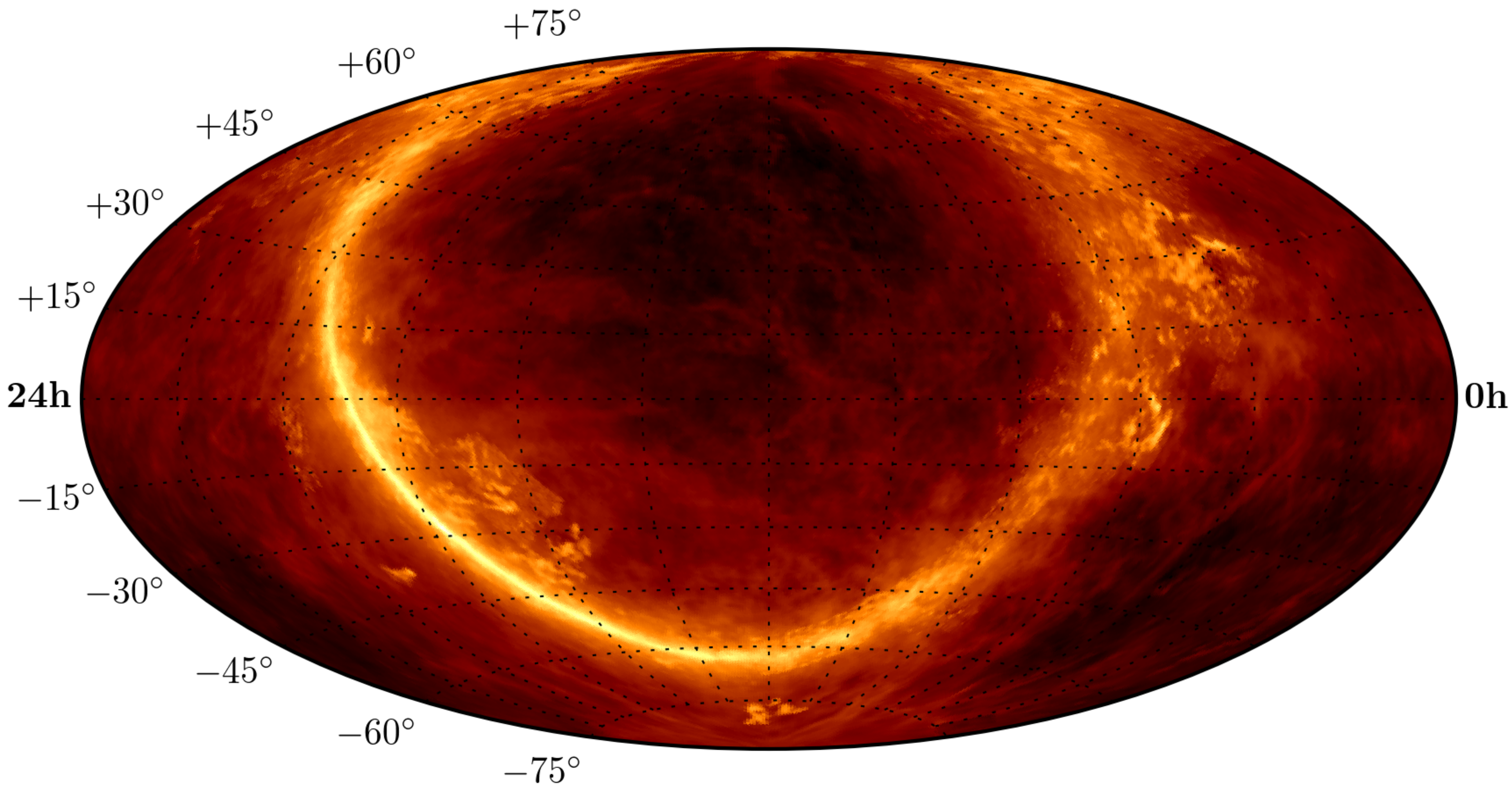
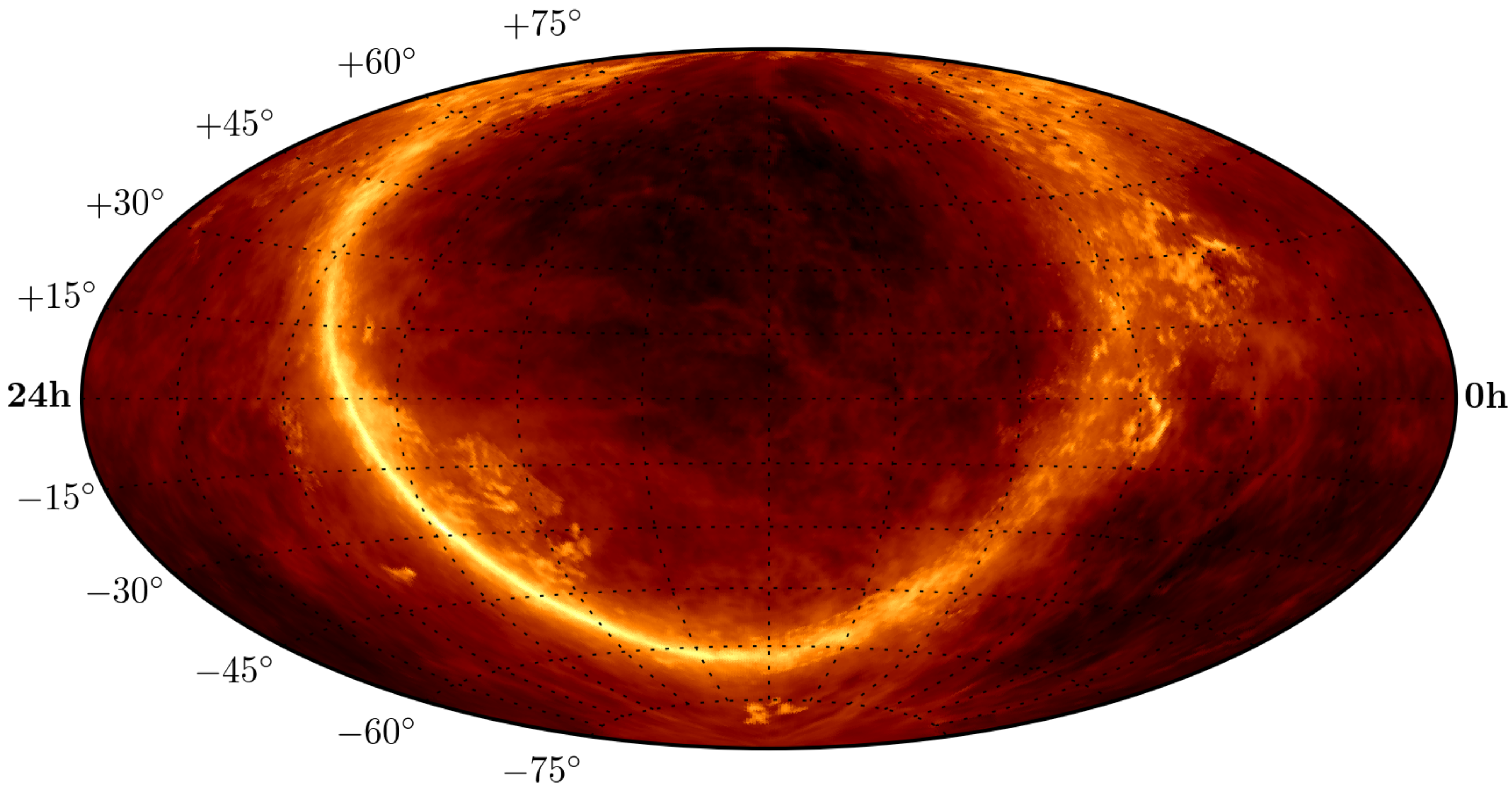


GAMMA RAYS AND NEUTRINOS FROM THE GALACTIC PLANE
(THE DIFFUSE COMPONENT)

Dario Grasso (INFN, Pisa)
with Daniele Gaggero (IFT/UAM) and A. Marinelli (INFN, Napoli)

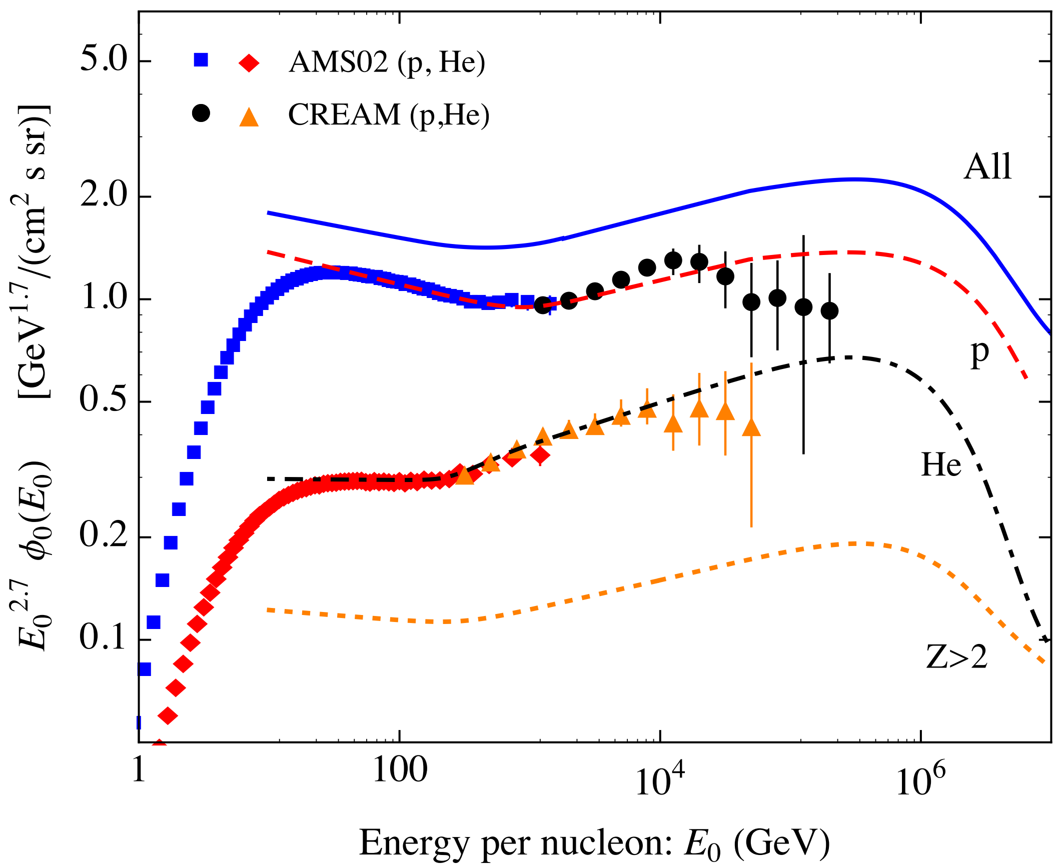
The Town Hall KM3NeT meeting, Marseille

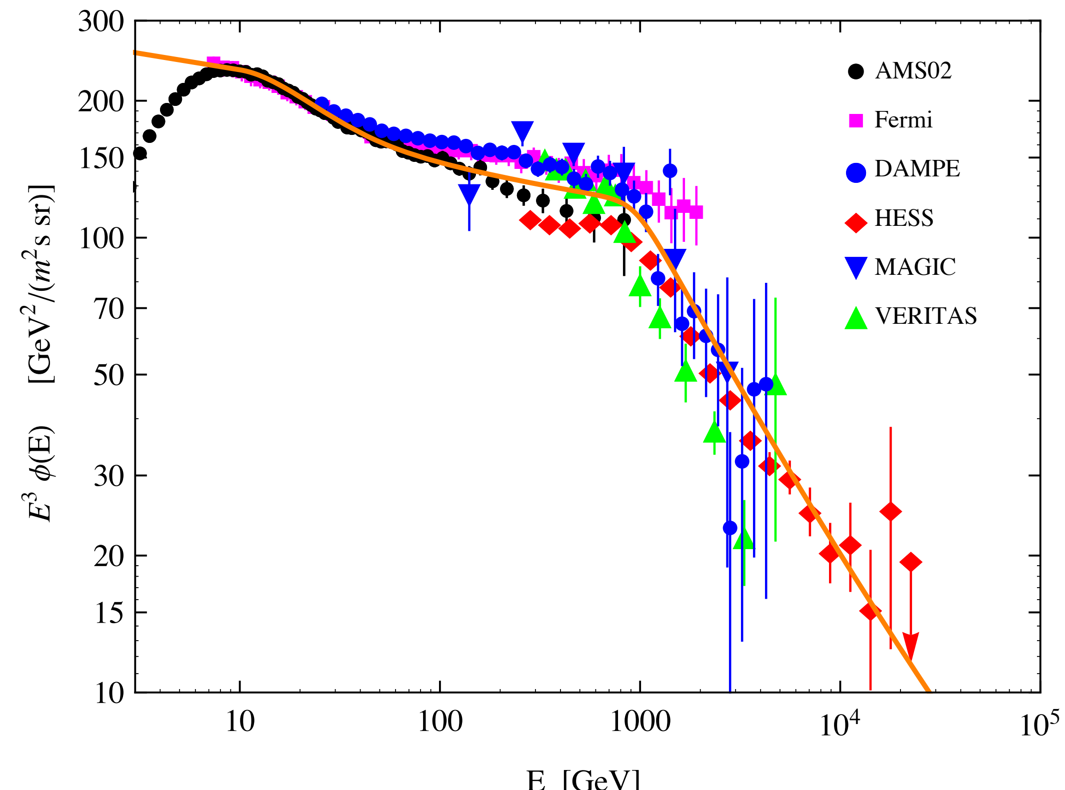


"THE RING OF FIRE"

Dario Grasso (INFN, Pisa)
with Daniele Gaggero (IFT/UAM) and A. Marinelli (INFN, Napoli)

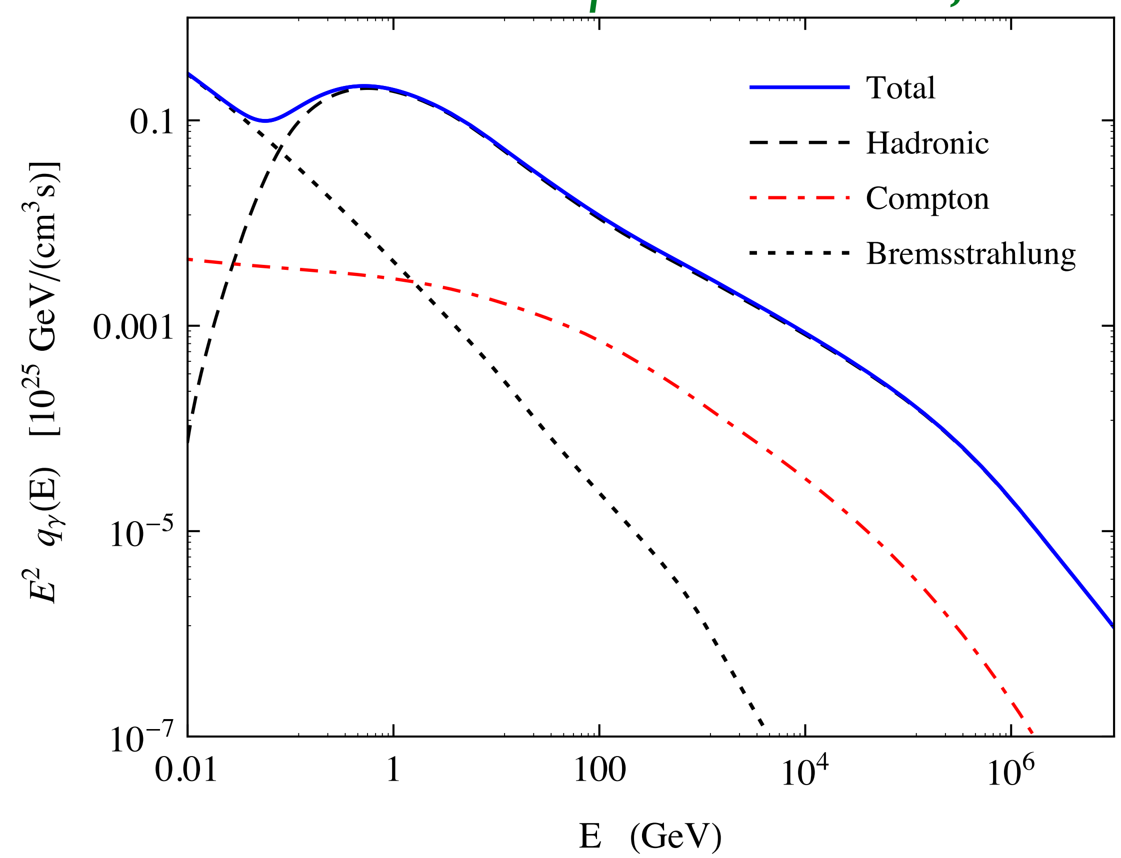
THE GAMMA-RAY DIFFUSE EMISSION OF THE GALAXY





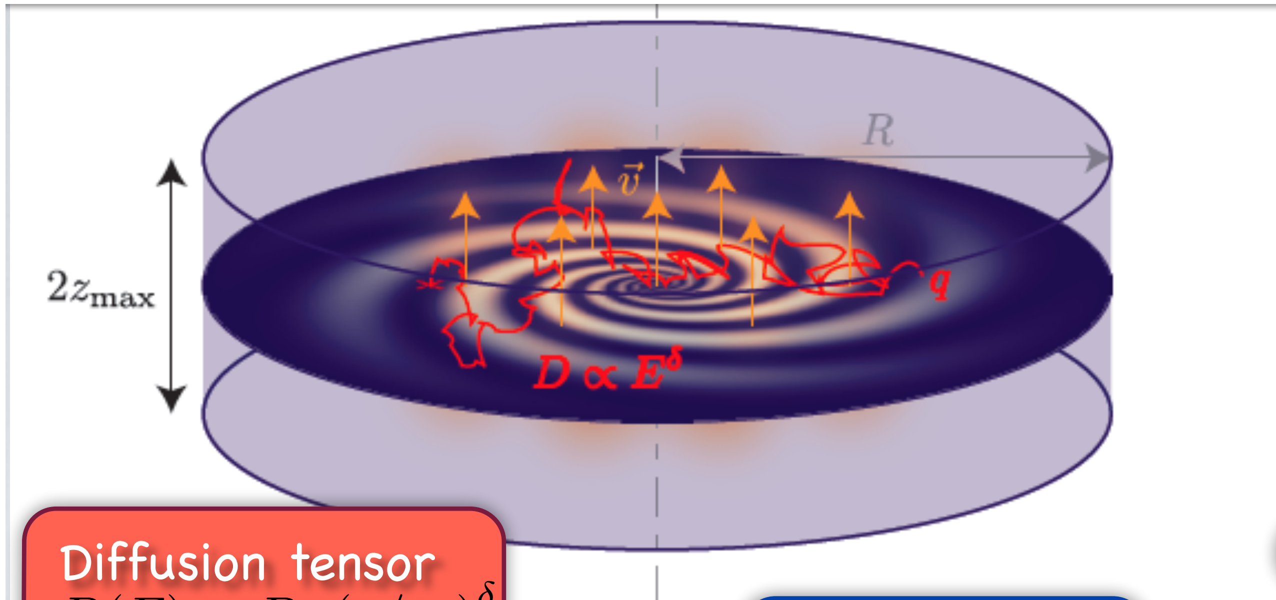
EXPECTED LOCAL EMISSION

Lipari & Vernetto, 2018



COSMIC RAY TRANSPORT

assuming uniform and isotropic diffusion (conventional scenario)



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

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

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

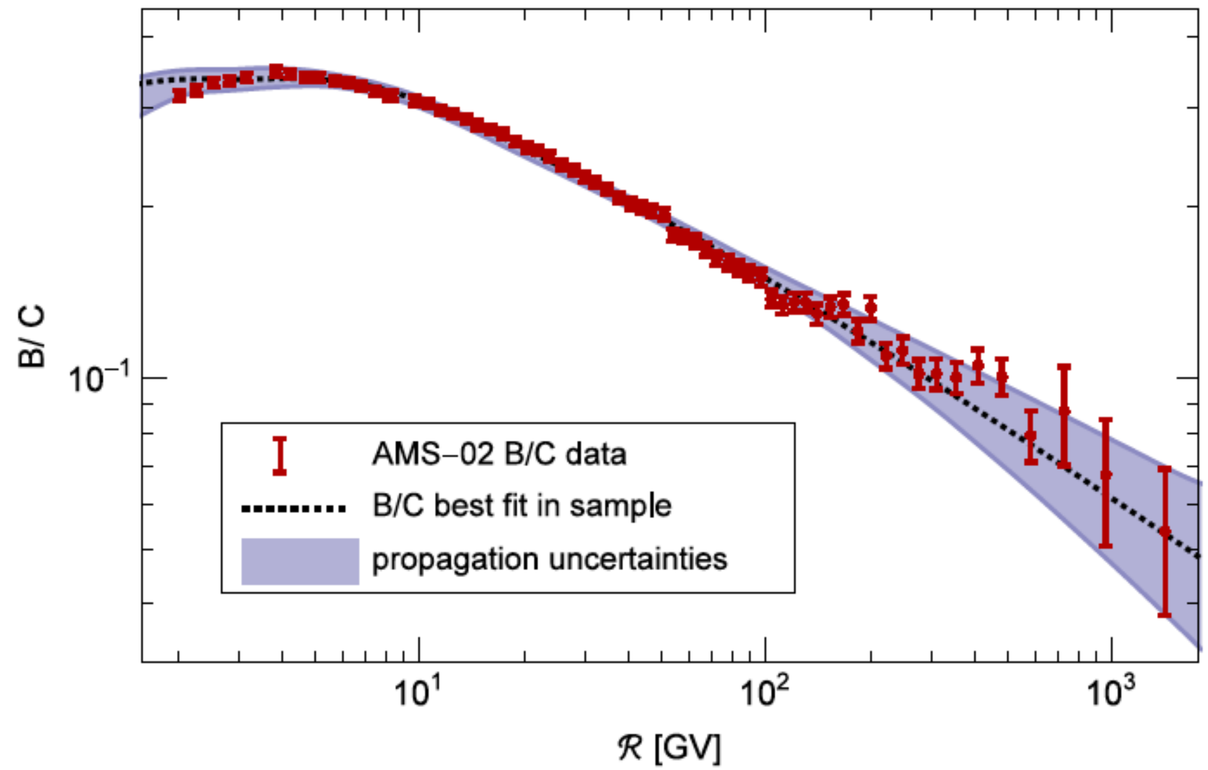
SN source term.
We assume everywhere
a power law energy spectrum

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

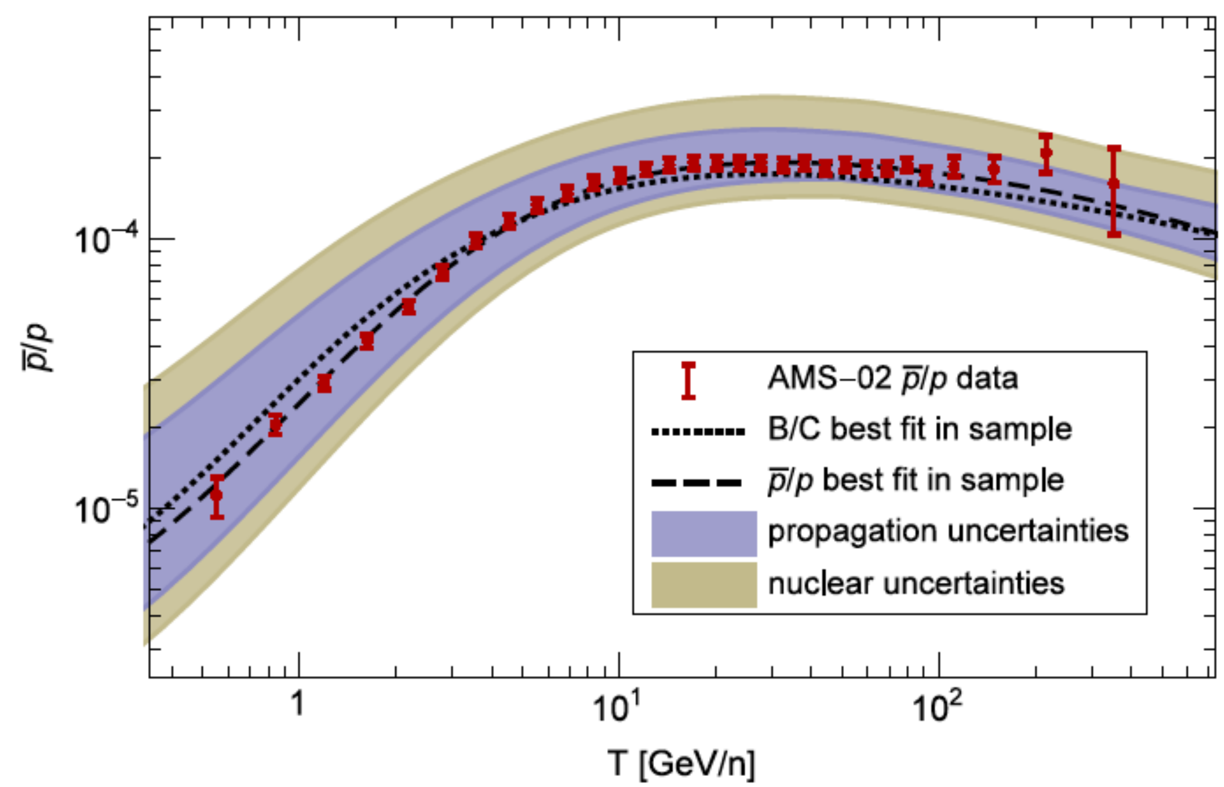
Total inelastic cross section.
Disappearance of nucleus i

