Shedding (gamma) Light on the Cosmic Ray Population in the Galactic Center Region

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Multimessenger Data analysis in the era of CTA - Sexten (Italy)

Outline

H.E.S.S. measurements: the TeV-excess & PeVatron scenario

From Conventional to Inhomogeneous Cosmic Rays Diffusion

The Galactic Center Region

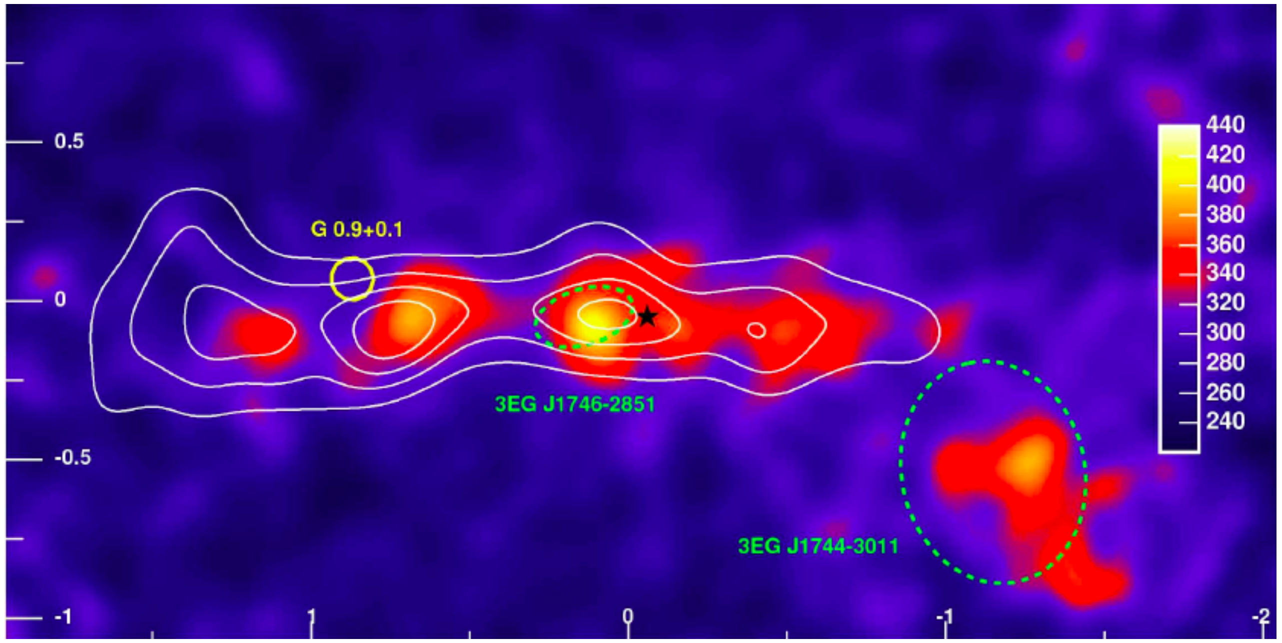
Results

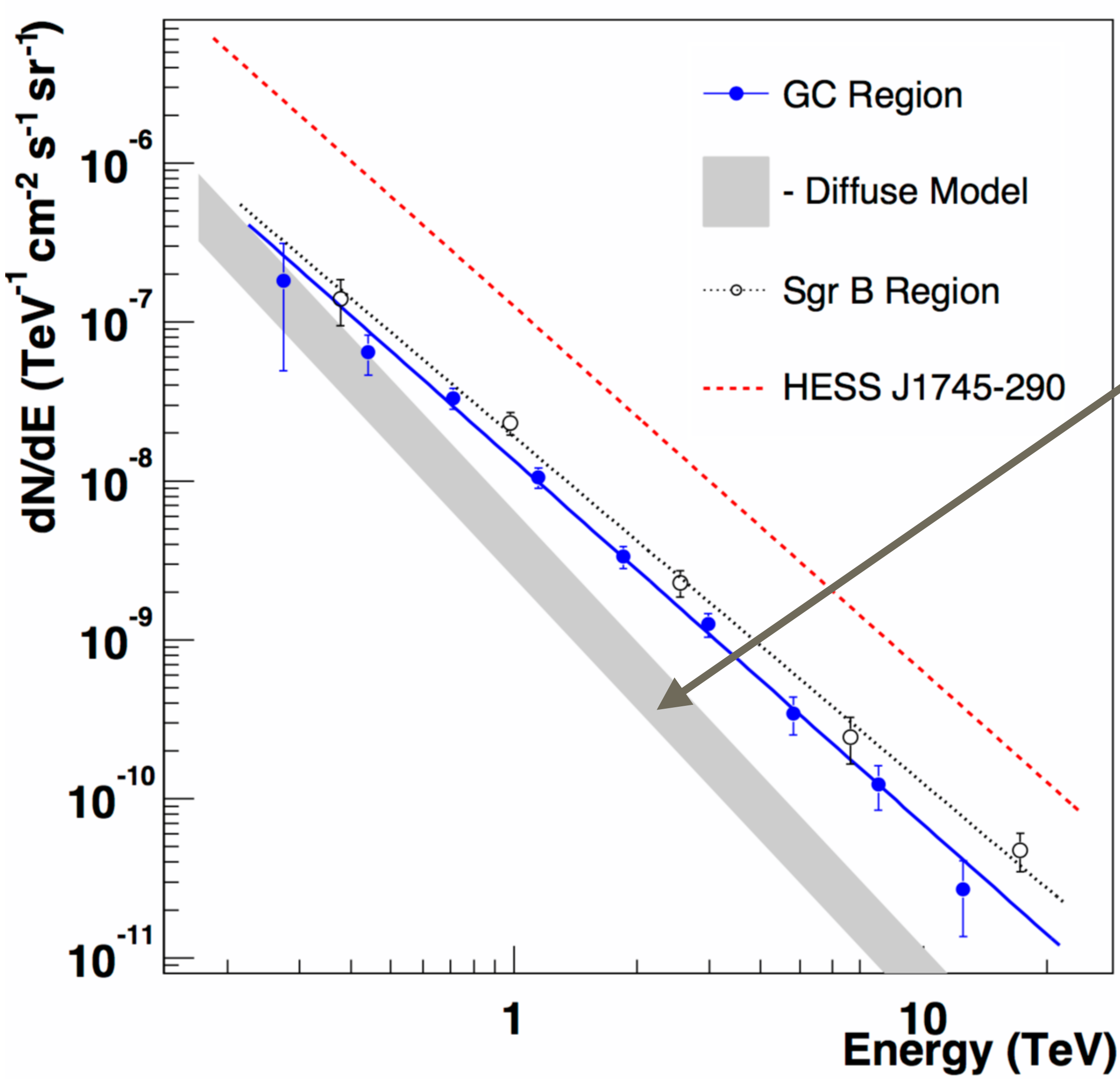
Conclusions

New Analysis & Future Work

Hot Gas in the Galactic Center - Credit: NASA/CXC/UCLA/MIT/M.Muno et al.

The TeV-excess Problem



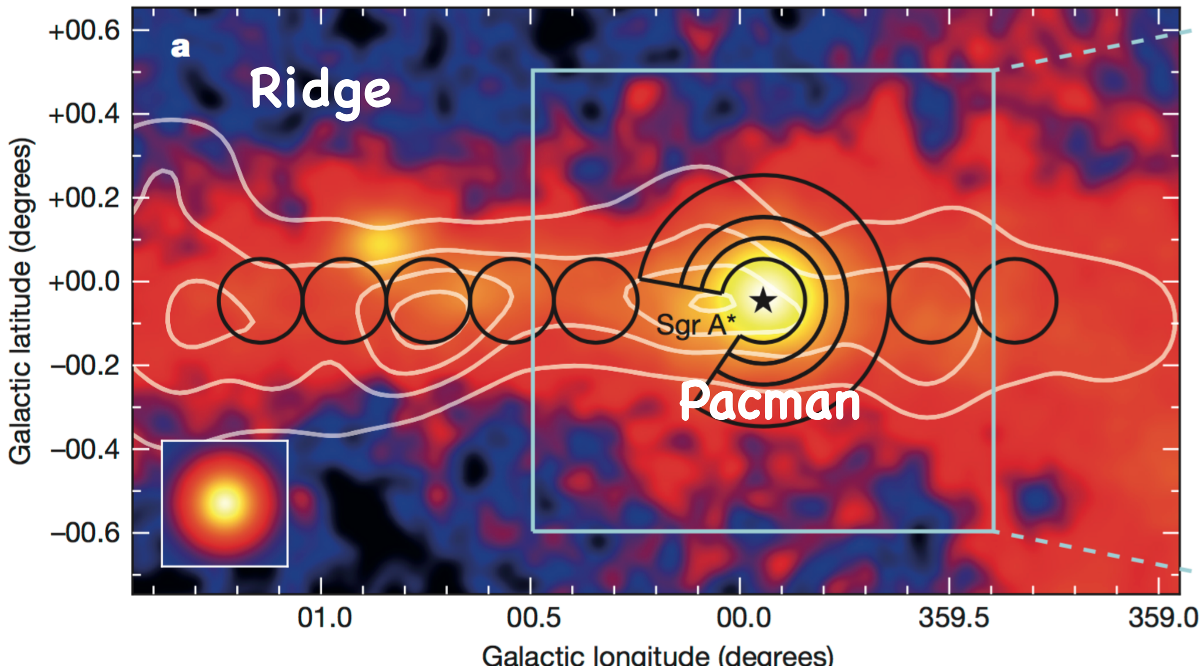


- The diffuse emission from the central molecular zone (CMZ) is correlated with the gas distribution (inferred by CO & CS maps)
- The spectrum is harder ($\Gamma \simeq 2.3$) than expected from the hadron scattering of Galactic cosmic rays (CR) if their spectrum is the same of that at the Earth ($\Gamma \simeq 2.7$)
- A freshly accelerated (hard) CR component was invoked to explain the emission

$\Gamma_{HESS06} = 2.29 \pm 0.07_{stat} \pm 0.20_{sys}$

Credit: Aharonian et al. (Nature - 2006)

