Diffuse gamma-ray emission as probe of PeV Galactic Cosmic Rays

From the Galactic CR sea to a local PeVatron?

Giulia Pagliaroli

INFN-Laboratori Nazionali del Gran Sasso

giulia.pagliaroli@lngs.infn.it

TRIESTE 2026: The Multimessenger sky at Extreme Energies:from Sources to Fundamental Physics

Open Questions

Can diffuse γ rays probe PeV protons?

What contaminates this inference?

Could the knee have a local origin?

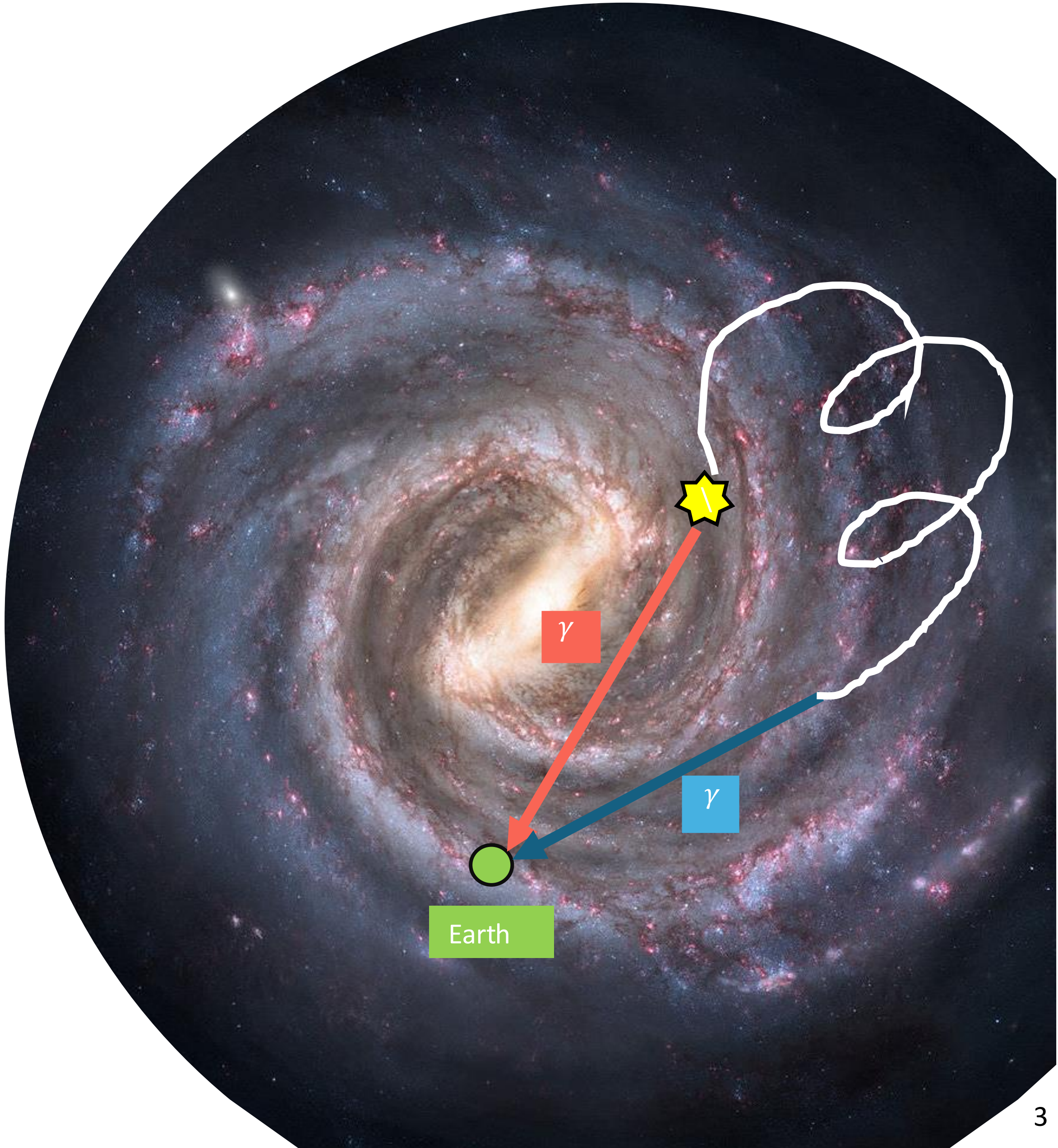
Total Galactic gamma-ray emission at TeV-PeV:

$$\phi_{\gamma,tot} = \boxed{\phi_{\gamma,s}} + \boxed{\phi_{\gamma,\mathrm{diff}}} + \cancel{\phi_{\gamma,IC}}$$

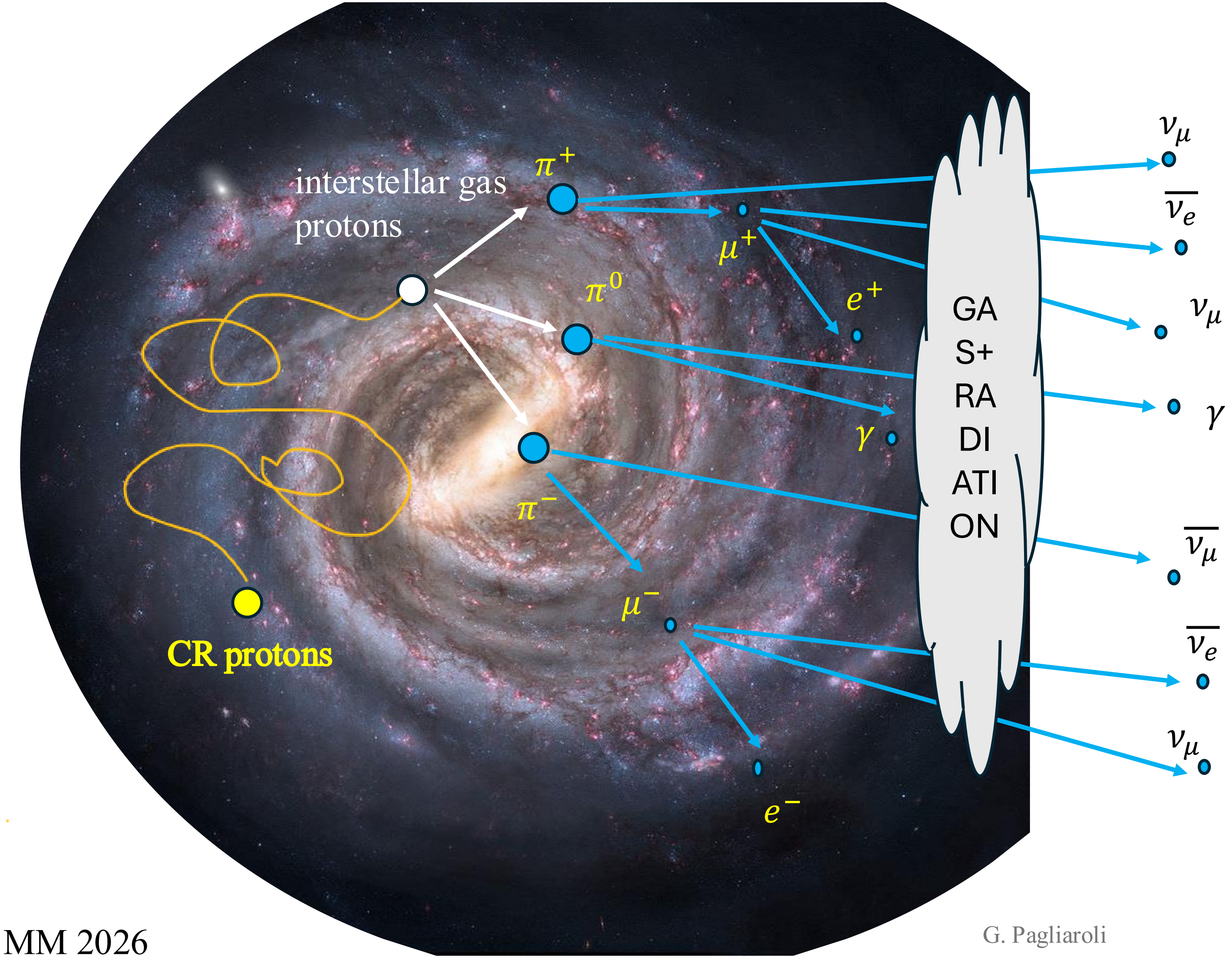
Source component is due to the interaction of accelerated particles (hadrons or leptons) with the ambient medium (ISM or CMB) within or close to an acceleration site (such as PWNe, SNRs).

Diffuse component is due to the interaction of accelerated hadrons with the interstellar medium;

Inverse Compton: is due to the interaction of accelerated leptons with the CMB ;



THE PROTON-PROTON PRODUCTION PROCESS OF DIFFUSE EMISSION



Correlated emission of HE Neutrinos and Gamma

- Spatial correlation with the interstellar gas
- Energy correlation due the kinematic of the process

$$E_\gamma \cong \frac{E_{CR}}{10}$$
$$E_\nu \cong \frac{E_{CR}}{20}$$

$$E_\nu \cong \frac{1}{2} E_\gamma$$

Large-scale HE Diffuse Galactic emission:

Gamma-ray absorption on CMB
Vernetto & Lipari, 2016

$$\phi_\gamma^{diff}(E_\gamma, l, b) = \int_{E_\gamma}^{\infty} dE_n \frac{d\sigma(E_n, E_\gamma)}{dE_\gamma} \int_0^{\infty} ds\, n_H(s, l, b) \Phi_{CR}(E_n, s, l, b) e^{-\tau(s, E_\gamma)}$$

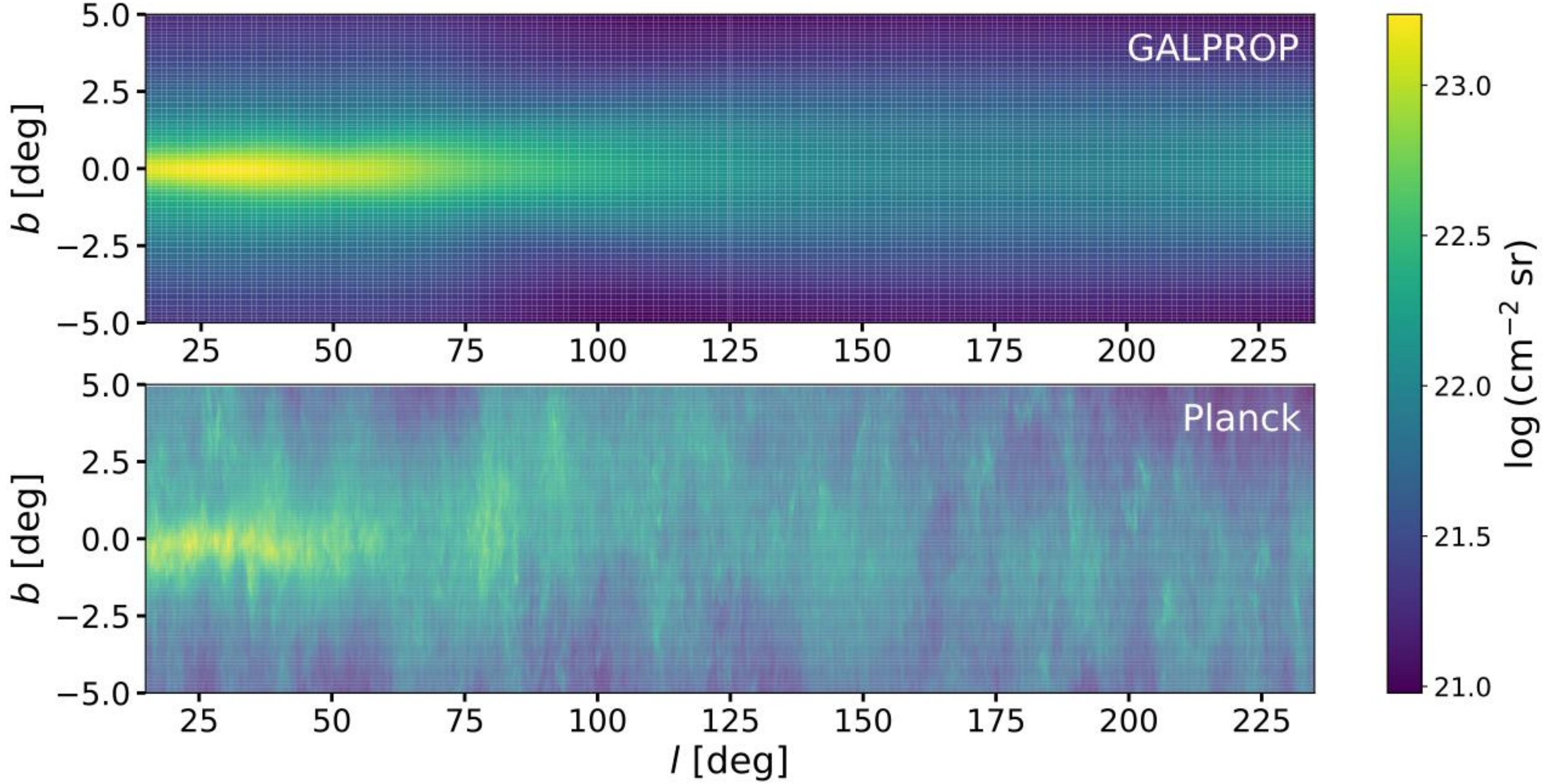
Differential inelastic cross section of pp interaction
AAFrag **Kachelriess et al., 2023**

Interstellar gas distribution in the Galaxy

Cosmic-ray energy and spatial distribution

The Galactic gas templates

+42% of contribution of heavier elements



- Atomic hydrogen traced by the 21-cm emission line, H_2 traced by CO emission line.

Porter et al., 2022 (GALPROP),
BenBekhti et al., 2016 (HI4PI),
Dame et al., 2001 (CO Survey)

- Hydrogen gas column density traced by dust opacity map (Planck).

Aghanim et al., 2016,
Ade et al., 2011

The role of Cosmic Ray distribution:

MODELS Providing TEMPLATES

De La Torre Luque et al., Astron.Astrophys. 672 (2023) A58,
Dundovic et al., Astron.Astrophys. 653 (2021) A18
D. Gaggero et al., Astrophys. J. Lett. 815, L25 (2015)

→ Propagation Code

Lipari et al., Phys.Rev.*D* 98 (2018) 4, 043003
Pagliaroli et al, JCAP (2016), Pagliaroli et al, JCAP (2018)
…..etc

→ Phenomelogical Approach

$$\Phi_{CR}(E_n, s, l, b) \equiv \Phi^{\odot}_{CR}(E_n)$$

Standard Case

Very similar to the π_0

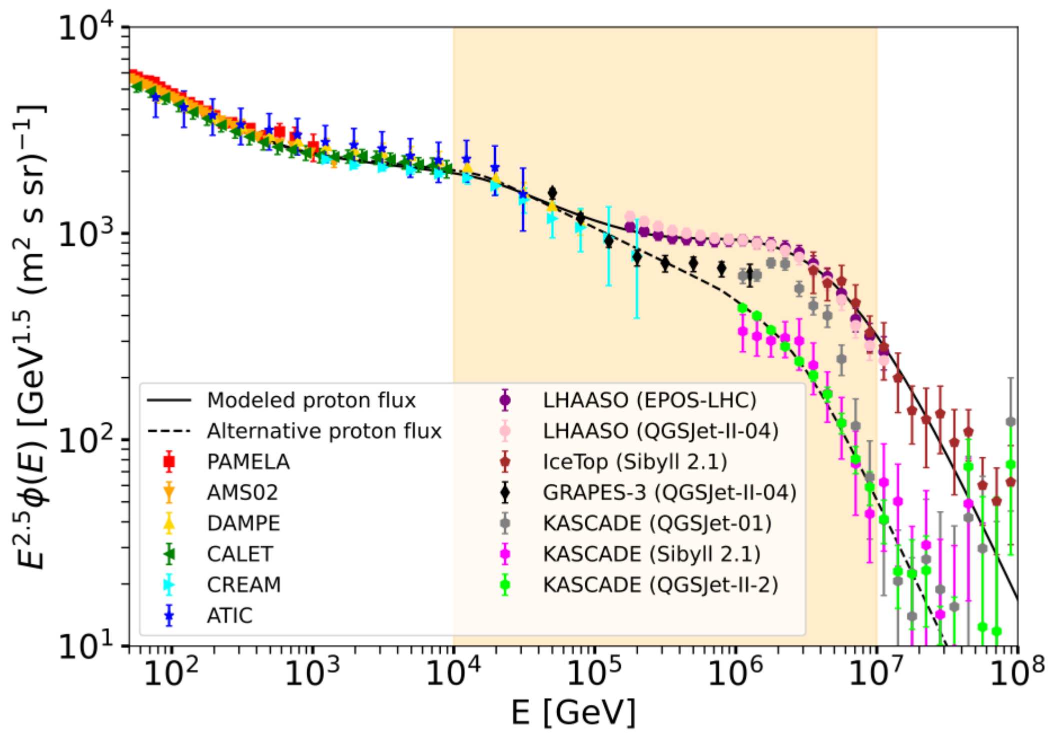
$$\Phi_{CR}(E_n, s, l, b) \equiv \Phi^{\odot}_{CR}(E_n) h(E_n, s, l, b)$$

Hardening Case

Very similar to the KRA_γ

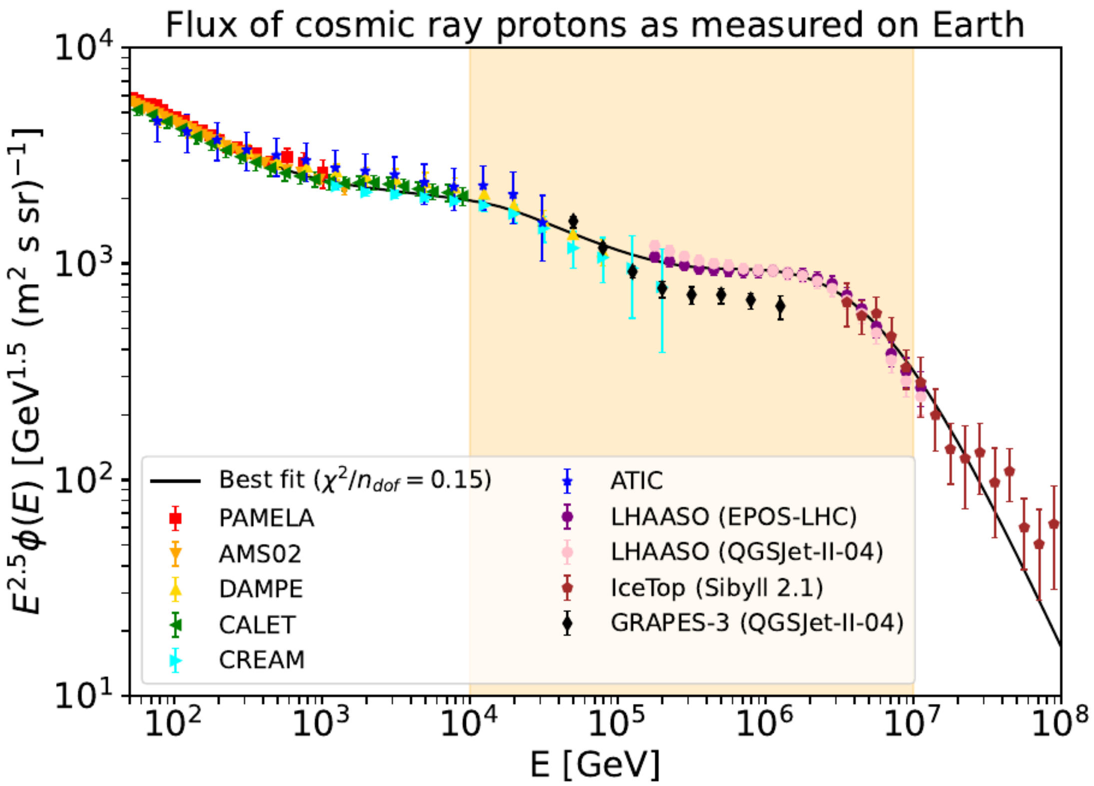
Proton energy spectra @2025

The gamma-ray (neutrino) flux at $E_\gamma = 1\,TeV$ ($E_\nu = 100\,TeV$) is determined by CRs with $E_{CR} = 10\,TeV$ ($E_{CR} = 2\,PeV$)



Clear tension between IceTop and KASCADE data-set

May 2025



LHAASO data align IceTop

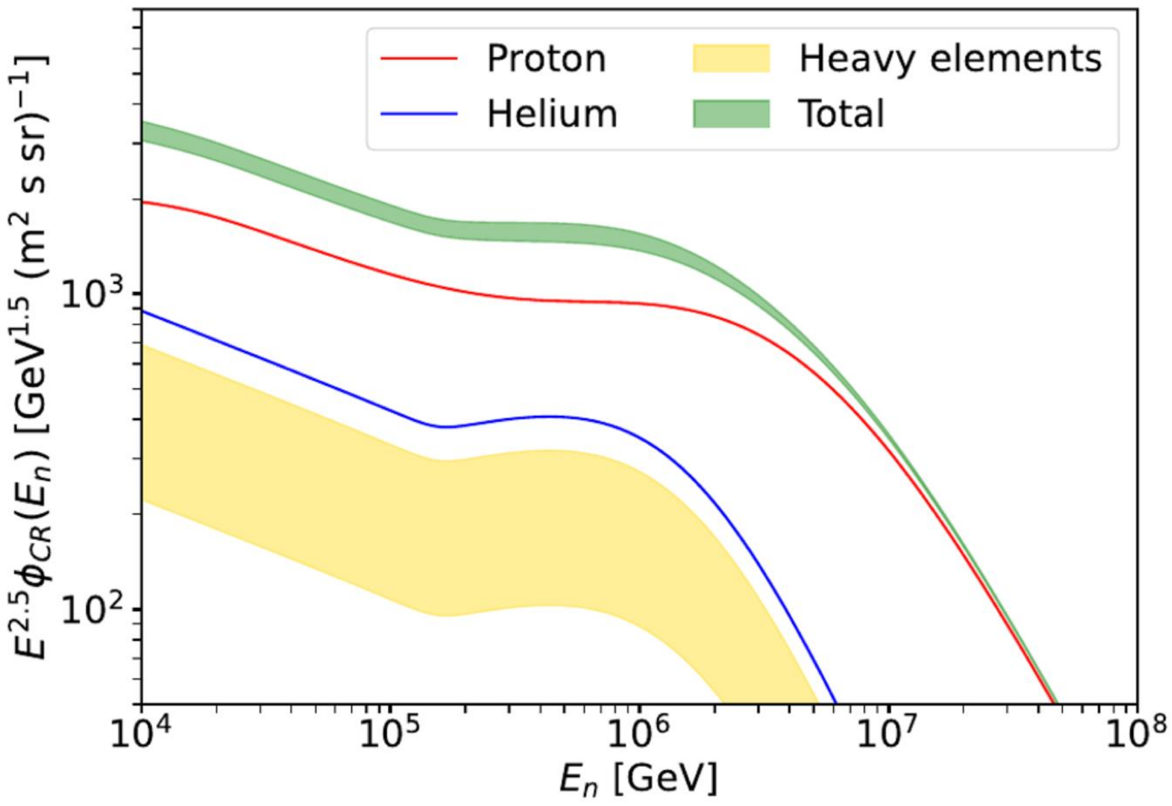
The contribution of heavy elements

Diffuse gamma and neutrino fluxes are determined by the total nucleon flux (that may depend on the assumed CR composition)

$$\Phi_{CR}^{\odot}(E_n) = \sum_A A^2 \Phi_A(AE_n)$$

If we increase heavy element contribution at expenses of hydrogen, we obtain a smaller CR flux (since the flux decrease faster than E^{-2})

- The contribution from Helium is 14% of the proton one.
- The uncertainty due to heavy elements is around 5% at 1 PeV



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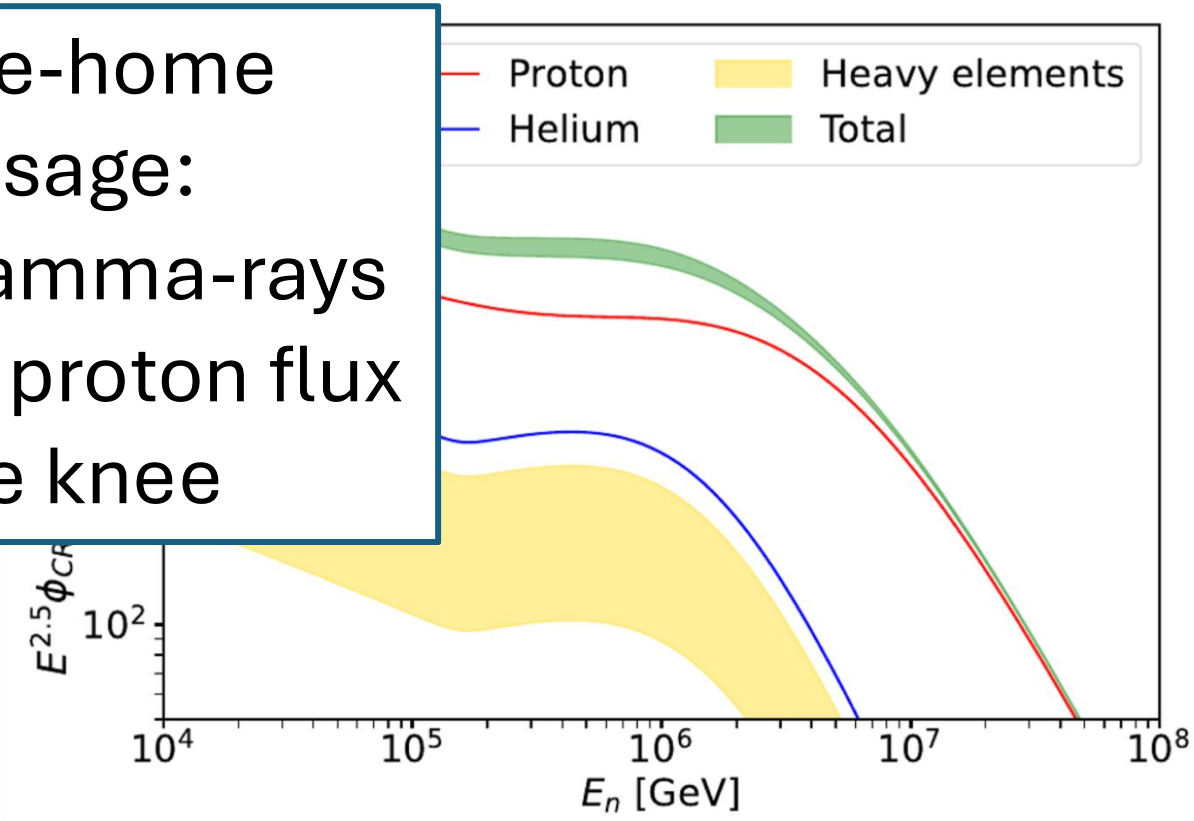
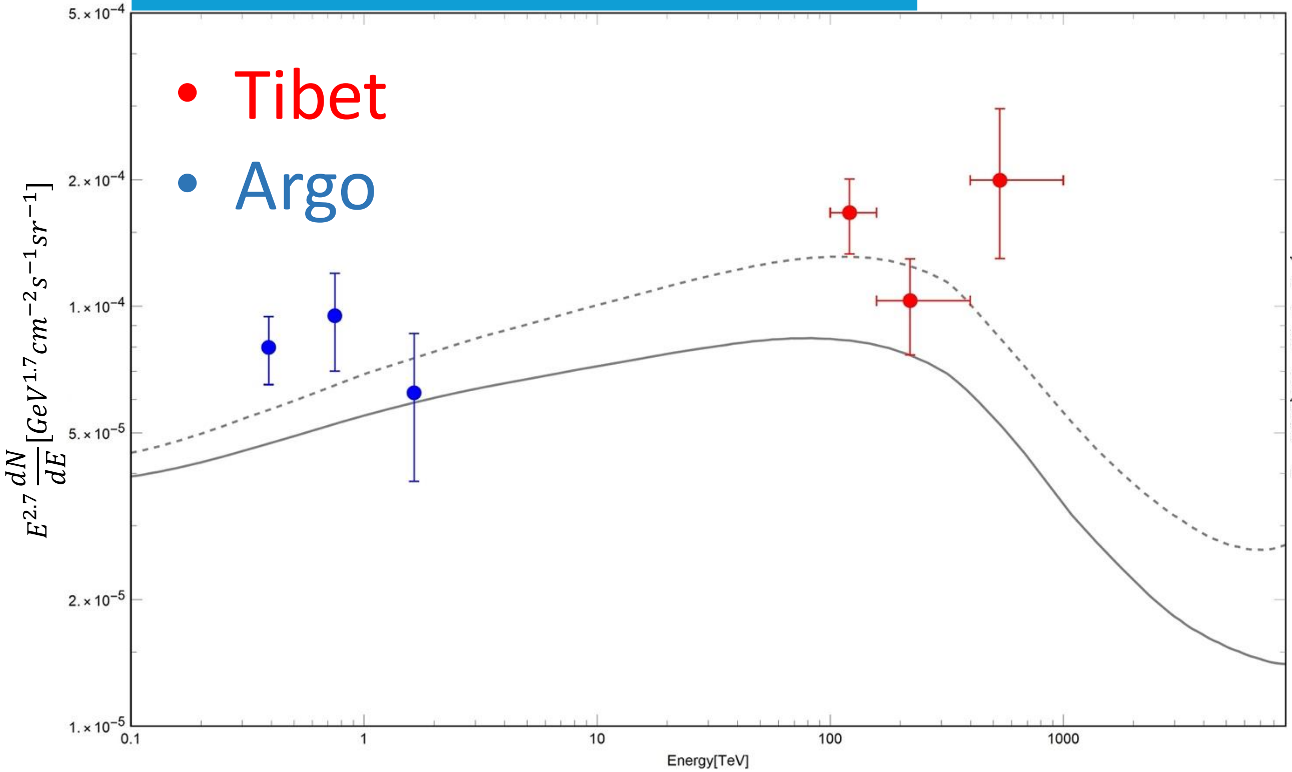
#1 Take-home message:
Diffuse gamma-rays probe the proton flux at the knee

