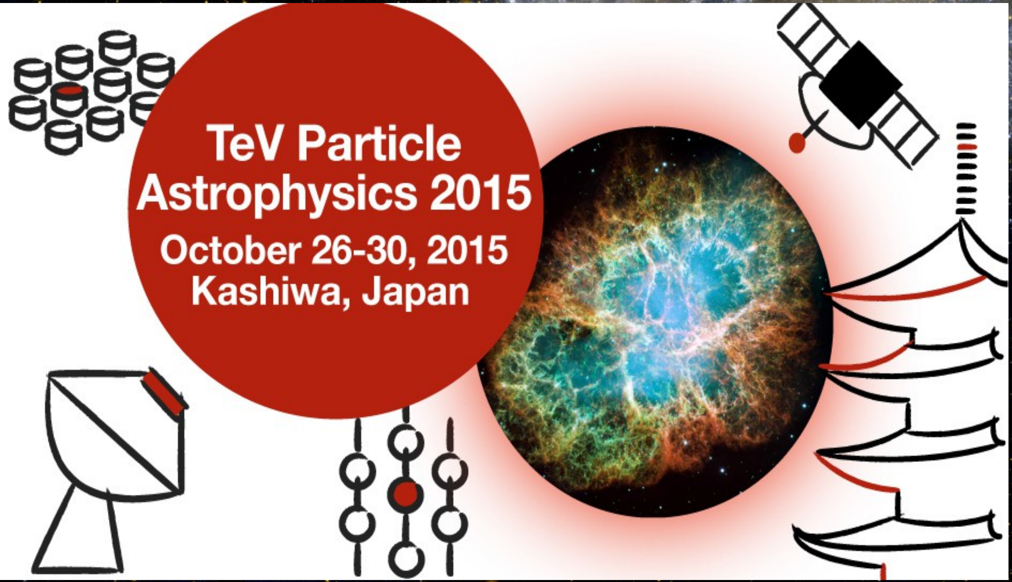
Radial gradients in cosmic-ray transport: Implications for TeV gamma and neutrino astronomy.



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GRavitation AstroParticle Physics Amsterdam

Outline

– Is it possible to infer how the properties of CR transport change through the Galaxy? A spectral anomaly in Fermi-LAT gamma-ray data provide a guideline.

– The $KRA\gamma$ model: a good fit of both gamma-ray data and CR local observables

– Implications for TeV gamma rays: A natural solution to the Milagro anomaly!

– Implication for neutrino astronomy: A novel interpretation of IceCube data, precise predictions for ANTARES, Km3Net, IceCube.

Gamma rays tell us something about CR transport

Basic picture of CR transport adopted so far: CR diffuse in homogeneous and isotropic way through all the halo.

$$
\begin{aligned}
\frac{\partial N^i(\vec{x},p,t)}{\partial t} &= \nabla\cdot(D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) + \\
&+ \frac{\partial}{\partial p}\left(\dot{p}-\frac{p}{3}\cdot\mathbf{v_C}\right) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i(\vec{x},p,t)}{p^2} \\
&+ Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\rm gas}\sigma_{ij}N^j - c\beta n_{\rm gas}\sigma_{\rm in}N^i(\vec{x},p,t)
\end{aligned}
$$

In other words: D is taken as a constant coefficient.
Is this approximation too rough to describe the data?

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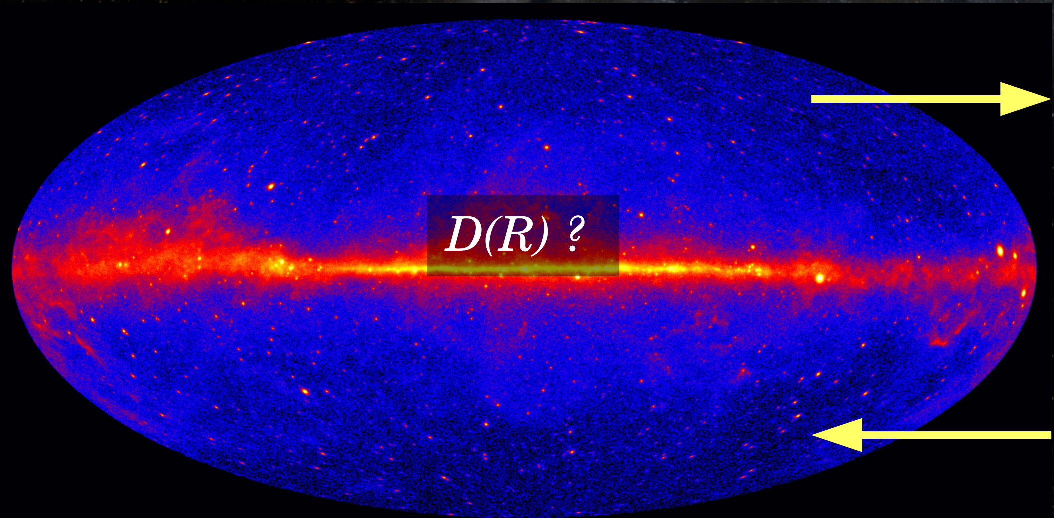
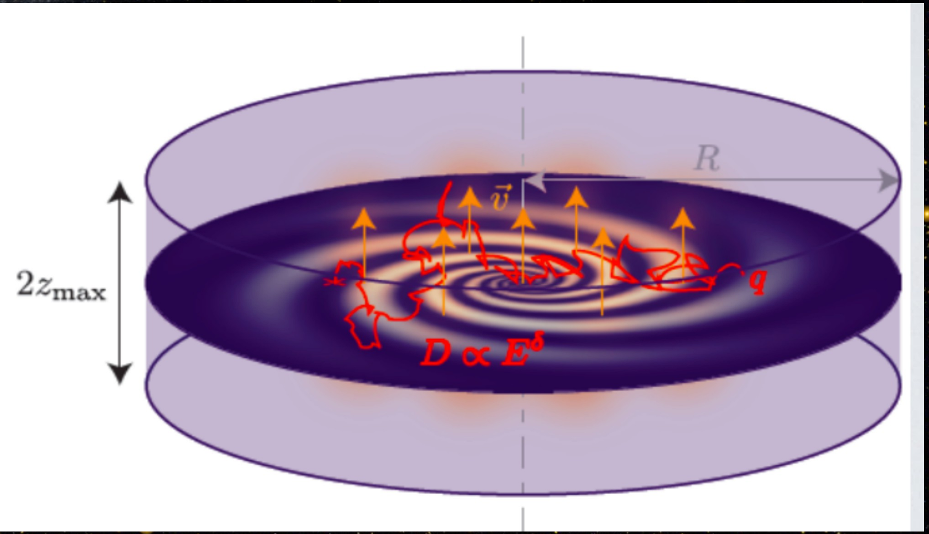
Let's look at Fermi-LAT gamma-ray data to answer this question!

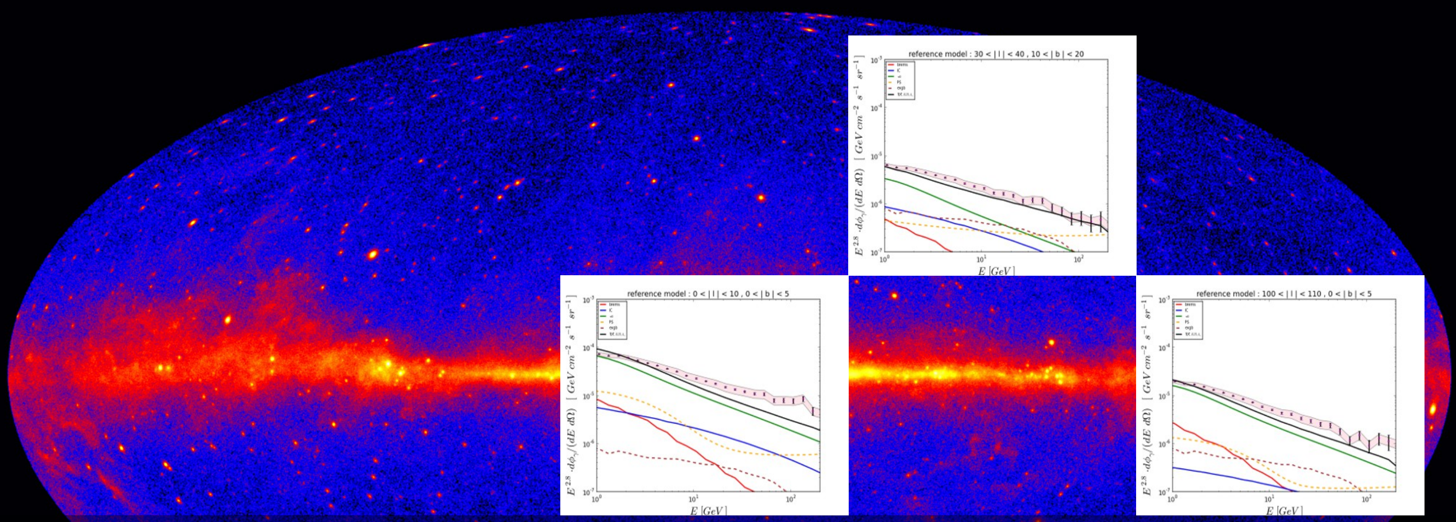




Gamma rays tell us something about CR transport

– CONVENTIONAL MODELS vs DATA –

There is actually a tension between conventional models and data



In the GC region the Fermi-LAT spectrum is harder than the conventional model prediction, see also Fermi collab., ApJ . 750 (2012)
The anomaly fades away moving towards larger longitudes and latitudes!

This is not connected at all with the well-known GeV excess from the inner Galaxy – that anomaly is pointed out by a template-fitting procedure, and such spectral anomaly is corrected by that algorithm

Gamma rays tell us something about CR transport

– AN UNCONVENTIONAL APPROACH –

D.Gaggero, A.Urbano, M.Valli, P.Ullio PRD 91 (2015)

We presented the KRA_γ phenomenological model

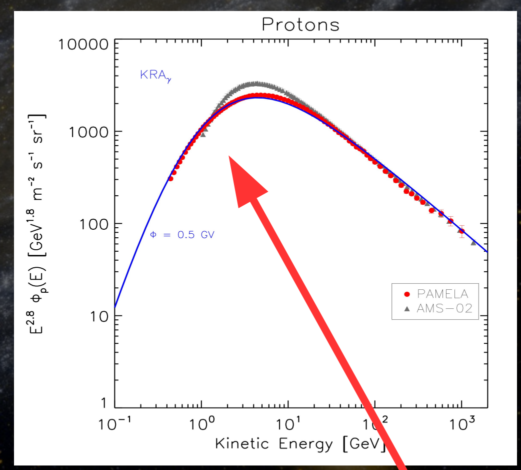
The model features:

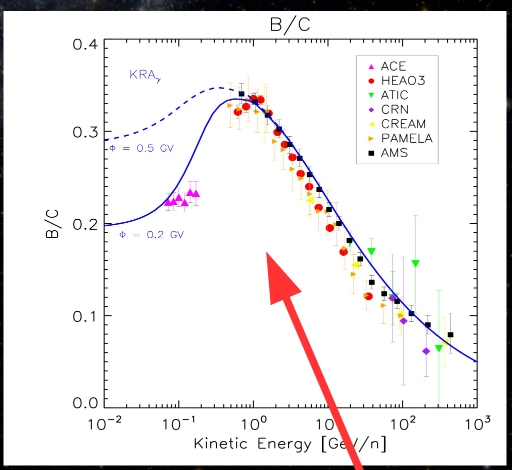
– a variable scaling of the diffusion coefficient with the Galactocentric radius R:

$\delta(R) = AR + B,\ R < 11\ kpc$
$\delta(Rsun) = 0.5$

and a convective velocity:

$dV/dz = 100\ km/s/kpc,\ R < 6.5\ kpc$





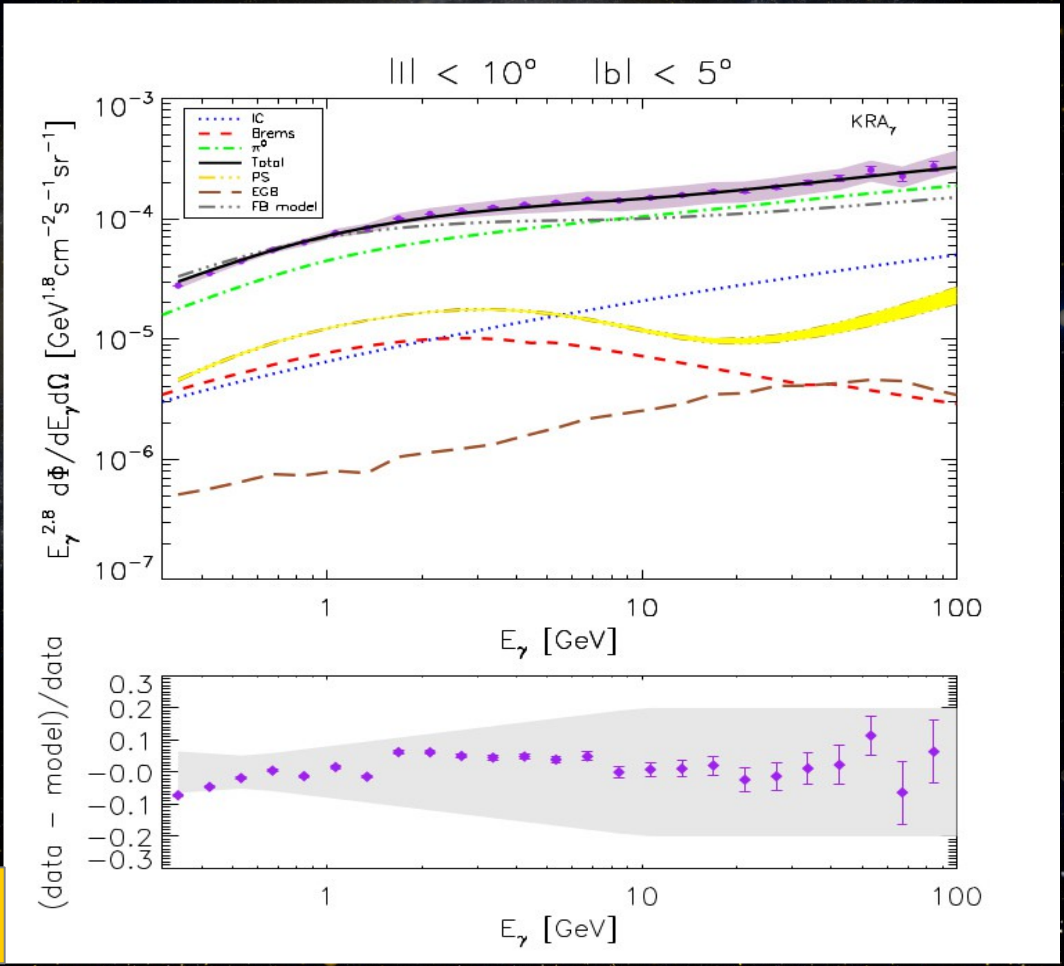
The model is **compatible with local CR observables** (protons, antiprotons, B/C), and…

Gamma rays tell us something about CR transport

– AN UNCONVENTIONAL APPROACH –

D.Gaggero, A.Urbano, M.Valli, P.Ullio PRD 91 (2015)

...The gamma-ray spectra are correctly reproduced both along the Galactic plane and at mid latitude!



Galactic Center

Gamma rays tell us something about CR transport

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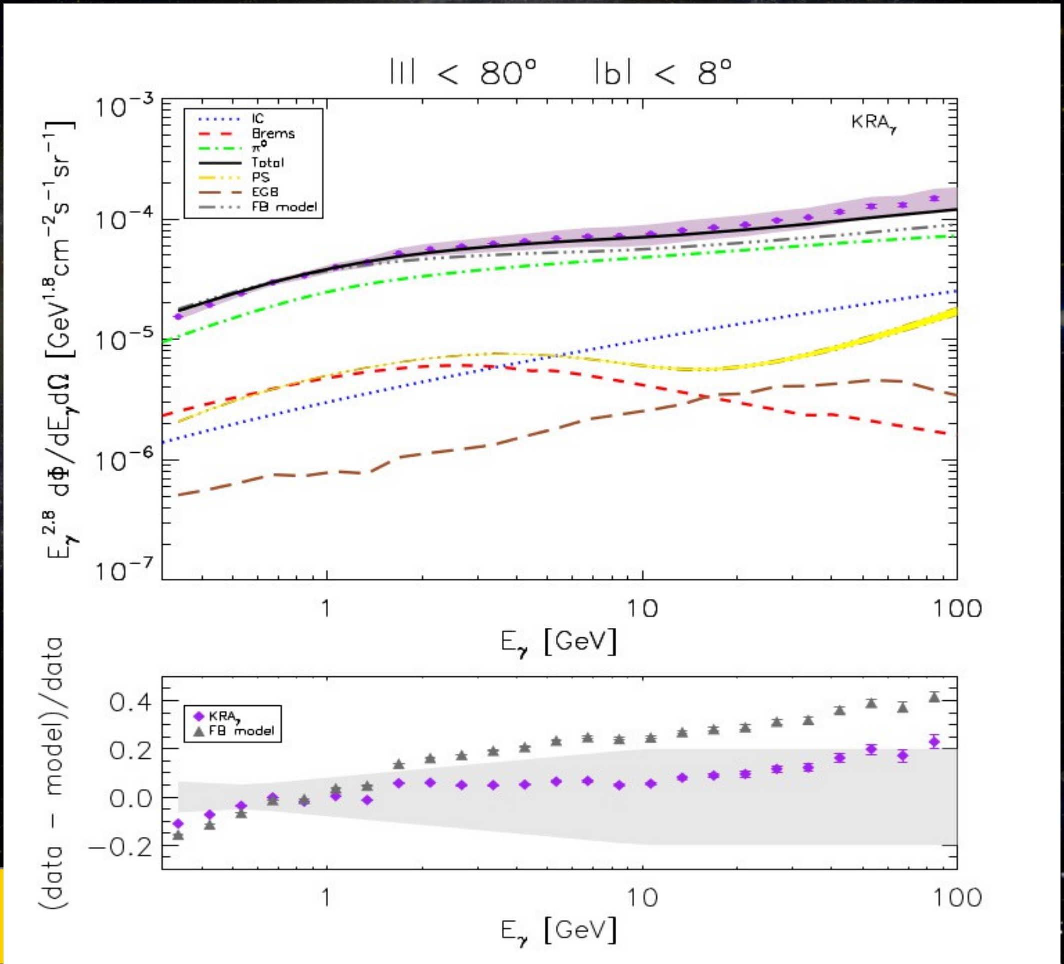

Galactic Plane

Gamma rays tell us something about CR transport

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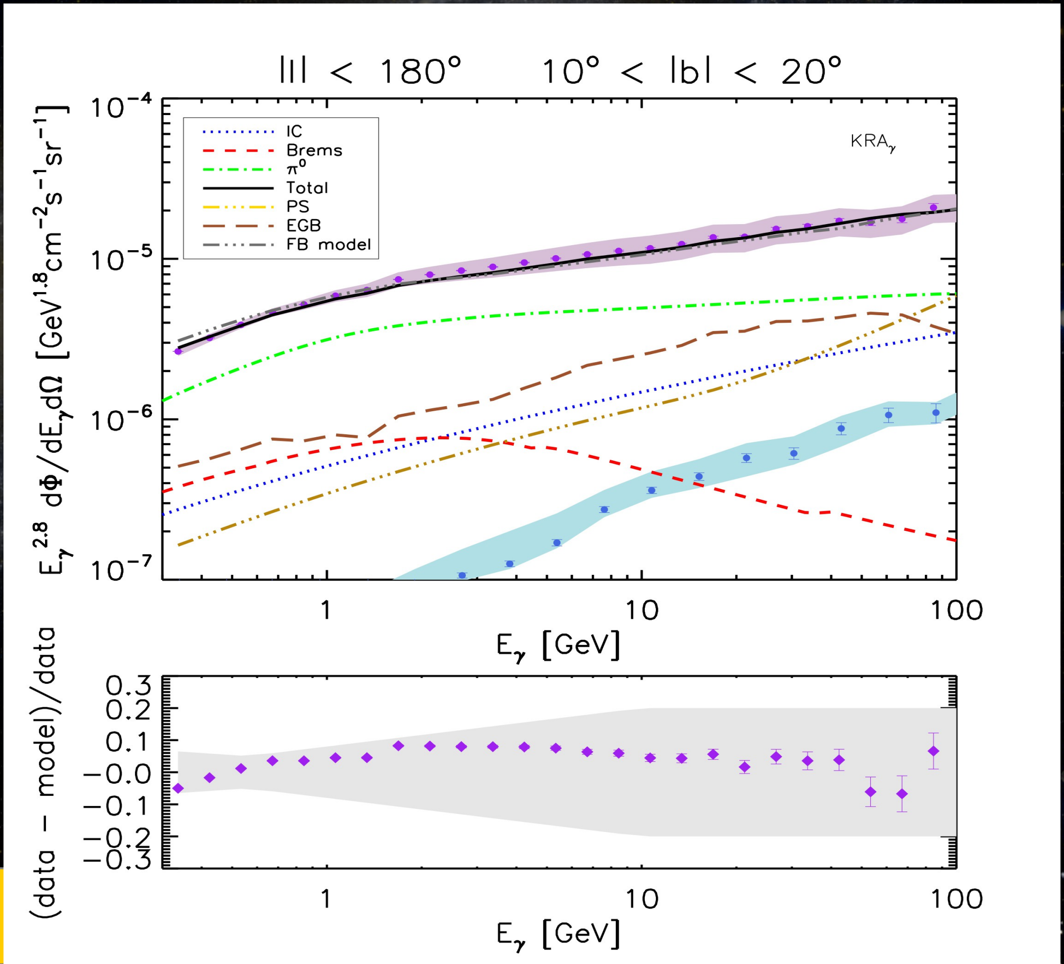


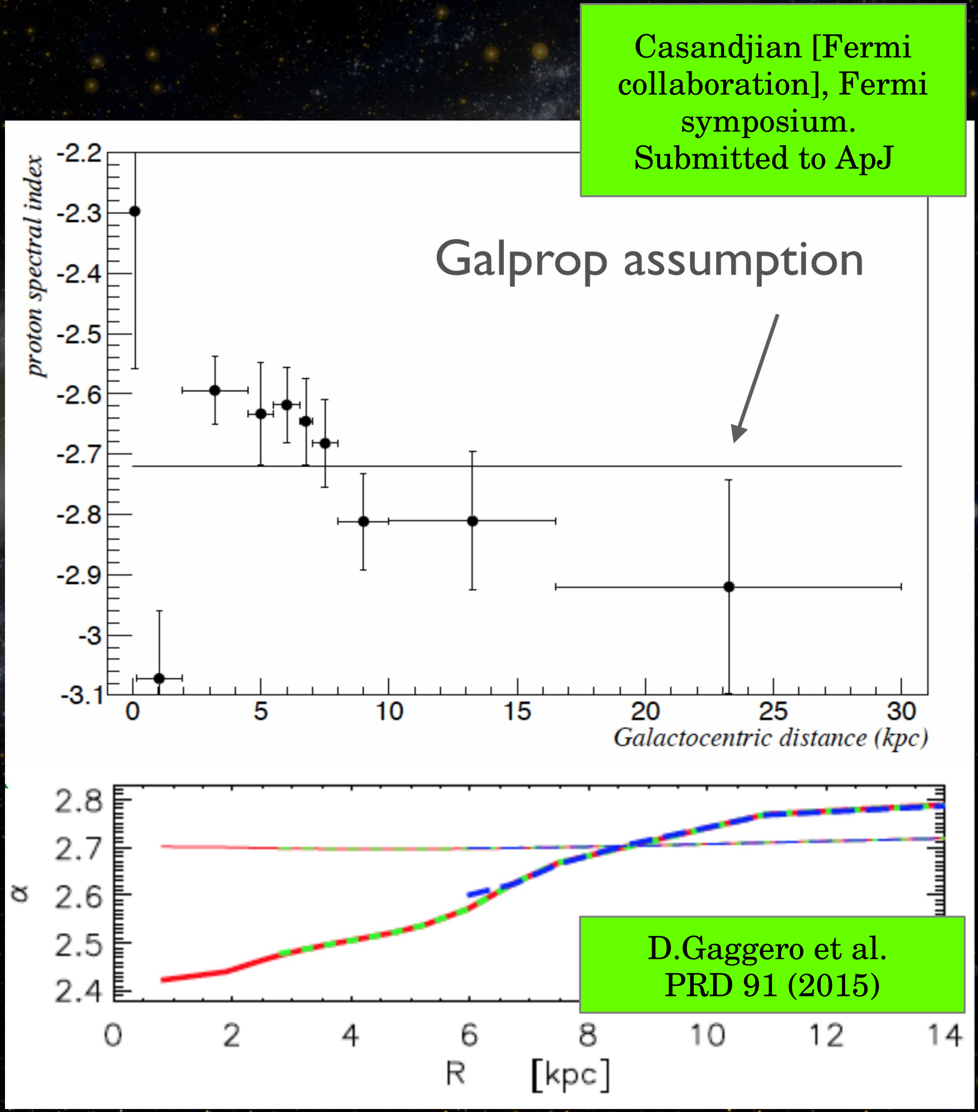
Mid Latitude

Gamma rays tell us something about CR transport

– AN UNCONVENTIONAL APPROACH –

D.Gaggero, A.Urbano, M.Valli, P.Ullio PRD 91 (2015)

