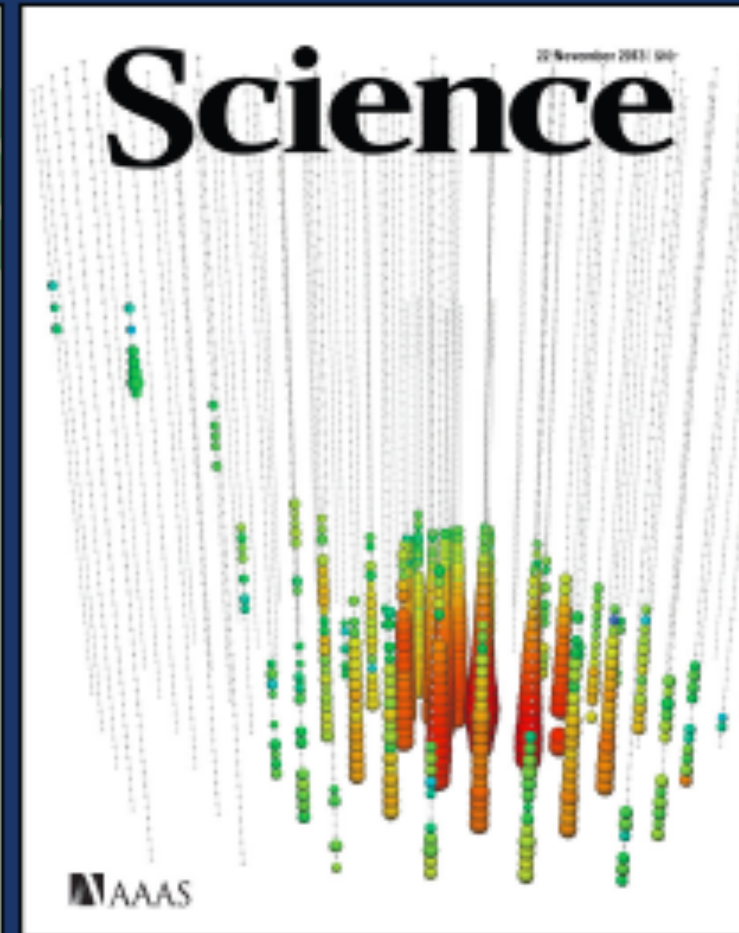
Gamma-ray and neutrino diffuse emissions of the Galaxy at very high energies

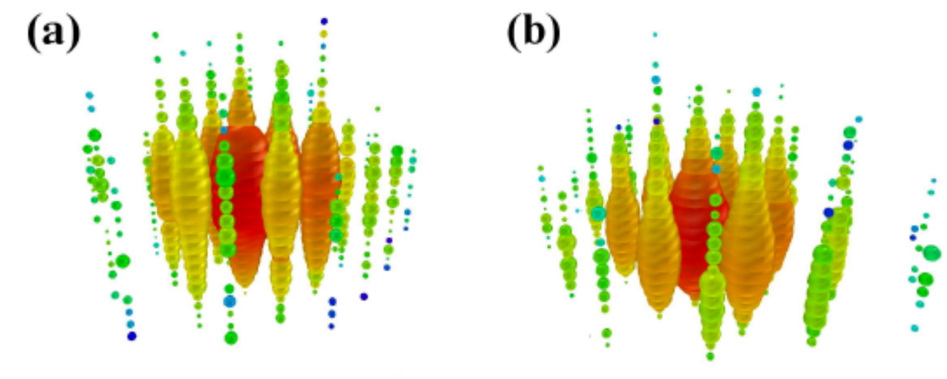
Dario Grasso (INFN, Pisa)



IceCube awarded the 2013 Breakthrough of the Year »

Major steps of IceCube observations from 2010 up to now

- April 2013 - First two PeV neutrino observed “Bert” and “Ernie” (Phys. Rev. Lett. 111, 021103 (2013))

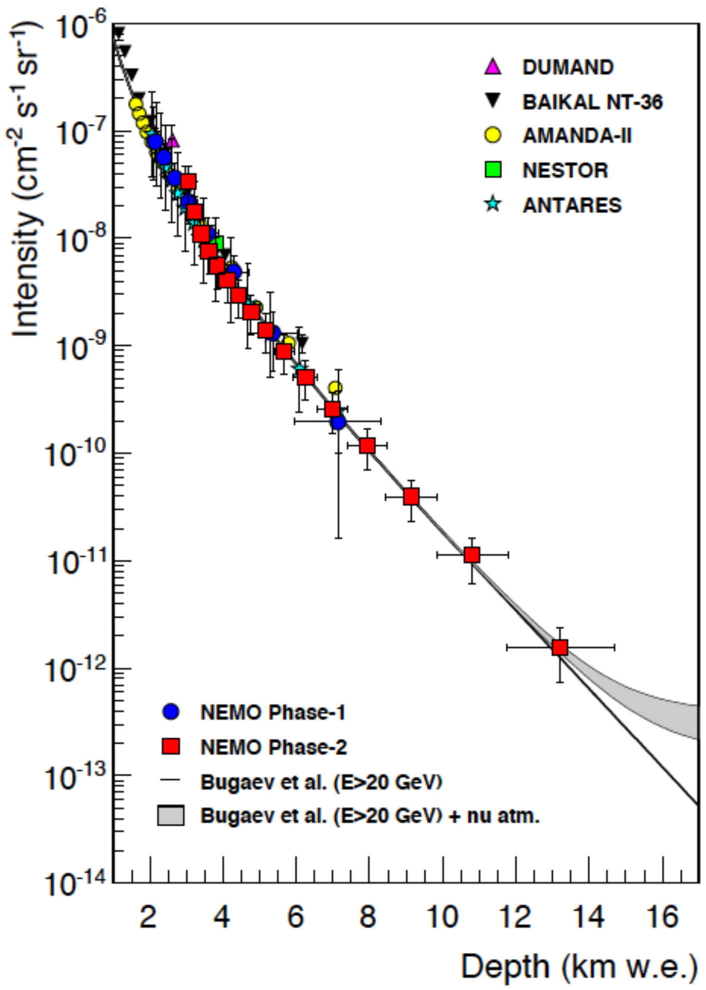


- November 2013 - 28 Astrophysical VHE neutrinos above 30 TeV (Science, Vol 342, Issue 6161 22 November 2013)

- May 2014 - 37 VHE neutrinos above 25 TeV with 5.7 σ excess respect to the expected atmospheric background (Phys. Rev. Lett. 113, 101101 (2014))

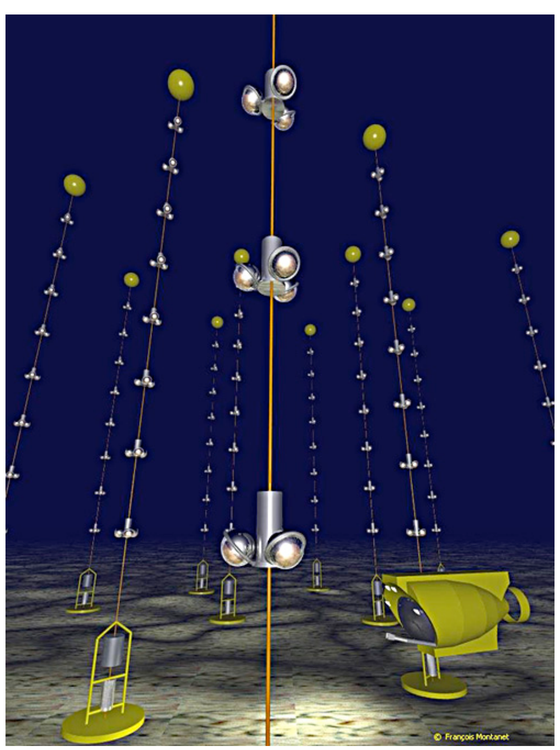
- ICRC July 2015 - 54 VHE neutrinos above 25 TeV with 7 σ excess respect to the expected atmospheric background (arXiv:1510.05223)

The path to the discovery

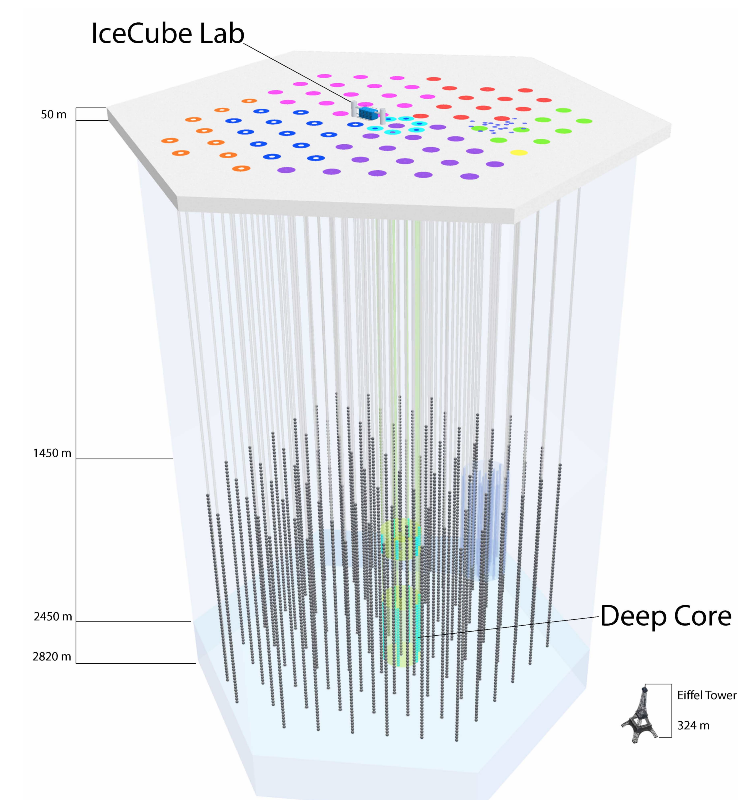


From DUMAND(1975), BAIKAL(1981), NESTOR (90's), AMANDA(1996), NEMO (1998) Mostly:

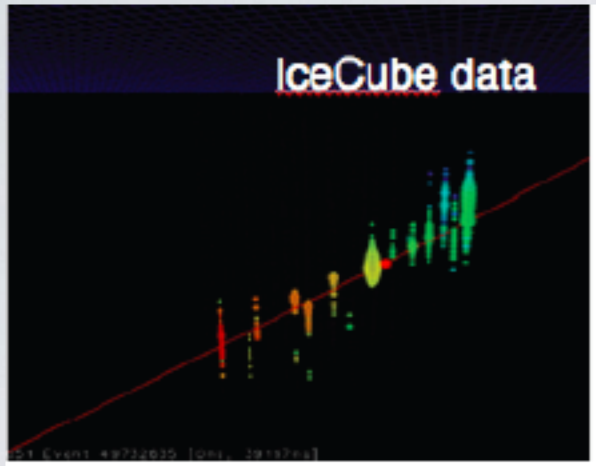
- Characterization of the sites
- Optimization of the detector geometry
- Measurements of Atmospheric muon flux

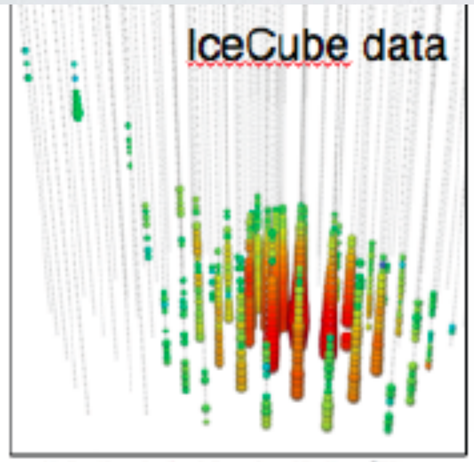


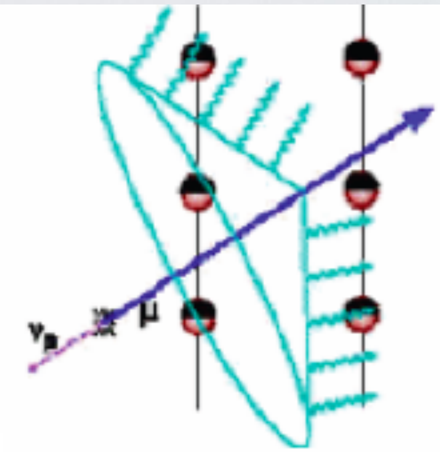
With IceCube and ANTARES : Starting of VHE neutrino astrophysics



Neutrino signatures

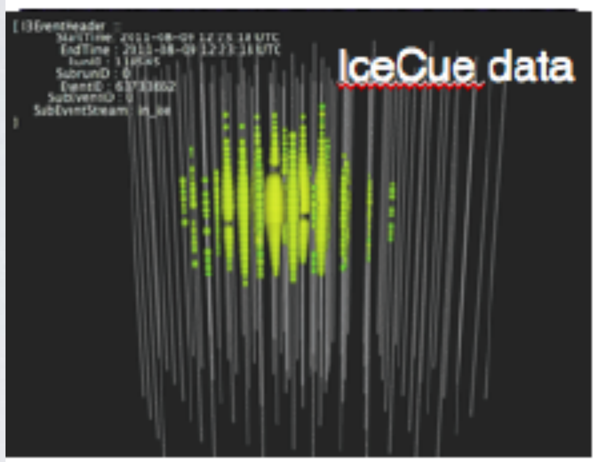


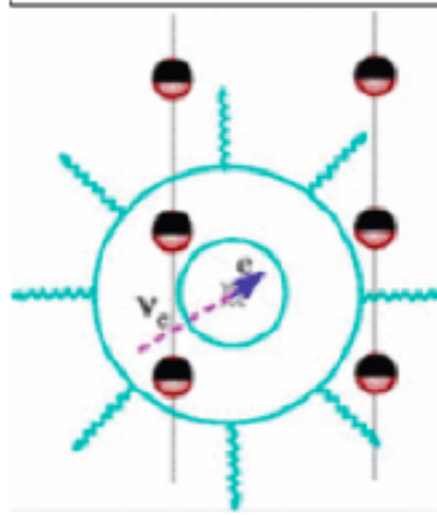




μ Tracks:

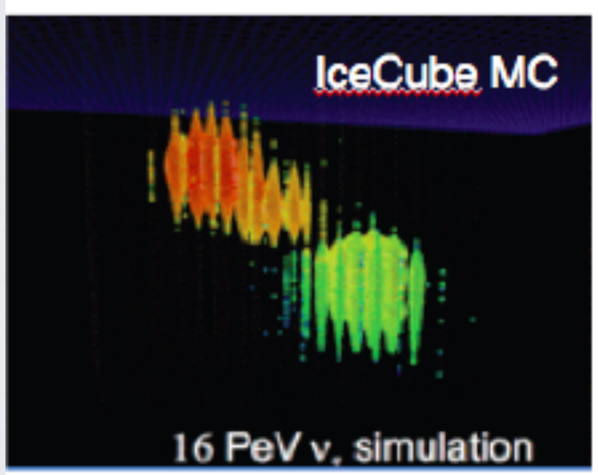
- $\nu_\mu + N \rightarrow \mu + X$
- through-going muons
- visible energy resolution~20%
- pointing resolution <1°





Cascades:

- e-m and hadronic cascades
- $\nu_{e(\tau)} + N \rightarrow e(\tau) + X$
  $\nu_f + N \rightarrow \nu_f + X \quad f = e, \mu, \tau$
- Resolutions, cascades contained in the detector
  - visible energy < ~ 20%
  - angular ~ 10°-40°

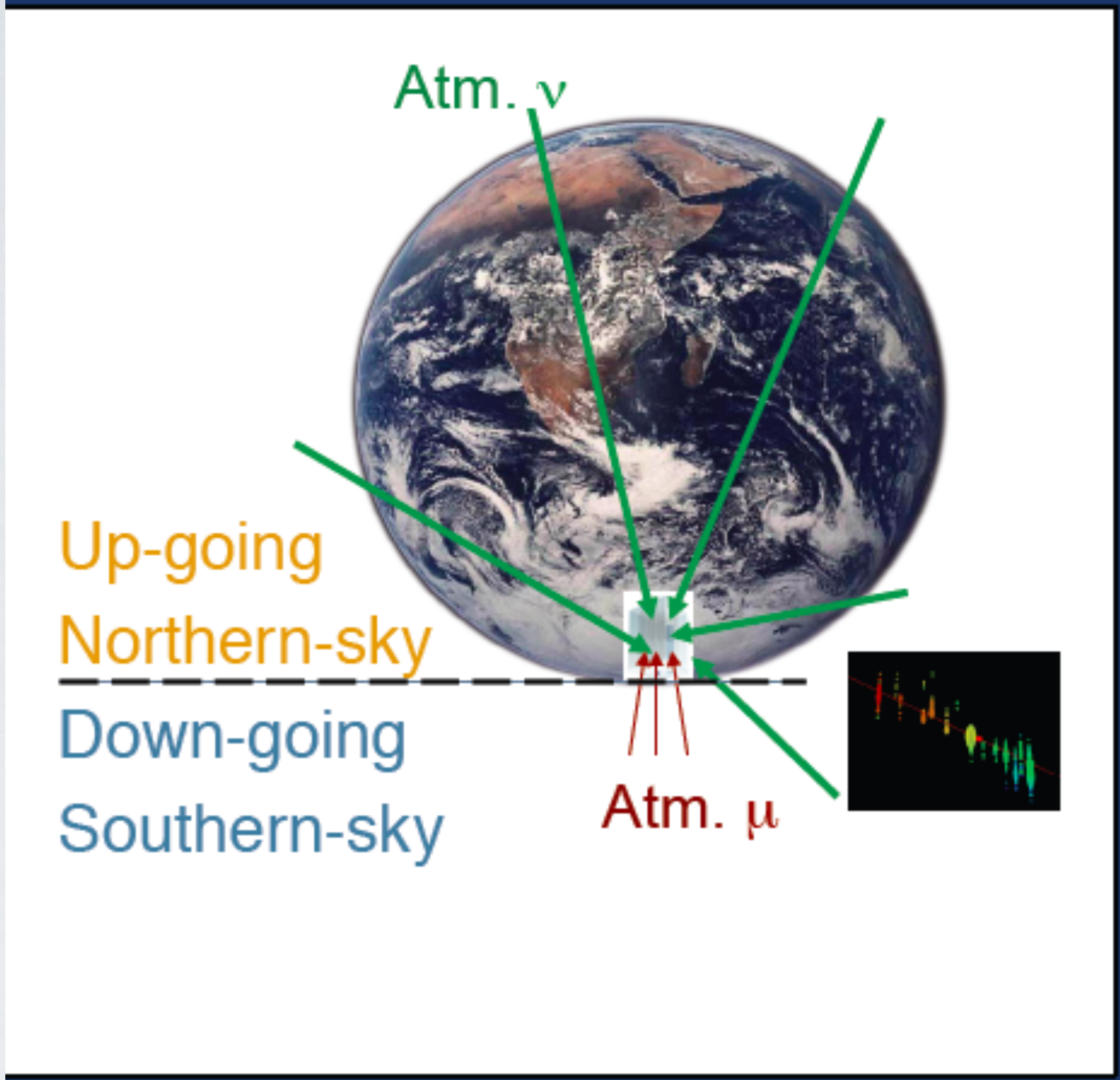


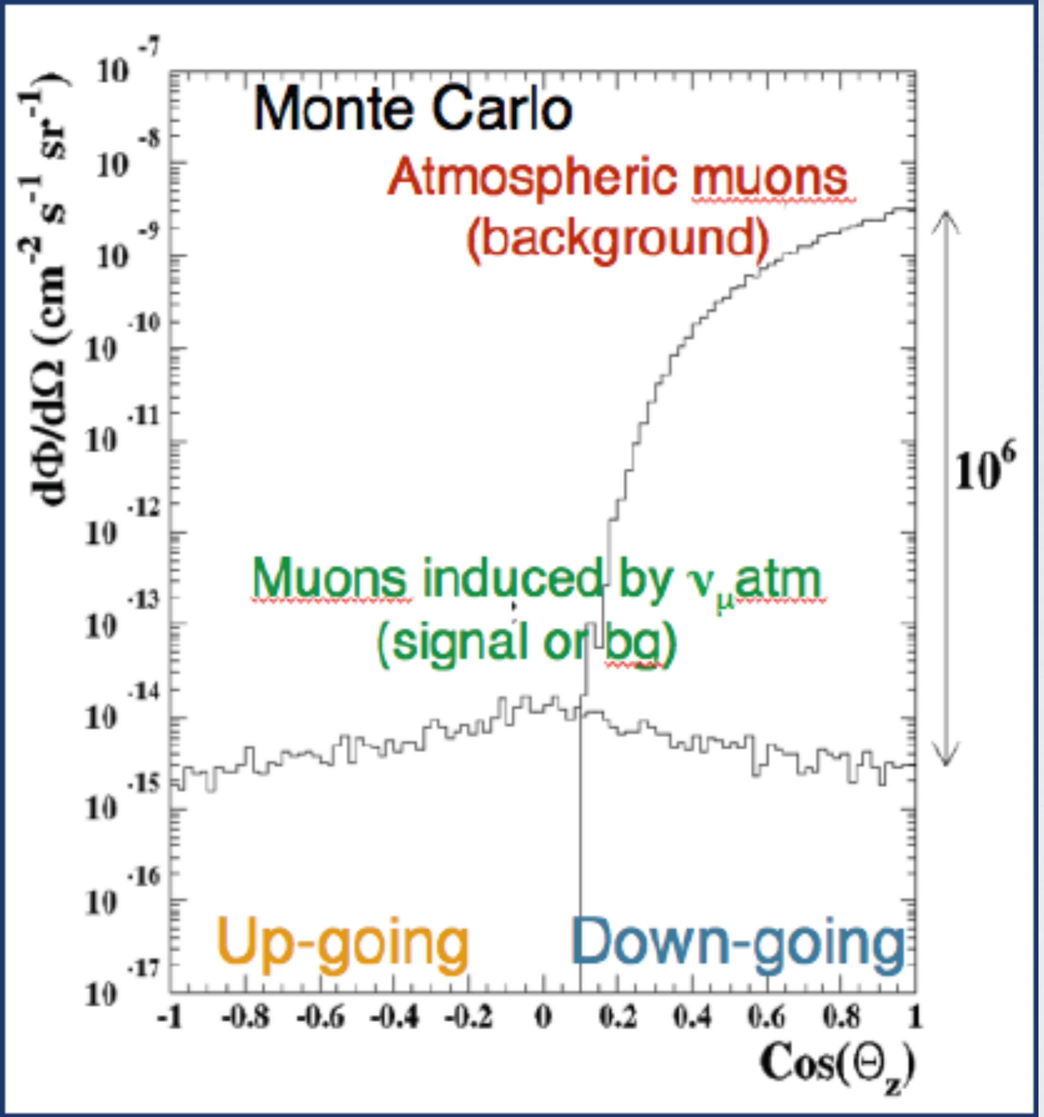
Composites (not yet observed)

- starting tracks
- tau double bangs
- good directional and energy resolution

Neutrino signatures

Atm.	μ 10^3 Hz
Atm.	ν 10^{-3} Hz
Astro.	ν 10^{-6} Hz

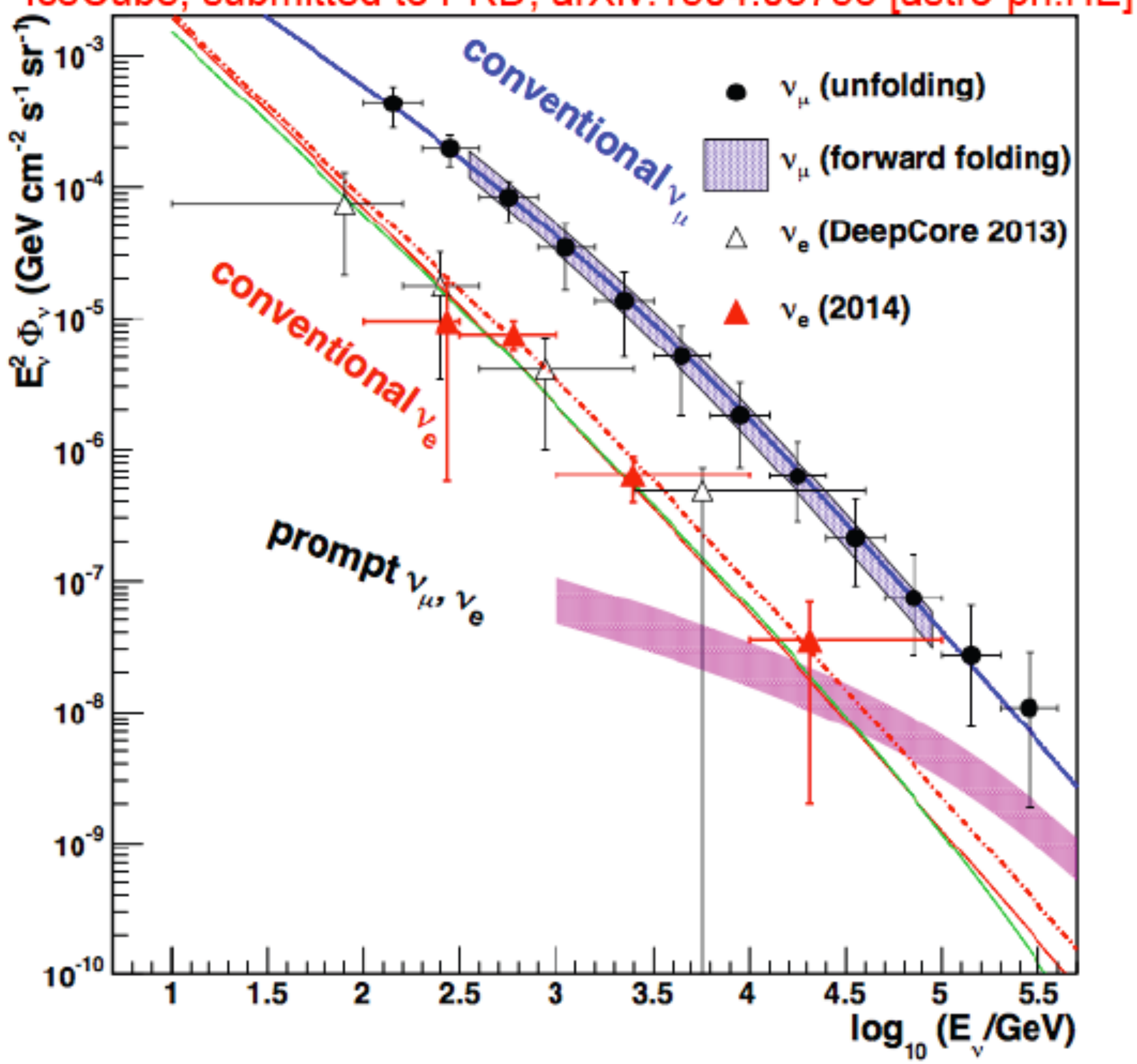




Reconstruct μ tracks and identify their origin (μ vs ν_μ) by their direction
ν_μ - from the Northern sky ("up-going" μ only)

J. Kiryluk (SBU), CIPANP2015, May 19-24 (2015)

Atmosferic Neutrinos



Conventional neutrino flux
Decays of π,K mesons

- steeply falling spectrum ($E^{-3.7}$)
- flux peaked at horizon
- ν_μ dominated

Prompt neutrino flux
decays of D,B mesons

- spectrum follows CR ($E^{-2.7}$)
- flux isotropic
- equal parts ν_μ and ν_e

○ not yet directly observed

Prompt ν flux component depends on the assumed astrophysical flux and shape.

For: $\Phi_{astro} \sim E^{\gamma} \Rightarrow \Phi_{prompt} = 0.0^{+3.0}_{-0.0} \Phi_{ERS}$

ERS: R. Enberg et. Al.,Phys. Rev. D78, 043005 (2008)
A. Bhattacharya et.al. (2015), arXiv:1502.01076

IceCube measured ν events

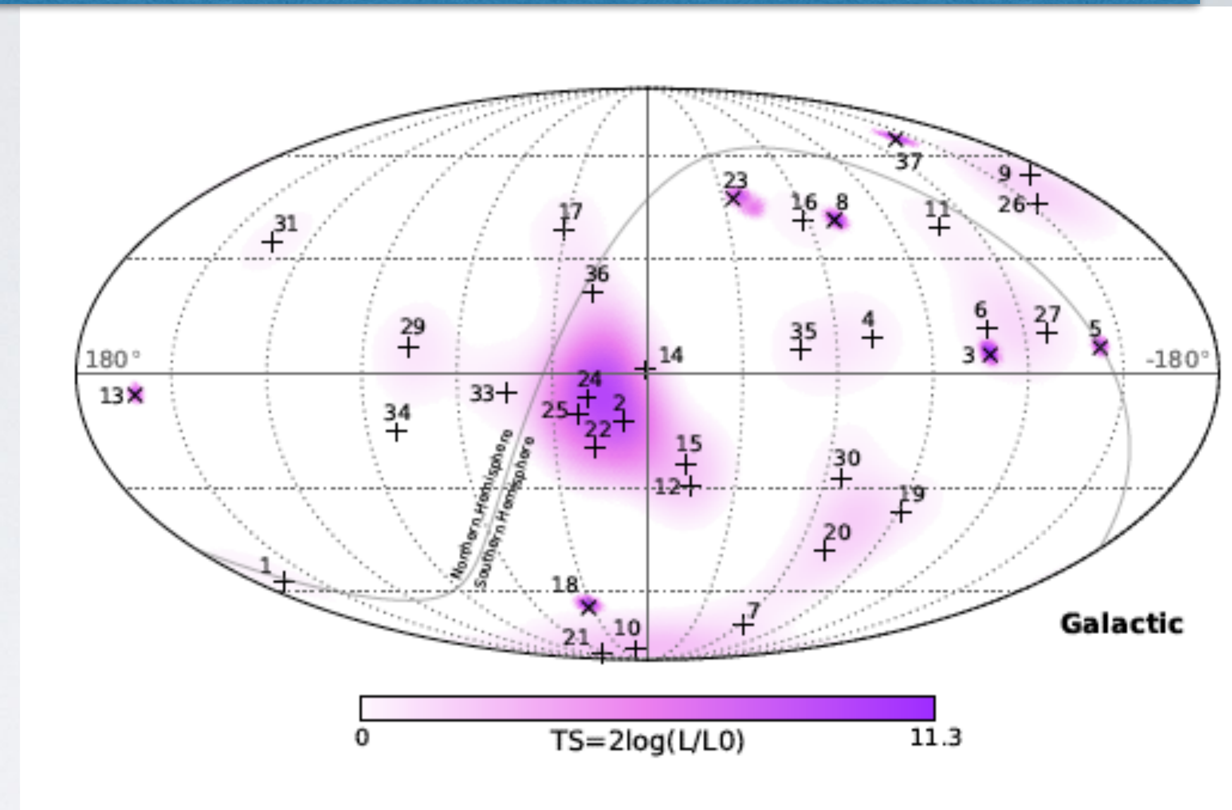
IceCube found evidence for 28 (2 years, PRL 2013) then 37 events (3 yrs PRL 2014) with reconstructed direction above 30 TeV corresponding to a
5.7σ excess respect to the atm. bkg.

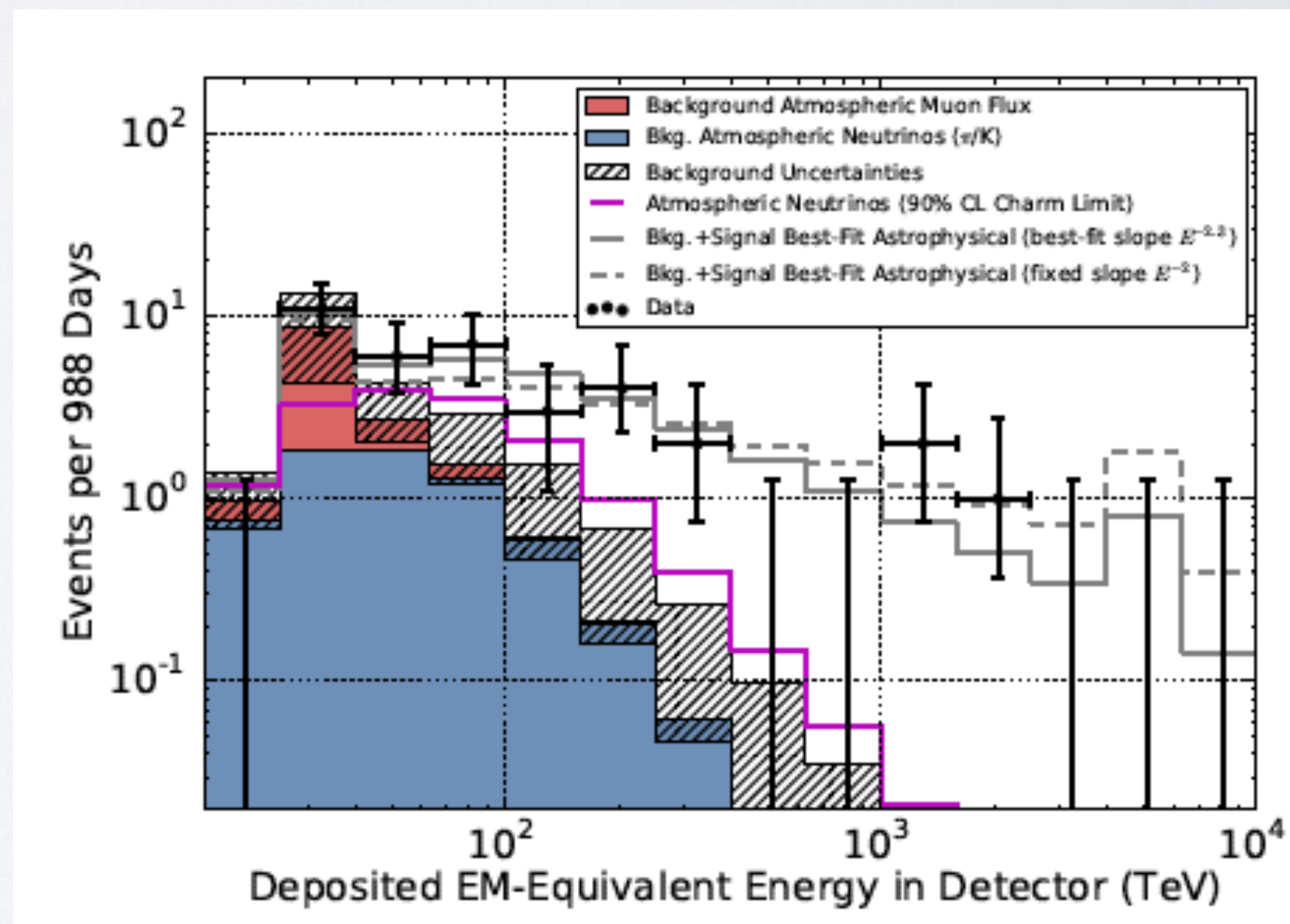
angular distribution compatible with isotropy (see however below)

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

Best fit spectral index - 2.3 ± 0.3

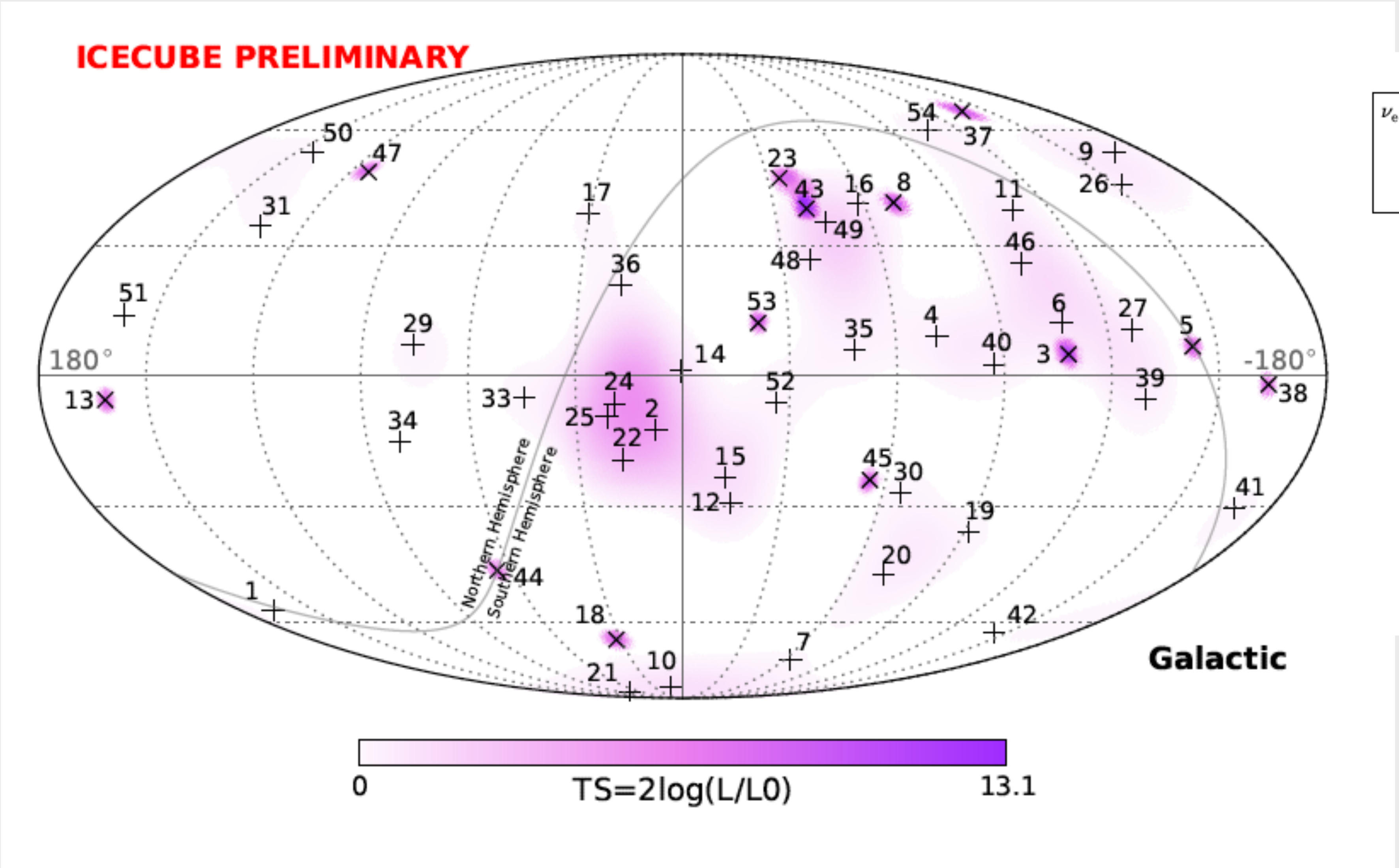
Slightly softer than expected for extragalactic astrophysical source

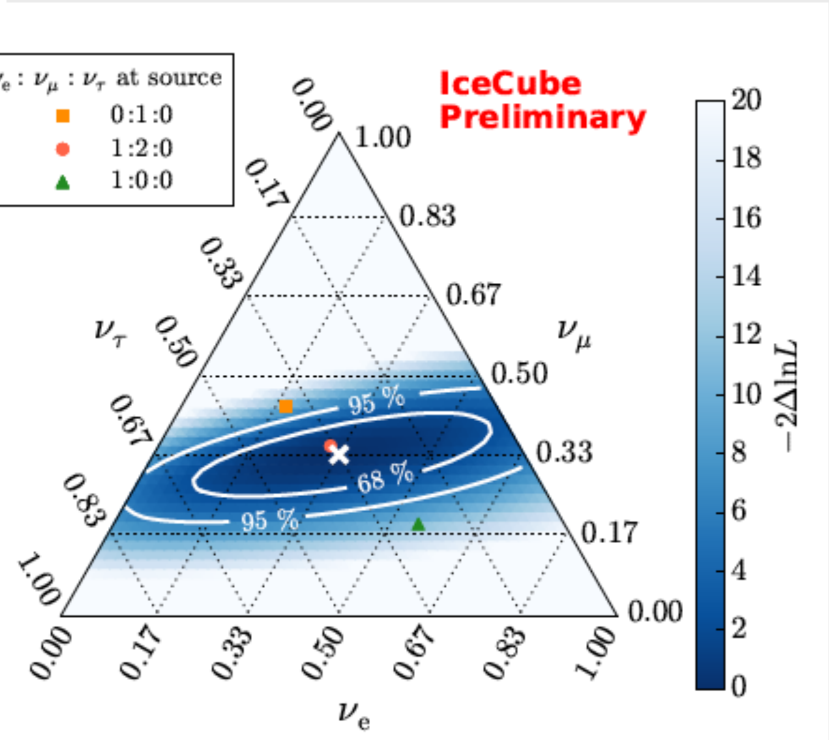




IceCube astrophysical neutrinos: present status

arXiv1510.05223, ICRC2015





$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

see also

Palladino, Pagliaroli, Villante & Vissani PRL 2015

X (track) angular res ~1°   + (shower) angular res ~10°-30°

For the full sky analysis of 4 years of HESE data IceCube reconstruct 13 track events and 41 shower events.