LOCAL (d < few kpc) PROBES

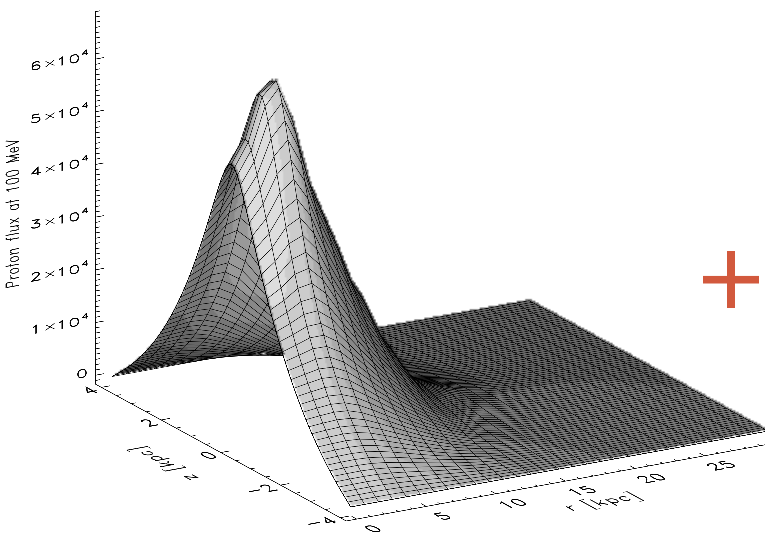
- B/C

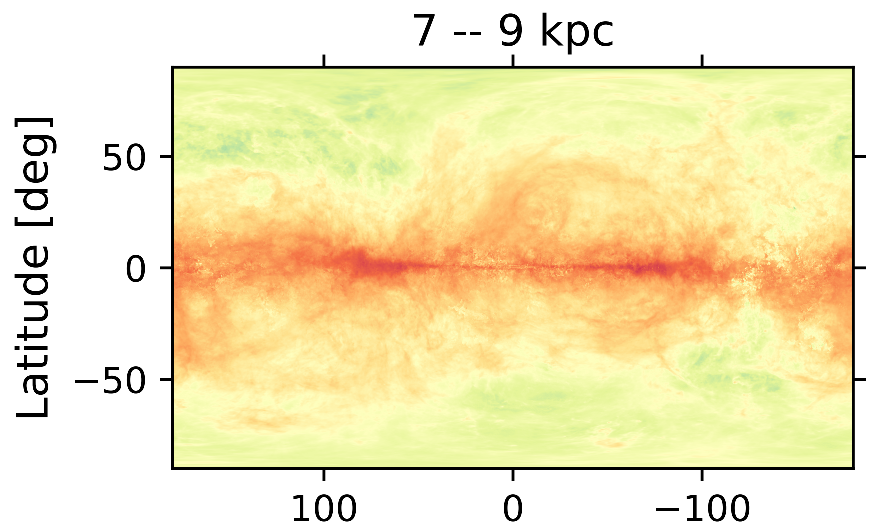


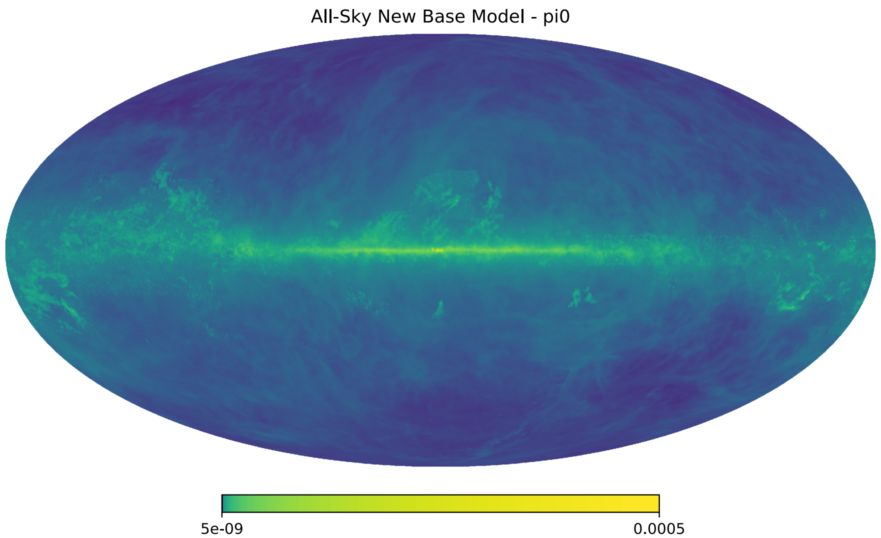
- antiprotons



BUILDING SIMULATED MAPS OF THE GAMMA DIFFUSE EMISSION





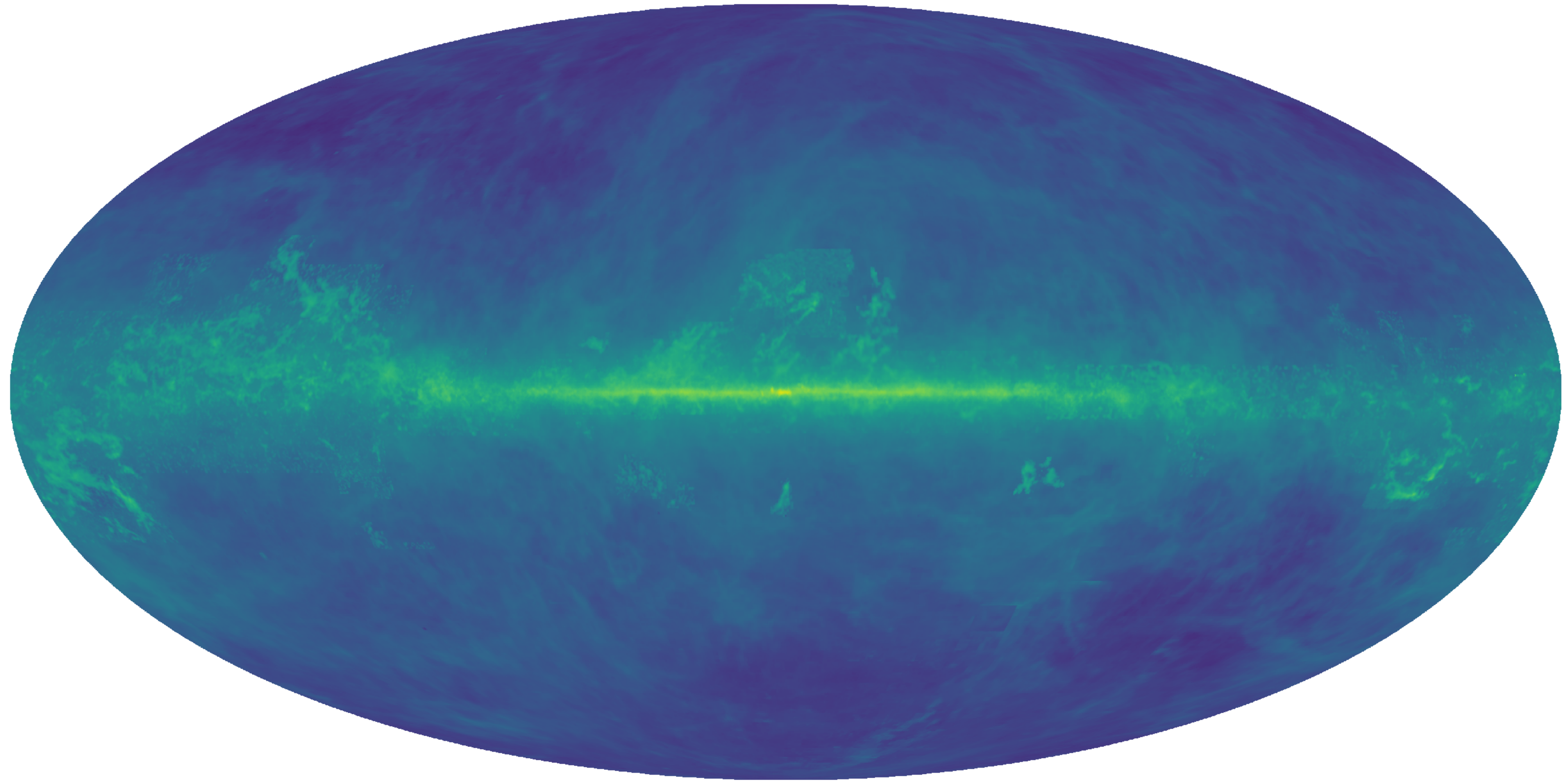


transport eq. → CR spatial/energy distribution

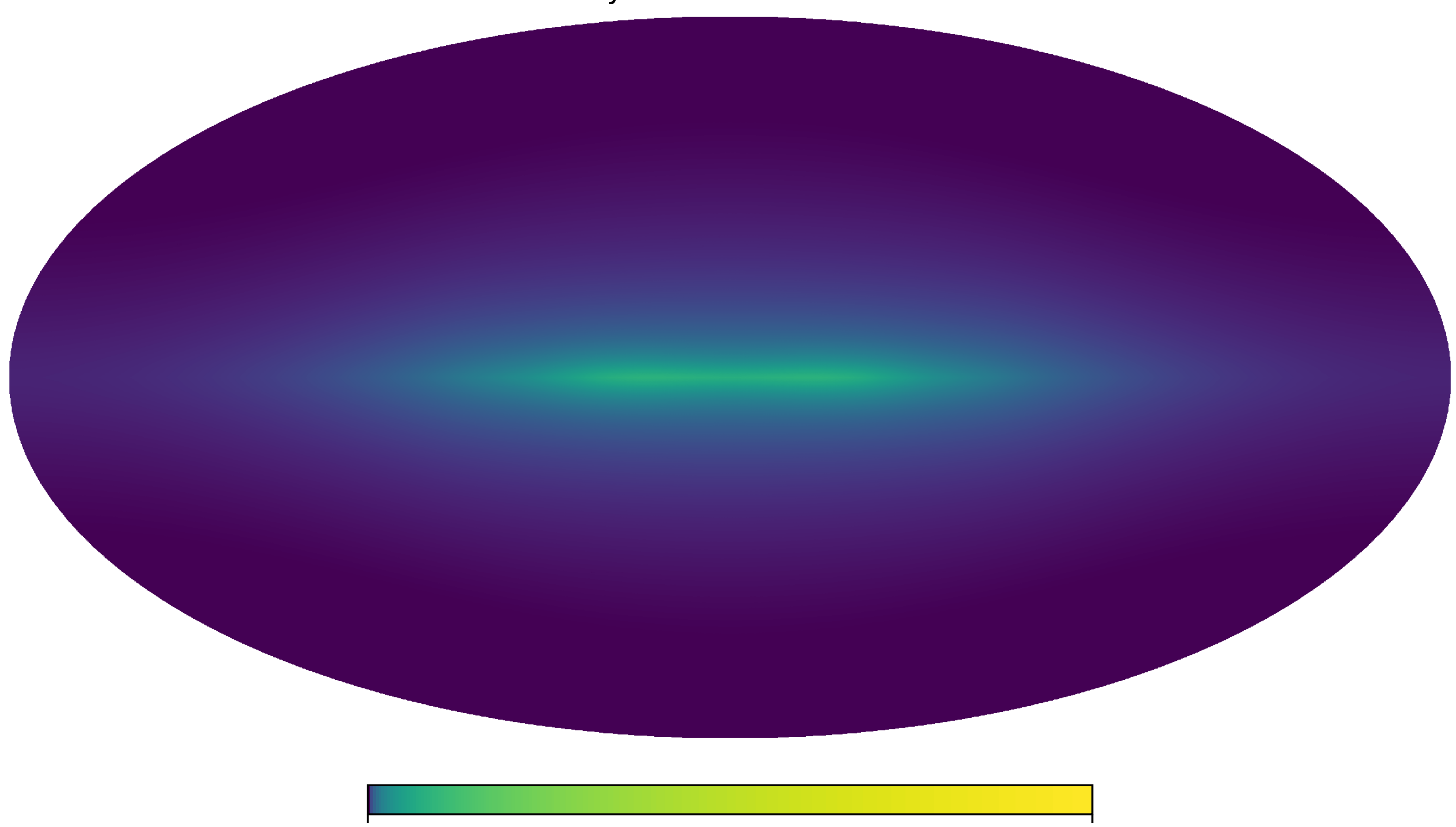
CO maps in several rings. requires a X_{CO} profile to get H_2

HI obtained from 21cm emission maps

All-Sky New Base Model - pi0

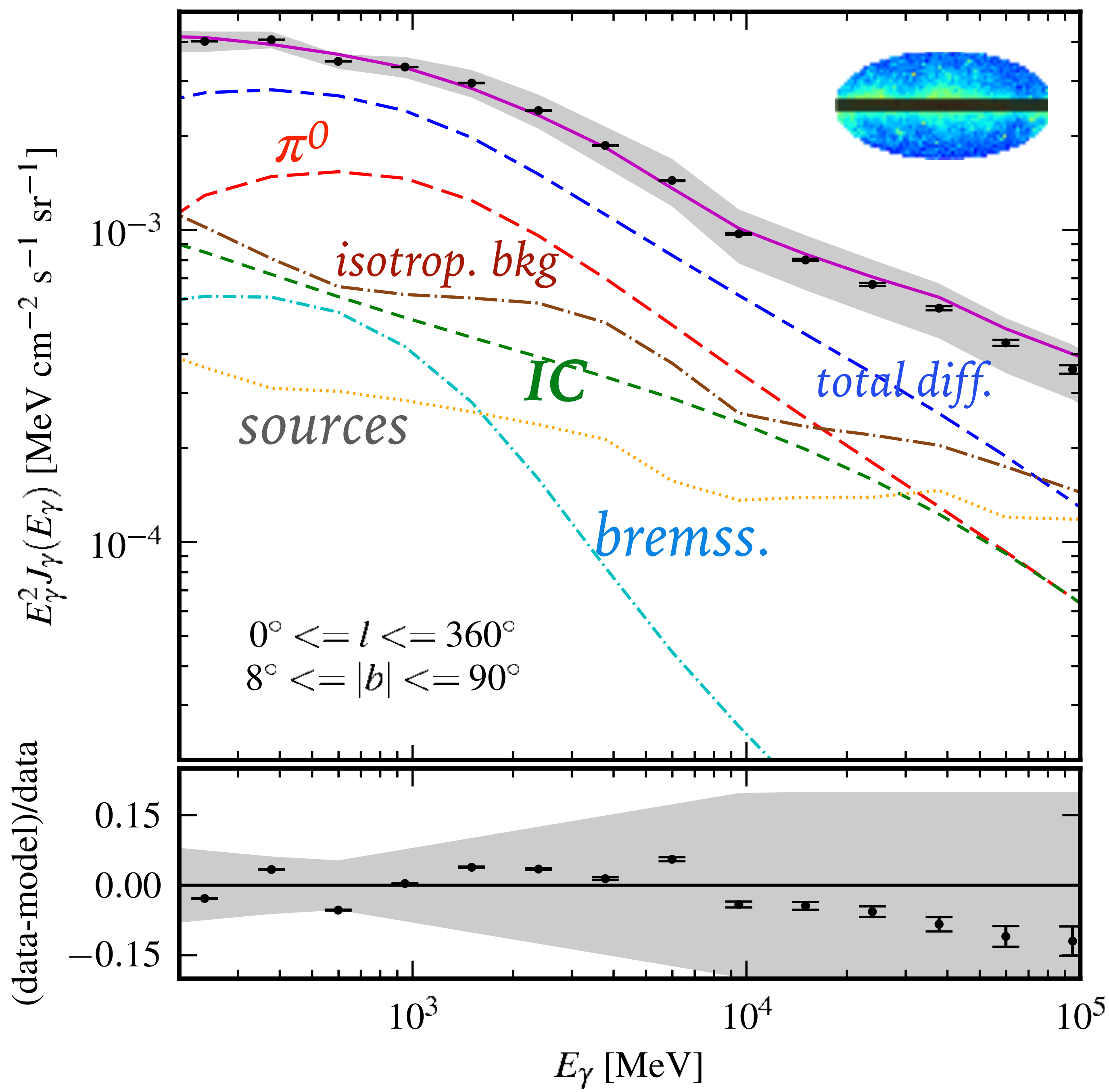


All-Sky New Base Model - IC



CONVENTIONAL MODELS AGAINST FERMI-LAT

Away from the Galactic Plane (GP) conventional models provide a good description of the morphology and spectrum of the emission measured by Fermi-LAT

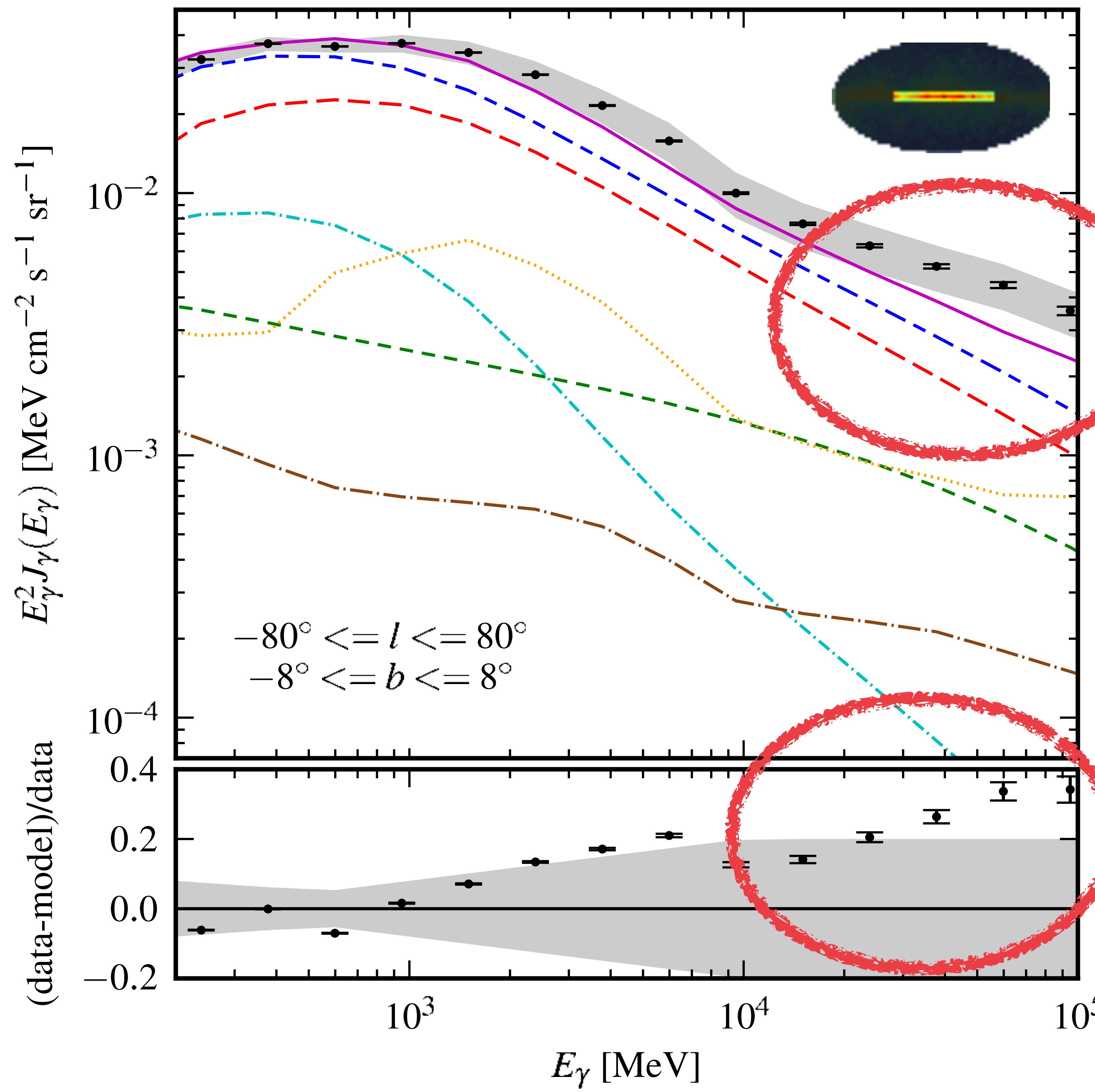


CONVENTIONAL MODELS AGAINST FERMI-LAT

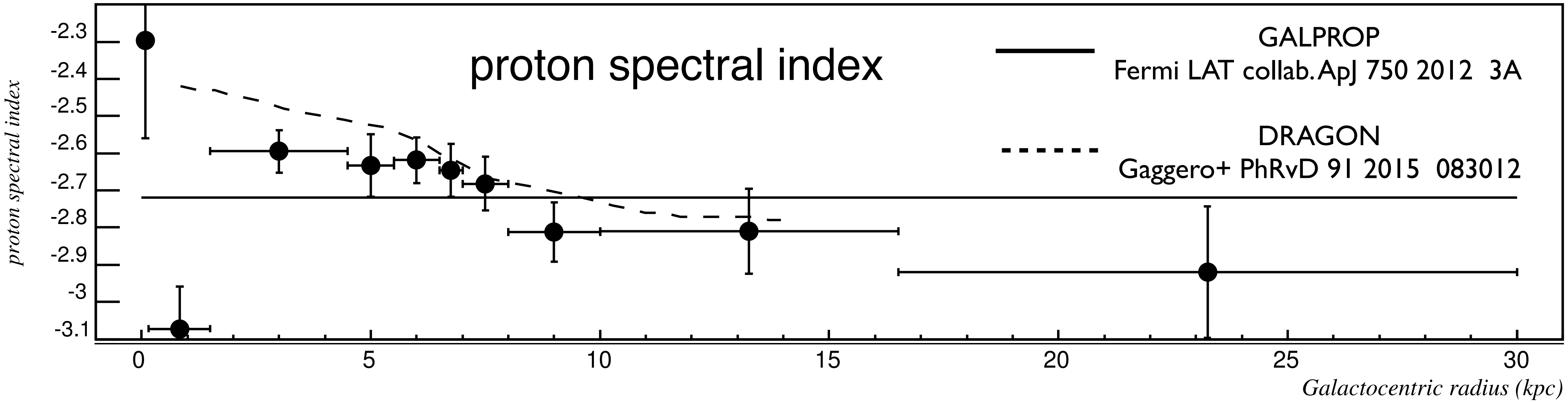
inner GP emission

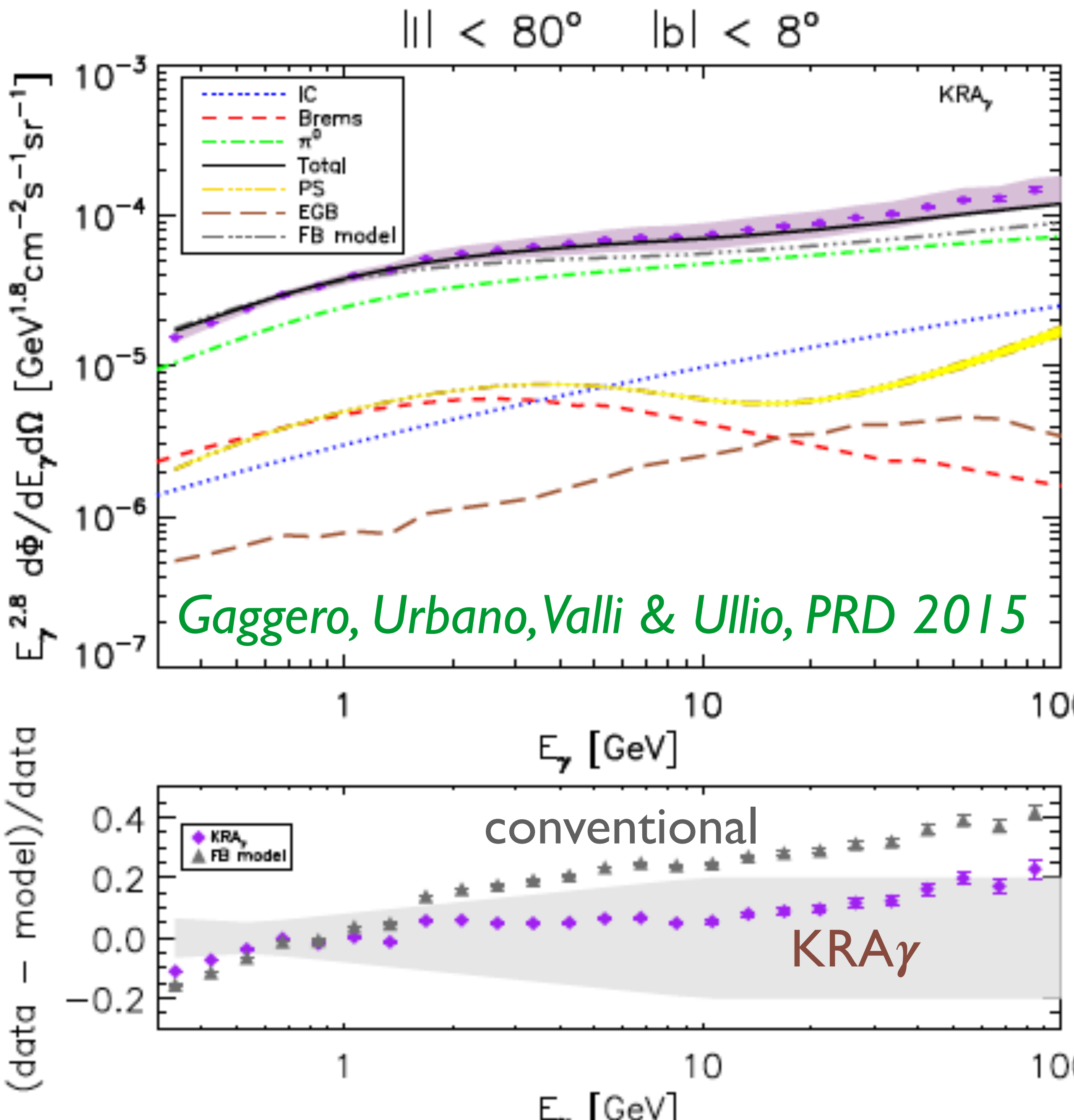
Something may be wrong with the conventional scenario in the inner galactic plane !

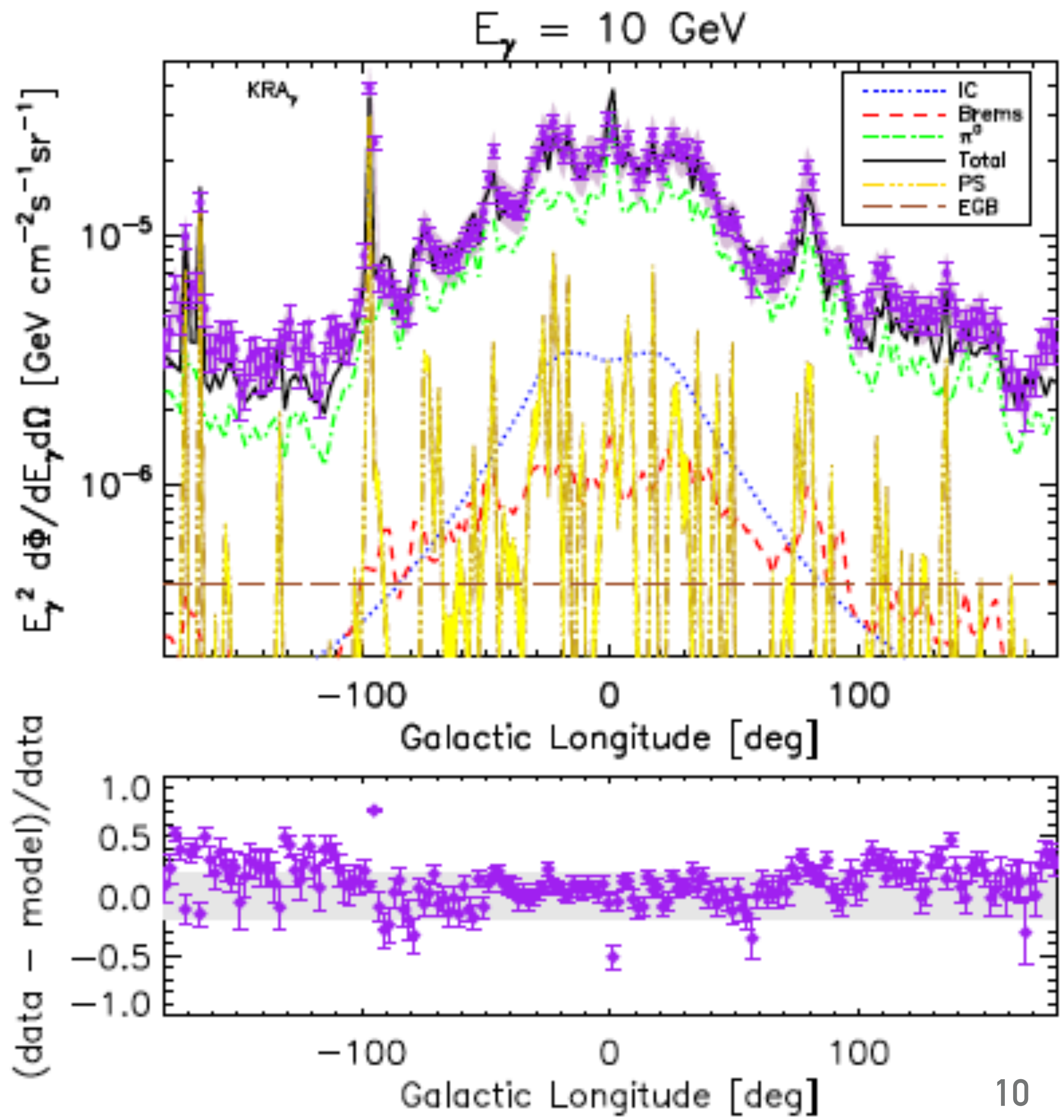
Is that do to unconventional CR propagation or to unresolved sources ?