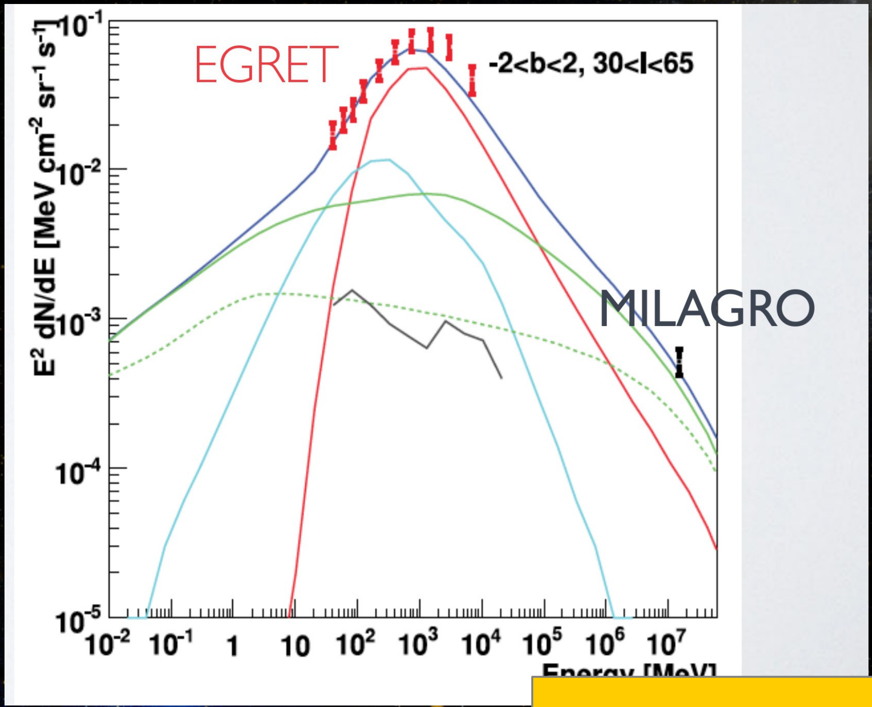
→ The spectral index we find is confirmed by Fermi-LAT collaboration!



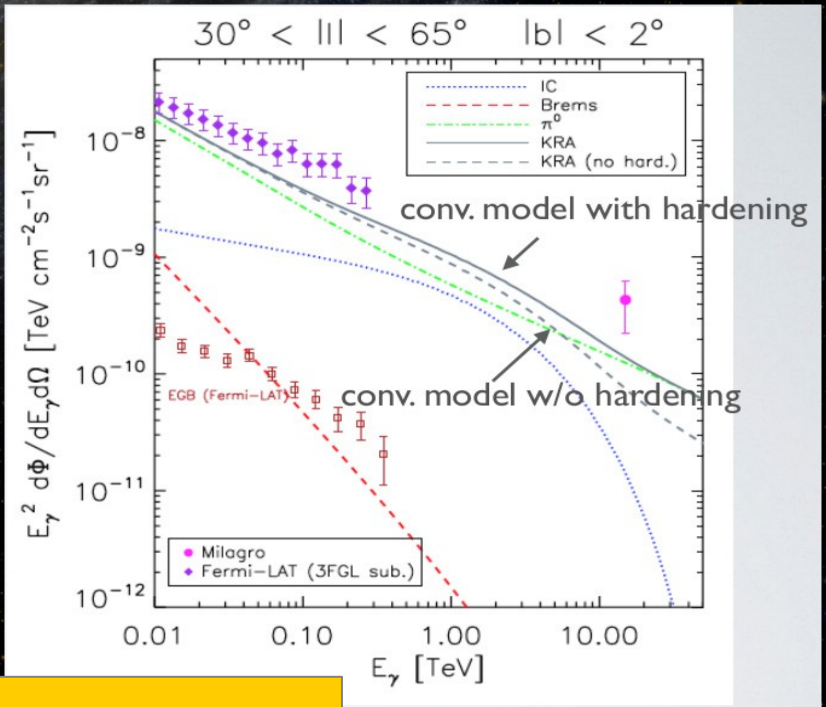
Let's now see a posteriori how our model performs above the TeV

D.Gaggero, D.Grasso, A.Marinelli, A.Urbano, M.Valli, arXiv:1504.00227 (2015)
D.Gaggero, D.Grasso, A.Marinelli, A.Urbano, M.Valli, arXiv:1507.07796, arXiv:1508.03681

There is a (long-standing, almost forgotten) anomaly also at that energy



EGRET era



Fermi-LAT era

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D.Gaggero, D.Grasso, A.Marinelli, A.Urbano, M.Valli, arXiv:1504.00227 (2015)
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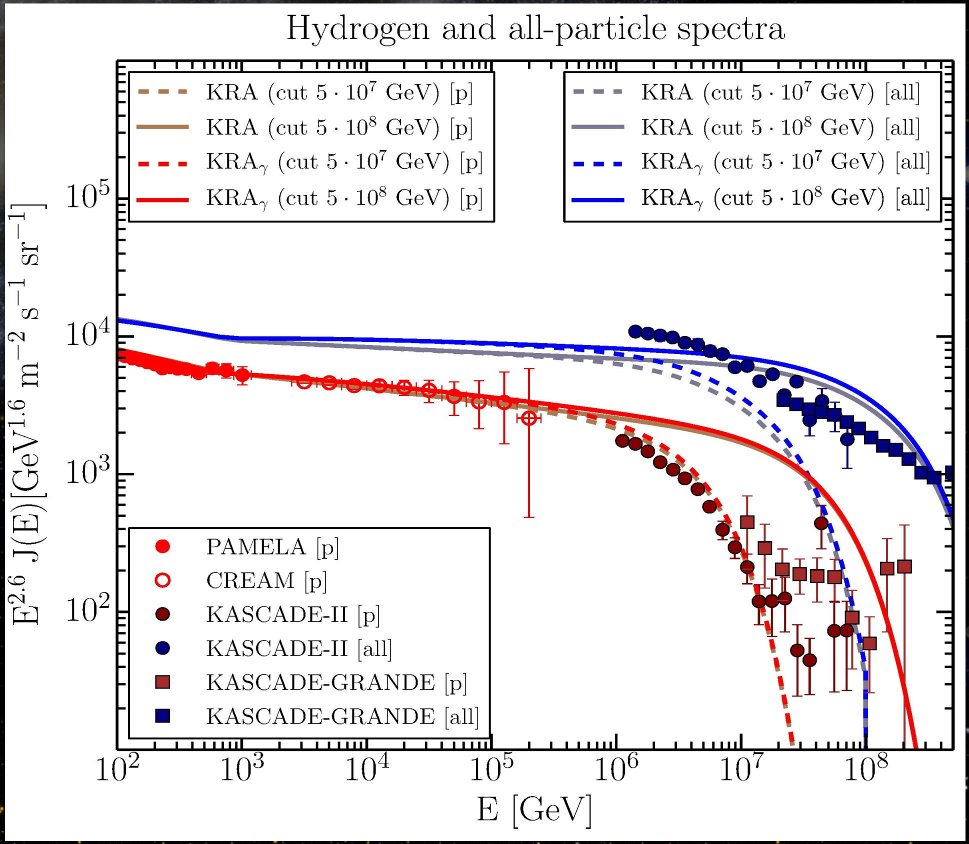
So we extrapolate both the conventional (KRA) and the KRA_γ model at high energies

We consider two different choices of the high-energy proton and Helium cutoff,

consistent with CREAM and bracketing the uncerteinties in KASCADE and KASCADE-Grande datasets.



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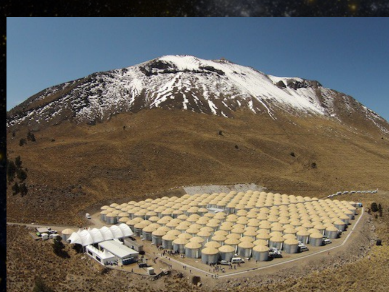
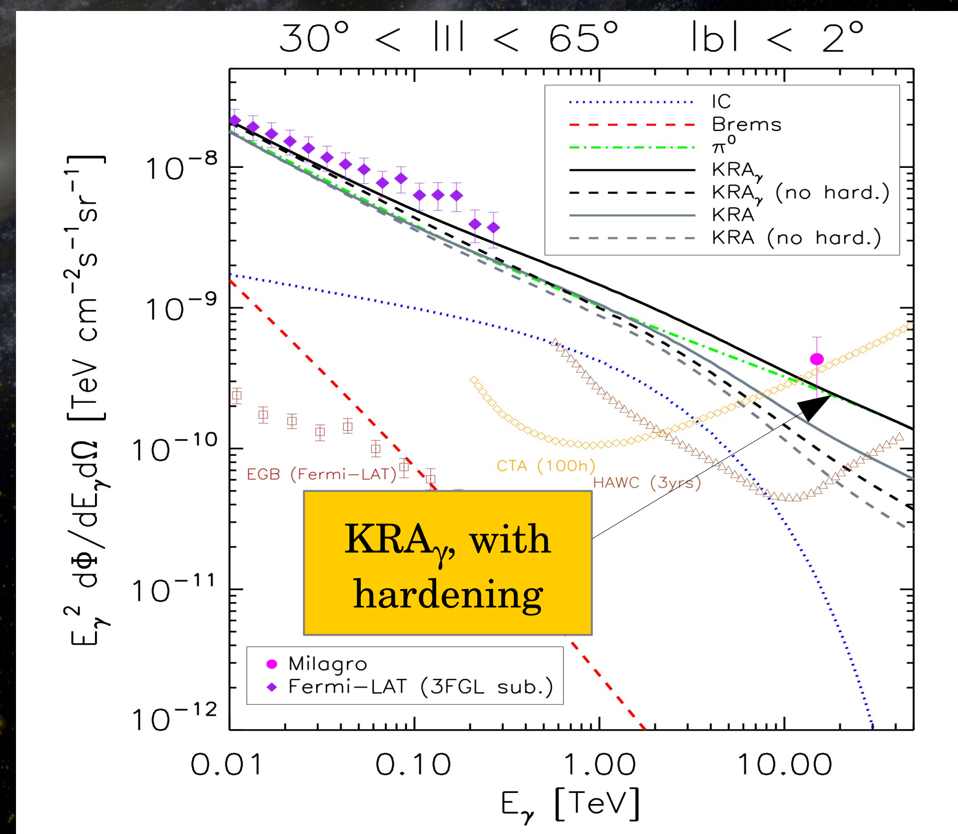
The KRA_γ nicely matches MILAGRO consistently with Fermi data (point sources cleaned) without further tuning !

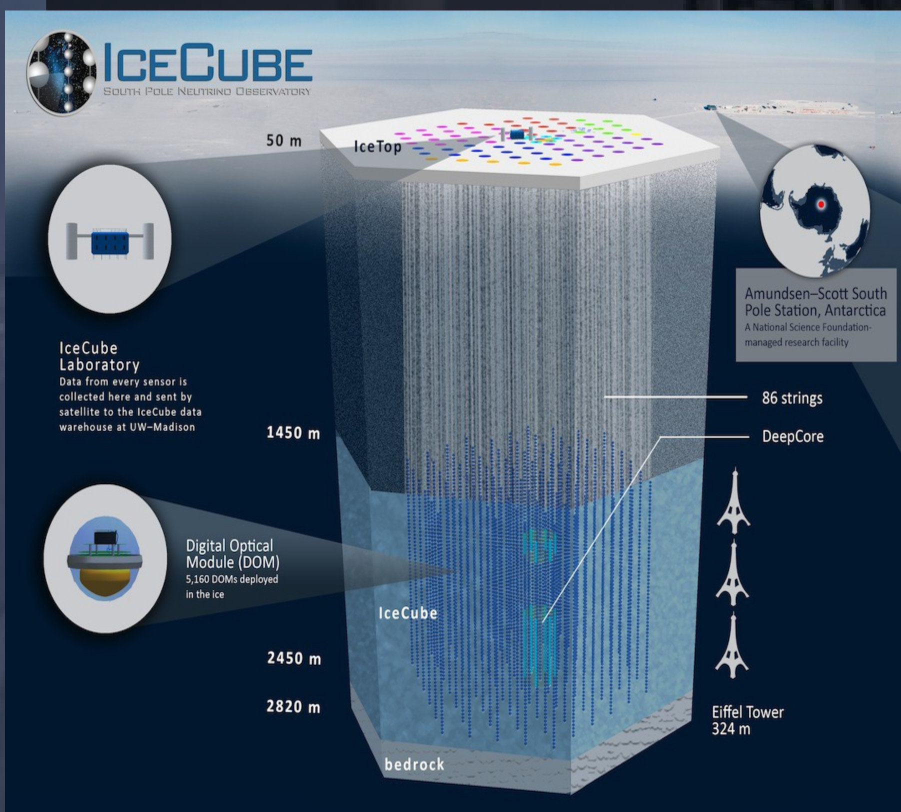
→ *This result is testable by the HAWK observatory*





A novel interpretation and some precise predictions for the IceCube neutrinos

Based on D.Gaggero, D.Grasso, A.Marinelli, A.Urbano, M.Valli, arXiv:1504.00227 (2015)
D.Gaggero, D.Grasso, A.Marinelli, A.Urbano, M.Valli, arXiv:1507.07796, arXiv:1508.03681



A novel interpretation and some precise predictions for the IceCube neutrinos

– IceCube reported the detection of **37** high-energy starting neutrino events (HESE) of extraterrestrial origin [PRL 2014, 1405.5303] above 30 TeV in 3 years of data taking, and, more recently, a preliminary analysis of **54 HESE** events [ICRC 2015] in 4 years of data.