IceCube measured ν events (4-years)

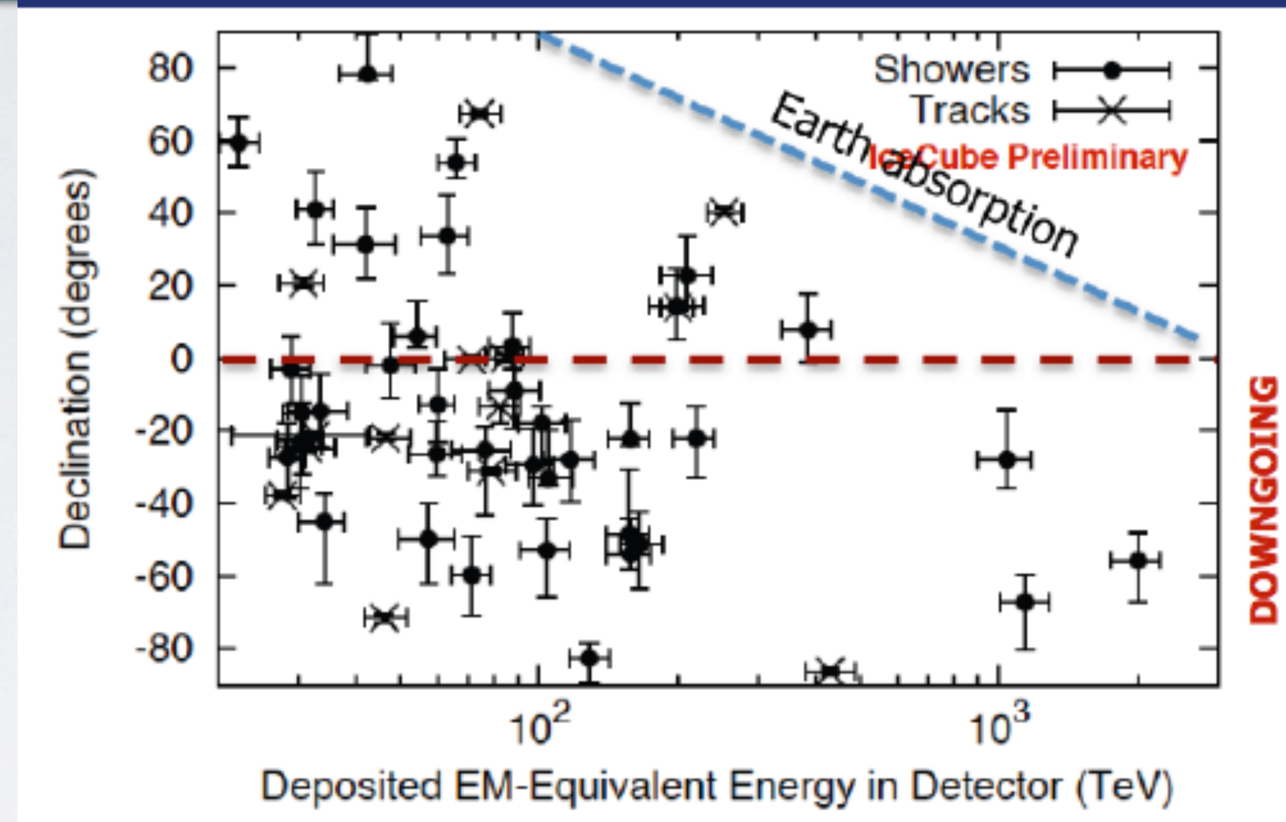
IceCube found evidence for 54 events (4 yrs preliminary) with reconstructed direction above 30 TeV corresponding to 7σ excess respect to the atm. bkg. $(9^{+8}_{-2.2})$

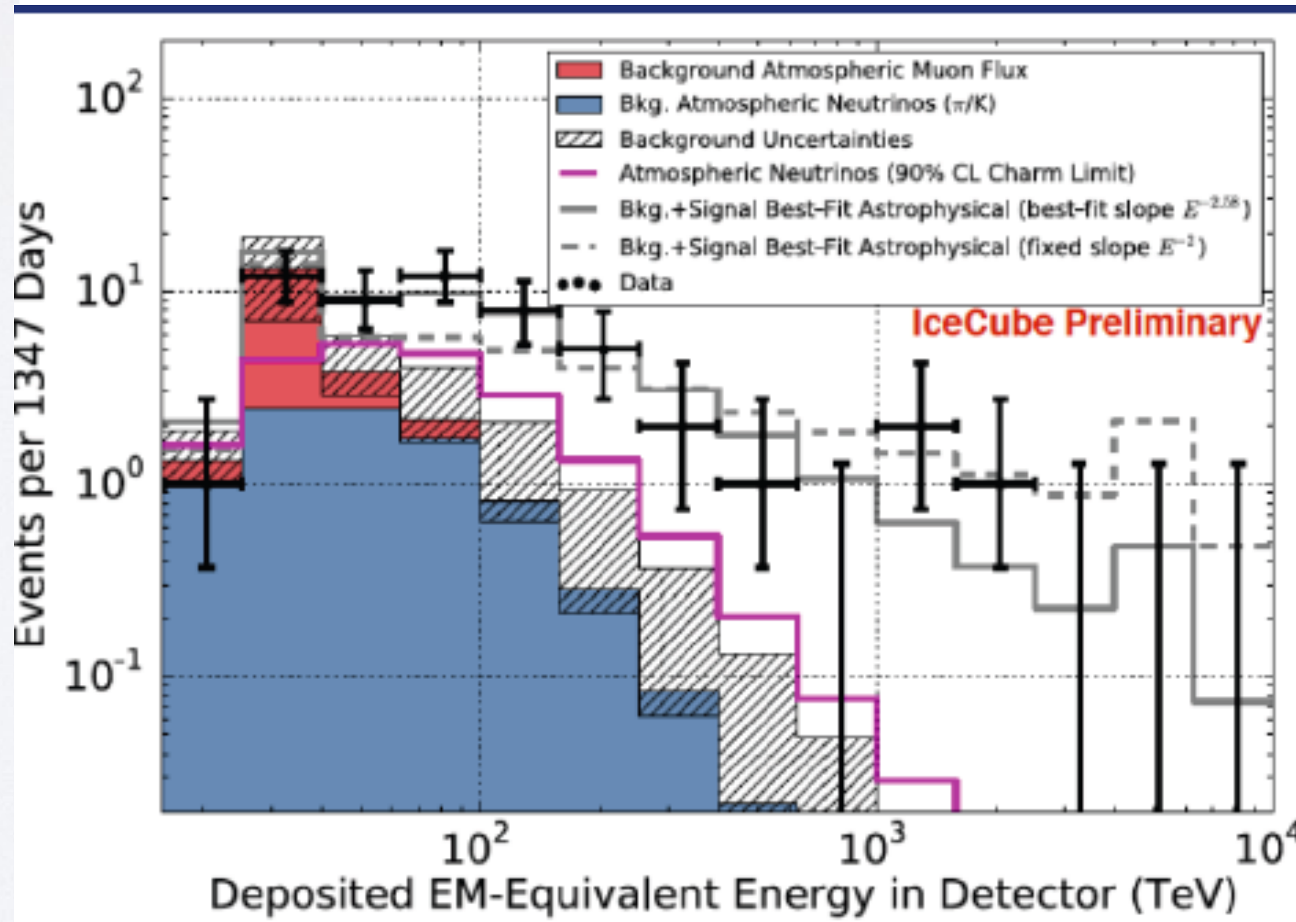
angular distribution compatible with isotropy (see however below)

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

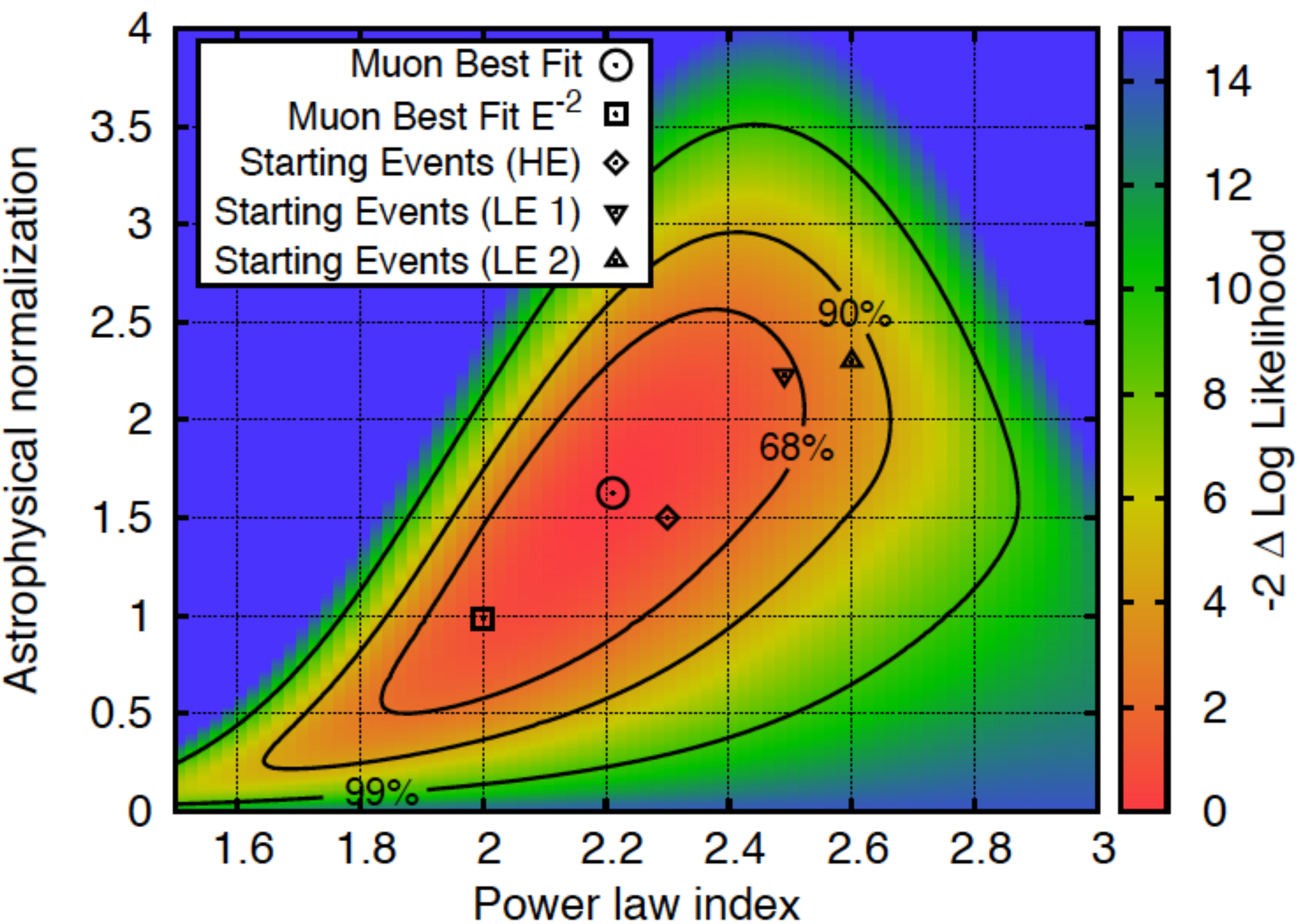
Significantly softer than expected for extragalactic astrophysical source

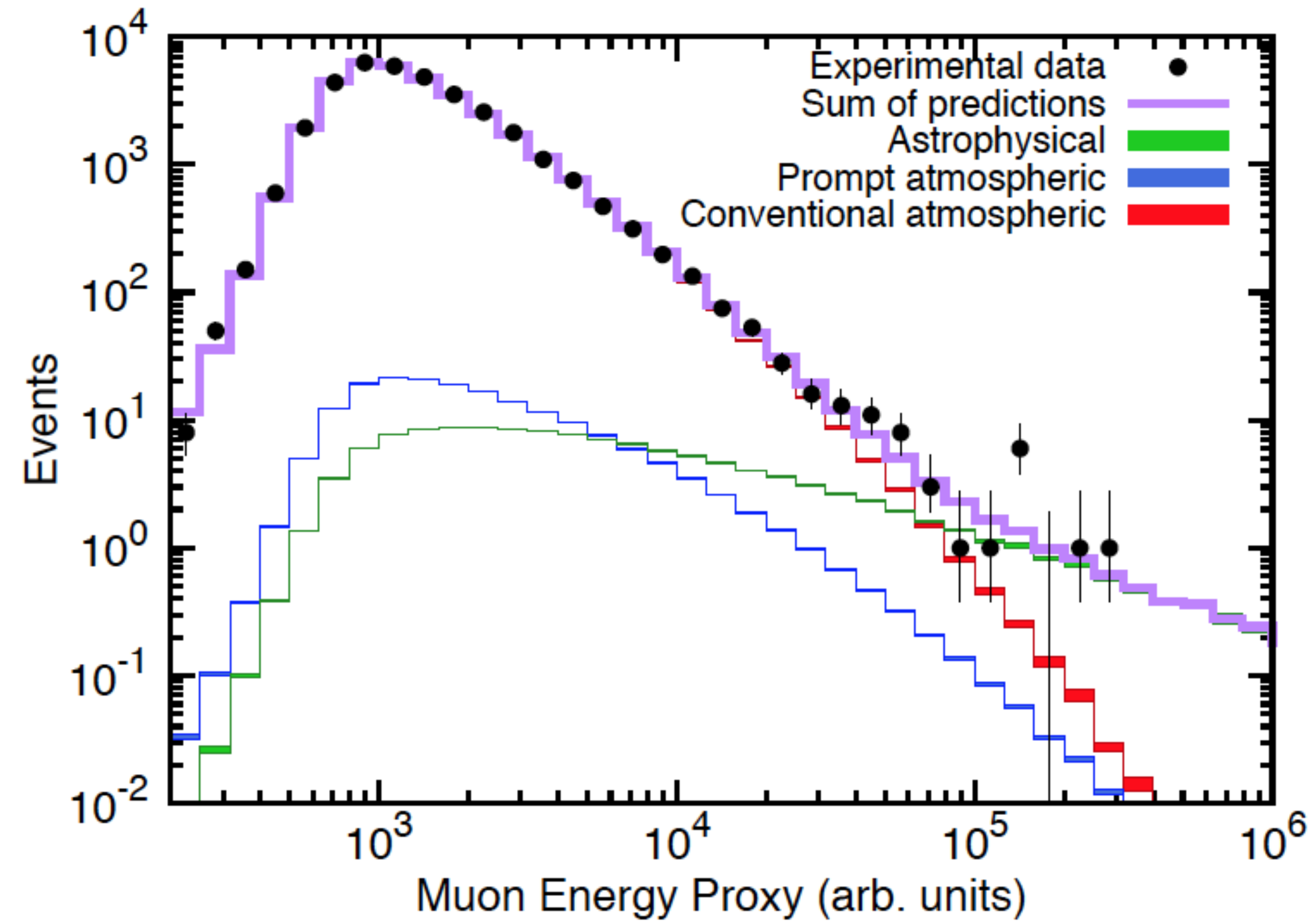




Muon neutrinos from the North hemisphere

IceCube coll., PRL, vol.115, 2015





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

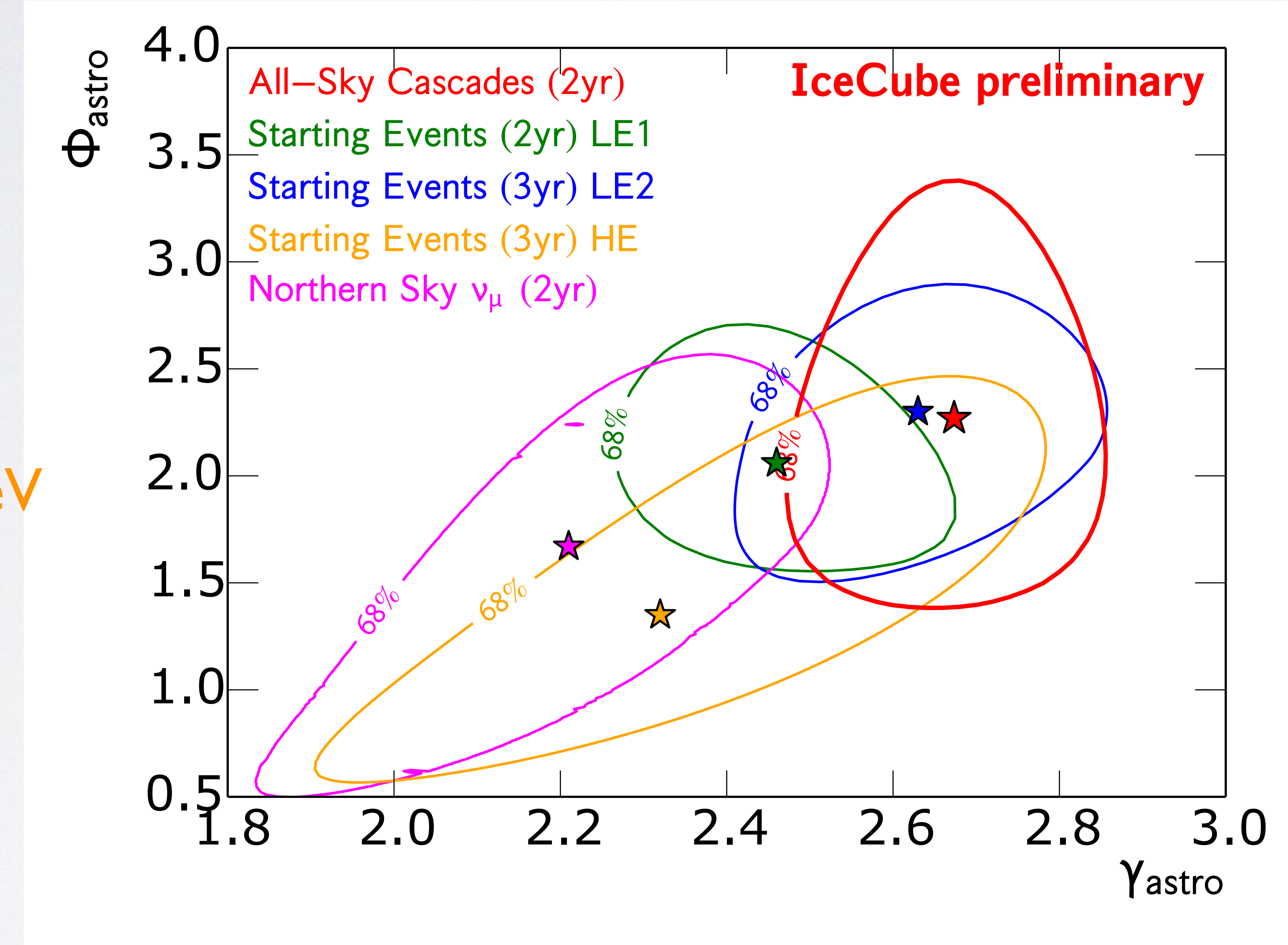
The neutrinos collected during 659.5 days of live time between May 2010 and May 2012 are inconsistent with the background at the level of **3.7 σ**.

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

A fluid situation

IceCube coll., Niederhausen, ICRC 2015 arXiv:1510.05223

ICRC (2015), E > 10 TeV
PRD 91, (2015) all event E > 1 TeV
PRL 114 (2015), HESE E > 35 TeV
PRL 101101 (2014), HESE E > 60 TeV
PRL 115 (2015) ν_μ, E > 100 TeV



Hints of an anisotropic flux ?

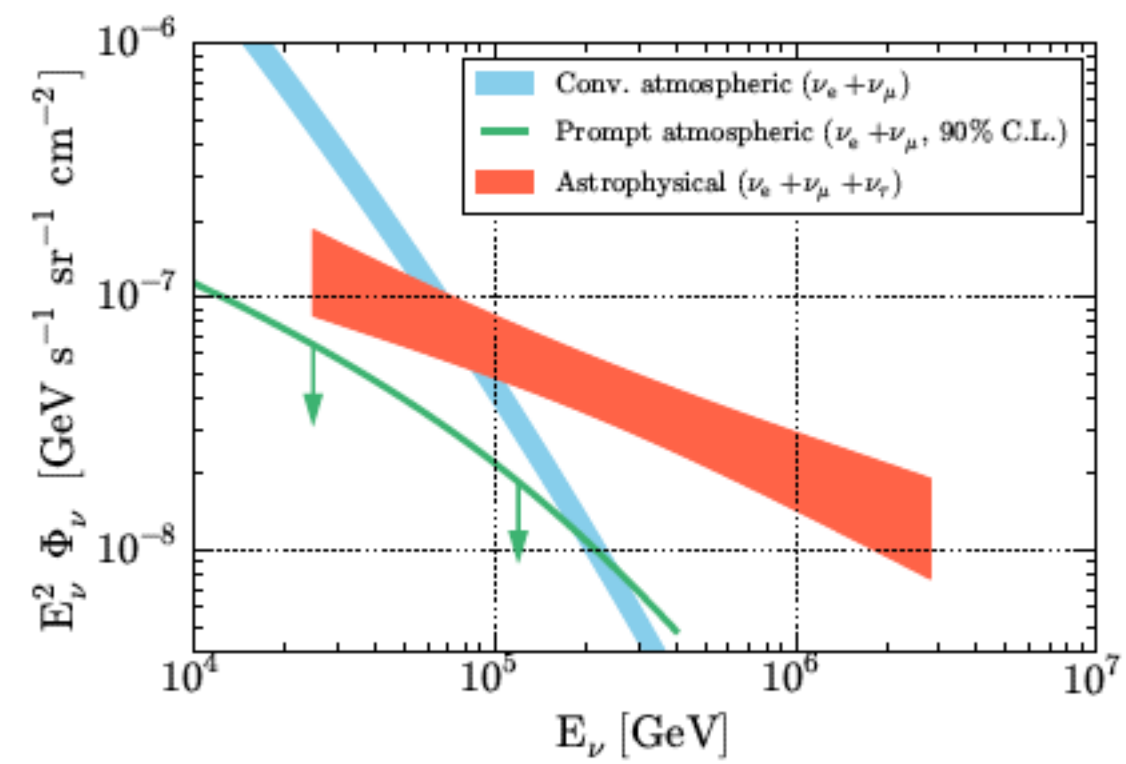
ApJ 2015

A recent template fitting analysis of a larger number of events, including those with unreconstructed direction and with E > 25 TeV found a steeper spectrum for the astrophysical neutrino component.
Best fit single power-law spectral index

- 2.50 ± 0.09

a North-South analysis favors (low significance take with caution !) a larger and flatter spectrum from the South hemisphere

all this might be indicating the presence of a significant Galactic component !



Parameter	Best fit	68% C.L.	90% C.L.
ϕ_N	2.1	0.5 – 5.0	0.1 – 7.3
γ_N	2.0	1.6 – 2.3	1.2 – 2.5
ϕ_S	6.8	5.3 – 8.4	4.4 – 9.5
γ_S	2.56	2.44 – 2.67	2.36 – 2.75

Note. — ϕ_N and ϕ_S are the all-flavor neutrino fluxes at 100 TeV in the northern and southern sky, respectively; γ_N and γ_S are the corresponding spectral indices. The fluxes are given in units of $10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}$.

Hints of an anisotropic flux ?

Neronov & Semikoz arXiv:1509.03522

To reduce contamination from atm. ν they use only events above 100 TeV in the IC 4-year sample (19 events, 1 bkg)

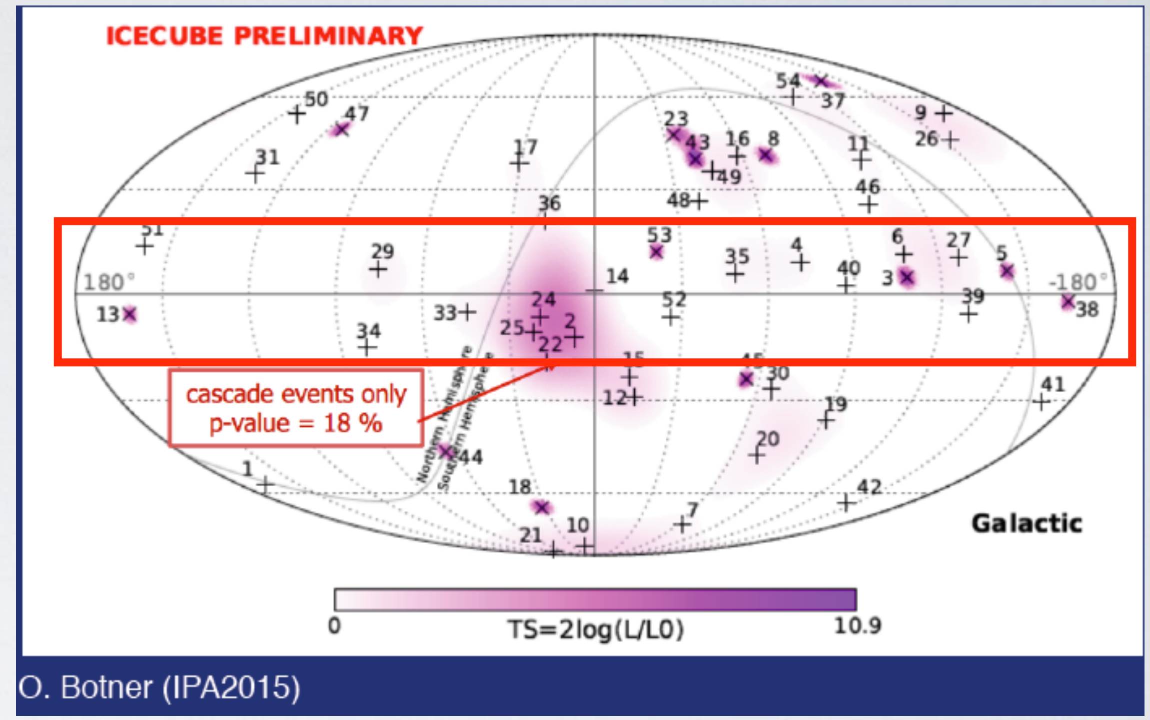
9 events are found for | b | < 10°
0 events are found for | b | > 50°

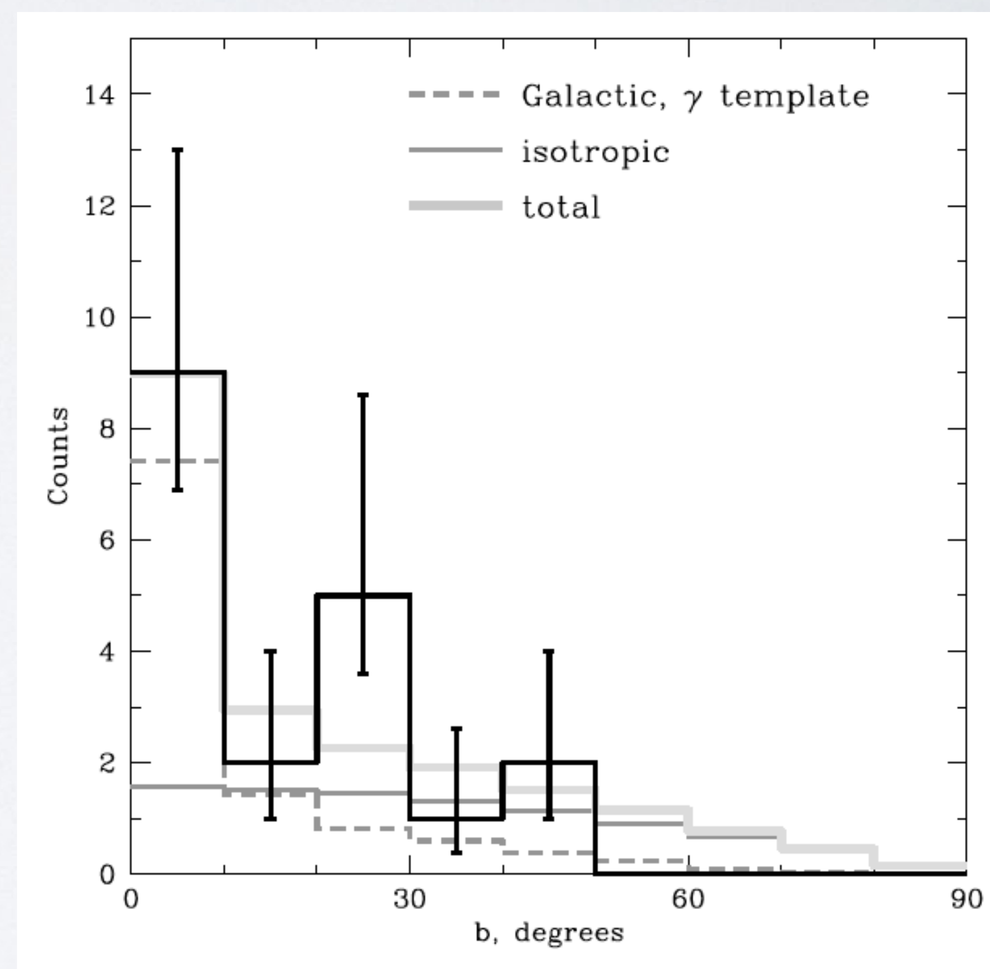
A MC with an isotropic flux gives the same results with $p = 7 \times 10^{-5}$ (~ 4 σ inconsistency)

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

this is the maximum contribution from the Galactic plane allowed by IC according to

Ahlers et al. 2015 on the basis of 3 years HESE





Which neutrino emission we expect from the Milky Way ?

The Galactic diffuse neutrino emission
a short history

Neutrino from hadronic interaction of Galactic cosmic ray with the interstellar gas
Uniform CR and gas distributions were generally adopted

Berezinsky & Smirnov 1975

462 V. S. BEREZINSKY AND A. YU. SMIRNOV

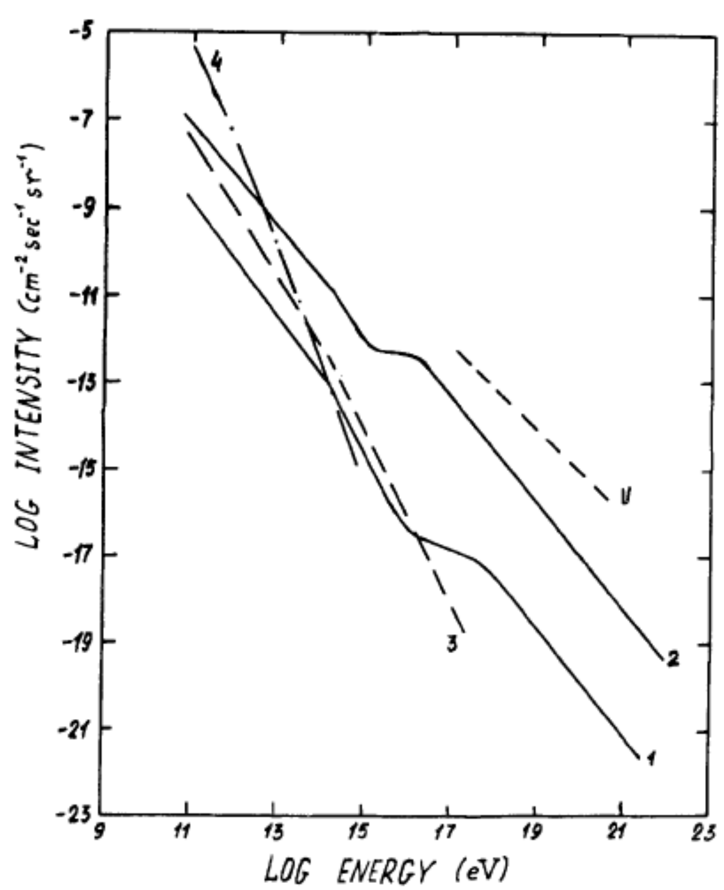


Fig. 1. The integral neutrino spectra. Curve *U* gives the rigorous upper bound for the neutrino flux, curve 1 – neutrino from the normal galaxies, 2 – from evolving sources, 3 – from our Galaxy in the direction of Galactic centre, 4 – atmospheric neutrino spectrum.

Stecker 1979

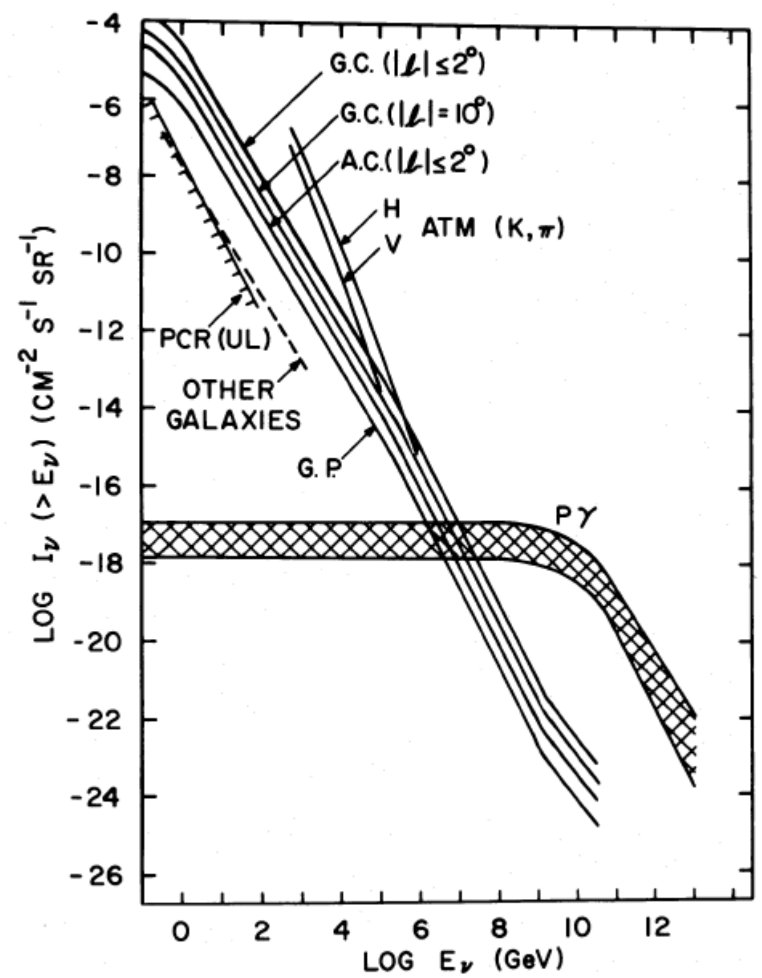
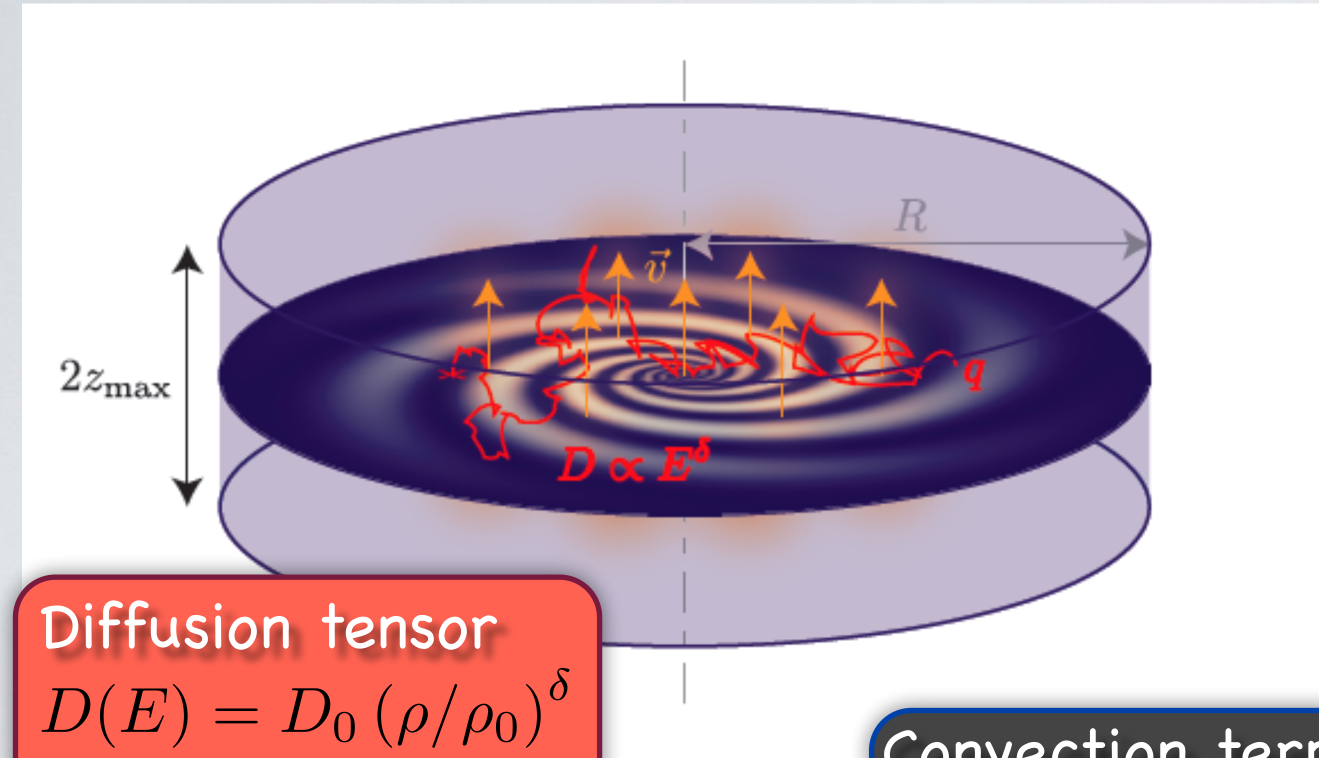


FIG. 5.—Integral $\nu_\mu + \bar{\nu}_\mu$ fluxes from cosmic sources and atmospheric π and K decay.

Gaisser, Berezinsky, Halzen, Stanev 1993 use a more realistic gas distribution

The predicted flux above 1 TeV is typically a few 10^{-11} $(cm^2\ s\ sr)^{-1}$
with spect. index - 2.7 , exceeding the atm. flux above ~ 100 TeV

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

The CR Galactic population

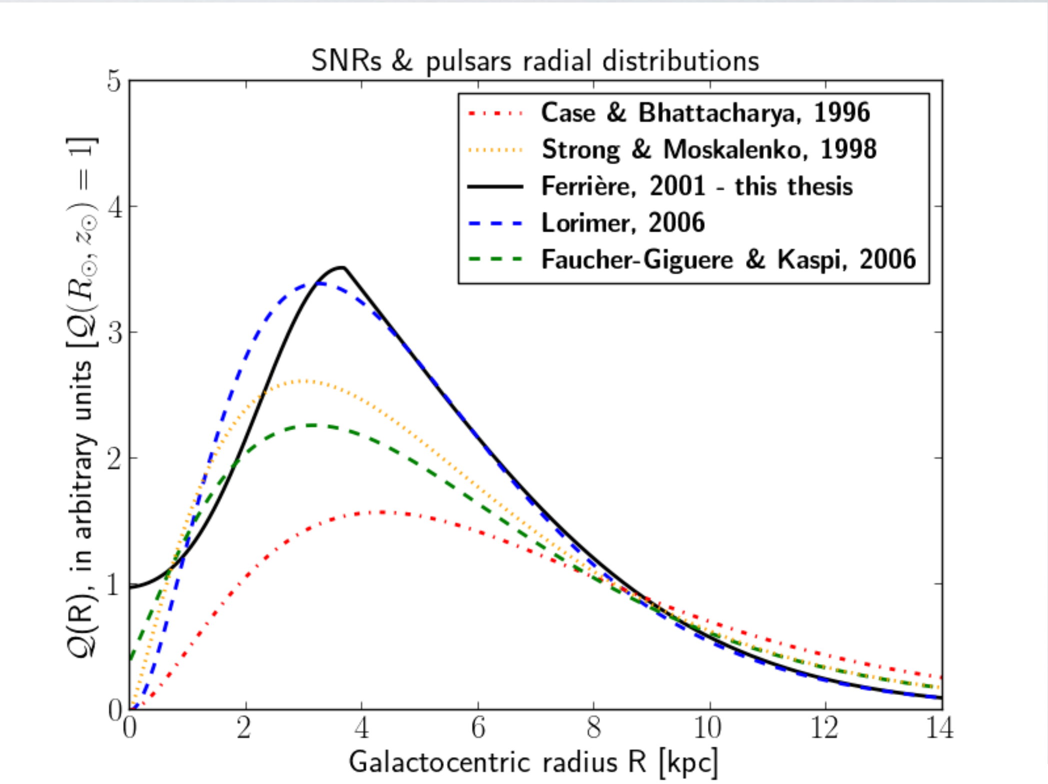
Many parameters to be fixed -> many approximations

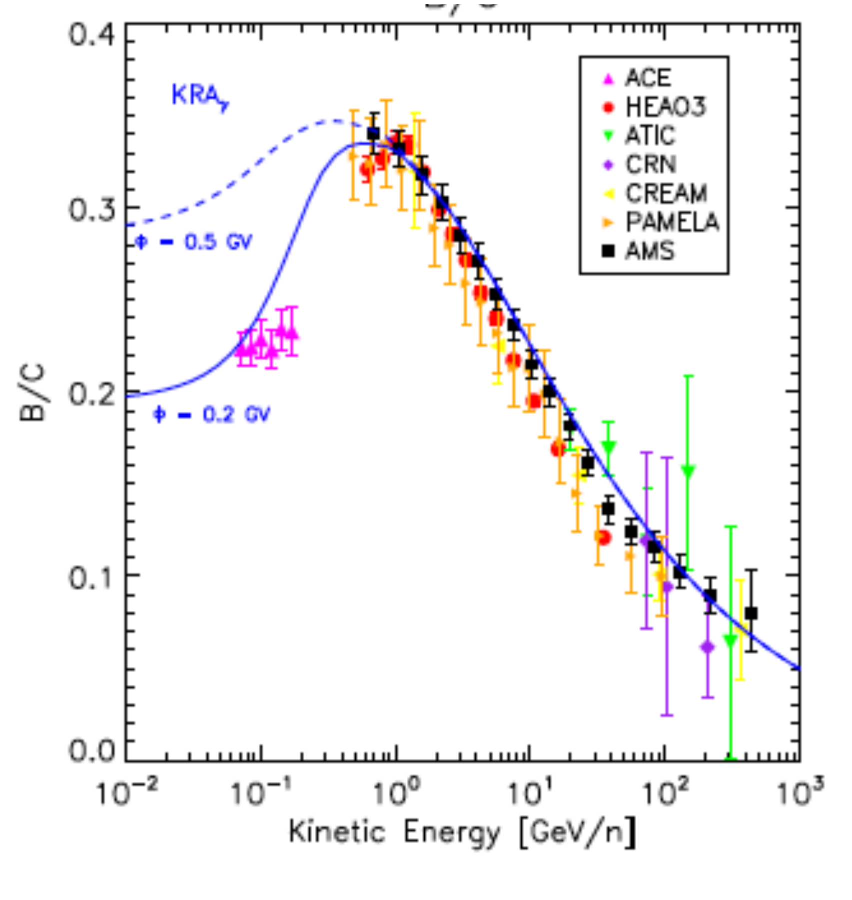
source term $Q(E, R) \propto Q(R)\, E^{-\alpha}$

diffusion coefficient $D(E) \propto D_0\, (E/E_0)^{-\delta}$

warning !!

D_0 and δ tuned against local observables (secondary nuclear species come from few kpc) and **assumed to be uniform** (***conventional models***)





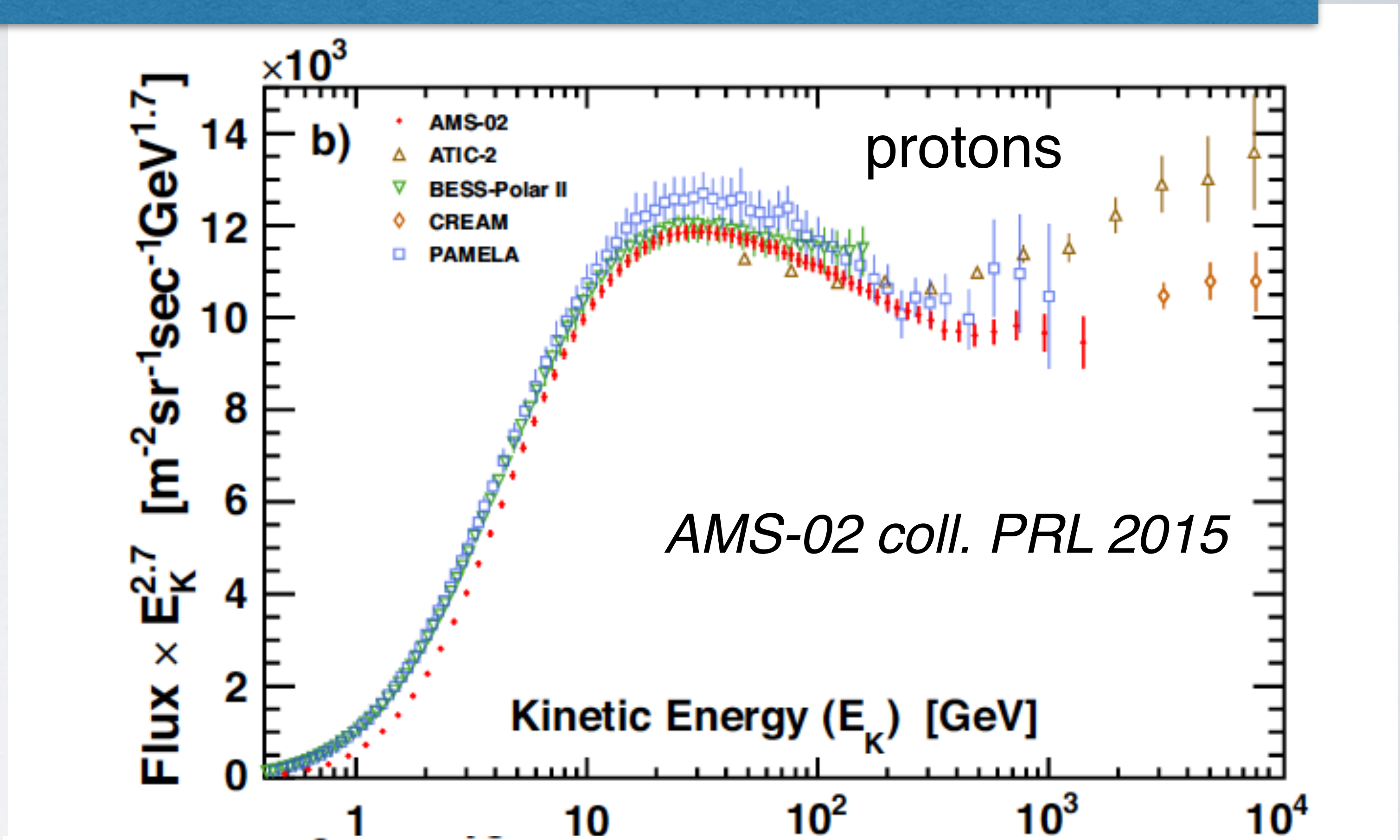
The CR Galactic population: PAMELA anomaly

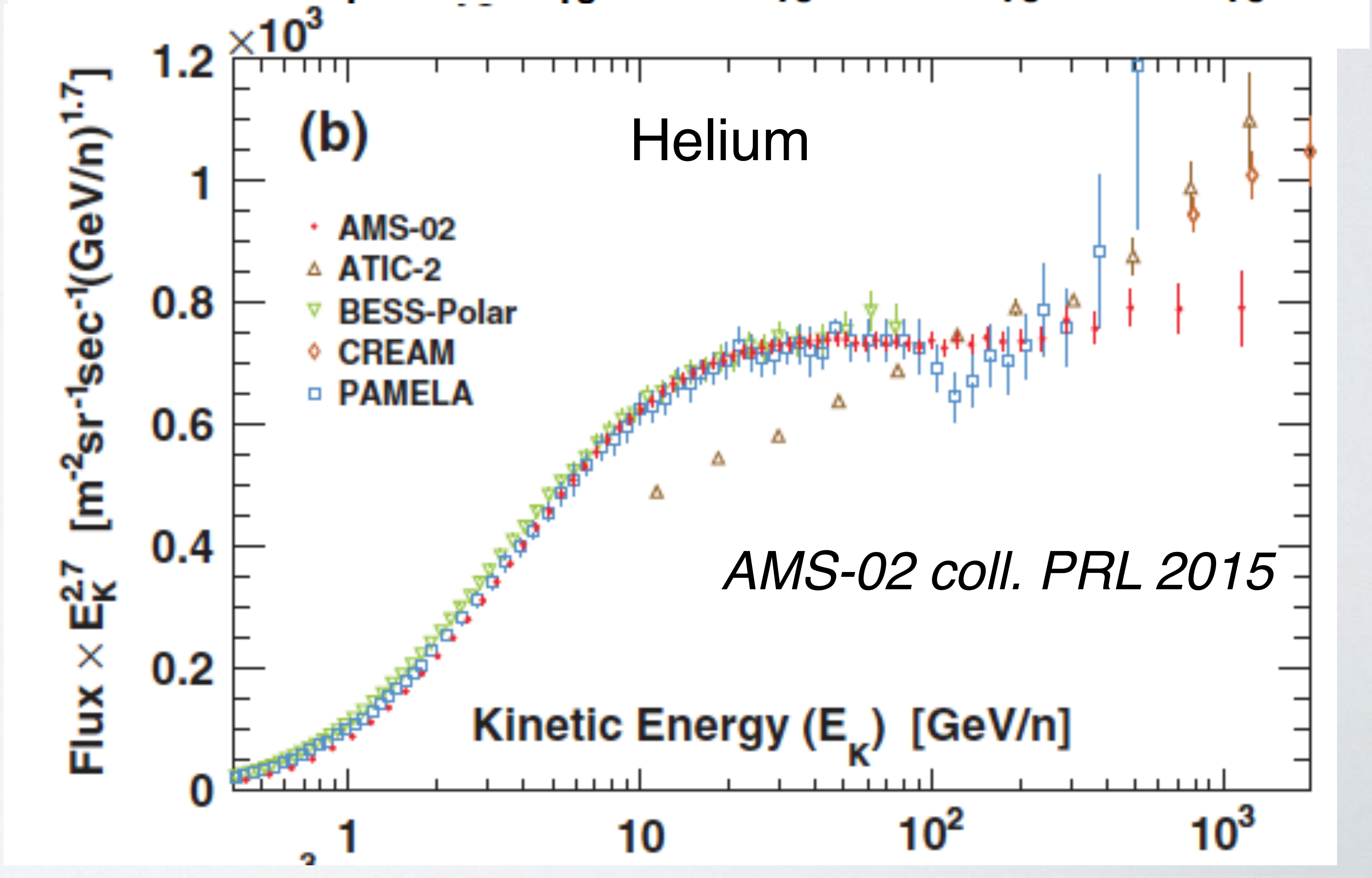
PAMELA (*Science 2011*) found an hardening of the p and He spectra at ~ 250 GeV/n AMS-02 confirmed the feature (slightly smoother and starting at ~ 300 GeV/n)

