EFFECTIVE CONFINEMENT OF COSMIC RAYS NEAR ACCELERATORS

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outline

1. ***Excess*** **of galactic diffuse emission**

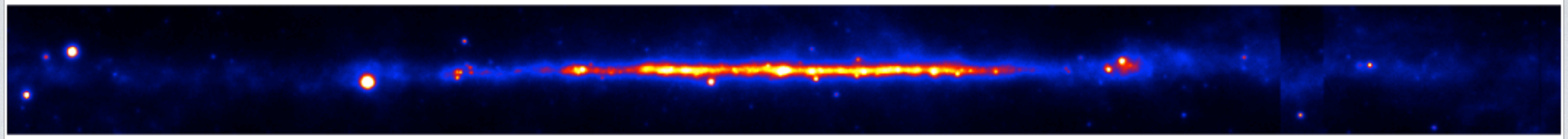
2. ***Anomalies*** **in direct measurement of secondary cosmic rays (CRs)**

3. ***Effective confinement*** **of CRs as an unified explanation**

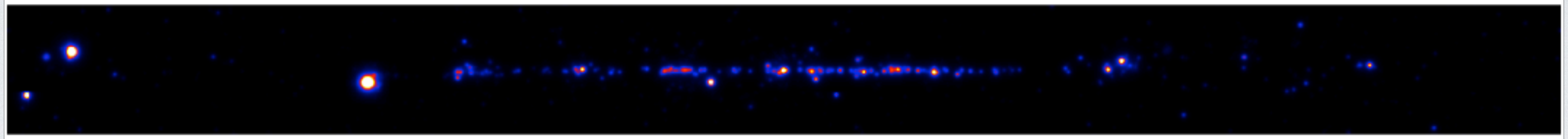
DIFFUSE GAMMA

DIFFUSE GAMMA-RAY EMISSIONS

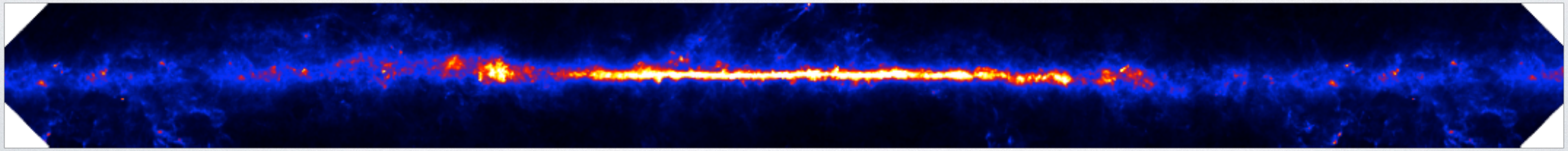
Gamma-ray counts map



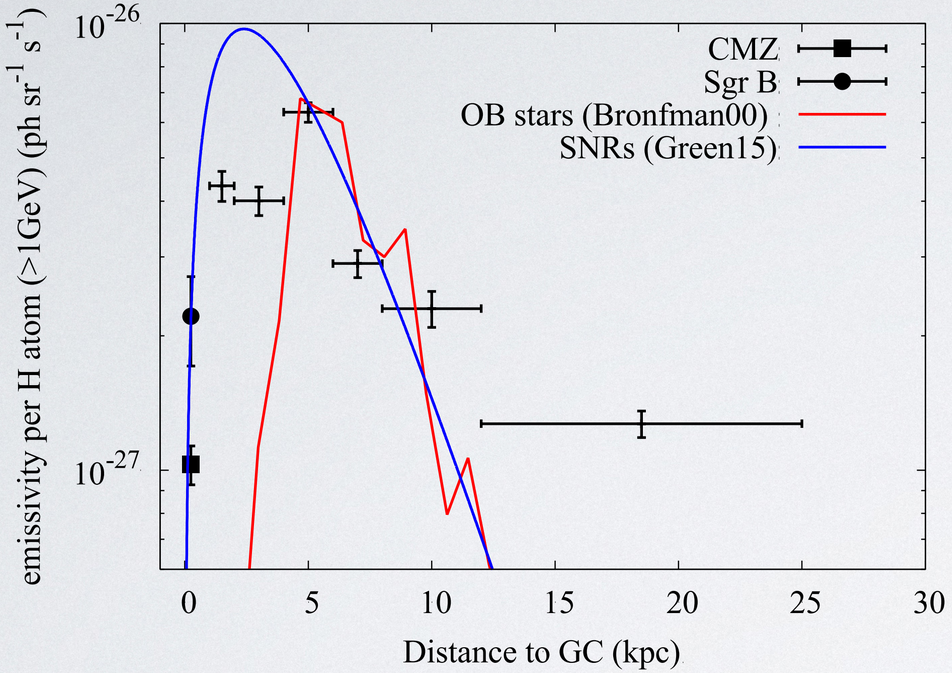
Point source contribution

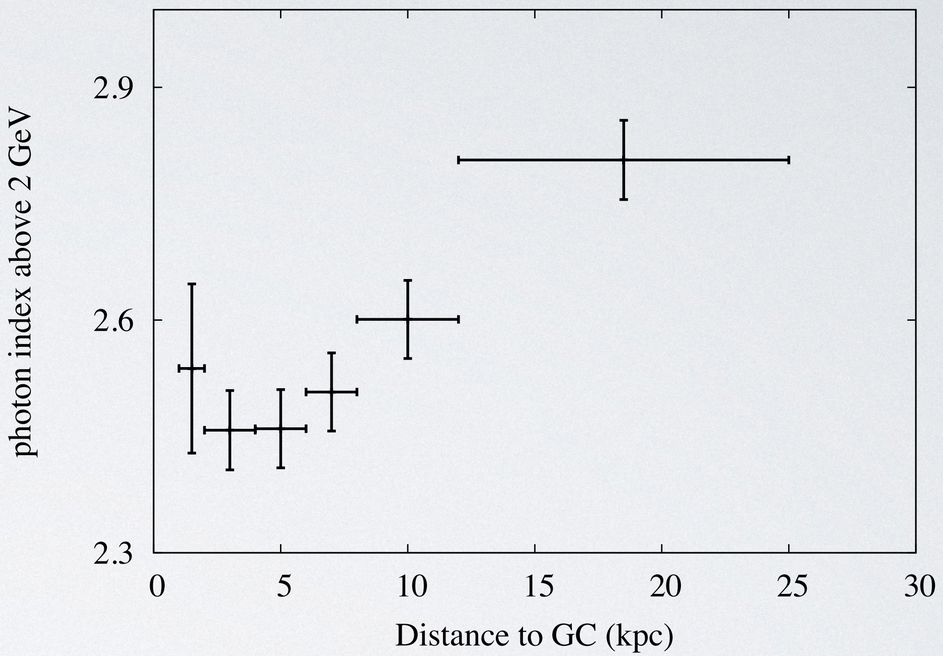


Dust opacity map (gas column)



