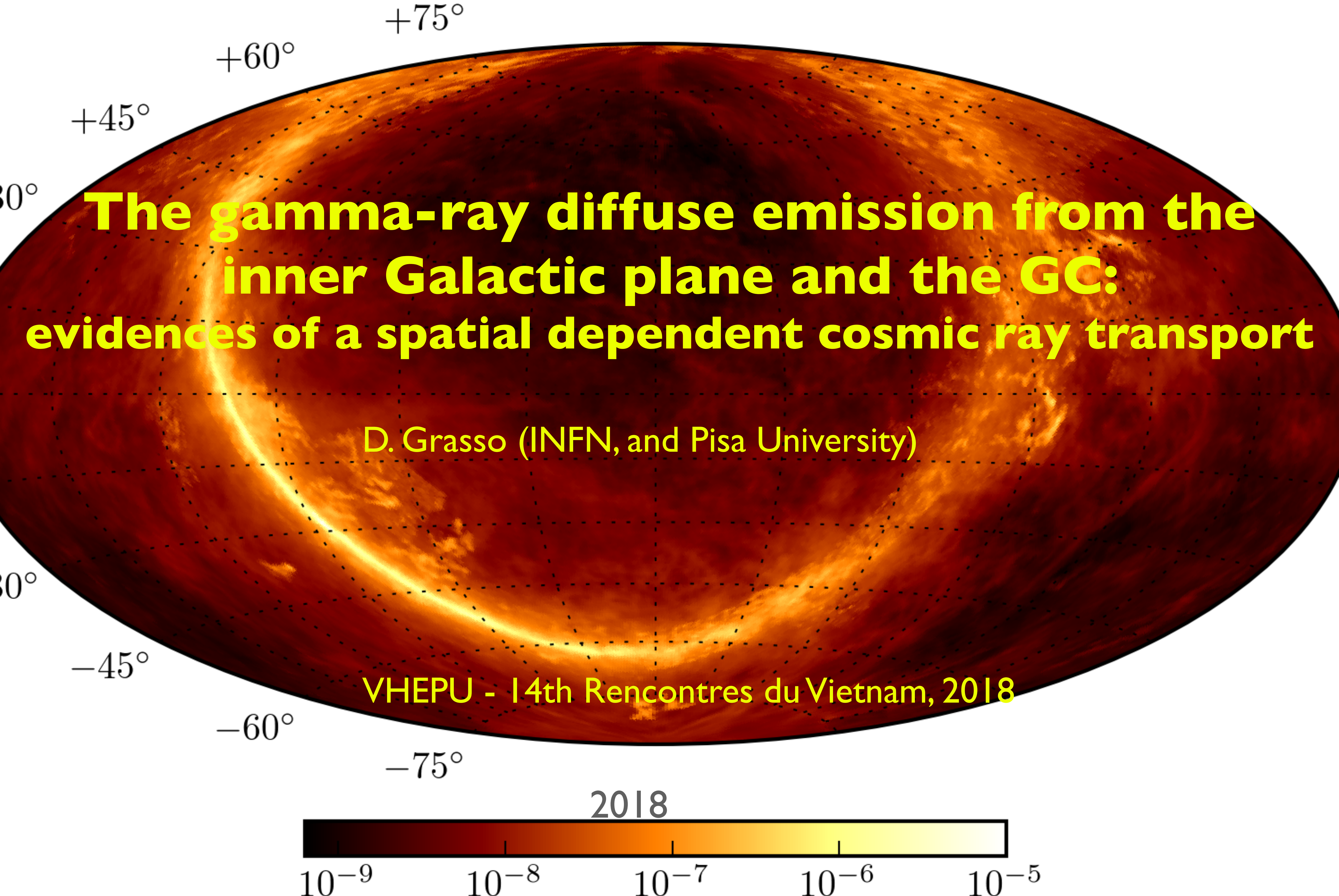
The gamma-ray diffuse emission from the inner Galactic plane and the GC:

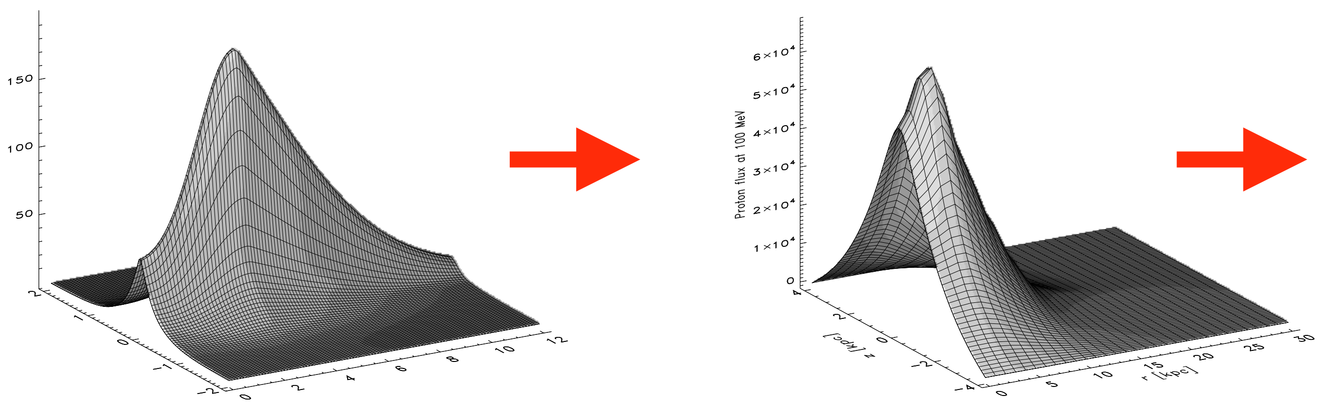
evidences of a spatial dependent cosmic ray transport

D. Grasso (INFN, and Pisa University)

VHEPU - 14th Rencontres du Vietnam, 2018



The γ-ray diffuse emission of the Galaxy



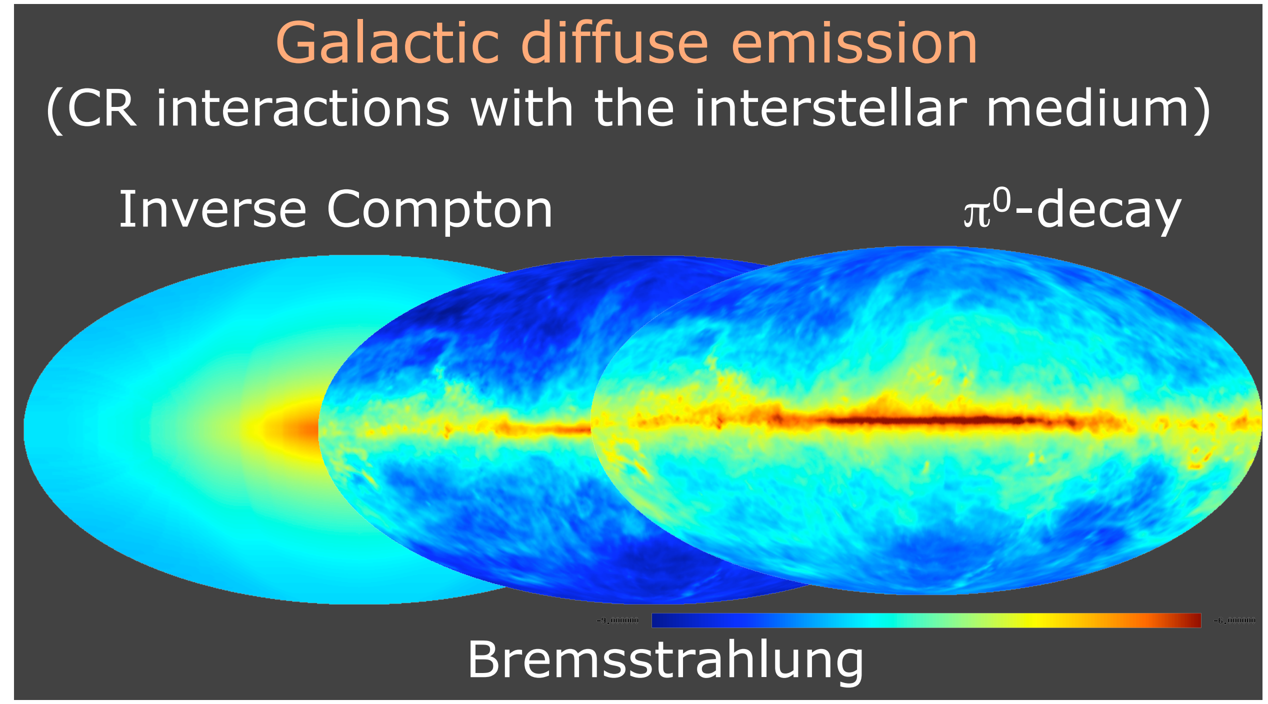
(a) Source term

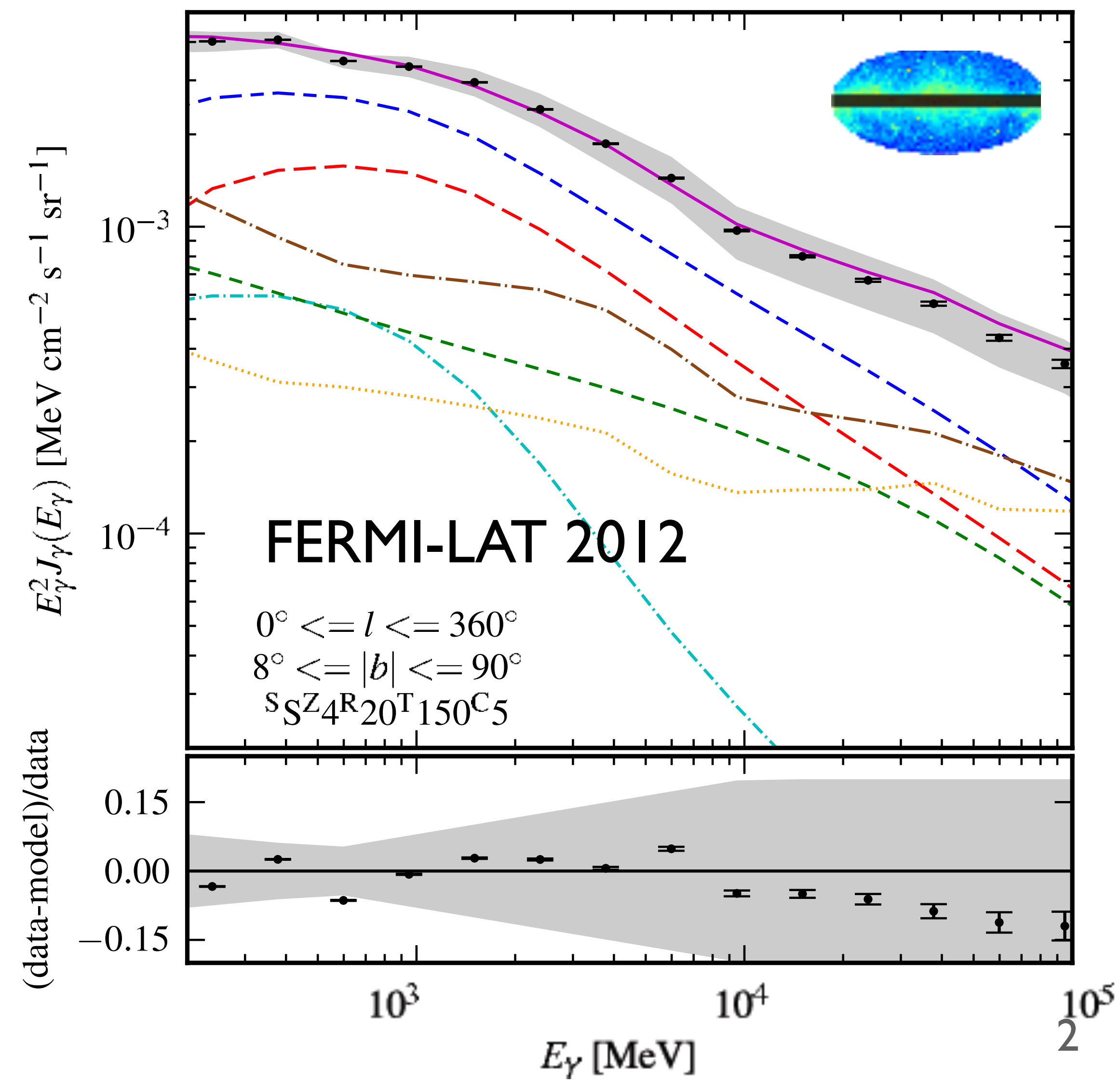
(b) Propagated protons at 100 MeV

Obtained by the convolution of the cosmic ray (CR) distribution with the interstellar gas (**π^0-decay** and **bremsstrahlung**) and radiation (**Inverse Compton**) and the proper cross-sections

It offers a deep probe of the CR population but requires detailed numerical modeling (e.g. GALPROP or DRAGON codes).

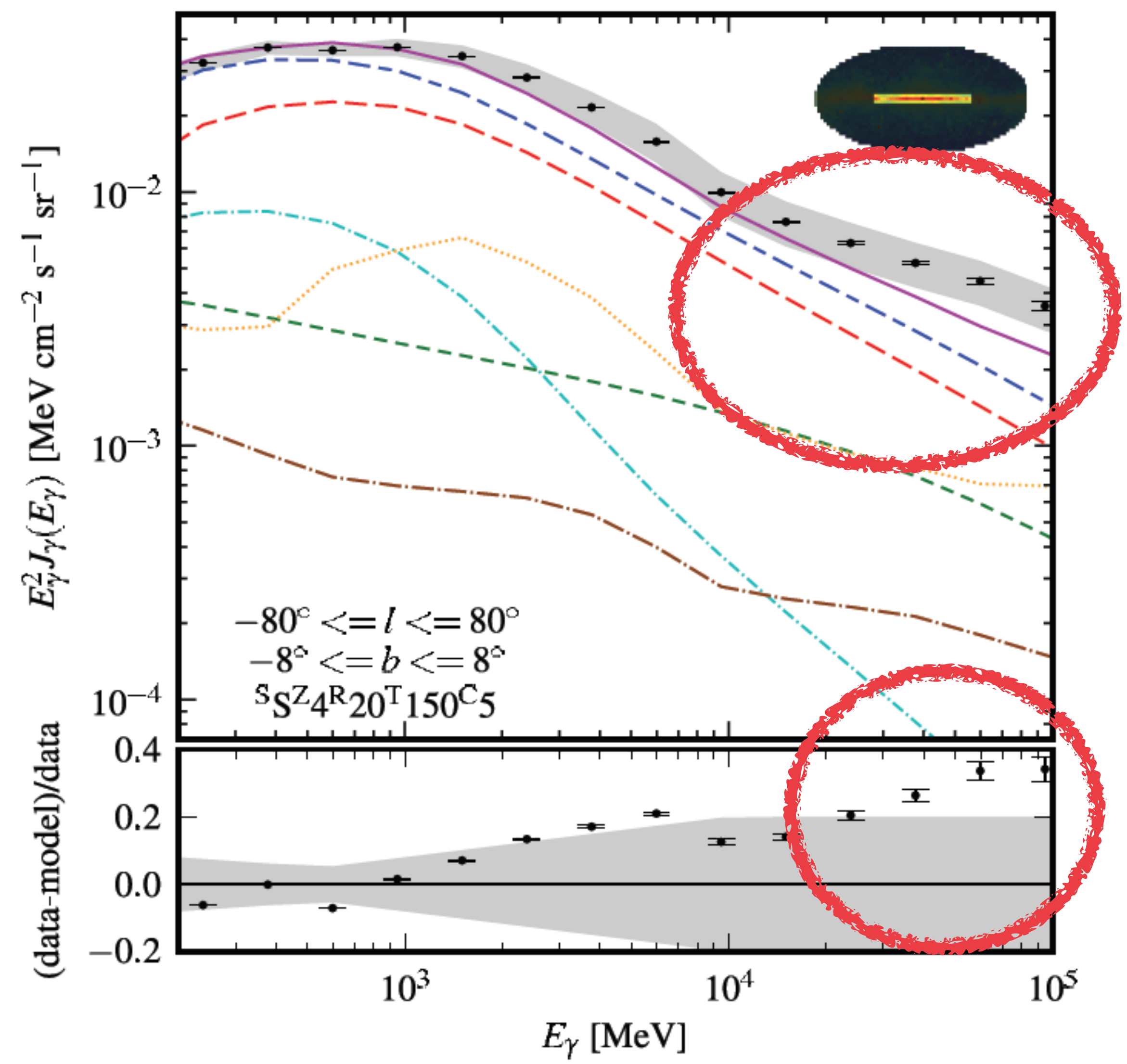
The conventional approach (uniform propagation properties) provides a reasonable description of the emission spectrum away from the Galactic plane.





The spectral index gradient problem

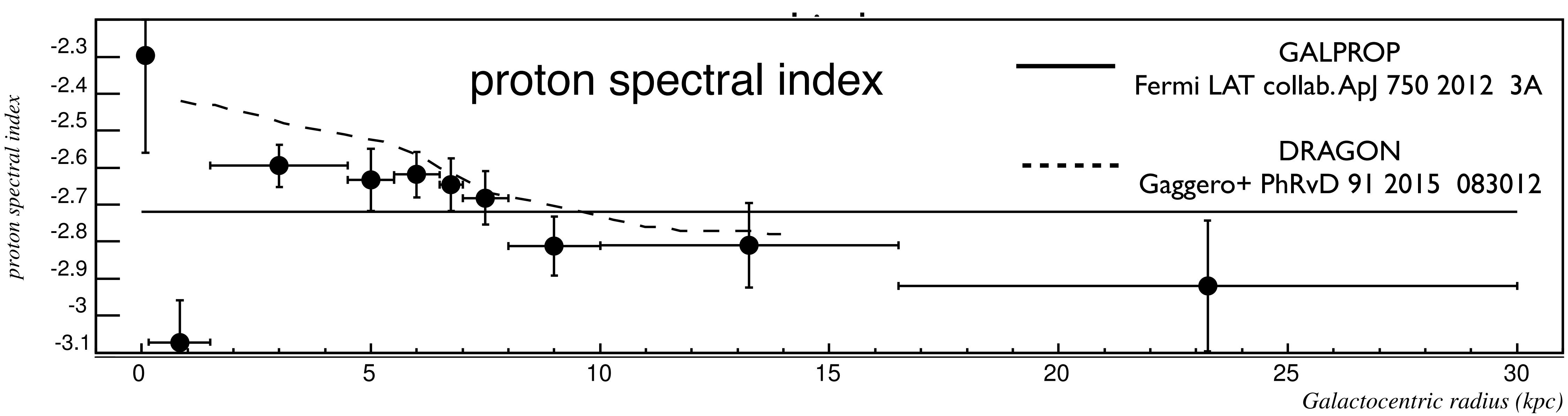
Fermi-LAT coll. 2012



Conventional models, based on local CR data, while reproducing the γ-ray diffuse emission outside the Galactic plane (GP), under predict it in the inner GP above tens of GeV

A template fit analysis of Fermi-LAT data shown that the effect is due to a radial dependent CR spectral index *Gaggero, Urbano, Valli & Ullio 2015*
Yang, Aharonian & Evoli, 2016

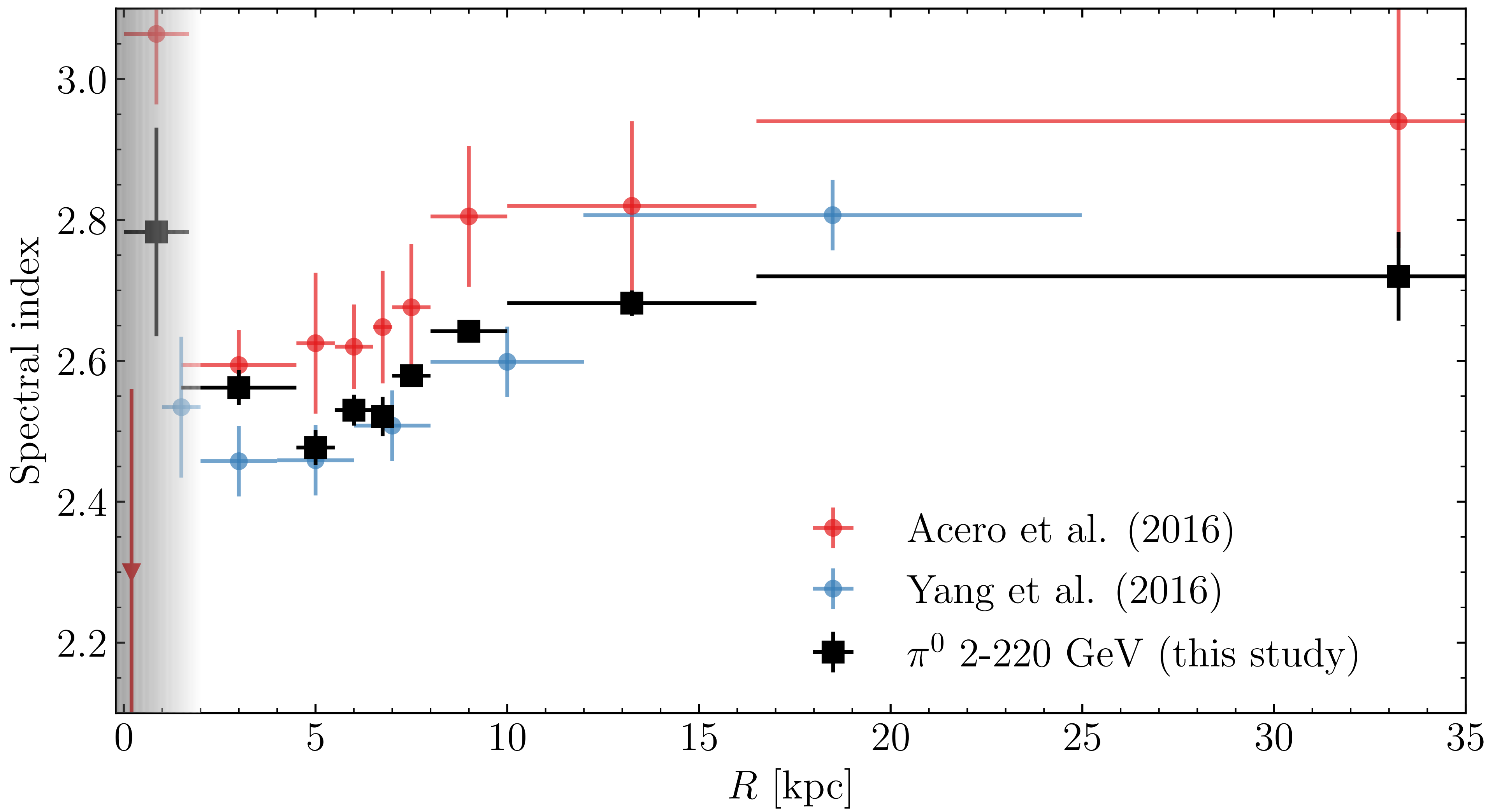
Confirmed by
Fermi-LAT coll. 2016



The spectral index gradient problem

Prothast, Gaggero, Strom, Weniger, 2018

proton spectral index
using SkyFact: *adaptable* template fitting tool [*Storm, Veniger & Calore 2017*]

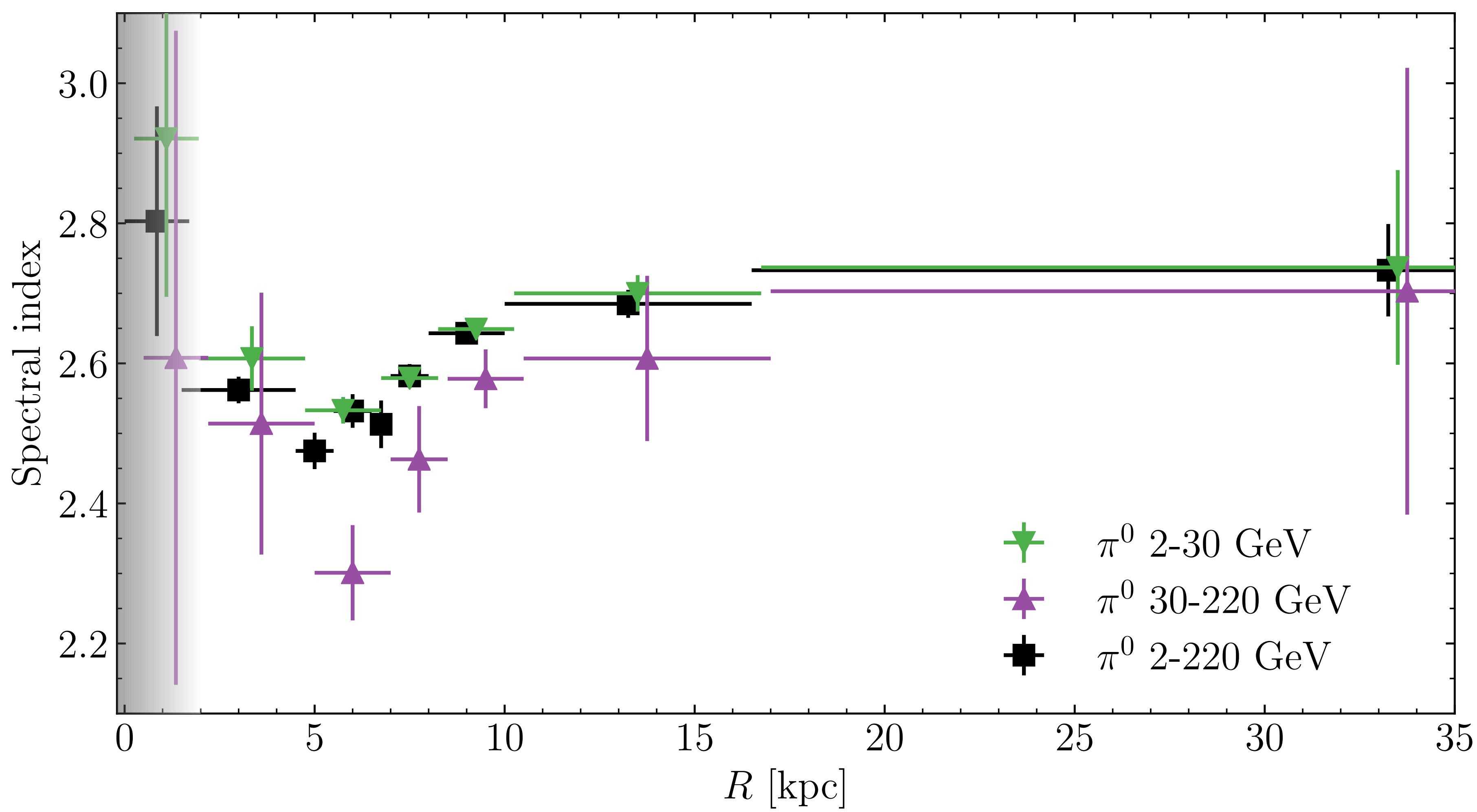


Clear evidence of a progressive hardening in the inner Galaxy towards the GC
Large uncertainty in the GC region !