This is also required to match CREAM

spectral index p/He ≃ -0.077

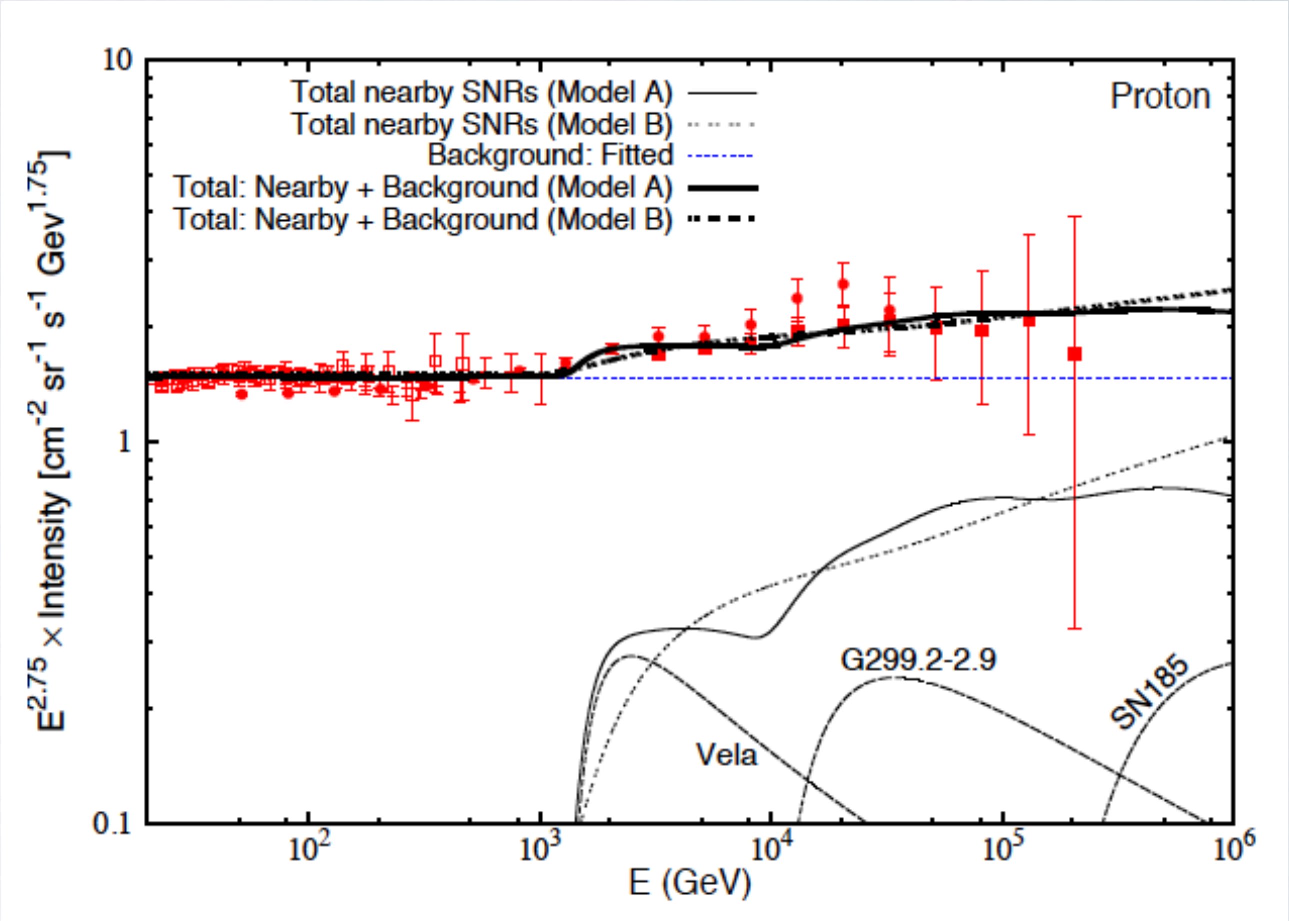
A similar effect is found for heavier nuclei



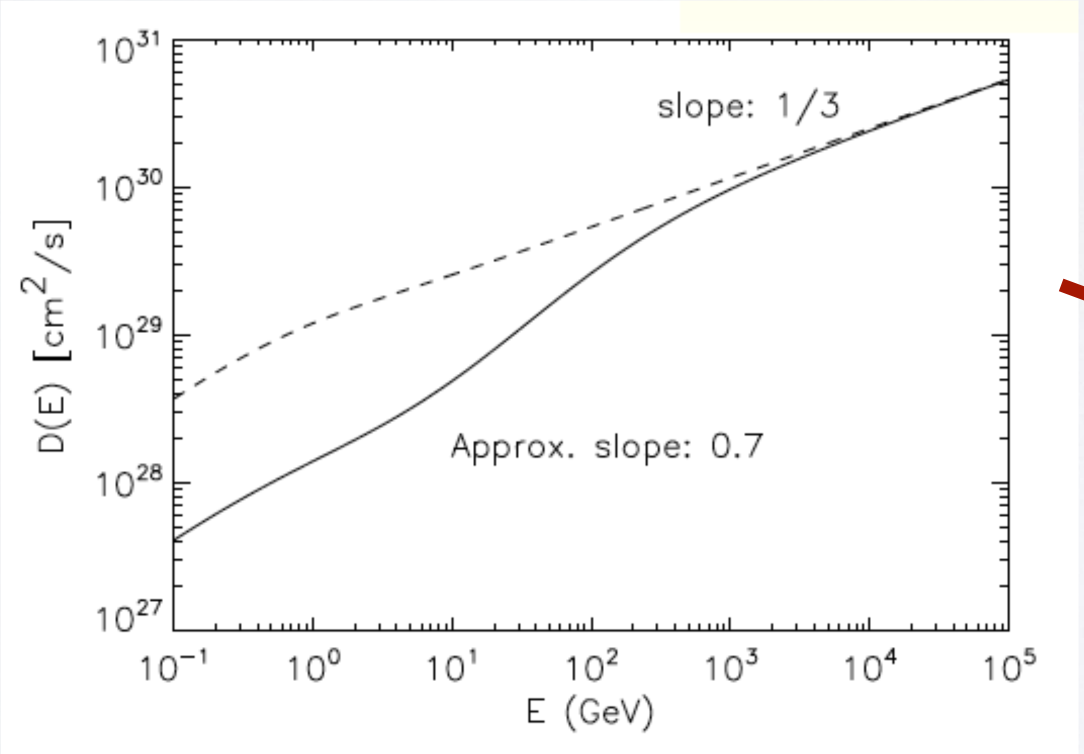


The CR Galactic population: PAMELA anomaly

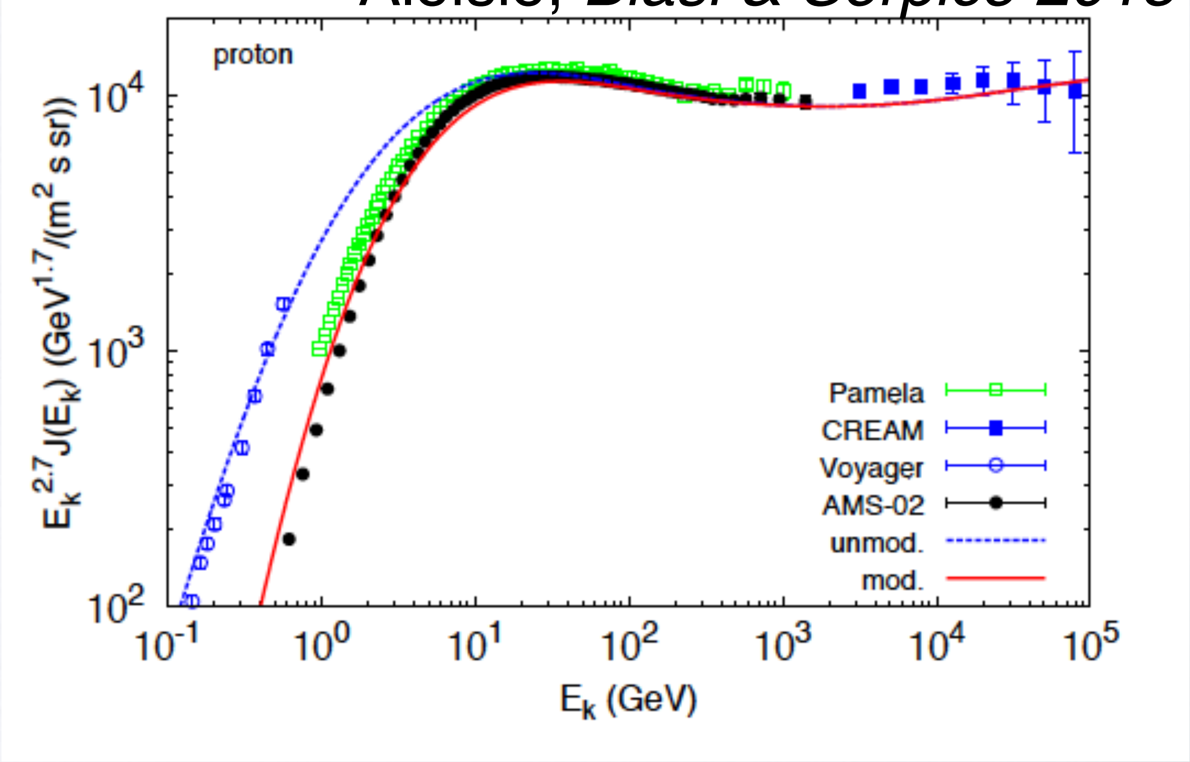
The CR hardening may be a local effect e.g. due to nearby SNR, see e.g. *Thoudam & Hoerandel 2011*



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



Aloisio, *Blasi & Serpico 2015*



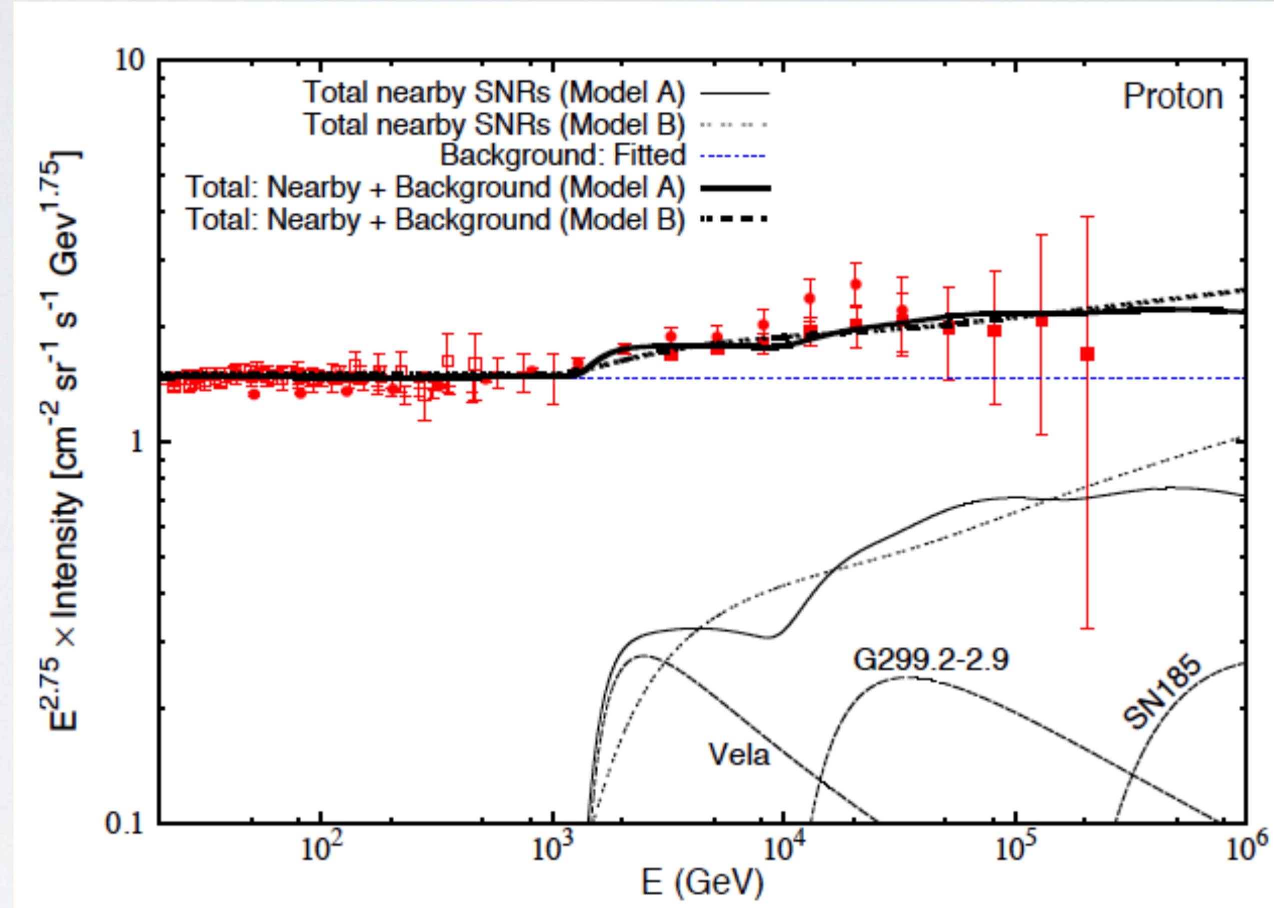
the effect may be spatial dependent !

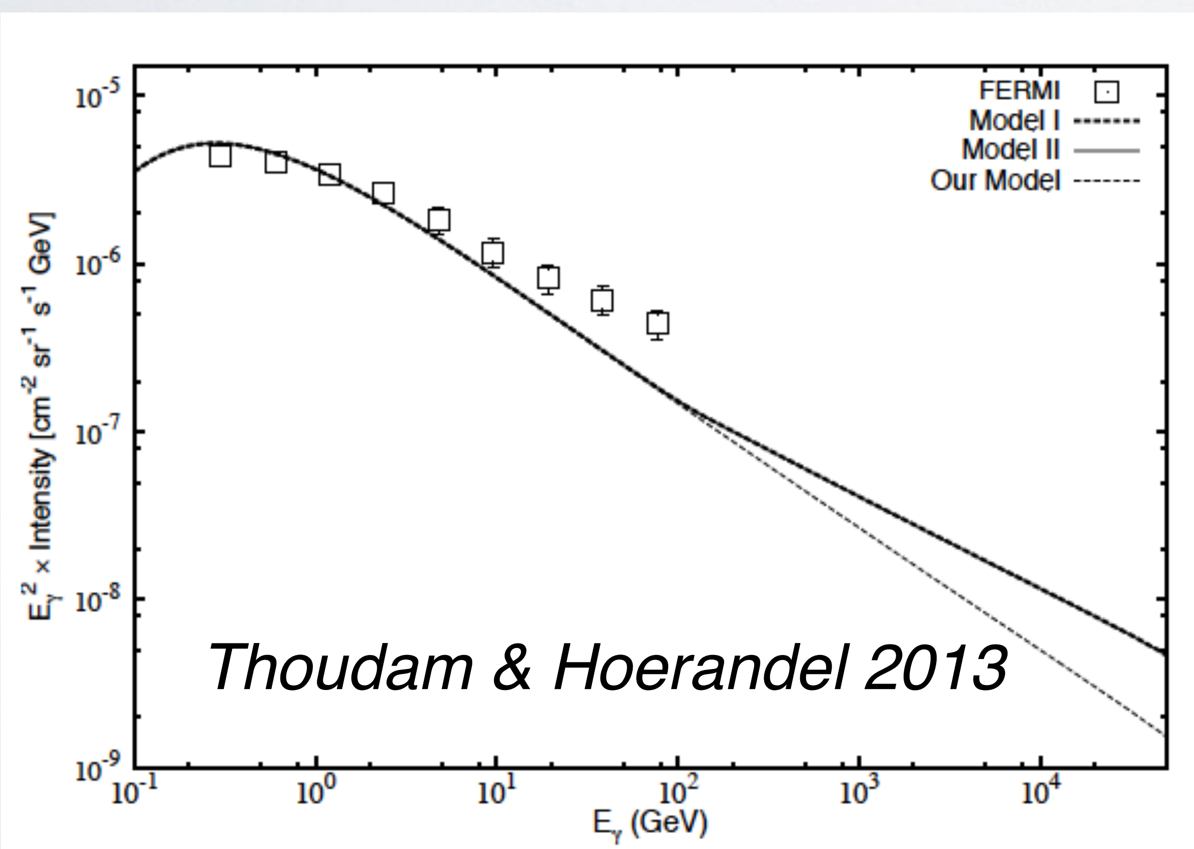
The CR Galactic population: PAMELA anomaly

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

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

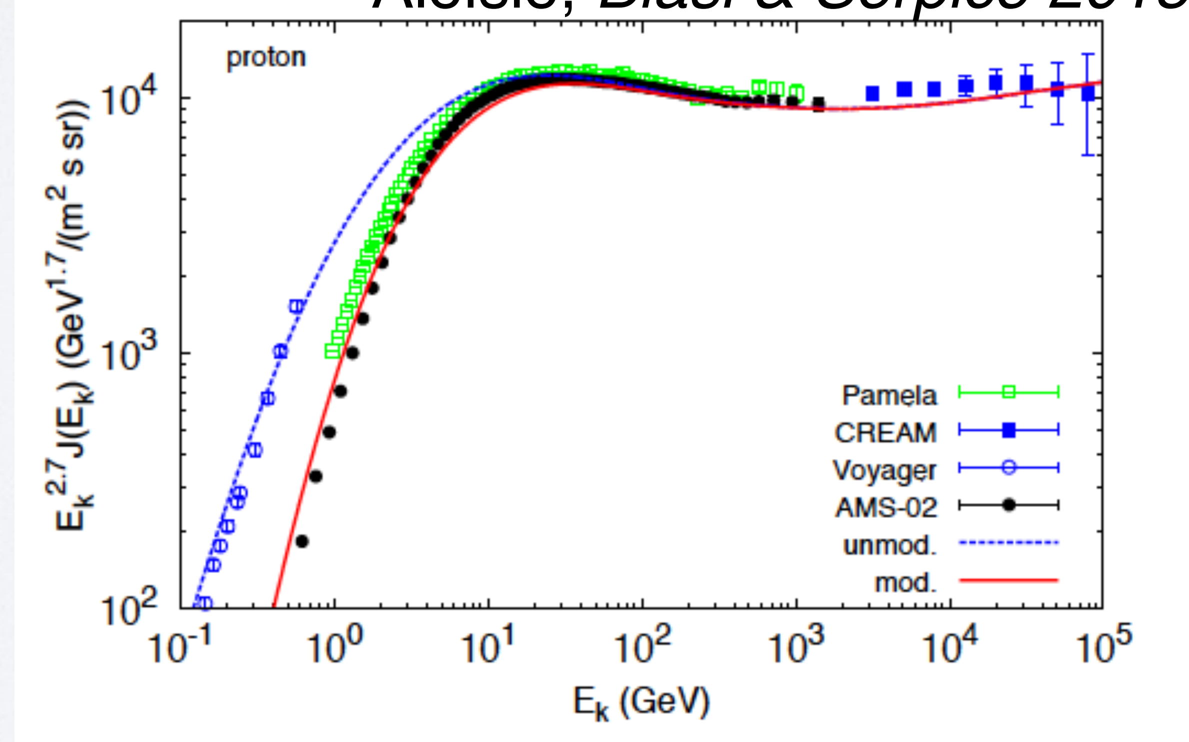
Those scenarios should have different impact on the diffuse **γ**-ray emission



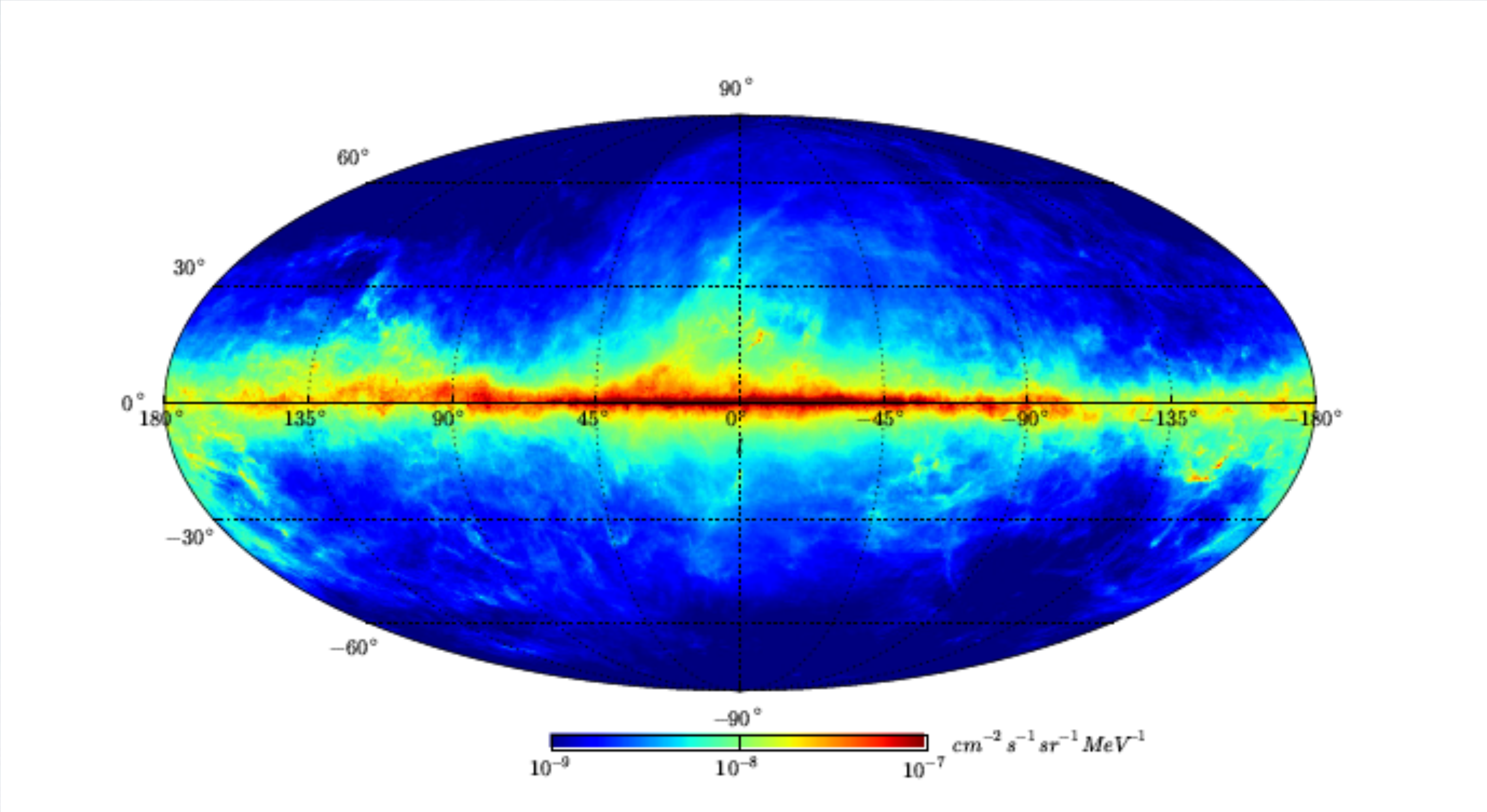


Thoudam & Hoerandel 2013

Aloisio, *Blasi & Serpico 2015*



The gamma-ray diffuse emission



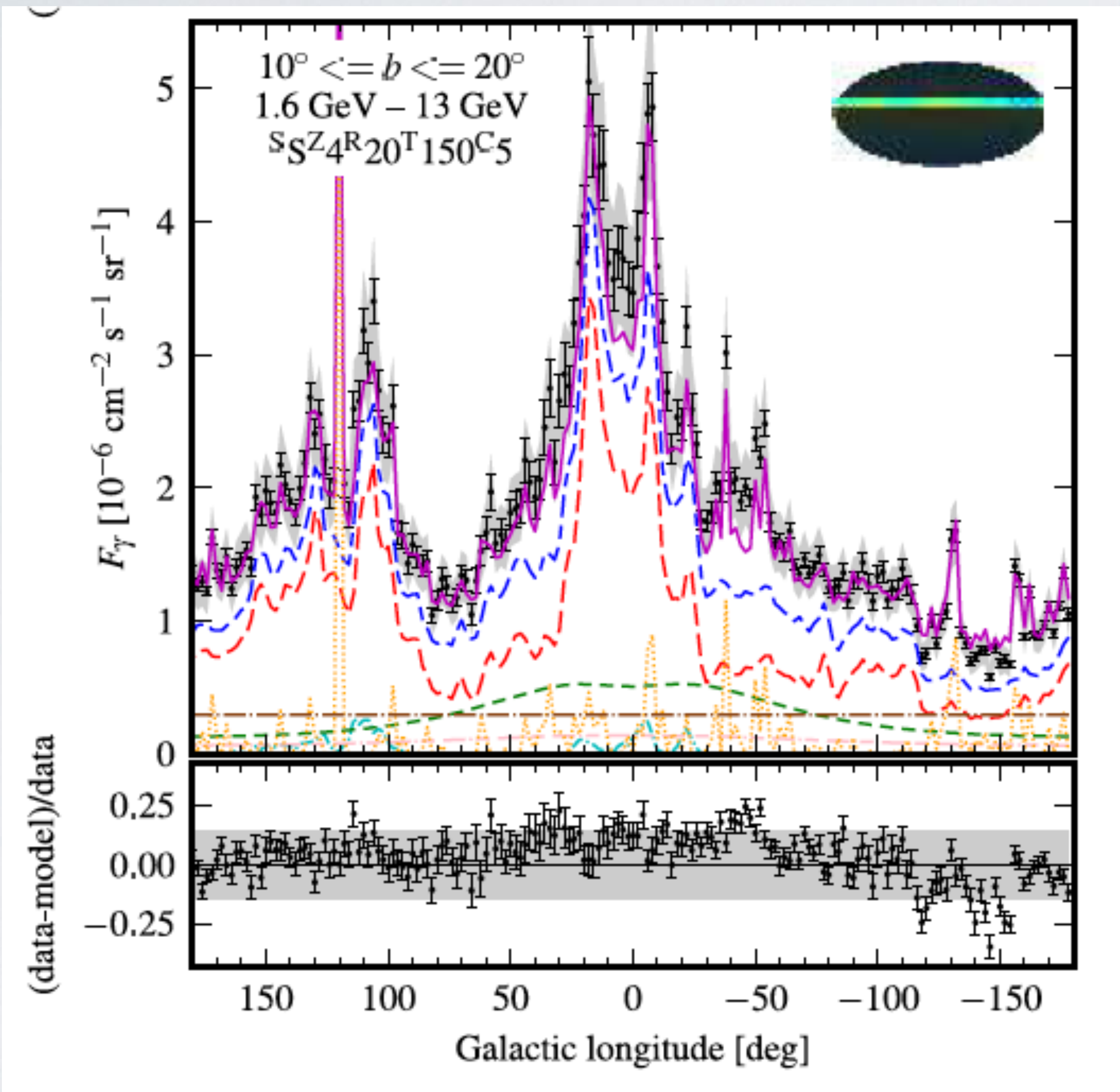
Main contributions:

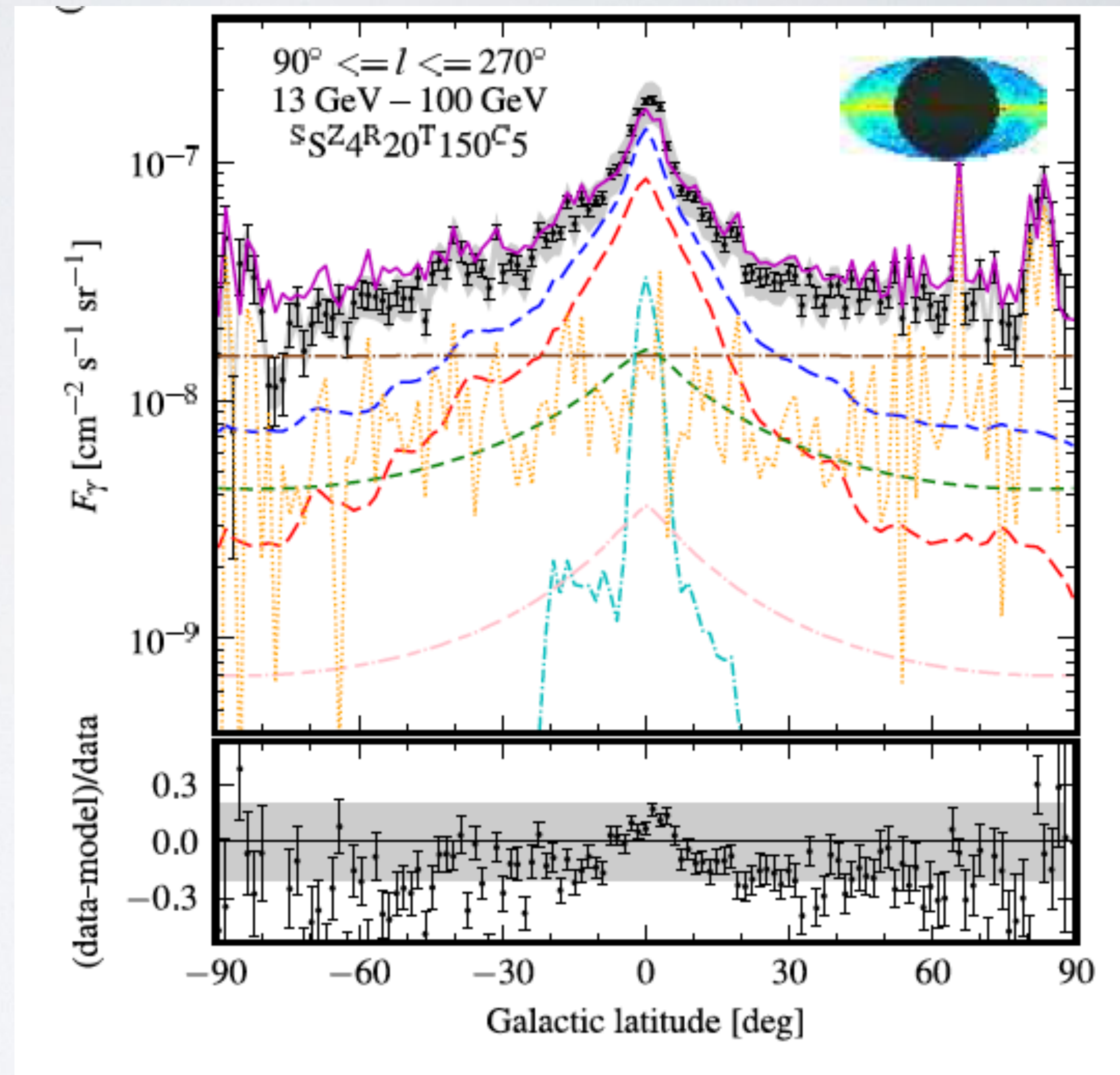
- p(He) $_{RC}$ + p (He) $_{ISM}$ → … + π_0 → … 2 γ — **hadron scattering**
- e $_{RC}$ + γ_{ISRF} → e + γ — **inverse Compton (IC)**
- e $_{RC}$ + A → e + A + γ — **bremsstrahlung**

The gamma-ray diffuse emission

Fermi data against benchmark model based on GALPROP

Fermi coll. ApJ 2012





π^0-decay (red, long-dashed), IC (green, dashed), and bremsstrahlung (cyan, dash-dotted)

The gamma-ray (and neutrino) diffuse emission

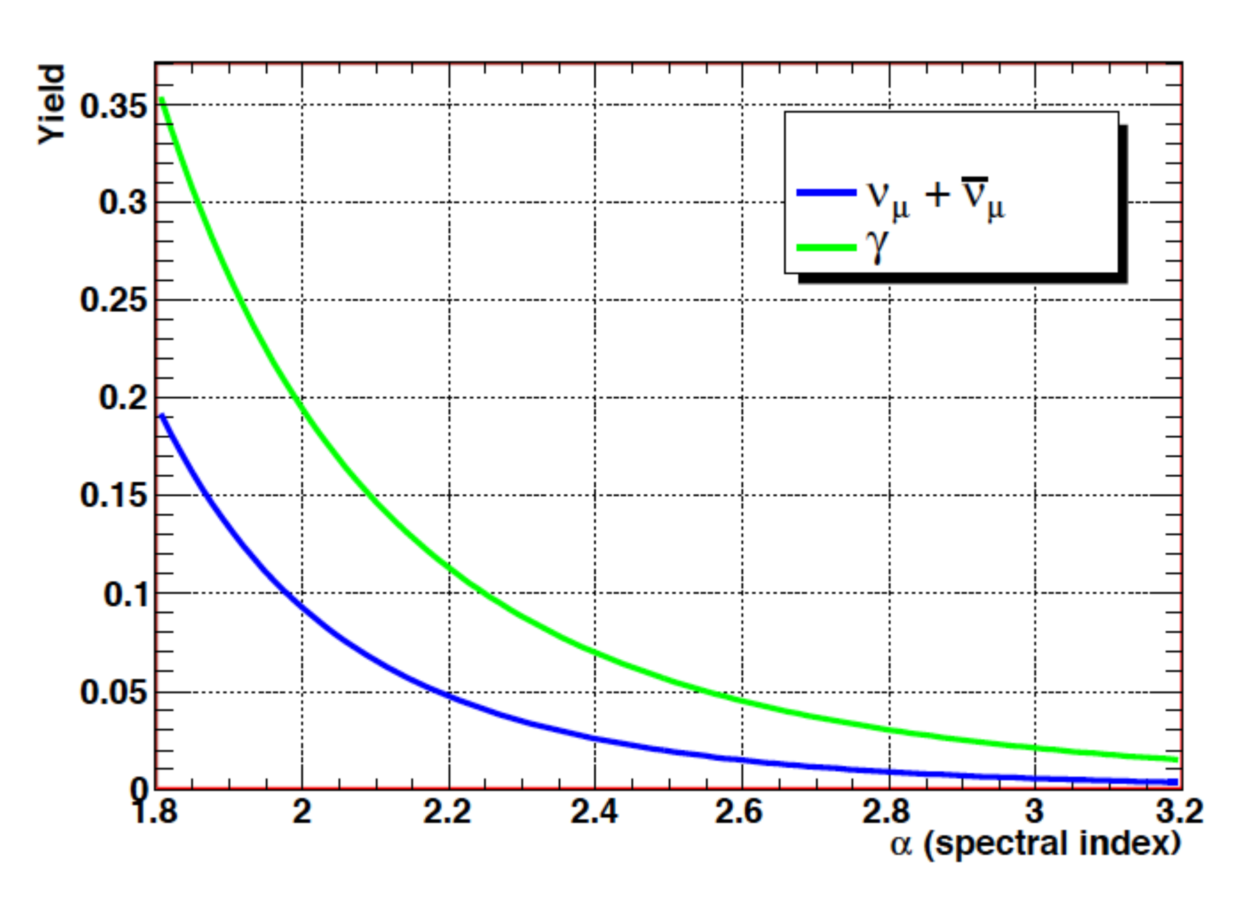
for the **hadron scattering**

emissivity

$$Q_{\gamma\ (\nu_\mu+\bar{\nu}_\mu)}(E_\nu; r, z) = f_N \frac{dn_p(E_\nu, r, z)}{dE}\ \sigma_{pp} c\, n_H(r, z)\, Y_{\gamma\ (\nu_\mu+\bar{\nu}_\mu)}(\alpha)$$

emission intensity

$$I_{\gamma(\nu_\mu+\bar{\nu}_\mu)}(E_\nu;\ b, l) = \frac{1}{4\pi} \int Q_{\gamma\ (\nu_\mu+\bar{\nu}_\mu)}(E_\nu;\ b, l, s)\ \mathrm{ds}$$

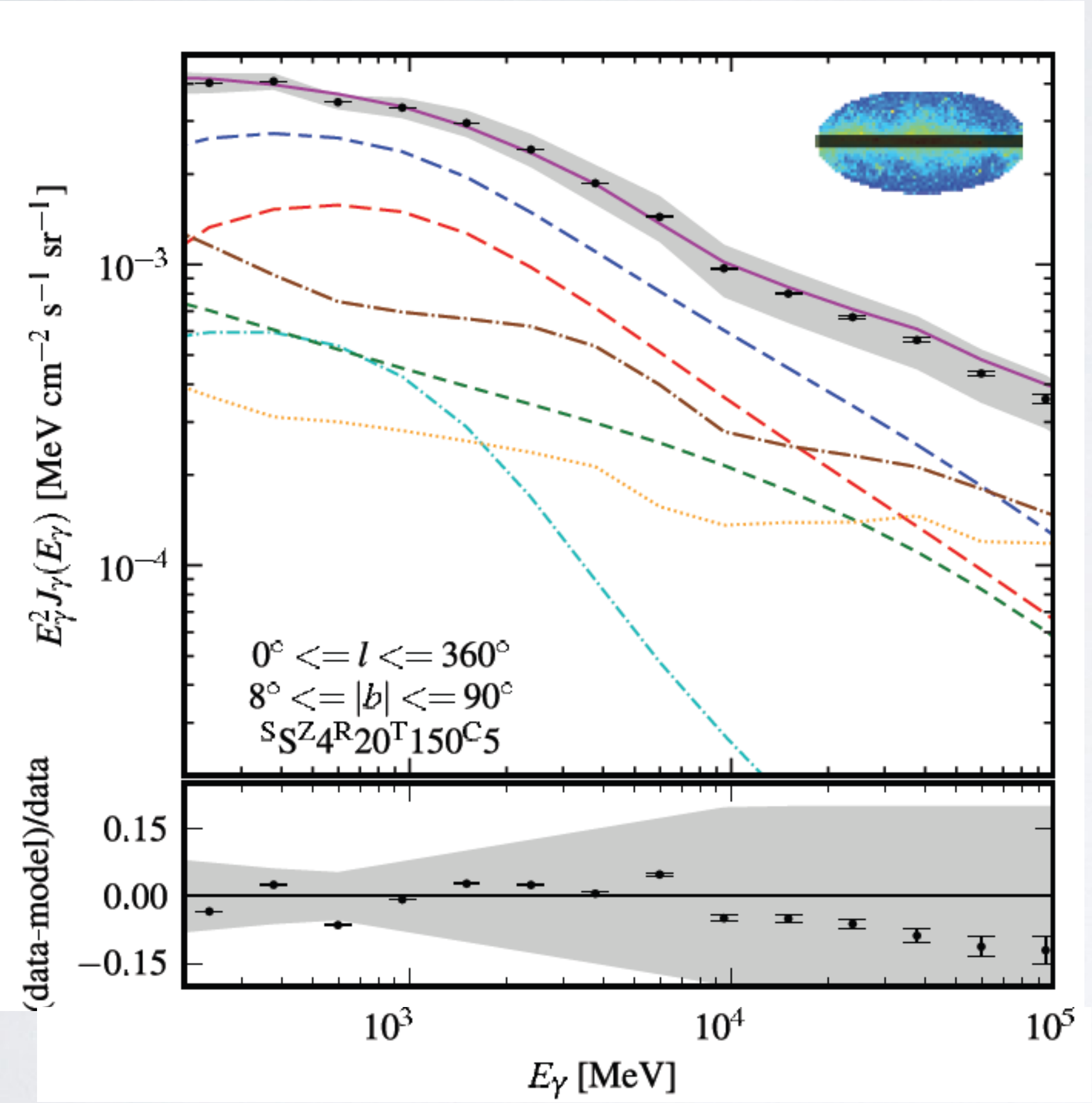


Neutrino yields computed accounting for oscillations
Evoli, DG, Maccione
astro-ph/0701856, JCAP

see also
Costantini & Vissani 2005

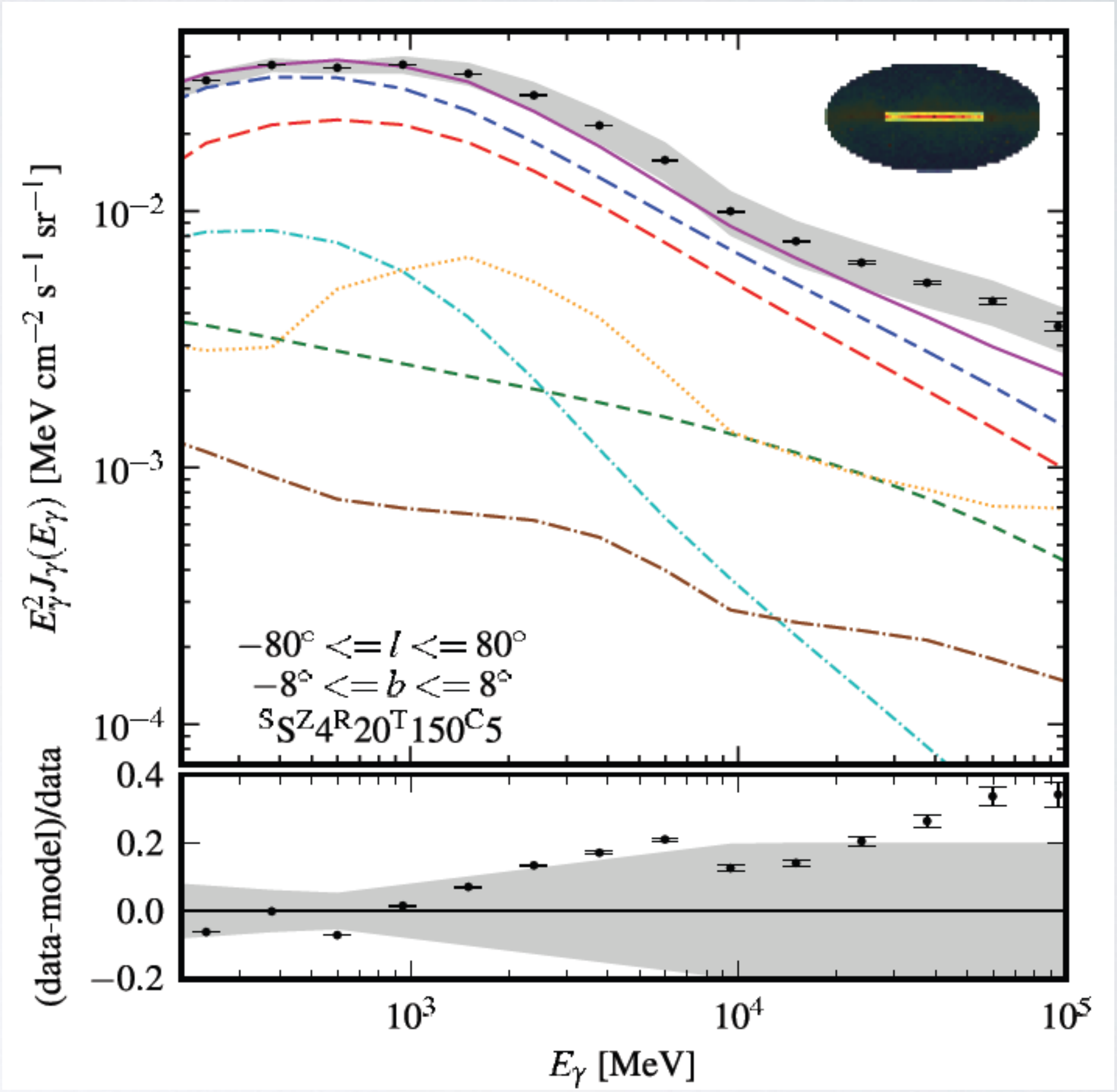
Conventional models against Fermi data

full-sky but the GP



inner GP

Fermi coll. ApJ 2012



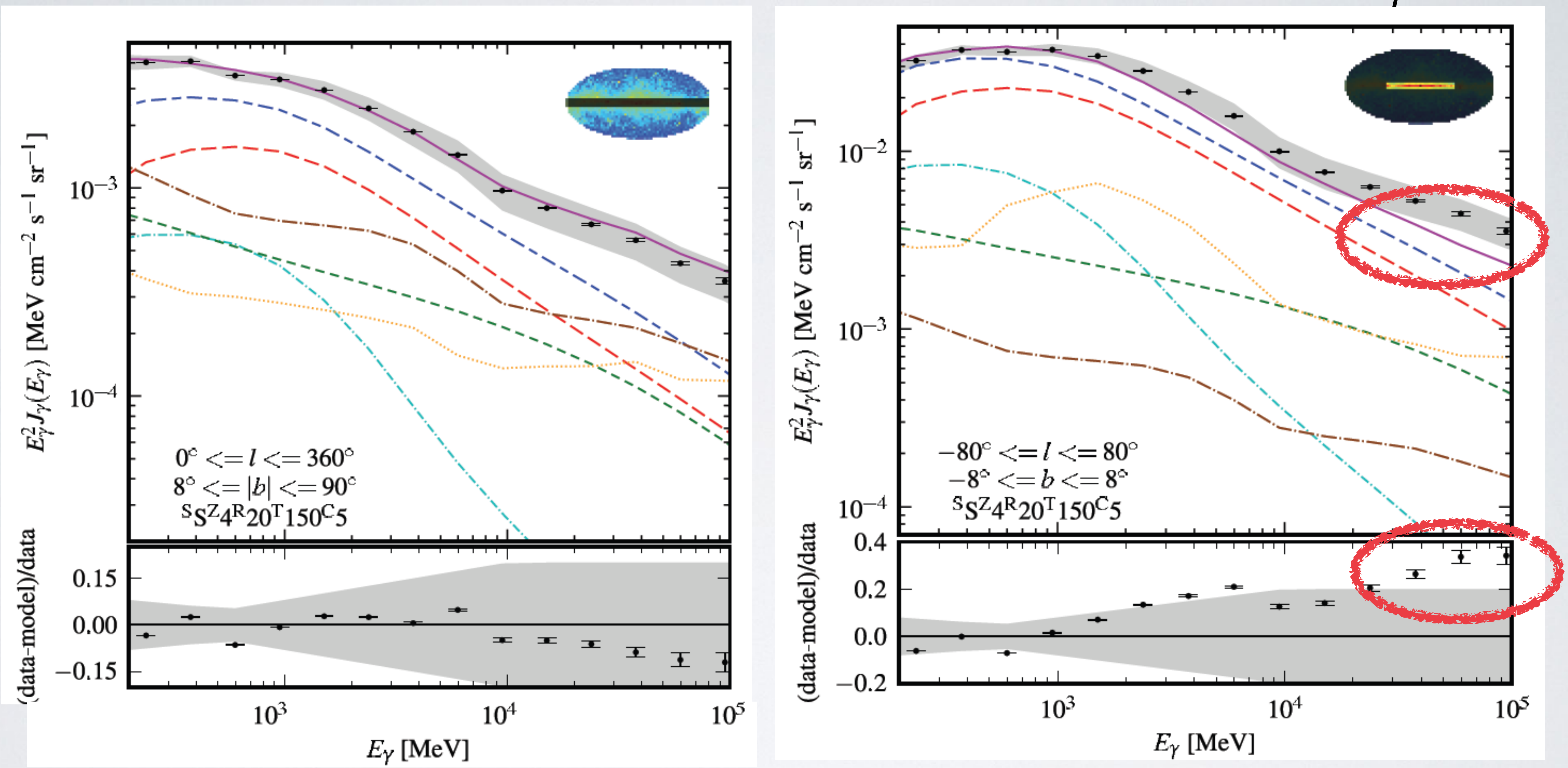
Fermi Benchmark (FB) conventional model:

$\delta = 0.3$, $\gamma_P = 2.72$ in the whole Galaxy (the model does not account CR hardening)

$z_h = 4$ kpc

Conventional models against Fermi data

full-sky but the GP | inner GP | *Fermi coll. ApJ 2012*



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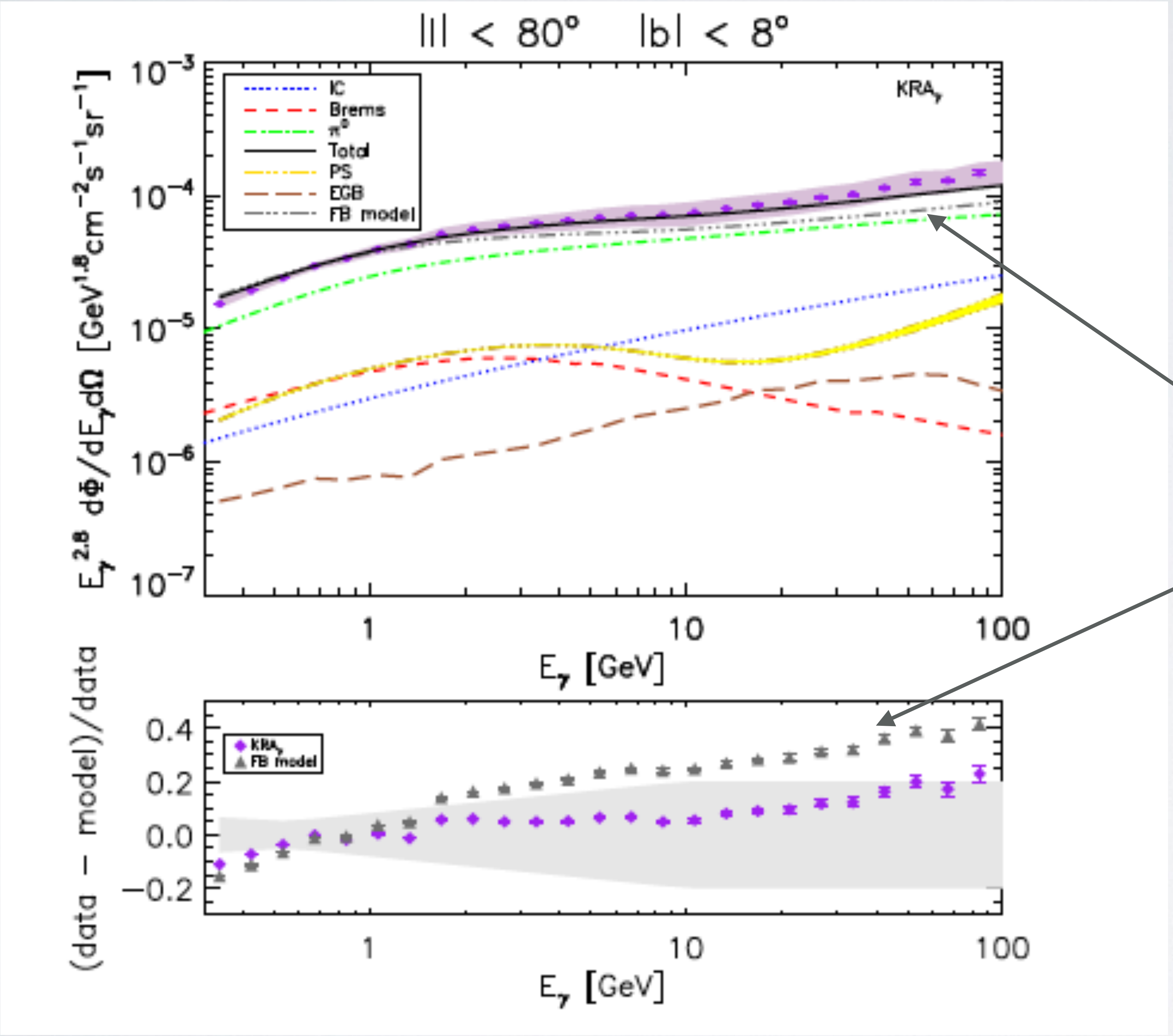
$z_h = 4$ kpc

Conventional models against Fermi data

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



FERMI benchmark model based on GALPROP

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

Some of the main innovative features

- spatial dependent diffusion coefficient(s) (both normalization $D_0(R,\mathbf{z})$ and rigidity dependence index $\delta(R,z)$)

- 3D: it allows spiral arm source distribution

- allow anisotropic diffusion

it reproduces GALPROP results under the same conventional conditions

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

The KRAγ model: Radial dependency of CR transport

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

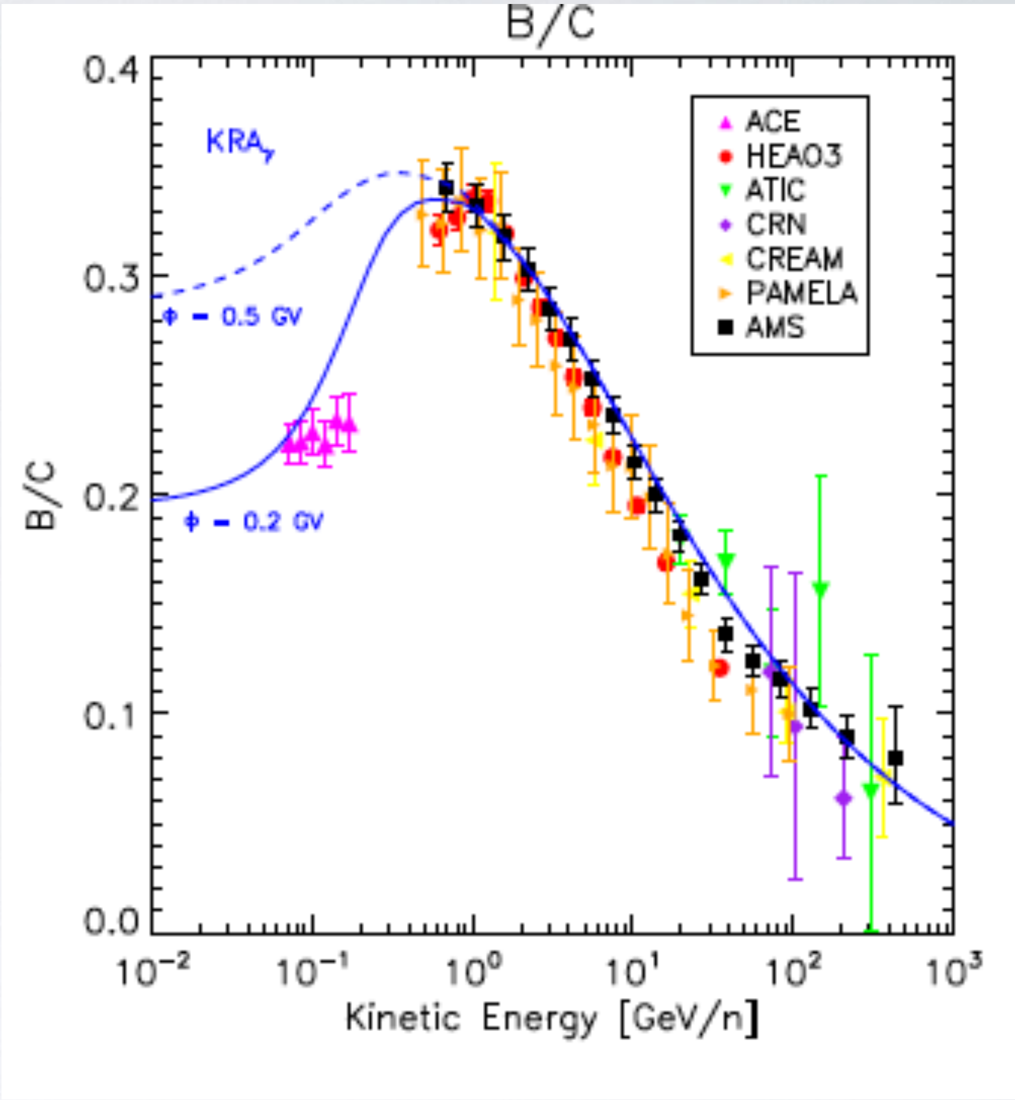
The **KRAγ model** - implemented with the DRAGON code - adopts a radial dependent diffusion coefficient

$\delta(R) = A\,R + B$ for R < 11 kpc, const. above

such that $\delta(R_{sun}) = 0.5$

and convective velocity

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

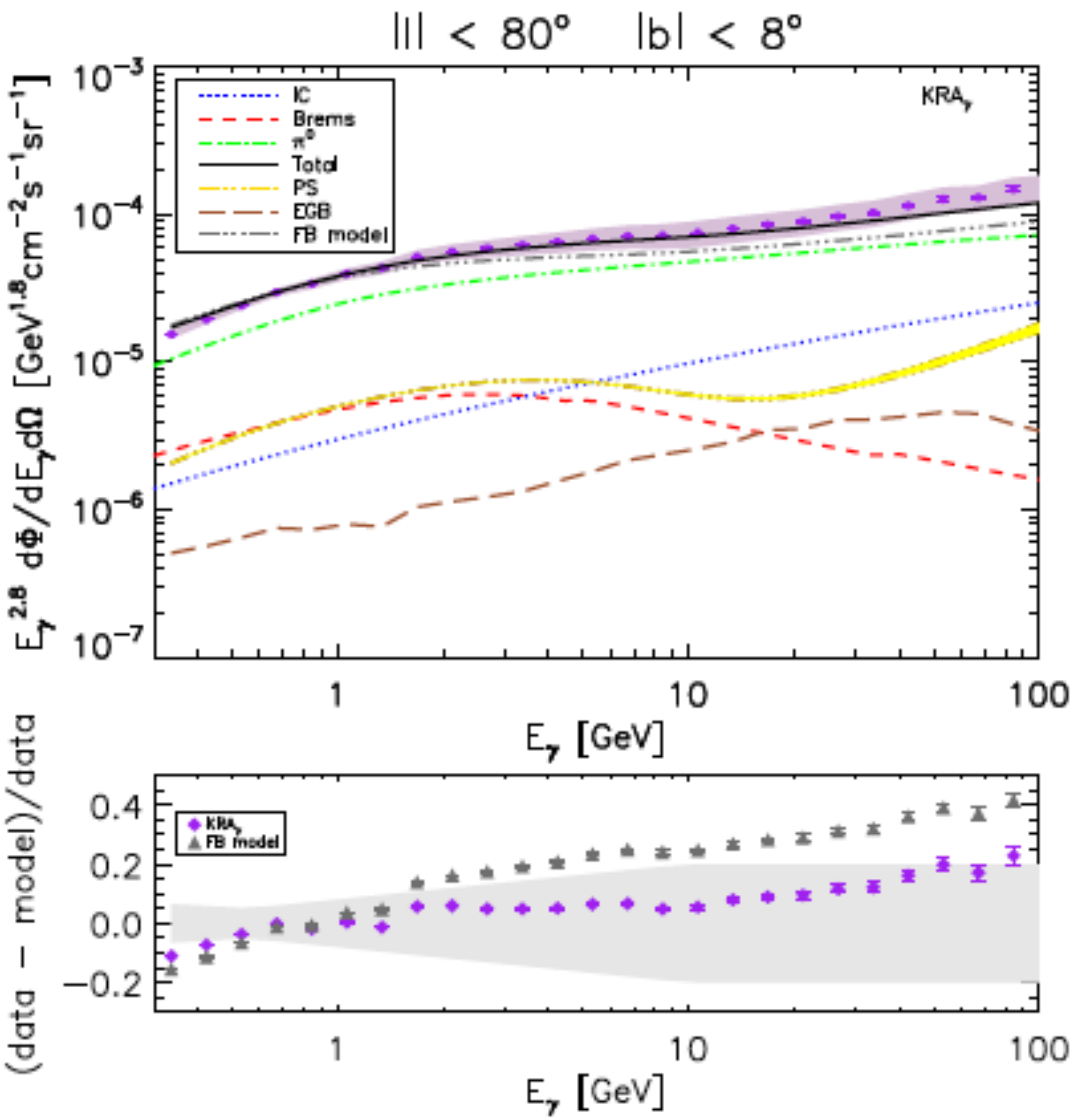


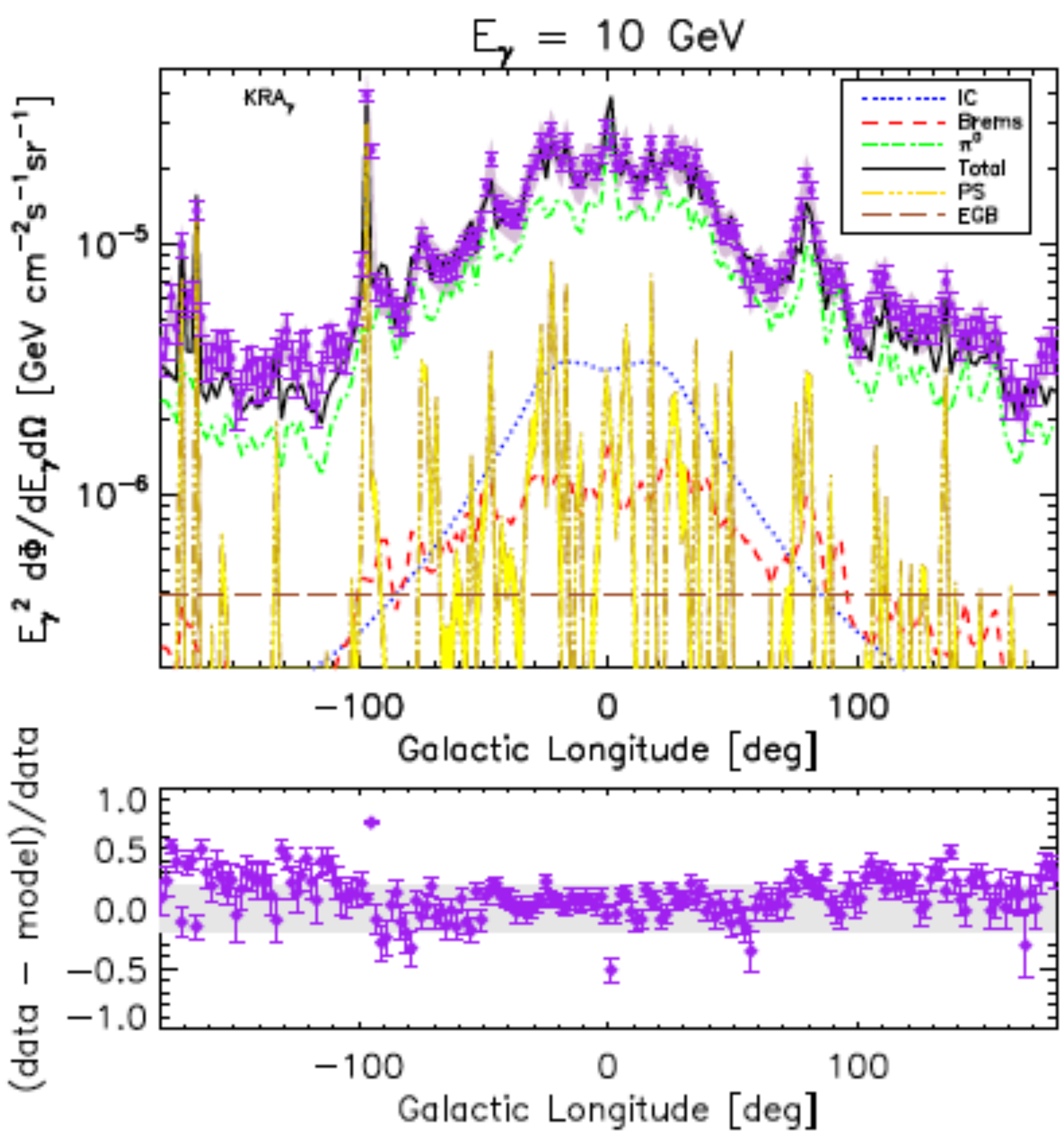
The model is tuned to reproduce the proton spectrum measured by PAMELA (including the hardening @ 250 GeV/n) up to 1 TeV, the B/C (antiprotons also matched by secondary prod.) as well as updated diffuse γ-ray Fermi data

The KRAγ model: Radial dependency of CR transport

The KRAγ 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





The case of a spatial dependent δ

- *Non-linear effects* may induce a radial or vertical dependence *Erlykin & Wolfendale 2012, Yan & Evoli ApJ 2014*

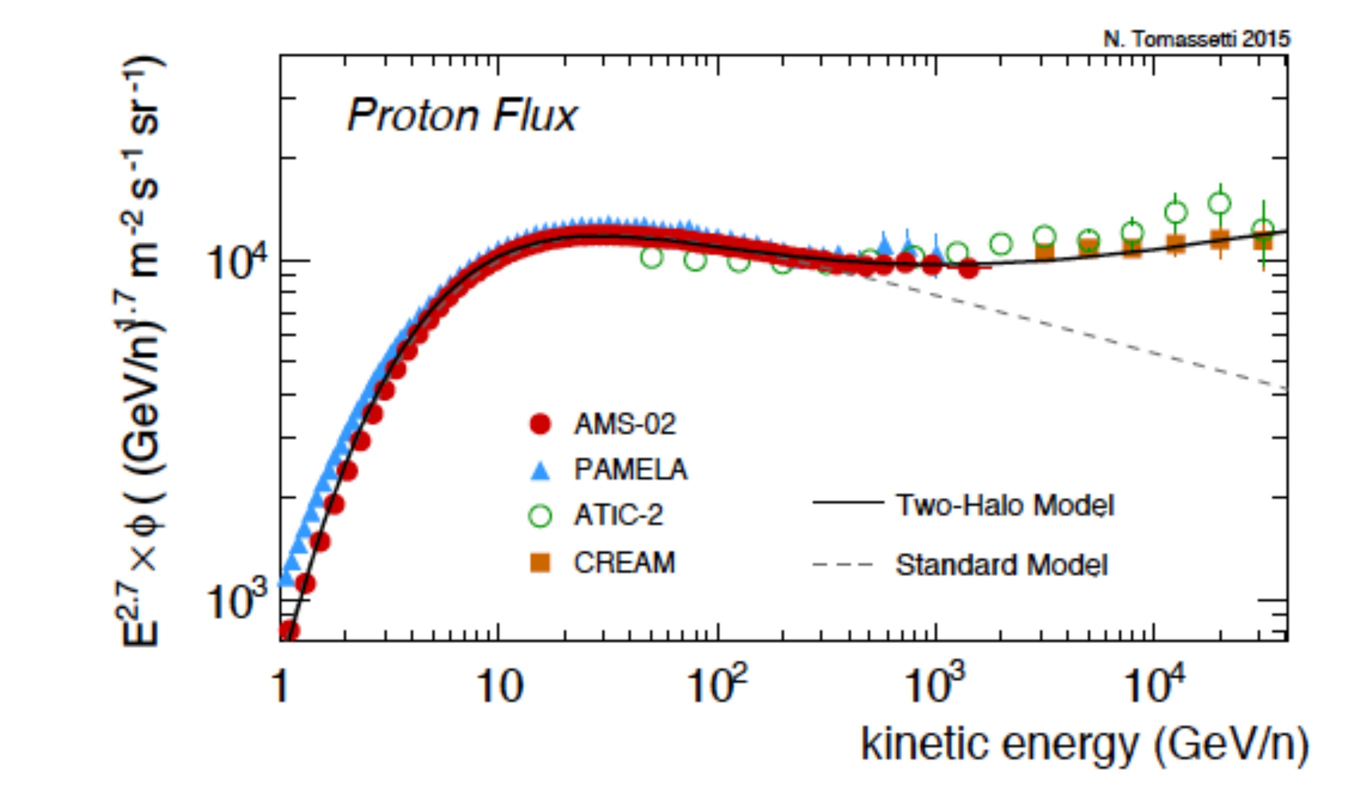
- *Tomassetti ApJ 2012* considered the case of a two-zone regime showing that this may explain the hardening in the primary CR spectra observed by PAMELA, AMS-02 … at ~ 250 GeV/n

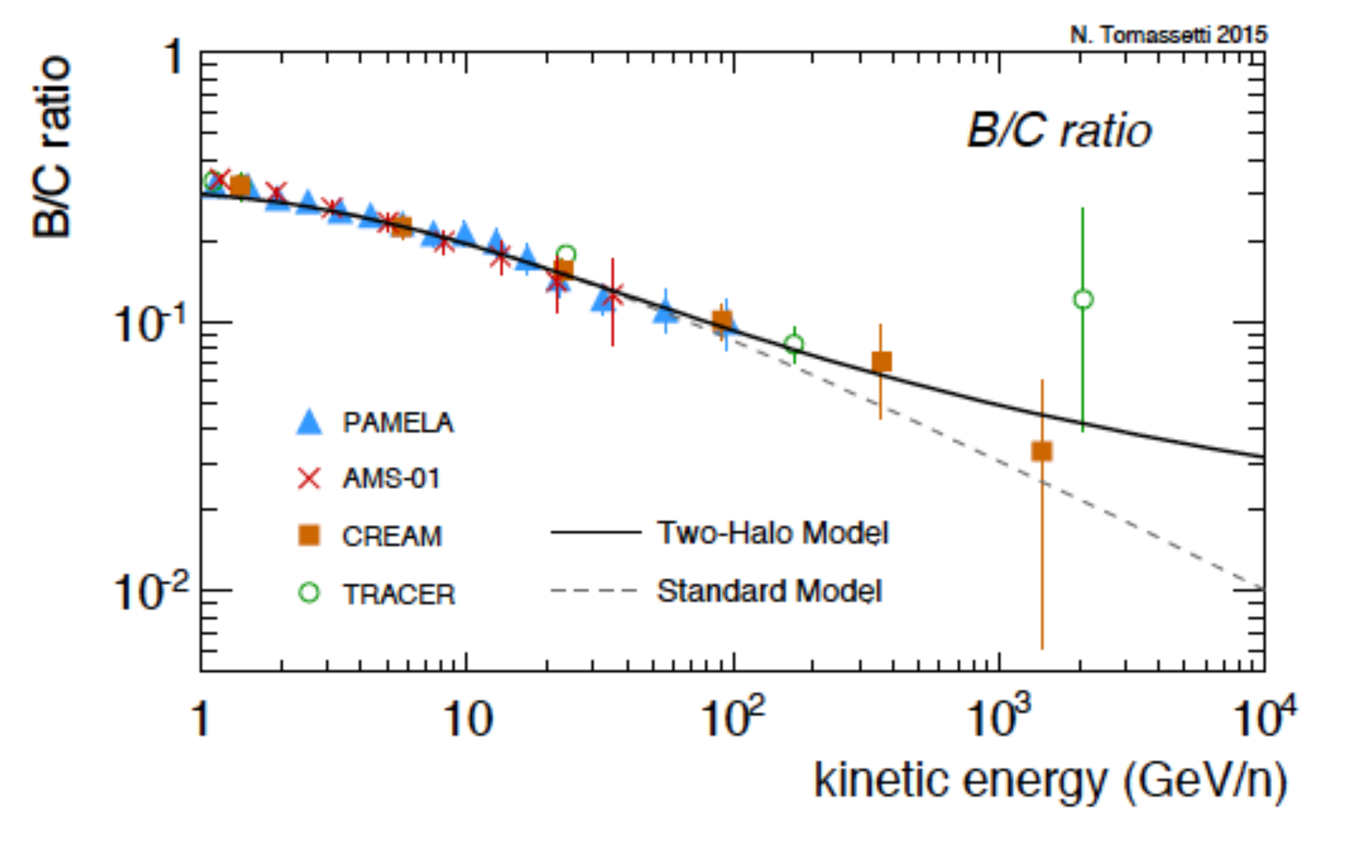
$\Delta \simeq 0.5 - 1$

see also backup slides

$$D(z,\rho) = \begin{cases} k_0 \beta \rho^{\delta} & for\ |z| < \xi L\ (inner\ halo) \\ k_0 \beta \rho^{\delta+\Delta} & for\ |z| > \xi L\ (outer\ halo) \end{cases}$$

Tomassetti, ICRC 2015, using DRAGON



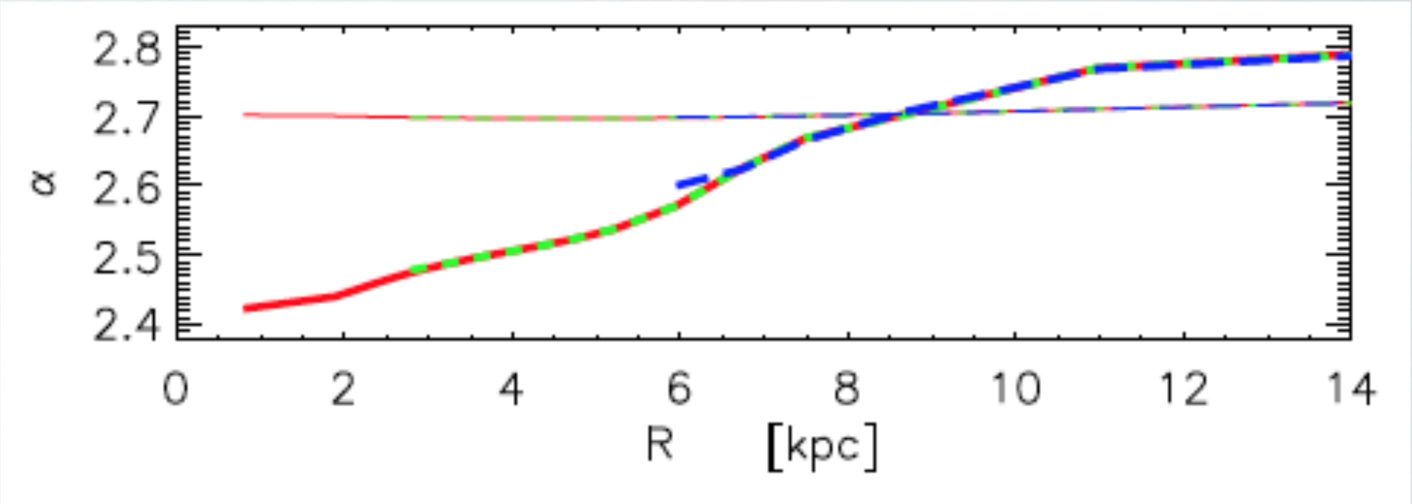


The KRAγ model: Radial dependency of CR transport

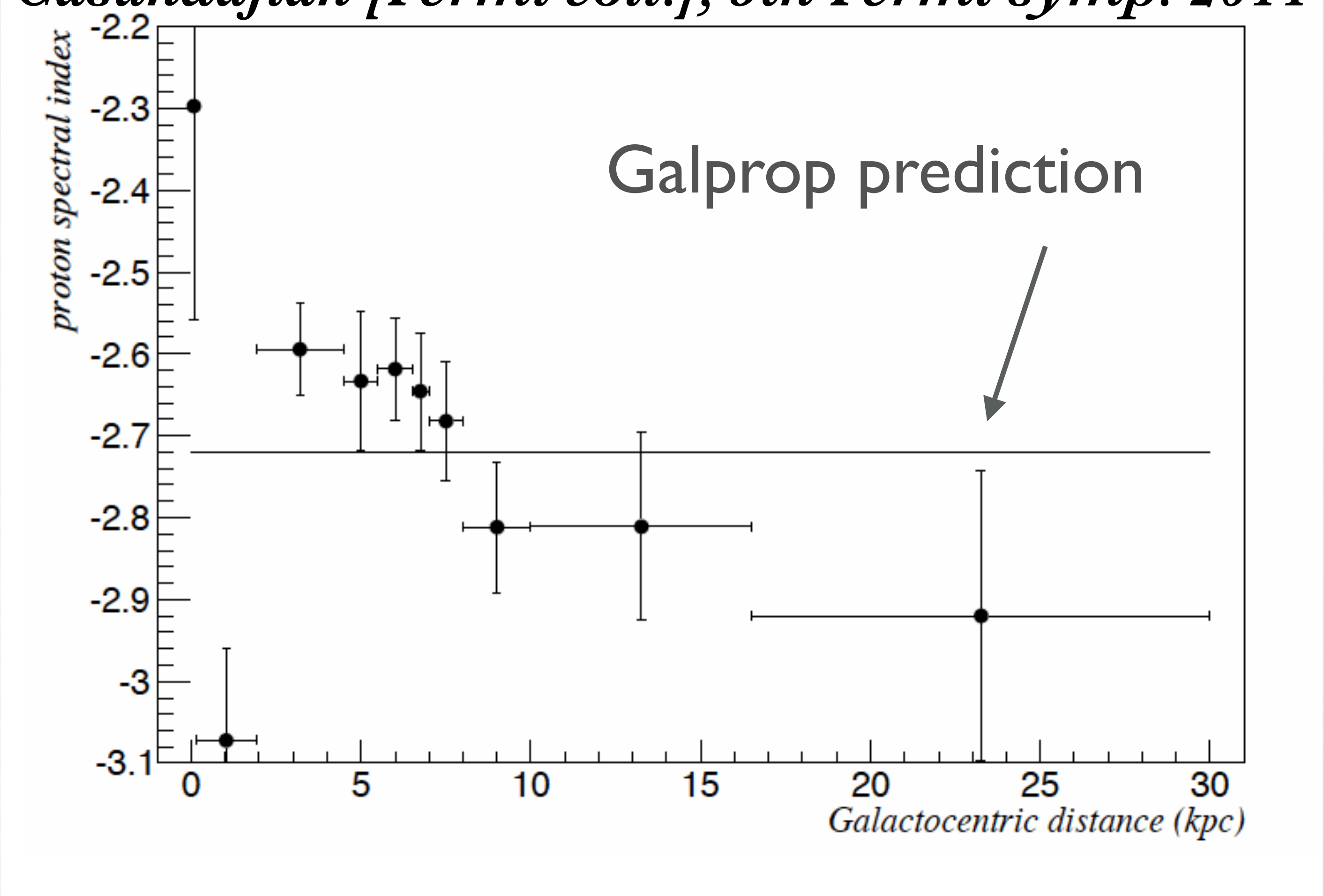
the model predicts a radial dependence of the CR spectral index, hence of the γ-ray emission spectrum

hints of such a behavior were reported by Fermi coll. almost at the same time and confirmed recently (see below)

this is incompatible with conventional models implemented with GALPROP

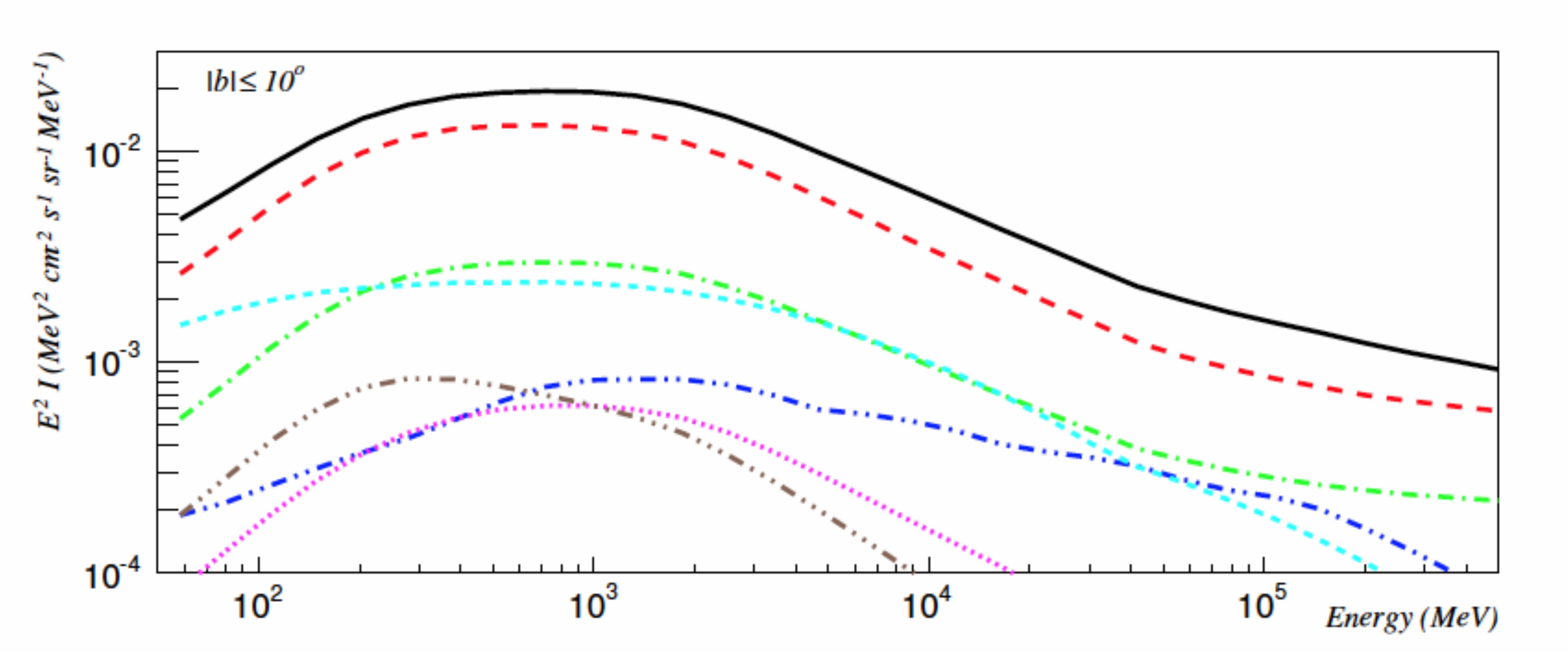


Casandajian [Fermi coll.], 5th Fermi symp. 2014



Fermi results

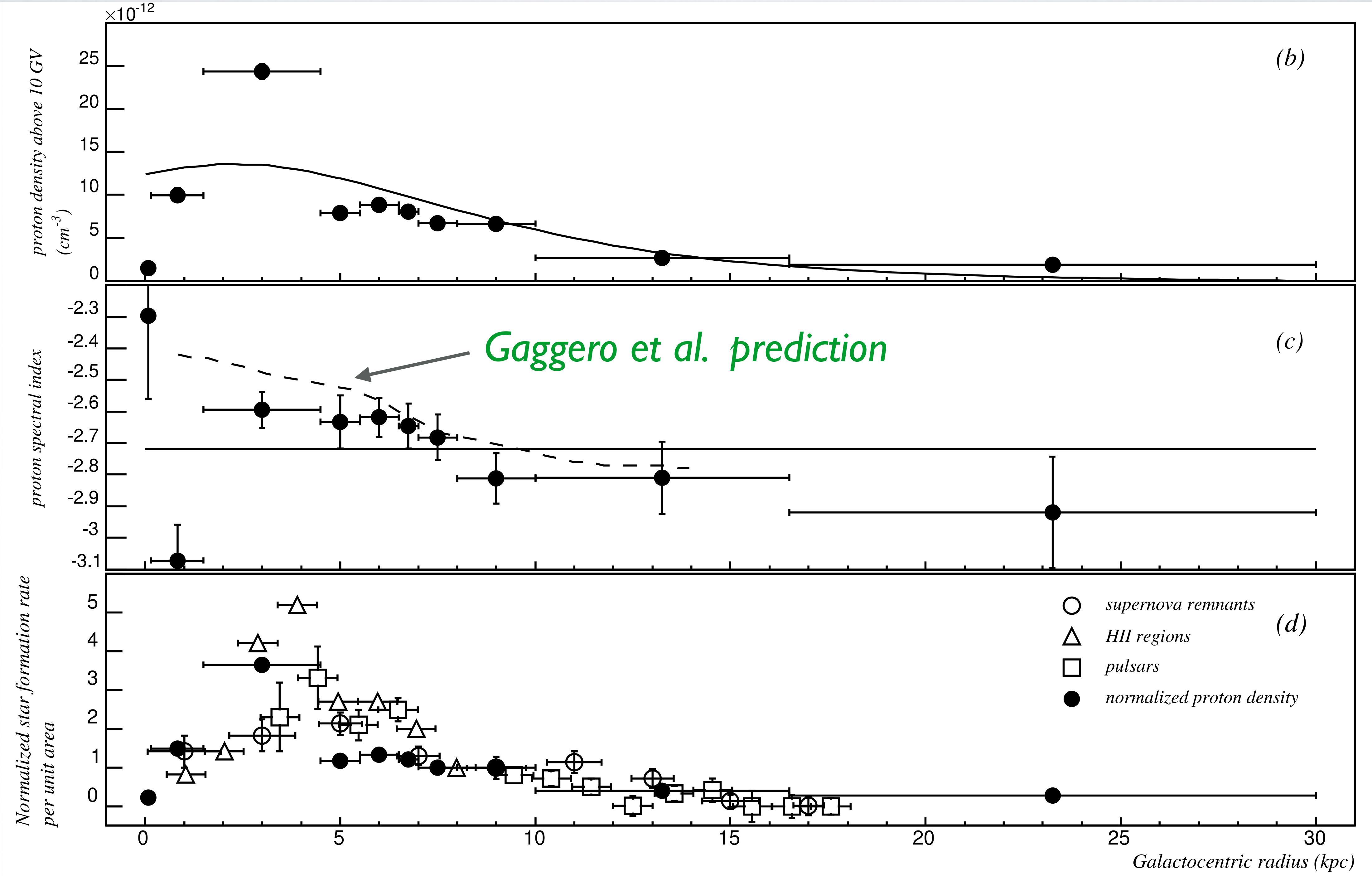
FERMI coll. arXiV:1602.07246; APJ supp.



$$
\begin{aligned}
N_{pred}(l,b,E) = & \sum_{i=annulus} q_{\mathrm{HI}_i}(E)\widetilde{N}_{\mathrm{HI}_i}(l,b) + \sum_{i=annulus} q_{\mathrm{CO}_i}(E)\widetilde{W}_{\mathrm{CO}_i}(l,b) \\
& + q_{\mathrm{DNM}}(E)\widetilde{N}_{\mathrm{H}}^{\mathrm{DNM}}(l,b) + q_{\mathrm{HI}\,corr}(E)\widetilde{N}_{\mathrm{HI}}^{\mathrm{corr}}(l,b) \\
& + C_{IC_p}(E)\widetilde{I}_{IC_p}(l,b,E) + C_{iso}(E)\widetilde{I}_{iso} \\
& + C_{\mathrm{limb}}(E)\widetilde{I}_{\mathrm{limb}}(l,b) + \widetilde{I}_{\mathrm{Sun\_Moon}}(l,b,E) \\
& + \sum_{j=point\ src} N_{pt_j}(E)\widetilde{\delta}(l-l_j, b-b_j) + \sum_{k=extend\ src} C_{ext_k}(E)\widetilde{I}_{ext_k}(l,b)
\end{aligned}
$$

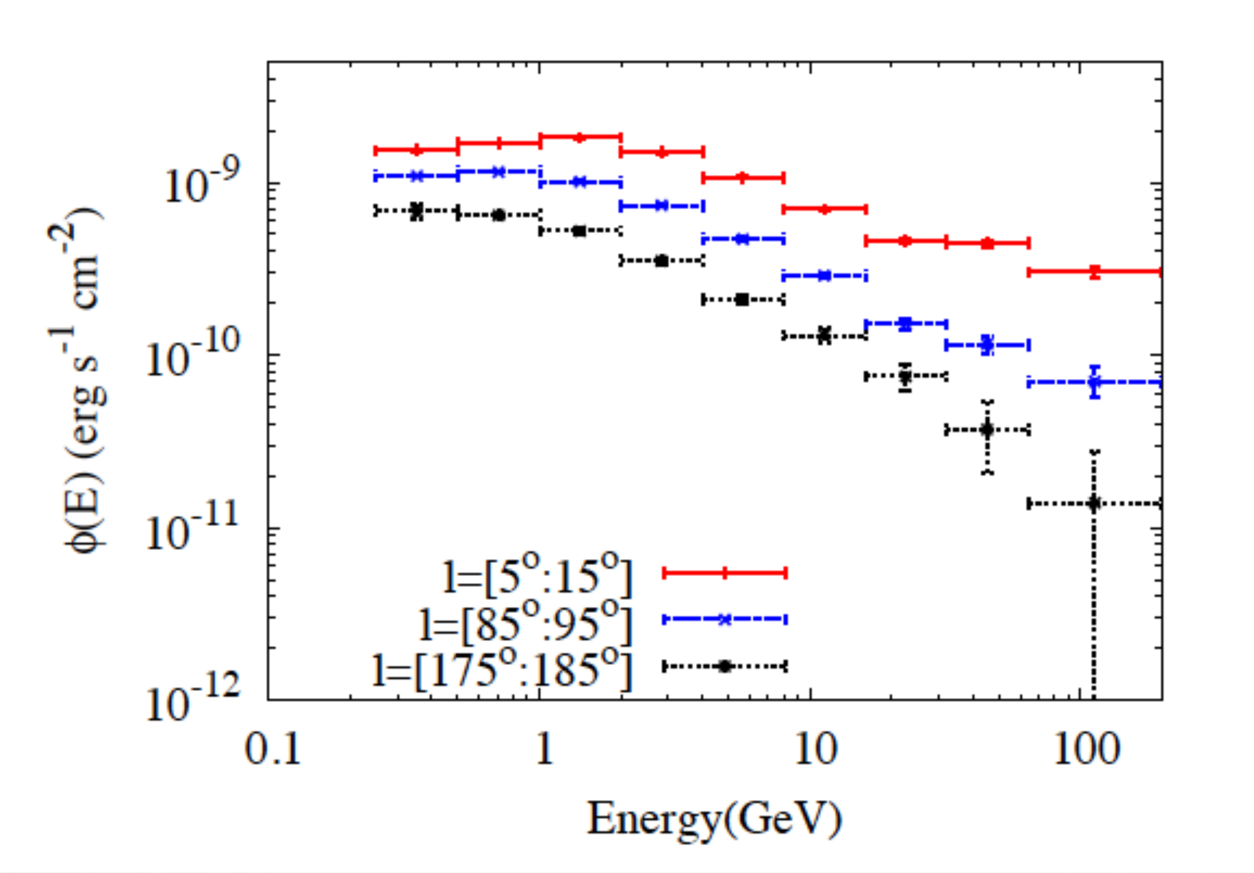
Fermi results

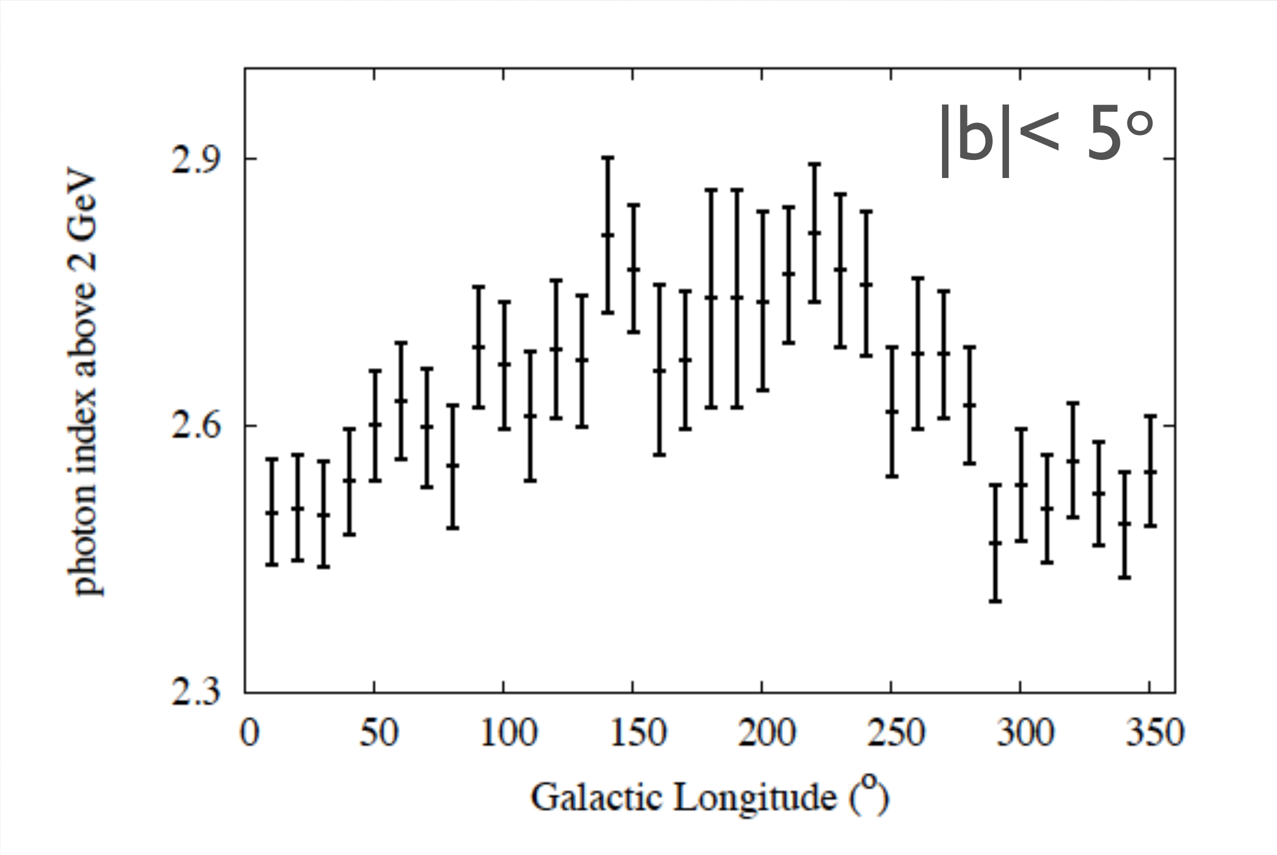
FERMI coll. arXiV:1602.07246; APJ supp.



