Gamma and neutrino diffusion emissions of the Galaxy:

implications for the interpretation of the astrophysical excess measured by the IceCube experiment

Dario Grasso (INFN, Pisa)
with
D. Gaggero, A. Marinelli, A. Urbano, M. Valli

SciNeGHE 2016

IceCube astrophysical neutrinos: HESE

IceCube coll., arXiv1510.05223, ICRC2015

IceCube found evidence for 54 events in 4 yrs with reconstructed direction and E > 30 TeV corresponding to
7σ excess respect to the atm. bkg.

angular distribution compatible with isotropy (see however below)

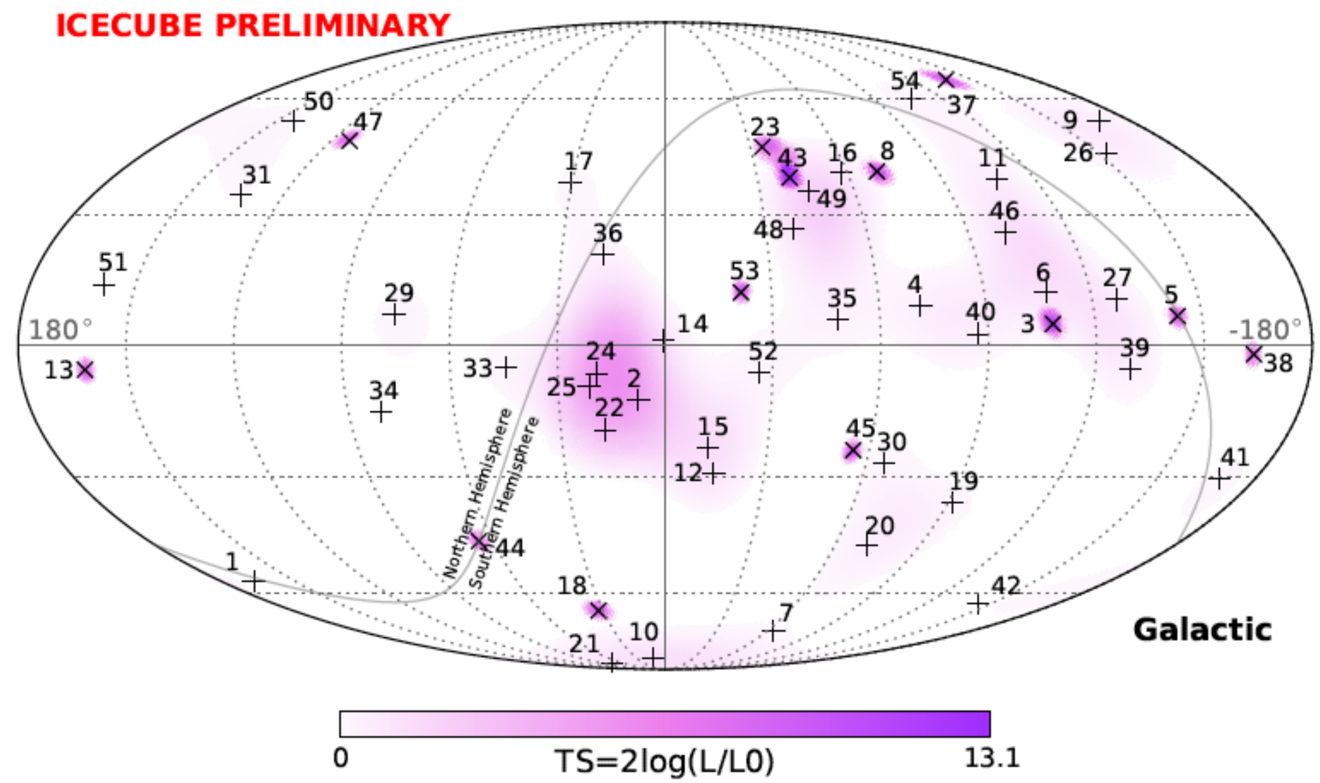
composition compatible with a equal mixture of e, μ, τ as expected for astrophysical generated neutrino

HESE events spect. index

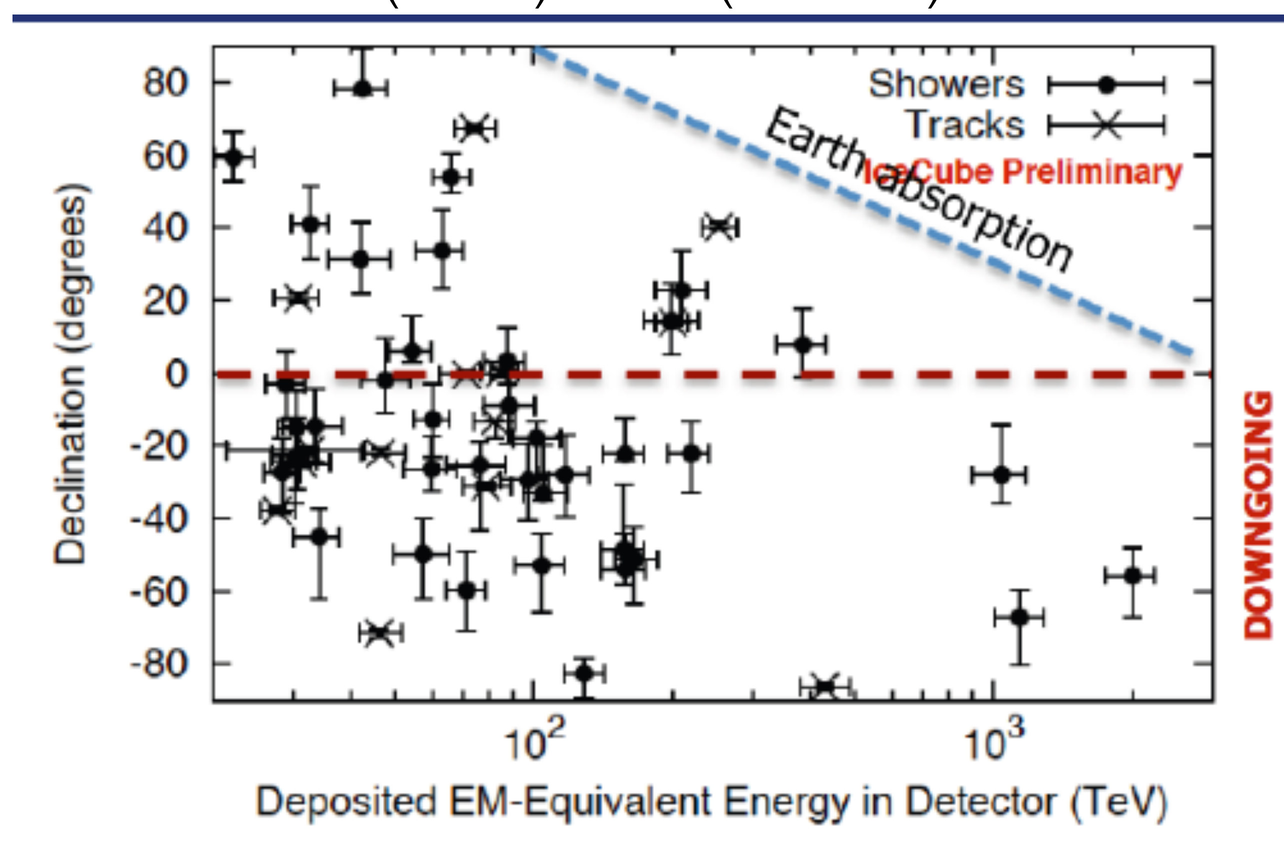
γ_{astro} = - 2.58 ± 0.25 (E > 60 TeV)

A combined analysis including several kind of events found (*IceCube coll. ApJ 2015*)

γ_{astro} = - 2.50 ± 0.09 (E > 25 TeV)



X (track) **+** (shower)



IceCube astrophysical neutrinos: passing muons

IceCube coll., PRL 2015

2 years analysis

γ_{astro} = - 2.2 ± 0.2 (E > 200 TeV)

arXiv:1607.08006 6 years events with interaction vertex outside the detector gives

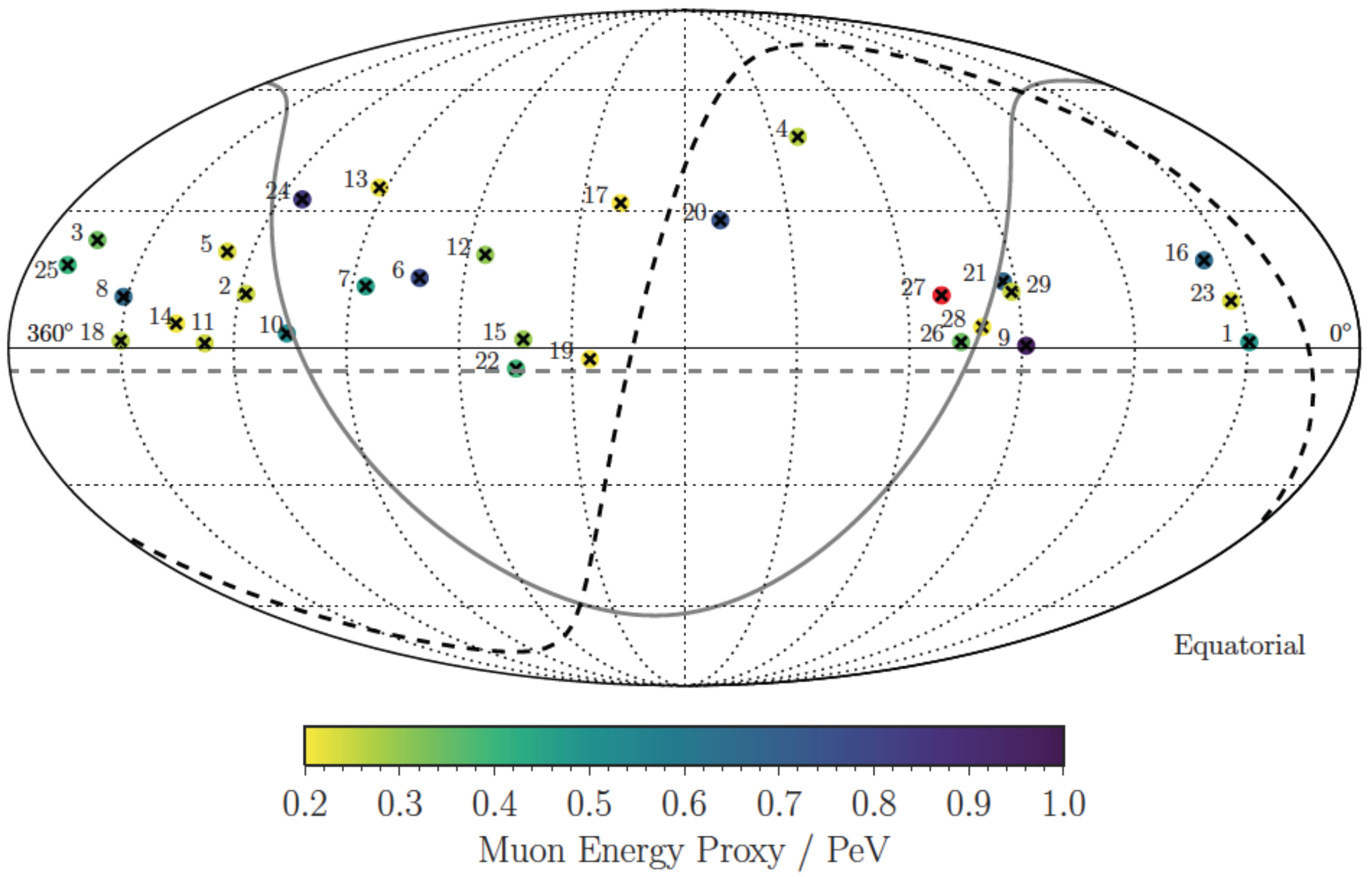
γ_{astro} = - 2.13 ± 0.13 (E > 200 TeV)

5.6 σ excess respect to the atmospheric bkg.

no correlation with TeV γ-rays sources

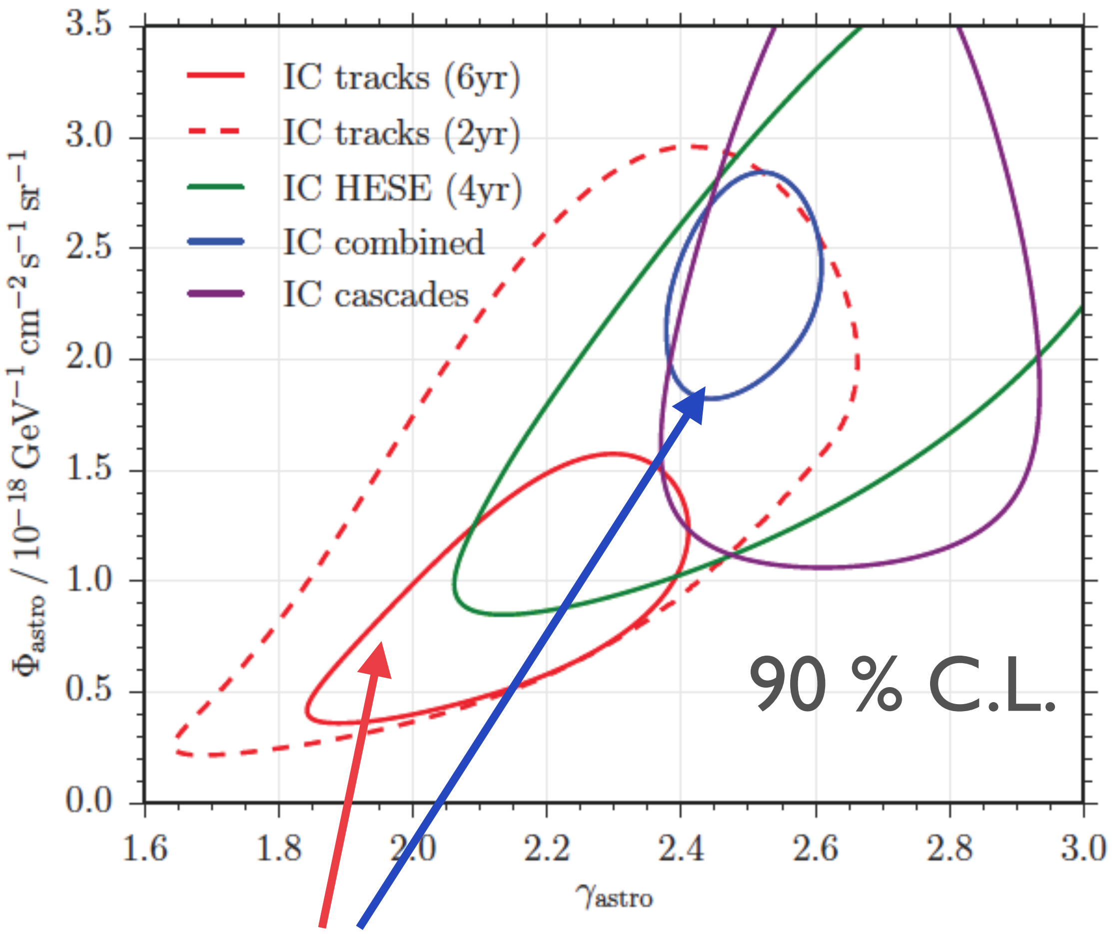
no hot-spots

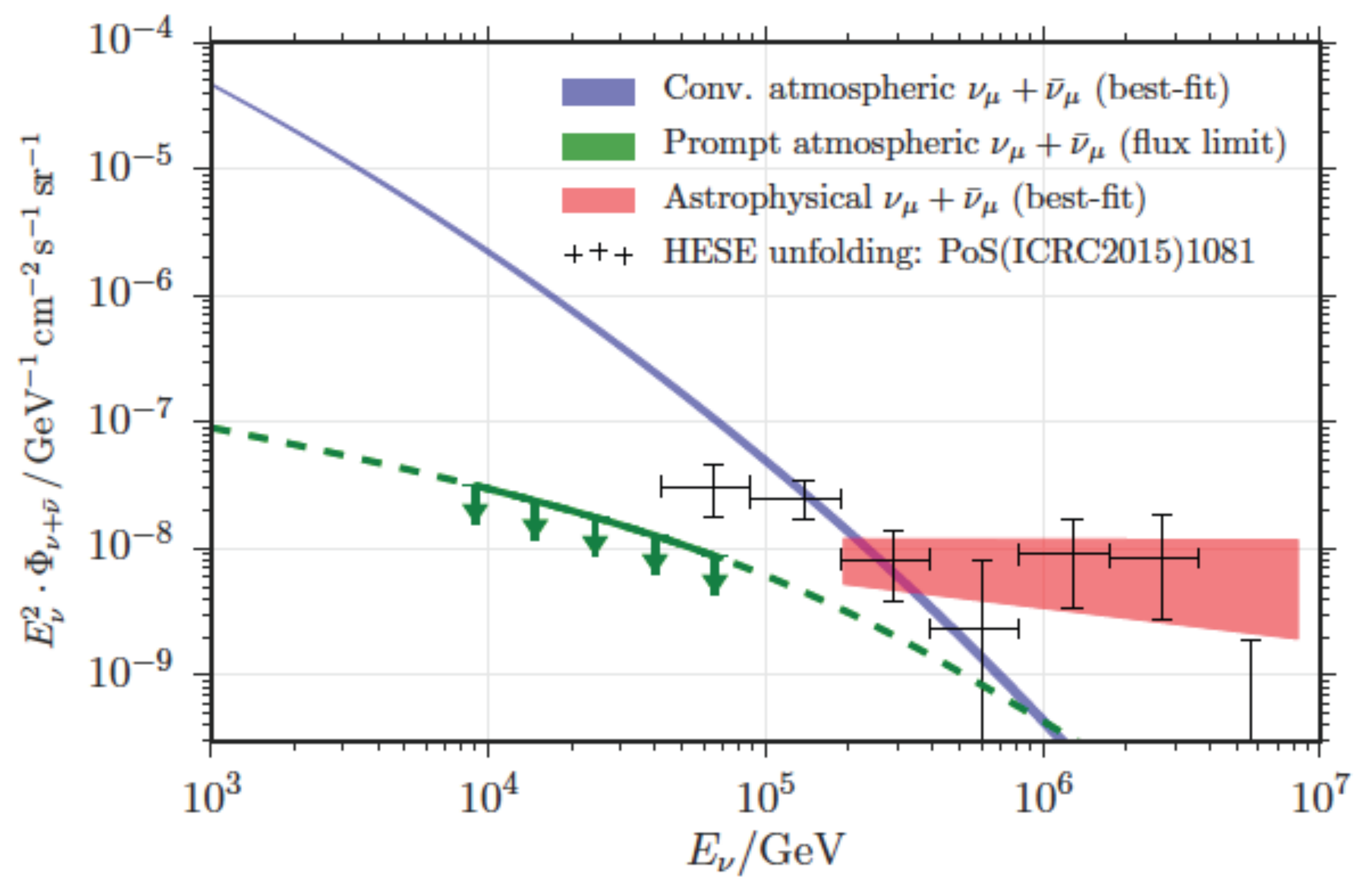
Northern hemisphere only



Hints of a Galactic component ?

IceCube coll. arXiV:1607.08006



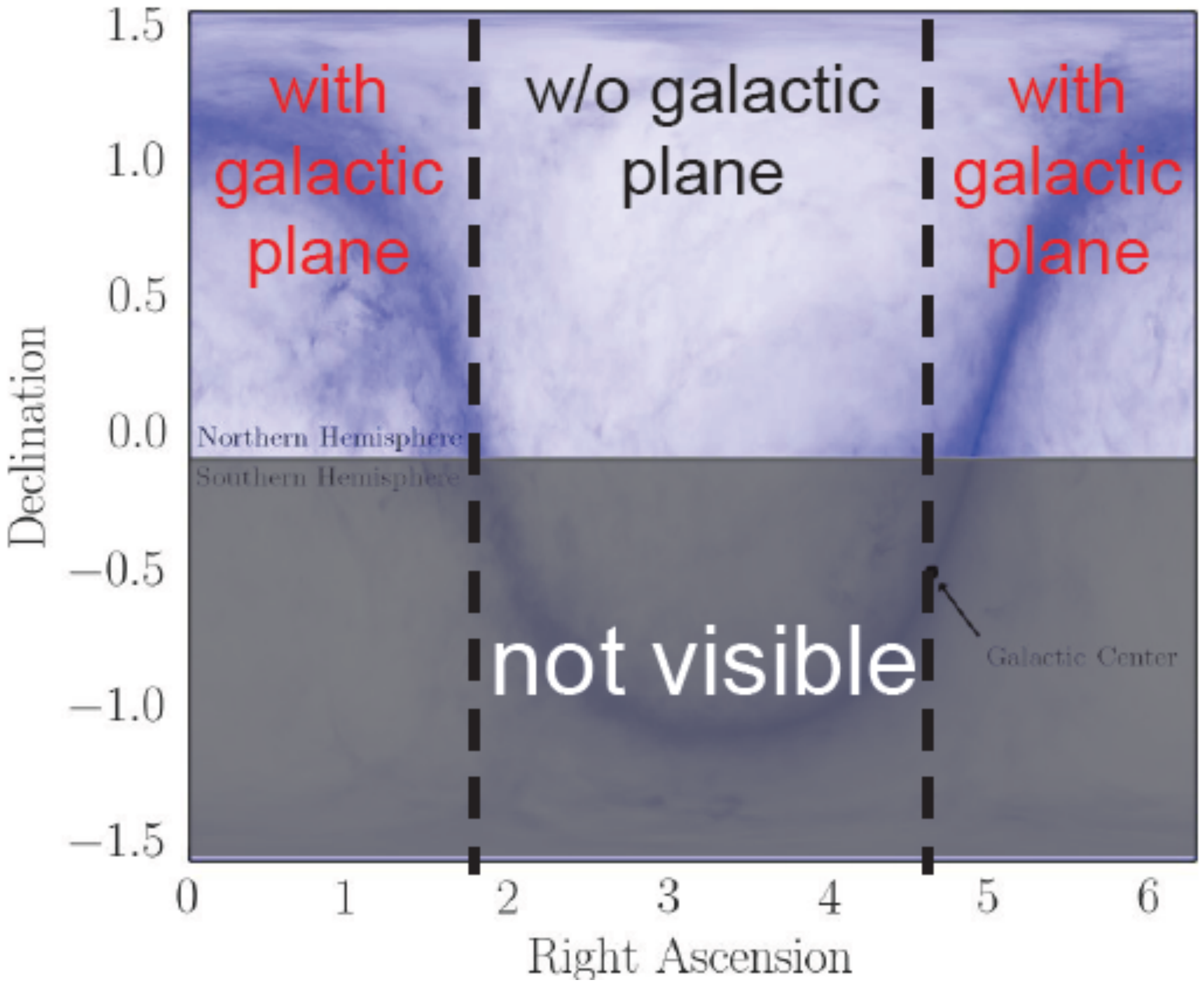


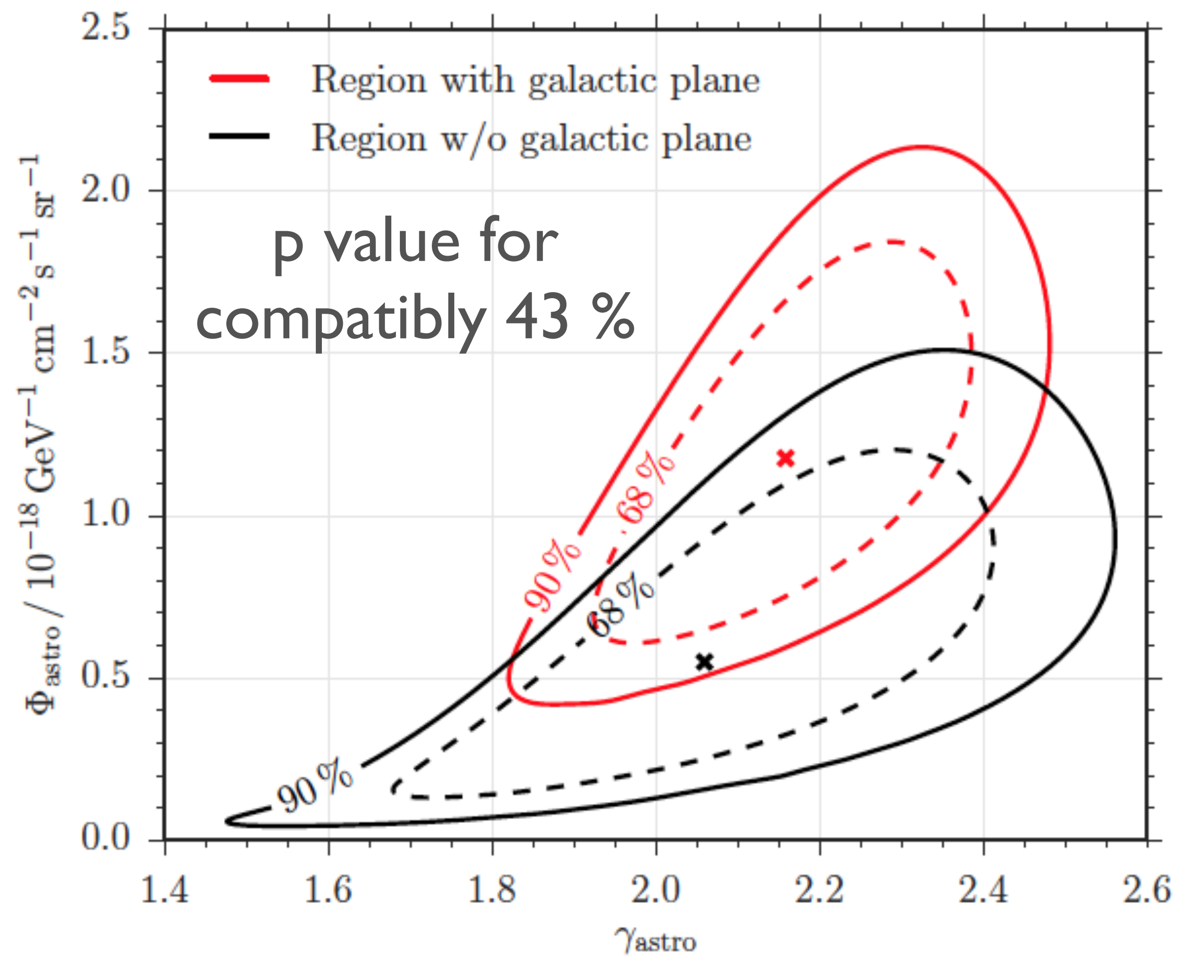
The different (3.3 σ) spectral indexes and normalizations may either be due to

- the different energy thresholds in the presence of a spectral break (at ~ 100 TeV) of the astrophysical source
- **different spectra in the two hemisphere possibly due a large Galactic component**

Hints of a Galactic component ??

