

The Origin of the Fermi Halo-like Emission: A New Model of the Fermi Bubbles

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w/ Ilias Cholis, Leo Hu, arXiv: 2610.10695

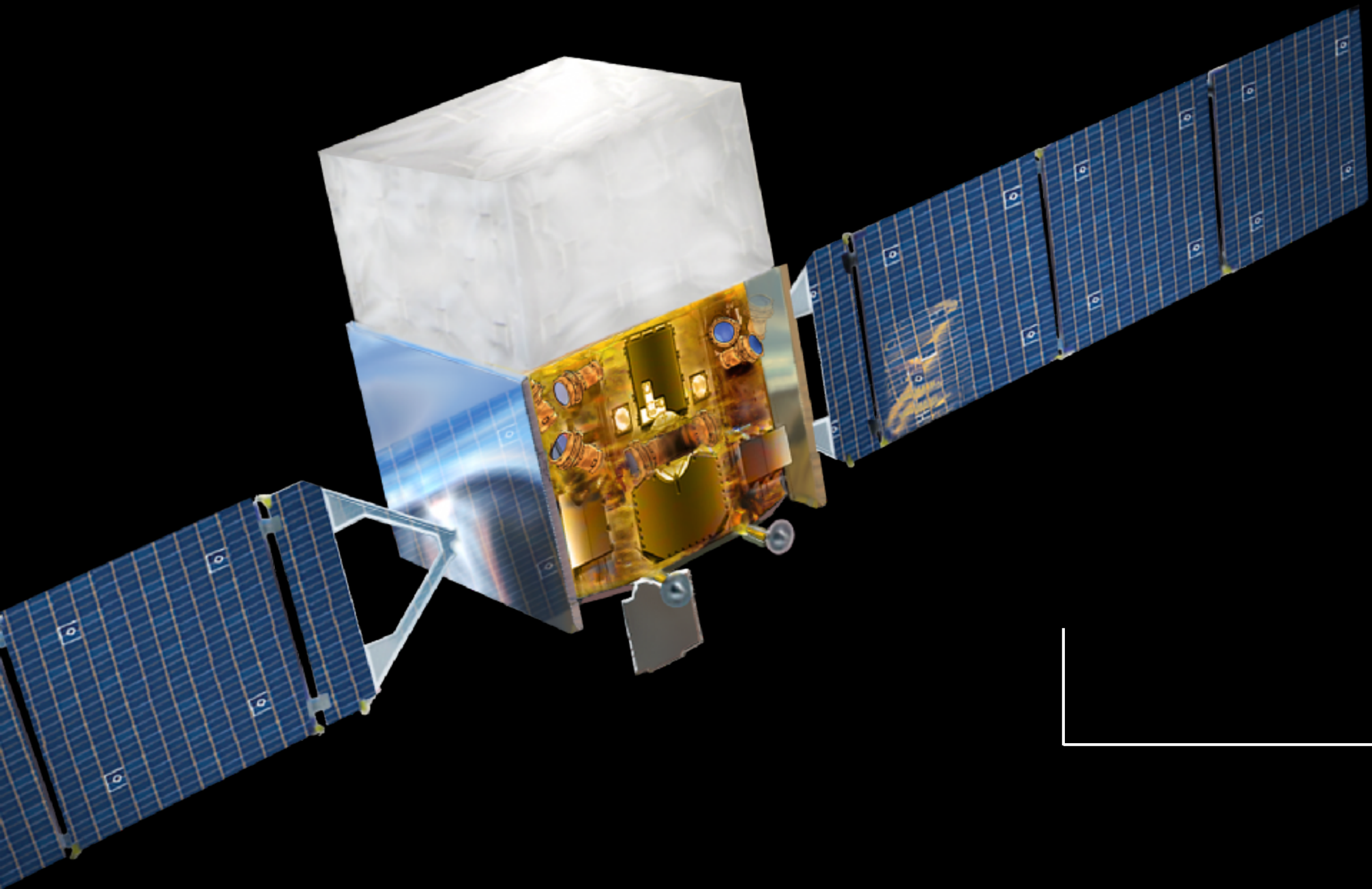
7th Joint Workshop on the Standard Model and Beyond, 29 Oct 2026



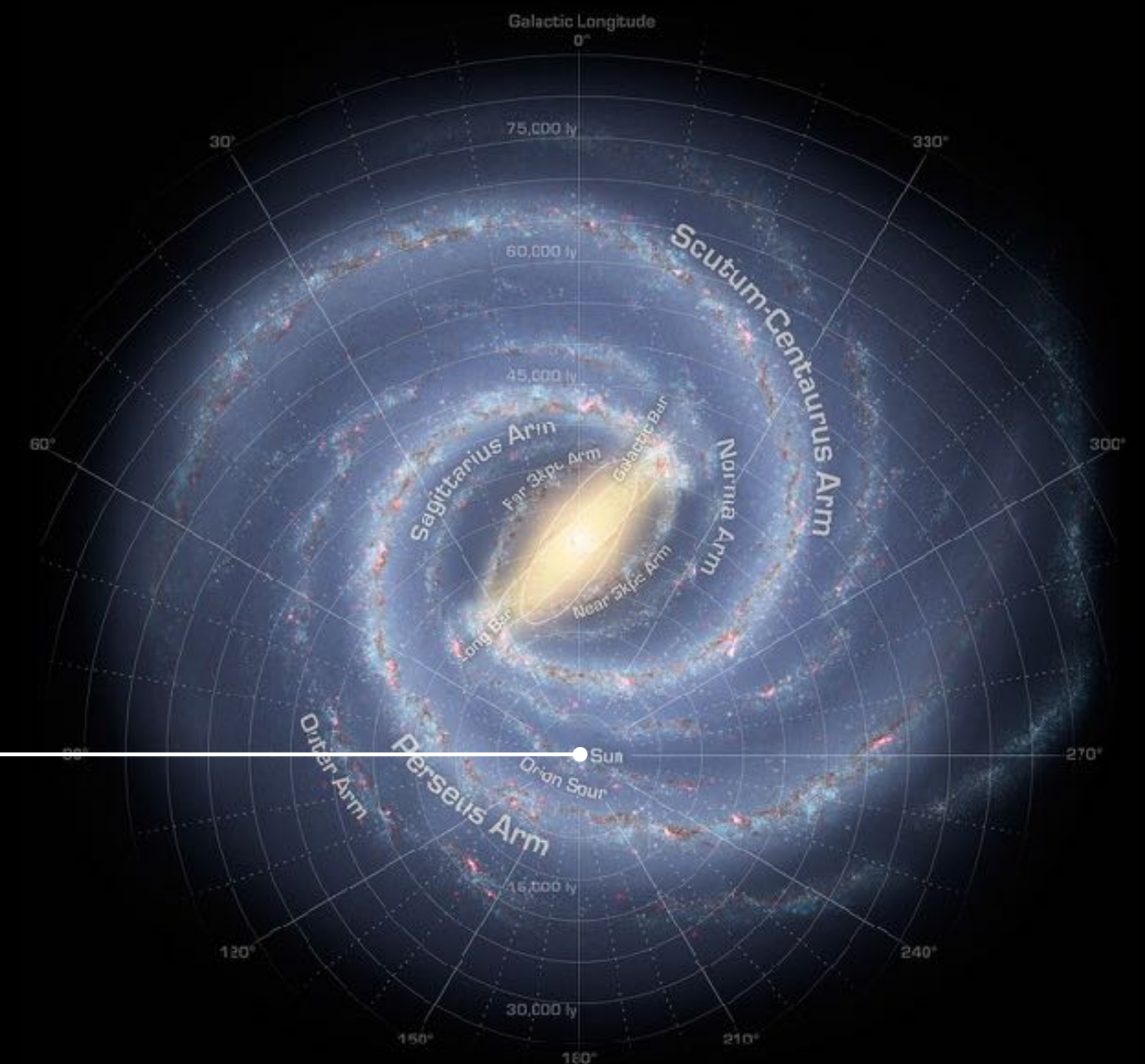
Outline

- Introduction
- Template fitting setup
- Fitting the halo-like excess: is it real? Is it dark matter?
- A new model of the Fermi Bubbles
- Summary

The Fermi Large Area Telescope

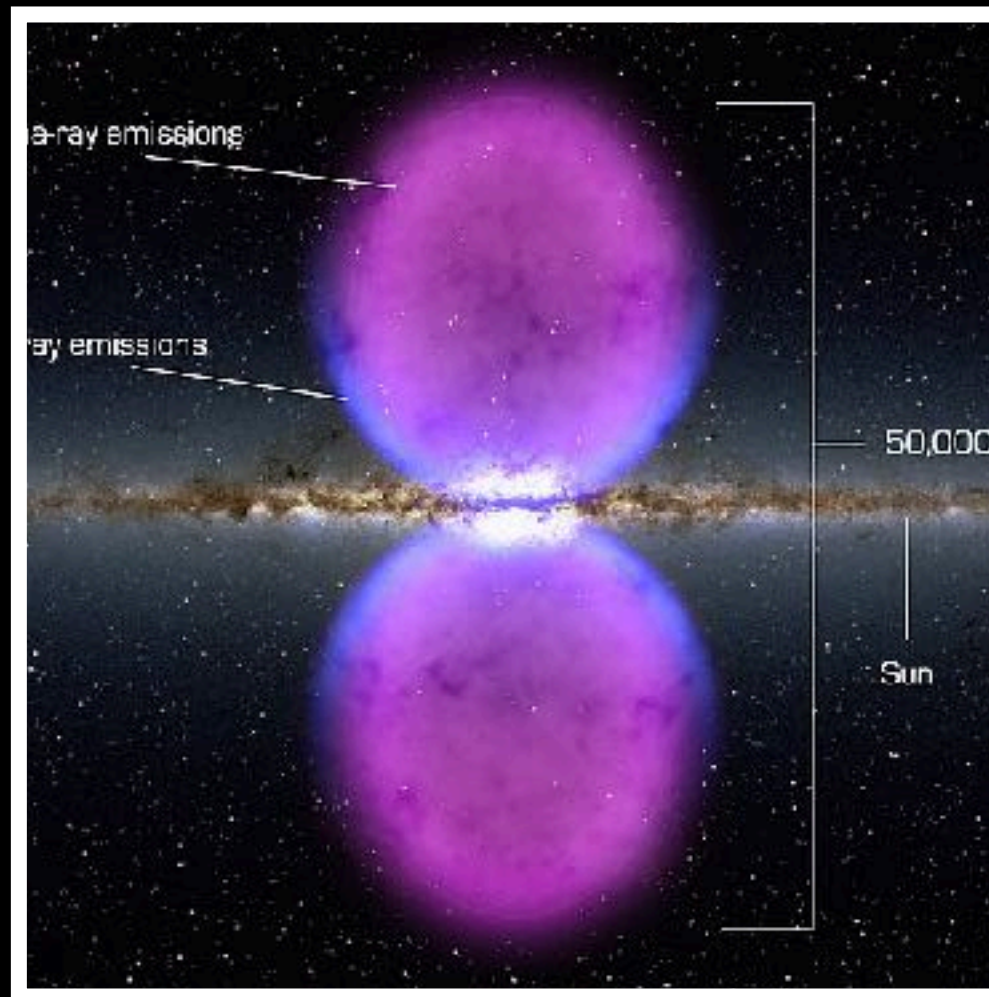


2008 to present



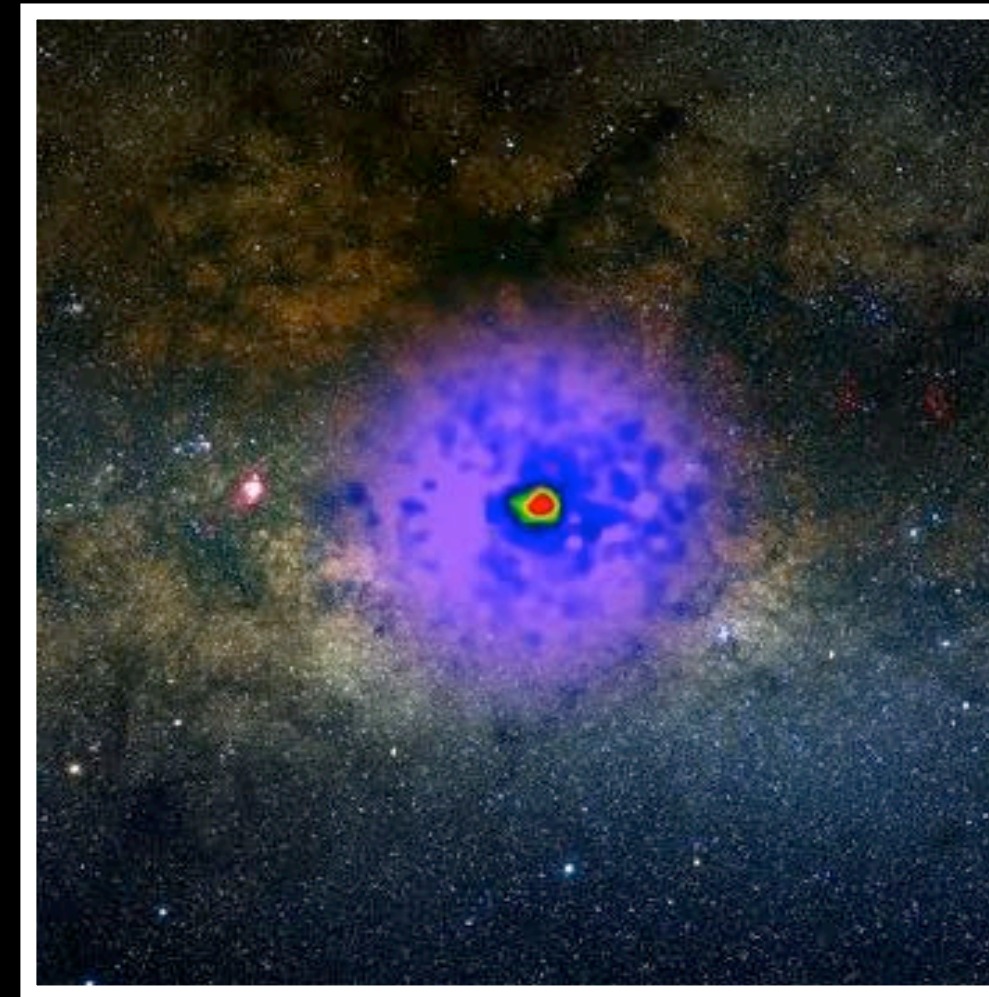
Three unexpected discoveries

The Fermi Bubbles
(Su, Slatyer &
Finkbeiner '10)



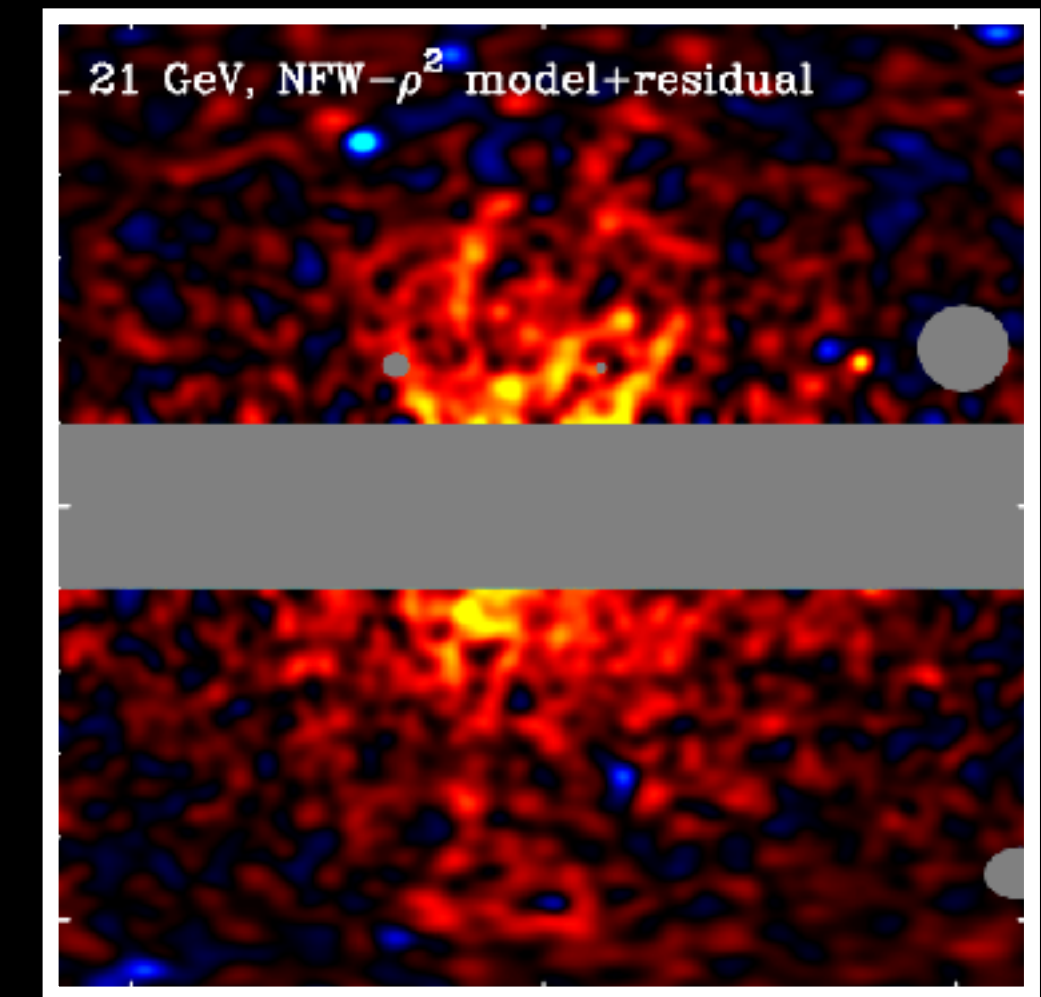
Confirmed

The Galactic Center
Excess (GCE,
Goodenough &
Hooper '09)



Confirmed

The halo-like
emission (HLE,
Totani '25)

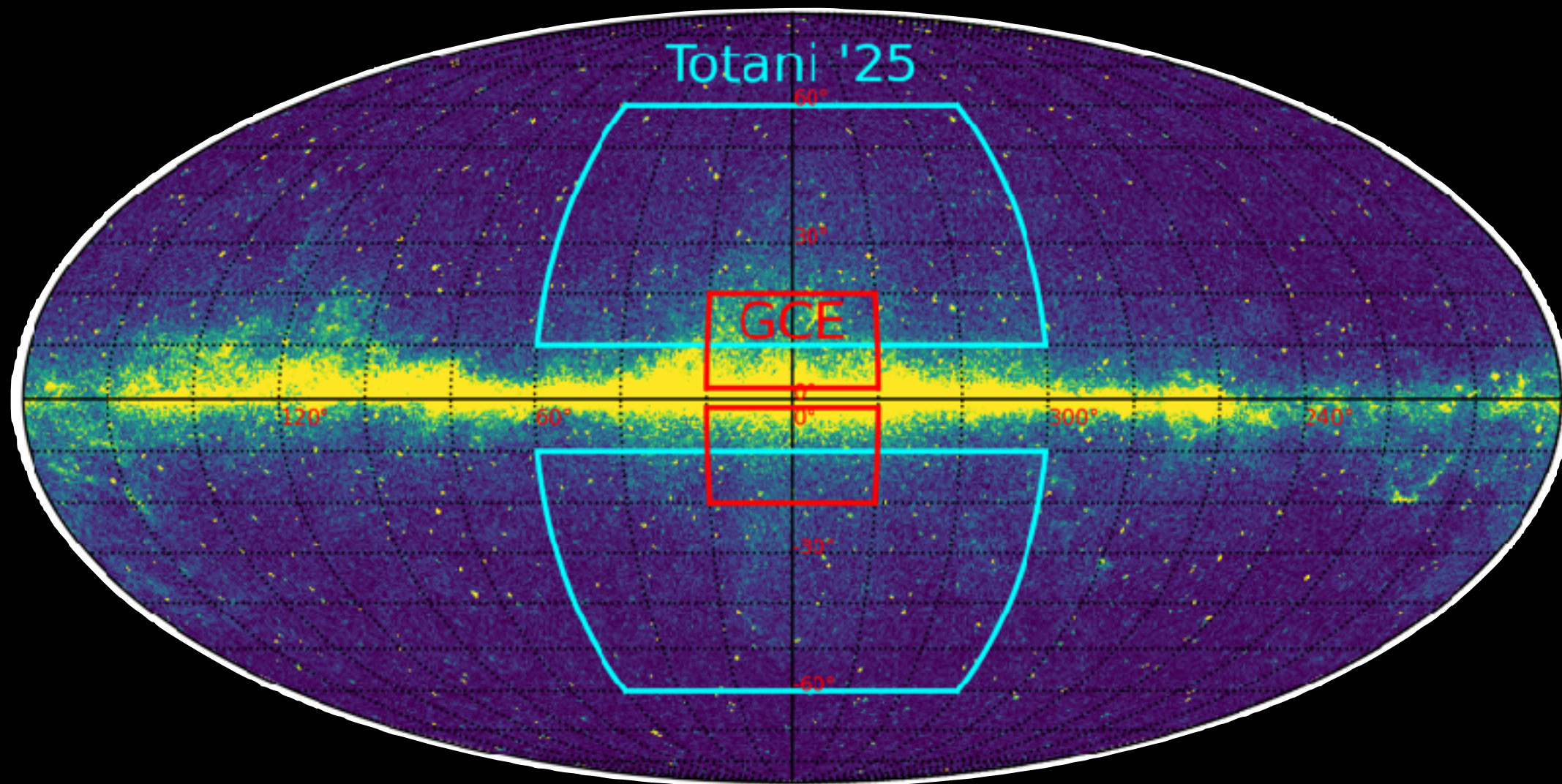
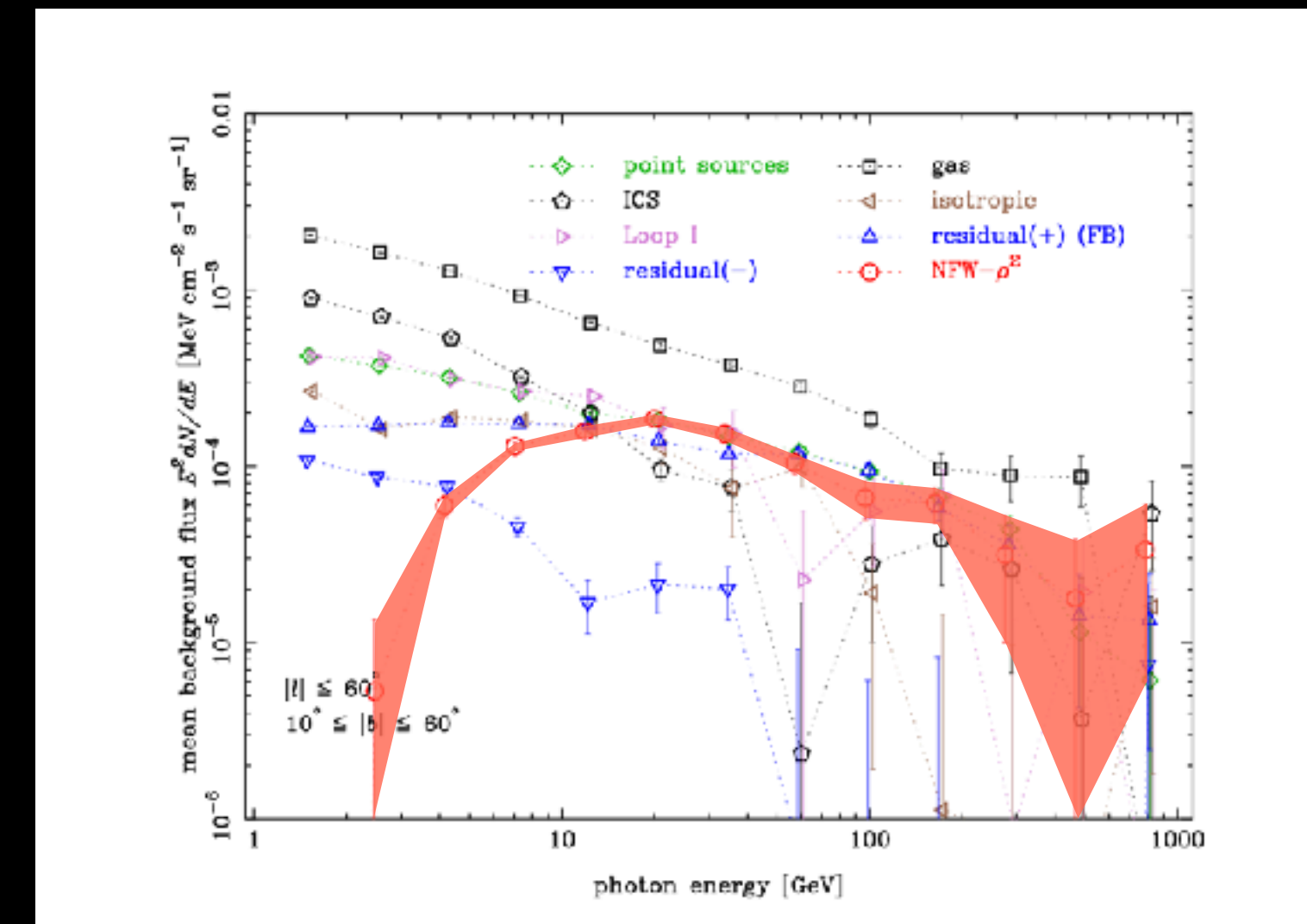


?

Totani '25: a 20 GeV halo-like emission (HLE)

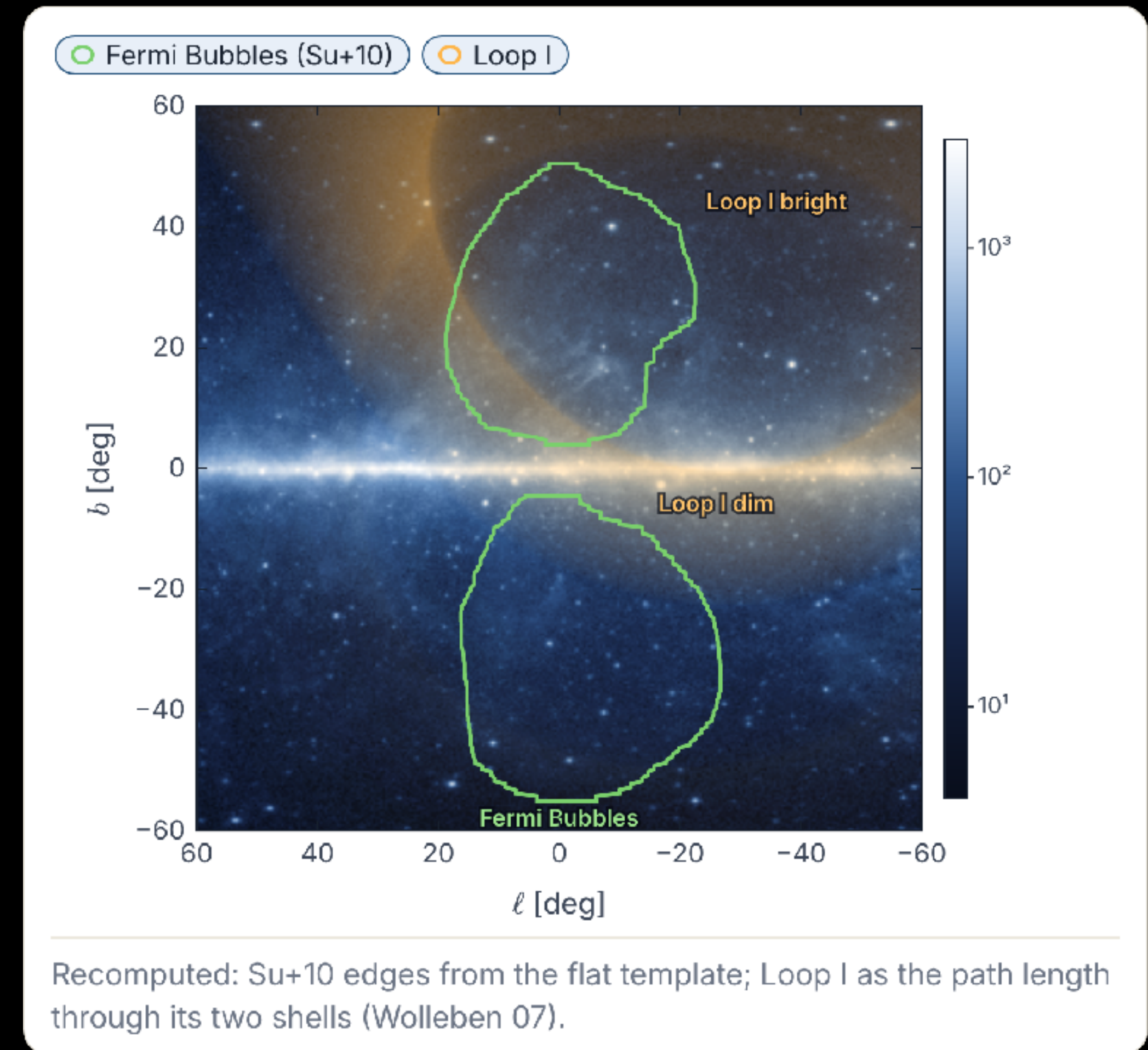
- Totani '25 searches the $[-60^\circ, 60^\circ]^2$ region with $|b| < 10^\circ$ excluded
- It reports a spectrum peaked at 20 GeV and extended to $\gtrsim 200$ GeV
- Best fit by a NFW halo w/ $\chi\chi \rightarrow b\bar{b}$ w/ mass 0.5 TeV.

