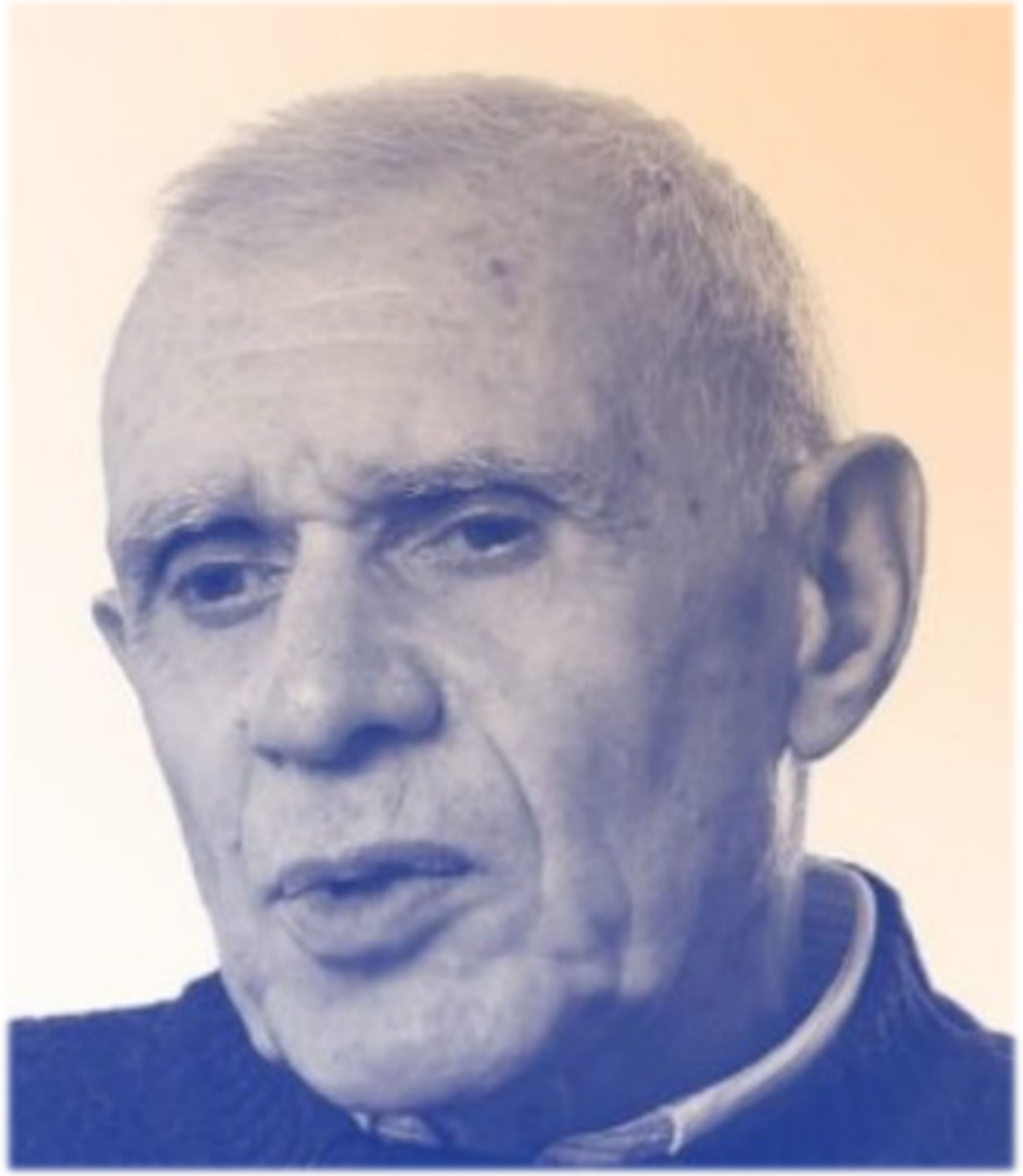
The Galactic Neutrino Diffuse Emission

The Galaxy is not a neutrino desert !

Dario GRASSO (INFN, Pisa)

Conference in memory of Veniamin Sergeyevich Berezinsky - GSSI 1-3 Oct. 2024



Thank you Venia !

Galactic neutrinos: The early papers

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

Galactic emission (mostly from the center) was estimated as a background to extragalactic

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

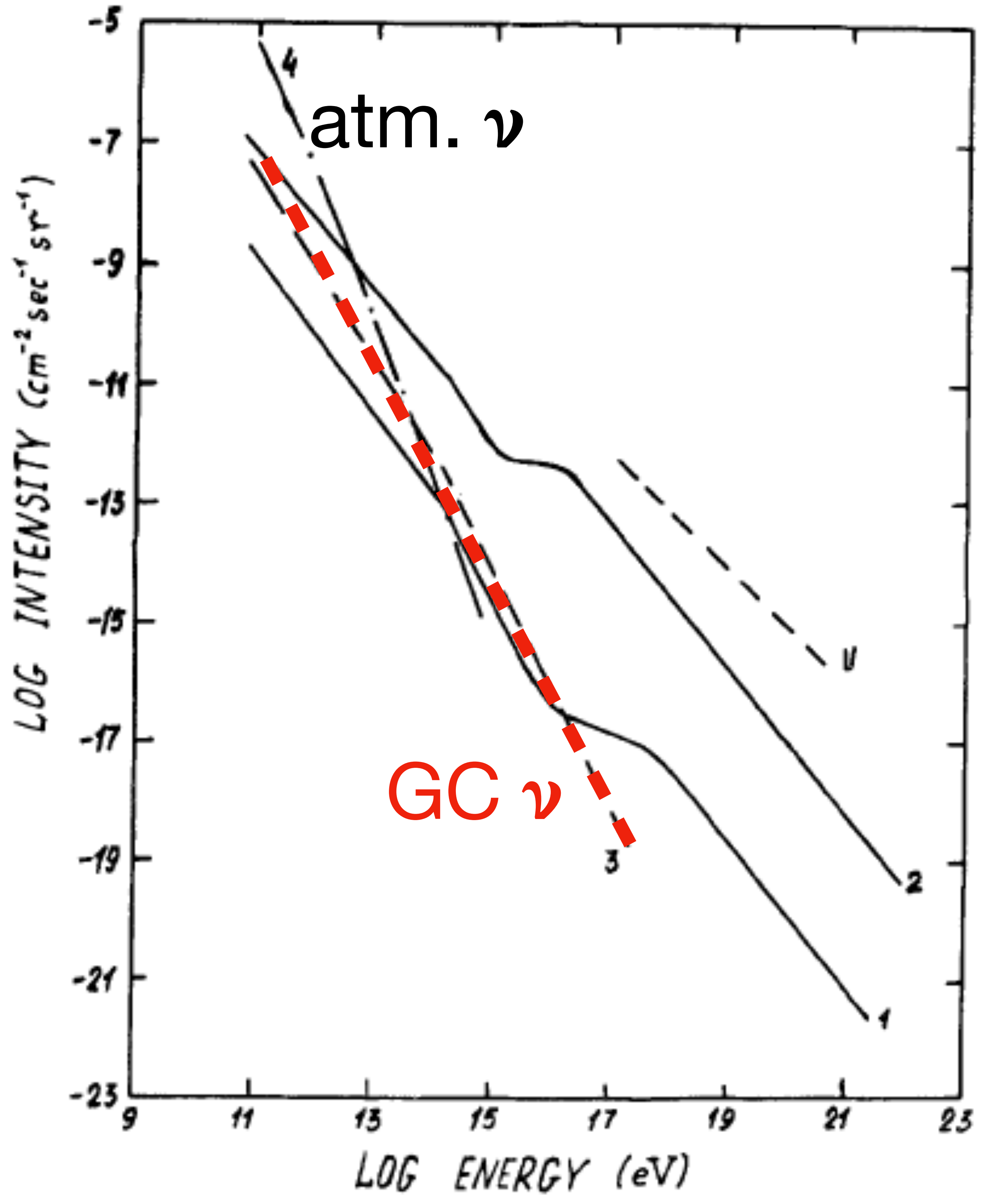


Fig. 1. The integral neutrino spectra. Curve *U* gives the rigorous upper bound for the neutrino flux, curve 1 – neutrino from the normal galaxies, 2 – from evolving sources, 3 – from our Galaxy in the direction of Galactic centre, 4 – atmospheric neutrino spectrum.

Berezinsky & Smirnov 1975

Astroparticle Physics 1 (1993) 281–287
North-Holland

Astroparticle Physics

Diffuse radiation from cosmic ray interactions in the galaxy

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We perform a realistic estimate of the emission of TeV–PeV gamma rays and neutrinos by galactic matter irradiated by cosmic rays. Our calculation is directly based on profiles of matter in the galactic disk compiled by Bloemen. Our results can be compared with recent experimental limits. We investigate the consequences of hints associated with COS-B data, that cosmic ray spectrum is harder in the outer Galaxy and find that present air shower data rule out a straigtforward extrapolation of a hard spectrum up to 100 TeV. We show that we need neutrino telescopes of order 1 km^2 area to map the galaxy in TeV neutrinos.

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = f_A \int_0^{R_{max}} \mathrm{d}R \int_{E_\gamma}^{E_{CR}^{max}} \frac{\mathrm{d}N_{CR}}{\mathrm{d}E_{CR}} \, Y_\gamma(E_p, E_\gamma) \, \sigma_{pp}(E_p) \, n_H \eta(E_\gamma, R) \, \mathrm{d}E_{CR}$$

nuclear enhancement factor — γ-ray transparency

- Assume uniform CR spectrum as locally measured
- Use gas density distribution (in galactocentric rings) as determined from CO and HI emission (*Bloemen*)
- Account for γ-ray opacity (only on CMB)
- Use γ-ray production yields from p-p computed (with SIBYLL 1.0)
- Compute the neutrino emission
- Use the first γ-ray measurements (COS-B) extrapolated to higher energies (as a comparison)

A not uniform spectral index ?

COS-B suggested a harder (γ = -2.3) CR spectrum in the outer Galaxy ($90^o < l < 270^o$) respect to the inner one ($310^o < l < 50^o$) (γ = -2.7). This might have implied a strong enhancement in the emission at VHE

This may have had relevant consequences also for the neutrino emission: 10 detection/year in a 10^5 m^2 detector at the South Pole may have grown up to 15 for a hard CR spectrum in the outer galaxy (though remaining well below the atmospheric background).

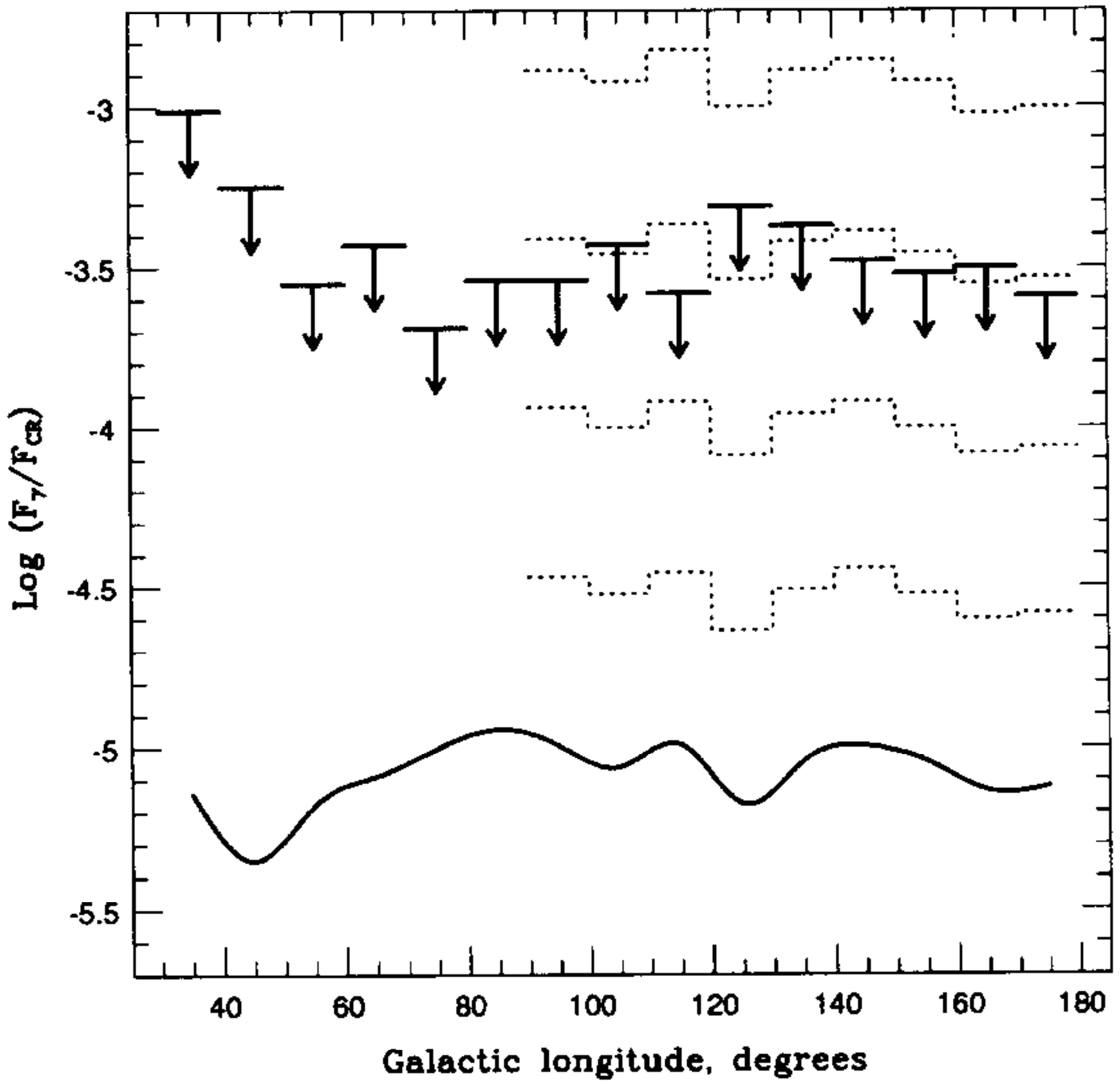


Fig. 6. Expected (solid curve) galactic plane γ-ray emission for the experimental conditions of the Utah–Michigan array compared to experimental limits. The dotted histograms show the expectations from the outer galaxy for $\Delta_\gamma = 0.1$, 0.2, 0.3, and 0.4 (from top to bottom).

Important messages holding true

reported in the conclusions of *Berezinsky et al. 1993*

The detection of the galactic plane will be extremely difficult for current air shower arrays if the cosmic ray spectrum is as steep elsewhere in the galactic plane as observed locally. However, ***the comparison of > TeV γ-ray fluxes with GeV satellite results can place important limits on possible cosmic ray spectral differences in different galactic regions, which may arise from cosmic ray source distribution and propagation phenomena.***

The VHE and UHE γ-ray fluxes from cosmic ray interactions with the matter in our Galaxy should be viewed as a standard candle for these energy regions, although the luminosity is low. Understanding the diffuse galactic radiation, with its predictable latitude and longitude dependence, is a precondition for the exploration of the deeper universe in this energy range.

Releasing the CR homogeneity assumption

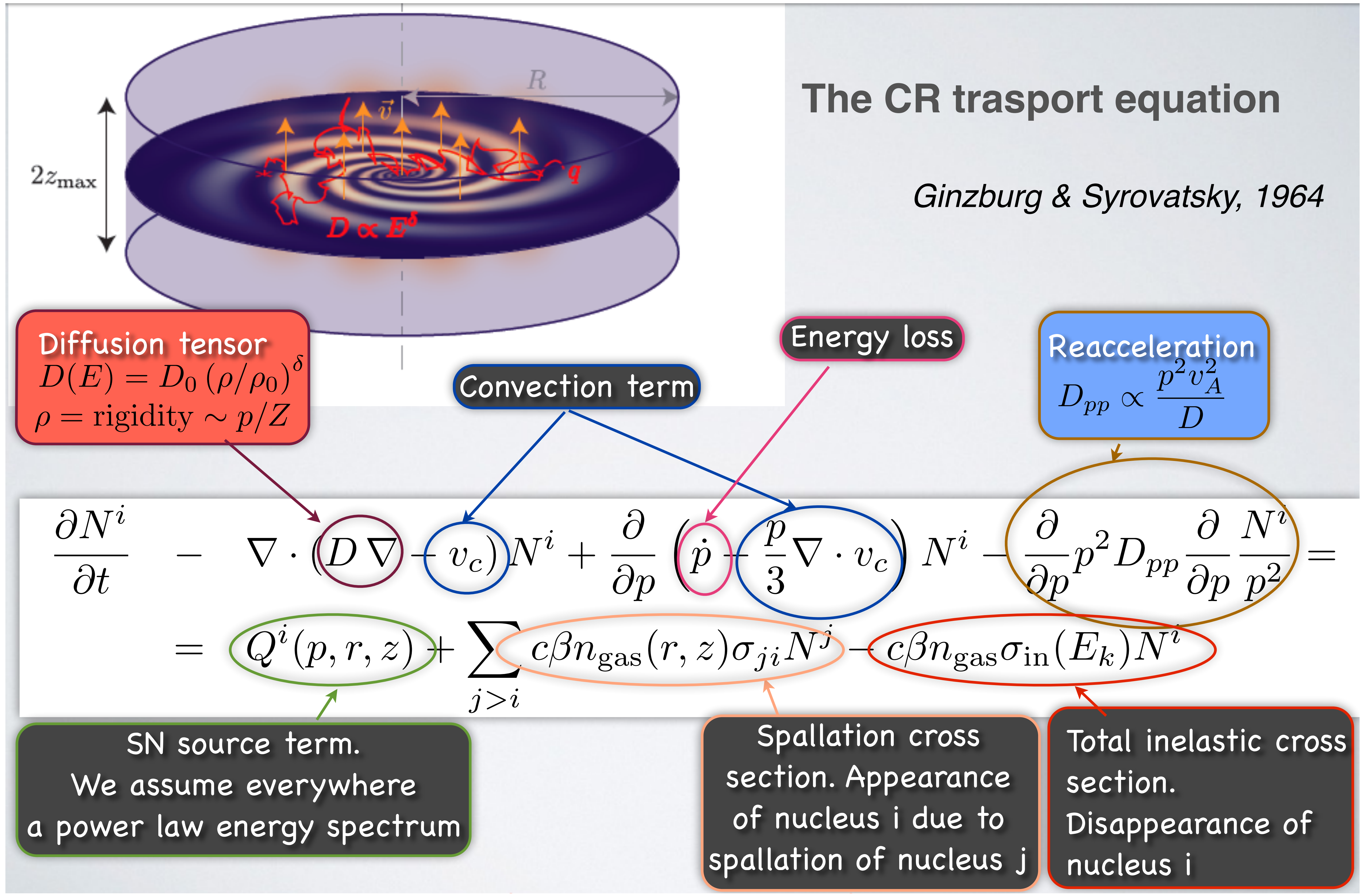
Main motivations:

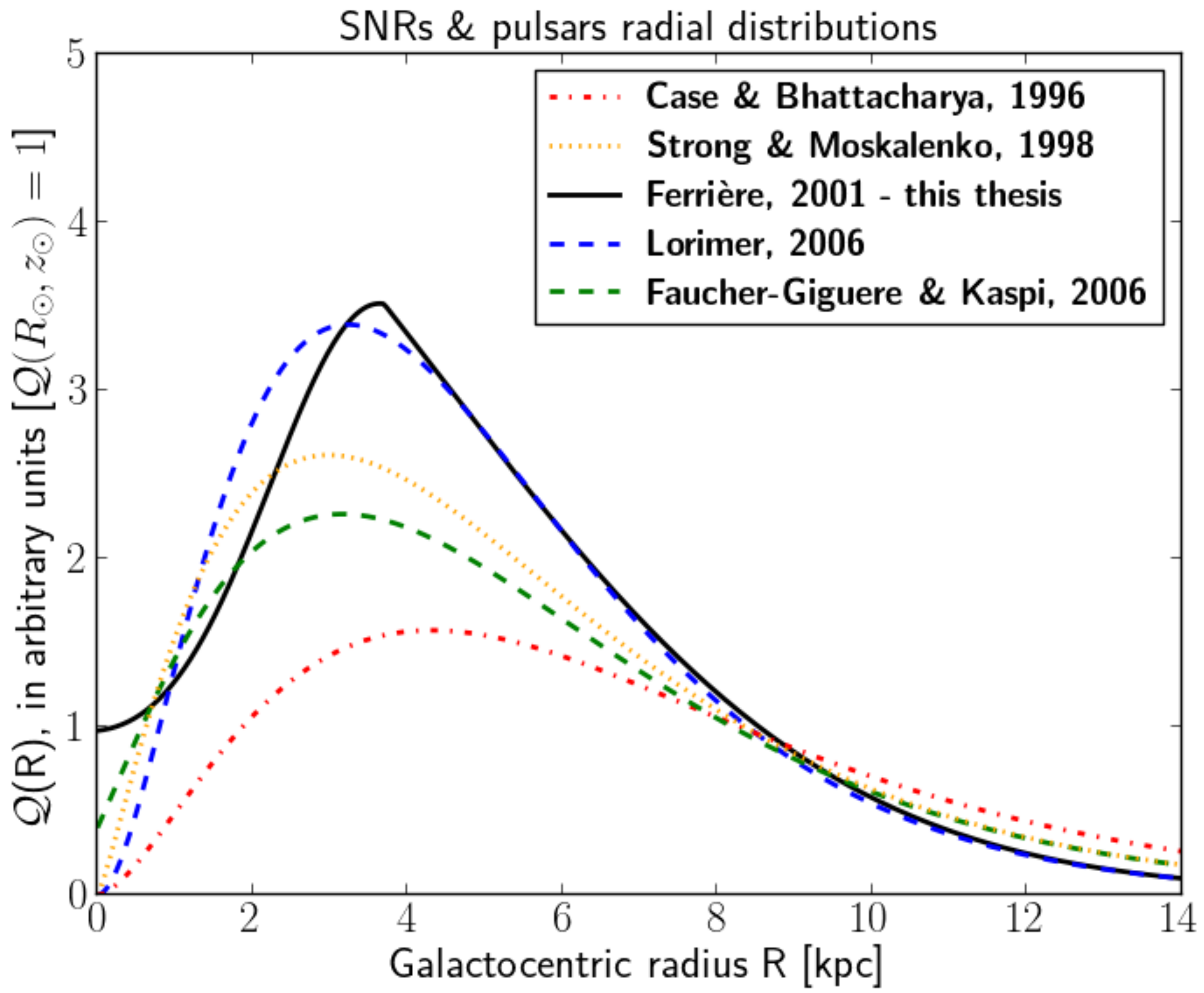
1. **Inhomogeneos CR sources**
   after propagation a footprint of the source distribution remains in the CR density
   (The leaky box approximation is not good enough). When convoluted with the inhomogenous gas distribution this turns into a quite peaked γ and ν emissions

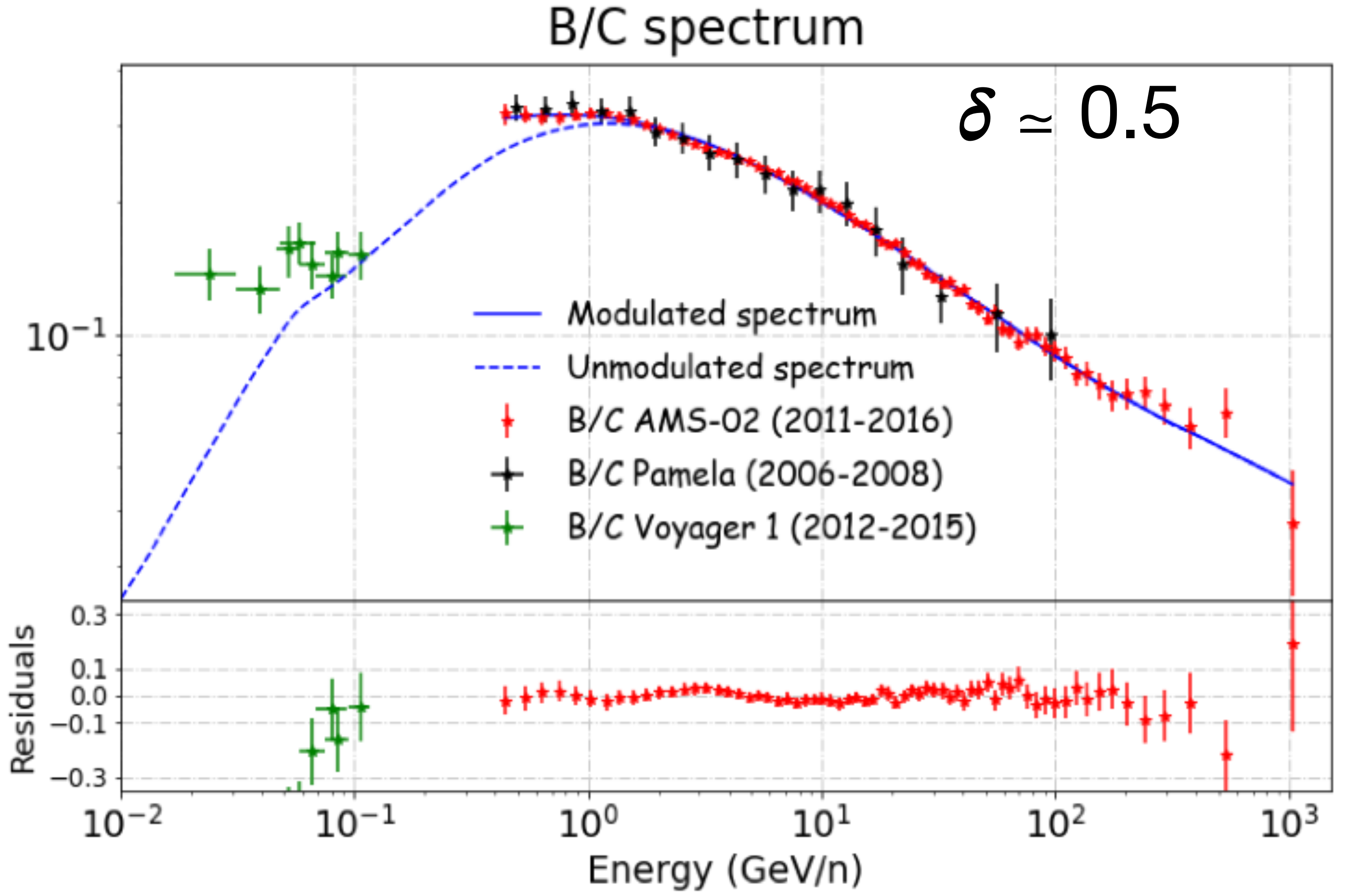
2. **Inhomogeous and anisotropic CR transport** has to be expected and may boost the emission

3. **γ-ray data** require it !

The effect of inhomogeous CR sources





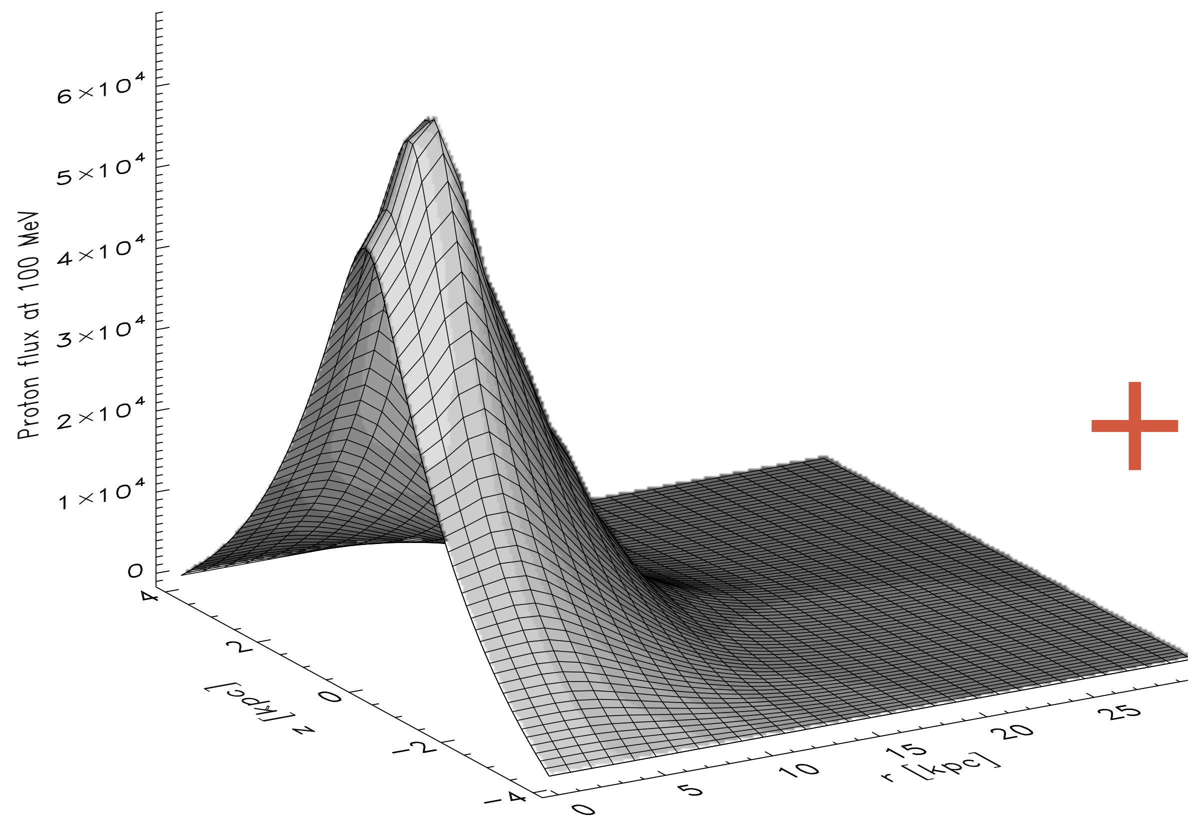


Solved imposing it reproduces the locally measured CR spectra

$D(\rho, x) \propto D_0(x)\, \rho^{-\delta}$

In the **conventional approach** D is assumed to be a space independent scalar tuned against secondary/primary CR

This has to be convolved with the gas distribution resulting in a quite peaked emission profile !



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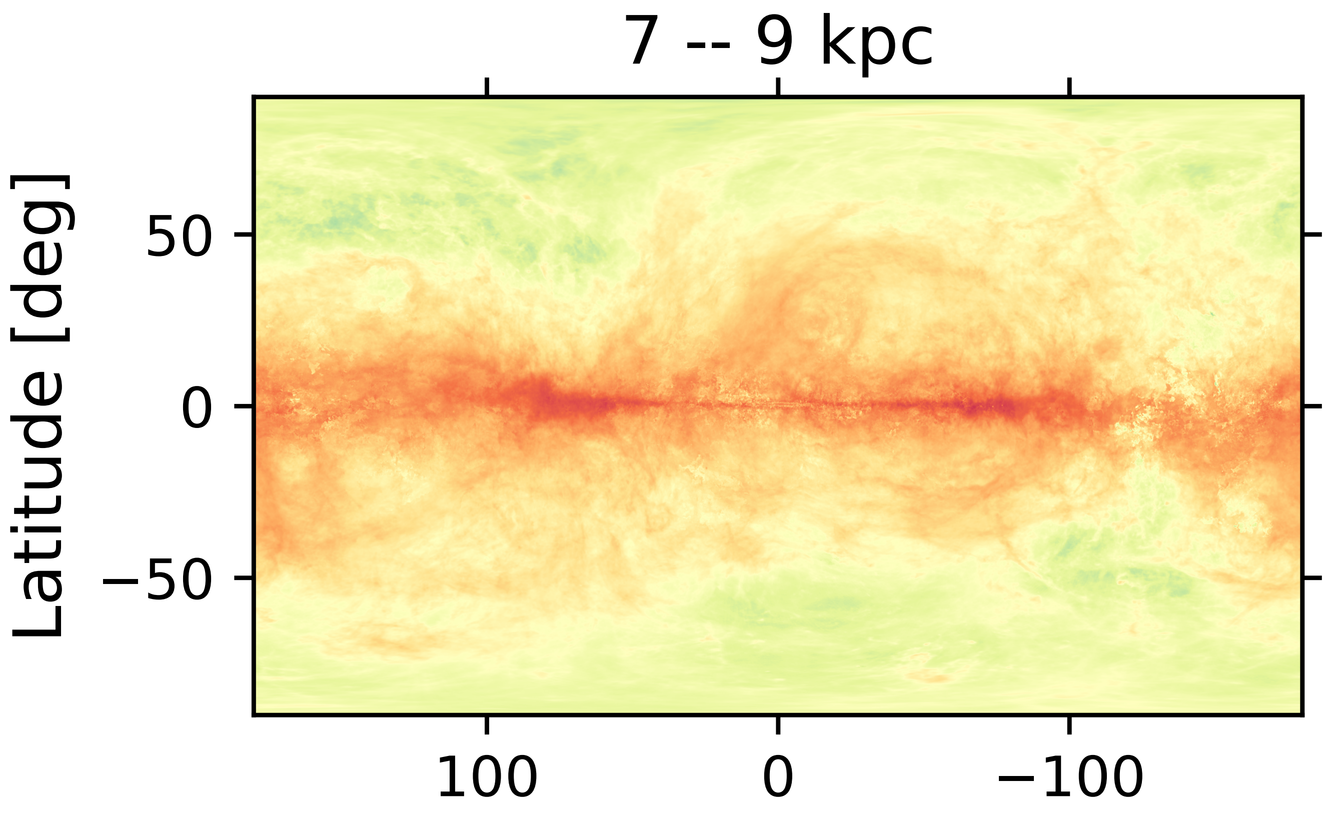
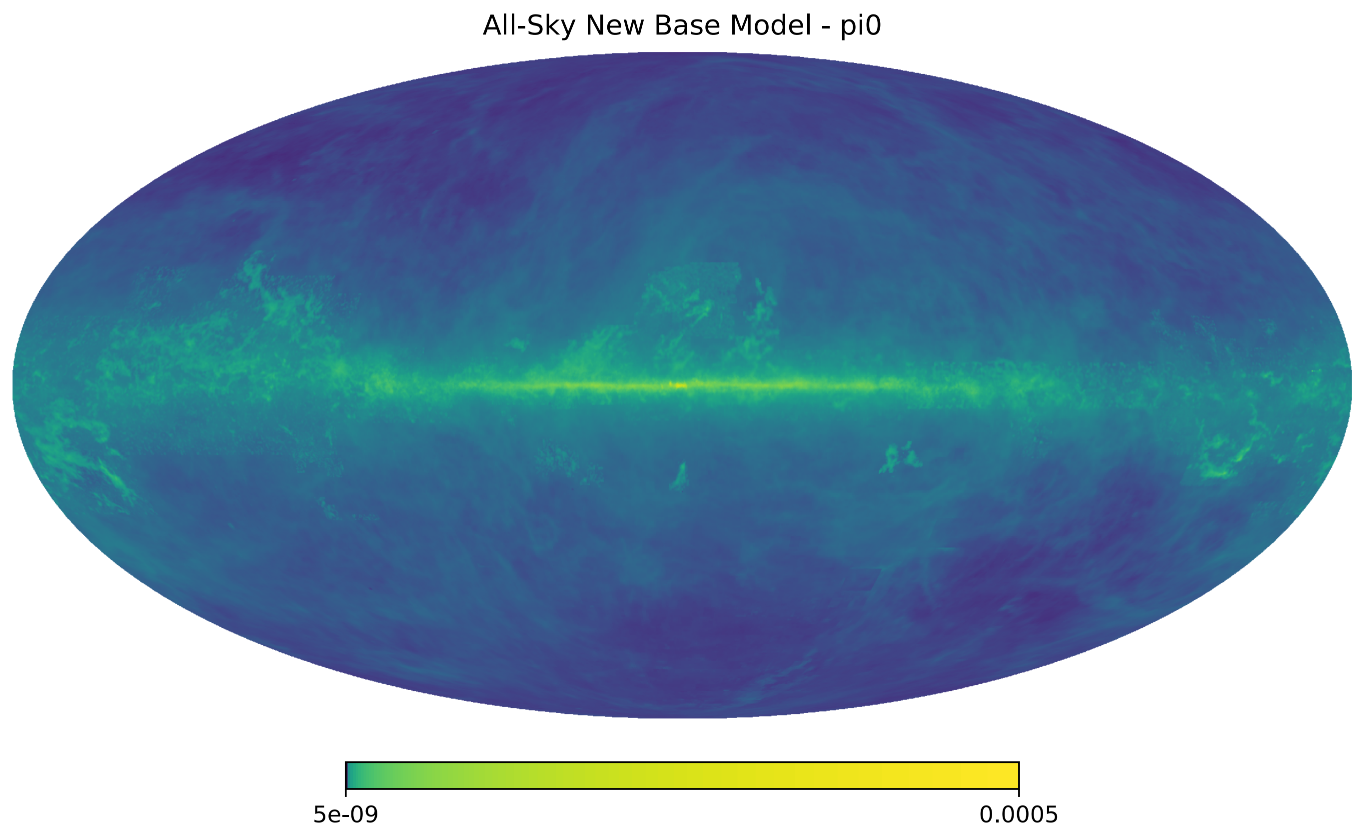




