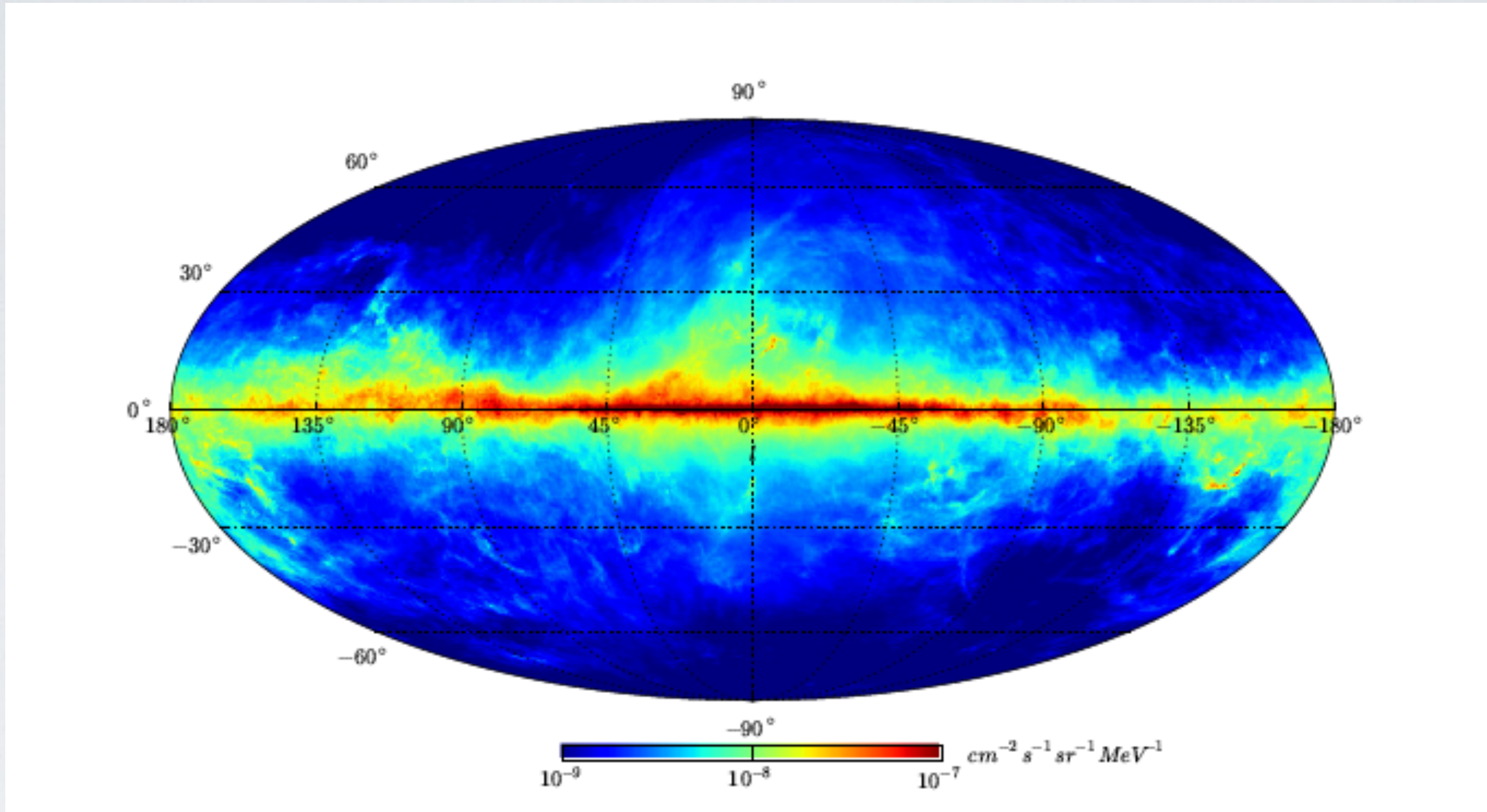
Gamma-ray and neutrino diffuse emission of the Galaxy at very high energies

Dario Grasso (INFN, Pisa)

CRIS 2016

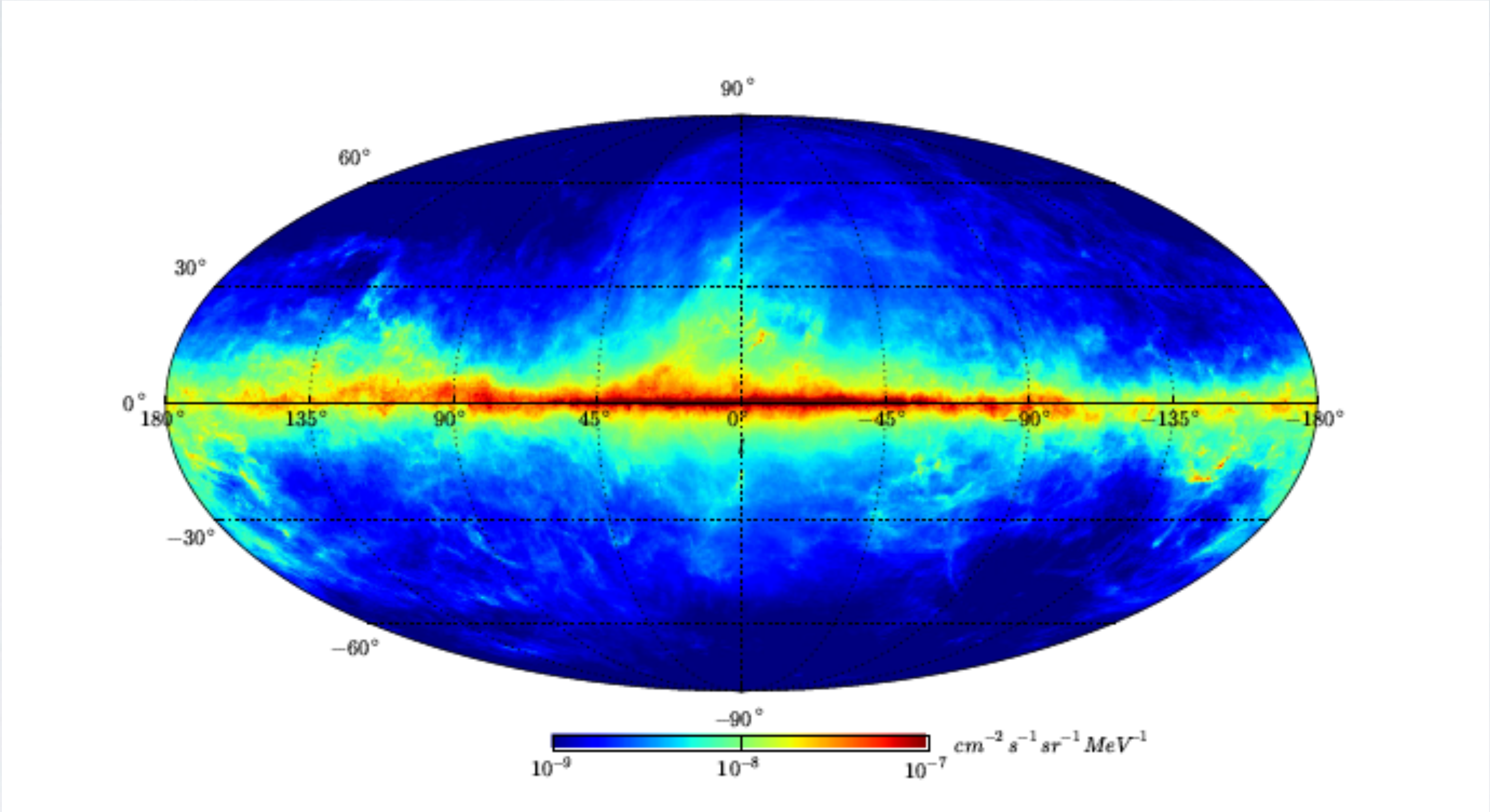
The γ-ray diffuse emission of the Galaxy



$p(He)_{RC} + p\ (He)_{ISM} \rightarrow \ \ldots + \pi_0 \rightarrow \ldots 2\,\gamma$ hadron scattering

- $e_{RC} + \gamma_{ISRF} \rightarrow e + \gamma$ inverse Compton (IC)
- $e_{RC} + A \rightarrow e + A + \gamma$ bremsstrahlung

The γ-ray (and ν) diffuse emission of the Galaxy



- $p(He)_{RC} + p\,(He)_{ISM} \rightarrow \ldots + \pi^0 \rightarrow \ldots 2\gamma$ — hadron scattering

  $p(He)_{RC} + p\,(He)_{ISM} \rightarrow \ldots + \pi^{\pm} \rightarrow \ldots \mu^{\pm} + \nu_e + \nu_\mu$

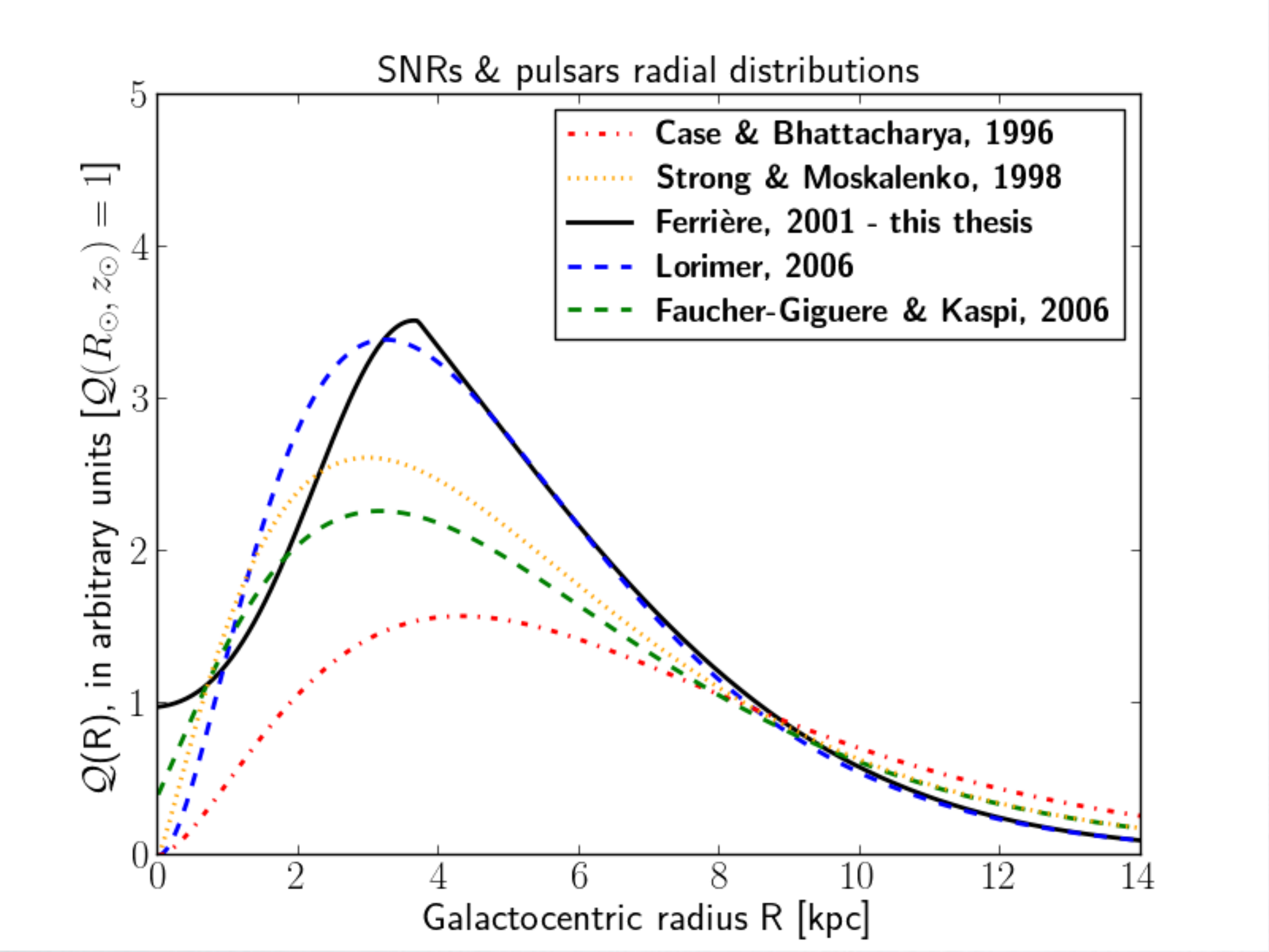
- $e_{RC} + \gamma_{ISRF} \rightarrow e + \gamma$ — inverse Compton (IC)

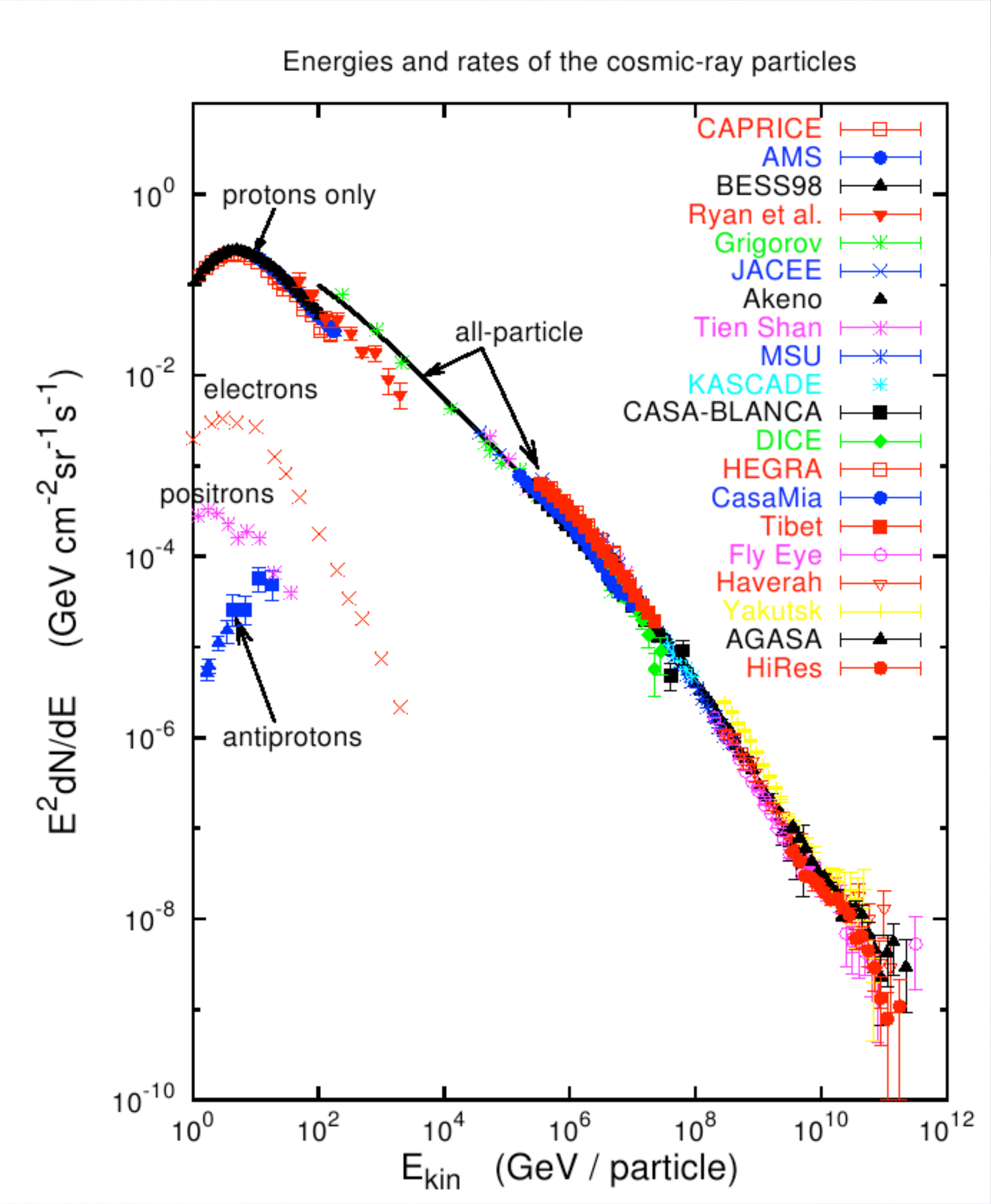
- $e_{RC} + A \rightarrow e + A + \gamma$ — bremsstrahlung

The cosmic ray local population

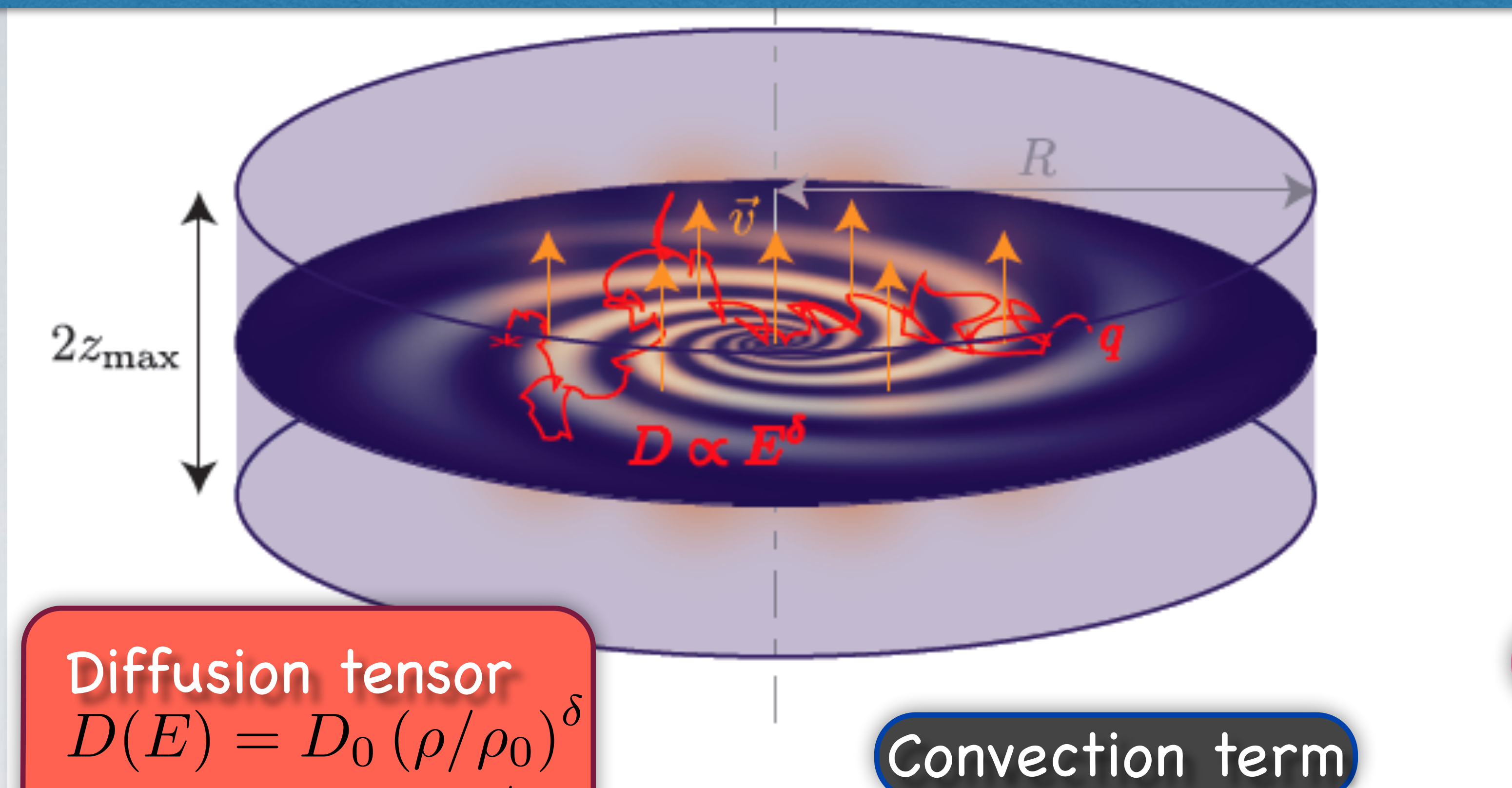
It is not expected to be representative of the entire Galaxy !

Radial distribution of sources





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 !

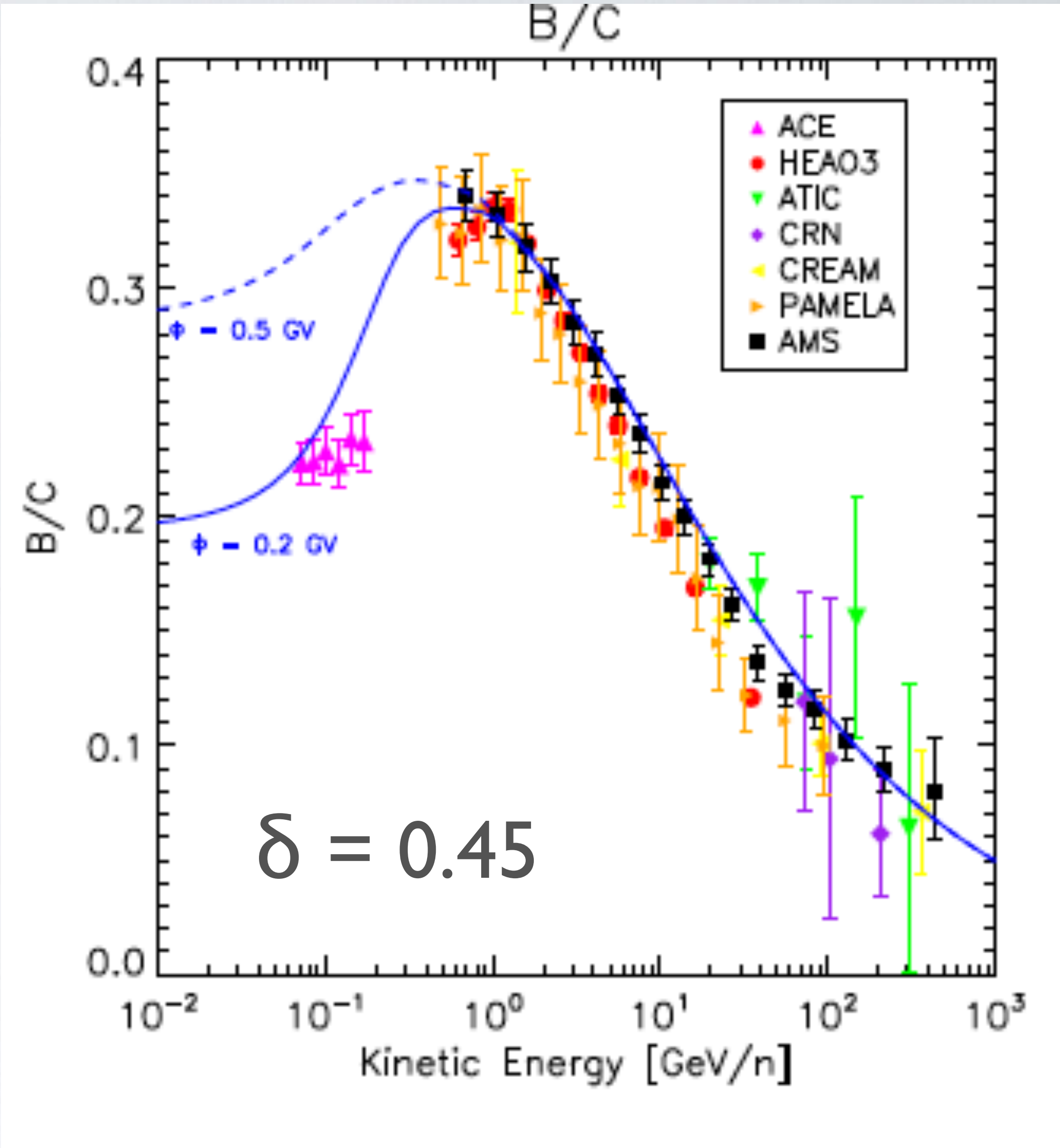
The CR Galactic population

Commonly, propagation parameters are fixed on the basis of local observables

e.g. the diffusion coefficient

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

is fixed on the basis of the secondary/primary CR nuclei ratio (the B/C most importantly) and assumed (for ***conventional models***) to be spatially uniform



warning !!

due to CR vertical escape and nuclear inelastic scattering onto the interstellar gas **secondary nuclei probes only few kpc around us**. Propagation may behave differently in the central region of the Galaxy

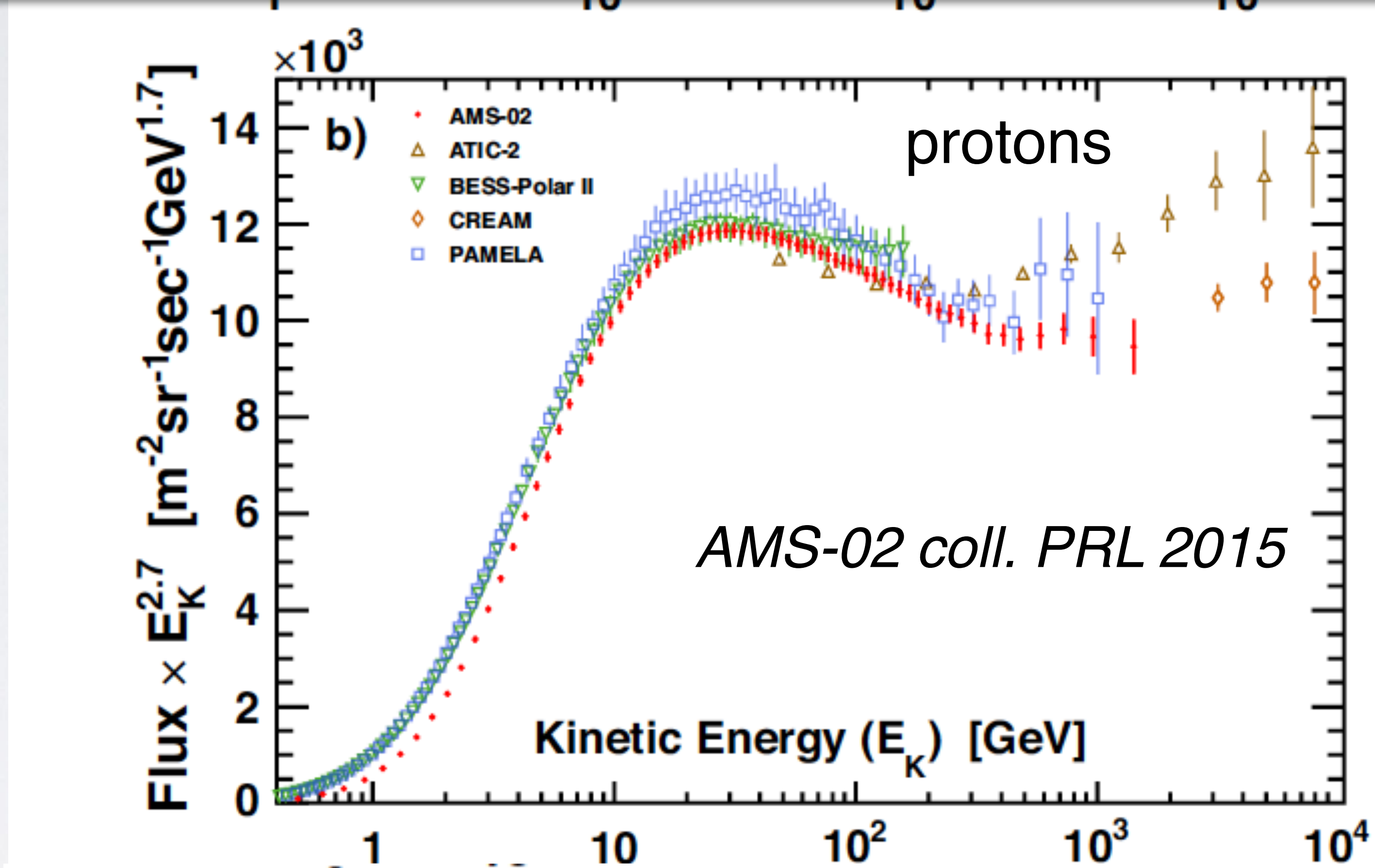
The CR Galactic population: PAMELA anomaly

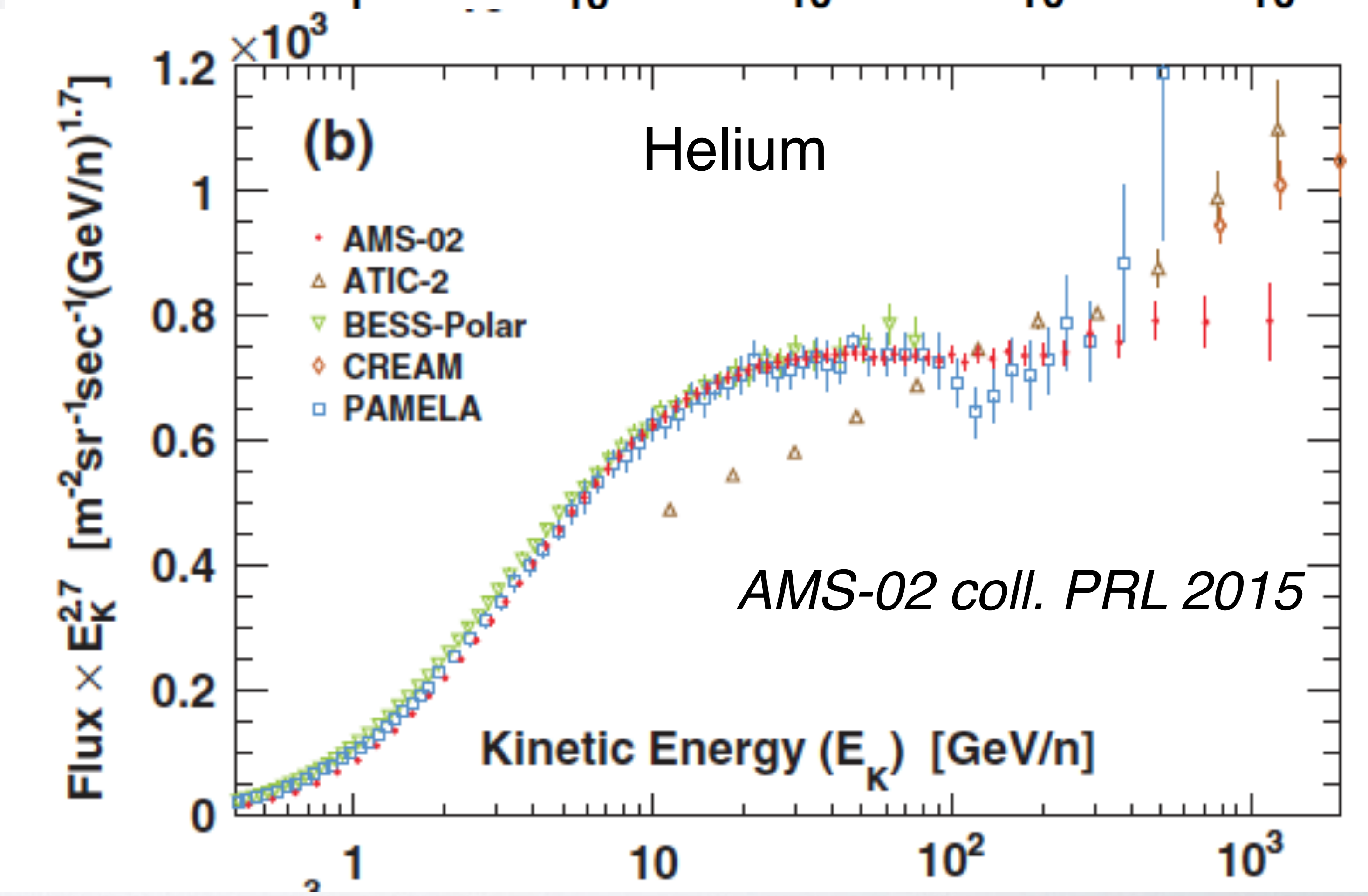
PAMELA (*Science 2011*) found an hardening of the p and He spectra at ~ 250 GeV/n **AMS-02** confirmed the feature (slightly smoother and starting at ~ 300 GeV/n)

