Evidences of a hard cosmic ray population in the Galactic Center region and their possible interpretations

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with
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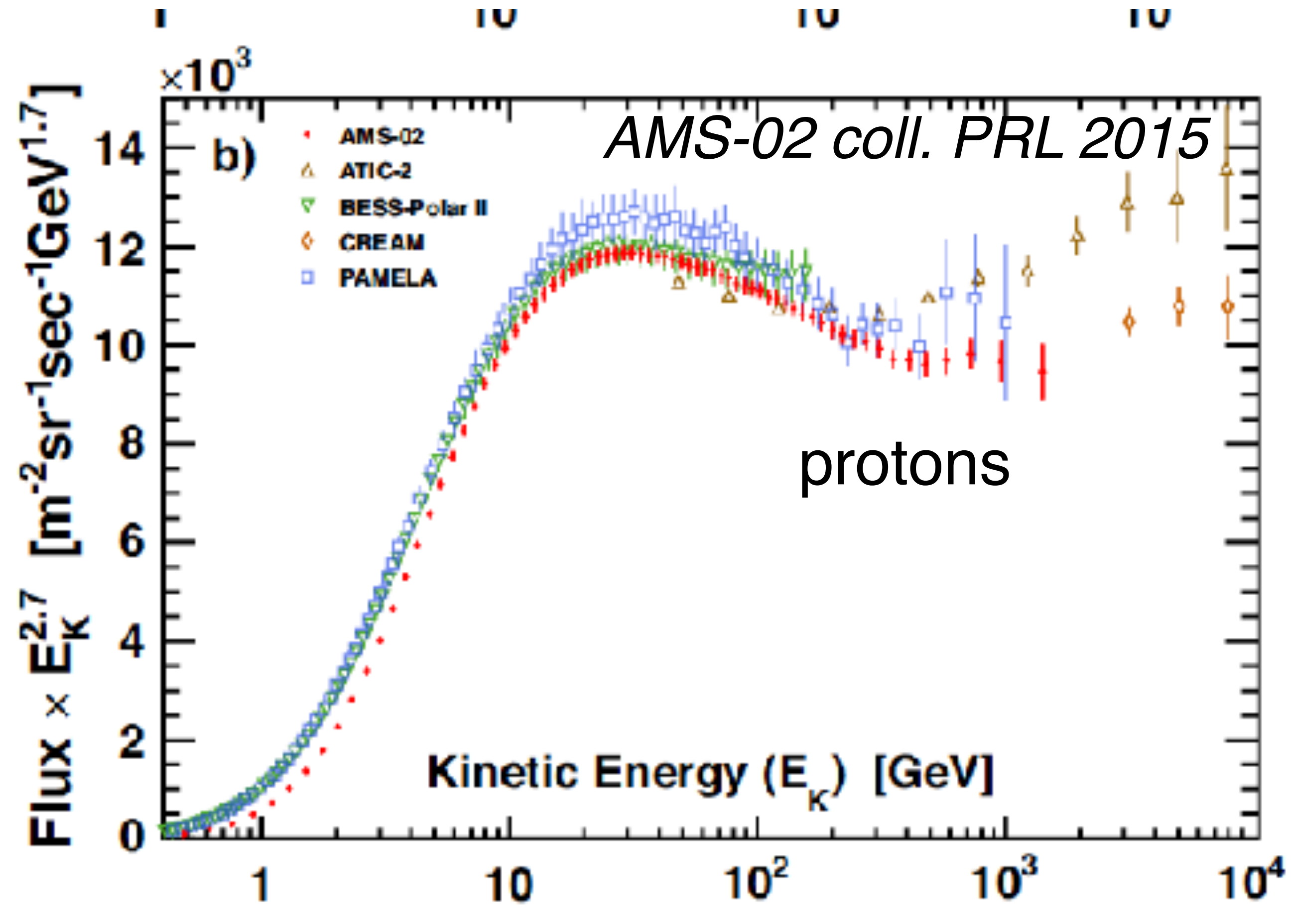
CRATER Workshop 2018

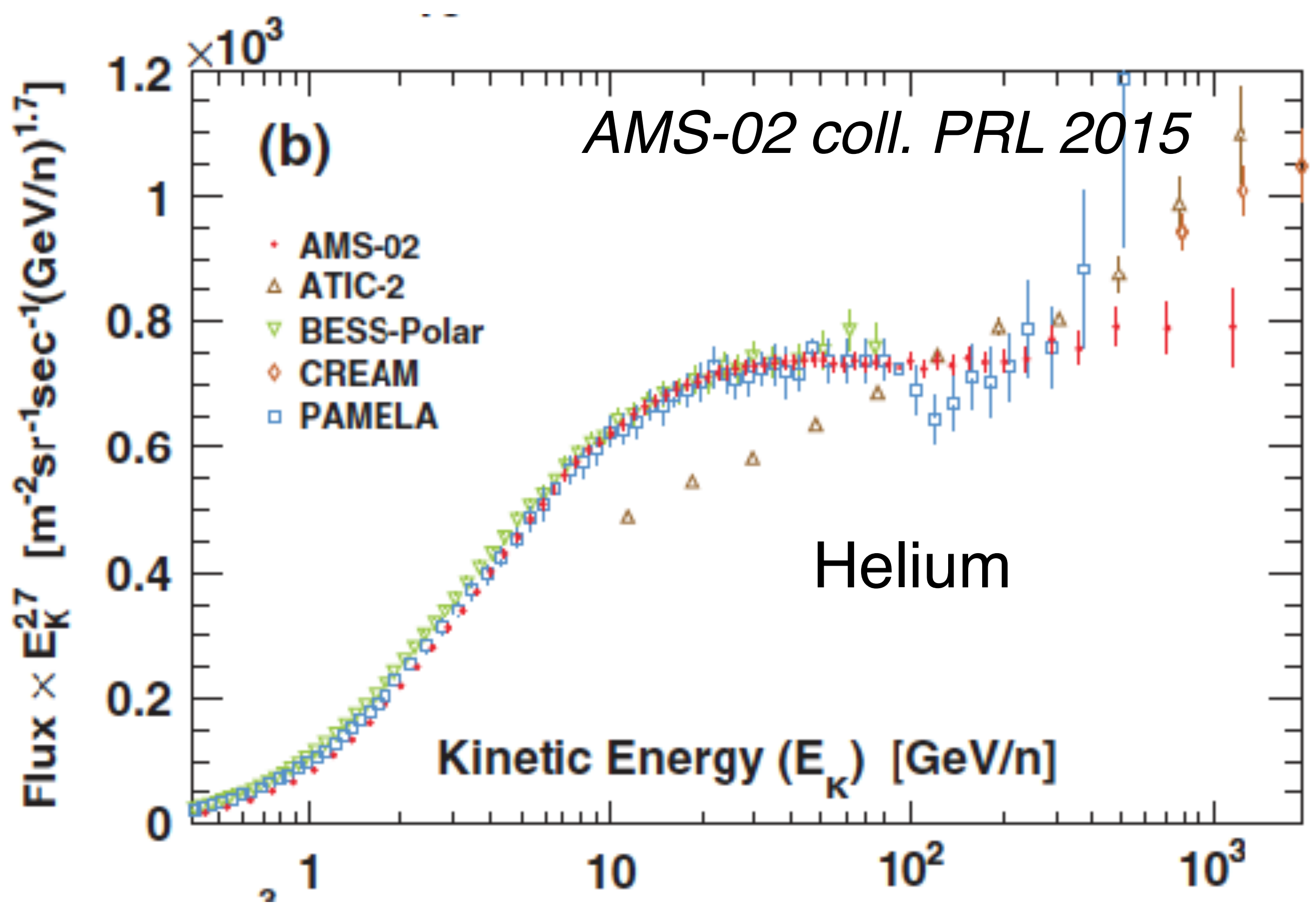
CR hardening @ ~ 300 GeV/n

CREAM coll. ApJ Lett. 2010
PAMELA coll. SCIENCE 2011
AMS-02 coll. PLR 2015

PAMELA found an hardening of the p and He spectra at ~ 250 GeV/n **AMS-02** confirmed the feature (slightly smoother and starting at ~ 300 GeV/n). This is also required to match **CREAM**

A similar effect was found for heavier nuclei





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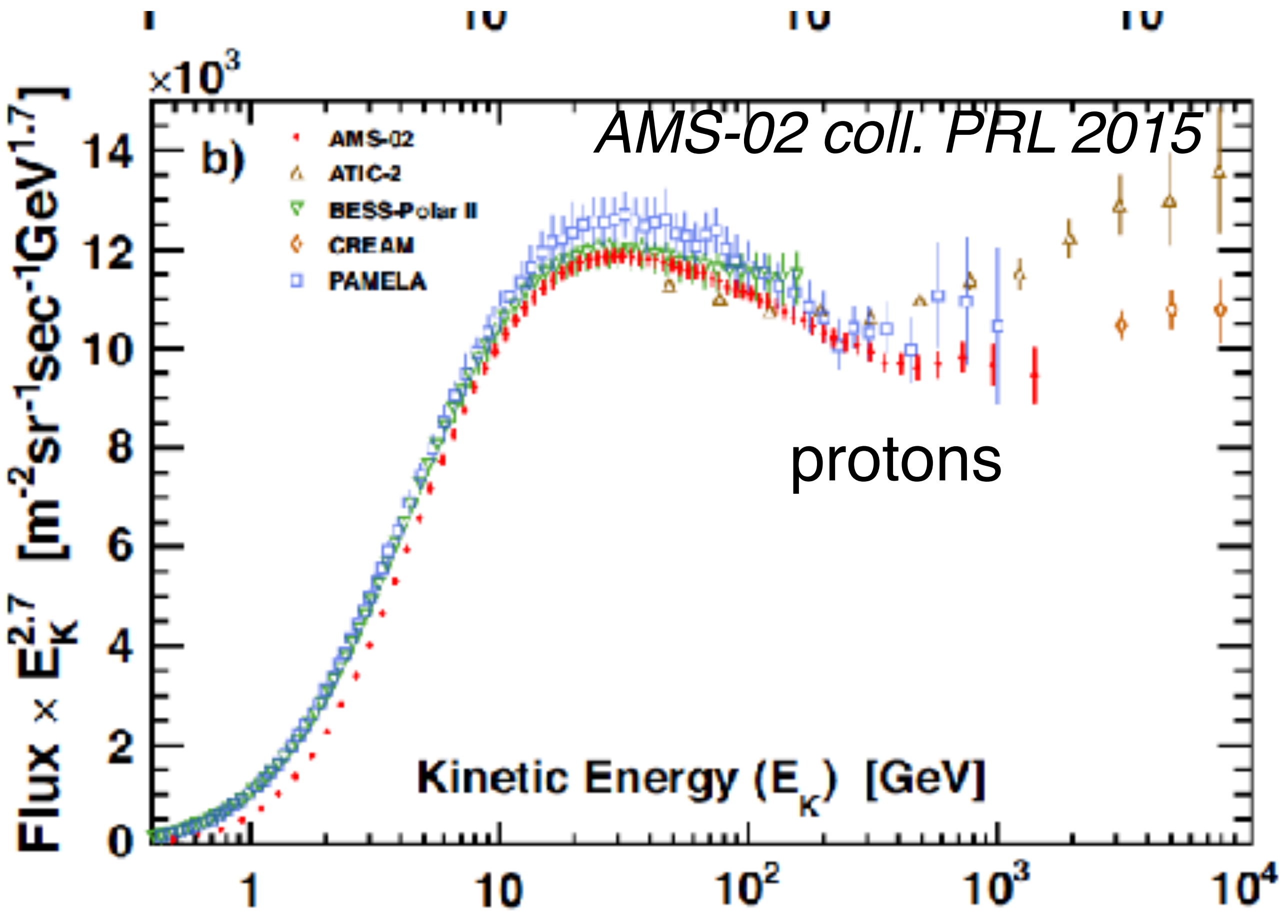
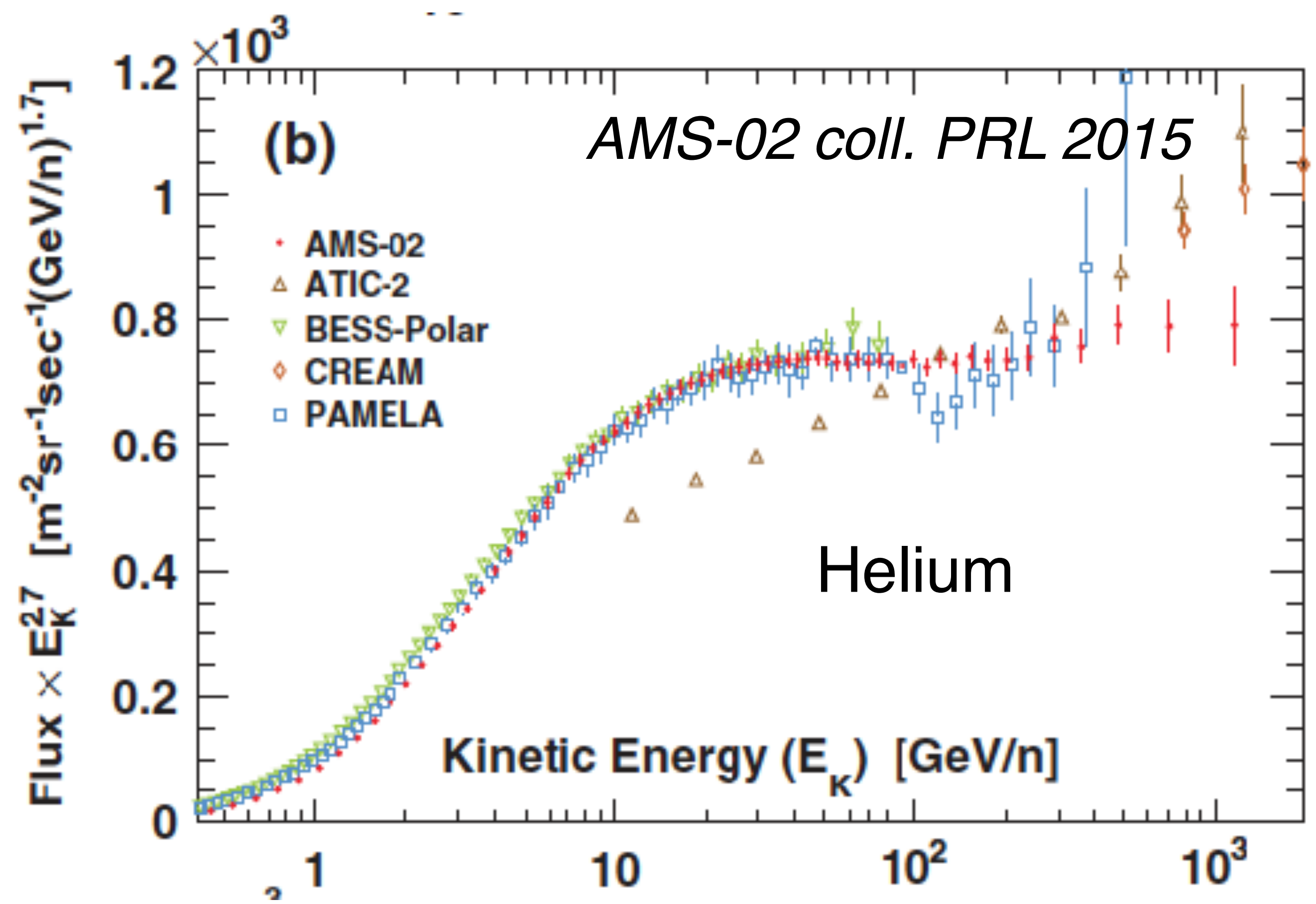
- Is this a local effect or present in the whole Galaxy ?
- How it depends on the ISM conditions ?



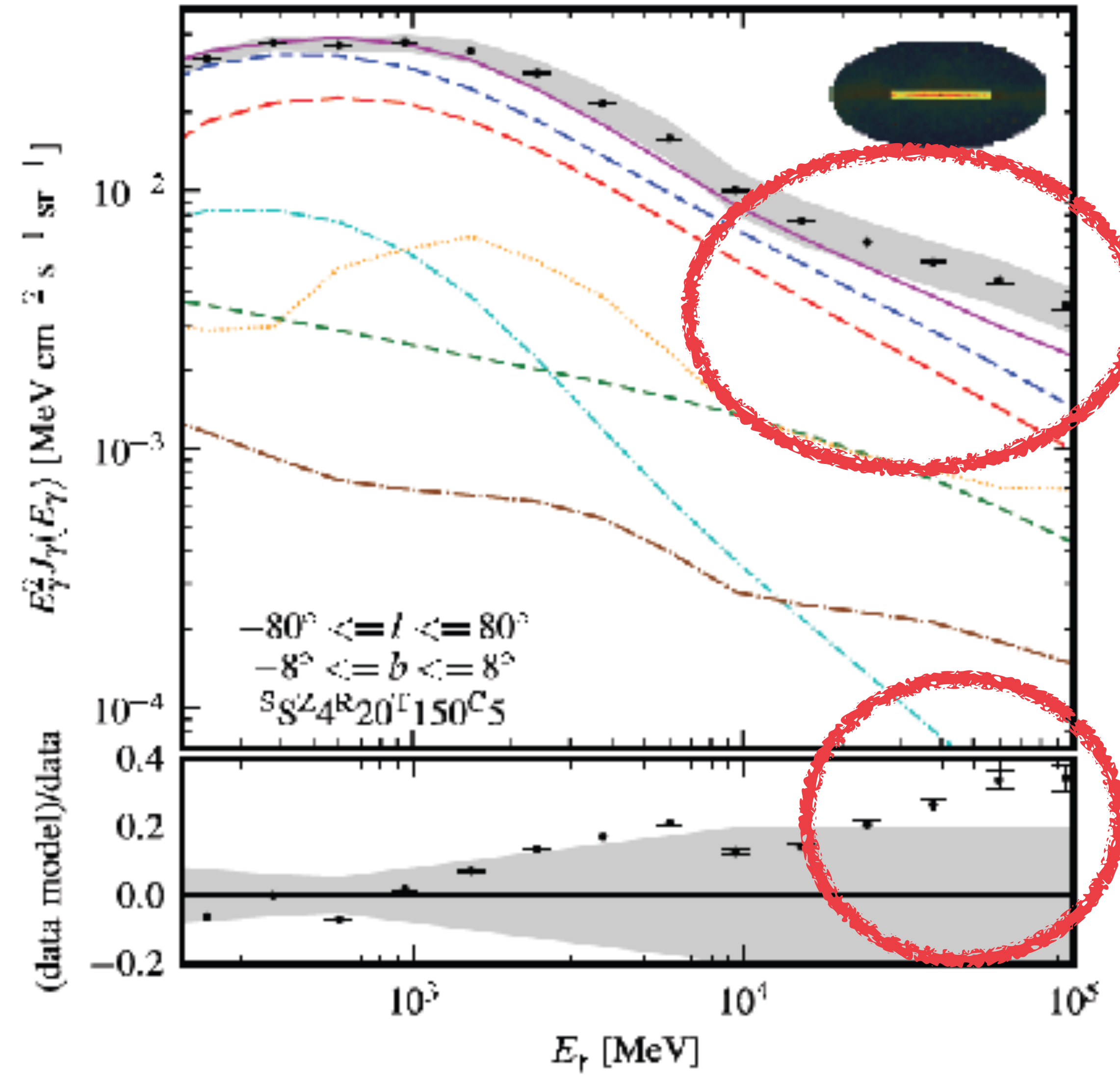


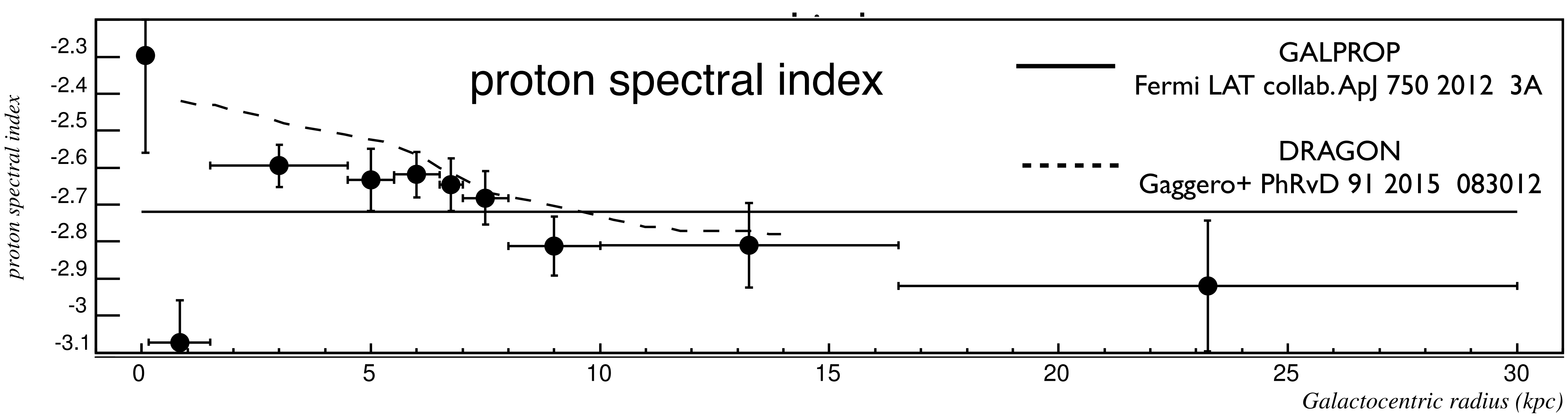
The spectral index gradient problem

Conventional models, tuned on local CR data and reproducing the γ-ray diffuse emission outside the Galactic plane (GP), fall short in the inner GP above tens of GeV

In 2016 a template fit analysis of Fermi-LAT data shown that the effect is due to a radial dependent CR spectral index confirming a previous finding by *Gaggero, Urbano, Valli & Ullio 2015*