transport eq. → CR spatial/energy distribution

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

HI obtained from 21cm emission maps

γ-ray or ν diffuse emission

simulated maps at several energies

This has to be done with dedicated numerical codes, like

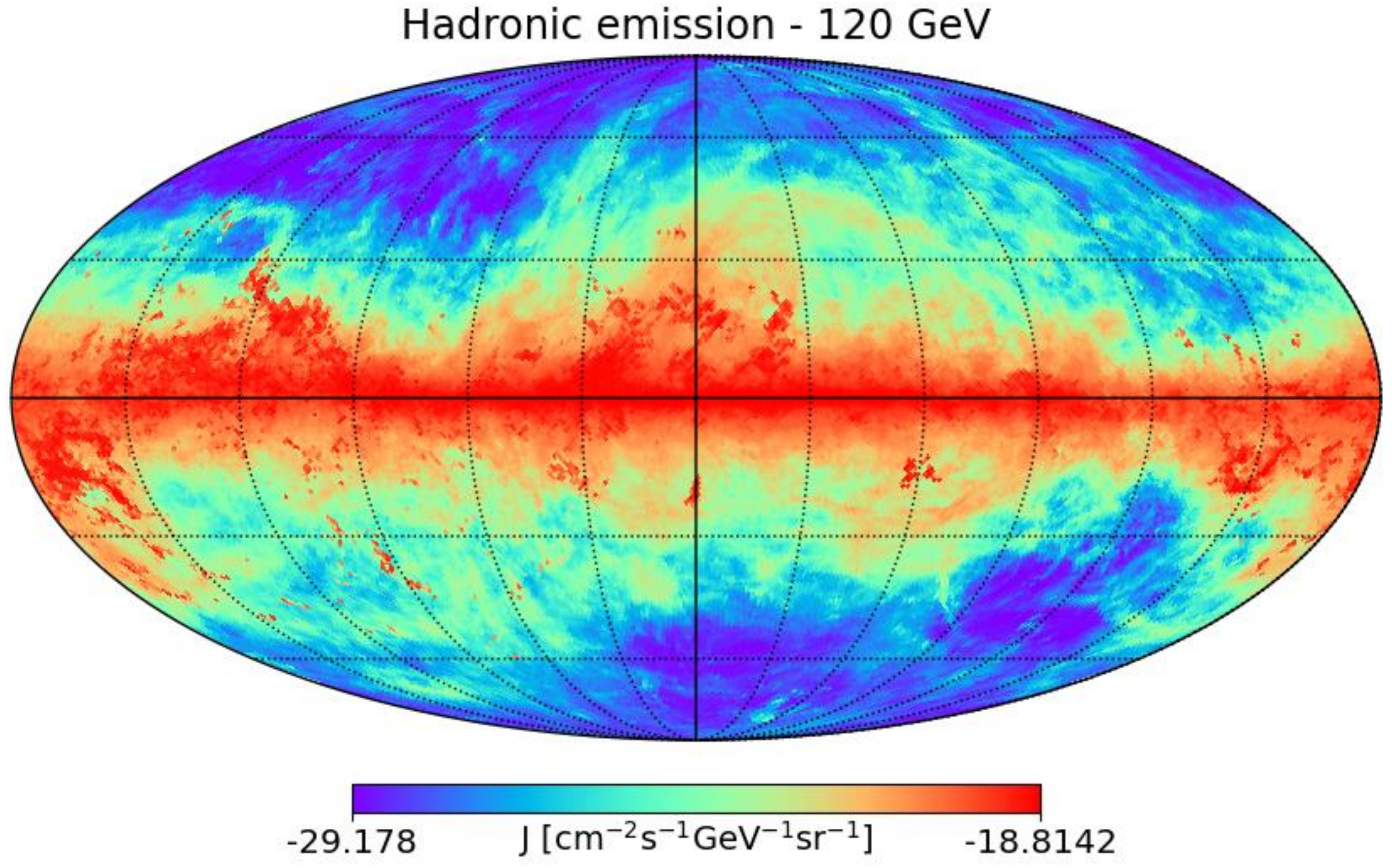
GALPROP *Strong, Moskalenko et al. 1998, 2000* *https://galprop.stanford.edu/publications.php*

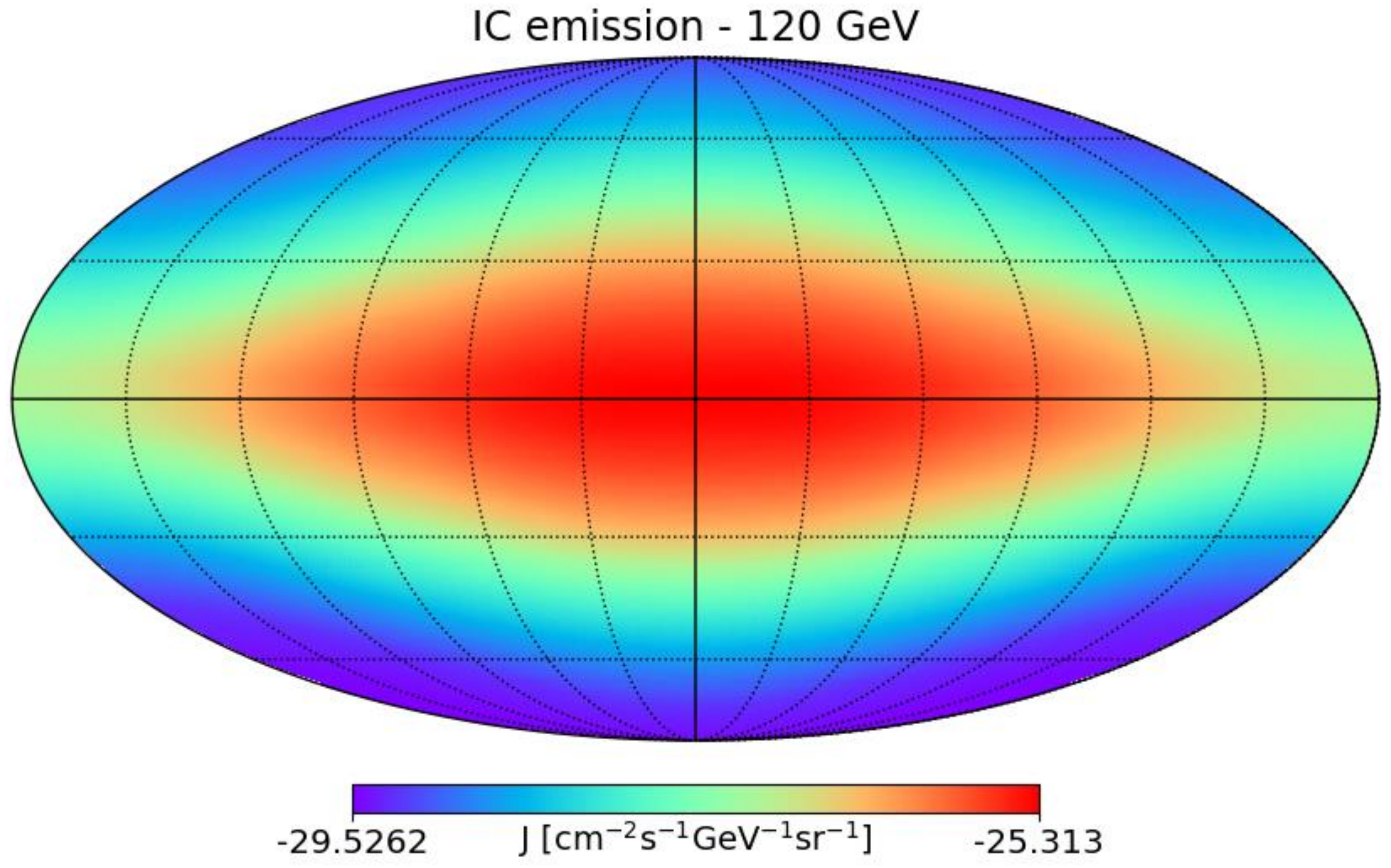
DRAGON *Evoli et al. JCAP 2008, JCAP 2017* *https://github.com/cosmicrays/*

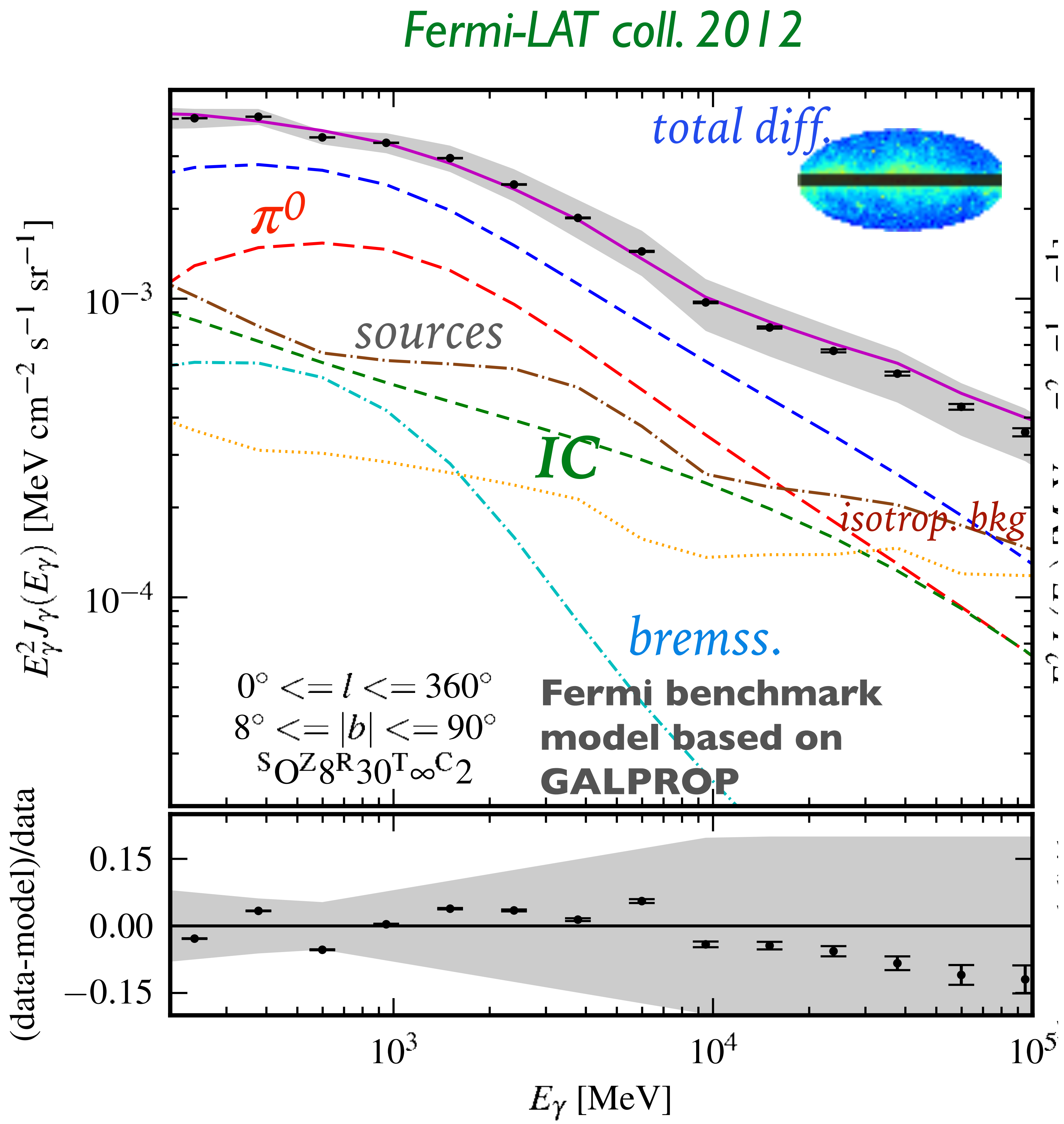
which compute the CR spatial and rigidity distributions obtained solving transport equation (in 2 or 3D) compute emissivities and integrate them along the l.o.s.

γ-ray diffuse emission

Conventional models







$$p + p \rightarrow \pi_0 + \text{hadrons}$$

$$e^{\pm} + \gamma \rightarrow e^{\pm}\gamma$$

$$\pi_0 \rightarrow \gamma\gamma$$

These tools were generally used for photon energies up to ~ 1 TeV but rarely at larger energies for neutrinos !

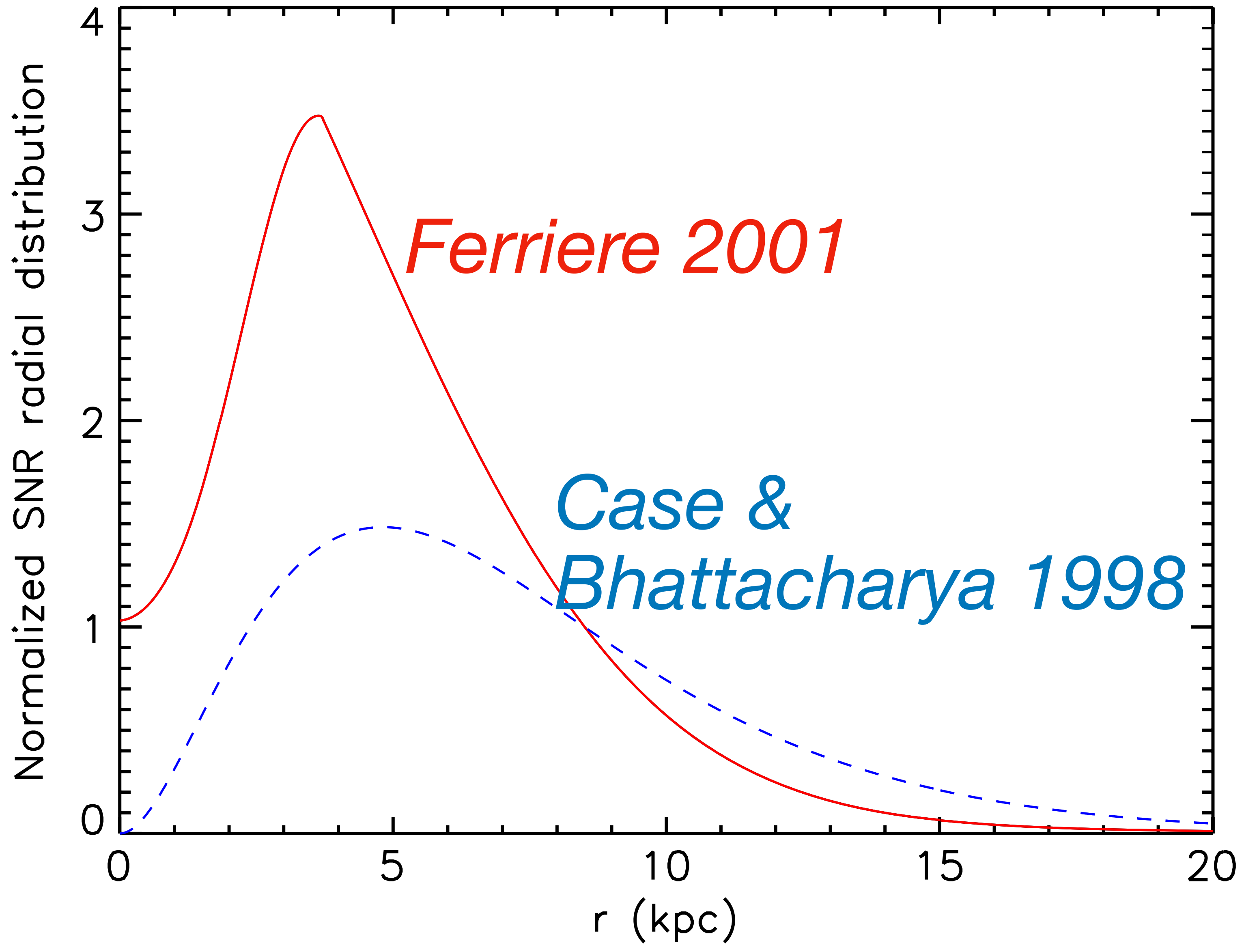
Neutrino diffuse emission: *ingredients*

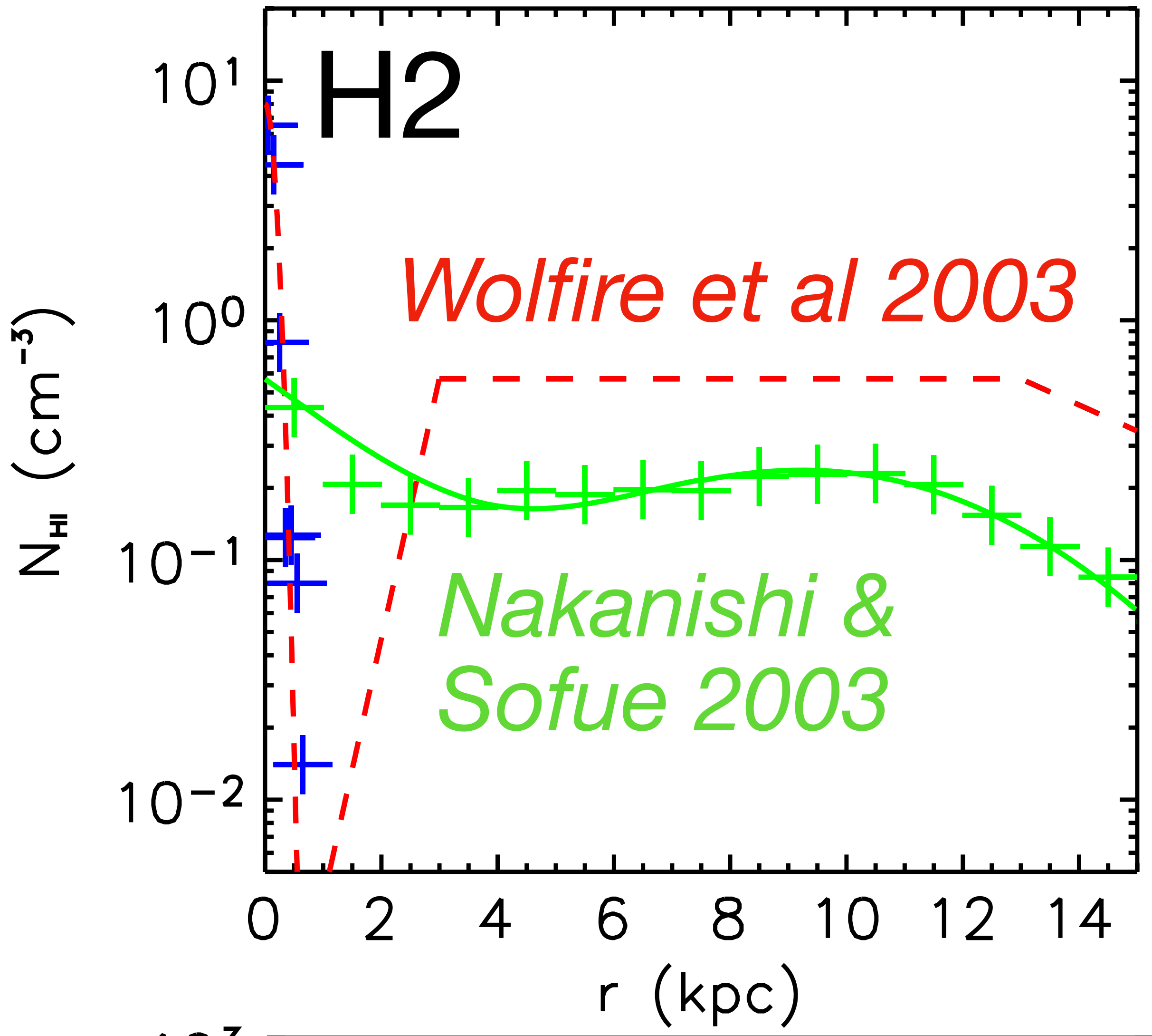
A first computation within the same “conventional” approach

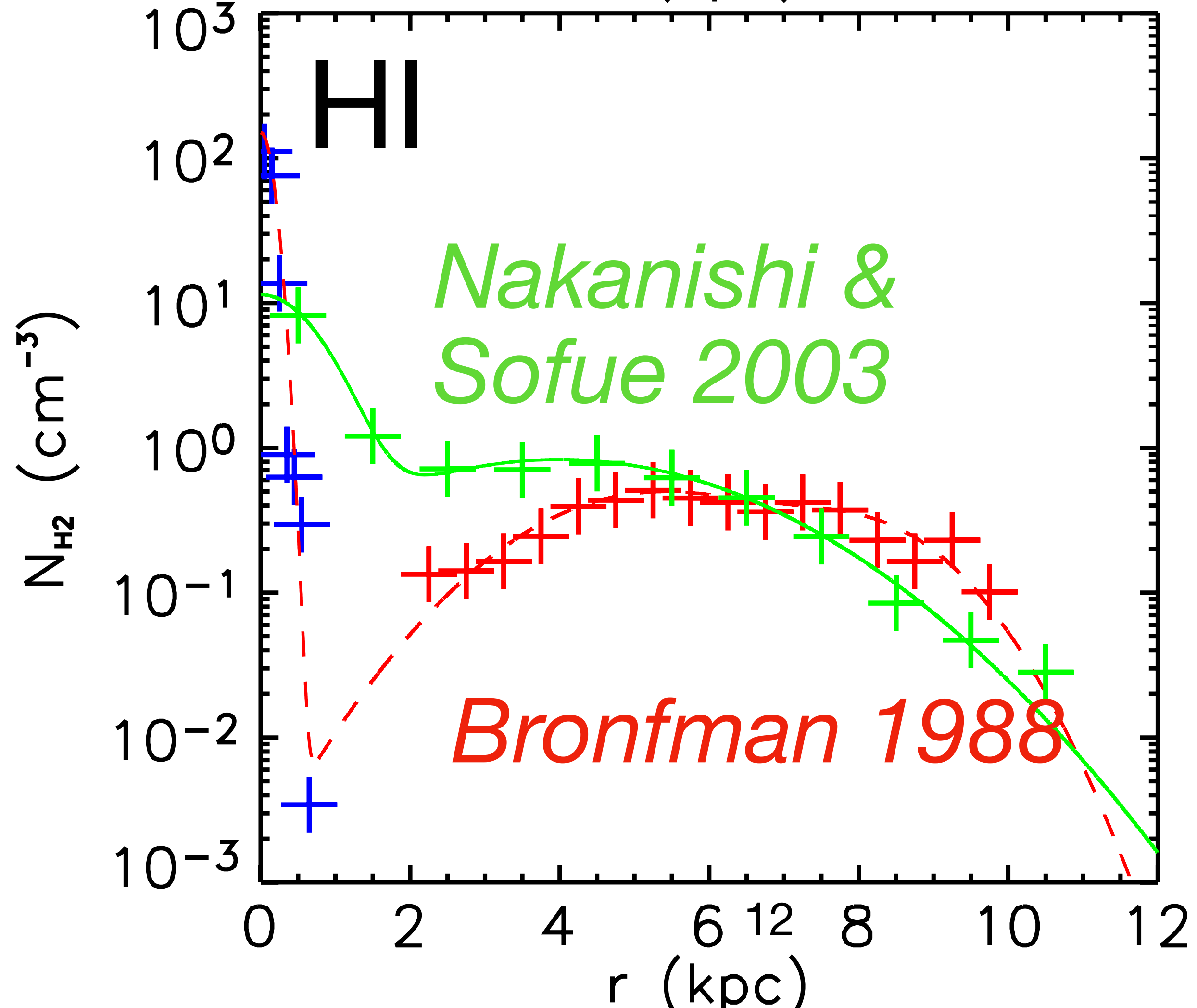
C. Evoli, D.G. & L.Maccione, JCAP 2007 Solving numerically the transport equation

Gas distribution

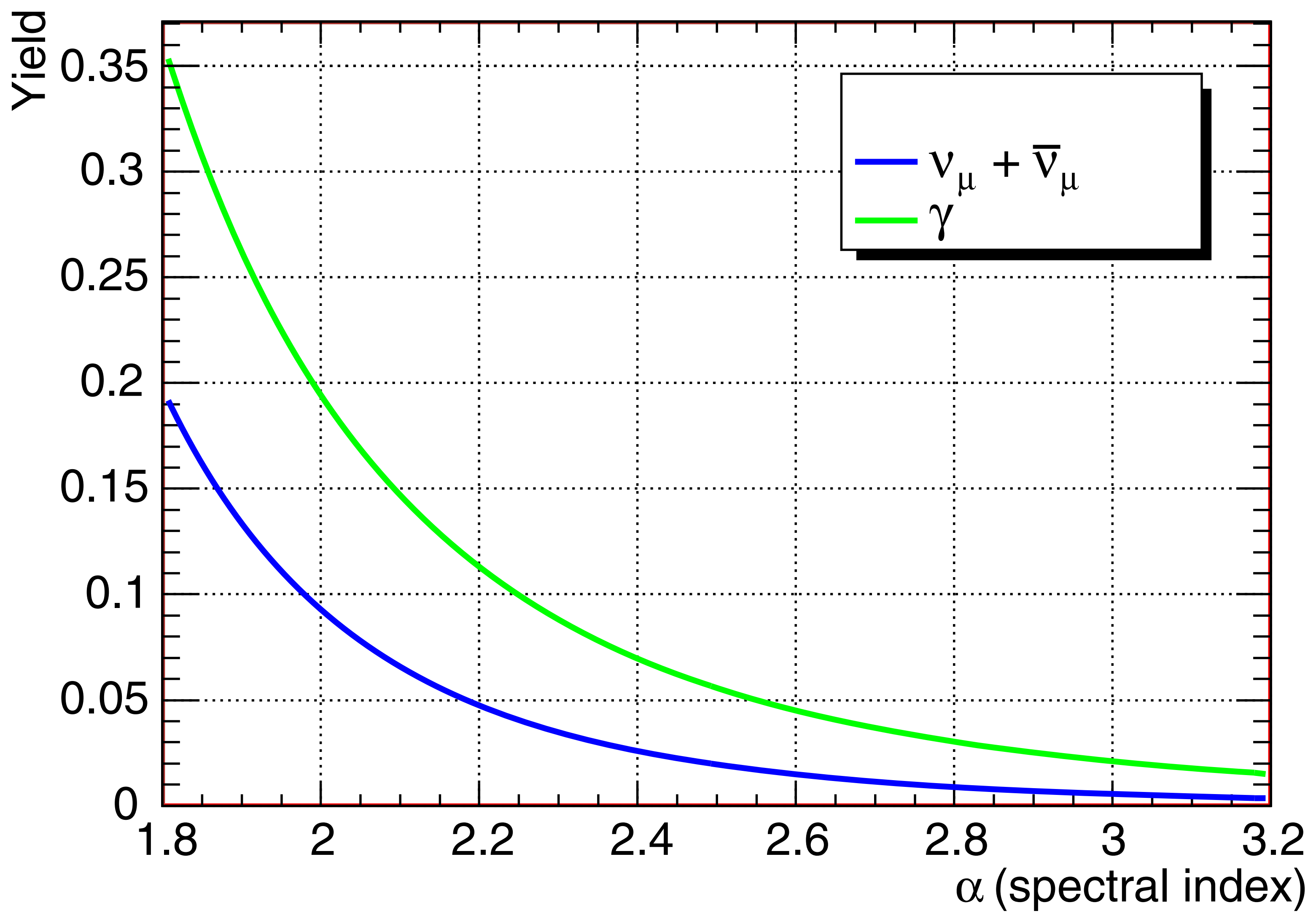
SNR distribution







Production yields semi-analytical computation

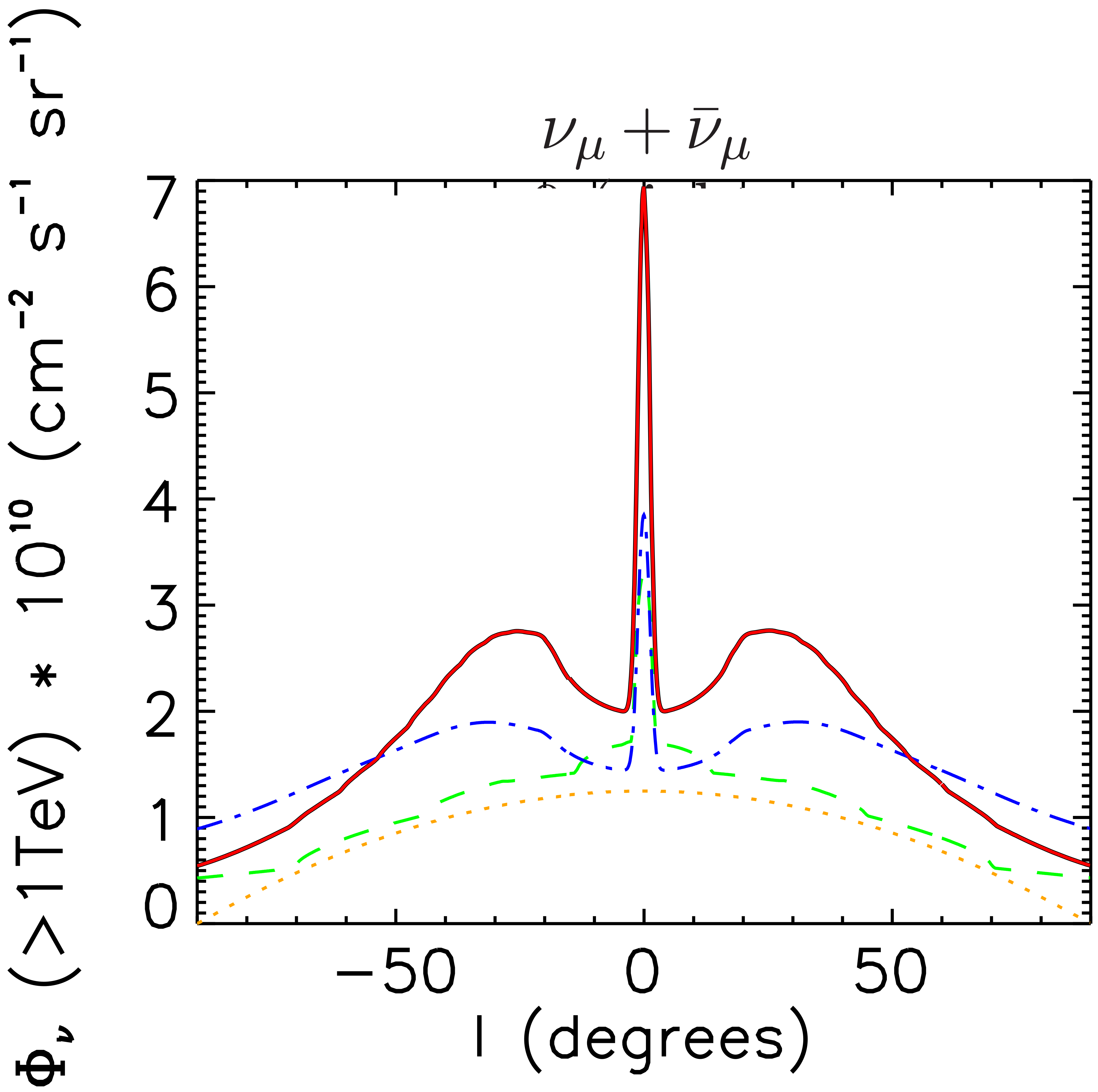


Neutrino oscillations accounted for

Neutrino diffuse emission: *results*

A first computation within the same "conventional" approach

C. Evoli, D.G. & L.Maccione, JCAP 2007   Solving numerically the transport equation



Our reference model (Bronfman gas)

Same gas but uniform CR

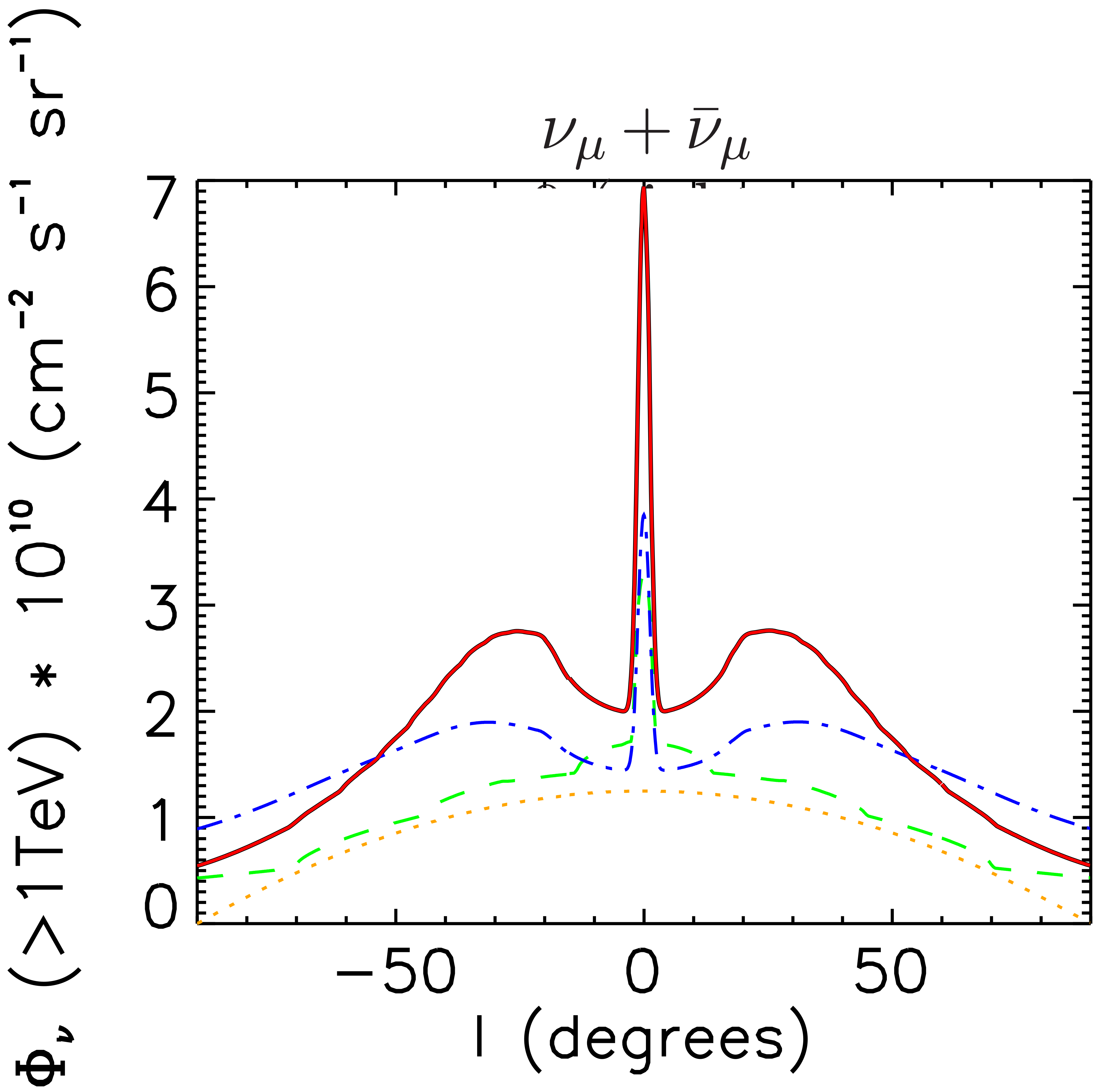
Berezinsky, et al. 1993

Ingelman & Thunman 1996

Neutrino diffuse emission: *results*

A first computation within the same "conventional" approach

C. Evoli, D.G. & L.Maccione, JCAP 2007   Solving numerically the transport equation



Our reference model (Bronfman gas)

Same gas but uniform CR

Berezinsky, et al. 1993

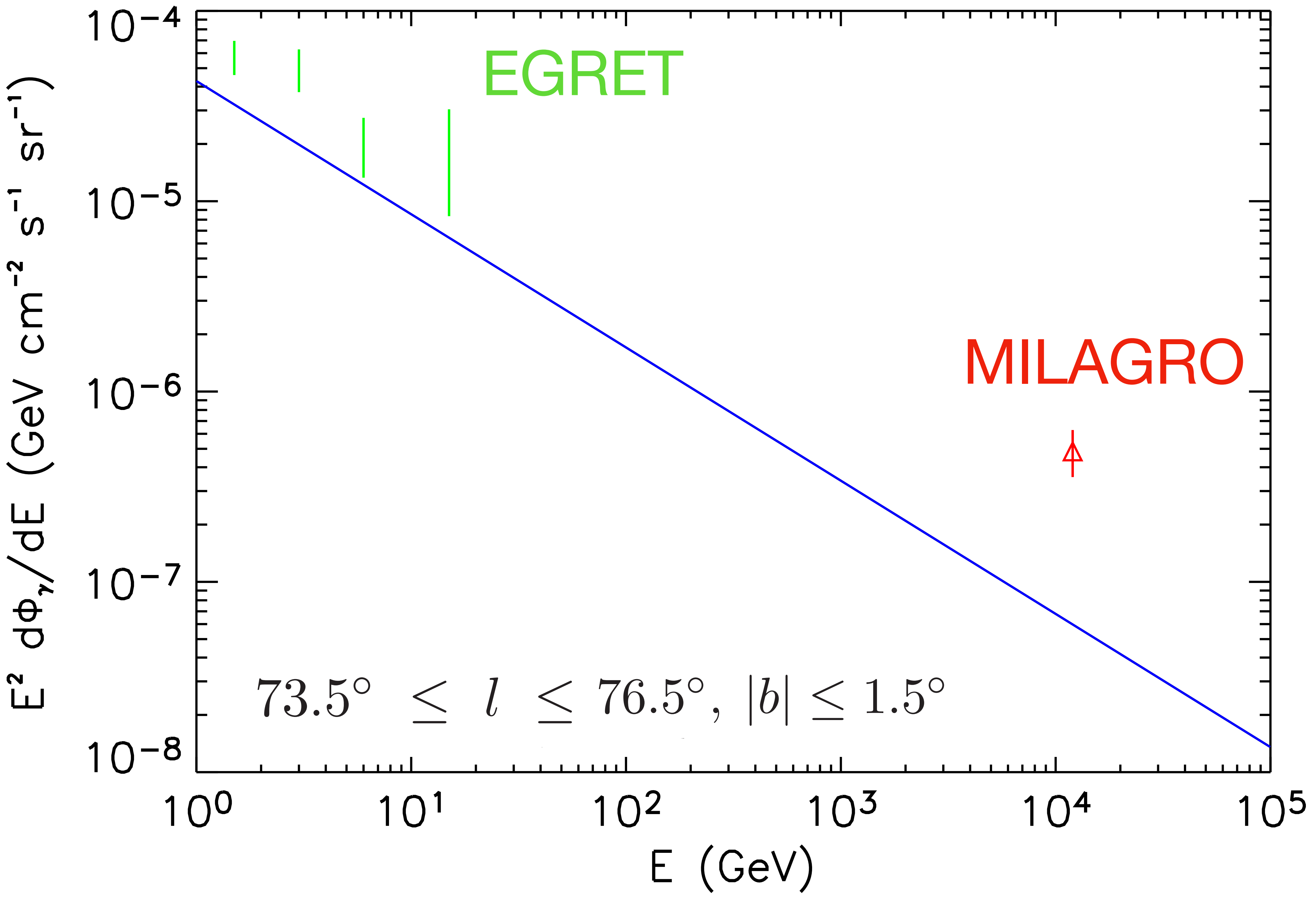
Ingelman & Thunman 1996

The neutrino signal was anyhow estimated to be 2 order of magnitudes smaller than ANTARES upper limits and hardly detectable by a KM3 experiment in the North hemisphere in 10 years !