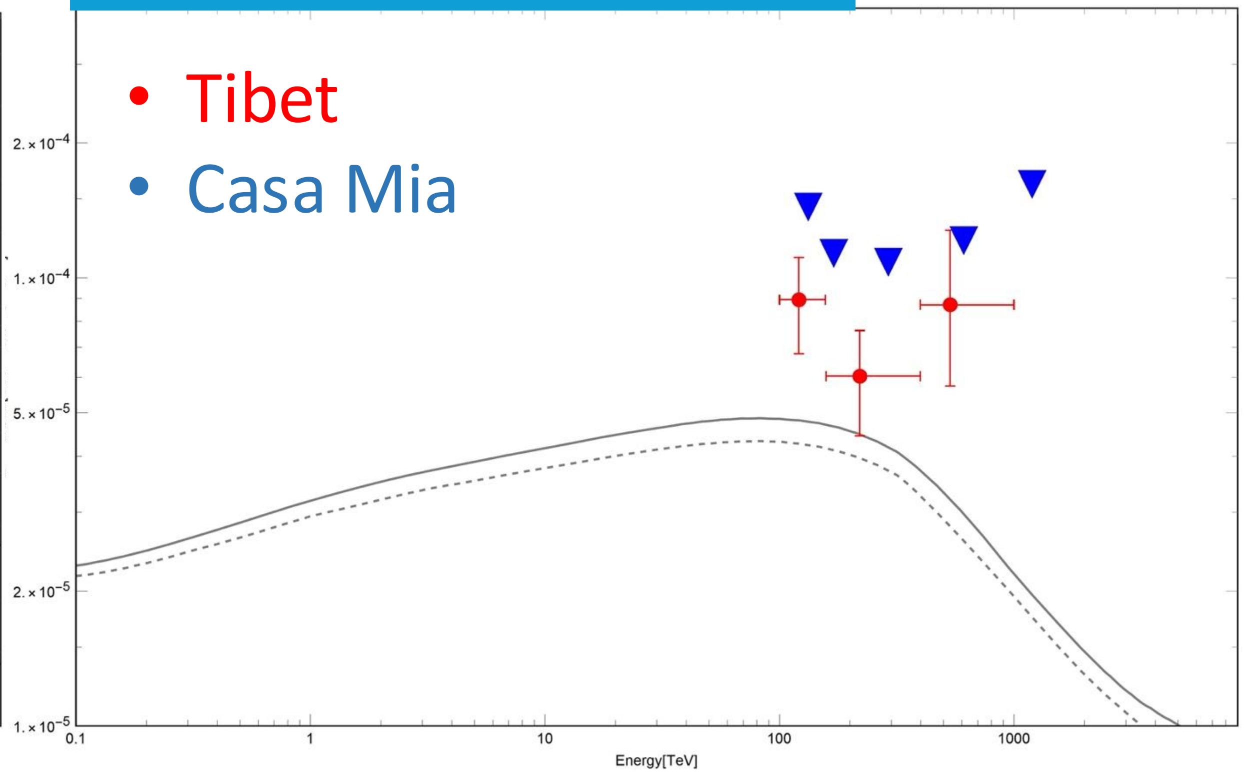


Diffuse Galactic HE gamma-ray from TIBET-AS:

$25° < l < 100°, |b| < 5°$



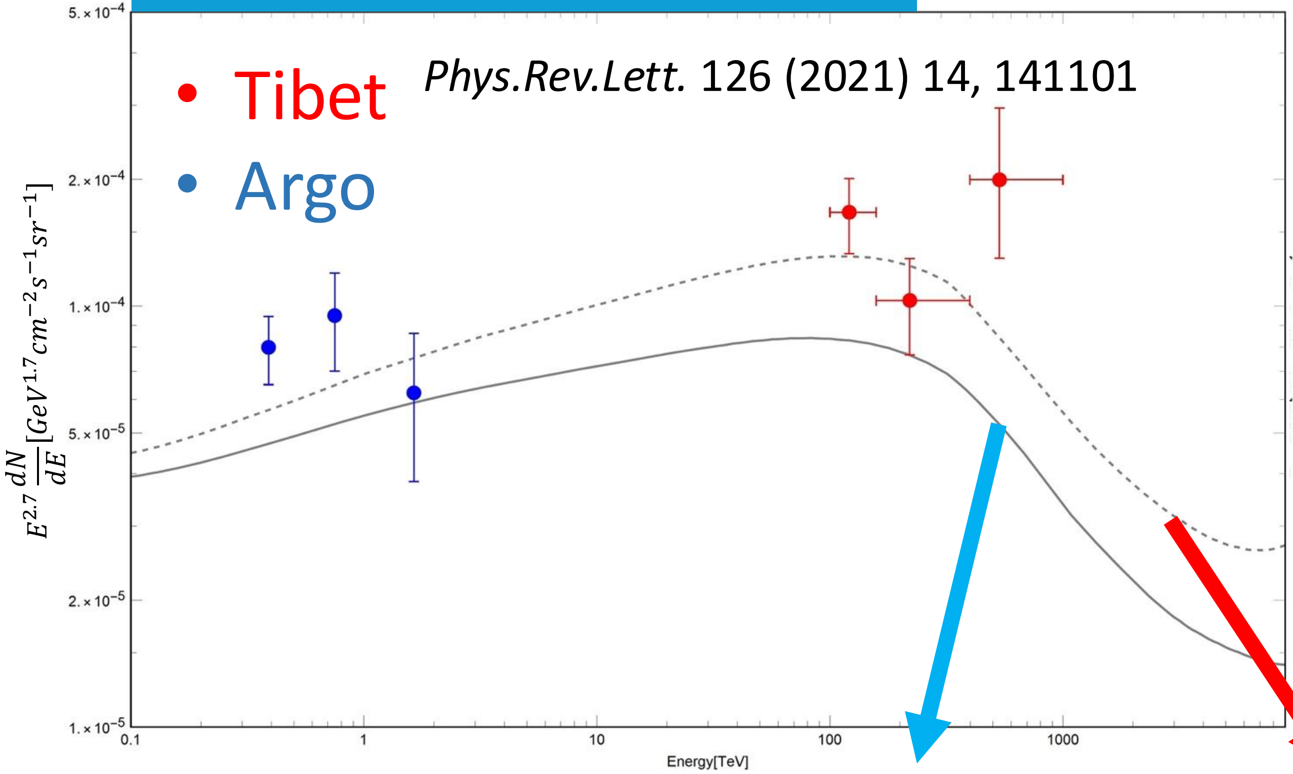
$50° < l < 200°, |b| < 5°$



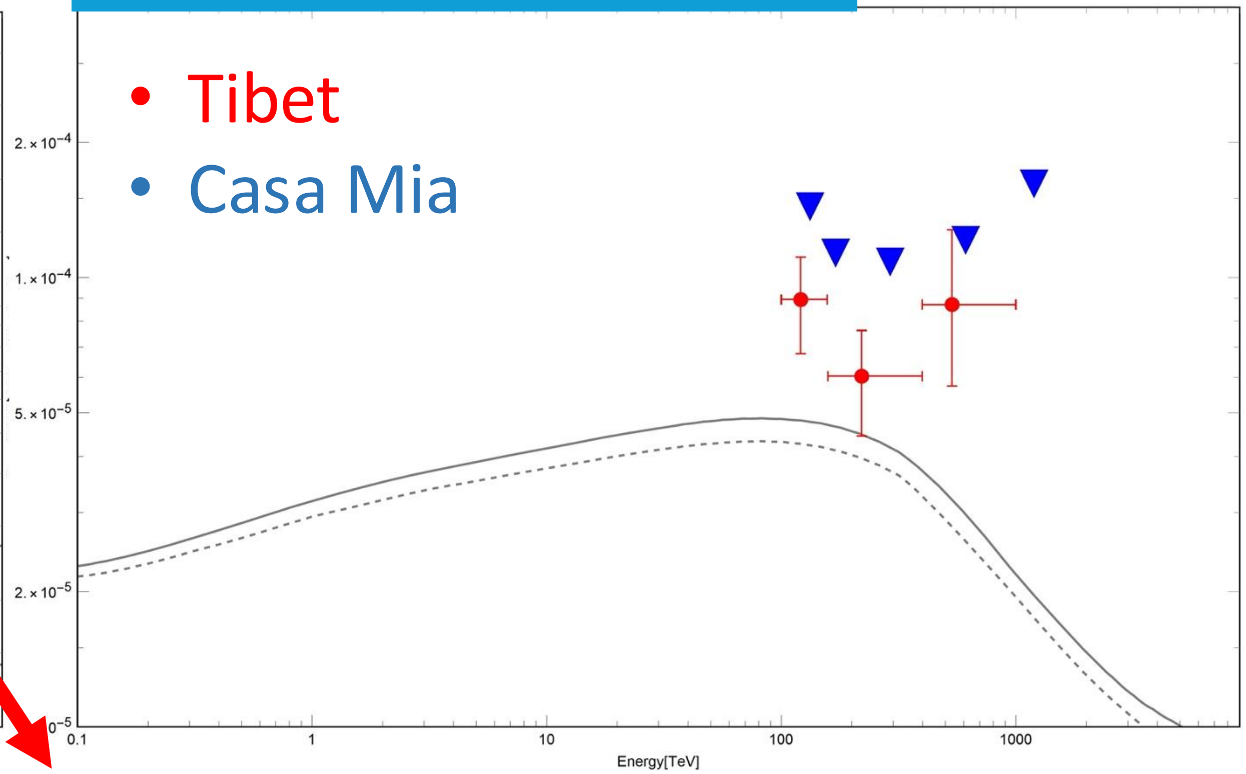
Tibet As-gamma, Phys.Rev.Lett. 126 (2021) 14, 141101
Lipari & Vernetto, Phys.Rev.D 98 (2018) 4, 043003

Diffuse Galactic HE gamma-ray models vs data:

$25° < l < 100°, |b| < 5°$



$50° < l < 200°, |b| < 5°$



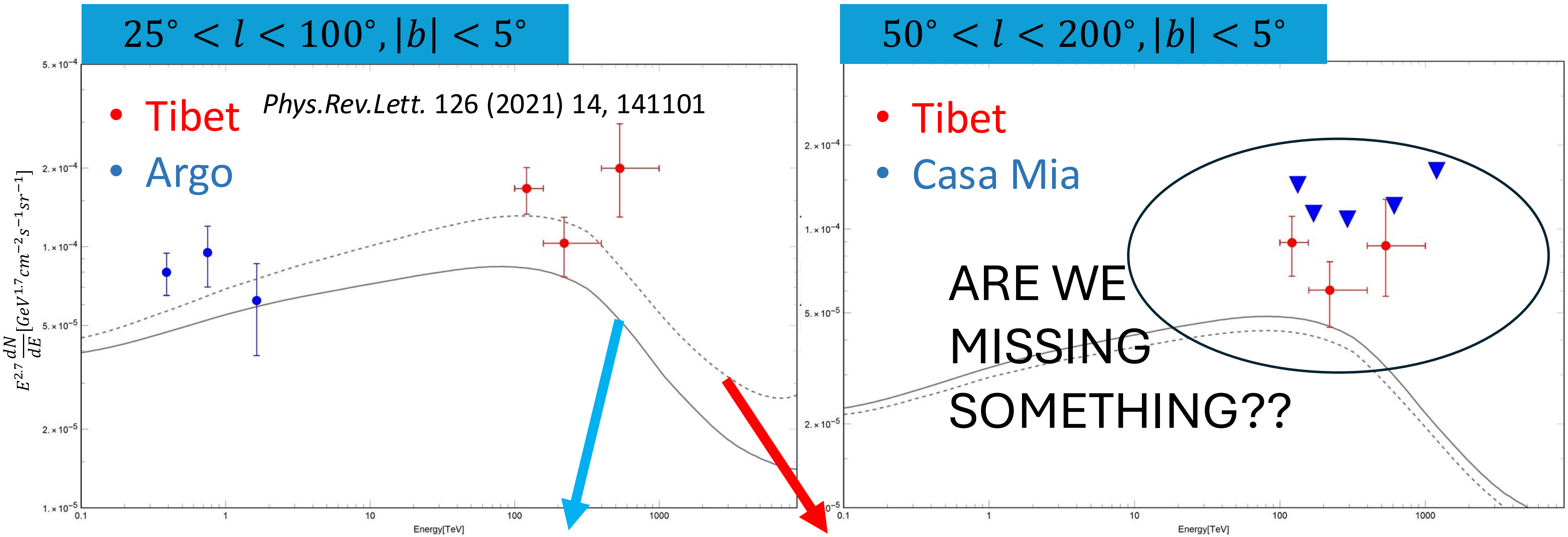
• Standard Case (Solid line)

The Spectrum of the CR is uniform inside the Galaxy and corresponds to the one we measure at the Earth

• Hardening Case (Dashed line)

The Spectrum of CR changes inside the Galaxy and becomes harder toward the inner Galaxy

Diffuse Galactic HE gamma-ray models vs data:



- **Standard Case (Solid line)**

The Spectrum of the CR is uniform inside the Galaxy and corresponds to the one we measure at the Earth

- **Hardening Case (Dashed line)**

The Spectrum of CR changes inside the Galaxy and becomes harder toward the inner Galaxy

Galactic High-Energy Gamma Sources

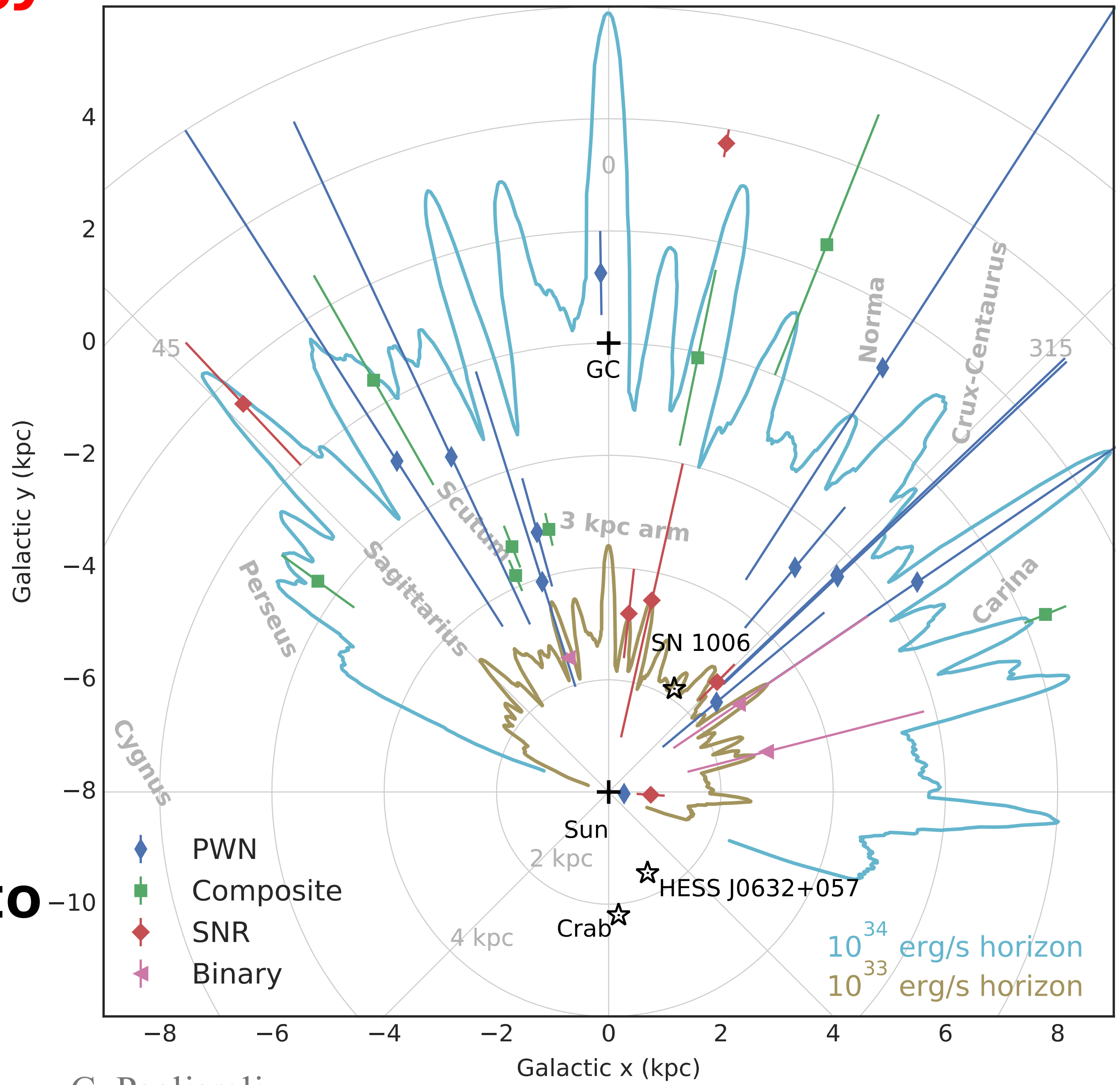
Source component includes the contribution of all the Galactic hadronic gamma-ray sources **both** **resolved** **and** **unresolved** by gamma-ray detectors

Sources catalogs

Sources Population study based on HGPS catalog of H.E.S.S.

Pagliaroli *et al.*, *Universe* 9 (2023) 9, 381
Cataldo et al., *Astrophys.J.* 904 (2020) 2, 85
Steppa *et al.*, *Astron.Astrophys.* 643 (2020) A137

The Total flux contribution due to unresolved sources is not negligible

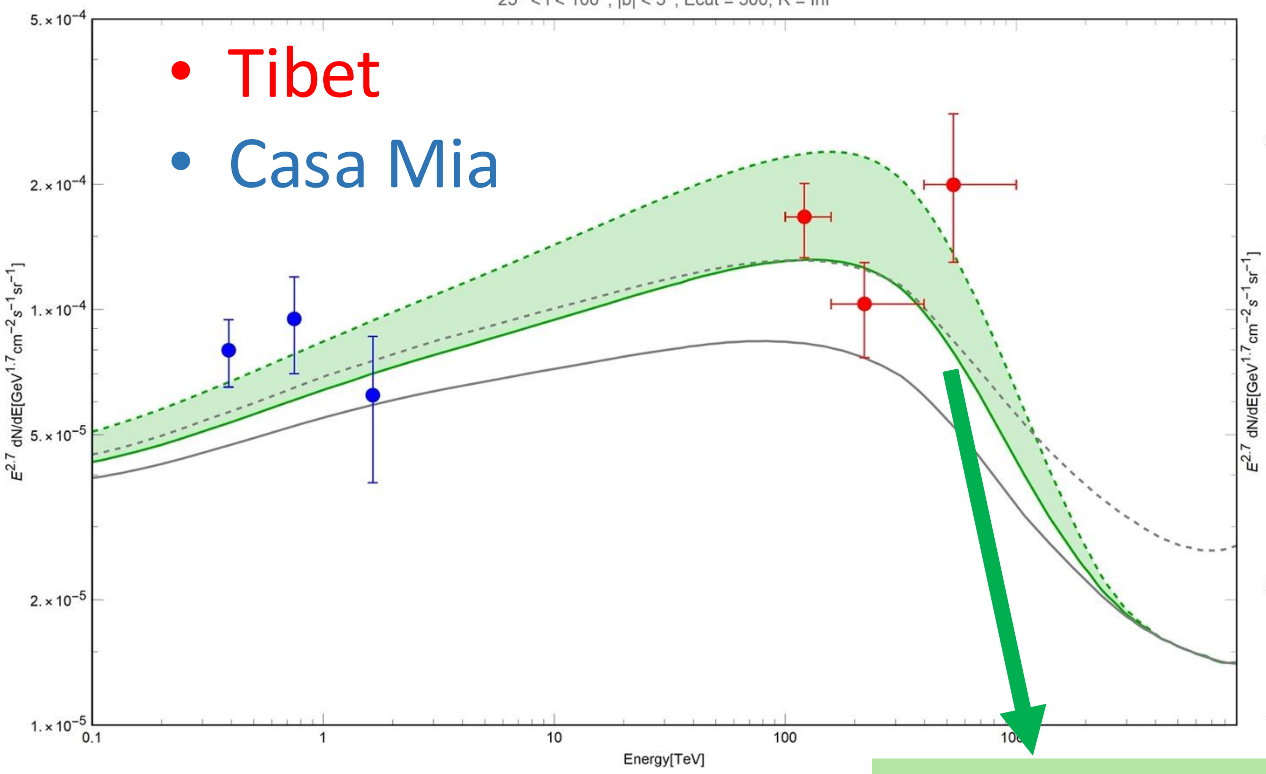


G. Pagliaroli

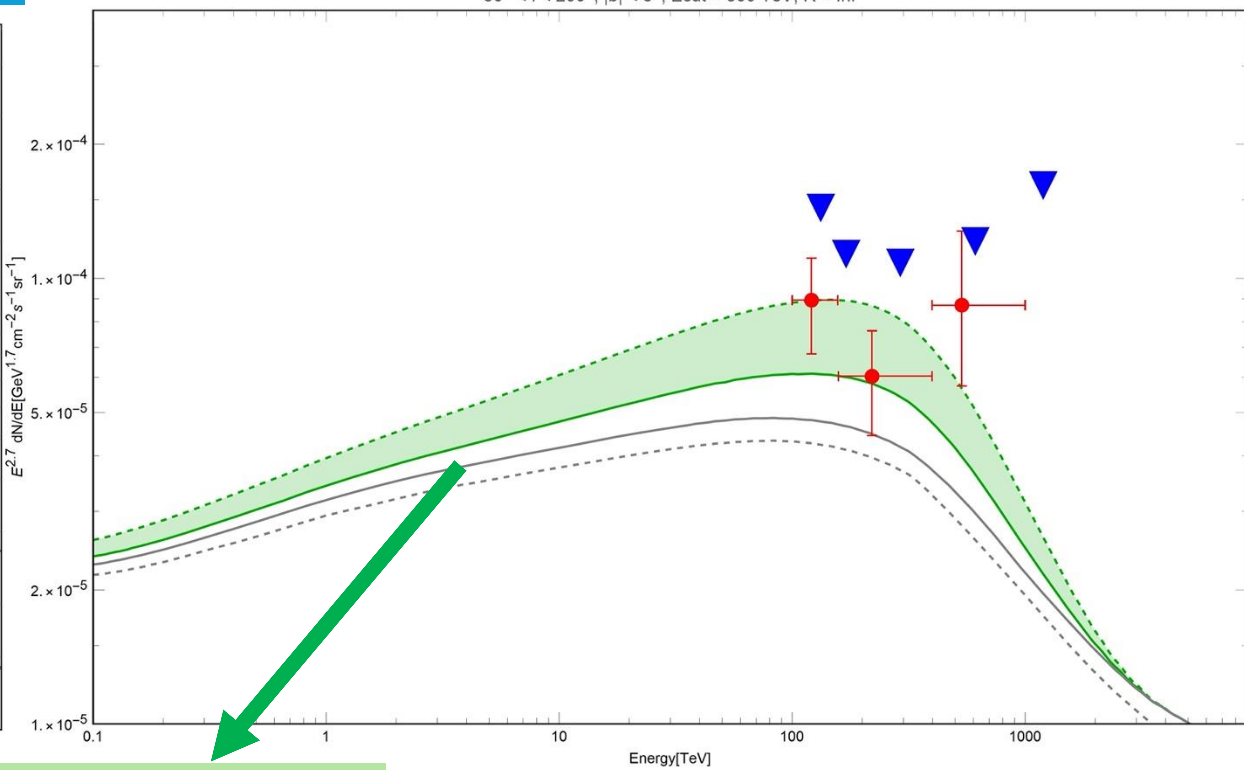
Tibet ASγ : We add the contribution of unresolved sources to the truly diffuse emission without the hypothesis of CR spectral hardening.

