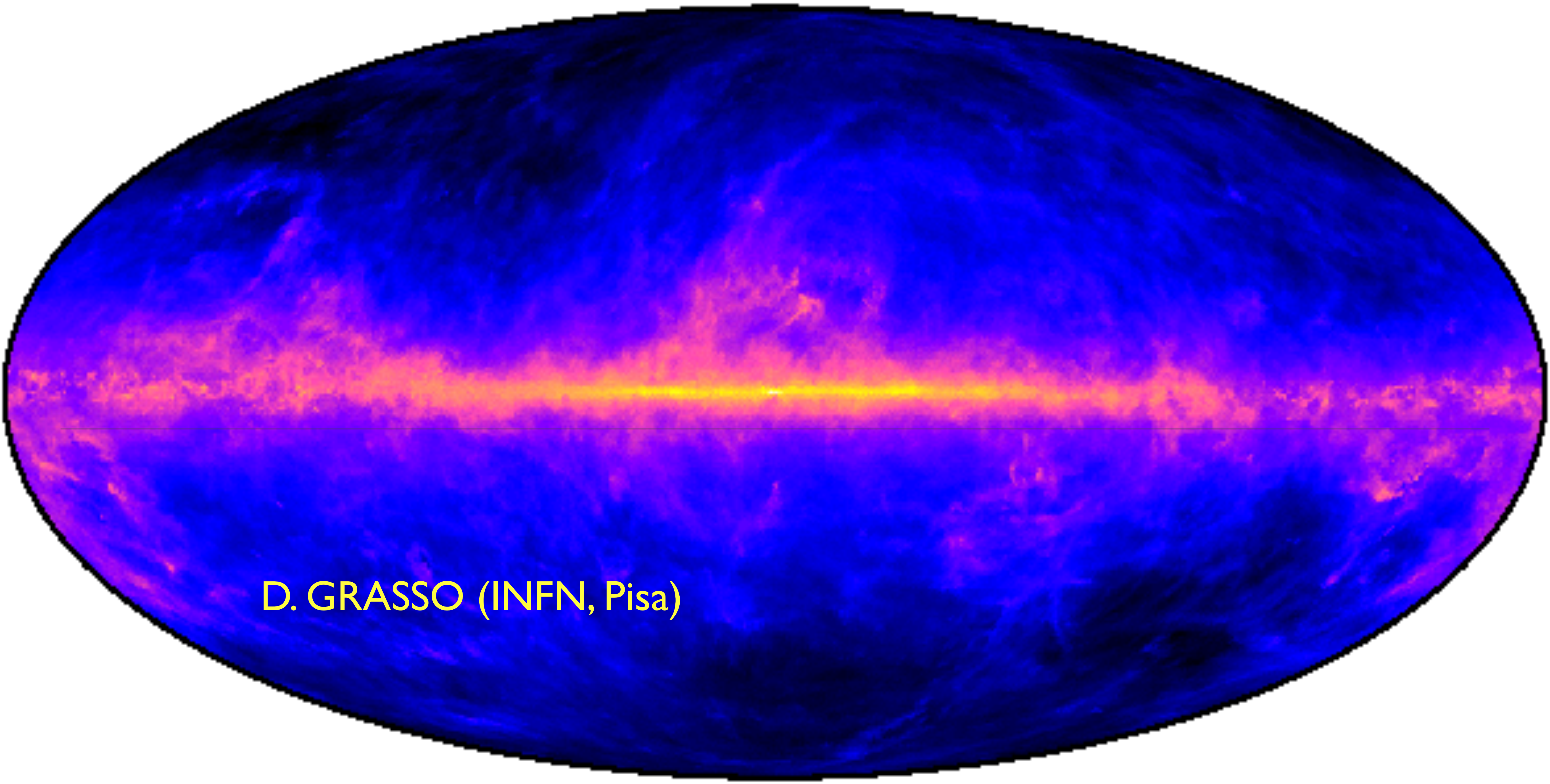
Probing particle transport in the Galaxy with gamma rays



D. GRASSO (INFN, Pisa)

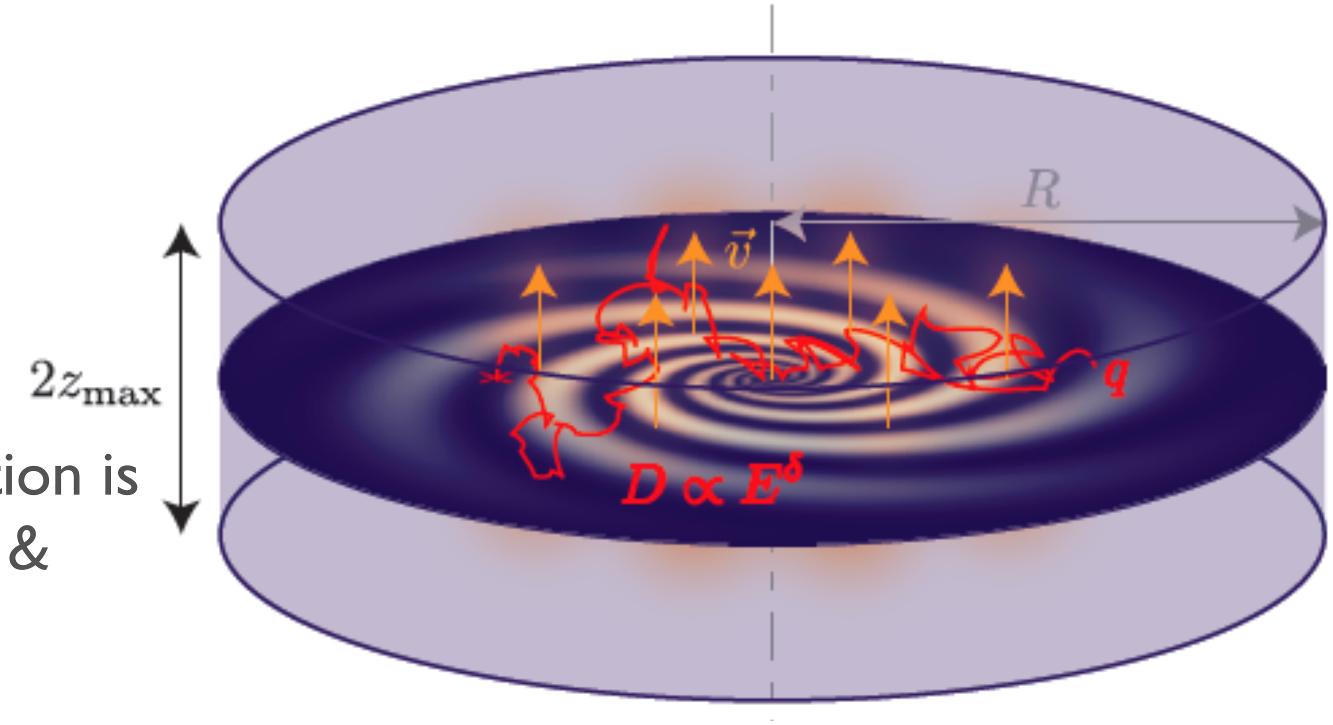
GGI Conference: Collider Physics and the Cosmos, Arcetri 2017

OUTLINE

- The conventional treatment of cosmic ray (CR) propagation in the Galaxy and γ-ray diffusion emission modelling
- some anomalies in the CR and γ-ray data
- theoretical reasons to go beyond the conventional approach
- possible solutions of some anomalies and their implications

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*) under **several assumptions**

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

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

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

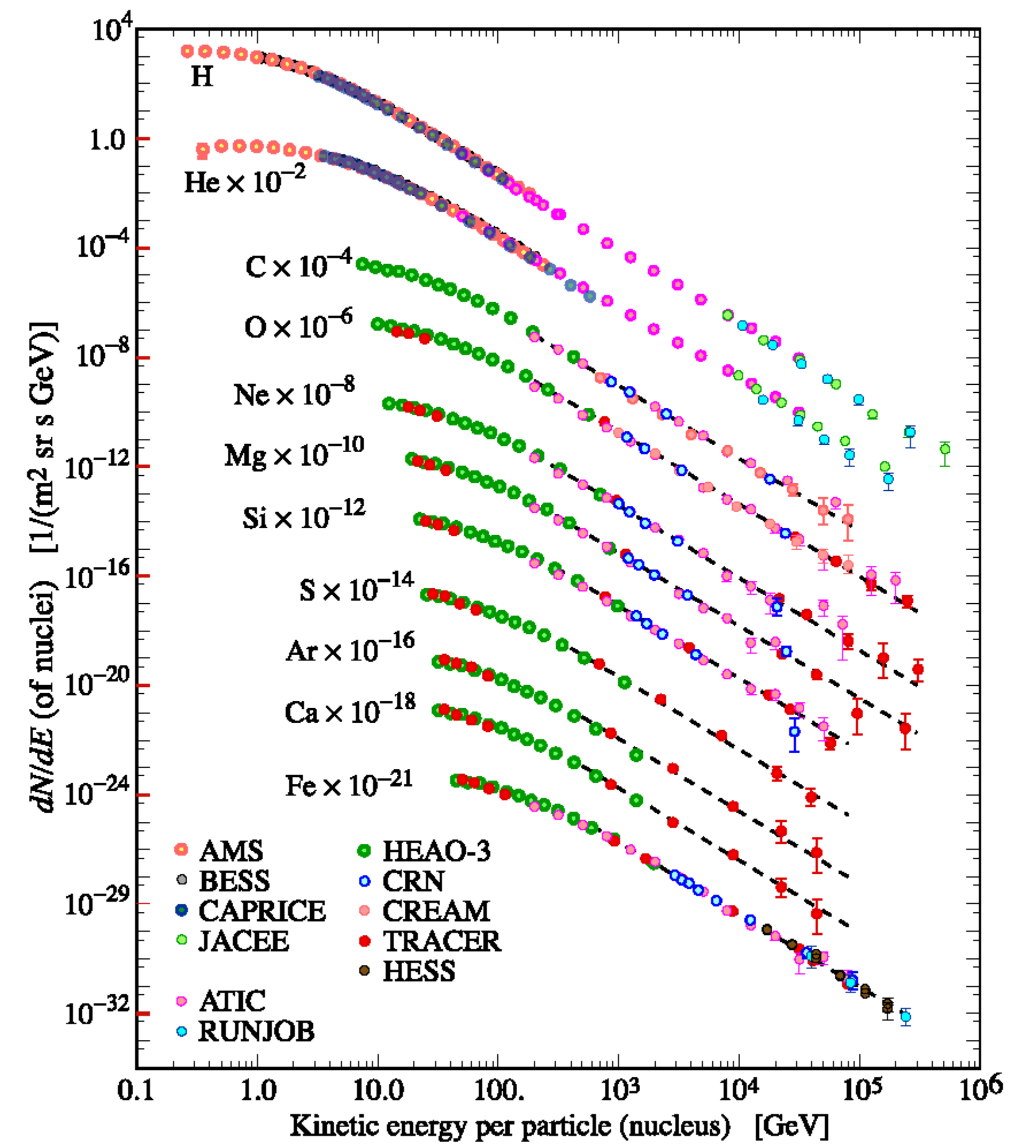
$$D(E) = D_0\ (E/E_0)^{+\delta}$$

D_0 and δ are free parameters to be tuned on data assumed to be uniform

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

$$\Phi_i(E) \propto Q/D \propto (E/E_0)^{-(p(i) + \delta)}$$

single power-law spectra expected



CR transport in the Galaxy

charged secondary species

The interaction of primary with the interstellar medium give rise to several secondary charged species: rare nuclei, antiprotons, positrons

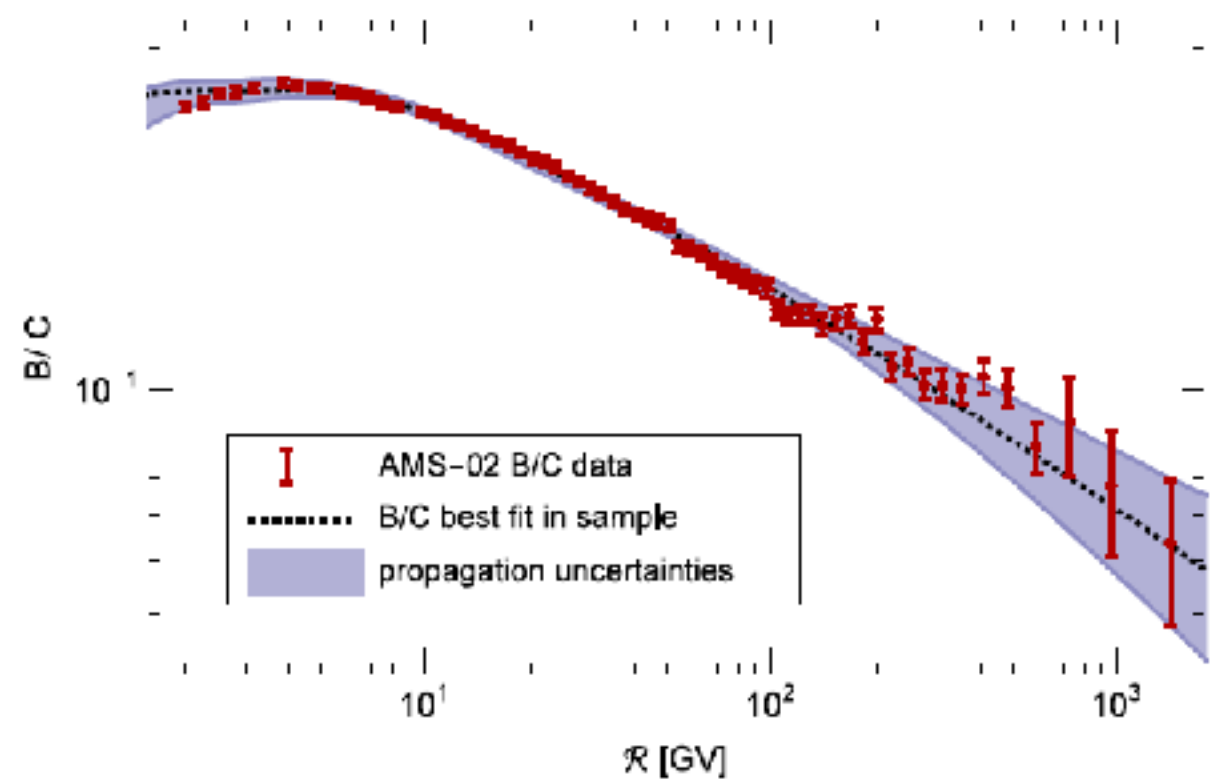
their spectrum is expected to be steeper than primaries (for E ≫ 10 GeV/n). For nuclei

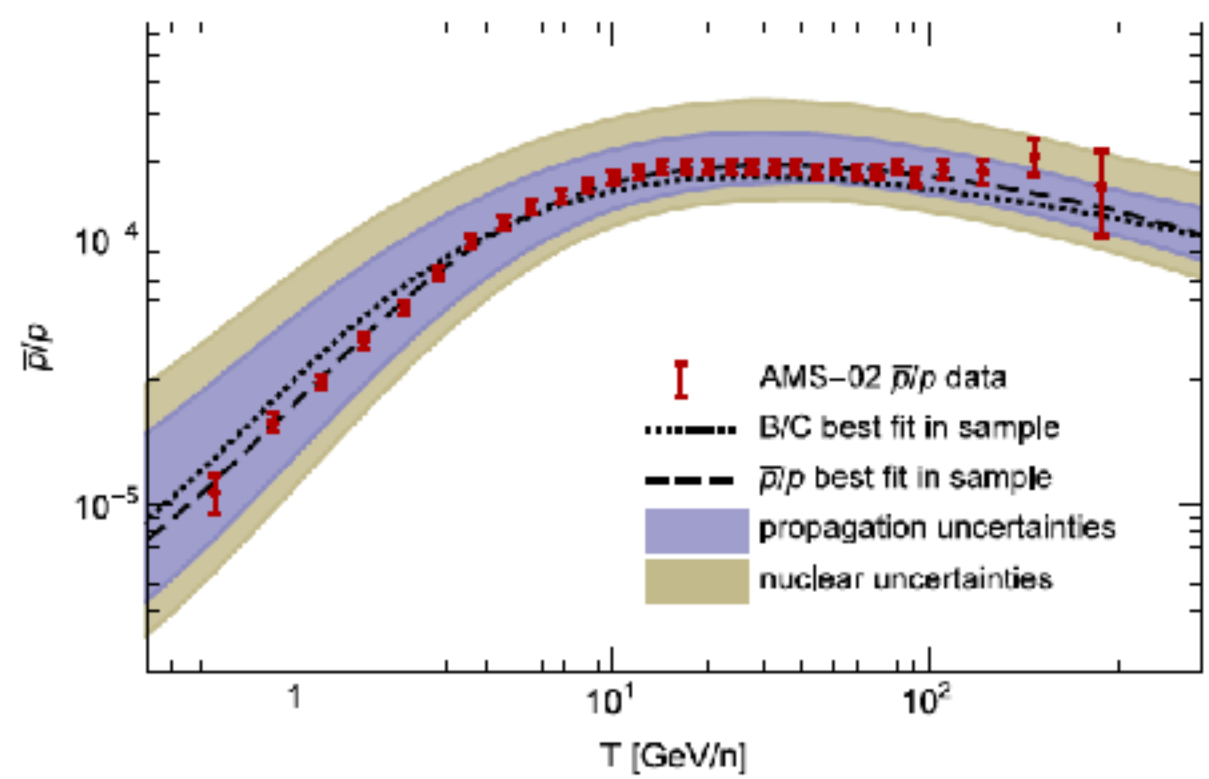
$$\Phi_S(E)/\Phi_P(E) \propto \tau_{esc} / \tau_{int} \propto E^{-\delta}$$

their spectrum is used to estimate propagation parameters (keep in mind however that charged secondaries probe a relatively small region around the Earth ~ few kpc)

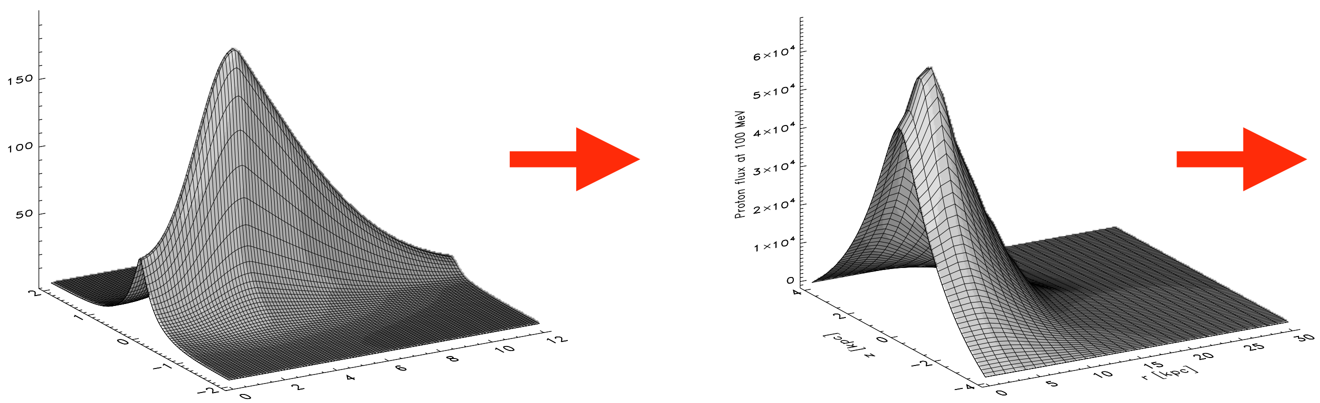
they are a background for indirect dark-matter search

R. Kappl & M.W. Winkler, 1506.04145

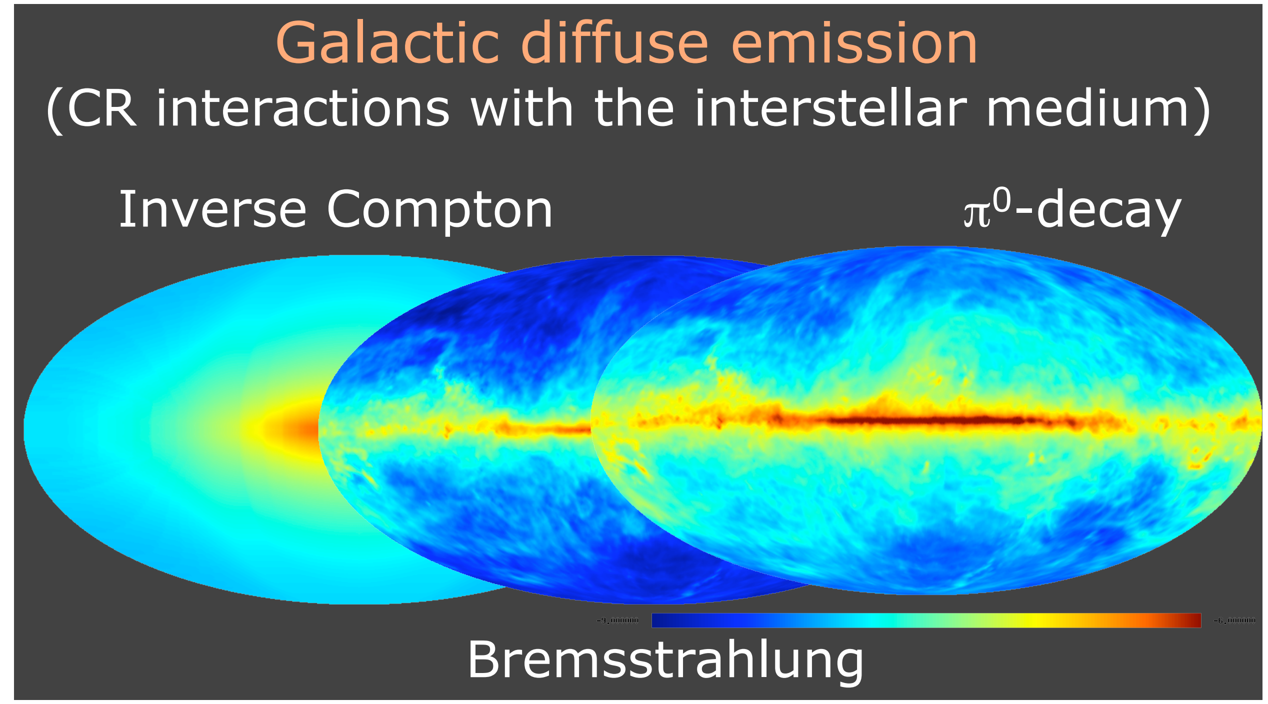


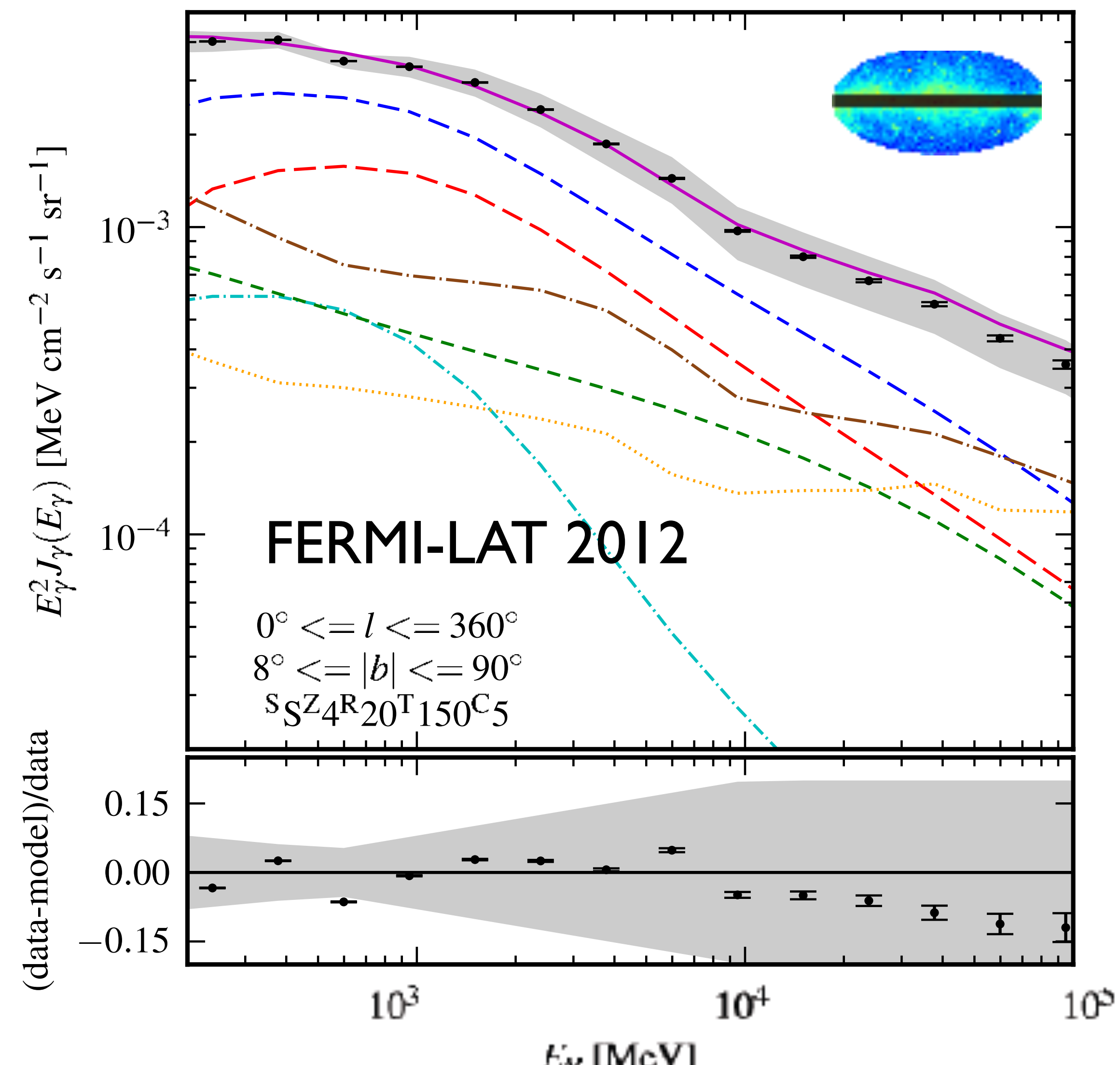


The γ-ray diffuse emission



(a) Source term (b) Propagated protons at 100 MeV





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 but requires detailed numerical modelling (see below)