The corresponding γ-ray (hadronic) emission

A first computation within the same approach

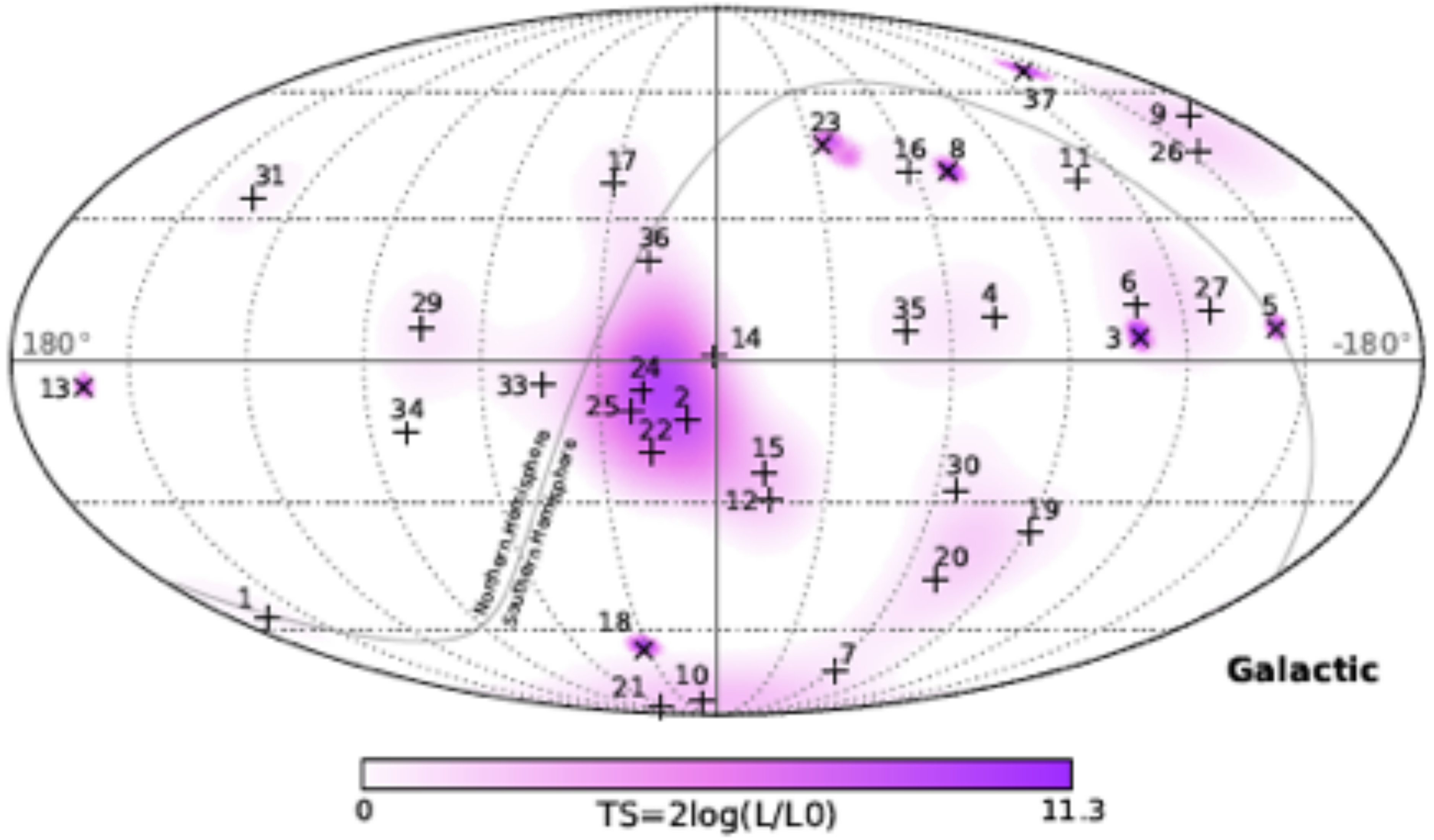
C. Evoli, D.G. & L.Maccione, JCAP 2007

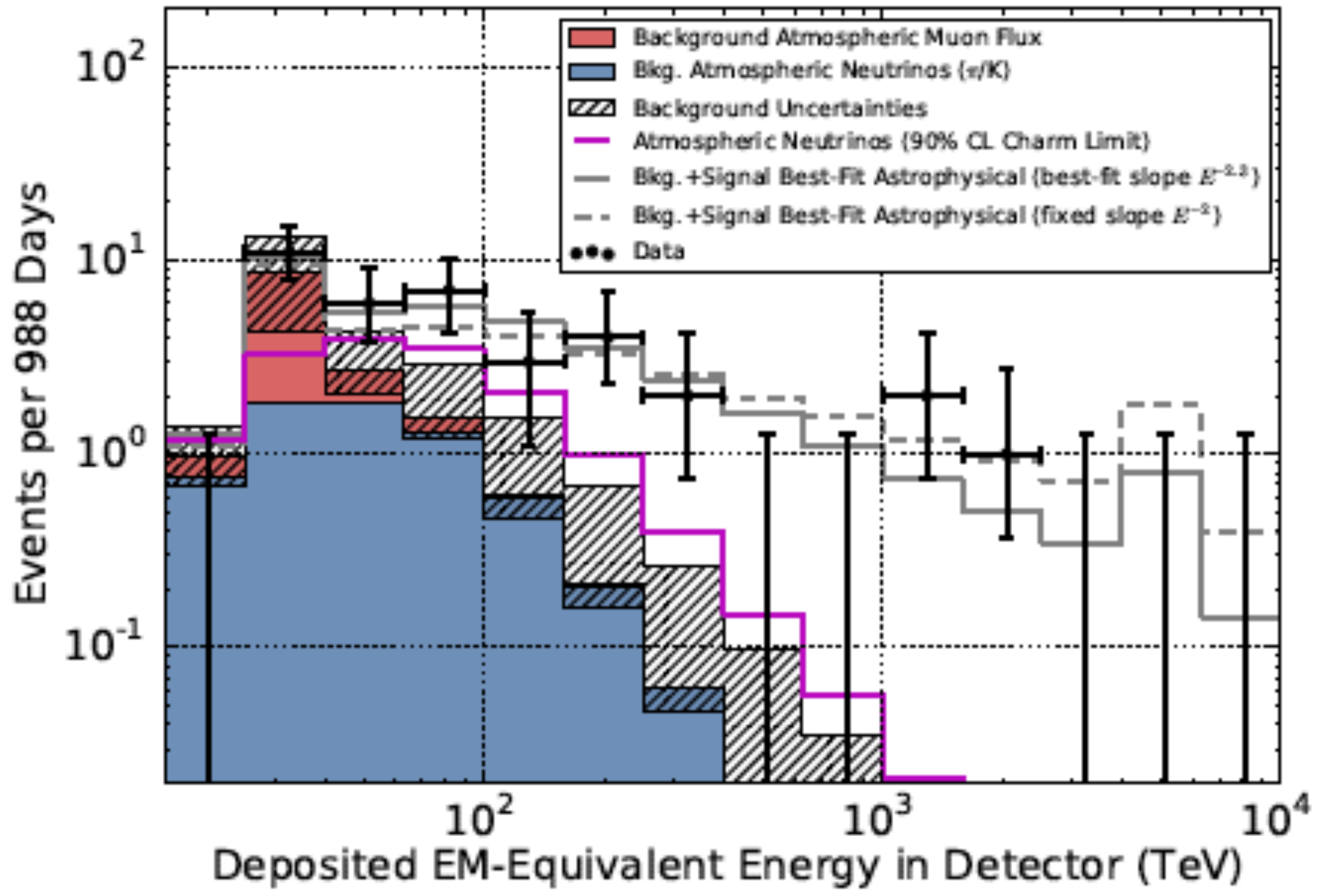


Even neglecting IC the emission was found to match EGRET relatively well. However it is significantly lower than observed in some dense region like that found by MILAGRO and the GC region !

2013: IceCube first detects cosmic νs !

The beginning of high energy neutrino astronomy





28 (2 years, PRL 2013) then 37 events (3 yrs PRL 2014). 5.7σ excess respect to the atmosf. bkg. !

Isotropic distribution !

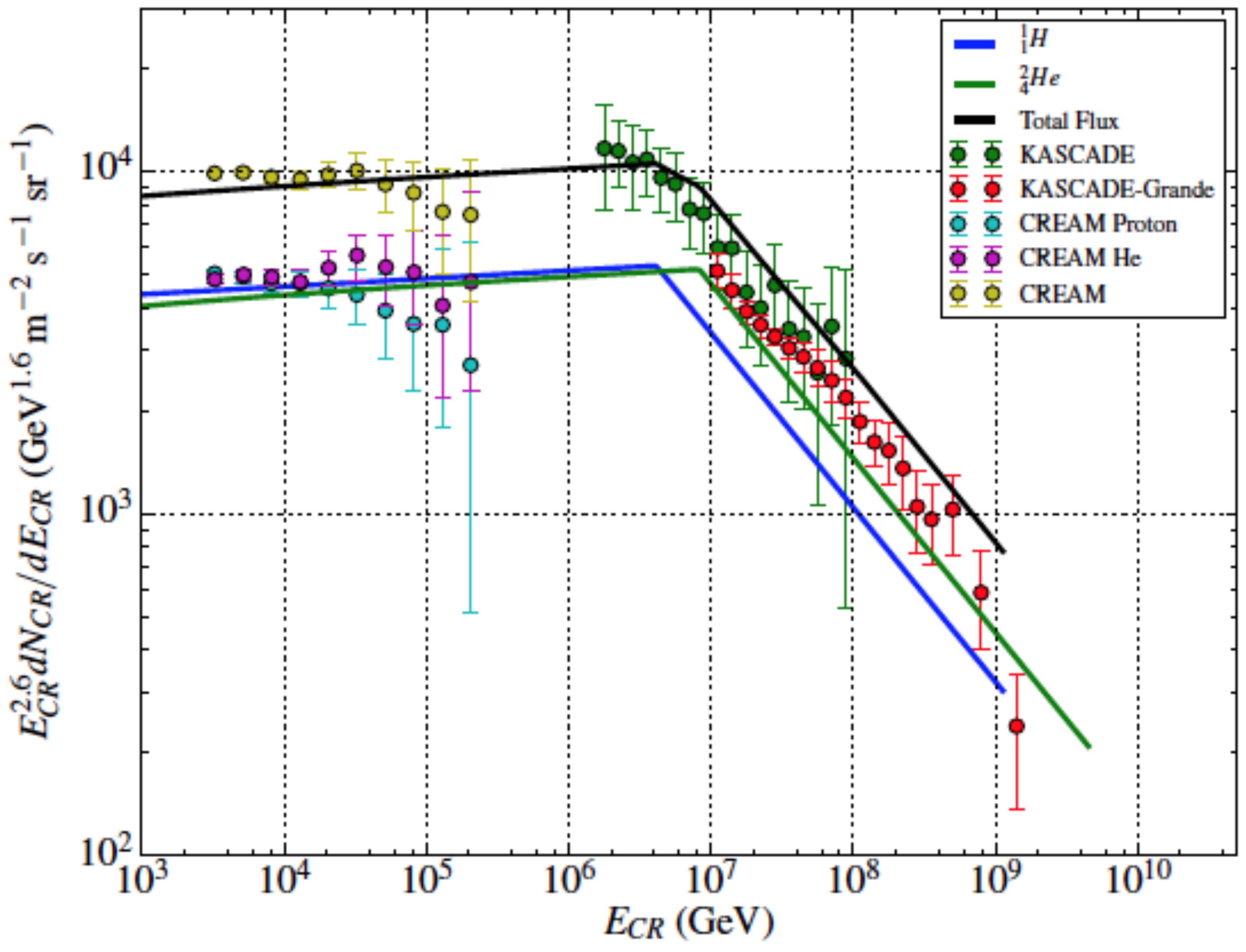
Best fit spectral index - 2.3 ± 0.3

Conventional models against the first IC results

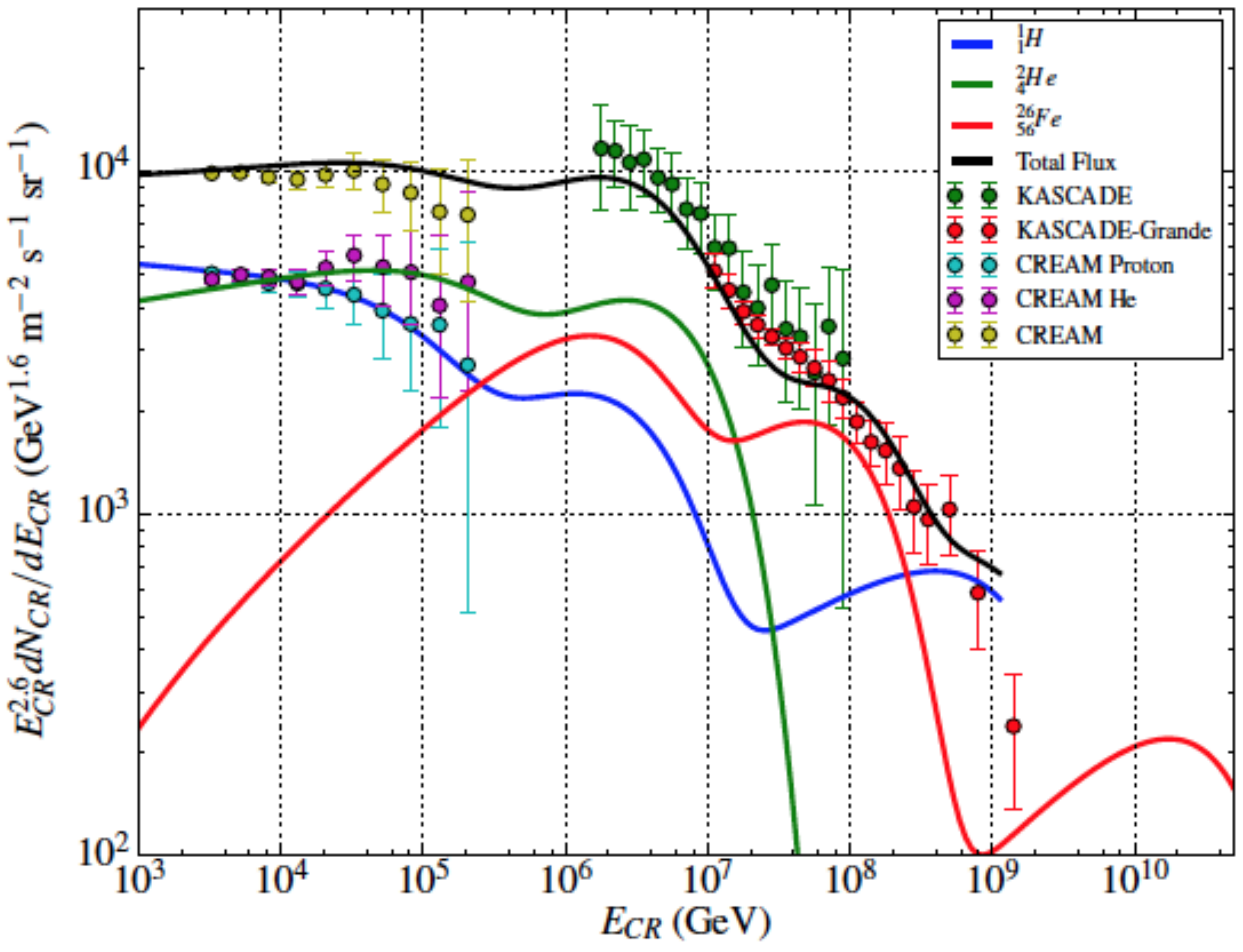
Ahlers et al. PRD 2016

first use GALPROP (updated gas maps, model tuned against Fermi data).
Extend *model* $S_S Z_4 R_{20} T_{150} C_5$ *up to* PeV. Source spectra are modelled to reproduce CR data well above that energy

Broken power-law



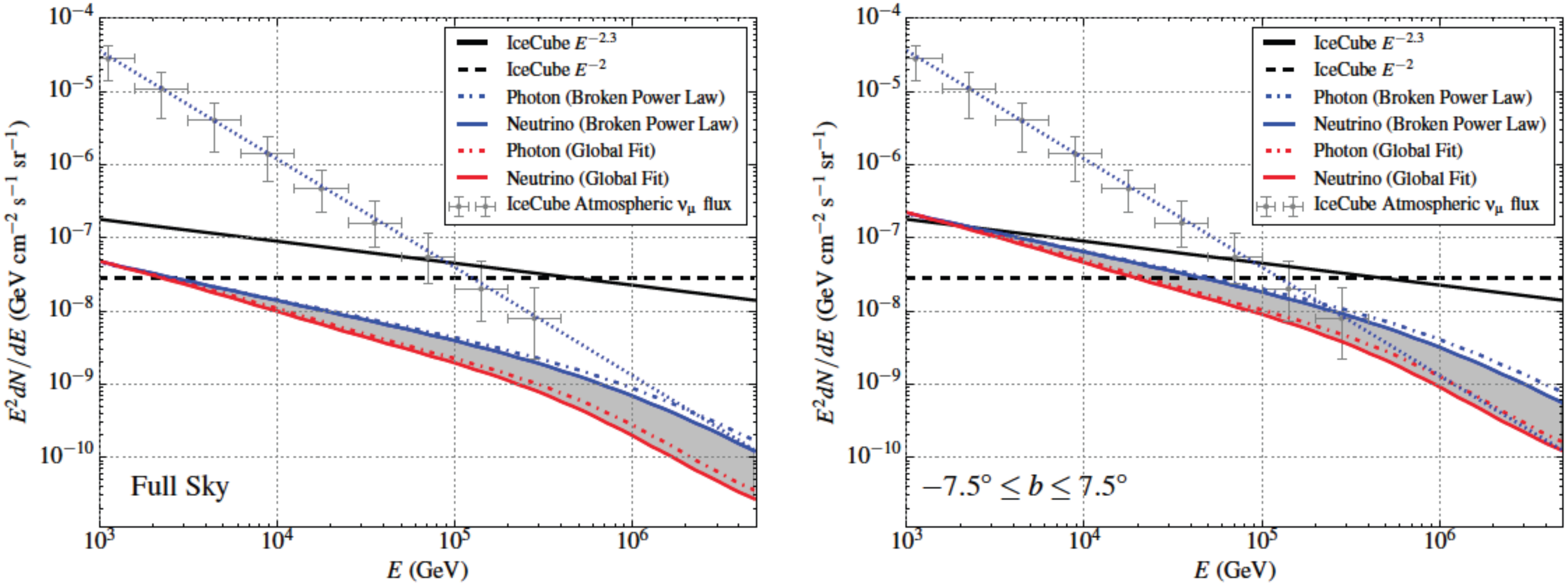
Global fit, based on *Gaisser, Stanev & Tilan 2013*



Conventional models against the first IC results

Ahlers et al. PRD 2016

Starting from GALPROP model
$S_S Z_4 R_{20} T_{150} C_5$



Expected Galactic emission < 8% (> 60 Tev) of IceCube HESE (2013) signal !

IC sensitivity in 3 years to the Gal. fraction 30% (HESE), 25% (ν_μ North)

THE END OF THE STORY ?

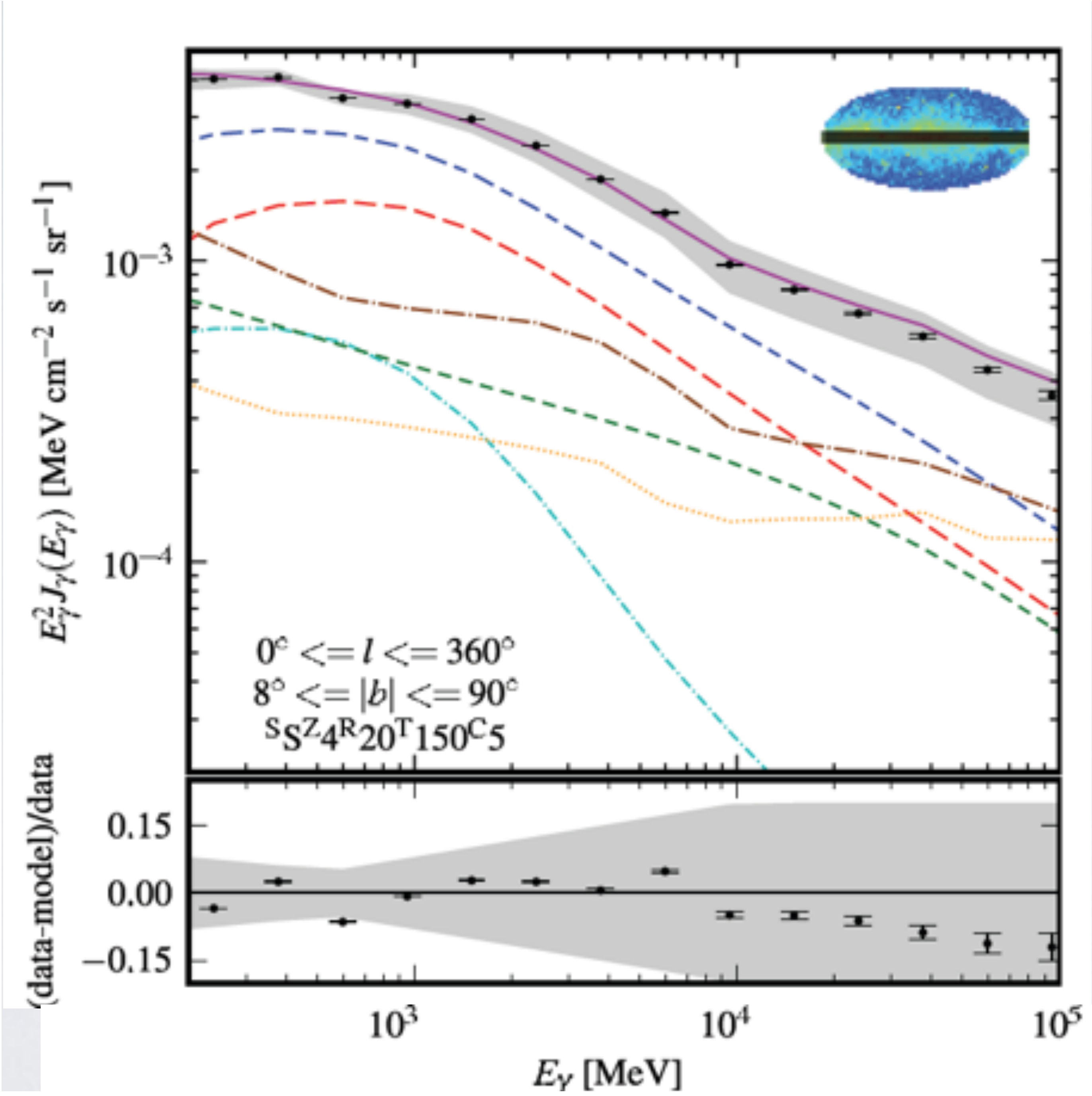
Inhomogeous CR spectrum

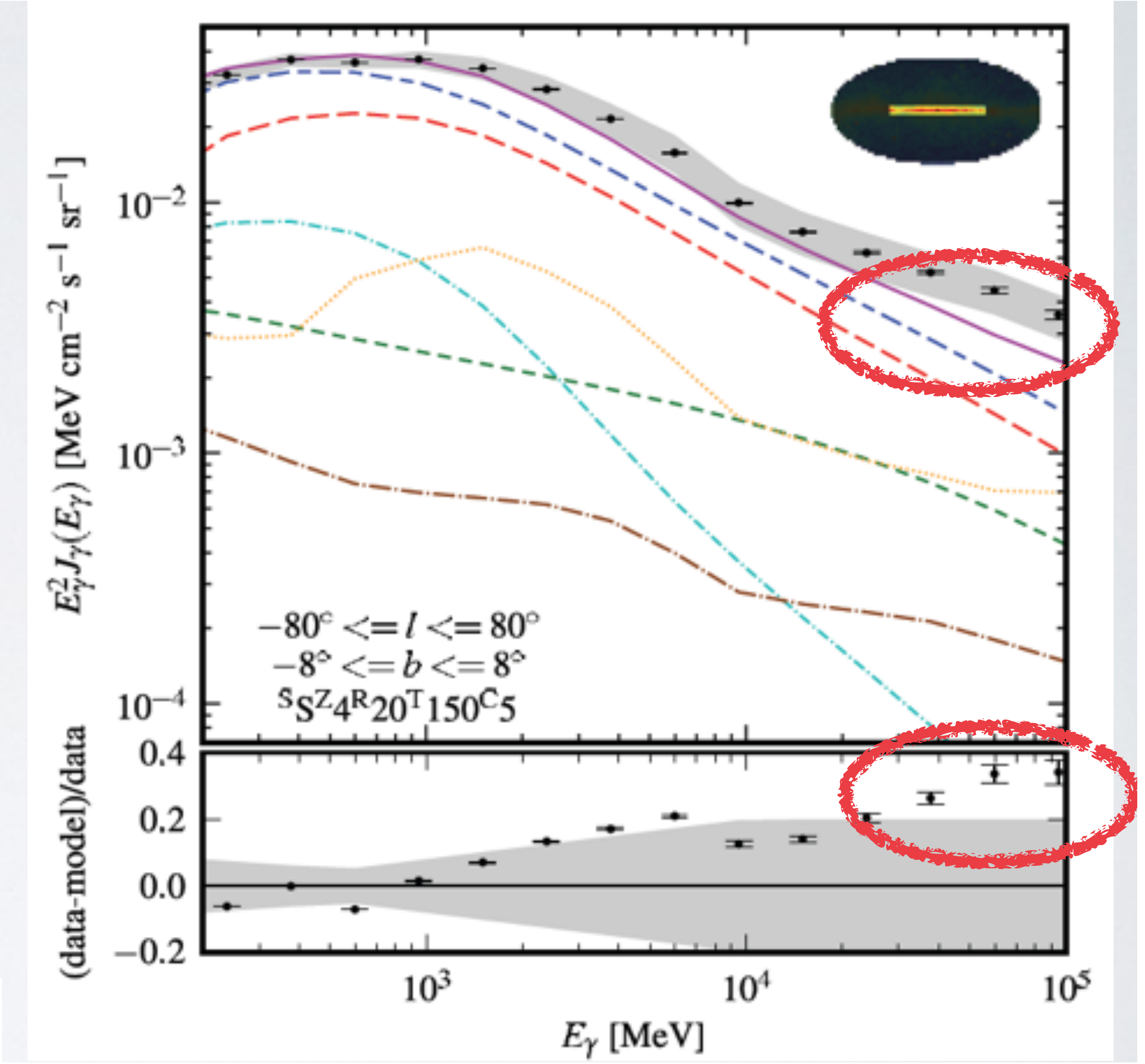
Observational motivations

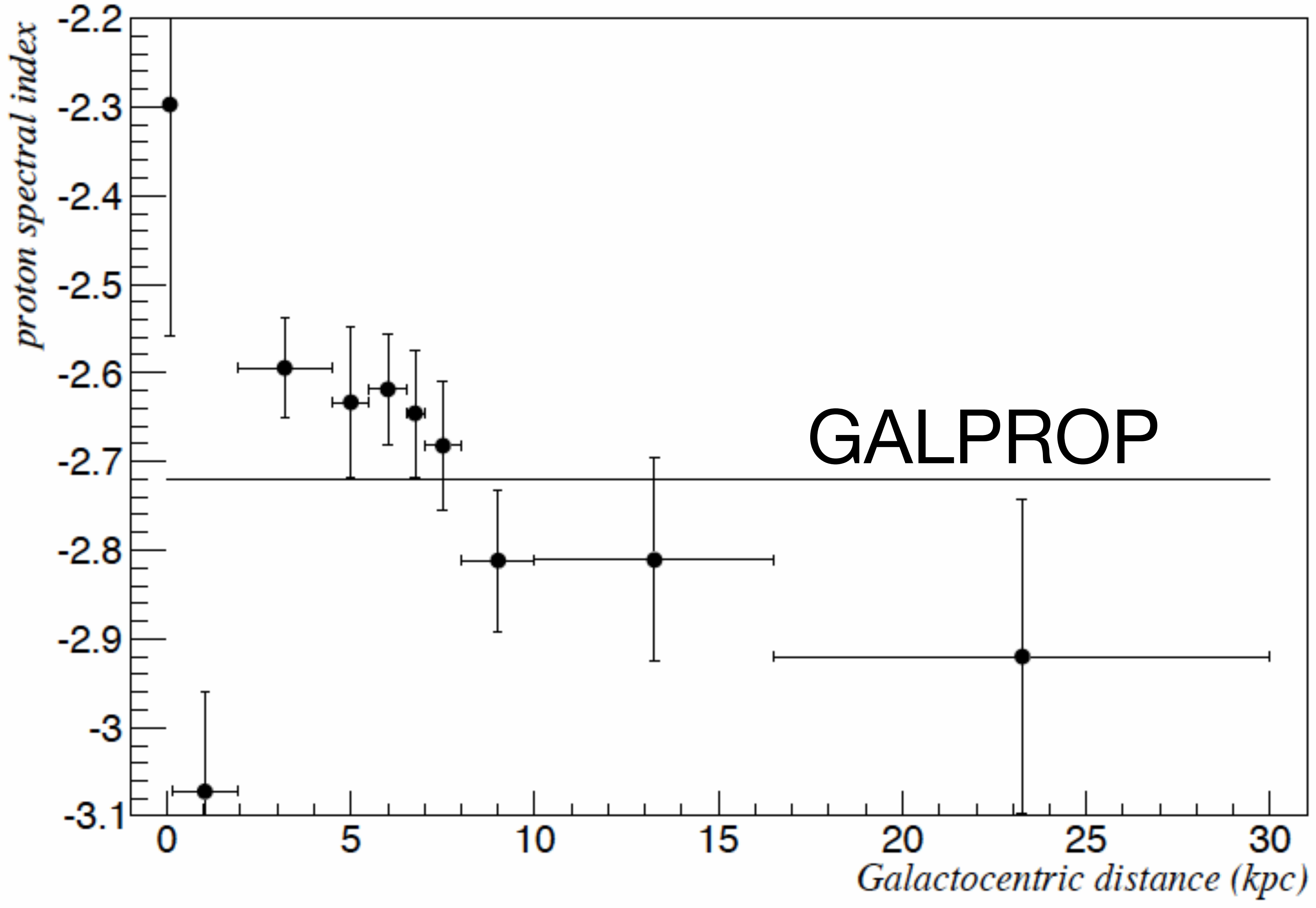
Gaggero, Urbano, Valli & Ullio, PRD 2015

FERMI-LAT coll. ApJS 223 2016

FERMI-LAT coll. ApJ 2012 Model $^{S}S^{Z}4^{R}20^{T}150^{C}5$







To keep in mind: a part a rescaling this is the very same π_0 model used by IceCube (see below) !

