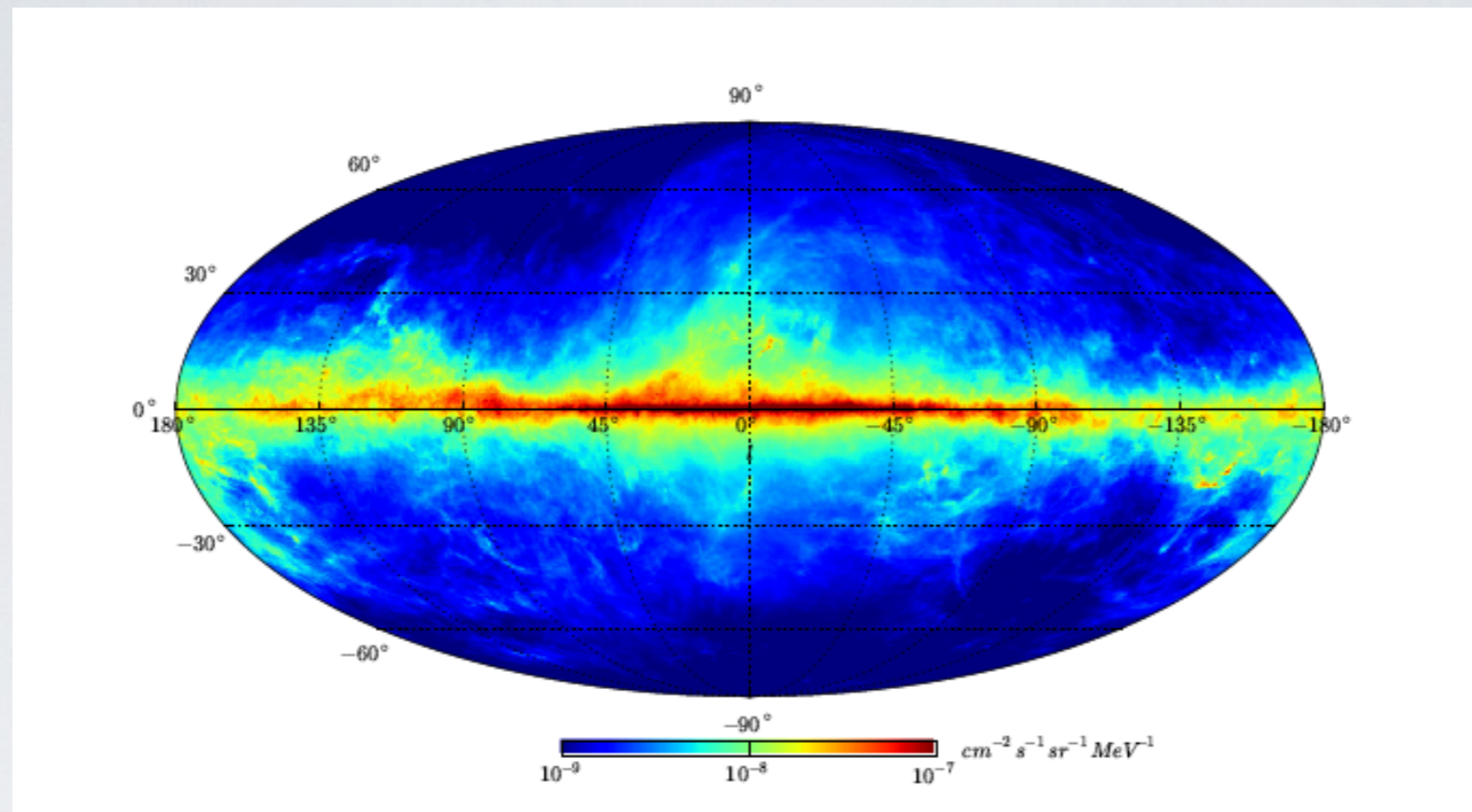


Anomalies in the gamma-ray diffuse emission of the Galaxy and implications for the interpretation of IceCube results

Dario Grasso (INFN, Pisa)

RICAP 2016

The γ -ray diffuse emission of the Galaxy



hadron scattering

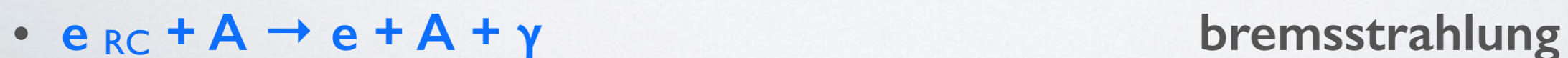
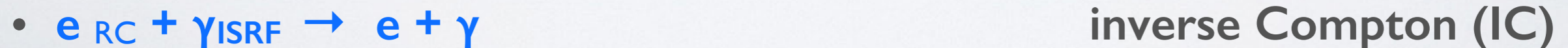
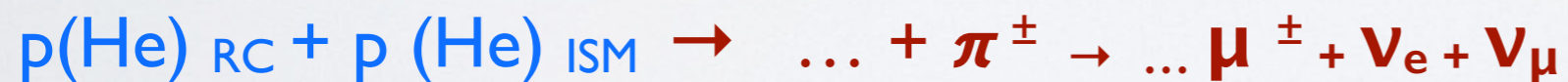
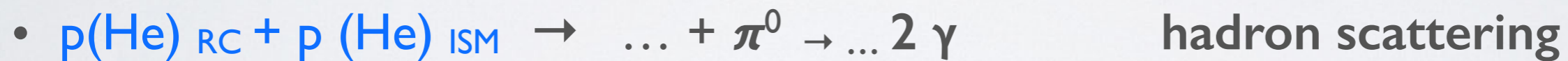
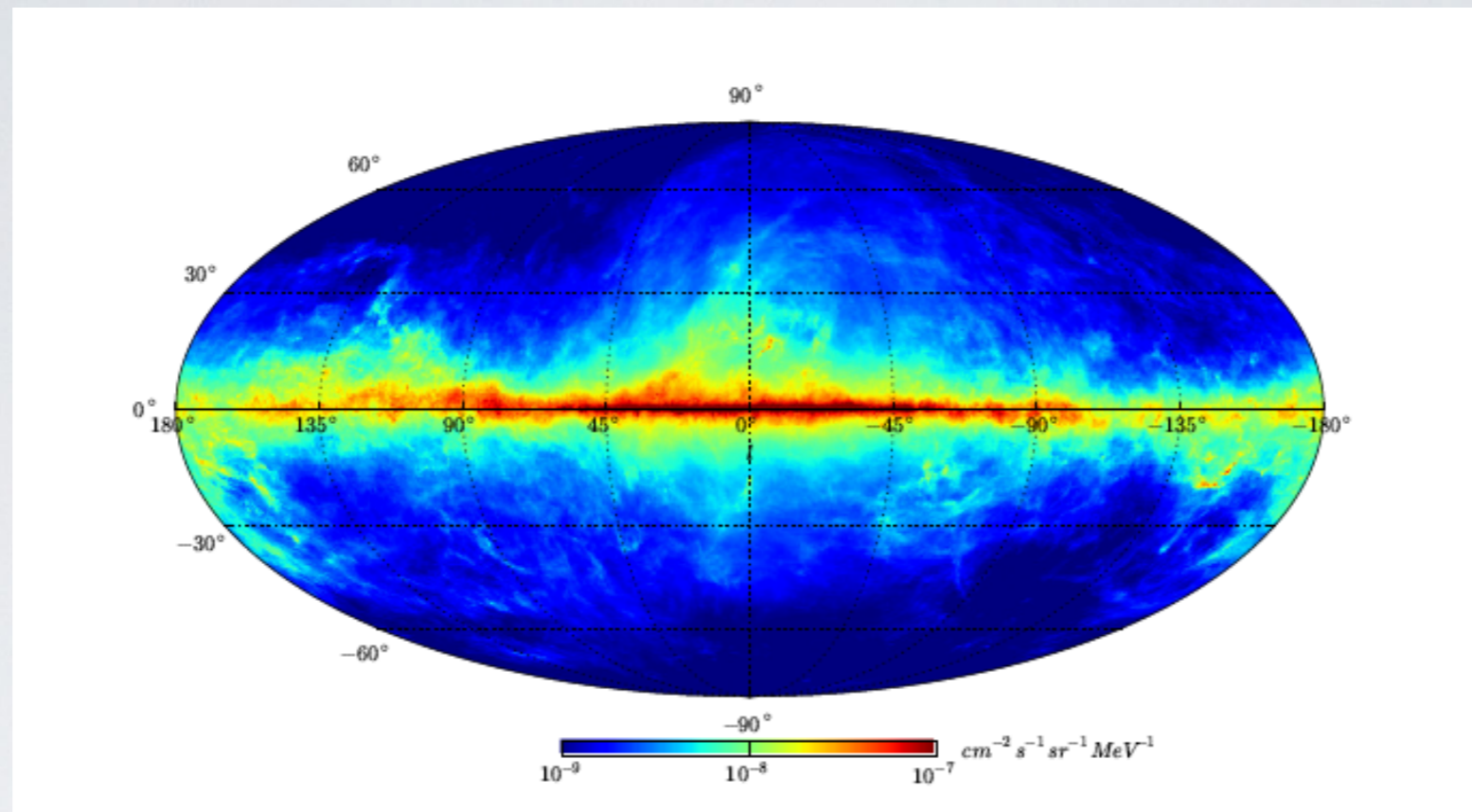


inverse Compton (IC)



bremsstrahlung

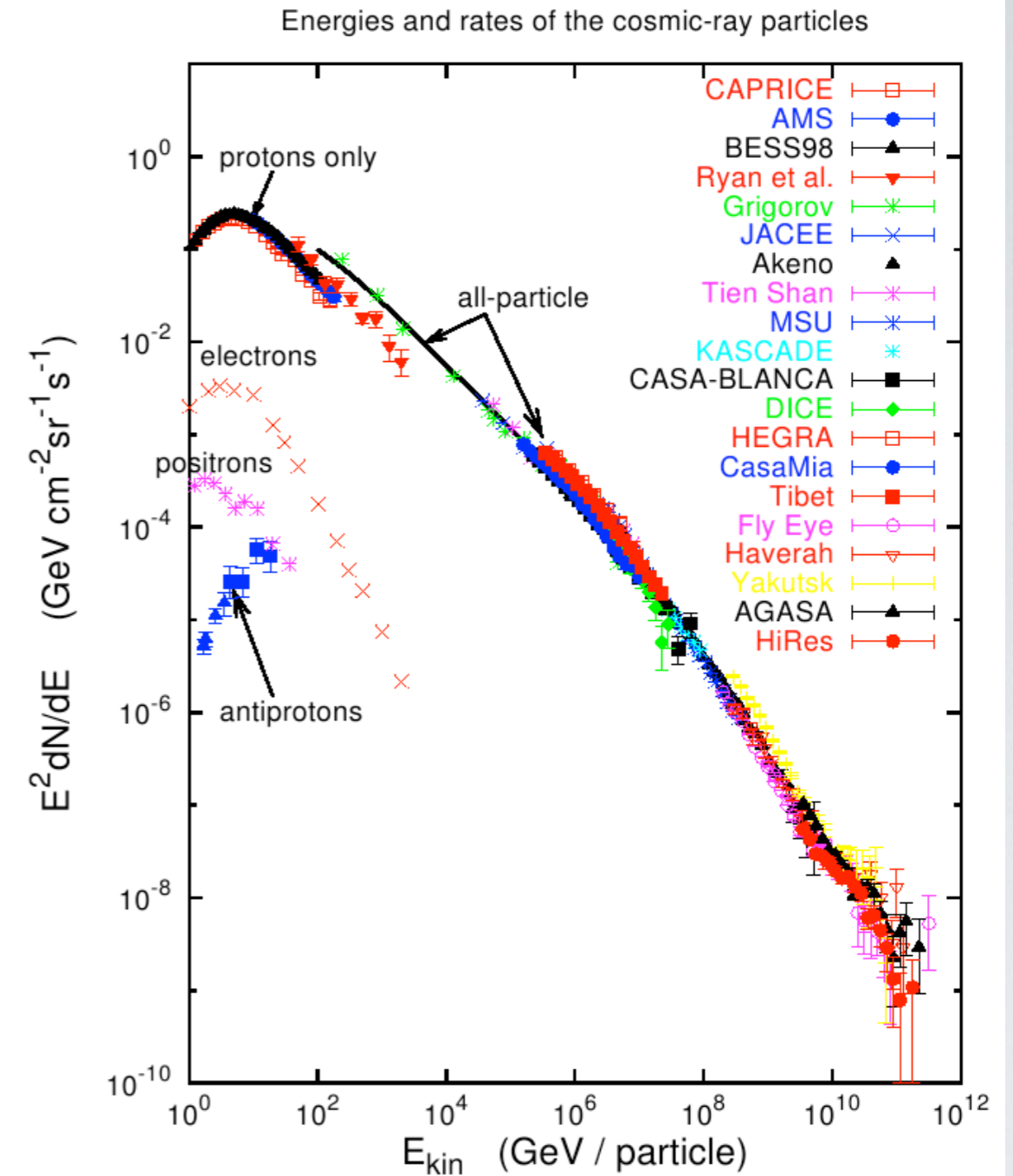
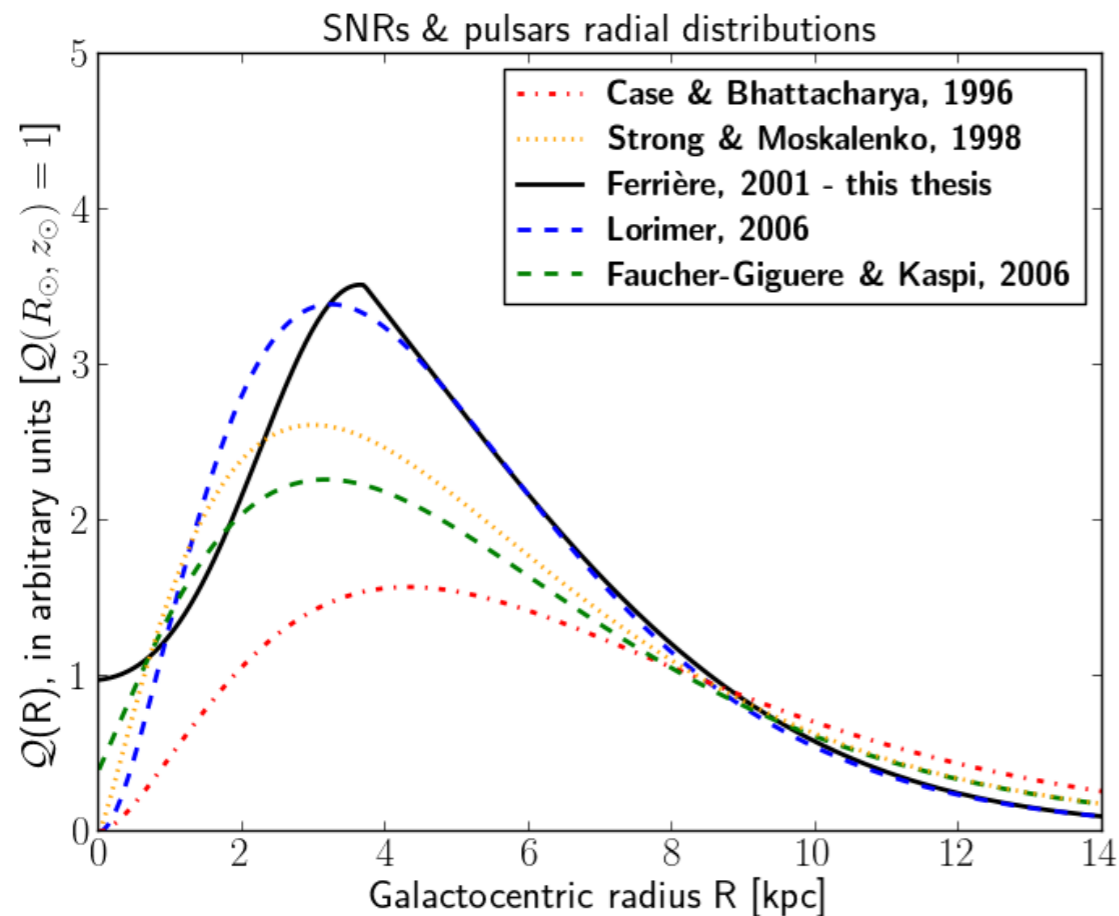
The γ -ray (and ν) diffuse emission of the Galaxy



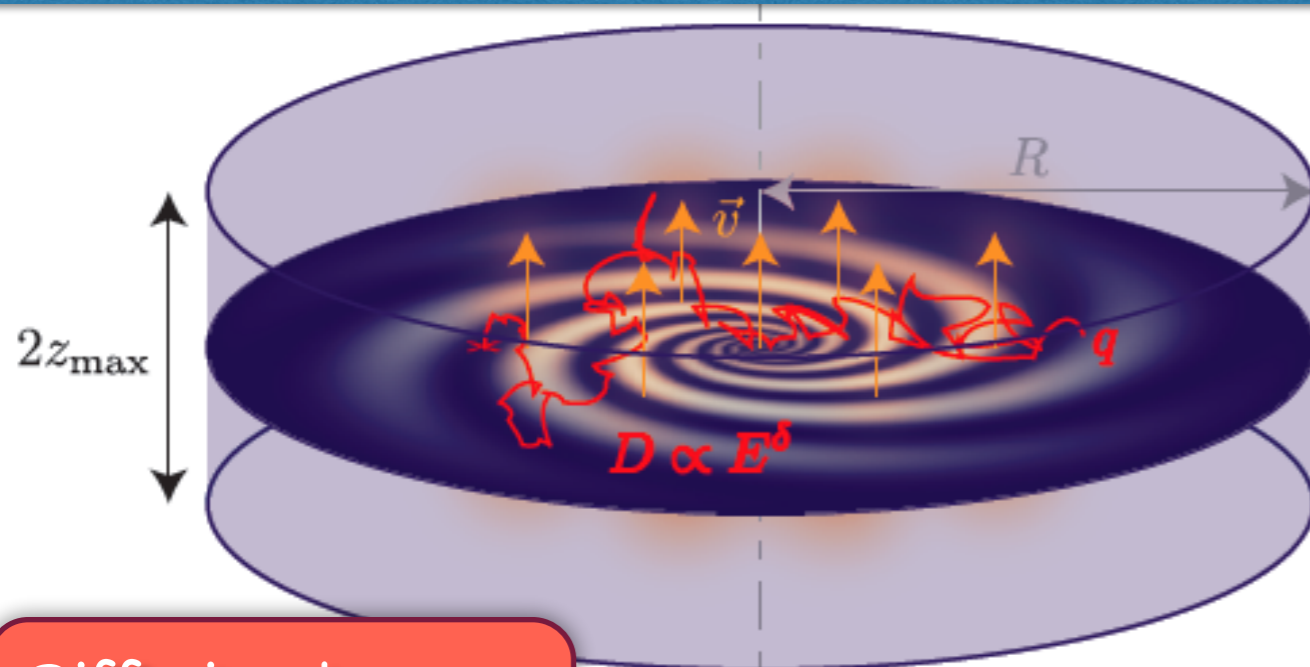
The cosmic ray local population

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

Radial distribution of sources



The CR Galactic population



The CR transport 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
 $D_{pp} \propto \frac{p^2 v_A^2}{D}$

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

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

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

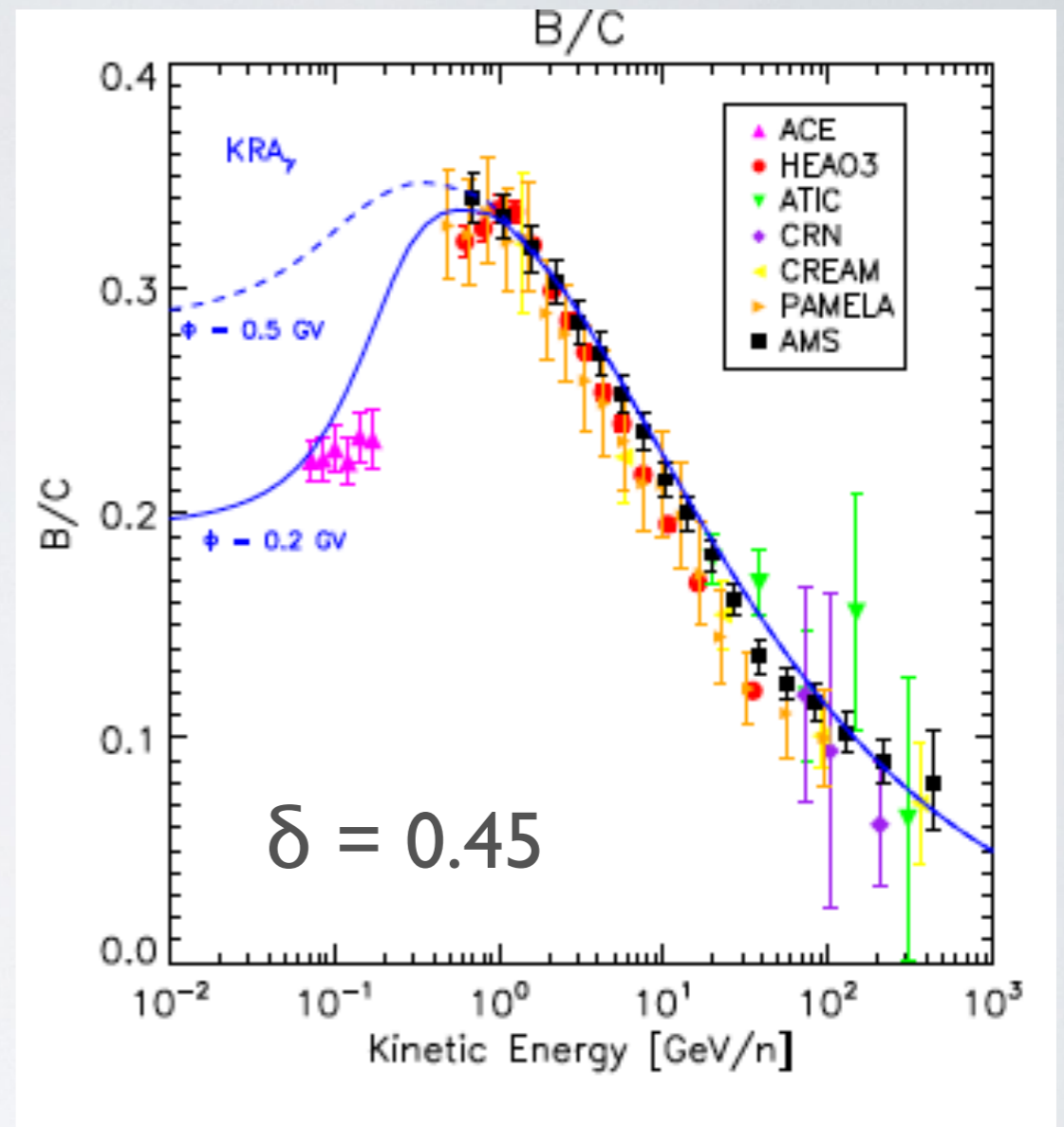
$$D(E) = D_0 (E/E_0)^{-\delta}$$

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



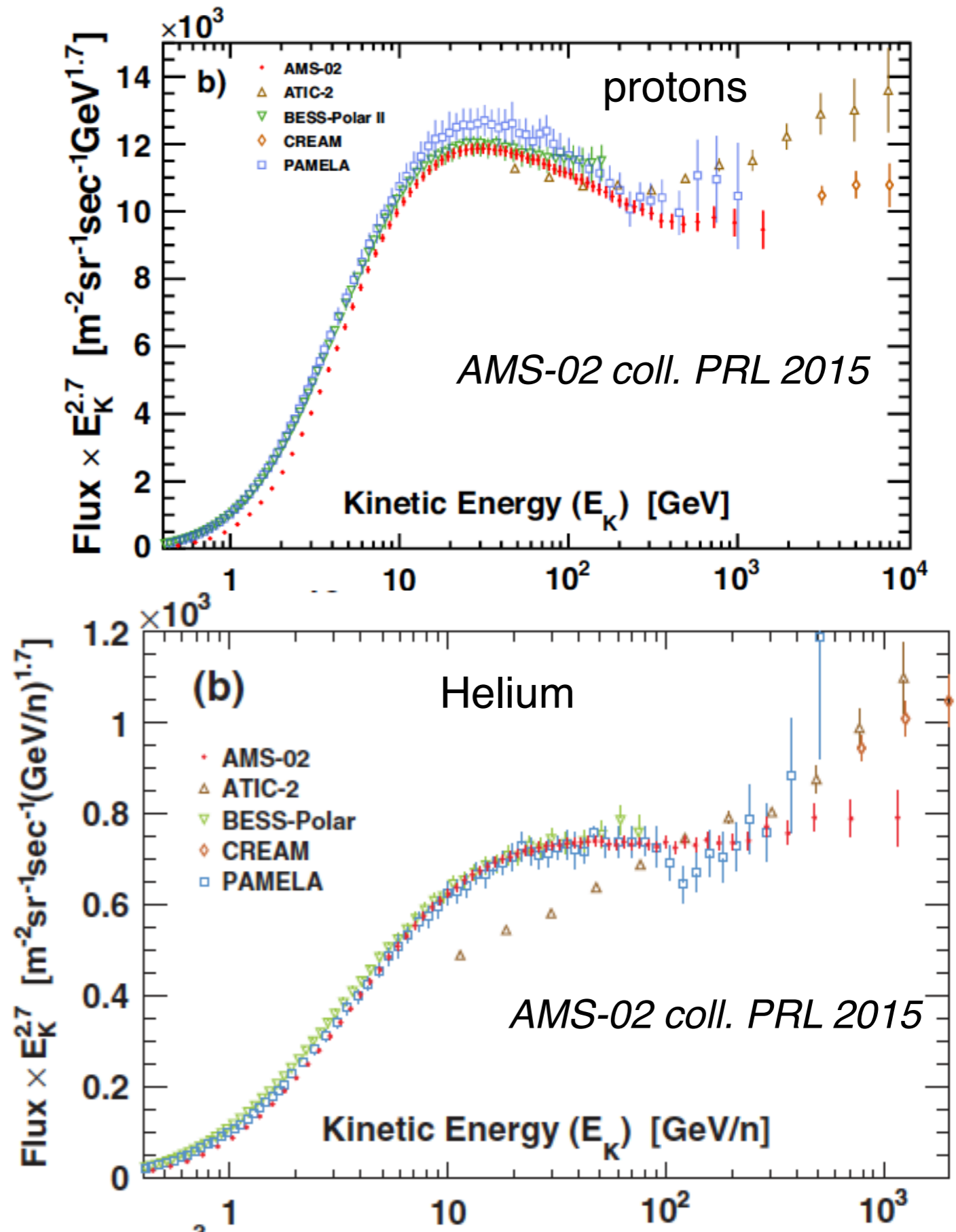
The CR Galactic population: PAMELA anomaly

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

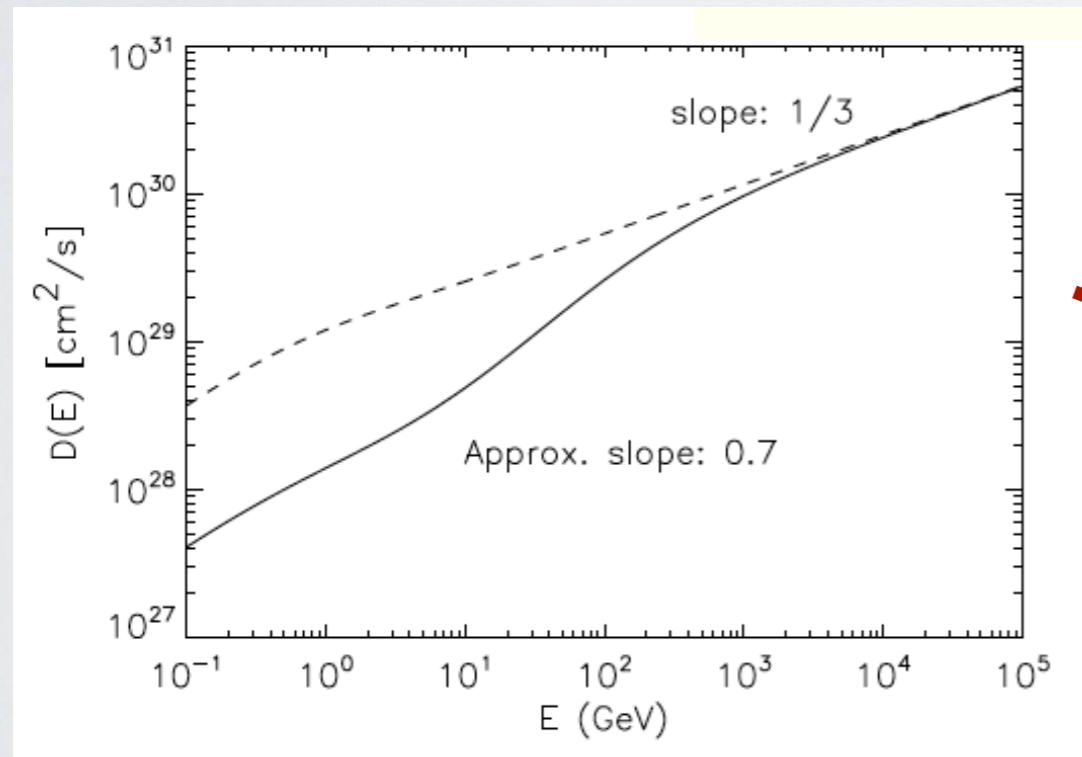
A similar effect is found for heavier nuclei



