Towards a realistic astrophysical interpretation of the Galactic center excess

(the GC excess brought back-to-Earth)

based on: D.Gaggero, M.Taoso, P.Ullio, A.Urbano, M.Valli, arXiv:1507.06129, submitted to JCAP

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Outline

- Introductory remarks on the GC excess
- The GC environment
- Our phenomenological model
- Spike model VS DM, pulsar model
- Discussion

We agree that a "inner Galaxy anomaly" is present in Fermi-LAT data

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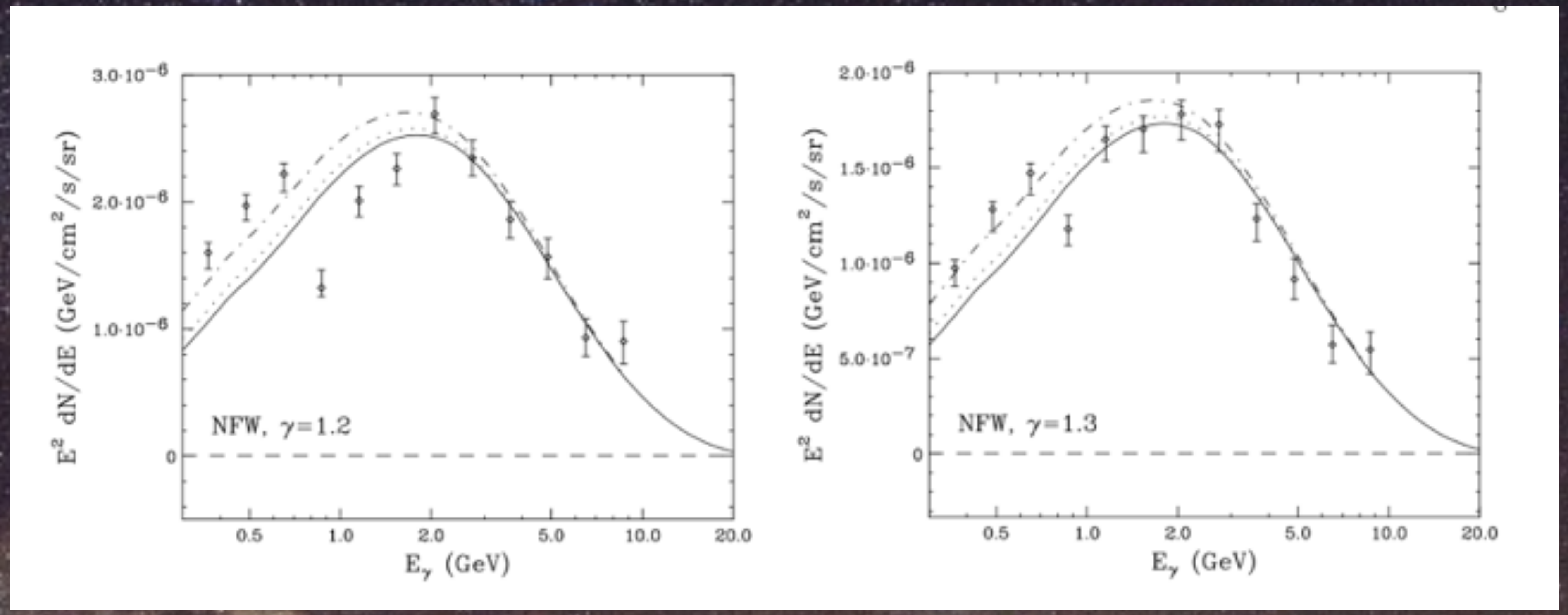

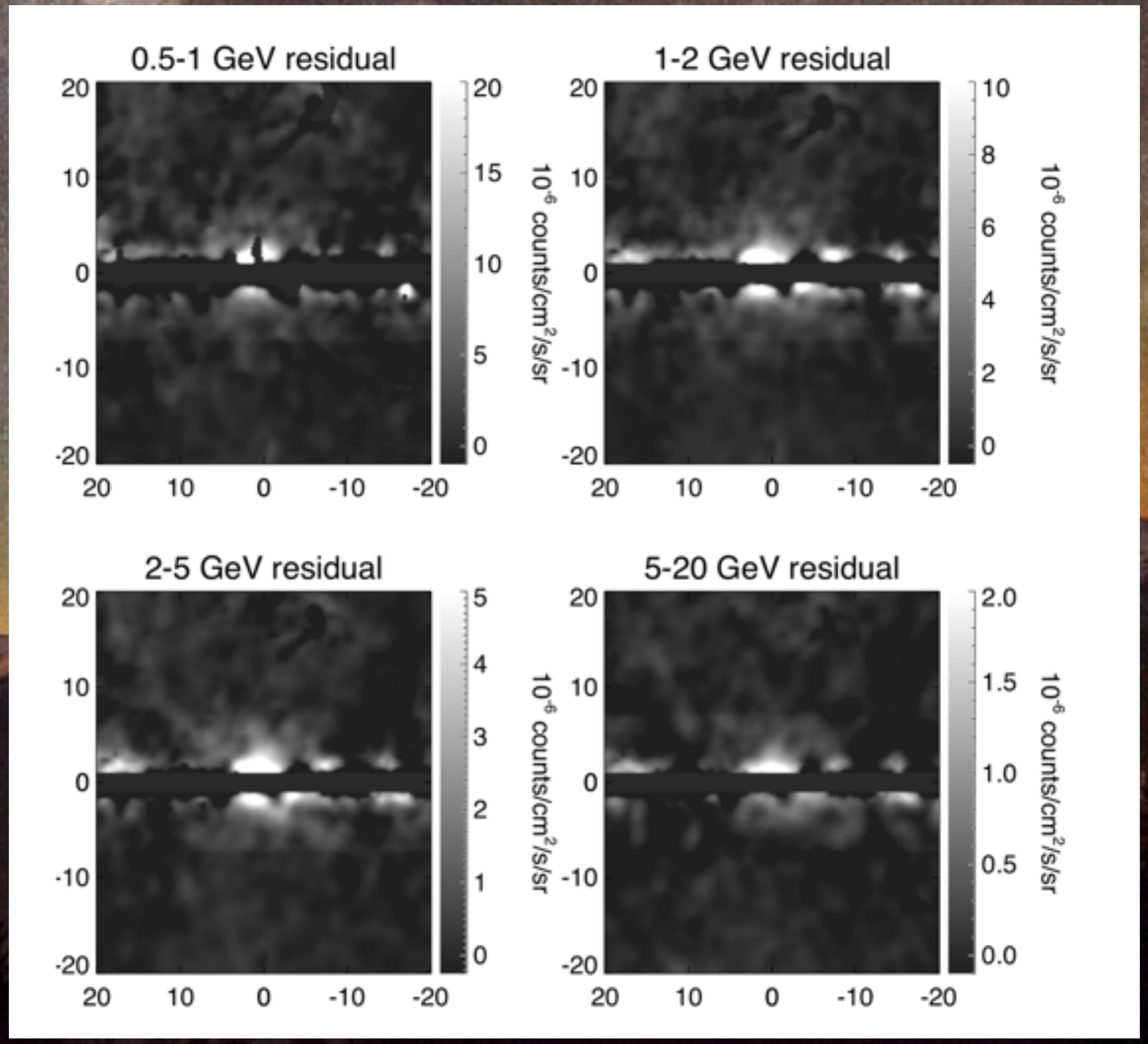

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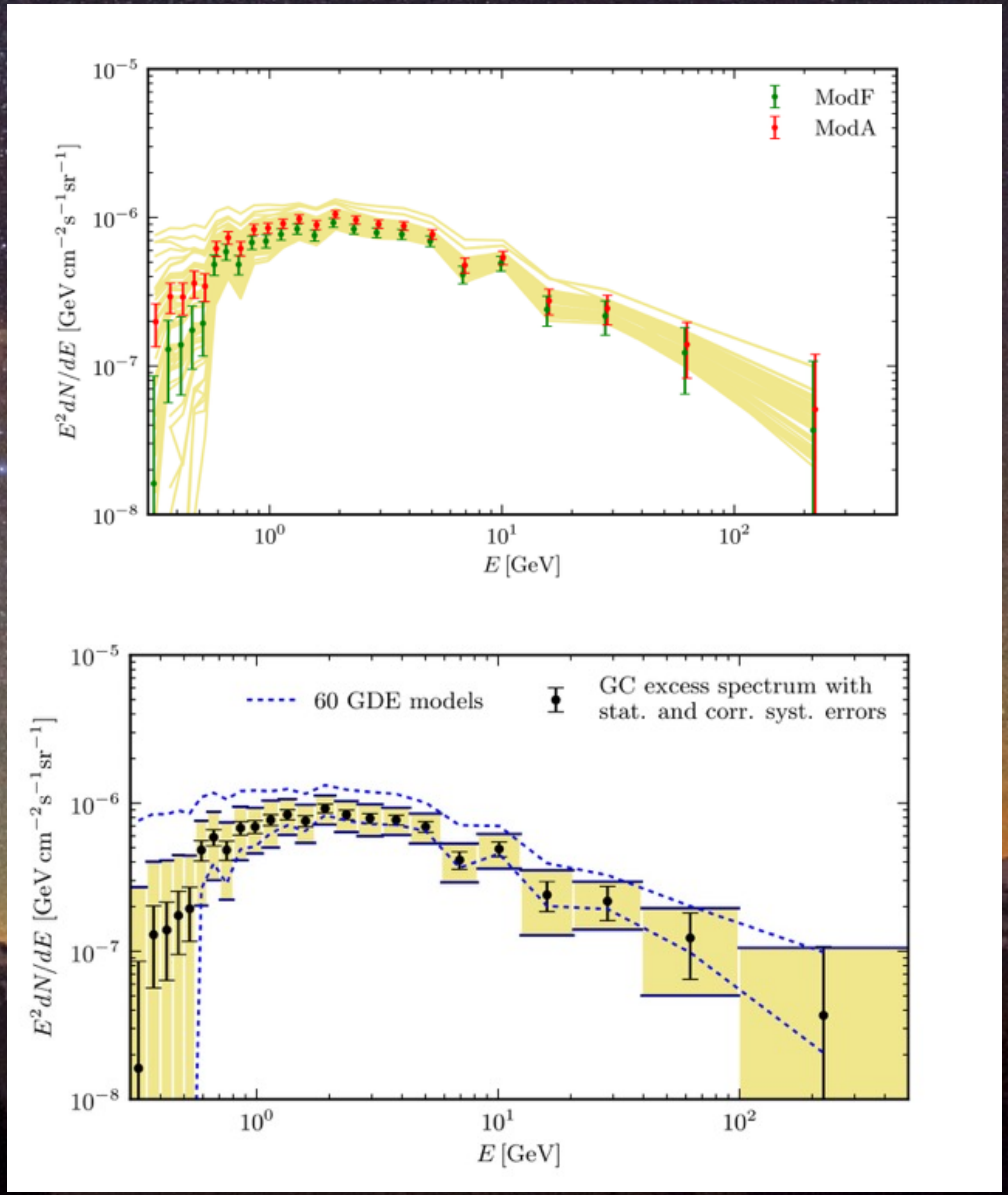