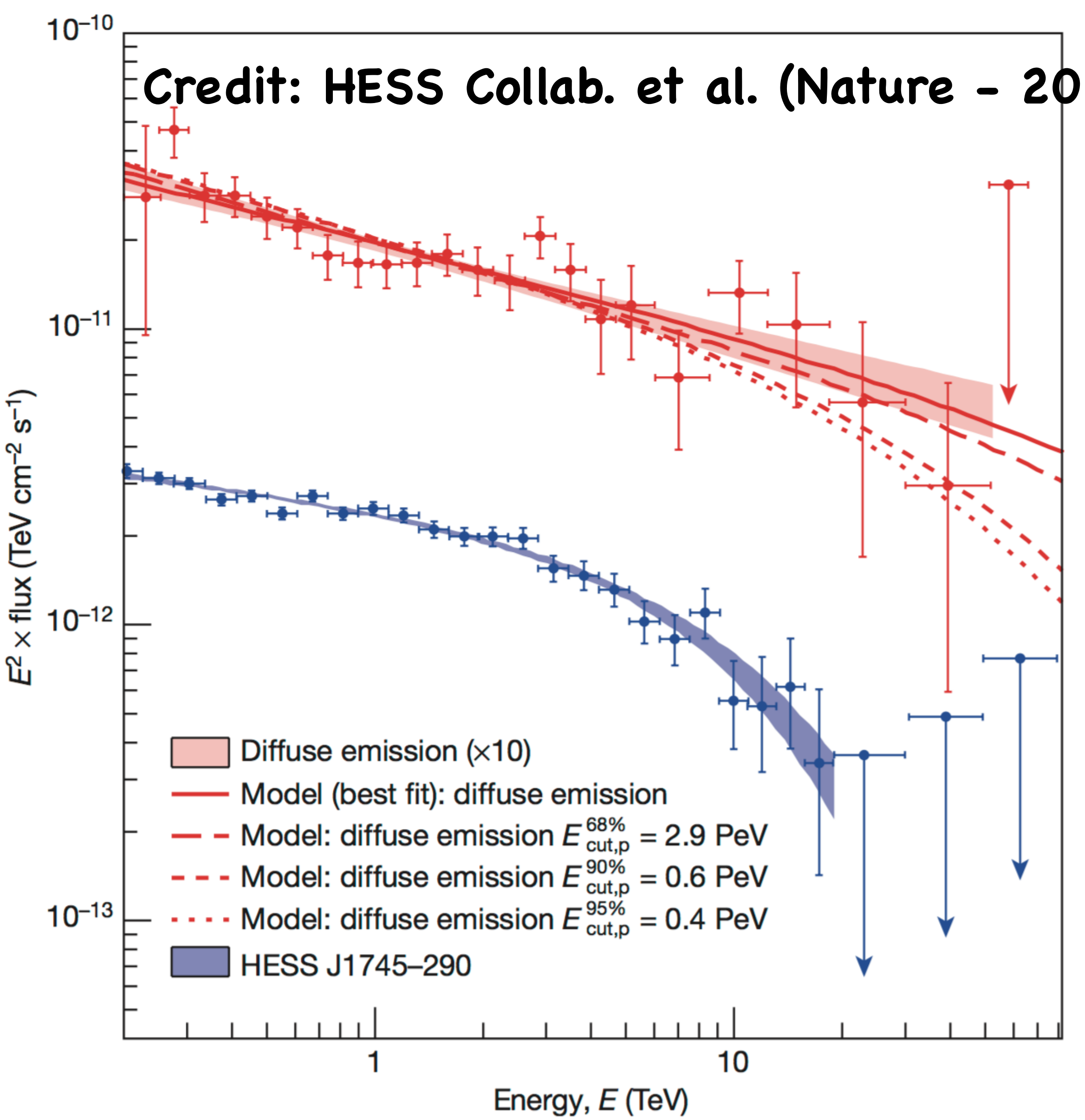
The TeV-excess Problem



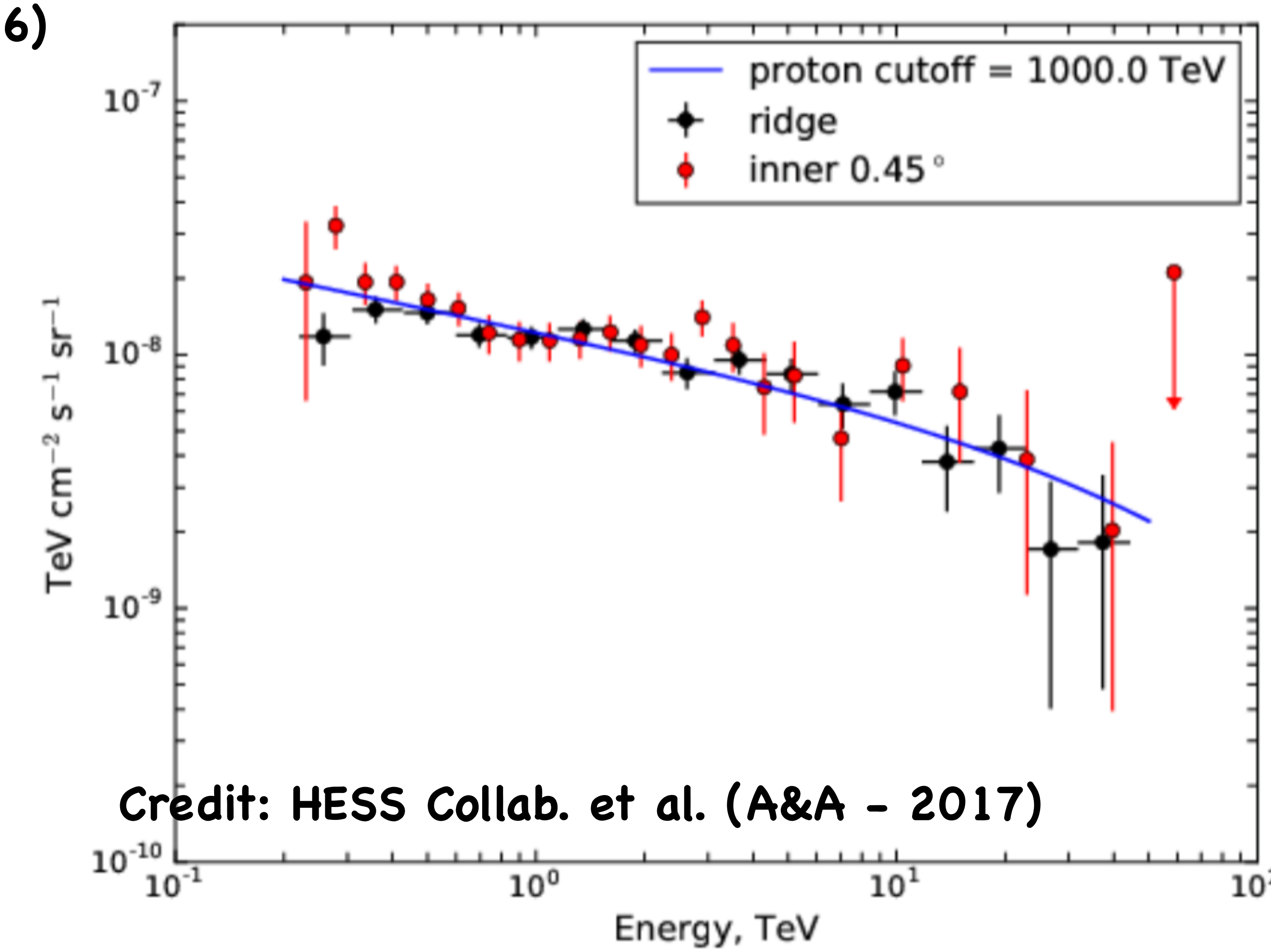
Same spectra in the Ridge & Pacman

Γ_{HESS16} = 2.32 ± 0.05$_{stat}$ ± 0.11$_{sys}$ (Pacman)
0.15° < θ < 0.45° , 22 < d < 67 pc

Γ_{HESS17} = 2.28 ± 0.03$_{stat}$ ± 0.2$_{sys}$ (Ridge)
(| l | < 1° , | b | < 0.3°), d < 150 pc

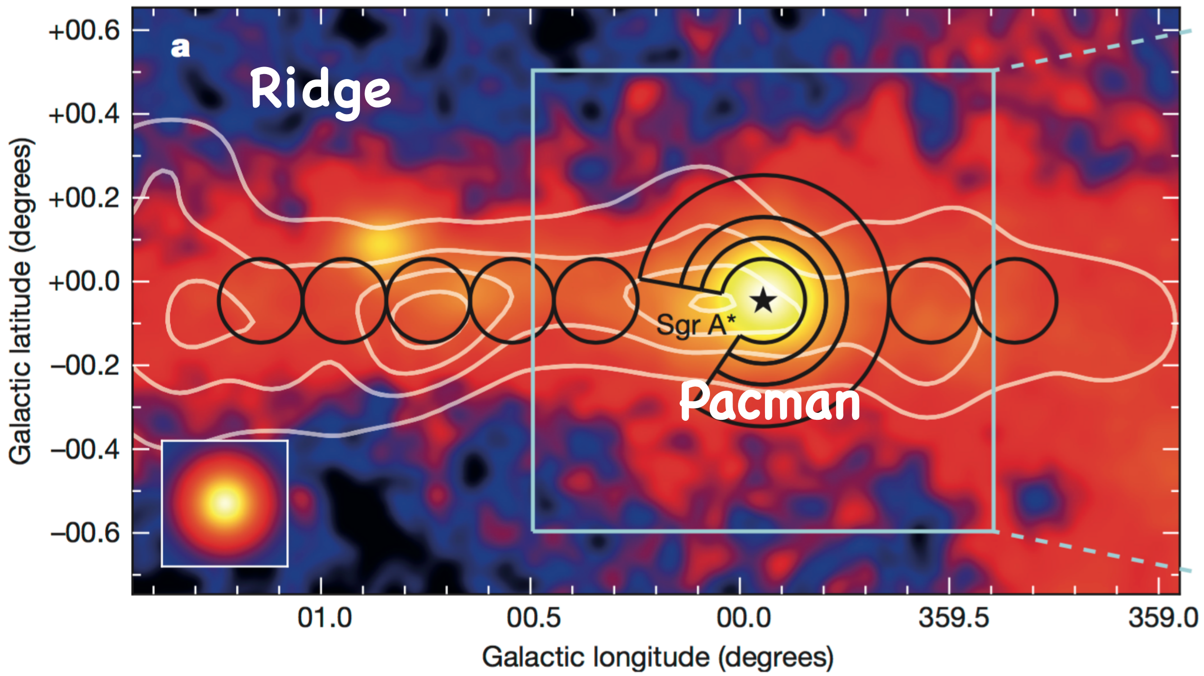


Credit: HESS Collab. et al. (Nature - 2016)



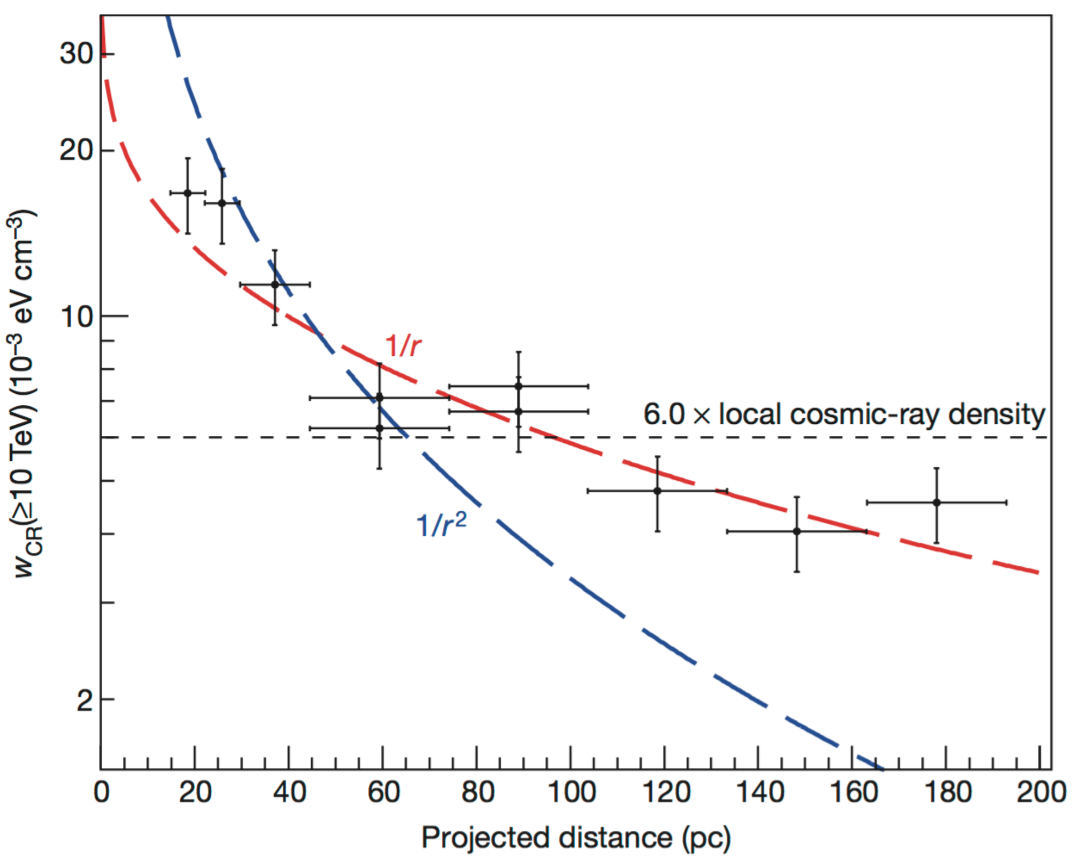
Credit: HESS Collab. et al. (A&A - 2017)

What is the PeVatron?



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

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



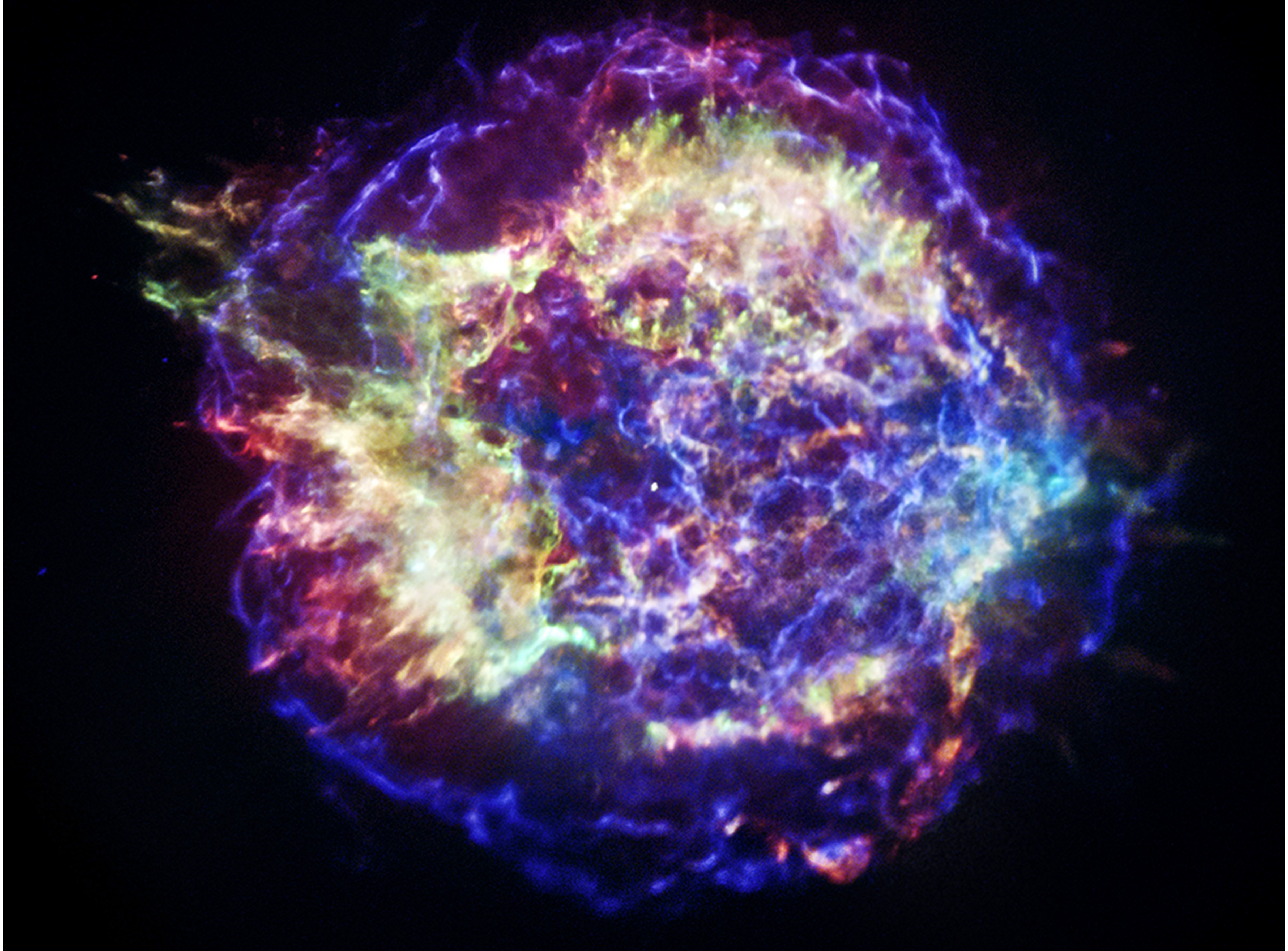
The inferred CR density profile is consistent with that expected from CR diffusing out a stationary source (but is may also be compatible with a constant for R > 50 pc)

Because of the strong energy losses suffered by leptons, the γ-ray emission is due to the hadronic component of CRs

Signature of FRESHLY acceleration of CRs & continuous CRs injection in the CMZ

Credit: HESS Collab. et al. (Nature - 2016)

How are CRs accelerated?



Cassiopea A (CasA) - Credit: NASA/CXC/

How are CRs accelerated?

Acceleration occurs in
strong diffusive shocks
associated with
Supernova Remnants (SNRs)

Nonlinear DSA theory
able to explain
CRs spectrum till knee

Other sources:
Super-Bubbles (SB)
Supernovae in association
with OB-WR stars (SN-OB)

No galactic sources
have still been observed
to accelerate CRs
till PeV energies

How do CRs propagate?

