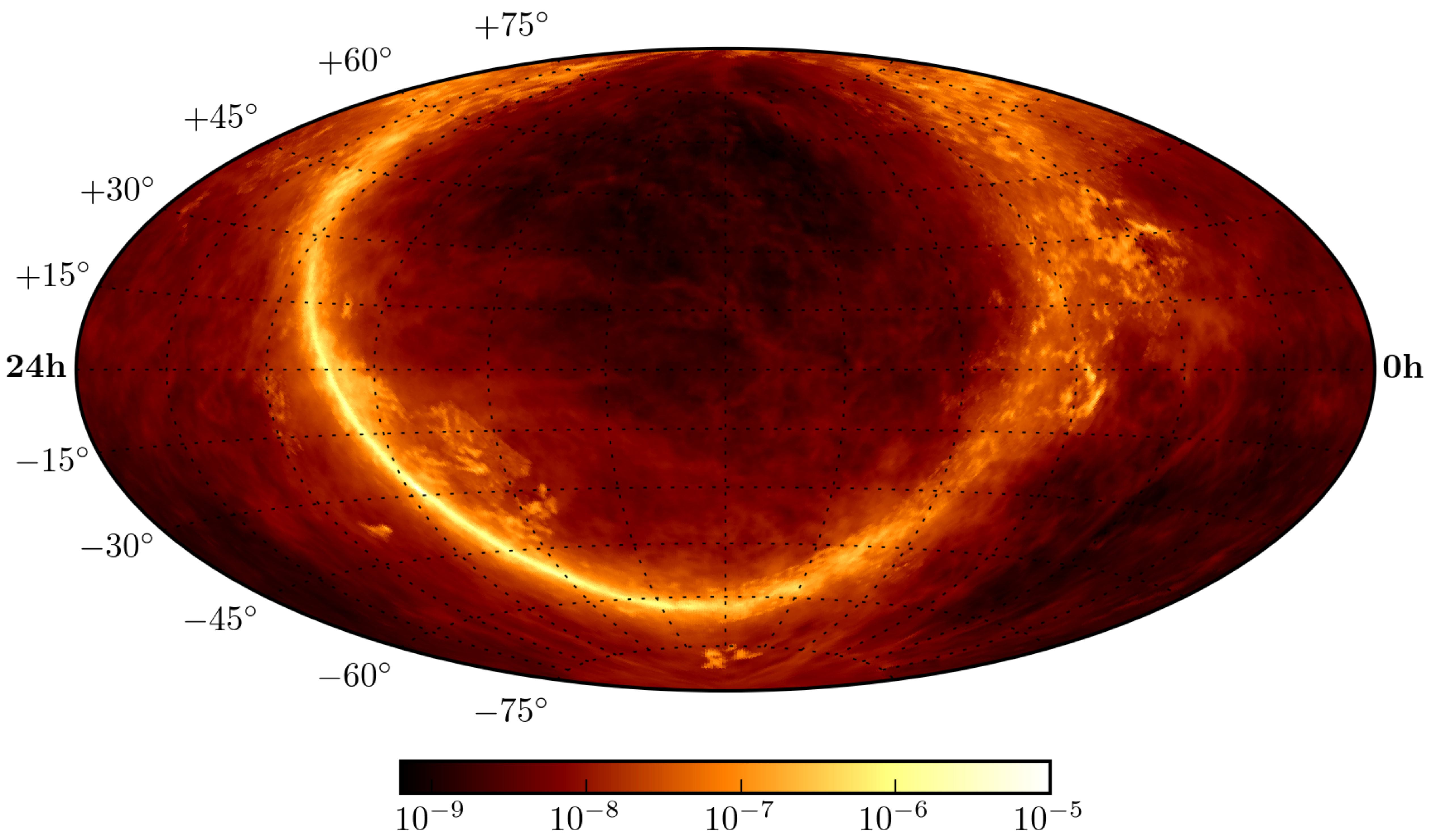
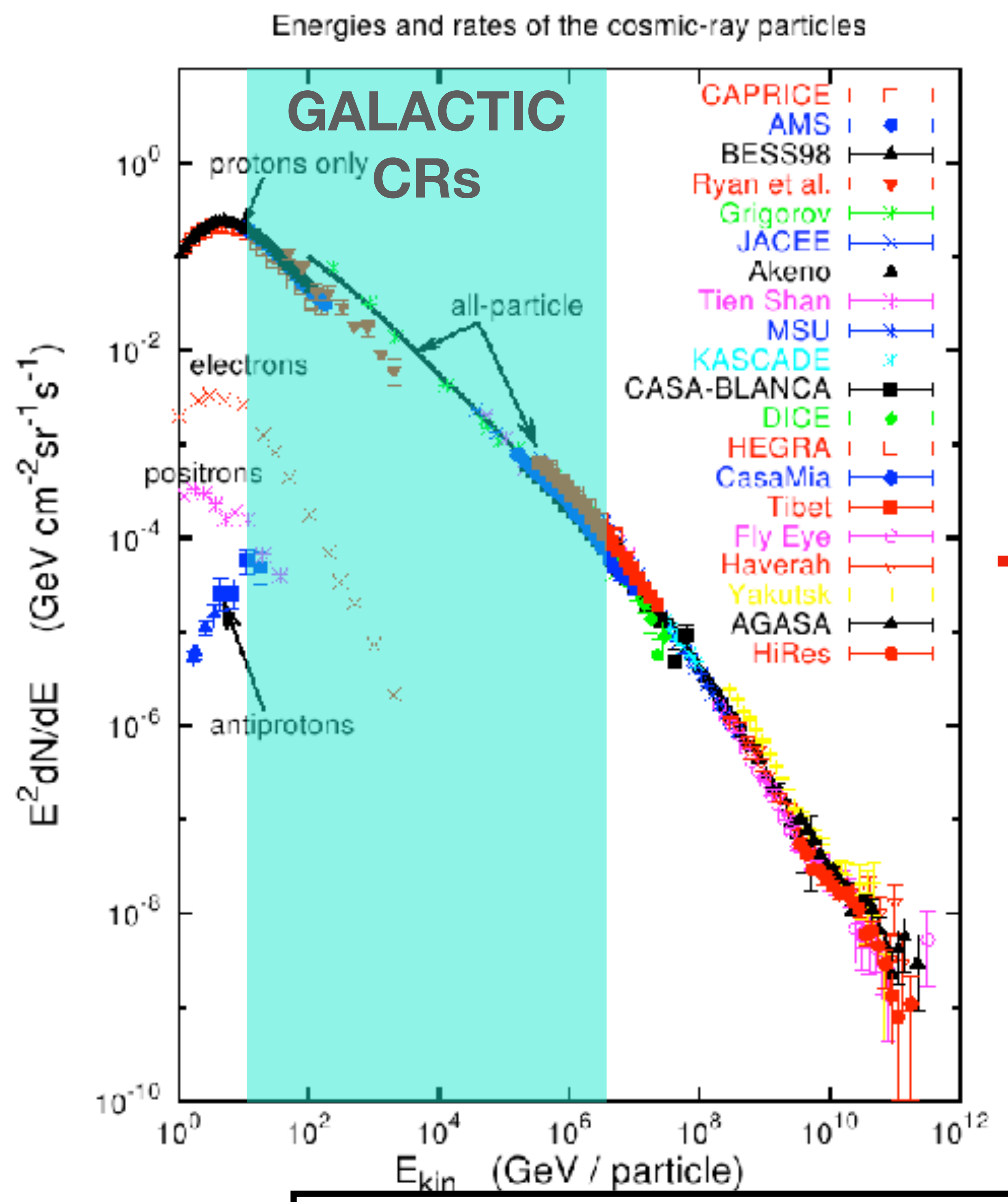


GAMMA-RAY AND NEUTRINO DIFFUSE EMISSIONS OF THE MILKY-WAY: WHAT DO THEY IMPLY ?

D. Grasso (INFN, Pisa & Embassy of Italy in the Netherlands, The Hague)

P. De la Torre Luque (Madrid), D. Gaggero (INFN) and A. Marinelli (Naple Un.& INFN)

ν AND γ-RAY DIFFUSE EMISSIONS FROM GALACTIC COSMIC RAYS



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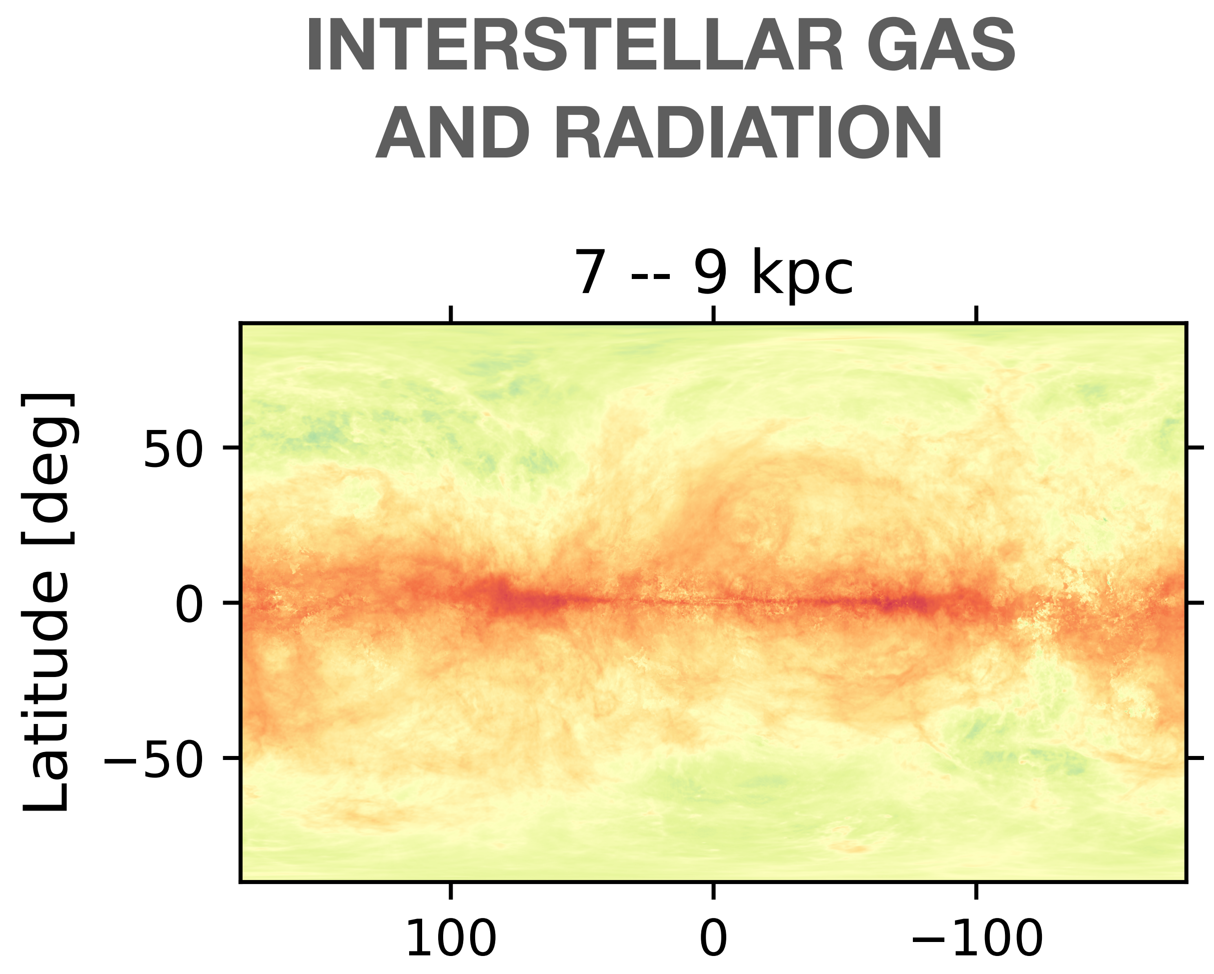
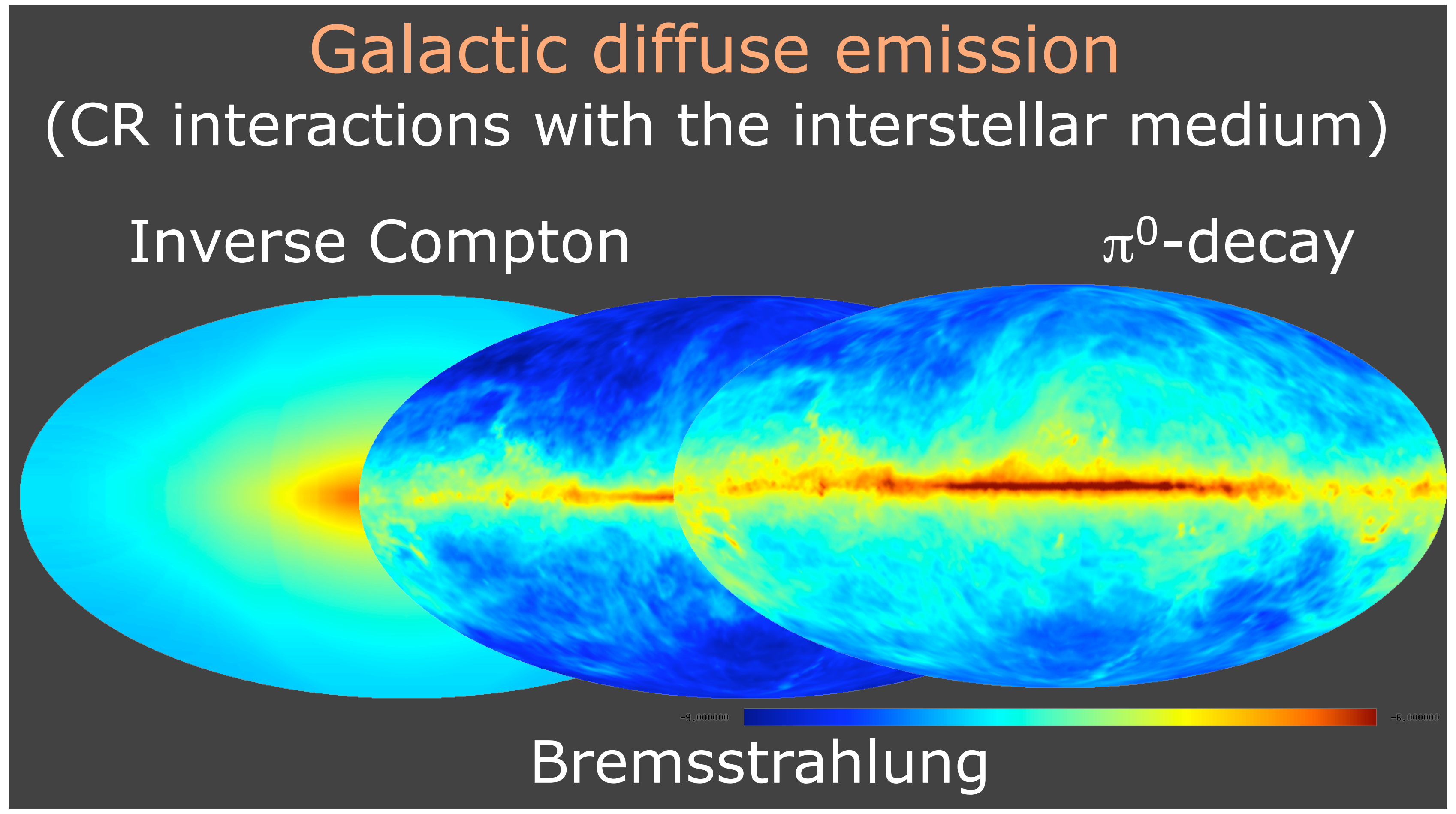


⇒

OBSERVED (only recently up to PeV !)



$$p + p \rightarrow \pi_0 \pi_+ \pi_-$$

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

GUARANTEED NEUTRINO DIFFUSE EMISSION

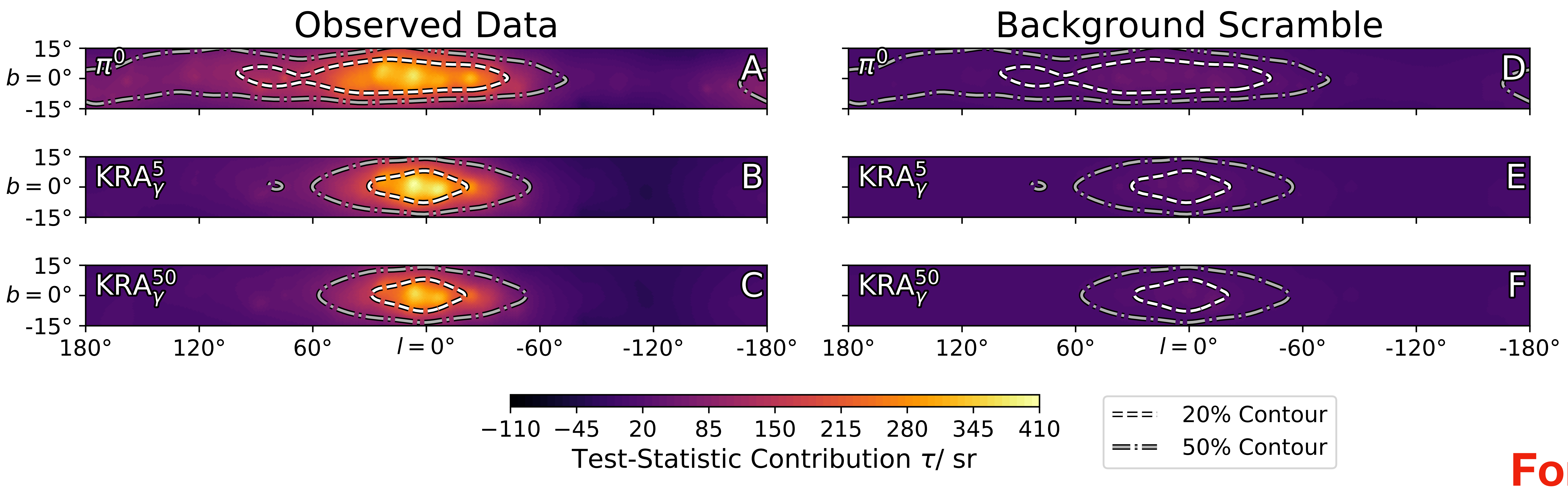
Its observations would however be very important to

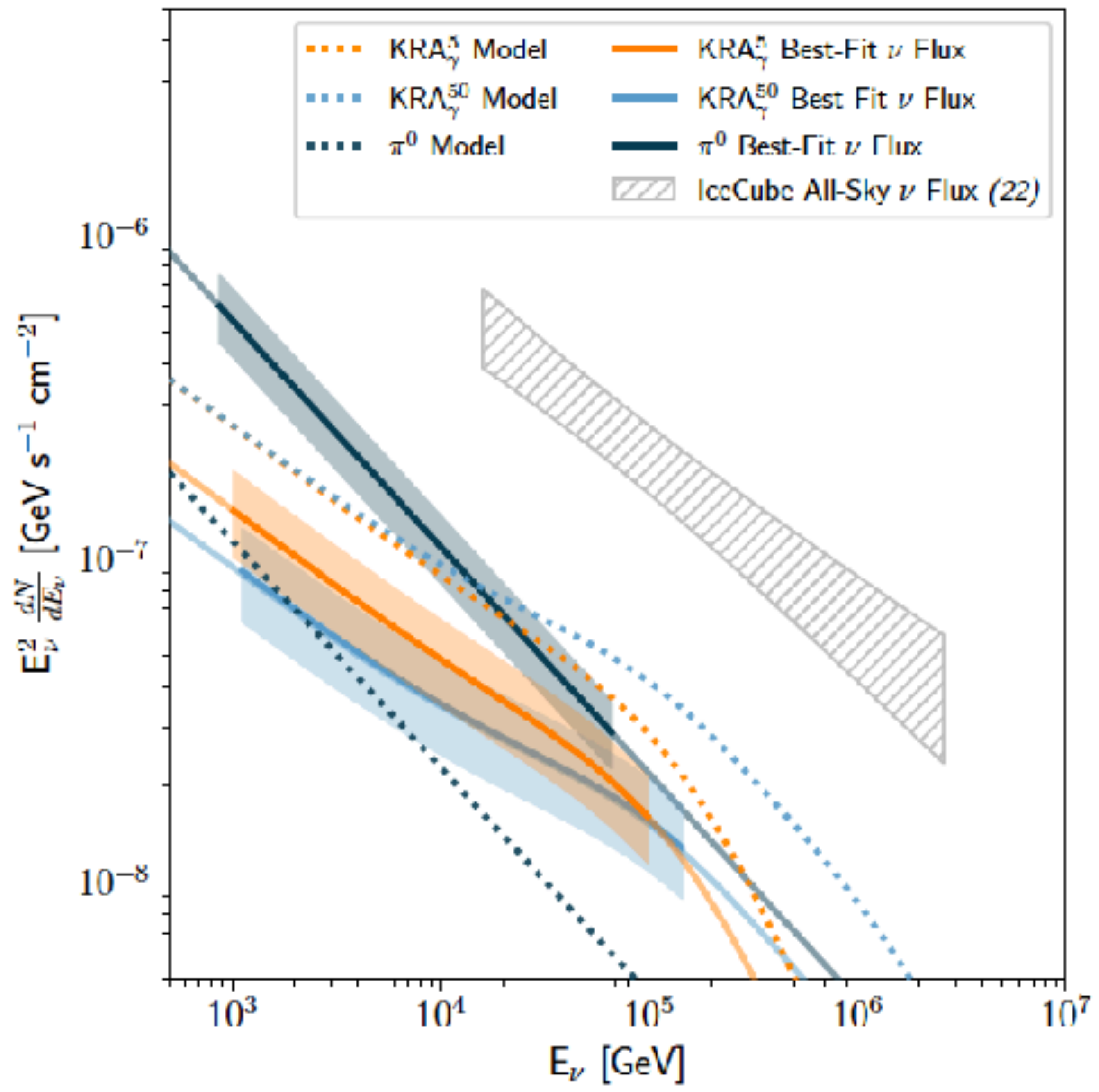
- Confirm the hadronic origin of the emission (possibly constraining the contribution of unresolved sources)
- Probe the CR spectrum above the PeV hence the source nature
- Probe CR propagation at very high energies

ICECUBE DISCOVERY OF THE ν DIFFUSE EMISSION OF THE GALAXY

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





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

The emission might be also be originated by unresolved sources !