The reference Fermi coll. model IS NOT a GALPROP model !

The KRAγ model

Gaggero, Urbano, Valli & Ullio, PRD 2015 **implemented with the DRAGON code**

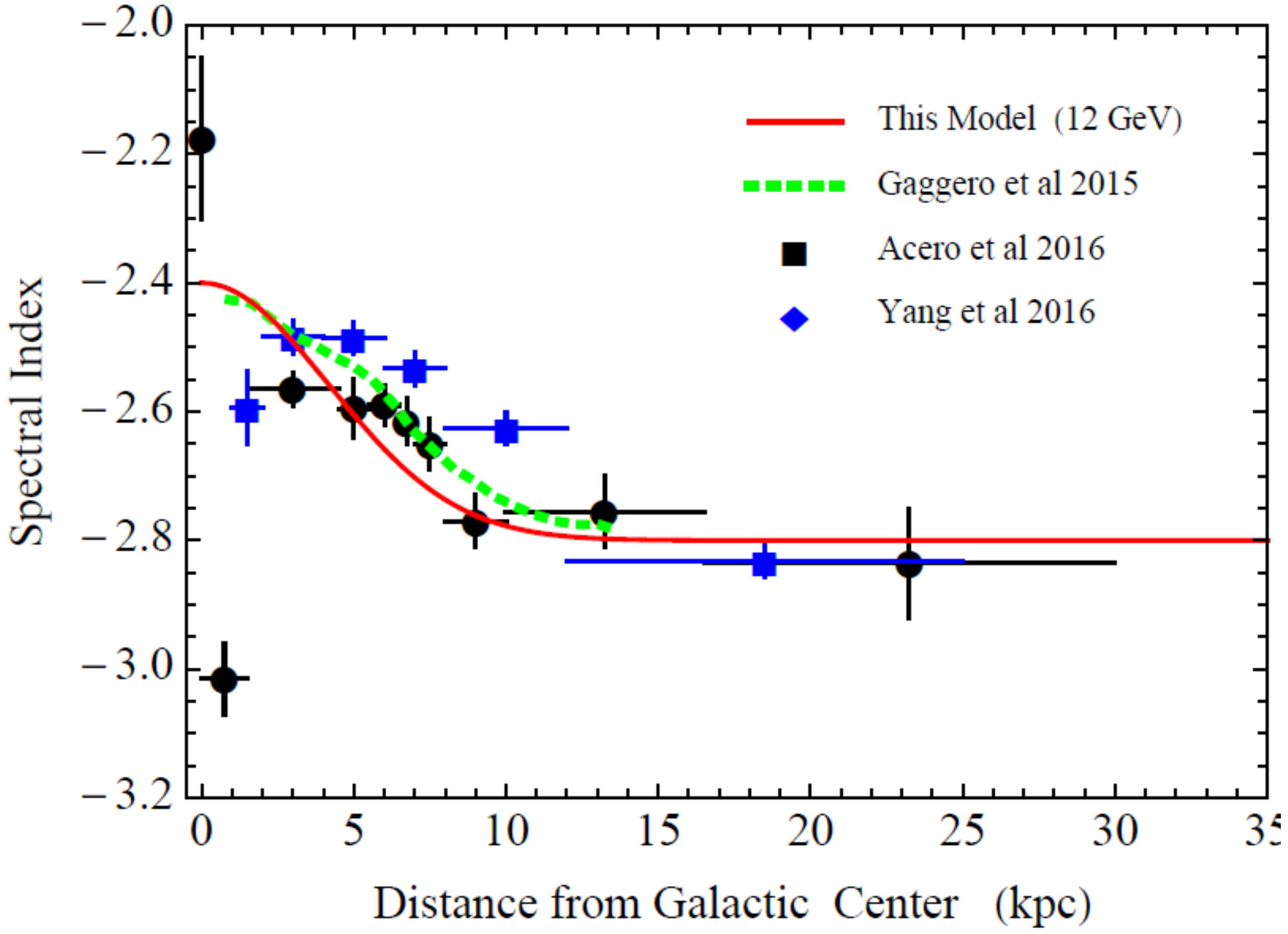
$\delta(R) = A\,R + B$ for $r < 11$ kpc

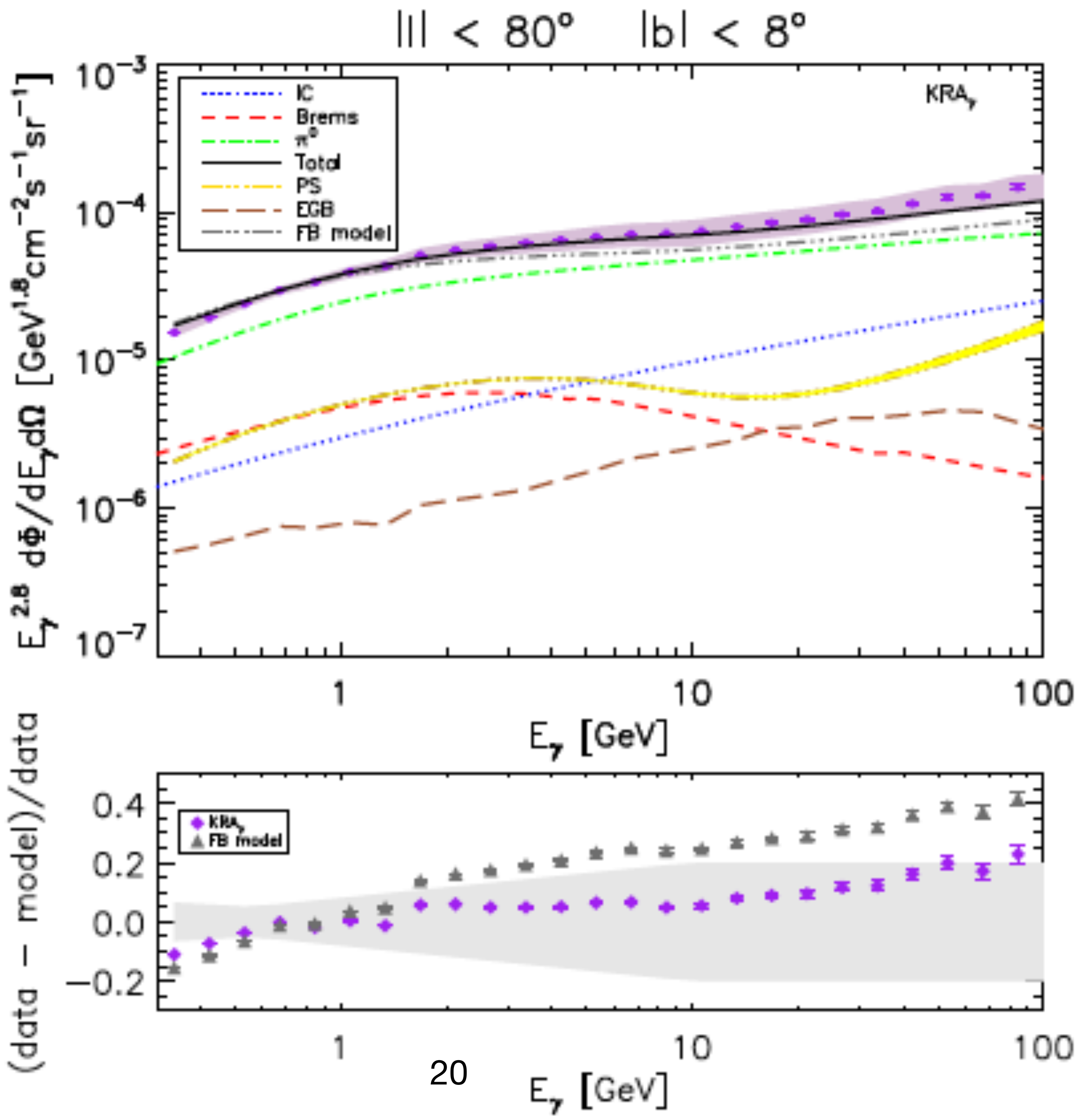
Non-factorized rigidity-position dependence

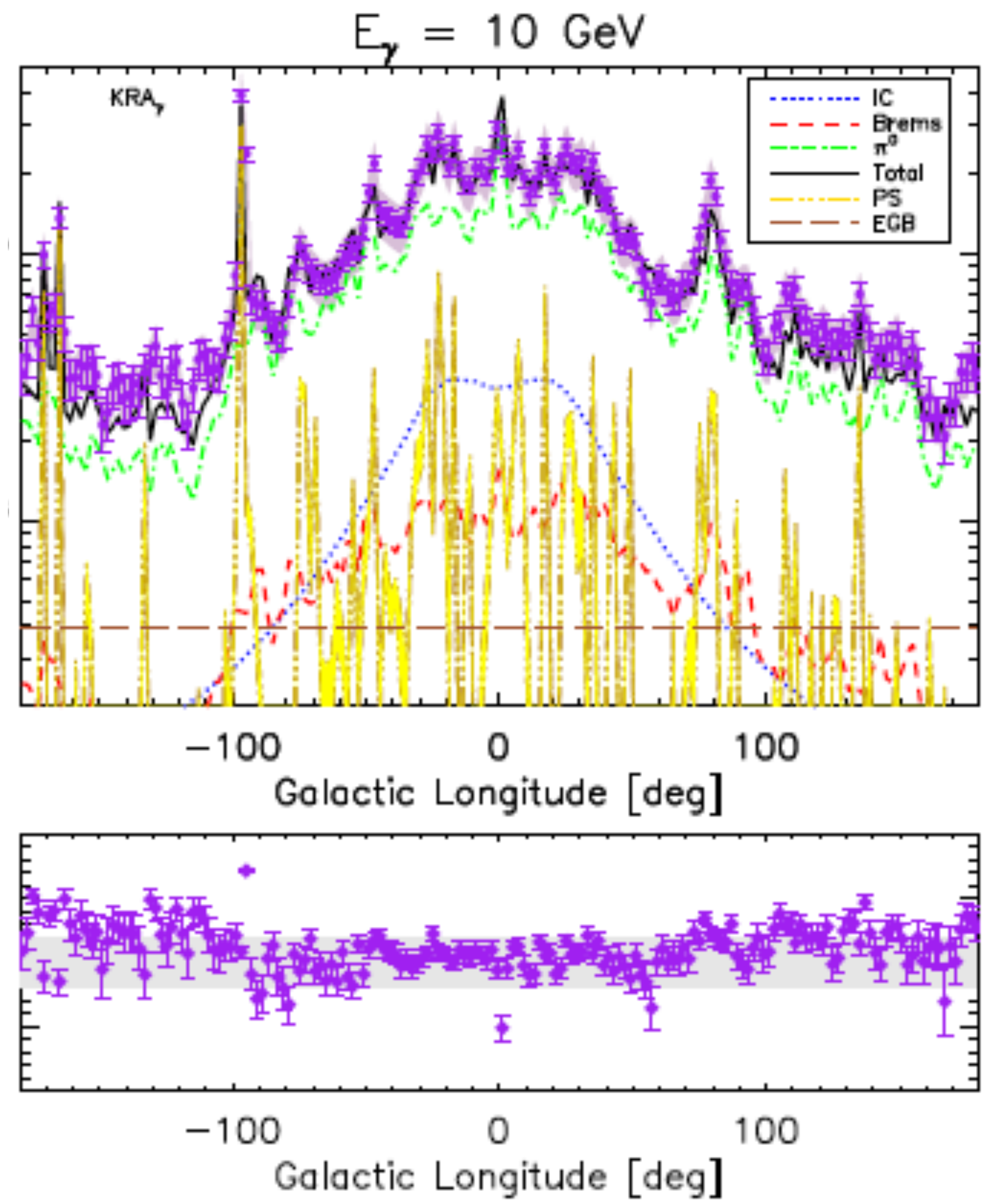
assuming a uniform source spectrum $J_S(\rho, \mathbf{x}) \propto n_S(\mathbf{x})\,\rho^{-\alpha}$

for **not uniform** diffusion coefficient $D(\rho, \mathbf{x}) \propto D_0\,\rho^{-\delta(R)}$

$\Rightarrow$ $J_{CR}(\rho, \mathbf{x}) \propto J_0(\mathbf{x})\,\rho^{-(\alpha + \delta(R))}$







The DRAGON project

Diffusion **R**eacceleration and **A**dvection of **G**alactic cosmic rays

C. Evoli, D. Gaggero, DG, L. Maccione https://github.com/cosmicrays/

JCAP 2008, JCAP 2017

Started in 2007. Like GALPROP reproduce consistently primary and secondary CR spectra

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
- it allows anisotropic diffusion (2D)

In combination with HERMES (see below) it is used by many experimental collaborations to model/interpret CR, γ-ray and ν data

The KRAγ (improved) model

The effects on the high energy γ-ray emission

Strong flux enhancement in the inner galactic plane above the TeV keeping it almost unchanged below 10 GeV !

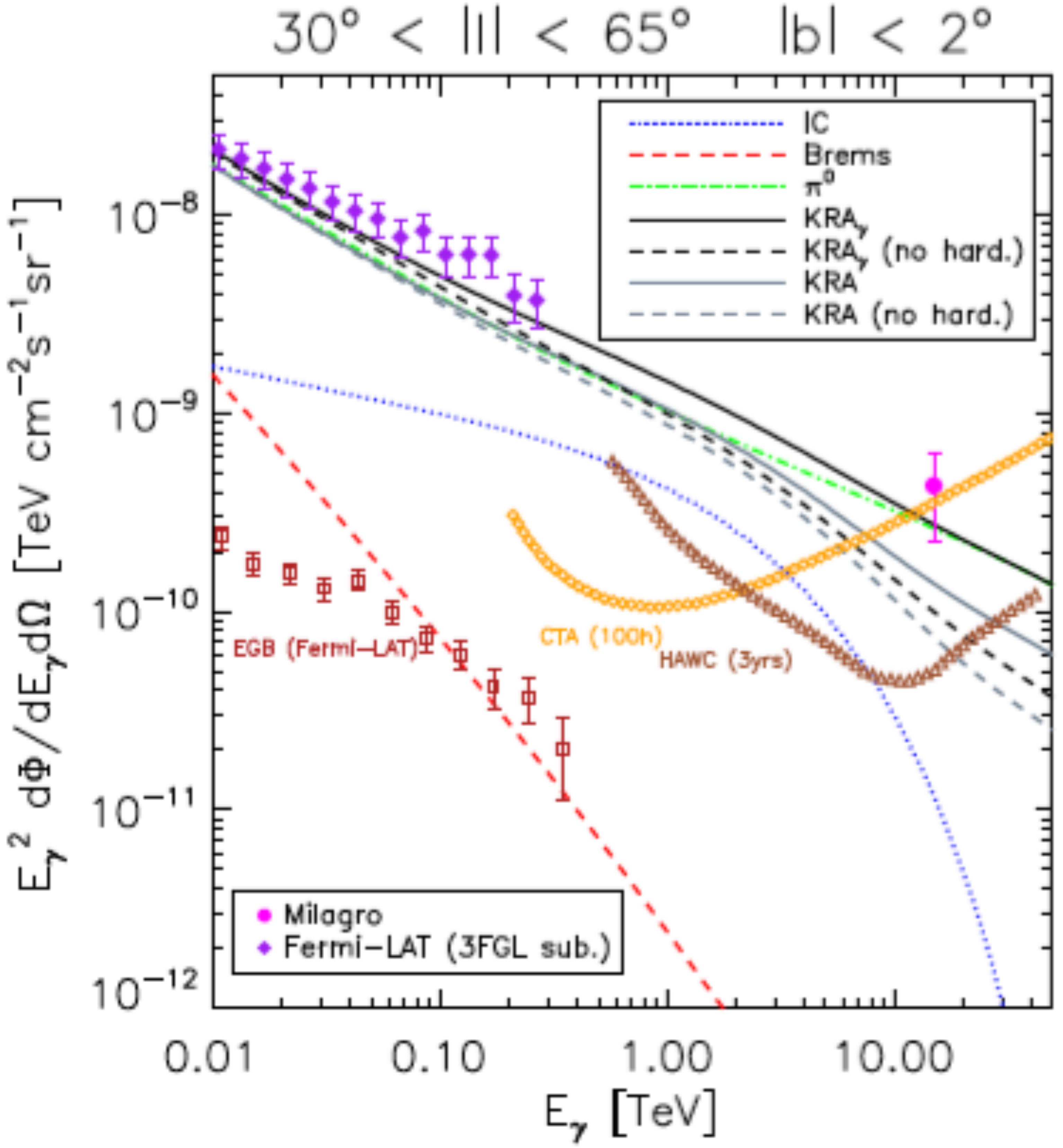
THIS ALLOWS TO MATCH FERMI AND VERY HIGH ENERGY DATA CONSISTENTLY !

Hard spectrum in the inner GP (**spectral index ~ - 2.5** !)

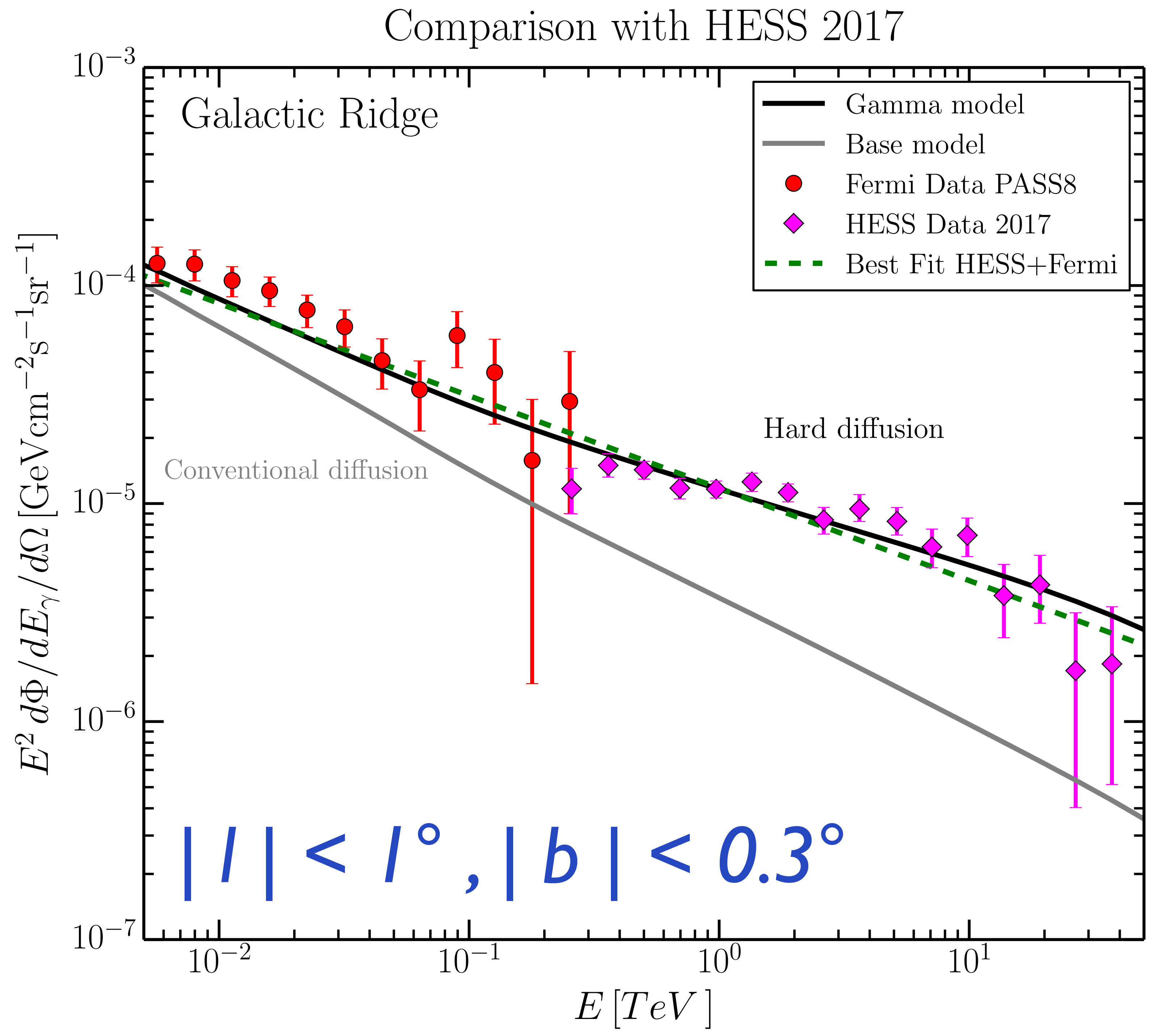
Gaggero, D.G., A. Marinelli, Urbano, Valli ApJ L 2015

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

Inner Galactic plane



Galactic centre ridge



The boost !

This kind of models predict hard CR spectrum in the innermost (dense) GP regions

Pagliaroli, Evoli & Villante JCAP 2016 and

Lipari & Vernetto, 2018 studied a phenomenological implementation of this scenario

A possible theoretical interpretation

The secondary/primary CR ratio probe the diffusion coefficient only within few kpc's !

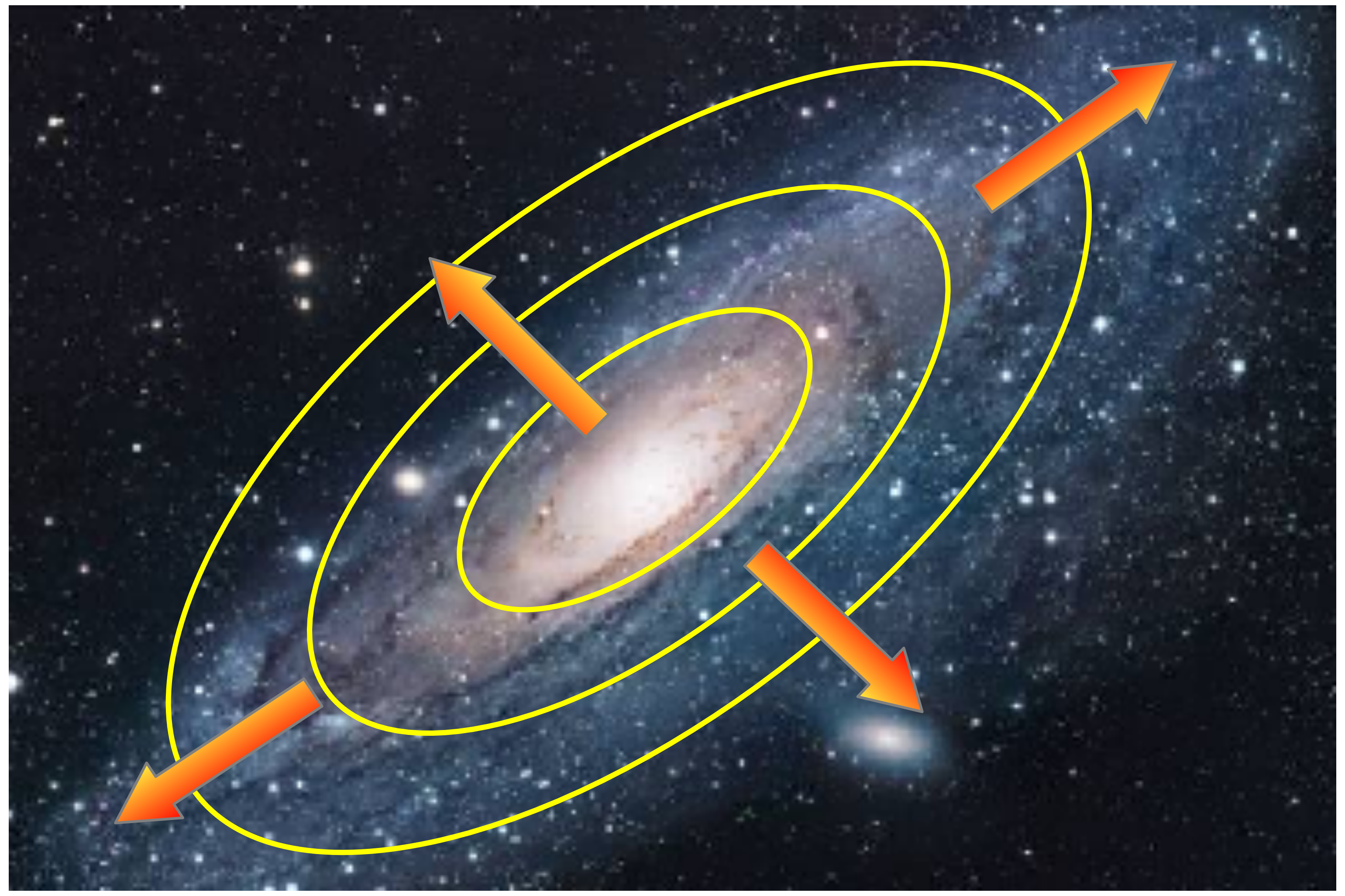
Moreover the regular magnetic field (with versor ***b***) breaks isotropy

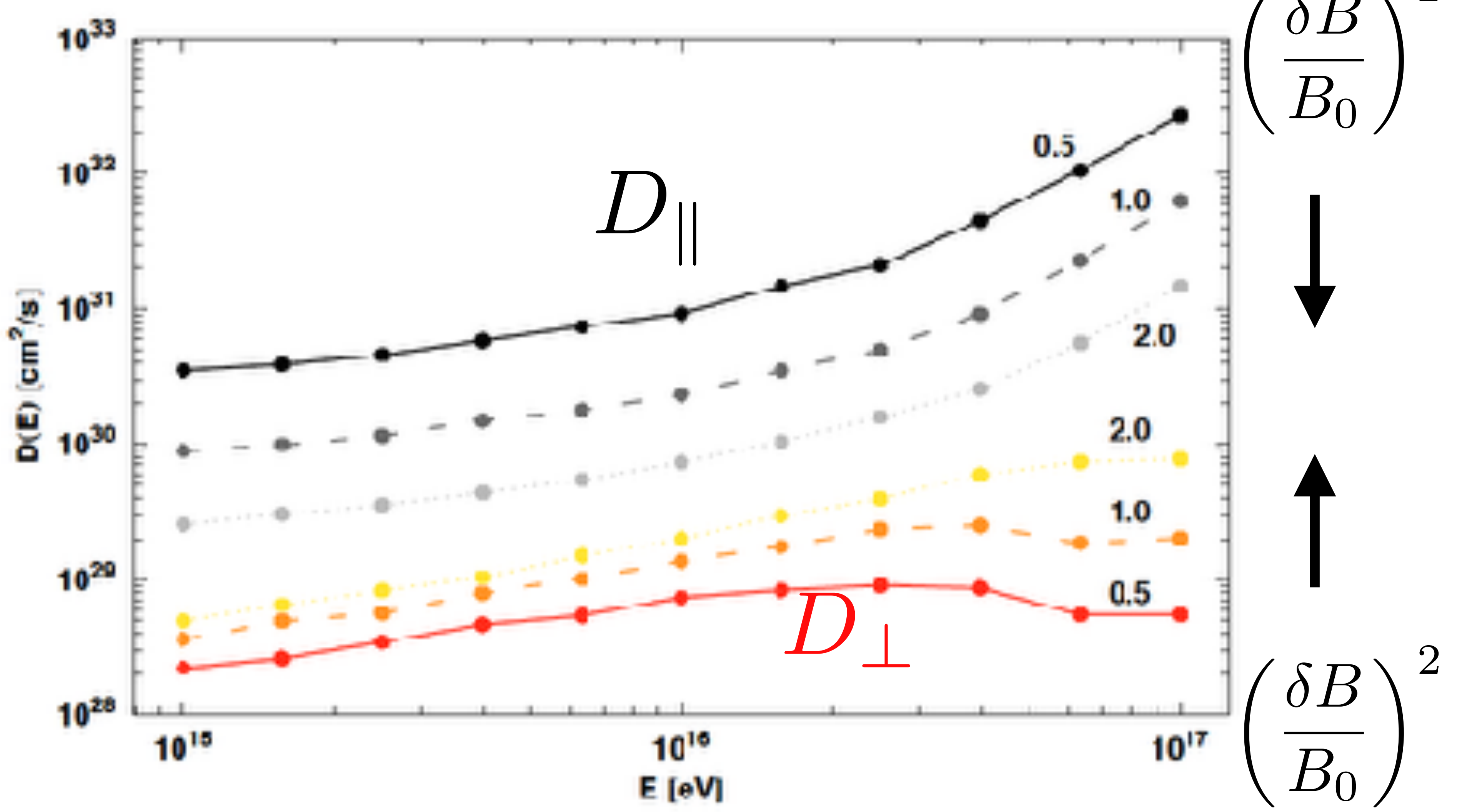
$$D_{ij} = (D_{\parallel} - D_{\perp}) b_i b_j + D_{\perp} \delta_{ij} + D_A \epsilon_{ijk} b_k$$

if ***b*** is purely azimuthal only $D_{\perp}$ matters. Isotropy is restored for strong turbulence but for realistic conditions

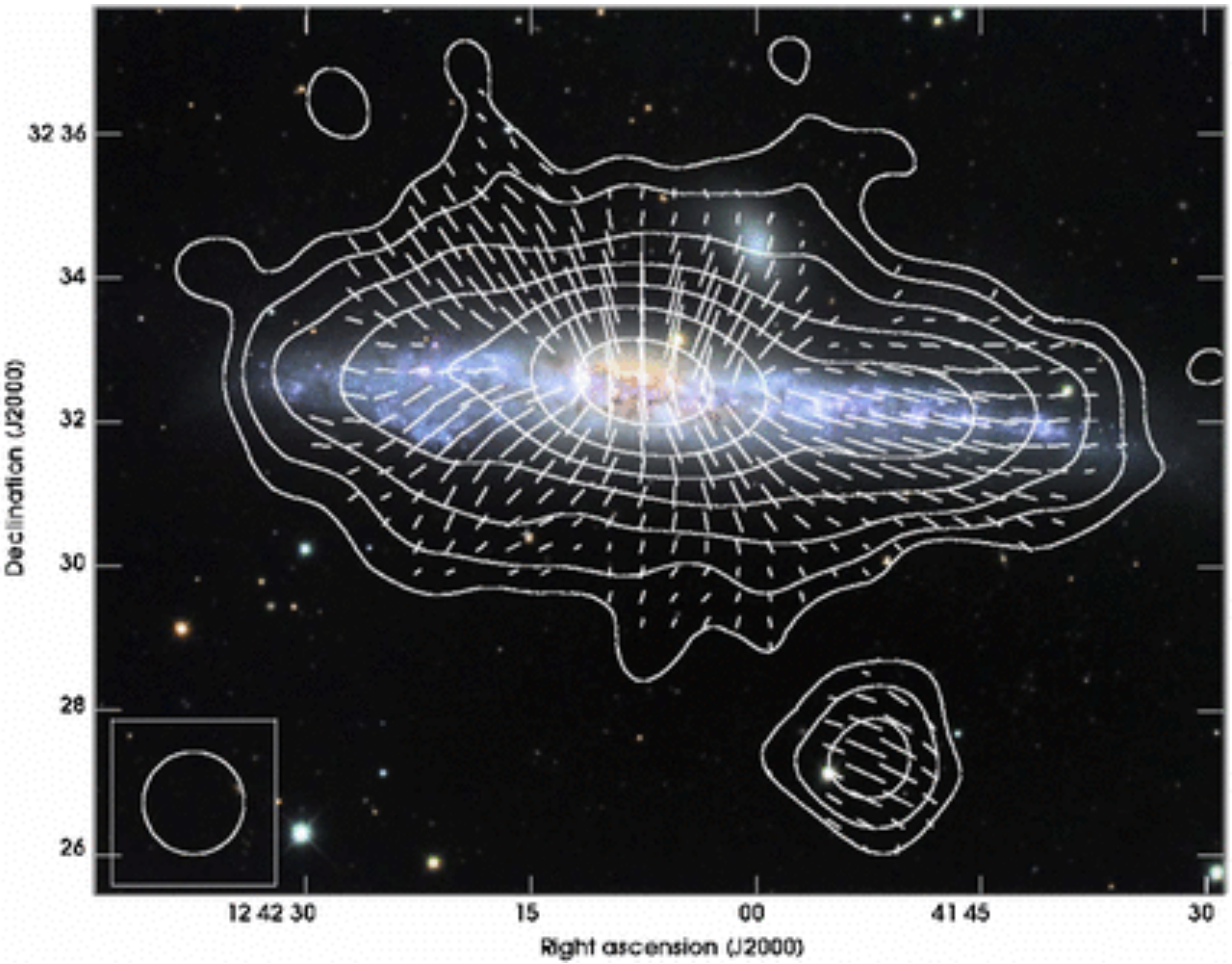
$D_{\perp} / D_{\parallel} \sim 0.01 - 0.1$

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





De Marco, Blasi & Stanev 2007



32 36
34
32
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Declination (J2000)
12 42 30
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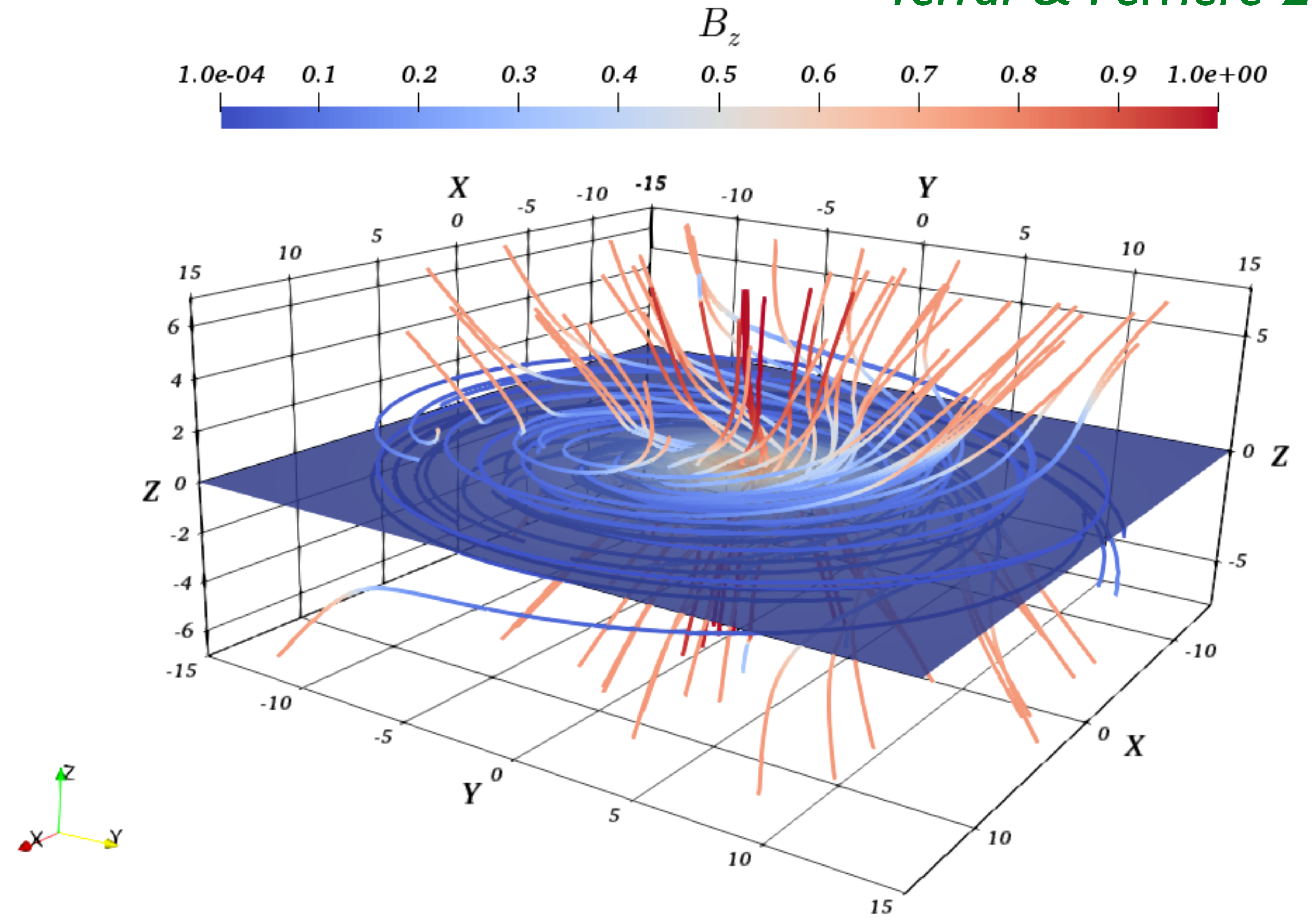
Right ascension (J2000)