This is also required to match **CREAM**

spectral index p/He ≃ -0.077

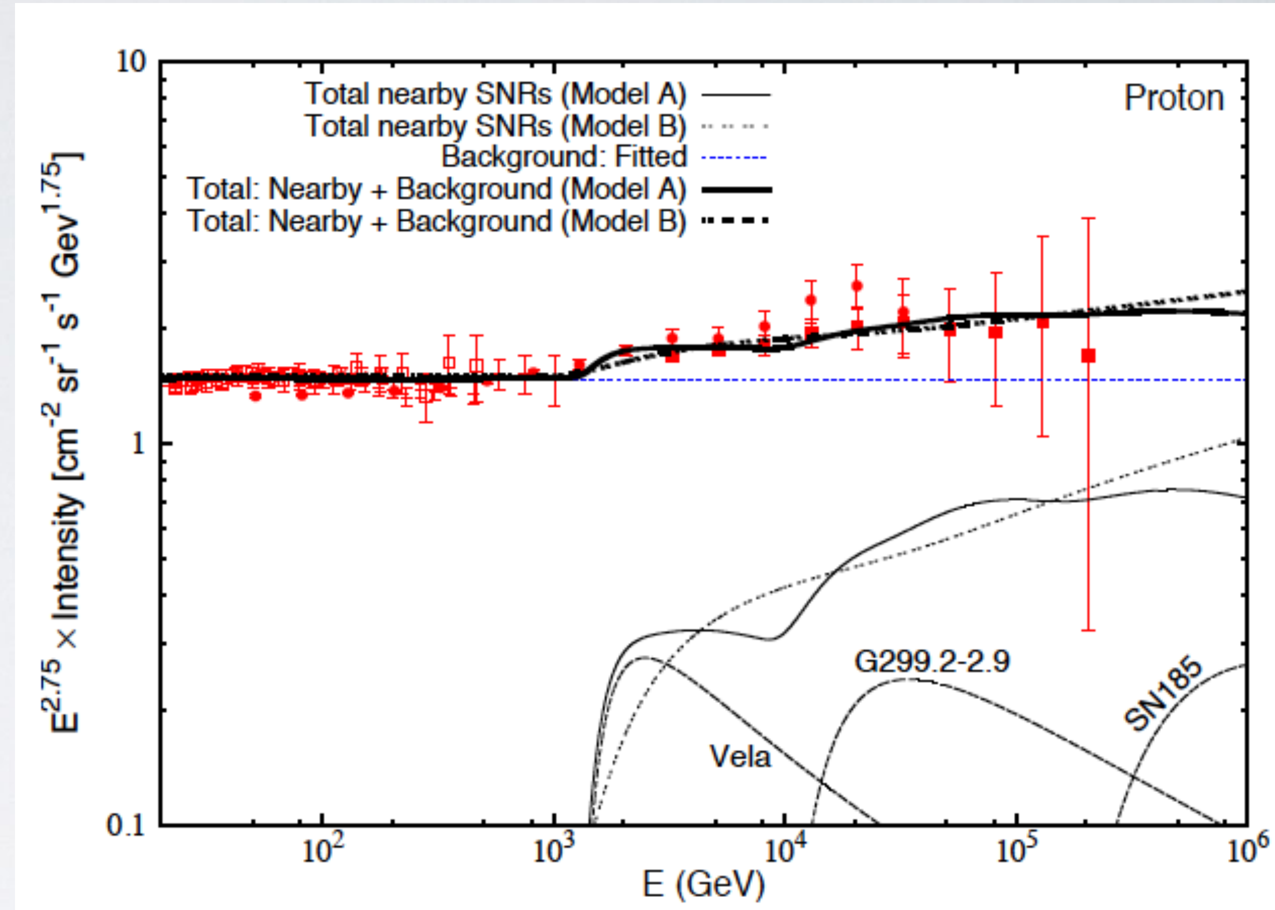
A similar effect is found for heavier nuclei



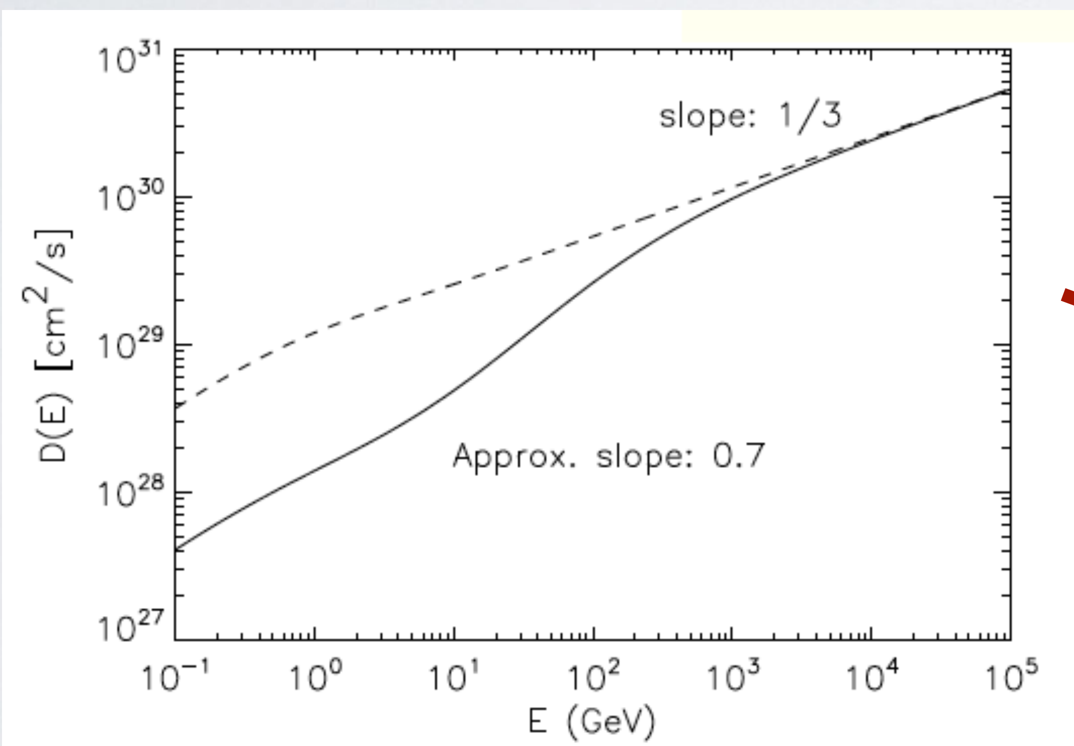


The CR Galactic population: PAMELA anomaly

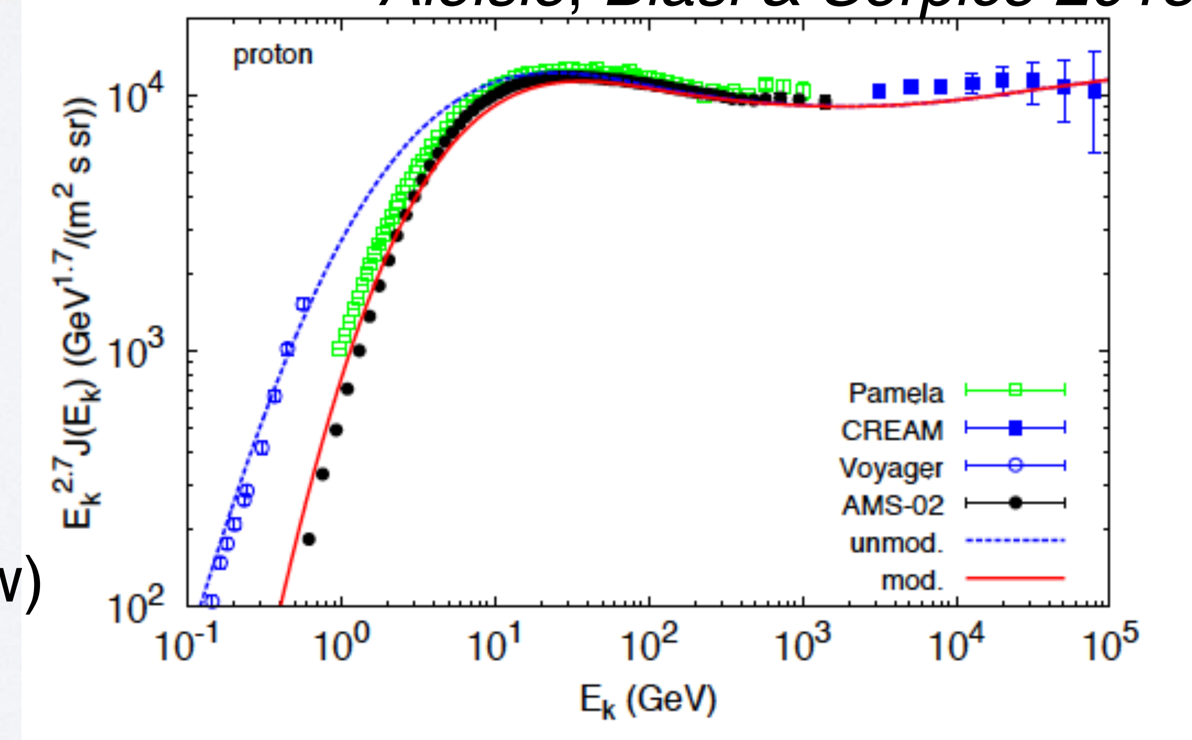
The CR hardening may be a local effect e.g. due to nearby SNR, see e.g. *Thoudam & Hörandel 2011*



or a large scale one due to propagation see e.g. *Blasi, Amato & Serpico 2012*)



Aloisio, Blasi & Serpico 2015



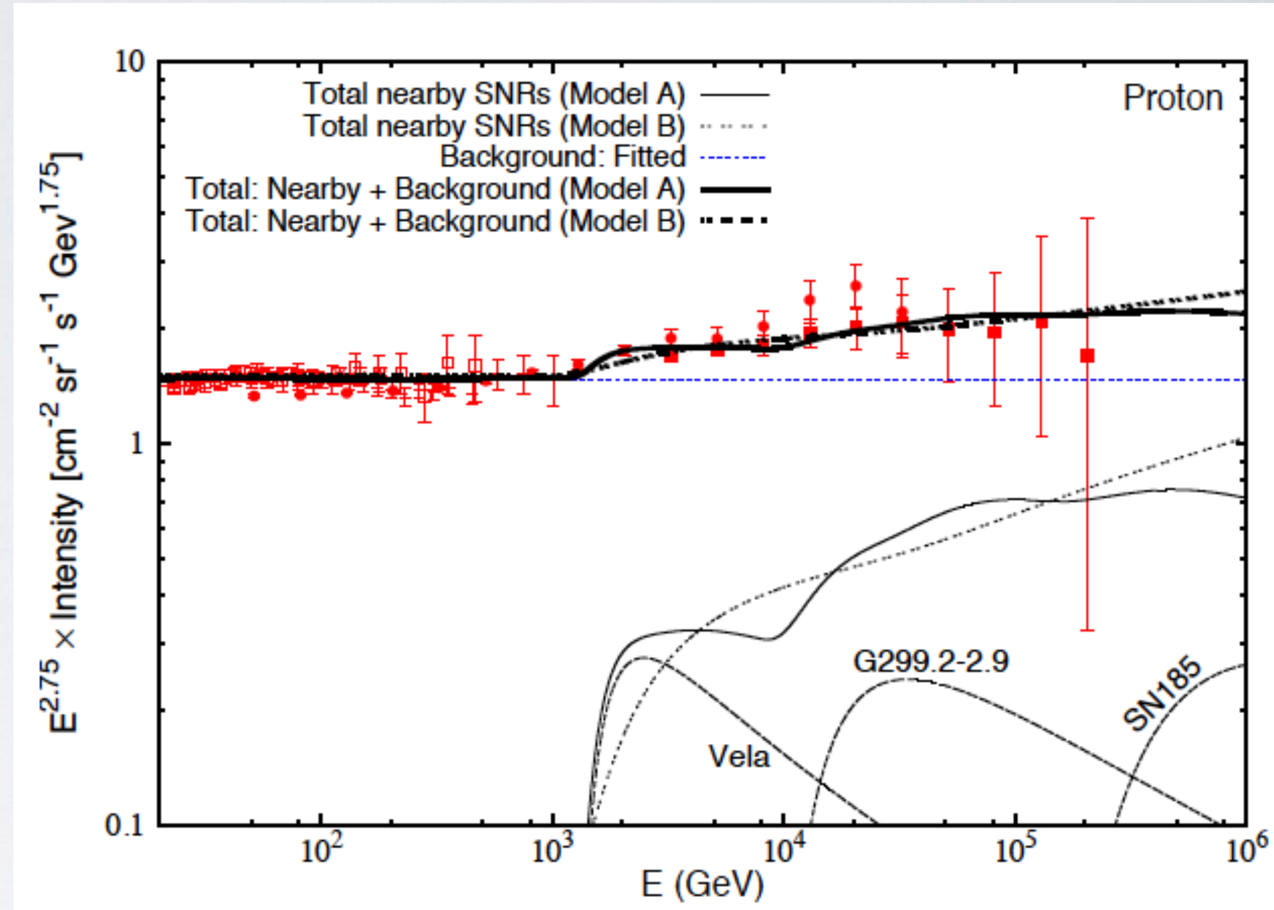
the effect may be spatial dependent ! (see below)

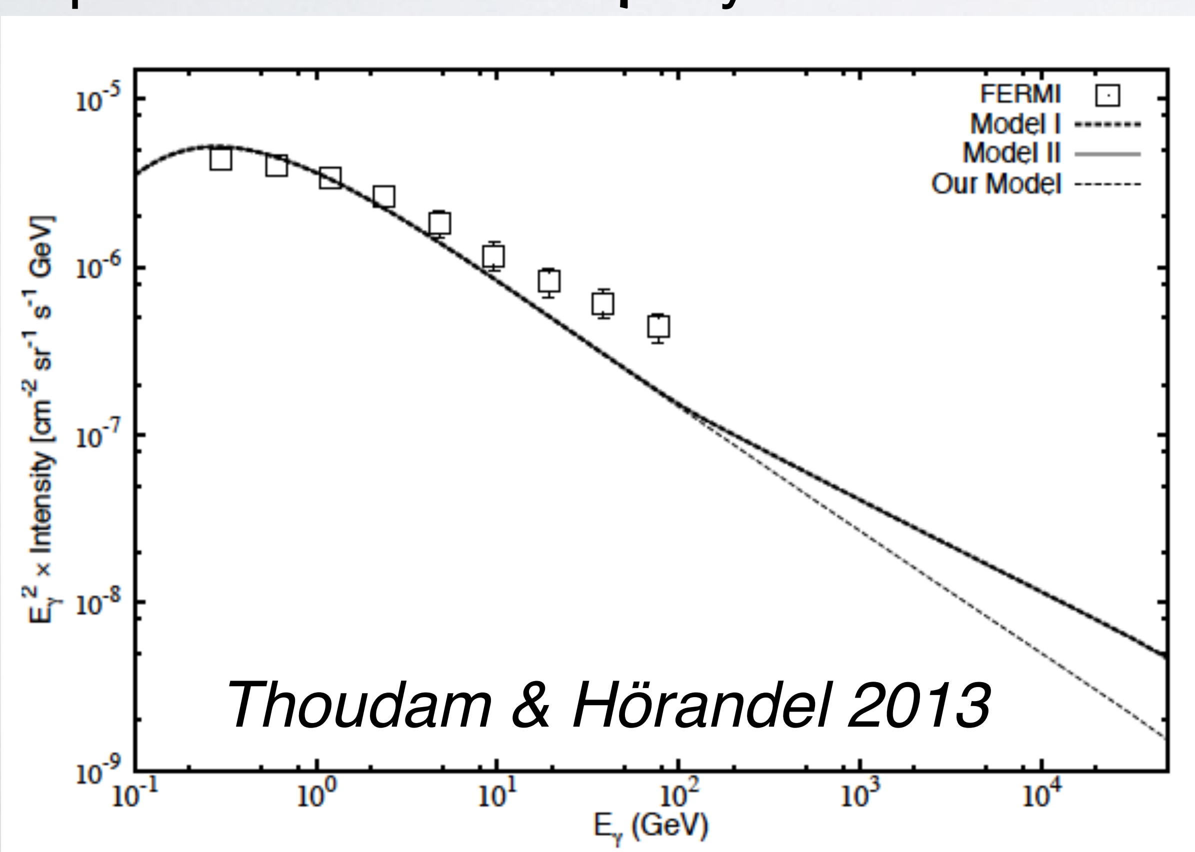
The CR Galactic population: PAMELA anomaly

The CR hardening may be a local effect e.g. due to nearby SNR, see e.g. *Thoudam & Hörandel 2011*

or a large scale one due to propagation see e.g. *Blasi, Amato & Serpico 2012)*

Those scenarios should have different impact on the diffuse **γ**-ray emission





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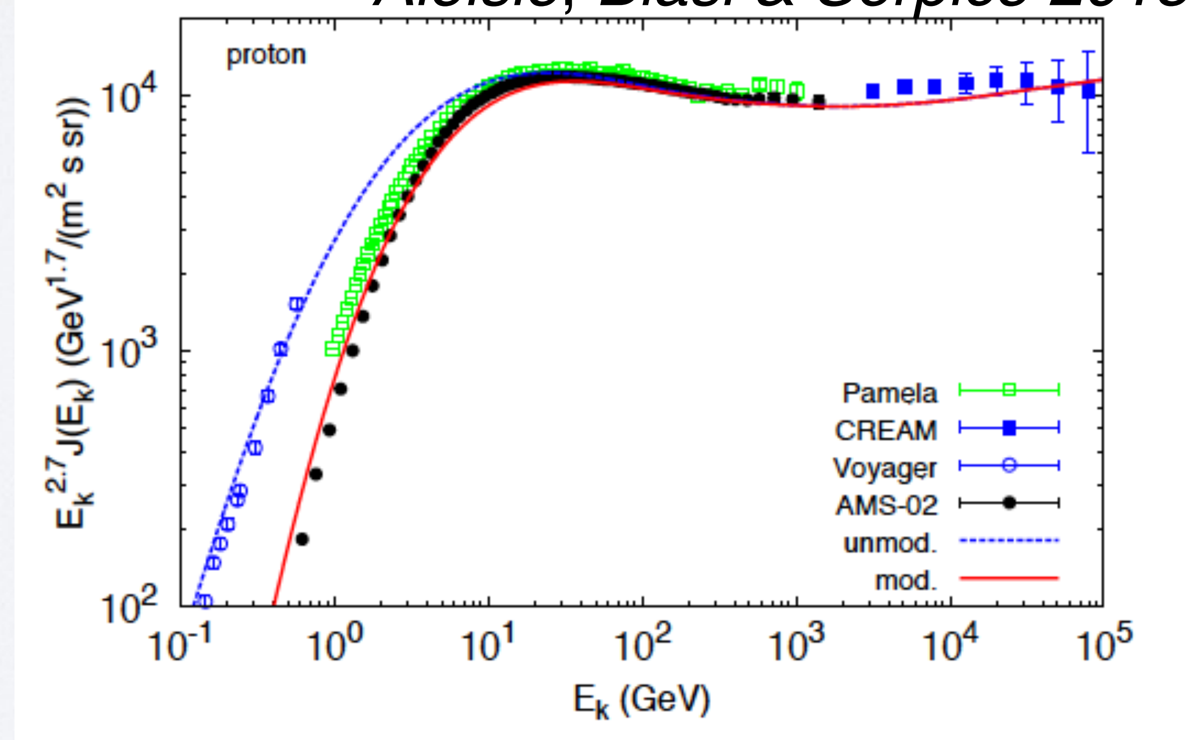


The Milagro anomaly in the inner Galactic Plane

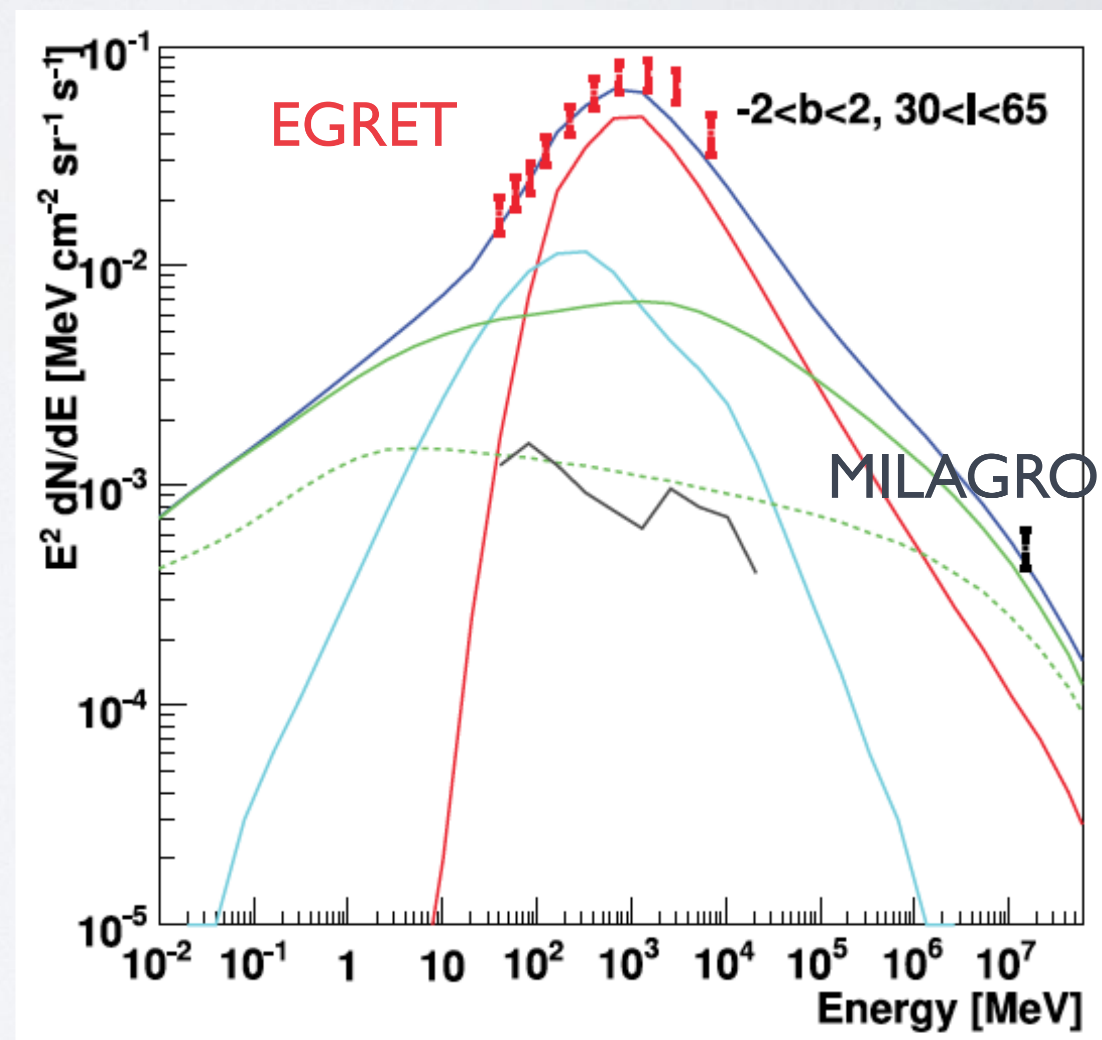
ABDO ET AL. *ApJ 2008*

TABLE 1

GAMMA-RAY EMISSION FROM THE GALACTIC PLANE AROUND 15 TeV

Region for $\|b\| < 2^\circ$ (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

- the measured flux is 5 times (4 σ) larger than computed with the reference conventional model
- 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 model.
  MILAGRO anomaly strikes again !



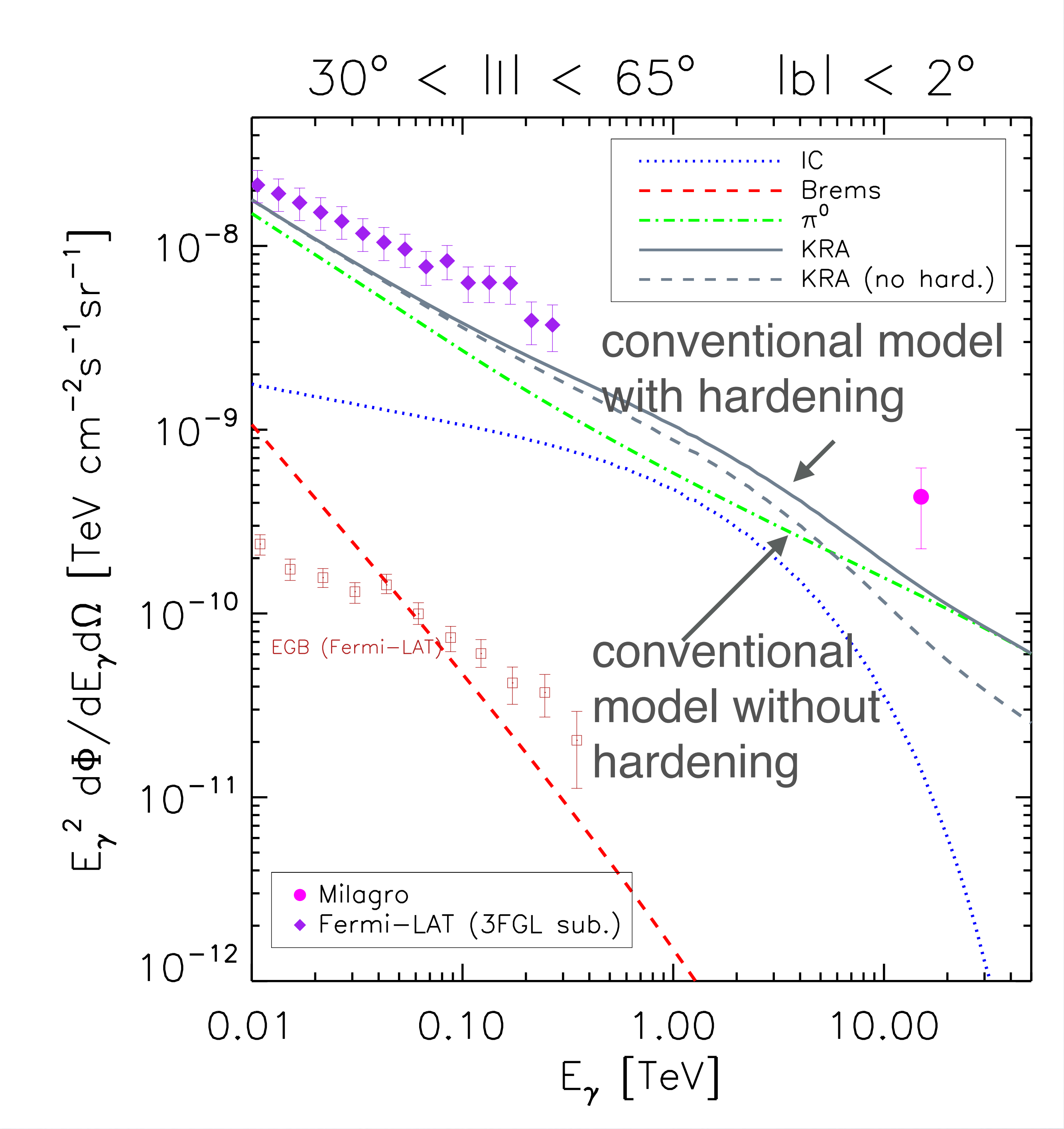
The Milagro anomaly in the inner Galactic Plane

- the excess is present also respect to updated conventional models tuned on CR data and <u>all-sky</u> Fermi-LAT data

- this holds also accounting for the CR hardening at ~ 250 GeV/n assuming it is a large scale effect.

(the proton and He spectra were assumed to match CREAM data up to 100 TeV/n)

5 years of FERMI data, within the event class ULTRACLEAN according to Fermi tools V9R32P5



The Milagro anomaly in the inner Galactic Plane

Troubles, however, start already at low energy !!

- the excess is present also respect to updated conventional models tuned on CR data and all-sky Fermi-LAT data

- this holds also accounting for the CR hardening at ~ 250 GeV/n assuming it is a large scale effect.

