Cosmic ray hardening in the inner Galaxy and its gamma-ray and neutrino imprints

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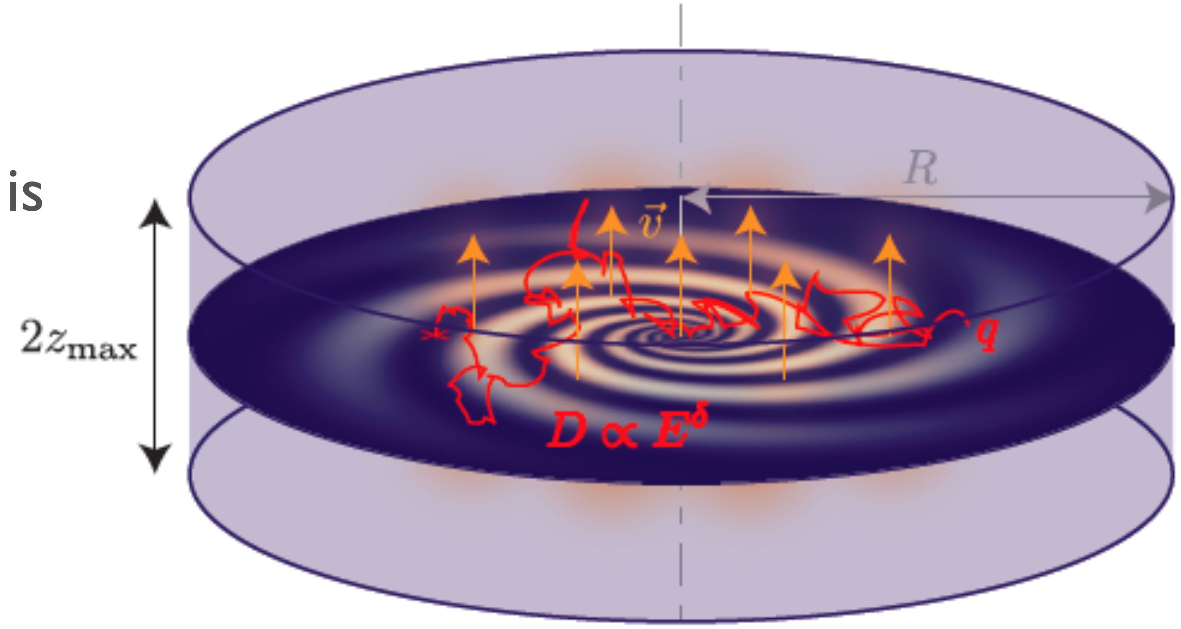
PAHEN 2017, Napoli

CR transport in the Galaxy

the conventional approach

The primary cosmic ray spatial and energy distribution is computed solving the transport equation (*Ginzburg & Syrovatsky 1964*).



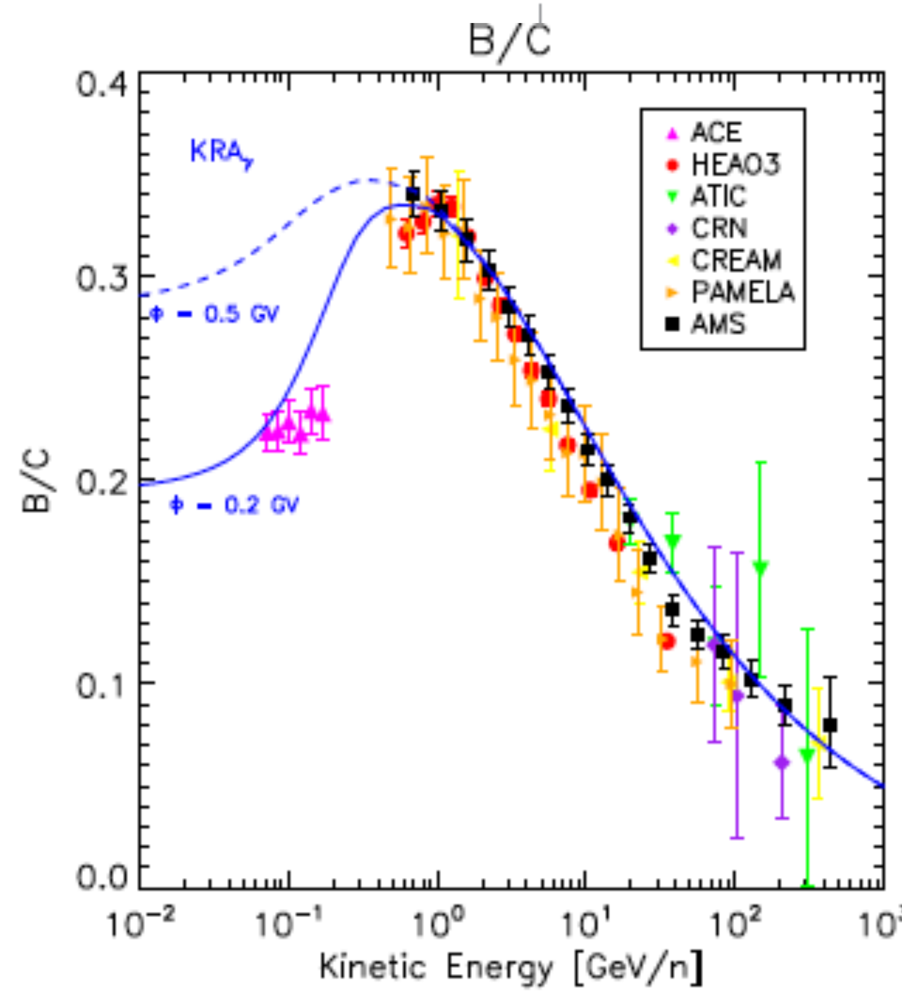
A source spectrum (power-law) and spatial distribution (based on SNR catalogues) has to be assumed

$$Q(E,r) = Q_0(r)\ (E/E_0)^{-p}$$

Diffusion is treated as isotropic and homogeneous. The diffusion coefficient only depends on rigidity. For E ≫ m

$$D(E) = D_0\,(E/E_0)^{+\delta}$$

D_0 and δ are tuned on the basis of the secondary/primary CR nuclei ratio (the B/C most importantly)



Warning: secondary nuclei probes only few kpc around us.

Under this conditions and at high energies (E ≫ 10 GeV/n)

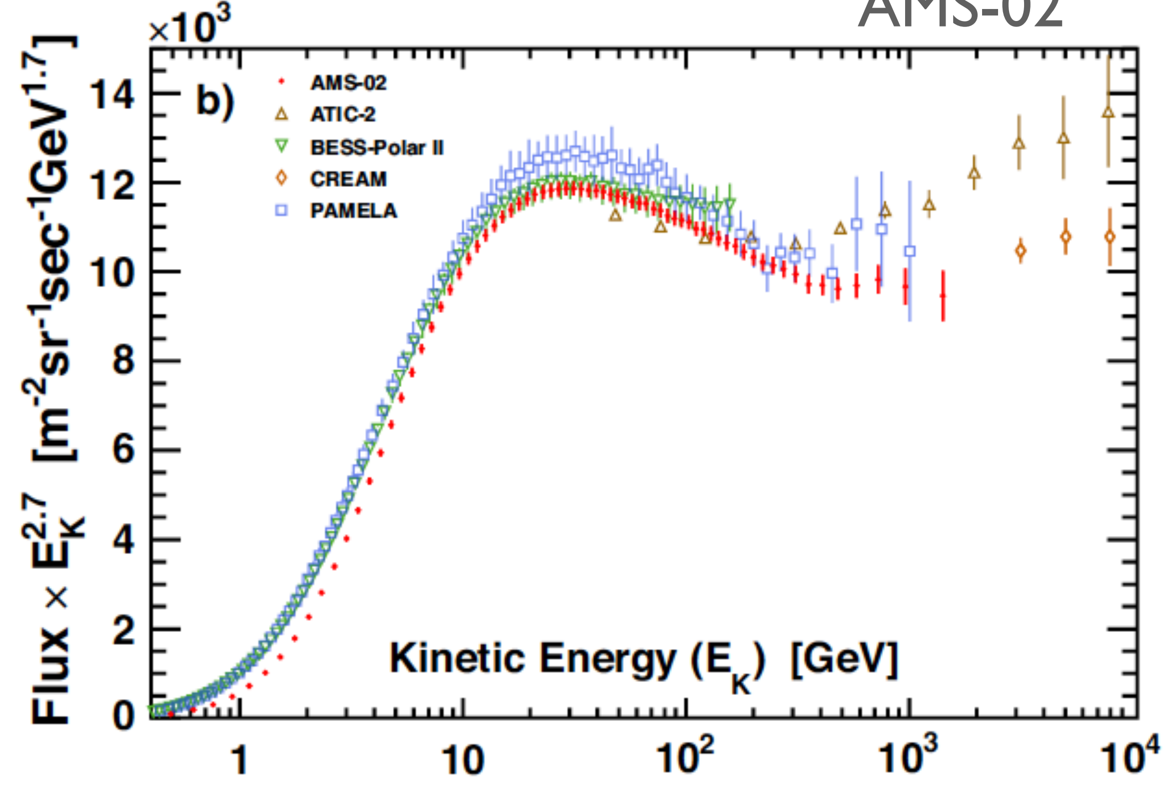
$$\Phi(E) \propto Q/D = \Phi_0\,(E/E_0)^{-(p+\delta)}$$

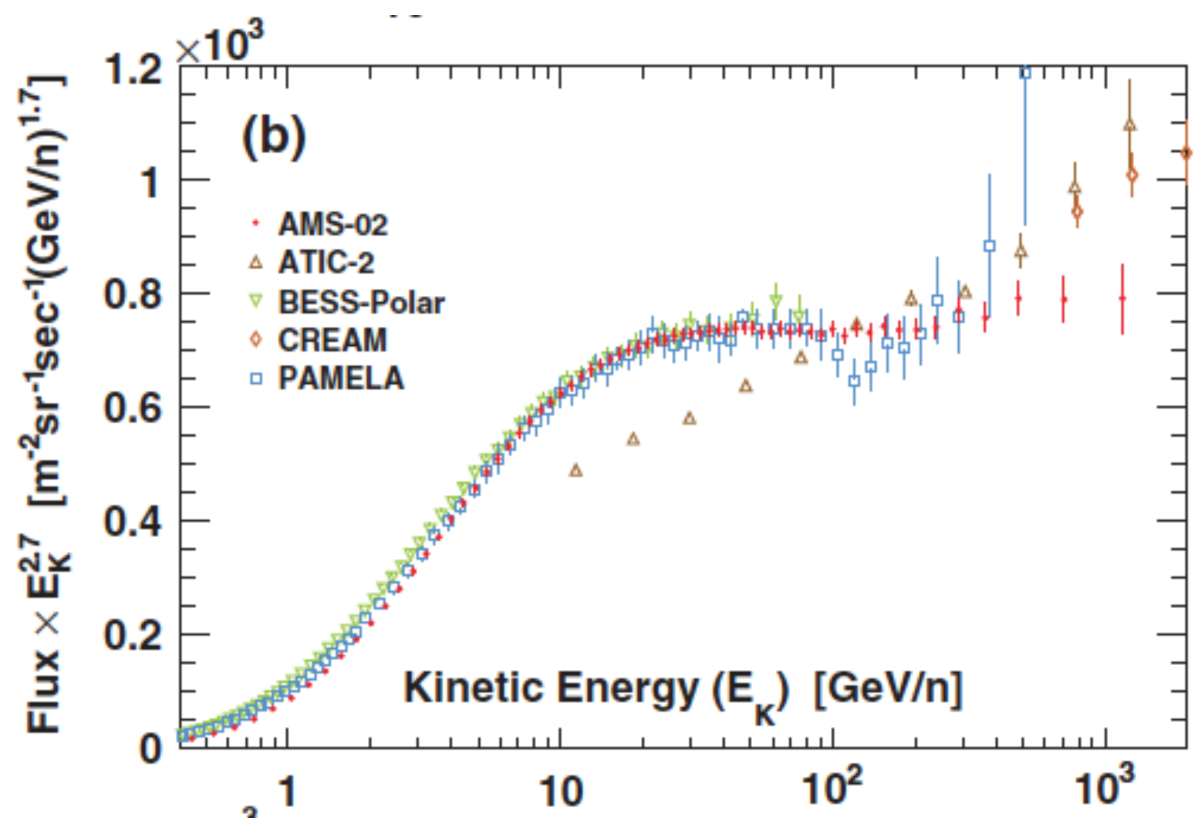
CR hardening @ 300 GeV/n

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

A hardening ($\Delta\gamma \simeq 0.1$) found for proton and helium at 300 GeV/nucleon
Strong hints that a similar feature also affects other nuclei

AMS-02





CR hardening @ 300 GeV/n

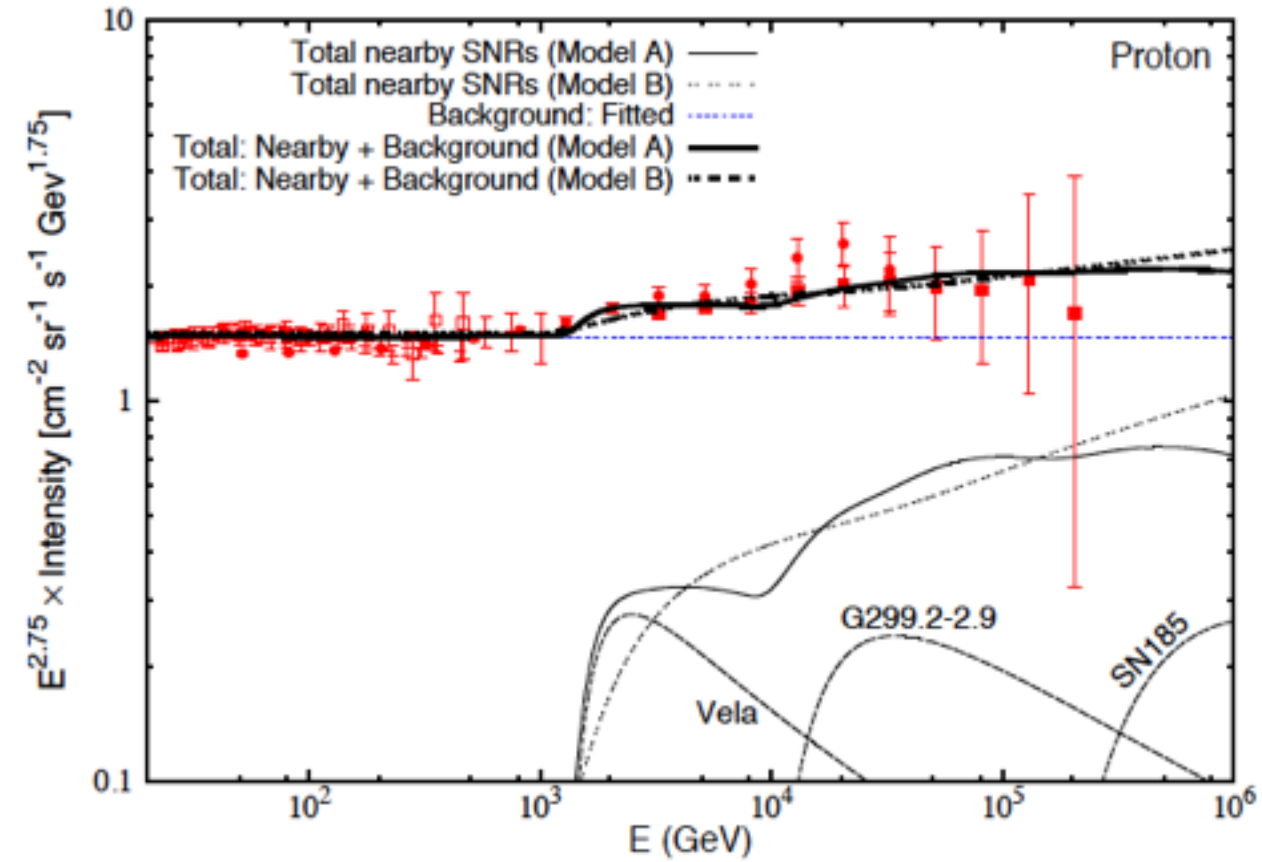
CREAM coll. ApJ Lett. 2010
PAMELA coll. SCIENCE 2011
AMS-02 coll. PLR 2015

Several hypothesis for its origin:

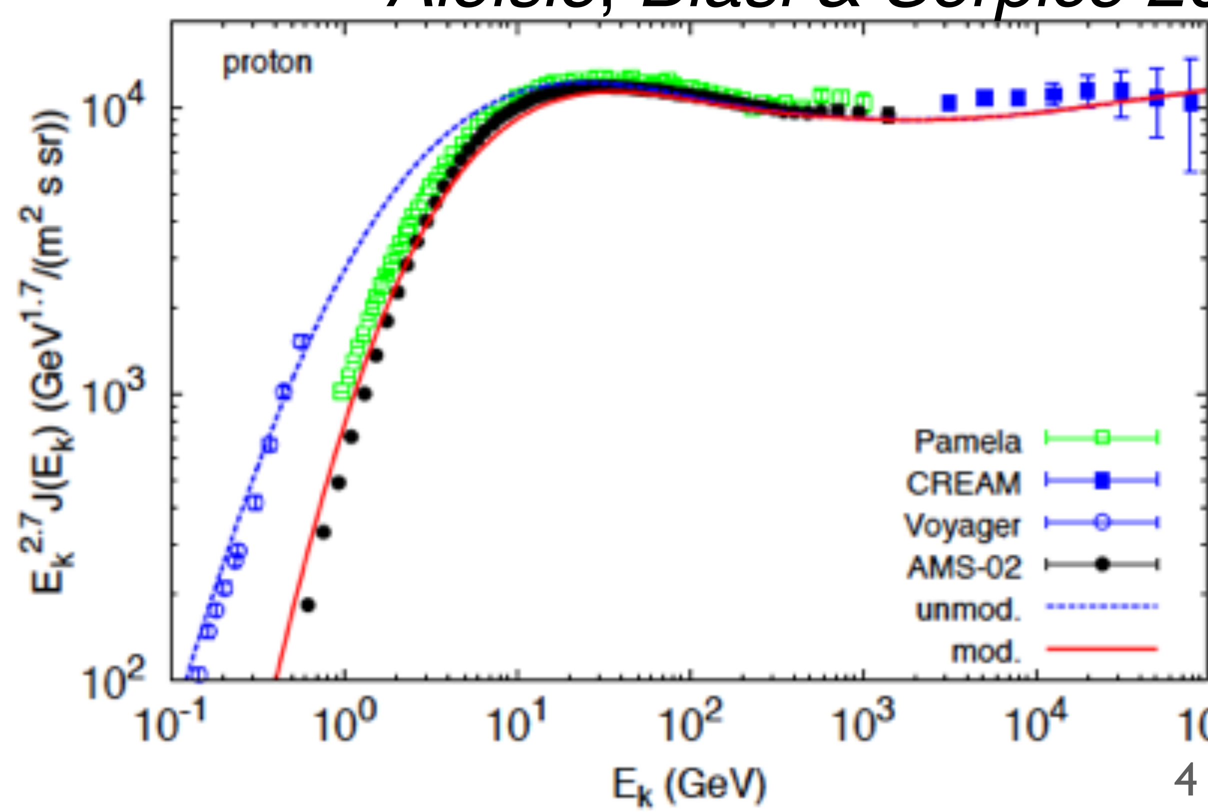
- **local effect:** nearby SNR (*Thoudam & Hörandel 2011*)

- **global effect:** due to propagation due e.g. to inhomogeneous diffusion (*Tomassetti 2012*) or non-linear action between CR and MHD waves (*Blasi, Amato & Serpico 2011*)

different imprints on the γ-ray diffuse emission are expected for $E_\gamma \gg 10$ GeV

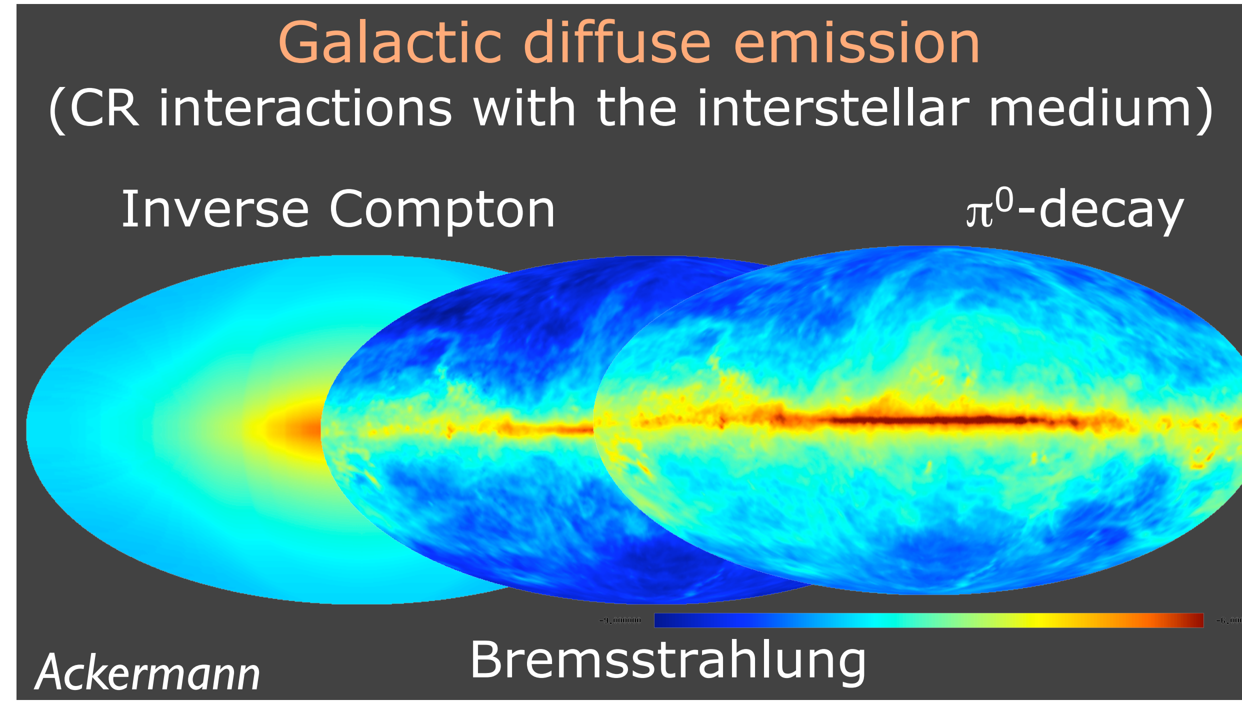


Aloisio, Blasi & Serpico 2015



The γ-ray diffuse emission

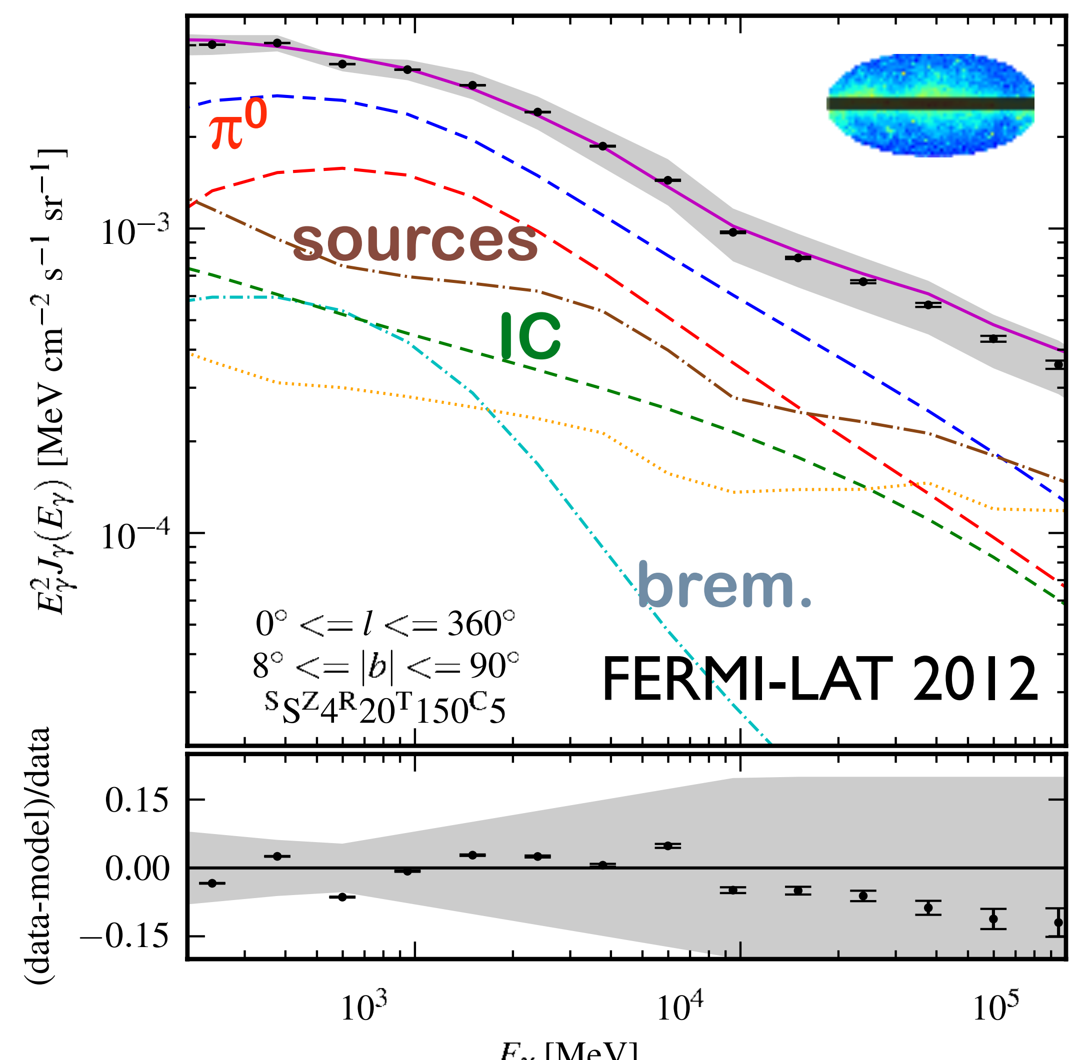
Obtained by the convolution of the cosmic ray distribution with the interstellar gas (**π^0-decay** and **bremsstrahlung**) and radiation (**Inverse Compton**) and the proper cross-sections



It offers a much deeper probe of the CR population

The conventional approach provides a reasonable description of the emission away from the Galactic plane.

On the plane several anomalies have been founds



The Milagro anomaly

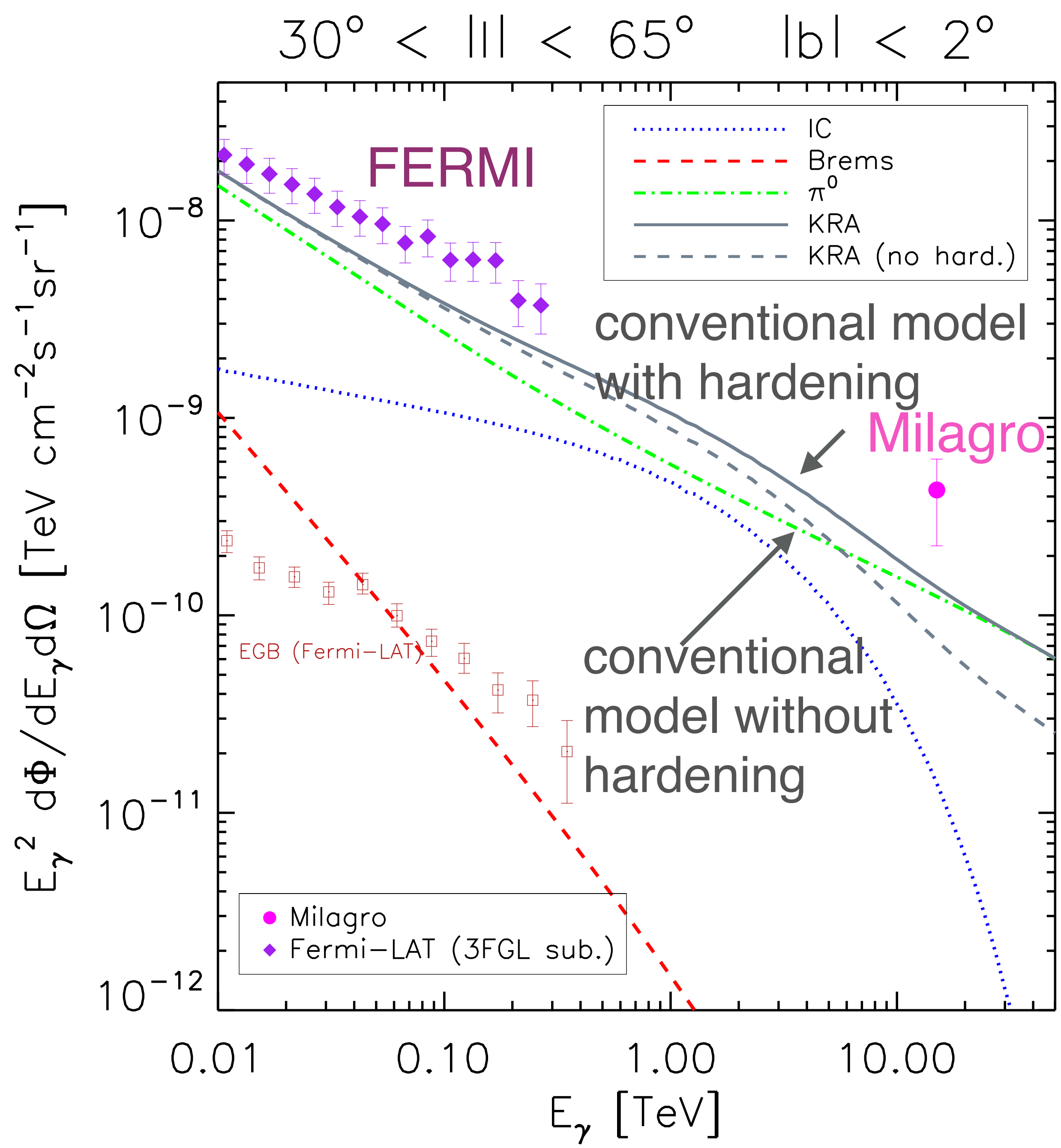
Abdo et al. , ApJ 2008

- the measured flux at 15 TeV is 5 times (4 σ) larger than computed with the reference *conventional model* based on GALPROP

- an *optimized model* (augmented IC contribution) - proposed to account for the EGRET GeV excess - was found to match Milagro

- GeV excess disproved by Fermi-LAT (*PRL 2009*) $\Longrightarrow$ back to conventional models.

- Accounting for CR global hardening only ameliorate the problem



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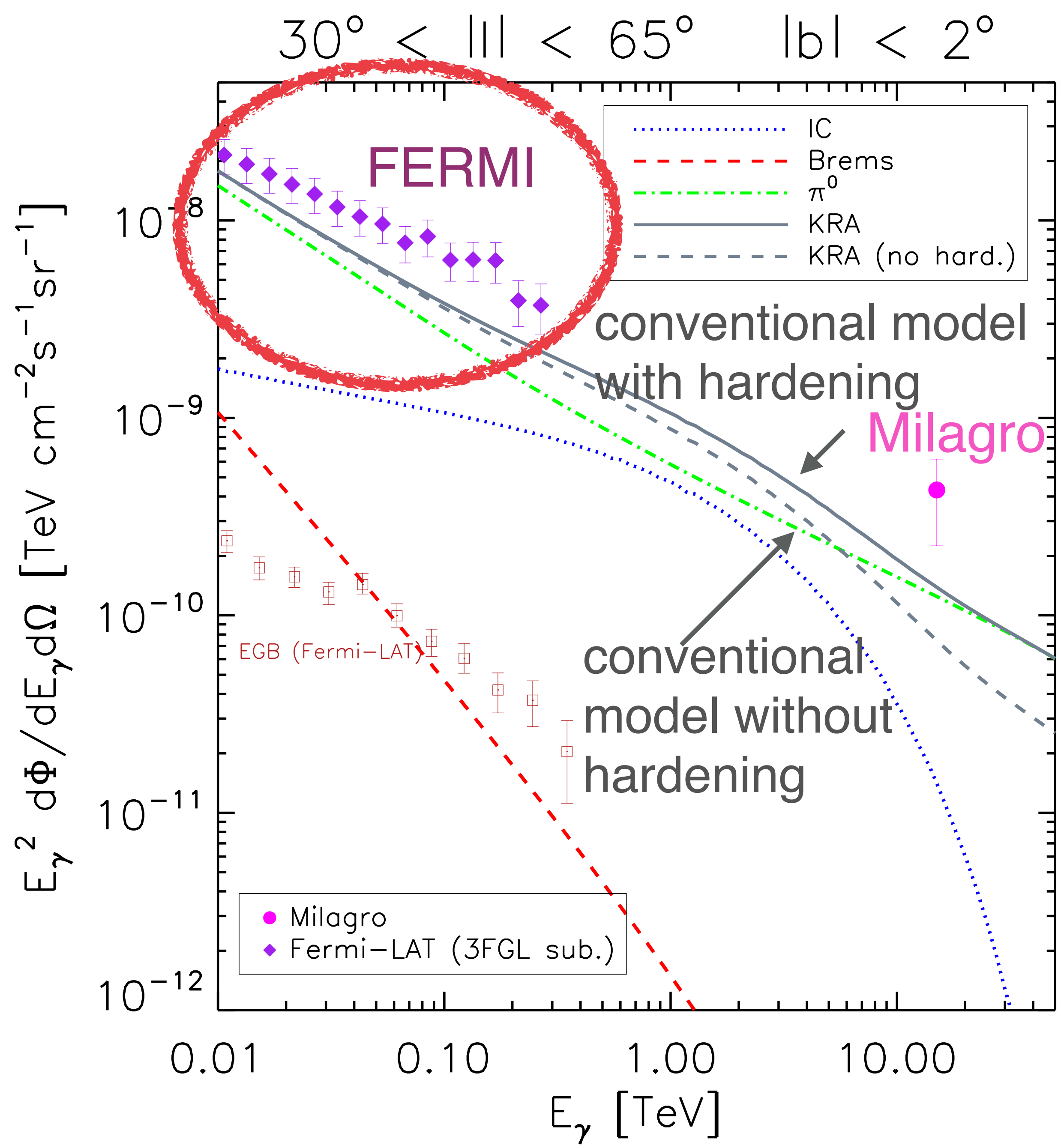
- Accounting for CR global hardening only ameliorate the problem