CR RADIAL DISTRIBUTIONS IN THE MILKY WAY



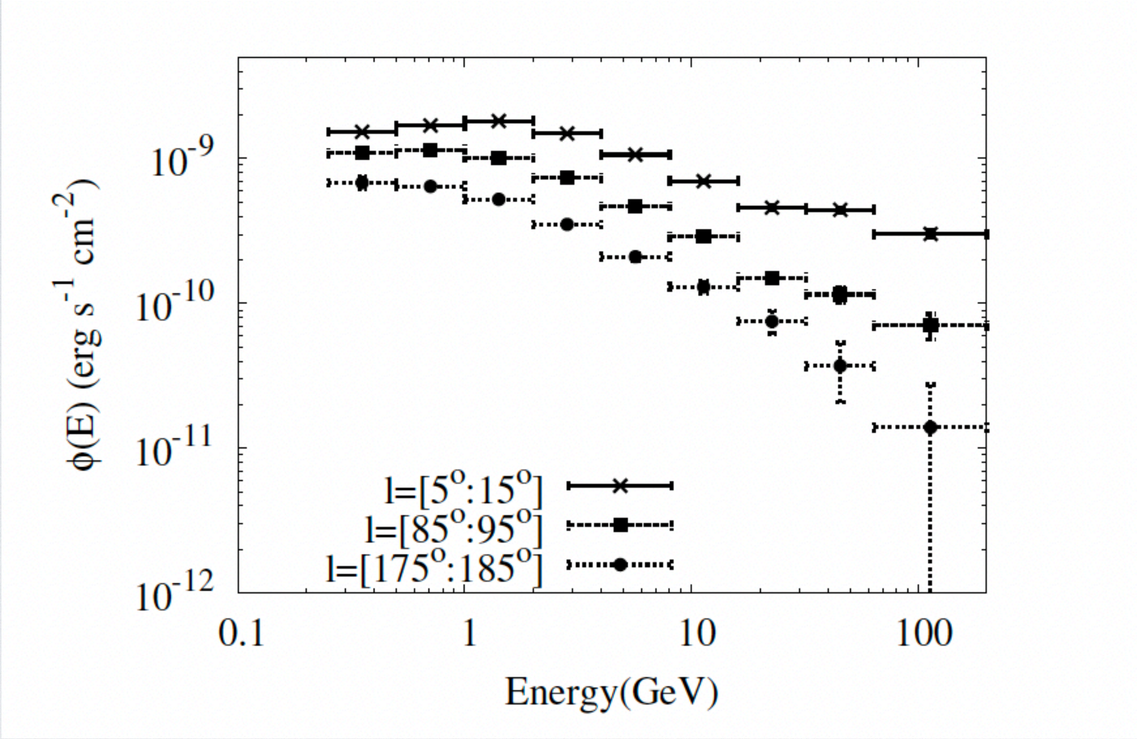


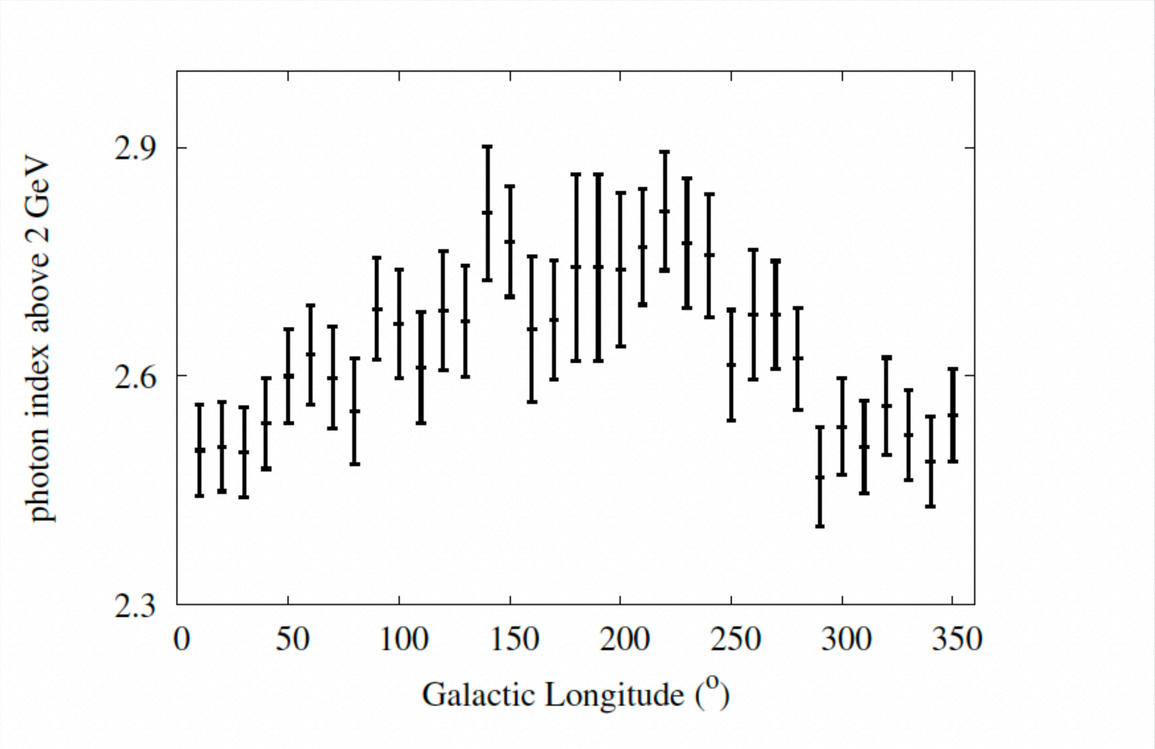
Yang et.al 2016

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

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

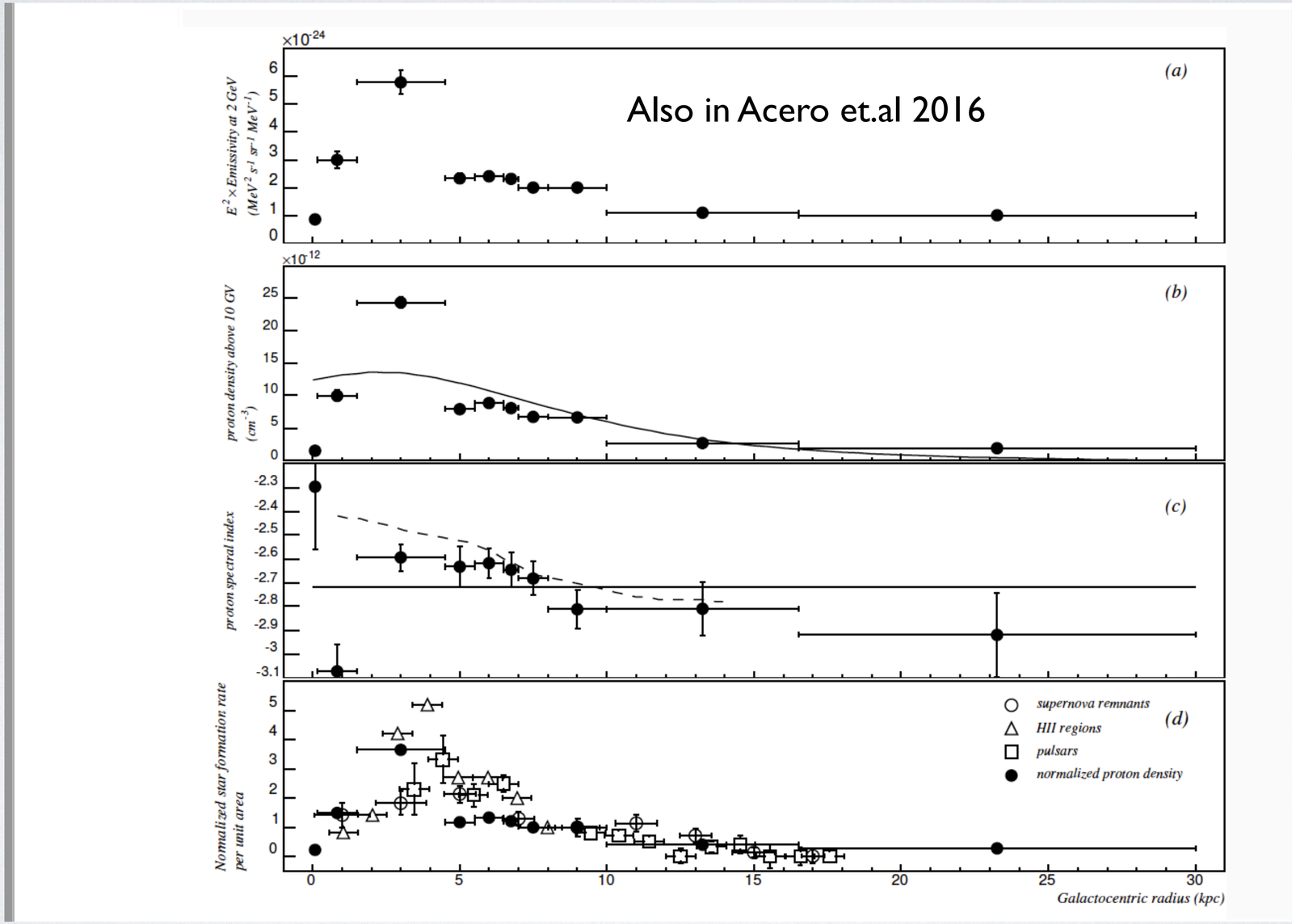
CR RADIAL DISTRIBUTIONS IN THE MILKY WAY



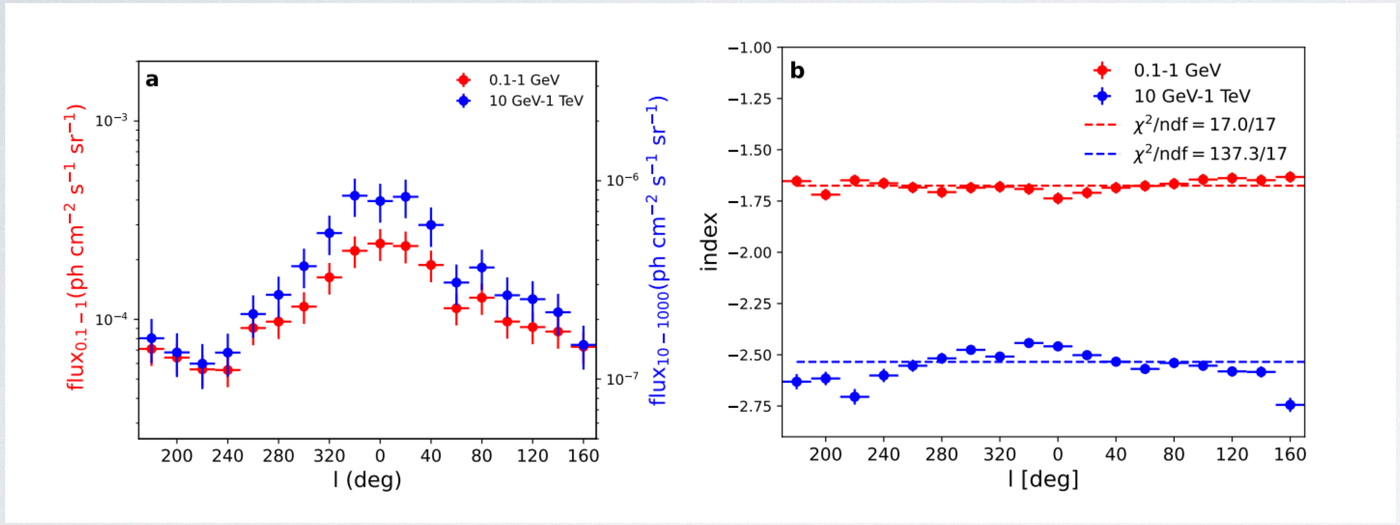


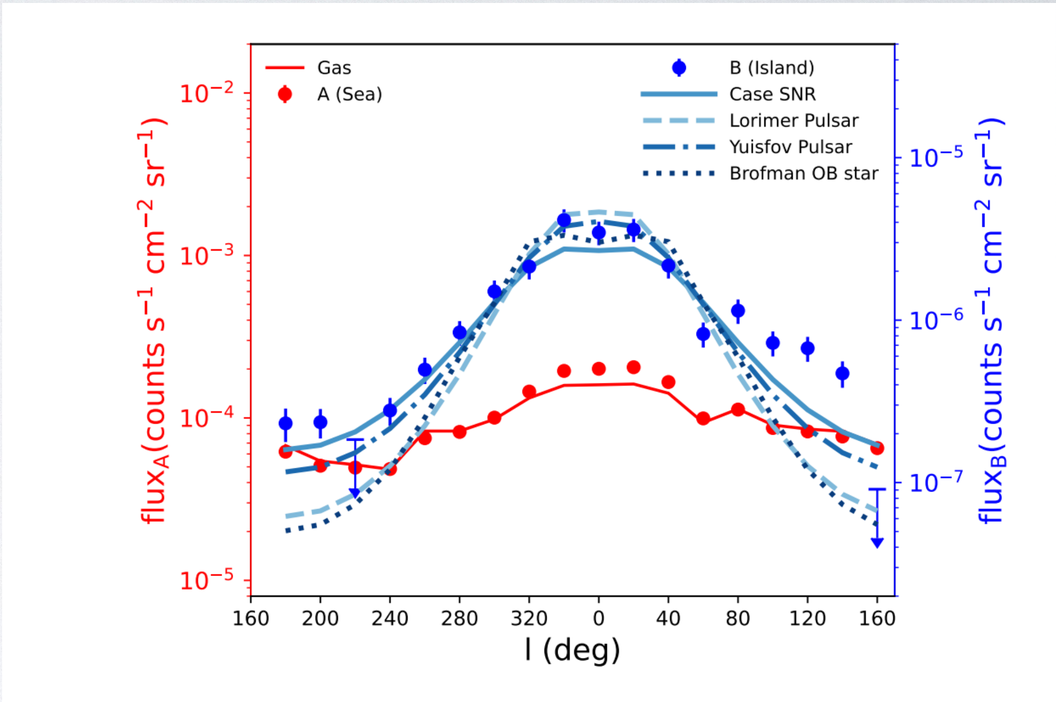
Yang et.al 2016
significant variation of index in different LOS

CR RADIAL DISTRIBUTIONS IN THE MILKY WAY



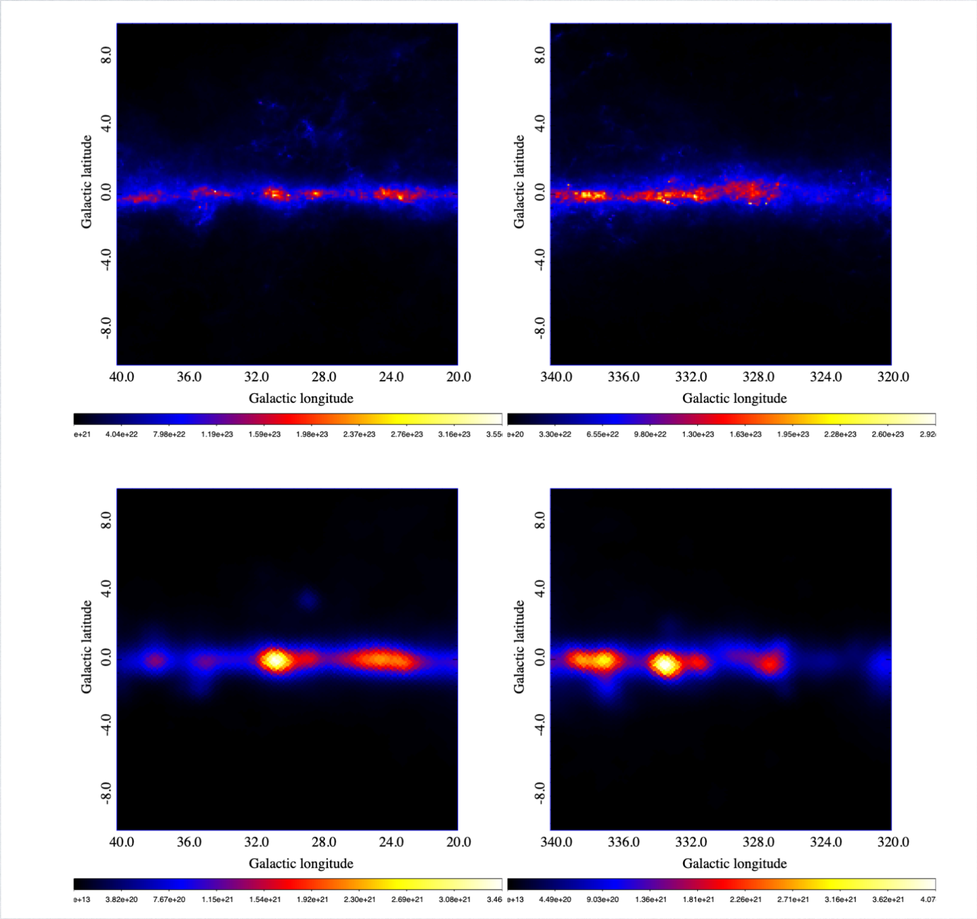
TWO COMPONENT CR/DIFFUSE GAMMA?