$$\rho_{\text{NFW}} = \rho_s (r/r_s)^{-1} (1 + r/r_s)^{-2}$$

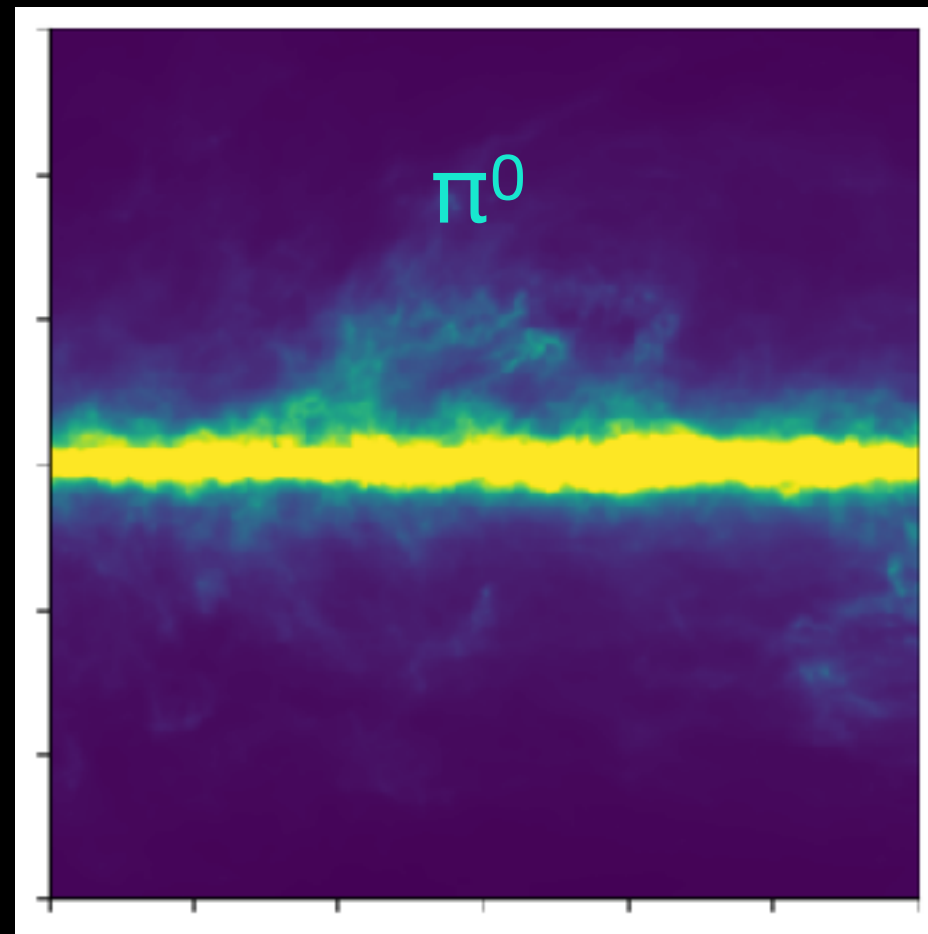
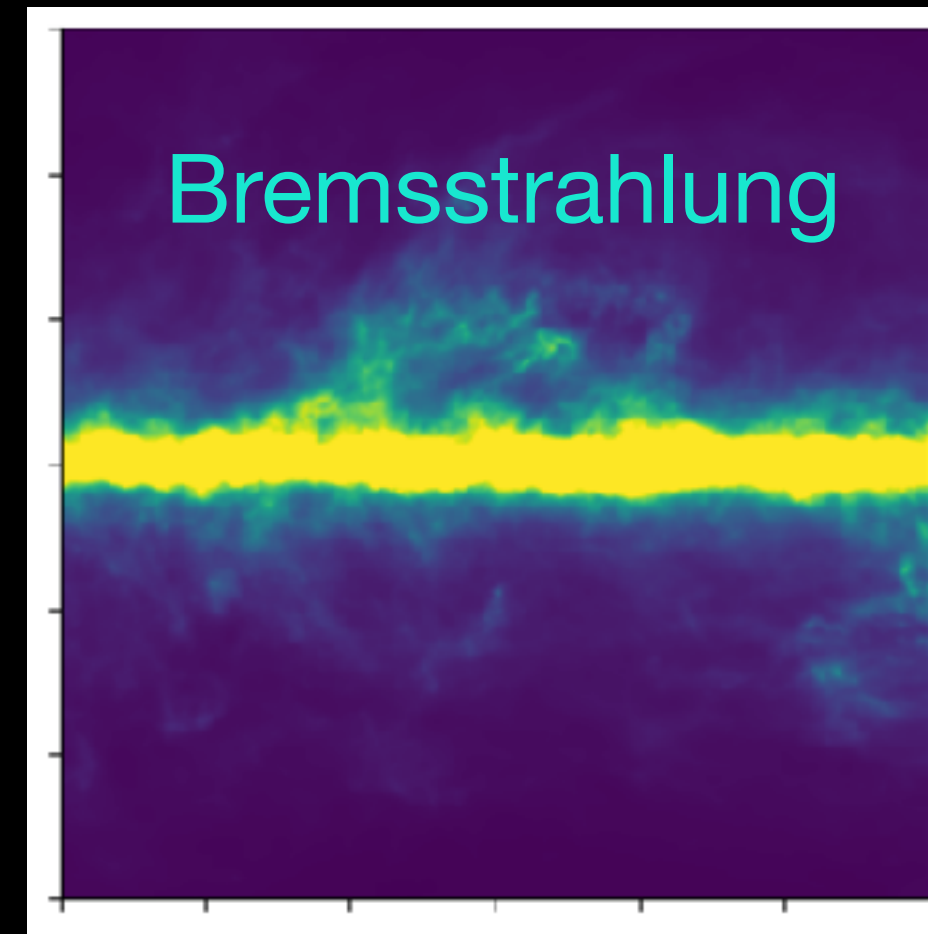
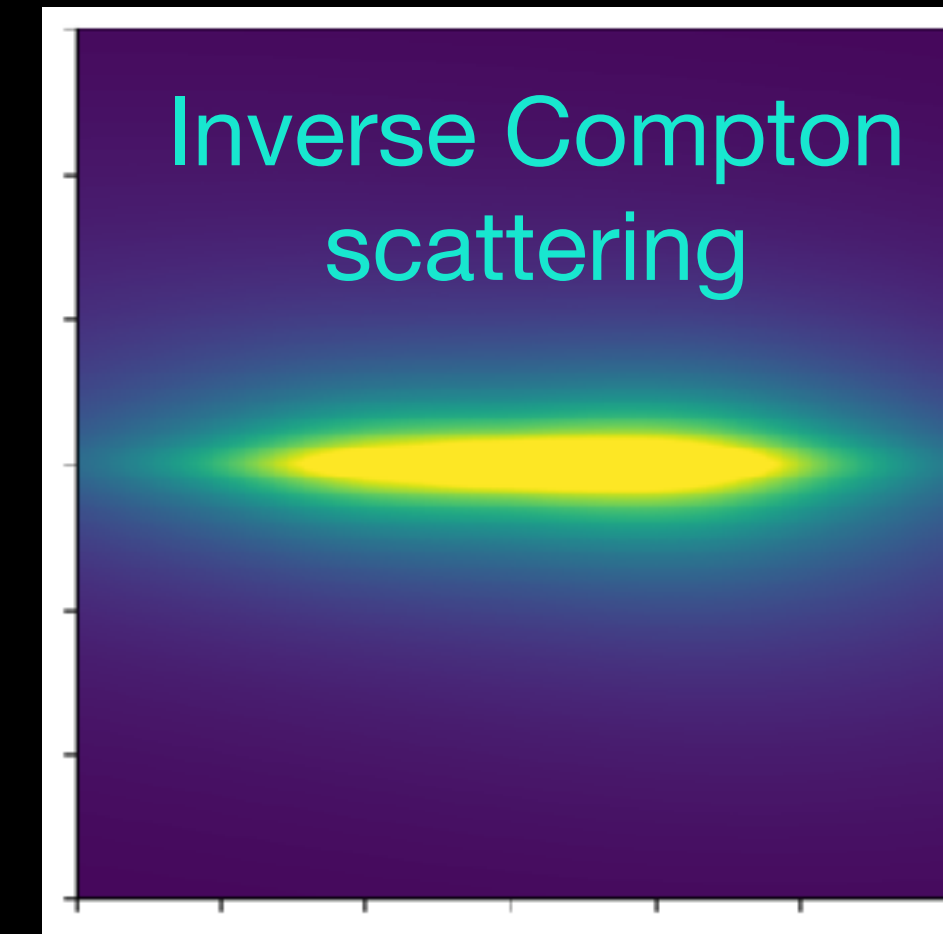
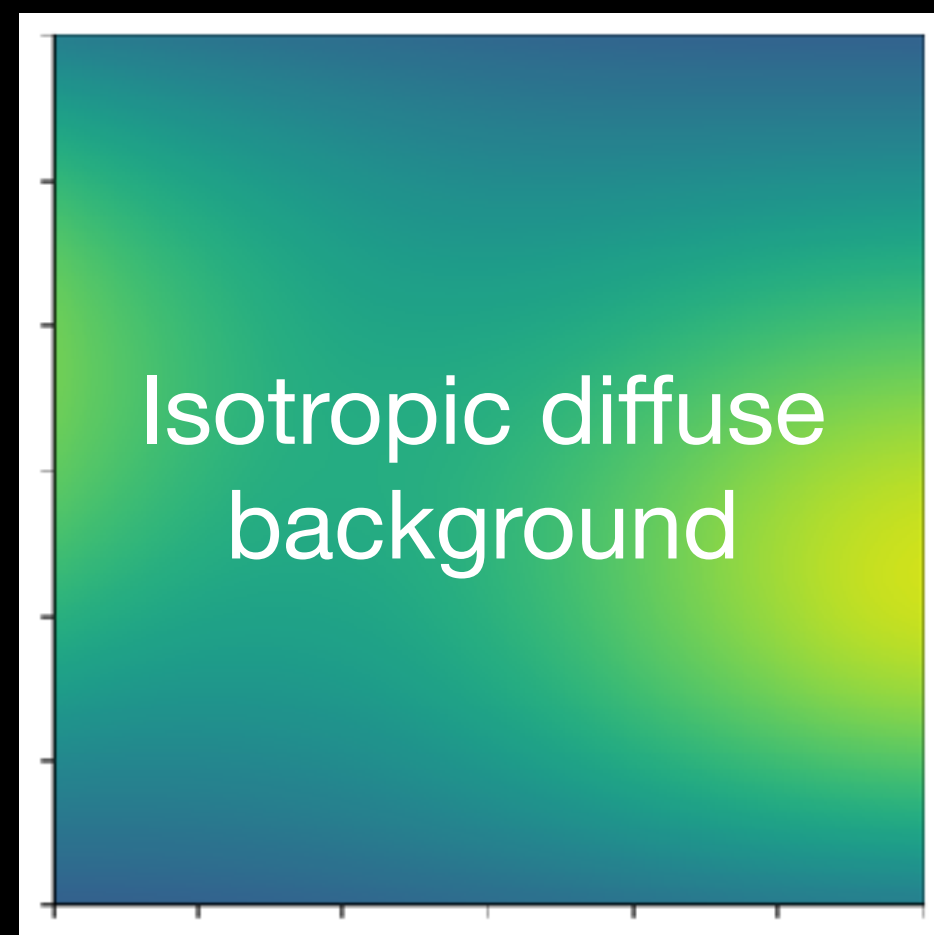
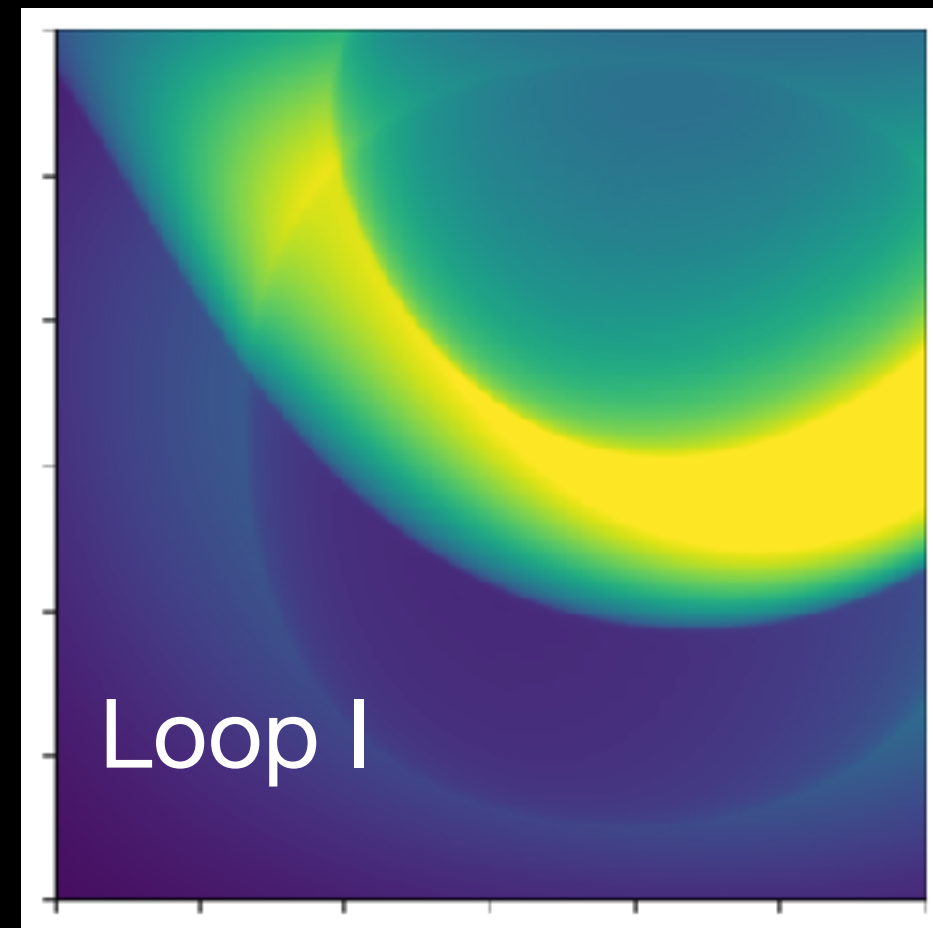
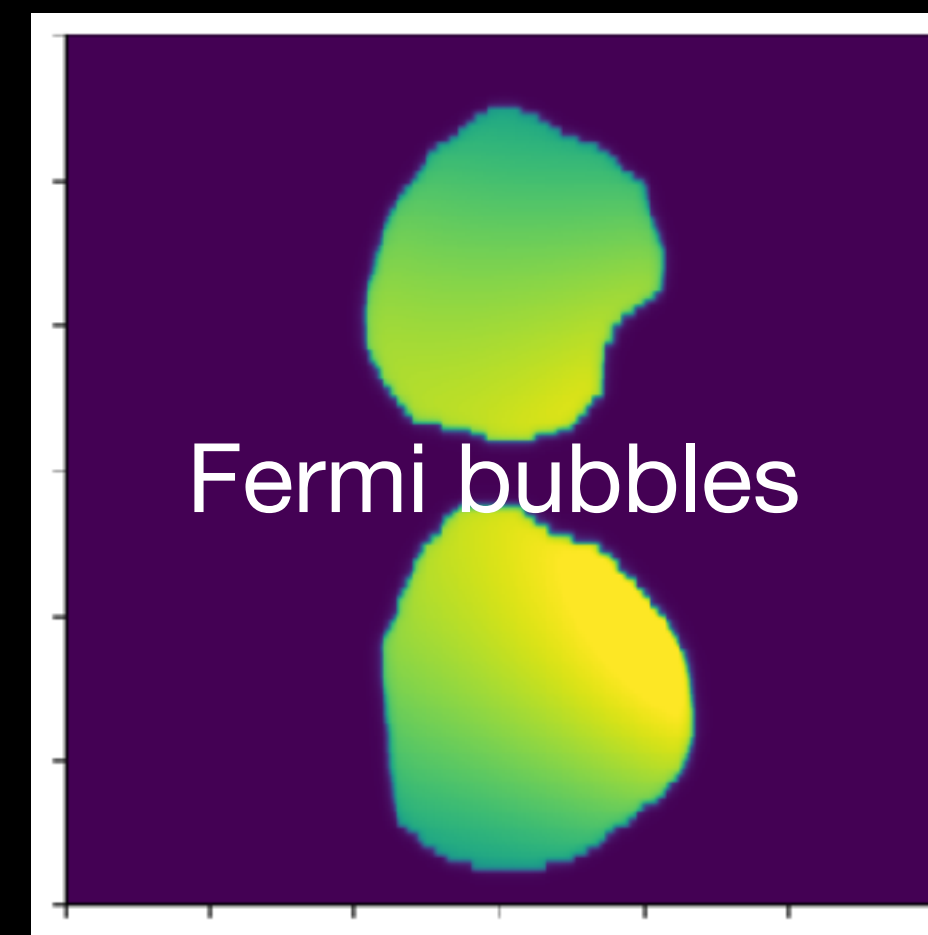
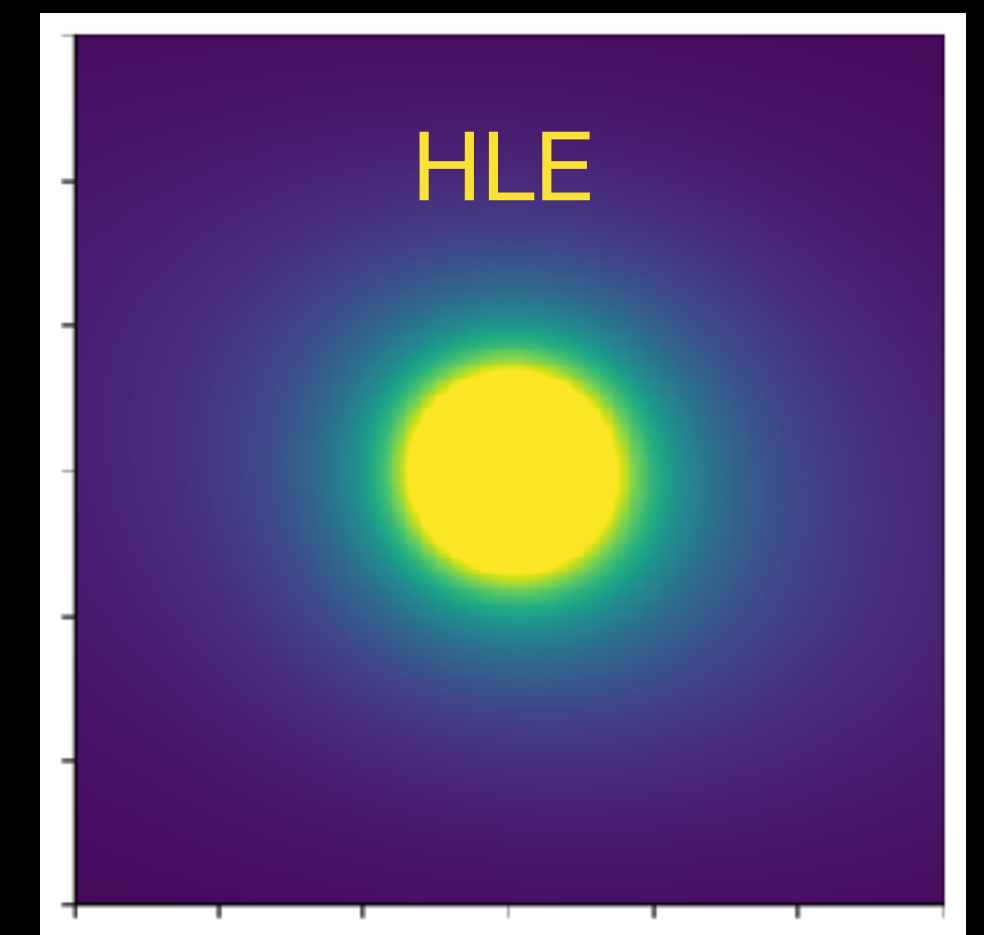


Some confirmation is needed

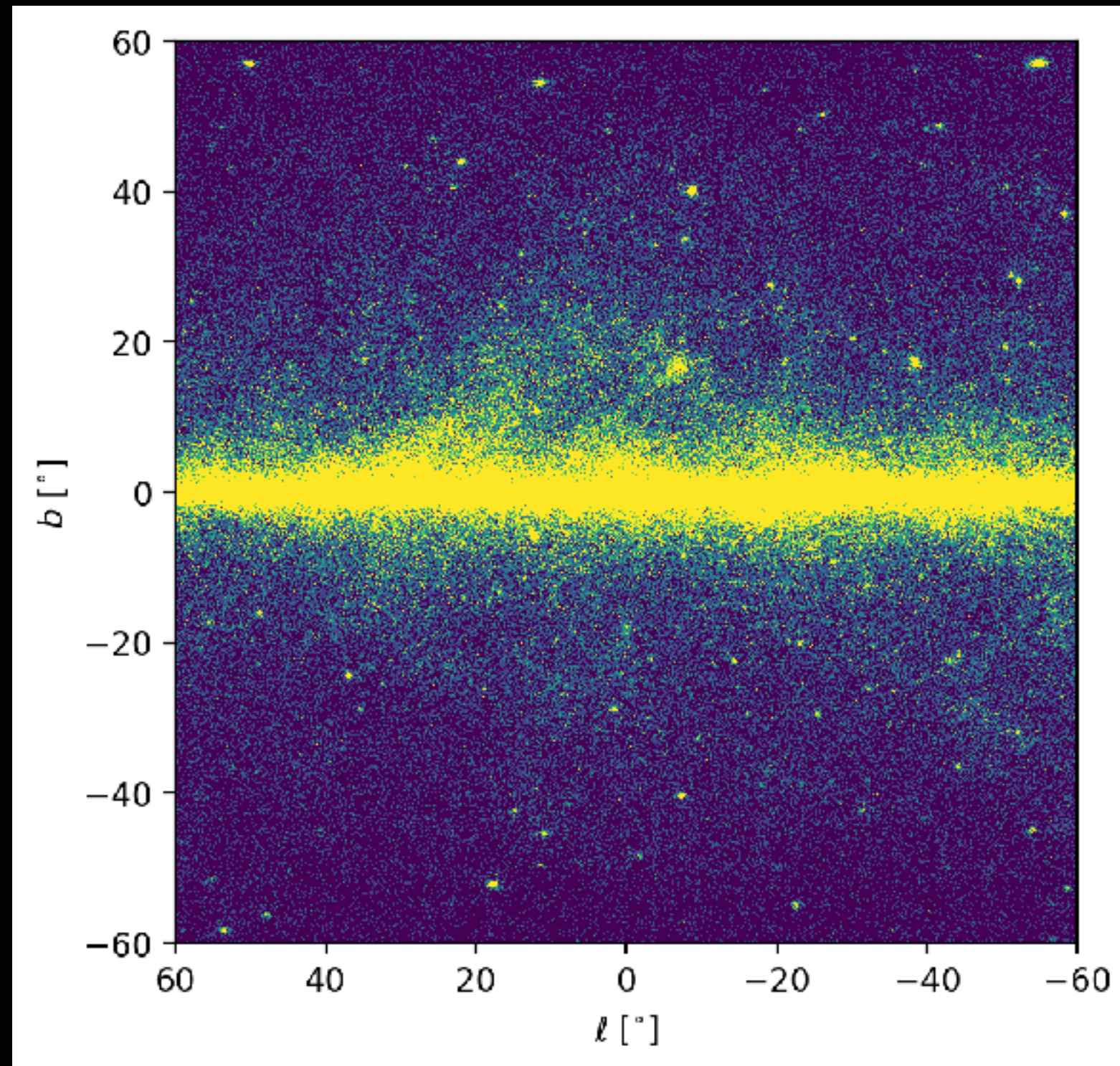
- Is the HLE real?
- Is the HLE from dark matter annihilation?
- Is the HLE part of other giant structures in gamma rays?
 - Loop I, Bubbles, Cocoon



Template fitting

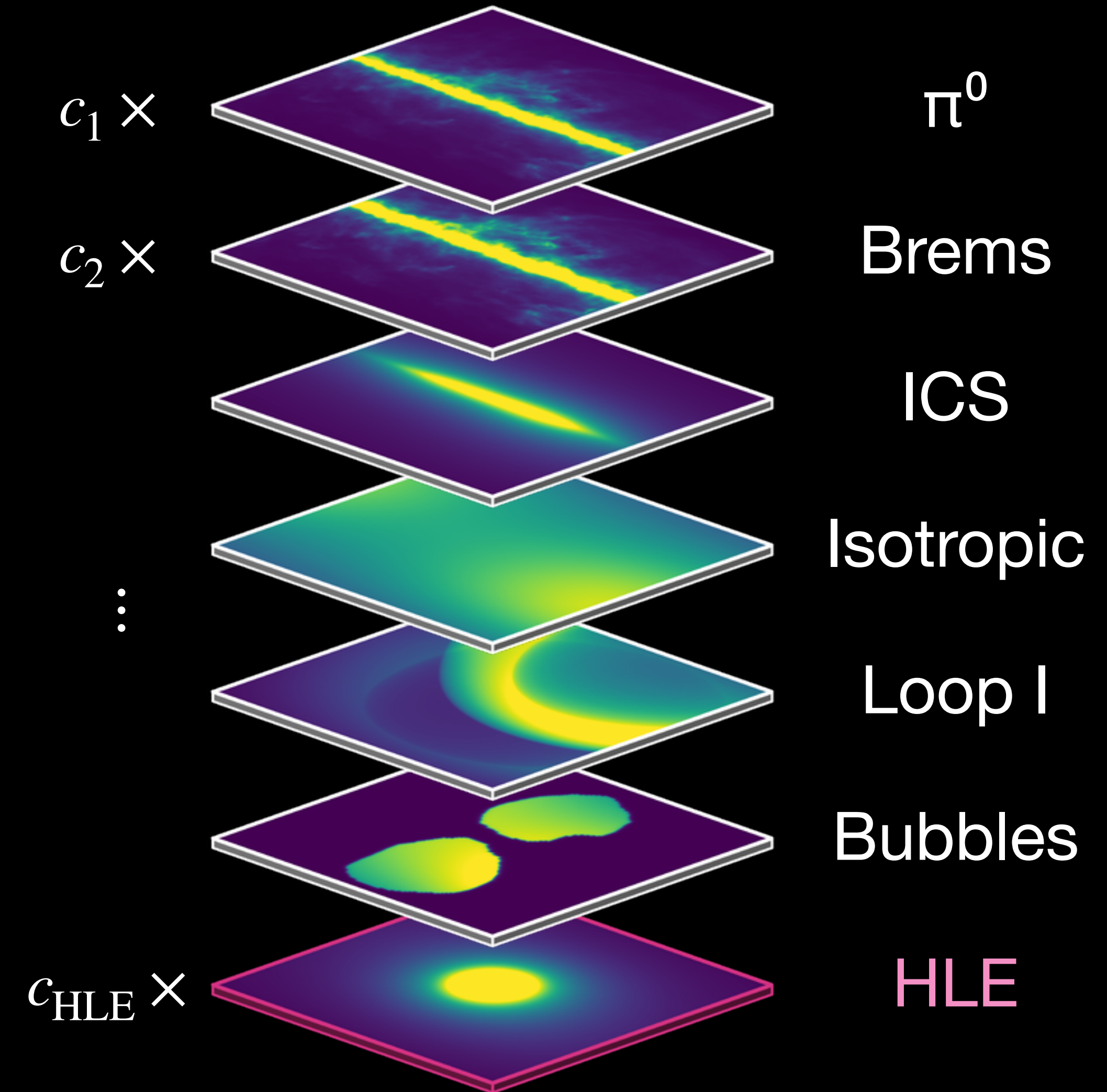


Fermi data



VS.

Weighted sum over all background & HLE templates



More mathematically speaking

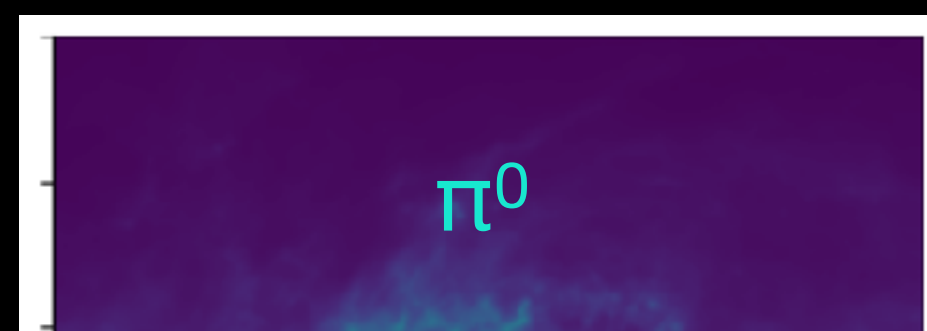
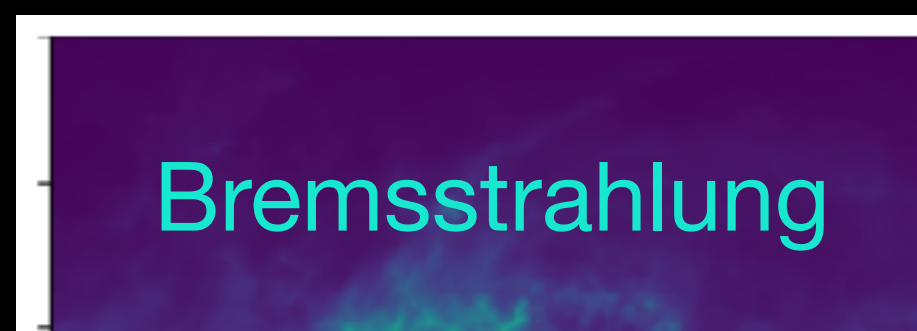
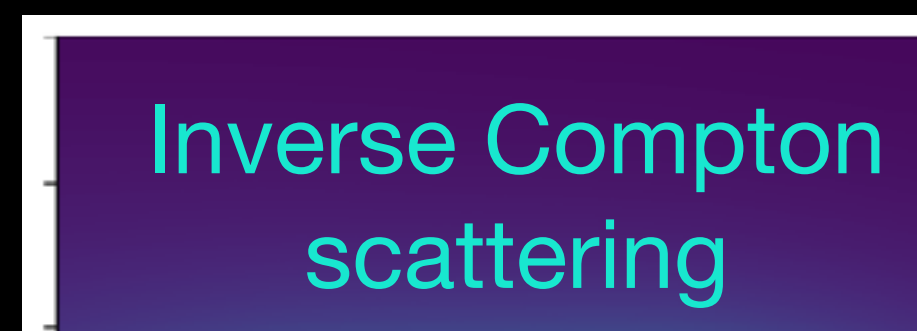
$$\mathcal{C}_{j,p} = c_j^{\text{gas}} \Phi_{j,p}^{\text{Pi0}} + c_j^{\text{ICS}} \Phi_{j,p}^{\text{ICS}} + \dots + c_j^{\text{HLE}} \Phi_{j,p}^{\text{HLE}}$$

Weighted sum
of templates,
 j : energy bins,
 p : pixels

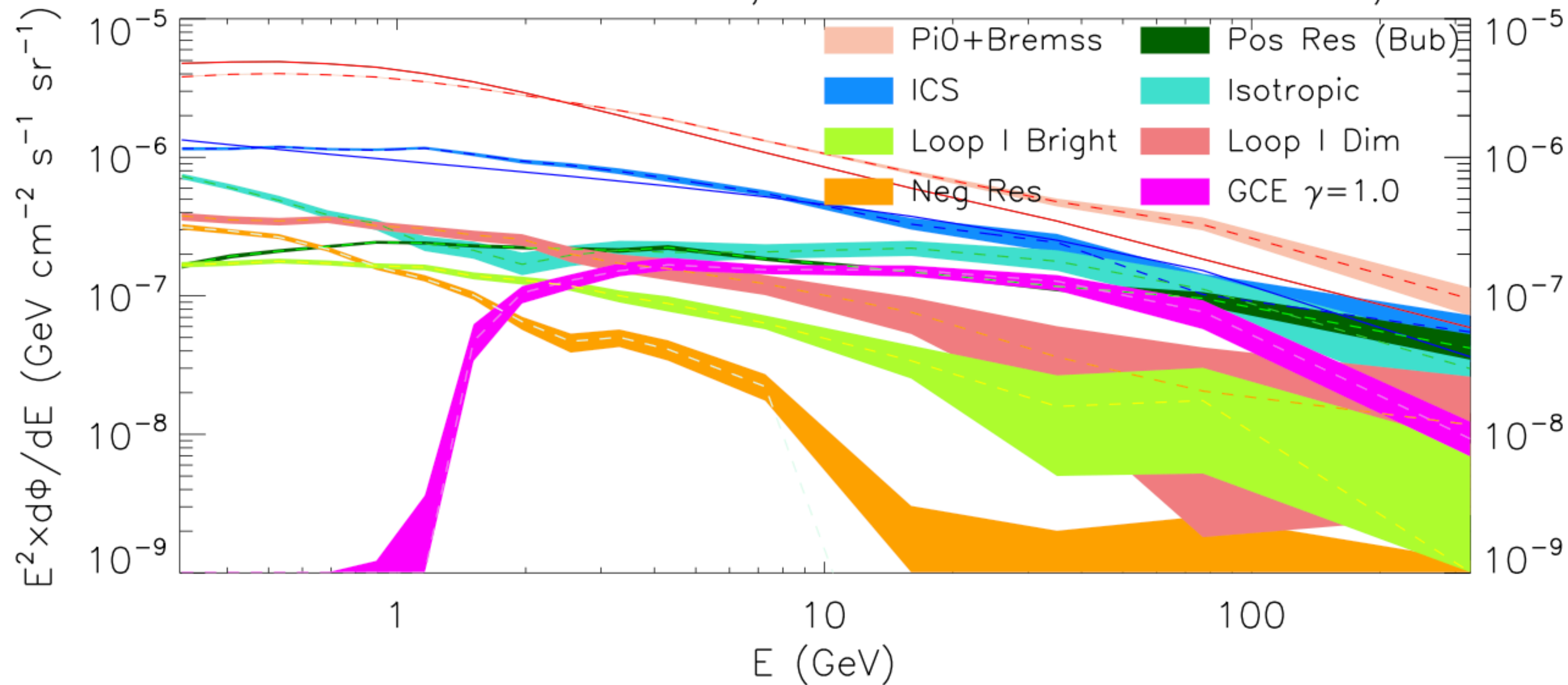
$\mathcal{D}$ = Fermi Data

Which weights maximize the log-likelihood?

