The impact of the Cosmic-Ray diffusion in the gamma-ray observations of the Galactic Centre region

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RICAP 2024 - September 25, 2024

OUTLINE

- Context
- Towards Inhomogeneous CR Diffusion Scenario
- The Galactic Center Region
- IACTs observations: PeVatron Scenario (local continuous injection
- Models Comparsion
- Results
- Conclusions

Context

EGRET

Fermi-LAT

Observation of γ-ray diffuse emission ⇒ large-scale background emission expecially along the GP

It is crucial to not under/over estimate the galactic diffuse large-scale background (foreground) emission

building icreasingly realistic large-scale background models

Context

Large-scale background detected by Fermi-LAT explained in terms of galactic CR populations (CR-sea) diffusing within the Galaxy

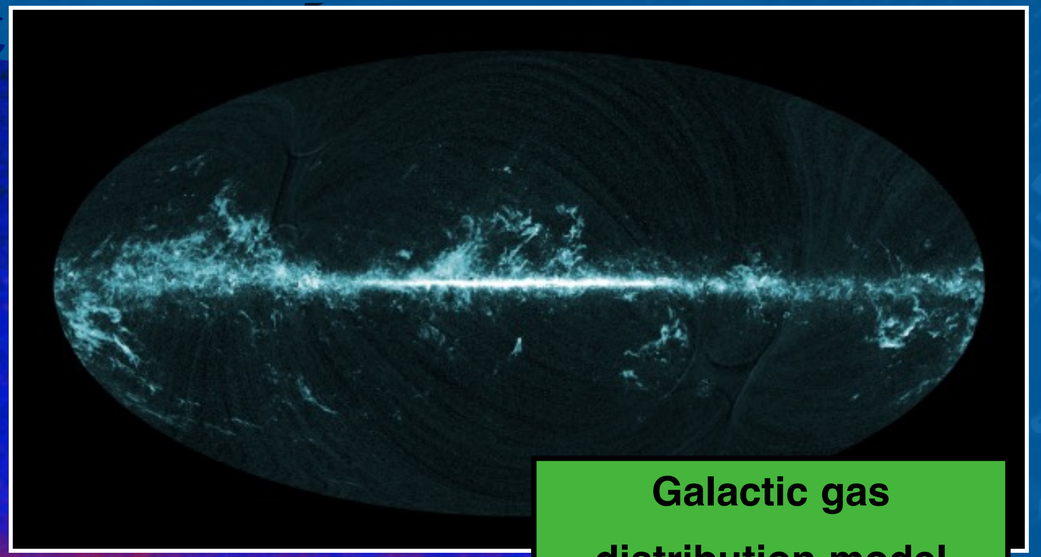
CR interactions with gaseous matter locked in the Galaxy produce gamma rays

Interstellar Emission represents a passive source of gamma rays

Large scale component models could differ in predicted flux

(i.e. depending on diffusion parametrization)

Reconstructed spectrum/ morphology of source could vary & depends on adopted diffuse model



Galactic gas distribution model divided by rings

Towards Inhomogeneous CR Diffusion Scenario

Beyond the conventional (homogeneous) diffusion (constant diffusion coefficient δ):

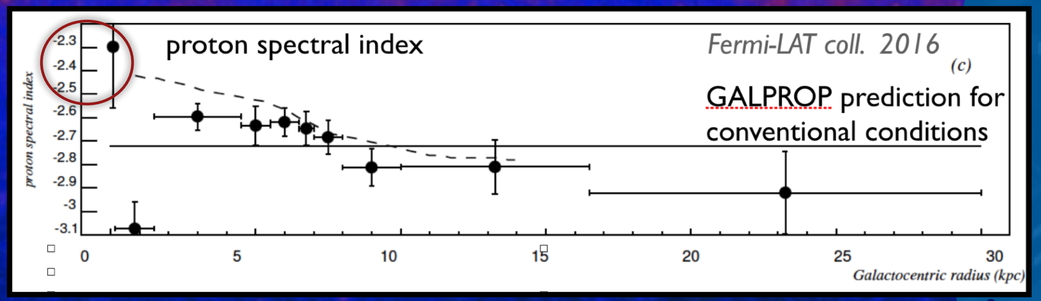
Gamma Model

- **CRs undergo to inhomogeneous diffusion**
- **Motivated by several independent analyses of Fermi-LAT data**
- **Additional hardening at** $300\ \mathrm{GeV/n}$ **(PAMELA, AMS-02, CREAM - Gaggero et al., 2015)**

Linear dependence of diffusion coefficient with galactocentric distance & rigidity (Gaggero et al., 2015)

Spectral index of γ-ray diffuse emission increase from $\Gamma \sim 2.8$ to $\Gamma \sim 2.3$ **for R decreasing** from 10 kpc to 0 kpc

Reproduce $15\ \mathrm{TeV}$ **Milagro anomaly**



Acero et al. (2016)

Due to large uncertainties of proton spectral index in the inner galaxy, this hypothesis represents an extrapolation for $\mathrm{R} \sim 0$ **of the trend between** $8 < R < 3$ kpc

$$D(E) = D_0 \left(\frac{E}{E_0} \right)^{\delta(r)}$$

$$\delta(r) = Ar + B$$

The Galactic Center Region

- One of the most interesting regions for the astroparticle physics & high energy astrophysics
- The perfect laboratory for studying phenomena & physical processes may be occur in other galactic nuclei
- CMZ is one of the densest region of the MW
- Thick target for CR hadron collisions
- $M_{\rm gas} \sim 3 \cdot 10^7\ M_\odot$ inner 150 pc
- $N_{\rm H_2} \sim 10^3\ {\rm cm}^{-3}$
- Extends up to ~ 250 pc away from the GC along the GP