SNRs inject CRs & energy into ISM → Galactic MF confine CRs into Milky Way → **DIFFUSION**

Conventional Approach (for E >> 10 GeV)

Transport equation (Ginzburg & Syrovatsky, 1964) is solved under several approximations:

- Source spectrum (power-law) & spatial distribution (SNR catalogues) are assumed →

$$Q(E,r) = Q_0(r)\left(\frac{E}{E_0}\right)^{-\Gamma_{source}(i)}$$

- Diffusion is treated as isotropic and homogeneous. The diffusion coefficient only depends on rigidity. For E ≫ m, D_0 and δ assumed to be uniform →

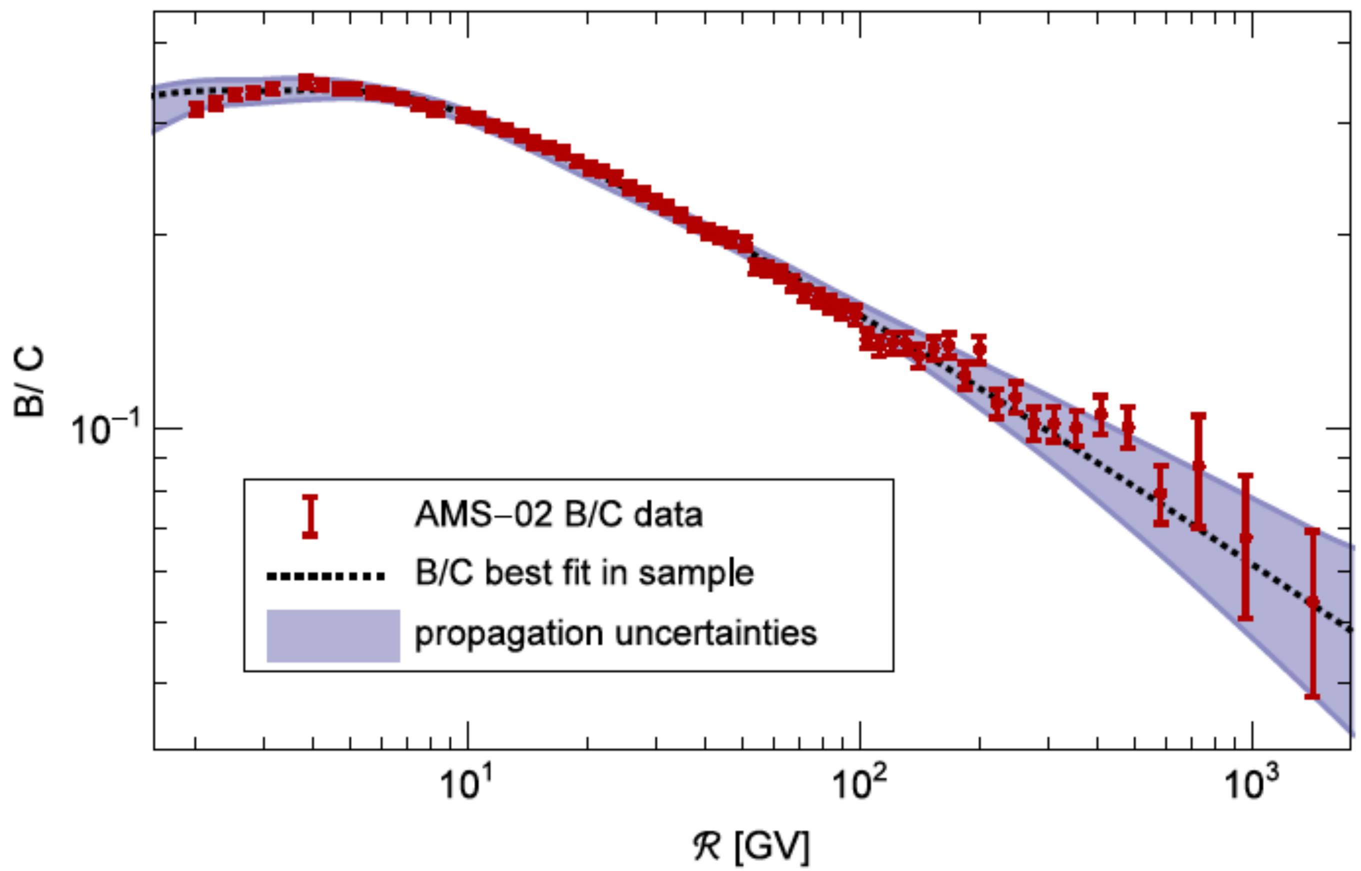
$$D(E) = D_0\left(\frac{E}{E_0}\right)^{\delta}$$

For E ≫ 10 GeV/n
single power-law spectra expected →

$$\Phi_i(E) \propto \frac{Q}{D} \propto \left(\frac{E}{E_0}\right)^{-(\Gamma_{source}(i)+\delta)}$$

How do CRs propagate?

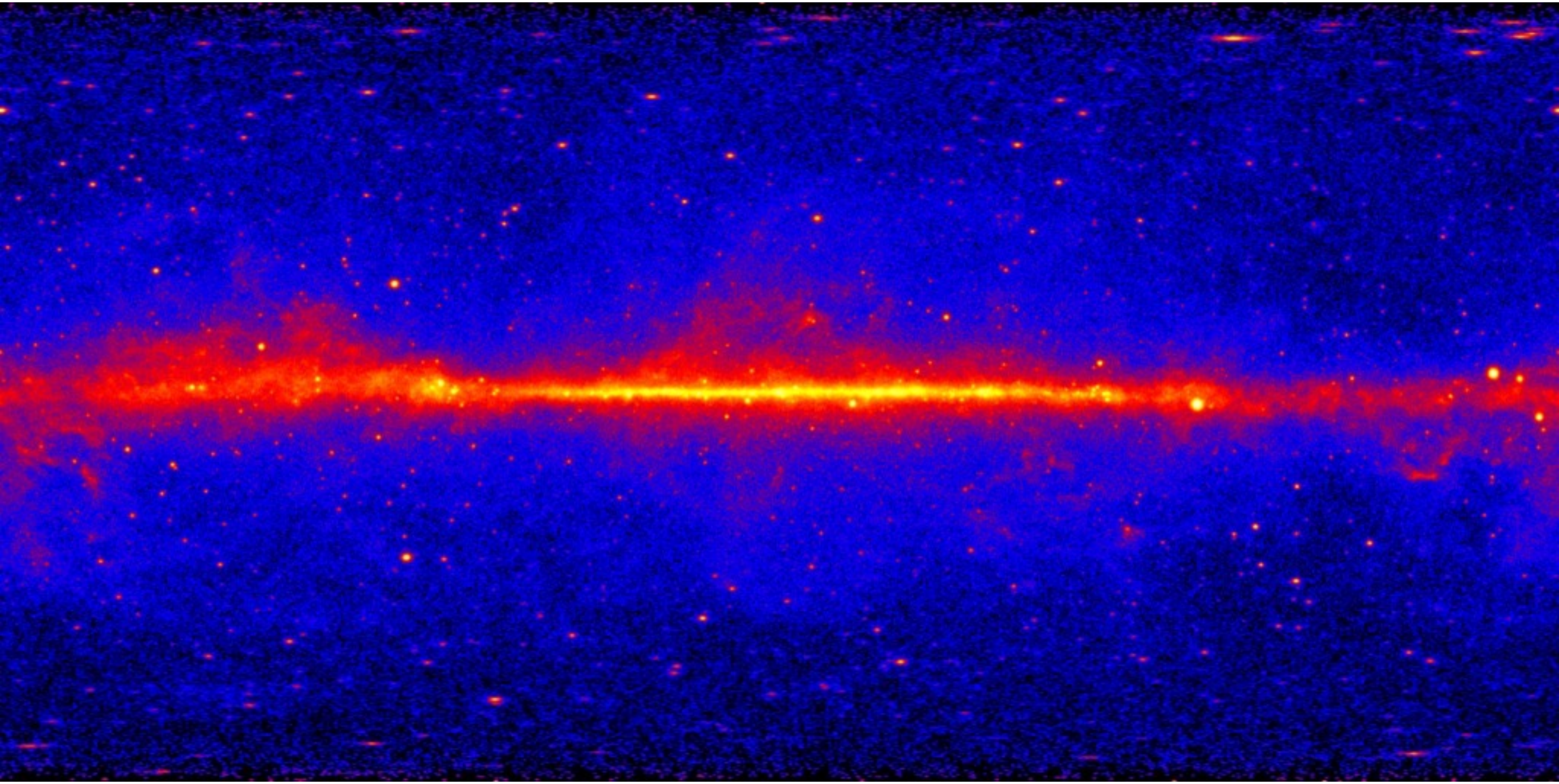
R. Kappl & M.W. Winkler, 1506.04145



The diffusion coefficient is determined on the basis of the secondary/primary ratio of light nuclear species (the B/C most commonly)

This method gives only local informations on index δ

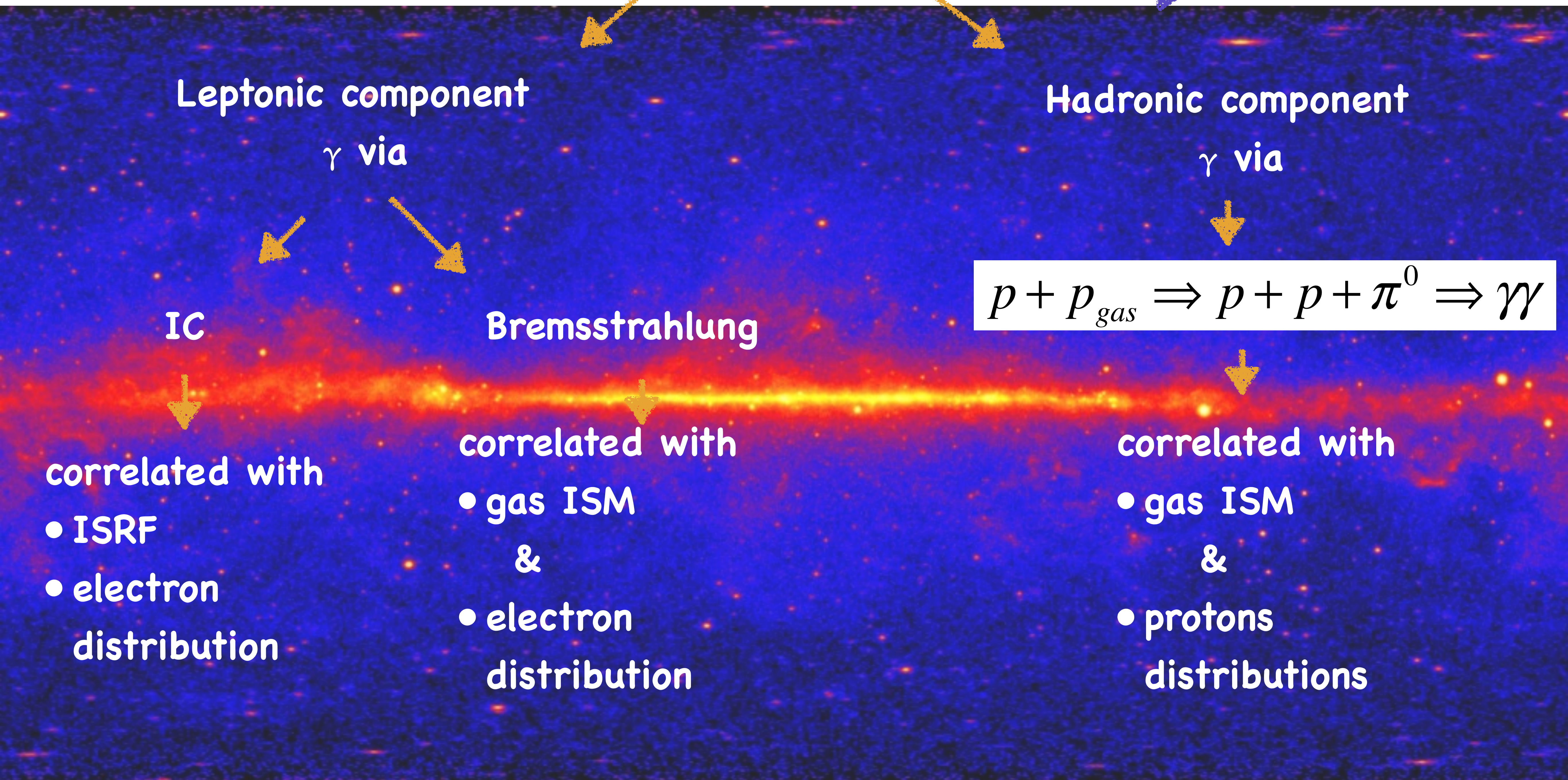
From CRs to Gamma-Ray Diffuse Emission



Credit: https://fermi. gsfc.nasa.gov/science/eteu/diffuse/

From CRs to Gamma-Ray Diffuse Emission

CRs interactions with Interstellar Medium (ISM)



Credit: https://fermi. gsfc.nasa.gov/science/eteu/diffuse/

A Model for Gamma-Ray Diffuse Emission

Large-scale CR background (CR-sea) described by

↓

Homogeneous & isotropic diffusion
tuned on local CR data

↓

Conventional Diffusion
(Base Model)

↓

uniform diffusion coefficient

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

uniform spectral index
(Γ ~2.7)

A Model for Gamma-Ray Diffuse Emission

Large-scale CR background (CR-sea) described by

↓

Inhomogeneous diffusion

↓

Hard Diffusion (Gamma Model)

↓

linear dependence of diffusion coeff. with radius & rigidity

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

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

Gaggero et al. (PRD 2015) ← radial dependence spectral index $\Gamma(r) = \Gamma_{source} + \delta(r)$

+

Introduced by Gaggero et al. (ApJ L. 2015). Able to explain MILAGRO anomaly at 15 TeV ← **hardening 300 GeV/n (PAMELA, AMS-02, CREAM)**

A Model for Gamma-Ray Diffuse Emission

Large-scale CR background (CR-sea) described by

inhomogeneous & anisotropic diffusion (disk & halo component)

Hard Diffusion (Gamma Model)

linear de[…] rigidity

$D(\ldots)$ $\ldots = Ar + B$

Base & Gamma Models are implemented in the numerical code DRAGON+GAMMASKY

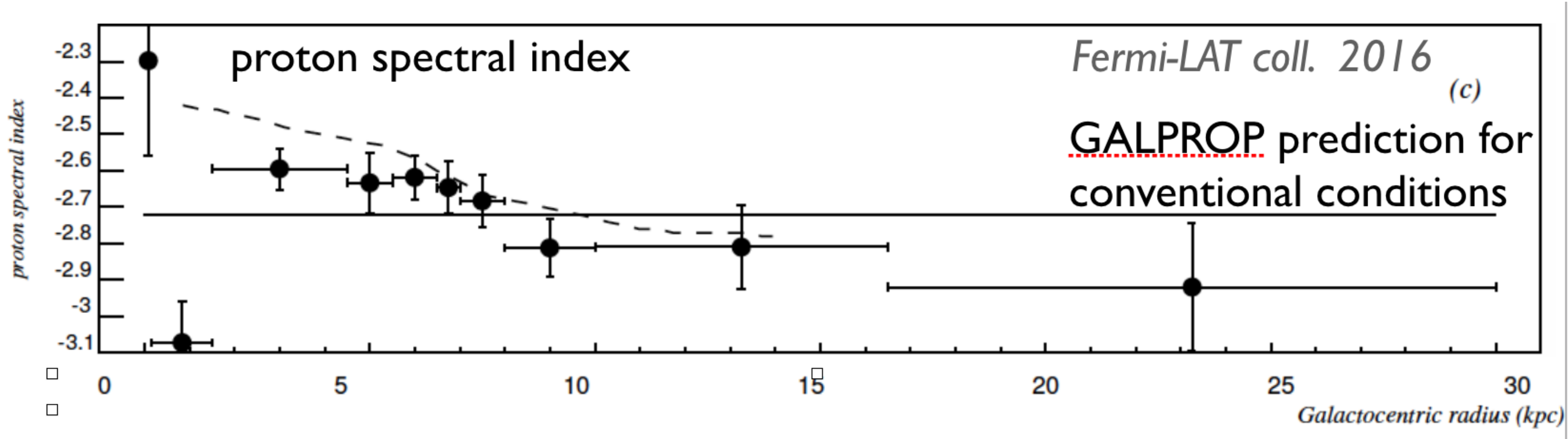
radial dependence spectral index $\Gamma(r) = \Gamma_{source} + \delta(r)$

+

hardening 300 GeV/n

(PAMELA, AMS-02, CREAM)