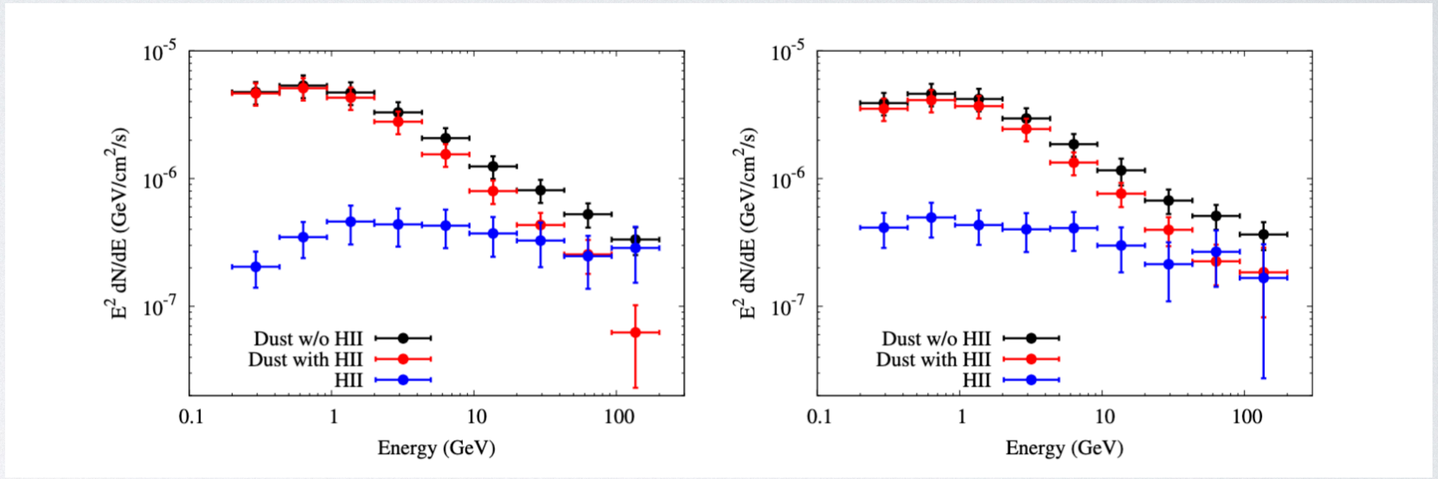




ALSO SEE arXiv:2509.26290 using spectral component separation

TWO COMPONENT CR/DIFFUSE GAMMA?

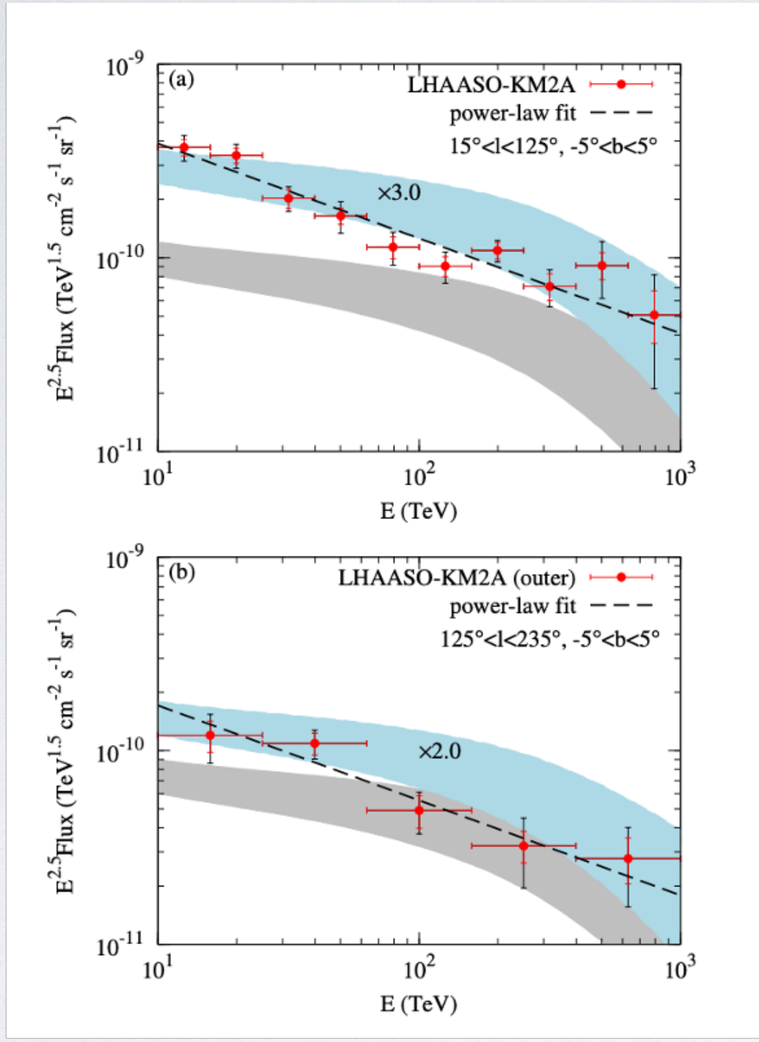




- After considering HII component the CR distributions looks **“more homogeneous”**
- The former inhomogeneity is simply due to the mixing of “true” diffuse (sea) component with hard “source” (island) regions

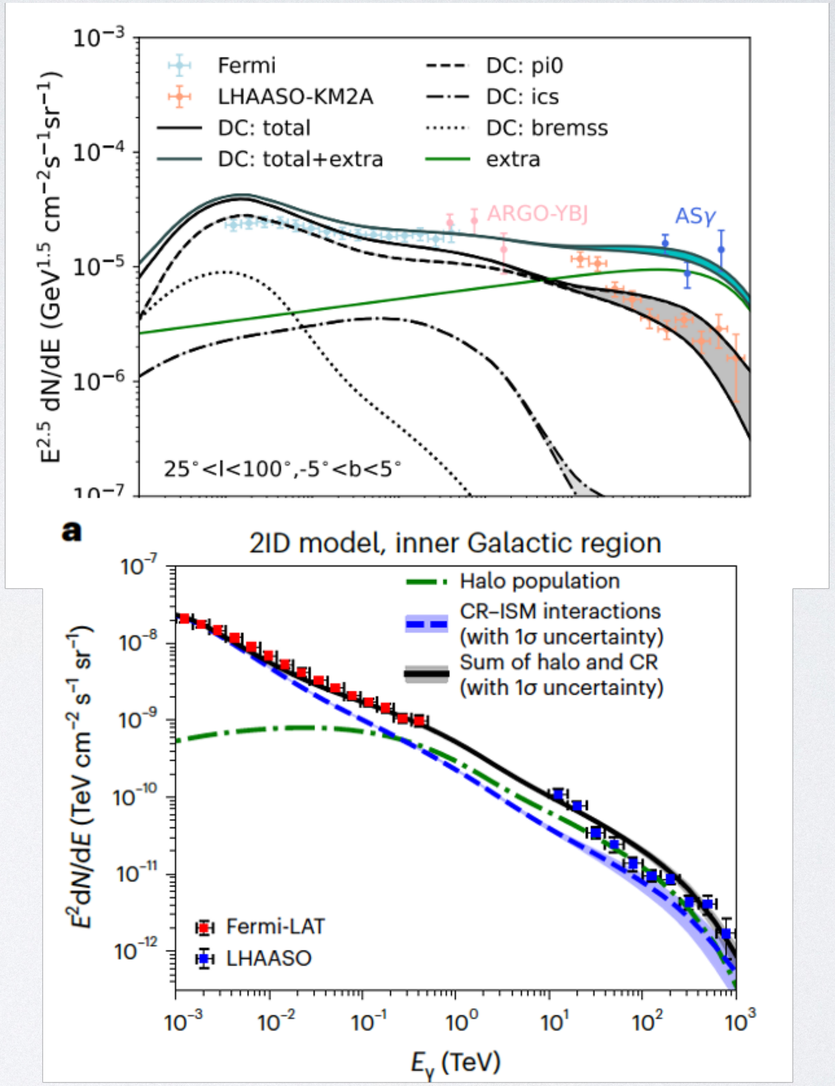
Liu et.al A&A 659, A101 (2022)

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?

SECONDARY CRS

‘STANDARD’ CR PROPAGATION PICTURE

- Diffusion in an extended halo

- Primary injection spectrum (e.g, from DSA)

  $Q(E) \sim E^{-\Upsilon}$

- Confinement time (leaky box or diffusion model)