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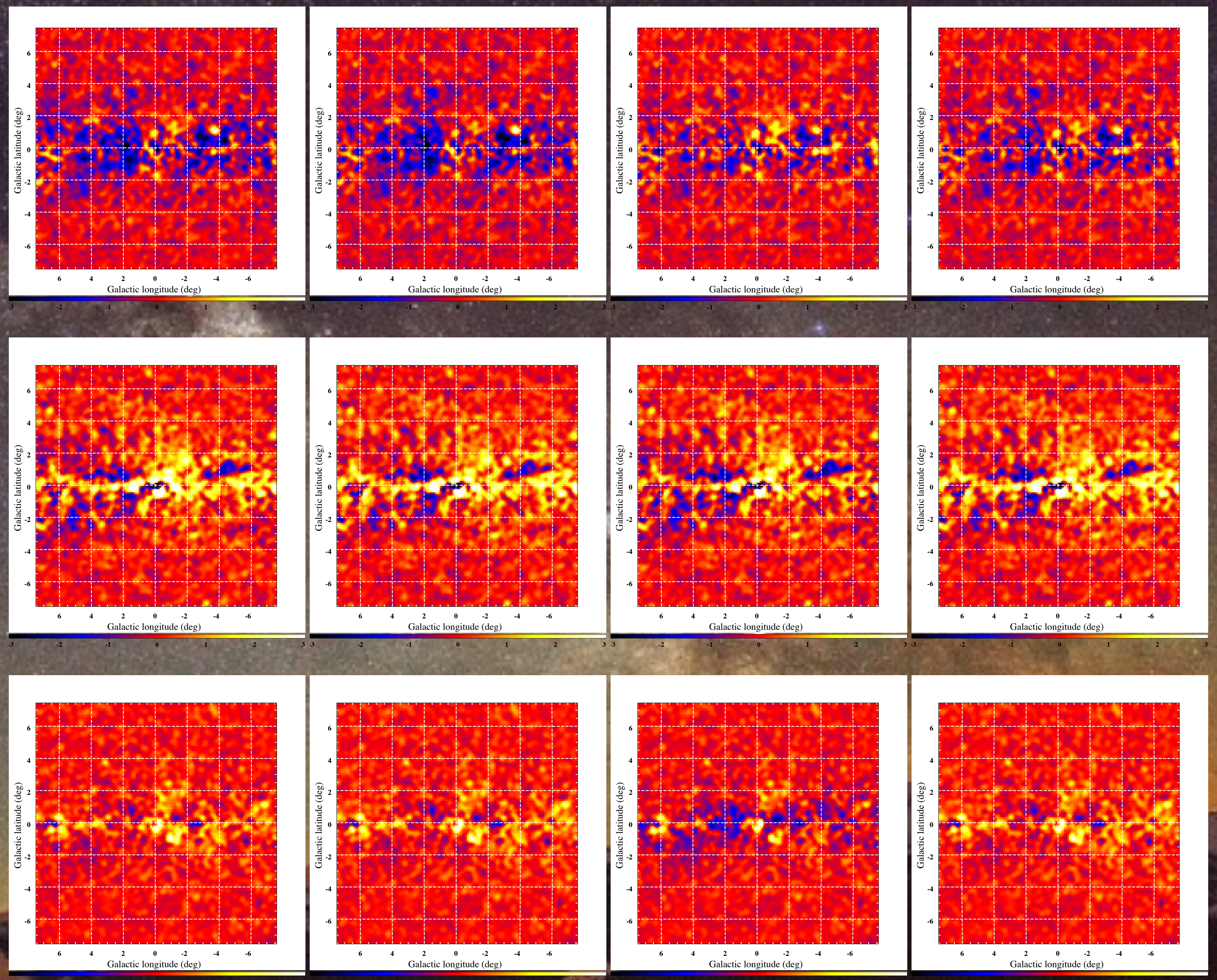

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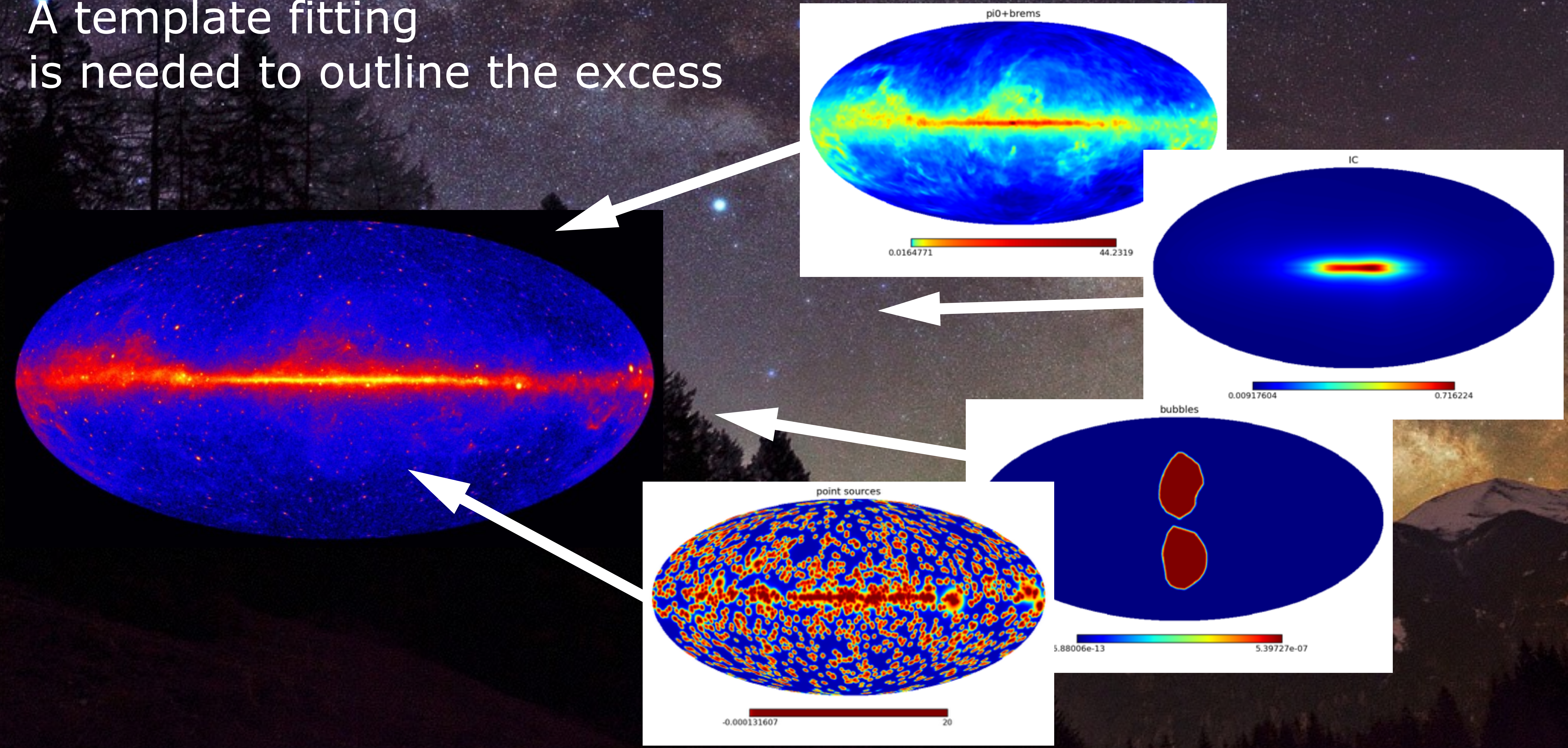
A template fitting
is needed to outline the excess



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A template fitting
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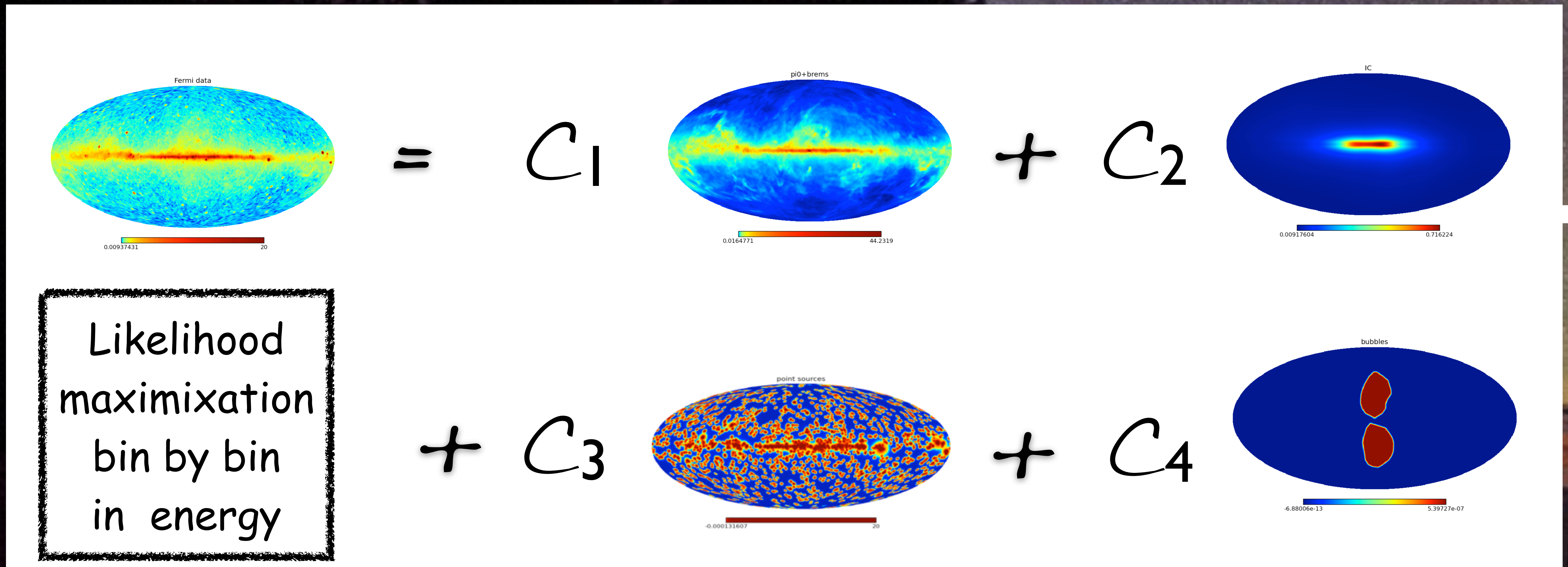
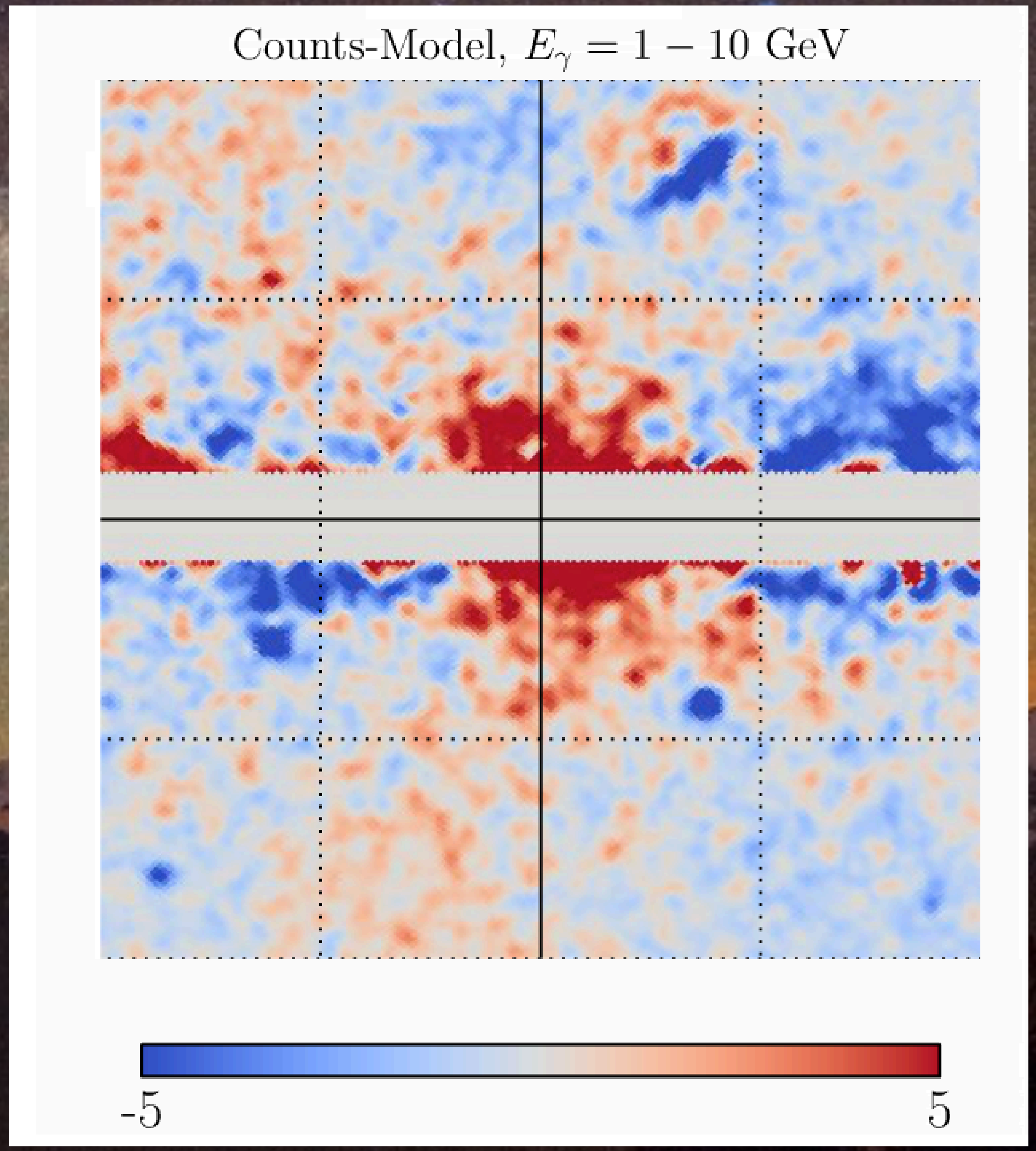
With no additional DM-like template:



you are clearly missing something
in the inner Galaxy!



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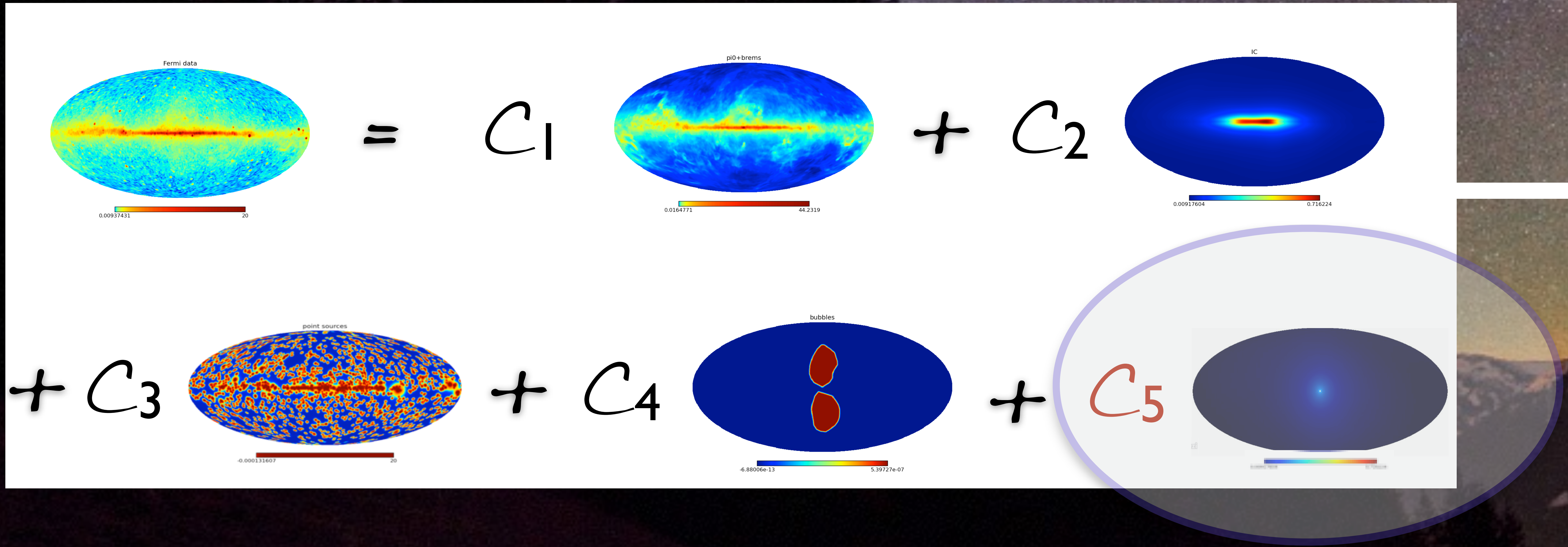
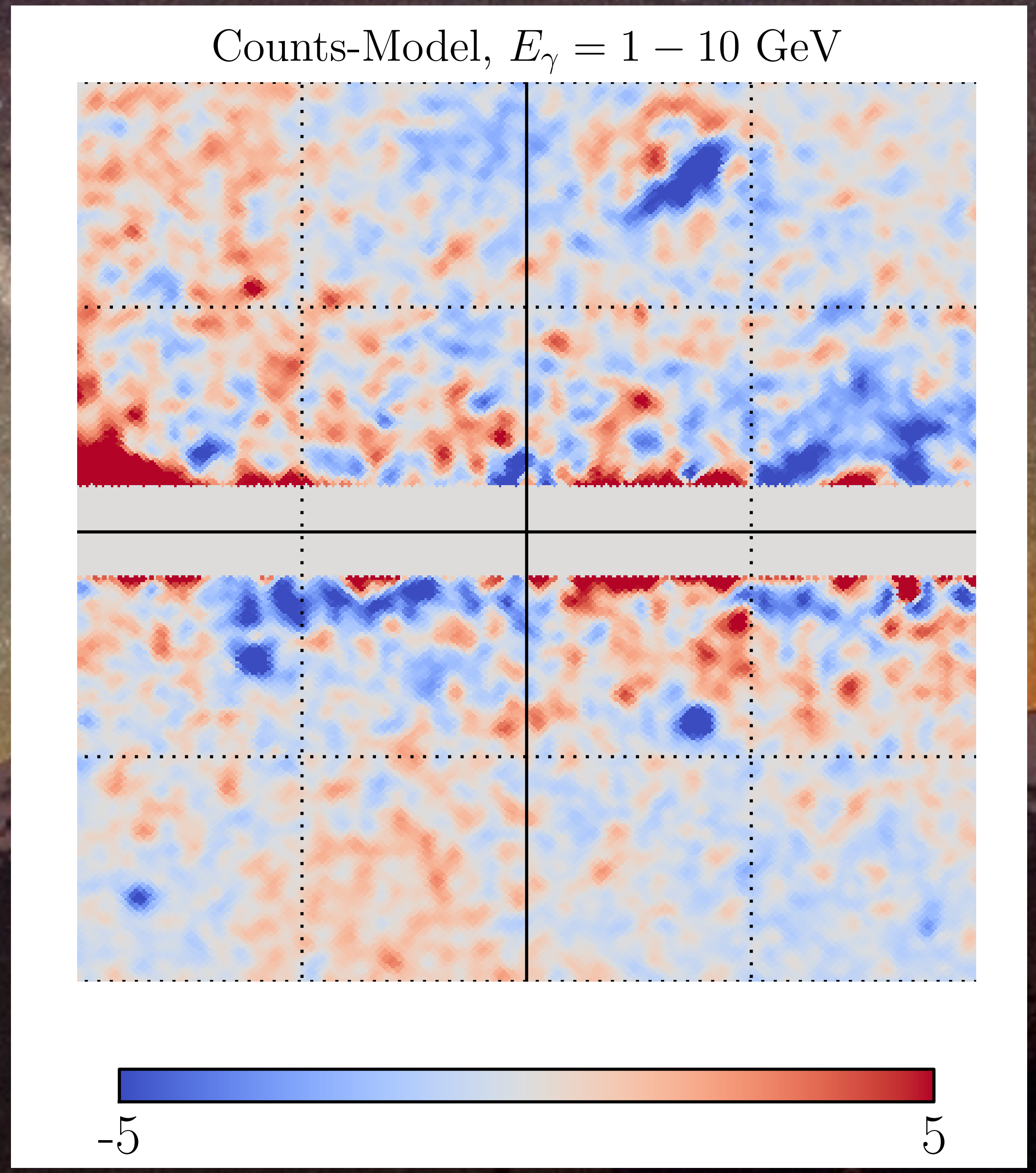
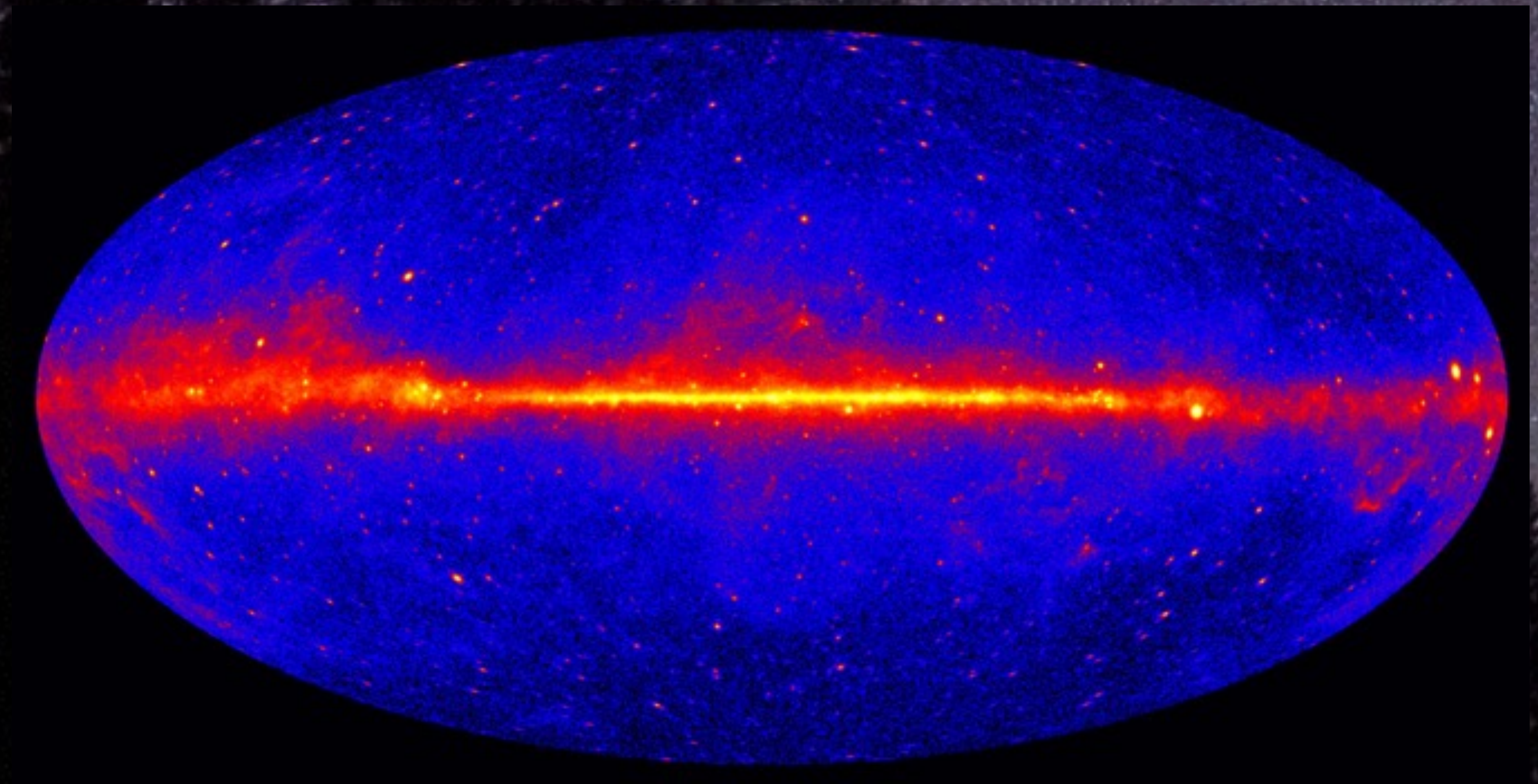
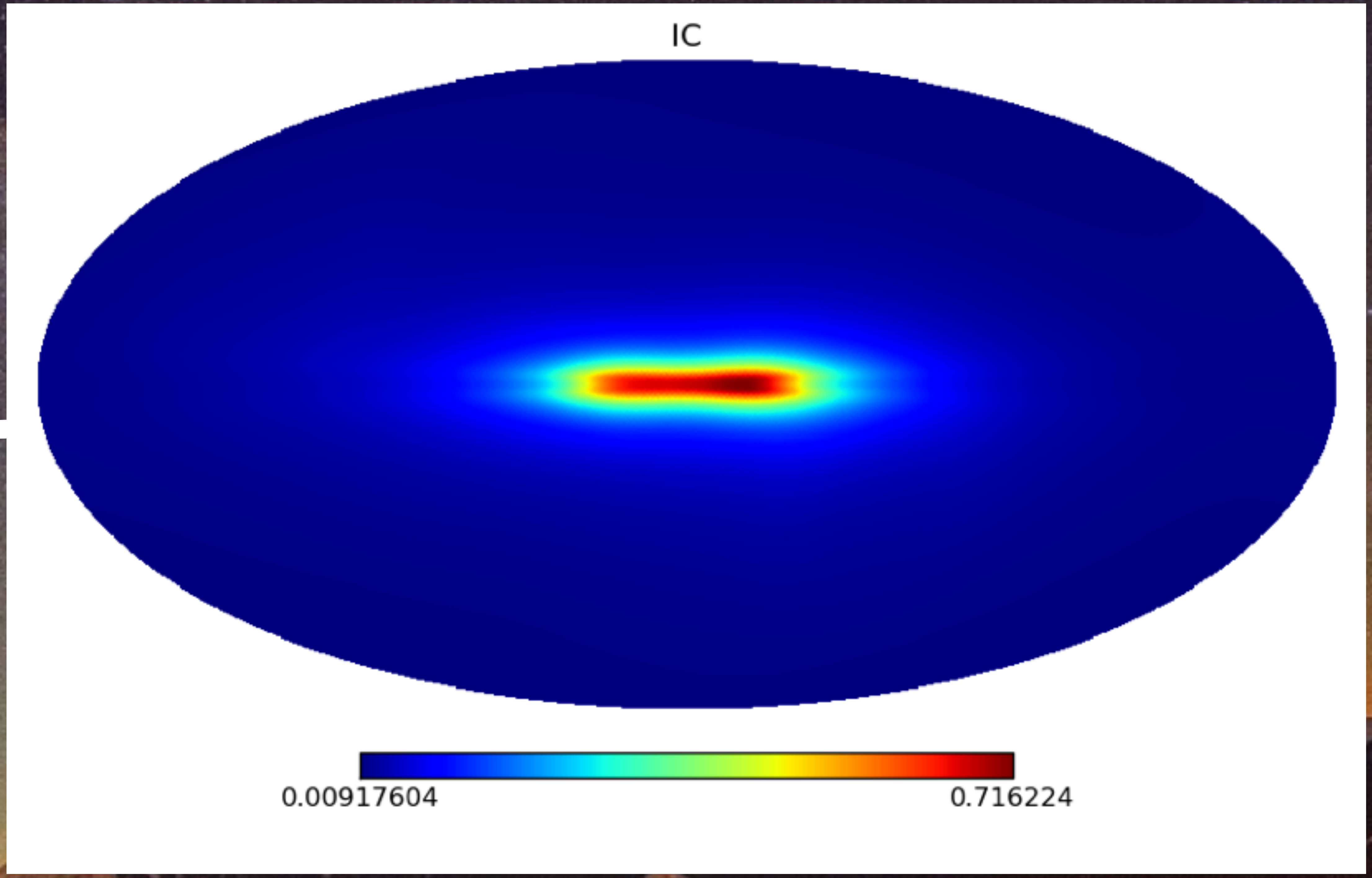