IceCube coll. arXiV:1607.08006





- No evidence of a dominant Galactic component in the **Norther hemisphere**

- A fit in a region with the Galactic plane shows hint of a larger normalization and spectral index. Is the effect of a small Galactic component ?

In the Northern hemisphere the Galactic emission quite smaller than in the Southern

Hints of a Galactic component ???

Ahlers et al. 1505.03156 using only HESE angular distribution concluded that up to *50% (90% C.L.) Galactic contribution is permitted*

Neronov & Semikoz arXiv:1509.03522
use only events above 100 TeV in the IC 4-year HESE sample (19 events) found ~ ***4 σ inconsistency with isotropy.*** It is claimed that "50% Galactic contributions provides a satisfactory fit to the data"

Troiysky arXiV: 15011.01708 use both the HESE and passing muons above 100 TeV.
Found full consistency with isotropy

Palladino & Vissani arXiV :1601:06678 found that although pure extragalactic cannot be excluded, a **Galactic fraction**

35^{+32}_{-18} % (on the basis of spectral analysis)

26 ± 15 % (on the basis of HESE angular distribution)

is statistical favored. (The analysis assumes $\gamma_{EG} = -2$ $\gamma_{GAL} = -2.7$ the Galactic component dominating at low energy)

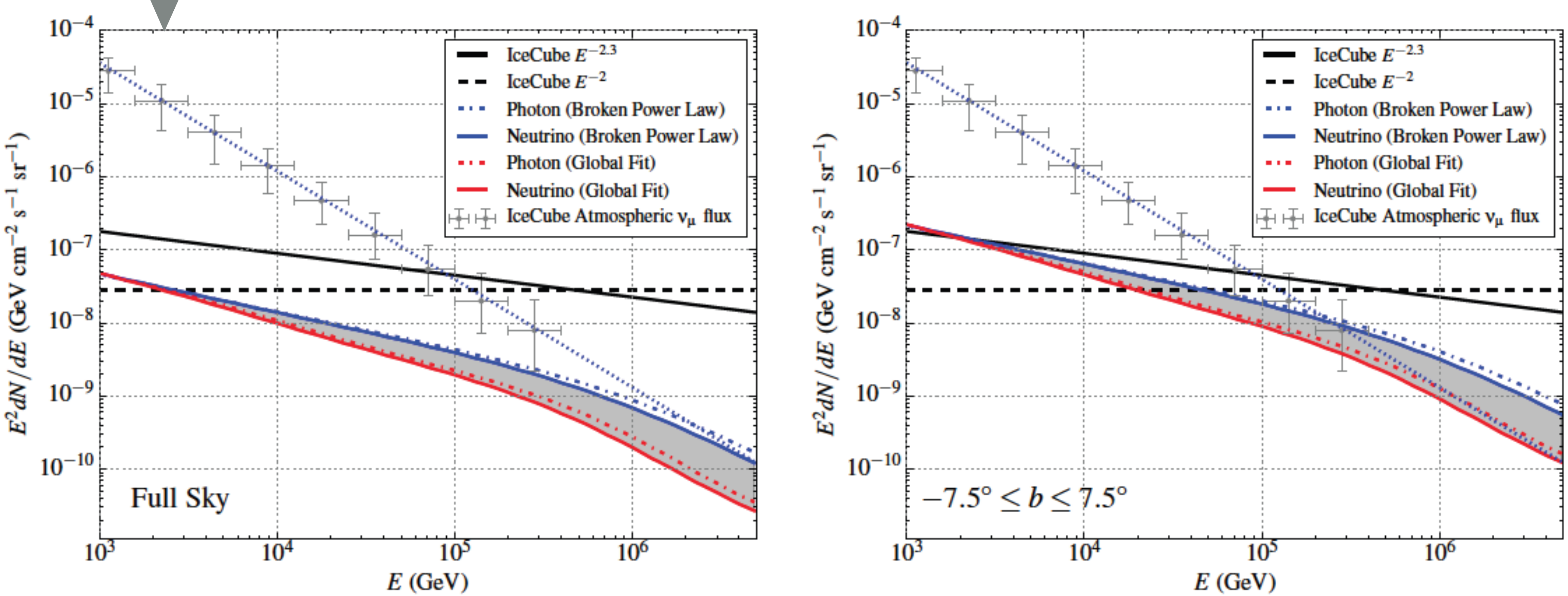
Which Galactic neutrino emission we may expect from updated gamma-ray data and advanced CR modeling ?

The diffuse neutrino emission of the Galaxy: previous computations

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

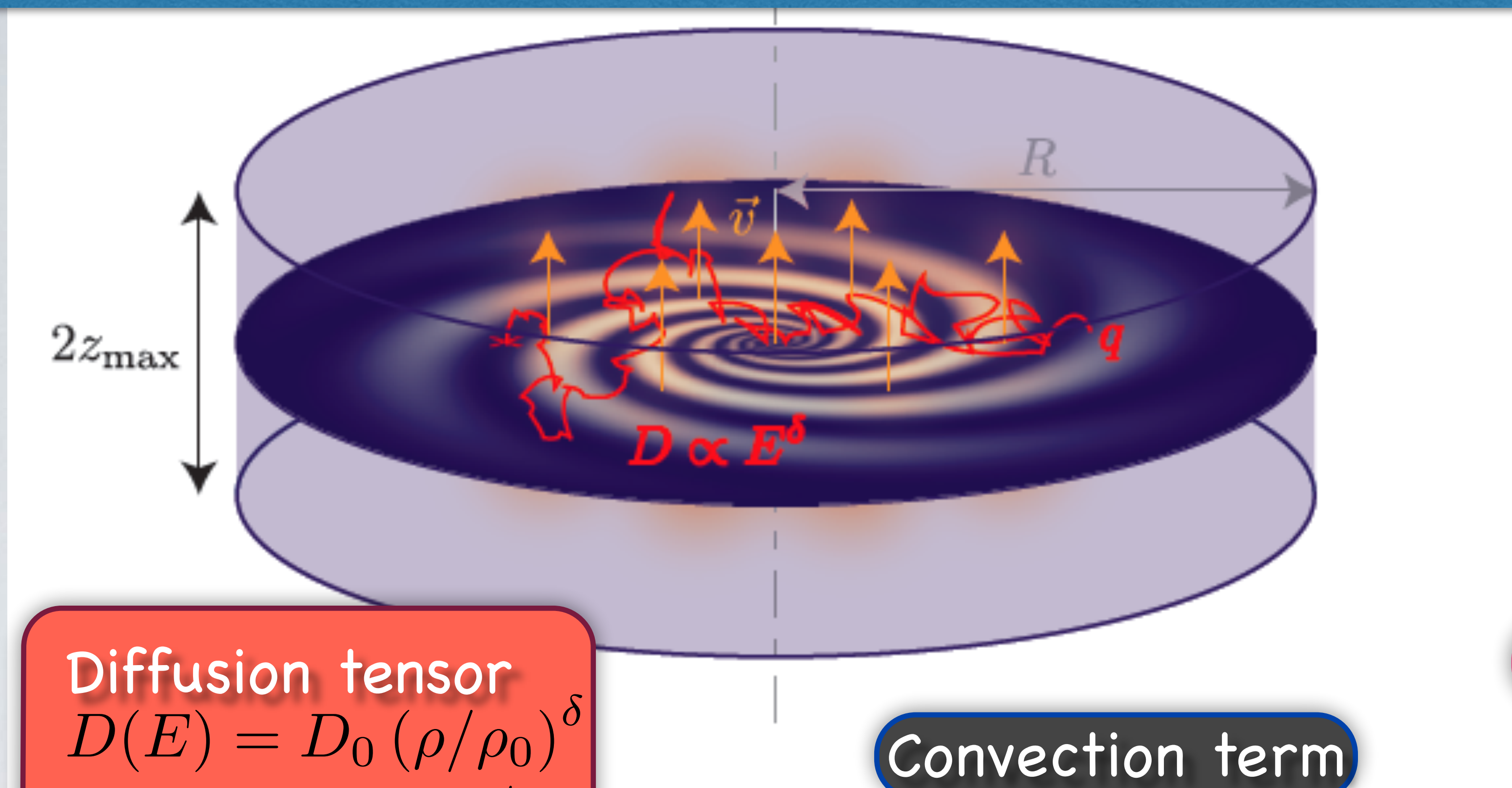
- ***Berezinsky & Smirnov 1975*** (uniform CR and gas densities)
- ***Stecker 1979*** "
- ***Gaisser, Berezinsky, Halzen, Stanev 1993*** (uniform CR, realistic gas distribution)

- ***Evoli, DG, Maccione, 2007*** (<u>CR distribution computed with diffusion code</u>, realistic gas)
- ***Ahlers et al.*** *arXiV:1505.03156* (<u>CR distribution computed with GALPROP</u>, realistic gas)



8% of IceCube HESE (2013) signal at most

The CR Galactic population



The CR trasport equation

Ginzburg & Syrovatsky, 1964

Diffusion tensor
$D(E) = D_0\,(\rho/\rho_0)^{\delta}$
$\rho = \text{rigidity} \sim p/Z$

Convection term

Energy loss

Reacceleration
$D_{pp} \propto \frac{p^2 v_A^2}{D}$

$$\frac{\partial N^i}{\partial t} - \nabla\cdot(D\,\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla\cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$= Q^i(p,r,z) + \sum_{j>i} c\beta n_{\rm gas}(r,z)\sigma_{ji}N^j - c\beta n_{\rm gas}\sigma_{\rm in}(E_k)N^i$$

SN source term. We assume everywhere a power law energy spectrum

Spallation cross section. Appearance of nucleus i due to spallation of nucleus j

Total inelastic cross section. Disappearance of nucleus i

A large number of parameters to be fixed against data !

Conventional computations of the CR Galactic population

numerical codes like GALPROP solve the transport equation using the **local** primary and secondary CR spectra as an input.

The propagation parameters, as those fixing the diffusion coefficient

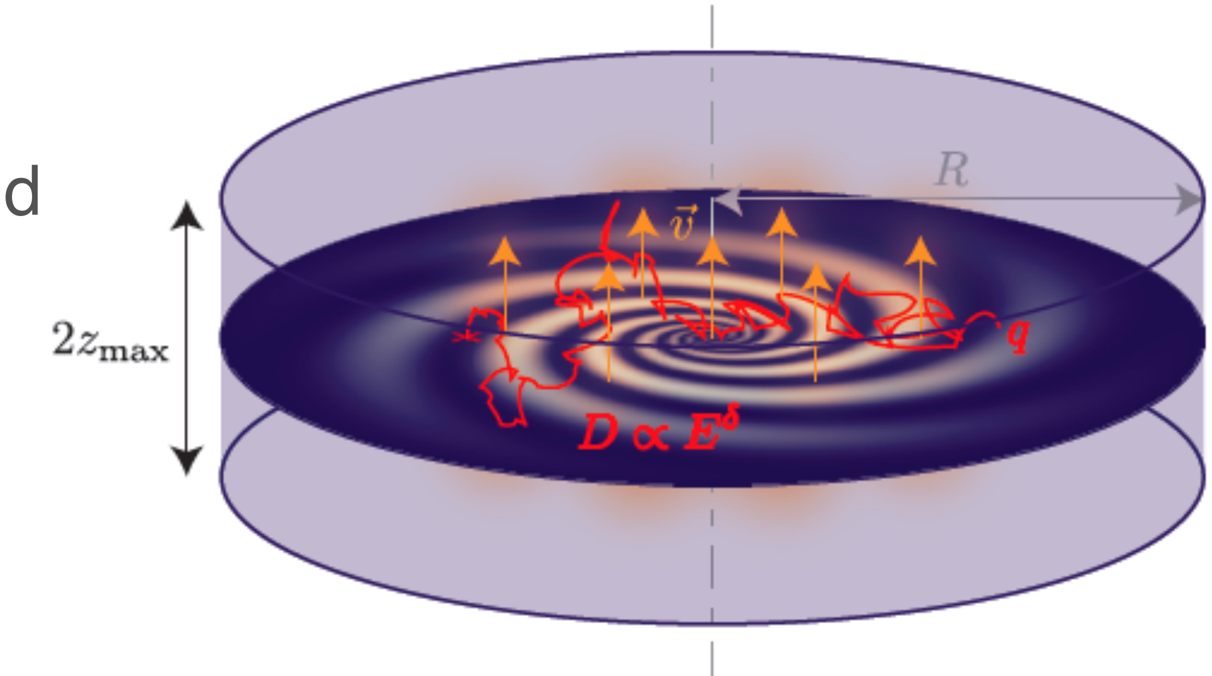
$$D(E) = D_0 \, (E/E_0)^{-\delta}$$

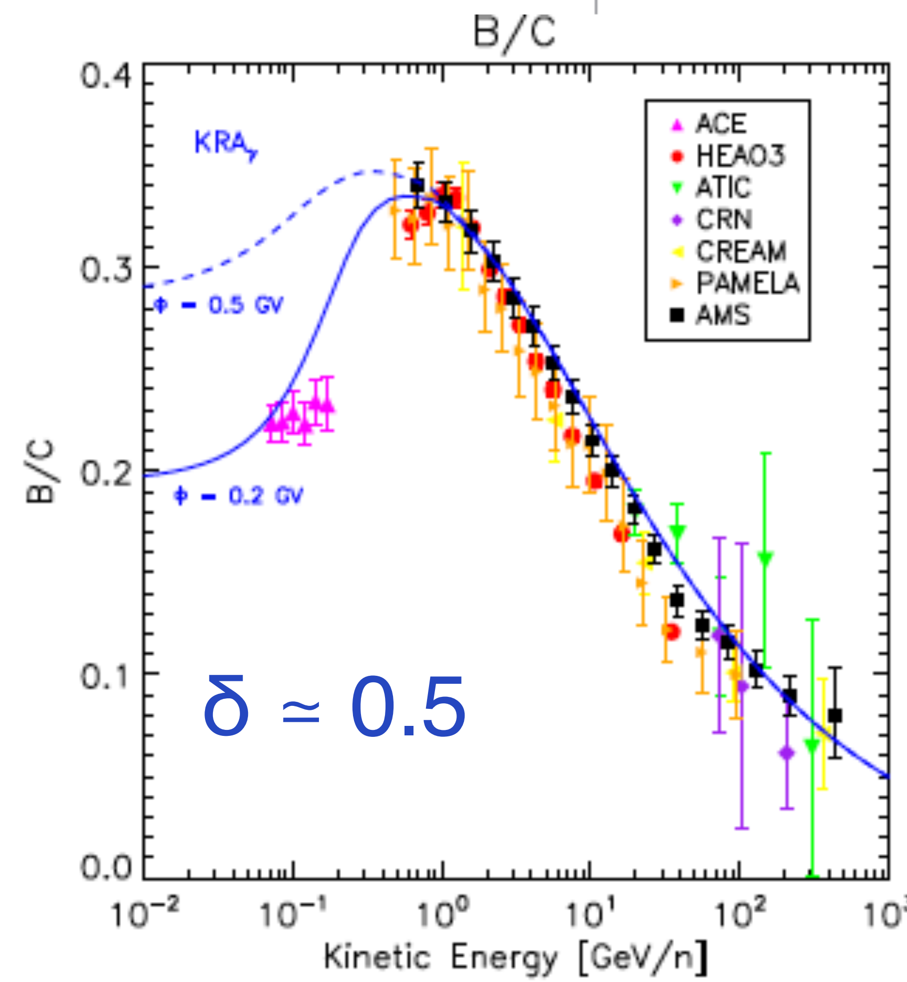
are tuned on the basis of the secondary/primary CR nuclei ratio (the B/C most importantly) and assumed to be **spatially uniform**

warning !!

secondary nuclei probes only few kpc around us. Propagation may behave differently in the central region of the Galaxy

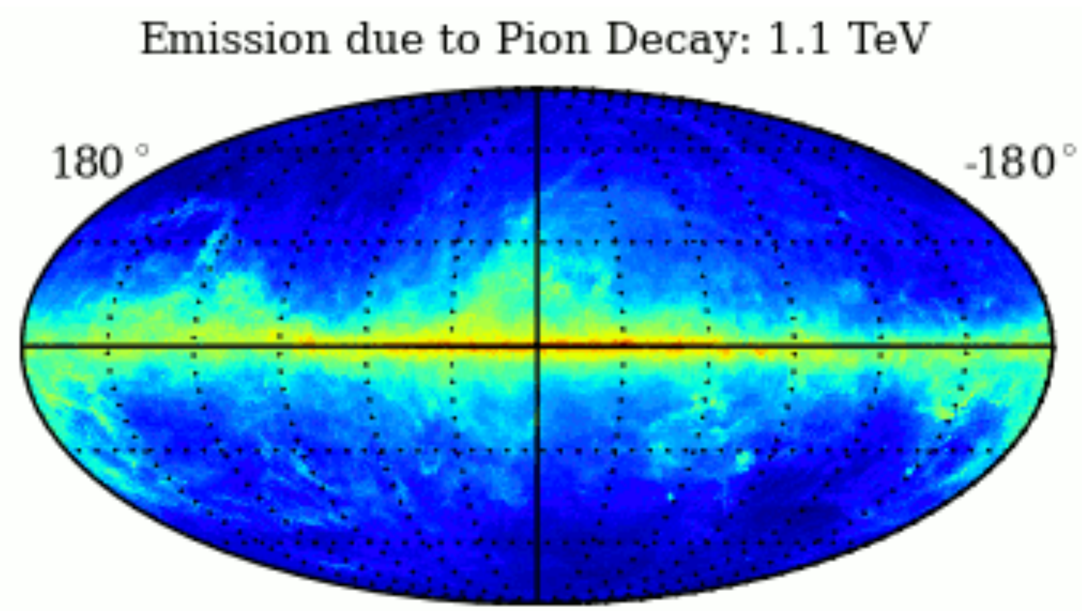
<u>**γ-rays are essential to validate the models**</u>

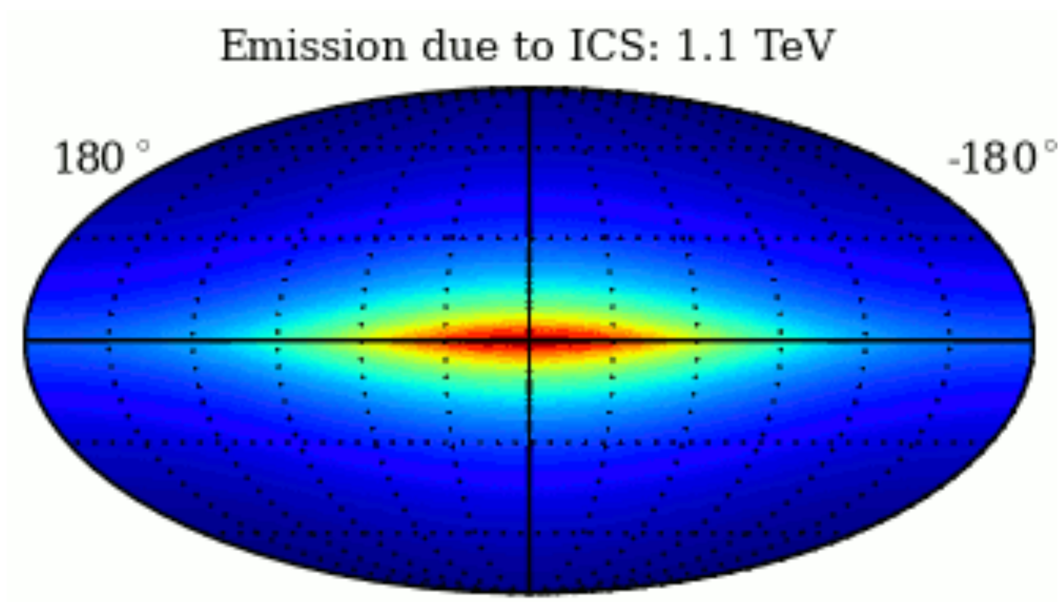




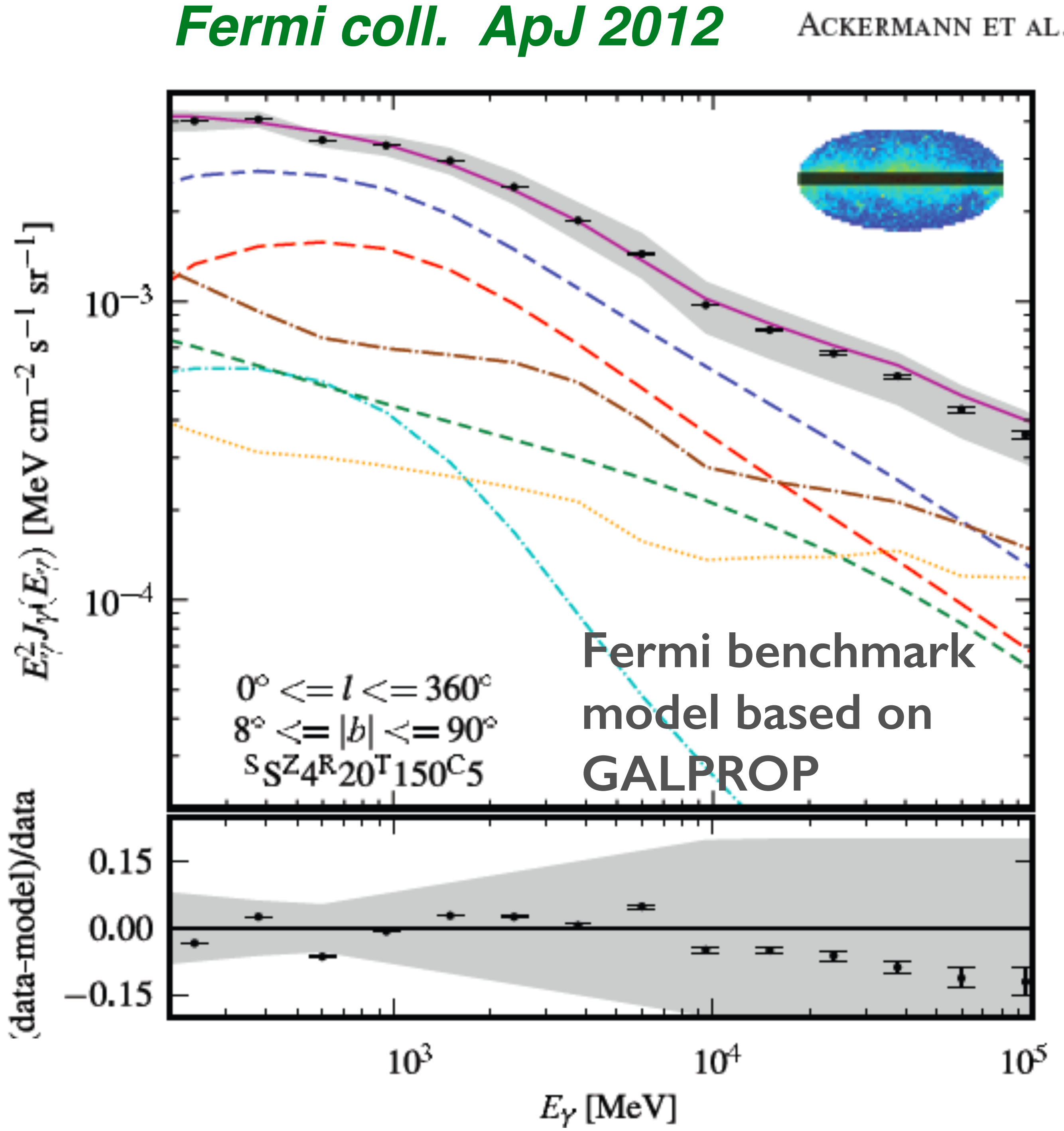
The gamma-ray diffuse emission probe

The line of sight convolution of CR density, target density, and production cross sections give