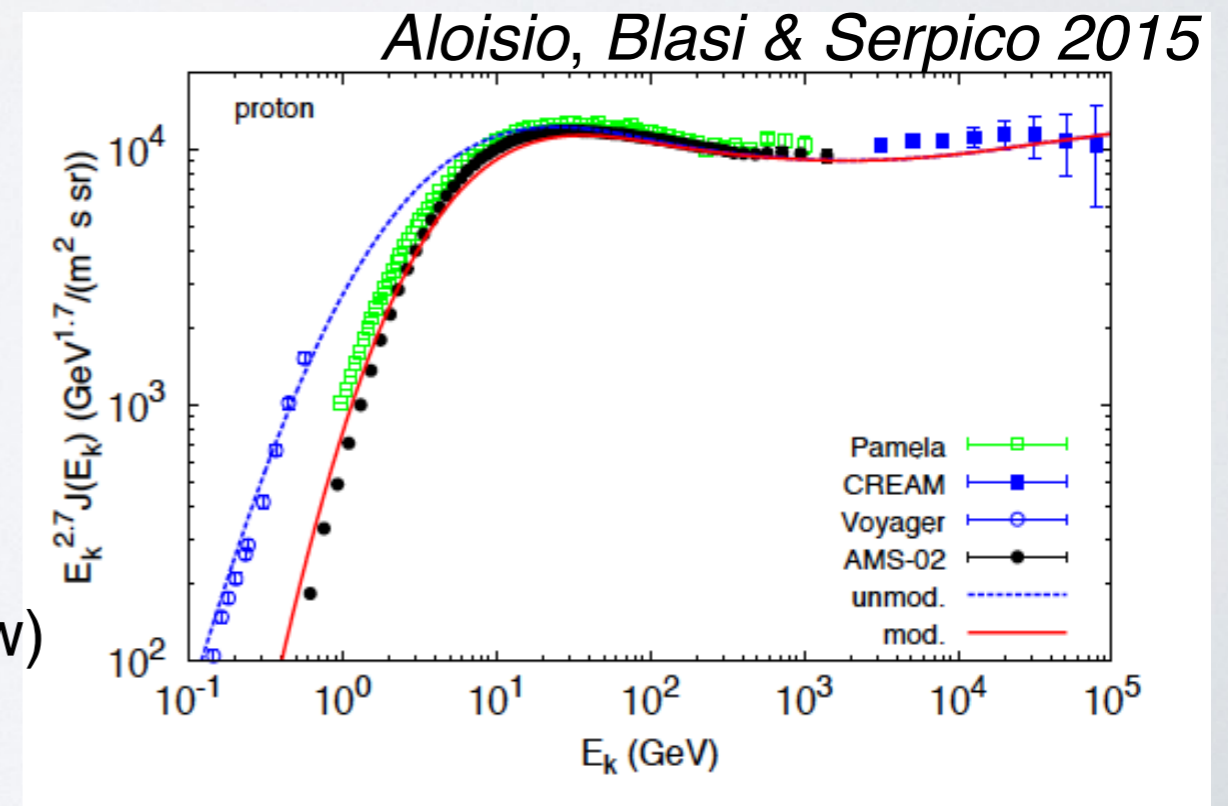
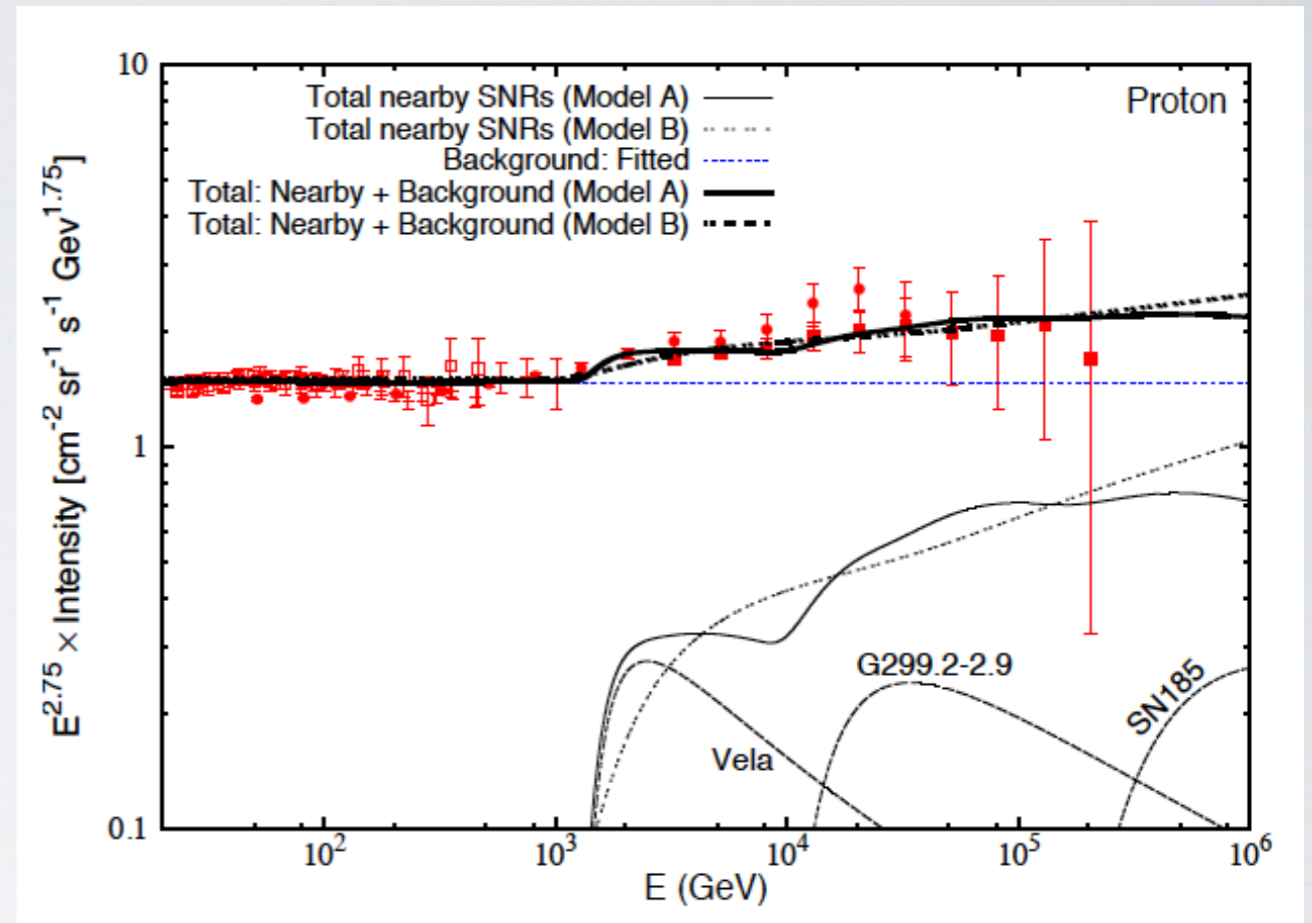
The CR Galactic population: PAMELA anomaly

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*



the effect may be spatial dependent ! (see below)



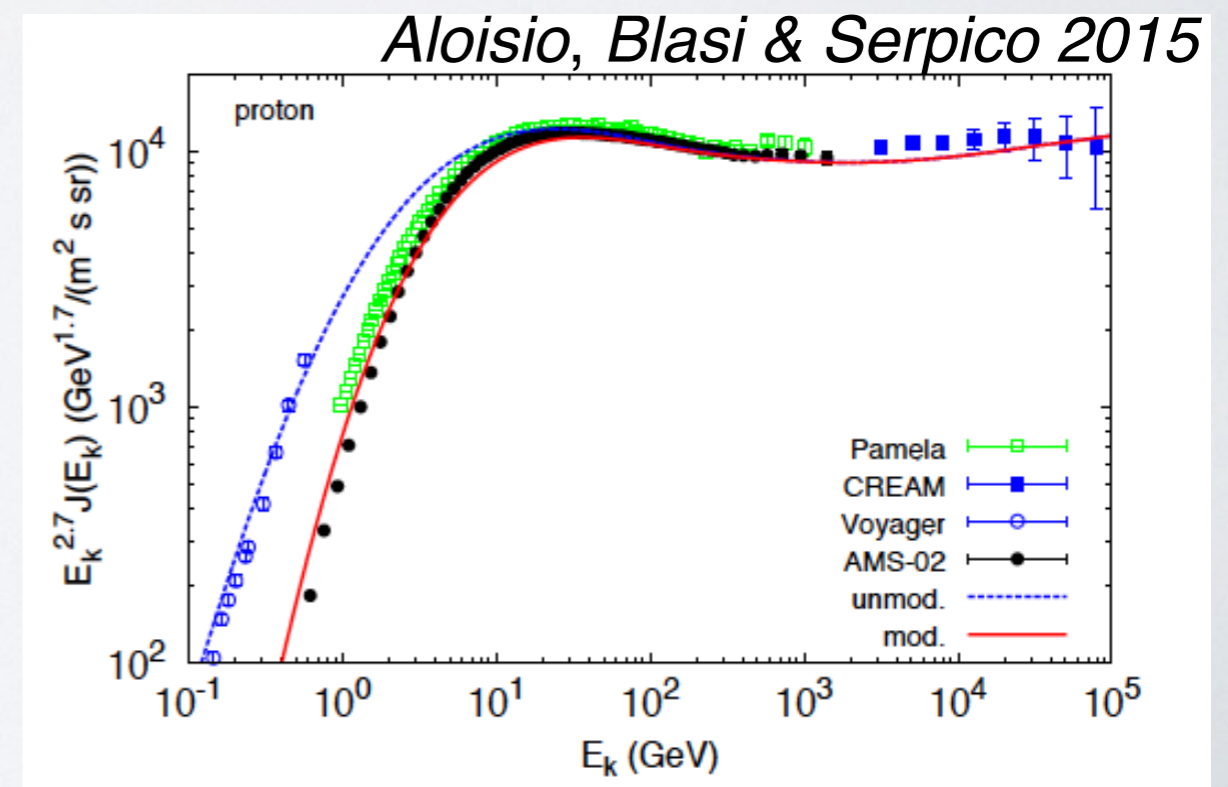
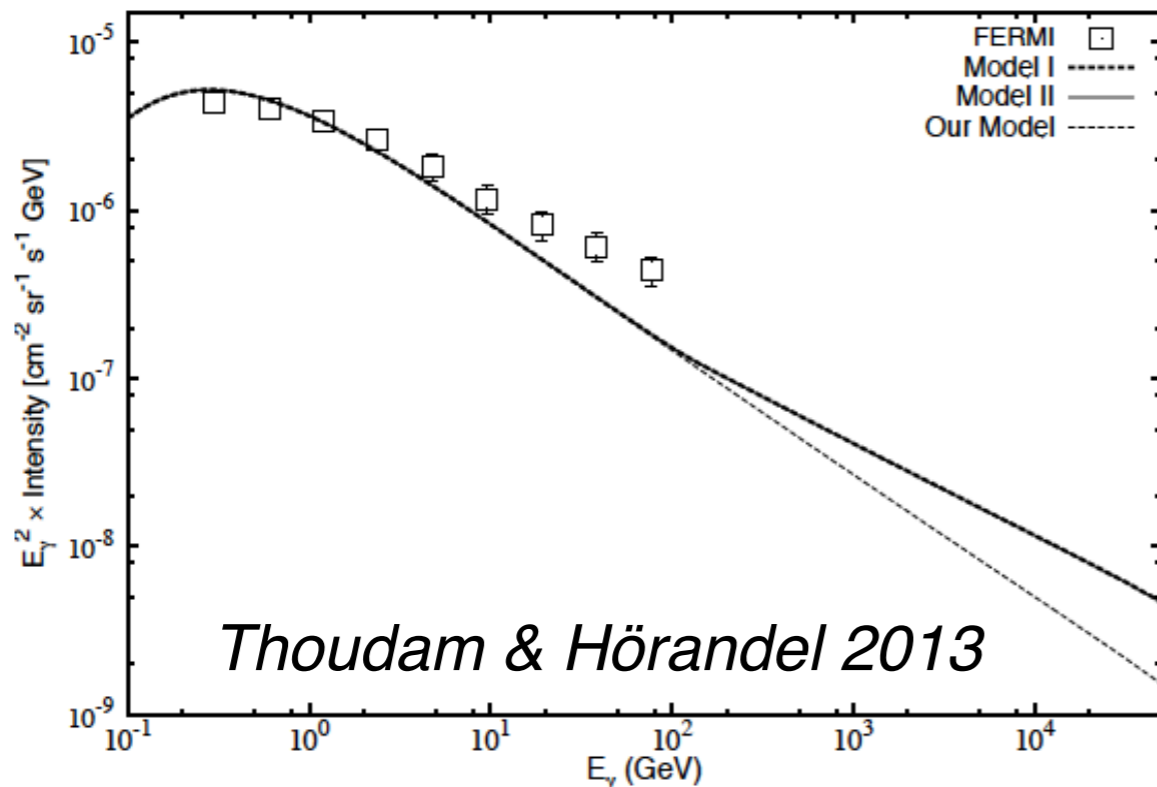
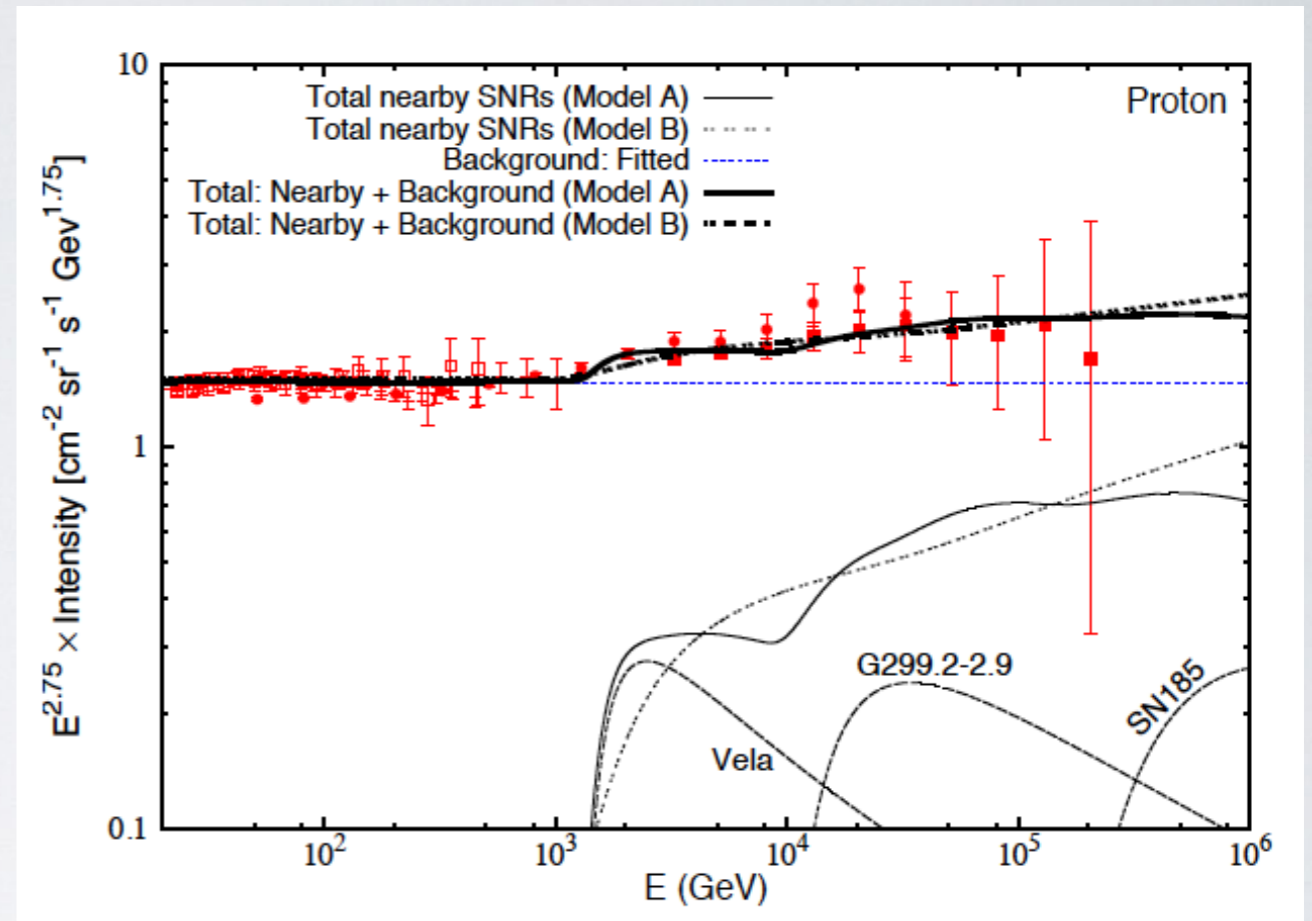
The CR Galactic population: PAMELA anomaly

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



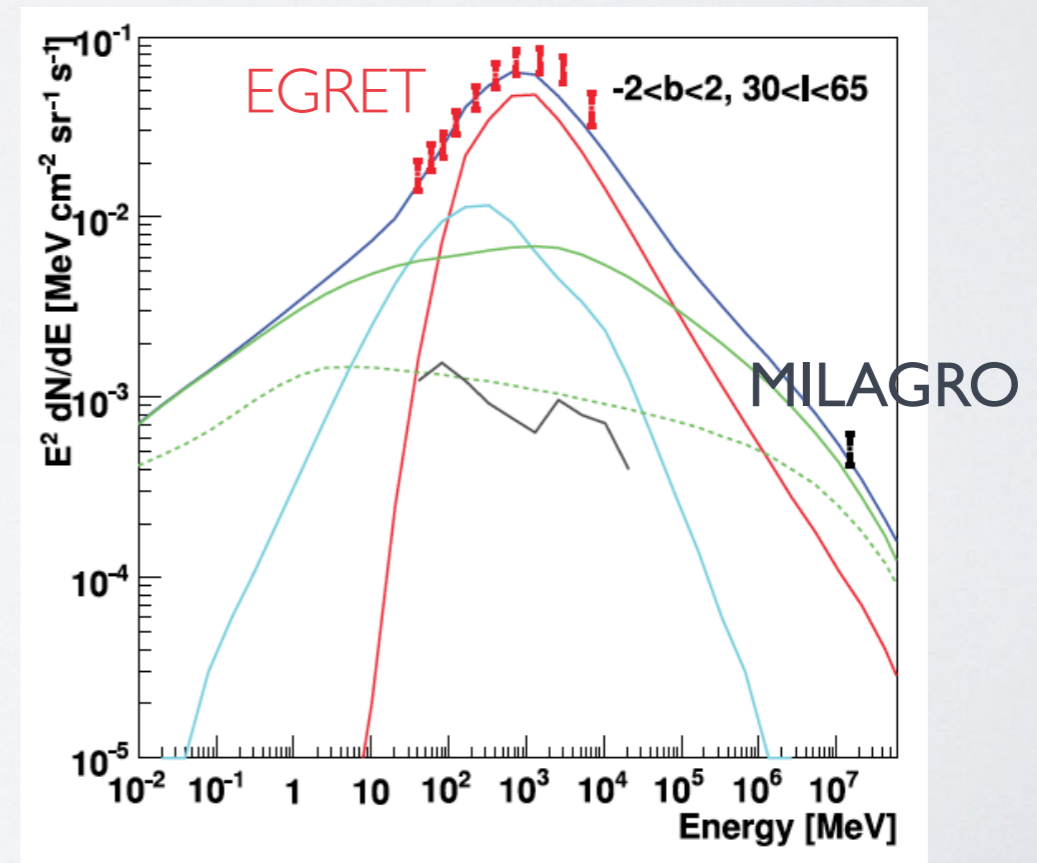
The Milagro anomaly in the inner Galactic Plane

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 ($\times 10^{-13} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$)		
		GALPROP		
		Milagro ^a	Optimized	Conventional
30–65.....	5.1	$23.1 \pm 4.5^{+7.0}_{-8.0}$	20.0	4.9

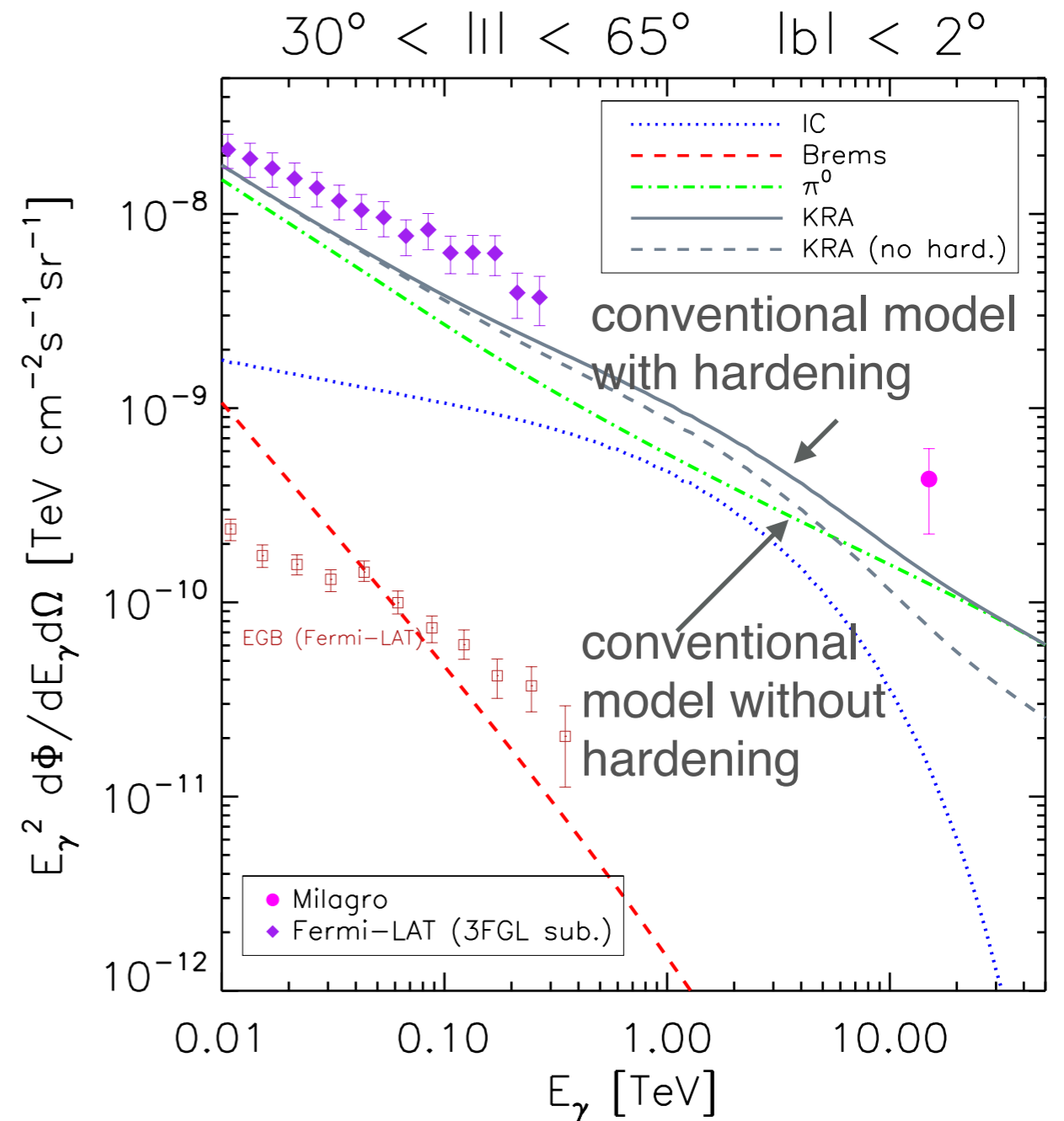
- the measured flux is 5 times (4σ) larger than computed with the reference conventional model
- an optimized model (augmented IC contribution) - proposed to account for the EGRET GeV excess - was found to match Milagro



The Milagro anomaly in the inner Galactic Plane

- 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)

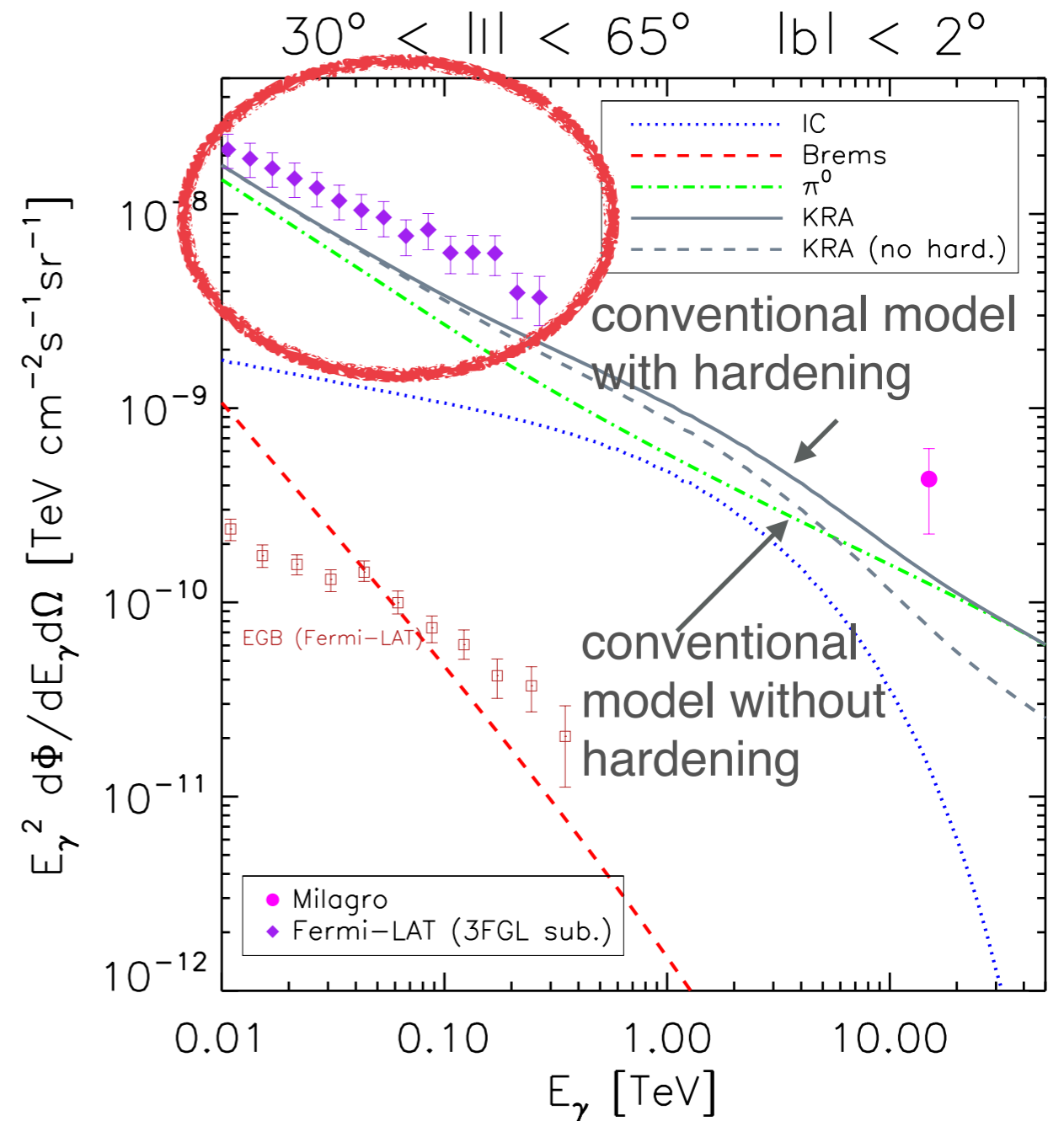


The Milagro anomaly in the inner Galactic Plane

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)

