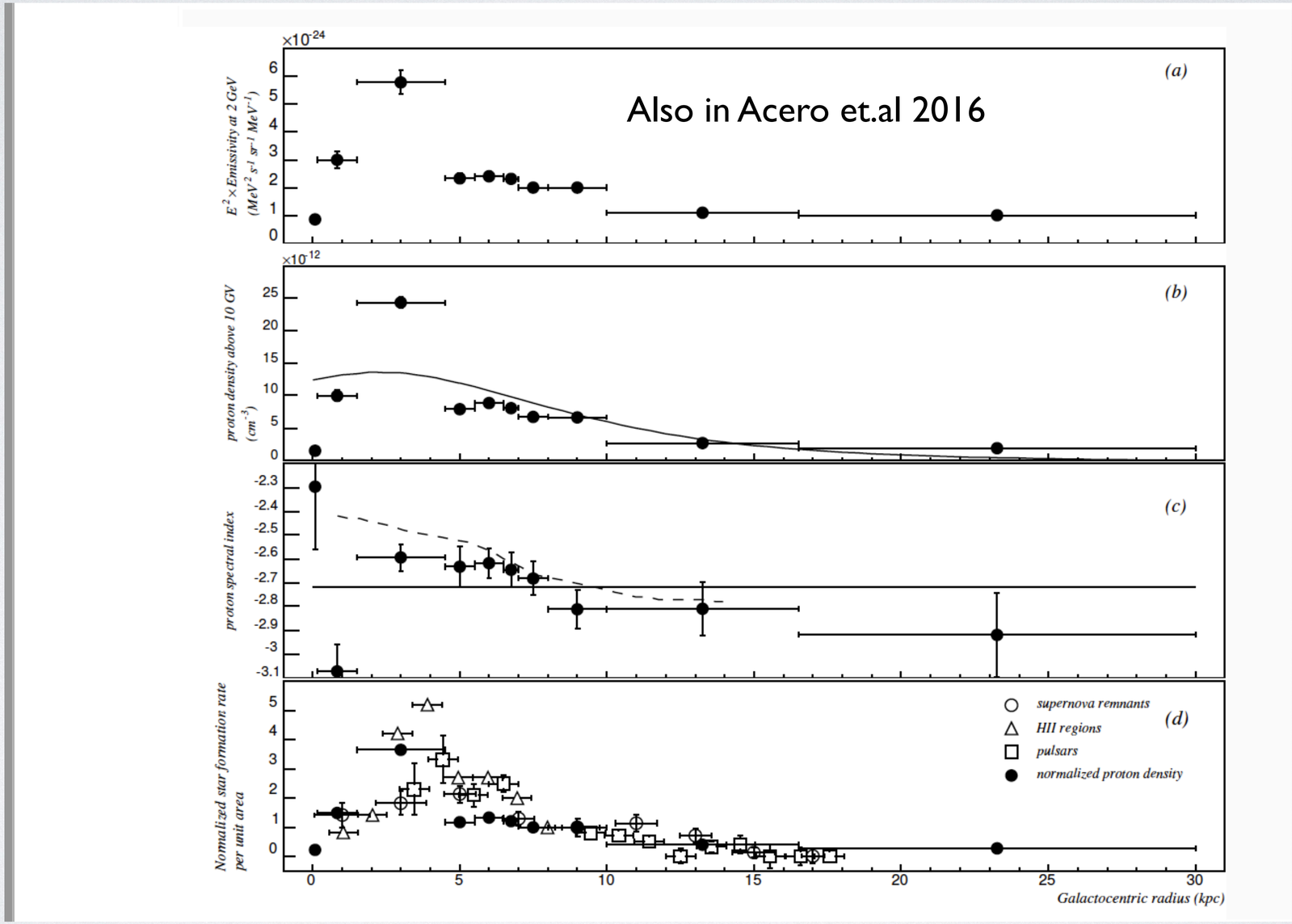


Yang et.al 2016

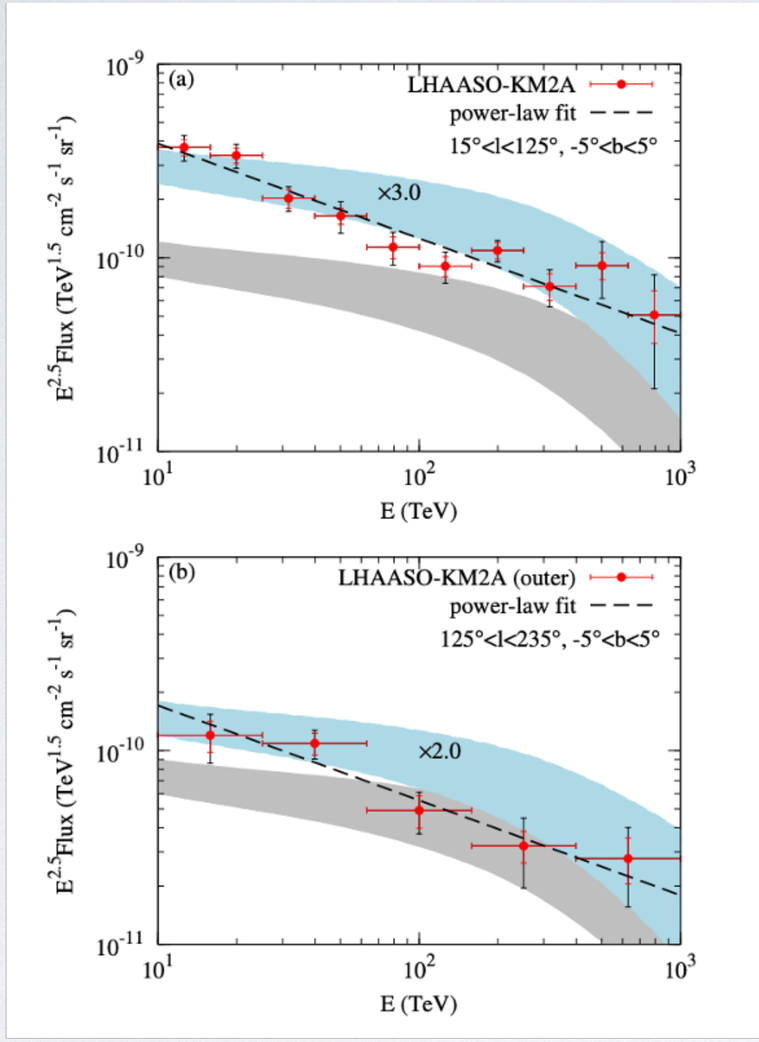
Inhomogeneity in large scale, both in spectra and in densities:

- Softening towards outer Galaxy
- Peak of density at 4-6 kpc ring

CR RADIAL DISTRIBUTIONS IN THE MILKY WAY

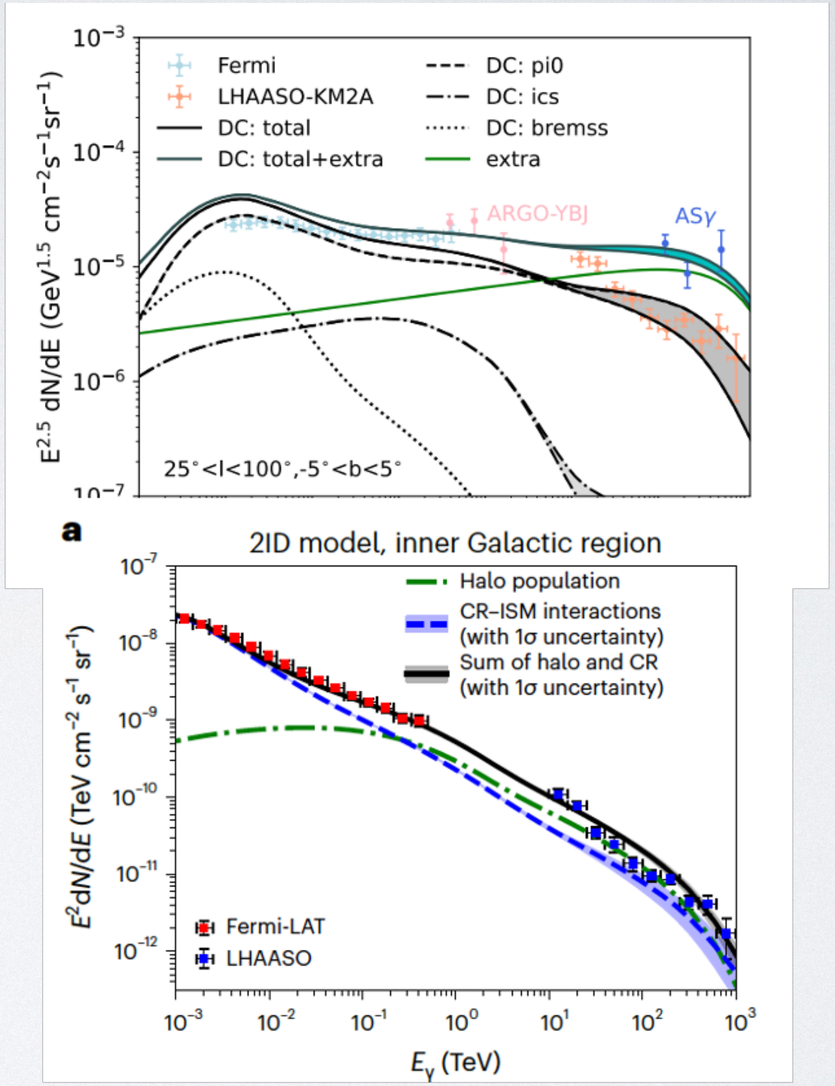


LHAASO RESULTS



Phys. Rev. Lett. 131, 151001 (2023)

`Excess' revealed in multi-TeV band

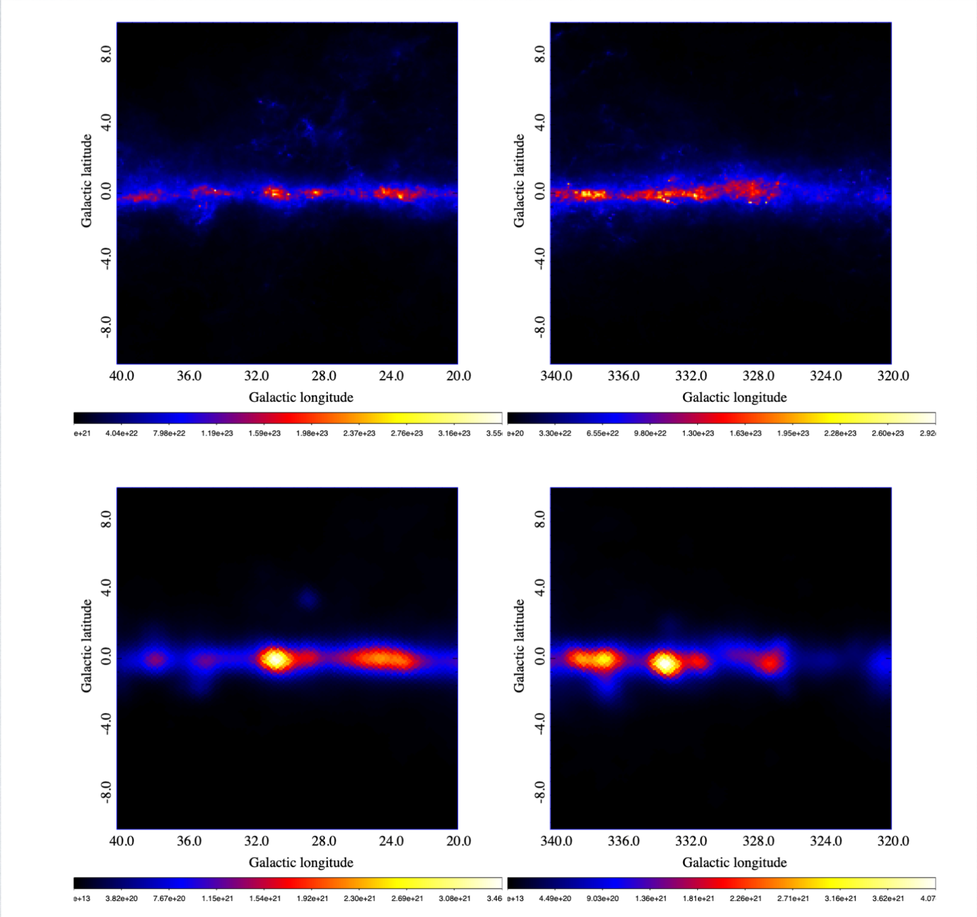


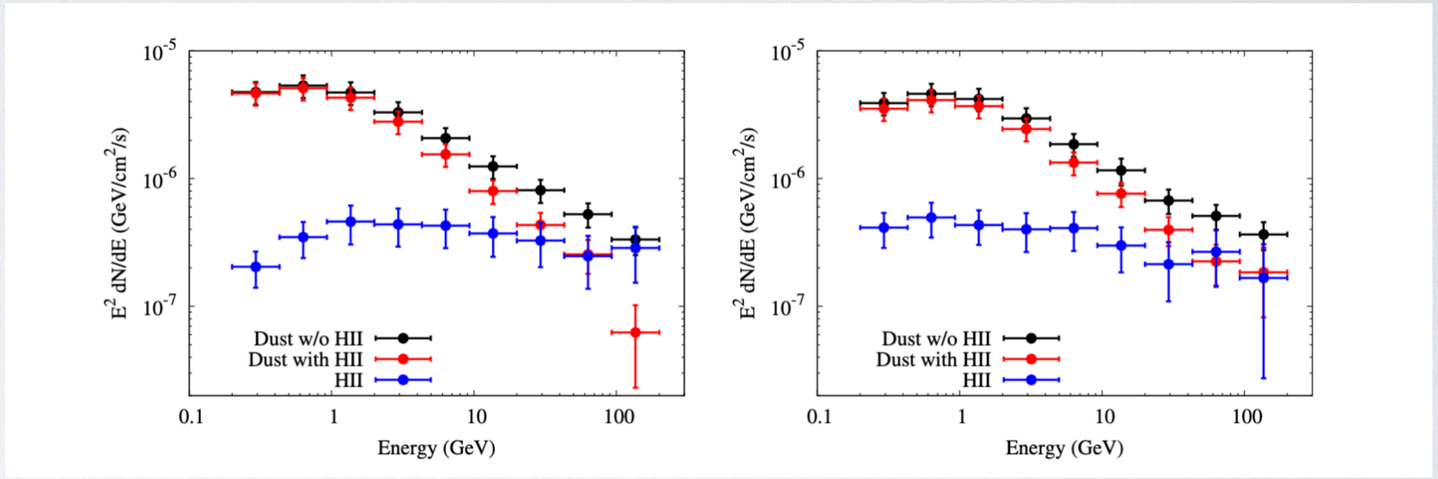
Zhang et.al 2023

Yan et.al 2024

A new component in GDE? From Pulsar halos?