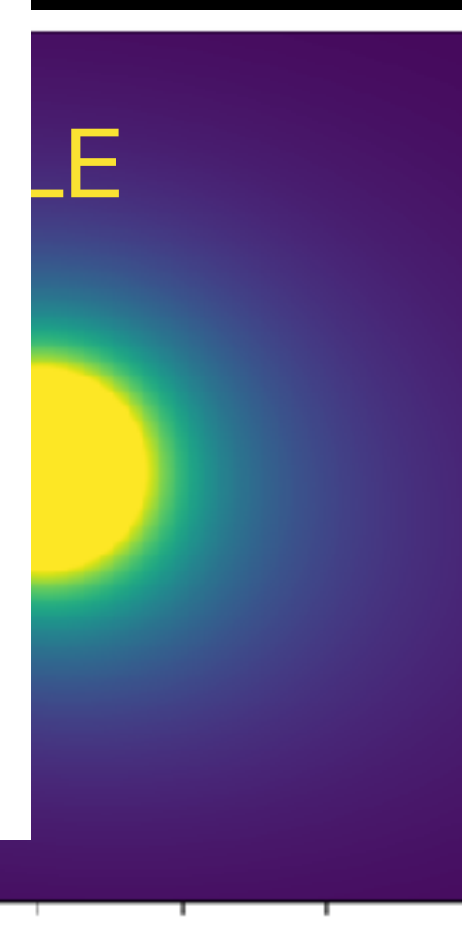
$$2 \ln \mathcal{L}_j = 2 \sum_p \ln \text{Pois}(\mathcal{D}_{j,p} | \mathcal{C}_{j,p}) - \chi_{\text{prior},j}^2$$



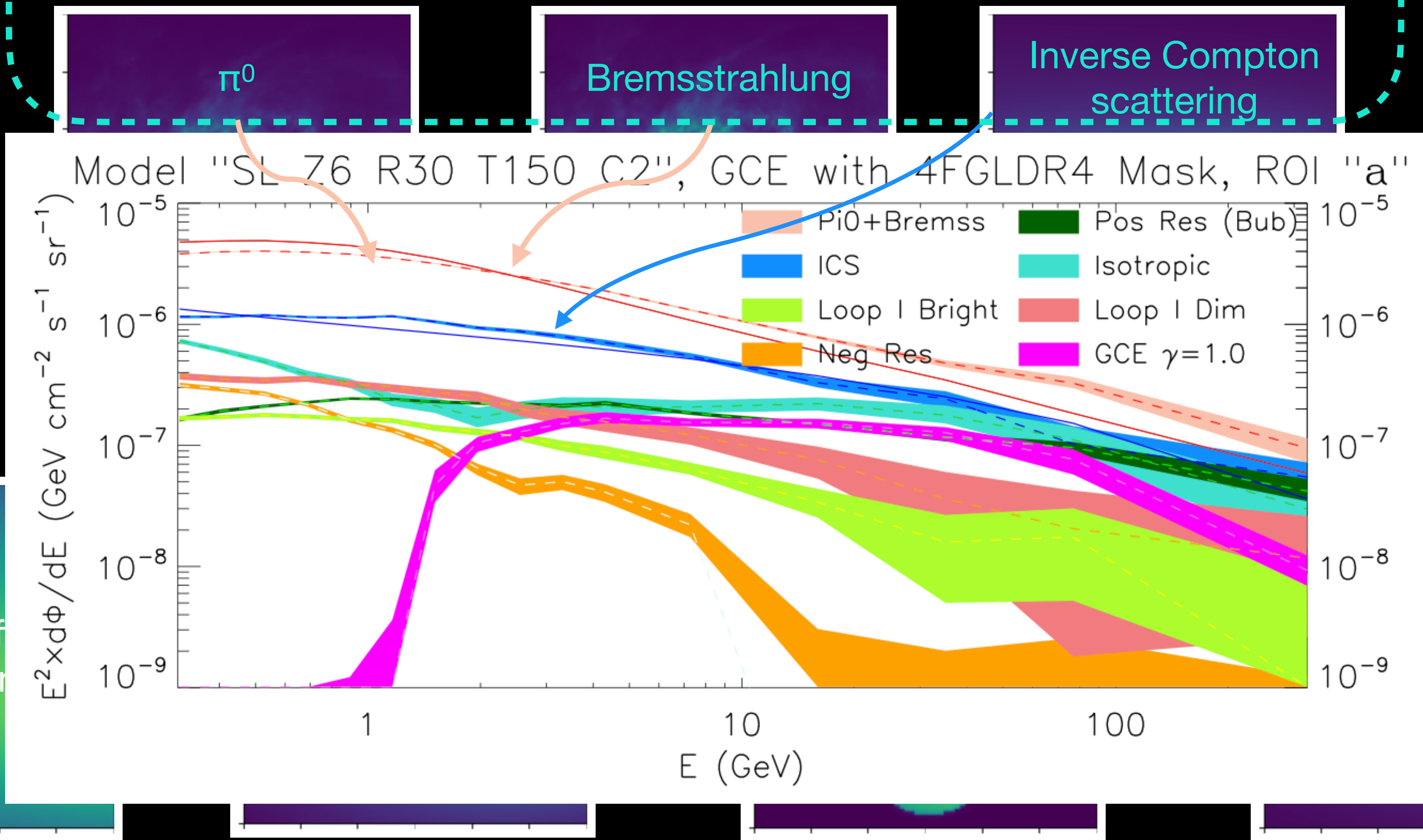
Model "SL Z6 R30 T150 C2", GCE with 4FGLDR4 Mask, ROI "a"



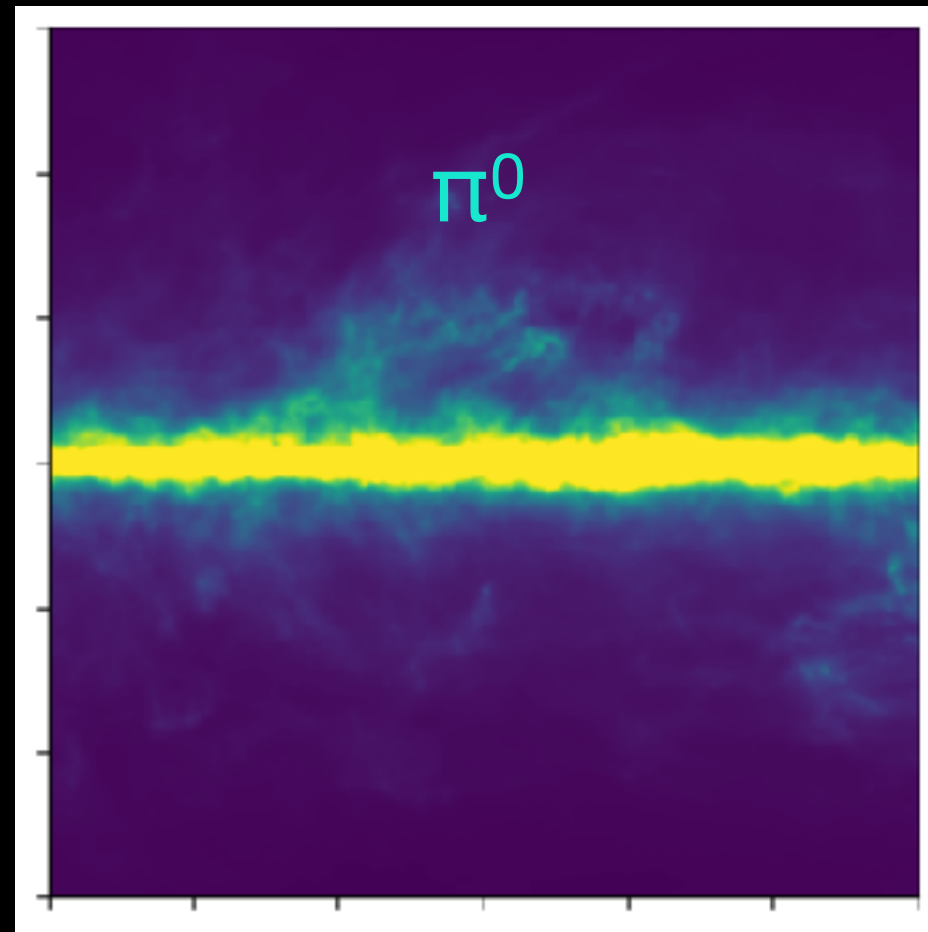
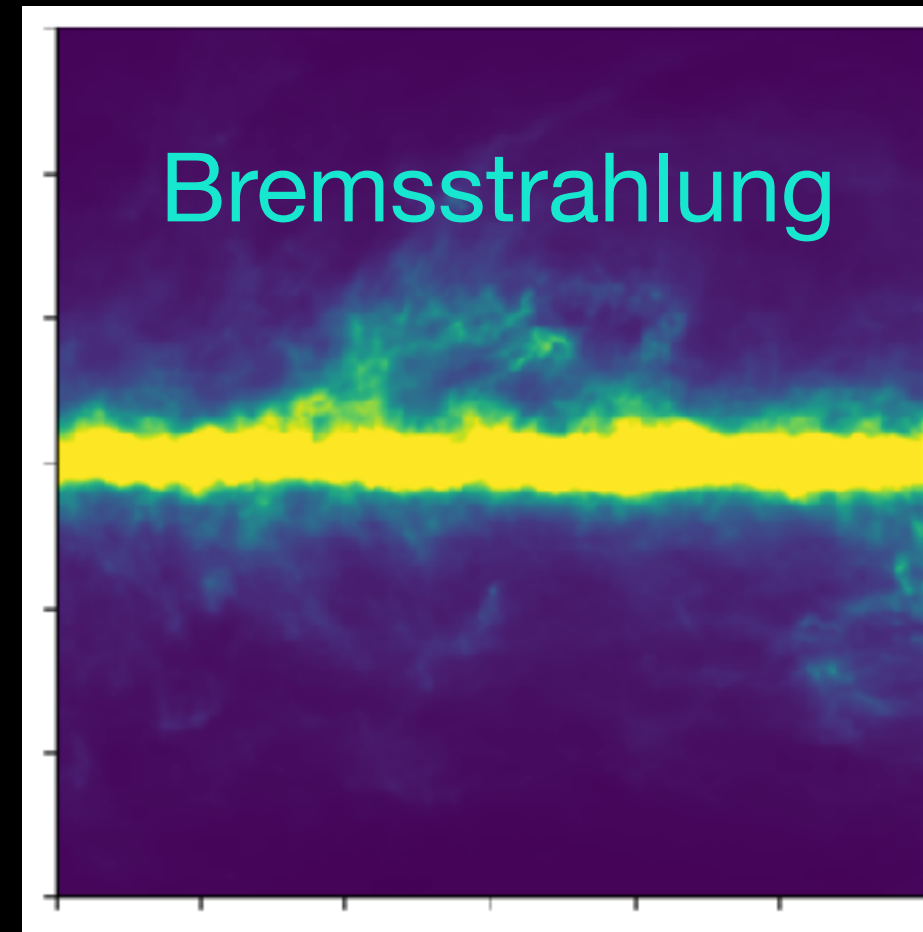
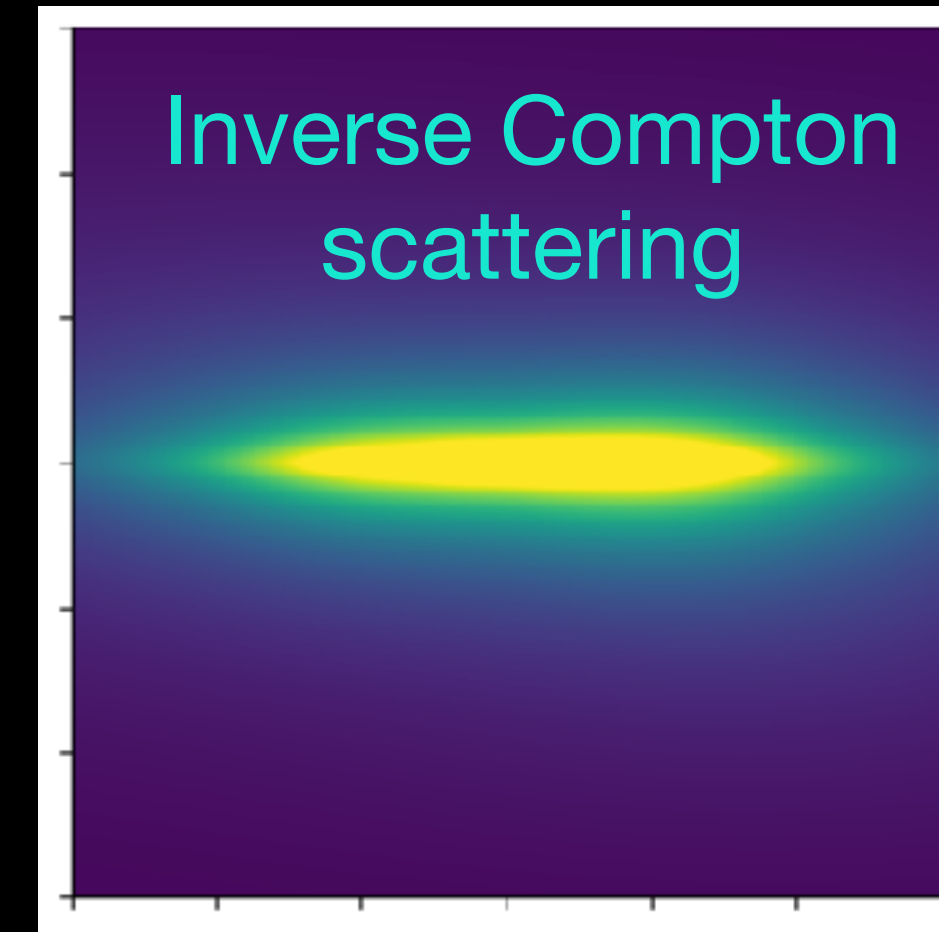
Isotropic dif
background



Galactic Diffuse Emissions (GDE)

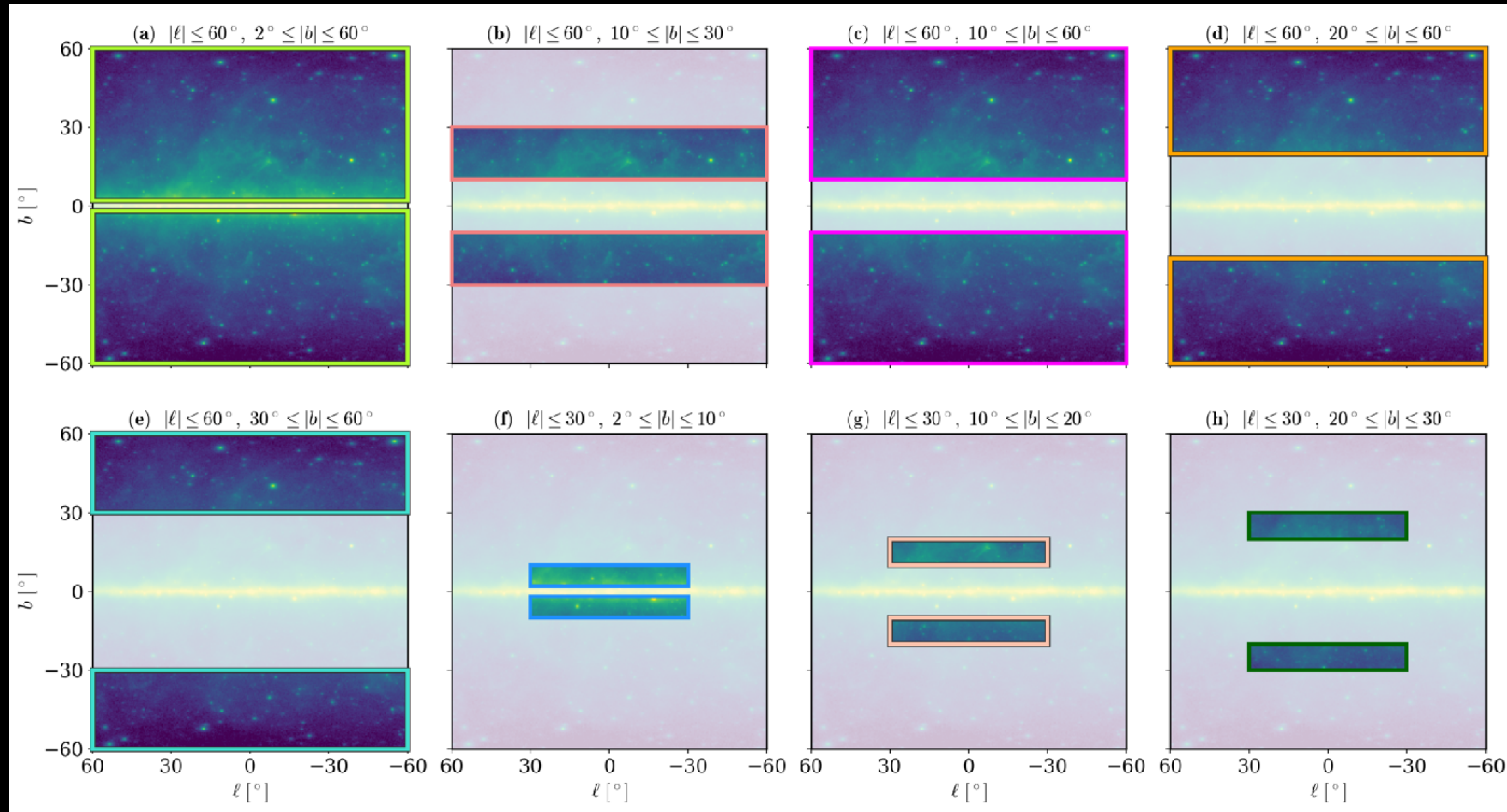


Galactic Diffuse Emissions



- 20 GDE sets from Fermi-LAT covering the 4π sky.
- 80 GDE sets from Cholis+ (+YZ) '21 covering the $[-30^\circ, 30^\circ] \times [-30^\circ, 30^\circ]$ sky.

We repeat the fit in eight regions of interest



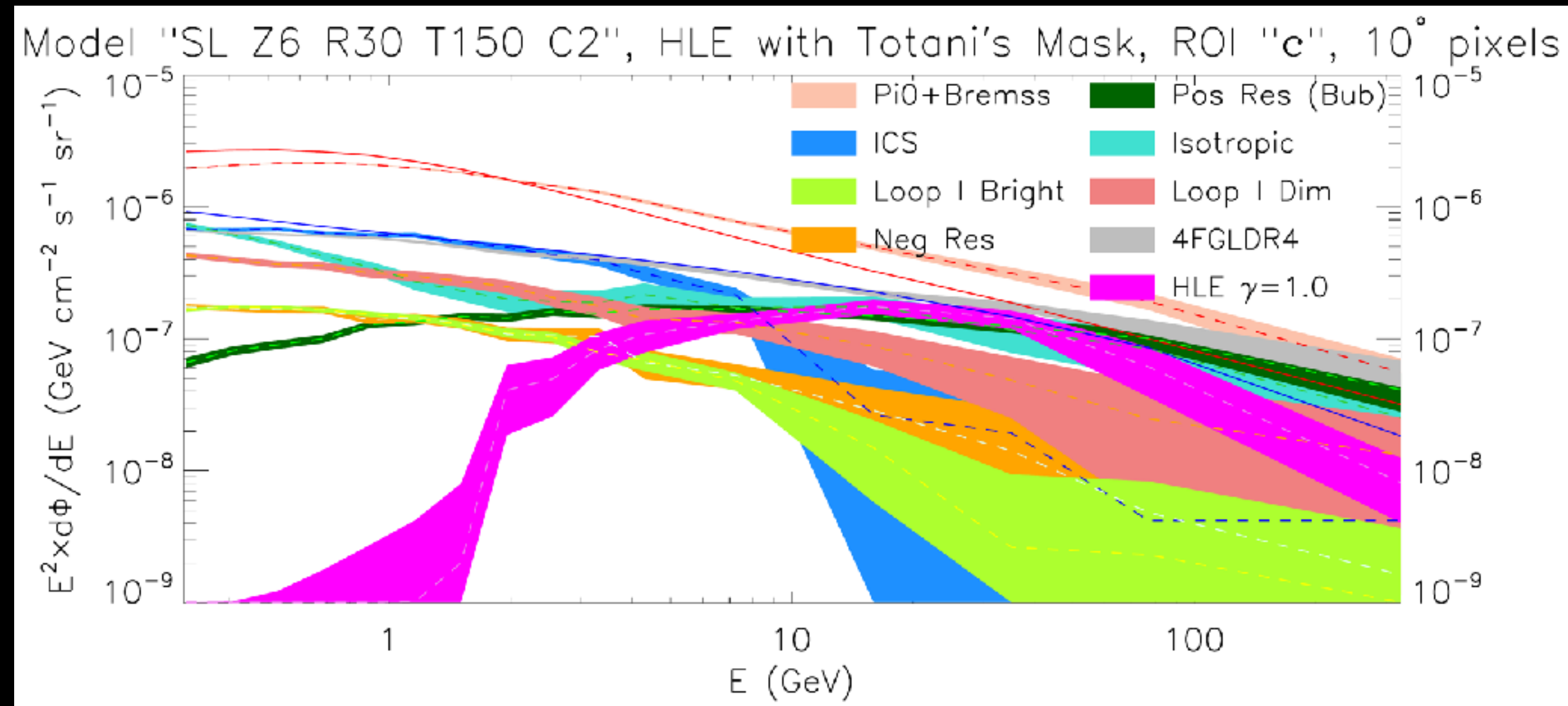
Fitting the HLE

Four fit schemes, from 6 to 9 free templates

- Data: Fermi-LAT Pass 8, Aug 2008 – Apr 2025; 16 energy bins for 0.275–928 GeV

Name	ROI	Mask	Templates	Diffuse (GDE) models
6-param	a, b, c, d, e	4FGL-DR4	π^0 +brems, ICS, isotropic, Bubbles, Loop I, HLE	SL Z6 R30 T150 C2
7-param	a, b, c, d, e, f, g, h	4FGL-DR4	π^0 +brems, ICS, isotropic, Bubbles, Loop I bright, Loop I dim, HLE	Fermi-LAT '12 and Cholis+ '21 (up to 100 models)
8-param	a, b, c, d, e	4FGL-DR4	π^0 +brems, ICS, isotropic, Pos Res, Neg Res, Loop I bright, Loop I dim, HLE	SL Z6 R30 T150 C2
9-param	c	Totani	π^0 +brems, ICS, isotropic, Pos Res, Neg Res, Loop I bright, Loop I dim, 4FGL-DR4 sources, HLE	SL Z6 R30 T150 C2

Reproducing Totani '25

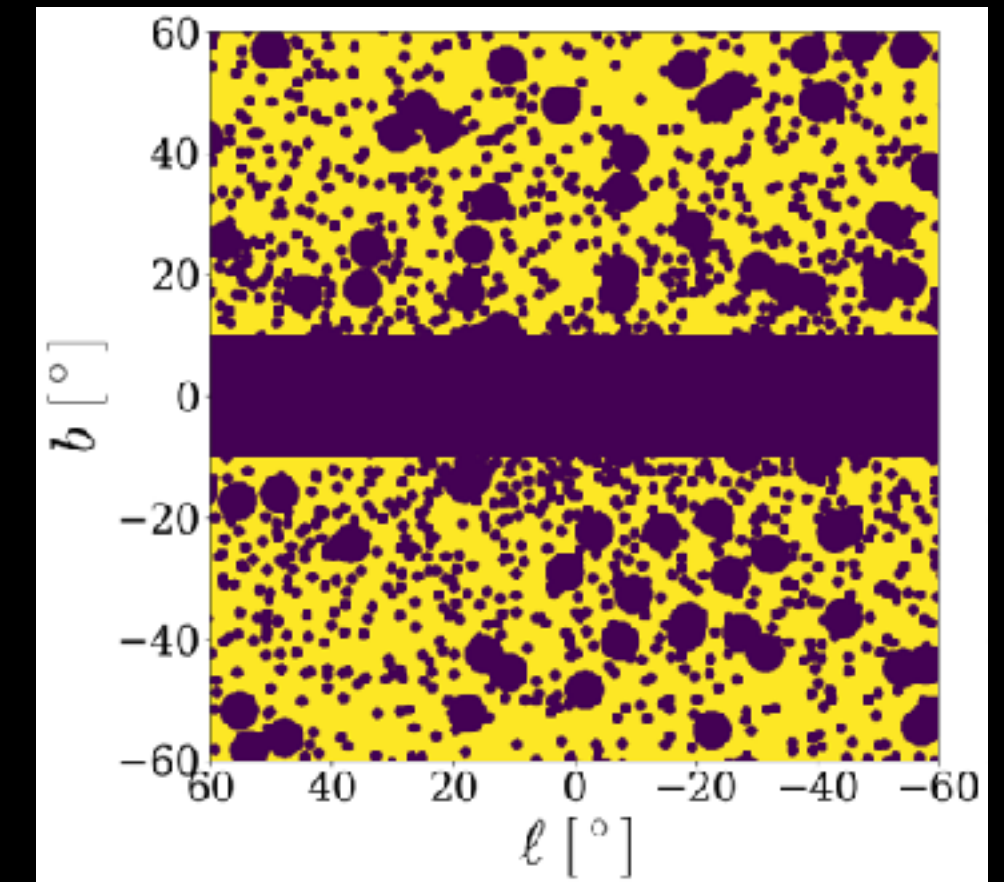


10° pixels (Totani)

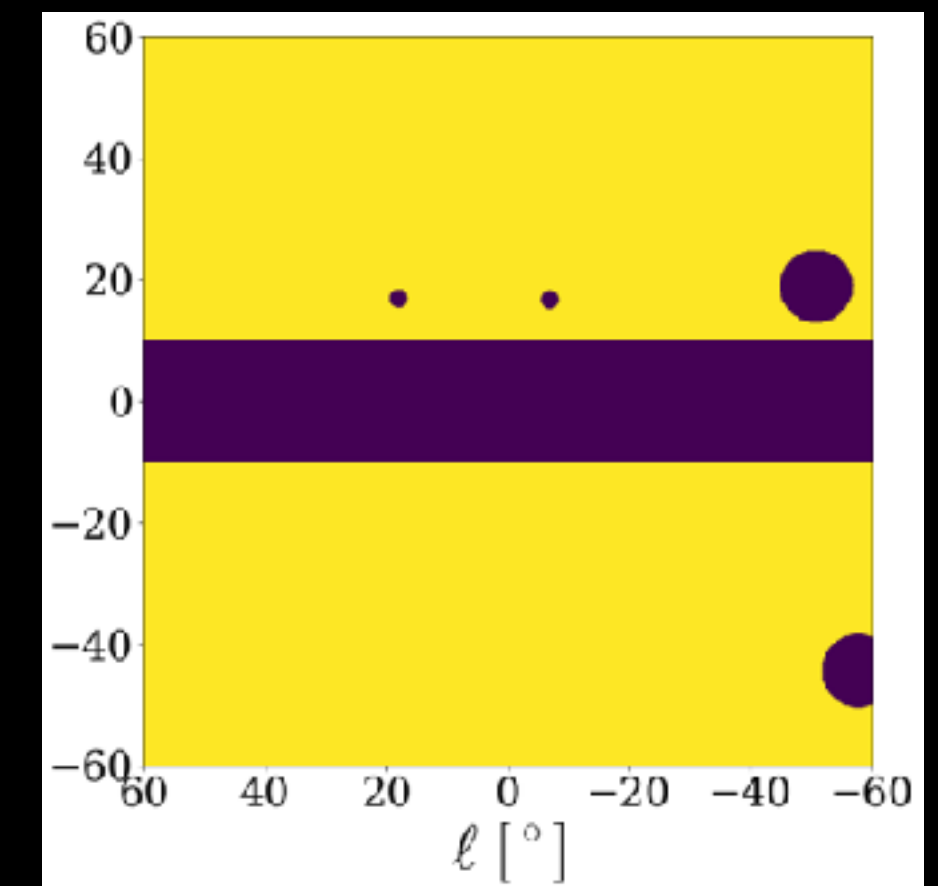
- Totani's setup (ROI c, his mask, residual maps): a similar HLE.
- Grouping pixels shifts every template; the negative map grows.
- ICS falls up to 10× below GALPROP above 10 GeV.
- Loop I Bright : Loop I Dim $\approx 1 : 2$, not 3 : 1 as in radio.

Perform our fittings

- Use positive-flux templates (100 sets in total)
- $0.1^\circ \times 0.1^\circ$ pixels
- Mask all 4FGL-DR4 point and extended sources
- Test eight ROIs



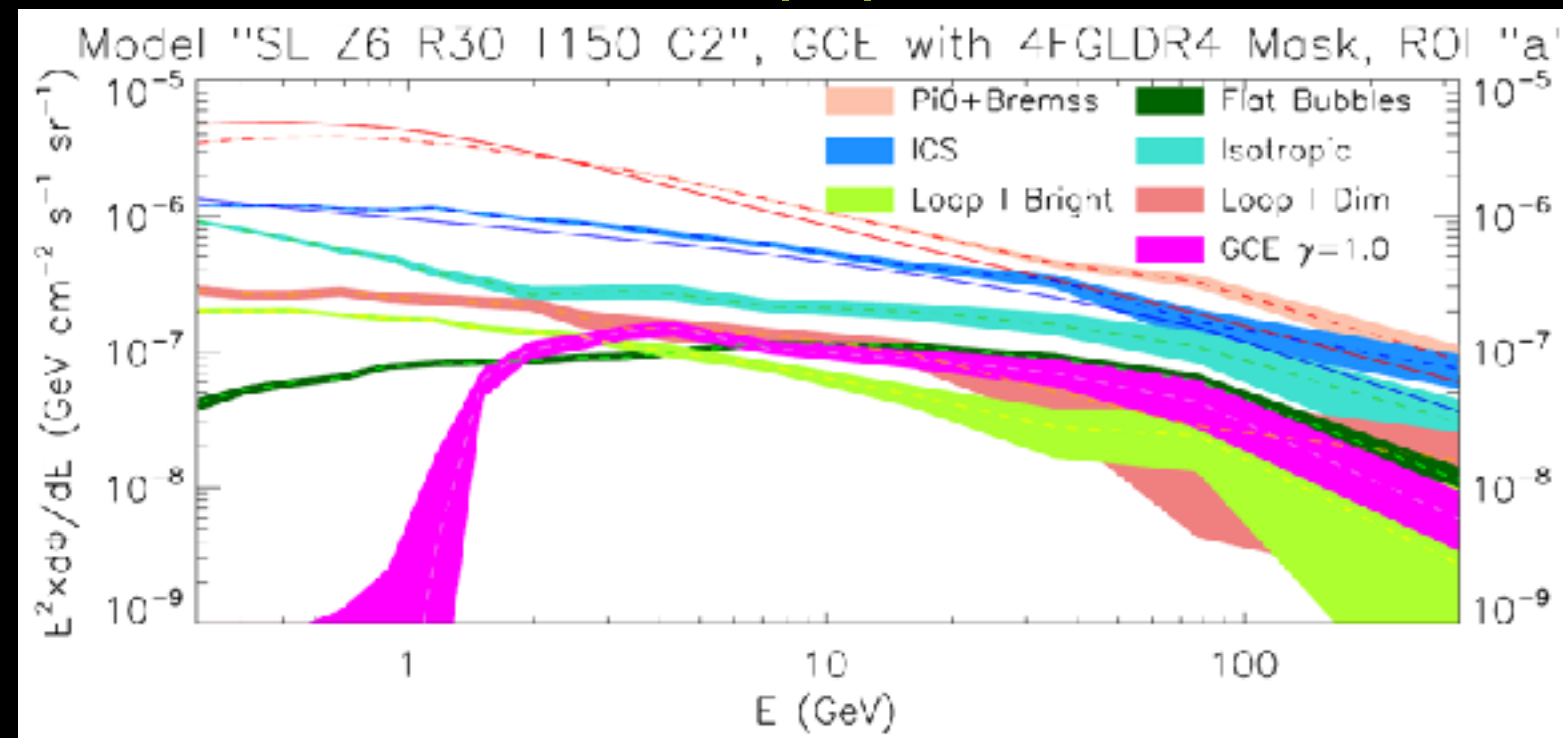
4FGL-DR4 mask (ours)