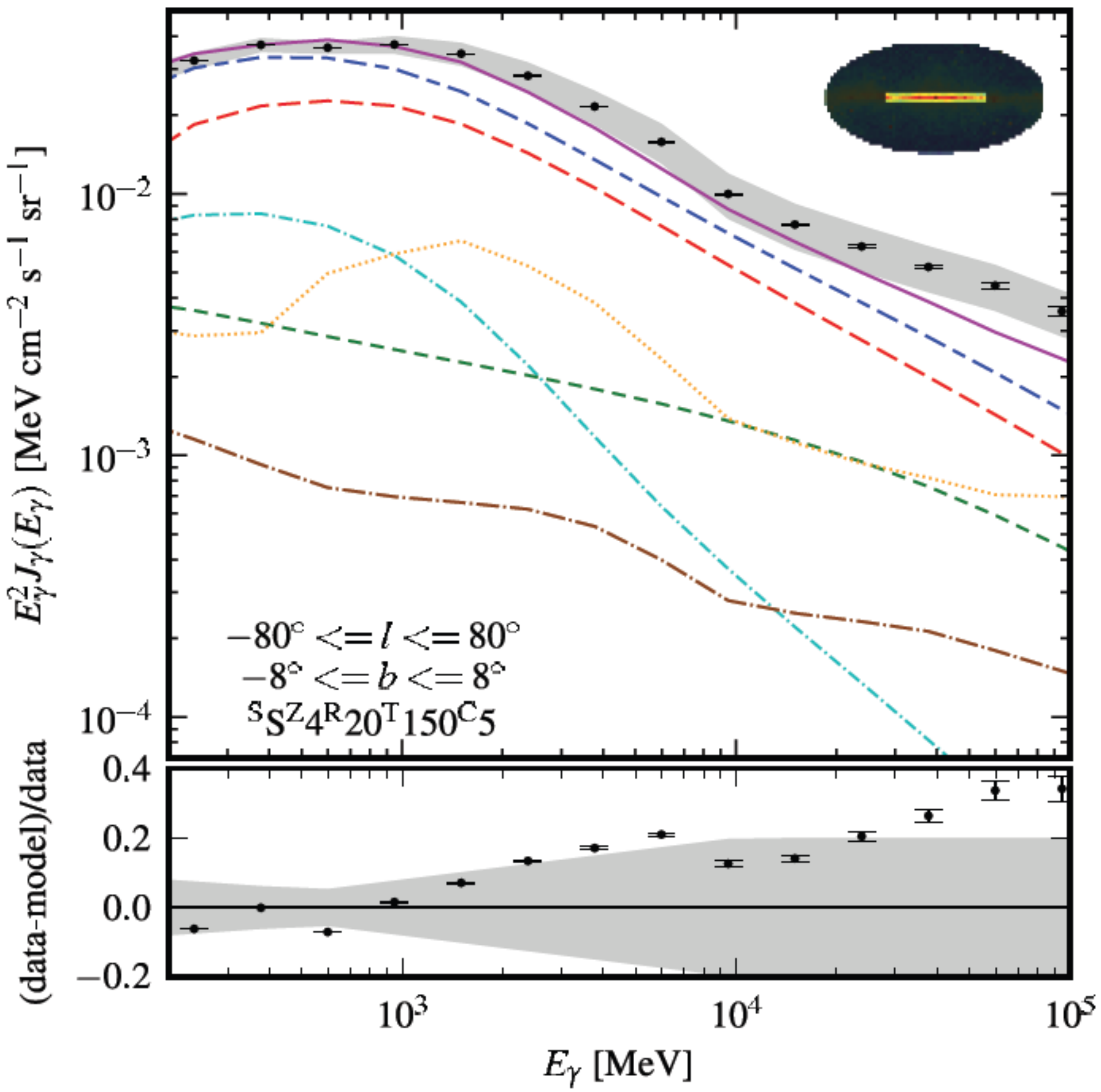
Fermi coll. ApJ 2012



The Inner Galactic Plane Fermi anomaly

Fermi coll. ApJ 2012

inner GP



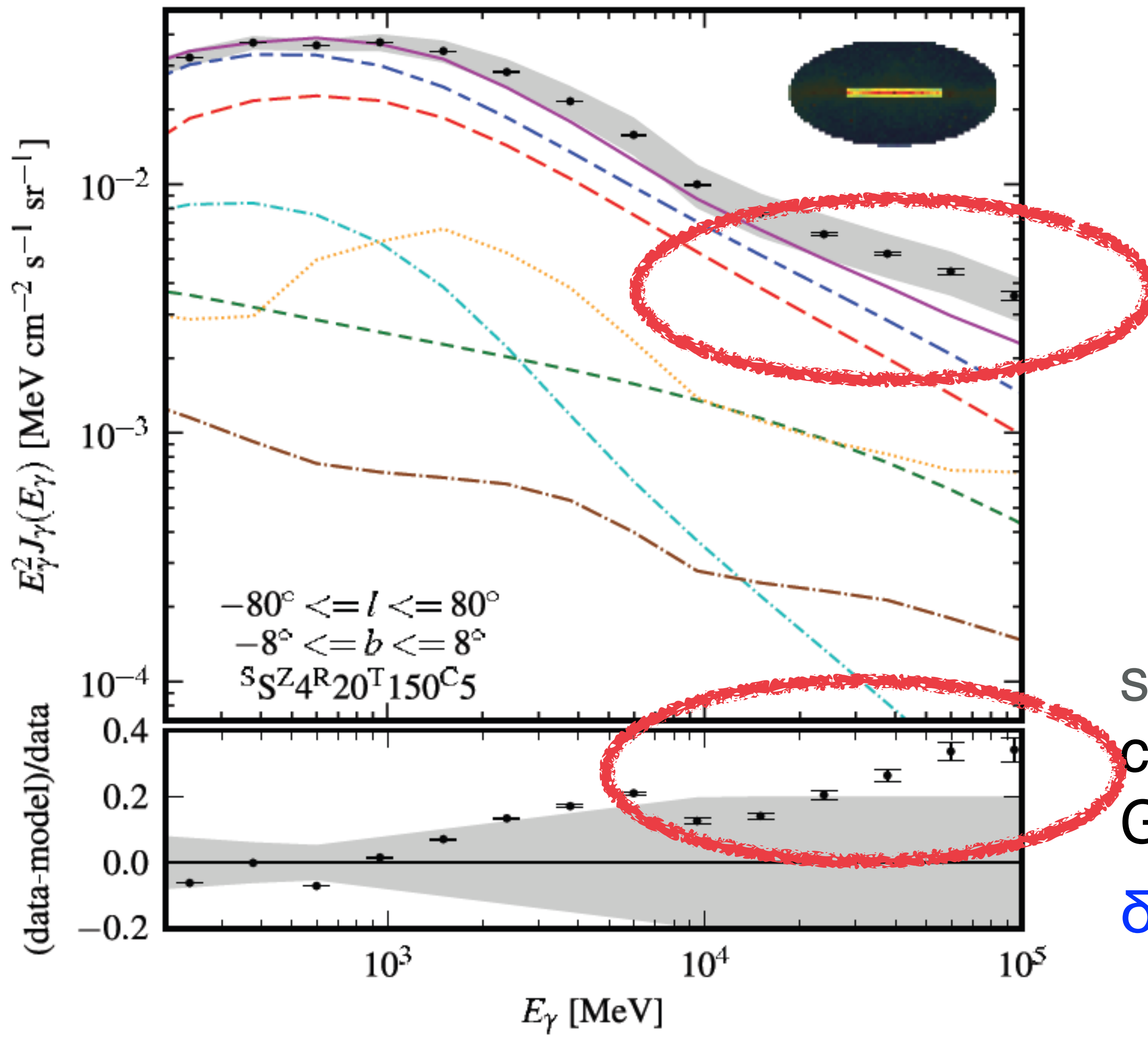
solid line: Fermi Benchmark (FB) conventional model based on GALPROP (*Moskalenko, Strong et al.*).

$\delta = 0.3$, $\gamma_P = 2.72$ in the whole Galaxy

The Inner Galactic Plane Fermi anomaly

Fermi coll. ApJ 2012

inner GP



solid line: Fermi Benchmark (FB) conventional model based on GALPROP (*Moskalenko, Strong et al.*).

$\delta = 0.3$, $\gamma_P = 2.72$ in the whole Galaxy

The Milagro anomaly in the inner Galactic Plane

ABDO ET AL.
THE ASTROPHYSICAL JOURNAL, 688:1078–1083, 2008

TABLE 1

GAMMA-RAY EMISSION FROM THE GALACTIC PLANE AROUND 15 TeV

REGION FOR $\|b\| < 2°$ (l, deg)	STATISTICAL SIGNIFICANCE σ	DIFFUSE FLUX ($\times 10^{-13}$ TeV^{-1} cm^{-2} s^{-1} sr^{-1}) Milagro[a]	GALPROP Optimized	GALPROP Conventional
30–65	5.1	$23.1 \pm 4.5^{+7.0}_{-8.0}$	20.0	4.9
65–85	8.6	$21.8 \pm 2.5^{+7.2}_{-7.8}$	10.2	2.7
85–110	1.3	<7.1 (95% CL)	5.8	1.3
136–216	0.8	<5.7 (95% CL)	3.1	0.9

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

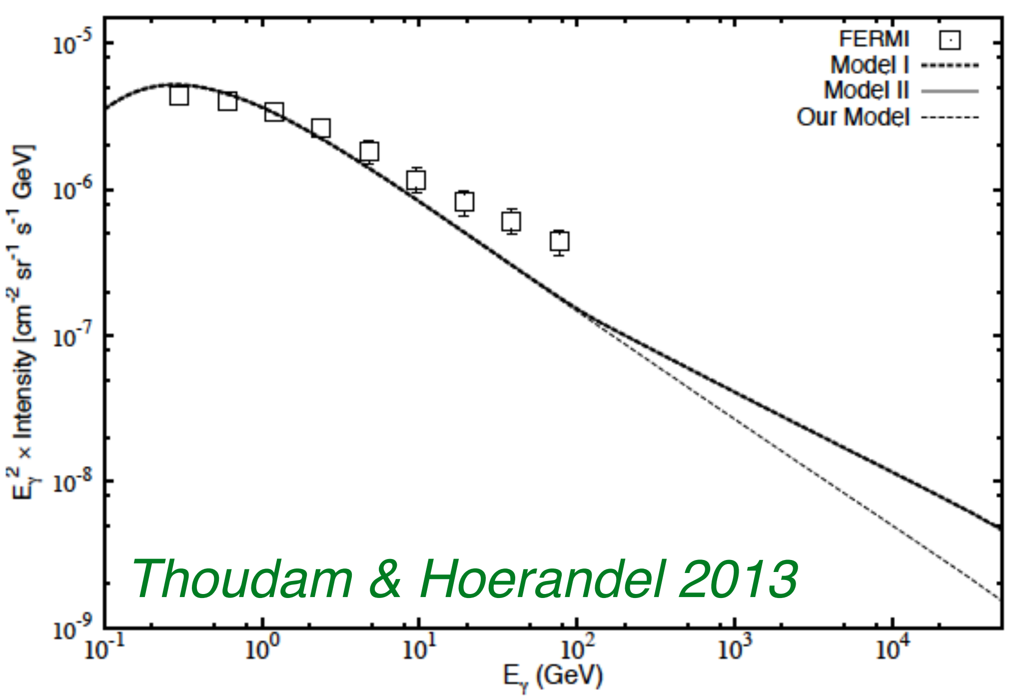
- an *optimized model* (augmented IC contribution) - proposed to account for the EGRET GeV excess - was found to match Milagro

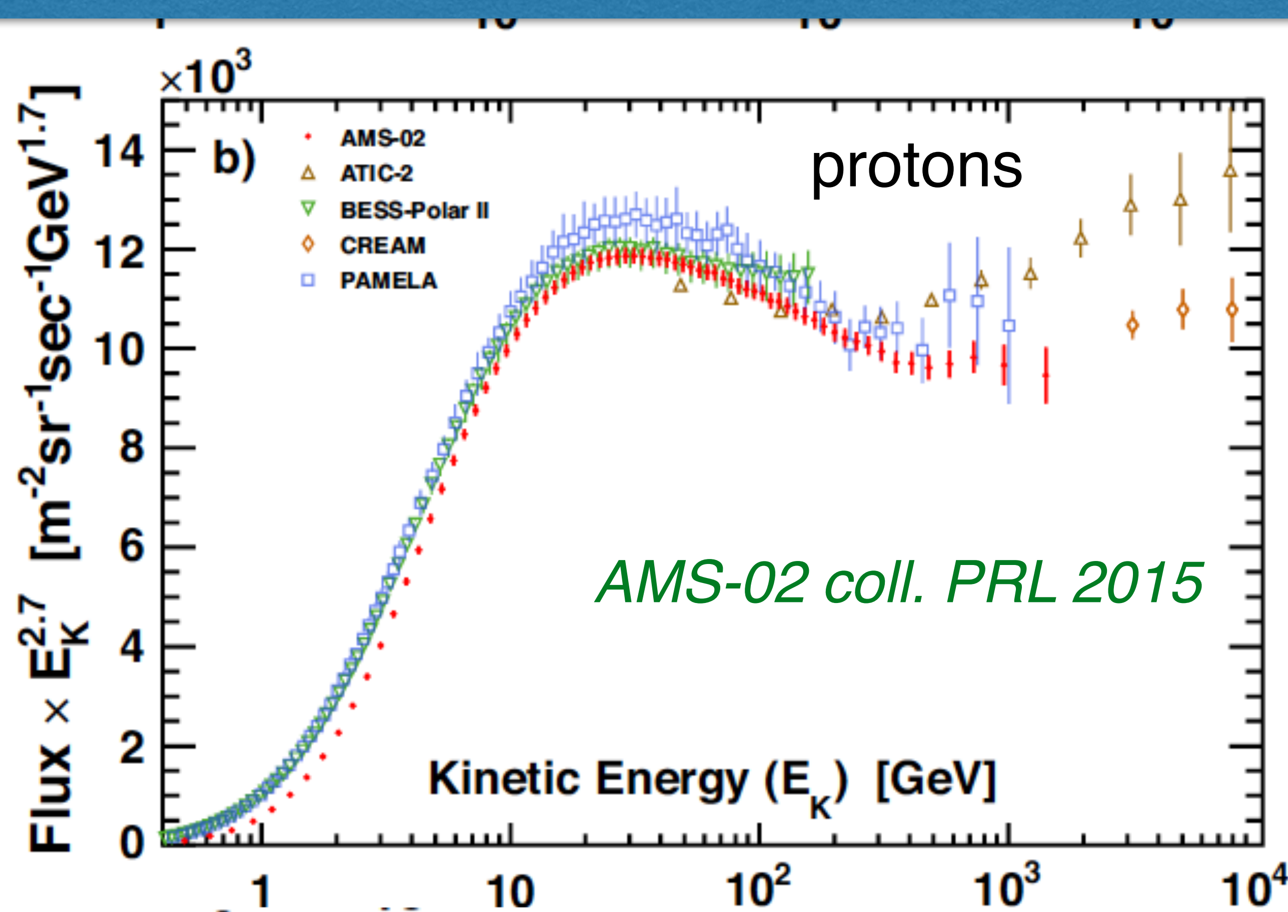
- GeV excess disproved by Fermi-LAT (*PRL 2009*)
  $\Longrightarrow$ back to conventional models. MILAGRO anomaly strikes again !

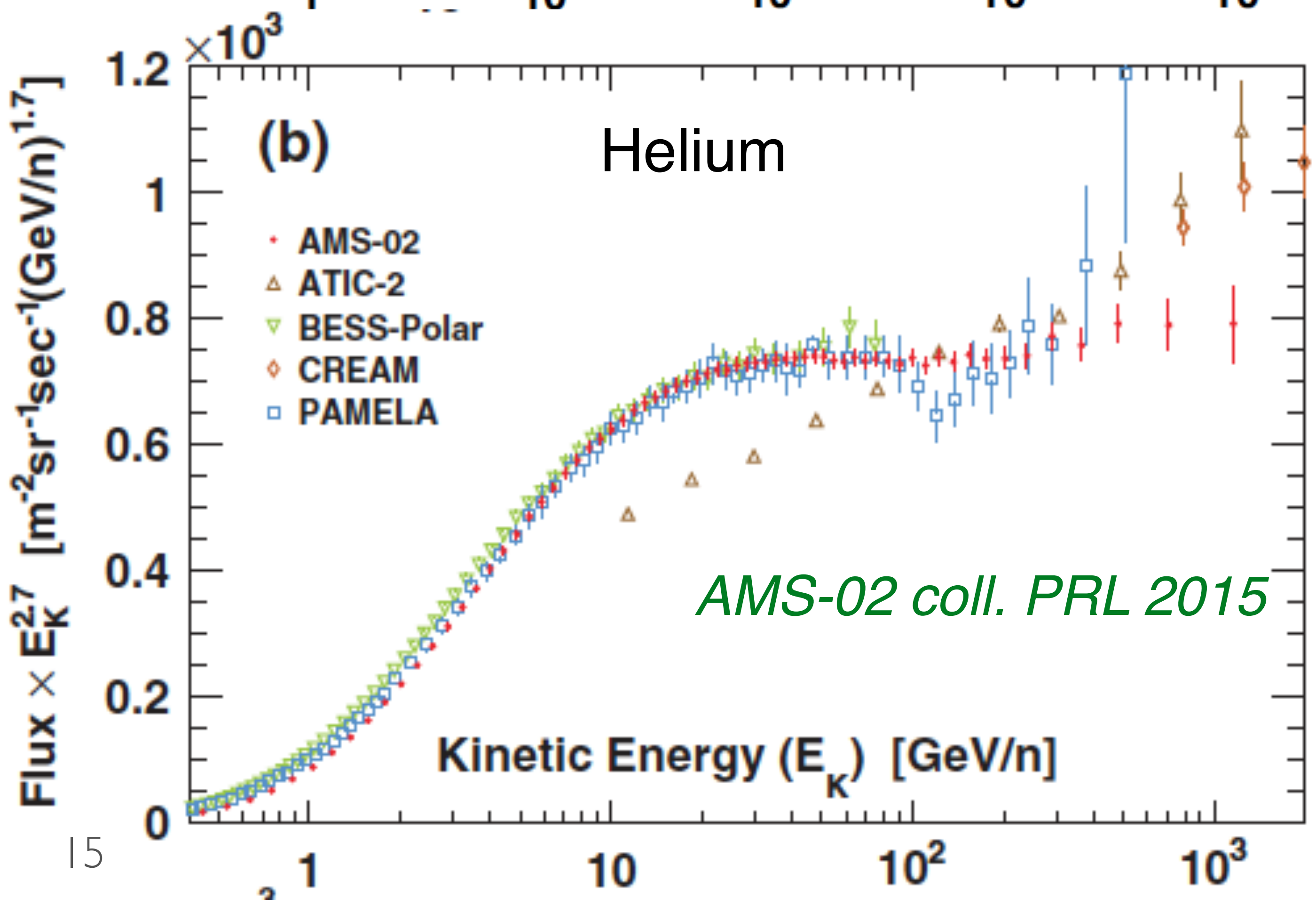
Can "Pamela make a Milagro" ?

PAMELA (***Science 2011*** **)** found an hardening of the p and He spectra at ~ 250 GeV/n . **AMS-02** confirmed the feature which is also required to match **CREAM**

If the effect is present in the whole Galaxy - as expected if due to CR propagation (see e.g. *Blasi et al. 2012, 2015*) - *it should affect the diffuse* **γ** *-ray emission spectrum*



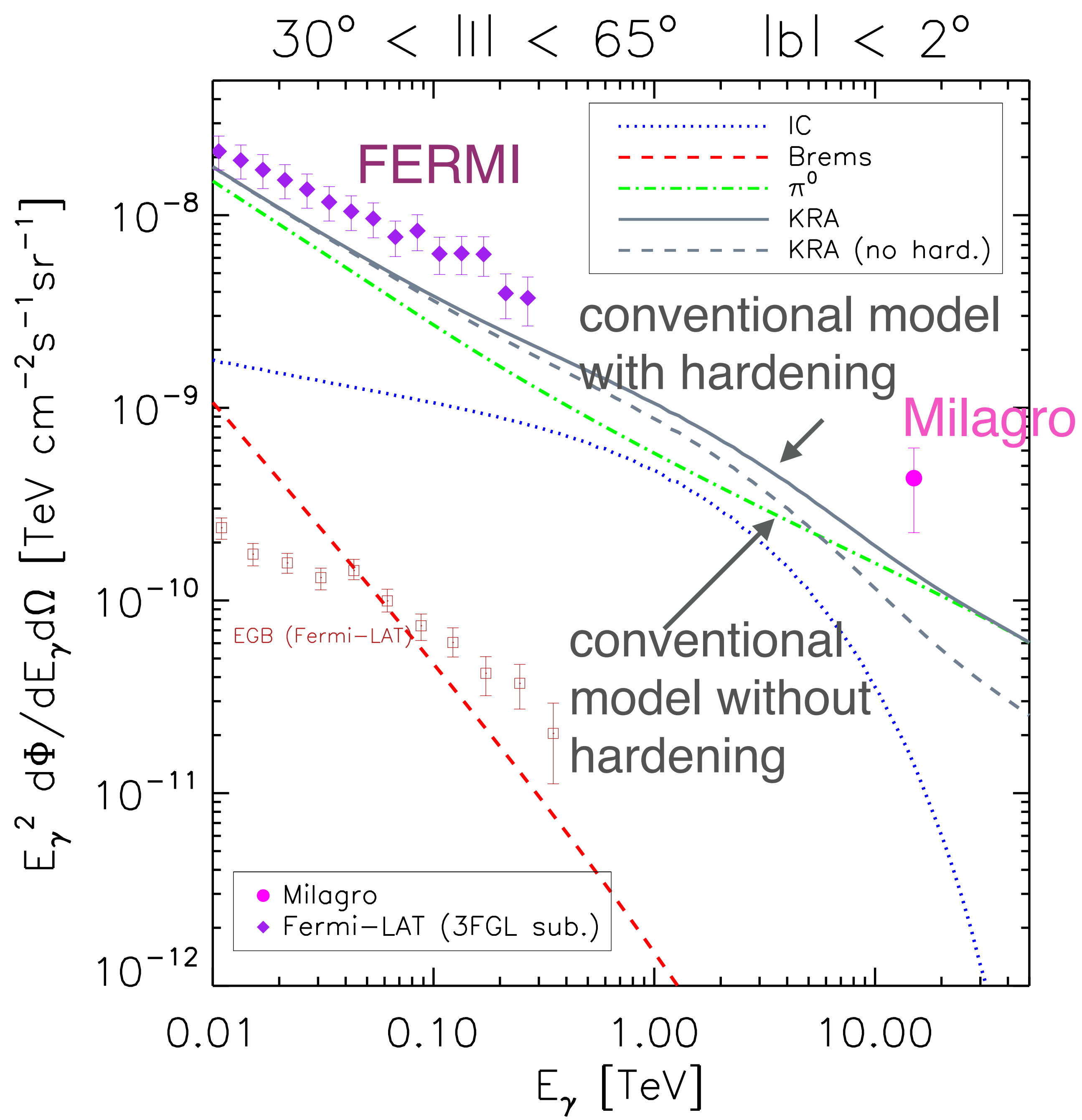




The Milagro anomaly in the inner Galactic Plane

CR "Pamela" hardening at ~ 250 GeV/n is not sufficient even assuming it is a large scale effect.
(the excess is present for all conventional models tuned on CR data and all-sky Fermi-LAT data)

moreover …..