– **Spectral index**:

-2.3 ± 0.3 for the 37 HESE [PRL 2014, 1405.5303]

-2.58 ± 0.25 for the 54 HESE [ICRC 2015]

-2.46 ± 0.12
for a larger sample E > 1 TeV [PRD 2014, 1410.1749]

-2.50 ± 0.09
for a combined maximum-likelihood analisys
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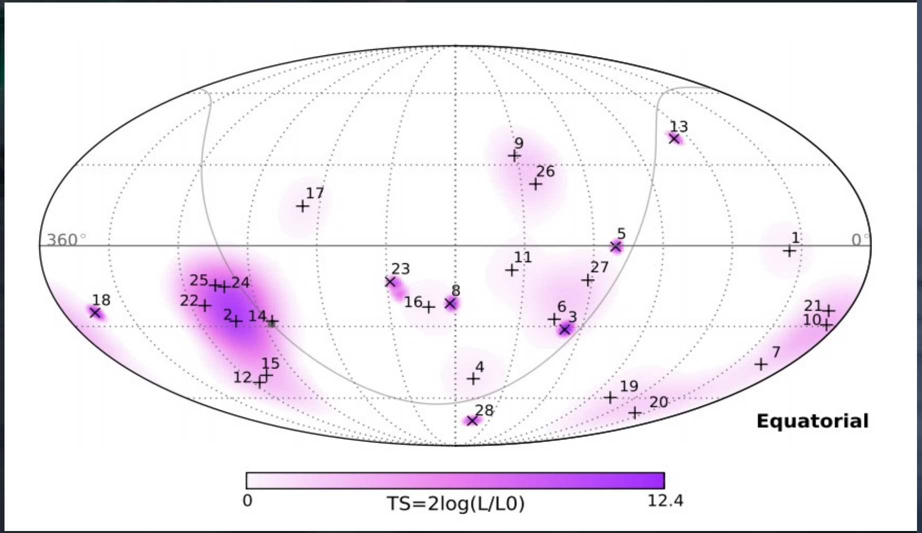

– Hint of a **flatter slope in the Northern hemispher**e [PRL 2015, 1507.04005]
This part of the sky does not include the inner Galaxy
→ *maybe a hint of a soft Galactic component (peaked in the Southern hemisphere) superimposed to a harder, isotropic extra-Galactic one?*

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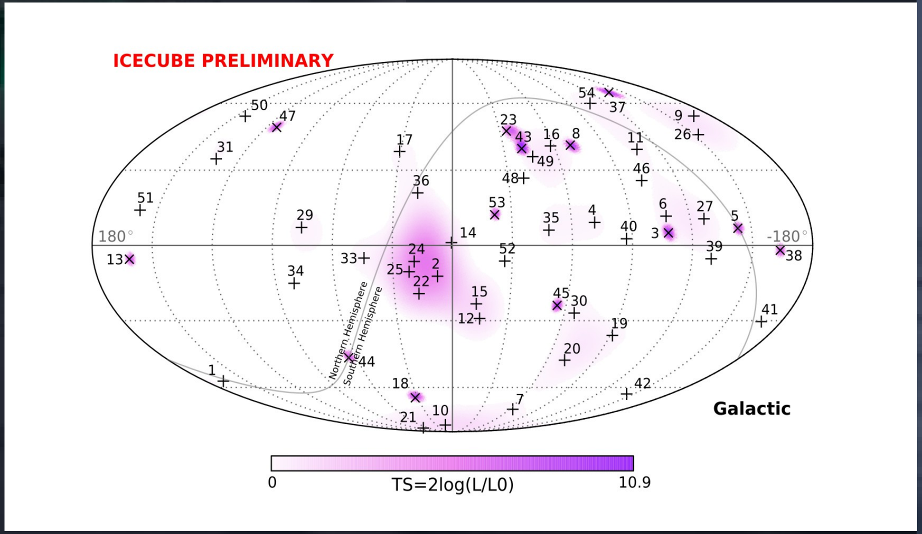

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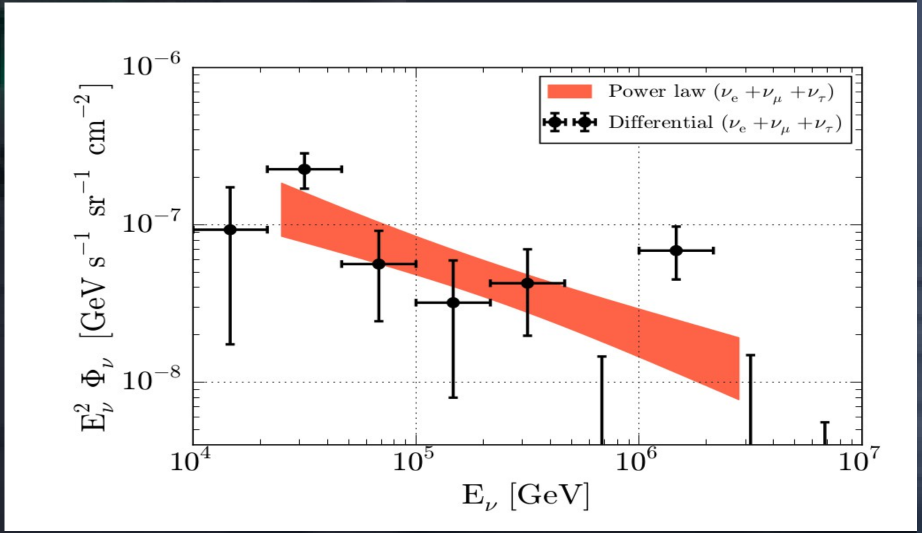

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D.Gaggero, D.Grasso, A.Marinelli, A.Urbano, M.Valli, arXiv:1504.00227 (2015)
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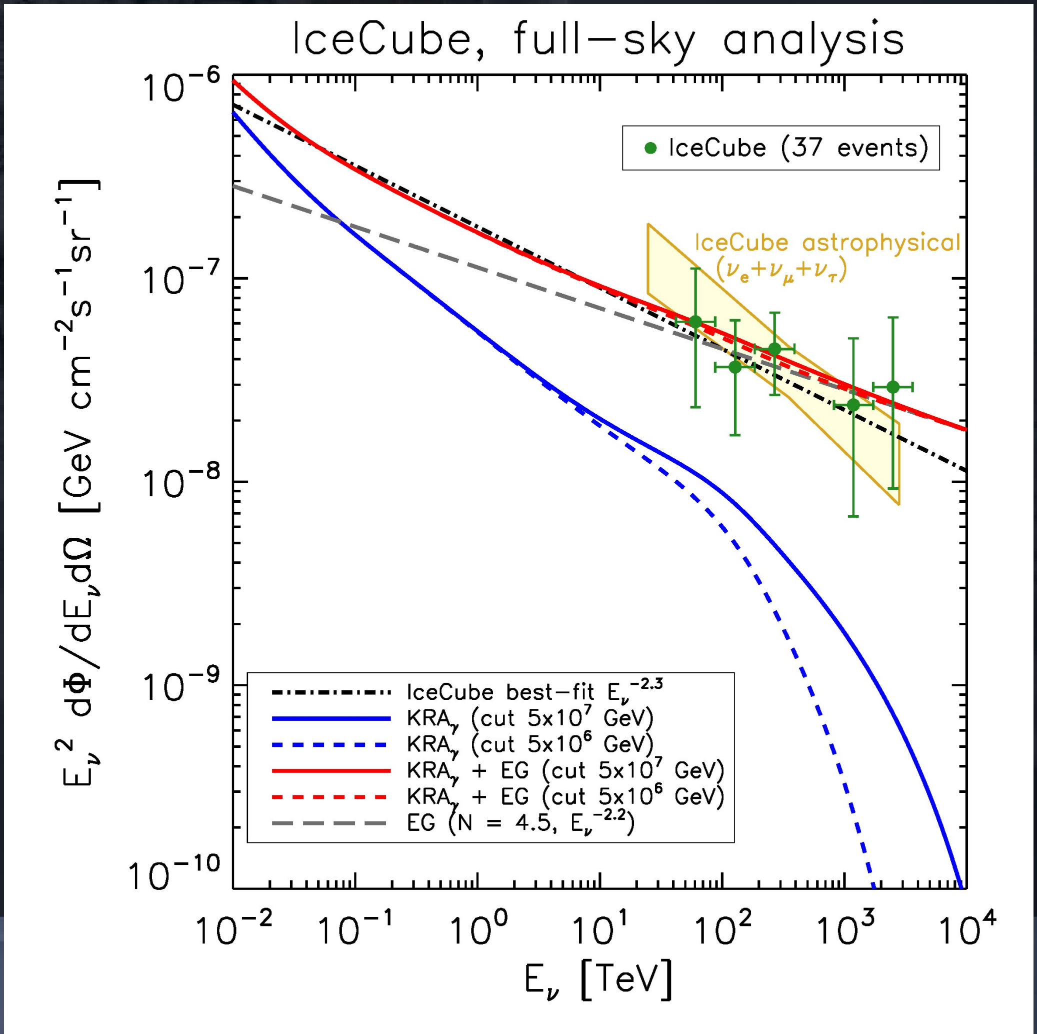
Differently from conventional models [Ahlers et al. 2015], the KRA_γ setup predicts a non-negligible neutrino flux from the Galaxy, due to the hardening in the inner region.

Even if it is still premature to draw conclusive statements, the KRA_γ model **can expain the difference between the hard spectrum in the northern Hemisphere and the soft full-sky one**.



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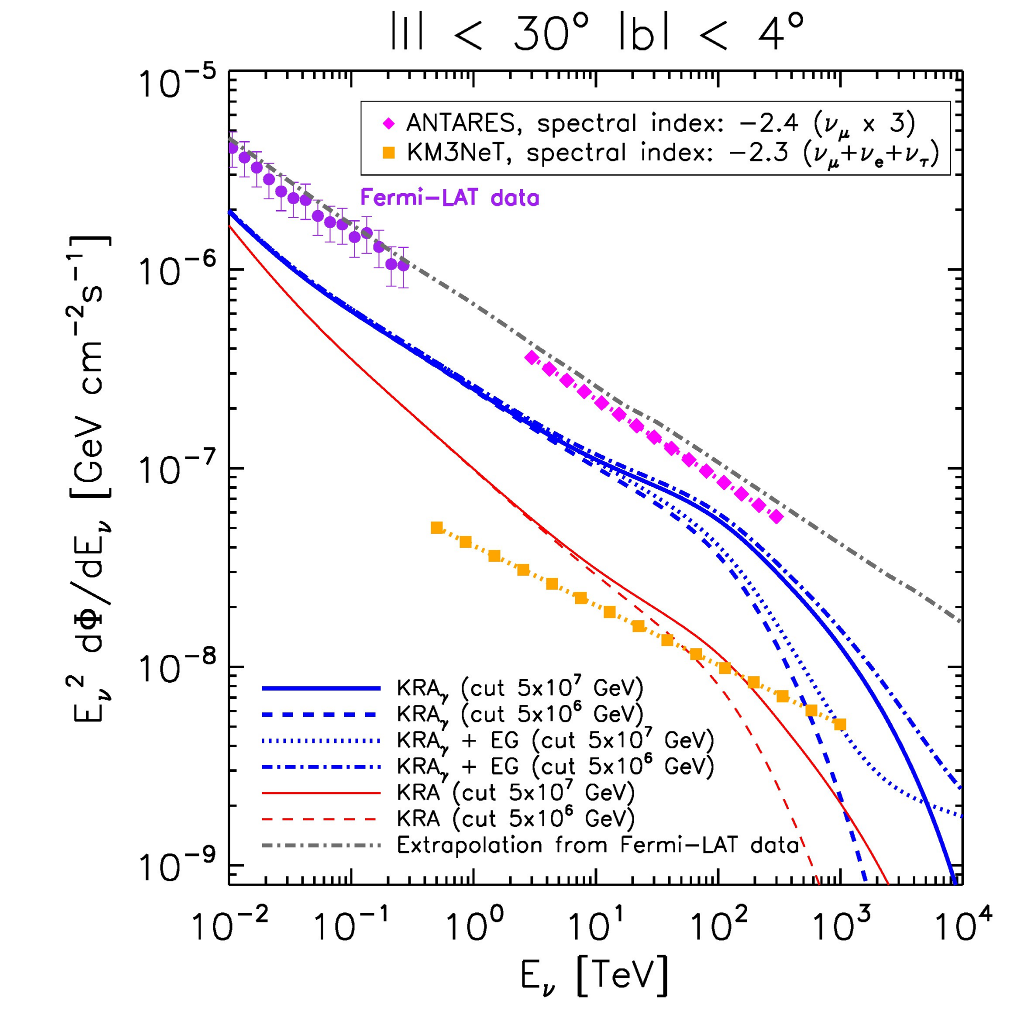
Remarkably, **our scenario is predictive and can be tested in the near future!**

The model predicts a large flux from the Galactic plane region. The signal is close to the current upper limits from ANTARES, and will be within the sensitivity of Km3Net

Sensitivity for 1500 days of livetime.
ANTARES sensitivity taken from L.Fusco, ICRC 2015
Km3Net sensitivity taken from P. Piattelli, ICRC 2015



Conclusions

1) We presented a CR propagation model based on a harder diffusion coefficient rigidity scaling in the inner Galaxy.
This phenomenological model is able to reproduce both local CR observables and gamma-ray Fermi-LAT spectra correctly.