A Model for Gamma-Ray Diffuse Emission

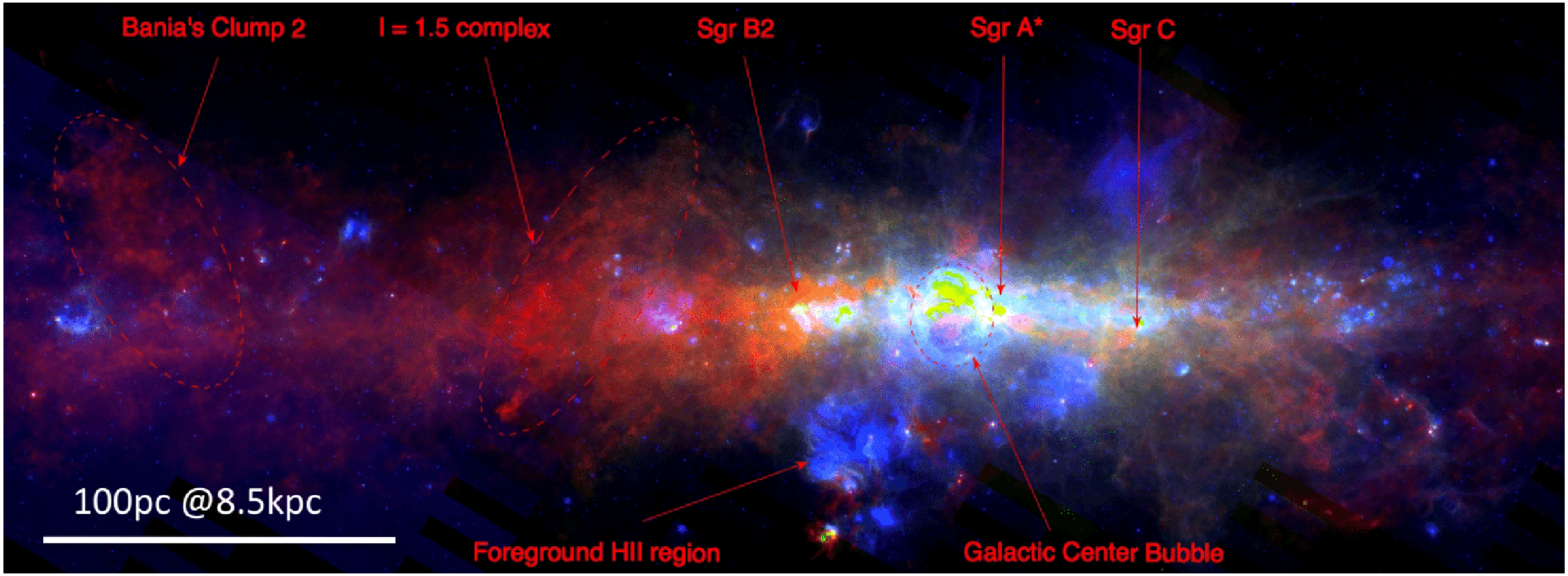


Dashed Line: Gaggero et al. (PRD 2015) $\Gamma(r \to 0) \approx 2.4$

Inhomogeneus &
Hard diffusion
is able to reproduce
Fermi-LAT data

Acero et al. (ApJ - 2016)

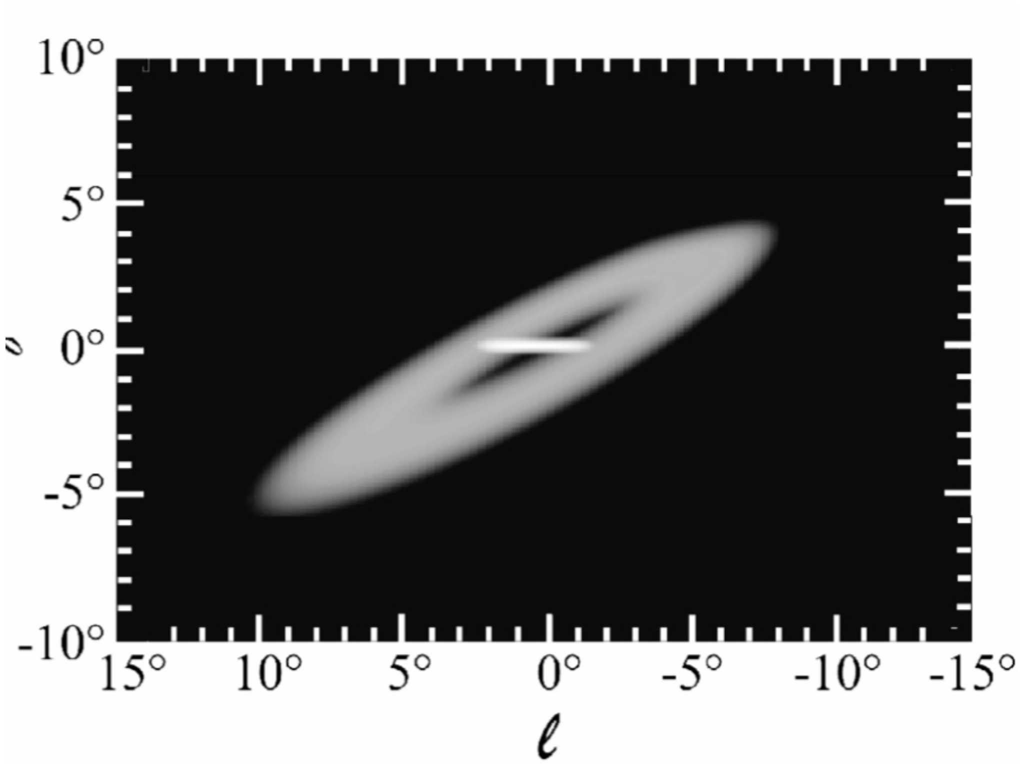
The Case of the Galactic Center



24μm, 70μm, 350μm

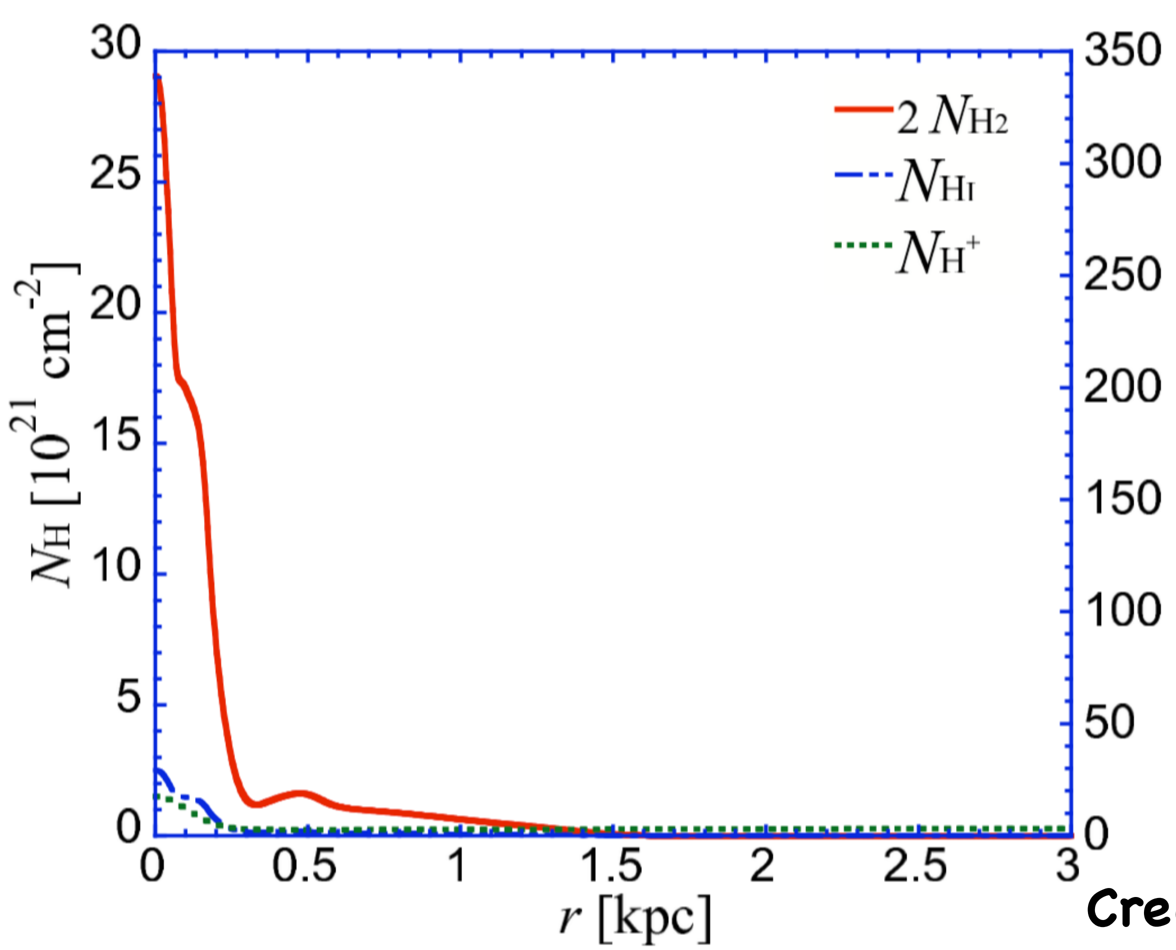
Credit: Bally et al. (2010)

The Galactic Center Region



The CMZ is an asymmetric region composed by several molecular clouds

The molecular hydrogen column density is estimated from transition line $^{12}CO(J = 1 \rightarrow 0)$



at 2.6 mm through the conversion factor

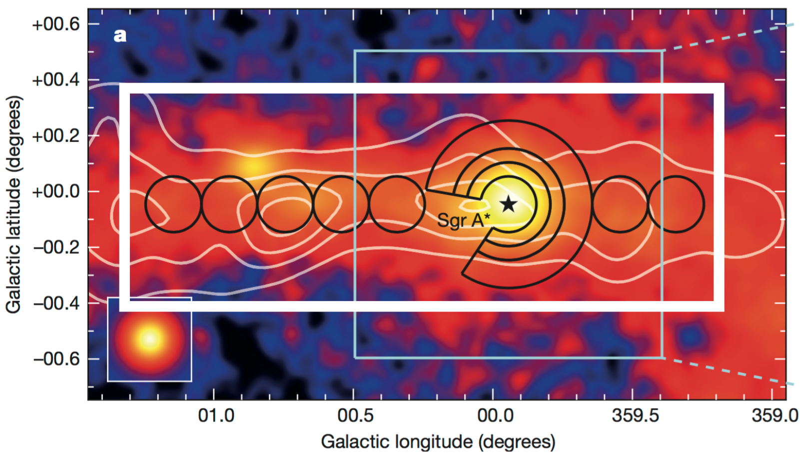
$$X_{CO} = \frac{N_{H_2}}{W_{CO}}$$

Strong et al. (2004) showed the radial dependence of the conversion factor.

$$X_{CO}(r \rightarrow 0) \approx 0.5 \times 10^{20} (cm^{-2} K^{-1} km^{-1} s)$$

Credit: Ferriere et al. (A&A - 2007)

Galactic Ridge



(| l | < 1° , | b | < 0.3°), d < 200 pc

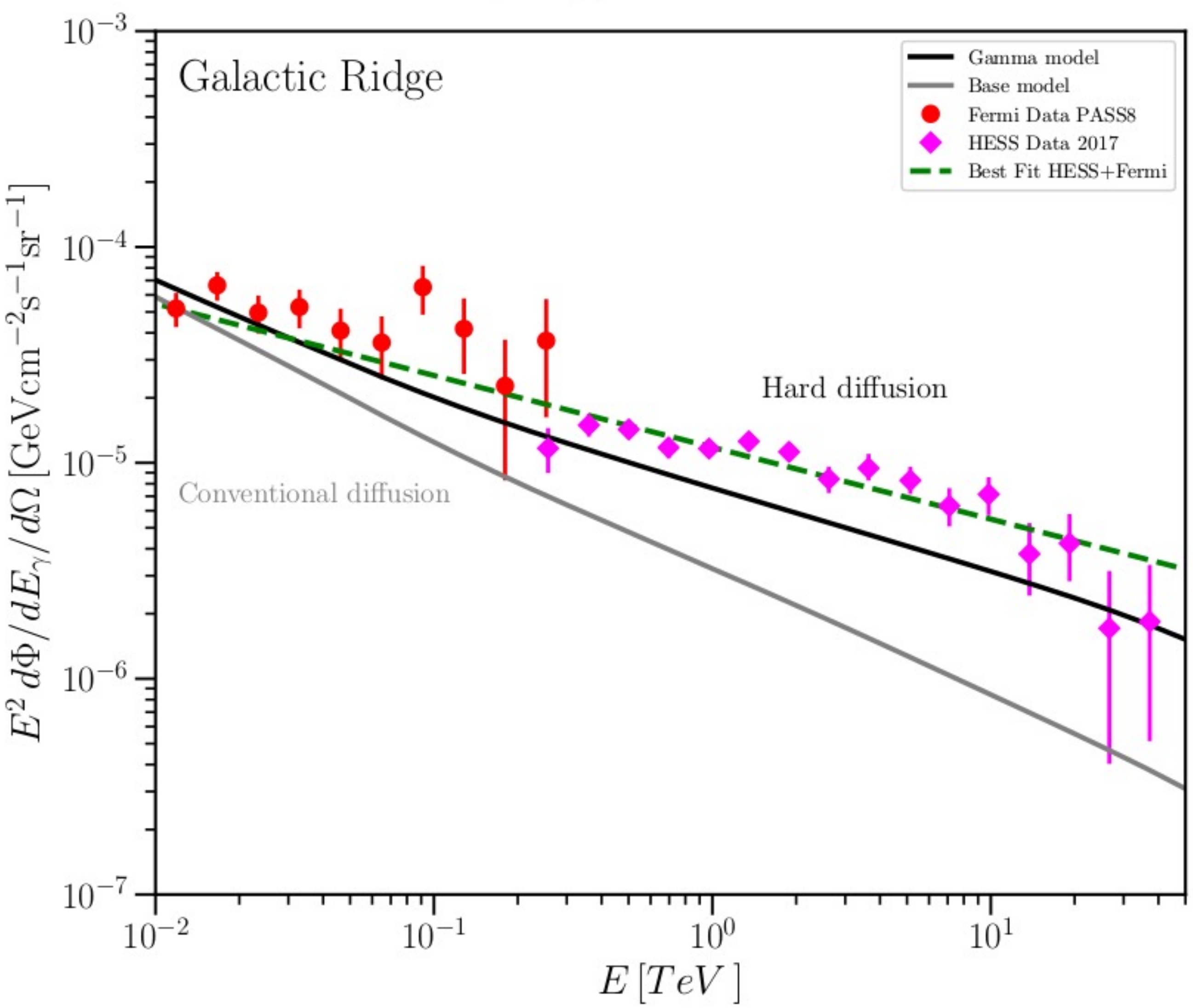
$$\Phi_{3FGL} = (1.19 \pm 0.04) \times 10^{-5} \left(\frac{E_\gamma}{1TeV} \right)^{-2.42\pm0.02} \quad (GeV^{-1}cm^{-2}s^{-1}sr^{-1})$$