The spectral index gradient problem

Prothast, Gaggero, Strom, Weniger, 2018

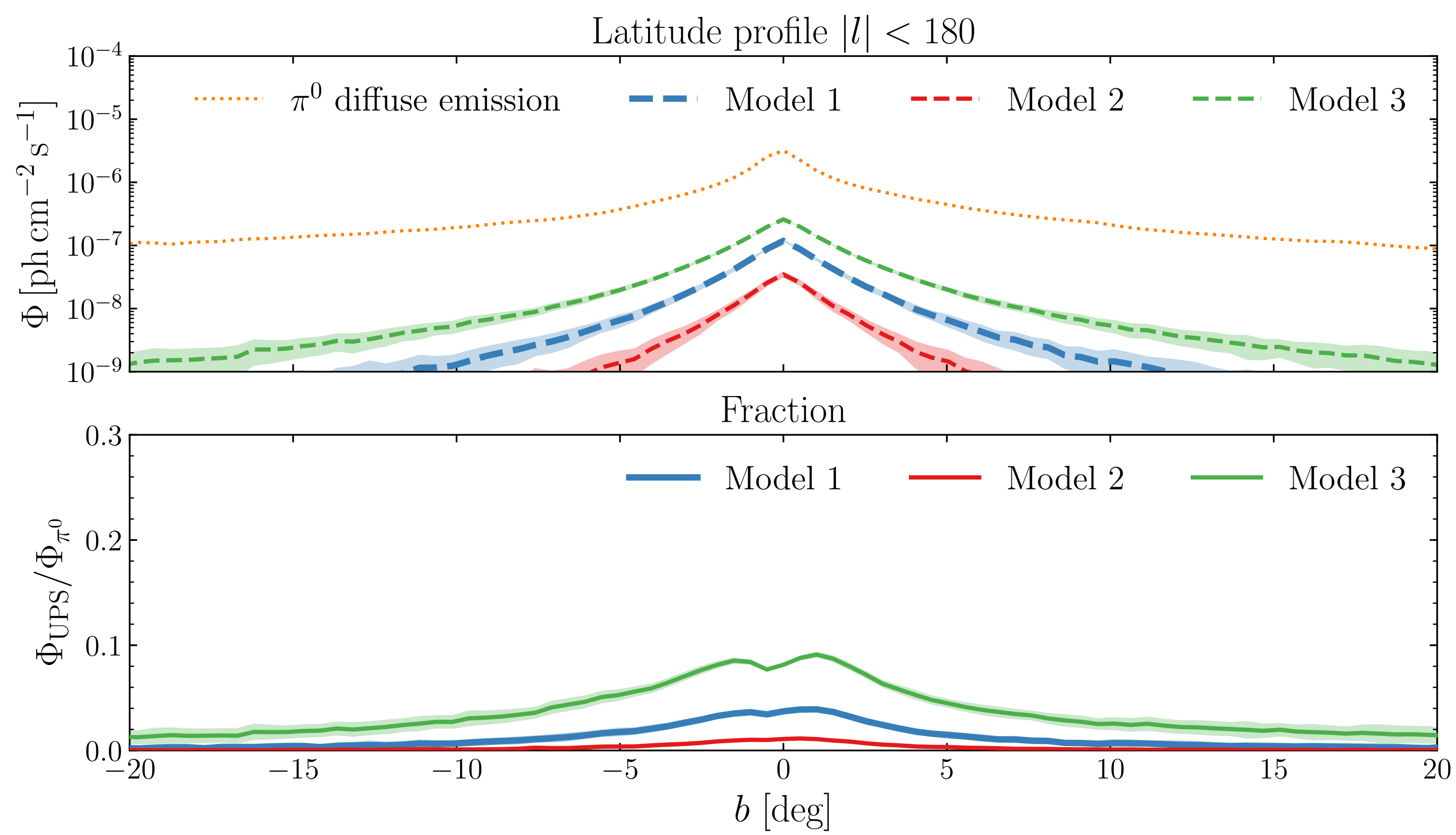
proton spectral index in several energy intervals
using SkyFact: *adaptable* template fitting tool [*Storm, Veniger & Calore 2017*]



The radial dependent hardening is present in two energy intervals with hints of a harder spectrum at high energies which *may be an evidence that the CR hardening found by Pamela and AMS is present in the whole Galaxy*

Can the progressive hardening be due to unresolved sources ?

Prothast, Gaggero, Strom, Weniger, 2018

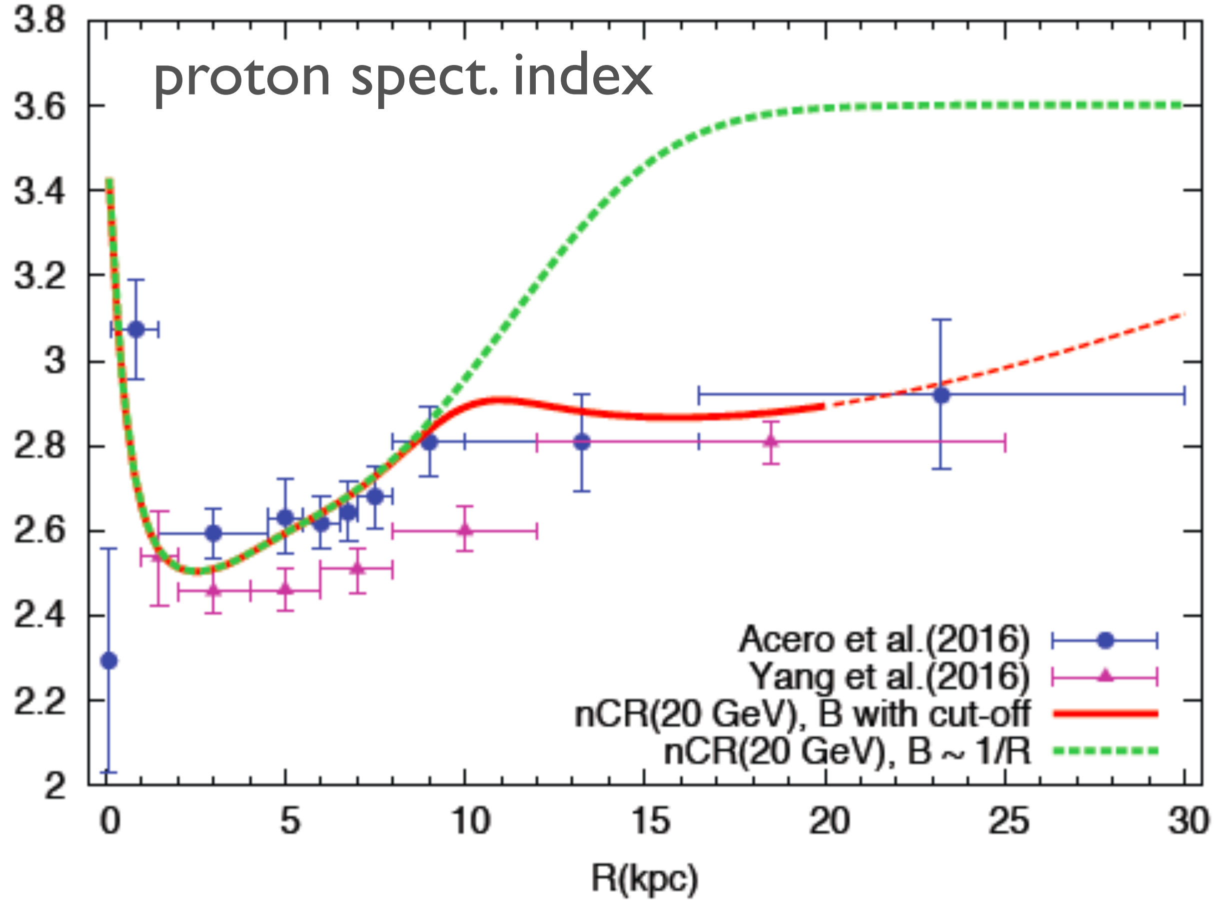


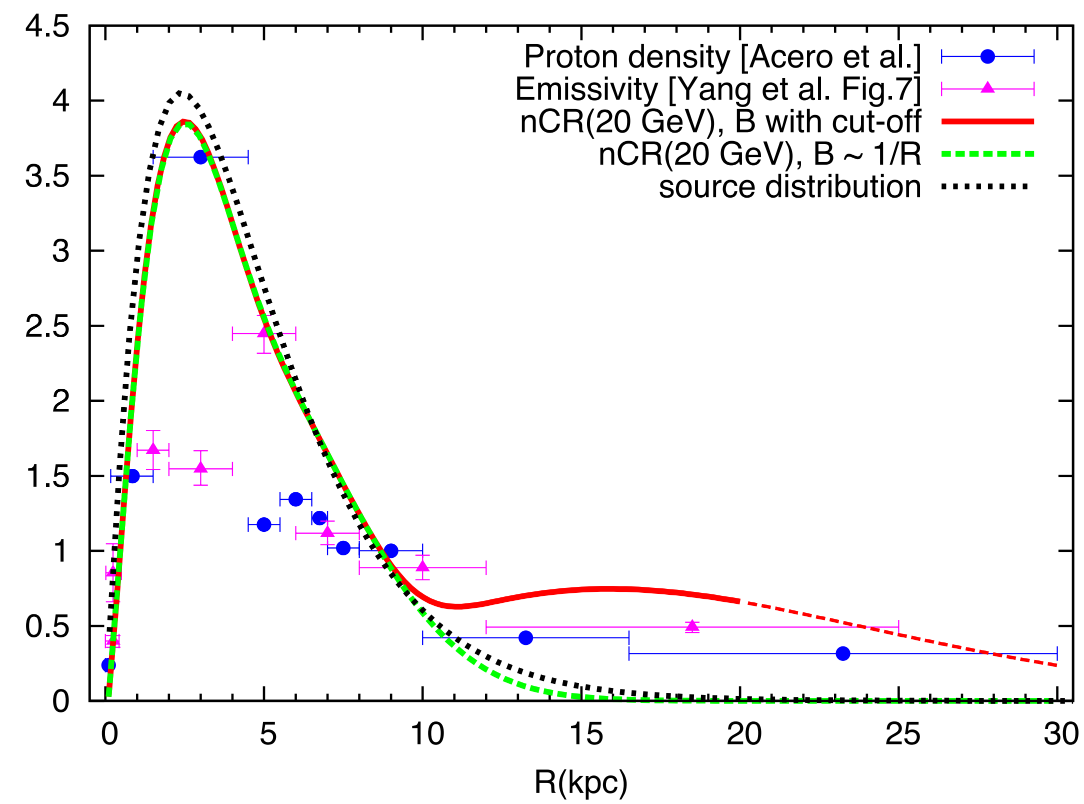
NO !

Small contribution for any reasonable source distribution model

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

<u>Energy dependent effect</u>: at high energy it should be absent
The results of *Prothast et al.* already disfavor this interpretation

A scenario based on spatial dependent diffusion

Gaggero, Urbano, Valli & Ullio, PRD 2015

The CR spectral index gradient problem is interpreted as a consequence of the radial dependence of the diffusion coefficient

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

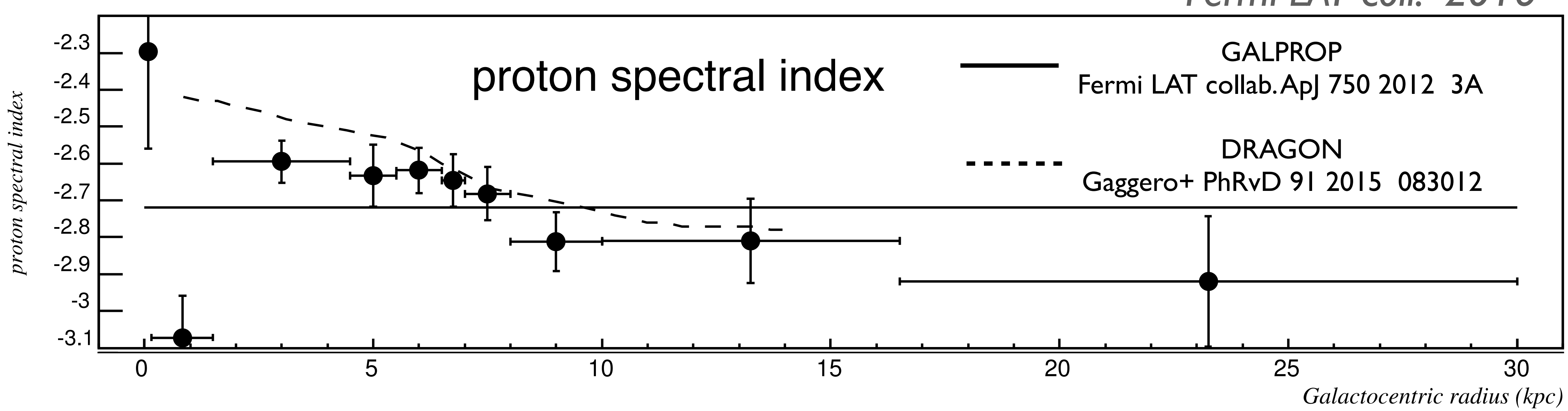
Evoli, Gaggero, DG. & Maccione 2008

Evoli, Gaggero, Di Mauro, Vittino, Mazziotta & DG 2017,18

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

so that $\Gamma(r) = \Gamma_{\rm source} + \delta(r)$ "KRAγ model"

Fermi-LAT coll. 2016



A scenario based on spatial dependent diffusion

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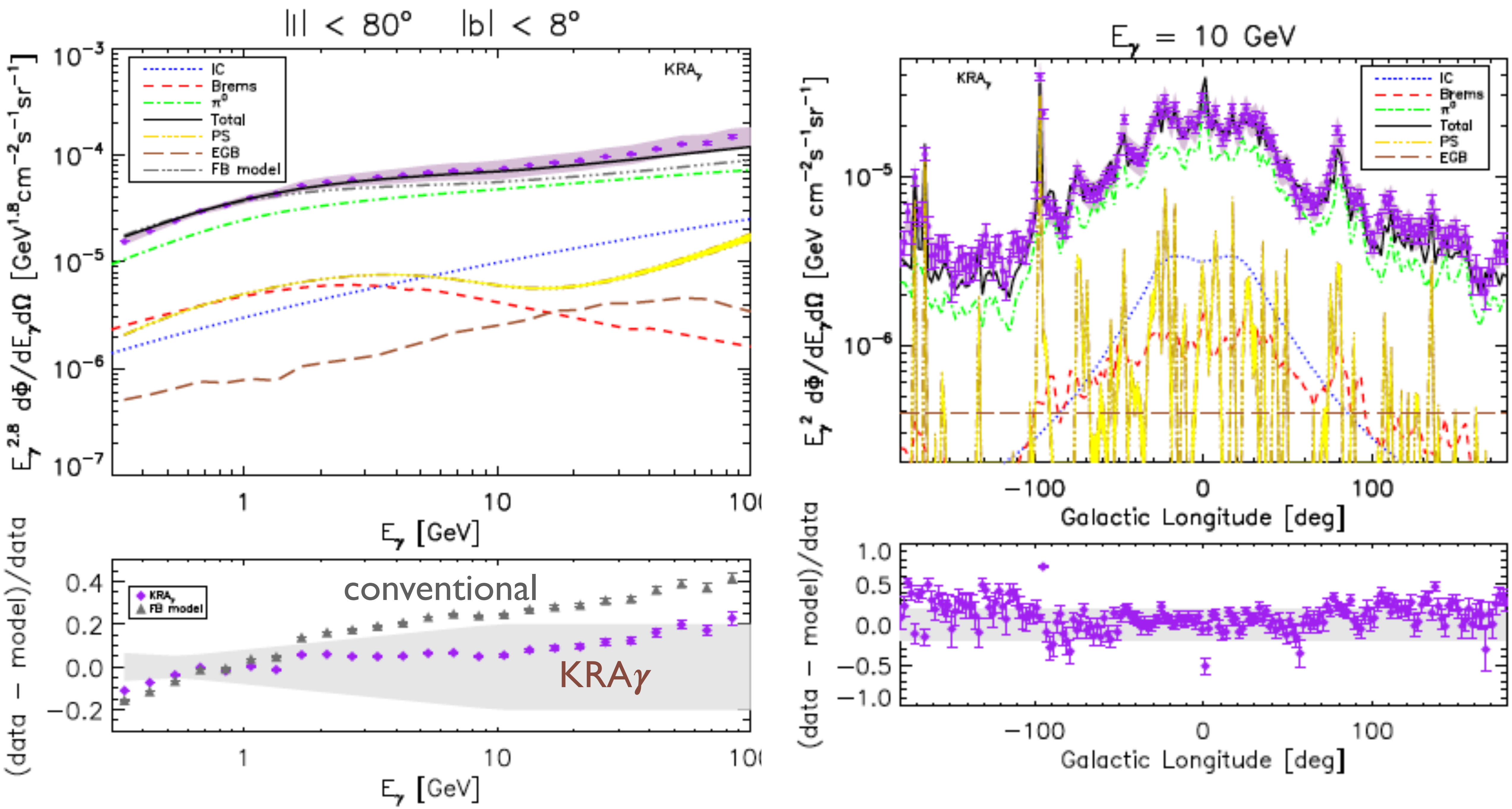
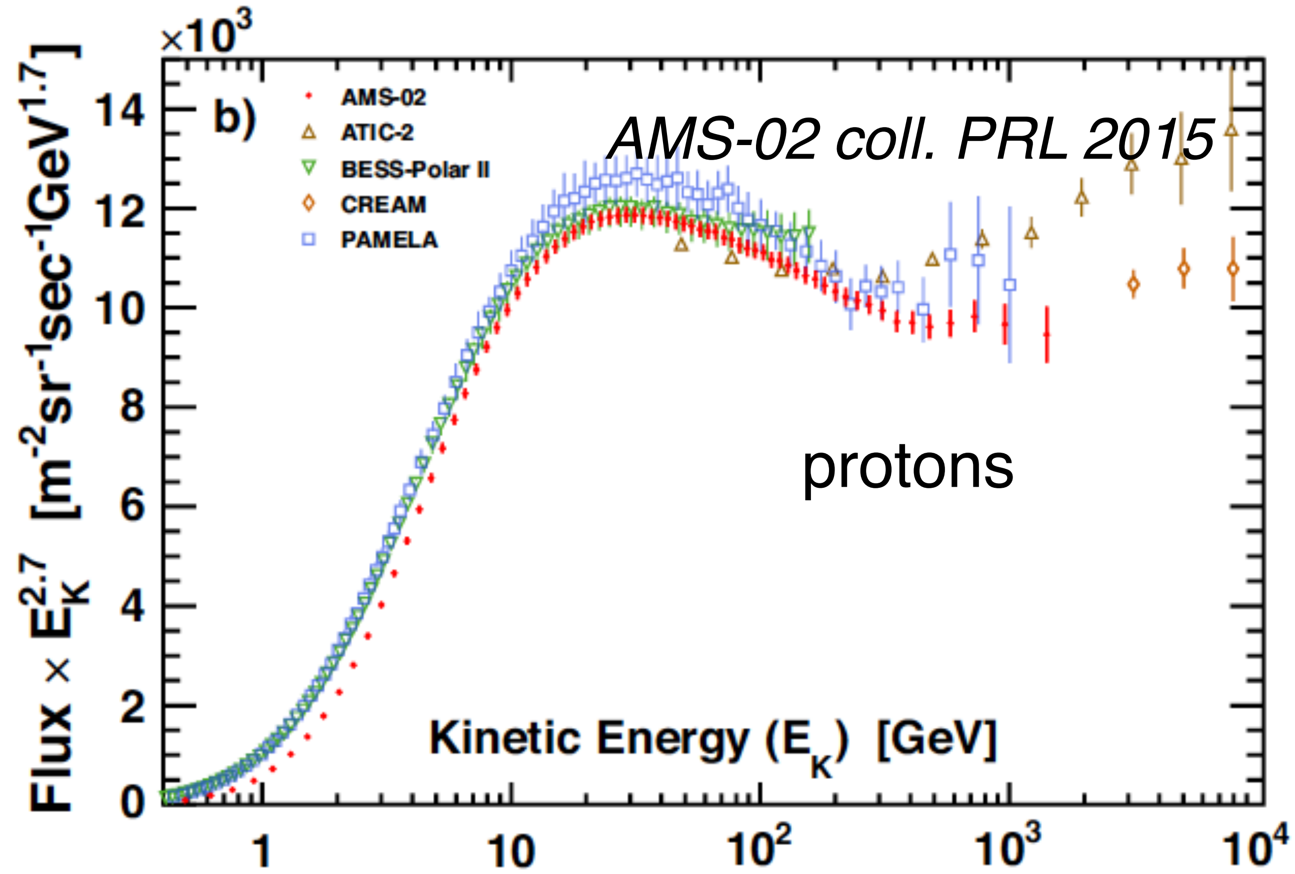