  $\tau(E) \sim E^{-\delta}$

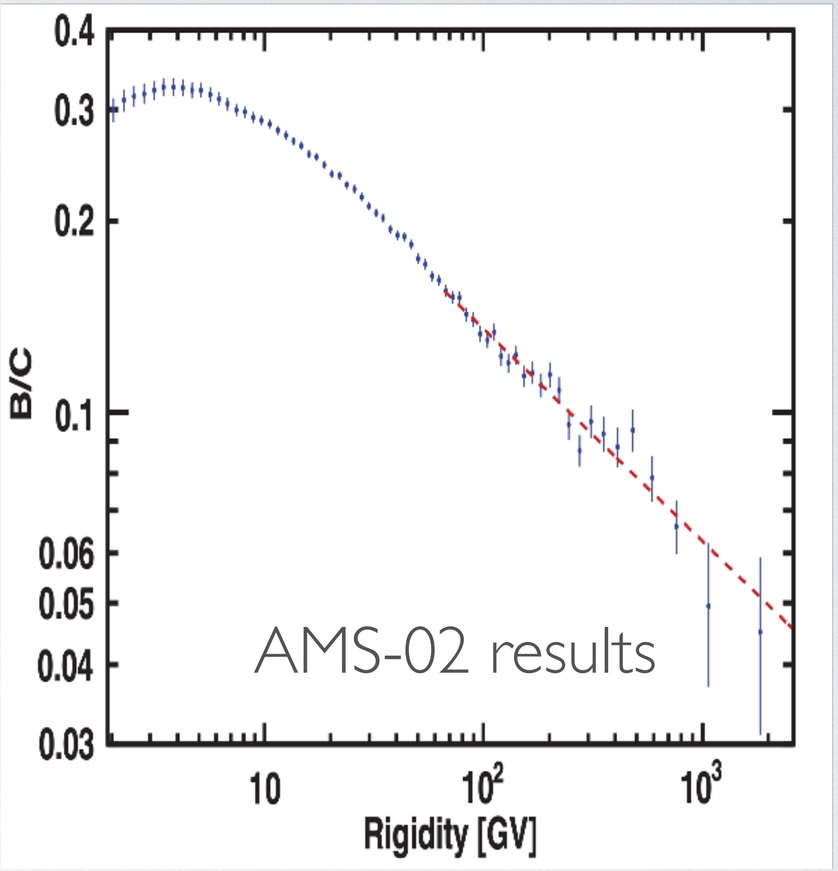
- Steady state primary spectrum

  $N(E) \sim Q(E)\,\tau(E) \sim E^{-(\Upsilon+\delta)}$

- Steady state secondary spectrum

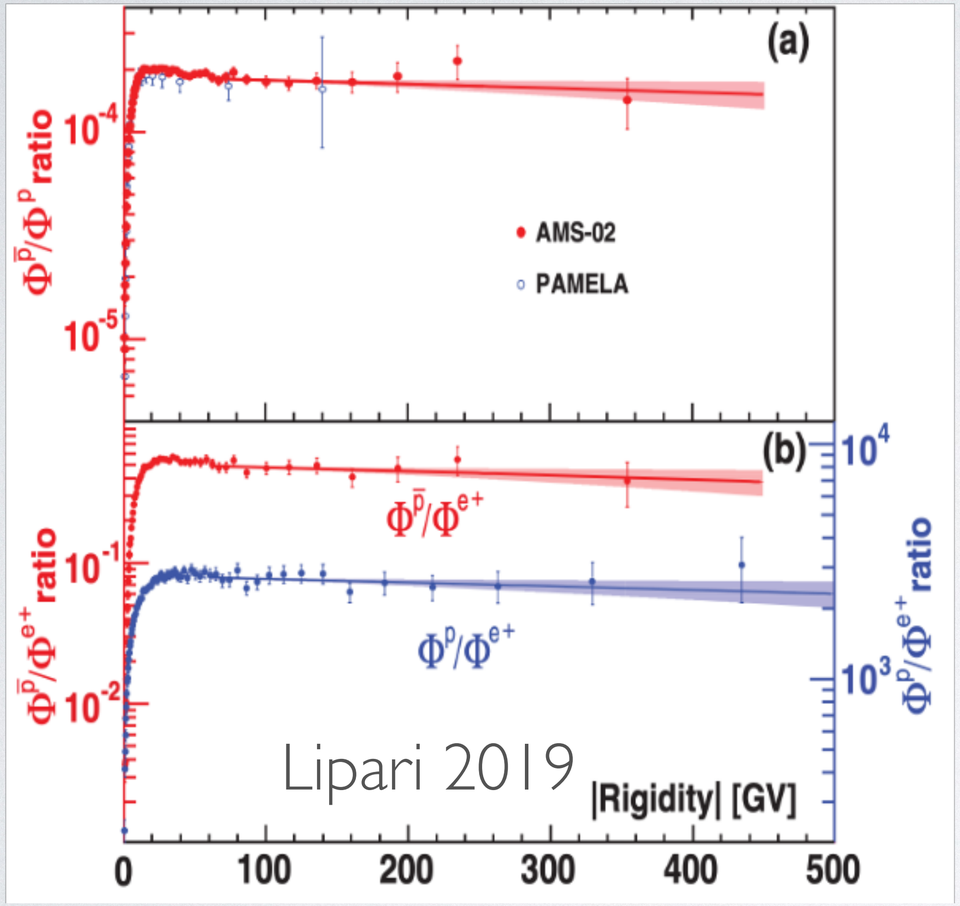
  $N(E) \sim Q(E)\,\tau 2(E) \sim E^{-(\Upsilon+2\delta)}$

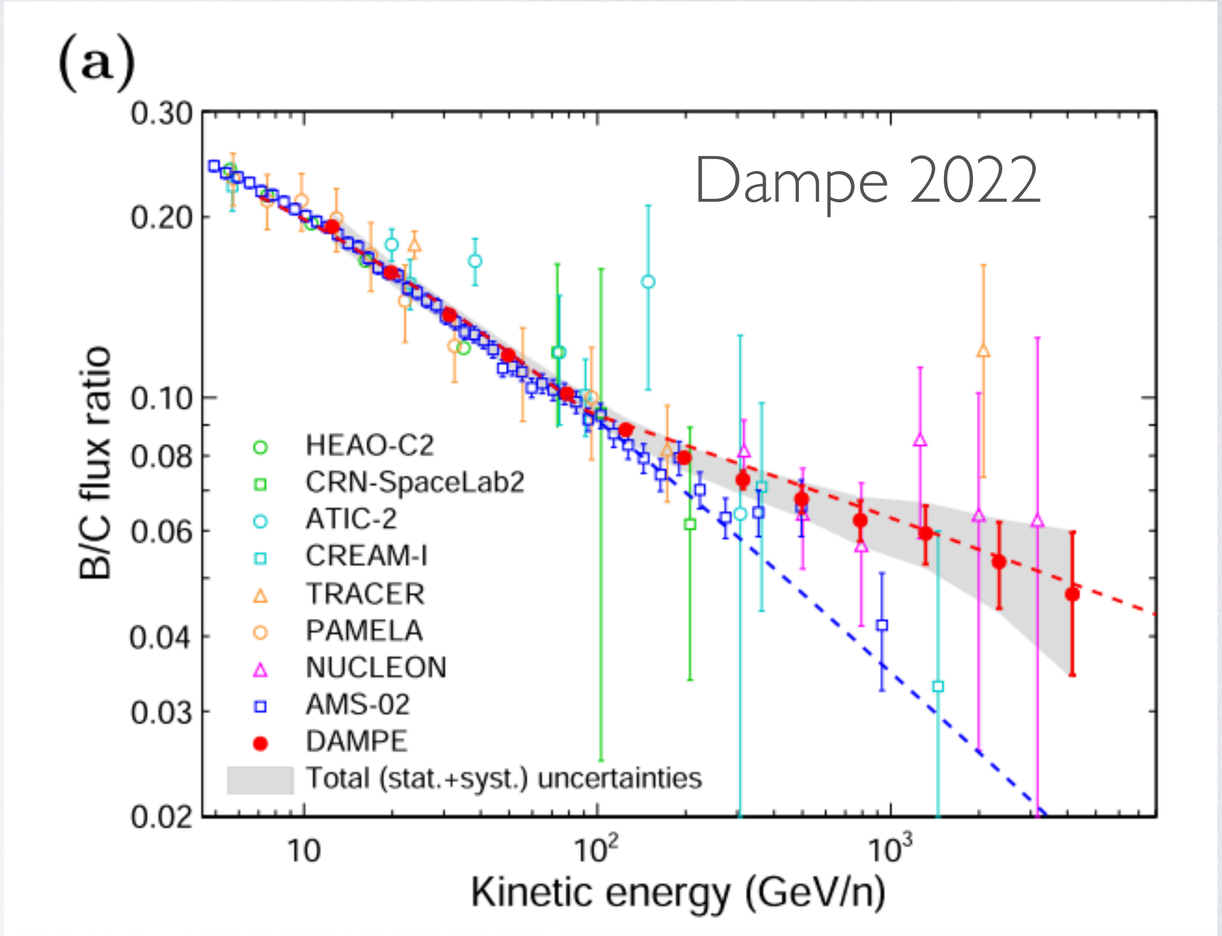
- Secondary/primary ratio ~ $E^{-\delta}$ (B/C observations)



in consistent below 1 TeV

ANTIPROTON/POSITRON/BORON TO CARBON

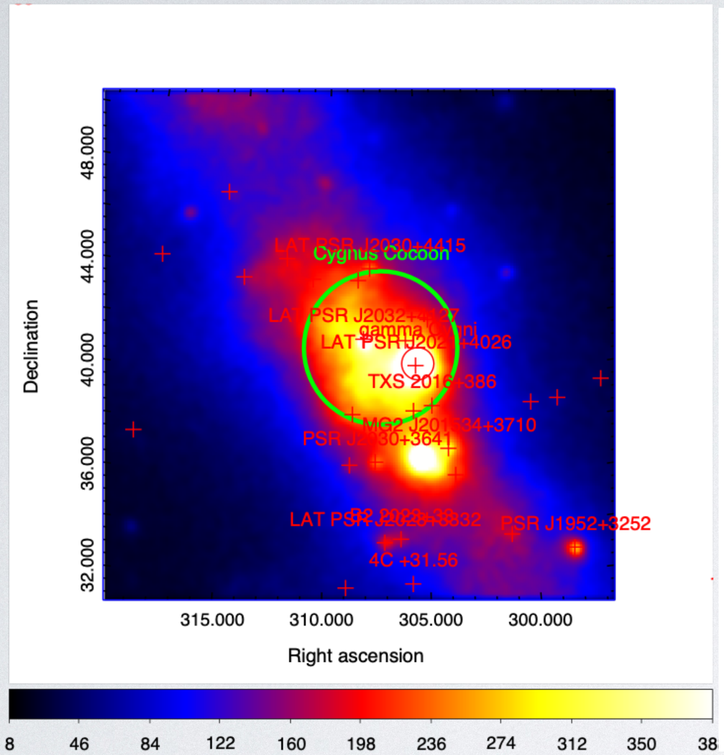


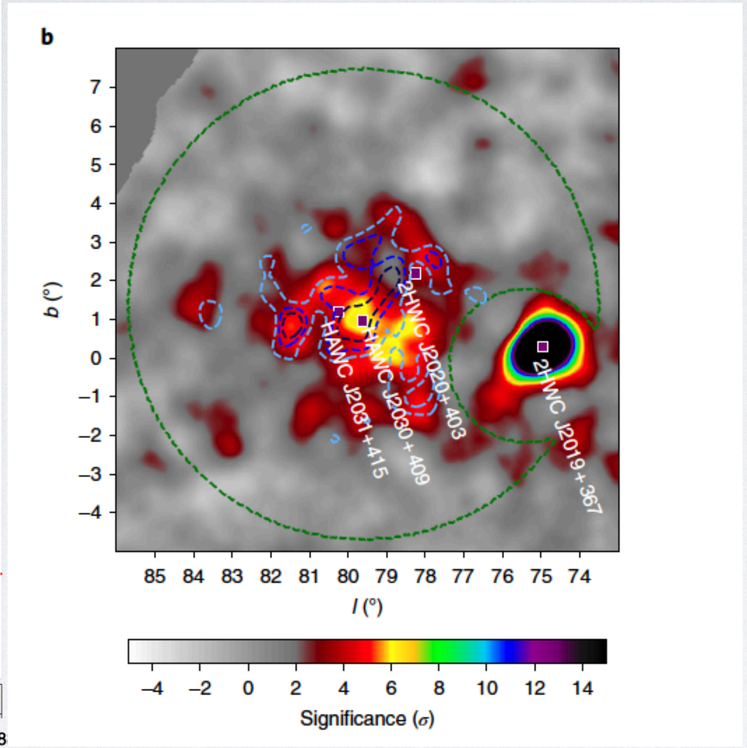


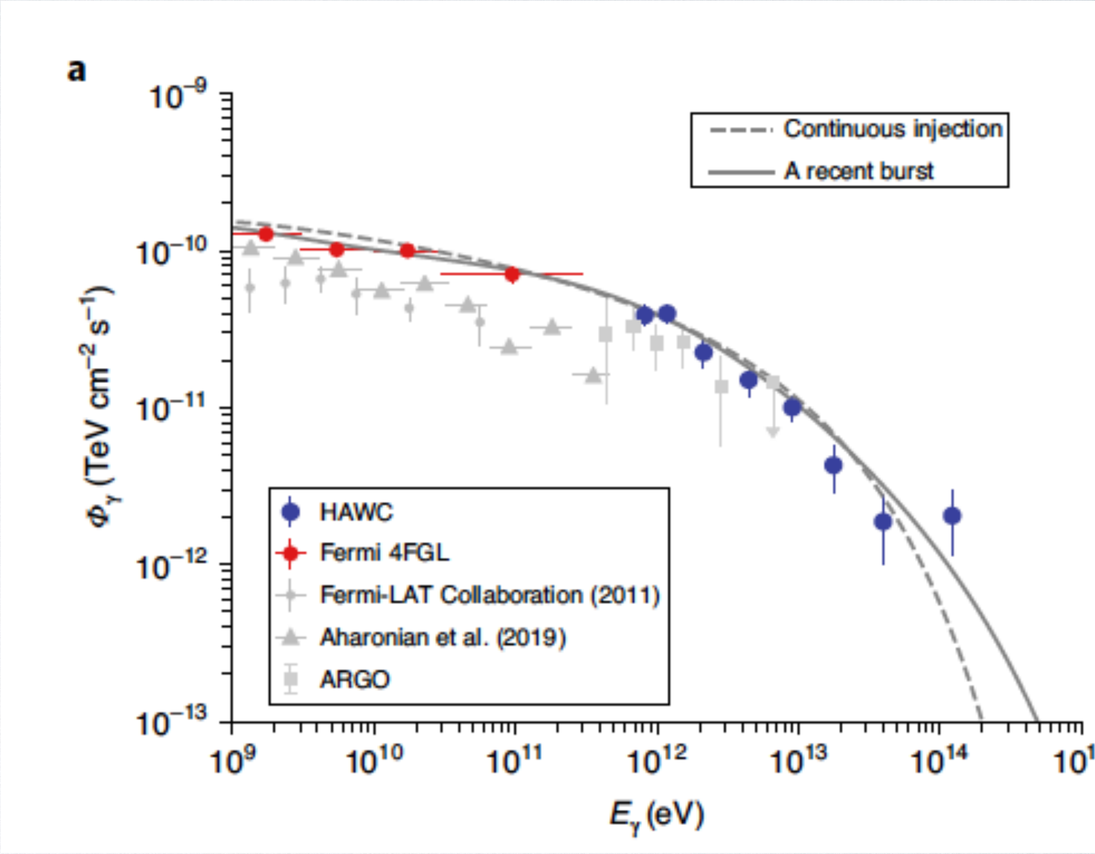
Significant excess require modification to the "standard" model