a featureless
residual!



Are we sure that we really have the IC template under control?





Are we sure that we really have the IC template under control?

The ingredients are:

— CR electron and positron distribution, obtained by solving the transport equation with a numerical code like DRAGON or GALPROP

$$\frac{\partial \mathcal{N}_i(\vec{x},p,t)}{\partial t} = \nabla \cdot (D_{\vec{x}\vec{x}} \nabla \mathcal{N}_i - \vec{v}_c \mathcal{N}_i) - \frac{\partial}{\partial p}\left(\dot{p}\mathcal{N}_i - \frac{p}{3}(\nabla \cdot \vec{v}_c)\mathcal{N}_i\right) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{\mathcal{N}_i}{p^2} + Q(\vec{x},p,t) - \frac{\mathcal{N}_i}{\tau_f} - \frac{\mathcal{N}_i}{\tau_r}$$

— ISRF distribution and spectrum

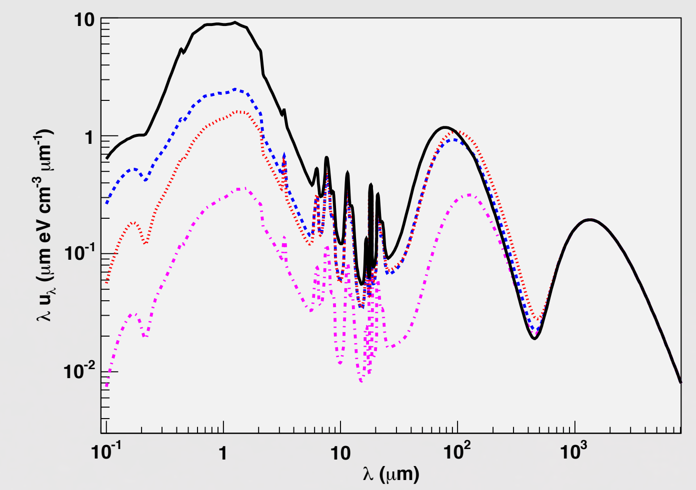
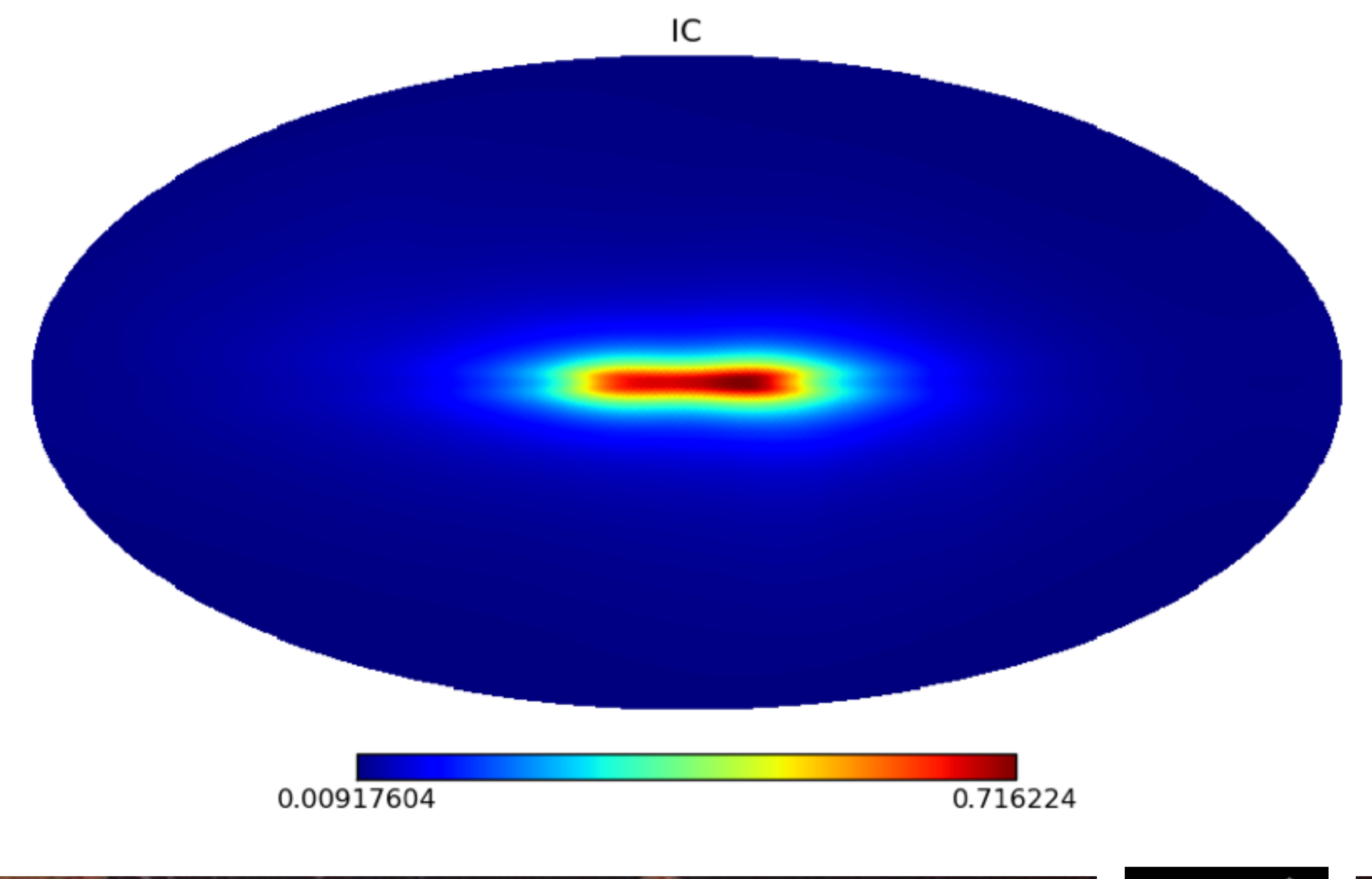


FIG. 1.— Interstellar radiation field energy density: solid line, $R = 0$ kpc, $z = 0$ kpc; dashed line, $R = 3$ kpc, $z = -0.05$ kpc; dotted line, $R = 4$ kpc, $z = 0$ kpc; dash-dotted line, $R = 7.5$ kpc, $z = 0$ kpc.