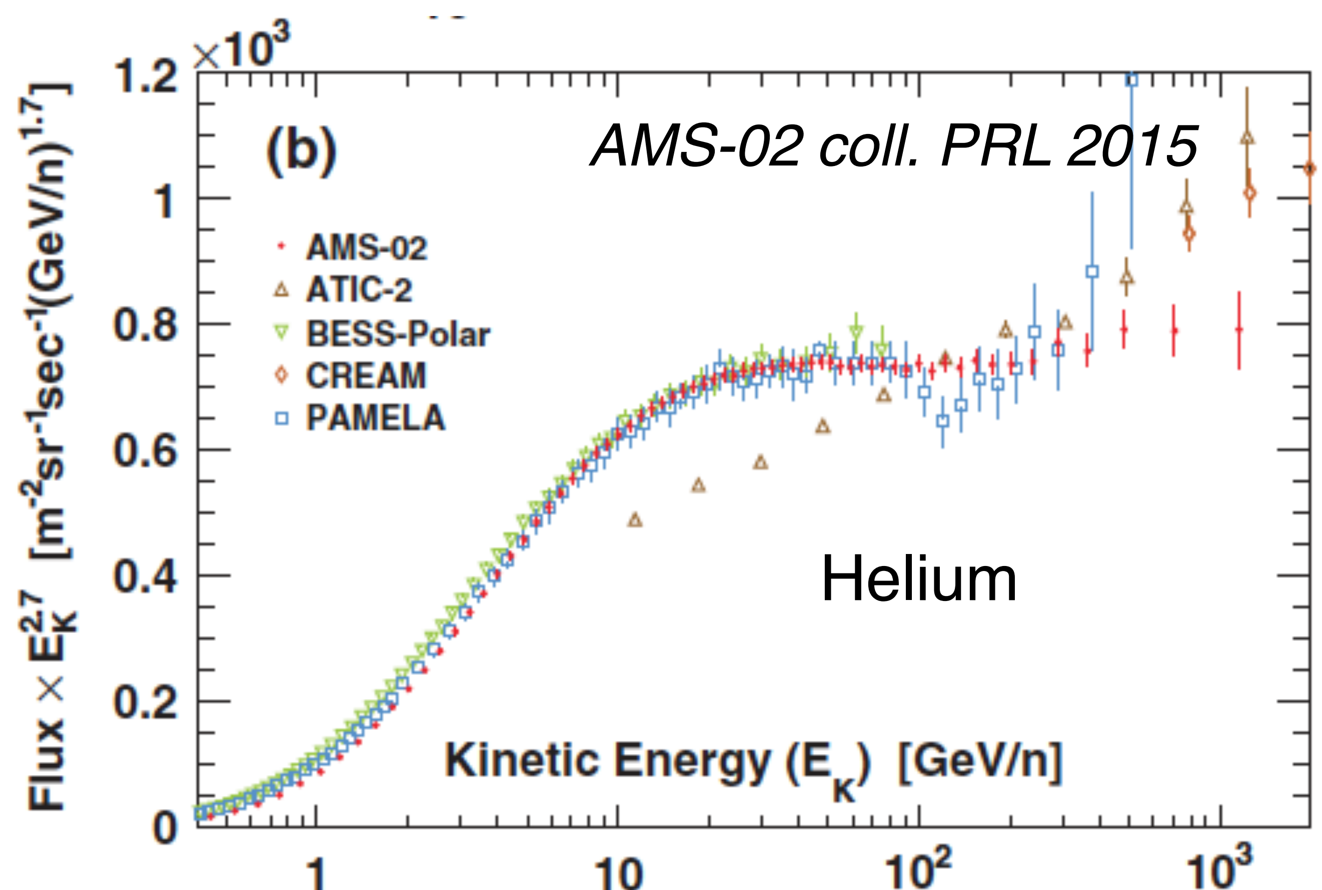
CR hardening @ ~ 300 GeV/n

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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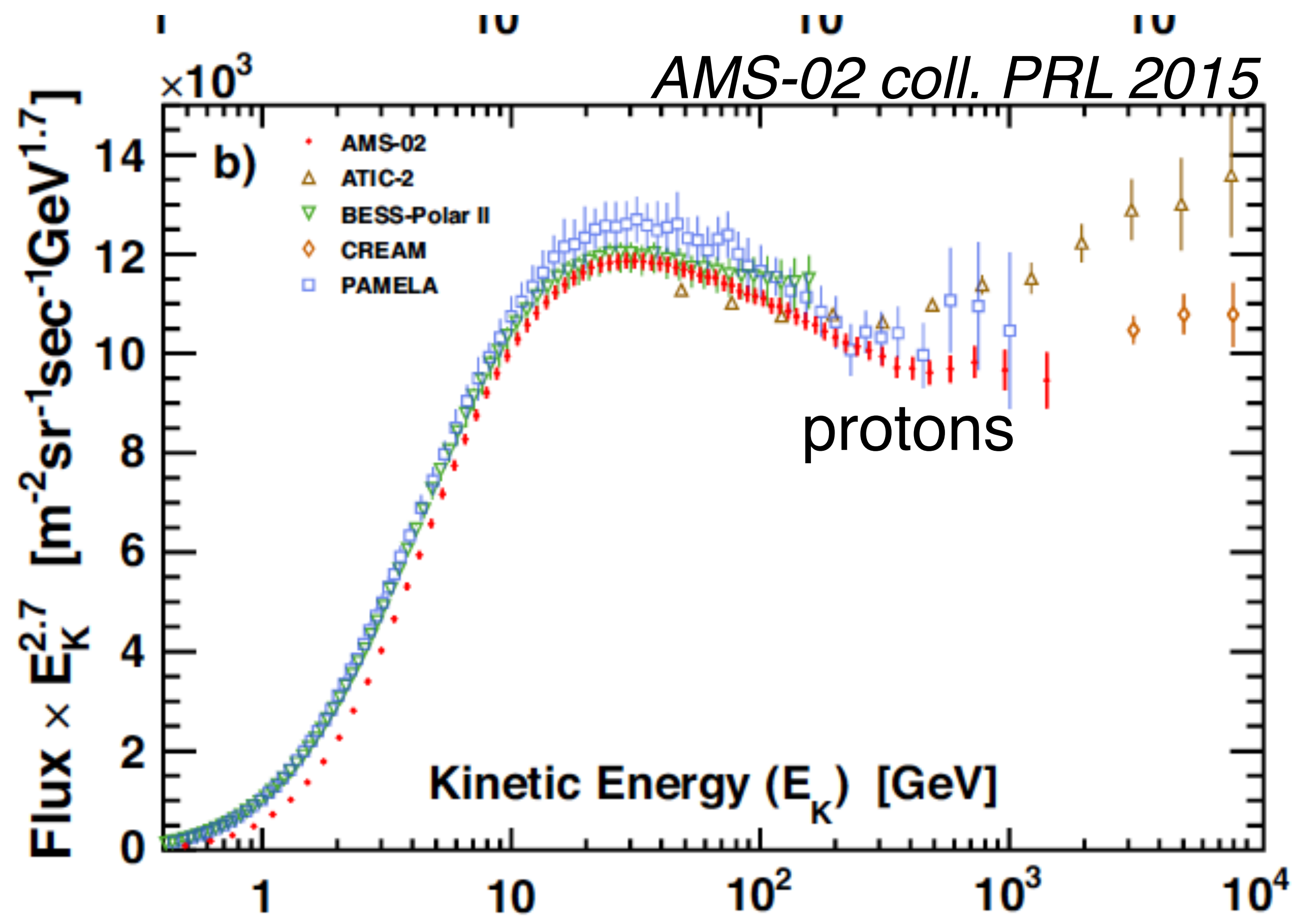
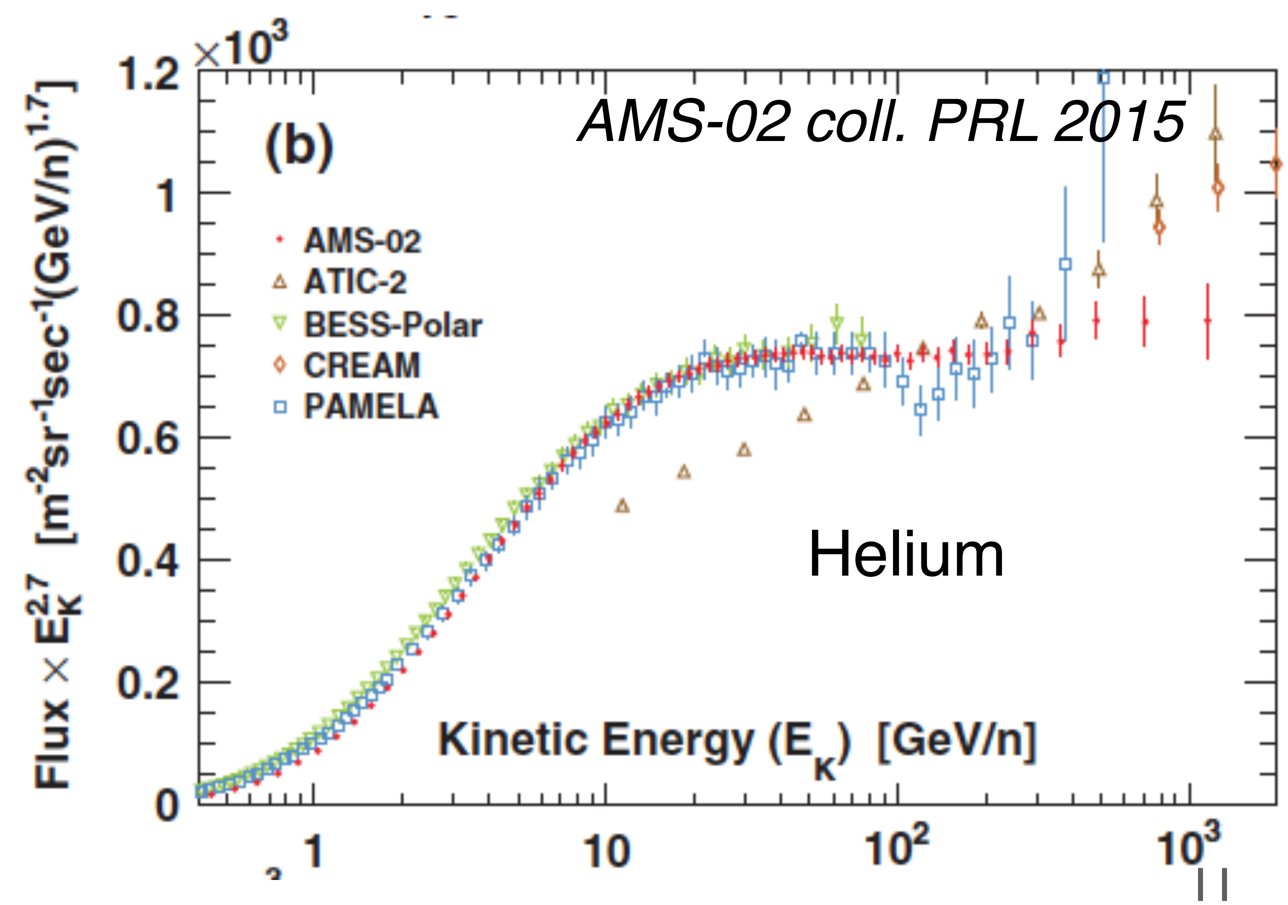
A similar effect was found for heavier nuclei

- What is the origin of such feature ?
- Is this a local effect or it is present in the whole Galaxy ?





CR hardening @ 300 GeV/n, *secondaries vs primaries*

AMS-02 coll.

PHYSICAL REVIEW LETTERS **120,** 021101 (2018)

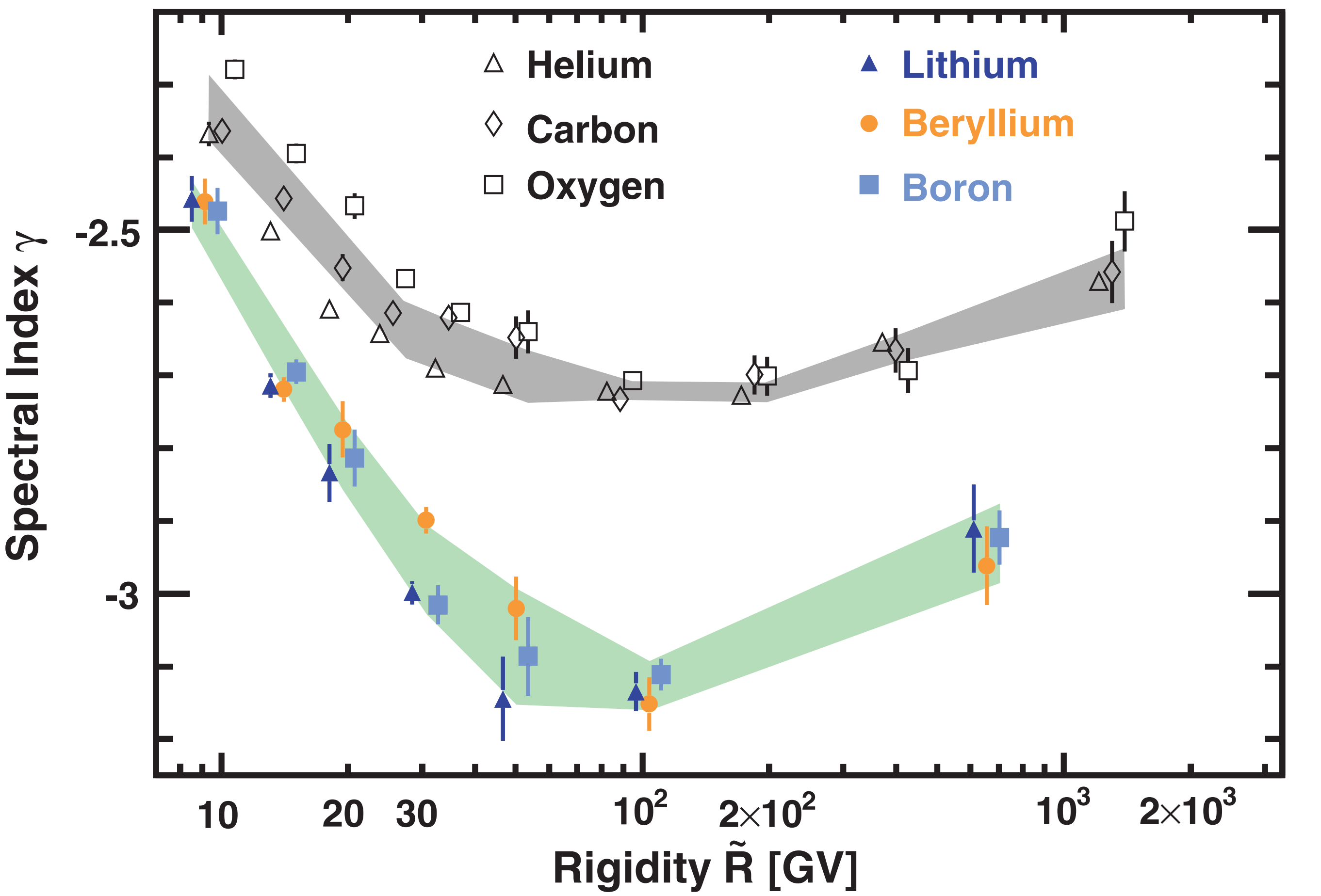
Editors' Suggestion   Featured in Physics

Observation of New Properties of Secondary Cosmic Rays Lithium, Beryllium, and Boron by the Alpha Magnetic Spectrometer on the International Space Station

above 200 GeV/n secondaries harden more than primaries
($\Delta\gamma \sim 0.13$ on average)

this is just what expected if the effect would be produced by propagation

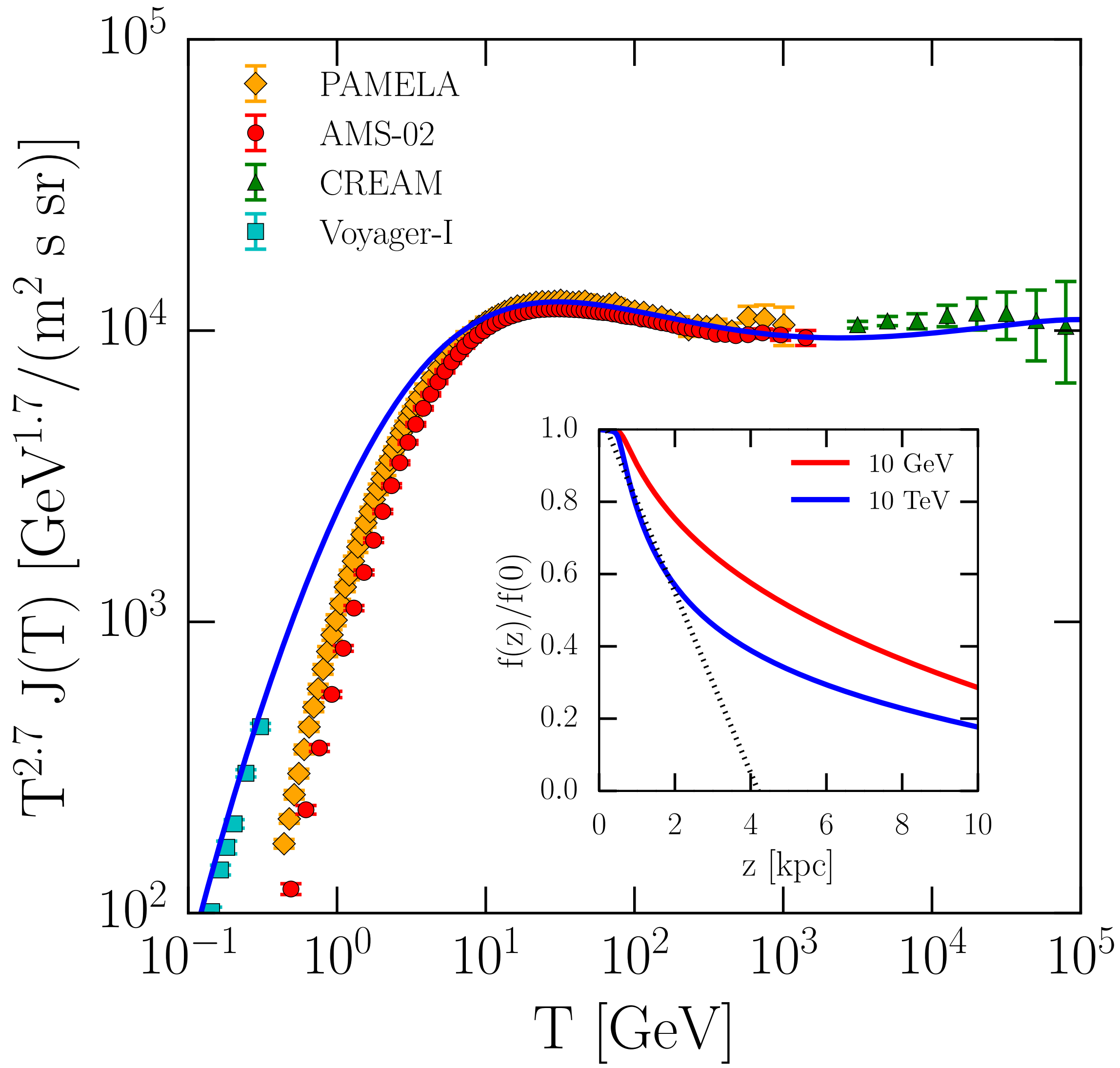
Secondary nuclei, however, probe only few kpc around us.
γ-rays provide a much deeper probe !



PRL 2018

Origin of the Cosmic Ray Galactic Halo Driven by Advected Turbulence and Self-Generated Waves

Carmelo Evoli,[1,2,*] Pasquale Blasi,[1,2,3,†] Giovanni Morlino,[1,2,3,‡] and Roberto Aloisio[1,2,§]



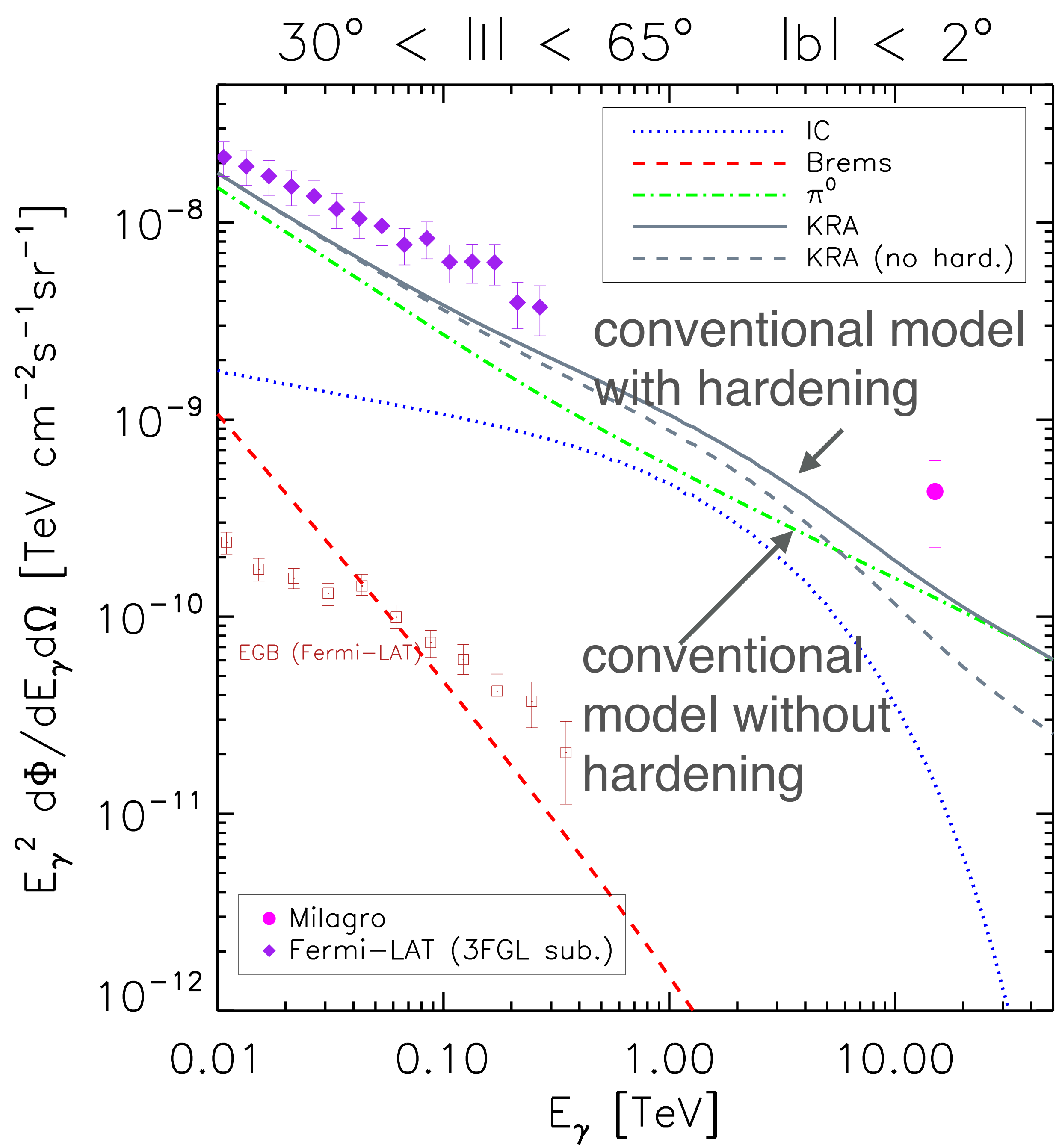
First steps beyond the TeV

a possible solution of the Milagro anomaly

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)