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

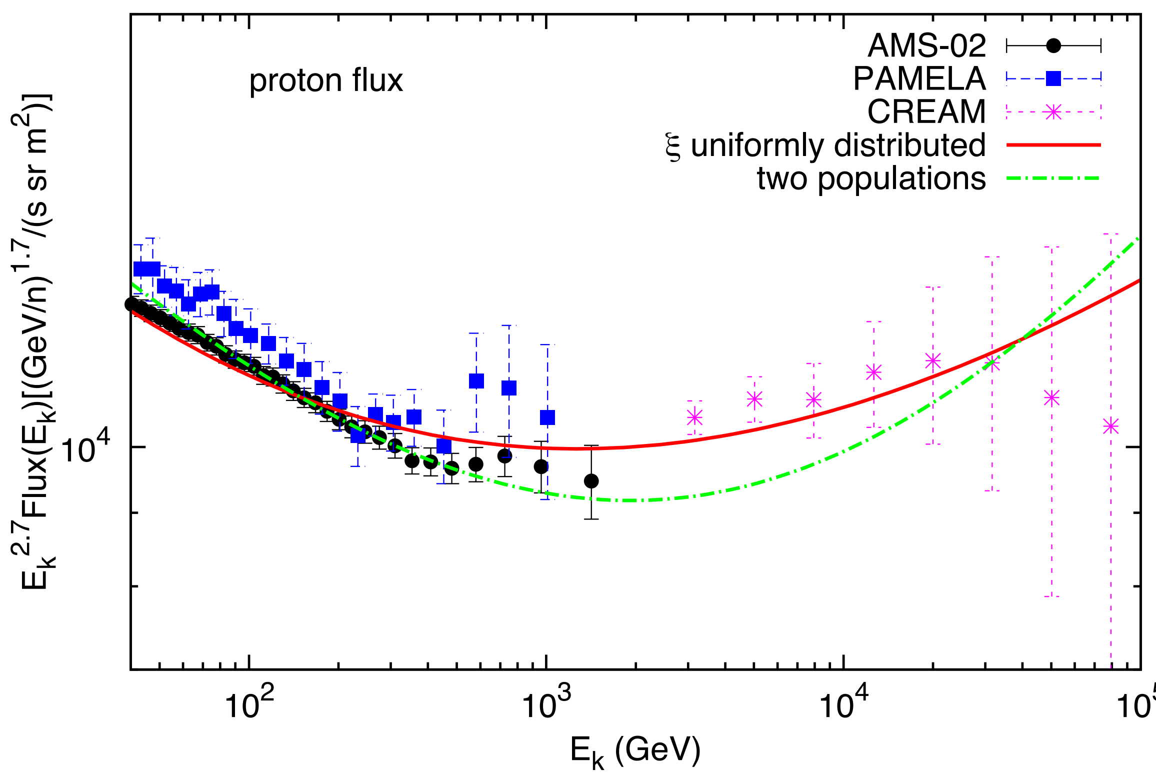
A successful approach

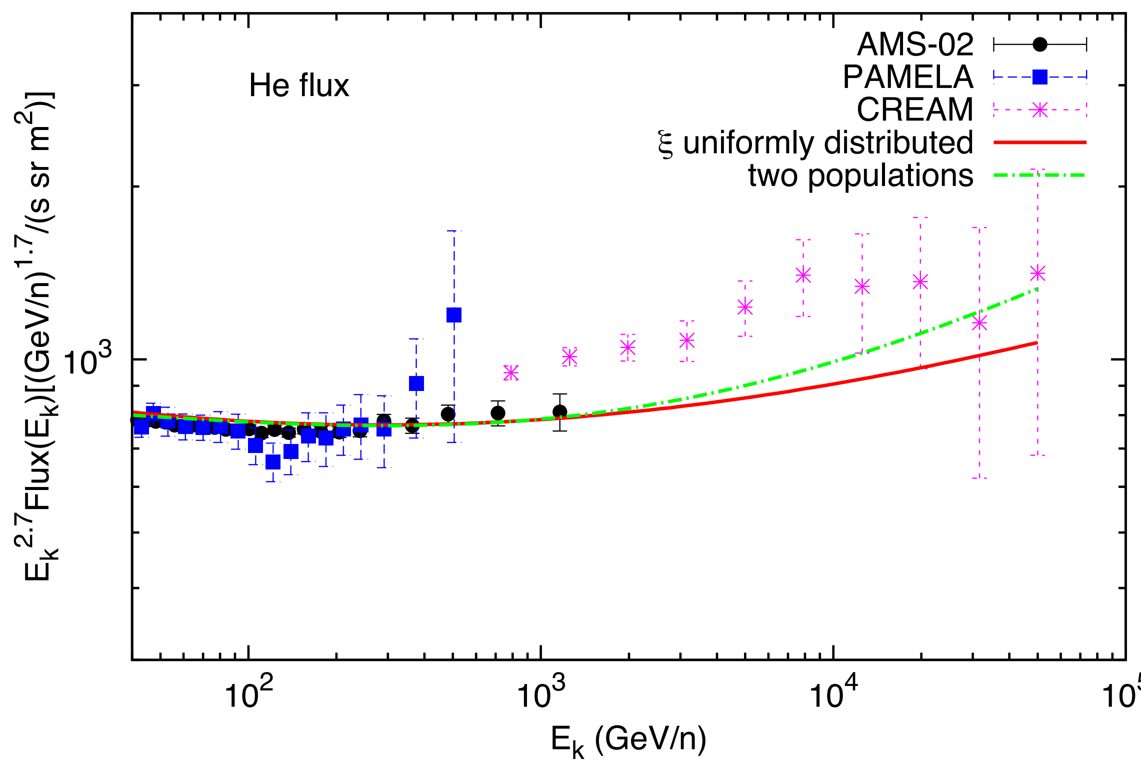
BUT ....

CR hardening @ 300 GeV/n

CREAM coll. ApJ Lett. 2010
PAMELA coll. SCIENCE 2011
AMS-02 coll. PLR 2015 , CALET ICRC 2017

Recchia & Gabici 2017





Several hypothesis for its origin:

- **source effect:** e.g. some modification of the acceleration spectrum due to non-linear effects (see e.g. *Caprioli 2012, Recchia & Gabici 2017*)
- **local effect:** nearby SNR (see e.g. *Thoudam & Hörandel 2011, Kachelriess, Neronov & Semikoz 2017*)
- **propagation effect:** e.g. due to inhomogeneous diffusion (*Tomassetti 2012*) or non-linear action between CR and MHD waves (*Blasi, Amato & Serpico 2011*)

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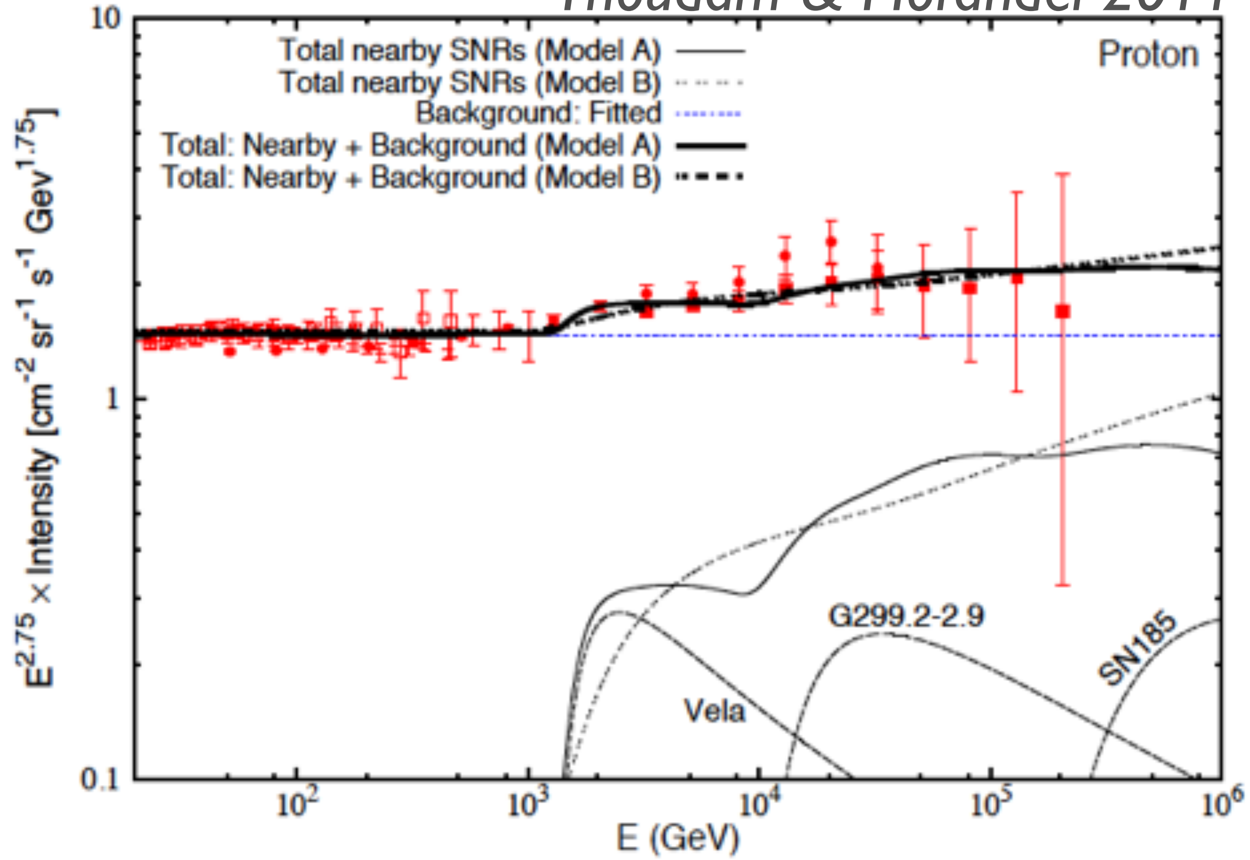
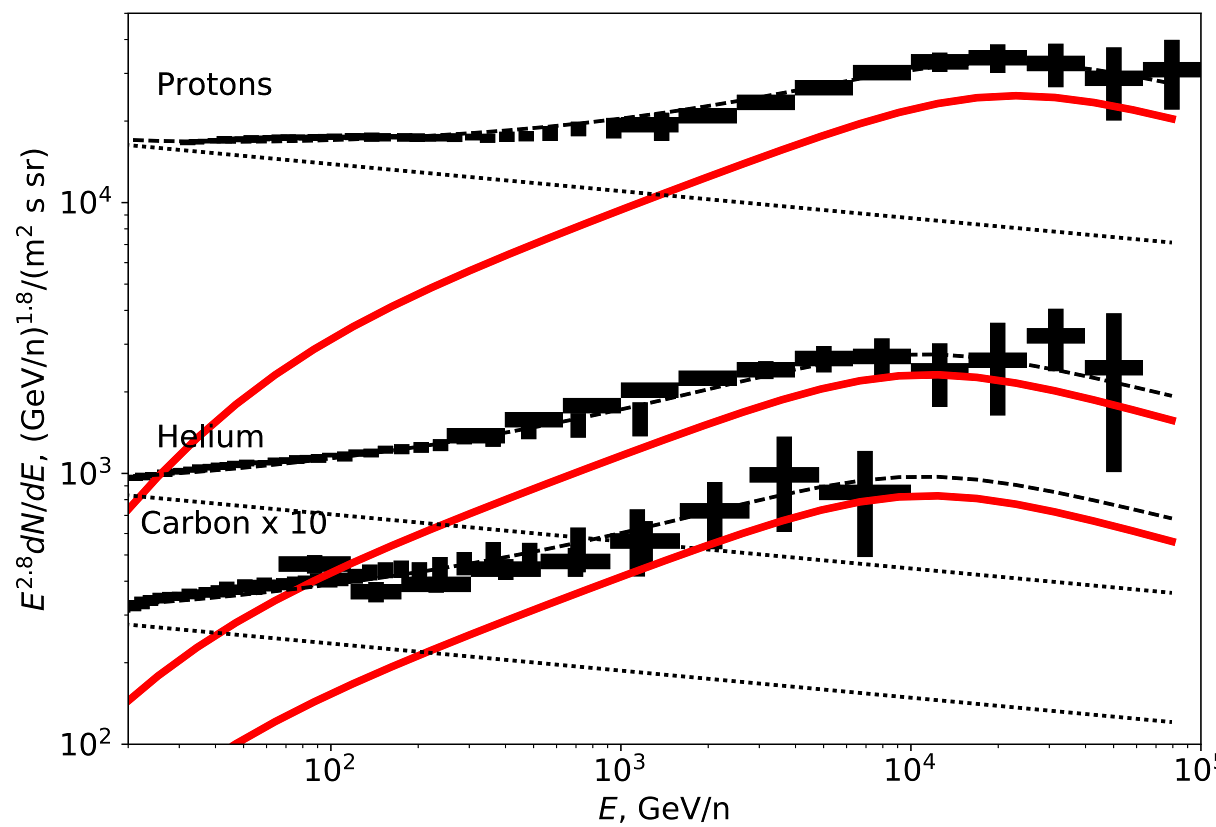
Thoudam & Hörandel 2011



Kachelriess et al. 2017



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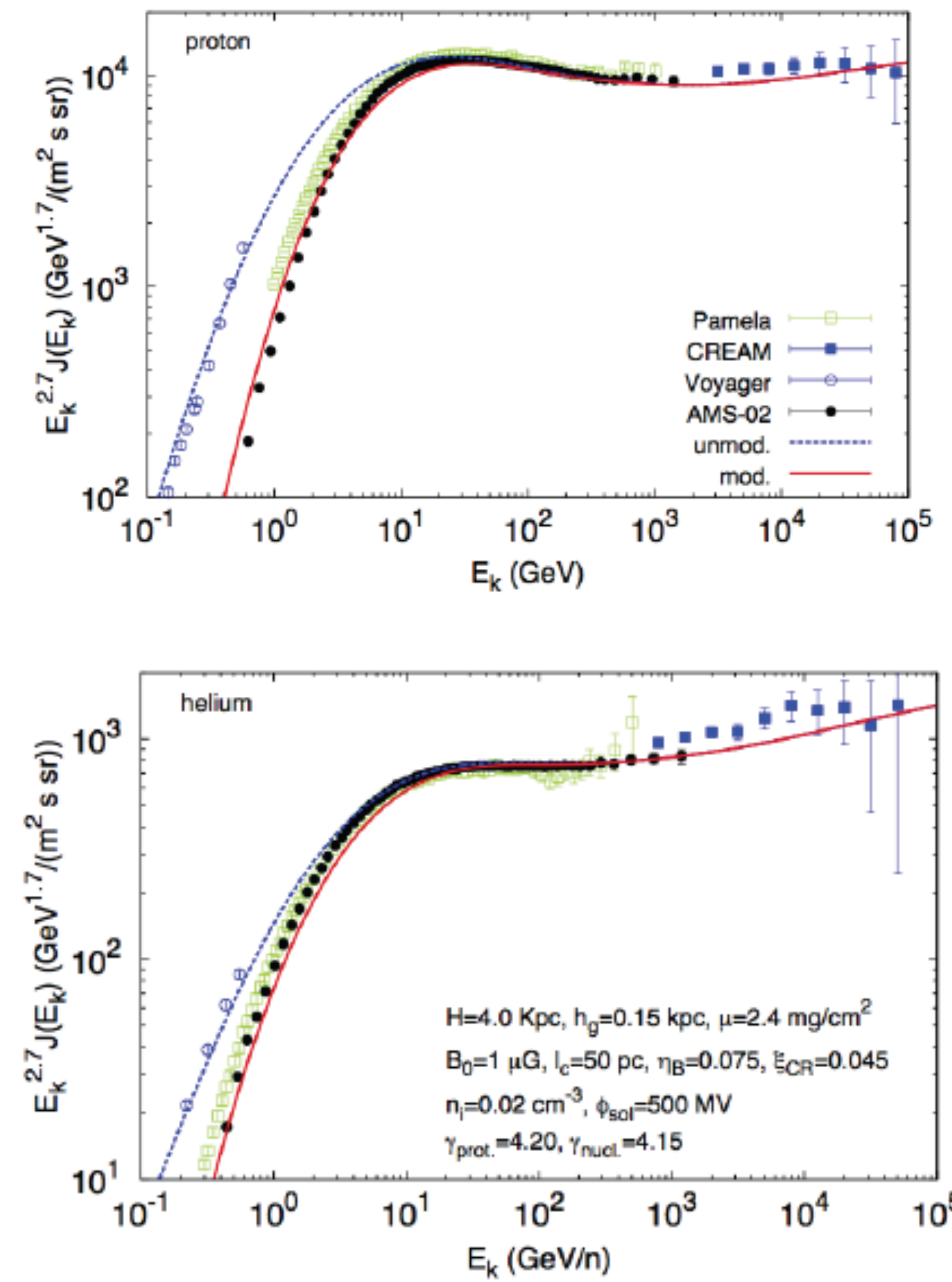
Tomassetti 2012



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- **propagation effect:** e.g. due to inhomogeneous diffusion (*Tomassetti 2012*) or the feedback of CR onto MHD waves responsible for CR diffusion (*Blasi, Amato & Serpico 2011*)

CR hardening @ 300 GeV/n

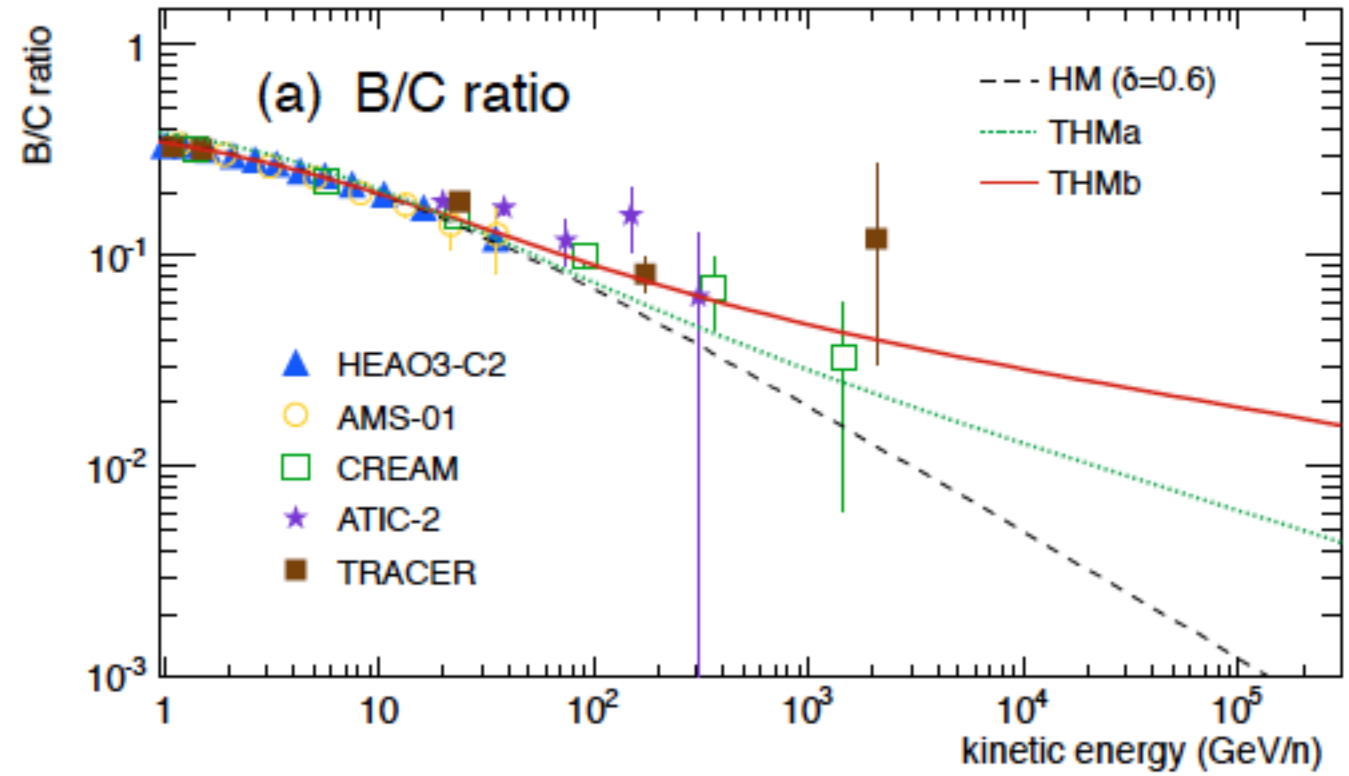
complementary signatures

which may disentangle the puzzle

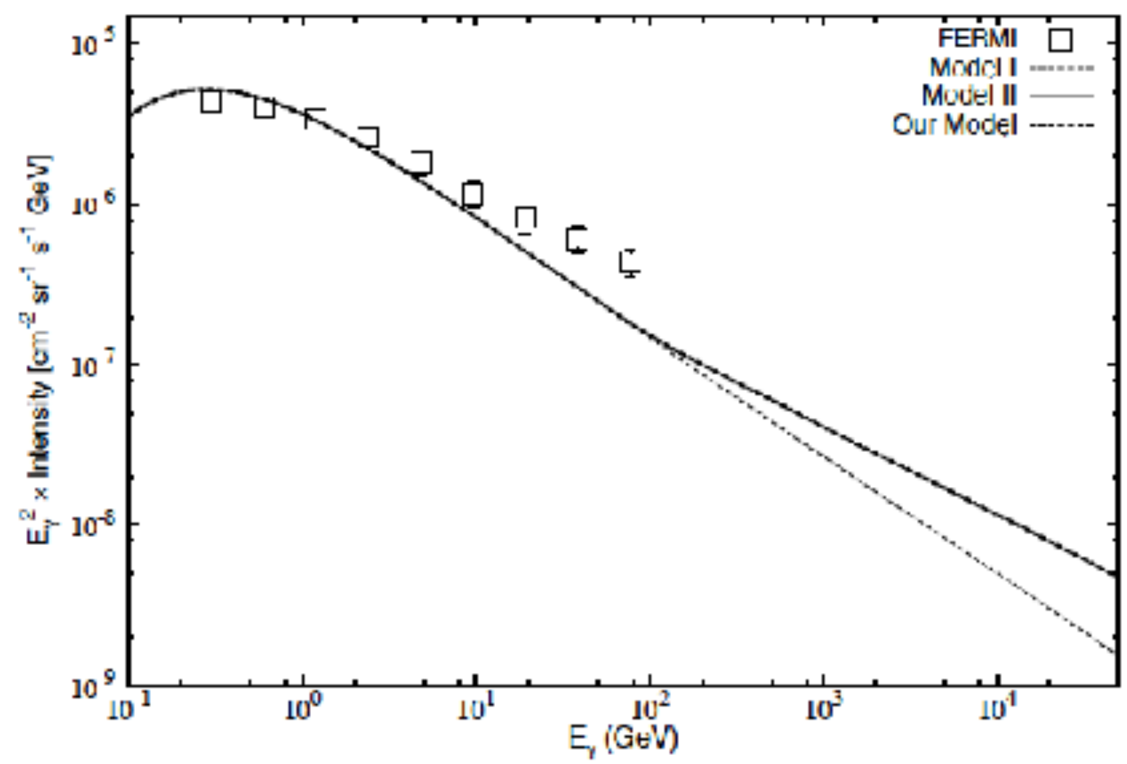
- **B/C flattening** (hints in the AMS data)
  - ☐ source effect (a residual grammage in the sources may however be present)
  - ☐ local effect
  - ☑ propagation origin