PRELIMINARY

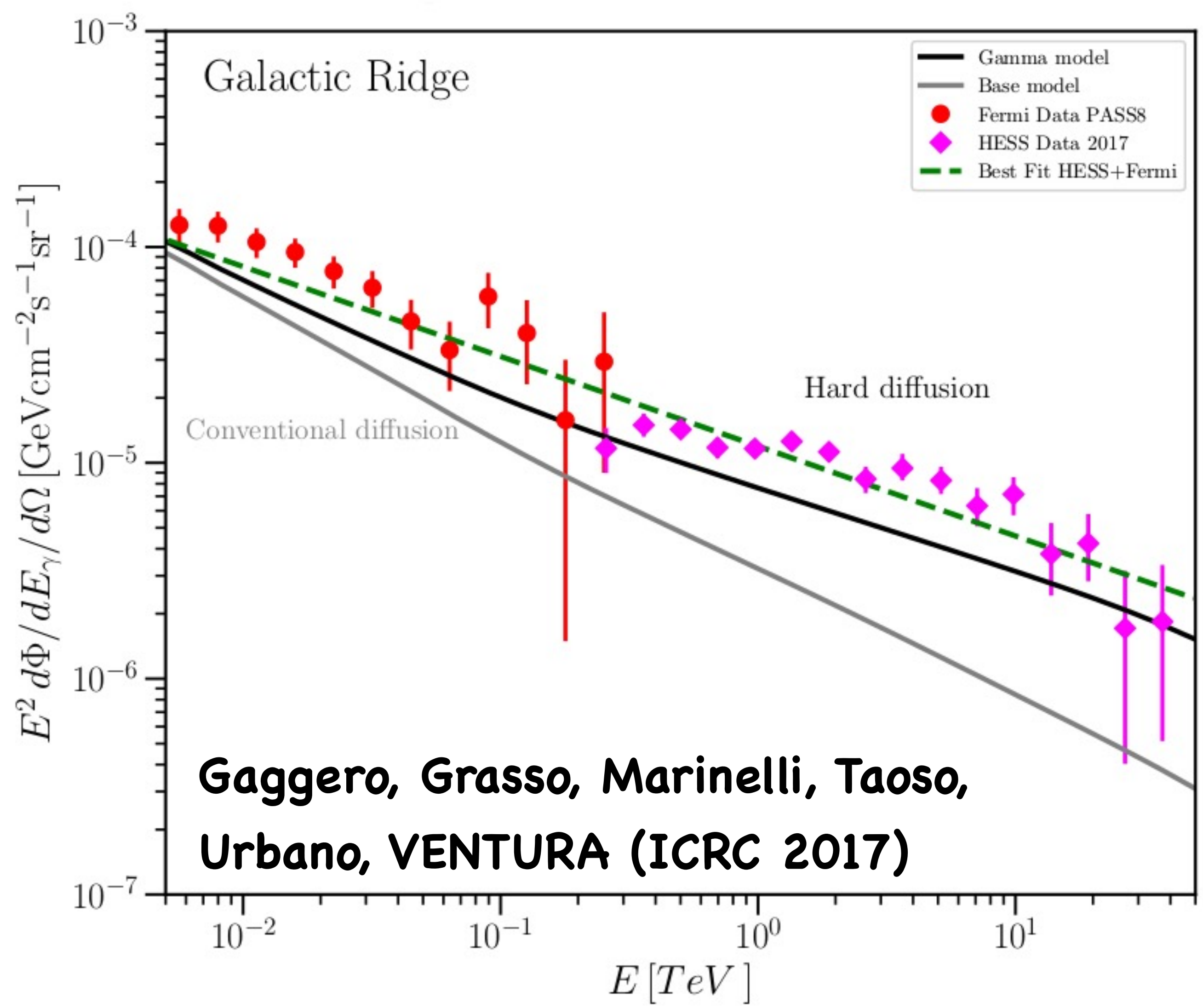
$$\Phi_{3FHL} = (1.18 \pm 0.04) \times 10^{-5} \left(\frac{E_\gamma}{1TeV} \right)^{-2.33\pm0.02} \quad (GeV^{-1}cm^{-2}s^{-1}sr^{-1})$$

$$X_{CO}(r \to 0) \approx 0.65 \times 10^{20} (cm^{-2}K^{-1}km^{-1}s)$$

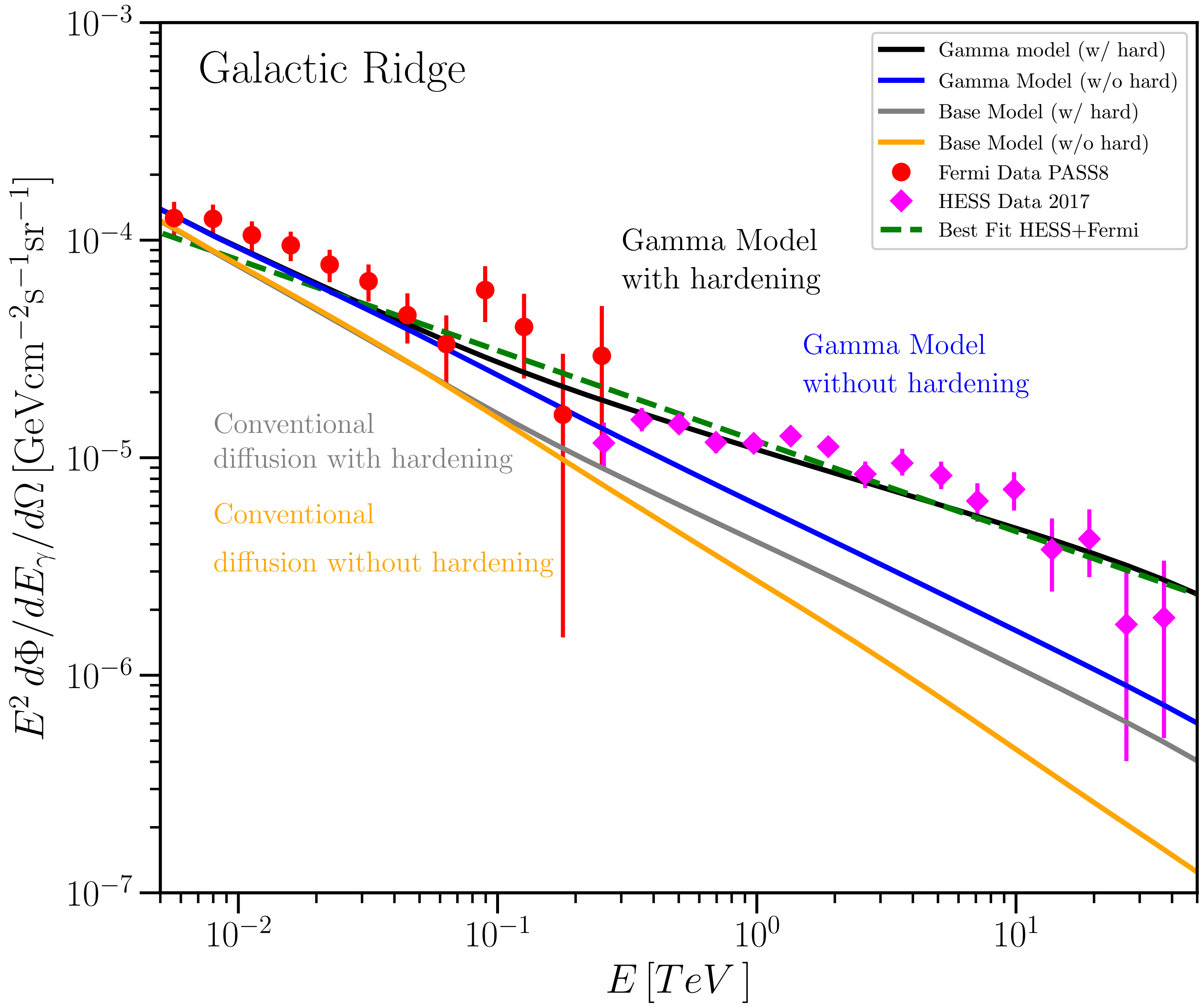
3FHL Point Sources Subtraction



3FGL Point Sources Subtraction

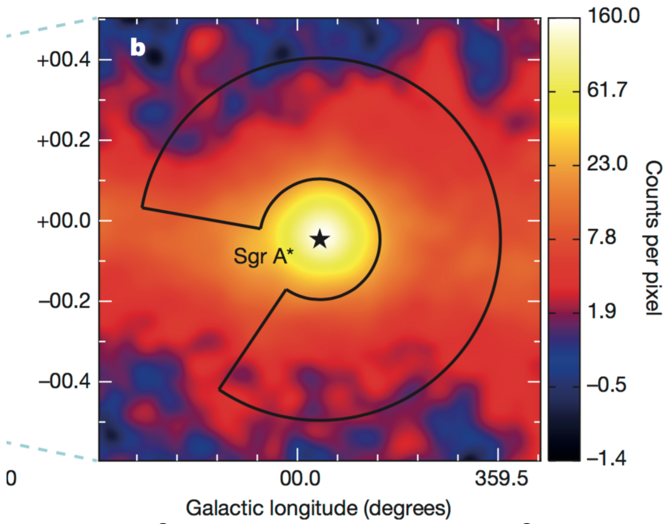


Galactic Ridge



$$X_{CO}(r \to 0) \approx 0.85 \times 10^{20} (cm^{-2} K^{-1} km^{-1} s)$$

Pacman Region



$$\Phi_{3FGL} = (1.33 \pm 0.06) \times 10^{-5} \left(\frac{E_\gamma}{1TeV} \right)^{-2.45 \pm 0.02} \quad (GeV^{-1} cm^{-2} s^{-1} sr^{-1})$$

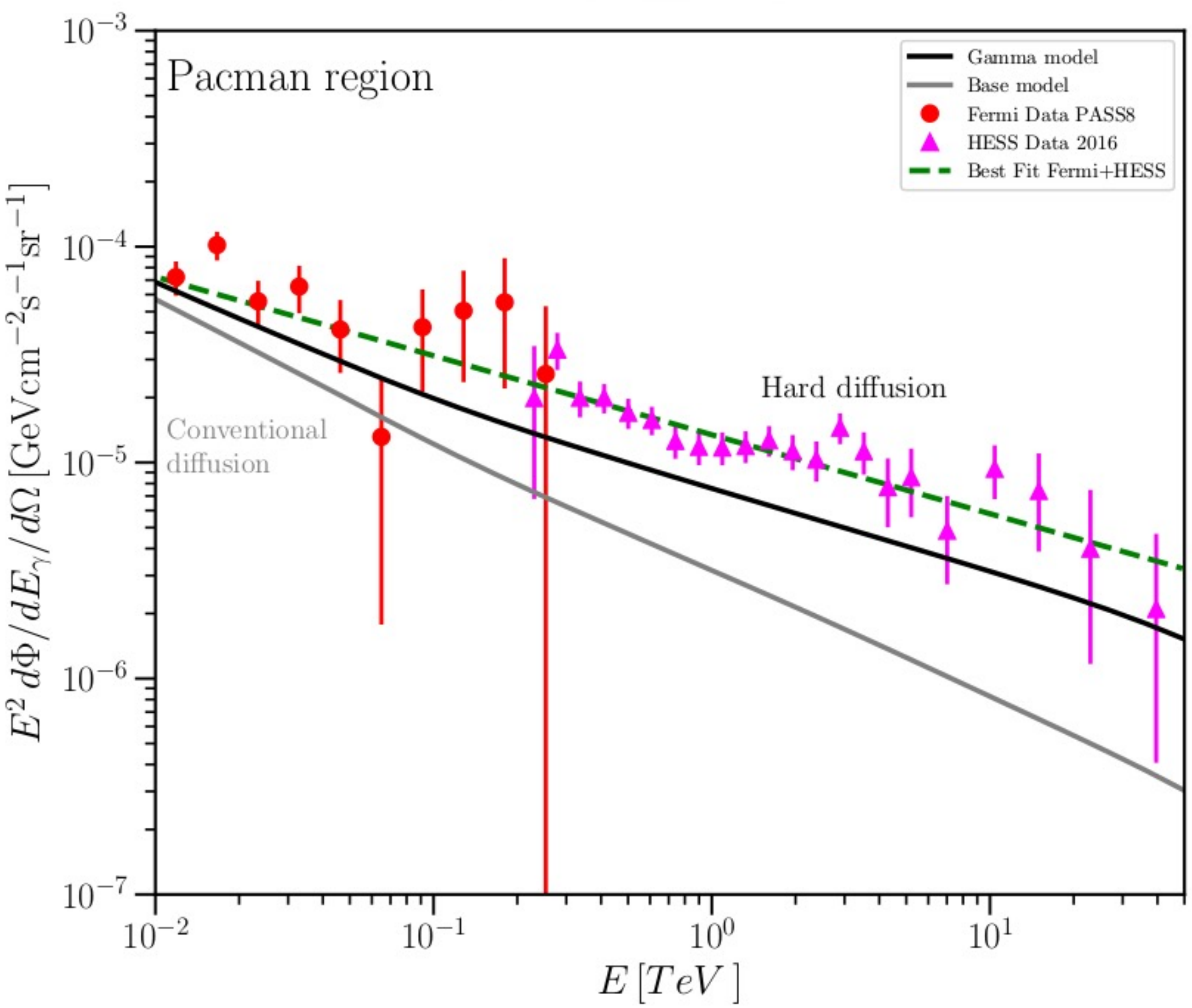
PRELIMINARY

$$\Phi_{3FHL} = (1.35 \pm 0.06) \times 10^{-5} \left(\frac{E_\gamma}{1TeV} \right)^{-2.37 \pm 0.03} \quad (GeV^{-1} cm^{-2} s^{-1} sr^{-1})$$

0.15° < θ < 0.45° , 22 < d < 67 pc

$$X_{CO}(r \rightarrow 0) \approx 0.65 \times 10^{20} (cm^{-2} K^{-1} km^{-1} s)$$