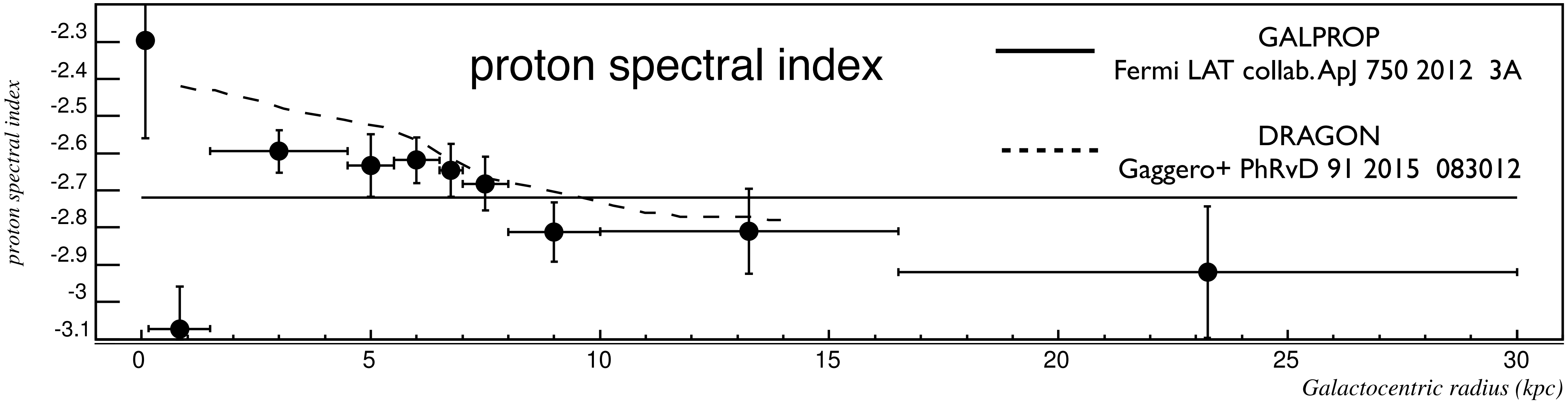
Fermi-LAT coll. 2016

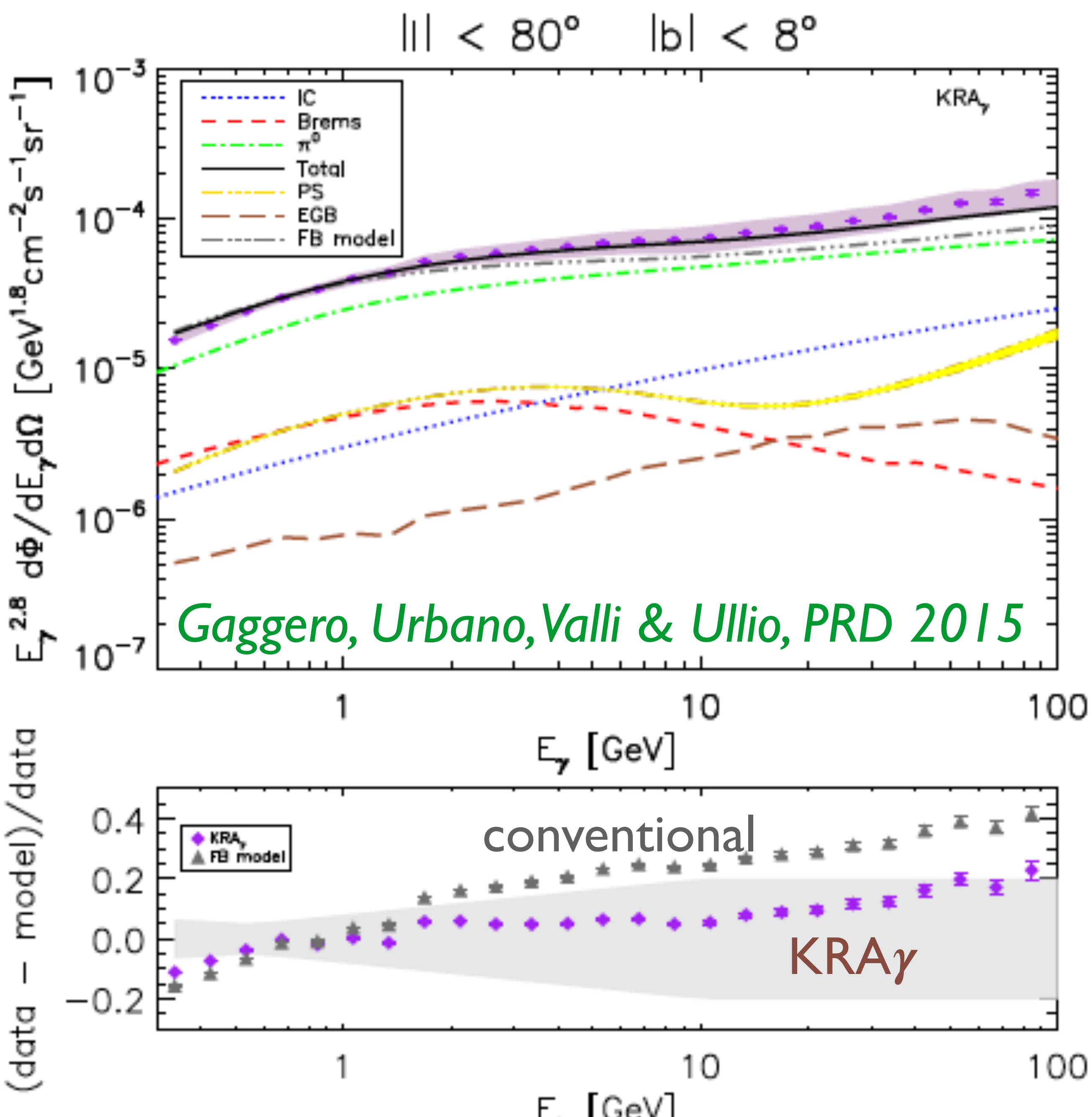






Fermi-LAT coll. 2016





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

$\delta(r) = A\, r + B$ for $r < 11$ kpc

so that $\Gamma(r) = \Gamma_{source} + \delta(r)$

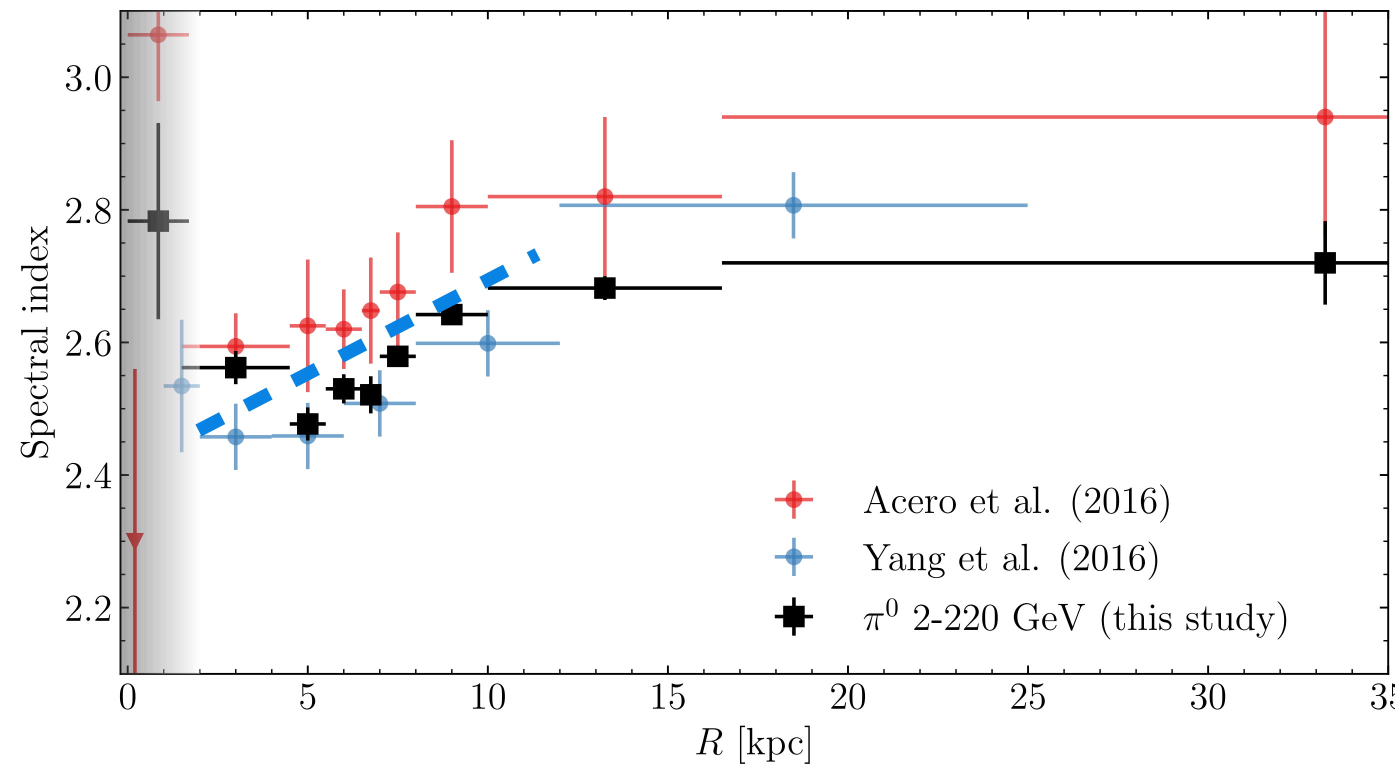
factorized energy-space dependence of CR transport

"KRAγ or *gamma* model"

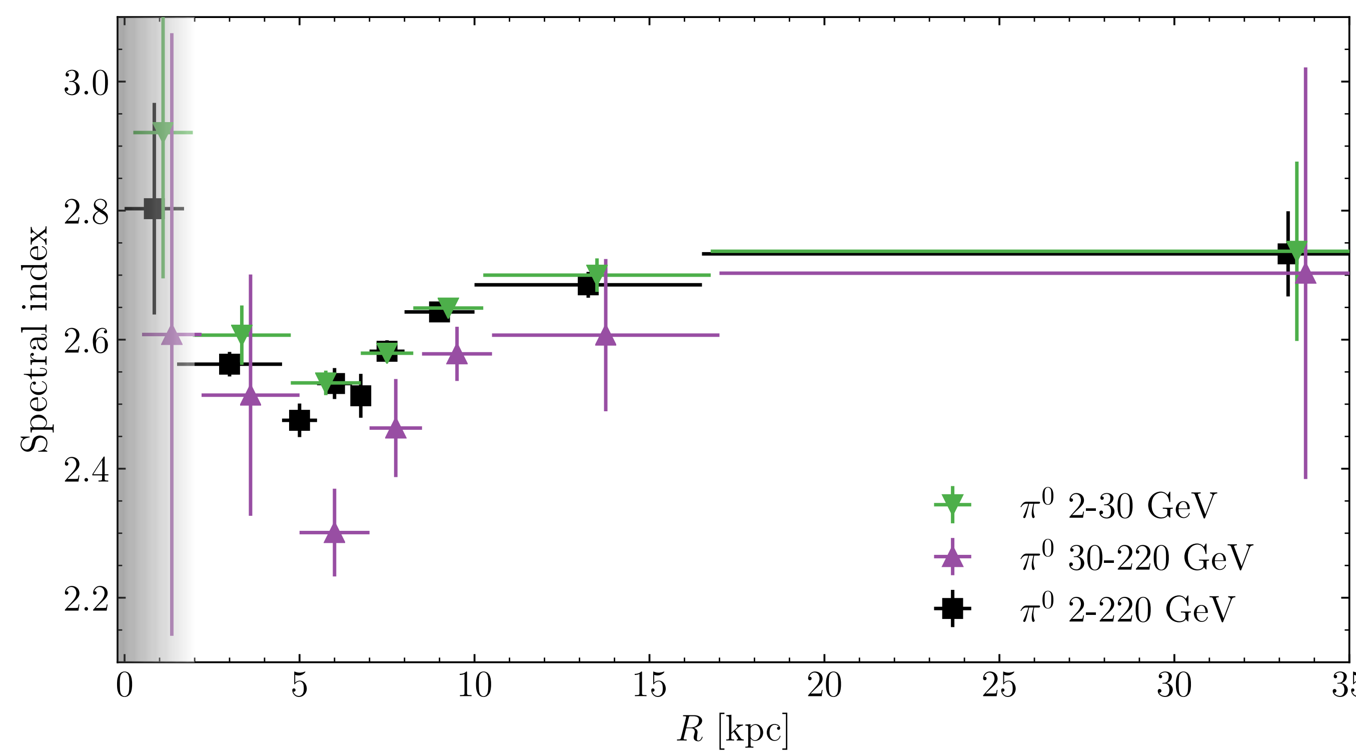
THE SPECTRAL INDEX GRADIENT PROBLEM

Prothast, Gaggero, Strom, Weniger, 2018

Several independent analysis of Fermi-LAT data (most recent: 10 years PASS 8) agree finding a progressive hardening for R → 0 in the inner Galaxy. No clear trend for R < 2 kpc.

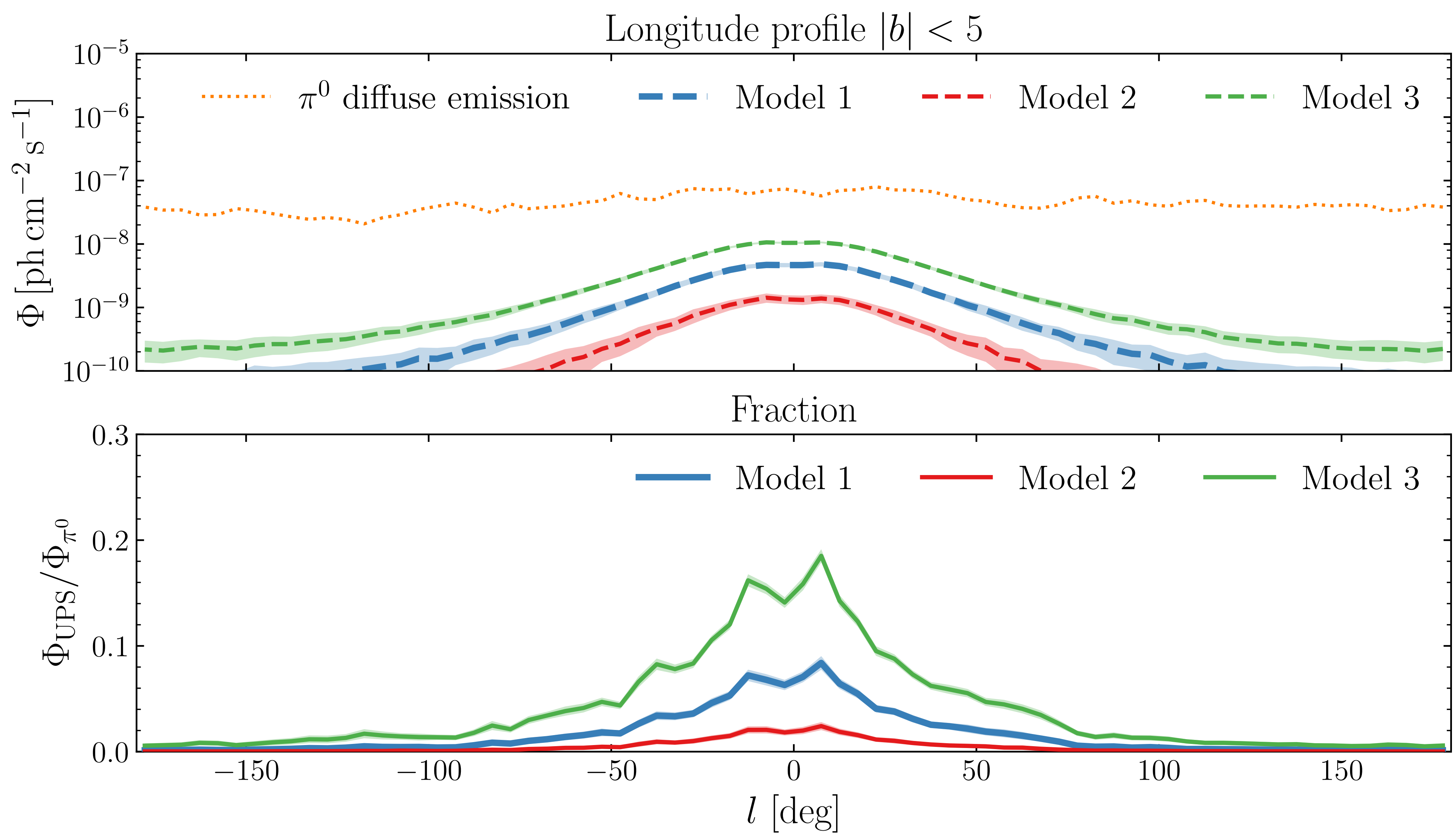


The same trend has been found in two different energy intervals as may be expected if originated by CR transport



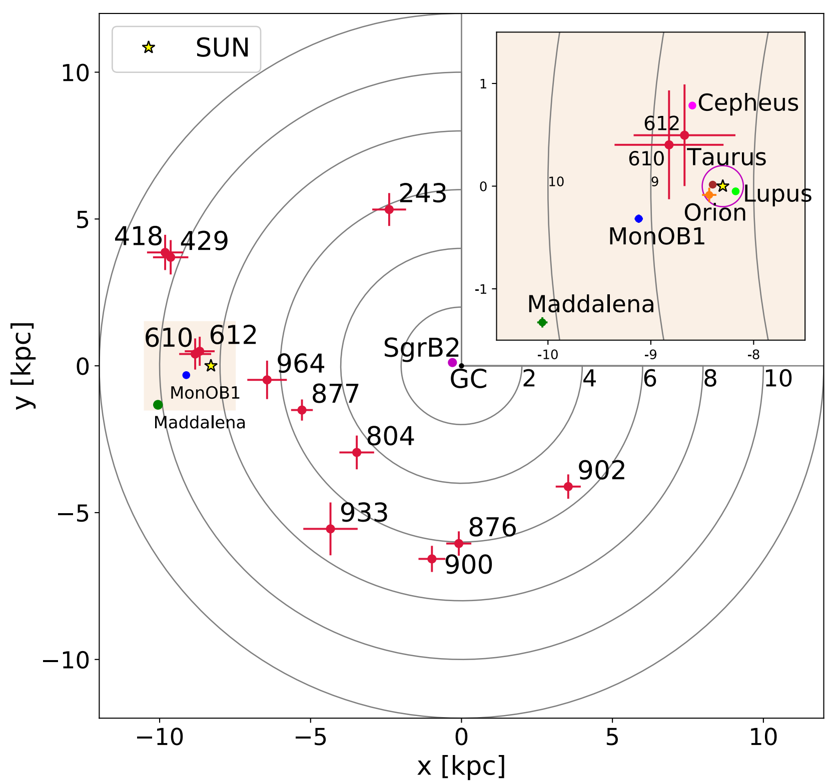
THE POSSIBLE ROLE OF UNRESOLVED SOURCES

Prothast, Gaggero, Strom, Weniger, 2018

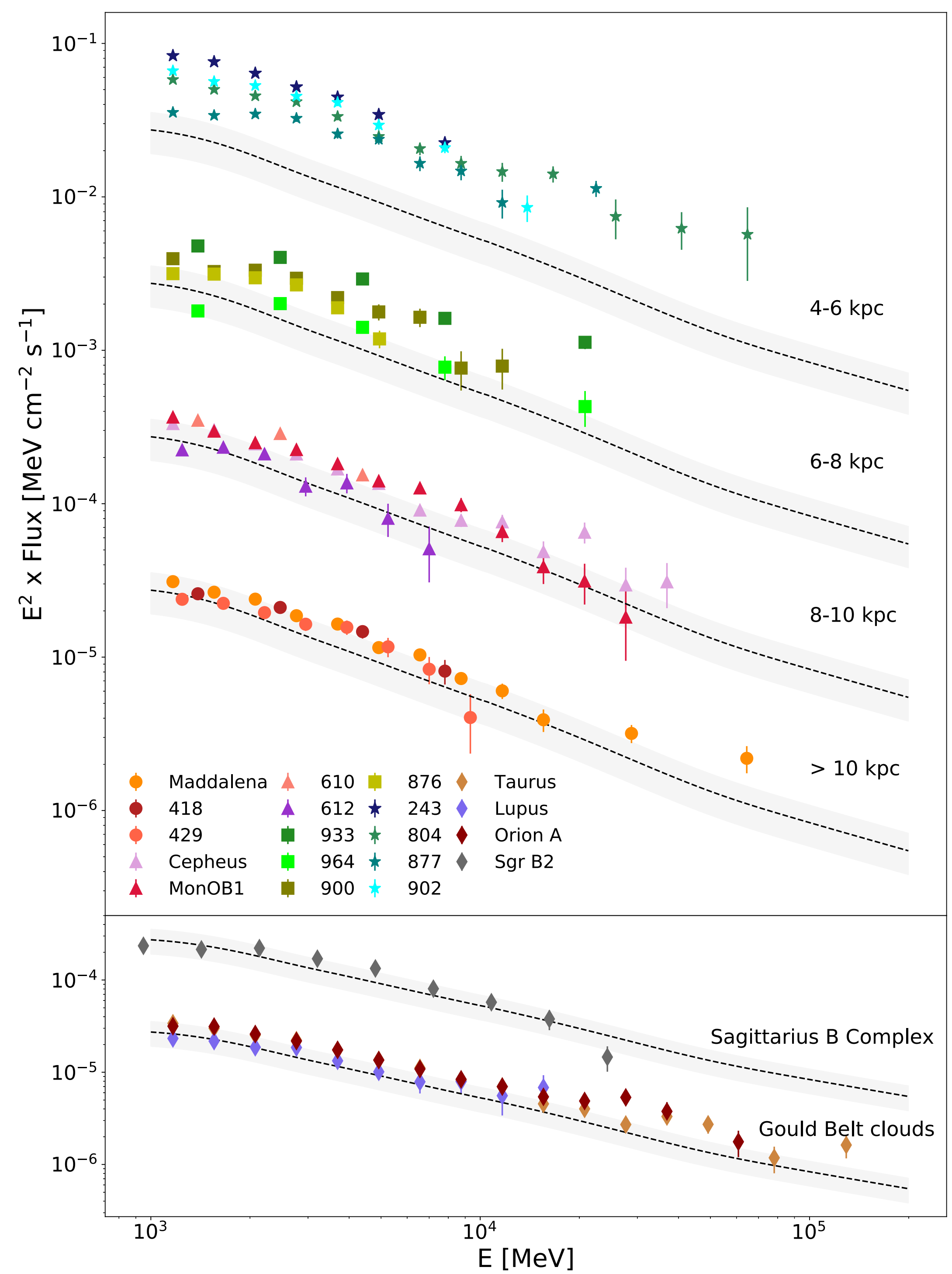


MOLECULAR CLOUDS AS A PROBE OF THE CR SEA

Aharonian, Peron, Yang, Zanin, Casanova, 2018



Use Fermi-LAT data for selected isolated clouds



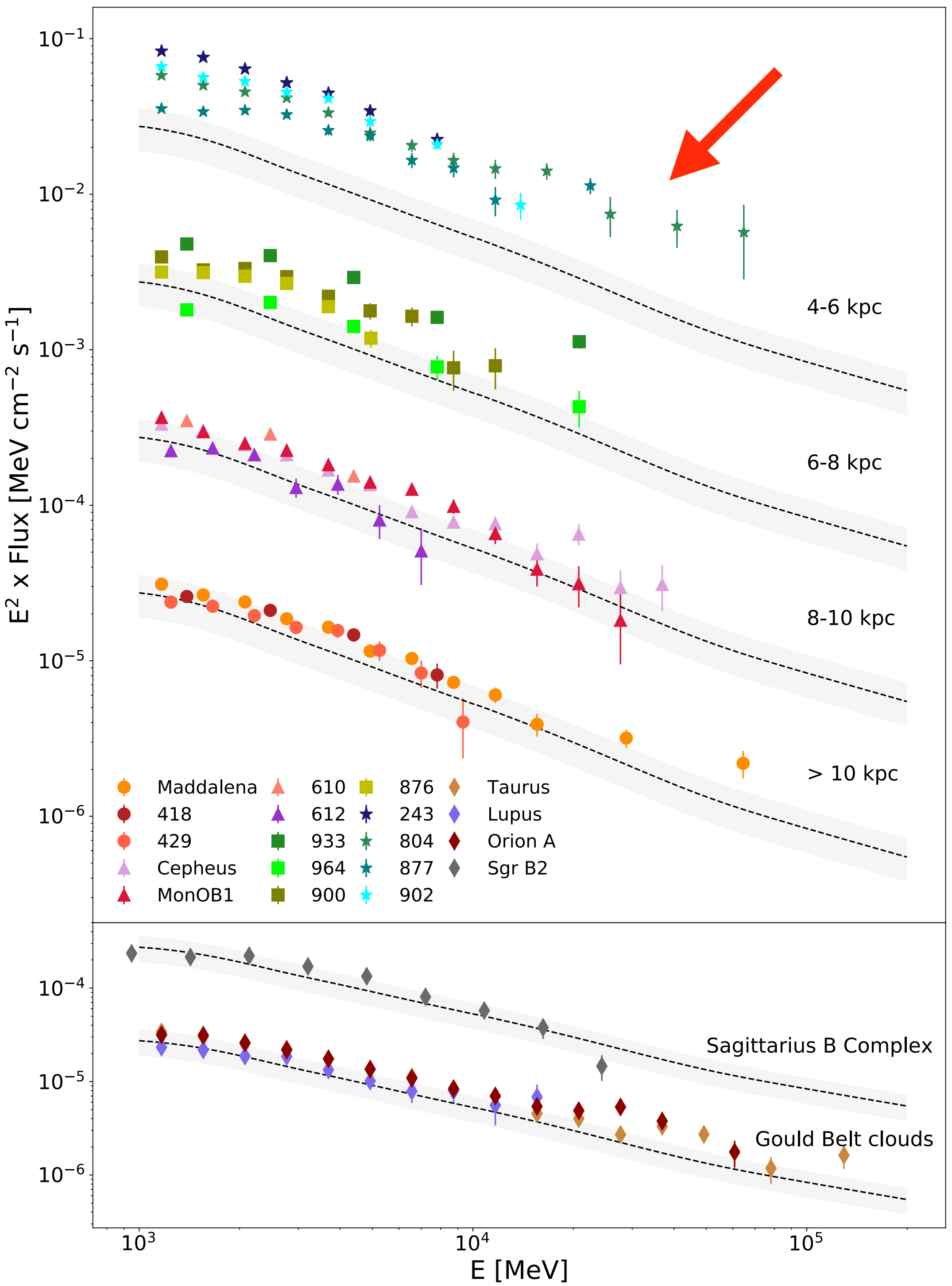
MOLECULAR CLOUDS AS A PROBE OF THE CR SEA

Aharonian, Peron, Yang, Zanin, Casanova, 2018

"... all four clouds located in the 4-6 kpc ring, show significantly, by a factor of 2-3, enhanced γ-ray fluxes, as well as systematically harder energy spectra compared to γ rays induced by the sea of CRs (see Fig.2). This generally agrees with the results derived from the diffuse γ-radiation of the Galactic disk."