- **hardening of the γ-ray diffuse emission spectrum :**
  - ☑ source effect
  - ☐ local effect
  - ☑ propagation origin (γ-rays may allow to probe the effects of spatial dependent ISM conditions)

Tomassetti 2012



Thoudam & Hörandel 2011



The CR anisotropy problem

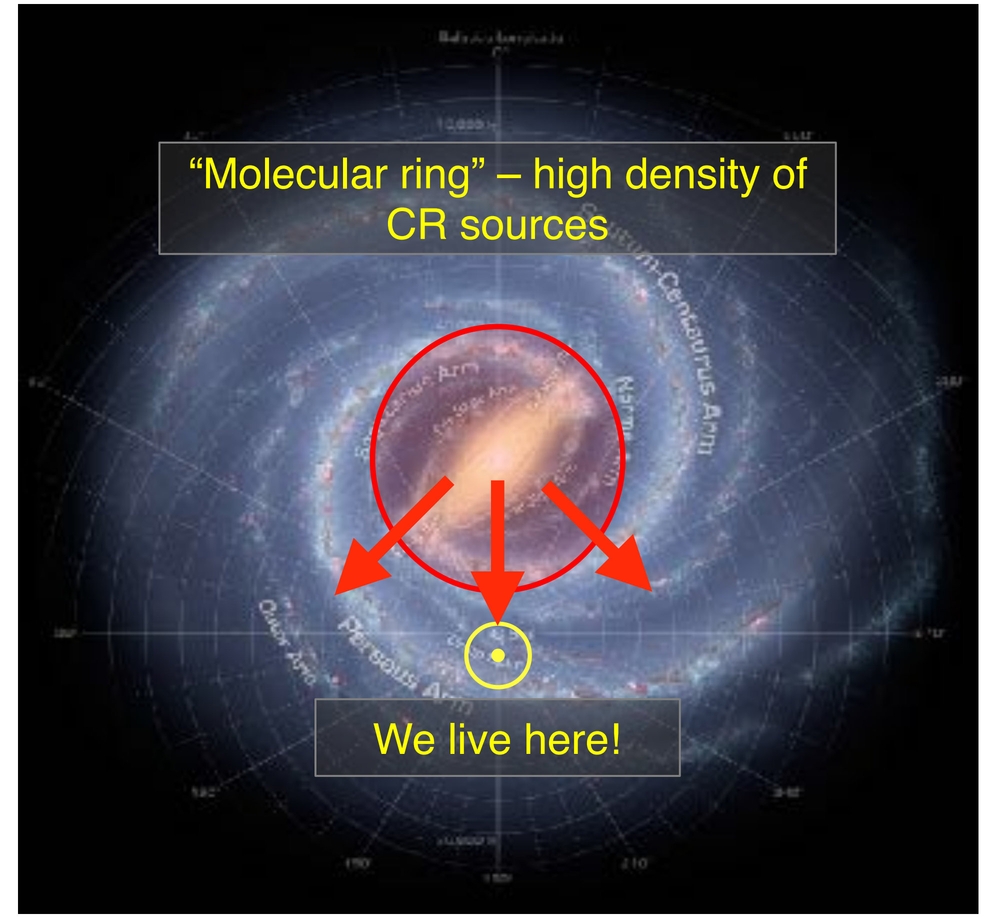
a longstanding puzzle

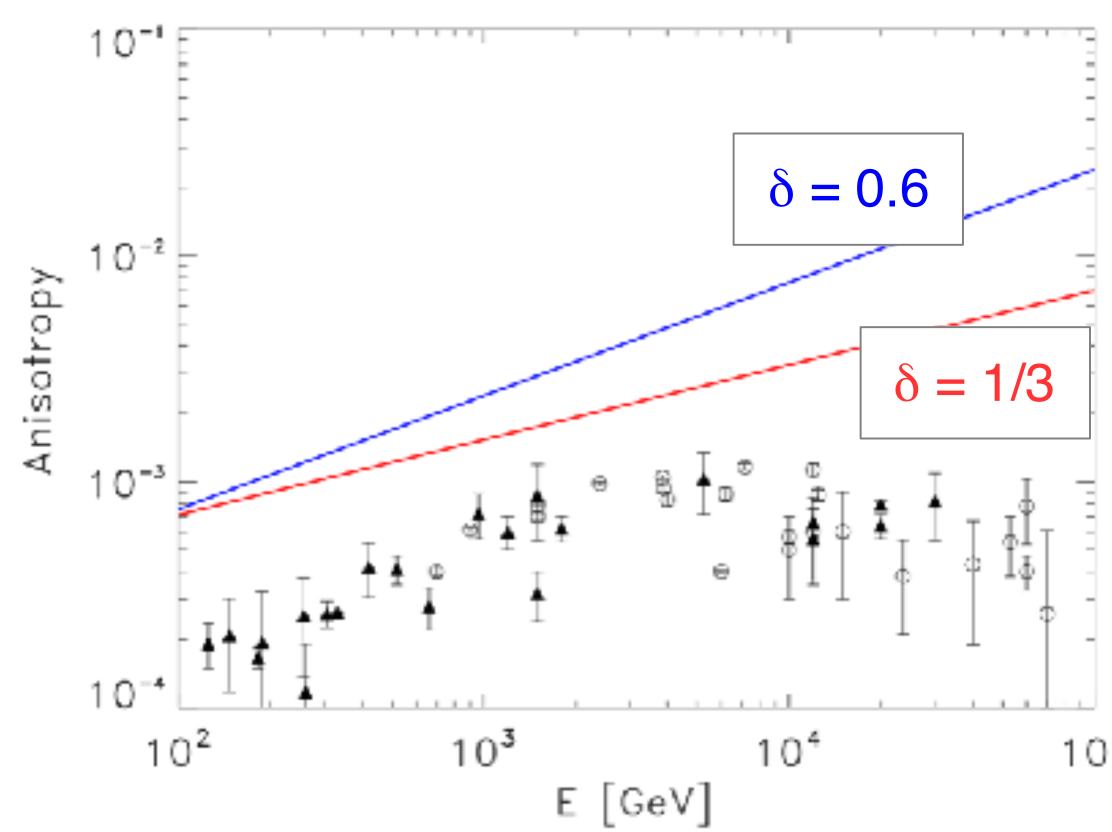
We expect a CR radial gradient hence a energy-dependent **dipole anisotropy** with maximum pointing towards the Galactic center and amplitude proportional to the diffusion coefficient

$$\delta_{\vec{x}} = \frac{3D(E)}{c} \frac{\nabla_{\vec{x}} n_{CR}(E, \vec{r}, t)}{n_{CR}},$$

The anisotropy is expected to be energy dependent since $D(E) \sim E^{\delta}$

The amplitude and slope (preferred by B/C data) are at odd with the large scale anisotropy measured by EAS experiments

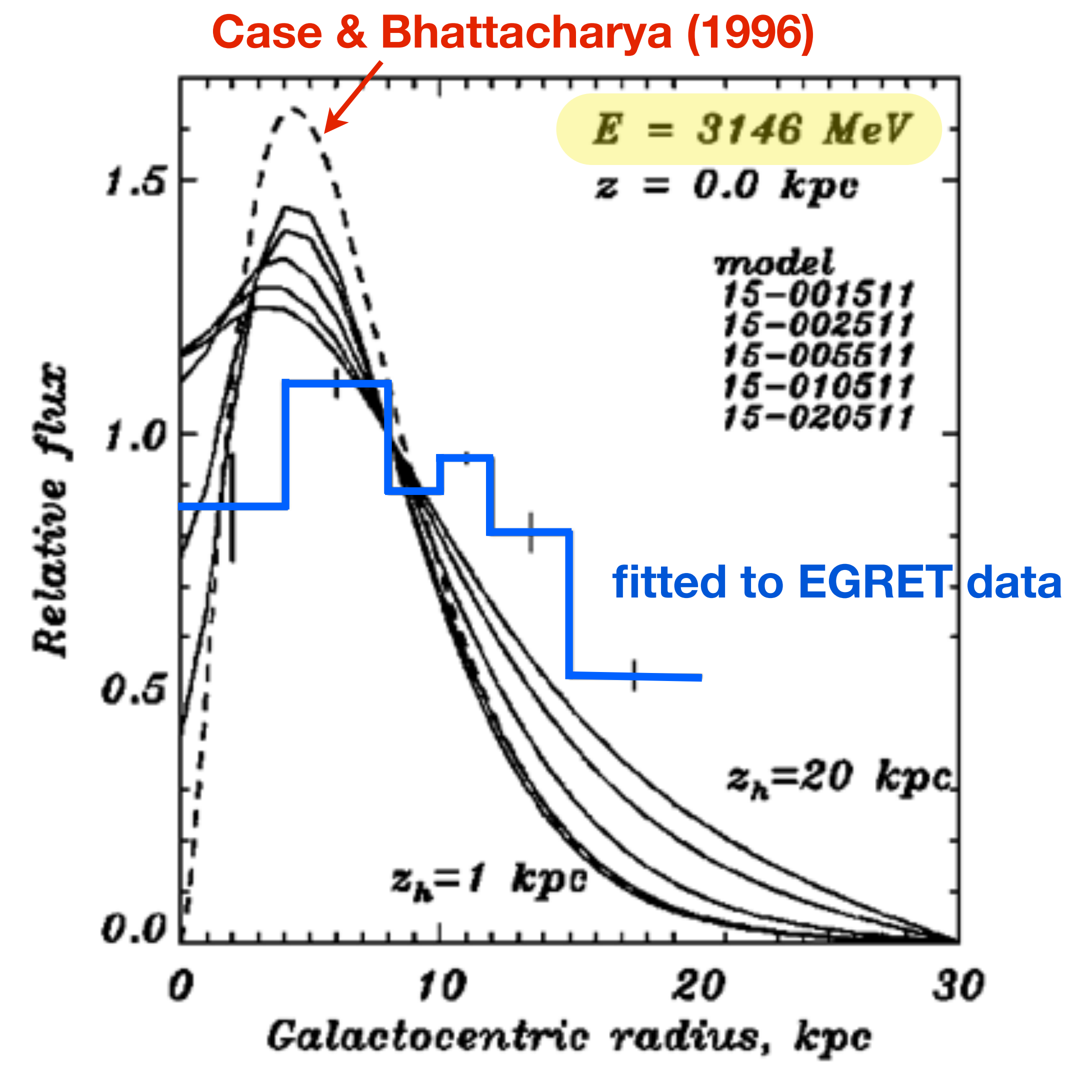


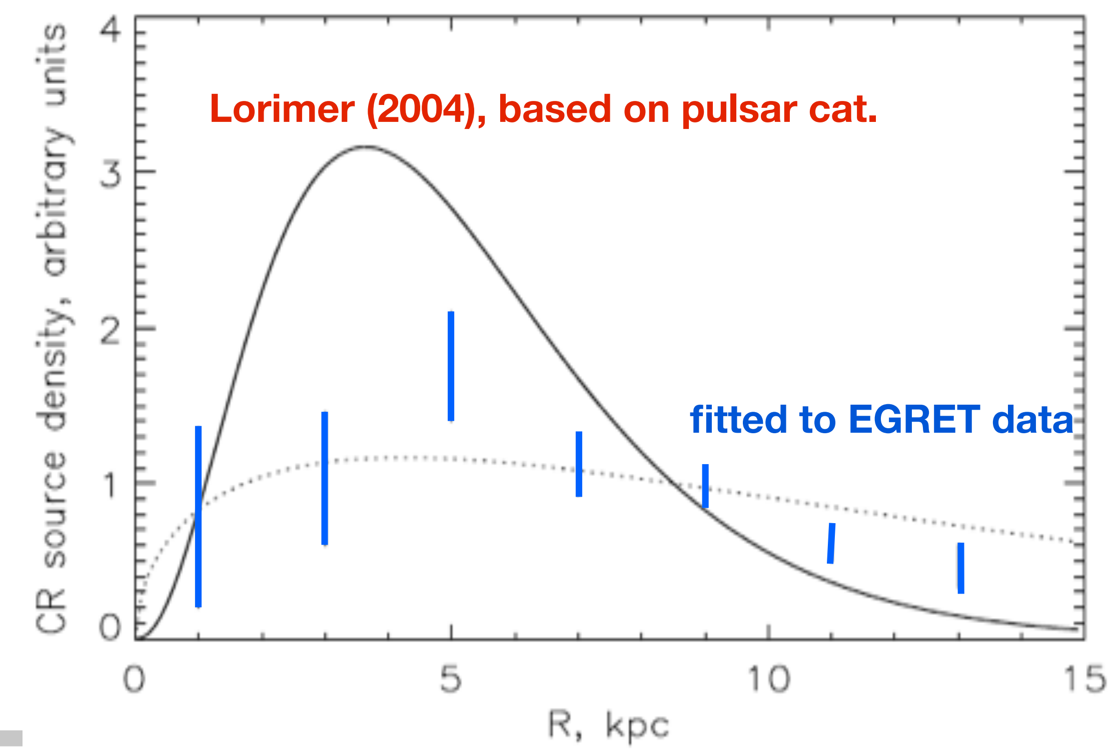


The CR gradient problem

The problem was already evident in the longitude profile of the γ-ray diffuse emission of the Galaxy measured by EGRET: the inferred CR density profile is flatter that expected on the basis of SNR catalogues !

Before Fermi-LAT a possible way-out was left opened: the H_2 gas radial distribution may be flatter than inferred from the CO emission due to the (poorly known) radial dependence X_{CO}



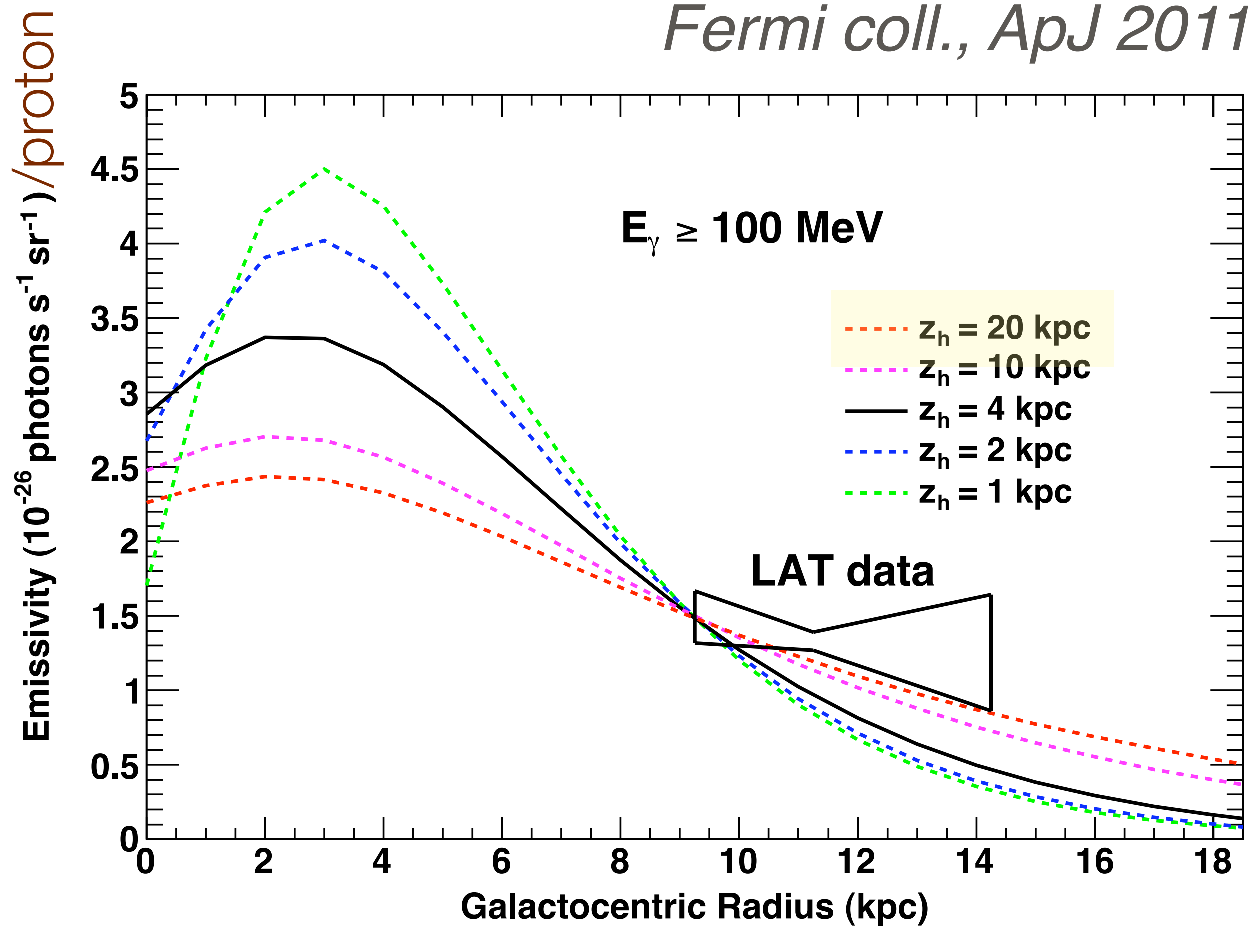


The CR gradient problem

Fermi coll. determined the γ-ray emissivity independently on the X_{CO} (which was shown to be quite flat) confirming the problem !

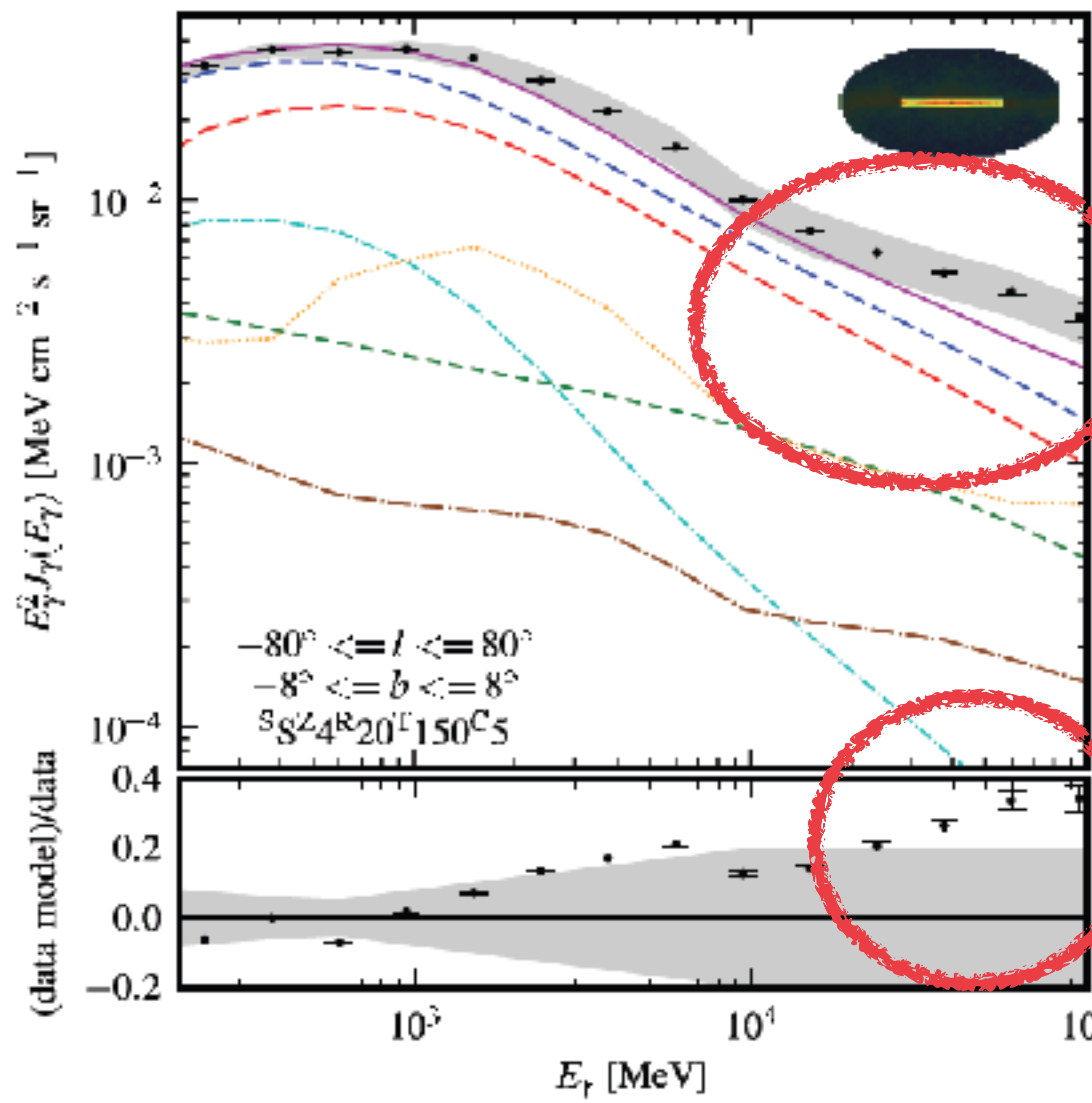
Fermi results are marginally compatible with a conventional scenario only for extreme thickness of the diffusive halo which however is disfavoured by $^{10}Be/^{9}Be$ CR data