Fermi-LAT coll. 2012



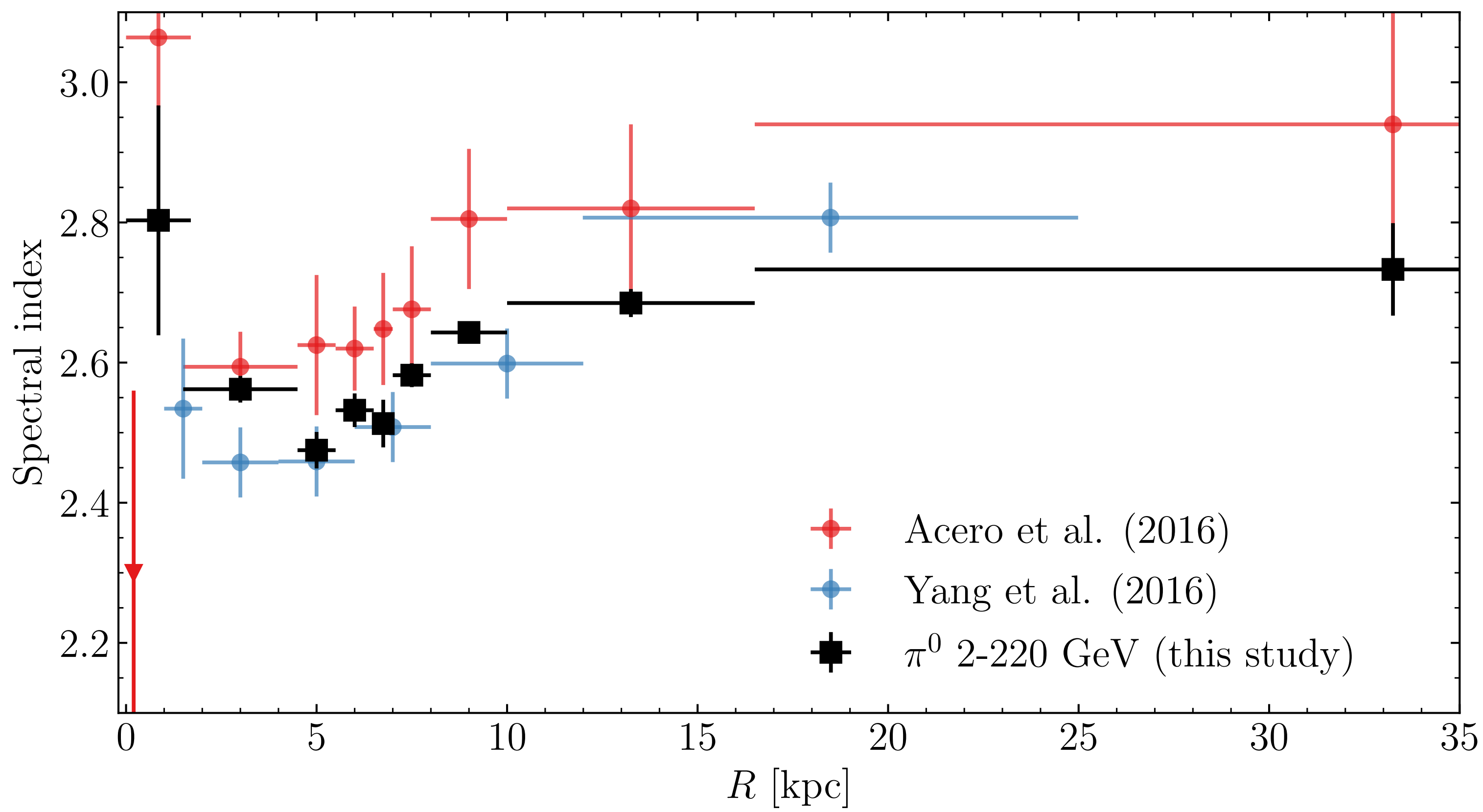


The spectral index gradient problem

Prothast, Gaggero, Strom, Weniger, 2018

preliminary

proton spectral index



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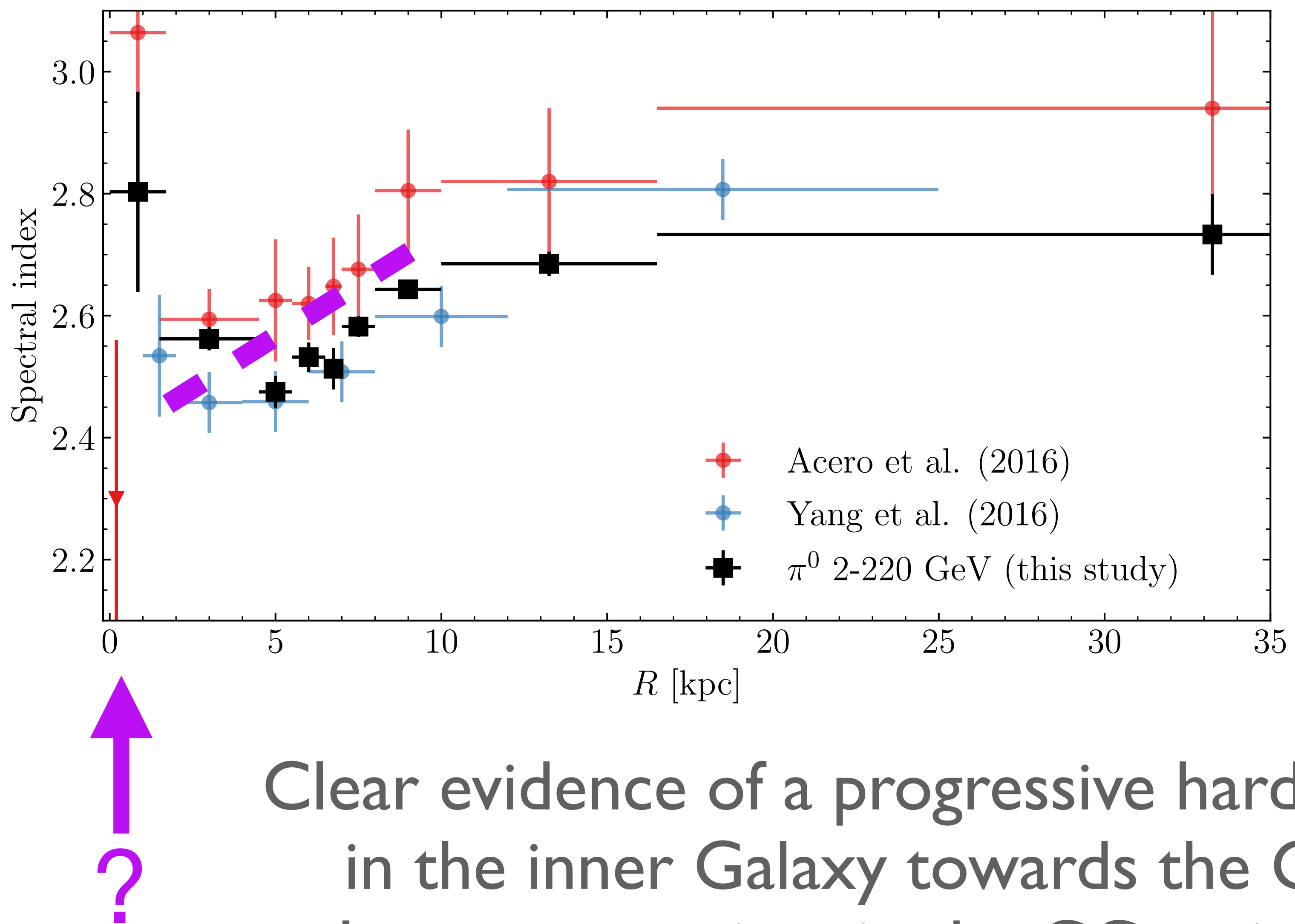
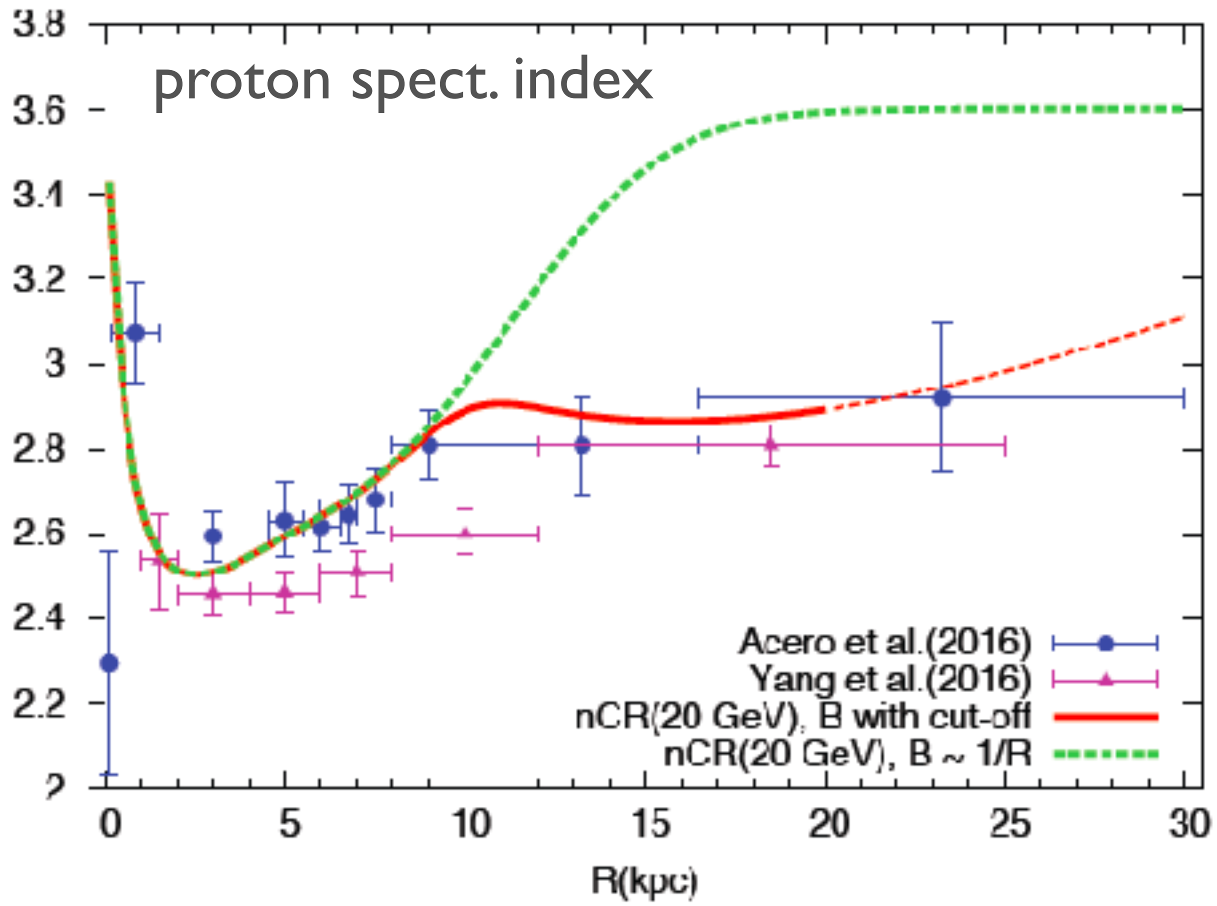


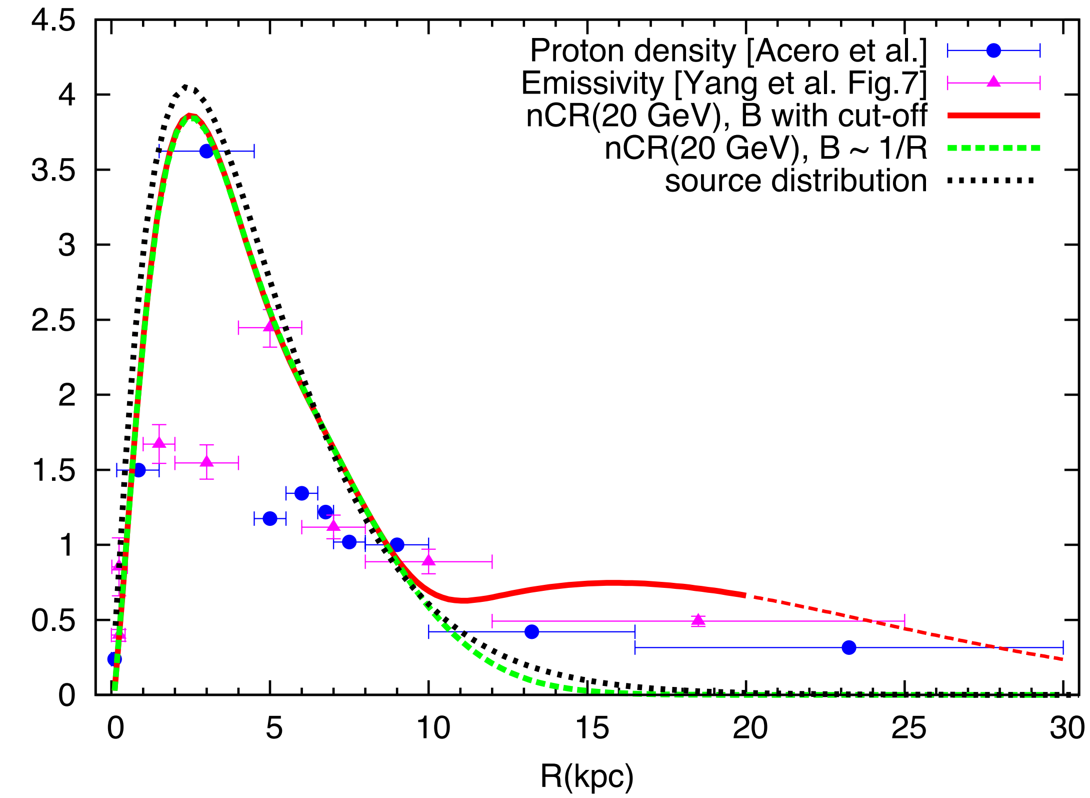
Clear evidence of a progressive hardening in the inner Galaxy towards the GC

Large uncertainty in the GC region !

A possible solution based on non-linear propagation

Recchia, Blasi & Morlino 2016



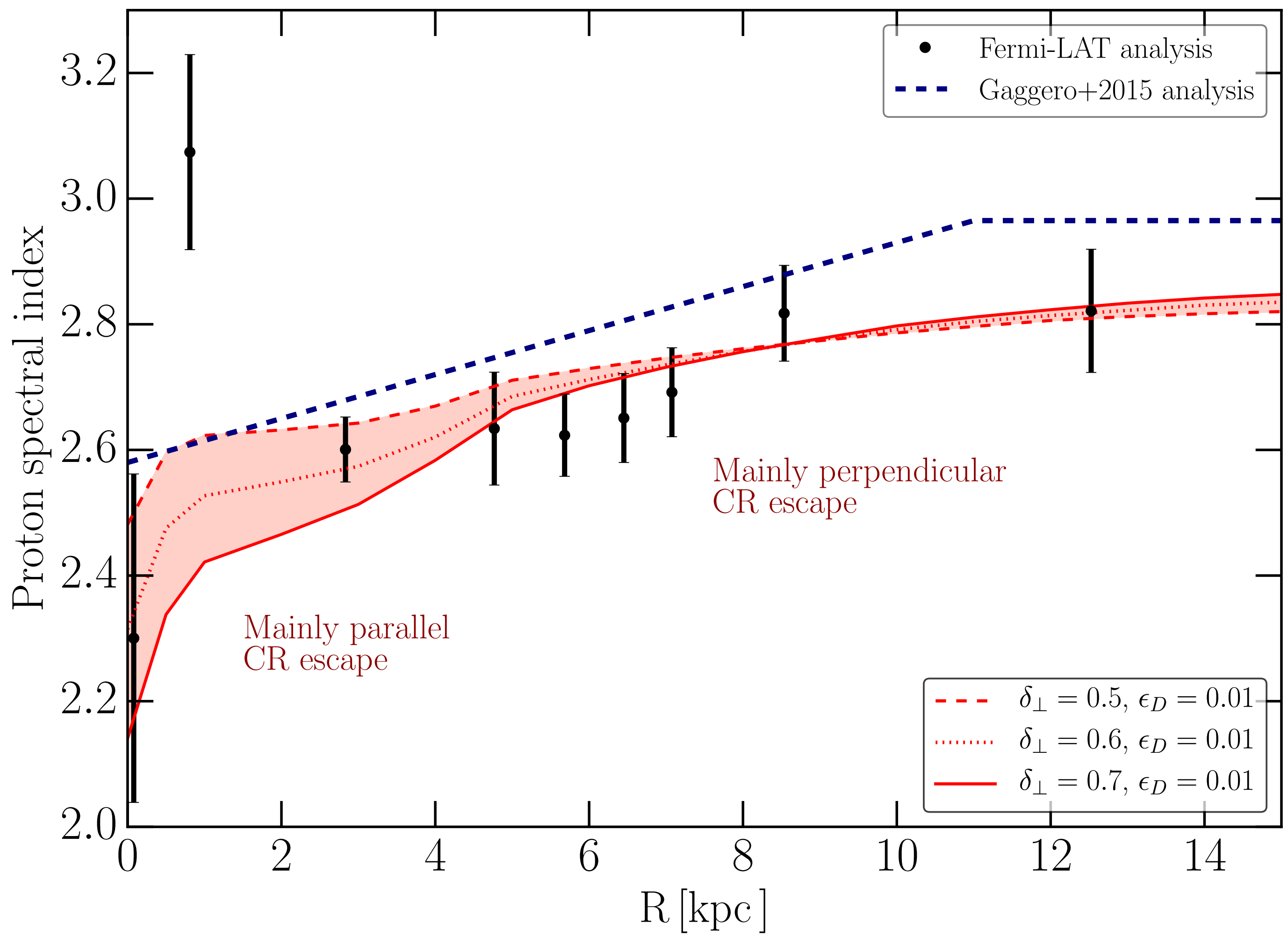


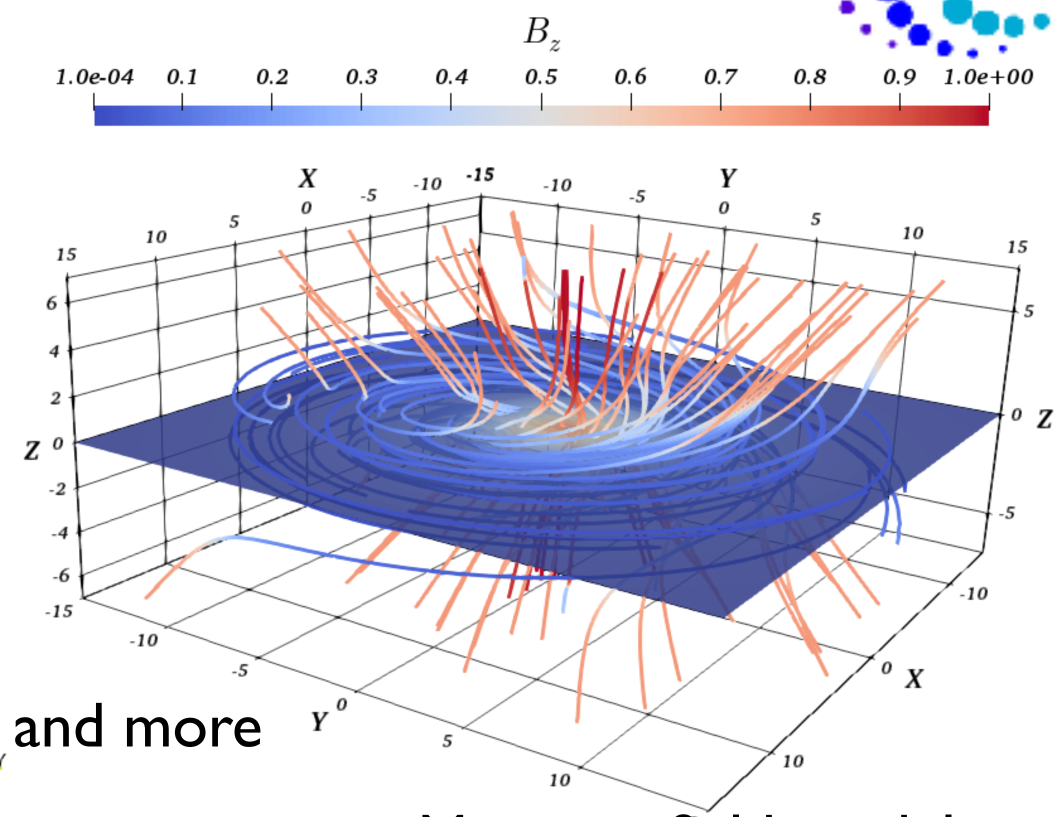
More sources ➜ smaller diffusion coefficient due to streaming instability
➜ advection dominates CR escape ➜ harder CR spectrum

Energy dependent effect: at high energy it should be absent

Another solution based on anisotropic diffusion

Cerri, Gaggero, Vittino, Evoli & DG, 2017
using ***DRAGON 2 (JCAP 2017)***





Magnetic field model
Jansson & Farrar ApJ 2012
Terral & Ferriere 2016

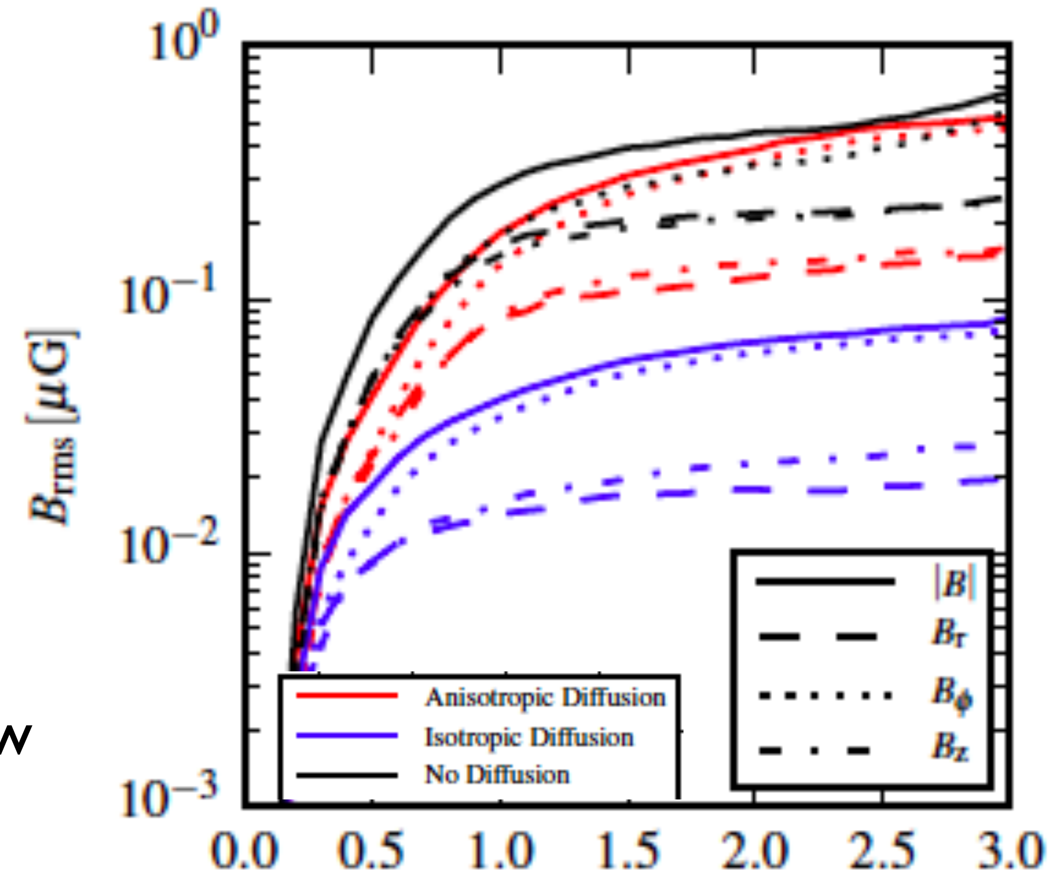
- Poloidal magnetic field become larger toward the GC
- Parallel diffusion irrelevant at large radii becomes more and more relevant for R
- Particle tracing numerical simulations *Casse+ 2001, De Marco+ 2007, Snodin + 2015*

$$D_{||} \propto \rho^{1/3} \qquad D_\perp \propto \rho^{1/2}$$

➜ CR spectrum becomes harder for R ➜ 0

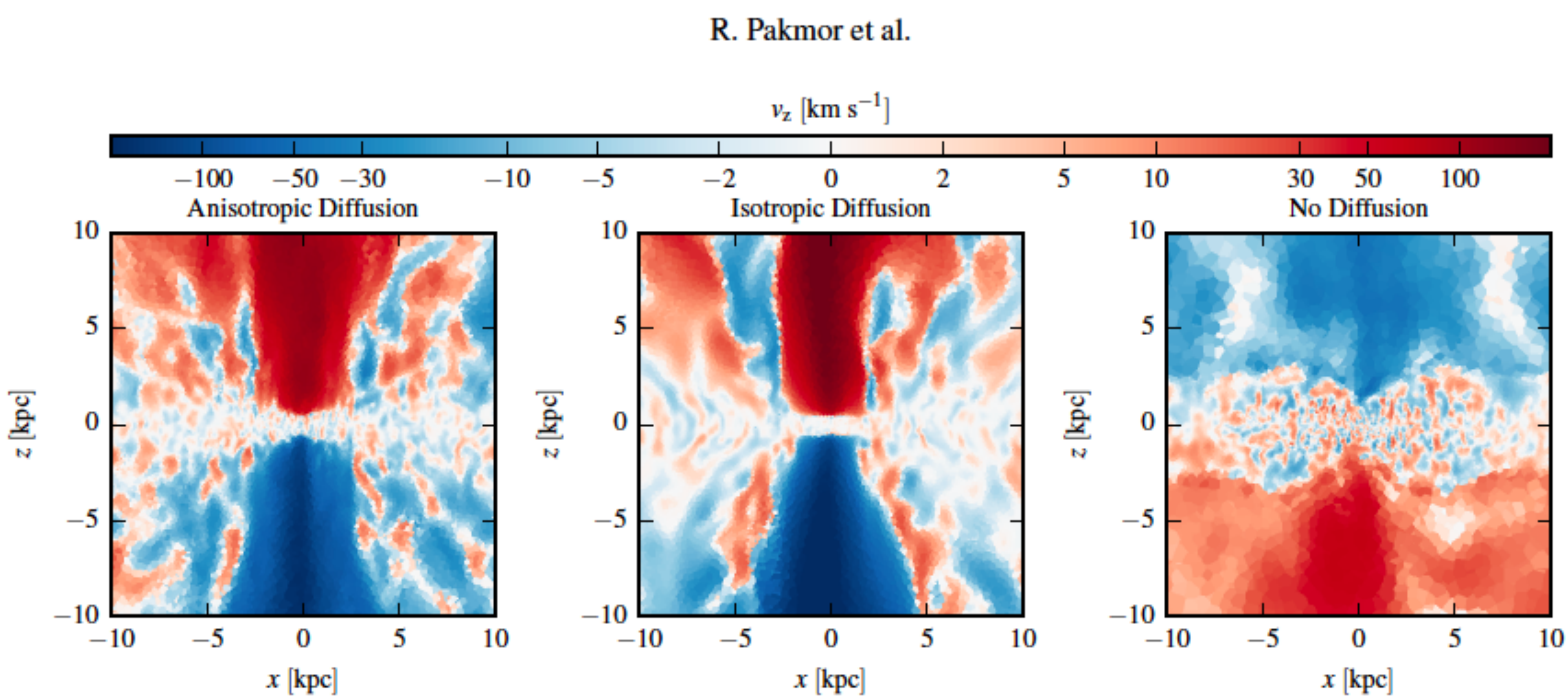
Another motivation for anisotropic diffusion

Pakmor, Pfrommer, Simpson & Springel, 2016



N-body simulation of the Galaxy with stars, magnetic field and CR based on the code AREPO

Wind speed and galactic magnetic field were found too low for isotropic diffusion.



