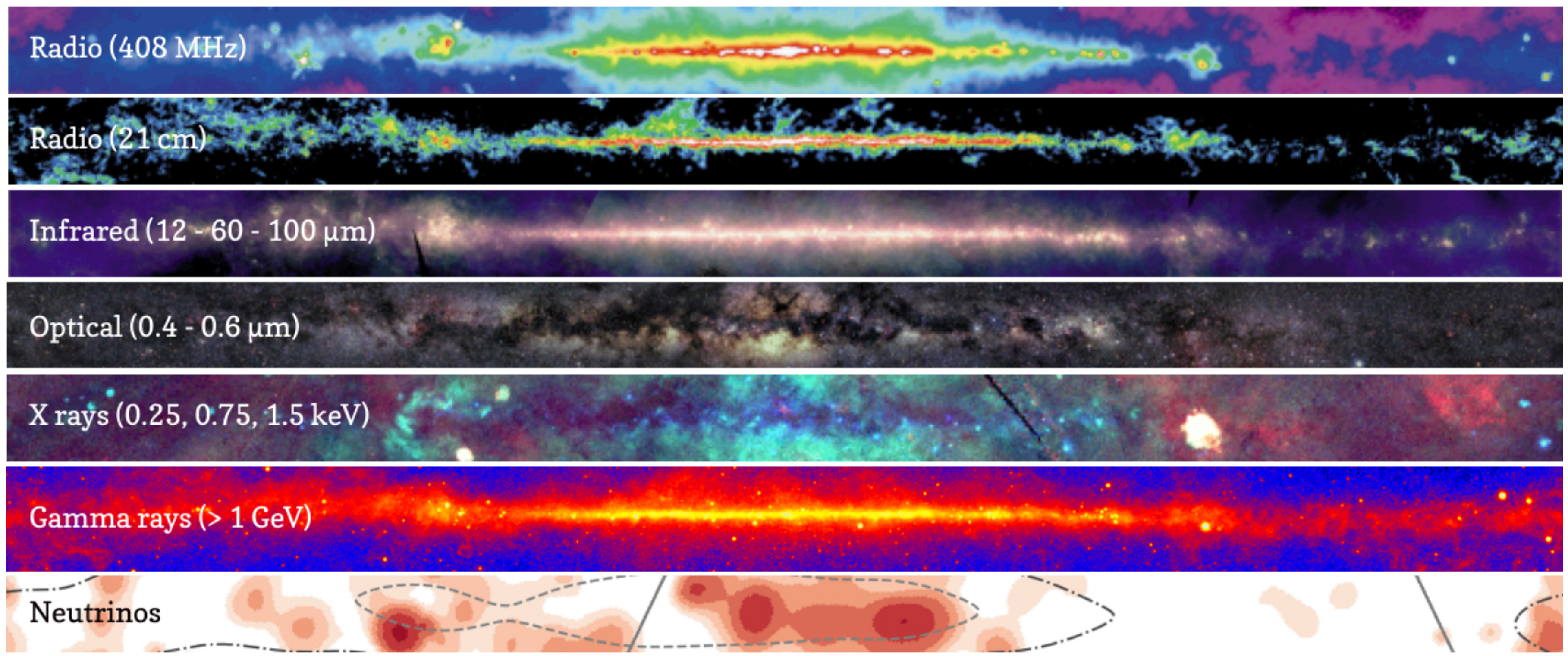
The Galactic diffuse gamma-ray and neutrino emission at the PeV frontier



Heidelberg Intenational Symposium - Milano

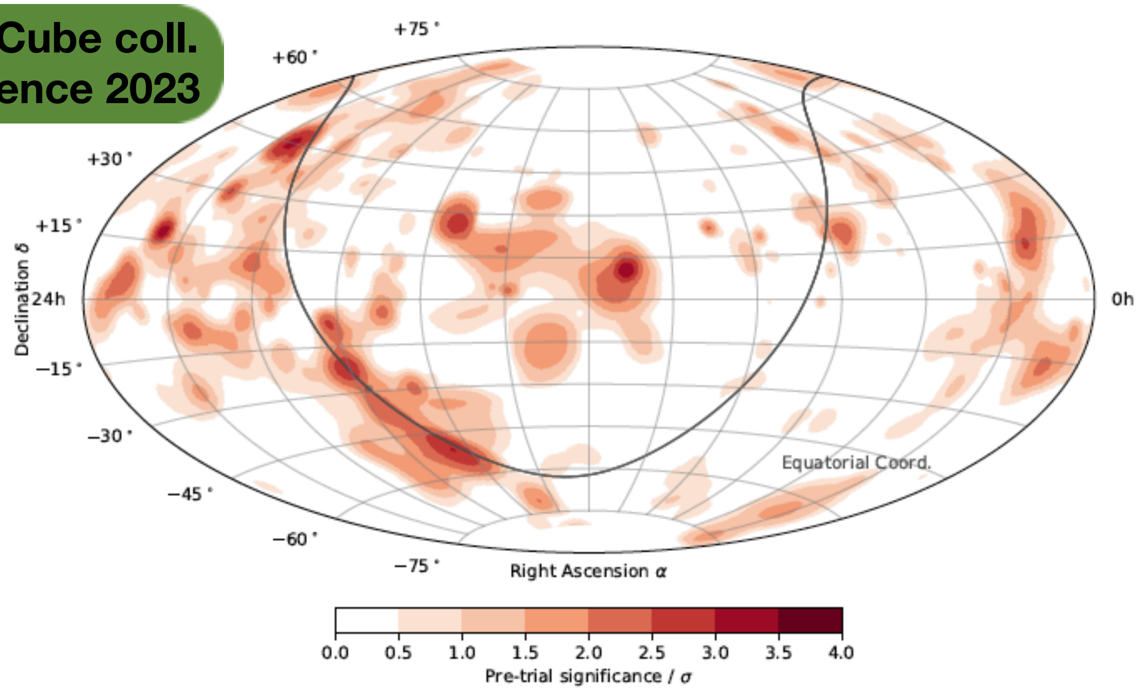
in collaboration with
- Pedro De La Torre Luque
- Dario Grasso
- Antonio Marinelli

Daniele Gaggero

INFN PISA

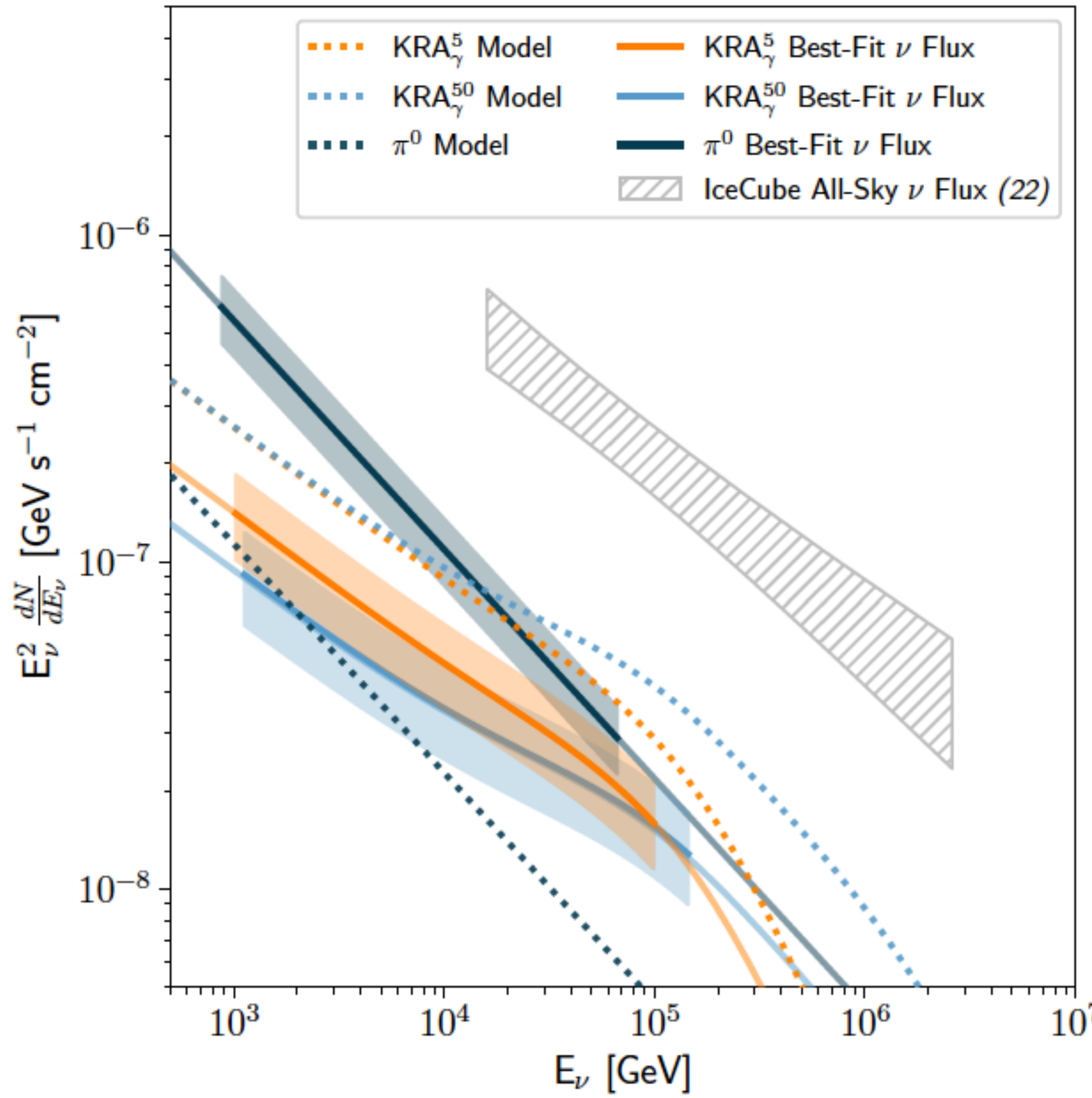
Observation of high-energy neutrinos from the Galactic plane

IceCube coll. Science 2023



IceCube CASCADE best fit pre-trial significance distribution map

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	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF



- 10 years of data
- *Cascade* events were analyzed *(lower background, better energy resolution, and lower energy threshold of cascade events compensate for their inferior angular resolution)*
- Neutrino emission from GP is **detected**. Three models tested.

Is the Milky Way a “Neutrino Desert”?

nature › nature astronomy › articles › article

Article | Open access | Published: 27 November 2023

The Milky Way revealed to be a neutrino desert by the IceCube Galactic plane observation

Ke Fang, John S. Gallagher & Francis Halzen

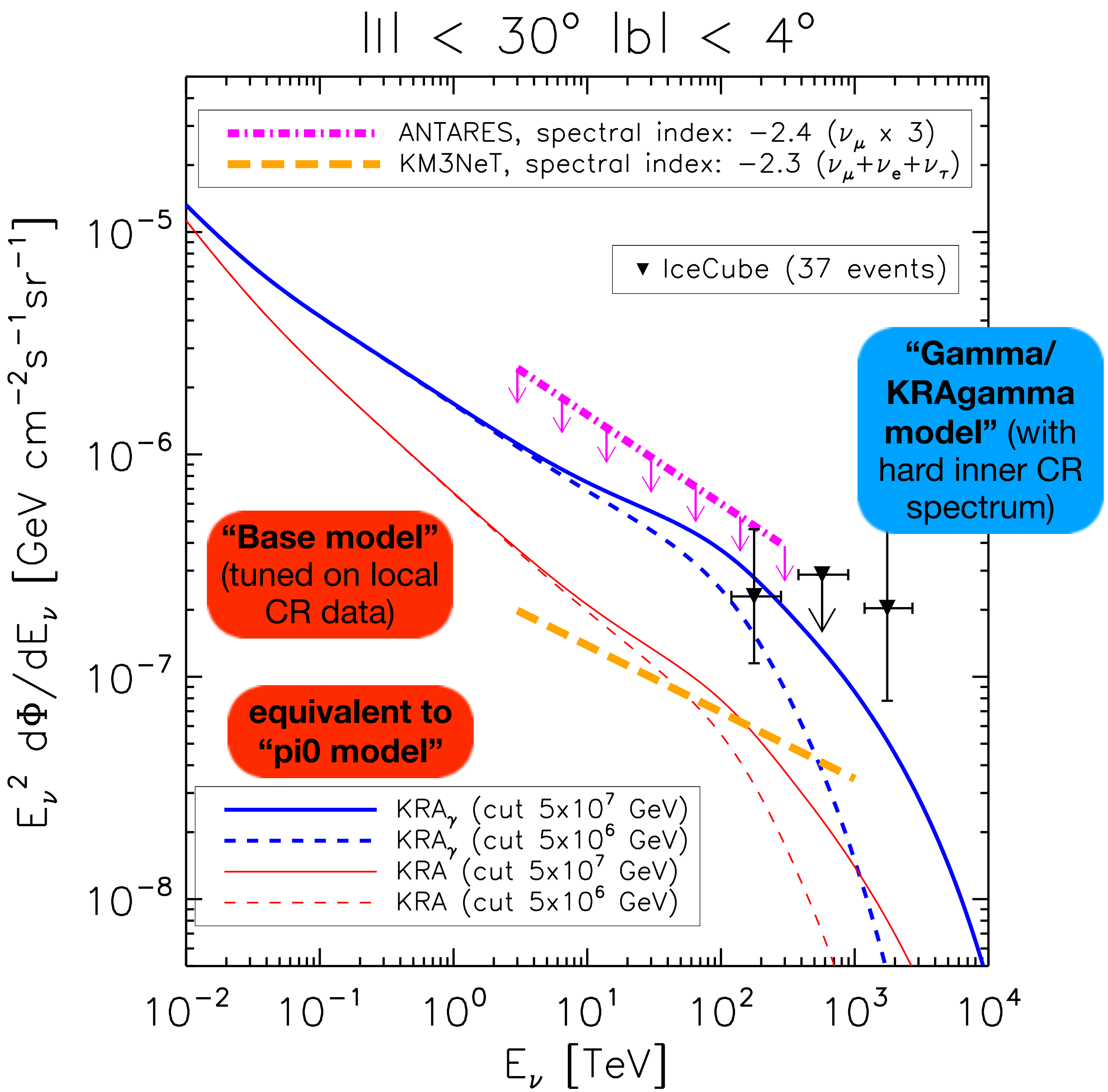
Nature Astronomy **8**, 241–246 (2024) | Cite this article