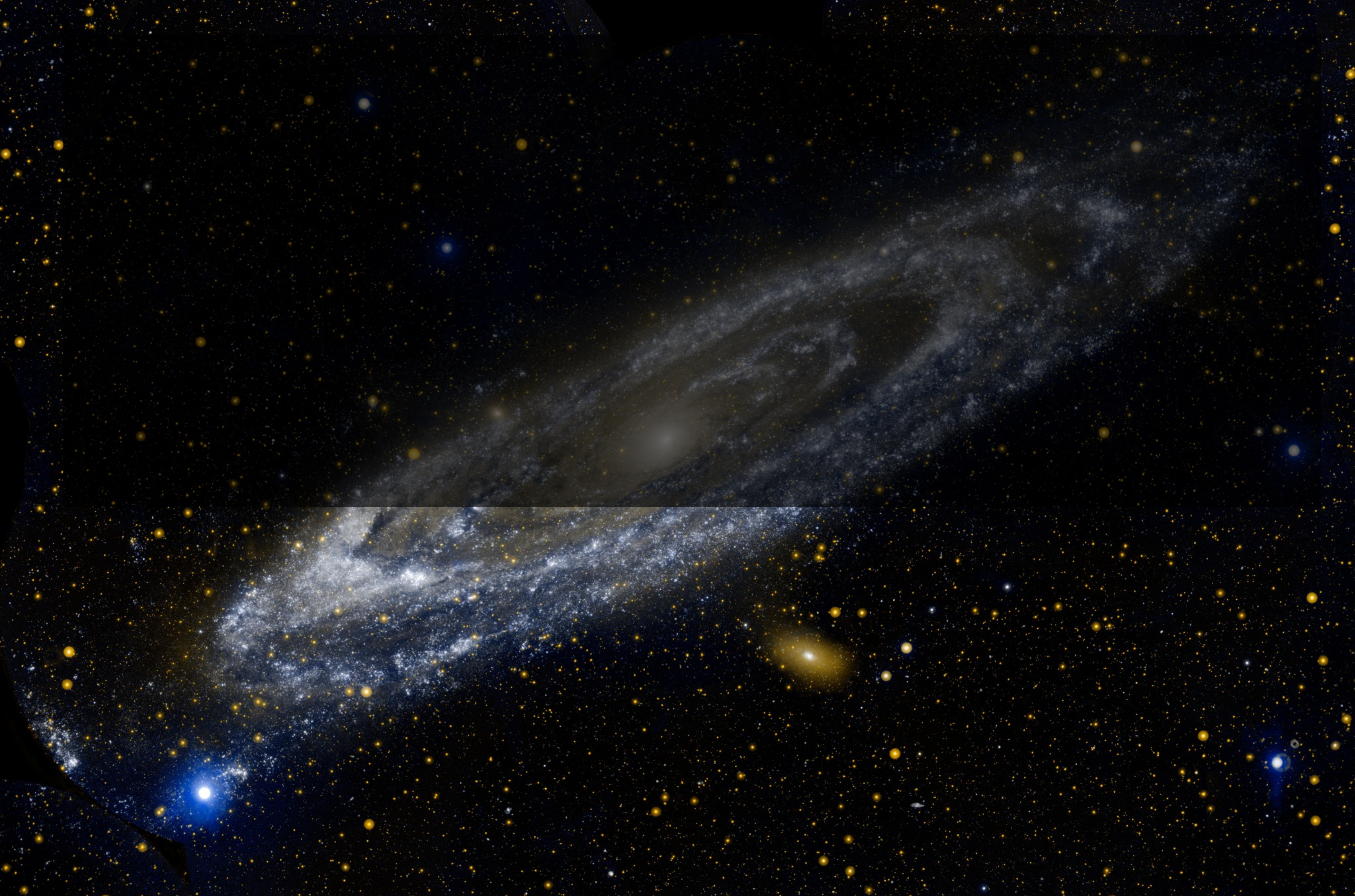
2) When extrapolated above the TeV, our model provides:

– a natural explanation to the long-standing gamma-ray anomaly detected by MILAGRO

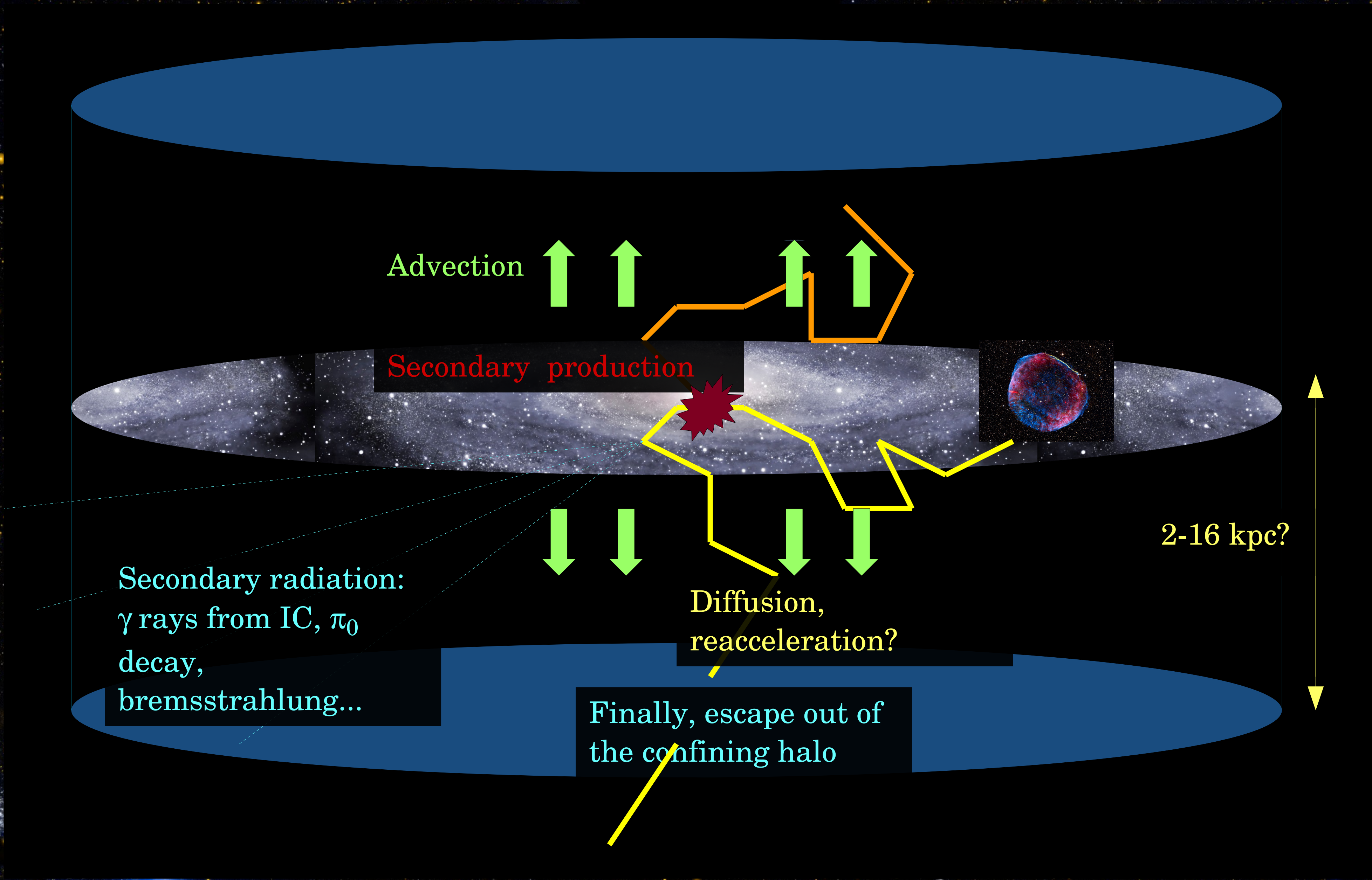
– a novel interpretation of IceCube neutrino data: An enhanced Galactic contribution is present in our model, compared to conventional ones.

3) Our scenario can be tested by ANTARES, Km3Net and IceCube with analyses focused on Galactic plane, and with a deeper investigation of the slopes in the Southern and Northern hemispheres.

Backup slides



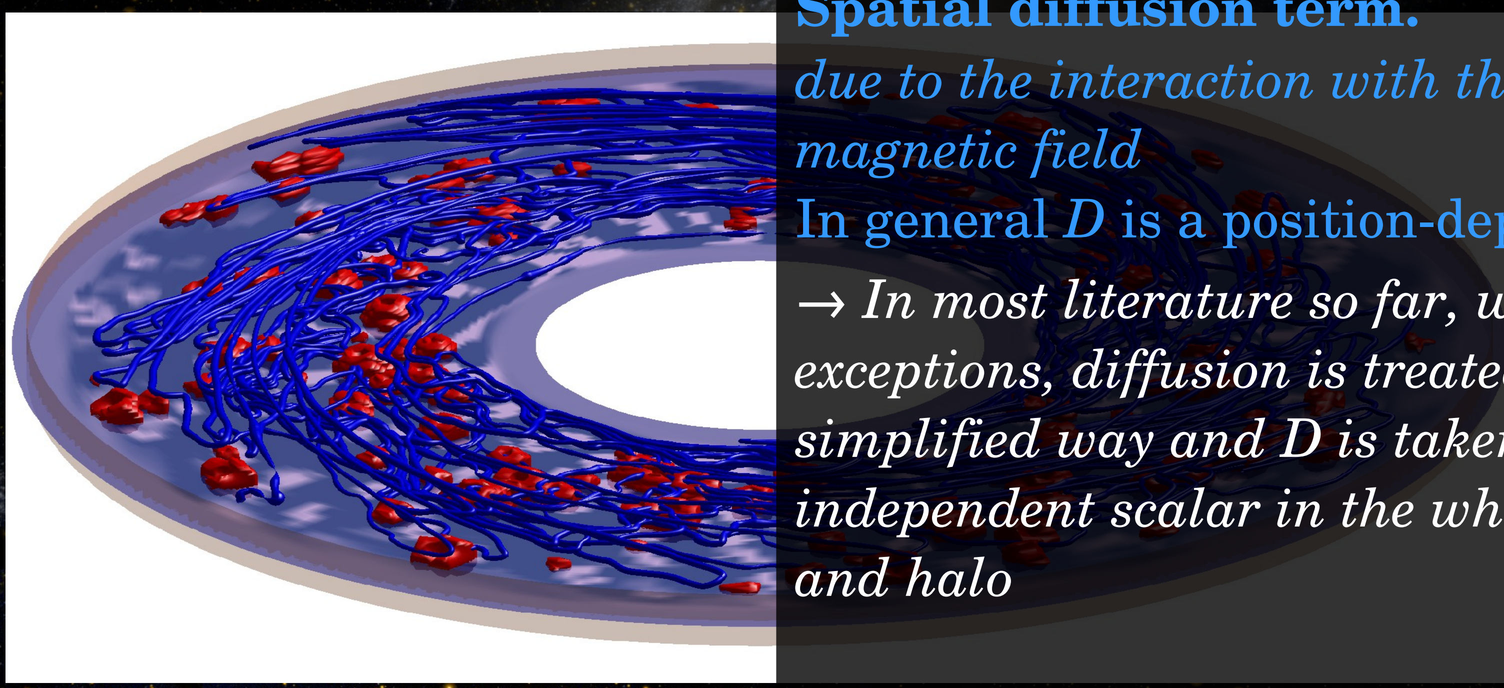
The basic picture of CR propagation



The basic picture

The equation describing CR propagation is the following:

$$\frac{\partial N^i(\vec{x},p,t)}{\partial t} = \nabla\cdot(D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) + \\ + \frac{\partial}{\partial p}\left(\dot{p}-\frac{p}{3}\cdot\mathbf{v_C}\right) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i(\vec{x},p,t)}{p^2} \\ + Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\rm gas}\sigma_{ij}N^j - c\beta n_{\rm gas}\sigma_{\rm in}N^i(\vec{x},p,t)$$