Gamma rays from the Galactic Center region

The nature of the Very High Energy (VHE)

gamma-ray diffuse emission

in the Galactic Center (GC) region is still unknown & debated

Two main scenarios:

I. **Local PeVatron**

II. **Inhomogeneous Galactic CR-sea**

I

SMBH (SGR A*)

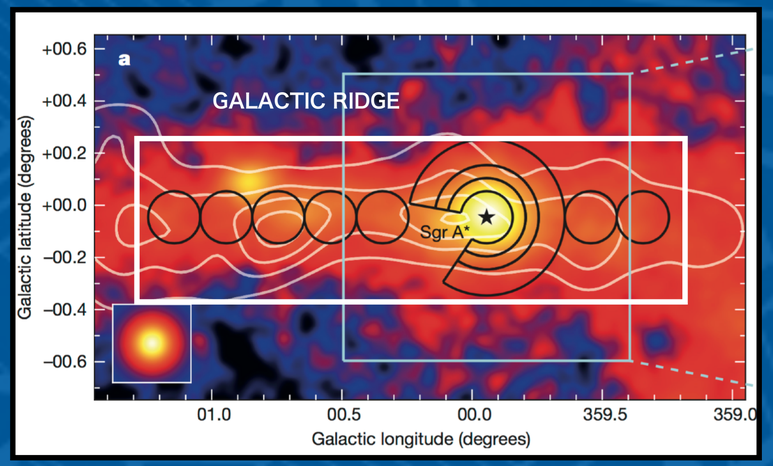
Unknown population of SNRs, PWNe & Stellar Wind Cluster

II

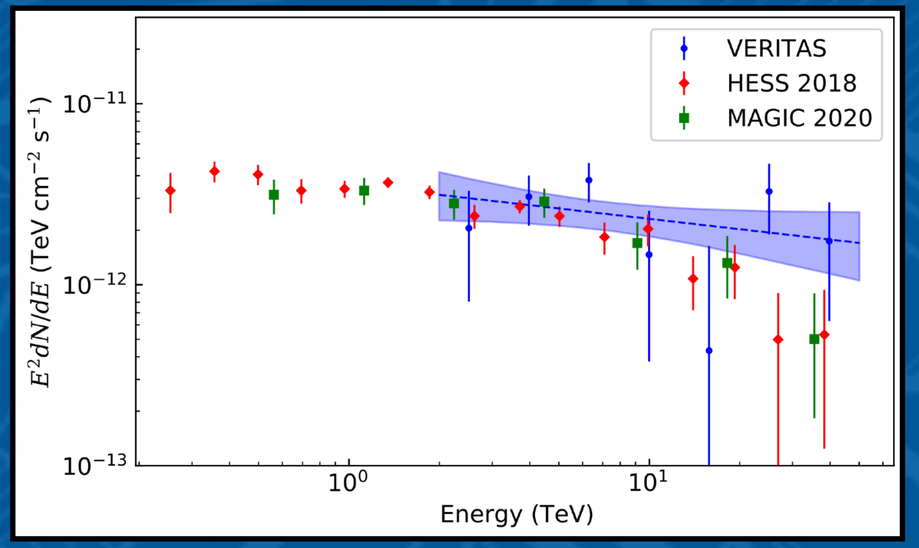
Motivated by Fermi-LAT, Milagro, HAWC, Tibet ASγ, LHAASO results

Extrapolation at the GC position of the diffuse emission tuned on local observations

IACTs observations: the PeVatron scenario

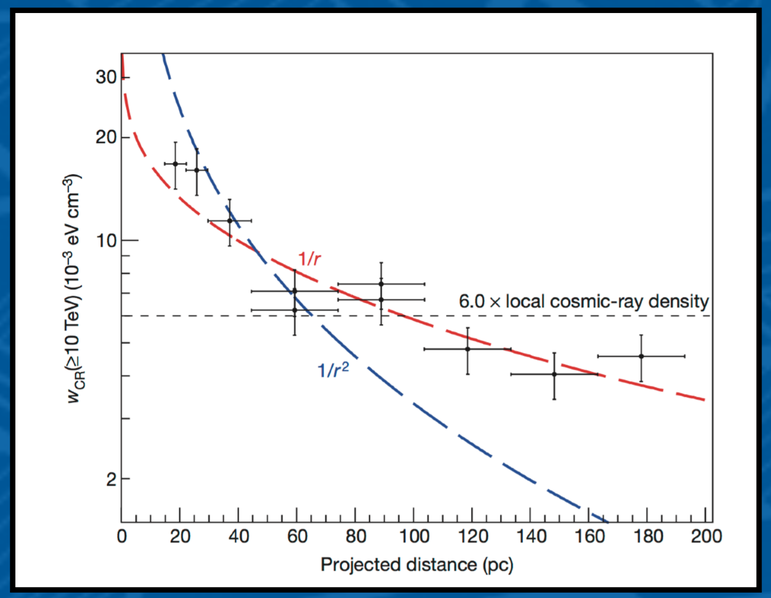


- diffuse emission from CMZ correlated with gas distribution
- The observed spectrum is harder ($\Gamma \sim 2.3$, $\Gamma_{\rm Earth} \sim 2.7$)
- Fresh accelerated (hard) CR hadron (PeVatron)



VERITAS Coll. (2021)

HESS Coll. (2016)



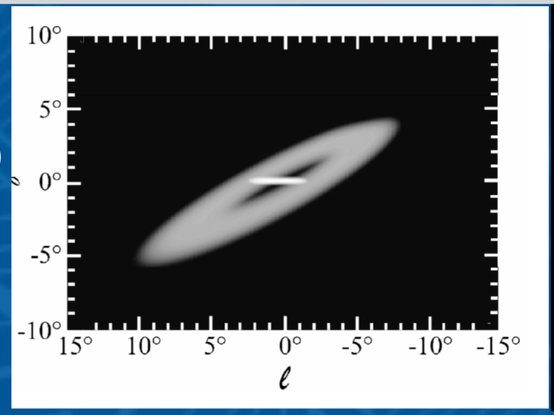
Inferred CR density profile consistent with that expected from CR diffusing out stationary source & continuous CRs injection in the CMZ