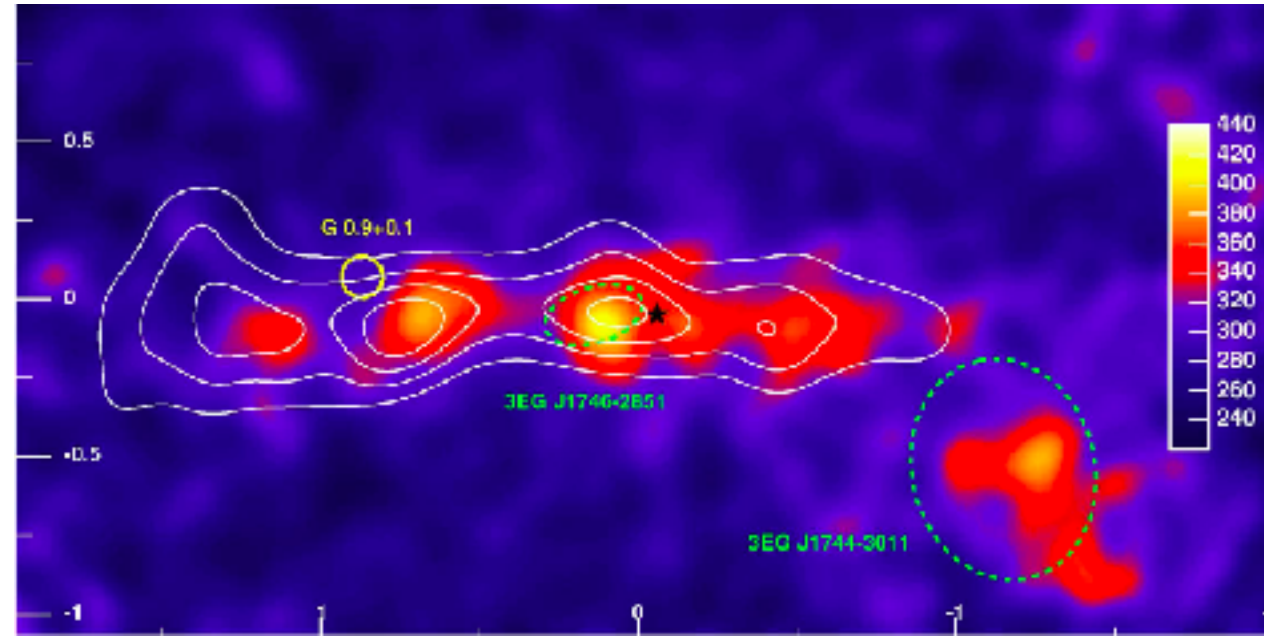
Why to look at the GC ?

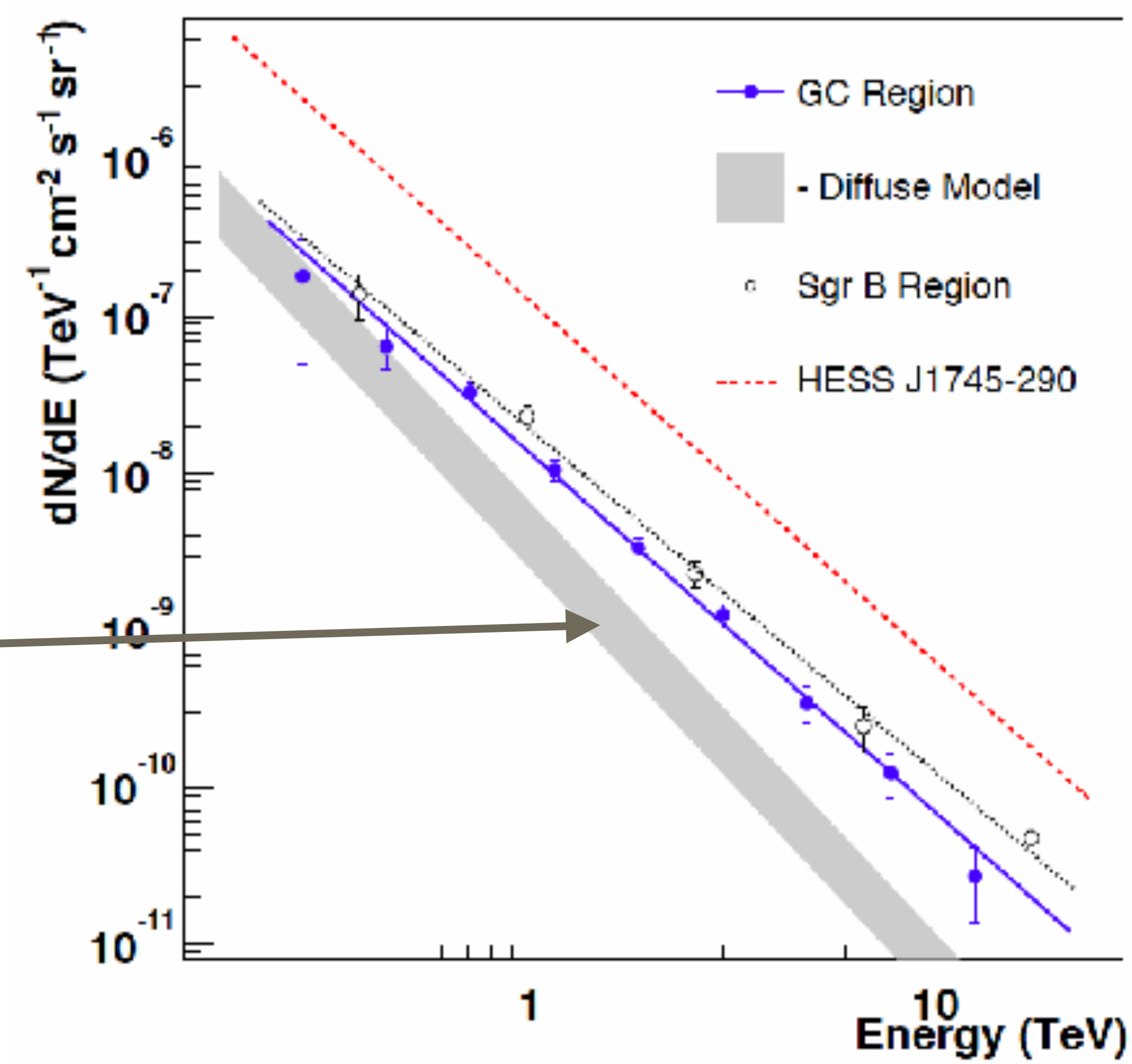
- Different models predict different spectra
- The GC is one of the few regions where we measured the diffuse emission up to tens of TeV

The Galactic center TeV excess

H.E.S.S. , Nature 2006

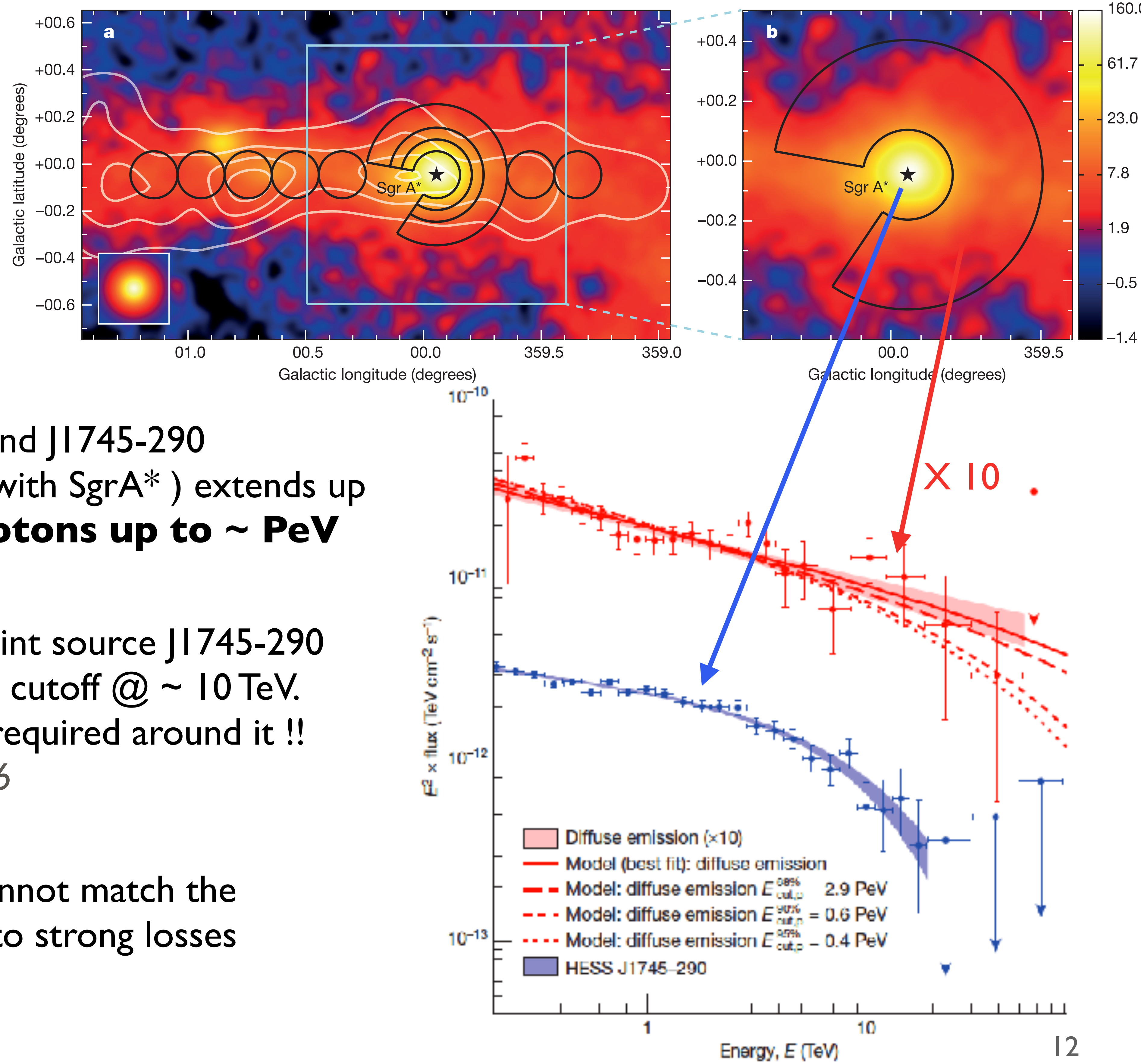
- The diffuse emission from the central molecular zone (CMZ) is correlated with the gas distribution (inferred from CO and CS emission maps)
- IC and synchrotron losses too strong in that region ⇒ hadronic emission
- The spectrum is harder ($\Gamma \simeq - 2.3$) than expected from the hadron scattering 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





10 years later ....

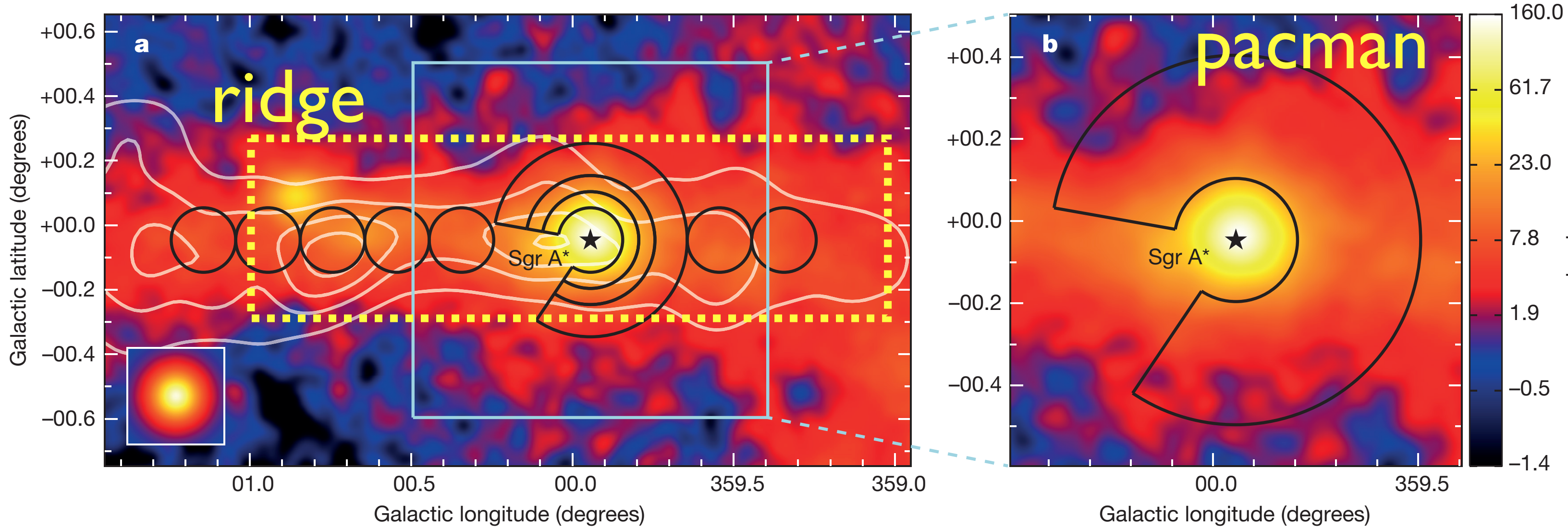
H.E.S.S. Nature 2016



- the diffuse emission around J1745-290 (positionally compatible with SgrA*) extends up to ~ 50 TeV ➡ **CR protons up to ~ PeV**
- same spectrum of the point source J1745-290 which however display at cutoff @ ~ 10 TeV. Very strong attenuation required around it !! *See e.g. S. Celli et al. 2016*
- leptonic emission (IC) cannot match the observed spectrum due to strong losses

H.E.S.S. Nature 2016

+ arXiv 1706.04535



Same spectra in the ridge

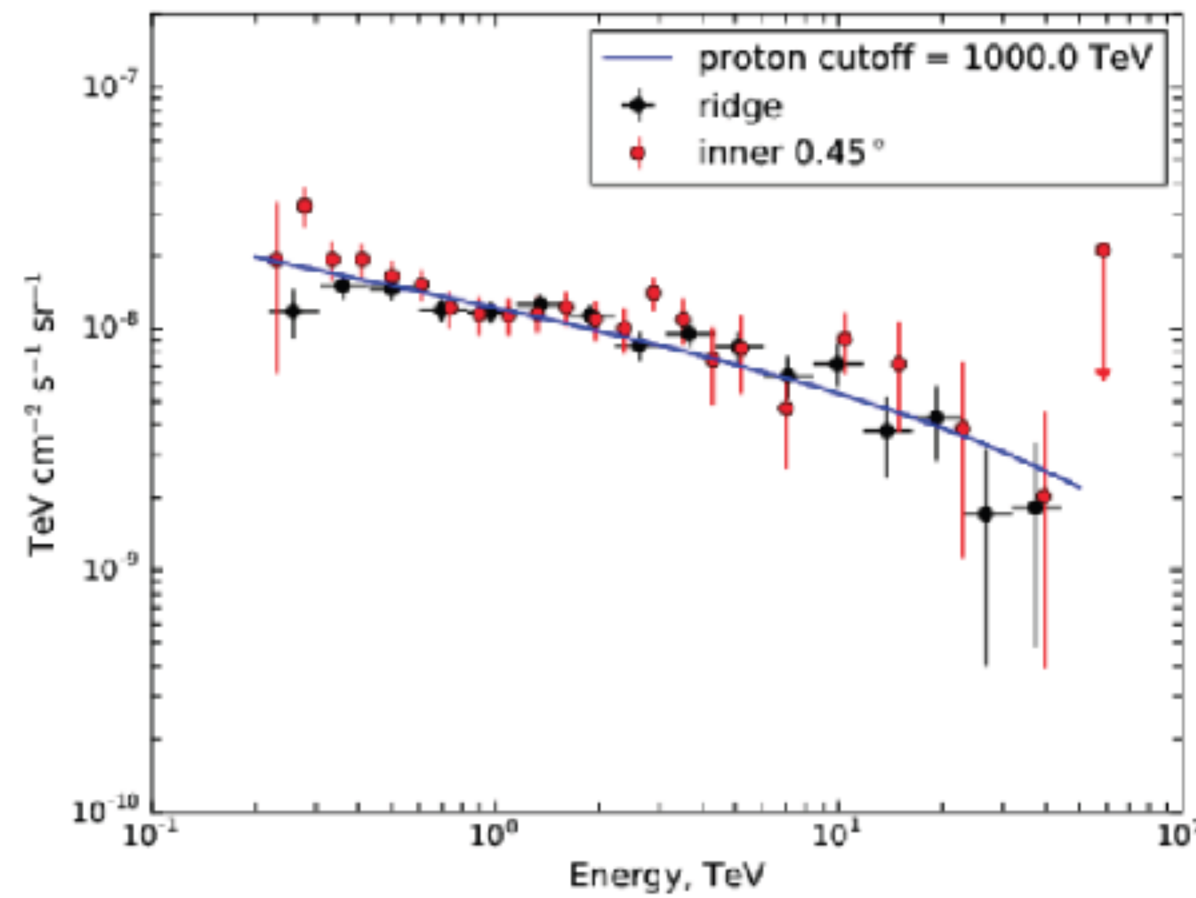
(| l | < 1° , | b | < 0.3°), d < 150 pc

$\Gamma_{HESS17} = 2.28 \pm 0.03_{stat} \pm 0.2_{sys}$

and in the "*pacman*"

0.15° < θ < 0.45° , 22 < d < 67 pc

$\Gamma_{HESS16} = 2.32 \pm 0.05_{stat} \pm 0.11_{sys}$



The PeVatron scenario

H.E.S.S. Nature 2016 + arXiv 1706.04535

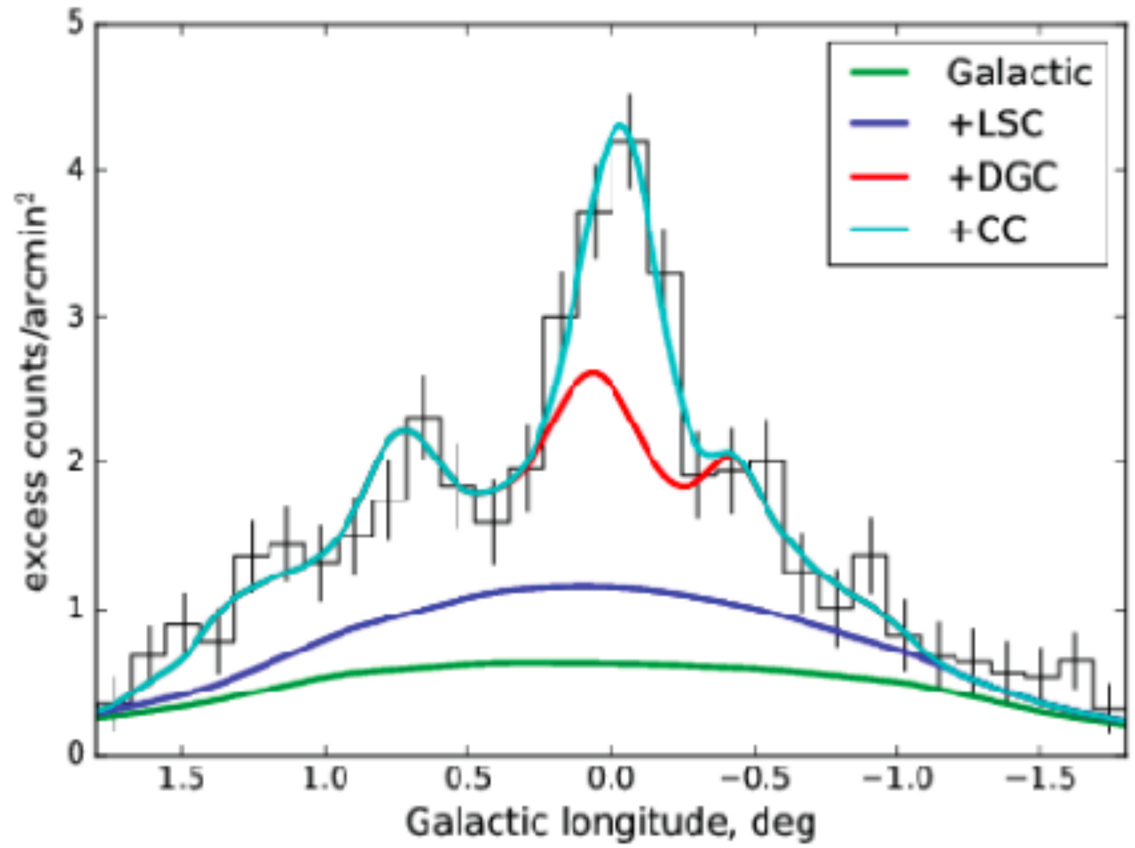
- At the GC the emission profile seems more peaked than the estimated gas distribution.