Are we sure that we really have the IC template under control?

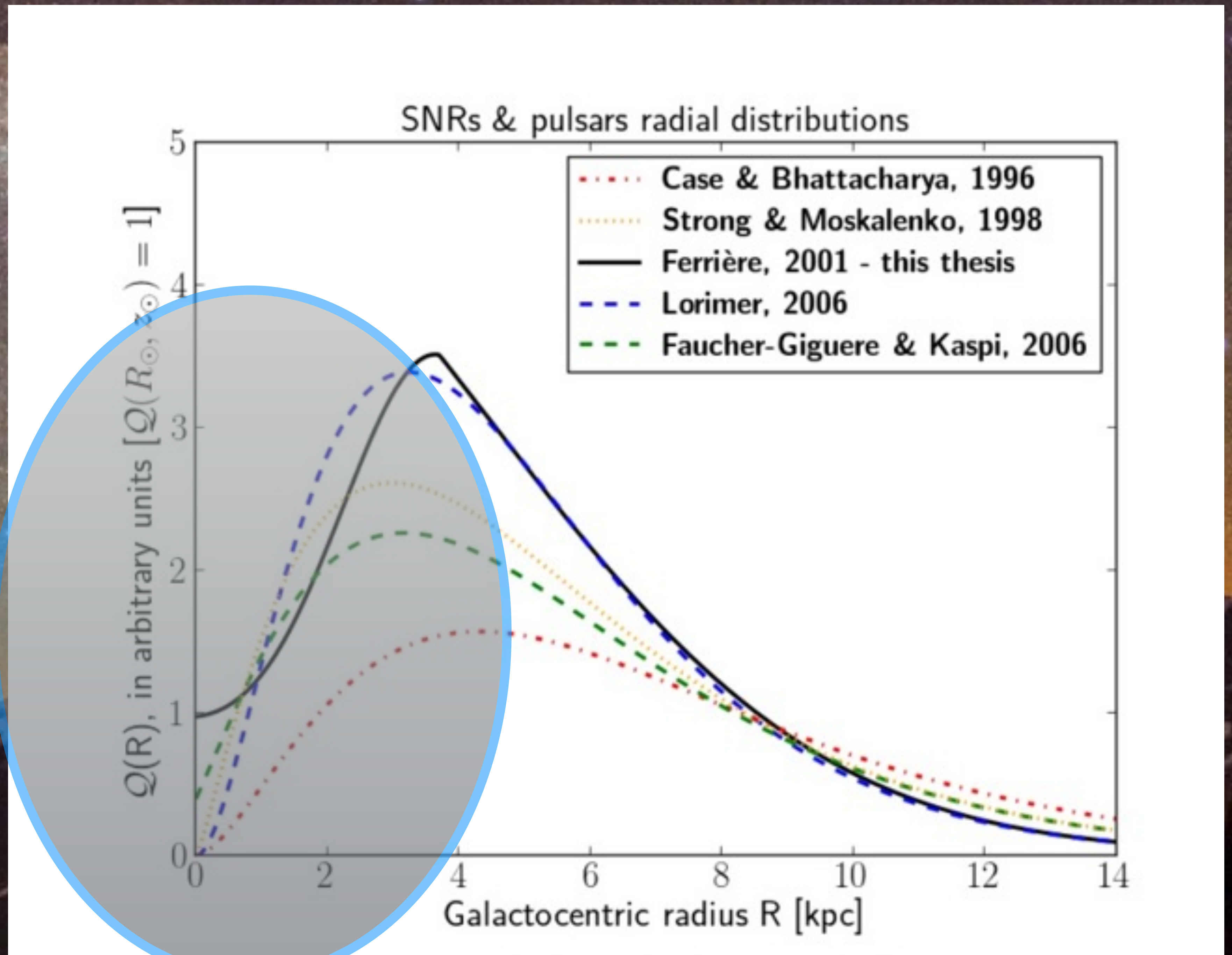
Many caveats on the CR distribution in the inner part of the Galaxy!

$$\frac{\partial \mathcal{N}_i(\vec{x},p,t)}{\partial t} = \nabla \cdot (D_{\vec{x}\vec{x}} \nabla \mathcal{N}_i - \vec{v}_c \mathcal{N}_i) - \frac{\partial}{\partial p}\left(\dot{p}\mathcal{N}_i - \frac{p}{3}(\nabla \cdot \vec{v}_c)\mathcal{N}_i\right) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{\mathcal{N}_i}{p^2} + Q(\vec{x},p,t) - \frac{\mathcal{N}_i}{\tau_f} - \frac{\mathcal{N}_i}{\tau_r}$$

1) Do we really know the CR source function over there?

2) Do we really understand diffusion of CR particles in the inner region?

it drops to 0!



(a) *Radial profile of the distribution functions of the CRs sources*

Are we sure that we really have the IC template under control?

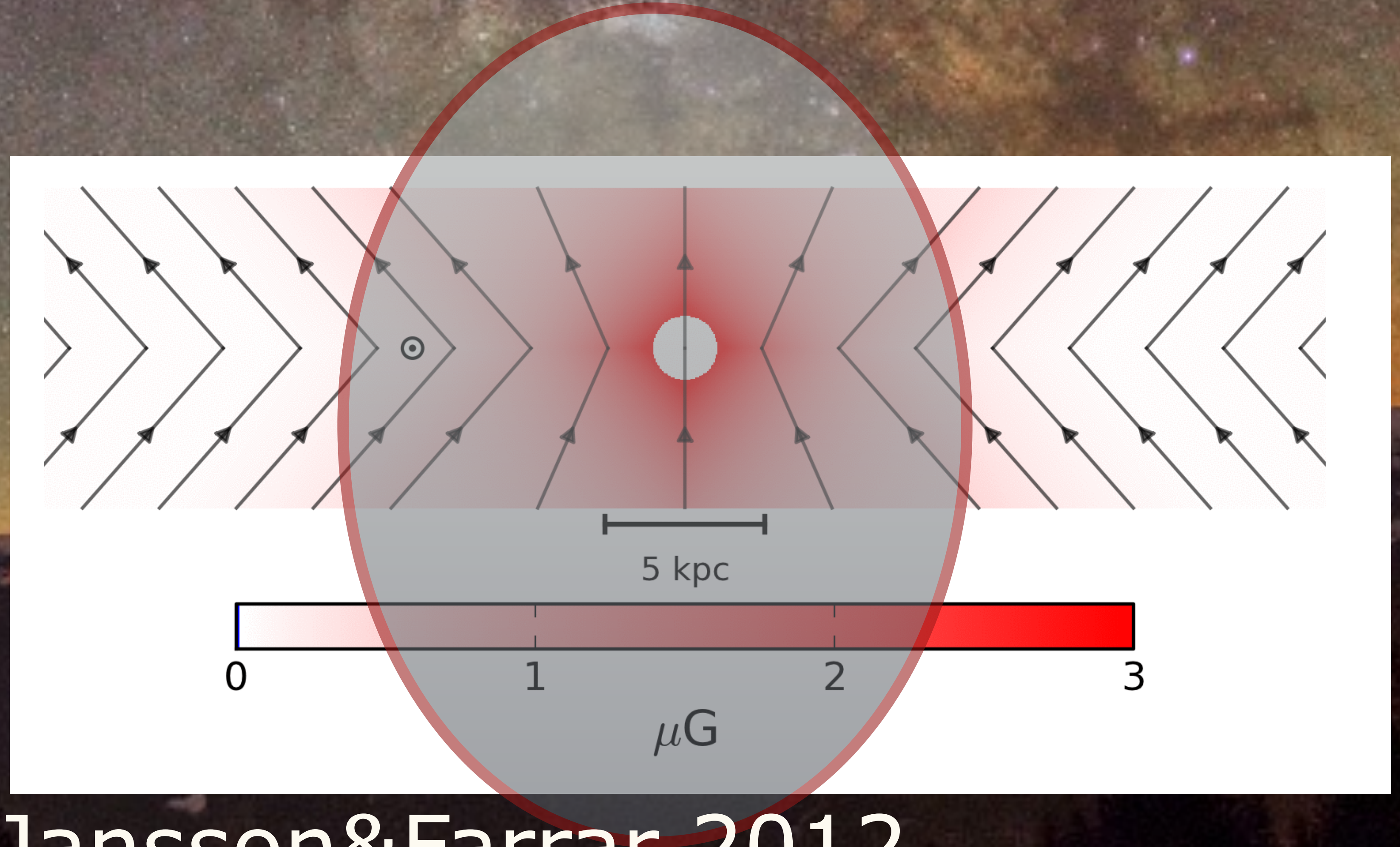
Many caveats on the CR distribution in the inner part of the Galaxy!

$$\frac{\partial \mathcal{N}_i(\vec{x},p,t)}{\partial t} = \nabla \cdot (D_{\vec{x}\vec{x}} \nabla \mathcal{N}_i - \vec{v}_c \mathcal{N}_i) - \frac{\partial}{\partial p}\left(\dot{p}\,\mathcal{N}_i - \frac{p}{3}(\nabla \cdot \vec{v}_c)\,\mathcal{N}_i\right) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\mathcal{N}_i}{p^2} + Q(\vec{x},p,t) - \frac{\mathcal{N}_i}{\tau_f} - \frac{\mathcal{N}_i}{\tau_r}$$

anisotropic diffusion along the X-shaped magnetic field lines?

1) Do we really know the CR source function over there?

2) Do we really understand diffusion of CR particles in the inner region?