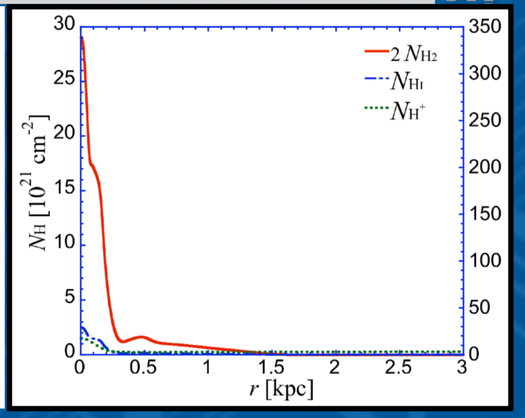
$$w_{CR}(E,r) = \frac{Q_{source}(E)}{4\pi D(E)}\frac{1}{r} \propto E^{-(\Gamma_{source}+\delta)}$$

$$D(E) \propto E^{\delta}$$

Models comparison

- Inner ring ⇒ analytical 3D model gas distribution (smooth w/o cluds)
- 4 models comparison:
  - I. Gamma model: radial depedence diffusion coefficient, hardening at 300 GeV
  - II. Gamma model w/o hardening at 300 GeV
  - III. Base model: constant diffusion coefficient, hardening at 300 GeV
  - IV. Conventional model: constant diffusion coefficient w/0 hardening at 300 GeV