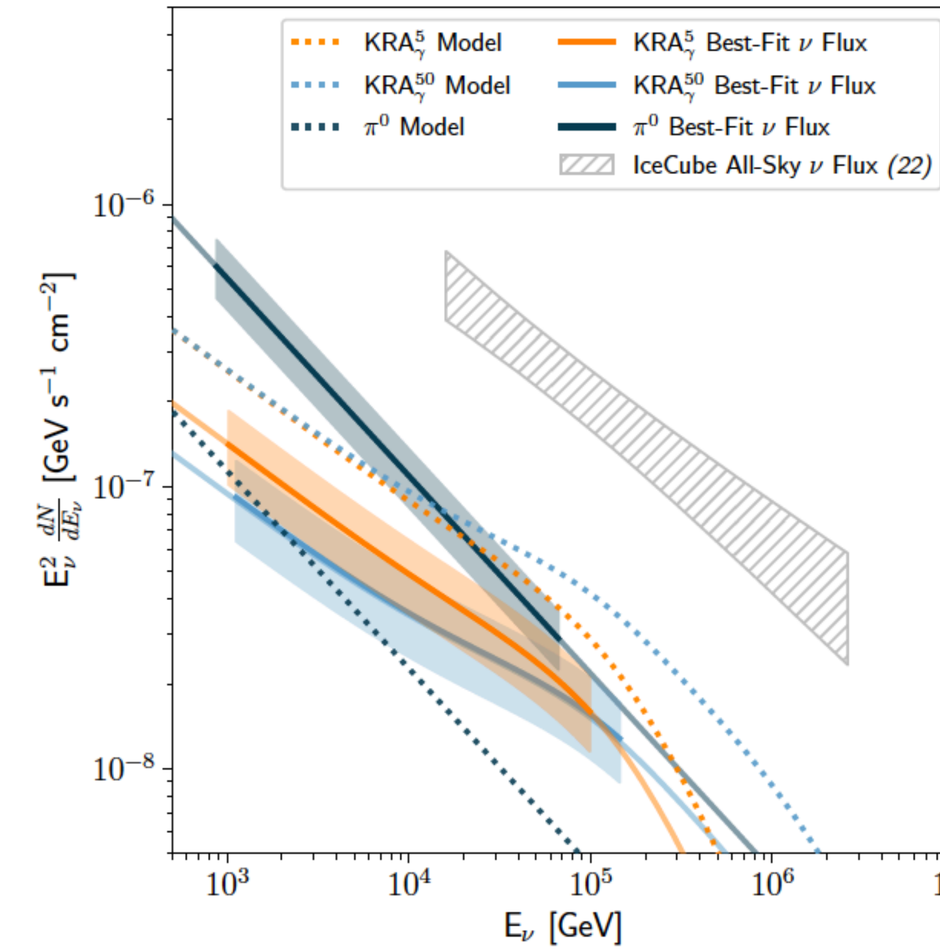
1992 Accesses | **4** Citations | **37** Altmetric | Metrics

*“the neutrino luminosity of the Milky Way is **one-to-two orders of magnitude lower than the average of distant galaxies**. This finding implies that our Galaxy has not hosted the type of neutrino emitters that dominates the isotropic neutrino background at least in the past few tens of kiloyears.”*

… actually, more neutrino emission than formerly expected!

Base (“pi0”/“Conventional”) models VS **Gamma** (“KRAgamma”) models

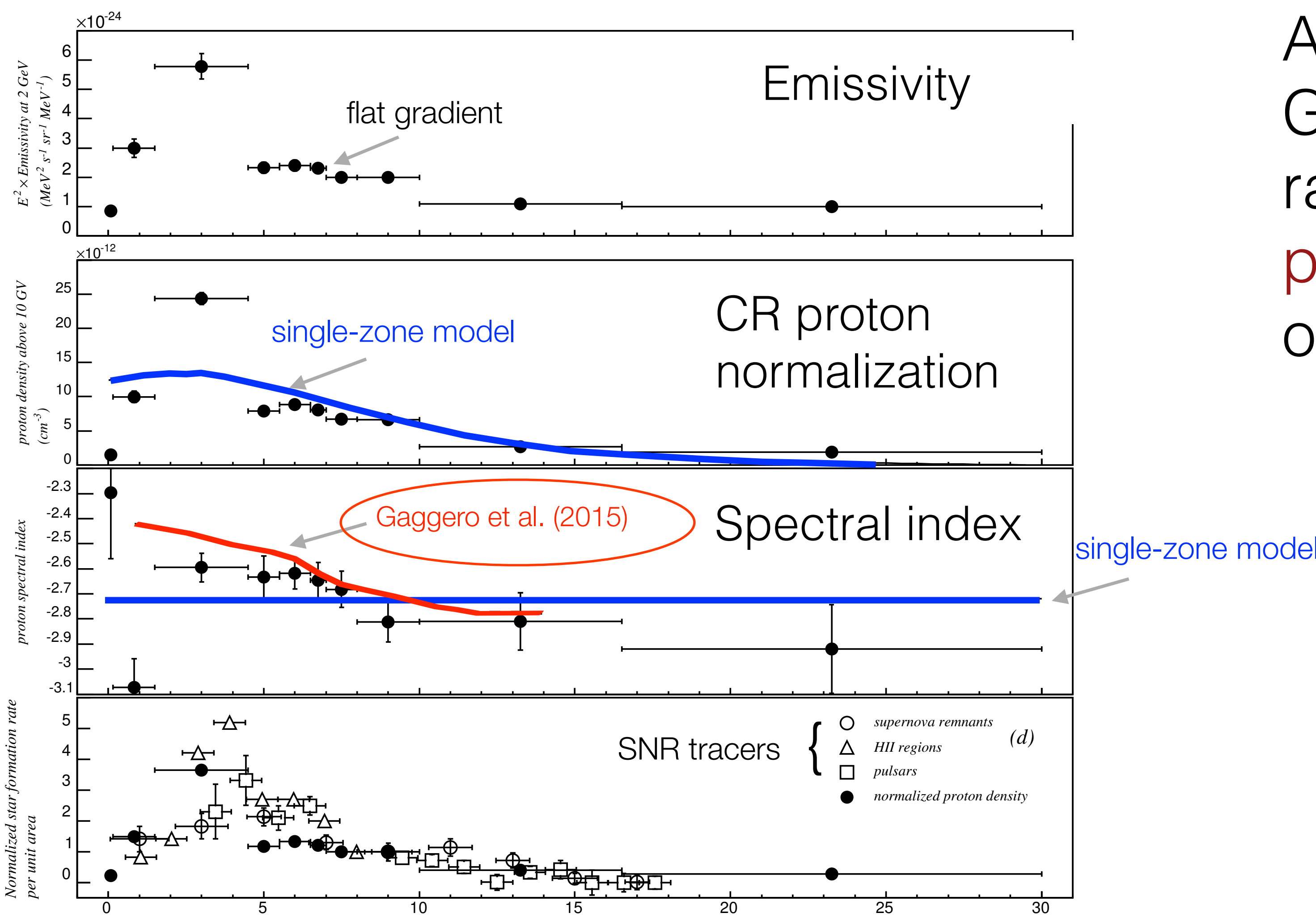




*“our model also provides a different interpretation of the full-sky neutrino spectrum measured by IceCube with respect to the standard lore, since **it predicts a larger contribution of the Galactic neutrinos to the total flux**, compared to conventional models. These predictions will be **testable in the near future** by neutrino observatories such as ANTARES, KM3NeT, and **IceCube itself** via dedicated analyses that are focused on the Galactic plane”*

DG, D. Grasso, A. Marinelli, A. Urbano, M. Valli, ApjL, 2016

so, does the IceCube discovery inform about a harder CR spectrum in the inner Galaxy?



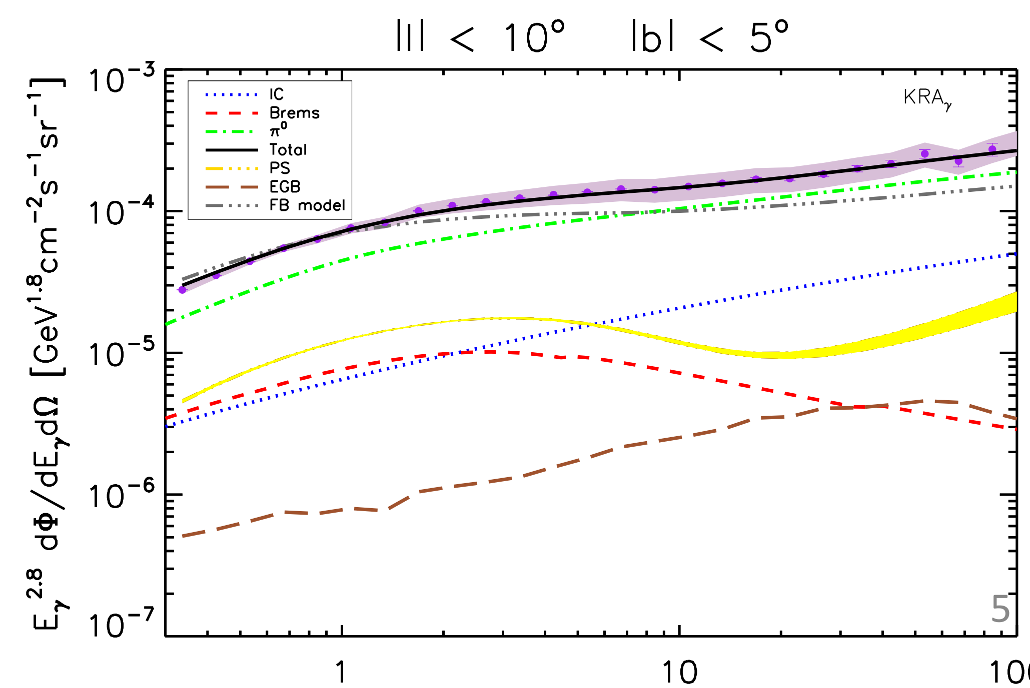
Fermi-LAT collaboration, 2016

Galacto-centric radius [kpc]

A **CR hardening** in the inner Galaxy inferred by gamma-ray data interpreted as a progressively harder scaling of the diffusion coefficient

$$D(\rho) = D_0 \beta^\eta \left(\frac{\rho}{\rho_0}\right)^{\delta(r)}$$

$$\delta(r) = ar + b$$



DG, A. Urbano, M. Valli, P. Ullio, PRD 2015

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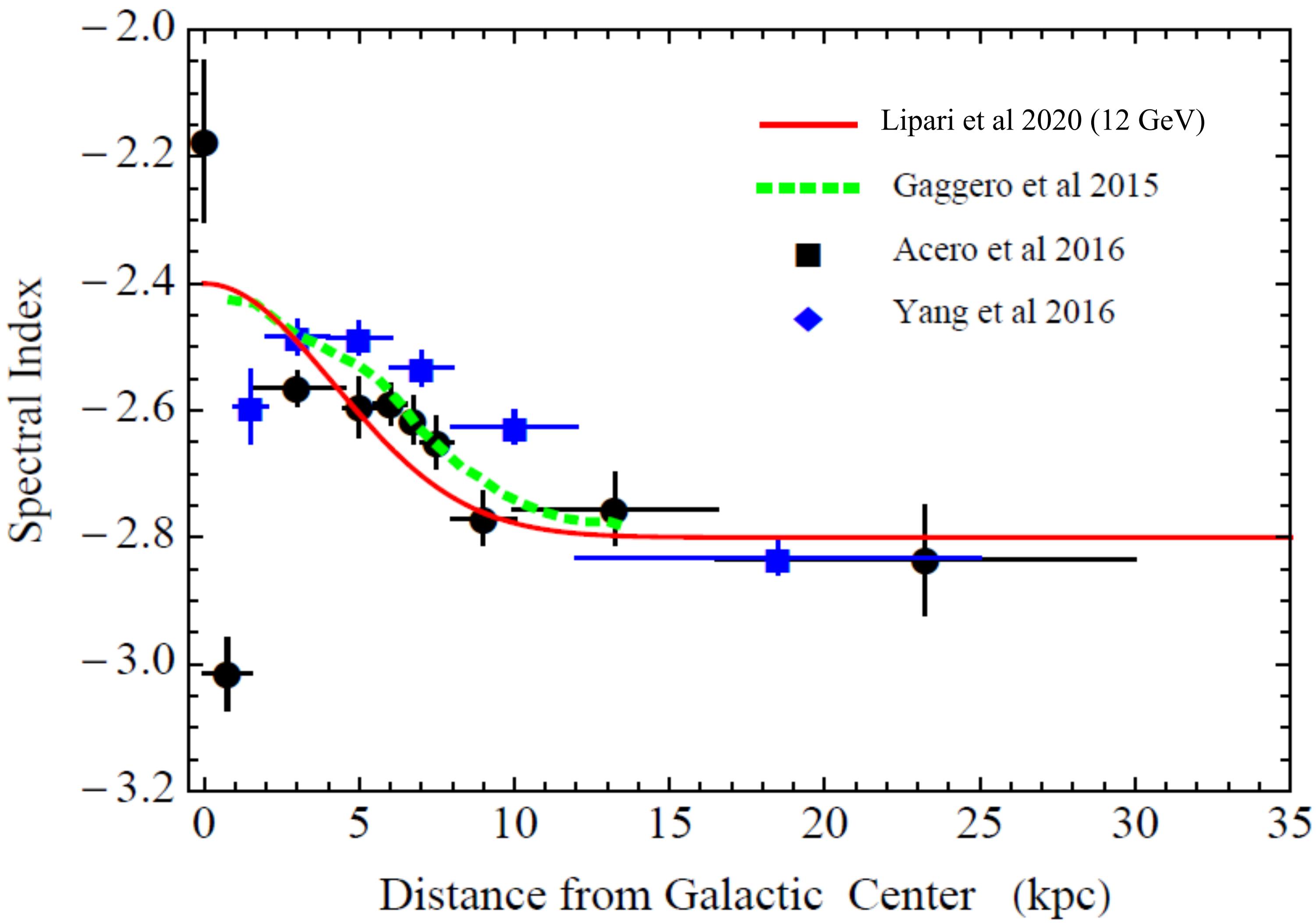