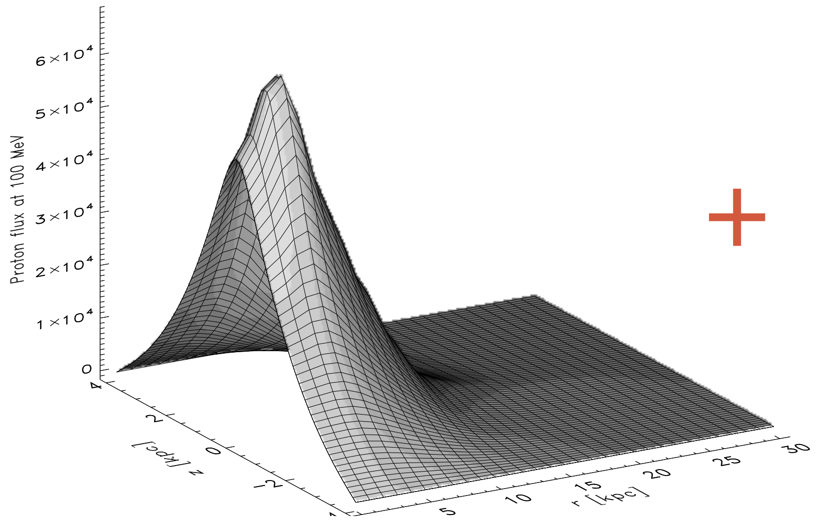
For all considered templates the background hypothesis is rejected !!

Setting up physically motivated templates is a relevant piece of the discovery !

MODELLING THE INTERSTELLAR DIFFUSE EMISSION

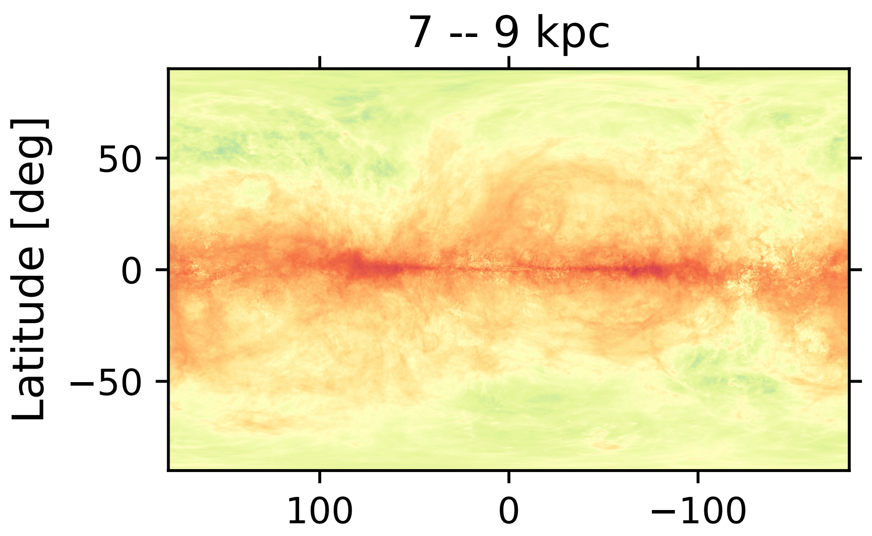
The conventional scenario

CR spatial/energy distribution from numerical codes (GALPROP/ DRAGON)



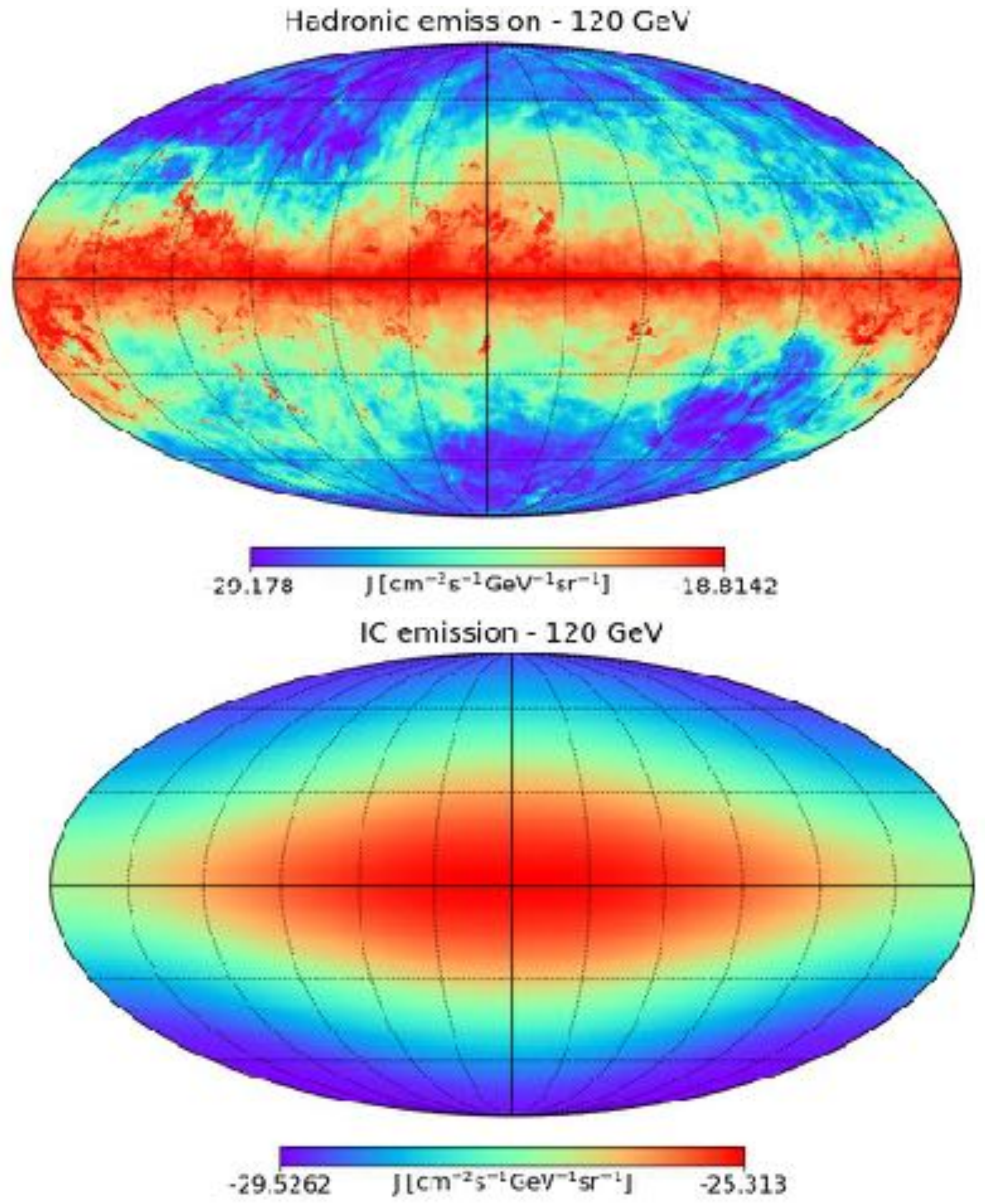
+

Astrophysical inputs : gas maps , interstellar radiation fields, magnetic fields



LOS integration

GALPROP/HERMES



ρ : particle rigidity

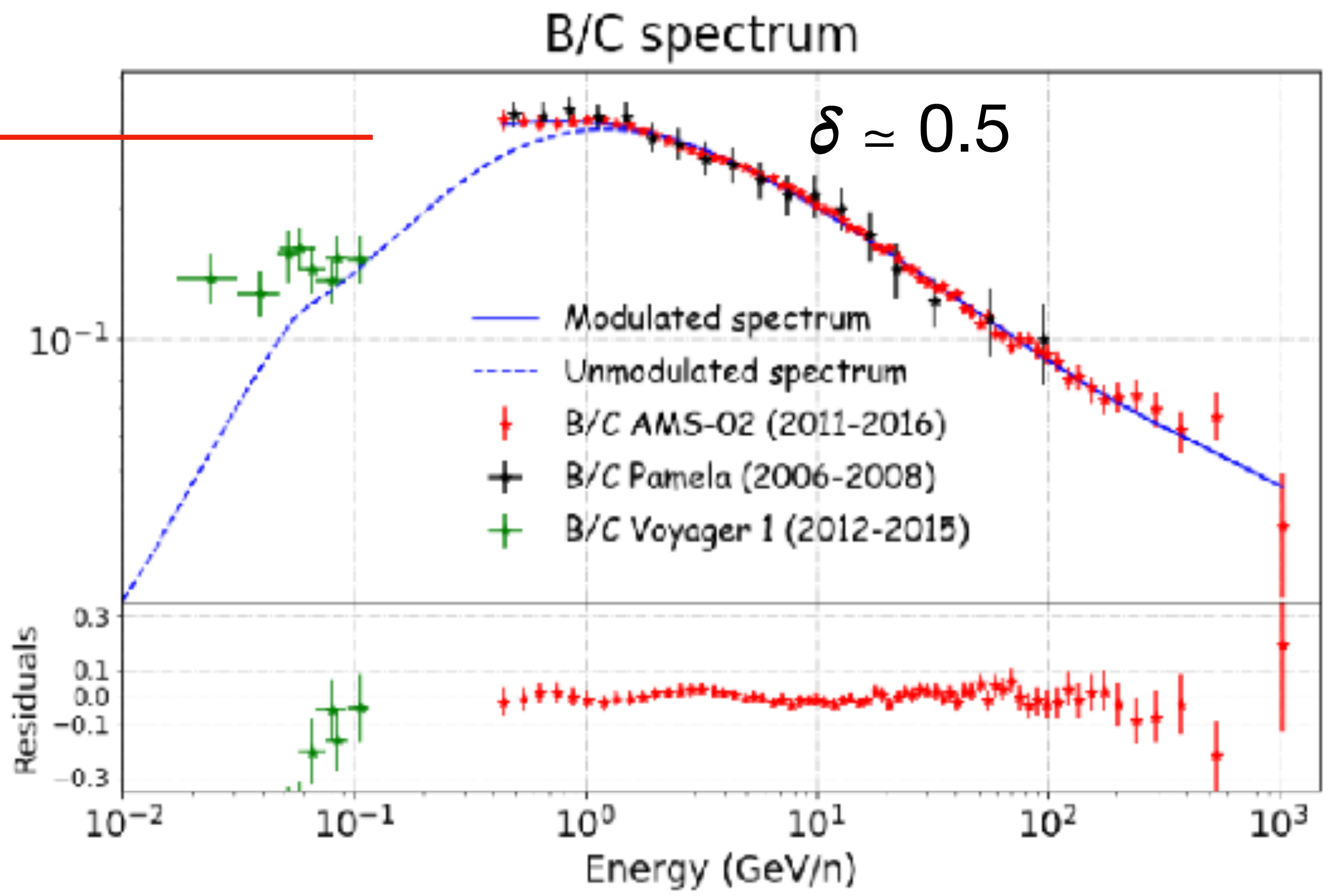
Schematically, for CR nuclei

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

for a <u>uniform</u> diffusion coefficient $D(\rho, \mathbf{x}) \propto D_0\, \rho^{-\delta}$

$$\boxed{J_{CR}(\rho, \mathbf{x}) \propto J_0(\mathbf{x})\, \rho^{-(\alpha+\delta)} \quad \text{in the whole Galaxy}}$$

<u>**Factorized rigidity - position dependence**</u>



Warning : this data probe only a relatively nearby region !!
d < few kpc

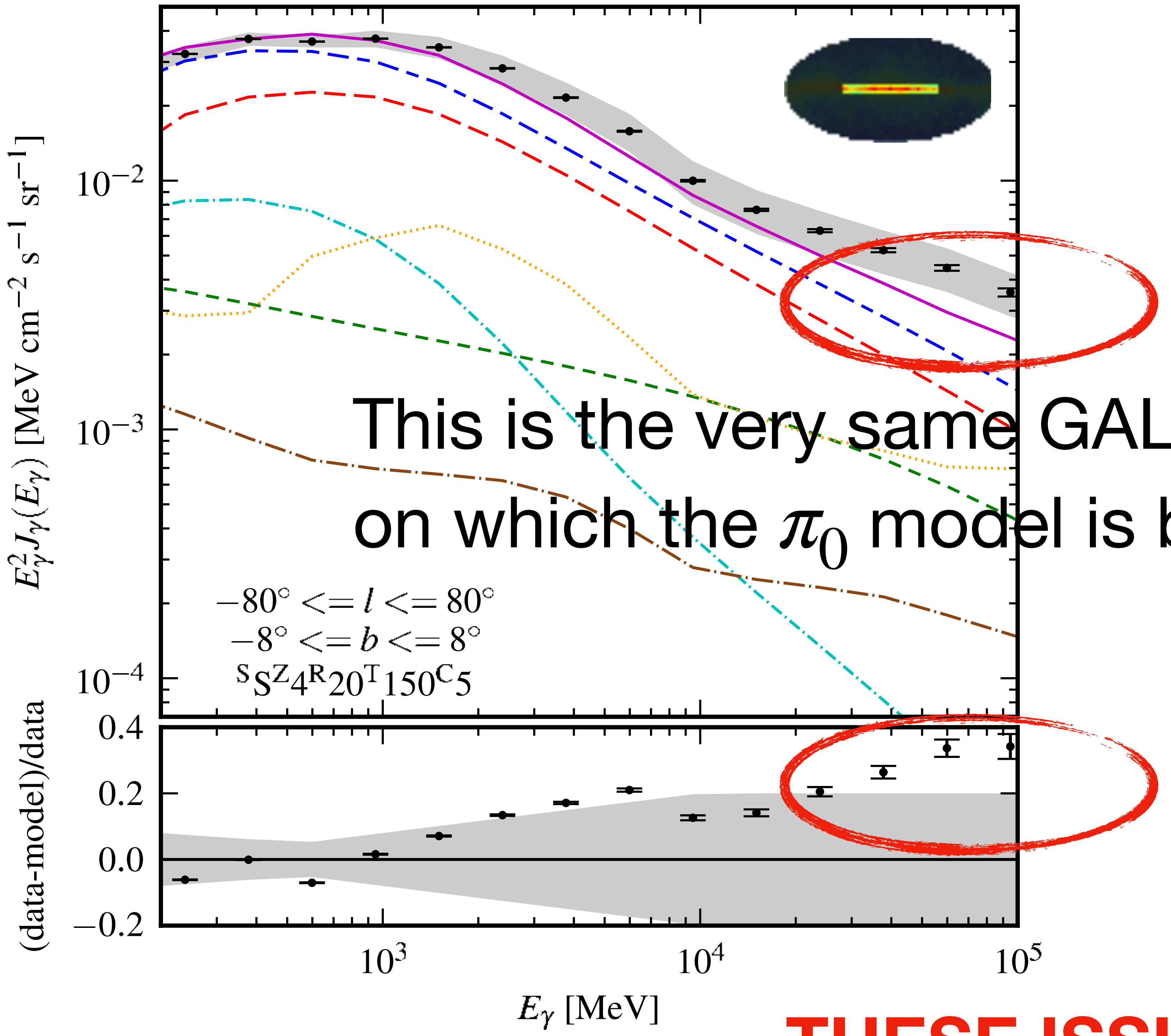
δ may be different in the innermost regions !

THE π_0 MODEL

It is a conventional model based on the locally observed CR spectrum (spectral index - 2.7) matching the γ-ray diffuse emission measured by Fermi and extrapolated above the TeV !!

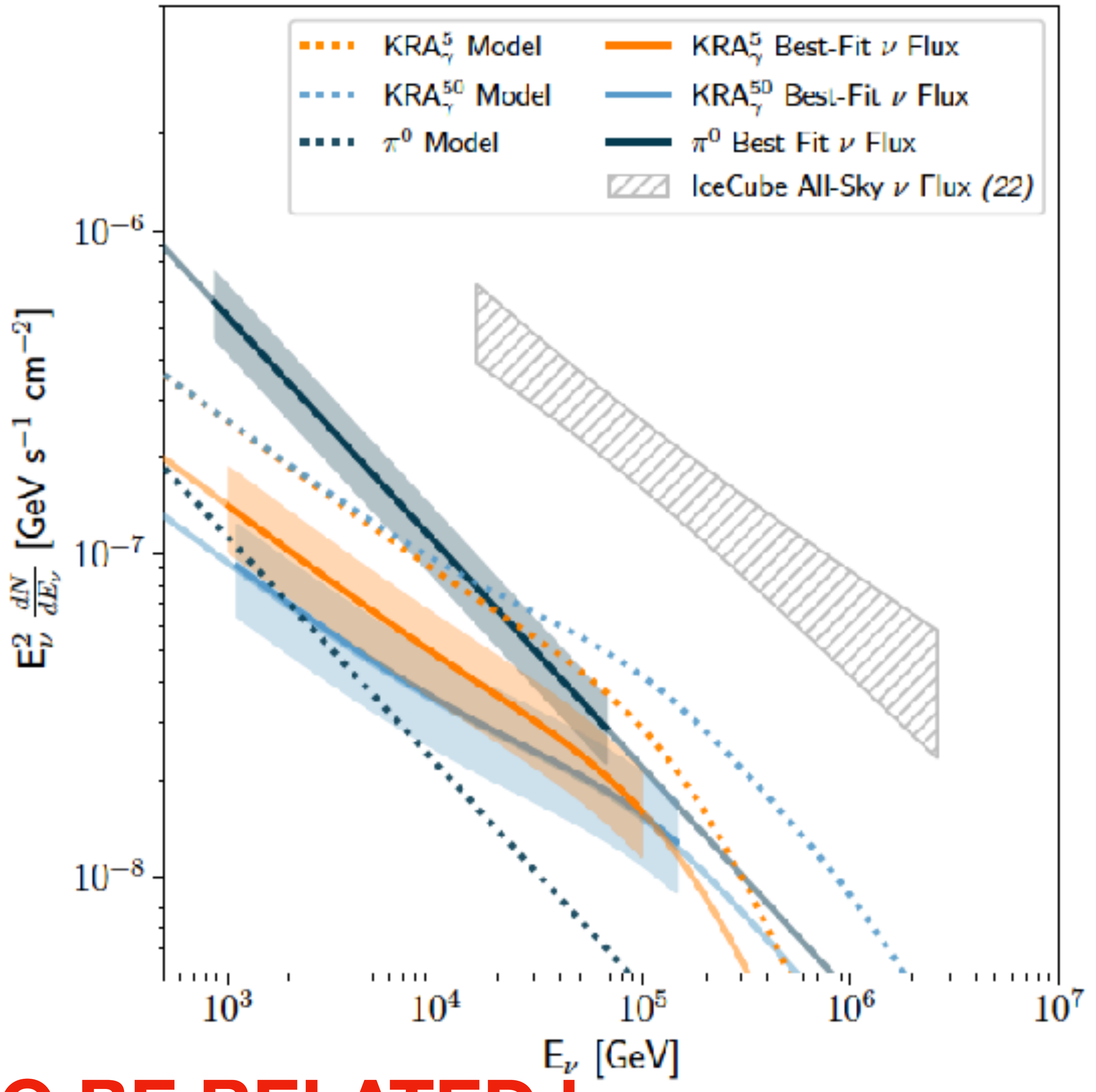
DRAWBACKS

It does not account 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 !

Its normalization has to be x 5 in order to match IceCube !



THESE ISSUES ARE LIKELY TO BE RELATED !

THE π_0 MODEL

It is a conventional model based on the locally observed CR spectrum (spectral index - 2.7) matching the γ-ray diffuse emission measured by Fermi and extrapolated up to the PeV !!