- Problems with conventional models starts already with Fermi data (where the hardening play no role)



The Fermi Galactic plane anomaly

Fermi coll., ApJ 2012

Gaggero, Urbano, Valli & Ullio PRD 2015

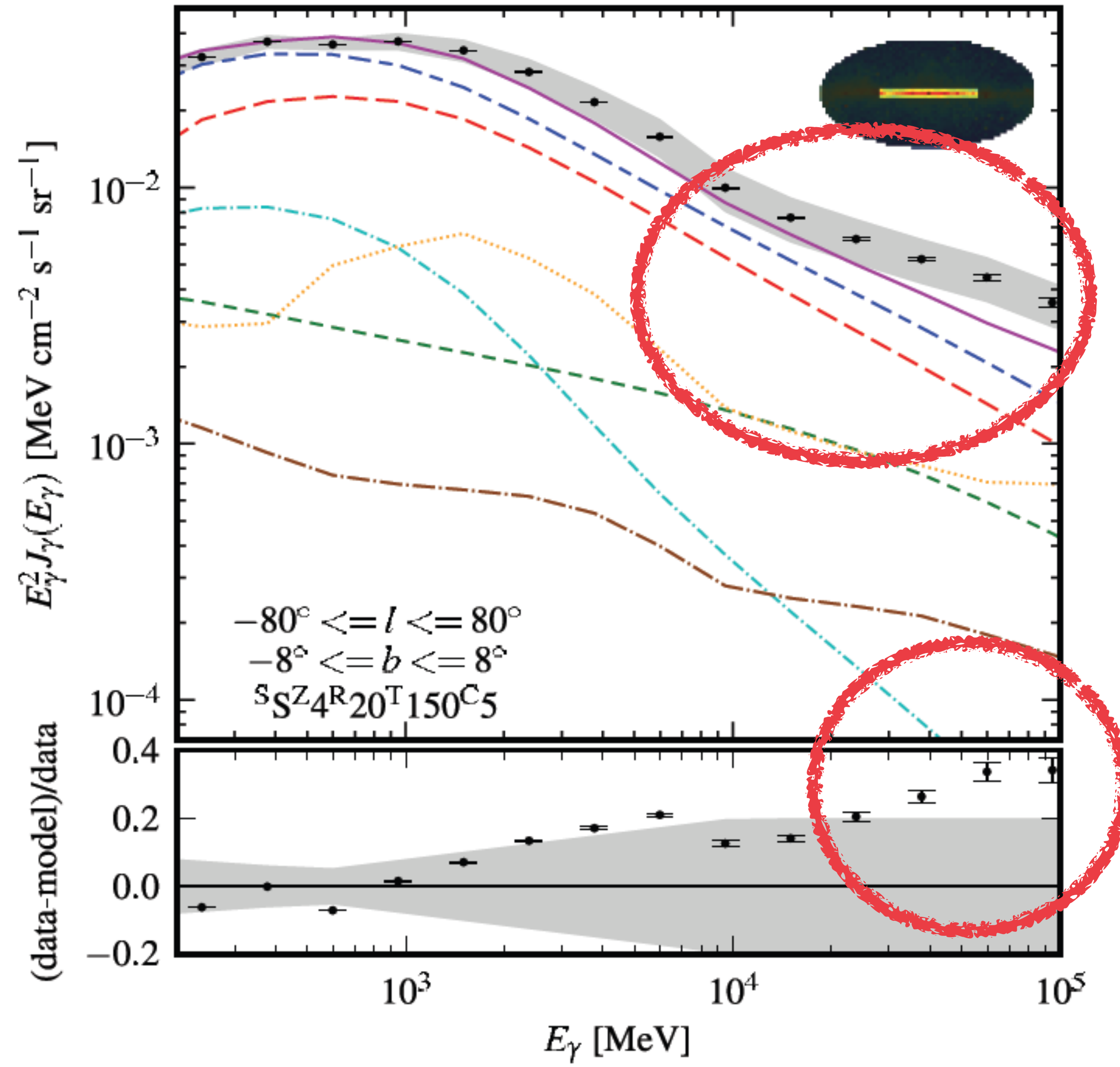
interpreted the effect as due to a

CR spectral index radial gradient
due to a radial dependent diff. coeff.
(KRAγ model)

$$D(E) = D_0 \, (E/E_0)^{+\delta(r)}$$

$$\delta(r) = A\, r + B$$

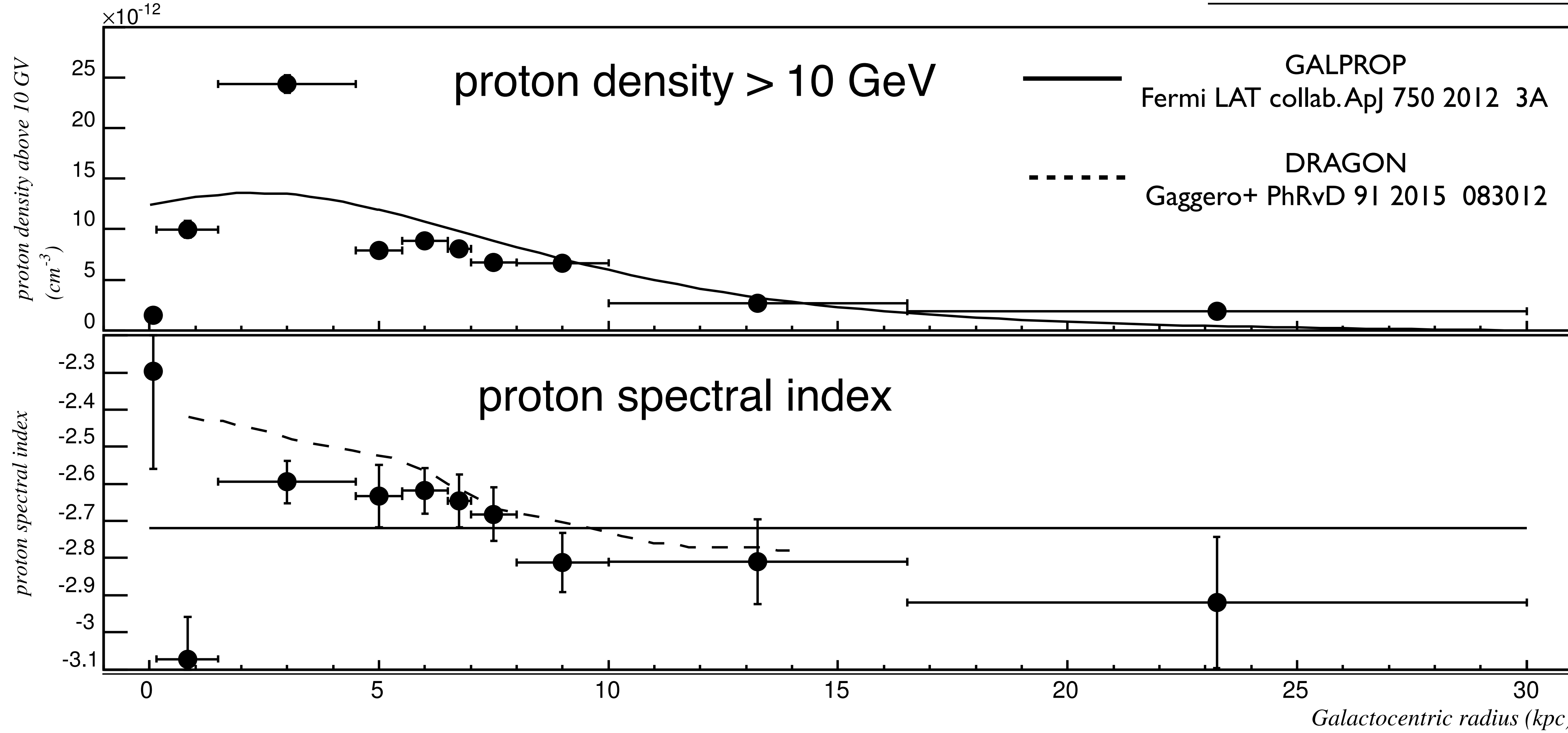
$$\Gamma(r) = p + \delta(r)$$

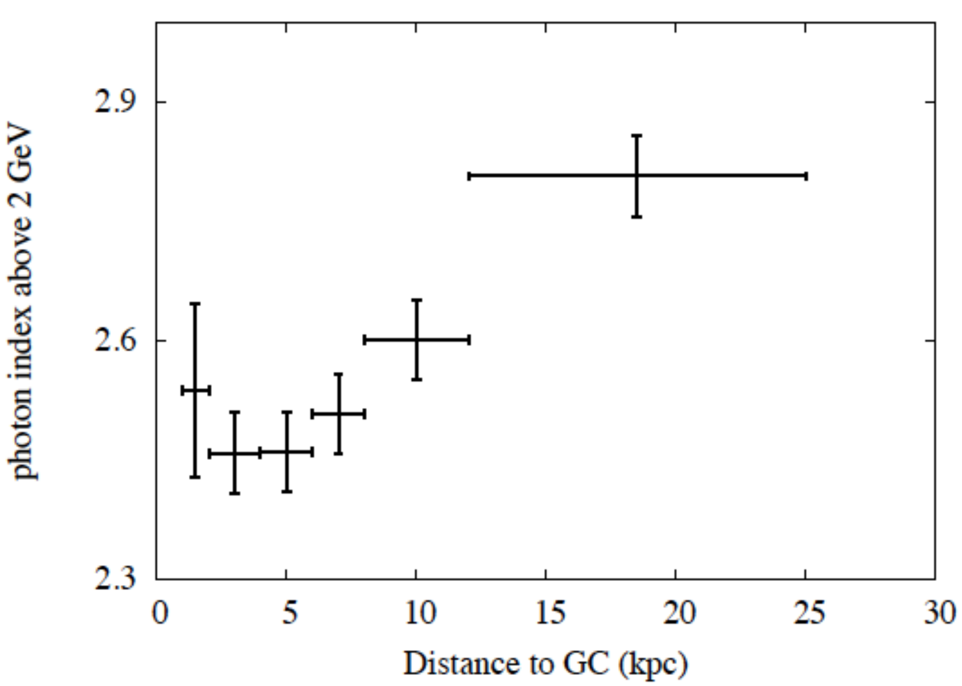


solid line: Fermi Benchmark (FB) conventional model based on GALPROP (*Moskalenko, Strong et al.*).
$\delta = 0.3$, $p = 2.72$ in the whole Galaxy

CR spectral index radial gradient

Fermi-LAT coll. 2016





← *Yang, Aharonian & Evoli 2016*

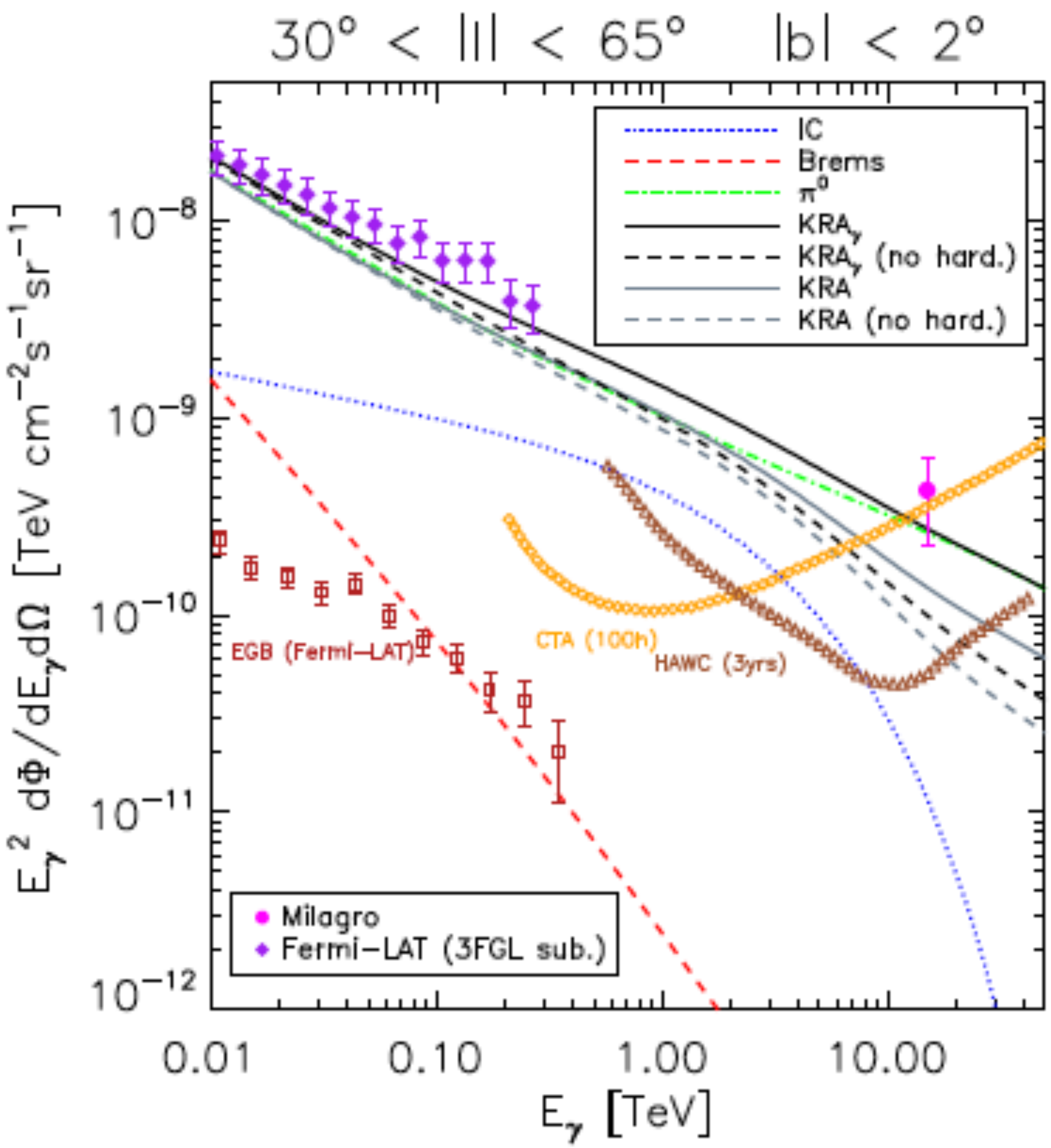
A first step above the TeV:
solution of the Milagro anomaly

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

Incorporate the CR spectral hardening in the KRAγ model (assuming it is present in the whole Galaxy).

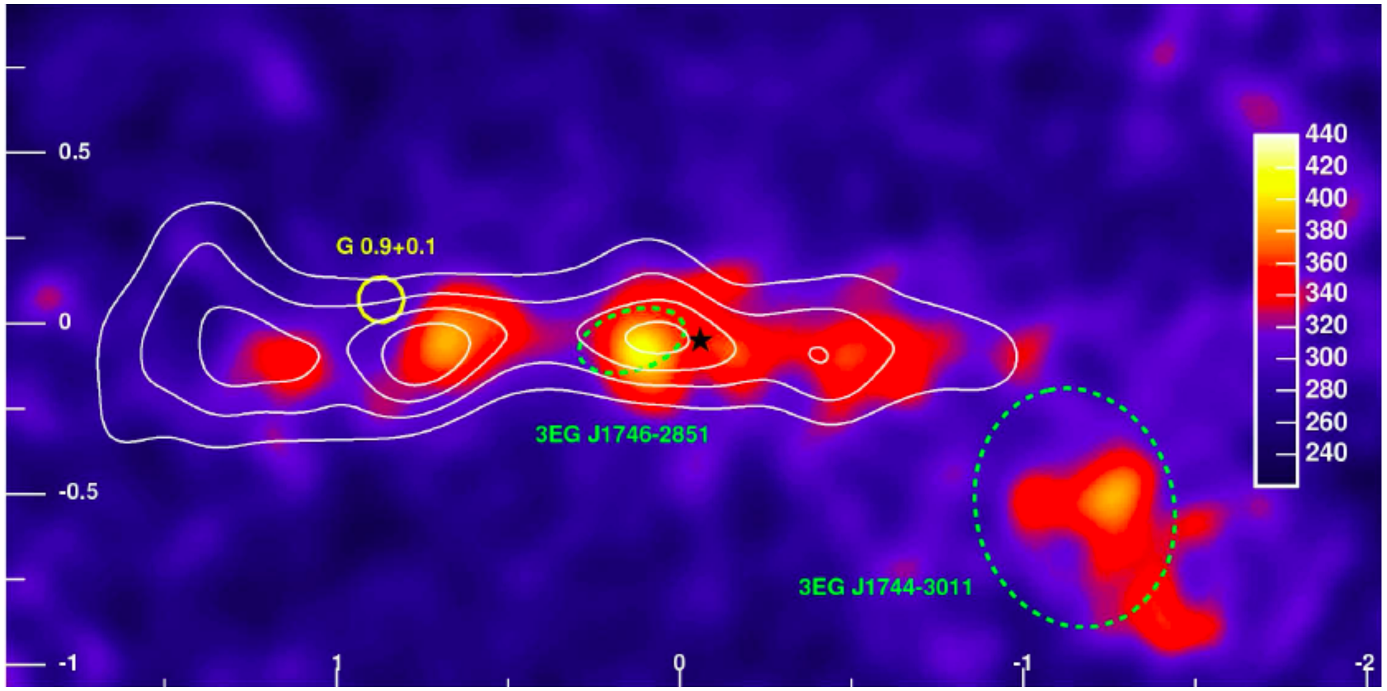
This automatically reproduces Milagro observed flux @ 15 TeV

testable by HAWC (work in progress) and CTA !