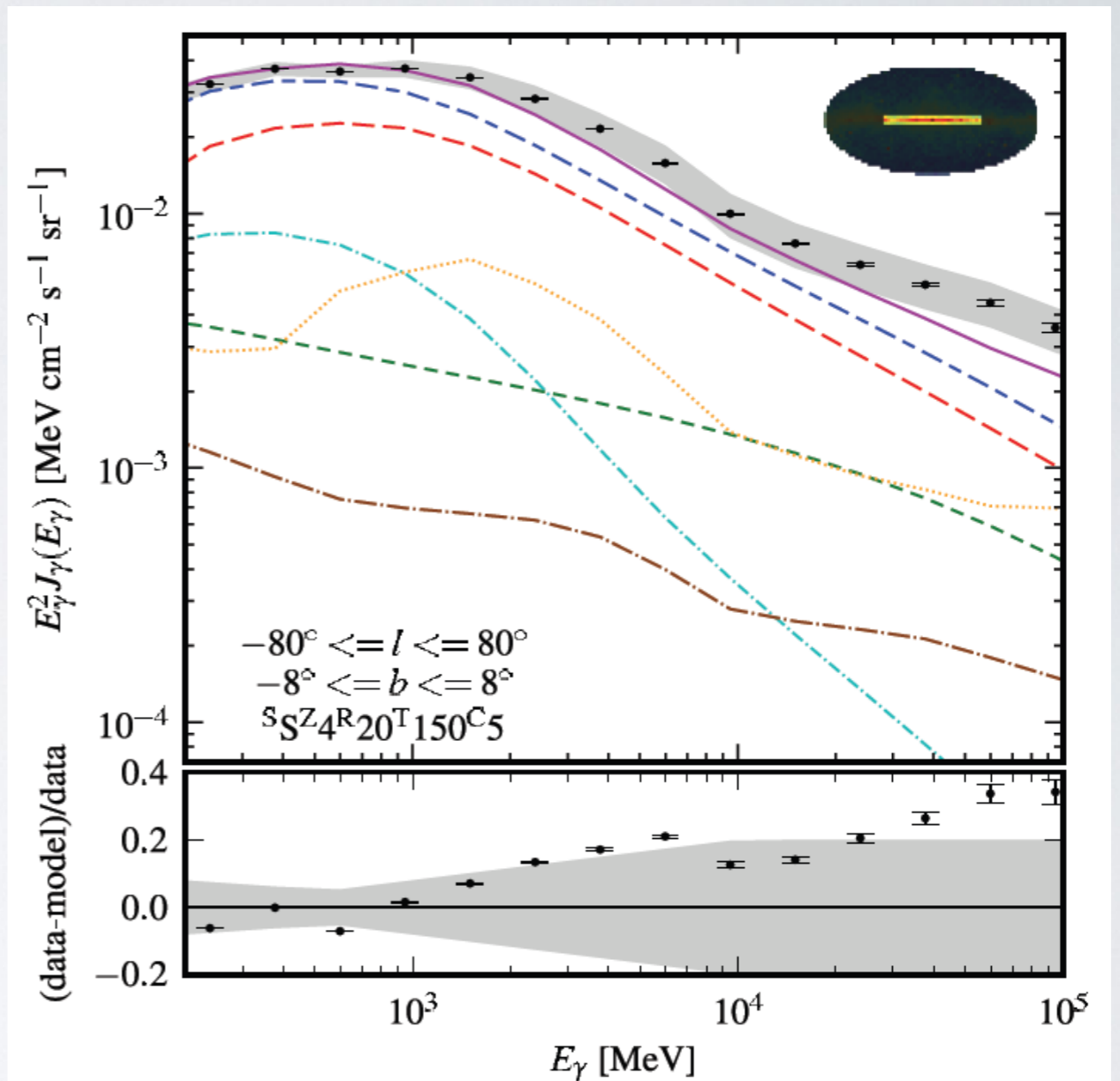
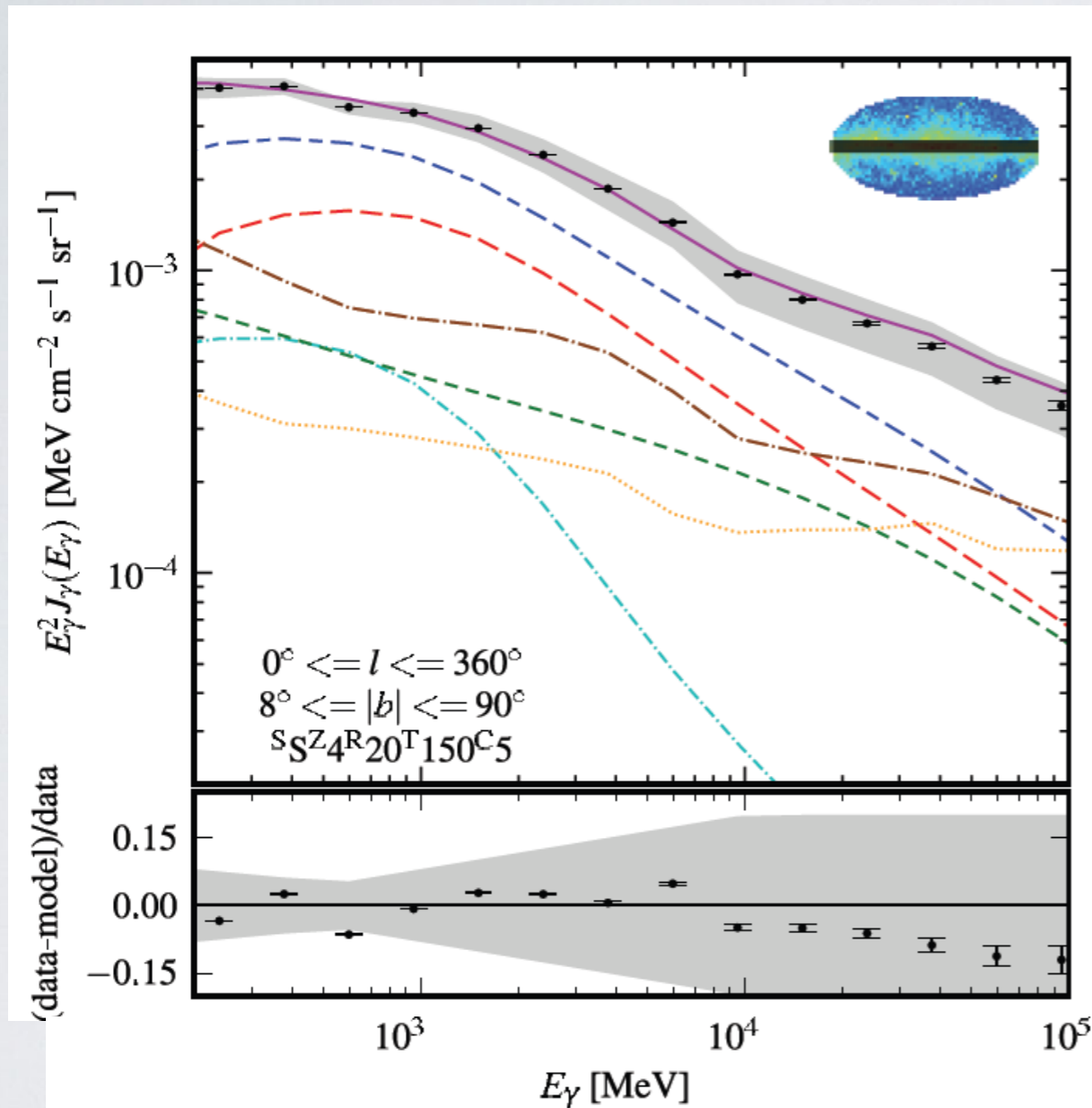


Conventional models against Fermi data

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

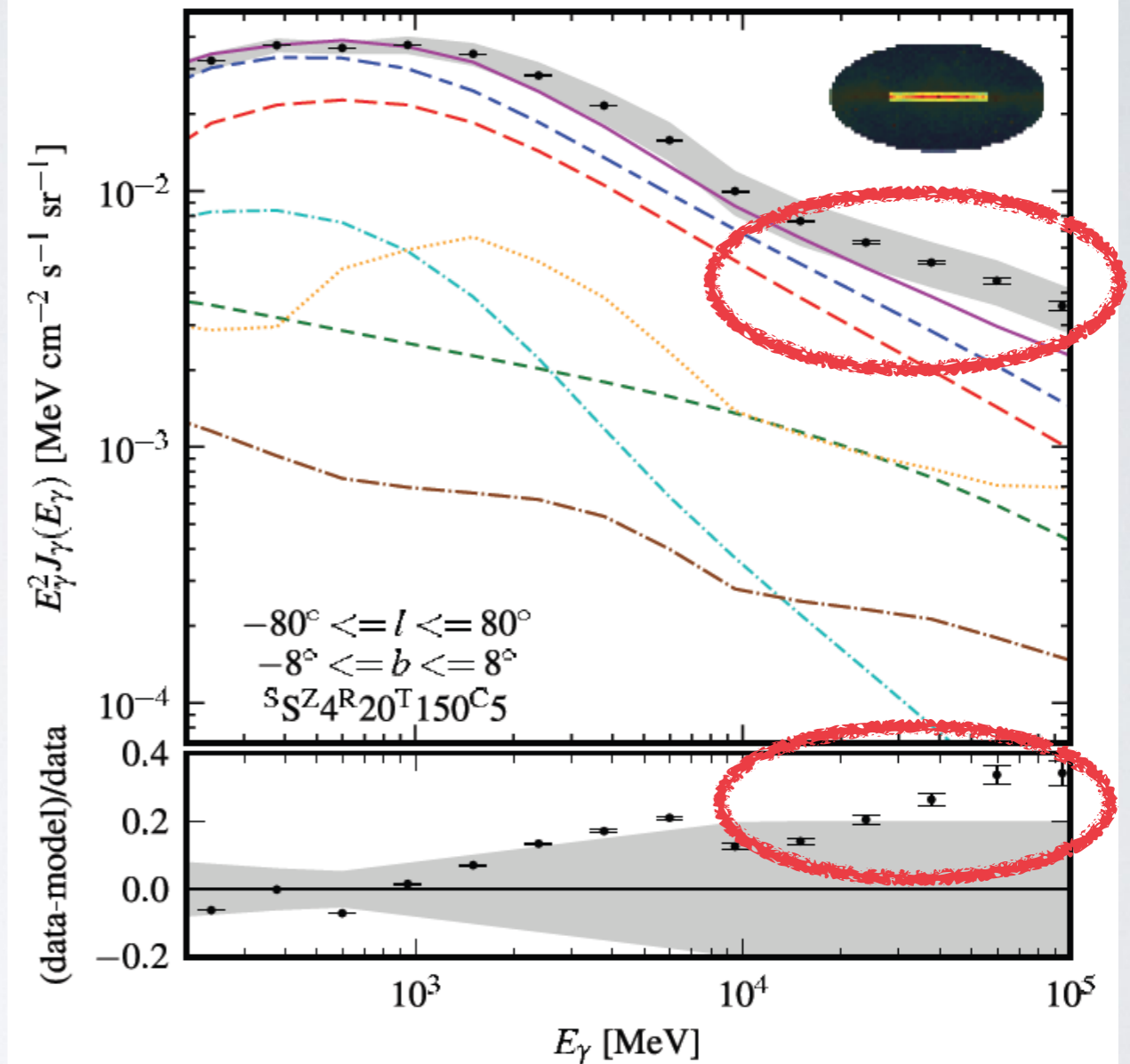
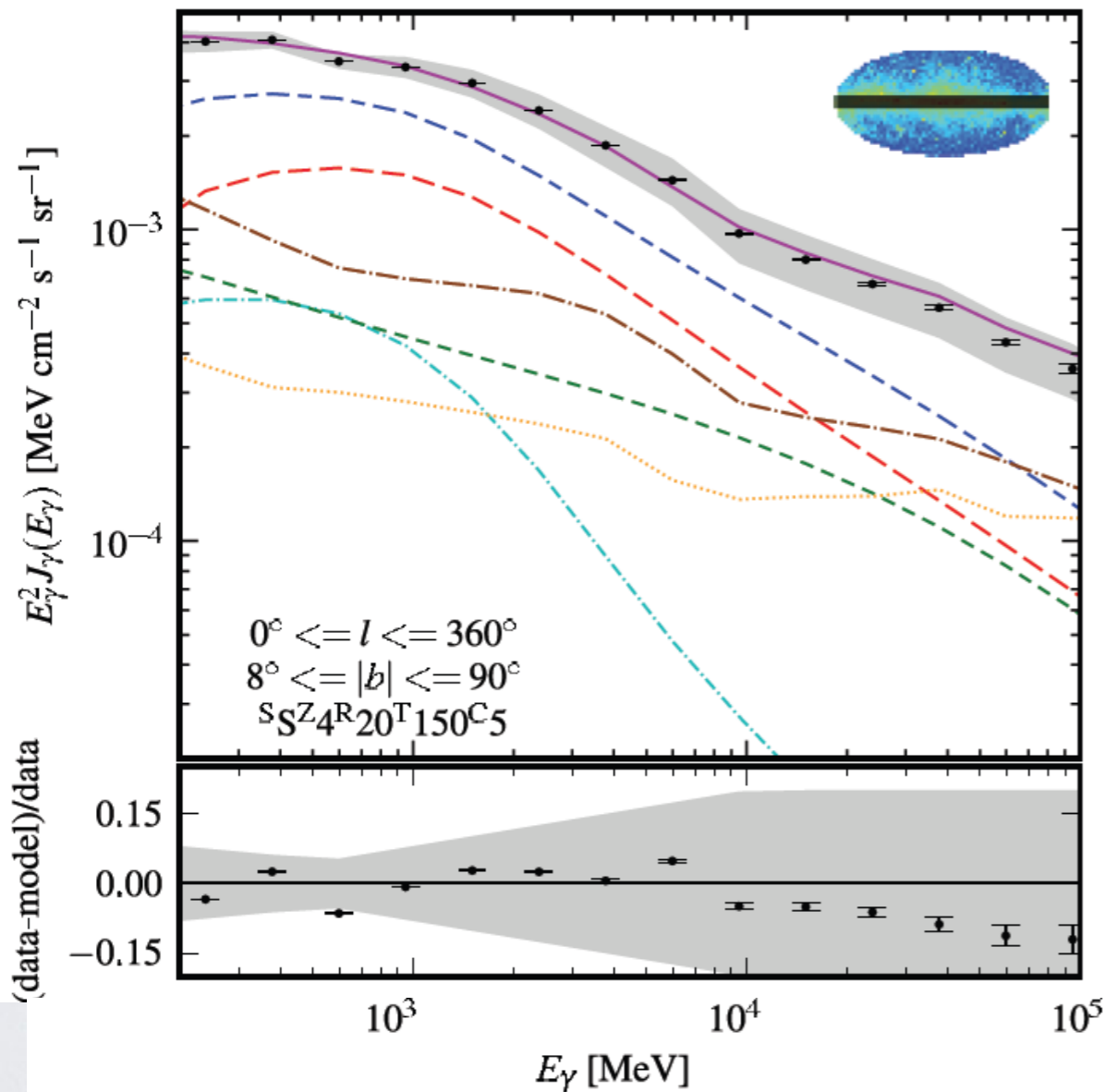
$z_h = 4$ kpc

Conventional models against Fermi data

full-sky but the GP

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

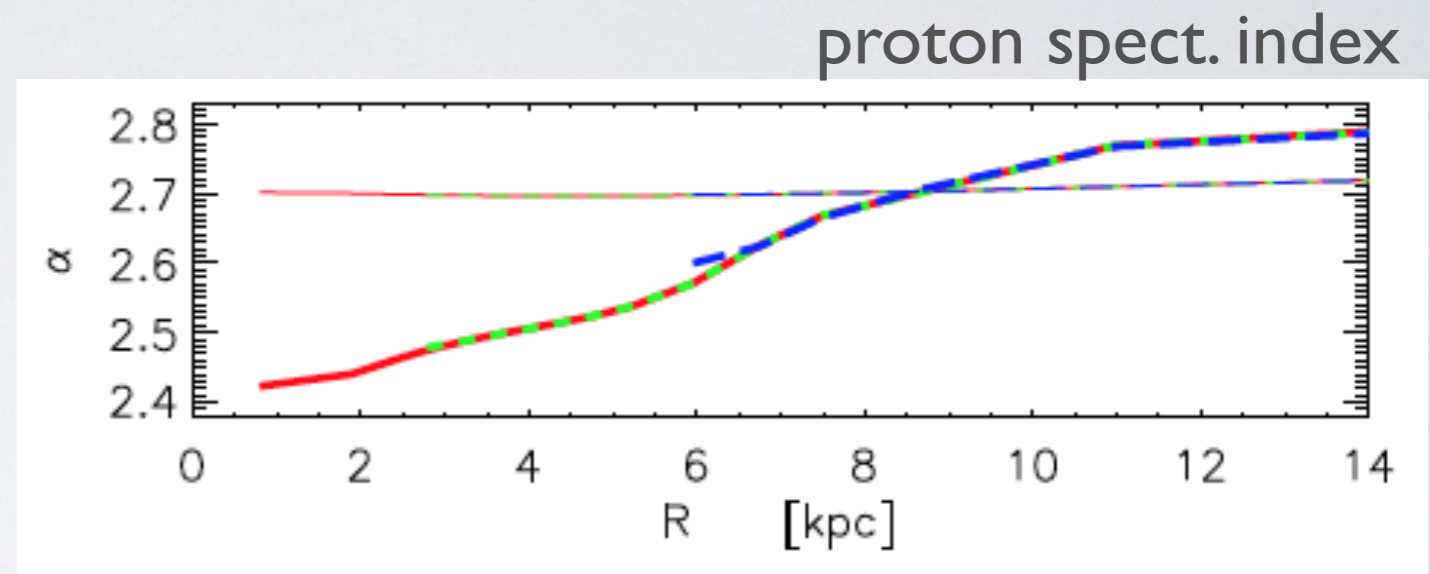
Beyond conventional models: Radial dependency of CR transport

Gaggero, Urbano, Valli & Ullio 2014

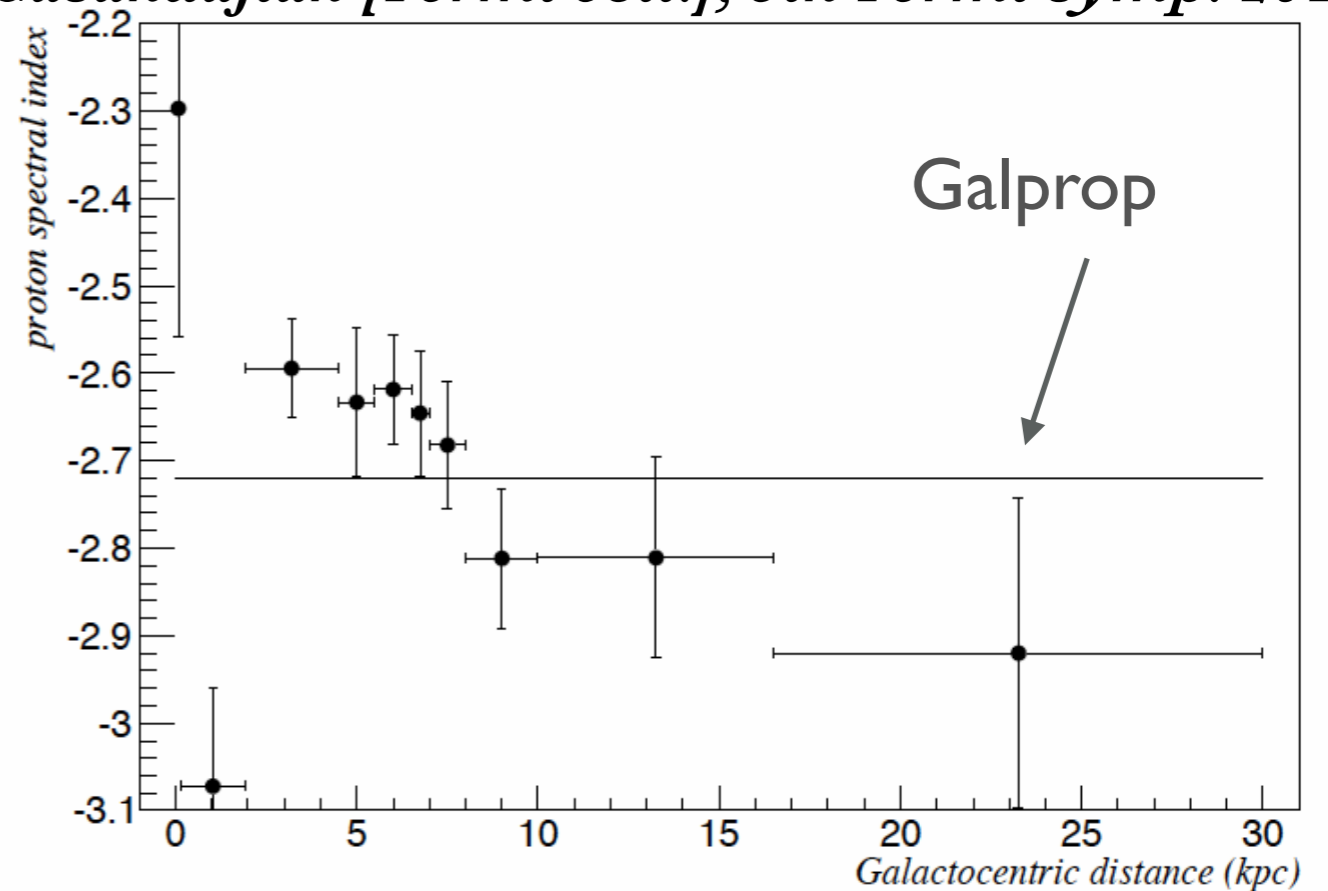
showed also that Fermi data requires a radial dependence of the CR spectral index, hence of the γ -ray emission spectrum

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

This is clearly incompatible with conventional models implemented with GALPROP



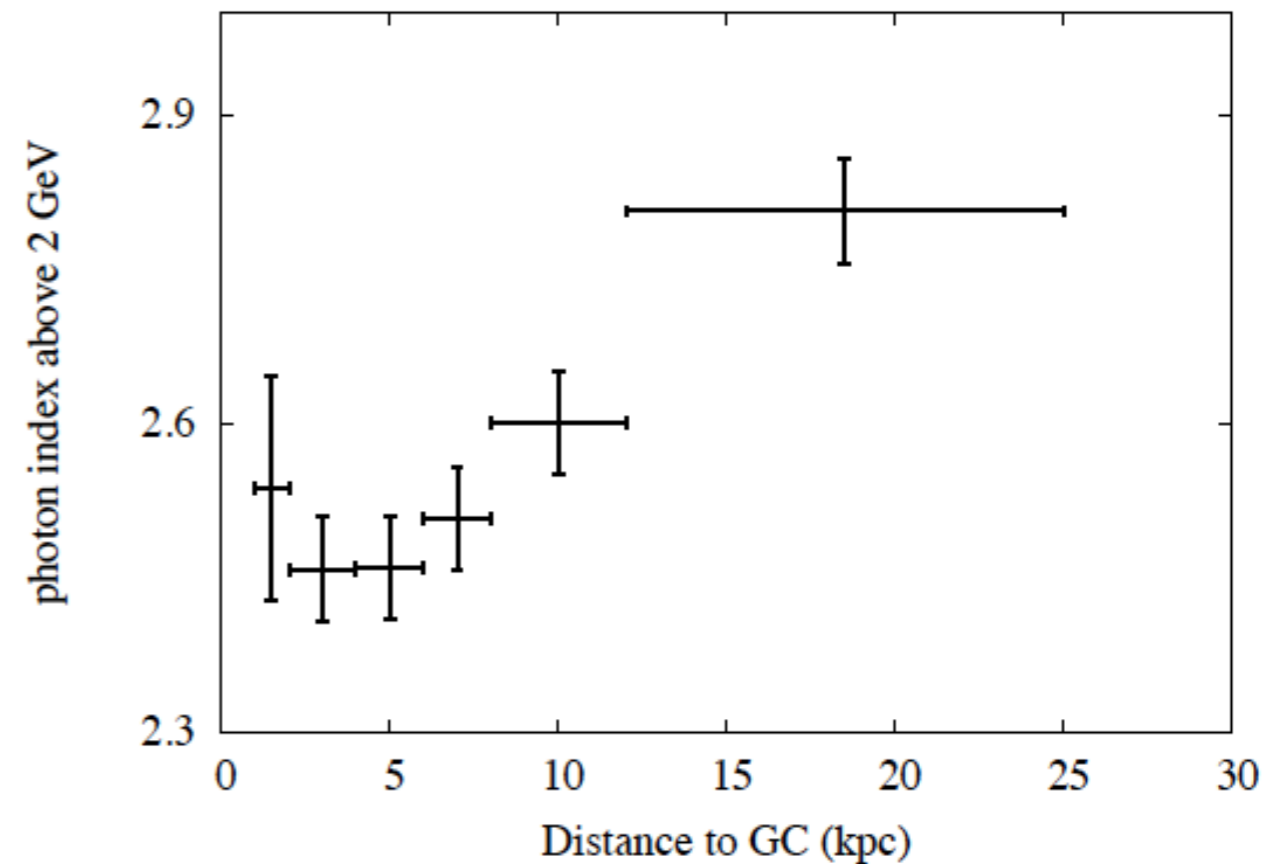
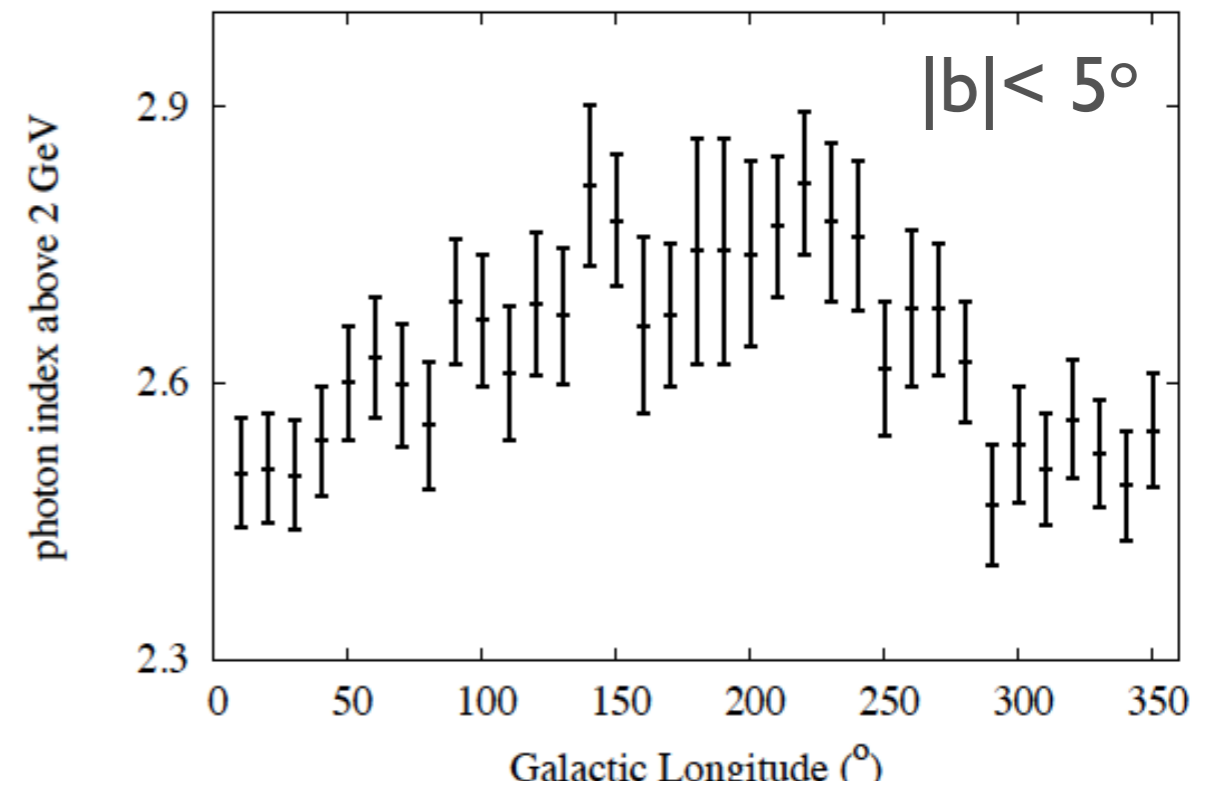
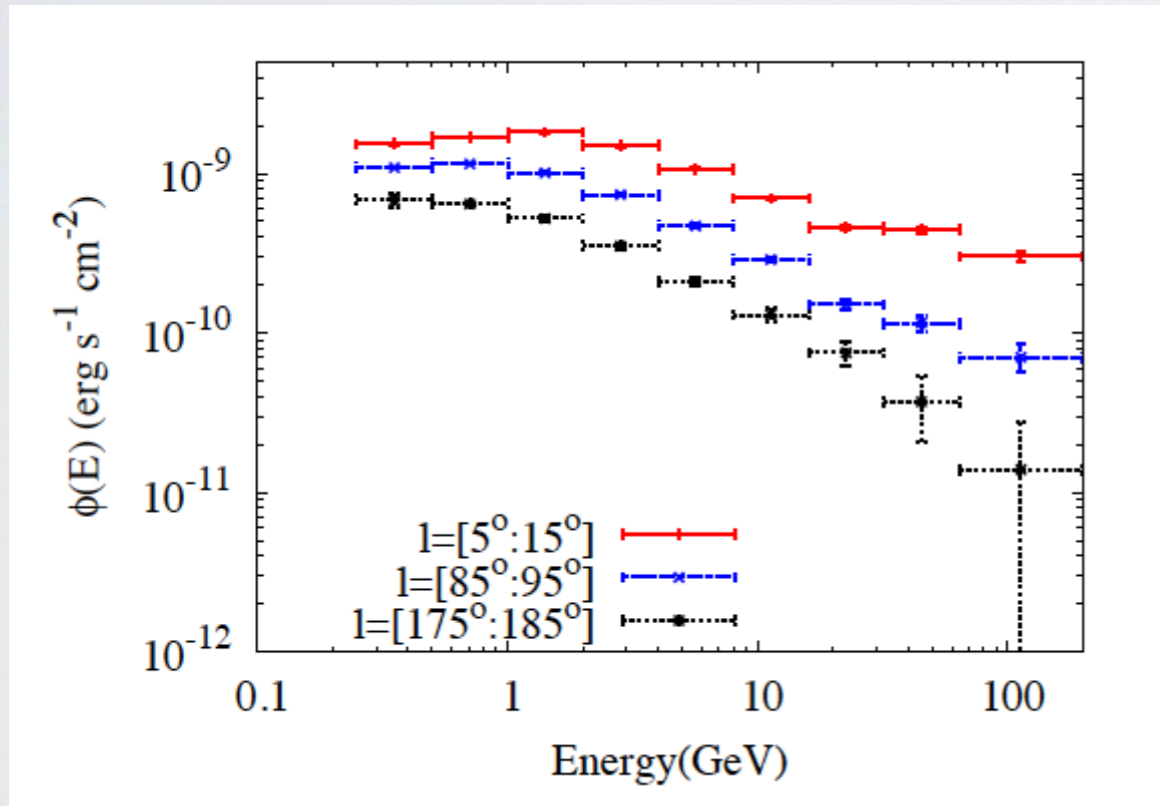
Casandajian [Fermi coll.], 5th Fermi symp. 2014