The authors however argue that the effect is not statistically significant and it may be due to contamination from sources in that dense region

Very promising proof of concept which will be fully exploited by CTA!



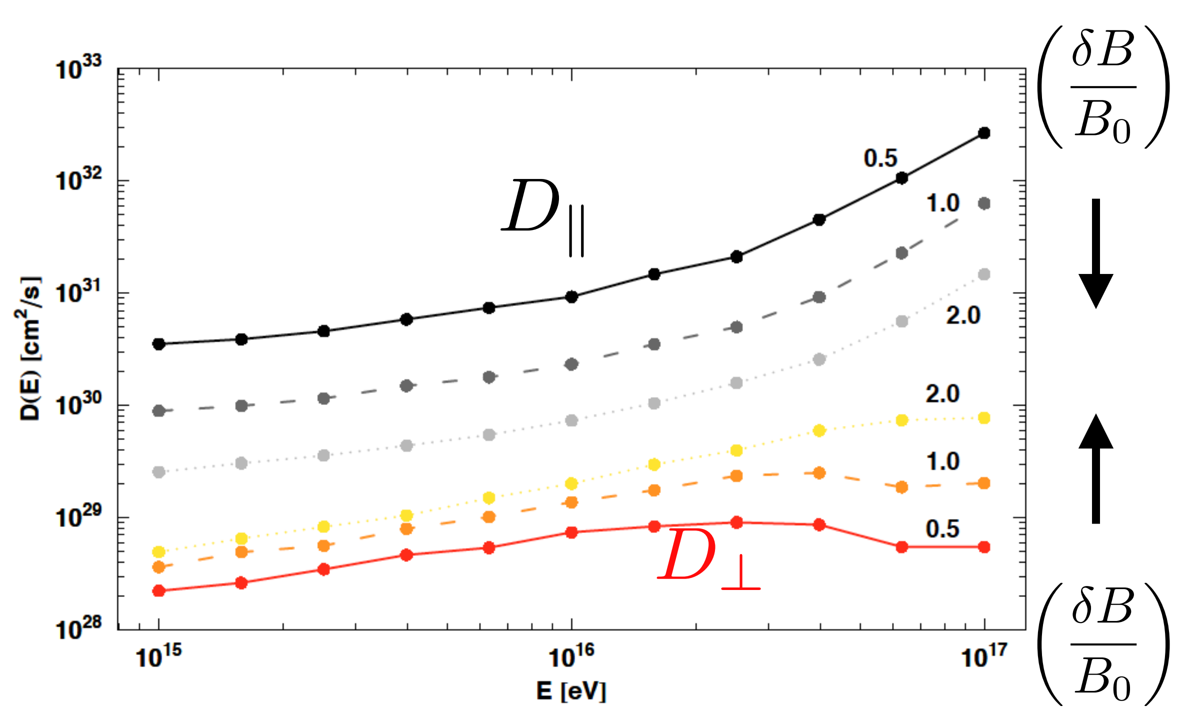
THEORETICAL INTERPRETATION

The regular magnetic field (with versor ***b***) breaks isotropy

$$D_{ij} = (D_{\parallel} - D_{\perp}) b_i b_j + D_{\perp} \delta_{ij} + D_A \epsilon_{ijk} b_k$$

if ***b*** is purely azimuthal only $D_{\perp}$ matters. Isotropy is restored for strong turbulence but for realistic conditions $D_{\perp} / D_{\parallel} \sim 0.01 - 0.1$

Perpendicular diffusion however may be dominant due to the quasi-azimuthally symmetric geometry of the regular magnetic field

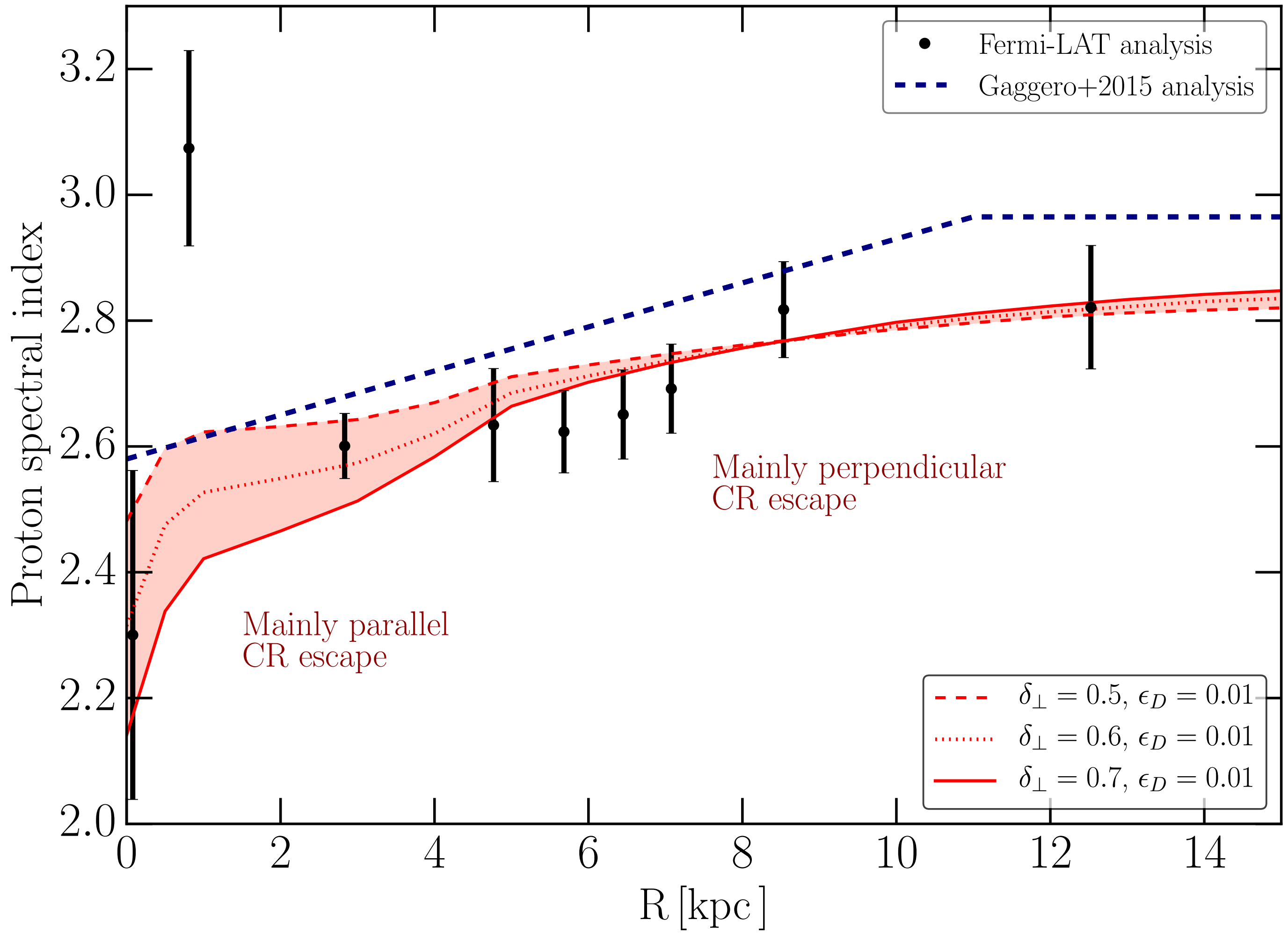


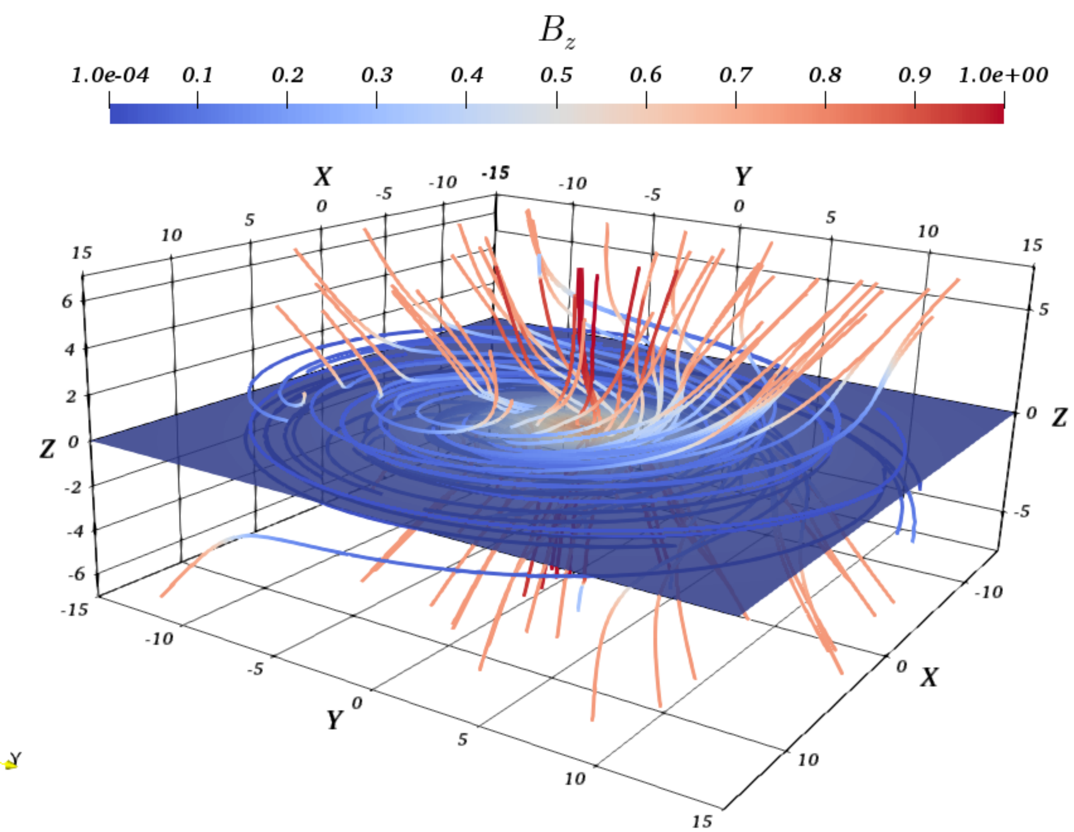
De Marco, Blasi & Stanev 2007

THEORETICAL INTERPRETATION

Cerri, Gaggero, Vittino, Evoli & DG, JCAP 2017

using ***DRAGON 2 (JCAP 2017)***





- Poloidal magnetic field become larger toward the GC
- Parallel diffusion (irrelevant at large radii) becomes more and more relevant for small R
- Particle tracing numerical simulations
  Casse+ 2001, De Marco+ 2007 , Snodin + 2015

$$D_{||} \propto \rho^{1/3} \qquad D_{\perp} \propto \rho^{1/2}$$

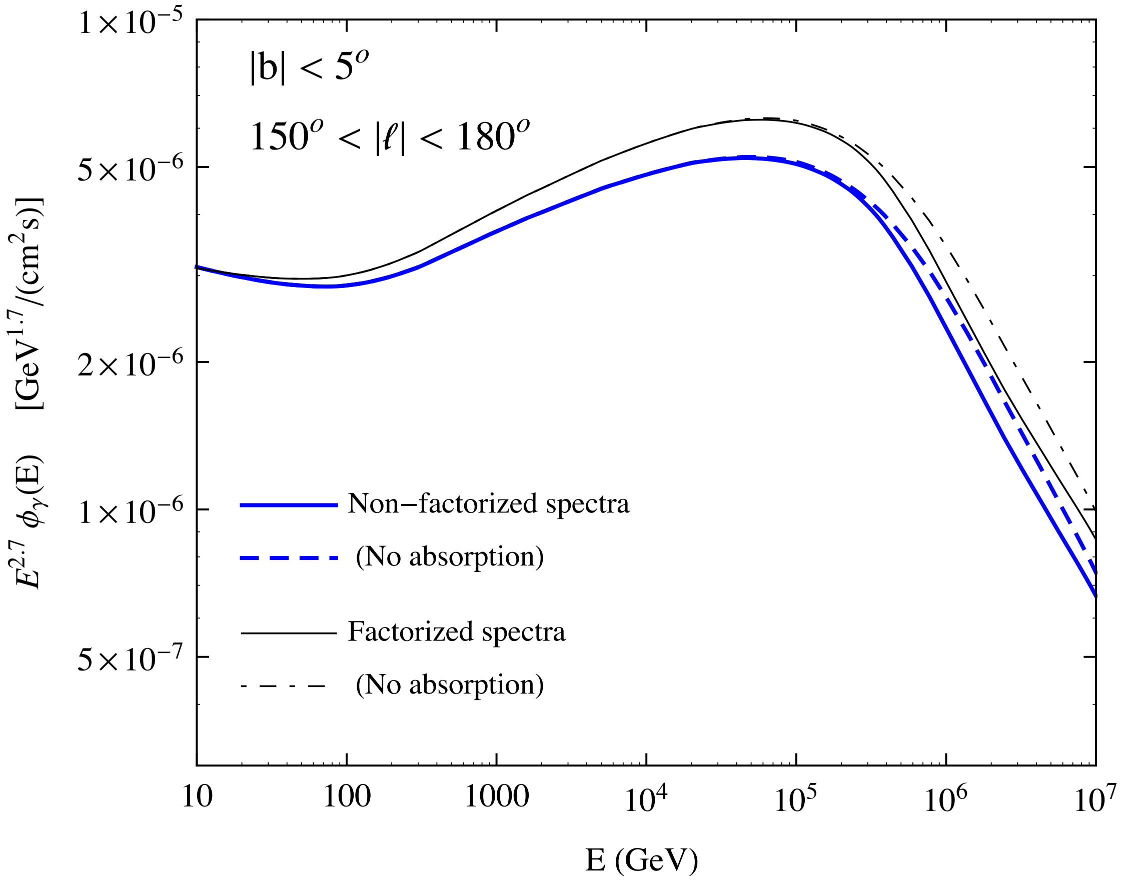
Magnetic field model
Jansson & Farrar ApJ 2012
Terral & Ferriere 2016

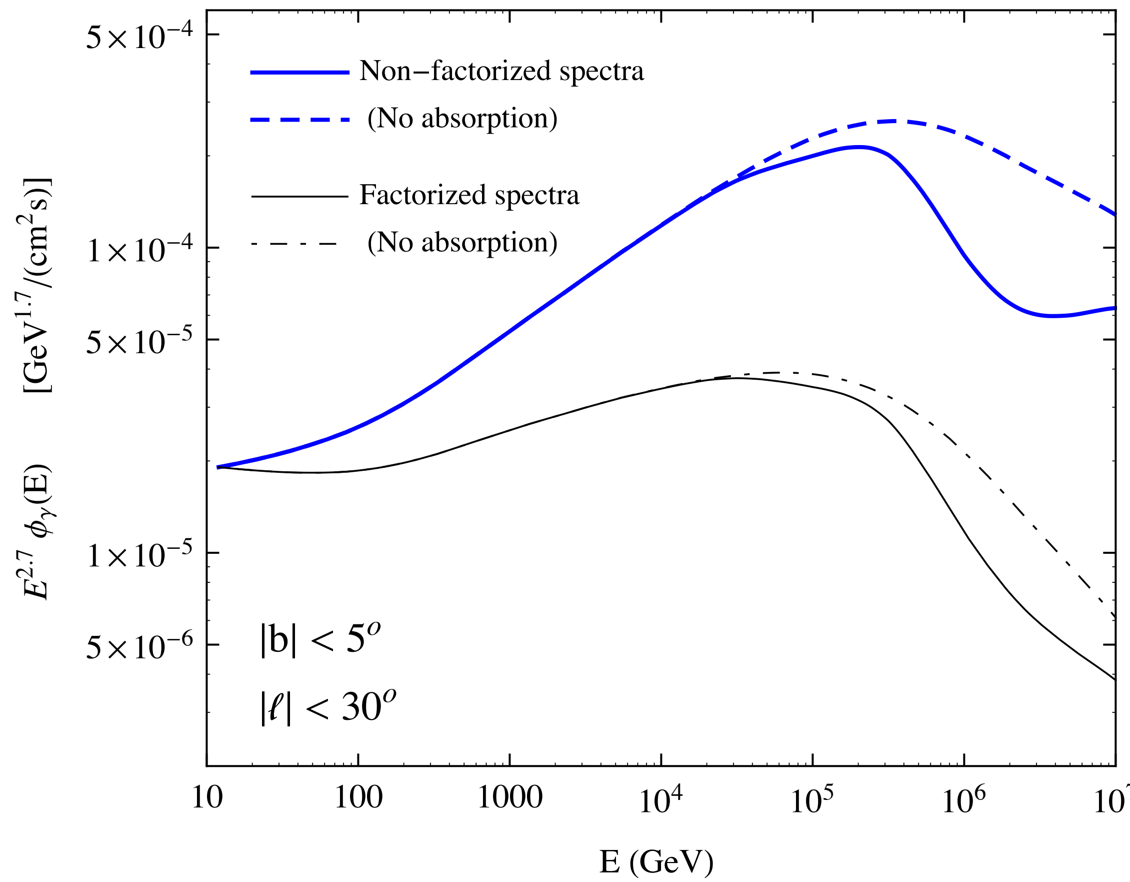
➜ CR spectrum becomes harder for R ➜ 0 . The effect holds at large energies

IMPLICATIONS FOR THE GAMMA-RAY AND NEUTRINO ASTRONOMY ABOVE THE TEV

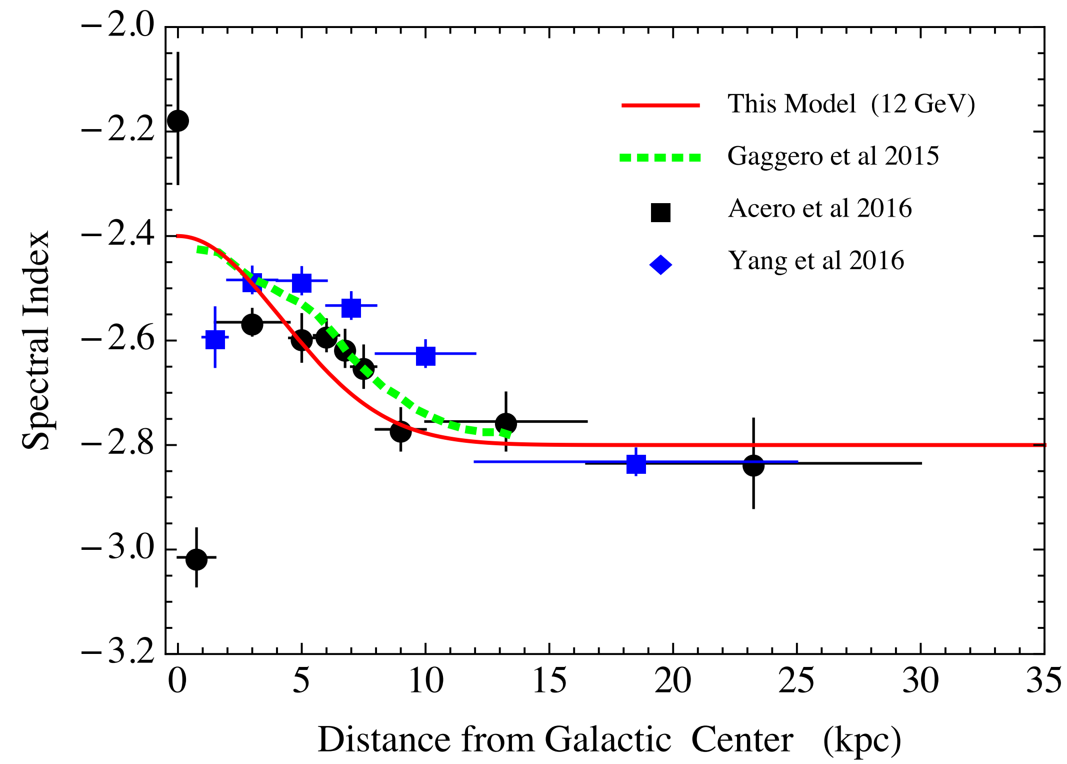
AN ANALYTICAL IMPLEMENTATION

Lipari & Vernetto, 2018





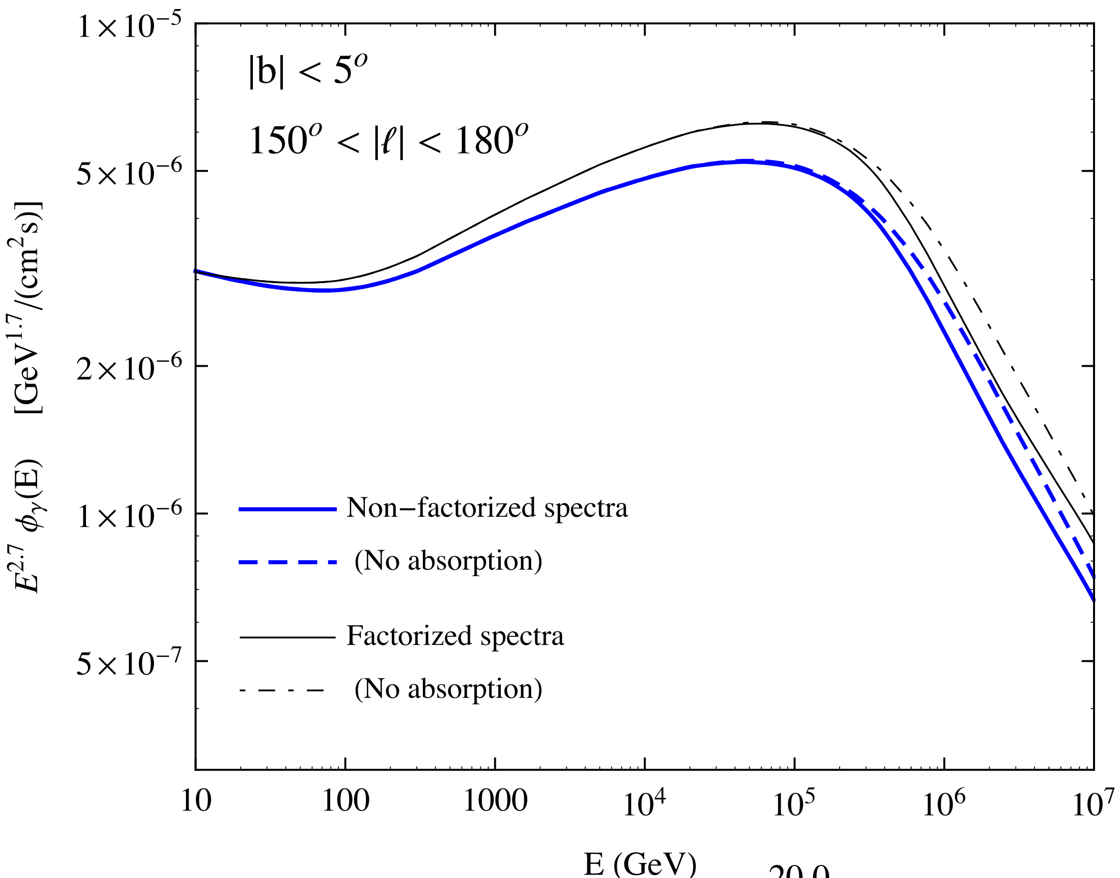
Parametric model implementing a factorized CR spectrum mimicking the numerical gamma-model

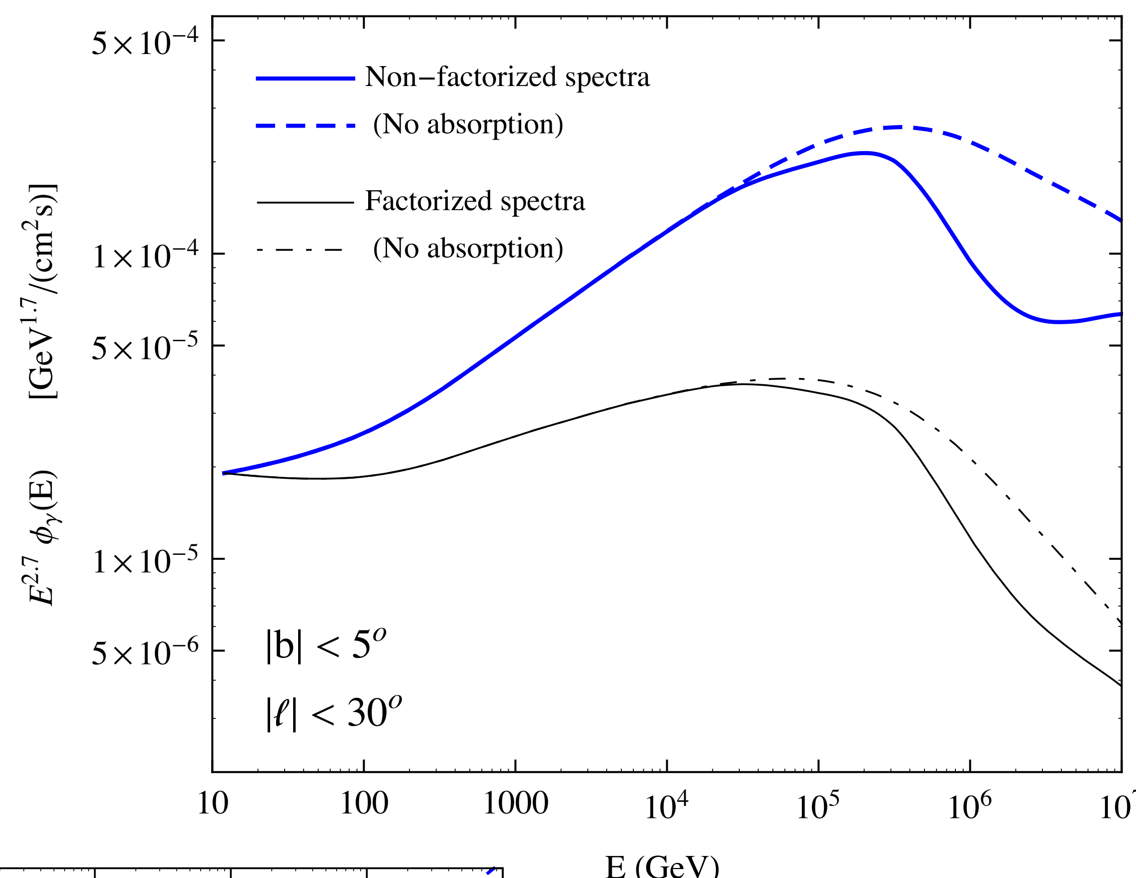


Dramatic flux enhancement at low longitudes above the TeV !!