First steps beyond the TeV

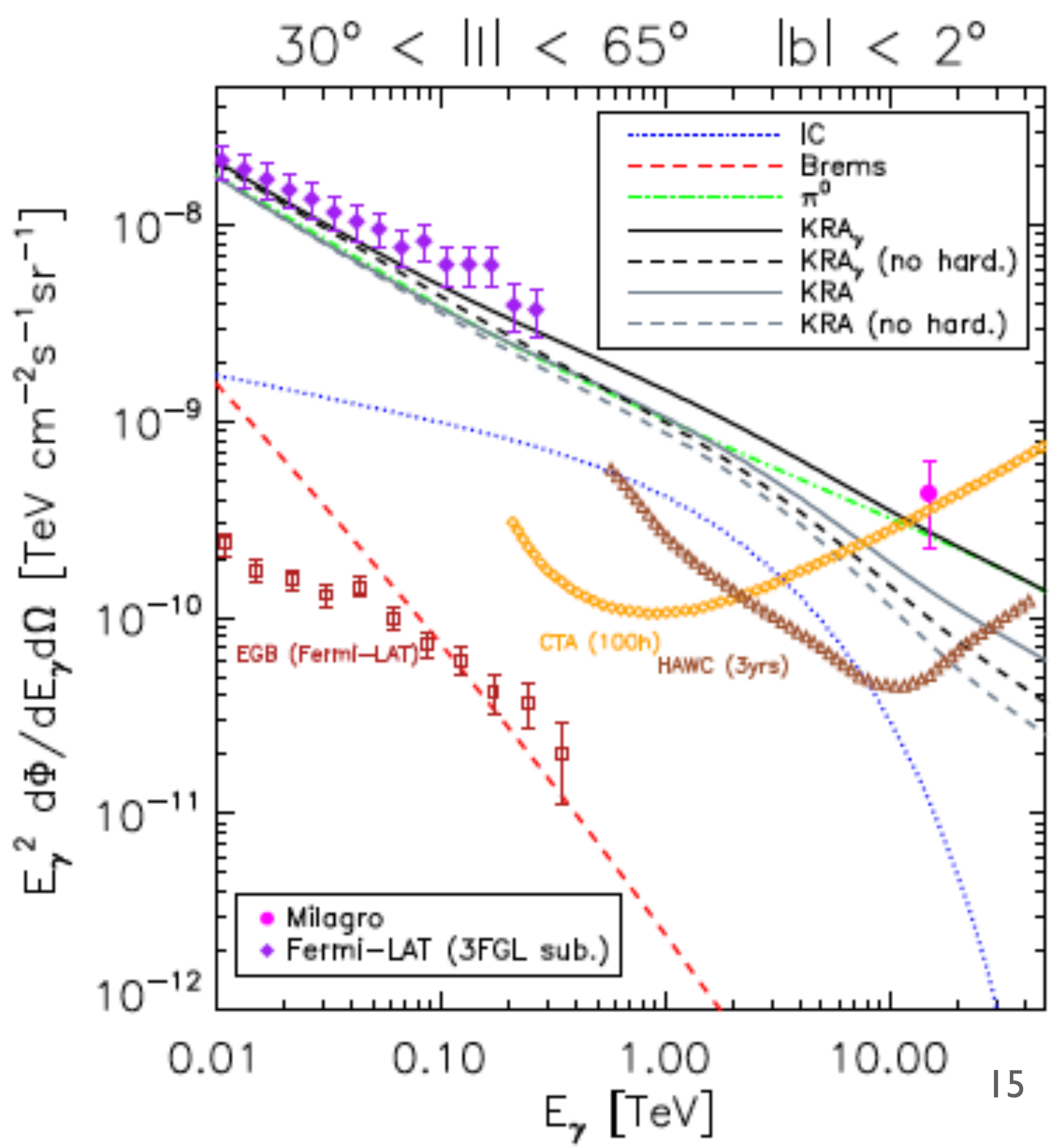
a possible solution of the Milagro anomaly

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

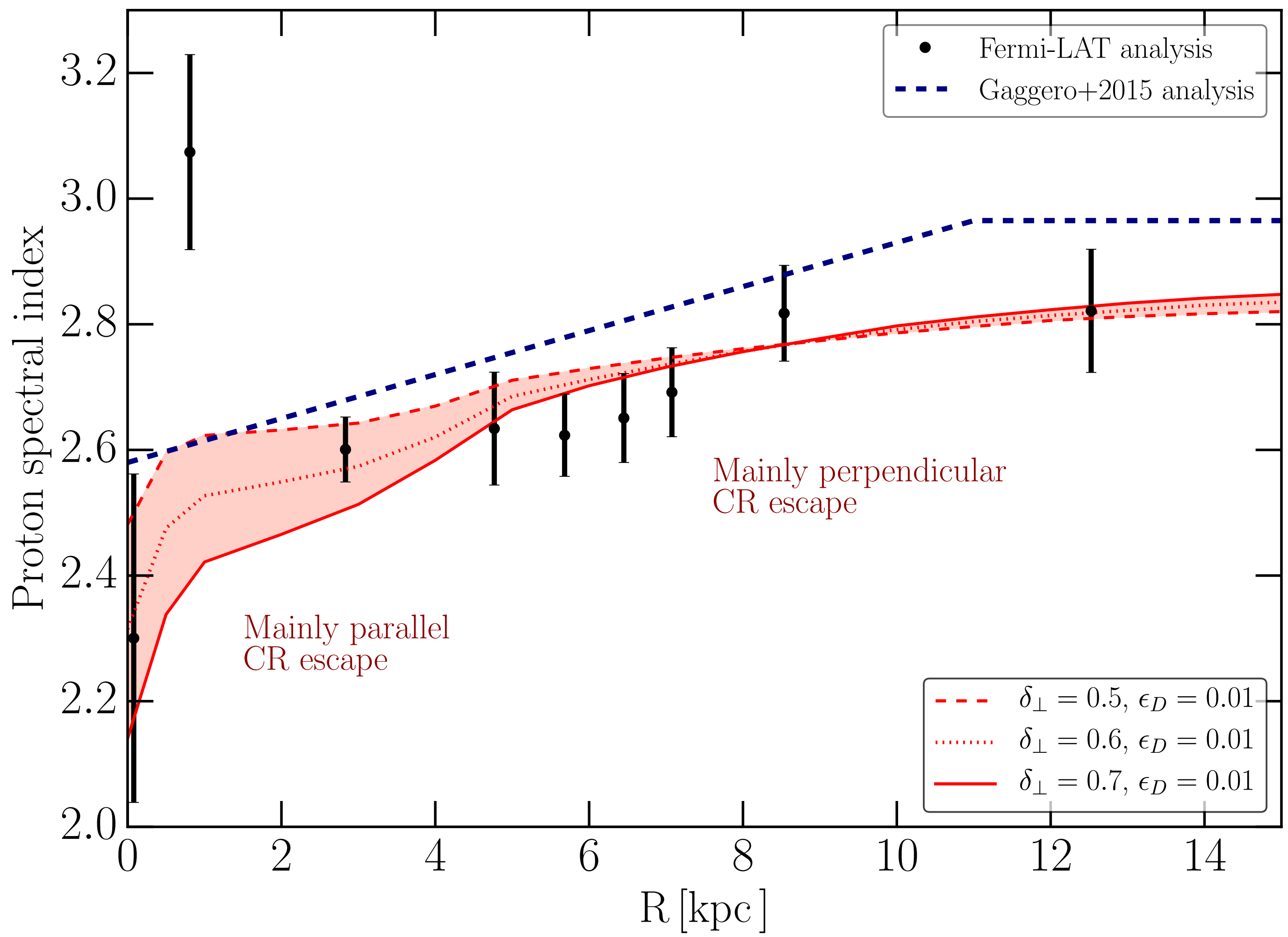
We extended the KRAγ model including the CR spectral hardening assuming it to be present in the whole Galactic plane (**gamma model**)

This allows to match FERMI data and Milagro observed flux @ 15 TeV consistently !

HAWC collaboration will check and extend Milagro results providing a further test of our scenario

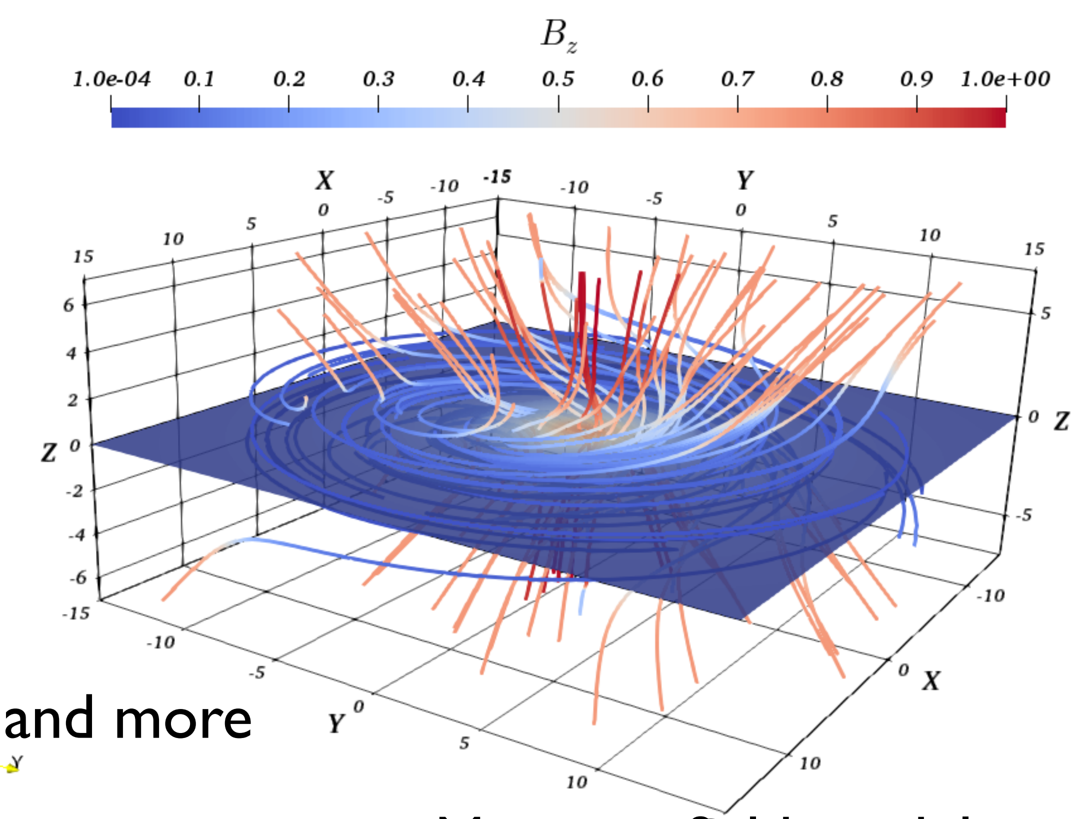


A solution of the spectral index gradient problem based on anisotropic diffusion



Cerri, Gaggero, Vittino, Evoli & DG, 2017

using ***DRAGON 2***



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*

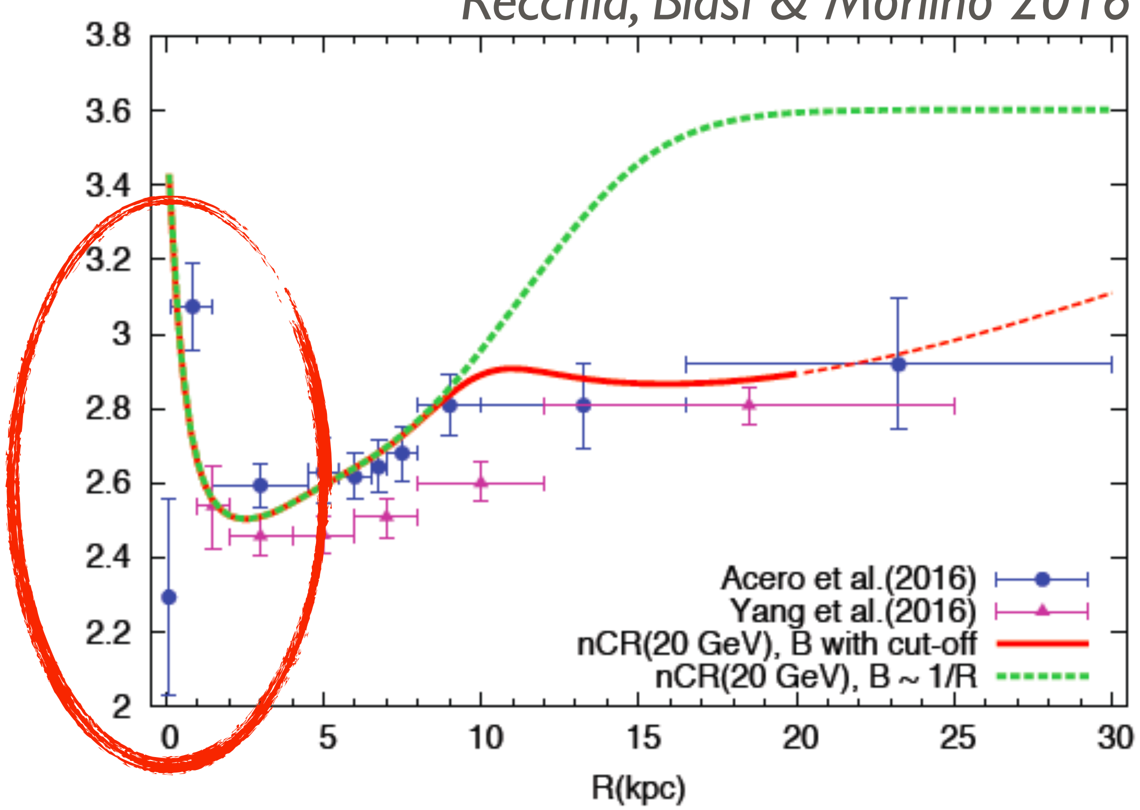
$$D_{||} \propto \rho^{1/3} \qquad D_\perp \propto \rho^{1/2}$$

➜ CR spectrum becomes harder for R ➜ 0. The effect holds at large energies

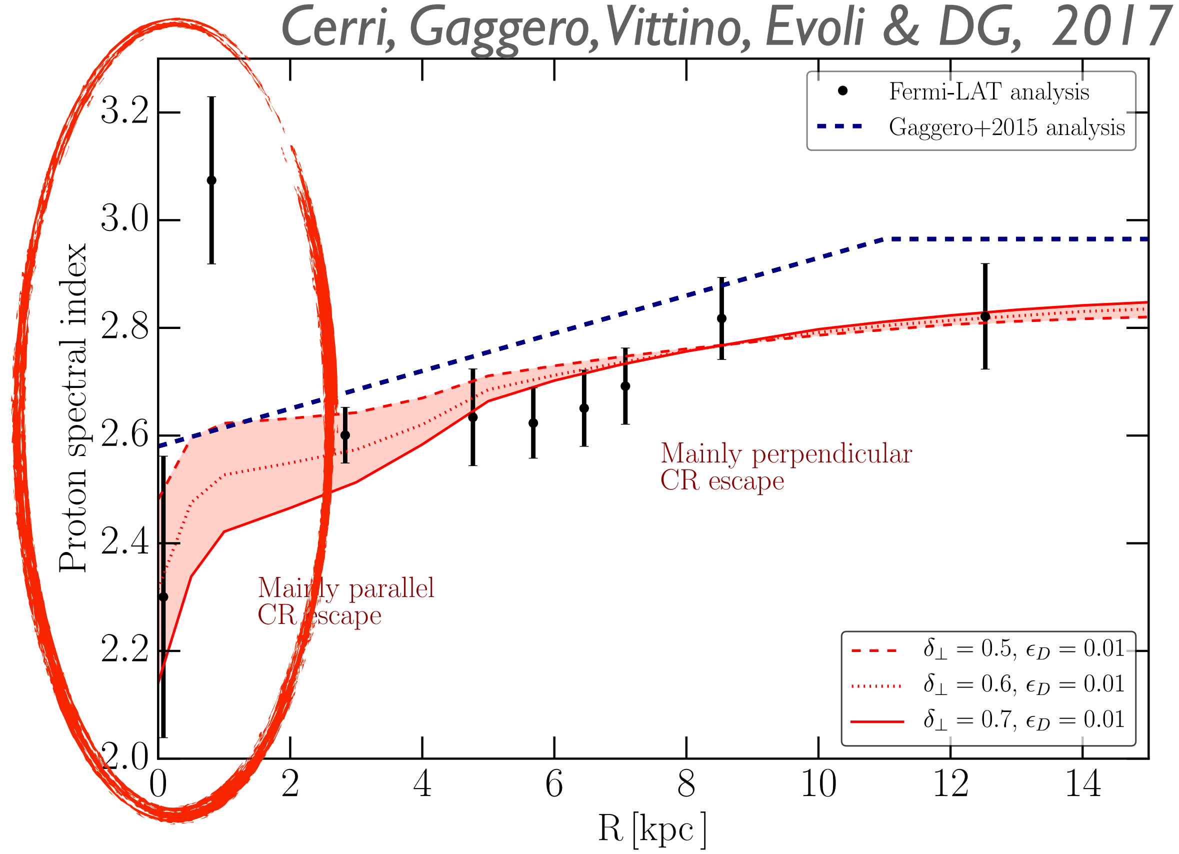
Relevance of / implications for the Galactic Center diffuse emission

- To understand CR propagation/γ-ray diffuse emission in that region is crucial for DM indirect search and to interpret Fermi bubbles
- The GC is one of the few regions where the diffuse emission spectrum was measured up to tens of TeV
- Different interpretations of the spectral index gradient predicts different γ-ray spectra at the GC

Recchia, Blasi & Morlino 2016



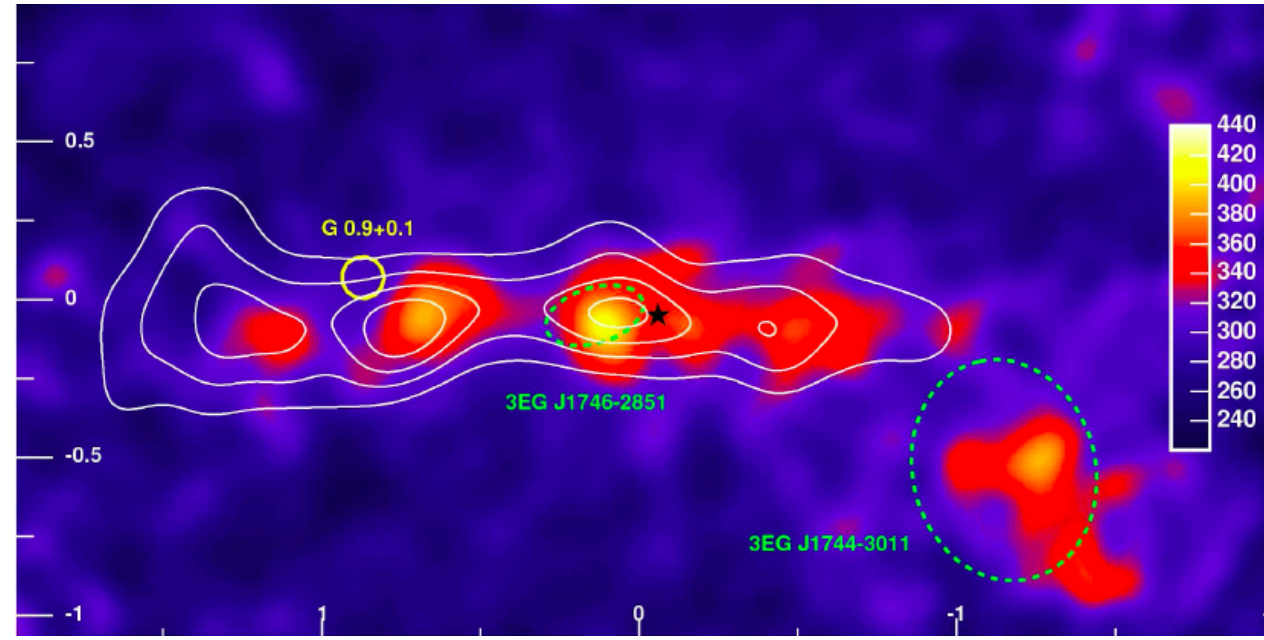
Cerri, Gaggero, Vittino, Evoli & DG, 2017

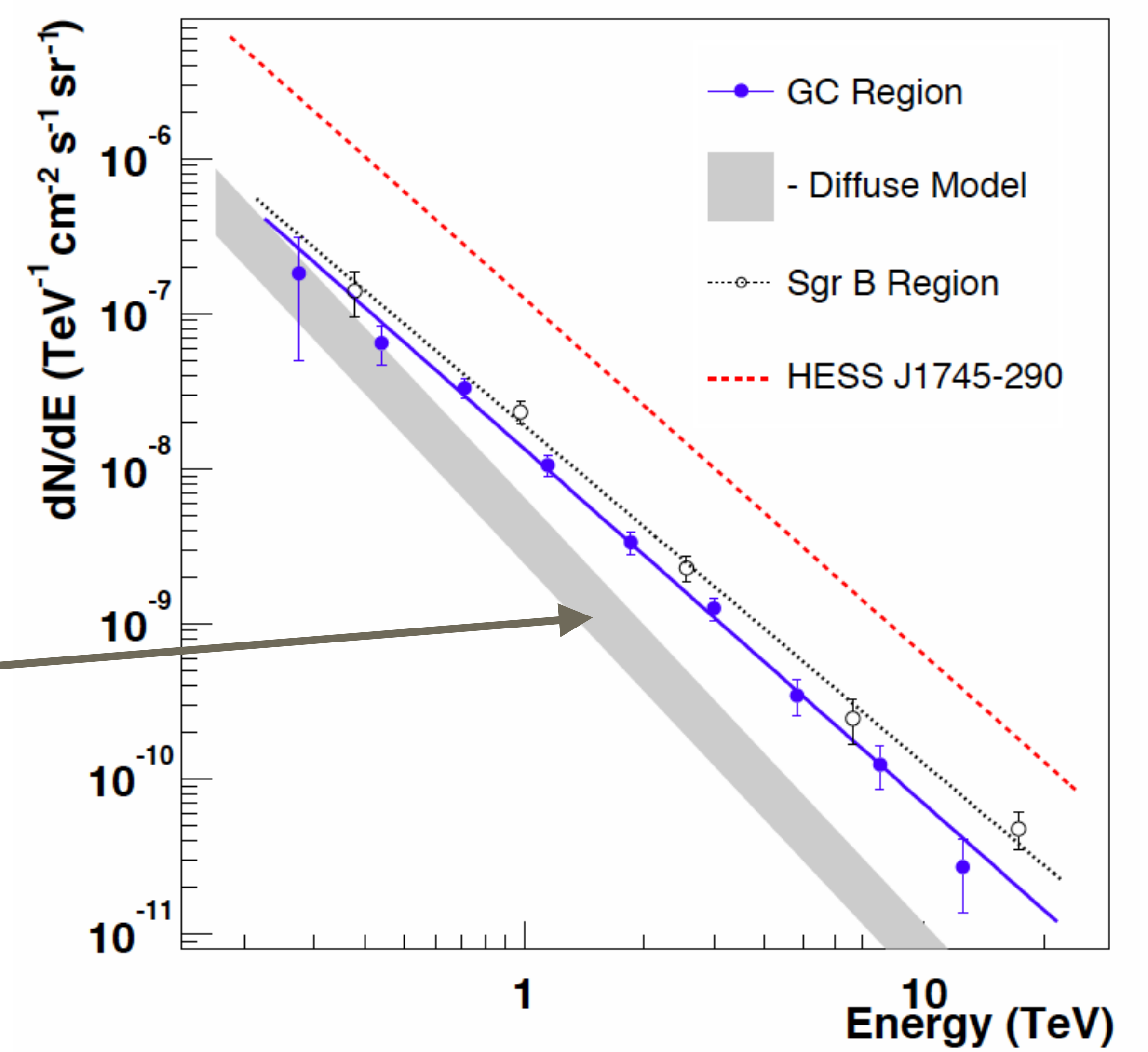


The Galactic center TeV excess

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

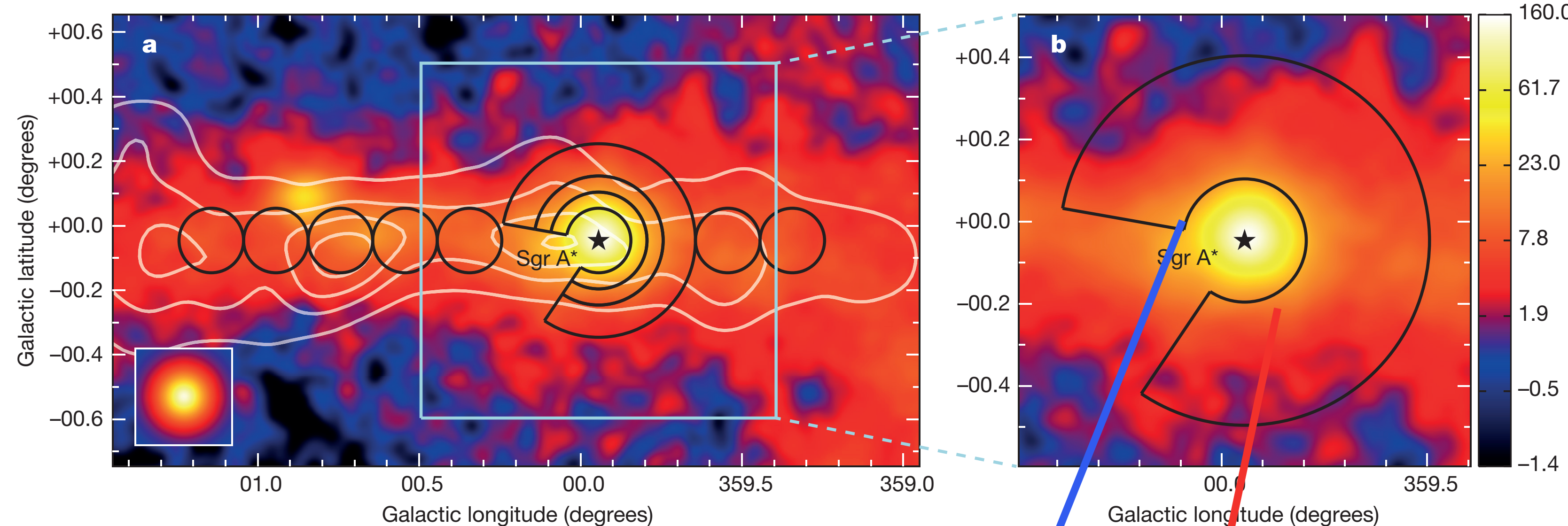




The Galactic center TeV excess

10 years later ….