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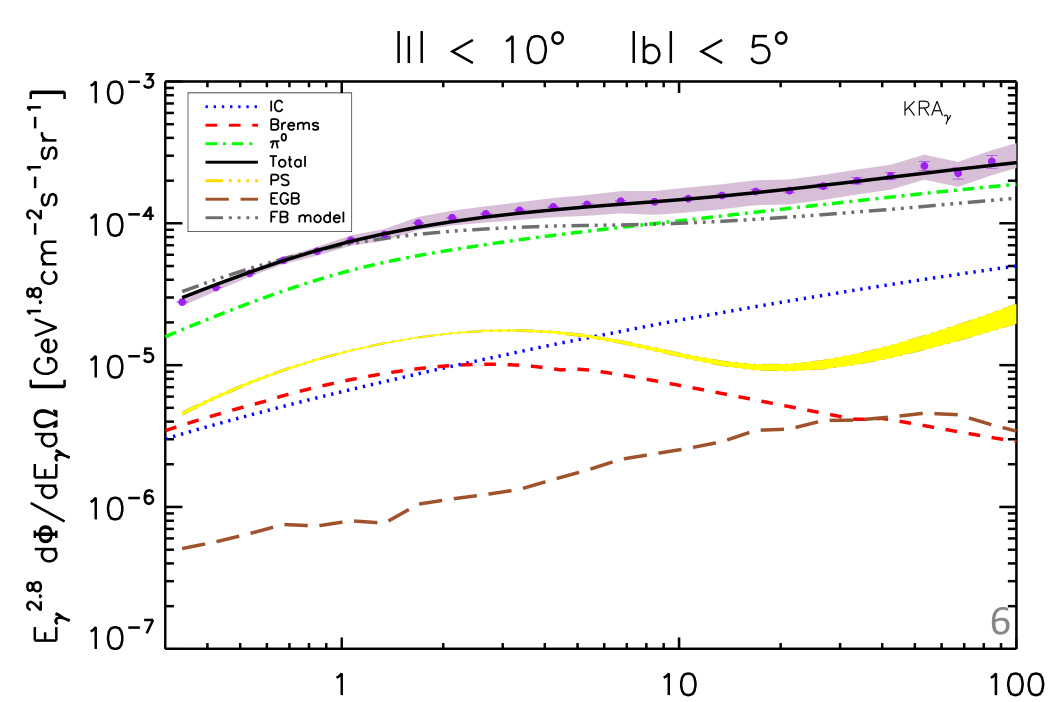
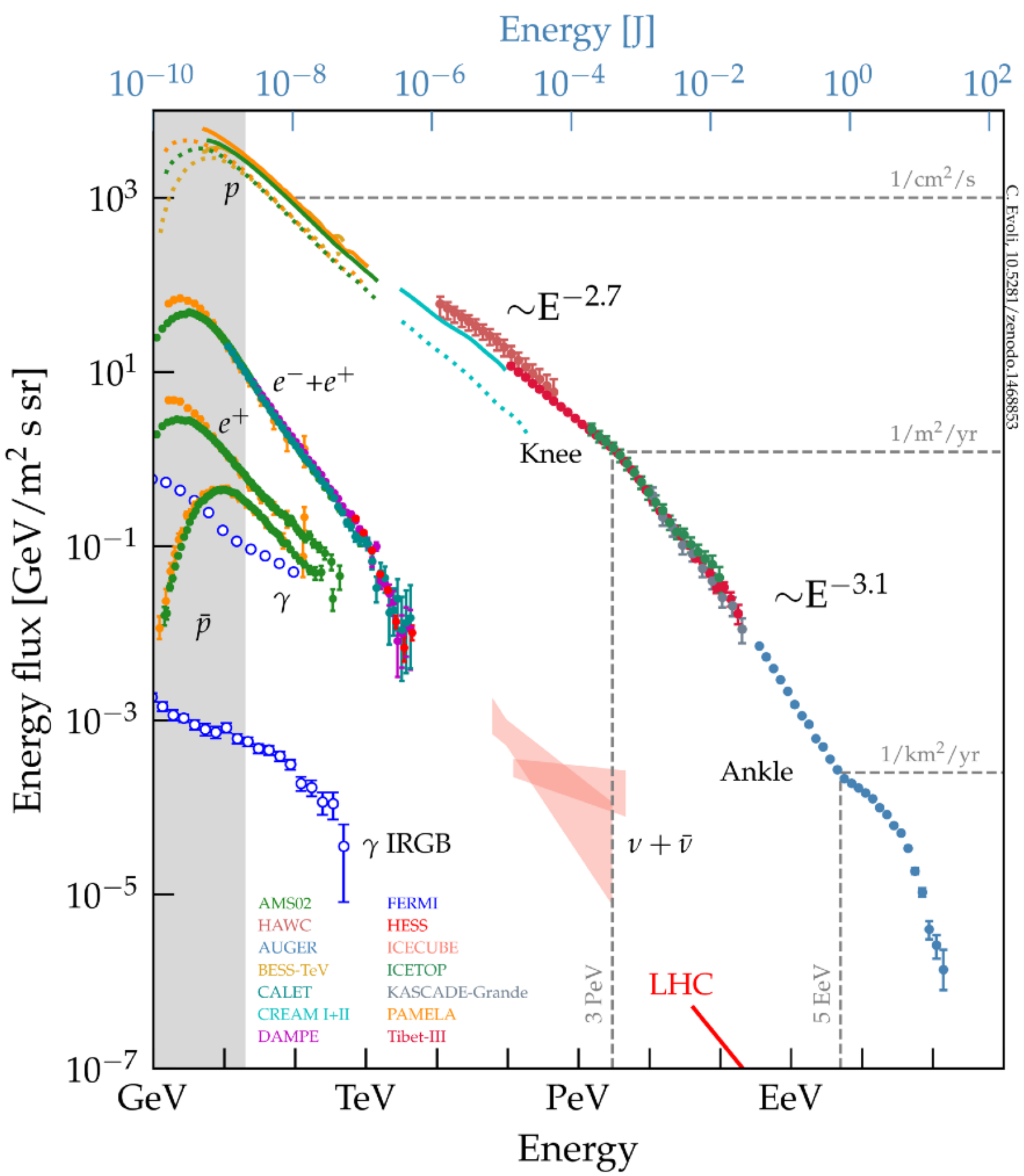


DG, A. Urbano, M. Valli, P. Ullio, PRD 2015

A bit more about these models



- They are tuned on local CR data

- The CR density is computed everywhere *(typically with the DRAGON code)* by solving the CR transport equation

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] = Q + \sum_{i<j}\left(c\beta n_{\mathrm{gas}}\,\sigma_{j\to i} + \frac{1}{\gamma \tau_{j\to i}}\right) N_j - \left(c\beta n_{\mathrm{gas}}\,\sigma_i + \frac{1}{\gamma\tau_i}\right) N_i$$

$$J_i = -D_{ij}\nabla_j N$$

https://github.com/cosmicrays/DRAGON

- "Base models" -> homogeneous diffusion
- "KRAgamma models" -> CR hardening in the inner Galaxy

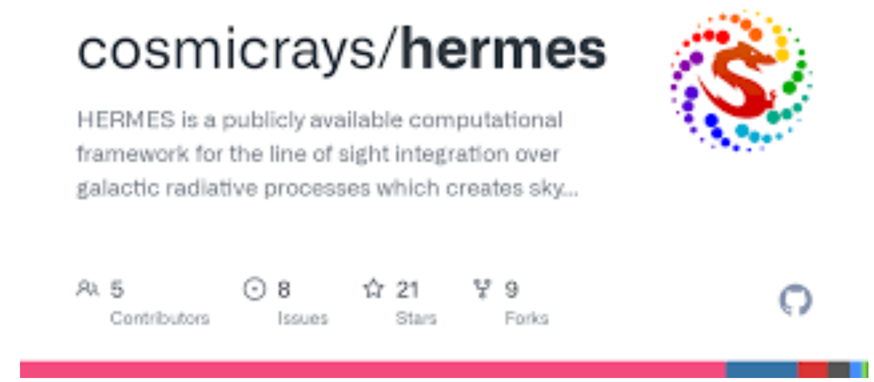
$$D(\rho) = D_0 \beta^{\eta}\left(\frac{\rho}{\rho_0}\right)^{\delta(r)}$$

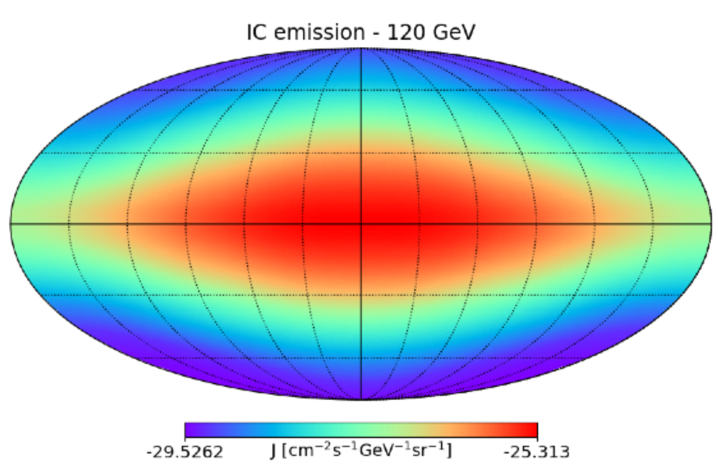
$$\delta(r) = ar + b$$

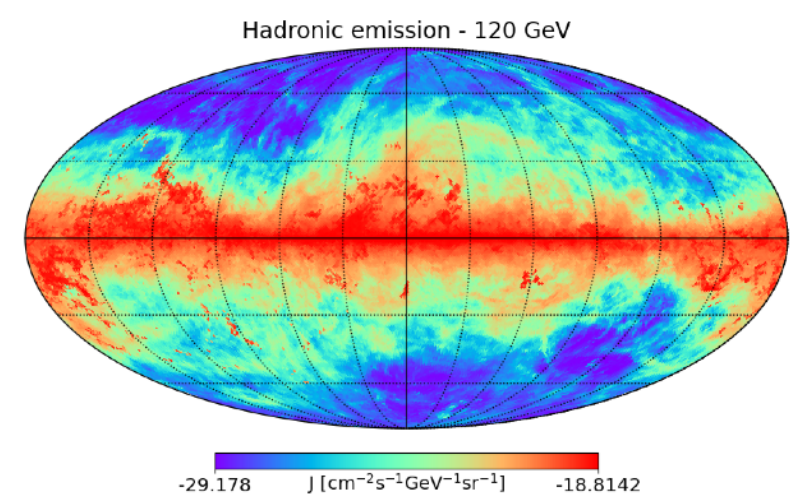
A bit more about these models

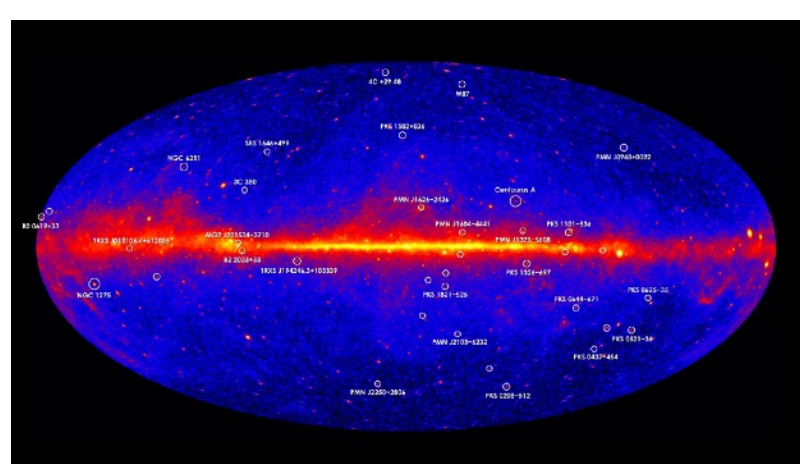
- The associated radio/ gamma-ray/neutrino flux due to synchrotron, bremsstrahlung, IC scattering, pion decay is computed with HERMES and tested on all available data