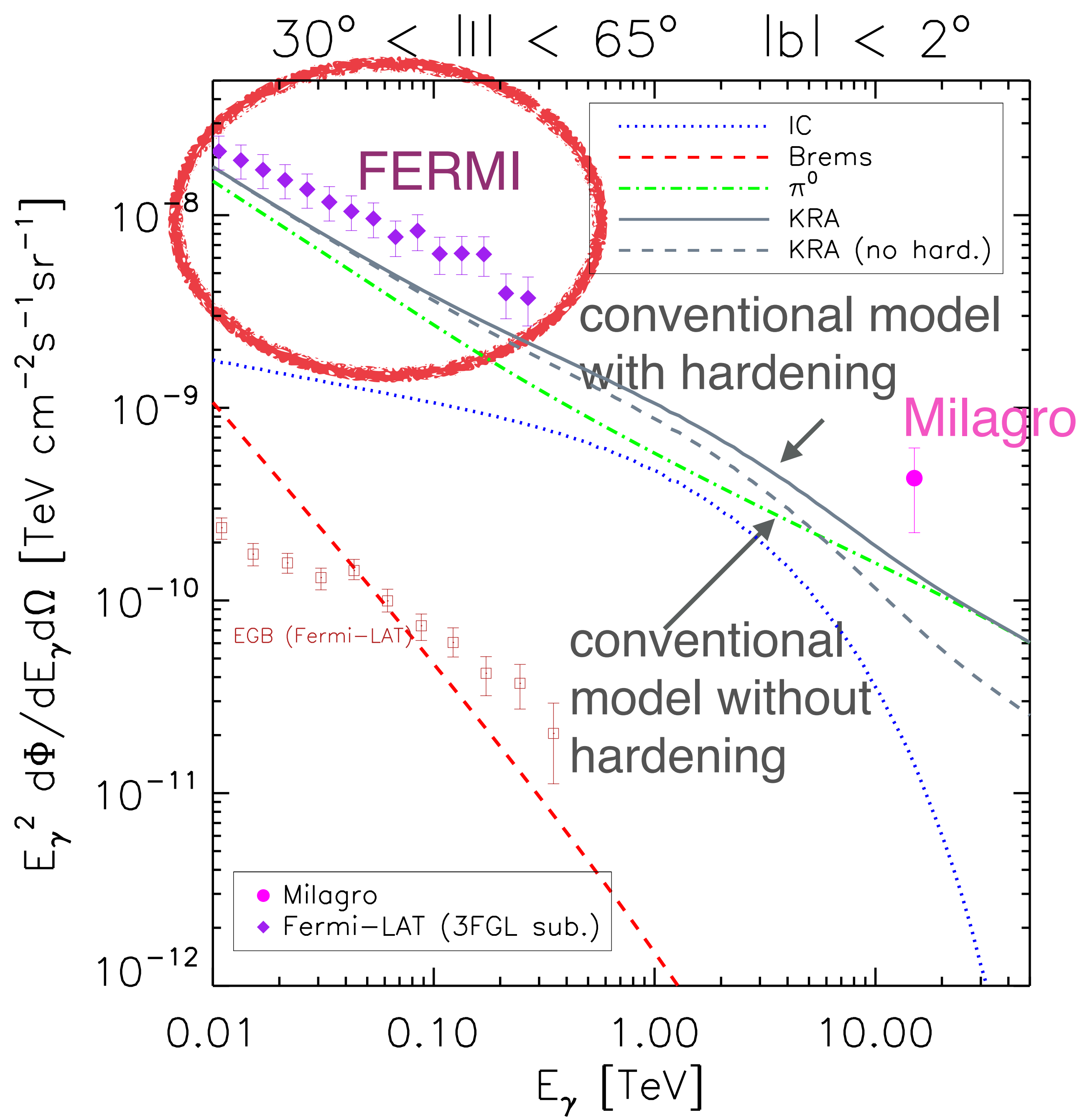
The Milagro anomaly in the inner Galactic Plane

…troubles start already at low energy !!

- cleaned and point source subtracted Fermi-LAT data (PASS 7) taken in the same window of Milagro exceed the conventional models including the Fermi benchmark one (see below)

  the excess holds (with larger significance using PASS8)

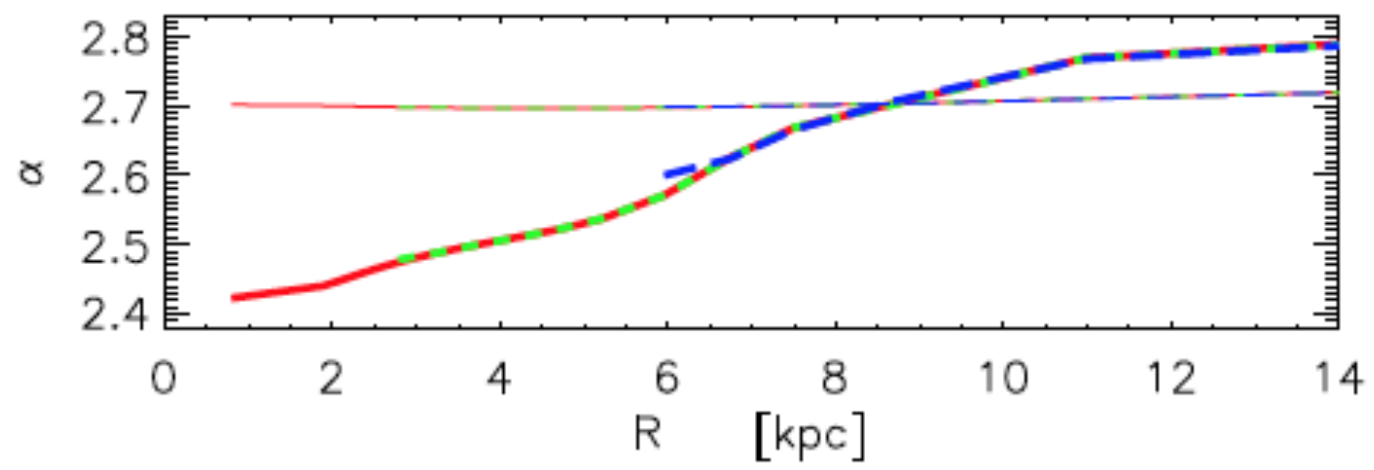
  Fermi-LAT and Milagro anomalies in the inner Galactic plane are likely to be related !



The evidence of a CR spectral index radial dependence

Gaggero, Urbano, Valli & Ullio arXiV: 1411.7623 PRD 2015

proton spect. index

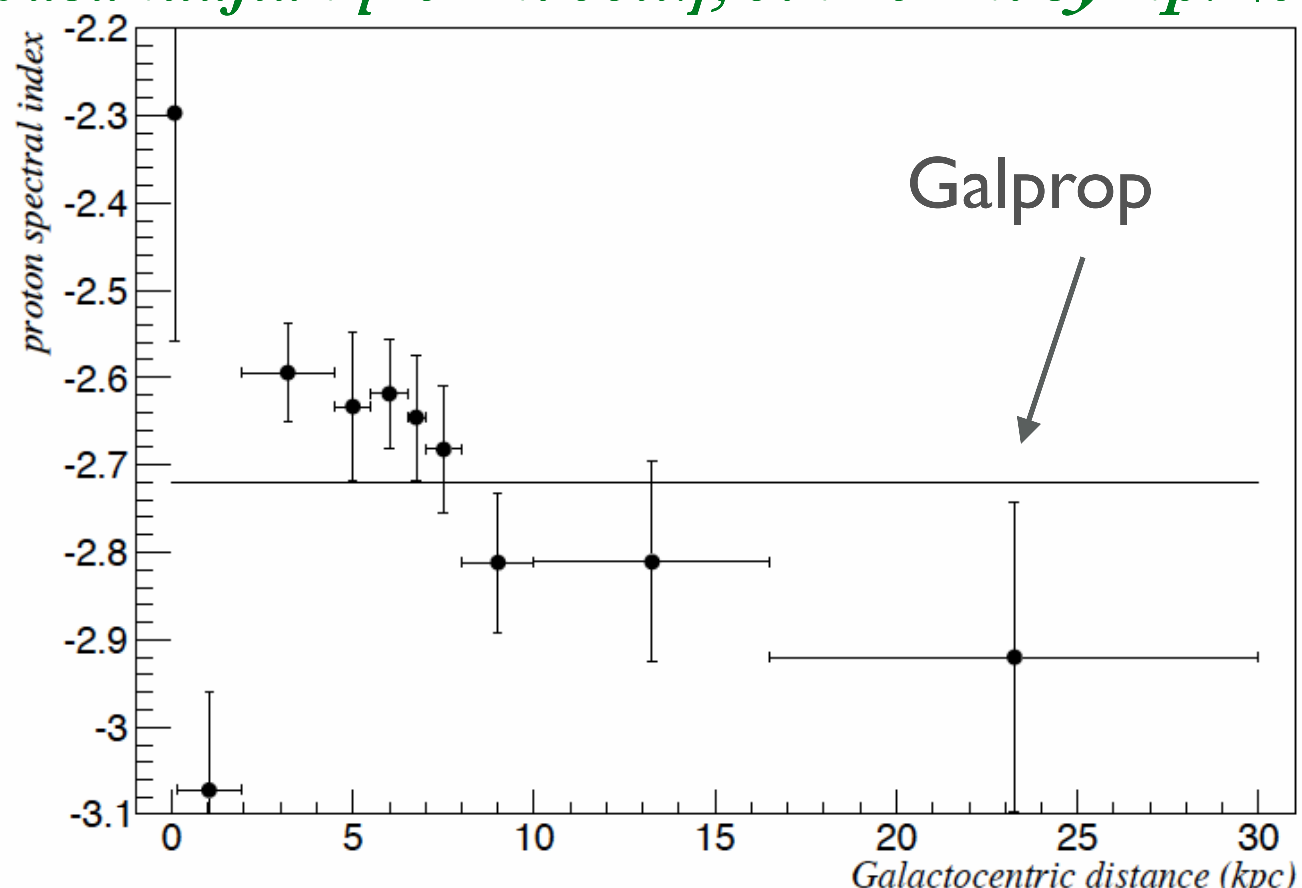


showed also that Fermi data requires a radial dependence of the CR spectral index, hence of the γ-ray emission spectrum

This was independently reported by the Fermi collaboration and confirmed recently (see also below)

This is clearly incompatible with conventional models implemented with GALPROP

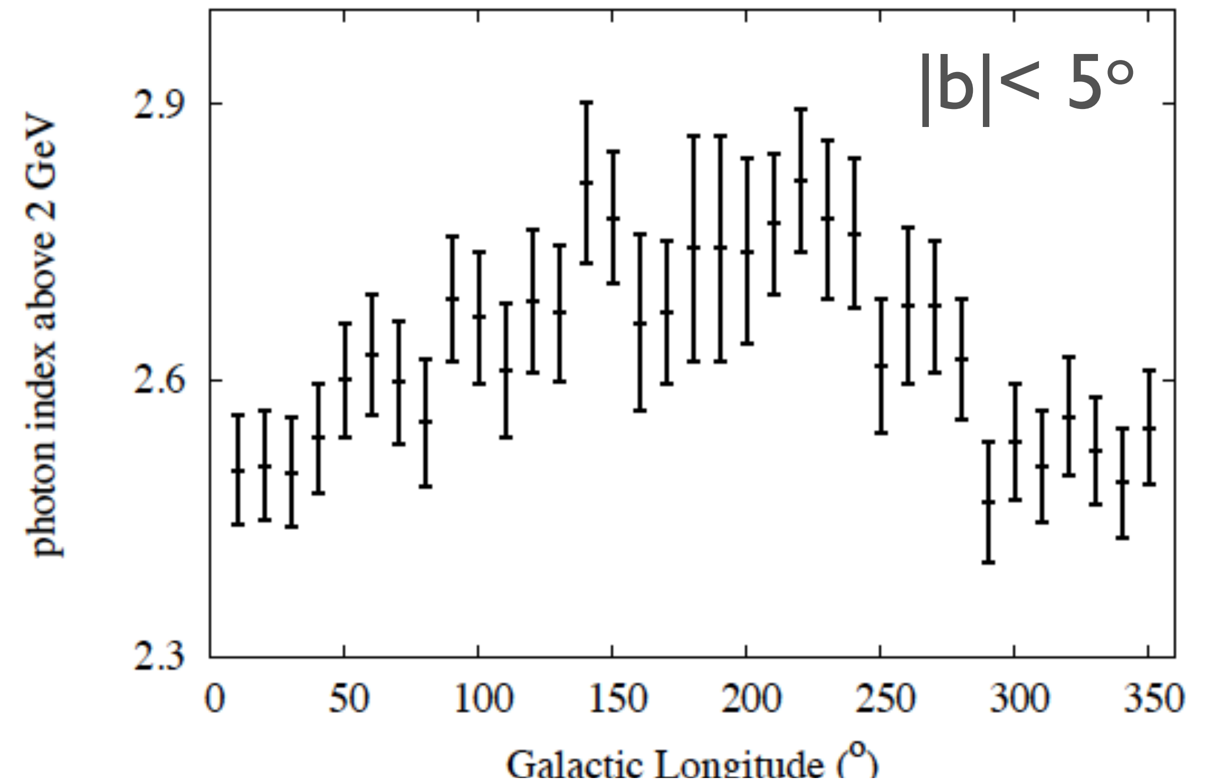
Casandajian [Fermi coll.], 5th Fermi symp. 2014

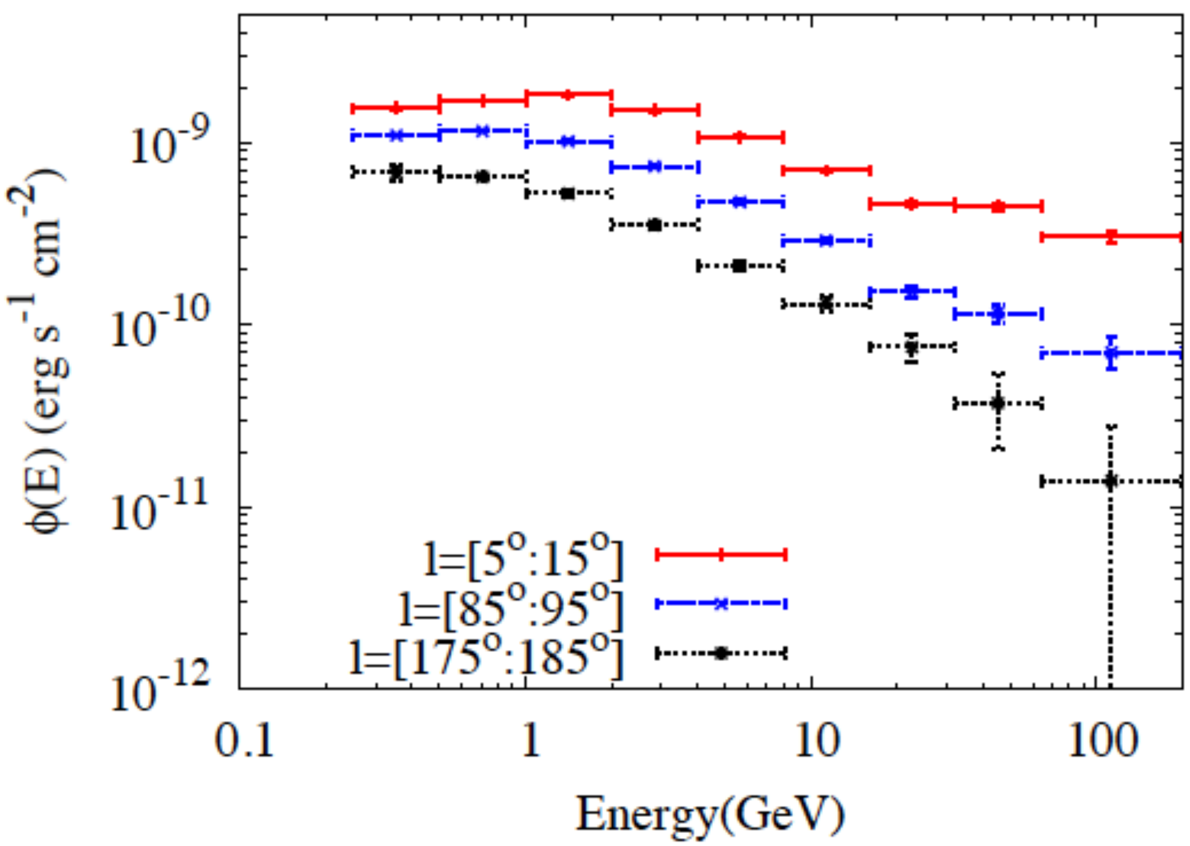


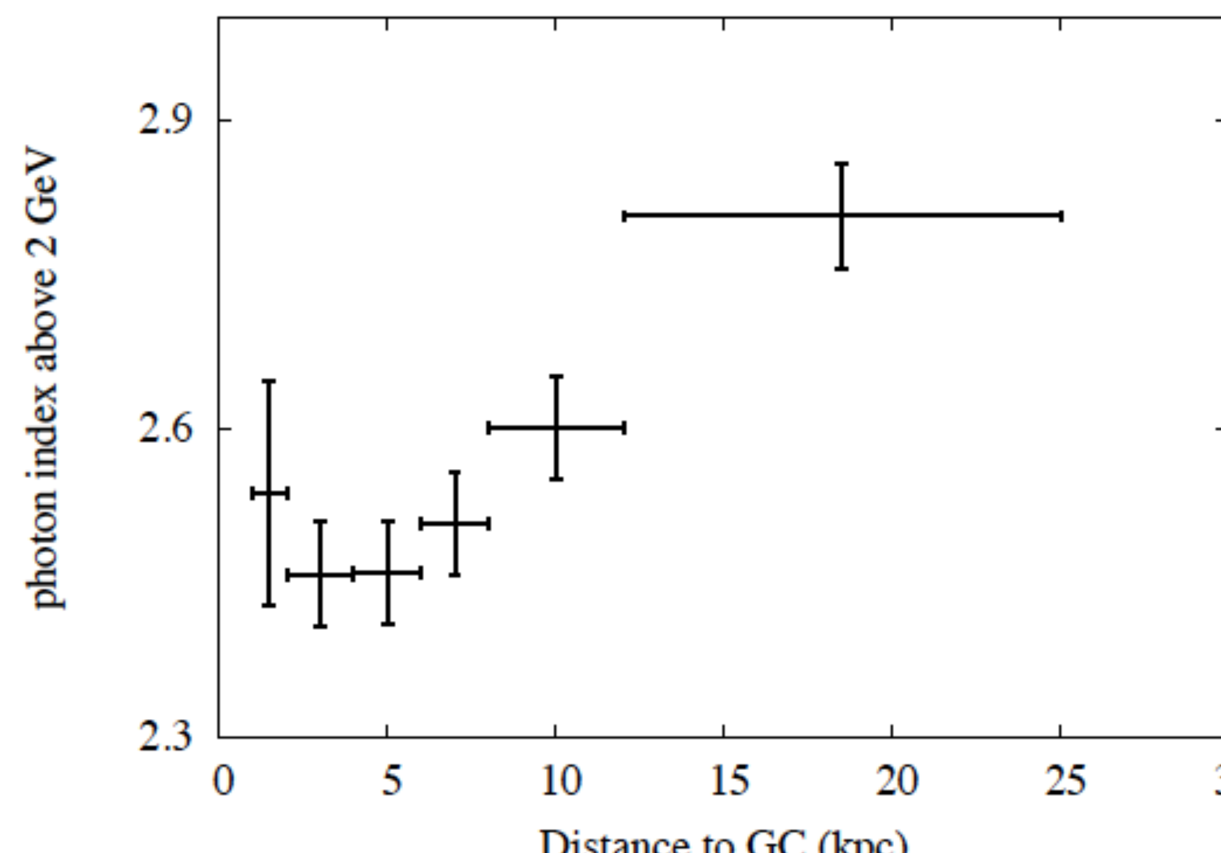
The evidence of a CR spectral index radial dependence

Yang, Aharonian & Evoli arXiV:1602.04710

also found a similar dependence of the γ-ray spectral index on the longitude/distance to GC







The KRAγ model: Radial dependency of CR transport

Gaggero, Urbano, Valli & Ullio arXiV: 1411.7623 PRD 2015

The **KRAγ model** - implemented with our DRAGON code

adopts for the diffusion coeff.

$D(E) = D_0\,(E/E_0)^{-\delta(R)}$ with

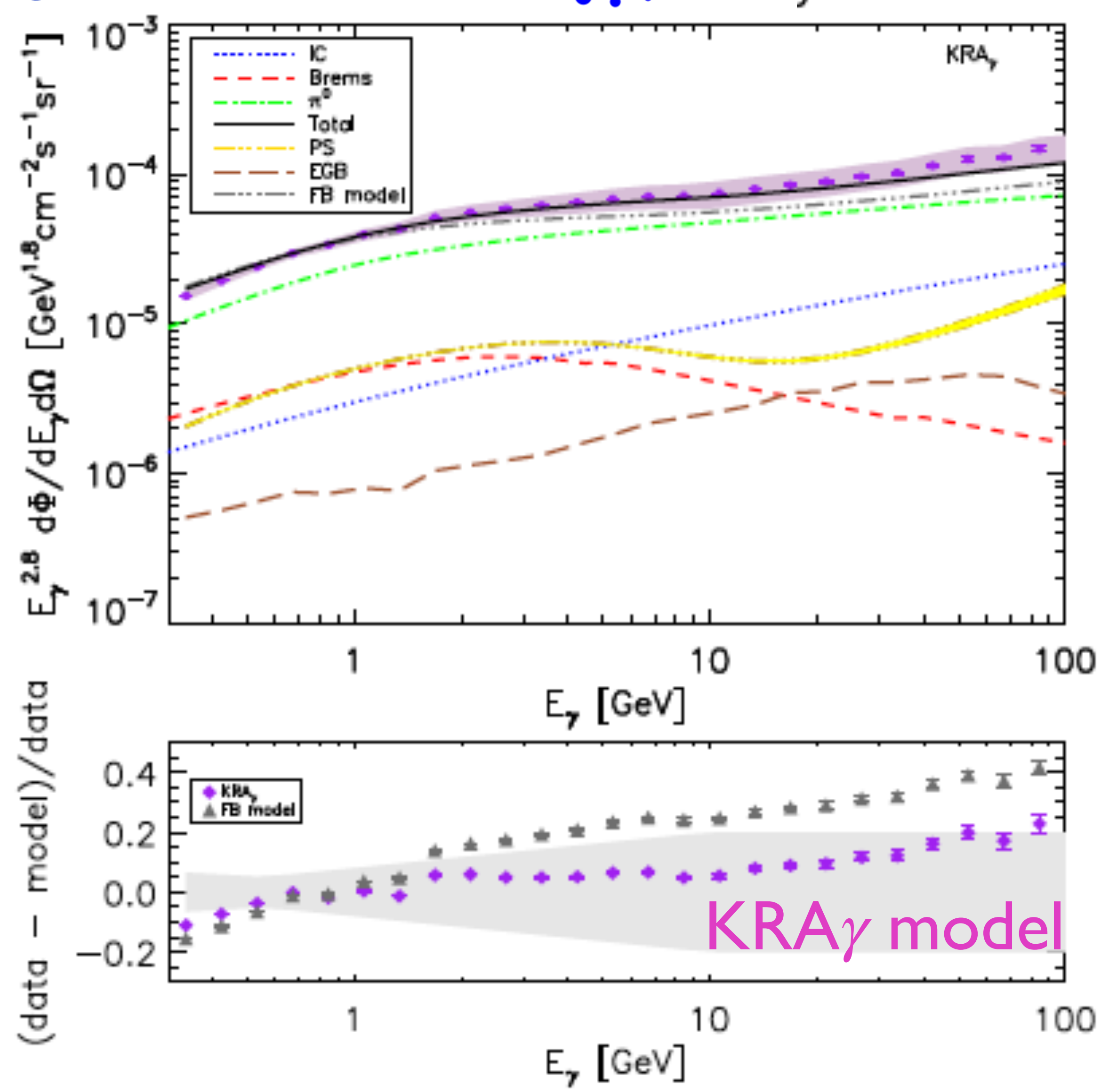
$\delta(R) = A\,R + B$ for R < 11 kpc, so that $\delta(R_\odot) = 0.5$

constant at larger radii

and convective velocity

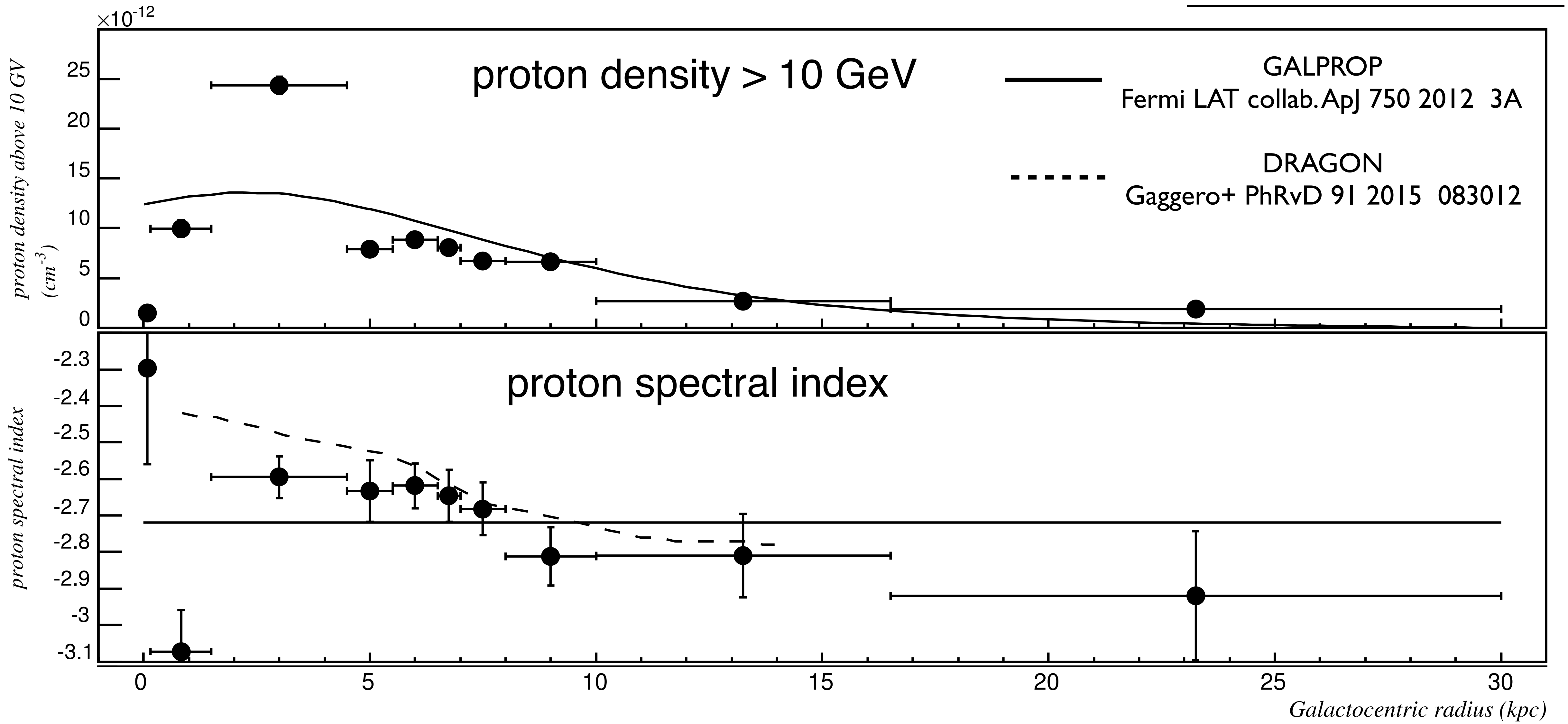
$$\frac{dV_C}{dz} = 100\ \mathrm{km\ s^{-1}\ kpc^{-1}}$$ for R < 6.5 kpc