TWO COMPONENT CR/DIFFUSE GAMMA?

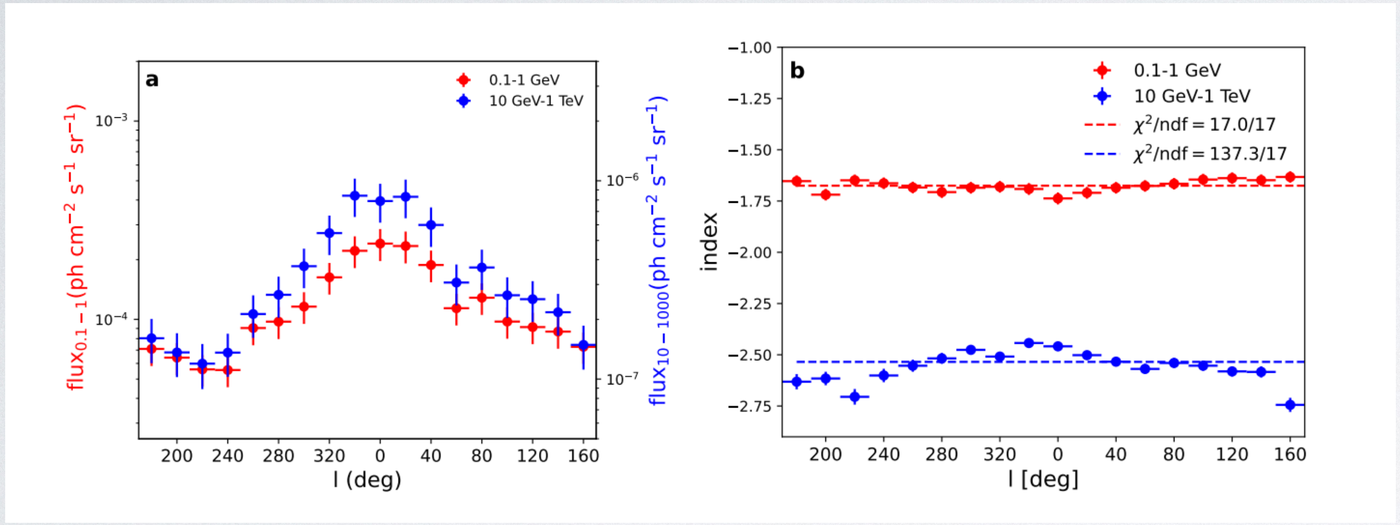


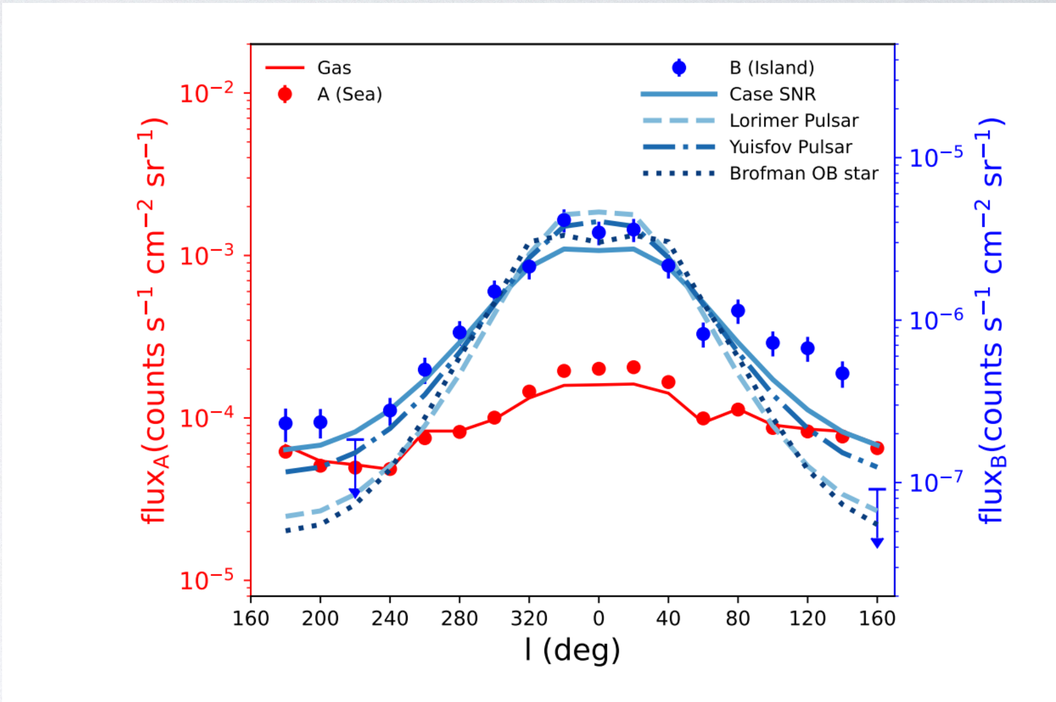


- After considering HII component the CR distributions looks "more homogeneous"
- The former inhomogeneity is simply due to the mixing of "true" diffuse (sea) component with hard "source" (island) regions

Liu et.al A&A 659, A101 (2022)

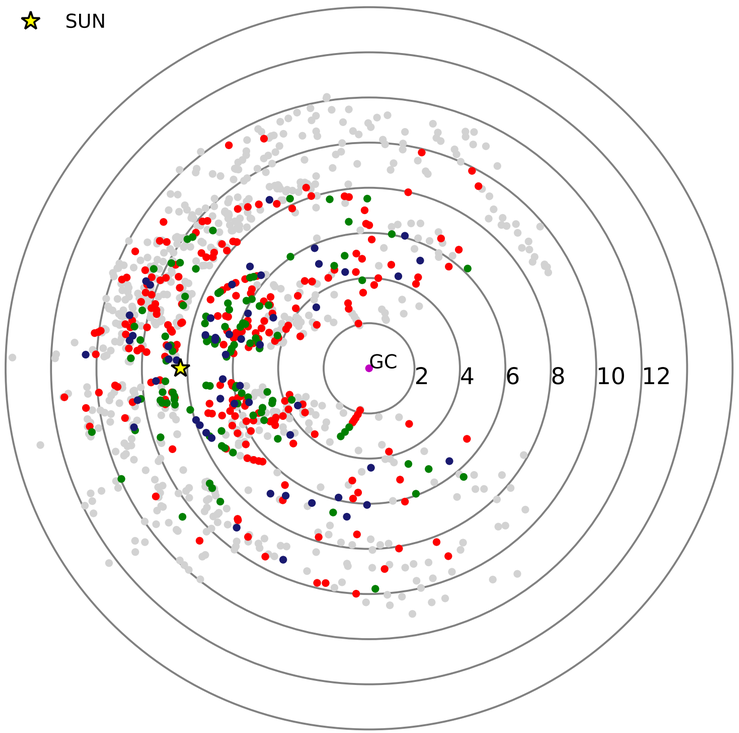
TWO COMPONENT CR/DIFFUSE GAMMA?





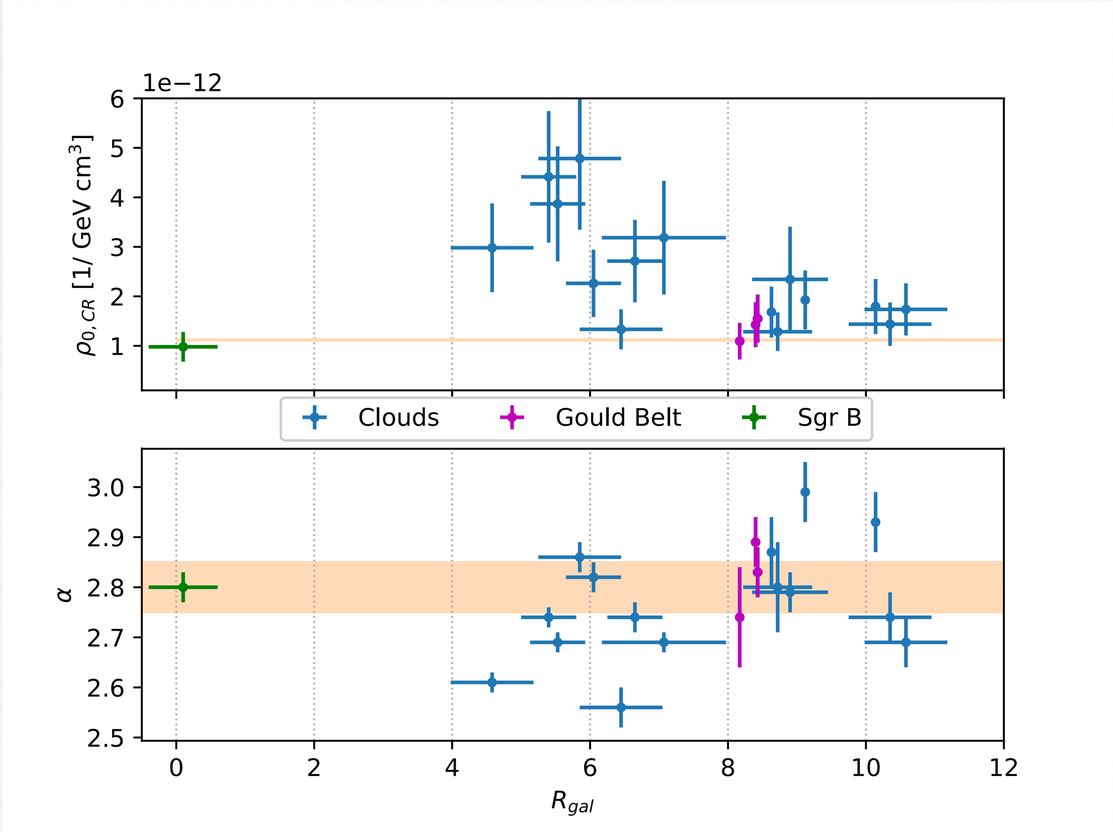
ALSO SEE arXiv:2509.26290 using spectral component separation

USING GMCS FOR IN-SITU MEASUREMENT OF CRS

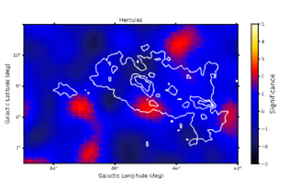


Aharonian et.al 2019

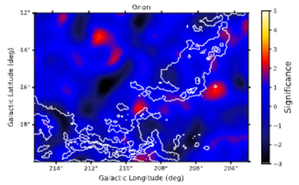
- Rice et.al (2016) have identified thousands of Molecular Clouds in the Galaxy
- Possible to measure CR density in each position of the Galaxy.