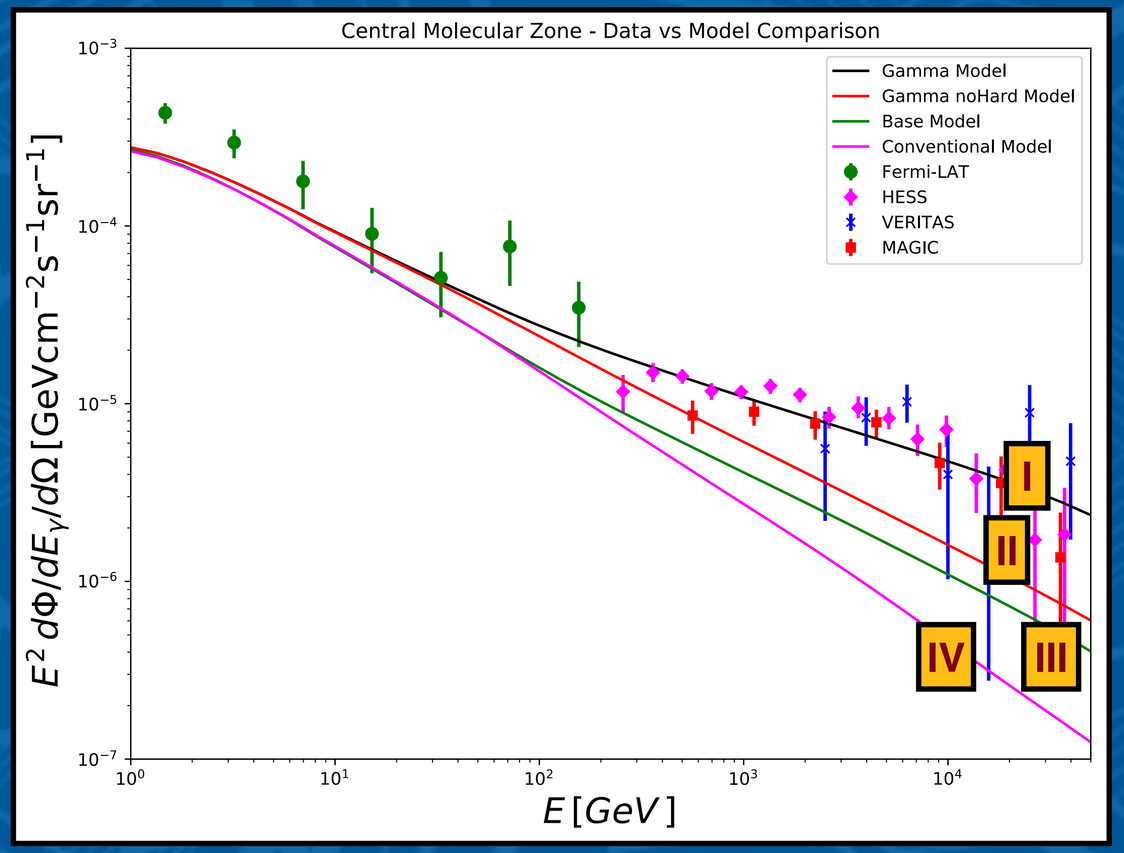


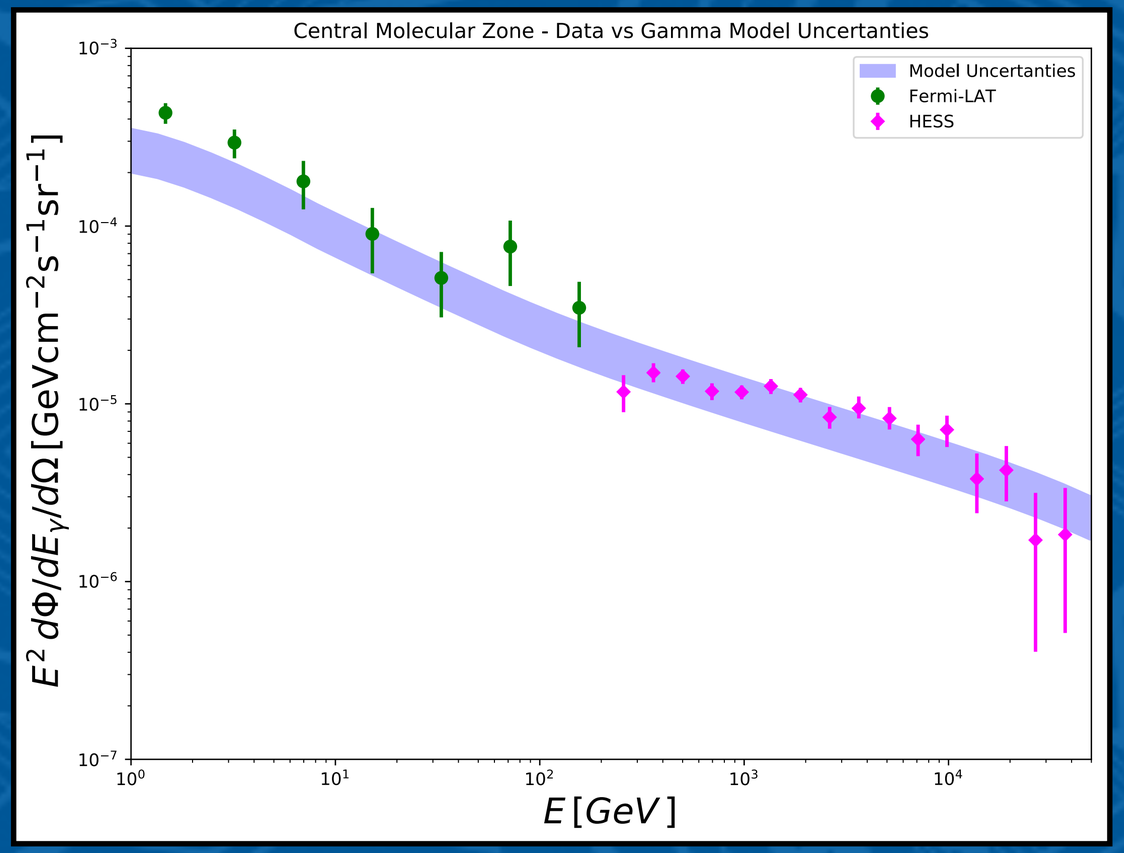
Ferriere et al. (2007)

DRAGON code to compute CR distribution
GAMMASKY to perform integration along the line-of-sight