Vecchiotti et al. *Astrophys.J.* 928 (2022) 1, 19

$25° < l < 100°, |b| < 5°, E_{cut} = 500\ TeV$



$50° < l < 200°, |b| < 5°, E_{cut} = 500\ TeV$

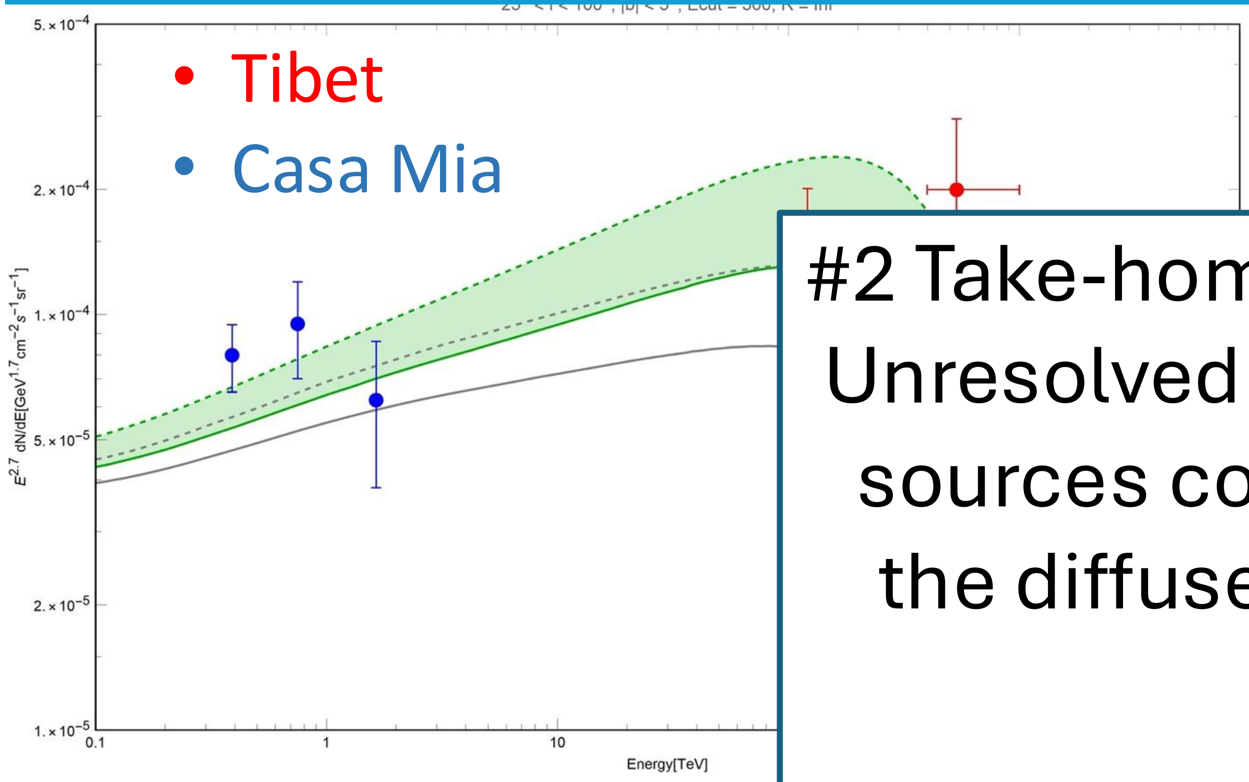


Standard case +
Unresolved PWNe sources

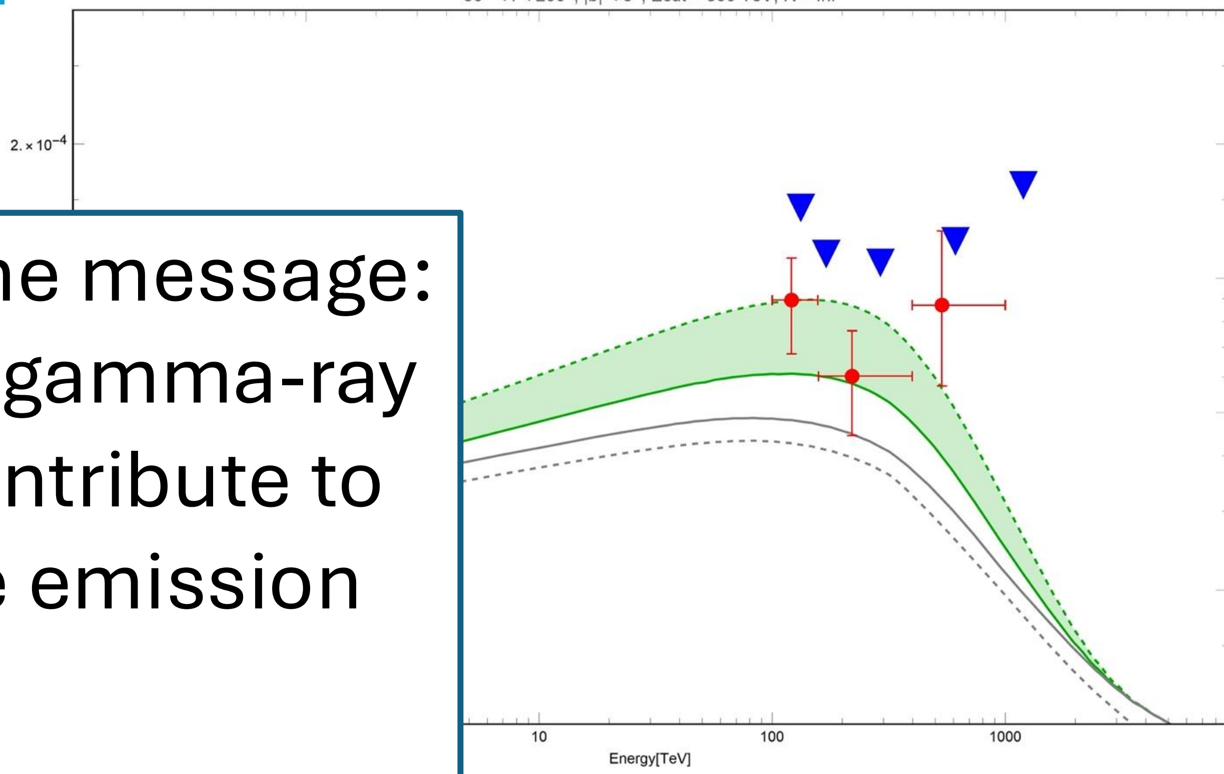
Tibet ASγ : We add the contribution of unresolved sources to the truly diffuse emission without the hypothesis of CR spectral hardening.

Vecchiotti et al. *Astrophys.J.* 928 (2022) 1, 19

$25° < l < 100°, |b| < 5°, E_{cut} = 500\ TeV$



$50° < l < 200°, |b| < 5°, E_{cut} = 500\ TeV$



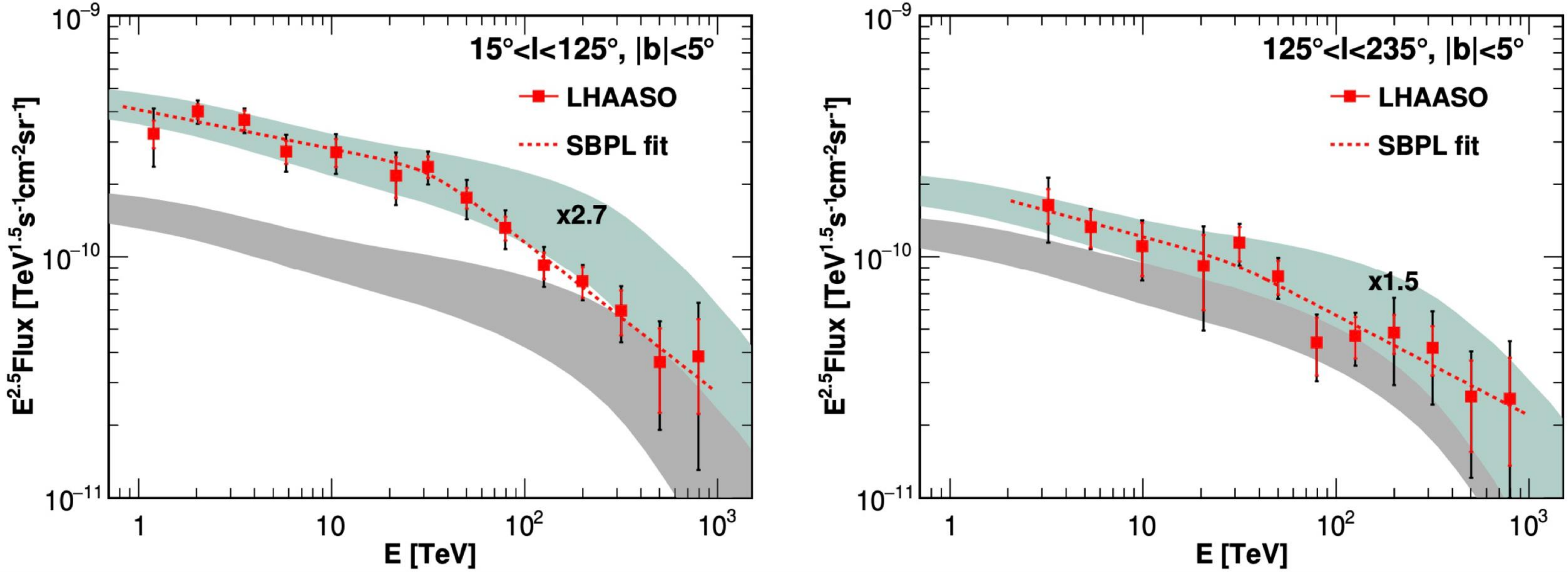
#2 Take-home message: Unresolved gamma-ray sources contribute to the diffuse emission

See also **P. Lipari & S. Vernetto, PRD 111, 063035 (2025)**

LHAASO brings the diffuse Galactic emission into the PeV domain

Cao et al., LHAASO Coll., Phys. Rev. Lett. 134, 081002 (2025)

November 2024

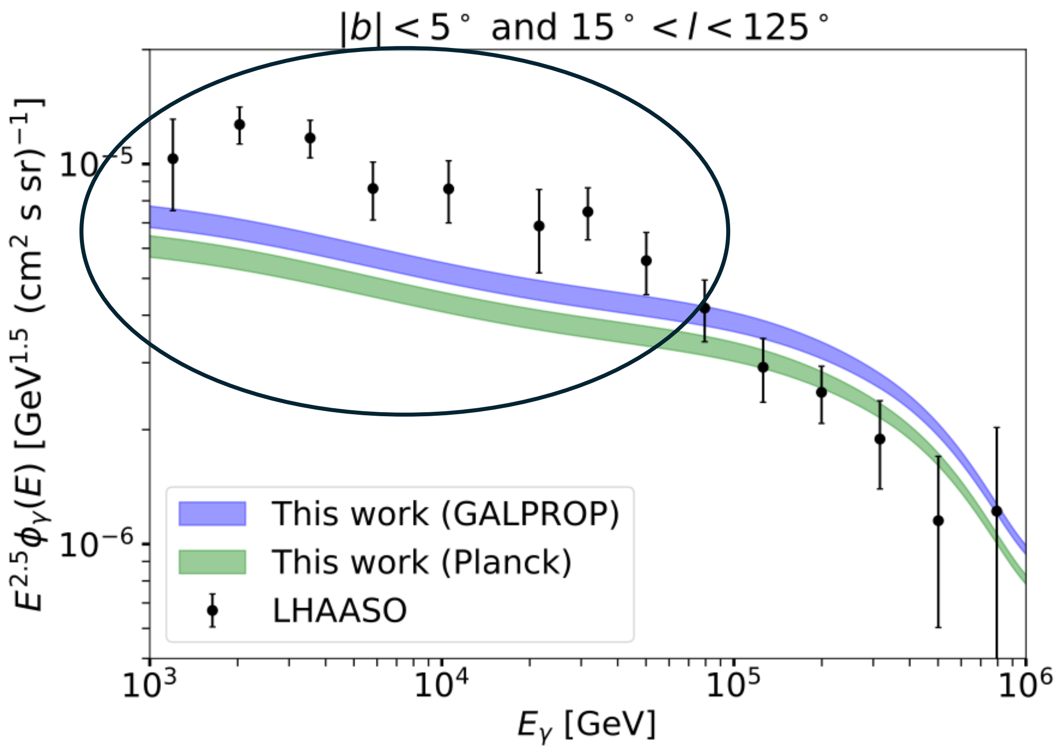


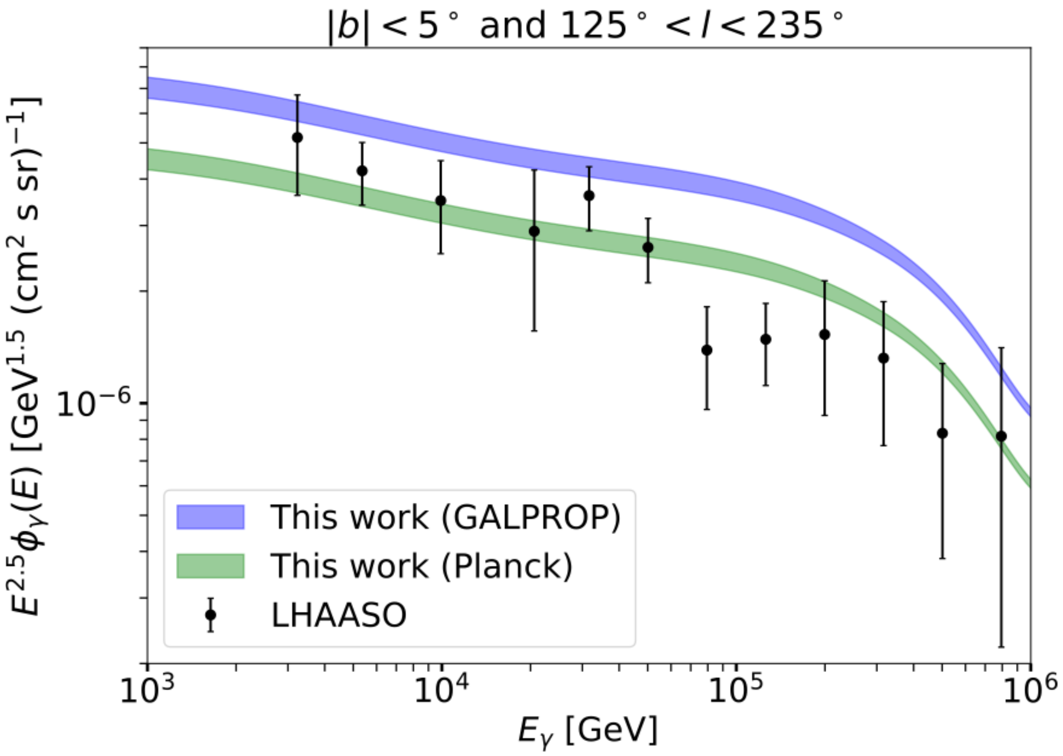
LHAASO reports an excess relative to the adopted baseline prediction (gray band)

Using LHAASO protons to predict LHAASO gamma rays

Espinosa Castro *et al.* *Mon.Not.Roy.Astron.Soc.L* 20 (2025) L26

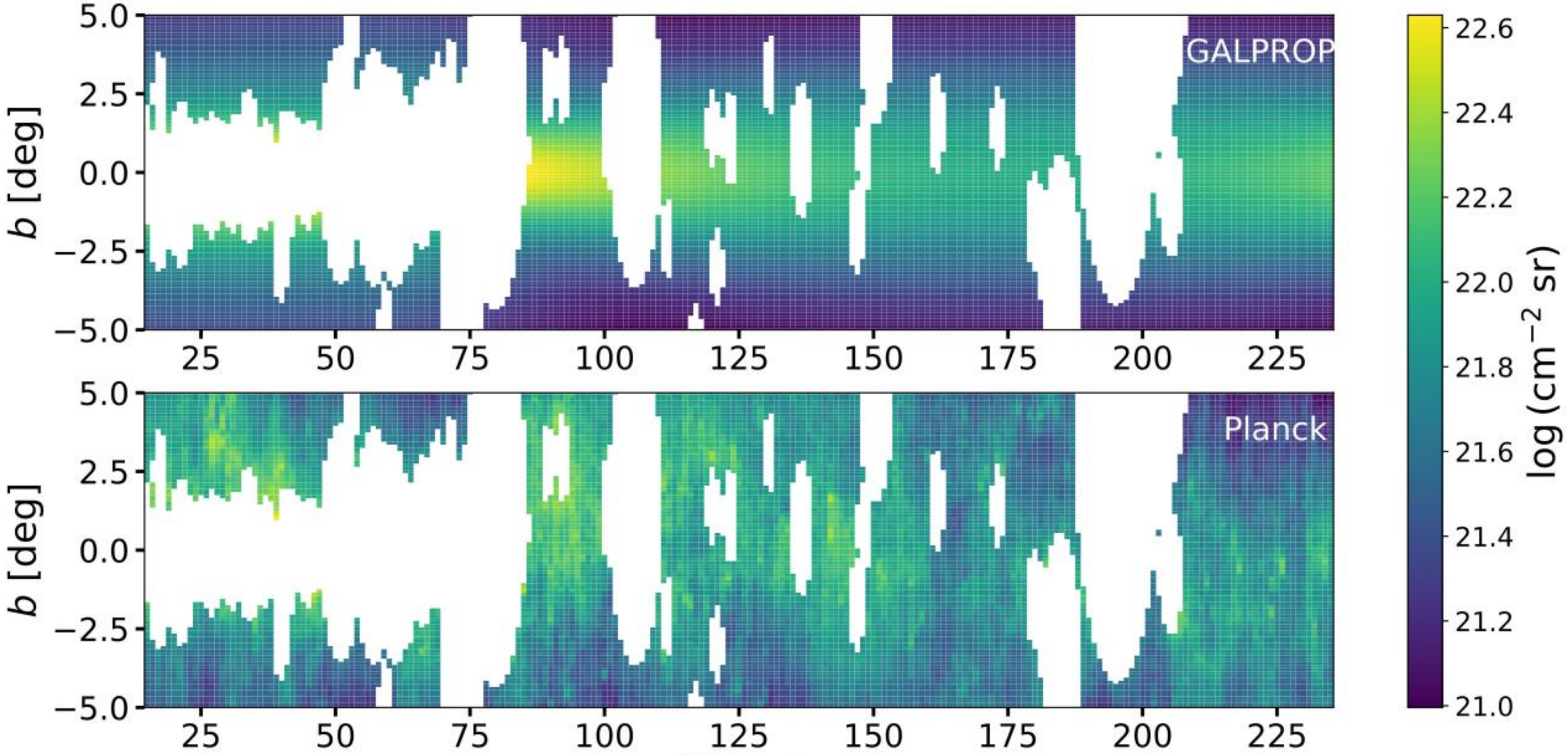
- **Inner Galaxy:** tension mainly at lower energies.
- **Outer Galaxy:** the normalization changes significantly with the gas template





Planck column density template 20 % lower in inner region and 40% lower in lateral region

Taking into account the LHAASO MASK



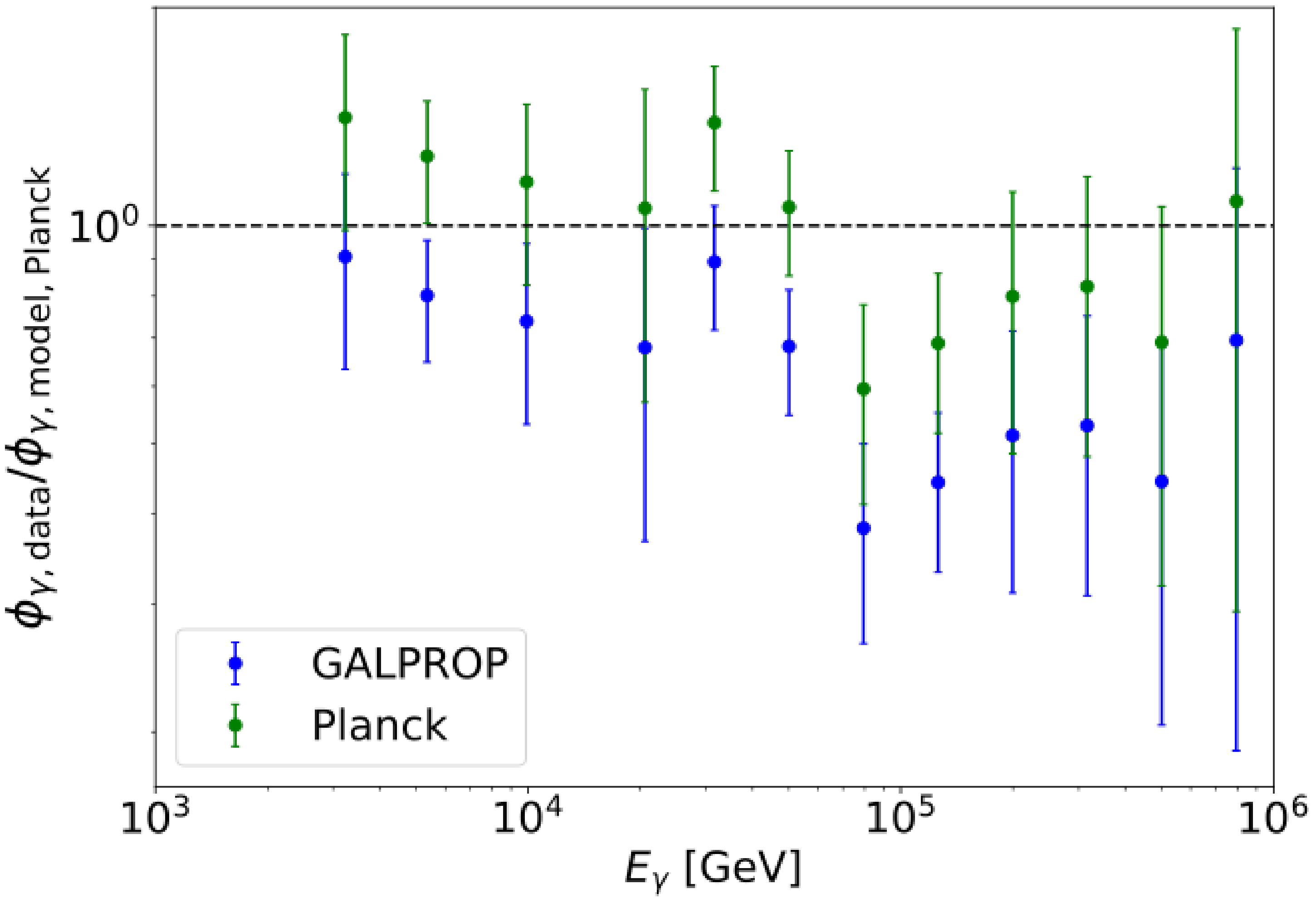
The presence of an hardening of CR spectrum toward the GC is also negligible in the inner Lhaaso region due to the mask

Ref: He et al. Astrophys.J. 991 (2025) 1, 4.
He et al. Astrophys.J. 980 (2025) 1, 17.
Vecchiotti et al., JCAP 09 (2025) 041
Kaci et al., Astrophys.J. 975 (2024) 1, L6
Menchiari et al., Astron.Astrophys. 695 (2025) A175
Ambrosone et al. Astron.Astrophys. 698 (2025) L18
etc.

Unresolved Sources are distributed on the plane and their contribution is nearly destroied by the mask in the inner Lhaaso region

The tension is spectral, not only in normalization

- LHAASO proton knee overshoots the diffuse gamma-ray flux at E>30 TeV in LHAASO outer Galactic region.
- Diffuse flux presents a break at 30 TeV, not naturally matching the knee at 4 PeV (LHAASO Coll., Phys. Rev. Lett. 134, 081002 (2025)).



What if the proton knee is partly local?

$$\boxed{\Phi_p^{\mathrm{Earth}}(E) = \Phi_p^{\mathrm{Galactic\ sea}}(E) + \Phi_p^{\mathrm{local}}(E)}$$

Diffuse γ rays
probe the CR population
along Galactic lines of sight

Direct CR measurements
probe the CR spectrum
here, at Earth

A nearby source could enhance the PeV proton flux measured at Earth without producing the same enhancement in gamma-ray throughout the Galaxy.

Ambrosone et al., A&A 698, L18 (2025)
Fang & Halzen, ApJL 999, L13 (2026)
S. Kaci, G. Giacinti, F. Aharonian, J.-S. Wang, arXiv:2510.01369 (2025)

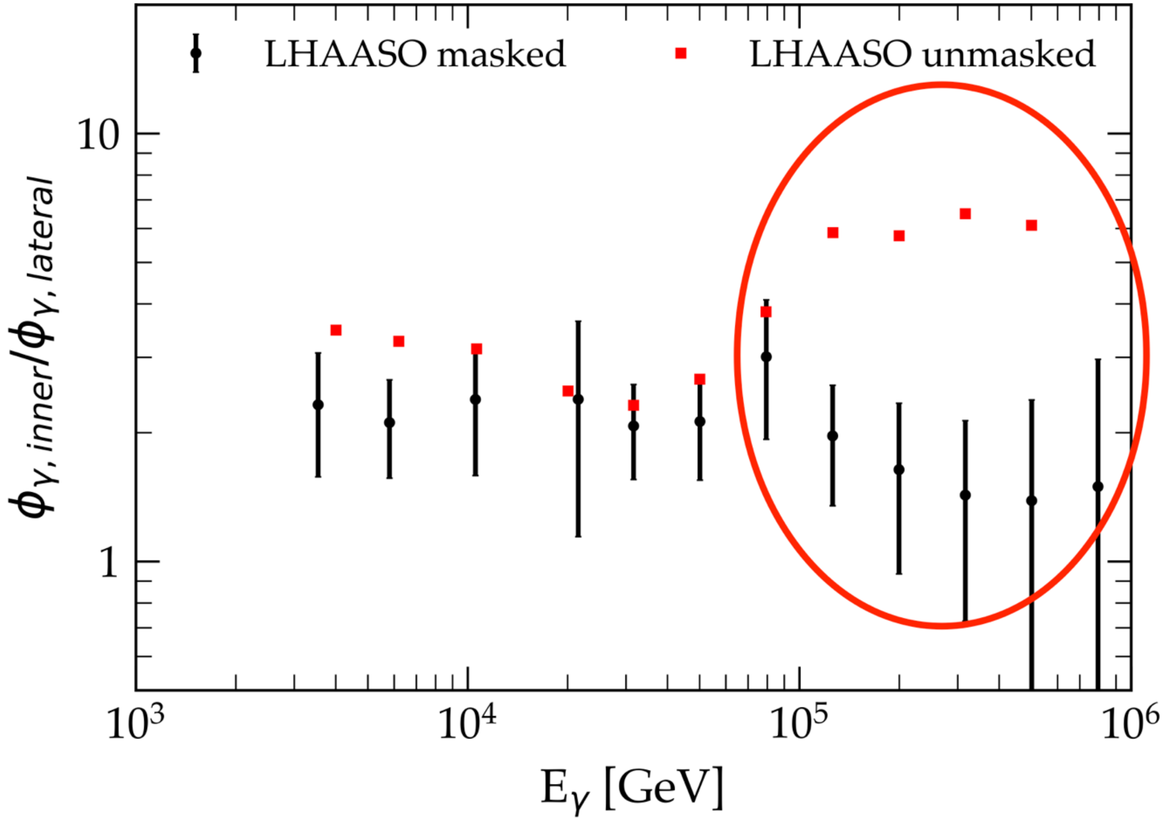
HE Gamma-ray measurements of different sky regions can probe this hypothesis

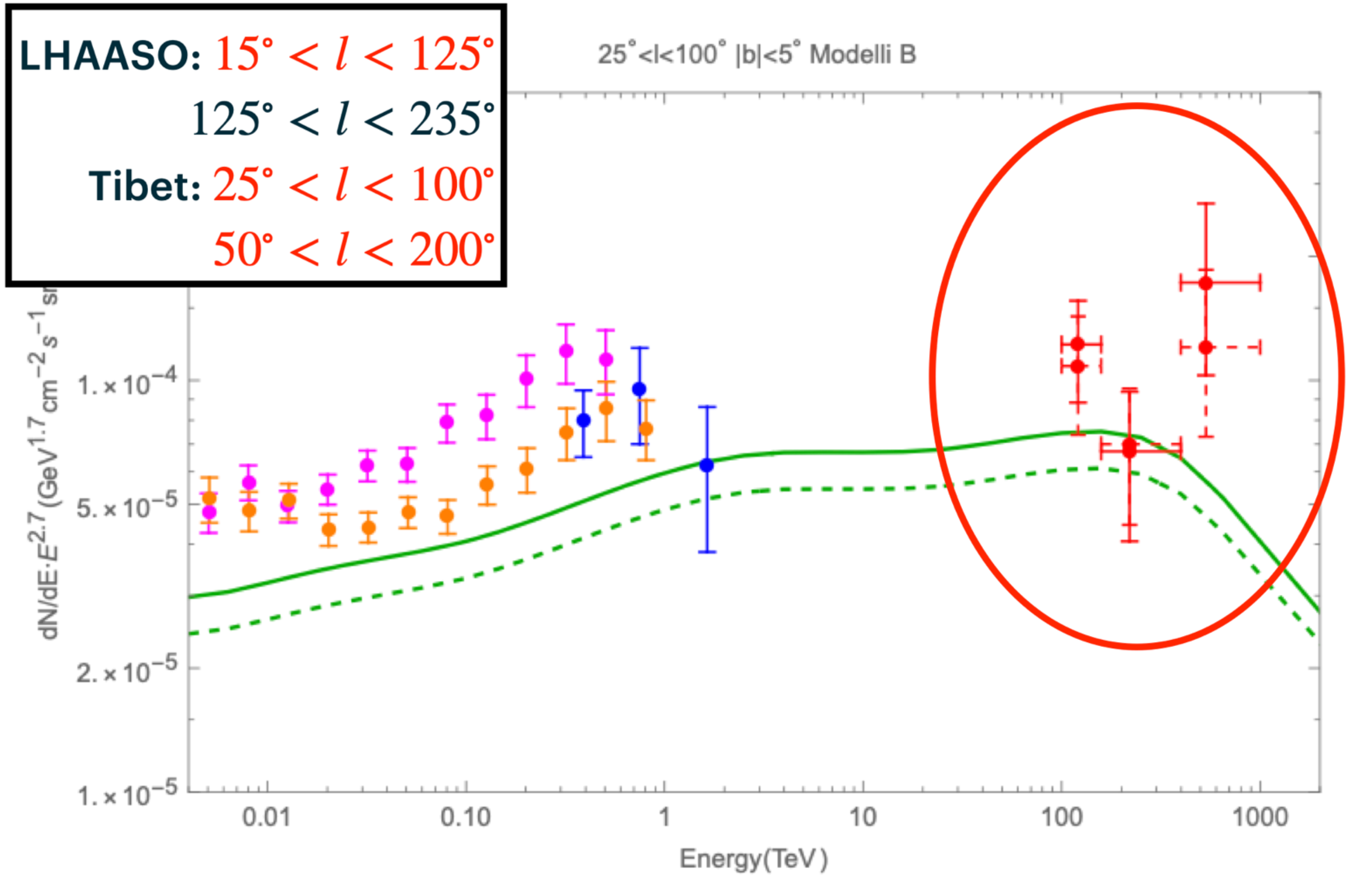
Different sky regions to test the local-knee hypothesis

Kato et al., arXiv:2411.11524

- Inner Galactic region contains a $E_\gamma \gtrsim 100\,\mathrm{TeV}$ component, possibly associated to PeVatron contribution.