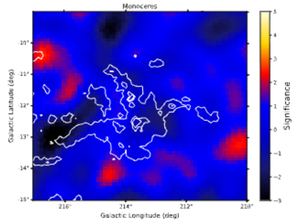
GMCS WITH LHAASO



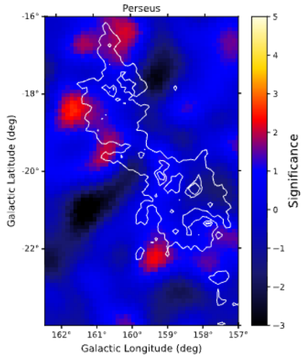
(a) Hercules



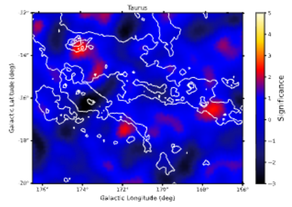
(b) Monoceros



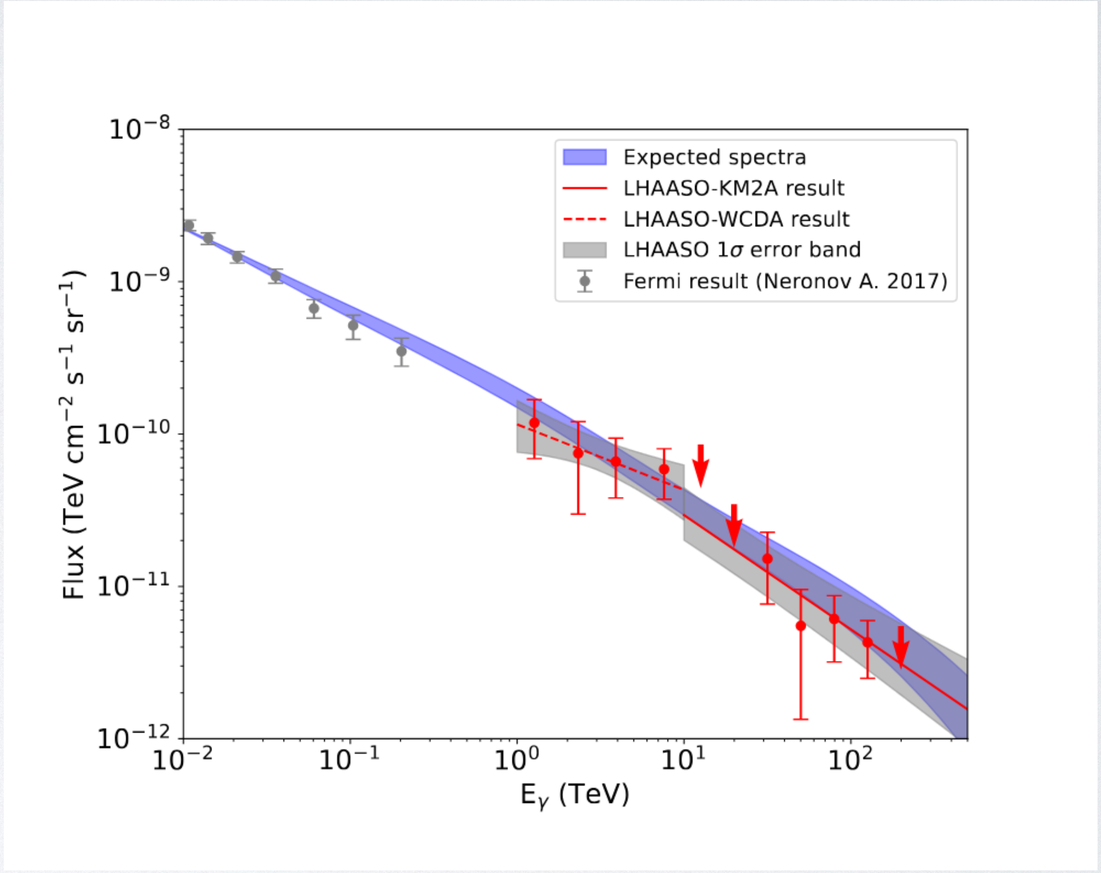
(c) Orion



(d) Perseus

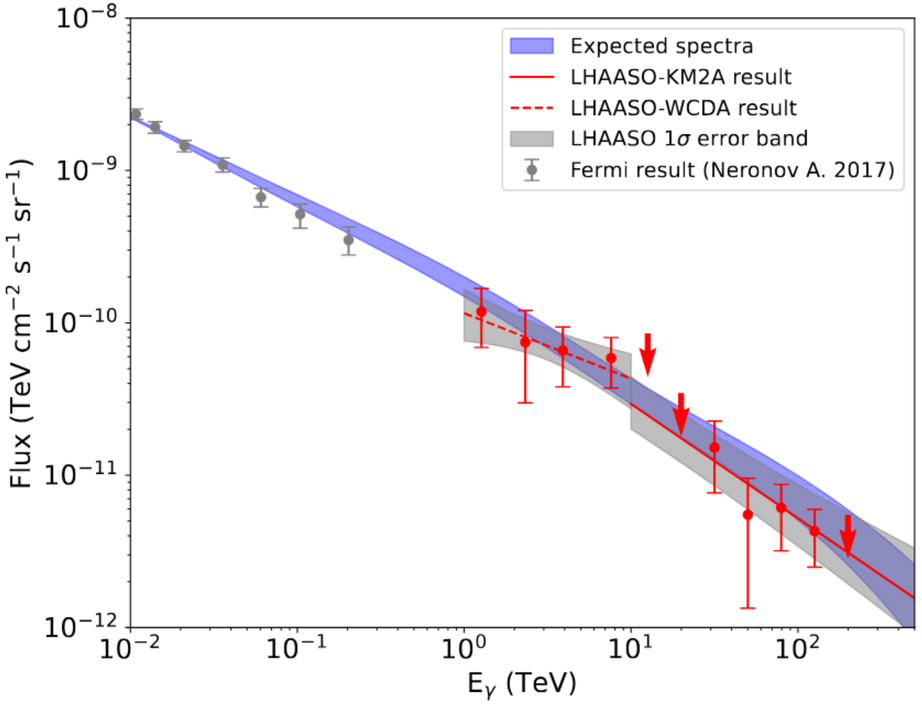


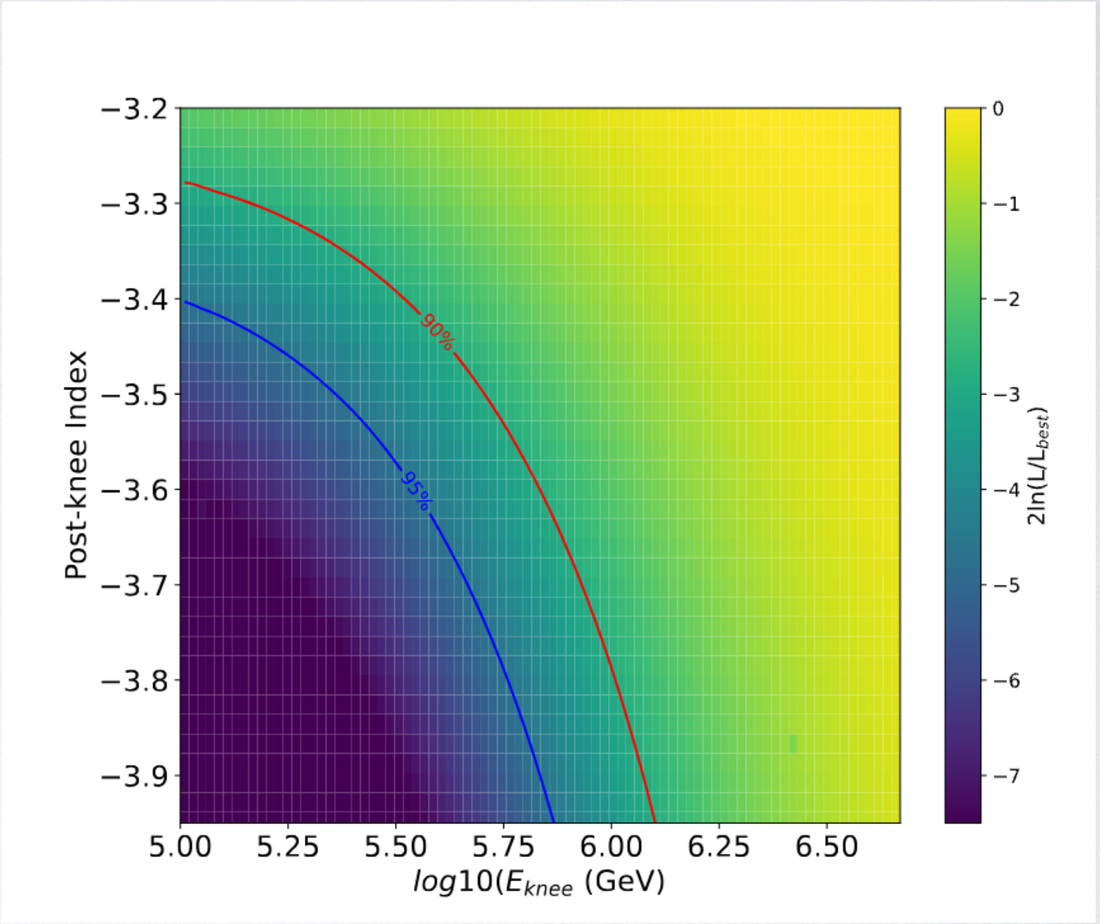
(e) Taurus



No single detection, 6 sigma signal in Stacking analysis

GMCS WITH LHAASO

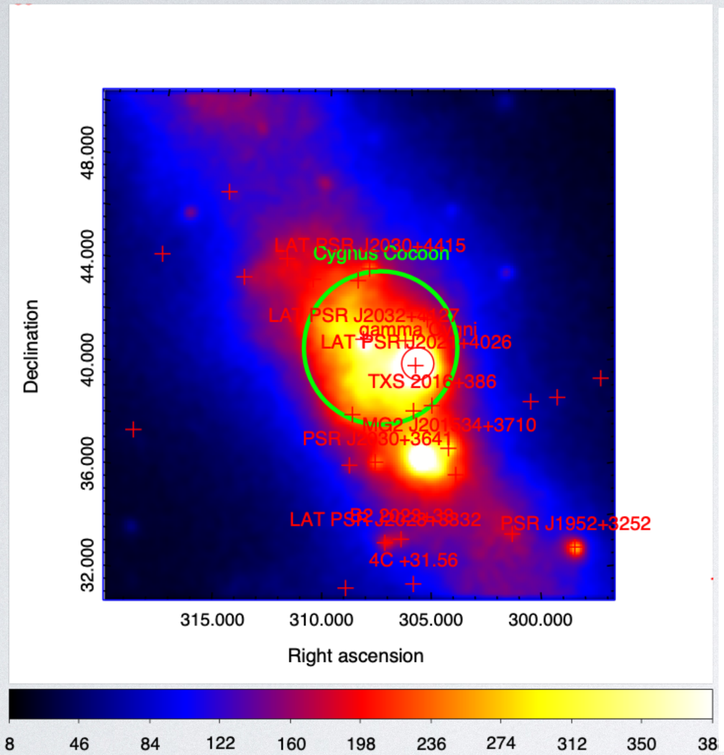


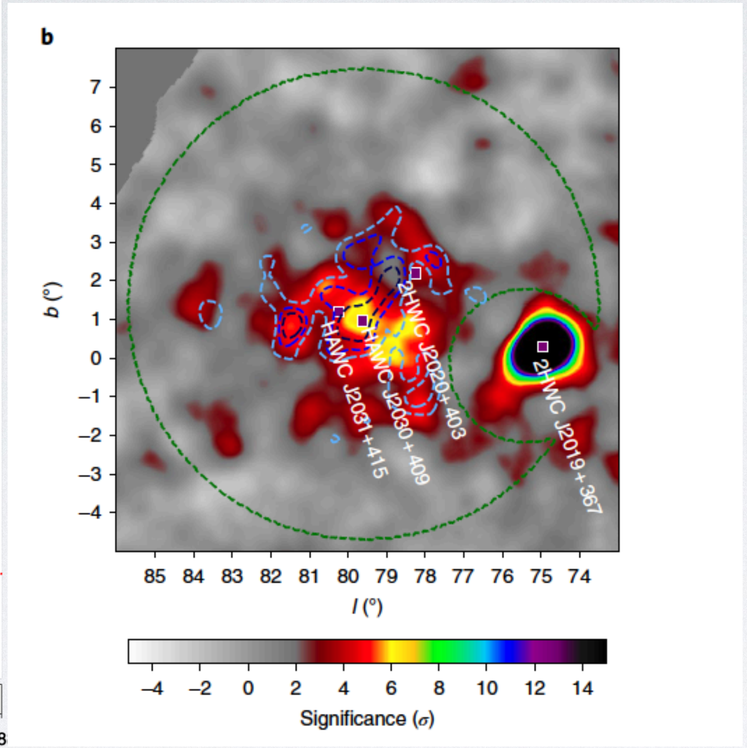


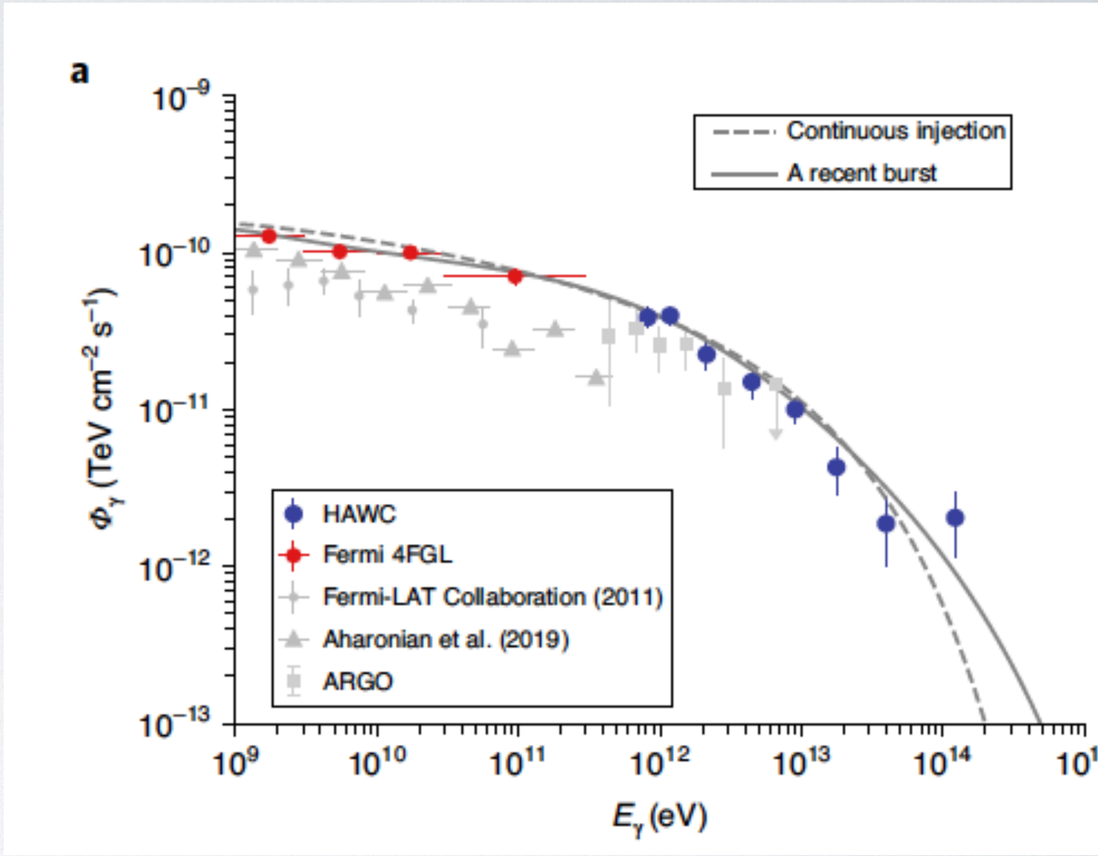
Also an independent measurement of proton knee, > 1TeV