https://github.com/cosmicrays/hermes







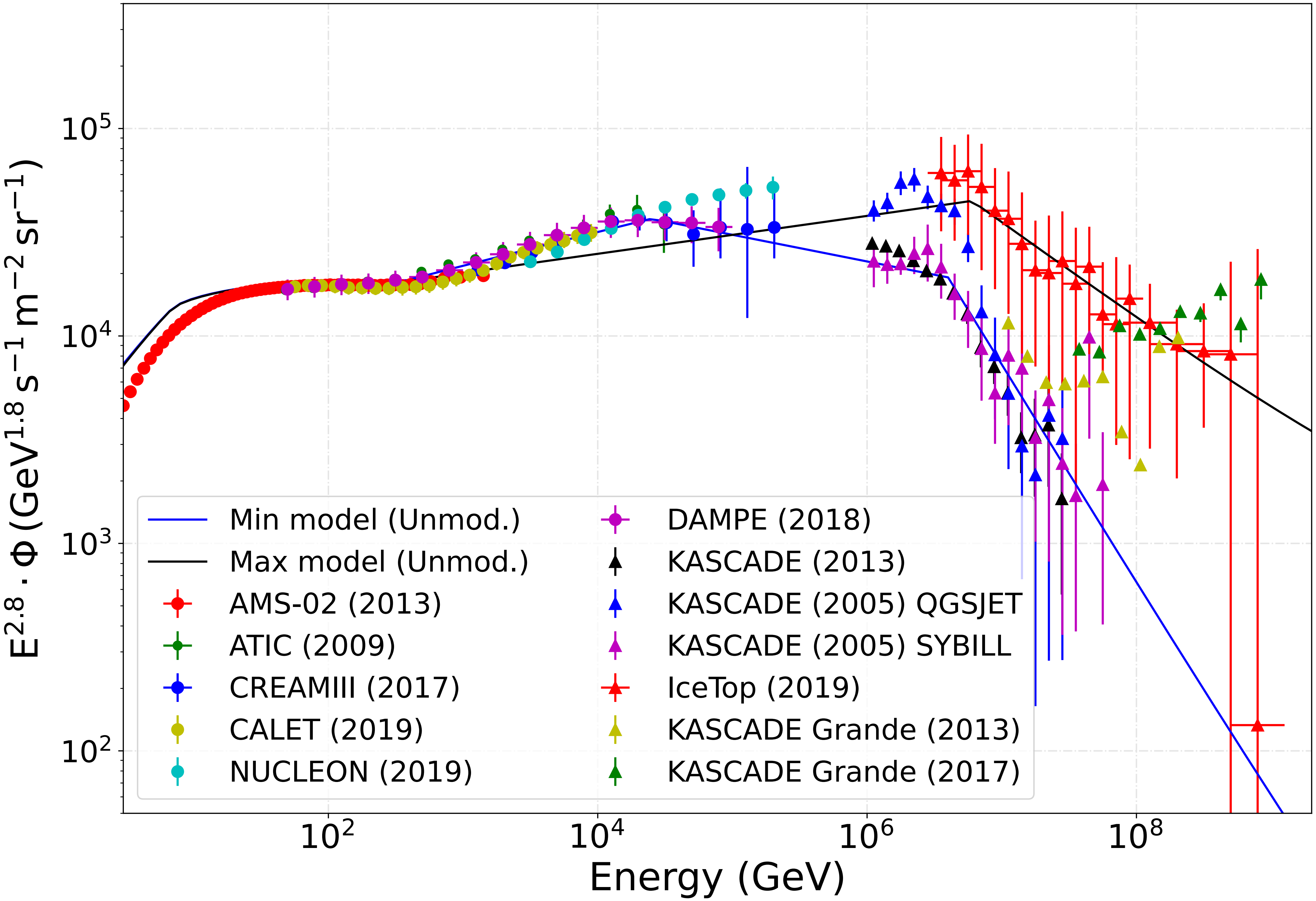


A multi-messenger analysis: Updated "Base" and "Gamma" models.

Local *hadronic* data

- De La Torre Luque *et al.*, Astron.Astrophys. 672 (2023)
- De La Torre Luque, **DG**, Grasso, Marinelli, Front.Astron.Space Sci. 9 (2022)

- De La Torre Luque, **DG**, Grasso, Marinelli, *in preparation*



A multi-messenger analysis: Updated “Base” and “Gamma” models.

Fermi-LAT diffuse gamma-ray data + High-energy diffuse gamma-ray data

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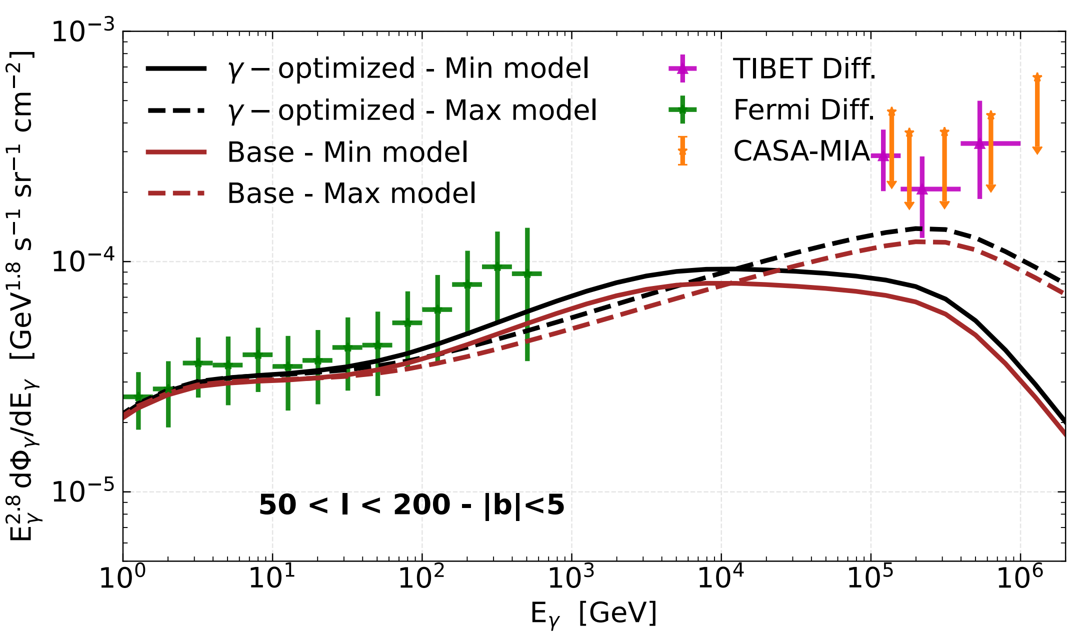

Fig. 5: Predicted γ-ray spectra for the different scenarios studied in this work and compared to Tibet ASγ (Amenomori et al. 2021) and Fermi-LAT data in the window $|b| < 5°$, $50° < l < 200°$. The experimental errorbars show the 1σ statistical uncertainty of the measurement. Fermi-LAT systematic uncertainties dominate above $\sim$ 200 GeV, while the systematic error associated to TIBET data in this region is estimated to be around 30% (Amenomori et al. 2009). CASA-MIA (Borione et al. 1998) upper limits in the same region are also reported.

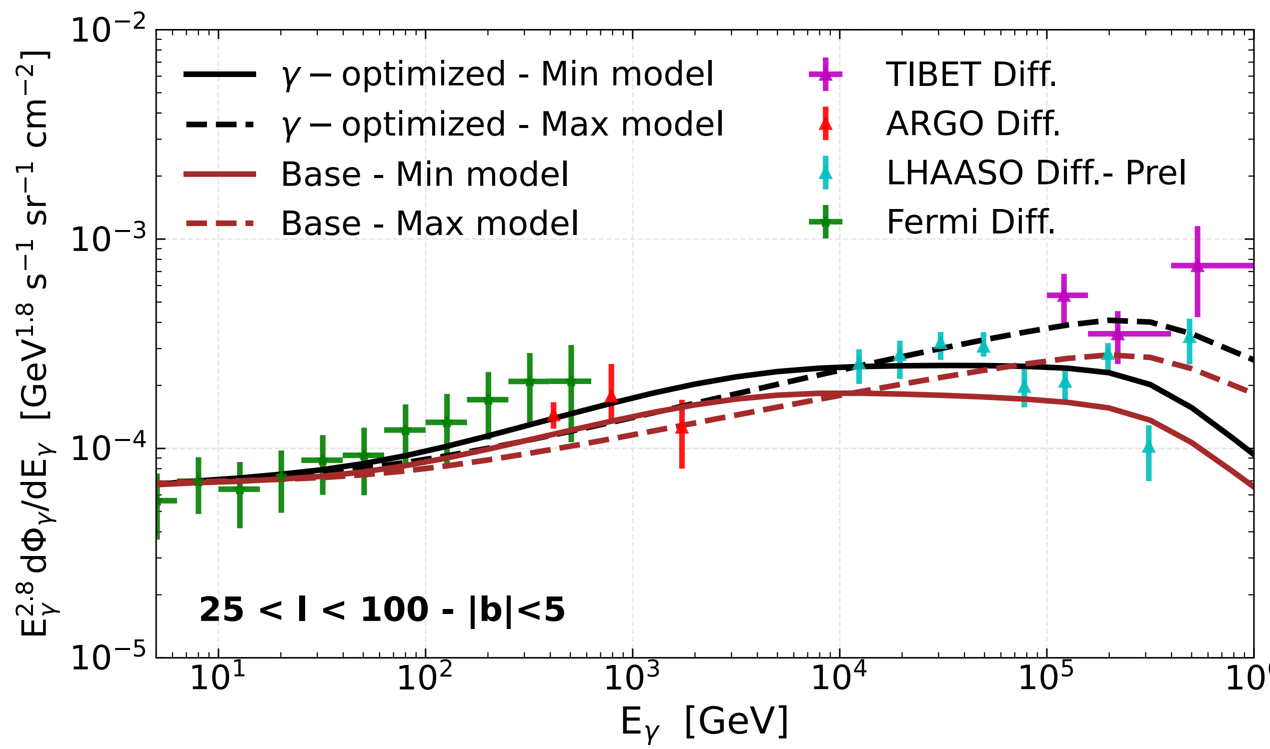

Fig. 4: The γ-ray spectra computed within the conventional (base) and γ-optimized scenarios are compared to Tibet ASγ (Amenomori et al. 2021) and LHAASO (Zhao et al. 2021) (preliminary) data in the window $|b| < 5°$, $25° < l < 100°$. The Galactic diffusion emission spectrum measured by Fermi-LAT and extracted as discussed in Sec. 2.2, as well as ARGO-YBJ data (Bartoli et al. 2015) in the same region, are also reported. The models account for the effect of γ-ray absorption onto the CMB photons (see Sec. 3.2).

A multi-messenger analysis: Updated “Base” and “Gamma” models.

Fermi-LAT diffuse gamma-ray data + High-energy diffuse gamma-ray data

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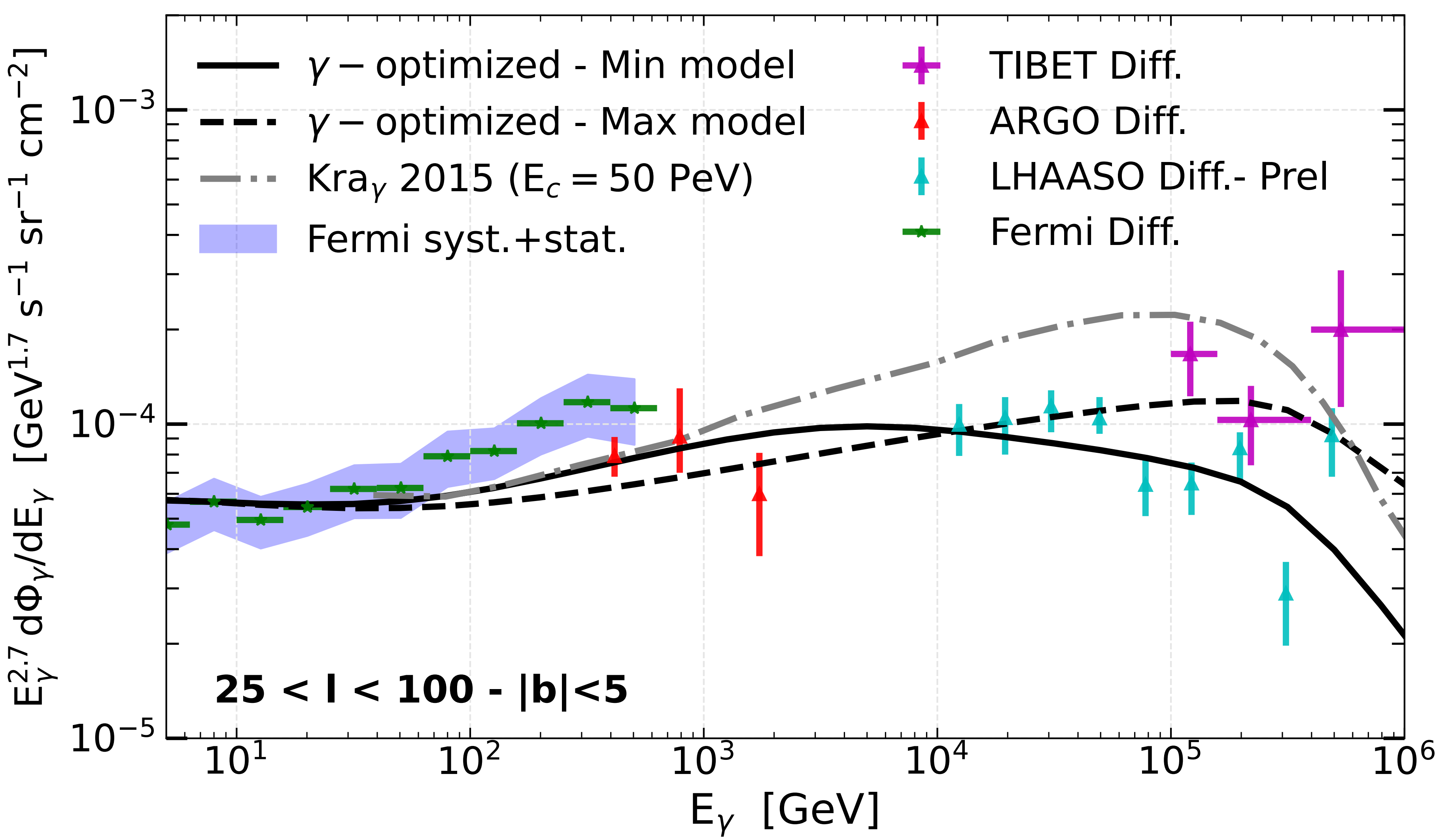

A multi-messenger analysis: Updated "Base" and "Gamma" models.