3FHL Point Sources Subtraction



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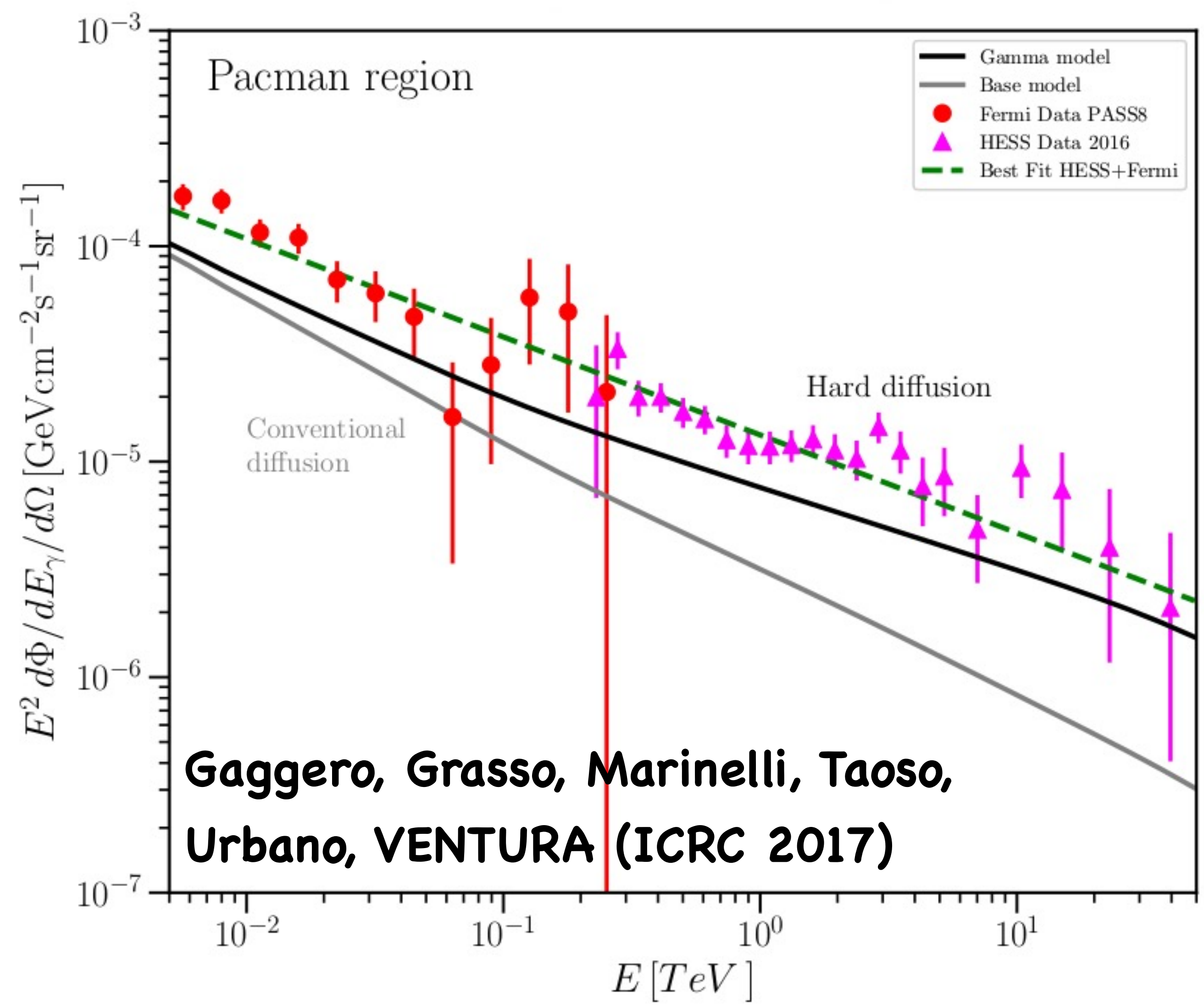
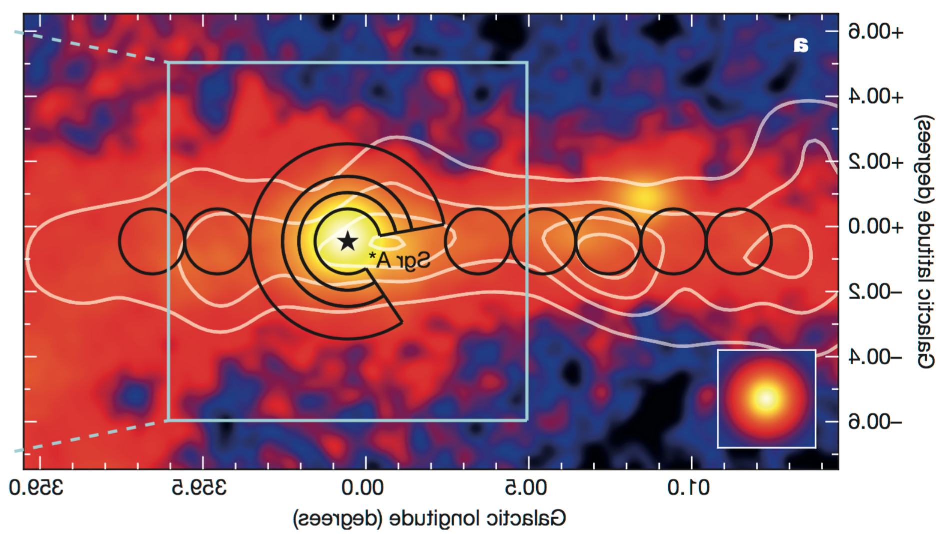
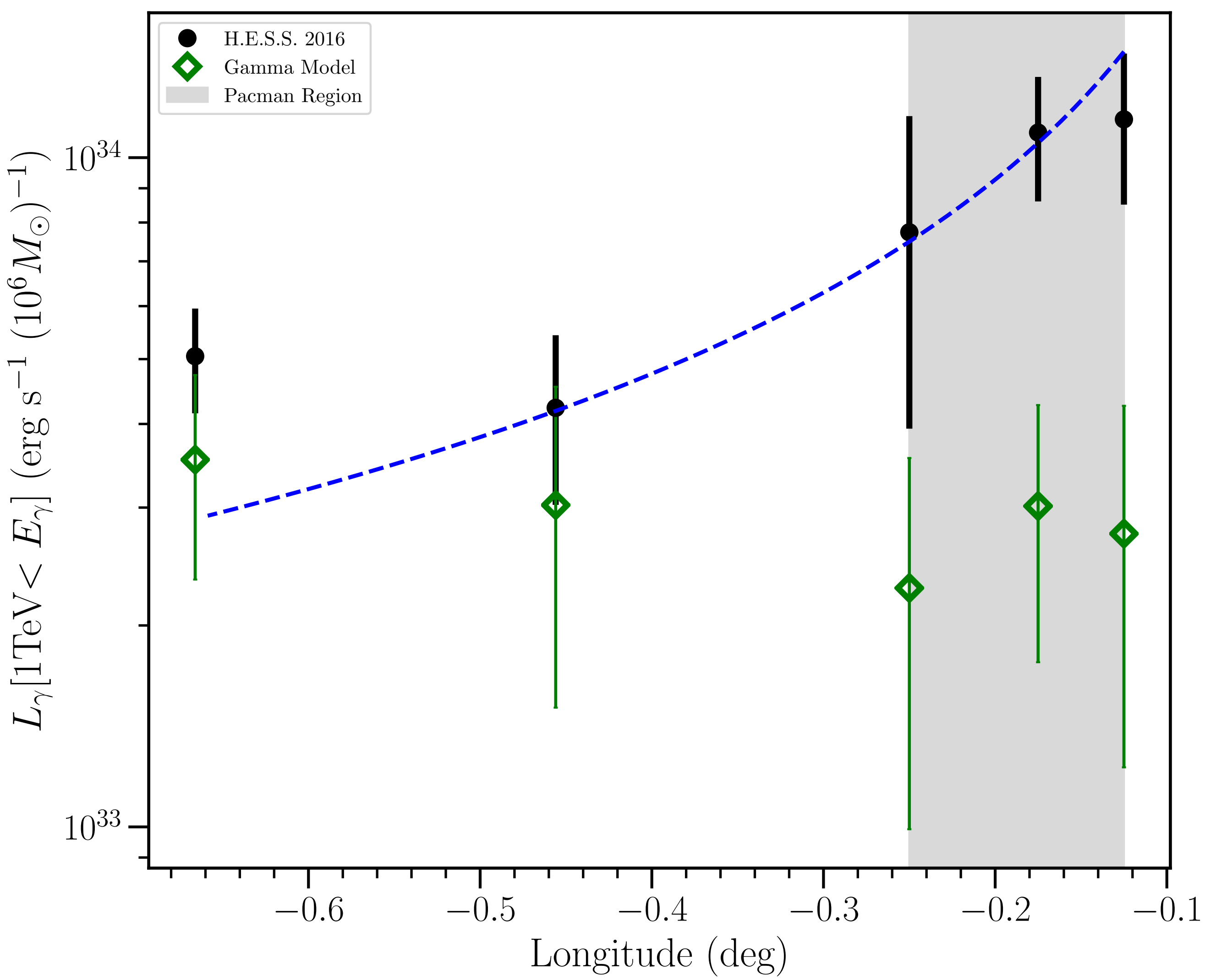
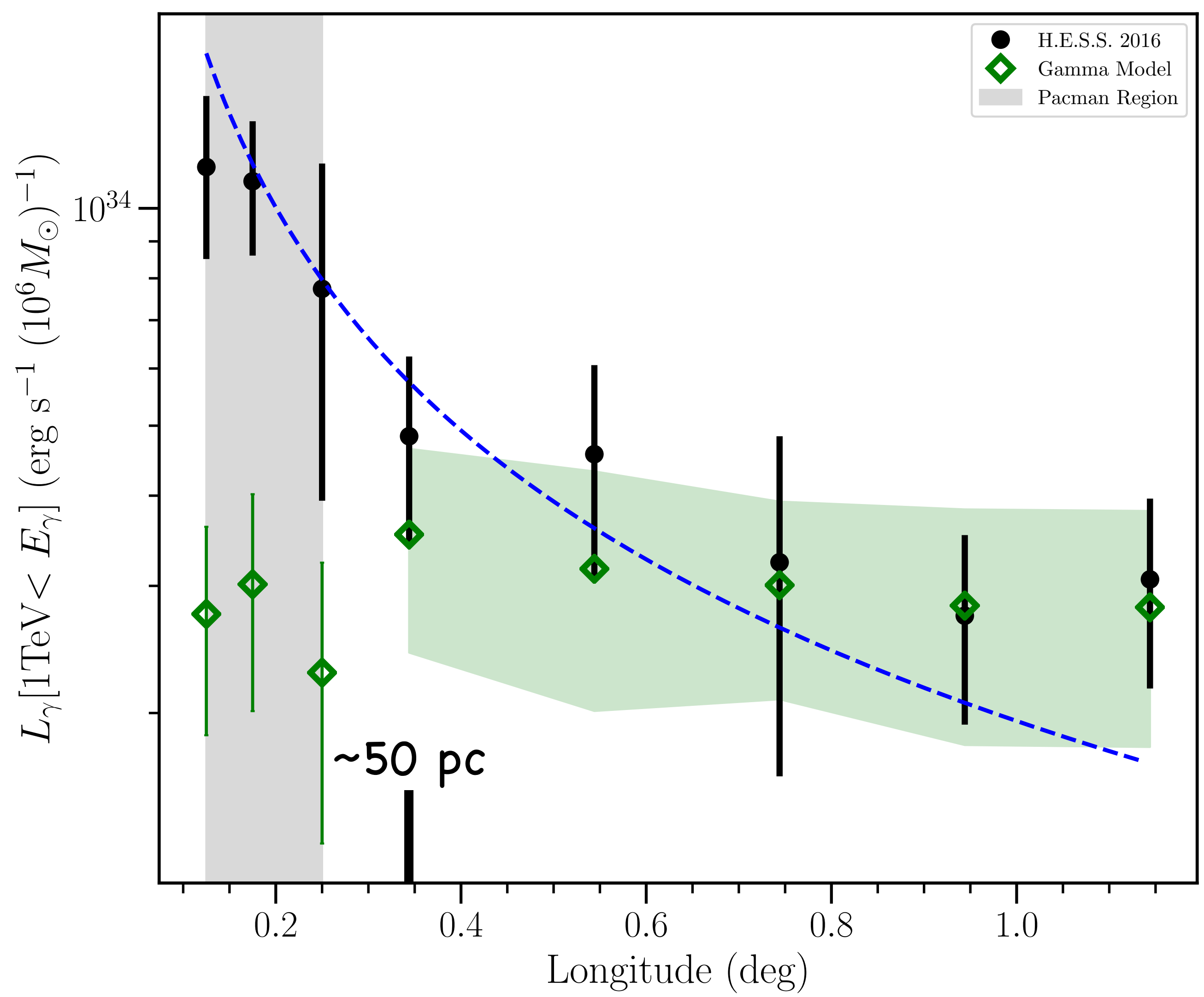


Luminosity Profile





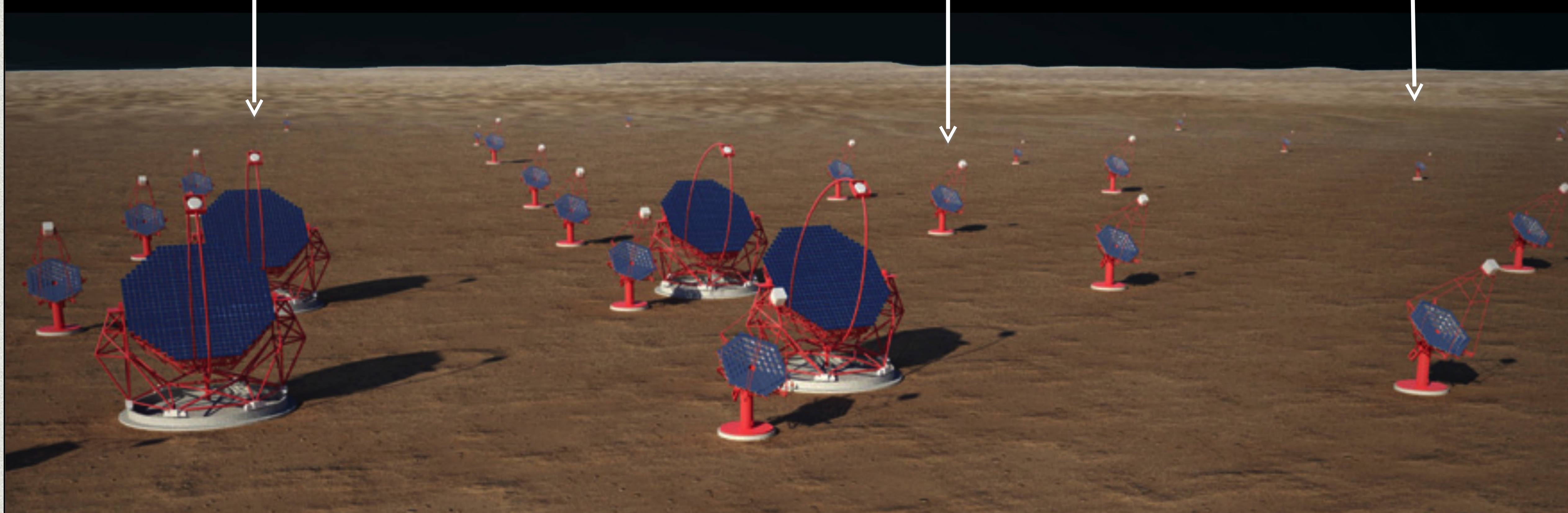


Cherenkov Telescope Array Design

Low energies
Energy threshold 20-30 GeV
23 m diameter
4 telescopes

Medium energies
100 GeV – 10 TeV
9.5 to 12 m diameter
25 single-mirror telescopes
24 dual-mirror telescopes