A possible theoretical interpretation

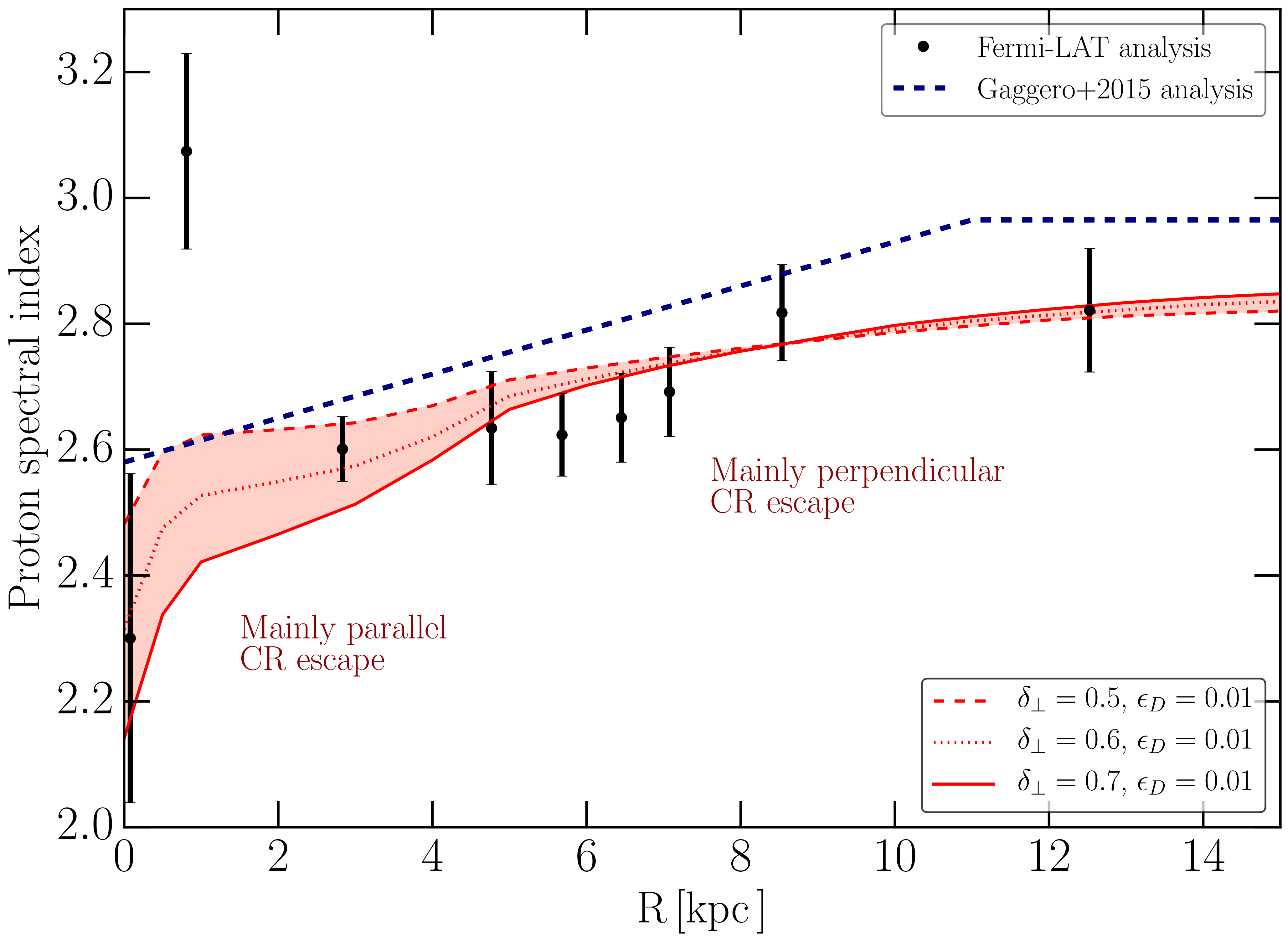
Magnetic field model *Jansson & Farrar ApJ 2012*

Terral & Ferriere 2016



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

using ***DRAGON 2***



- Poloidal magnetic field become larger close to 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

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

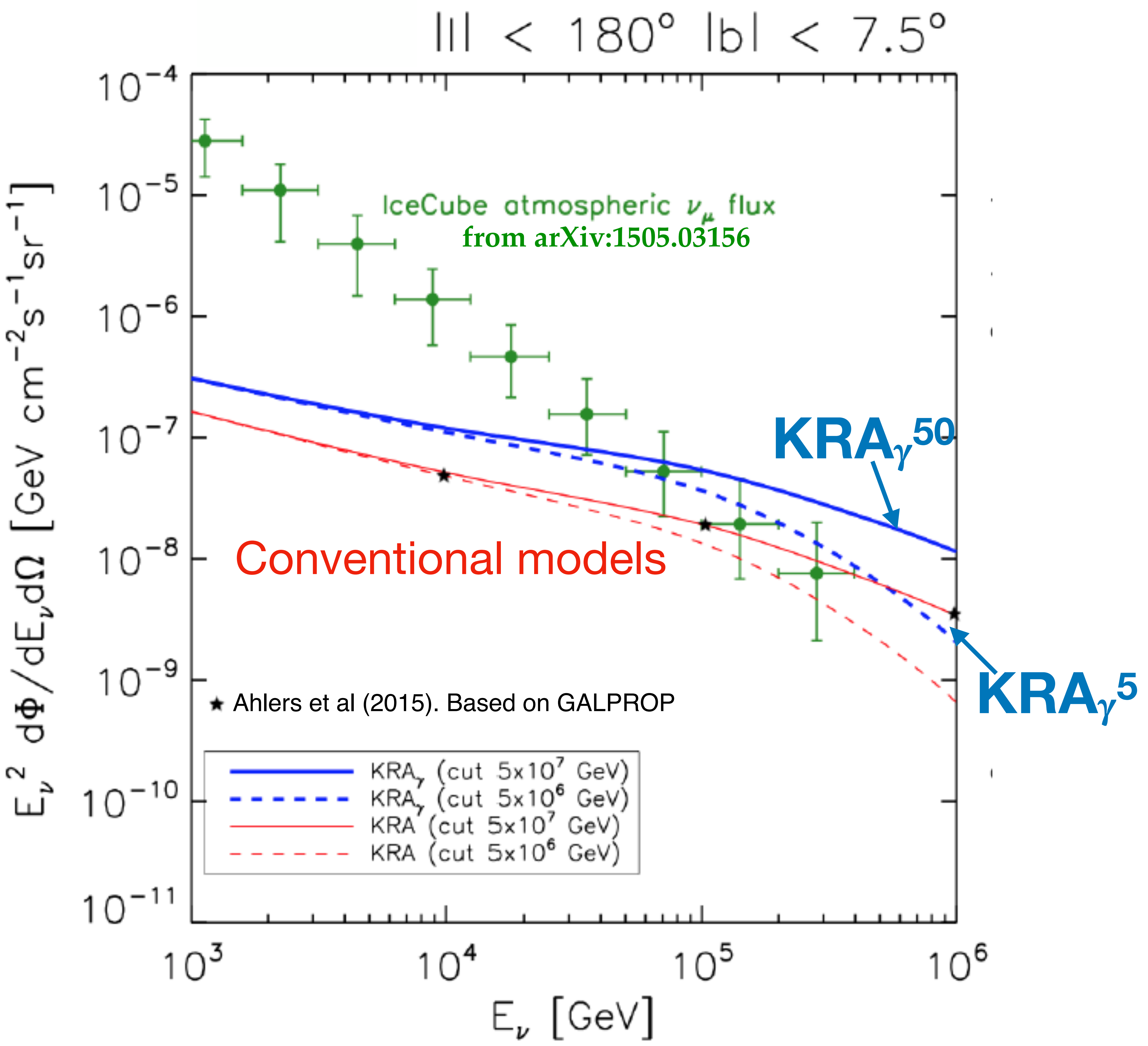
➜ CR spectrum becomes harder for R ➜ 0

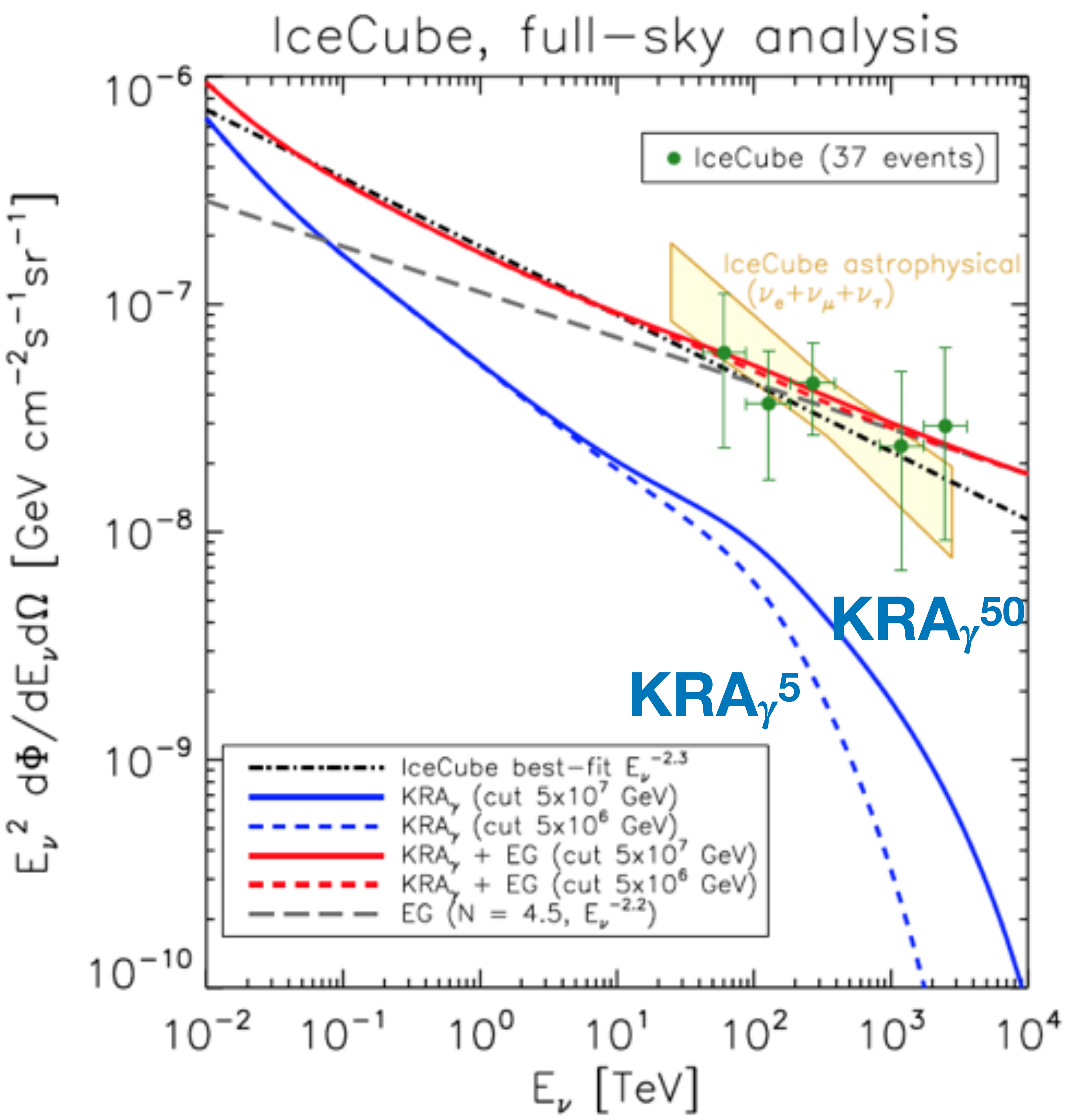
See also *Dundovic et al. 2020*

The effect of inhomogeous (and anisotropic) CR transport on the neutrino emission

KRAγ against the first IceCube results

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



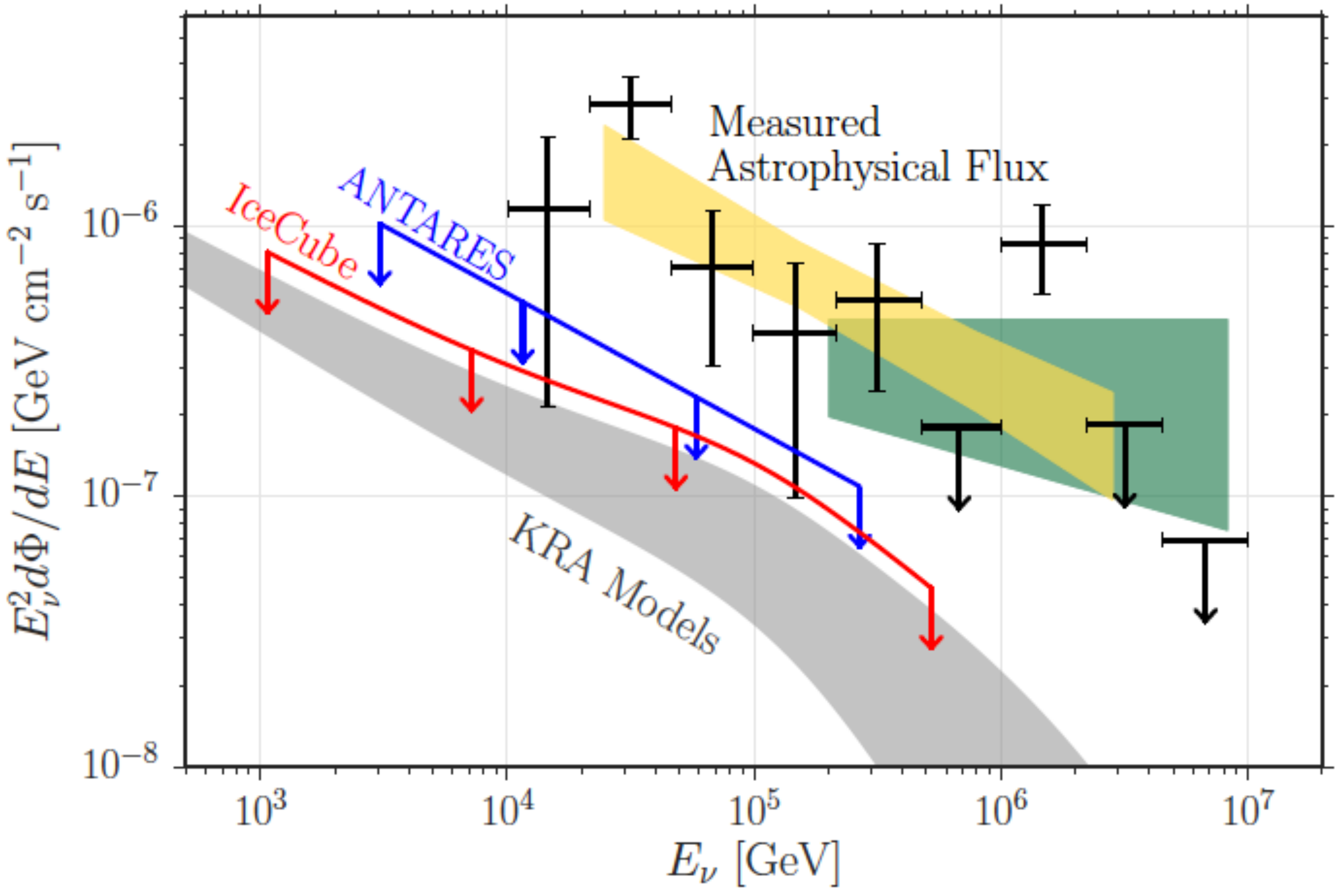


The KRAγ model can account up to ~ 15 % of the full- sky ν astrophysical flux measured by IceCube full-sky above 60 TeV (3 years HESE anal.)

The impact of the KRAγ model on ν astronomy

Gaggero, D.G., A. Marinelli, Urbano, Valli ApJ L 2015 :
ν **flux enhancement predicted**

ANTARES coll., Phys. Lett. B, 2016 (Gal. Ridge)
ANTARES coll. + D. Gaggero & D.G. PRD 2017
ANTARES + IceCube + D. Gaggero & D.G., APJ 2018 →



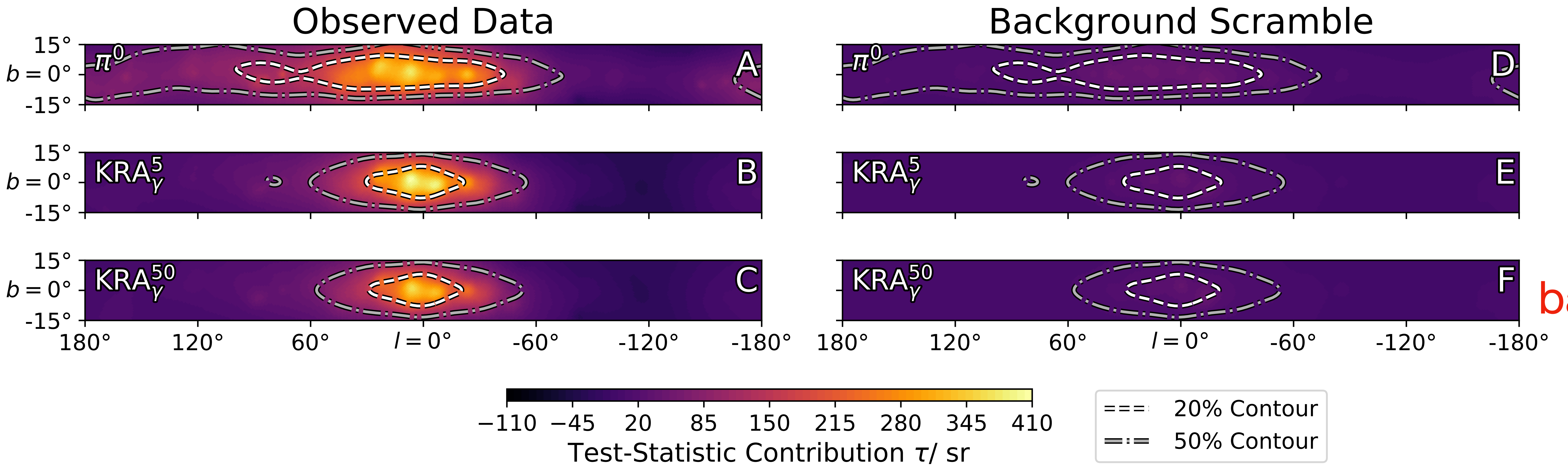
IceCube coll. ApJ 849 (2017) 67 ***a 2.0σ excess compatible with the 0.85 x KRA$_\gamma^5$ model was reported !*** *The conventional scenario was disfavoured.*

ANTARES coll., 2023
Gal. Ridge, positive hint 2.45 spect. Index !

The discovery !

IceCube coll., Science 2023

Due to the large μ background and low angular resolution for shower events the search of an extended emission in the Souther sky requires a maximum likelihood **analysis based on templates** (in energy and angular distributions) in combination with innovative deep learning techniques to identify shower



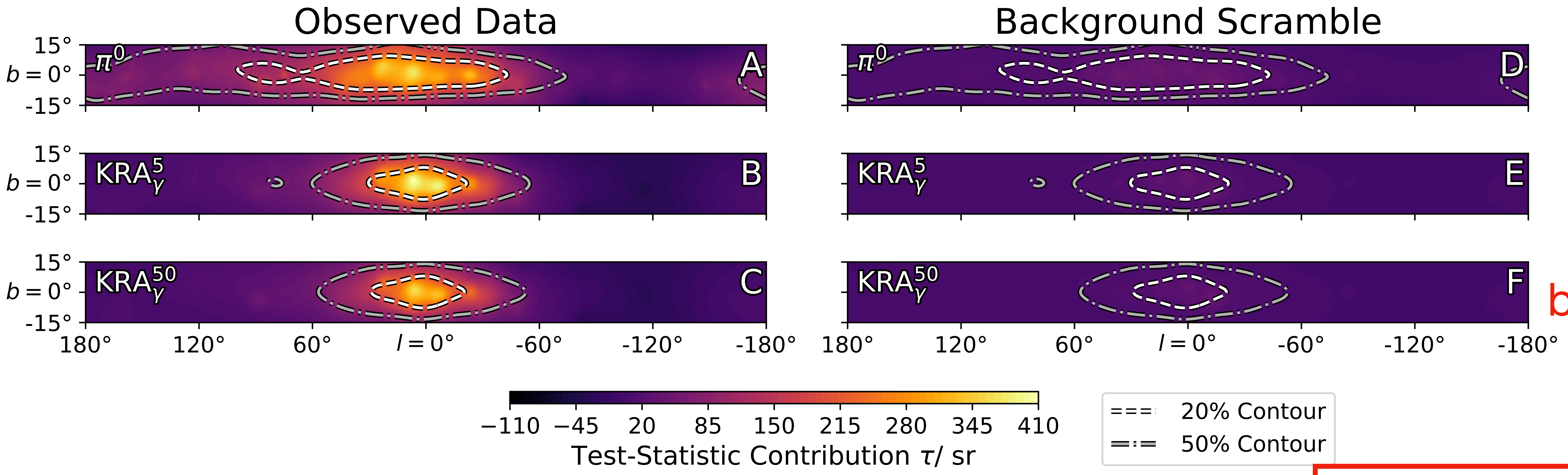
For all considered templates the background hypothesis is rejected !!

Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	0.16×MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	0.11×MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF

The discovery !

IceCube coll., Science 2023

Due to the large μ background and low angular resolution for shower events the search of an extended emission in the Souther sky requires a maximum likelihood analysis based on templates (in energy and angular distributions) in combination with innovative deep learning techniques to identify shower



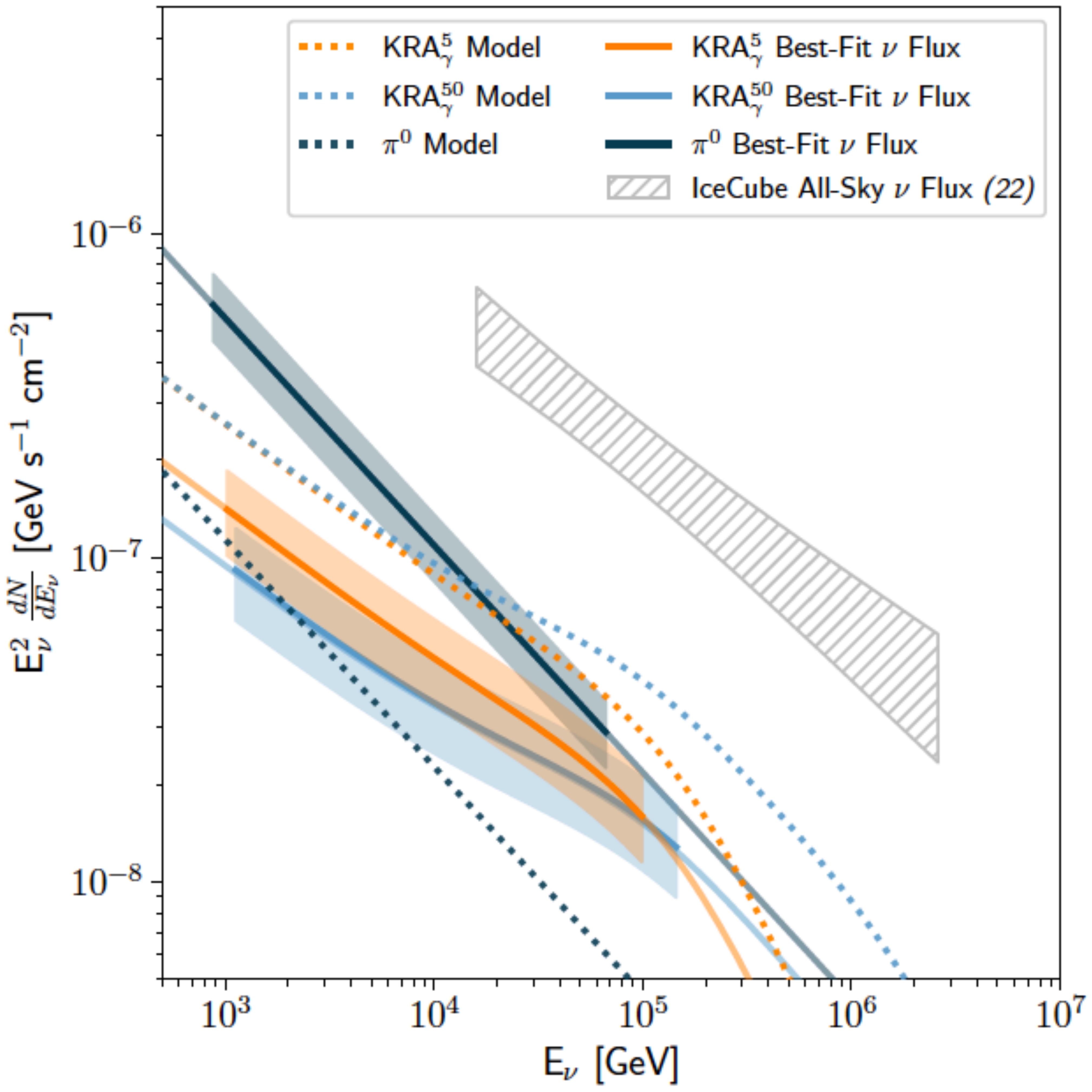
For all considered templates the background hypothesis is rejected !!

Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA^5_γ	0.16×MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}$×MF
KRA^{50}_γ	0.11×MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}$×MF

The KRAγ models were used under the DRAGON team permission.
The theoretical work leading to them has to be considered a relevant piece of the discovery both in the preliminary and analysis phases !

The discovery !

IceCube coll., Science 2023



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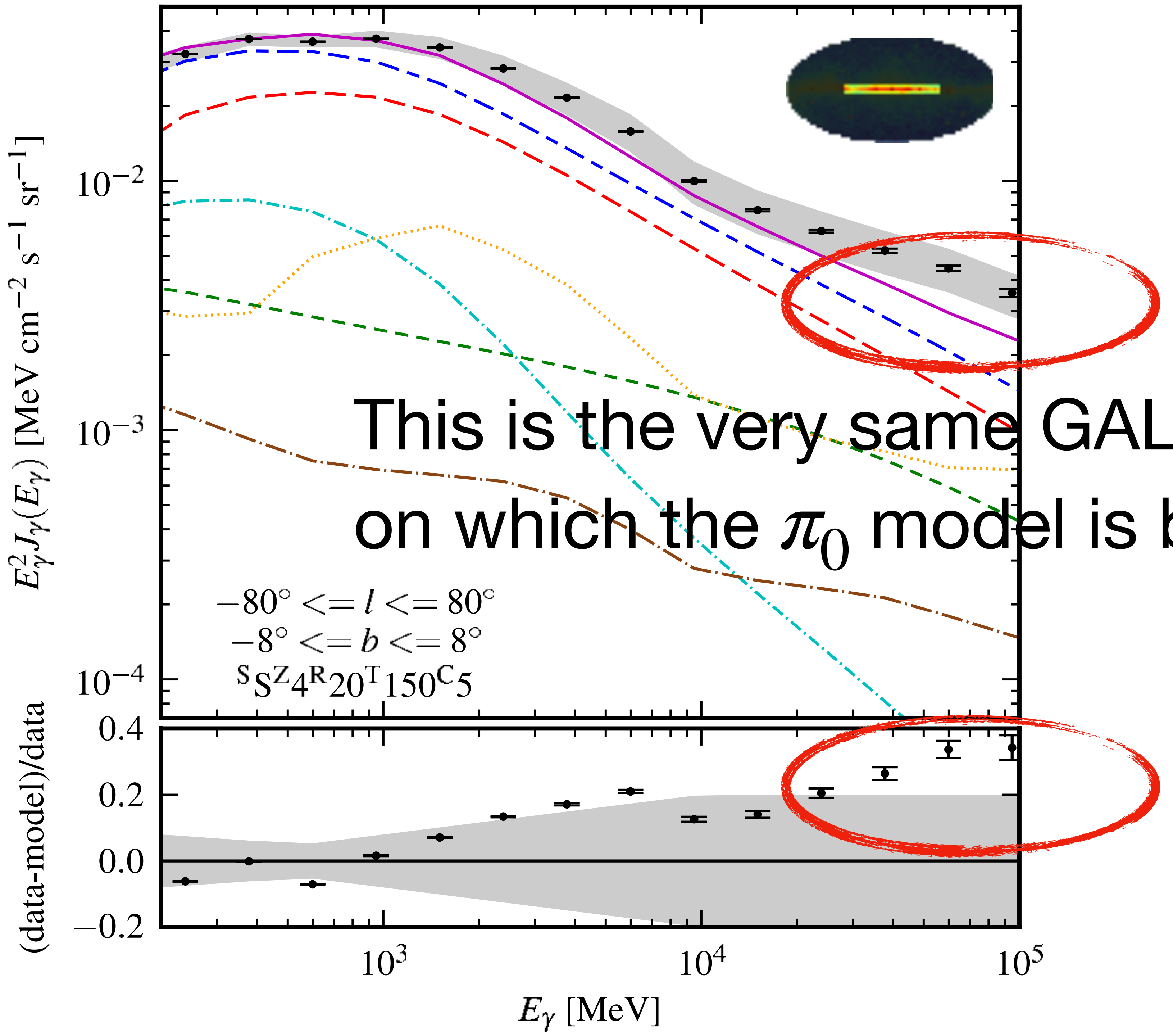
The π_0 model: a toy model ?

It is a conventional GALPROP model ($^{S}S^{Z}4^{R}20^{T}150^{C}5$) rescaled by a normalization factor X 5

(Related) DRAWBACKS :

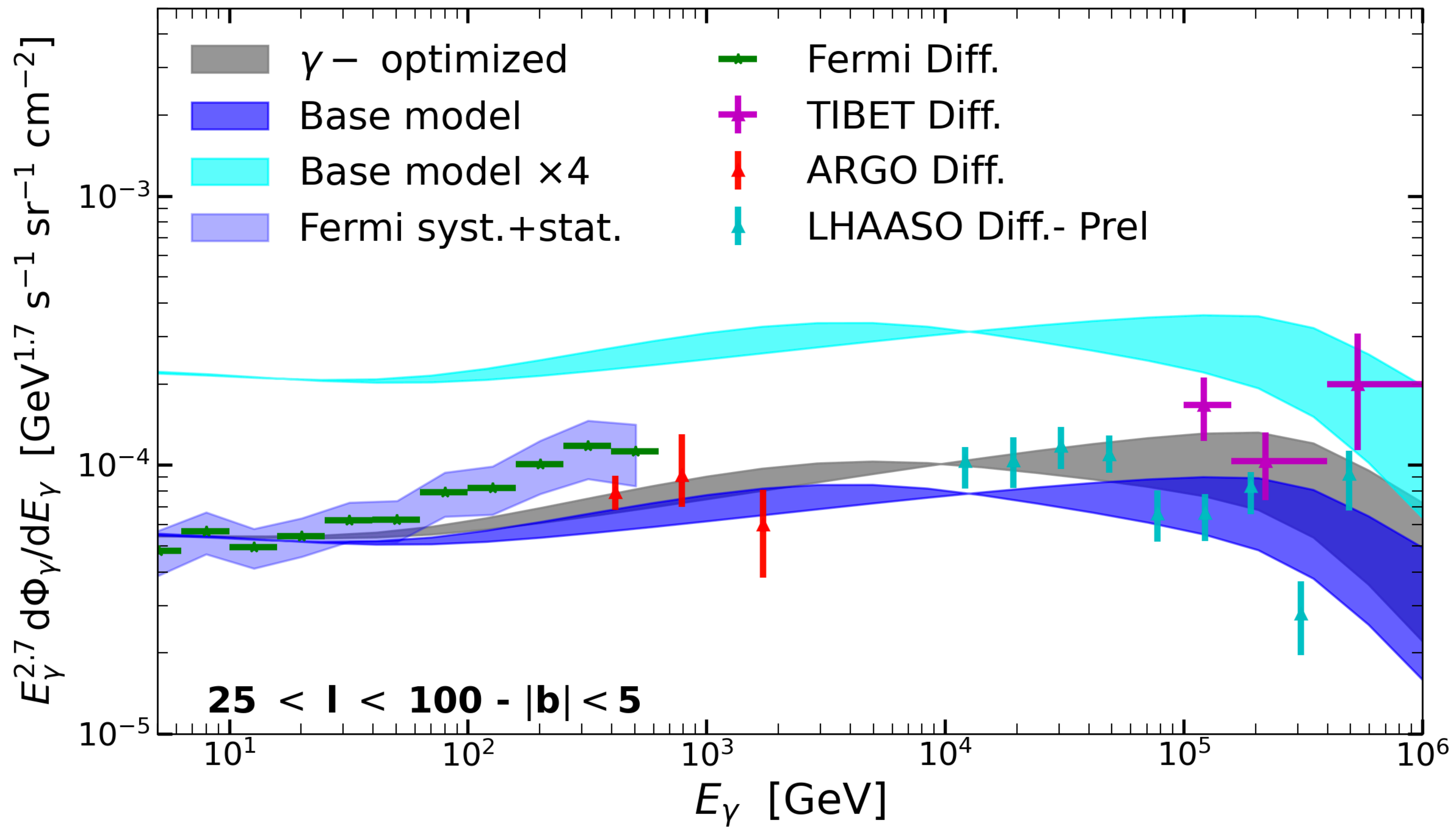
The original $^{S}S^{Z}4^{R}20^{T}150^{C}5$ does not account for the Fermi spectral hardening above 10 GeV in the inner GP



This is the very same GALPROP model on which the π_0 model is based !