DRAWBACKS

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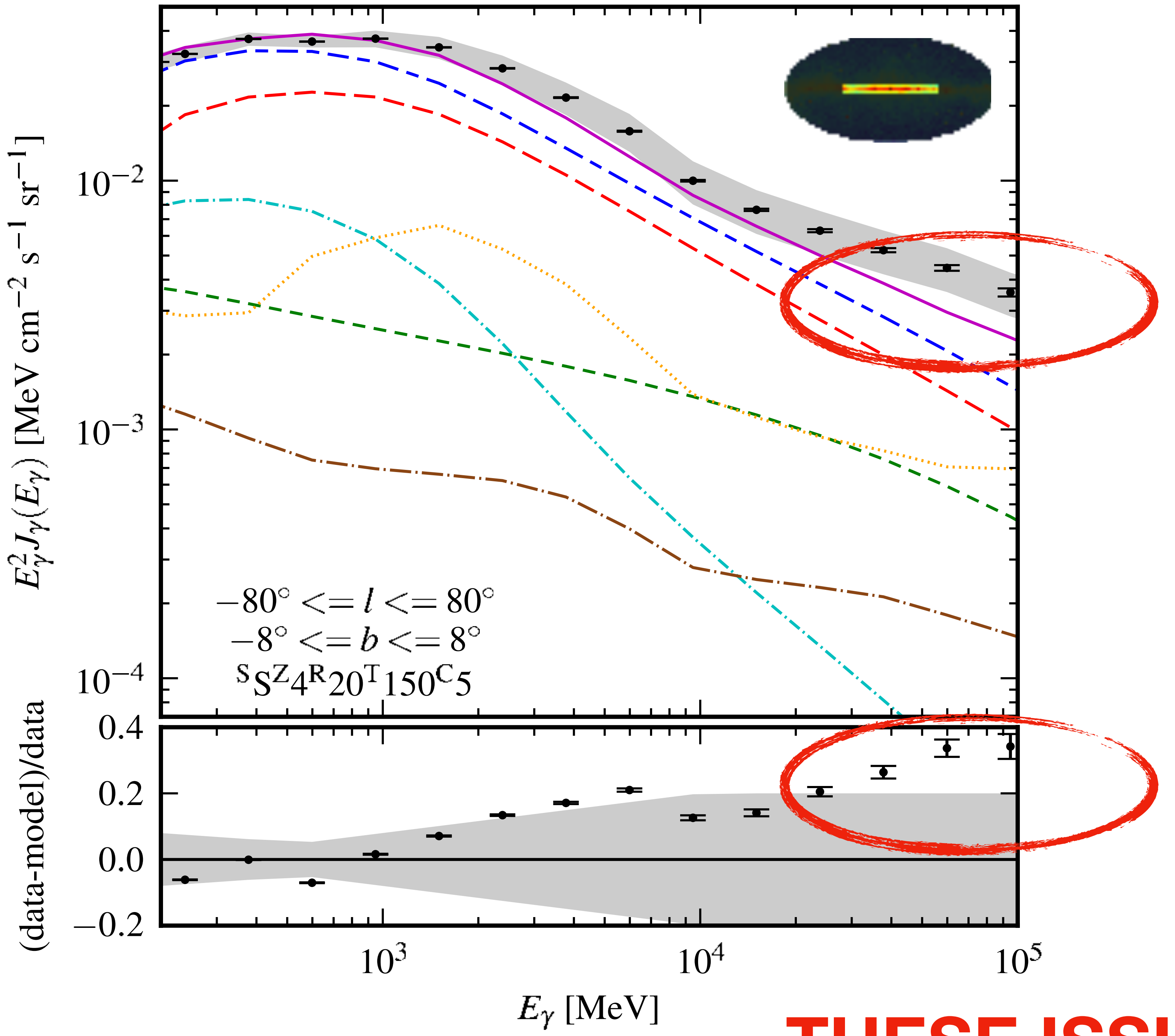

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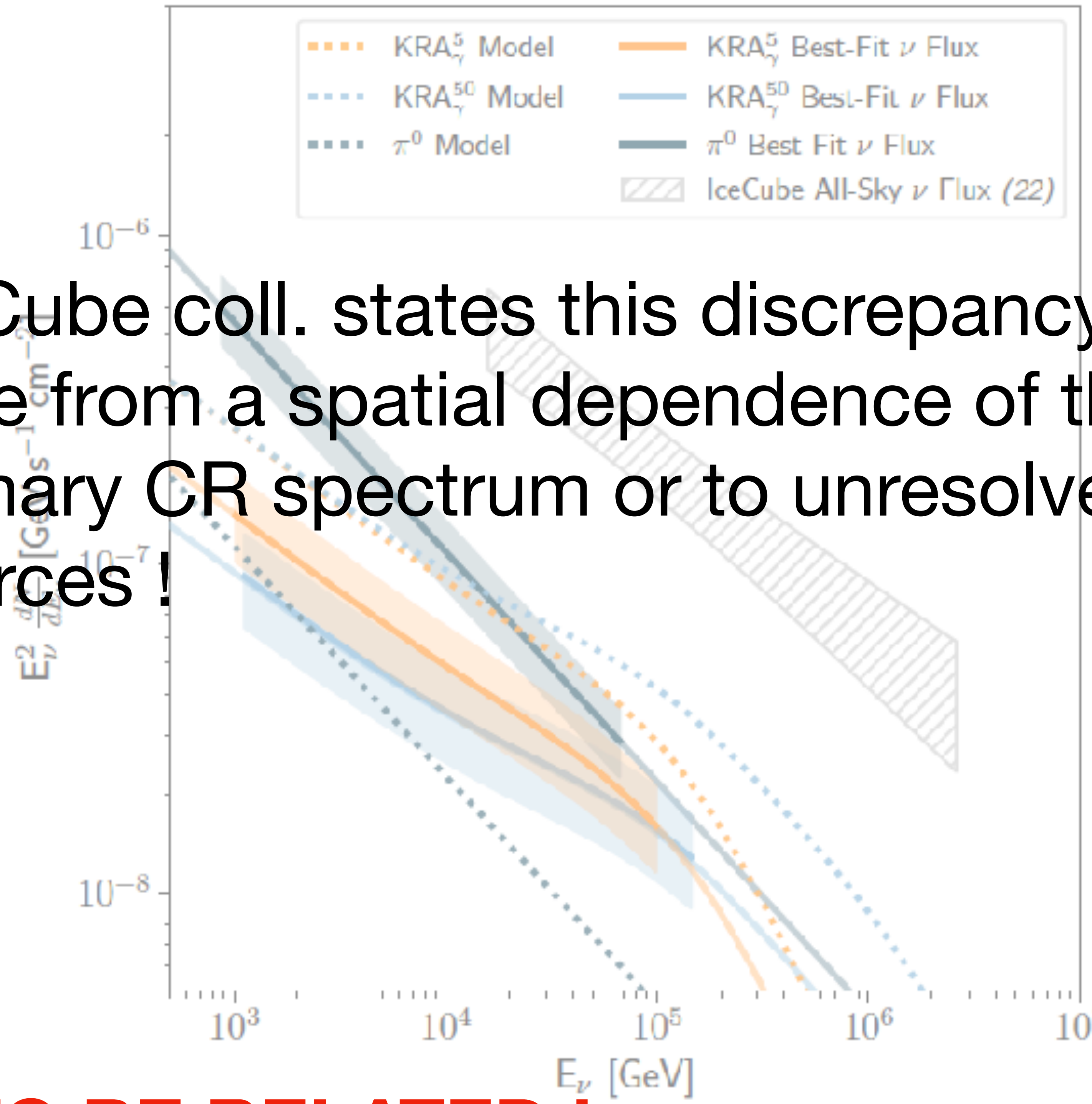


IceCube coll. states this discrepancy may arise from a spatial dependence of the primary CR spectrum or to unresolved sources !

THESE ISSUES ARE LIKELY TO BE RELATED !

THE γ-OPTIMIZED MODELS (KRAγ models)

Non-factorized rigidity-position dependence

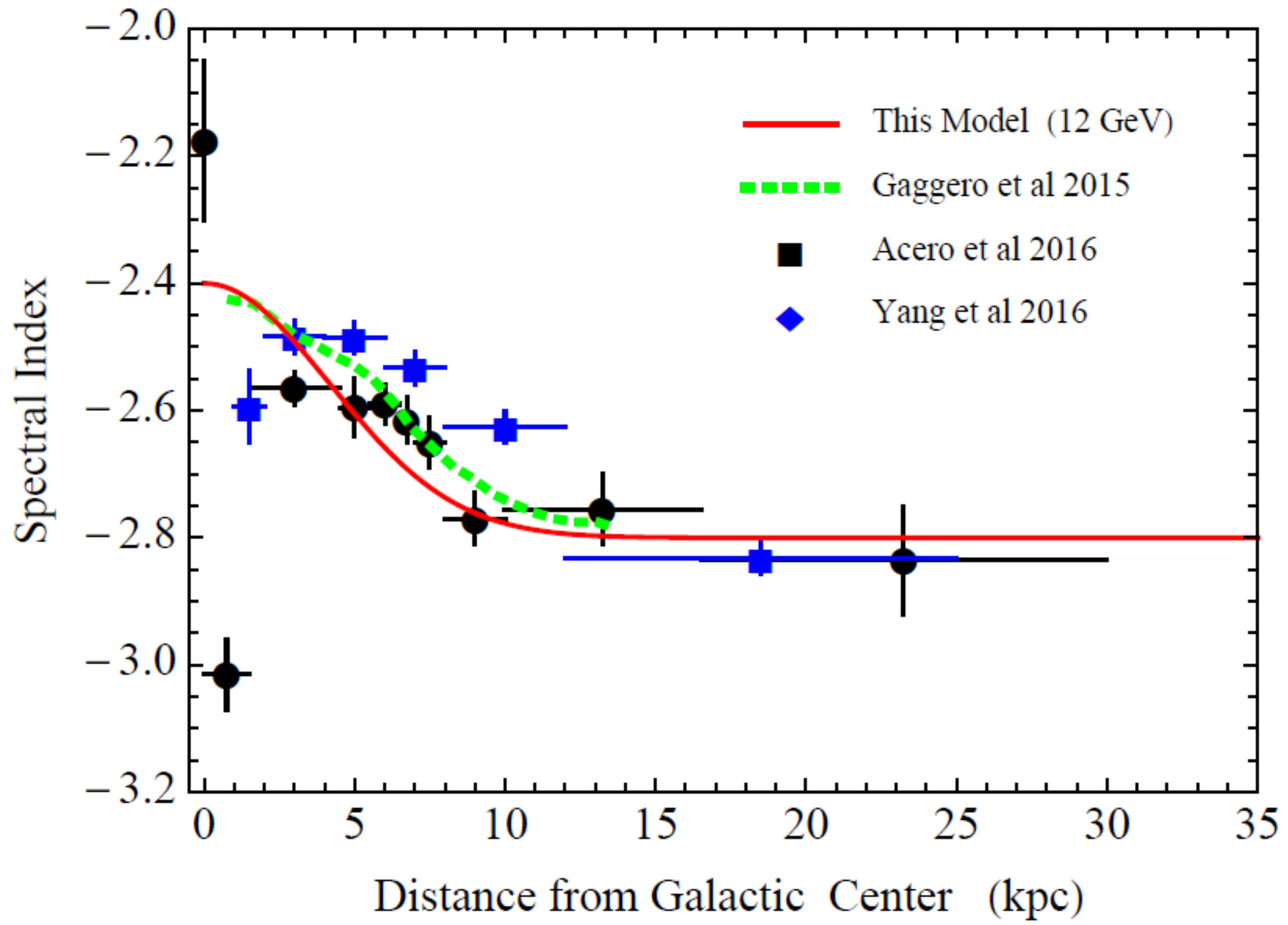
assuming a uniform source spectrum $J_S(\rho, \mathbf{x}) \propto n_S(\mathbf{x})\, \rho^{-\alpha}$

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

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

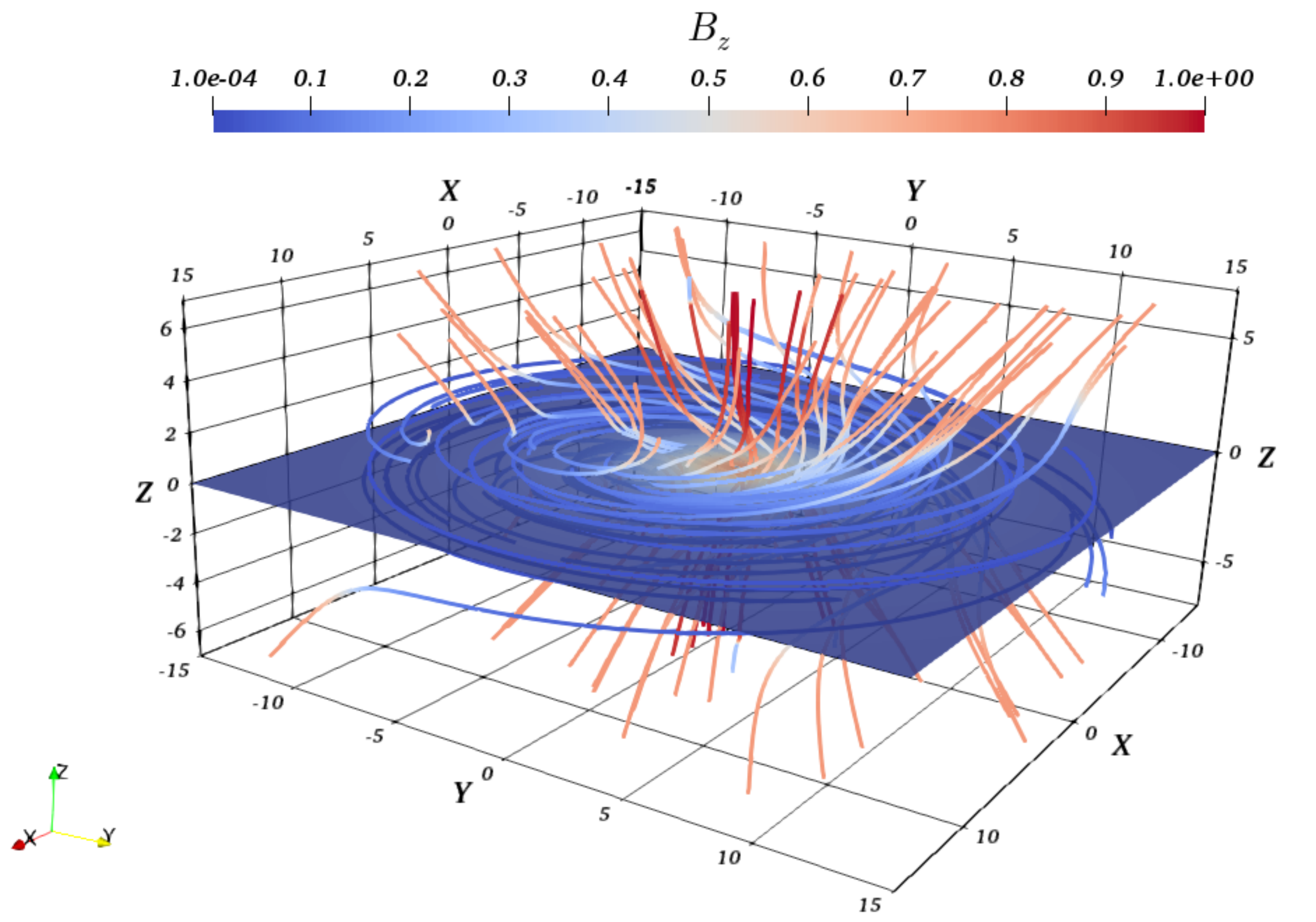
MOTIVATIONS

Suggested by FERMI results



Theoretically motivated (basis of MHD + new Galactic magnetic field measurements)

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



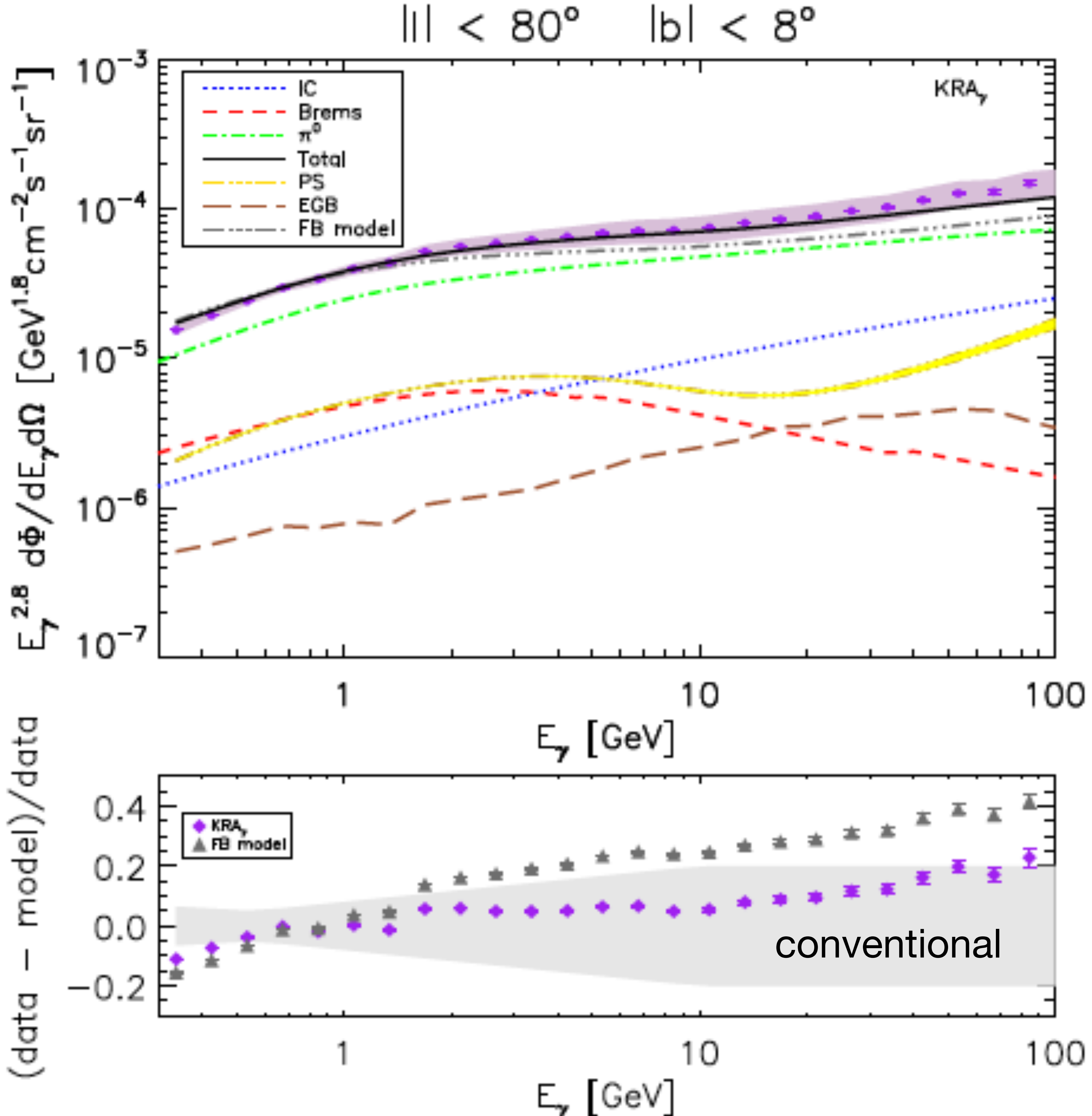
KRAγ PREDICTIONS AND MEASURMENTS γ-RAYS

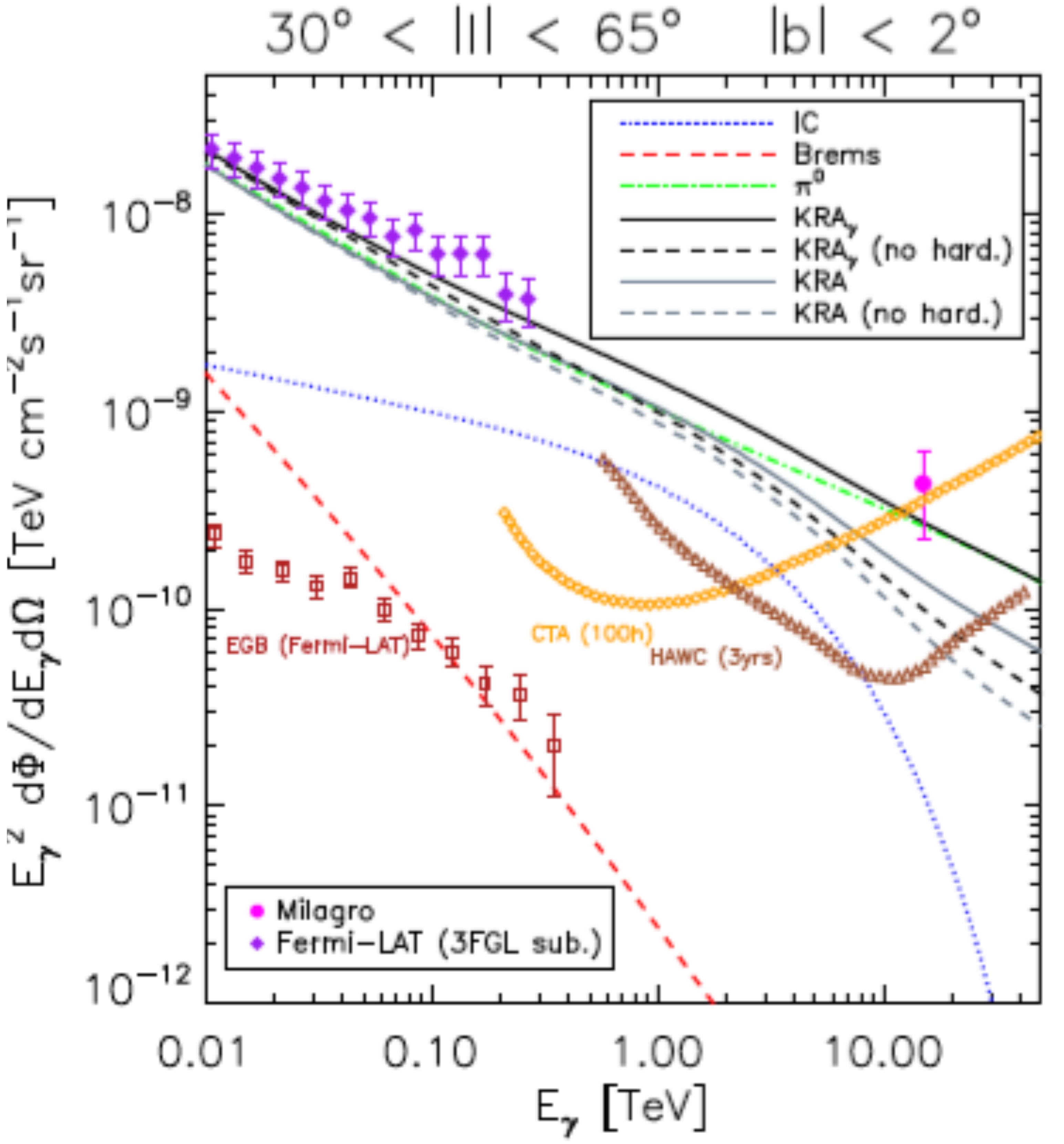
Using the DRAGON code allowing spatial dependent diffusion $\delta(R) = A\,R + B$ for $r < 11$ kpc