The Galactic center TeV excess

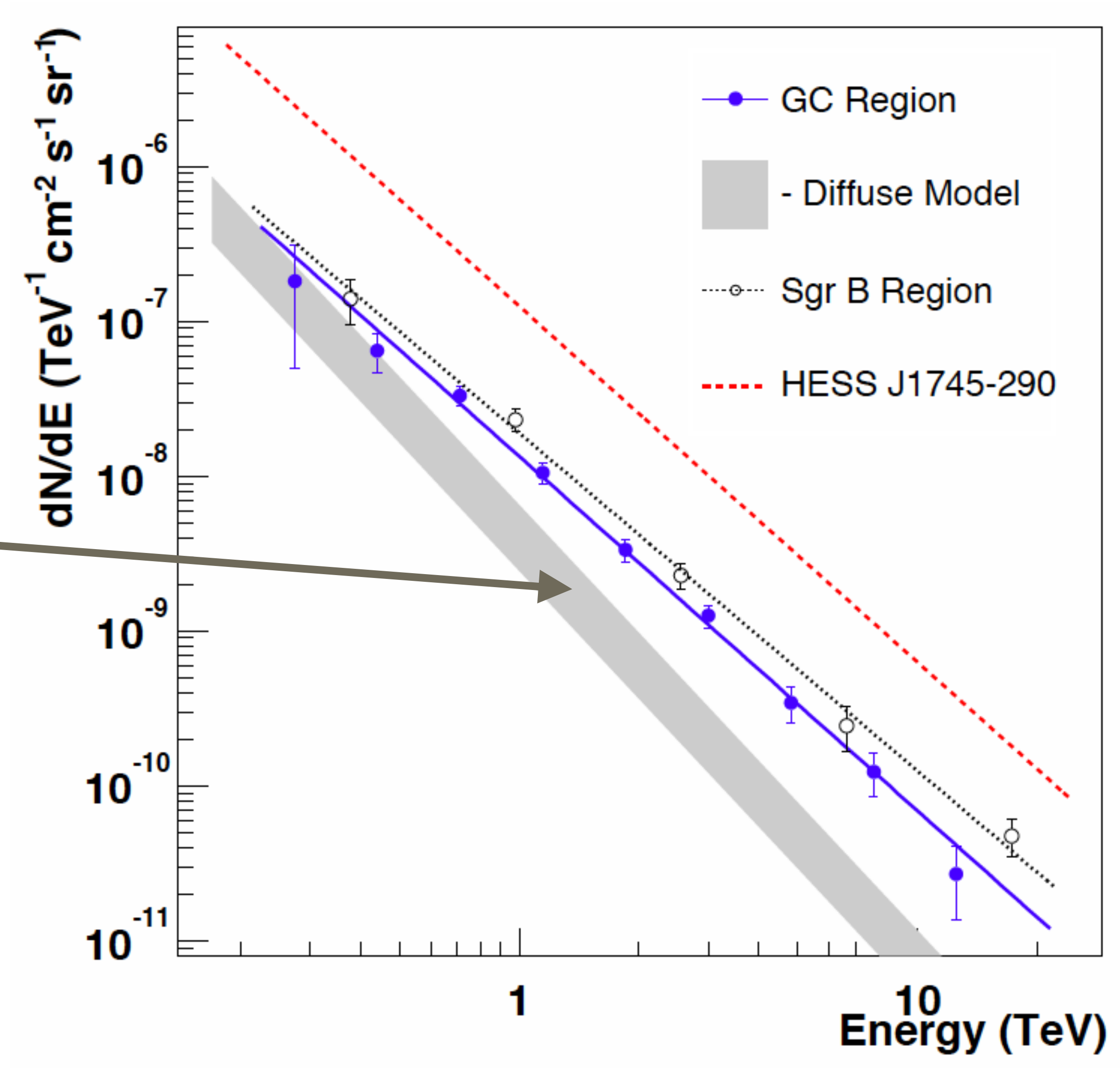
H.E.S.S., Nature 2006



- The diffuse emission from the CMZ is correlated with the gas distribution (inferred from CO and CS emission 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 ($\Gamma \simeq 2.7$)

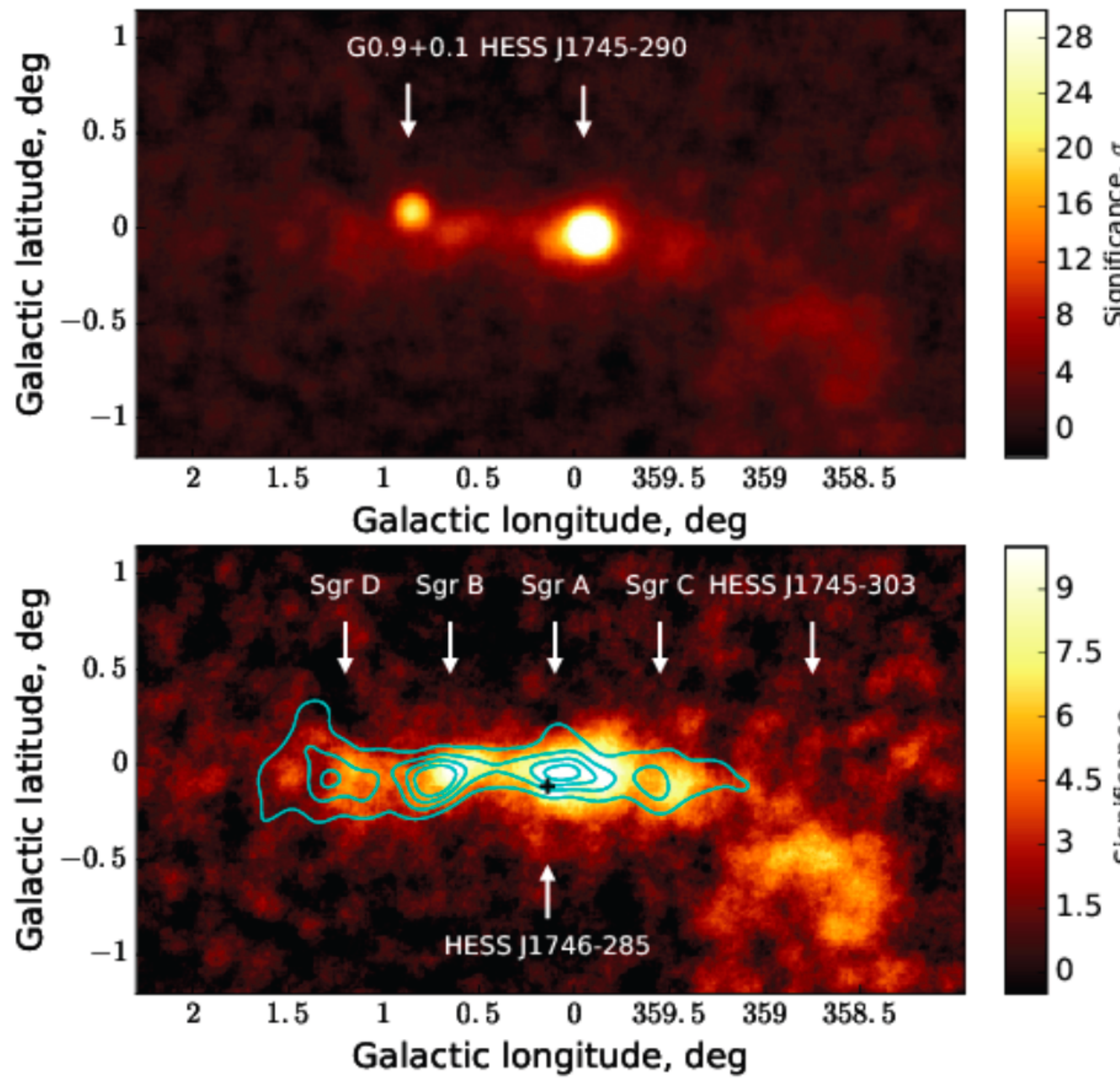
- A freshly accelerated (hard) CR component was invoked to explain the emission (see however below)



The Galactic center TeV excess

H.E.S.S. , Nature 2006

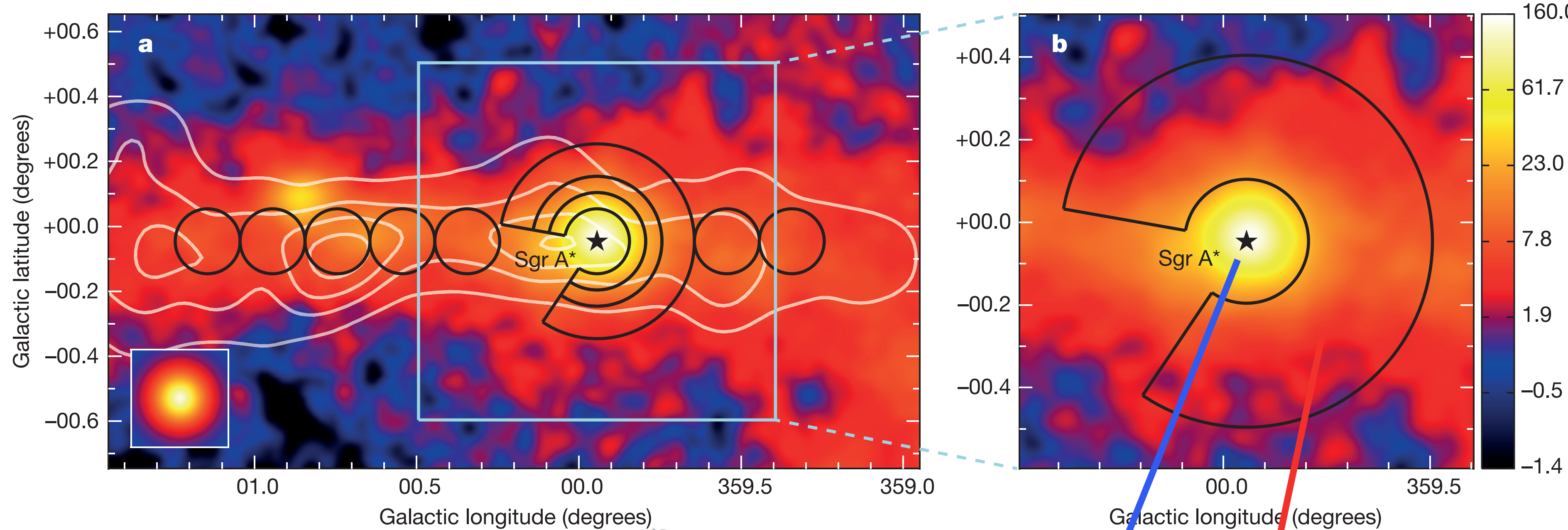
arXiv 1706.04535



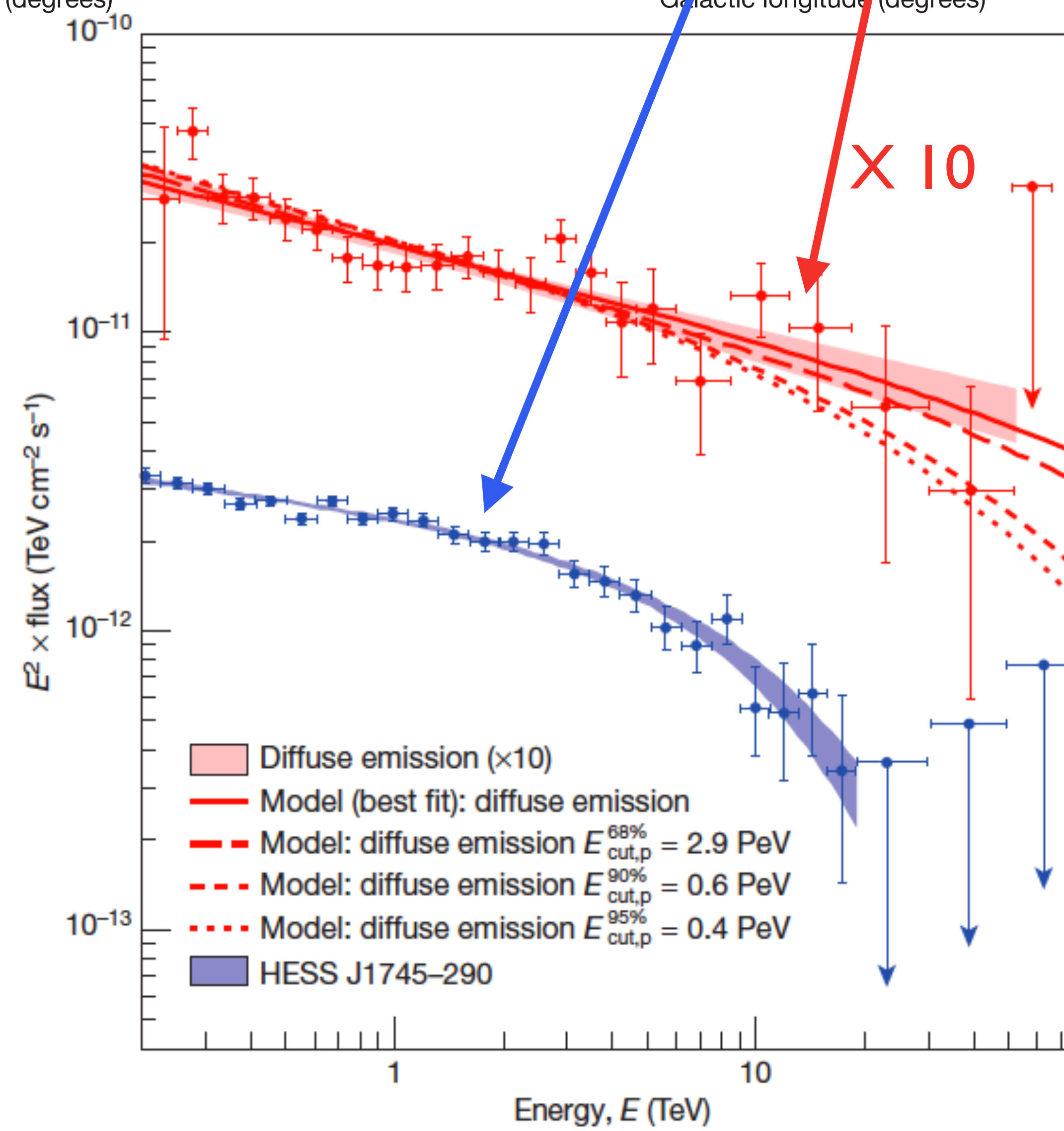
250 hours of observation of the γ-ray diffuse emission from 200 GeV to 50 TeV of the central molecular zone (CMZ) region performed with the 5 mirror set-up