(the proton and He spectra were assumed to match CREAM data up to 100 TeV/n)

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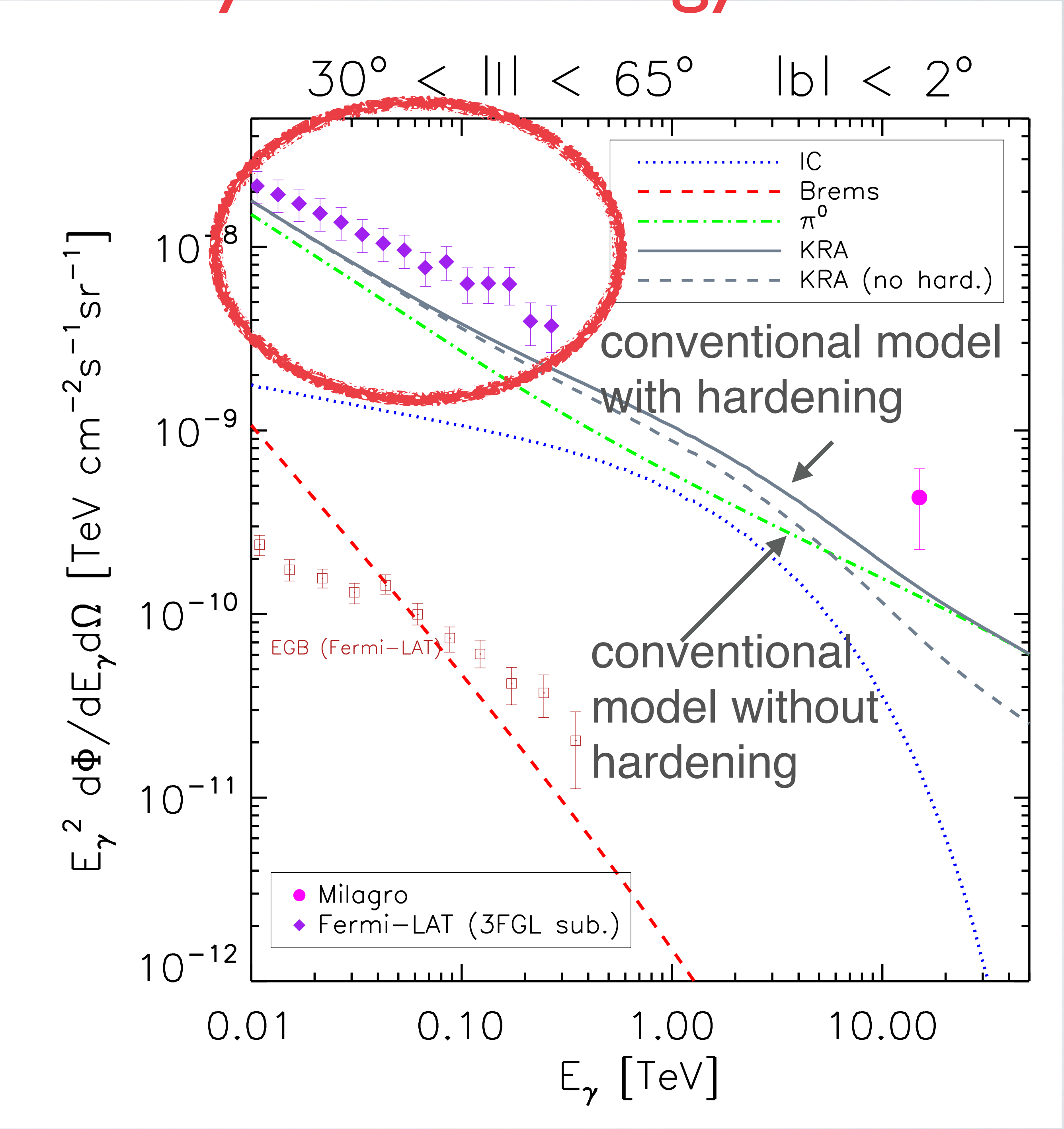
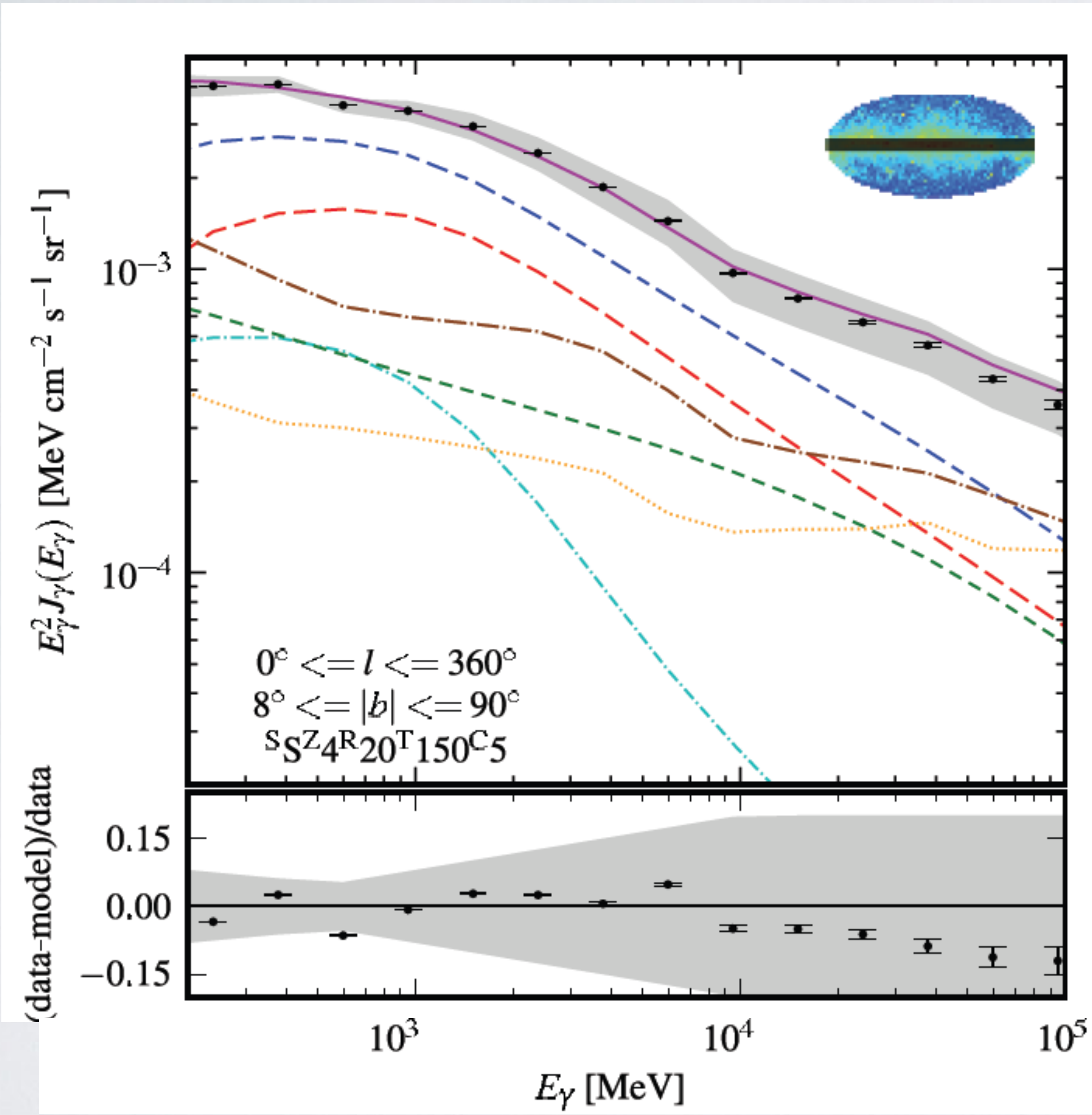


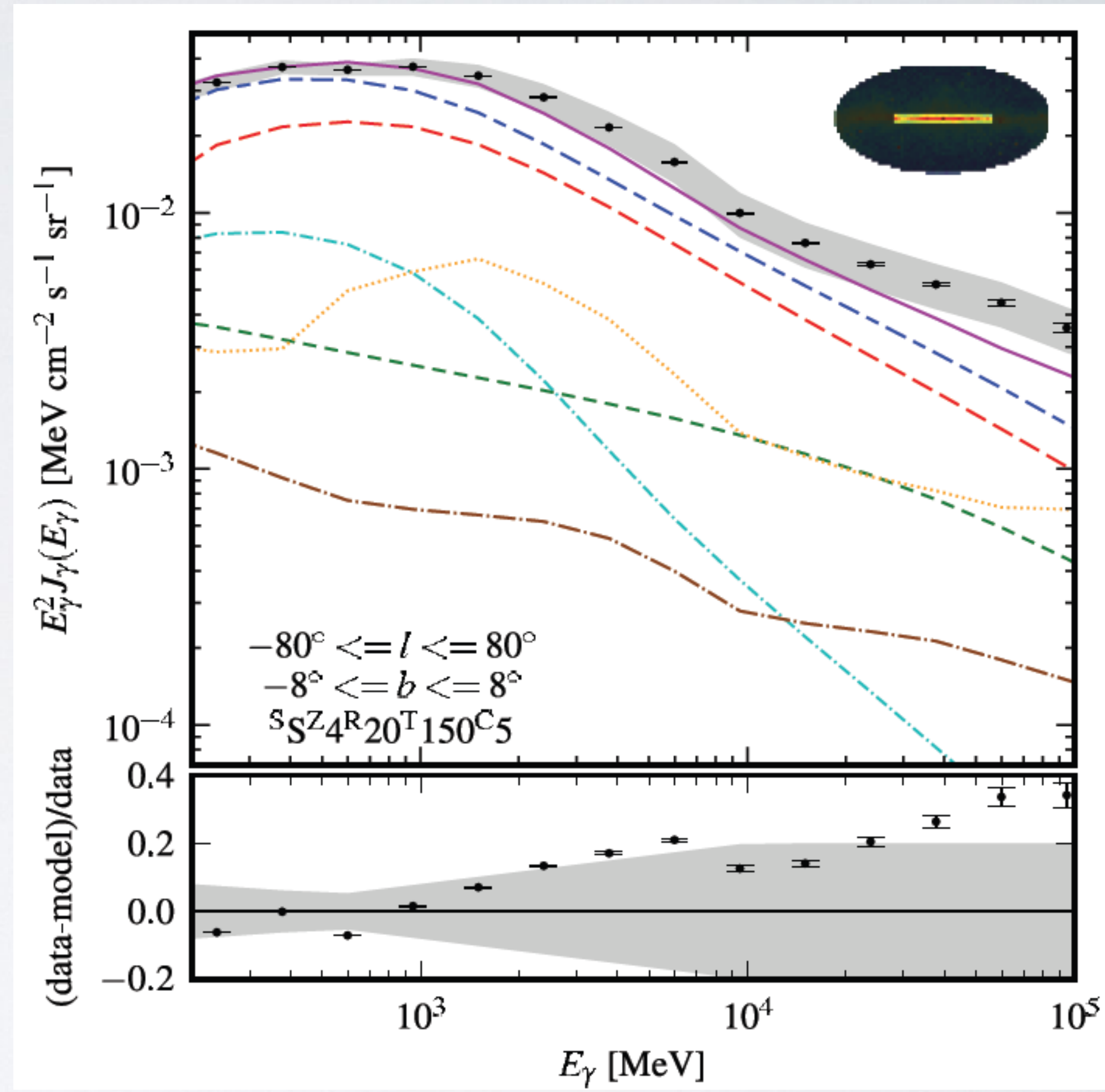
Conventional models against Fermi data

full-sky but the GP



inner GP

Fermi coll. ApJ 2012

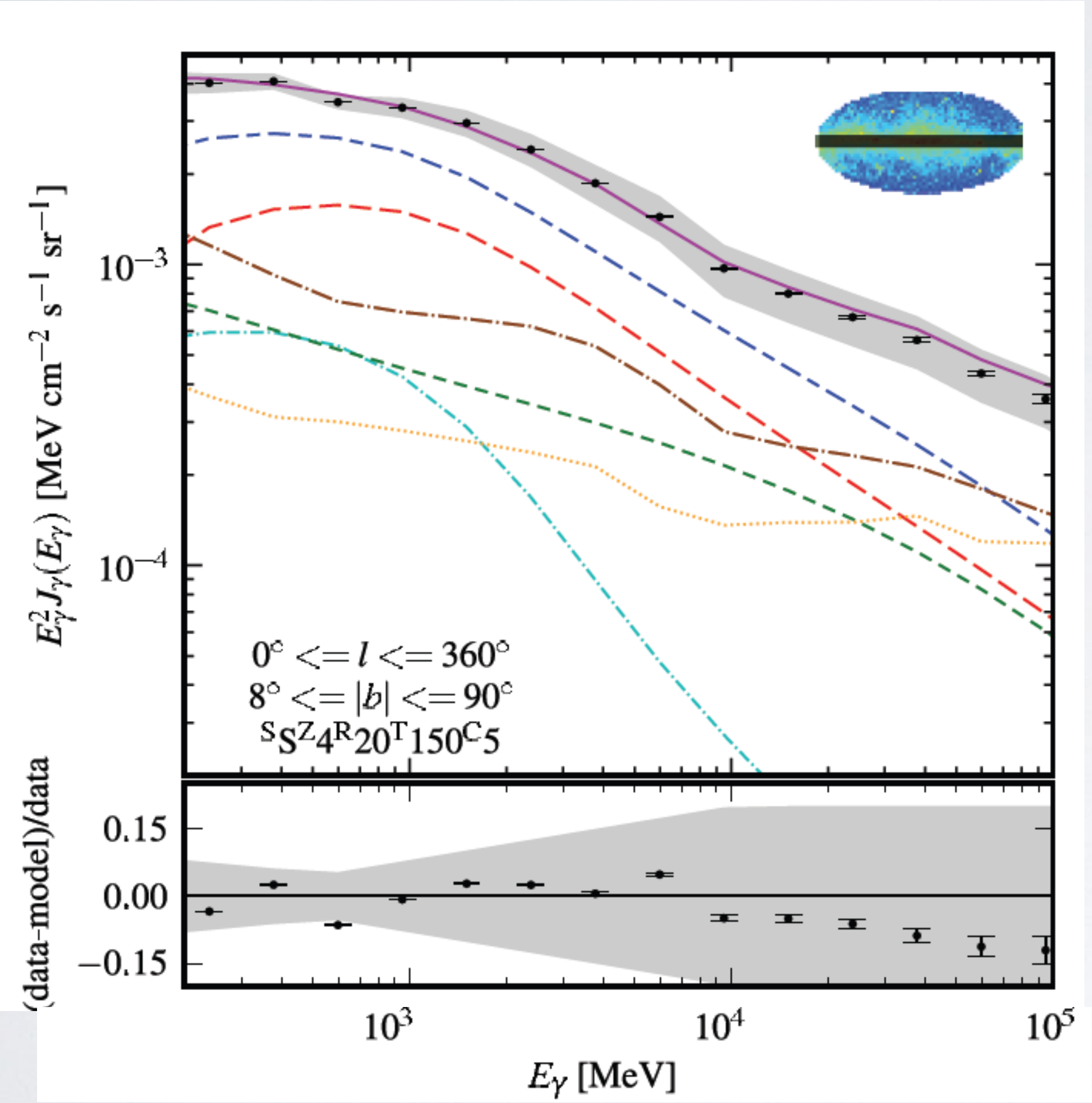


Fermi Benchmark (FB) conventional model based on GALPROP (*Moskalenko, Strong et al.*). The model does not account for CR hardening at ~ 250 GeV/n

$\delta = 0.3$, $\gamma_P = 2.72$ in the whole Galaxy $z_h =$ 4 kpc

Conventional models against Fermi data

full-sky but the GP



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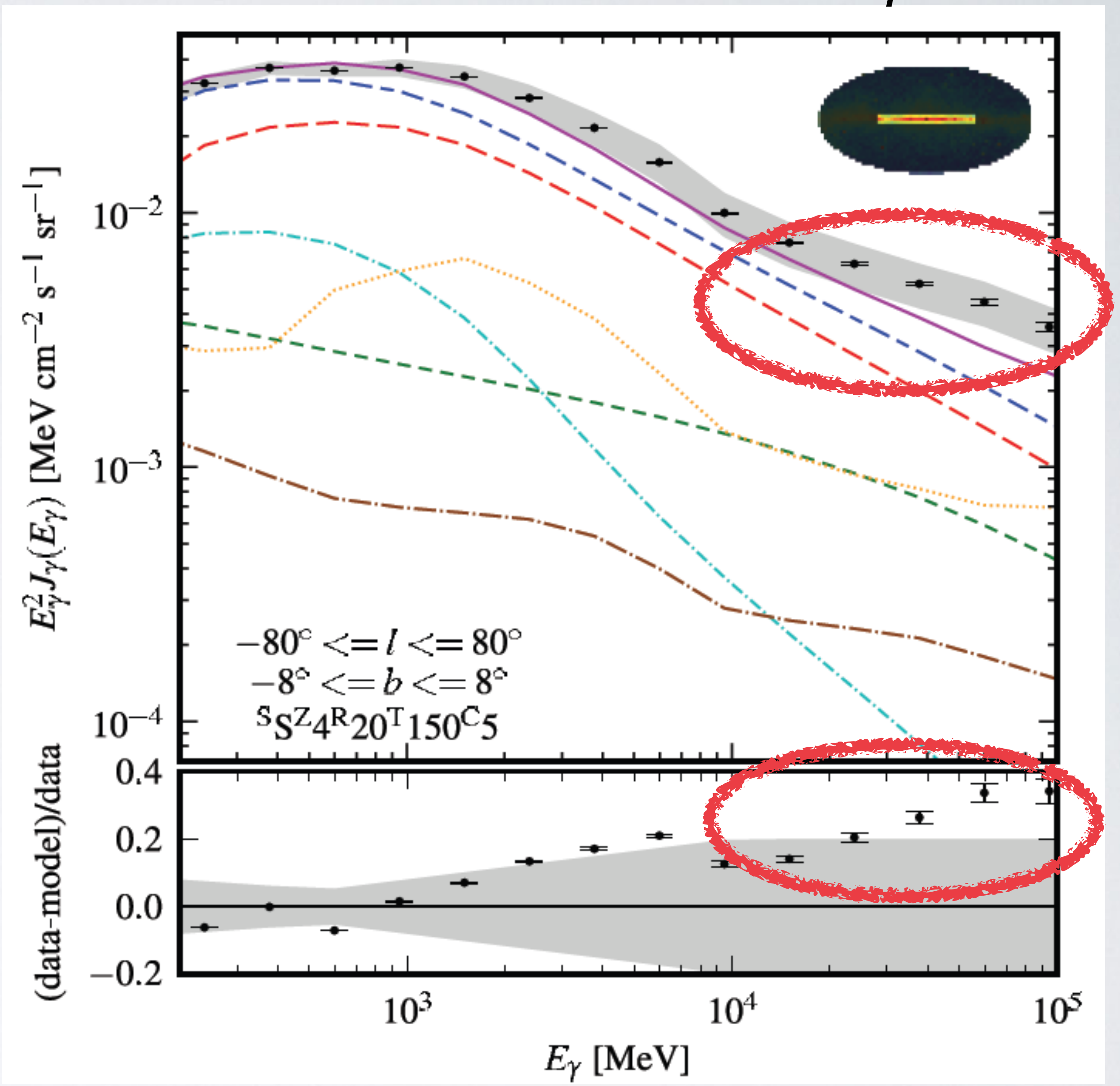


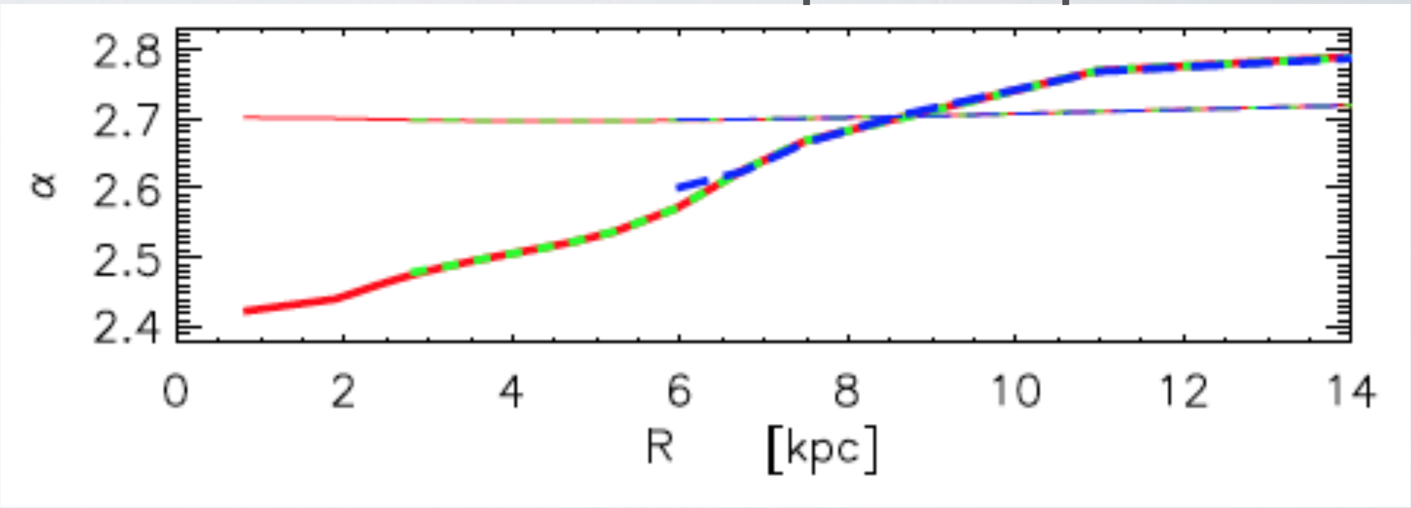
Fermi Benchmark (FB) conventional model based on GALPROP (Moskalenko, Strong et al.). The model does not account for CR hardening at ~ 250 GeV/n

$\delta = 0.3$, $\gamma_P = 2.72$ in the whole Galaxy $z_h =$ 4 kpc

Beyond conventional models:
Radial dependency of CR transport

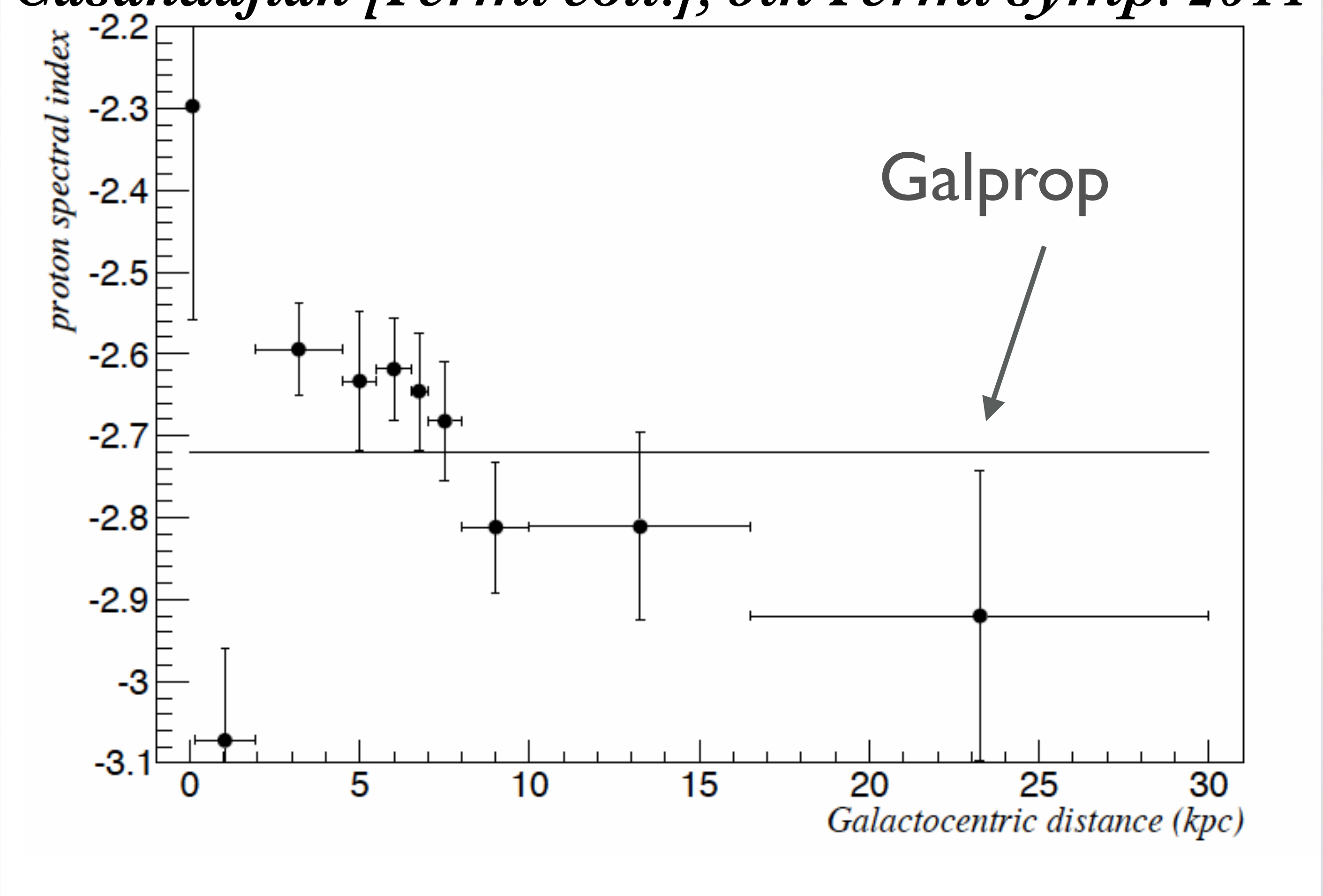
Gaggero, Urbano, Valli & Ullio, arXiV: 1411.7623 PRD 2015

proton spect. index



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

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



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

This is clearly incompatible with conventional models implemented with GALPROP

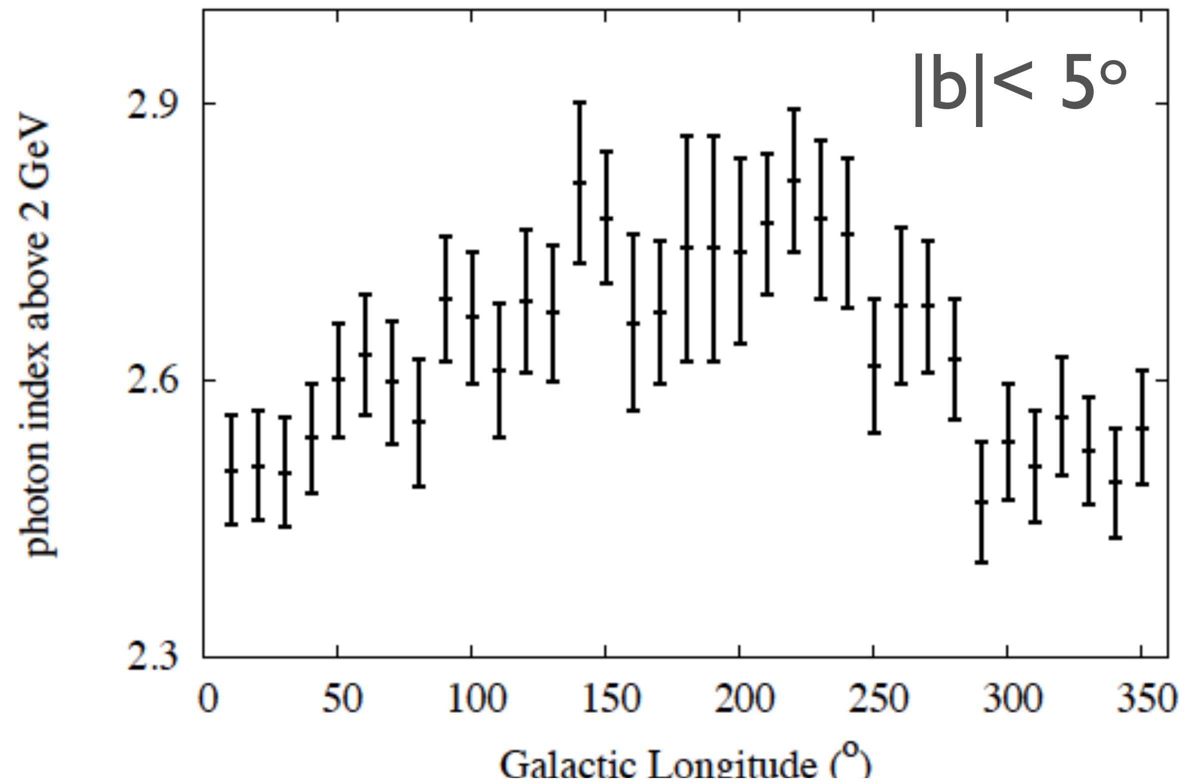
Fermi results: an independent analysis

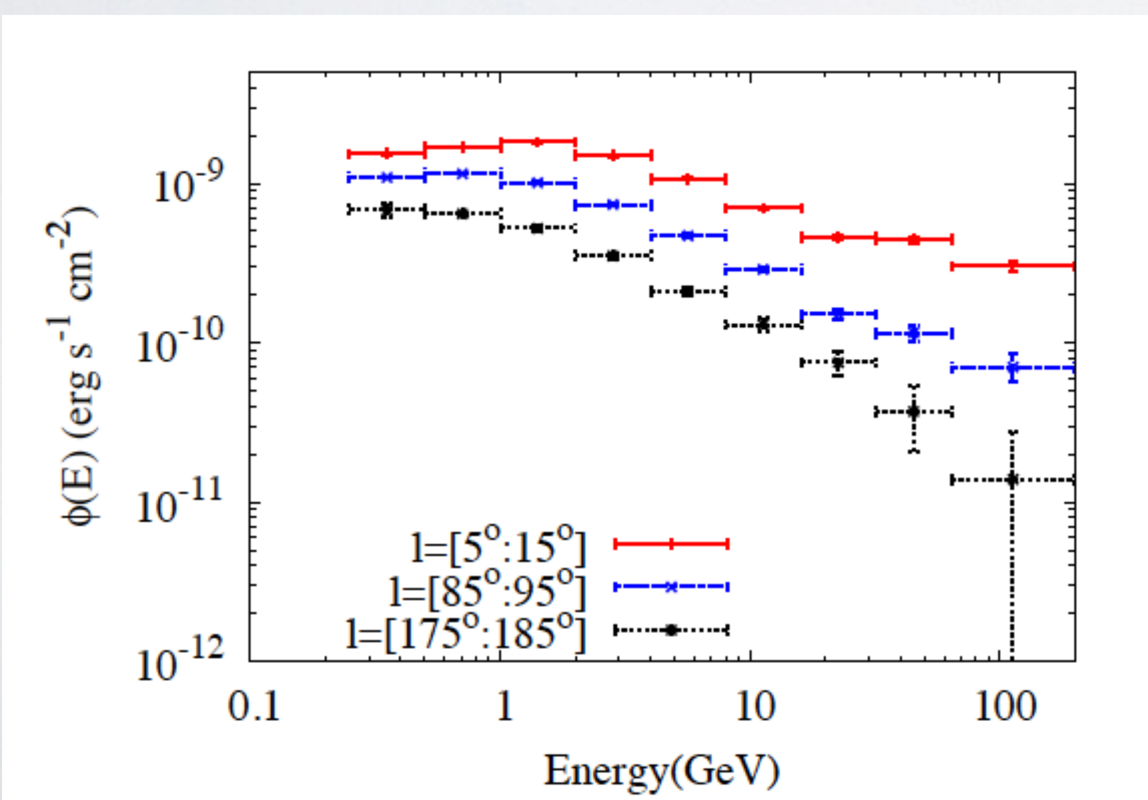
Yang, Aharonian & Evoli arXiV:1602.04710