Fermi-LAT diffuse gamma-ray data + High-energy diffuse gamma-ray data

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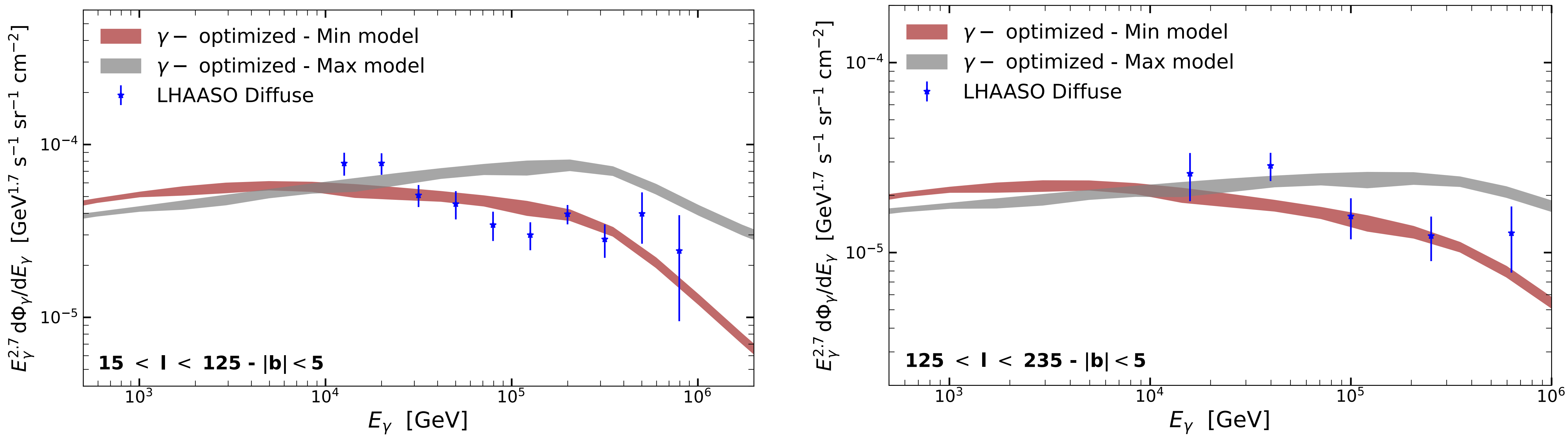
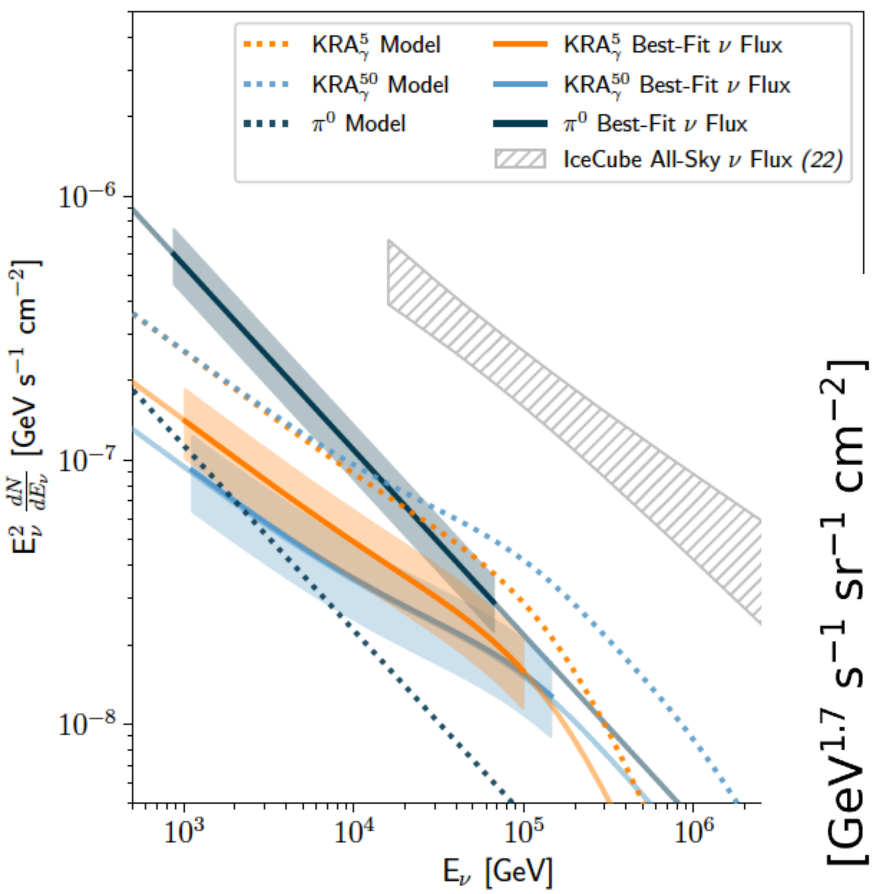
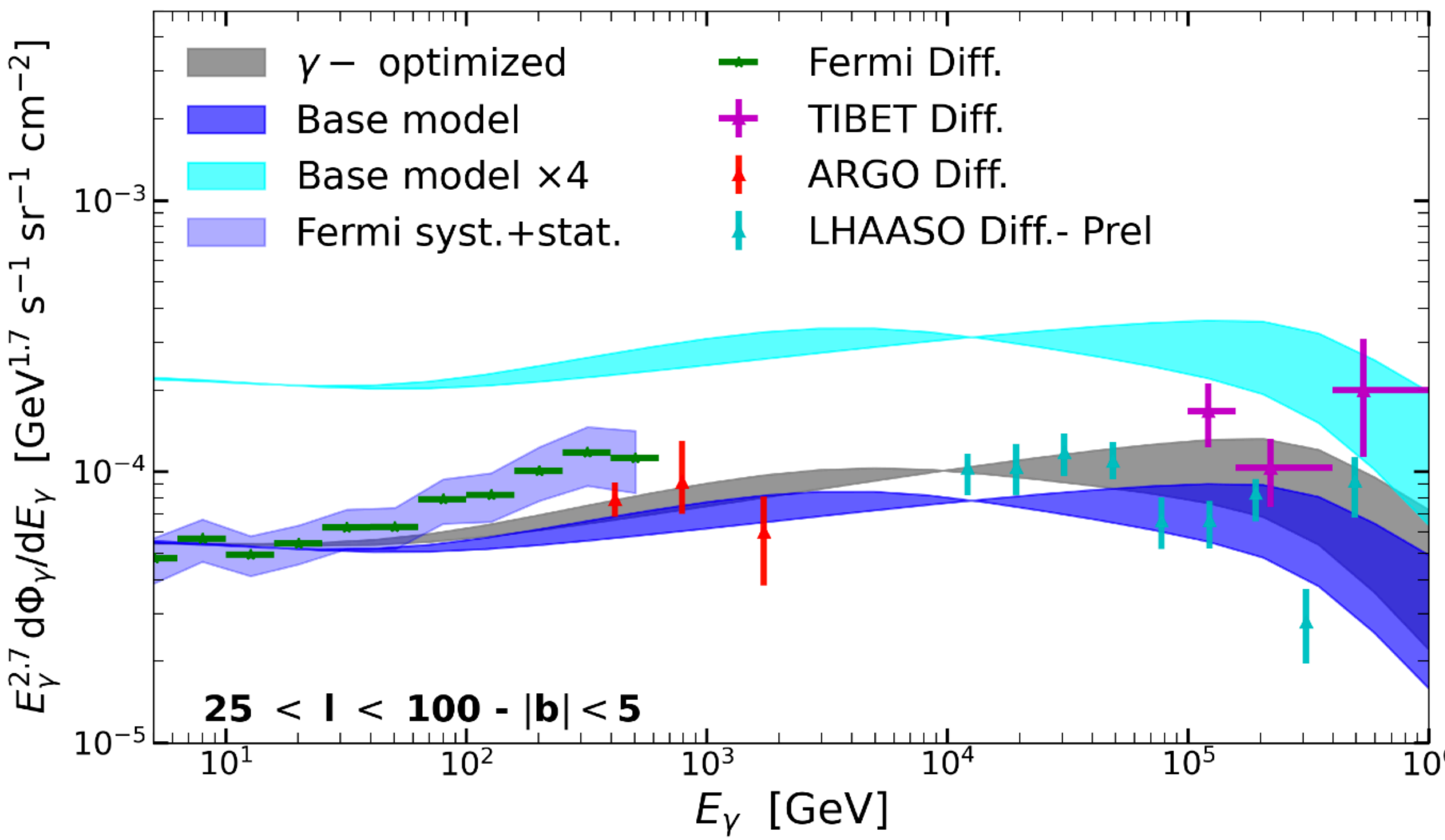


- with cross section uncertainty
- official data release from LHAASO collab. (arXiv:2305.05372)

The Gamma model is not equivalent to a *“rescaled base model”* when compared to gamma-ray data



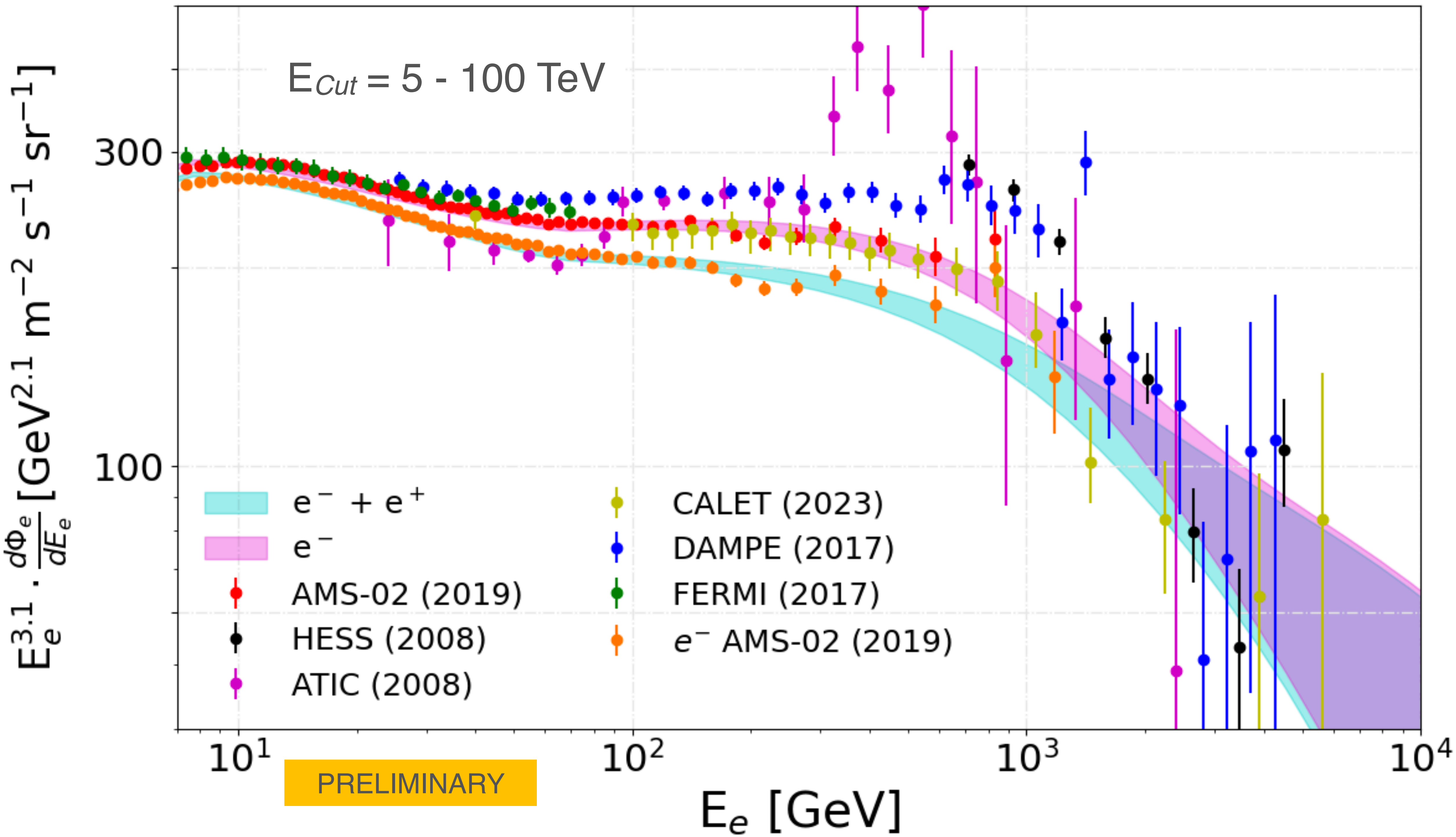


A more detailed update in progress…

Local *leptonic* data, 2D and 3D runs

- De La Torre Luque *et al.*, Astron.Astrophys. 672 (2023)
- De La Torre Luque, **DG**, Grasso, Marinelli, Front.Astron.Space Sci. 9 (2022)