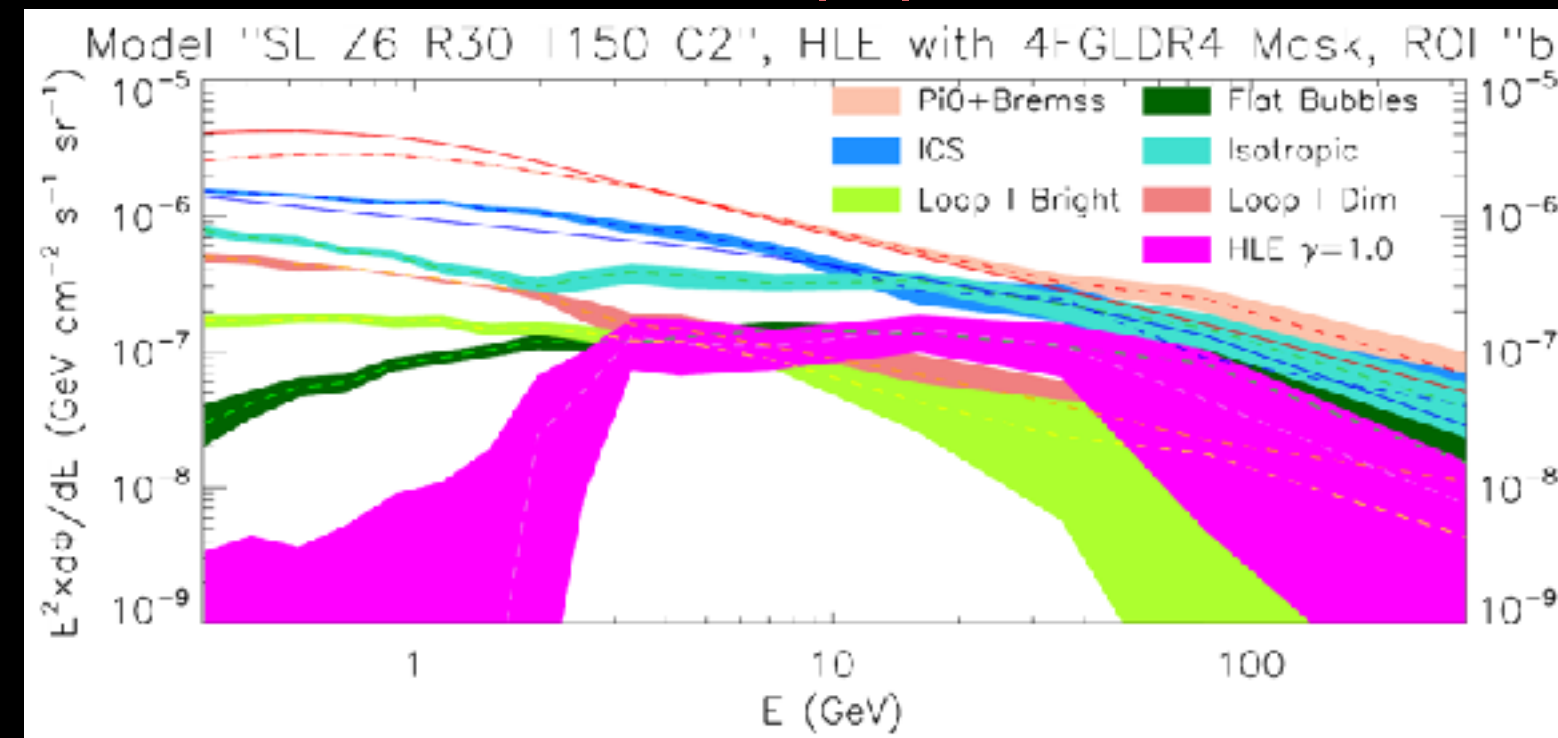
Totani mask

The HLE is real: every region and fit scheme wants it

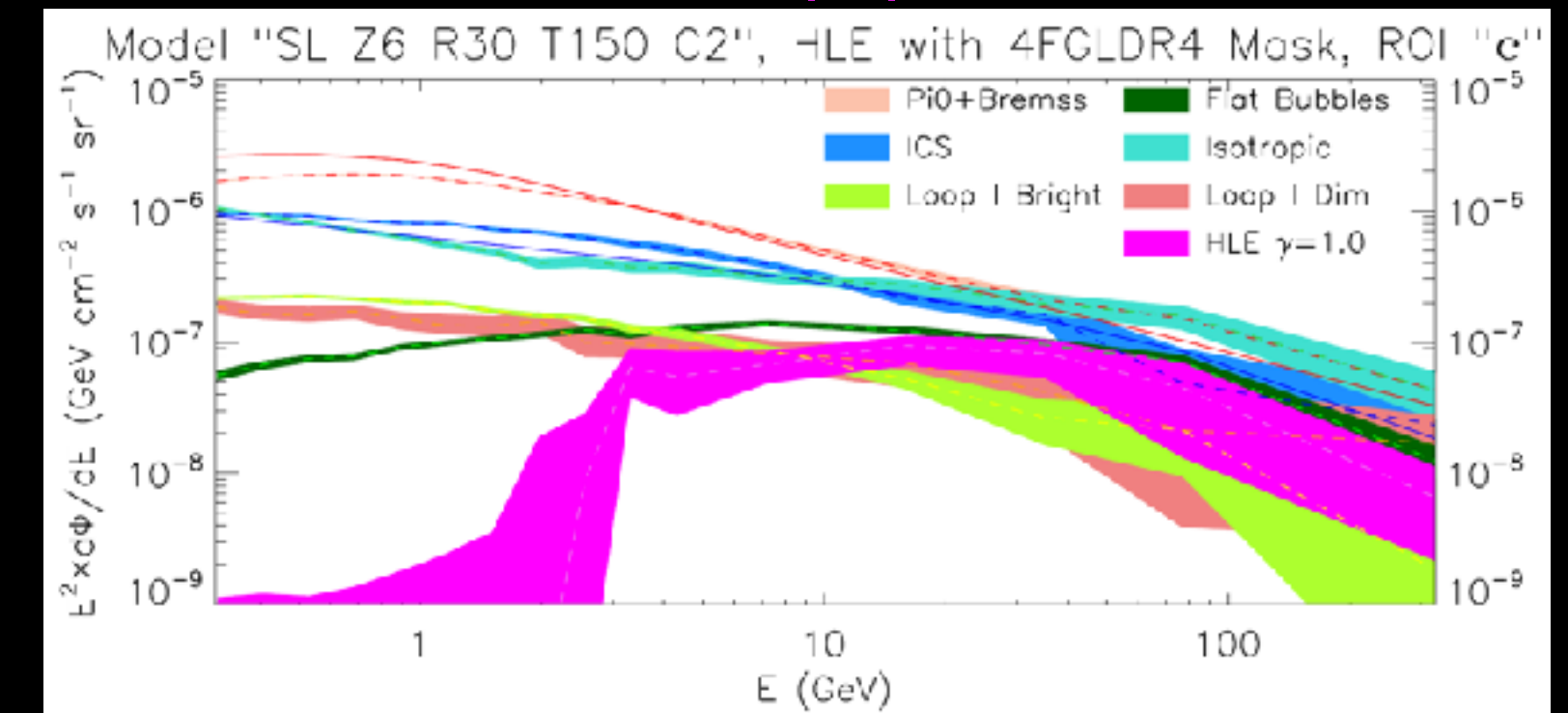
a: $2^\circ \leq |b| \leq 60^\circ$



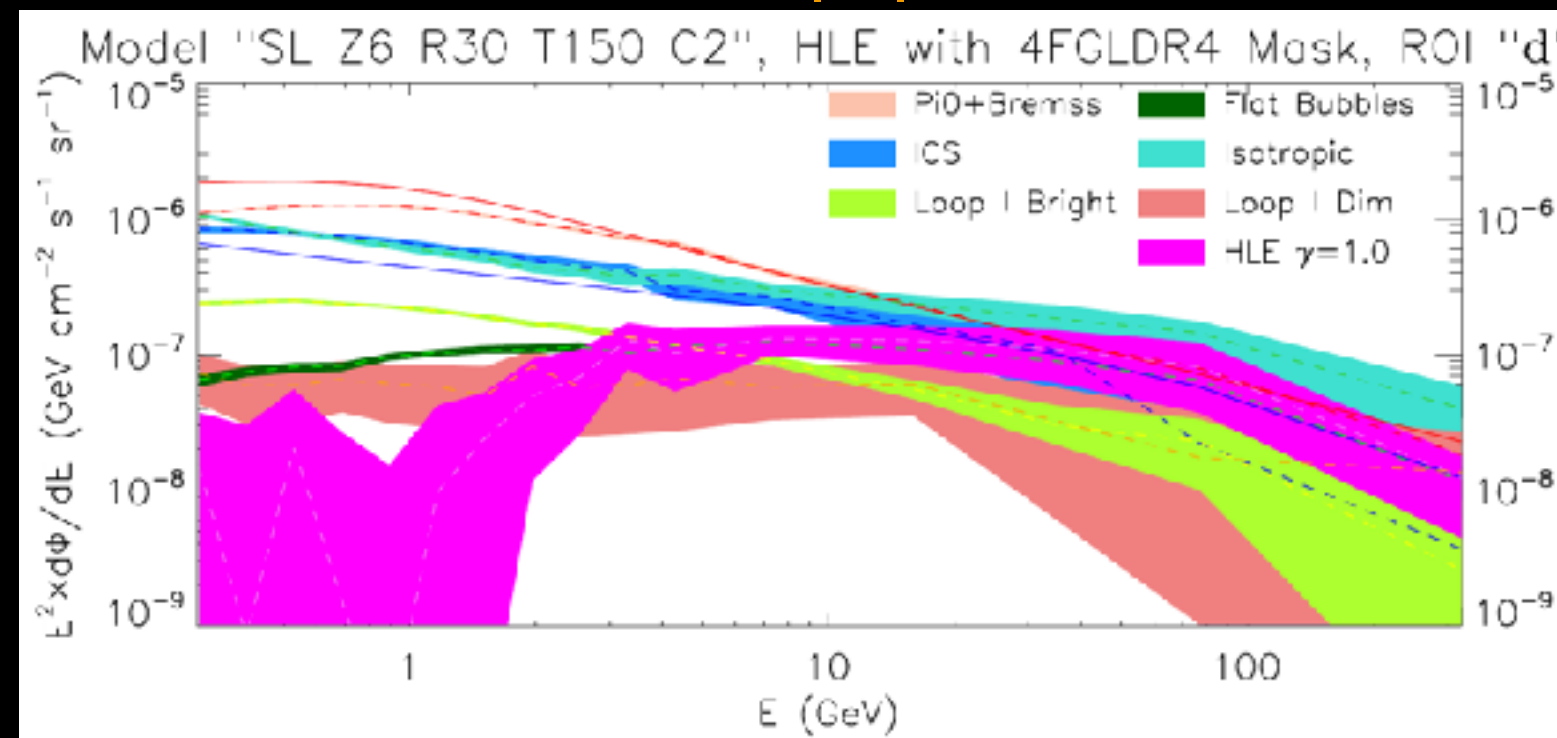
b: $10^\circ \leq |b| \leq 30^\circ$



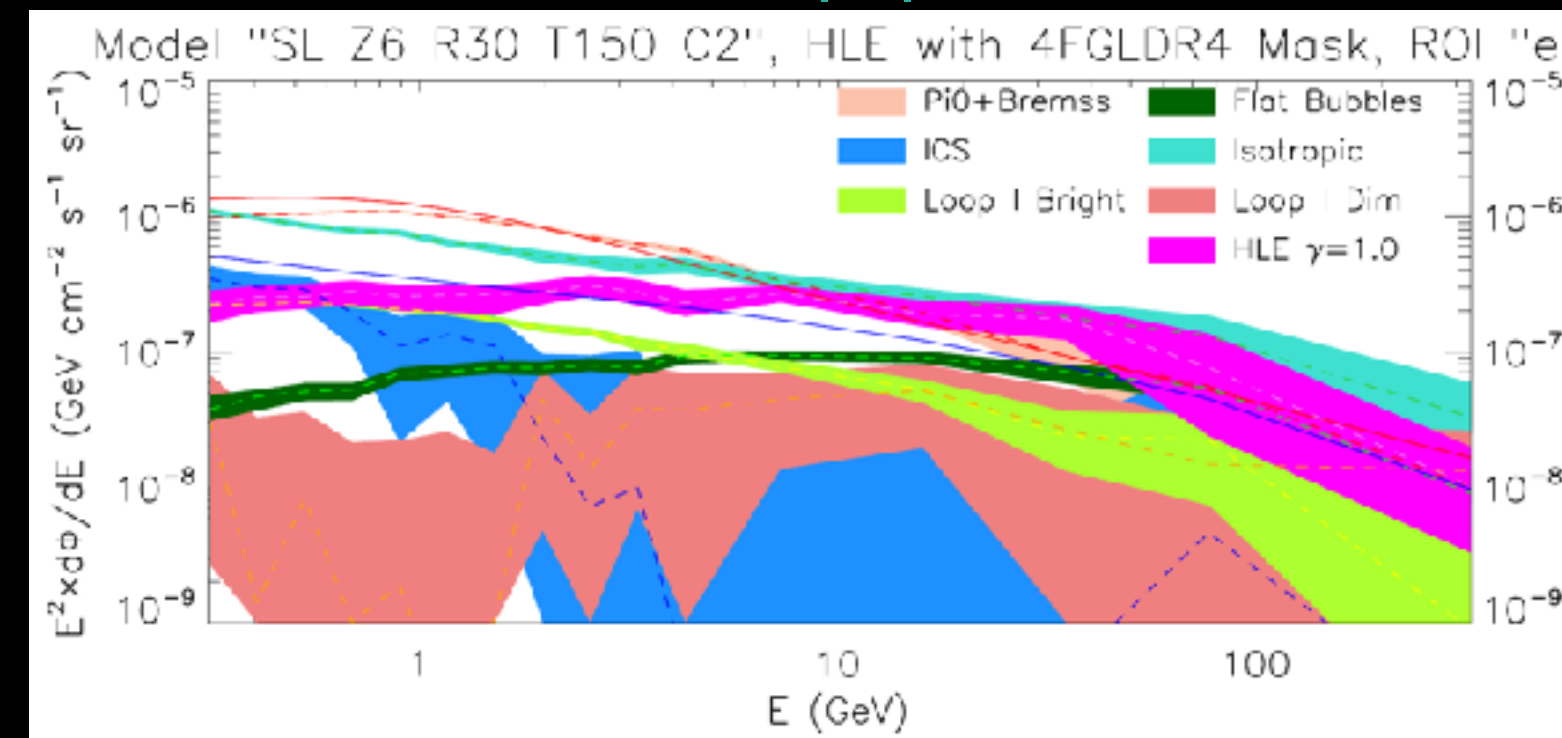
c: $10^\circ \leq |b| \leq 60^\circ$



d: $20^\circ \leq |b| \leq 60^\circ$

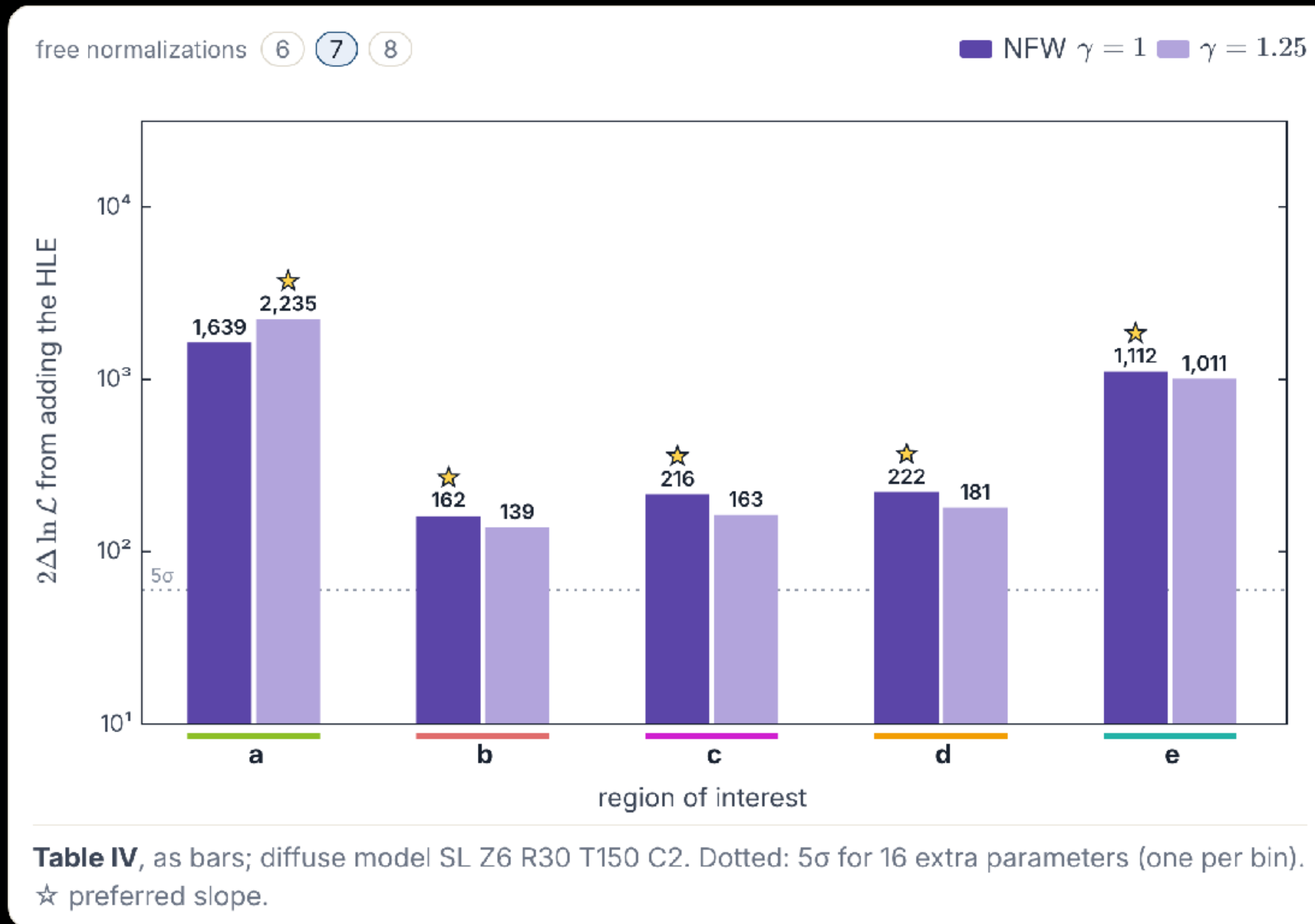


e: $30^\circ \leq |b| \leq 60^\circ$



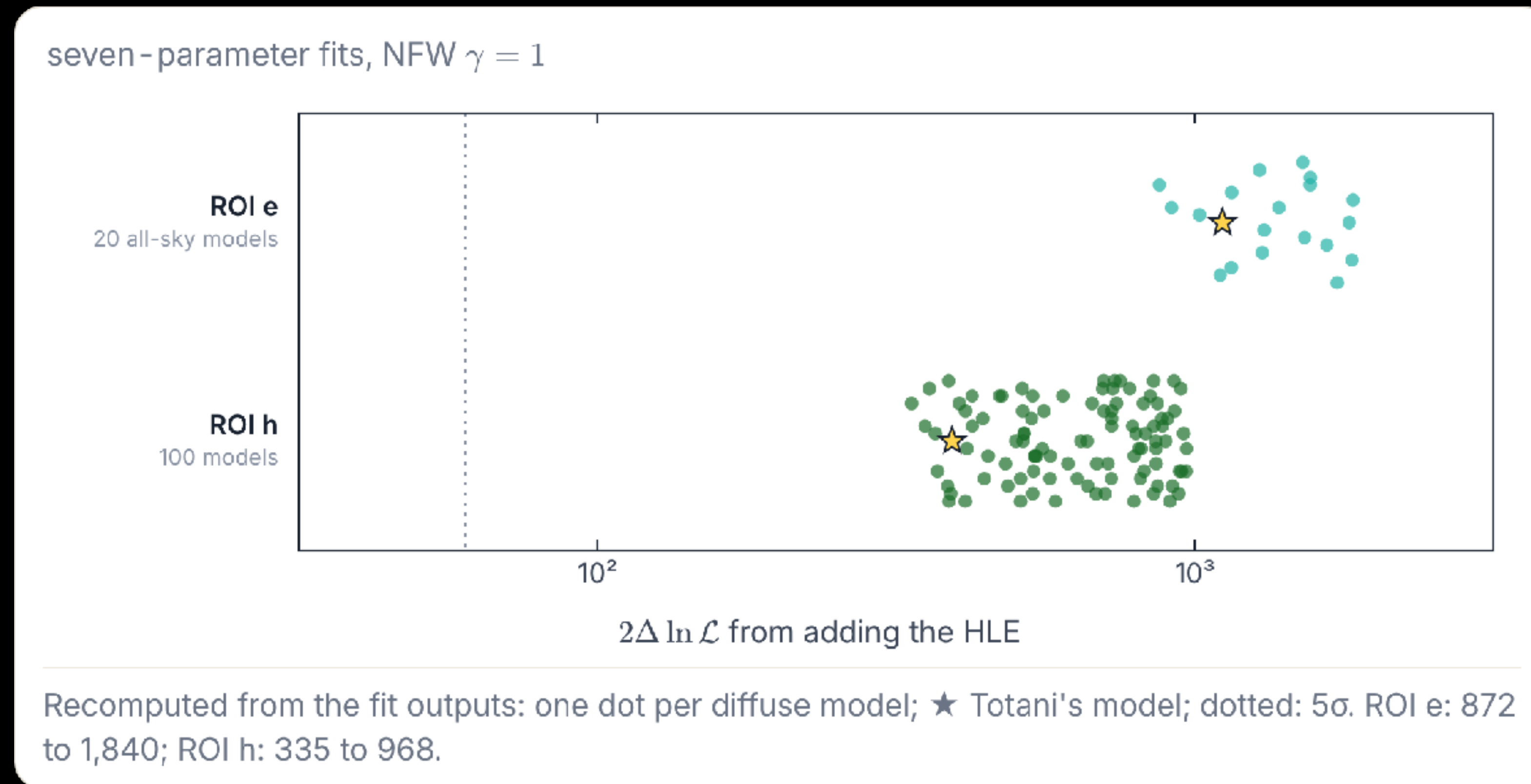
seven-parameter fits; $|l| \leq 60^\circ$; diffuse model SL Z6 R30 T150 C2; magenta: the HLE

A significant residual in every region and fit scheme



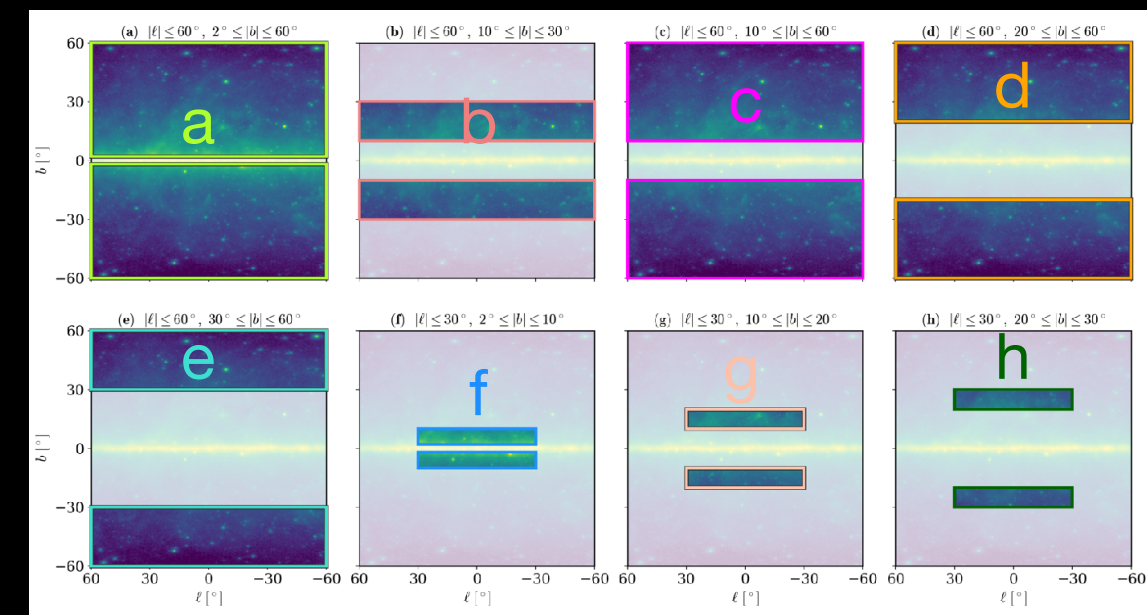
- In all ROIs, fit schemes and density profiles, adding the HLE/GCE template improves the fit by $2\Delta \ln \mathcal{L} \approx 10^2\text{--}10^4$.

It does not depend on the diffuse model either

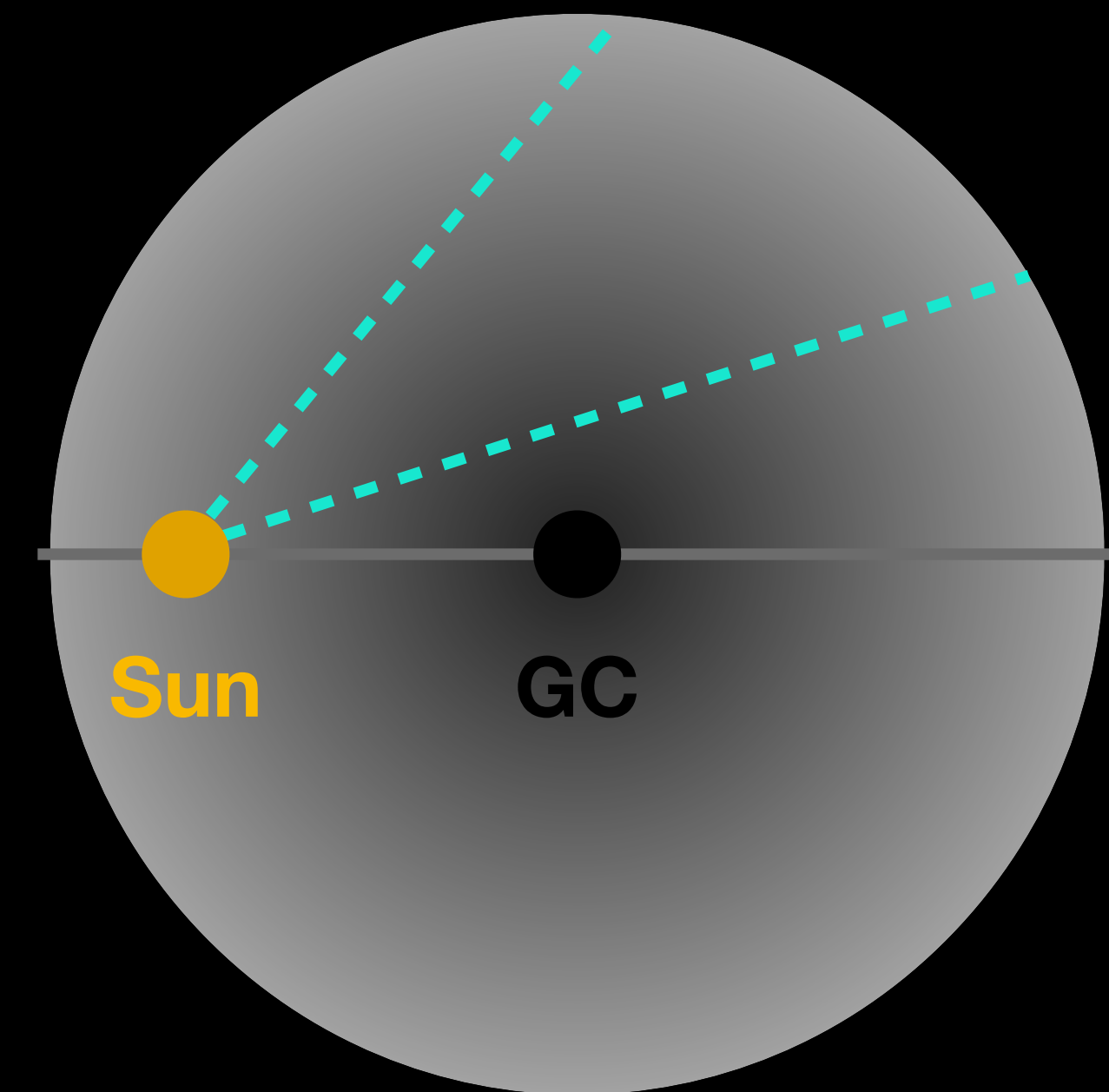


- Every one of the 20 all-sky models (ROI e) and of the 100 models (ROI h) wants the HLE, at $\gg 5\sigma$.

The HLE is significant.
Is it from dark matter annihilation?



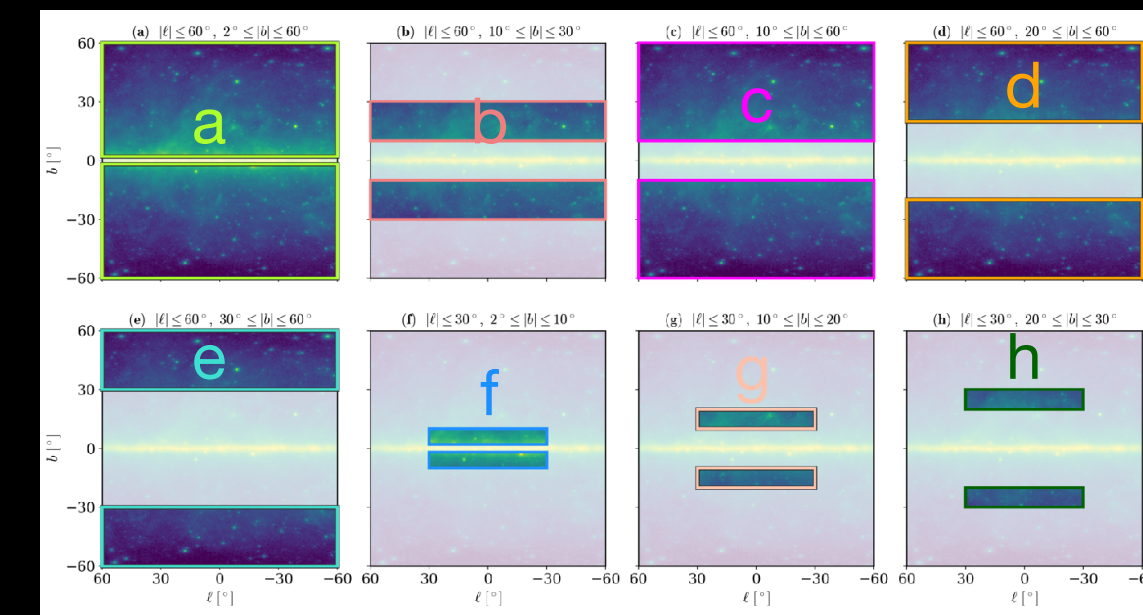
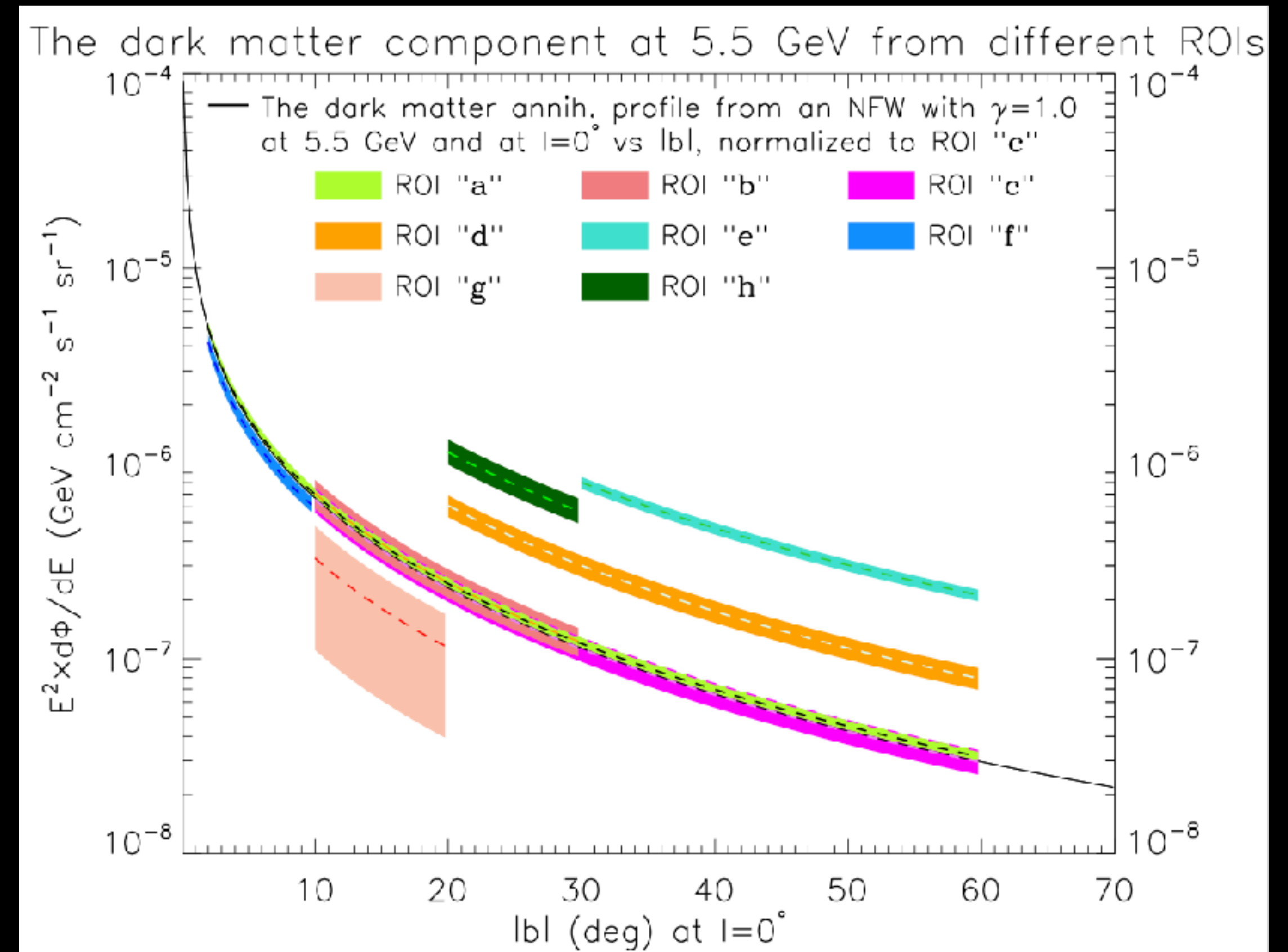
- Dark matter fixes how bright the HLE must be in each region, relative to the others.
- If the HLE were dark matter, one amplitude would fit every region: all bands on the line.



$$\int_{l_{\text{os}}} \rho(r)^2 ds$$

No universal amplitude

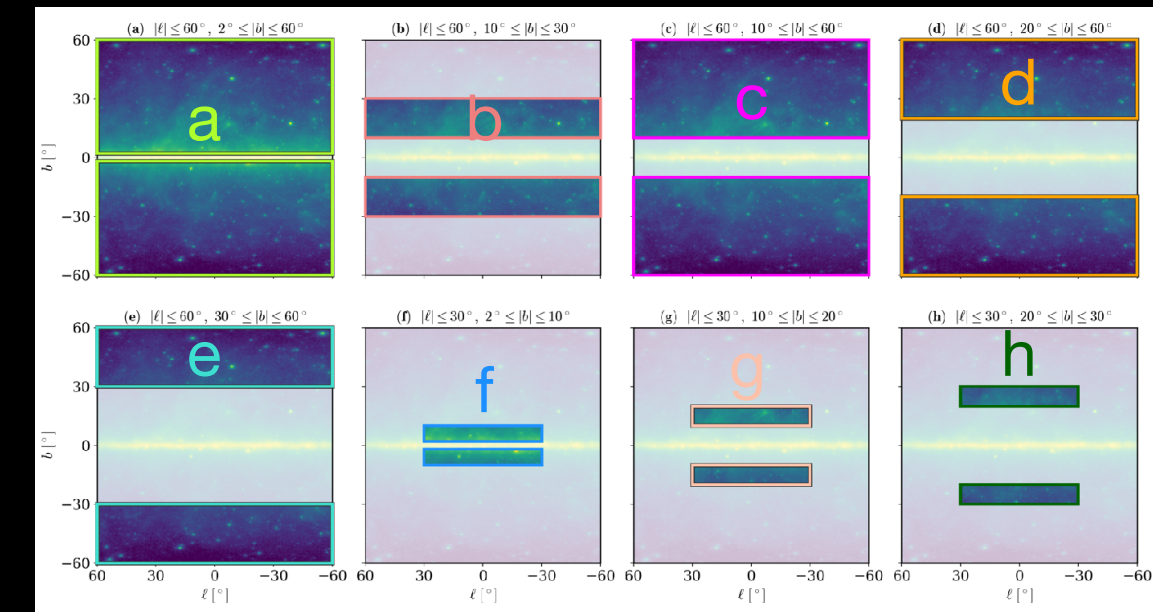
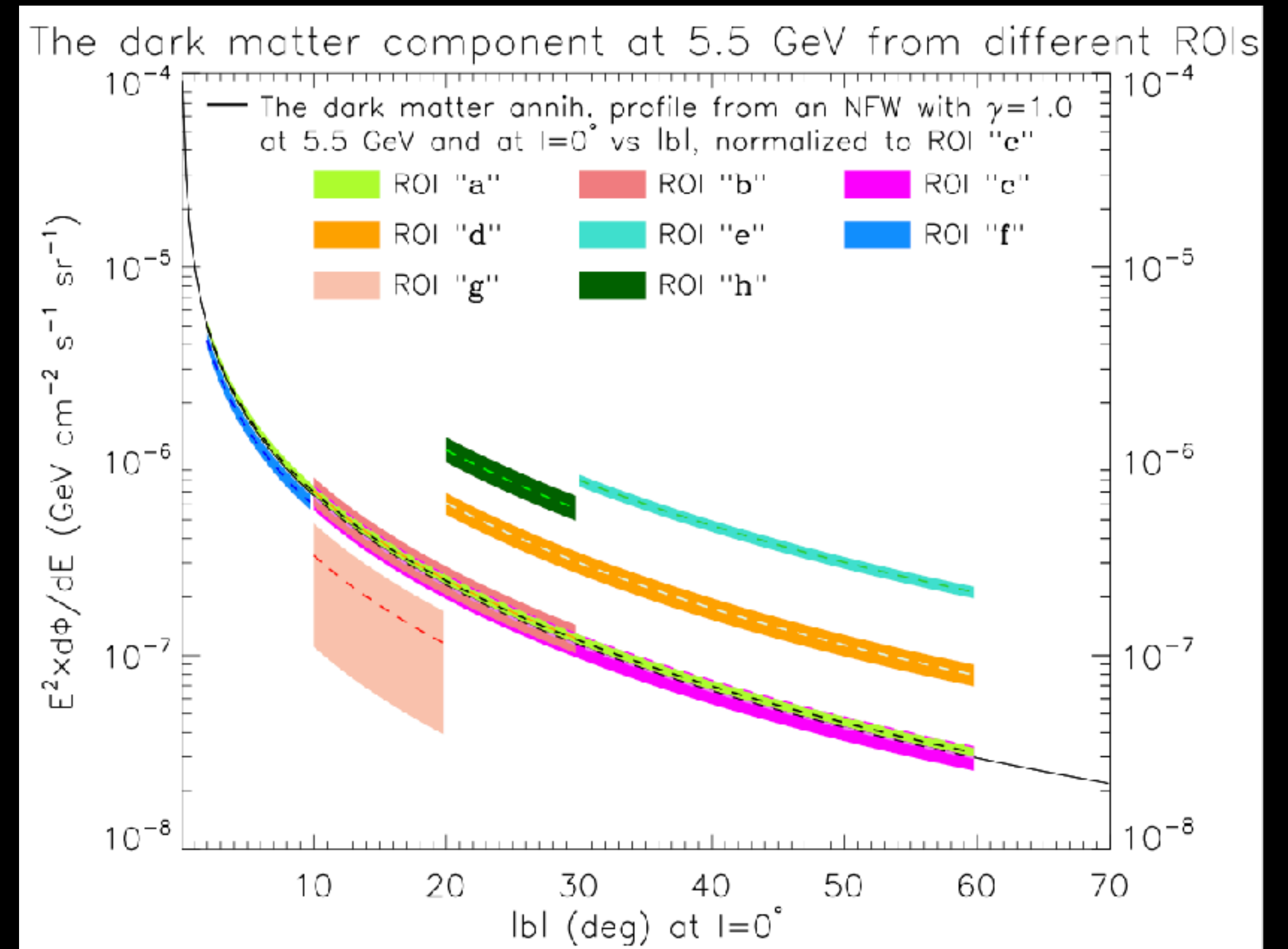
- Discrepancies for ROIs w/ $|b| \geq 20^\circ$ & those w/ $|b| < 20^\circ$
- ROIs **d**, **e** and **h** sit 3–7× above the dark-matter line.
- ROI **g** sits below it.