The model is tuned to reproduce the proton spectrum measured by PAMELA (including the hardening @ 250 GeV/n) up to 1 TeV, the B/C (antiprotons also matched by secondary prod.) as well as updated diffuse γ-ray Fermi data on the whole sky



The KRA$_\gamma$ model against Fermi results

FERMI coll. arXiV:1602.07246; ApJS 223 2016

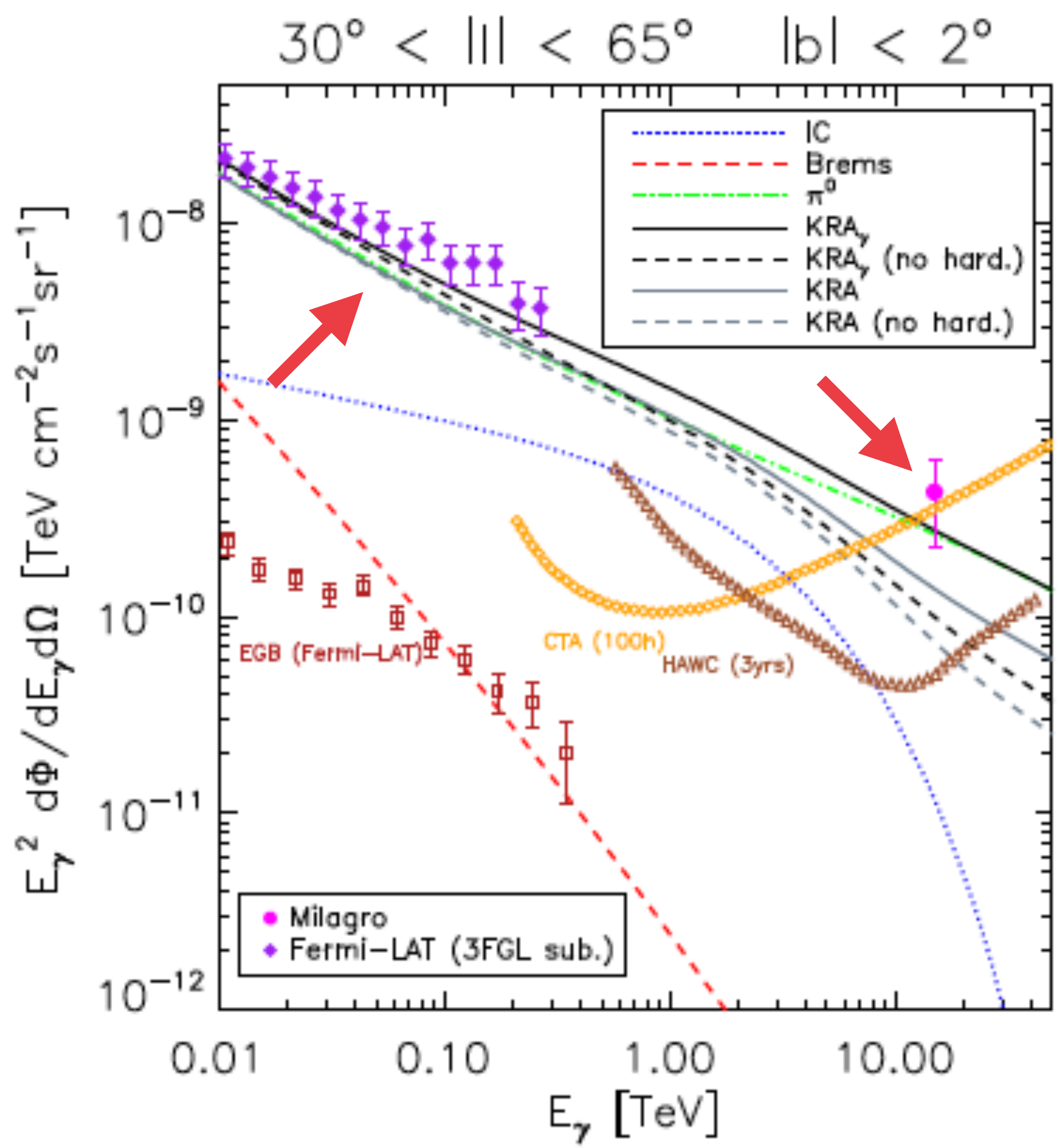


The KRAγ model solves Milagro anomaly

Gaggero, DG, Marinelli, Urbano &Valli arXiV: 1504:00227 ApJ L 2015

The KRAγ model matches Milagro consistently with Fermi data

point sources cleaned
no further tuning is required !



The KRAγ model solves Milagro anomaly

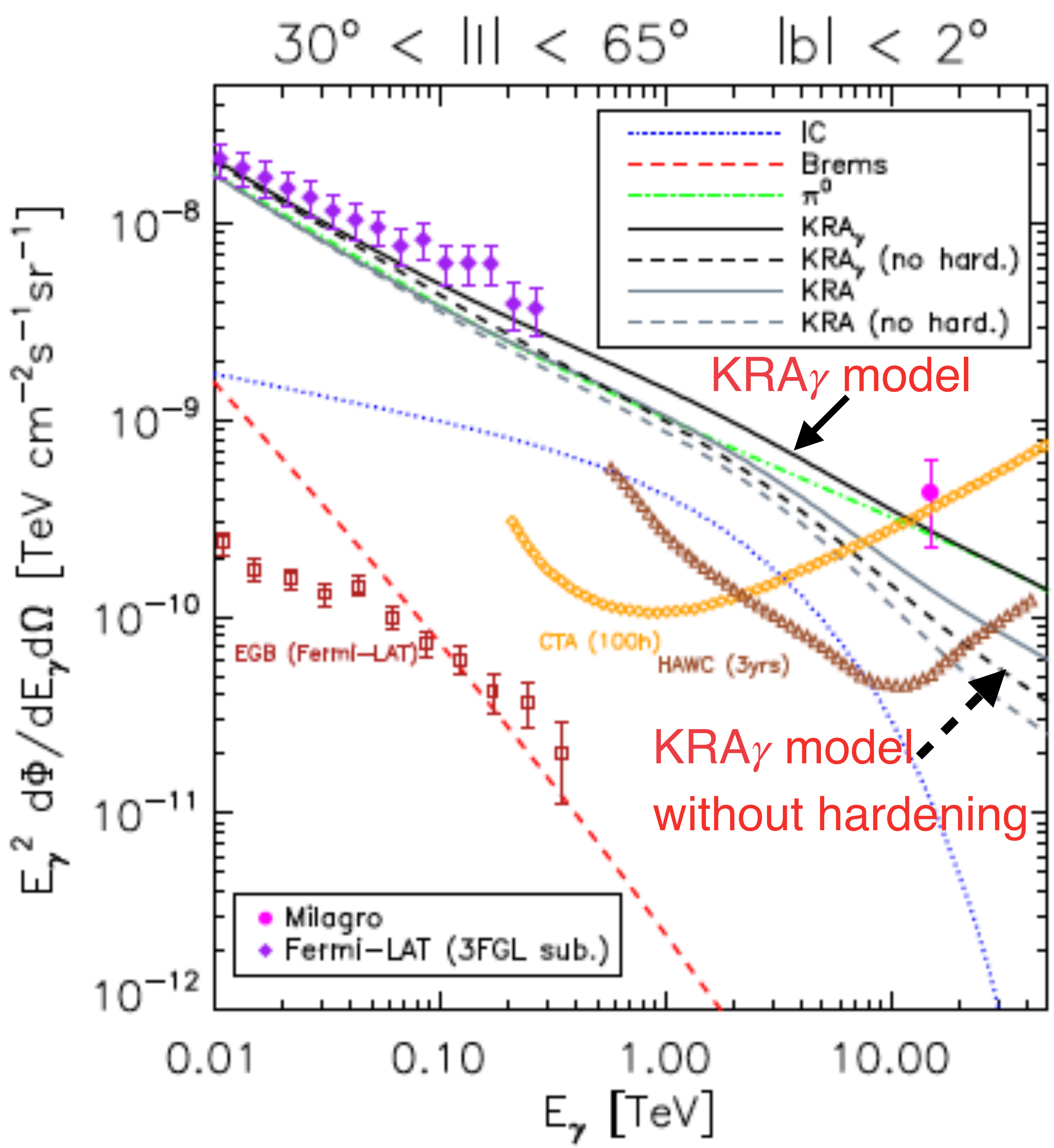
Gaggero, DG, Marinelli, Urbano &Valli arXiV: 1504:00227 ApJ L 2015

The KRAγ model matches Milagro consistently with Fermi data

point sources cleaned

no further tuning is required !

Both inhomogeneous diffusion and CR hardening at ~ 250 GeV/n are required !

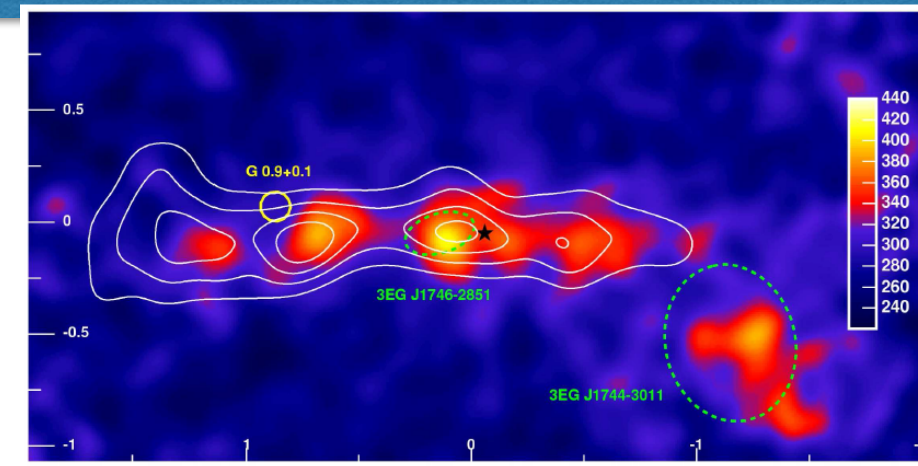


The KRAγ model against the Galactic Ridge emission

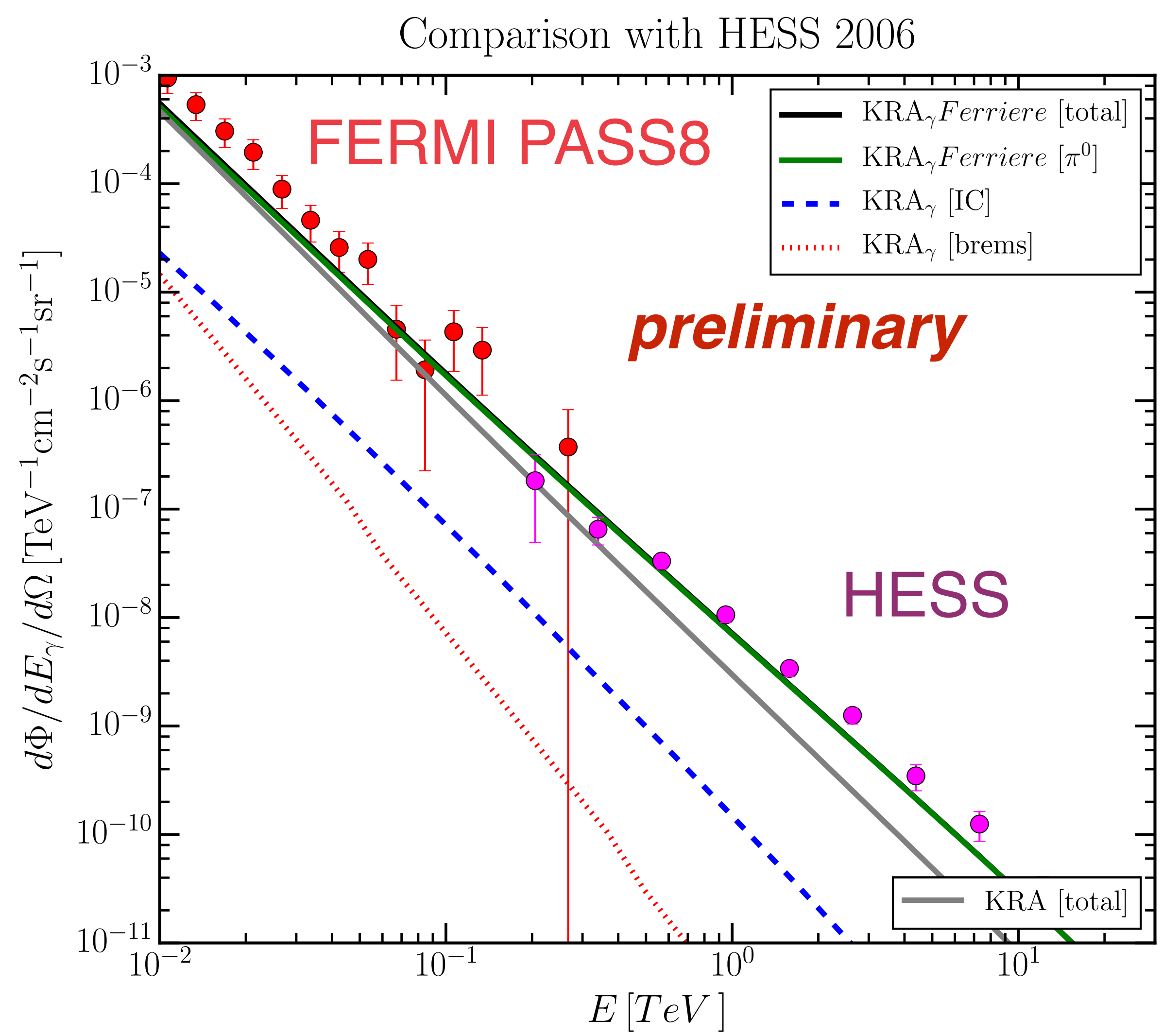
HESS (*Nature* *2006*) measured a spectrum harder ($\Gamma \sim -2.3$) than expected on the basis of conventional CR models, associated with the molecular complex in the inner 200 pc of Galaxy

this is also the case for the updated Fermi benchmark conv. model

the spectrum normalization is correctly reproduced using an improved gas model in the GC region (*Ferriere et al. 2007*)

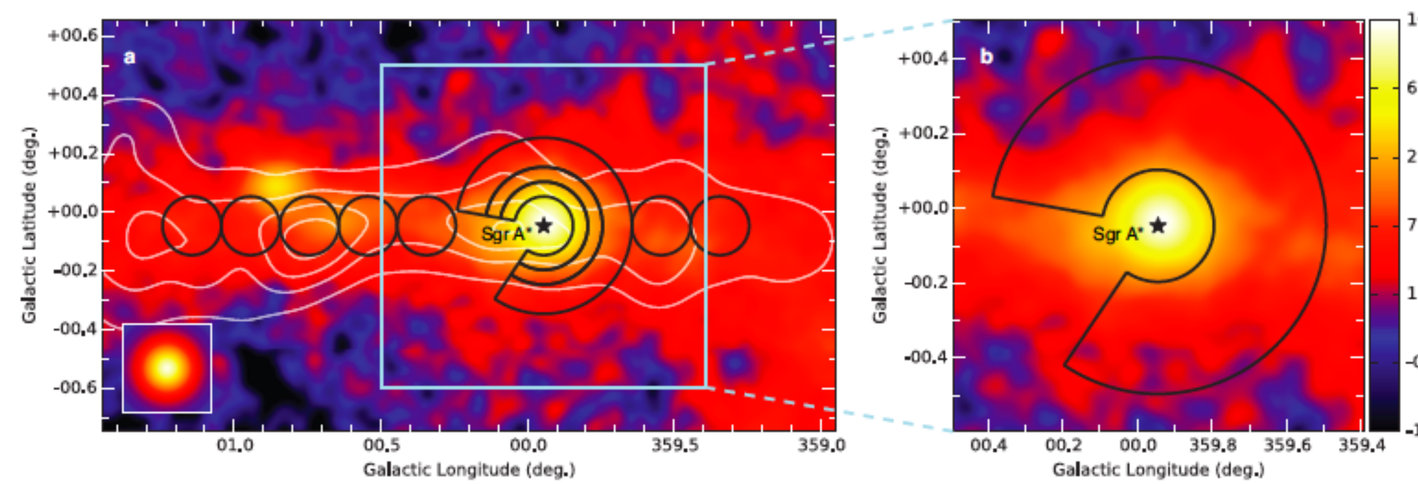


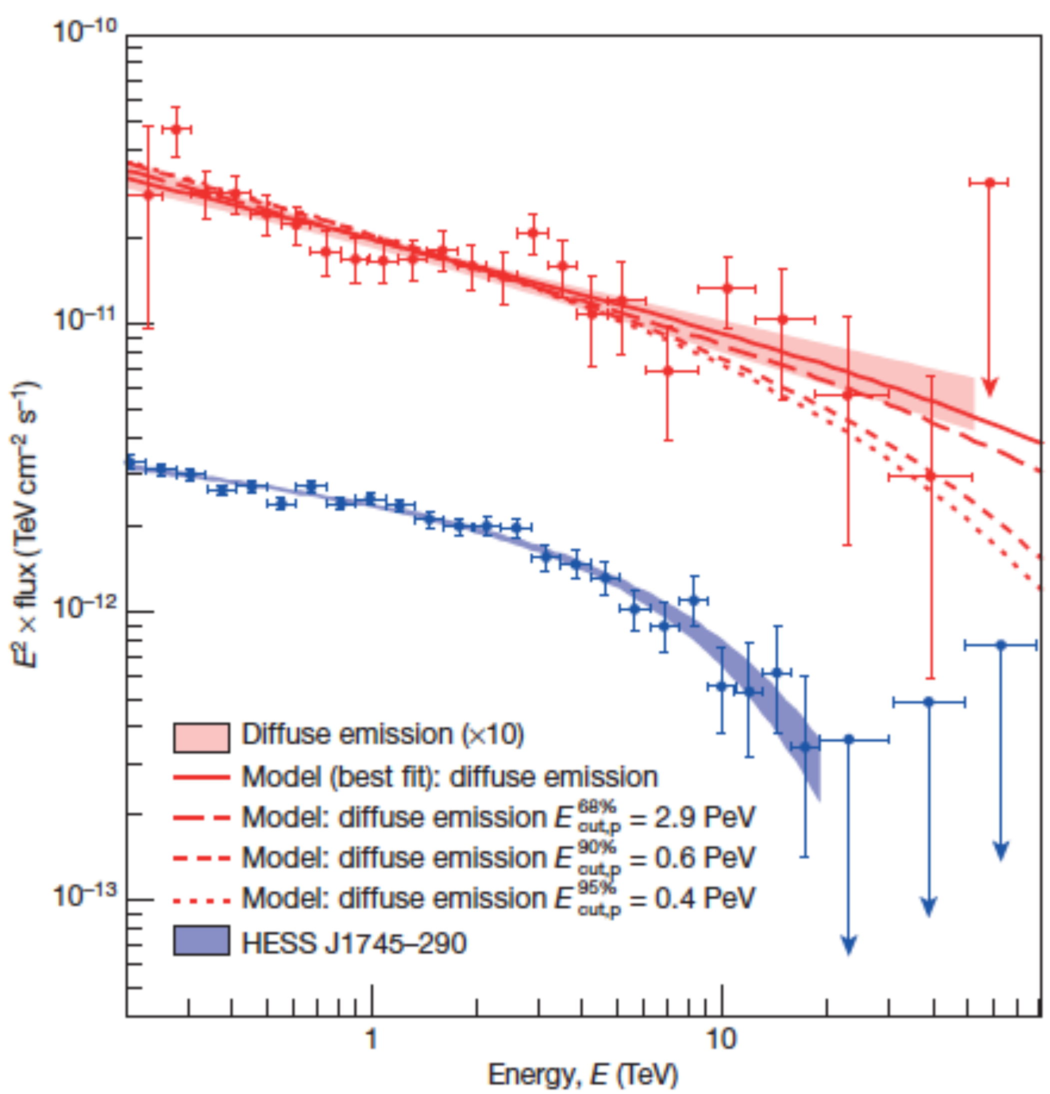
Gaggero, DG, Marinelli, Urbano & Valli :1505:03156
Evoli, Gaggero, DG, Urbano, Marinelli, Taoso, in progr.



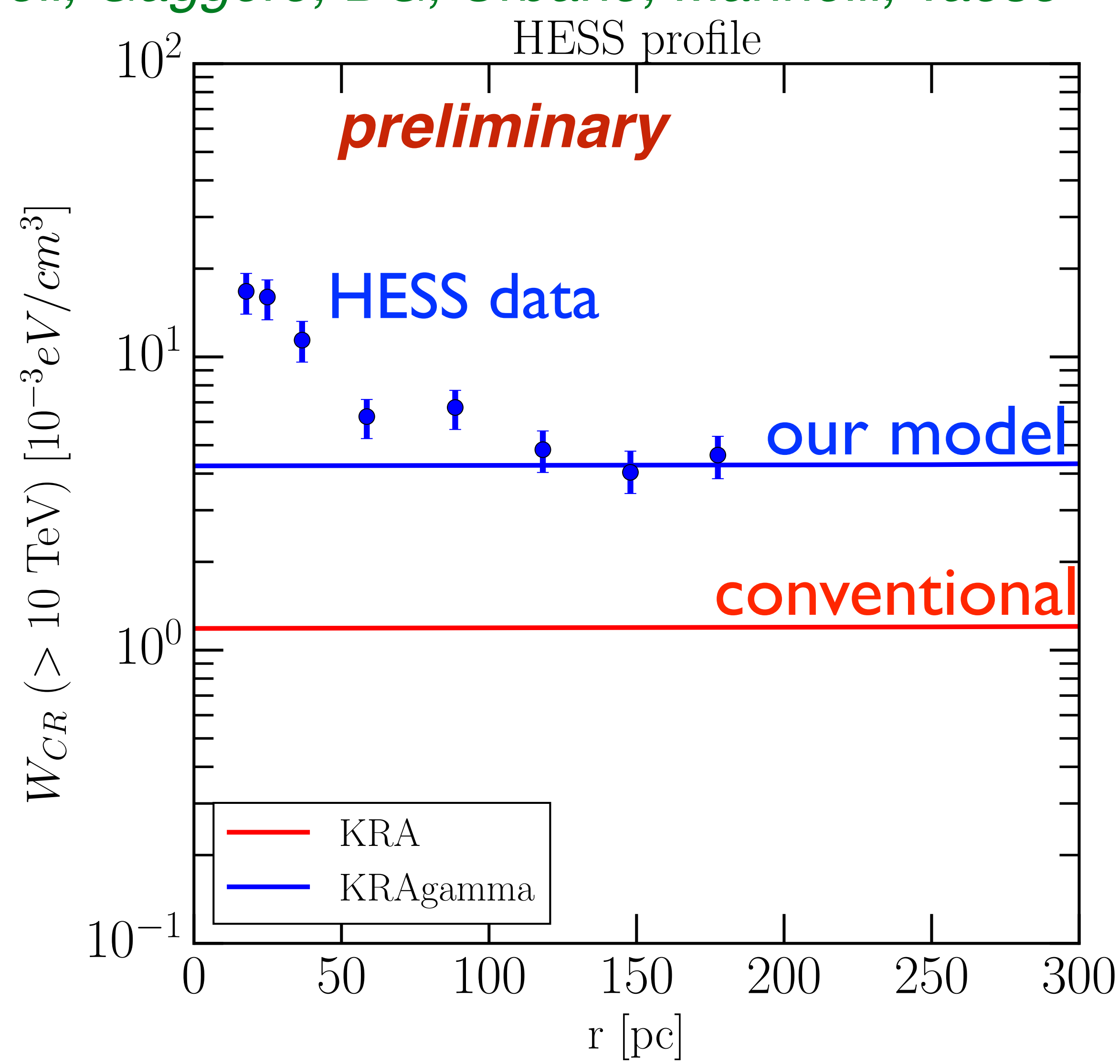
The KRA$_\gamma$ model against the Galactic Ridge emission

HESS (*Nature* *2016*) found a diffuse emission from a small region surrounding the GC with $\Gamma \sim -2.32 \pm 0.05 \pm 0.11$ with no evidence of a cutoff up to 50 TeV





Evoli, Gaggero, DG, Urbano, Marinelli, Taoso



The case for a spatial dependent δ
Is it due to anisotropic diffusion ?