Results: Galactic Ridge

Ventura, 2018, 2019, 2022, 2023

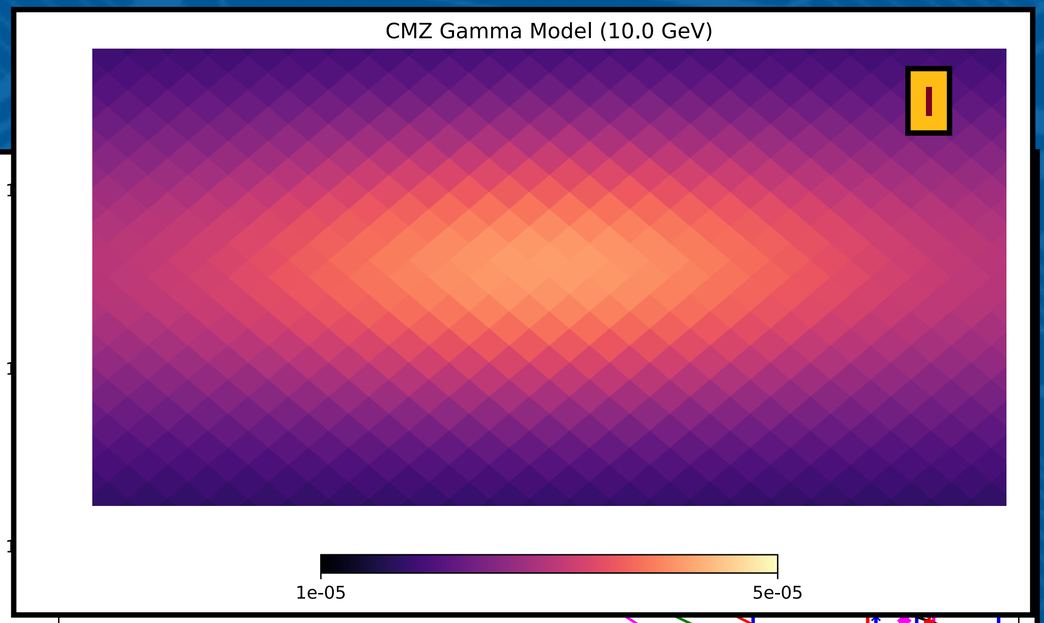


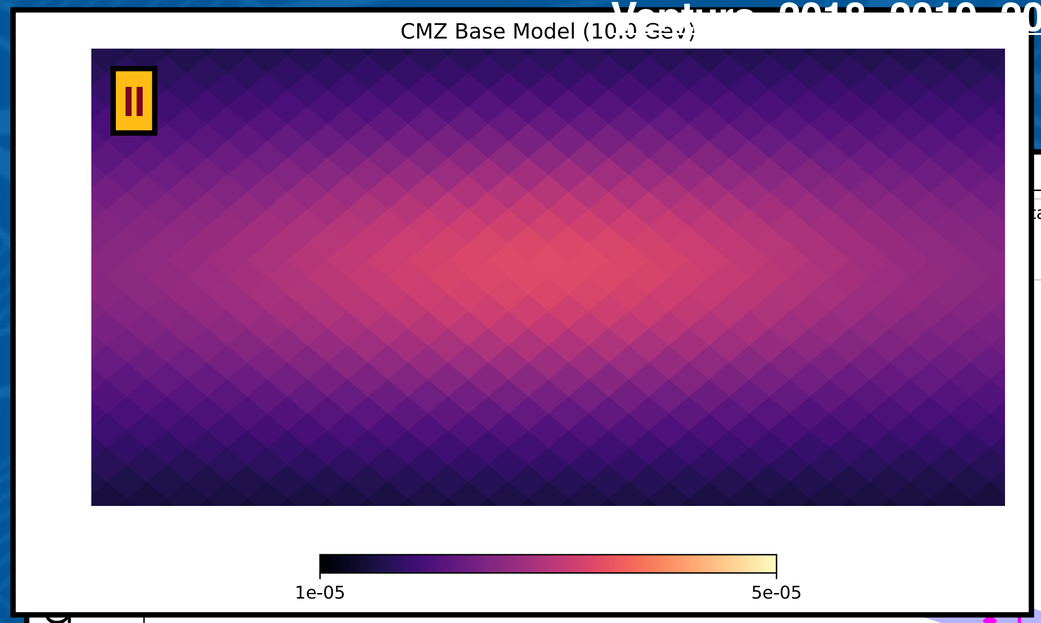


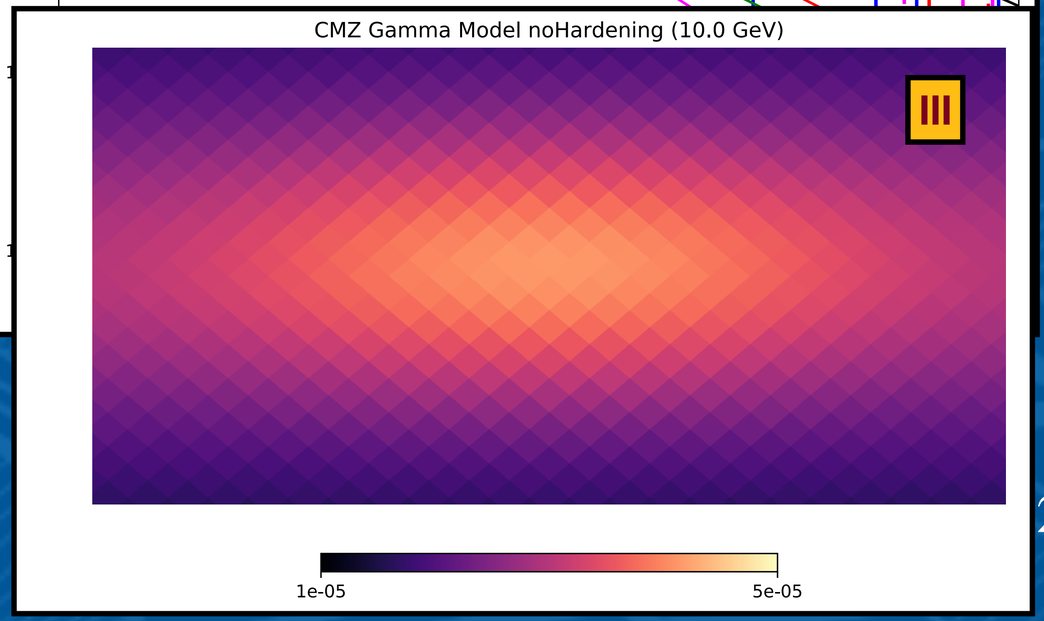
$$\Gamma = 2.36 \pm 0.08$$

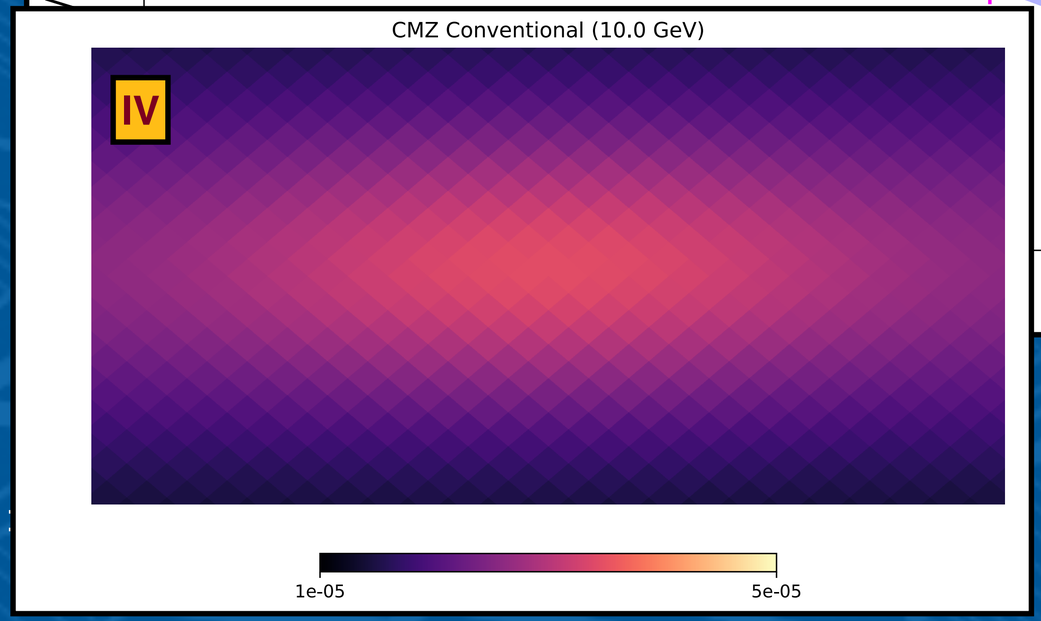
Results: Galactic Ridge

Ventura, 2018, 2019, 2022, 2023





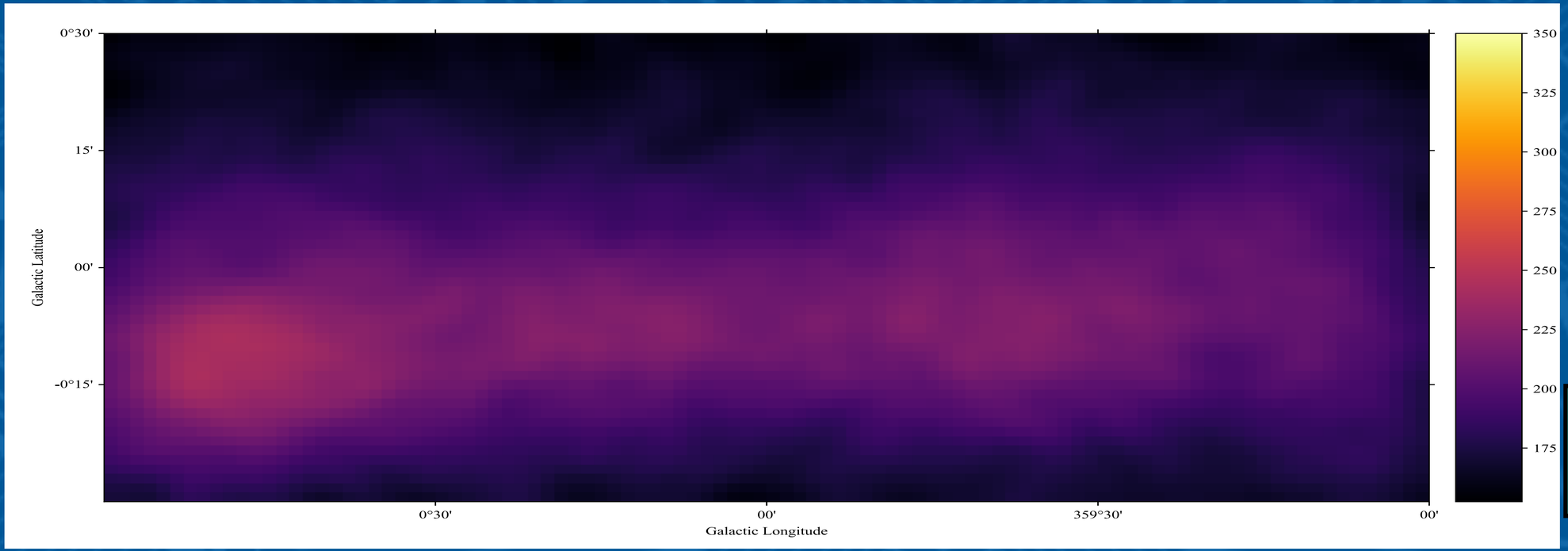