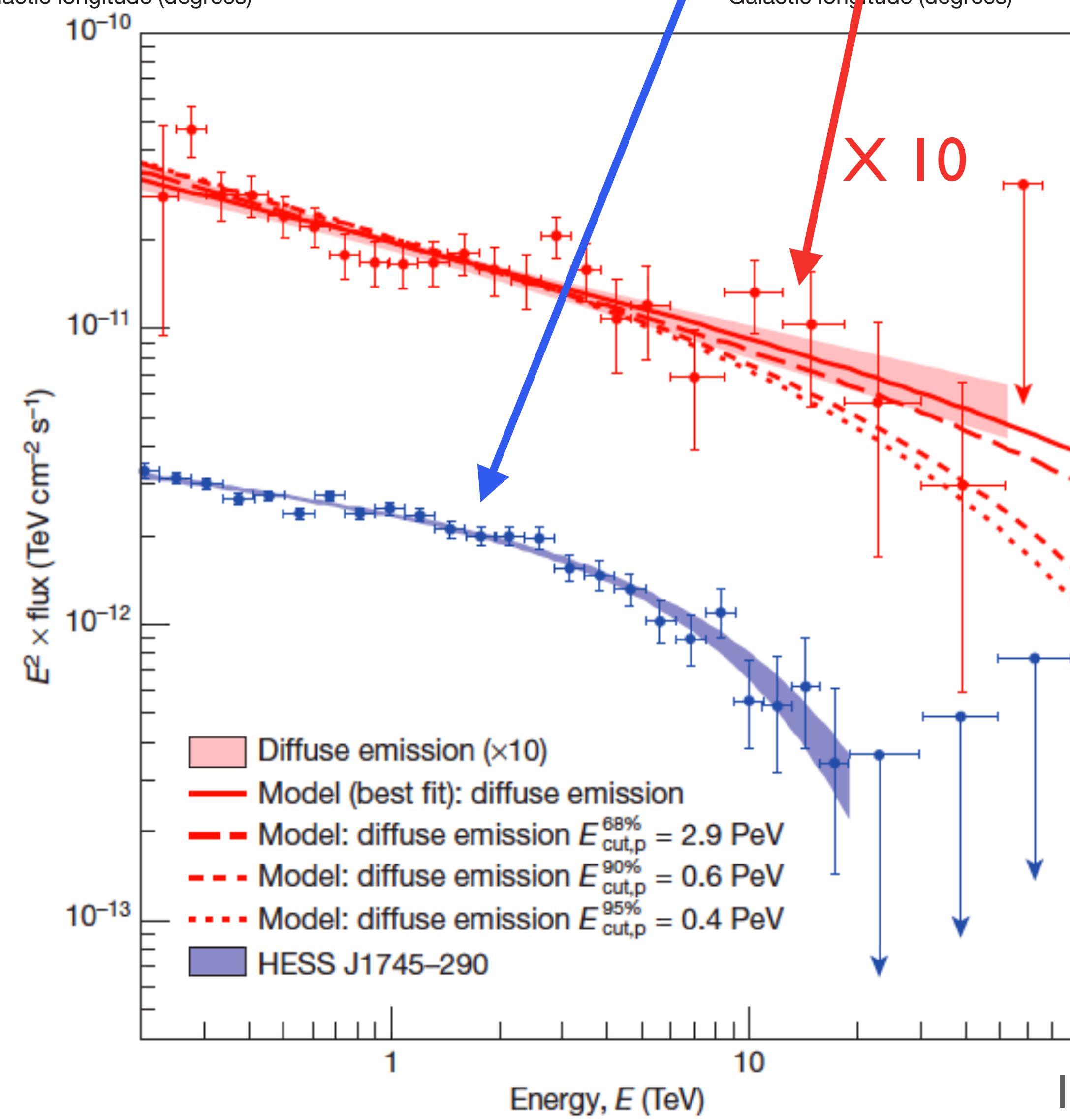
H.E.S.S. Nature 2016



- the diffuse emission around J1745-290 (positionally compatible with SgrA*) extends up to ~ 50 TeV ➡ **CR protons up to ~ PeV**

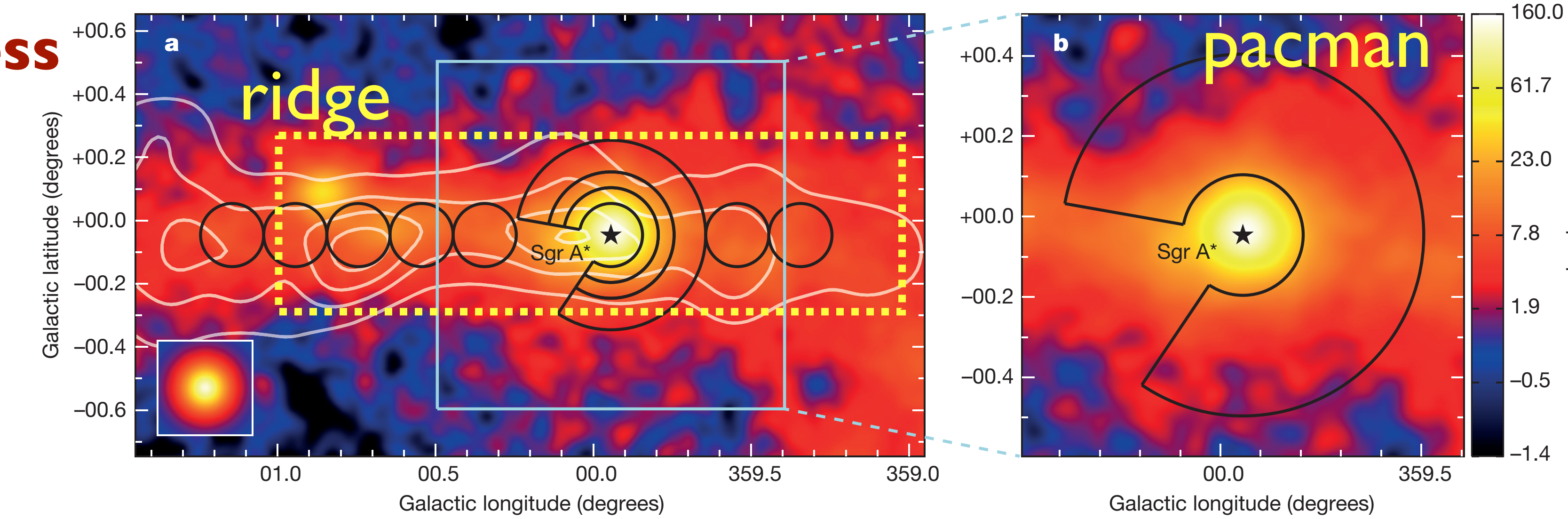
- same spectrum of the point source J1745-290 which however display at cutoff @ ~ 10 TeV. Very strong attenuation required around it !! *See e.g. S. Celli et al. 2016*

- leptonic emission (IC) cannot match the observed spectrum due to strong losses



The Galactic center TeV excess

Nature 2016 + A&A 2018



Same spectra in the ridge

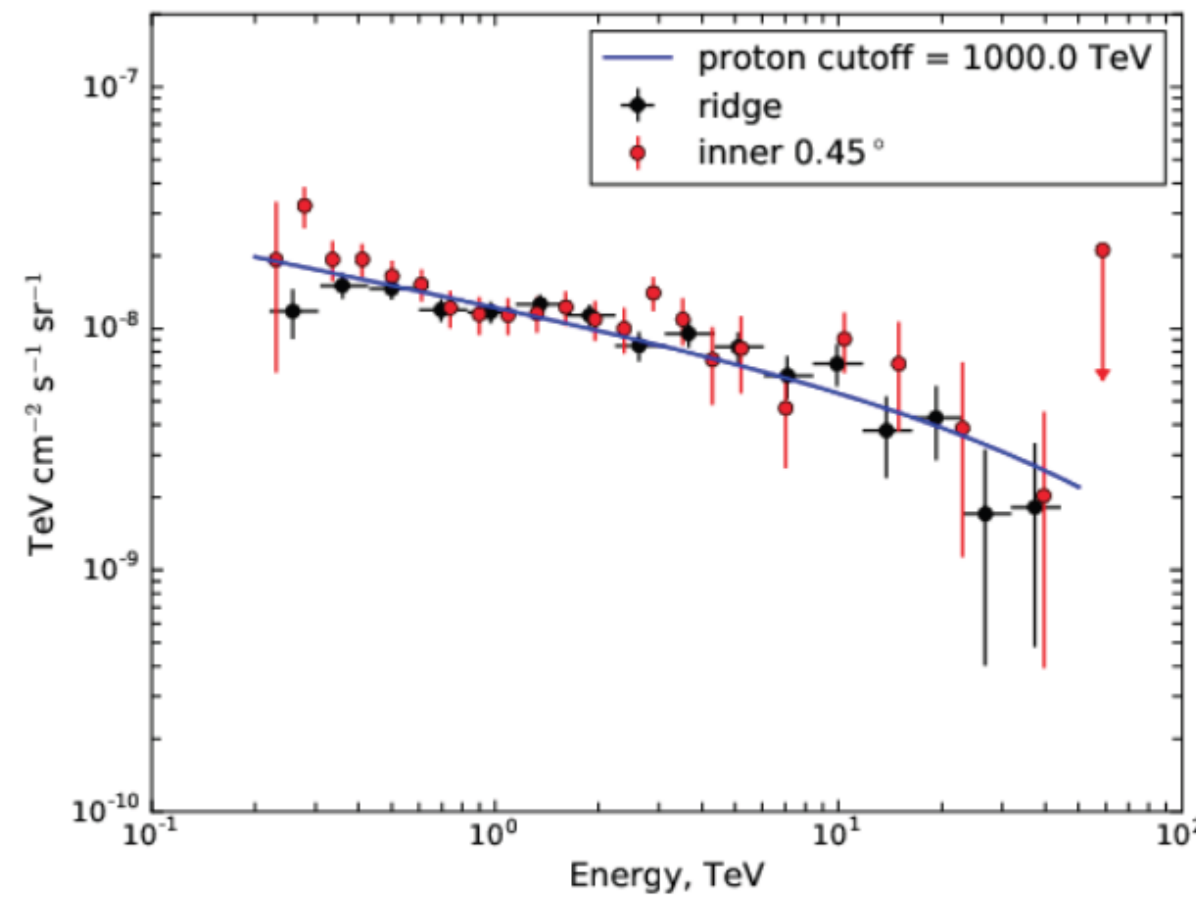
$(\,|\, l \,|\, < 1° \,, |\, b \,|\, < 0.3° \,), \; d < \; 150 \; pc$

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

and in the "*pacman*"

$0.15° < \; \theta \; < \; 0.45° \;\;, \; 22 < d < 67 \; pc$

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



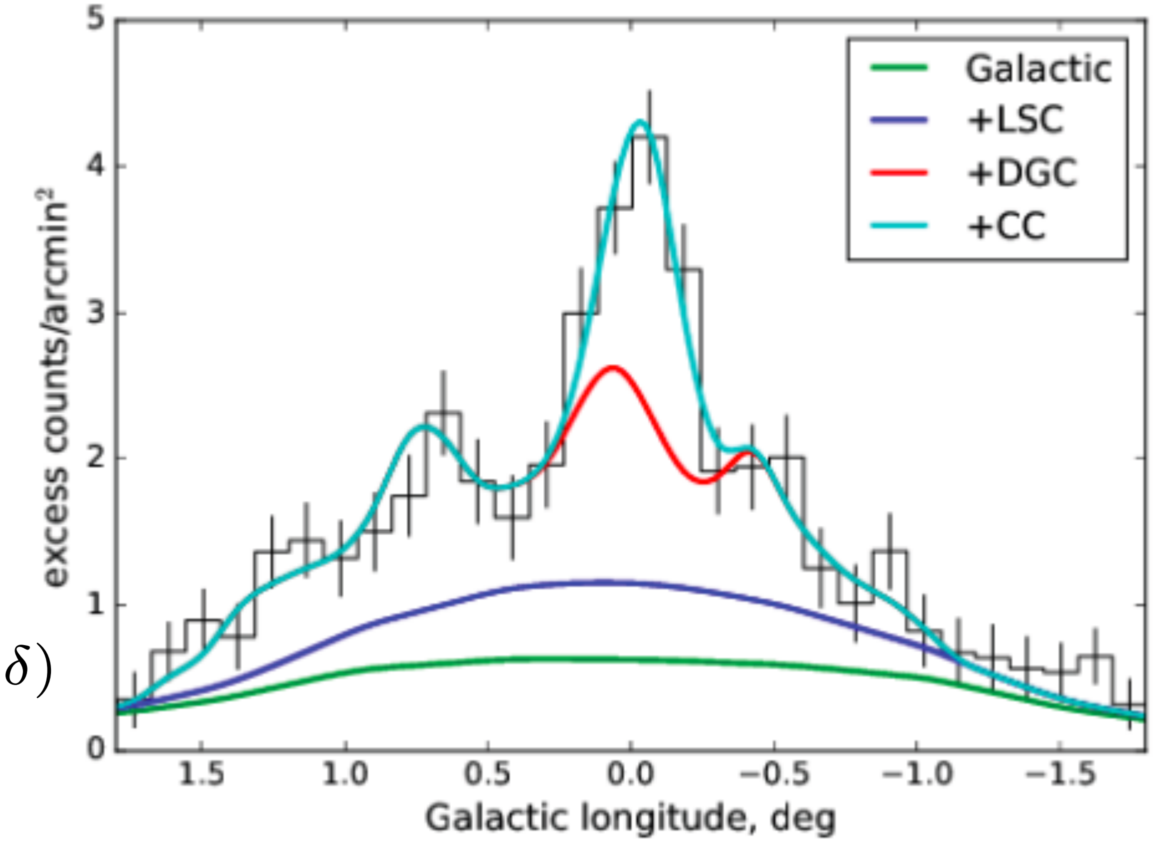
The PeVatron scenario

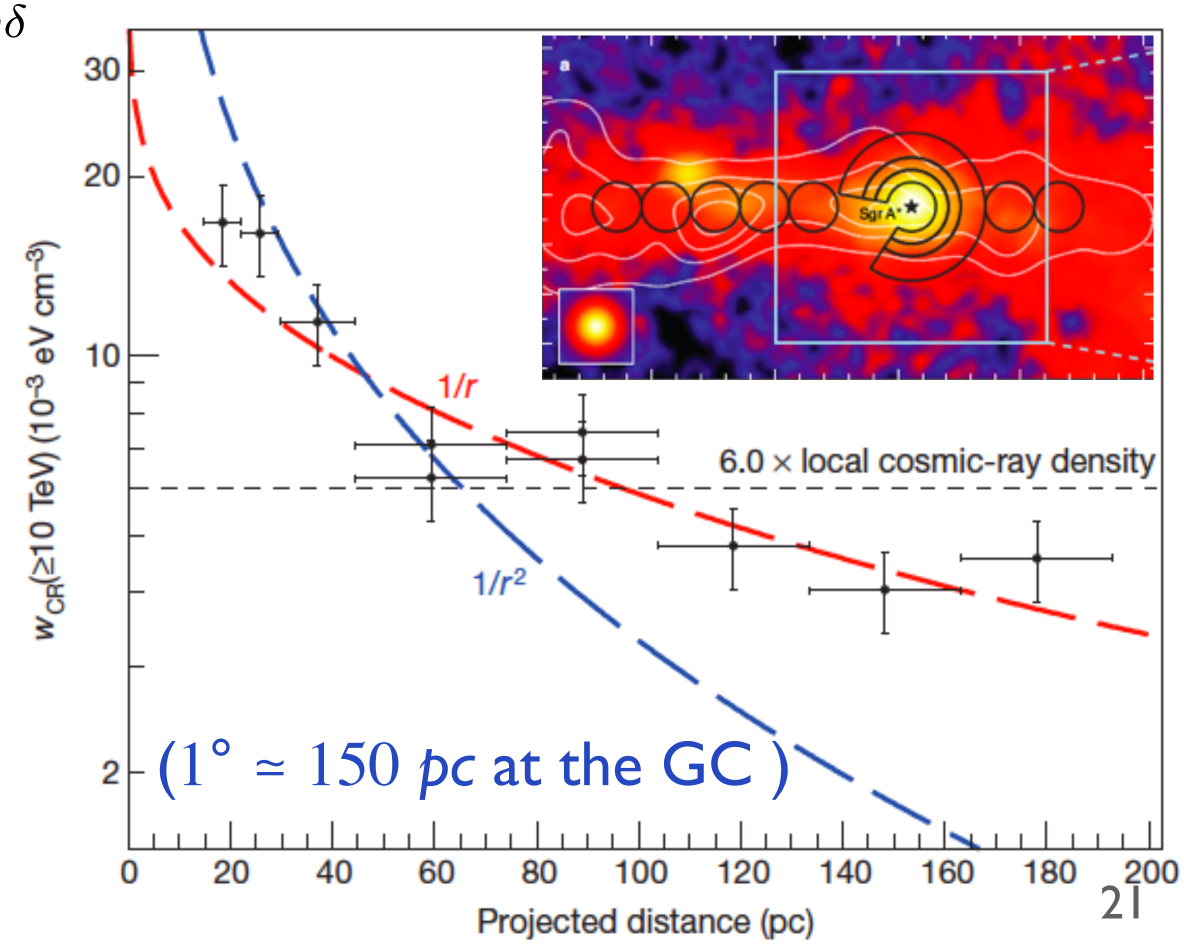
H.E.S.S. Nature 2016 + *A&A 2018*

At the GC the emission profile seems more peaked than the estimated gas distribution. The inferred CR density profile is consistent with that expected from CR diffusing out a stationary source.

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

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





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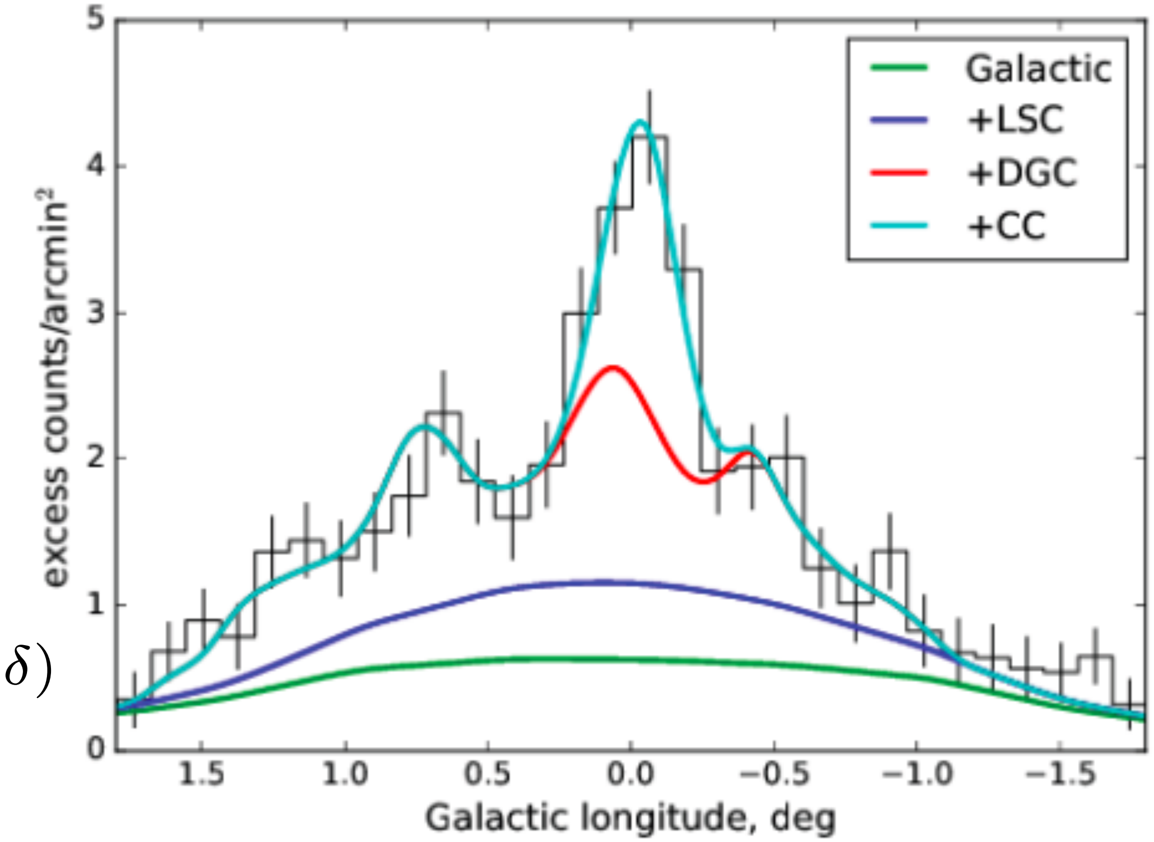
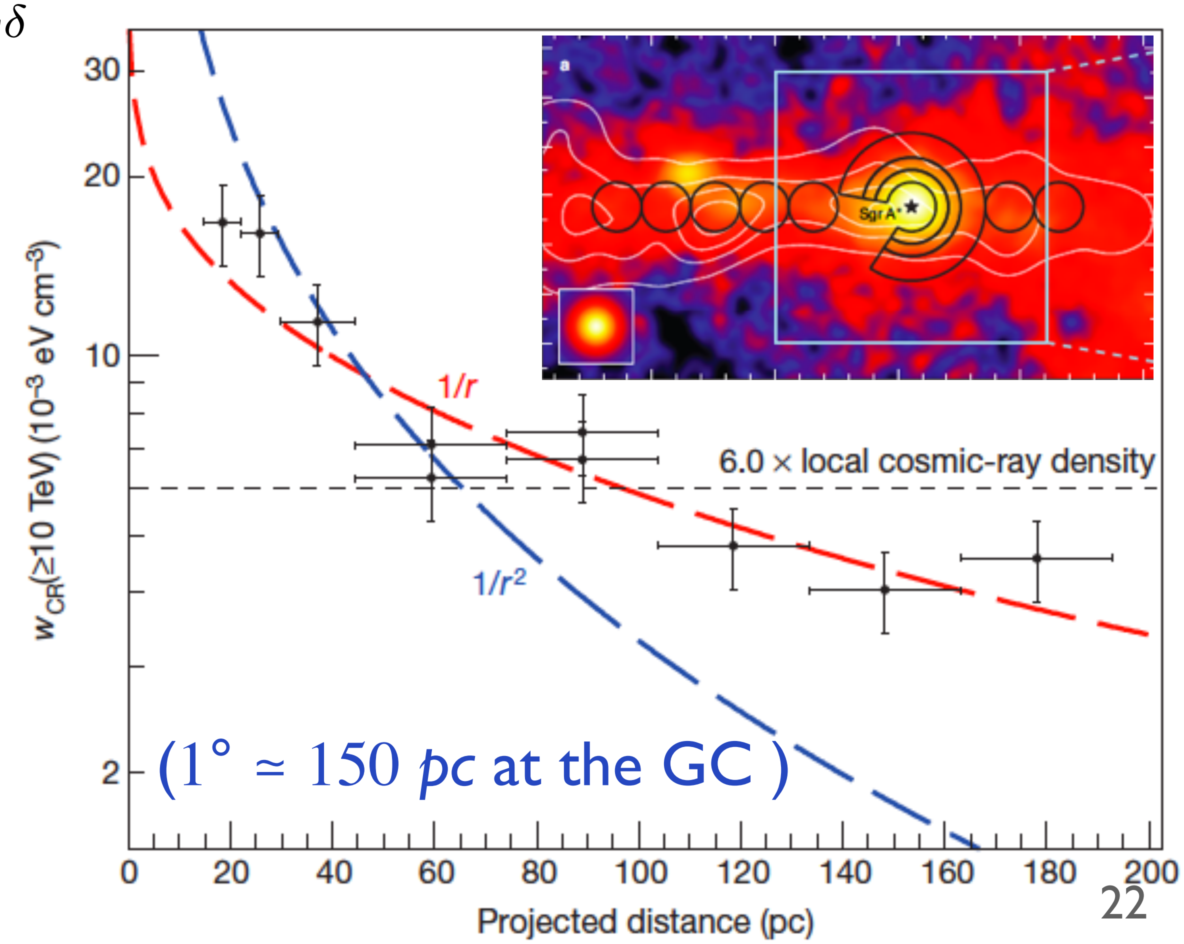