Jansson&Farrar 2012

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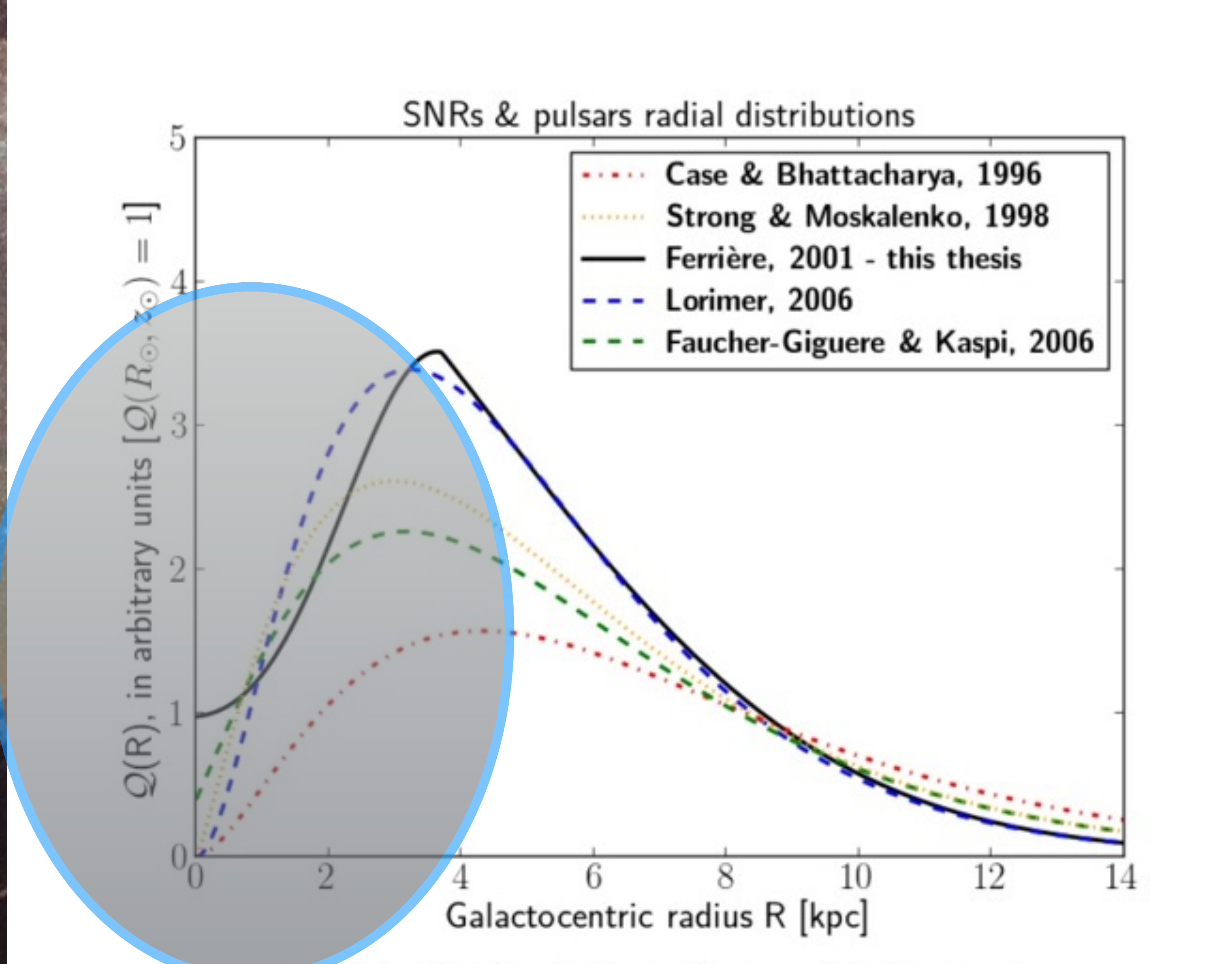
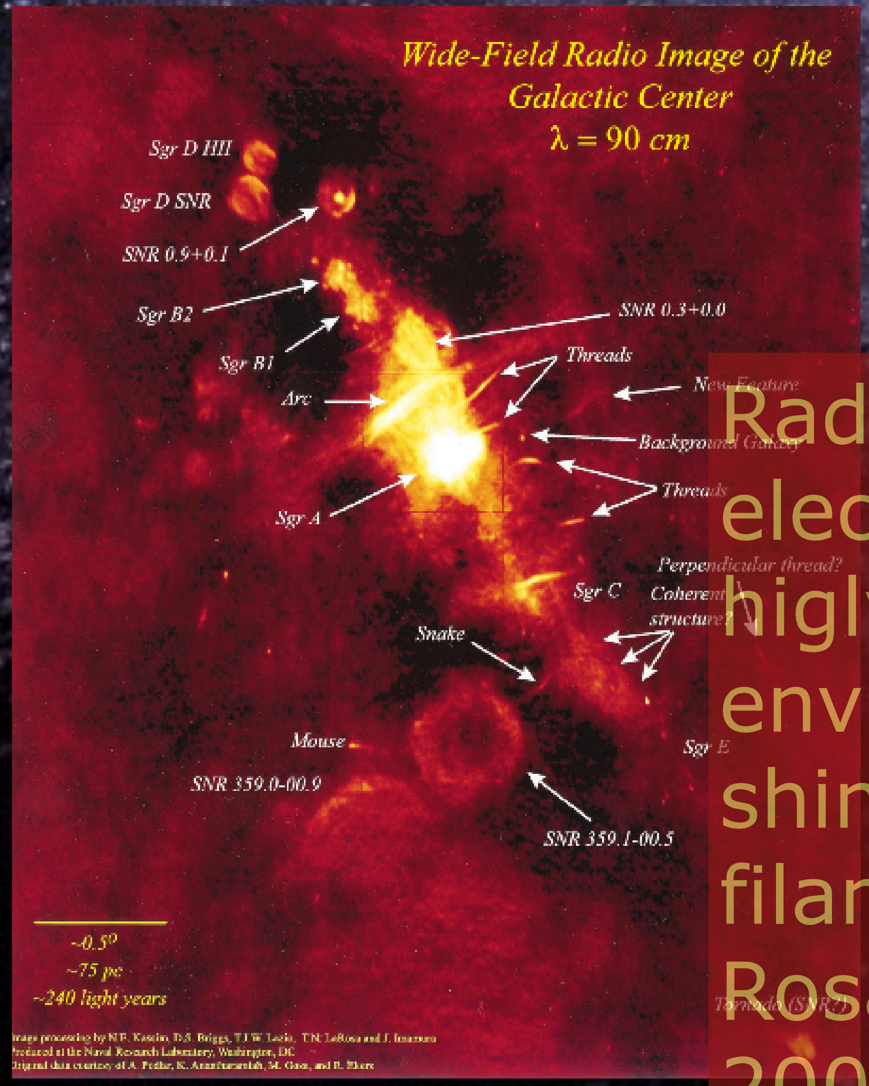
1) Do we really know the CR source function over there?

We are now going to address this issue…



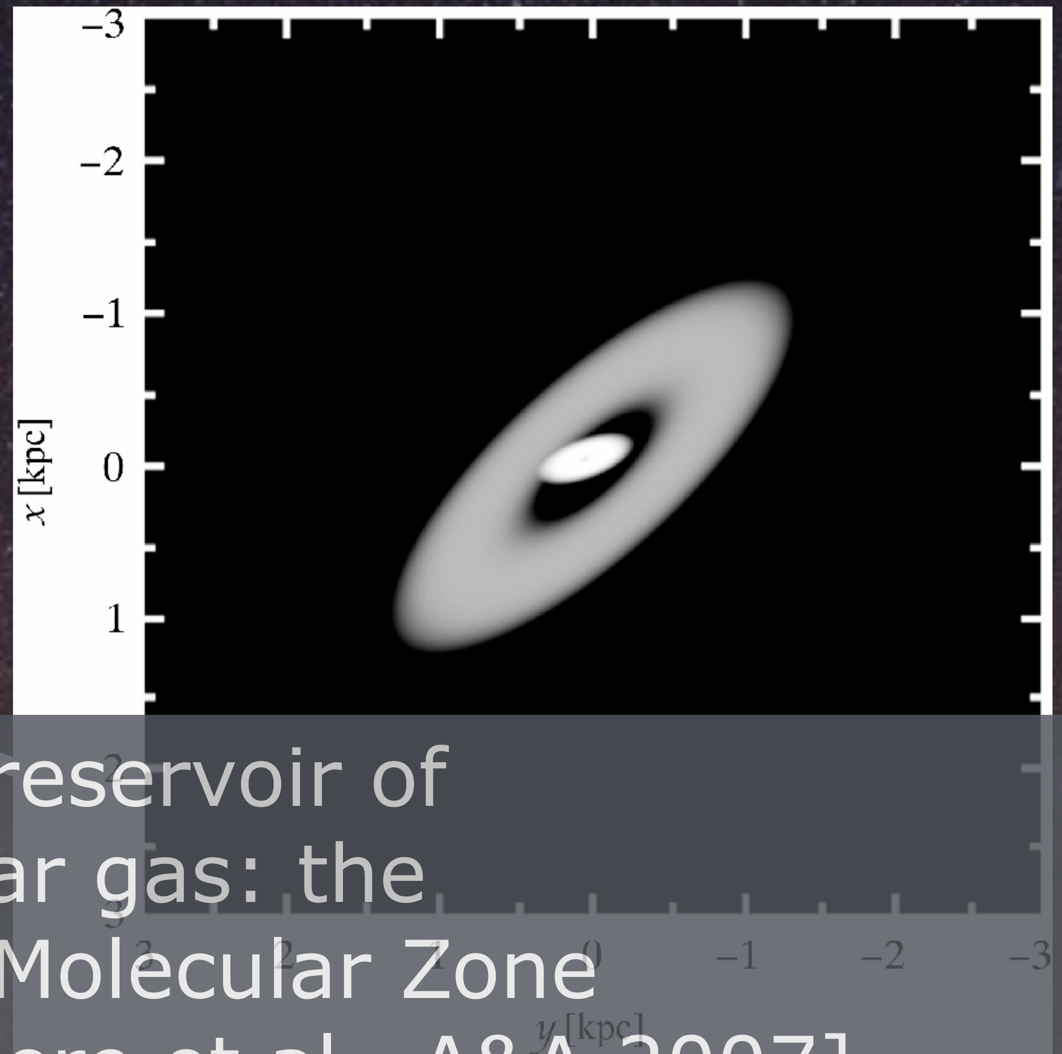
(a) Radial profile of the distribution functions of the CRs sources

Some considerations about the inner Galactic environment

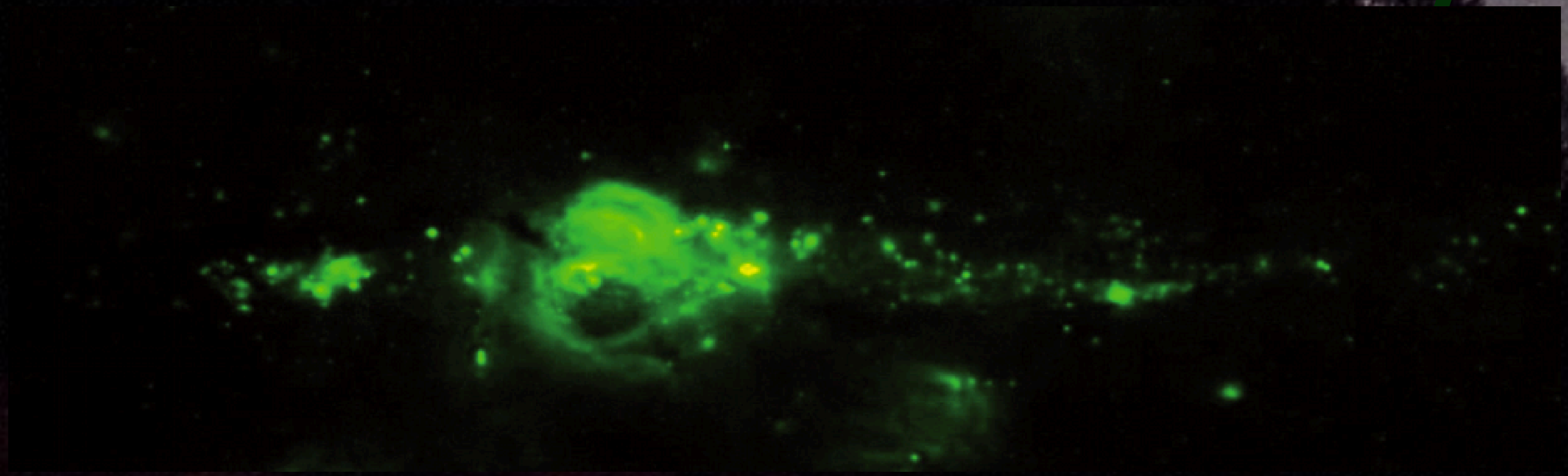


Radio (90 cm): electrons spiraling in a higly magnetized environment are shining. Nonthermal filaments, SNRs... [La Rosa et al. ApJ 119 2000]

A very efficient star formation is going on!
According to [Figer et al. 2004 ApJ 581 2002] 1% of the total SFR takes place in the inner 2-300 pc
(2 order of magnitude more than the average)
see also [Longmore et al. 1208.4256]