The PeVatron scenario

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

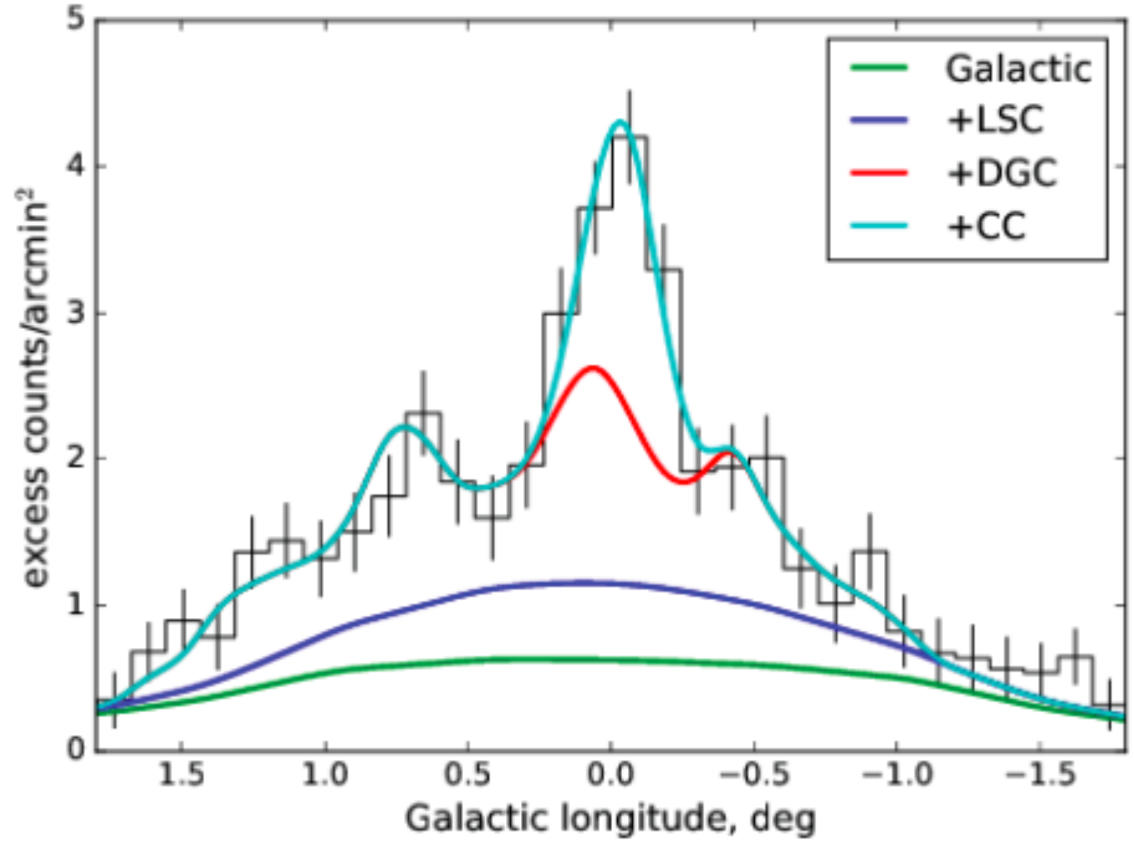


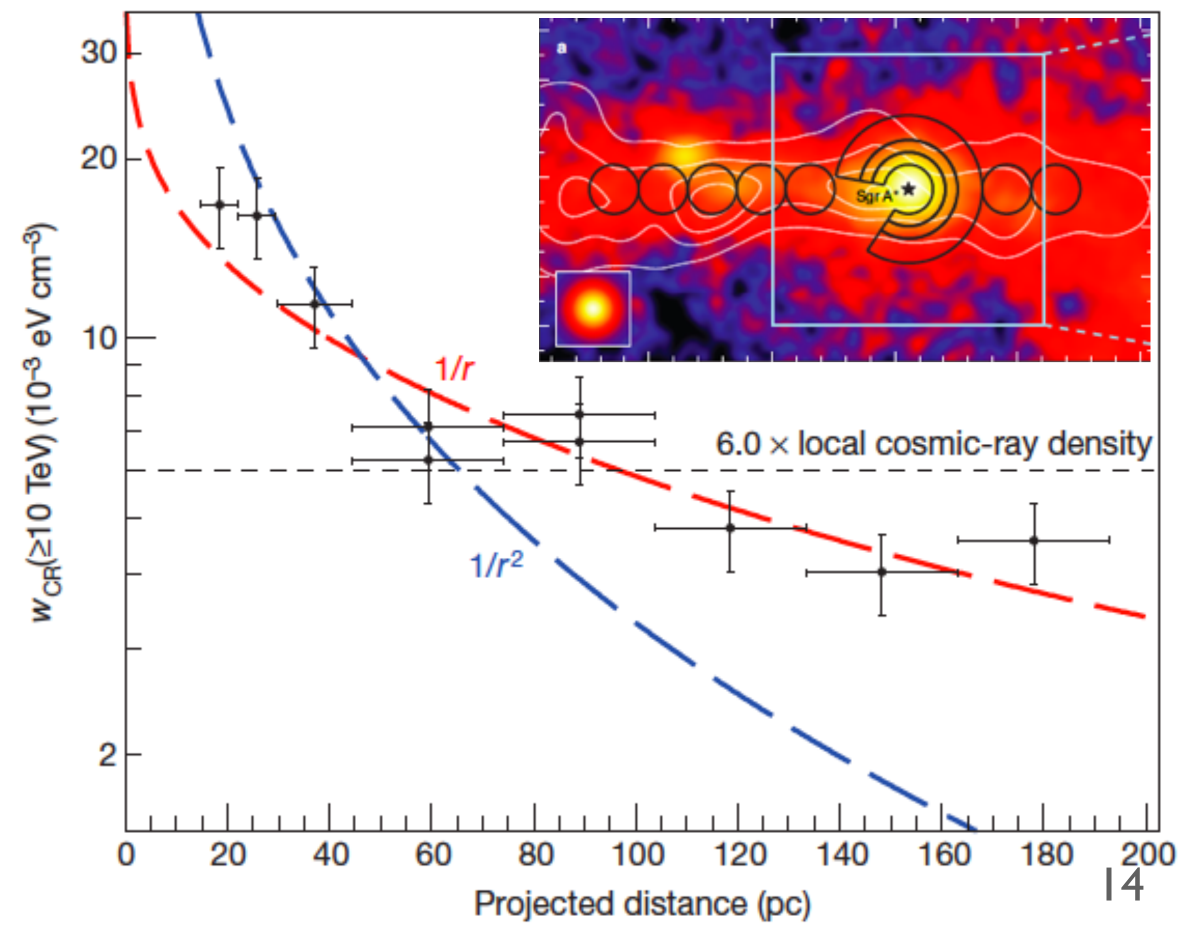
The PeVatron scenario

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

- At the GC the emission profile seems more peaked than the estimated gas distribution. The same effect however may be due to underestimated gas density in the inner 50 pc ($1^\circ \simeq 150\ pc$ at the GC)

- The inferred CR density profile (which again is based on the poorly known gas distribution) is consistent with that expected from CR diffusing out a stationary source.





H.E.S.S. Nature 2016
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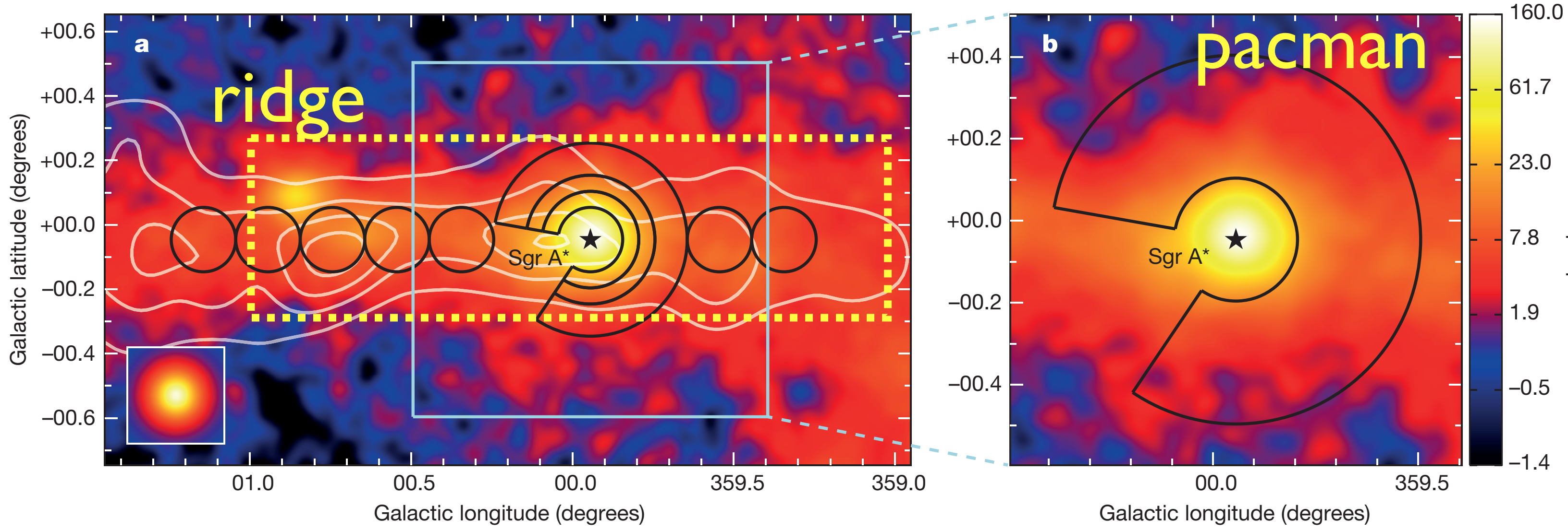


Same spectra in the ridge

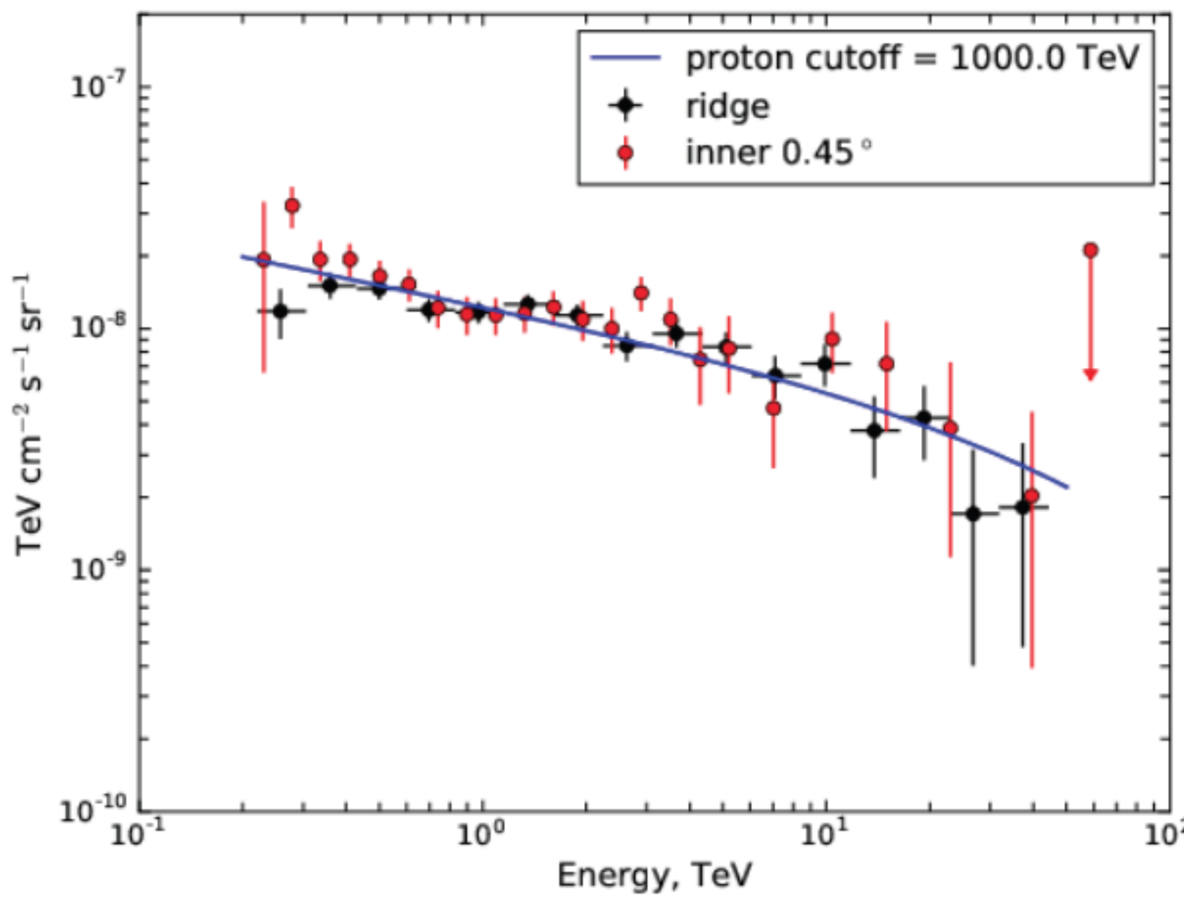
(| l | < 1° , | b | < 0.3°), d < 150 pc

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

and in the "*pacman*"

0.15° < θ < 0.45° , 22 < d < 67 pc

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

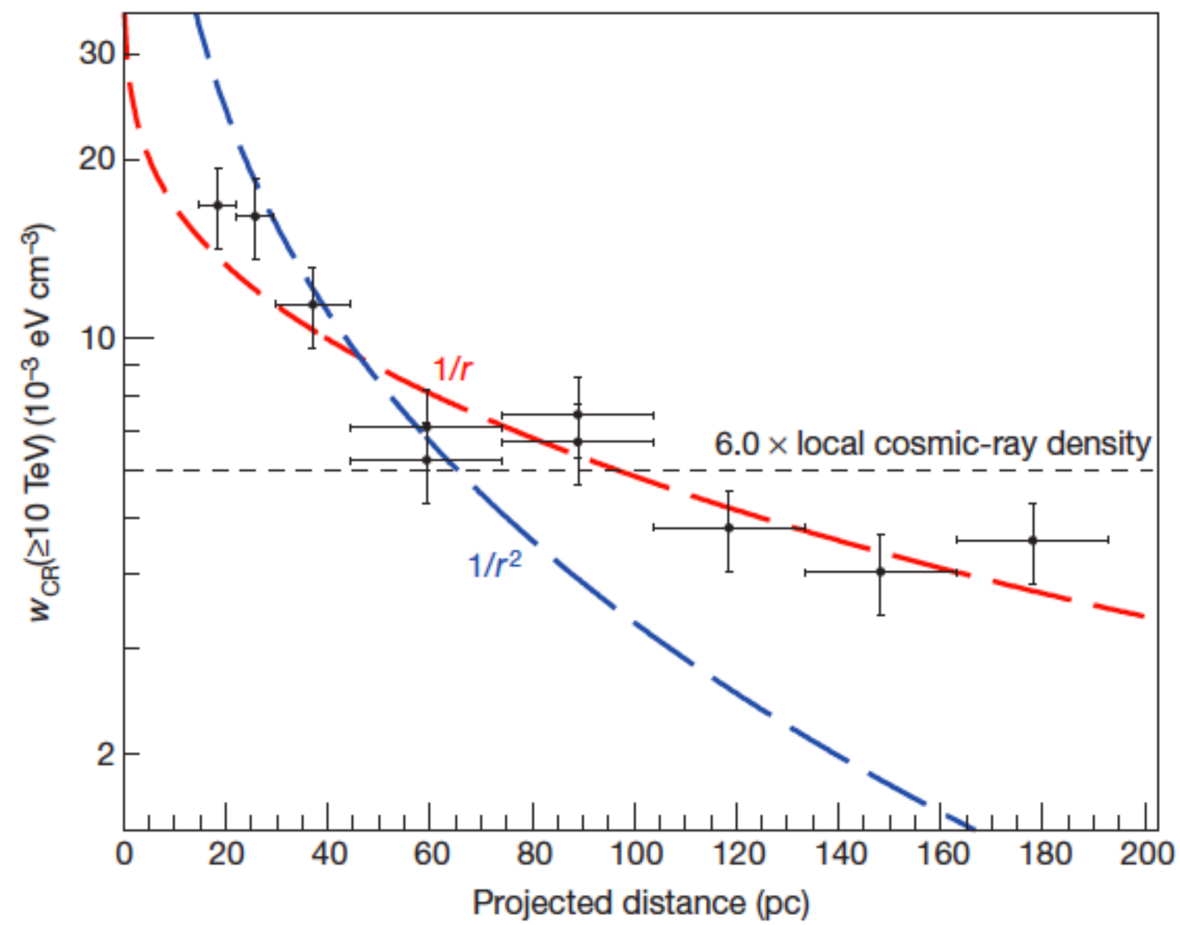


- At the GC the emission profile seems more peaked than the estimated gas distribution which, however, may have been underestimated in the inner 50 pc ($1^\circ \simeq 150$ *pc* at the GC)

- The inferred CR density profile (which again is based on the poorly known gas distribution) 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 $D(E) \propto E^{\delta}$