Fermi coll., ApJ 2011



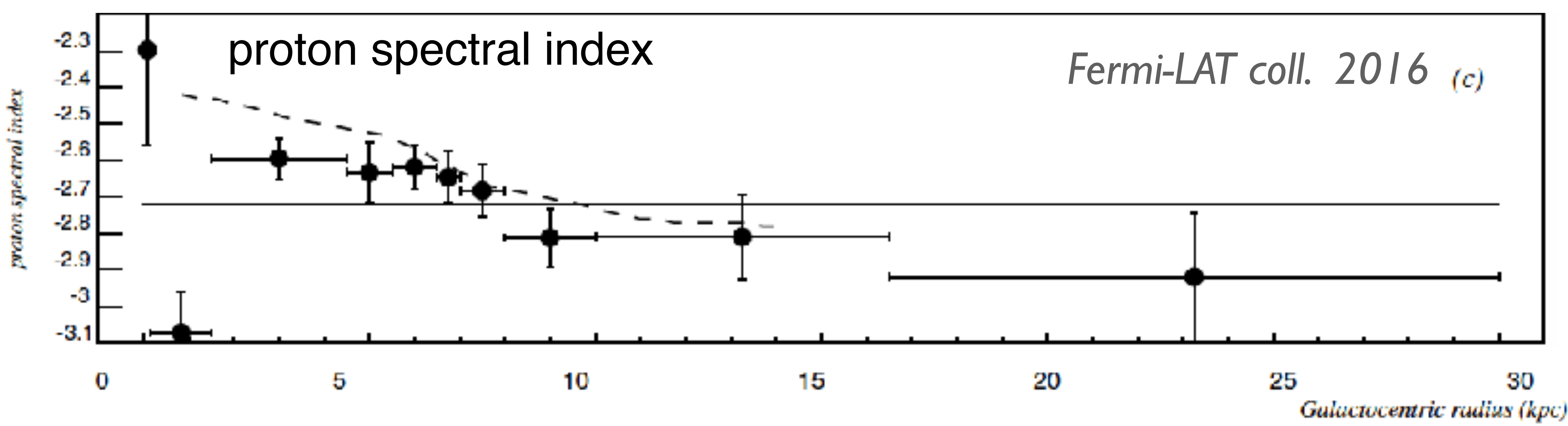
The galactic plane anomaly

(spectral index gradient problem)



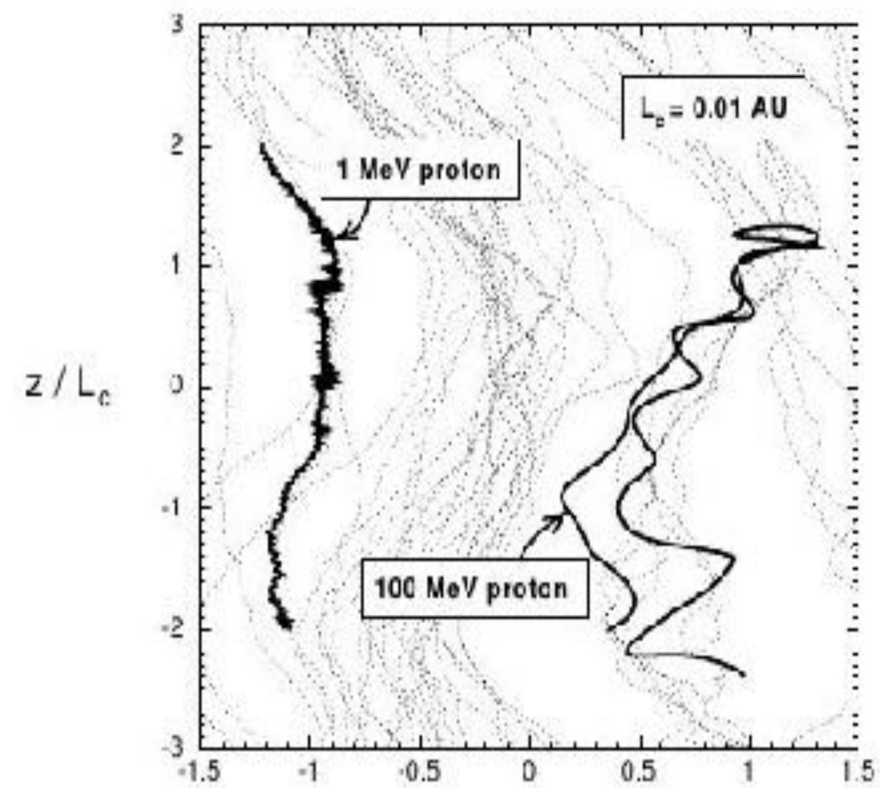
Conventional models, tuned on local CR data and reproducing the γ-ray diffuse emission outside the Galactic plane (GP), fall short on the inner GP above tens of GeV

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



Few theoretical motivations to go beyond the conventional approach

I. relaxing the homogeneous diffusion approximation

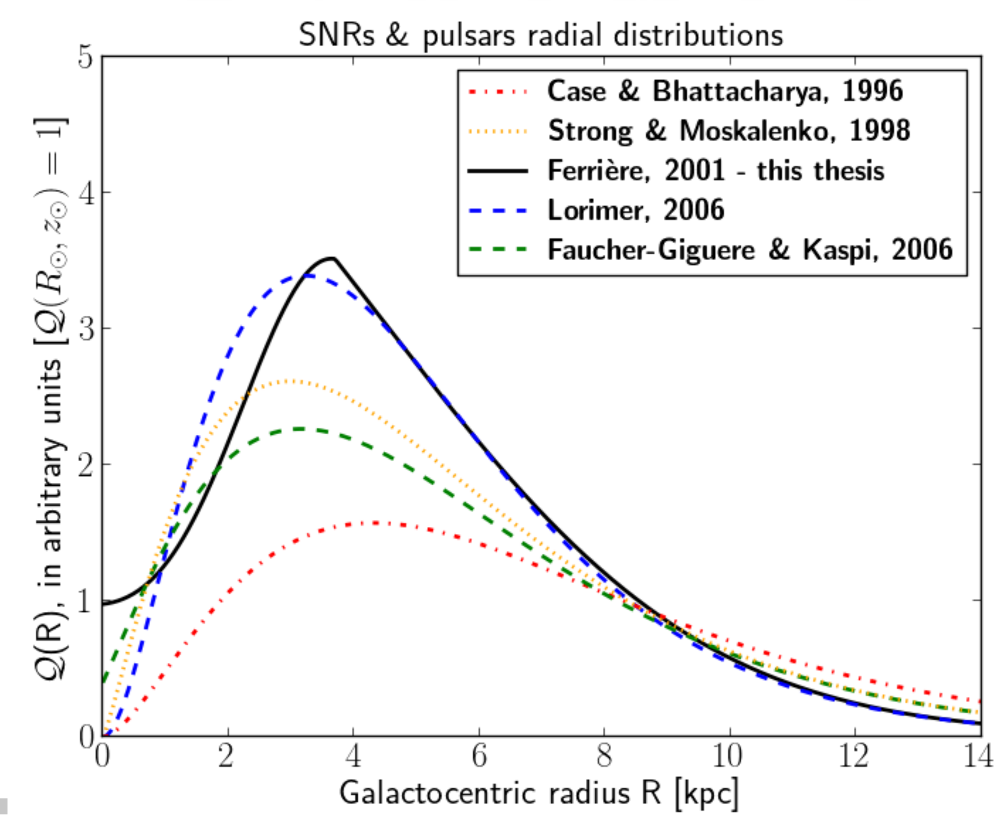


The Galaxy is permeated by regular and turbulent magnetic fields of comparable strength ~ μG

The turbulent field (MHD waves) is responsible for CR diffusive propagation (resonant particle-waves scattering : $r_L \sim 1/p$)

In quasi-linear theory ($(\delta B / B_0)^2 \ll 1$)

$$D_{\parallel} = \frac{1}{3} r_L c \left(\frac{\delta B}{B_0}\right)^{-2} \qquad D_{\perp} = \frac{1}{3} r_L c \left(\frac{\delta B}{B_0}\right)^{2}$$



Turbulent fields may be produced by kinetic energy released by SNR or by CR themselves by streaming instability. In both cases a strong spatial (anti)correlation between $D_{(\parallel)\perp}$ and the SNR density is expected

Few theoretical motivations to go beyond the conventional approach

II. relaxing the isotropic approximation

The regular magnetic field (along ***b***) breaks isotropy

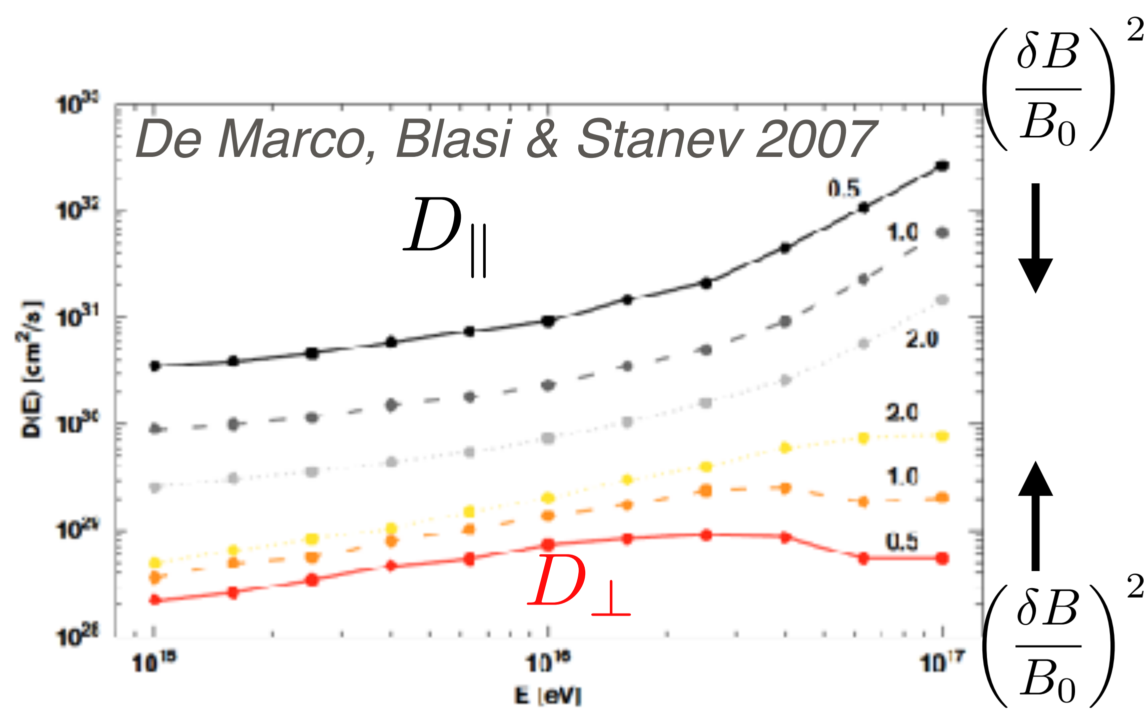
$$D_{ij} = (D_{\parallel} - D_{\perp}) b_i b_j + D_{\perp} \delta_{ij} + D_A \epsilon_{ijk} b_k$$

if ***b*** is purely azimuthal only $D_\perp$ matters. Isotropy is restored for strong turbulence but that holds only at the coherence length of the turbulent field $l_C \sim 100$ pc. At the resonance scale $\lambda \sim r_L$ the power is suppressed by the turbulent cascade.

parallel diffusion along spiral arms is subdominant if the halo thickness is < 10 kpc

Note that $D_\perp$ is expected to increase with the turbulence strength as confirmed by numerical simulations

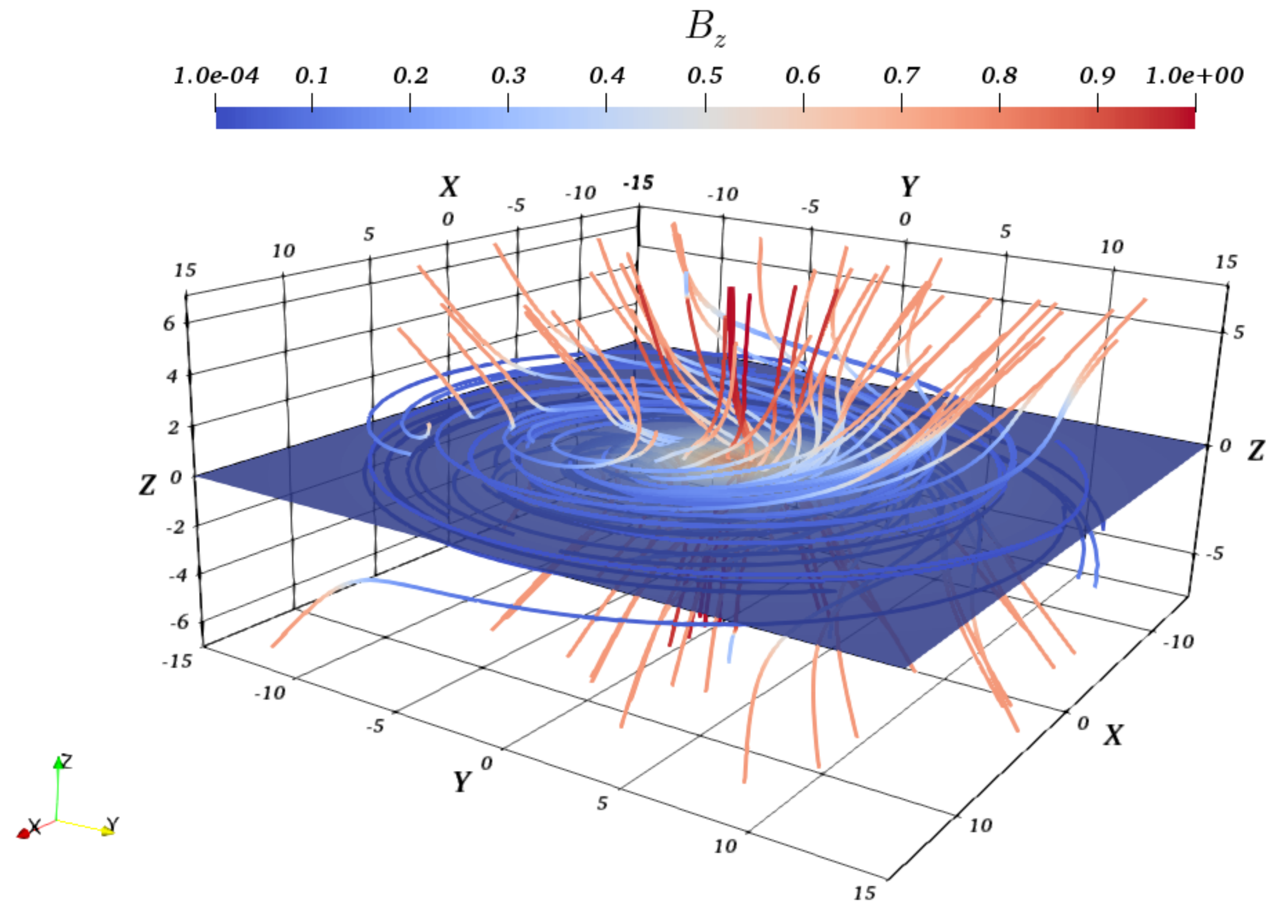
➔ CR escape more rapidly where more turbulence (sources) is present (see below)



II. relaxing the isotropic approximation with a more realistic magnetic field

Cerri, Gaggero, Vittino, Evoli & DG, arXiv: 1707.07694 accepted by JCAP

Radio data (synchrotron + Faraday rotation measur.) show that a strong poloidal component is present in the Galactic center (GC) region.
This can revive parallel diffusion in that region

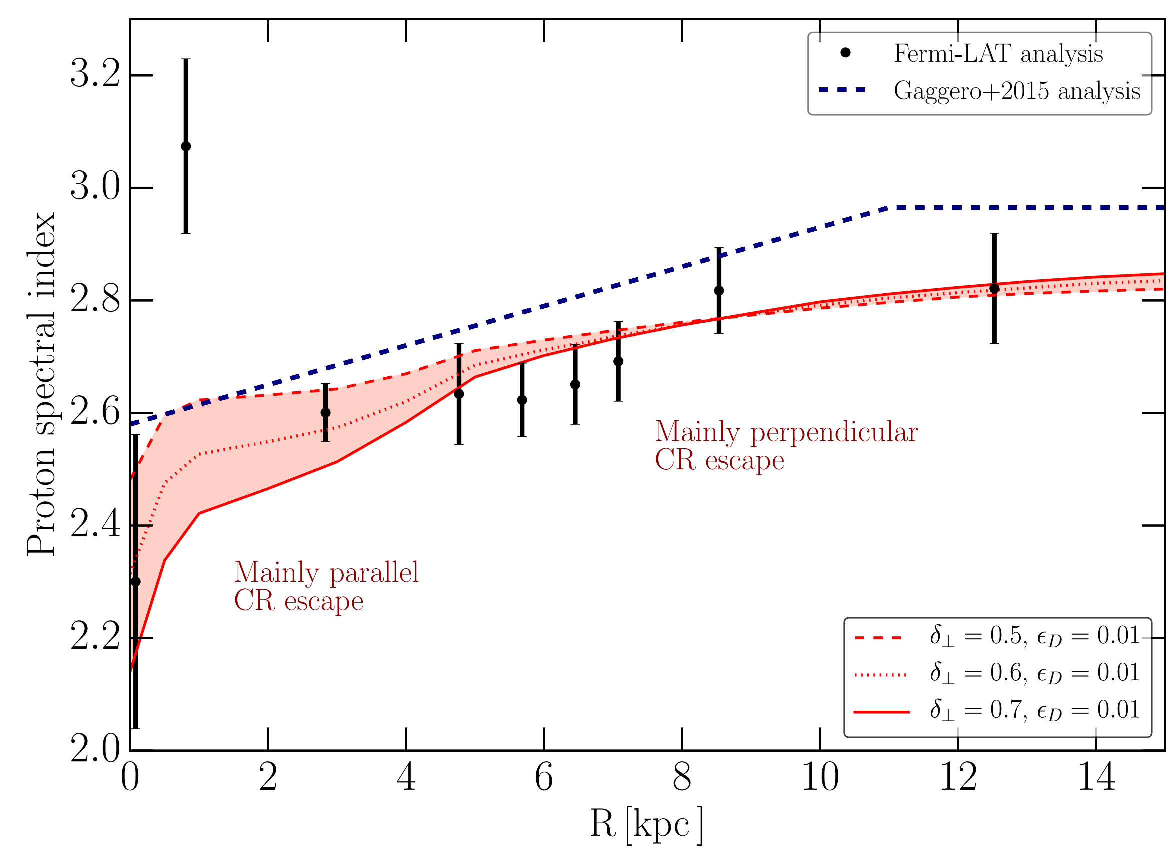


Moreover, since $D_{||}$ and $D_{\perp}$ are expected to have different rigidity dependence (*Blasi, De Marco, Stanev 2007 and Snodin et al. 2012*) e.g.

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

for Kolmogorov turbulence,
the propagated CR spectral index may get harder at low Galactocentric radii

We incorporated this behaviour in the DRAGON 2 code (*see below*) allowing for anisotropic diffusion



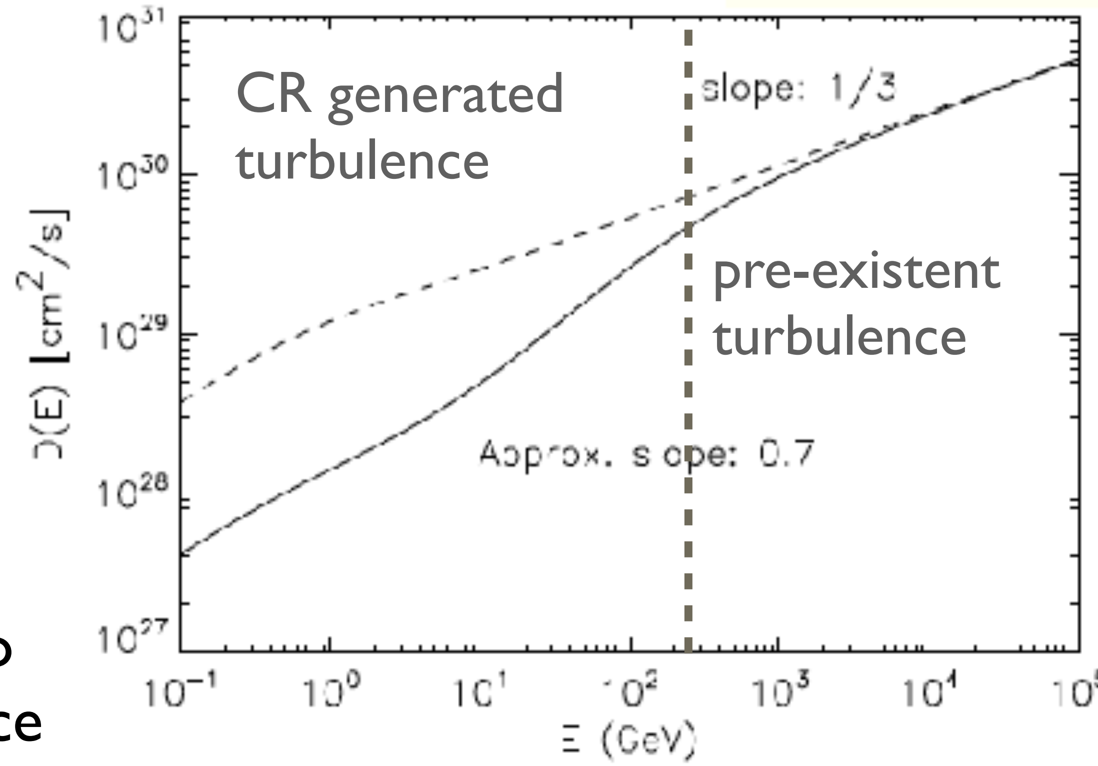
Few theoretical motivations to go beyond the conventional approach

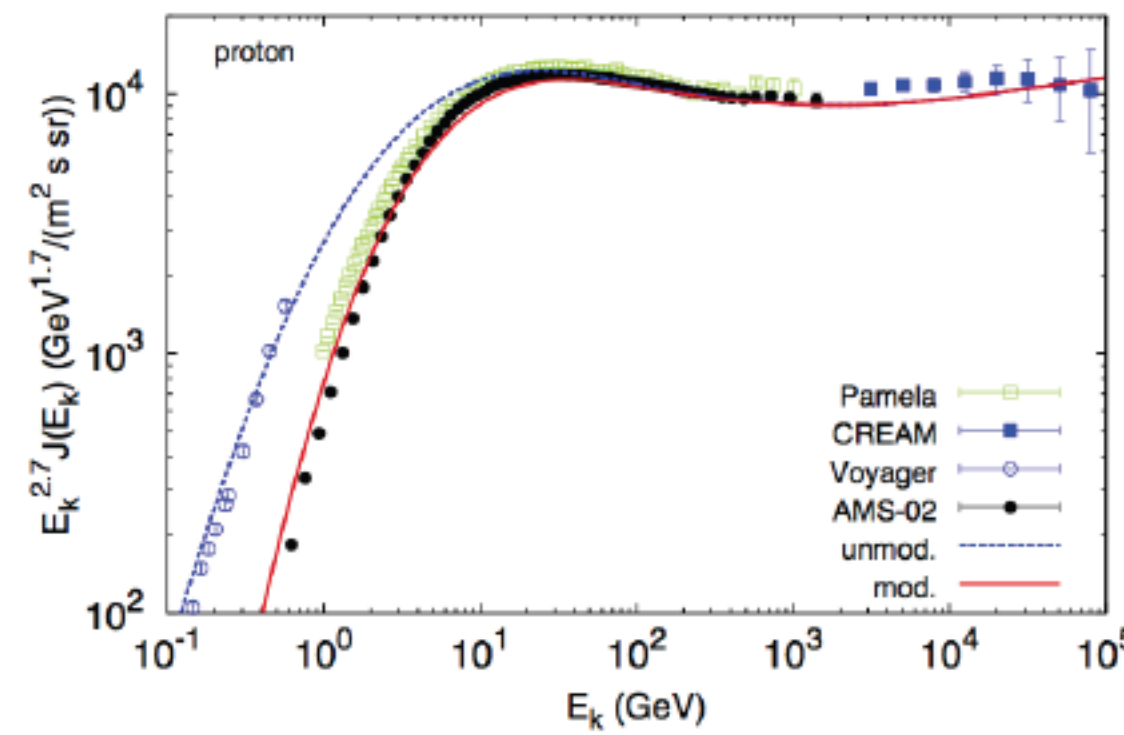
III. relaxing the passive propagation approximation