CONFINEMENT NEAR THE SOURCES

CYGNUS COCOON

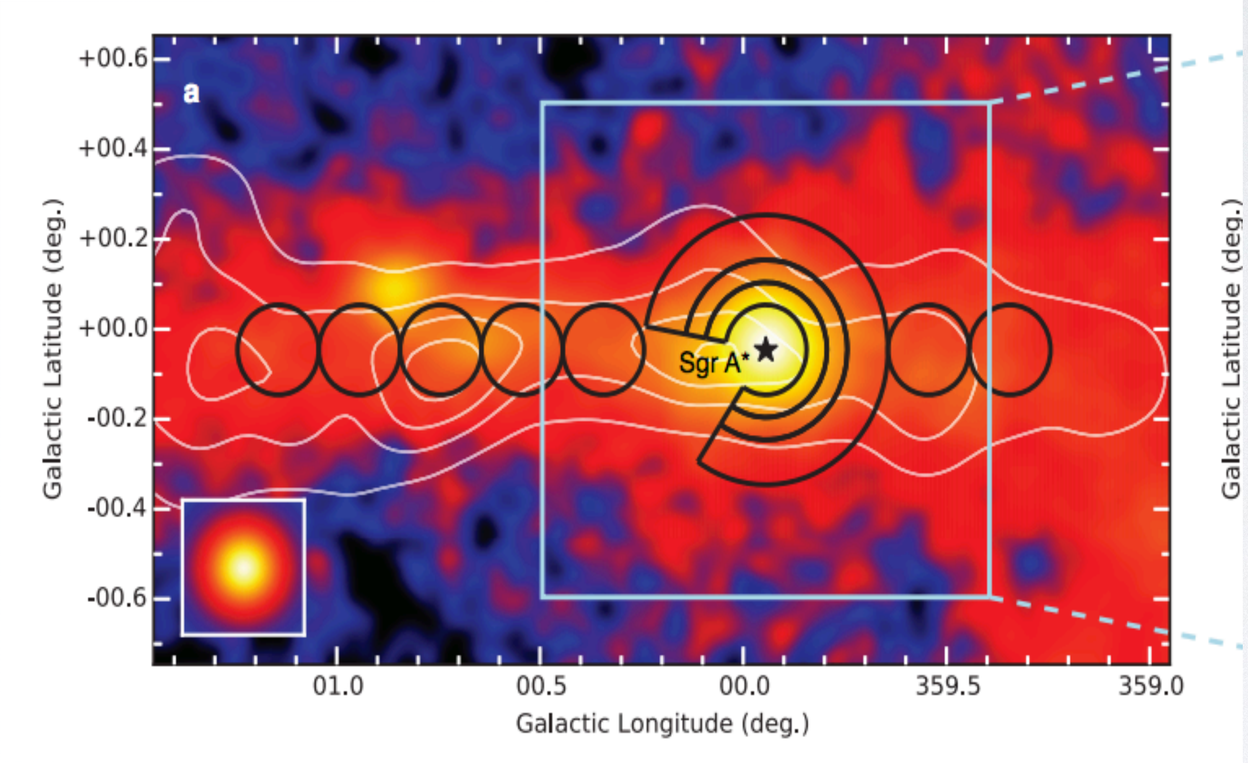


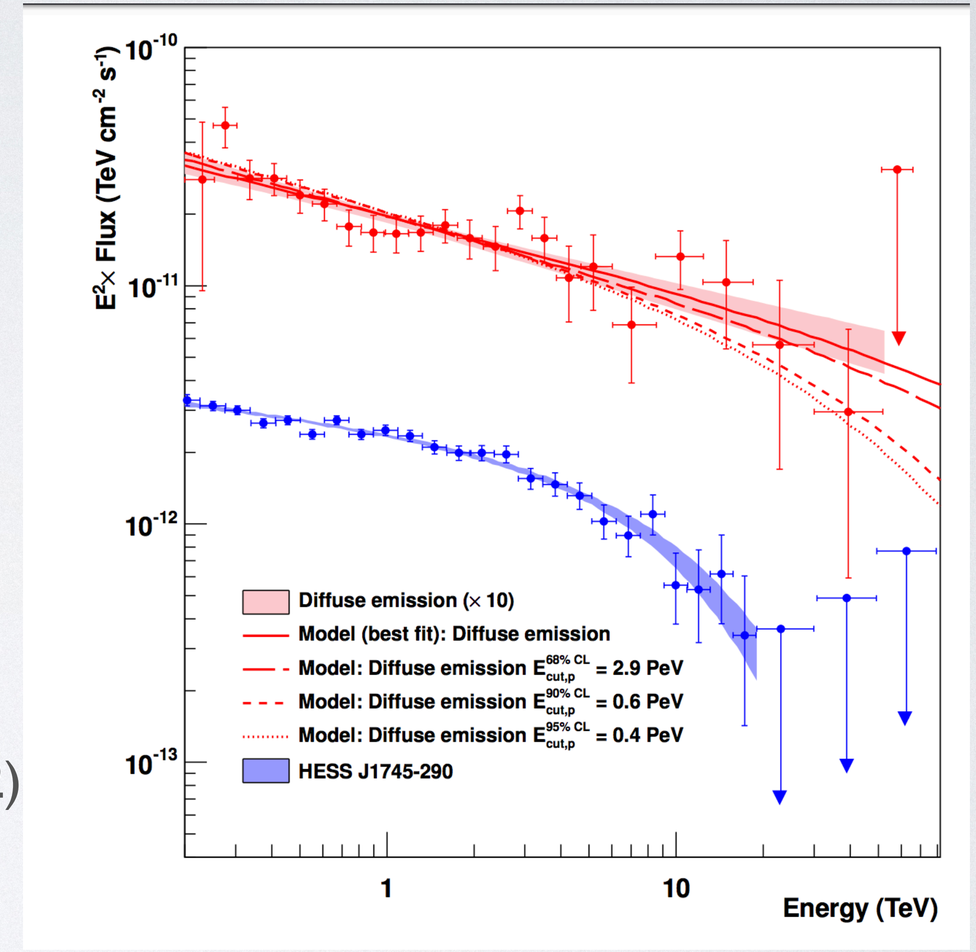




- Observed by Fermi LAT, ARGO-YBJ & HAWC
- extended emission up to more than 50 pc (150 pc from LHAASO)
- Hard spectrum in GeV band, softening above TeV

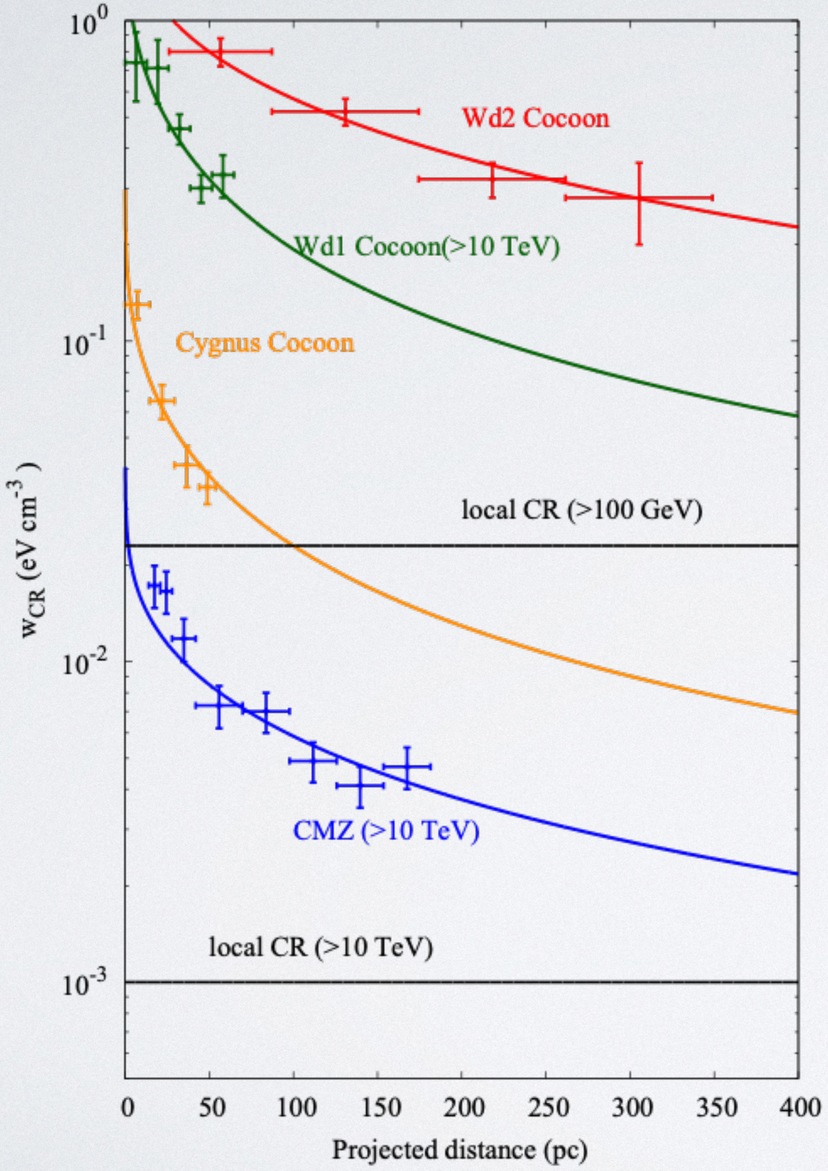
GALACTIC CENTER (HESS 2016)