CONFINEMENT NEAR THE SOURCES

CYGNUS COCOON

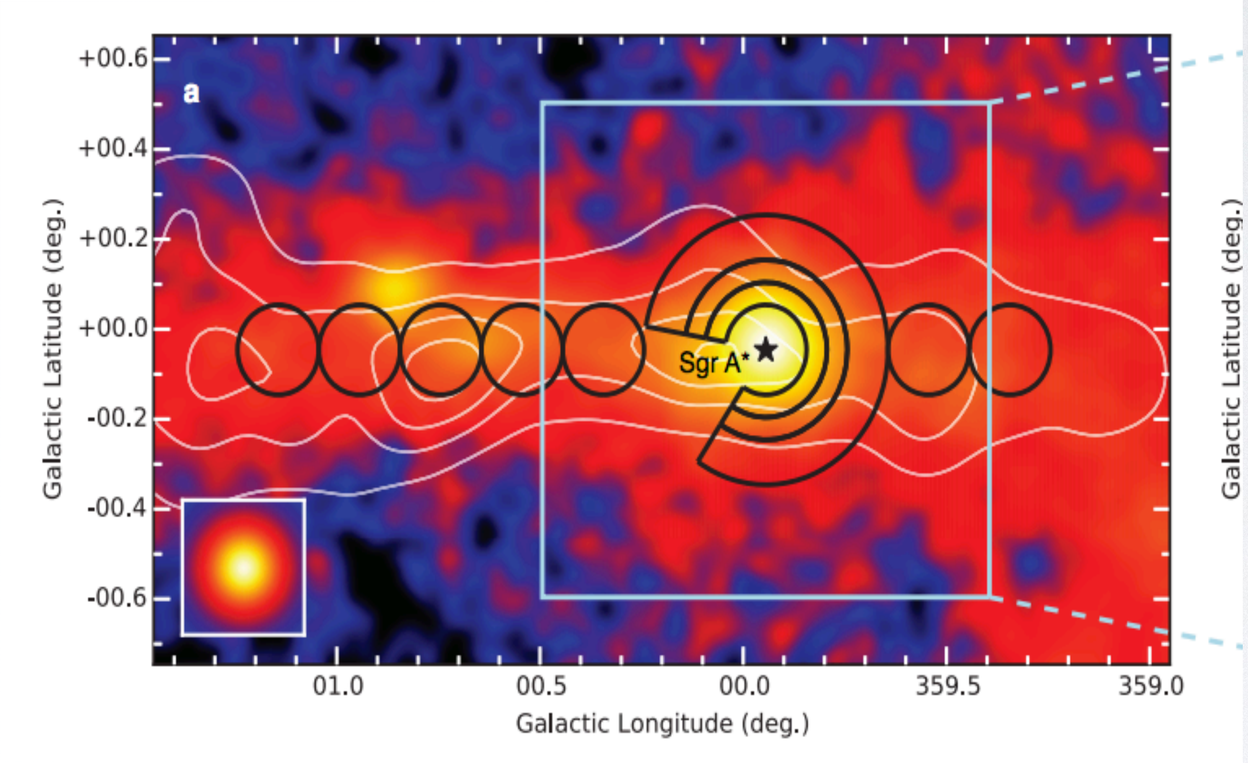


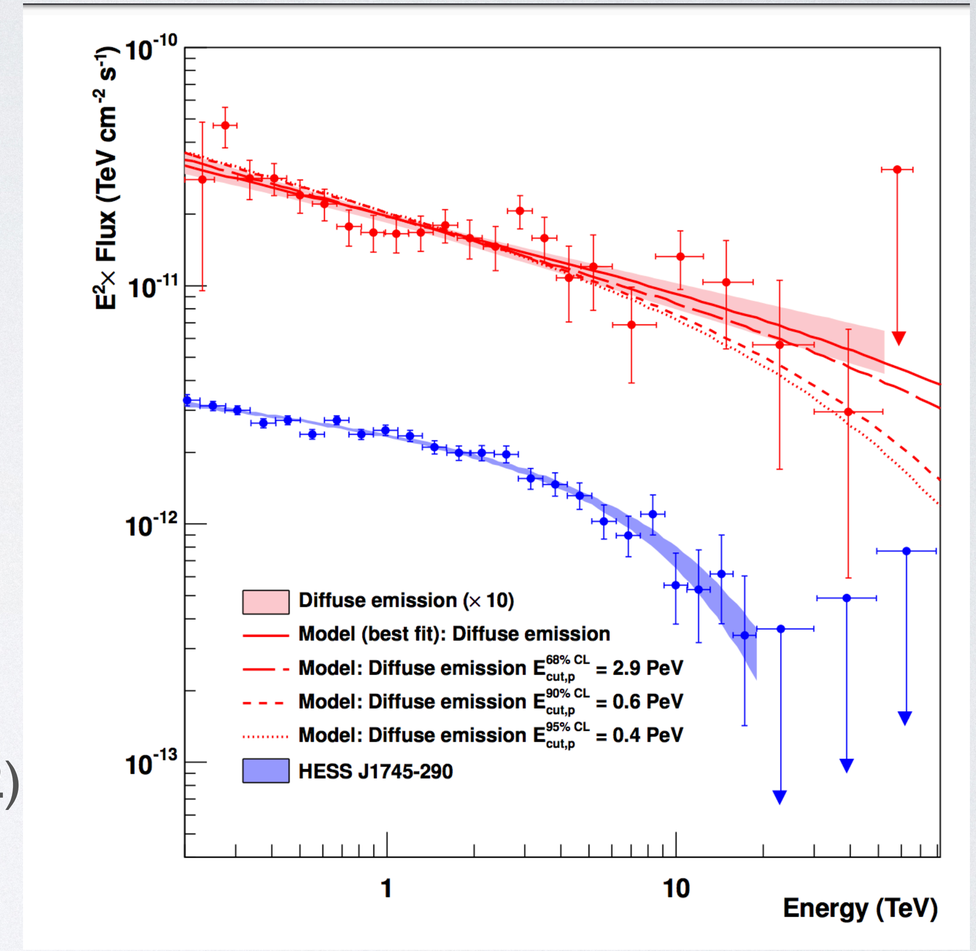




- Observed by Fermi LAT, ARGO-YBJ & HAWC
- extended emission up to more than 50 pc (150 pc from LHAASO)
- Hard spectrum in GeV band, softening above TeV

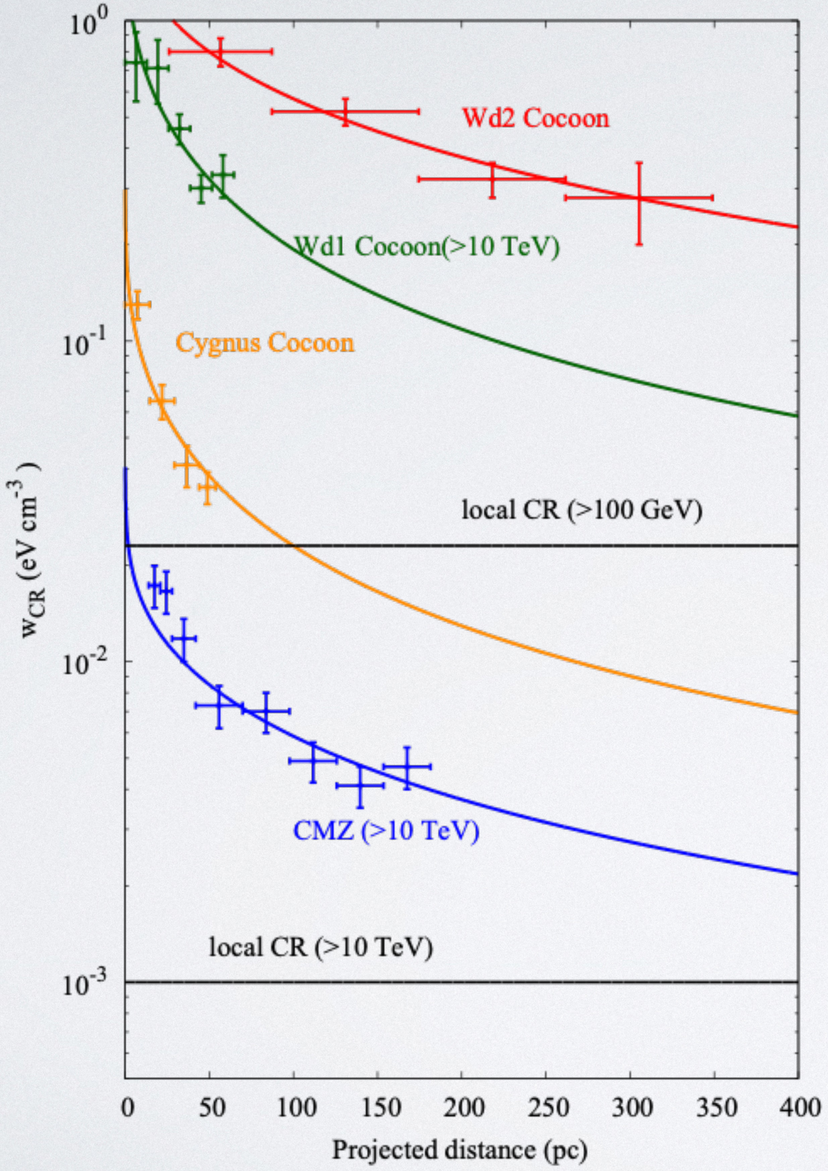
GALACTIC CENTER (HESS 2016)





- Also reveal extended emission and hard spectrum (index ~ 2.2)
- Diffuse emission up to more than 150 pc
- GC region harbors Arches, Quintuplet and Nuclear cluster

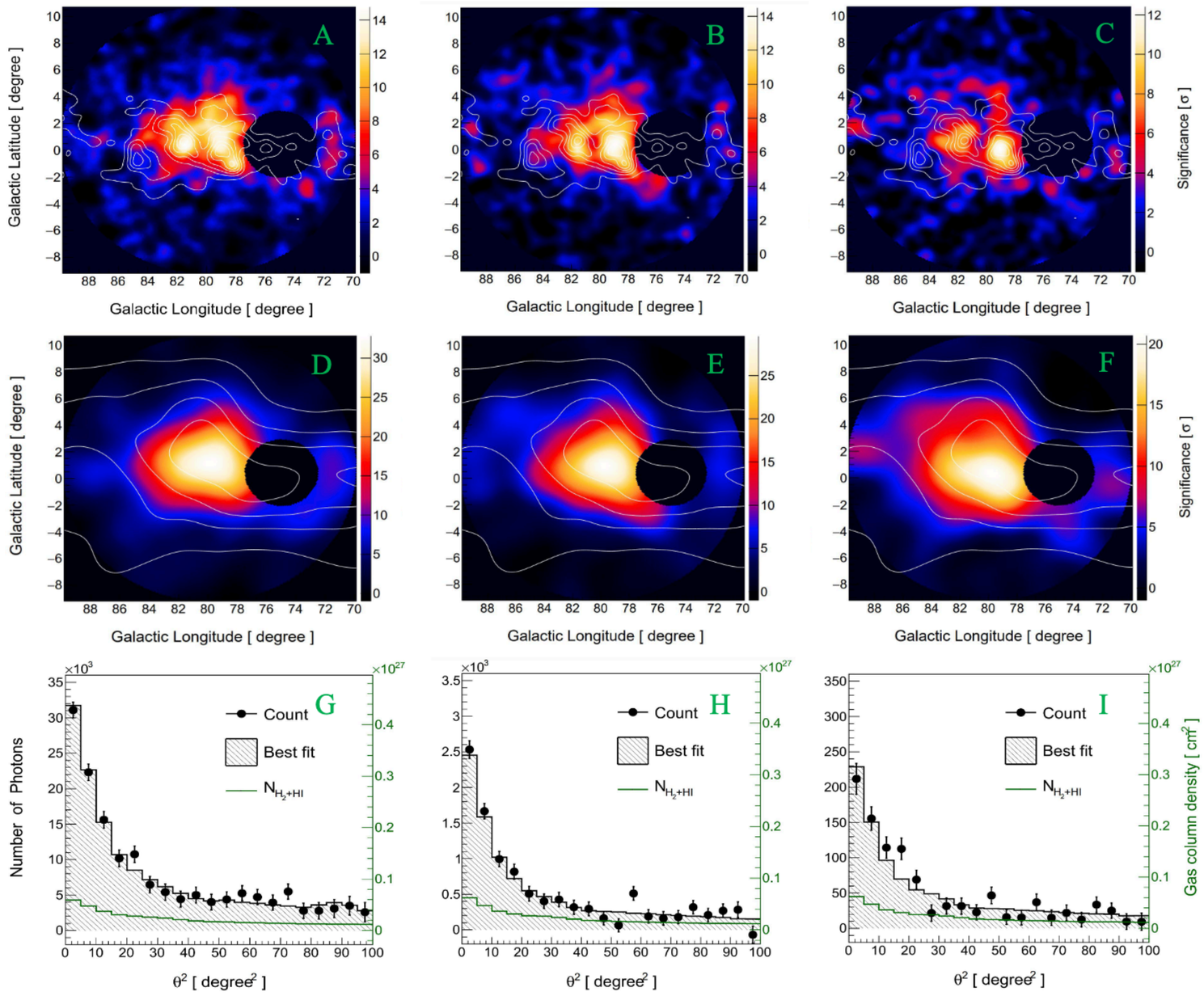
RADIAL DISTRIBUTION OF COSMIC RAYS



- CR distribution derived by gamma-ray profile and gas distributions
- All four sources (Wd1, Wd2, Cygnus cocoon, GC) show 1/r distribution of CRs
- In diffusion, 1/r profile implies a **continuous** injection, multiple SNRs or stellar winds
- Slow diffusion required by the total energy budget