7-parameter fit; SL Z6 R30 T150 C2

Any GC-centred halo fails

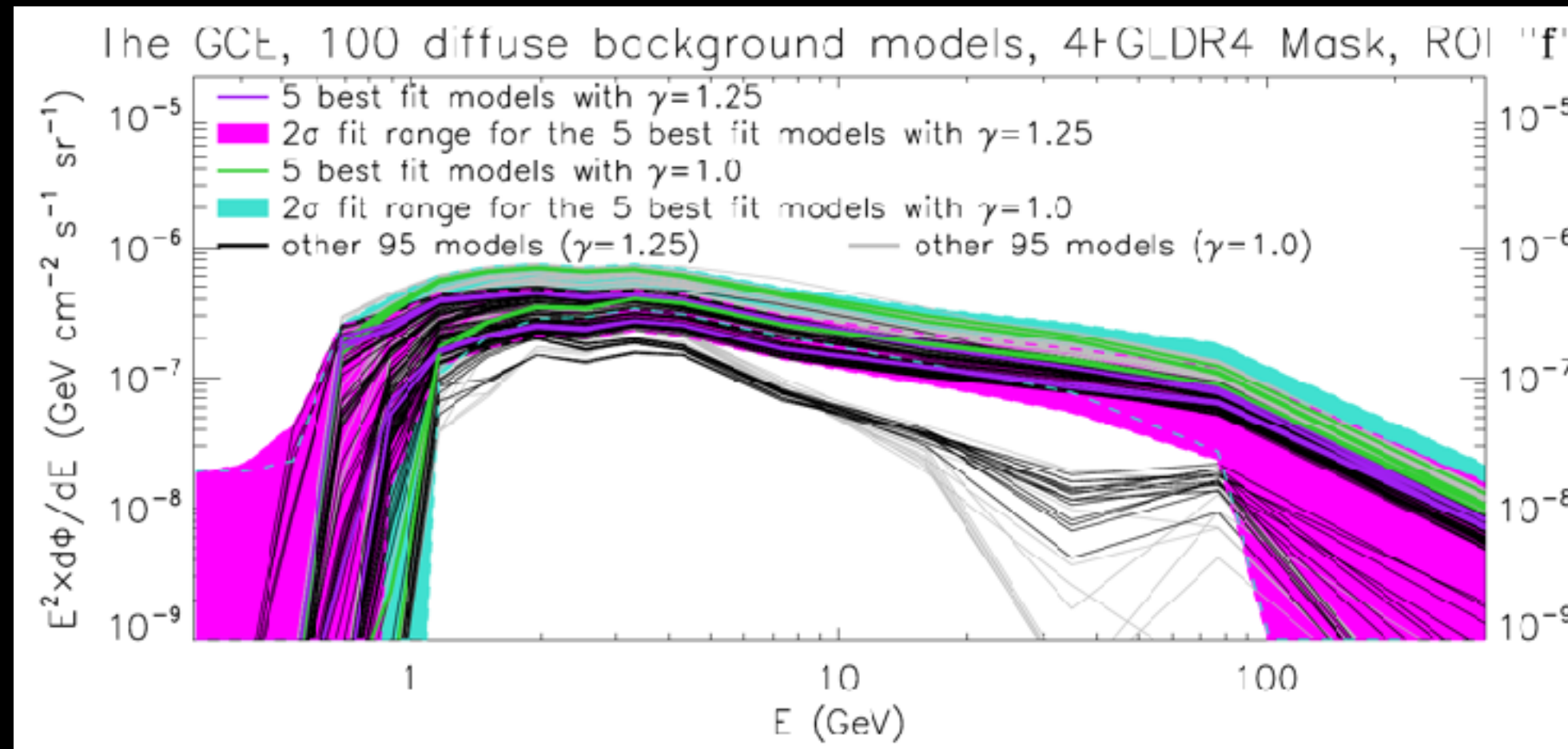
- Any emission that falls off with distance from the GC (ρ^2 or ρ , any profile) is dimmer per steradian farther from the GC.
- So ROI **d** $\geq$ ROI **e** and ROI **g** $\geq$ ROI **h**.
- The fits show **e** $>$ **d** and **h** $>$ **g**.



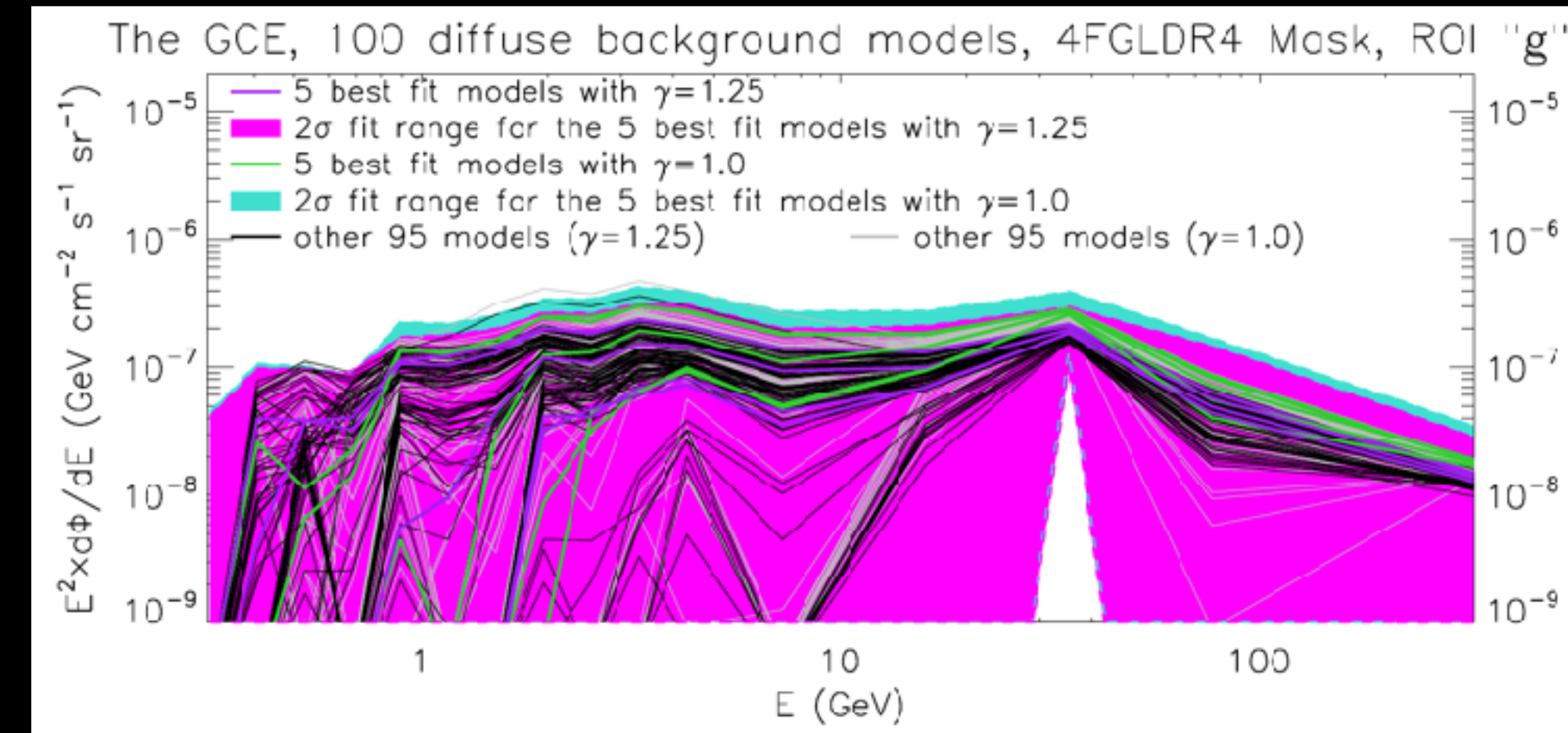
7-parameter fit; SL Z6 R30 T150 C2

The GCE and the HLE are two distinct components

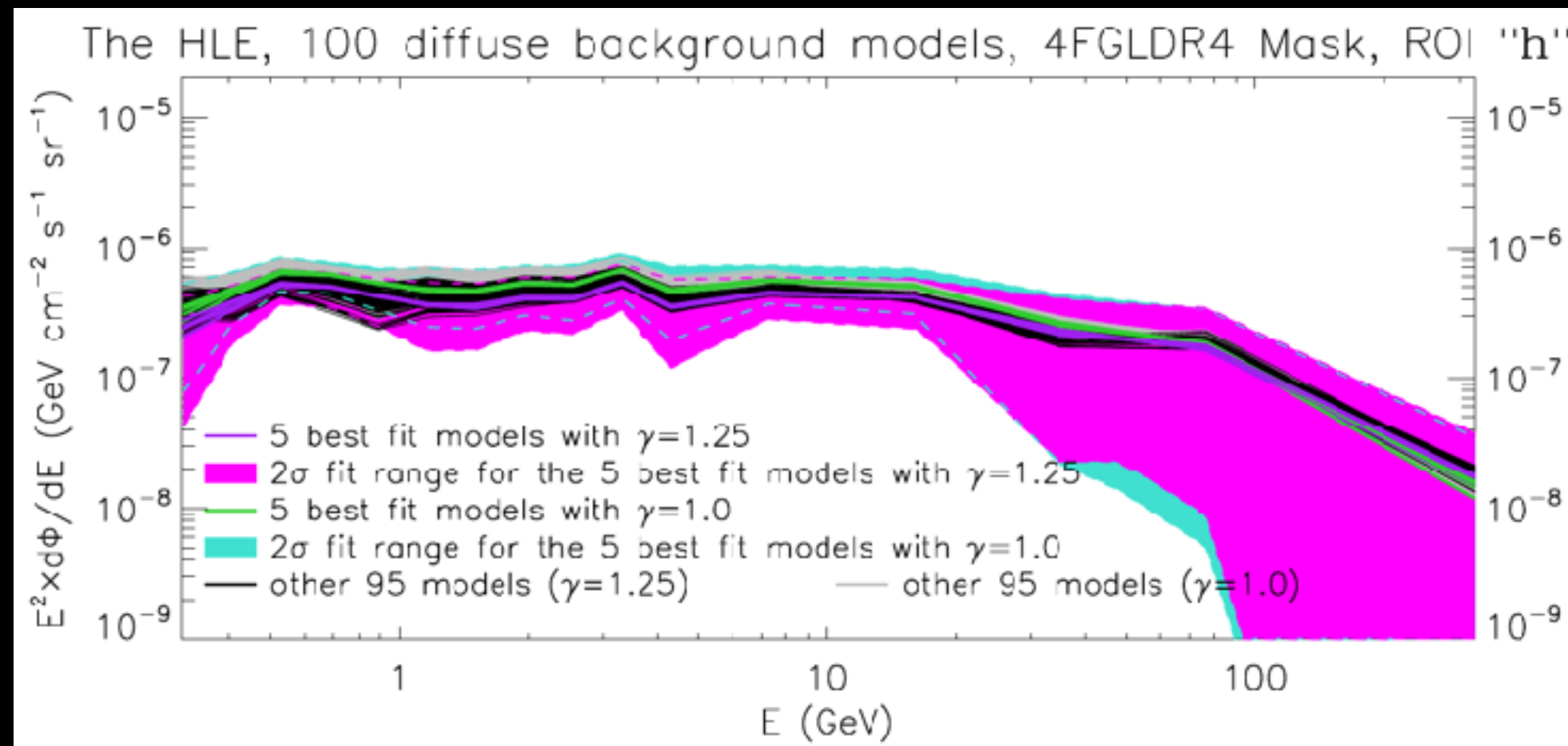
GCE · f: $2^\circ \leq |b| \leq 10^\circ$ · 100 diffuse models



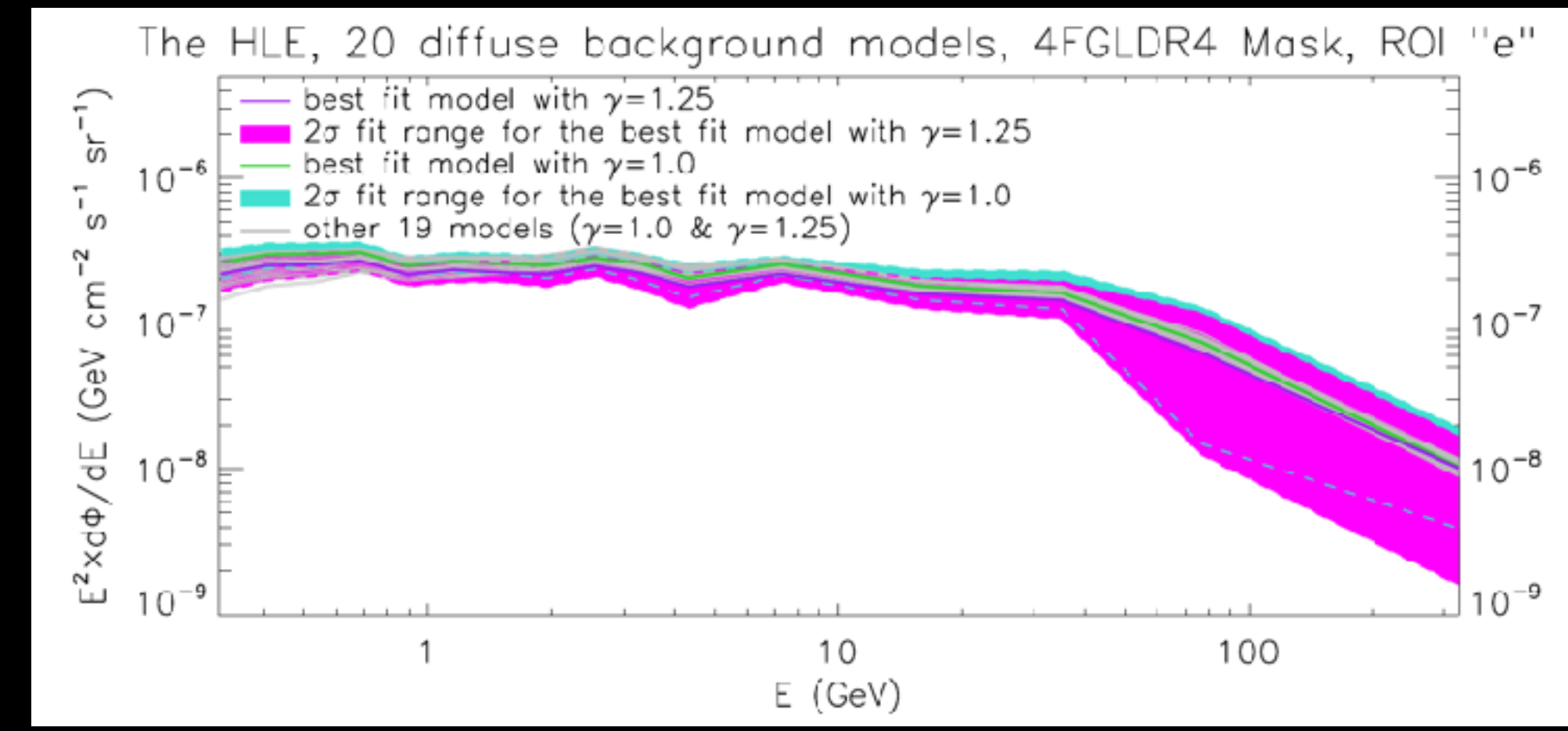
GCE · g: $10^\circ \leq |b| \leq 20^\circ$ · 100 diffuse models



HLE · h: $20^\circ \leq |b| \leq 30^\circ$ · 100 diffuse models

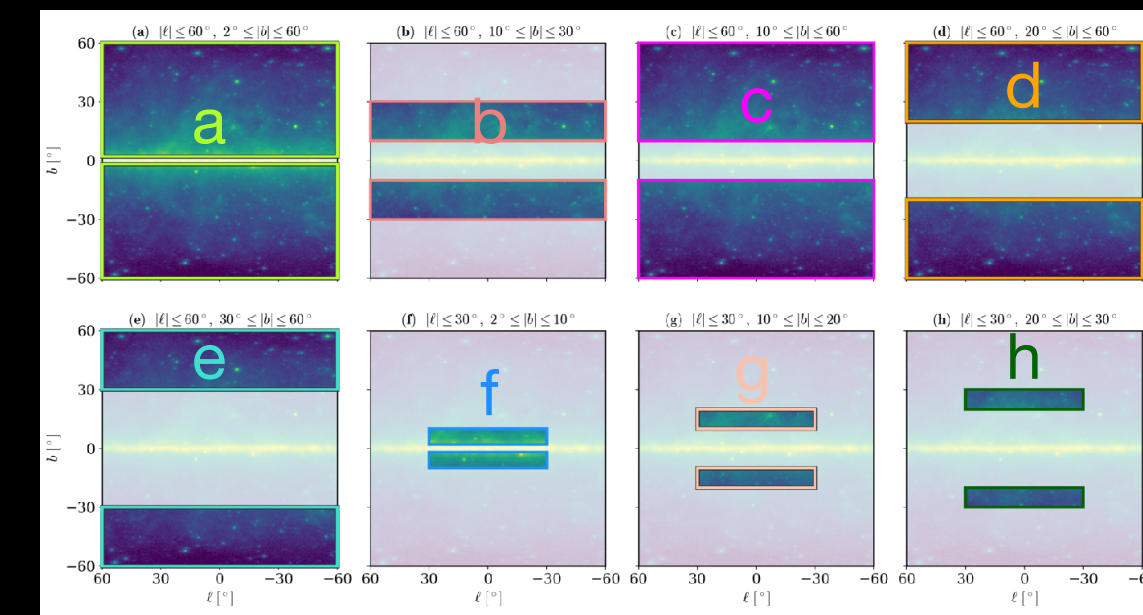
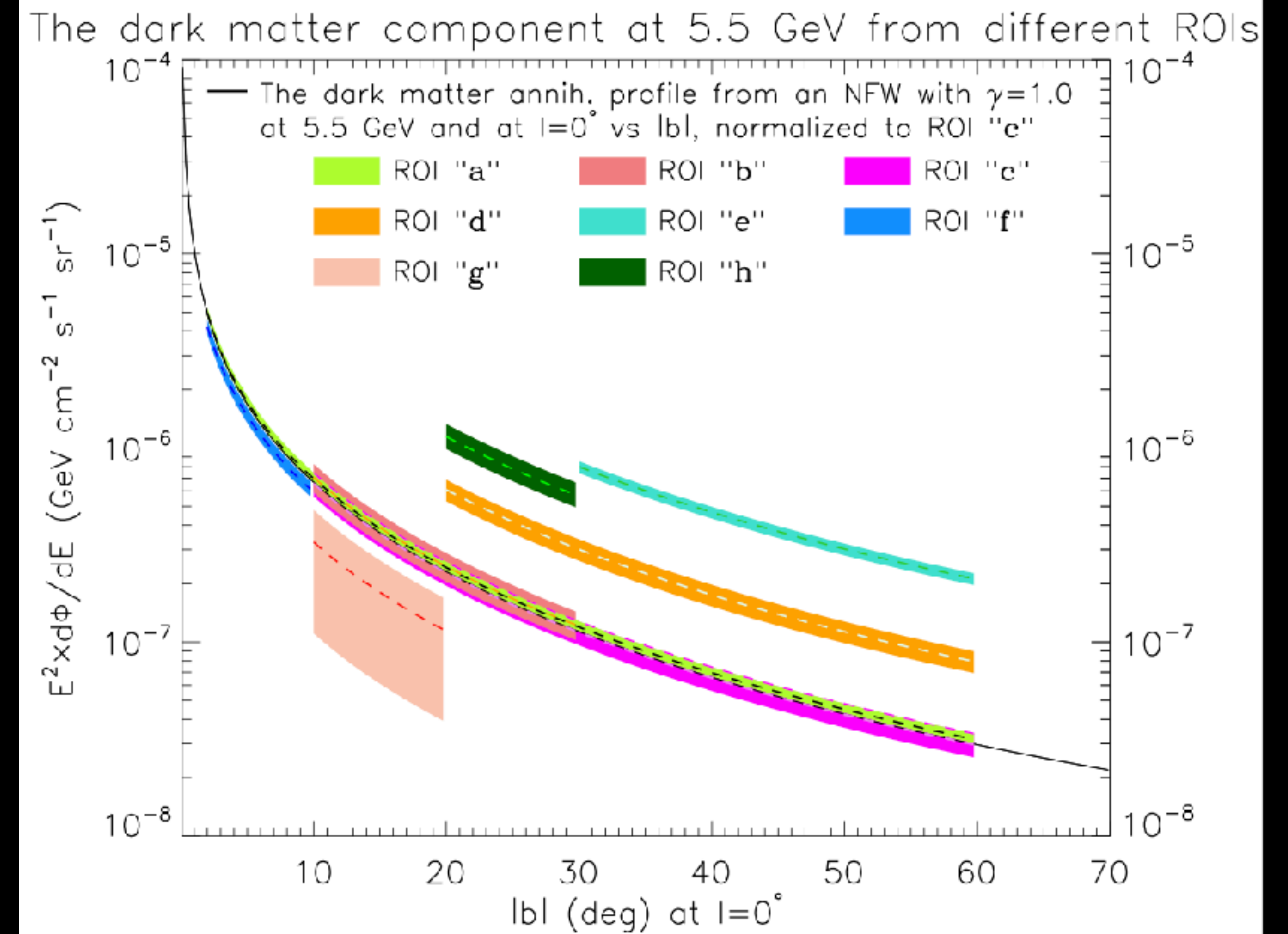


HLE · e: $30^\circ \leq |b| \leq 60^\circ$ · 20 all-sky models



Two components?

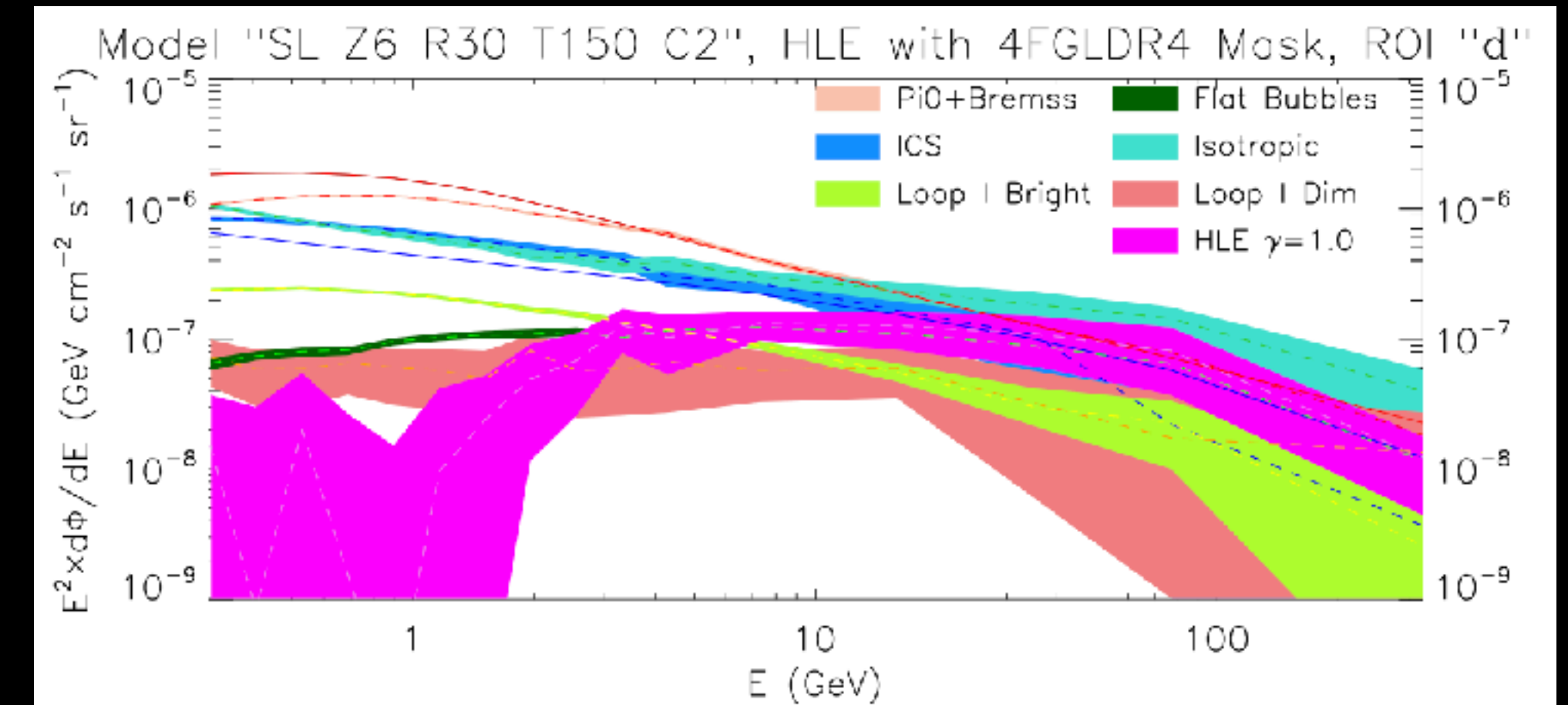
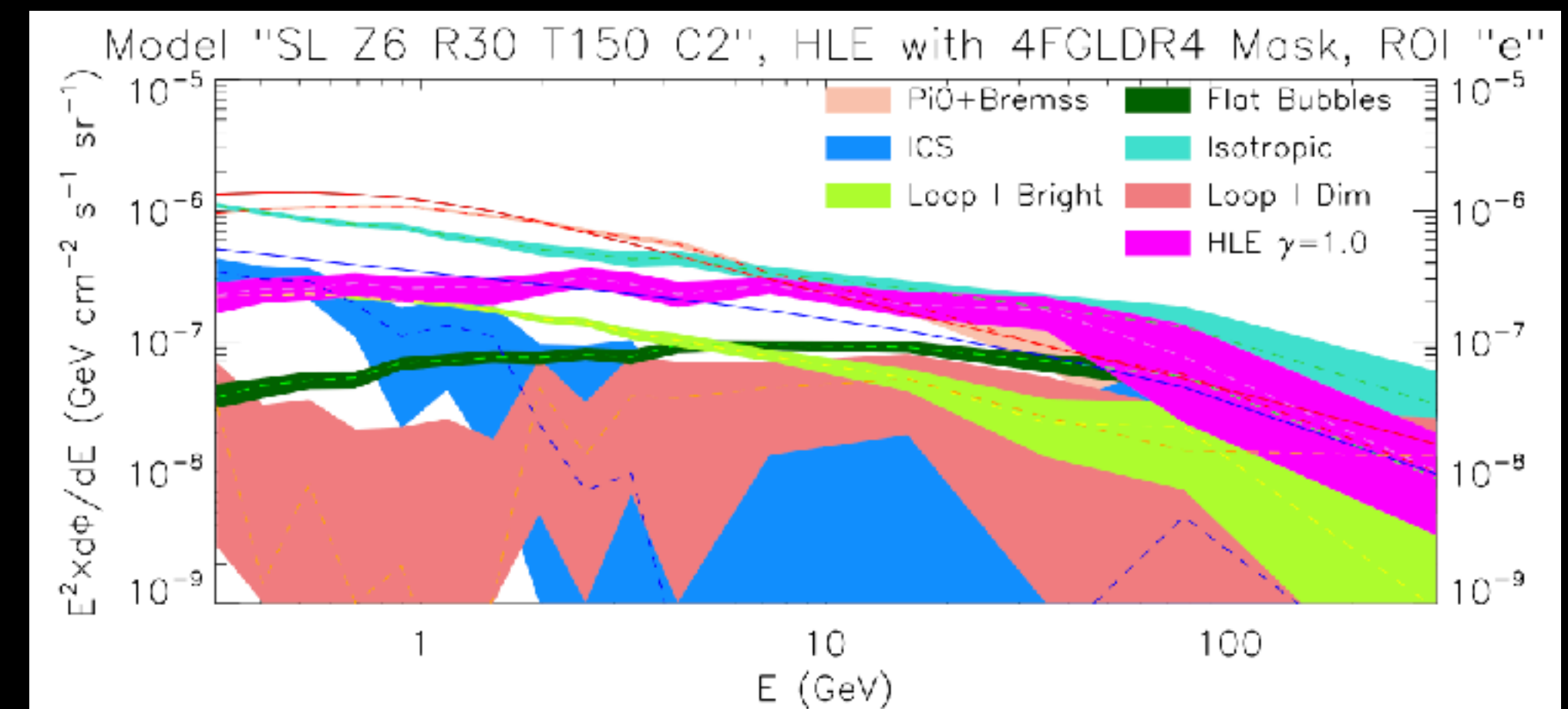
- A second, dark-matter-like halo this bright would also outshine the GCE in ROIs **f** and **g**.
- It does not.



7-parameter fit; SL Z6 R30 T150 C2

The HLE trades off against ICS and the Bubbles

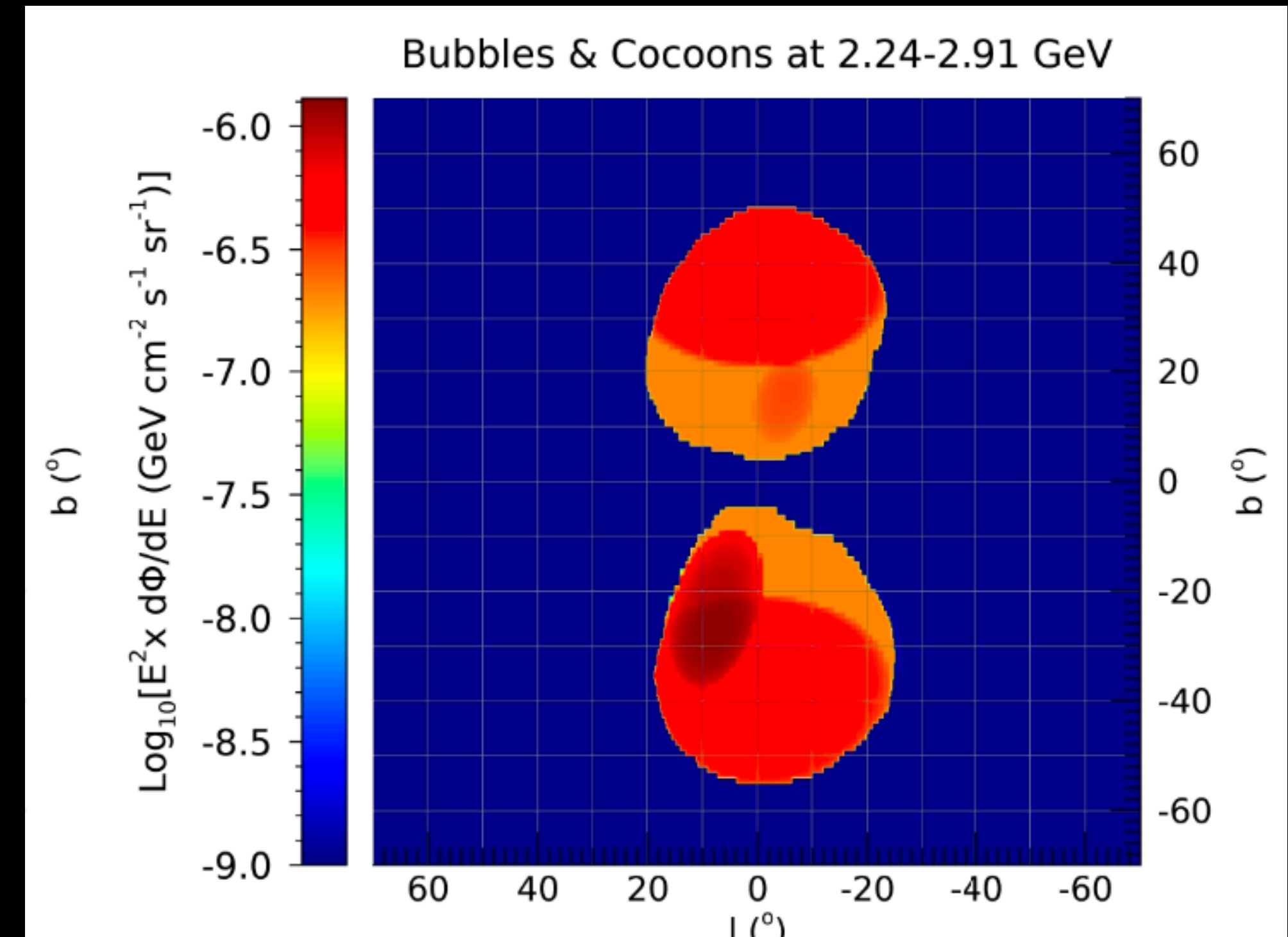
- In the fits, the **HLE** is degenerate with **ICS** and with the **Bubbles**, in particular for $|b| \geq 20^\circ$.
- HLE is absorbing some other emission connected to the Bubbles or the ICS.
- Combining the discrepancy between high- and low-latitude HLE
 $\Rightarrow$ motivates us to remodel the Bubbles.