The rescaling makes the π_0 model clearly incompatible with Fermi and ARGO data

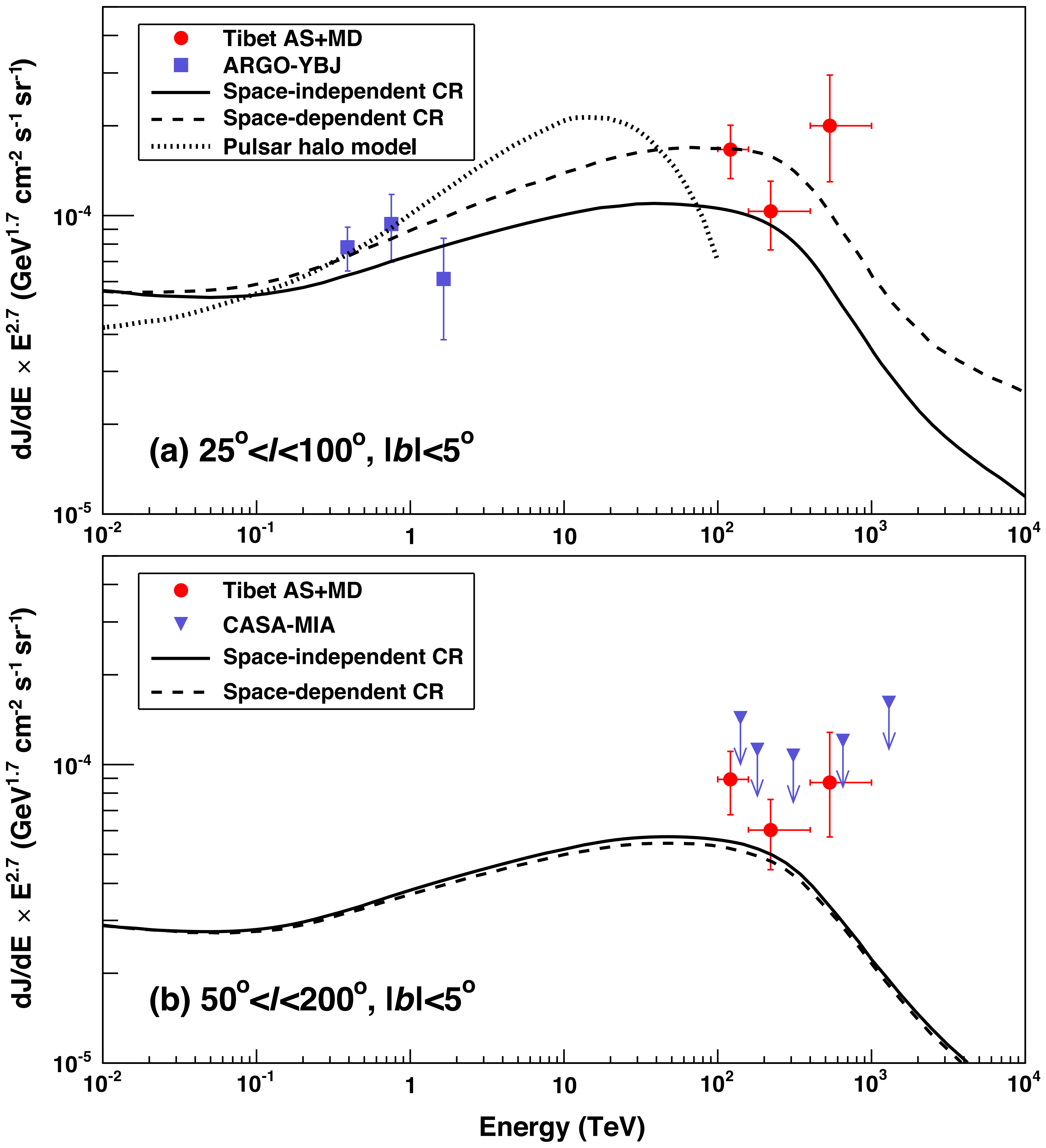
We would have had NO discovery if conventional models were correct !



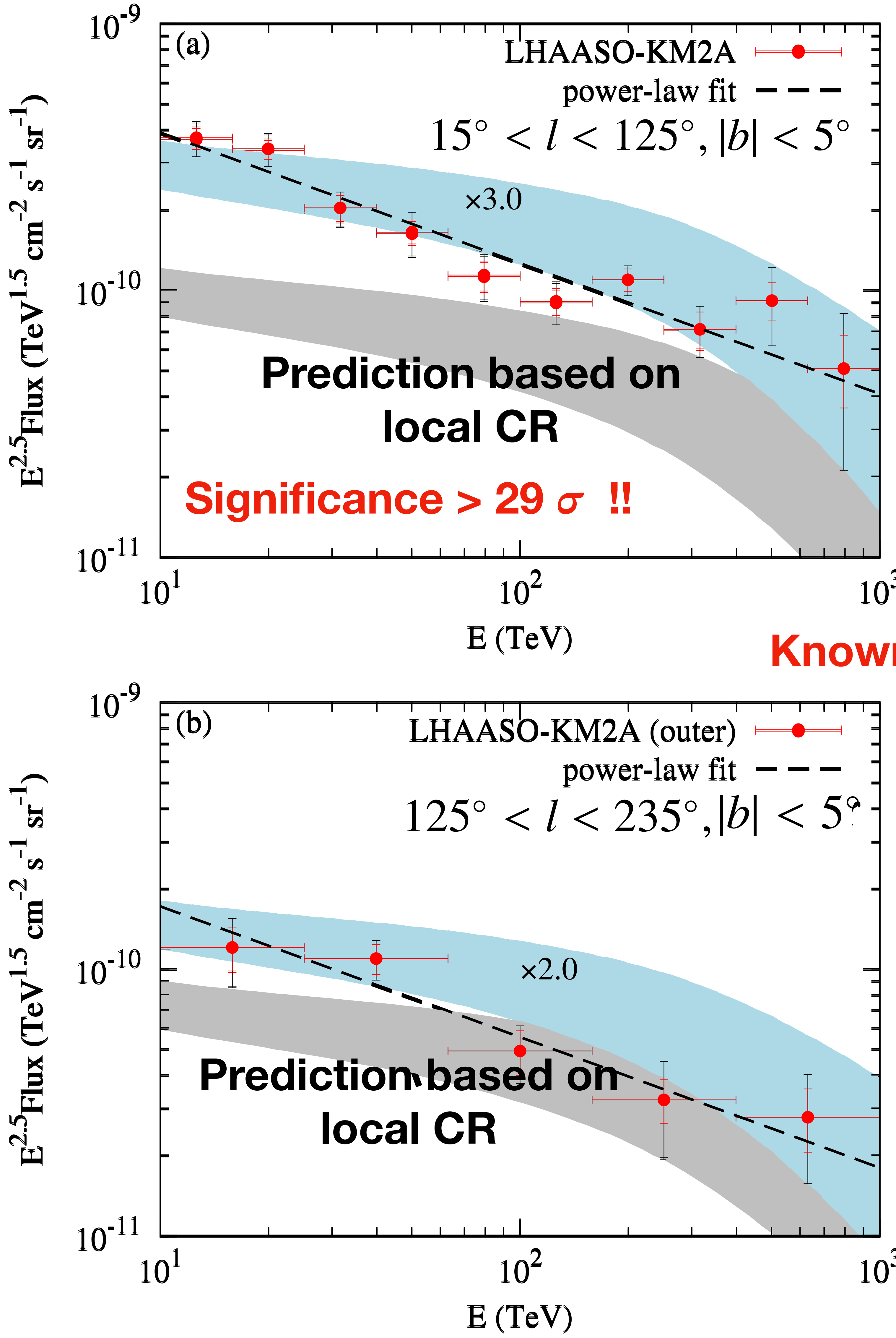
A new actor on the stage : PeV γ-ray astronomy

Tibet and LHAASO results

Tibet ASγ coll., PRL 2021



S.P. Zhao et al. - LHAASO coll., PRL 2023

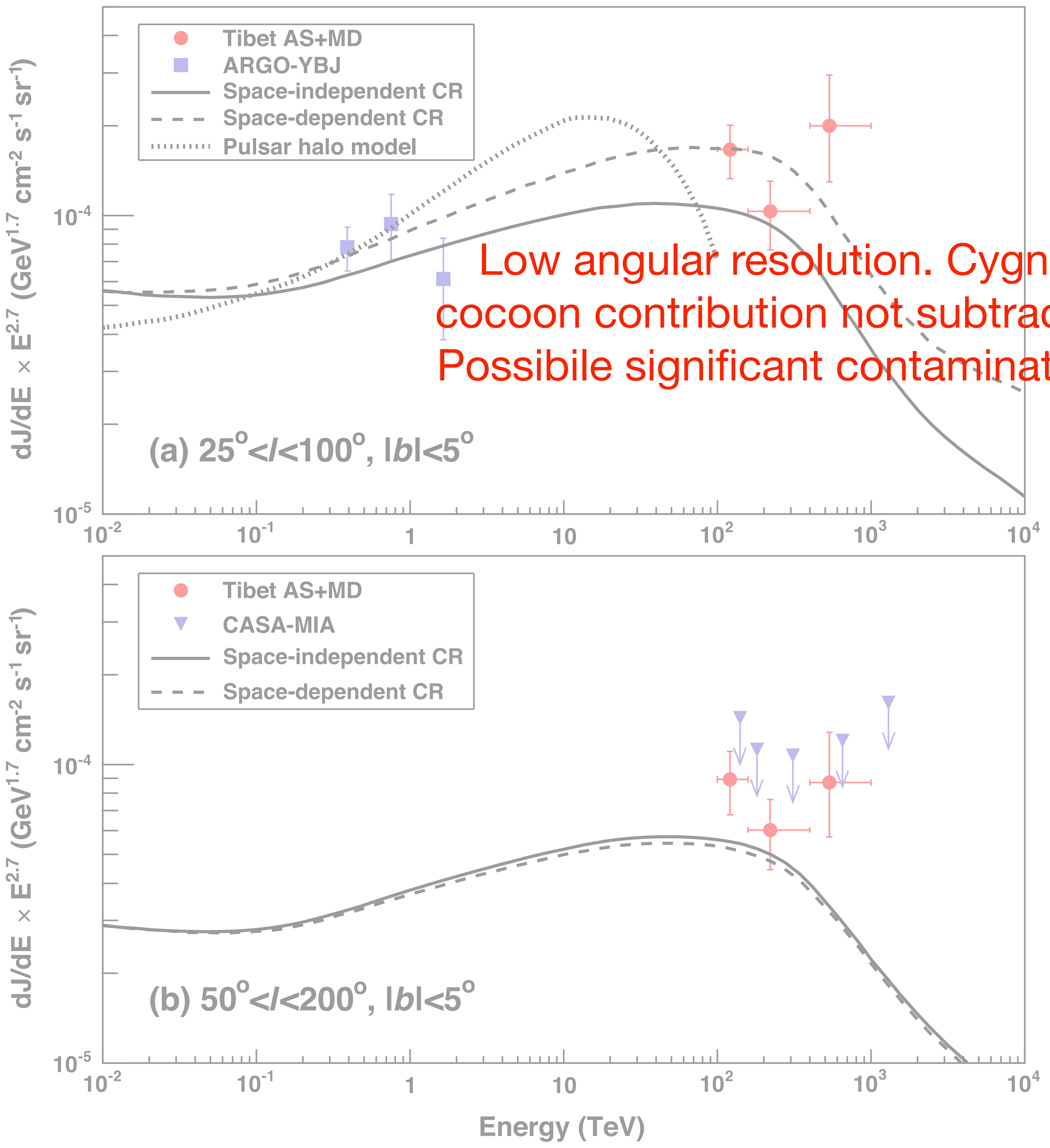


Known sources masked

A new actor on the stage : PeV γ-ray astronomy

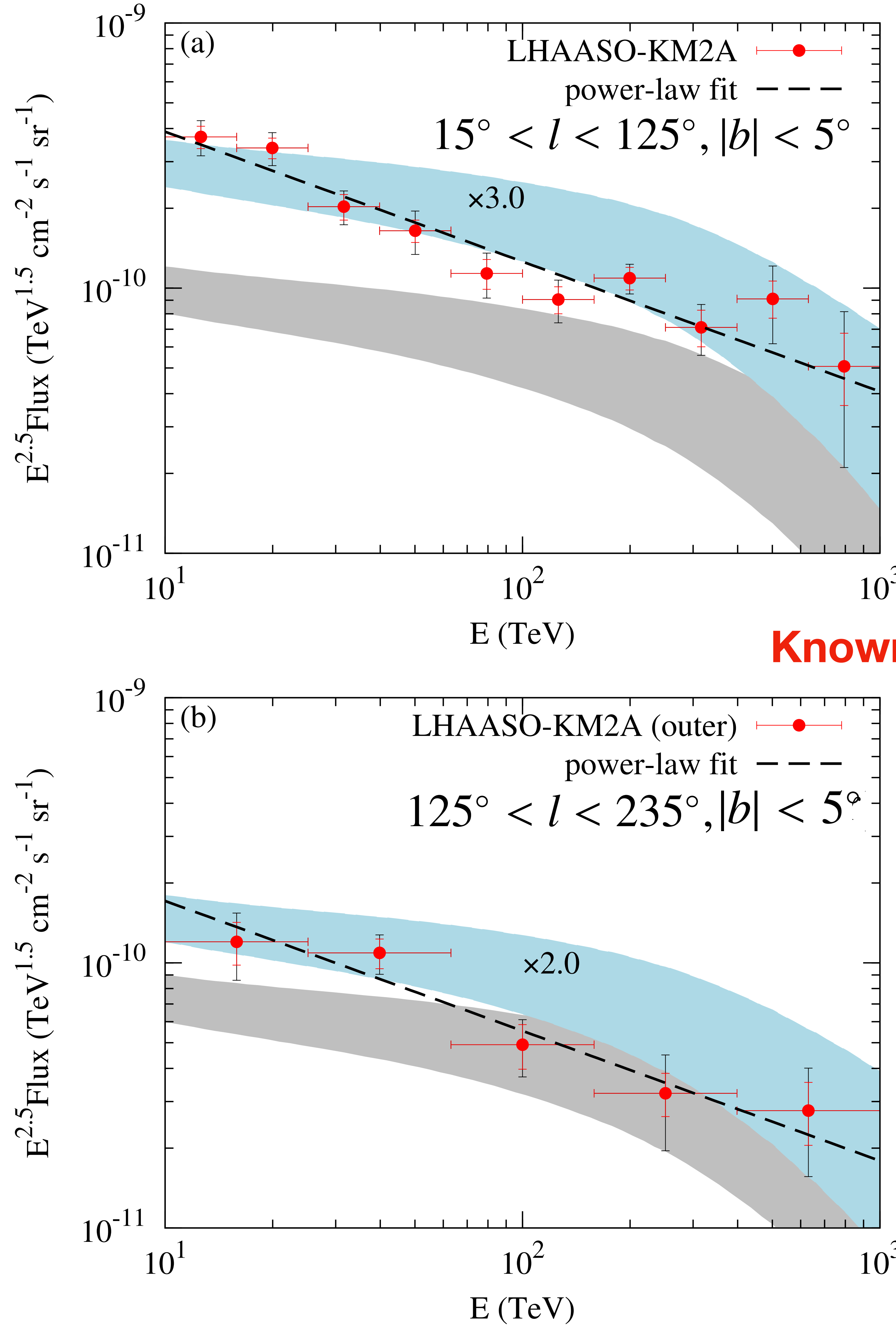
Tibet and LHAASO results

Tibet ASγ coll., PRL 2021



Low angular resolution. Cygnus cocoon contribution not subtracted. Possibile significant contamination !

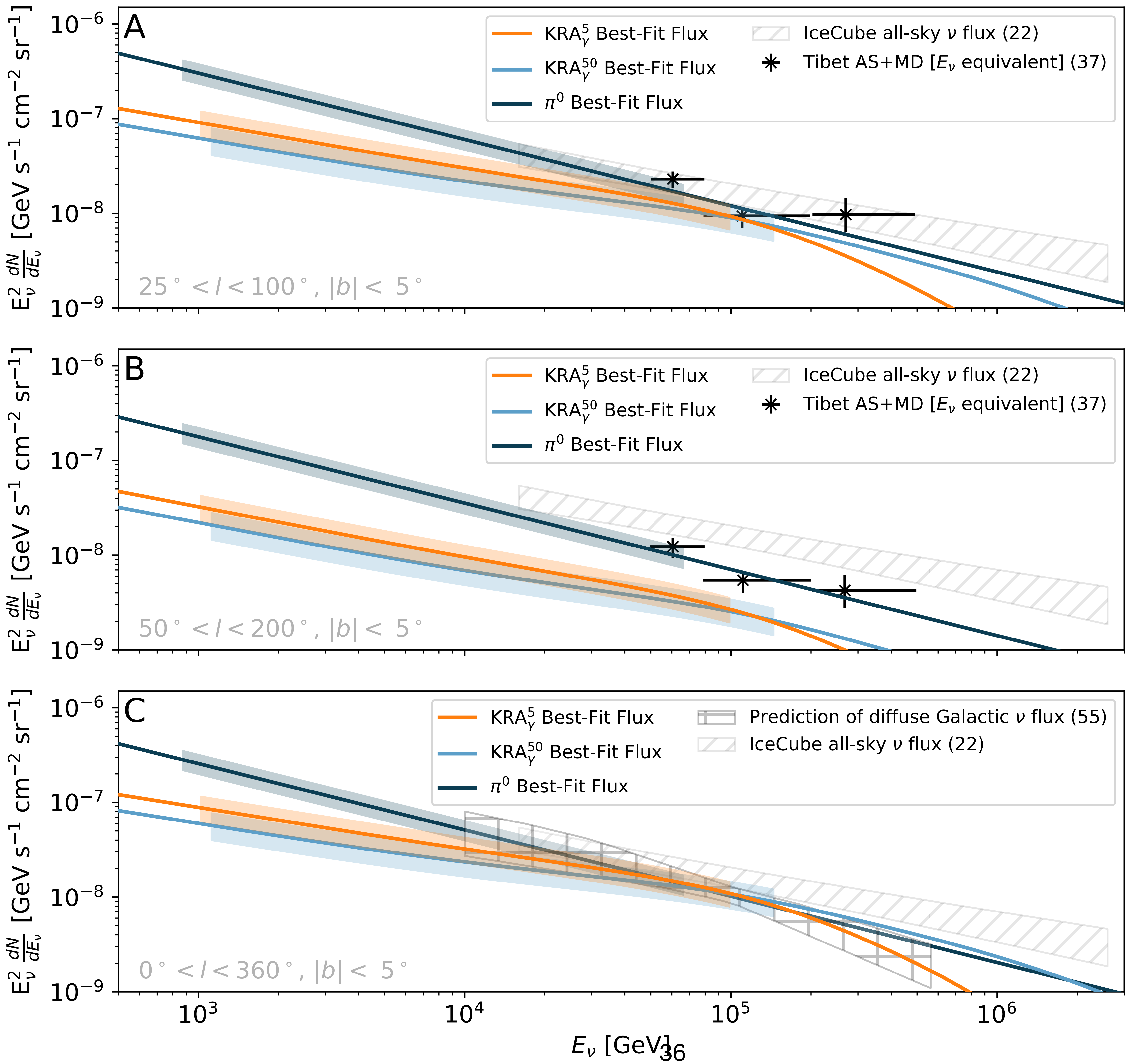
S.P. Zhao et al. - LHAASO coll., PRL 2023



Known sources masked

A new actor on the stage : PeV γ-ray astronomy

IceCube coll., Science 2023



KRAγ model upgrade

To test our models against those very high energy data we need:

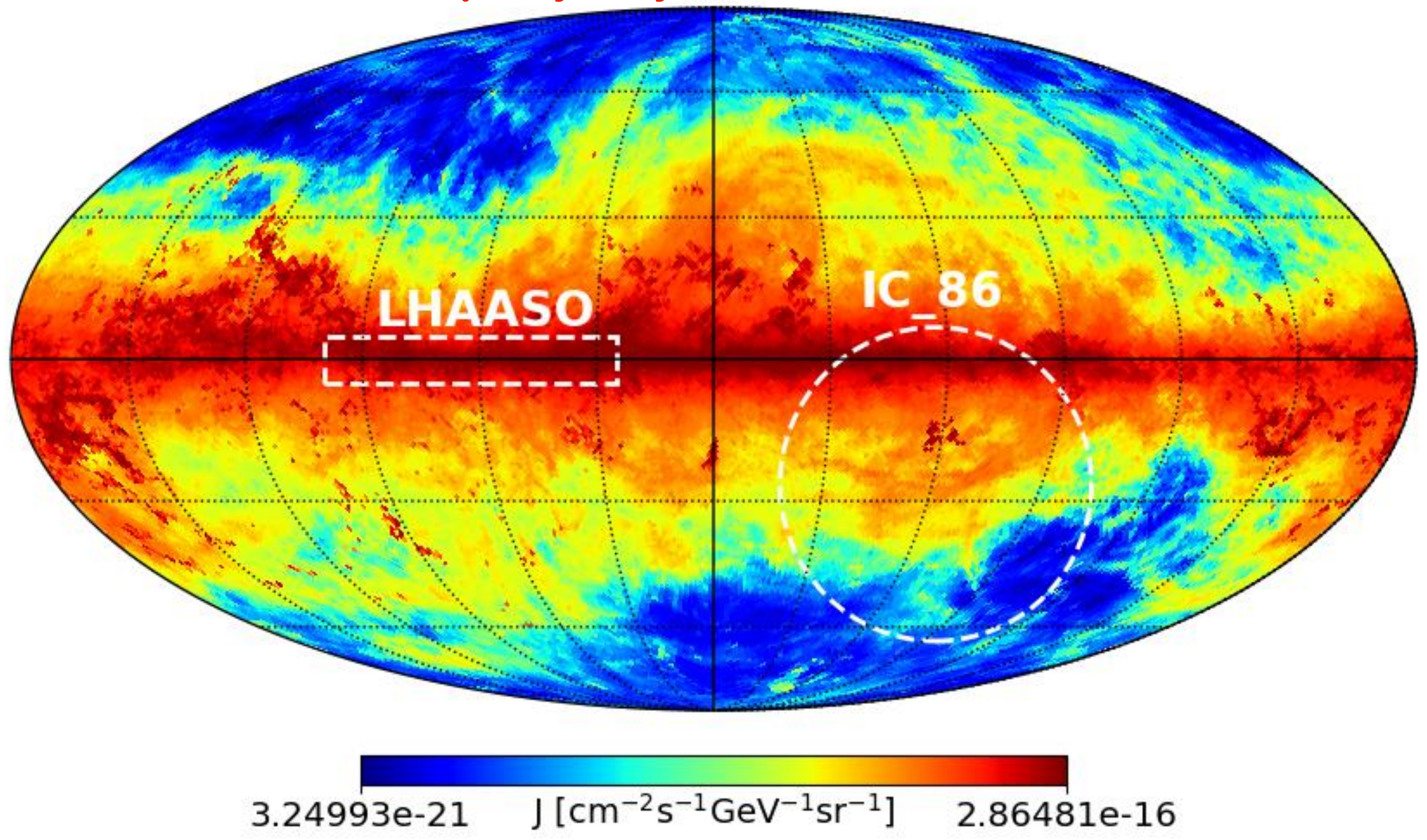
- ➤ To use more realistic p and He CR source spectra above 10 TeV accounting for the strong experimental uncertainties
- ➤ To account for gamma-ray attenuation
- ➤ To account for uncertainties on the cross-sections

We do that with our

HERMES code *Dundovic, Evoli, Gaggero & DG, A&A 2021.*

https://github.com/cosmicrays/hermes

100 TeV γ-ray sky simulated with HERMES

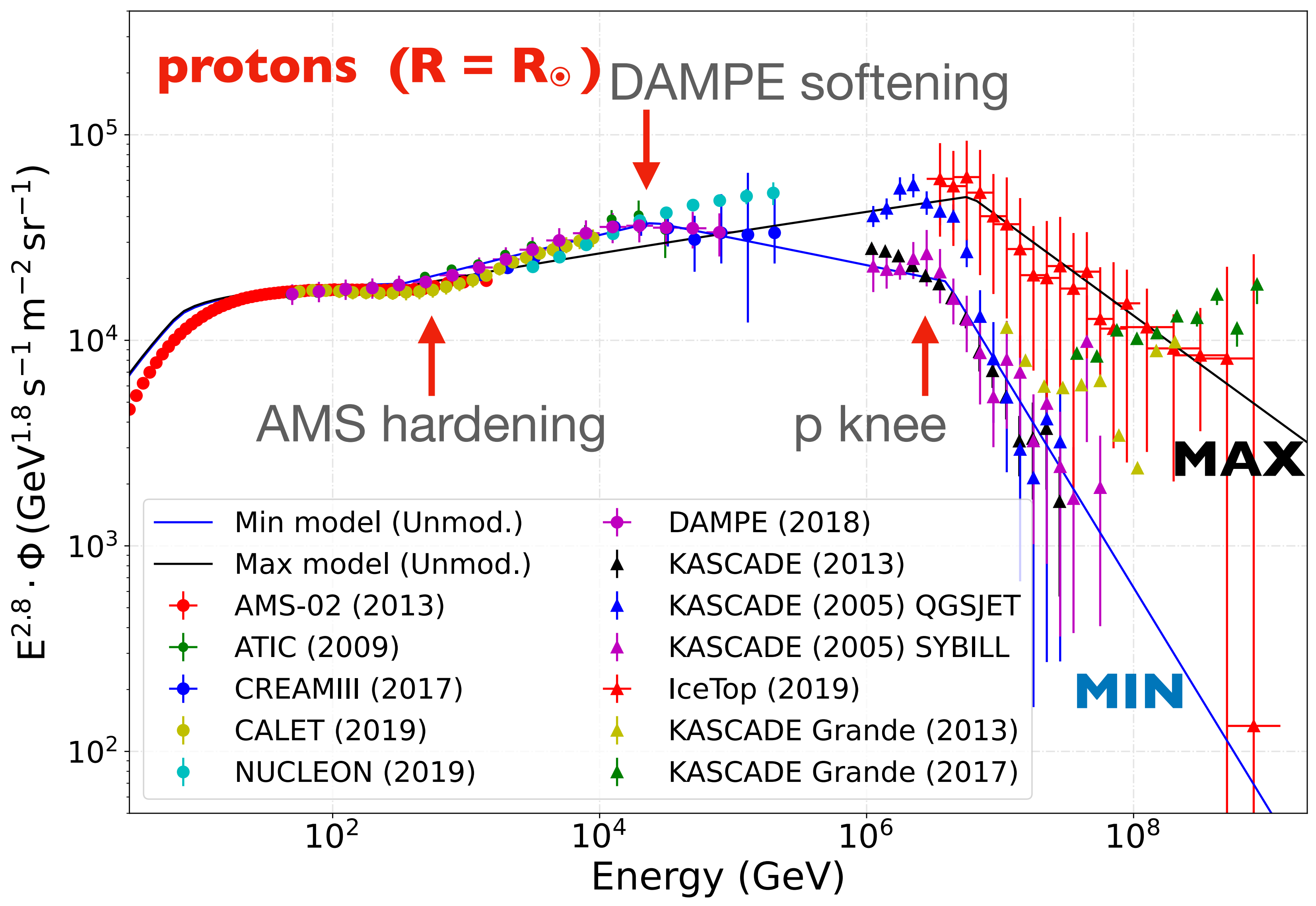


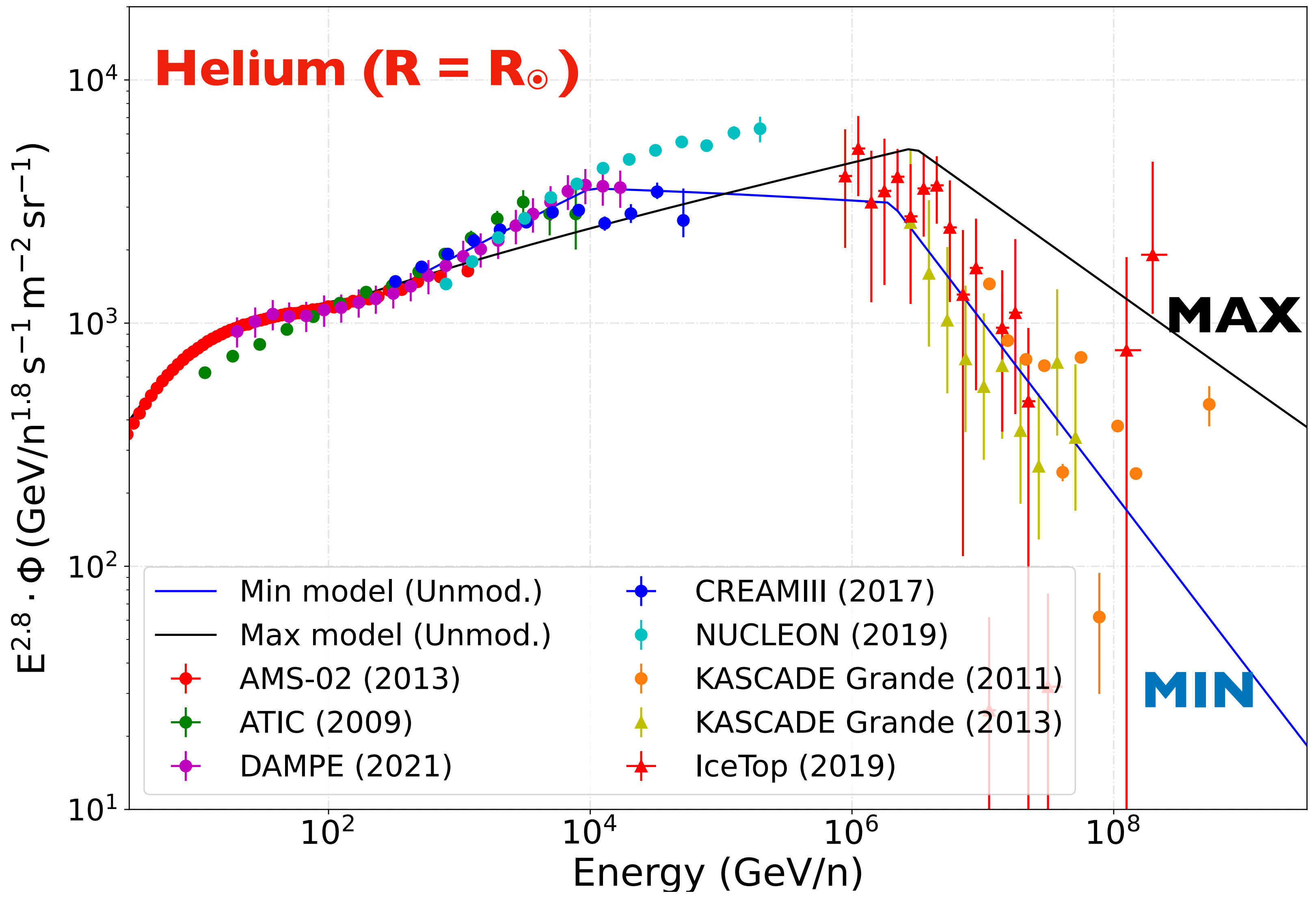
fed with the CR space and energy distribution computed with DRAGON for each model.

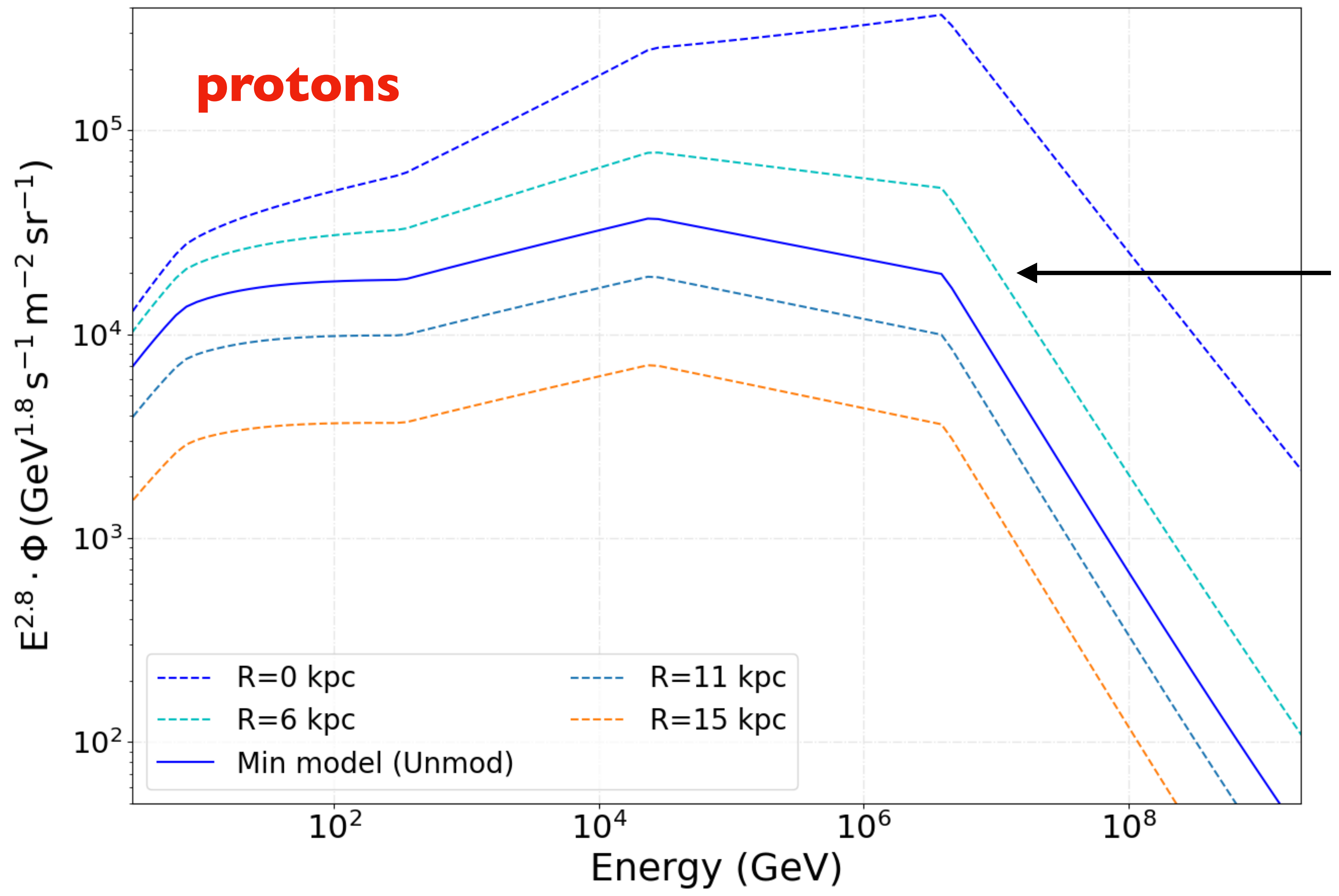
More realistic CR source spectra around the PeV

MIN/MAX models

P. De La Torre Luque et al., A&A 2023







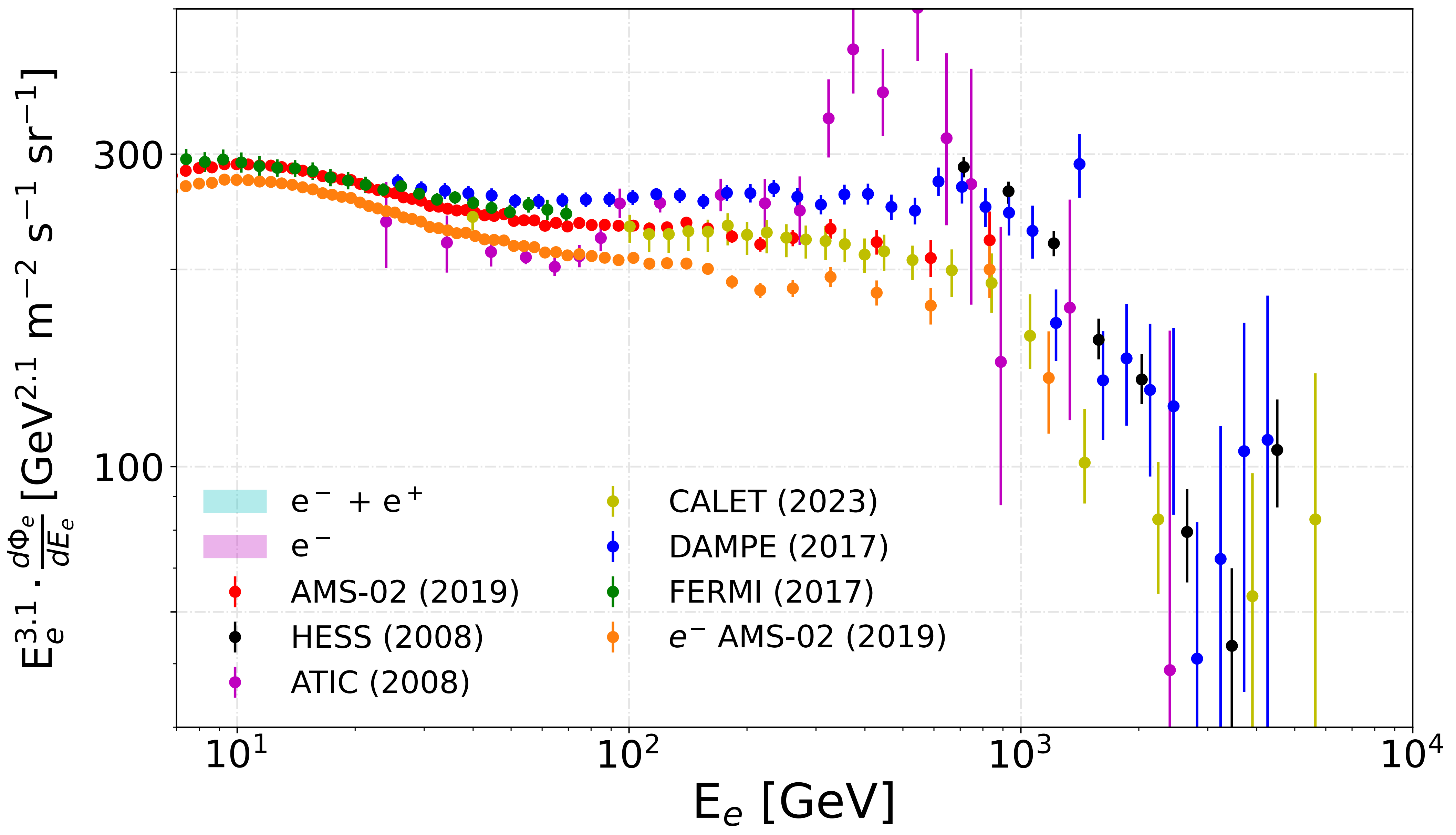
We assume broken power law to better match air shower data