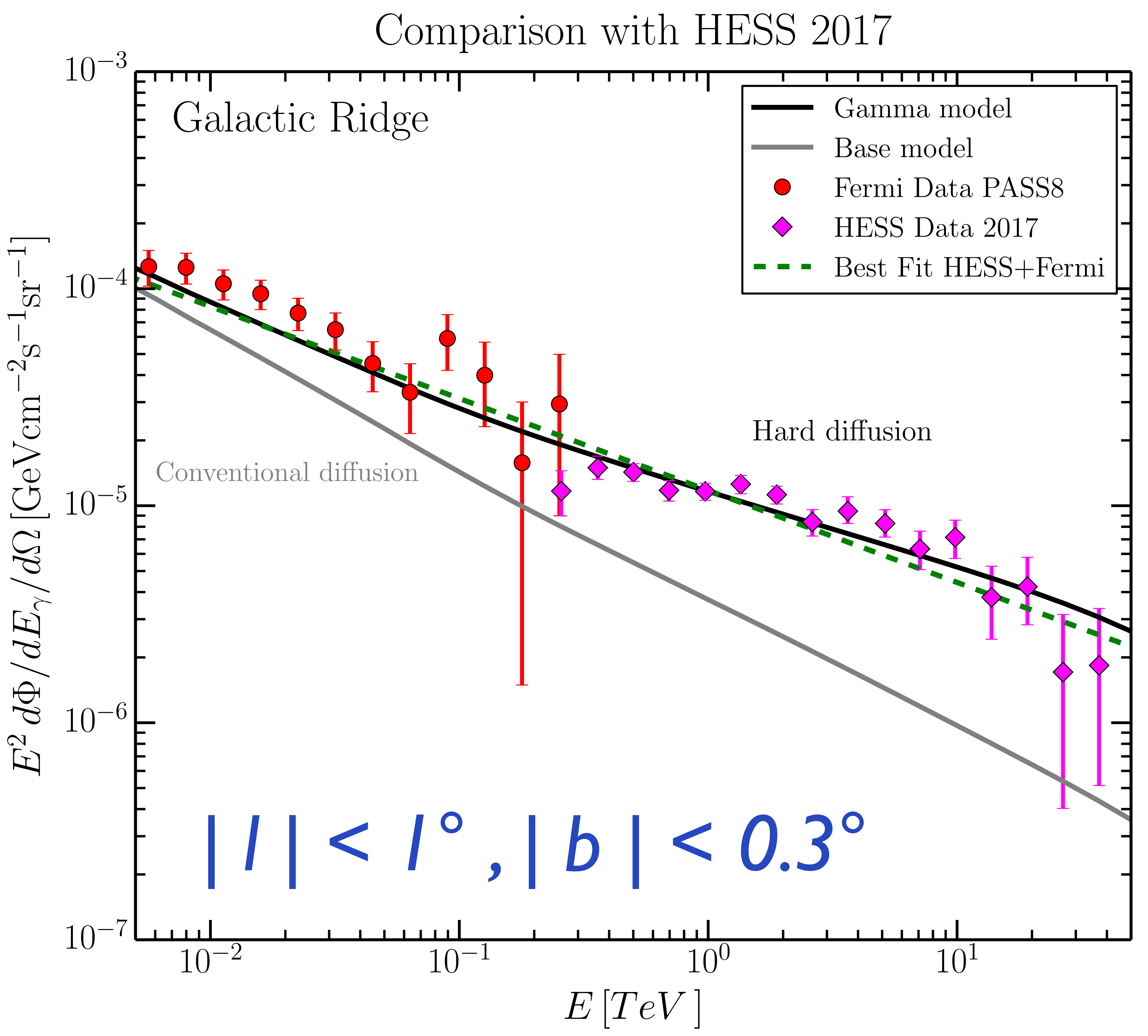
Solves FERMI data anomaly **Better match very high energy γ ray data**

Gaggero, Urbano, Valli & Ullio, PRD 2015 *Gaggero, D.G., A. Marinelli, Urbano, Valli ApJ L 2015* *Gaggero, D.G., A. Marinelli, Taoso & Urbano, PRL 2017*

“

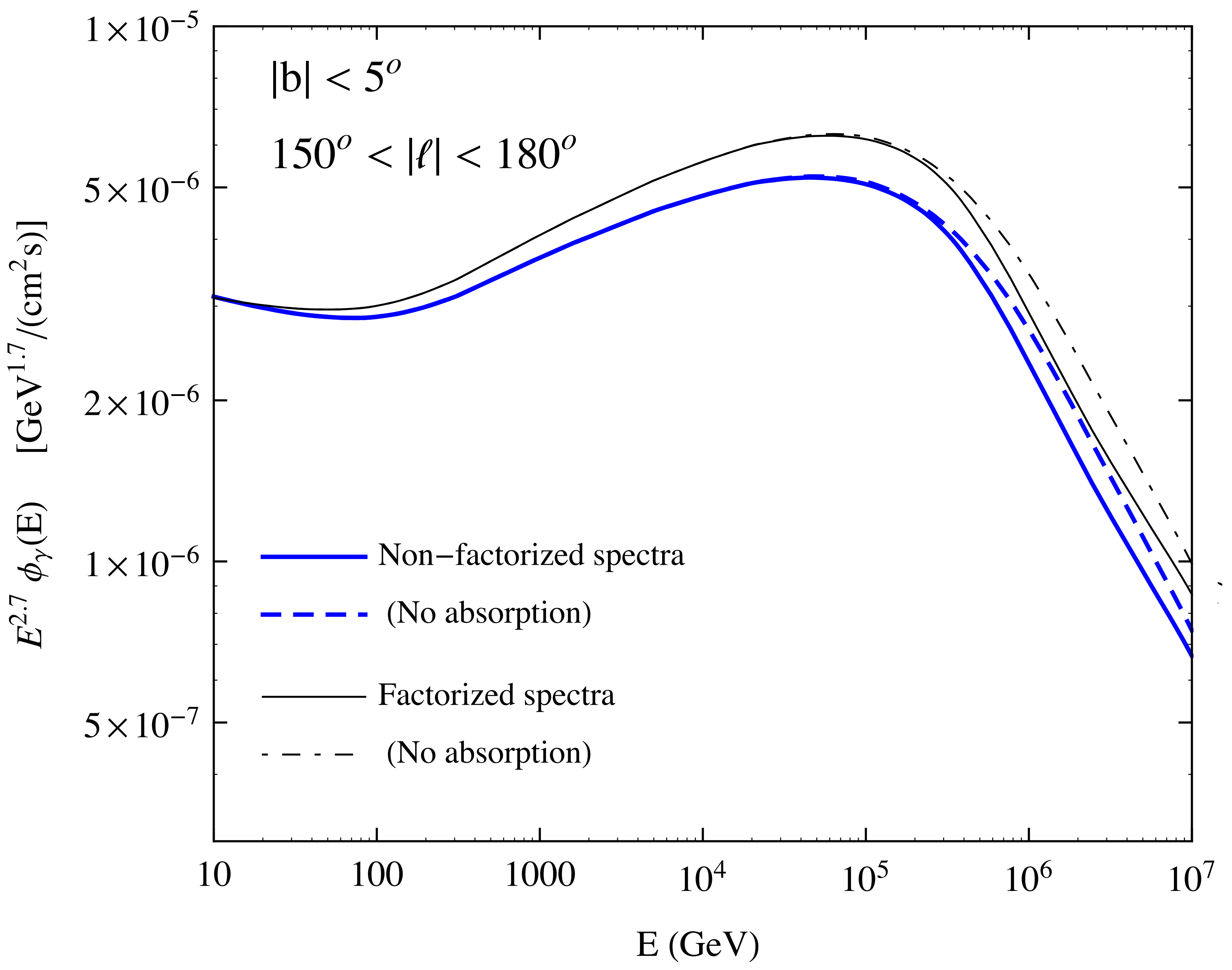


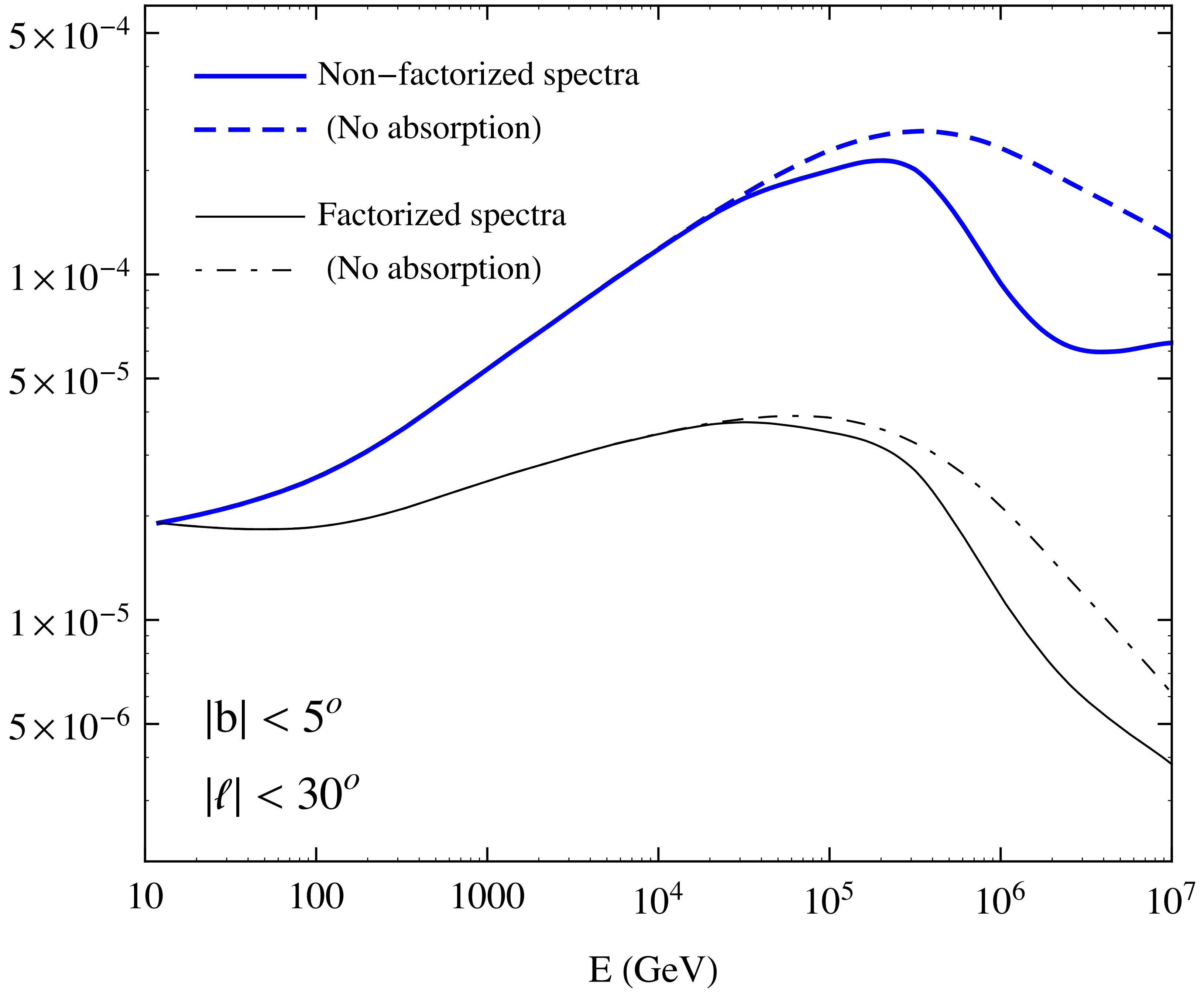


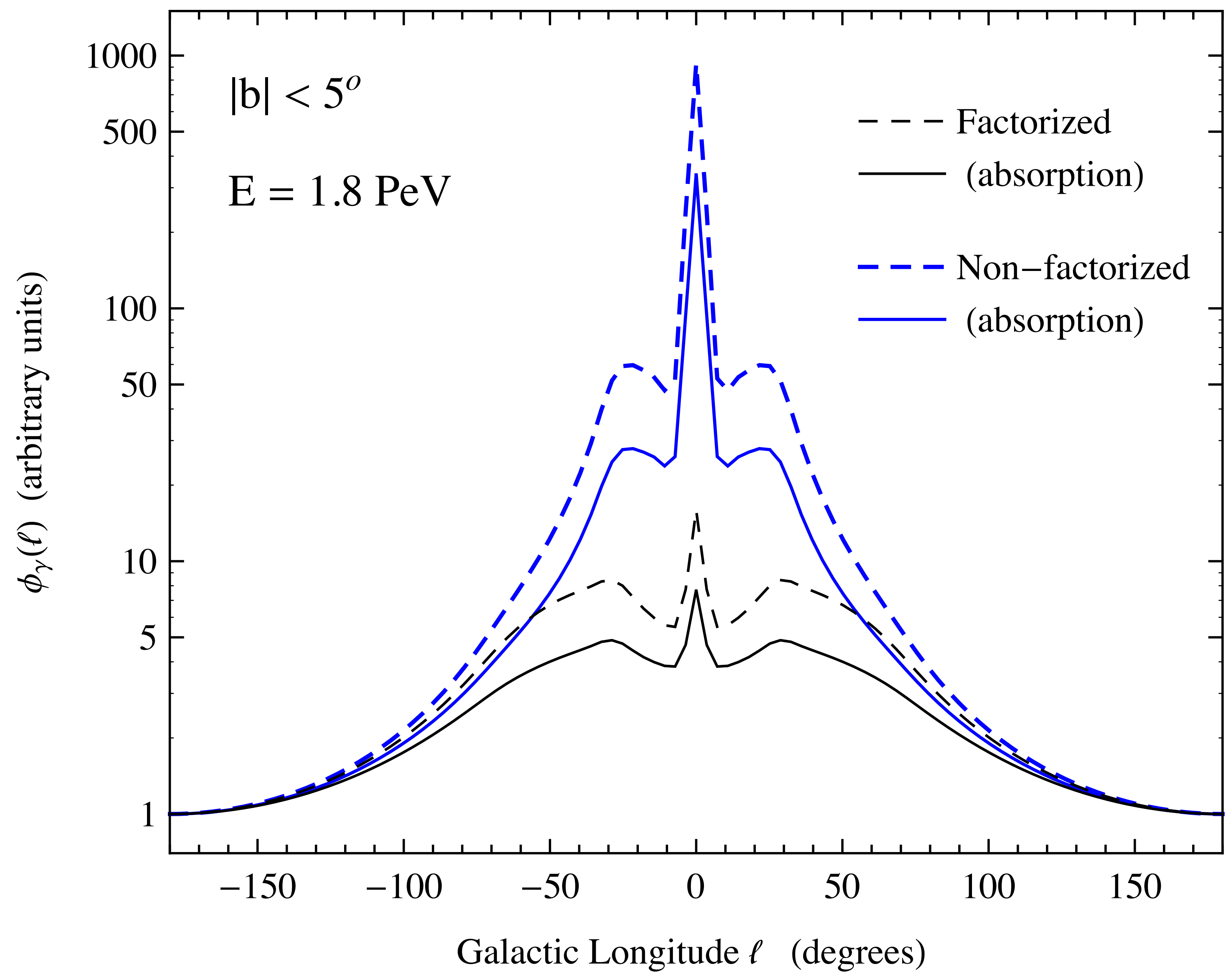


THE γ-OPTIMIZED MODEL MAIN FEATURES

Lipari & Vernetto, 2018 Using an analytical implementation of the same scenario







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

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 !

KRAγ PREDICTIONS AGAINST ν MEASURMENTS

The IceCube and ANTARES search

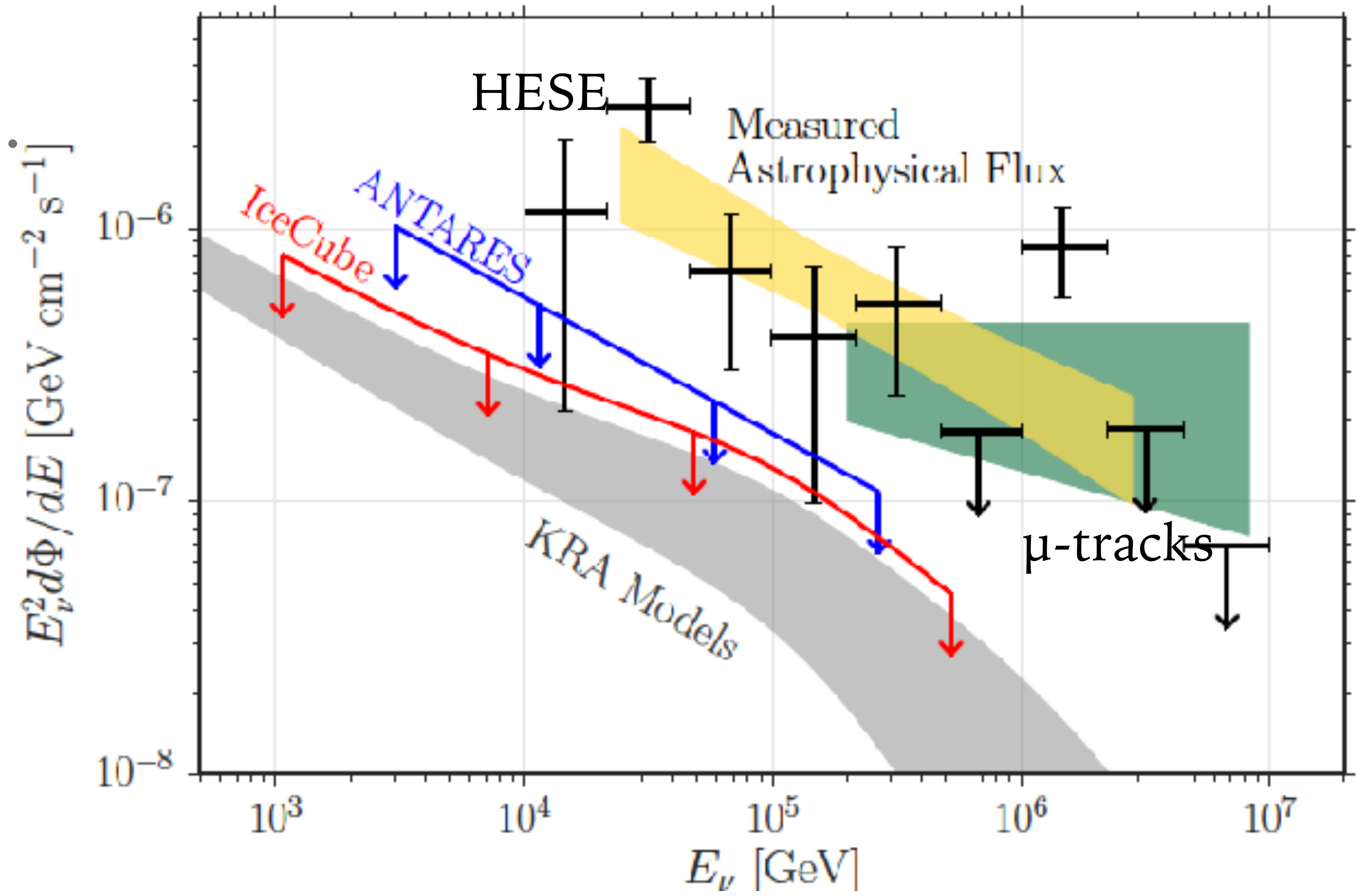
Gaggero, D.G., A. Marinelli, Urbano, Valli ApJ L 2015 : ν **flux enhancement predicted**