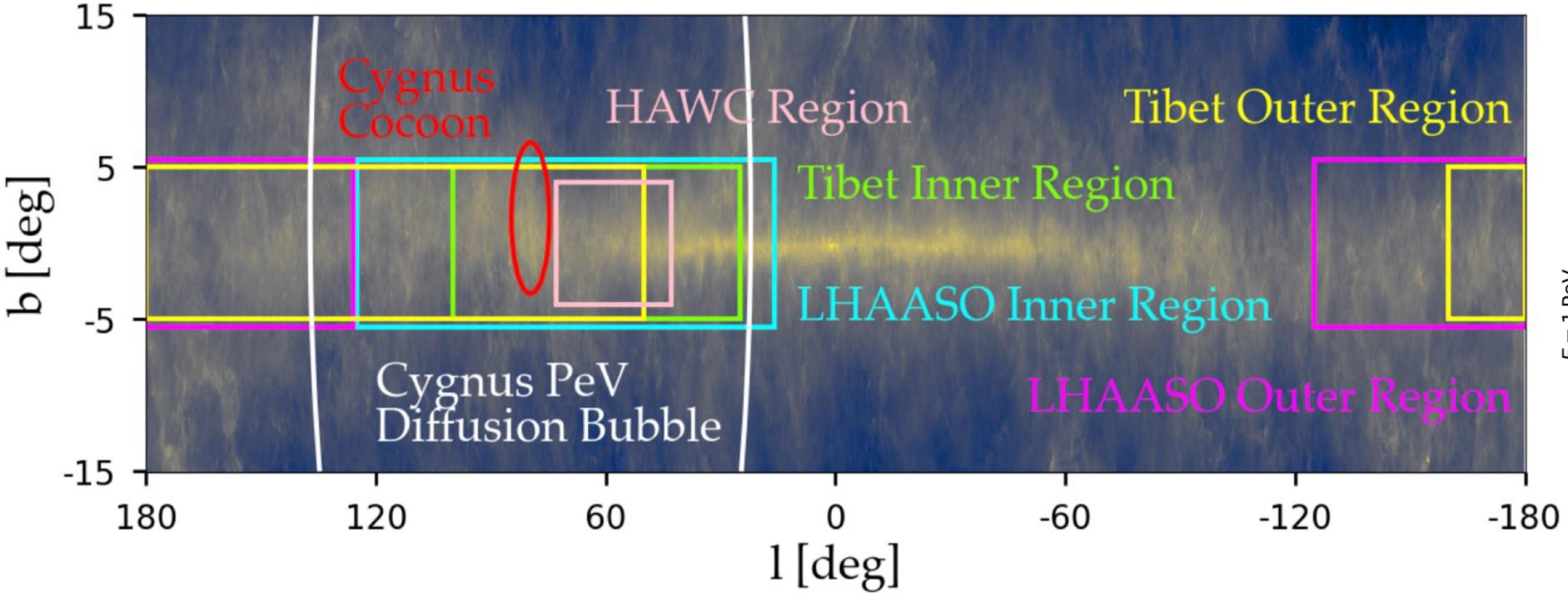
- Another experiment, Tibet ASγ, does not find a similar excess. But the two sky regions probed by Tibet ASγ overlap with LHAASO inner region.

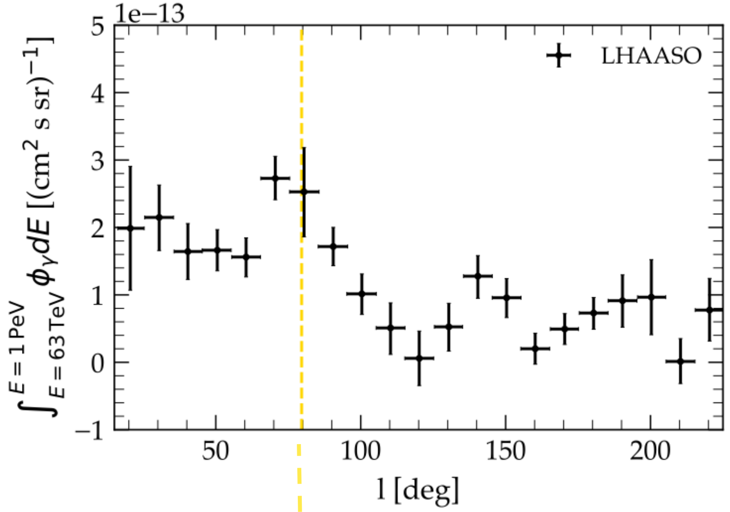


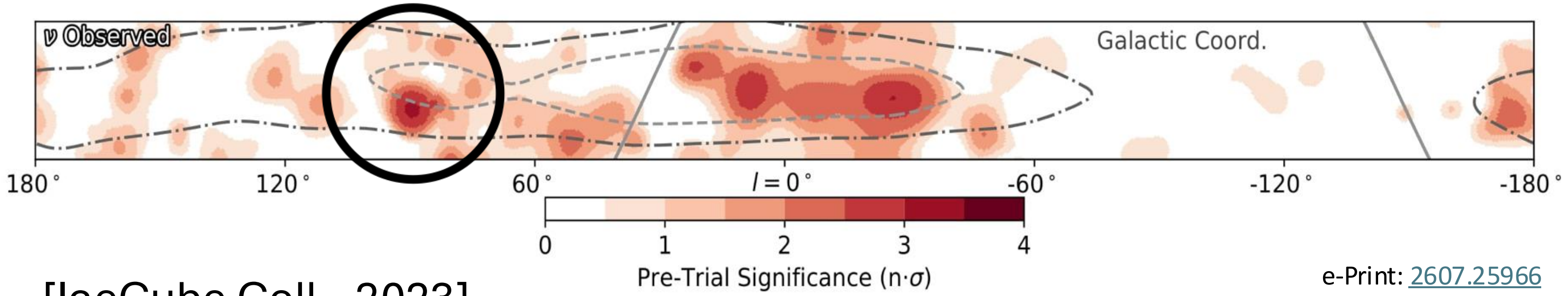


“Why Cygnus?

Cygnus is a sky region in common for all VHE gamma-ray observatories.
Neutrino observations along Galactic Plane by IceCube show a slightly higher-significance in the same sky region.
Longitudinal profile of gamma-rays show an small excess in Cygnus region only at the highest energies.



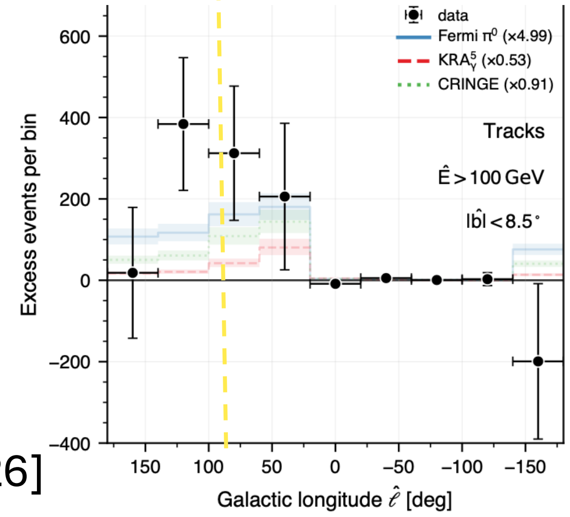




[IceCube Coll., 2023]

e-Print: 2607.25966

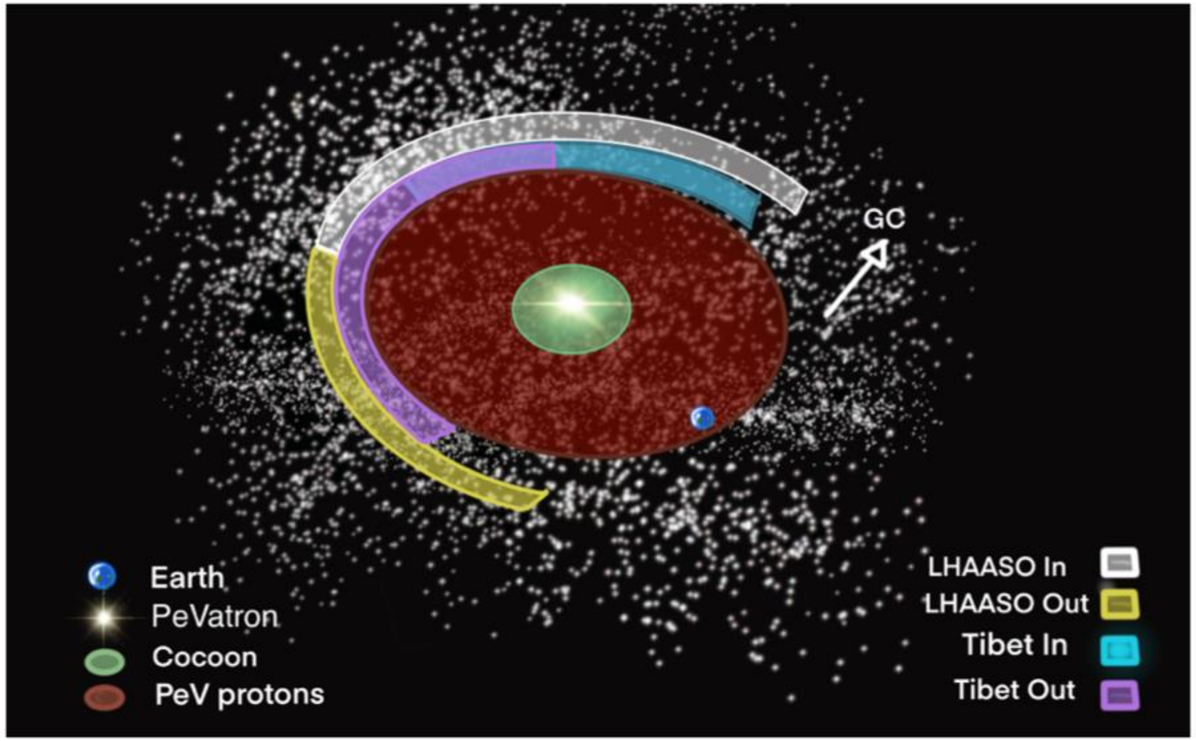
[IceCube Coll., 2026]

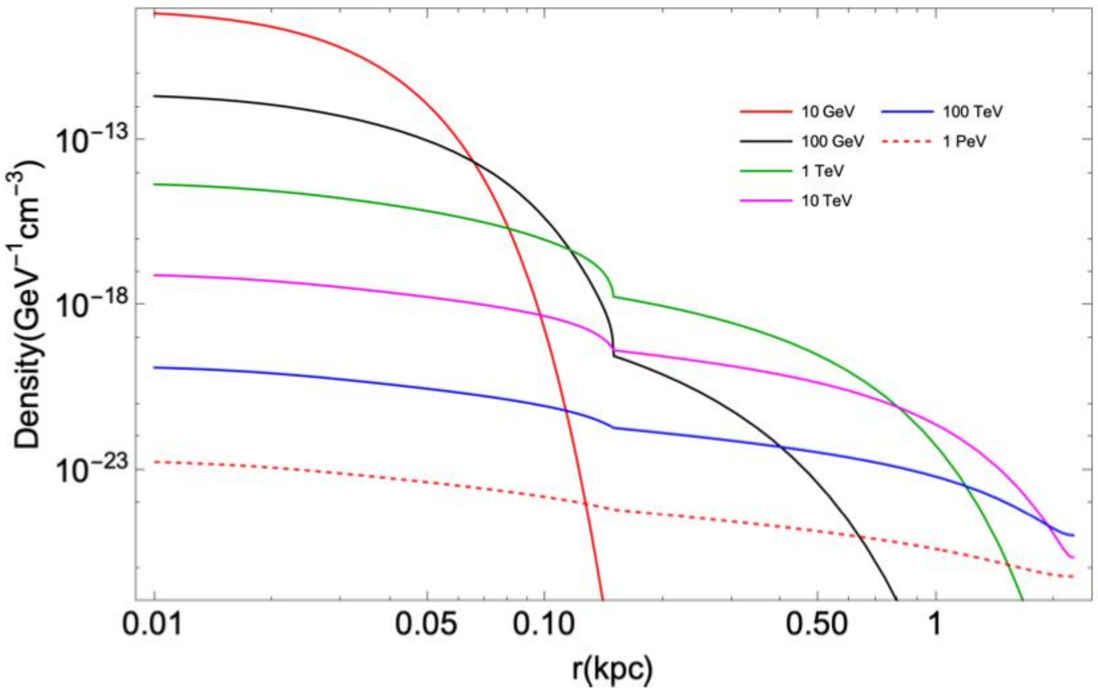


Two CR populations: the Galactic sea and a local PeVatron

- Main idea: Galactic cosmic rays composed of a "low-energy" population (the **CR sea**, associated to SNR) and a "high-energy" contribution from **local PeVatron**.
- LHAASO and TibetASγ suggest such a source could be localised in $\left(50^\circ < l < 100^\circ, |b| < 5^\circ\right)$ region
- **Cygnus region** contains a UHE gamma-ray cocoon at ~ 1.4 kpc from Earth.

Abeysekara et al. (HAWC), Nature Astron. 5, 465 (2021), LHAASO Coll., Sci. Bull. 69, 449 (2024)





The Cygnus Contribution to the Proton Knee

Cygnus proton injection spectrum inferred by gamma-ray emission [**LHAASO Coll., Sci. Bull. 69, 449 (2024)**]

$$L_p = 3 \times 10^{37} \mathrm{erg/s} \qquad \alpha = 2.1$$

CR propagation following a two-zone model:

where $D(r, E_p) = \begin{cases} D_0 (E_p/E_0)^{\delta_0} & 0 < r < r_c, \\ D_1 (E_p/E_0)^{\delta_1} & r \geq r_c, \end{cases}$

Zhan & Wang, MNRAS 525, 5245 (2023)

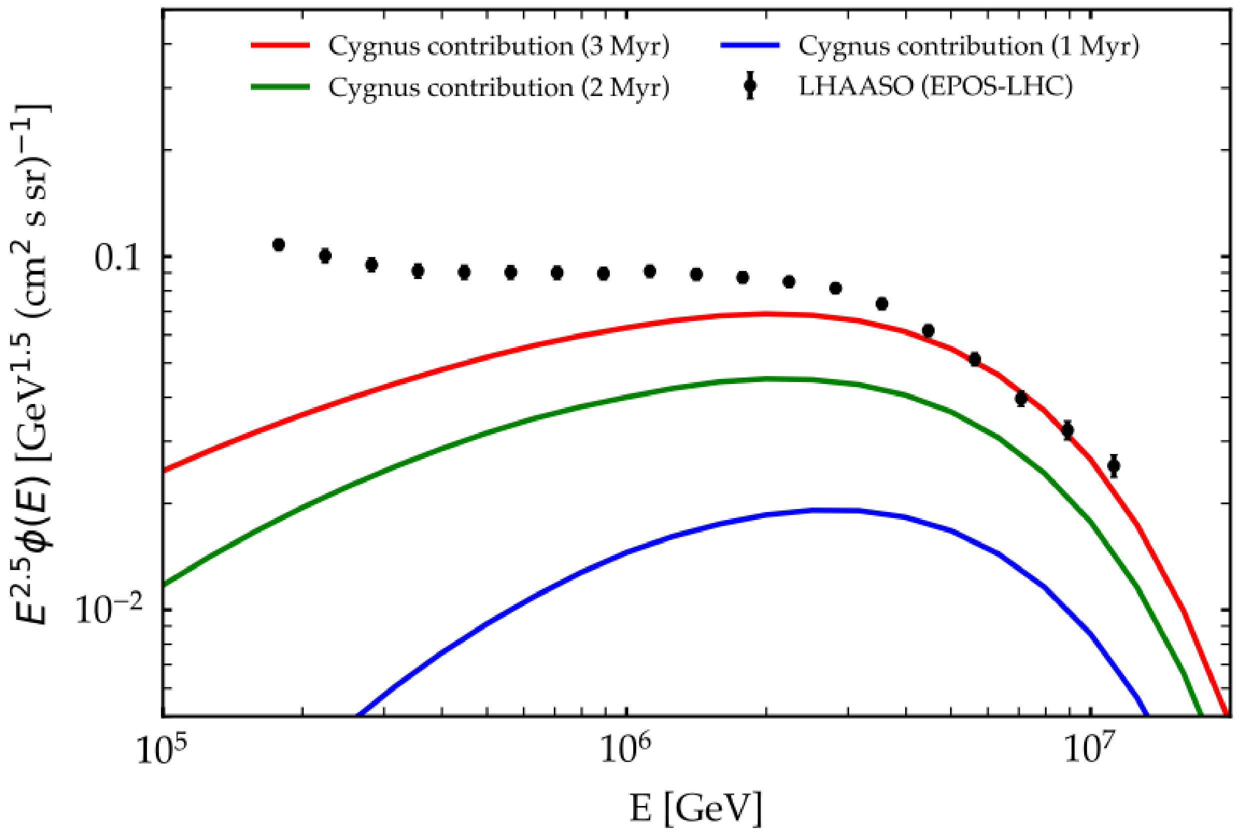
$$r_c = 150 \text{ pc}$$

$$D_0 = 3 \times 10^{26} \text{ cm}^2/\text{s} \quad \delta_0 = 0.7 \quad E_0 = 1\text{TeV}$$

$$D_1 = 10^{28} \text{cm}^2/\text{s} \qquad \delta_1 = 1/3$$

Solution to transport equation.

$$E_{cut} \simeq 5\text{PeV} \quad t_{age} = 3\text{Myr}$$

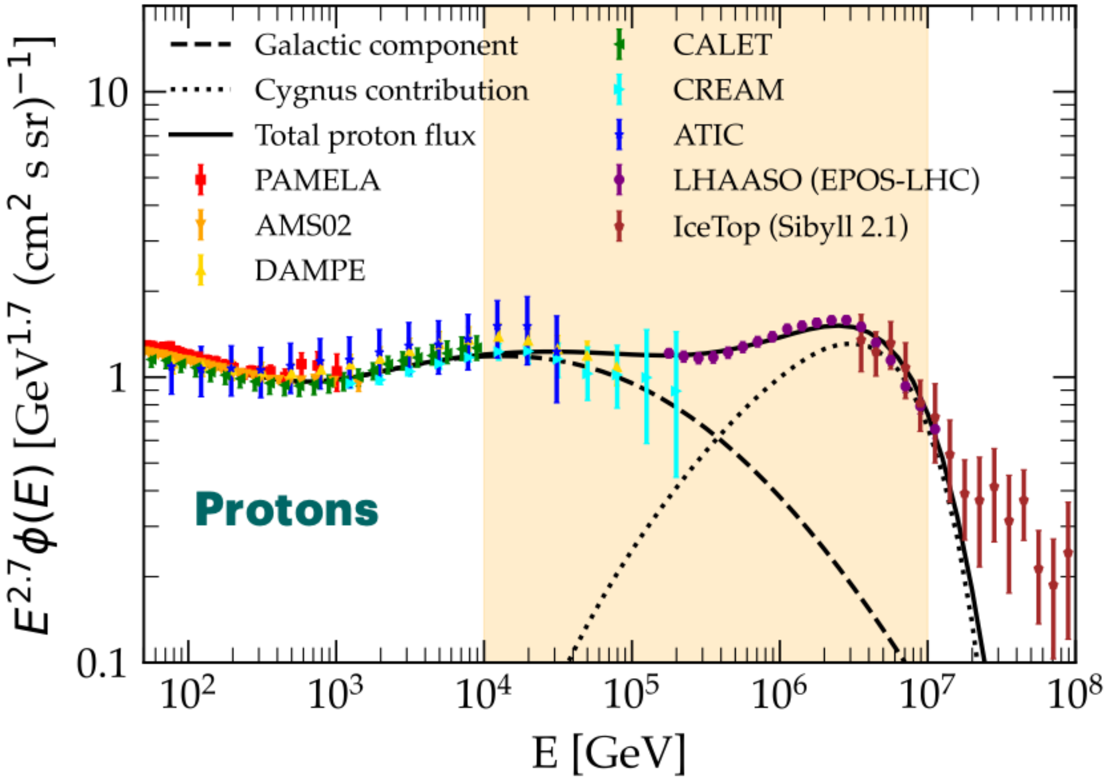


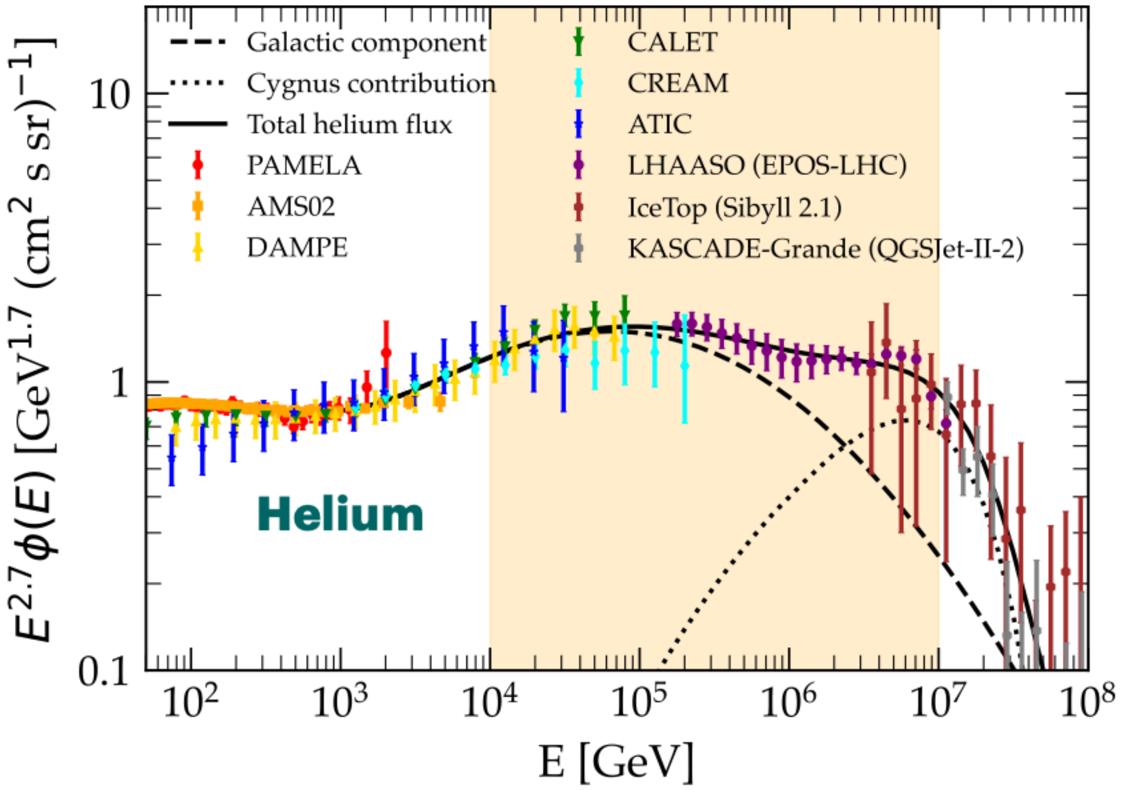
Cygnus proton flux dominates the «knee»

Galactic Cosmic Rays

"CR sea" flux modelled as $\phi_p^{\mathrm{Gal}}(E_p) = N\left(\frac{E_p}{\bar{E}}\right)^{-\alpha_1} \Pi_i \left[1 + \left(\frac{E_p}{E_{b,i}}\right)^{\frac{1}{\omega_i}}\right]^{-\Delta\alpha_i \omega_i}$

Then, total CR proton flux at Earth is $\phi_p(E_{\mathrm{n}}, \mathbf{r}_\odot) = \phi_p^{\mathrm{Cyg}}(E_{\mathrm{n}}, \mathbf{r}_\odot) + \phi_p^{\mathrm{Gal}}(E_{\mathrm{n}})$