Spatial diffusion term.

due to the interaction with the Galactic magnetic field

In general D is a position-dependent tensor D_{ij}

→ *In most literature so far, with only very few exceptions, diffusion is treated in a over-simplified way and D is taken as a spatial-independent scalar in the whole Galactic disk and halo*

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The equation describing CR propagation is the following:

$$
\begin{aligned}
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+ \quad & \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\cdot \mathbf{v_C}\right) - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{N^i(\vec{x},p,t)}{p^2} \\
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\end{aligned}
$$

Energy losses due to the interaction with the ISM: gas, magnetic fields, diffuse radiation field in the IR, optical, UV

→ this term is important for low-energy hardons and high-energy leptons (IC scattering, synchrotron emission)

The basic picture

The equation describing CR propagation is the following:

$$
\begin{aligned}
\frac{\partial N^i\,(\vec{x},p,t)}{\partial t} &= \nabla\cdot(D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) \;+ \\
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\end{aligned}
$$

Reacceleration

The basic picture

The equation describing CR propagation is the following:

$$
\begin{aligned}
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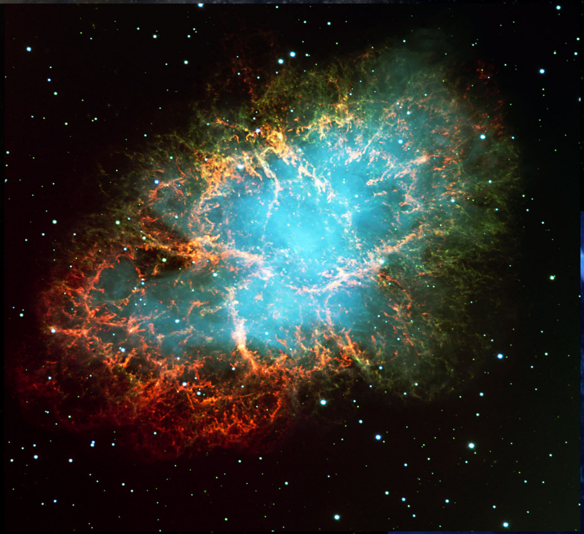
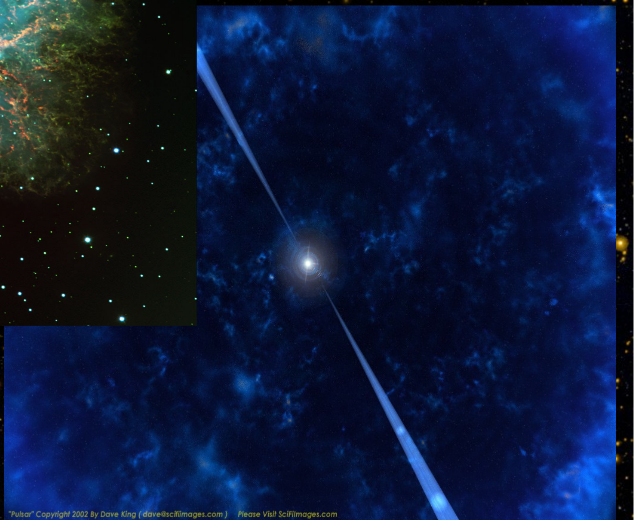
\end{aligned}
$$

Primary source term.

Protons, nuclei, electrons are accelerated by SNR shocks





→ Other classes of CR accelerators? (maybe pulsars?)

→ *CRs coming from DM annihilation / decay?*

The basic picture

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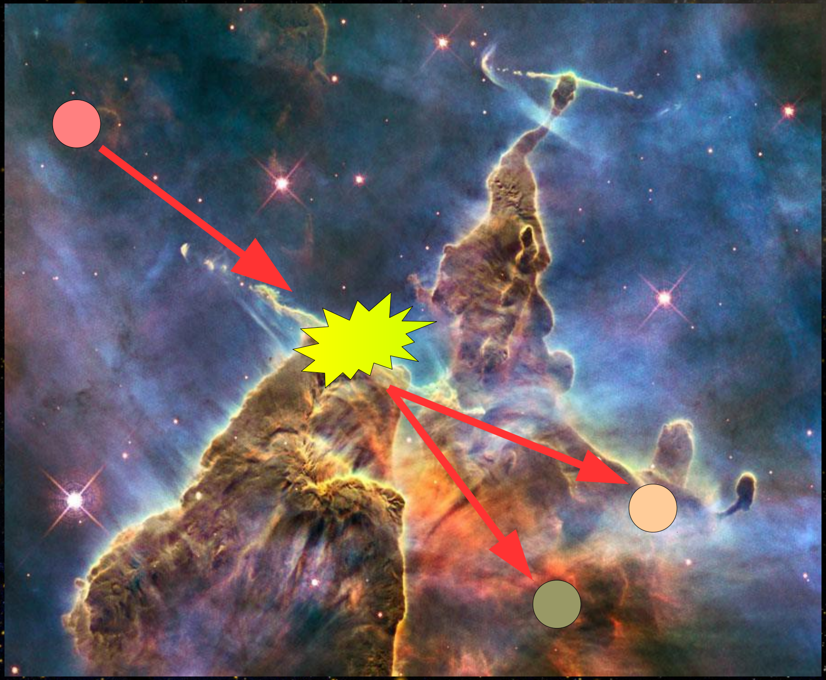

Spallation source term from heavier nuclei interacting with interstellar gas.

For Li, Be, B and antiparticles (positrons, antiprotons) this is the dominant source term.

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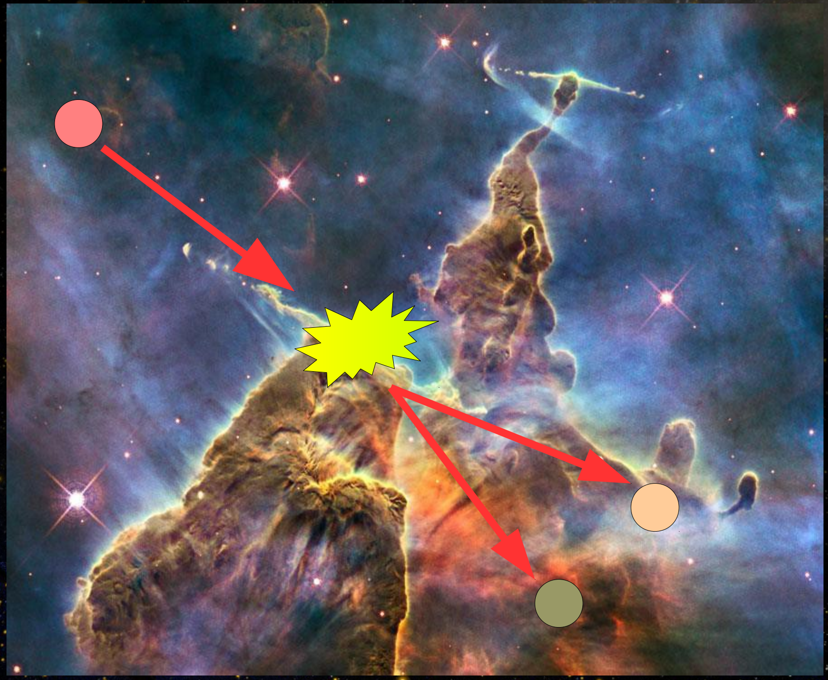


Spallation loss term

Going beyond the standard lore

1. The spiral arm structure of the Galaxy and its impact on CR leptonic spectra

Two numerical codes in the market for CR propagation:
→ Galprop (http://galprop.stanford.edu, Strong & Moskalenko 1998)
→ DRAGON (www.dragonproject.org Evoli *et al.* JCAP 2008, Gaggero *et al.* PRL 2013)

With DRAGON it is possible to solve the diffusion equation in the most general 3D anisotropic mode.

$$\frac{\partial f}{\partial t} = Q + \alpha_{xx}\partial_x^2 f + \alpha_{yy}\partial_y^2 f + \alpha_{zz}\partial_z^2 f$$
$$+2\delta_{xy}\partial_x\partial_y f + 2\delta_{xz}\partial_x\partial_z f + 2\delta_{yz}\partial_y\partial_z f$$
$$+u_x\partial_x f + u_y\partial_y f + u_z\partial_z f$$

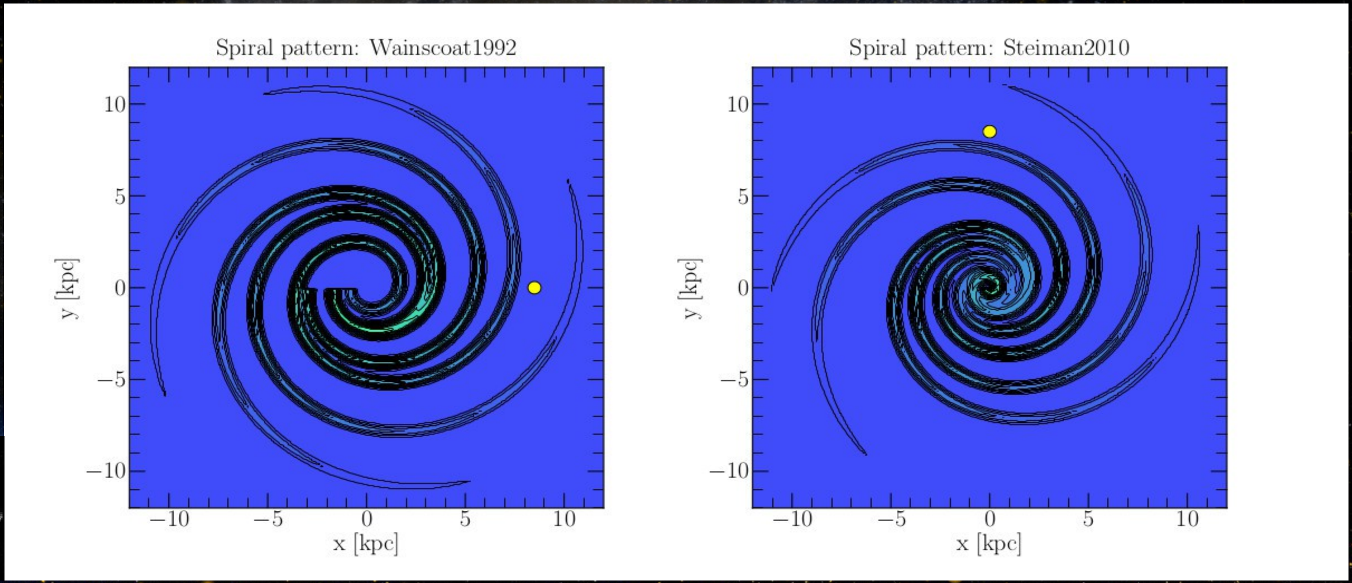
$$\begin{aligned}
\alpha_{xx}(x,y,z) &= (D_{\parallel} - D_{\perp})b_x^2 + D_{\perp} \\
\alpha_{yy}(x,y,z) &= (D_{\parallel} - D_{\perp})b_y^2 + D_{\perp} \\
\alpha_{zz}(x,y,z) &= (D_{\parallel} - D_{\perp})b_z^2 + D_{\perp} \\
\delta_{xy}(x,y,z) &= (D_{\parallel} - D_{\perp})b_x b_y + D_{\perp} \\
\delta_{xz}(x,y,z) &= (D_{\parallel} - D_{\perp})b_x b_z + D_{\perp} \\
\delta_{yz}(x,y,z) &= (D_{\parallel} - D_{\perp})b_y b_z + D_{\perp} \\
u_x(x,y,z) &= \partial_x\alpha_{xx} + \partial_y\delta_{xy} + \partial_z\delta_{xz} \\
u_y(x,y,z) &= \partial_x\delta_{xy} + \partial_y\alpha_{yy} + \partial_z\delta_{yz} \\
u_z(x,y,z) &= \partial_x\delta_{xz} + \partial_y\delta_{yz} + \partial_z\alpha_{zz}
\end{aligned}$$

Going beyond the standard lore

1. The spiral arm structure of the Galaxy and its impact on CR leptonic spectra

Two numerical codes in the market for CR propagation:
Galprop (`http://galprop.stanford.edu`, Strong & Moskalenko 1998)
DRAGON (`www.dragonproject.org` Evoli *et al*. JCAP 2008, Gaggero *et al*. PRL 2013)

The 3D spiral structure of the Galaxy is implemented in DRAGON
(models from Wainscoat 1992, used also by Blasi&Amato 2011; Steiman 2010)