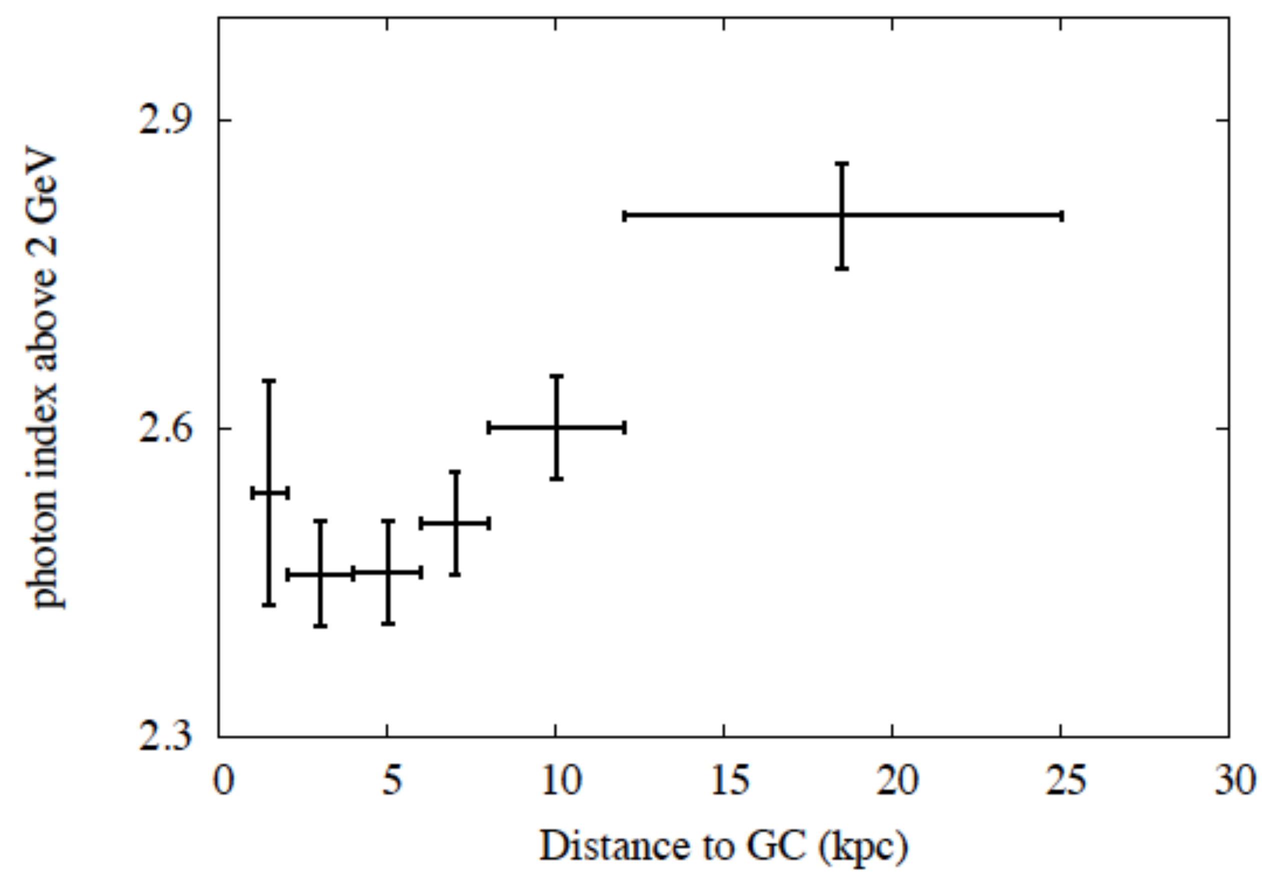
use 7 years Fermi-LAT data

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

CR density 1 order of magnitude larger than local at 1 TeV in the inner Galaxy







The KRAγ model: Radial dependency of CR transport

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

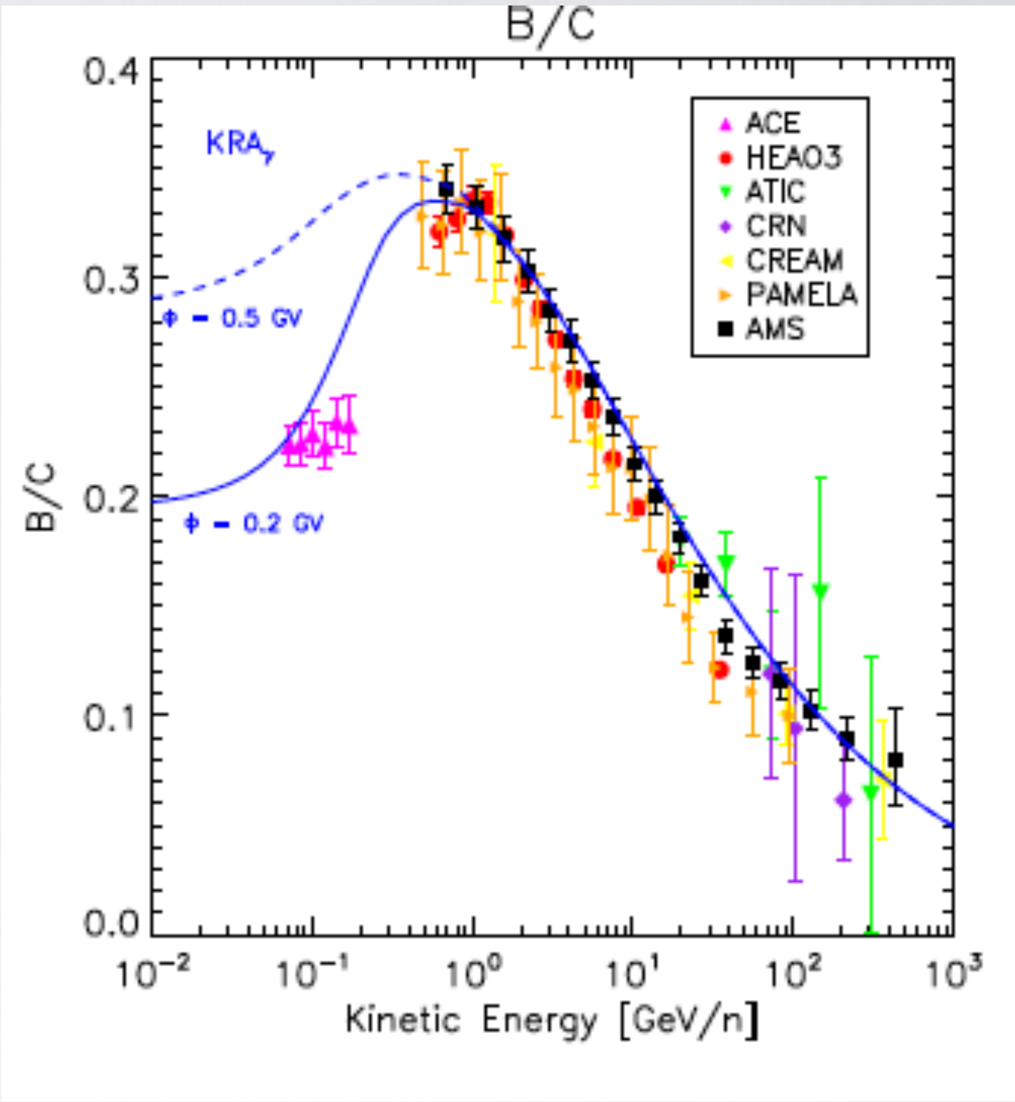
The **KRAγ model** - implemented with the **DRAGON code** - adopts a radial dependent diffusion coefficient

$\delta(R) = A\,R + B$ for R < 11 kpc, const. above
such that $\delta(R_{sun}) = 0.5$

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



The DRAGON code

DRAGON

Diffusion **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) $D_\perp \neq D_{||}$

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

The DRAGON code

A new version of DRAGON
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

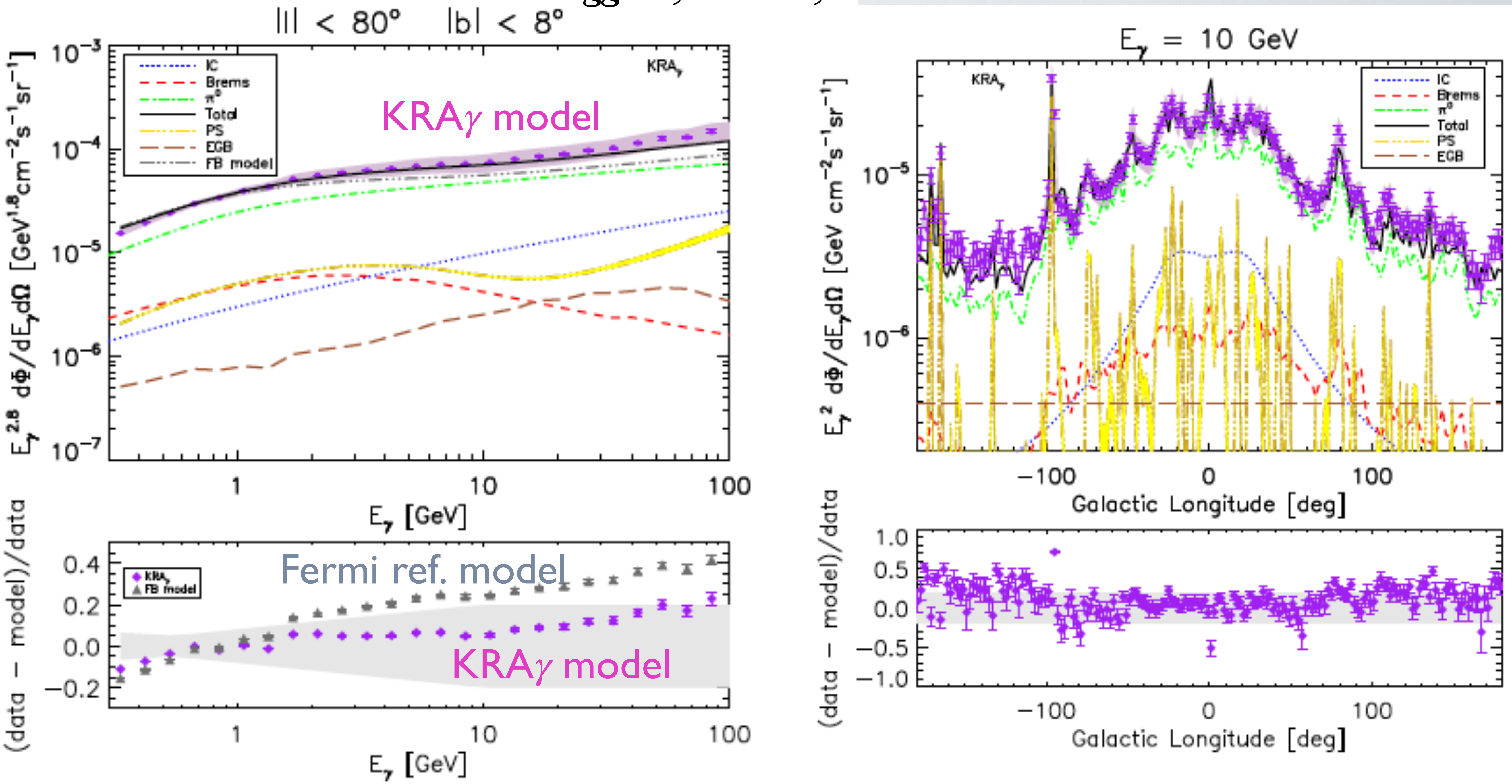
- anisotropic diffusion in 3D

<u>will soon be released</u>.

A first (of a series) of technical papers to appear in a few days.

The KRAγ model: Radial dependency of CR transport

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

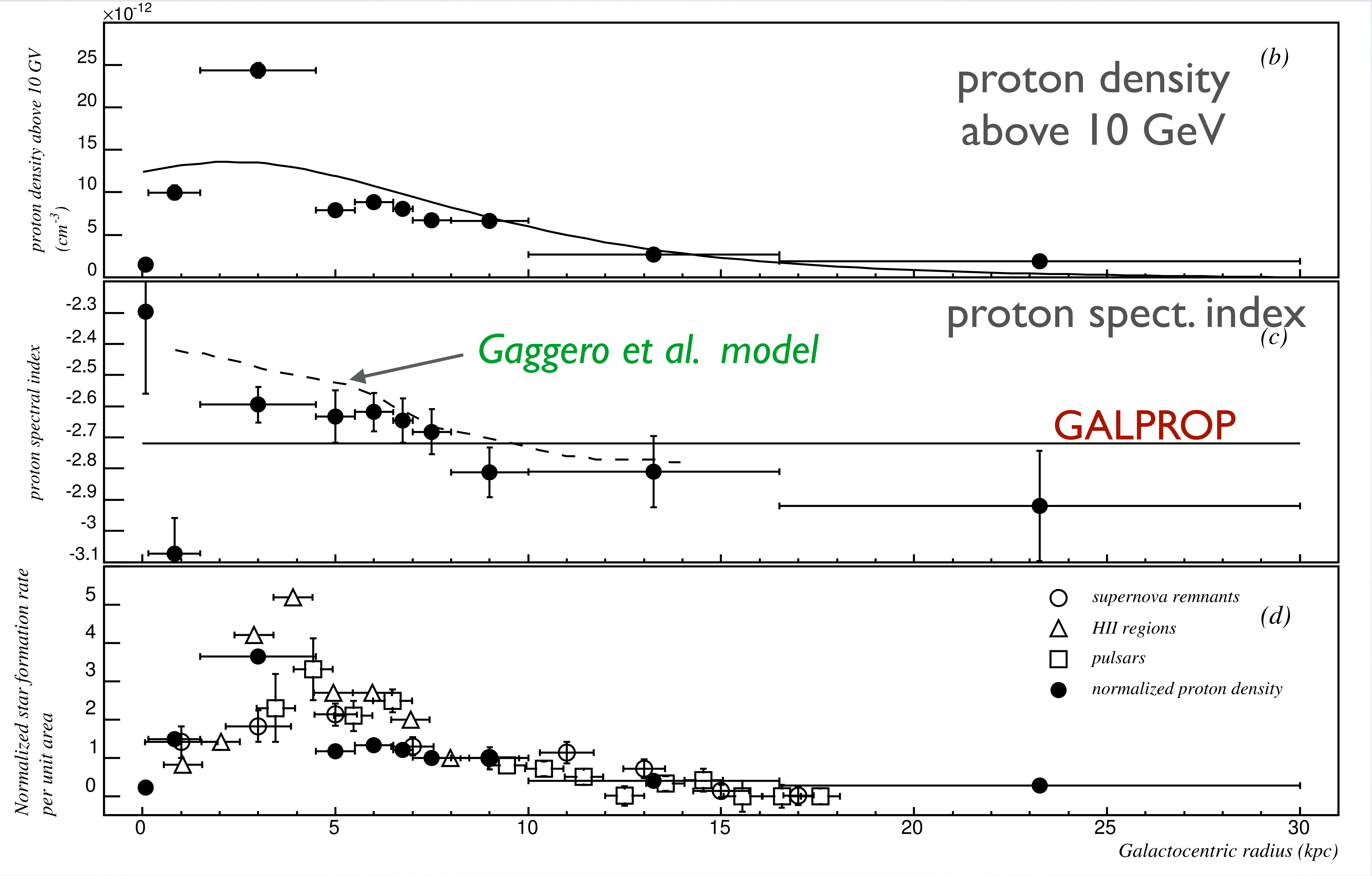


The KRAγ model reproduces the full-sky Fermi spectrum and angular distribution. It also provides a better fit in the inner GP region and all sky

Fermi results

FERMI coll. arXiV:1602.07246; APJ supp.

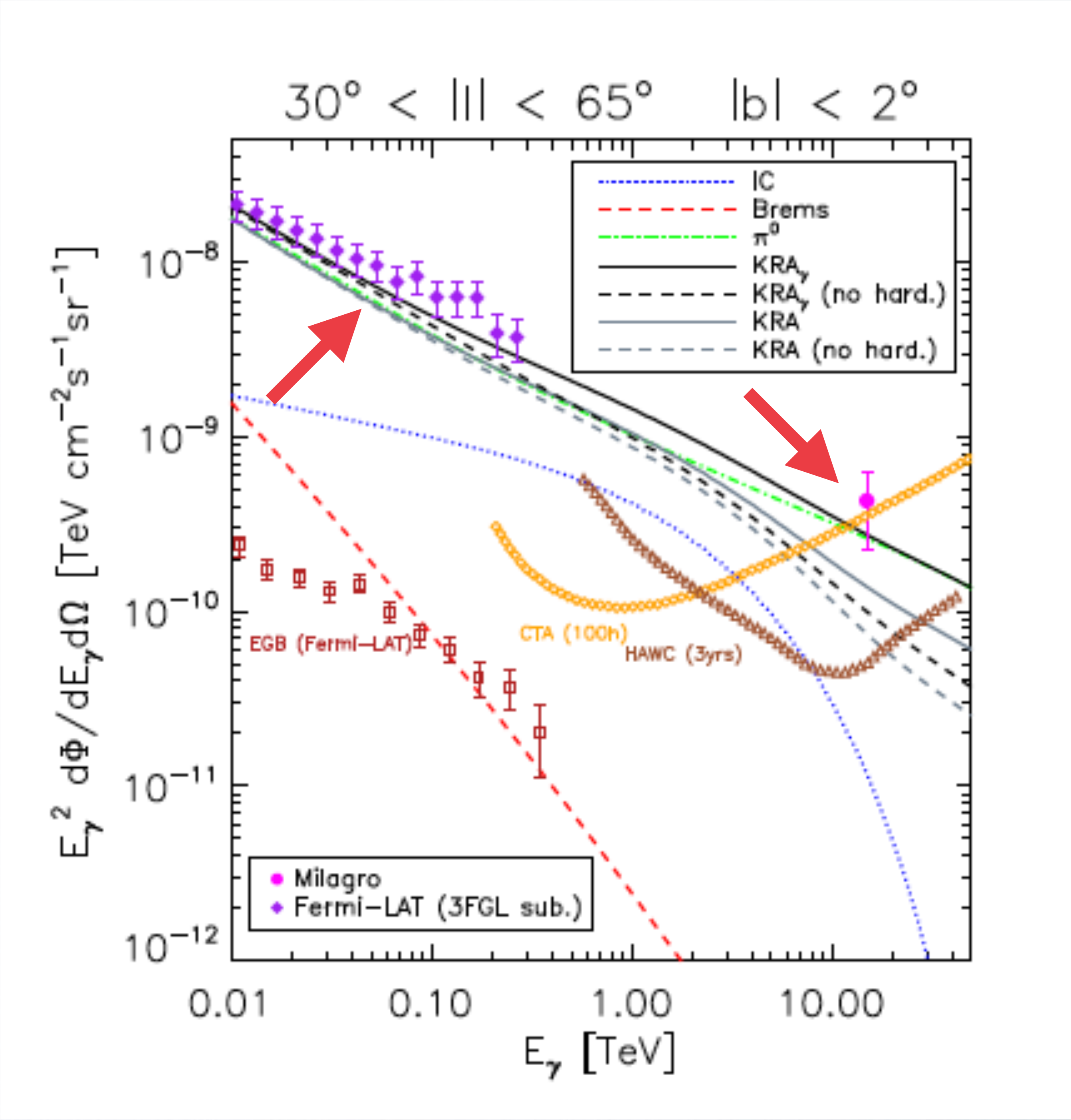
template fit analysis of 7 year data - model independent (IC based on GALPROP)



The KRAγ model against the Milagro anomaly at 15 TeV

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

The KRAγ model nicely matches MILAGRO consistently with Fermi data (point sources cleaned)
no further tuning is required !



5 years of FERMI data, within the event class ULTRACLEAN according to Fermi tools V9R32P5

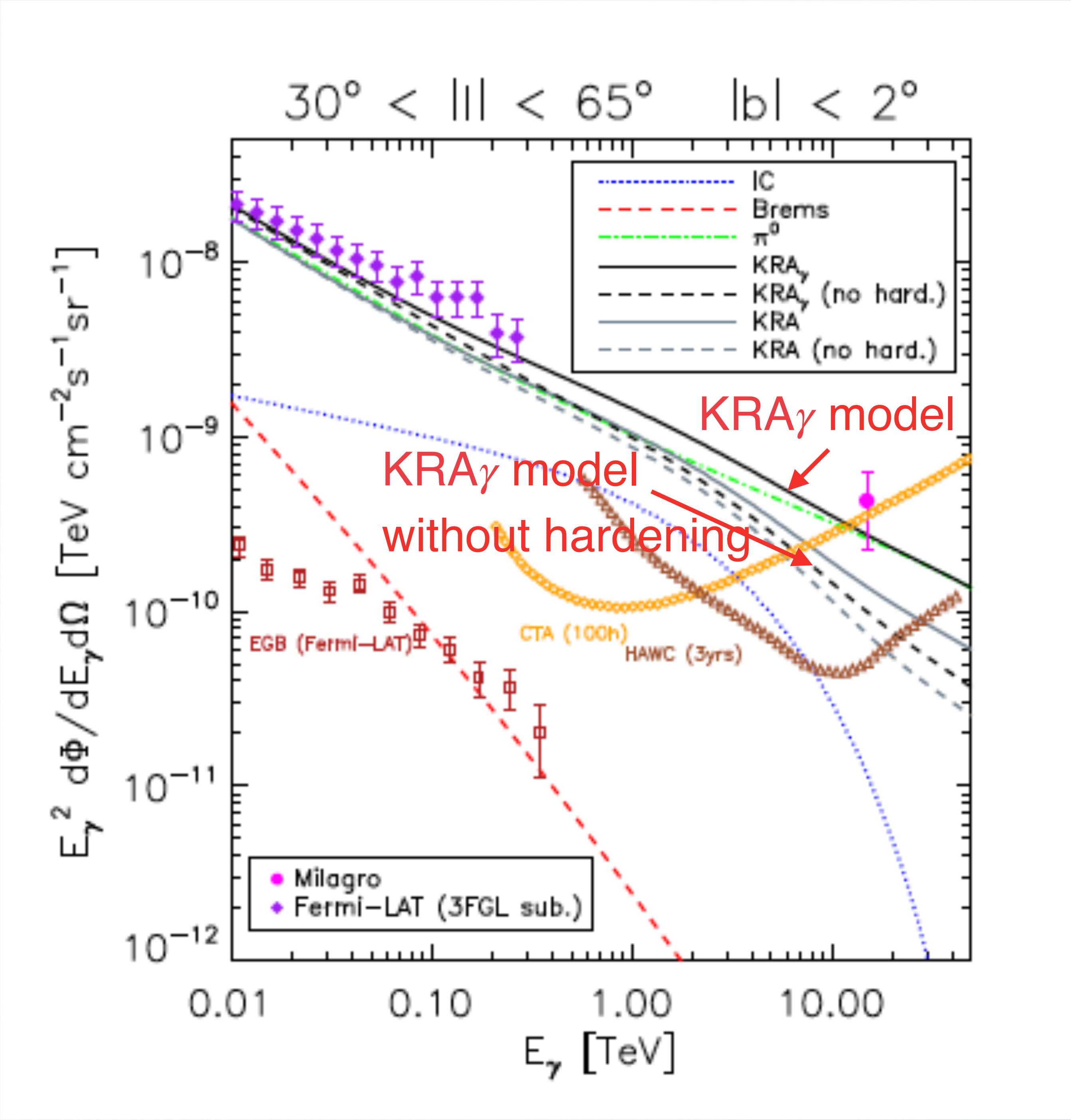
The impact on the Milagro anomaly at 15 TeV

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

The KRAγ model nicely matches MILAGRO consistently with Fermi data (point sources cleaned)
no further tuning is required !

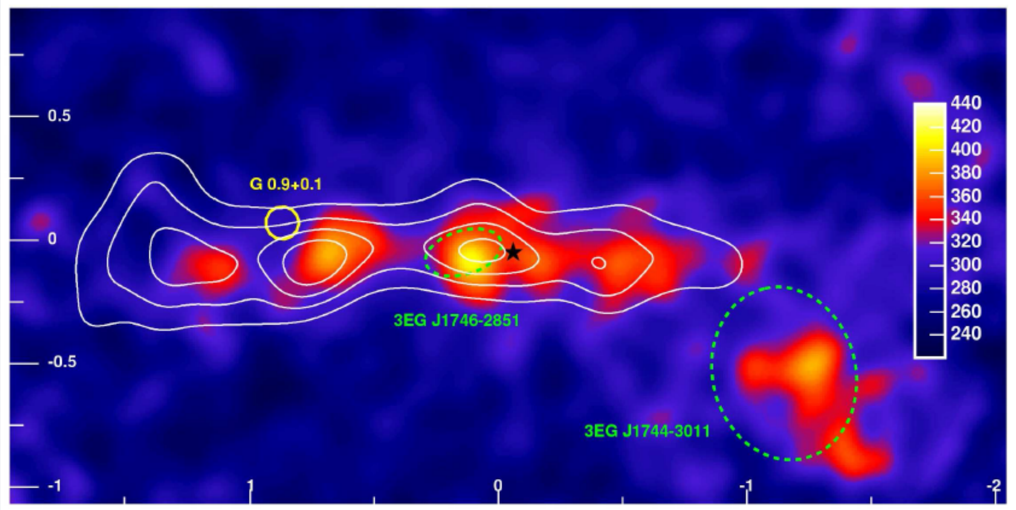
Beside inhomogeneous diffusion CR hardening at ~ 250 GeV/n must also be accounted for. This suggests that hardening is not a local feature but it is may also be related to unconventional diffusion !

5 years of FERMI data, within the event class ULTRACLEAN according to Fermi tools V9R32P5



The KRAγ model against the Galactic Ridge emission

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

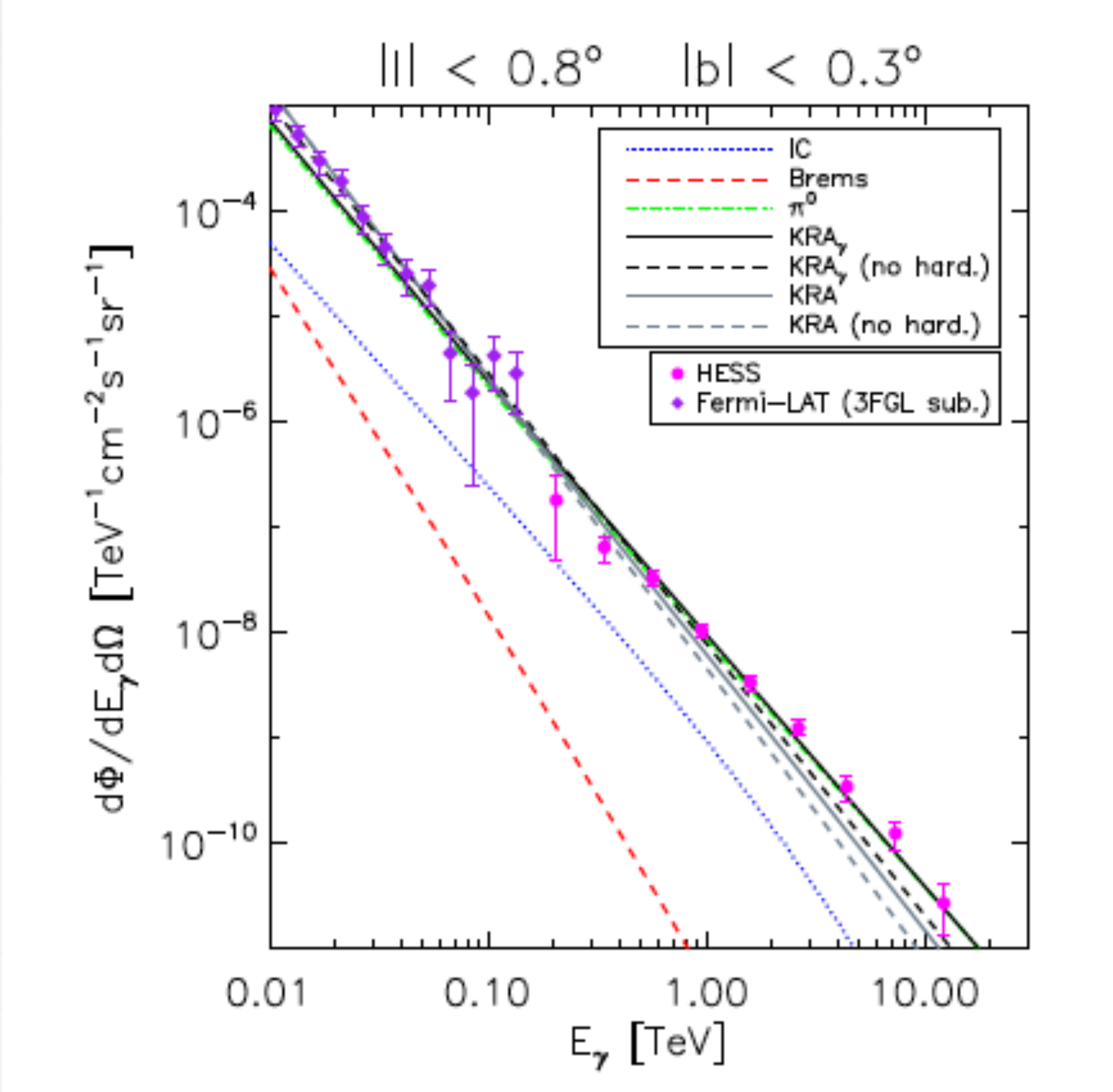


HESS (*Nature 2006*) measured a spectrum harder ($\Gamma \sim -2.3$) than expected on the basis of conventional CR models, associated with the molecular complex in the inner 200 pc of Galaxy

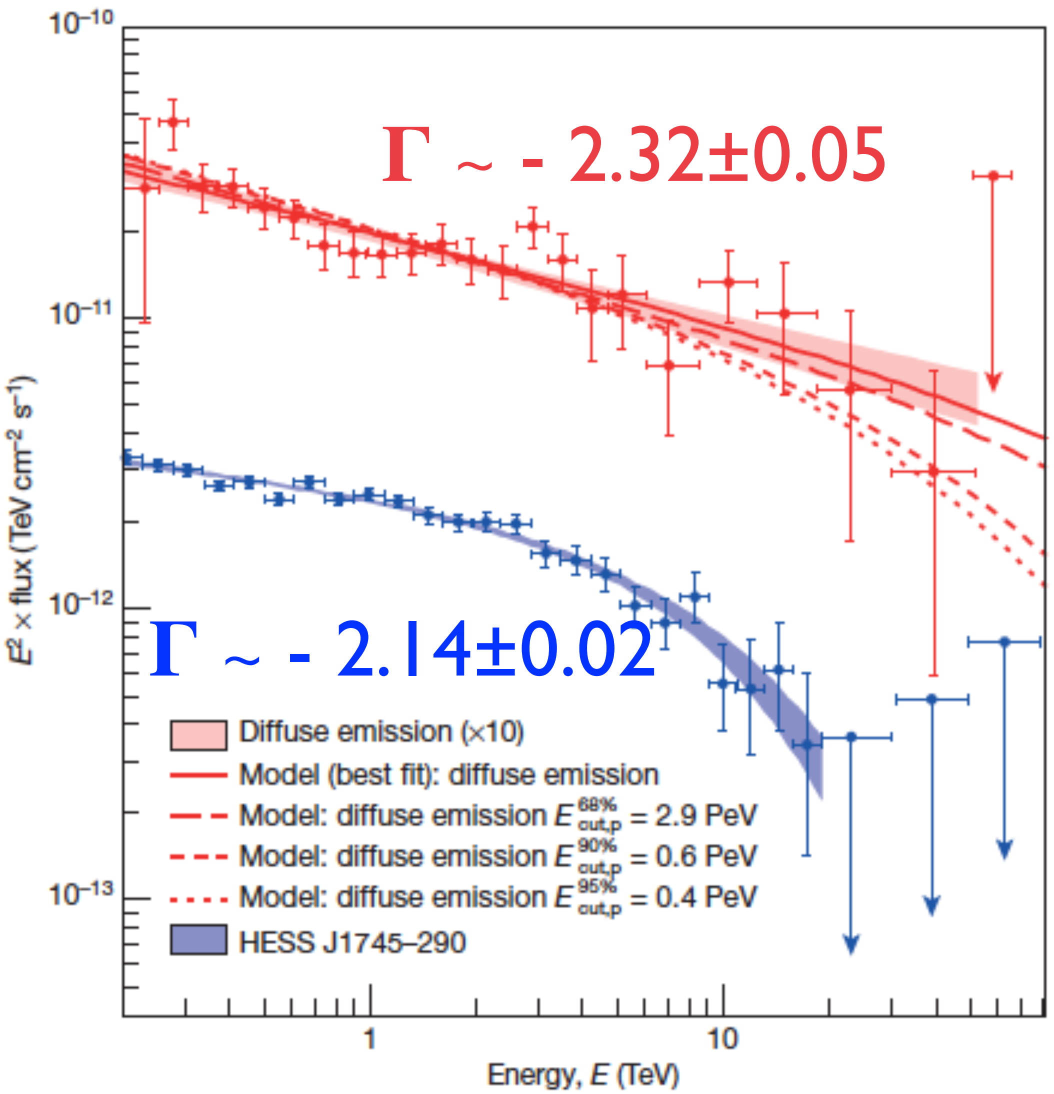
this is also the case for the updated Fermi benchmark conv. model

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

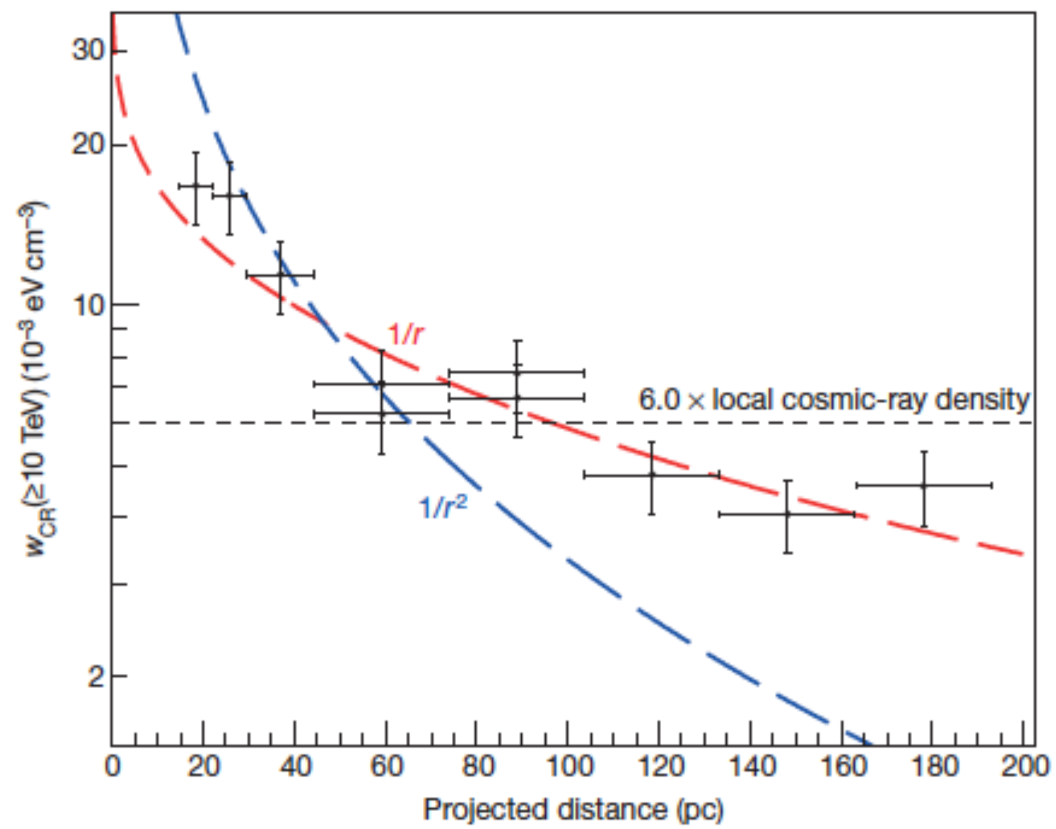
Fit against FERMI + HESS:
KRAγ: $\chi 2$ = 1.79 /2.27 with/w.o. hard.
KRA: $\chi 2$ = 2.92 /3.99 with/w.o. hard.