Evoli, Gaggero, Vittino,, Di Bernardo, Ligorini, Di Mauro, Ullio, DG
arXiv:1607.07886 using **DRAGON v2**

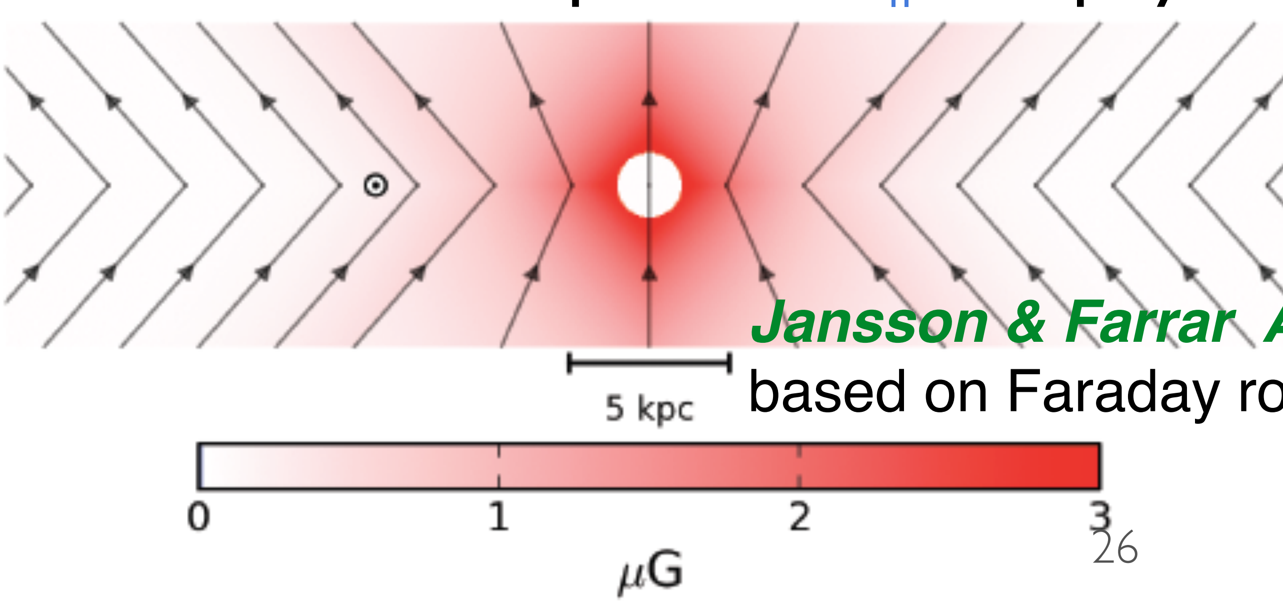
The presence of regular magnetic fields (with versor b_i) breaks isotropy.

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

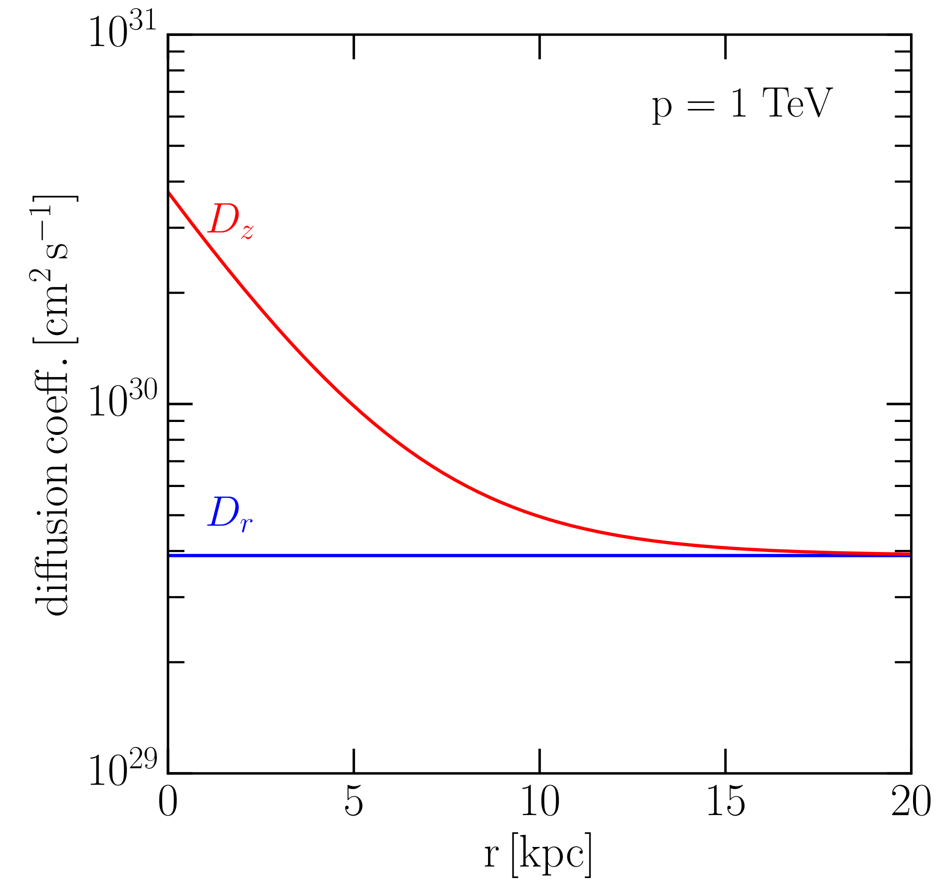
$D_{\parallel}$ and $D_{\perp}$ are expected to have different rigidity dependence (e.g. *Blasi, De Marco, Stanev 2007* found

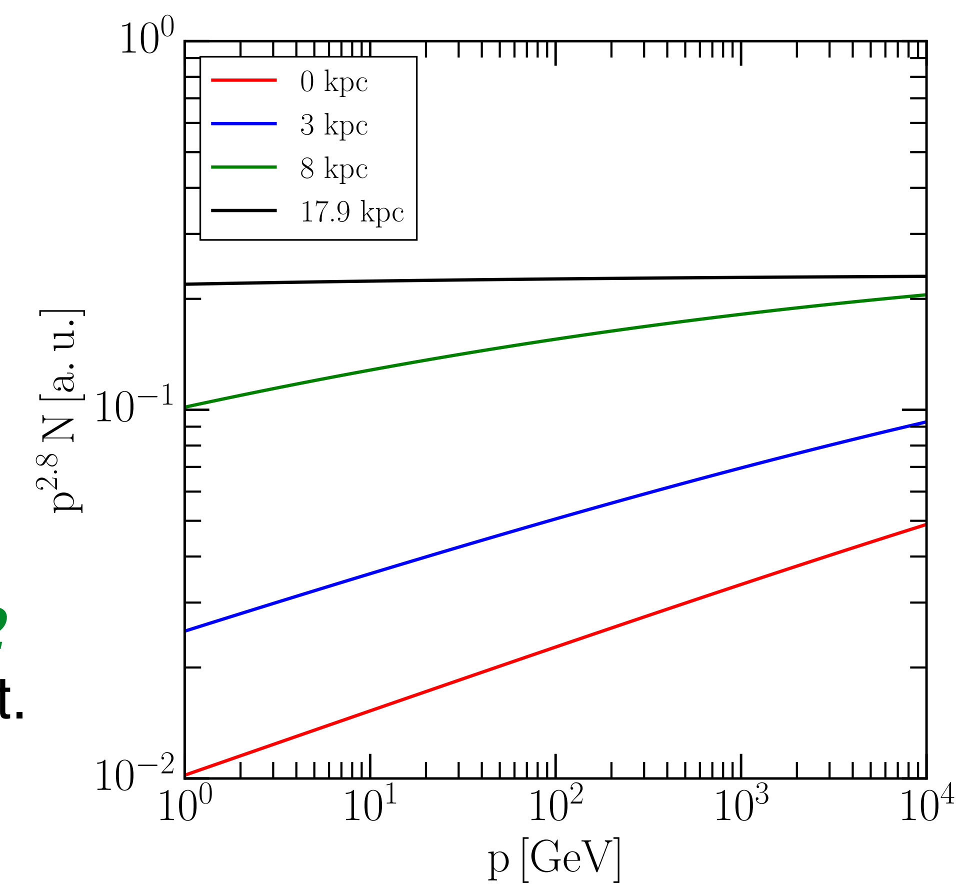
$D_{\parallel} \propto \rho^{1/3}$ $D_{\parallel} \propto \rho^{1/2}$ for Kolmogorov turbulence

While for azimuthal fields only $D_{\perp}$ matters, in the presence of vertical components $D_{\parallel}$ also play a role.



Jansson & Farrar ApJ 2012
based on Faraday rotation cat.

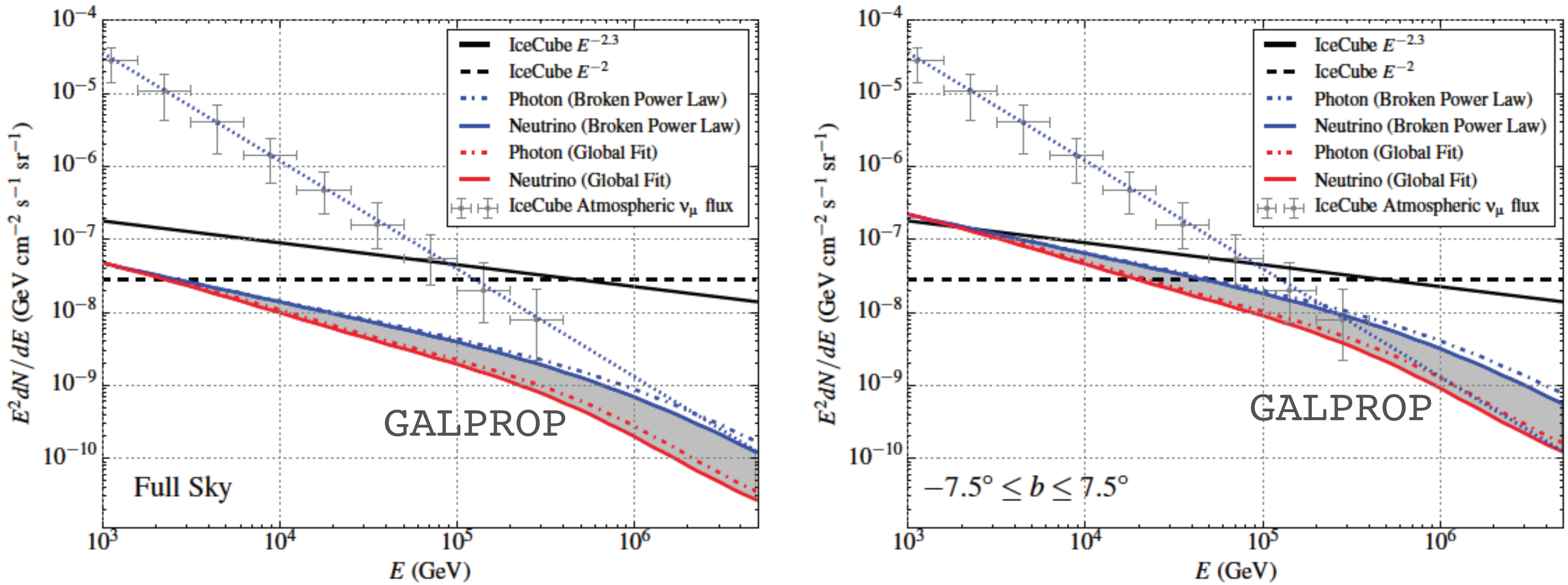




What all this implies for neutrinos ?

The Galactic ν emission with conventional models

Ahlers et al. arXiV:1505.03156

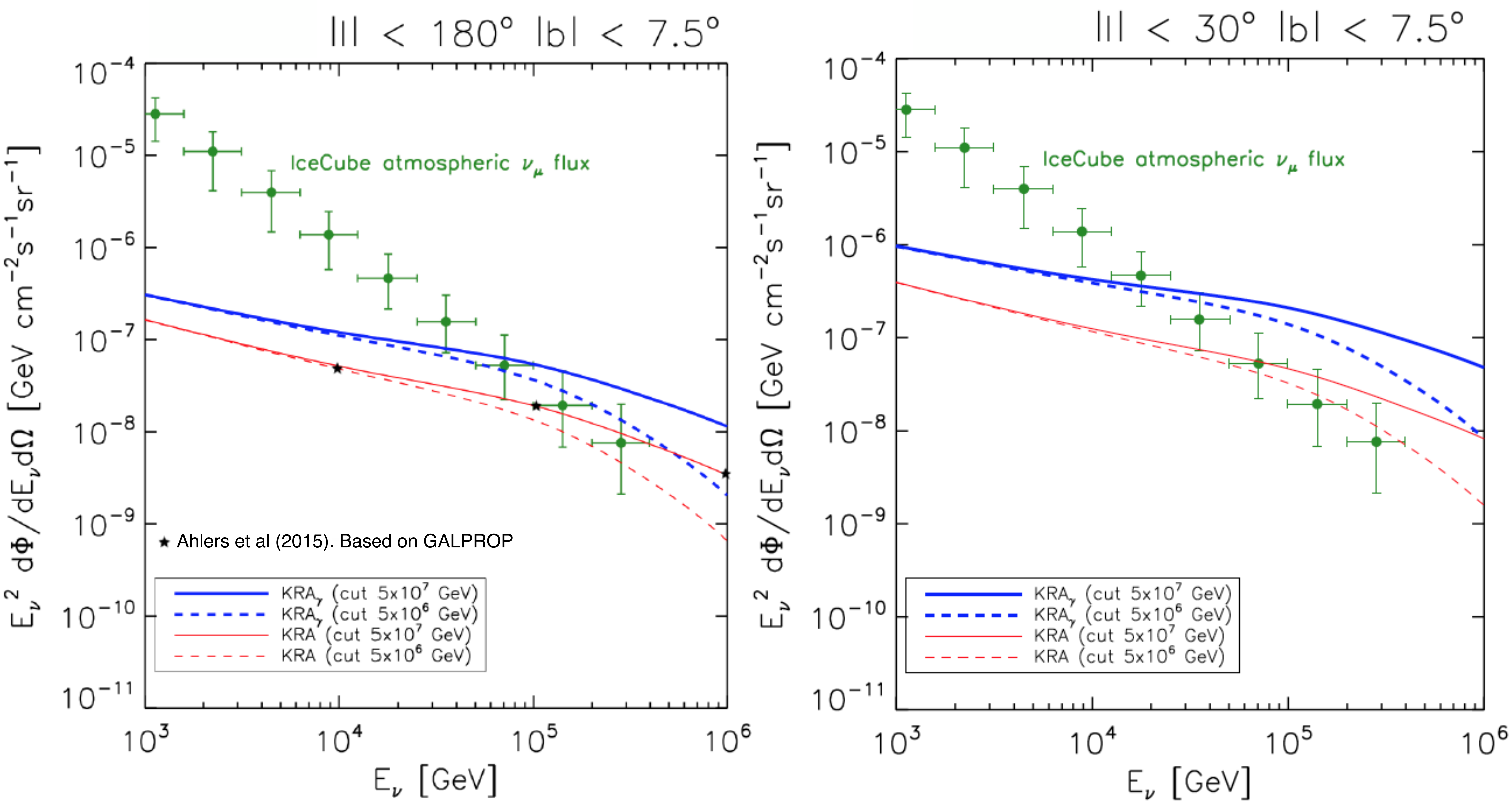


8% of IceCube HESE (2013) signal at most

- based on GALPROP
- it **adopts harder CR spectra above 250 GeV/n so to match CREAM**
- it adopts phenomenological models for CR spectra in the knee region (two different models: broken power-law and Gaisser et al.)

Galactic Plane neutrinos with a variable δ

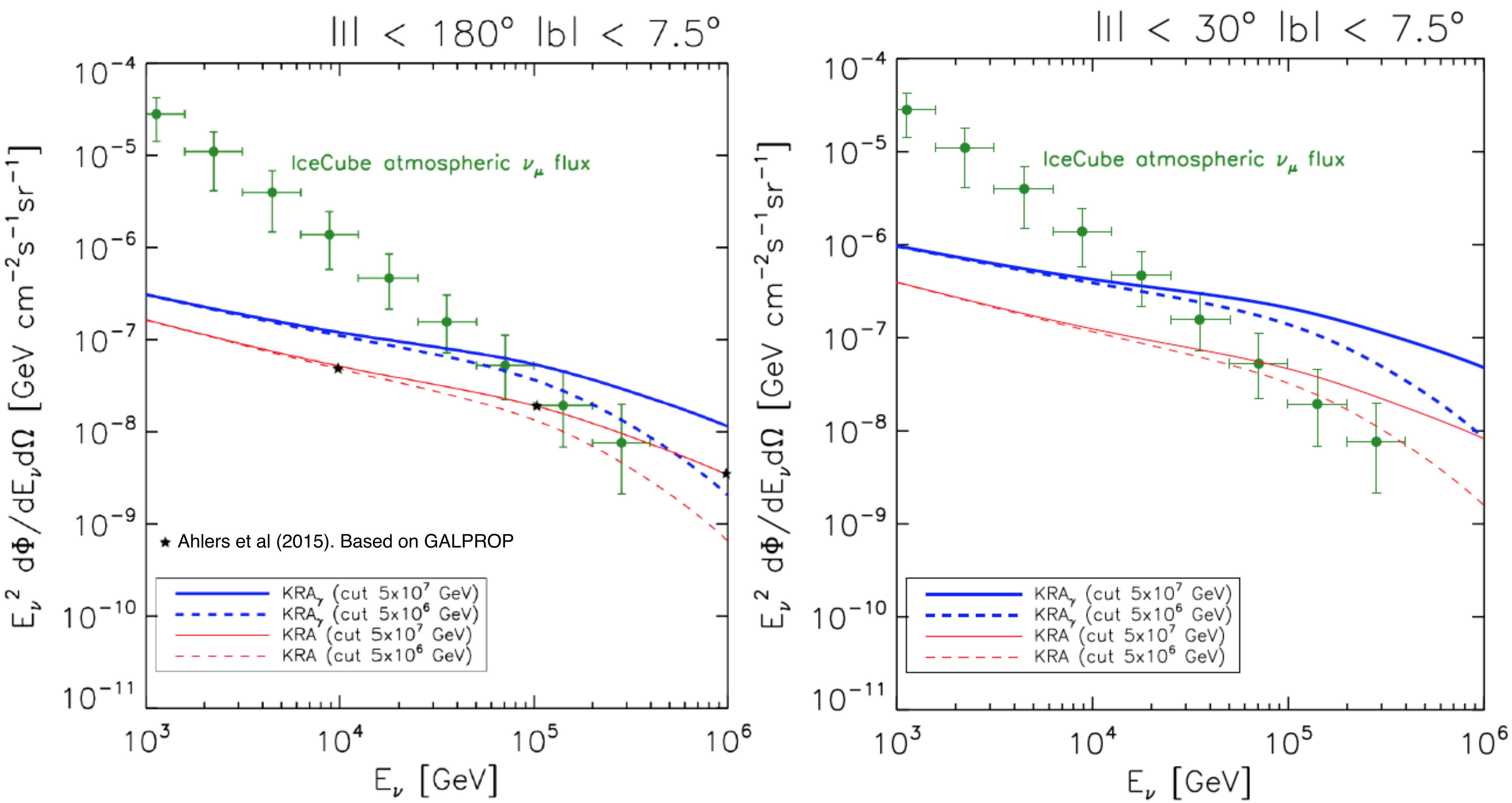
Gaggero, DG, Marinelli, Urbano &Valli arXiV: 1505:03156



- based on DRAGON (KRAγ model, the same which matches FERMI and Milagro)
- it **adopts harder CR spectra above 250 GeV/n so to match CREAM**
- it adopts phenomenological models for CR spectra in the knee region [two exponential cutoff at E/Z = 5, 50 PeV (dashed, solid lines)]

Galactic Plane neutrinos with a variable δ

Gaggero, DG, Marinelli, Urbano & Valli arXiV: 1505:03156



This may account for ~ 15 % of ν astrophysical flux measured by IceCube full-sky above 60 TeV (3 years HESE)

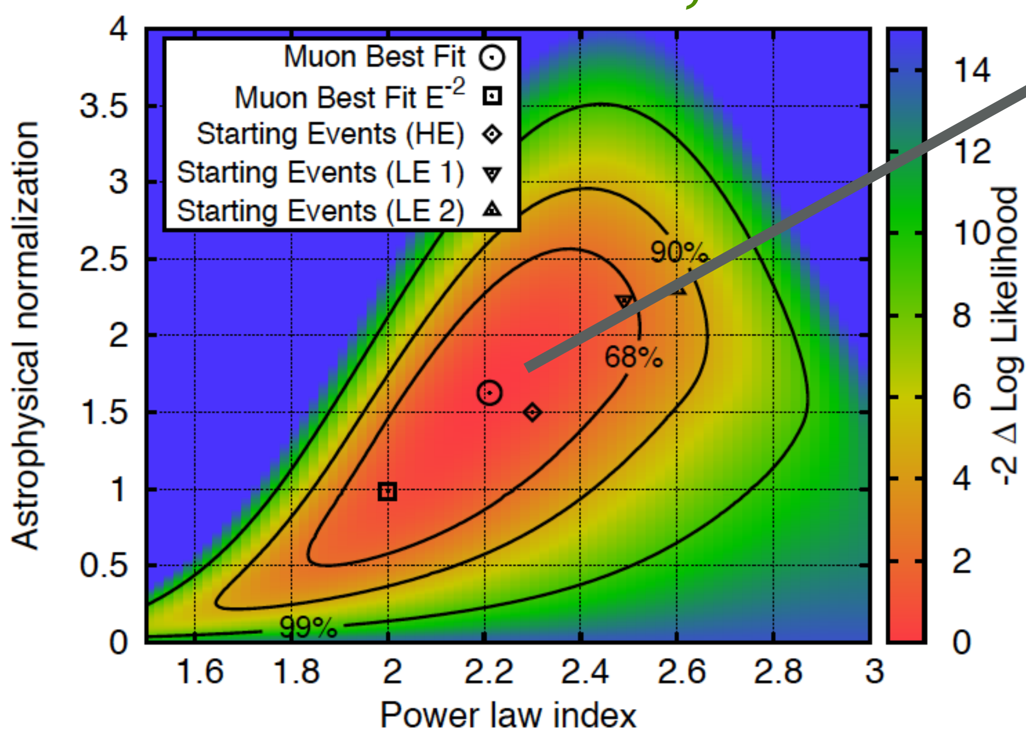
A larger fraction is expected along the Galactic plane