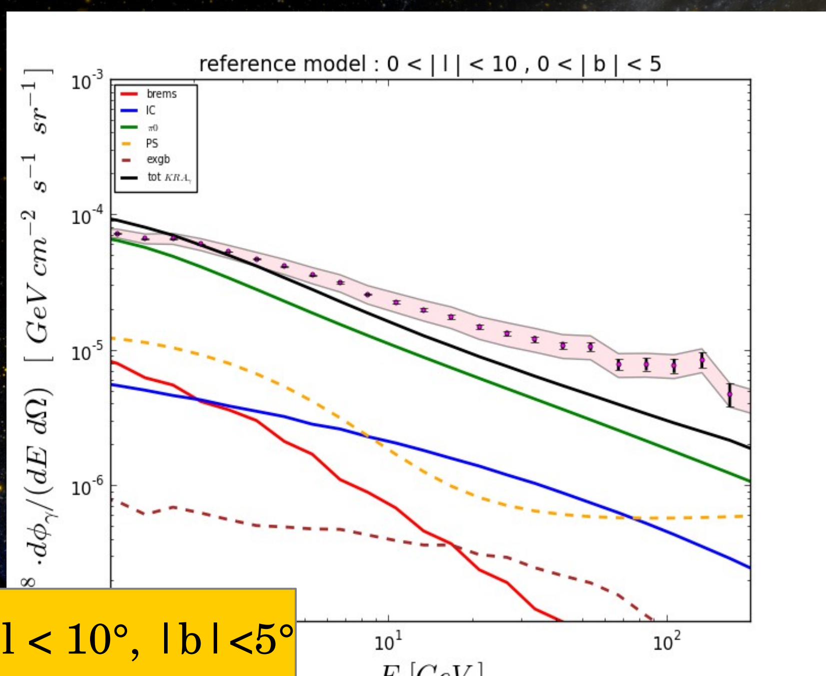
Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

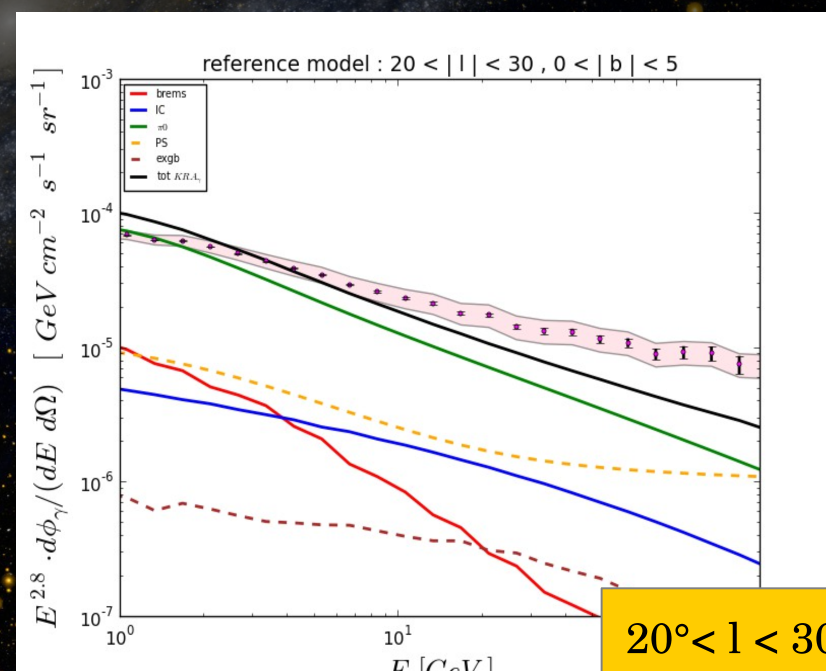
Motivation: **"slope problem"**

All CR propagation models underestimate the gamma-ray emission at high energy.

→ *the problem is more serious on the Galactic plane, especially looking at sky windows pointing towards the inner Galaxy!*



0°< l < 10°, |b|<5°



20°< l < 30°, |b|<5°

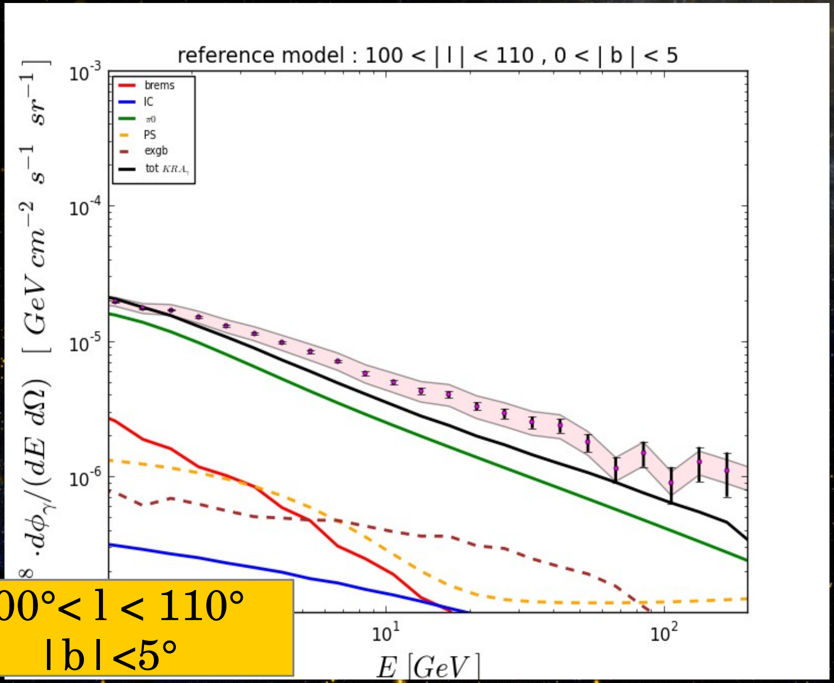
Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

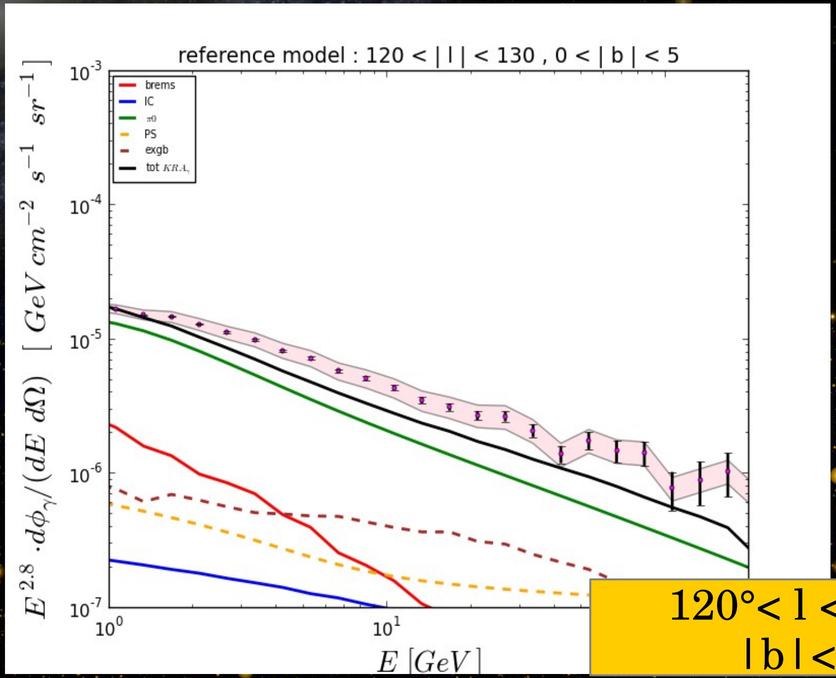
Motivation: **"slope problem"**

All CR propagation models underestimate the gamma-ray emission at high energy.

→ *looking far from the GC region, the discrepancy is less evident:*



100°< l < 110°
|b|<5°



120°< l <130°,
|b|<5°

Going beyond the standard lore

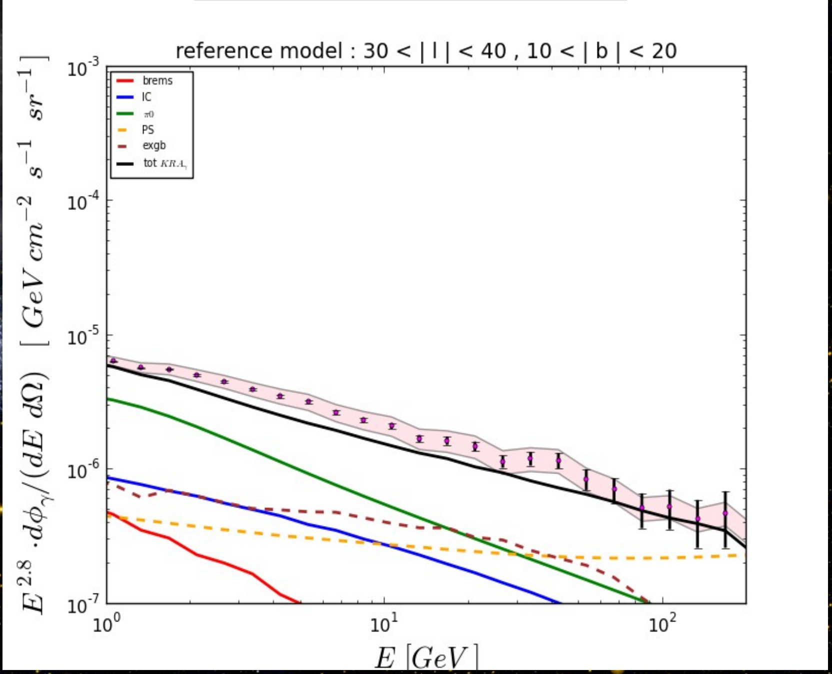
3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

Motivation: **“slope problem”**

All CR propagation models underestimate the gamma-ray emission at high energy.

→ *looking at high latitude, the discrepancy is less evident:*

30° < l < 40°
10° < |b| < 20°



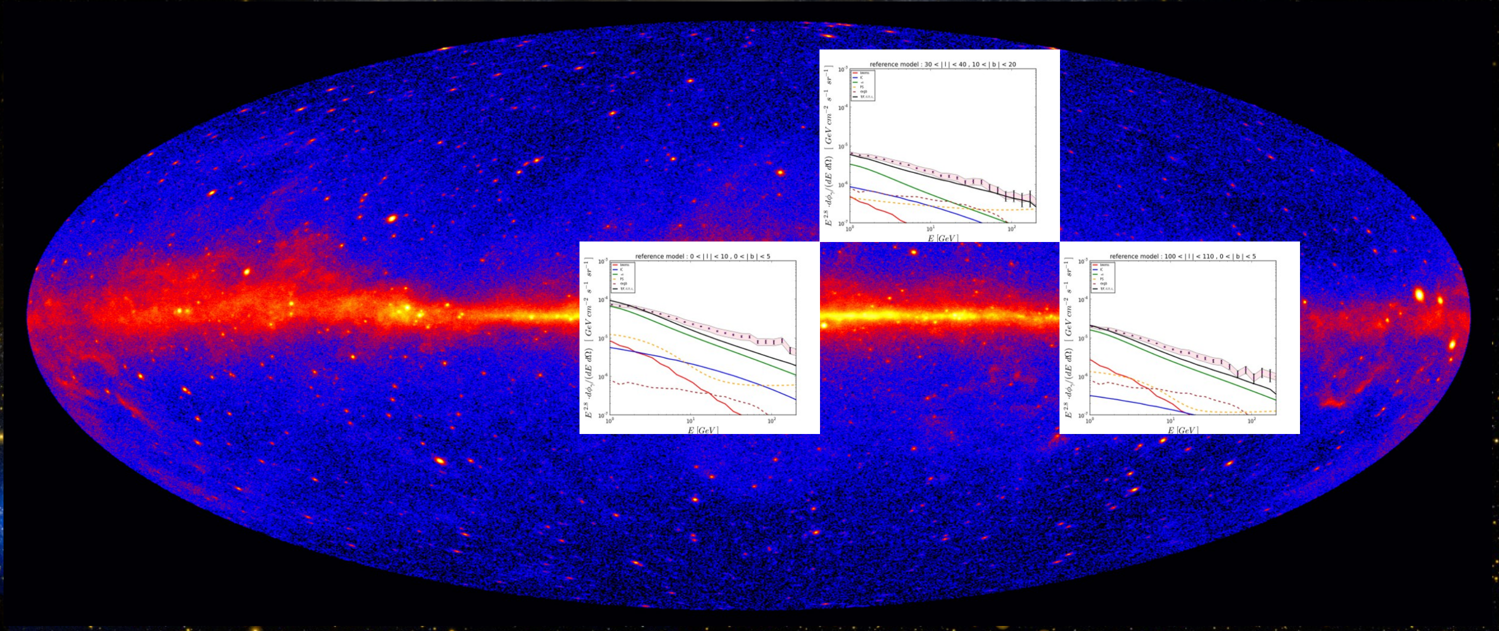
Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