Aharonian, Yang & de ona Wilhelmi Nature Astronomy(2019) 3,561

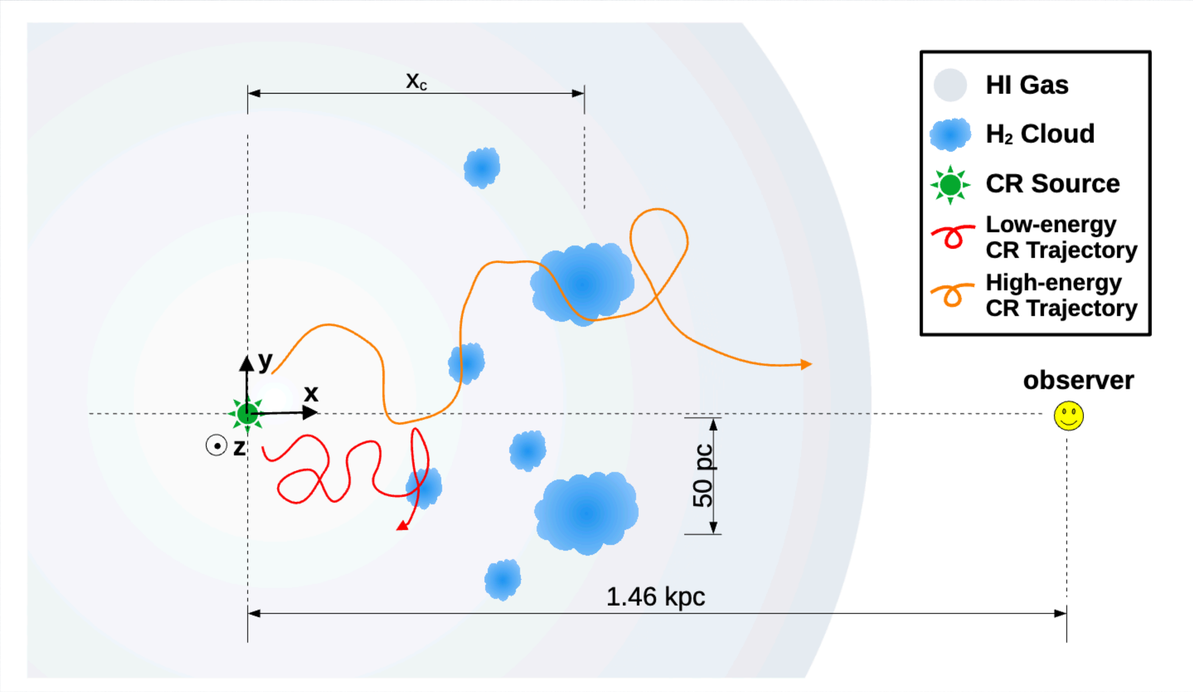
LHAASO VIEW ON CYGNUS



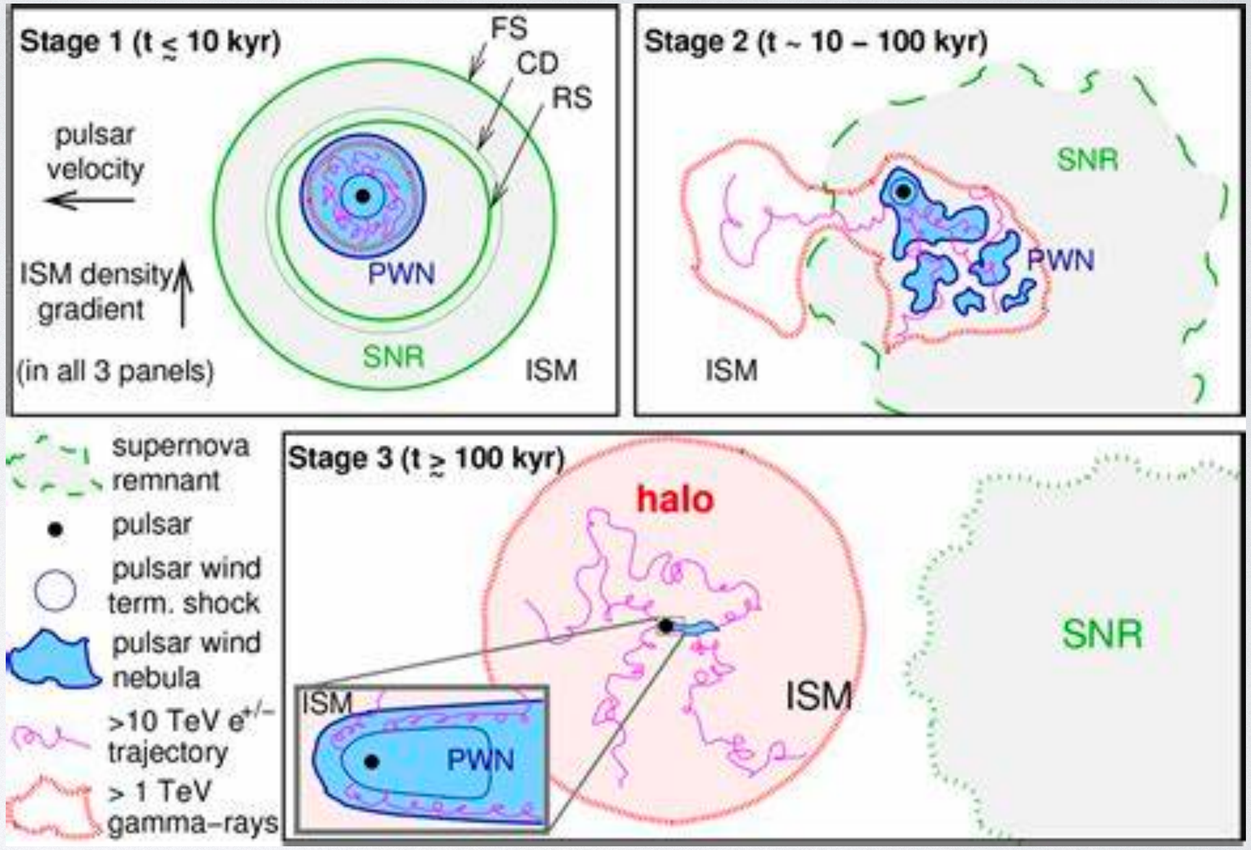
Huge bubble beyond ~10 degrees (200 pc)

LHAASO collaboration Science Bulletin (2024) 69,449

RELATED SOURCES TO THE DIFFUSE GAMMA?

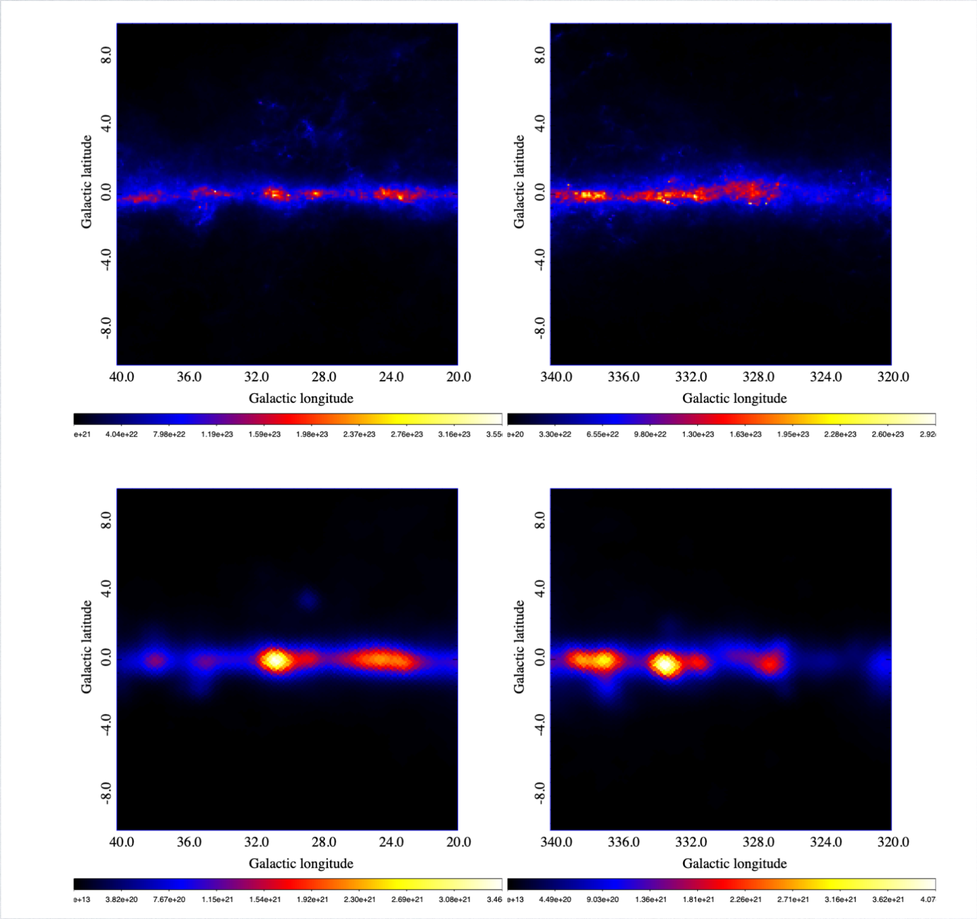


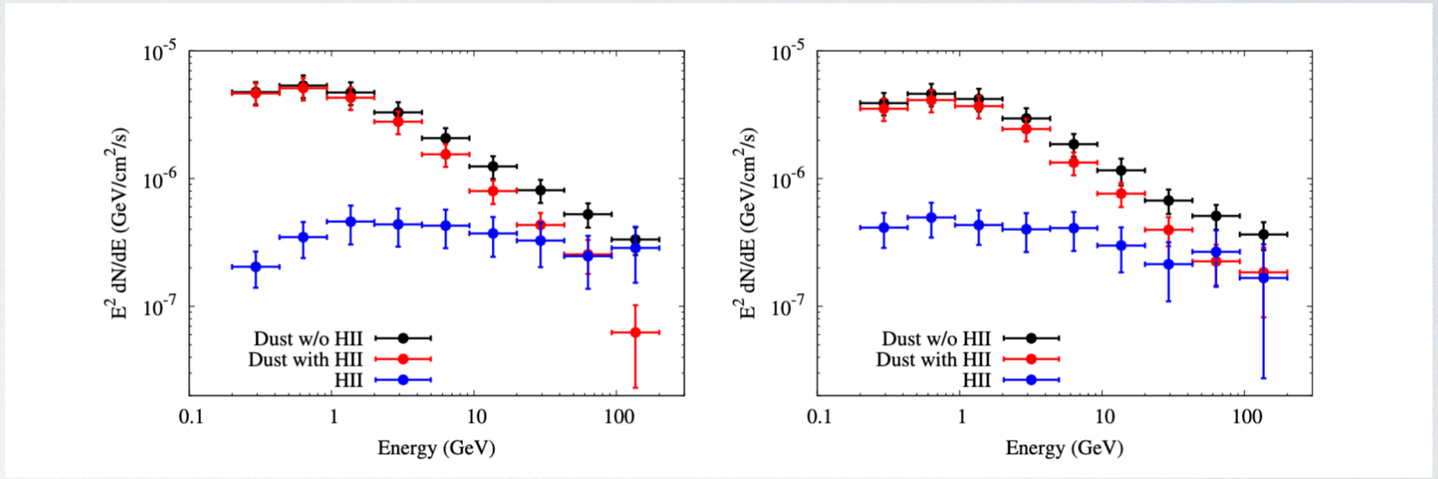
Slow diffusion region near CR accelerators
(Cygnus bubble as an example)



Slow diffusion inside pulsar Halos

TWO COMPONENT CR/DIFFUSE GAMMA?



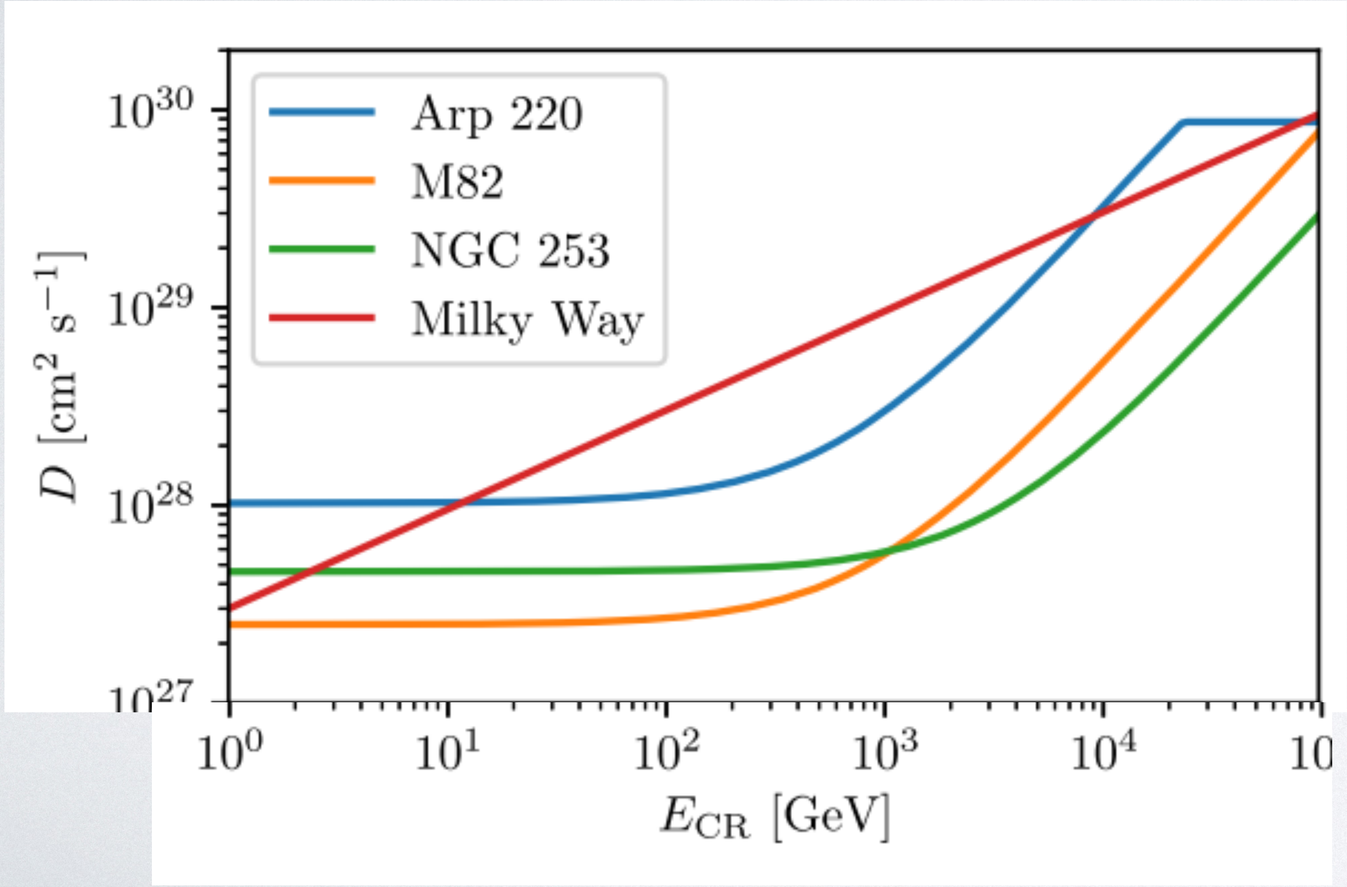


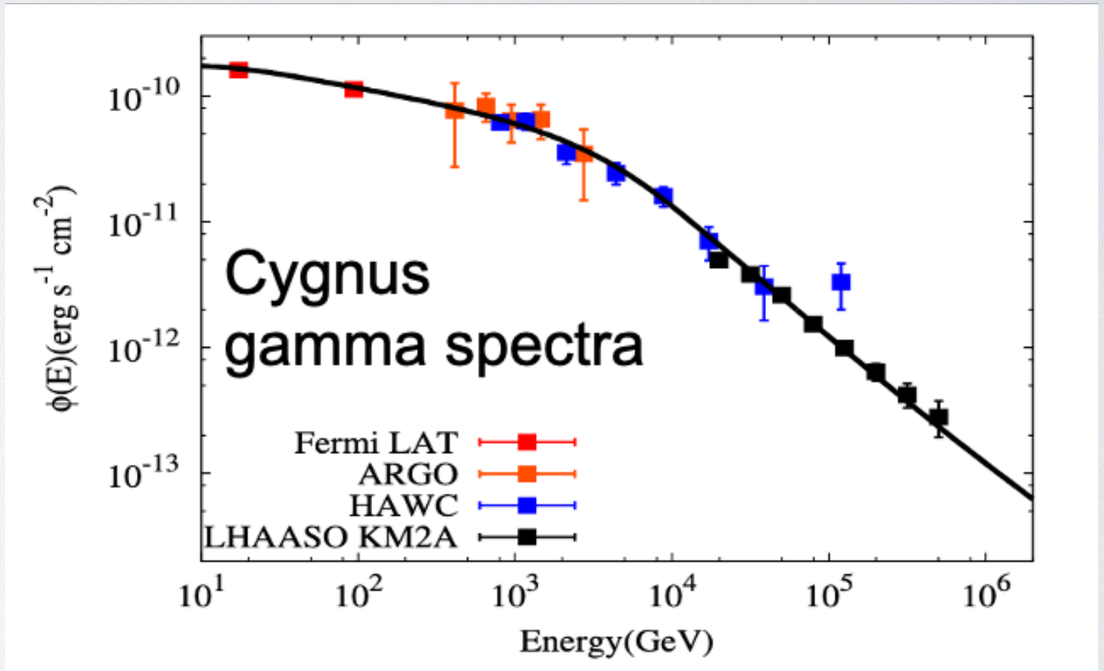
- After considering HII component the CR distributions looks "more homogeneous"
- The former inhomogeneity is simply due to the mixing of "true" diffuse (sea) component with hard "source" (island) regions