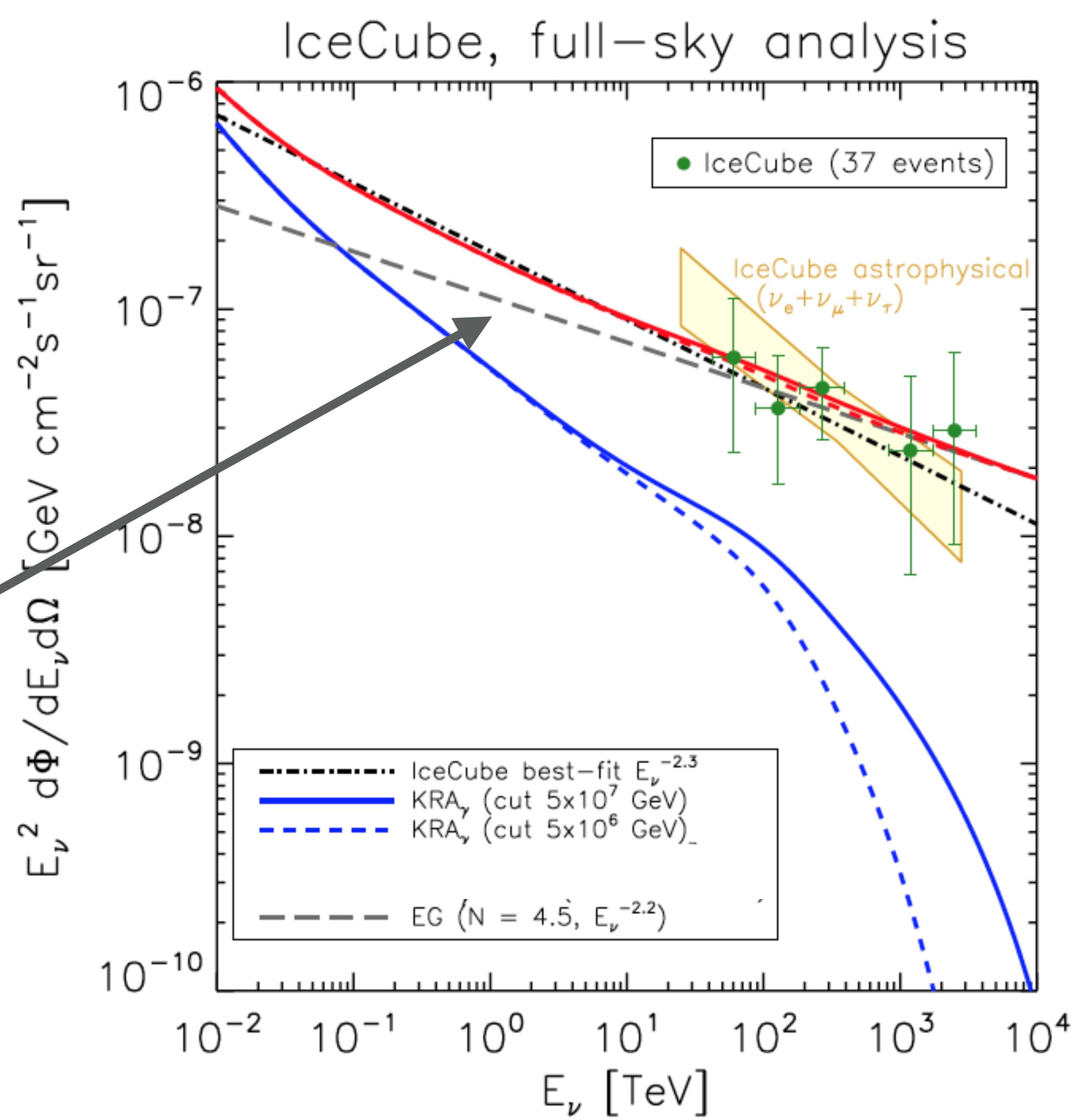
G+EG emission in the GP constrained by IceCube

For illustrative purposes

here we assume the ν_μ (tracks) flux (best-fit) measured by IceCube from the northern hemisphere to be representative of the extra-Galactic emission

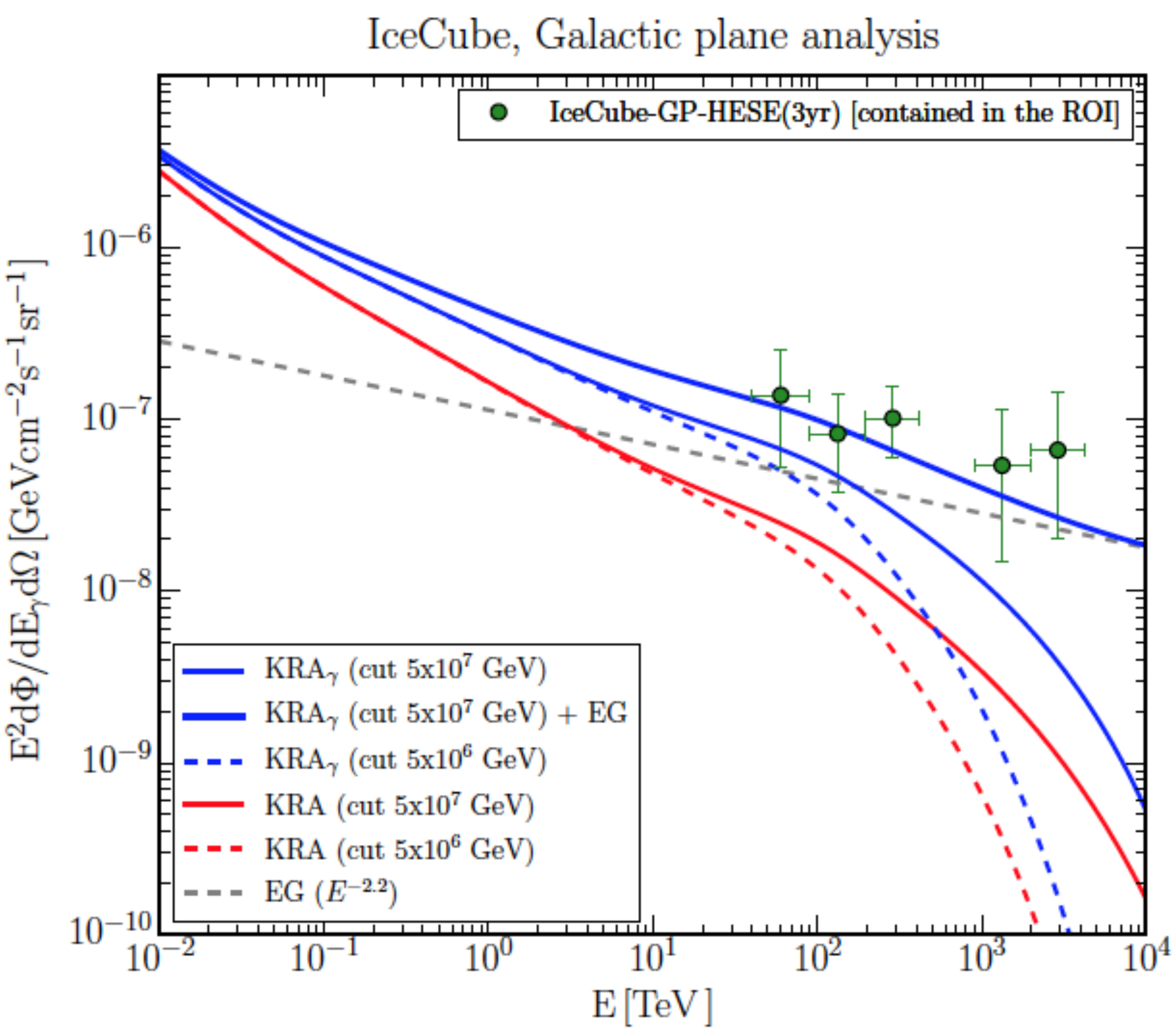
IceCube coll., PRL 2015

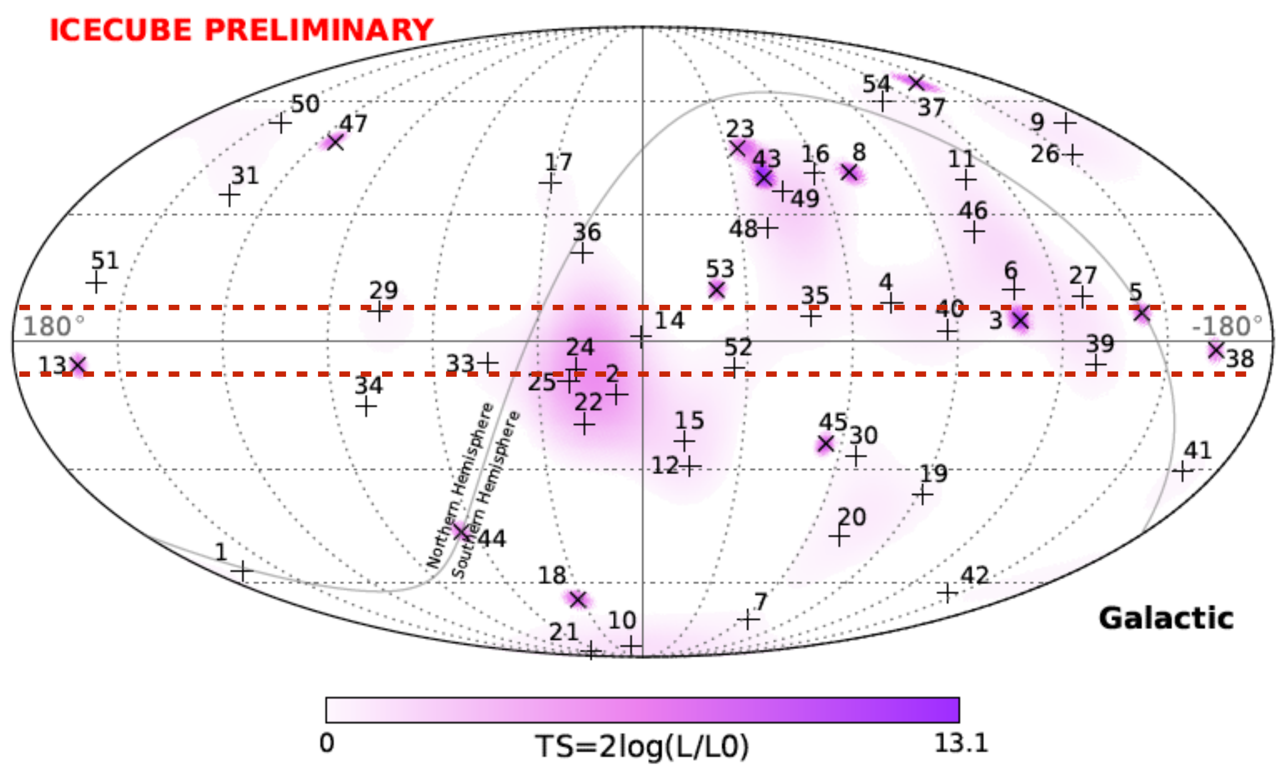




G+EG emission in the GP constrained by IceCube

Gaggero, DG, Marinelli, Urbano, Valli VLVNT2015

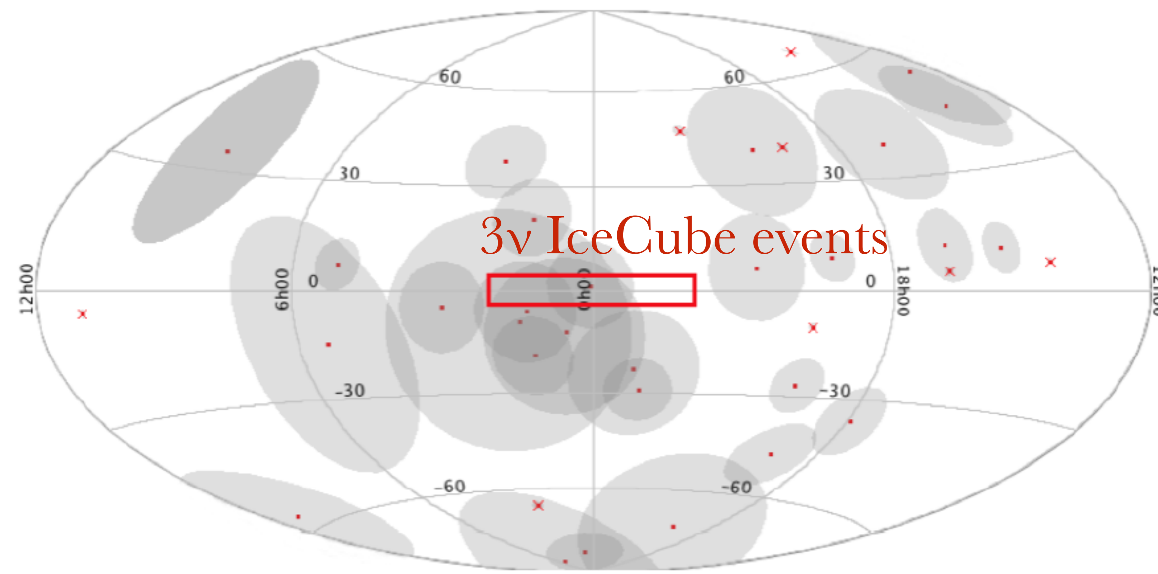




For the whole galactic plane with |b| < 7.5 half of astrophysical flux can be explained with KRA$_\gamma$ and the other half with EG best fit analysis. The IceCube spectrum is obtained considering the **contained events** for this region.

Comparison with exp. data in the inner GP

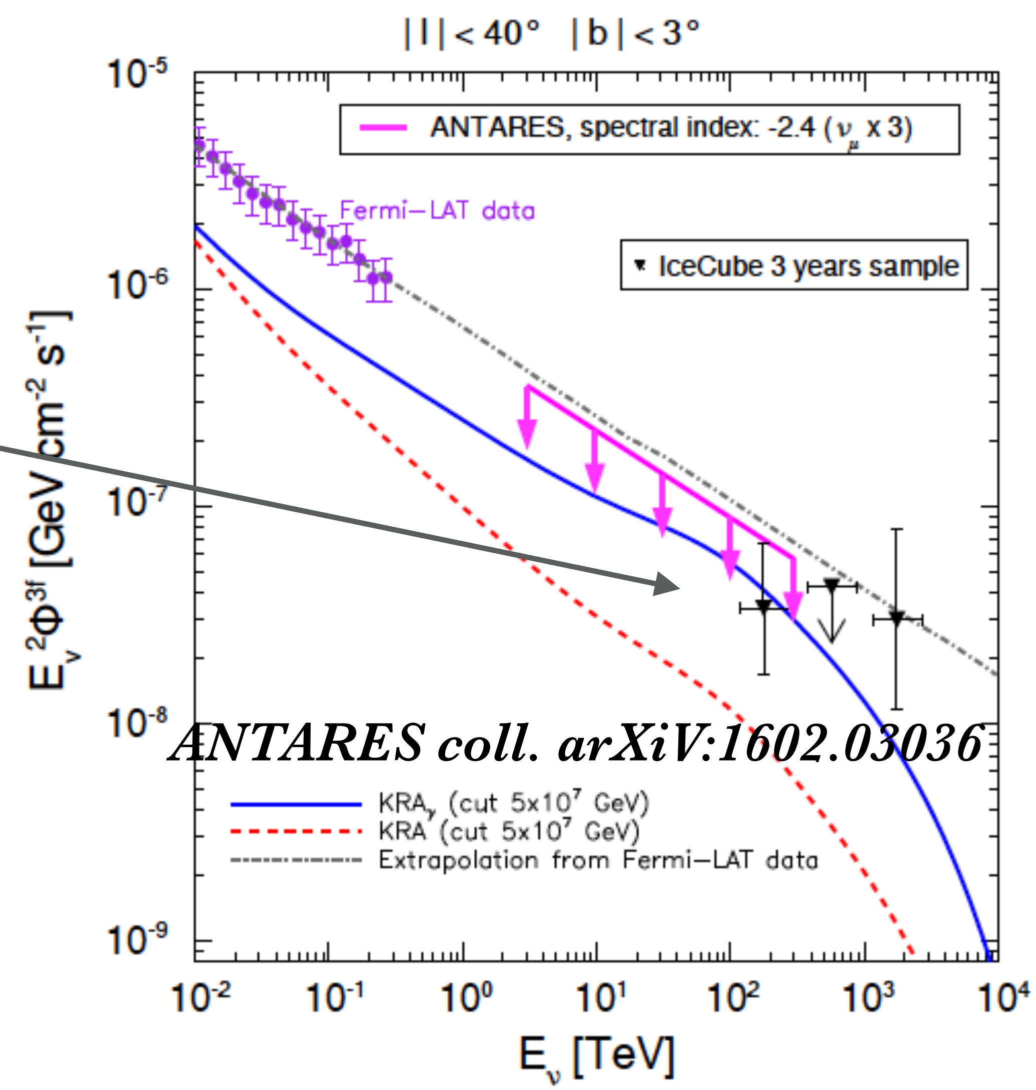
ANTARES coll. arXiV:1602.03036
Marinelli et al. ICRC 2015



2007-2013 ν_μ data E > 1 TeV
no astrophysical excess found in the sky region |b|<4° and |l|<30° which turns into an upper limit (in the fig. Γ = 2.5 is assumed)

- 3 IceCube (shower-like) events are reconstructed to be compatible with the same region . This turns in a maximal flux in that region

- From the neutrino spectra obtained with KRA and KRA$_\gamma$ models we can estimate the galactic component of the IceCube observation in this region of the sky.



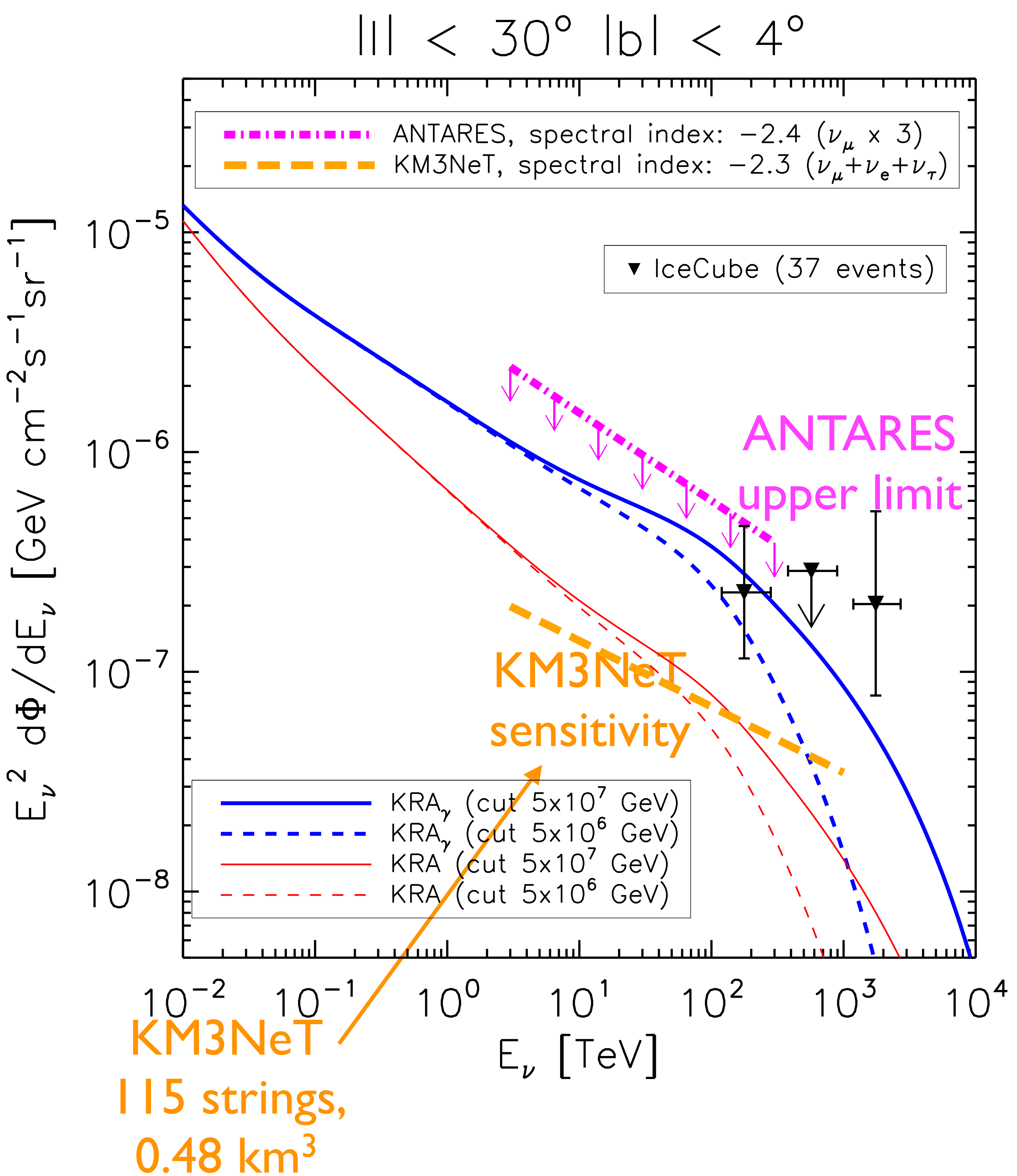
Comparison with exp. data in the inner GP

ANTARES coll. arXiV:1602.03036
Marinelli et al. ICRC 2015

2007-2013 ν_μ data E > 1 TeV
no astrophysical excess found in the sky region |b|<4° and |l|<30° which turns into an upper limit (in the fig. Γ = 2.5 is assumed)

- 3 IceCube (shower-like) events are reconstructed to be compatible with the same region . This turns in a maximal flux in that region

- From the neutrino spectra obtained with KRA and KRA$_\gamma$ models we can estimate the galactic component of the IceCube observation in this region of the sky.

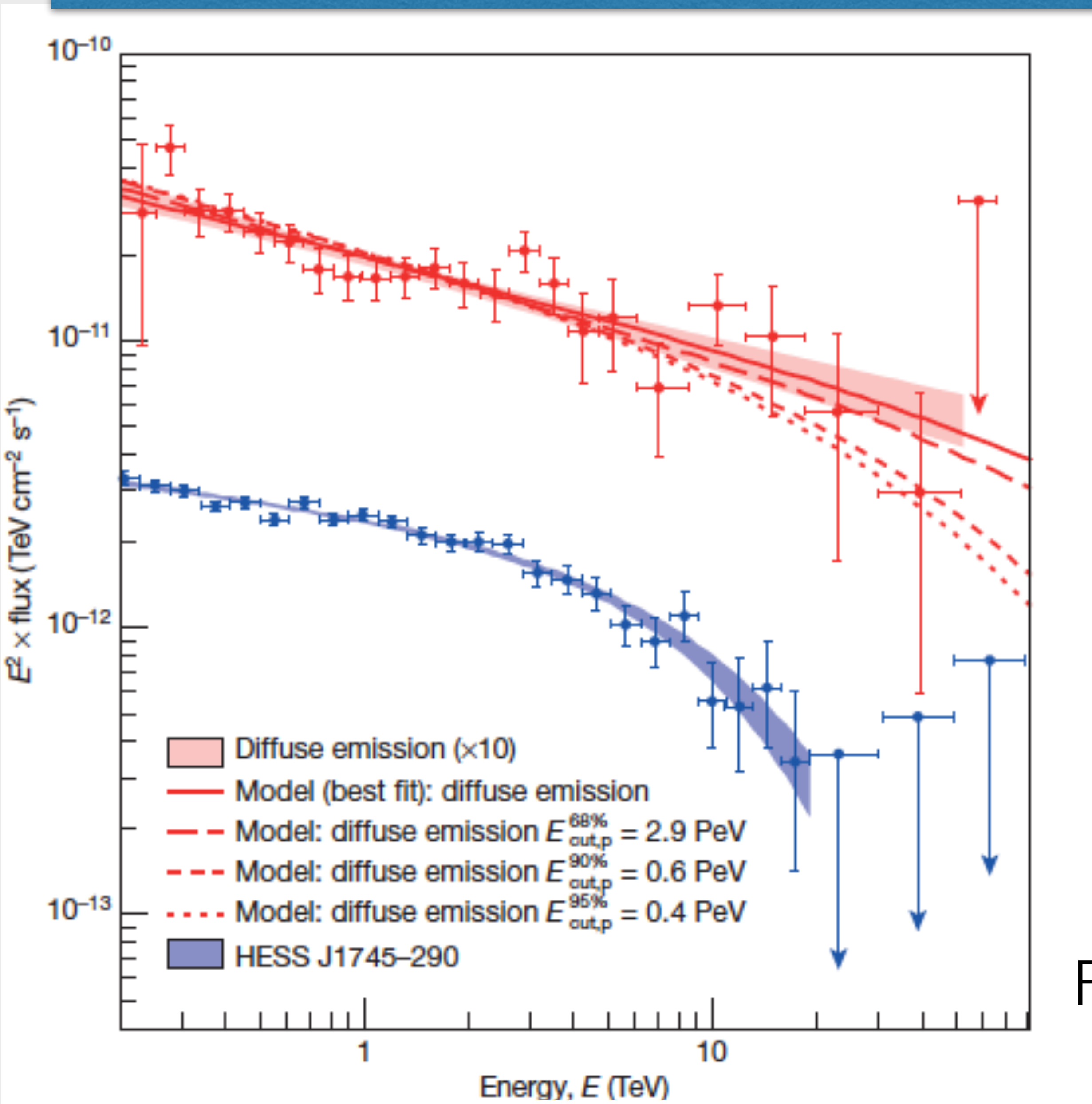


Conclusions

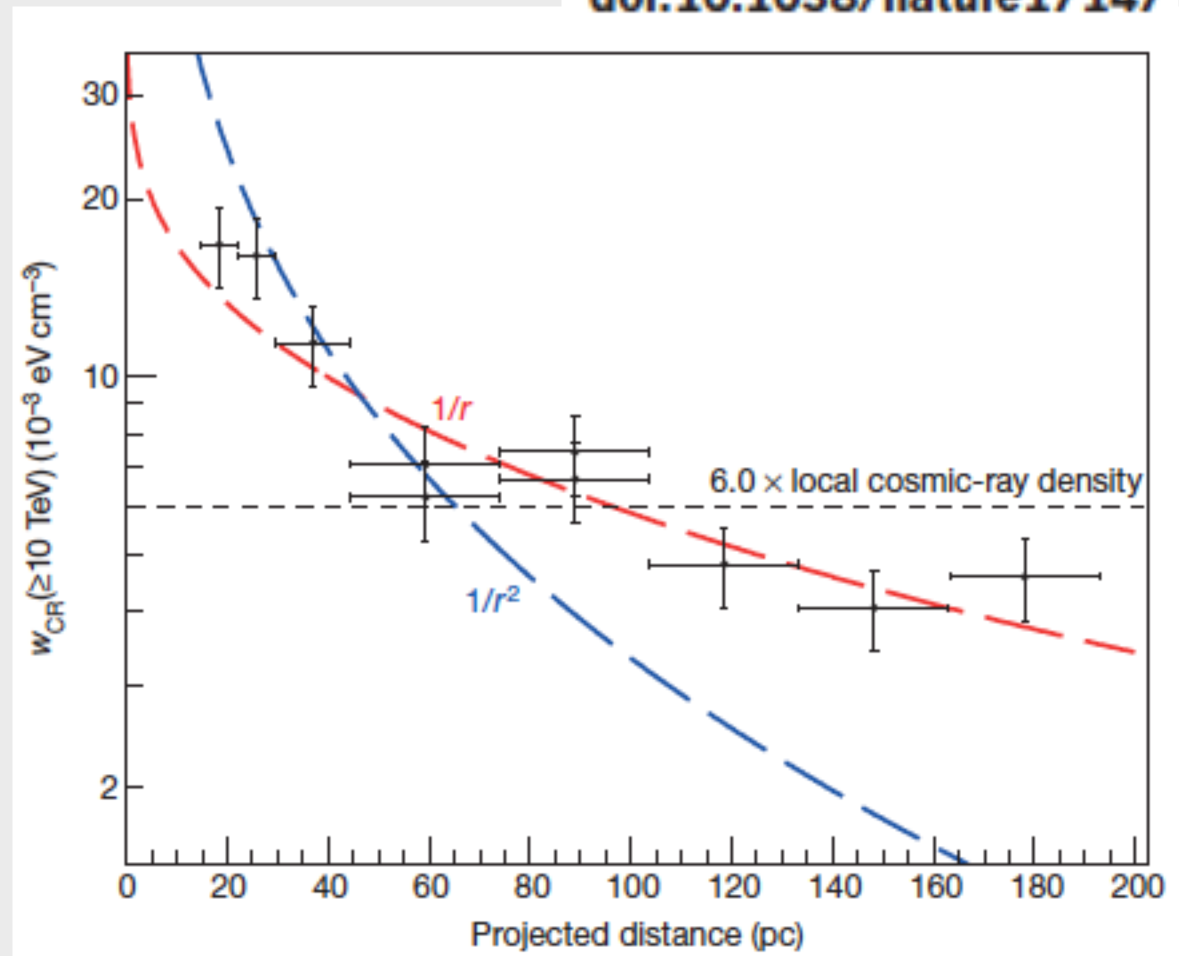
- High energy γ-ray data in the inner Galactic plane require to introduce new physics in the CR transport models. A consistent interpretation of most updated results seems possible in terms of spatial dependent diffusion.
- Respect to conventional models this scenario predicts a significantly larger Galactic neutrino flux along the inner Galactic plane which is testable by IceCube (hopefully), ANTARES (marginally) and Km3NeT (definitely).
- A dominant Galactic emission in the Souther hemisphere is unlikely.
- More theoretical work, propagation codes upgrading (DRAGON is already at the forefront), more γ-ray data (HAWC (sud ?), LHAASO, CTA ..)