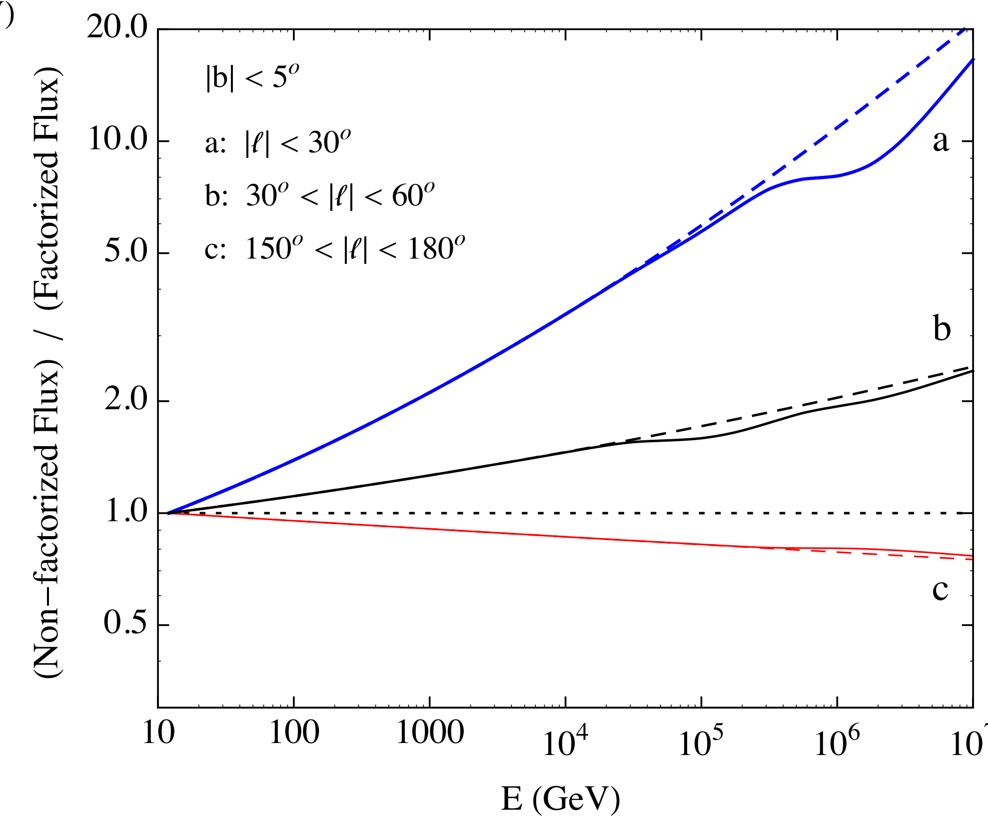
AN ANALYTICAL IMPLEMENTATION

Lipari & Vernetto, 2018





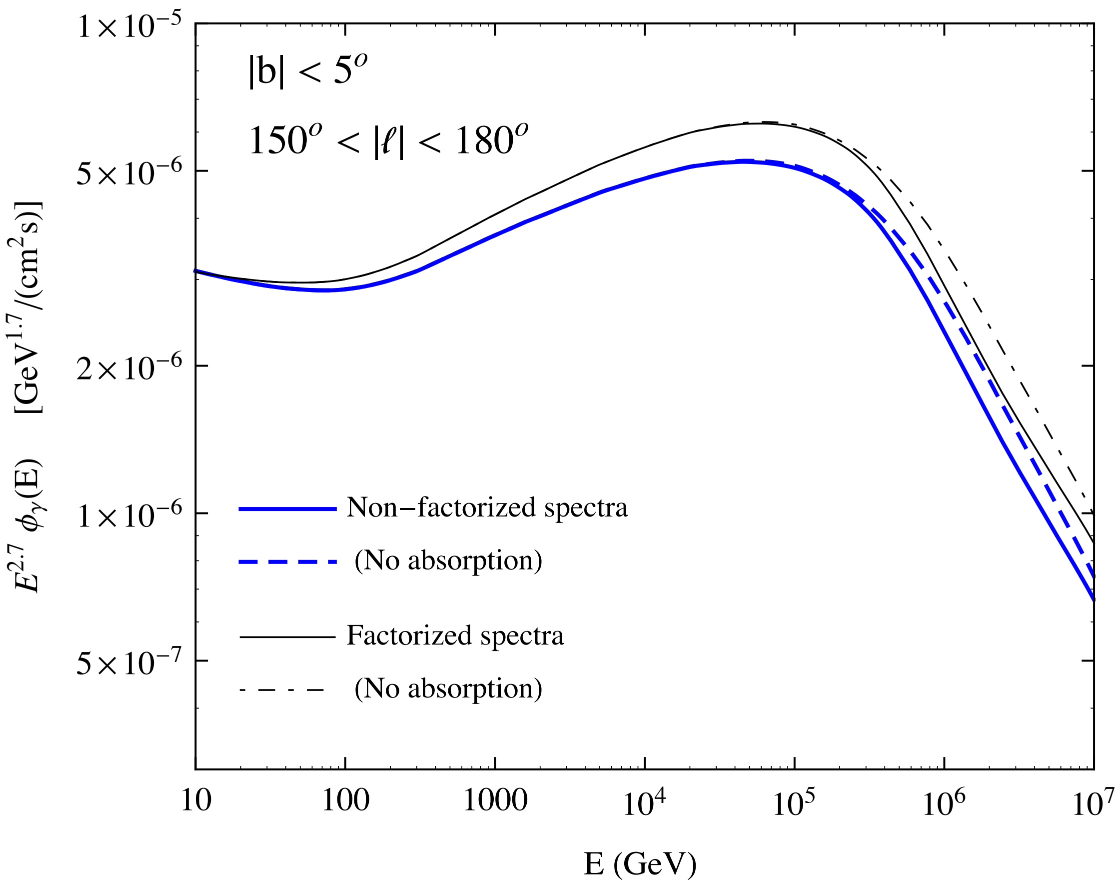
Parametric model implementing a factorized CR spectrum mimicking the numerical gamma-model

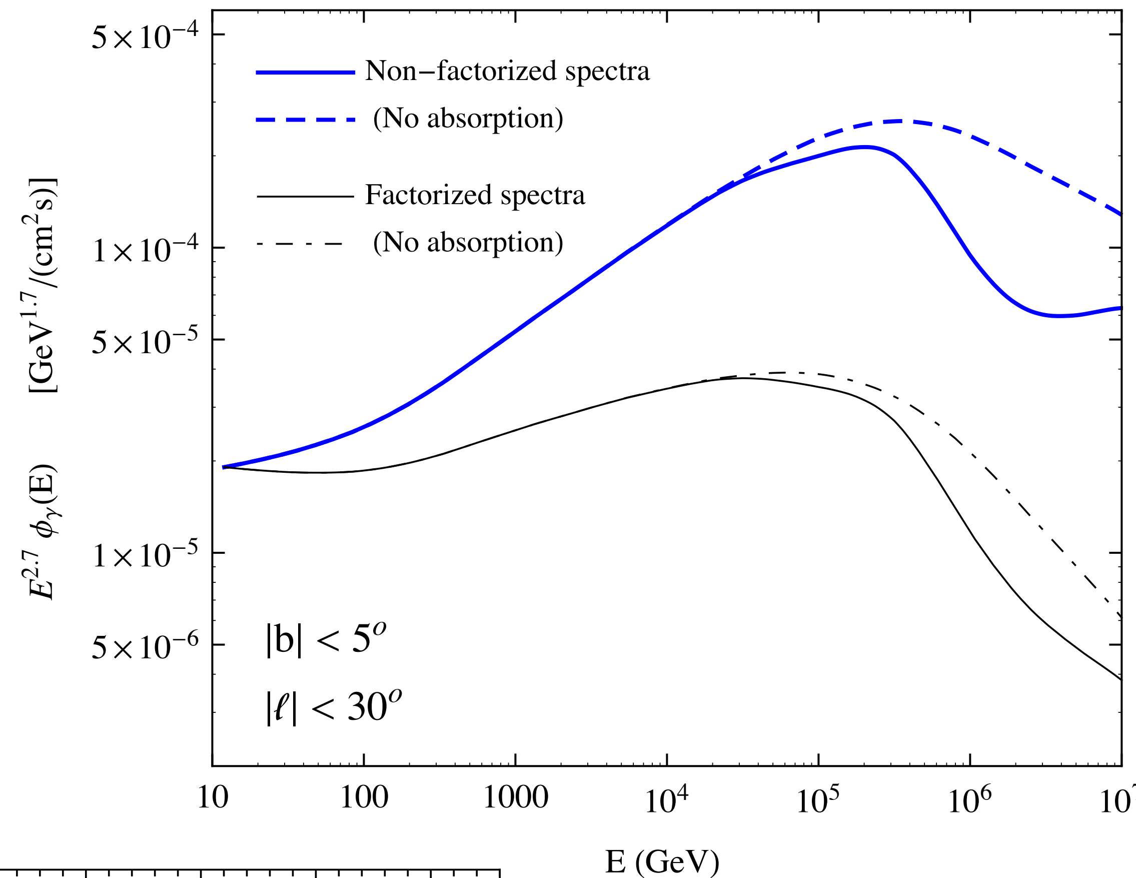


Dramatic flux enhancement at low longitudes above the TeV !!

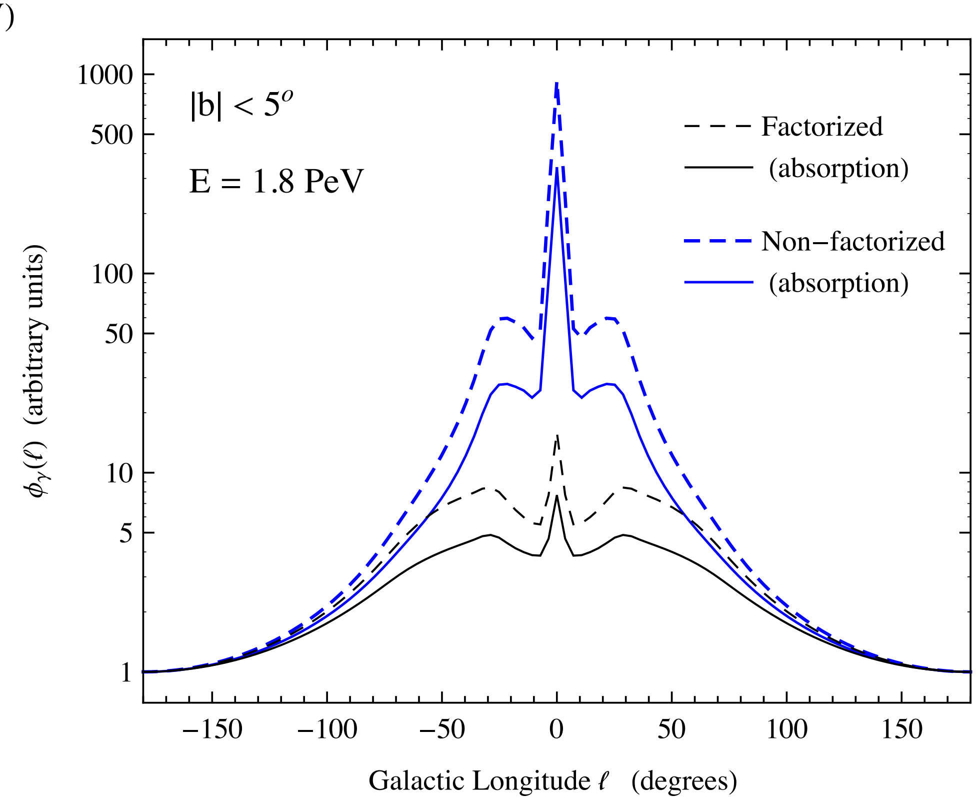
AN ANALYTICAL IMPLEMENTATION

Lipari & Vernetto, 2018



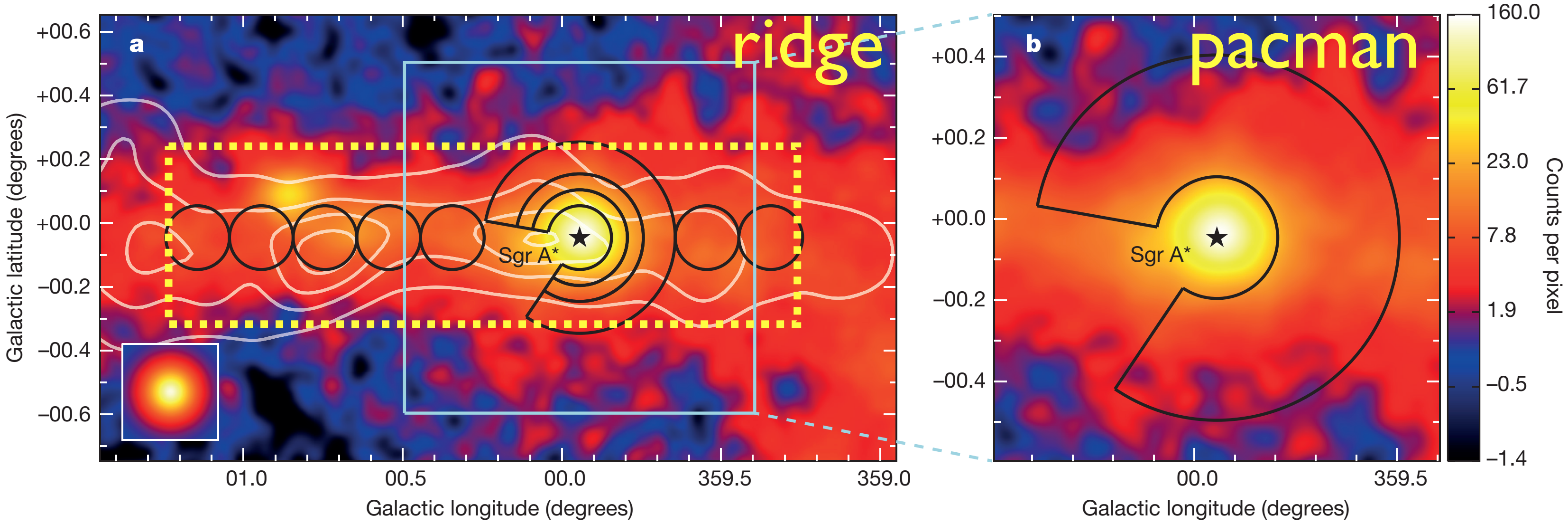


Parametric model implementing a factorized CR spectrum mimicking the numerical gamma-model



Dramatic flux enhancement at low longitudes above the TeV !!

DIFFUSE EMISSION FROM THE GALACTIC CENTER



H.E.S.S. coll. Nature 2006, Nature 2016 A&A 2017

Same spectra in the ridge

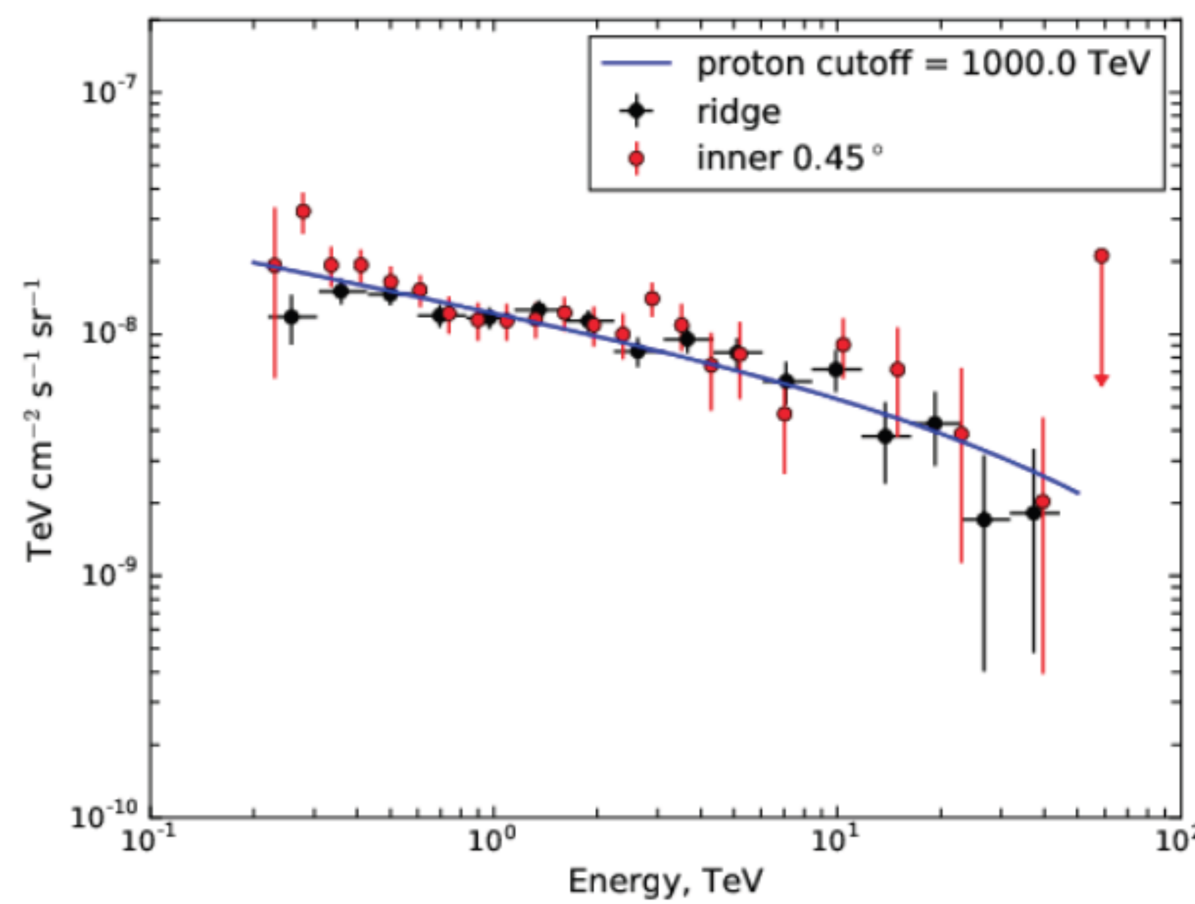
$(| l | < 1° , | b | < 0.3°), d < 150$ pc

$\Gamma_{HESS17} = 2.28 \pm 0.03_{stat} \pm 0.2_{sys}$

and in the "*pacman*"

$0.15° < \theta < 0.45°$, $22 < d < 67$ pc

$\Gamma_{HESS16} = 2.32 \pm 0.05_{stat} \pm 0.11_{sys}$



DIFFUSE EMISSION FROM THE GALACTIC CENTER

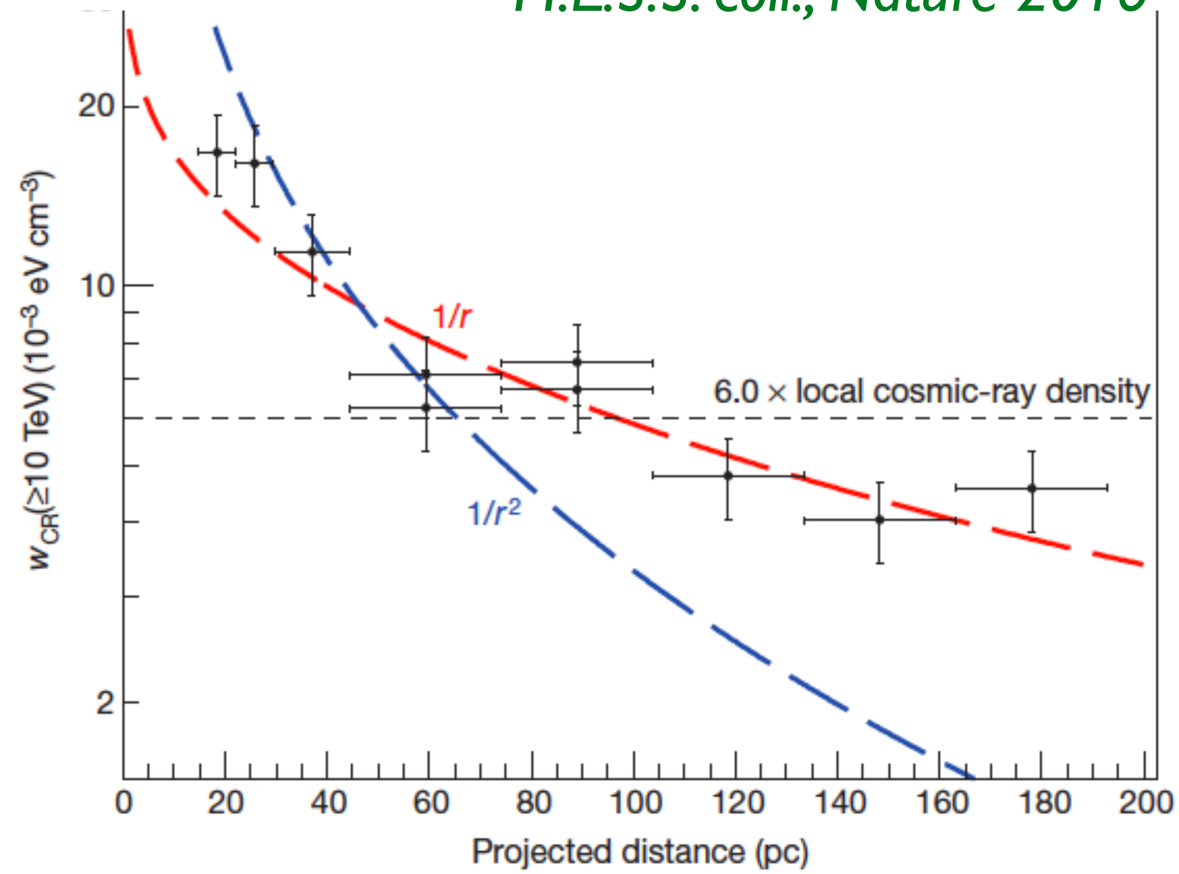
the PeVatron scenario

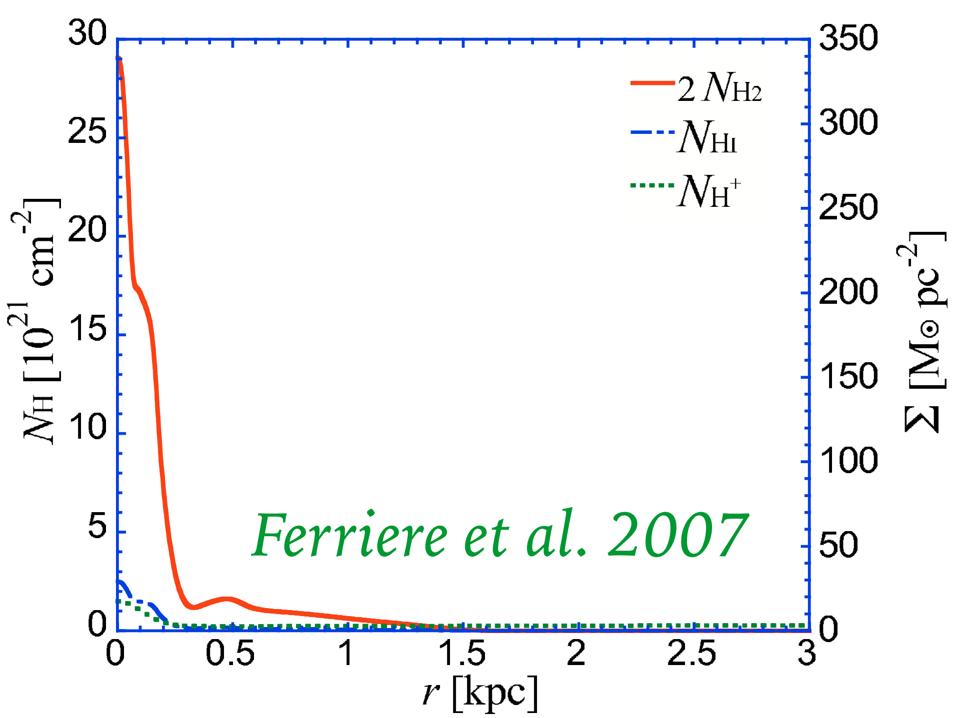
At the GC the emission profile seems more peaked than the estimated gas distribution.

The inferred CR density profile is consistent with that expected from CR diffusing out a stationary source

$$w_{\rm CR}(E,r) = \frac{Q_{\rm source}(E)}{4\pi D(E)}\,\frac{1}{r}$$

H.E.S.S. coll., Nature 2016





Possible loopholes:

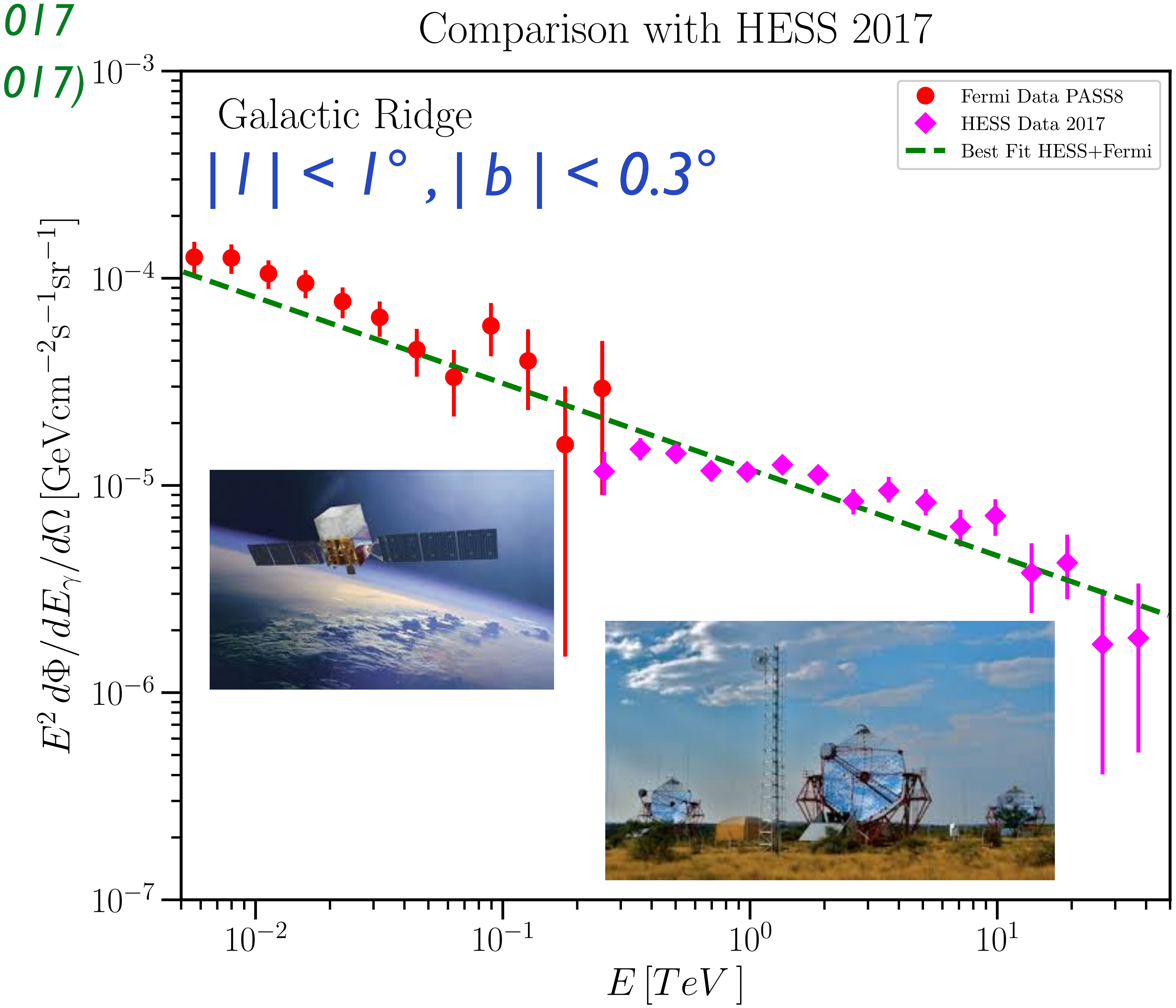
- *the H_2 tracer's emission (CO, CS .. lines) may be absorbed in high density clouds*
- *only the projected distance from the GC is observed. HESS collaboration assumes a uniform gas density along the line of sight in the CMZ. This may give rise to a bias.*

DIFFUSE EMISSION FROM THE GALACTIC CENTER

H.E.S.S. + Fermi

Gaggero, D.G., A. Marinelli, Taoso & Urbano, PRL 2017

“ + S.Ventura (ICRC 2017)



$\Gamma_{\mathrm{HESS + FERMI}} = 2.33 \pm 0.03$

implies $\Gamma \sim 2.45$ for primary protons

Data clearly suggest a unique origin of the emission from few GeV to ~ 40 TeV ! Notice that Fermi data are consistent with the emission being originated by the Galactic CR sea !!