- De La Torre Luque, **DG**, Grasso, Marinelli, *in preparation*

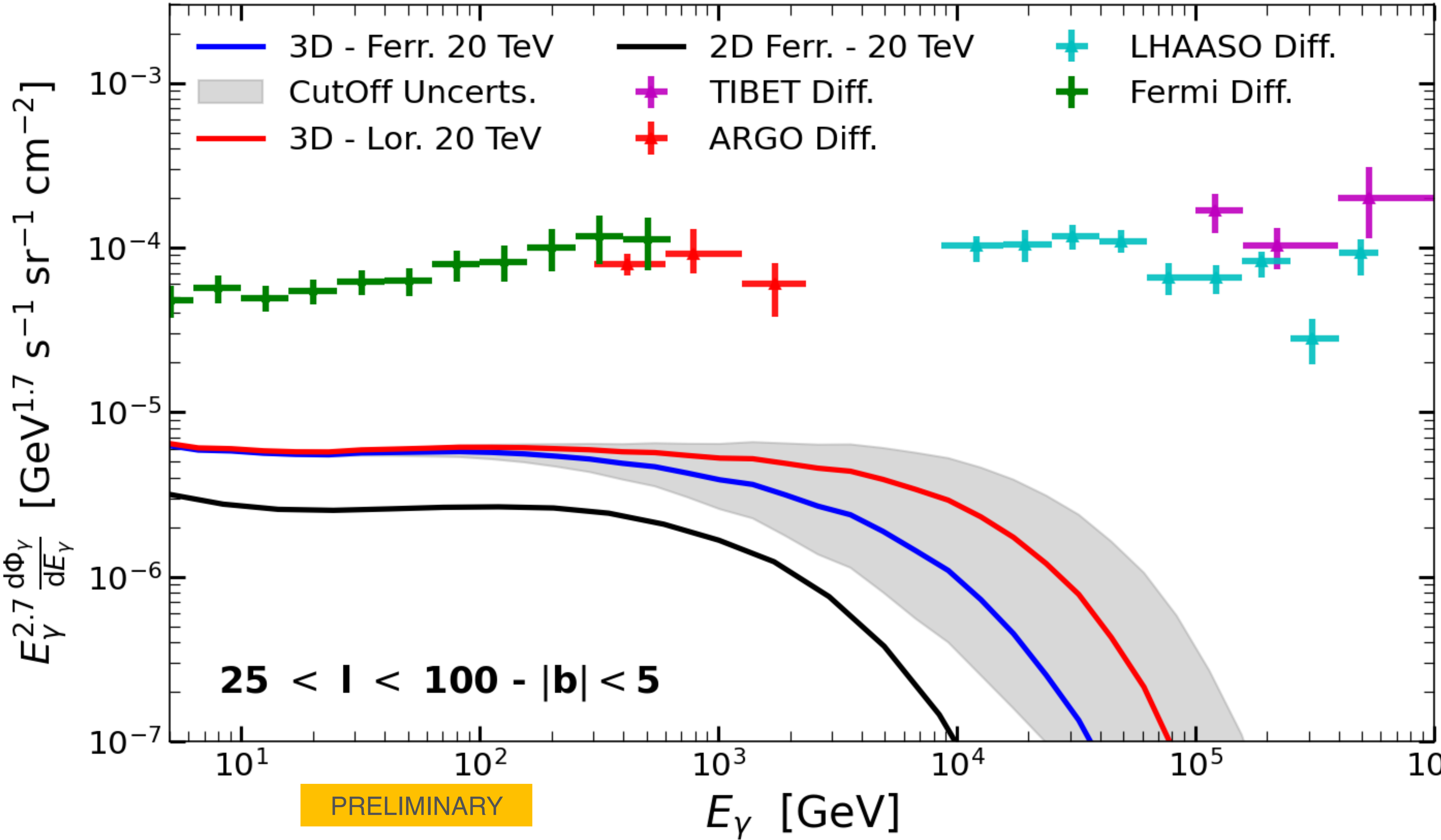


PRELIMINARY

A more detailed update in progress…

Gamma-ray data, leptonic part, 2D vs 3D

- De La Torre Luque, **DG**, Grasso, Marinelli, *in preparation*

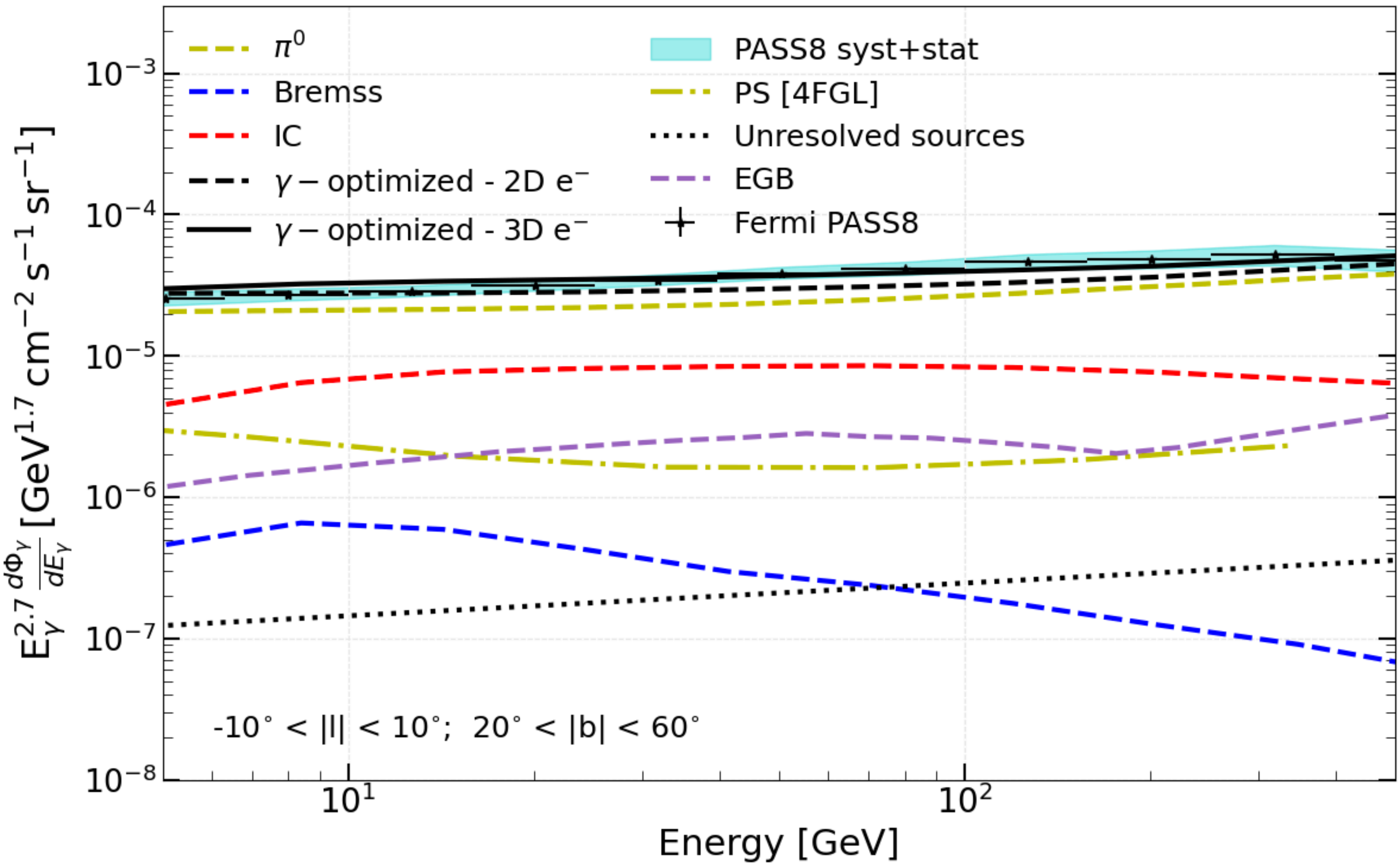


PRELIMINARY

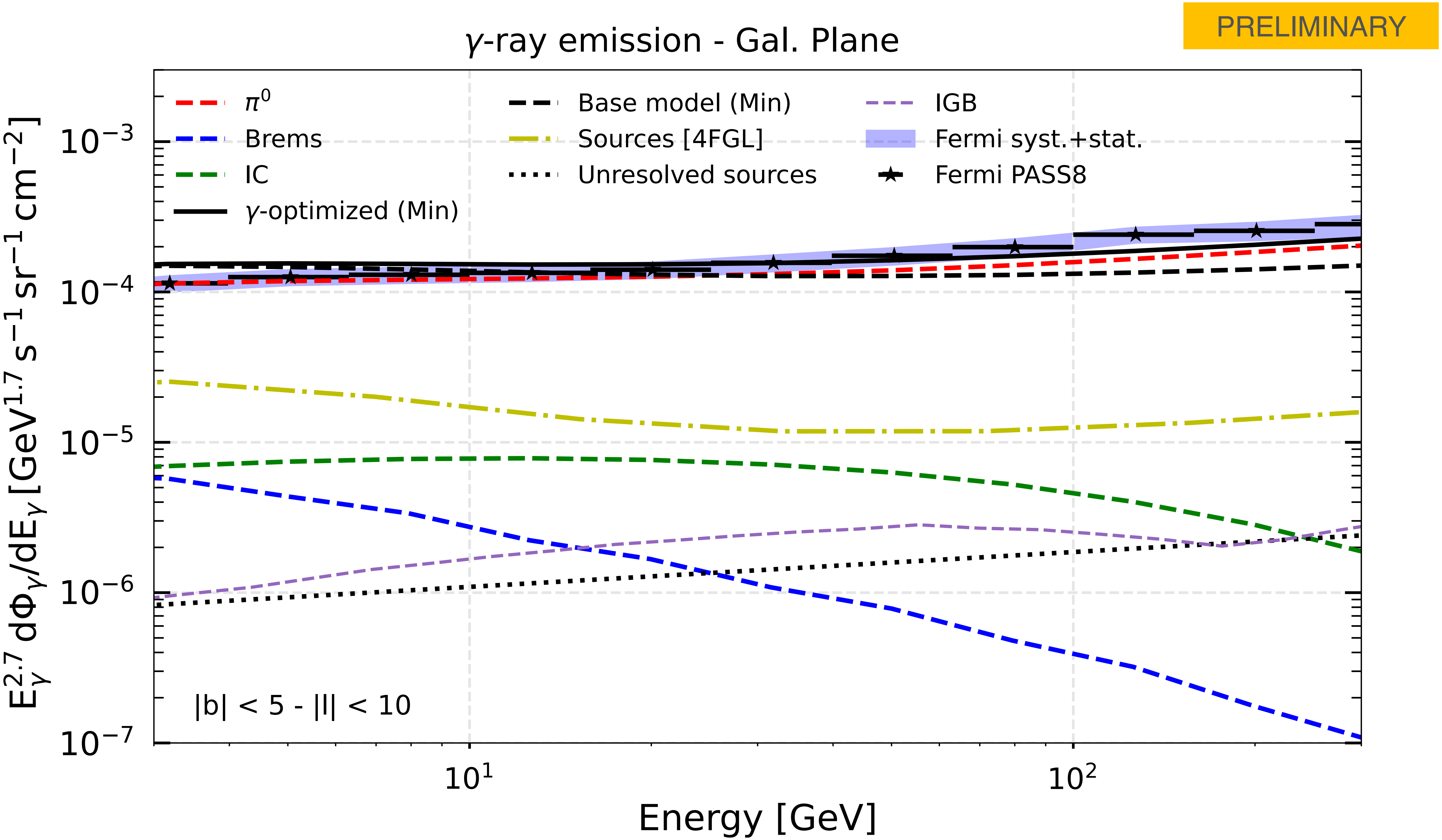
A more detailed update in progress…

Gamma-ray data, leptonic part, 2D vs 3D

PRELIMINARY

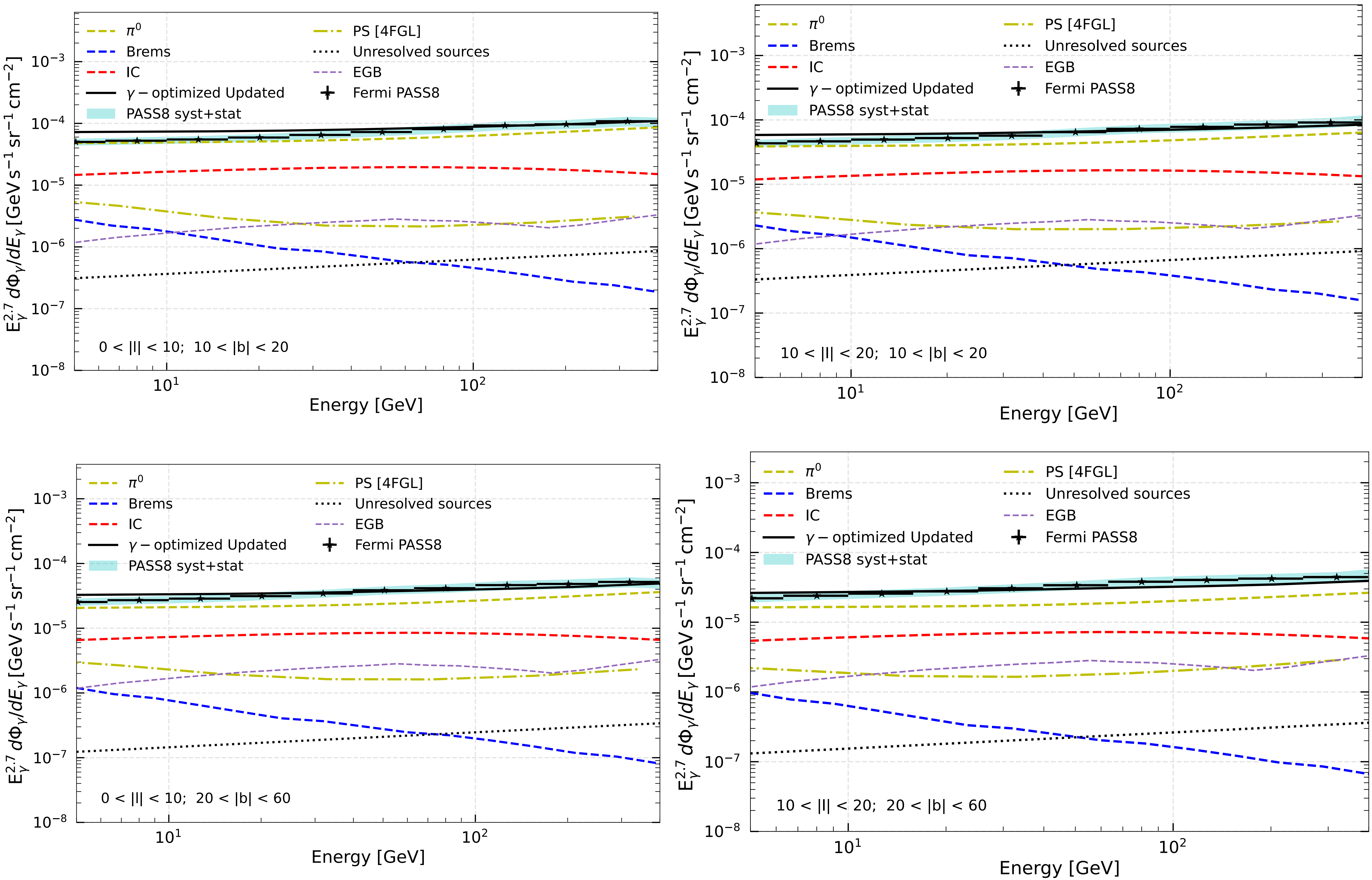


A more detailed update in progress…



A more detailed update in progress…

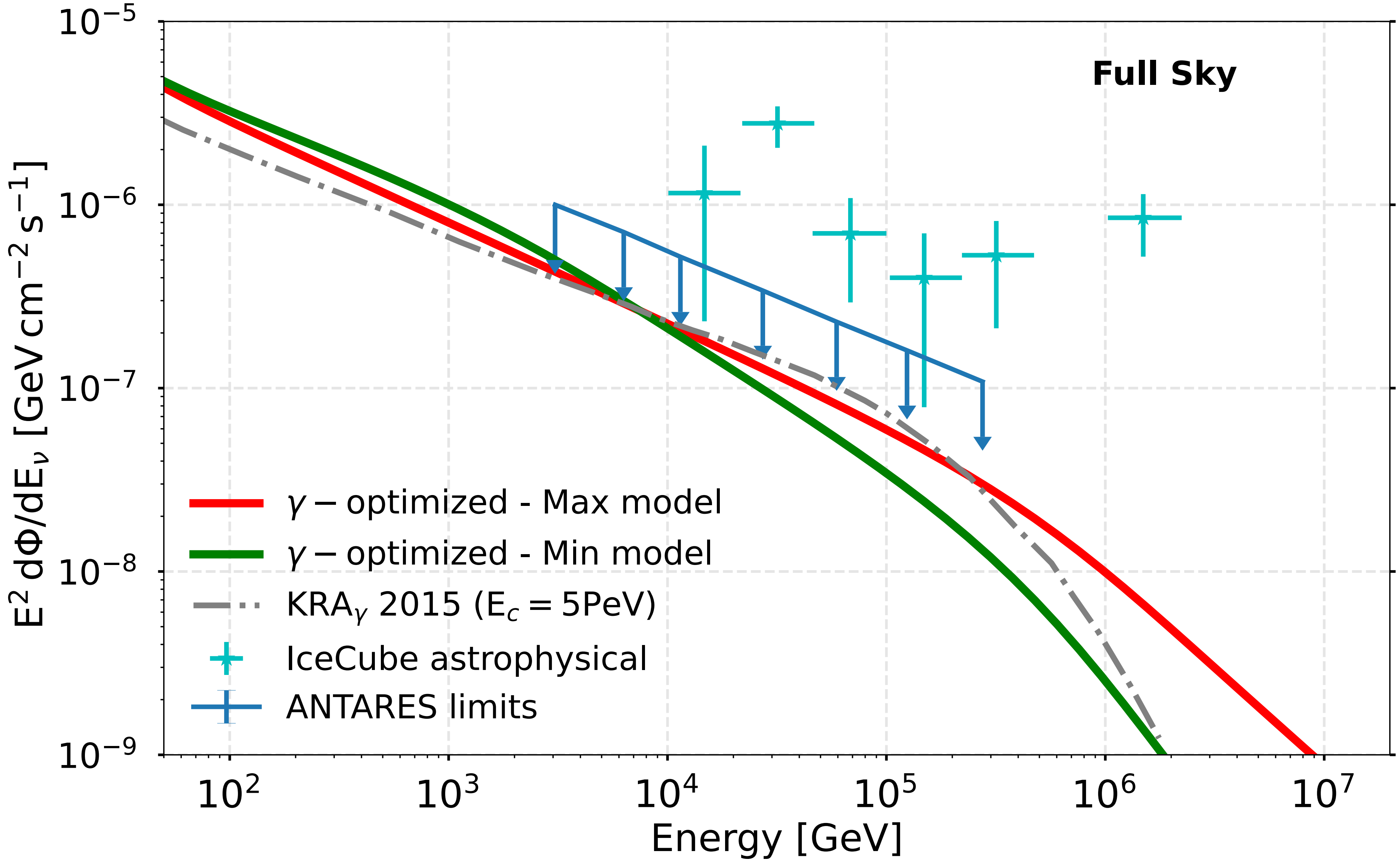
PRELIMINARY



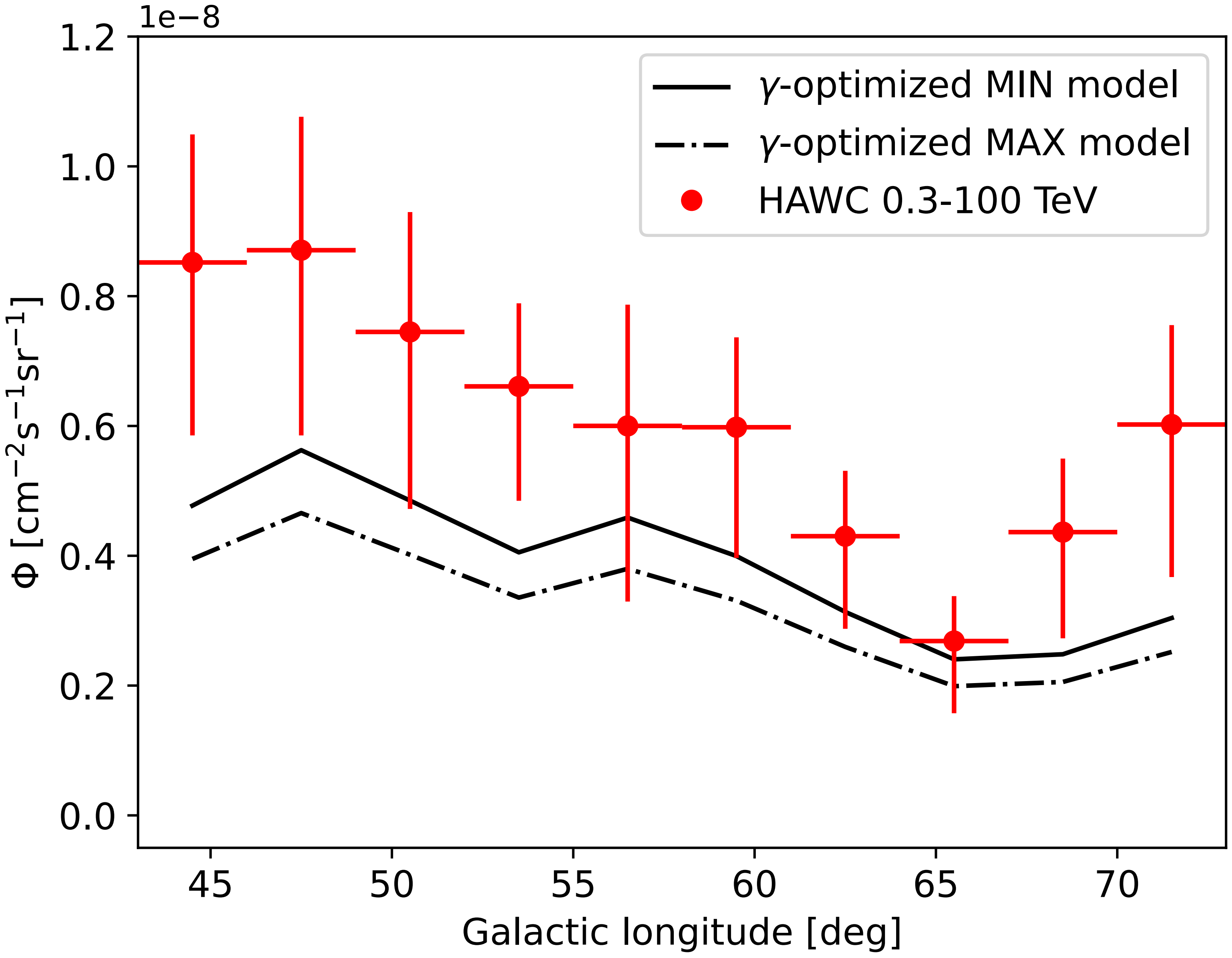