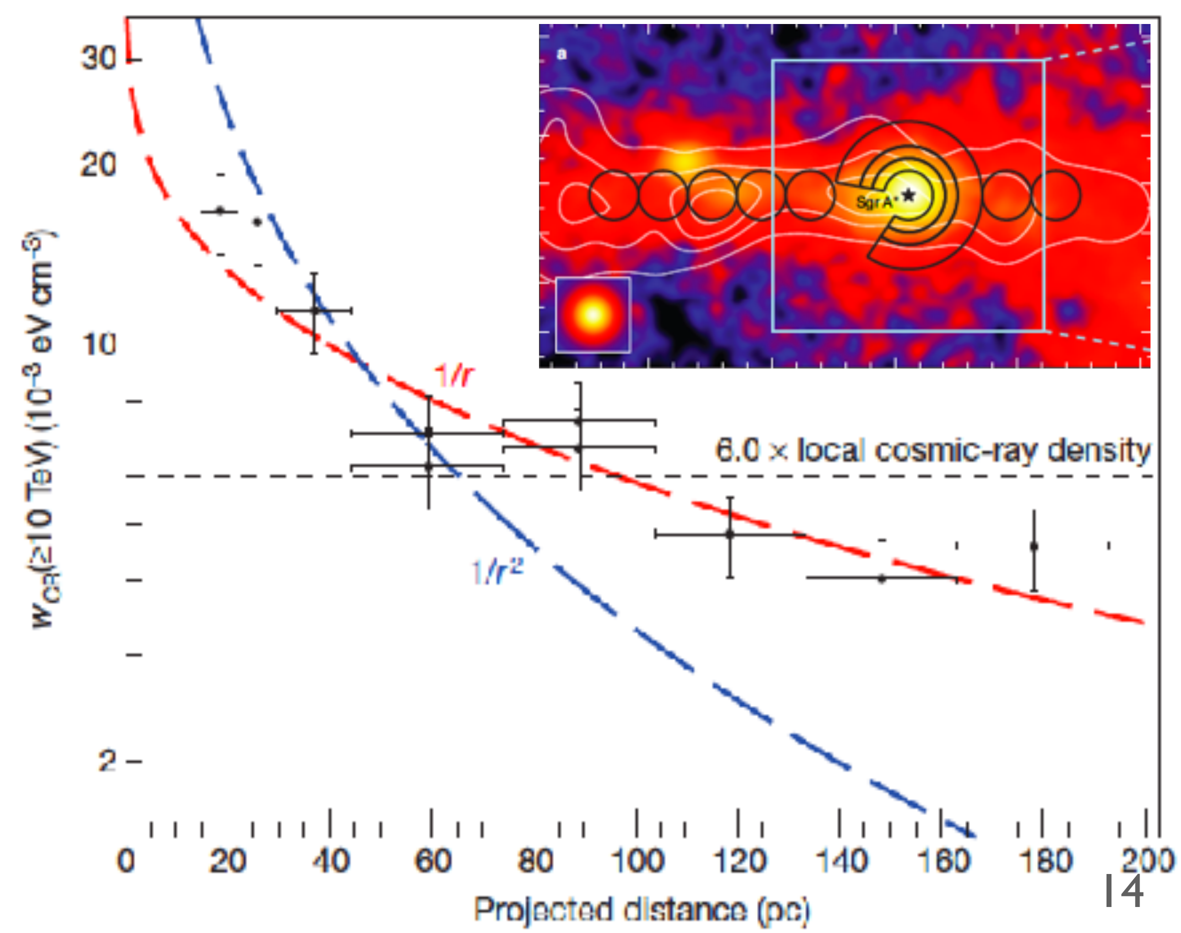
  ($1^\circ \simeq 150$ *pc* at the GC)

- The inferred CR density profile is consistent with that expected from CR diffusing out a stationary source

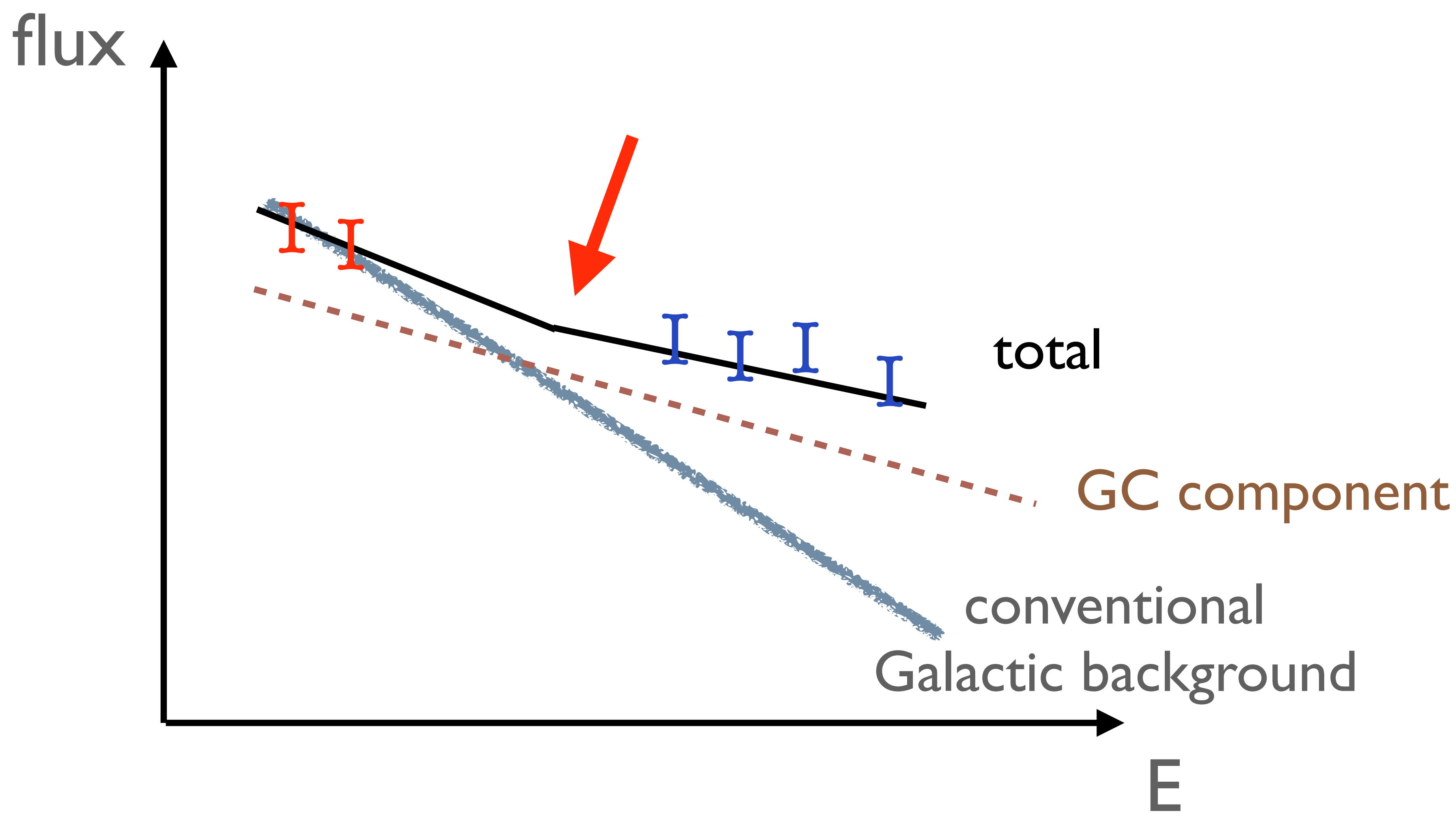
$$w_{\rm CR}(E,r) = \frac{Q_{\rm source}(E)}{4\pi D(E)}\,\frac{1}{r}$$
$$\propto E^{-(\Gamma_{\rm src}+\delta)}$$

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

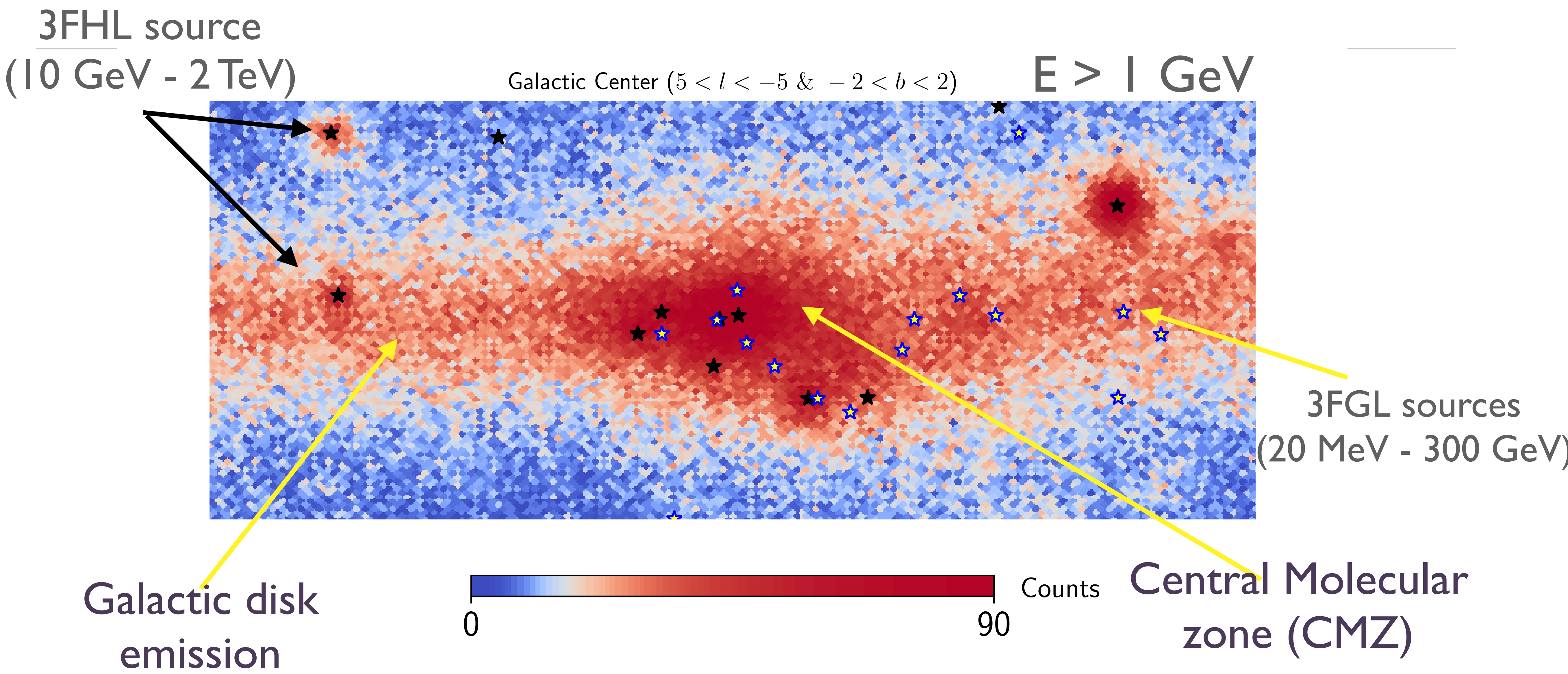




Looking for a feature



The Fermi counts from the central kpc of the Galaxy

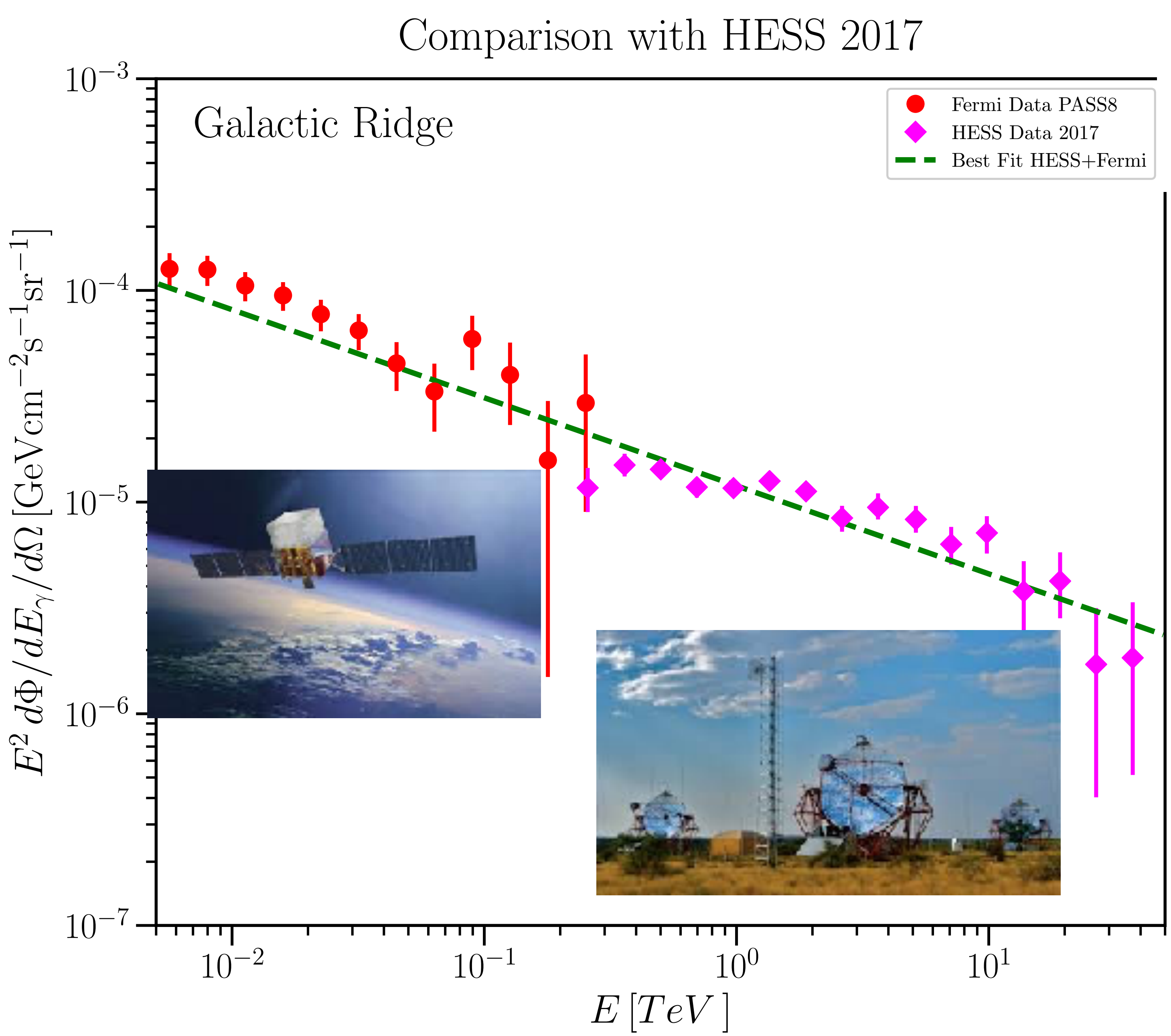


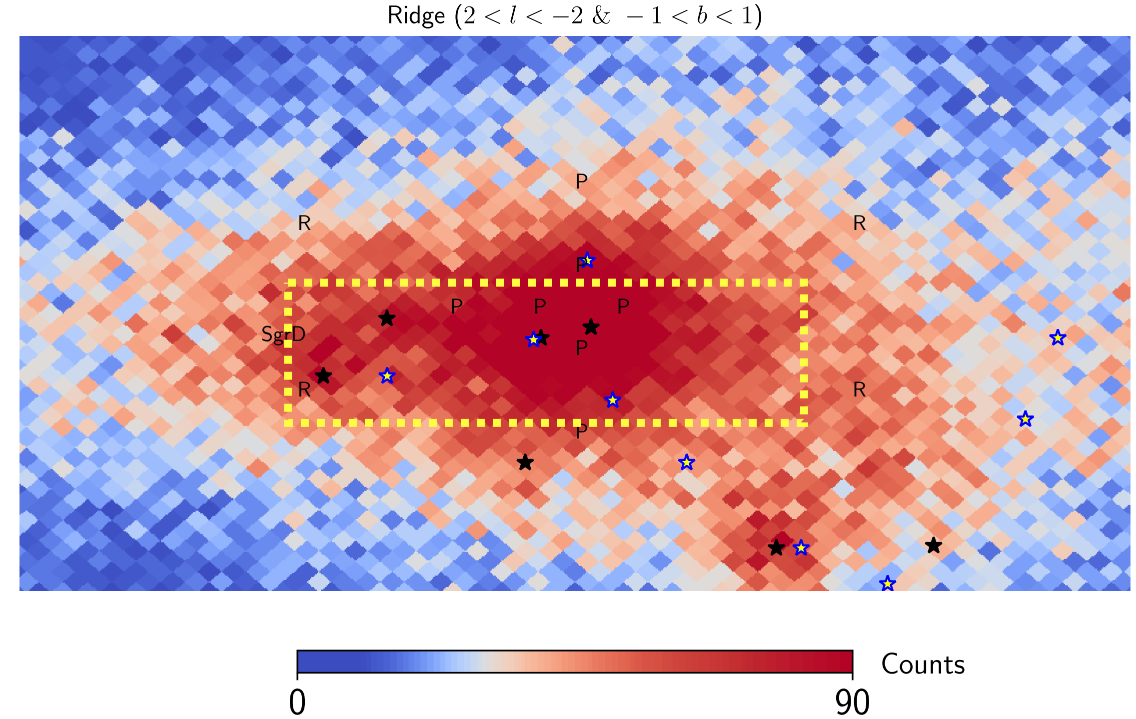
The emission is clearly dominated by the CMZ !

H.E.S.S. + Fermi-LAT

Gaggero, D.G., A. Marinelli, Taoso & Urbano, PRL 2017

" + S.Ventura (ICRC 2017)





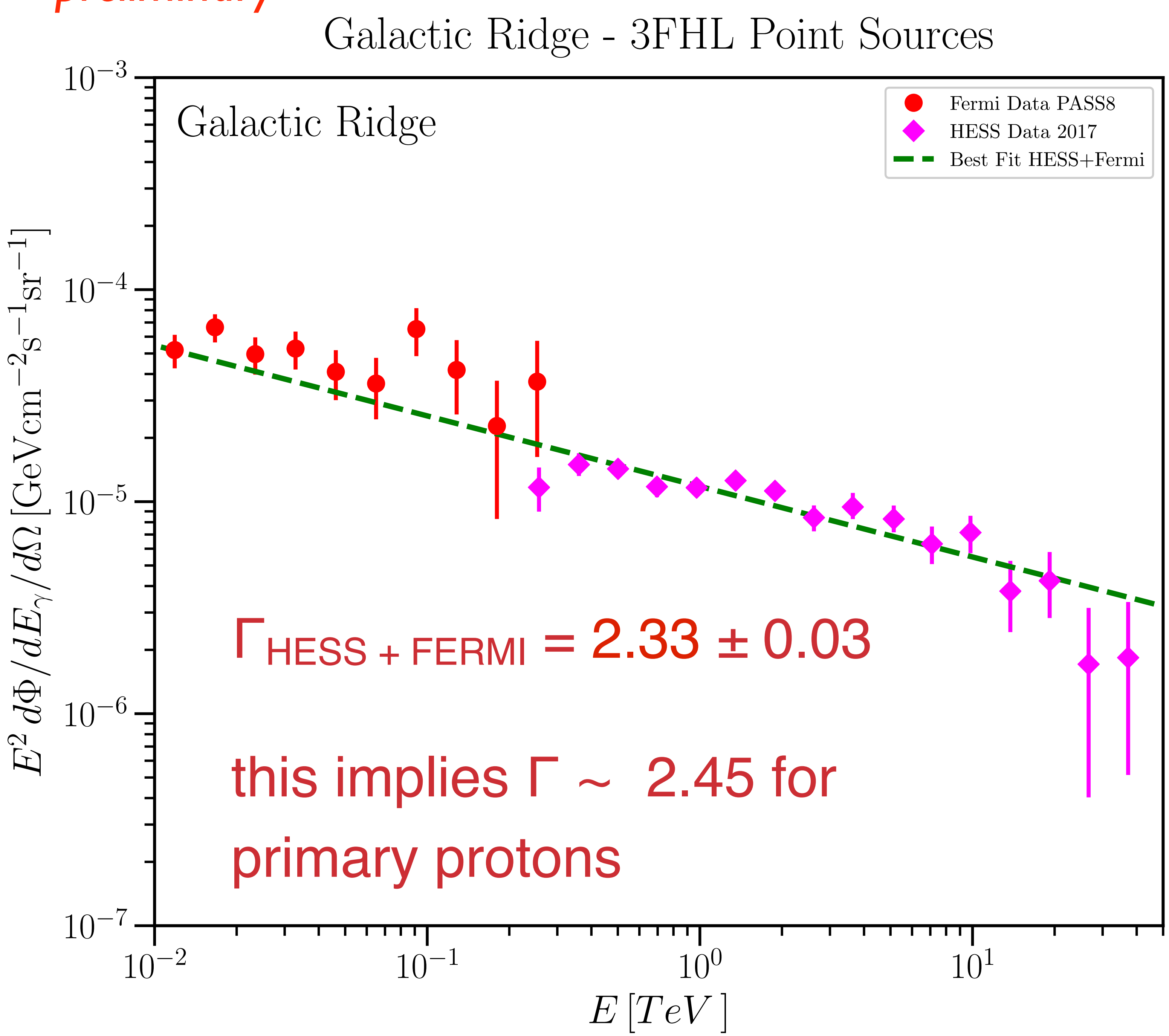
| l | < 1° , | b | < 0.3°

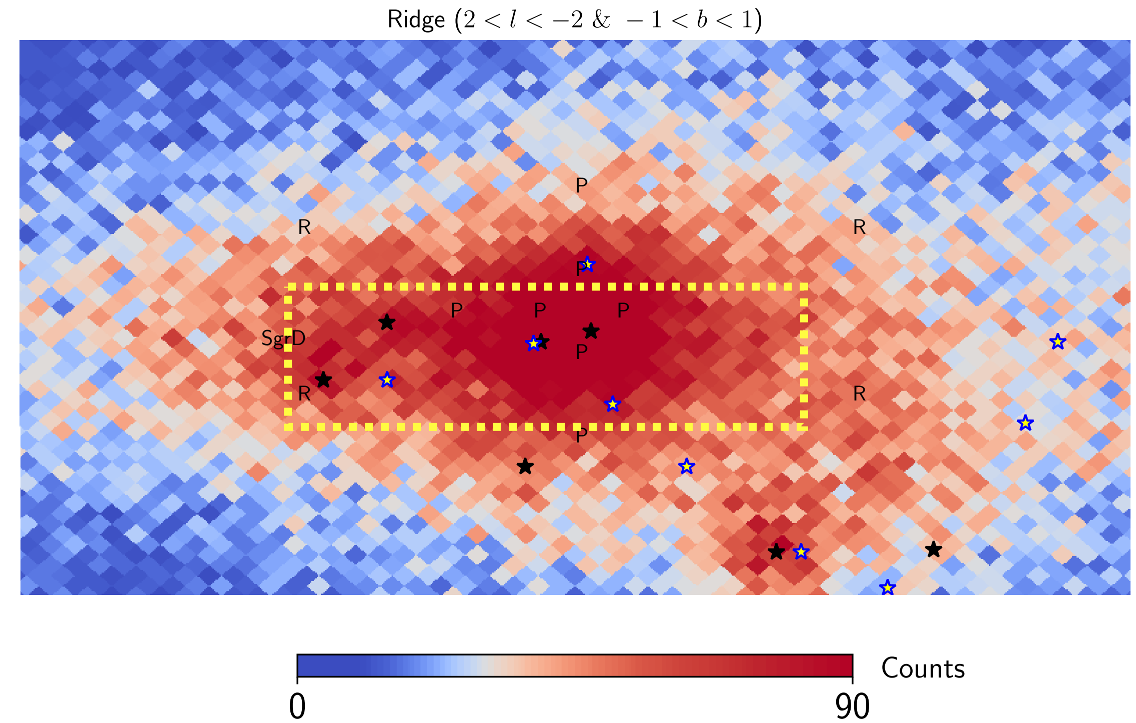
PASS8 Fermi-LAT 470 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FGL catalogue subtracted.