Fermi results: an independent analysis

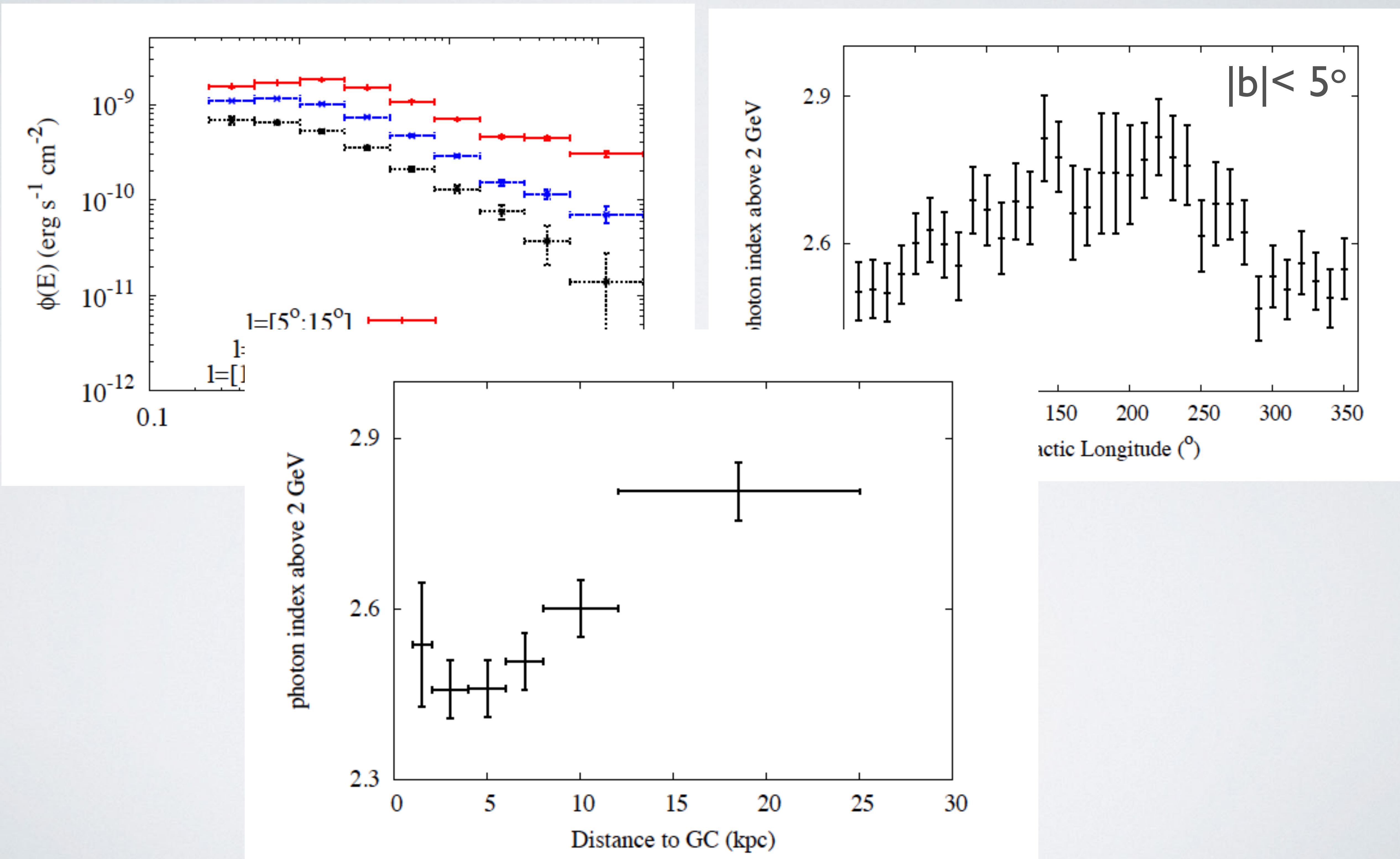
Yang, Aharonian & Evoli arXiV:1602.04710





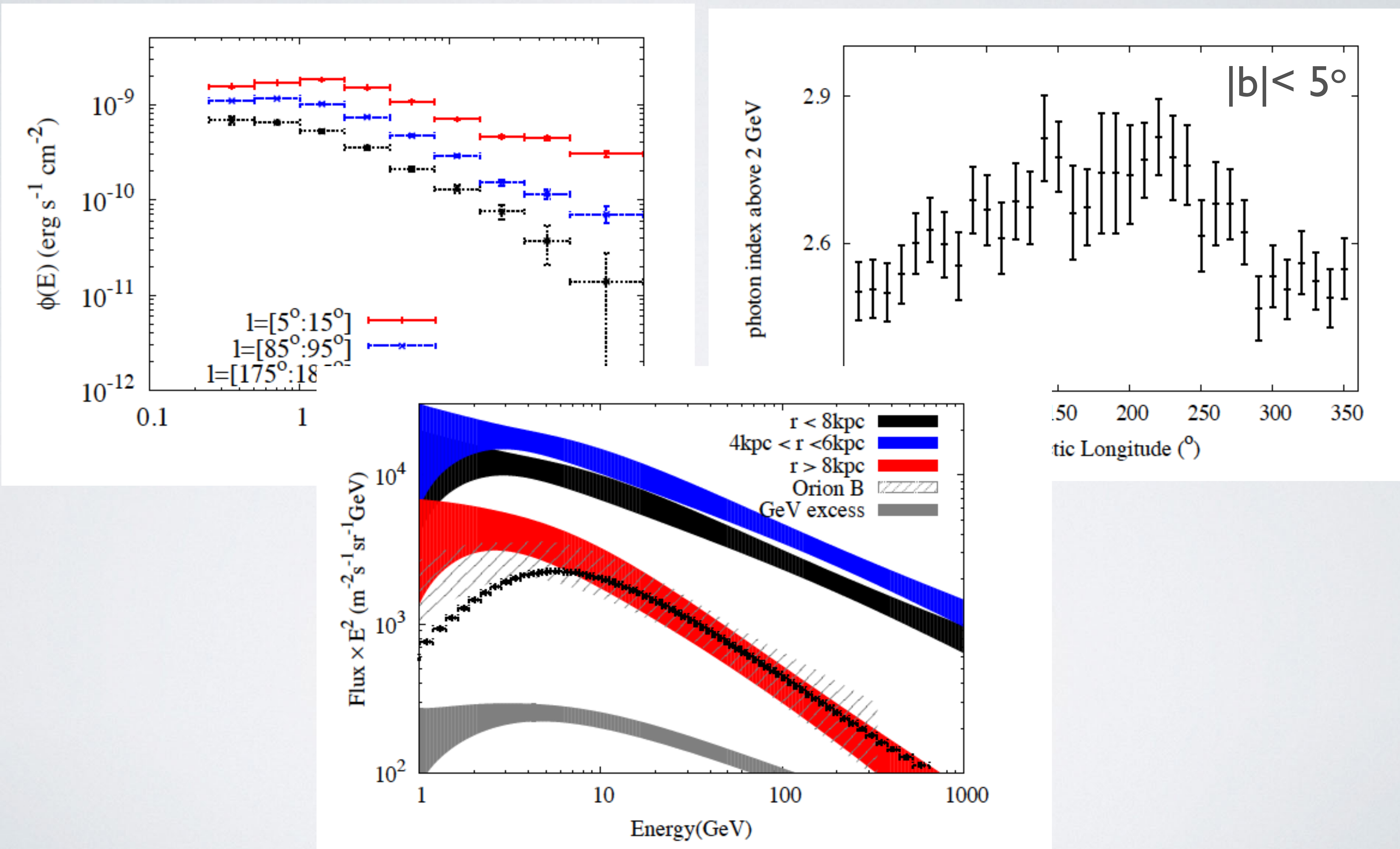
Fermi results: an independent analysis

Yang, Aharonian & Evoli arXiV:1602.04710



Fermi results: an independent analysis

Yang, Aharonian & Evoli arXiV:1602.04710



The Milagro anomaly in the inner Galactic Plane

ABDO ET AL.

ApJ 2008

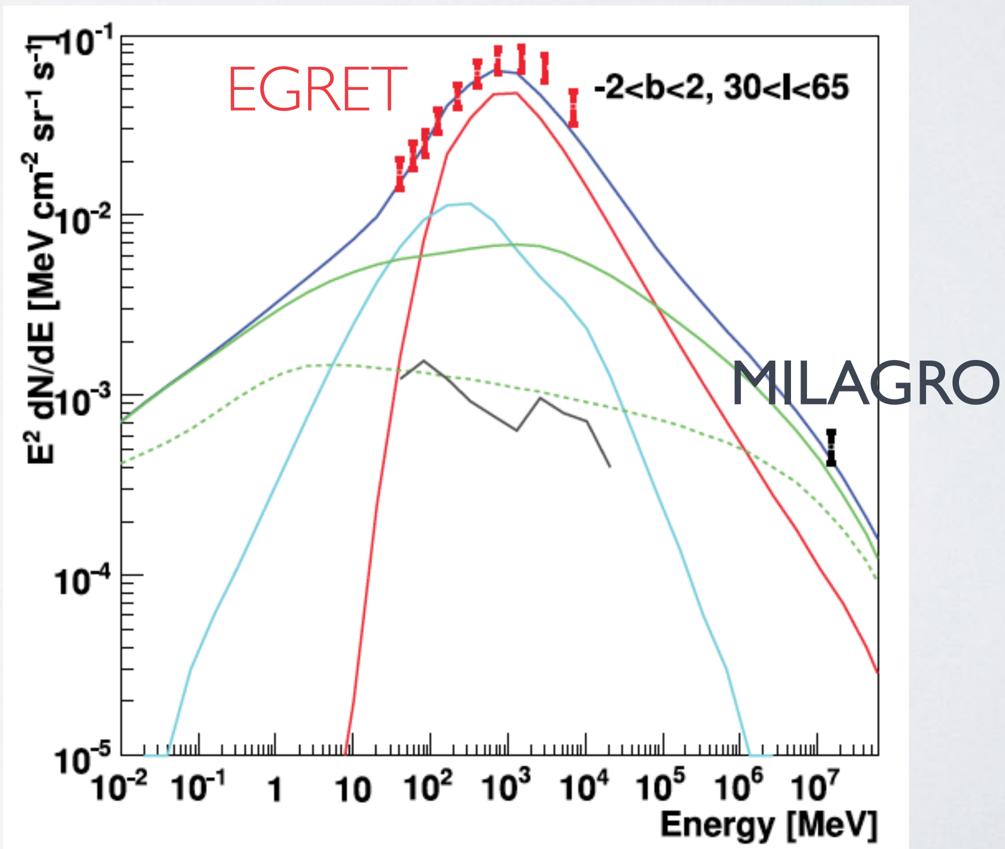
TABLE 1

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})		
			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 (4 σ) larger than computed with the conventional model

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

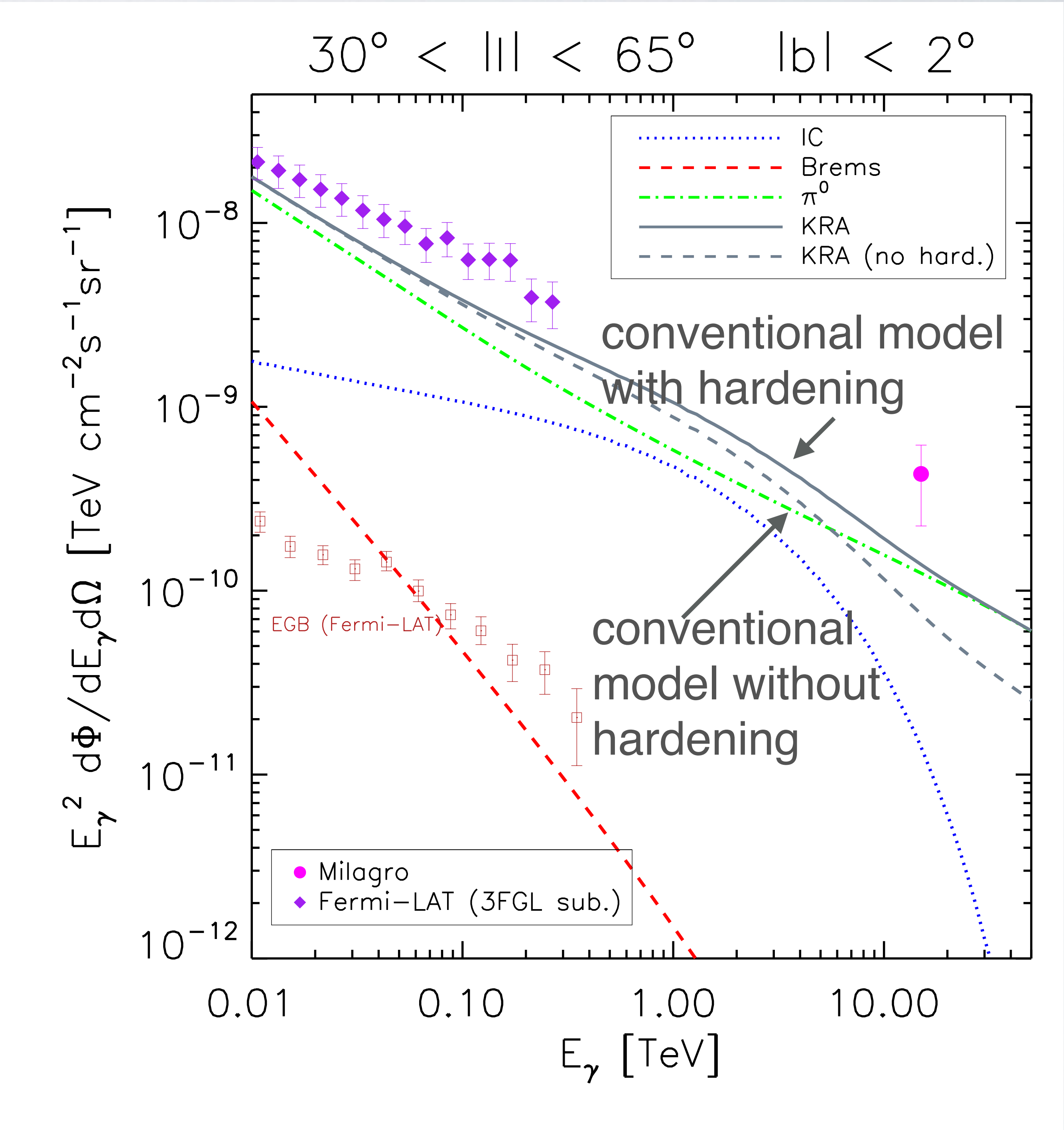


The Milagro anomaly in the inner Galactic Plane

- the excess is present also respect to updated conventional models tuned on CR data and <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)

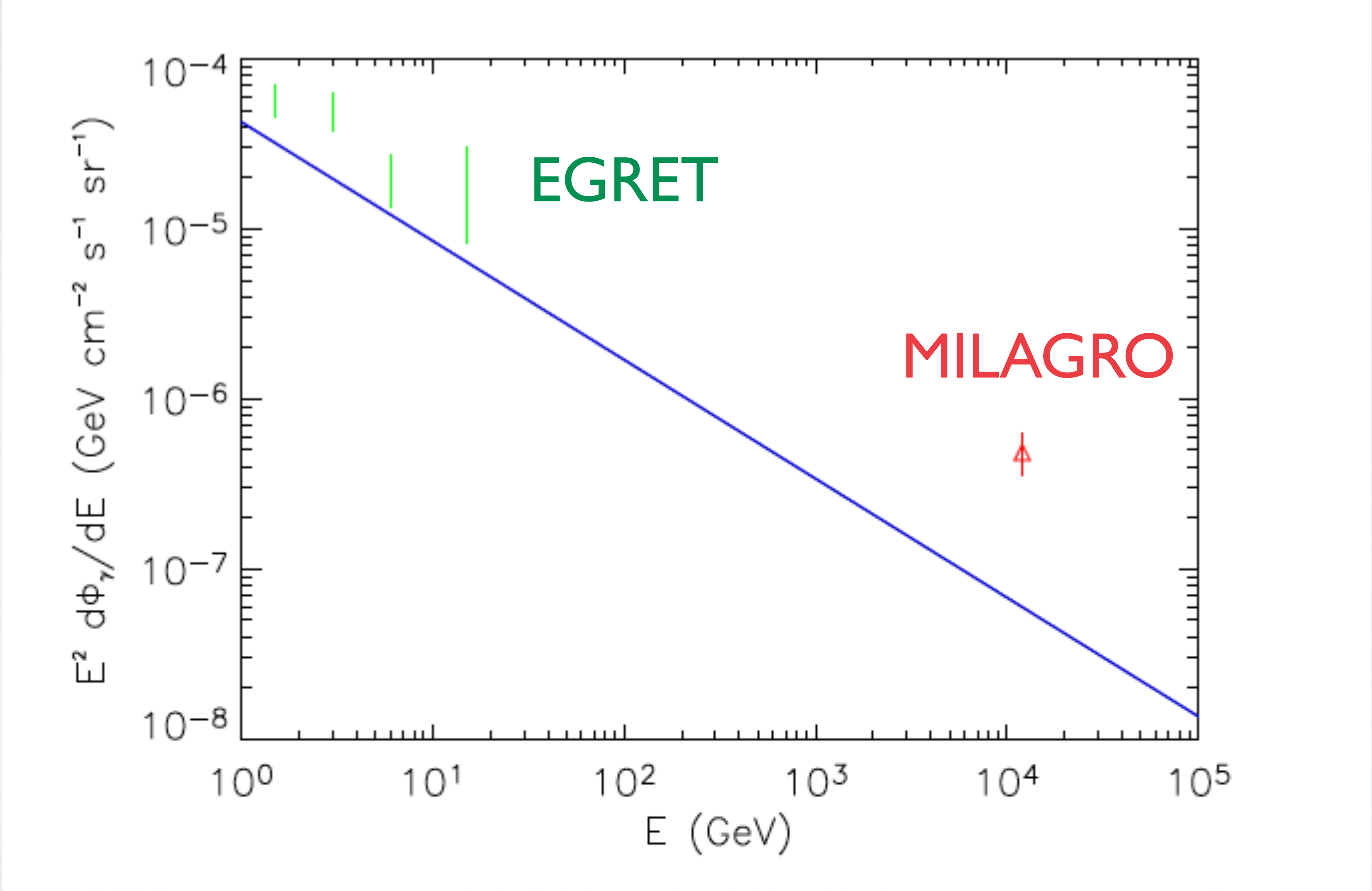


The possible relevance of Milagro excess for neutrinos

Evoli, DG, Maccione
astro-ph/0701856, JCAP

We used a pre-DRAGON CR diffusion code to compute the diffuse emission from the inner Galaxy

We noticed that an extra-contribution is required to match MILAGRO

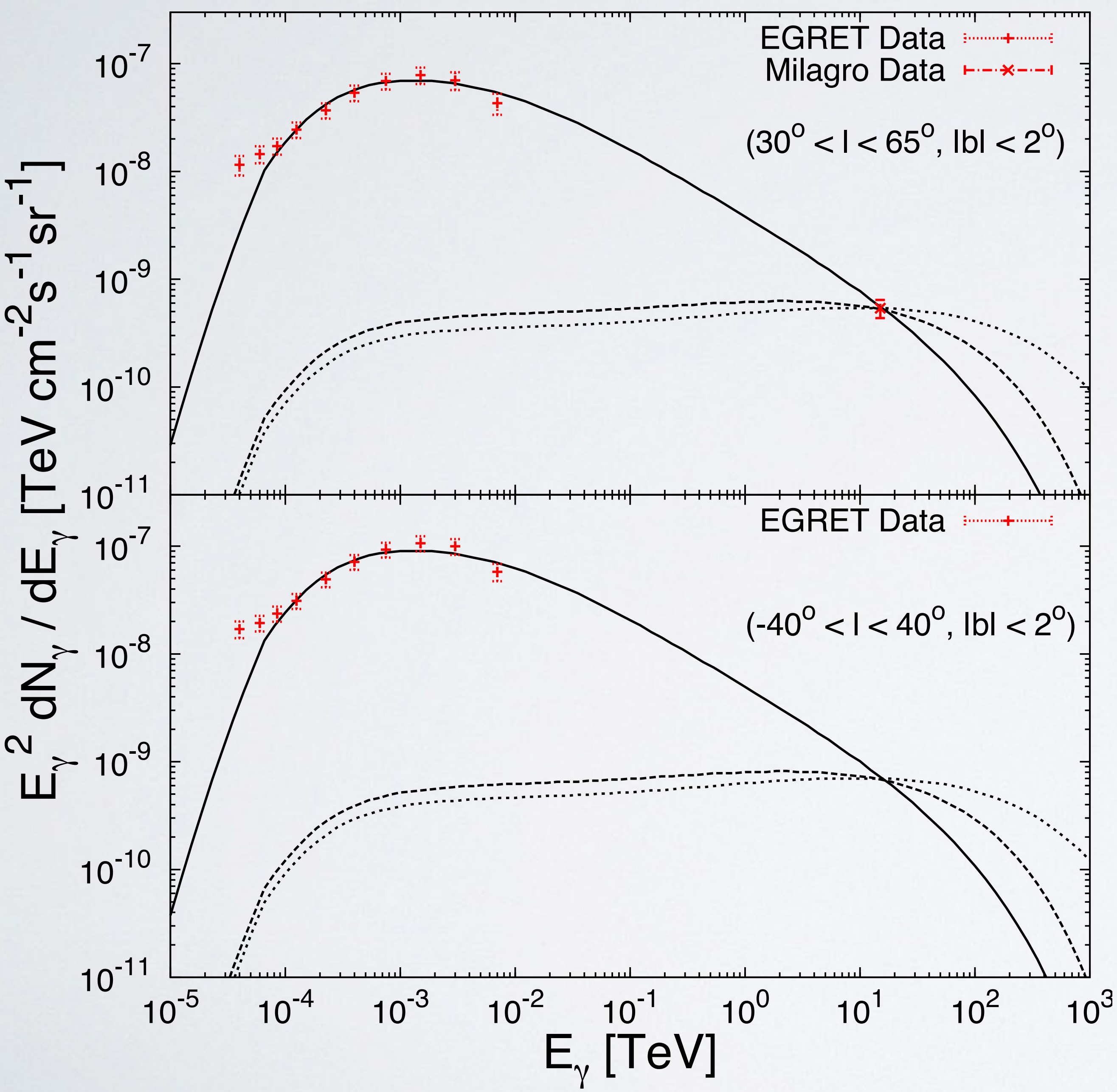


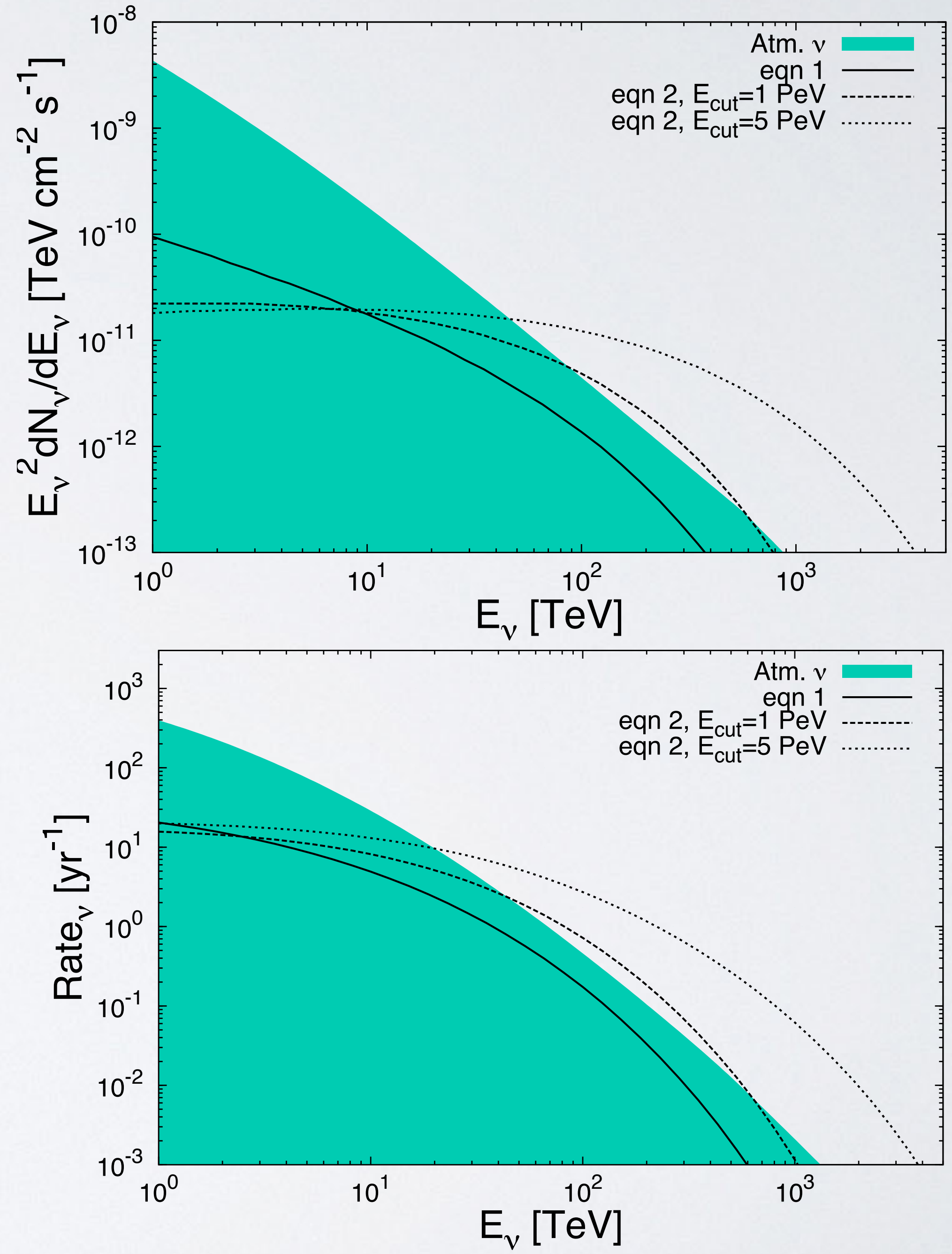
The possible relevance of Milagro excess for neutrinos

harder CR in the inner Galaxy

- spectral break
- harder component

Gabici et al. arXiV:0806.2459



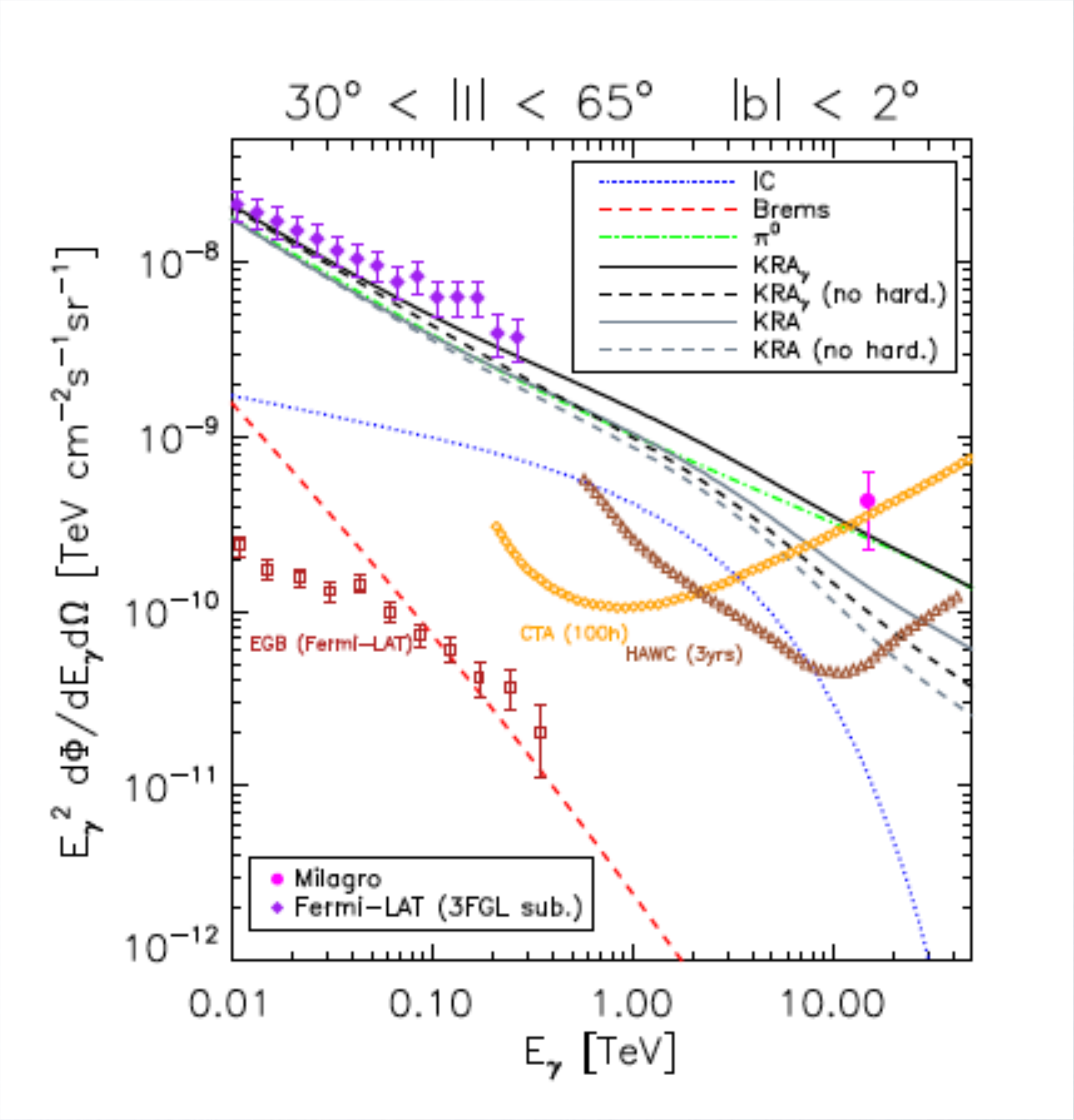


The KRAγ model against the Milagro anomaly at 15 TeV

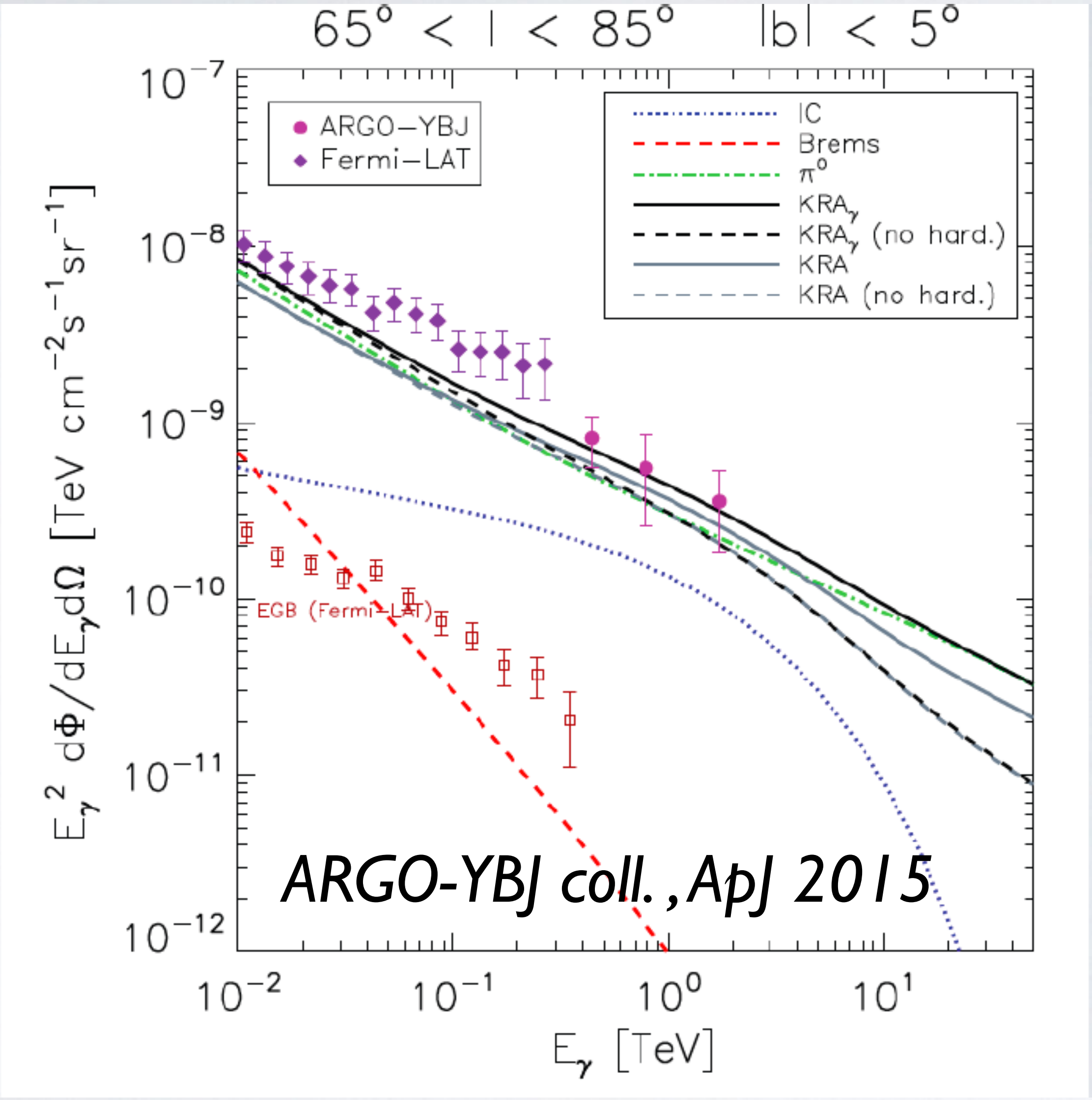
Gaggero, DG, Marinelli, Urbano &Valli arXiV: 1504:00227 ApJ L 2015

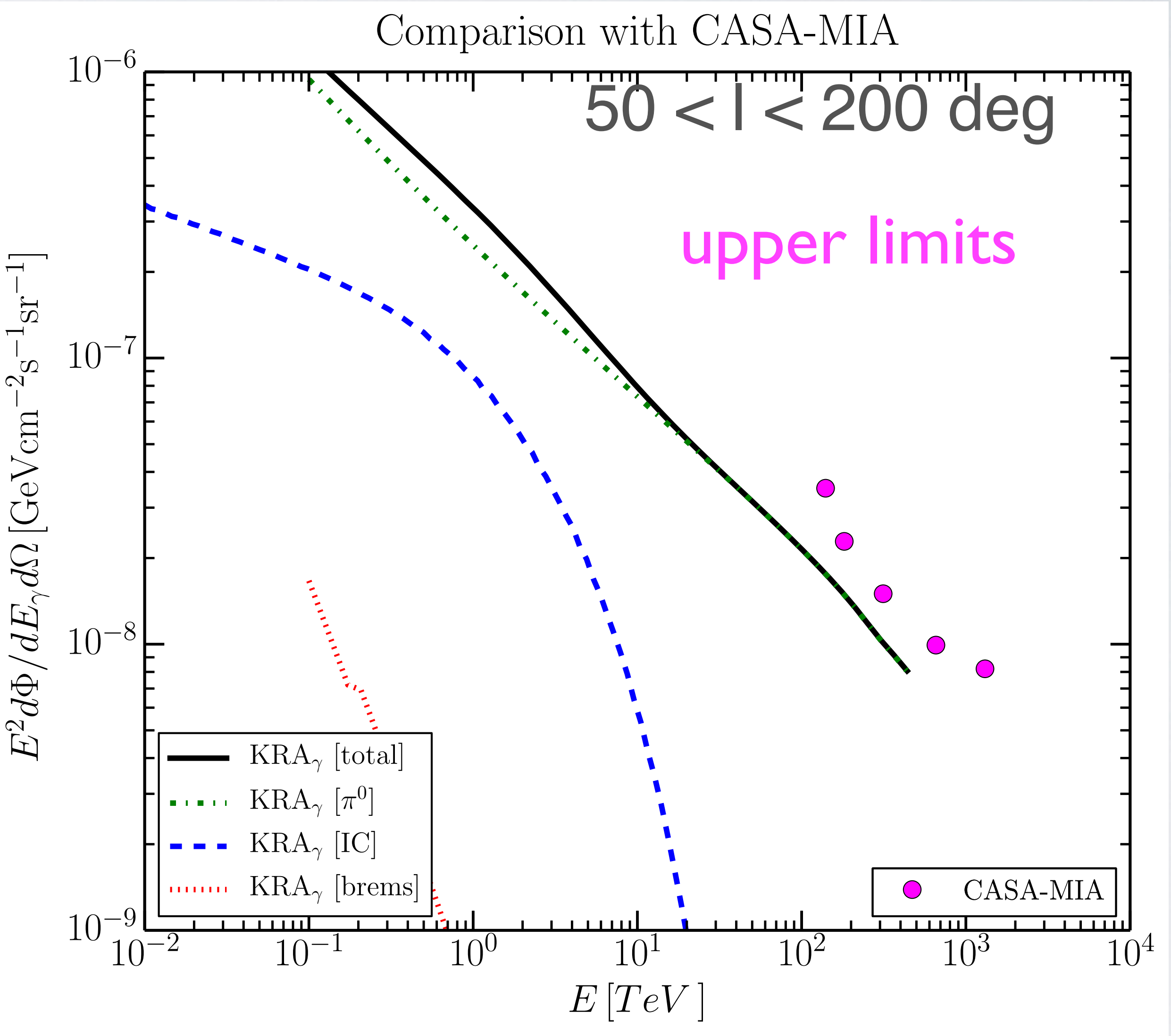
The KRAγ model nicely matches MILAGRO consistently with Fermi data (point sources cleaned) no tuning is required !

The CR hardening at ~ 250 GeV/n is also required (beside inhomogeneous diffusion). This result suggests that hardening is not a local feature but it must be related to unconventional diffusion !

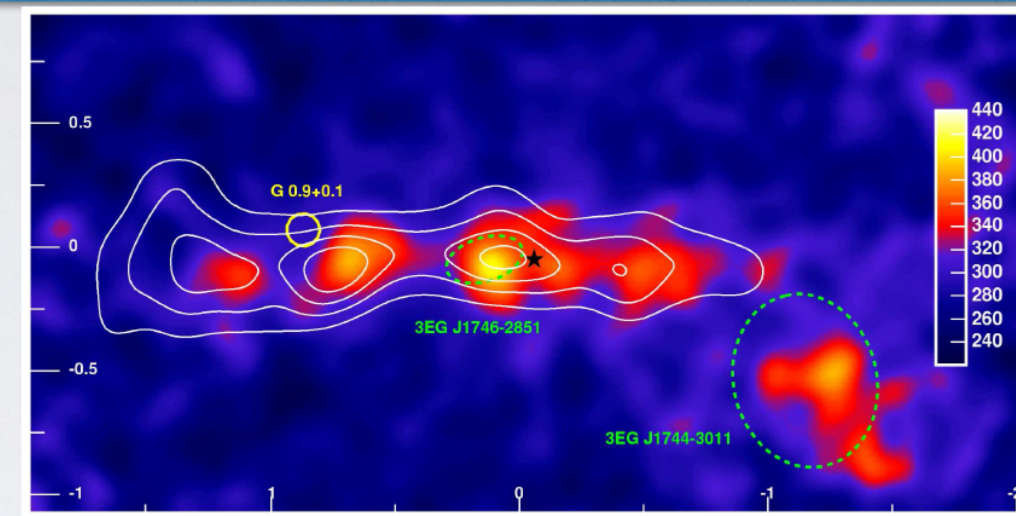


Comparison with other high energy γ-ray data





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, correlated with the molecular complex in the inner 200 pc of Galaxy

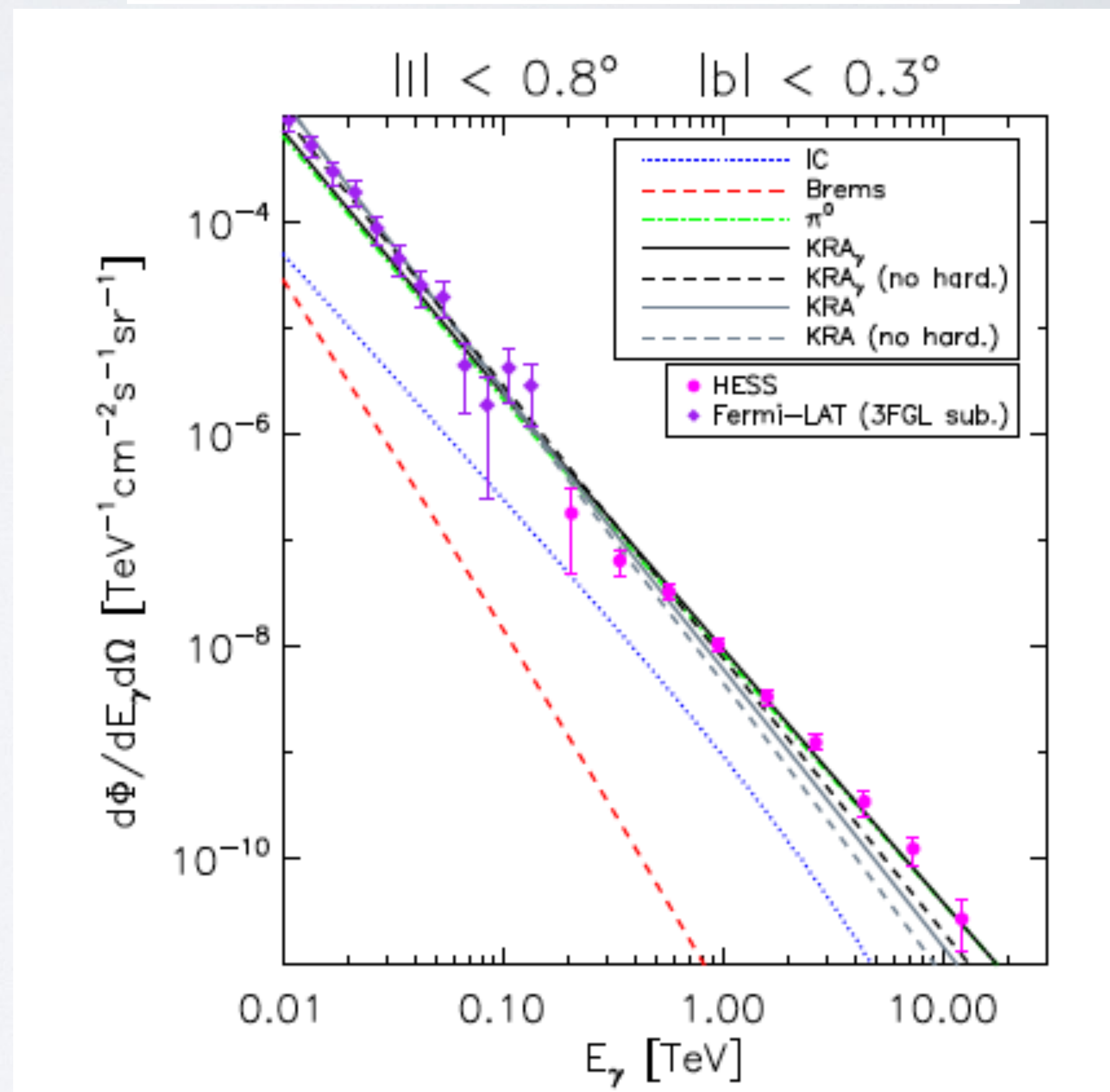
this is also the case for the updated Fermi benchmark conventional model

FERMI + HESS

KRAγ: $\chi2$ = 1.79 /2.27 with/w.o. hard.