2.36

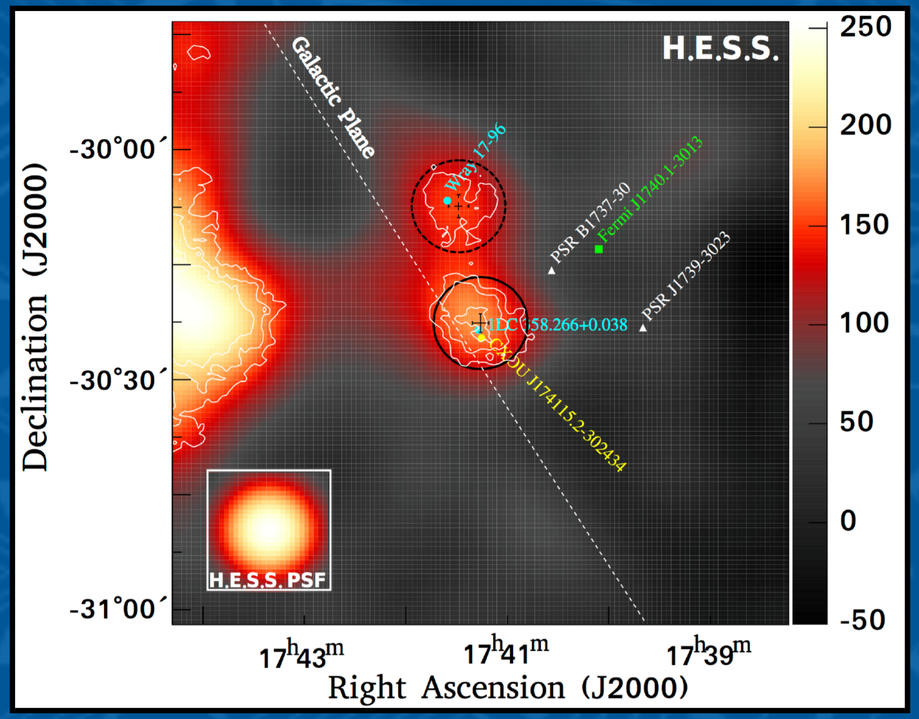
CTAO simulations

- 100 h, IRF: Prod 5 (South 50 h)
- Updated model: KRA gamma (D. Gaggero presentation; De La Torre Luque et al, 2023)
- Used to build GPS (CTAO consortium, 2023)



On the behalf GC-CTAO WG in collar. With G. Morlino, P. Cristofari, E. Amato, M. Fiori - WORK IN PROGRESS!