CR diffusion may not be a merely passive process : due to streaming instability CR can generate MHD waves which back-react onto CR
see Amato & Blasi 2017 for a review

the transition from a regime where diffusion is determined by self-generated turbulence diffusion to one dominated by pre-existing turbulence may induce a feature in the diffusion coefficient ➔ CR spectra

this may reproduce the observed CR hardening at 200-300 GeV/n under realist conditions
Blasi, Amato & Serpico 2012
Aloisio & Blasi 2013





Few theoretical motivations to go beyond the conventional approach

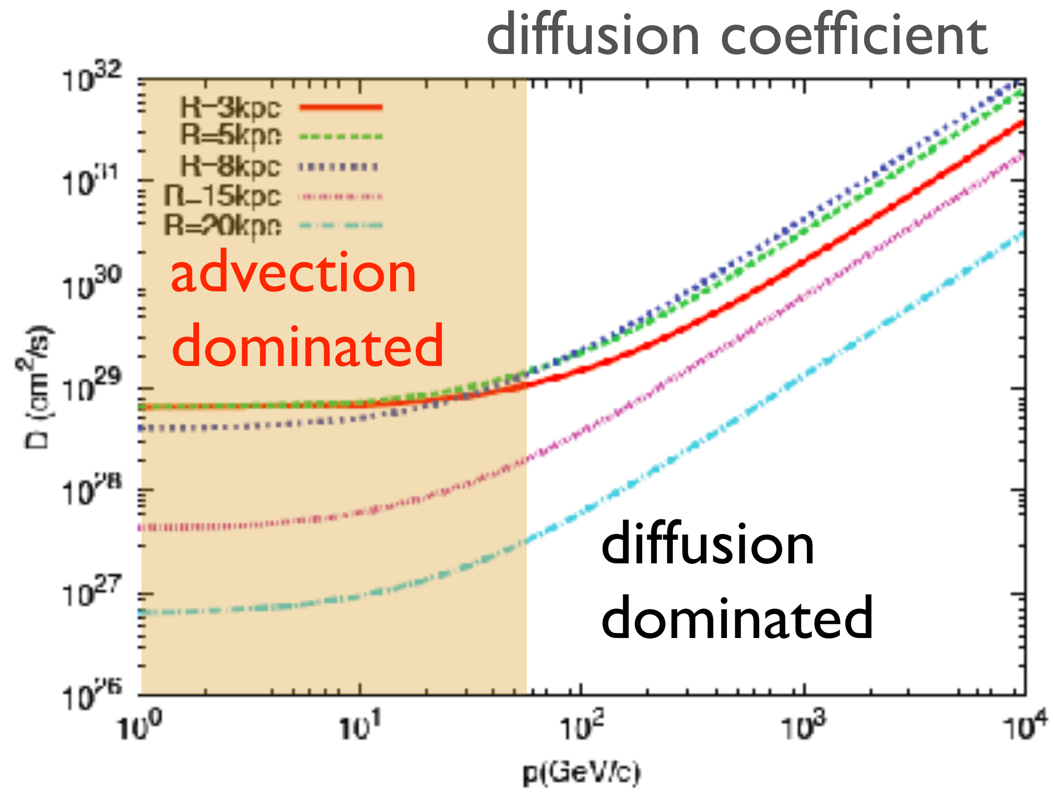
III. relaxing the passive propagation approximation

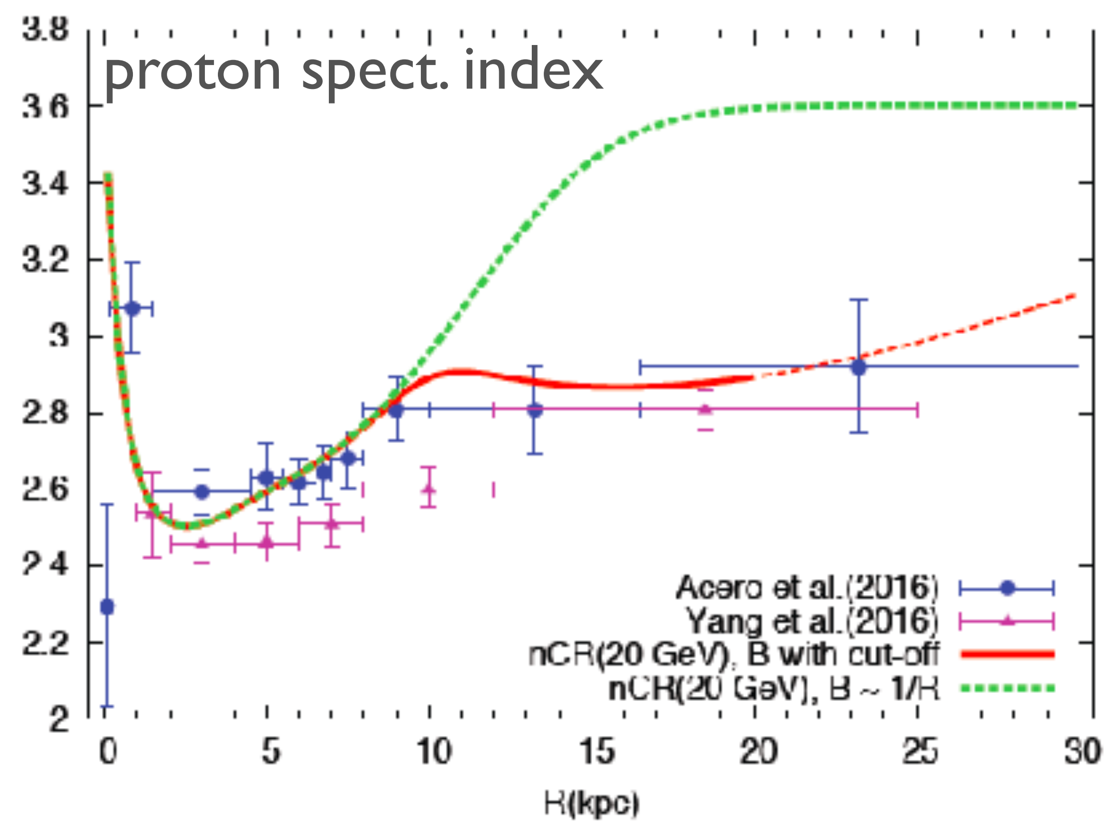
CR may advect/diffuse in self-generated Alfvén-waves below/above $\sim$ 50 GeV

- harder CR (hence γ-ray) spectrum in the advection dominated regime
- the effect is larger in the inner Galaxy, larger D → larger p at which diffusion start dominating

<u>The spectral flattening however should be absent at large energies</u>

Recchia, Blasi & Morlino 2016





The DRAGON code project

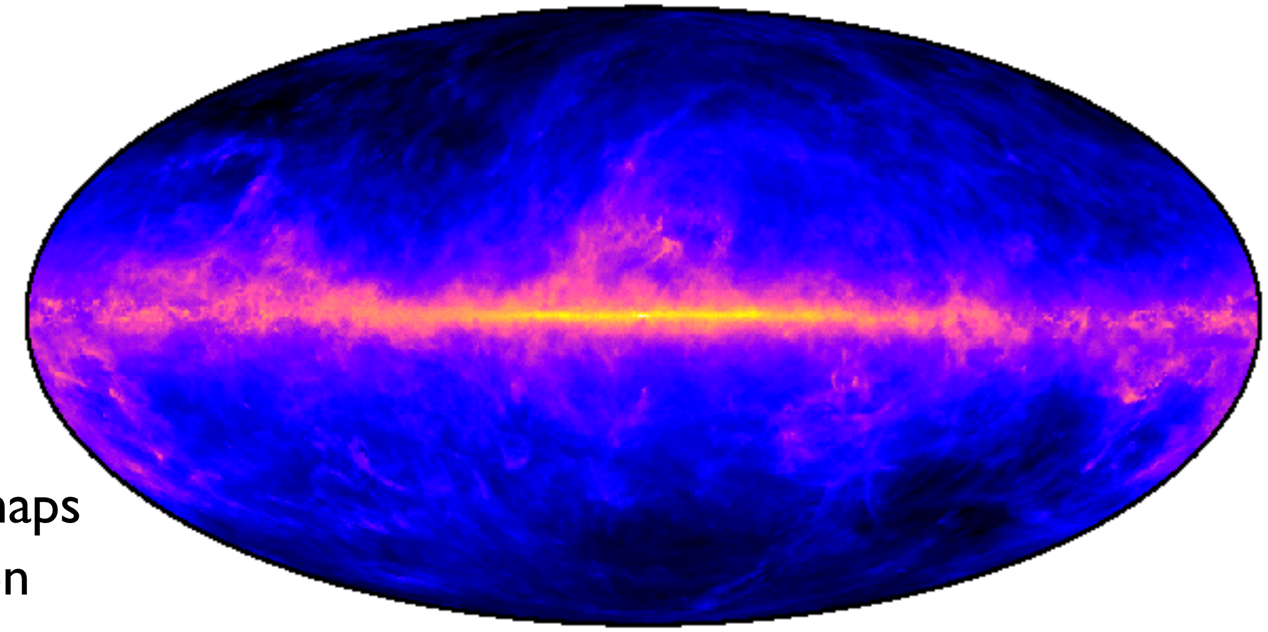
Some of the main innovative features

DRAGON code:
https://github.com/cosmicrays
Evoli, Gaggero, DG & Maccione JCAP 2008

DRAGON 2 code
to be released
Evoli, Gaggero, Vittino, Di Bernardo, Ligorini, Di Mauro, Ullio & DG, JCAP 2017

- **spatial dependent diffusion** coefficient(s) (both normalization $D_0(R,\mathbf{z})$ and rigidity dependence index $\delta(R,z)$)
- 3D: it allows spiral arm source distribution
- allow **anisotropic diffusion**
- better treatment of energy losses
- spatial dependent resolution
- new cross sections

Gamma-ray mapping



DRAGON use an auxiliary code (GammaSky) to produce maps and spectra of the secondary γ-ray, neutrino and synchrotron diffuse emissions

Other codes with built-in gamma-ray modelling capability

GALPROP code https://galprop.stanford.edu
Moskalenko, Strong, …
GALPROP Webrun, *Vladimirov et al.* *arxiv/1008.3642*
recently updated to account for 3D, inhomogeneous diff. , work in progress to introduce anisotropic diffusion

PICARD code: http://astro-staff.uibk.ac.at/~kissmrbu/CRs.html
Kissman, Reimer, Strong arxiv.org/1510.02580
3D diffusion , work in progress to introduce anisotropic diffusion

so far produced scientific results under conventional conditions only

A possible solution of the CR gradient and anisotropy problems

based on inhomogeneous diffusion

Evoli, Gaggero, DG, Maccione, PRL 2012

We used the DRAGON code (which is built to allow spatial dependent diffusion) to model CR propagation with

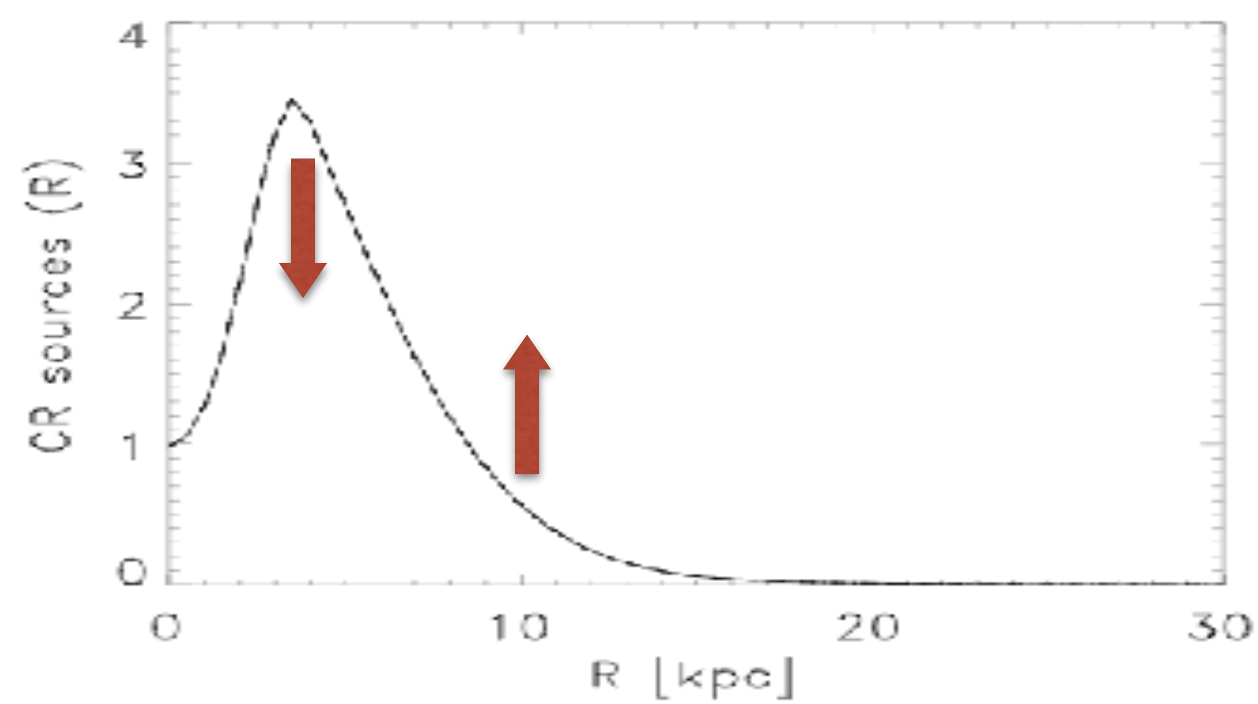
Q(R) : *source (SNR) profile*

$D(E, R) \propto Q(R)^{\tau}$

τ *free parameter* ~ 1

Model parameters are tuned to reproduce CR data (e.g. B/C)

larger $D_{\perp}$ ⇒ faster CR escape ⇒ flatter CR profile



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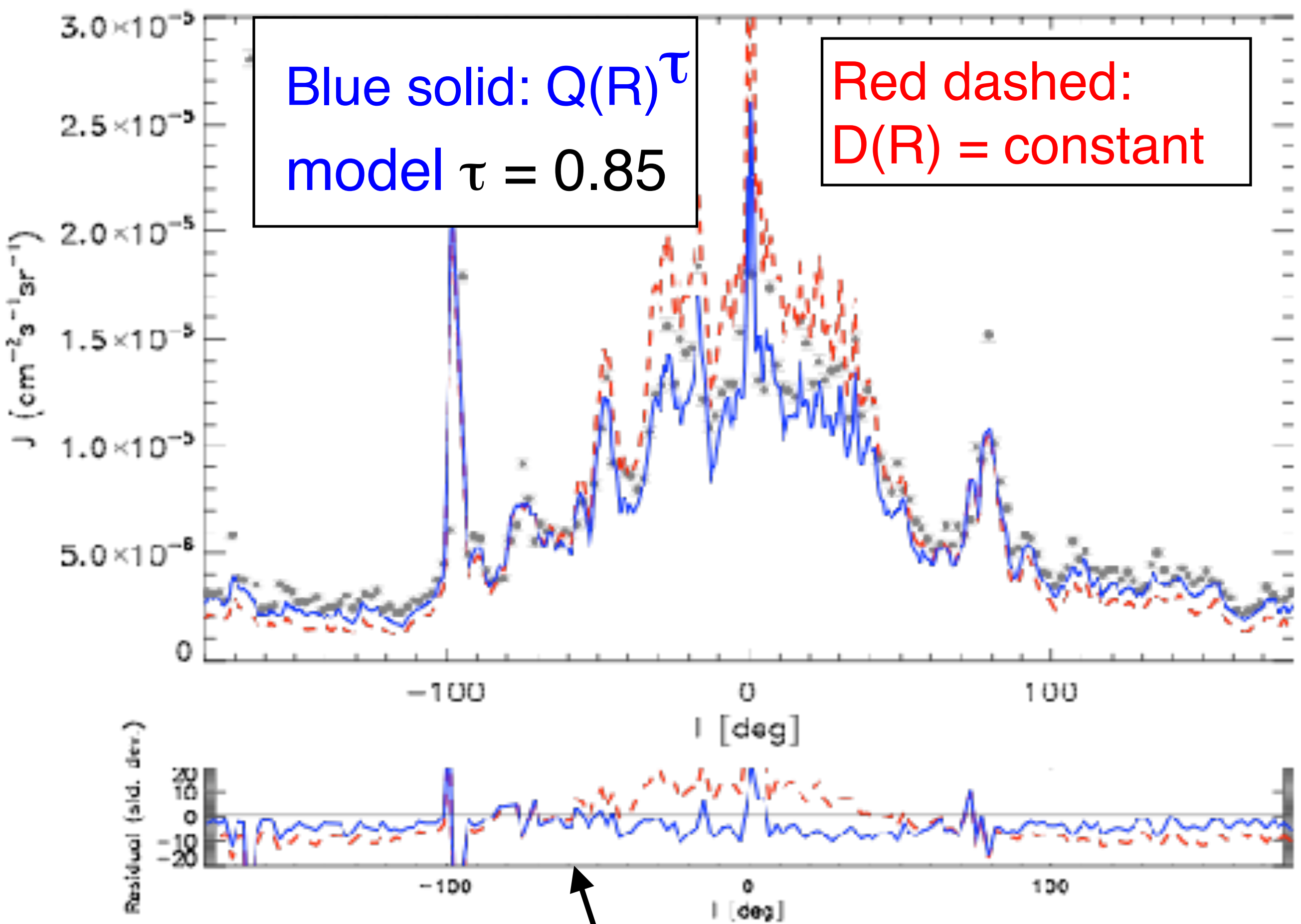
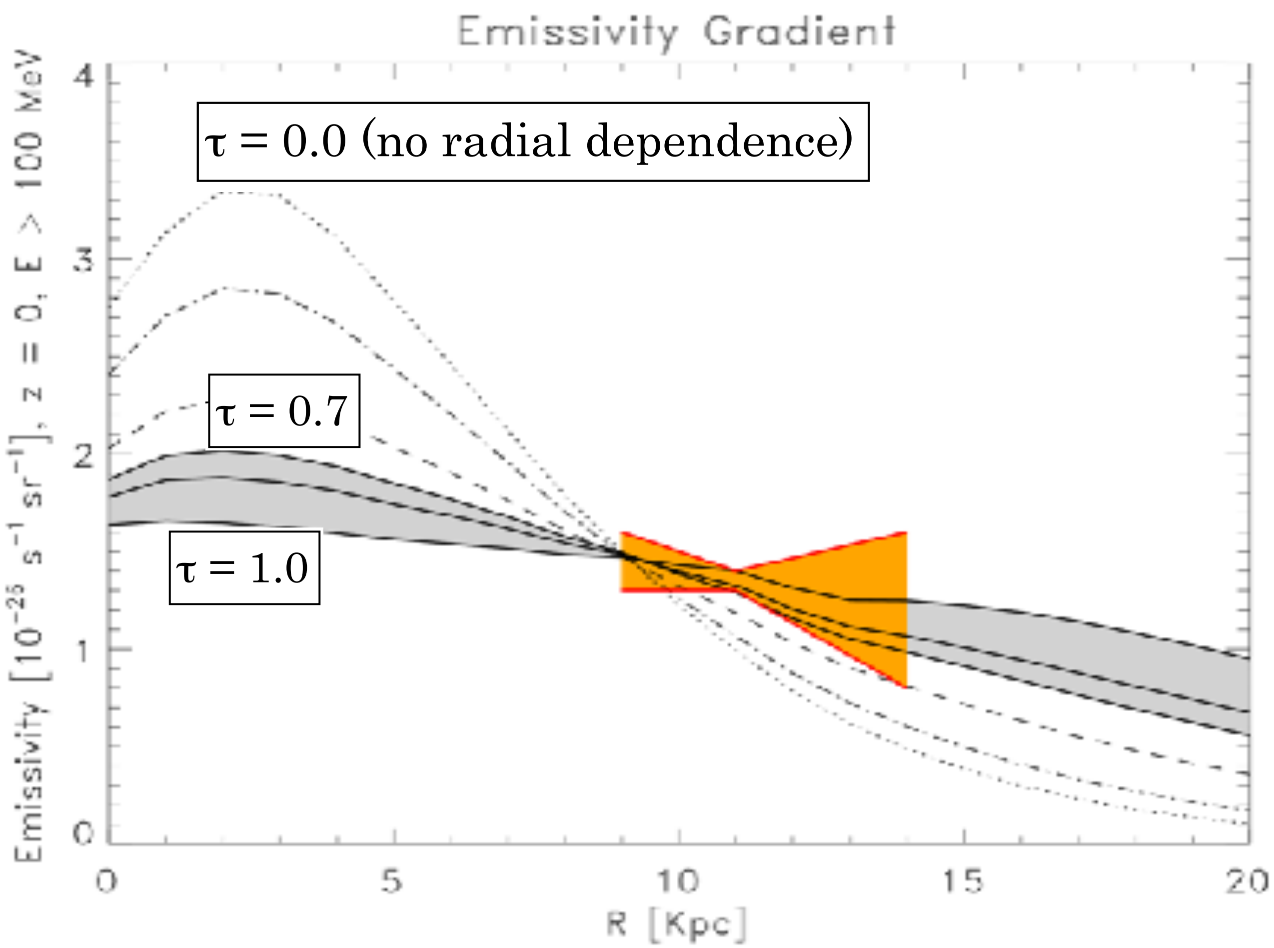