H.E.S.S. + Fermi-LAT

Gaggero, D.G., A. Marinelli, Taoso, S. Ventura

preliminary





$|\, l\, | < 1°$, $|\, b\, | < 0.3°$

PASS8 Fermi-LAT 516 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FHL catalogue subtracted.

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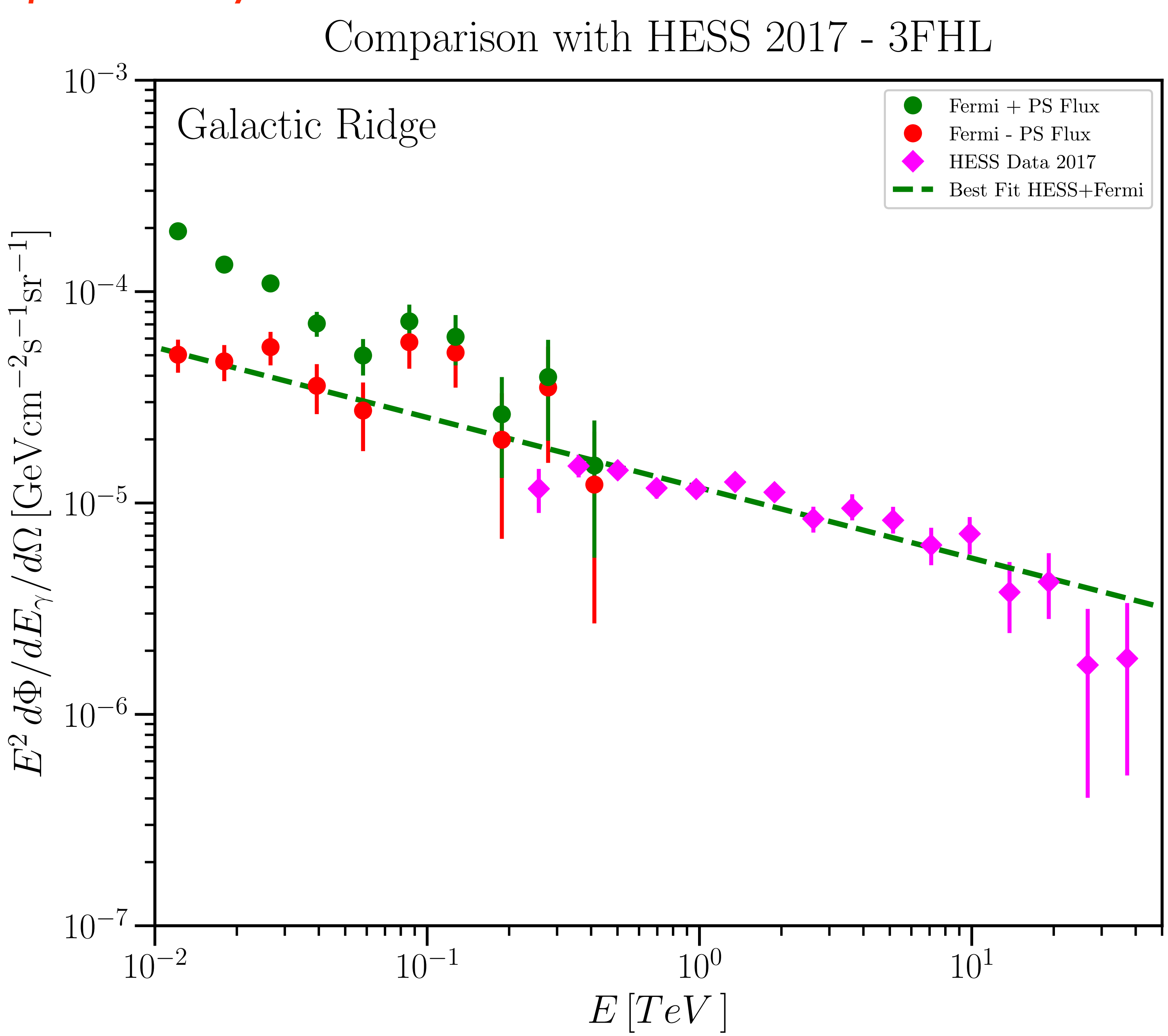
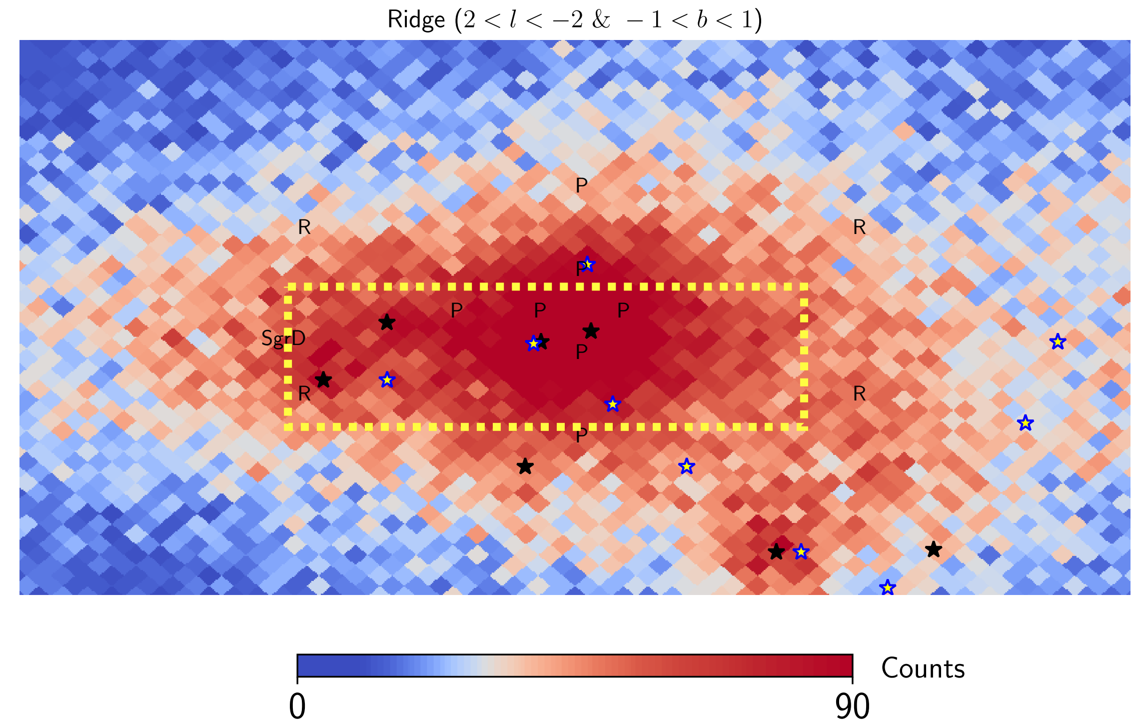




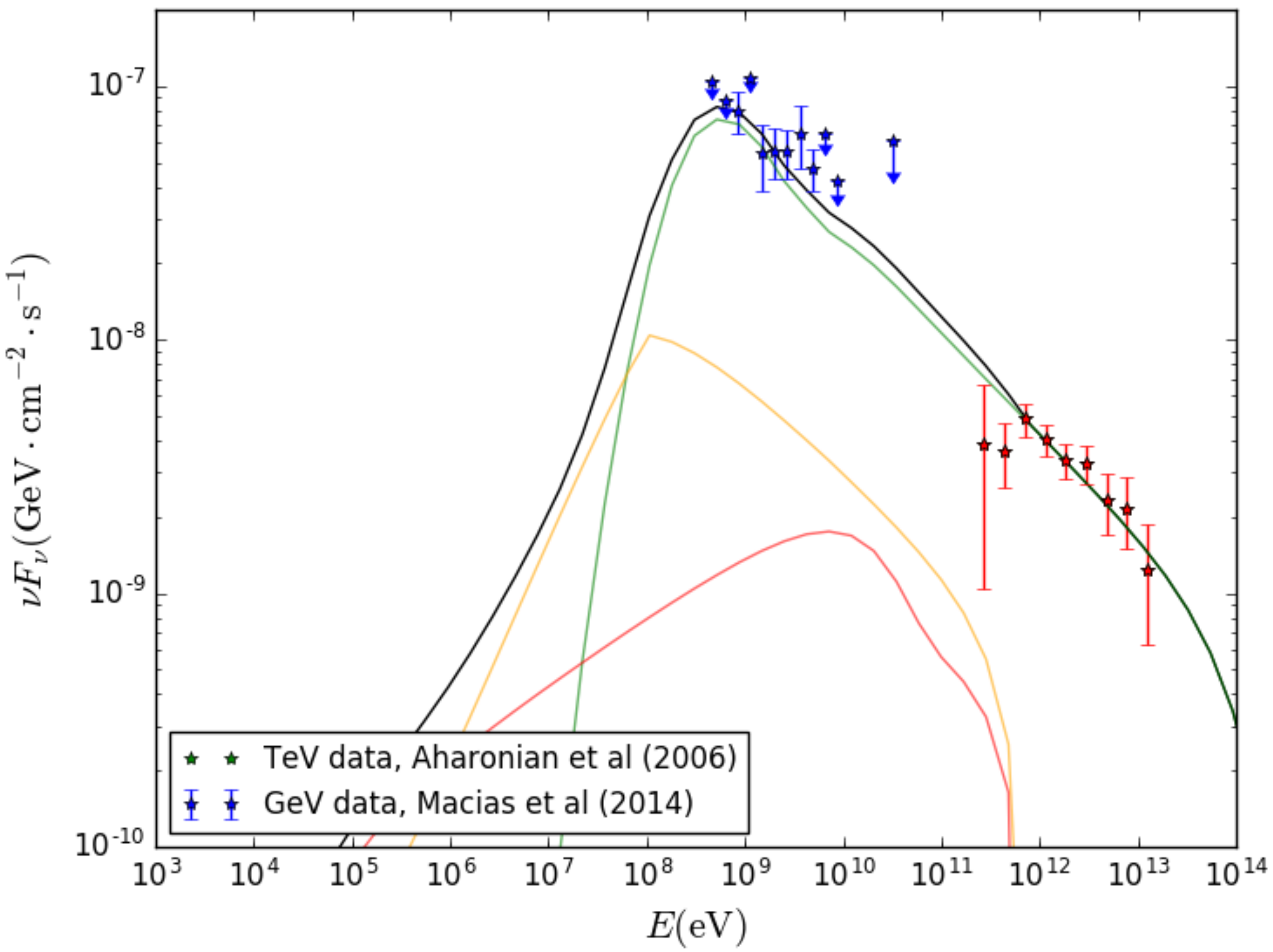
$|\, l\, | < 1°, |\, b\, | < 0.3°$

PASS8 Fermi-LAT 516 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FHL catalogue subtracted.

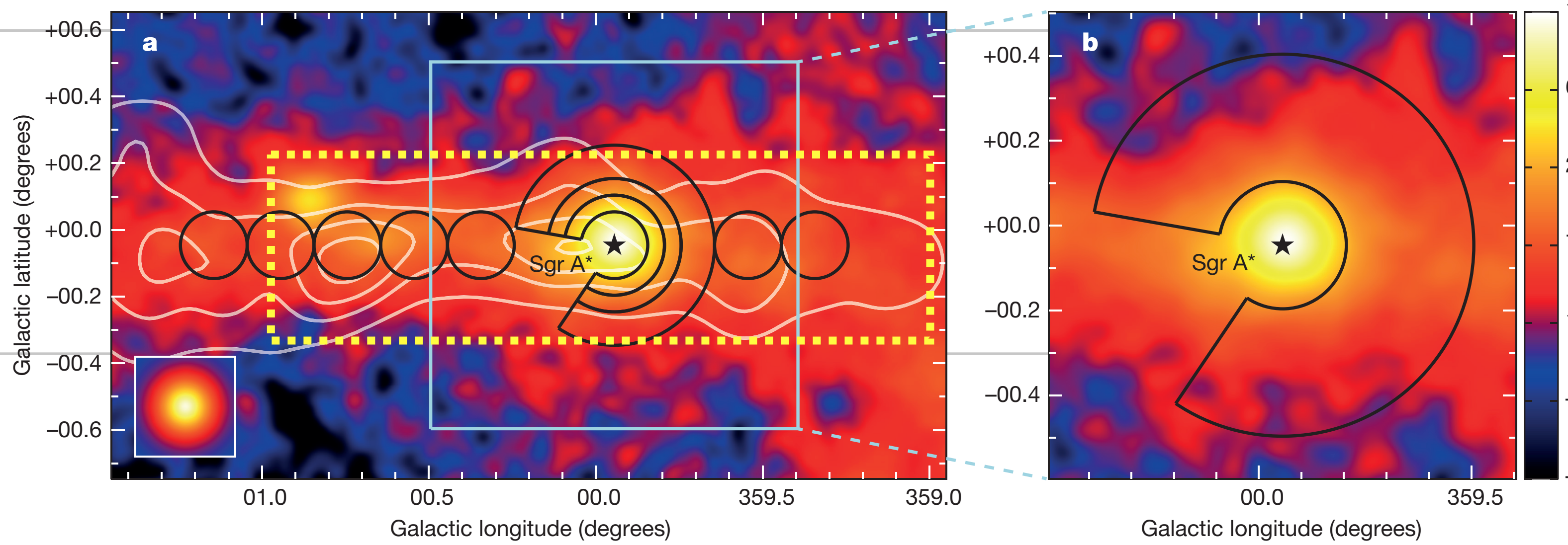
$\Gamma_{HESS\,+\,FERMI} = 2.33 \pm 0.03$

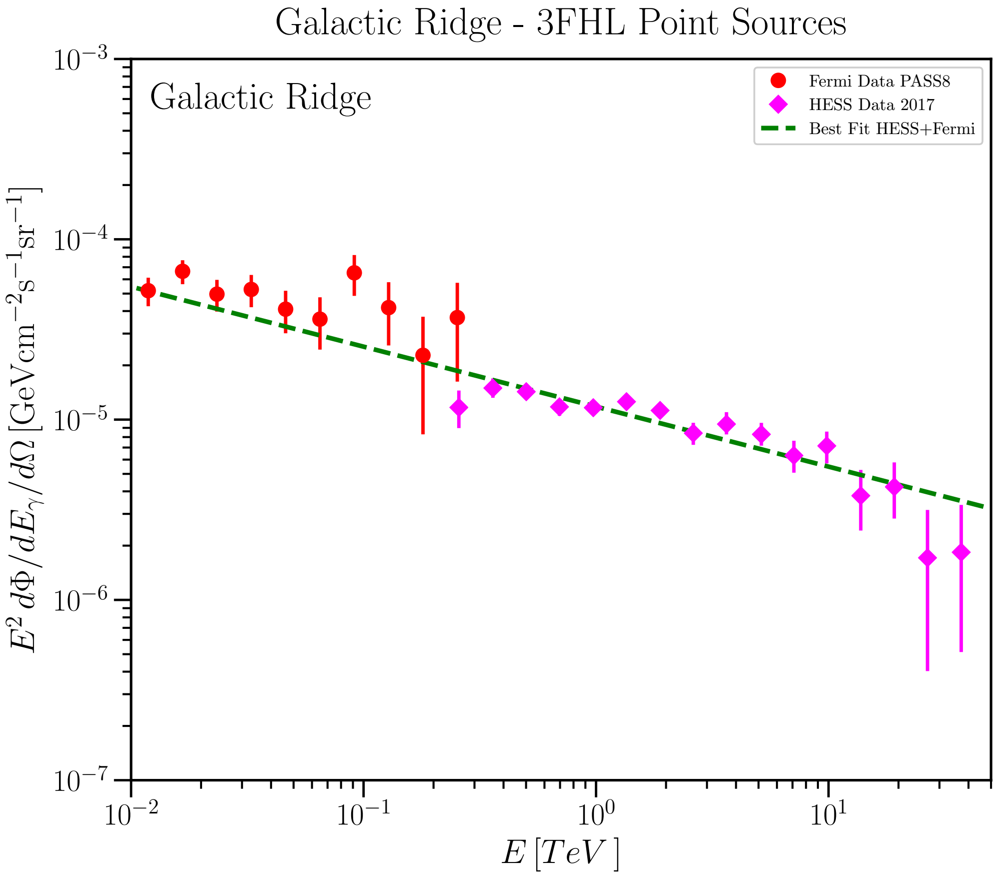
The data before 2016

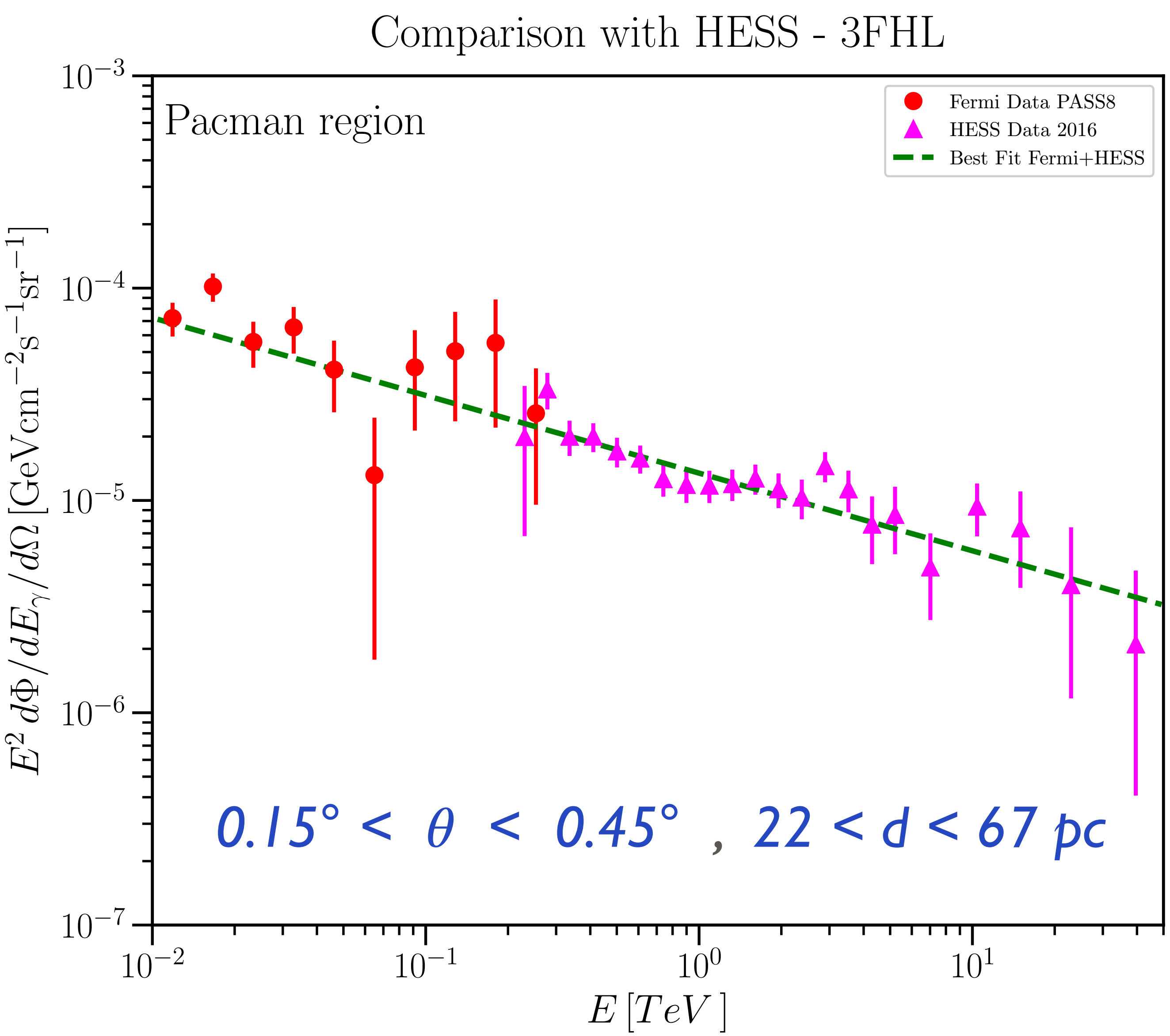
Jouvin et al. 2017



Pacman against ridge





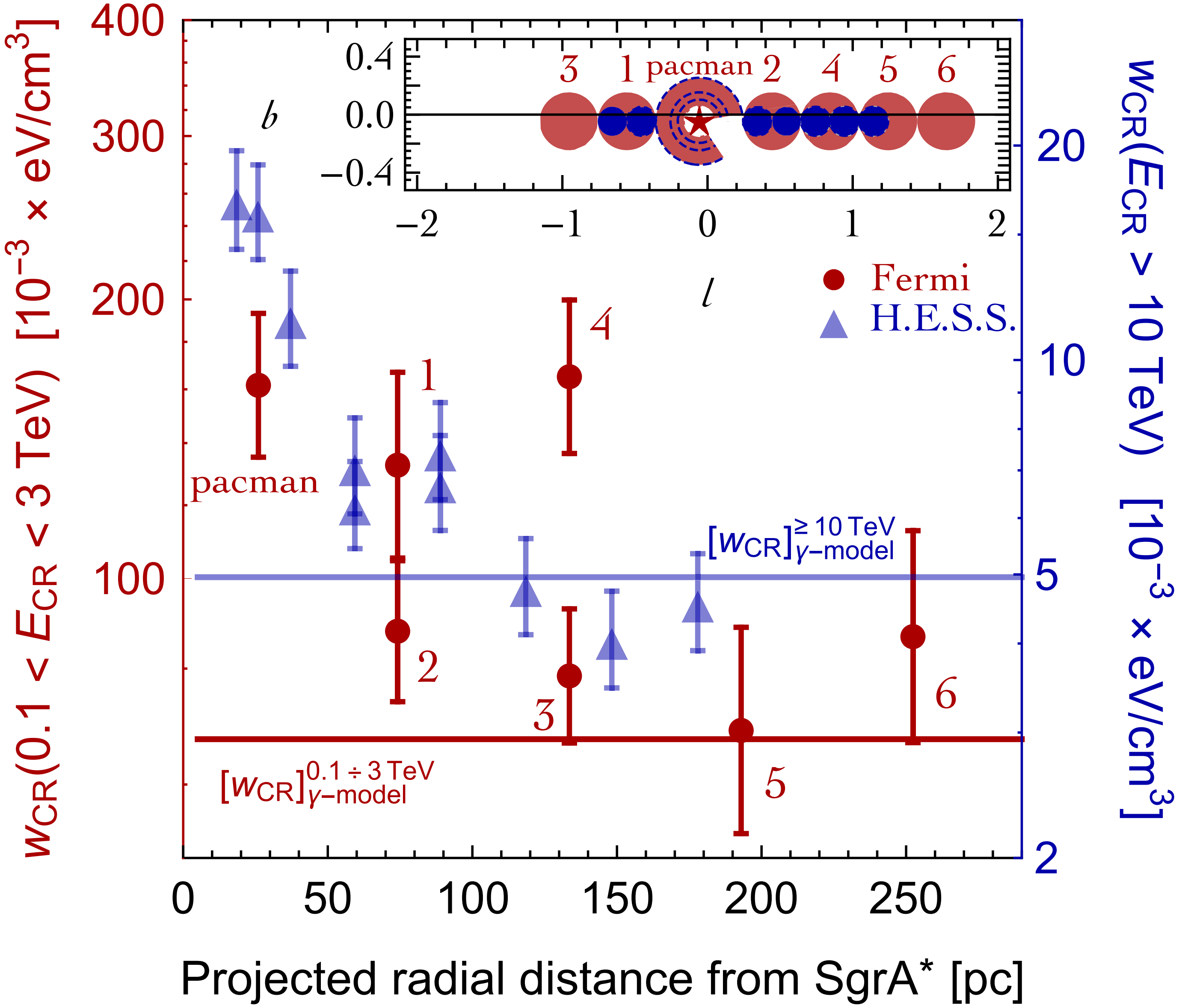


The CR energy density radial profile from HESS and FERMI

Gaggero, D.G., A. Marinelli, Taoso & Urbano, PRL 2017

Here we use the same approach, and same gas mass distribution based on the CS emission map, of the HESS coll. and compare the result with our model

We use larger region due to the smaller Fermi-LAT angular resolution



What we learn from the new data alone

- The spectrum in the ridge and in the most internal region (*pacman*) are practically the same from few GeV up to ~ PeV
- No strong evidence of a spectral feature. The emission seems to be dominated by a single population of particles !
- At few GeV the emission is compatible with what expected for a CR population similar to that at the Earth.