A large reservoir of molecular gas: the Central Molecular Zone [K. Ferriere et al., A&A 2007]



Infrared: dust is shining

X rays: hot gas heated by SNR shocks is shining

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in the inner 2-300 pc
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OUR IDEA:

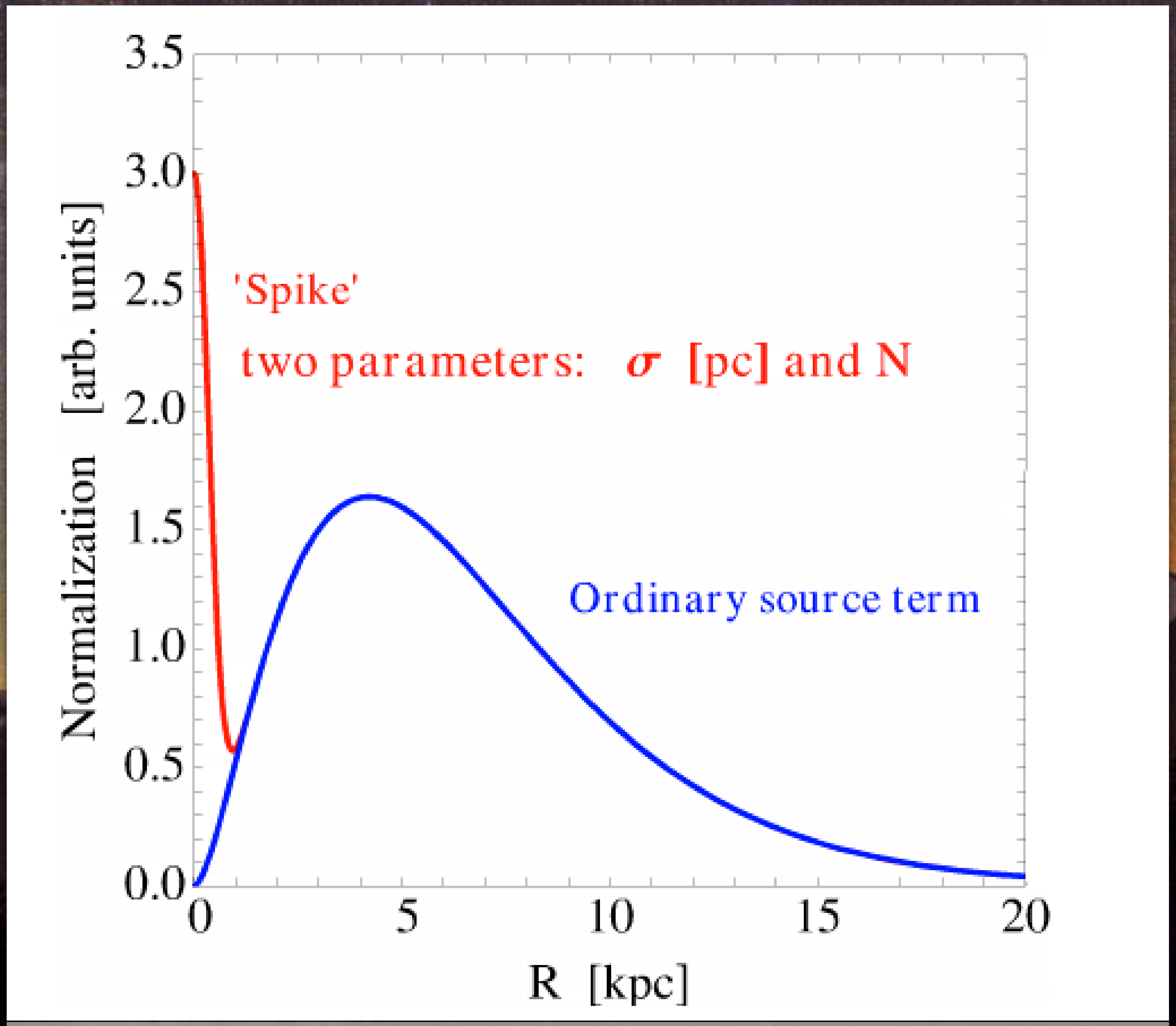
According to these considerations, a modification of the CR source term appears natural!

—> We modify the usual term adding a “spike” in the center, compatible with the observation above

$$Q(x,y,z) = \mathcal{N} \exp\left(-\frac{x^2+y^2+z^2}{\sigma^2}\right)$$

normalization compatibly with star formation rate estimate @ the GC

spike extension roughly matching CMZ one, i.e. O(100) pc

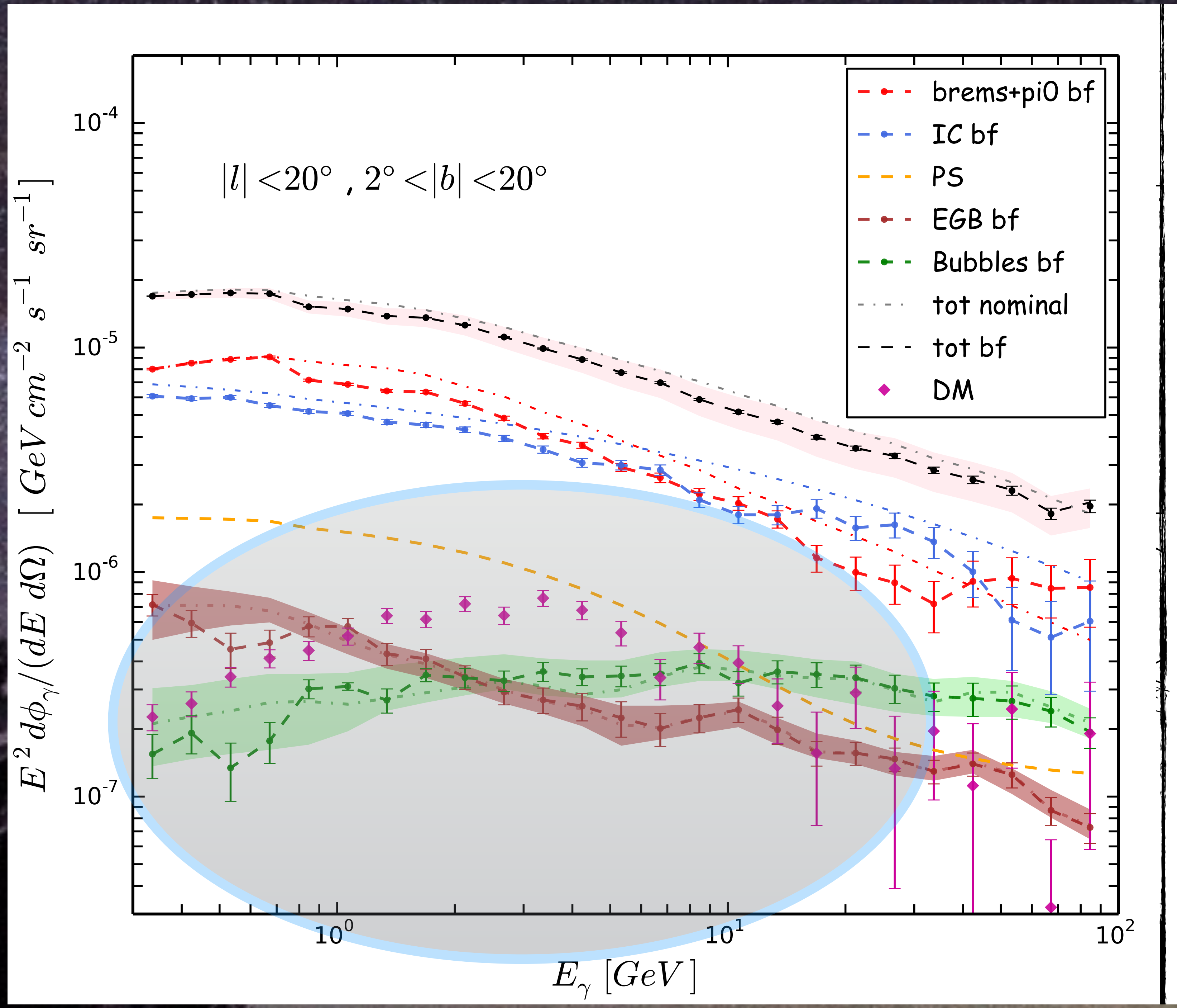


SPIKE vs DM

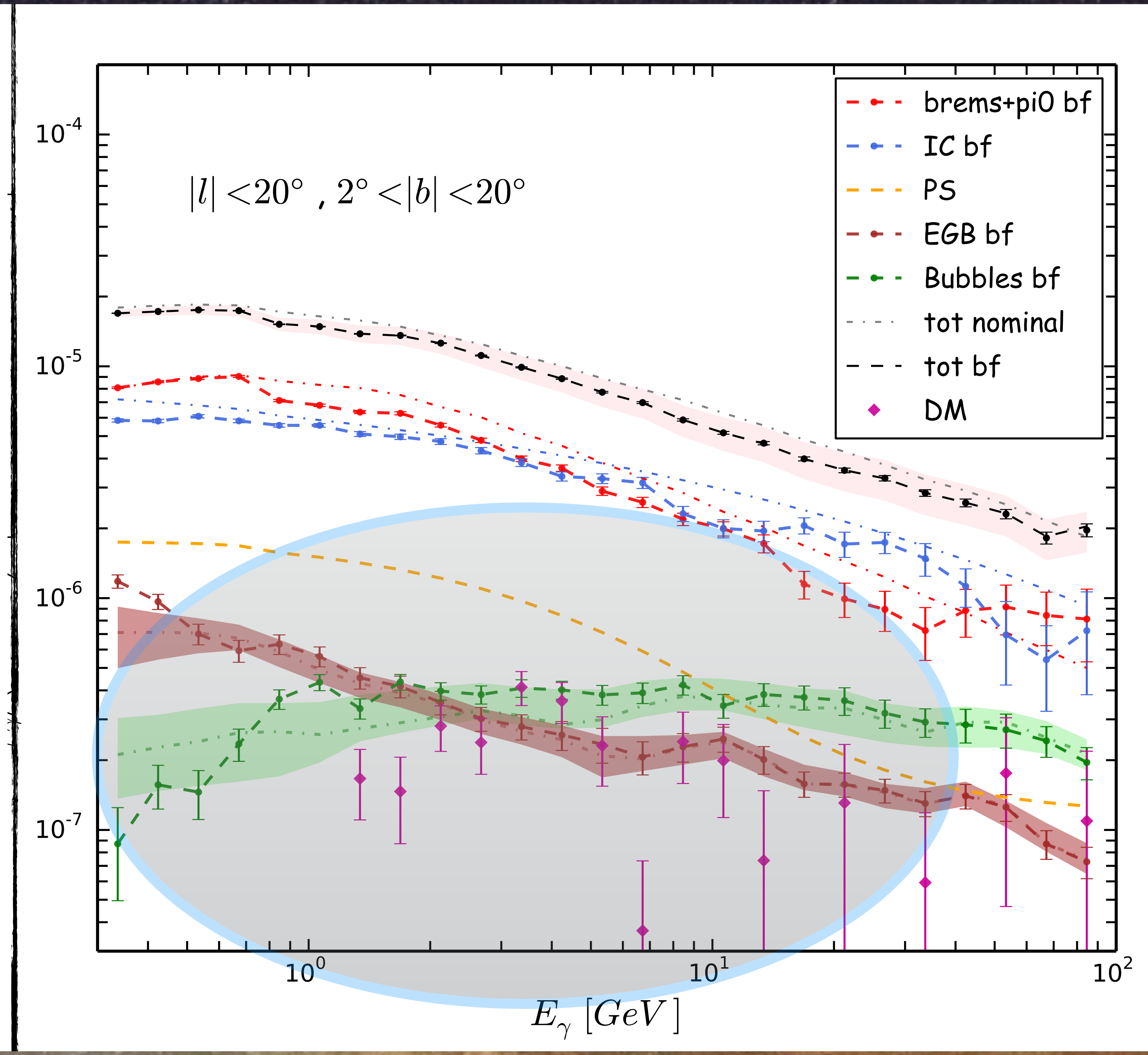
First important result

If the "spike" is added, the spectrum associated to the gNFW template is not meaningful anymore