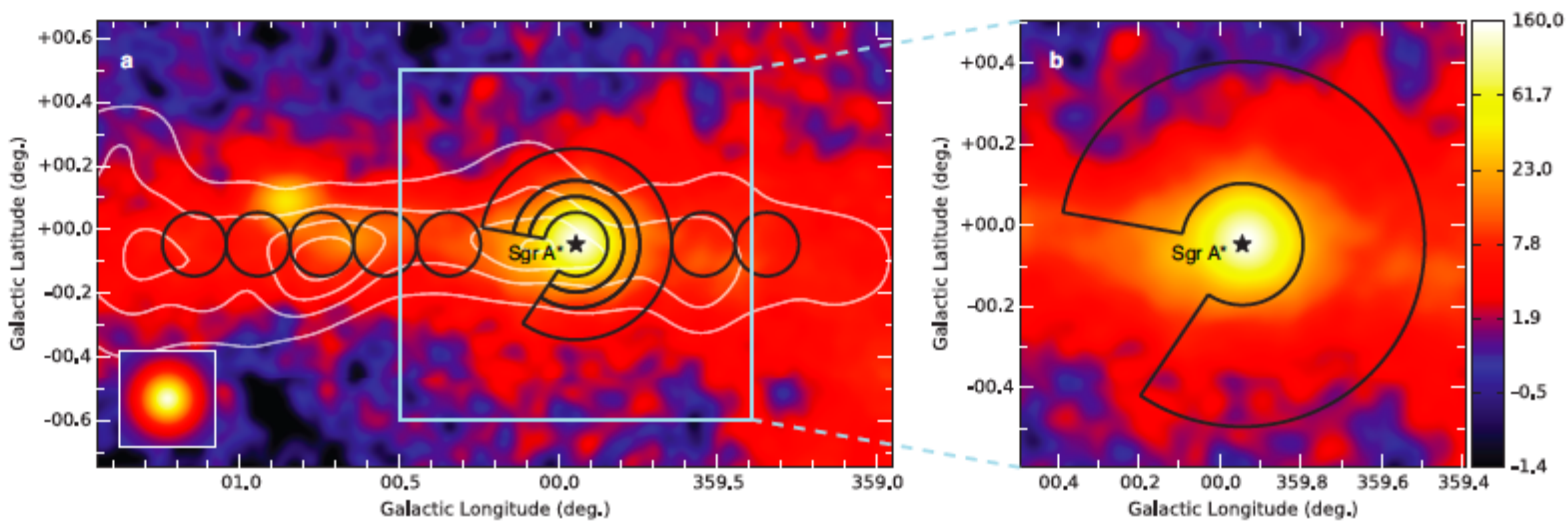
The case of the Pevatron observed by HESS



H.E.S.S.coll. doi:10.1038/nature17147

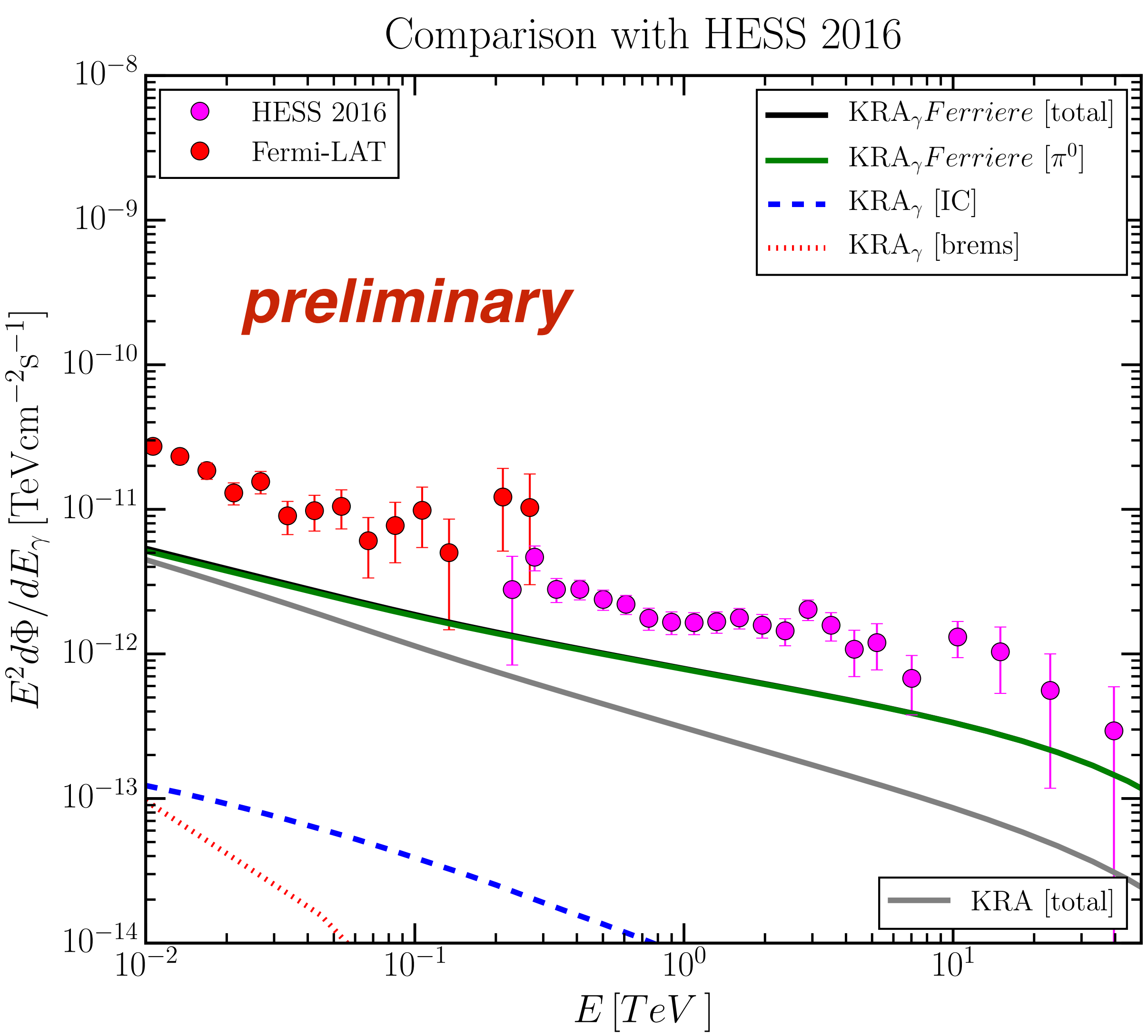


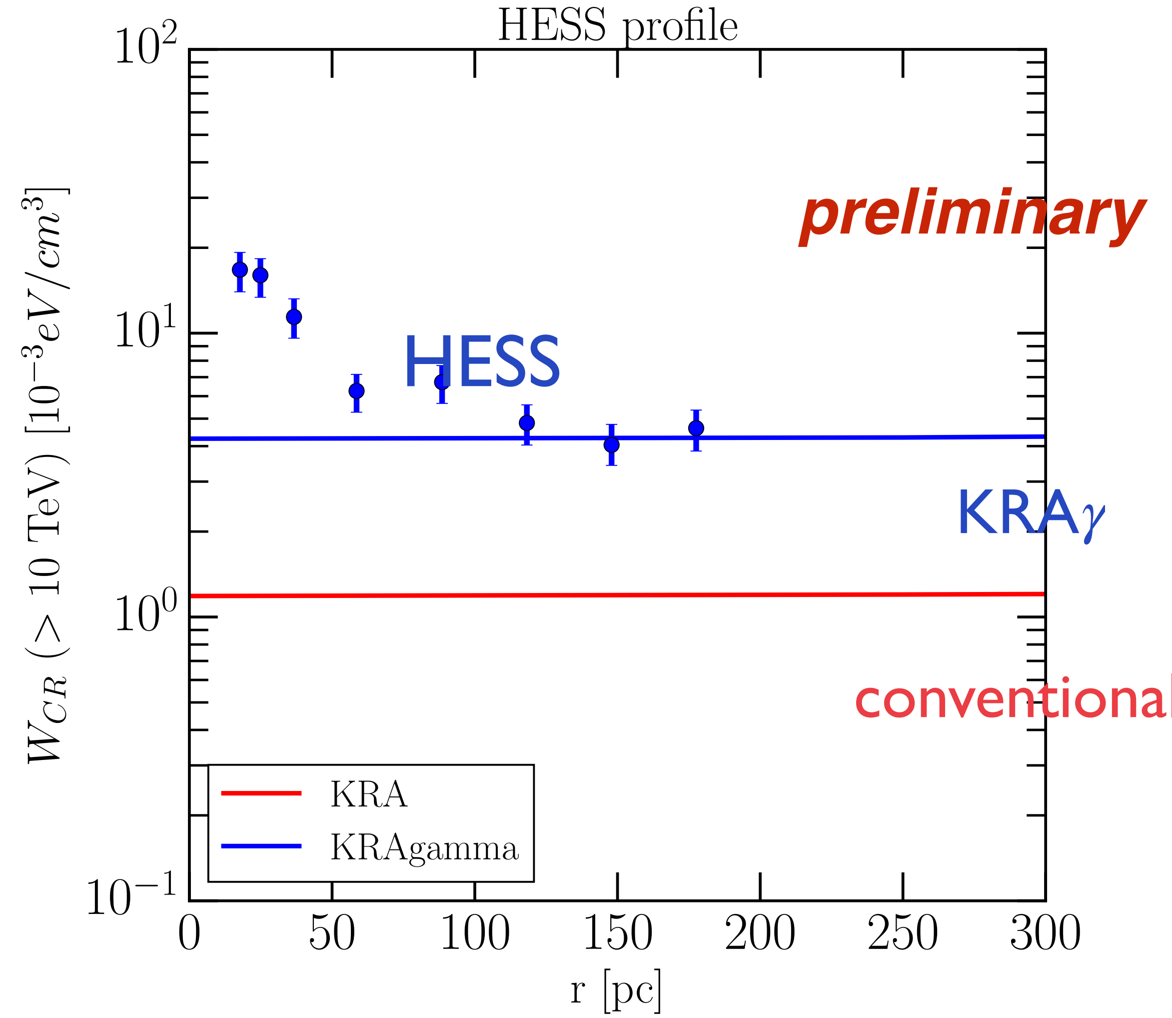
First Pevatron observed in gamma-ray from a diffuse region close to Sgr A*



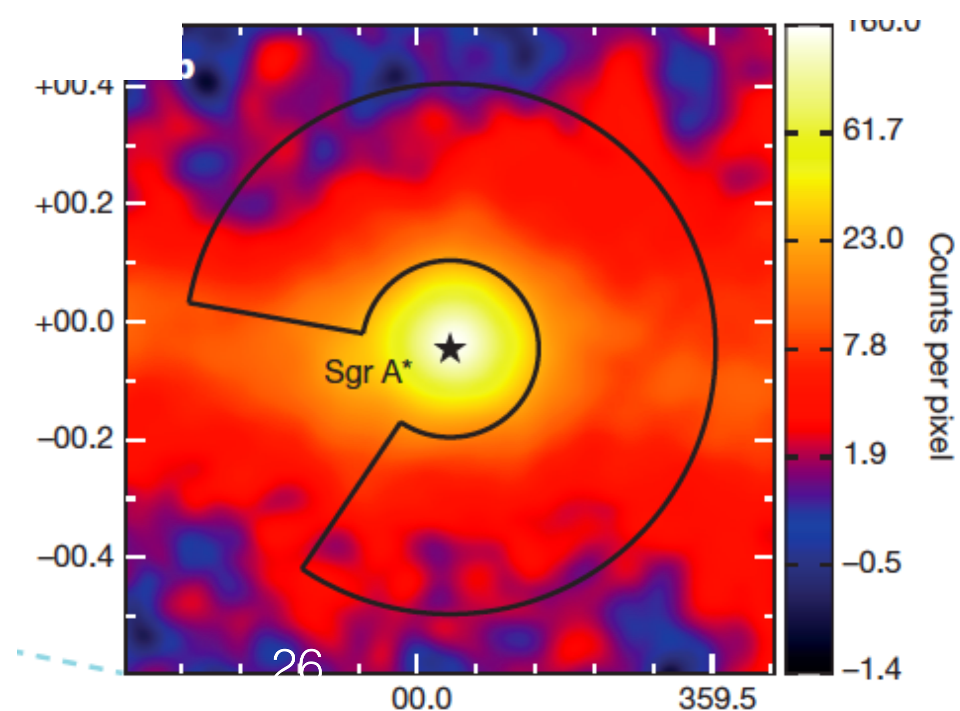
The expected diffuse sea with KRAγ compared to Pevatron

In Preparation: Evoli, Gaggero, DG, Marinelli, Urbano, Taoso





“pacman” region

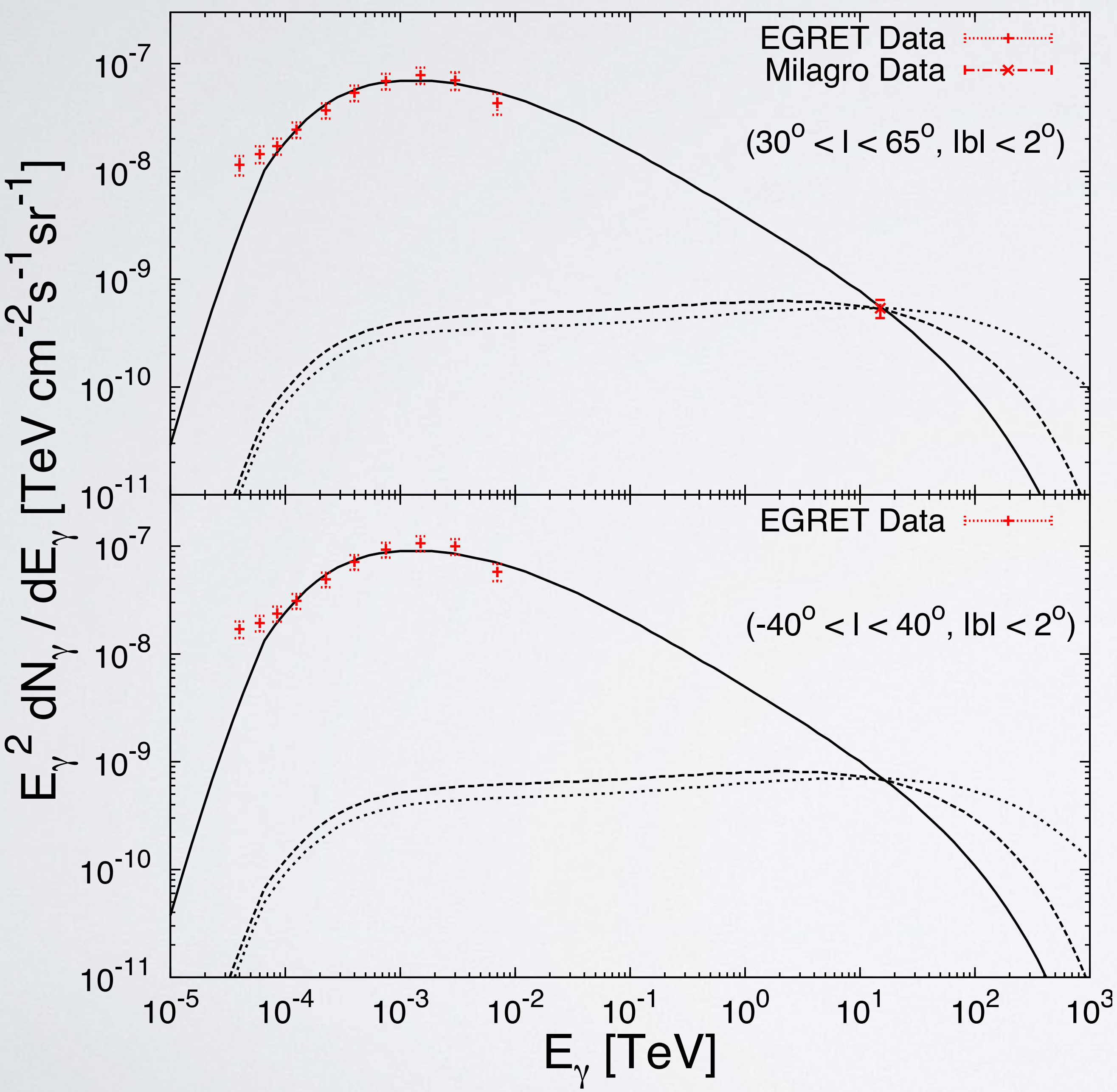


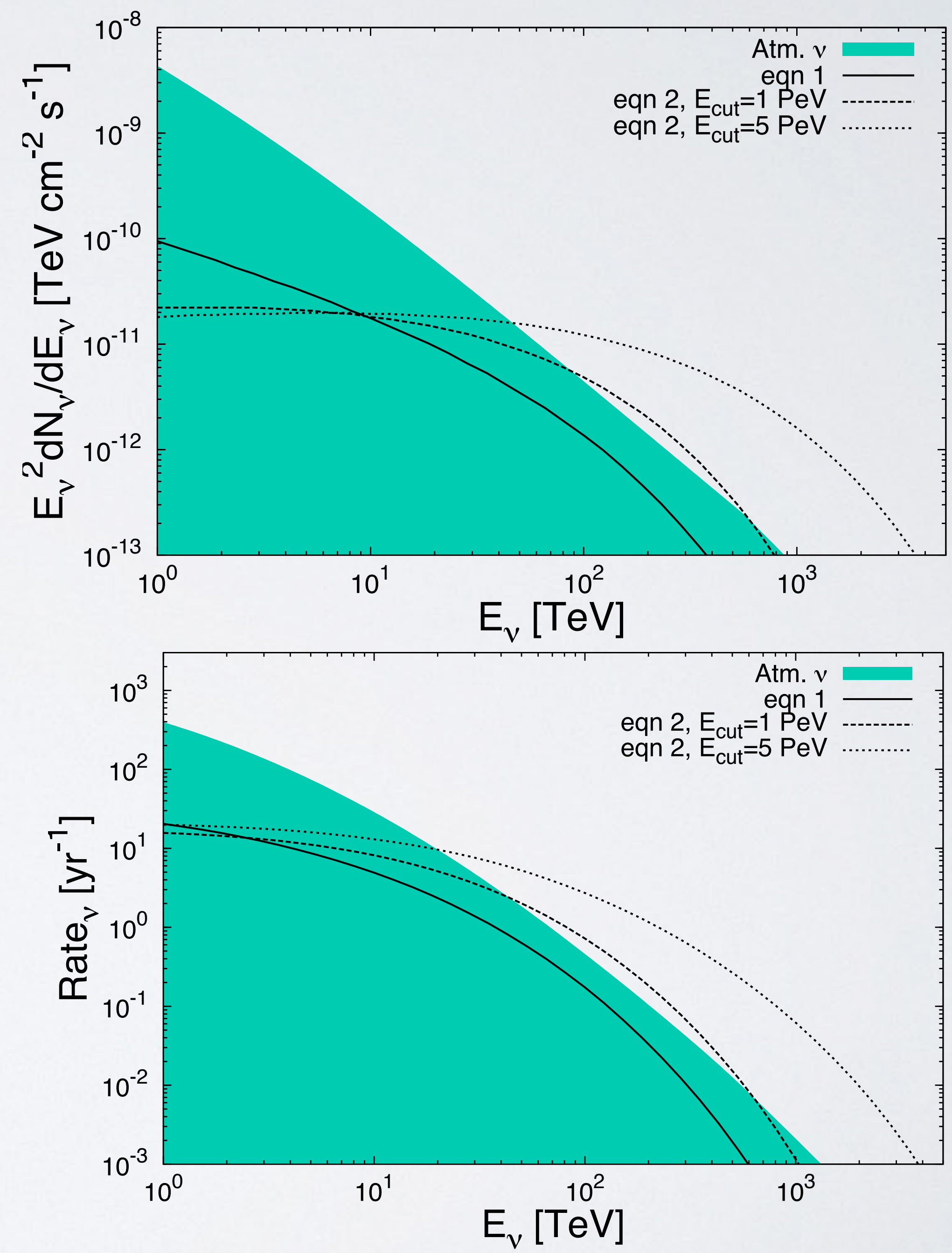
What all this implies for neutrinos ?

The possible relevance of Milagro excess for neutrinos

harder CR in the inner Galaxy
- spectral break (due e.g. to propagation)
- harder component

Gabici et al. arXiV:0806.2459





IceCube measured ν events

IceCube coll. PRL 2013 and PRL 2014

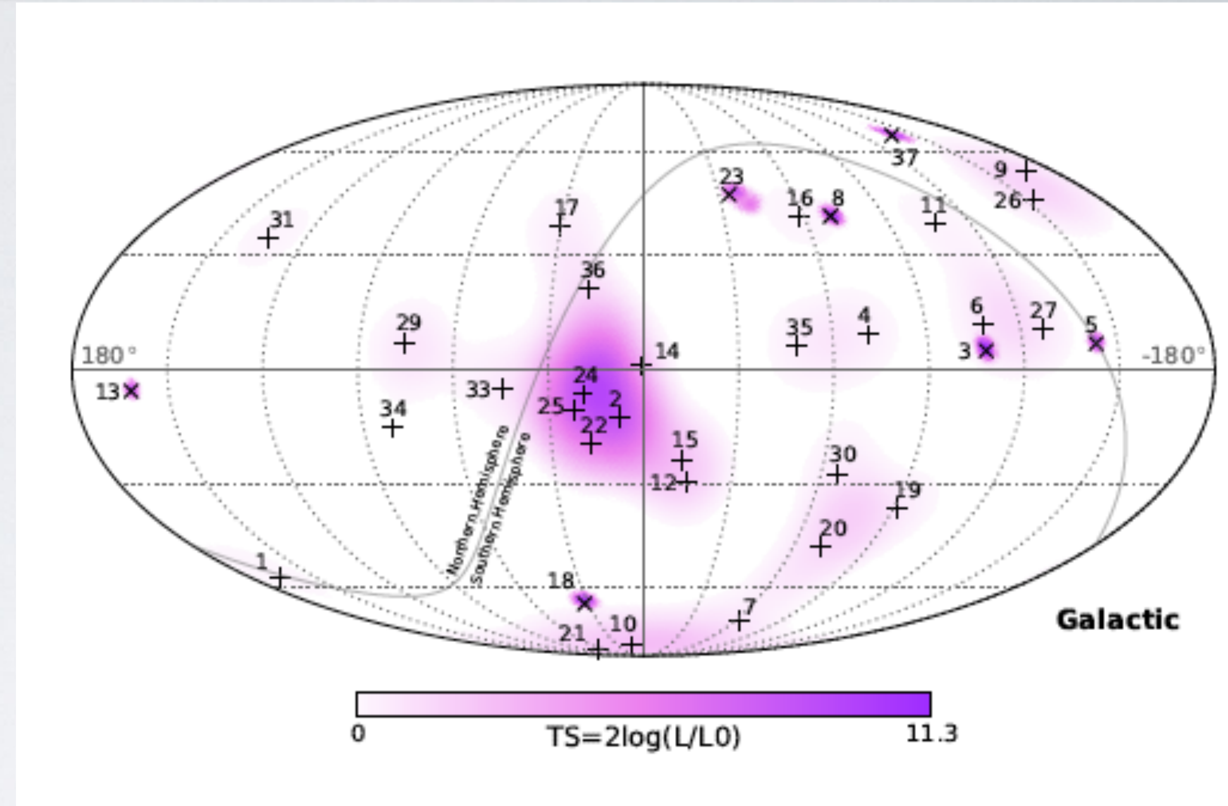
IceCube found evidence for 28 (2 years) then **37 HESE events** (3 yrs) with reconstructed direction above 30 TeV corresponding to a
5.7σ excess respect to the atm. bkg.

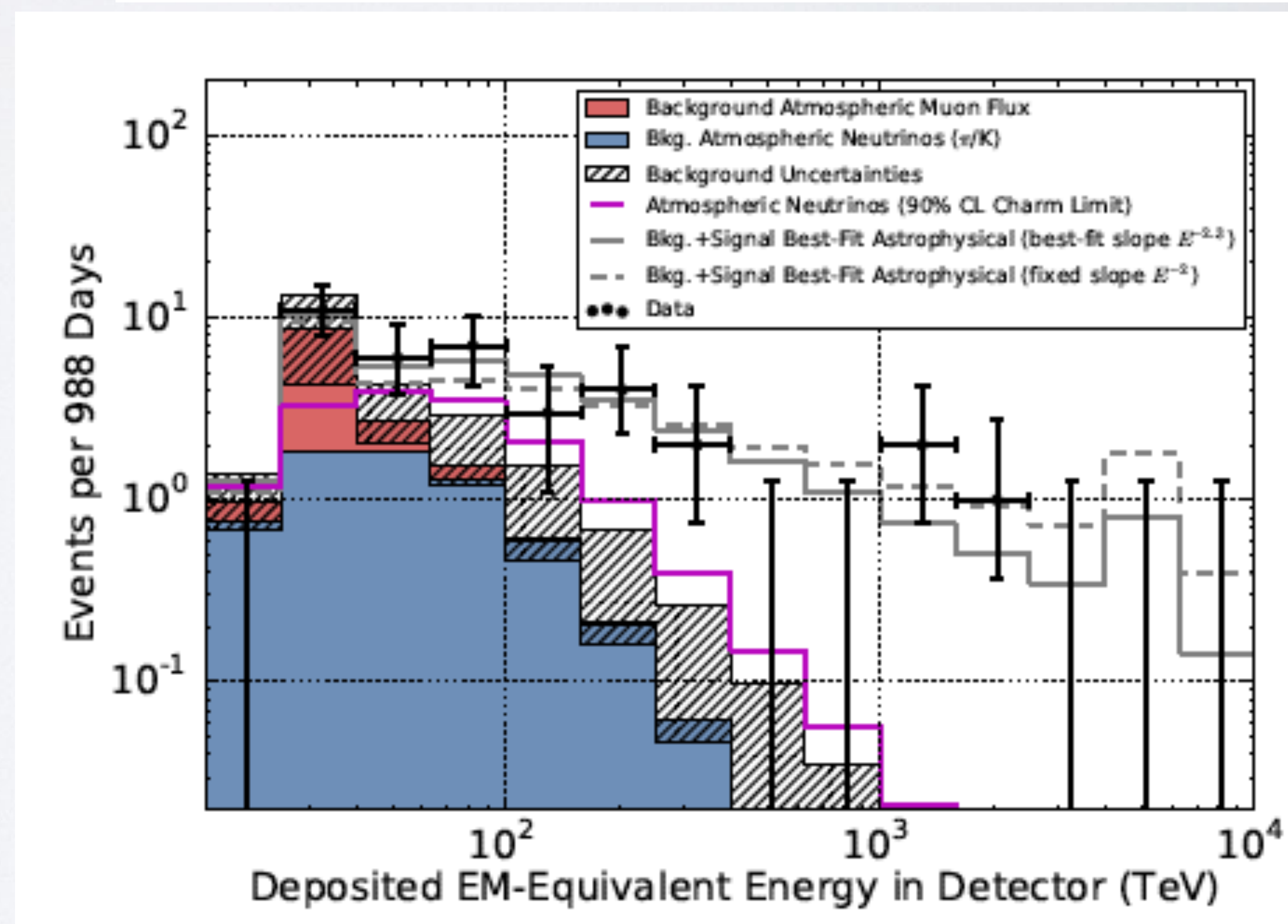
angular distribution compatible with isotropy (see however below)

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

Best fit spectral index above 60 TeV

- 2.3 ± 0.3





IceCube astrophysical neutrinos: present status

arXiv1510.05223, ICRC2015

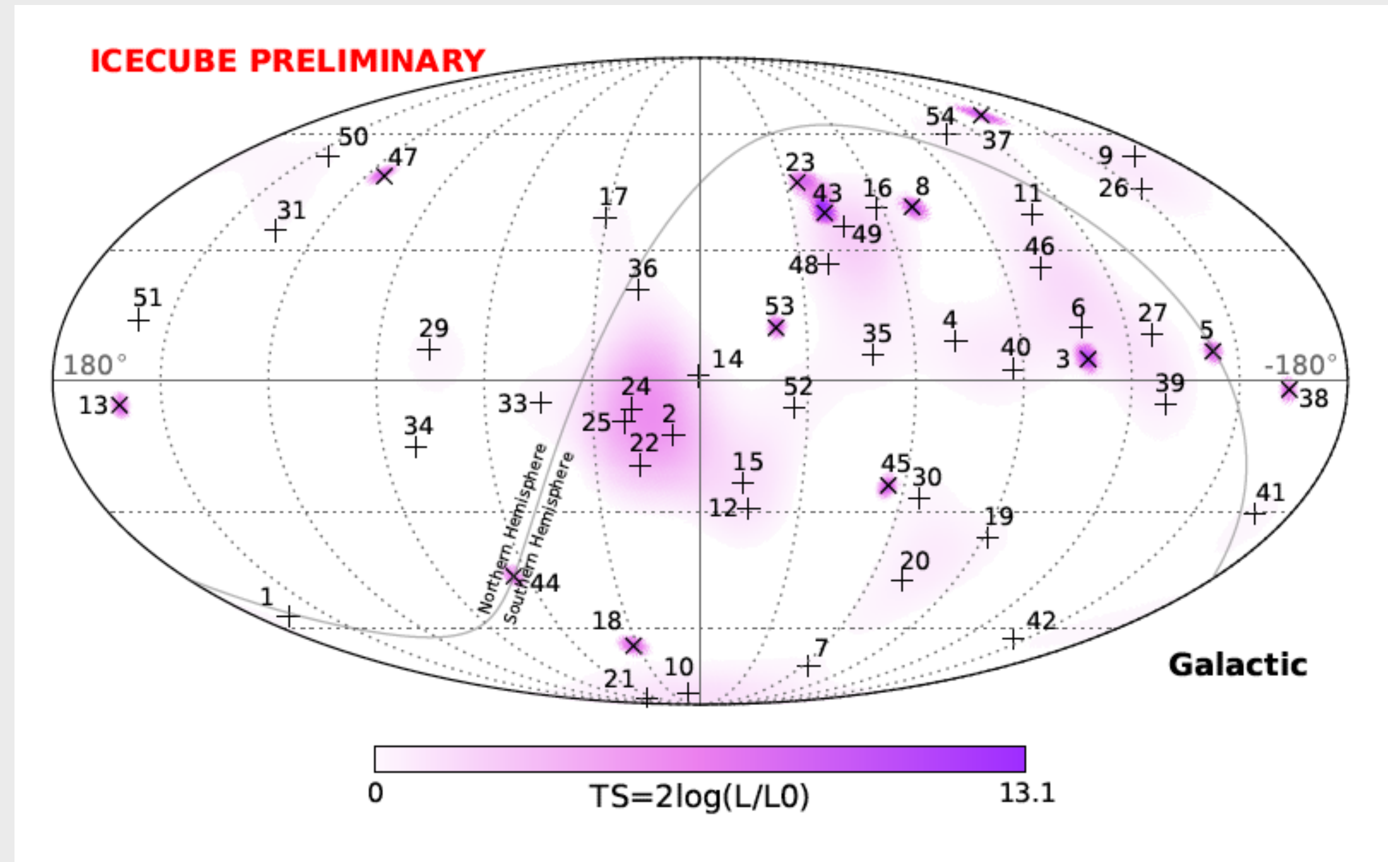
IceCube found evidence for 54 events (4 yrs preliminary) with reconstructed direction above 30 TeV corresponding to 7σ excess respect to the atm. bkg. ($9^{+8}_{-2.2}$)

angular distribution compatible with isotropy (see however below)