Possible loopholes:

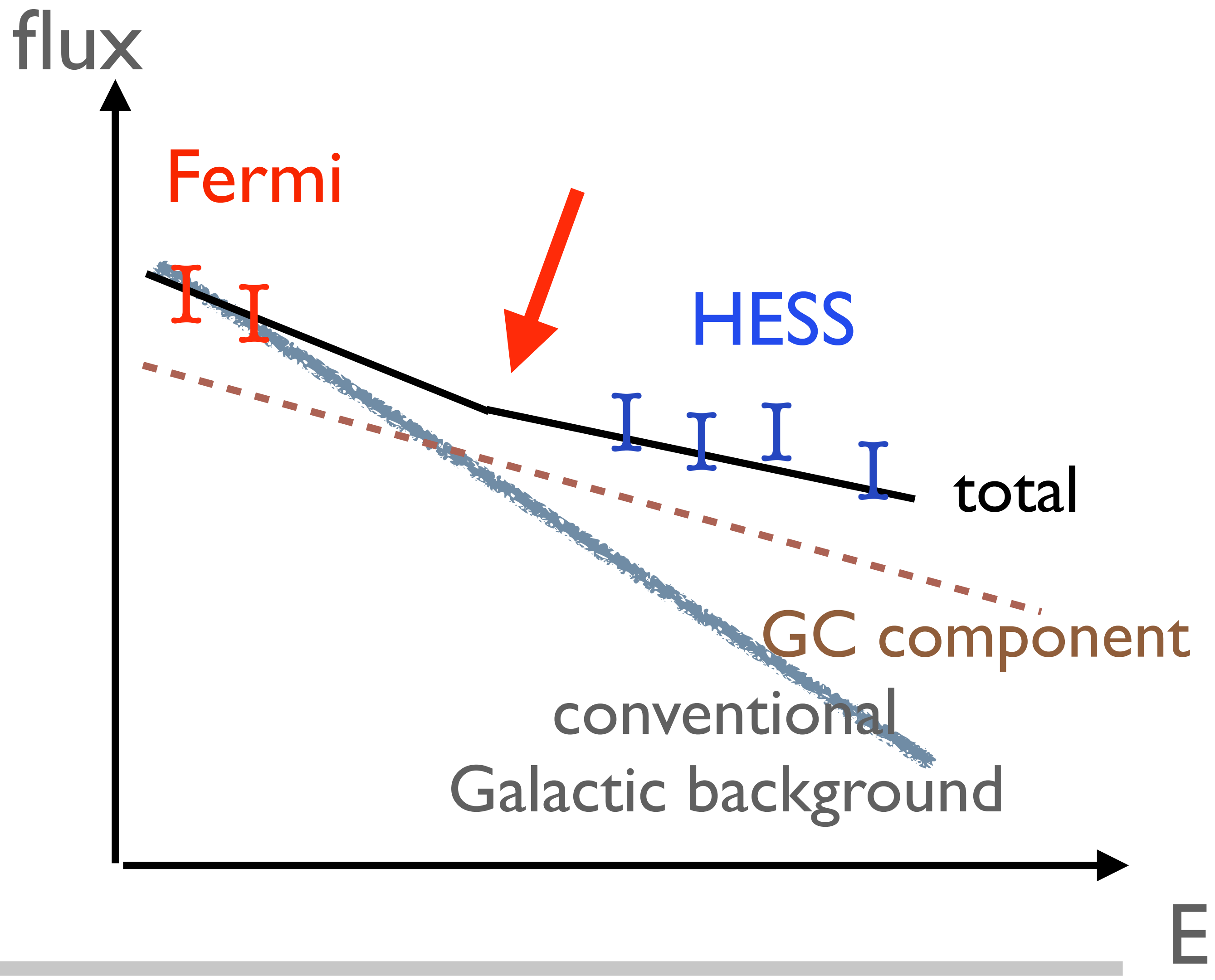
- the H_2 tracer's emission (CO, CS .. lines) may be absorbed in high density clouds
- only the projected distance from the GC is observed. HESS collaboration assumes a uniform gas density along the line of sight. This may give rise to a bias.

Extending the energy interval:
the role of 10 years of Fermi-LAT data

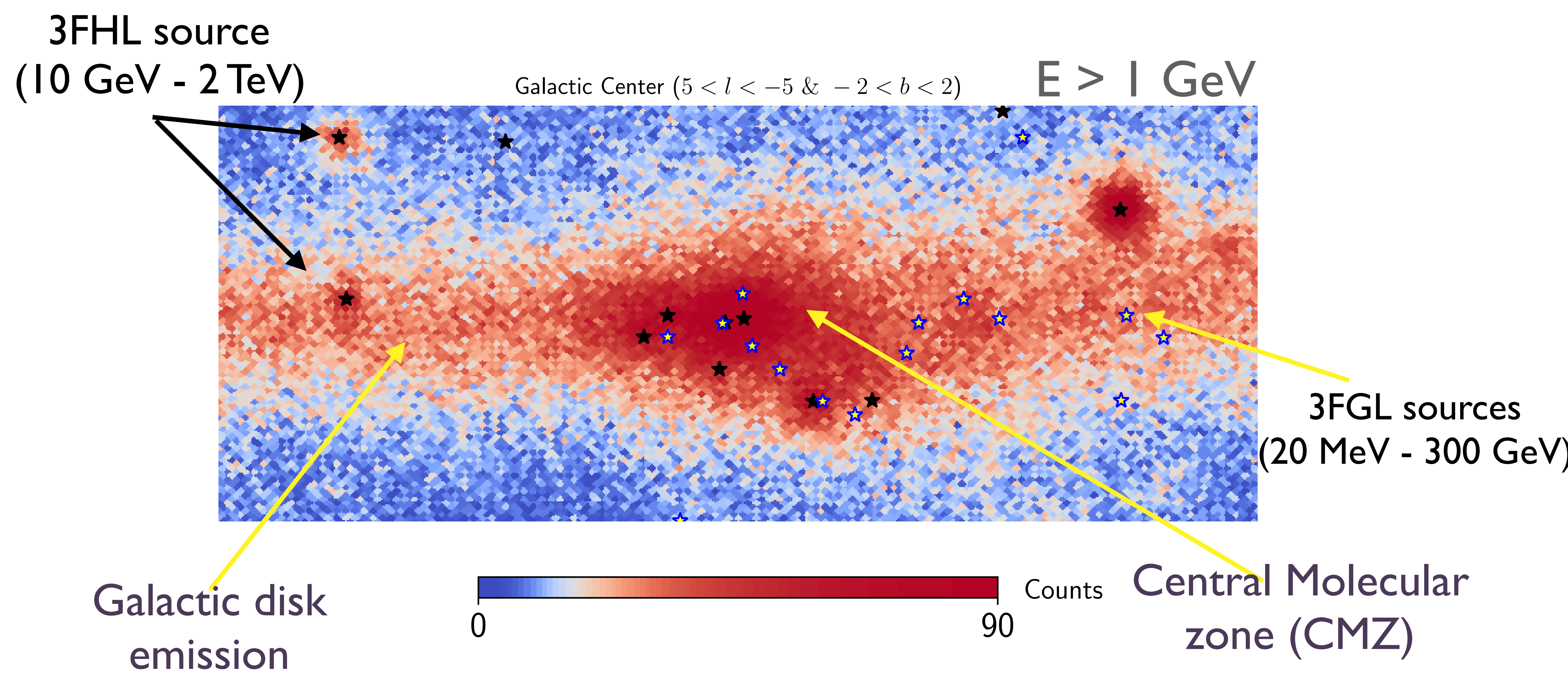
- The morphology of the emission may be different at different energies for non stationary sources

- In the conventional scenario the presence of a hard component taking over the softer large scale Galactic CR sea should give rise to a **spectral feature**

  keep in mind that below 10 GeV the diffuse emission measured by Fermi data agrees with what expected from a uniform CR sea



The Fermi counts from the central kpc of the Galaxy



The emission is clearly dominated by the CMZ !

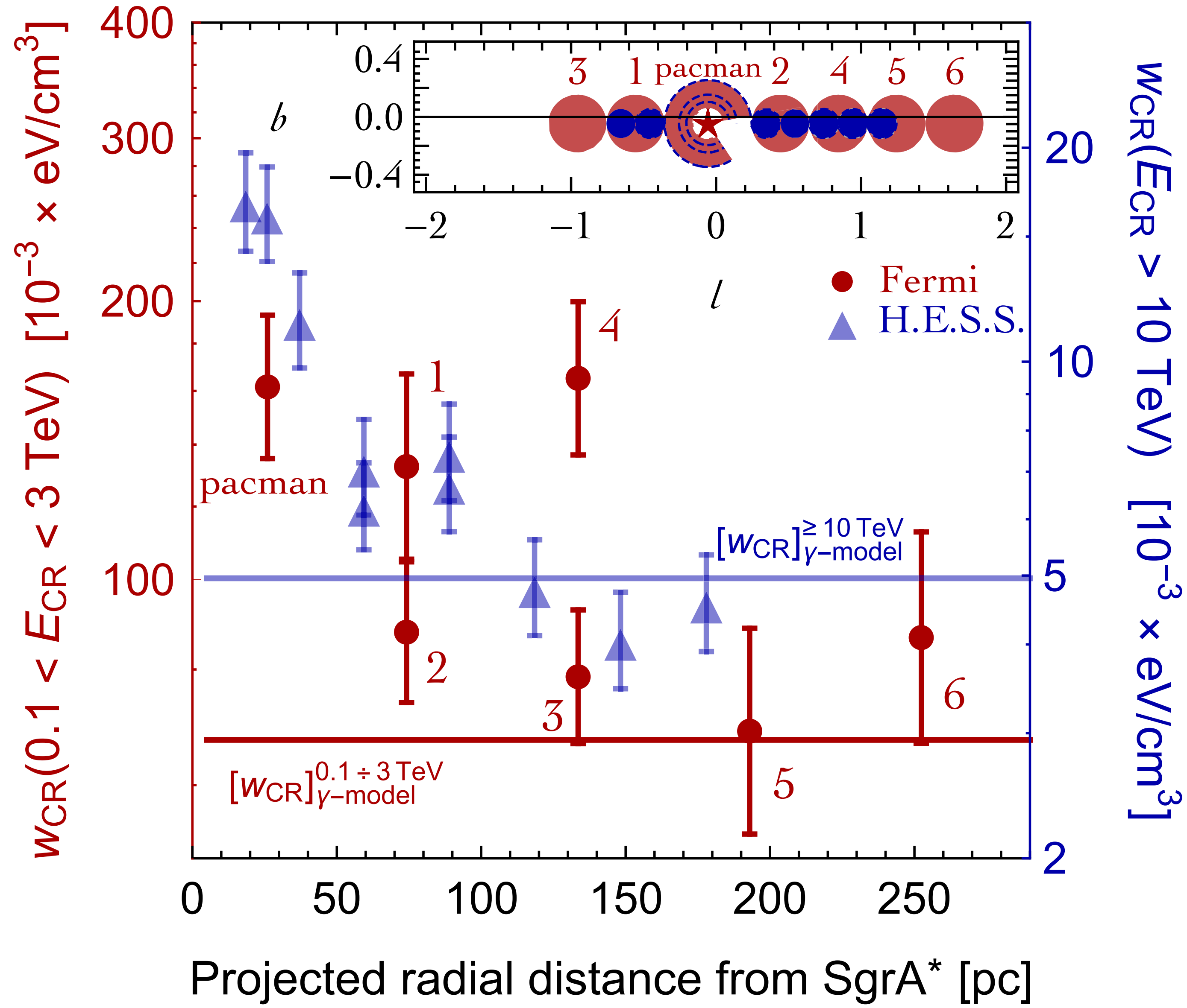
The CR energy density radial profile from HESS and FERMI

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

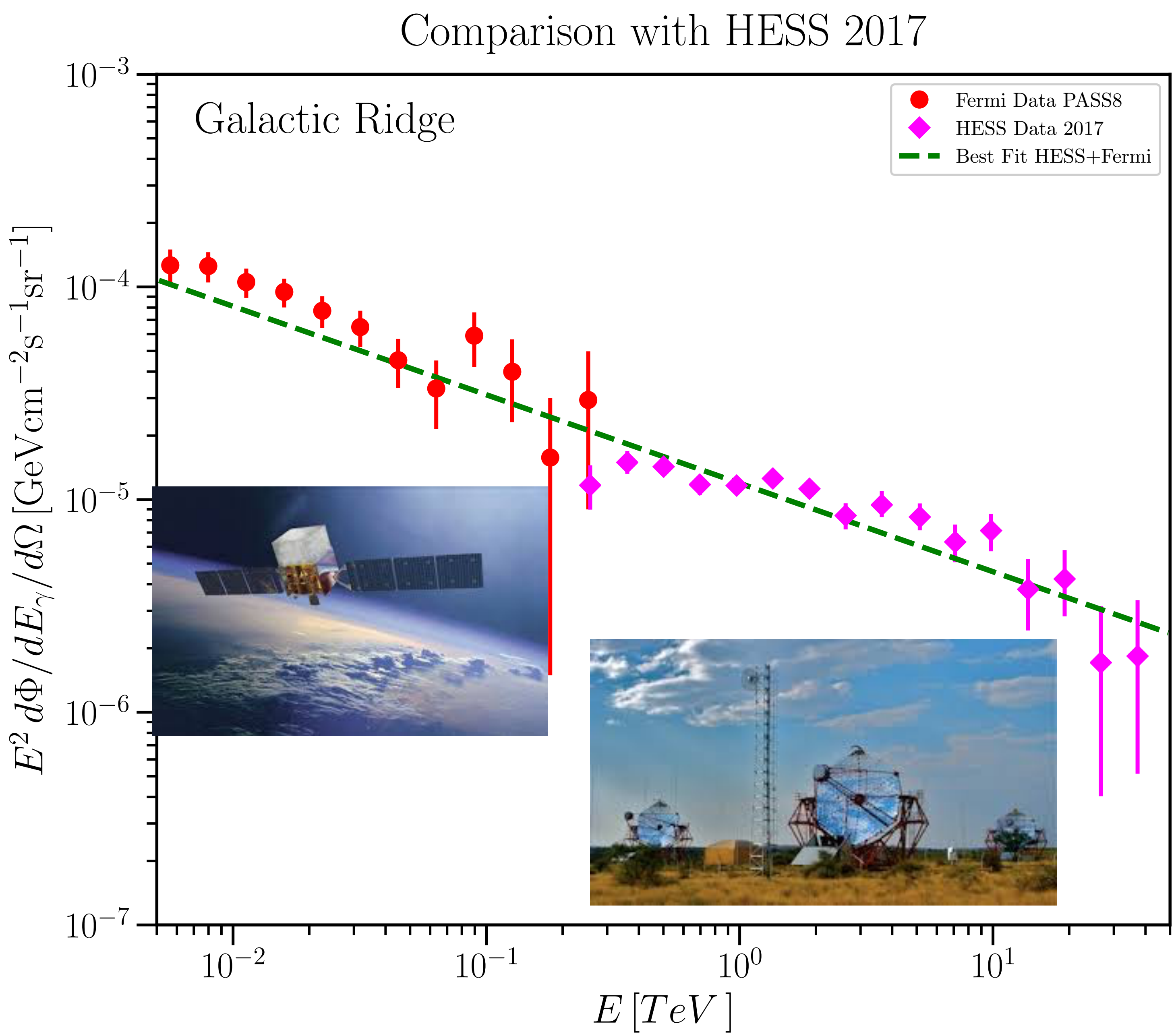
Good agreement with the **gamma model** for R > 50 pc consistent with an almost uniform CR density outside that region

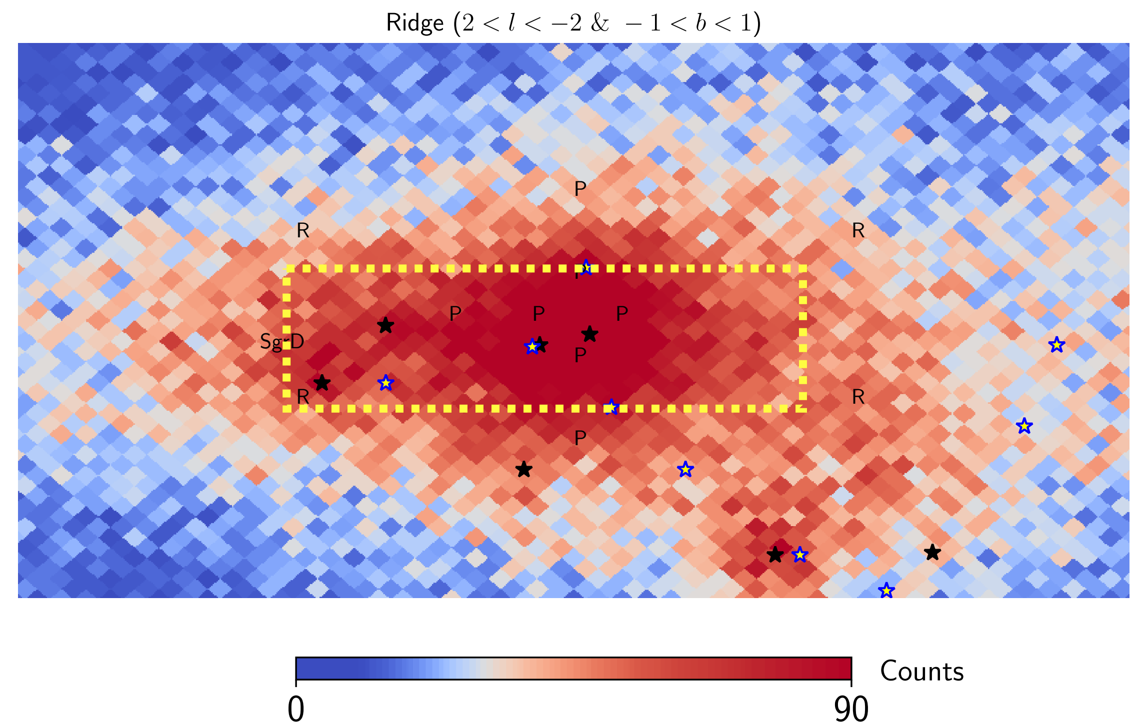


The diffuse emission spectrum of the GC from H.E.S.S. + Fermi-LAT

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

“ + S.Ventura (ICRC 2017)





$|l| < 1°, |b| < 0.3°$

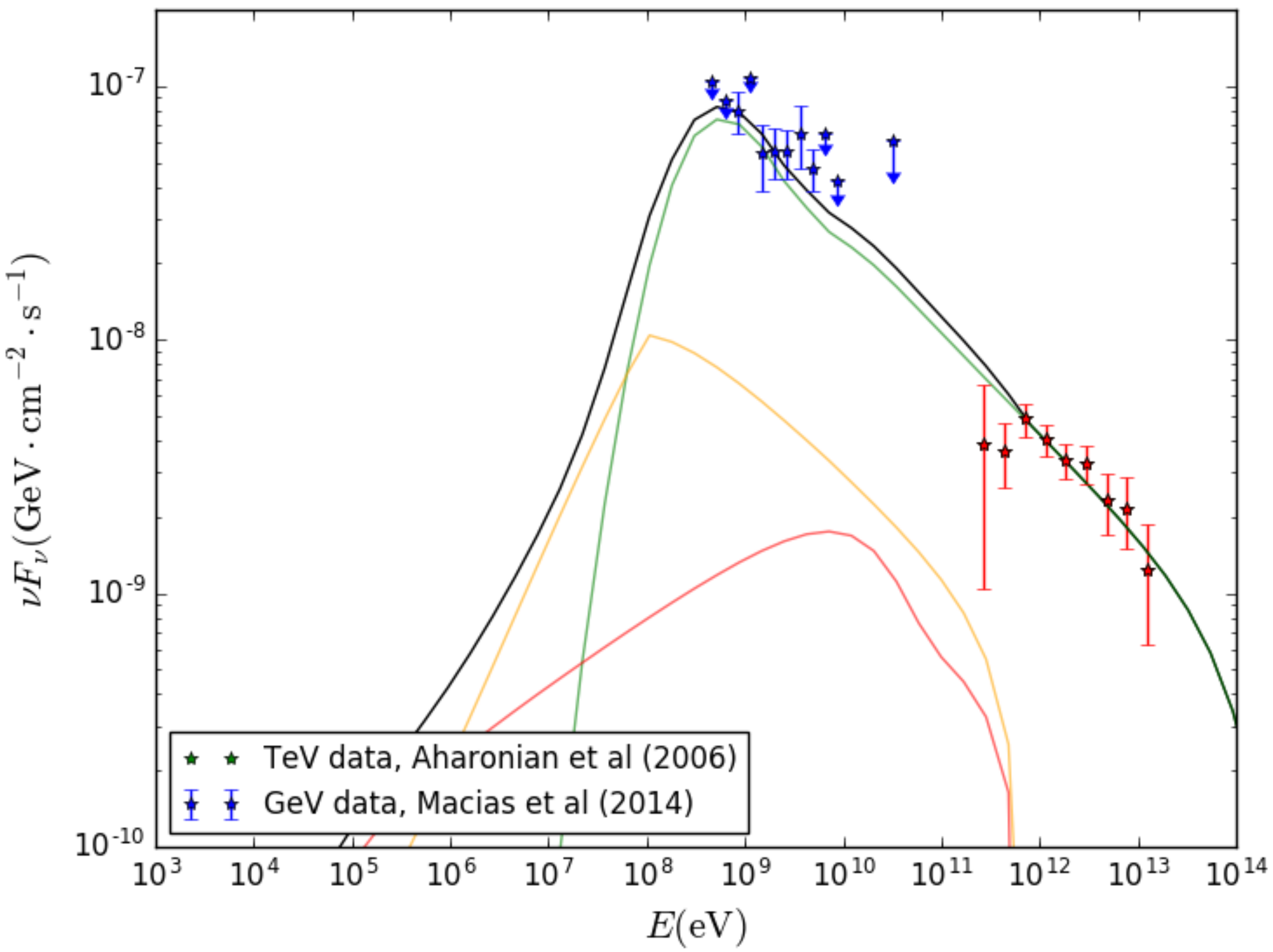
PASS8 Fermi-LAT 470 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FGL catalogue subtracted.