Fermi results: an independent analysis

Yang, Aharonian & Evoli arXiv:1602.04710

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



The KRA_γ model: Radial dependency of CR transport

Gaggero, Urbano, Valli & Ullio *arXiv: 1411.7623 PRD 2015*

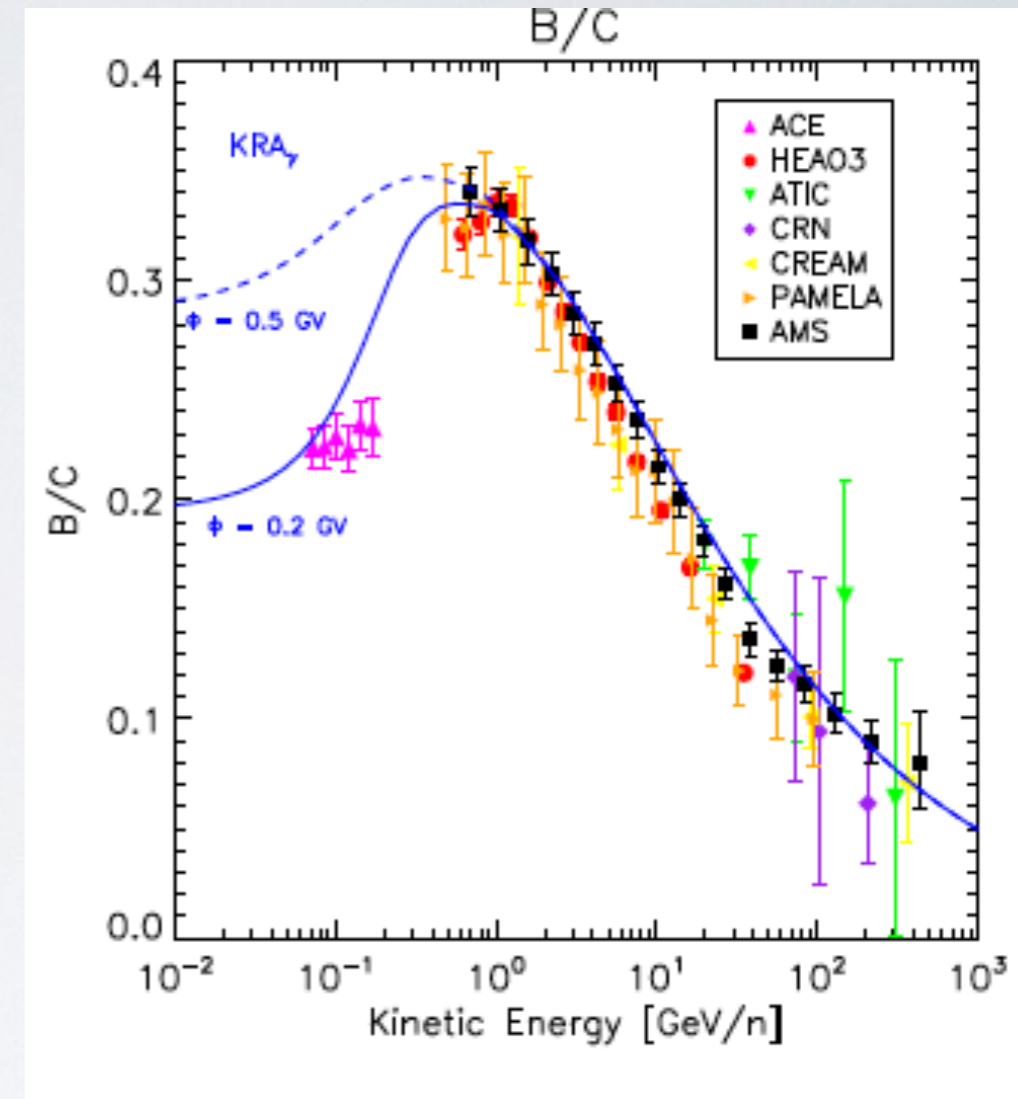
The KRA_γ model - implemented with the **DRAGON code** - adopts a radial dependent diffusion coefficient

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

and convective velocity

$\frac{dV_C}{dz} = 100 \text{ km s}^{-1} \text{ kpc}^{-1}$ 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



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 $D_0(R,z)$ 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 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

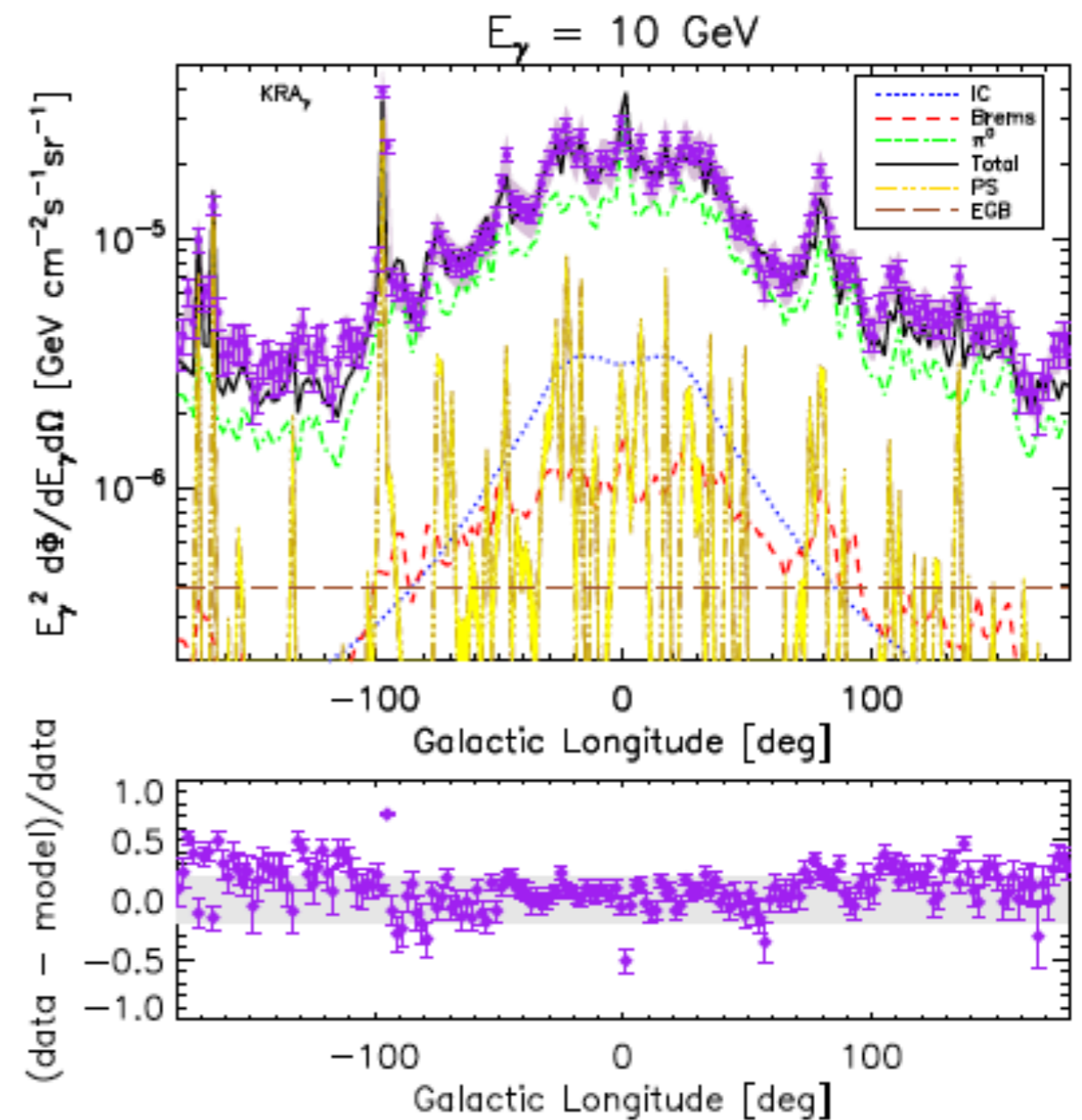
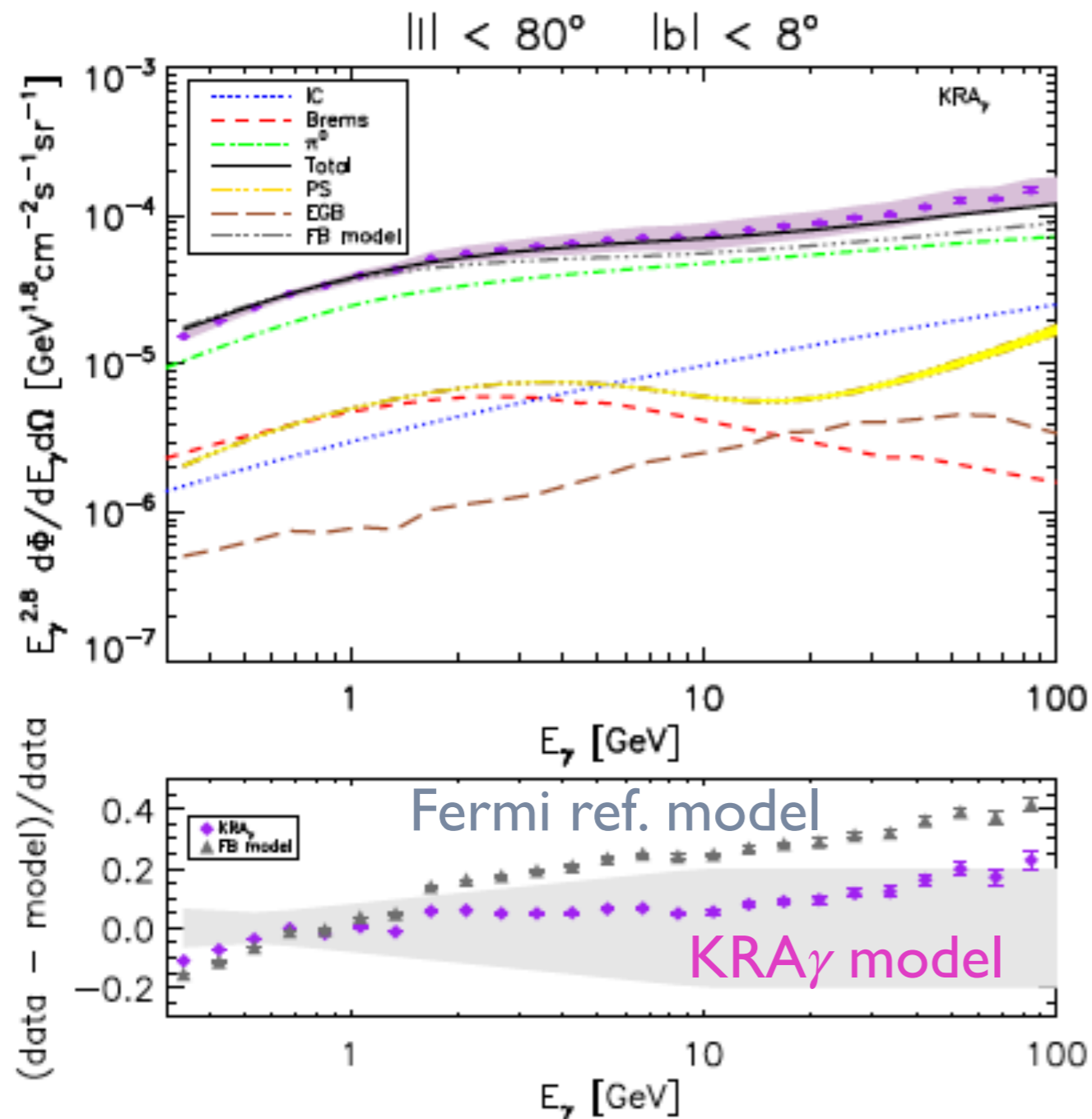
will soon be released.

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

The KRA_γ model: Radial dependency of CR transport

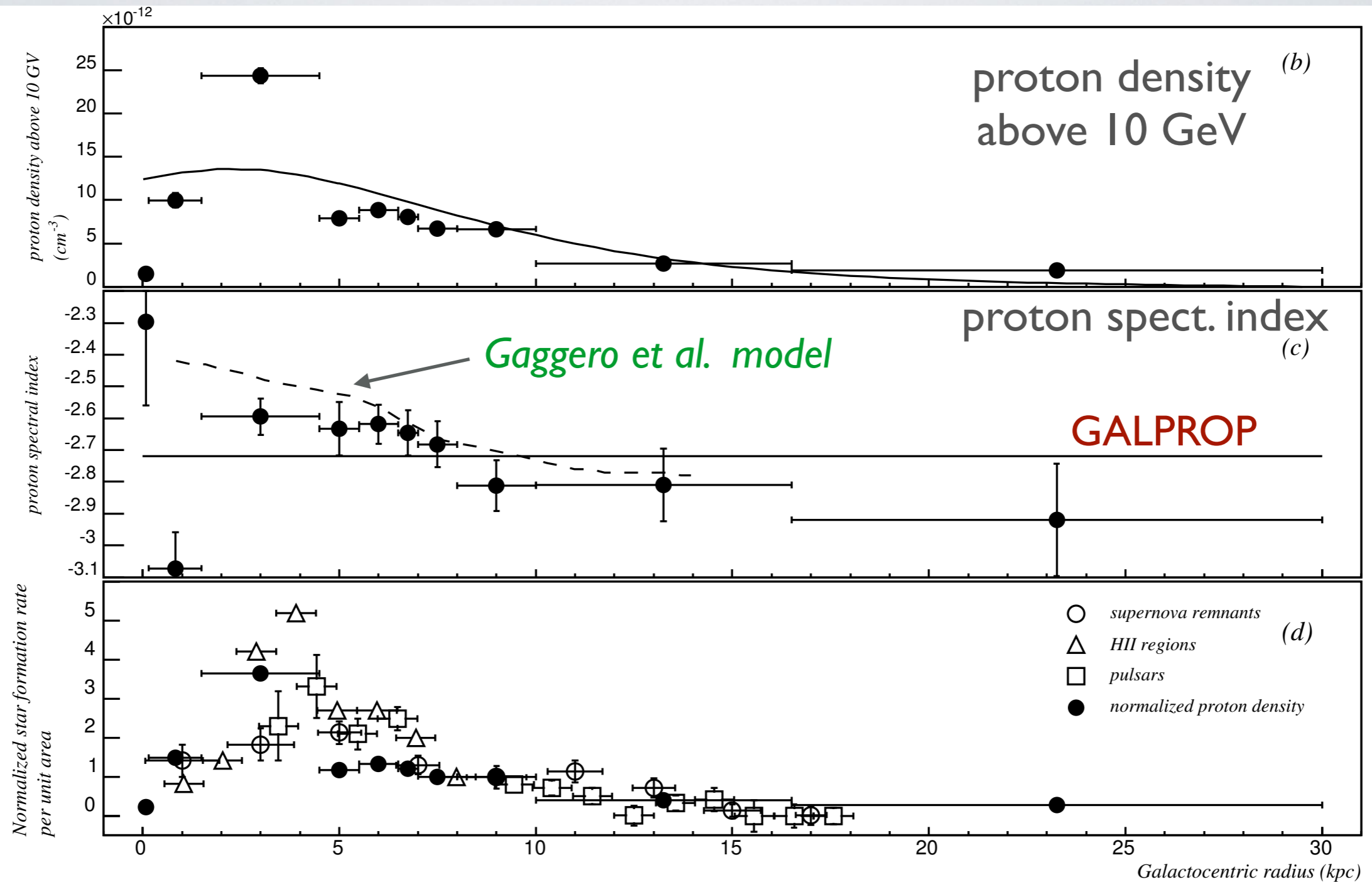
The KRA_γ model reproduces the full-sky Fermi spectrum and angular distribution. It also provides a better fit in the inner GP region

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



Fermi results

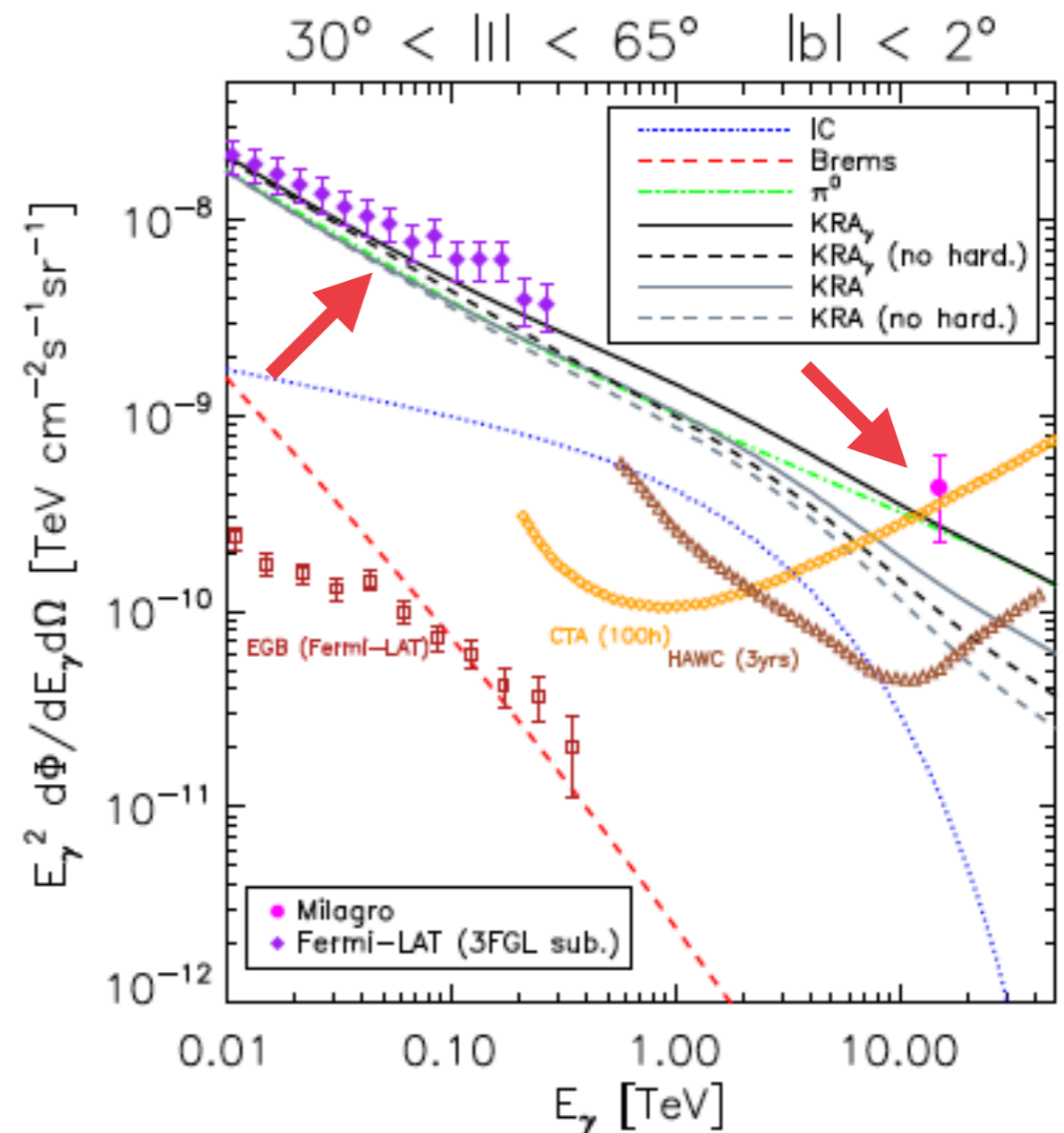
FERMI coll. arXiv:1602.07246; APJ supp.