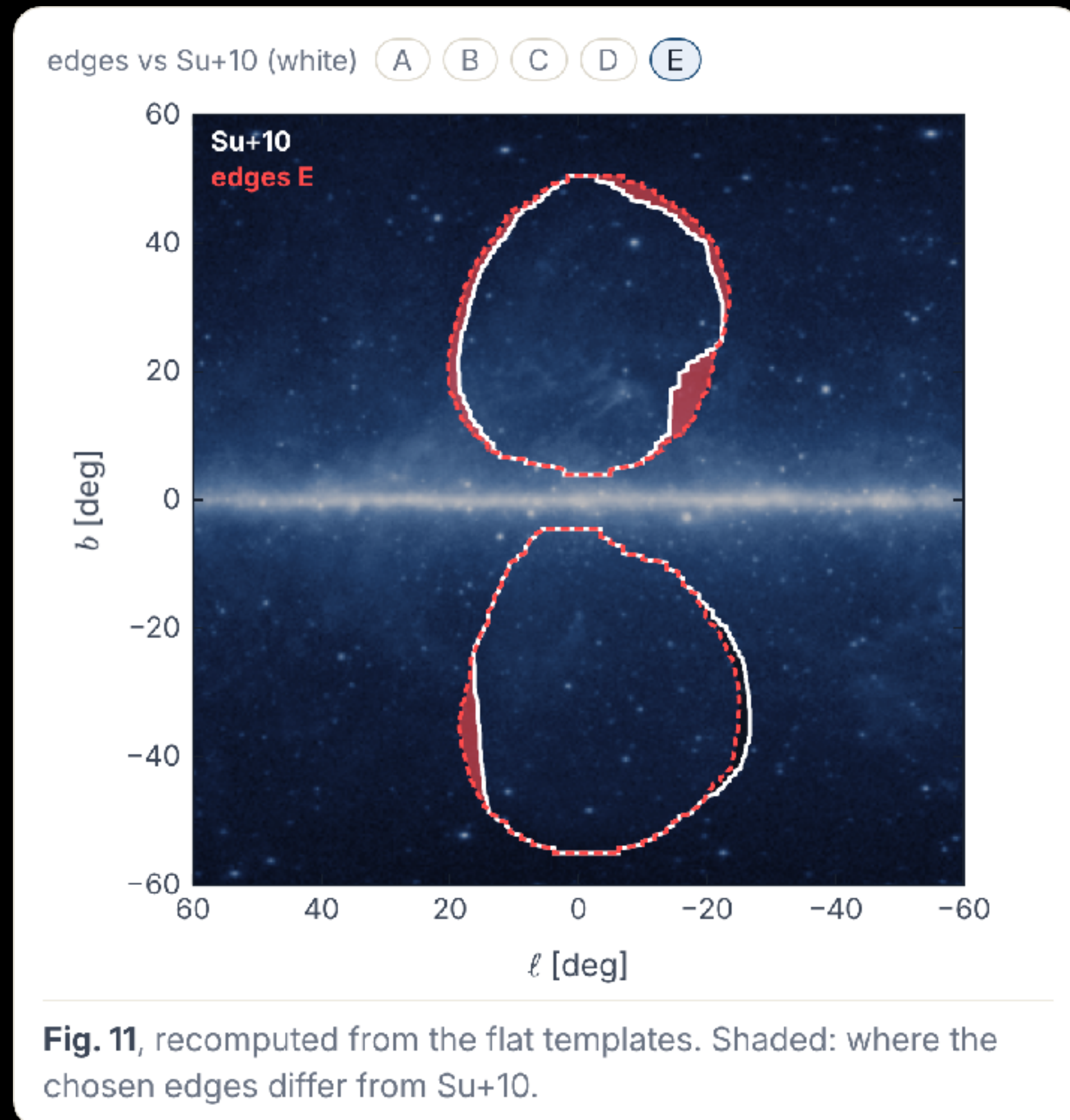
A New Model of the Fermi Bubbles

Our new Bubbles: flat lobes, Cocoons, Inner Bubbles

- **Flat Bubbles**: test different edges
- **Cocoons**: a tilted prolate pair, 3D rotated with center at the GC.
- **Inner Bubbles**: an oblate pair 6 kpc from the plane

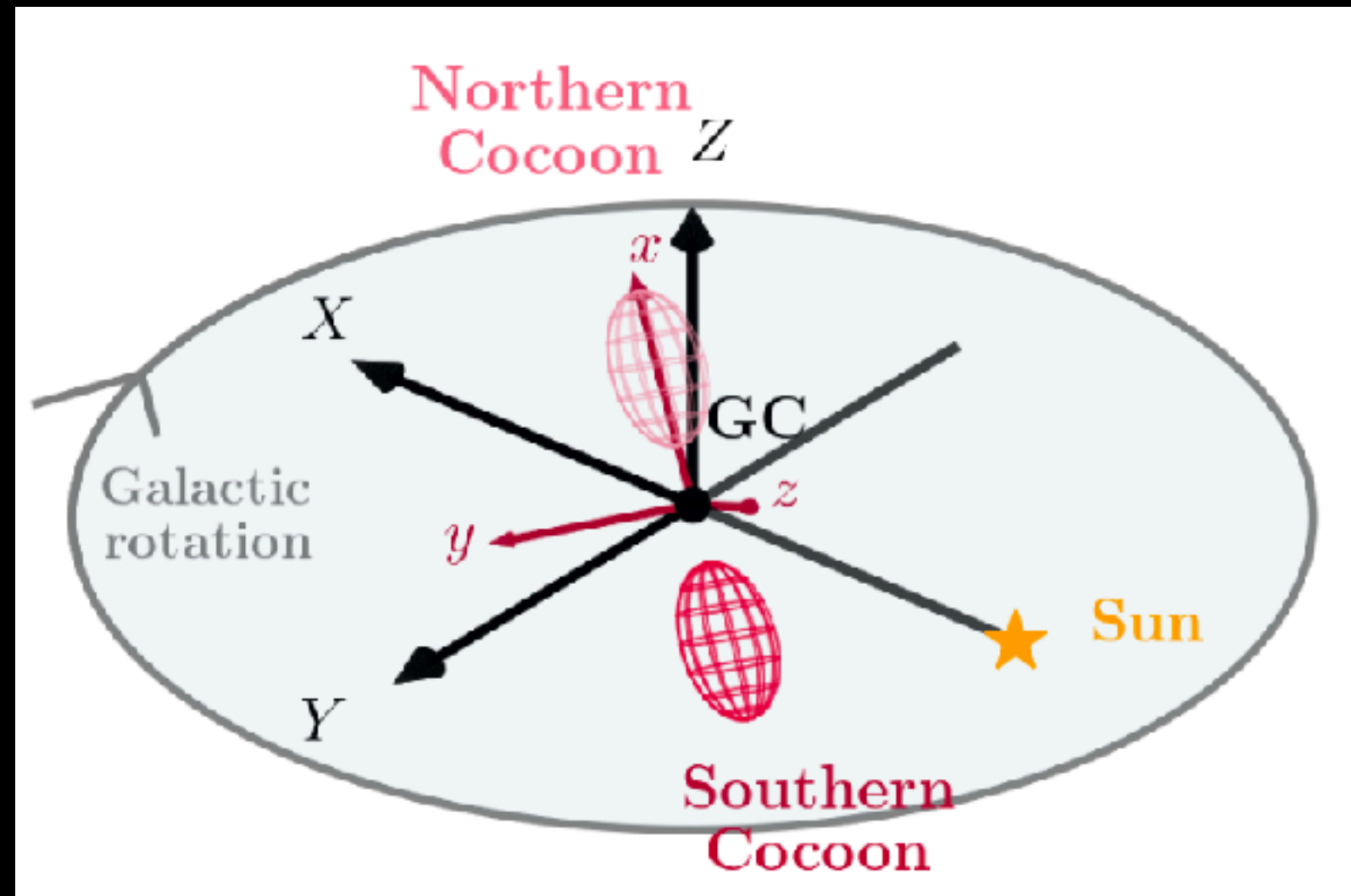


Slightly wider Bubble edges fit better

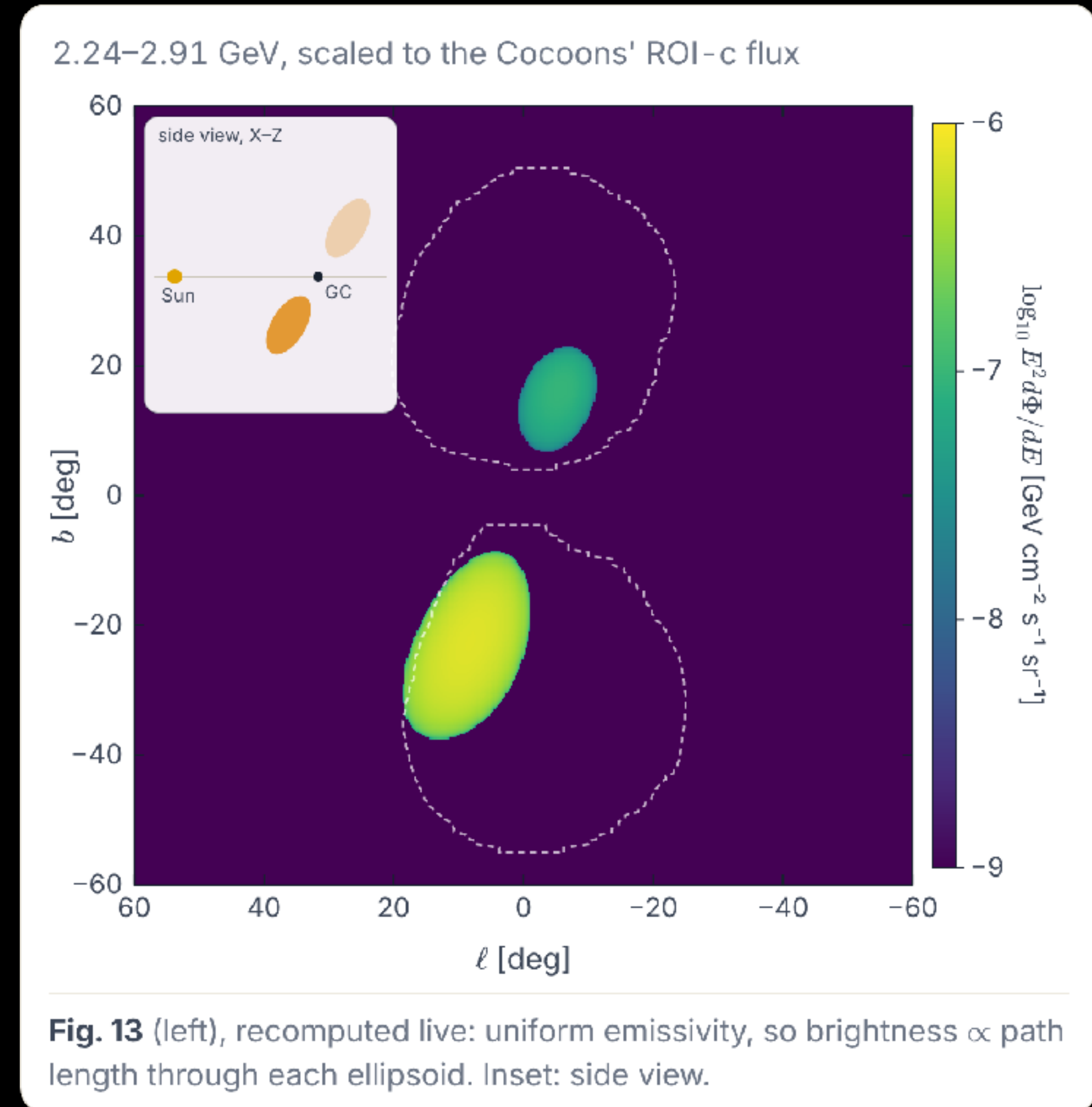


Improvement: $2\Delta \ln \mathcal{L} = 230 - 720$

The Cocoons: a tilted pair of ellipsoids

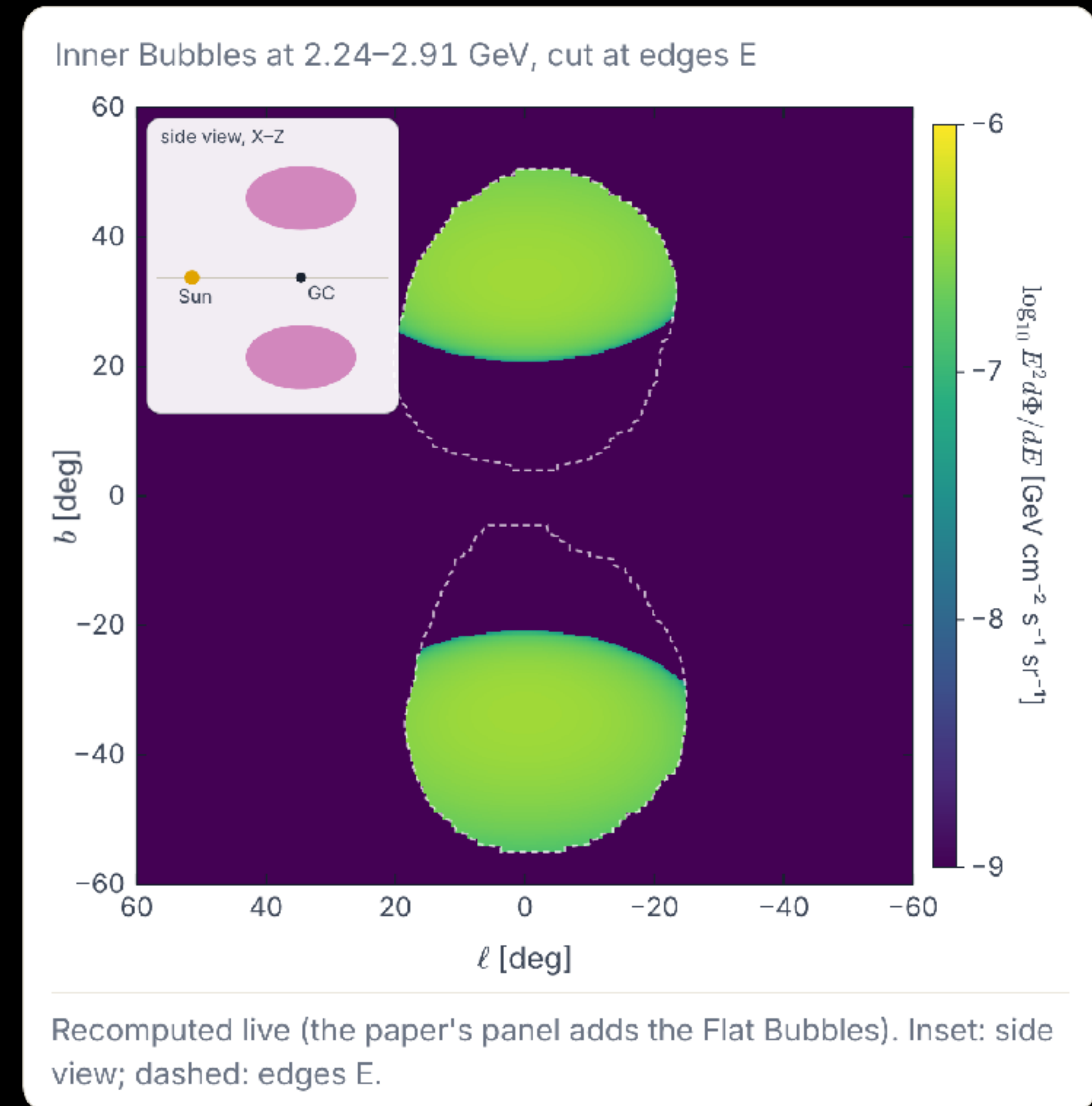


- Southern Cocoon is brighter than the Northern Cocoon.
- In this parametrization, the pitch puts the southern one nearer to us.
- Best-fit: $2\Delta \ln \mathcal{L} = +3998$



The Inner Bubbles: an oblate pair in place of the HLE

- Oblate ($a < b$), unlike the Cocoons; equal north and south; no tilt.
- 6 kpc from the plane.
- Best-fit: $2\Delta \ln \mathcal{L} = +5018$

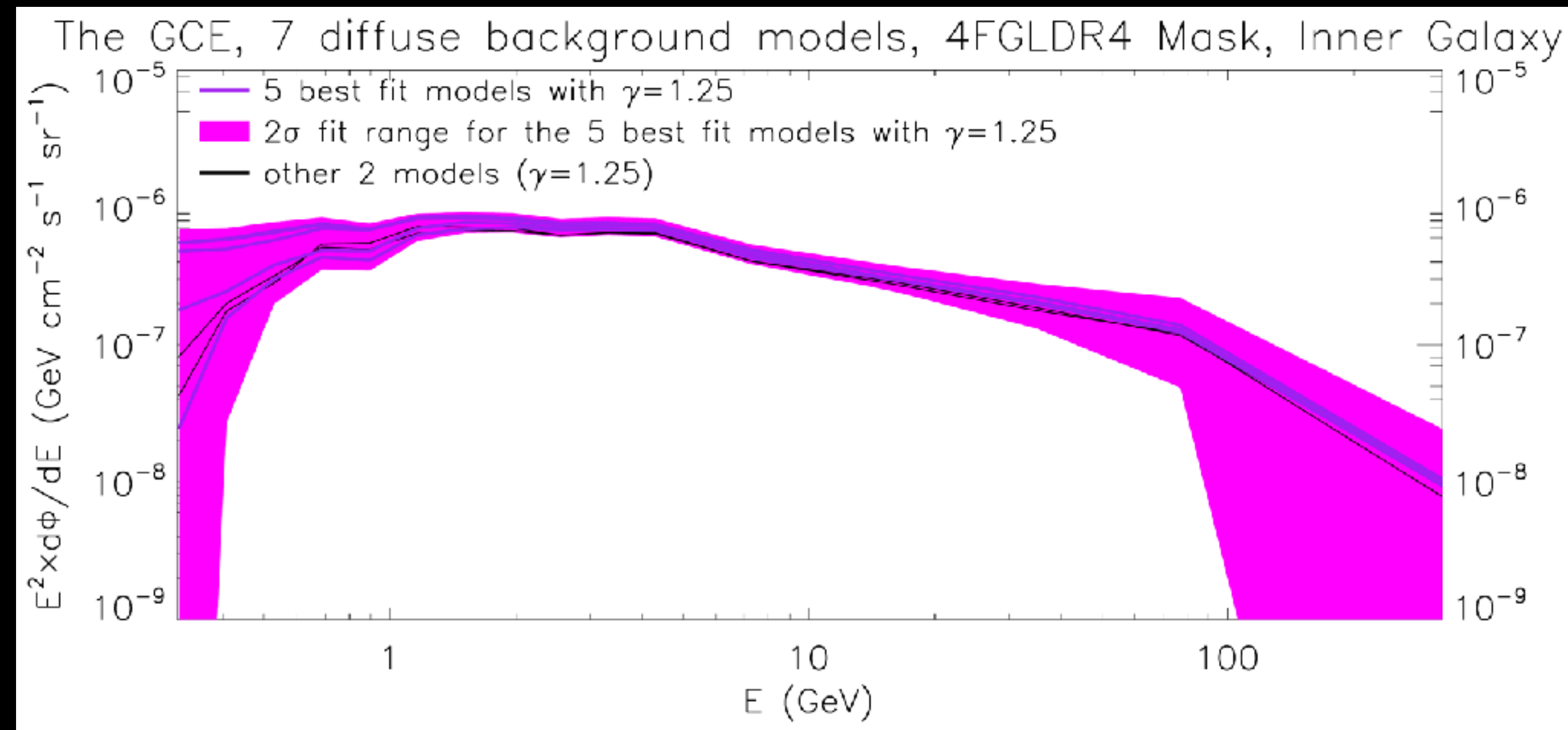


The new Bubbles absorb most of the HLE

- Replacing the HLE with the Inner Bubbles: $2\Delta \ln \mathcal{L} = 5018$.
- With Flat Bubbles + Cocoons, adding the HLE still gains $2\Delta \ln \mathcal{L} \approx 120$.
- With the full new model, the remaining NFW component behaves like the GCE.

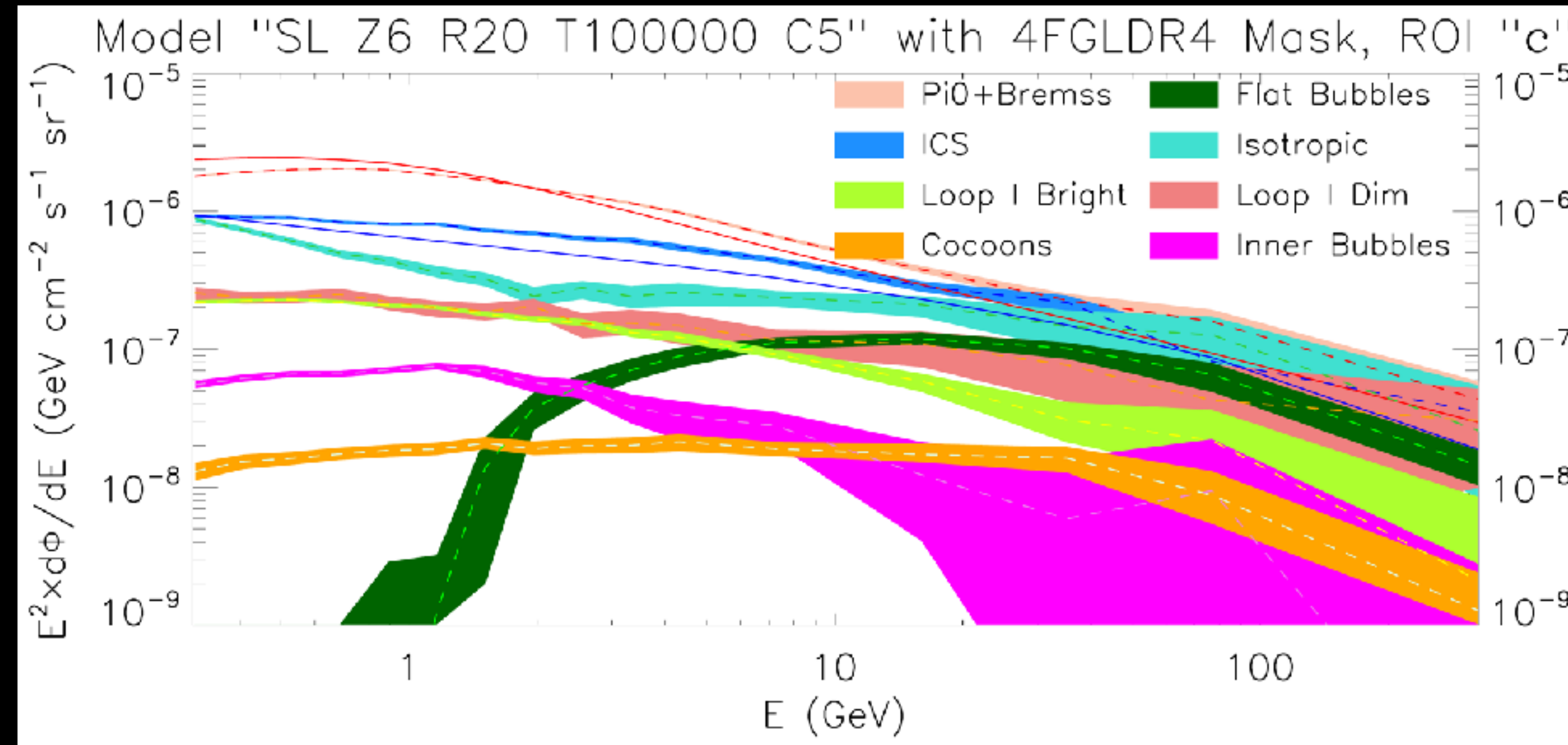


On top of the new Bubbles, the NFW component is the GCE



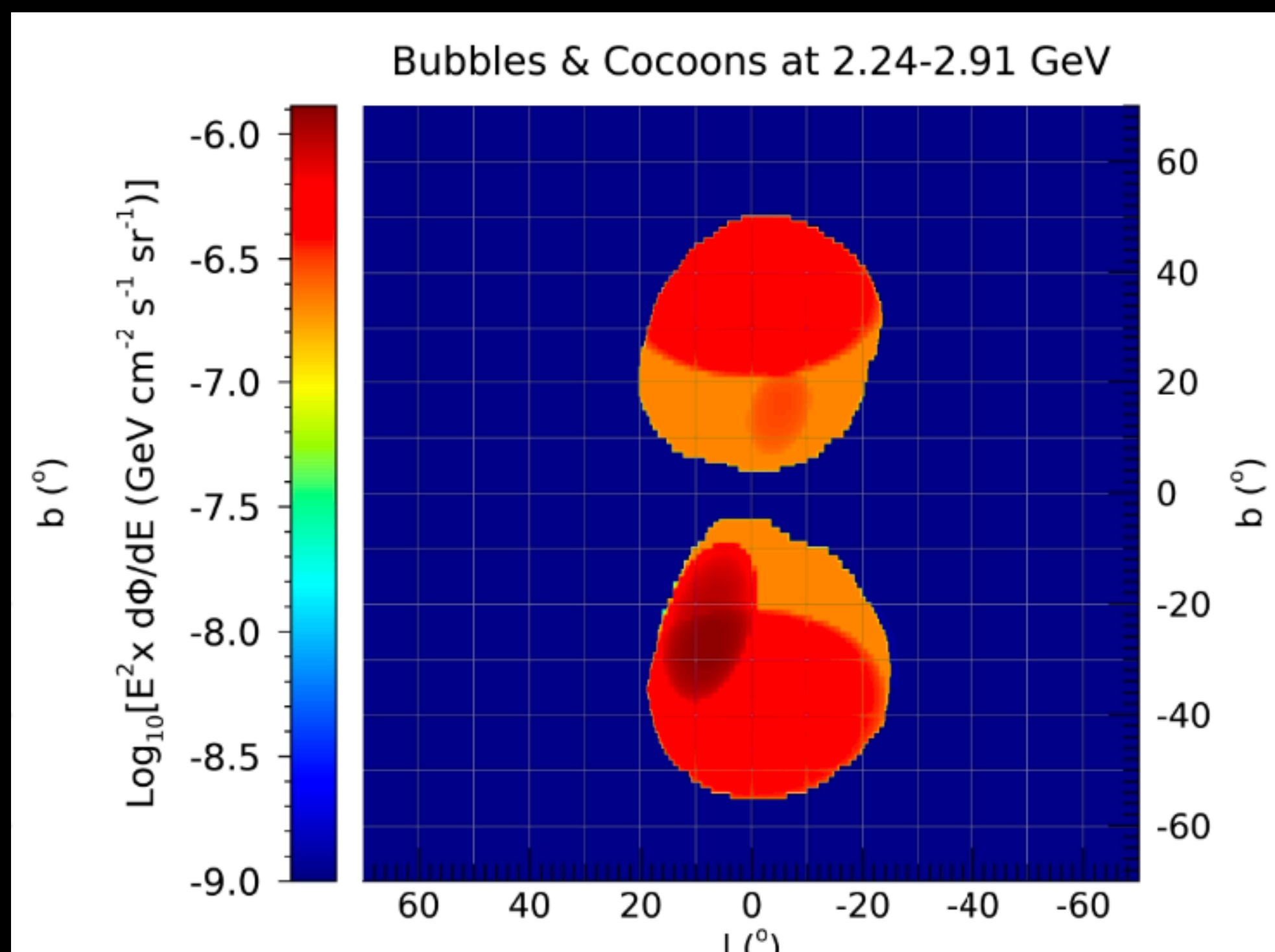
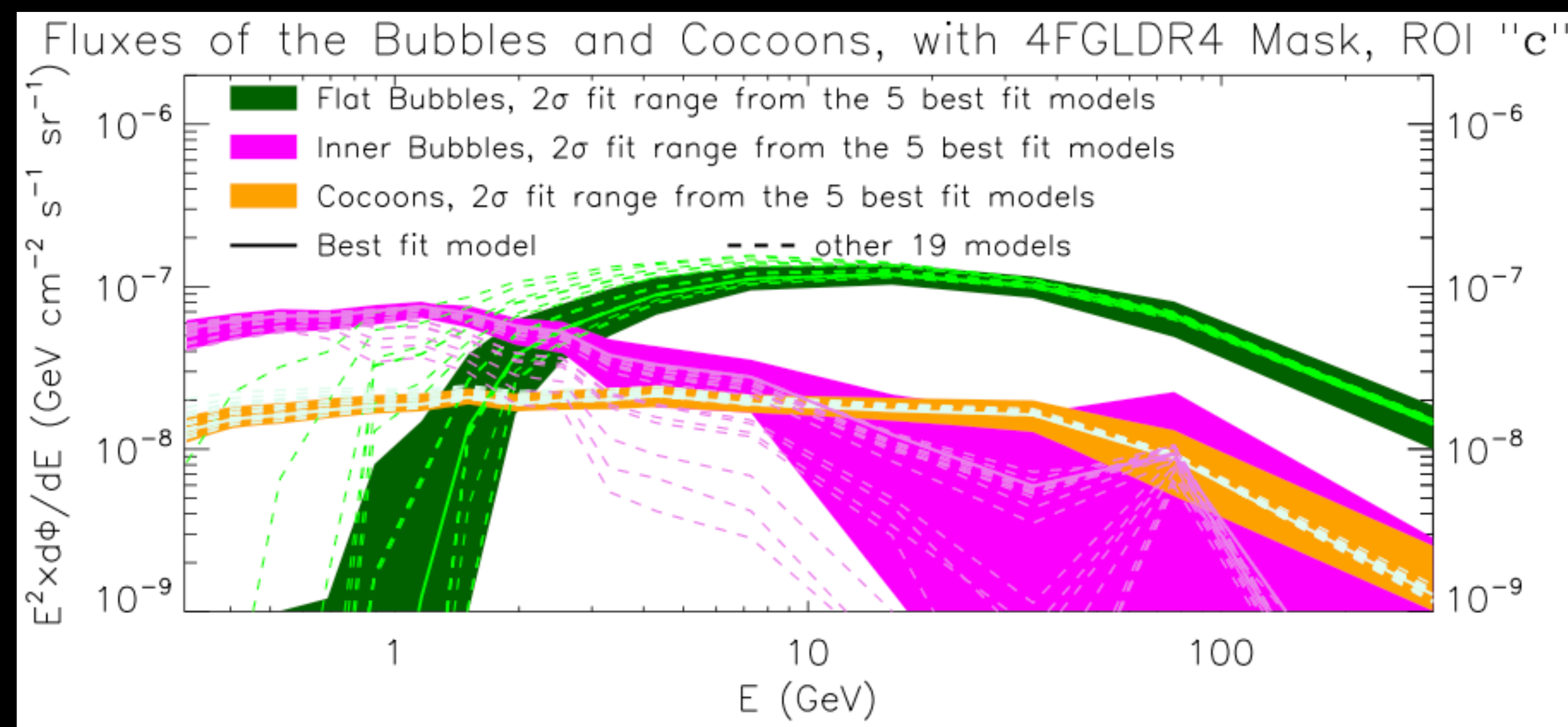
- Inner Galaxy, $|\ell| \leq 20^\circ$, $2^\circ \leq |b| \leq 20^\circ$, 7 diffuse models.
- GCE-shaped spectrum; the 10–50 GeV rise is gone.

The background templates look physical again



- ICS and π^0 now within O(10%) of their predictions.
- Loop I Bright $\sim$ Loop I Dim

Inner Bubbles below 2 GeV, Flat Bubbles above 3 GeV



Summary: the HLE is not a dark-matter halo

- The HLE is a significant residual over the standard templates, in every region, fit scheme and diffuse model.
- It cannot be a halo centred on the GC: per steradian, ROI $e > d$ and $h > g$.
- At $|b| \geq 20^\circ$ it is degenerate with the Bubbles and ICS.
- New Bubbles (wider edges + Cocoons + Inner Bubbles) absorb most of it; what remains behaves like the GCE.
- A much dimmer dark-matter signal at high latitude is still allowed.