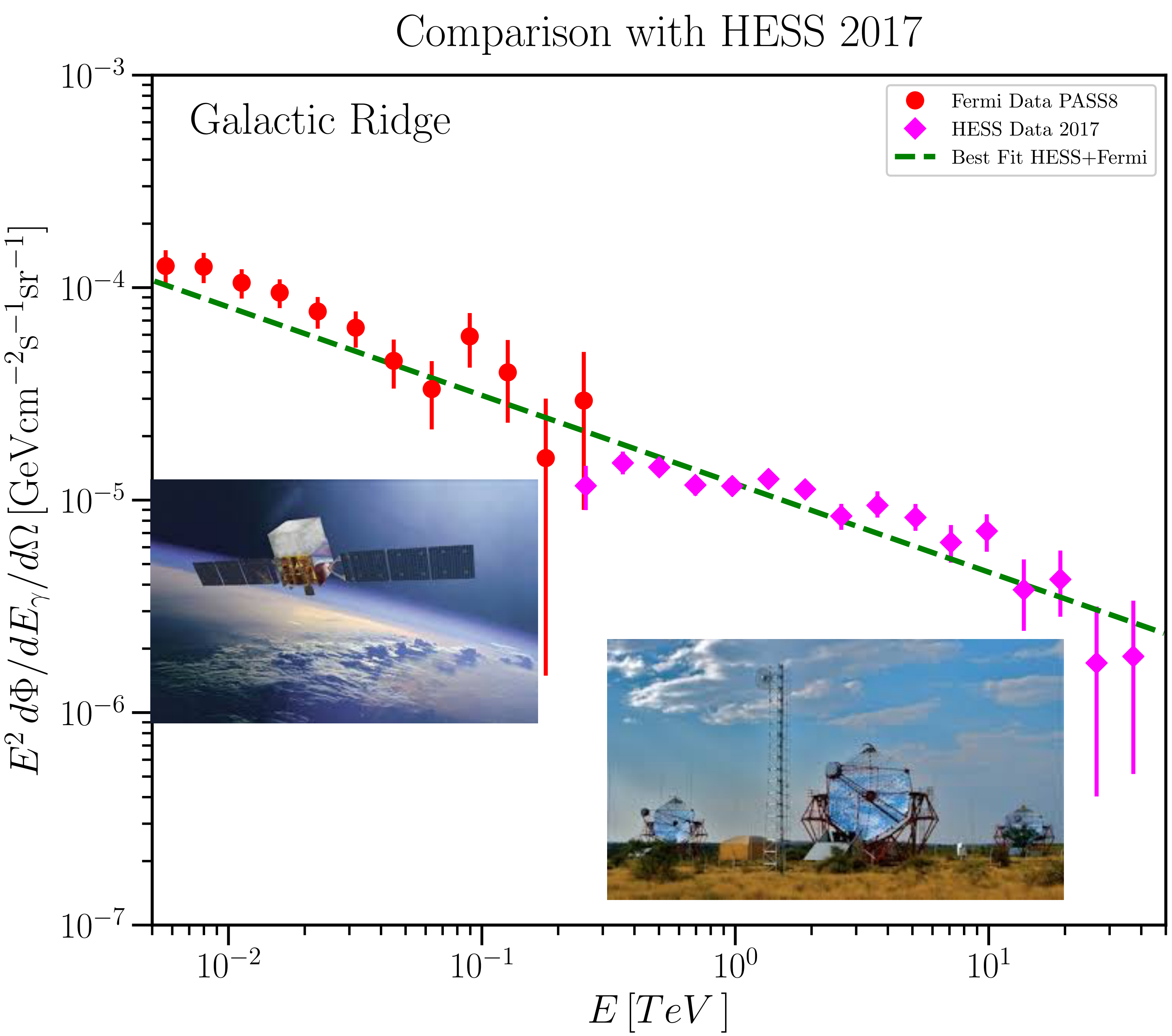
in order to explain the observed spectrum
either $\Gamma_{\rm src}$ or δ should be different from local values !

$|l| < 1°, |b| < 0.3°$

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

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

" + S.Ventura (ICRC 2017)



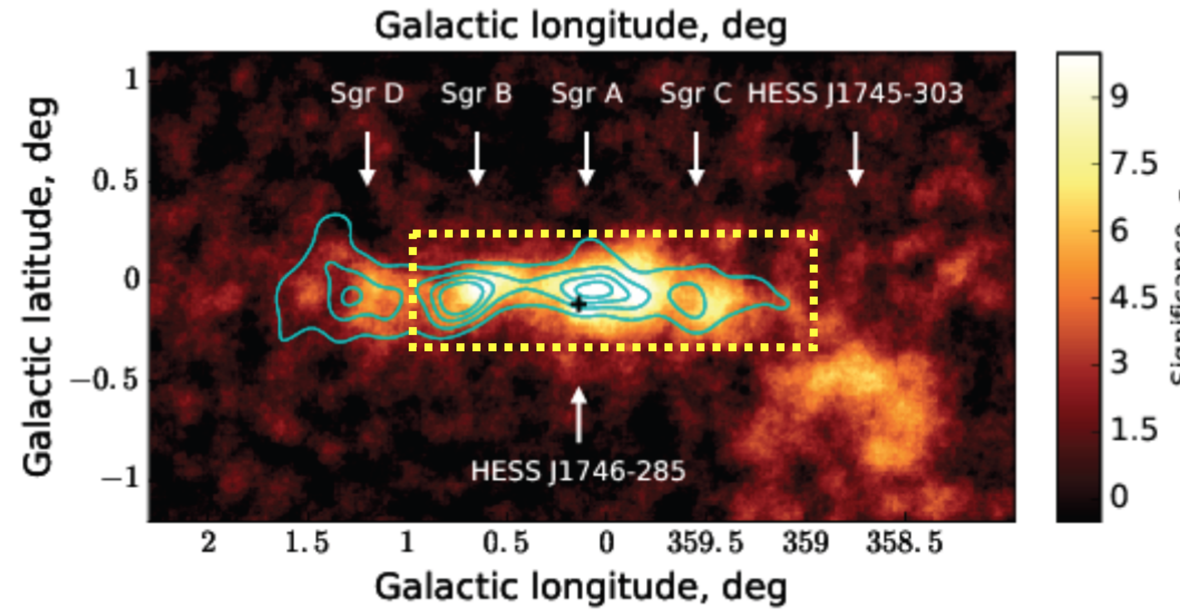


TABLE 4.1: *Power-law* model best-*fit* parameters.

Region	Normalization (GeV cm^2 s sr)$^{-1}$	Index Γ	χ^2_{red}
Galactic Ridge	$1.19 \cdot 10^{-5} \pm 0.05$	2.42 ± 0.02	2.18
Pacman	$1.33 \cdot 10^{-5} \pm 0.06$	2.45 ± 0.02	1.19
Sagittarius B	$2.05 \cdot 10^{-5} \pm 0.65$	2.33 ± 0.07	0.57

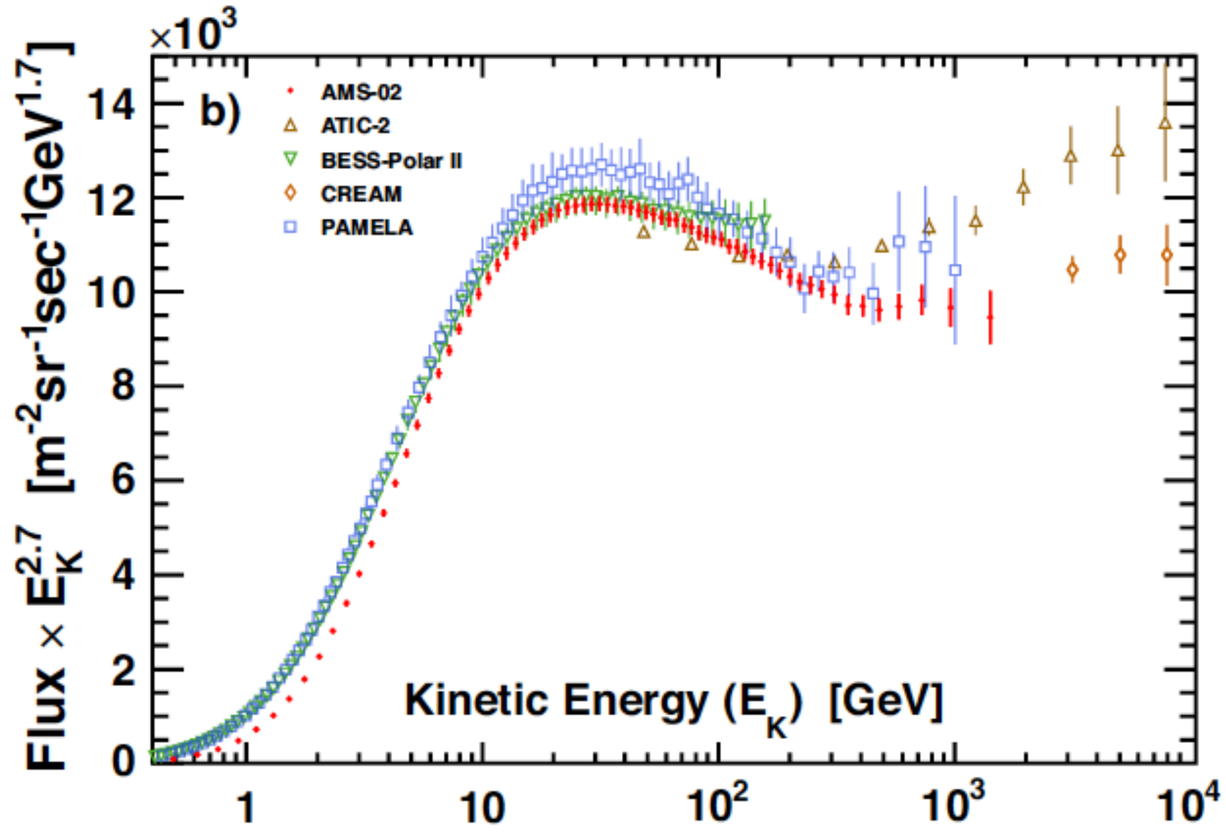
PASS8 Fermi-LAT 470 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FGL catalogue subtracted.

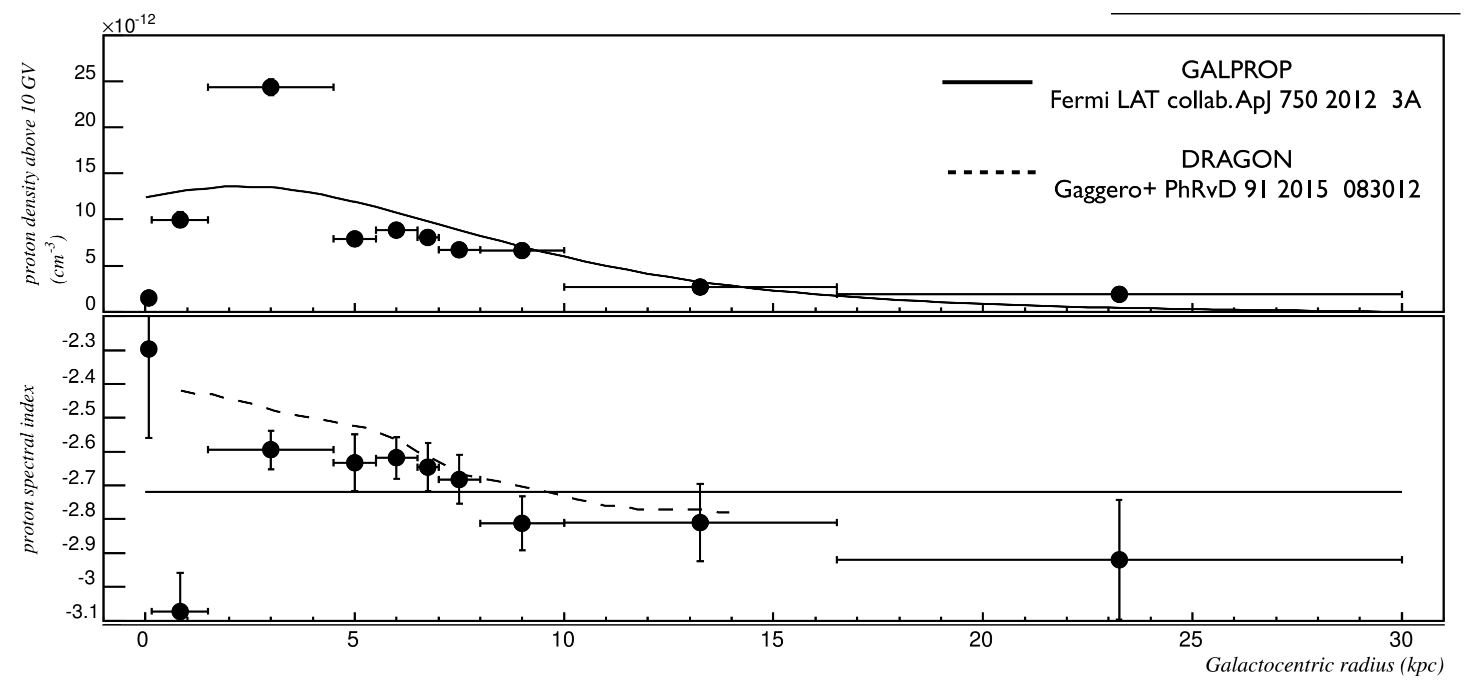
ADDING NEW PIECES TO THE PUZZLE

The GC PeVatron interpretation does not account for two new features which do not fit the conventional scenario