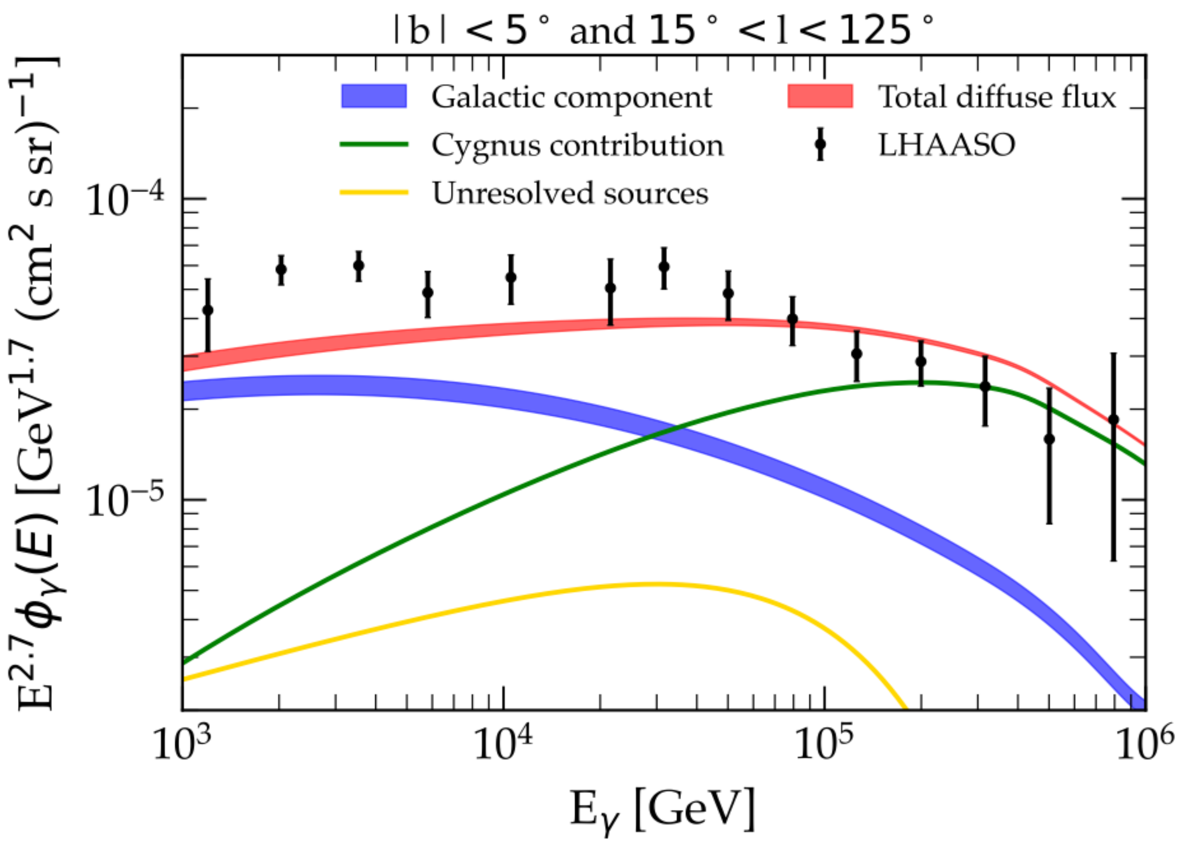


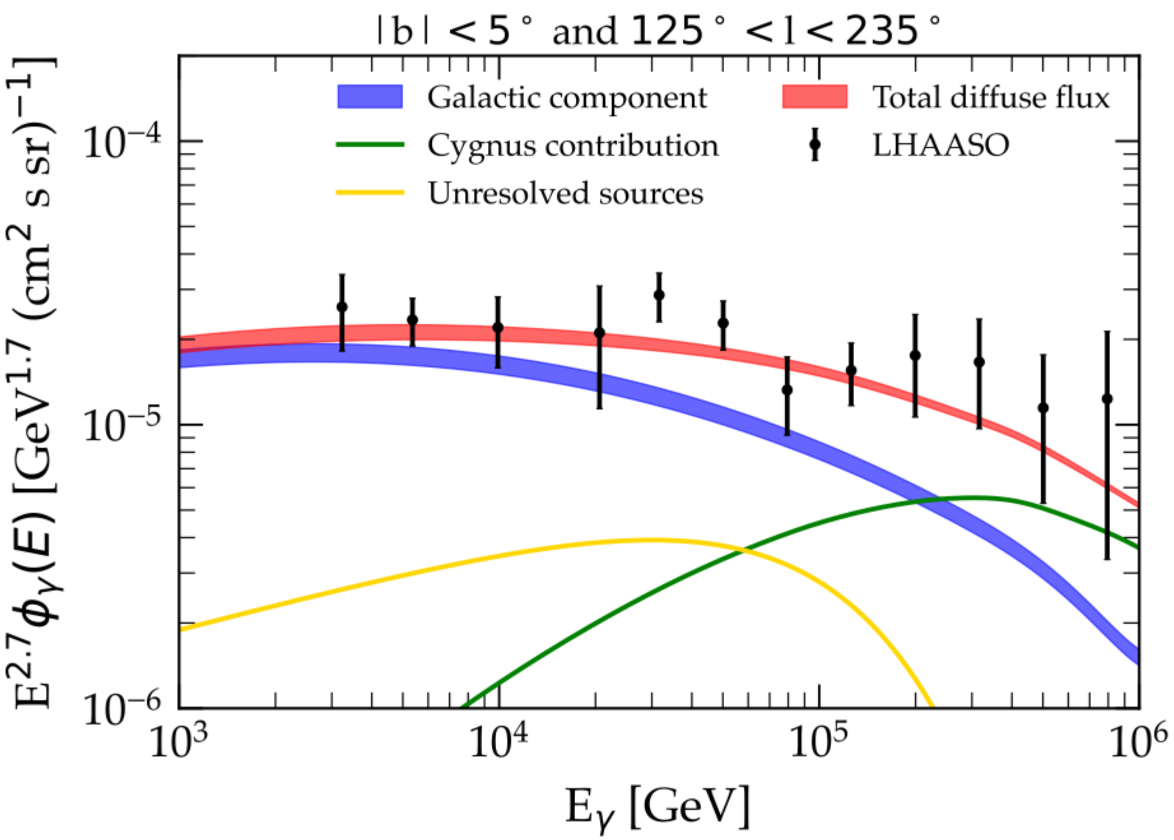
Diffuse Gamma-Ray Emission

Spectrum of diffuse flux in better agreement with VHE observations

Cygnus region contributes mainly to the inner Galactic region

Unresolved sources subdominant in both regions





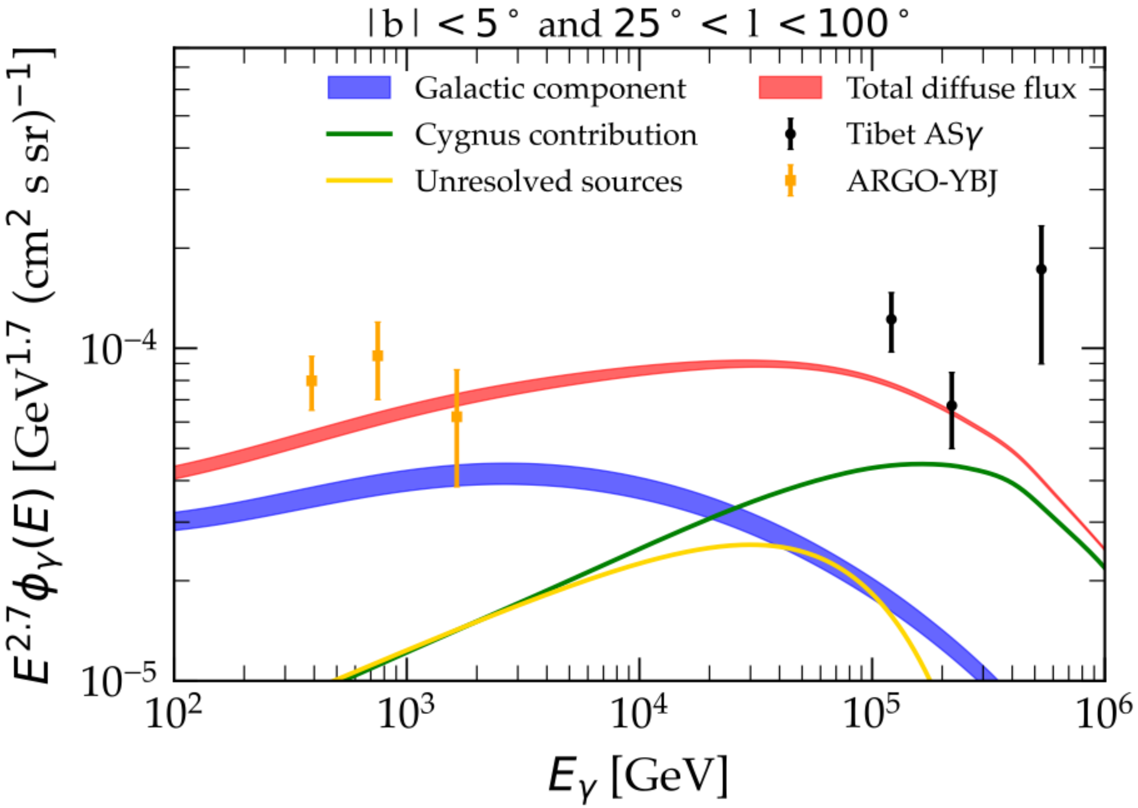
Diffuse Gamma-Ray Emission

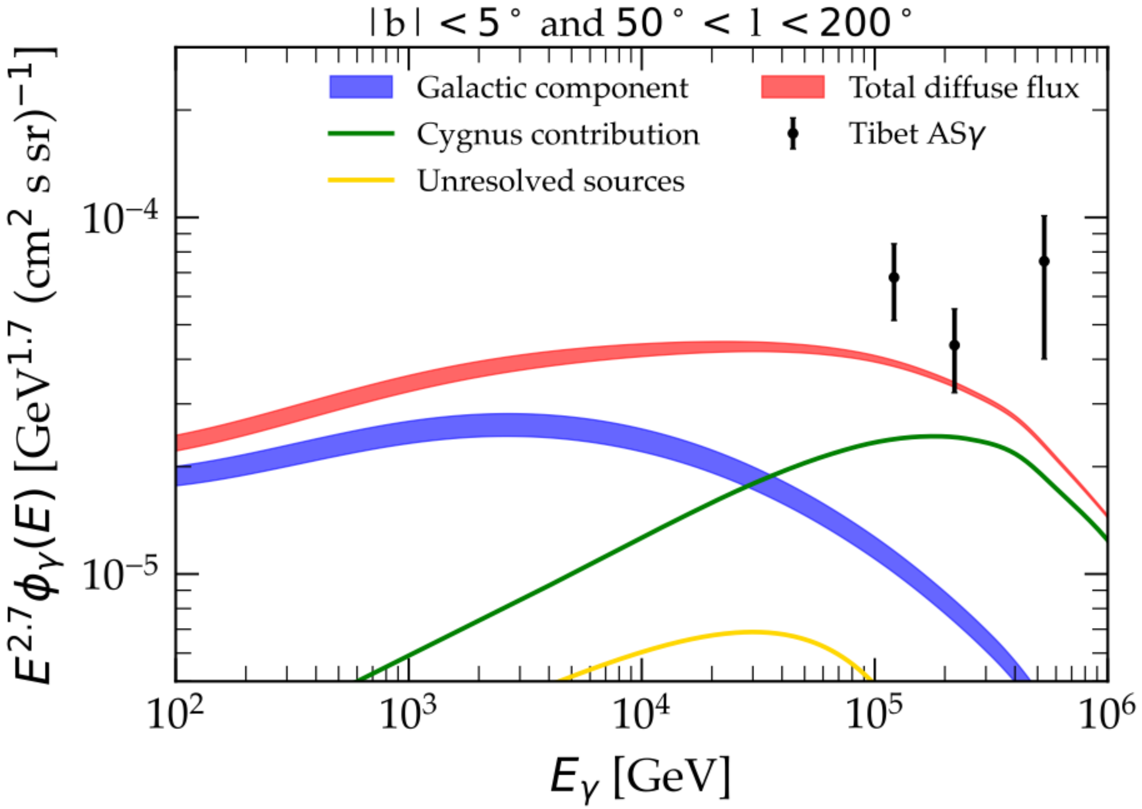
Diffuse flux start reaching VHE observations when subtracting contamination from sources

Cygnus region is the dominant component in both regions at ~ 100 TeV

Unresolved sources become relevant, specially at inner region

See [Kato et al., 2024]



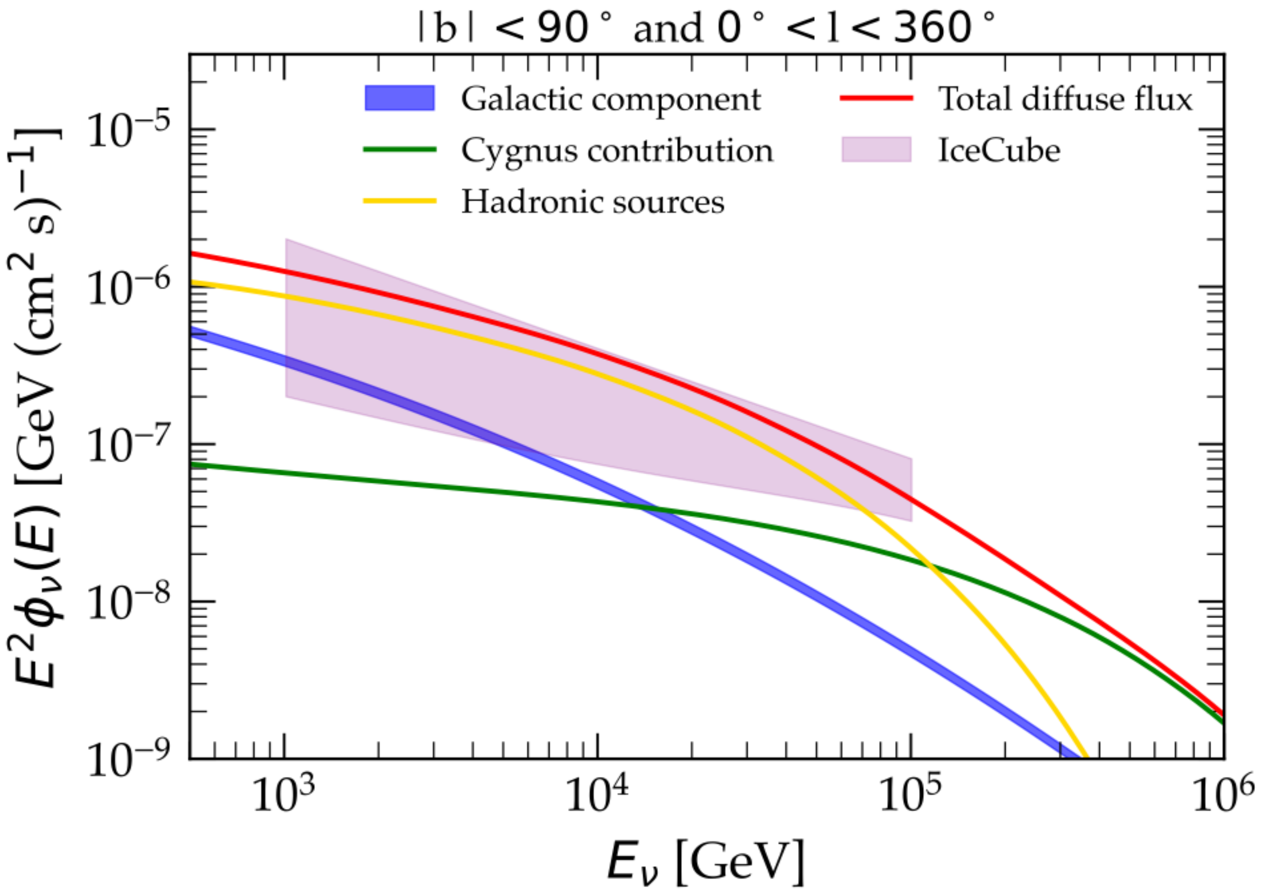


Diffuse Neutrino Emission

Observations of IceCube based on three templates: π^0, KRA_γ^5 and KRA_γ^{50}. Overall good agreement within uncertainties

Cygnus component dominates the CR diffuse neutrino emission above $E\nu \gtrsim 30\ TeV$ and becomes a prominent feature at higher energies ($E\nu \sim 100\ TeV$).

Up to 50% of sources can be considered as hadronic



For more details, see **Luis Espinosa Castro et al., arXiv:2603.21665**

SUMMARY

Can diffuse γ rays probe PeV protons?

-Yes , directly.

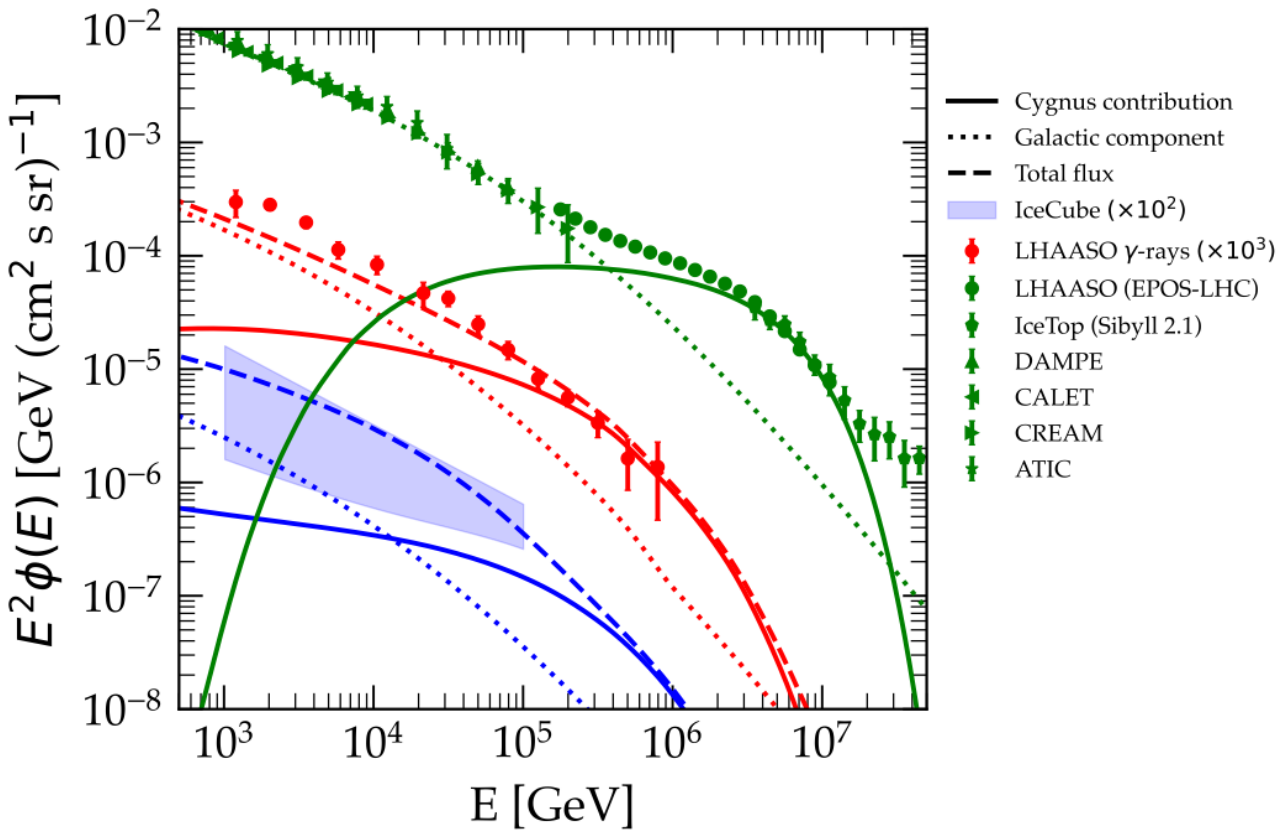
What contaminates this inference?

-Sources, gas and masking must be controlled.

Could the knee have a local origin?

-Cygnus provides a concrete, multimessenger-testable hypothesis.

Multi-messenger concordance



Thanks for your attention

For more details:

The Astrophysical Journal, 904:85 (10pp), 2020 December 1
https://doi.org/10.3847/1538-4357/abc0ee

CrossMark

The TeV Gamma-Ray Luminosity of the Milky Way and the Contribution of H.E.S.S. Unresolved Sources to Very High Energy Diffuse Emission

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Royal Astronomical Society

MNRAS **543,** L20–L26 (2025)
https://doi.org/10.1093/mnrasl/slaf085
Advance Access publication 2025 August 23

LHAASO protons versus LHAASO diffuse gamma-rays: a consistency check

Multimessenger Concordance for the Cygnus Region as the Source of the Cosmic-Ray Knee

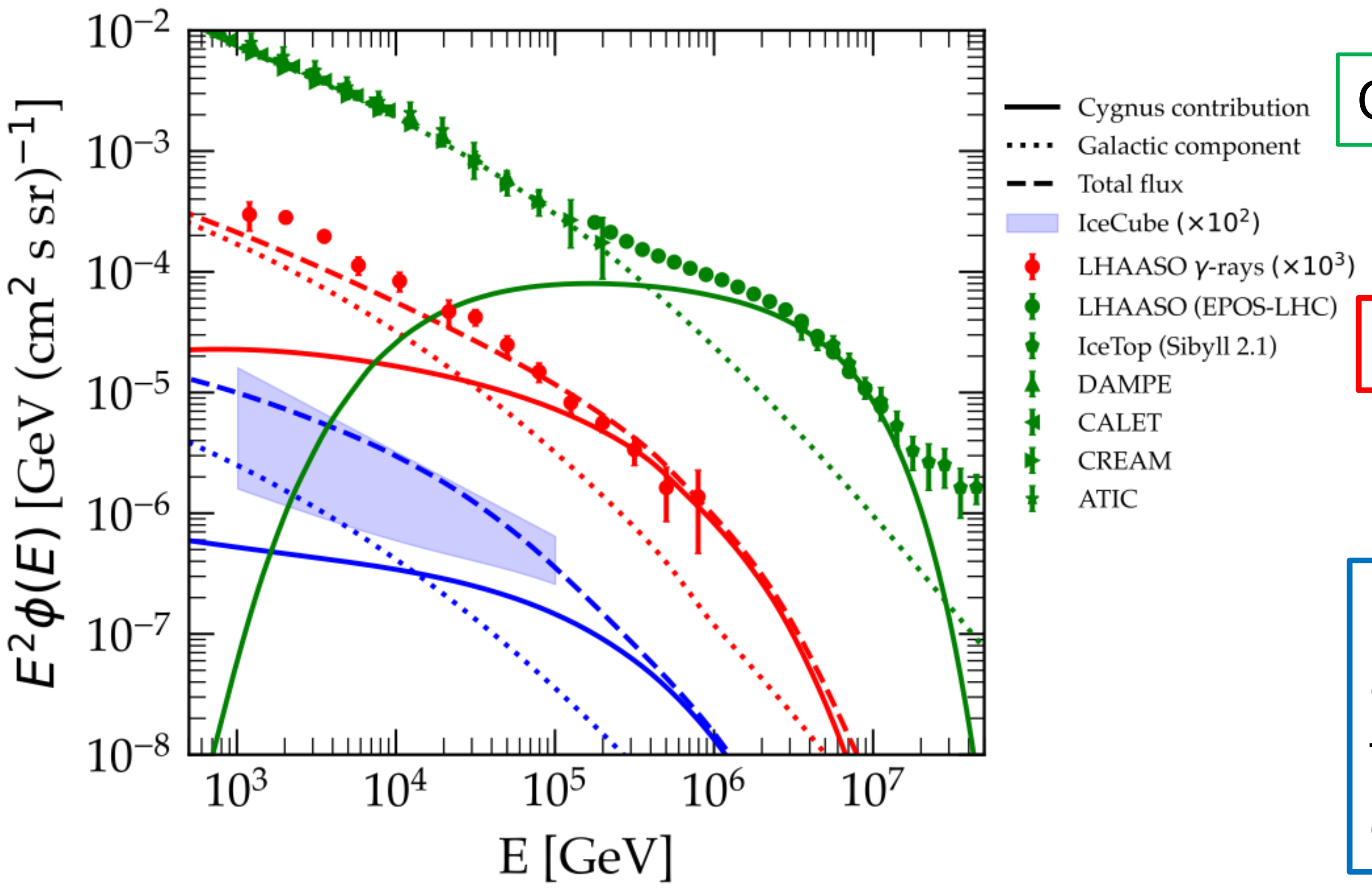
Submitted to ApJL

In collaboration with:

Luis Enrique Espinosa-Castro (PhD), Kotha Murase, Carlo Rizza, Francesco Villante, Maddalena Cataldo, Carmelo Evoli and Vittoria Vecchiotti

BACKUP SLIDES

The Cygnus Multimessenger emission



Gamma-ray of the Cygnus cocoon

Proton injection and diffusion

Diffuse extended gamma-ray and neutrinos emission at PeV that can be probed by future experiments

For more details, see Luis Espinosa Castro et al., arXiv:2603.21665

Galactic Cosmic Rays

- Cygnus proton injection spectrum [LHAASO Coll., 2024]:

$$\dot{Q}(E_p) = \dot{Q}_0 \left(\frac{E_p}{E_0}\right)^{-s} \exp\left(-\frac{E_p}{E_p^{\max}}\right)$$

$s = 2.1, \quad E_0 = 1\,\mathrm{TeV}, \quad E_{\max} = 5\,\mathrm{PeV}$ and $L_p = \int dE_p\, E_p Q(E_p) = 3 \times 10^{37}\,\mathrm{erg\,s^{-1}}$

- CR propagation following a two-zone model:

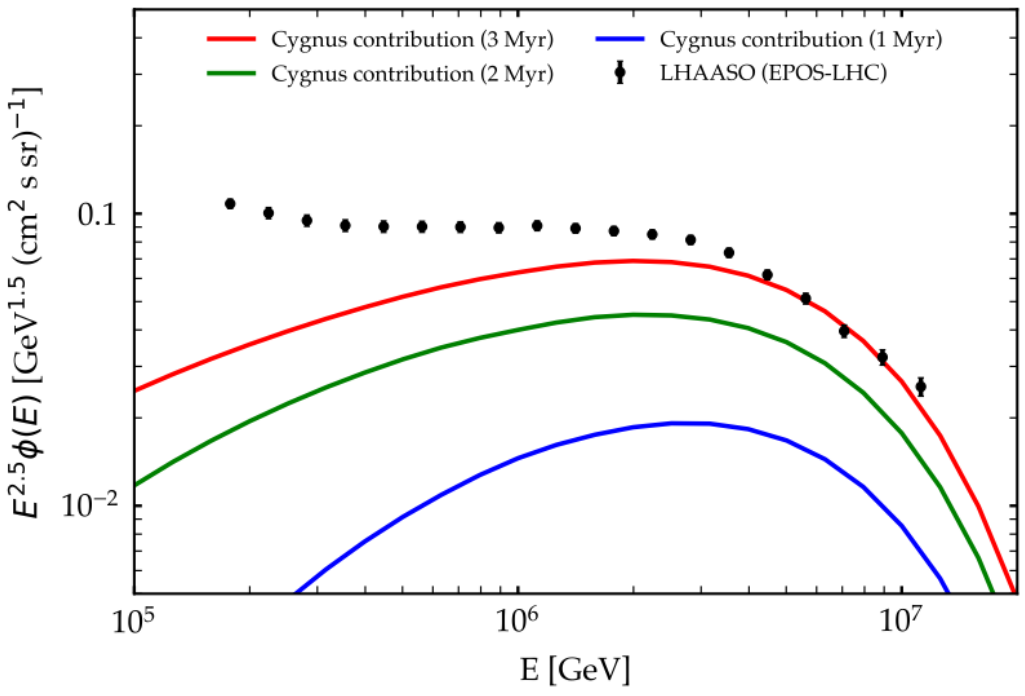
$$\frac{\partial n}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(Dr^2\frac{\partial n}{\partial r}\right) + Q$$

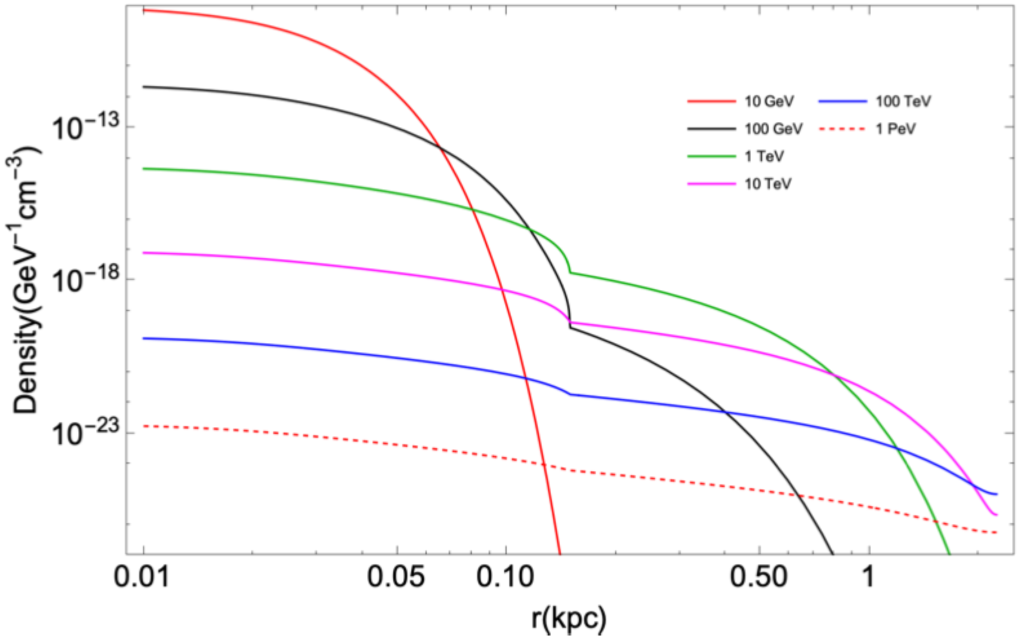
where $D(r, E_p) = \begin{cases} D_0(E_p/E_0)^{\delta_0} & 0 < r < r_c, \\ D_1(E_p/E_0)^{\delta_1} & r \geq r_c, \end{cases}$

$D_0 = 3 \times^{26}, \quad \delta_0 = 0.7, \quad D_1 \sim 10^{28}, \quad \delta_1 = \frac{1}{3}$ and $r_c \sim 150\,\mathrm{pc}$

Solution to transport equation: $Q(r, t, E_p) = \frac{1}{(2\pi R^2)^{3/2}} \exp\left(-\frac{r^2}{2R^2}\right) \dot{Q}(E_p)\theta(t),$

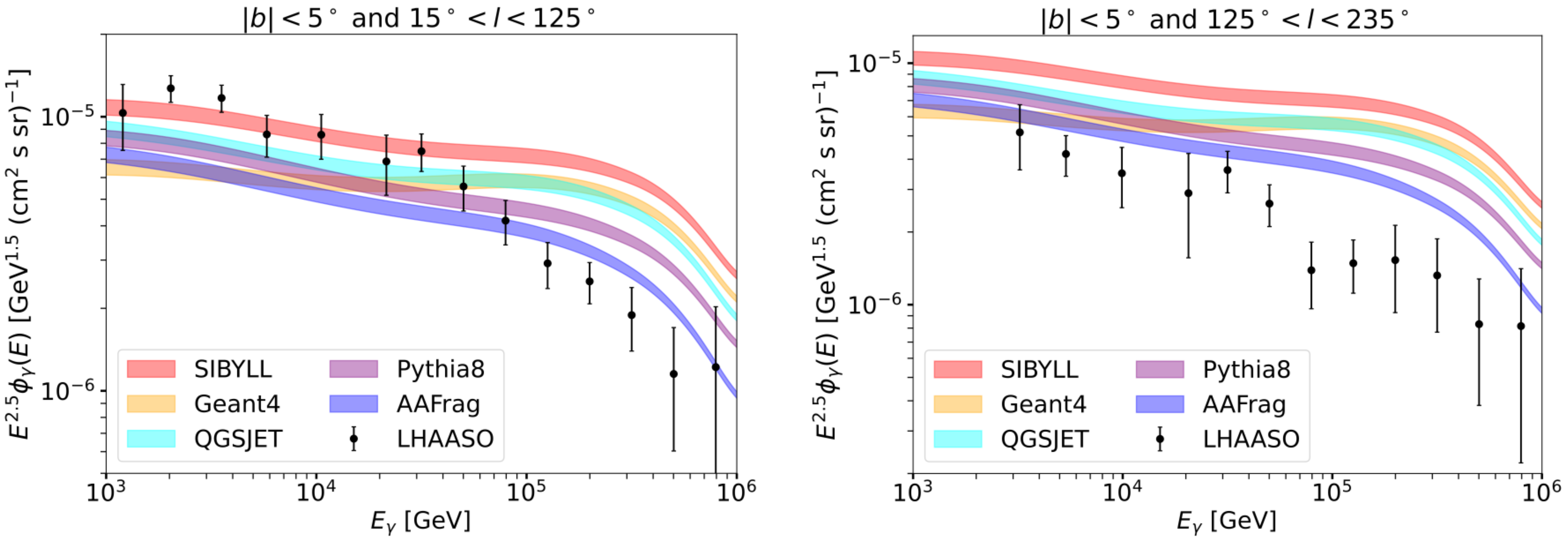
here $R = 1$ pc is source physical size.