Backup

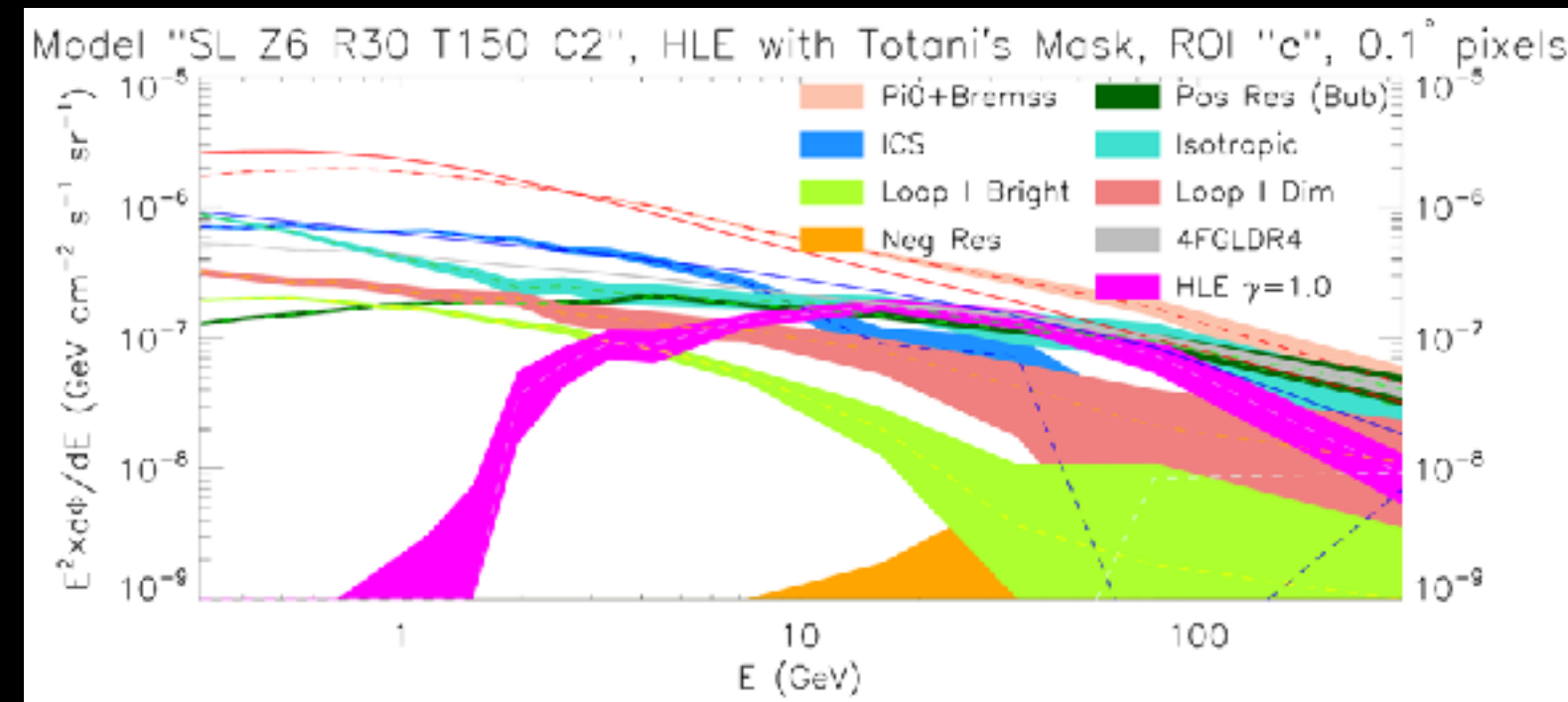
The 20 Fermi-LAT diffuse models we use

SL Z4 R30 T150 C5	SL Z10 R30 T150 C2	SS Z8 R20 T150 C5
SL Z6 R20 T150 C2	SL Z10 R30 T150 C5	SS Z10 R30 T150 C5
SL Z6 R20 T100000 C5	SO Z4 R30 T150 C5	SY Z6 R20 T100000 C2
SL Z6 R30 T150 C2	SO Z6 R30 T150 C2	SY Z6 R30 T150 C2
SL Z6 R30 T100000 C2	SO Z10 R30 T150 C5	SY Z6 R30 T100000 C5
SL Z6 R30 T150 C5	SS Z6 R20 T150 C5	SY Z10 R30 T150 C5
SL Z8 R30 T150 C5	SS Z6 R30 T150 C2	

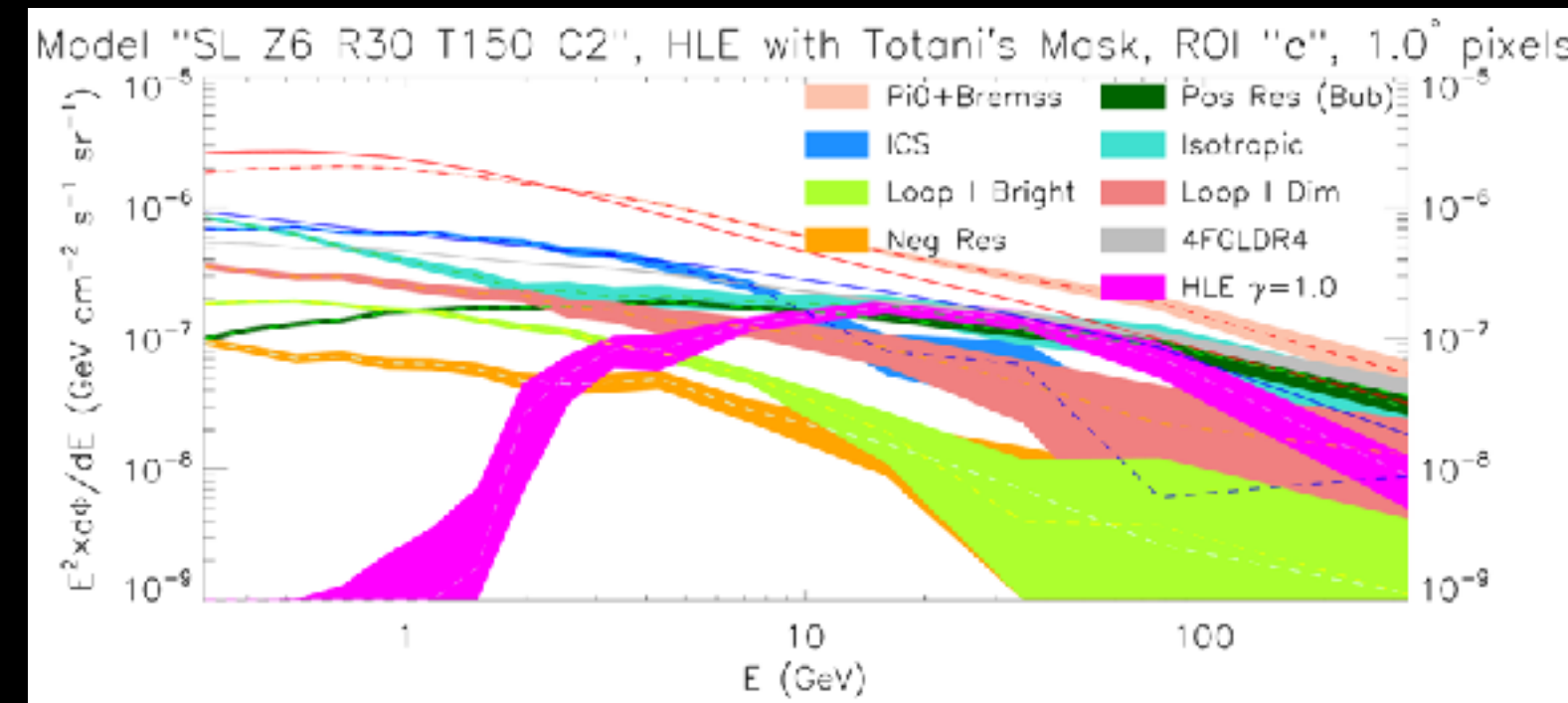
- Pink: best fit in ROI c; orange: Totani's model
- SL/SO/SS/SY: cosmic-ray sources · Z, R: halo size · T: spin temp. · C: E(B–V) cut
- Plus 80 Cholis+ '21 models: 100 in total

Reproducing Totani '25

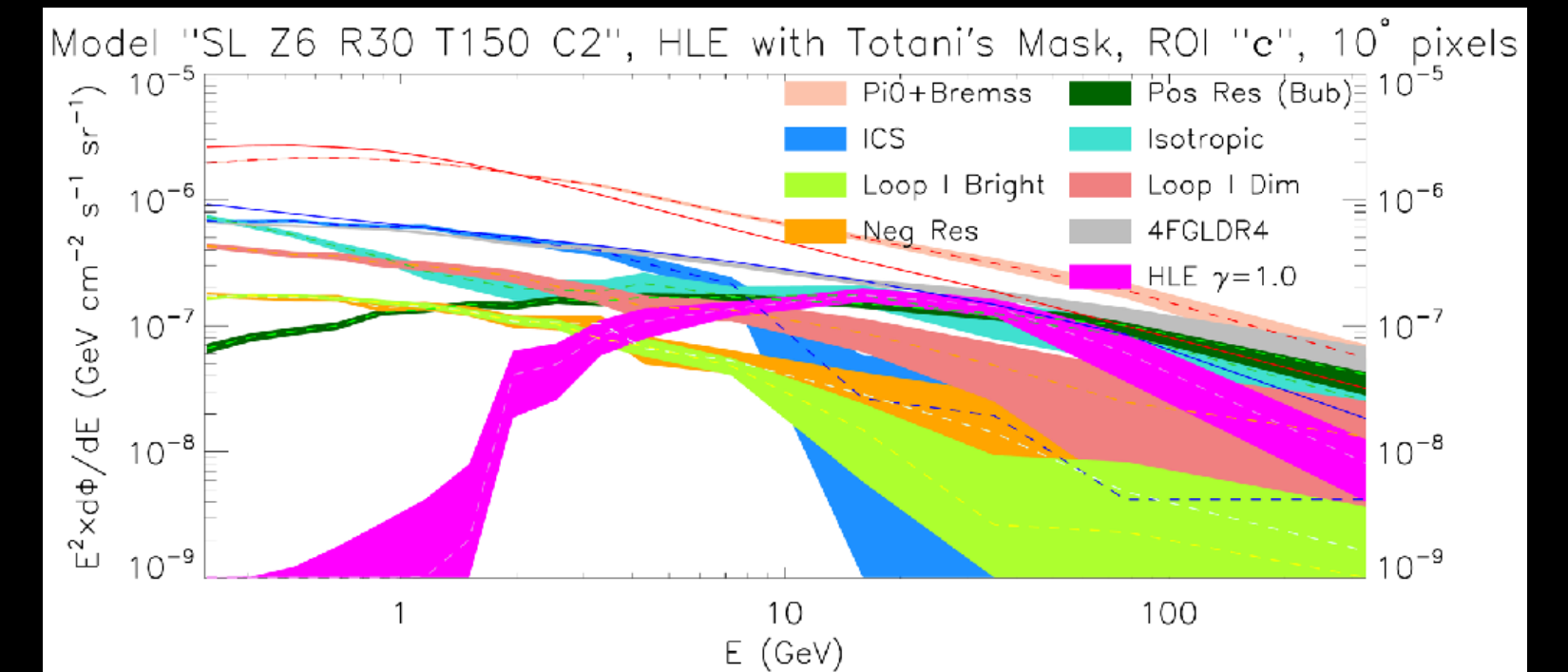
0.1° pixels (ours)



grouped to 1°



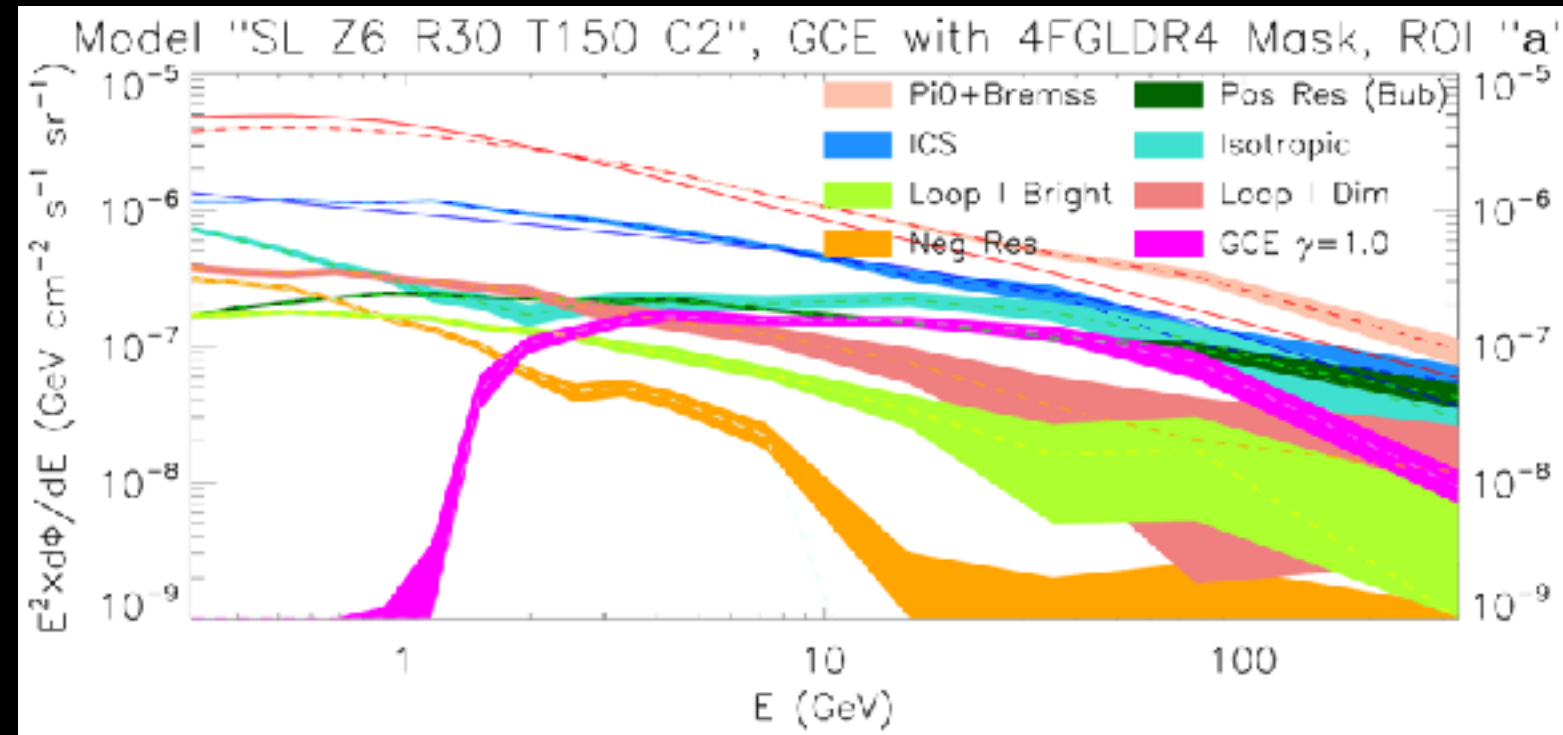
10° pixels (Totani)



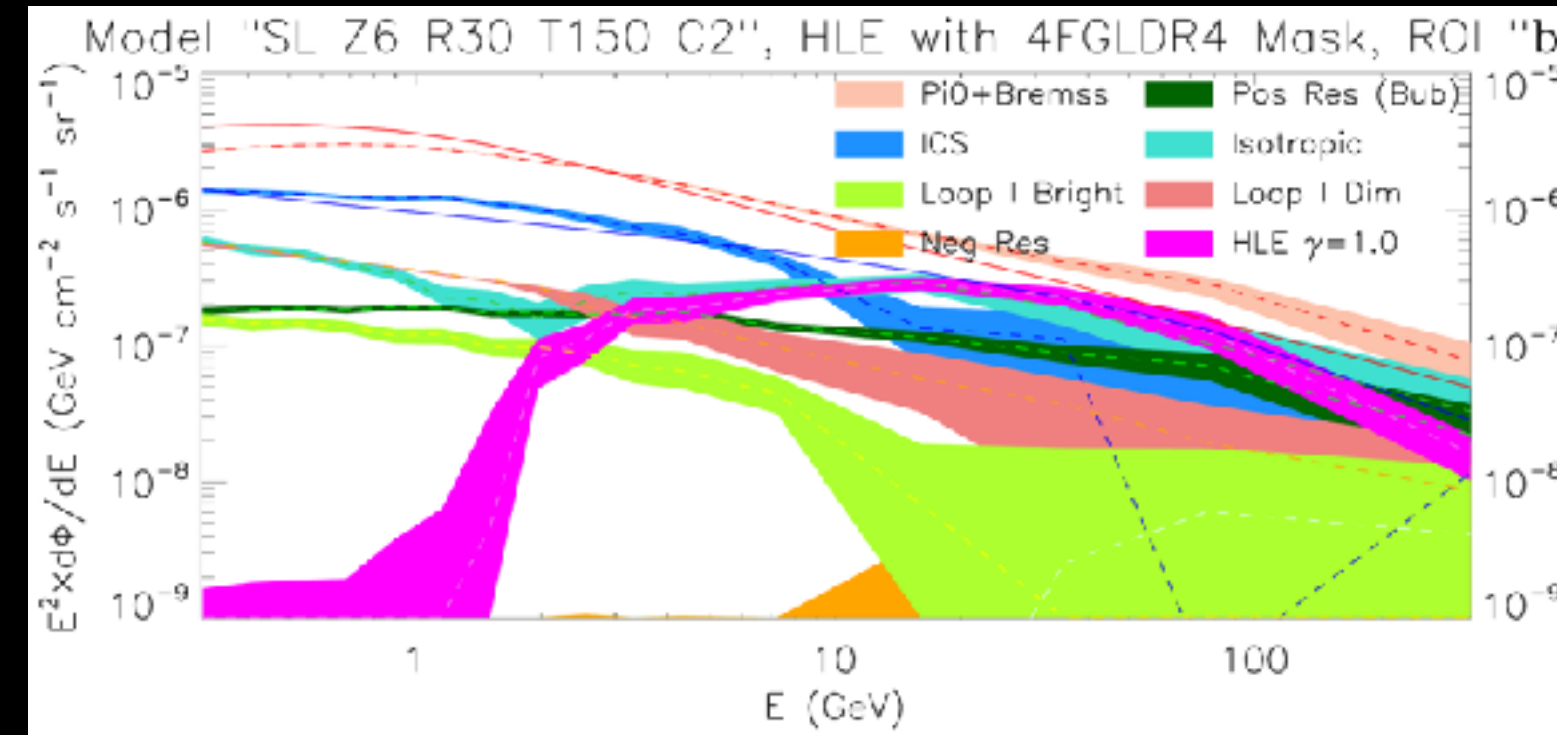
- Totani's setup (ROI c + Totani mask + residual maps): we find a similar HLE.
- Grouping pixels shifts every template; the negative map grows.

Eight-parameter fits with Totani's residual maps

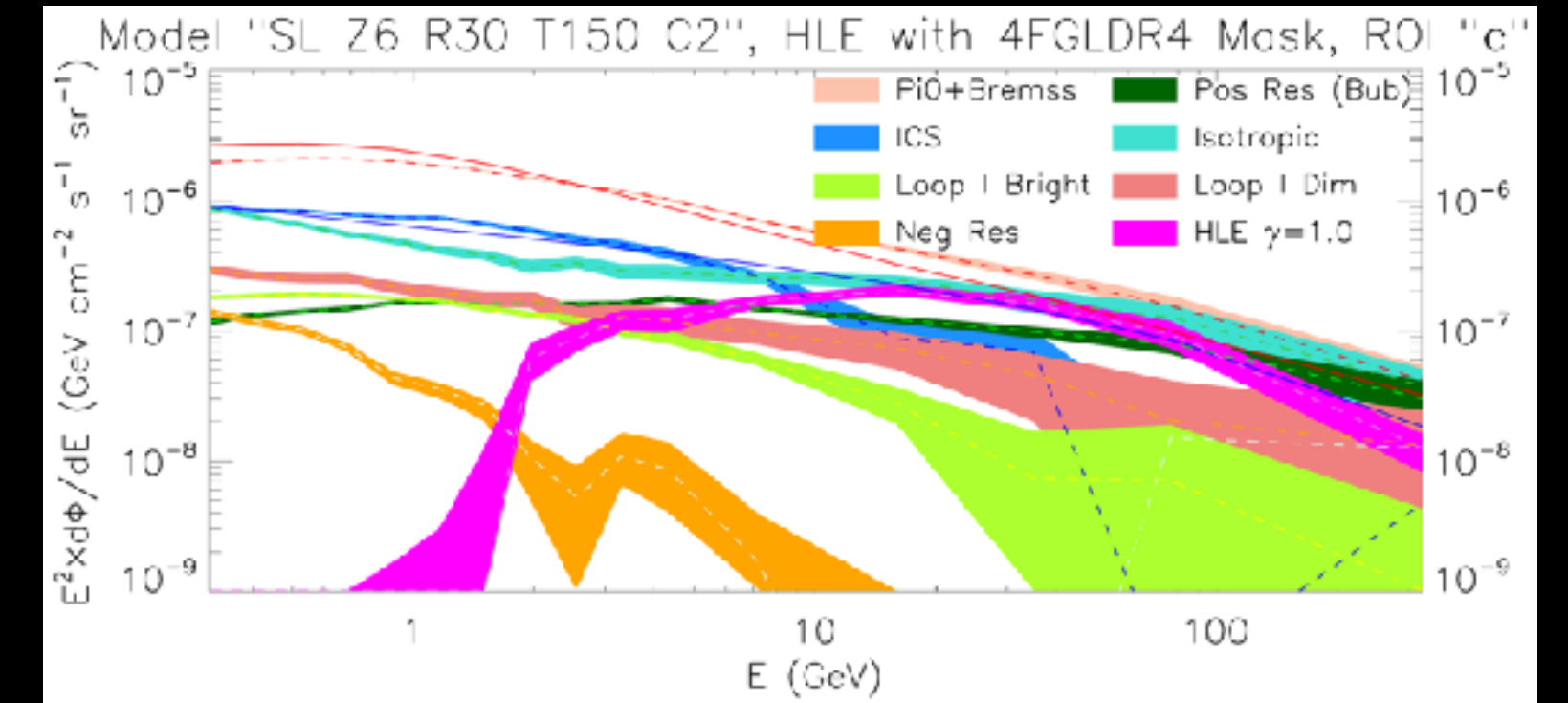
a: $2^\circ \leq |b| \leq 60^\circ$



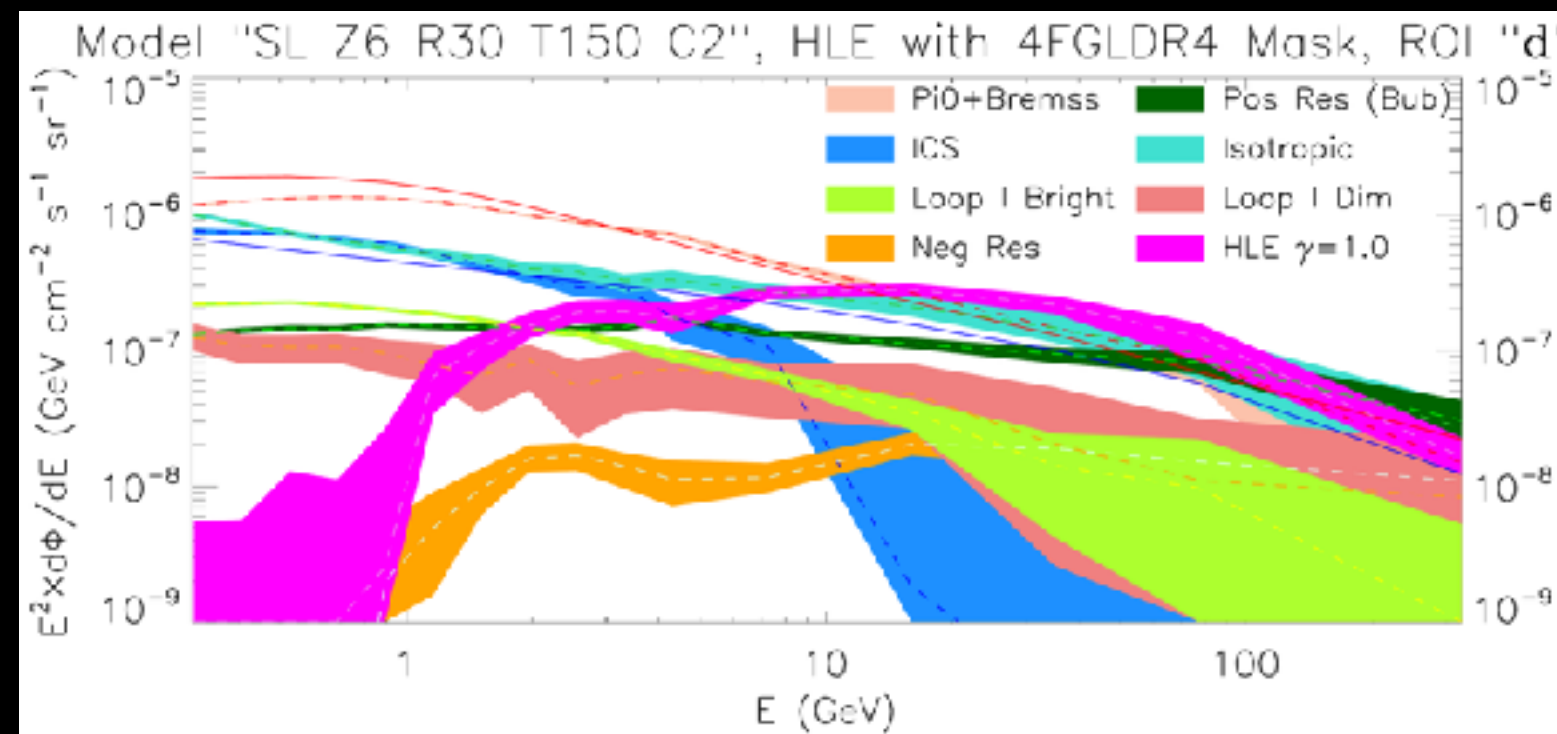
b: $10^\circ \leq |b| \leq 30^\circ$



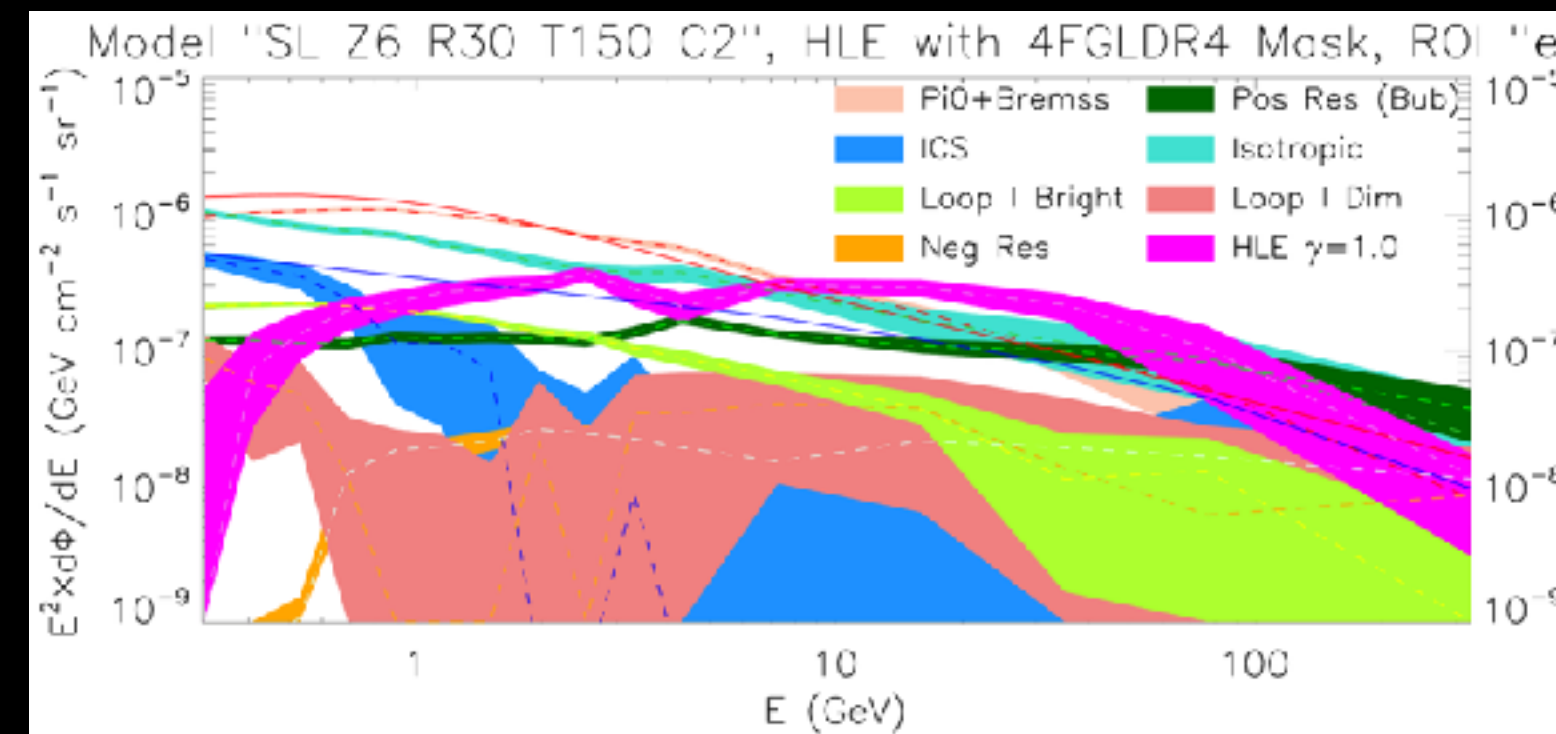
c: $10^\circ \leq |b| \leq 60^\circ$



d: $20^\circ \leq |b| \leq 60^\circ$



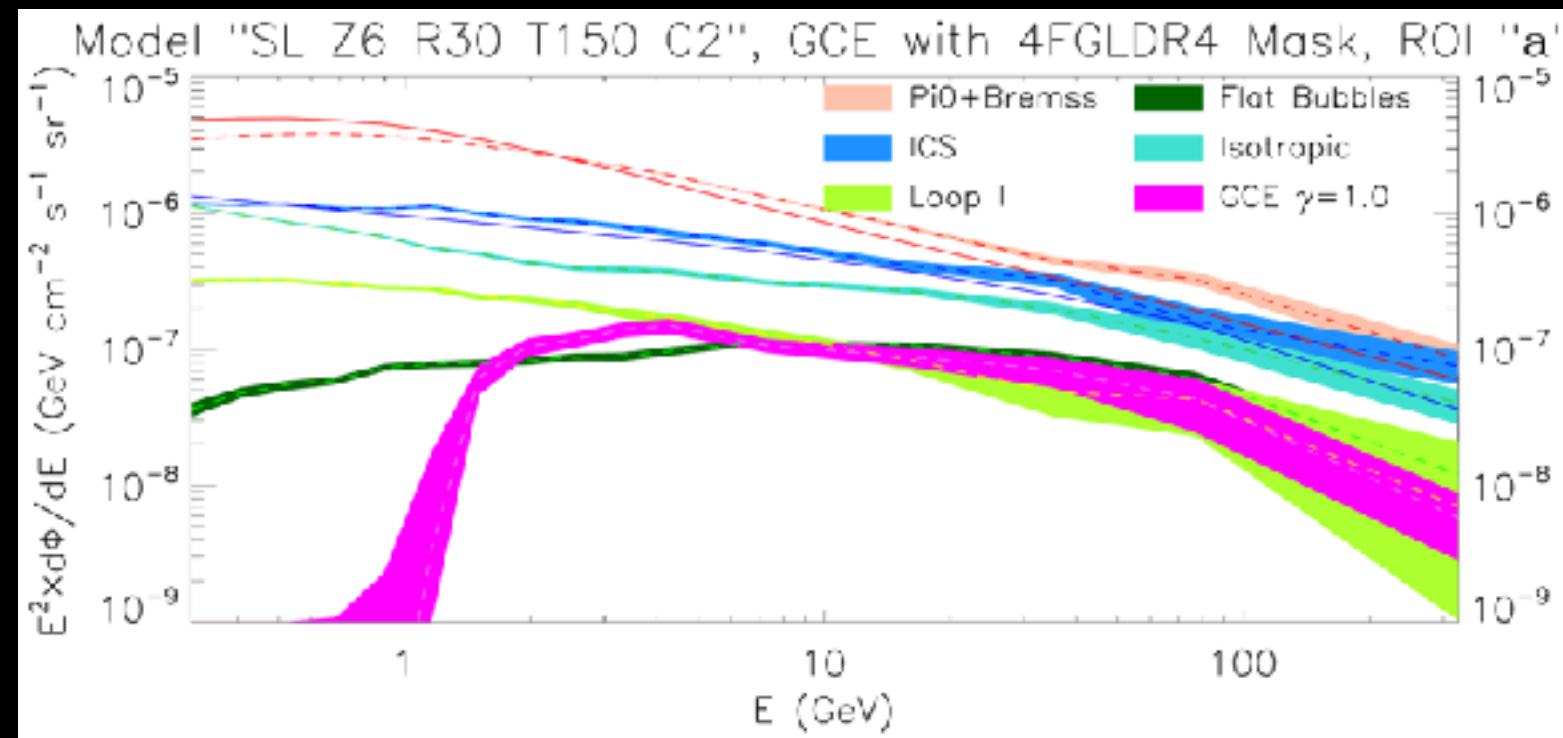
e: $30^\circ \leq |b| \leq 60^\circ$



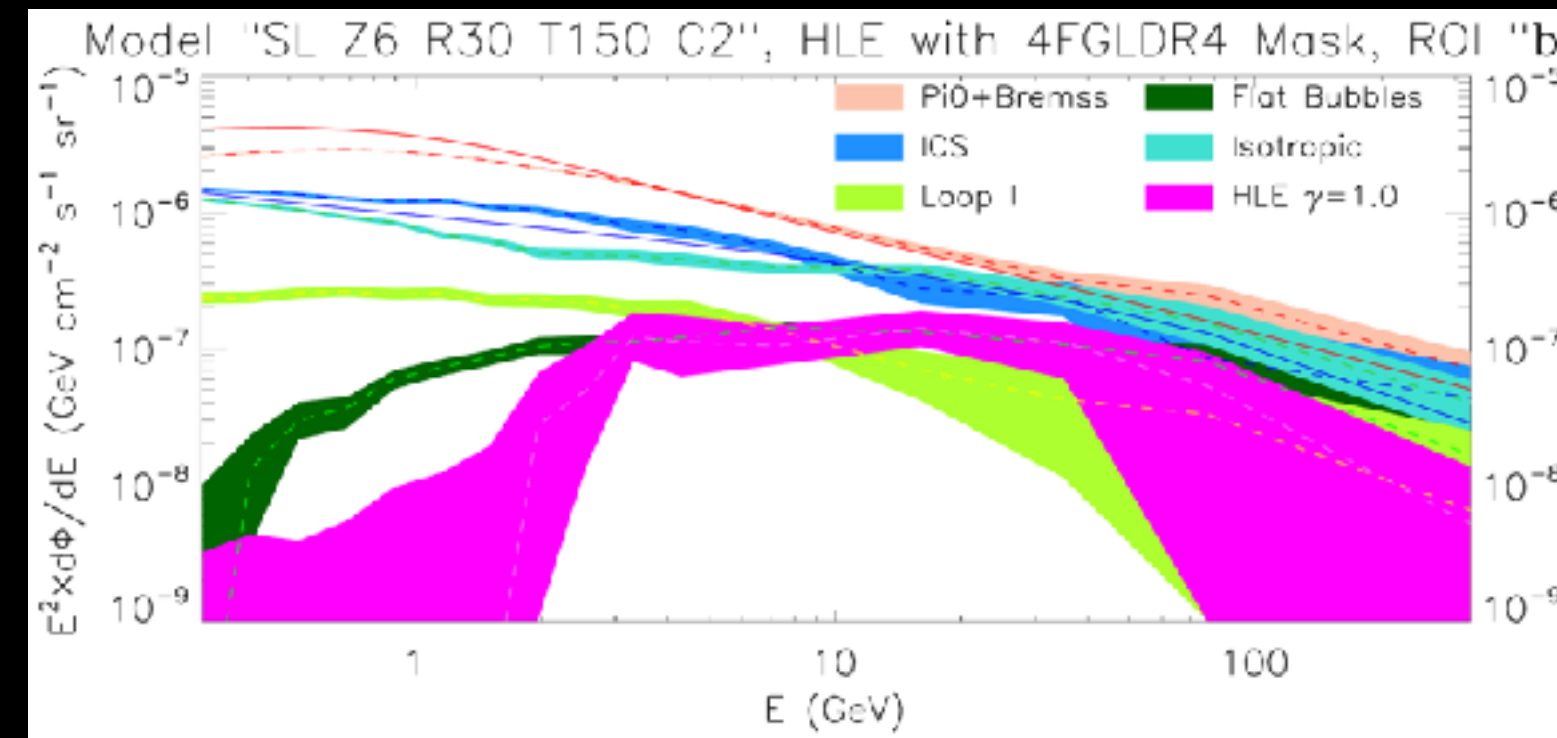
With the negative map the HLE is still not ρ^2 -like