High energies
10 km^2 area at few TeV
4 m diameter
up to 70 telescopes



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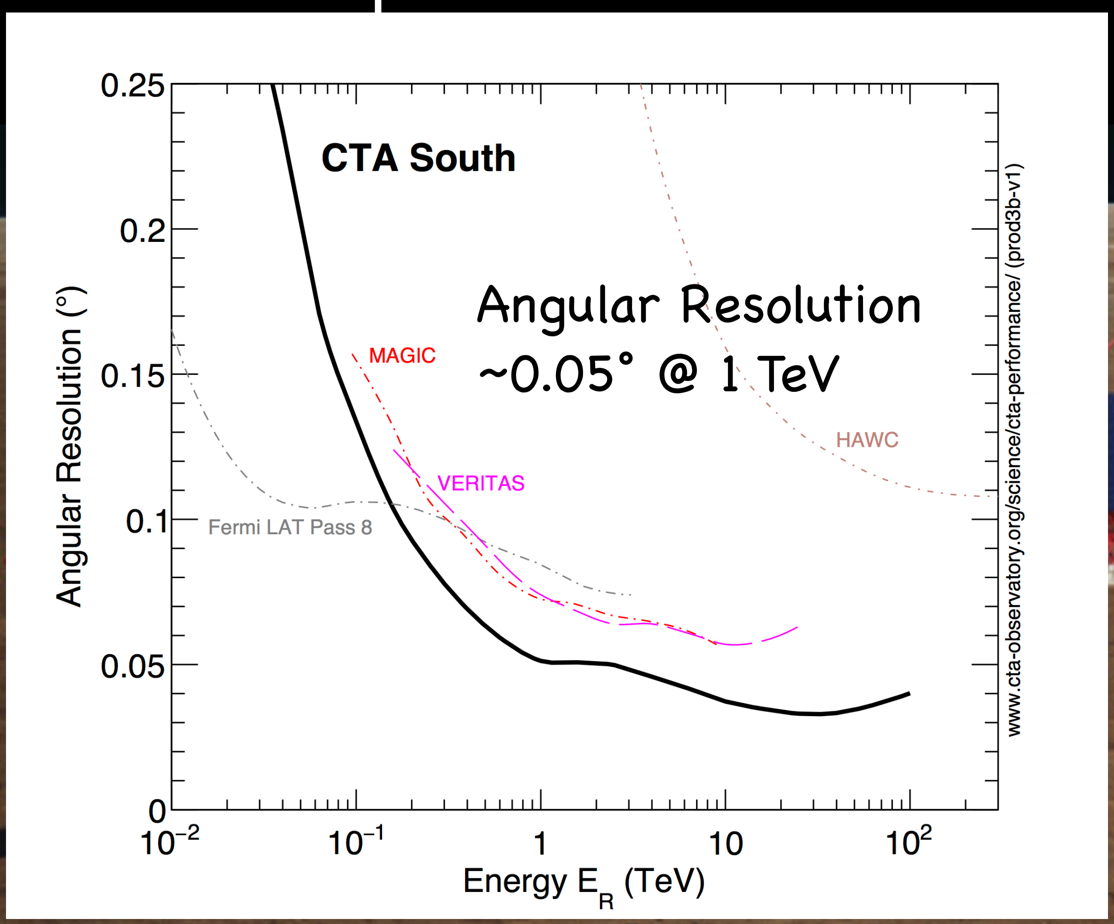
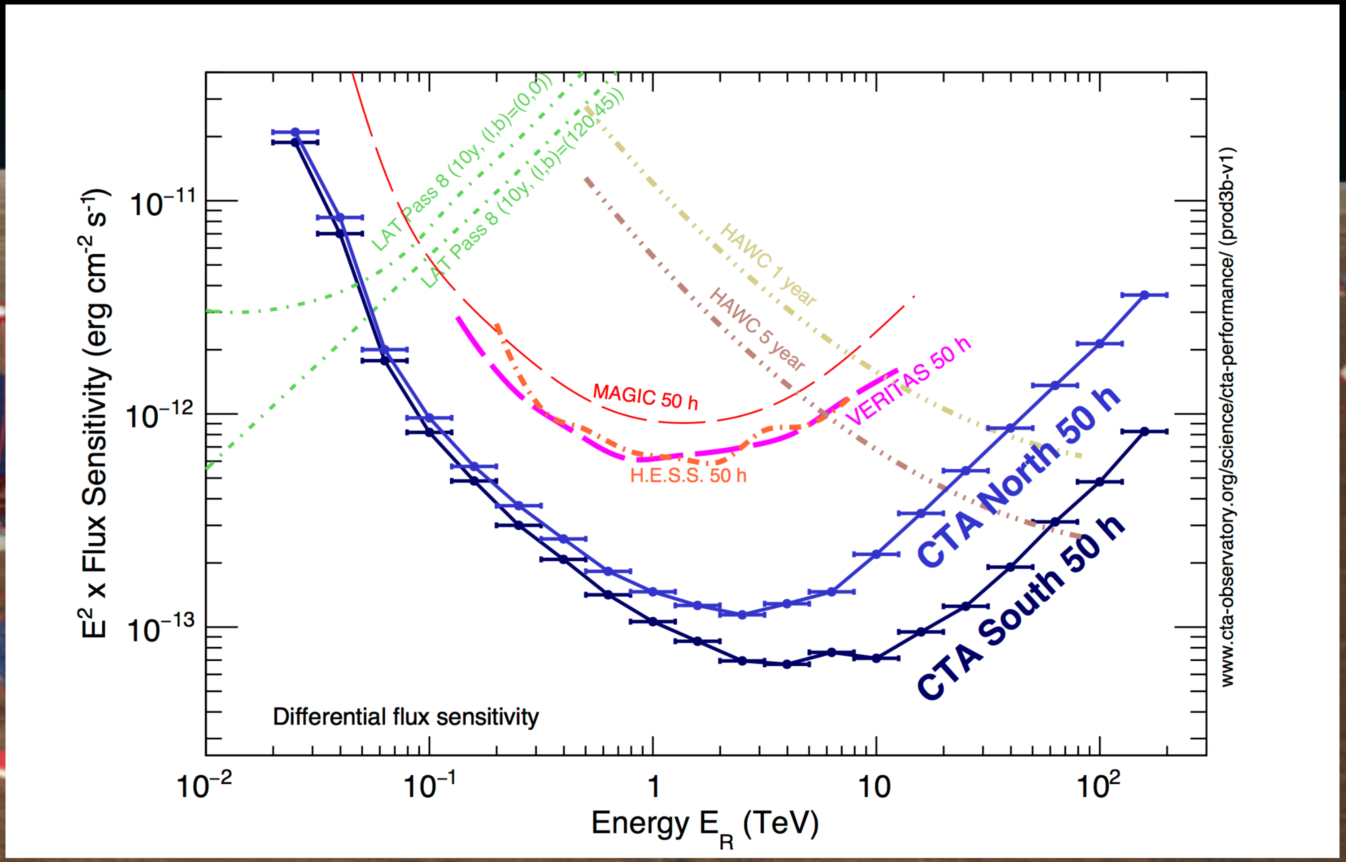
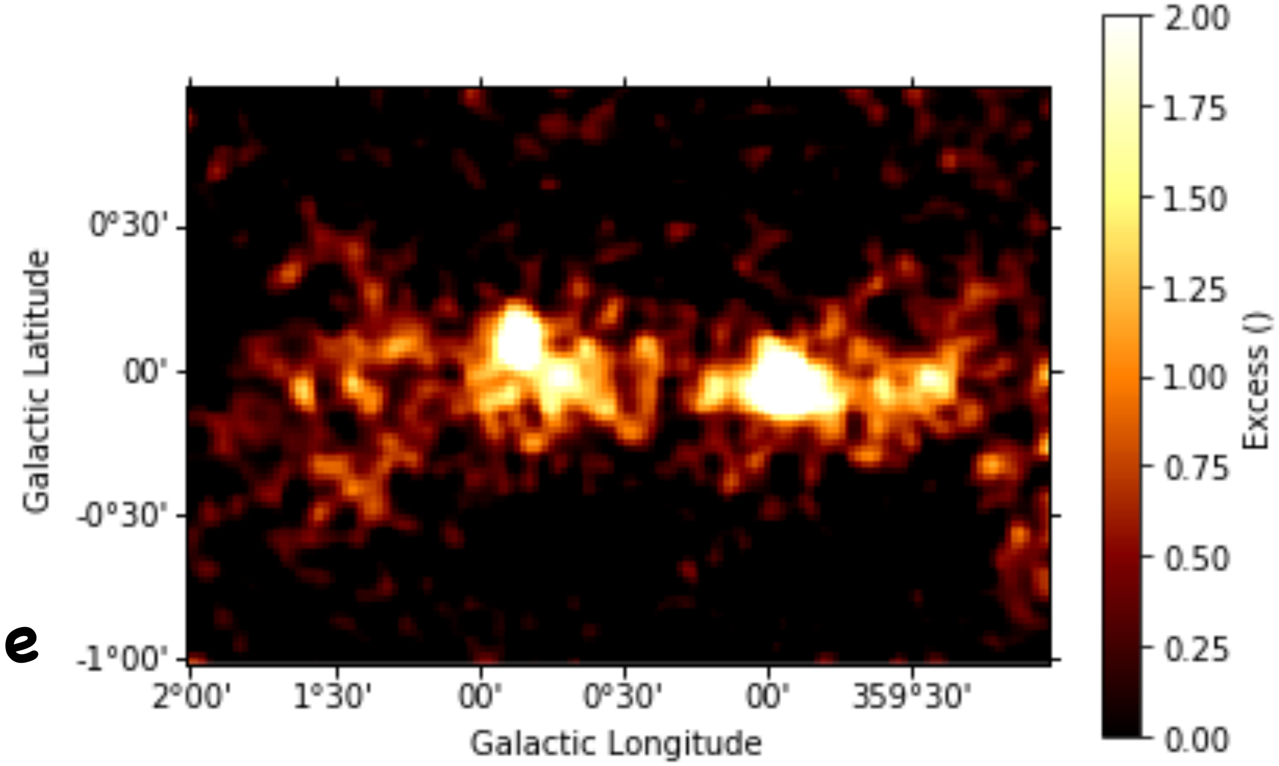


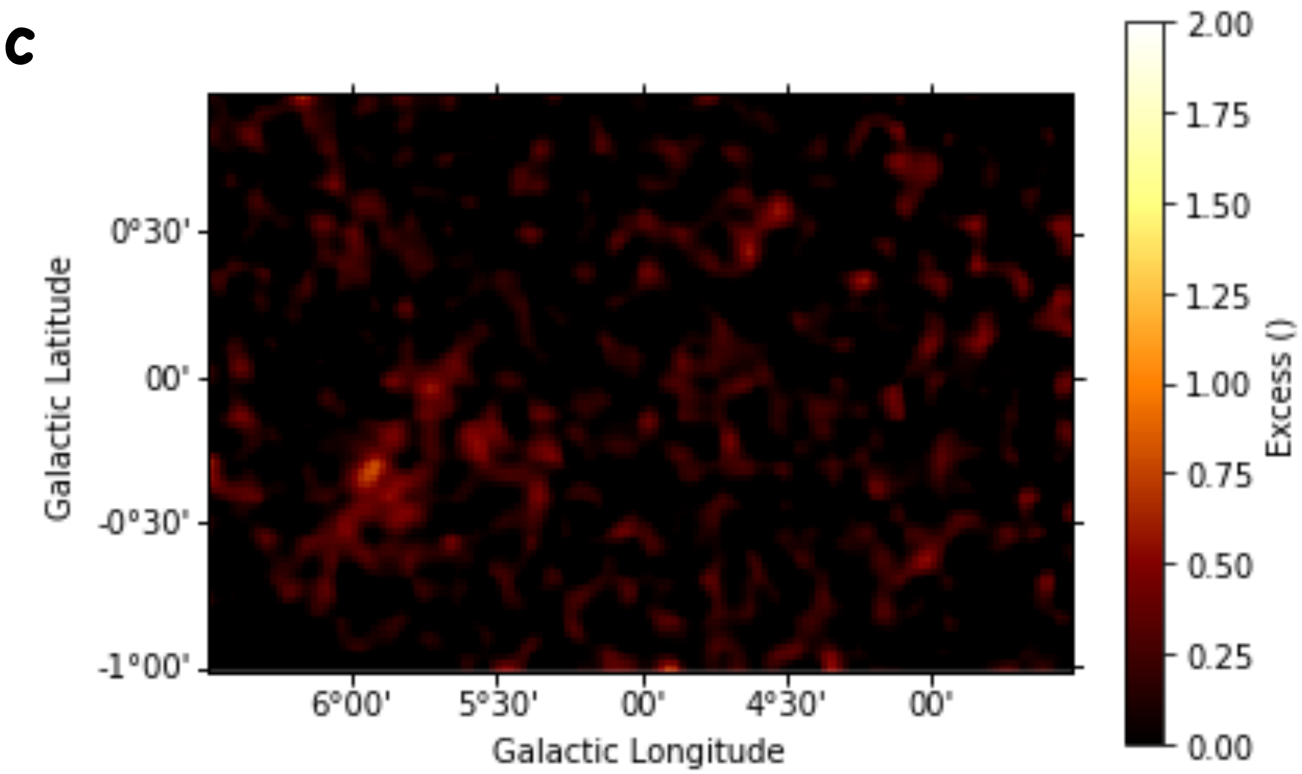


CTA Predictions



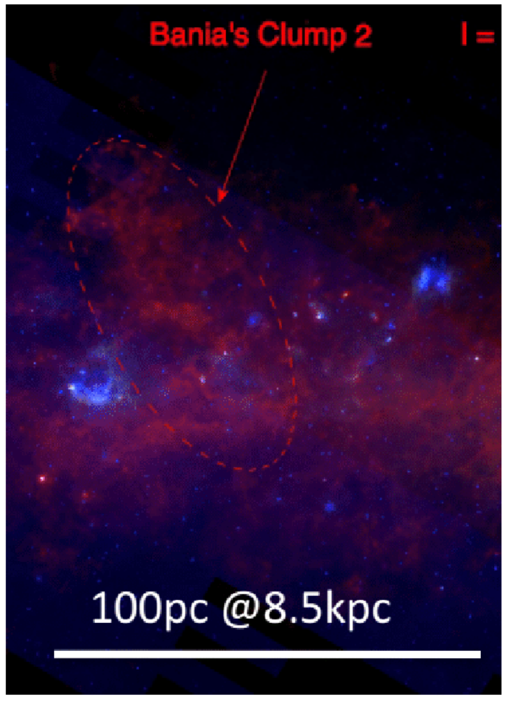
Expected γ-ray emission from CMZ (DC-I)