This suggests that a large part the emission may due to the Galactic CR sea which however needs to be harder than at the Earth

CAN THE GALACTIC CR SEA AT THE GC BE LARGER AND HARDER THAN EXPECTED ?

Our reference model

Gaggero, Urbano, Valli & Ullio, PRD 2015

The CR spectral index gradient problem is interpreted as an effect due to the radial dependence of the diffusion coefficient (KRAγ model).

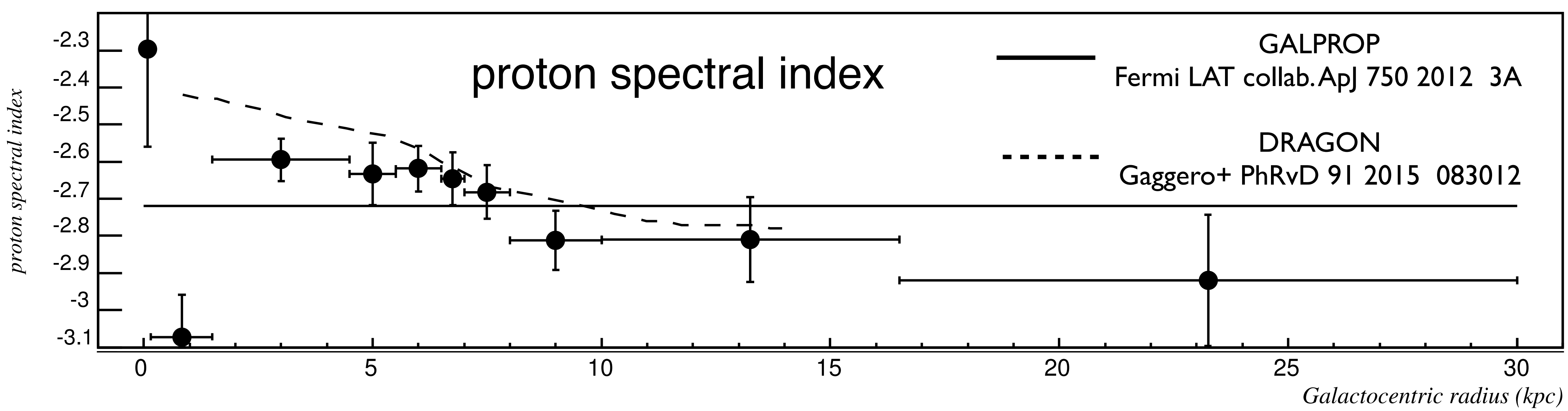
This was implemented with the **DRAGON code**.

$D(E) = D_0\,(E/E_0)^{\delta(r)}$ with $\delta(r) = A\,r + B$ for $r < 11$ kpc

so that $\Gamma(r) = p_{source} + \delta(r)$

Although this is a phenomenological model it can be motivated in terms of anisotropic diffusion

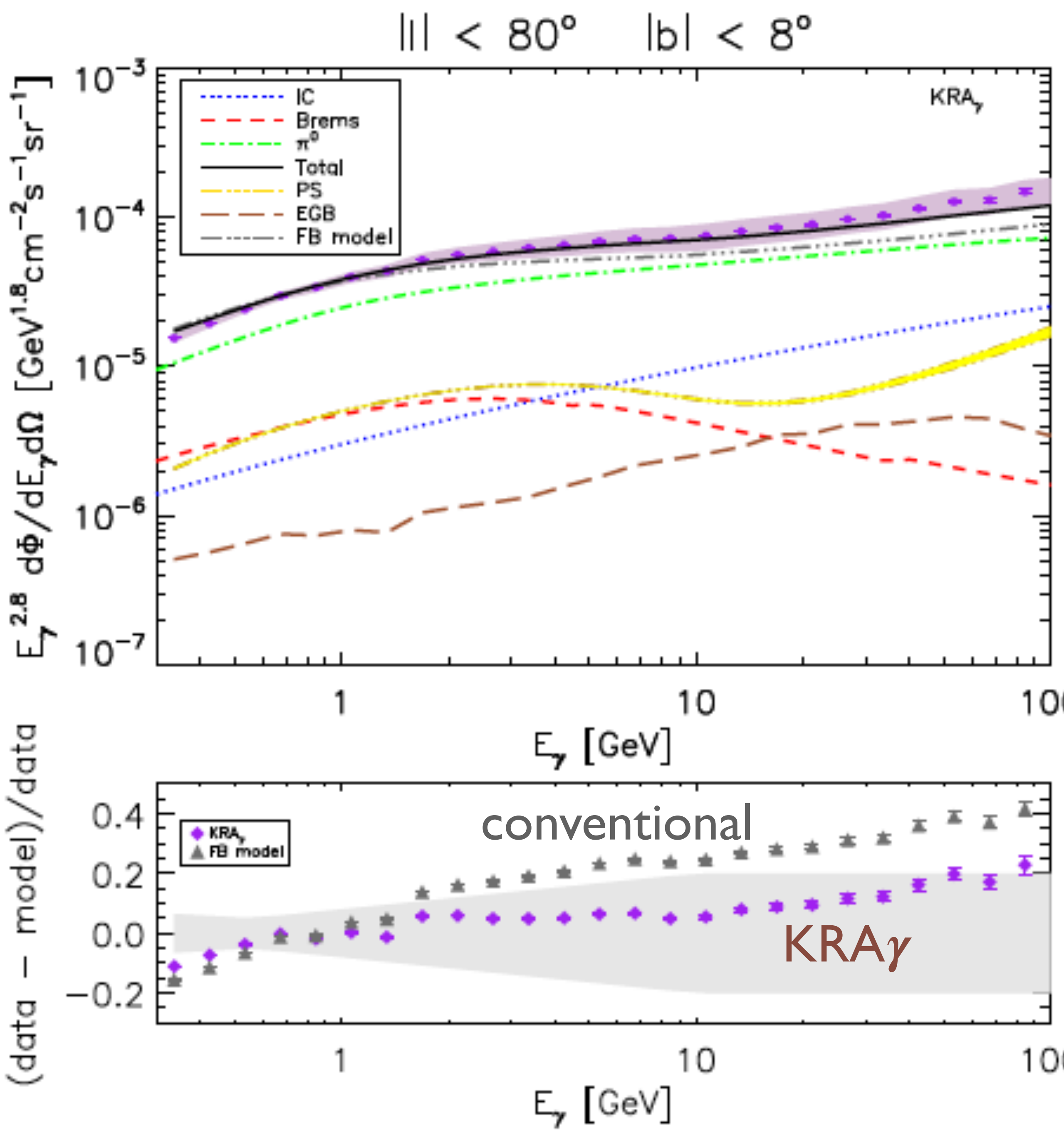
Fermi-LAT coll. 2016

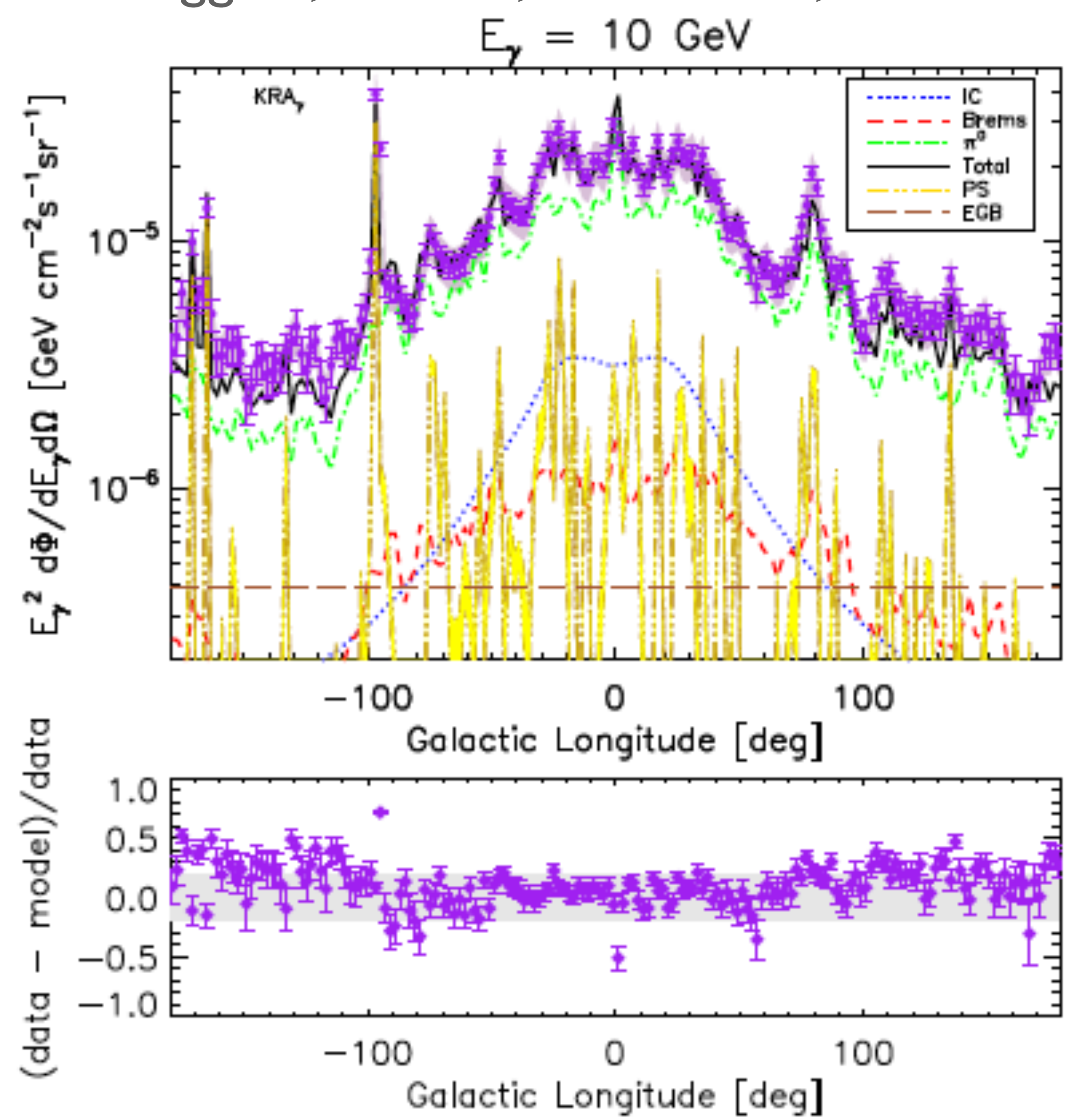


Our reference model

against Fermi-LAT data for the inner Galactic plane

Gaggero, Urbano, Valli & Ullio, PRD 2015





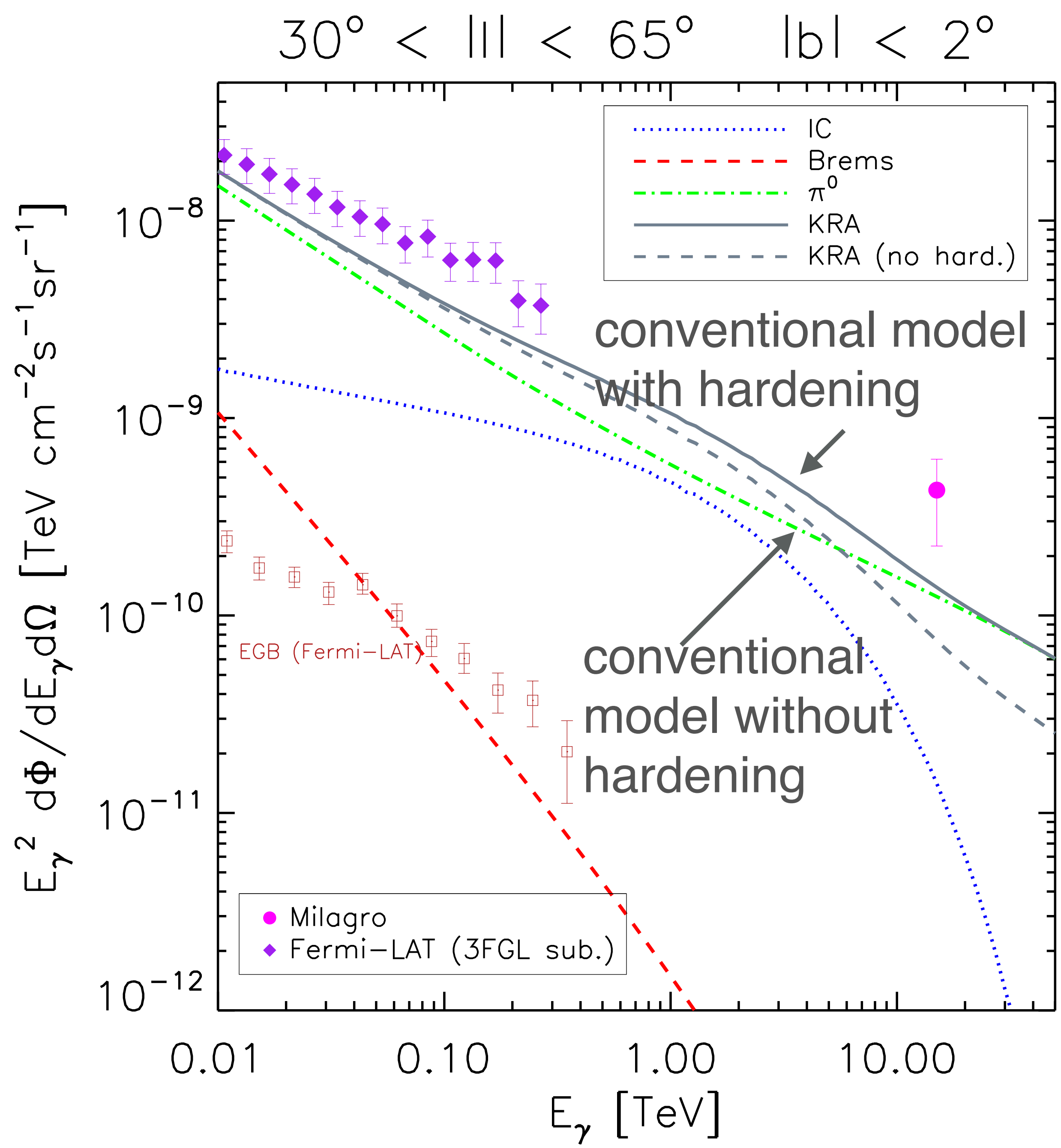
Our reference model

against Fermi-LAT and Milagro data

Milagro observed an excess (4 σ) at 15 TeV in the inner GP respect to the prediction of conventional models (*Abdo et al. ApJ 2008*)

We checked that the excess is present also respect to updated conventional CR propagation models based on Fermi data

The excess holds also accounting for a CR hardening at 300 GeV/n as require by Pamela ad AMS-02 results (assuming it is present in the whole Galaxy as expected if it is originated by sources or by propagation)



Our reference model

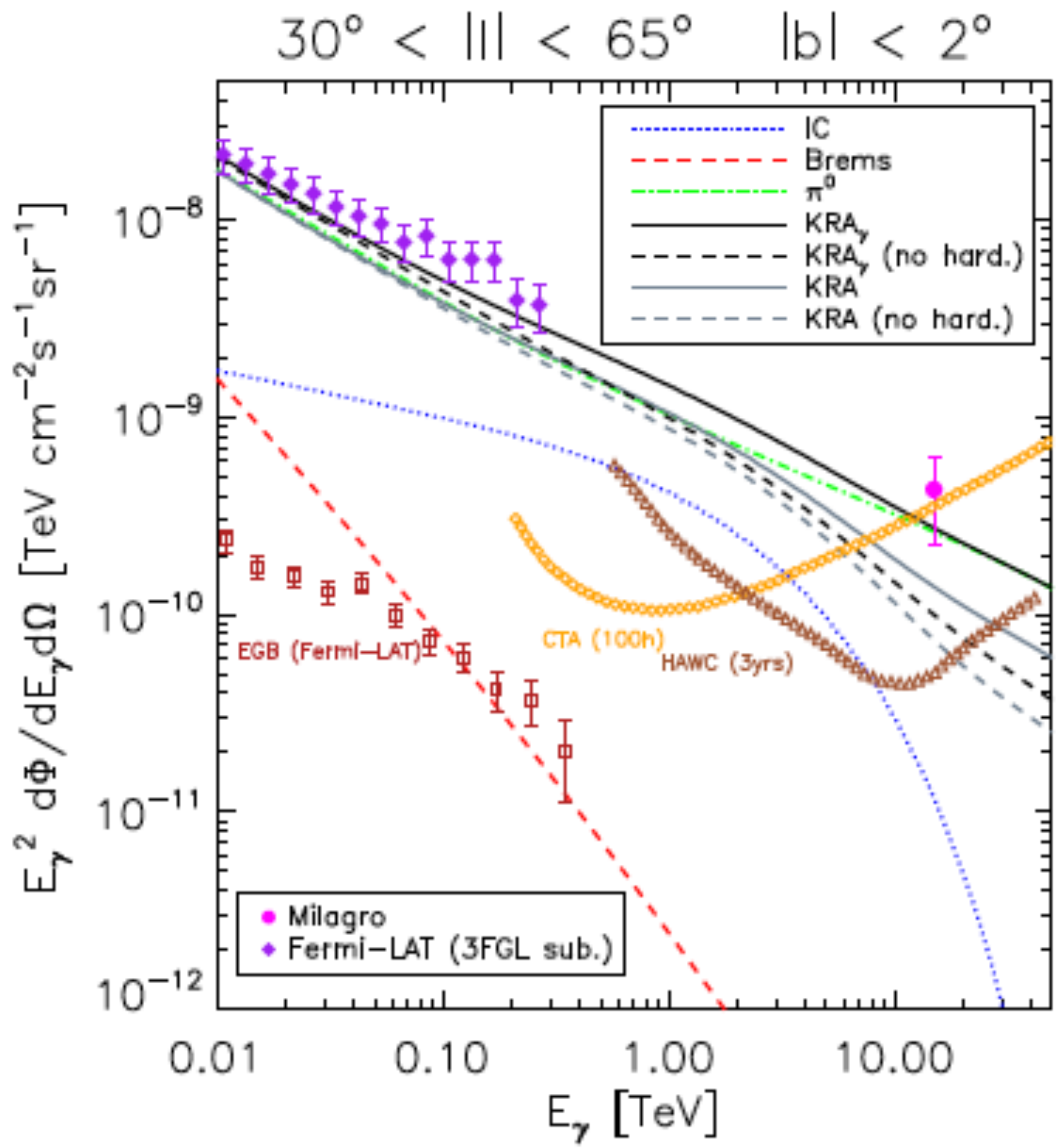
against Fermi-LAT and Milagro data

Gaggero, D.G., A. Marinelli, Urbano, Valli ApJ L 2015

Then we incorporate the CR spectral hardening in the KRAγ model (**gamma model**)
assuming it is present in the whole Galaxy (we introduced it in the source term).

Accounting for the harding at 300 GeV/n to be present in the whole GP this allows to match FERMI data and Milagro observed flux @ 15 TeV consistently !