The KRA_γ model against the Milagro anomaly at 15 TeV

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

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

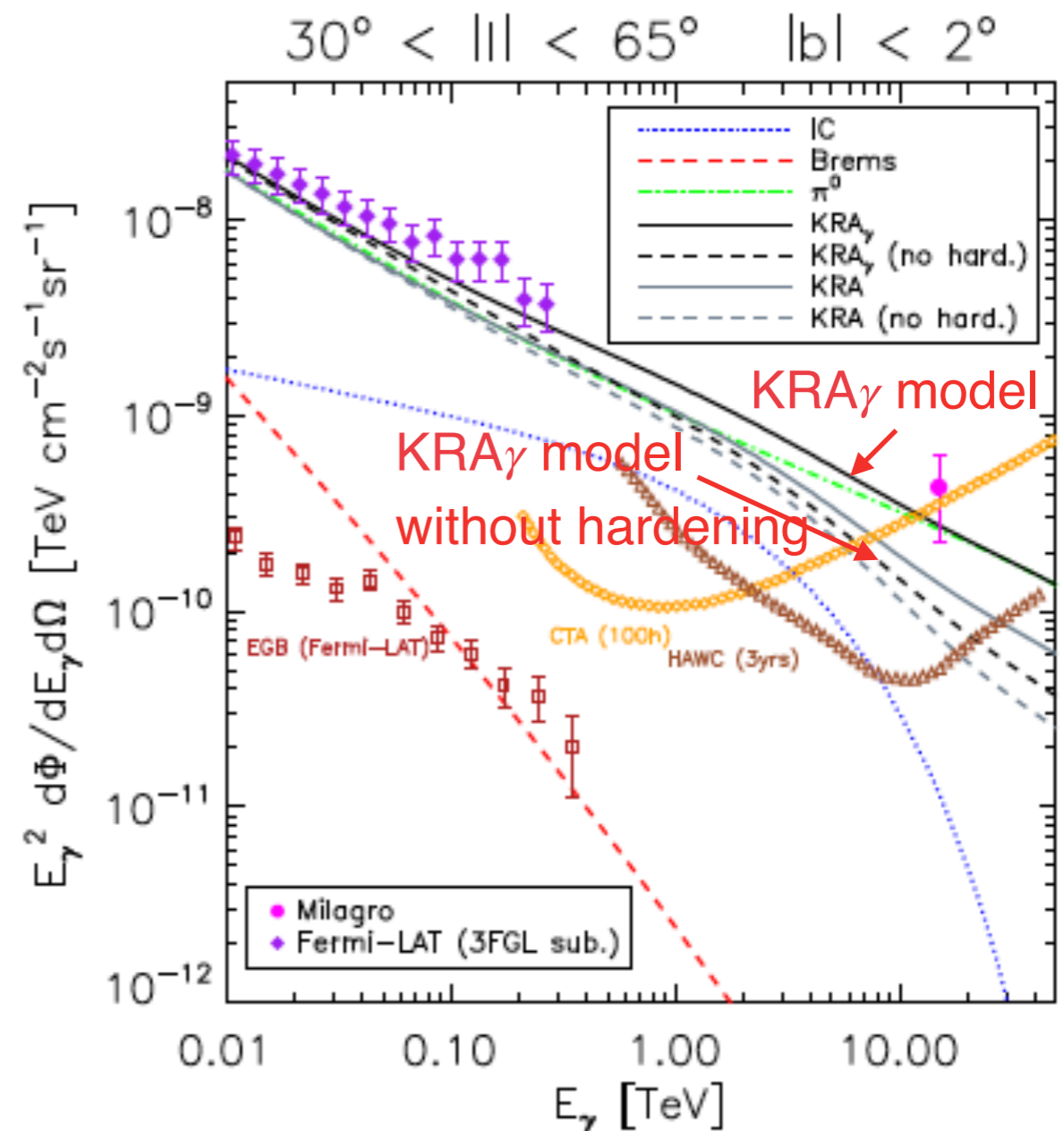


The impact on the Milagro anomaly at 15 TeV

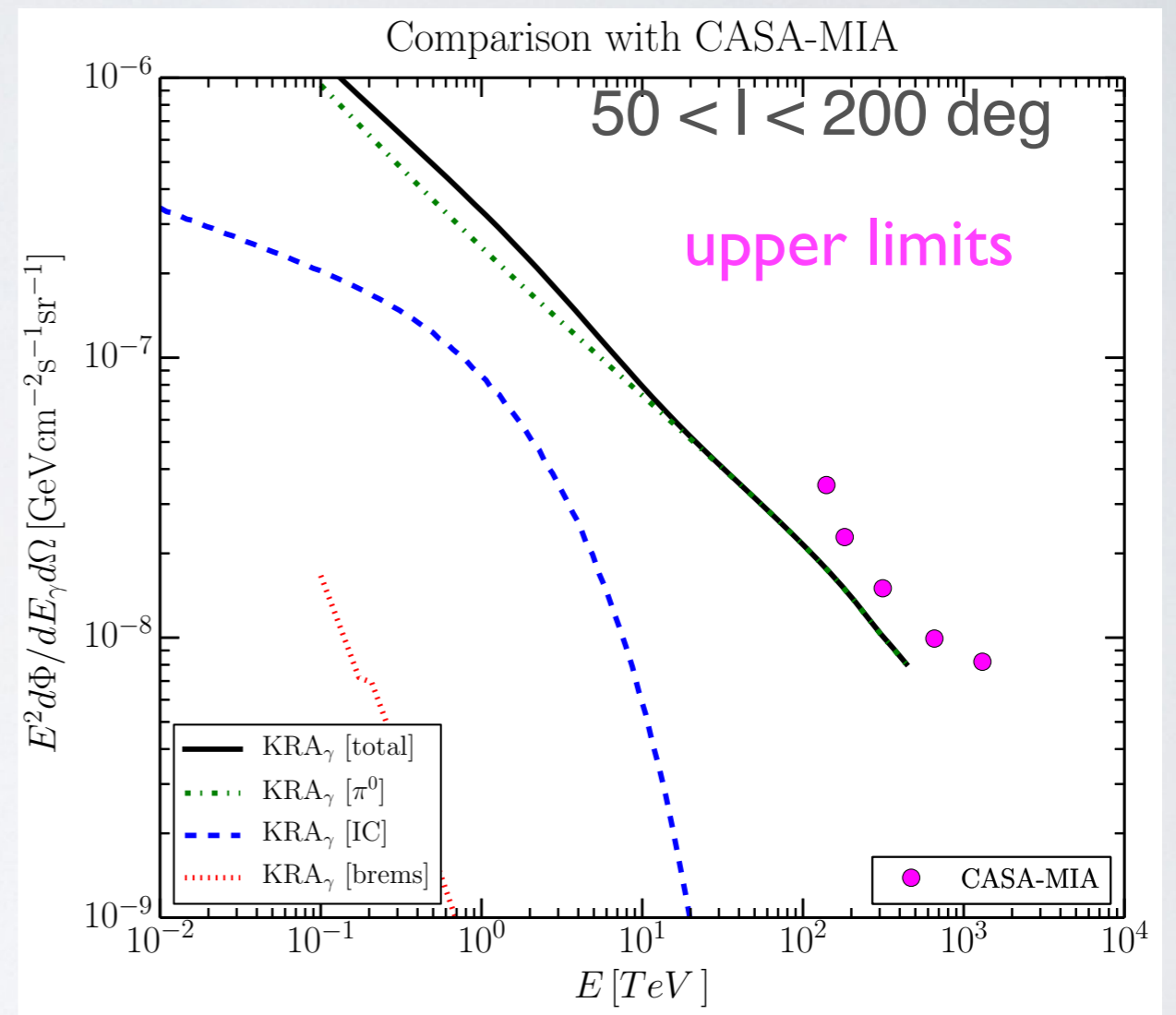
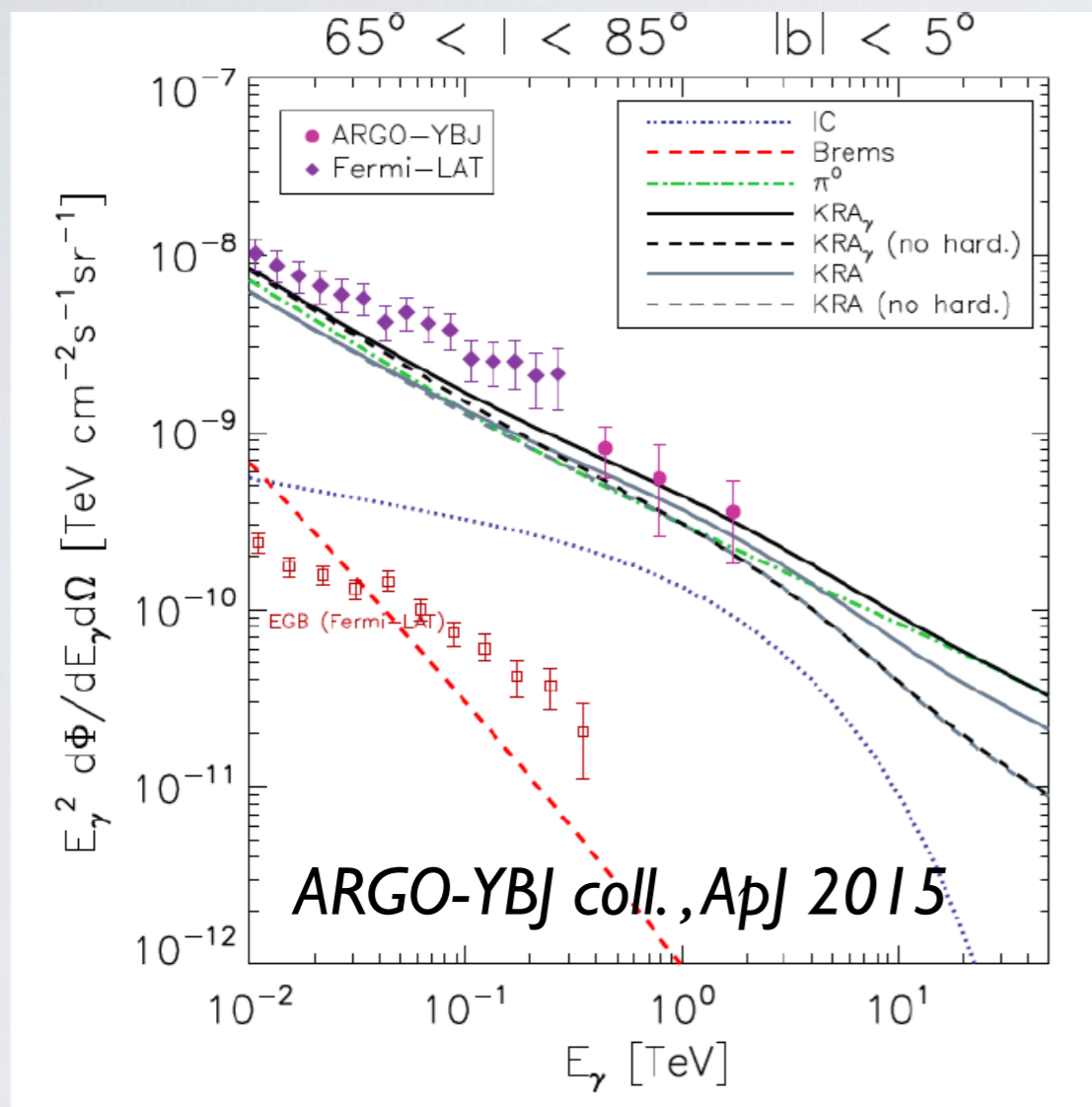
Gaggero, DG, Marinelli, Urbano & Valli *arXiv: 1504:00227 ApJ L 2015*

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

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



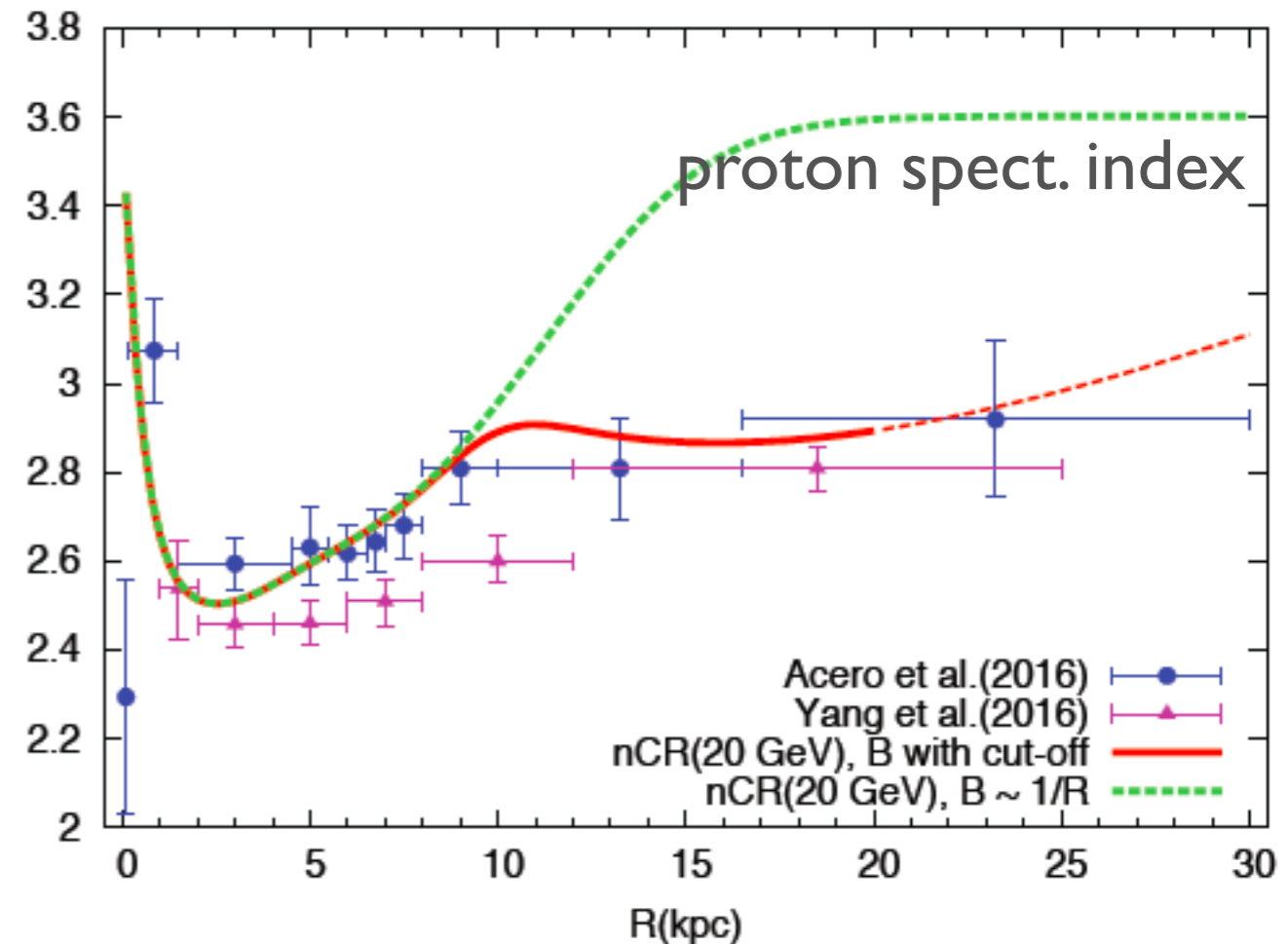
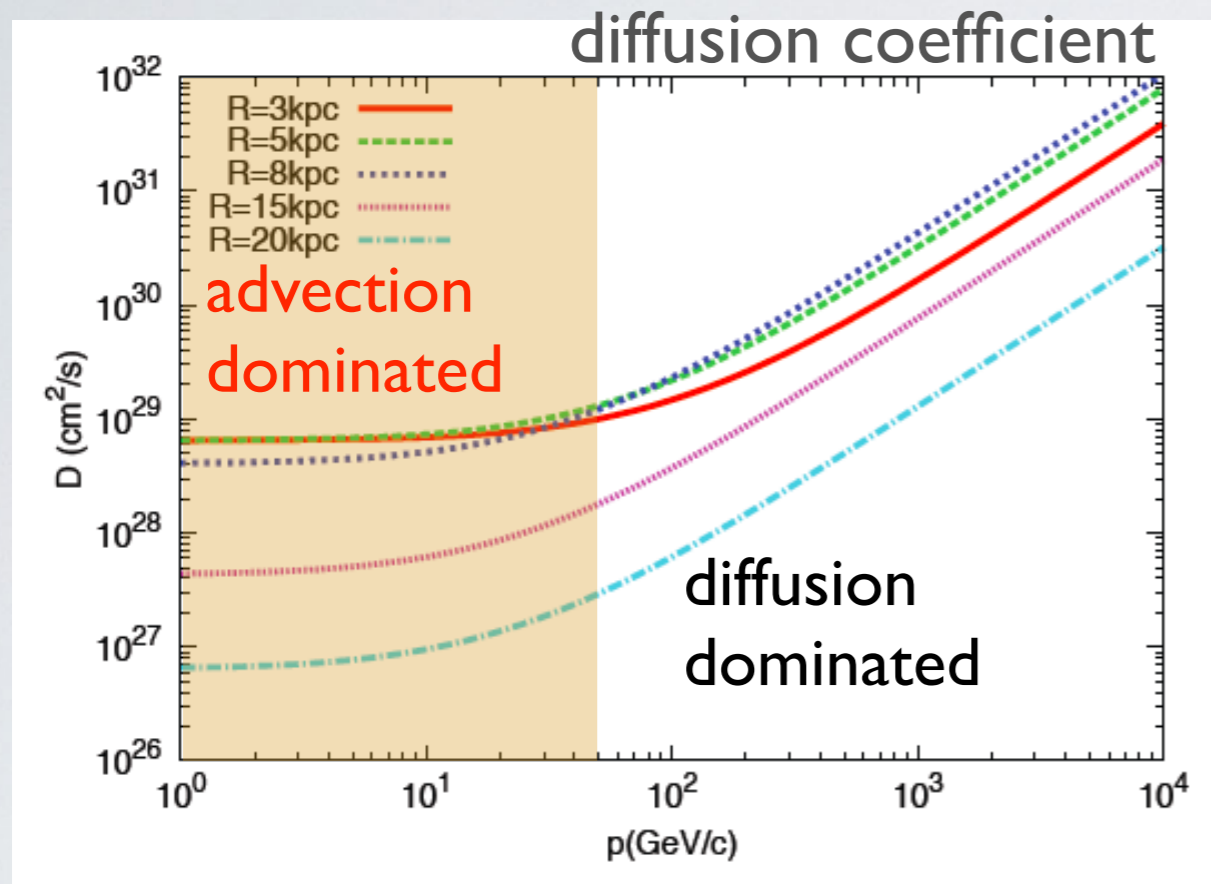
Comparison with other high energy γ -ray data



The case for a spatial dependent δ

A possible interpretation ?

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 dominates
- the effect is larger in the inner Galaxy, larger $D \rightarrow$ larger p at which diffusion dominates

Note however that **this is a low energy effect !!**

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

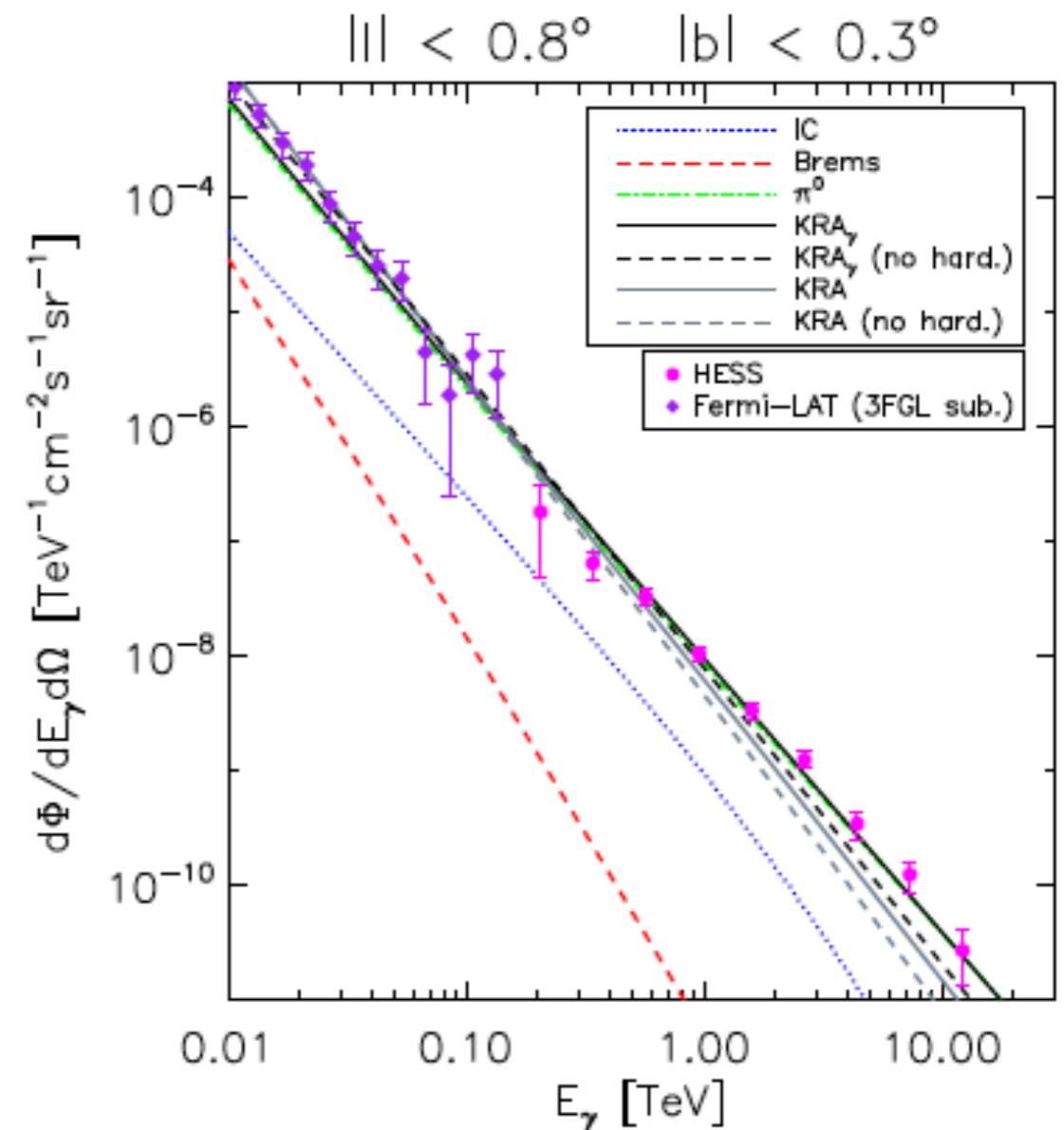
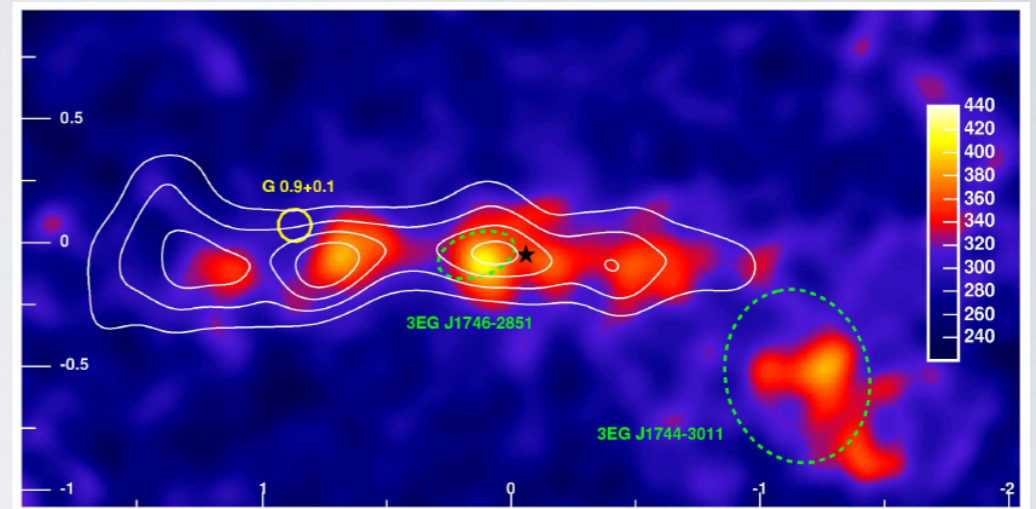
The KRA_γ model against the Galactic Ridge emission

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*)

See A. Marinelli talk in a few min !



What all this implies for neutrinos ?

IceCube measured ν events

IceCube coll. PRL 2013 and PRL 2014

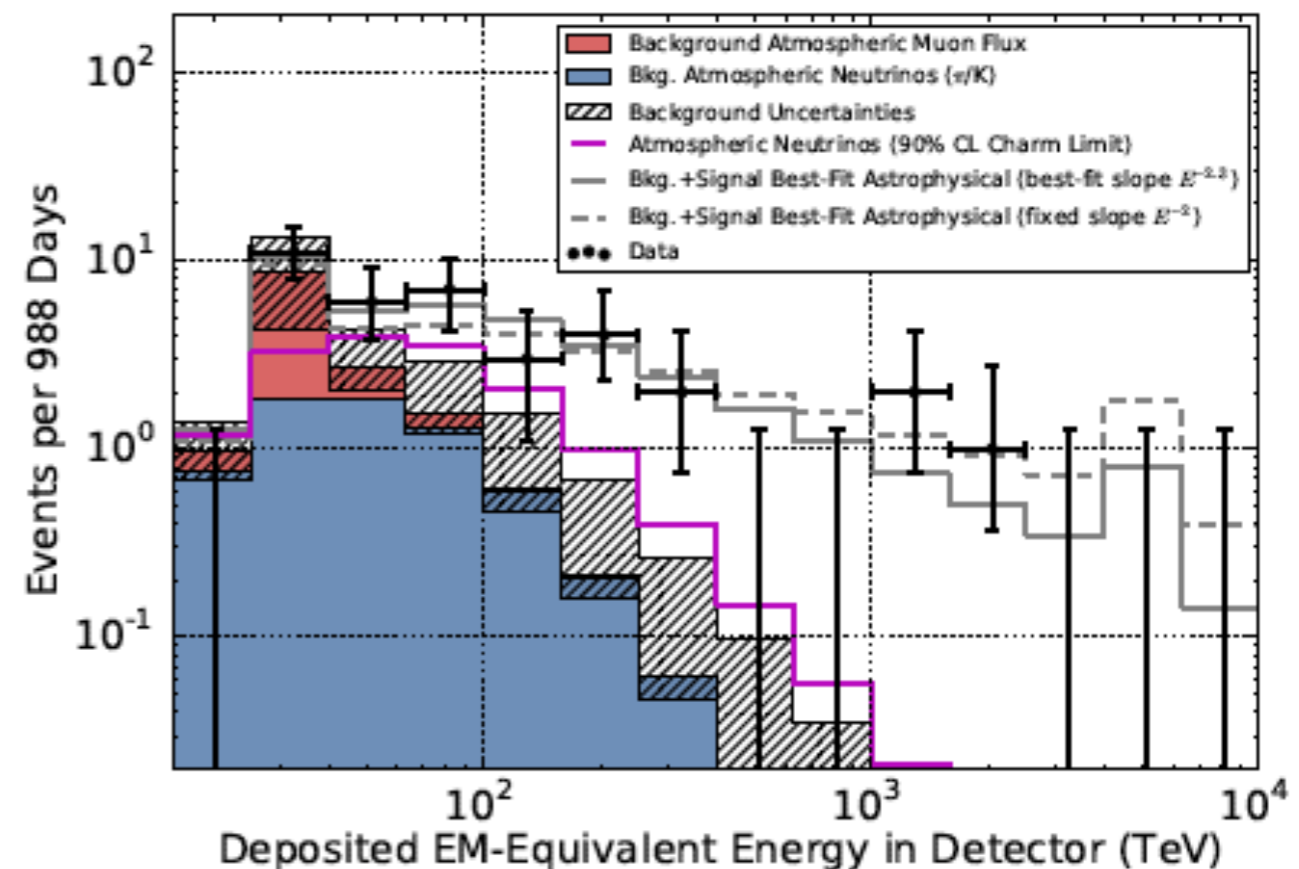
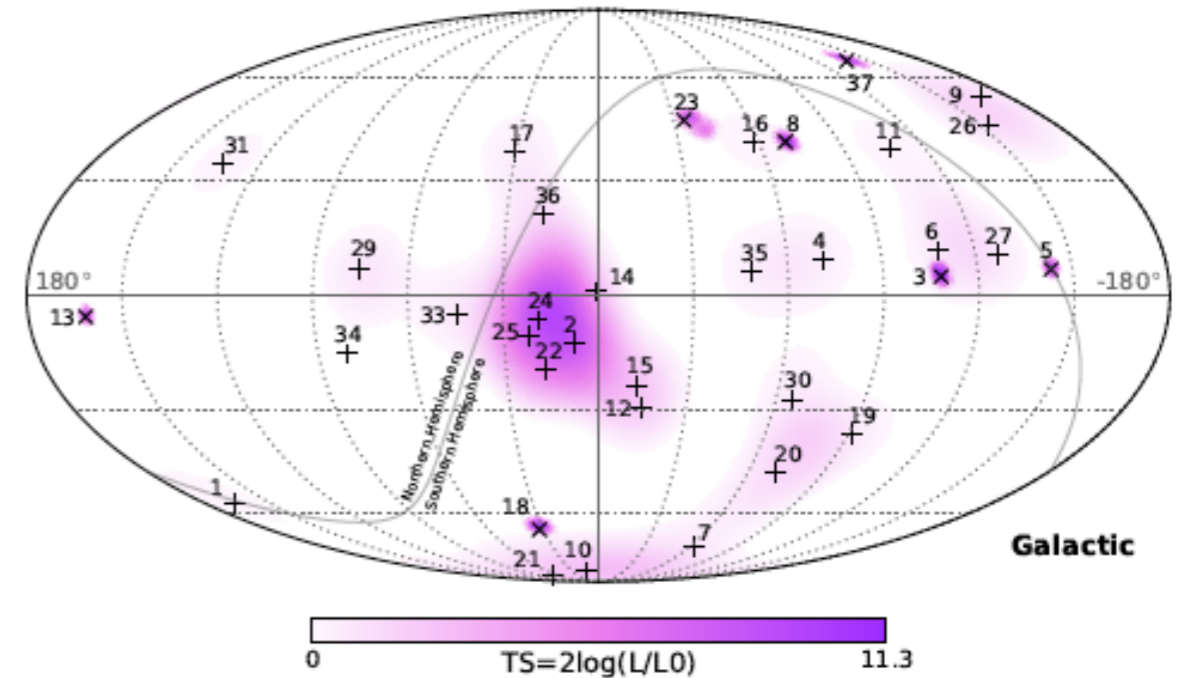
IceCube found evidence for 28 (2 years) then **37 HESE events** (3 yrs) with reconstructed direction above 30 TeV corresponding to a **5.7 σ excess** respect to the atm. bkg.

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

$$- 2.3 \pm 0.3$$



IceCube astrophysical neutrinos: present status

arXiv1510.05223, ICRC2015

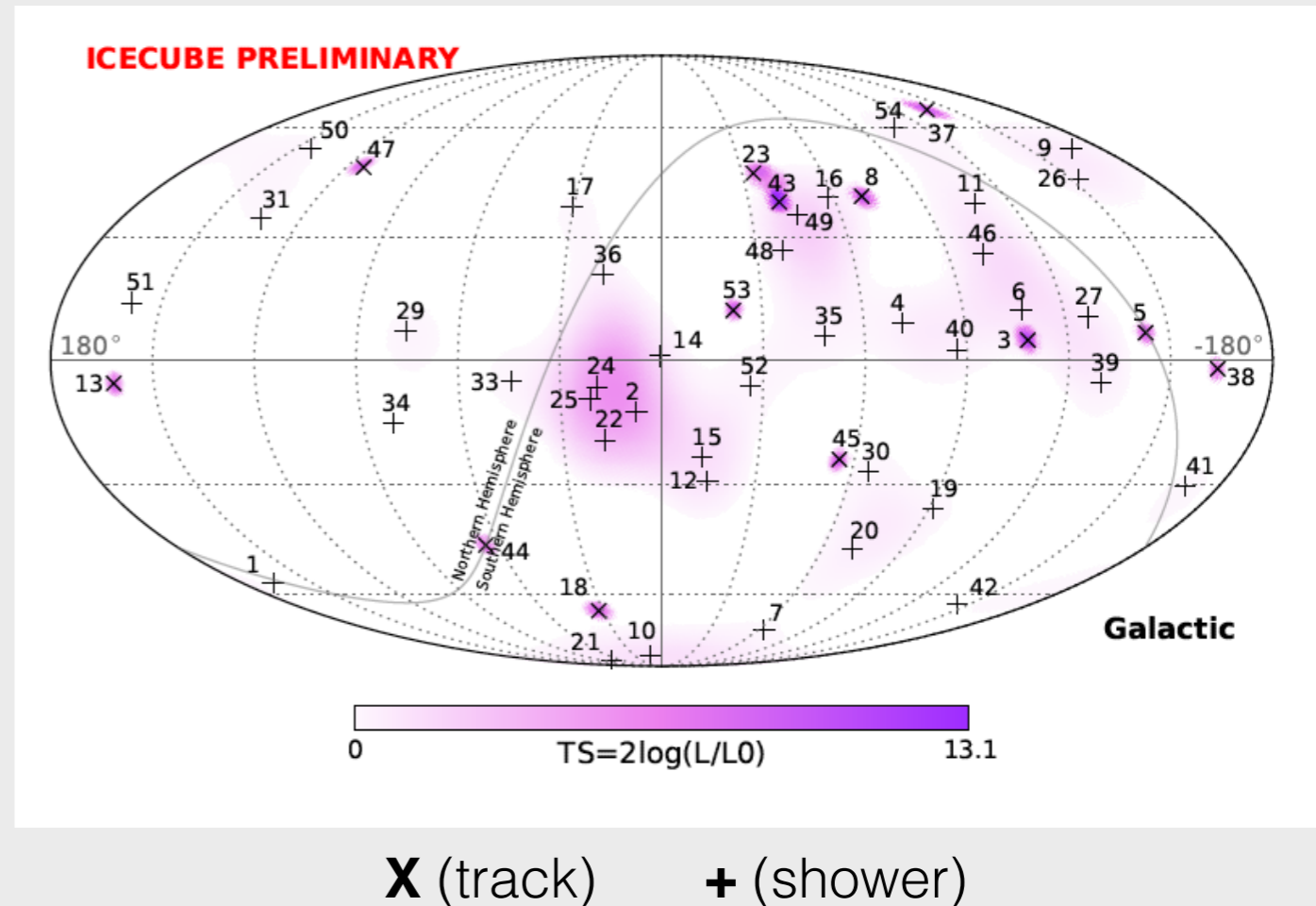
IceCube found evidence for 54 events (4 yrs preliminary) with reconstructed direction above 30 TeV corresponding to **7σ excess respect to the atm. bkg. ($9^{+8}_{-2.2}$)**

angular distribution compatible with isotropy (see however below)

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

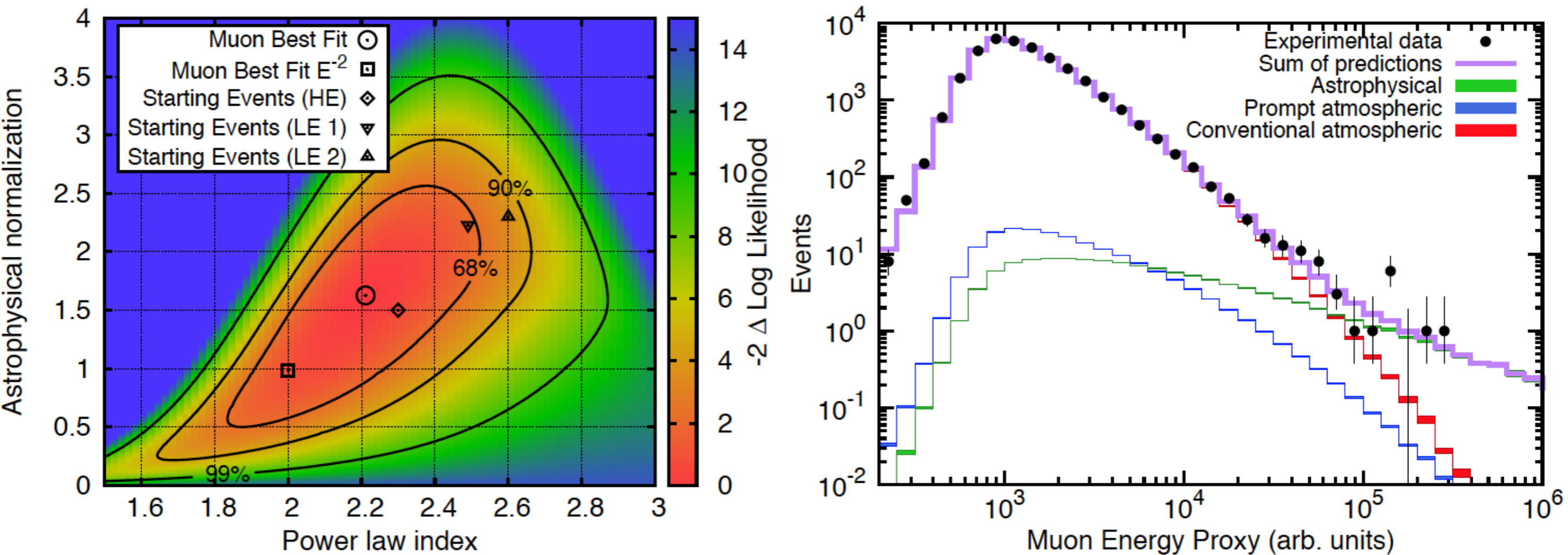
Best fit spectral index $\Gamma \sim -2.58 \pm 0.25$

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



Muon neutrinos (tracks) from the North hemisphere

IceCube coll., PRL, vol.115, 2015



- astrophysical muon neutrinos from the Northern hemisphere with $E > 100 \text{ TeV}$.
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 3.7σ .