Six-parameter fits with one Loop I template

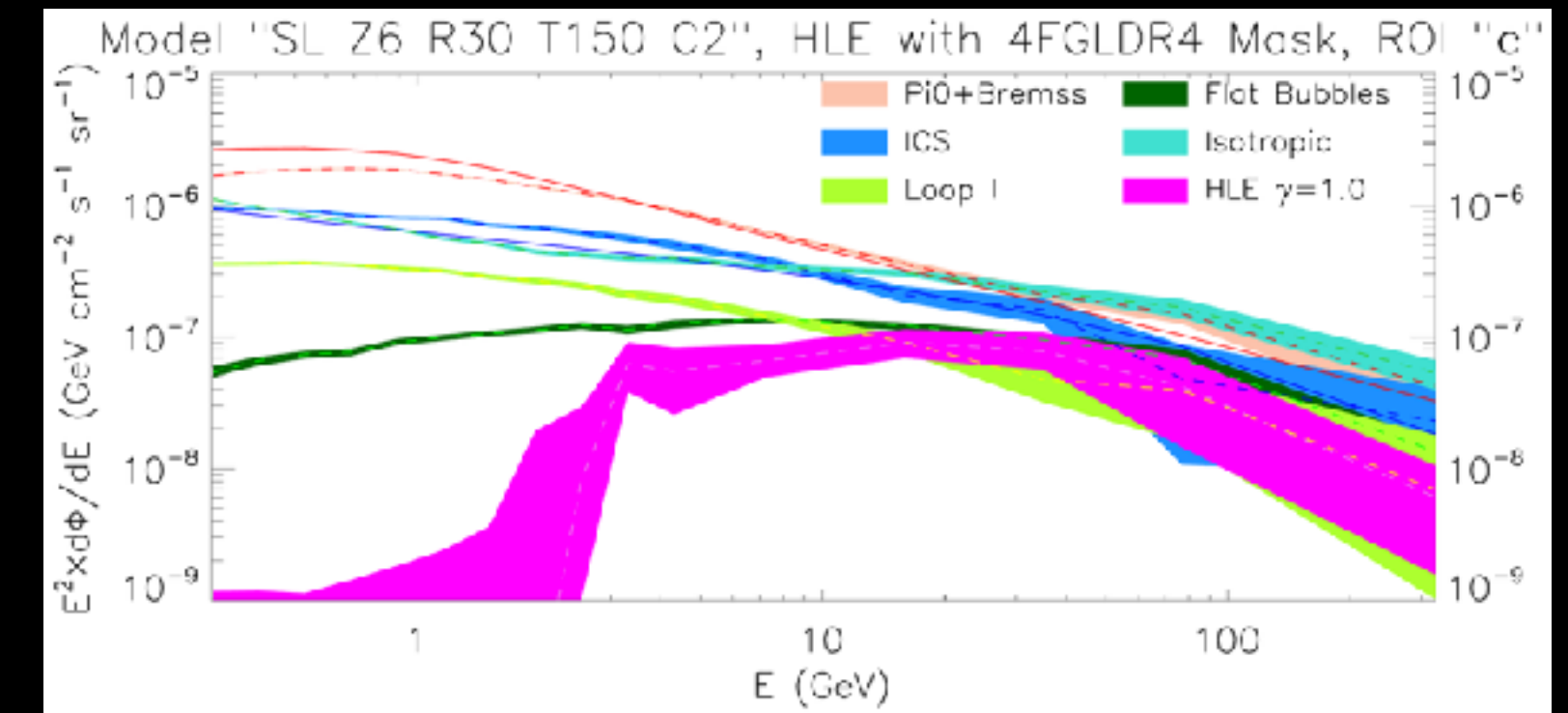
a: $2^\circ \leq |b| \leq 60^\circ$



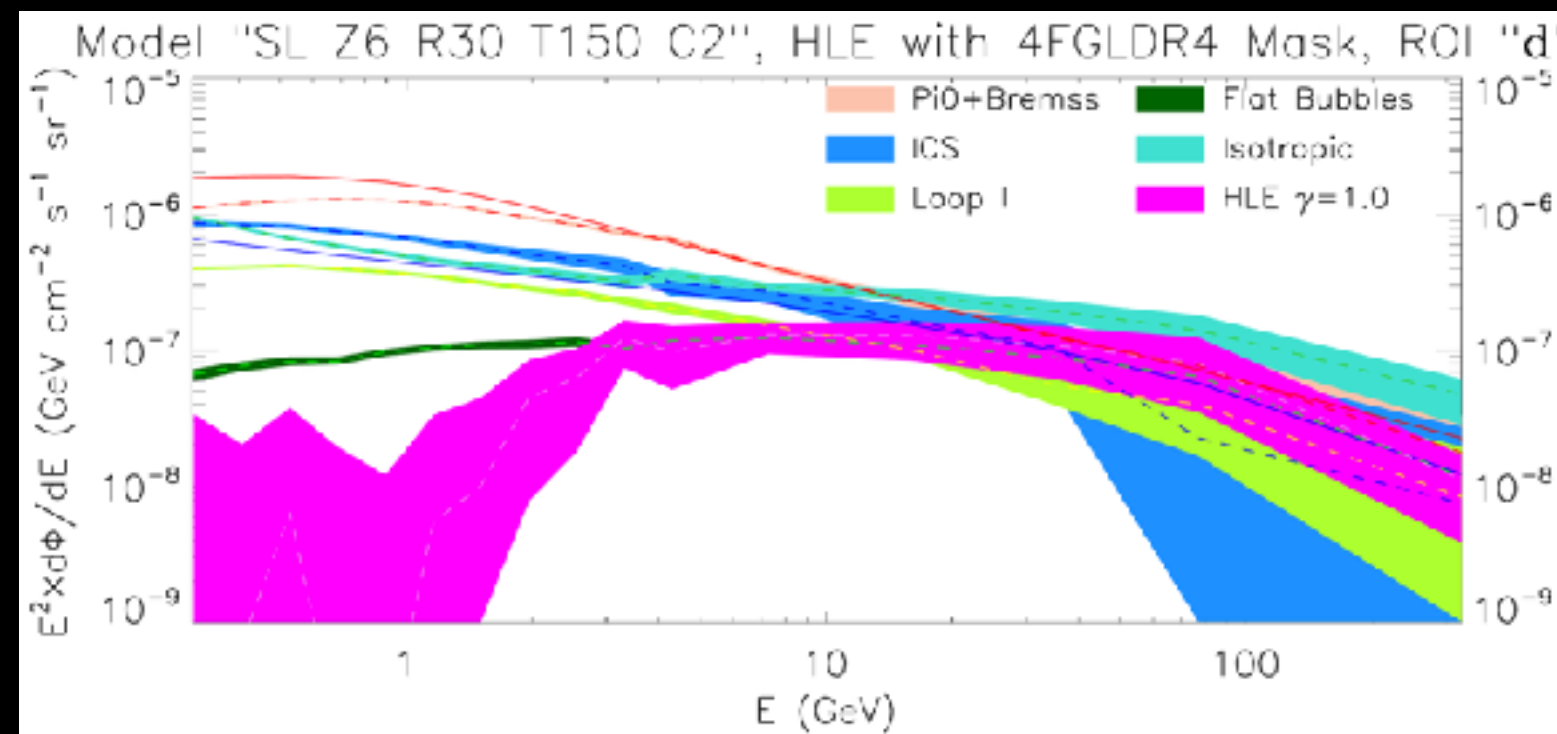
b: $10^\circ \leq |b| \leq 30^\circ$



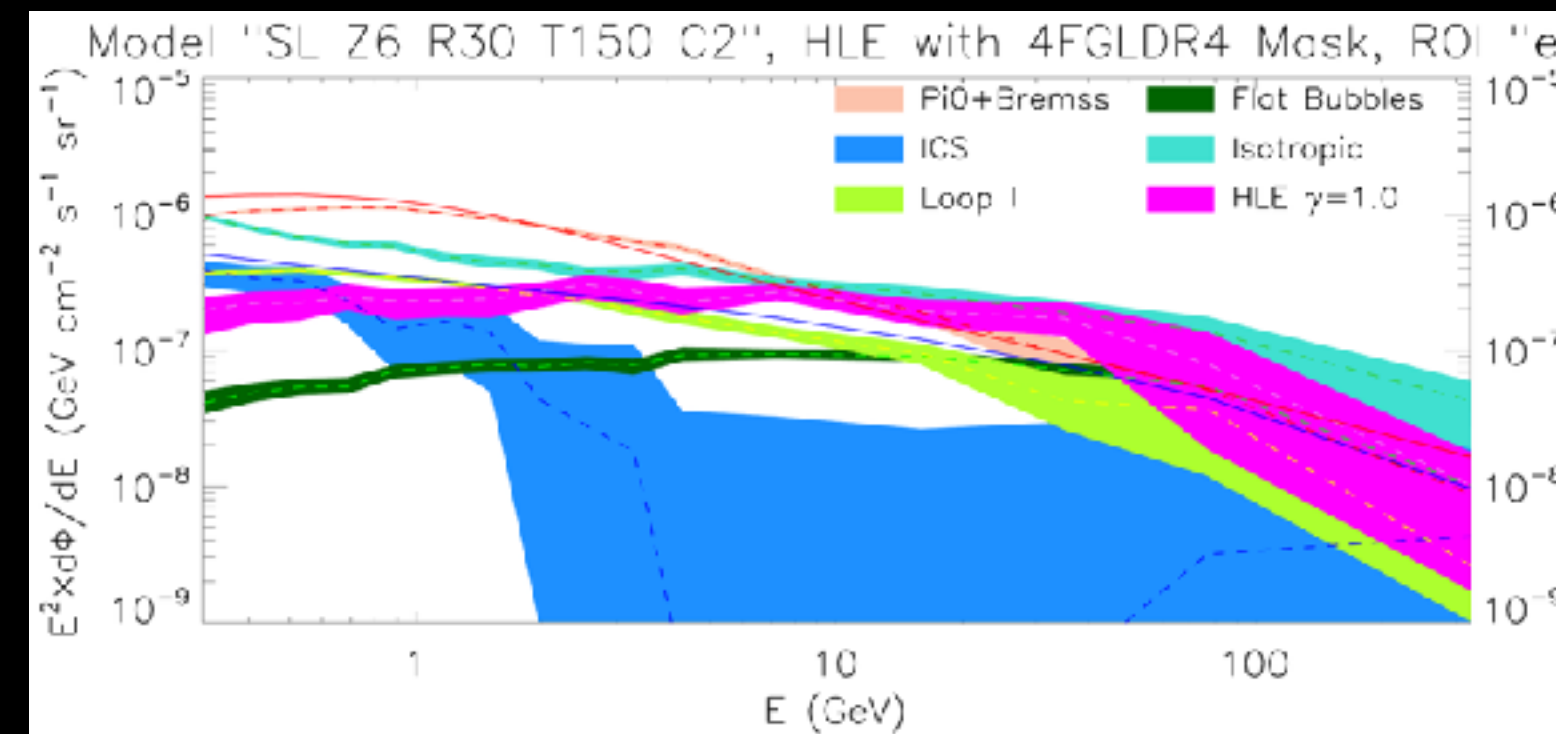
c: $10^\circ \leq |b| \leq 60^\circ$



d: $20^\circ \leq |b| \leq 60^\circ$



e: $30^\circ \leq |b| \leq 60^\circ$



At $|b| \geq 20^\circ$ the HLE absorbs Bubbles and ICS flux

The HLE is real: every region and fit scheme wants it

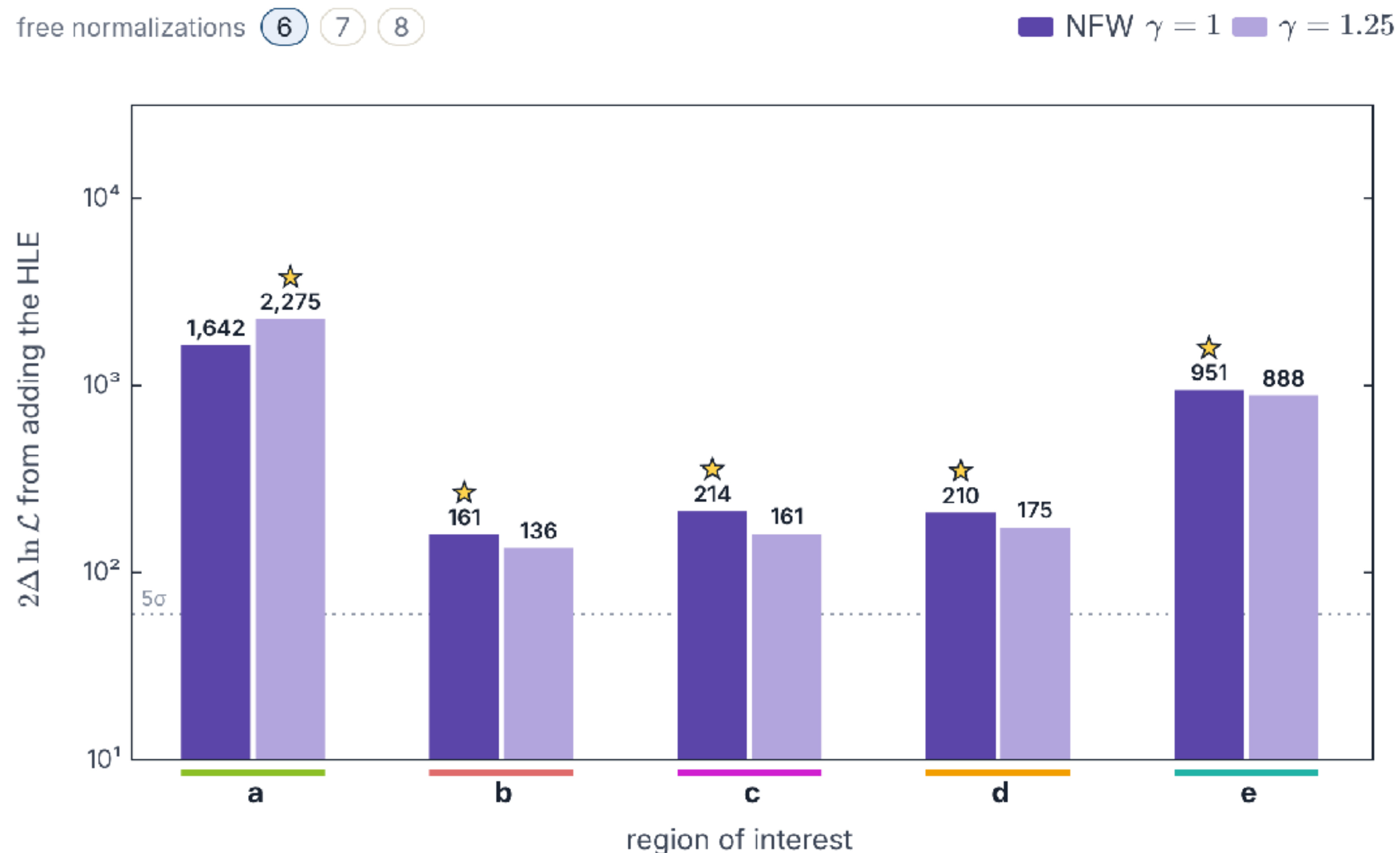


Table IV, as bars; diffuse model SL Z6 R30 T150 C2. Dotted: 5 σ for 16 extra parameters (one per bin).
★ preferred slope.

- 6: one Loop I template
- 7: Loop I's two shells free
- 8: Totani's residual maps instead of the Bubbles
- $\gamma = 1.25$ wins only in ROI a, which contains the GCE.

The HLE is real: every region and fit scheme wants it

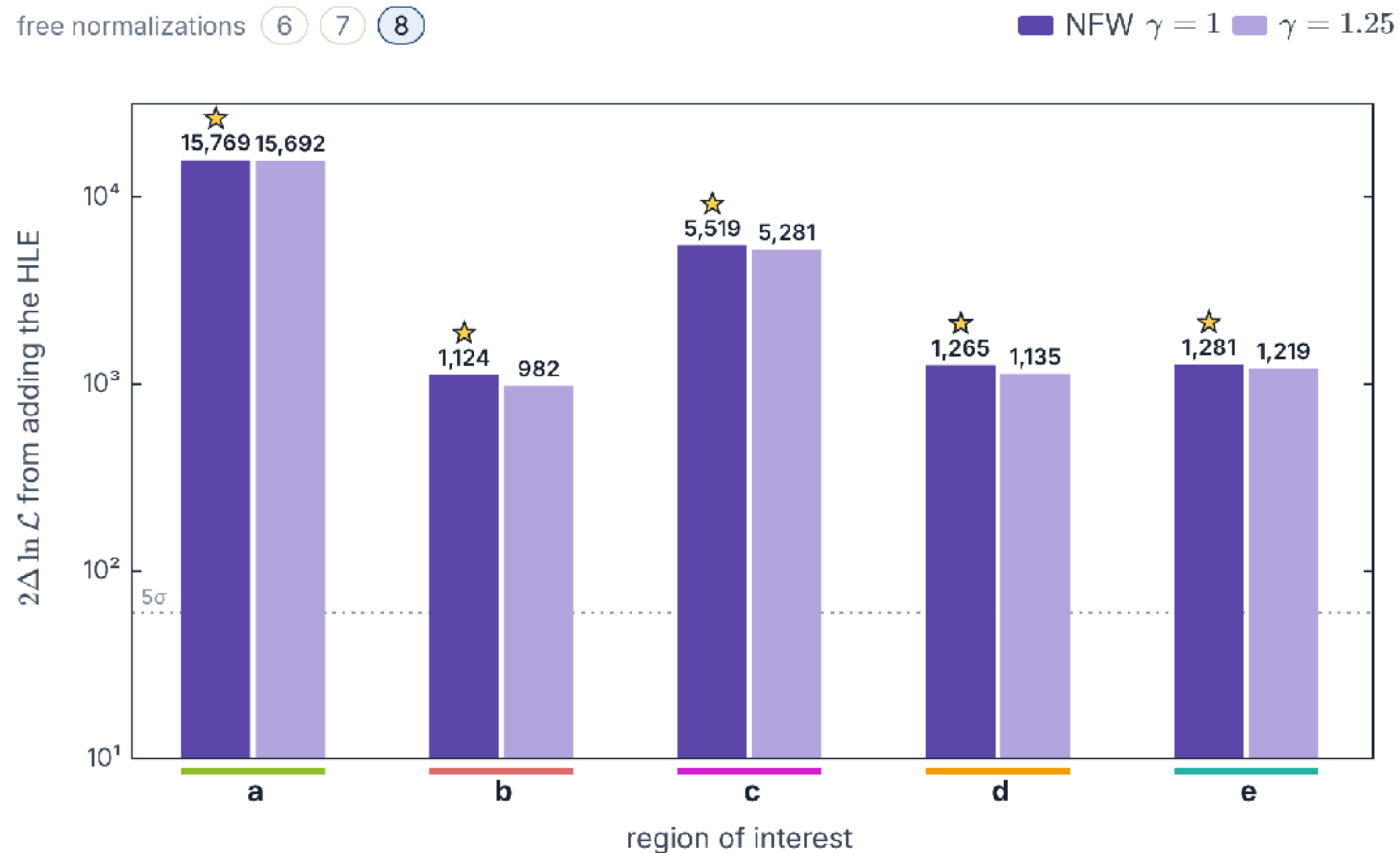
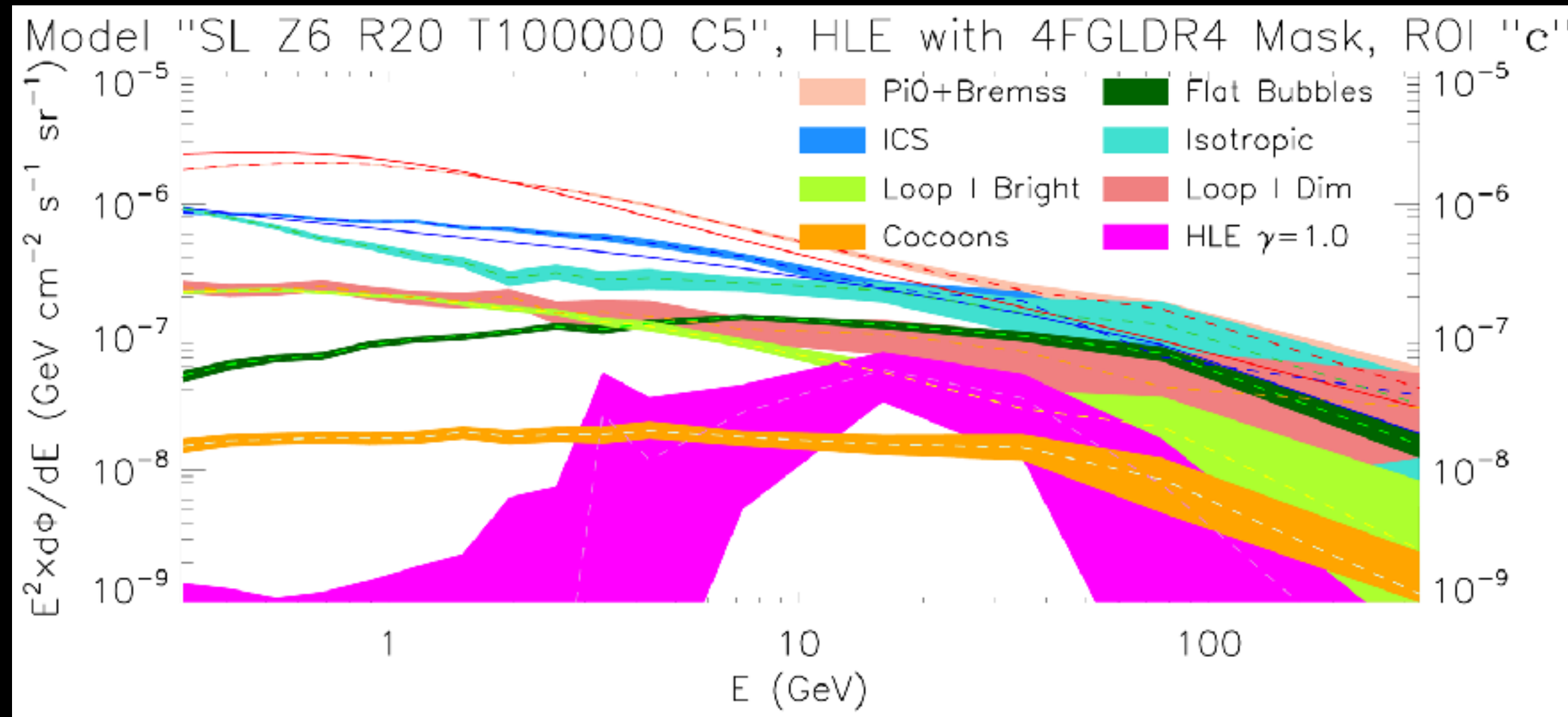


Table IV, as bars; diffuse model SL Z6 R30 T150 C2. Dotted: 5 σ for 16 extra parameters (one per bin).
 ☆ preferred slope.

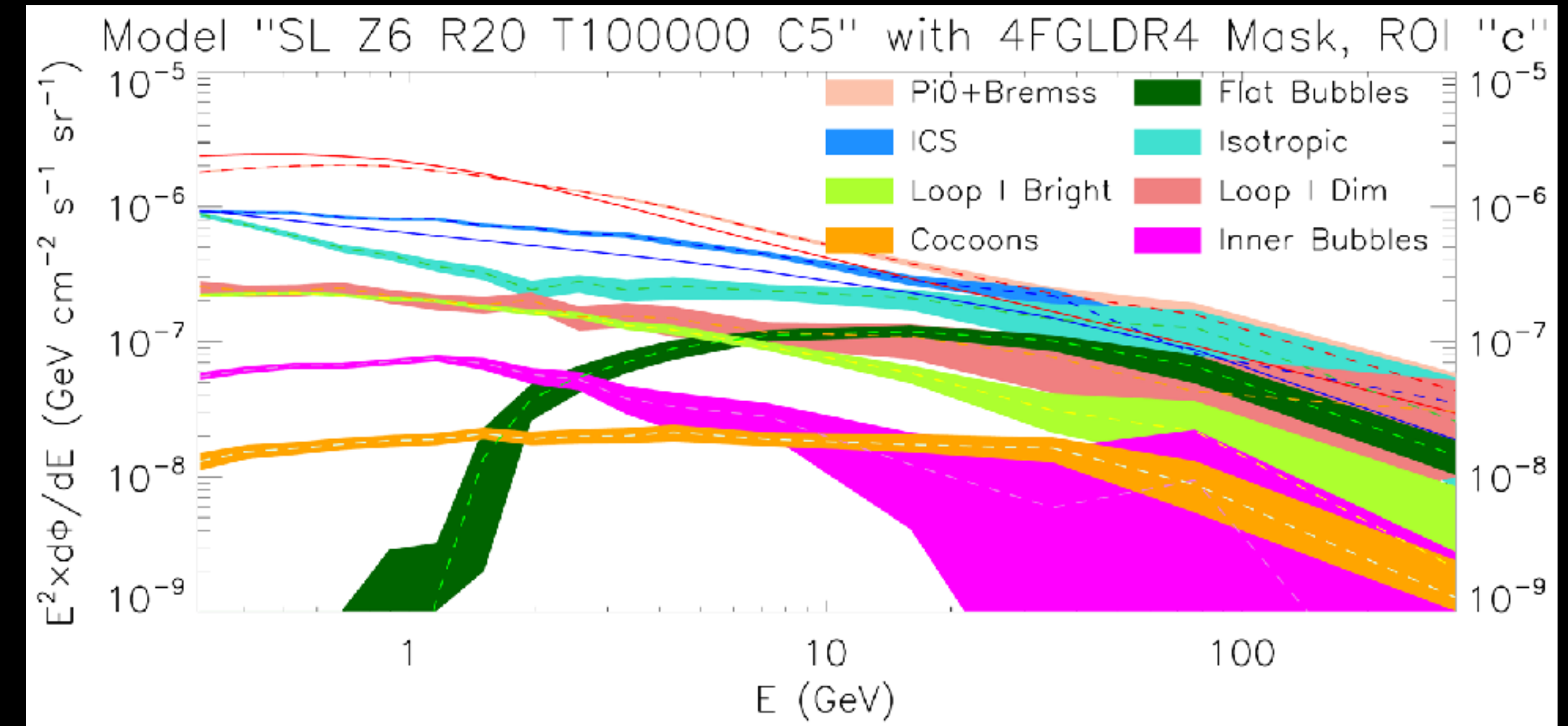
- 6: one Loop I template
- 7: Loop I's two shells free
- **8: Totani's residual maps instead of the Bubbles**
- $\gamma = 1.25$ wins only in ROI a, which contains the GCE.

In ROI c, Cocoons and Inner Bubbles replace the HLE

Edges E + Cocoons + HLE



Final: Inner Bubbles, no HLE



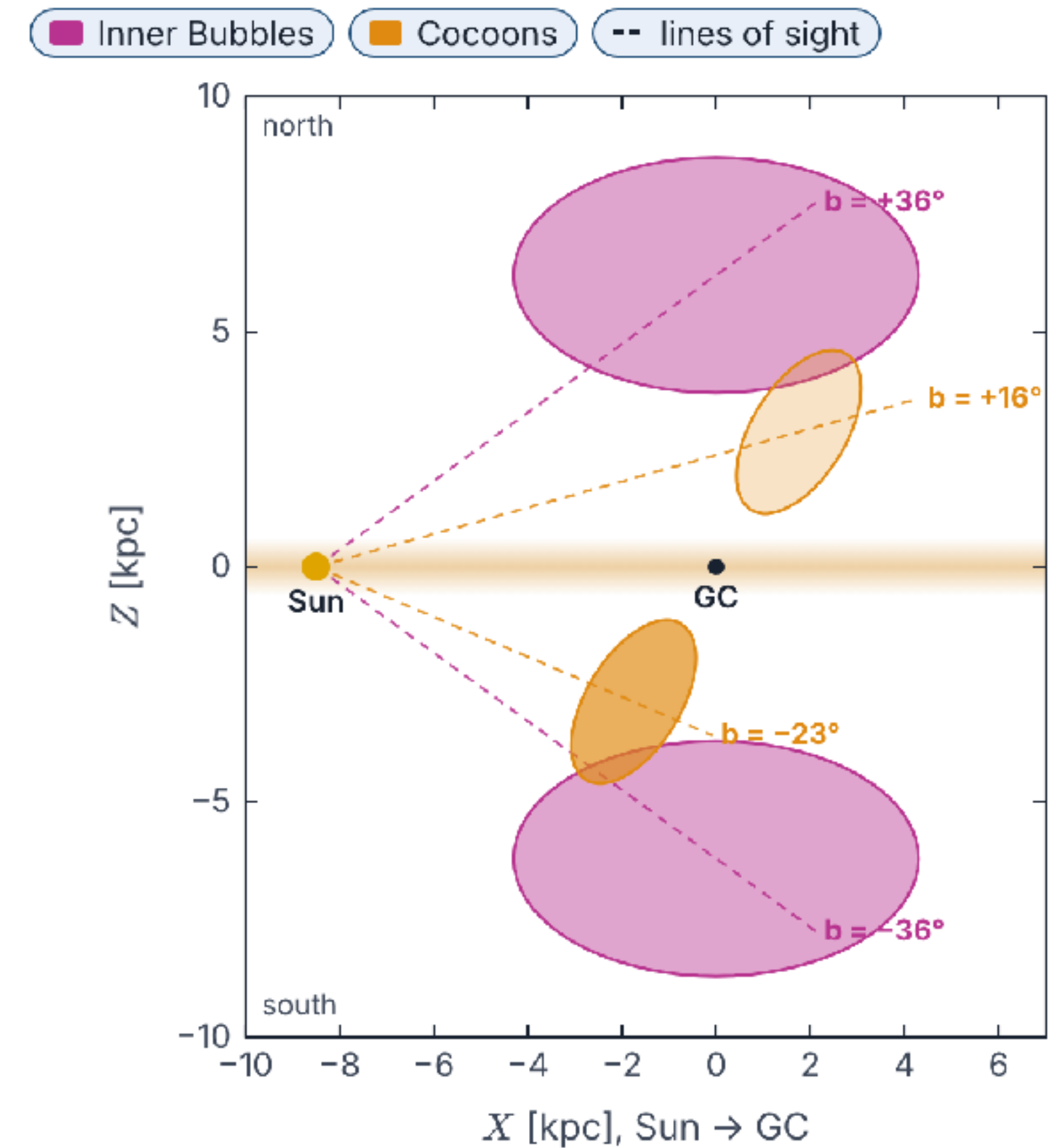
- Adding the Cocoons strongly suppresses the HLE.
- The Inner Bubbles replace it ($2\Delta \ln \mathcal{L} = 5018$); they are softer than the Flat Bubbles.

Best-fit geometry of the Cocoons and Inner Bubbles

	Cocoon	Inner Bubble
Ratio south / north	10	1
Centre z_0	3.5 kpc (fixed)	6.2 kpc
Semi-axis a	2.0 kpc	2.5 kpc
Semi-axis b	1.0 kpc	4.3 kpc
Pitch θ	35°	0°
Yaw ϕ	-29°	0°

Speculation: more than one outburst?

- All three structures are smooth: their γ -rays most likely come from ICS.
- **Cocoons**: tilted and elongated $\Rightarrow$ a later, shorter outburst than the main Bubbles.
- **Sharp flat edges**: cosmic-ray diffusion is suppressed at the boundaries $\Rightarrow$ stochastic 2nd-order Fermi acceleration around the edges
- **Inner Bubbles** may have risen buoyantly, like a mushroom cap.



Recomputed: the best-fit ellipsoids projected onto the X - Z plane, with the Sun's lines of sight to their centres.