Liu et.al A&A 659, A101 (2022)

SLOW DIFFUSION REGIONS

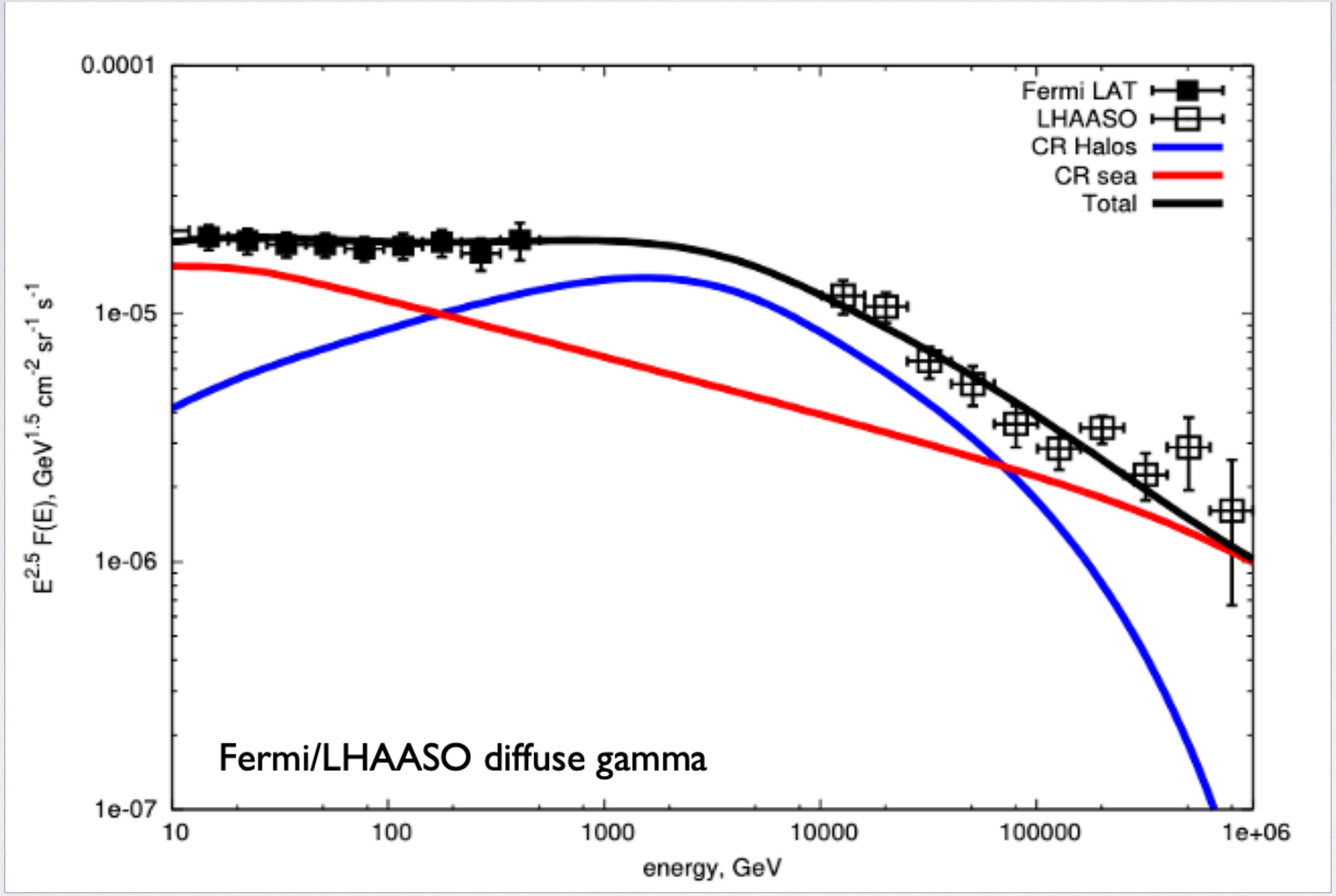
- Possible energy independent escape from Source regions (normal assumption if CR streaming dominate the magnetic turbulence, e.g. Krumholz 2019)





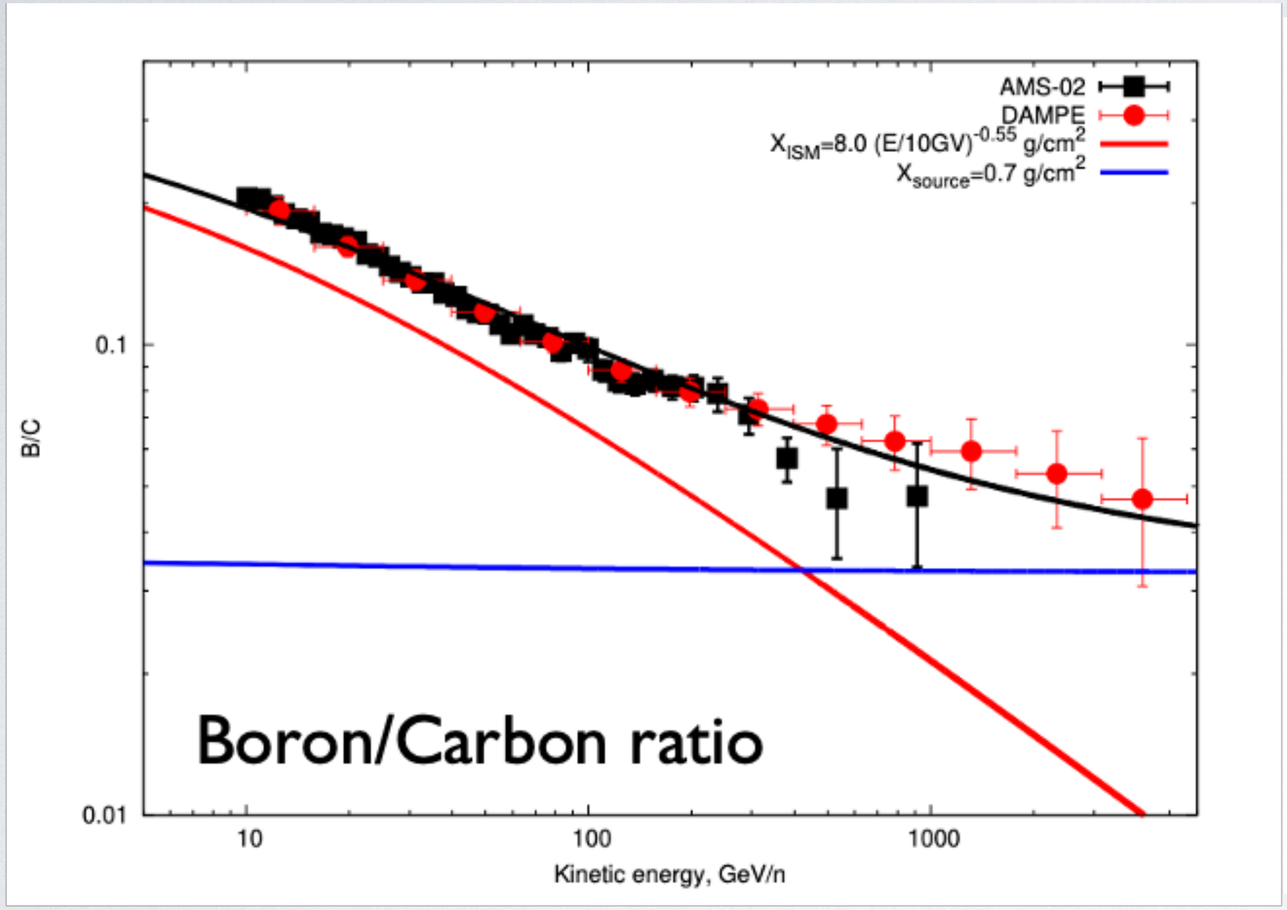
- Effective confinement (slow diffusion) of CR near accelerators
- energy independent below ~10 TeV, from Cygnus spectra