1. the CR hardening found by PAMELA, AMS and CREAM @ 300 GeV/nucleon

2. the CR proton spectral index radial gradient found in the Fermi-LAT data

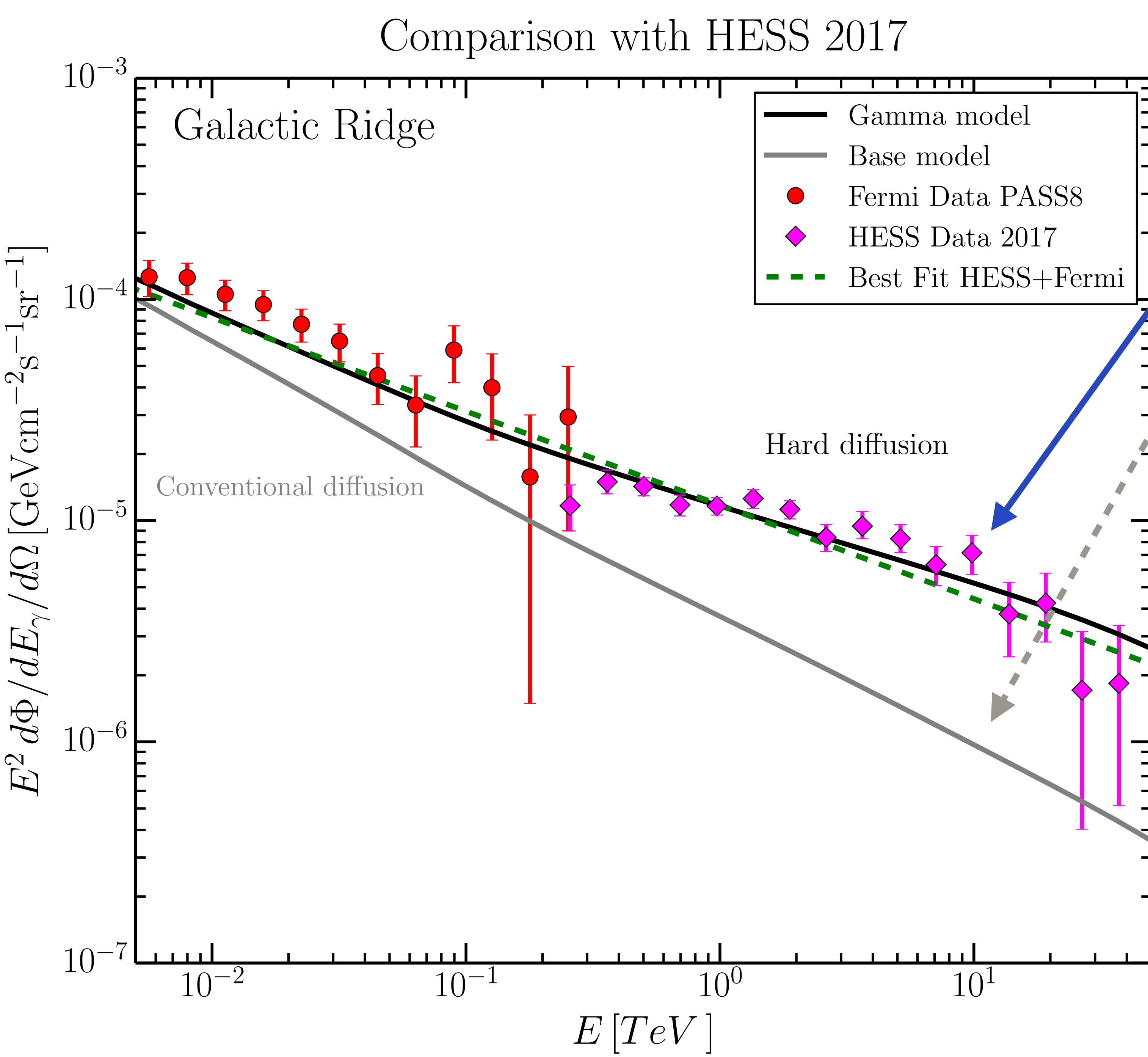




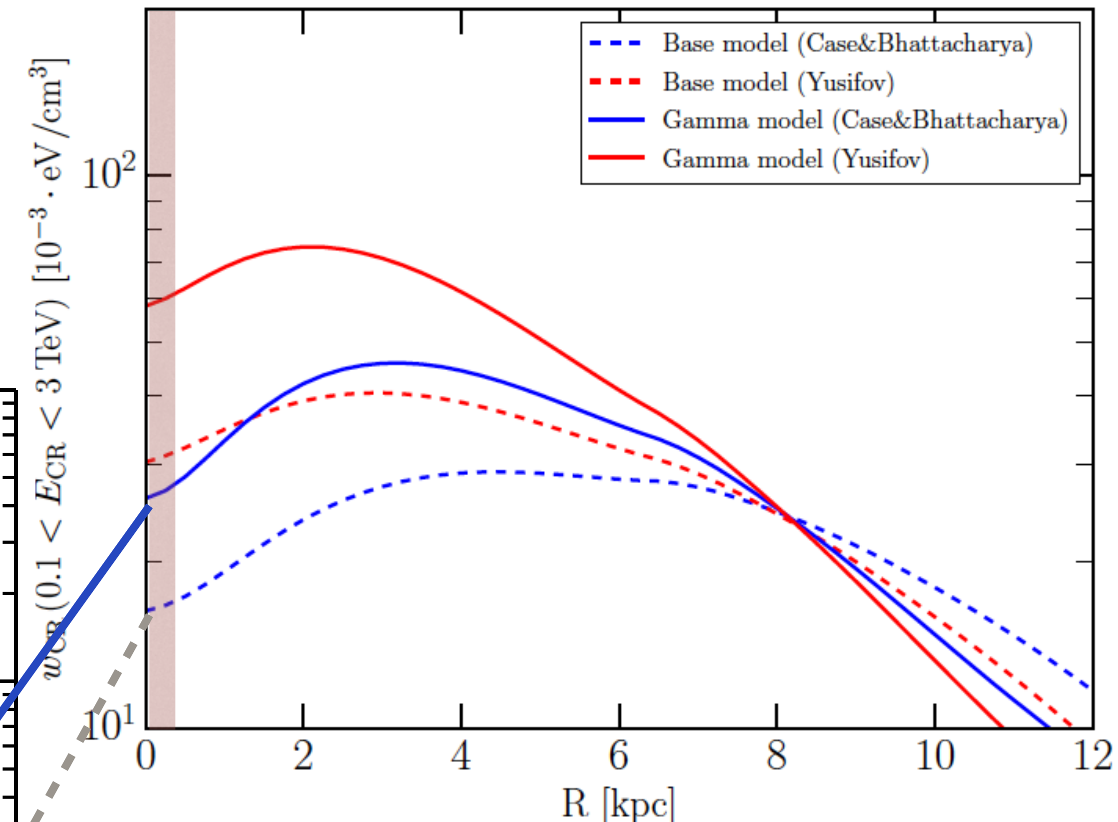
The effect of the new CR sea at the GC

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

" + *S. Ventura (ICRC 2017)*



| l | < 1° , | b | < 0.3°



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

Here we use the *Ferriere 2007* 3-D gas model choosing a normalisation (X_{CO}) such to match the gas column density maps adopted by HESS and *Case & Batthacharya* SNR distribution.

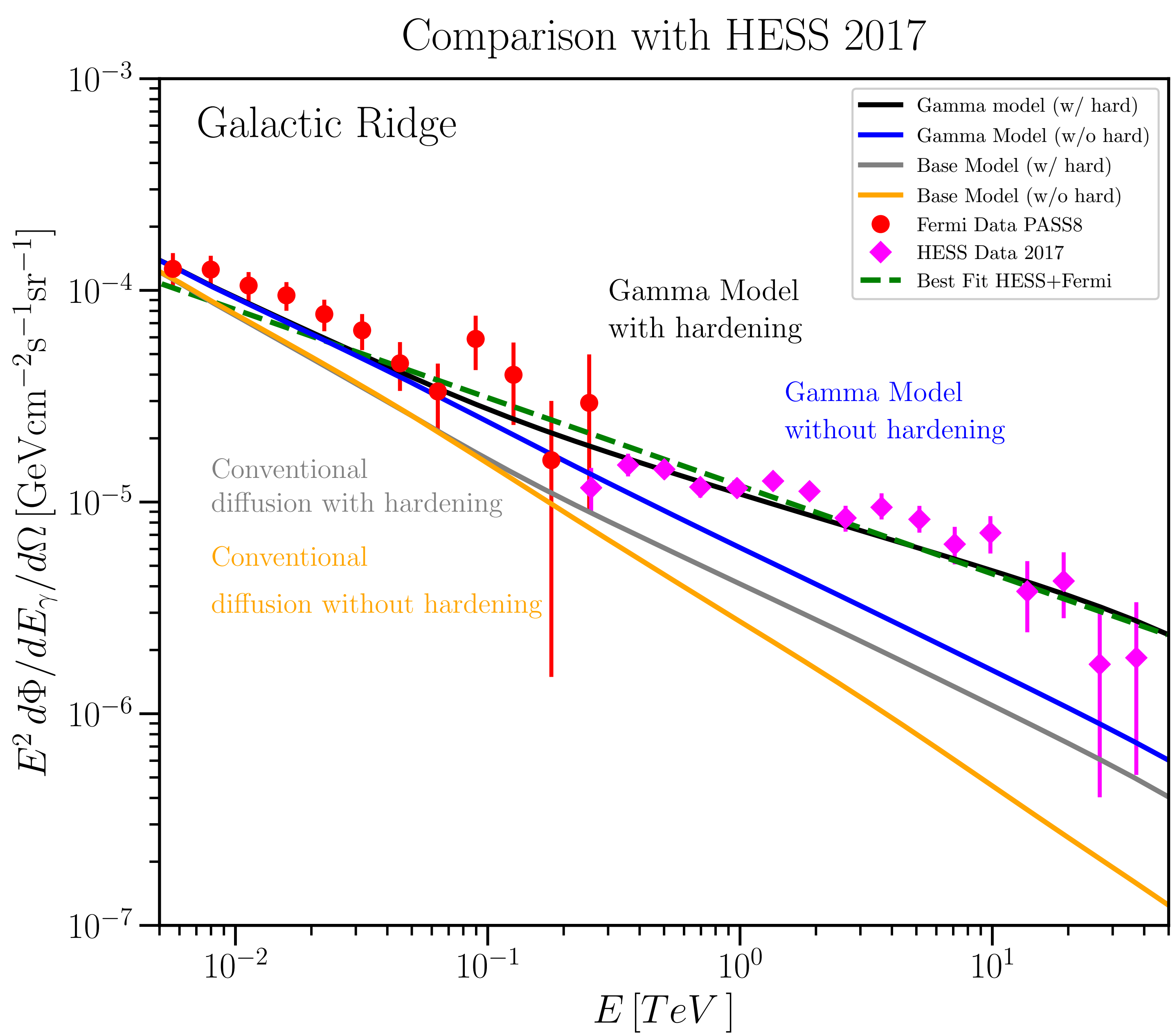
The effect of the new CR sea at the GC

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

“ + S.Ventura (ICRC 2017)

$|l| < 1°, |b| < 0.3°$

Similarly to the solution of the Milagro anomaly
both the radial hardening and CR global hardening are required to match the data.



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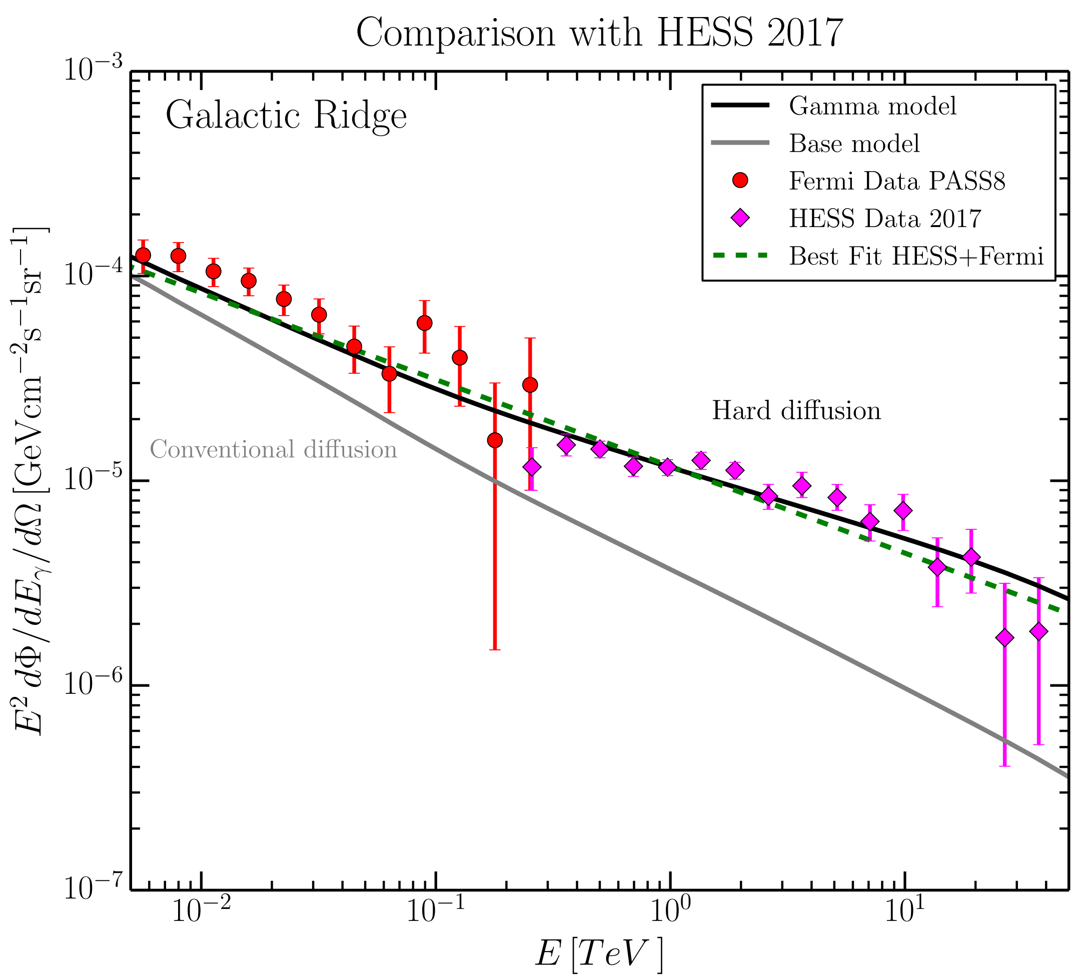
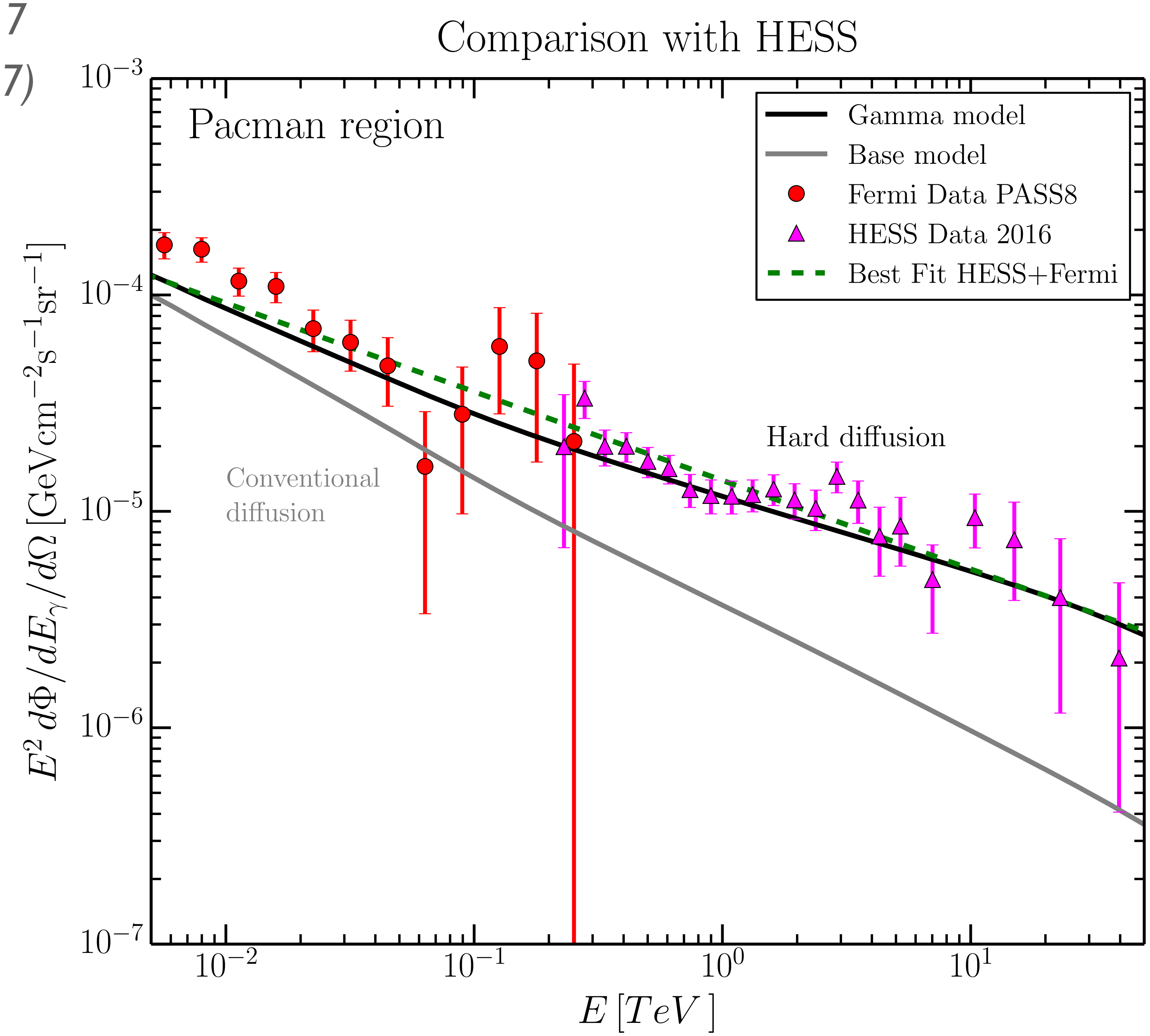
" + S.Ventura (ICRC 2017)

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

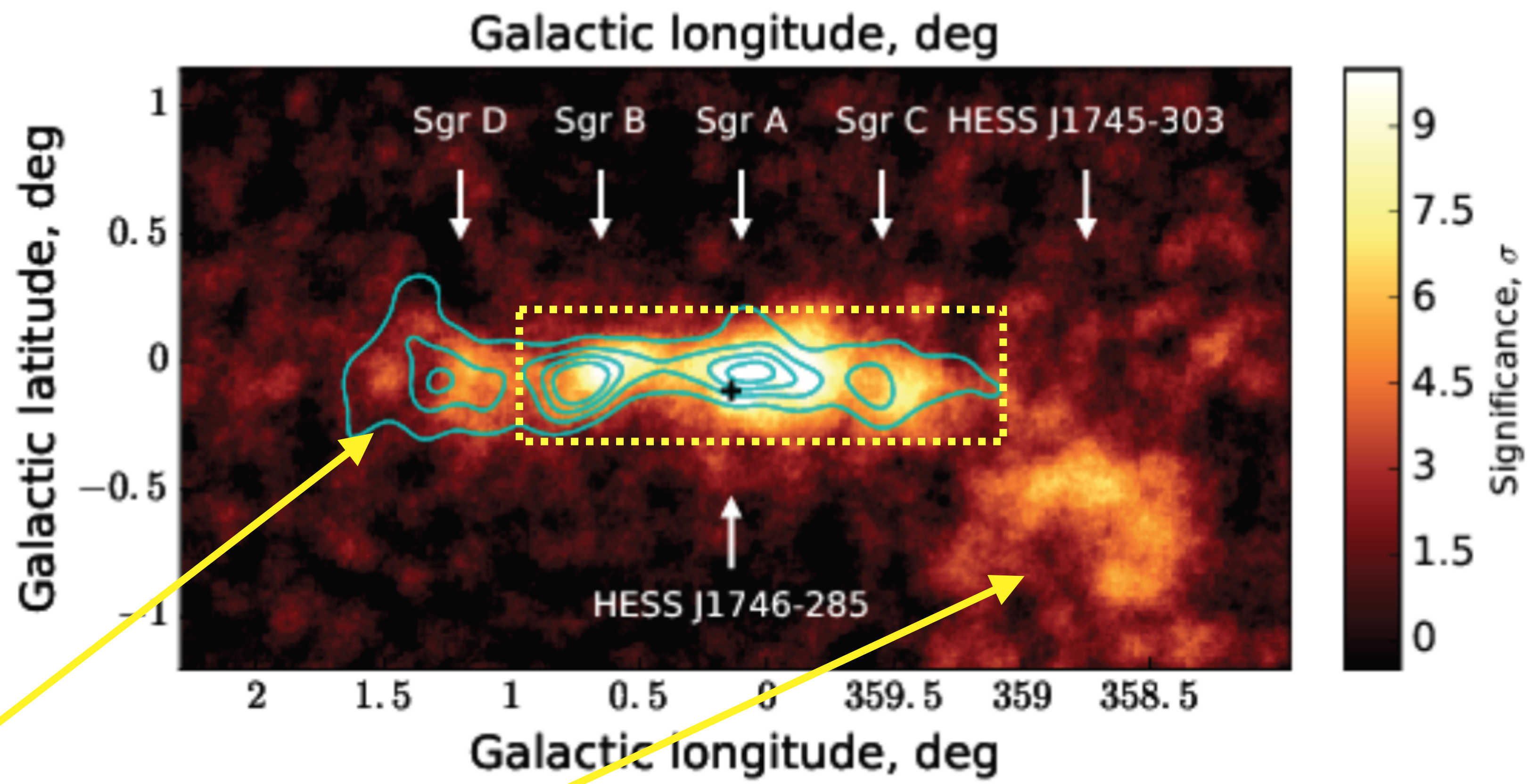




No need of a PeVatron if the CR radial and global hardening at the GC

Future perspectives

CTA may observe more external clouds where the PeVatron scenario predicts a lower CR density than that expected in our scenario