KRA: $\chi2$ = 2.92 /3.99 with/w.o. hard.

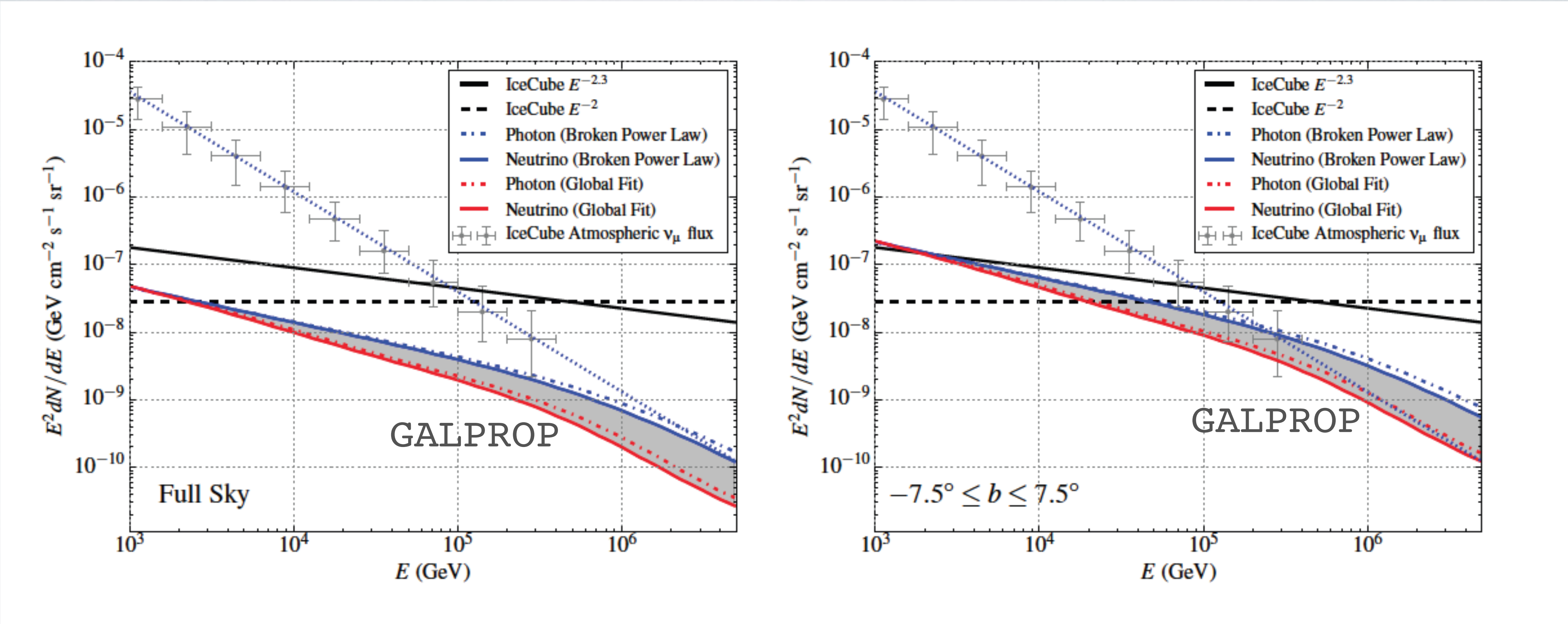
the spectrum normalization is correctly reproduced using an improved gas model in the G.C. region (*Ferriere et al. 2007*)



Our predictions for the neutrino emission

The Galactic diffuse neutrino emission recent computations for conventional models

Ahlers et al. arXiV:1505.03156



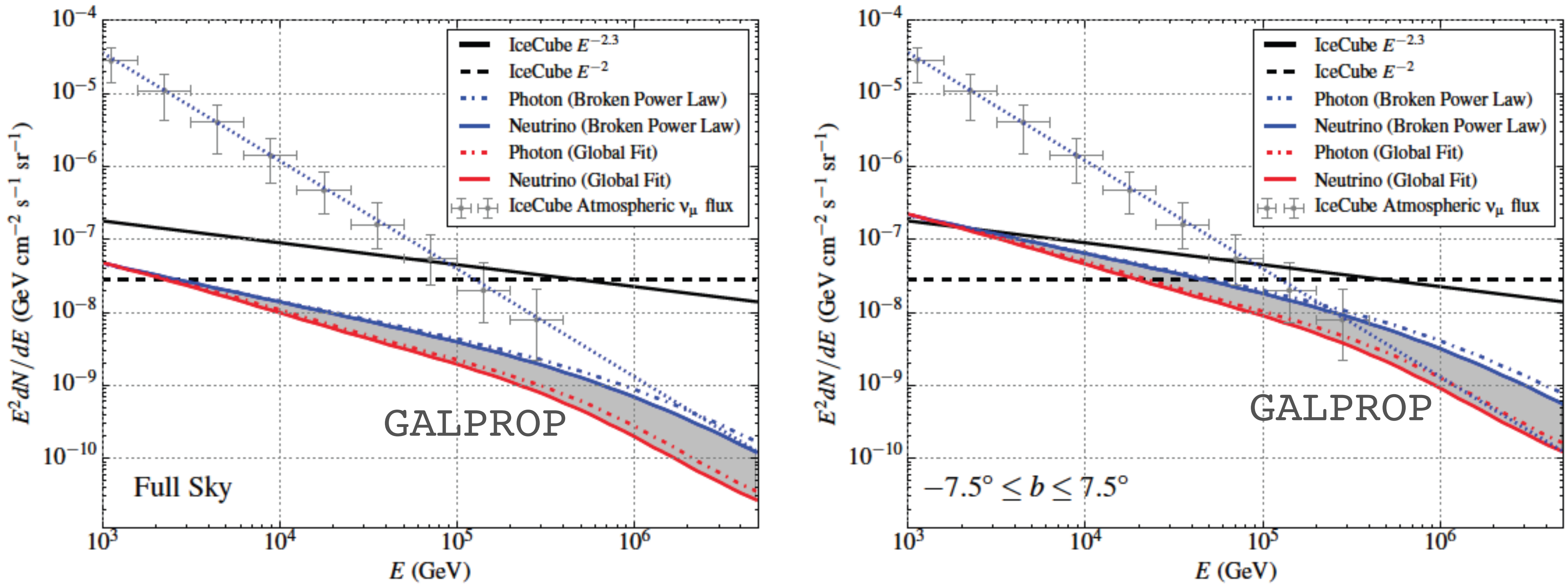
8% of IceCube HESE (2013) signal at most

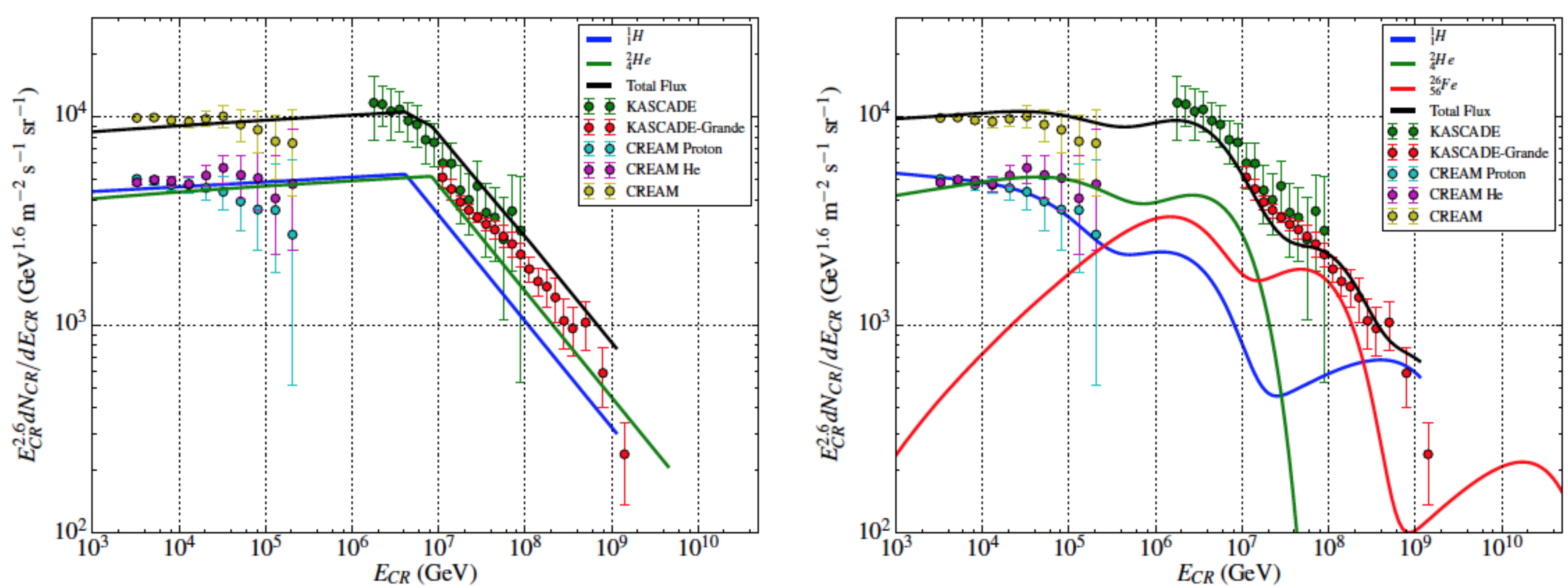
Main novelties:

- based on GALPROP (updated gas model, match Fermi results. *See however below !*)
- updated cross-sections
- it **adopts harder CR spectra above 250 GeV/n so to match CREAM**
- it adopts phenomenological models for CR spectra in the knee region

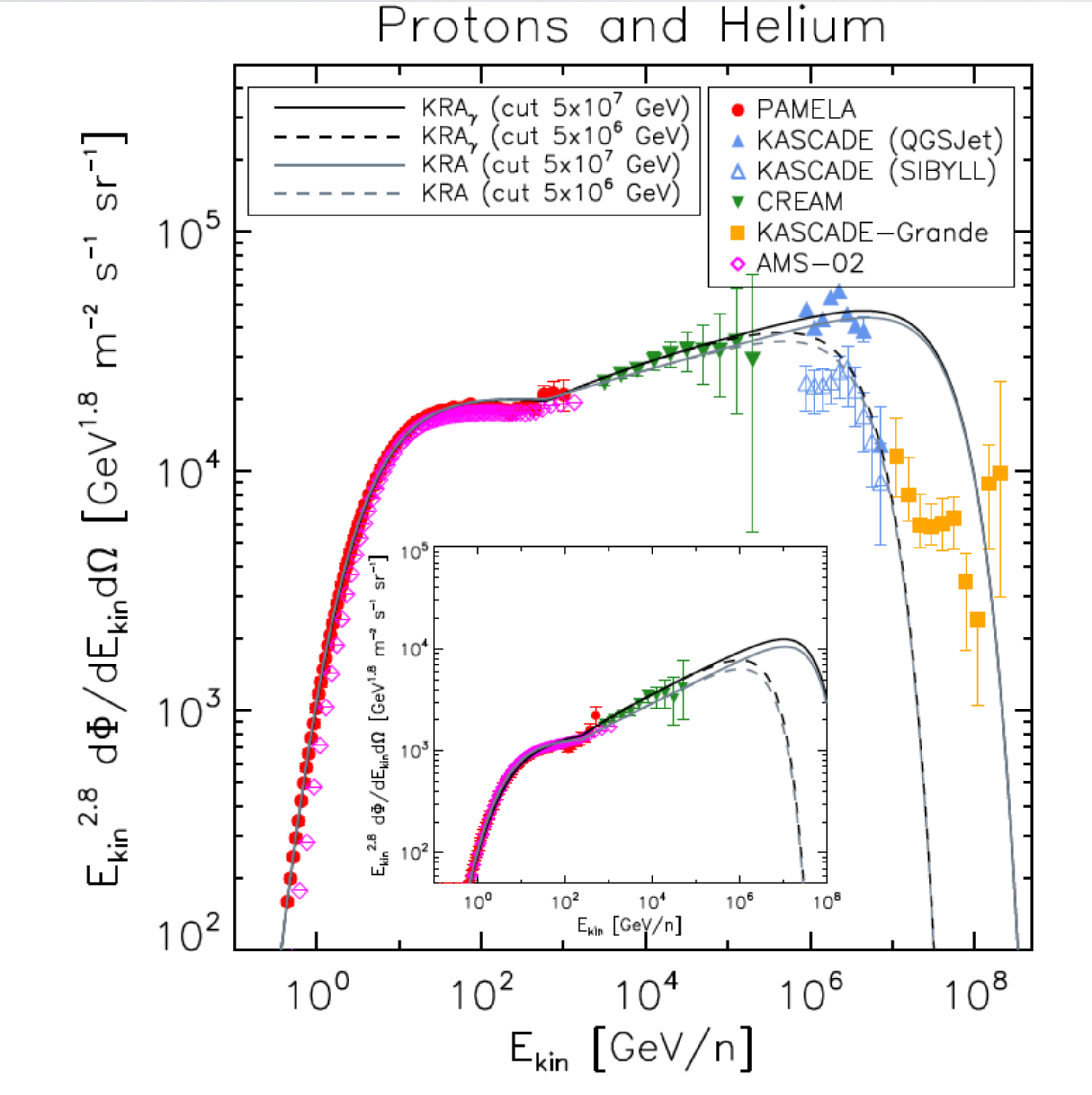
The Galactic diffuse neutrino emission
a recent computation

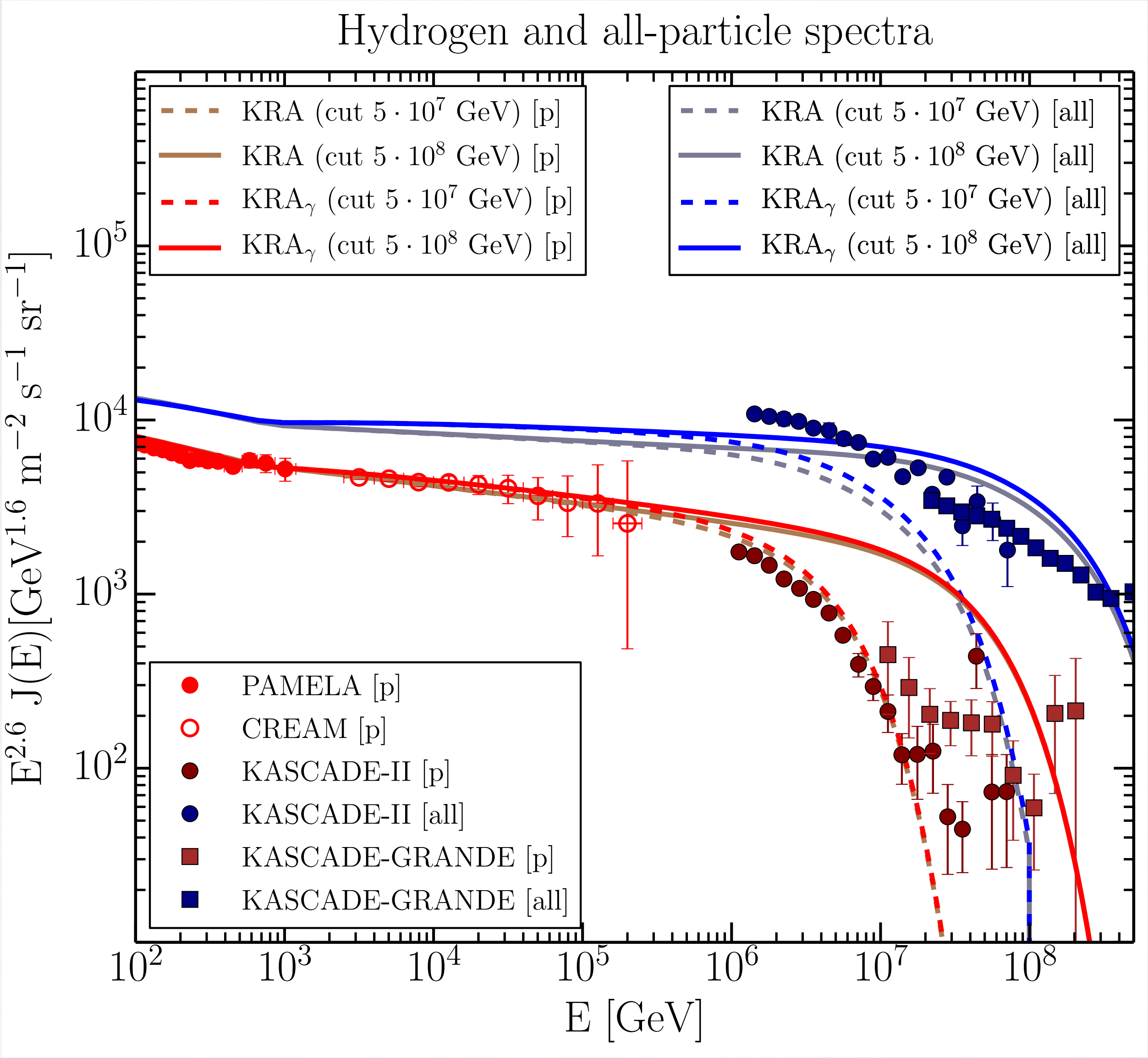
Ahlers et al. arXiV:1505.03156



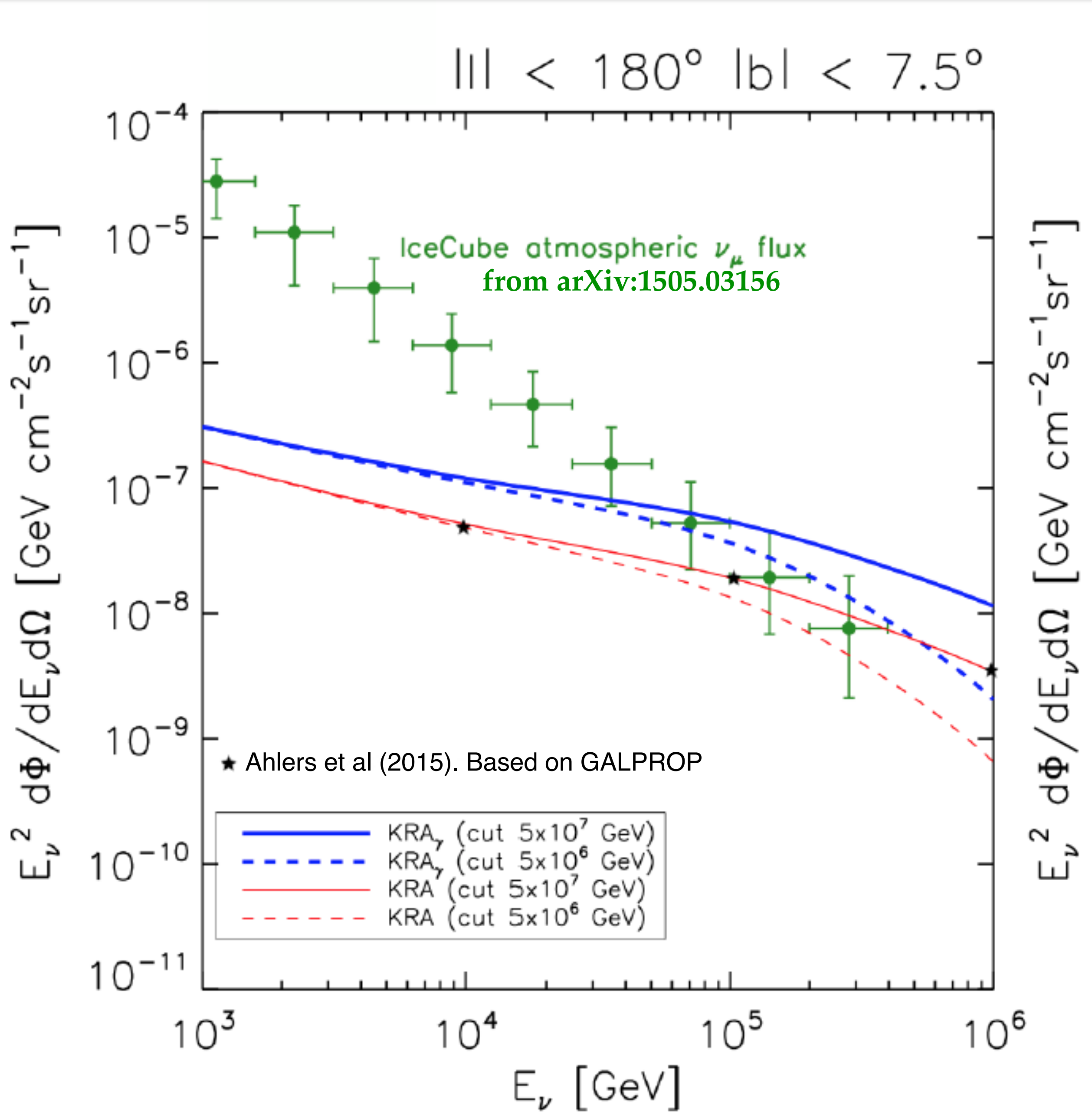


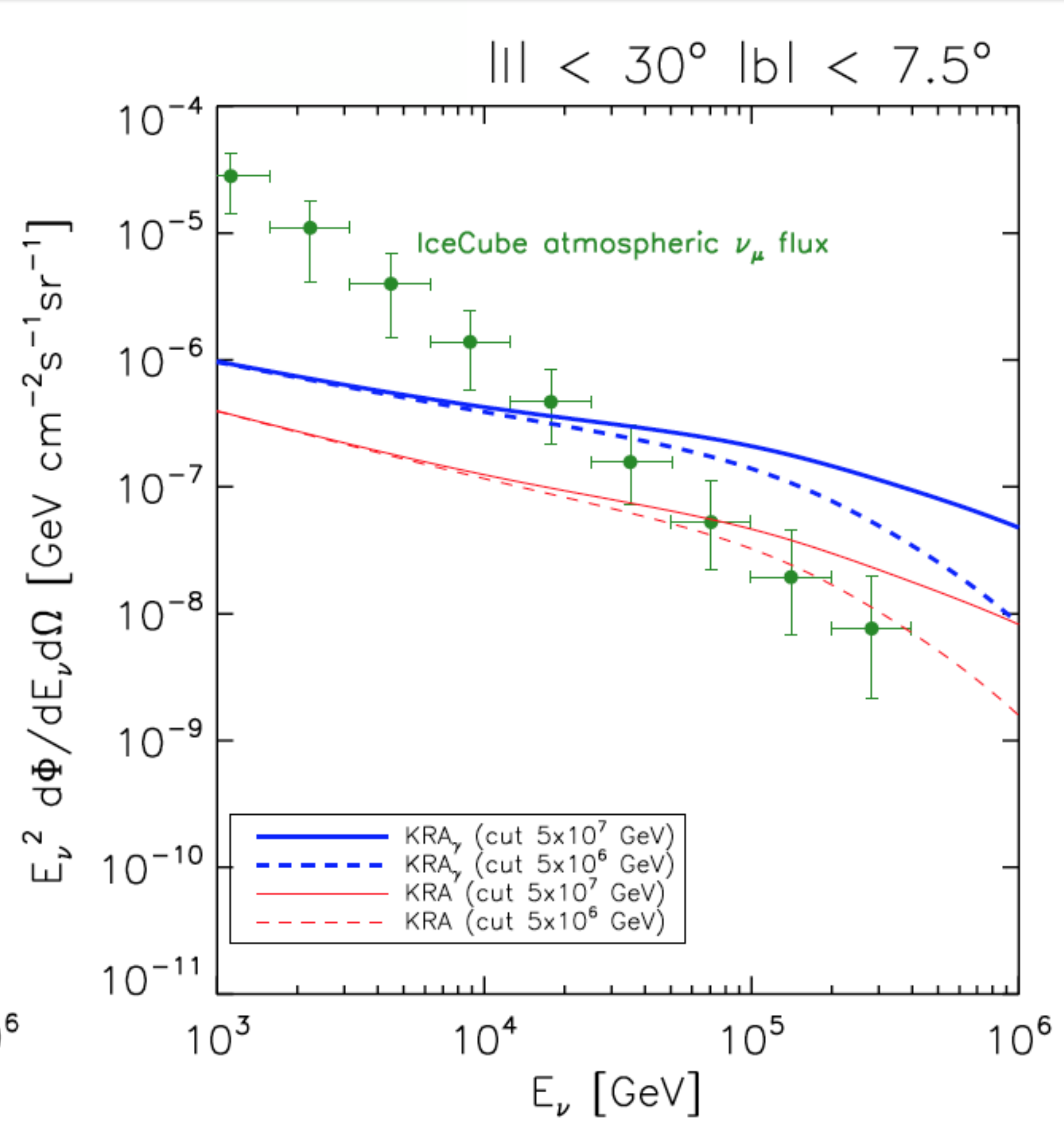
Our CR primary spectra





Galactic Plane neutrino with KRA (δ uniform) & KRAγ (δ variable)

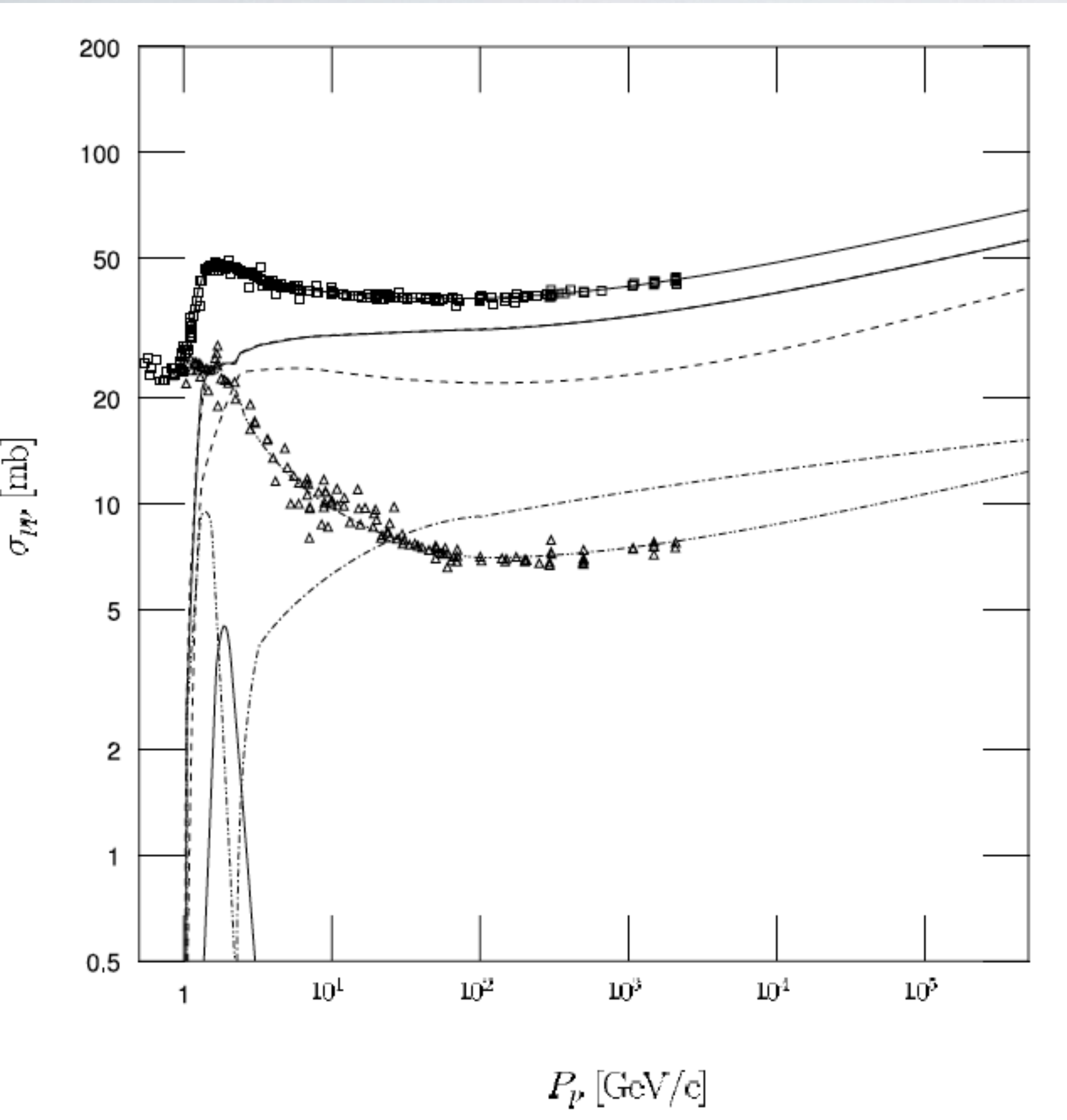




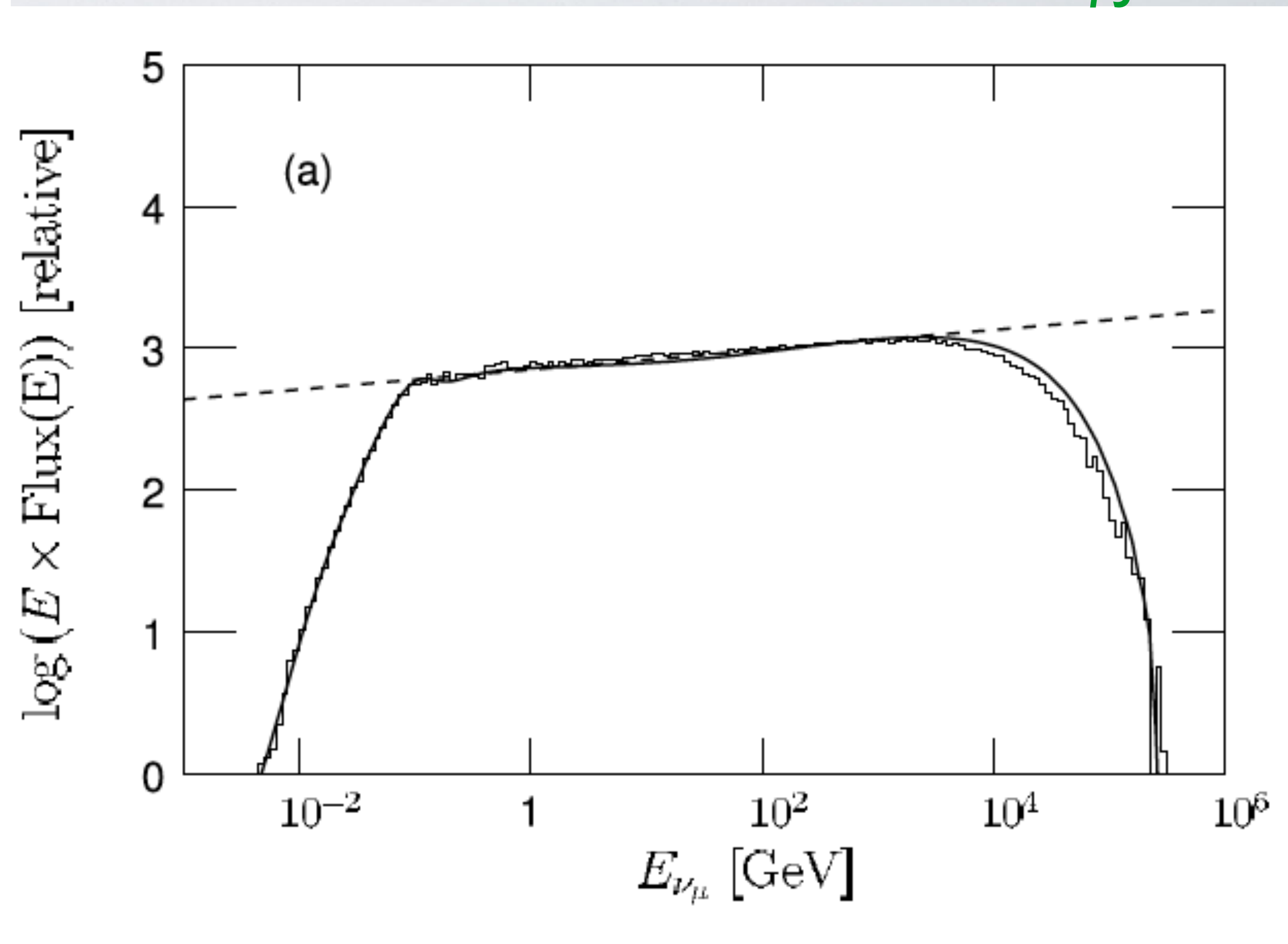
Comparison between neutrino spectrum produced with standard KRA model and the new KRAγ model from the entire galactic plane. The black stars show the equivalence between standard KRA (based on DRAGON code) and standard GALPROP obtained spectra.

The diffuse neutrino spectrum obtained considering the <u>KRAγ model for the inner galactic plane can exceed the atmospheric neutrino flux measured by IceCube above 20 TeV</u>

Computing the neutrino emission from CR scattering



T. Kamae et al. ApJ 2006



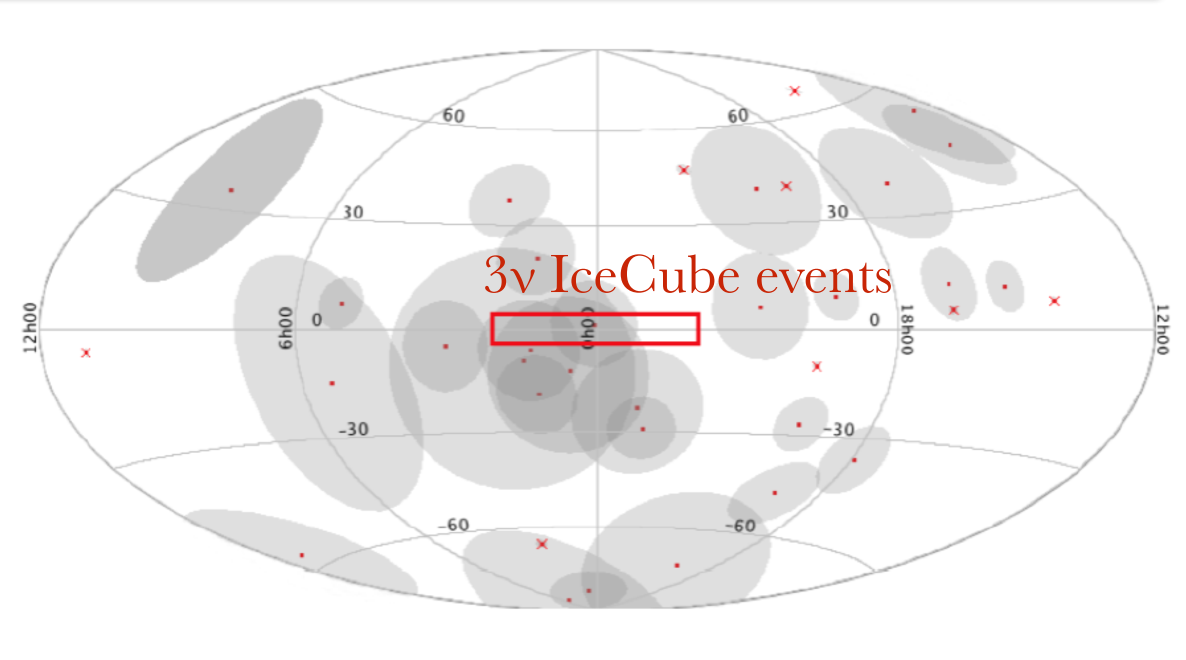
also *Kelner, Aharonian & Bugayov, 2006*

Main processes: $p + p(He) \to \pi + \mathrm{hadrons} \to \nu_{\mu,\ e} + \ldots$

ANTARES constraints in the inner GP

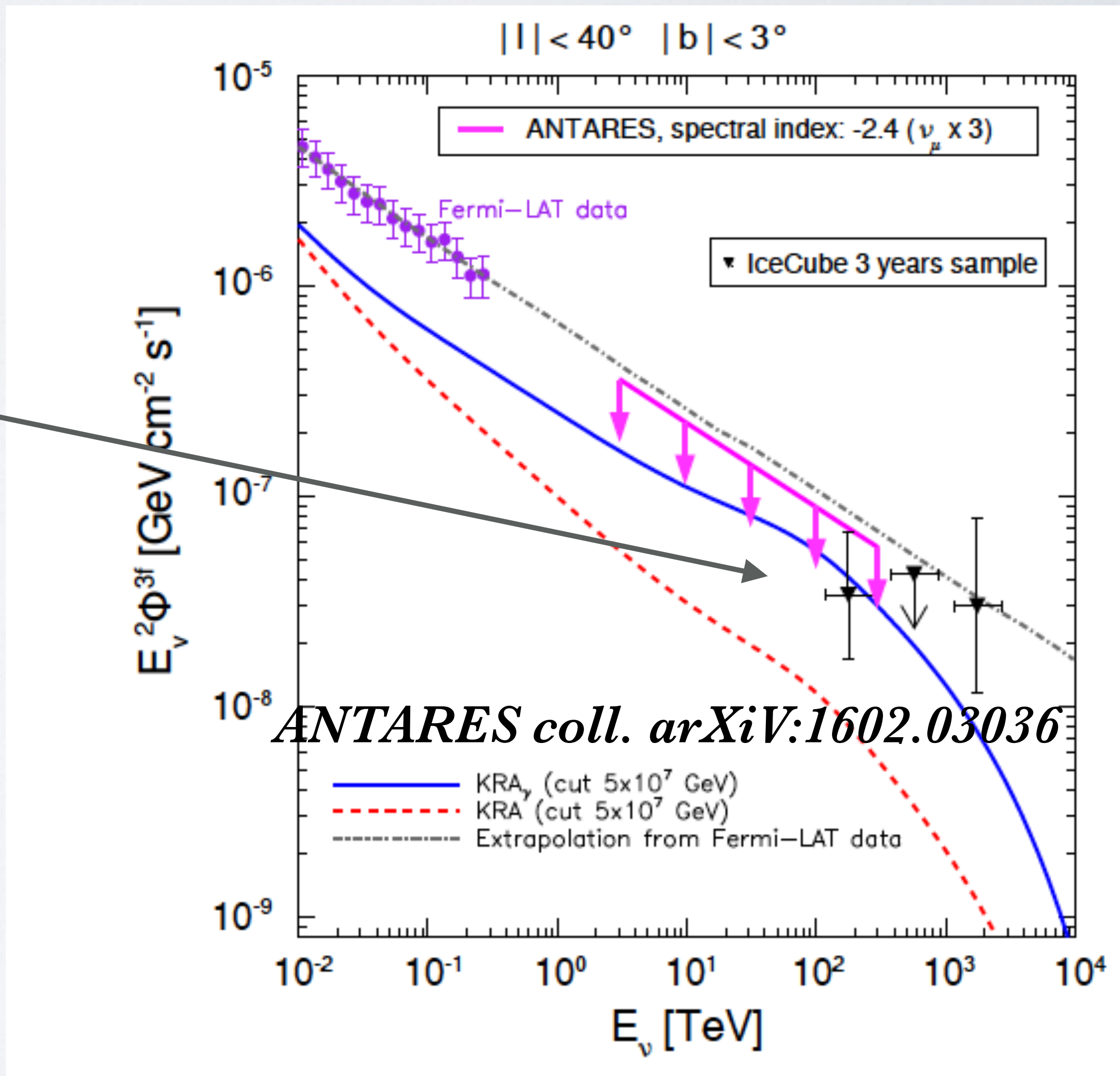
ANTARES coll. arXiV:1602.03036
Marinelli et al. ICRC 2015

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. $\Gamma = 2.5$ 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$_\gamma$ models we can estimate the galactic component of the IceCube observation in this region of the sky.

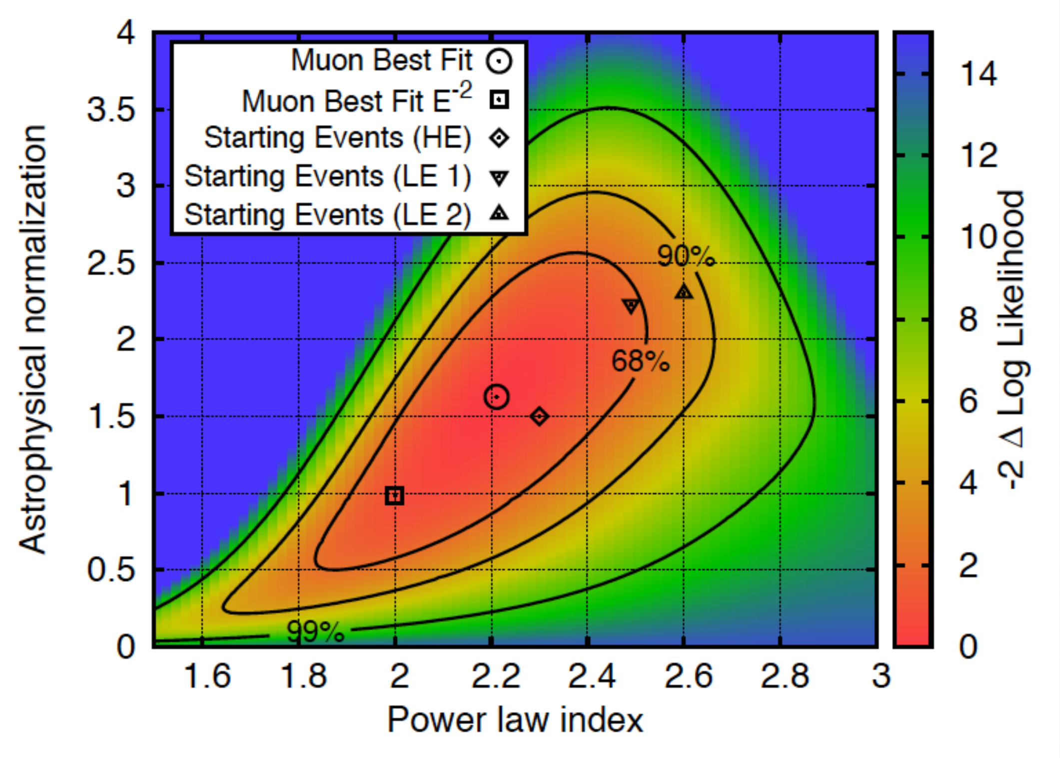


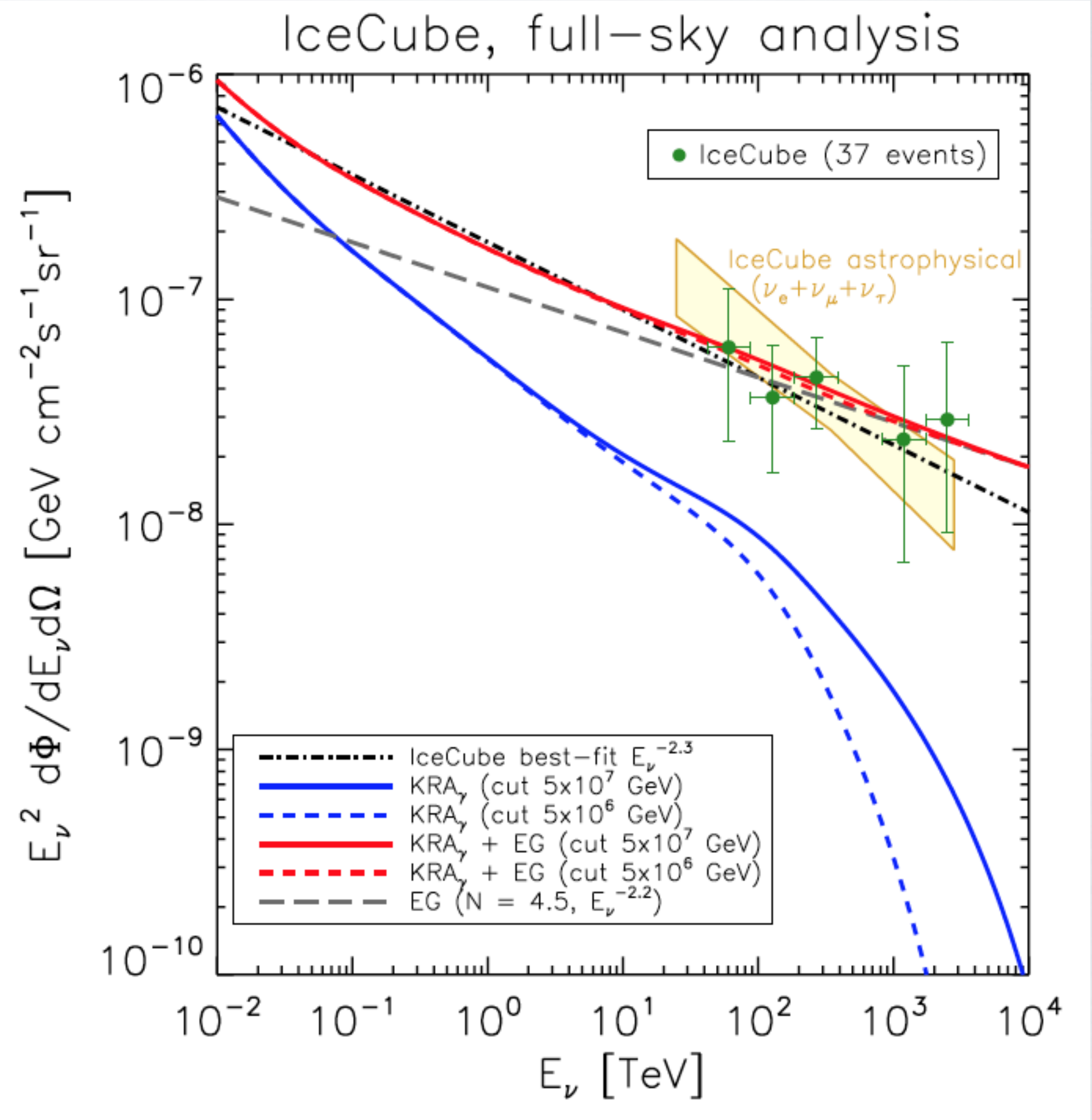
KRAγ full-sky ν emission against IceCube

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

clearly, a dominant extra-Galactic contribution is required.