HESS J1741-302



H.E.S.S. Collab. (2018)

$$M = 6.8 \cdot 10^4 \, M_\odot$$

$$l = -1.7^\circ \; ; \; d \sim 260 \text{ pc}$$

$$\Gamma \sim 2.3$$

The energy spectrum extends up to 10 TeV with no evidence of a cutoff

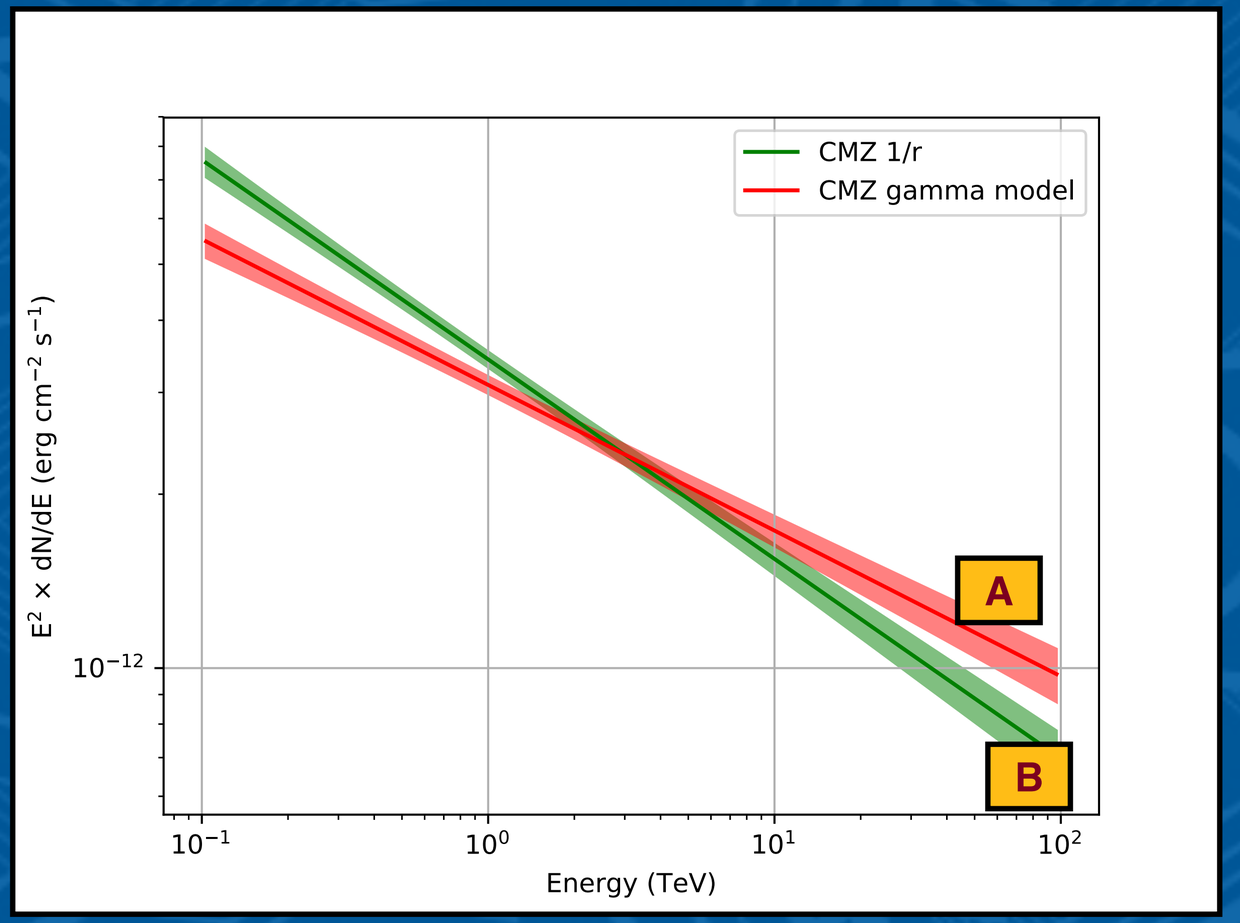
The source is a natural target to probe how/if the CR population properties change with R

Hadronic scenario favored

Active or passive source?

HESS J1741-302: CTAO simulations

- Simulation of 10 h
- HESS J1741-302 + DC I sources
- IRF: Prod 5 (South 50 h)



CTAO could be a PeVatron discriminator?And discriminate among different scenarios?

A. central PeVatron as detected by H.E.S.S. illuminates CMZ (inner ring) + foreground illuminated by Gamma Model

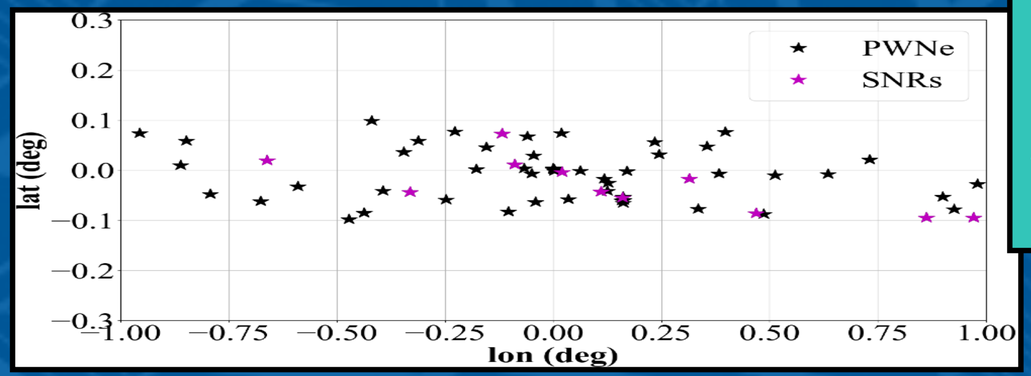
B. Gamma Model (foreground + CMZ) ⇒ passive source

Ventura 2019, 2023

Conclusions

- Several independent observations support the hardening of CR-sea approaching the GC and the CR inhomogeneous Diffusion: this evidence is of crucial relevance for studying complex regions
- For shedding light on the nature of observed emission from GC realistic models of gas density distribution & dynamical description of inner Galaxy are required (3D gas modeling)
- Source confusion prevents to discriminate among different emission components
- At higher energies contribution of diffuse emission is highly depedent to CR transport parameterization
- Molecular clouds reside farther from the GC (within the 1 kpc) may be the ideal targets to understand the impact of central PeVatron & hard diffusion scenario (Bania Clump, HESS J1848-018 — Ventura, 2018, 2019, 2022, 2023)
- Cherenkov Telescope Array (CTAO) with increased sensitivity & angular resolution may lead to definitive conclusions
- Inclusion of Synthetic population of unknown SNRs, PWNe and YSCs (CTAO GC WG)