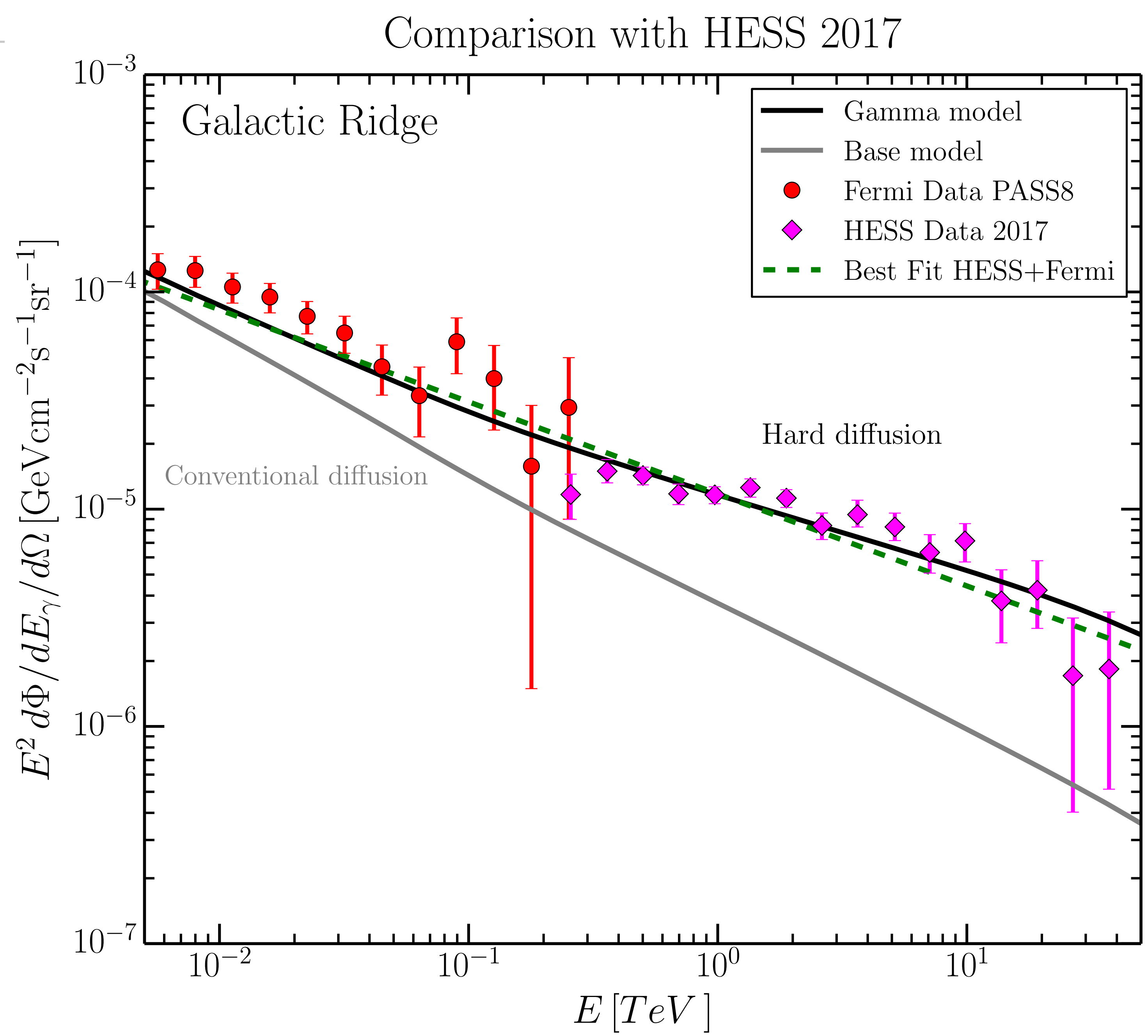
HAWC collaboration is working to check and to extend Milagro results which will allow to test our model



The models against FERMI + HESS at the GC

Gaggero, D.G., A. Marinelli, Taoso & Urbano, PRL 2017
" + S.Ventura (ICRC 2017)

$|l| < 1°, |b| < 0.3°$



We use the *Ferriere 2007* 3-D gas tuning the X_{CO}

$X_{CO}(R = 0) = 0.6 \times 10^{20}\ \mathrm{cm^{-2}\ (K\ km/s)^{-1}}$

for the Case & Bhattacharya (1998) source distribution

We found that the same model solving the GP FERMI anomaly and matching Milagro (gamma model) reproduces FERMI + HESS data in the ridge and inner region

The models against FERMI + HESS

Gaggero, D.G., A. Marinelli, Taoso & Urbano, S. Ventura 2018

$|l| < 1°, |b| < 0.3°$

We use the *Ferriere 2007* 3-D gas tuning the X_{CO}
$X_{CO}(R = 0) = 0.8 \times 10^{20}\ cm^{-2}\ (K\ km/s)^{-1}$

for the Case & Bhattacharya (1998) source distribution

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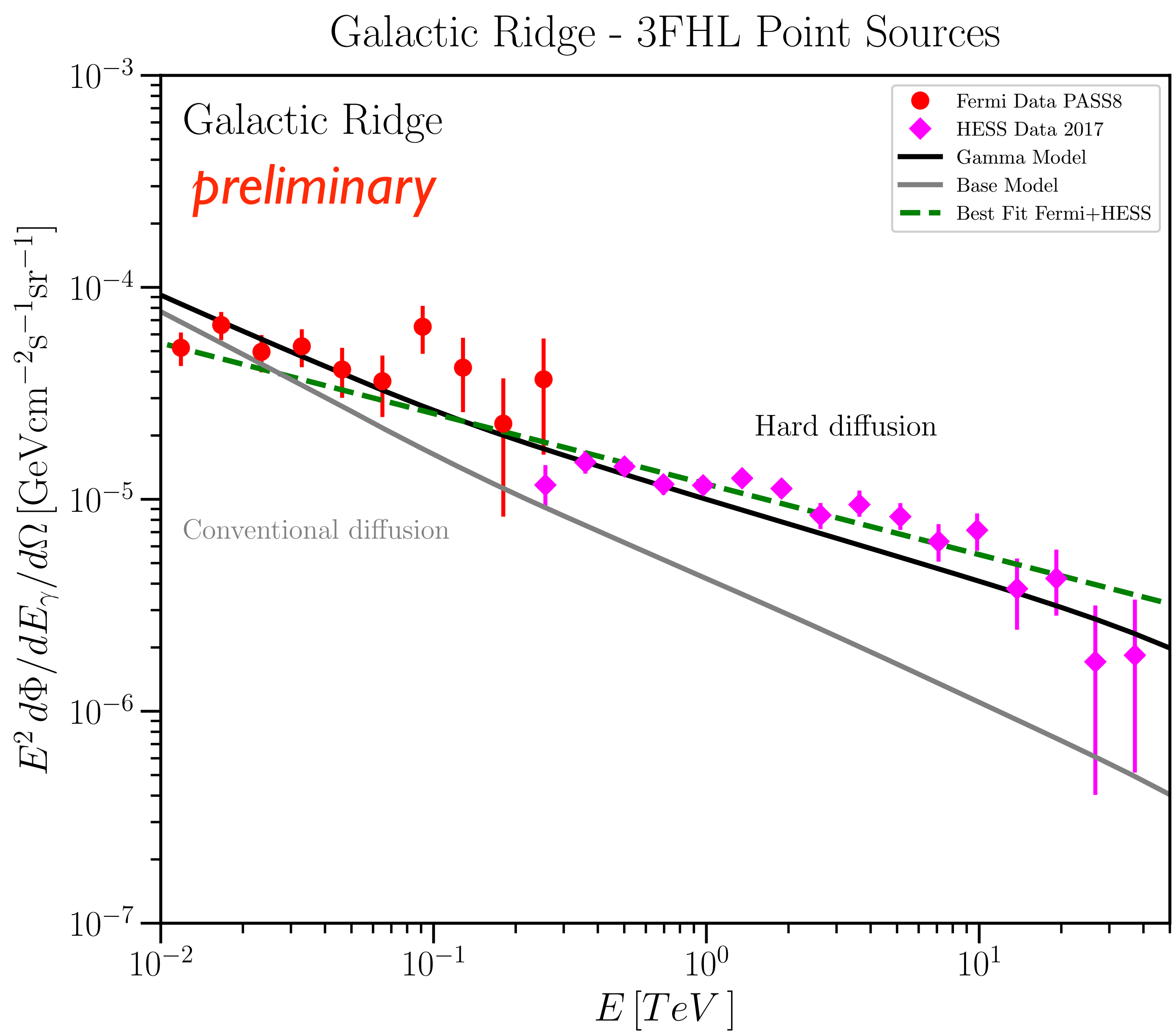
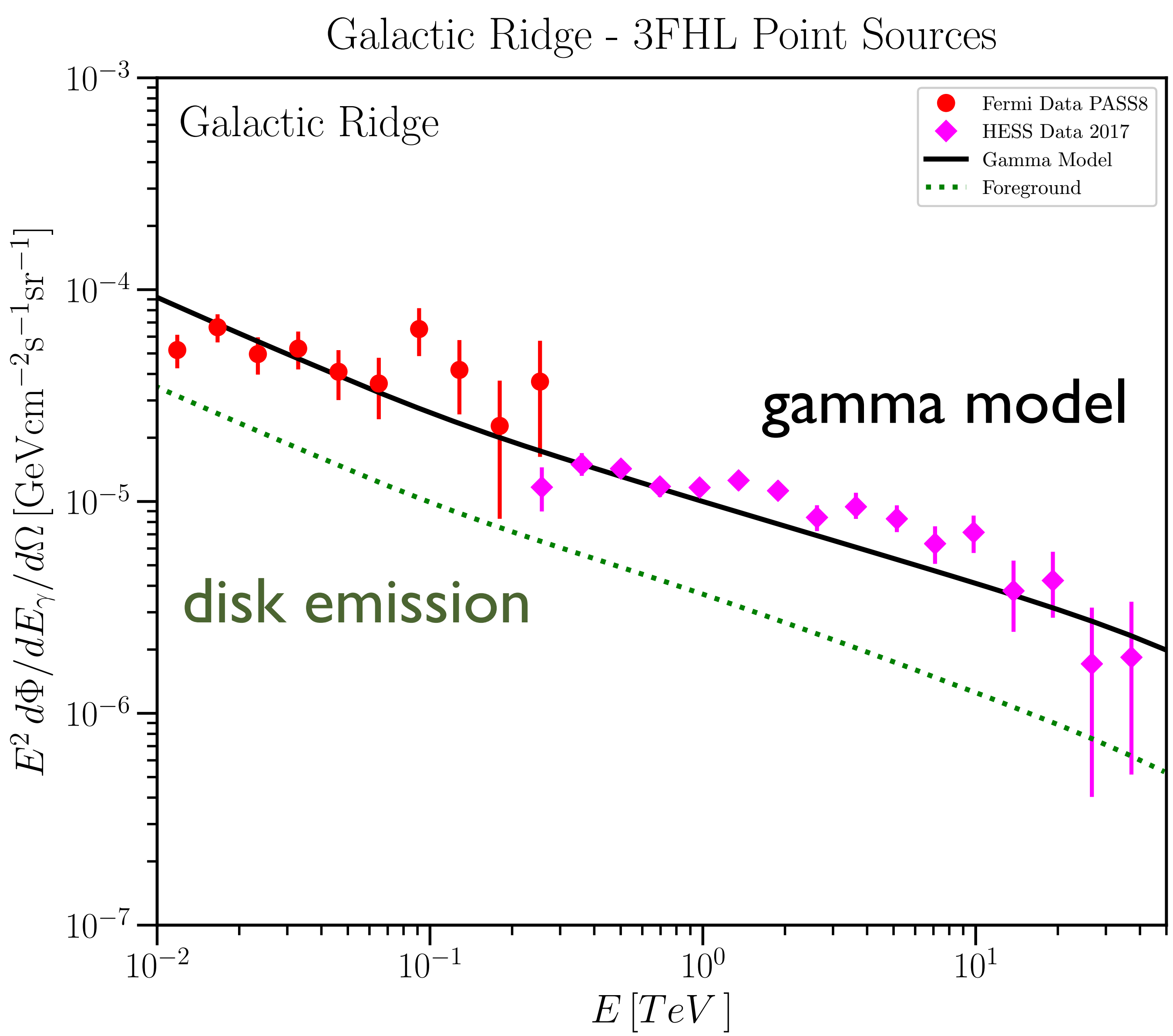
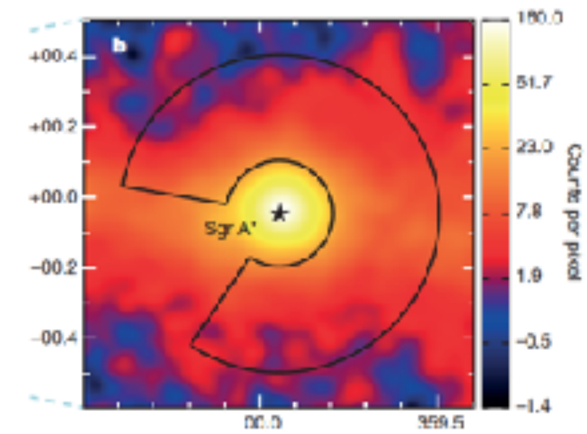