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

Comparison to HESE 4 year

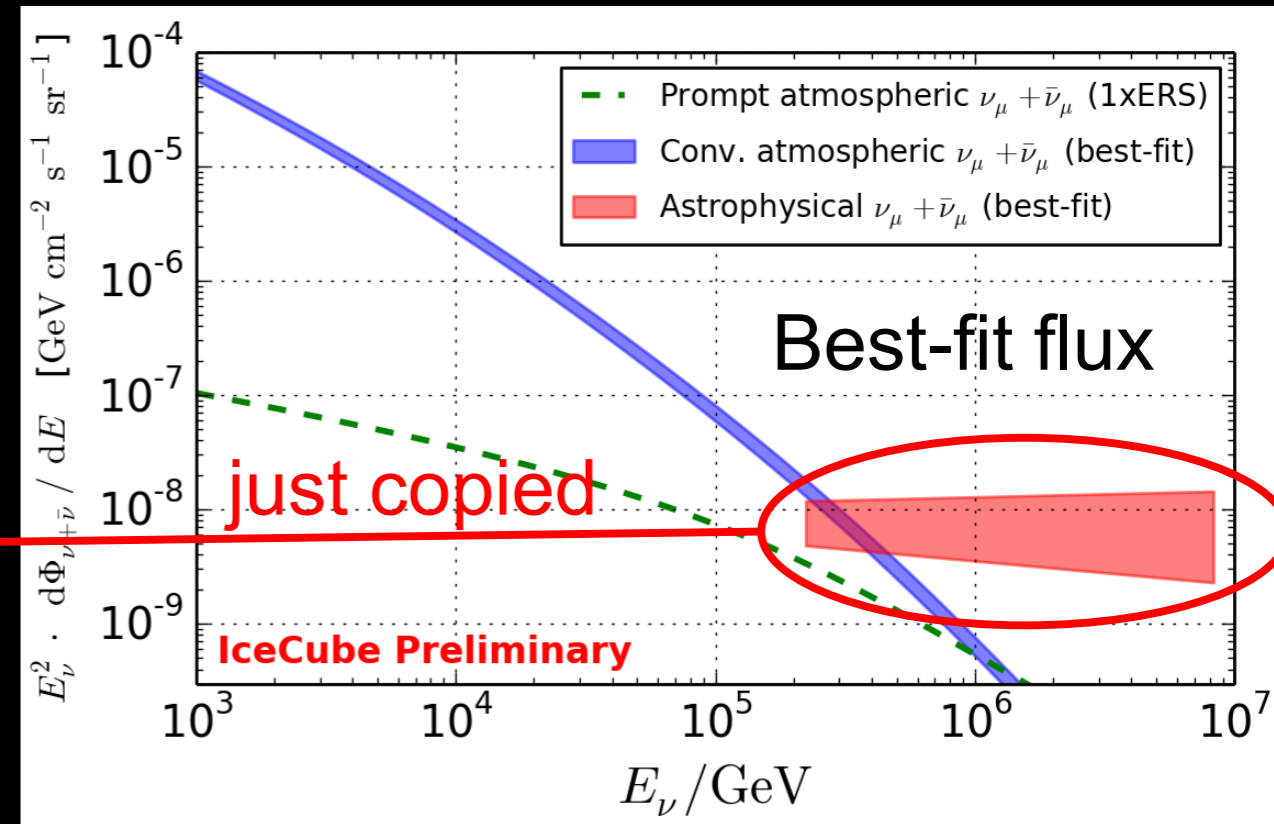
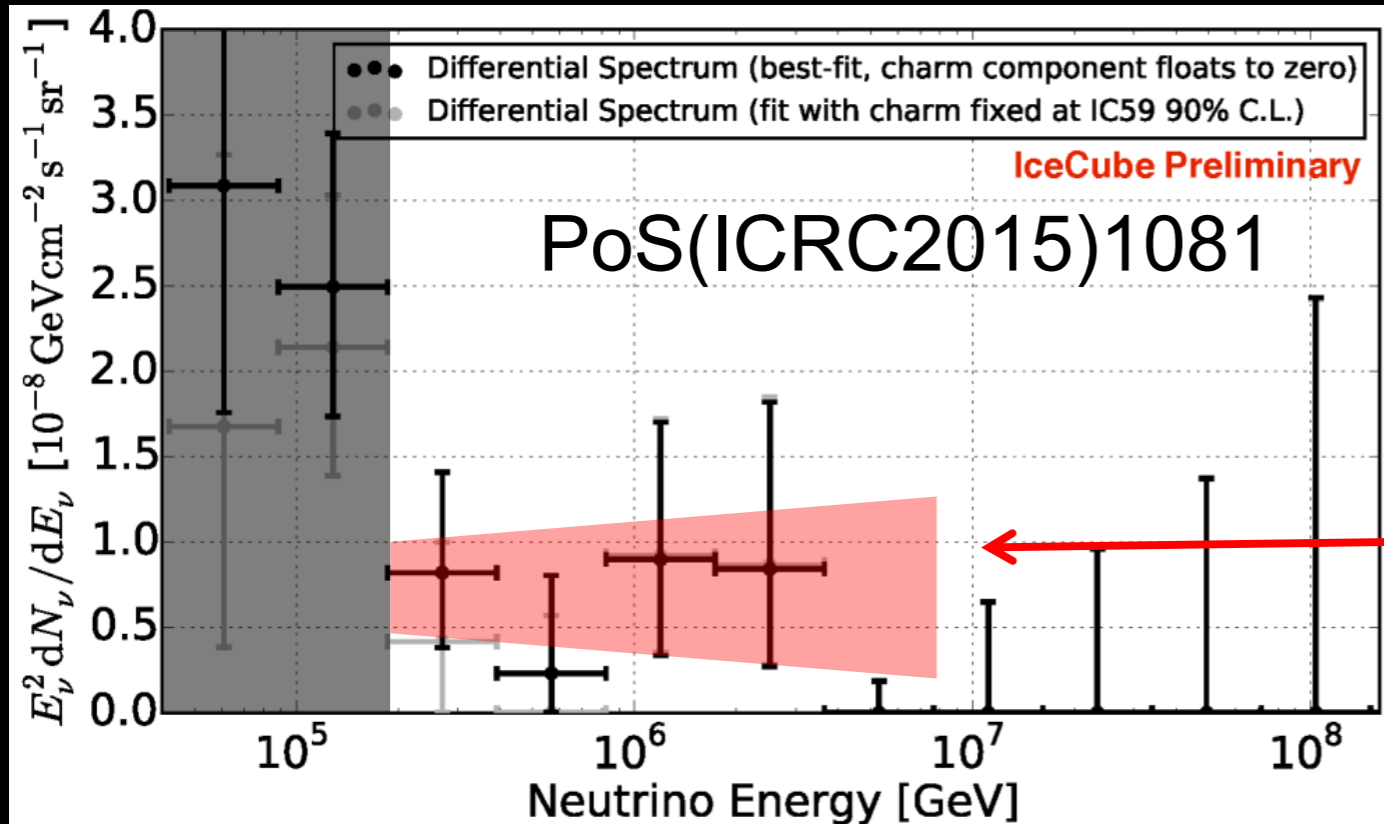


III. Physikalisches Institut



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}

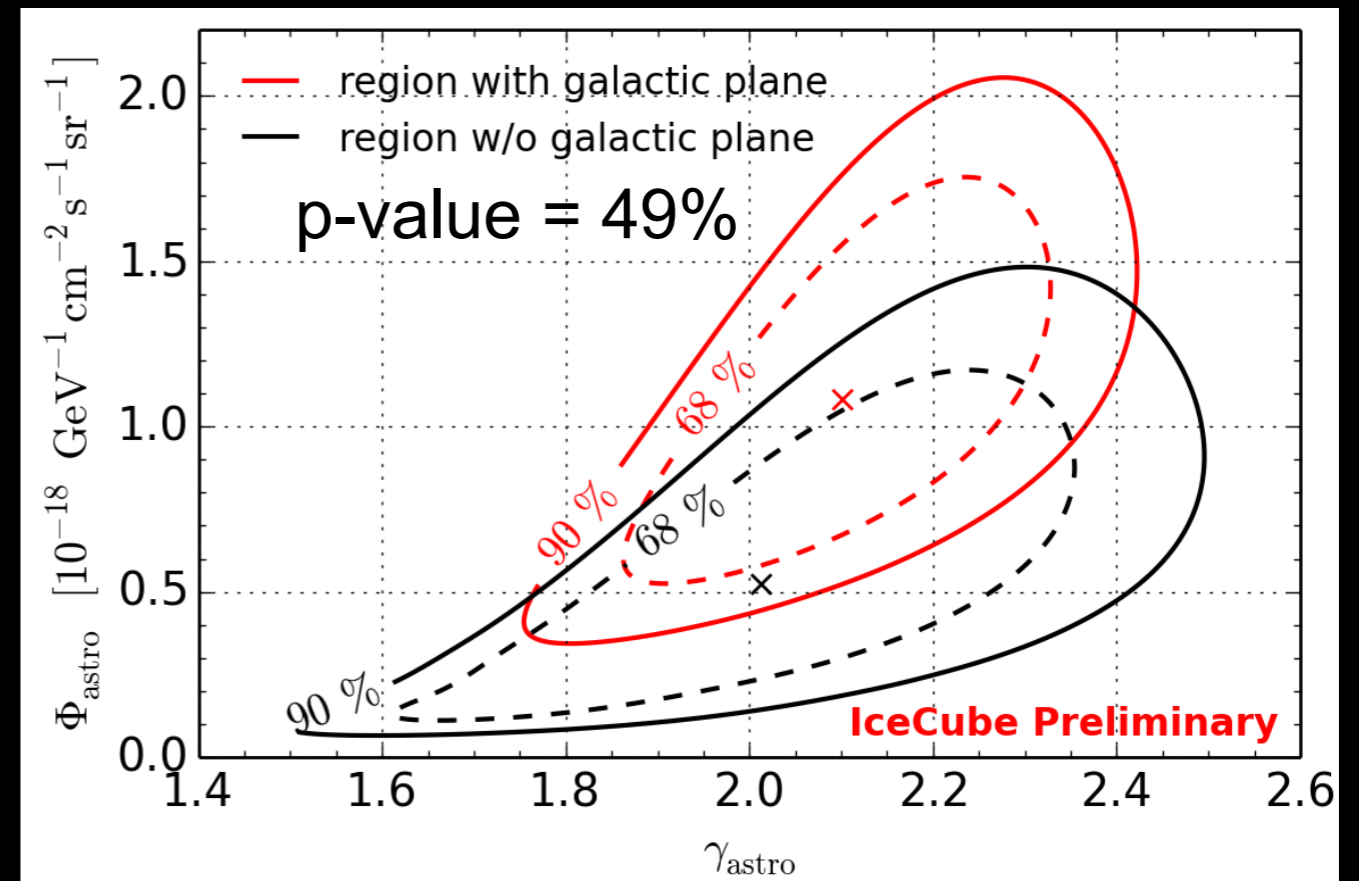
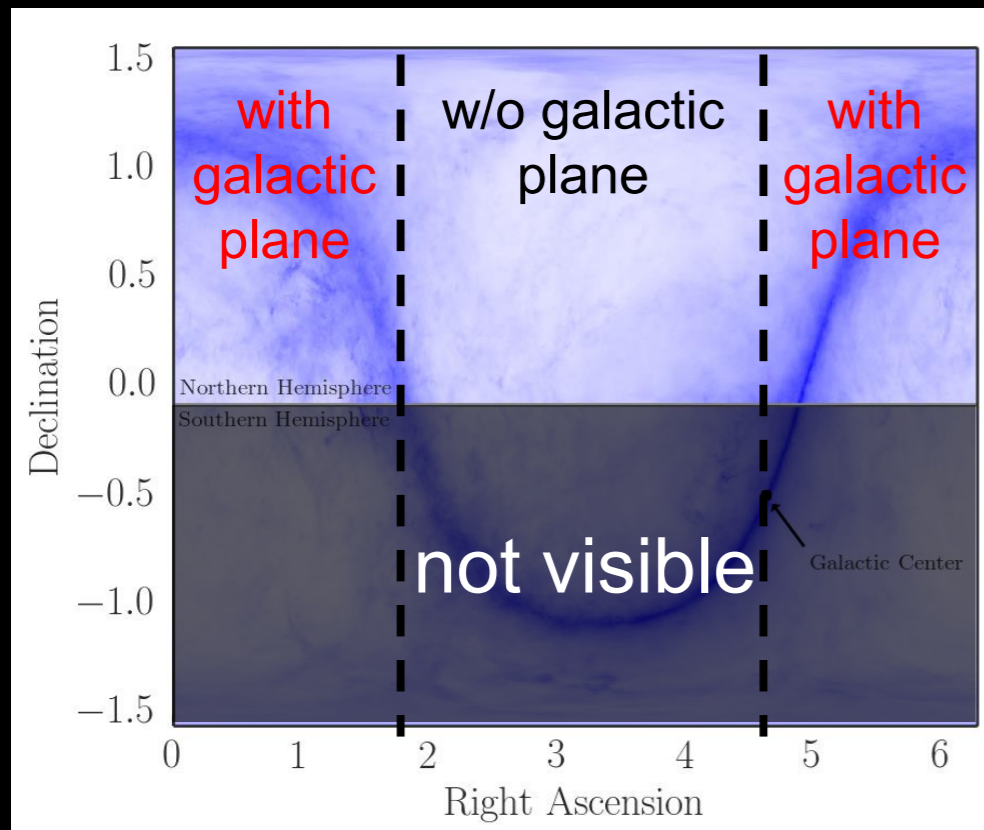
Results of a simple galactic plane analysis



III. Physikalisches
Institut



- 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

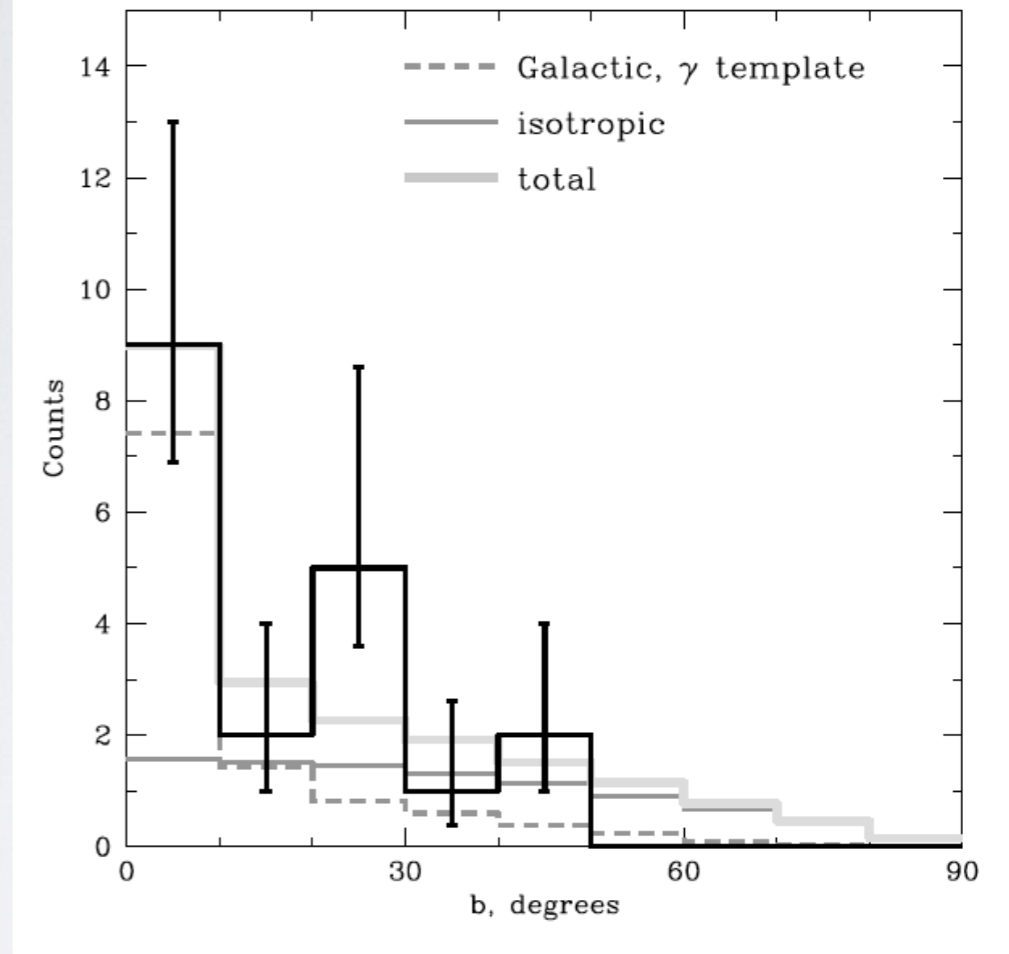
use only events **above 100 TeV** in the IC 4-year sample (19 events, 1 bkg)

9 events for $|b| < 10^\circ$; 0 events for $|b| > 50^\circ$

They found **$\sim 4 \sigma$ inconsistency with isotropy**

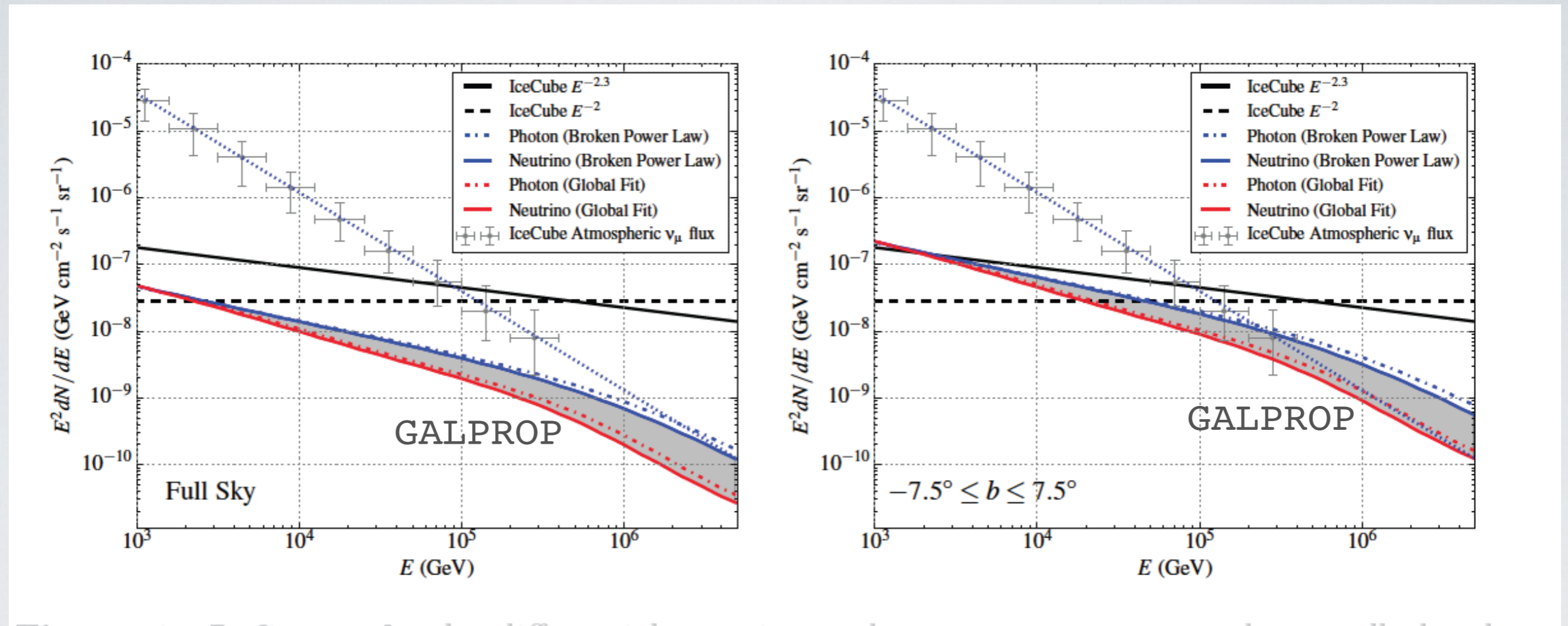
It is claimed that “a model which contains 50% contributions from the Galactic and extragalactic components provides a satisfactory fit to the data”

A more recent analysis by *Palladino & Vissani arXiv:1601:06678(v2)* found that a $\sim 20\%$ contribution is more likely



The Galactic ν emission with conventional models

Ahlers et al. arXiv:1505.03156

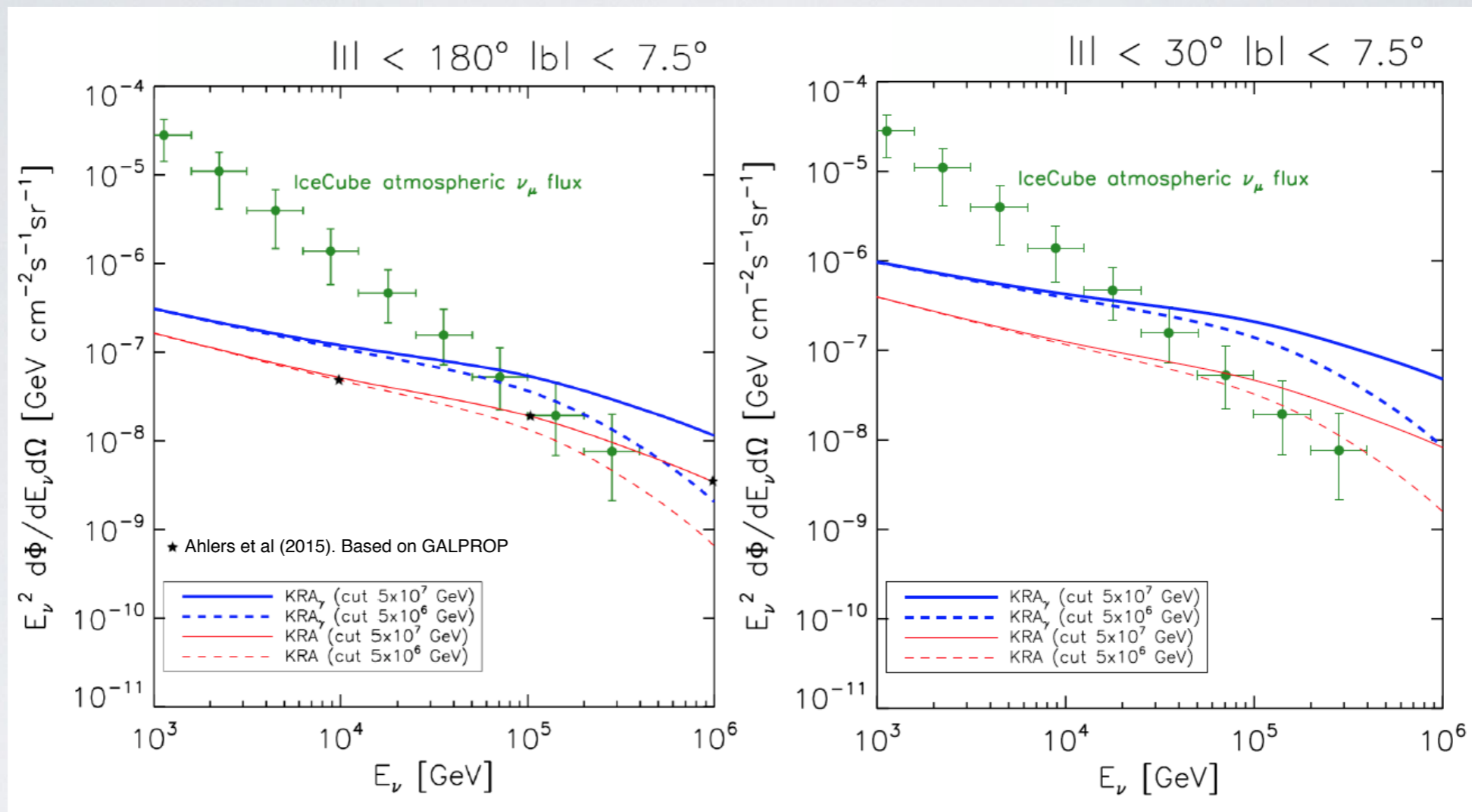


8% of IceCube HESE (2013) signal at most

- 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_γ 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)]