Conclusions

- “(KRA)-Gamma models” featuring a harder CR spectrum in the inner Galaxy are compatible with most multi-messenger data available
- Rescaled conventional models are compatible with neutrino data but overshoot the gamma-ray data at all energies
- The Galaxy may be a **“neutrino desert”**, but with a **“KRAgamma oasis”**

Backup Slides

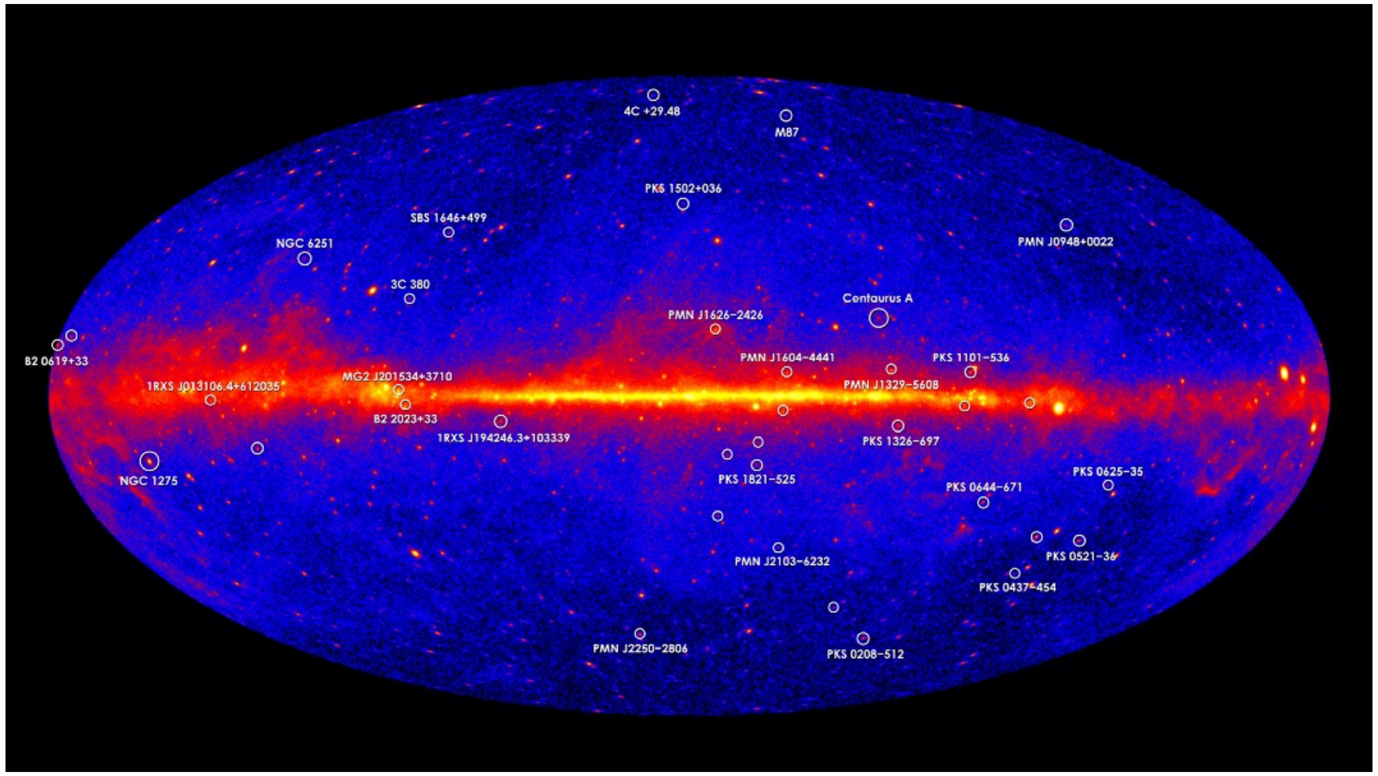


Full Sky
$E^2\, d\Phi/dE_\nu$ [GeV cm^{-2} s^{-1}]
Energy [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^2
10^3
10^4
10^5
10^6
10^7
γ − optimized - Max model
γ − optimized - Min model
KRA$_\gamma$ 2015 (E_c = 5PeV)
IceCube astrophysical
ANTARES limits