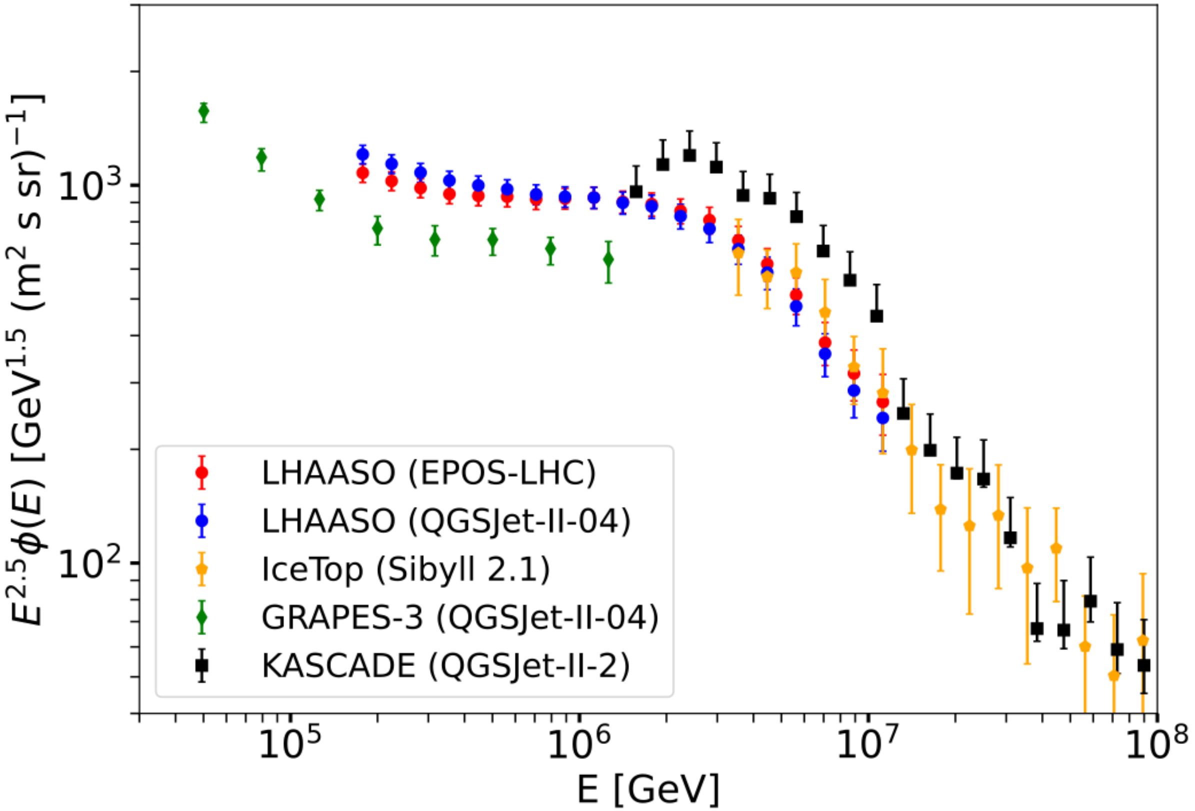
COMPARISON OF CROSS-SECTION MODELS

- AAFrag cross-section gives the smaller (and softer) γ-ray predictions.
- Tension with LHAASO γ-ray observations would increase for other parameterisations.



KASKADE new data-set nearly aligns …Finally ONE single proton flux!

Discrepancy in proton flux at high-energies could be alleviated, but the discrepancy with diffuse gamma-rays would be persistent.

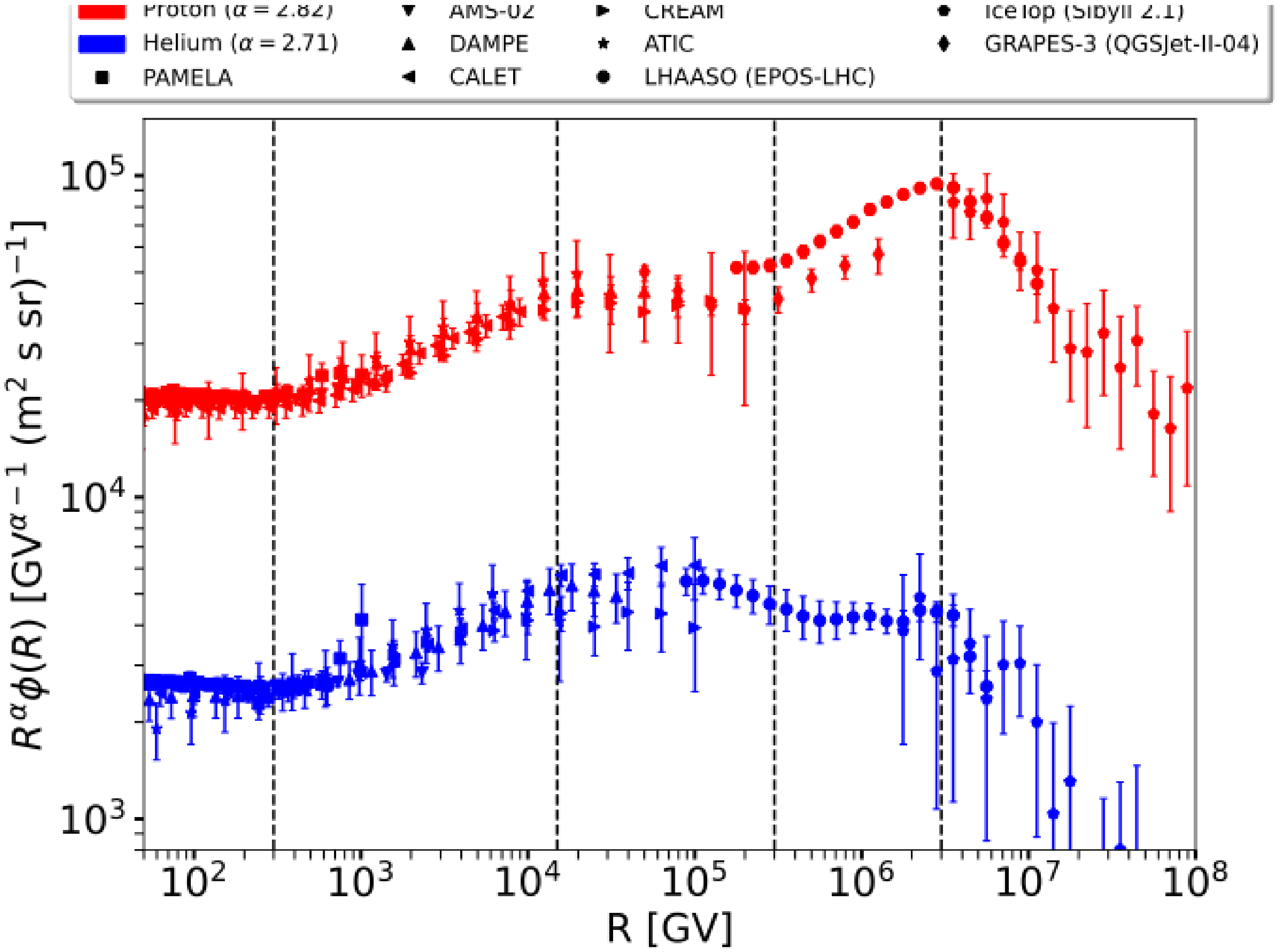


Recent re-analysis of KASCADE cosmic ray data by Kuznetsov et al. suggest a higher flux of protons at PeV energies.

This proton flux measurement shows better agreement at high-energies with LHAASO and IceTop, but imply even higher proton and gamma-ray fluxes.

Kuznetsov et al., 2024

Slide from Luis

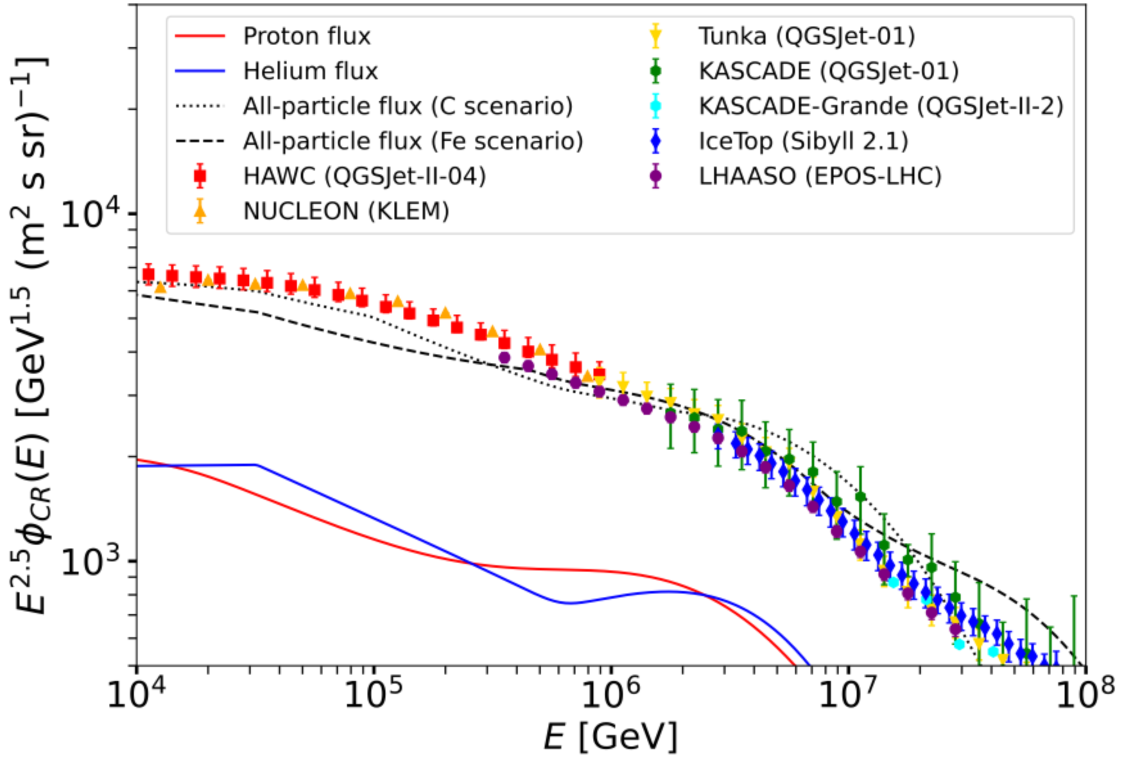


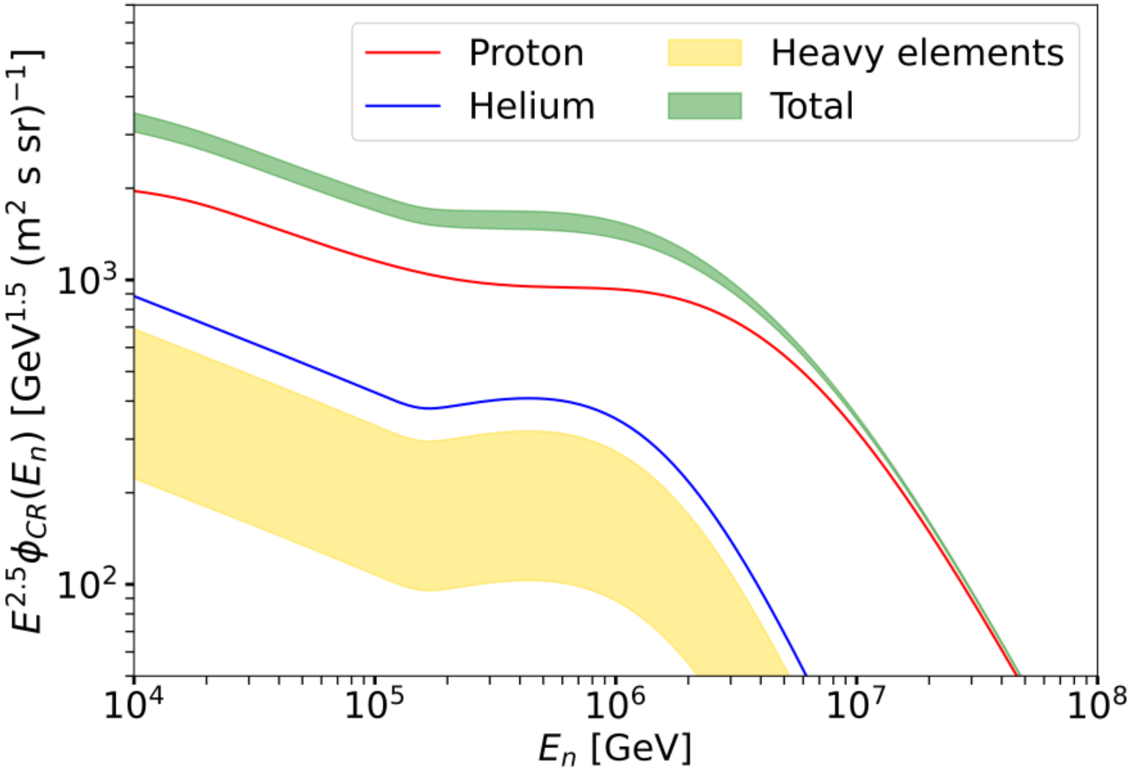
Proton ($\alpha = 2.82$)
Helium ($\alpha = 2.71$)
PAMELA
AMS-02
DAMPE
CALET
CREAM
ATIC
LHAASO (EPOS-LHC)
IceTop (Sibyll 2.1)
GRAPES-3 (QGSJet-II-04)
$R^{\alpha}\phi(R)$ [GV$^{\alpha-1}$ (m^2 s sr)$^{-1}$]
R [GV]

Relevant flux is in energy per nucleon, for which **proton component is dominant**

$$\phi_{CR}(E_n) = \sum_A A^2 \phi_A(AE_n)$$

$$\phi_{CR,\odot}(E_n) = \phi_p(E_n) + (1+k)\,\phi_{He,\,CR}(E_n) \quad \text{with} \quad k = \frac{\phi_{heavy}(E)}{\phi_{He}(E)}\left(\frac{A}{A_{He}}\right)^{2-\alpha_1(He)}$$





Galactic Cosmic Rays

"CR sea" flux modelled as $\phi_p^{\text{Gal}}(E_p) = N\left(\frac{E_p}{\bar{E}}\right)^{-\alpha_1} \Pi_i \left[1 + \left(\frac{E_p}{E_{b,i}}\right)^{\frac{1}{\omega_i}}\right]^{-\Delta\alpha_i \omega_i}$

Then, total CR proton flux at Earth is $\phi_p(E_n, \mathbf{r}_\odot) = \phi_p^{\text{Cyg}}(E_n, \mathbf{r}_\odot) + \phi_p^{\text{Gal}}(E_n)$

Two Break Model

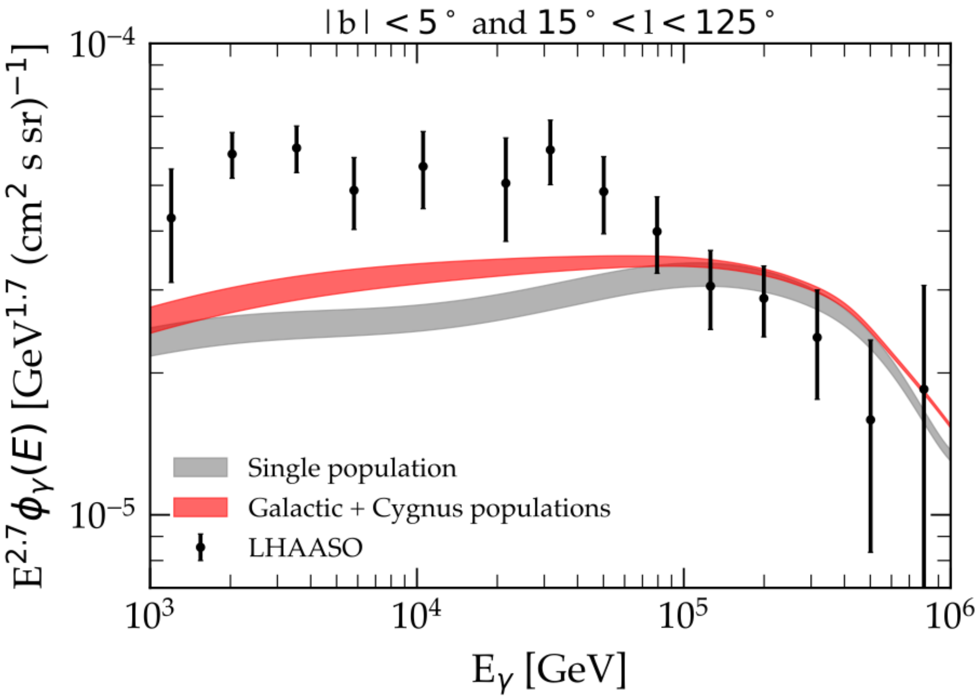
	Protons	Helium
$N\,[10^{-2}\,\text{GeV}^{-1}\,\text{m}^{-2}\text{s}^{-1}\,\text{sr}^{-1}]$	6.84	4.62
Spectral indexes	2.71 2.17 3.87	2.62 2.04 3.88
Break energies [TeV]	0.77 TeV 0.17 PeV	1.62 TeV 0.39 PeV
Break width	0.64 3.03	0.63 2.98

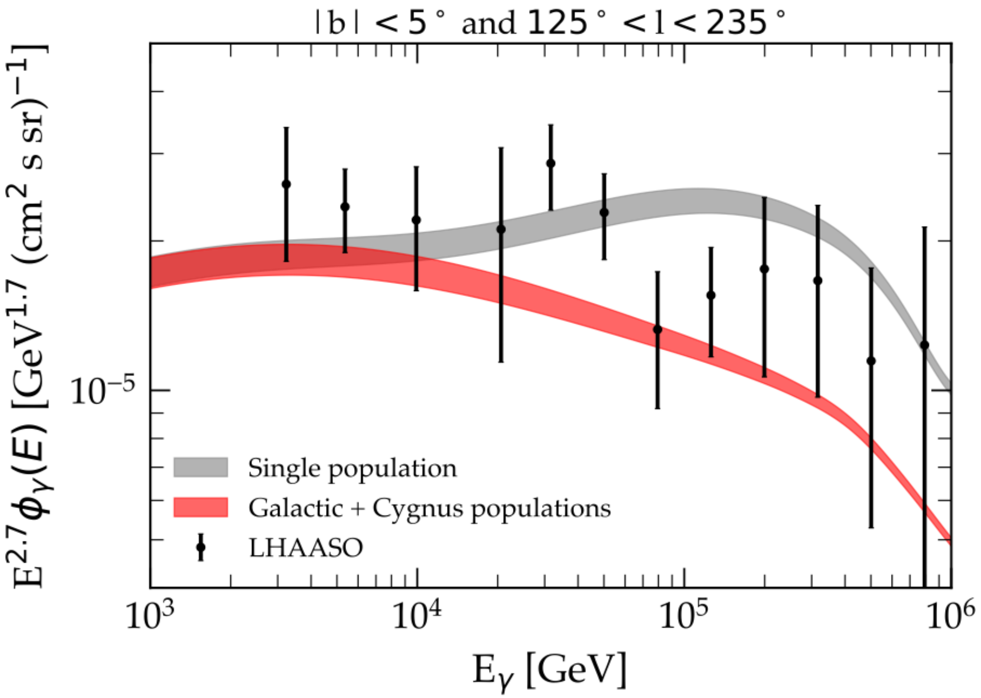
Three Break Model

	Protons	Helium
$N\,[10^{-2}\,\text{GeV}^{-1}\,\text{m}^{-2}\text{s}^{-1}\,\text{sr}^{-1}]$	5.32	3.91
Spectral indexes	2.77 2.37 2.35 3.83	2.49 1.81 1.62 4.24
Break energies [TeV]	0.69 TeV 16 TeV 0.32 PeV	1.23 TeV 32 TeV 0.62 PeV
Break width	0.49 0.33 2.56	0.67 14.09 4.44

Diffuse Gamma-Ray Emission

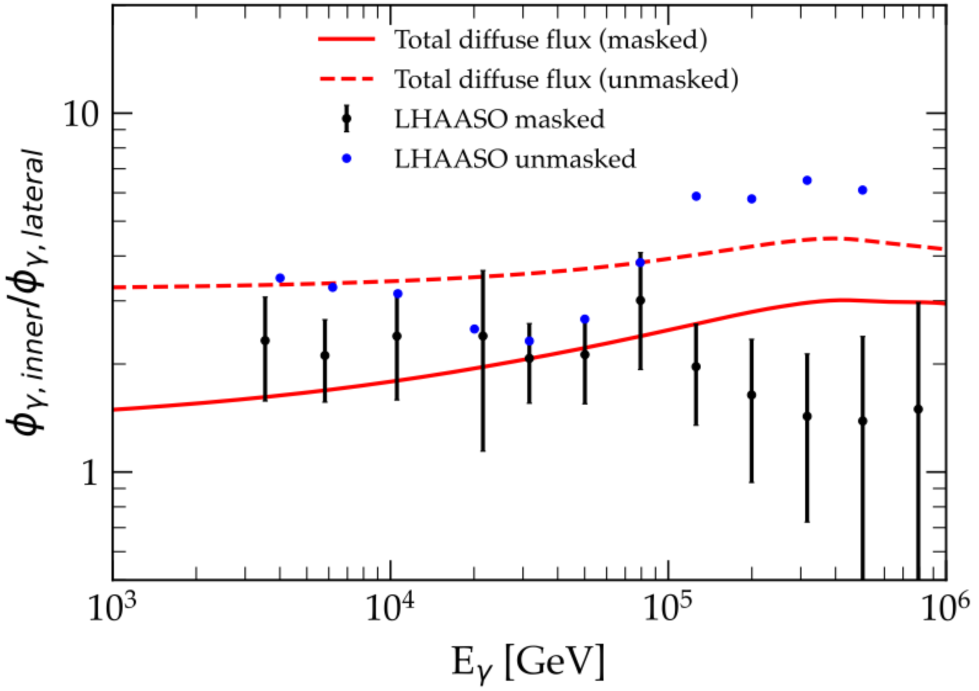
- Better agreement for the two-population model (specially in inner Galactic region) in contrast to previous π^0 model in [Espinosa Castro et al., 2025] which only considers one Galactic CR population.

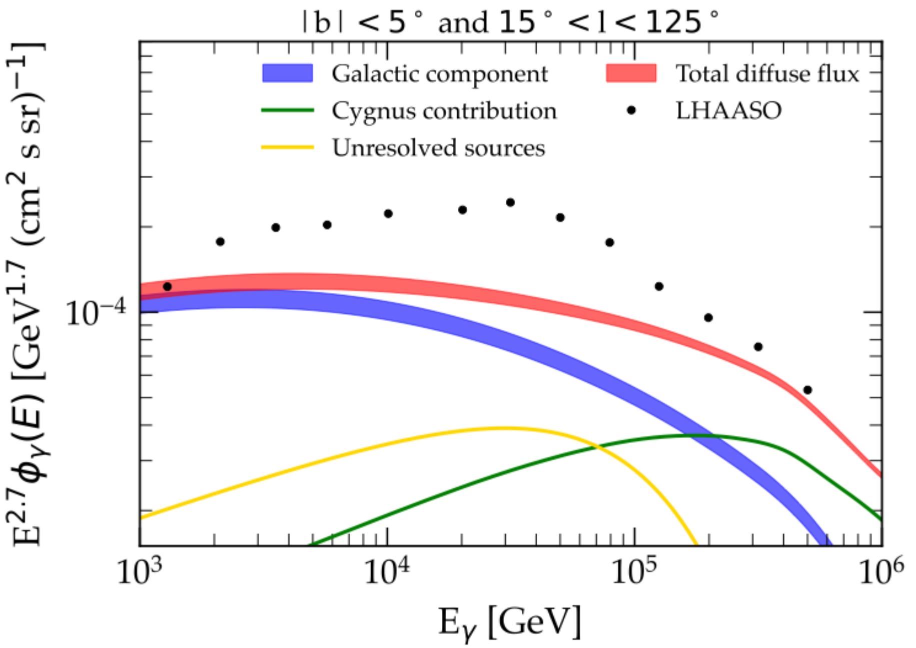


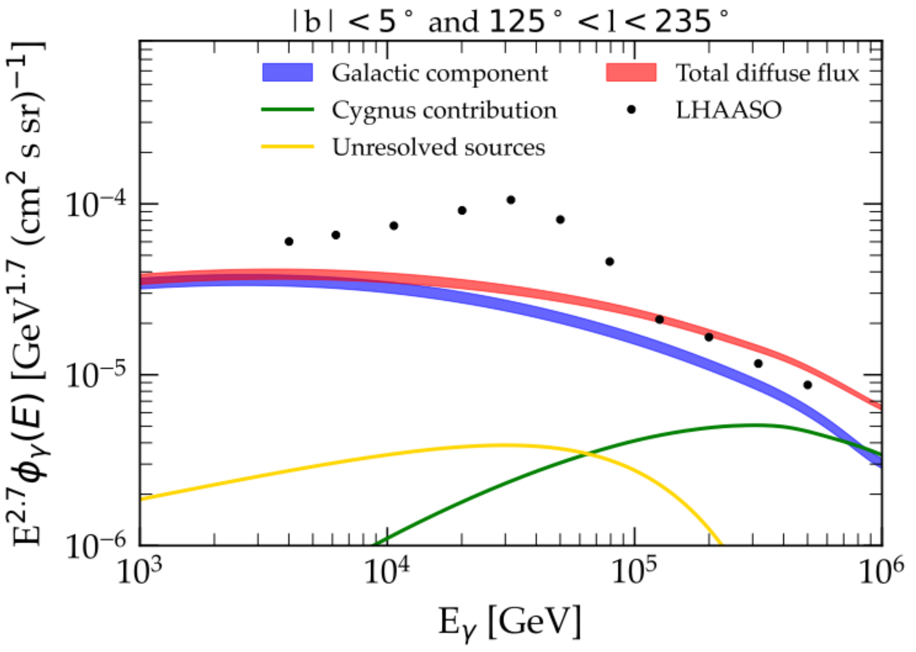


Diffuse Gamma-Ray Emission

- When we remove the mask, Cygnus region contribution still significant but still leave room for other Galactic sources, according to LHAASO observations.
- Spectrum at lower energies differs from Fermi-LAT observations, particularly in inner Galactic region.