CTA Galactic Plane Survey (gps) 3054 simulations along the Galactic Plane



Expected γ-ray emission from Bania Clump

CTA Predictions - Bania Clump

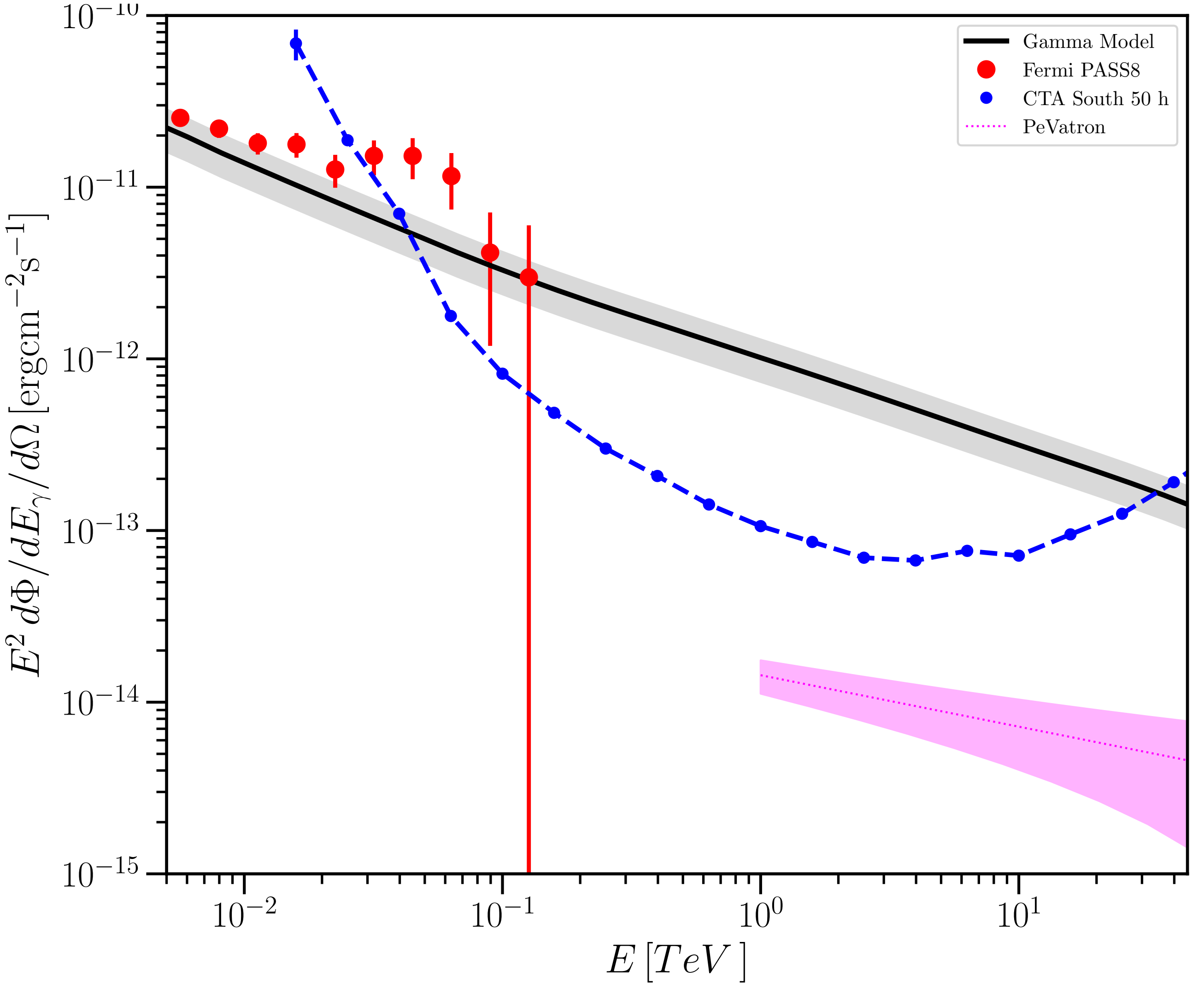


Almost 800 pc away from GC

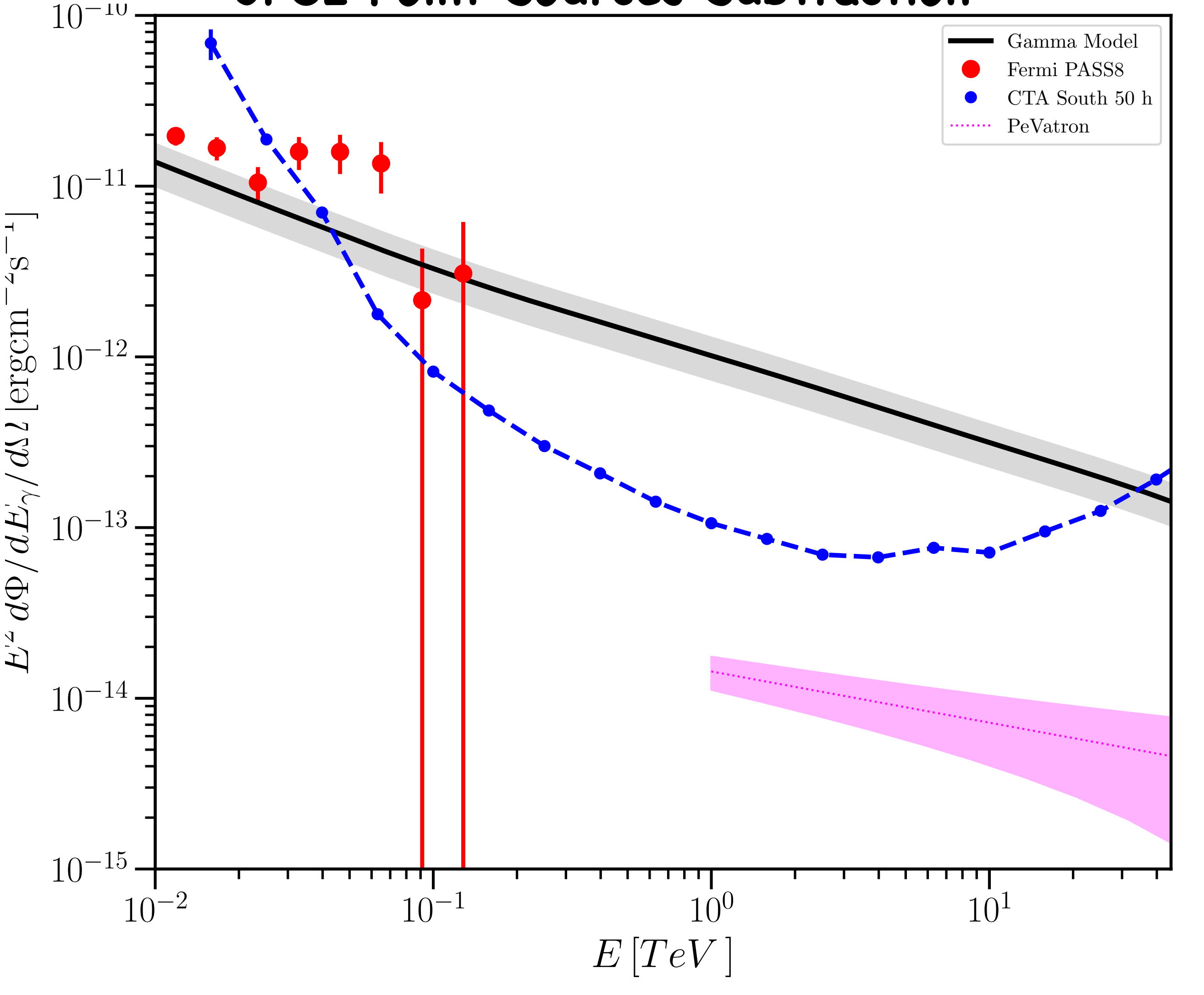
Selecting mask: circular with r=0.5°

PRELIMINARY

3FHL Point Sources Subtraction



3FGL Point Sources Subtraction



Conclusions

se γ-ray emission from the CMZ measured by H.E.S.S. and Ferm
GeV up to 50 TeV can be originated by the interaction of the
CR population that shines in the Galactic Center because of the
clouds filling the region.

sults support the inhomogeneous diffusion scenario.

sistent observational uncertainties related with the gas content
rsecs of our Galaxy does not lead to definitive conclusions.

ming Cherenkov Telescope Array (CTA) could be able to discern
scenario and/or a steady-state CR background contribution to
from Central Molecular Zone. Moreover, our model is adopted t
ground model for the CTA data analysis tools (DC-I & DC-II).

New Analysis & Future Work

of the Fermi-LAT sample till May 2019

analyzed with both FL8Y & 4FGL catalogues

of new ideal targets such as HESS J1741-302 (an hidden accele
ource?)

sis of new Fermi-LAT data in order to estimate the normalizatio
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lations inside the GC-astro working group (SV + Paolo Da Vela)

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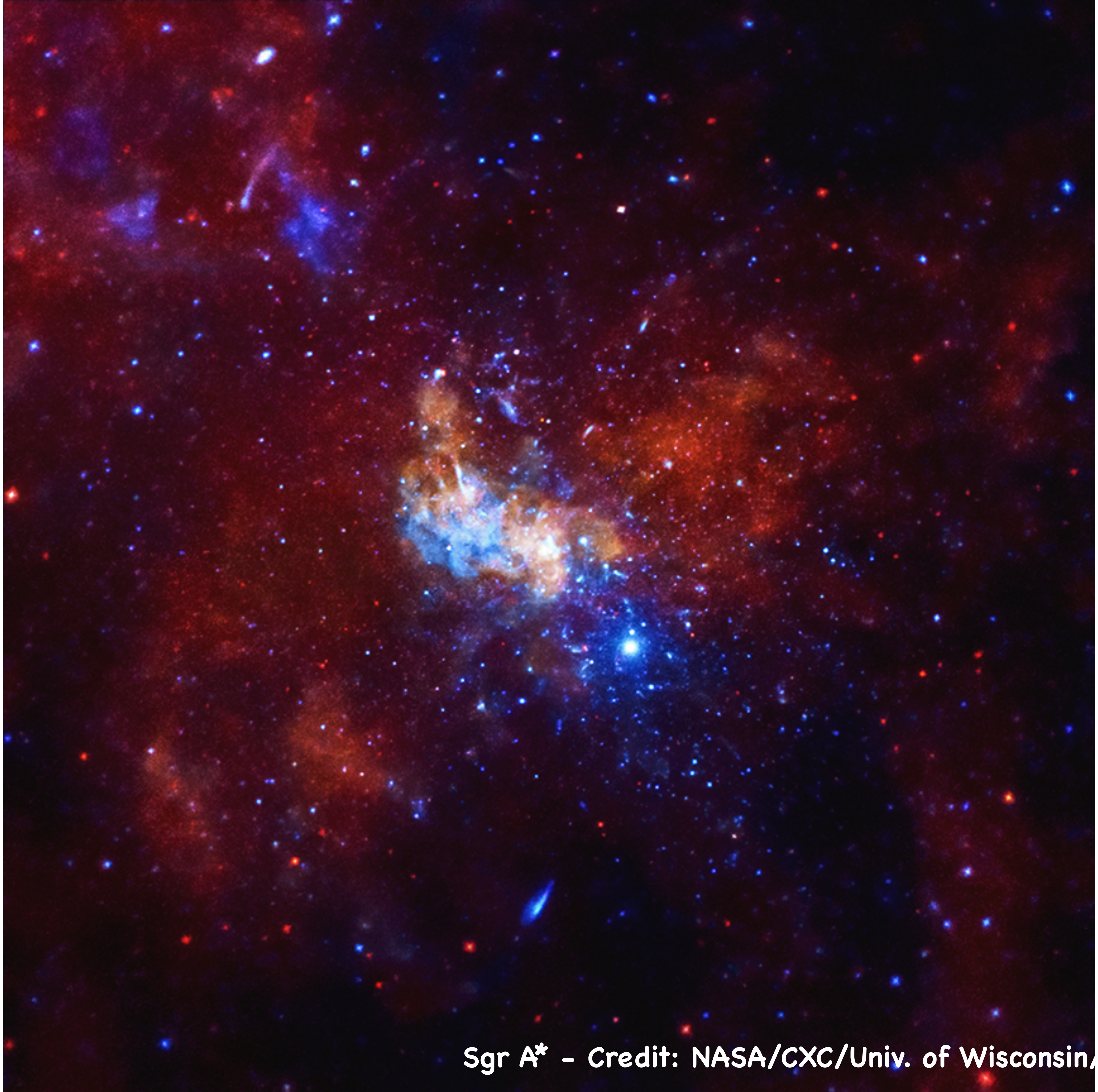
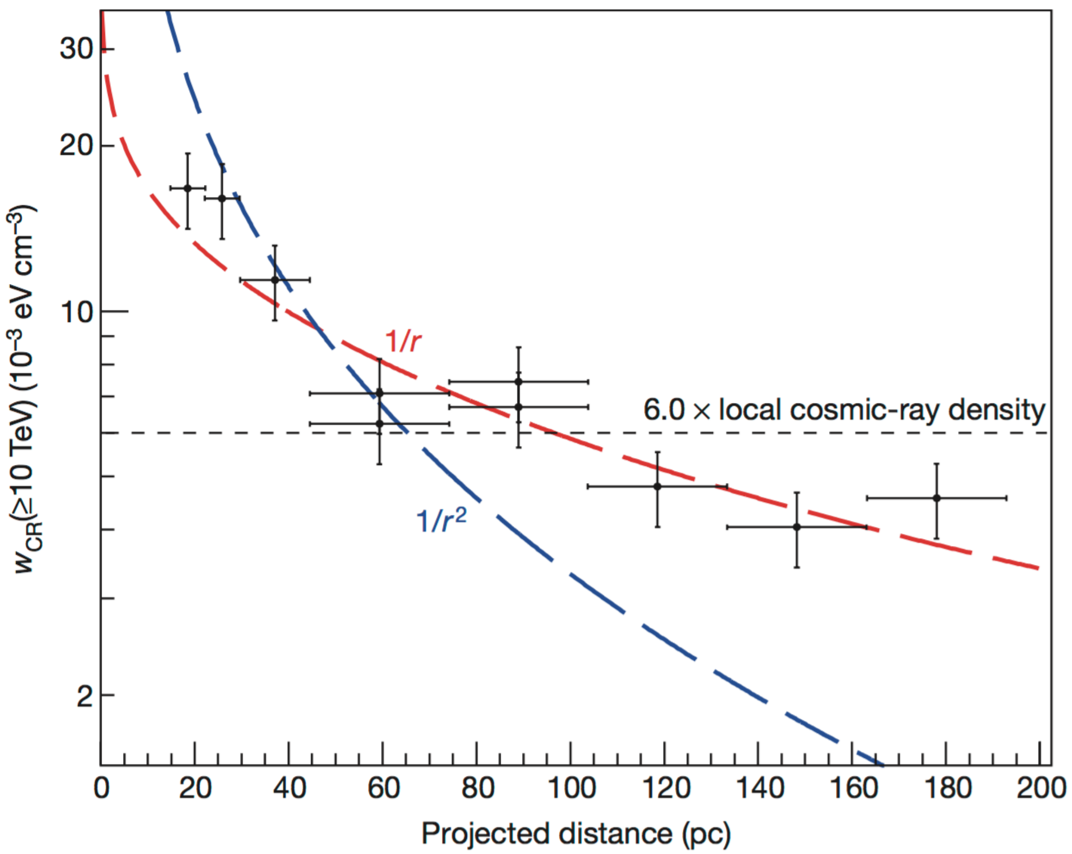
... see you in Madison
@ ICRC 2019


Sgr A* - Credit: NASA/CXC/Univ. of Wisconsin/

BACKUP SLIDE

Luminosity Profile



Starting from CRs density profile extimated by H.E.S.S. Coll. (Nature - 2016) in the CMZ as

$$w_{CR}(\geq E_\gamma) = \frac{W_p(\geq E_\gamma)}{V}$$

$$w_{CR}(\geq E_\gamma) \approx 1.8 \times 10^{-2} \left(\frac{\eta_N}{1.5}\right)^{-1} \frac{L_\gamma(\geq E_\gamma)}{10^{34}} \left(\frac{M}{10^6 M_\odot}\right)^{-1}$$

where V is the volume of the region.
So the Luminosity profile results

$$\boxed{\frac{L_\gamma}{10^6 M_\odot} \approx K \frac{1}{r}}$$