Residuals against Fermi-LAT data



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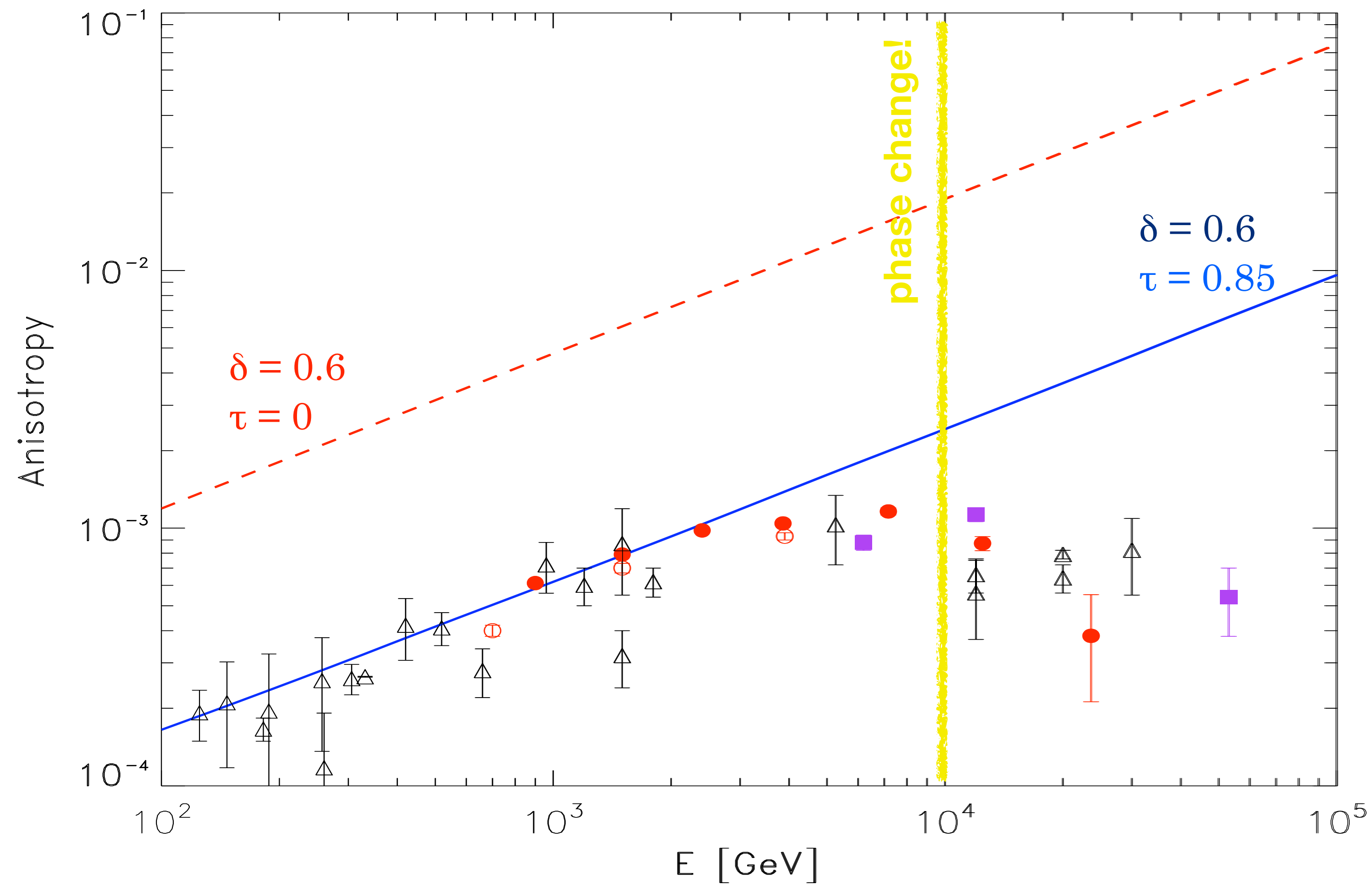
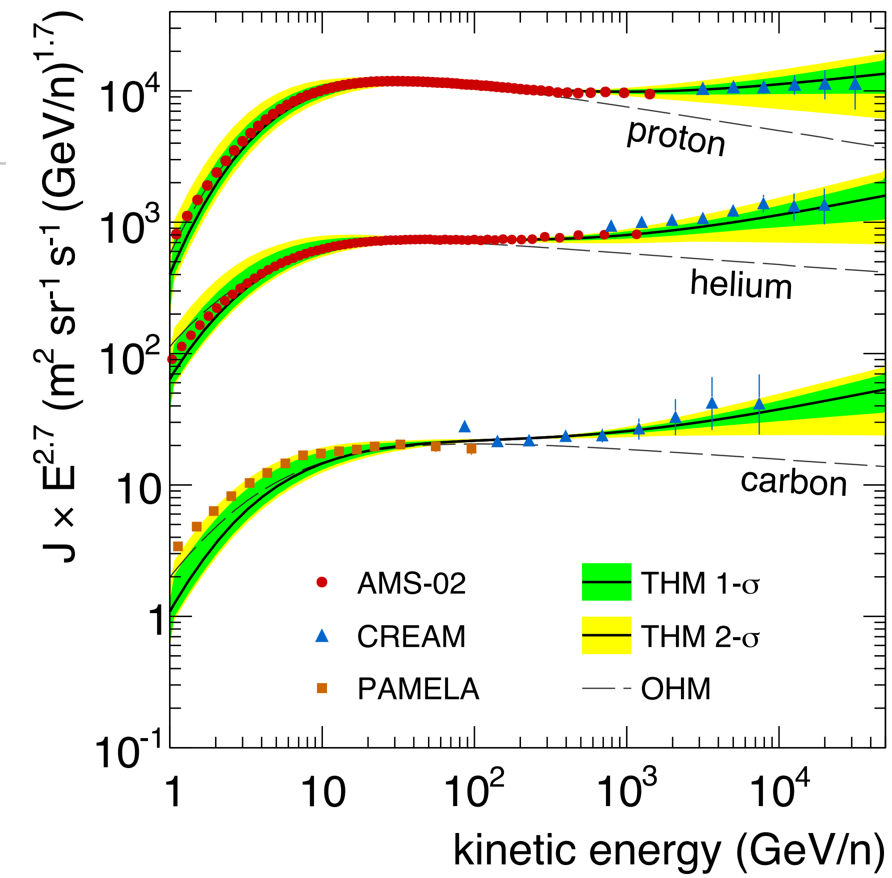


A possible solution of the hardening and anisotropy problems

based on inhomogeneous diffusion

N. Tomassetti et al., ApJL Lett. 2012, PRD 2016

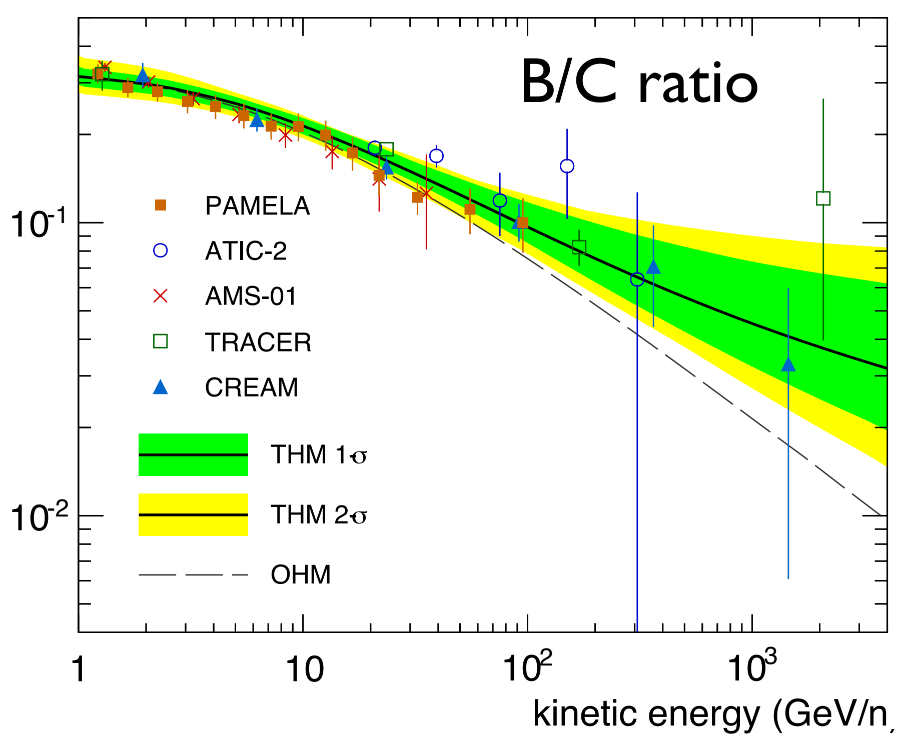


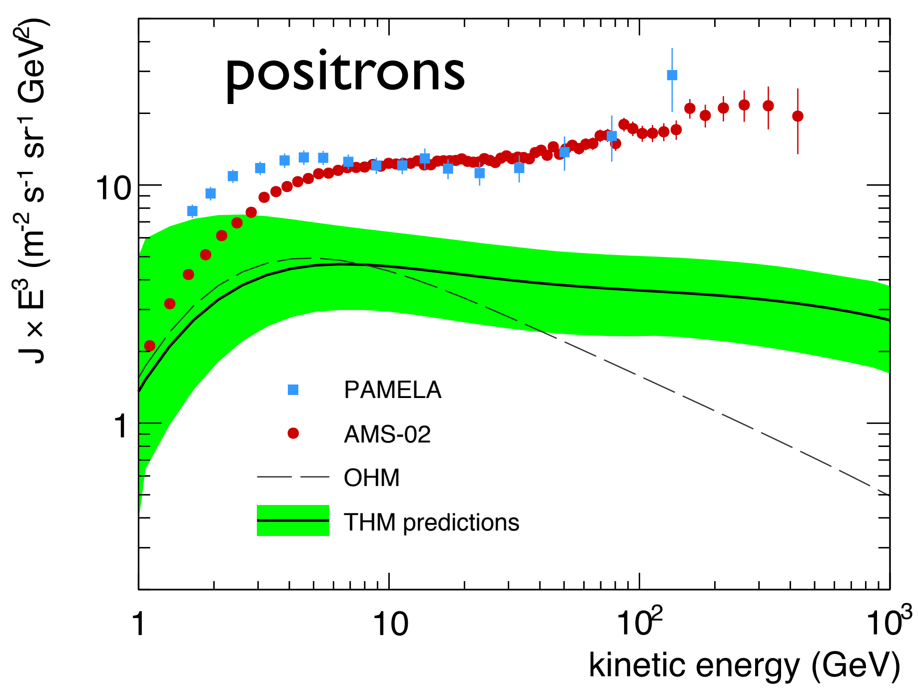
Motivated by the galactic plane anomaly and a theoretical model (*Erlykin & Wolfendale* 2012) adopt a two-halo (disk + halo) model (THM) with different scaling of the diffusion coeff. with rigidity

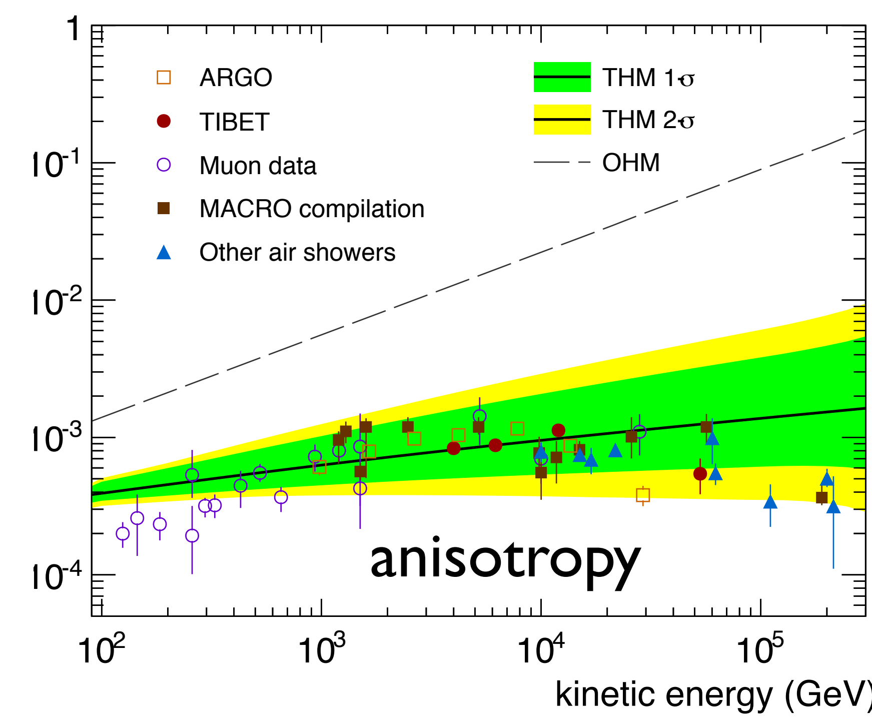
$$D(\mathcal{R}, z) = \begin{cases} D_0 \beta^\eta \left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^\delta & (|z| < \xi L) \\ \chi D_0 \beta^\eta \left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^{\delta+\Delta} & (|z| > \xi L) \end{cases}$$

best fit $\xi = 0.15$ $\delta = 0.15$ $\Delta = 0.5$

use analytical as well as DRAGON + MCMC data analysis



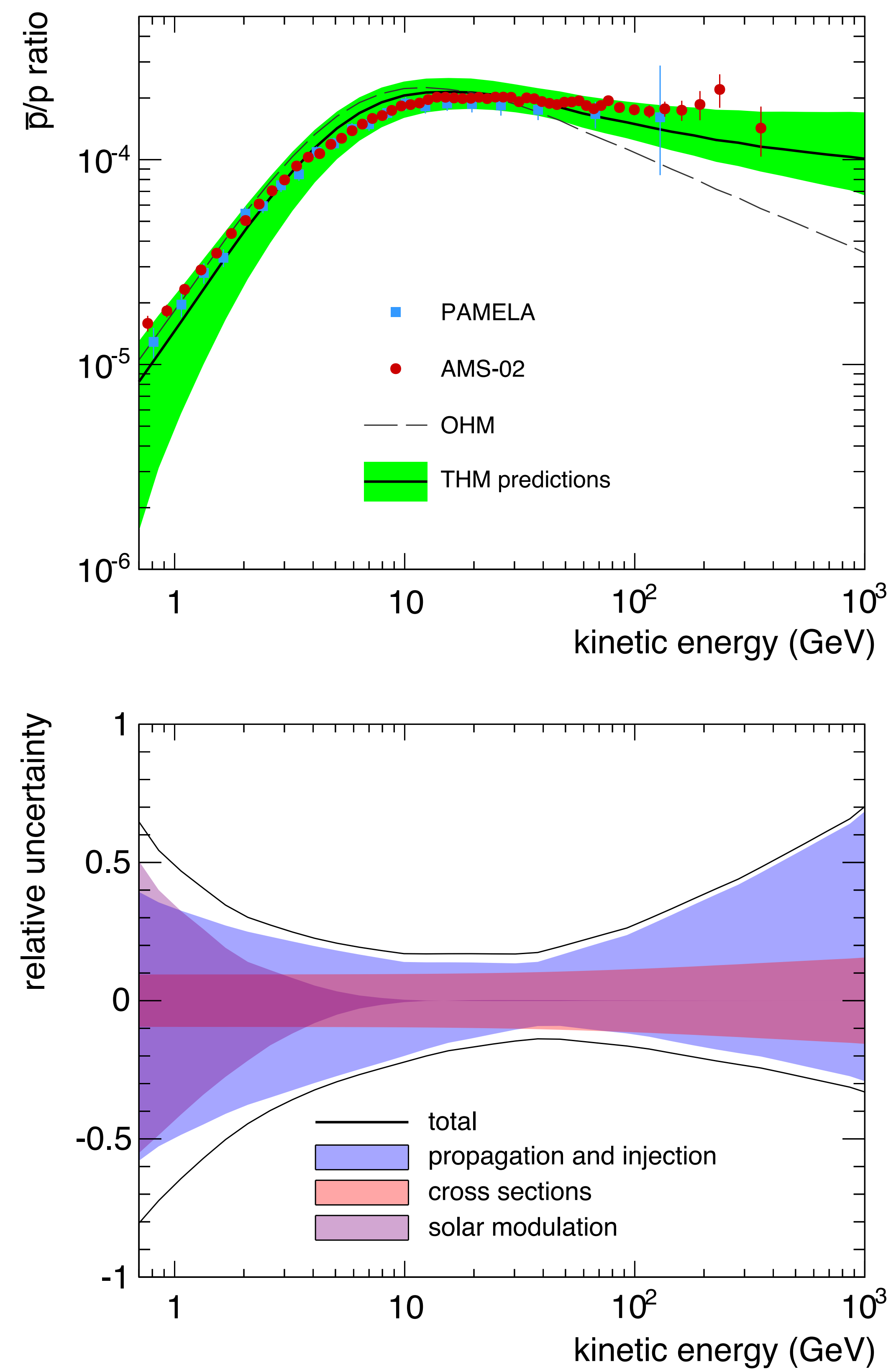




Feng, Tomassetti & Oliva, PRD 2016

antiprotons

OHM: one-halo model $\delta(r) = 0.56$



MCMC allows to estimate uncertainties

the propagation uncertainty band should be reduced including AMS02 B/C data but is likely to be larger than that of conventional models

A possible solution of the γ-ray Galactic plane anomaly

based on inhomogeneous diffusion

Gaggero, Urbano, Valli & Ullio, PRD 2015

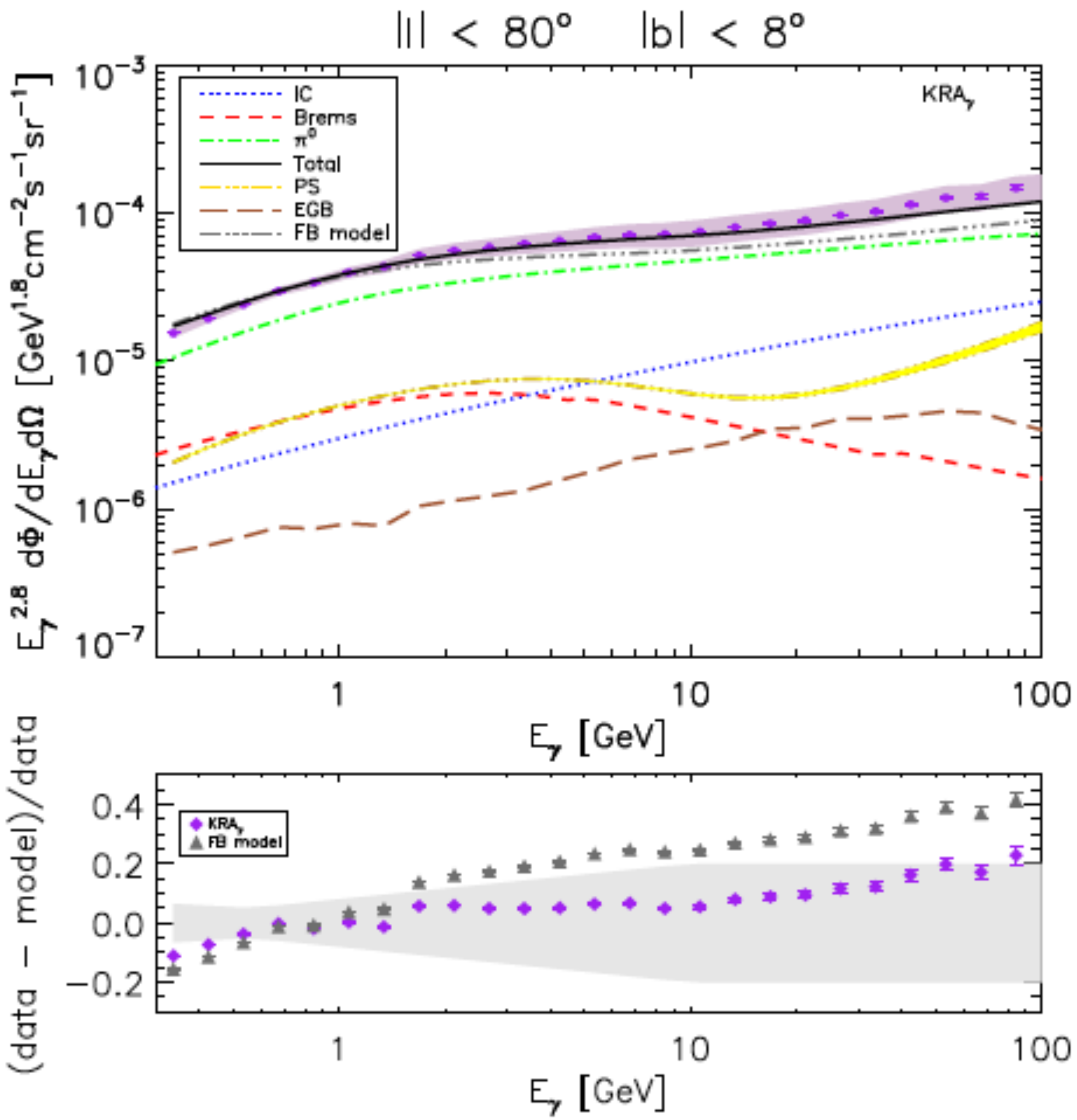
interpreted the effect as due to a radial dependent diffusion coefficient which was implemented with the DRAGON code.

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

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

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

(KRAγ model)



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interpreted the effect as due to a radial dependent diffusion coefficient which was implemented with the DRAGON code.

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

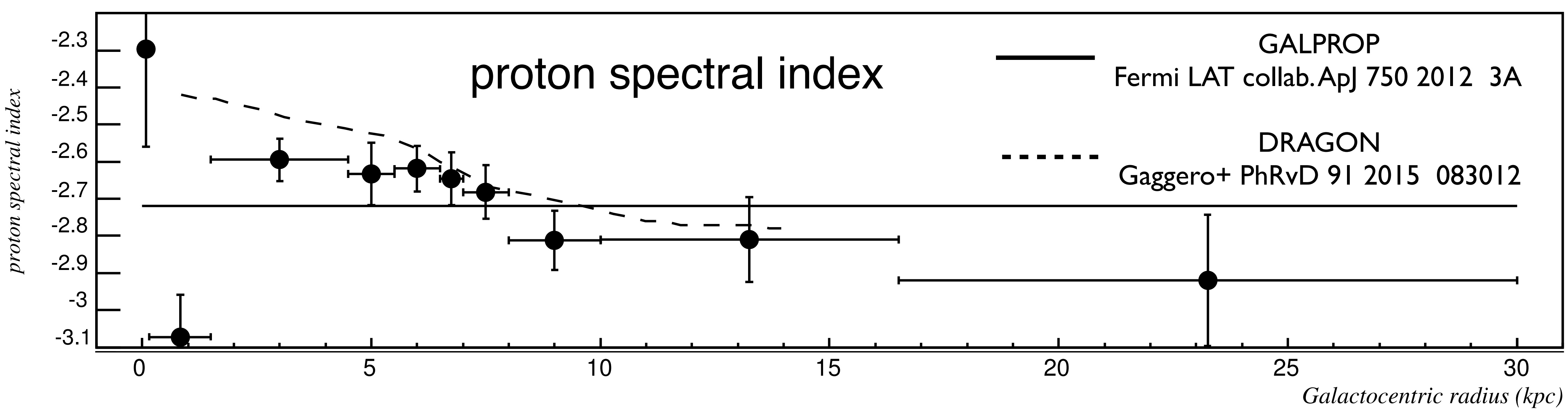
with $\delta(r) = A\,r + B$

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

(KRAγ model)

this is agreement with successive FERMI-LAT finding of a radial dependent spectral index !