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 !***

IceCube coll., Science 2023 : ***THE DISCOVERY !***



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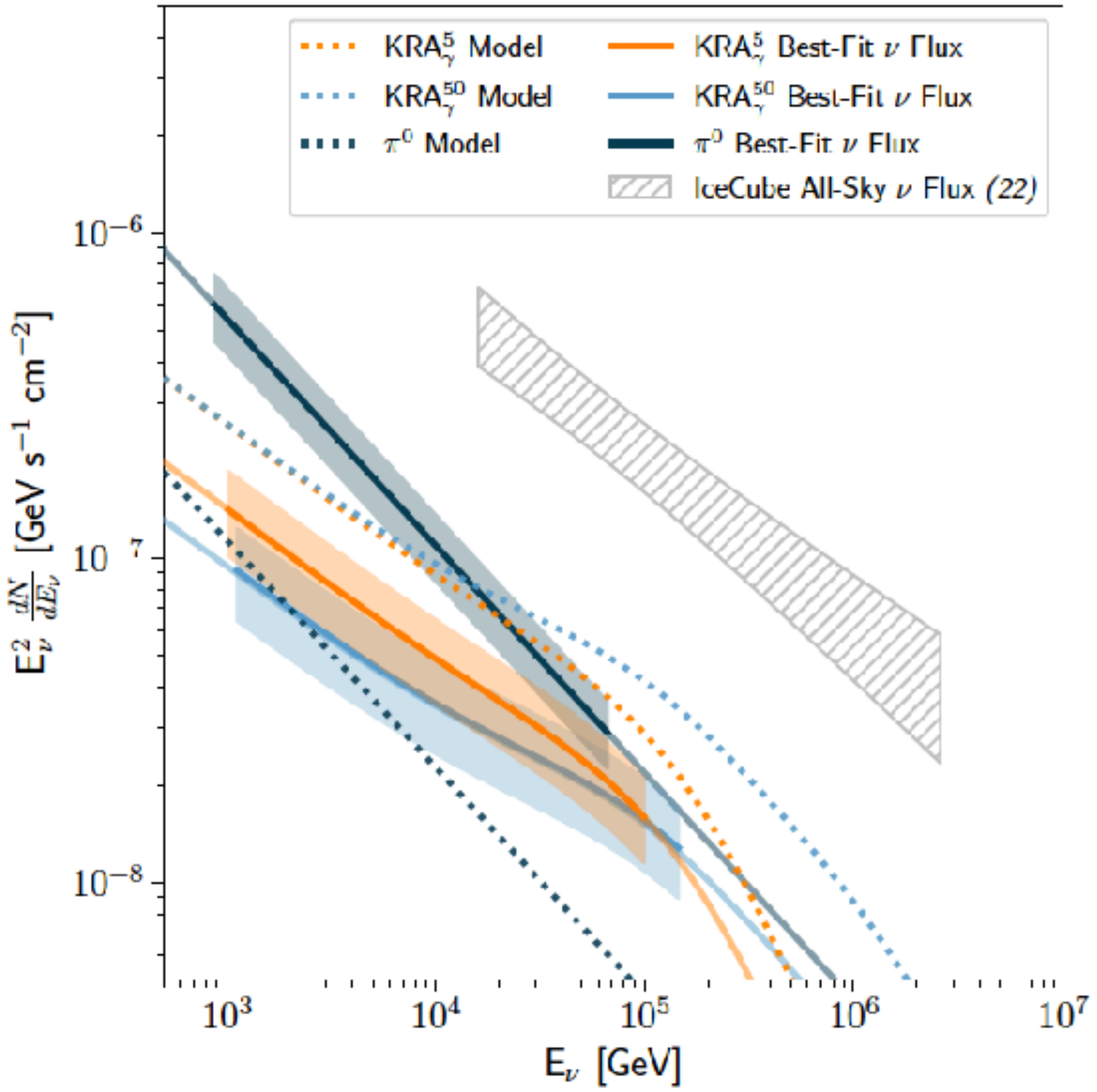
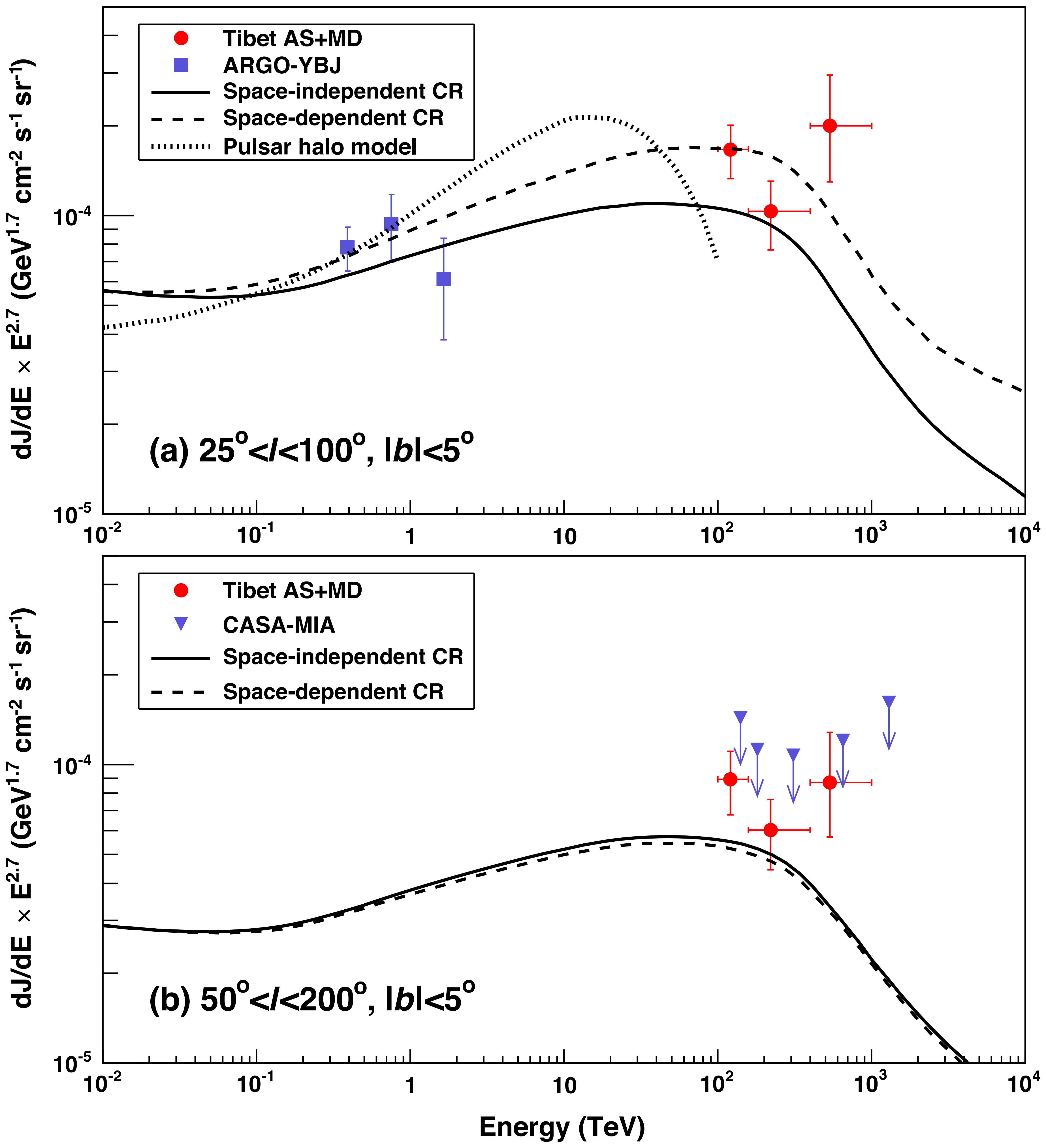
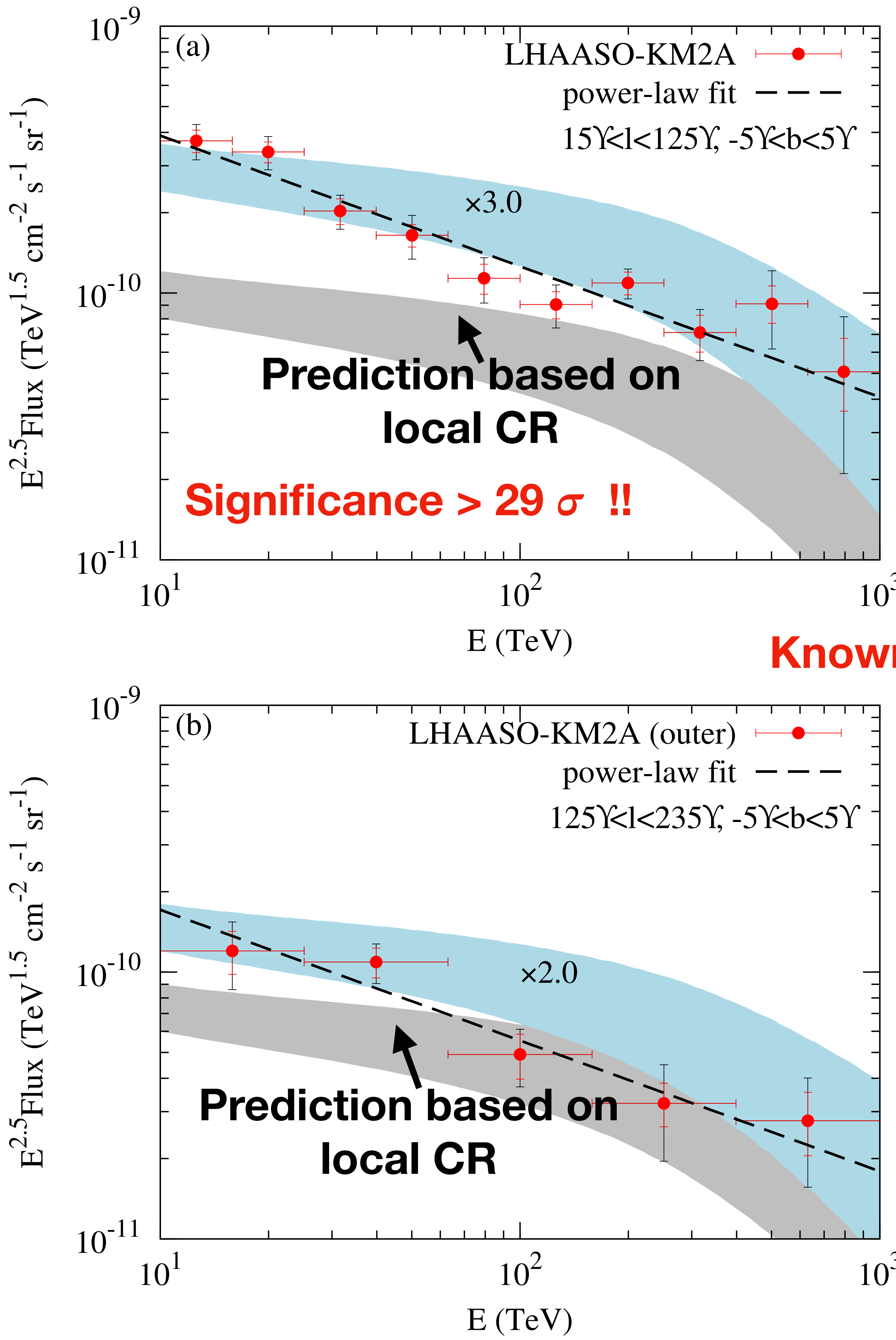


A NEW ACTOR ON THE STAGE : PEV GAMMA-RAY ASTRONOMY

Tibet ASγ coll., PRL 2021



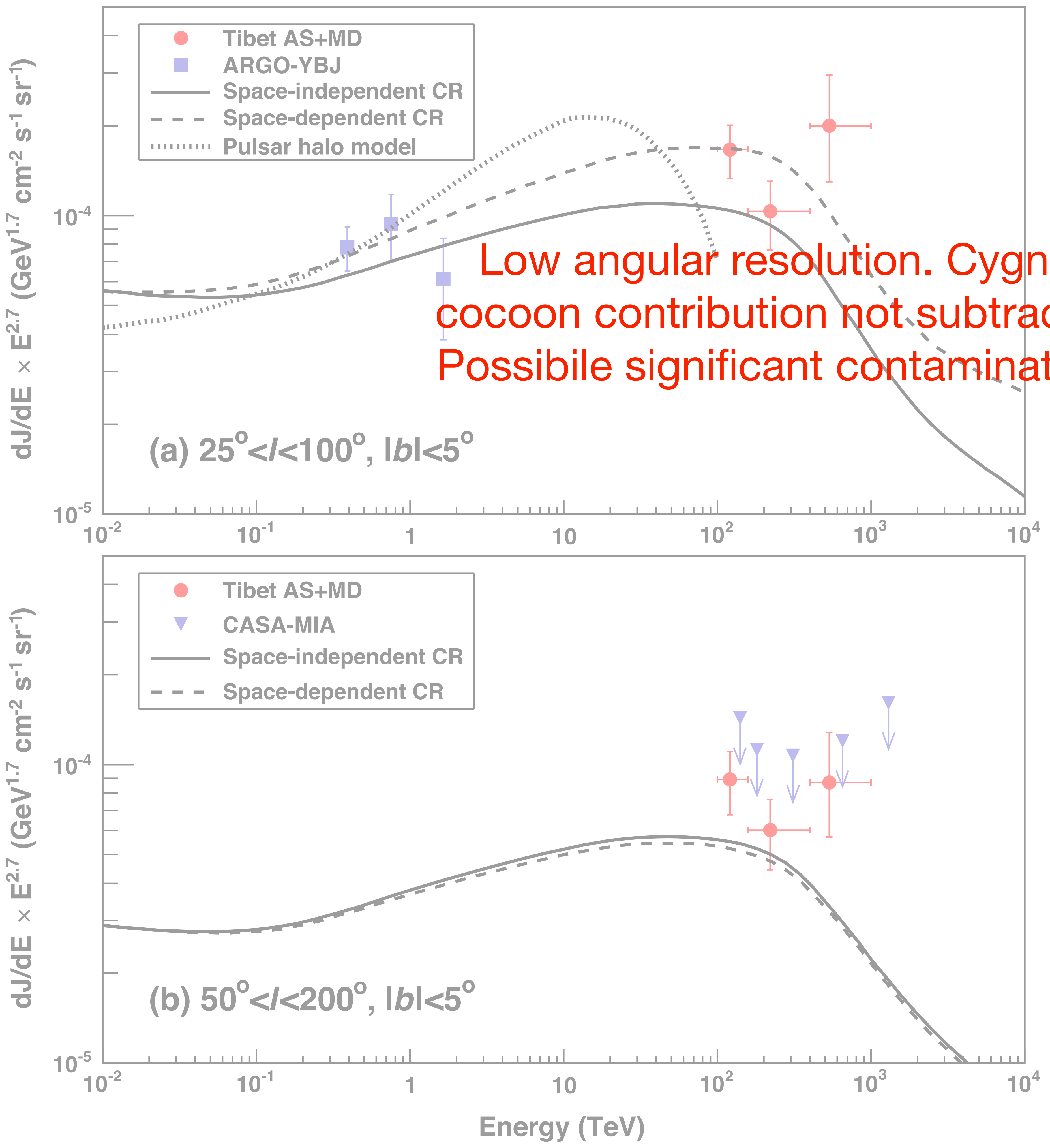
S.P. Zhao et al. - LHAASO coll., PRL 2023



Known sources masked

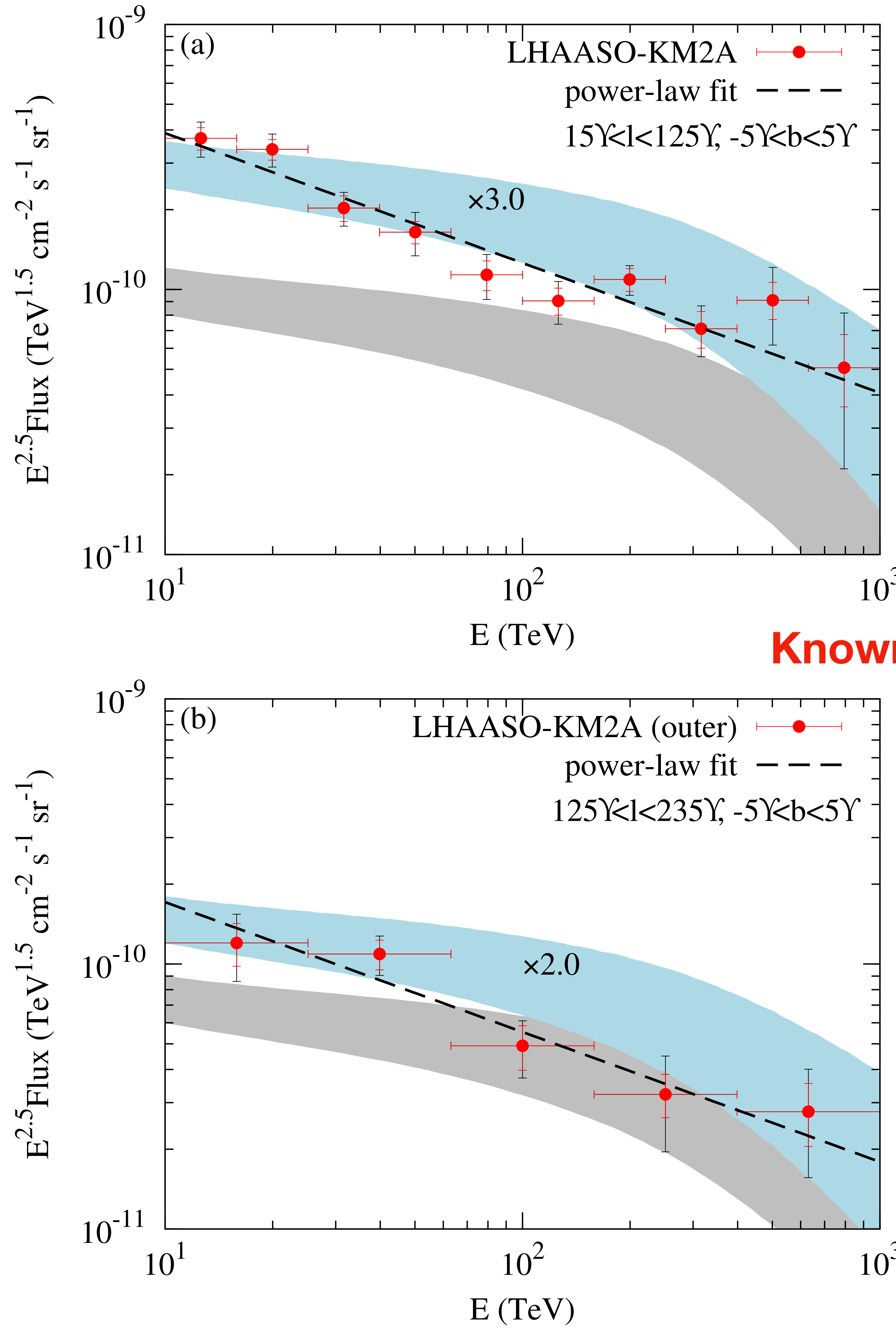
A NEW ACTOR ON THE STAGE : PEV GAMMA-RAY ASTRONOMY

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

ICECUBE BEST FIT MODELS AGAINST VERY HE γ-RAY DATA !

The IC π_0 best-fit model (rescaled x 5 respect to GALPROP) is in good agreement with Tibet ASγ results

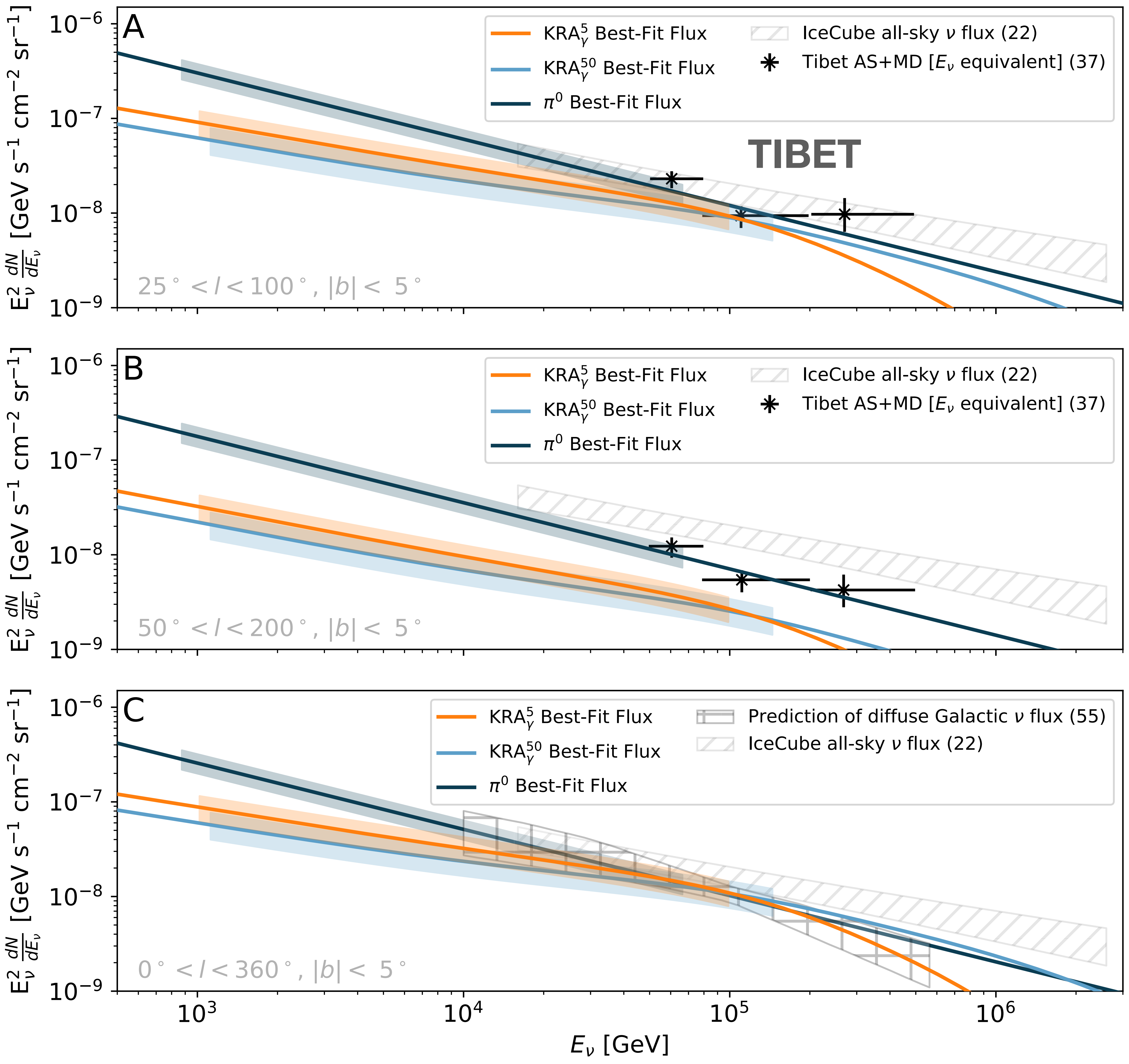
<u>It overpredicts Fermi (and ARGO) though !</u>

A consistent match was recently obtained *Fang, Galleger & Halzen 2306.17275* *w*ith a non-factorized energy-position (**spatial dependent**) CR distribution and adopting a local CR spectrum tracing IceTop data

It looks like we agree about the need of working with spatial dependent models !