PASS8 Fermi-LAT 516 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FHL catalogue subtracted.

DIFFUSE EMISSION FROM THE GALACTIC CENTER

comparison with the Gamma model

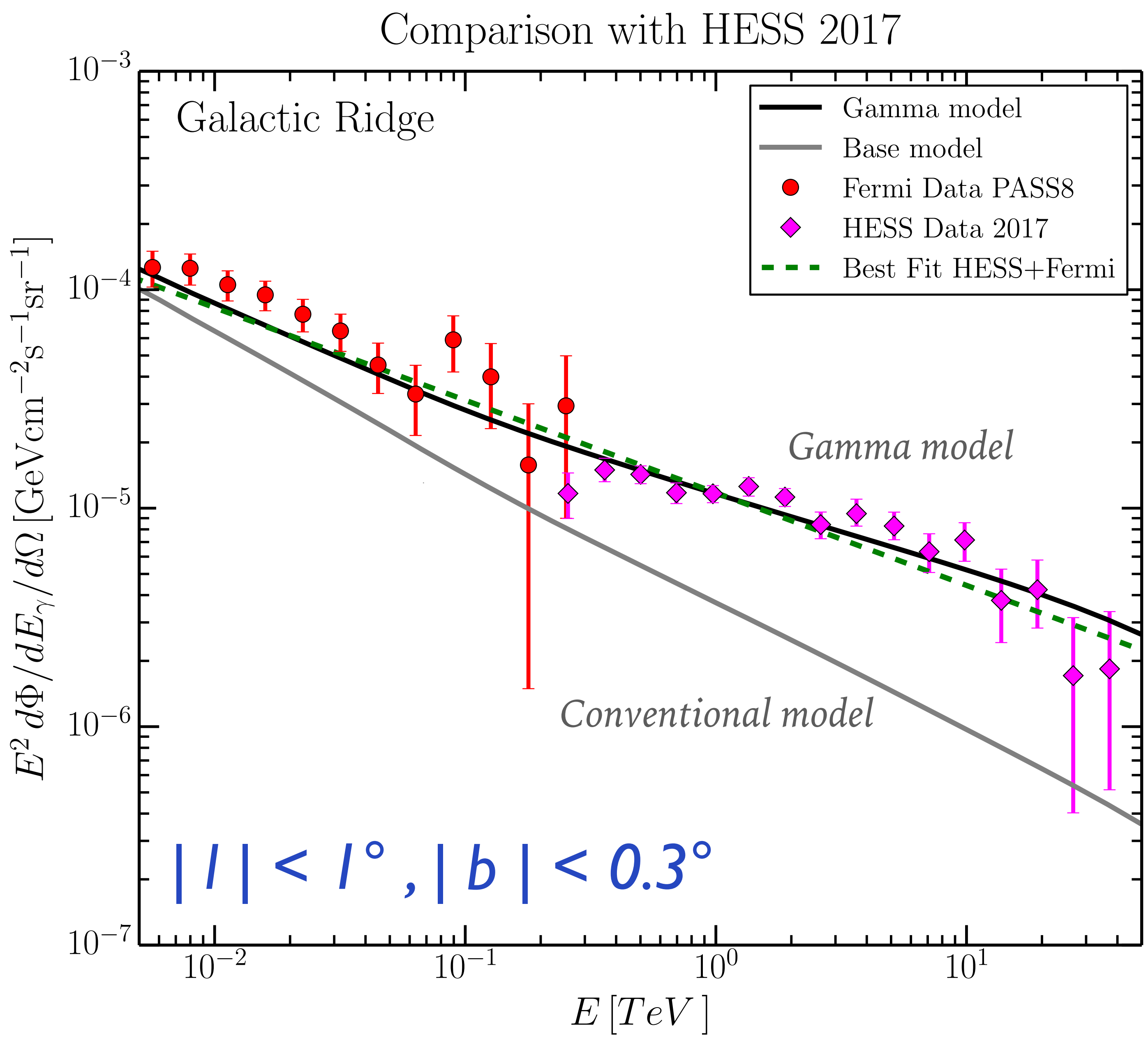
Gaggero, D.G., A. Marinelli, Taoso & Urbano, PRL 2017
" + S. Ventura (ICRC 2017)

The gamma model matches the diffuse emission spectrum inferred from FERMI + HESS data in the ridge and inner regions

Gas density is degenerate with the CR density normalization. Using Case & Bhattacharya (1998) SNR distribution and Ferriere 2007 3-D gas distribution

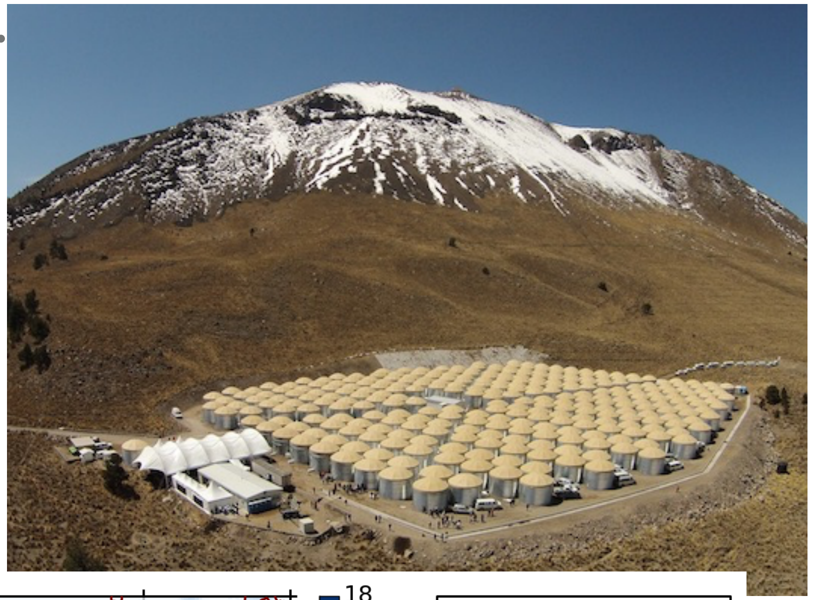
γ -ray data are matched if

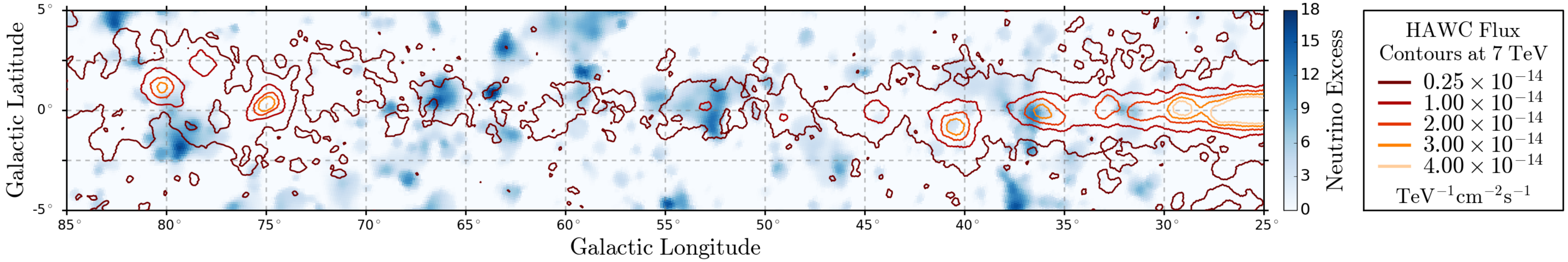
$X_{CO}(R = 0) = 0.6 \times 10^{20}\ cm^{-2}\ (K\ km/s)^{-1}$ which is a quite reasonable value.



DIFFUSE EMISSION FROM THE INNER GP ABOVE THE TEV

HAWC preliminary results





HAWC-IceCube Synergy

- ✓HAWC targets the portion of sky IceCube is the most sensitive.
- ✓HAWC operates at very high energies related to IceCube.
- ✓HAWC can study sources with any extension.

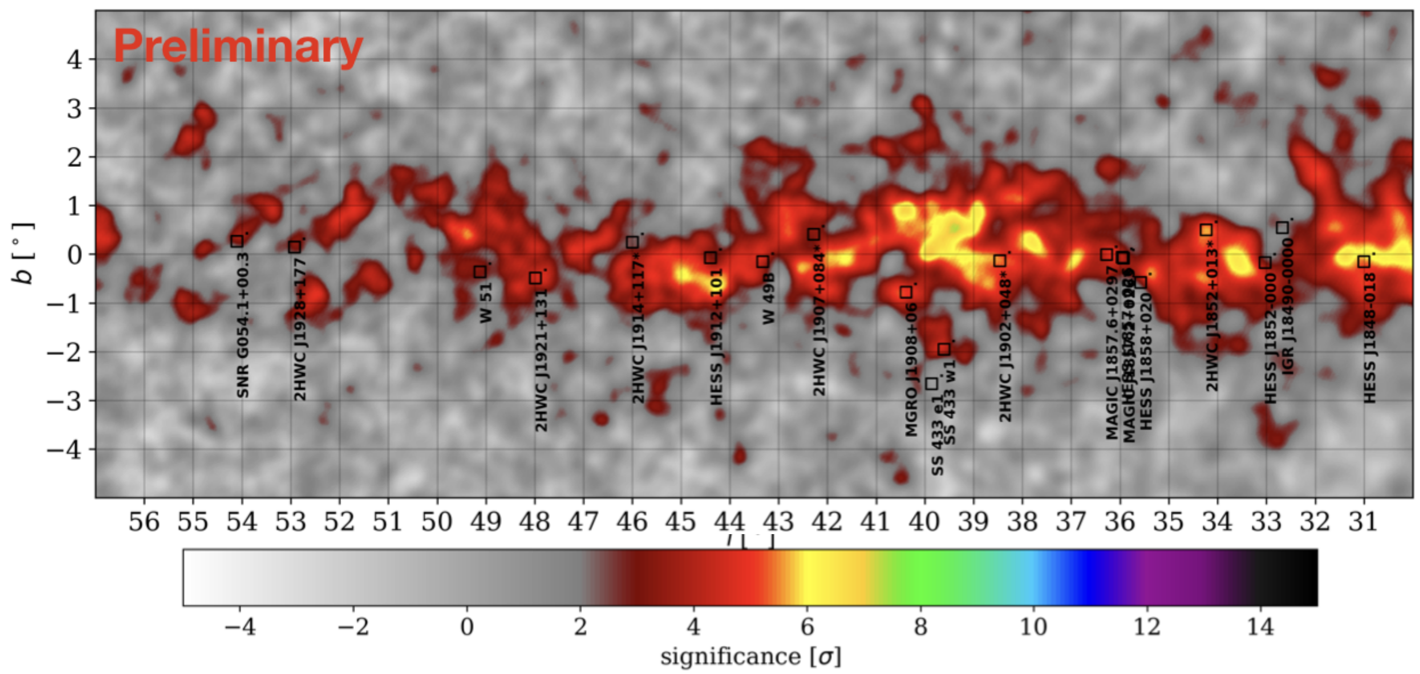
The contribution of Galactic sources to the IceCube neutrino flux is limited to less than 15%.

*Kheirandish, Wood + **HAWC** coll. ICRC 2019.*

DIFFUSE EMISSION FROM THE INNER GP ABOVE THE TEV

HAWC preliminary results

Nayerhoda, Salesa, Casanova, Gaggero, DG, Marinelli + ***HAWC*** *coll. , ICRC 2019.*



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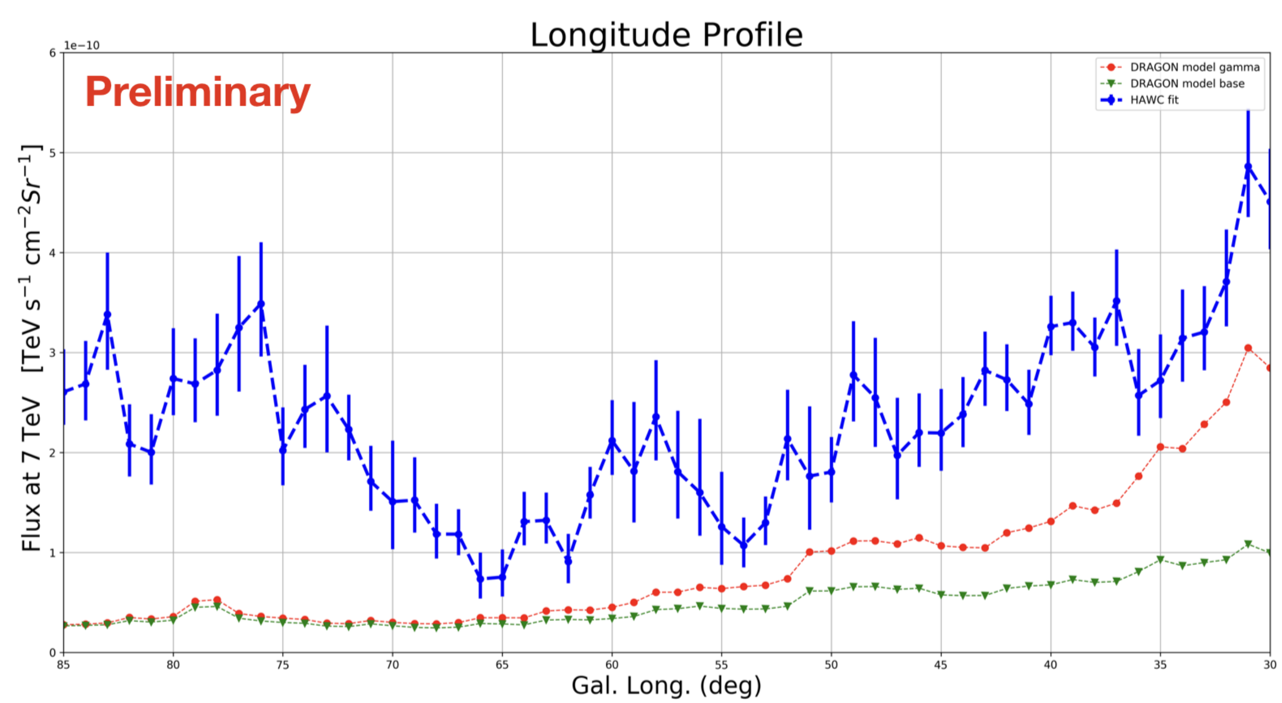


HAWC diffuse

KRAγ model

conventional model

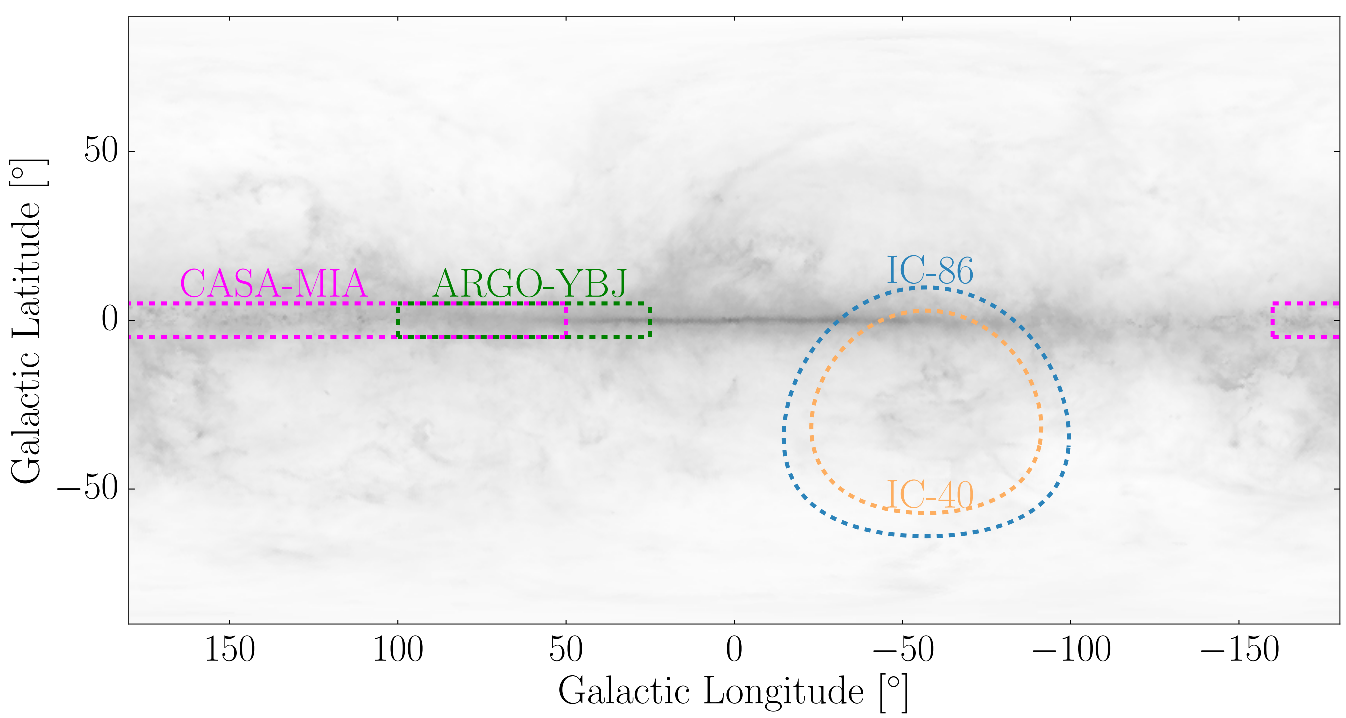
Galactic Longitude profile at 7 TeV.

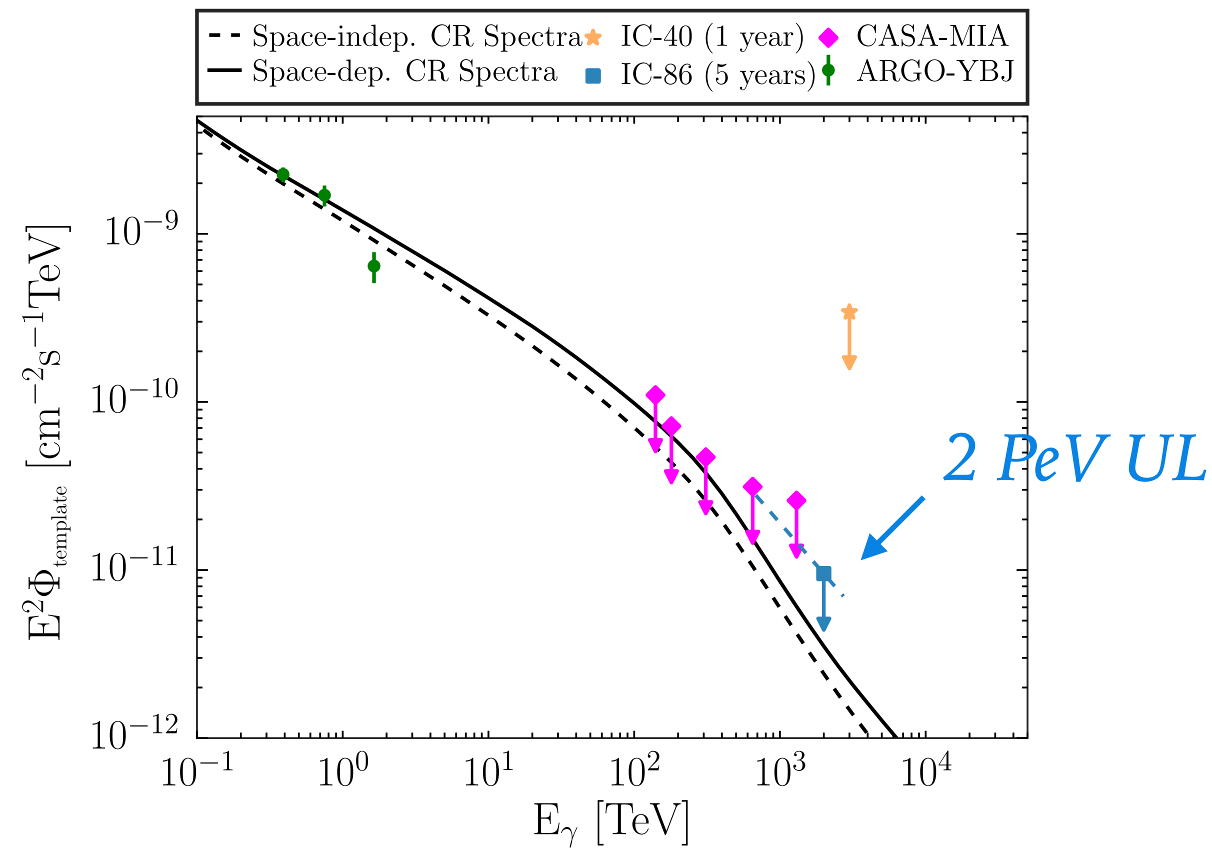
DIFFUSE EMISSION FROM THE INNER GP ABOVE THE TEV

results from air-shower experiments

IceCube coll. 1908.09918

IceTop + IceCube





The factorized scenario is compatible with IceCube + IceTop upper limits and at hand of its upgrades !

it accounts for opacity due to $\gamma\,\gamma$ scattering onto the ISRF based on Vernetto & Lipari PRD 2018

NEUTRINOS FROM THE GP

Gaggero, D.G., A. Marinelli, Urbano, Valli ApJ L 2015

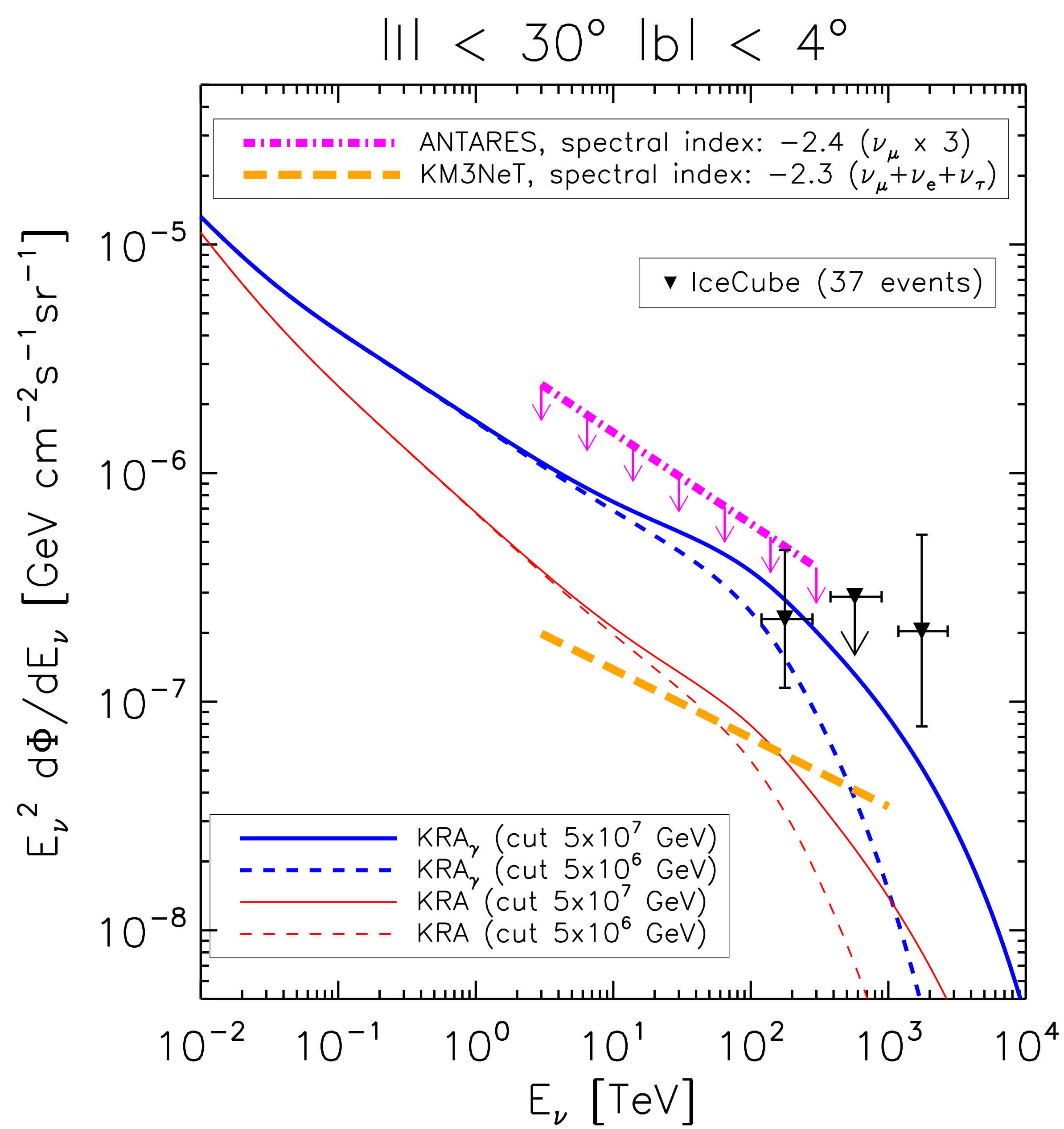
- Most of the emission predicted by the the KRAγ in the inner GP is hadronic ⇒ strong neutrino flux enhancement

- On the whole sky the KRAγ model predict a flux which is 15 % at most (8 % for conventional models) [for $E_{p,\,cut}$ = 50 PeV] of the astrophysical one measured by IceCube.

- In the innermost region of the GP the gain factor is much larger

- A neutrino telescope in the North hemisphere is more suited to detect the Galactic component. We computed the upper limit on the basis of ANTARES data in the region.

- Observable by KM3NeT !