For building a more realistic model of the observed gamma-ray diffuse emission



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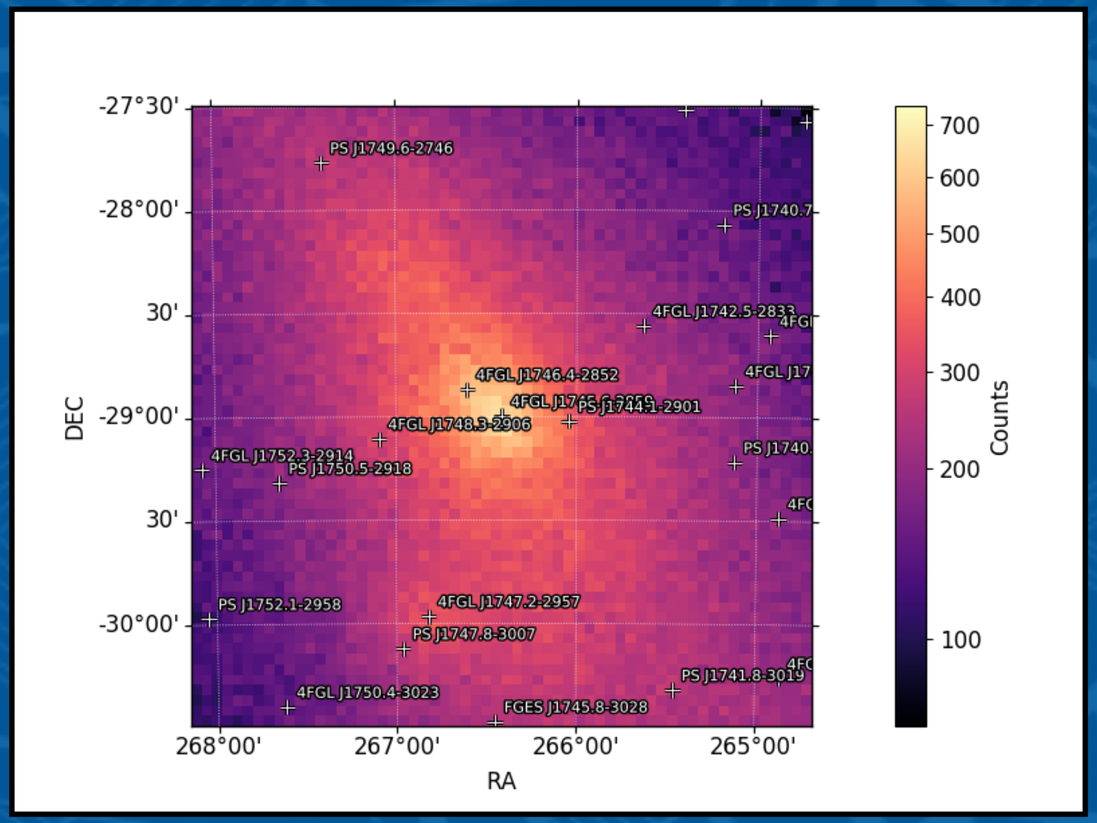
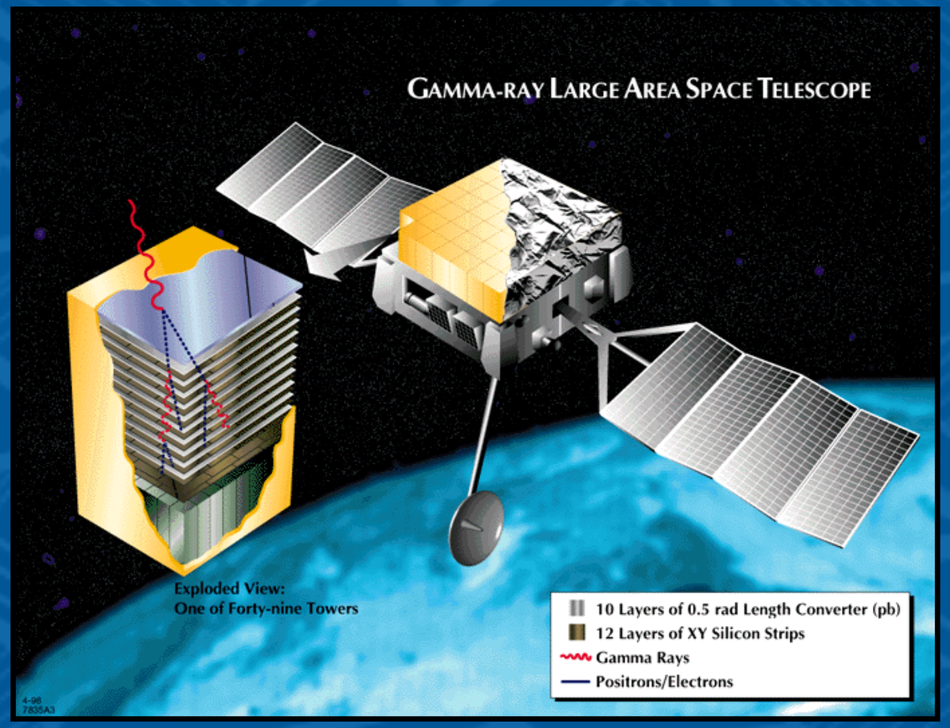
INFN
Istituto Nazionale di Fisica Nucleare

BACKUP

Titolo presentazione

- Fermi-LAT analysis ~ 10 yr
- 4FGL-DR2 catalog
- P8R3_CLEAN_V2
- iso_CLEAN_V2





HEASARC