We assume the $\boldsymbol{\nu}_\mu$ flux measured by IceCube from the northern hemisphere is representative of such emission (Gal. emission negligible)





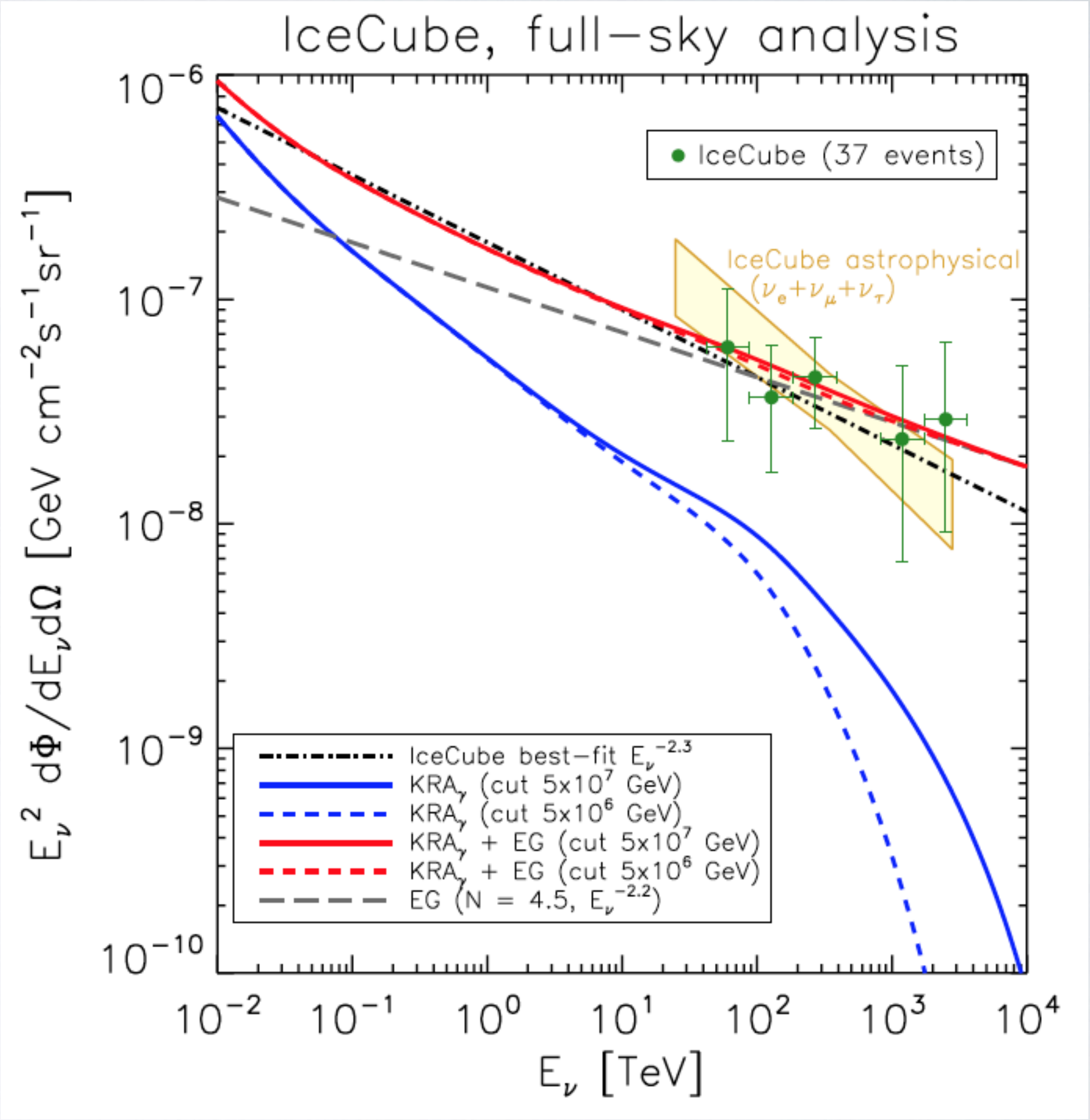
We use here the best-fit spectrum (grey dashed line)

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.)

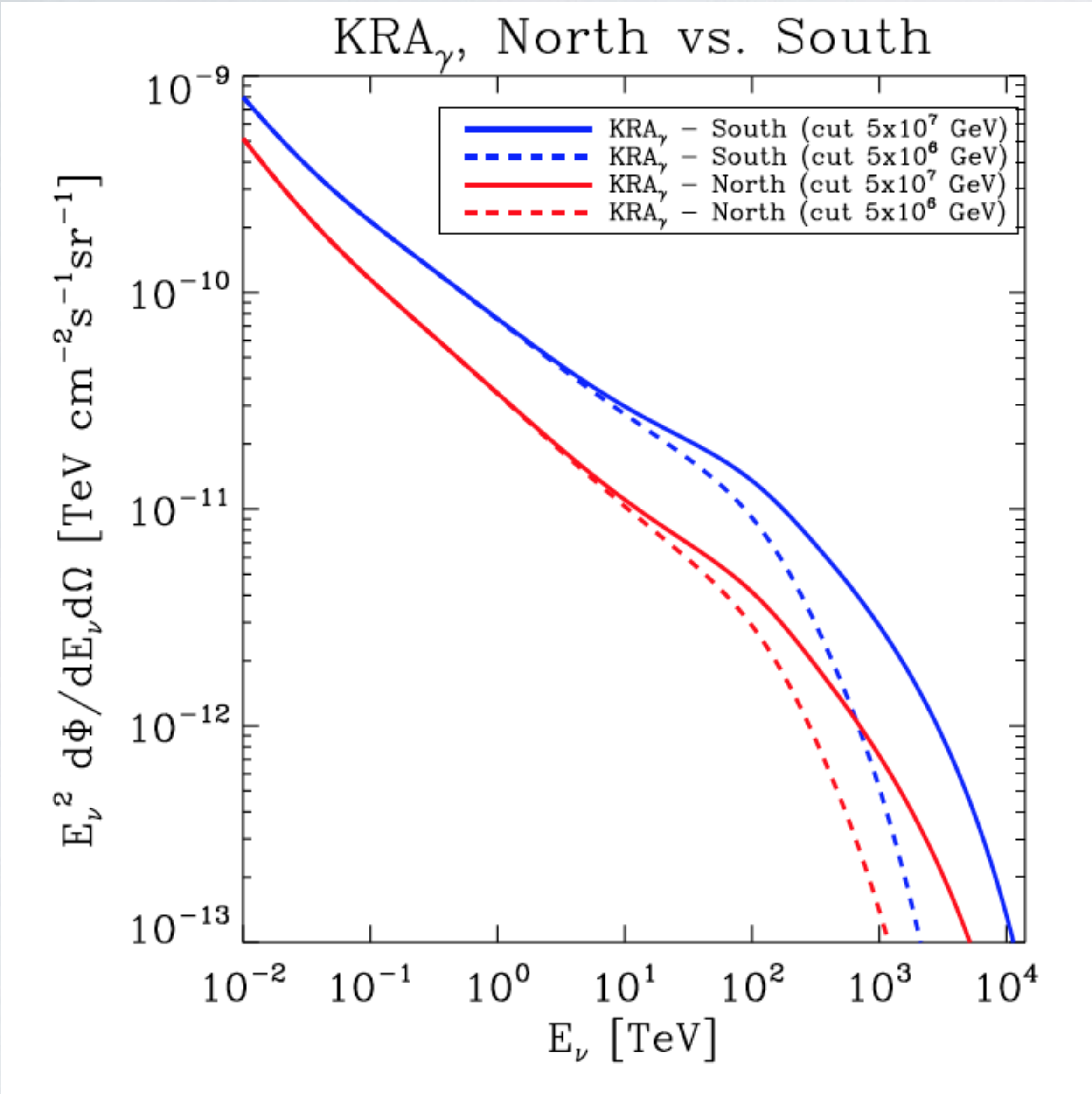


this is clearly compatible with the IC events angular distribution

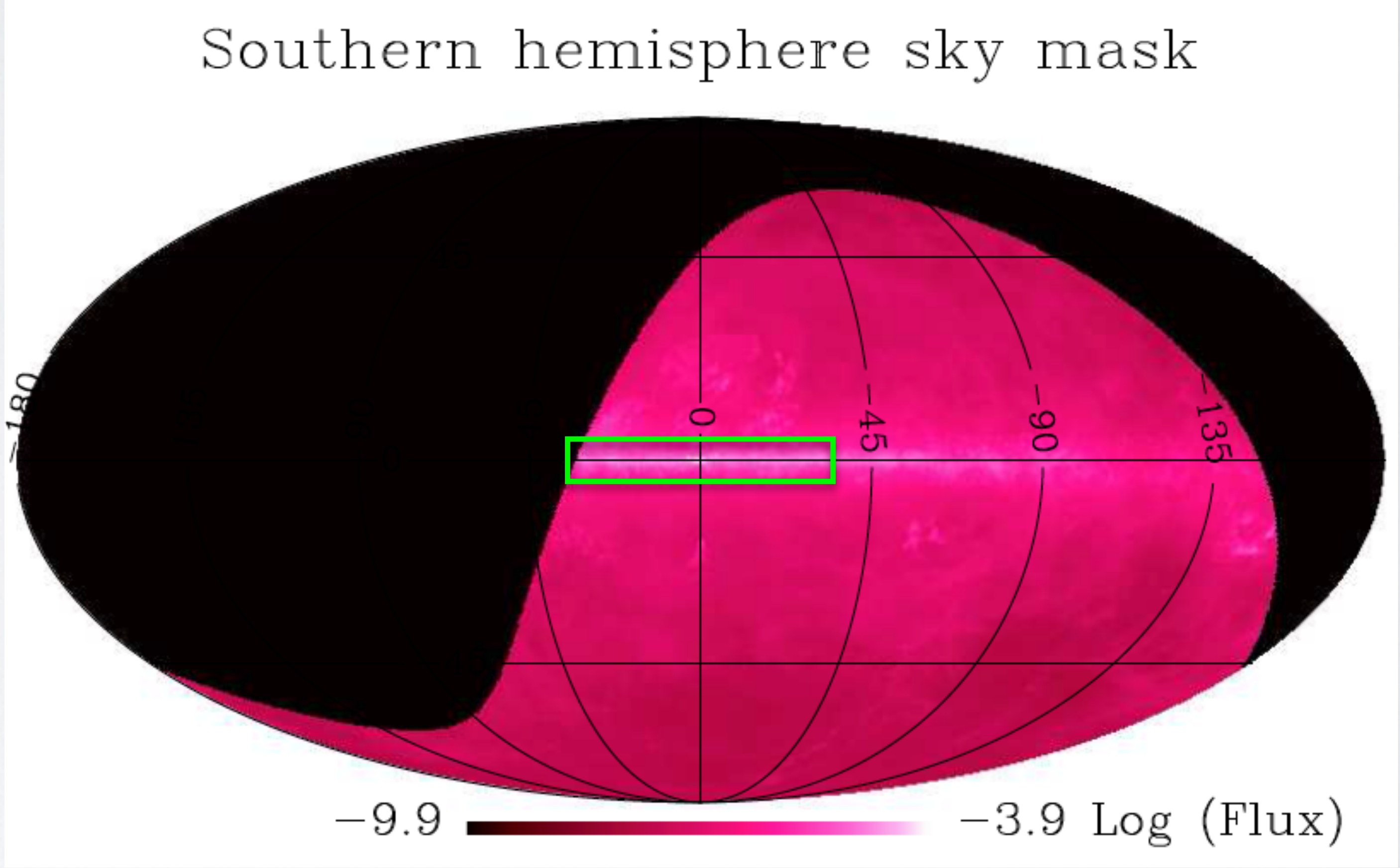
clearly, a dominant extra-Galactic contribution is required

see also ***Palladino & Vissani 2016*** who claim a 30 % Galactic contribution ! This may at odd with ANTARES

The expected KRAγ neutrinos from north/south hemisphere



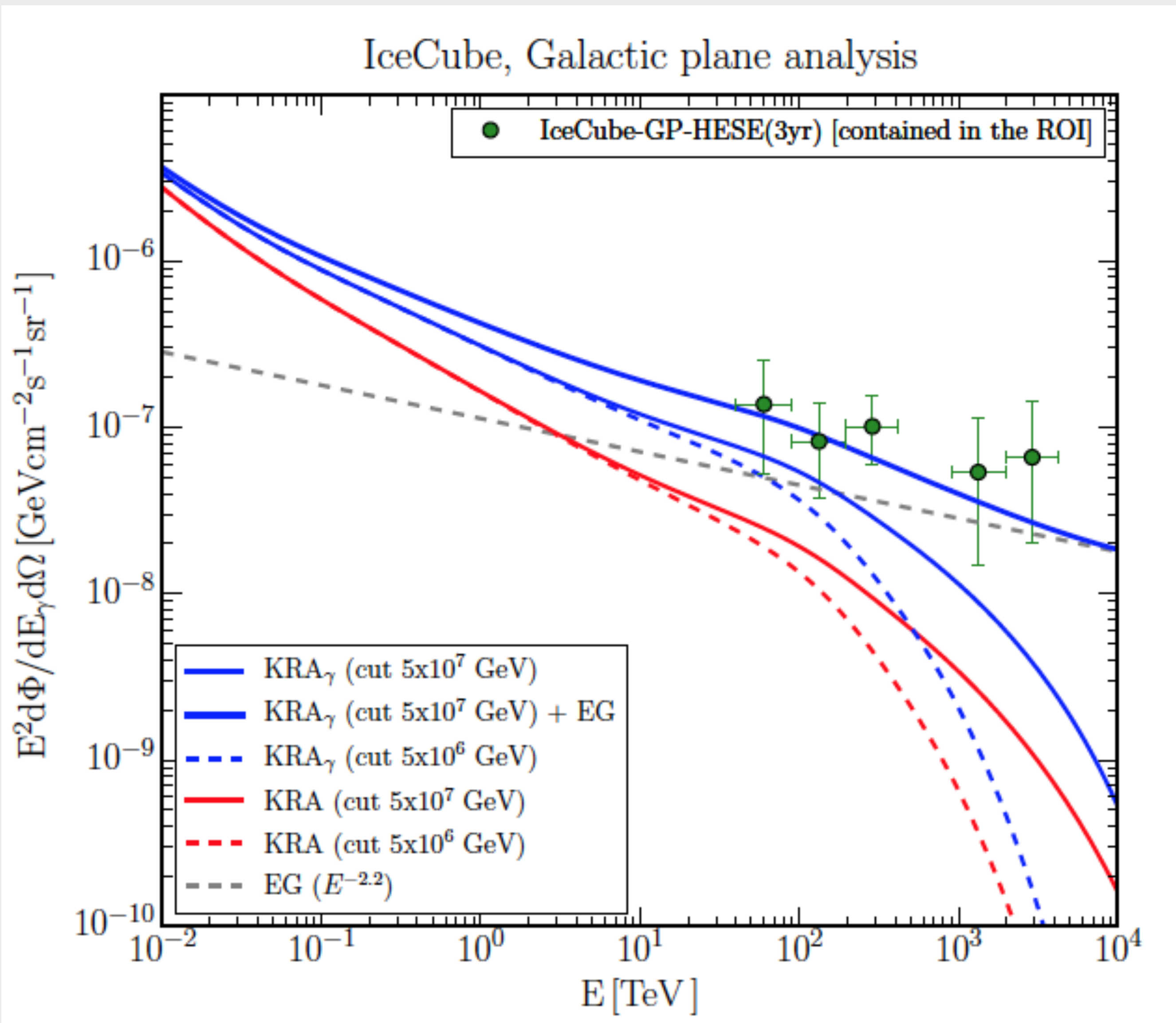
The Southern hemisphere expected neutrinos, obtained with KRAγ scenario, are more than double the expected from the Northern one.

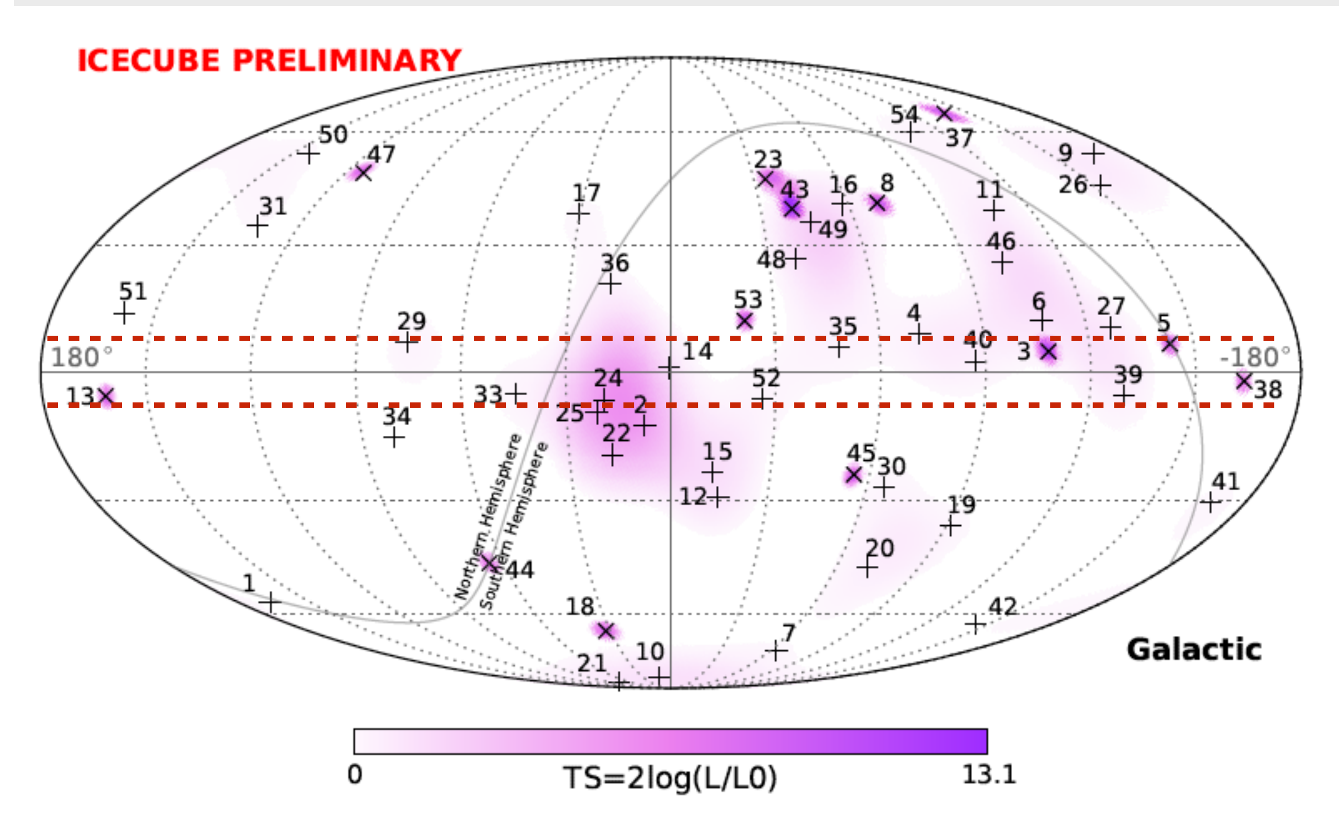


The inner galactic plane neutrino diffuse emission mostly comes from the Southern hemisphere.

G+EG emission in the GP constrained by IceCube

Gaggero, DG, Marinelli, Urbano, Valli VLVNT2015





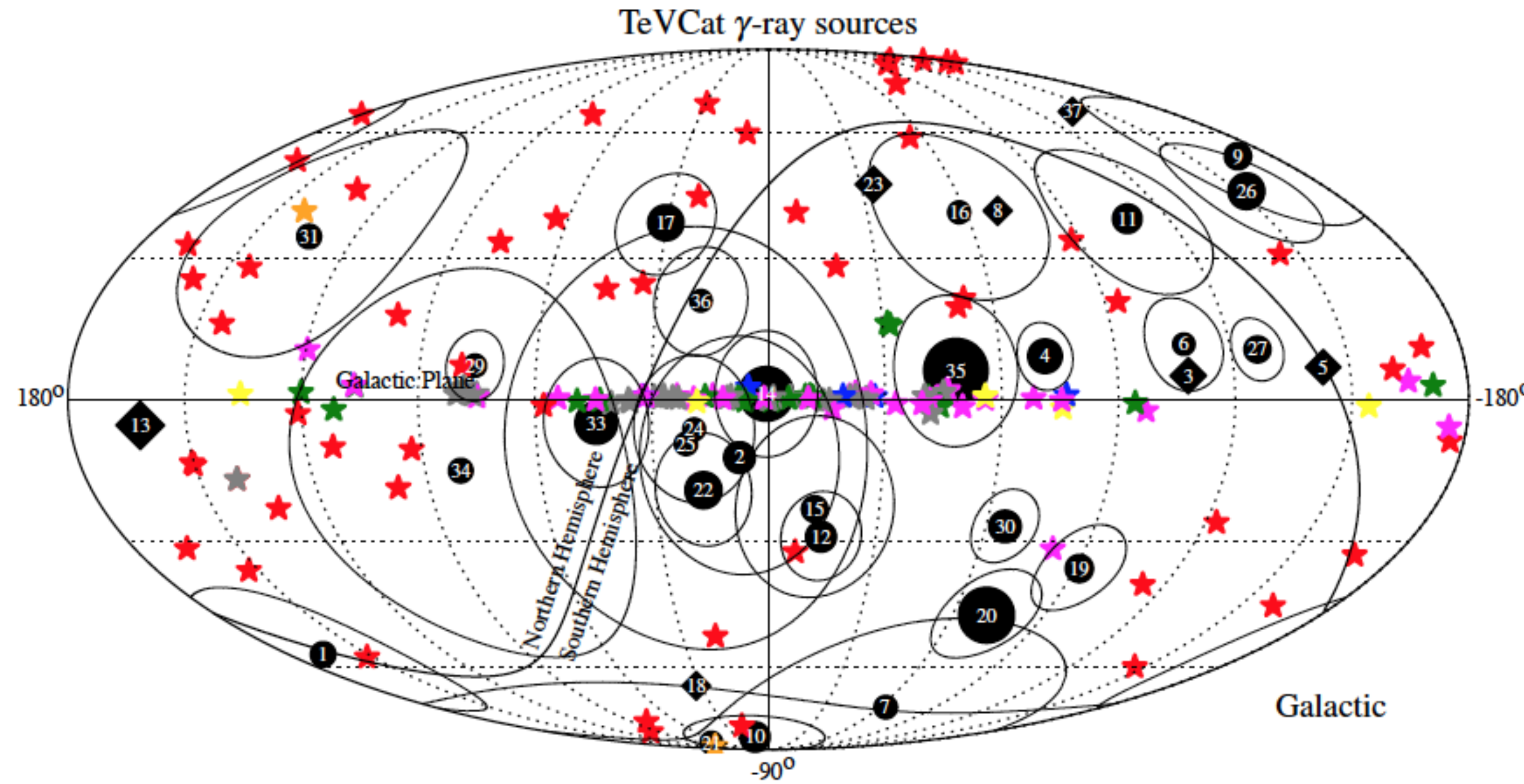
For the whole galactic plane with |b| < 7.5 half of astrophysical flux can be explained with KRA$_\gamma$ and the other half with EG best fit analysis. The IceCube spectrum is obtained considering the **contained events** for this region.

What about extra-galactic neutrinos ?

Which sources are responsible of EG emission?

HBL, IBL, LBL, FRI-II, FSRQ,
Star Burst Galaxies

Spatial association seems to be difficult at the moment, <u>we need more muonic neutrino events!!</u>



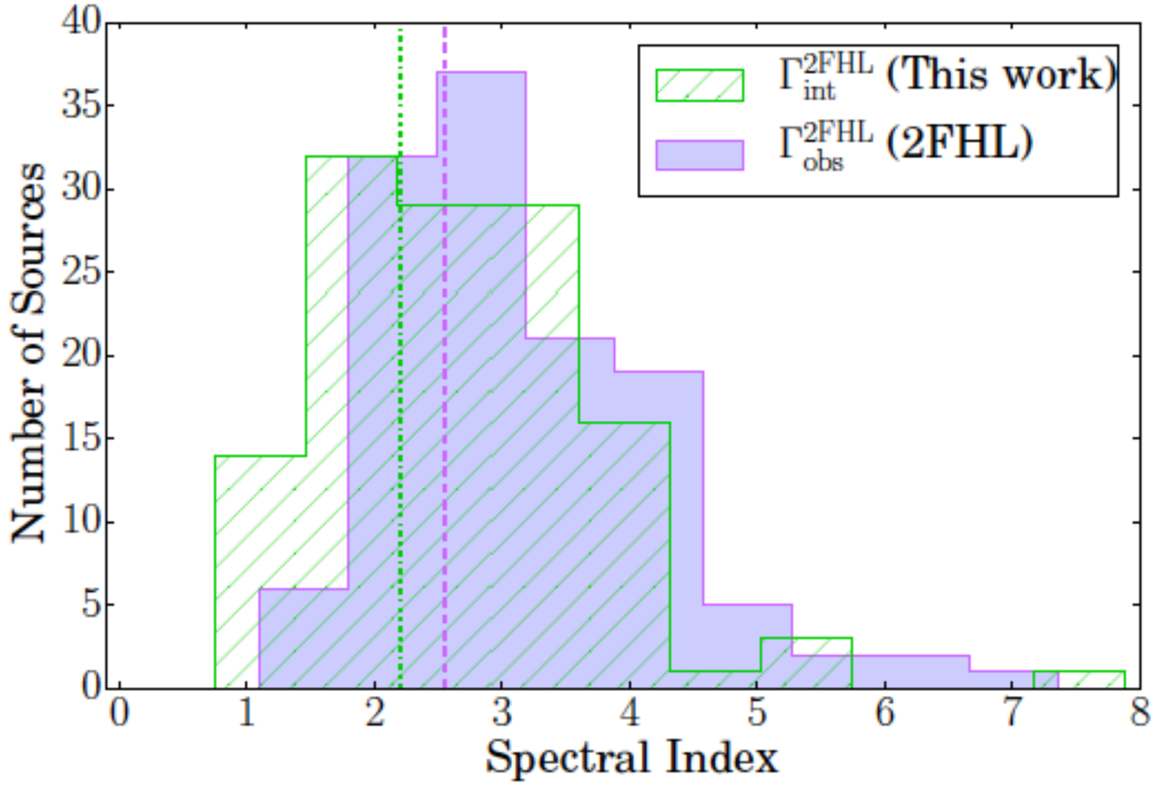
IceCube HESE 3 years

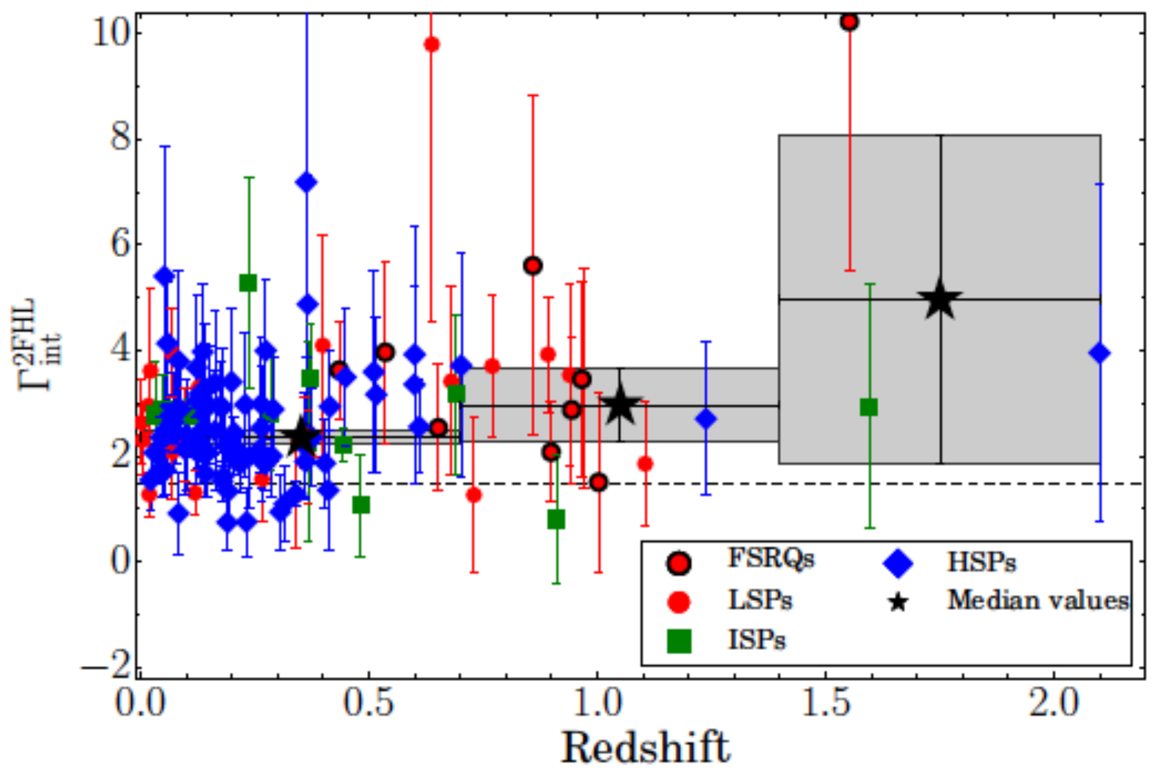
Proposed Source Candidates II

- Extragalactic:
- Association with sources of UHE CRs [Kistler, Stanev & Yuksel'13] [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
- Association with diffuse gamma-ray background [Murase, MA & Lacki'13] [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
- Active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13] [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14] [Padovani & Resconi'14; Petropoulou, Dimitrakoudis, Padovani, Mastichiadis & Resconi'15]
- Gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
- Galaxies with intense star-formation [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13] [Murase, MA & Lacki'13; Anchordoqui, Paul, da Silva, Torres& Vlcek'14] [Tamborra, Ando & Murase'14; Chang & Wang'14; Liu, Wang, Inoue, Crocker& Aharonian'14] [Senno, Meszaros, Murase, Baerwald & Rees'15; Chakraborty & Izaguirre'15]
- Galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
- . . .

Γ from BL-Lacs & FSRQ survey and IceCube measured Γ

Dominguéz & Ajello, ArXiv:1510.07913





- A analysis of 128 extragalactic sources (mostly Blazars) from the 2FHL (E>50 GeV) catalog set the average intrinsic (unattenuated from the EBL) spectral index at Γ ~ 2.2 versus the measured average Γ ~ 2.5

- If the gamma-ray are produced through pion decay we can expect a corresponding neutrino spectrum described by the obtained intrinsic Γ ~ 2.2 .

- This spectrum is well compatible with Northern hemisphere analysis of IceCube (Γ ~ 2.2) but not with the full sky IceCube (4 years HESE) analysis (Γ ~ 2.58)

A possible role of starburst Galaxies ?

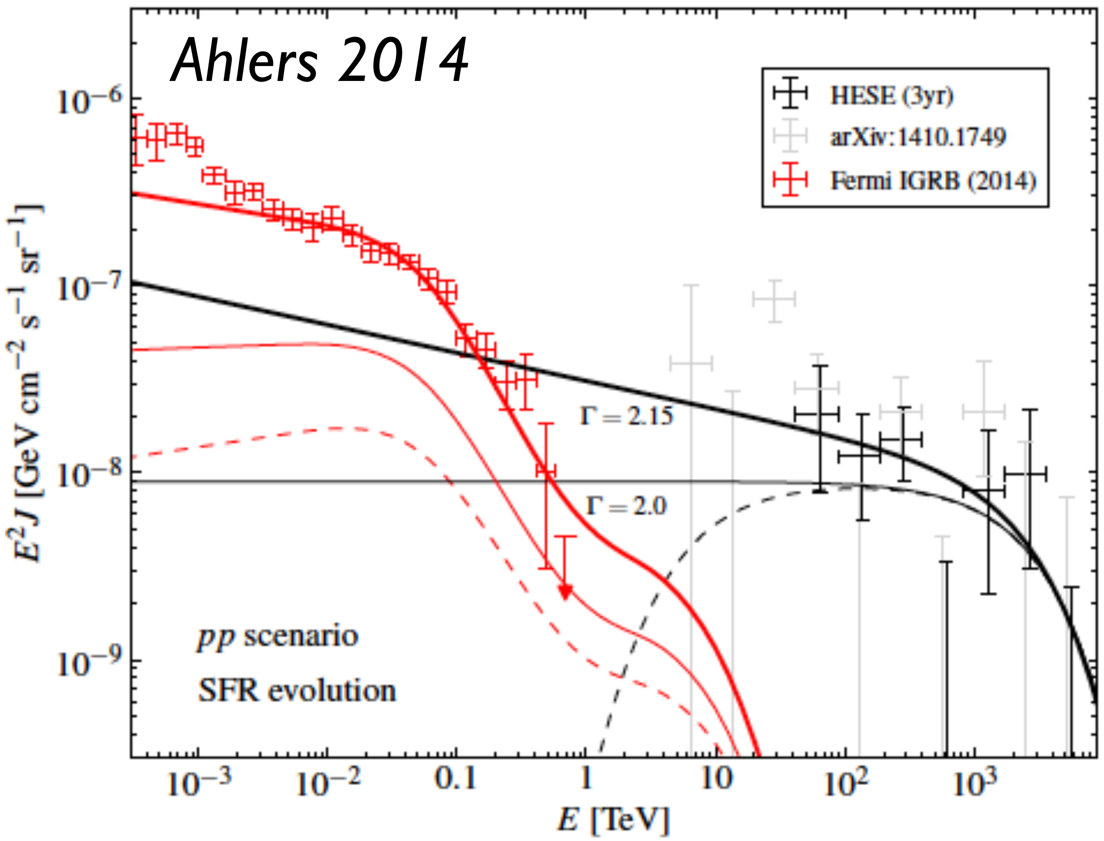
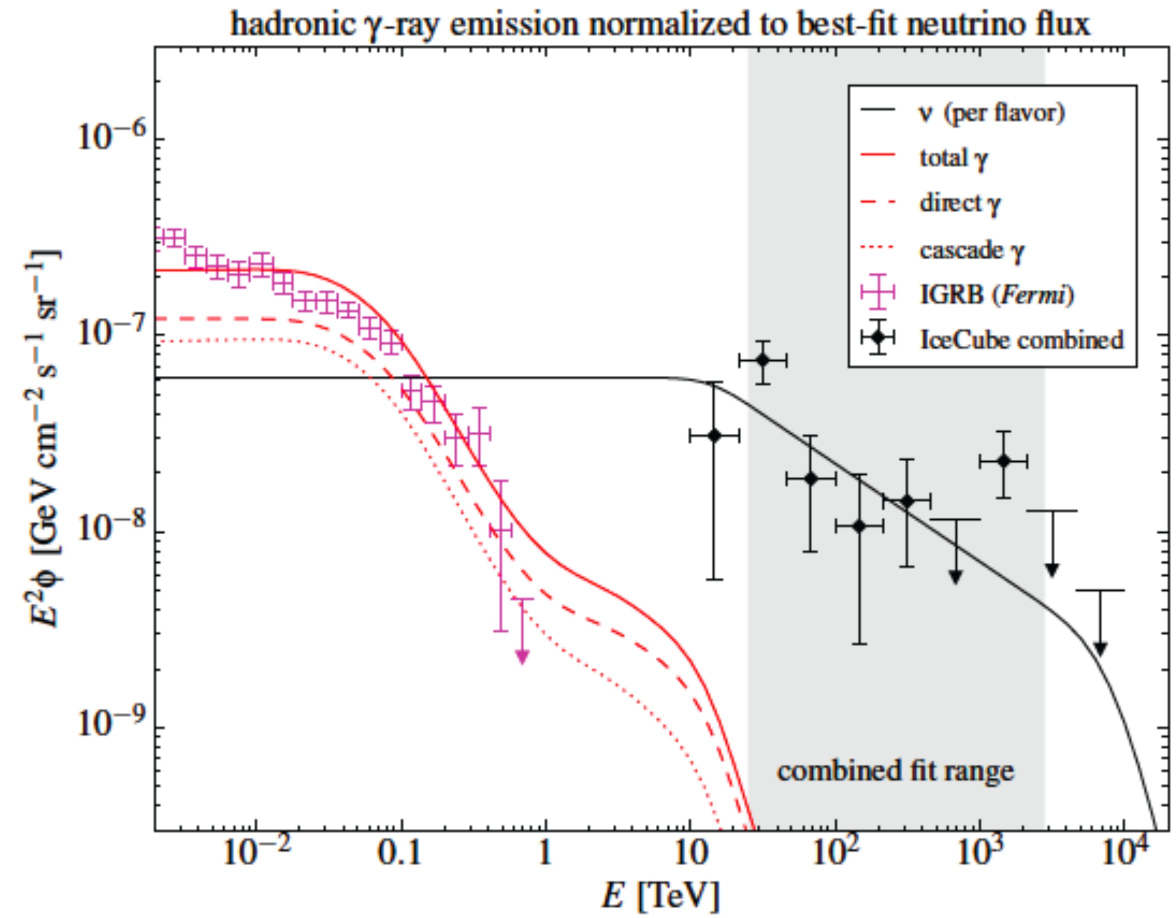


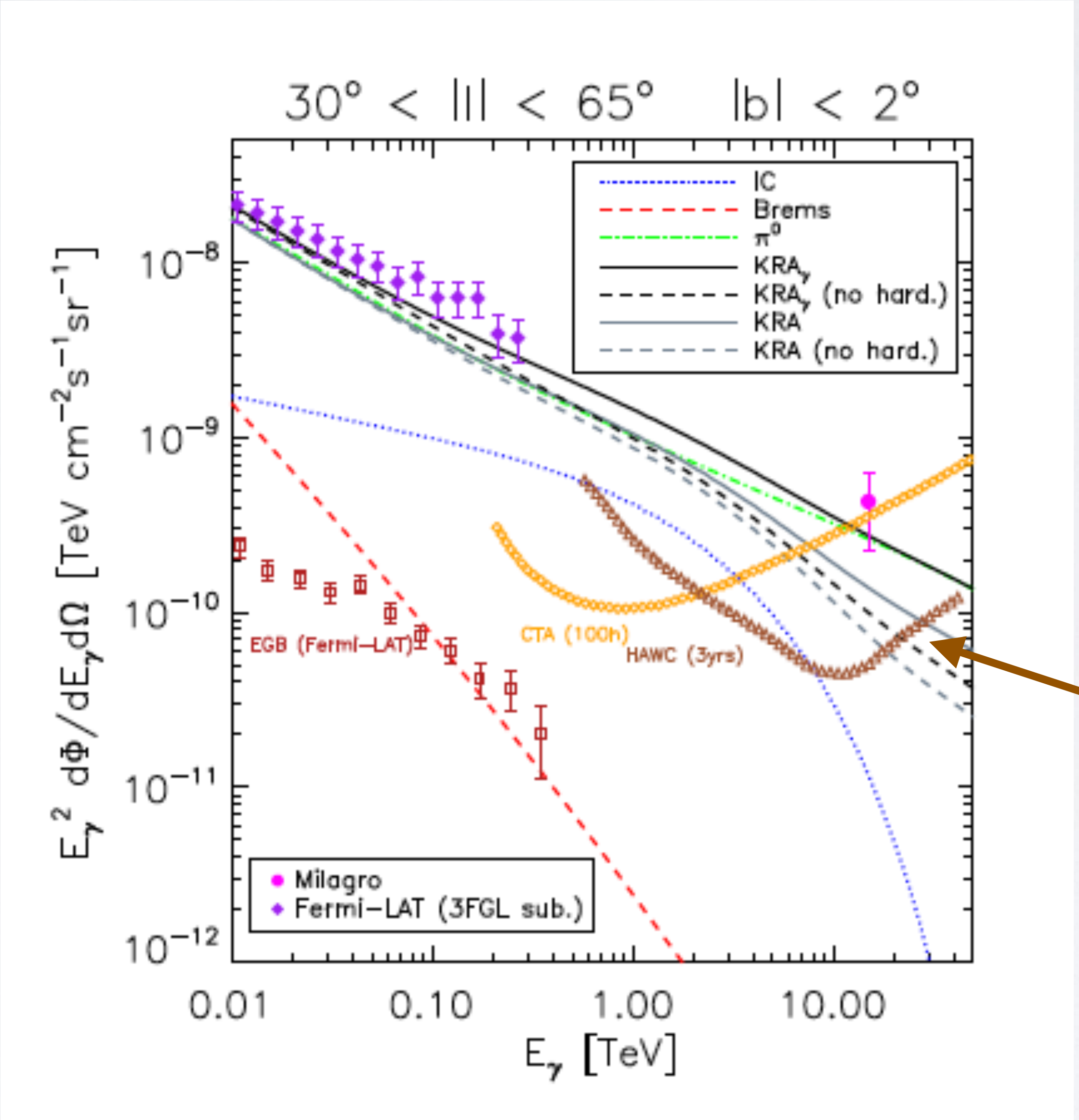
Figure 3: Isotropic γ-ray background (IGRB) inferred by *Fermi* [70] compared to the diffuse per-flavor neutrino flux observed by IceCube[1, 4] (updated plot of Ref. [36]). The black lines show possible neutrino models consistent with the IceCube data. The red lines are the corresponding γ-rays of pp scenarios reprocessed in the cosmic radiation background. The thick and thin solid lines show a power-law emission with $\Gamma = 2.15$ and $\Gamma = 2$, respectively, with an exponential cutoff around PeV. The dashed lines show an emission that is peaked in the 10TeV-PeV and only contributes in the γ-ray emission via cascades photons.