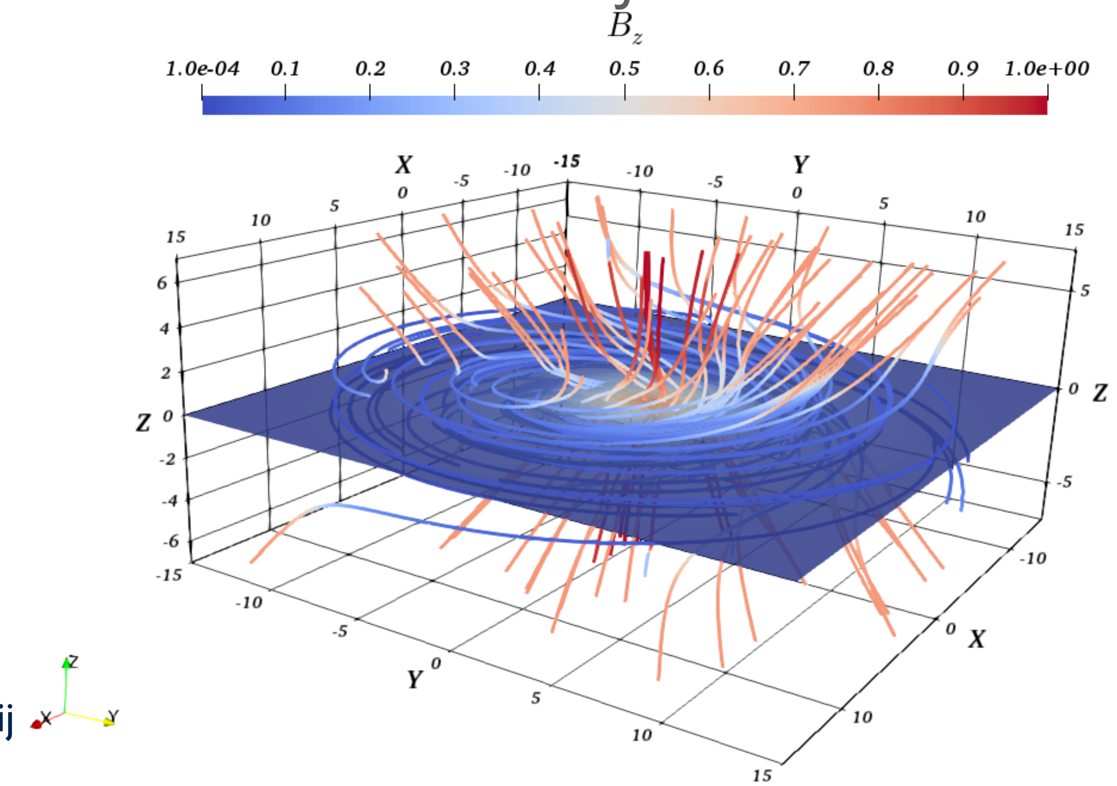


A possible theoretical interpretation

Cerri, Gaggero, Vittino, Evoli & DG, arXiv:1707.07694

Anisotropic CR diffusion is expected for theoretical reasons and may be required to explain the CR gradient and isotropy problem in the presence of a poloidal magnetic field component (see e.g. *Evoli et al. PRL 2012*)

MF model *based on Jansson & Farrar 2012*



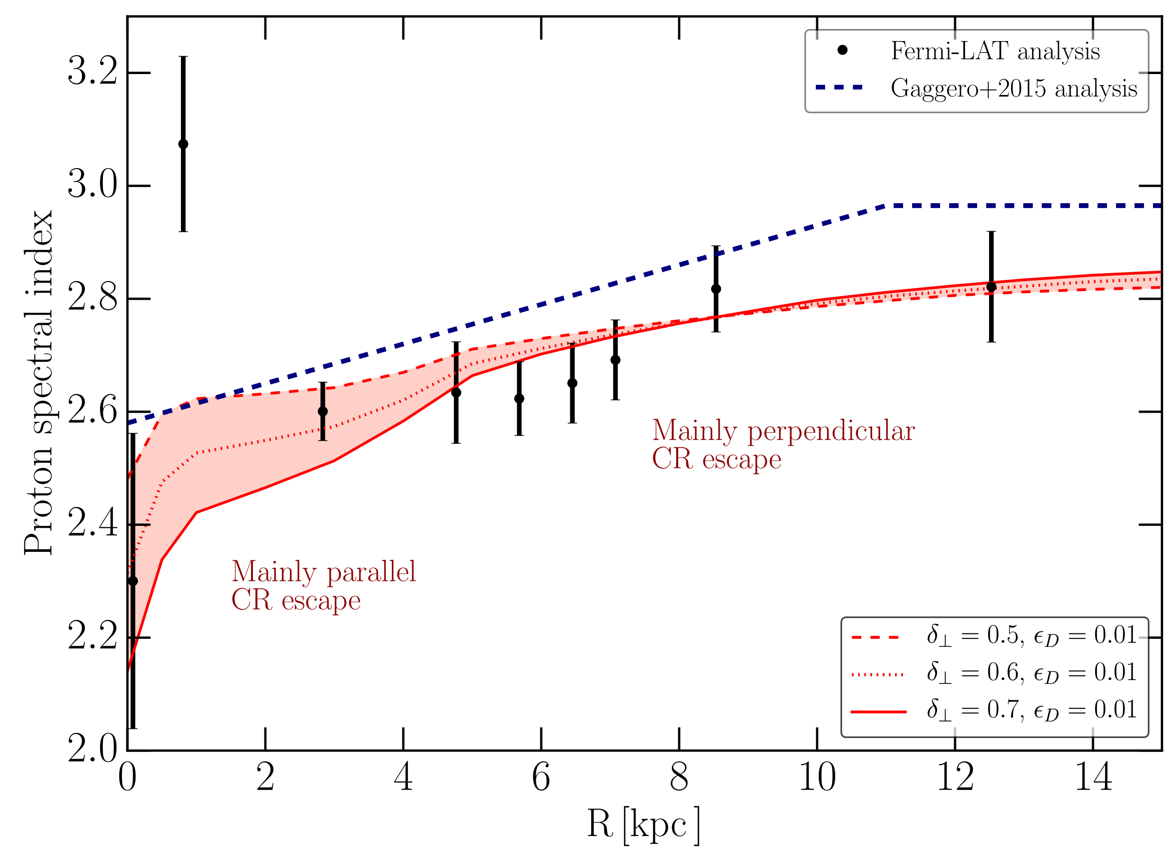
$$D_{ij}(\mathbf{x},\rho) = [\, D_{\parallel}(\mathbf{x},\rho) - D_{\perp}(\mathbf{x},\rho)\,]\, b_i\, b_j + D_{\perp}(\mathbf{x},\rho)\, \delta_{ij}$$

$D_{\parallel}$ and $D_{\perp}$ are expected to have different rigidity dependence (*Blasi, De Marco, Stanev 2007 and Snodin et al. 2012*) found

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

for Kolmogorov turbulence.

We incorporated this behaviour in the DRAGON 2 code (*Evoli, Gaggero, Vittino,, Di Bernardo, Ligorini, Di Mauro, Ullio, DG , JCAP 2017)* allowing for anisotropic diffusion



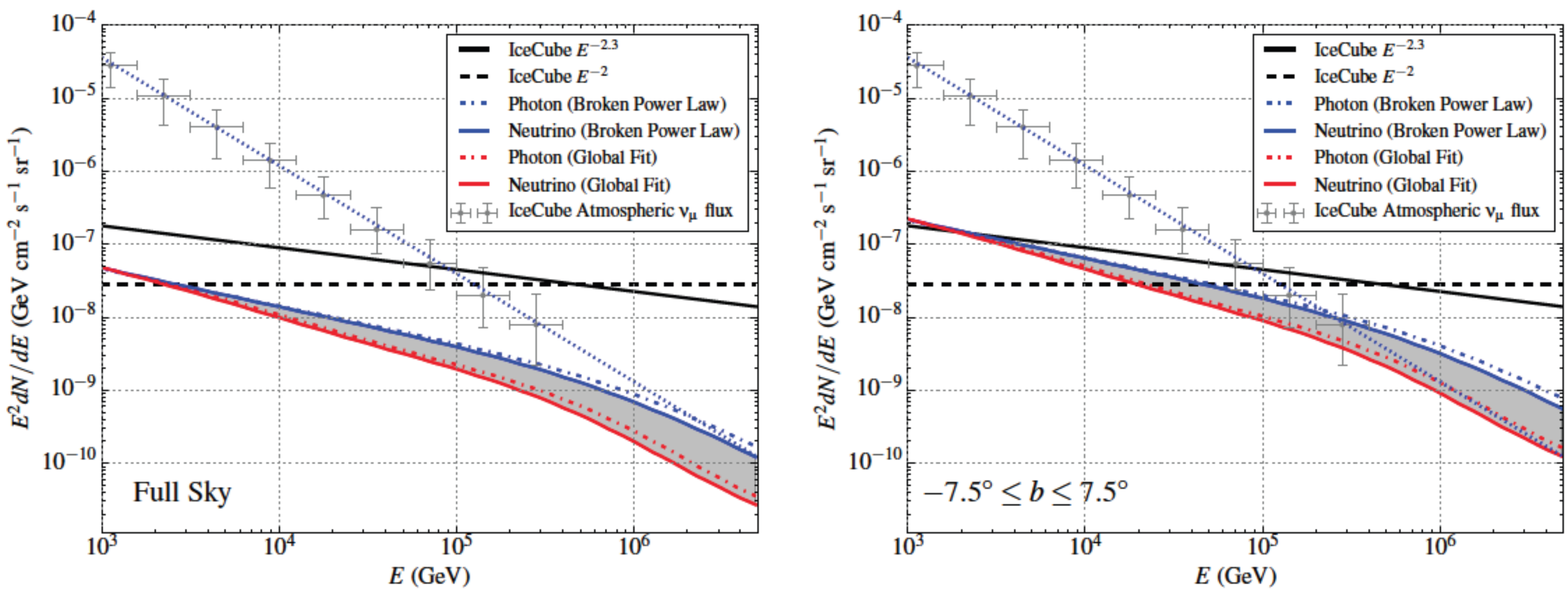
Implications for neutrino astronomy

Due to the interaction of the hadronic component of Galactic cosmic rays with the ISM gas

- *Berezinsky & Smirnov 1975* (uniform CR and gas densities)
- *Stecker 1979* “
- *Gaisser, Berezinsky, Halzen, Stanev 1993* (uniform CR, realistic gas distribution)
- *Evoli, DG, Maccione, 2007* (CR distribution computed with diffusion code, realistic gas)

- *Ahlers et al. 2015* (CR distribution computed with GALPROP, realistic gas)

8% of IceCube HESE (2013) signal at most



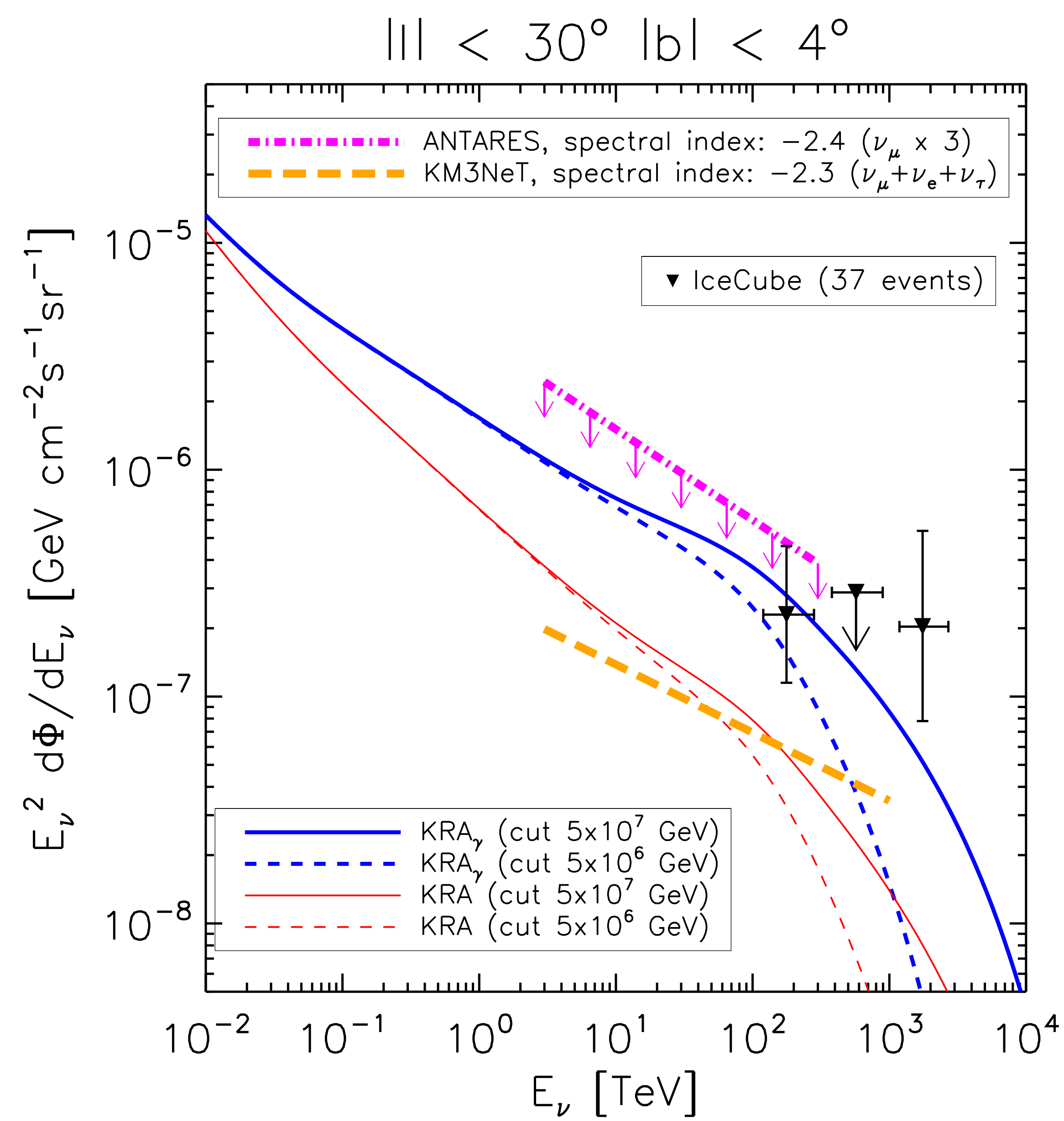
Implications for neutrino astronomy

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

ANTARES coll. , Phys. Lett. B, 2016

ANTARES coll. + *D. Gaggero, D.G.* arXiV:1705.00497

- On the whole sky the diffuse flux due to the Galaxy is 15 % **at most** (8 % for conventional models) of that measured by IceCube. IceCube limit 16 % (*M. Ackermann this workshop*)
- In the inner Galactic plane however the gain is much larger ➡
- A neutrino telescope in the North hemisphere is more suited to detect the Galactic component. IceCube coll. is using our templates to look for this Galactic component. ANTARES present upper limit is at 1.25 times our most optimistic prediction. Observable by KM3NeT (work in progress) !



see arXiv:1705.00497 PRD 2017 and Marinelli's talk for ANTARES updated limits

CONCLUSIONS

- Recent CR and γ-ray data show that the Galactic CR spectrum is not a single power-law and it may depend on the distance from the GC
- Accounting for those features FERMI, Milagro and HESS results can be consistently be reproduced in terms of the Galactic CR sea emission only. This suggests that the CR spectral index gradient is present also above the TeV and that CR hardening is a global effect.
- CTA may confirm the scenario we proposed observing the emission from molecular clouds at distances > 200 pc from the GC
- The neutrino emission from the Galactic ridge is expected to be significantly enhanced respect to conventional models and be detectable by KM3NeT . IceCube may also detect a larger emission from the galactic plane.
- Those results strongly motivate to go beyond conventional modelling of CR propagation in the Galaxy

BACKUP SLIDES

Sgr B

0.4° < l < 0.9° , - 0.3° < b < 0.2°