The idea:

→ we drop the over-simplified assumption of homogeneous diffusion
→ we consider a harder diffusion coefficient in the inner Galaxy

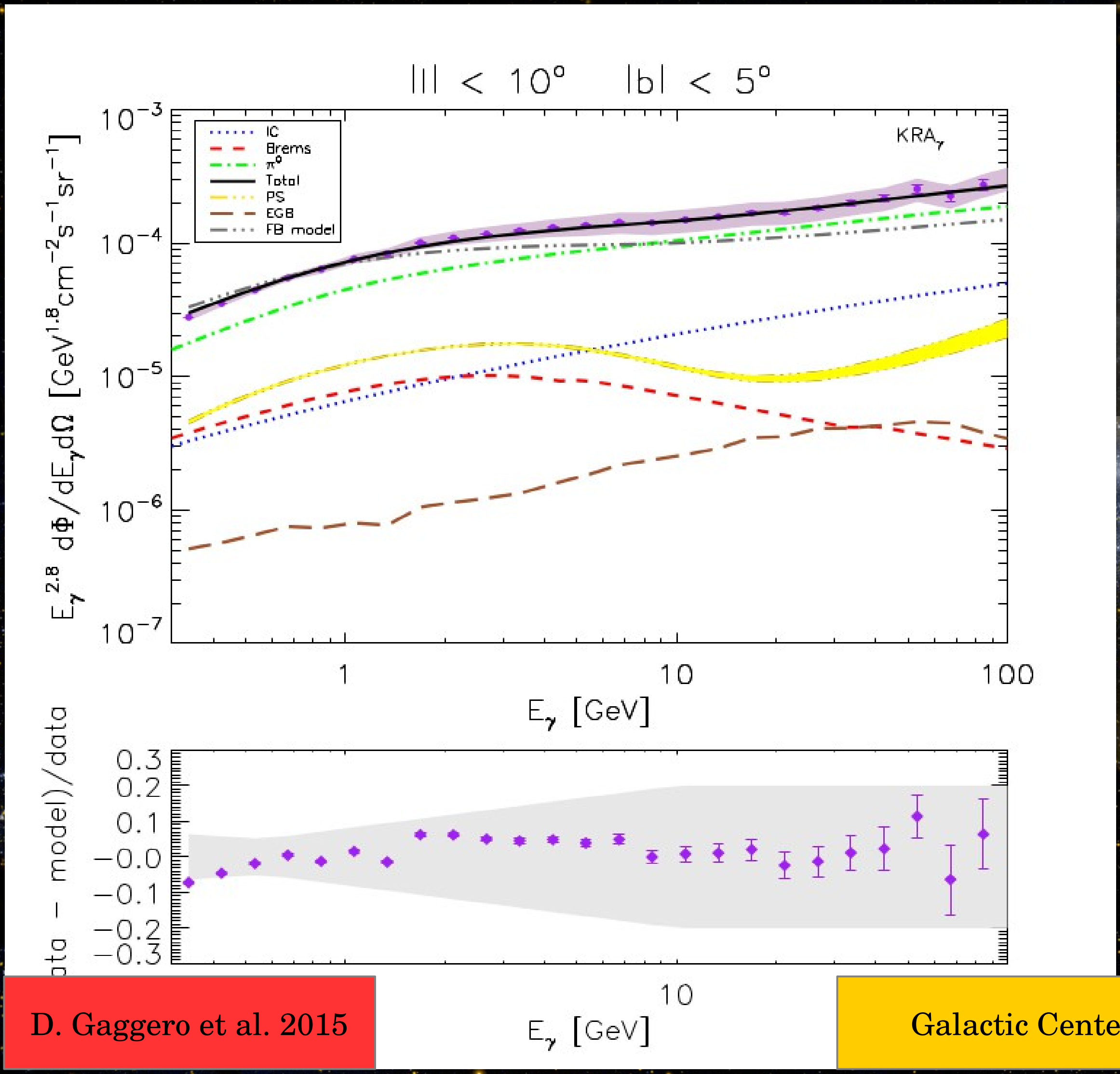
$$\delta(R) = aR + b$$



Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

Results obtained with DRAGON *and* GammaSky:



D. Gaggero et al. 2015

Galactic Center

Starting with a standard propagation models, we fit the data with the combination of two simple non-standard ingredients, namely:

→ a harder diffusion coefficient in the inner Galaxy

$\delta(R) = aR + b$

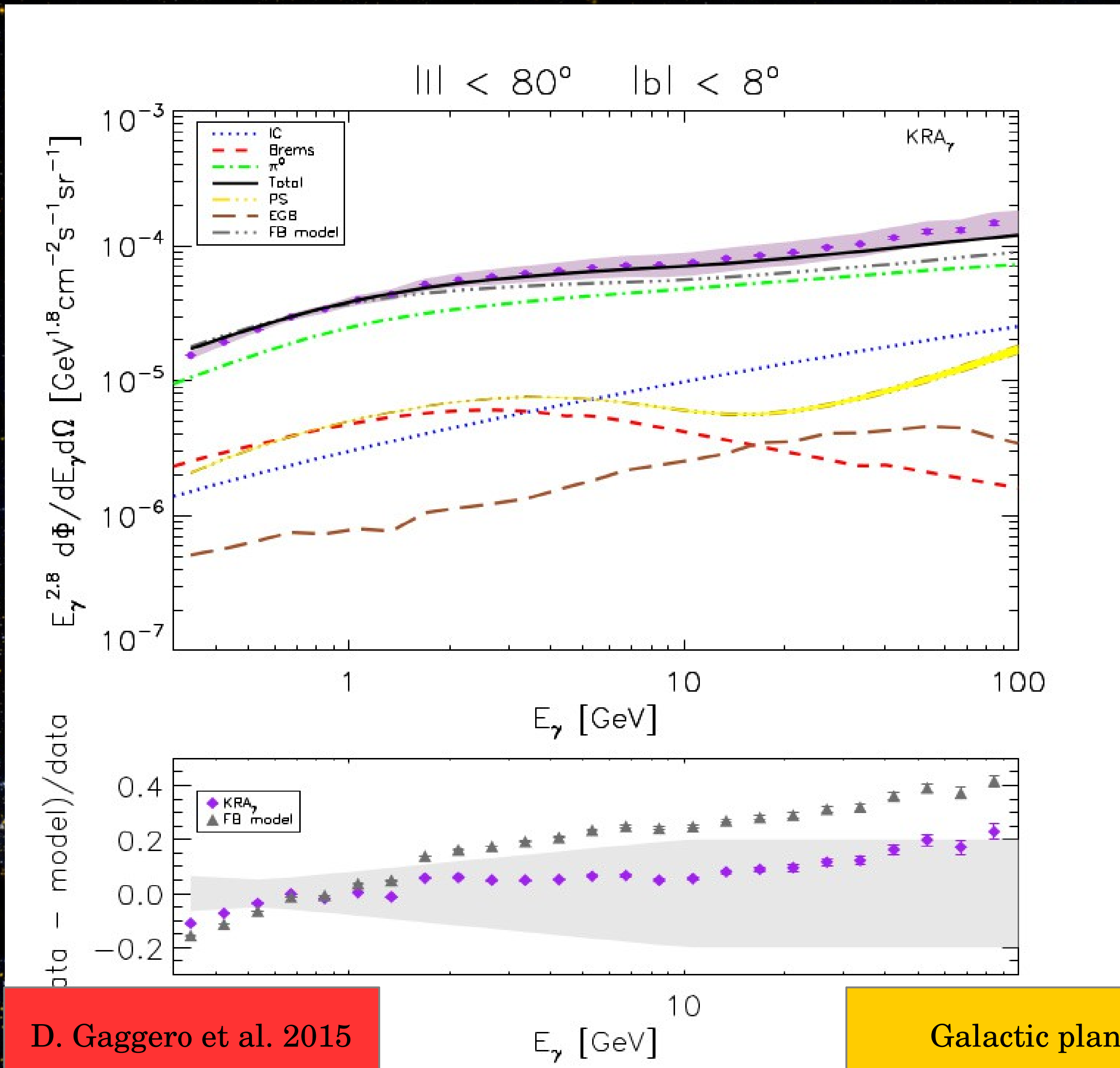
(physical interpretation: CRs near the sources propagate in SN-driven turbulence, while CRs in the outer Galaxy propagate in self-generated turbulence (see Blasi 2013, Tommassetti 2014)

→ a high convective wind in the inner Galaxy (observed e.g. by ROSAT and other experiment)

Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

Results obtained with DRAGON *and* GammaSky:



D. Gaggero et al. 2015

Galactic plane

Starting with a standard propagation models, we fit the data with the combination of two simple non-standard ingredients, namely:

→ a harder diffusion coefficient in the inner Galaxy

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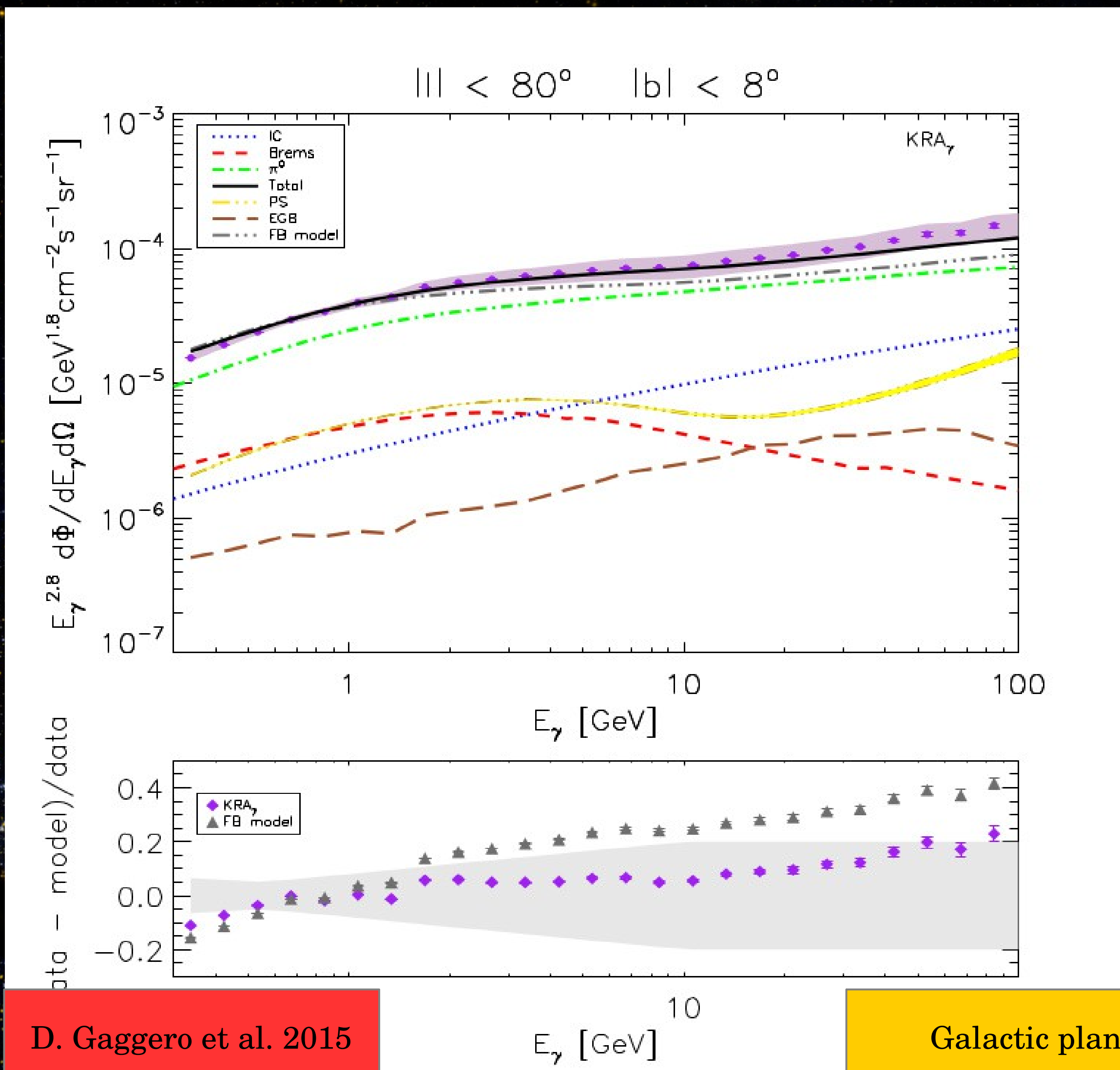
→ a high convective wind in the inner Galaxy (observed e.g. by ROSAT and other experiment)

Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

Results obtained with `DRAGON` *and* `GammaSky`*:*



D. Gaggero et al. 2015

Galactic plane

Check the talks by Dario Grasso and Antonio Marinelli for implications at the TeV!

The MILAGRO excess is explained with this framework