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

Best fit spectral index Γ ~ - 2.58 ± 0.25

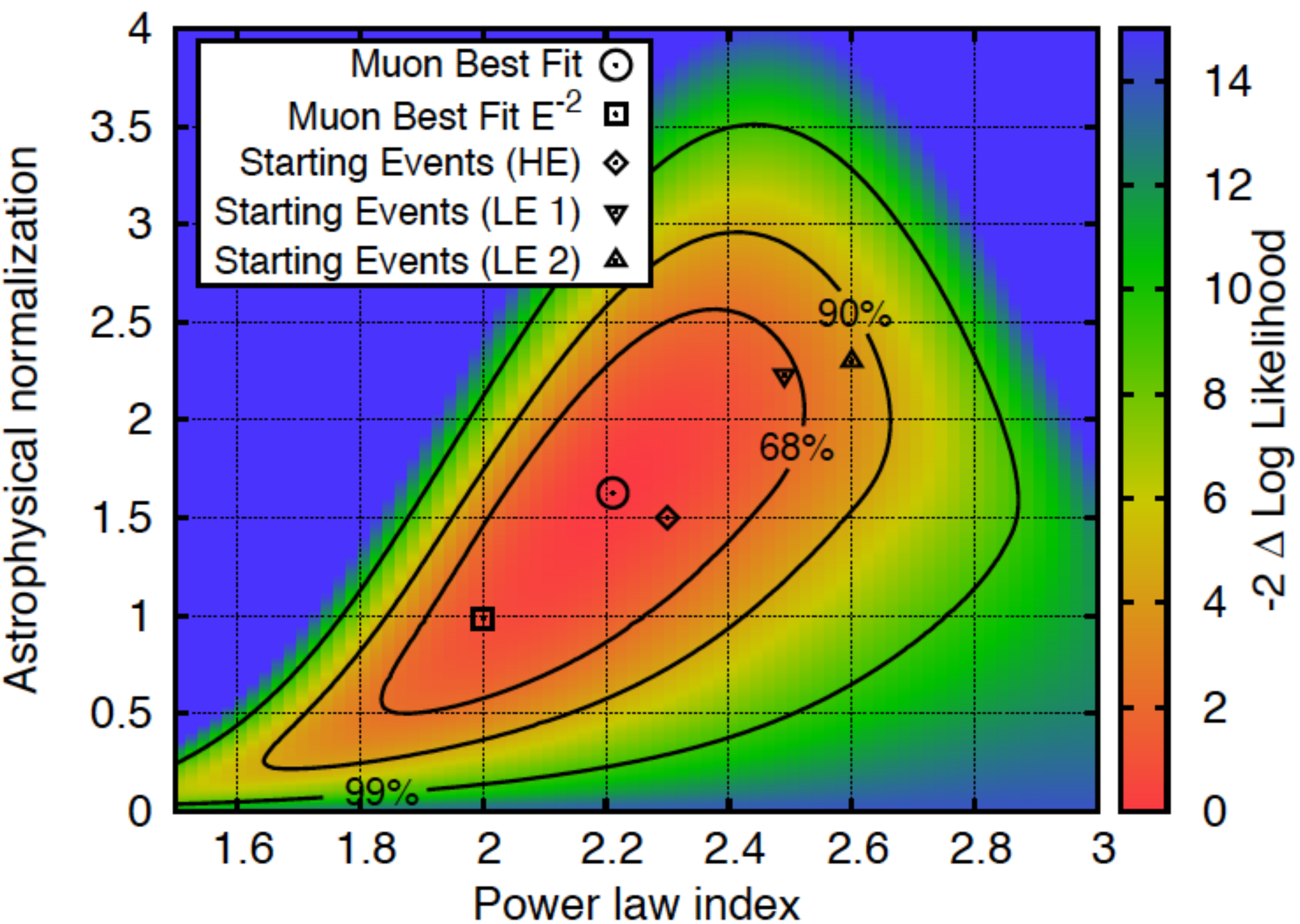
A similar spectrum found from a template fit analysis including severa kind of events down to 25 TeV, *IceCube coll. ApJ 2015*

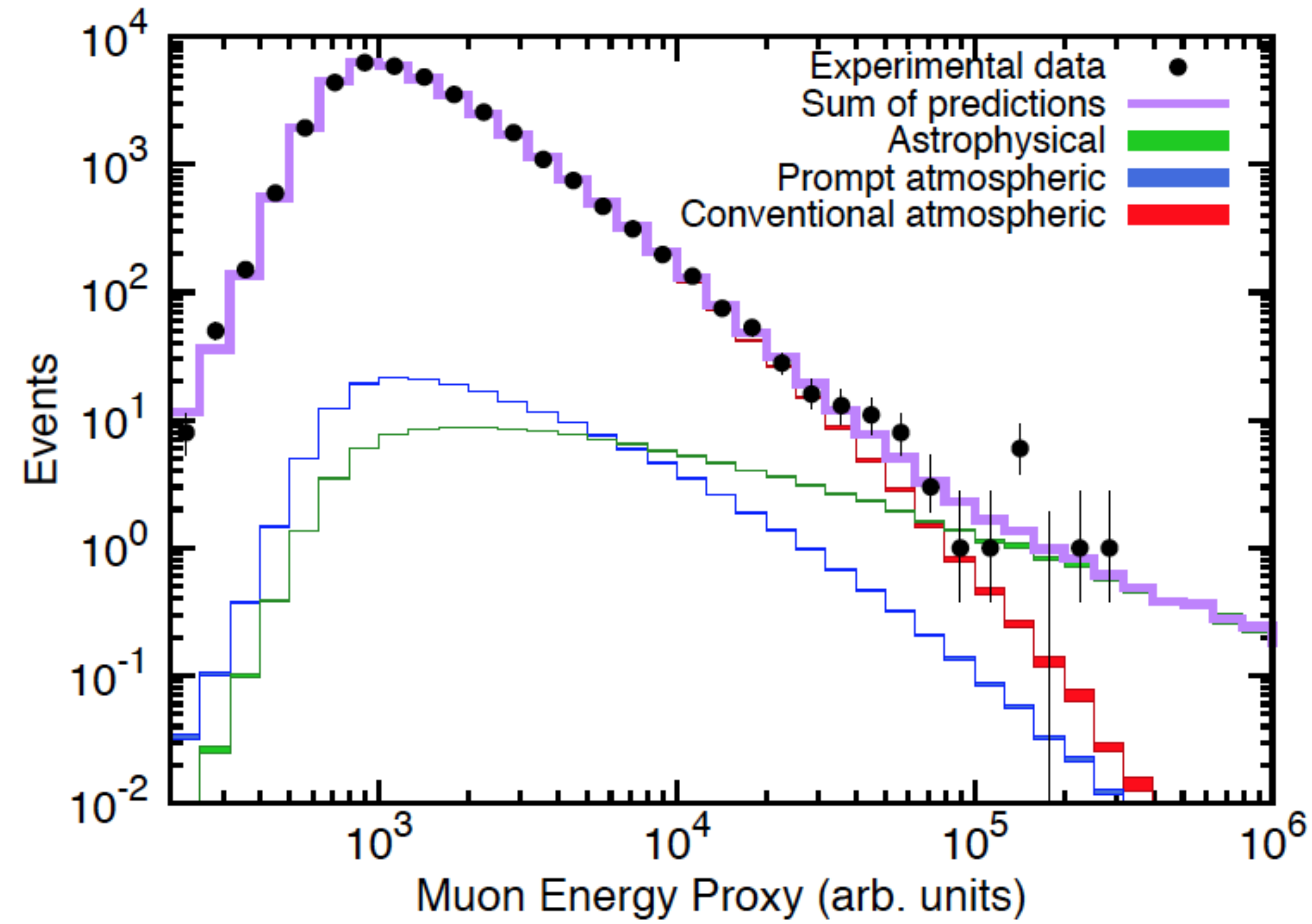


X (track) **+** (shower)

Muon neutrinos (tracks) from the North hemisphere

IceCube coll., PRL, vol.115, 2015





- astrophysical muon neutrinos from the Northern hemisphere with E > 100 TeV.

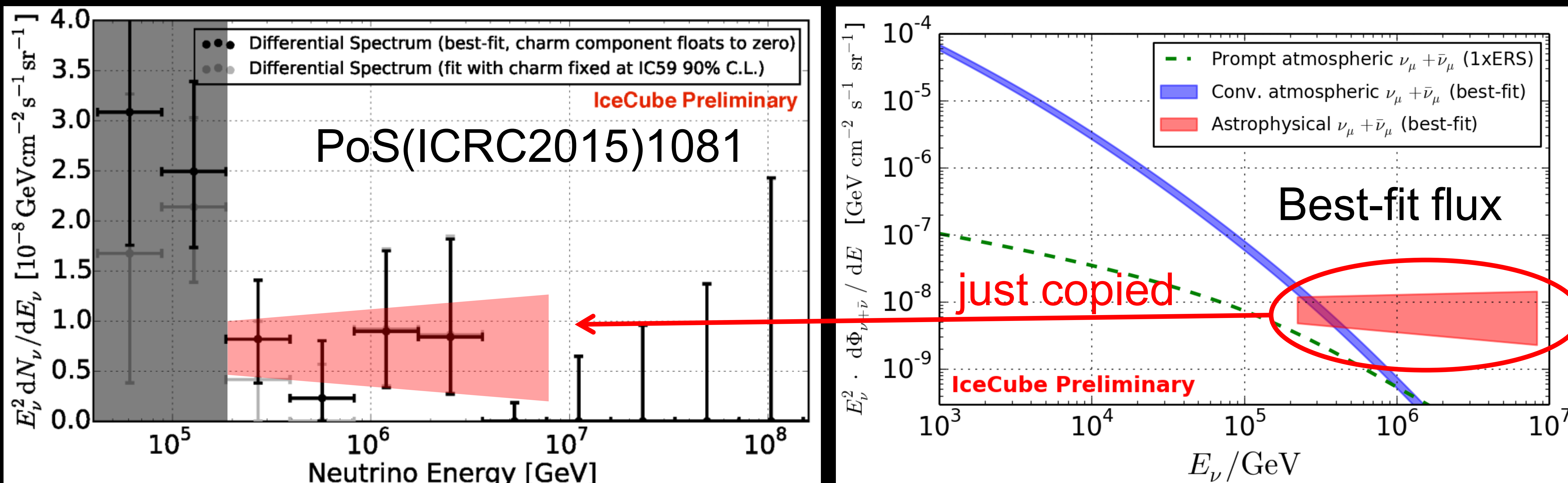
The neutrinos collected during 659.5 days of live time between May 2010 and May 2012 are inconsistent with the background at the level of **3.7 σ**.

- Assuming a single power-law the best-fit spectral index is $\Gamma = - 2.2 \pm 0.2$.

Comparison to HESE 4 year

HESE 4 year unfolding
(→ dominated by shower-like events)

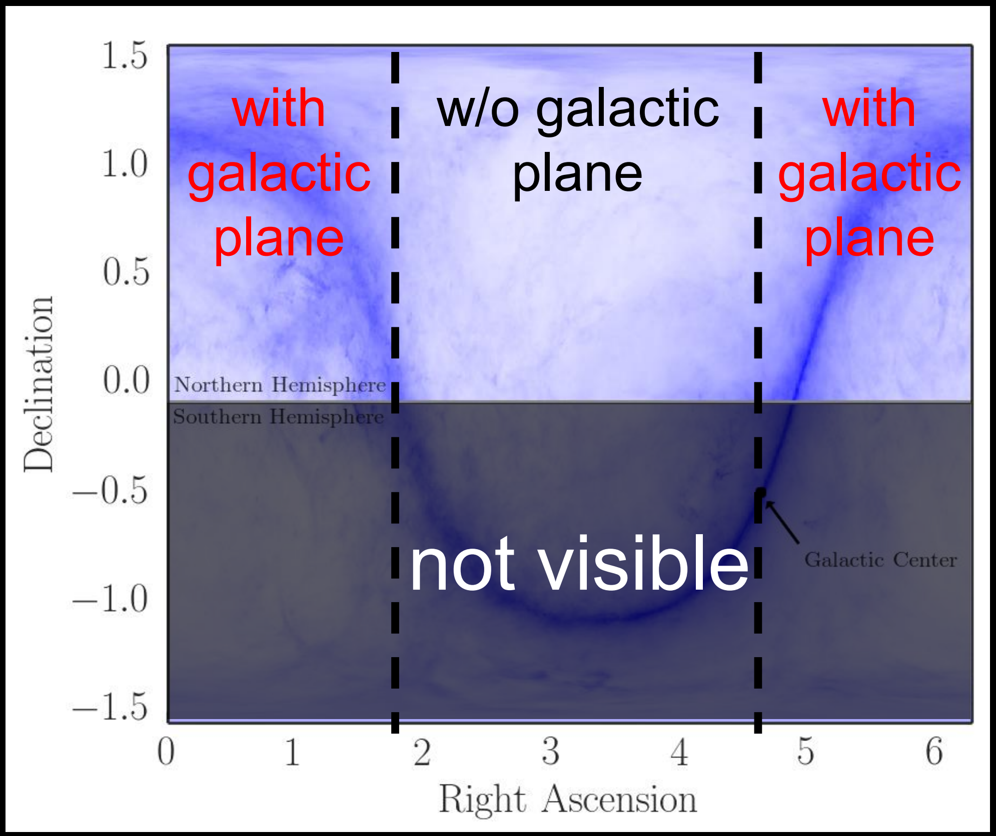
6 year up-going numu analysis

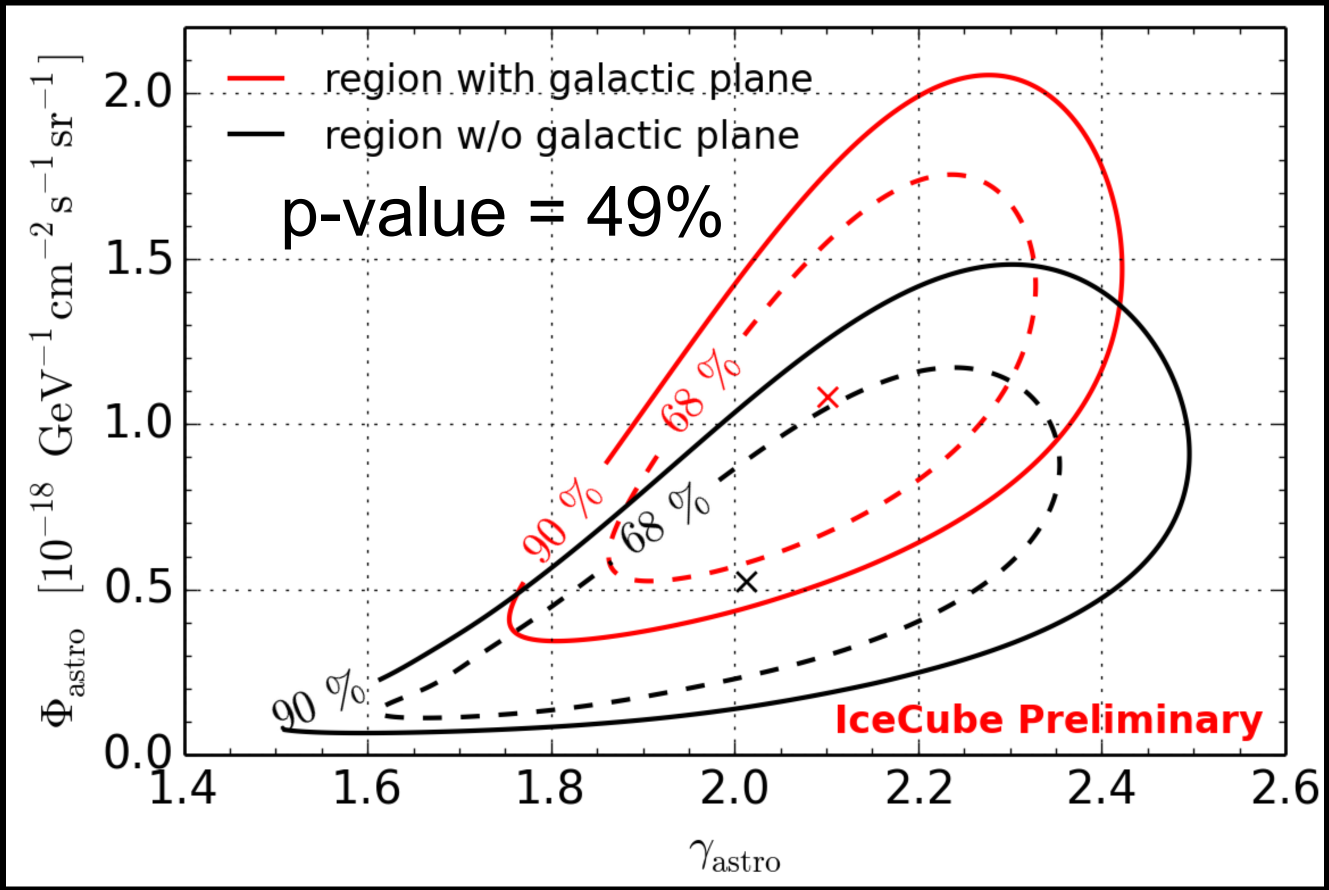


- Energy threshold @ about 60TeV
  → Softer spectral index currently driven by low energy bin
- Energy threshold @ about 200TeV
- @ high energies ($\gtrsim$ 200 TeV) HESE 4 year analysis (left) compatible with E^{-2}

Results of a simple galactic plane analysis

- Question: Could a dominant galactic component be the reason for the tension?
  - Split data into two right ascension regions with similar amount of statistics





- Fits compatible: p-value = 49%
  → No evidence for a dominant flux from the galactic plane
- Fit of region with galactic plane has slightly higher norm. and softer spectral index
  → Hint for a galactic component?

Other hints of an anisotropic flux ?

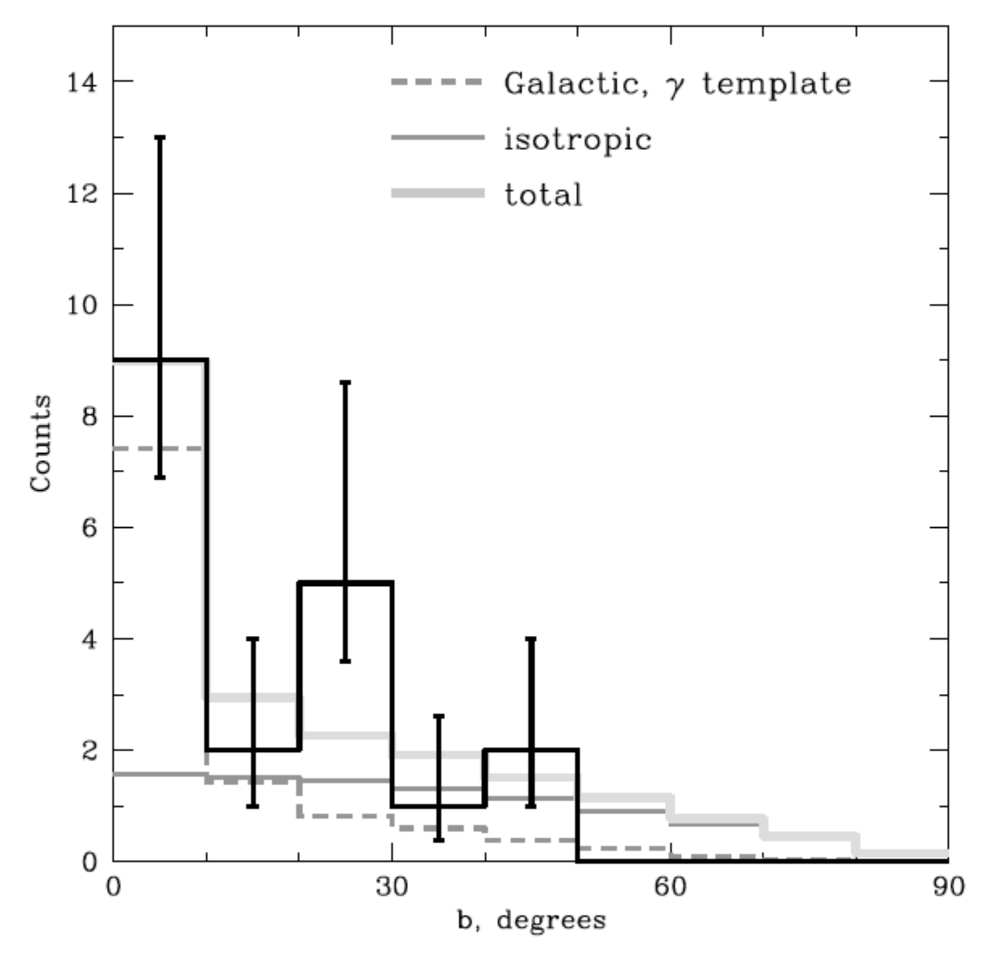
Neronov & Semikoz arXiv:1509.03522

use only events above 100 TeV in the IC 4-year sample (19 events, 1 bkg)

9 events for | b | < 10° ; 0 events for | b | > 50°

They found ~ 4 σ inconsistency with isotropy

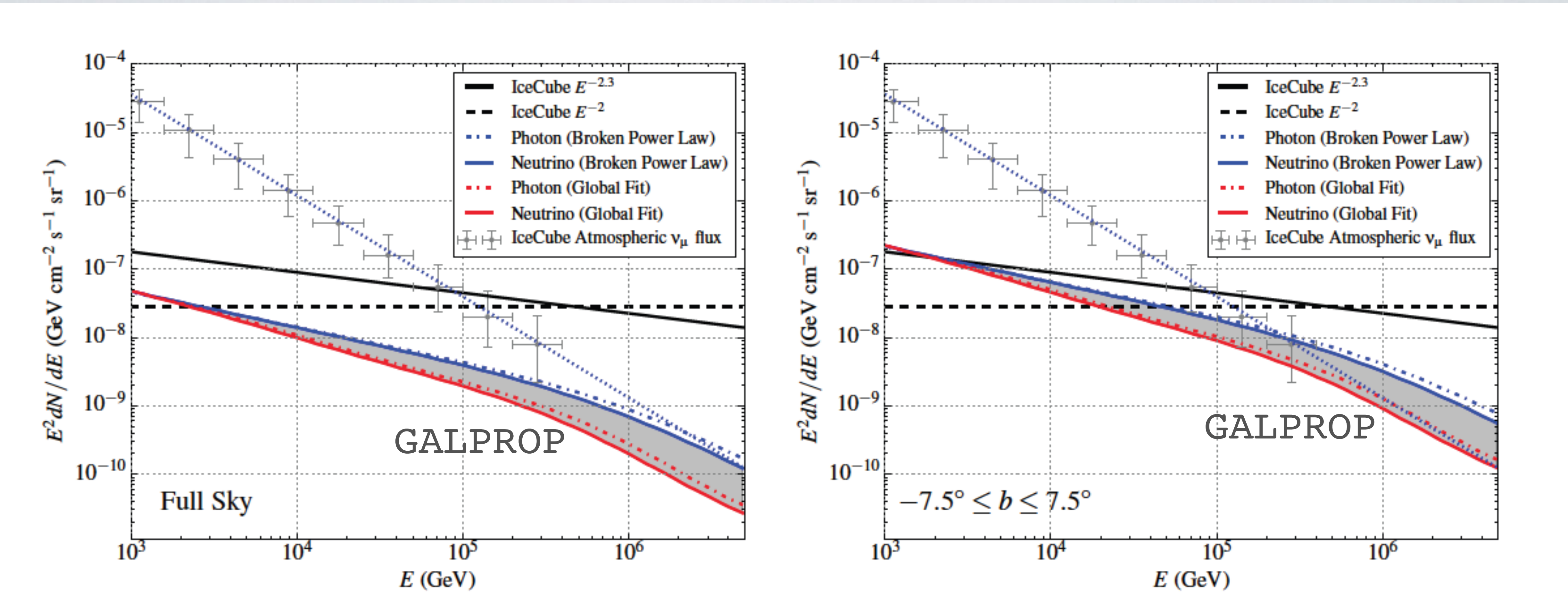
It is claimed that "*a model which contains 50% contributions from the Galactic and extragalactic components provides a satisfactory fit to the data*"



A more recent analysis by ***Palladino & Vissani arXiV :1601:06678(v2)*** found that a ~ 20 % contribution is more likely

The Galactic ν emission with conventional models

Ahlers et al. arXiV:1505.03156

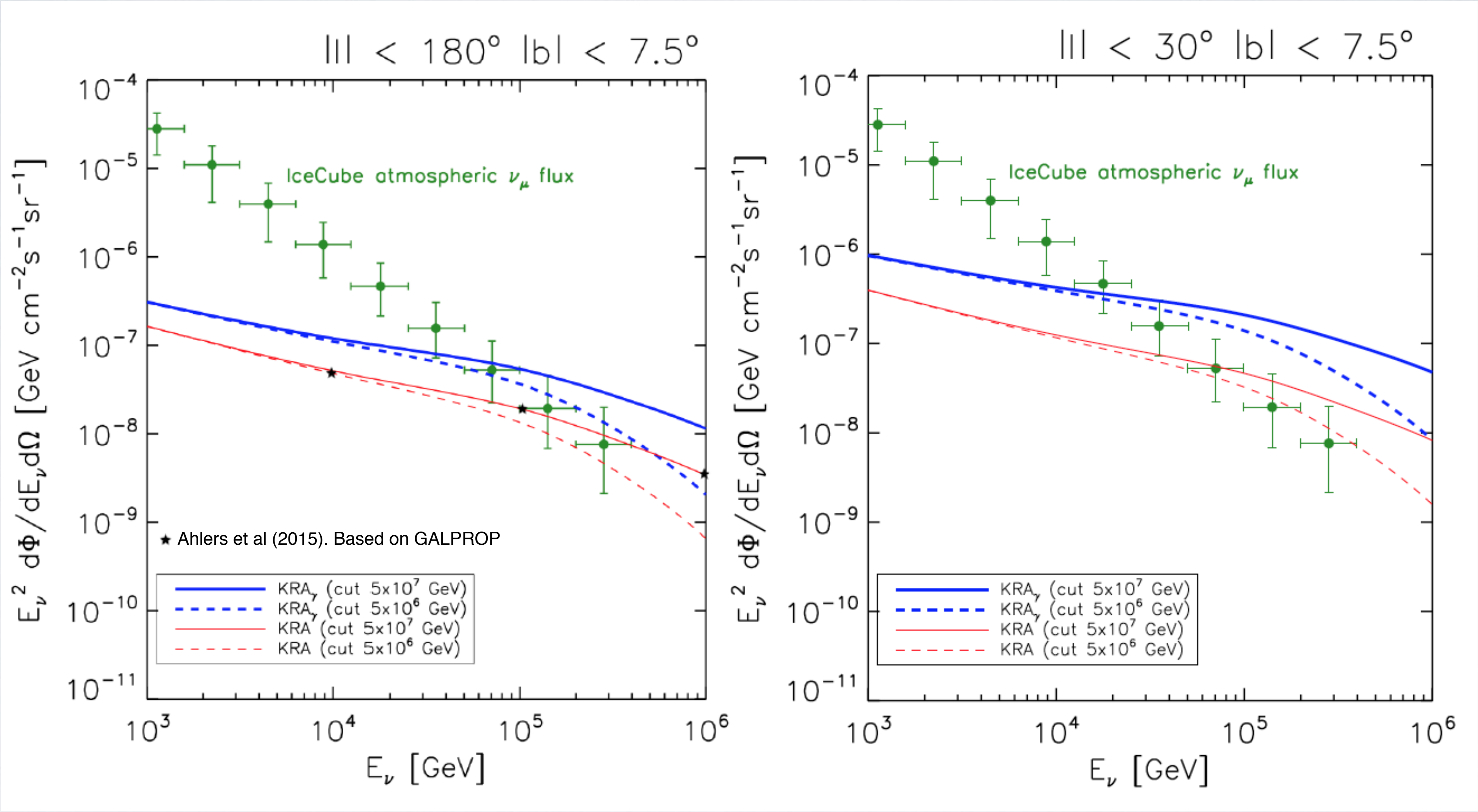


8% of IceCube HESE (2013) signal at most

- 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)

Galactic Plane neutrinos with a variable δ

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

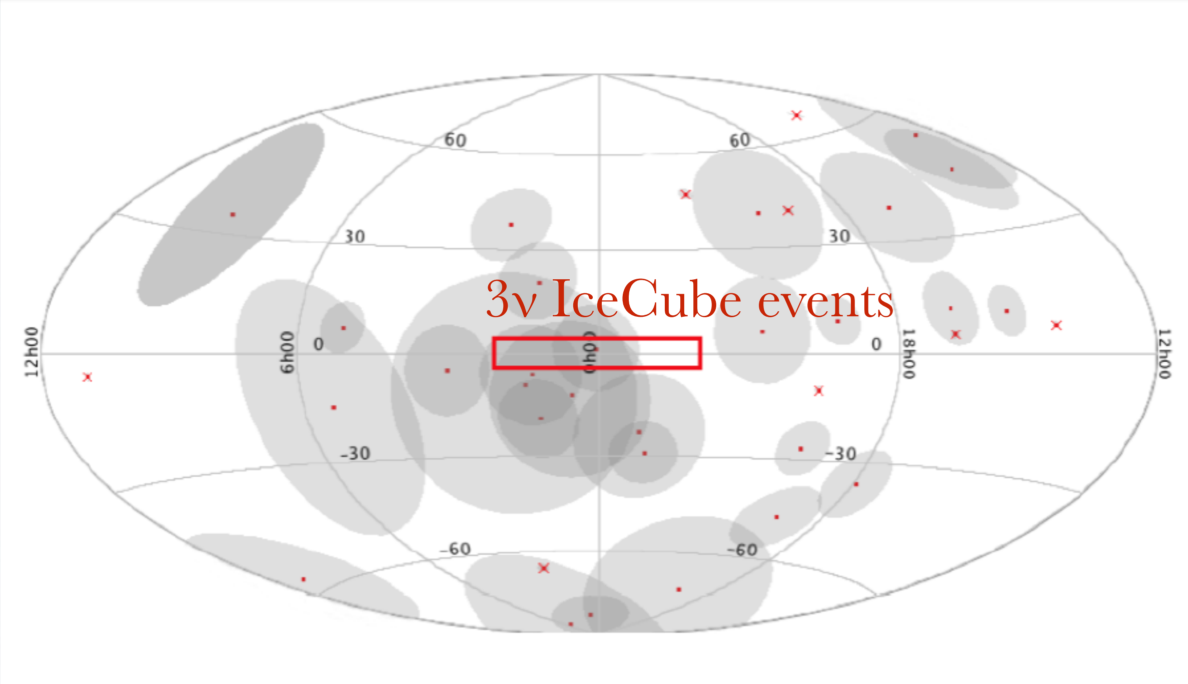


- based on DRAGON (KRA$_\gamma$ model, the same which matches FERMI and Milagro)
- it **adopts harder CR spectra above 250 GeV/n so to match CREAM**
- it adopts phenomenological models for CR spectra in the knee region [two exponential cutoff at E/Z = 5, 50 PeV (dashed, solid lines)]