Backup slides

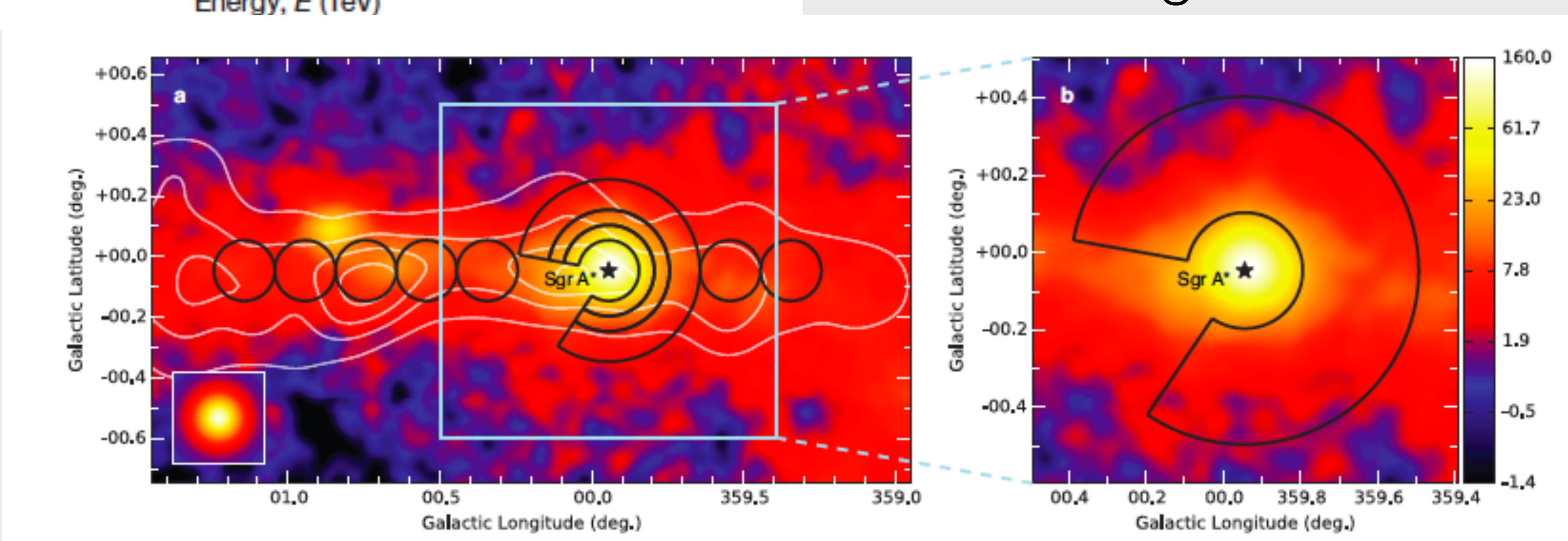
The case of the Pevatron observed by HESS



doi:10.1038/nature17147



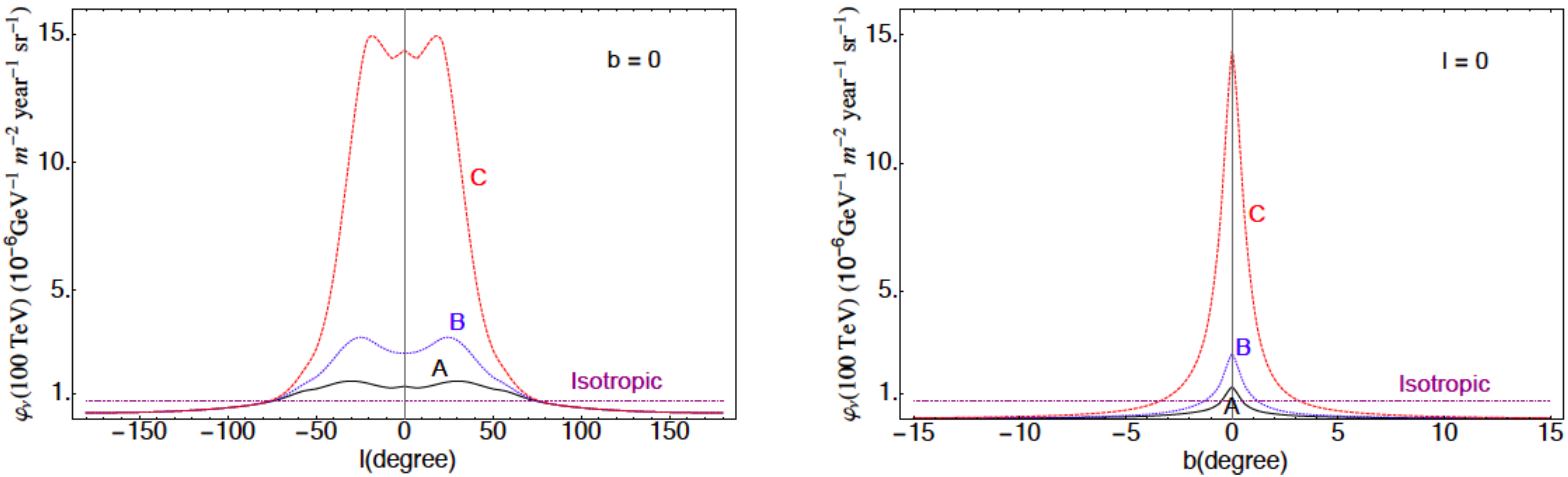
First Pevatron observed in gamma-ray from a diffuse region close to Sagittarius A



Galactic Plane neutrino with an analytical model with δ variable

Pagliaroli, Evoli & Villante arXiV:1606.04489

ν flux at 100 TeV



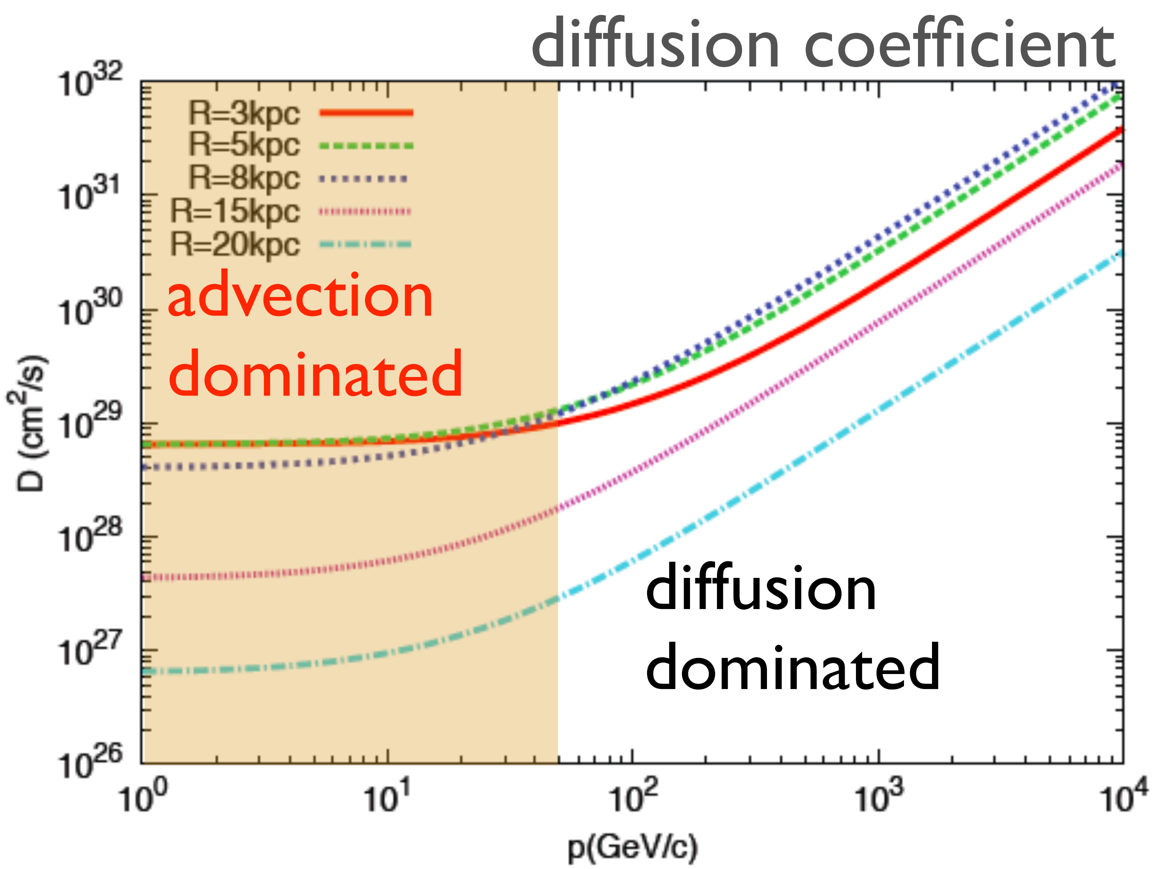
- A : uniform CR density — 5 % Gal. contribution to IC HESE E > 100 TeV
- B : CR density profile proportional to SNR — 7 % " "
- C : CR spectrum changing with R — 13 % " "

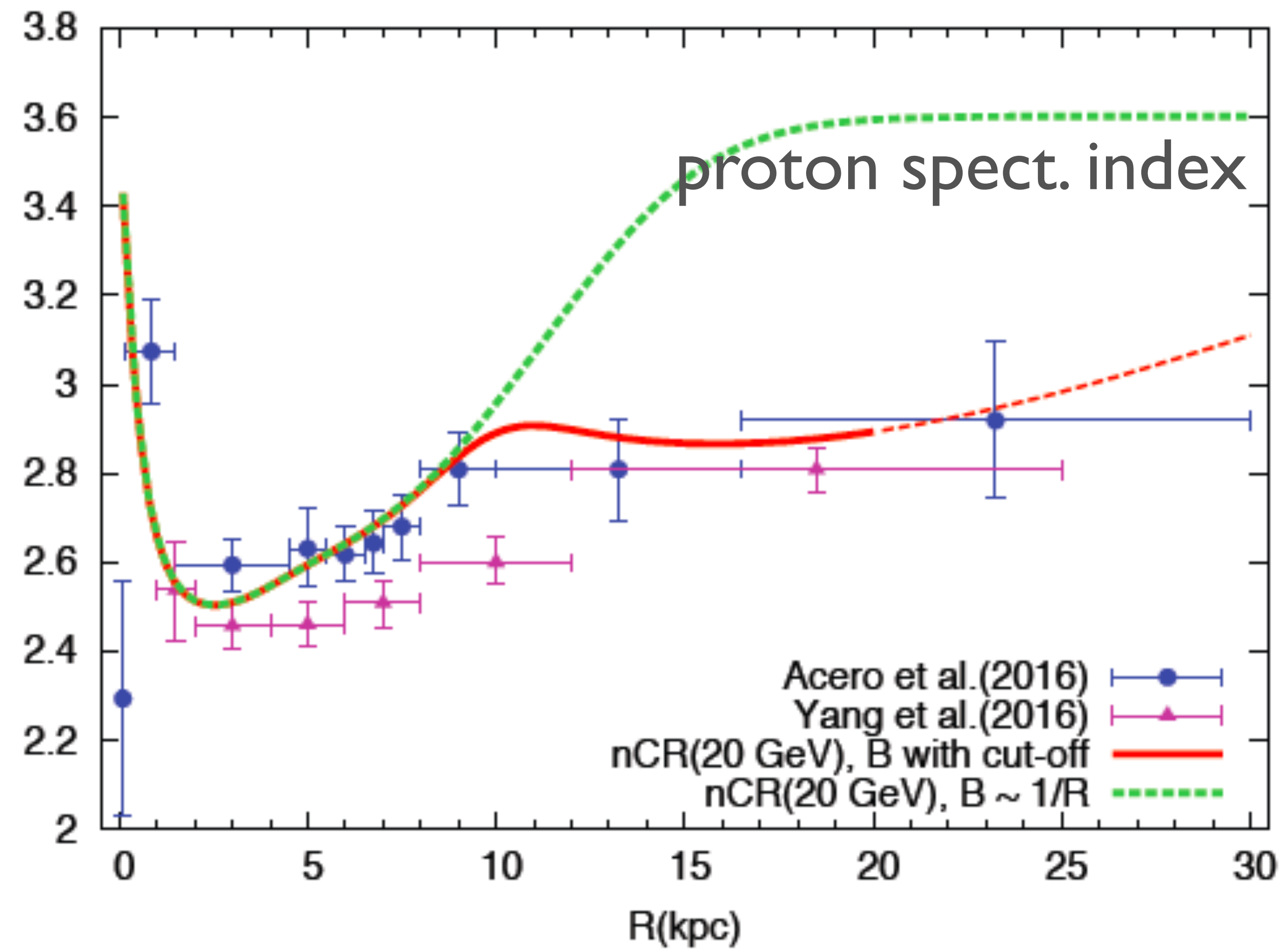
correction to CR density

$$h(E,\mathbf{r}) = \left(\frac{E}{\overline{E}}\right)^{\Delta(\mathbf{r})} \qquad \Delta(r,z) = 0.3\left(1 - \frac{r}{r_\odot}\right)$$

The case for a spatial dependent δ
Is it due to non-linear CR transport ?

Recchia, Blasi & Morlino arXiv:1604.07682





- CR advect/diffuse in self-generated Alfvén-waves below/above ~ 50 GeV
- harder CR (hence γ-ray) spectrum if advection dominate
- the effect is larger in the inner Galaxy, larger D ➞ larger p at which diffusion dominate

<u>This mechanism however should be absent at large energies</u>

which seems to be at odd with Fermi data and Milagro anomaly (HAWC may soon confirm !)

The DRAGON code

DRAGON: **D**iffusion **R**eacceleration and **A**dvection of **G**alactic cosmic rays: an **O**pen **N**ew code

Evoli, Gaggero, DG, Maccione *http://www.dragonproject.org*

The project started in 2008, more than 20 peer reviewed papers based on this code. The present version use (among other options) the same nuclear cross sections and gas distribution as in GALPROP
Main innovative features respect to previous codes:

- 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
- it allows anisotropic diffusion (2D) $D_\perp \neq D_\parallel$

See also the PICARD project: http://astro-staff.uibk.ac.at/~kissmrbu/Picard.html

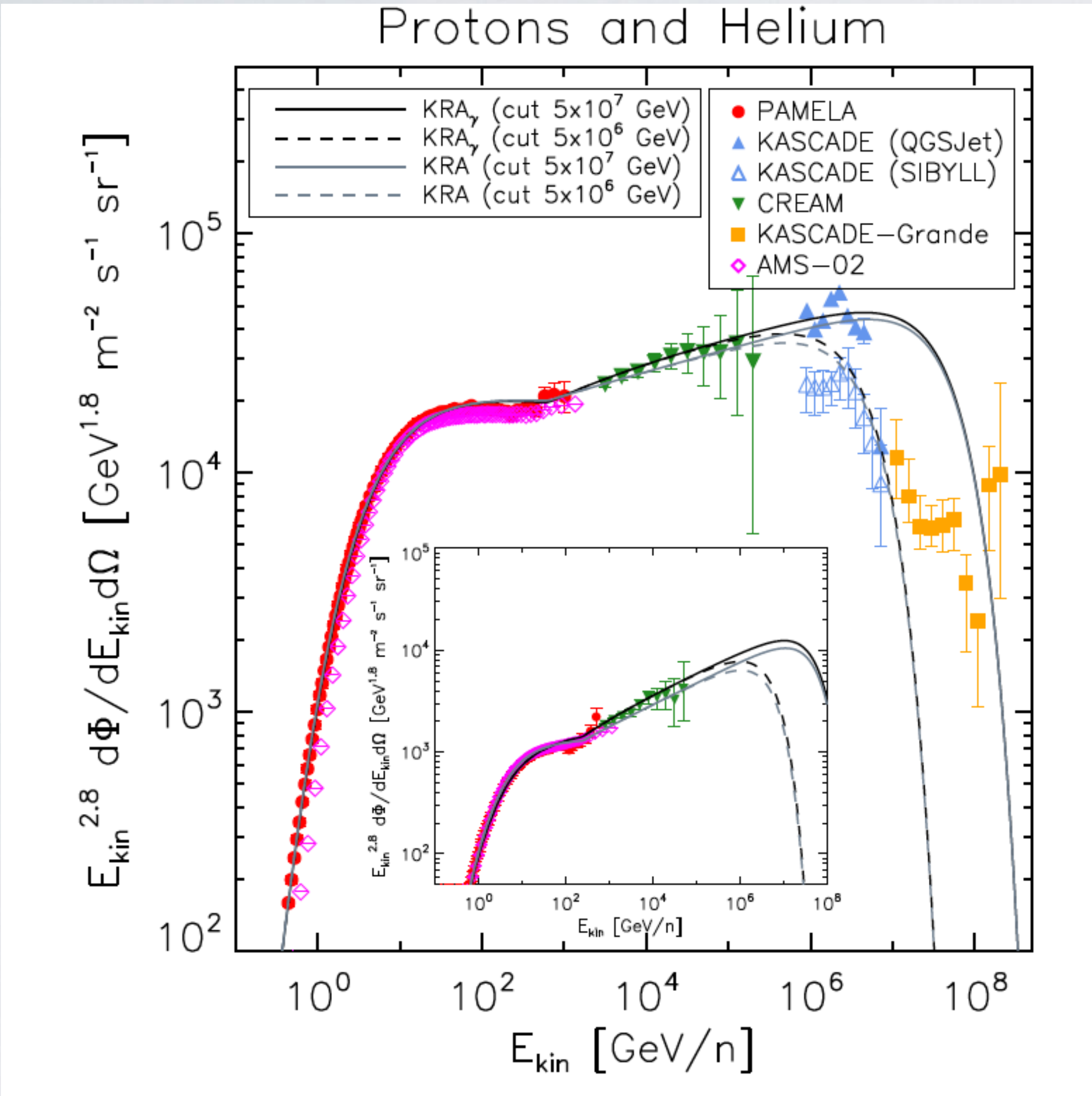
The DRAGON code

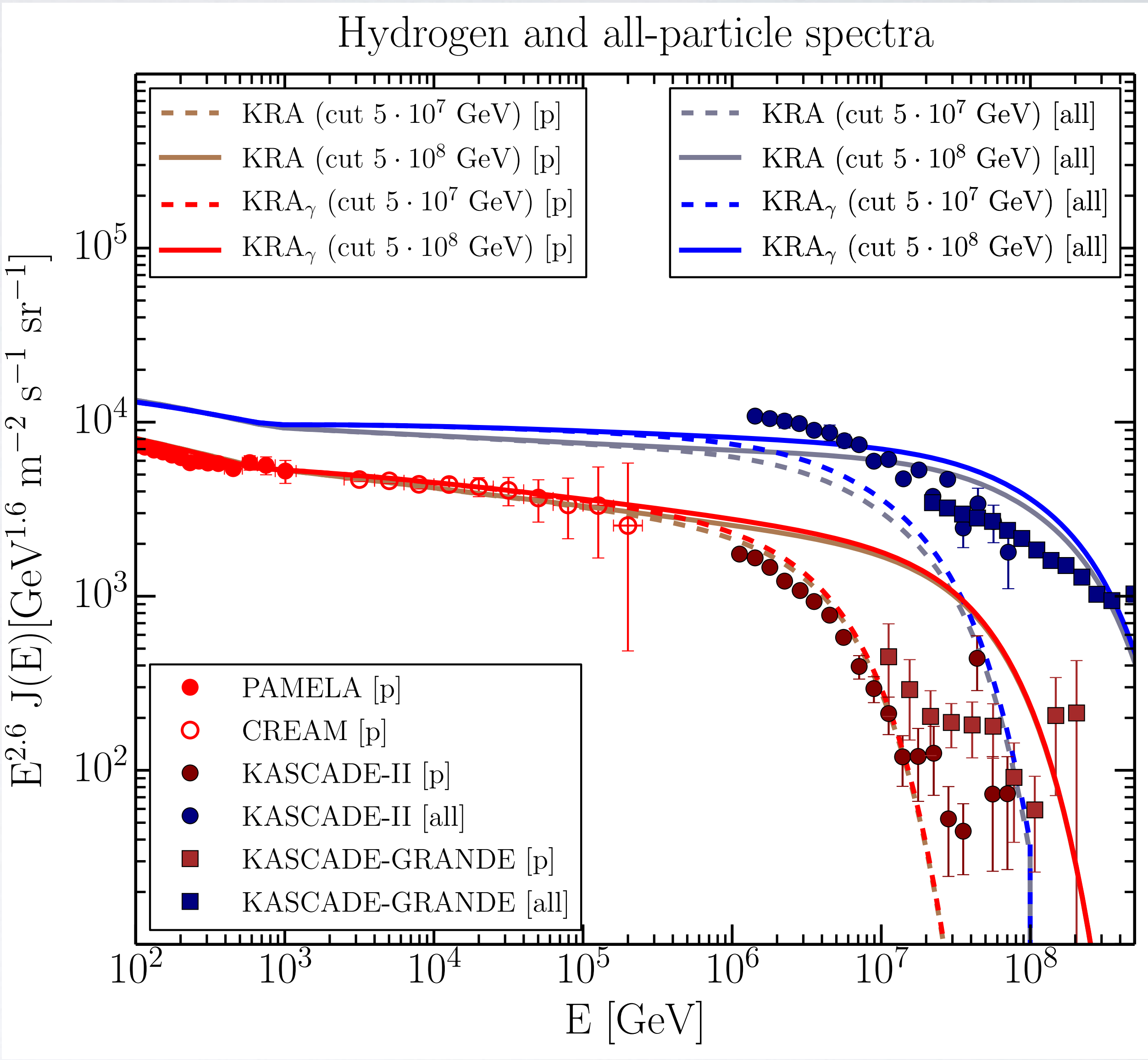
A new version: DRAGON 2
Evoli, Gaggero, Vittino, Di Bernardo, Di Mauro, Ligorini & DG

- updated spallation cross section based on Fluka (see *Mazziotta et al. 1510.04623, ApJ 2016*)
- many update in the solver, with significant improvements in the implementation of energy losses, advection and reacceleration
- non-equidistant spatial binning (to better probe local bubble, Gal. center, …) and the possibility to model transient sources
- anisotropic diffusion in 3D

<u>will soon be released</u>. For details on the solver and astrophysical ingredients see arXiv:1607.07886

Our CR primary spectra





Comparison with other high energy γ-ray data