- 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

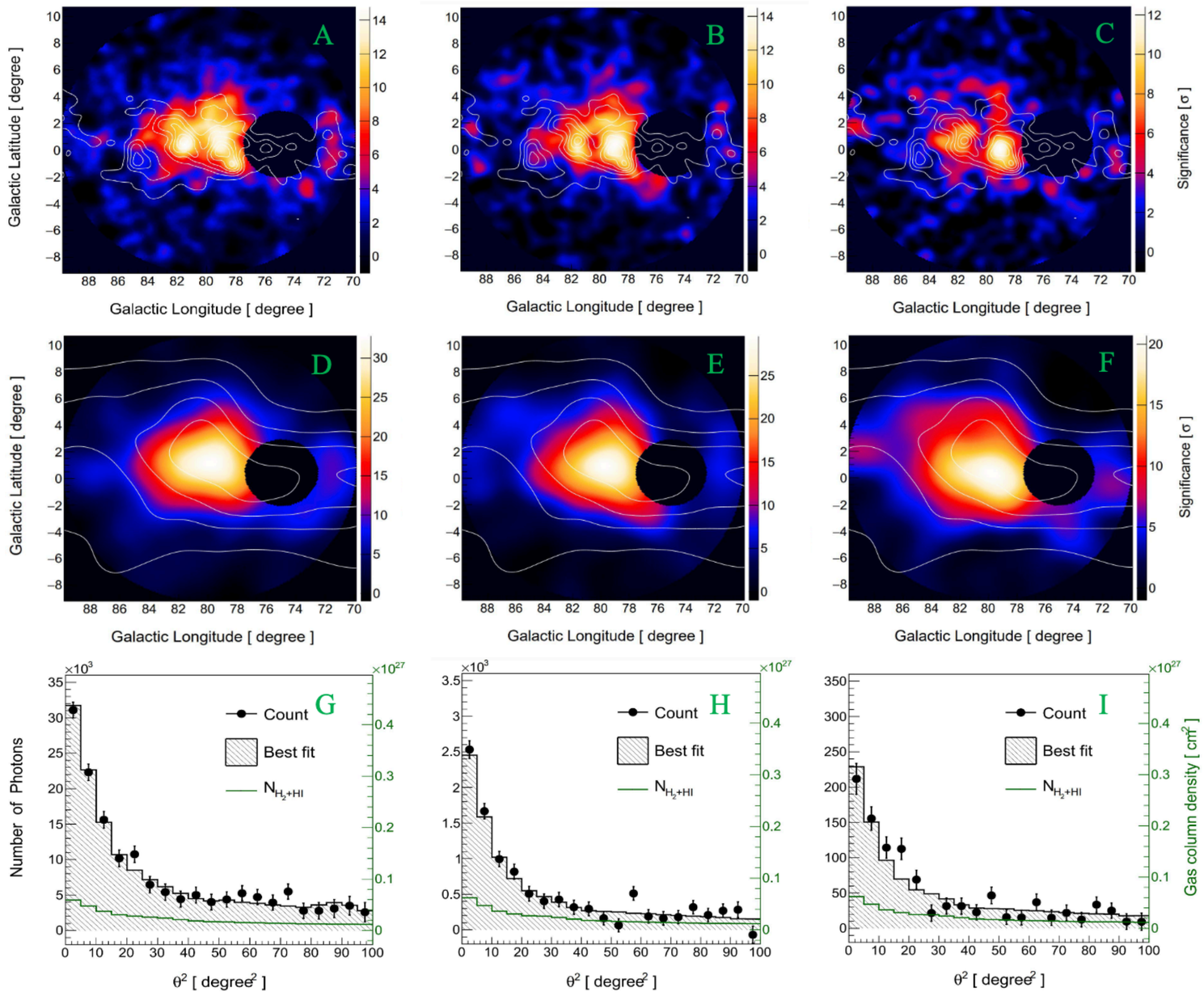
RADIAL DISTRIBUTION OF COSMIC RAYS



- 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

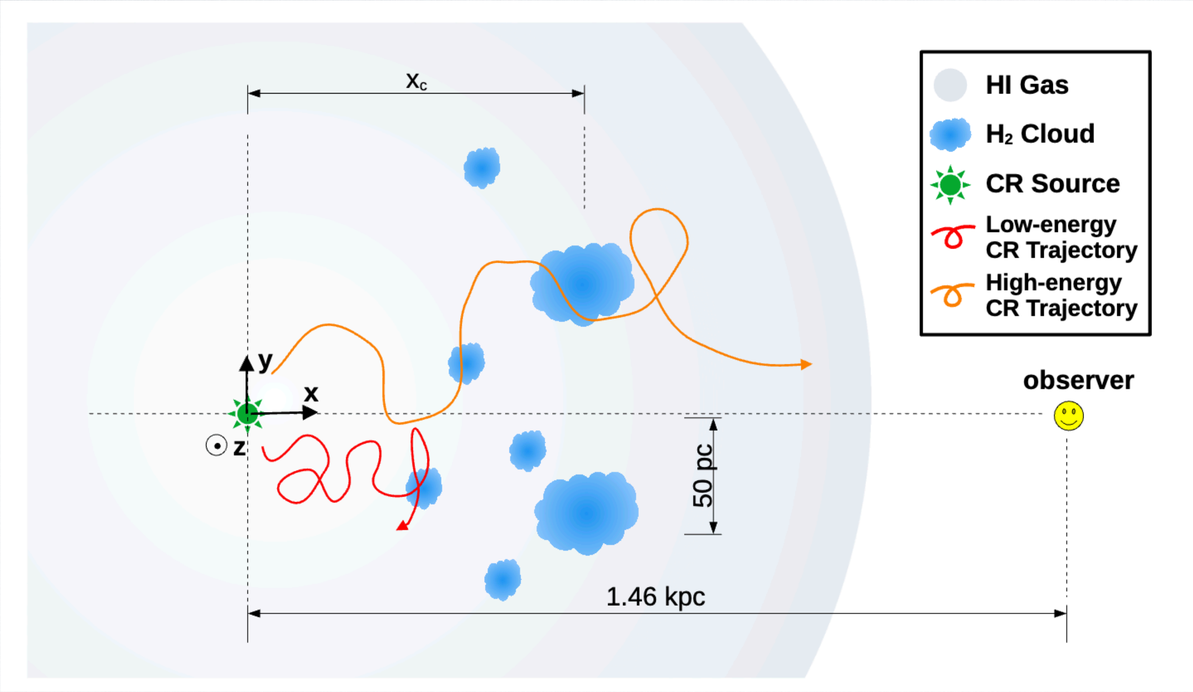
LHAASO VIEW ON CYGNUS

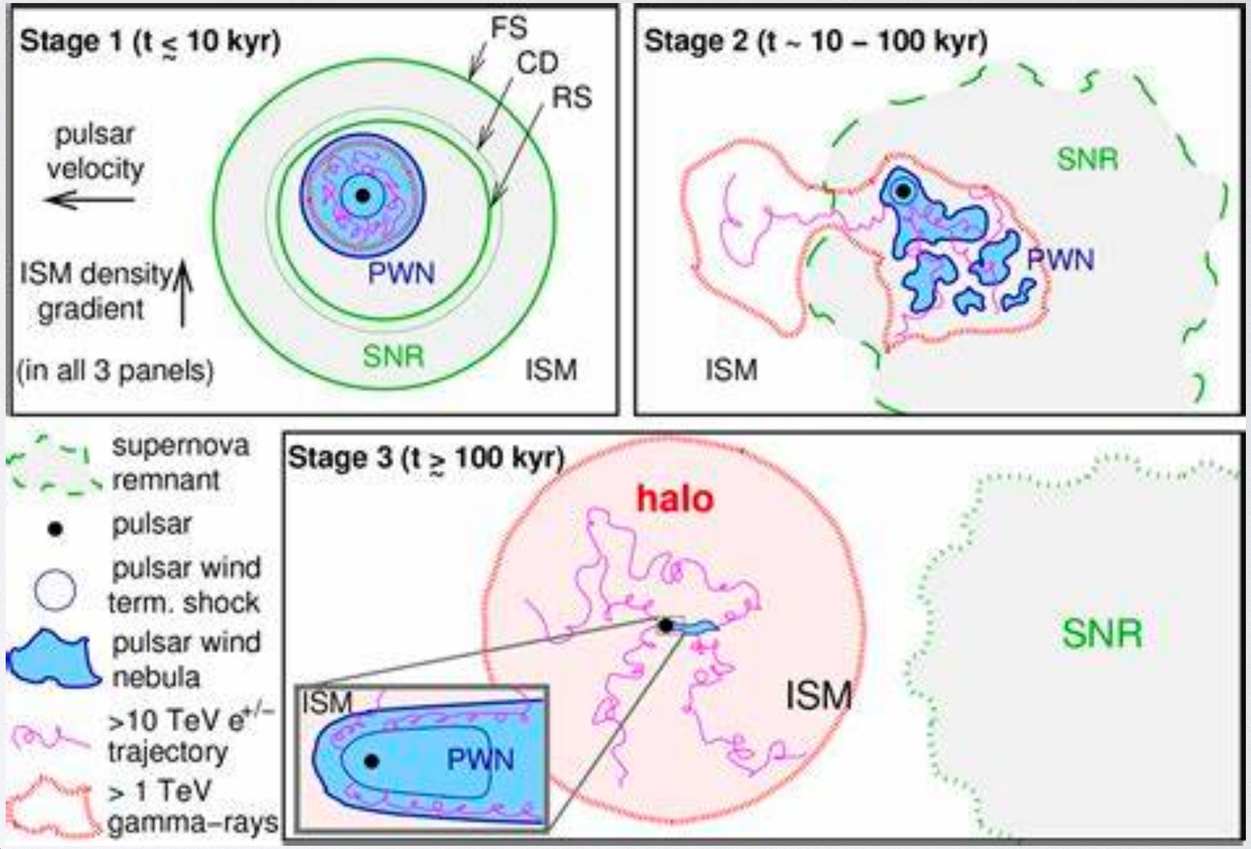


Huge bubble beyond ~10 degrees (200 pc)

LHAASO collaboration Science Bulletin (2024) 69,449

RELATED SOURCES TO THE DIFFUSE GAMMA?