A comparison with LHAASO should be performed !

IceCube coll., Science 2023



KRAγ MODEL UPGRADE

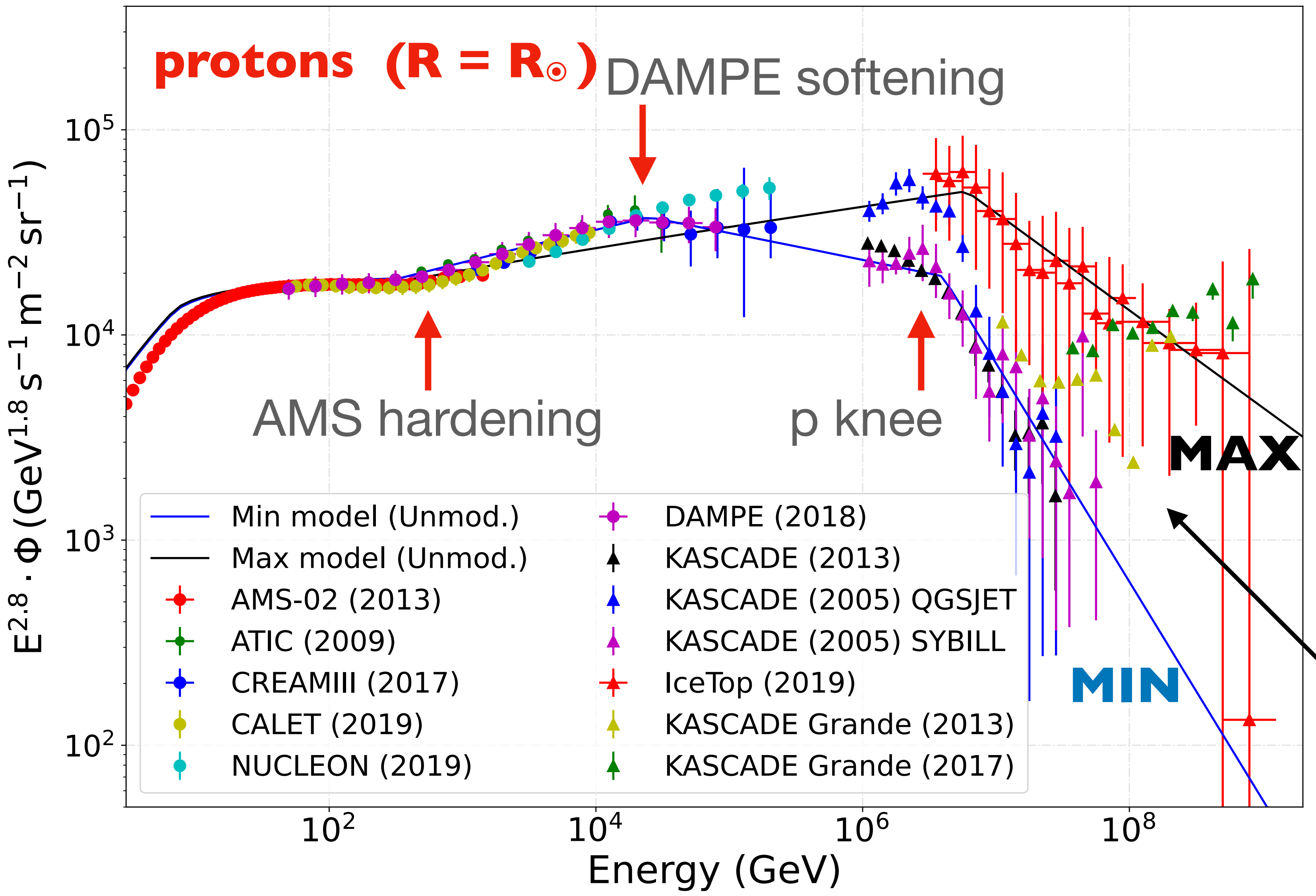
To test our models against those very high energy data we need:

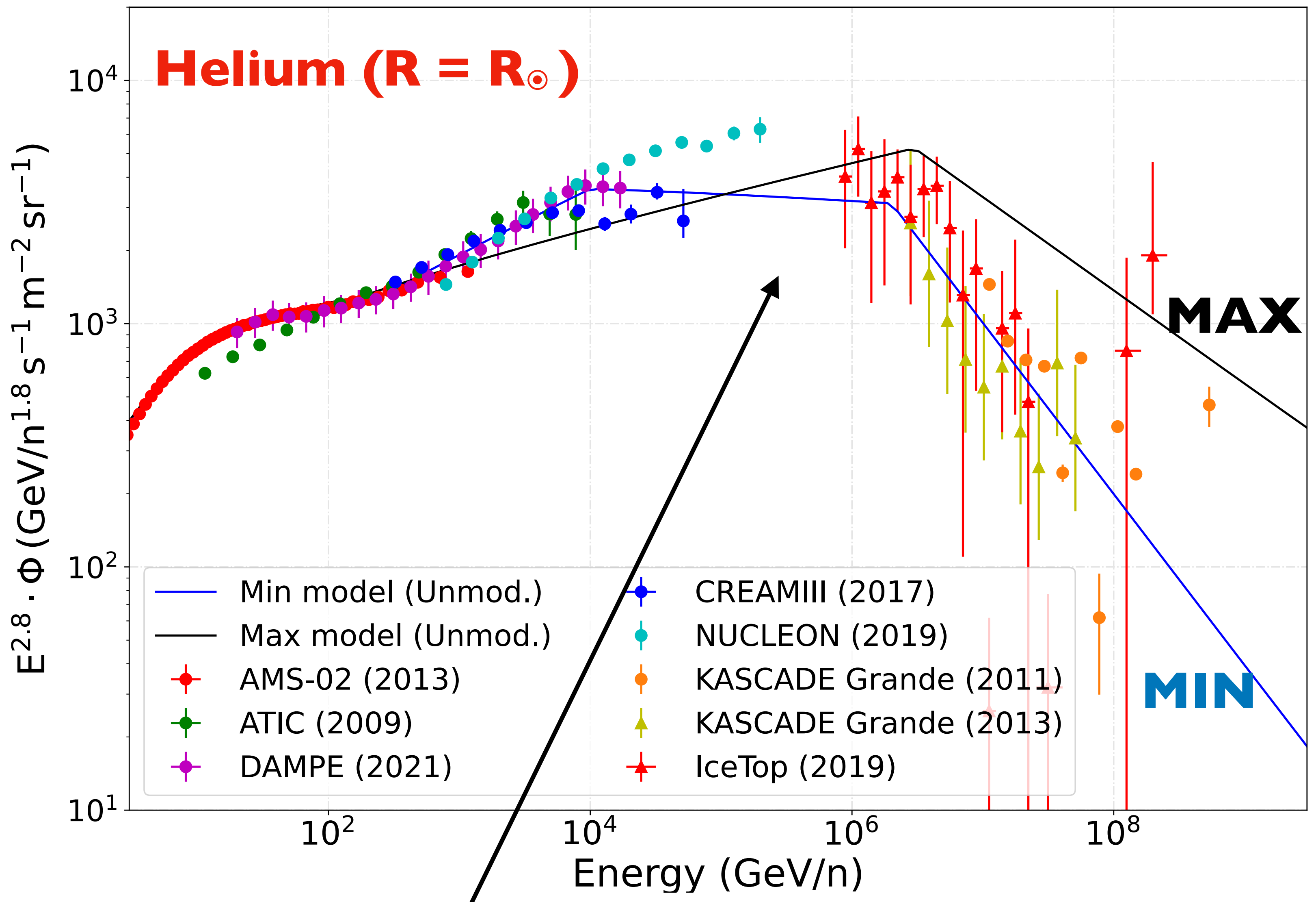
- To account for the uncertainty in the primary CR spectrum, composition above the PeV (*we can then use data to learn about CR at those high energies*)
- To account for the possible contribution of unresolved point-like sources
- To account for gamma-ray attenuation
- To account for uncertainties on the cross-sections

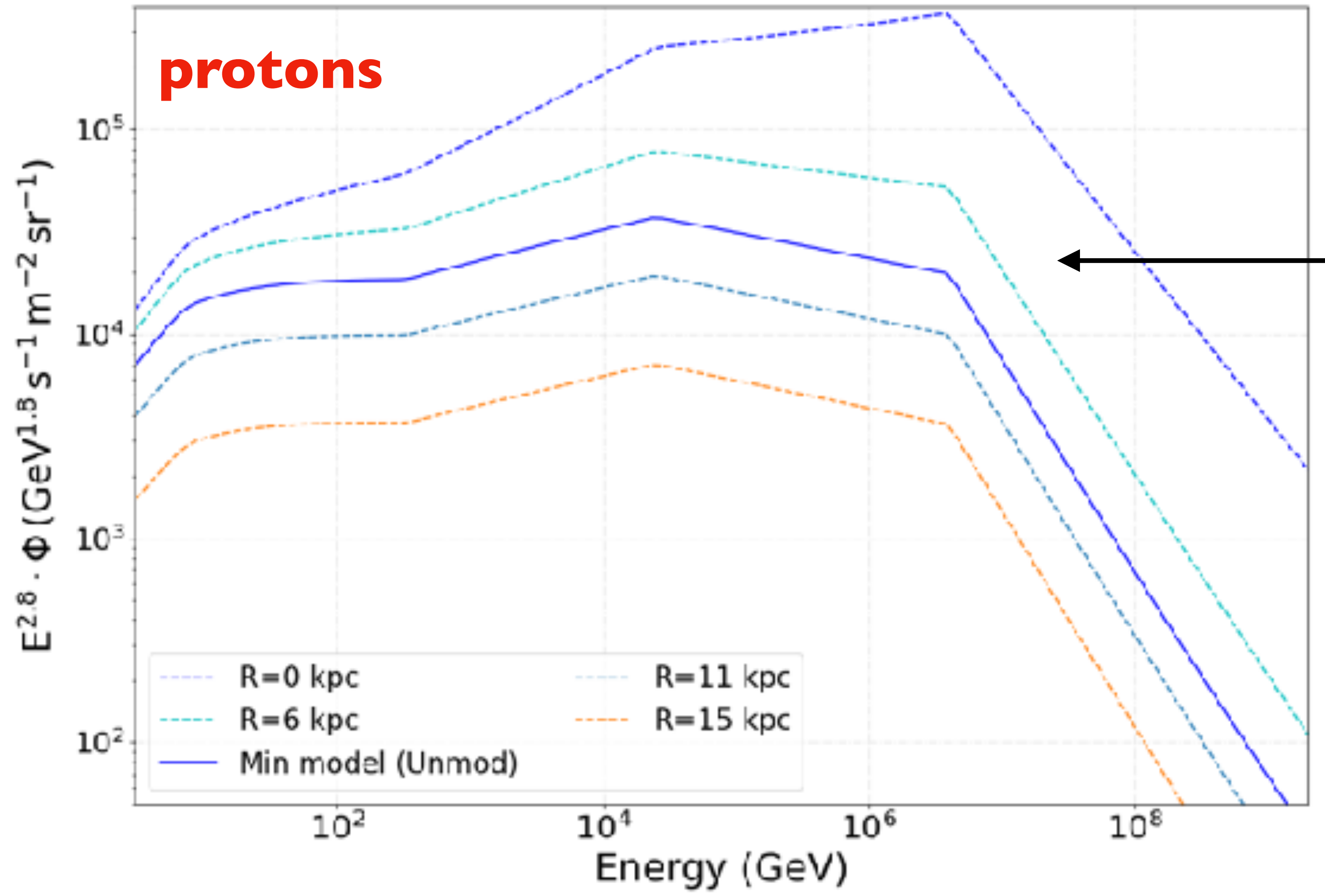
We do that with our HERMES code (*Dundovic et al.,A&A 2021*) fed with the CR space and energy distribution provided by DRAGON for each model.

WHICH PRIMARY CR SPECTRUM/COMPOSITION ABOVE 100 TEV ?

P. De La Torre Luque et al., 2203.15759







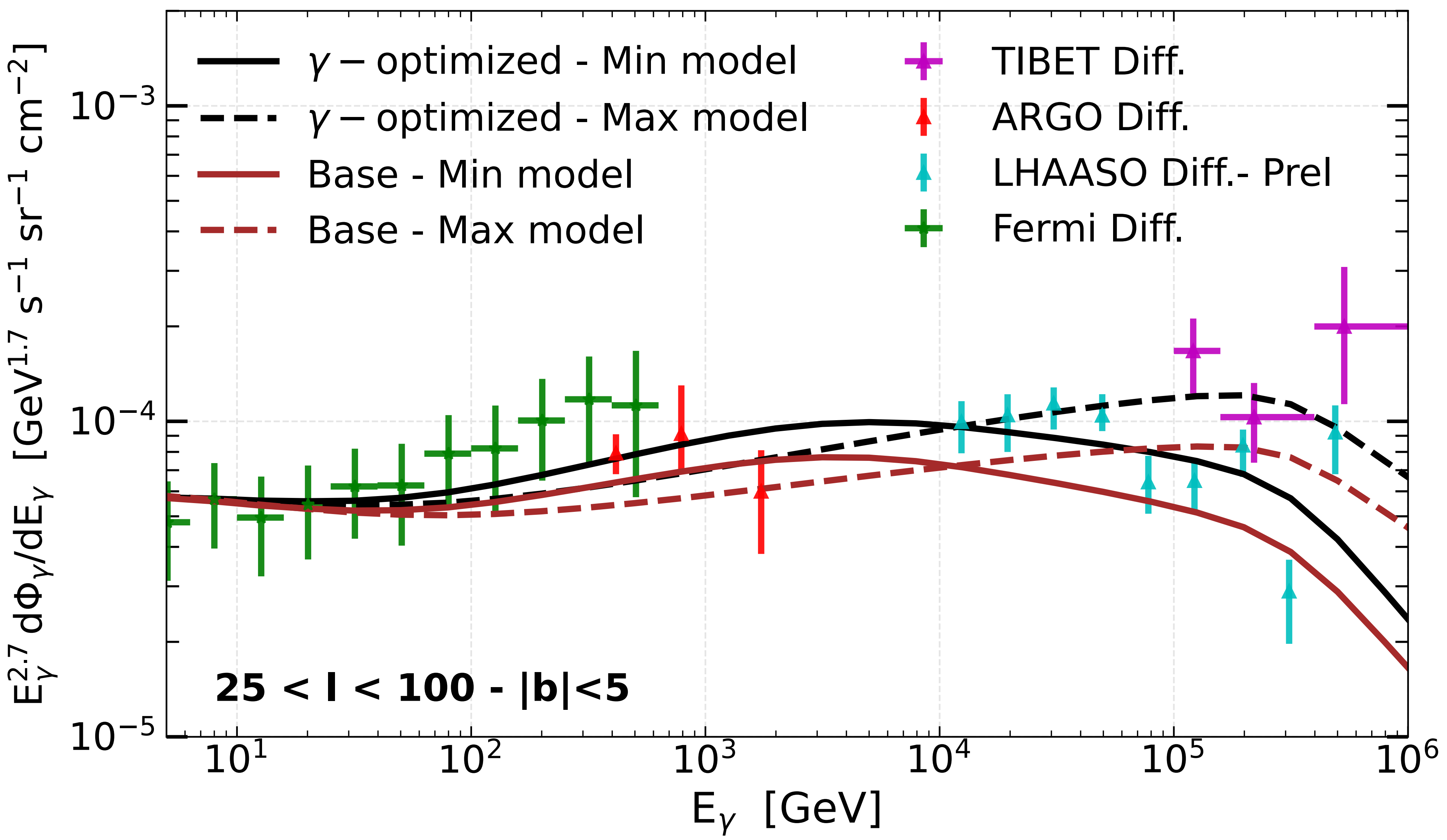
Lines represent local propagated spectra for both scenarios.

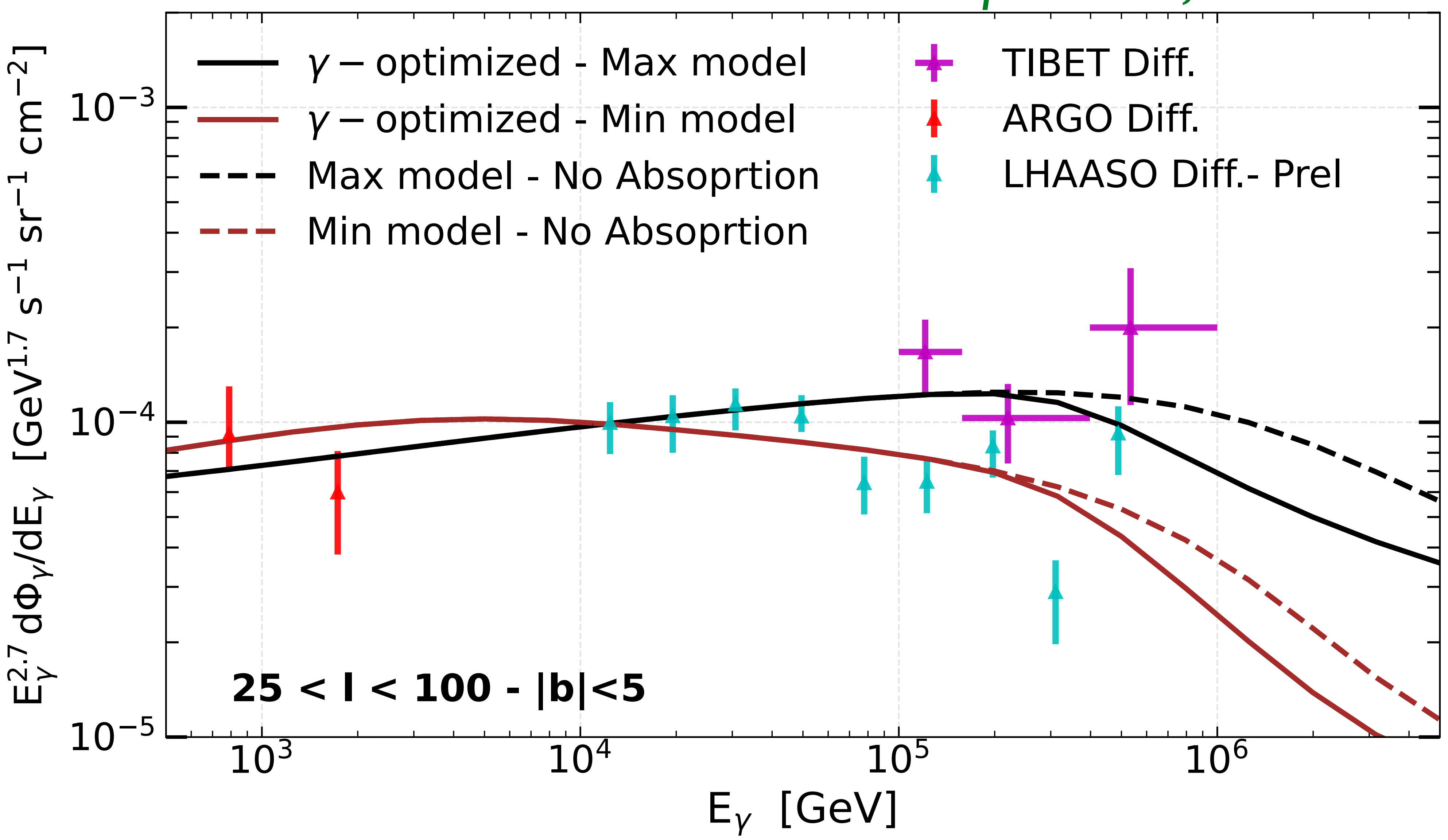
Propagated spectra at several galactocentric radii for the γ-optimized scenario

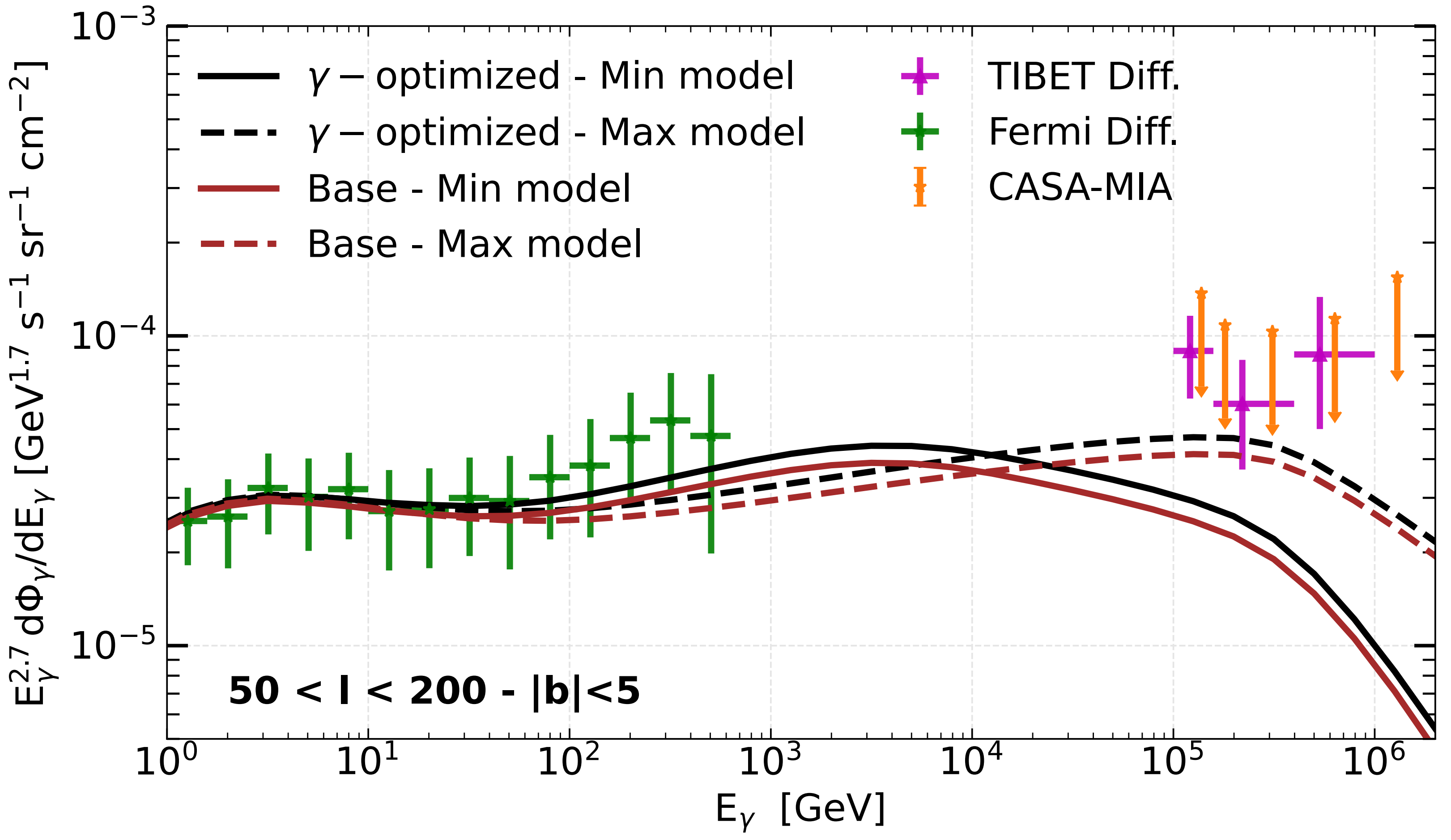
The source spectra is assumed to be the same in the whole Galaxy

UPGRADED MODELS AGAINST TIBET AND LHAASO (PREL.)