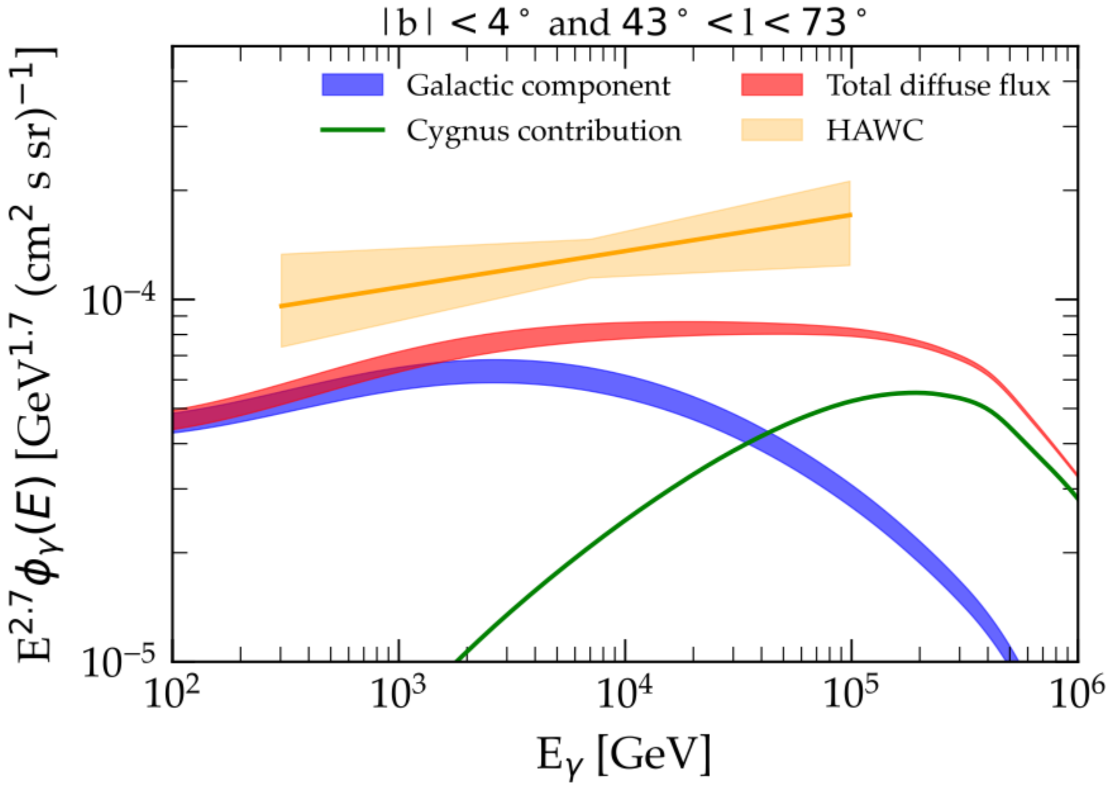


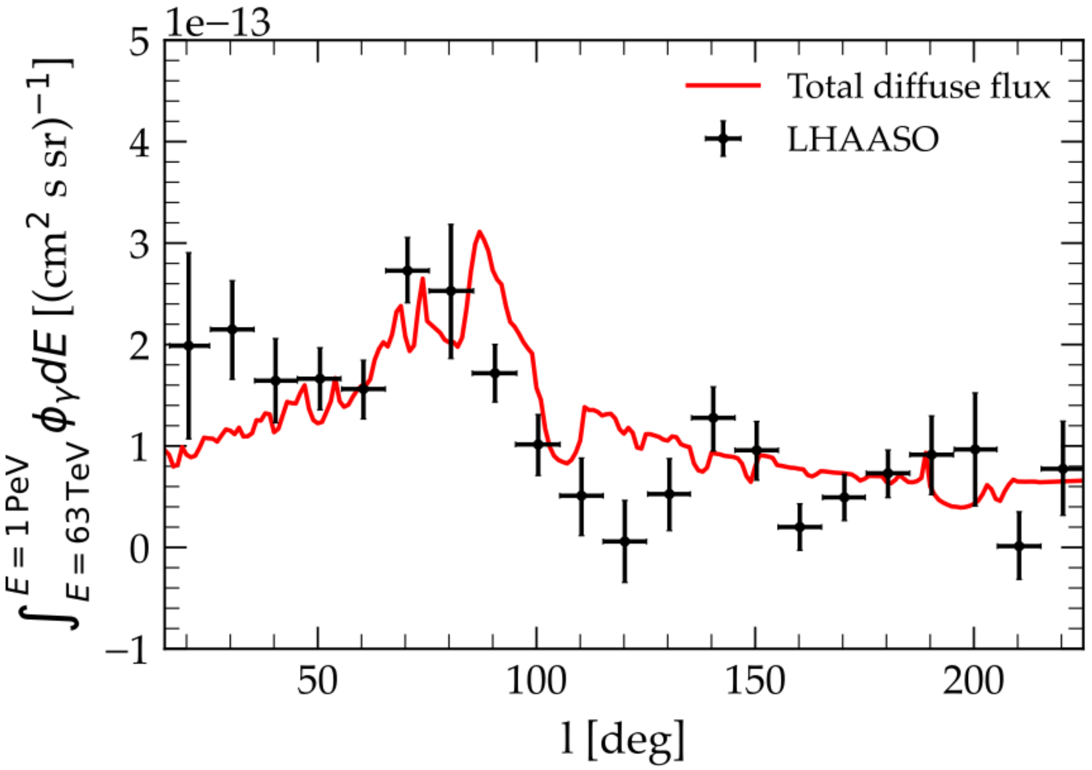
Diffuse Gamma-Ray Emission

Diffuse flux in good agreement with spectral shape but unresolved TeV component required

Reproduction of longitudinal profile at high energies around Cygnus region

PRELIMINARY

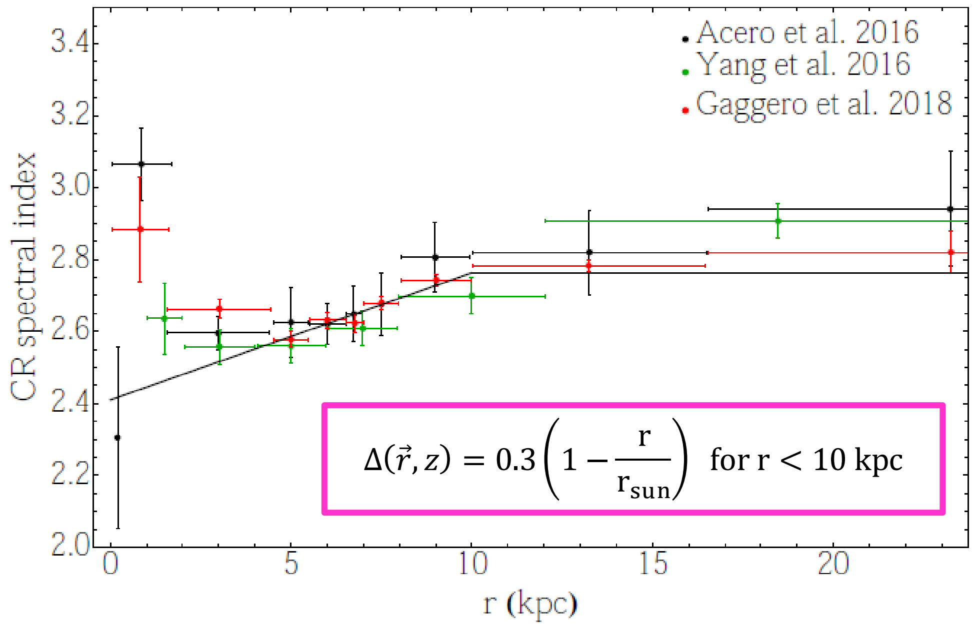


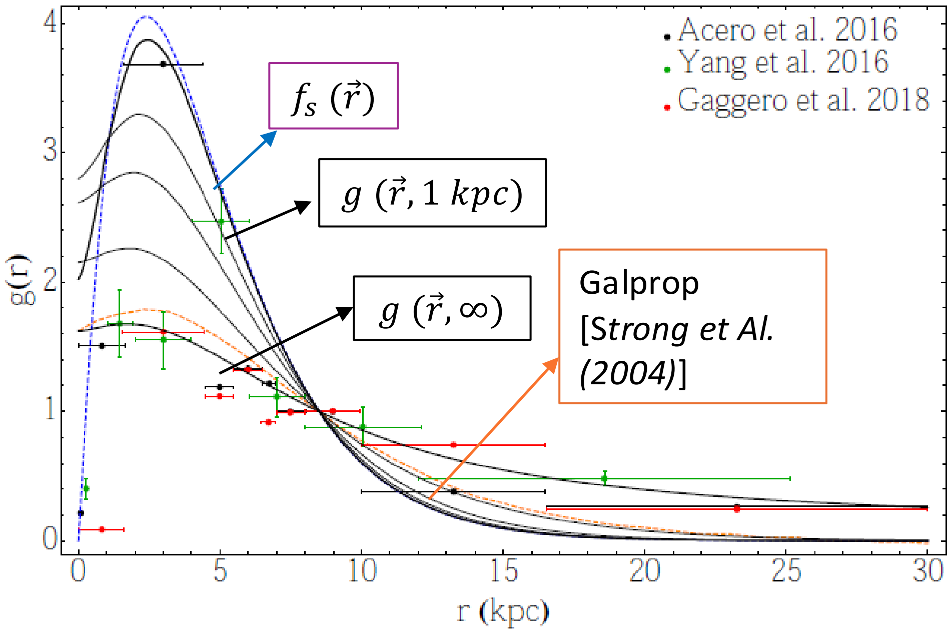


Cosmic ray distribution: $\varphi_{CR}(E,\vec{r}) = \varphi_{CR,Sun}(E)\, g(\vec{r},R)\, h(E,\vec{r})$

- Data driven local CR spectrum [*Dembinski, Engel, Fedynitch et al. (2018)*]
- g(r) is determined by the distribution of the CR sources $f_s(\vec{r})$ (proportional to the SNR number density by Green et al. (2015), and by the propagation of CR in the Galactic magnetic field.
- **2 cases: with and without spatially dependent CR spectral index** (from the analysis of the FermiLAT data at $\sim 20\ GeV$ [*Acero et al. (2016), Yang et al. (2016), Gaggero et al. (2018)*])

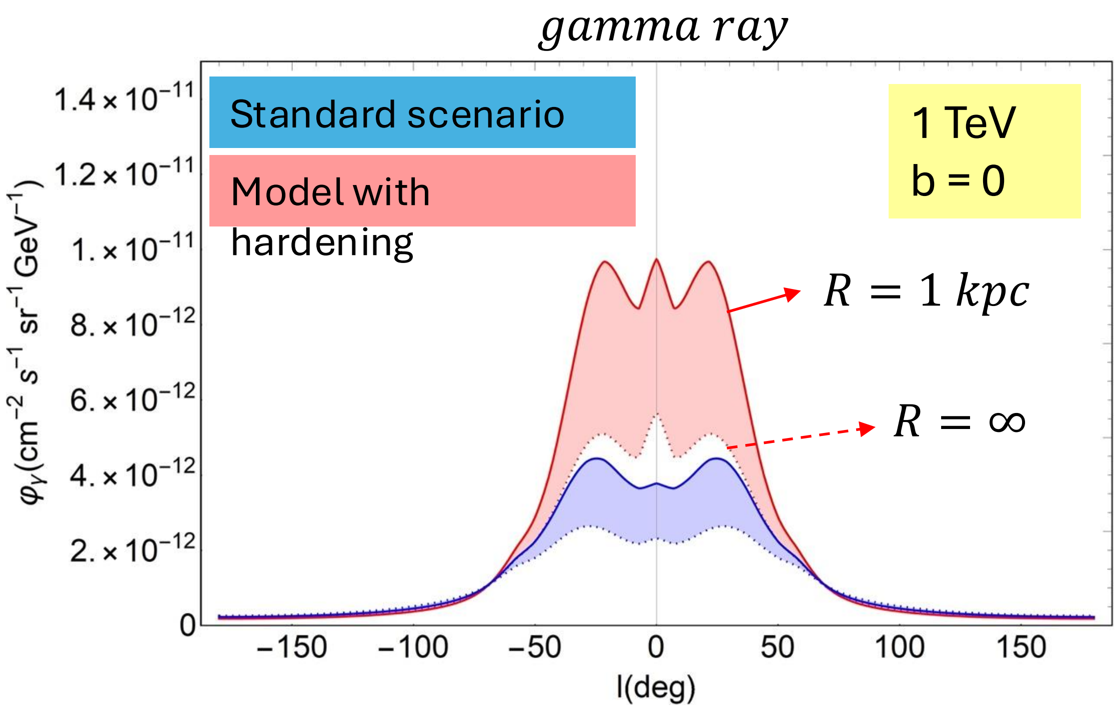
$$h(E,\vec{r}) = \left(\frac{E}{20\ GeV}\right)^{\Delta(\vec{r})}$$

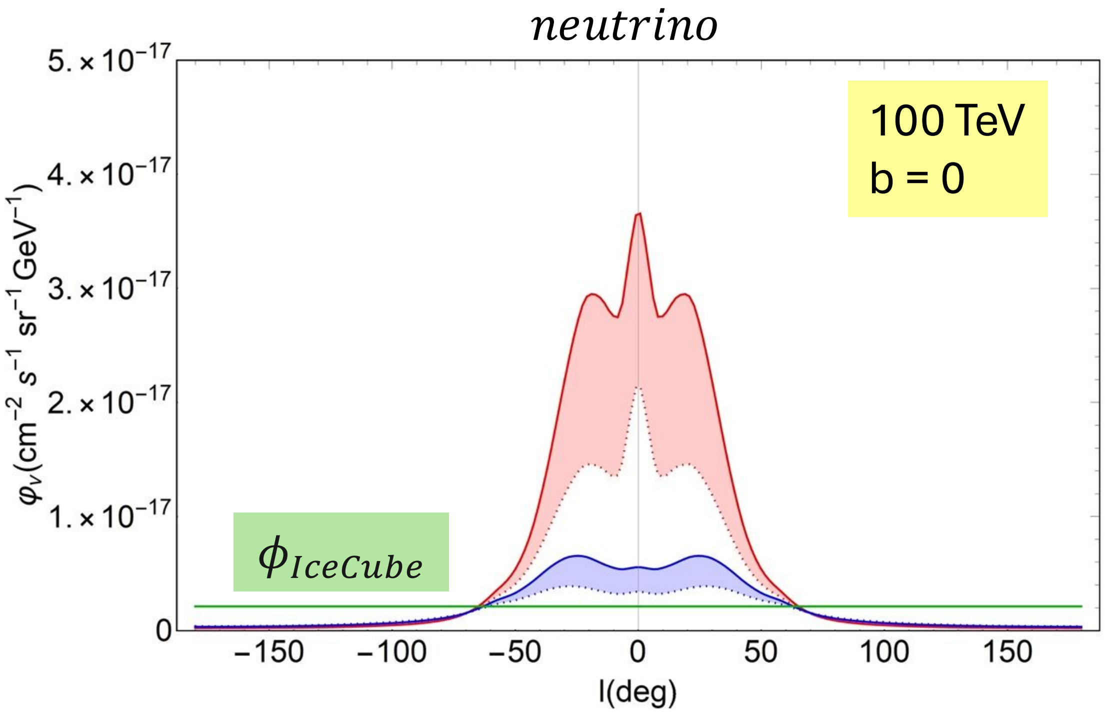




Diffuse Galactic γ and ν emission:

Abbasi et al, Phys. Rev. D. (2020)





- The angle integrated γ-ray flux in the standard scenario is: $\Phi_\gamma = (7.0 - 8.0) \times 10^{-13} cm^{-2} s^{-1} GeV^{-1}$, and increases of a factor ~ 1.2 in the hardening case.
- In the region $\mathrm{l} < |60°|, \mathrm{b} < |2°|$, this factor becomes $\sim 2 (\sim 3)$ for γ (ν) respectively;
- The angle integrated neutrino flux is 3.9 % - 4.4 % (5.8 % - 8.2%) of the isotropic flux observed by IceCube (*Abbasi et al, Phys. Rev. D. (2020)*). Potentially observable in specific region of the sky.

Pagliaroli et al, JCAP (2016), Pagliaroli et al, JCAP (2018)

TAKE INTO ACCOUNT THE LHAASO MASK

Unresolved Sources are distributed on the plane and their contribution is nearly destroied by the mask in the inner Lhaaso region

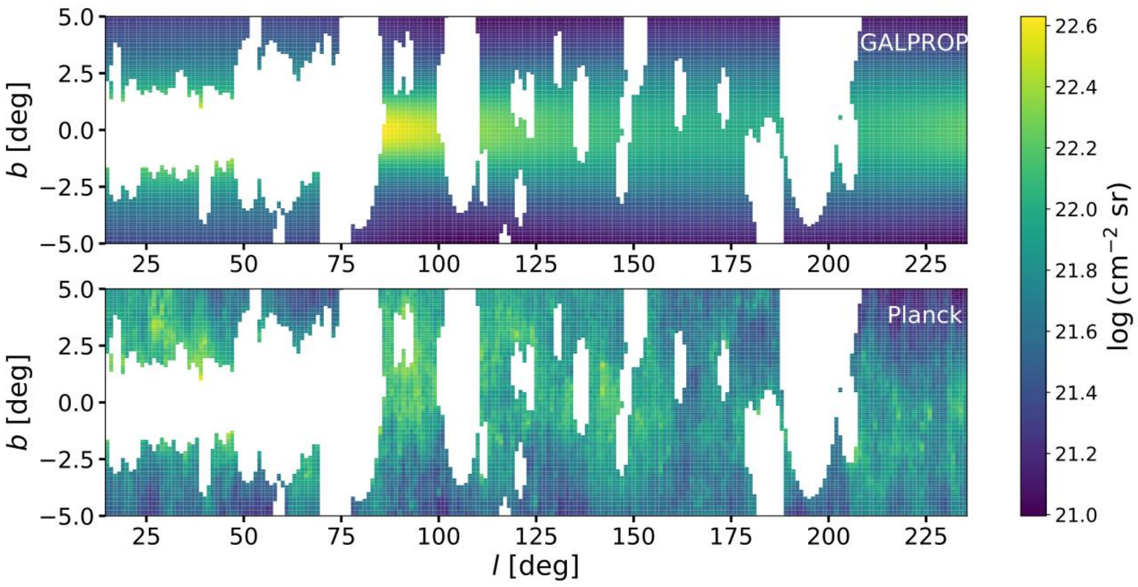
Not uniform CR distribution can provide only few % of increase in the inner Lhaaso region due to the mask (external region can be decreased of 10%)

The presence of an hardening of CR spectrum toward the GC is also negligible in the inner Lhaaso region due to the mask

GALACTIC GAS TEMPLATES

$+42\,\%$ contribution of heavier elements

Ferrière, 2001



- Atomic hydrogen traced by the 21-cm emission line, H_2 traced by CO emission line.

  Porter et al., 2022 (GALPROP), BenBekhti et al., 2016 (HI4PI), Dame et al., 2001 (CO Survey)

- Hydrogen gas column density N_H traced by dust opacity map (Planck).

  Aghanim et al., 2016, Ade et al., 2011

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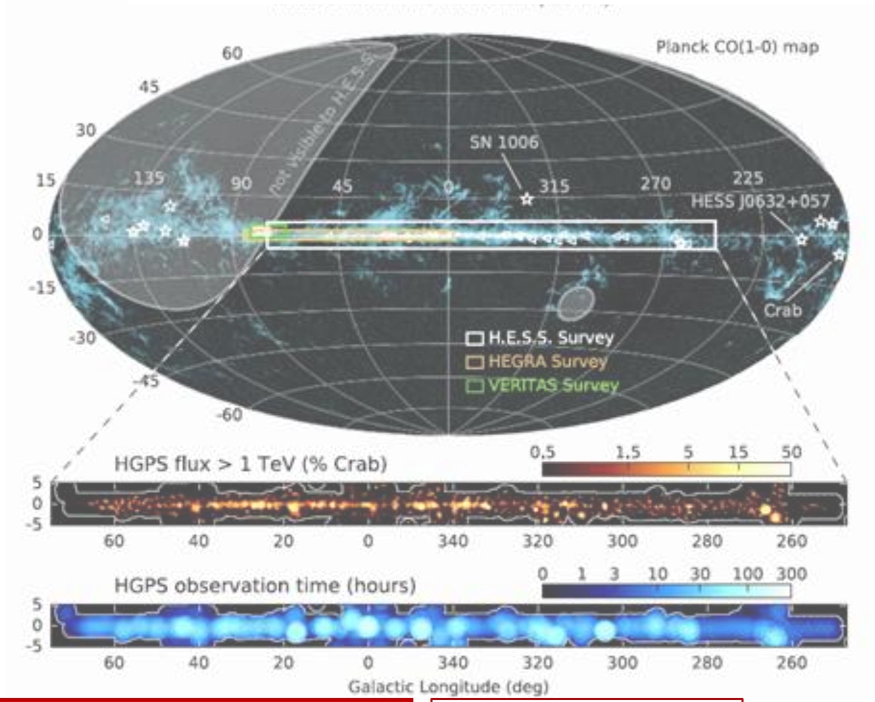
Abdalla et al, *A&A*, 612, A1 (2018)

Study of the sources population in the TeV range:

Cataldo et al. *Astrophys.J.* 904 (2020)



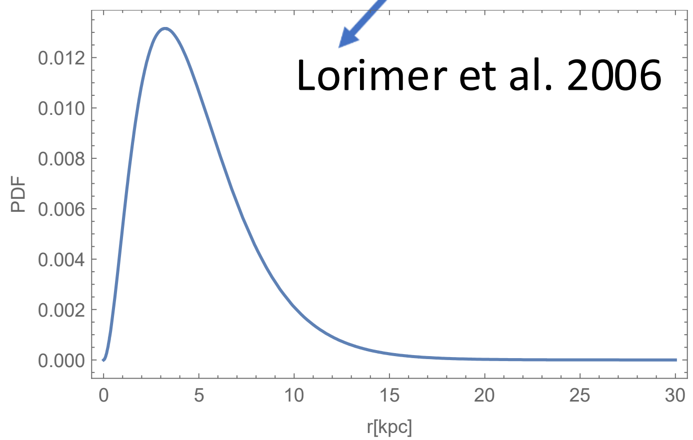
- The HGPS catalogue ($\phi > 0.1\phi_{Crab}$);
- Model for TeV source population:

we assume the spatial distribution and the luminosity distribution of the sources;

$$\frac{dN}{d^3r\,dL} = \rho(r)\,Y(L)$$

$$Y(L) = \frac{R\,\tau\,(\alpha - 1)}{L_{\max}}\left(\frac{L}{L_{\max}}\right)^{-\alpha}$$

$\alpha = 1.5$
$\alpha = 1.8$



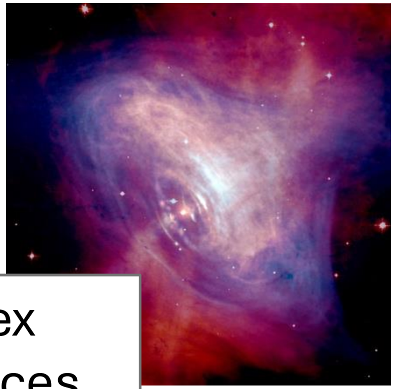
Lorimer et al. 2006

$$\alpha = 1/\gamma + 1$$

$$R = 0.019\,\mathrm{yr}^{-1}$$

For pulsar-powered sources:

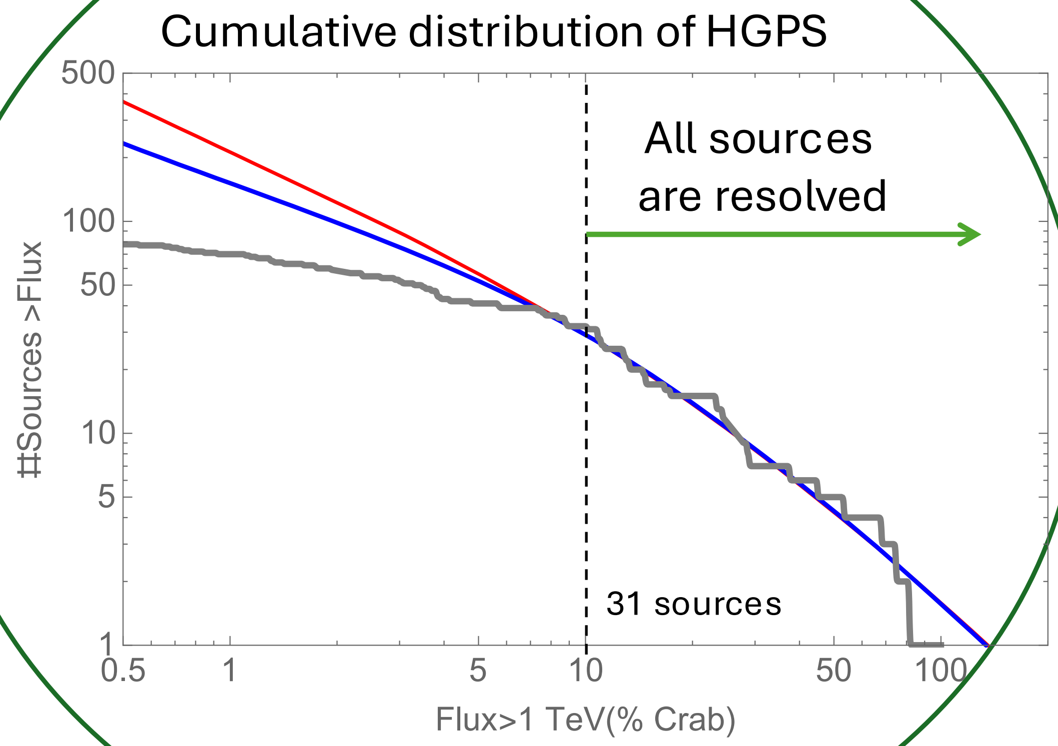
$$L(t) = L_{\max}\left(1 + \frac{t}{\tau}\right)^{-\gamma}$$



We assume a **power-law** energy spectrum with index $\boldsymbol{\beta_{TeV} = 2.3}$ that is the average index for all the sources in the HGPS catalogue.