Fermi-LAT coll. 2016



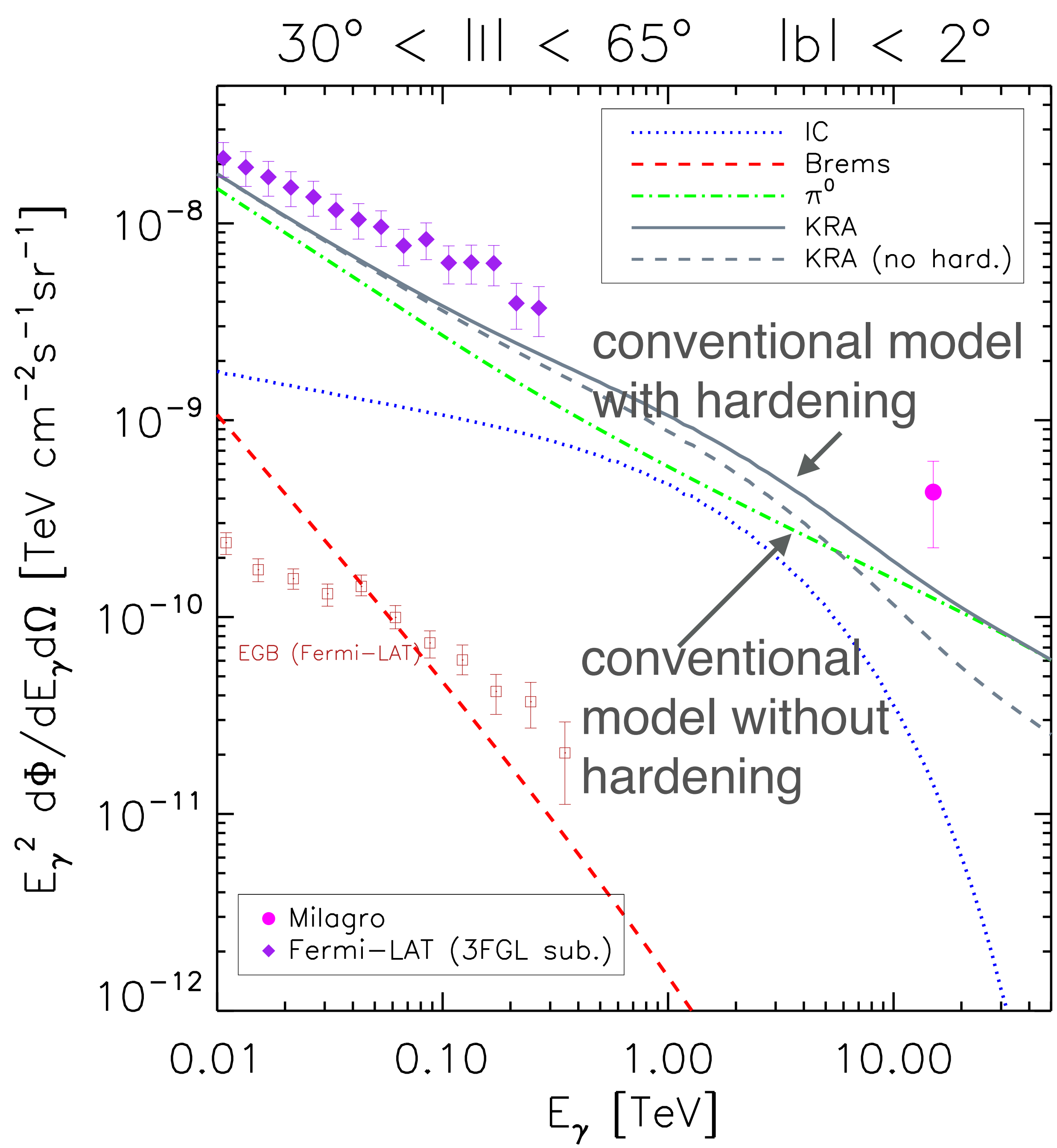
The Galactic plane above the TeV

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

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 the CR hardening at 250 GeV/n (assuming it is present in the whole Galaxy as expected if it is originated by sources or by propagation)



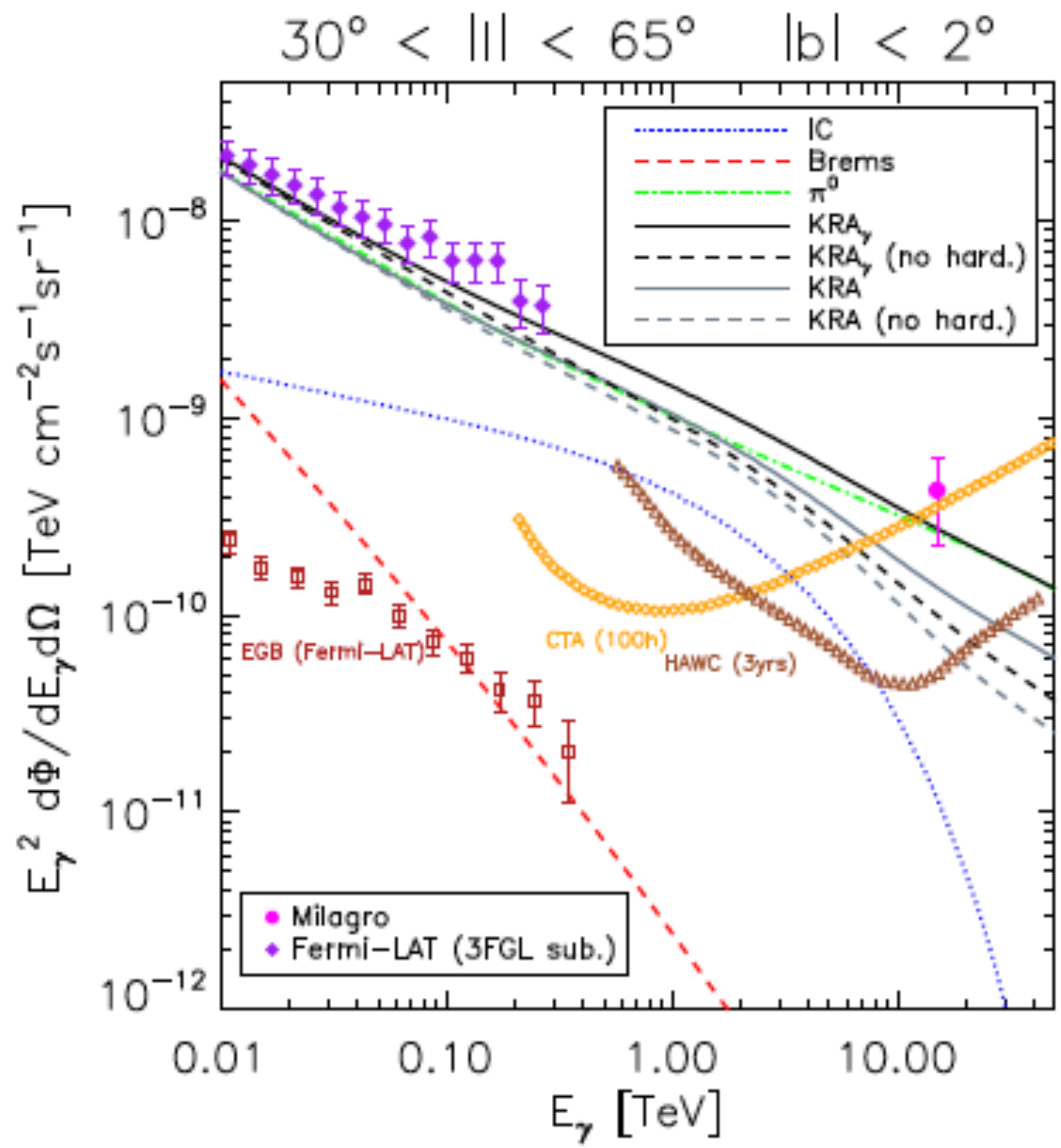
The Galactic plane above the TeV

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

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

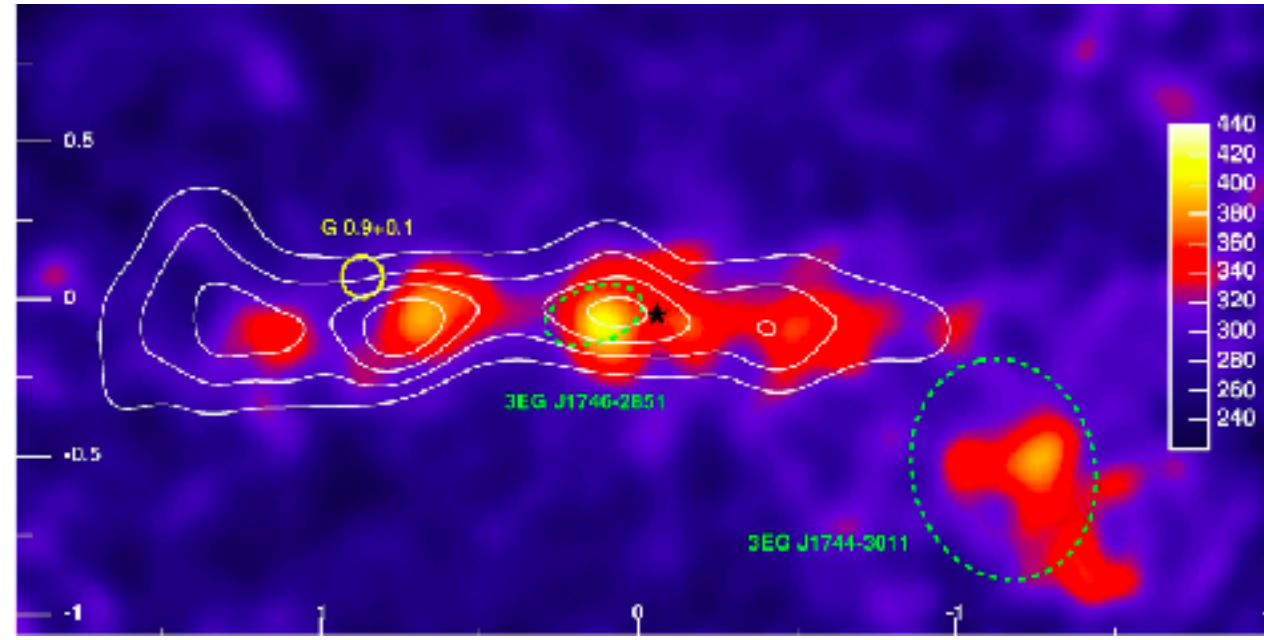
This automatically reproduces Milagro observed flux @ 15 TeV

testable by HAWC and CTA (work in progress)



The Galactic center TeV excess

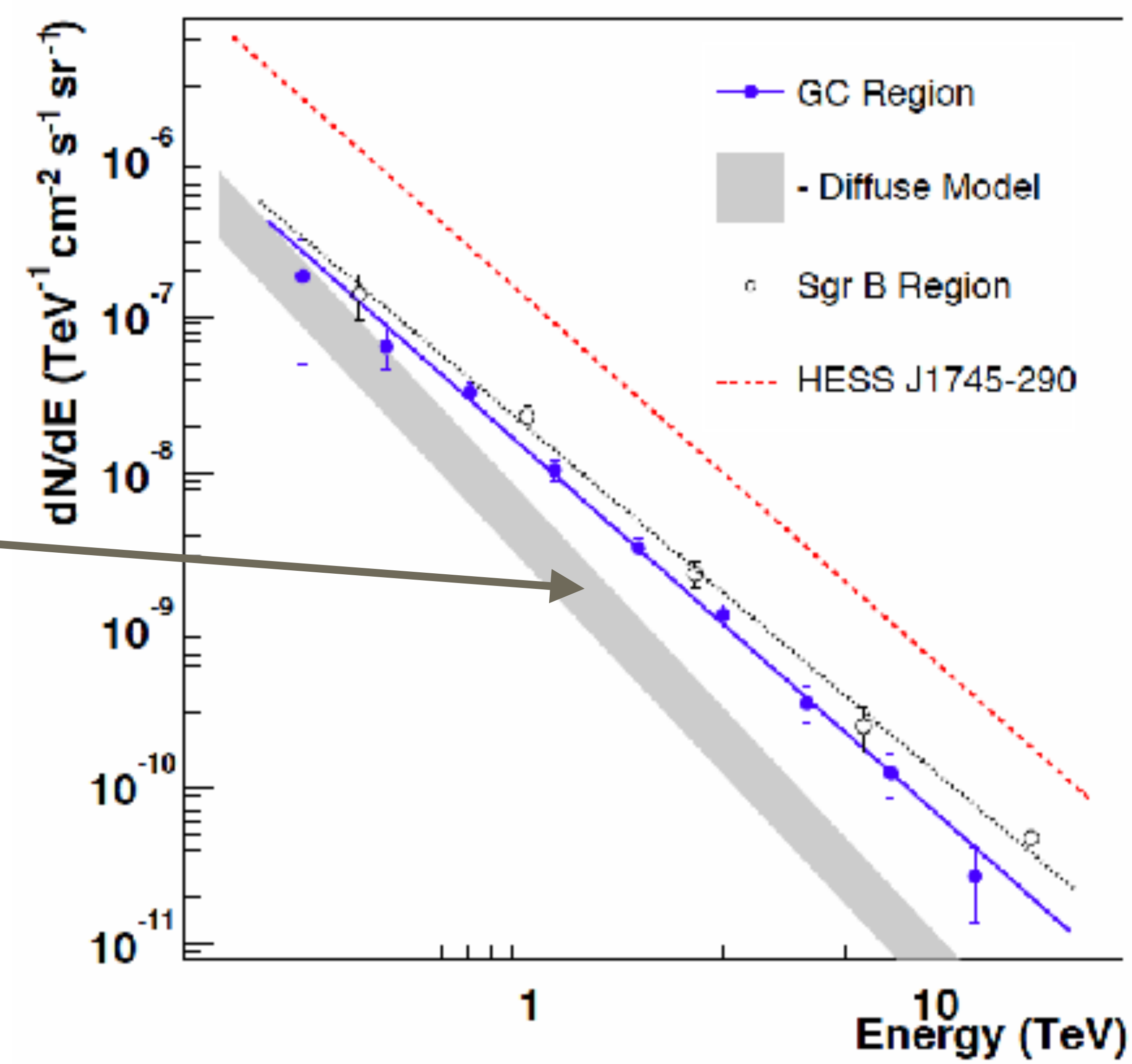
H.E.S.S. , Nature 2006



- The diffuse emission from the central molecular zone (CMZ) is correlated with the gas distribution (inferred from CO and CS emission maps)

- 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 ($\Gamma \simeq 2.7$)

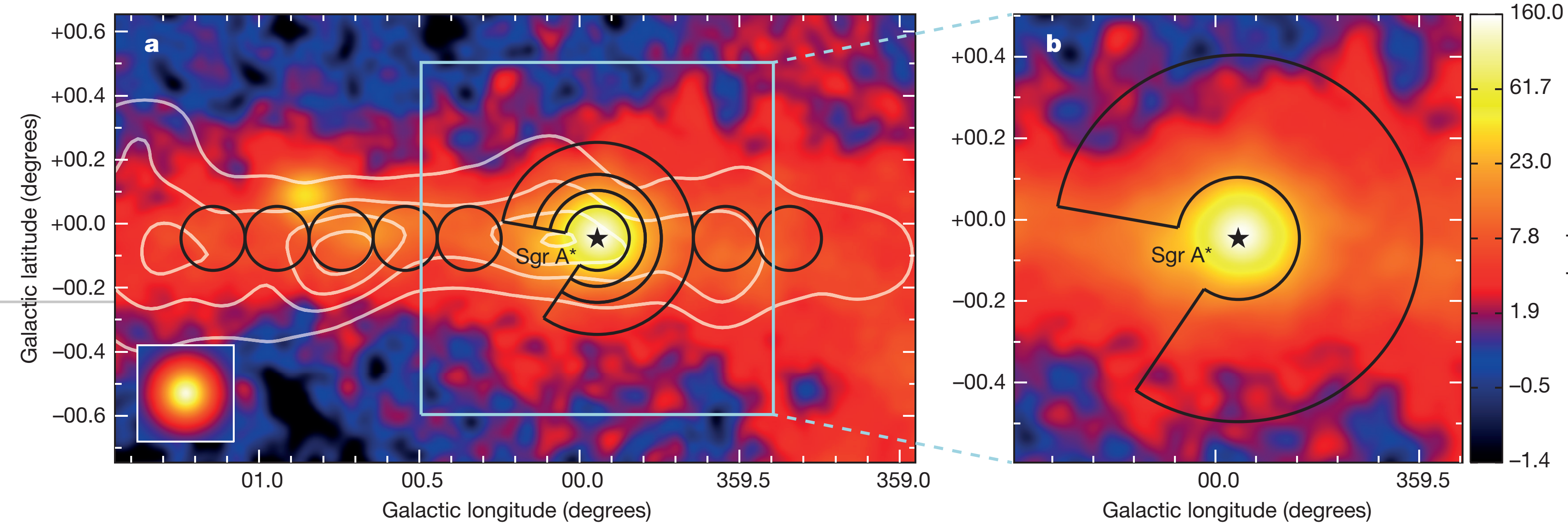
- A freshly accelerated (hard) CR component was invoked to explain the emission (see however below)



The PeVatron scenario

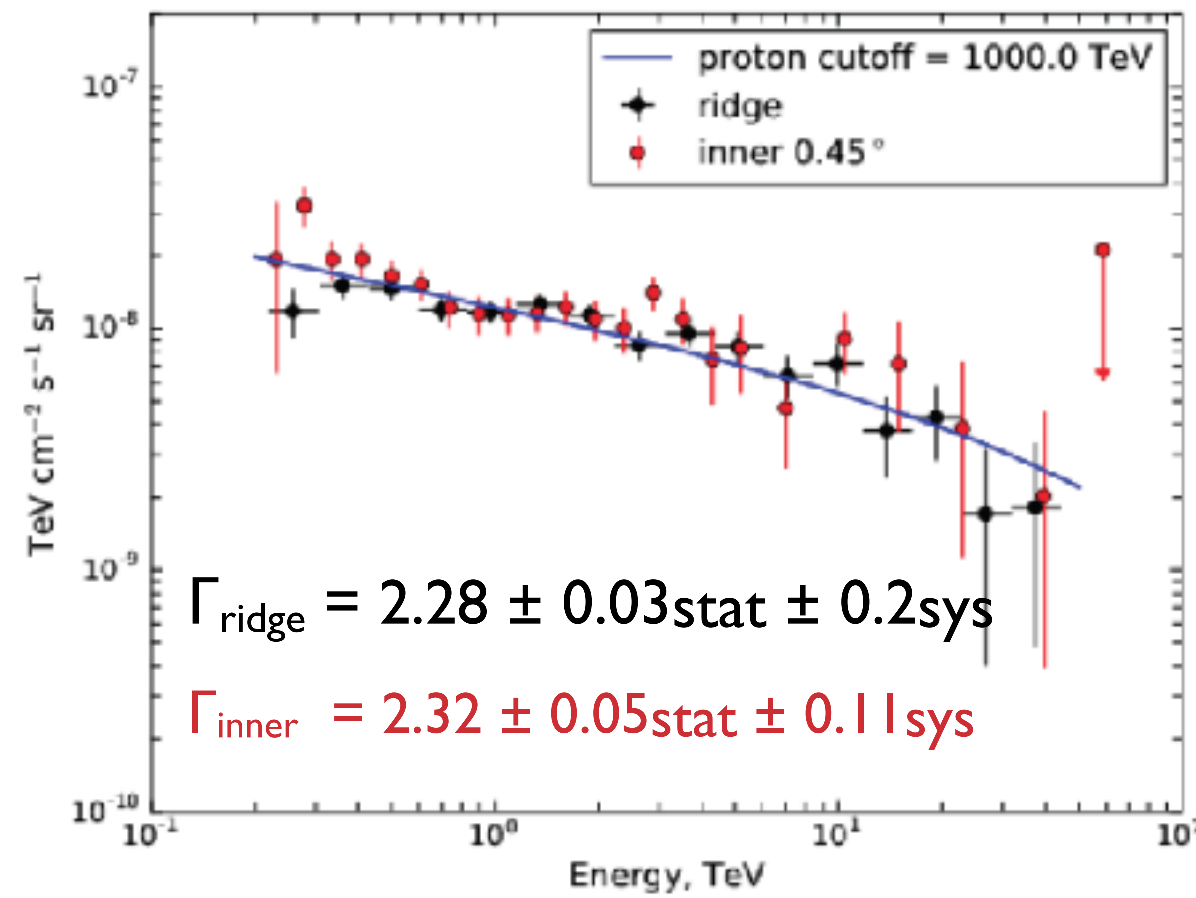
H.E.S.S. , Nature 2016

arXiv 1706.04535



larger statistics; extended the measurement up to 50 TeV ➡ CR protons up to ~ PeV

no evidence of a cutoff



Γ_{ridge} = 2.28 ± 0.03stat ± 0.2sys

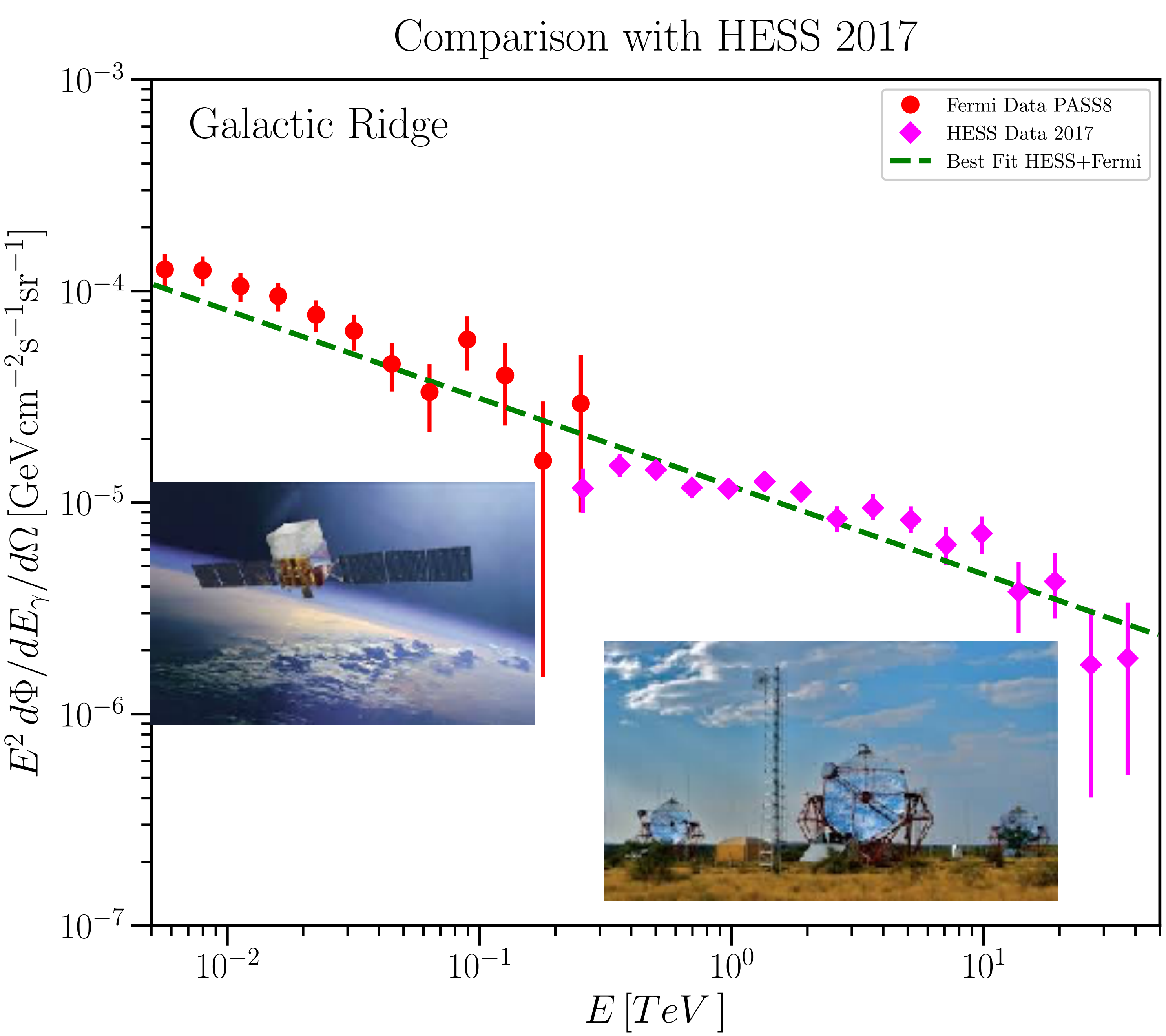
Γ_{inner} = 2.32 ± 0.05stat ± 0.11sys

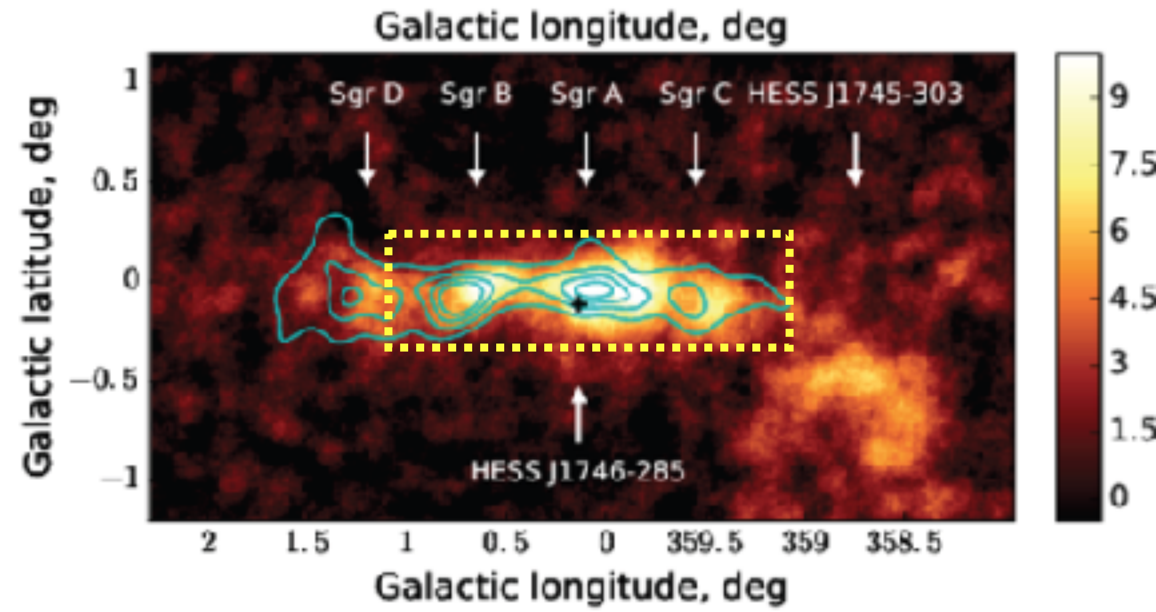
On the basis of the spectral uniformity (the GC source however display a cutoff at 10 TeV) and the angular distribution, the source of primary CR population in the CMZ was identified with J1745-290 (positionally compatible with SgrA*)

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.