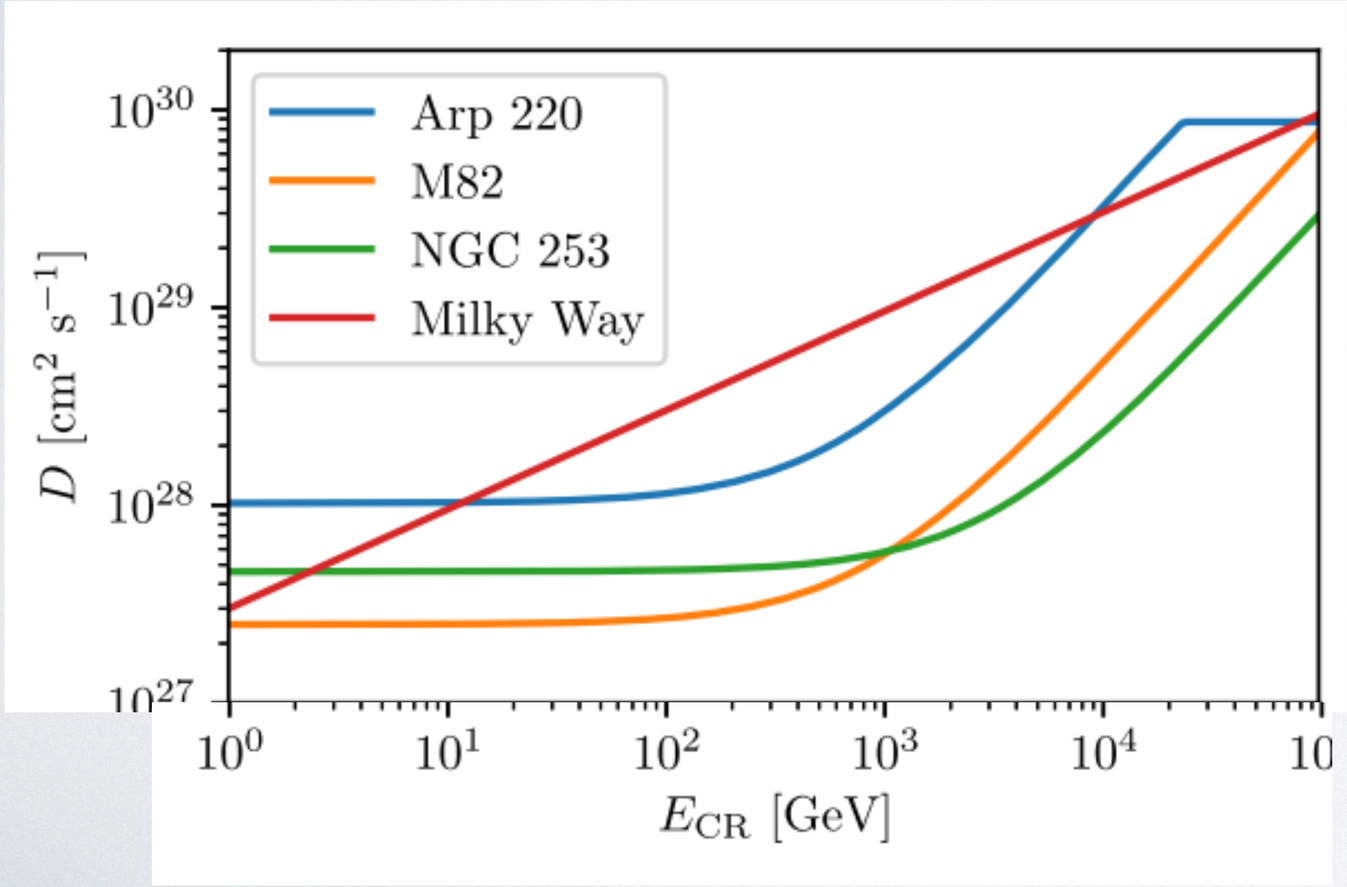


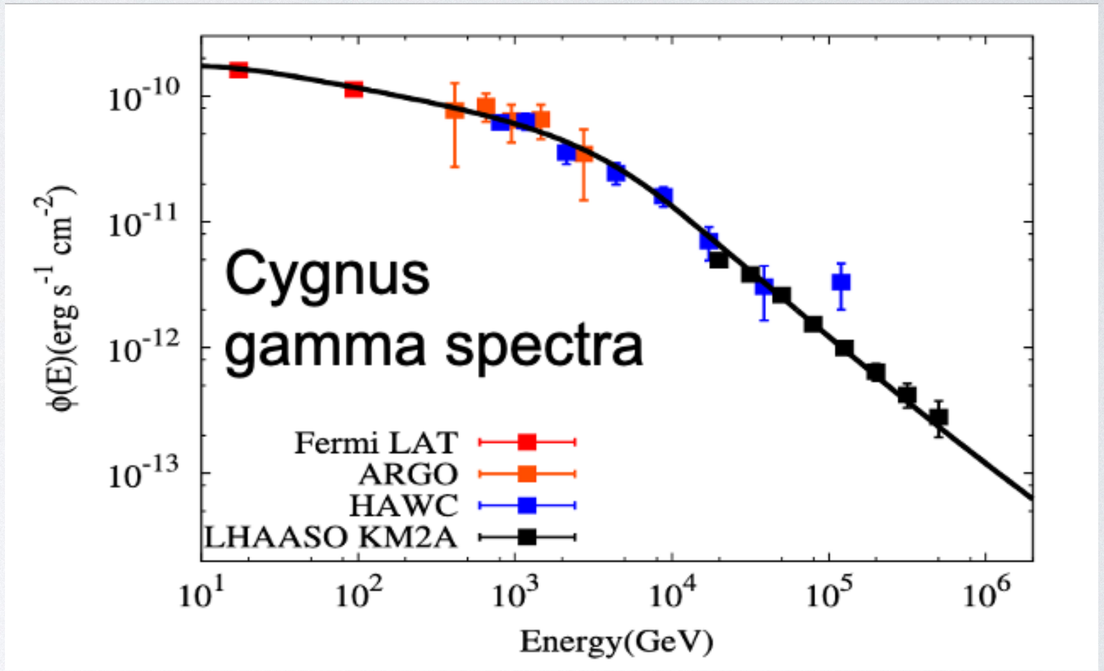
- Central continuous injection of CRs up to PeV
- **Slow diffusion** near the source (1/100 of fiducial value)
- Harder spectra from Molecular clouds

Slow diffusion inside pulsar Halos

SLOW DIFFUSION REGIONS

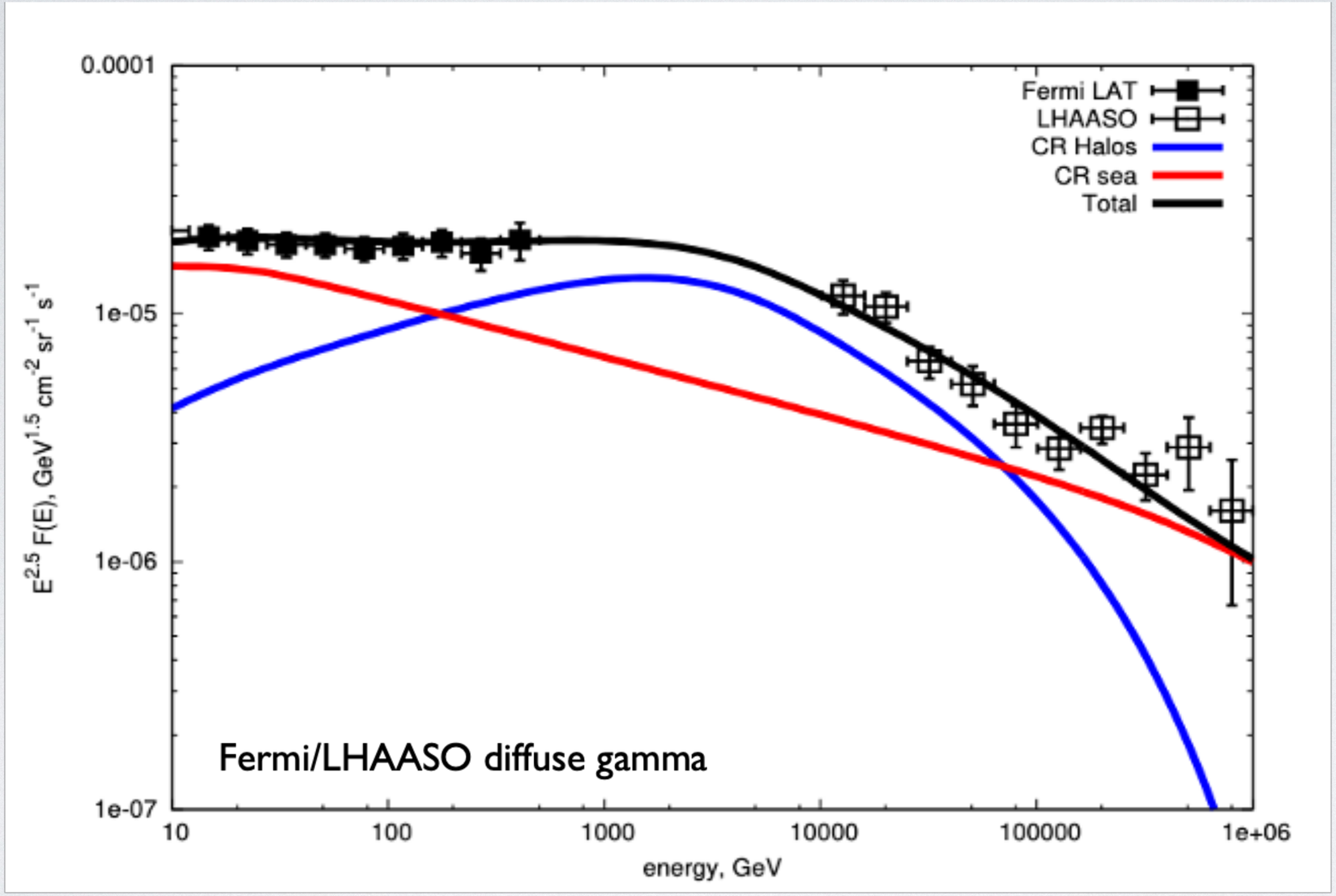
- Possible energy independent escape from Source regions (normal assumption if CR streaming dominate the magnetic turbulence, e.g. Krumholz 2019)





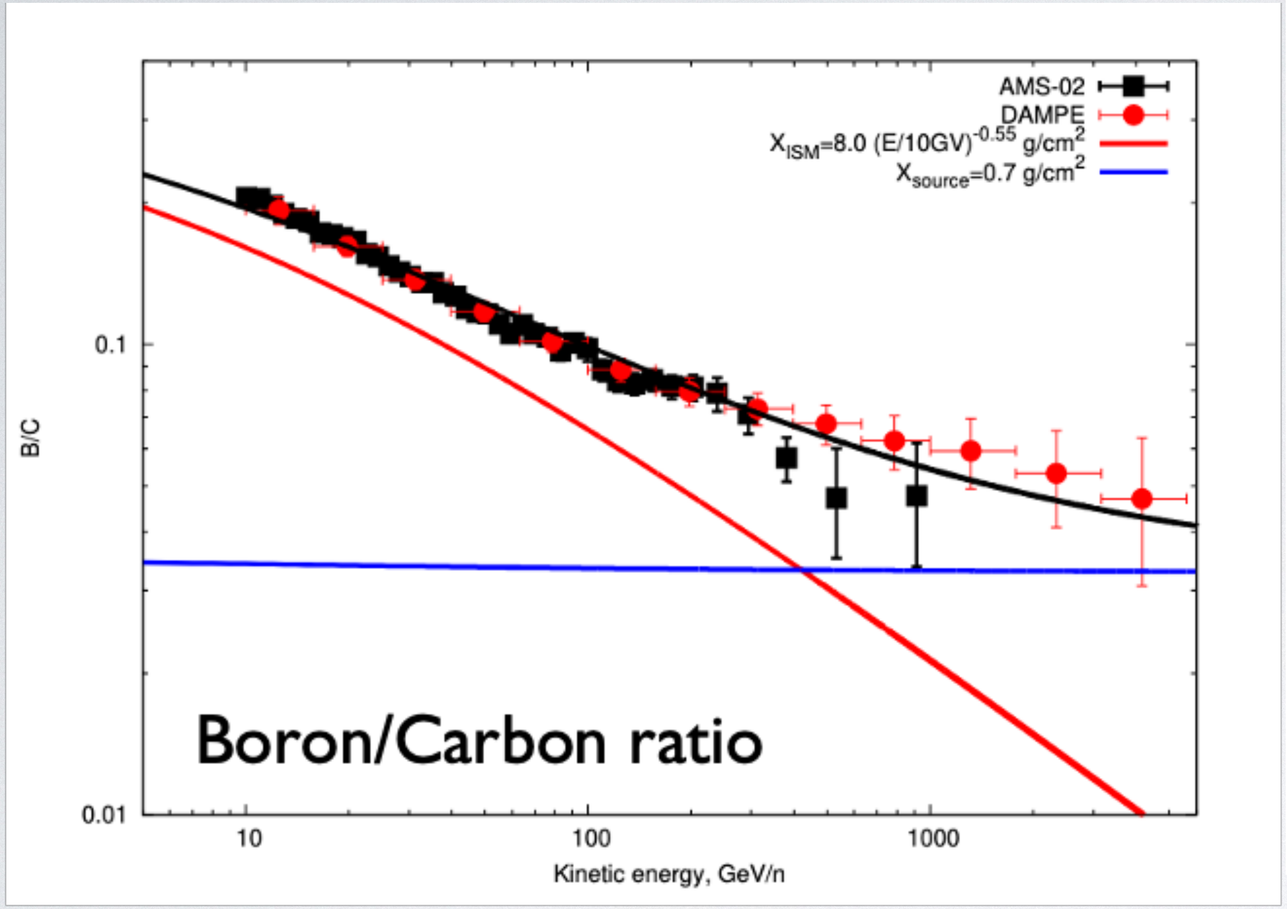
- Effective confinement (slow diffussion) of CR near accelerators
- energy independent below ~10 TeV, from Cygnus spectra