Source component:

We consider the brightest sources in the HGPS and we constrain the luminosity function of the entire popoulation of TeV gamma sources:



Cataldo et al. Astrophys.J. 904 (2020)

$$\boxed{\Phi_{\gamma,s}}$$

- Total gamma-ray flux due to all the sources integrated over 1-100 TeV energy range.
- It includes the contribution from both the sources observed by H.E.S.S. and the one from unresolved sources

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Connection gamma-ray to neutrino sources:

We have $\Phi_{\gamma,s}$ (1-100 TeV) in gamma-rays, we need:

- CR injected spectrum: $\phi_p(E; E_{cut}) = \left(\frac{E}{1\ TeV}\right)^{-\beta} Exp\left(-\frac{E}{E_{cut}}\right)$

$\beta = 2.4$ *(to reproduce the average index of the HGPS);*
$E_{cut} = 0.5 - 10\ PeV$

- Neutrino flux from sources:

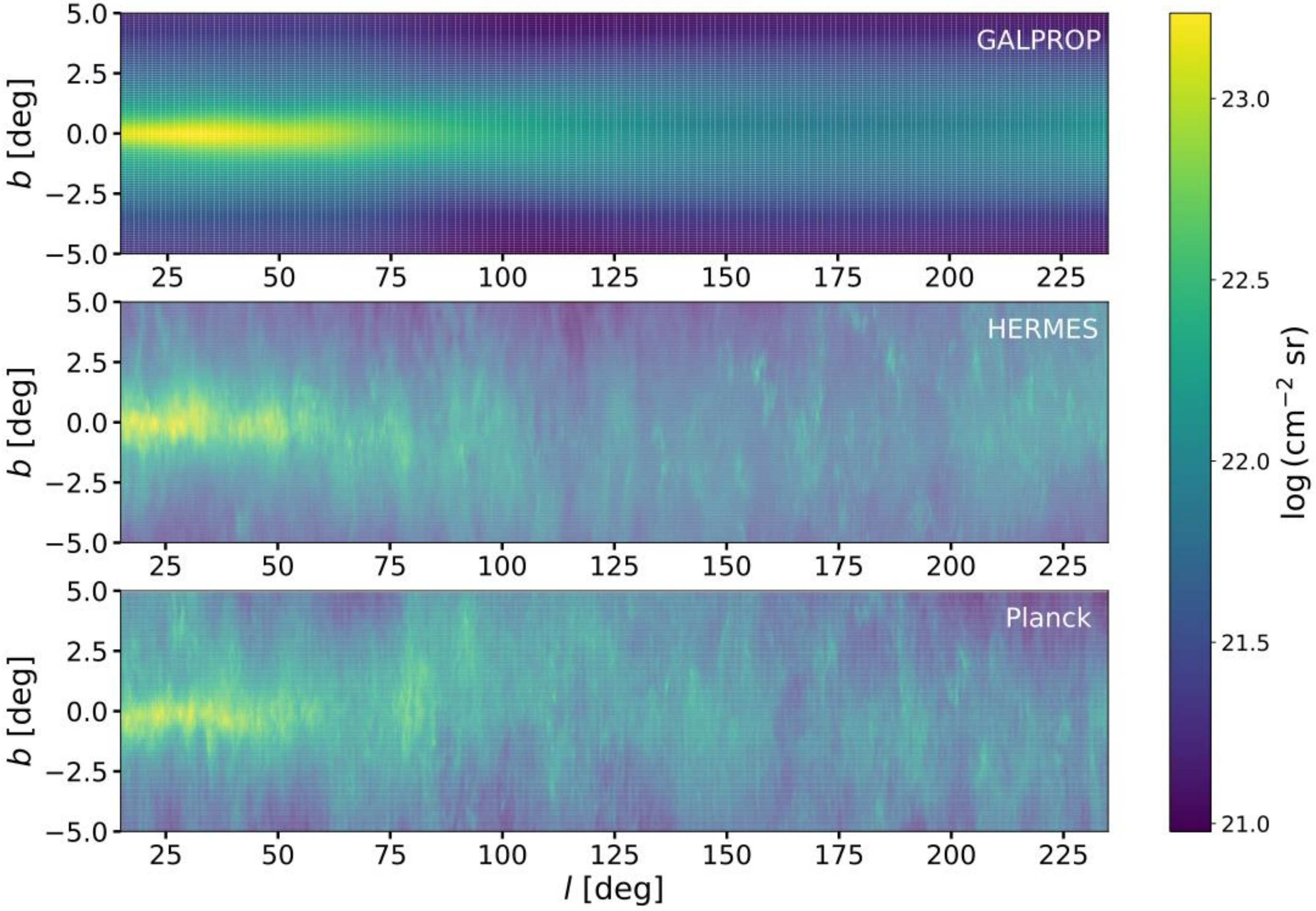
$$\varphi_{\nu,s}(E_\nu; E_{cut}, \xi) = \xi \Phi_{\nu,s}^{max}(E_{cut}) \phi_\nu(E_\nu; E_{cut})$$

Fraction of gamma-ray sources flux produced by hadronic interactions.

maximal neutrino flux from sources (1-100 TeV), the neutrino source contribution obtained by assuming that all the TeV gamma-ray sources are powered by hadronic processes

Neutrino spectrum. Normalized in the energy range 1-100 TeV

GALACTIC GAS TEMPLATES: HERMES



- HERMES gas template also traced by 21-cm and CO emission lines.

Dundovic et al., 2021 (HERMES), BenBekhti et al., 2016 (HI4PI), Dame et al., 2001, Dame et al., 2004 (CO Survey)

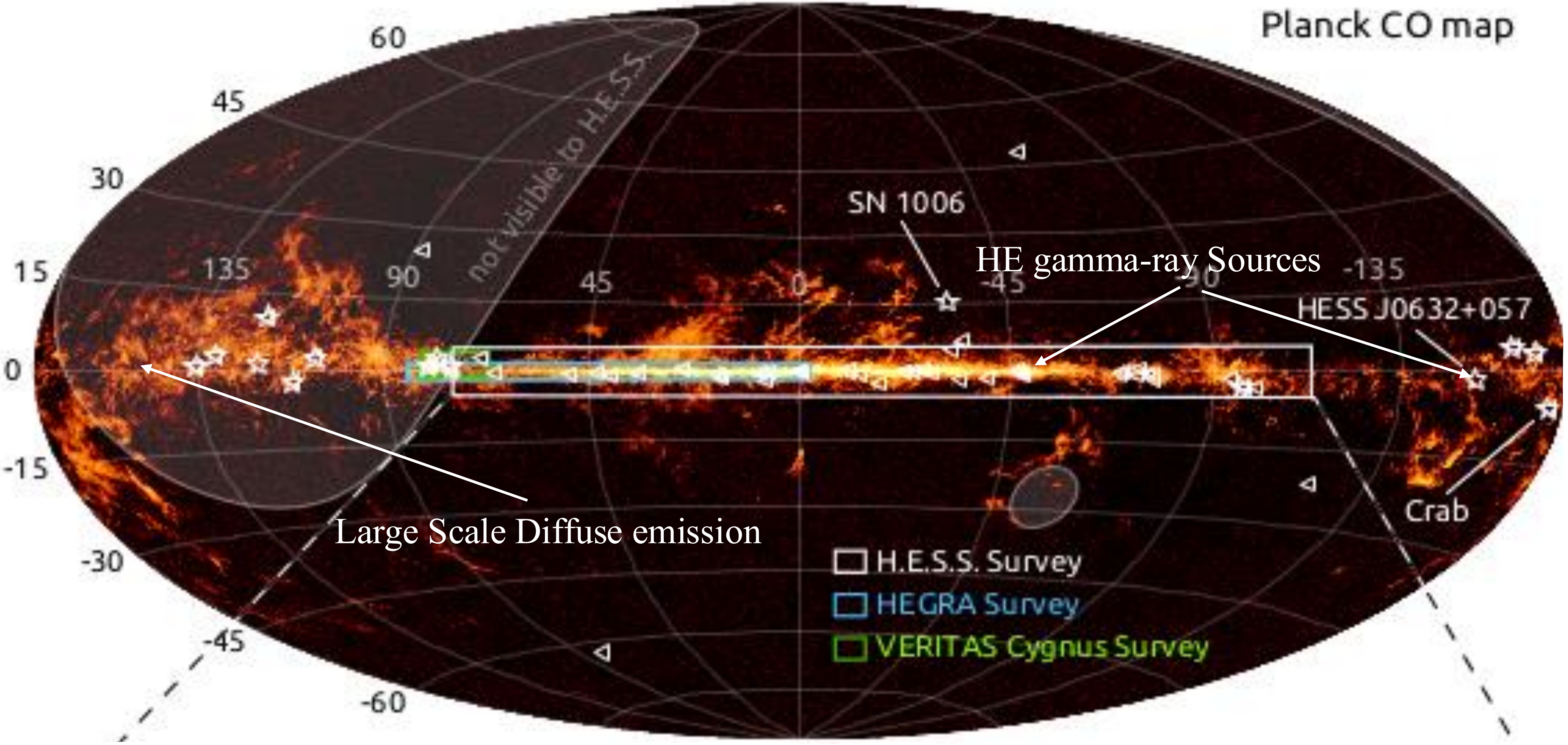
- HERMES column density differs from GALPROP but is still higher than Planck column density by $\sim 10\,\%$ (LHAASO inner region) and $\sim 20\,\%$ (LHAASO lateral region)

Unresolved Sources

- PULSAR WIND NEBOULAE and TeV Halo
- STAR CLUSTERS
- MICROQUASARS
- COCOONS

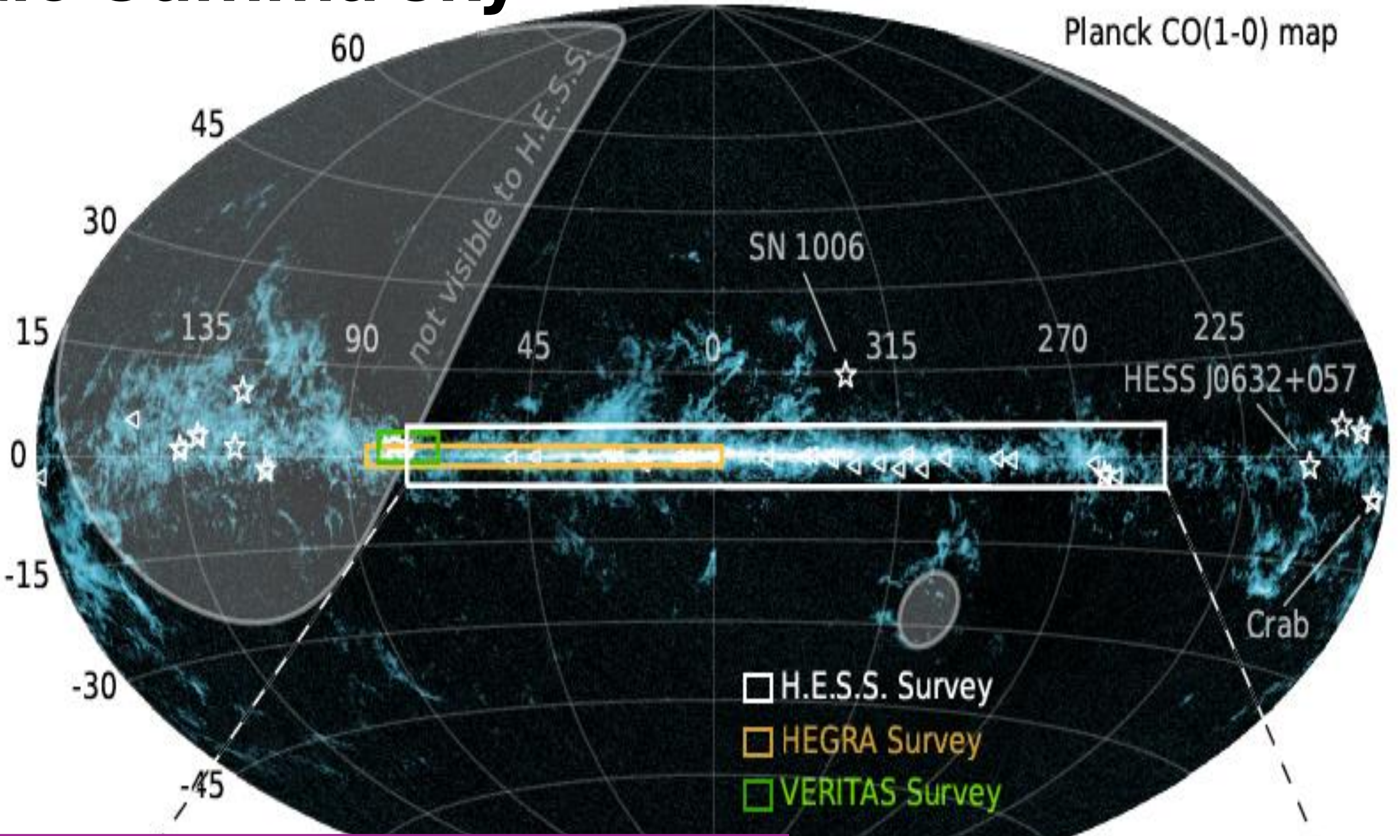
- *«Contribution from unresolved Globular Clusters negligible «*
***He et al. Astrophys.J.* 991 (2025) 1, 4**
- *«Contribution of unresolved sources using* nonparametric method to derive the source count distribution from the published first LHAASO source catalog is not enough in the inner region of Lhaaso», ***He et al. Astrophys.J.* 980 (2025) 1, 17**
- *«Unresolved pulsars contribution is l*ess than 21% ±6% above 100 TeV in the inner Lhaaso region», ***Kaci et al., Astrophys.J.* 975 (2024) 1, L6**
- «Young massive stellar clusters (YMSCs) » **Menchiari et al., *Astron.Astrophys*. 695 (2025) A175**
- «Cocoons contribution» from Ambrosone et al.,

GAMMA-RAY EMISSION AT TeV-PeV energy



The relative contribution of gamma-ray sources over the diffuse emission increases at higher energy

TeV Galactic Gamma sky @ 2019



Telescope	<E>	Gal longitude	Gal latitude
HESS	1 TeV	-75°≤l≤60°	|b|≤2°
HAWC	7 TeV	0°≤l≤60°	|b|≤2°
Milagro	15 TeV	30°≤l≤60°	|b|≤2°
Argo-JB	0.6 TeV	25°≤l≤60°	|b|≤5°

Neutrino Diffuse Galactic emission:

$$\varphi_{\nu,\mathrm{diff}}\ (E_\nu, \hat{n}_\nu) = \frac{1}{3} \sum_{l=e,\mu,\tau} \int_{E_\nu}^{\infty} dE \frac{d\sigma_l(E, E_\nu)}{dE_\nu} \int_0^{\infty} dl\, \varphi_{CR}(E, \bar{r}_{Sun} + l\hat{n}_\nu) n_H\ (\bar{r}_{Sun} + l\hat{n}_\nu)$$

Differential inelastic cross section of pp interaction from the SYBILL code *[Kelner,Aharonian,Bugayov (2006)]*

Cosmic-ray energy and spatial distribution

Interstellar gas distribution in the Galaxy [*Galprop*]

MODELS Providing TEMPLATES

The gamma-ray templates (spatial and energy dependences) are used to look for this component ....results are model dependent

Template selected by IceCube: KRAgamma and Pi0

MEASUREMENTS above 1 TeV

ANTARES without templates
ICECUBE with templates

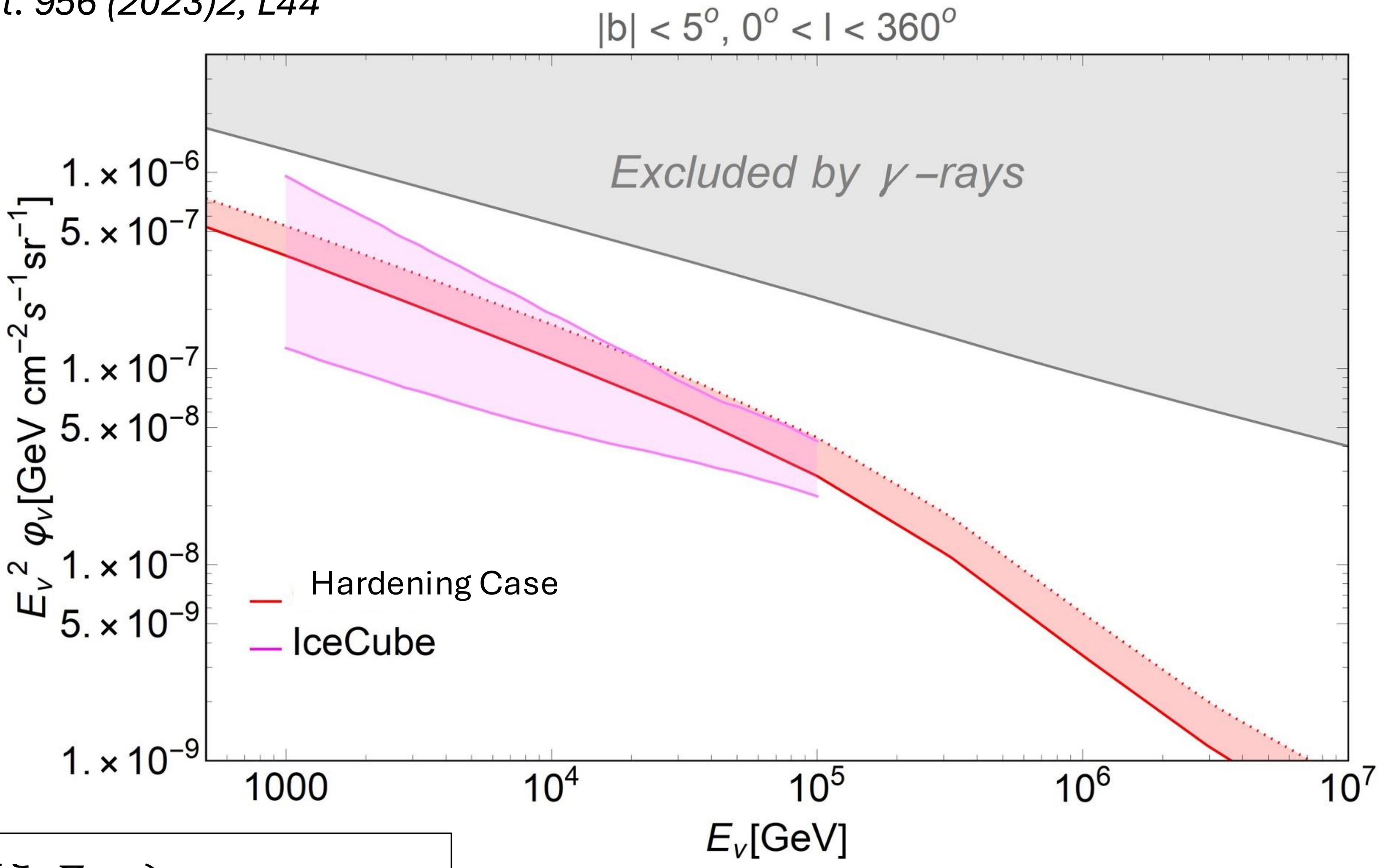
Main sensitivity around 100 TeV-
→Tibet, Lhaaso

IceCube vs Hardening Case:

Vecchiotti *et al. Astrophys. J. Lett. 956 (2023)2, L44*

- In the scenario with a CR spectral hardening there is not space for the contribution of hadronic sources.

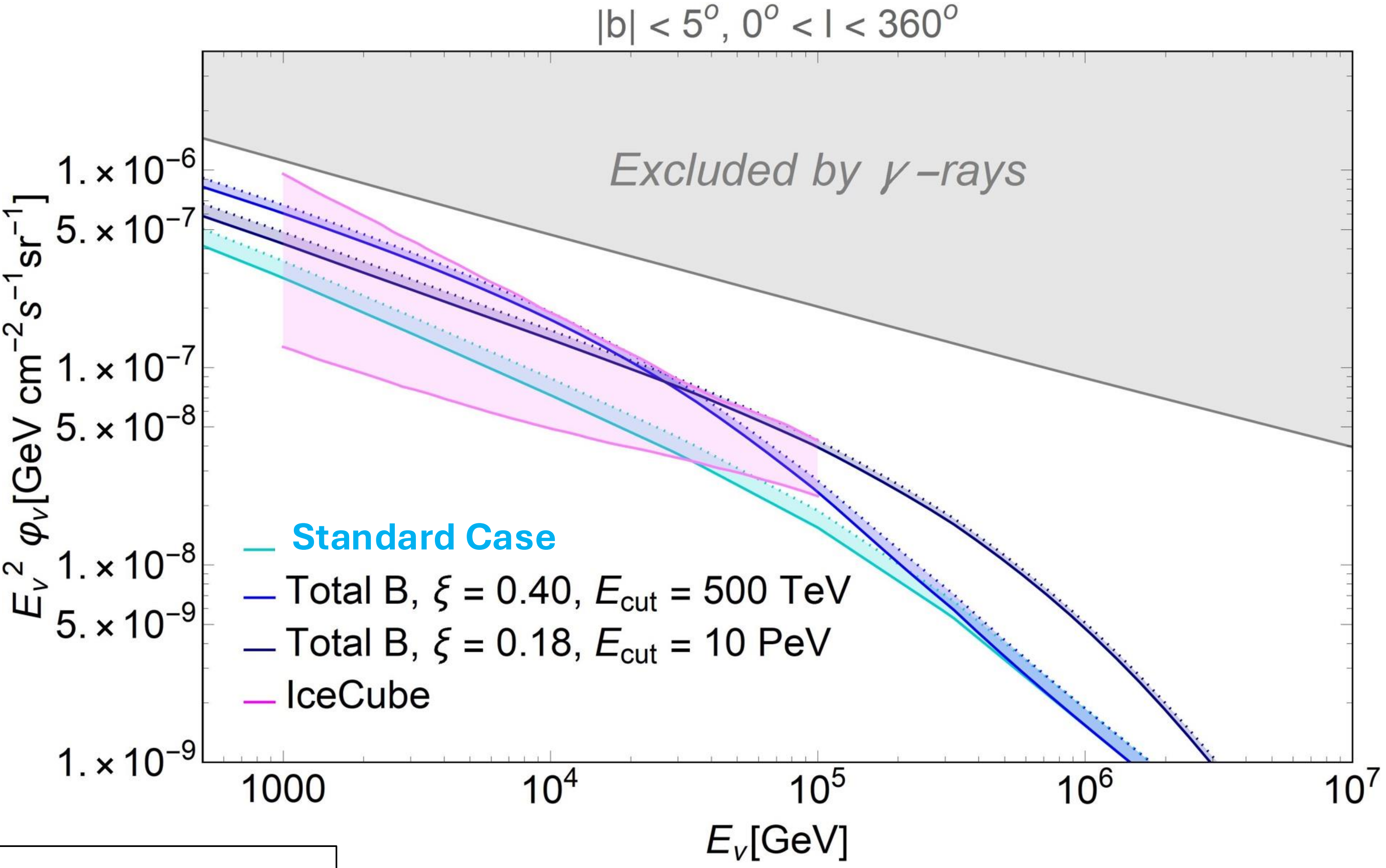
We expect PeVatrons in our Galaxy and the hardening case needs of hadronic sources to exists!



$$\varphi_{\nu,\text{tot}} = \varphi_{\nu,S}\,(\xi, E_{\text{cut}}) + \varphi_{\nu,\text{diff}}$$

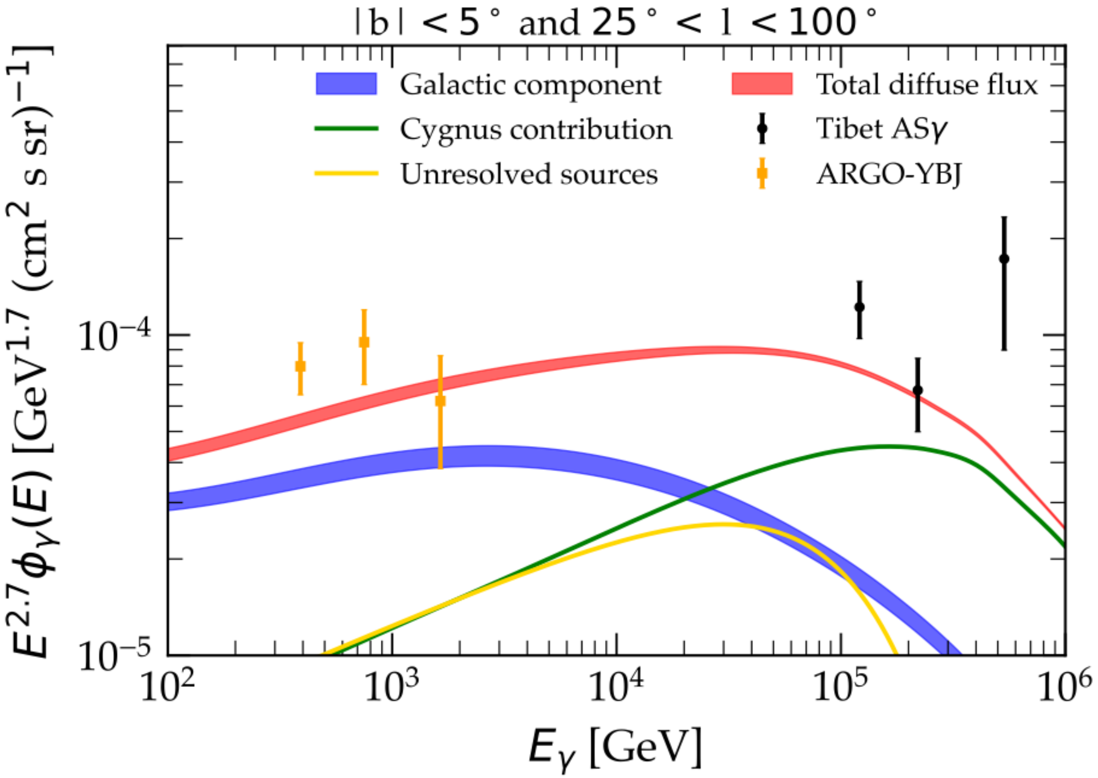
IceCube vs **Standard Case** :

- In the scenario in which the CR spectrum is uniform within the Galaxy, the maximally allowed fraction is $\xi < 0.40$ $(E_{cut} = 500\ TeV)$. If we require that Galactic sources should be able to accelerate particles up to the CR «knee» then the fraction reduces to $\xi \sim 0.20$

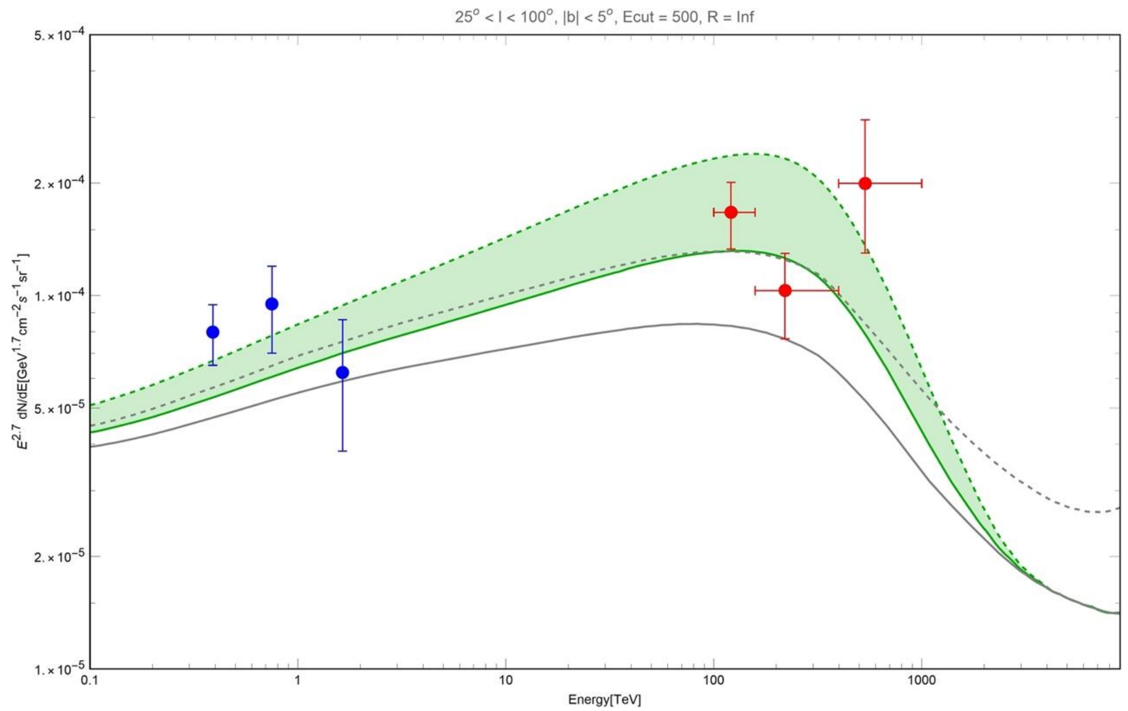


$$\varphi_{\nu,\mathrm{tot}} = \varphi_{\nu,S}\,(\xi, E_{\mathrm{cut}}) + \varphi_{\nu,\mathrm{diff}}$$

Vecchiotti *et al. Astrophys. J. Lett. 956 (2023)2, L44*



Dust gas 20% less of the Galprop one
PWNe with Ethr=LHAASO and Ecut= 100 TeV



Galprop gas
PWNe with \Phi_thr of 0.1Phi_CRAB for HESS
And Ecut 500 TeV