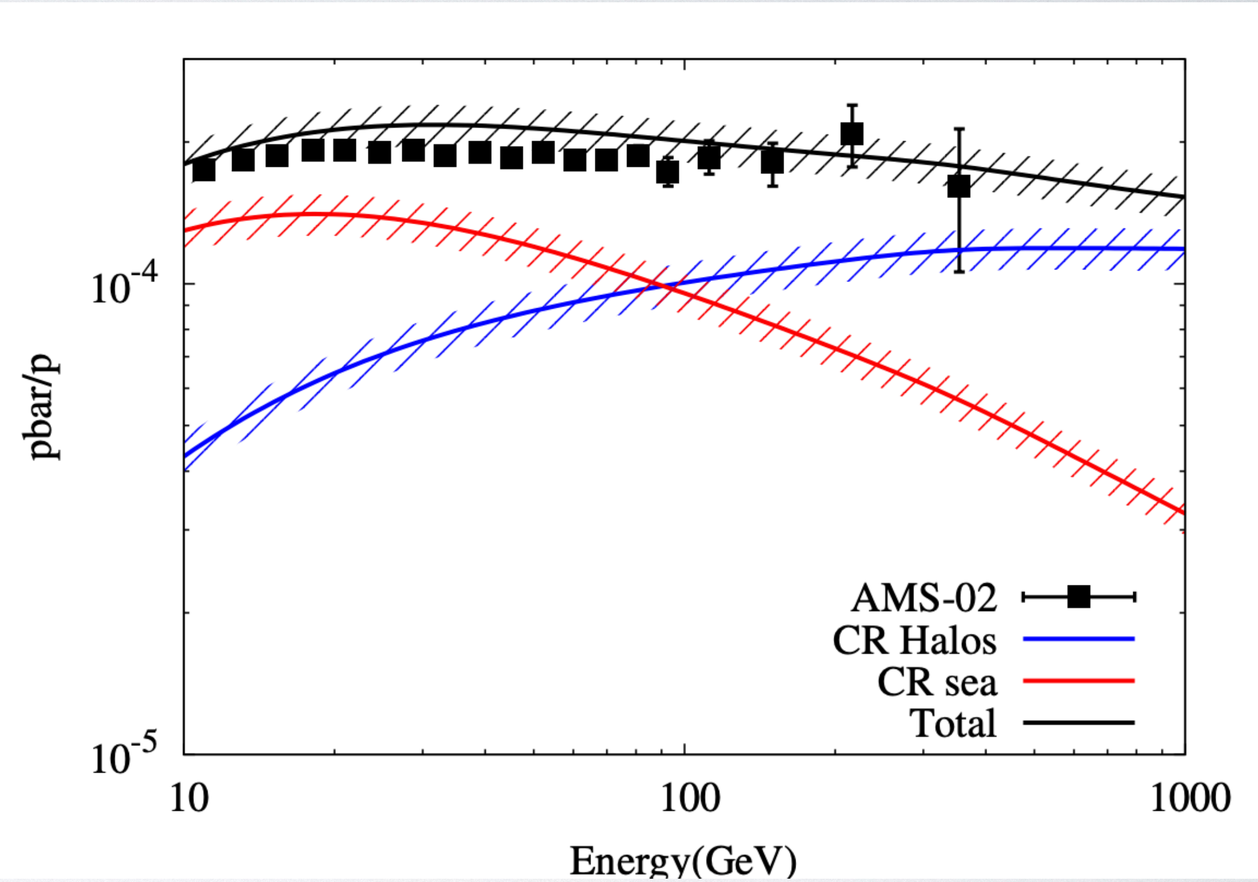
CONTRIBUTION TO DIFFUSE GAMMA



Yang and Aharonian, Phys. Rev. D 111, 083040

ACCUMULATION OF GRAMMAGE

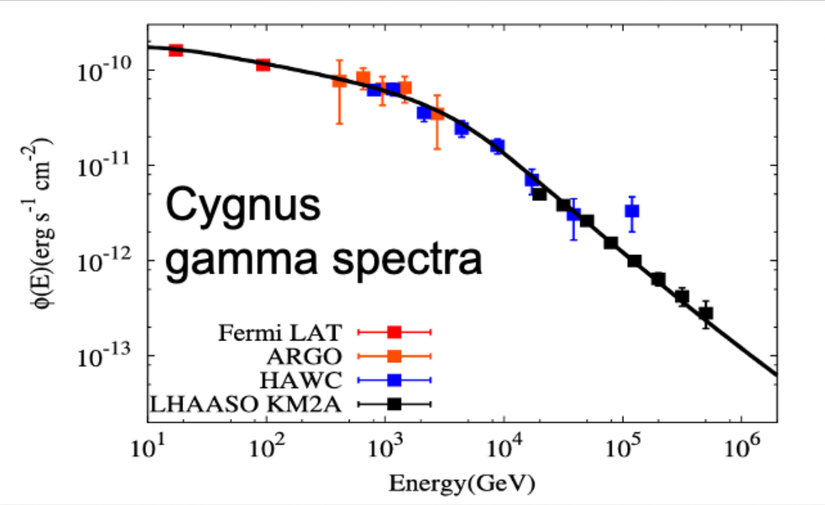


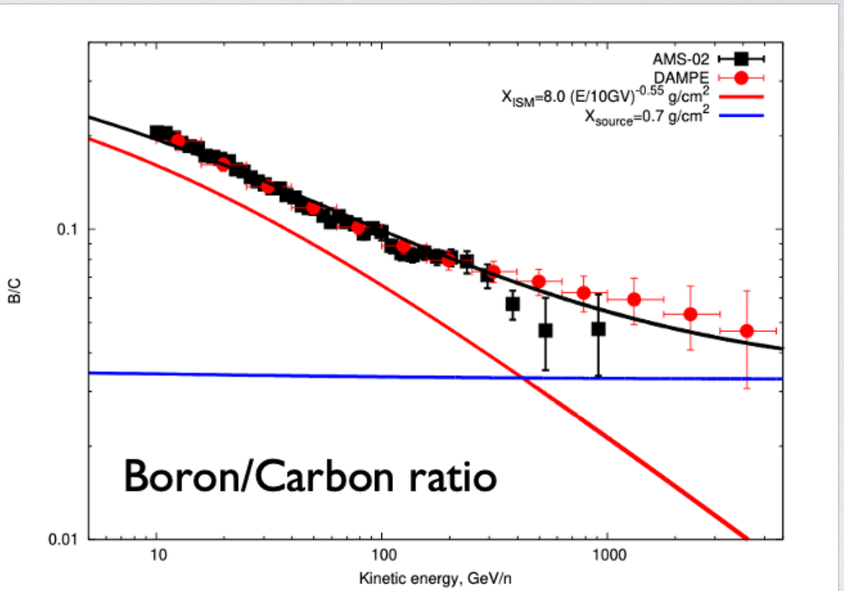


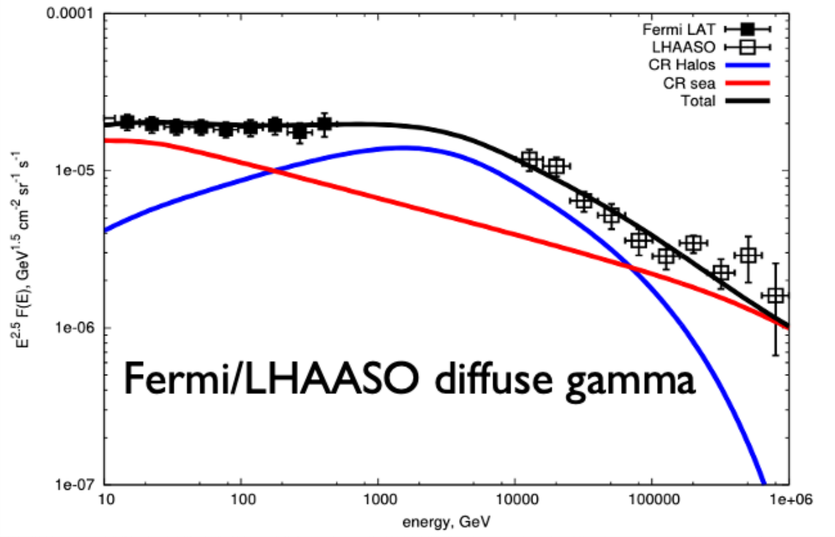
- Can also address the anomalies in CR direct measurement

Yang and Aharonian, Phys. Rev. D 111, 083040

MODIFIED PICTURE OF CR PROPAGATION







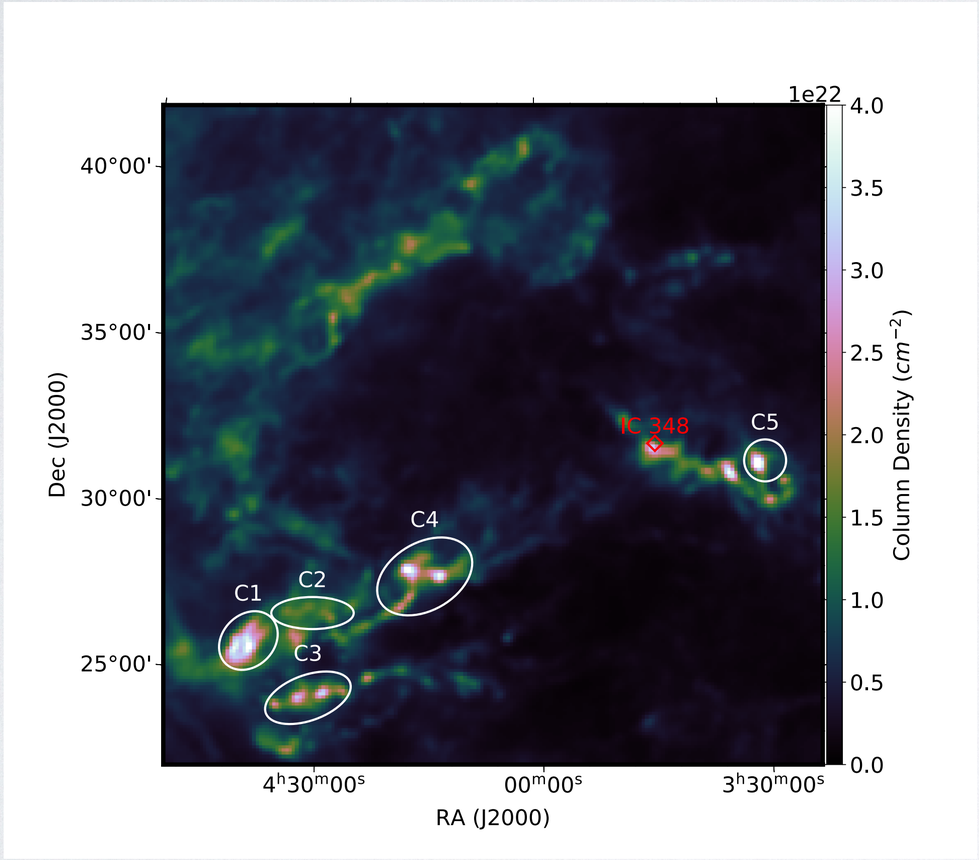
- Effective confinement (slow diffusion) of CR near accelerators
- Energy independent below ~10 TeV, from Cygnus spectra
- Accumulation of extra component of "grammage"
- Can account for both B/C and diffuse gamma

Yang and Aharonian, Phys. Rev. D 111, 083040

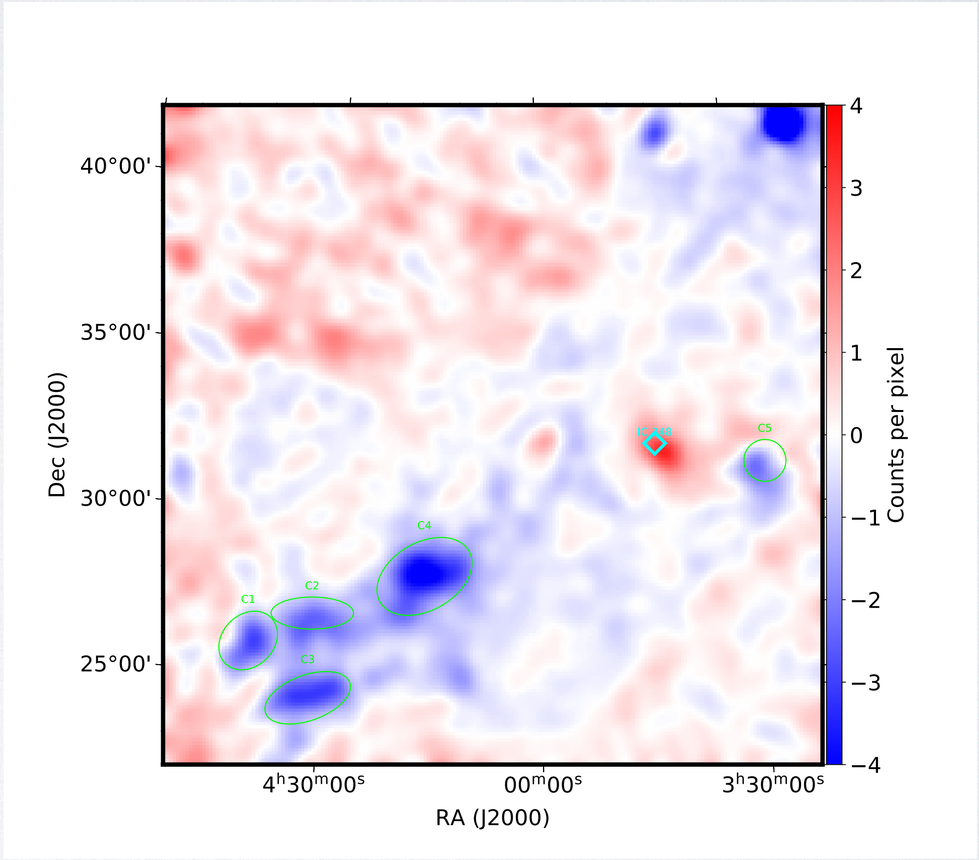
DIFFUSE GAMMA IN SMALL SCALE

INHOMOGENEITY IN SMALL SCALE

- **Taurus-Perseus region**
- **low gamma-ray emissivities in Highest density regions**



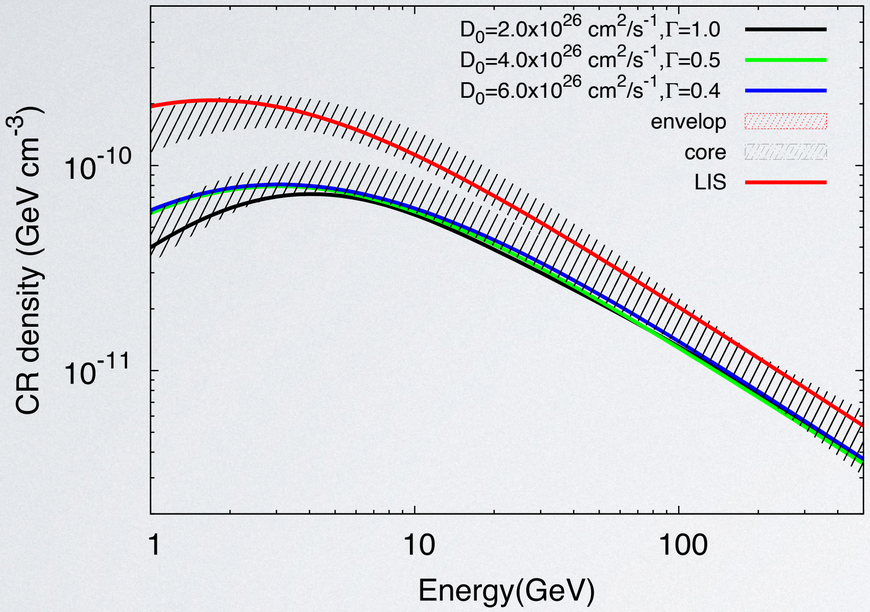
Dust opacity (gas distribution)

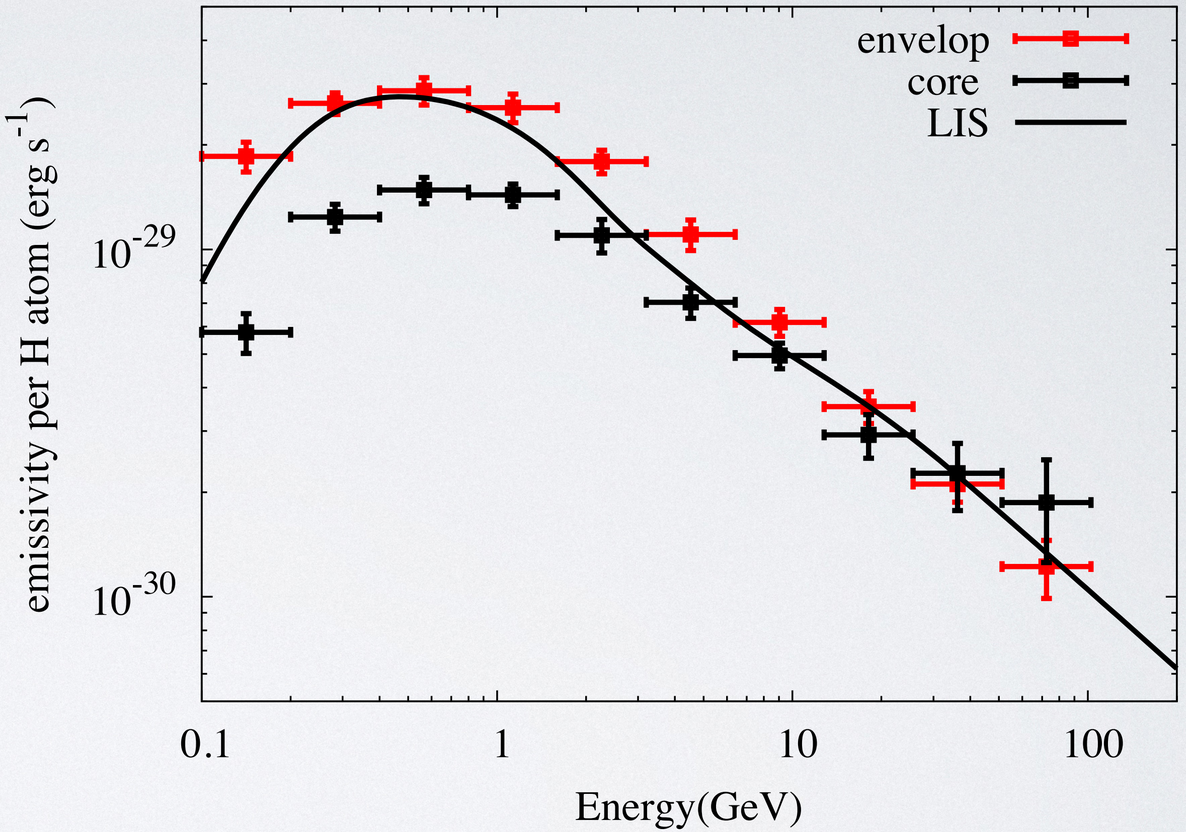


gamma residual (CR density)