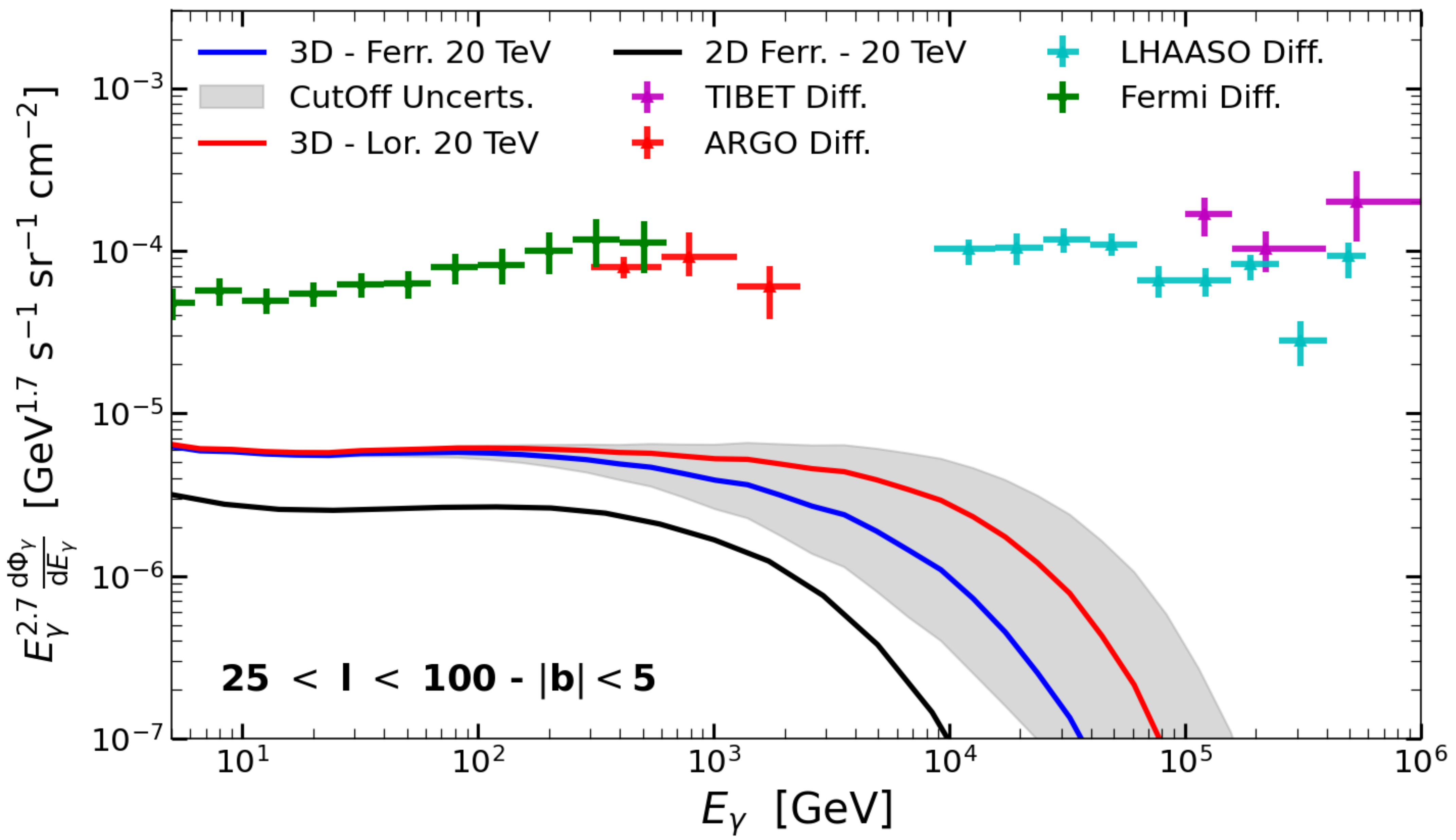
Propagated spectra at several galactocentric radii for the γ-optimized scenario

The source spectra is assumed to be the same in the whole Galaxy

CR electrons and IC emission

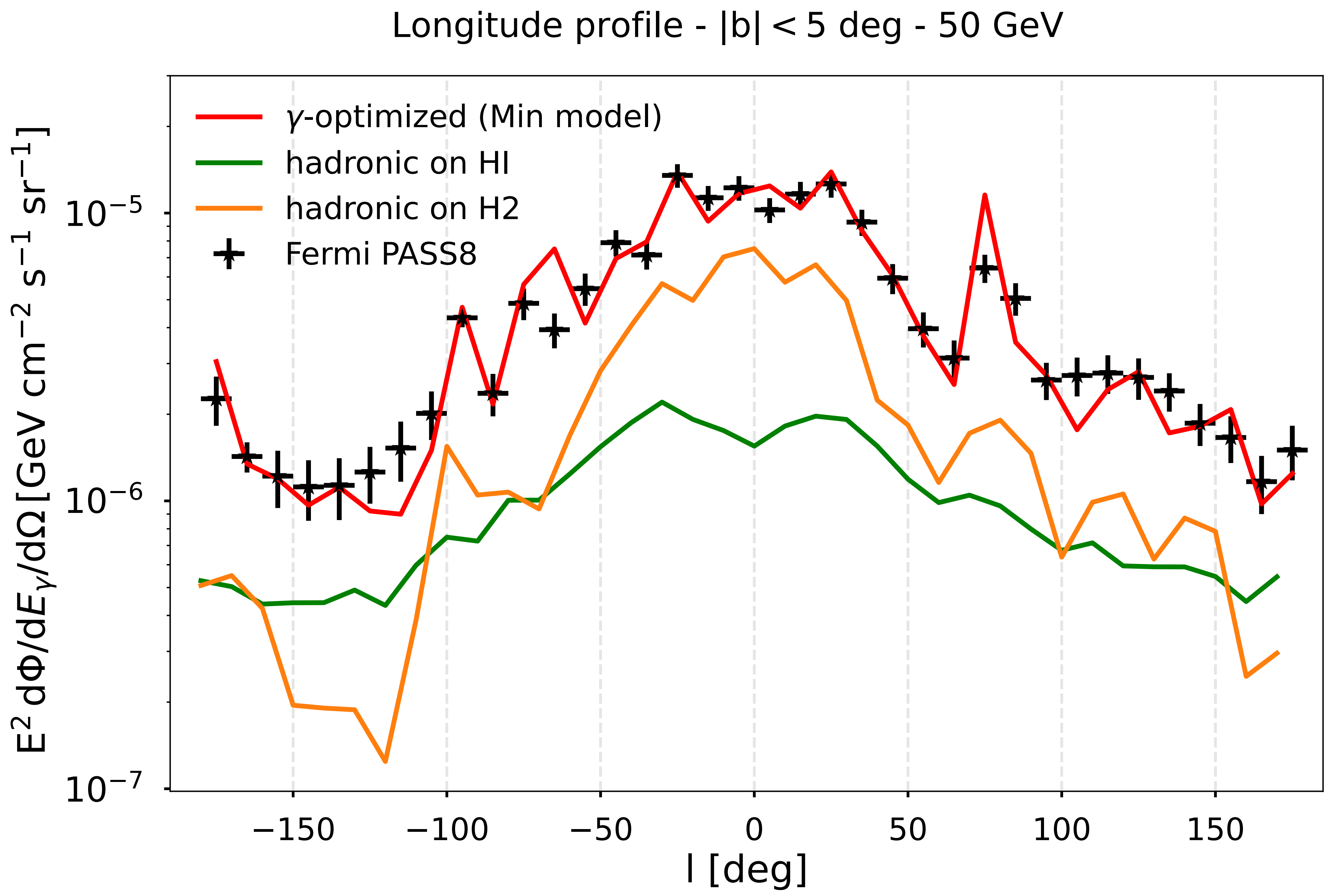
A subdominant contribution



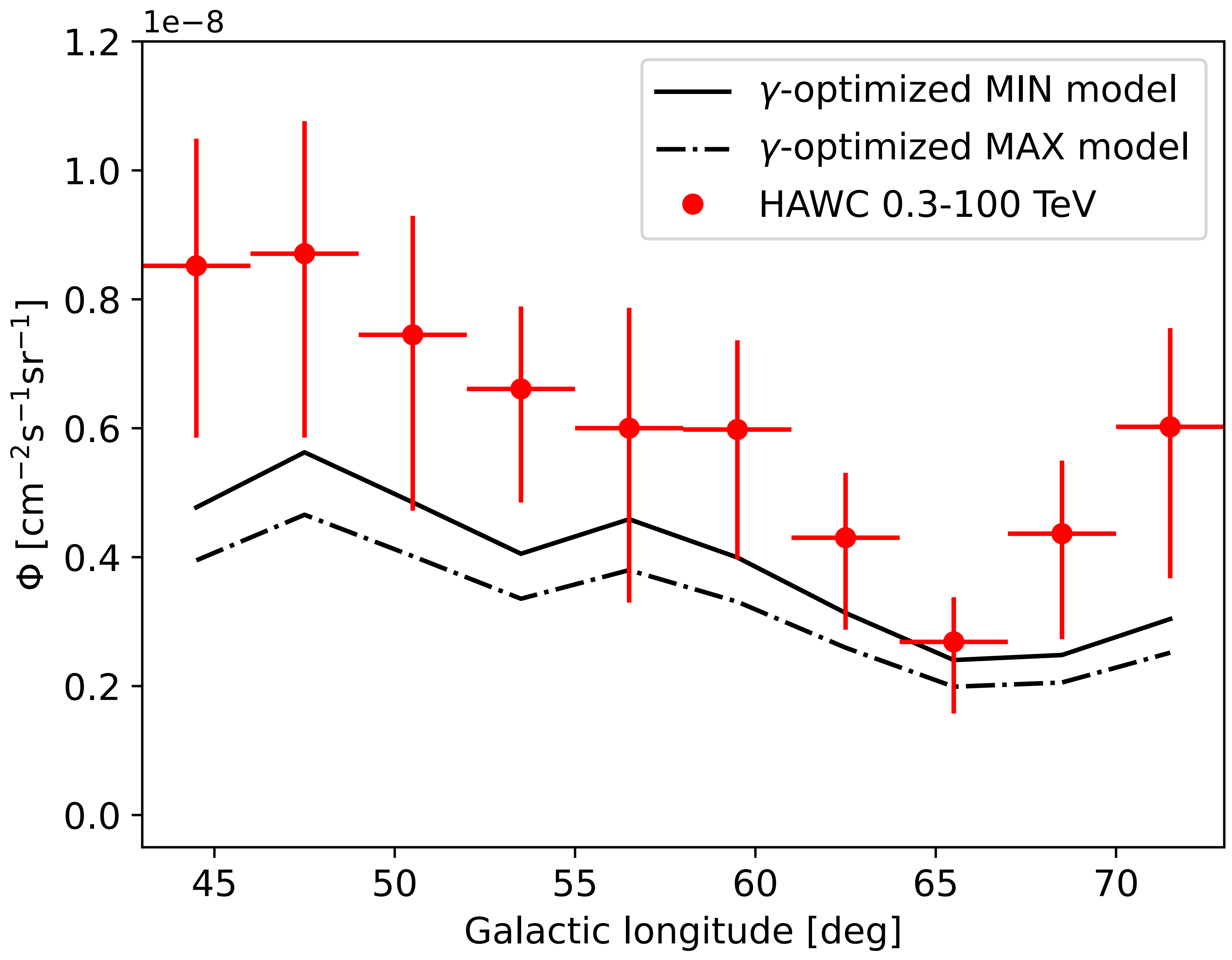


Comparison with HE γ-ray data

Della Torre Luque, Gaggero, DG, Marinelli, ICRC 2023

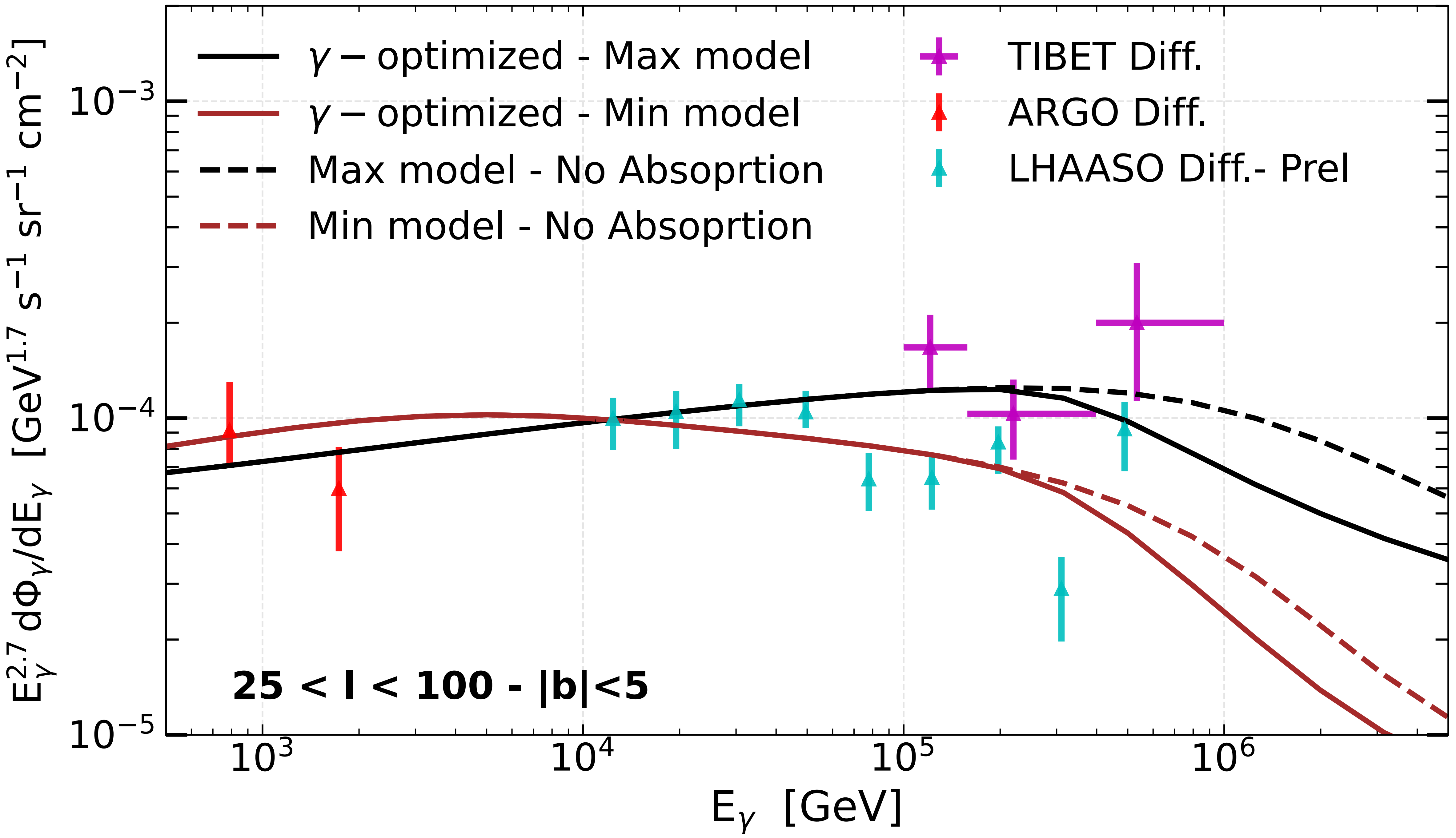


Della Torre Luque, Gaggero, DG, Marinelli, in progress



The effect of γ-ray opacity

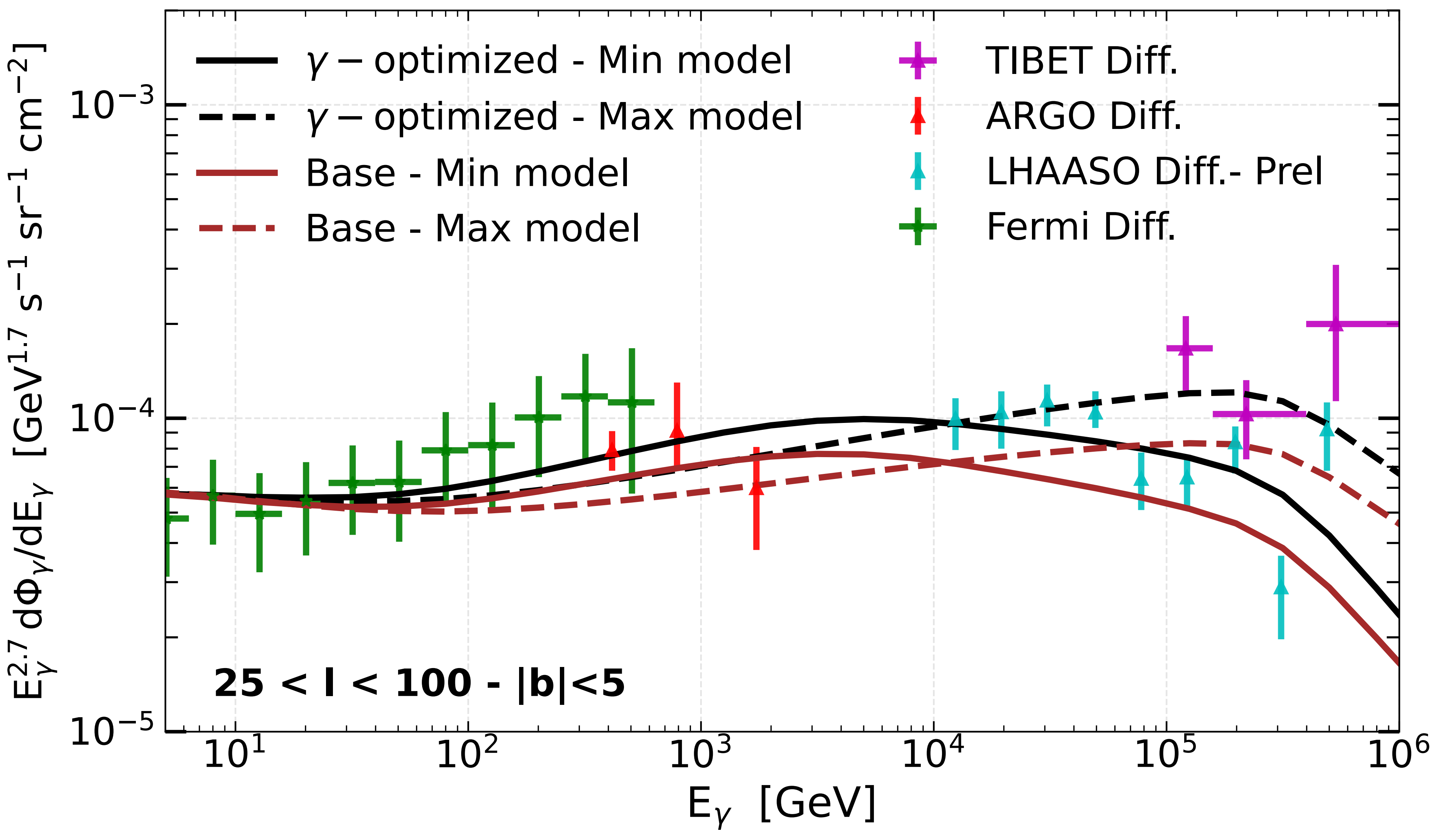
P. De La Torre Luque et al., A&A 2023

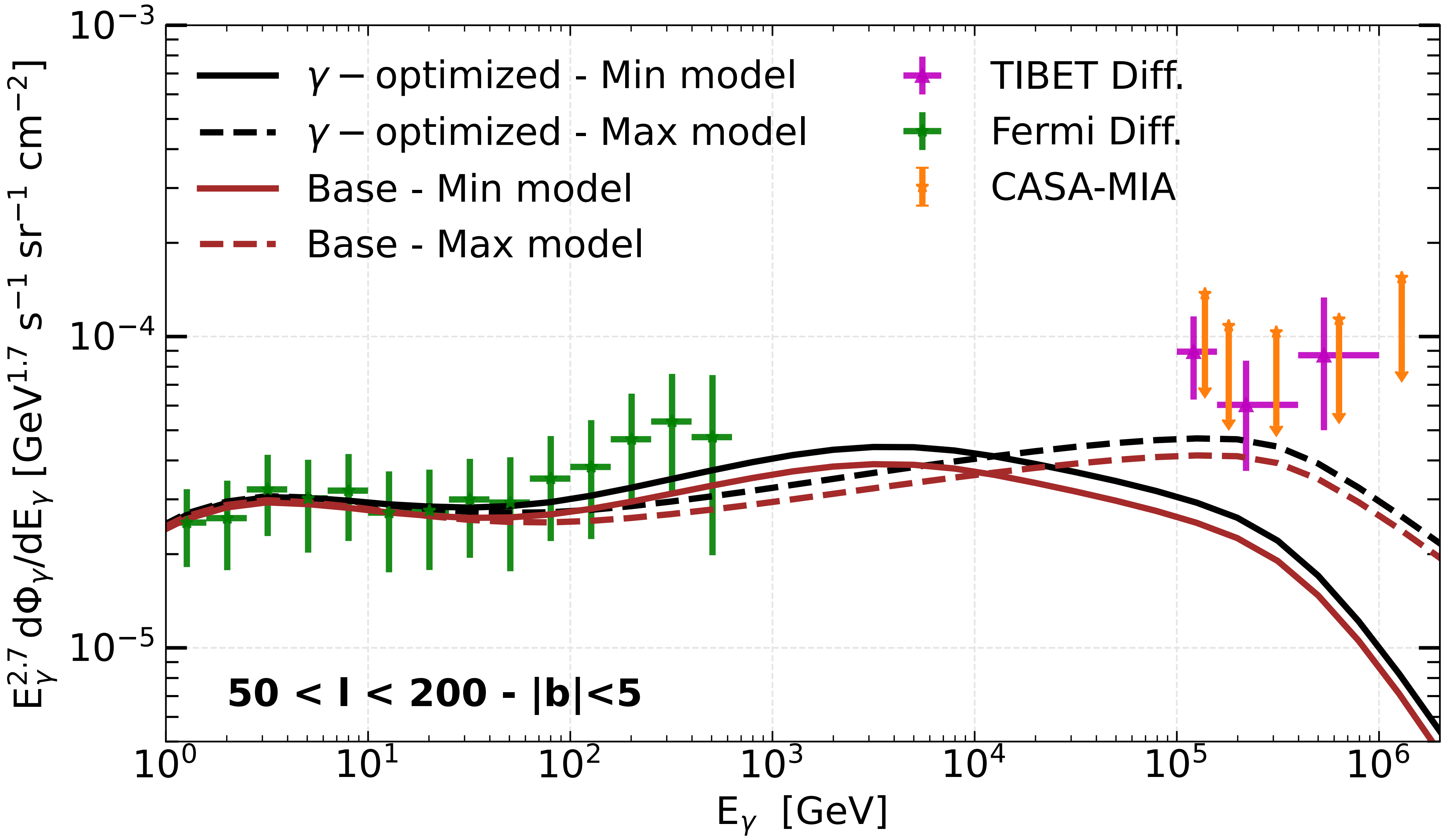


The effect of γ-ray opacity due to γ-γ_{CMB} (significant only for E > 100 TeV) is accounted.
ISRF (also accounted) is almost irrelevant !

Comparison with VHE γ-ray data

De La Torre Luque at al., A&A 2023





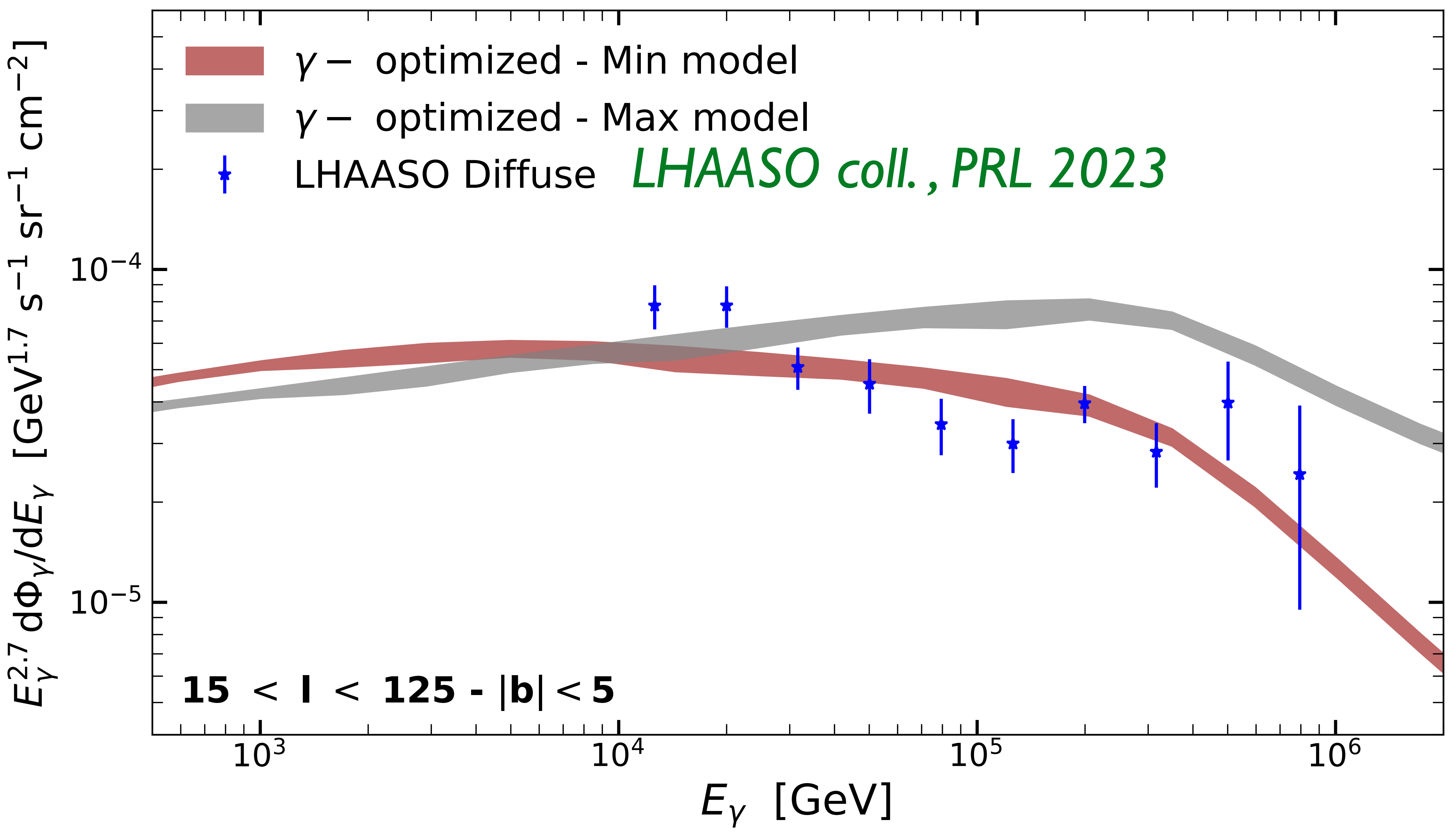
The **degeneracy between the CR transport scenario and the source spectral shape can be broken by the VHE γ-ray data allowing to probe the high energy tail of the CR in the inner Galaxy**

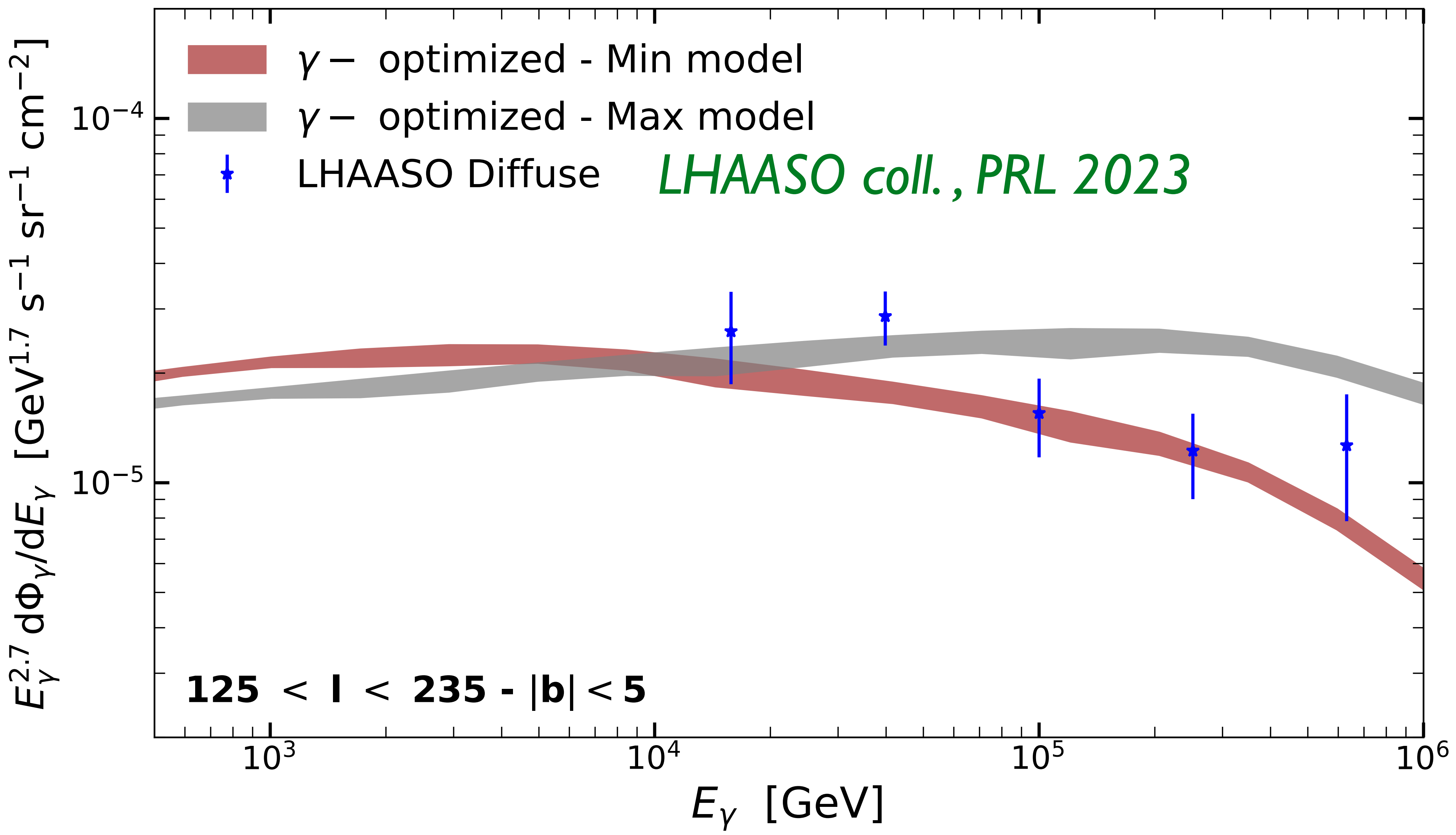
At large longitudes the observed spectrum is expected to be almost independent on the transport scenario. Measurements at low galactic longitudes would be resolutive !

LHAASO results favour the MIN setup !