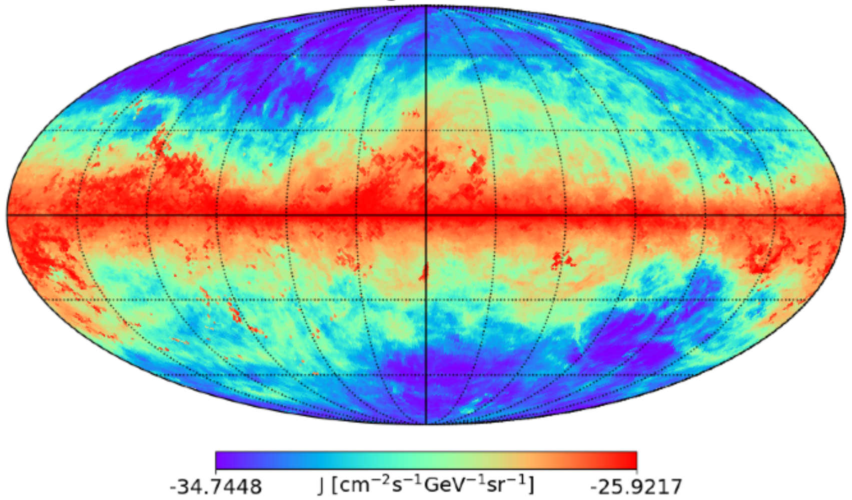


1e−8
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Φ [cm⁻²s⁻¹sr⁻¹]
45
50
55
60
65
70
Galactic longitude [deg]
γ-optimized MIN model
γ-optimized MAX model
HAWC 0.3-100 TeV

The GeV-TeV Gamma-ray diffuse sky: Diffuse emission components



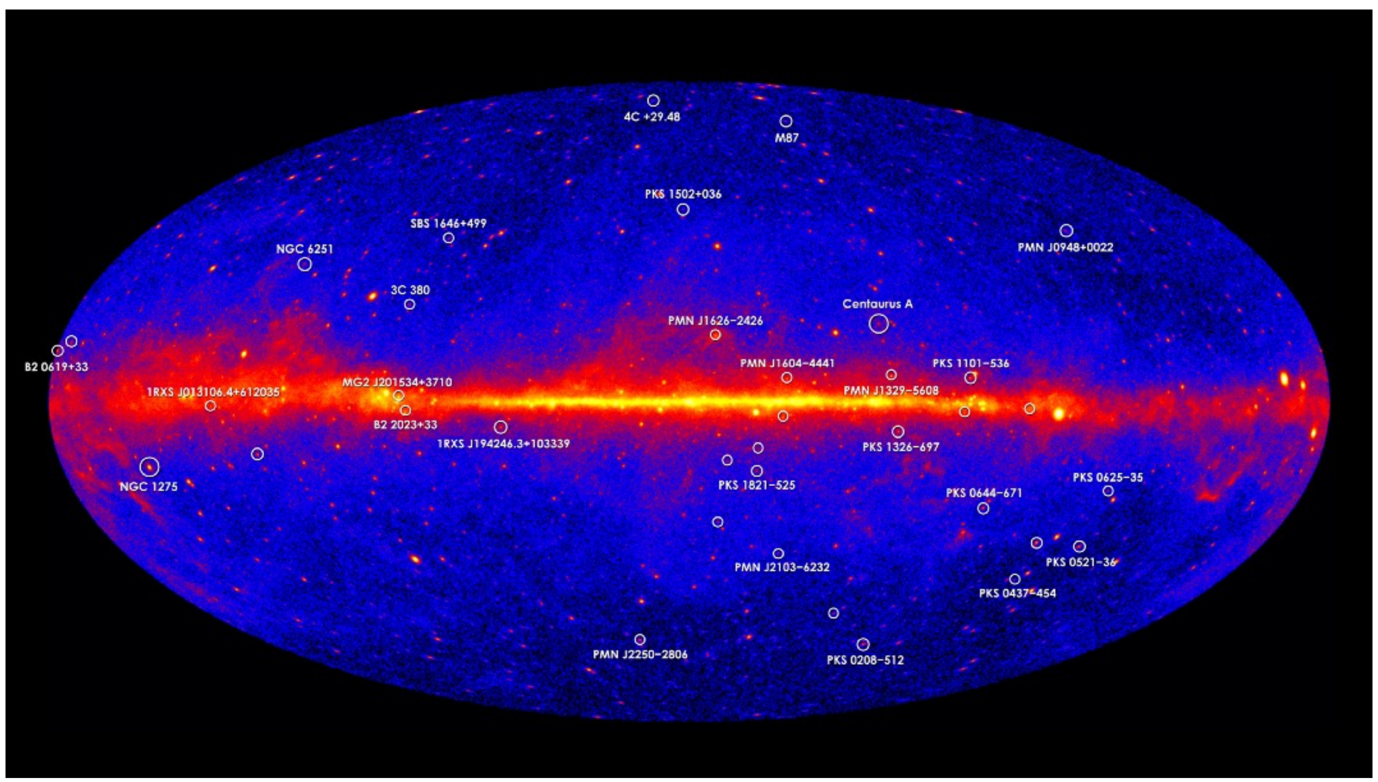
Bremsstrahlung: radiation is emitted by a lepton passing through the electric field of a particle in the ISM (electron or nucleus).

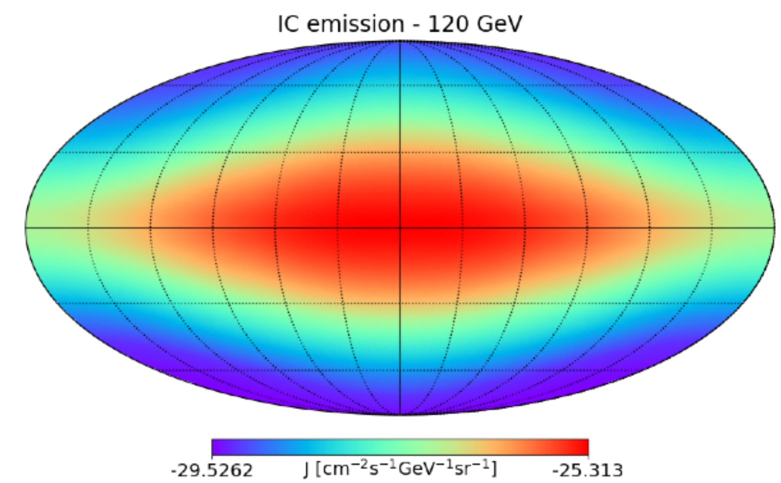


$$e + N \rightarrow e' + \gamma + N'$$

Bremsstrahlung emission follows the ISM gas distribution

The GeV-TeV Gamma-ray diffuse sky: Diffuse emission components

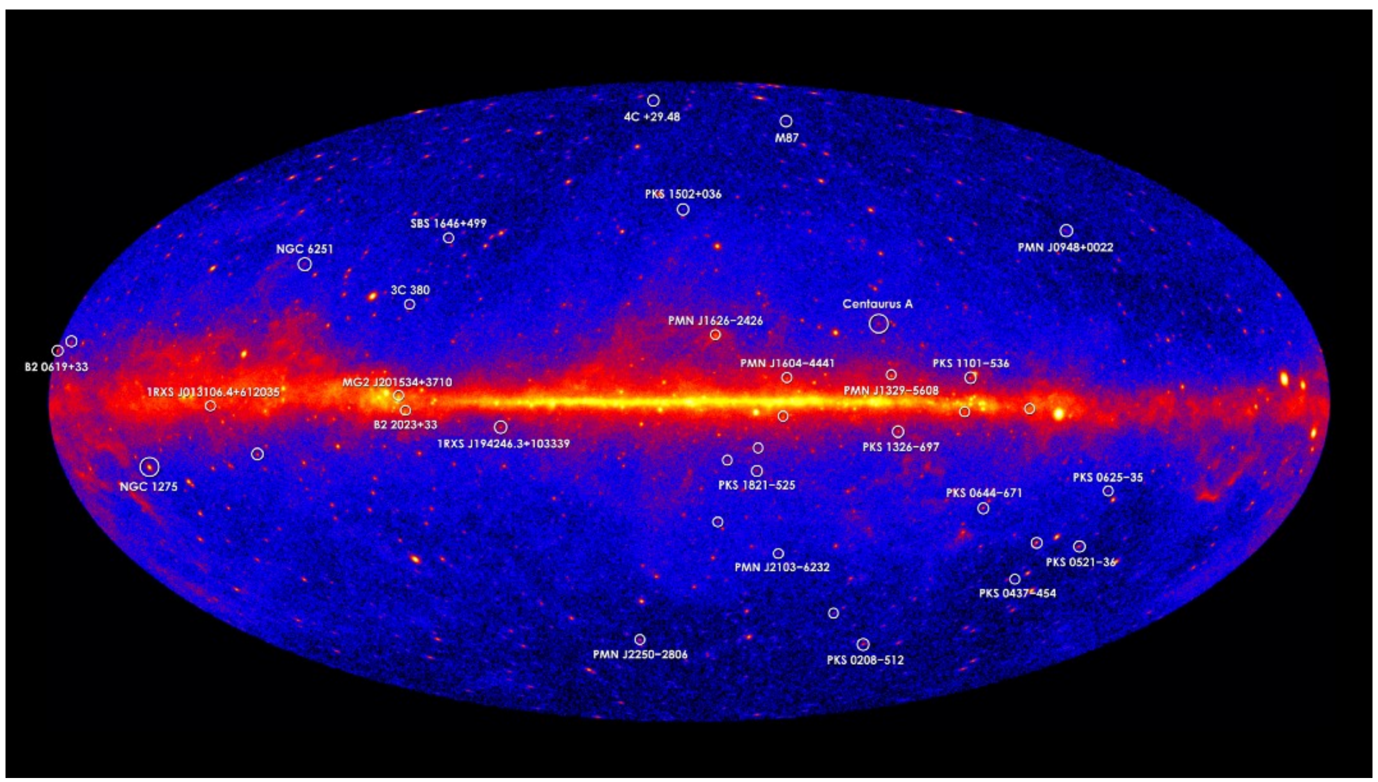


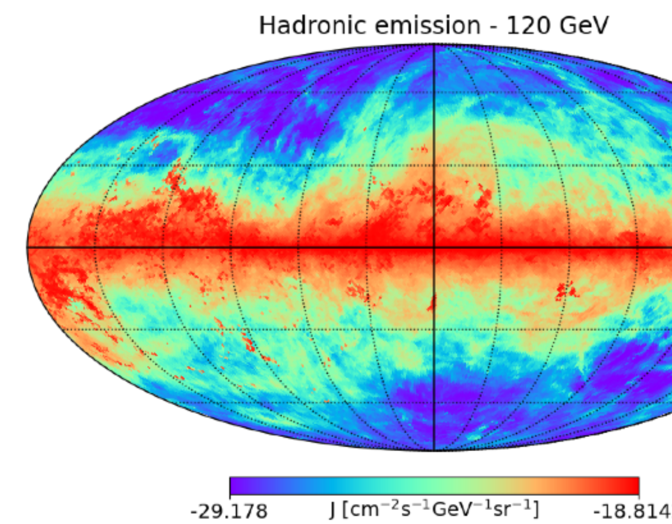


$$e + \gamma \rightarrow e^{'} + \gamma^{'}$$

IC emission depends on the energy density of the **ISRFs**

The GeV-TeV Gamma-ray diffuse sky: Diffuse emission components





$$p + p \rightarrow \pi_0 \pi_+ \pi_-$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

Diffuse emission totally correlated with the propagation of cosmic rays dominated by protons and He. Hadronic emission follows ISM gas distribution as well.