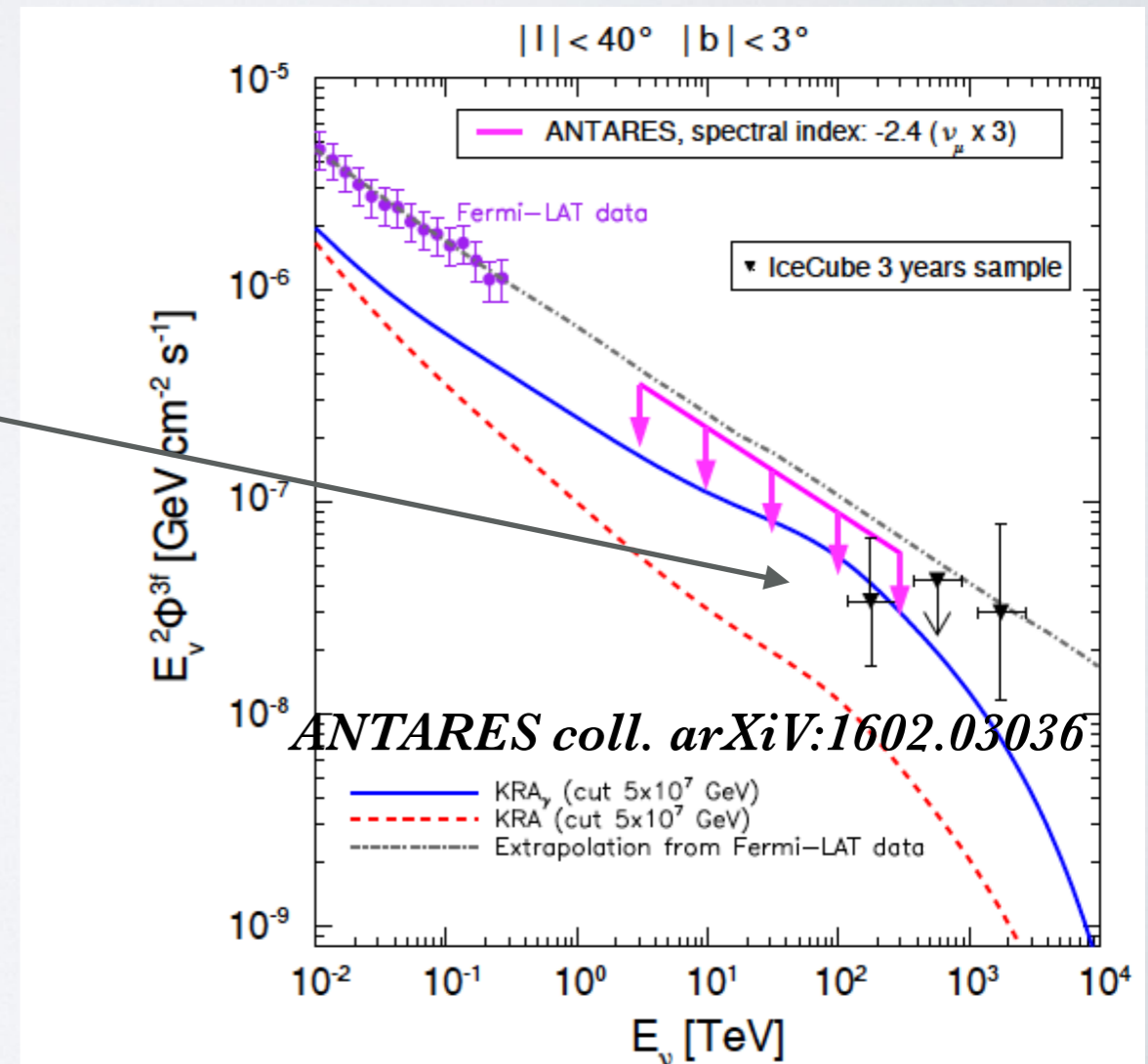
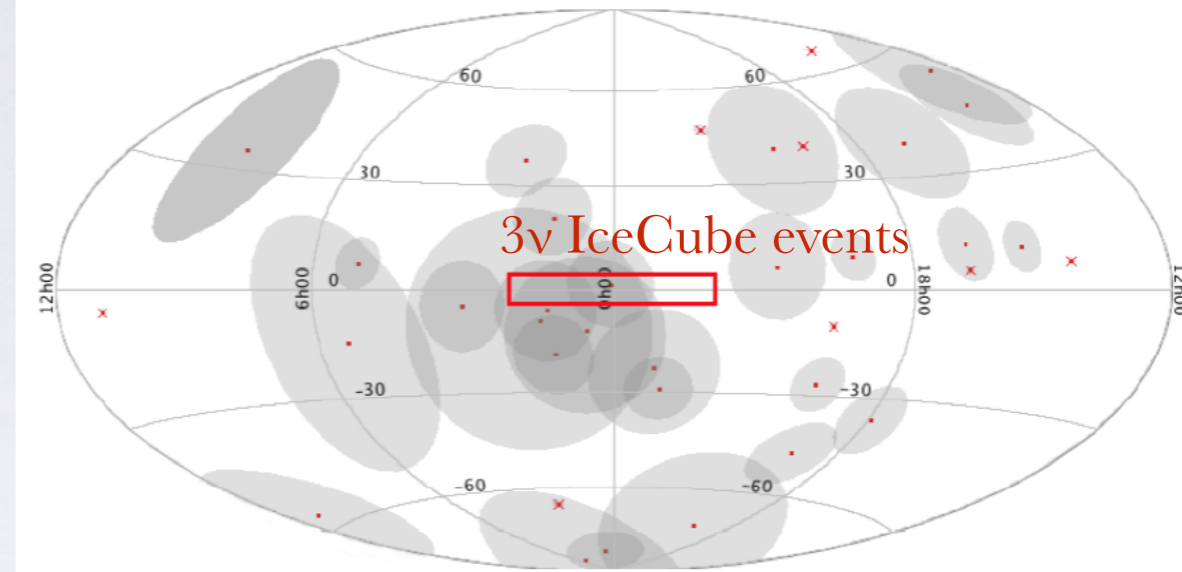
Comparison with exp. data in the inner GP

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
 $|l| < 4^\circ$ and $|l| < 30^\circ$ which turns into an
upper limit (in the fig. $\Gamma = 2.5$ 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_γ models we can estimate the galactic component of the IceCube observation in this region of the sky.



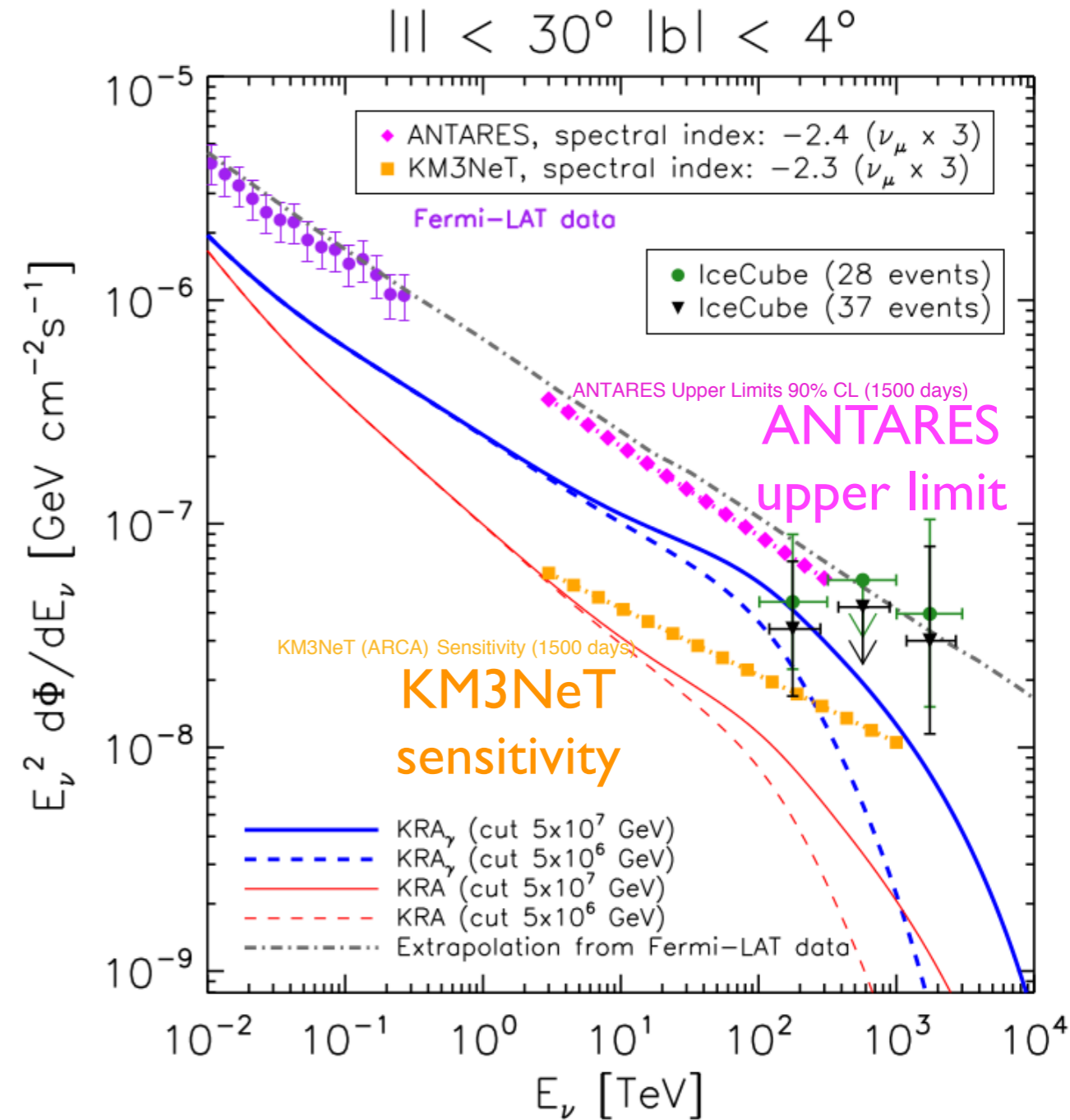
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KRA $_{\gamma}$ full-sky ν emission against IceCube

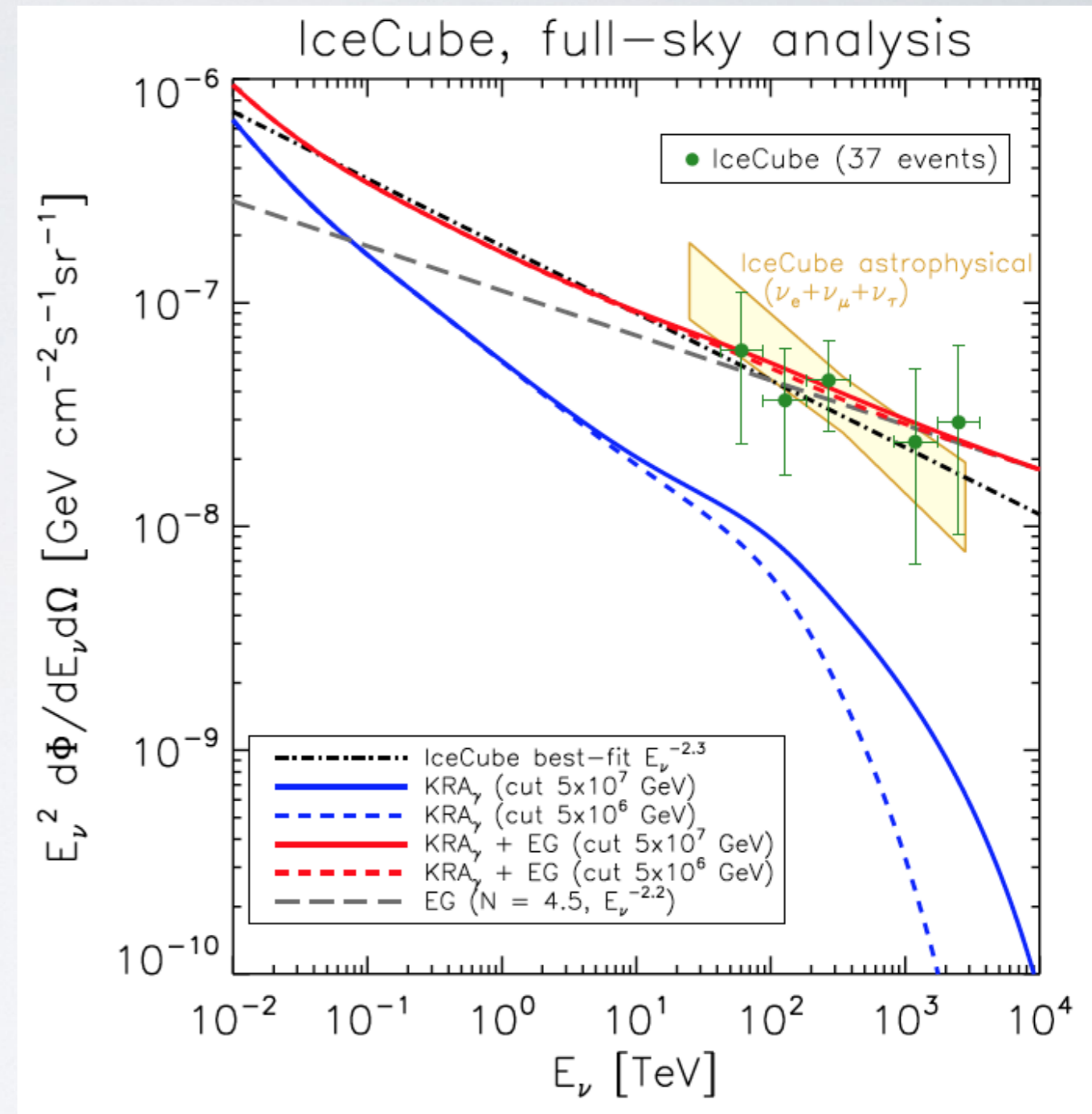
Gaggero, DG, Marinelli, Urbano, Valli, *arXiv:1504.00227*

The KRA $_{\gamma}$ setup predicts a flux which is \sim double and slightly harder than the corresponding conventional model.

This may account for \sim 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

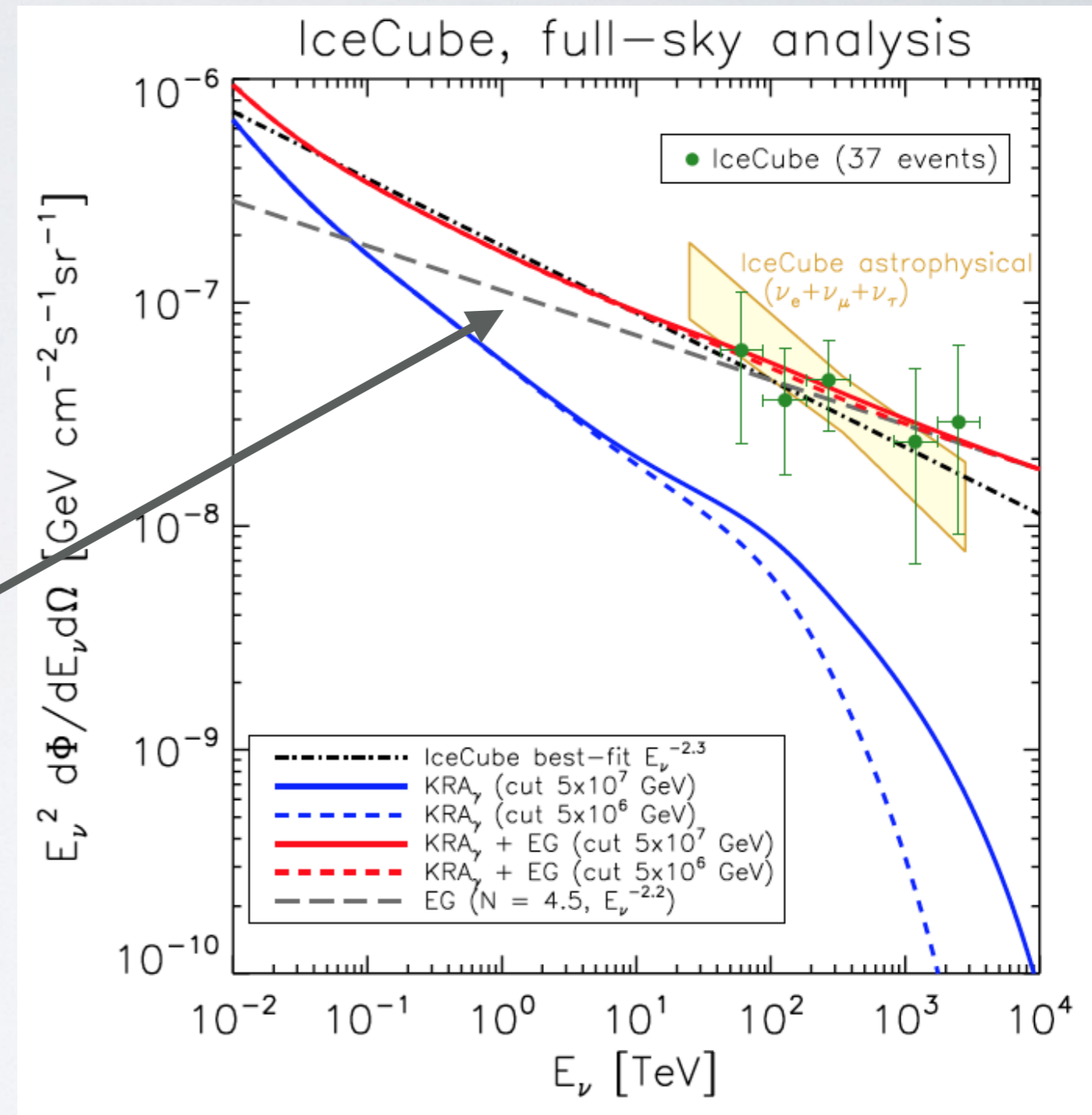
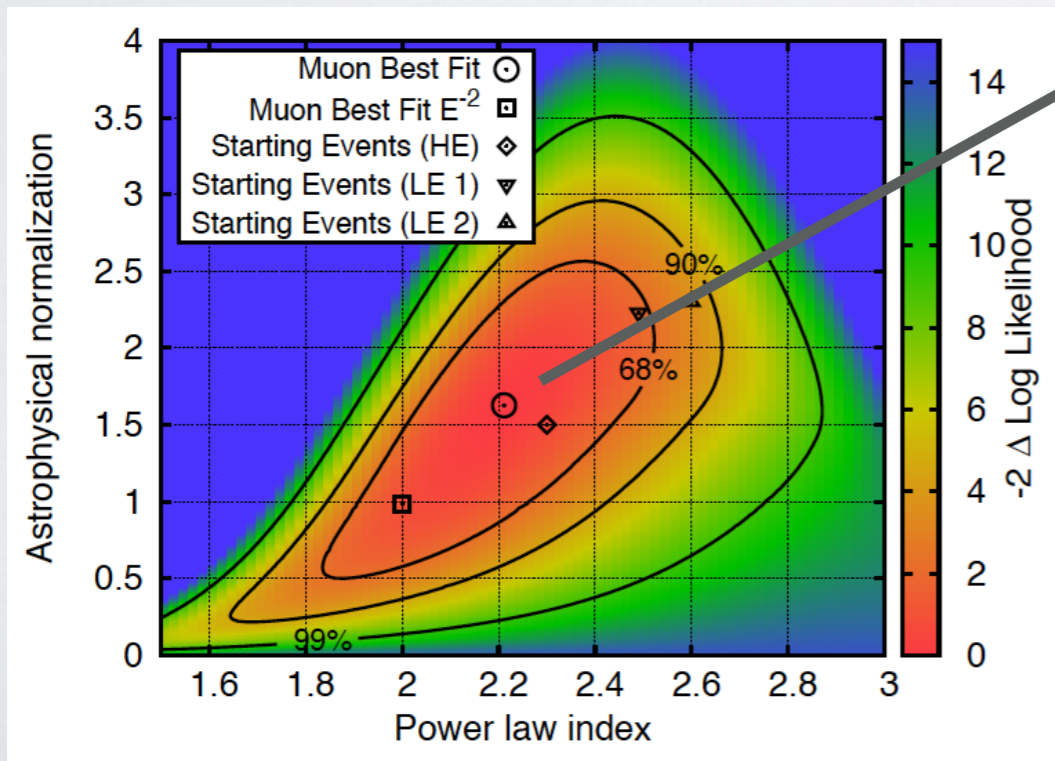


KRA γ full-sky ν emission against IceCube

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

For illustrative purposes

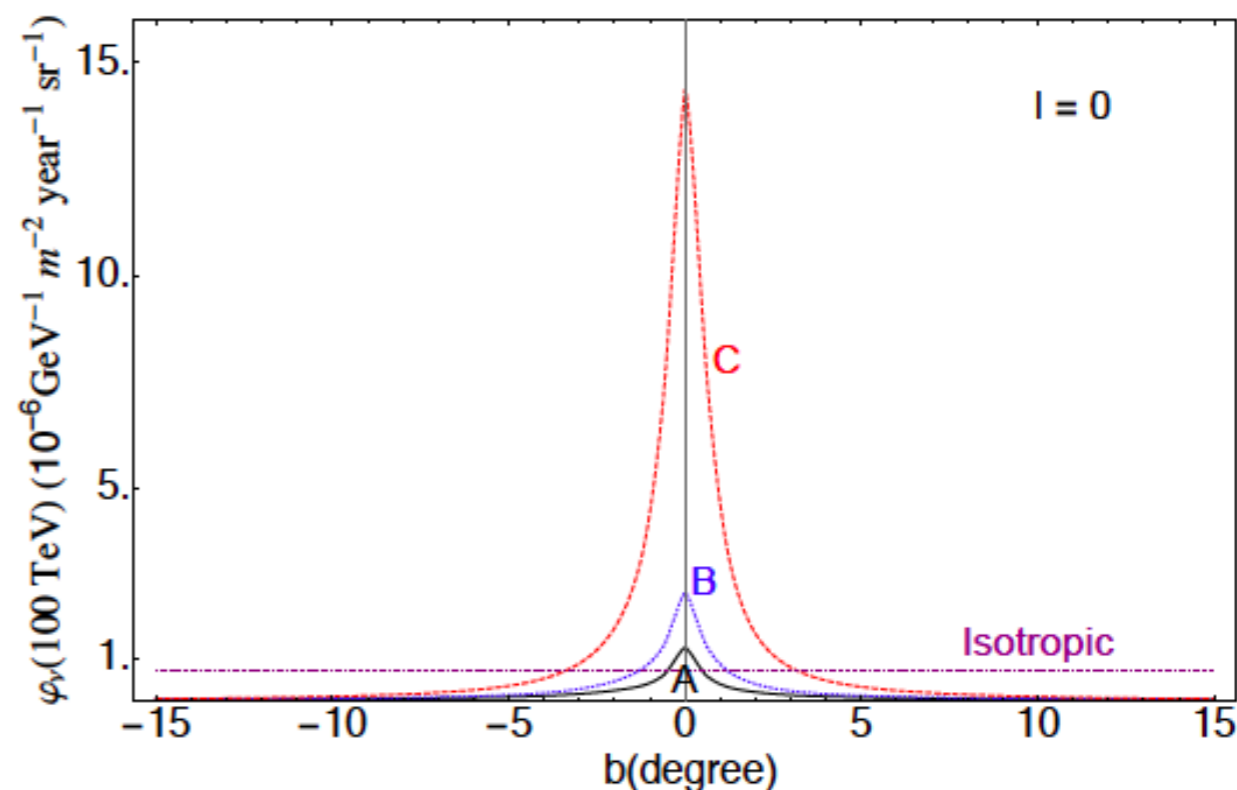
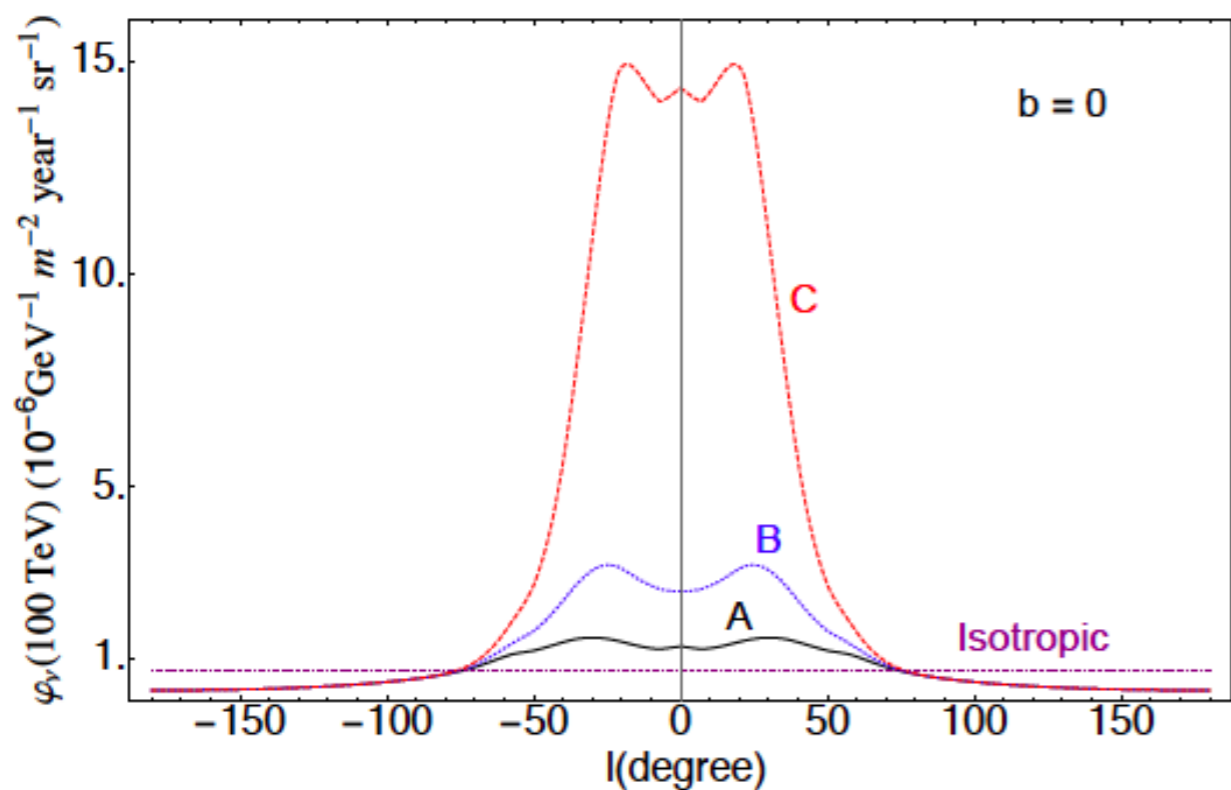
here we assume the ν_μ (tracks) flux (best-fit) measured by IceCube from the northern hemisphere to be representative of the extra-Galactic emission (Gal. emission negligible in that region)