Comparison with exp. data in the inner GP

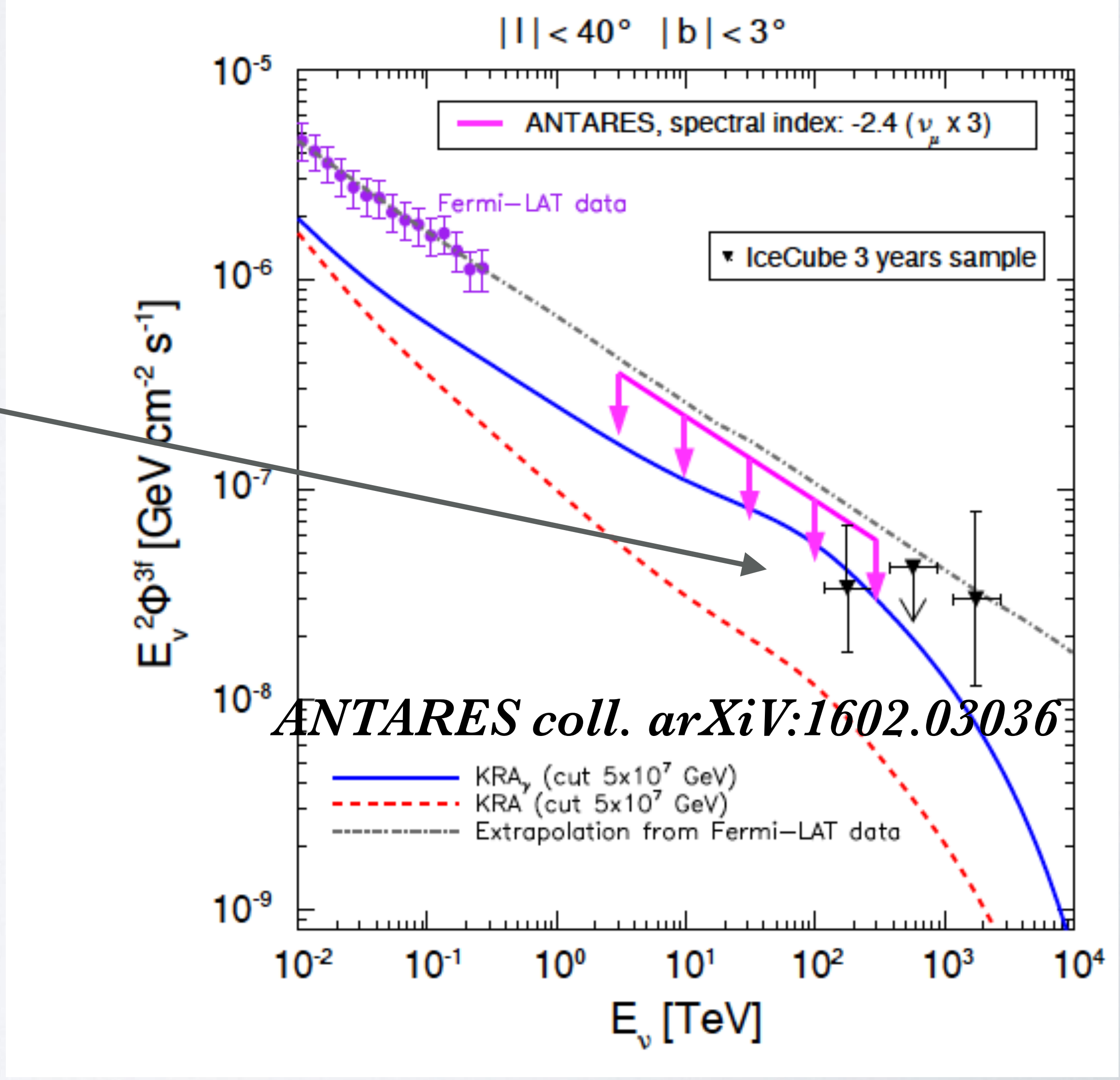
ANTARES coll. arXiV:1602.03036
Marinelli et al. ICRC 2015

2007-2013 ν_μ data E > 1 TeV
no events 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.



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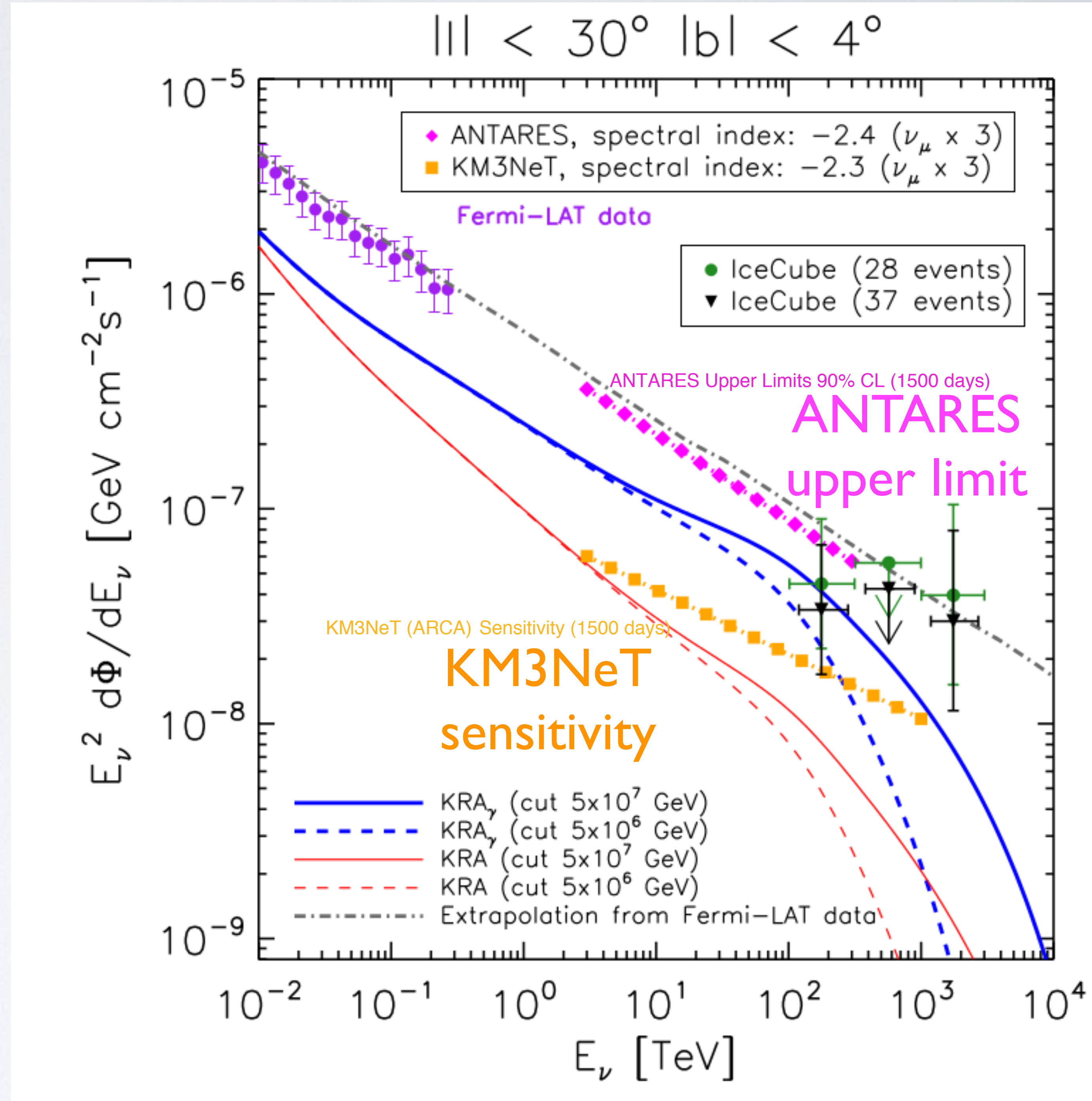


KRAγ full-sky ν emission against IceCube

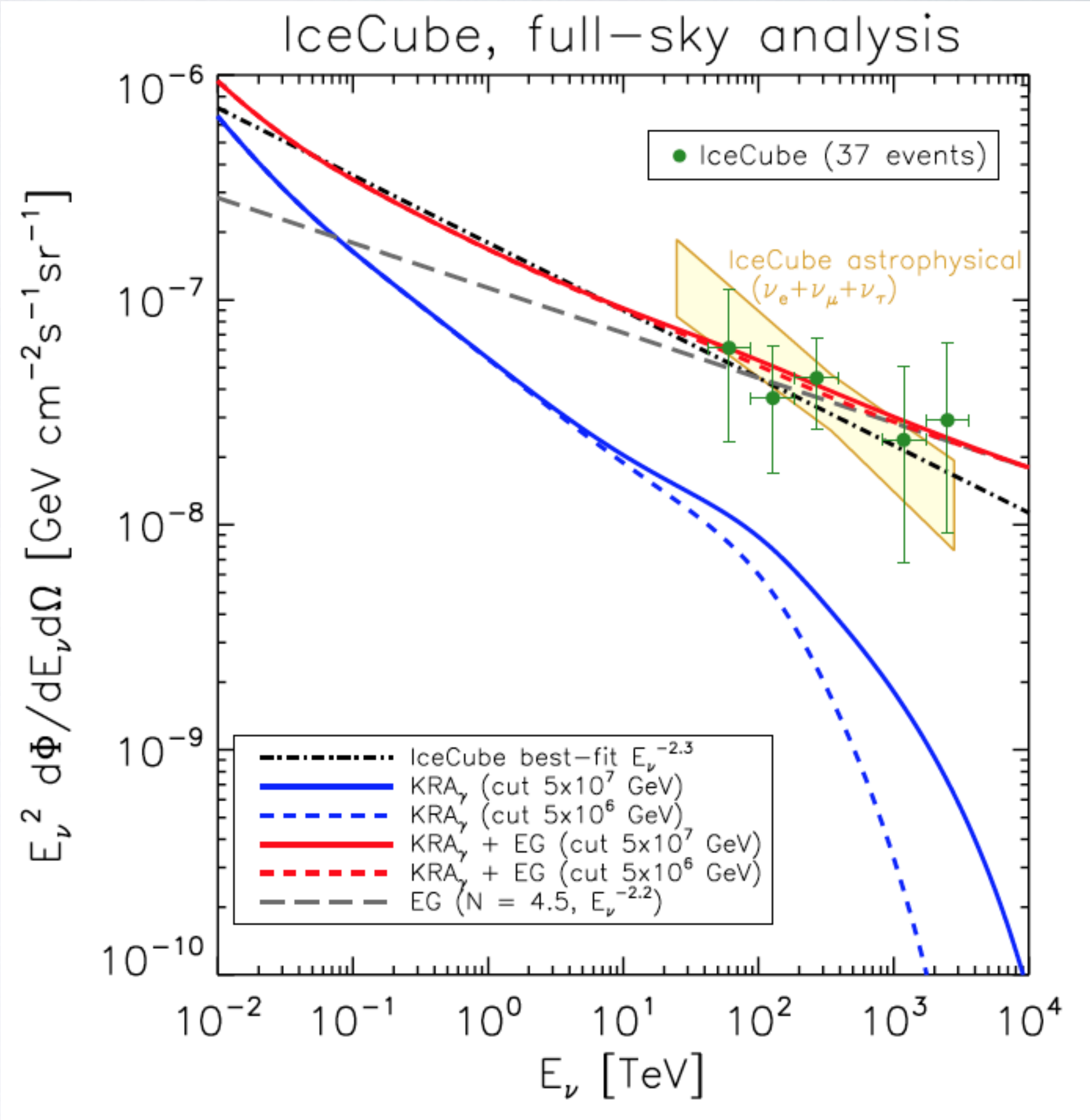
Gaggero, DG, Marinelli, Urbano, Valli, arXiv:1504.00227

The KRAγ setup predicts a flux which is ~ double and slightly harder than the corresponding conventional model.

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

this is clearly compatible with the IC events angular distribution

clearly, a dominant extra-Galactic contribution is required

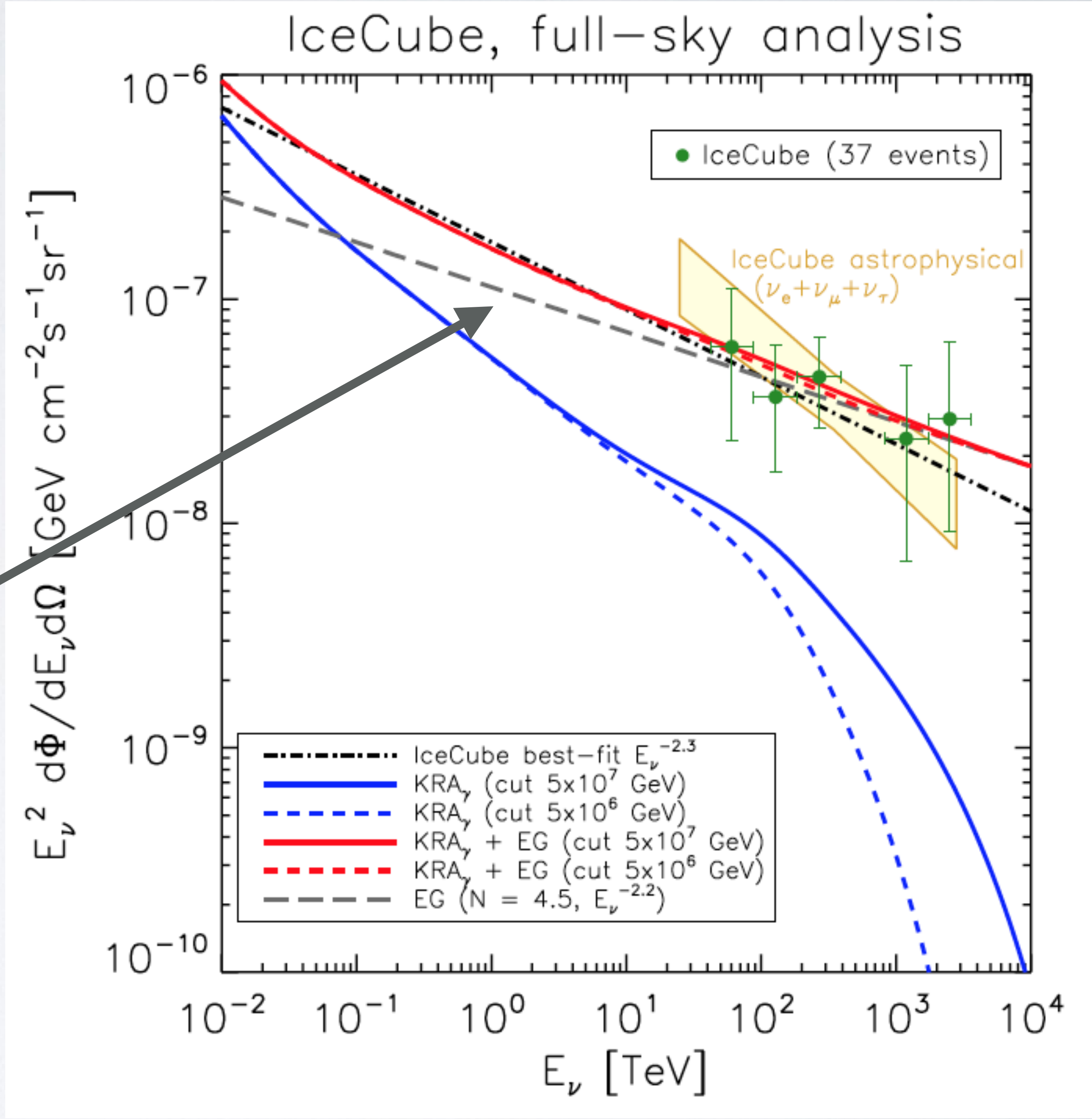


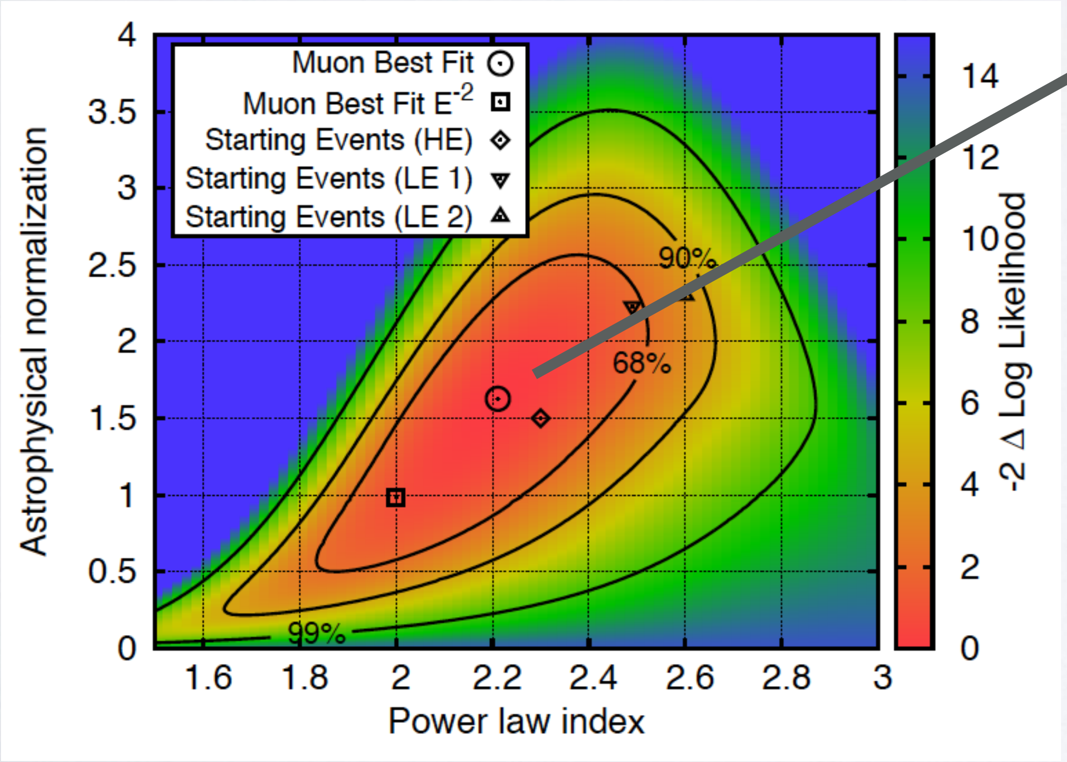
KRAγ full-sky ν emission against IceCube

Gaggero, DG, Marinelli, Urbano, Valli, arXiv:1504.00227

For illustrative purposes

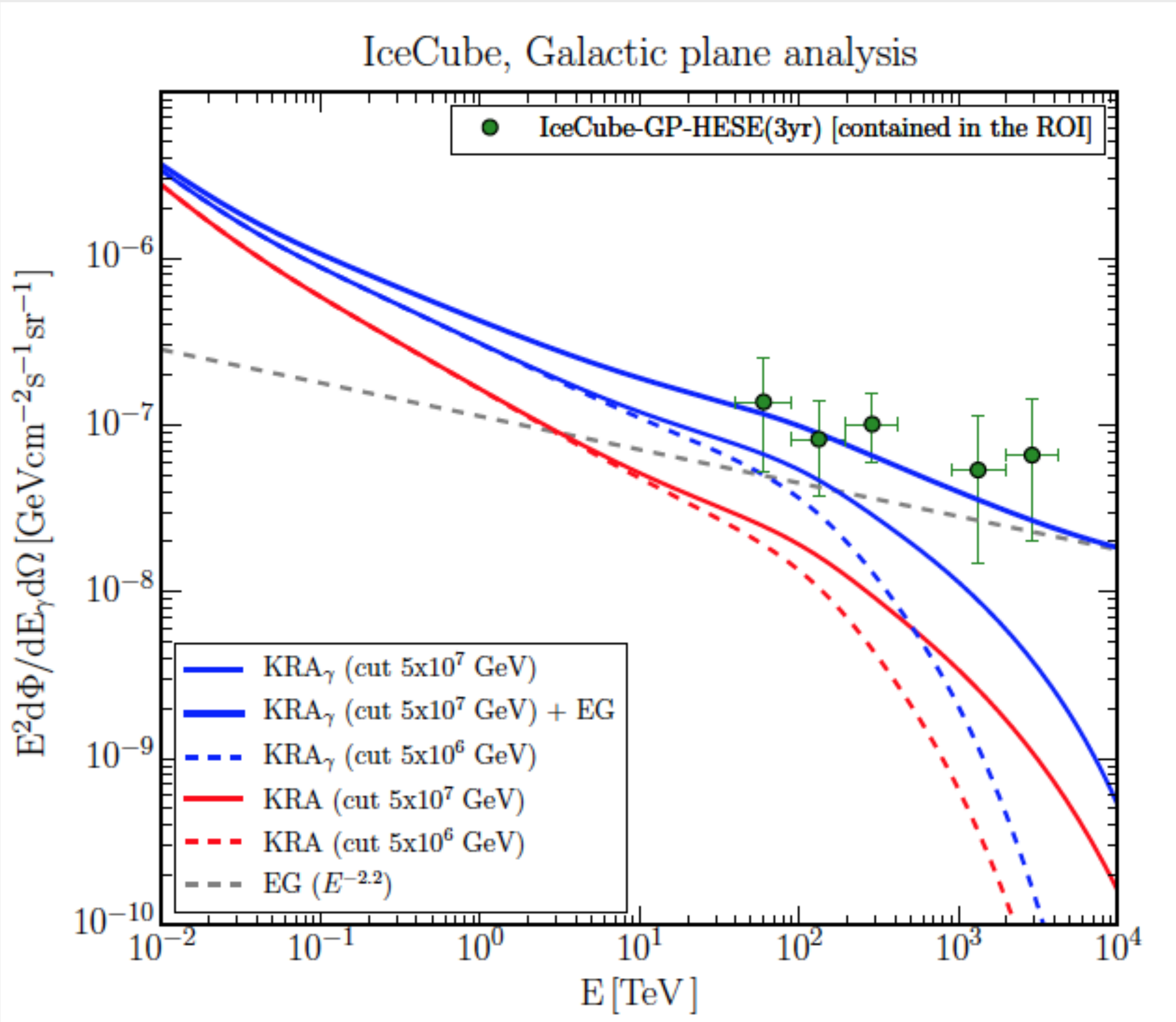
here we assume the ν_μ (tracks) flux (best-fit) measured by IceCube from the northern hemisphere to be representative of the extra-Galactic emission (Gal. emission negligible in that region)

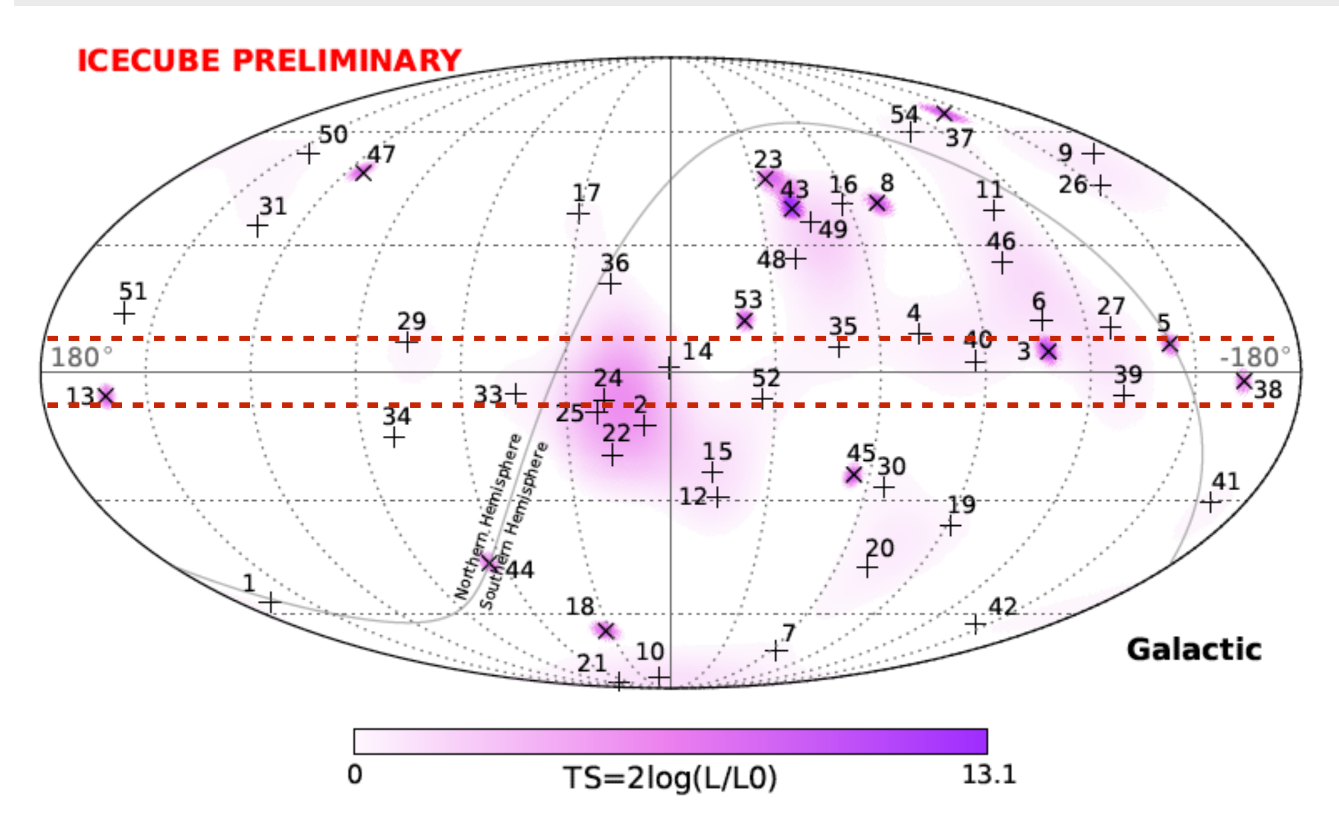




G+EG emission in the GP constrained by IceCube

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.

Forthcoming theoretical work

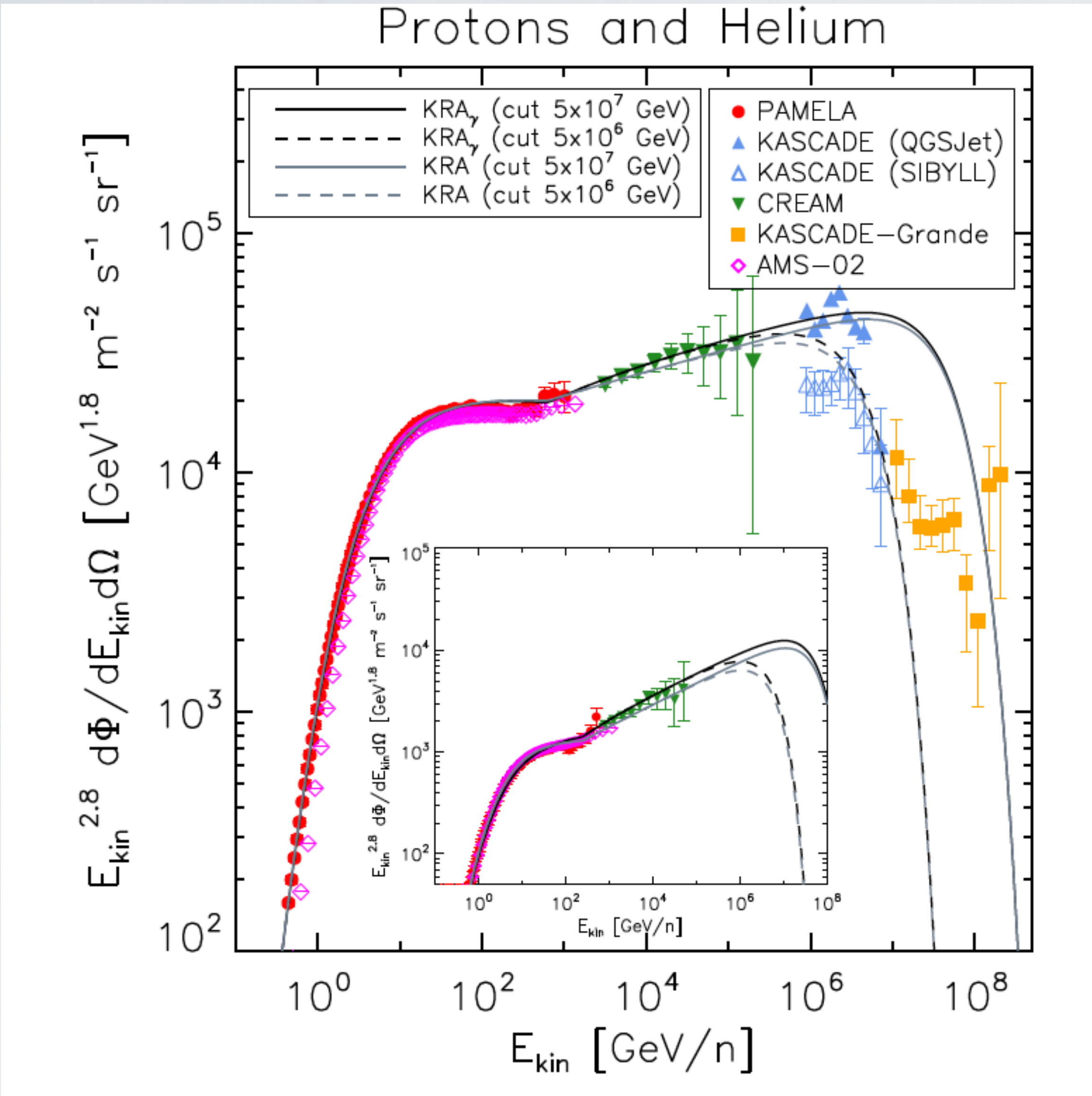
- use updated Fermi-LAT data (PASS8) to get better statistic at high energy and find-out a range of allowed models with δ(R) and make better predictions for HAWC
- use more (better/updated) CR models in the knee region
- explore different physically motivated models which may explain such behavior (anisotropic diffusion; non-linear diffusion; …)
- combine with models of extra-galactic emission (starting with including the emission of external normal galaxies)
- any other suggestion ?