Spectral energy distributions

Della Torre Luque, Gaggero, DG, Marinelli, ICRC 2023





Two γ-ray production cross-section parametrizations are considered (→ bands) :

Kelner-Aharonian, PRD 2008

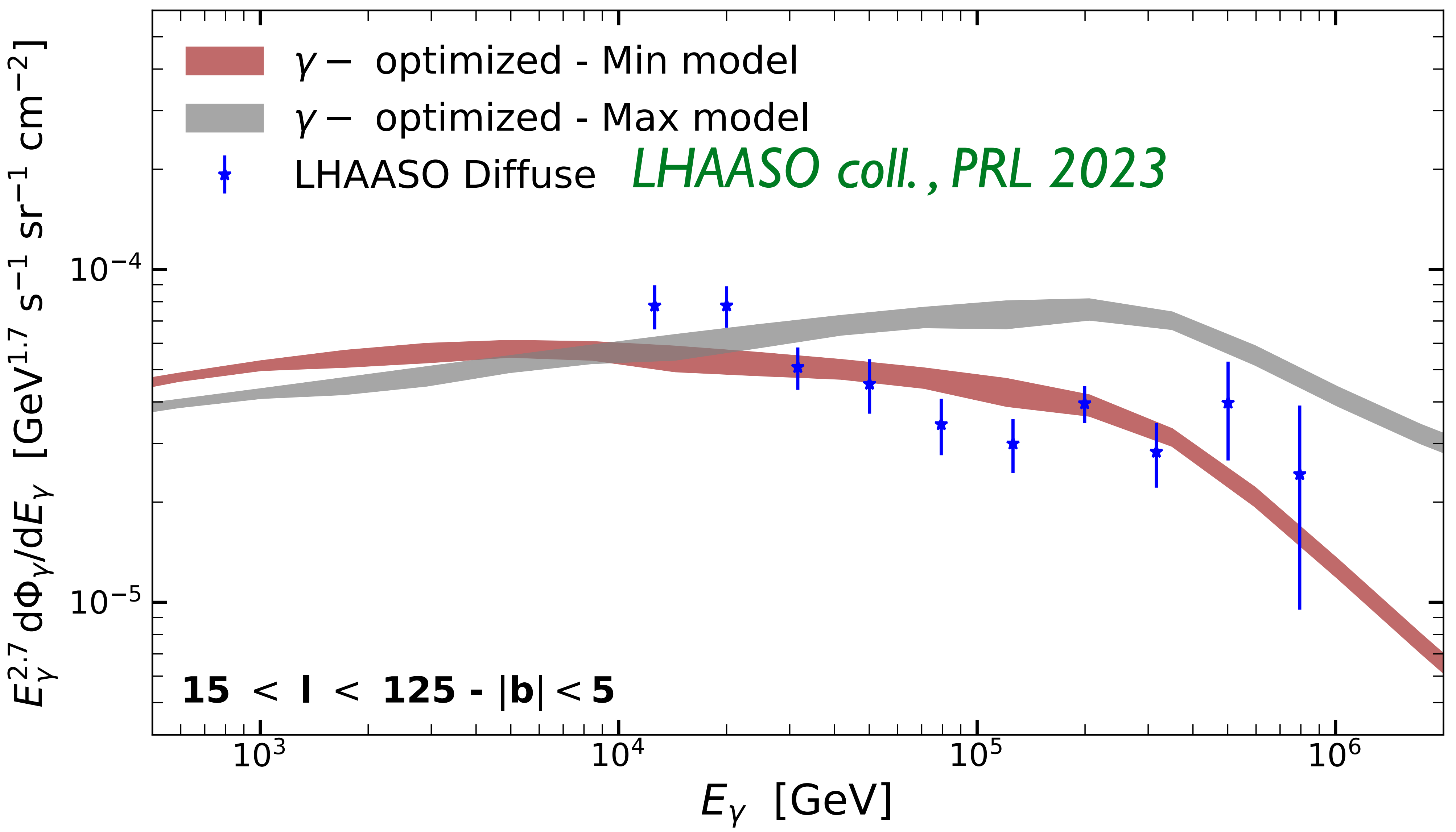
and

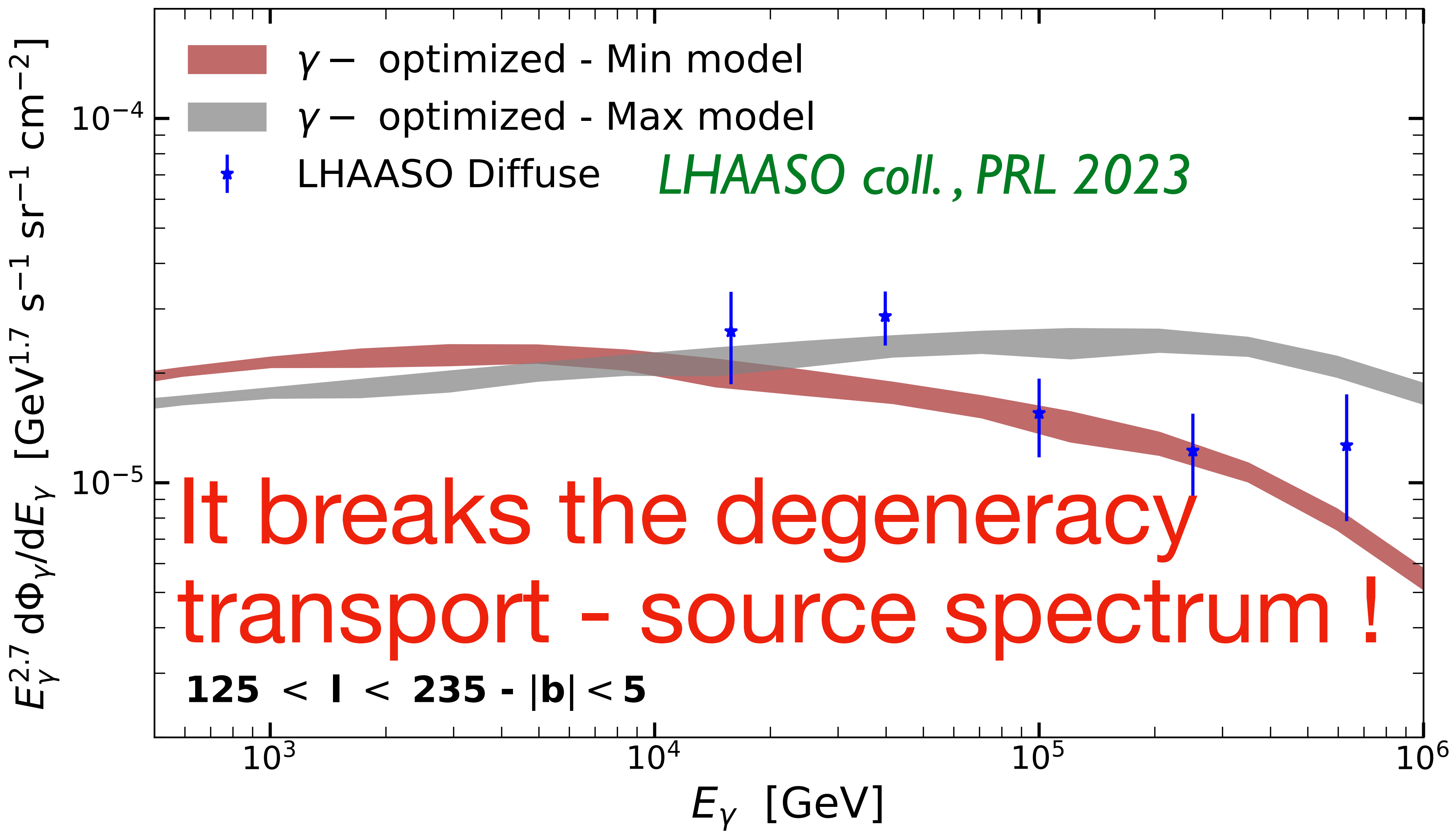
AAFRAG, *Koldobskiy et al. PRD 2021*

LHAASO results favour the MIN setup !

Spectral energy distributions

Della Torre Luque, Gaggero, DG, Marinelli, ICRC 2023





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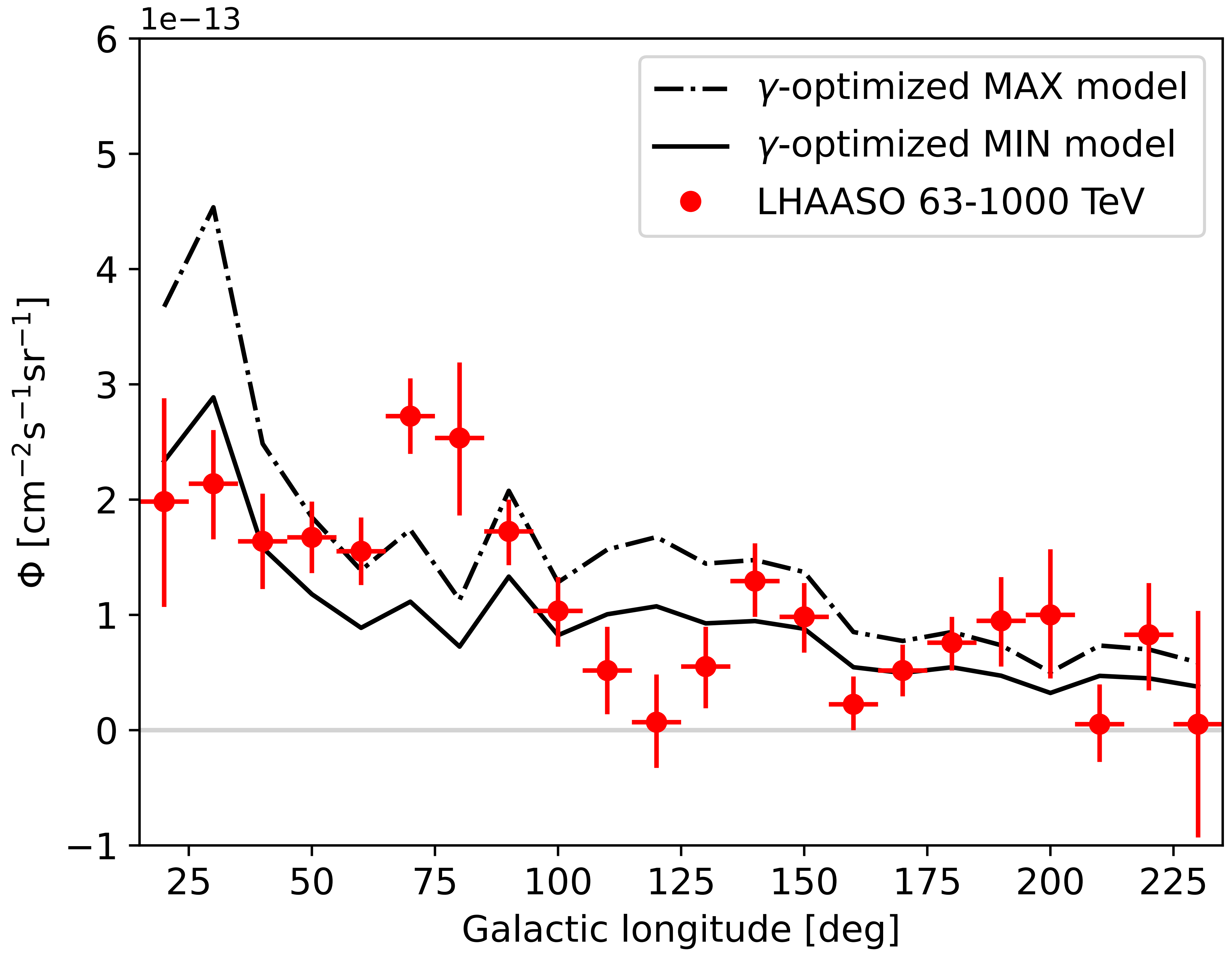
AAFRAG, *Koldobskiy et al. PRD 2021*

LHAASO results favour the MIN setup !

Longitude profile

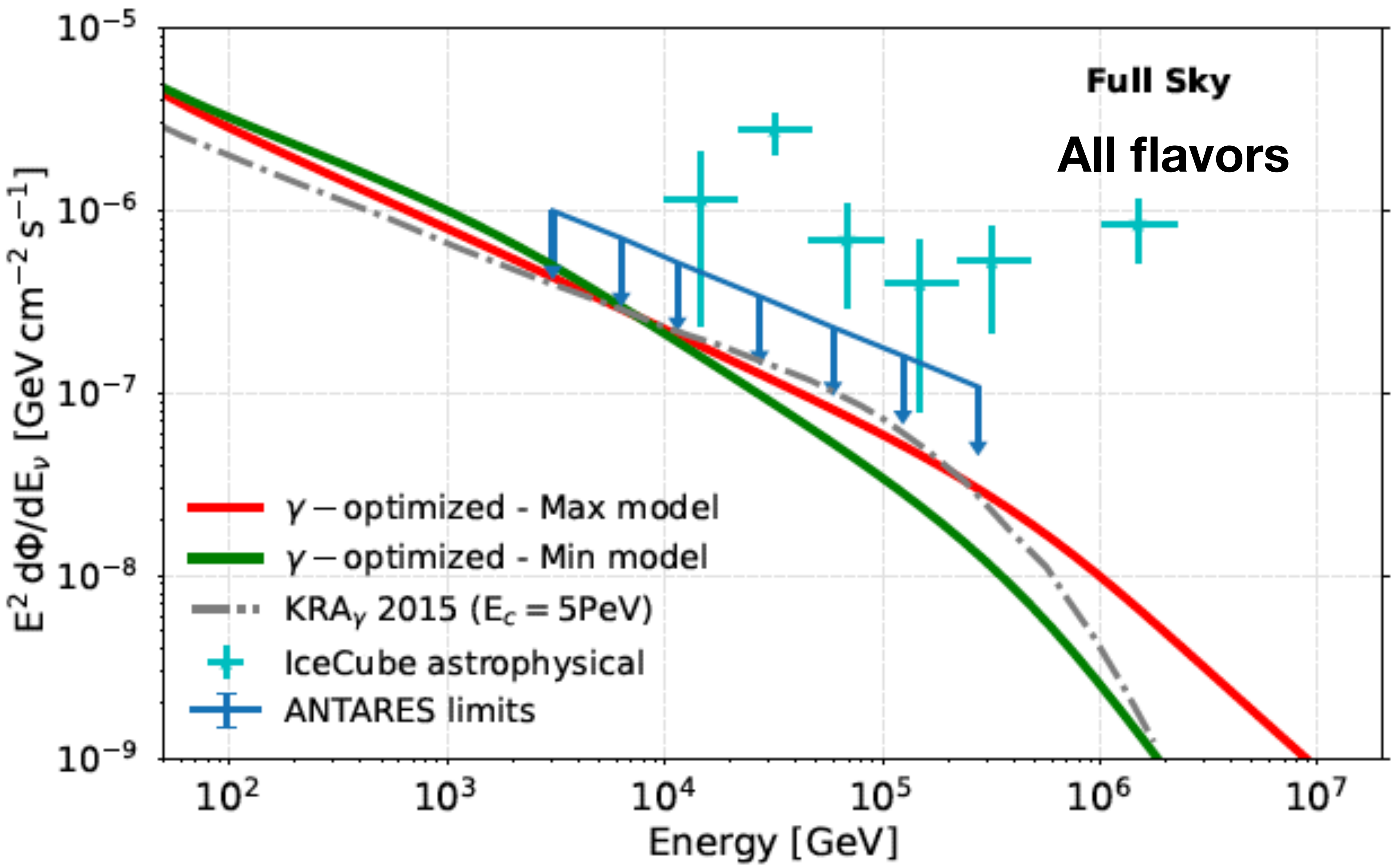
Della Torre Luque, Gaggero, DG, Marinelli, PRELIMINARY



Back to neutrinos

How this compare with the old KRA$_\gamma$[5] model ?

Della Torre Luque, Gaggero, DG, Marinelli, Frontiers 2023

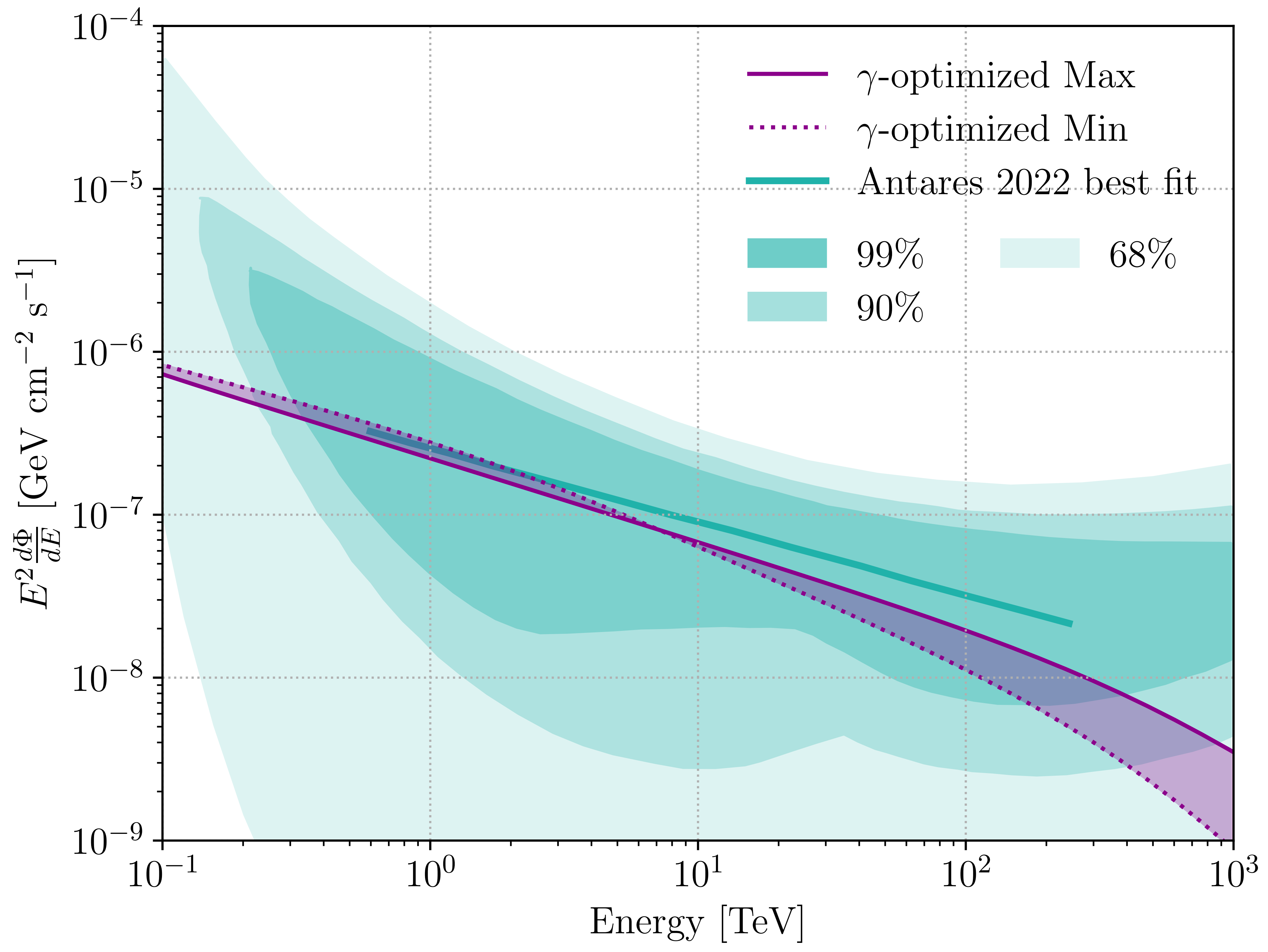


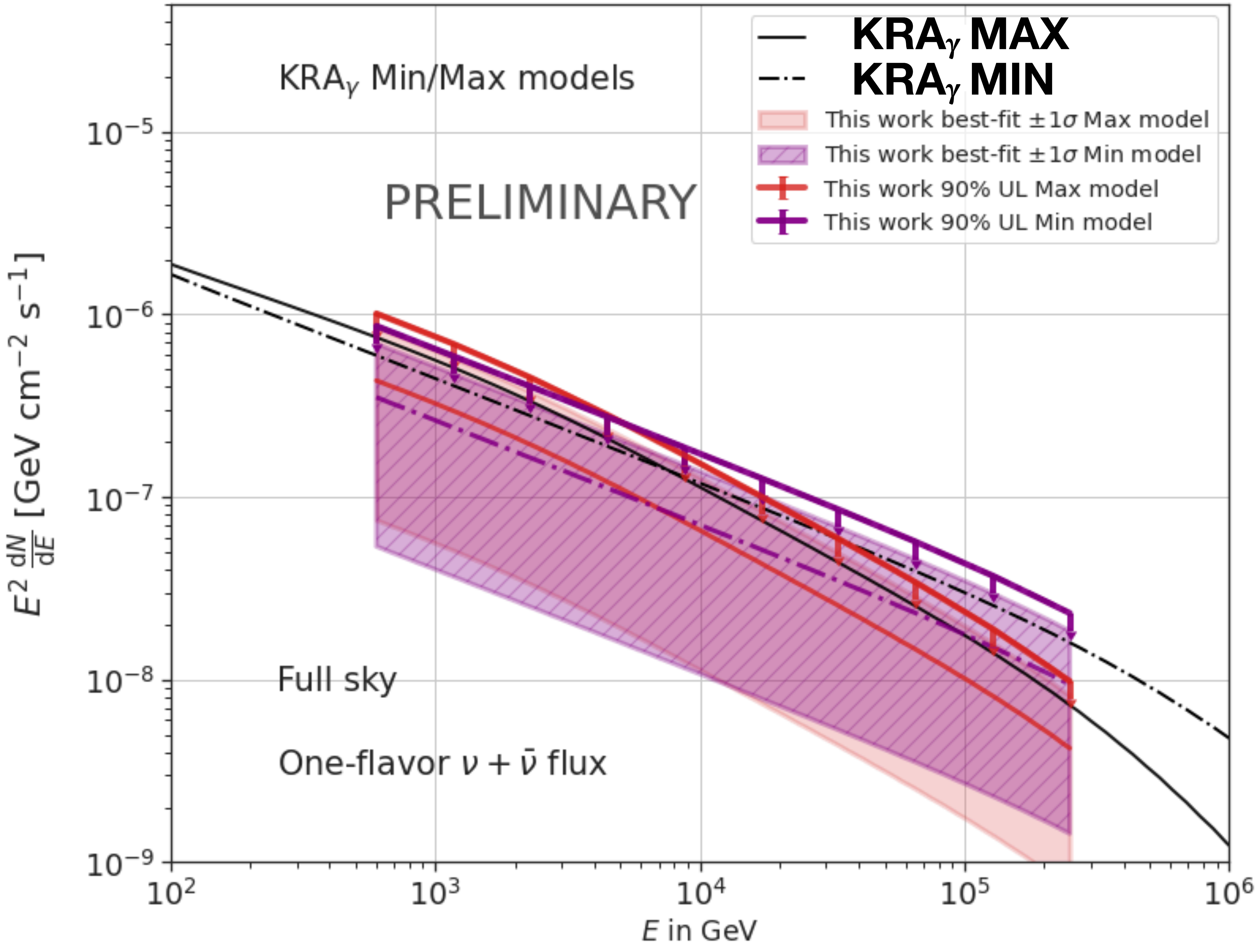
The flux corresponding to the MIN model should be slightly smaller than KRA$_\gamma$[5].
This looks consistent with the ~1/2 IceCube best fit normalization factor !

IC analysis should be repeated with this model

Comparison with ANTARES preliminary results

Cartaraud et al. [ANTARES coll.] with De La Torre Luque, DG, Benedittis, ICRC 2023





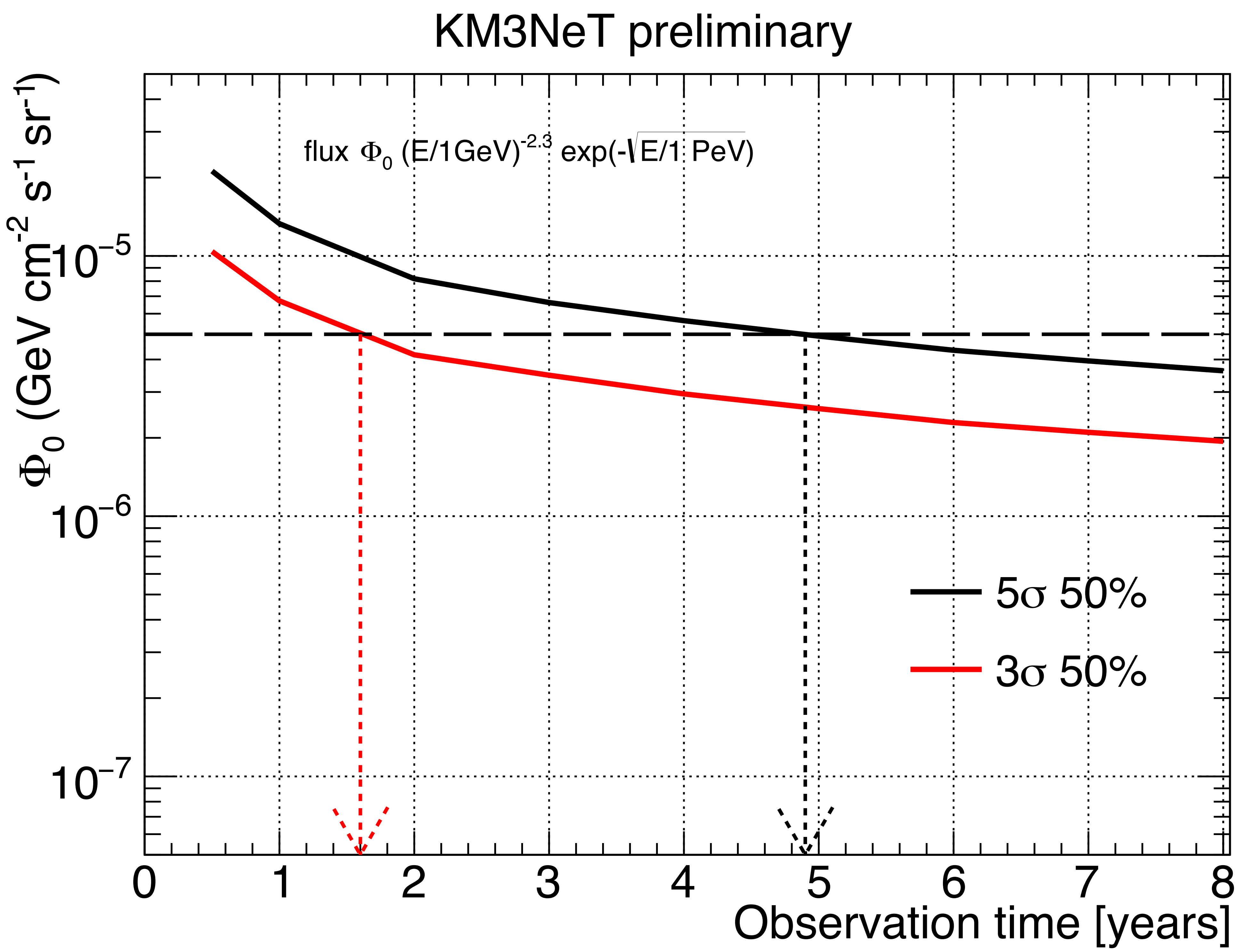
Template fit analysis using showers + tracks. Better angular resolution respect to IceCube , low μ contamination

Gamma-optimized MIN model statistically preferred (**only 1.7 σ** !)

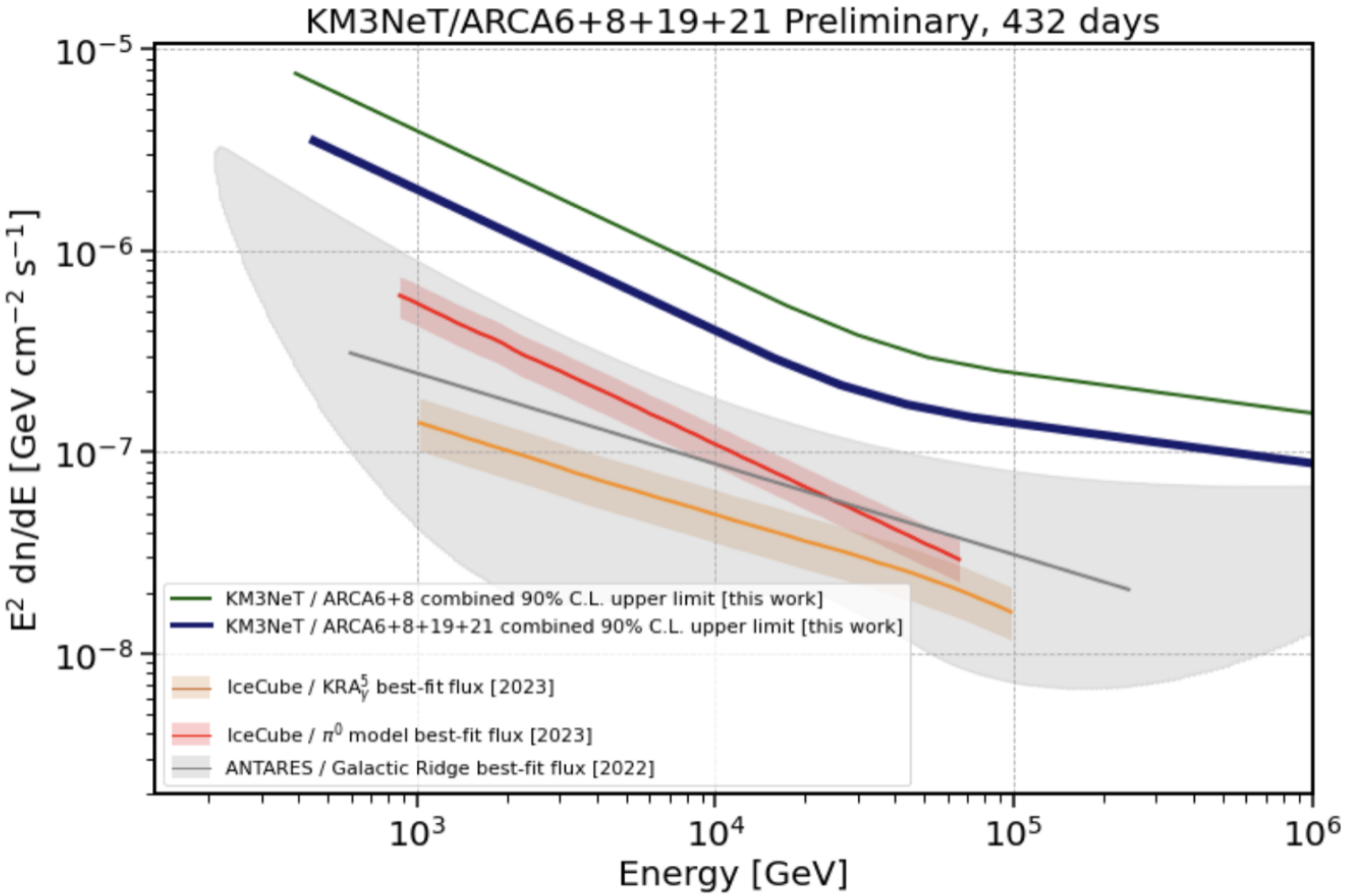
Little room left for a possible contribution of unresolved sources !

KM3NeT perspectives

Letter of intent for KM3NeT 2.0 (2016)



KM3NeT coll., ICRC 2023



KM3NeT has been estimated to be able to confirm this scenario in 5 years at 5σ (using tracks), **reasonably less** using also ANTARES data and showers analysis (**KRA$_\gamma^5$** model , under progress with the upgraded models)

Perspectives

- Release the new models to be used by more experiments possibly combining different data sets
- KM3NeT will be crucial to better determine the morphology of the emission
- Use even more accurate gas models including molecular clouds to identify possible hot spots
- Study the contribution of external galaxies, possibly also starbursts, to the extragalctic flux which may not be negligible especially a relatively low energies

Conclusions: some of Venja's dreams come true

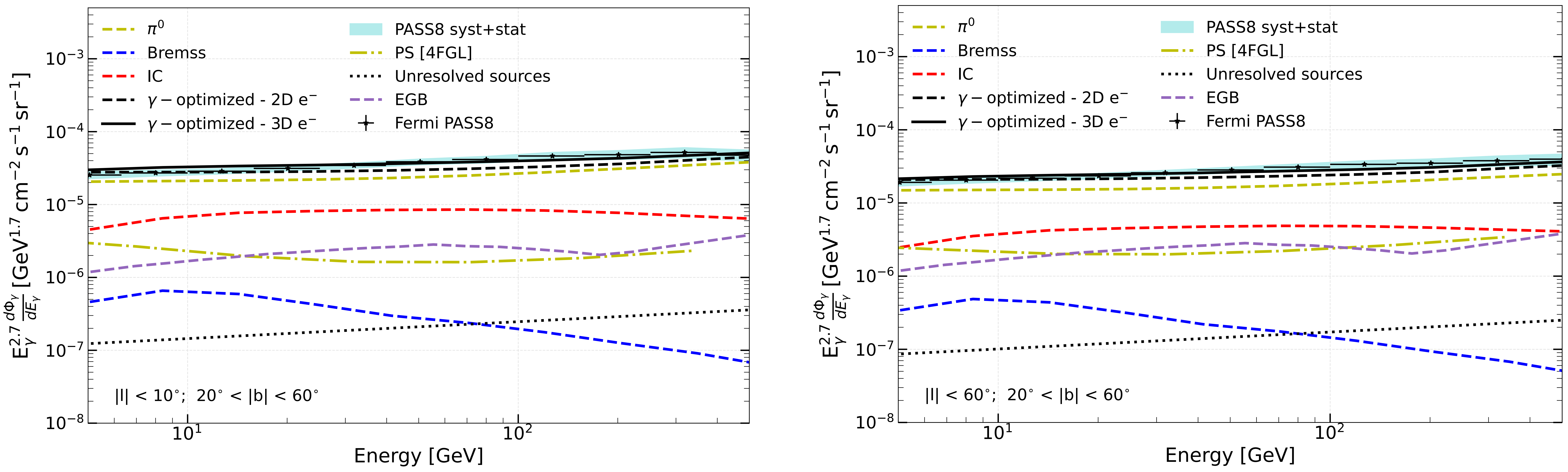
- The ν and γ diffuse emissions of the Milky Way have been observed up to the PeV !
- These emissions are consistent with (most) CR data !
- These results strongly points to a new propagation paradigm
- Even if the MW in ν looks much less prominent than in γ, his words

"The VHE and UHE γ-ray fluxes from cosmic ray interactions with the matter in our Galaxy should be viewed as a standard candle for these energy regions, although the luminosity is low. Understanding the diffuse galactic radiation, with its predictable latitude and longitude dependence, is a precondition for the exploration of the deeper universe in this energy range."

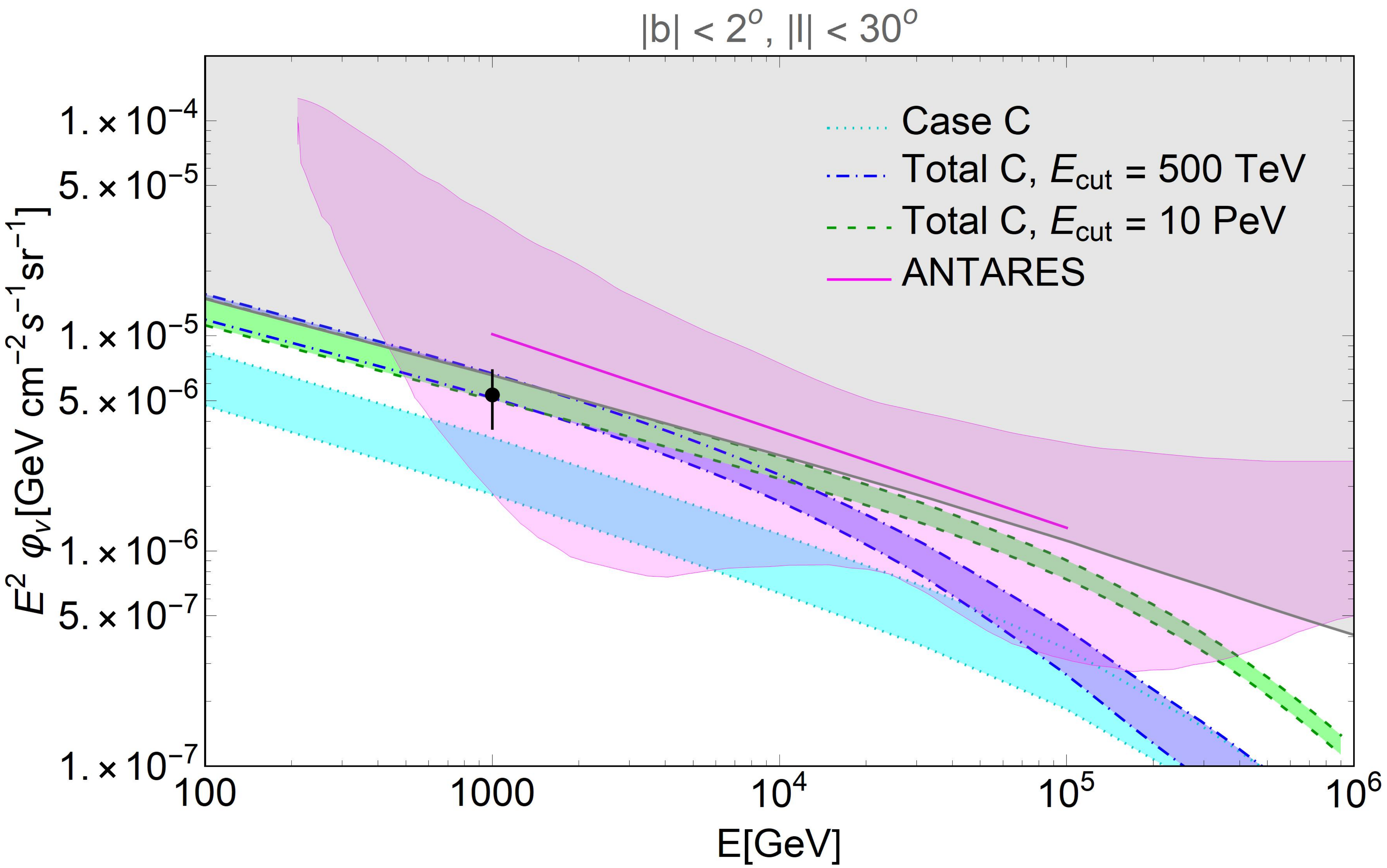
Hold true also for neutrinos !

Backup slides

Comparison with Fermi



Vecchiotti, Villante & Pagliaroli, *JCAP 2023*



W.Li at al. arXiv:2408.12123

Search for an excess (1.9 σ evidence) in IceCube tracks corresponding to LHAASO signal