Yang et.al 2023 Nature Astronomy 7,351

SLOWER DIFFUSION INSIDE CLUMPS/SUPPRESSION OF CR

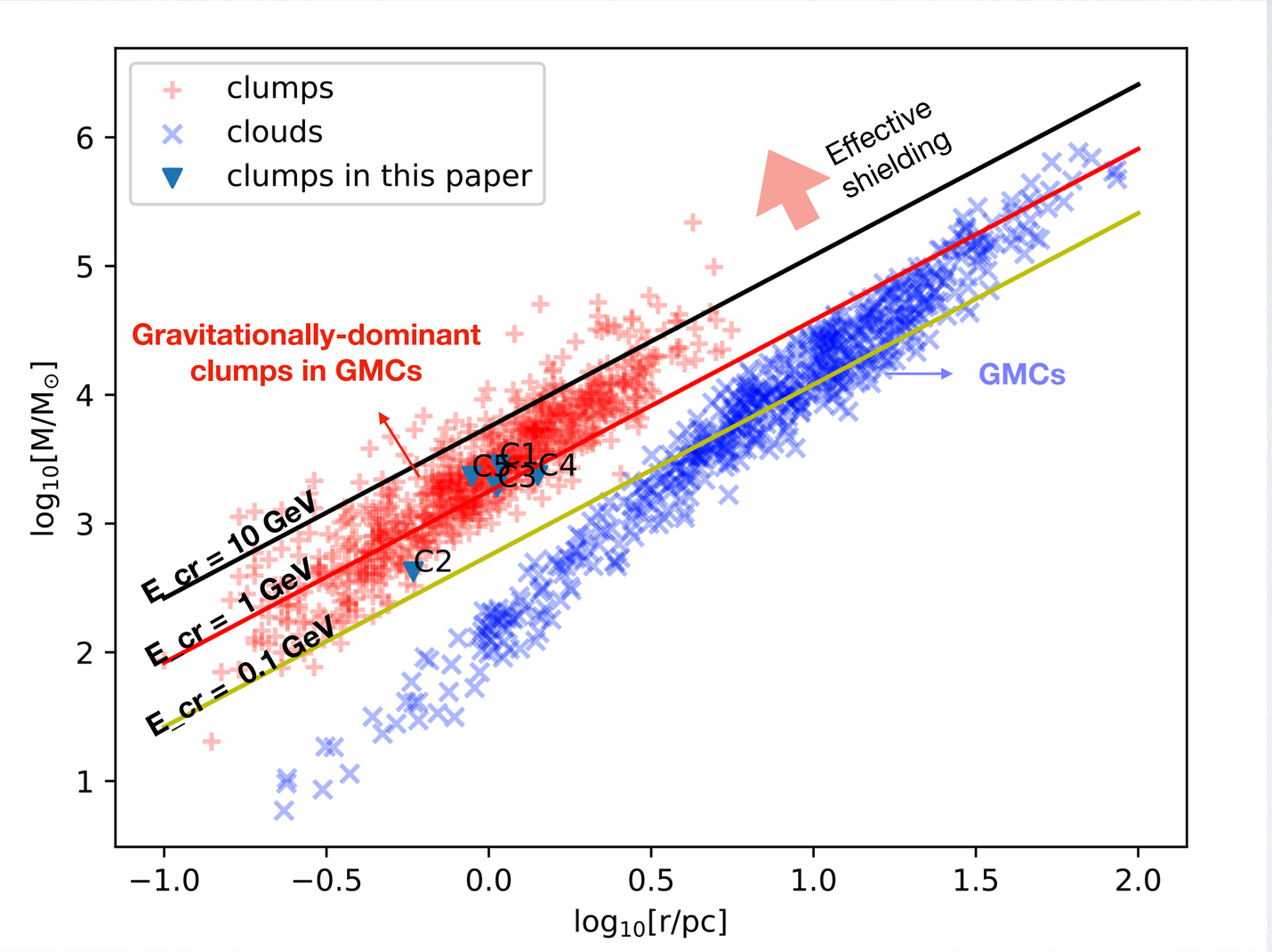




Also 100 times smaller than ISM in GeV

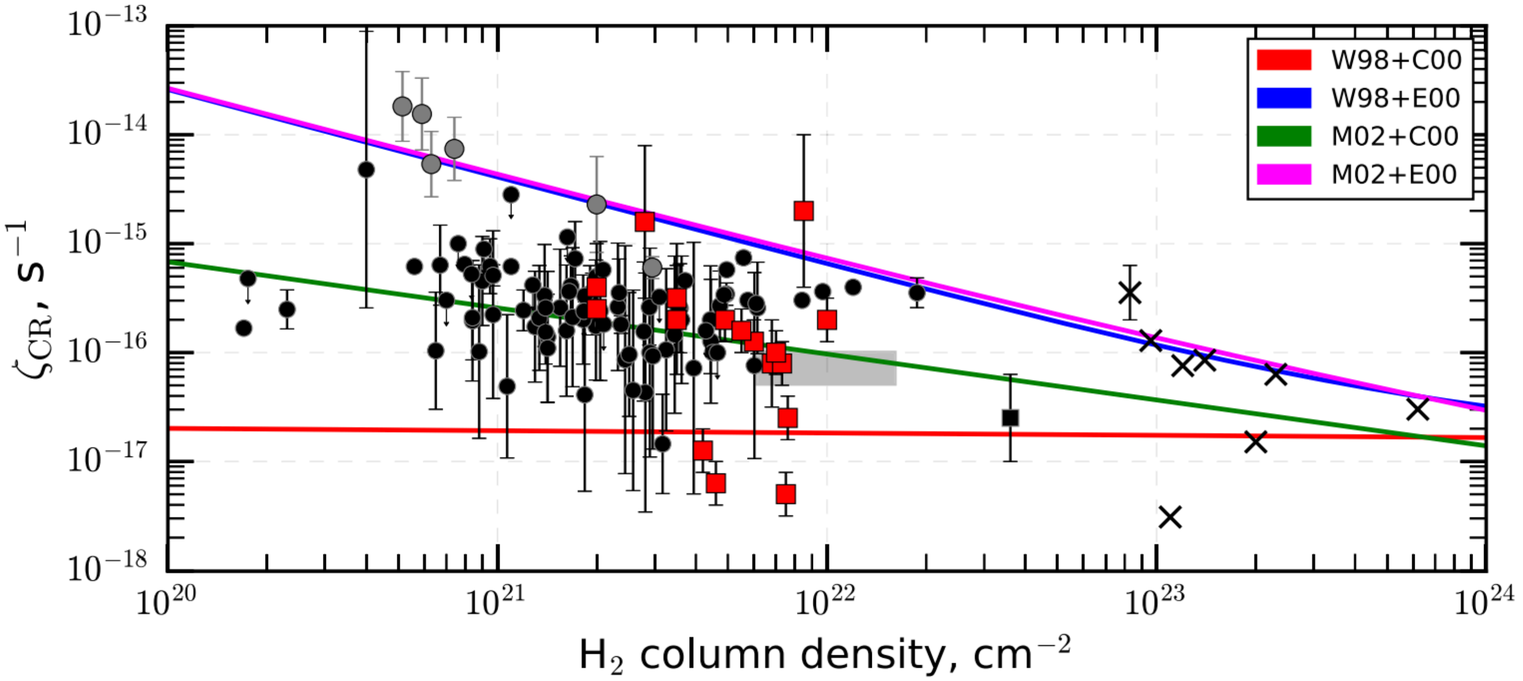
- CR distributed highly inhomegeneously
- low energy cosmic rays (LECR) cannot penetrate into clumps.
- Lower Ionization rate therein?

SLOWER DIFFUSION INSIDE CLUMPS



Possibly due to higher turbulence level in clumps

SMALLER IONIZATION RATE?

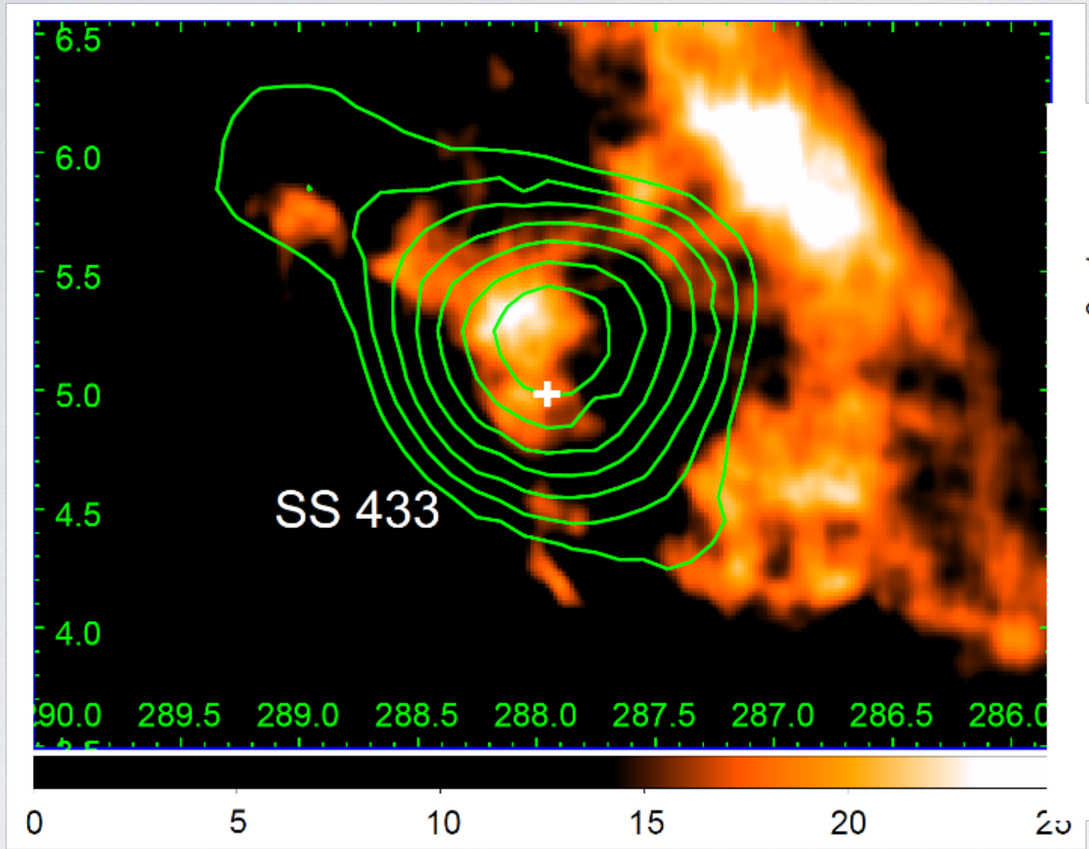


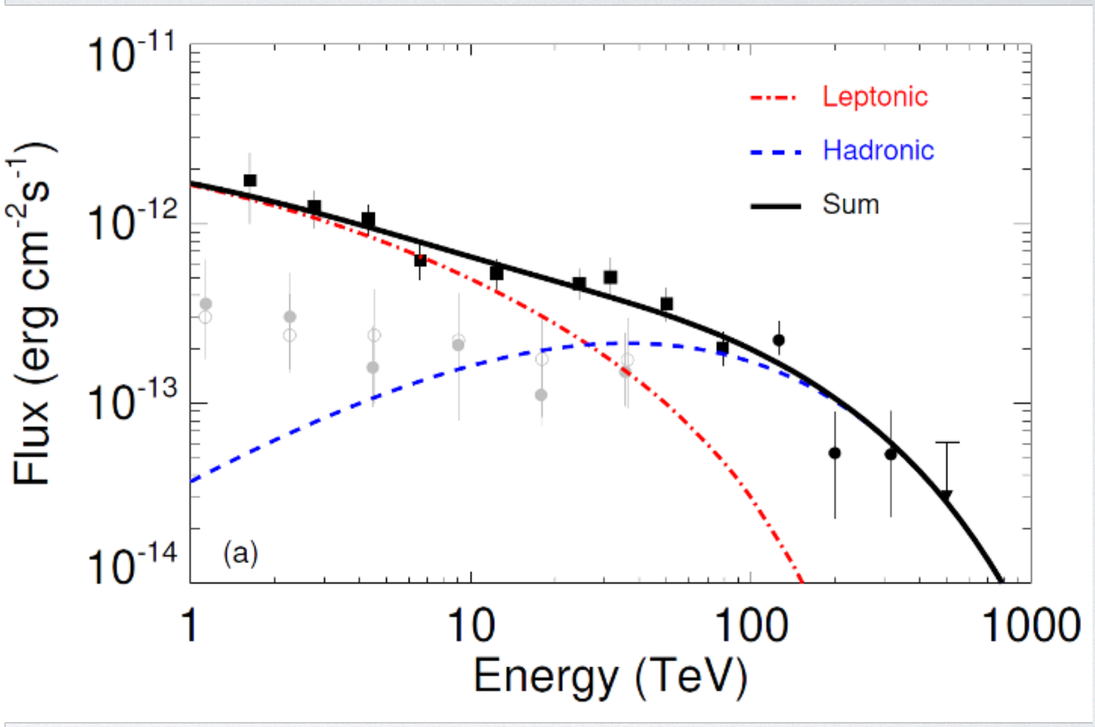
bserved sources with measured H_2 column densities and ζ_{CR}. The symbols specify the type of object in the observations as follows:

CONCLUSIONS

- Gamma-ray observations bring new hints for CR propagation.
- Slow diffusion near source region/ two component diffuse emission
- Slow diffusion in dense molecular clumps.

Microquasars SS 433





- Correlation with gas structures
- Hint for hadronic component at highest energy
- Lp~ 1e38 erg/s, hard spectrum with cutoff > PeV
- Potentially can explain the CRs near the knee

LHAASO collaborations arXiv: 2410.08988