- - - - - - single power-law fit

$\Gamma_{\mathrm{HESS + FERMI}} = -2.41 \pm 0.02$

The diffuse emission spectrum of the GC before 2016

Jouvin et al. 2017



The CR sea emission against FERMI + HESS at the GC

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

"   + S.Ventura (ICRC 2017)

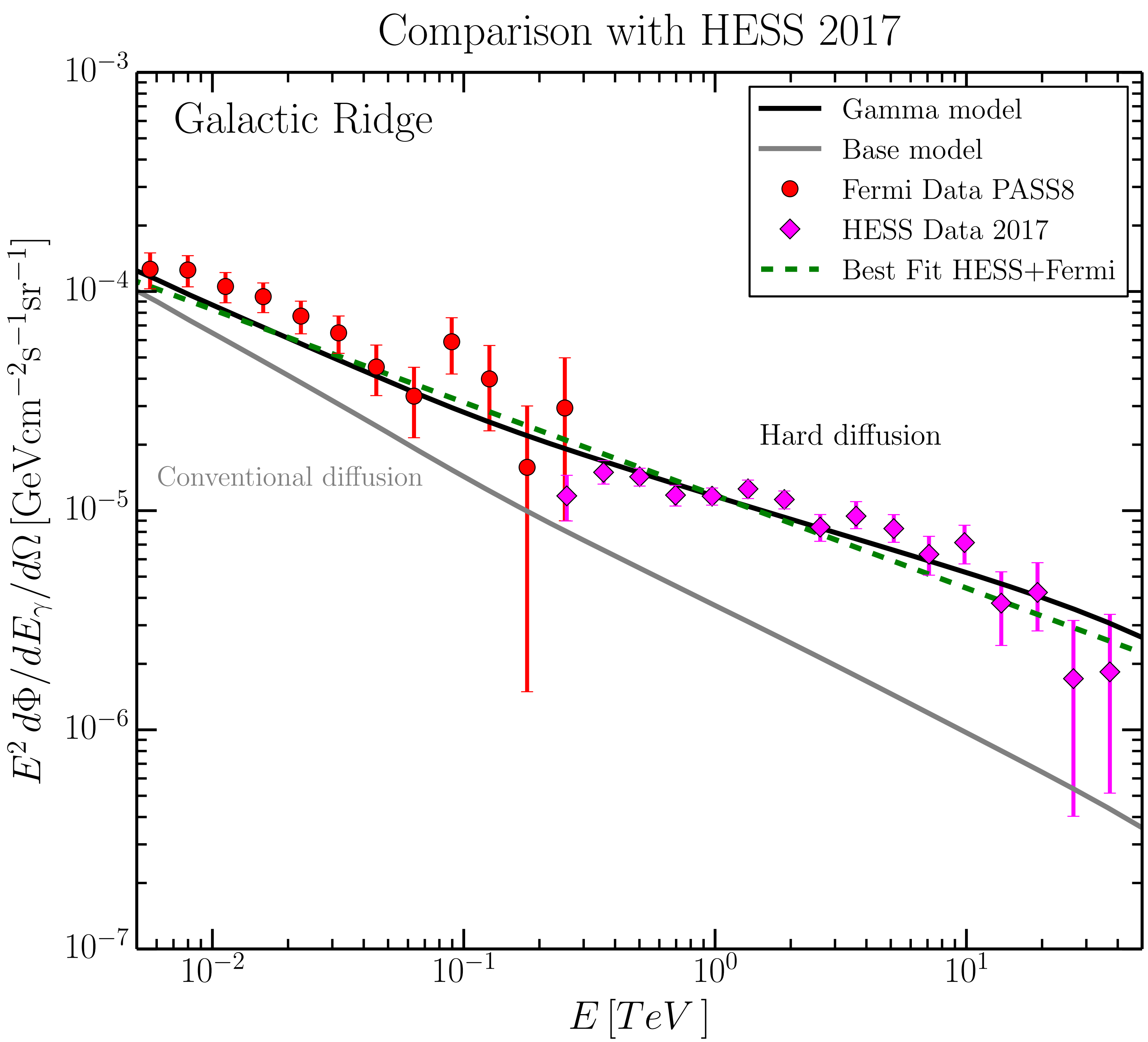
| l | < 1° , | b | < 0.3°

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

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

for the Case & Bhattacharya (1998) source distribution

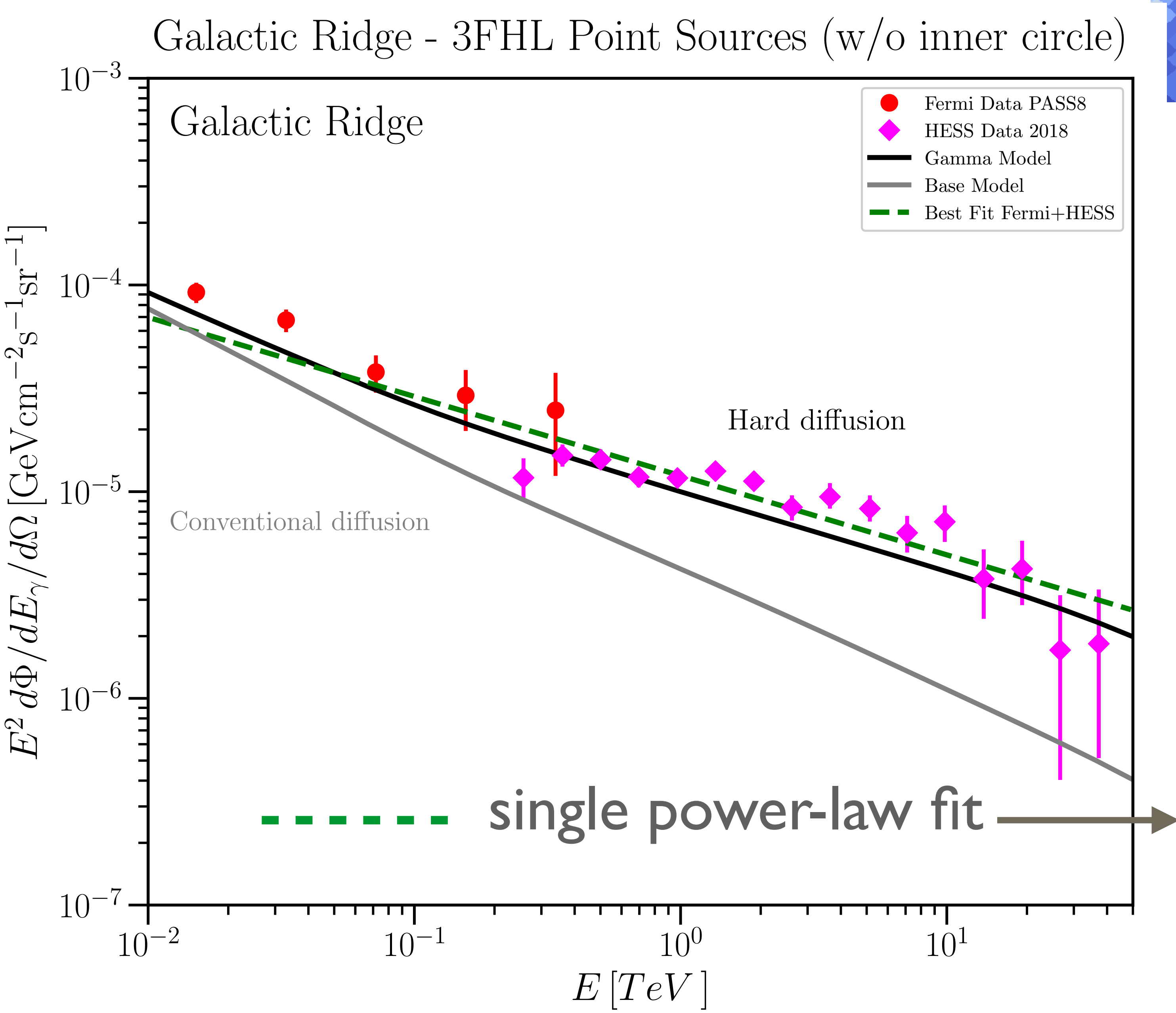
The same model solving the Fermi spectral index gradient problem and matching Milagro (gamma model) reproduces FERMI + HESS data in the ridge and inner region

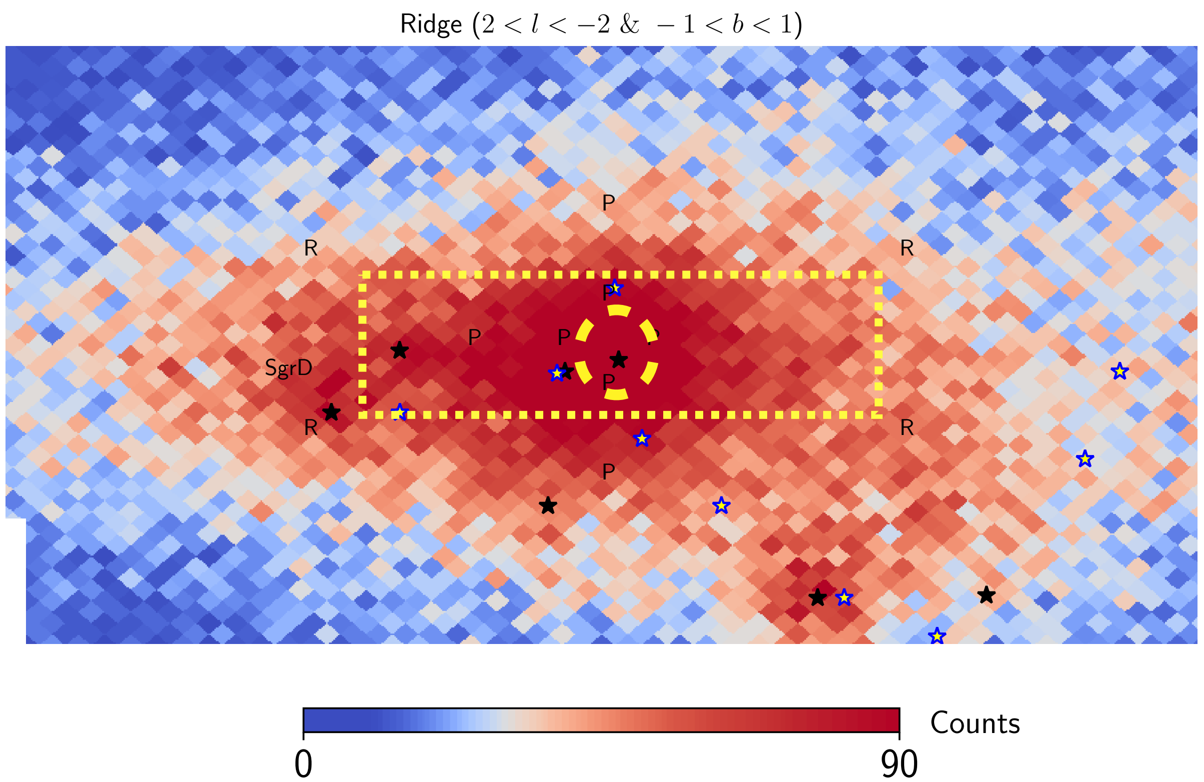


Recent updates

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.

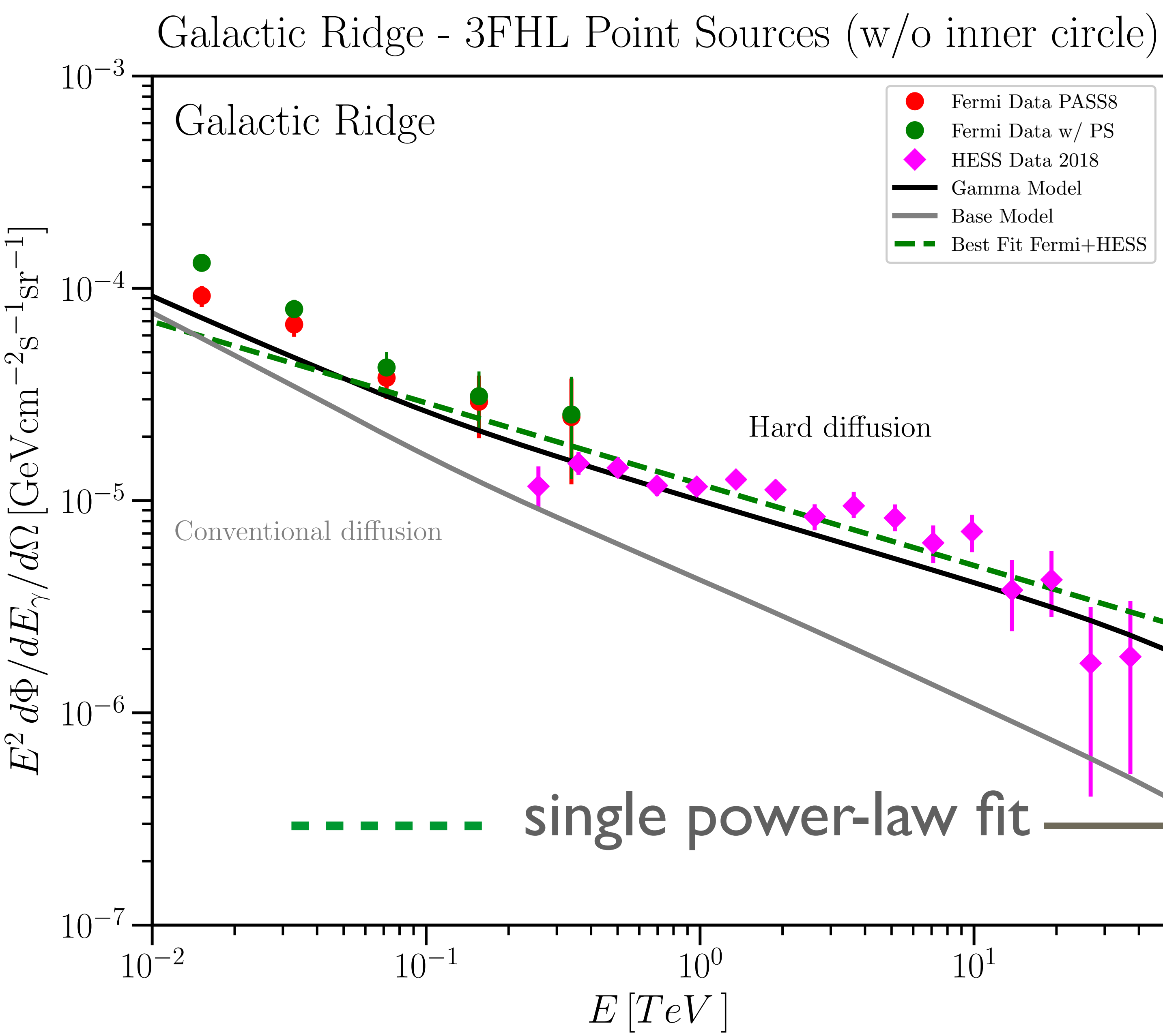
$\Gamma_{\mathrm{HESS\,+\,FERMI}} = 2.43 \pm 0.03$

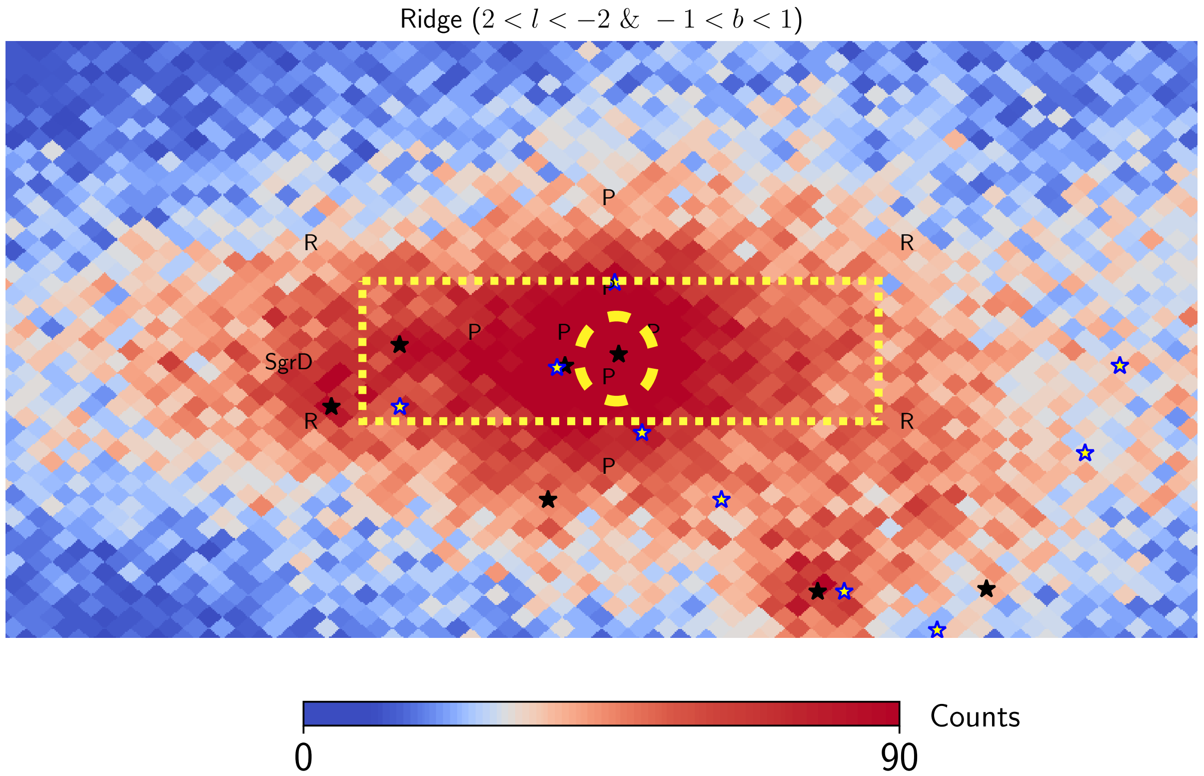
this implies Γ ~ 2.5 for primary protons

Recent updates

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

preliminary





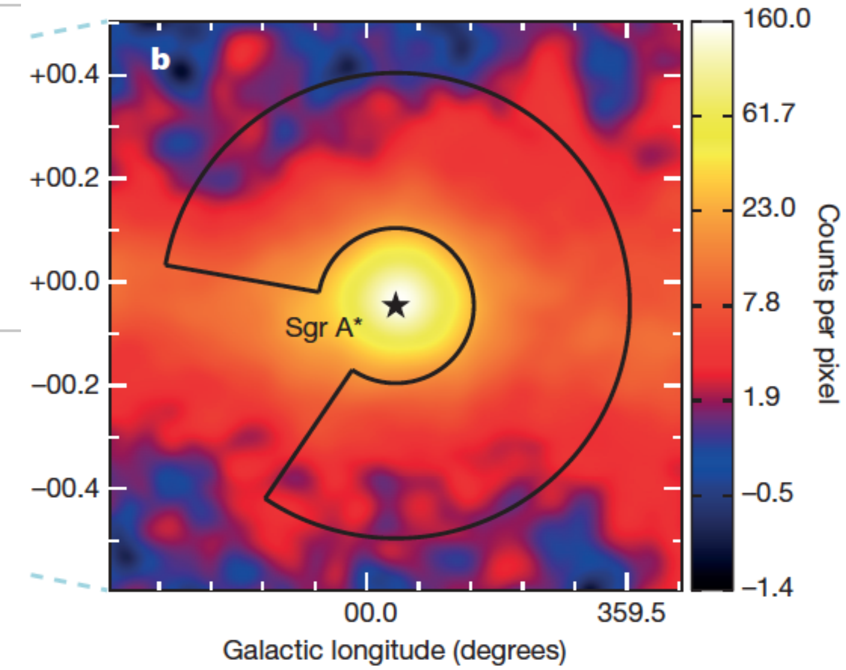
$|\, l \,| < 1°, |\, b \,| < 0.3°$

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

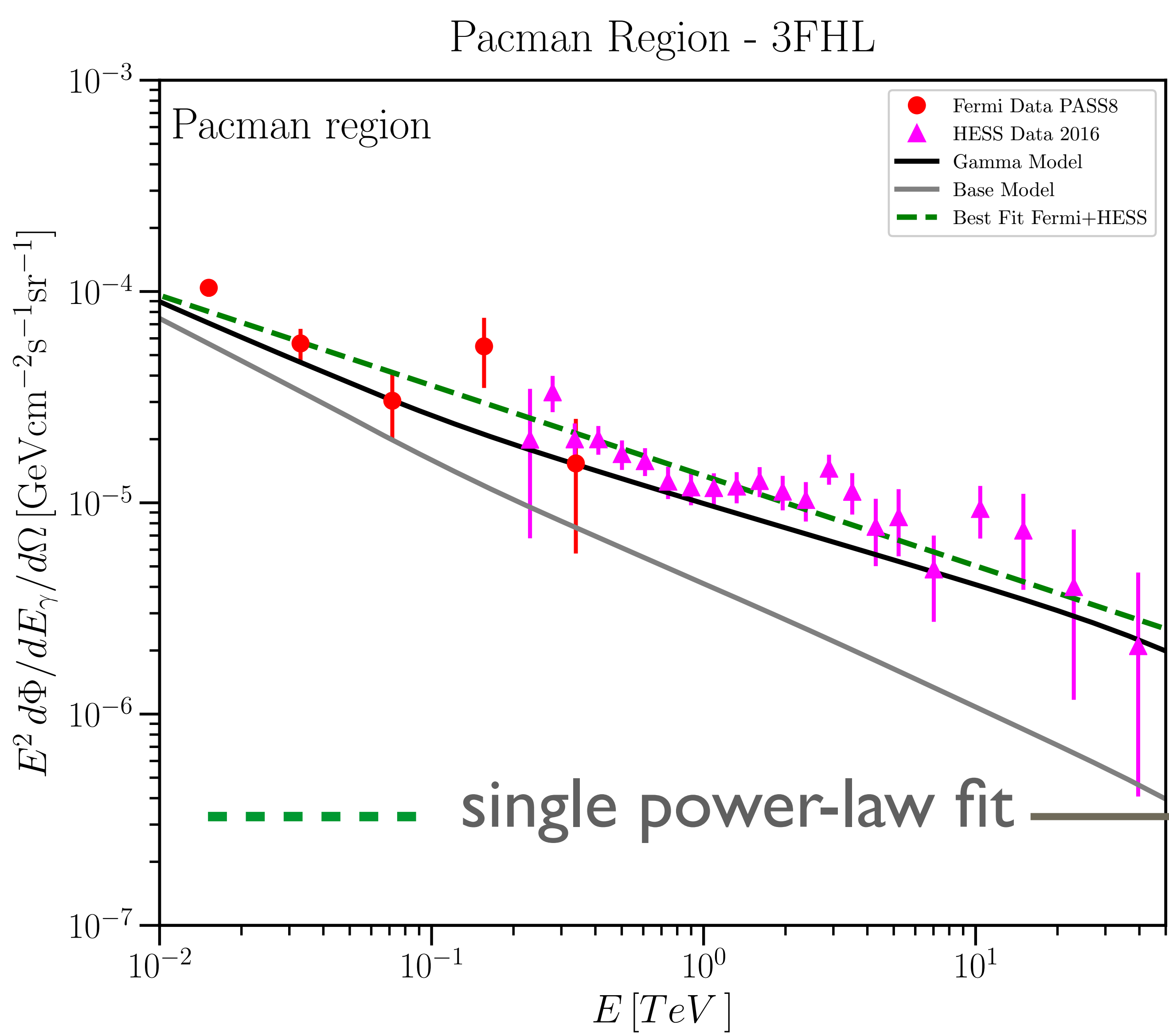
$\Gamma_{\mathrm{HESS\,+\,FERMI}} = 2.43 \pm 0.03$