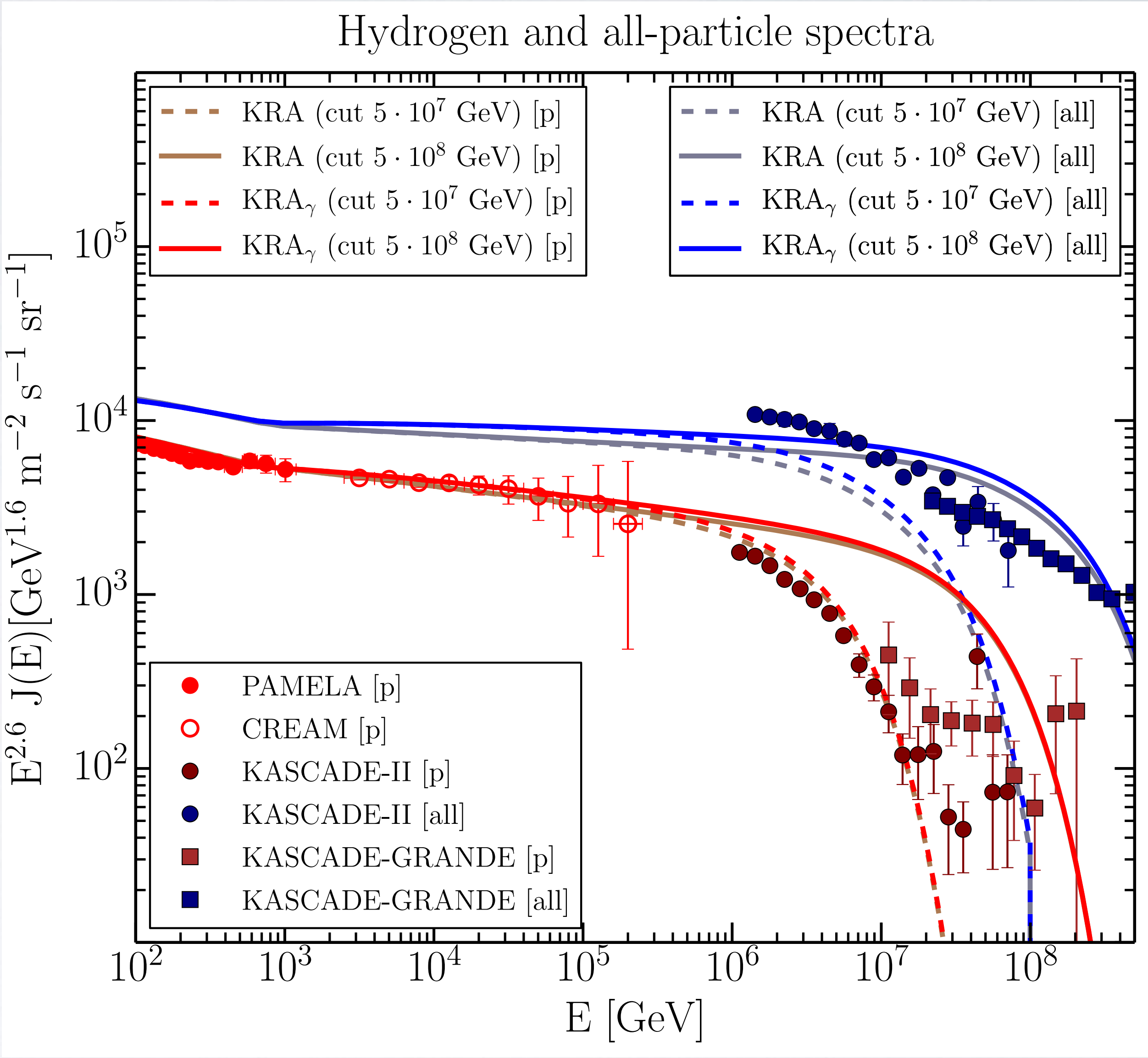
Conclusions

- The γ-ray Galactic diffuse emission measured by Fermi along the GP, which is not reproduced by conventional models, can be interpreted in terms of a radially dependent CR transport model. The same model, when accounting for the CR hardening at 250 GeV/n, allows to reproduce Milagro excess at 15 TeV
- Respect to conventional models this scenario predicts a significantly larger Galactic neutrino flux along the Galactic center/plane testable by IceCube, ANTARES (marginally) and Km3NeT
- The CR population in the Galactic center region is harder and higher than in conventional model which is in agreement with HESS 2006 results. It may account for a large fraction of the diffuse emission in the GC region found by HESS 2016 (pevatron excess).

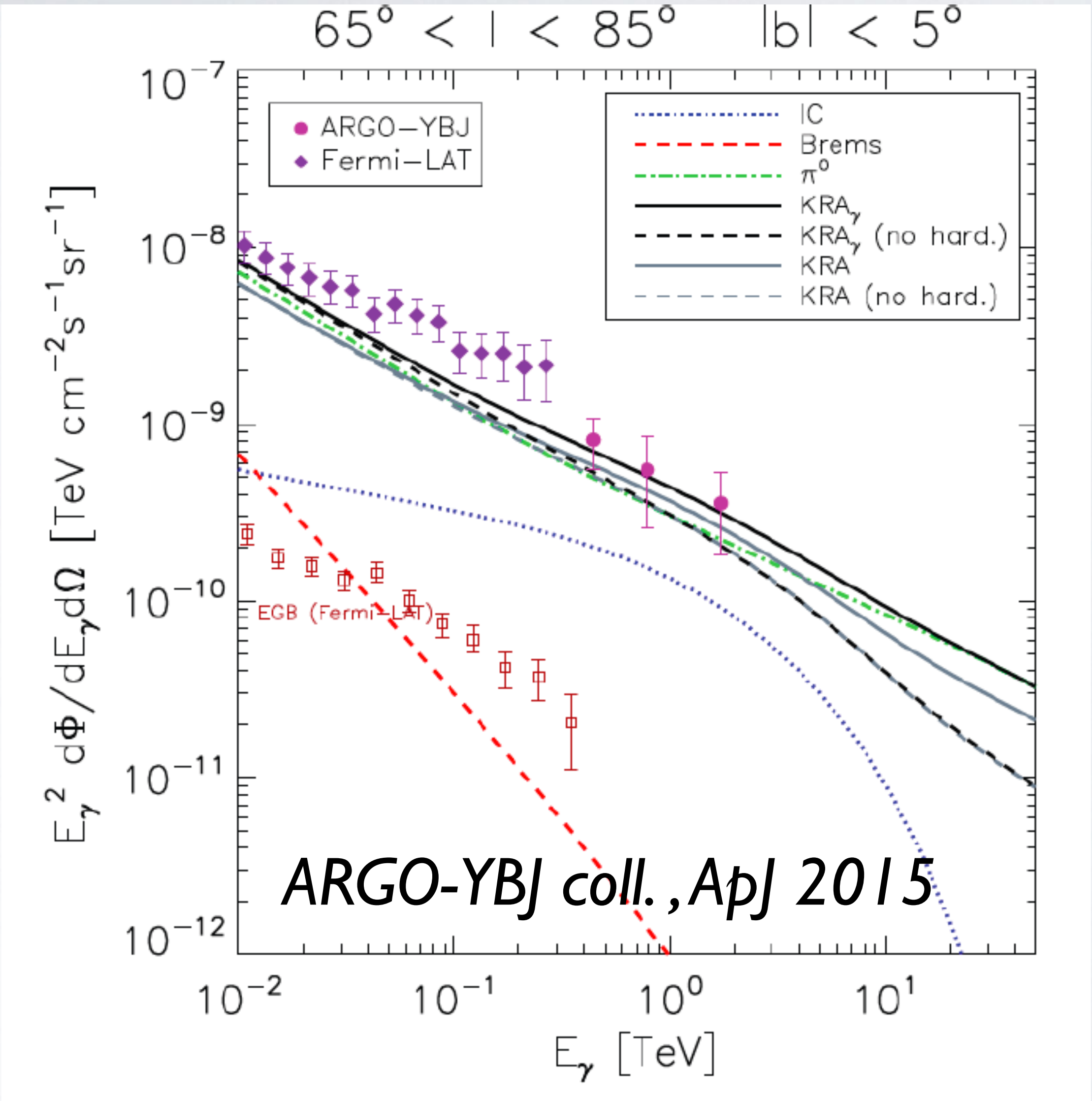
Backup slides

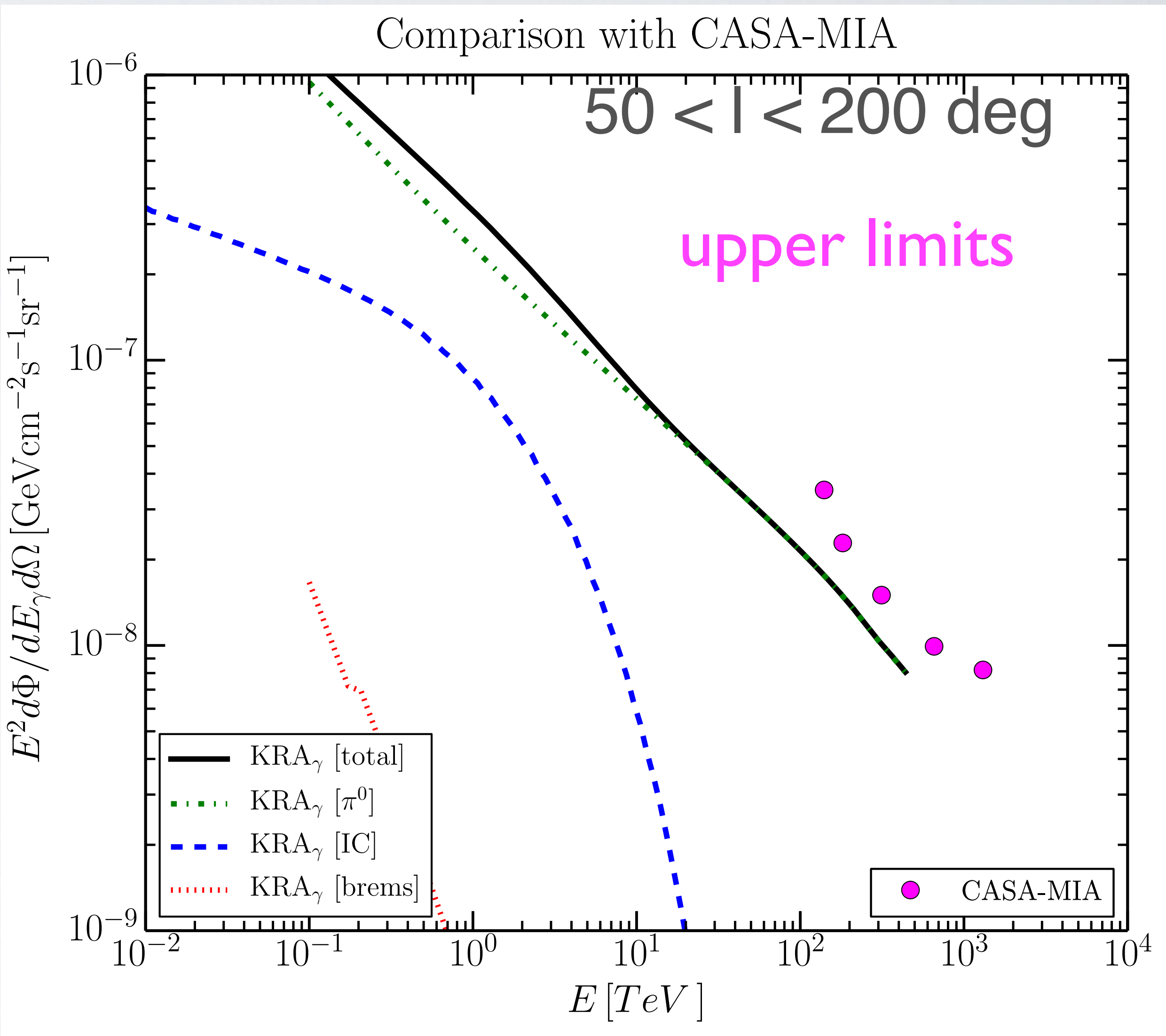
Our CR primary spectra





Comparison with other high energy γ-ray data



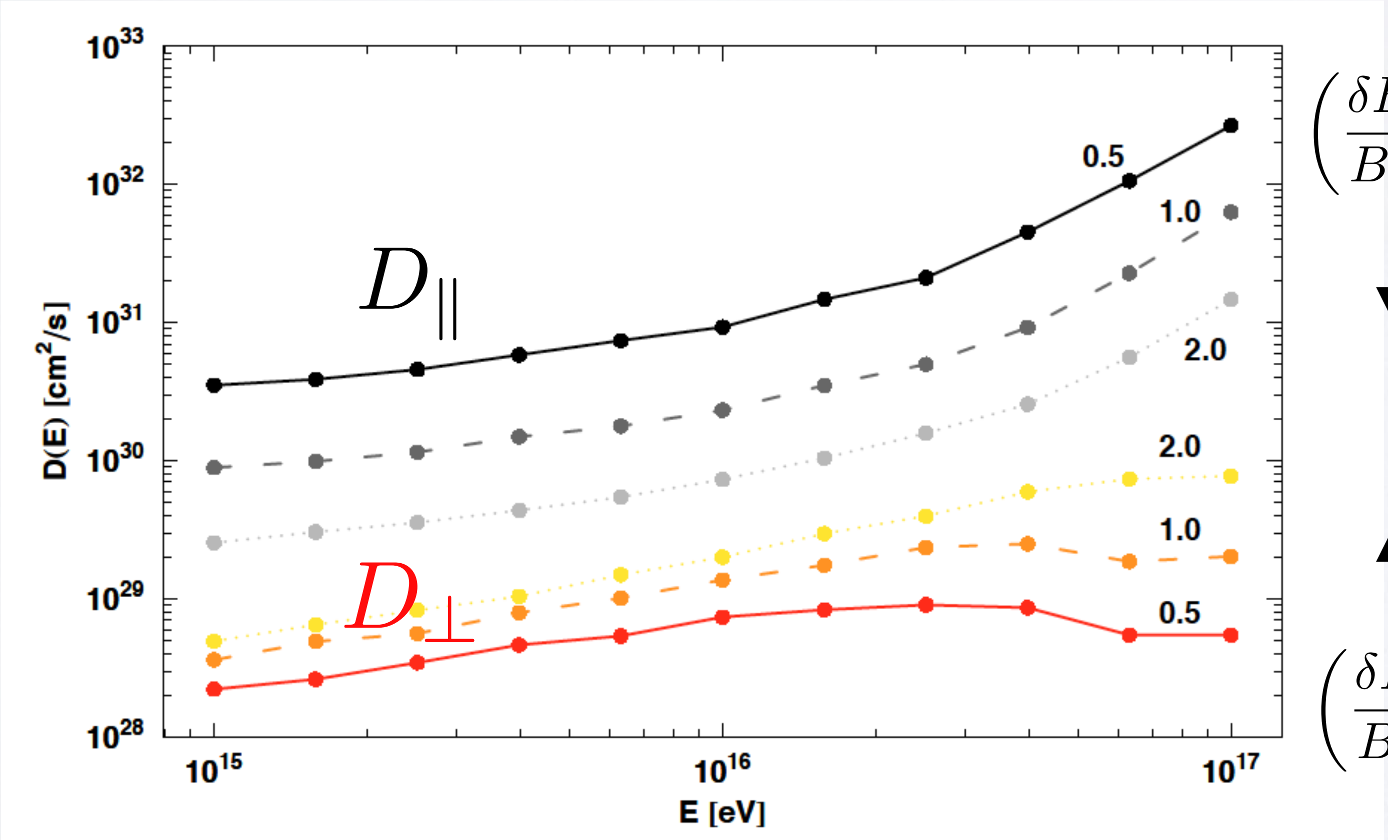


A possible origin of δ(R) from anisotropic diffusion

The presence of regular MF breaks isotropy D ⇒

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

Even in the quasi-linear theory $D_{\parallel}$ and $D_{\perp}$ have opposite dependence on the turbulent power. This is confirmed by ray tracing simulations in strong turbulence regime



$$\left(\frac{\delta B}{B_0}\right)^2 \downarrow \qquad \uparrow \left(\frac{\delta B}{B_0}\right)^2$$

De Marco, Blasi & Stanev 2007
(see also Casse et al. 2002)

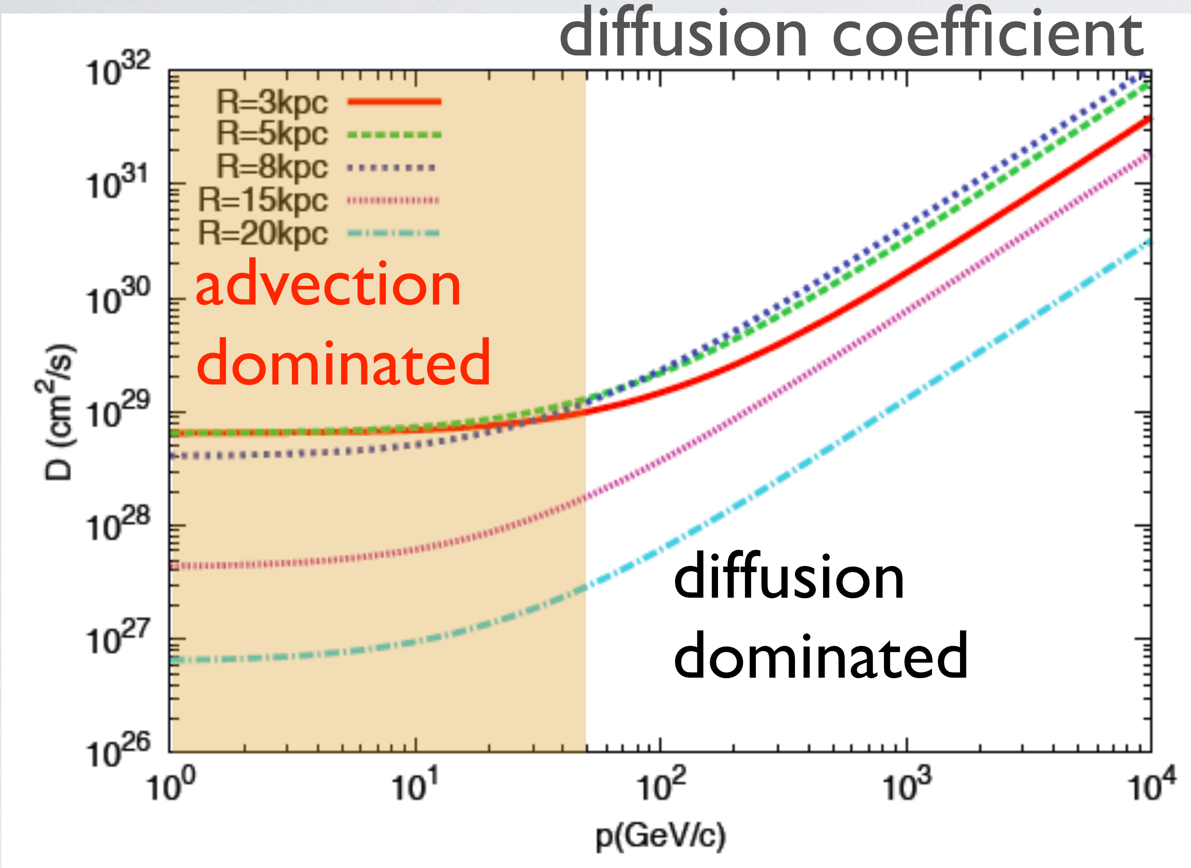
for Kolmogorov turbulence

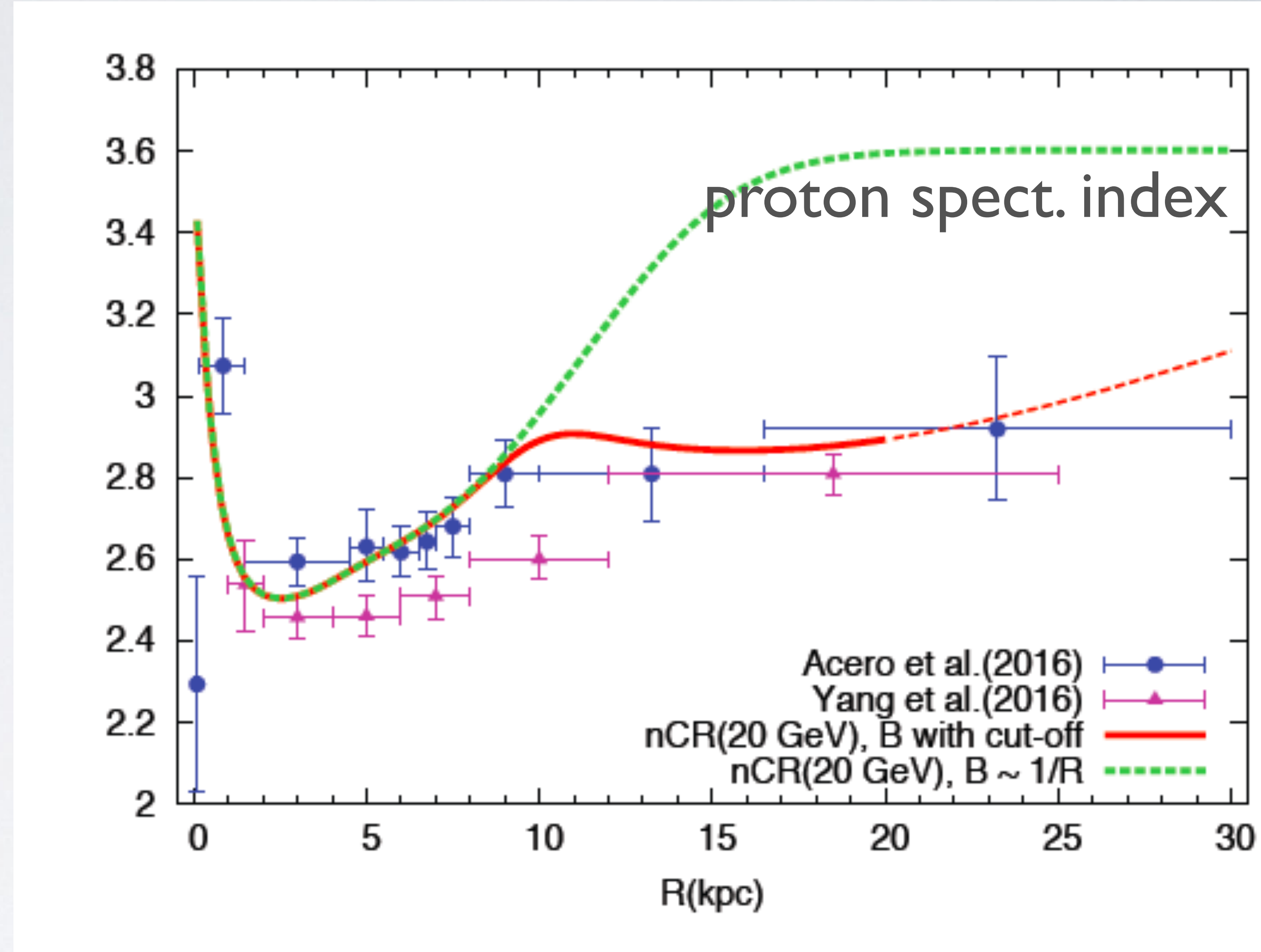
$$D_{\parallel}(E) \propto E^{1/3}$$

$$D_{\perp}(E) \propto E^{0.5\div 0.6}$$

The case for a spatial dependent δ
A possible interpretation ?

Recchia, Blasi & Morlino arXiv:1604.07682





- CR advect/diffuse in self-generated Alfven-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

Note however that this is a low energy effect !!

This is at odd with Fermi data and Milagro anomaly (HAWC may soon confirm !)

A possible origin of δ(R) from anisotropic diffusion

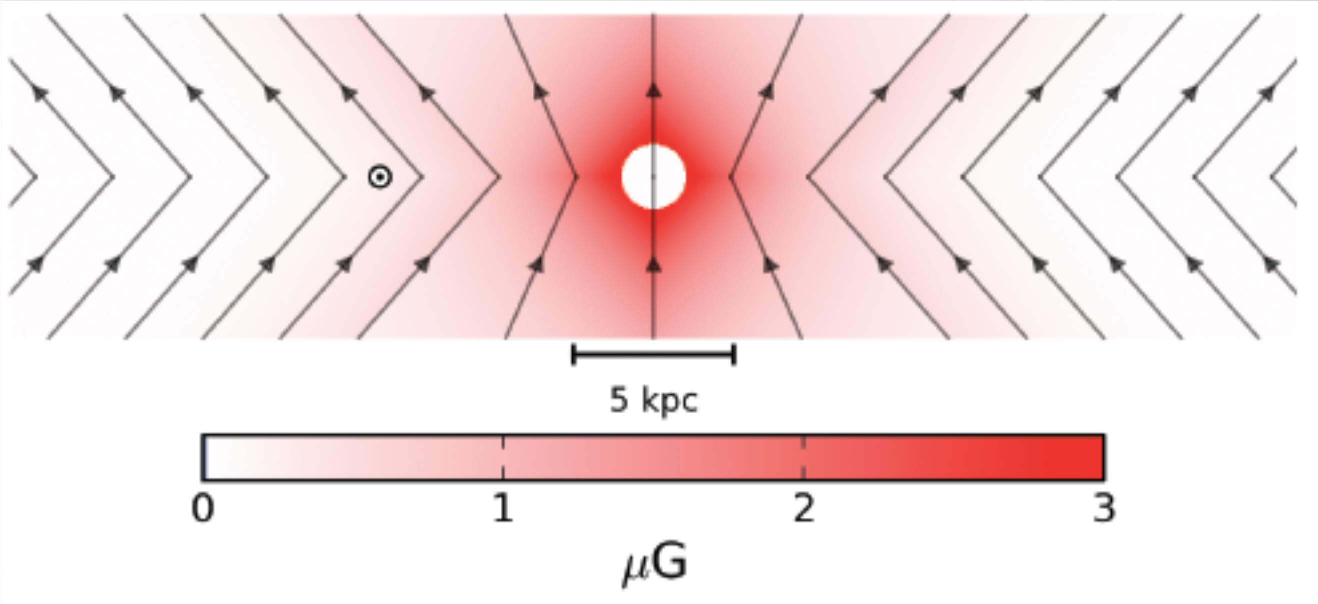
the presence of a poloidal component of the GMF in the GC region should make the role of $D_{||}$ growing respect to $D_{\perp}$ (standard case)

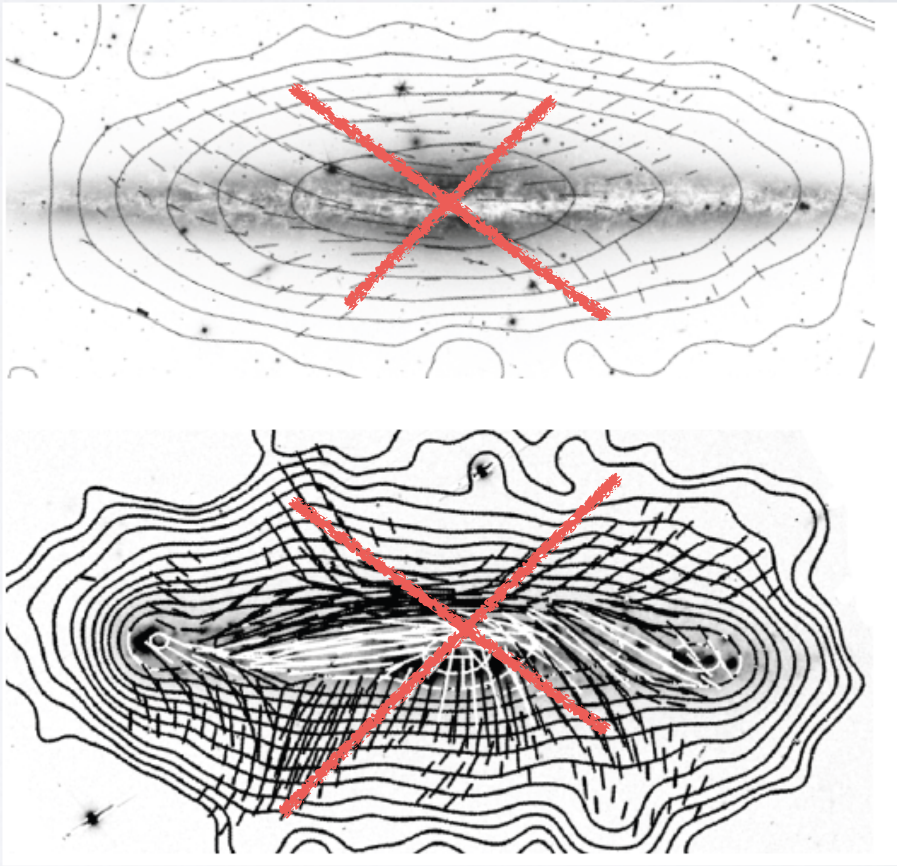
Since, for Kolmogorov turbulence

$$D_{||}(E) \propto E^{1/3} \quad D_{\perp}(E) \propto E^{0.5 \div 0.6}$$

this may cause the effective value of δ decreasing with R !

Jansson & Farrar ApJ 2012

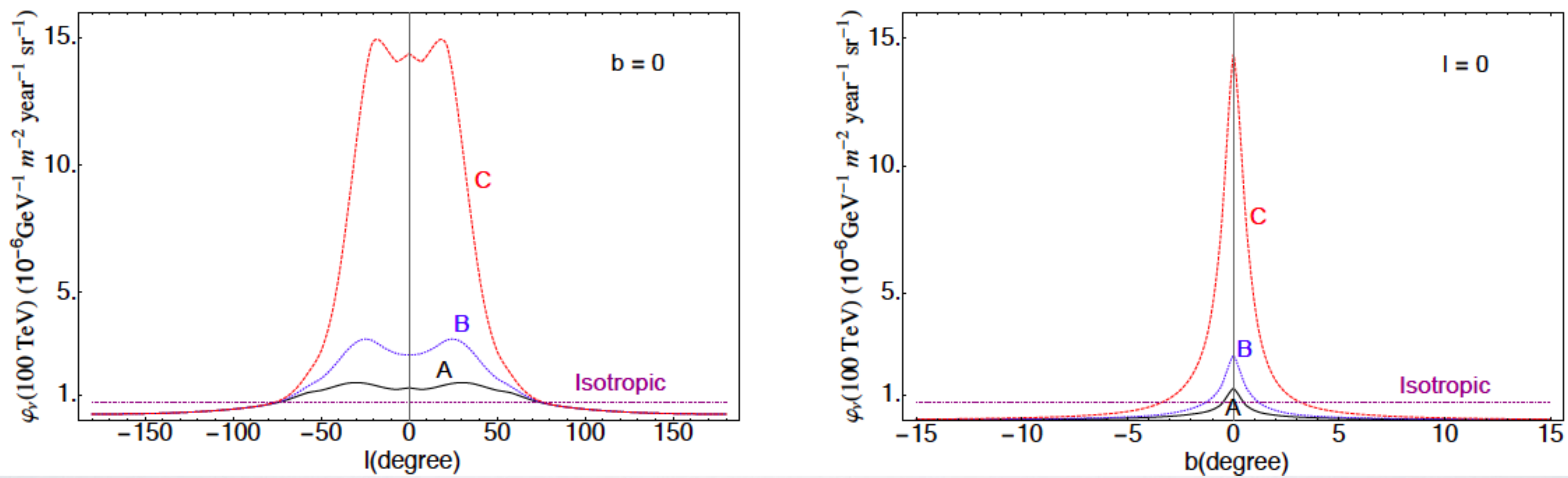




Galactic Plane neutrino with an analytical model with δ variable

ν flux at 100 TeV

Pagliaroli, Evoli & Villante arXiV:1606.04489



- 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

$$h(E,\mathbf{r}) = \left(\frac{E}{\overline{E}}\right)^{\Delta(\mathbf{r})}$$

$$\Delta(r,z) = 0.3\left(1 - \frac{r}{r_\odot}\right)$$

The Neronov & Semikoz model

The model assumes a harder CR spectrum (Γ ~ 2.4) in most of the Galaxy but the local bubble where a young SNR enhances the CR population producing an effective softening

This seems to be excluded by ANTARES upper limit

A. Neronov, D. Semikoz / Astroparticle Physics 72 (2016) 32–37