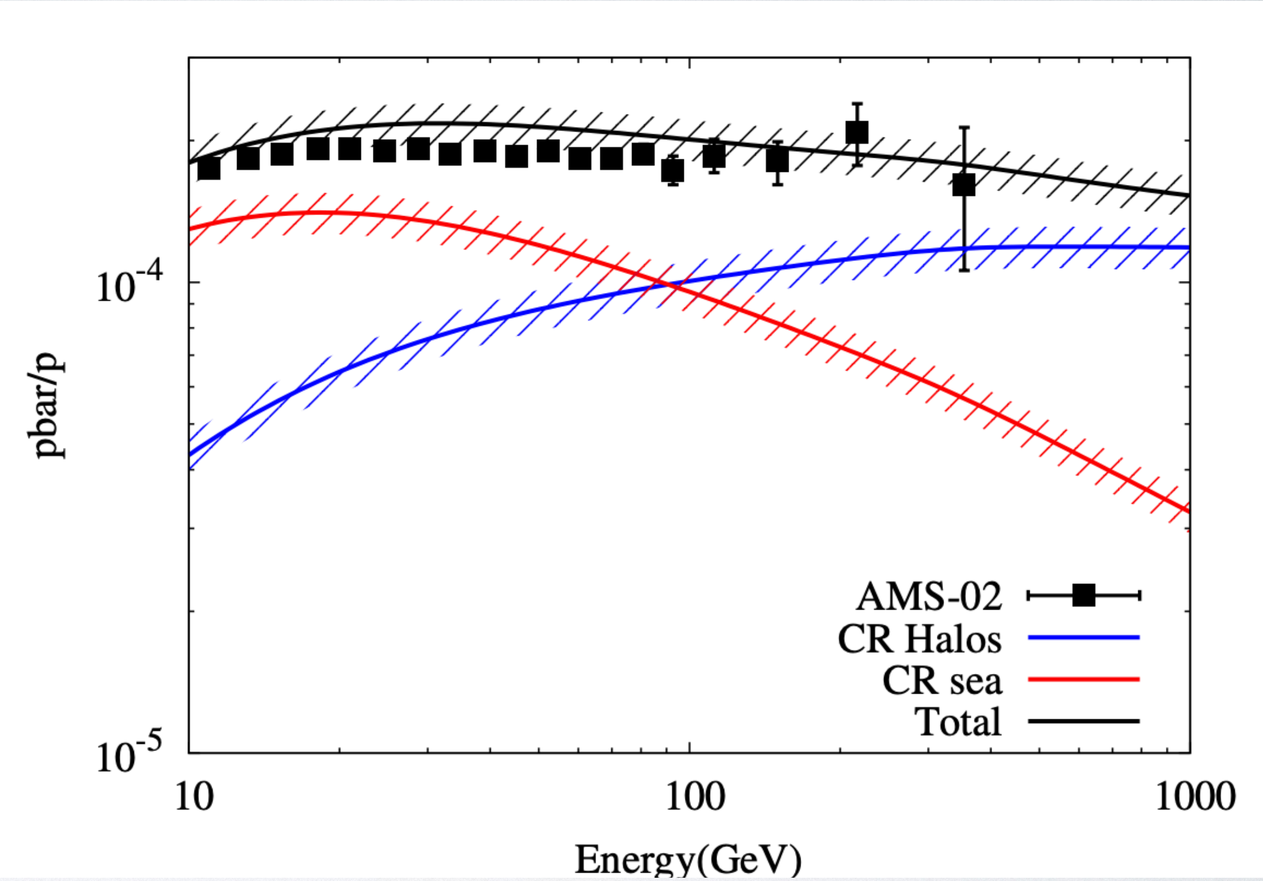
CONTRIBUTION TO DIFFUSE GAMMA



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

ACCUMULATION OF GRAMMAGE

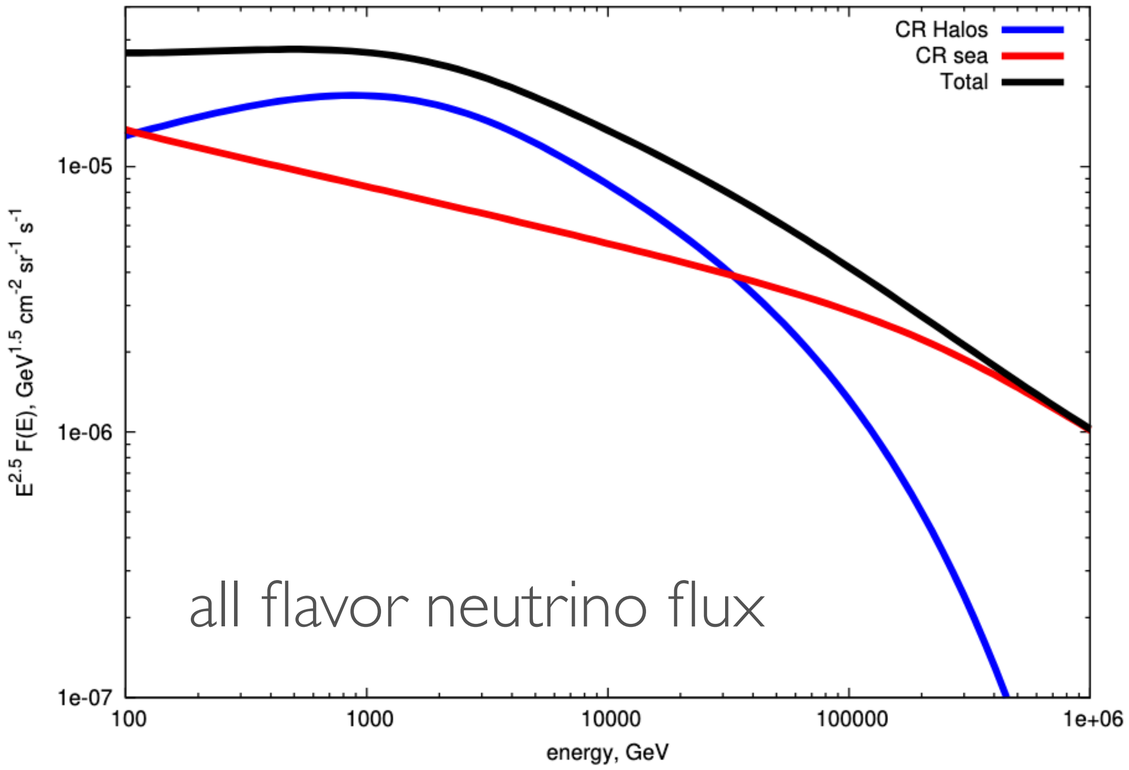




- Can also address the anomalies in CR direct measurement

Yang and Aharonian, Phys. Rev. D 100, 063020(2019)
Yang and Aharonian, Phys. Rev. D 111, 083040(2025)

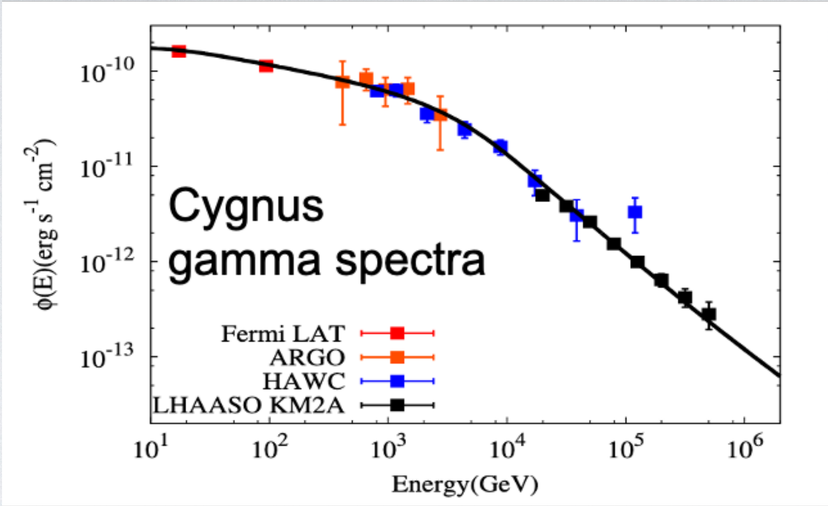
DIFFUSE NEUTRINO FLUX

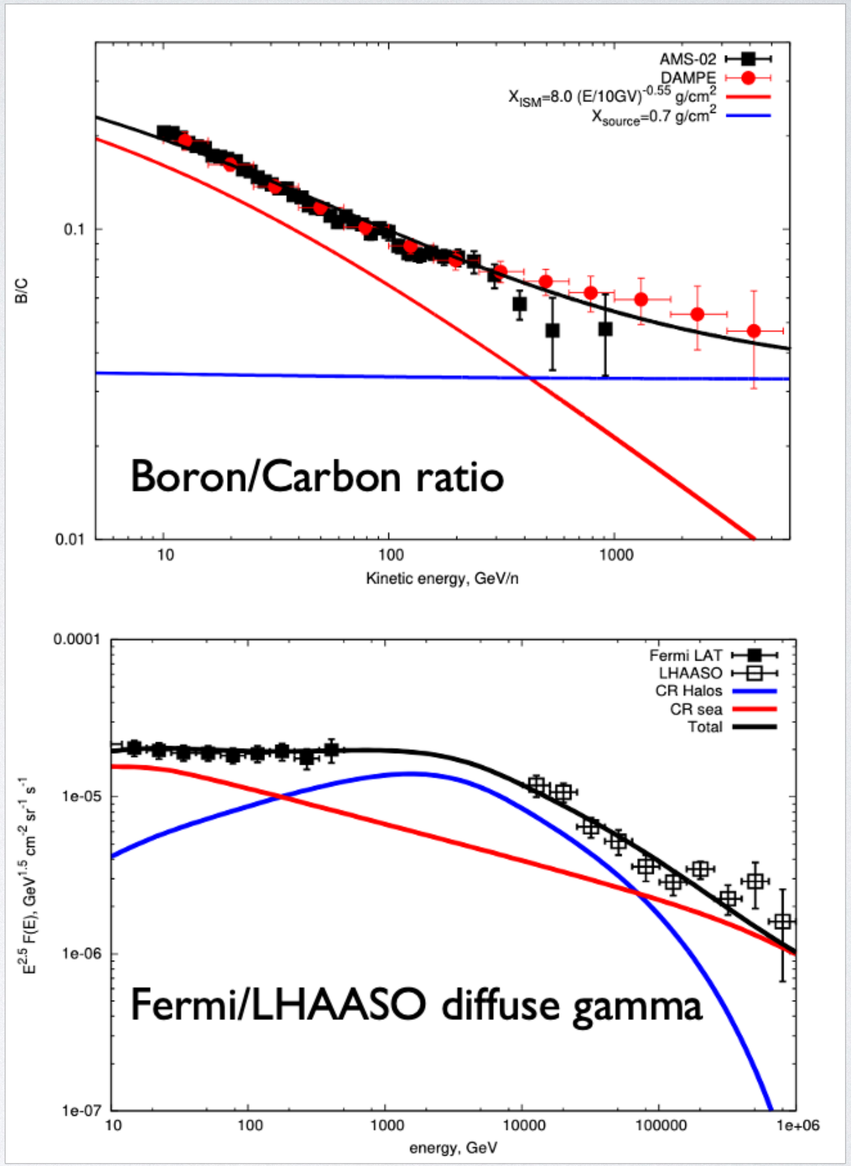


all flavor neutrino flux

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

MODIFIED PICTURE OF CR PROPAGATION





- Effective confinement (slow diffusion) of CR near "active" 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

CONCLUSIONS

- Gamma-ray observations bring new hints for CR propagation.
- Slow diffusion near source region in consistency with measurement of extended gamma-ray sources
- Can explain both the “excess” in GDE and “anomalies” in secondary CRs