NEUTRINOS FROM THE GP

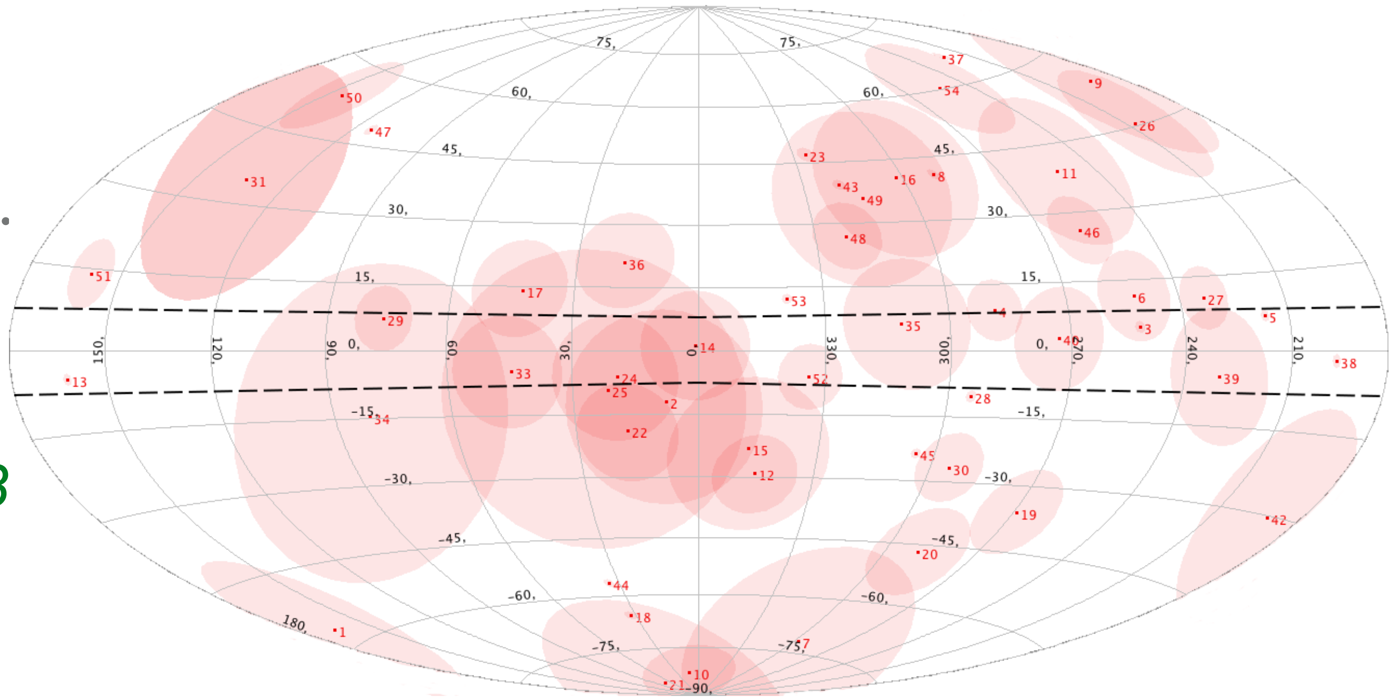
IceCube + ANTARES constraints

ANTARES coll., Phys. Lett. B, 2016

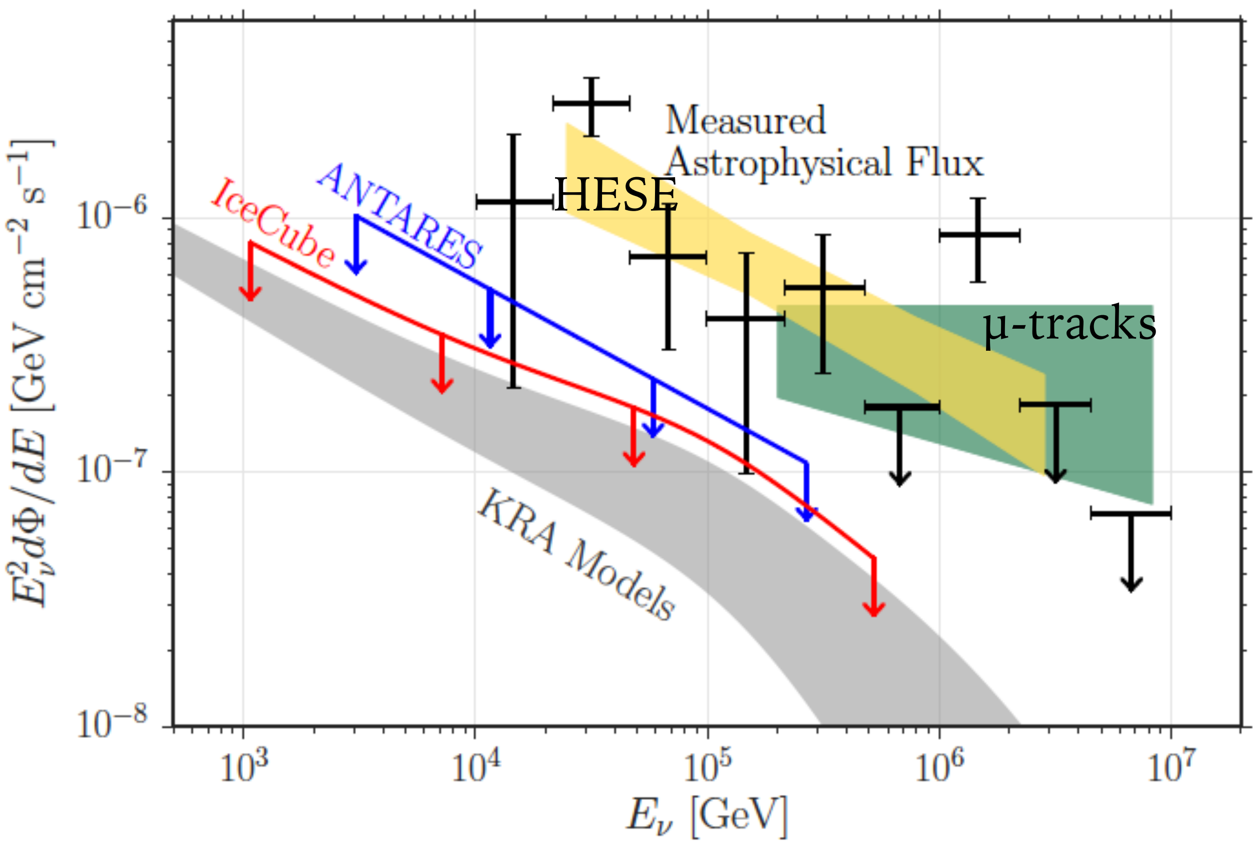
ANTARES coll. + D. Gaggero & D.G. PRD 2017

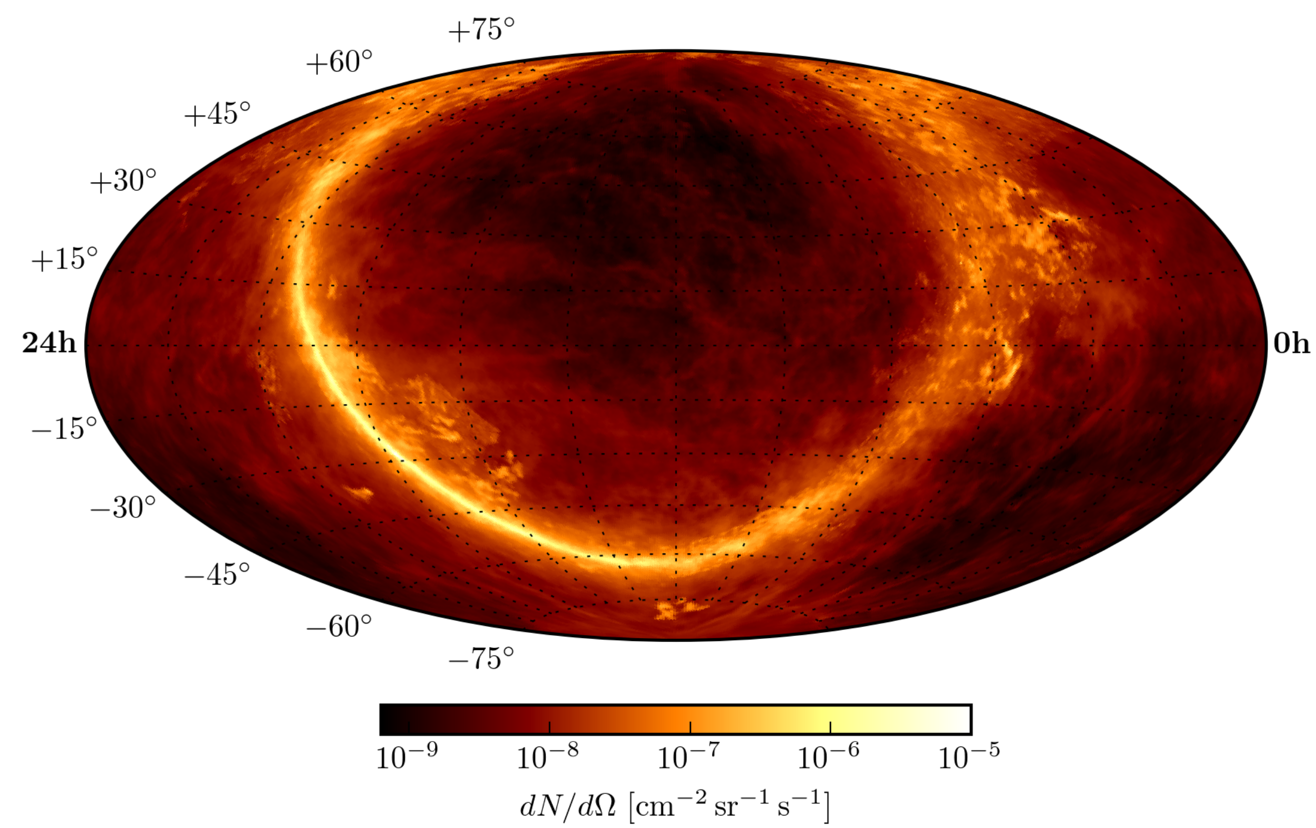
ANTARES + IceCube + D. Gaggero & D.G., APJ 2018

Based on 10 y of ANTARES data (showers + tracks) + 7 y IceCube (tracks)



Use KRAγ model ($E_{p,\,cut}$ = 5 PeV) as a template





NEUTRINOS FROM THE GP

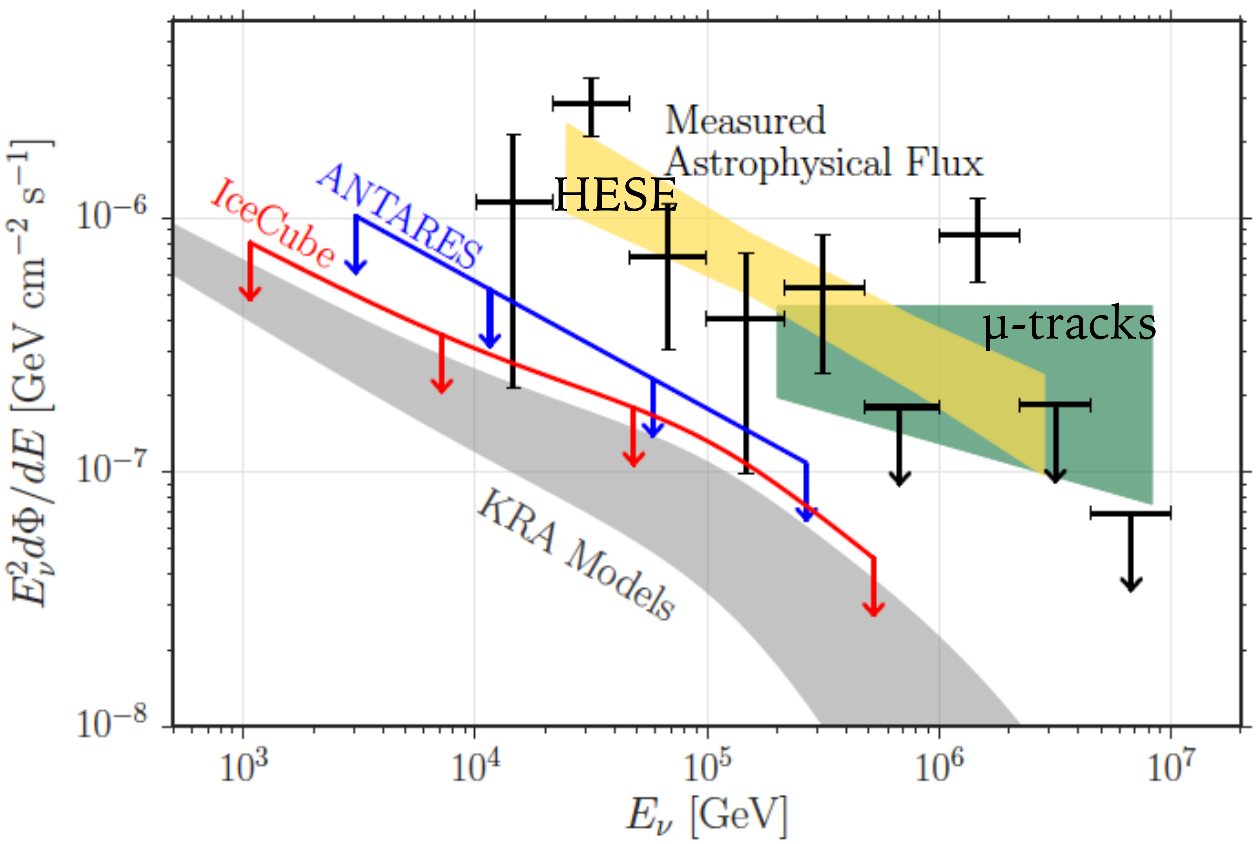
IceCube + ANTARES constraints

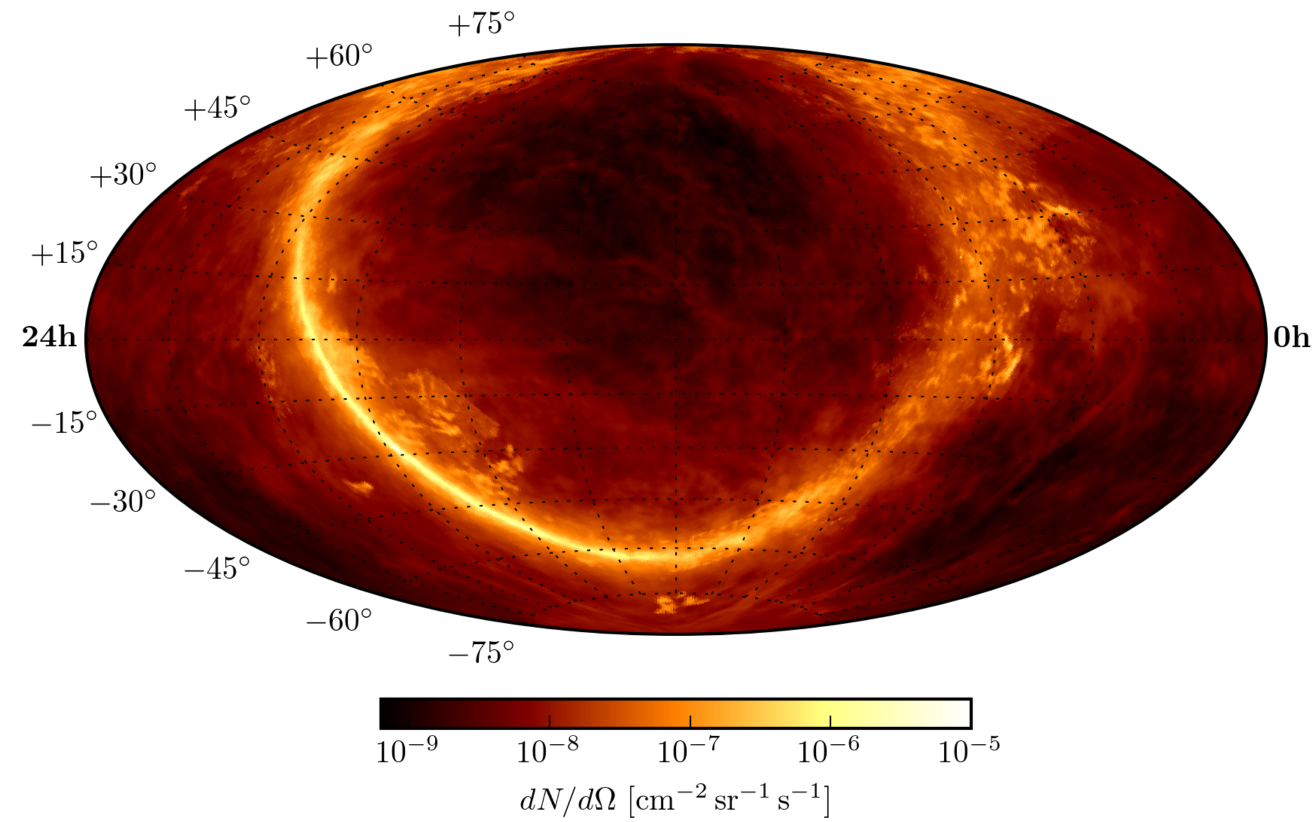
ANTARES coll., Phys. Lett. B, 2016
ANTARES coll. + D. Gaggero & D.G. PRD 2017
ANTARES + IceCube + D. Gaggero & D.G., APJ 2018

The diffuse emission from the GP is constrained to be < 8.5 % of the total astrophysical flux

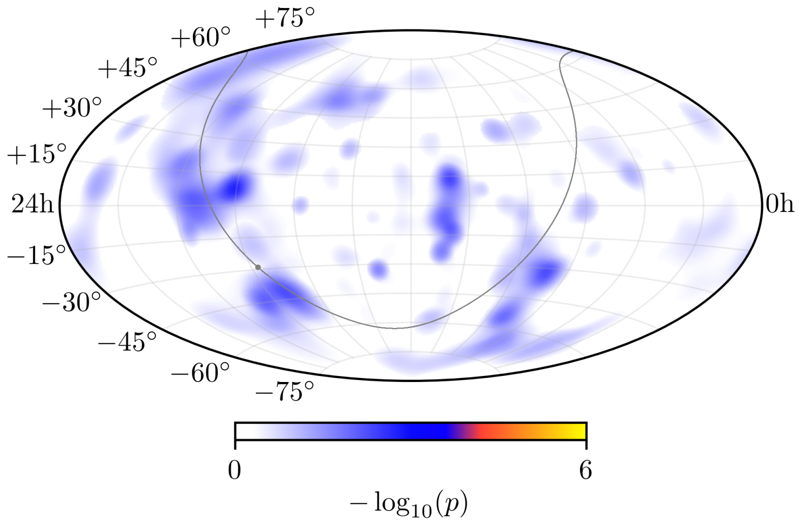
Table 1. Sensitivities and results of the analysis on the KRA_γ models with the 5 and 50 PeV cutoffs.

Energy cutoff	Sensitivity $[\Phi_{\mathrm{KRA}_\gamma}]$			Fitted flux	p-value	UL at 90% CL
	Combined	ANTARES	IceCube	$[\Phi_{\mathrm{KRA}_\gamma}]$	[%]	$[\Phi_{\mathrm{KRA}_\gamma}]$
5 PeV	0.81	1.21	1.14	0.47	29	1.19
50 PeV	0.57	0.94	0.82	0.37	26	0.90





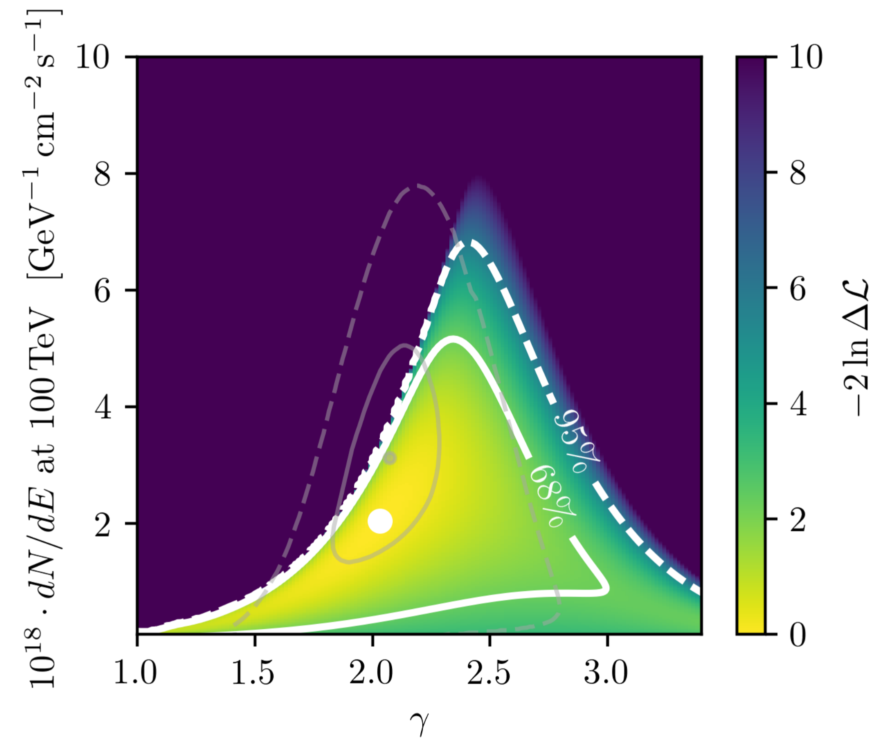
ICECUBE SHOWER EVENT ANALYSIS



IceCube, coll., ApJ 2019

7 years of data

New neural network reconstruction analysis



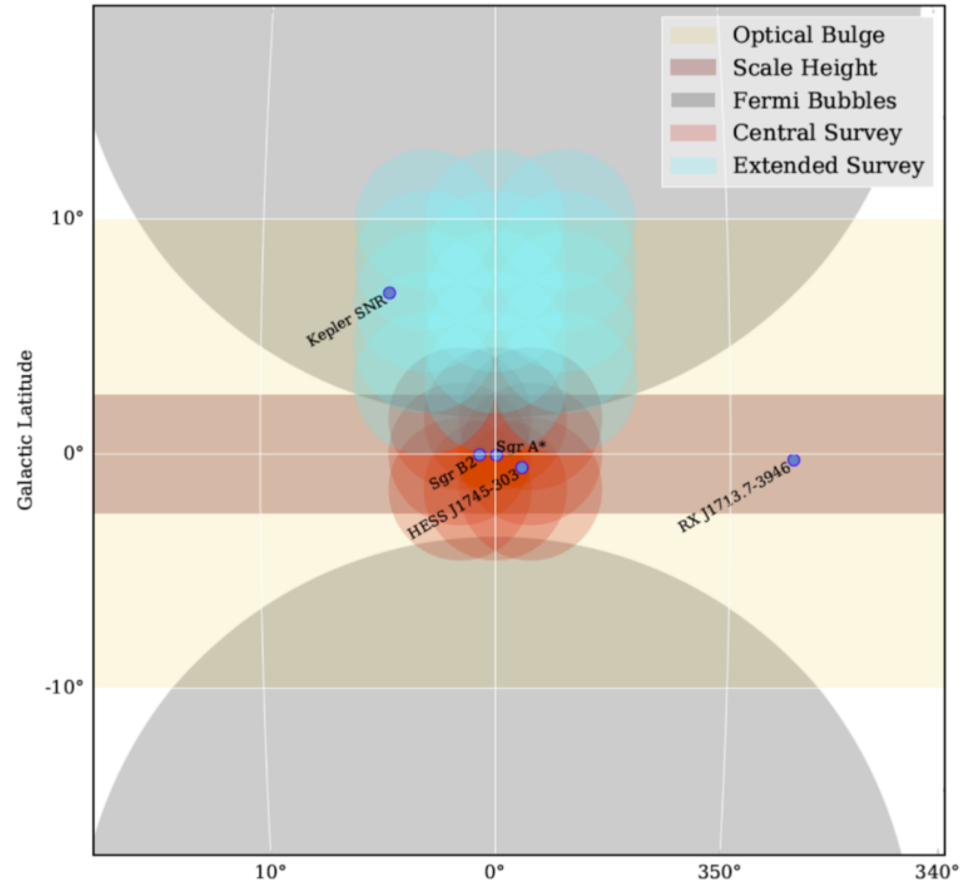
	7yr Cascades				Previous Work			
Template	p-value	Sensitivity	Fitted Flux	UL	p-value	Sensitivity	Fitted Flux	UL
KRA_γ^5	0.021	0.58	0.85	1.7	0.29	0.81	0.47	1.19
KRA_γ^{50}	0.022	0.35	0.65	0.97	0.26	0.57	0.37	0.90
Fermi-LAT π^0	0.030	2.5	3.3	6.6	0.37	2.97	1.28	3.83

Table 2. Sensitivity and results of the diffuse Galactic template analyses, compared to latest previous work: a joint IceCube-ANTARES (Albert et al. 2018) for KRA_γ models, and seven years of IceCube tracks (Aartsen et al. 2017b) for *Fermi*-LATπ^0 decay. Sensitivity, fitted flux, and ULs are given as multiples of the model prediction for KRA_γ models, and as $E^2 \cdot (E/100\,\mathrm{TeV})^{0.5} \cdot dN/dE$ in units $10^{-11}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}$ for *Fermi*-LAT π^0 decay.