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



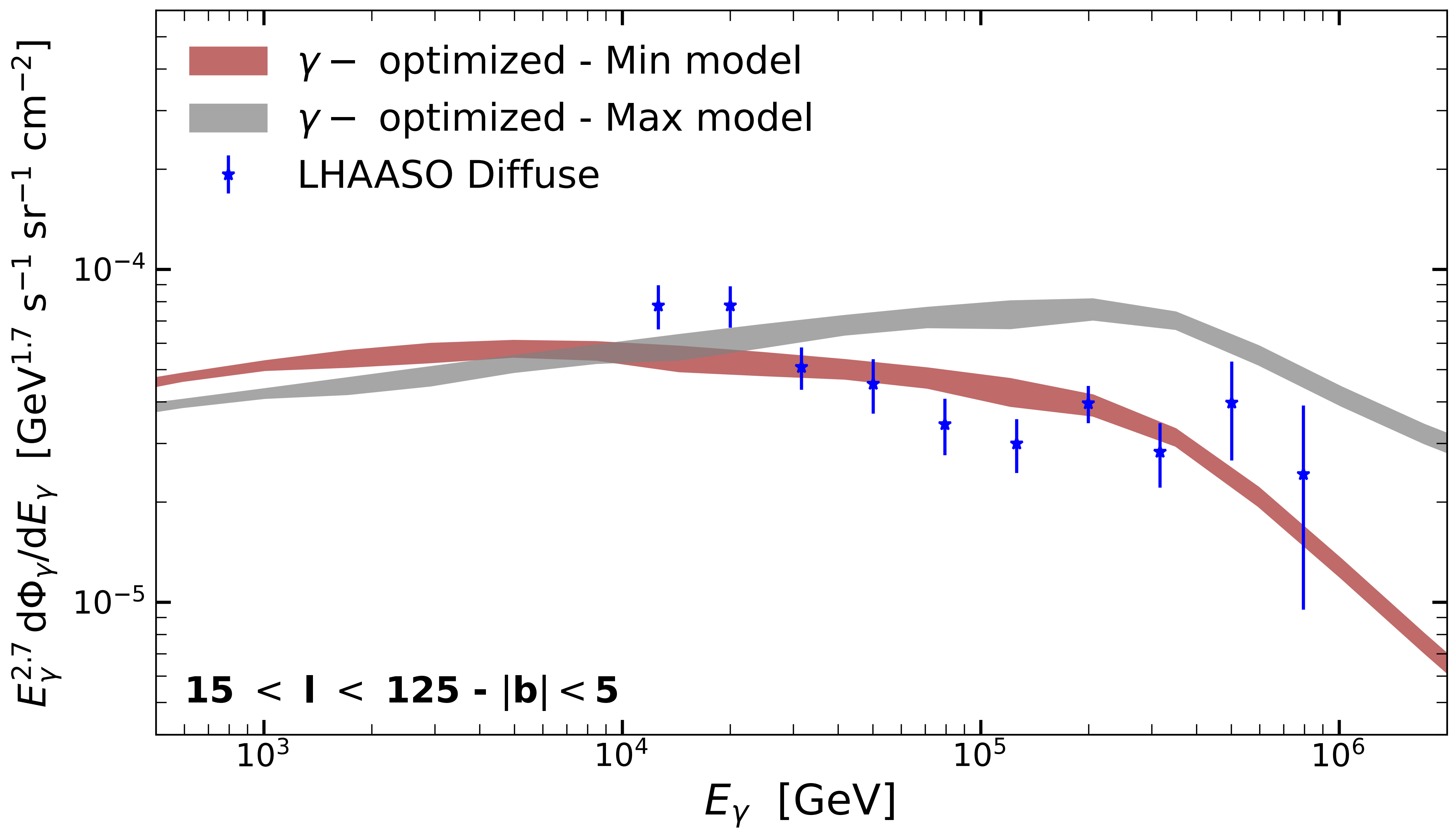


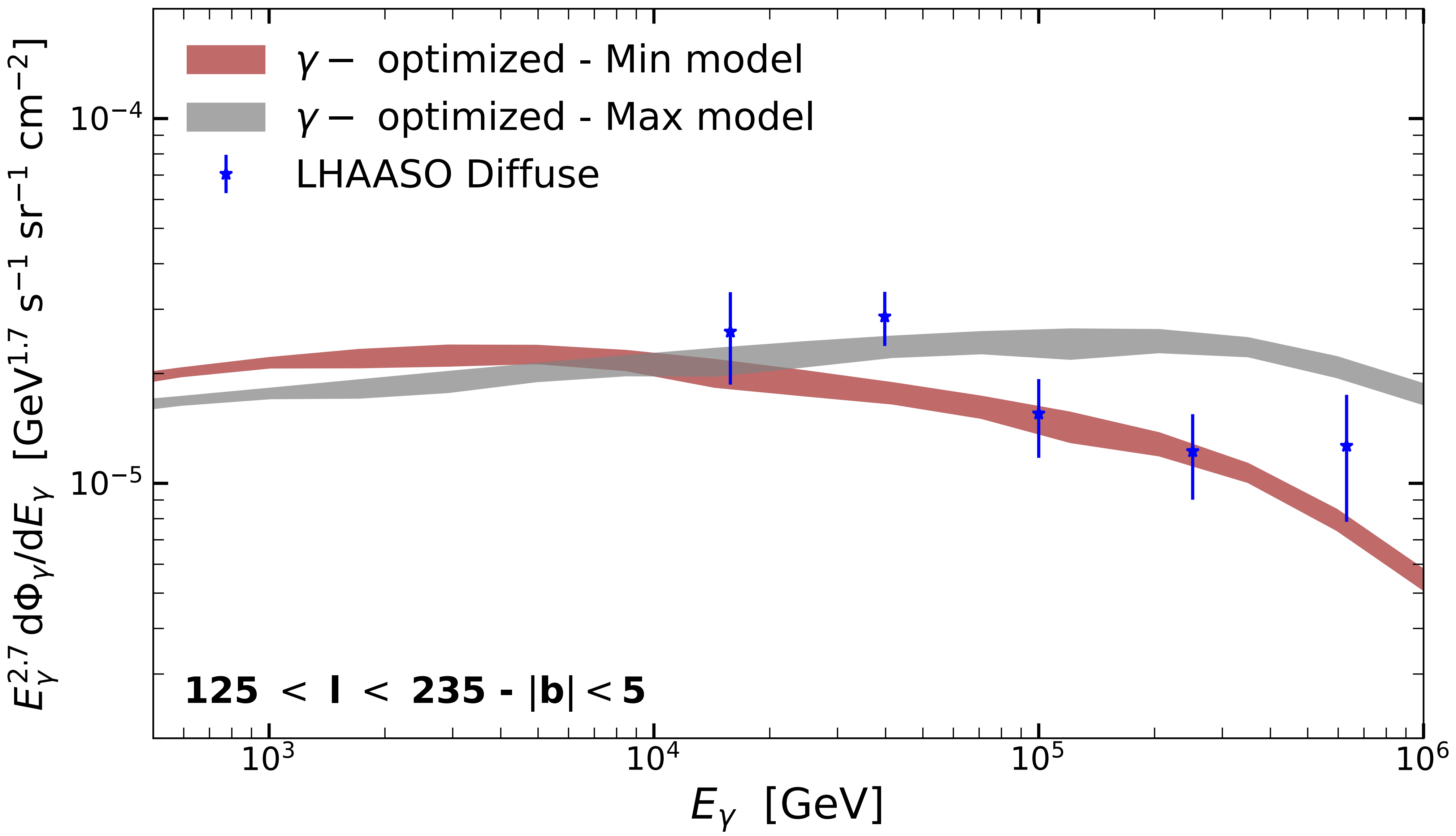


- Strong **degeneracy between the CR transport scenario and the source spectral shape** though LHAASO + ARGO + Fermi seems to favor the **γ**-optimized scenario
- LHAASO favour the MIN source spectrum setup
- **γ**-ray opacity due to **γ-γ**$_{CMB}$ significant only for E > 100 TeV . ISRF almost irrelevant
- At large longitudes the observed spectrum is expected to be almost independent on the transport scenario. Measurements at low galactic longitudes would be resolutive !

OPTIMIZED MODELS AGAINST LHAASO FINAL RESULTS

Della Torre Luque et al. ICRC 2023





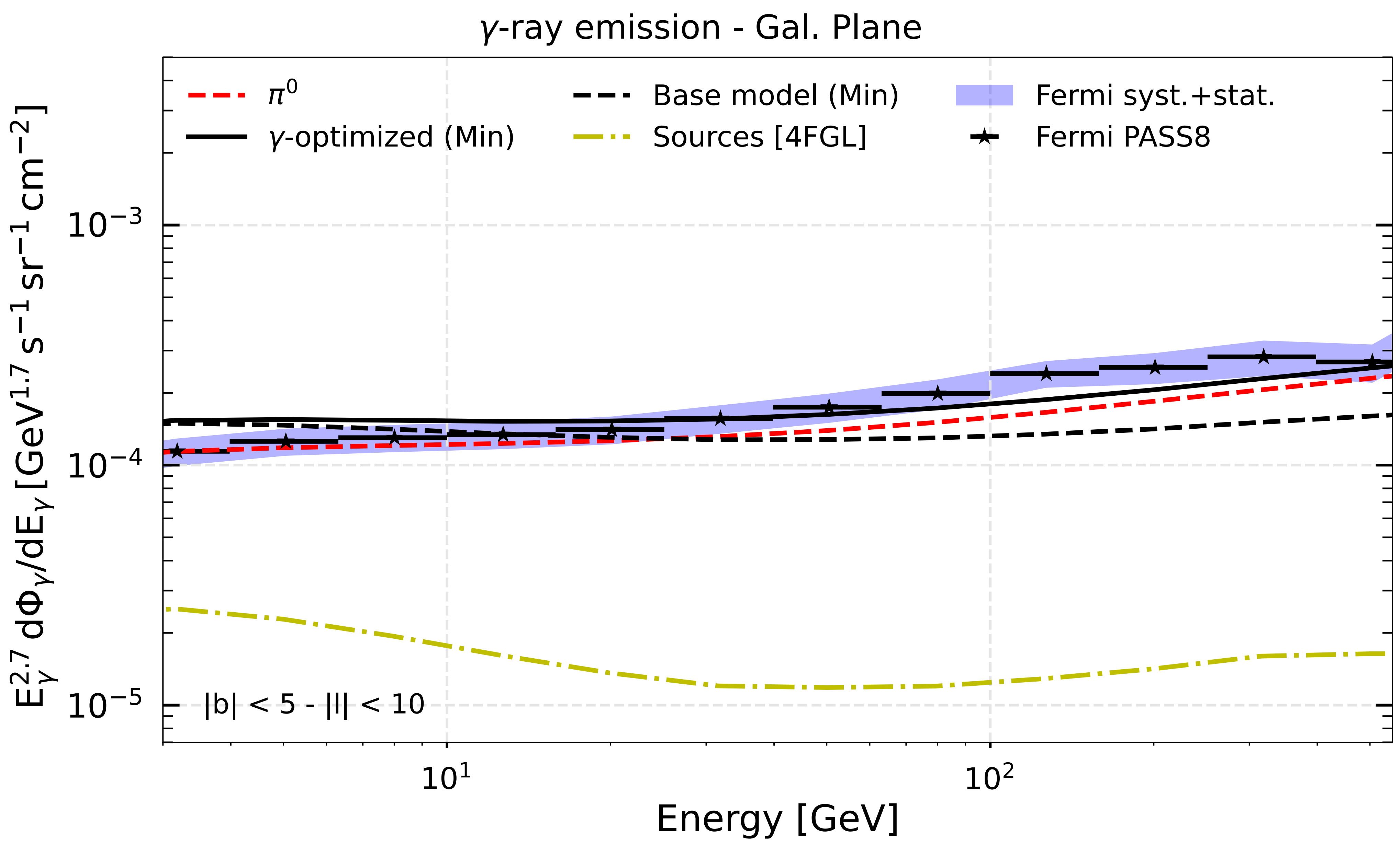
Photon attenuation due to γ-γ (CMB photons most relevant targets) scattering accounted.

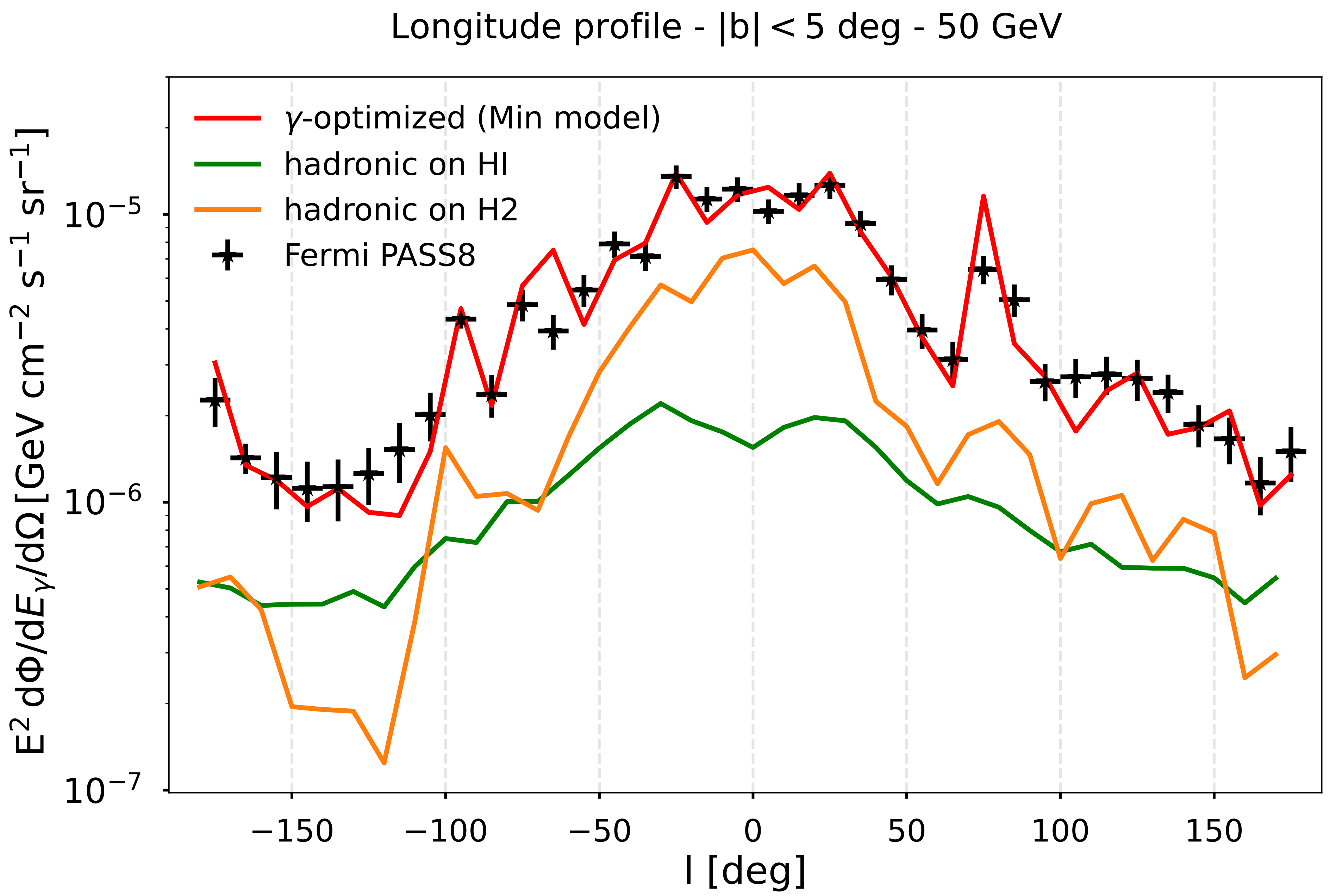
Two γ-ray production parametrization considered (-> bands): Kelner-Ahronian and AAFRAG

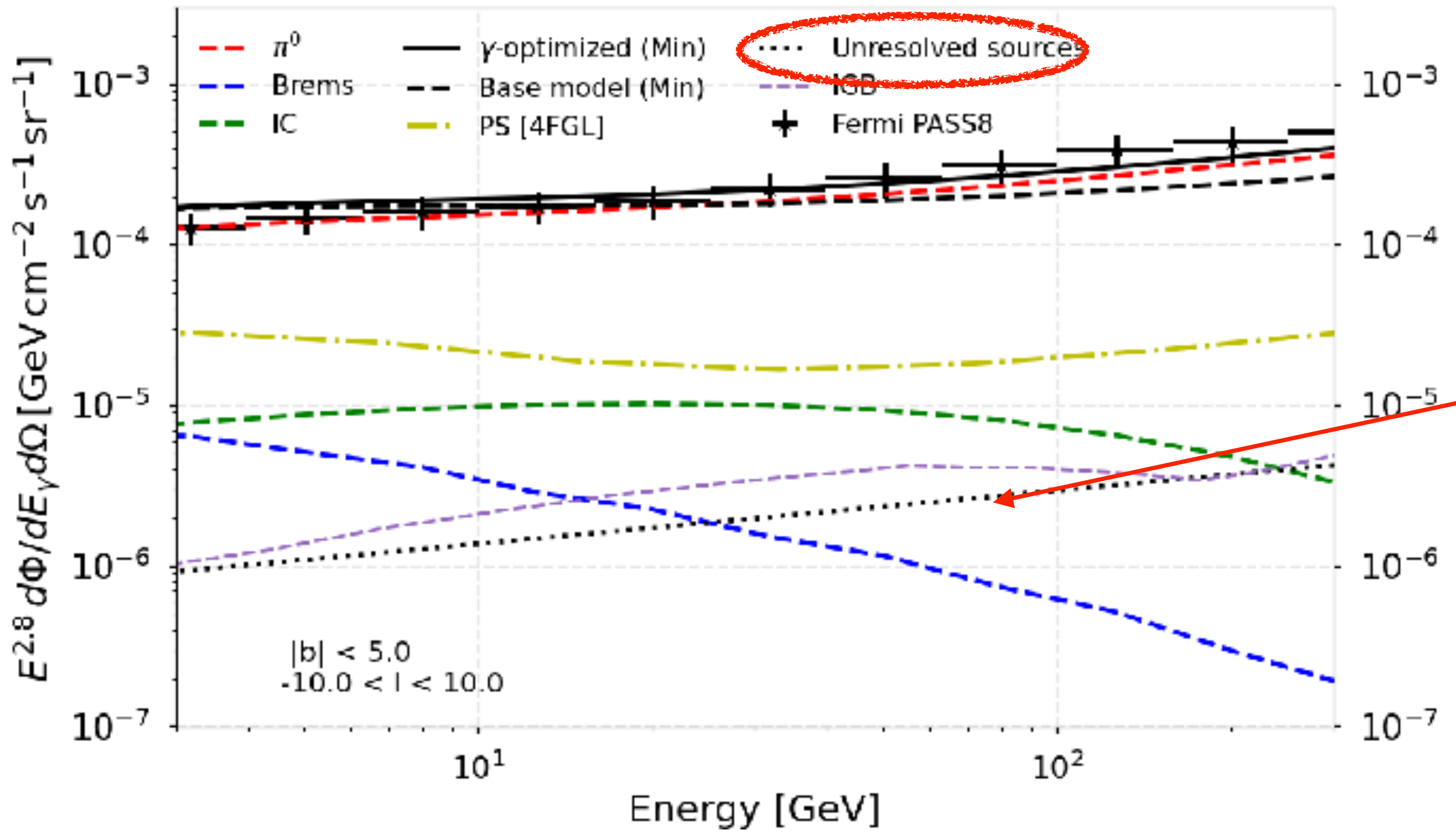
The γ-optimized (at low energy) scenario **successfully predict** LHAASO in both regions

If local CRs trace AMS+DAMPE+KASCADE (MIN setup) !