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 % “ “

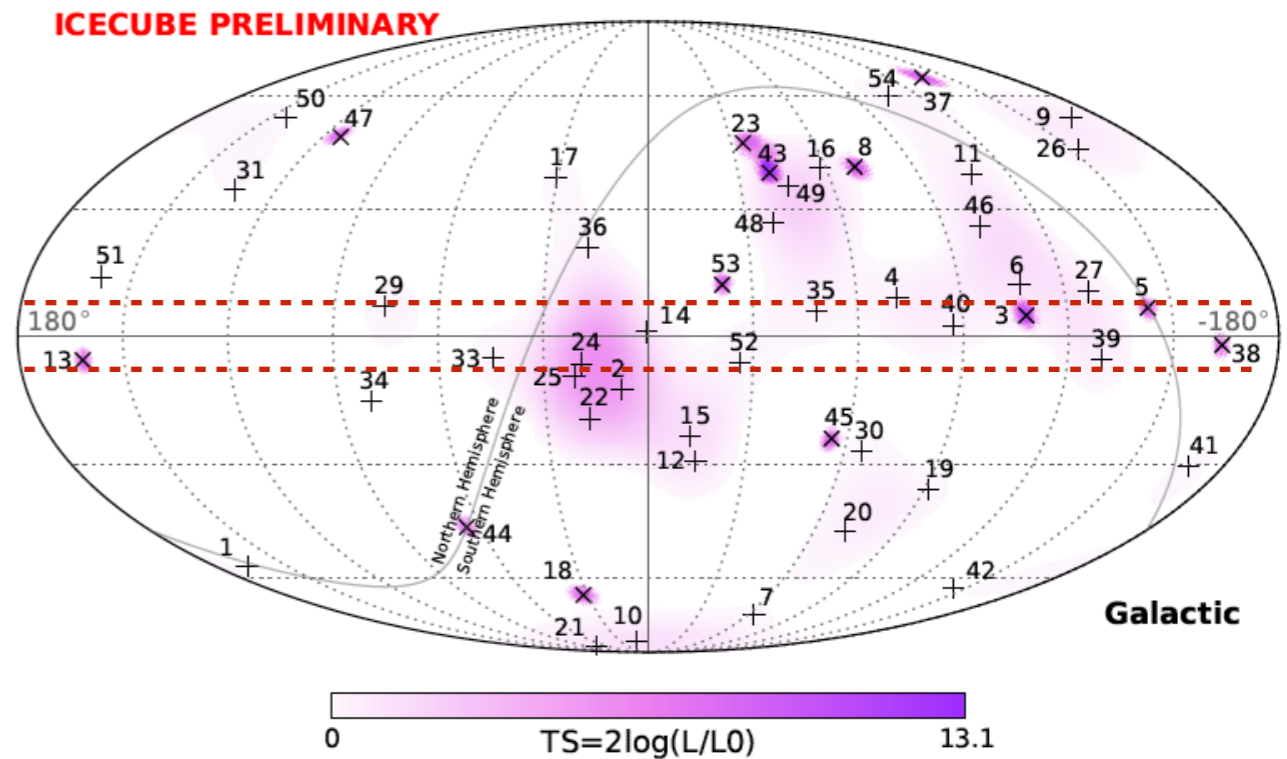
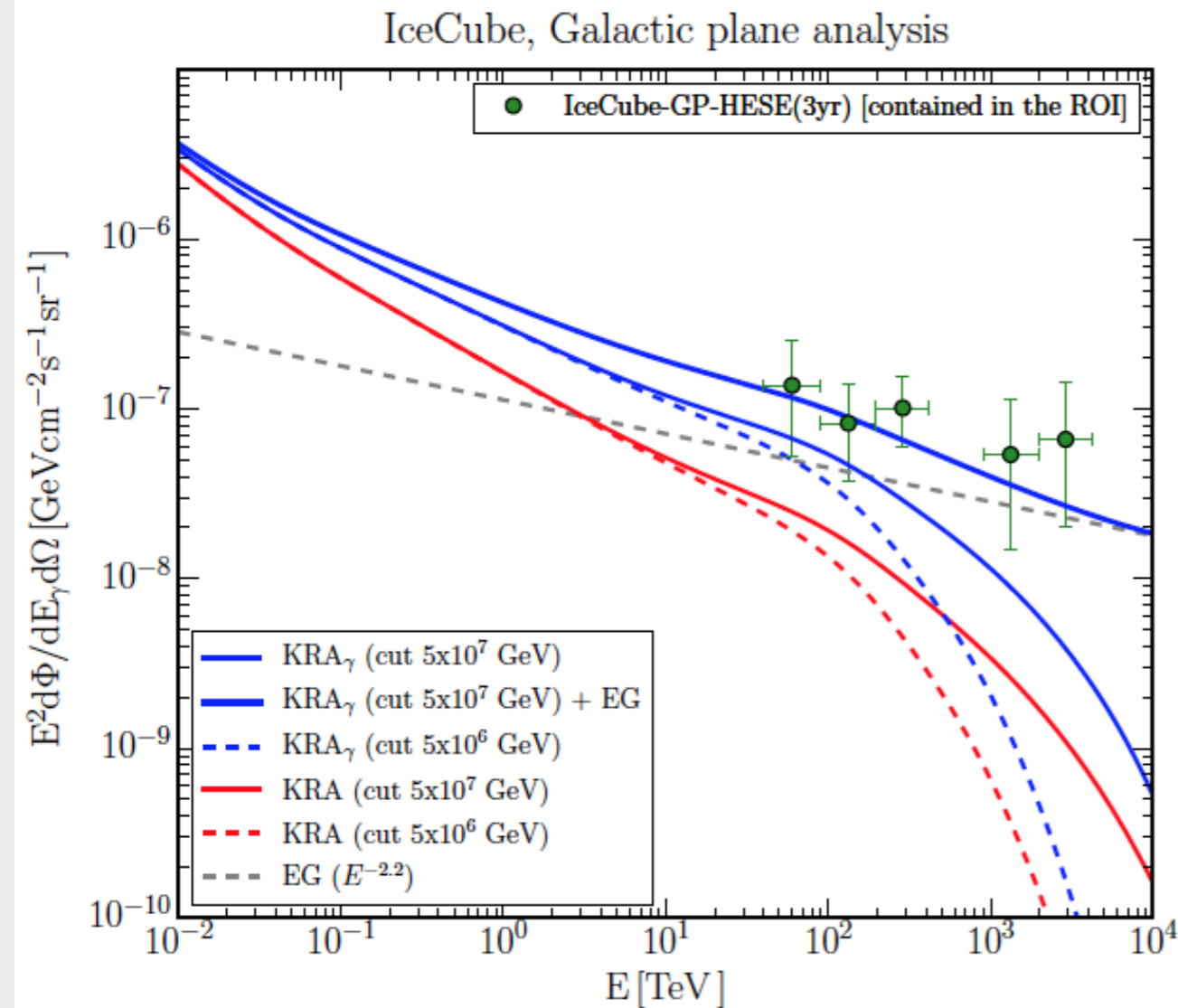
correction to CR density

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

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

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_γ 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 $\delta(R)$ 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 ?

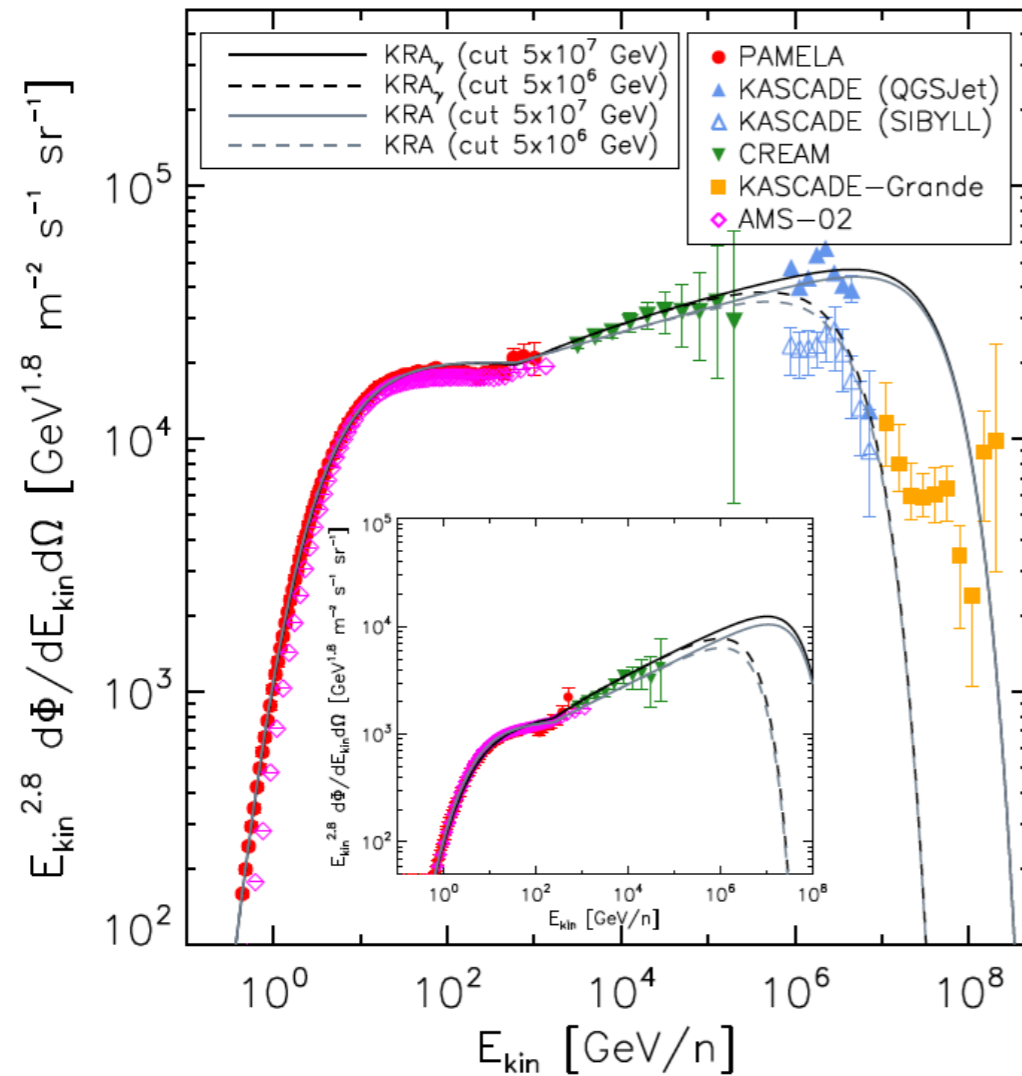
Conclusions

- 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 results (see Marinelli's talk)

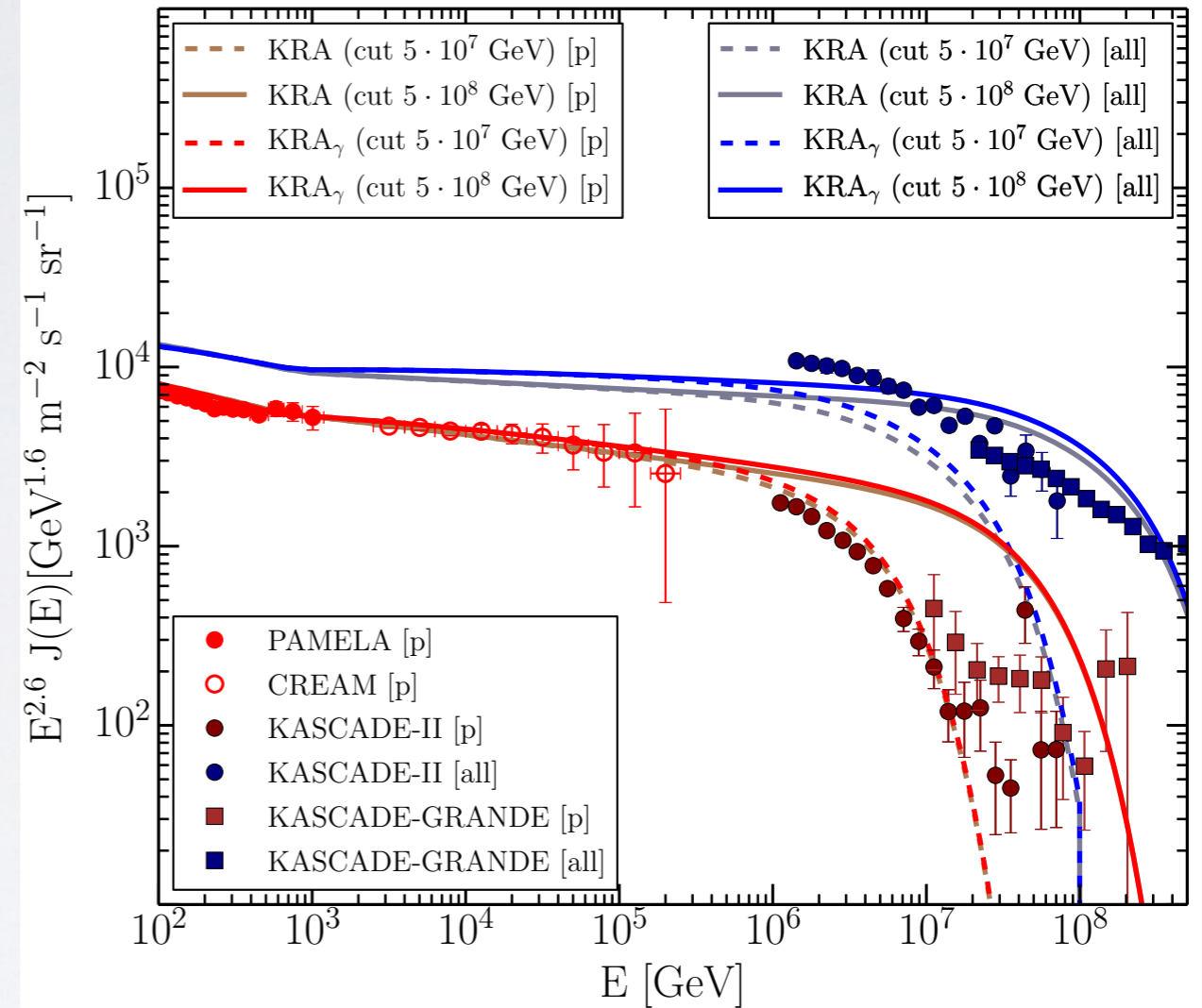
Backup slides

Our CR primary spectra

Protons and Helium



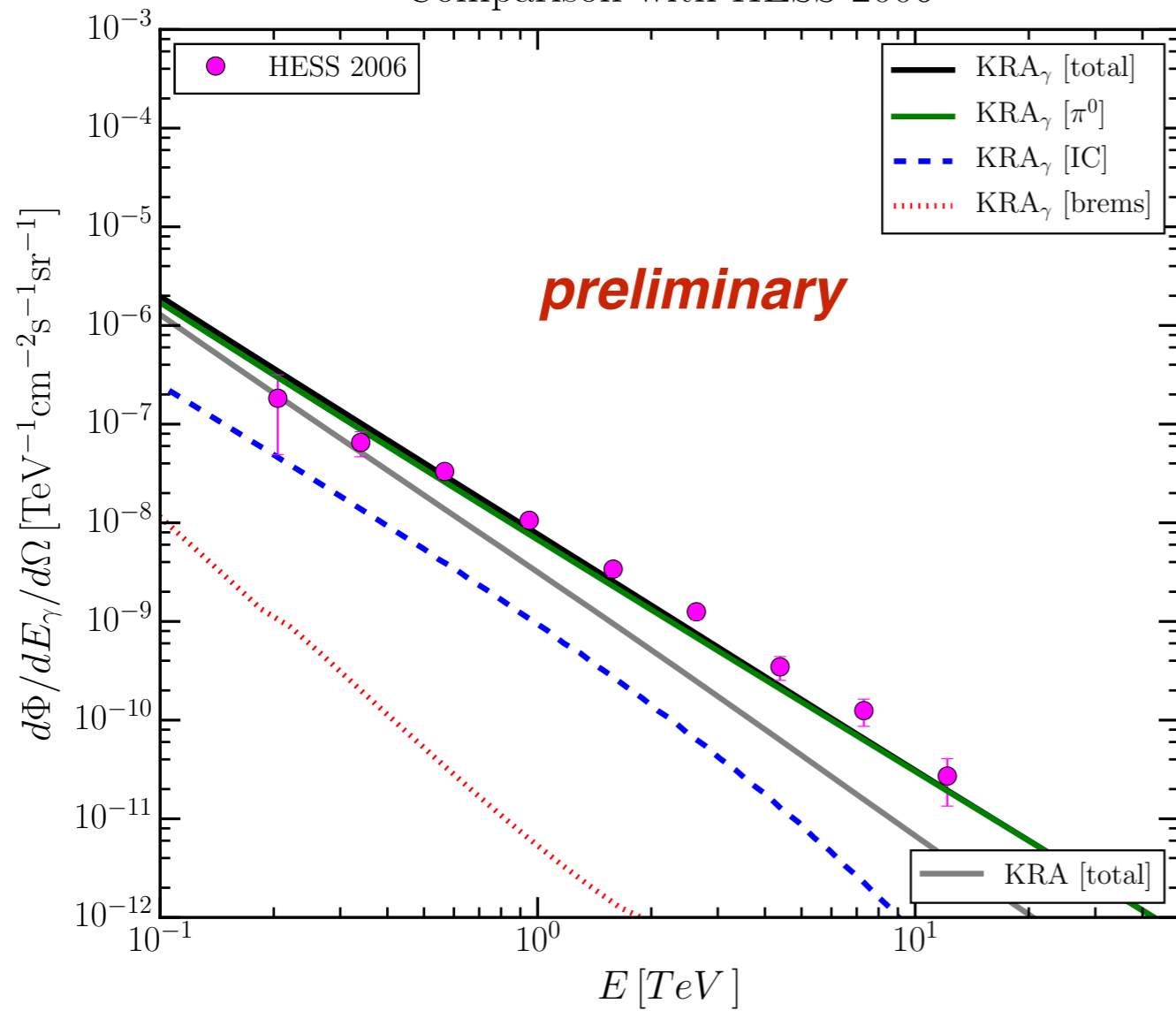
Hydrogen and all-particle spectra



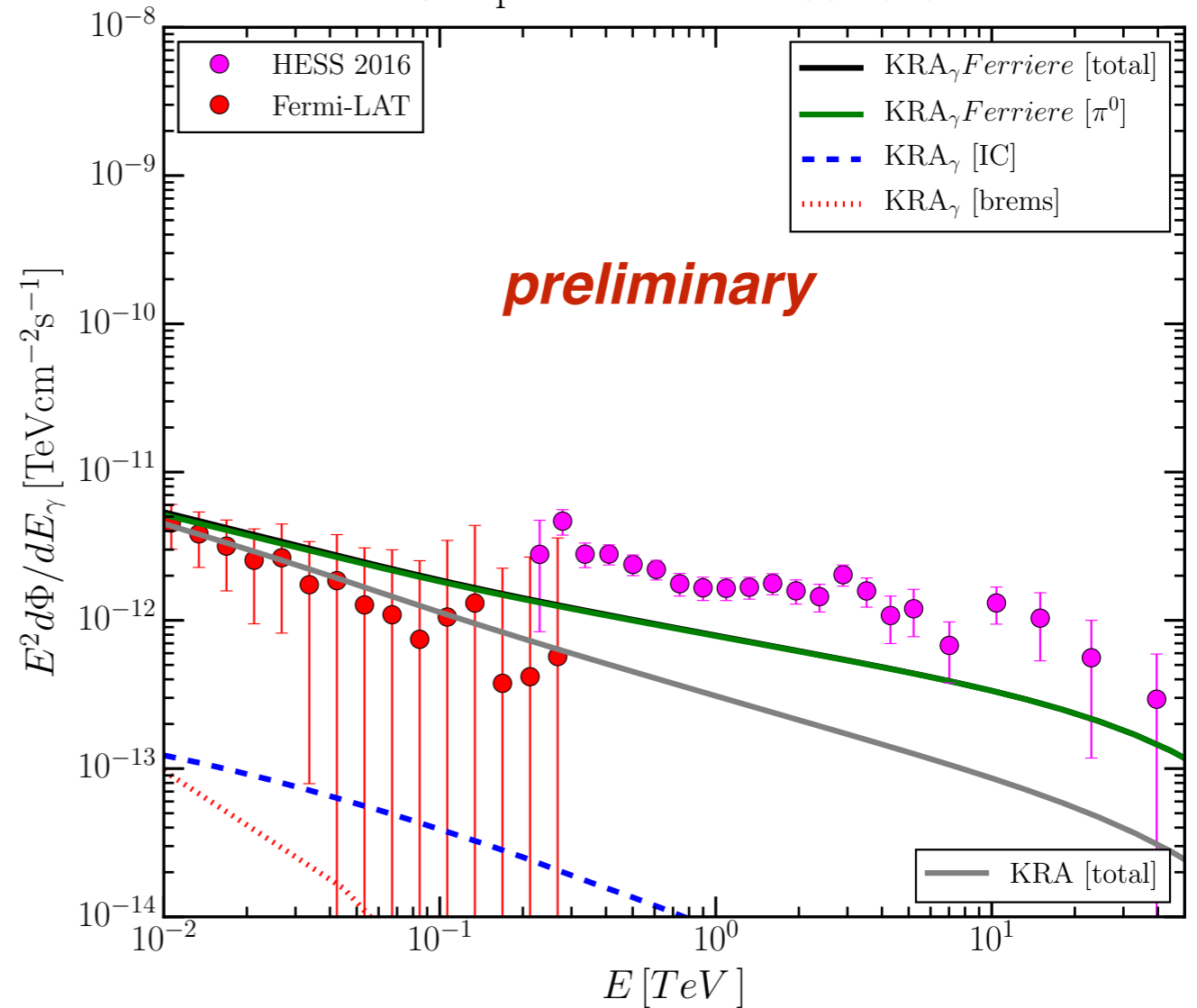
The expected diffuse sea with KRA_γ compared to Pevatron

In Preparation: Evoli, Gaggero, Grasso, Marinelli, Urbano

Comparison with HESS 2006



Comparison with HESS 2016



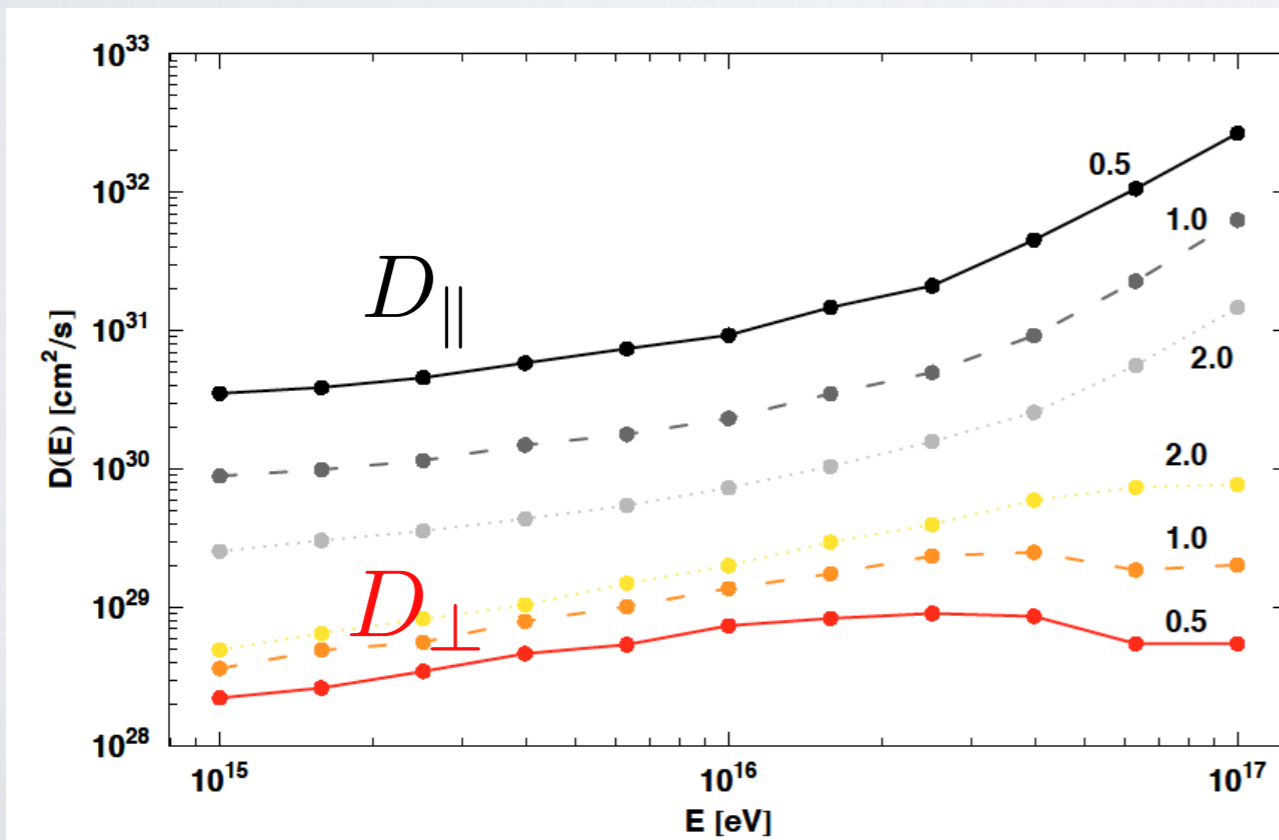
Applying the KRA_γ to the “pacman” region we can see how big is the slot left in the SED for the Pevatron injector.

A possible origin of $\delta(R)$ from anisotropic diffusion

The presence of regular MF breaks isotropy $D \Rightarrow$

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

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



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



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

for Kolmogorov turbulence

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

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

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



A possible origin of $\delta(R)$ from anisotropic diffusion

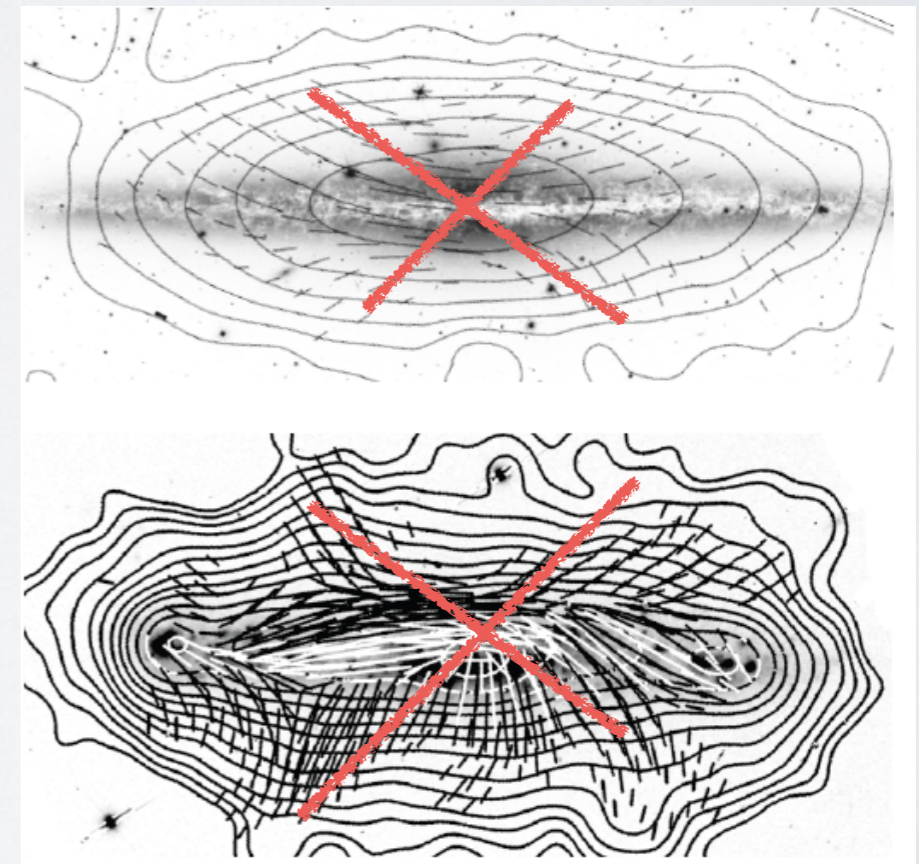
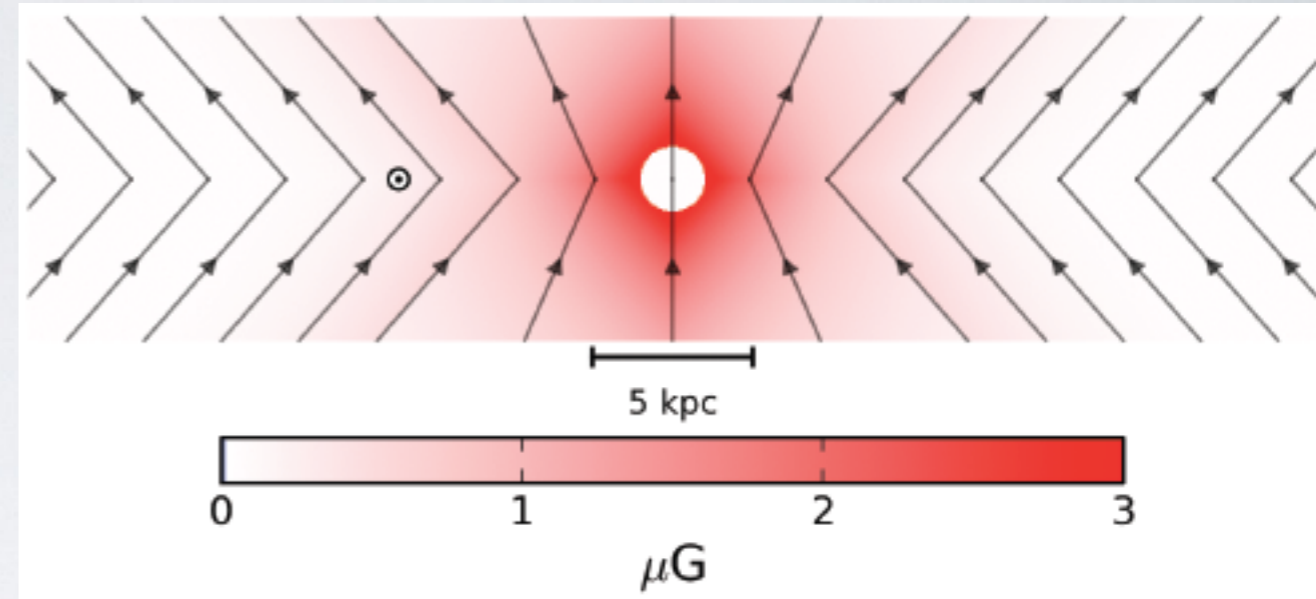
the presence of a poloidal component of the GMF in the GC region should make the role of D_{\parallel} growing respect to D_{\perp} (standard case)

Since, for Kolmogorov turbulence

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

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

Jansson & Farrar ApJ 2012



The Neronov & Semikoz model

The model assumes a harder CR spectrum ($\Gamma \sim 2.4$) 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