$\mathrm{KRA}\gamma^5$ ($E_{p,\,cut}$ = 5 PeV) model consistent with data at 2.0 σ ,

best fit: 0.85 × $\mathrm{KRA}\gamma^5$

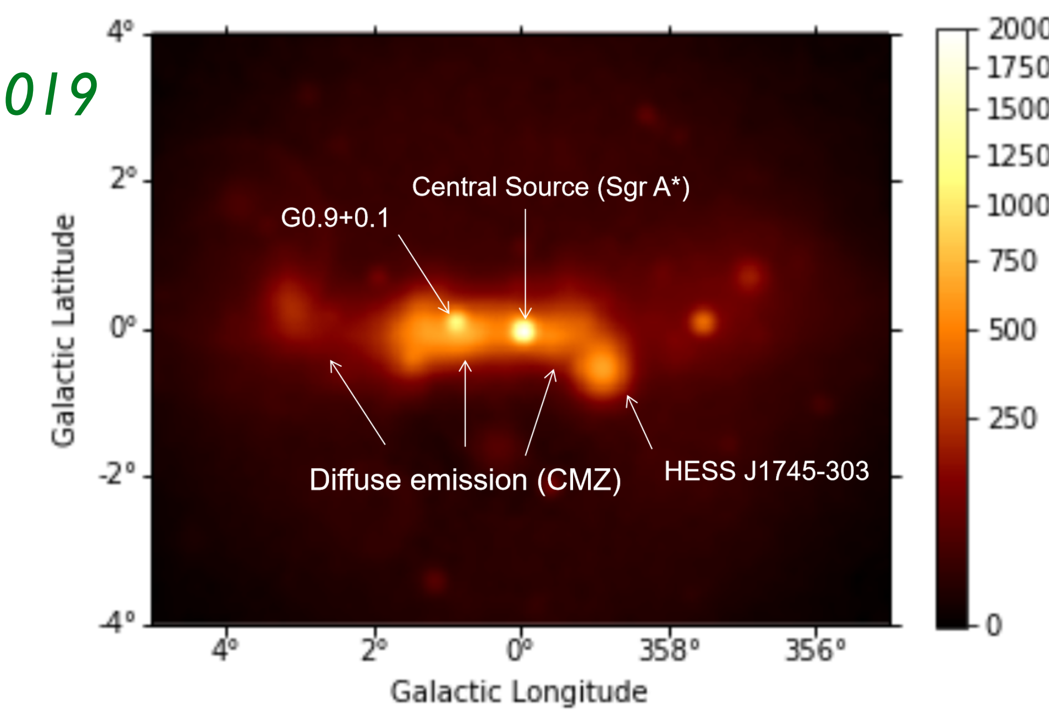
THE RELATED CTA KEY SCIENCE PROJECTS



- Galactic plane survey (GPS)
  It will assume an updated version of the *gamma model* for point source identification

- Galactic Center (GC) paper
  The factorized scenario will be tested against the peVatron one. The emission from massive clouds around the CMZ will be crucial

Viana et al., ICRC 2019
Simulation 825 h
above 100 TeV



CONCLUSIONS

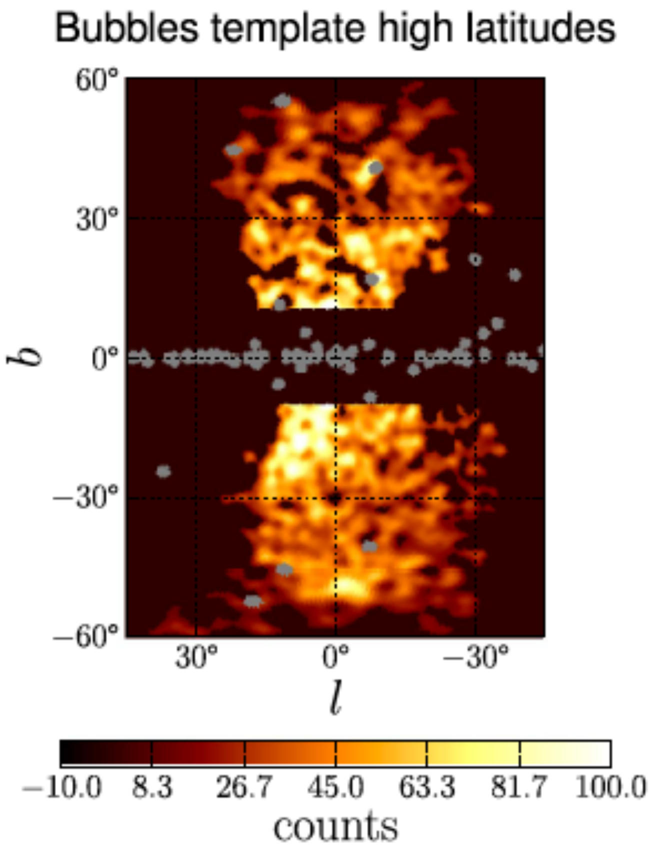
- Fermi-LAT gamma-ray data strongly suggest that conventional CR transport models are not adeguate and that a spatial dependent spectrum should be adopted
- This turns in a dramatically enhanced γ-ray and ν emission from the innermost regions of the Galactic plane with strong implication for the detectability of the diffuse emission and source identification
- The diffuse emission detected by HESS from the GC may be interpreted in that framework. CTA will be able to test it.
- Further checks will come from HAWC, IceTop/IceCube, LHAASO
- IceCube and ANTARES have already hints of a positive detection of a similar ν emission . Km3Net will confirm of disprove such scenario

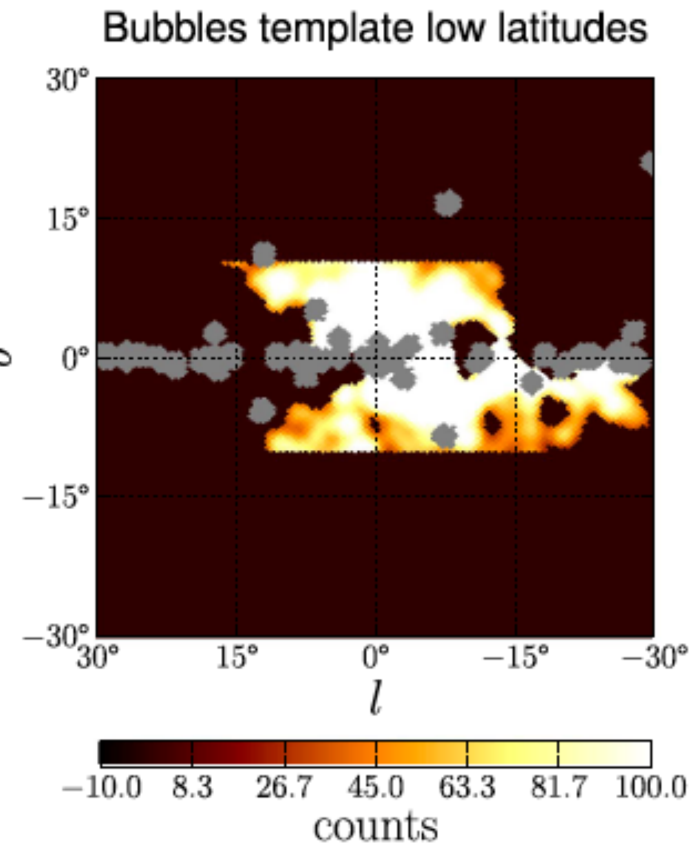
BACKUP SLIDES

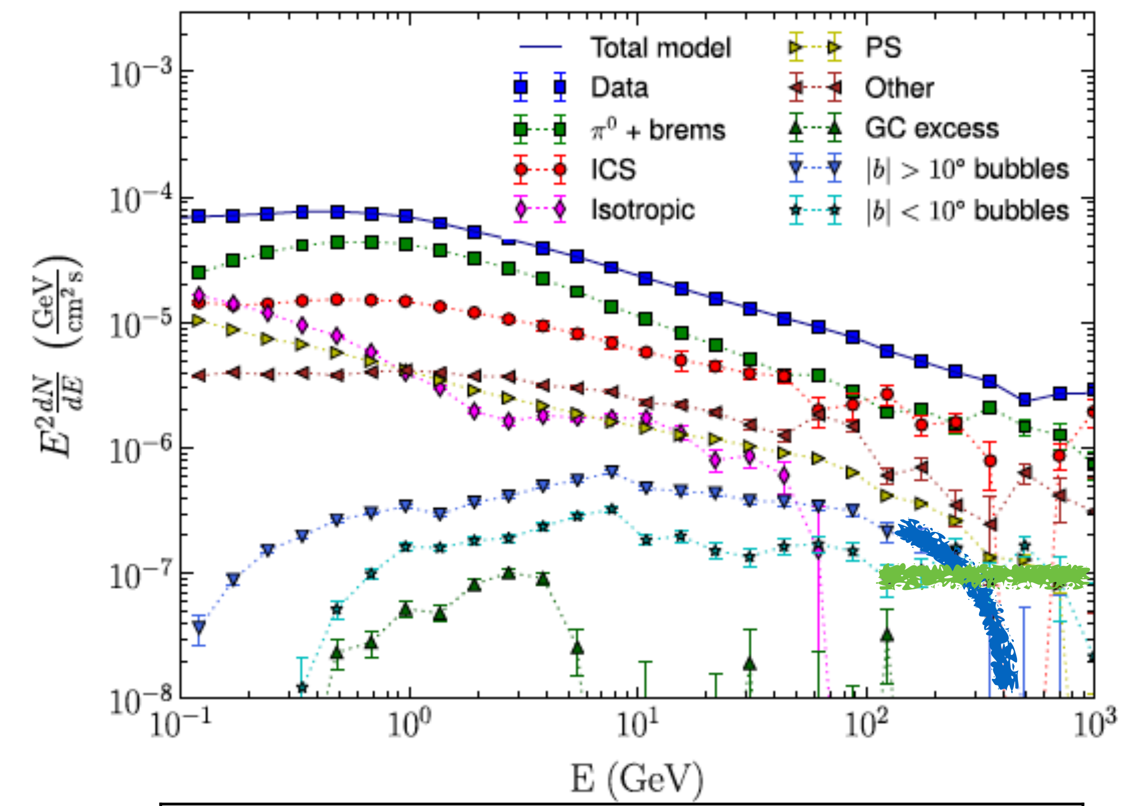
NEUTRINOS FROM LOW LATITUDE BUBBLES

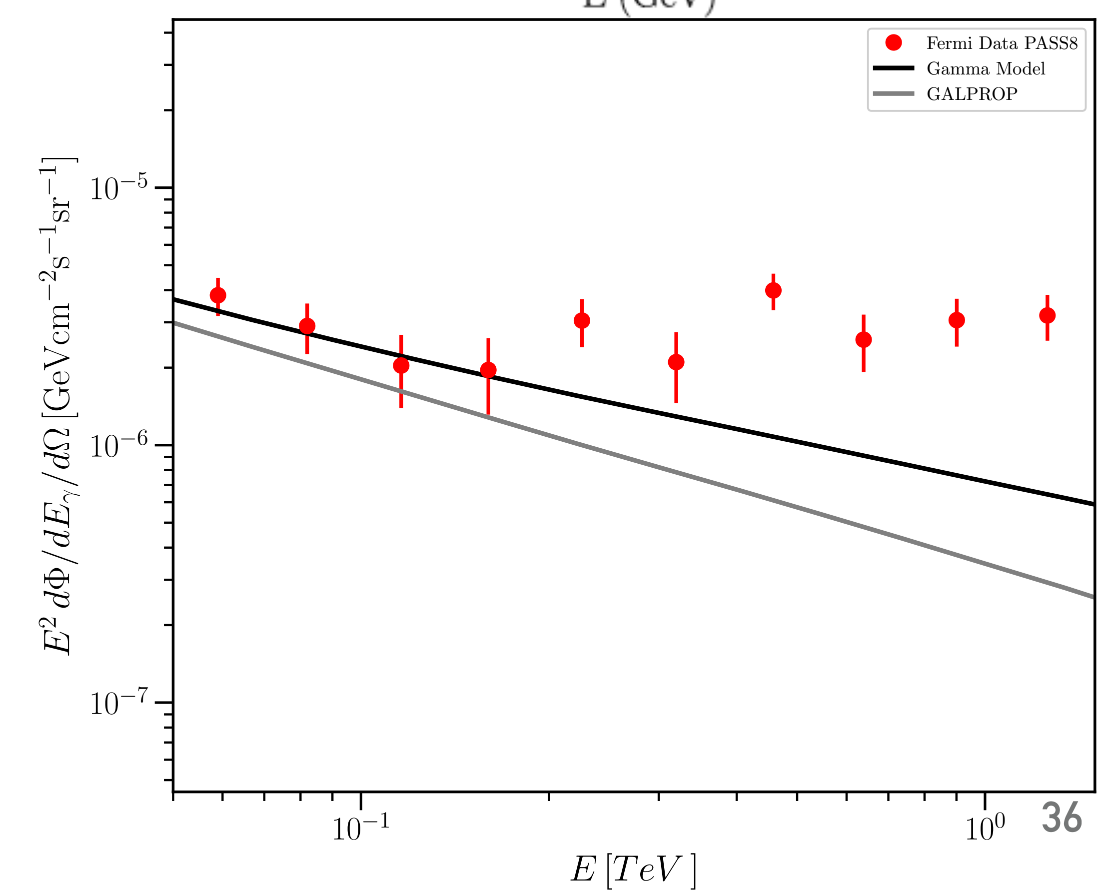
Bubbles |b|<10°

Bubbles |b|>10°





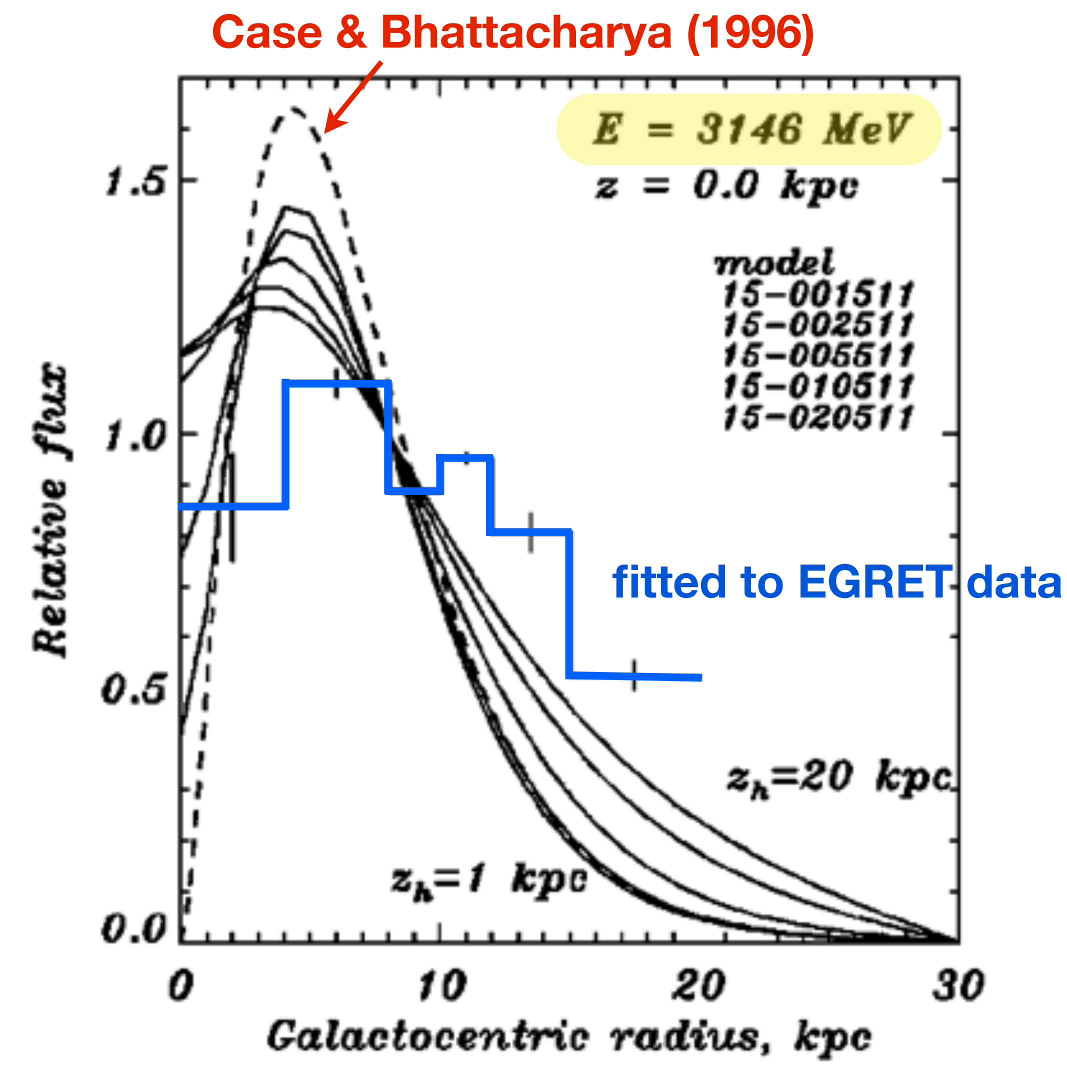


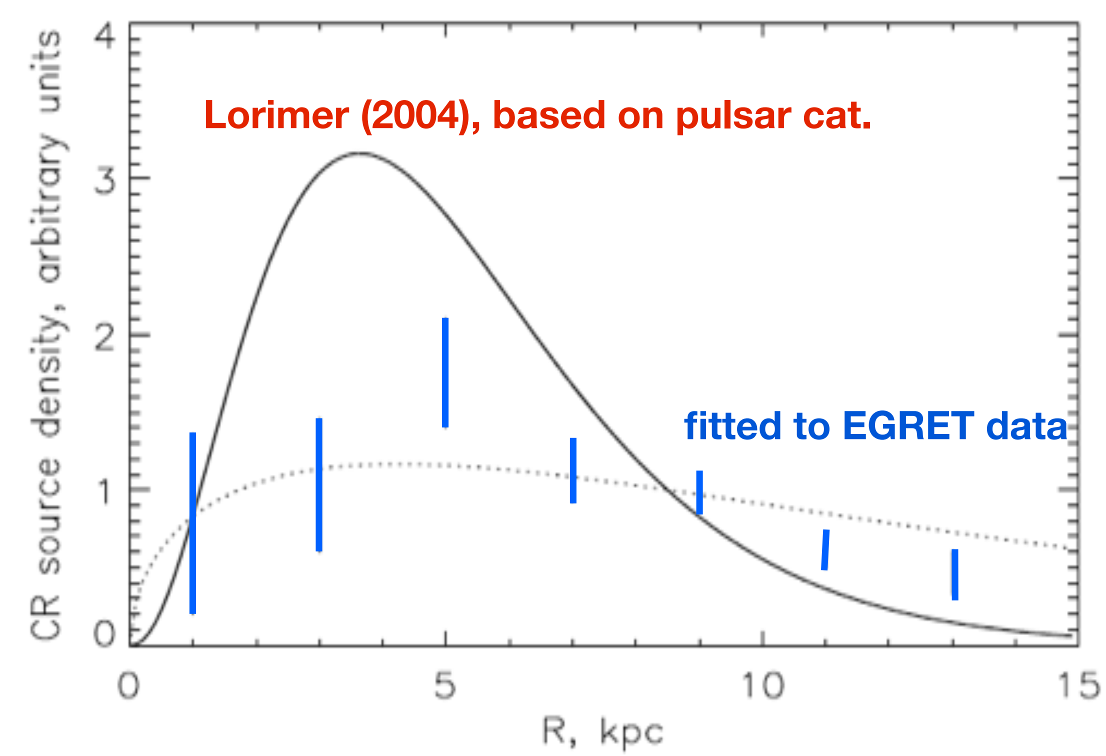


THE GRADIENT PROBLEM

The problem was already evident in the longitude profile of the γ-ray diffuse emission of the Galaxy measured by EGRET: the inferred CR density profile is flatter that expected on the basis of SNR catalogues !

Before Fermi-LAT a possible way-out was left opened: the H_2 gas radial distribution may be flatter than inferred from the CO emission due to the (poorly known) radial dependence X_{CO}

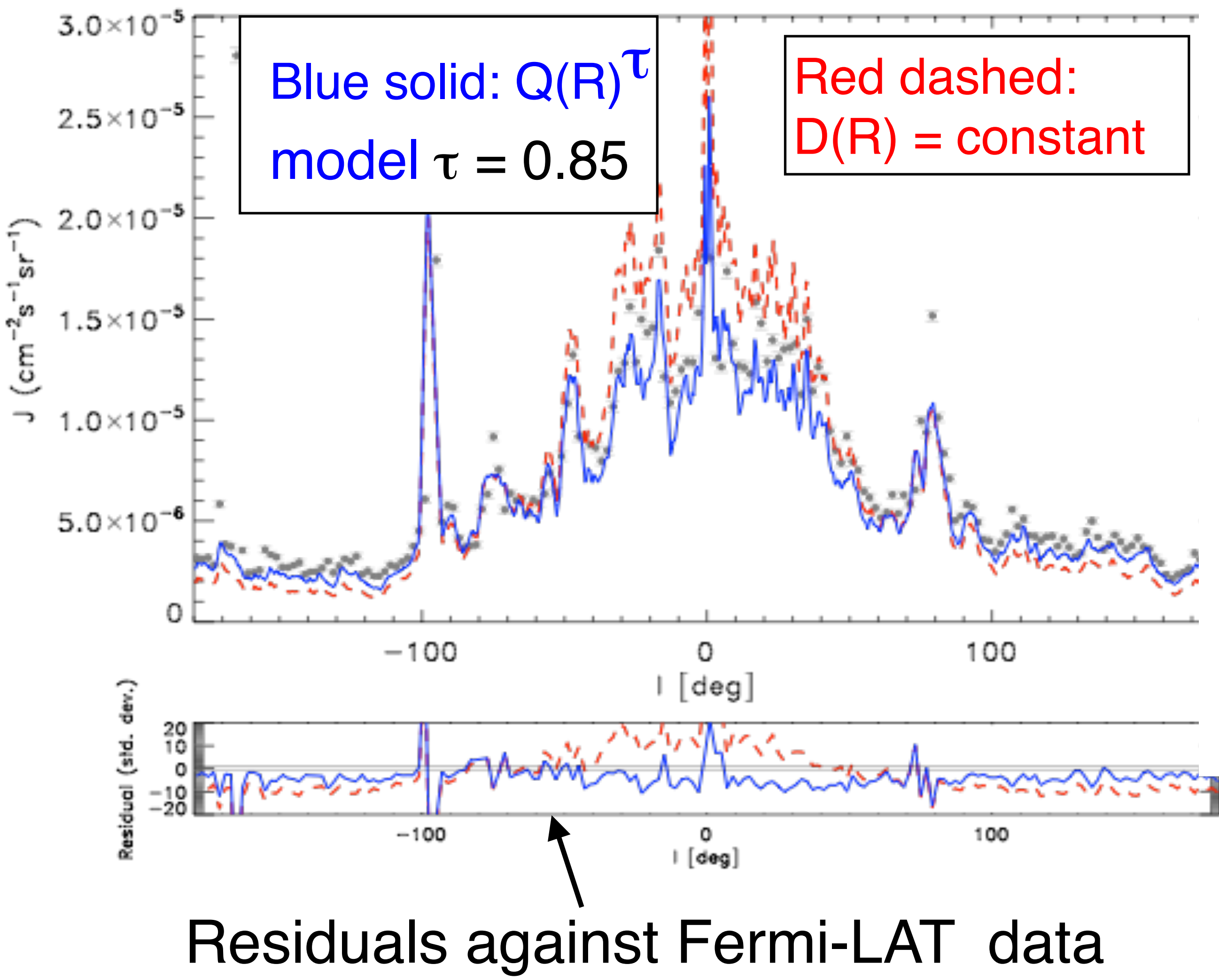


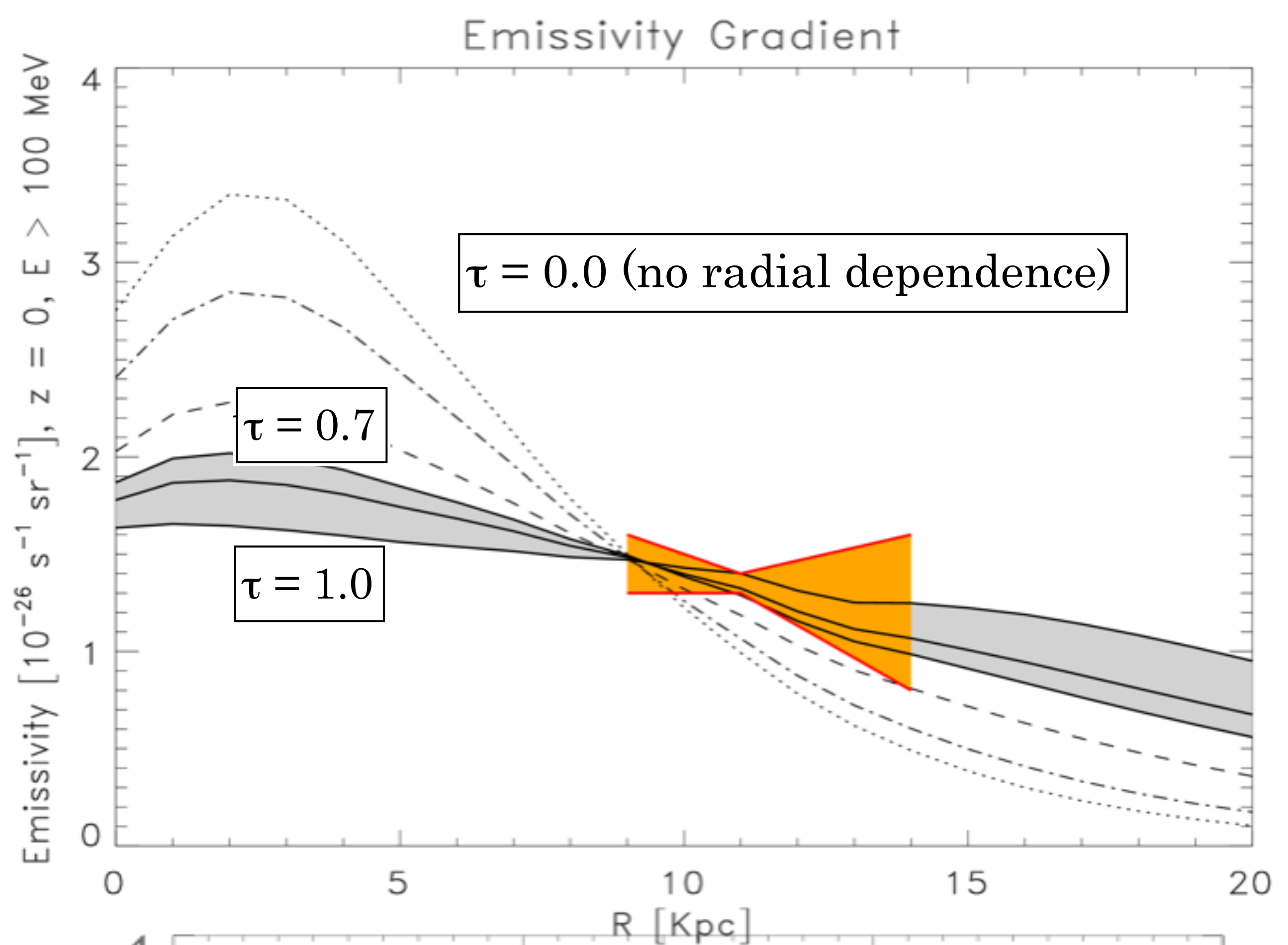


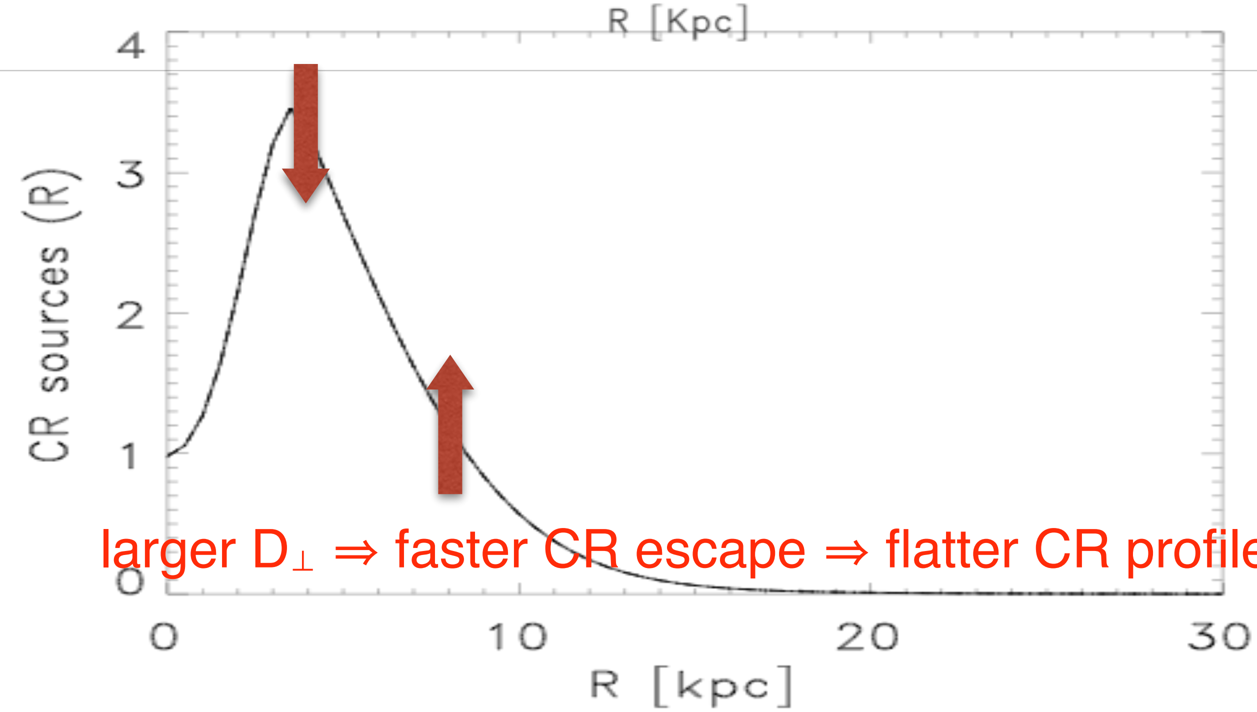
A POSSIBLE SOLUTION TO THE GRADIENT PROBLEM

Based on inhomogeneous/anisotropic diffusion

Evoli, Gaggero, DG, Maccione, PRL 2012







NEUTRINOS FROM THE CMZ

Marinelli et al. ICRC 2017