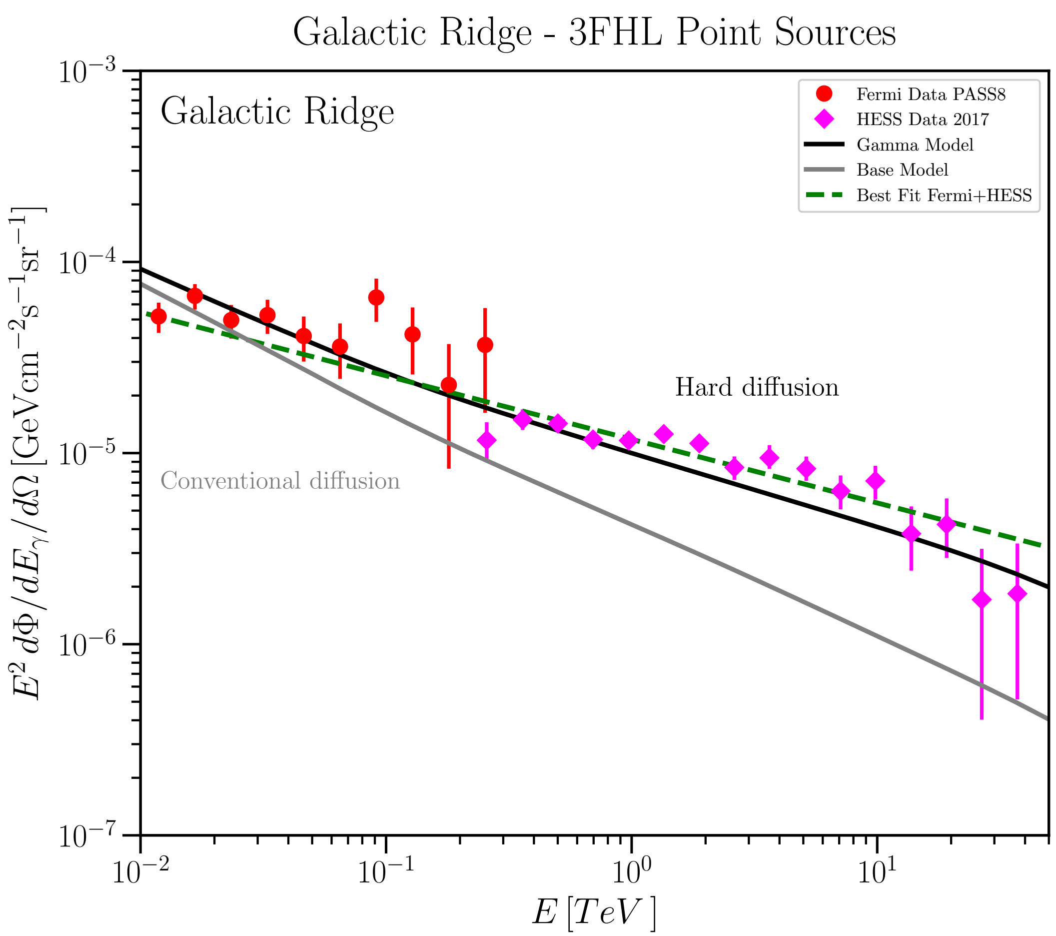
The models against FERMI + HESS

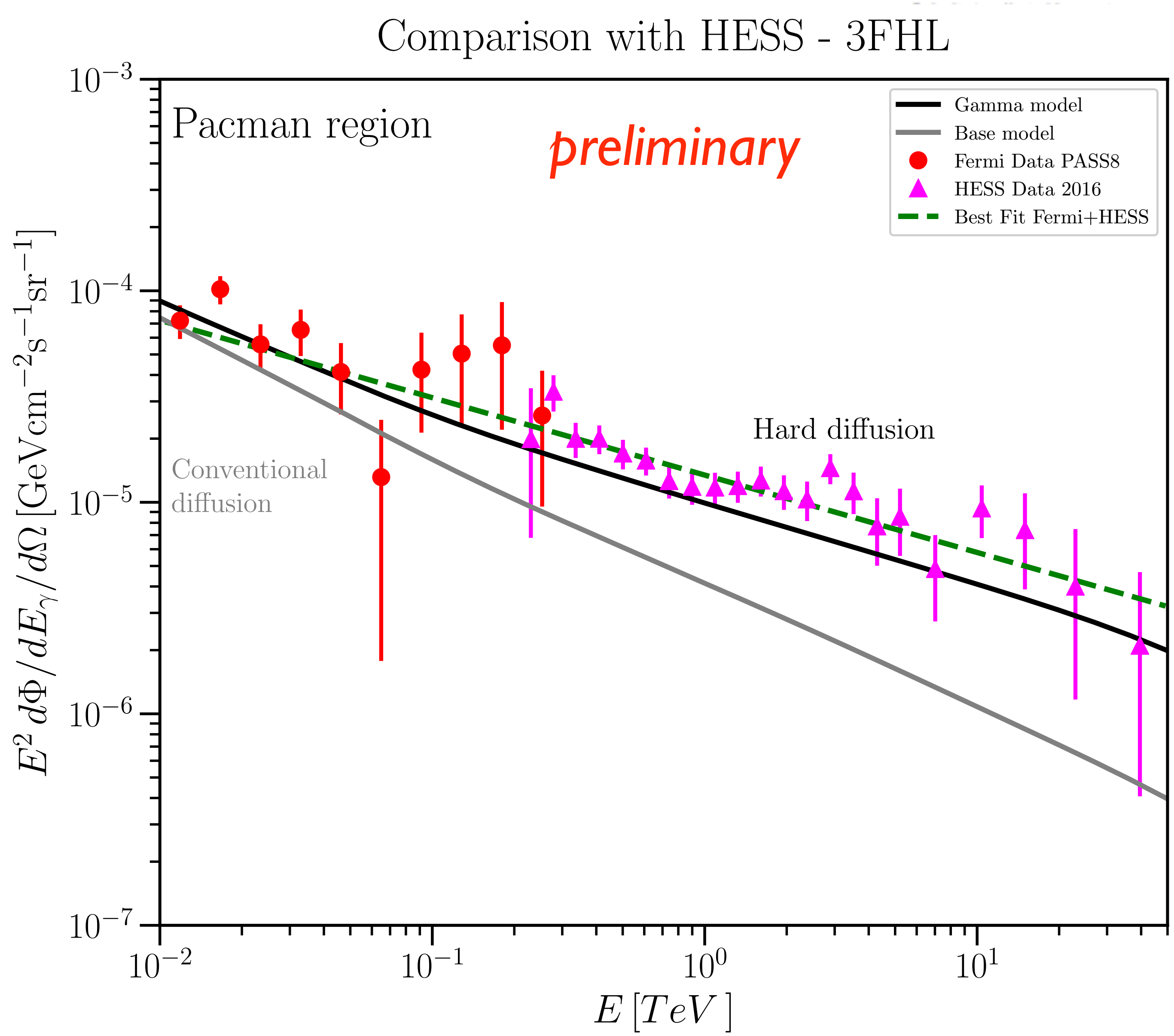


Pacman region

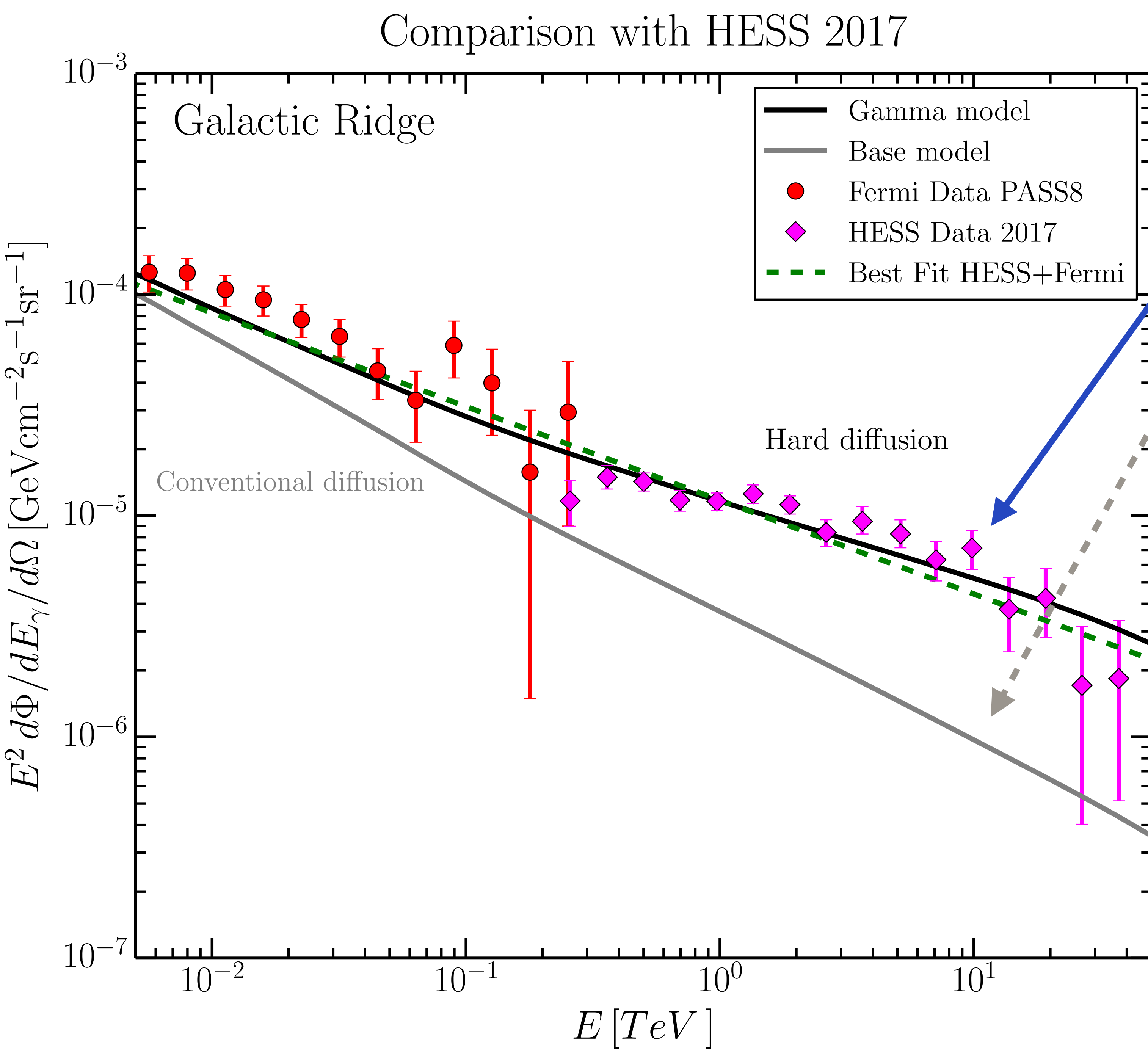
0.15° < θ < 0.45° , 22 < d < 67 pc



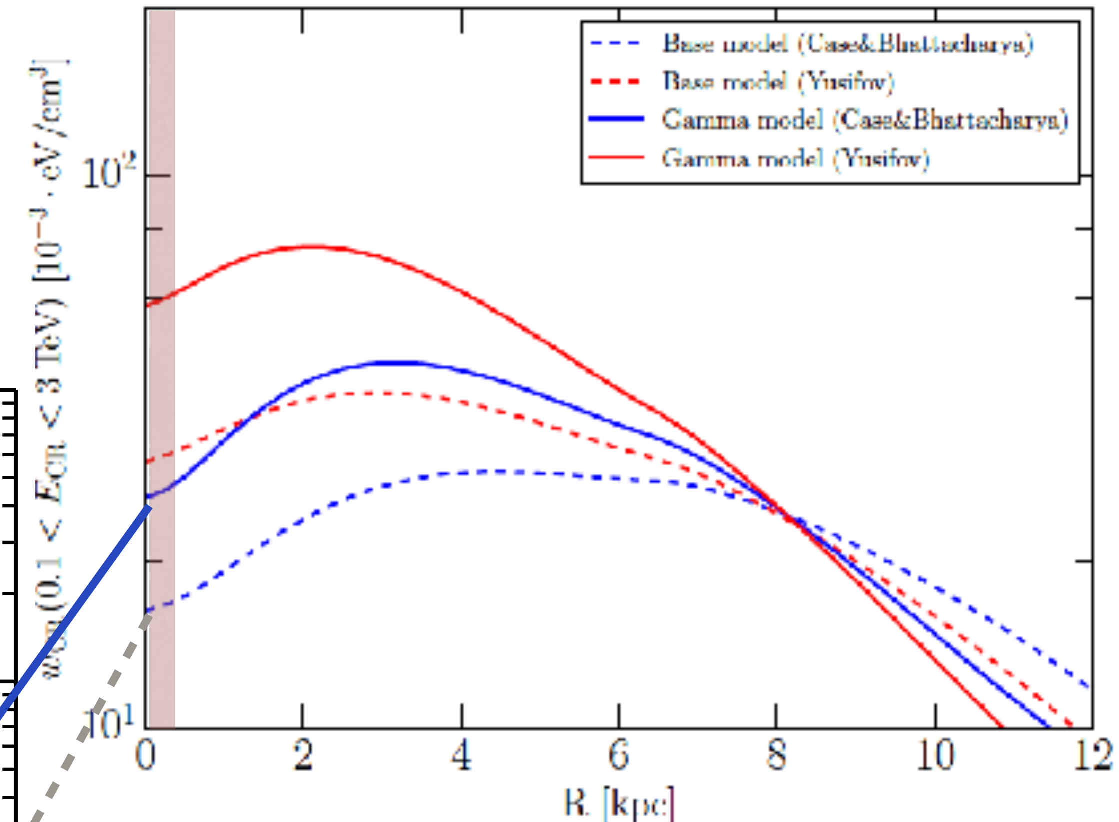




The effect of the CR sea at the GC



|*l*| < 1° , |*b*| < 0.3°



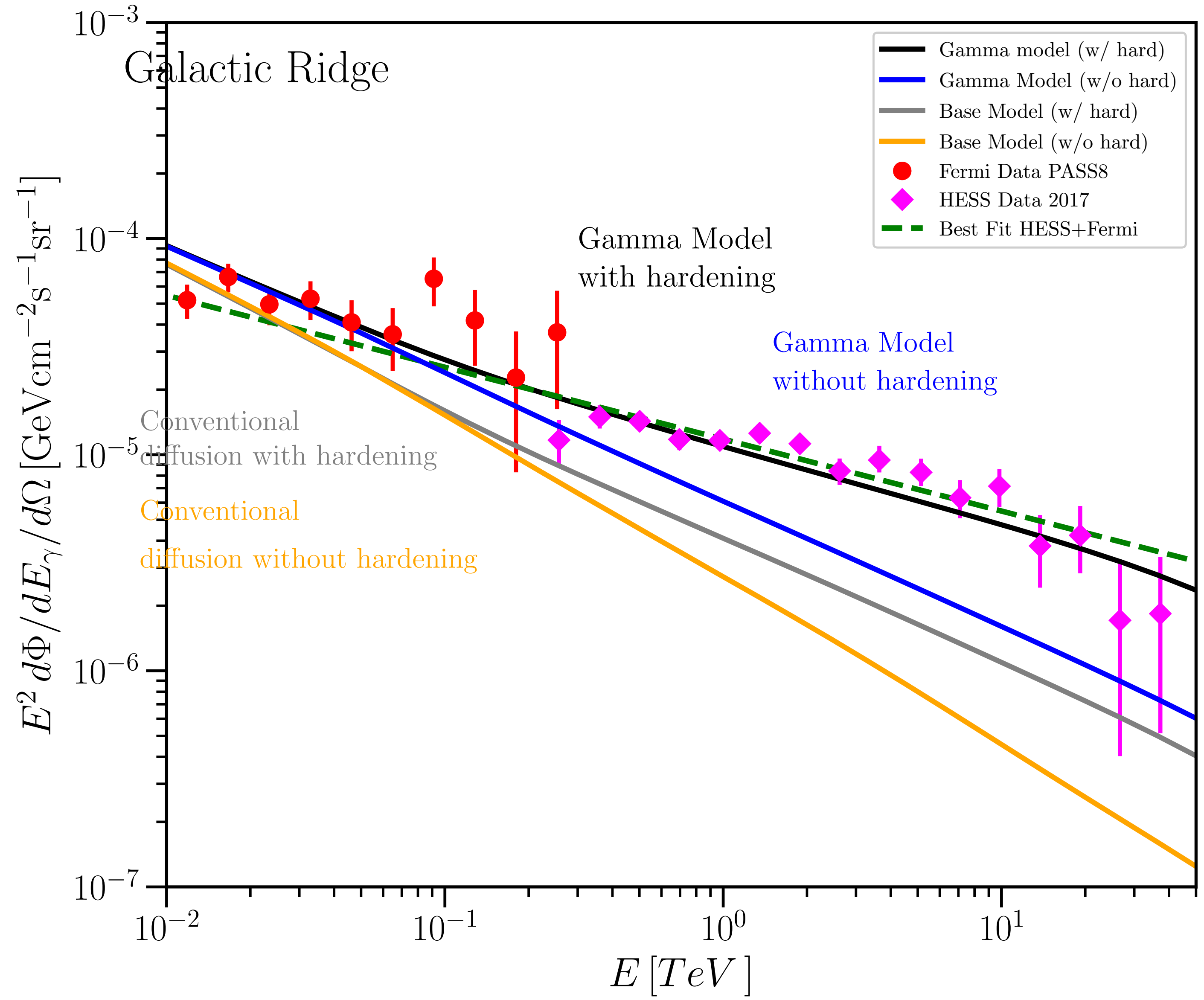
Degeneracy between poorly known gas and CR source densities at the GC

The role of the (global) hardening at few hundred GeV

Similarly to what required for the solution of the Milagro anomaly both the radial hardening and the global hardening are required to match the data. This implies:

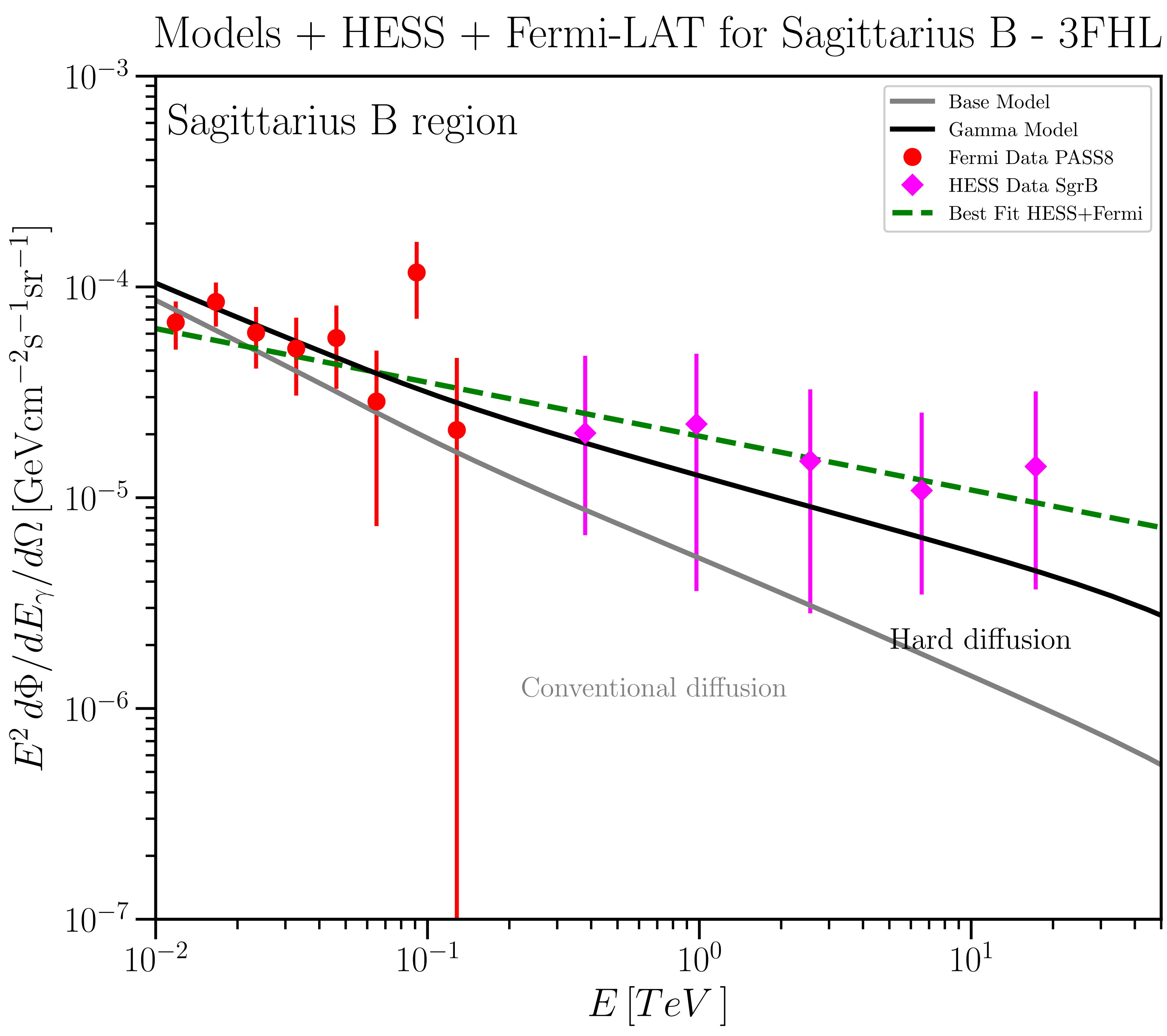
- further evidence for radial spectral index gradient. It presence at the GC and at E > 1 TeV disfavour interpretations based on non-linear CR propagation.

- first evidence of the presence of the CR hardening in the GC region suggesting this is a global effect (a source effect most likely).



Sgr B

$0.4° < l < 0.9°$, $-0.3° < b < 0.2°$



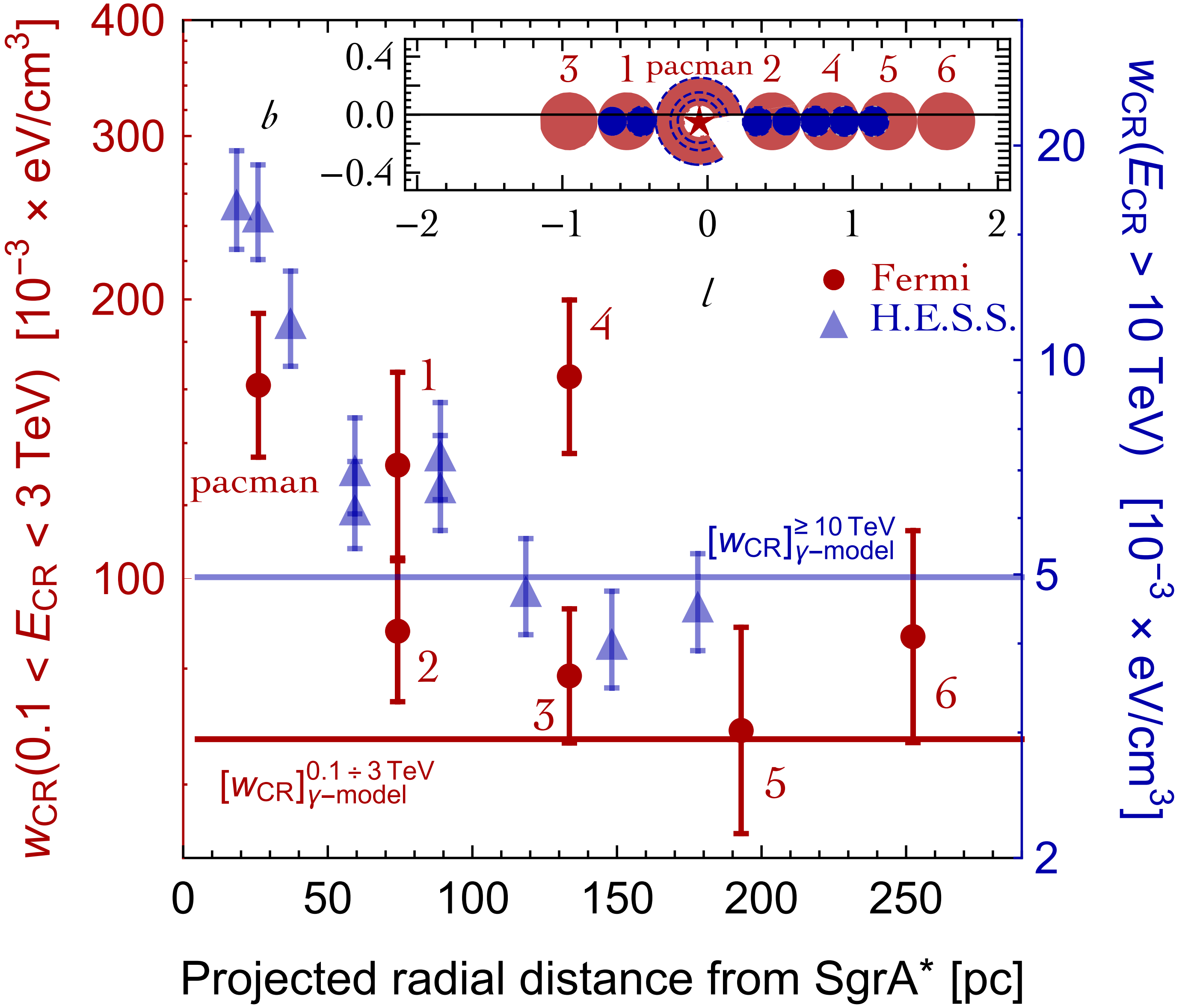
The CR energy density radial profile from HESS and FERMI

Gaggero, D.G., A. Marinelli, Taoso & Urbano, PRL 2017

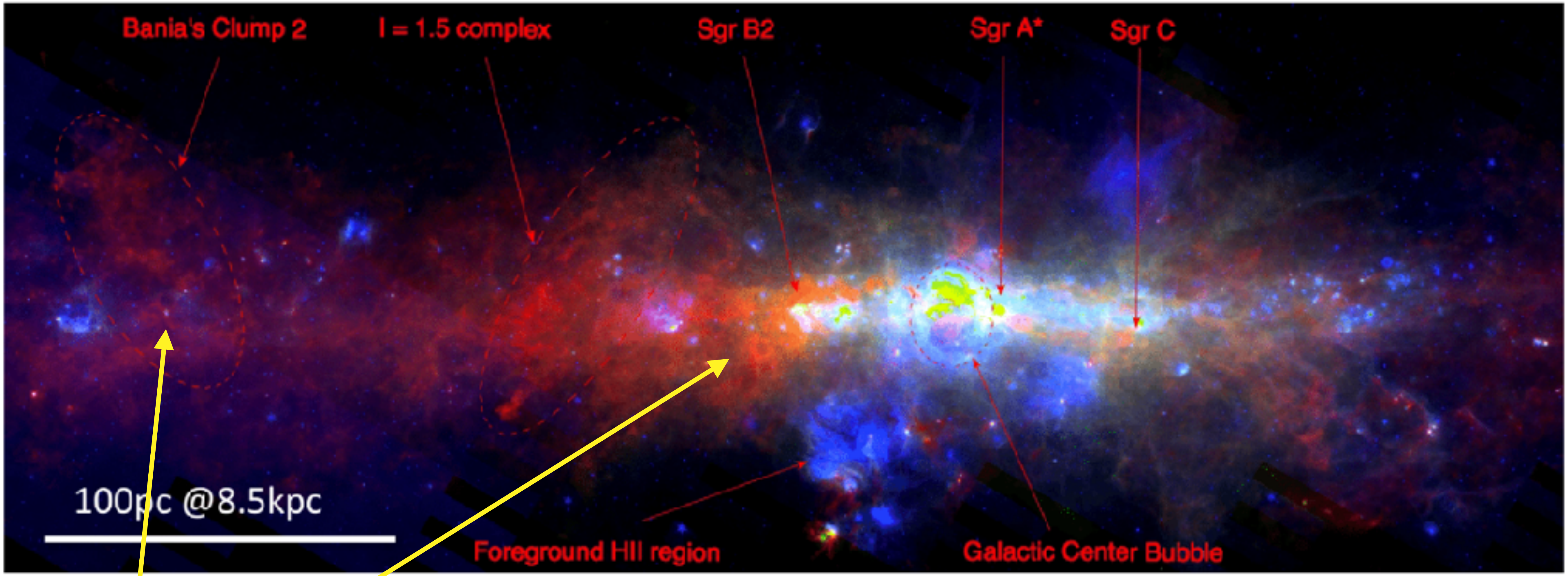
Here we use the same approach, and same gas mass distribution based on the CS emission map, of the HESS coll. and compare the result with our model

We use larger region due to the smaller Fermi-LAT angular resolution

Reasonable agreement for R > 50 pc consistent with an almost uniform CR density outside that region



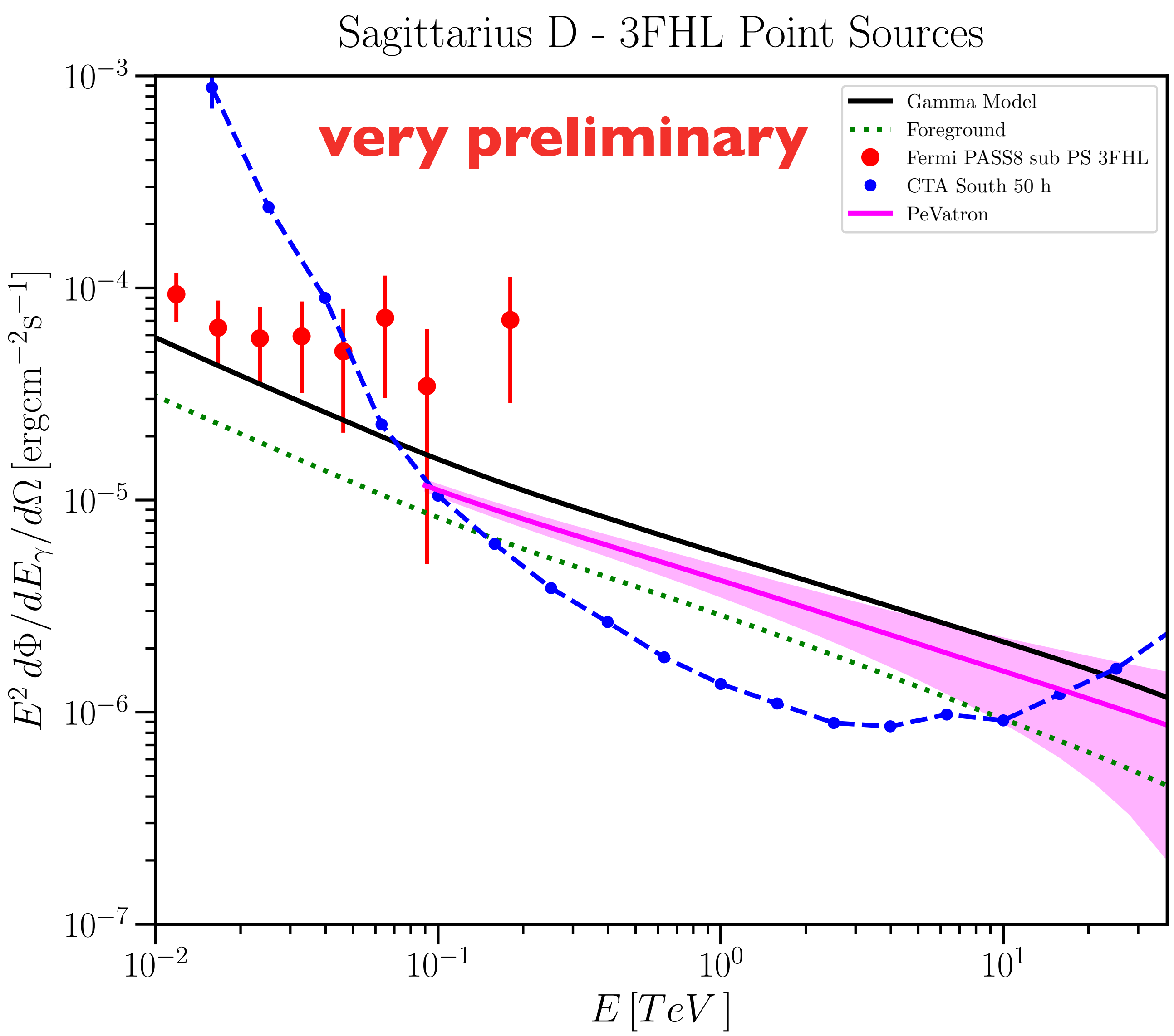
Future tests

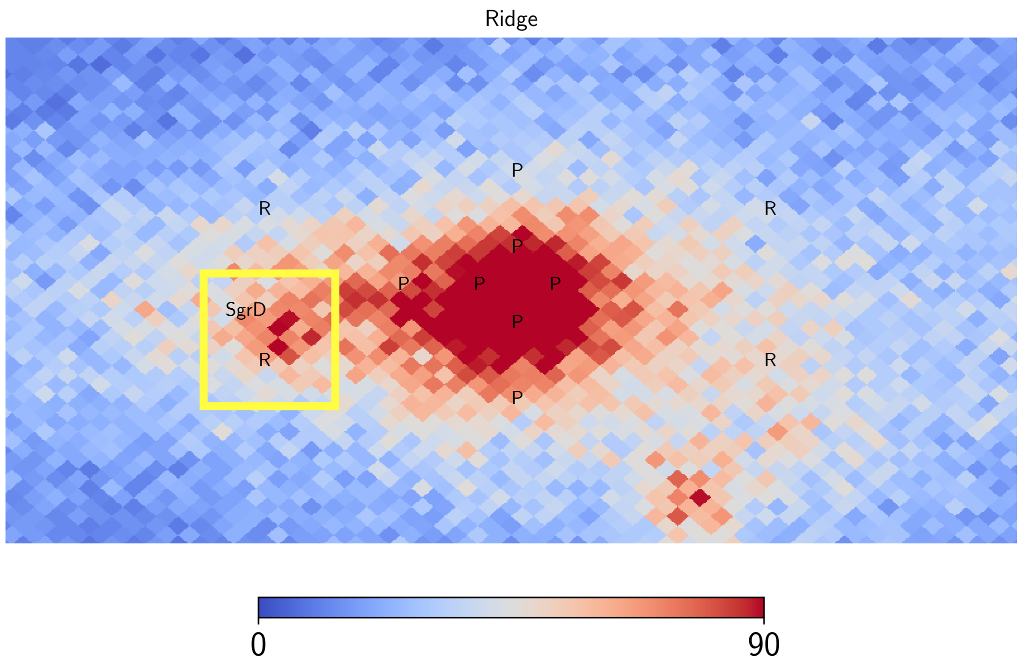


24μm, 70μm, 350μm

Sgr D : Pevatron vs CR sea
against CTA sensitivity (50 hr)

1.3° < *l* < 0.9° , - 0.3° < *b* < 0.1°





- PeVatron emission computed extrapolating HESS results assuming a - 2.3 spect. index
- foreground: computed with the gamma model for r > 1 kpc

CONCLUSIONS

- Fermi-LAT data in the inner galaxy may imply that the Galactic CR sea in the GC region is harder that the local one (which may be explained in terms of anisotropic transport)
- If a CR spectral hardening at 300 GeV (as that found by Pamela and AMS locally) is present in that region the bulk of the diffuse emission from the CMZ could be originated by the CR sea
- CTA may also confirm the scenario we propose observing the emission from molecular clouds outside the CMZ
- This would have relevant implications for understanding CR transport in the Galaxy