Bechtol et al. arXiv:1511.00688

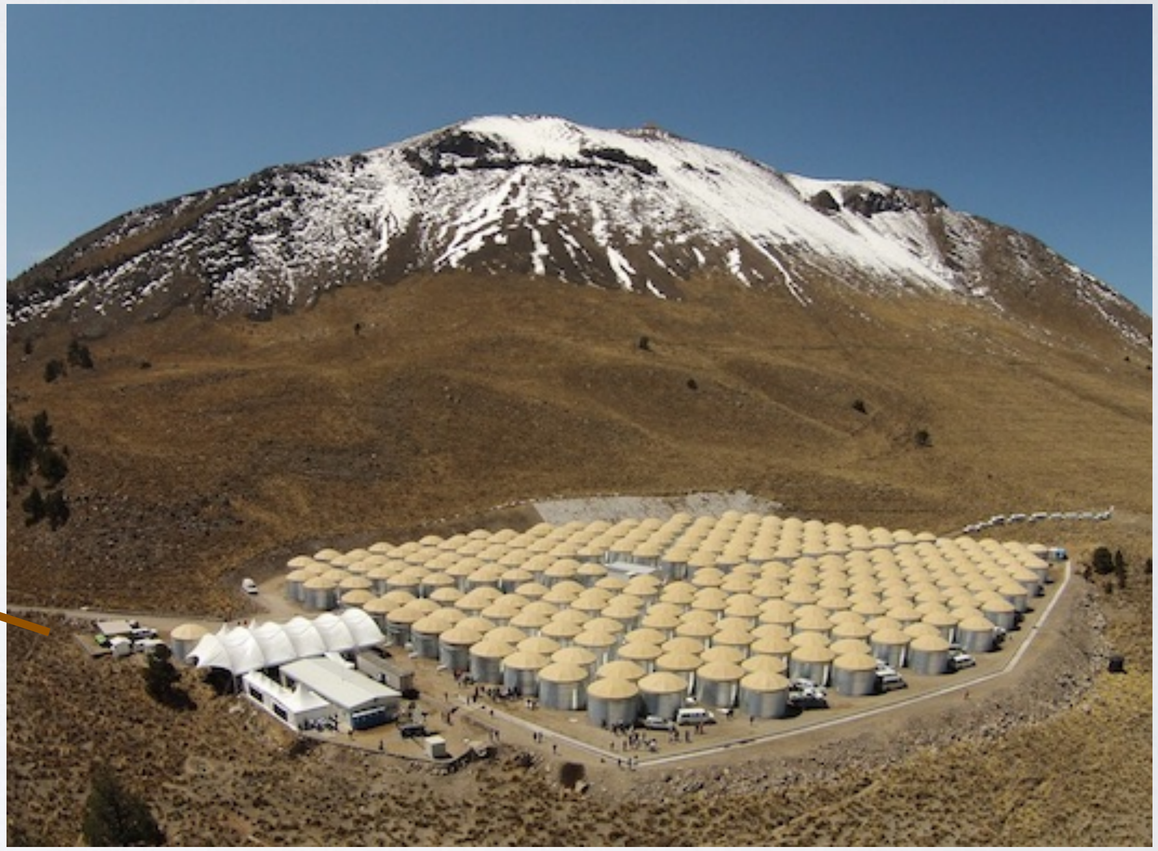


86 ± 15 % of the EGB measured by Fermi has been associated to blazars. Only a minor contribution is left for starburst Galaxies

The next future
γ-ray observatories



HAWC (Mexico)

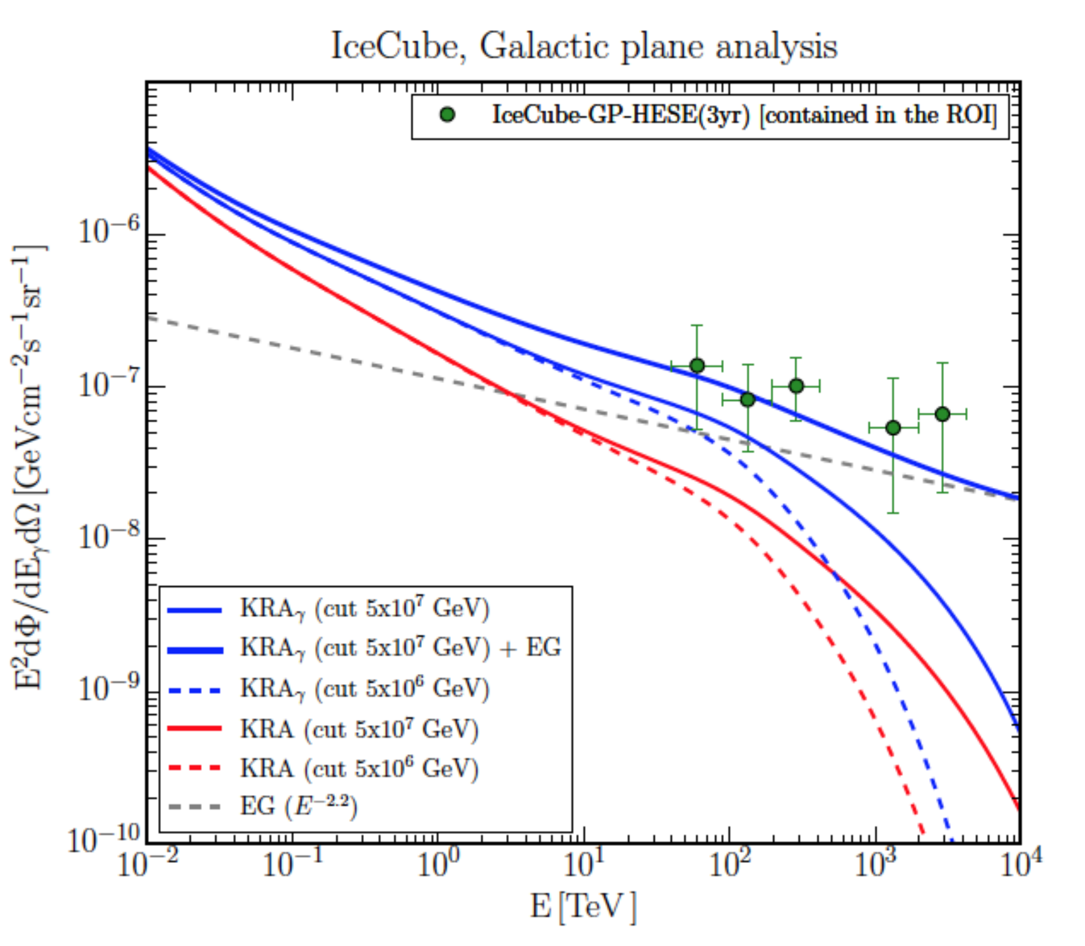


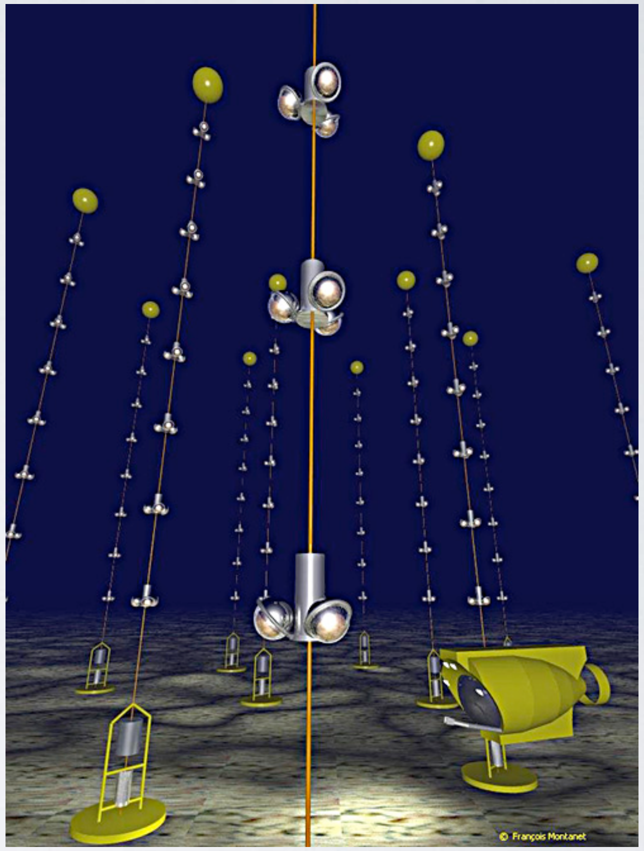
A South hemisphere twin may do even better to study the inner Galaxy

CTA and LHAASO will be also important

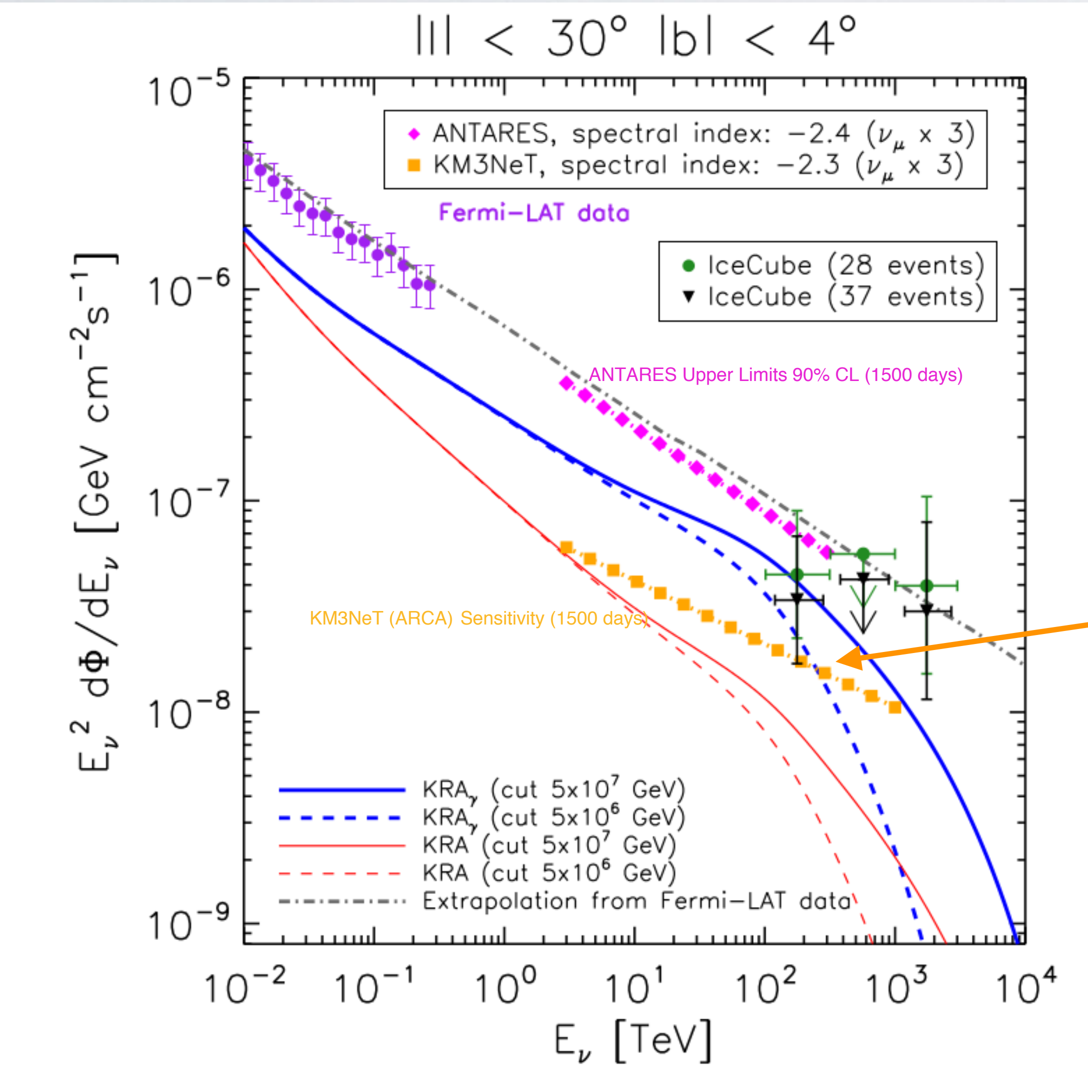
The next future
the search for a ν excess along the GP

A IceCube + ANTARES combined analysis to look for an excess along the Galactic plane is going to be performed

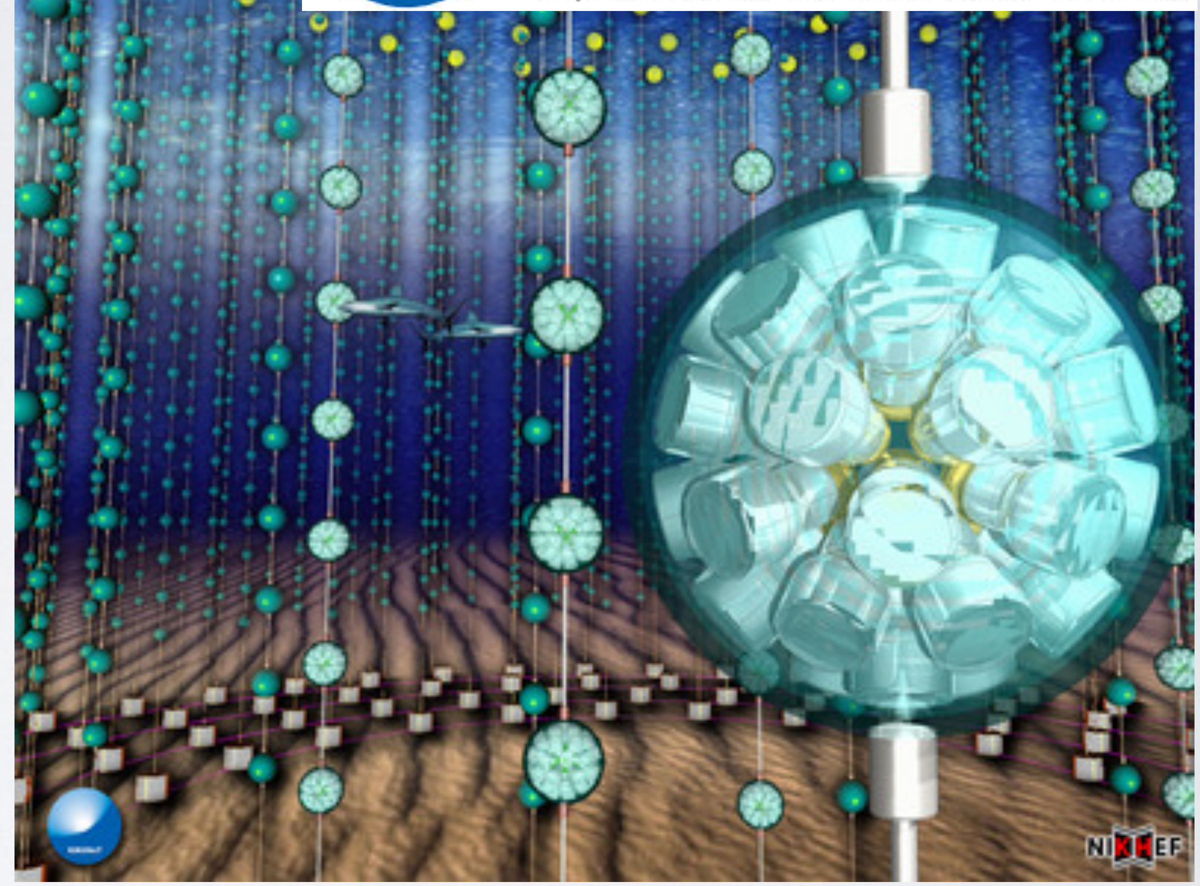




The next future
the search for a ν excess along the GP



KM3NeT
Opens a new window on our universe



Km3Net is best suited to look for the ν_μ (good angular resolution, lower background) from the inner Galactic plane

Among other important aims, it can provide valuable informations on the primary CR spectra in the knee region

Forthcoming theoretical work

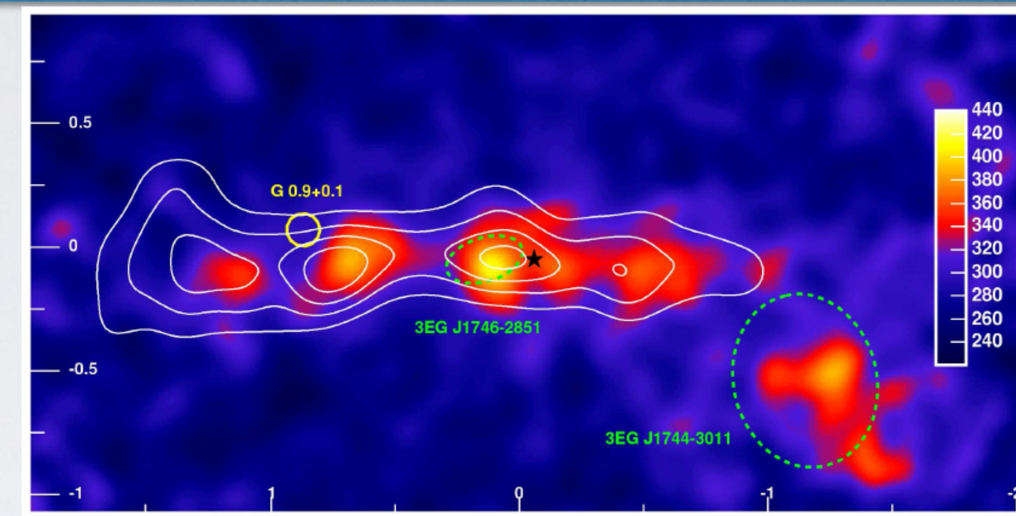
- use updated Fermi-LAT data (PASS8) to get a range of allowed models with $\delta(R)$
- use more (better/updated) CR models in the knee region
- explore different physically motivated models which may explain such behavior (anisotropic diffusion; non-linear diffusion; …)
- combine with models of extra-galactic emission (starting with including the emission of external normal galaxies)
- any other suggestion ?

Conclusions

- The γ-ray Galactic diffuse emission measured by Fermi 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
- Full-sky the Galactic emission which may partially help interpreting the possible evidences of a Galactic component in the IceCube signal.
- The soft spectrum ($\Gamma \sim 2.5$) measured by IceCube full-sky (if confirmed) remain an open issues which has to be explained

Backup slides

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

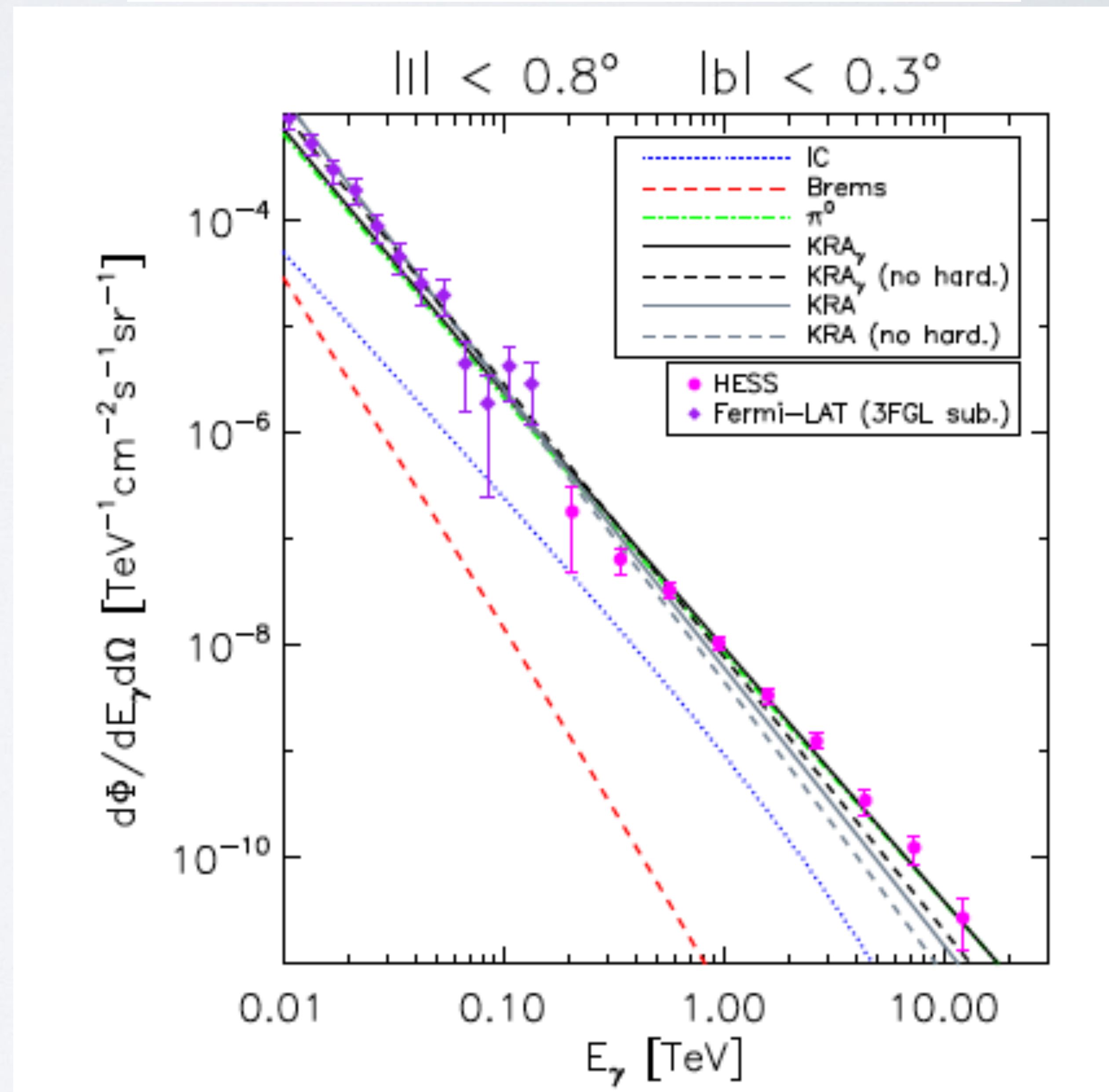
this is also the case for the updated Fermi benchmark conv. model

FERMI + HESS

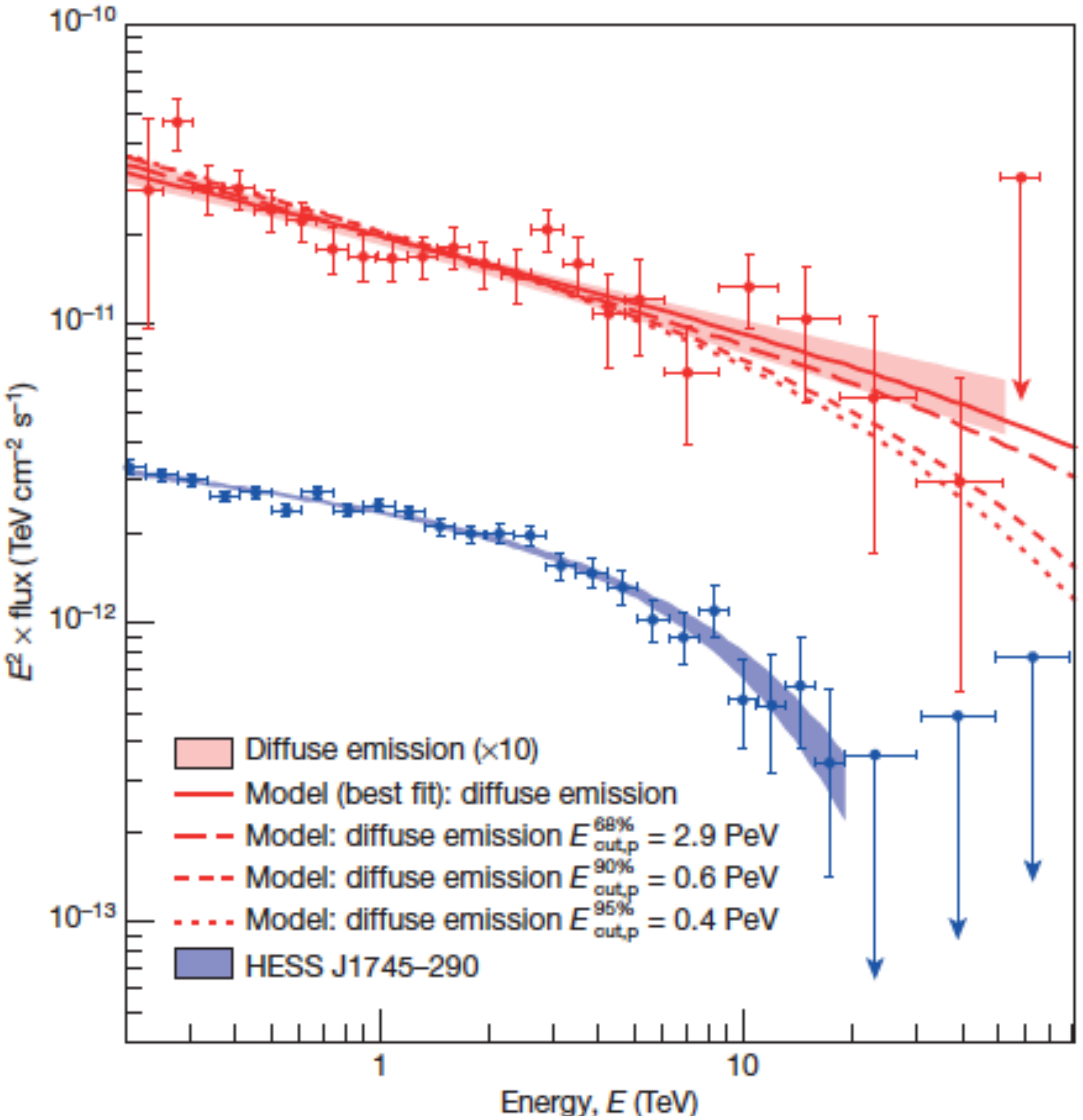
KRAγ: $\chi 2$ = 1.79 /2.27 with/w.o. hard.

KRA: $\chi 2$ = 2.92 /3.99 with/w.o. hard.

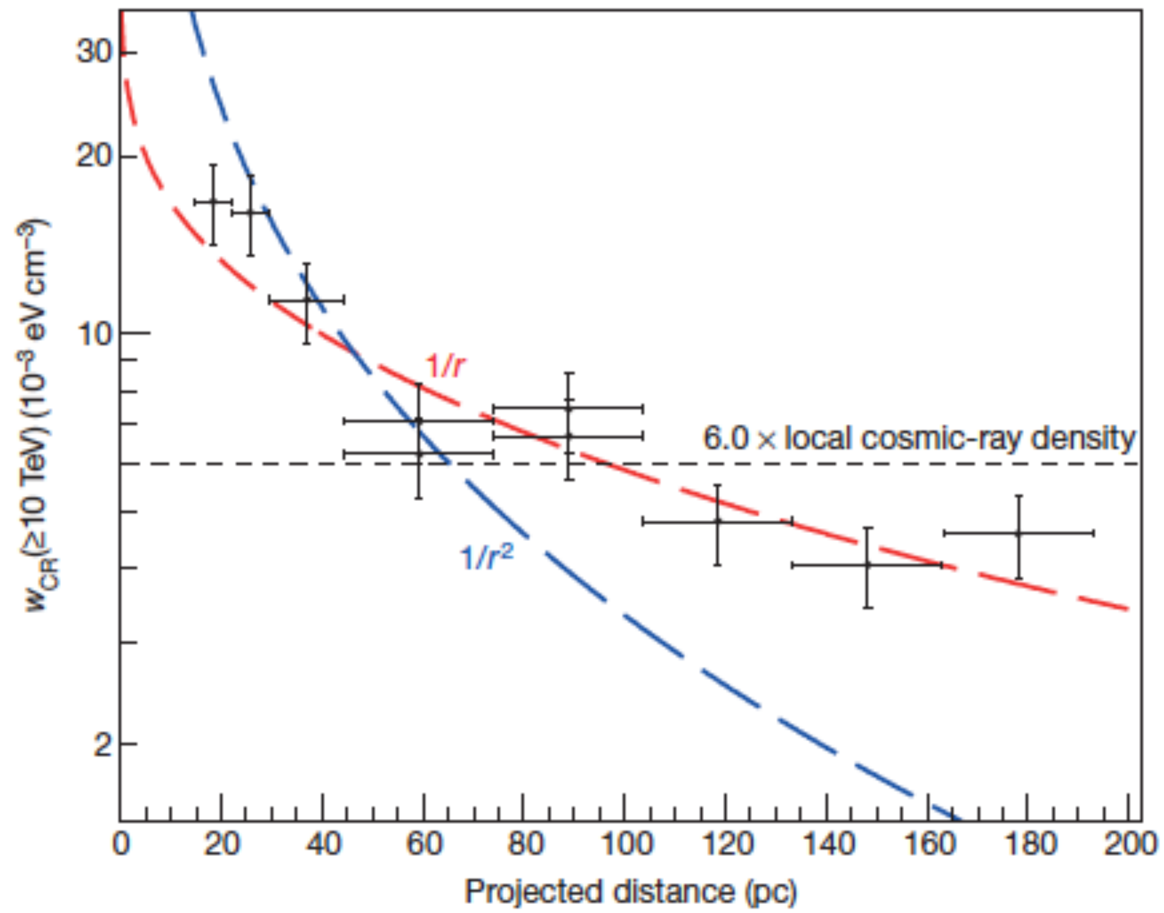
the spectrum normalization is correctly reproduced using an improved gas model in the GC region (*Ferriere et al. 2007*)



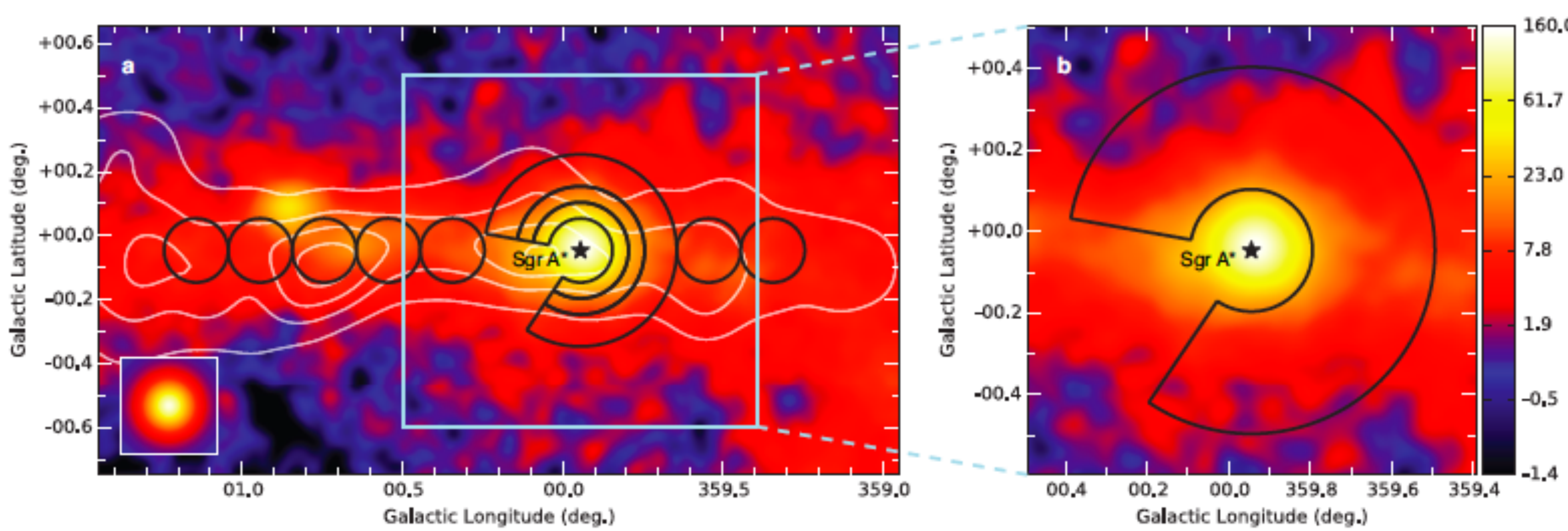
The case of the Pevatron observed by HESS



doi:10.1038/nature17147

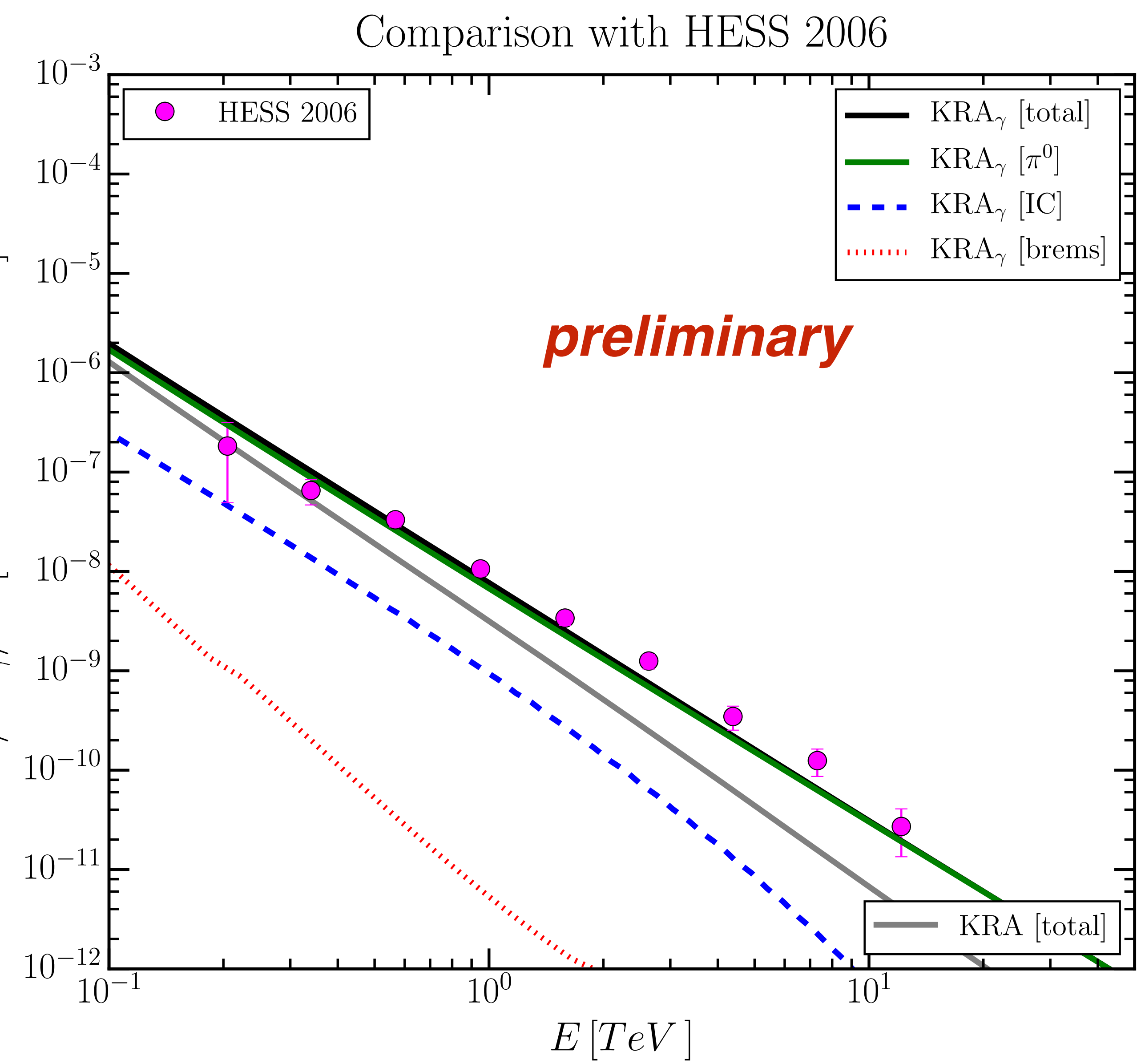


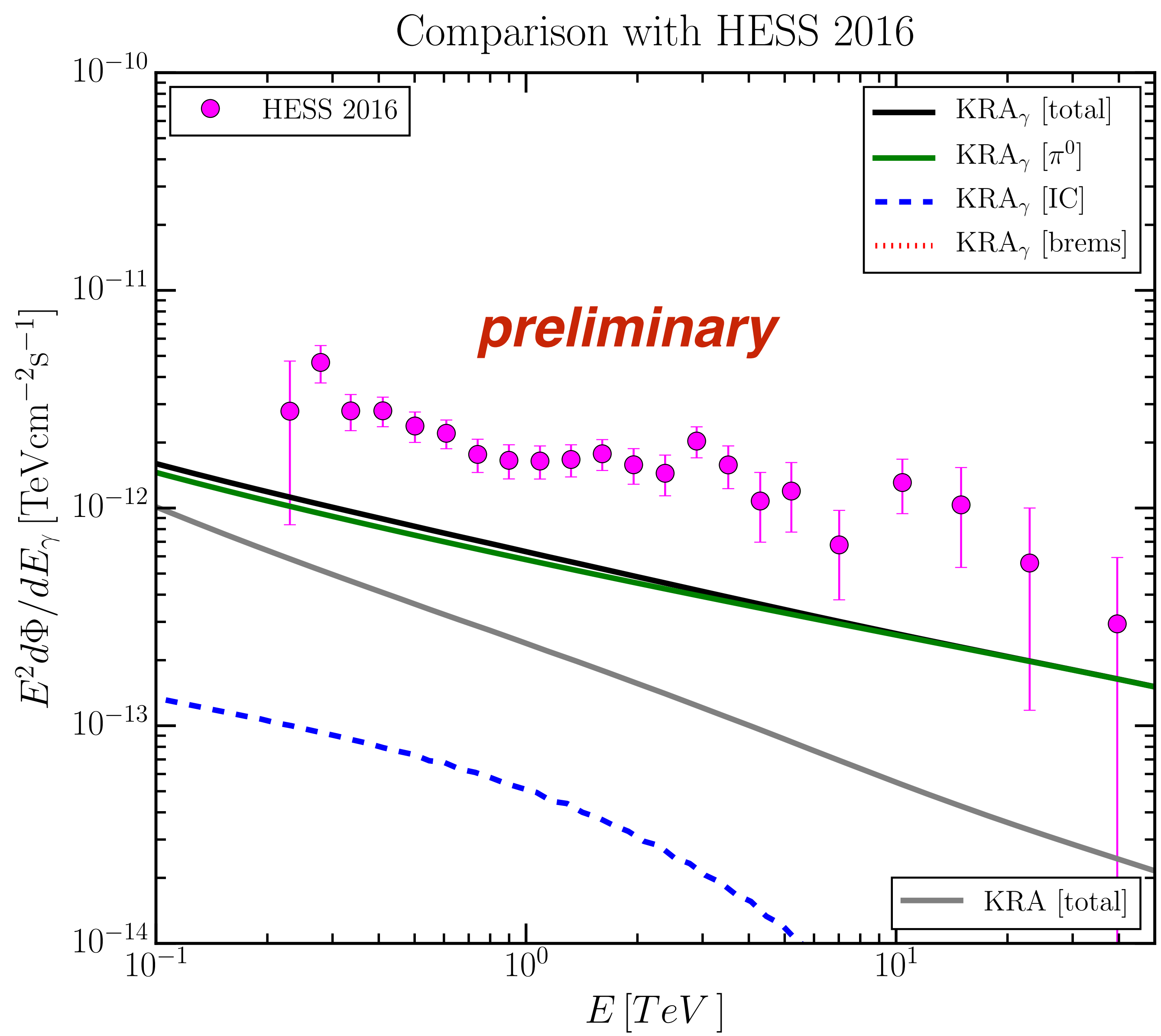
First Pevatron observed in gamma-ray from a diffuse region close to Sagittarius A



The expected diffuse sea with KRA$_\gamma$ compared to Pevatron

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





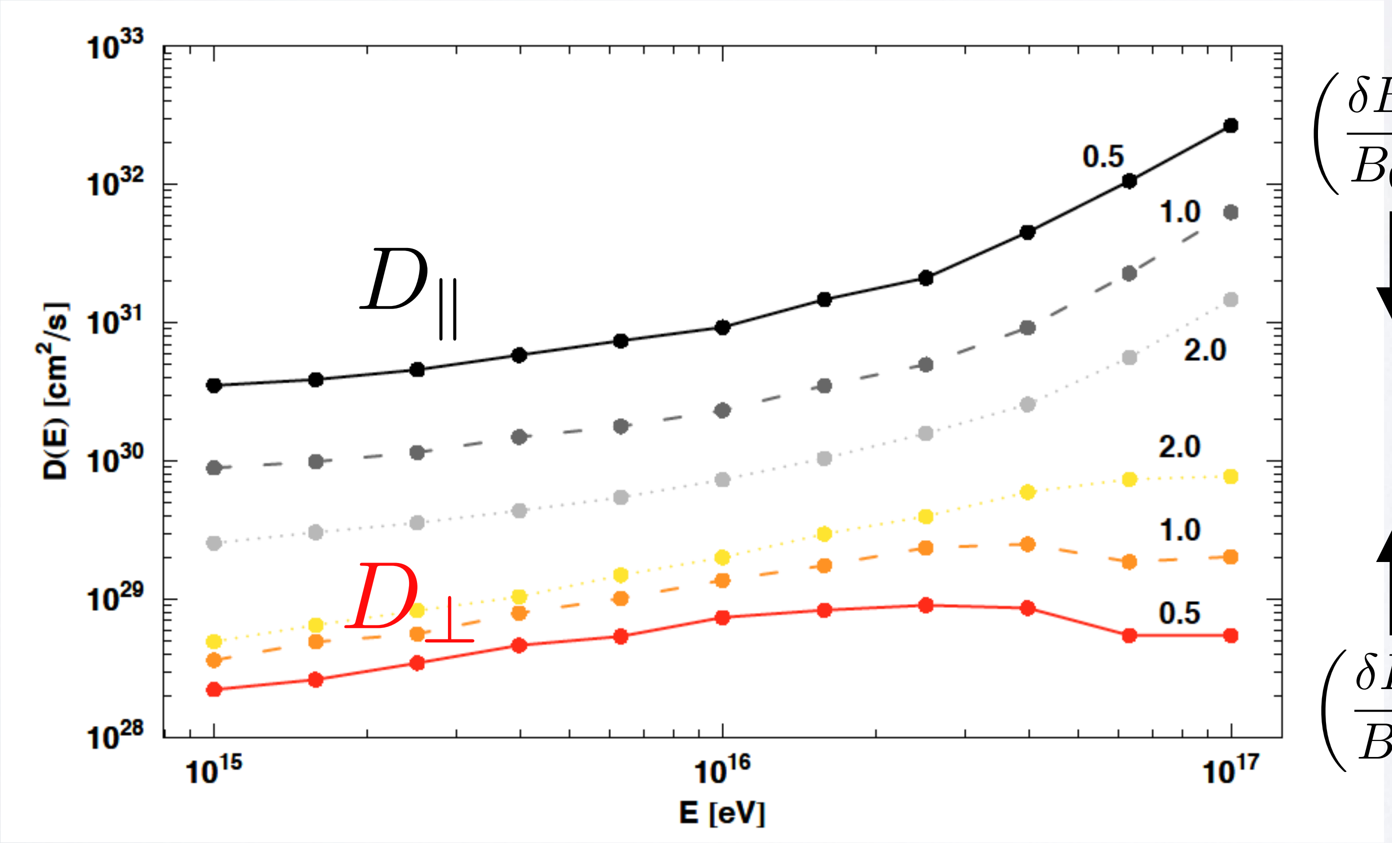
Applying the KRA$_\gamma$ to the “pacman” region we can see how big is the slot left in the SED for the Pevatron injector.

A possible origin of δ(R) from anisotropic diffusion

The presence of regular MF breaks isotropy D ⇒

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

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



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

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

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

for Kolmogorov turbulence

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

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

A possible origin of δ(R) from anisotropic diffusion

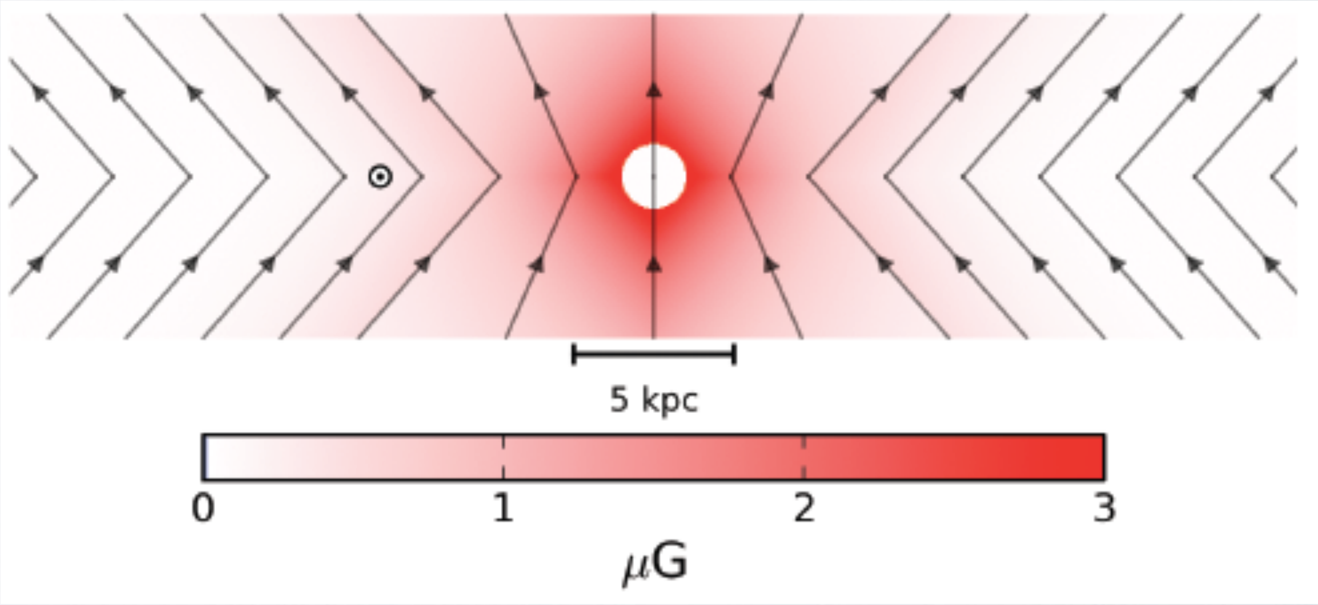
the presence of a poloidal component of the GMF in the GC region should make the role of $D_{||}$ growing respect to $D_{\perp}$ (standard case)

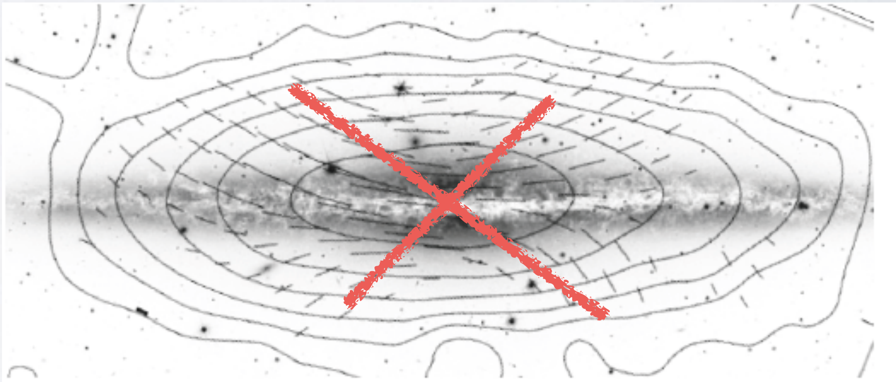
Since, for Kolmogorov turbulence

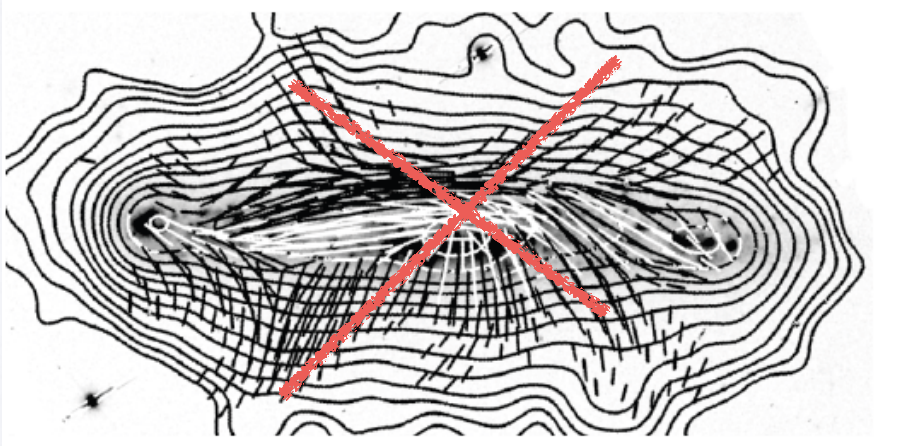
$$D_{||}(E) \propto E^{1/3} \quad D_{\perp}(E) \propto E^{0.5 \div 0.6}$$

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

Jansson & Farrar ApJ 2012







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