An alternative interpretation

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

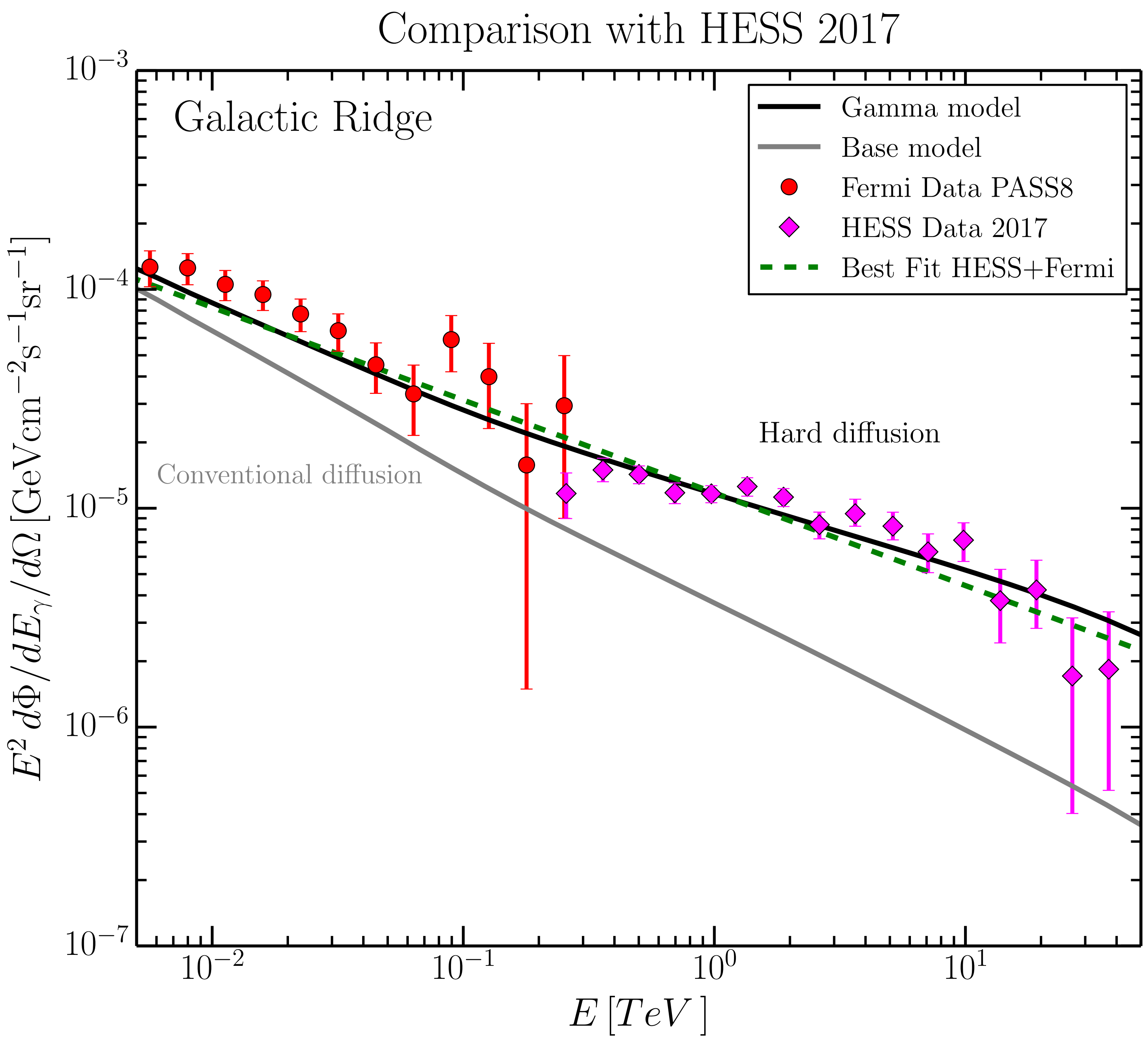
" + S.Ventura (ICRC 2017)

We use a 3-D gas model for the CMZ (*Ferriere 2007*)

We found that the same model solving the GP FERMI anomaly and matching Milagro (KRAγ model + CR hardening)

reproduce FERMI + HESS data in the ridge and inner region

The Galactic CR sea suffice to explain the CMZ emission over 3 energy decades with no need of a PeVatron at the GC

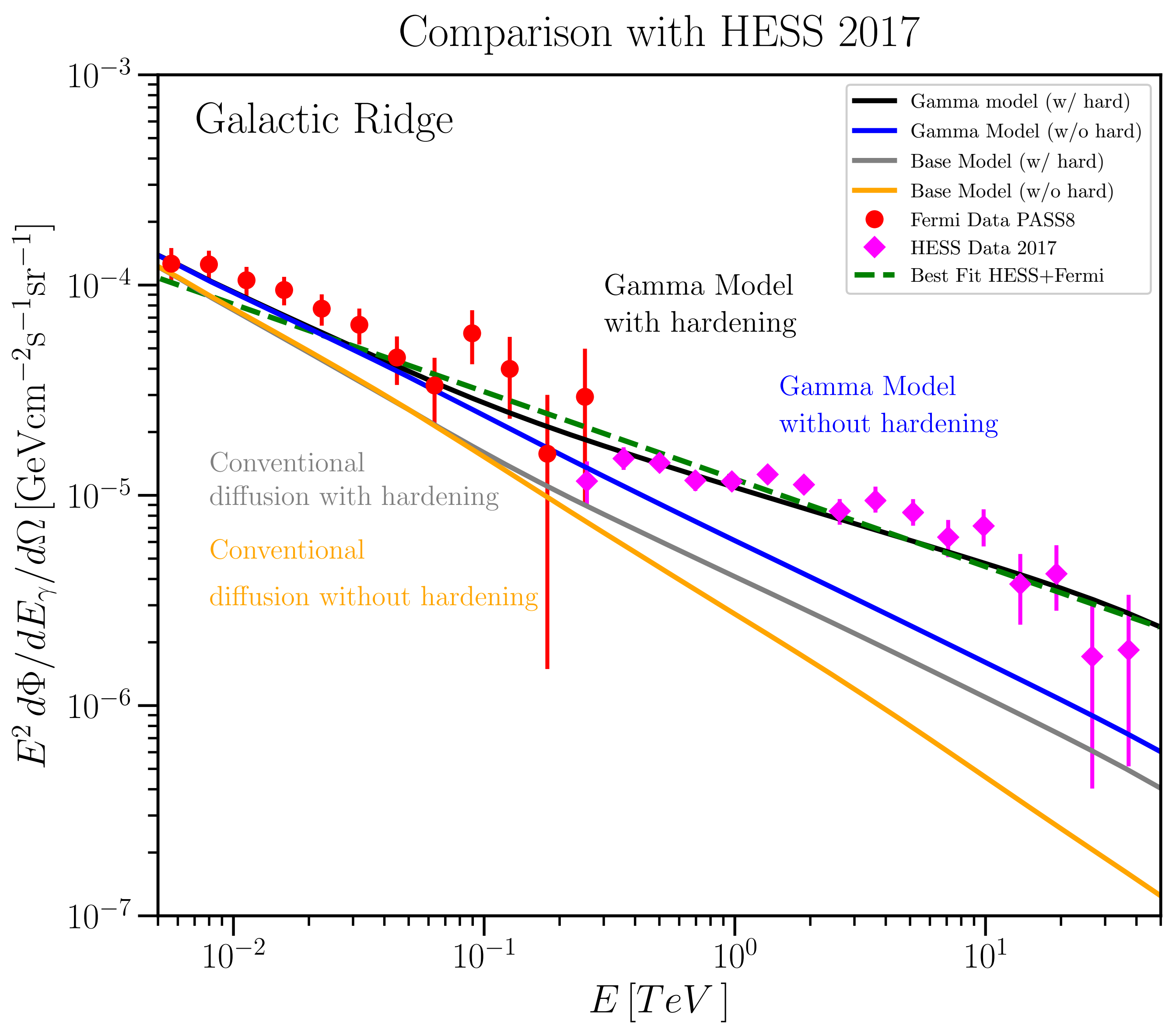


An alternative interpretation

and its possible implications

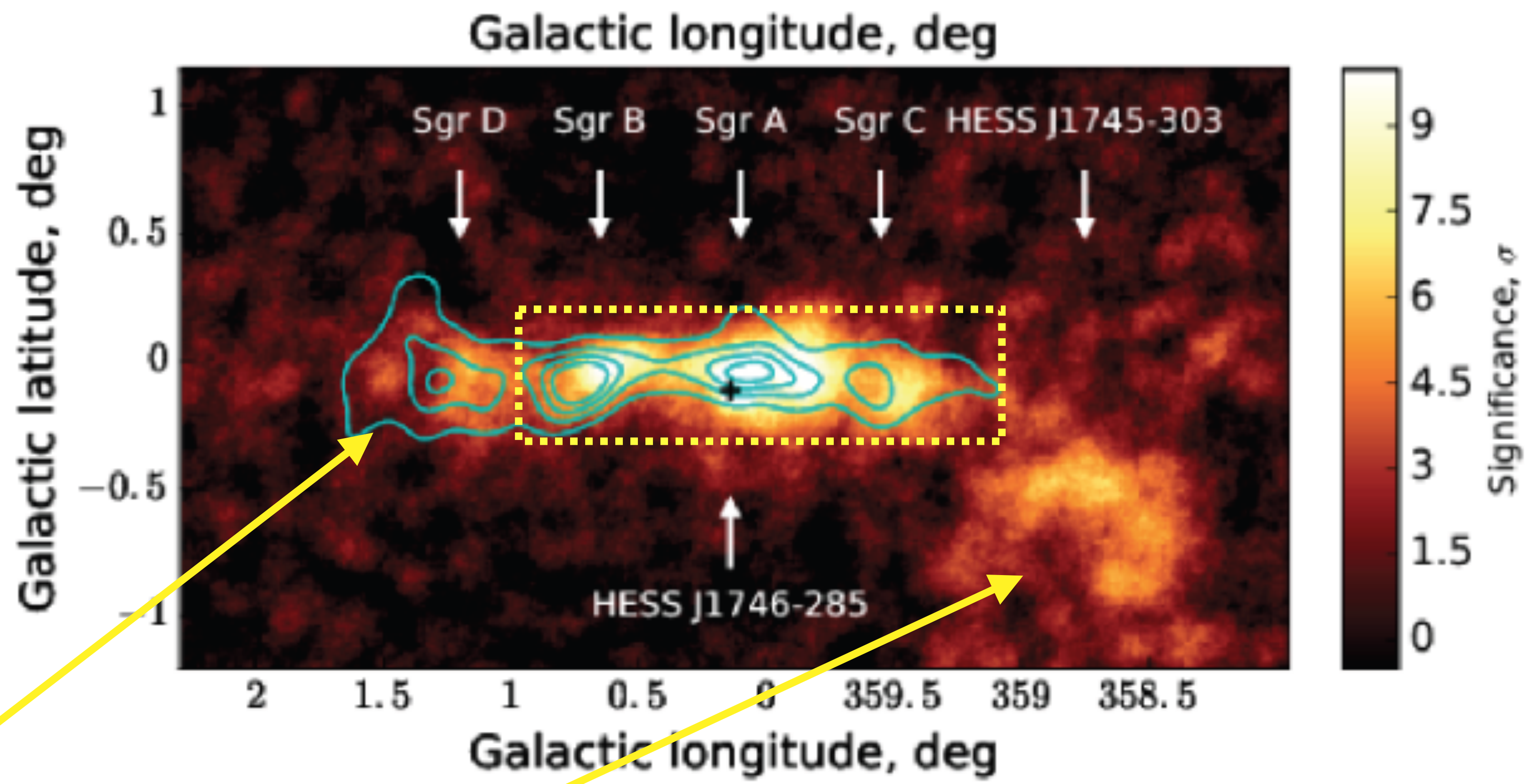
Similarly to the solution of the Milagro anomaly both the radial hardening and CR global hardening are required to match the data. This implies:

- 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 perspectives

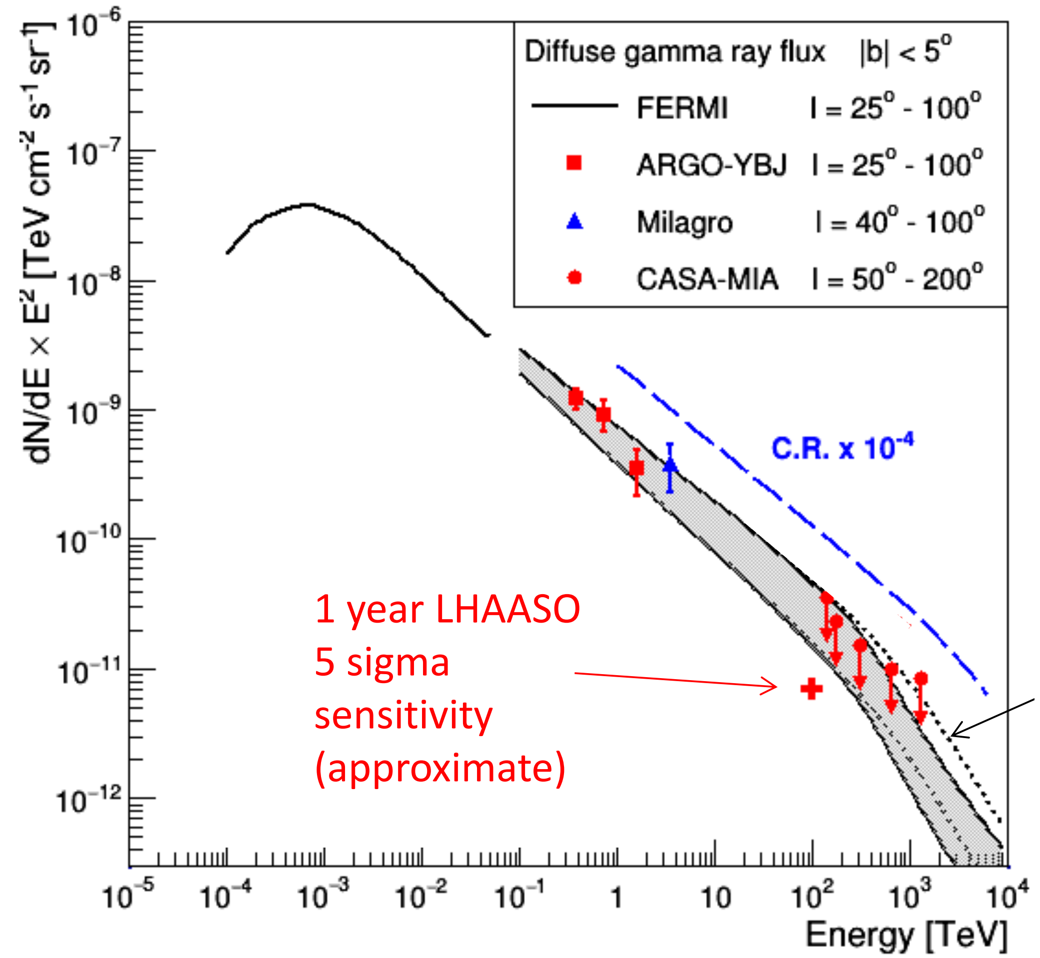
CTA may observe more external clouds where the PeVatron scenario predicts a lower CR density than that expected in our scenario



Future perspectives

wide field of view instruments would more suitable to study the diffuse γ-ray emission of the Galaxy above tens of TeV so to possible probe CR spectra up to the knee

HERD	Chinese space station
HAWC, LHAASO	North hemisphere
LATTES	South hemisphere



by S. Vernetto & P. Lipari: ICRC 2017

Implications for neutrino astronomy

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

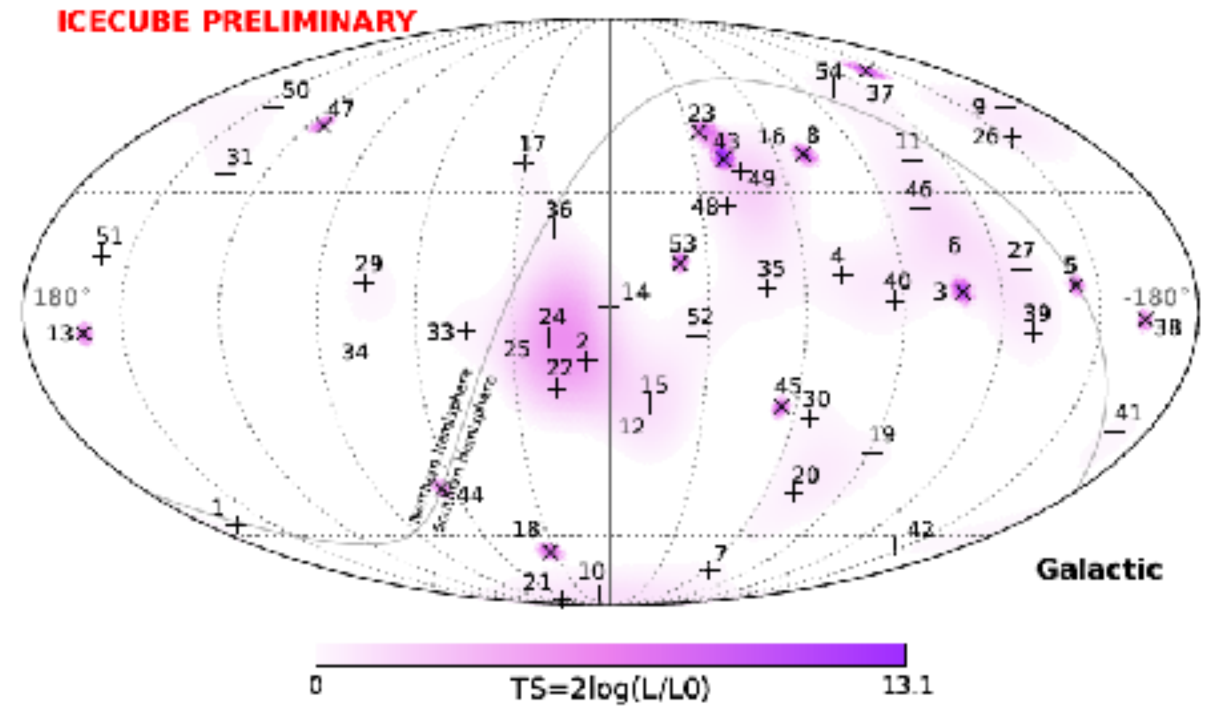
ANTARES coll. , Phys. Lett. B, 2016

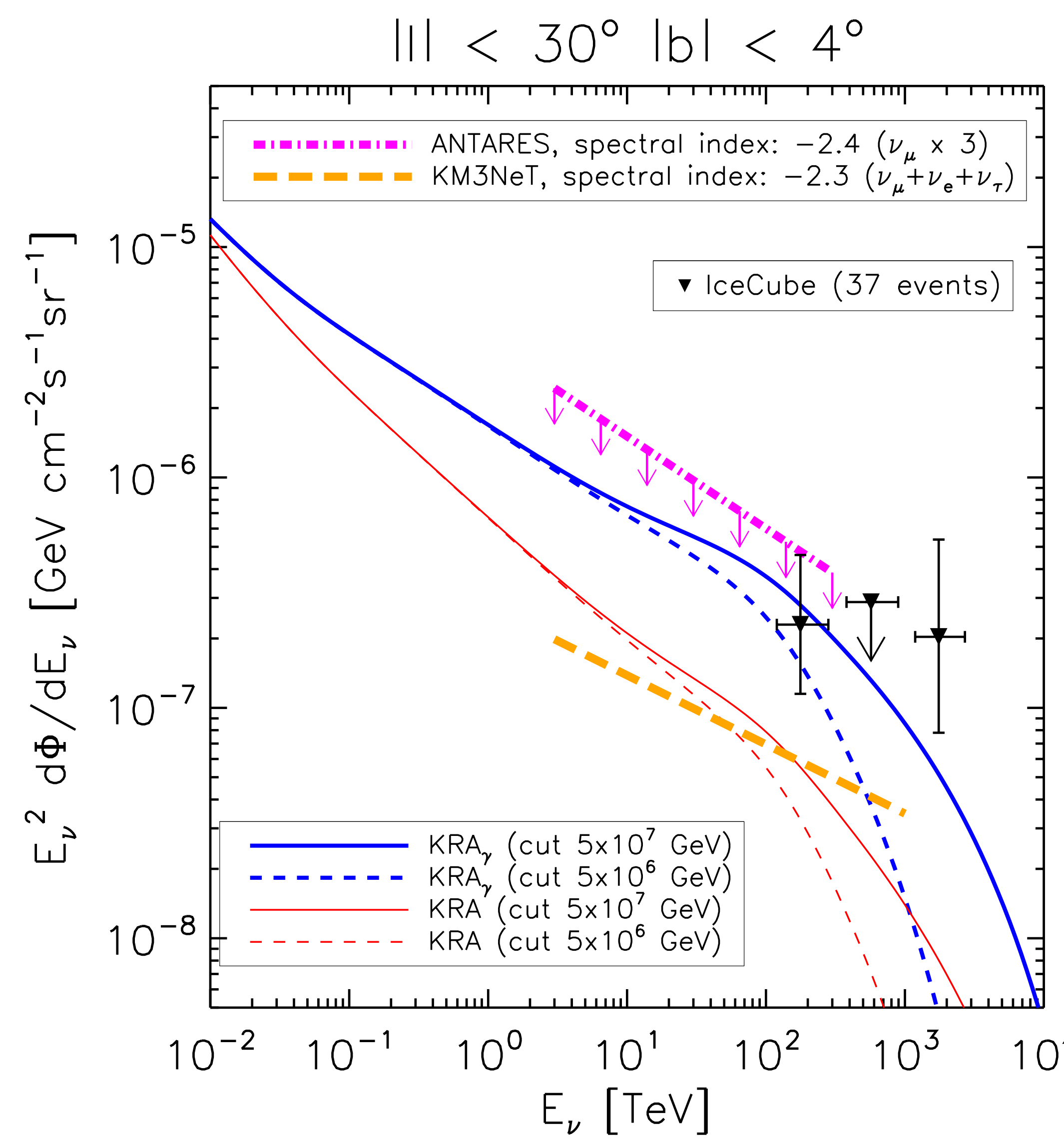
ANTARES coll. + *D. Gaggero, D.G.* PRD 2017

- 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 %

- 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. IceCube coll. is using our model 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) !





“TAKE HOME” MESSAGES

- Recent CR and **especially γ-ray** data and theoretical arguments strongly suggest that the conventional treatment of CR propagation in the Galaxy is not fully adeguate.
- This implies that propagation uncertainties, which may impact on dark-matter indirect search, may be larger than expected and be still dominating respect to cross-section ones.
- While some work has been done, a larger investment of the community should be done to develop more realistic modelling and analysis tools.
- Better data are also needed: while CTA will provide valuable info, a larger γ**-ray** detector in space (HERD ?) and a HAWC-type ground based one in the South hemisphere (LATTES ?) would be desirable