this implies Γ ~ 2.5 for primary protons

Pacman region



0.15° < θ < 0.45° , 22 < d < 67 pc

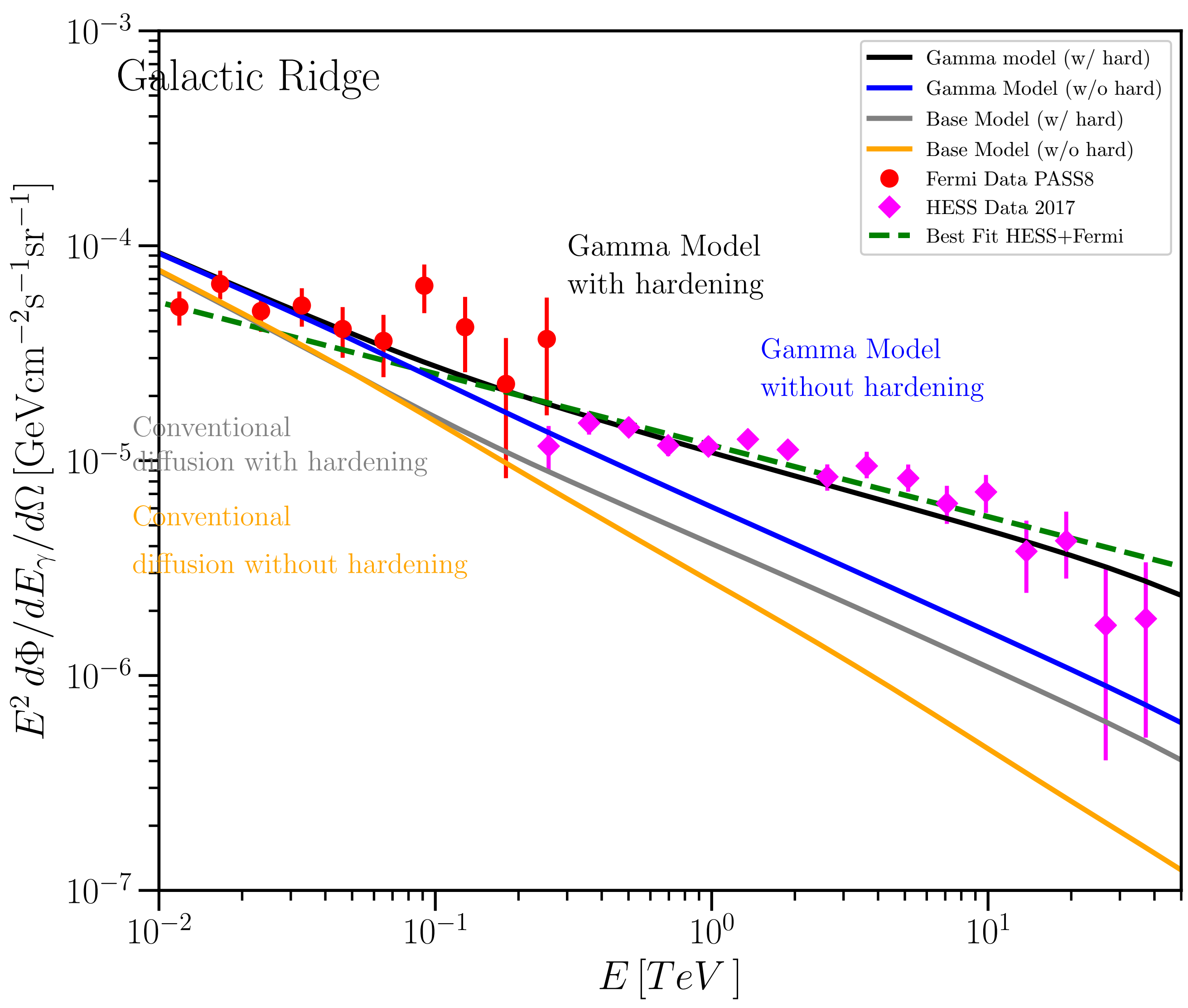


$\Gamma_{\mathrm{HESS\,+\,FERMI}} = 2.45 \pm 0.03$

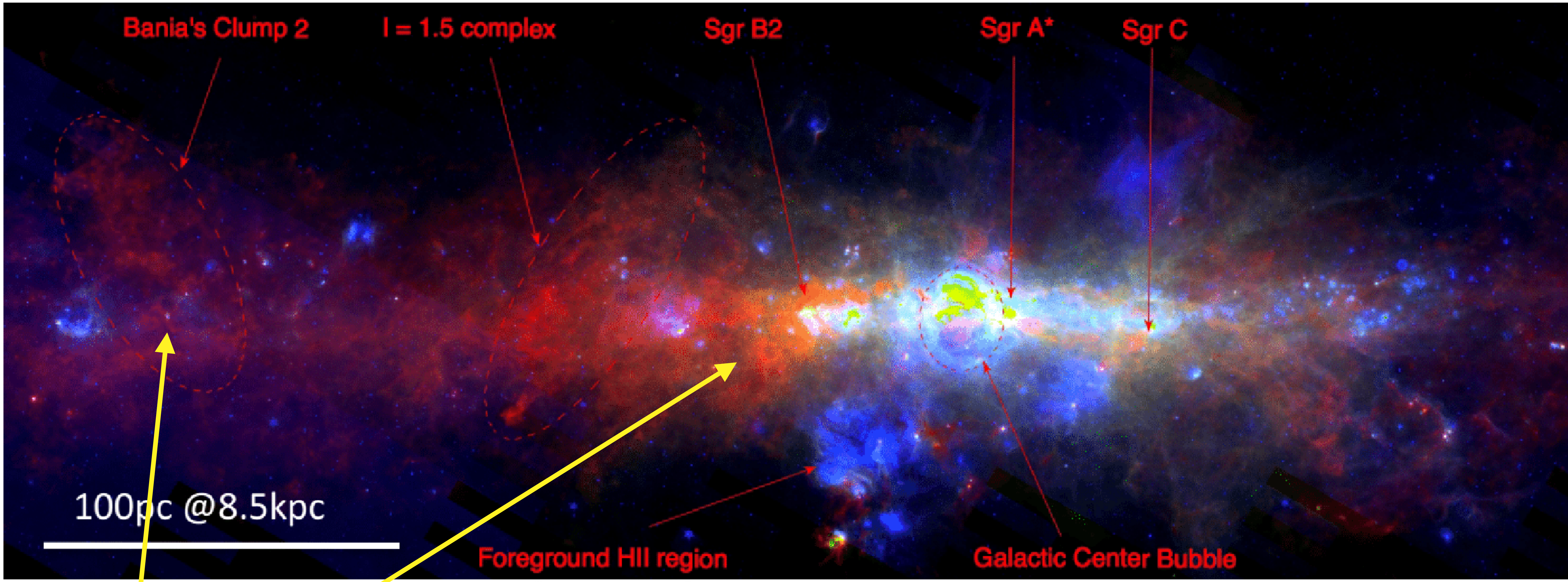
The role of the (global) hardening at few hundred GeV

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).



Future tests

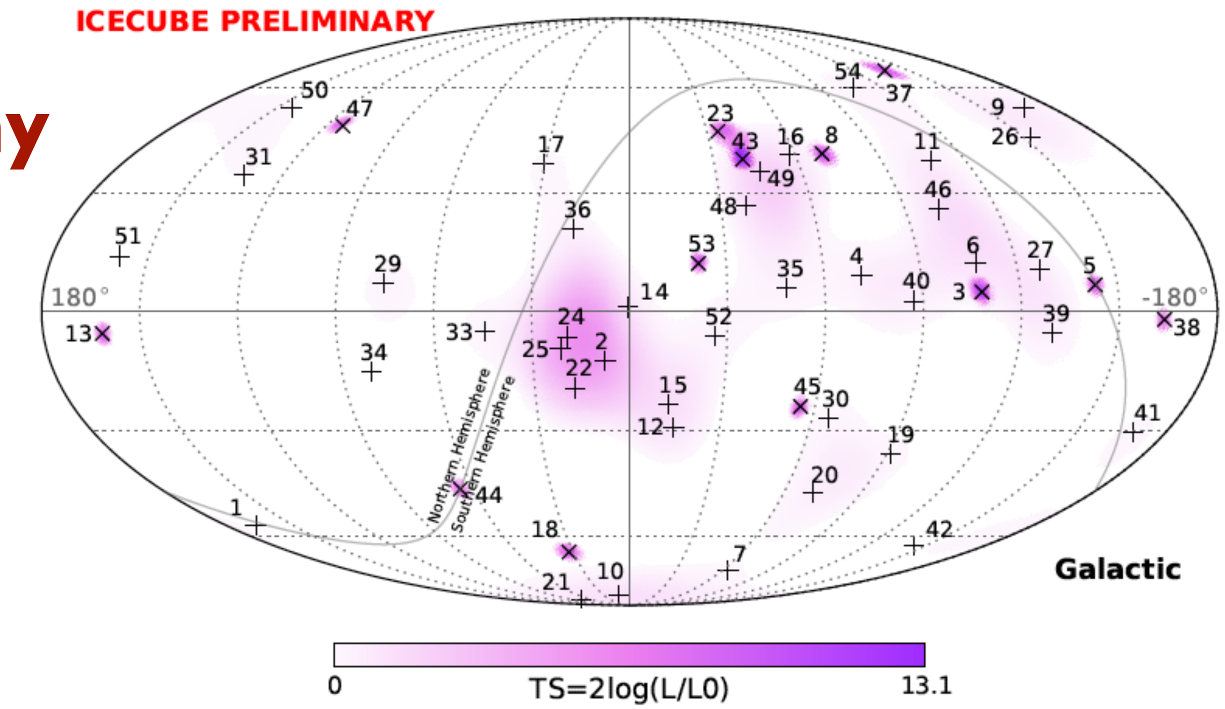


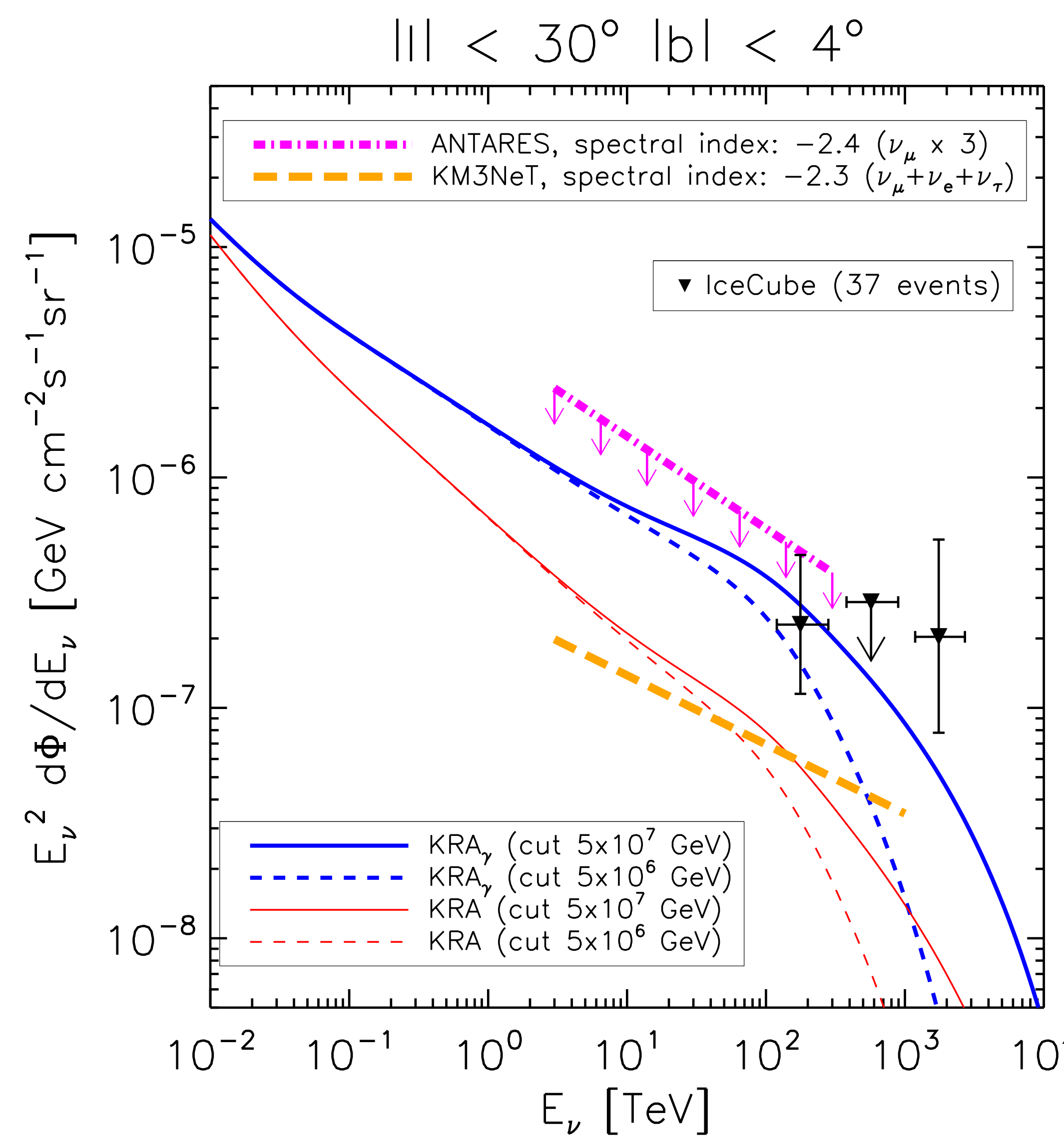
24μm, 70μm, 350μm

Implications for neutrino astronomy

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

- On the whole sky the diffuse flux due to the Galaxy is 15 % at most (8 % for conventional models) of that measured by IceCube.
- In the inner Galactic plane however the gain factor is much larger
- A neutrino telescope in the North hemisphere is more suited to detect the Galactic component. We computed the upper limit on the basis of ANTARES data in the region. *| l | < 30° , | b | < 4°*
- Observable by KM3NeT (work in progress) !



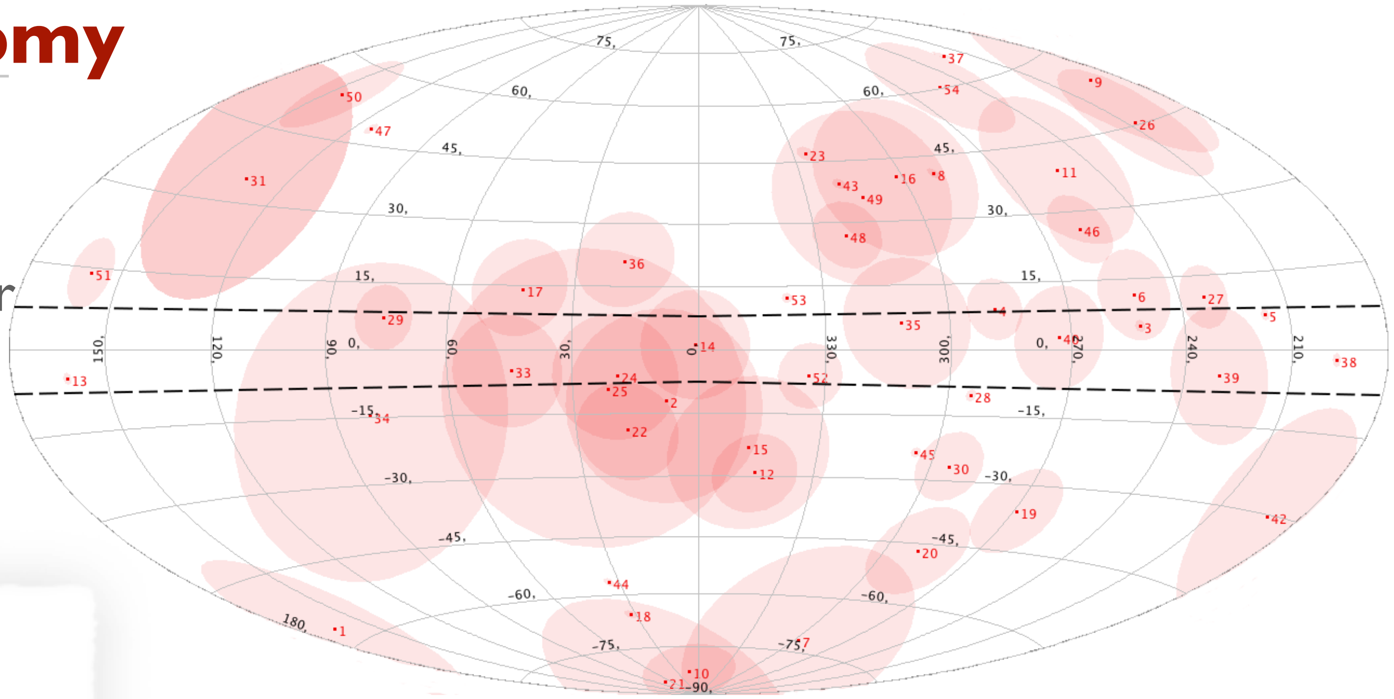


Implications for neutrino astronomy

ANTARES coll. , Phys. Lett. B, 2016

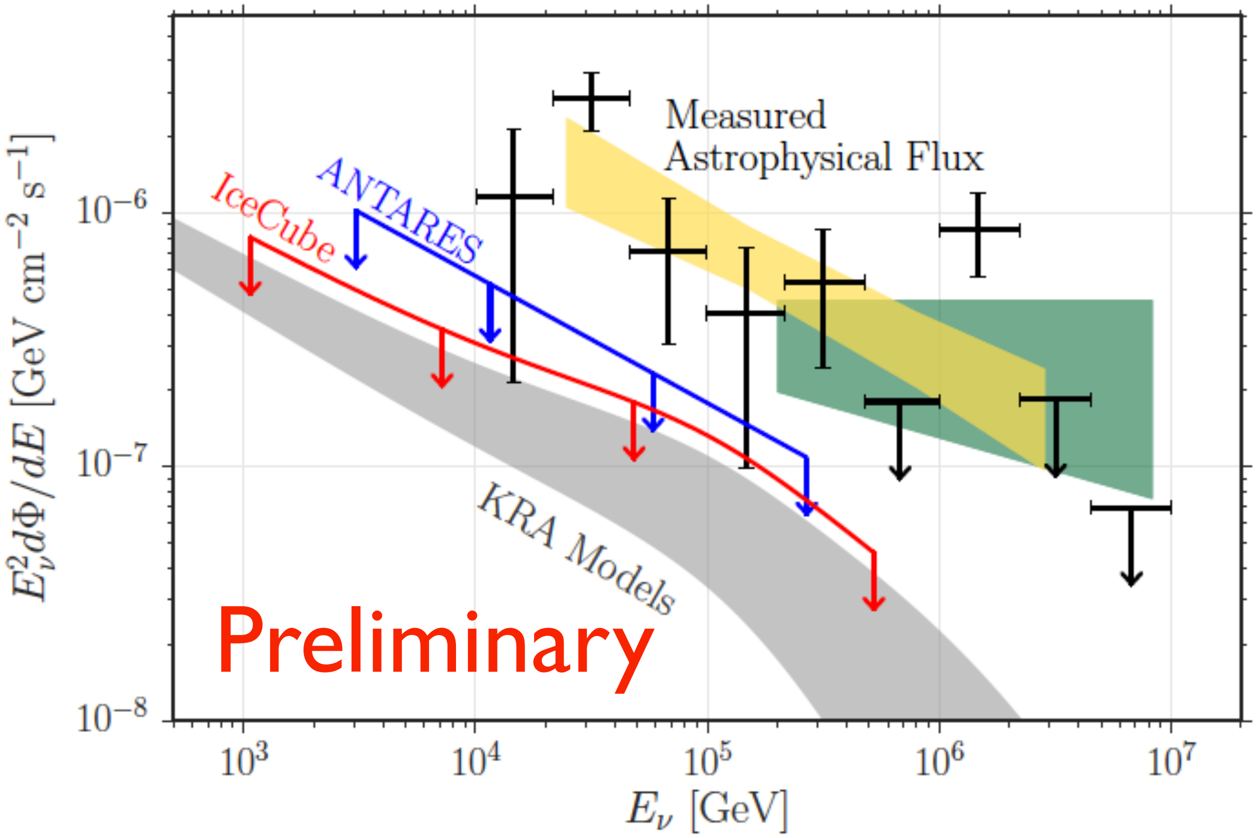
ANTARES coll. + *D. Gaggero & D.G.* PRD 2017

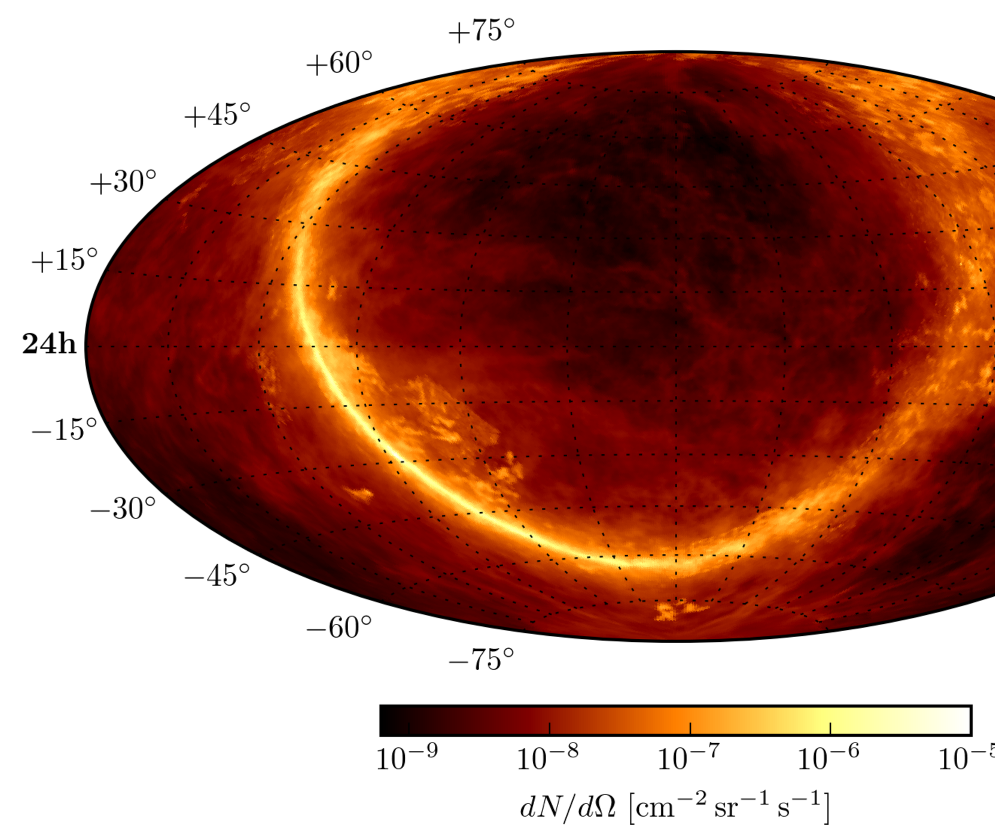
ANTARES + IceCube + *D. Gaggero & D.G.* , to appear



Galactic plane

ANTARES and IceCube constrained the maximum diffuse neutrino flux at a maximum value of ~20% of the total IceCube astrophysical measured flux.





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. This can hardly be explained by unresolved sources while inhomogeneous/anisotropic transport offers a viable interpretation of the spectral index gradient

- We used PASS8 Fermi-LAT data to extend the diffuse emission spectrum in the GC measured by HESS down to few GeV. An independent analysis by the Fermi-LAT coll. would be wishful

- Assuming that the CR spectral hardening at 300 GeV found by Pamela and AMS is present in the whole disk (as also favored by AMS 2018) the bulk of the diffuse emission from the CMZ may be originated by the Galactic CR sea.

- CTA should be able to confirm the scenario we propose observing the emission from molecular clouds outside the CMZ

- In this scenario the neutrino diffuse emission from the Galactic disk is significantly enhanced. ANTARES and IceCube may soon test it. Km3NeT can measure that emission with high accuracy.