OPTIMIZED MIN MODEL AGAINST FERMI DATA







The unresolved source model is based on the H.E.S.S. galactic plane survey

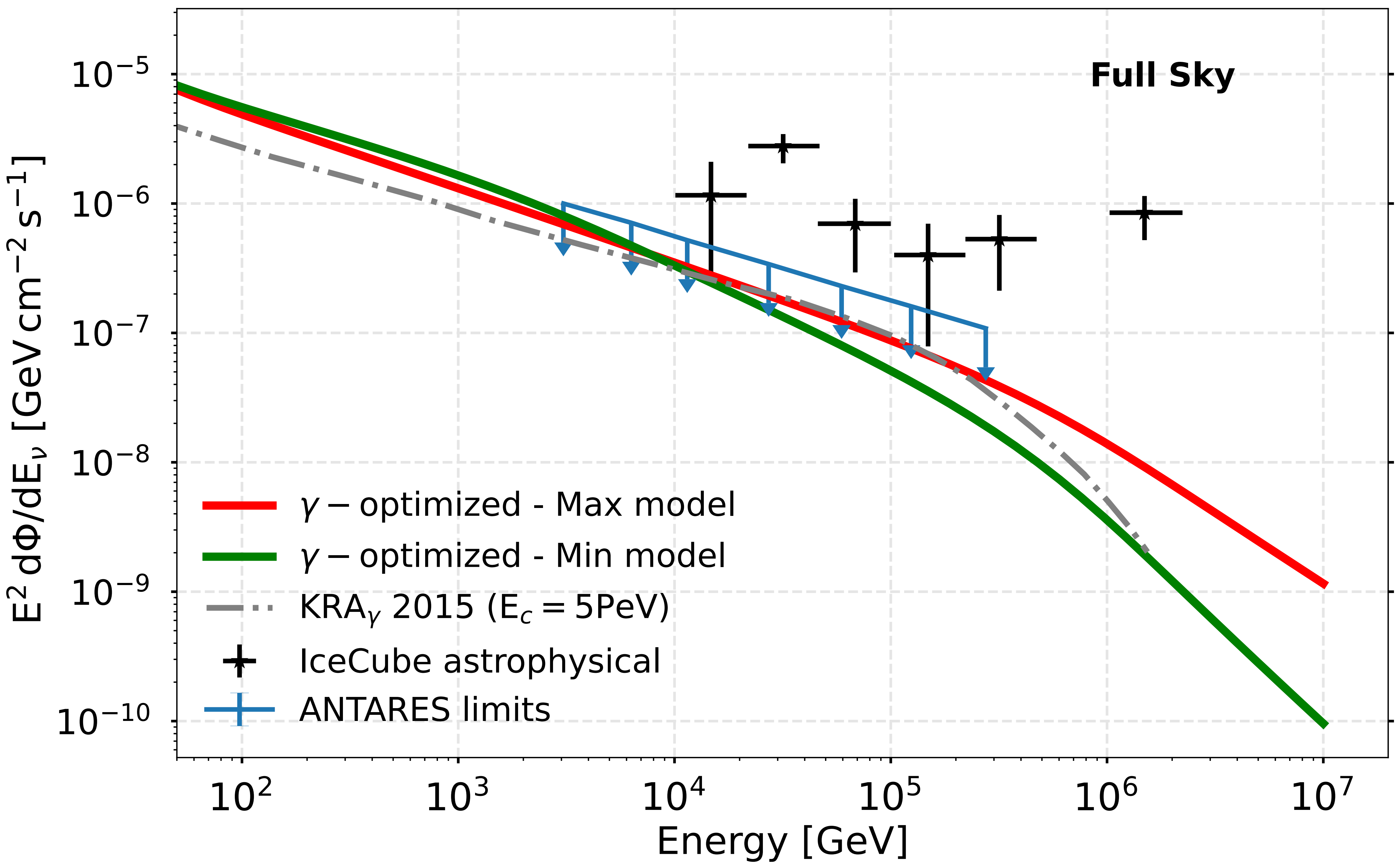
Steppa & Egberts A&A 2022

less than 1% in the Fermi range

NEUTRINOS EMISSION FOR THE UPGRADED MODELS

De La Torre Luque, DG, Gaggero, Marinelli, Frontiers. 2023

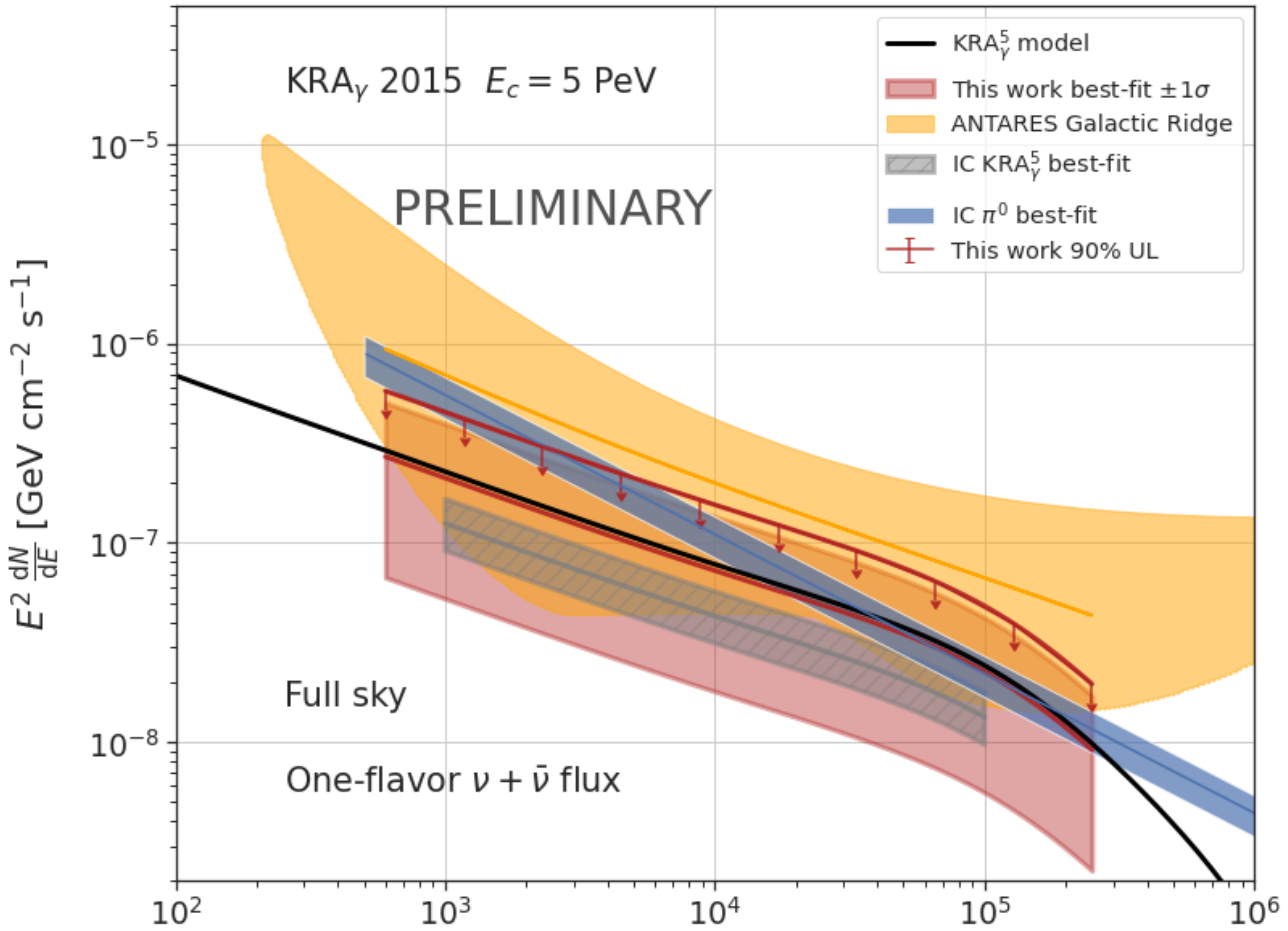
De La Torre Luque et al. ICRC 2023

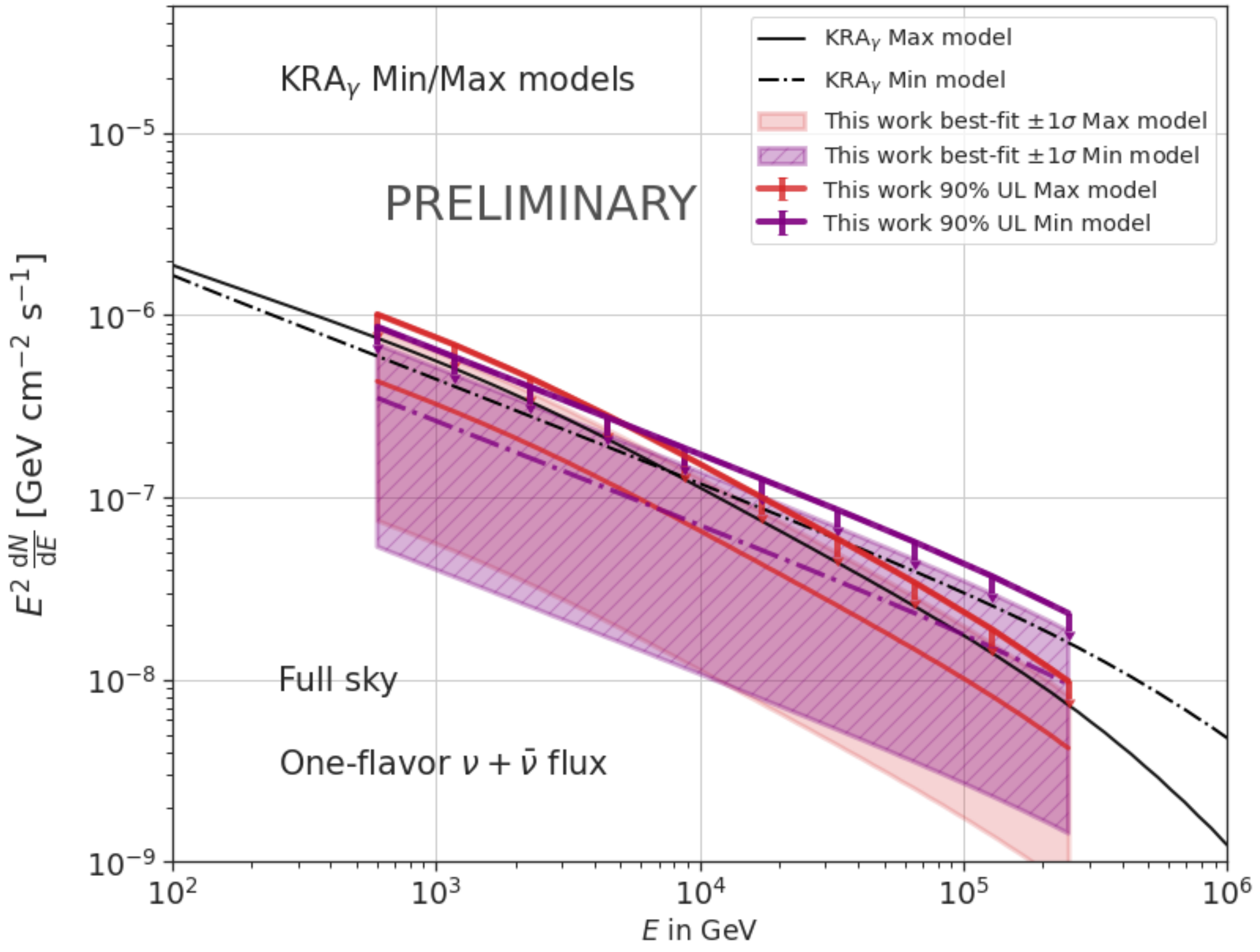


- Their predictions are rather close to that of the KRAγ^5 . A consistent description of IceCube and ~ PeV γ-ray data holds.
- However, the model preferred by LHAASO results predicts a lower ν flux around 100 TeV
- The updated models should be used in forthcoming template fit analysis

ANTARES PRELIMINARY RESULTS AND KM3NET PERSPECTIVES

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

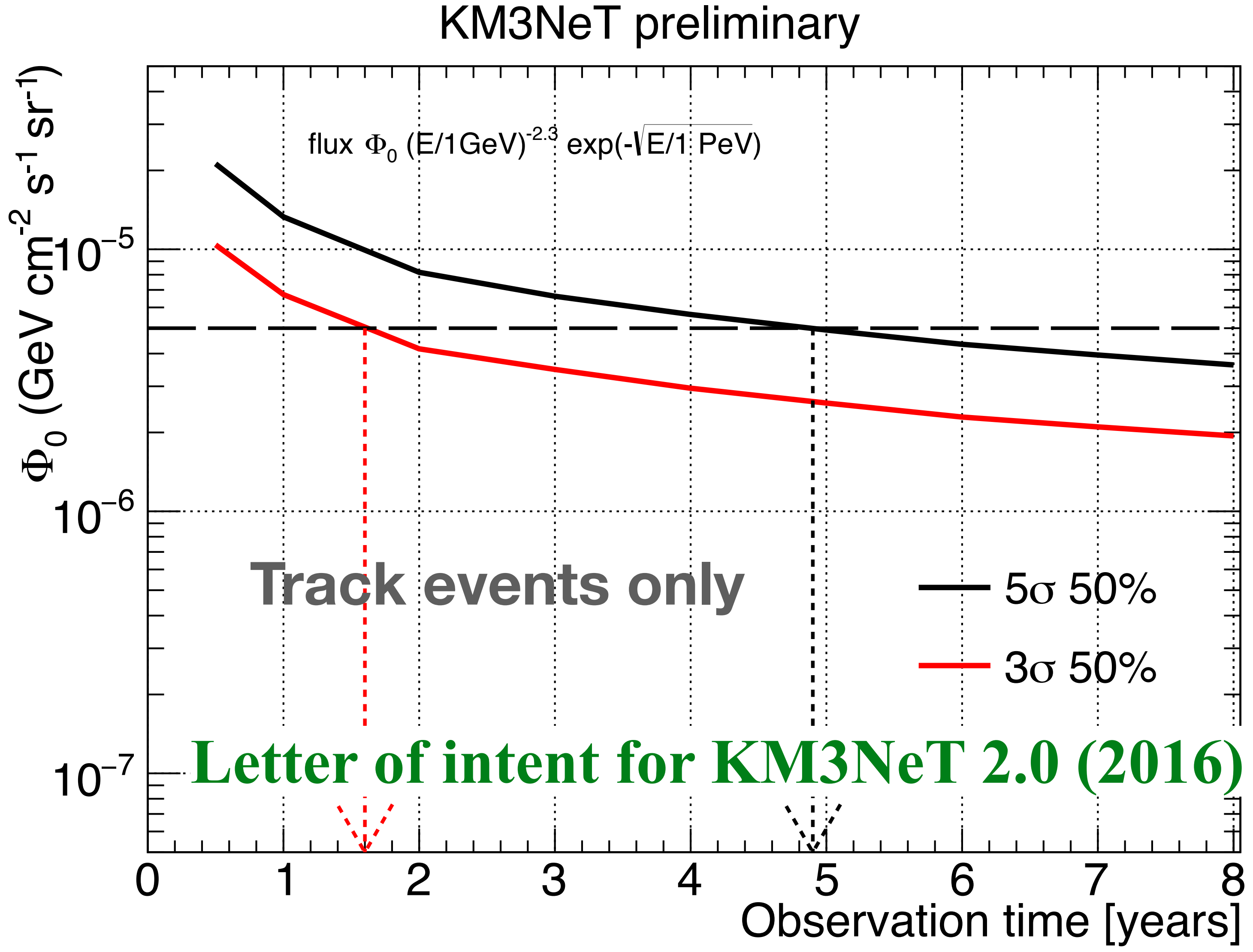


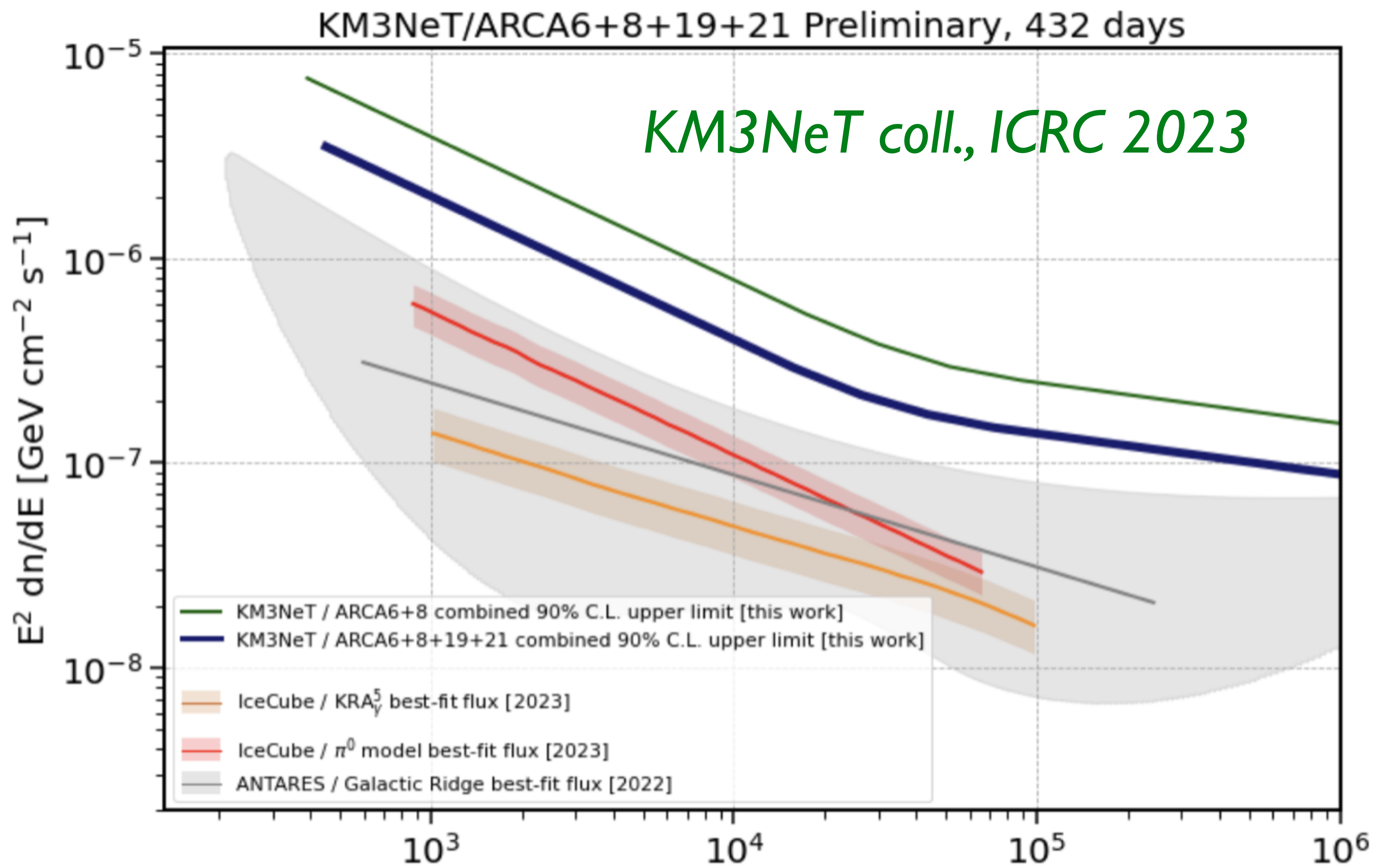


Template fit analysis using showers + tracks

Better angular resolution respect to IceCube , low μ contamination

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





KM3NeT was estimated to confirm this scenario in 5 years at 5σ (using tracks), reasonably less using ANTARES data and showers.

(Analysis performed for the **KRA$_\gamma$5** model , under progress with the upgraded models)

CONCLUSIONS

- IceCube discovered the neutrino diffuse emission of the Milky-Way. A template fit analysis using pre-existing CR propagation model was needed. The measured flux exceeds that computed on the basis of the locally measured CR spectrum.
- A consistent of IC, CR and γ-ray (from GeV to PeV) data is possible invoking unconventional (spatial dependent) CR propagation models.
- A small contribution from unresolved leptonic sources may be required to fill the gap between IC and the KRA model (the IC analysis should be repeated with the improved models).
- LHAASO results favour a CR spectral shape in the PeV region tracing KASCADE data
- Forthcoming result form IC, ANTARES and KM3NeT as well as γ-rays further analysis of HAWC data and SWGO will be crucial to better probe this scenario and study the contribution of point/extended sources.

EXTRA SLIDE WITH DETAILS

Title: Gamma-Ray and Neutrino diffuse emissions of the milky-way: what do they imply ?

Abstract: In this talk we will focus on the γ-ray and neutrino diffuse emissions of the Galaxy which recently has been both observed up to the PeV. One of the main aims of these measurements is to understand the origin and the propagation of Galactic cosmic-rays. In this framework, it is striking that the γ-ray diffusion emissions measured by LHAASO has been found more intense and harder than predicted by conventional cosmic-ray propagation models as it was also found — less prominently — at lower energies.
The possible forthcoming discovery of the neutrino counterpart of such emission would imply its hadronic origin hence disfavouring unresolved leptonic sources, as pulsars and TeV halos, to be responsible of such an excess. We will show that a physically motivated cosmic-ray propagation scenario featuring non-homogeneous transport, which has been developed over the latest years to reproduce γ-ray observations in different regions of the Galaxy, provides a consistent description of γ-ray and neutrino measurements up to the PeV as well as high energy cosmic ray data beyond that energy.

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