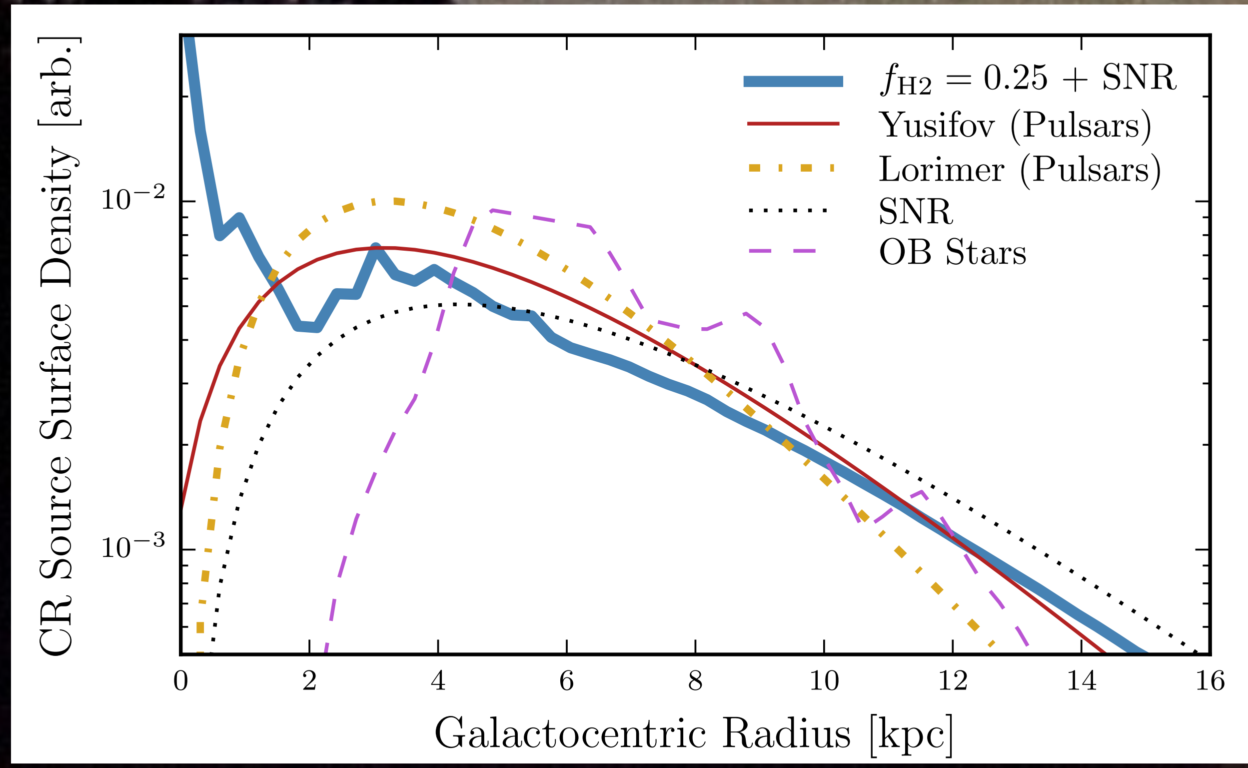
No spike

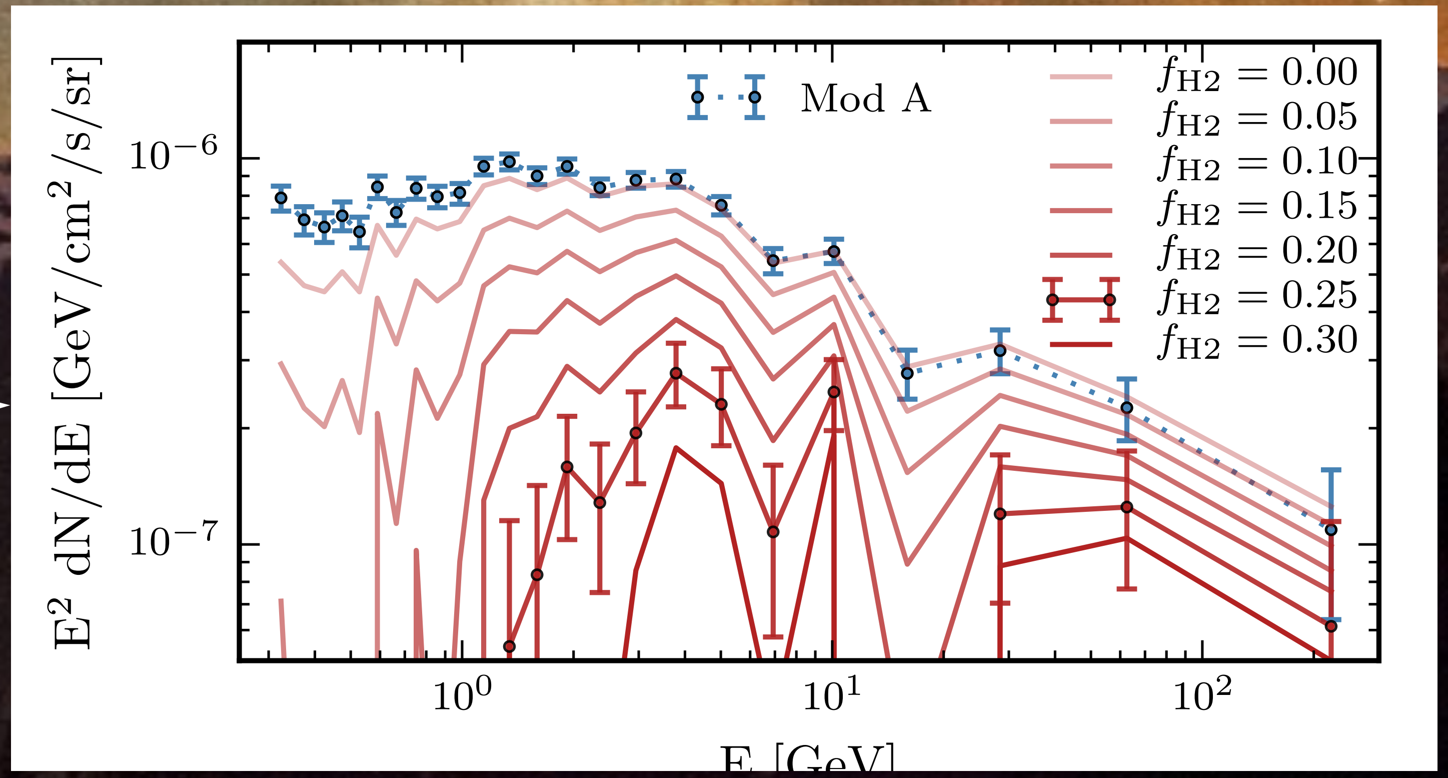


Spike



See also the recent [Carlson et al. 1510.04698] for a more detailed model, with the source term correlated with a 3D gas model

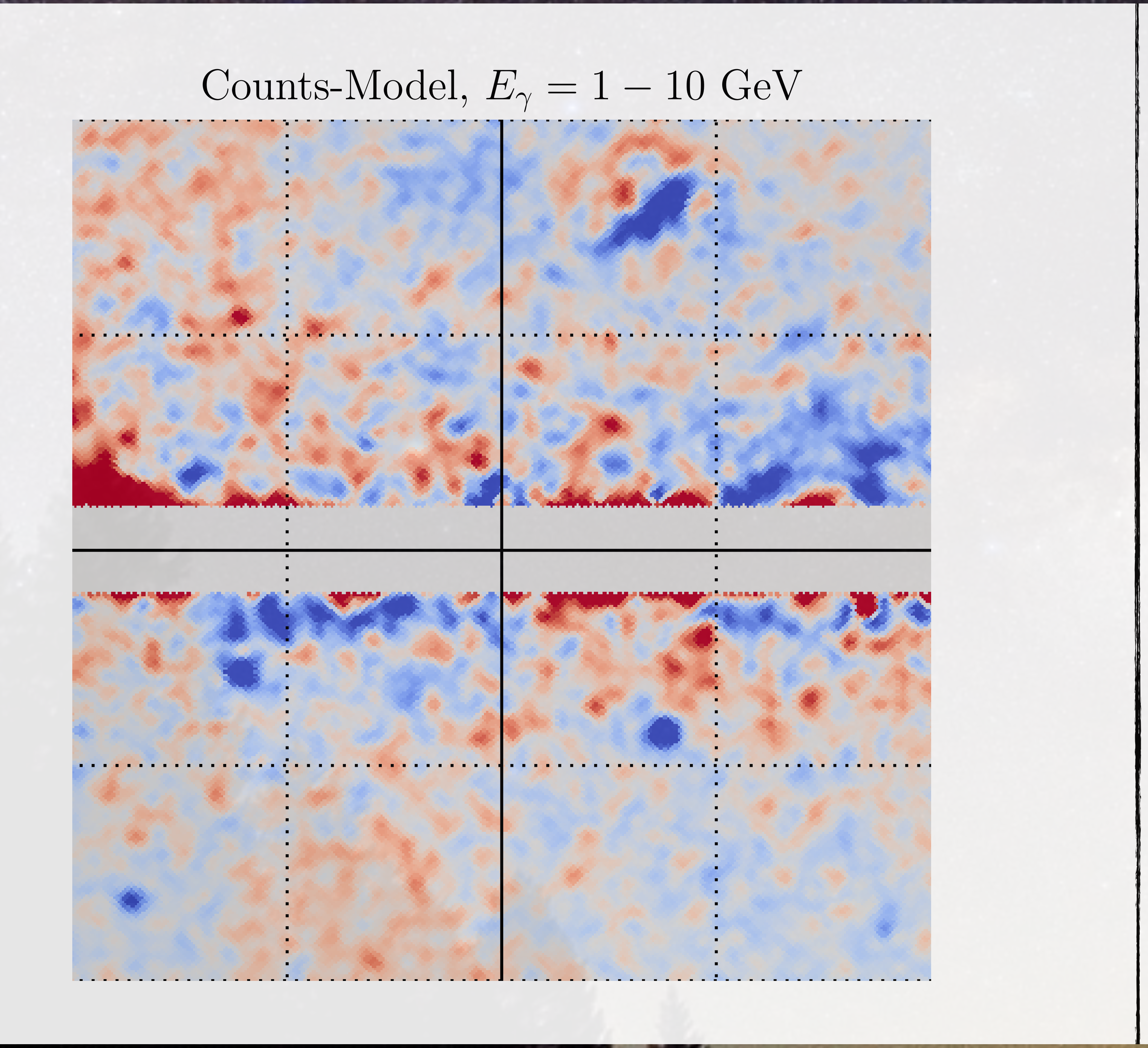




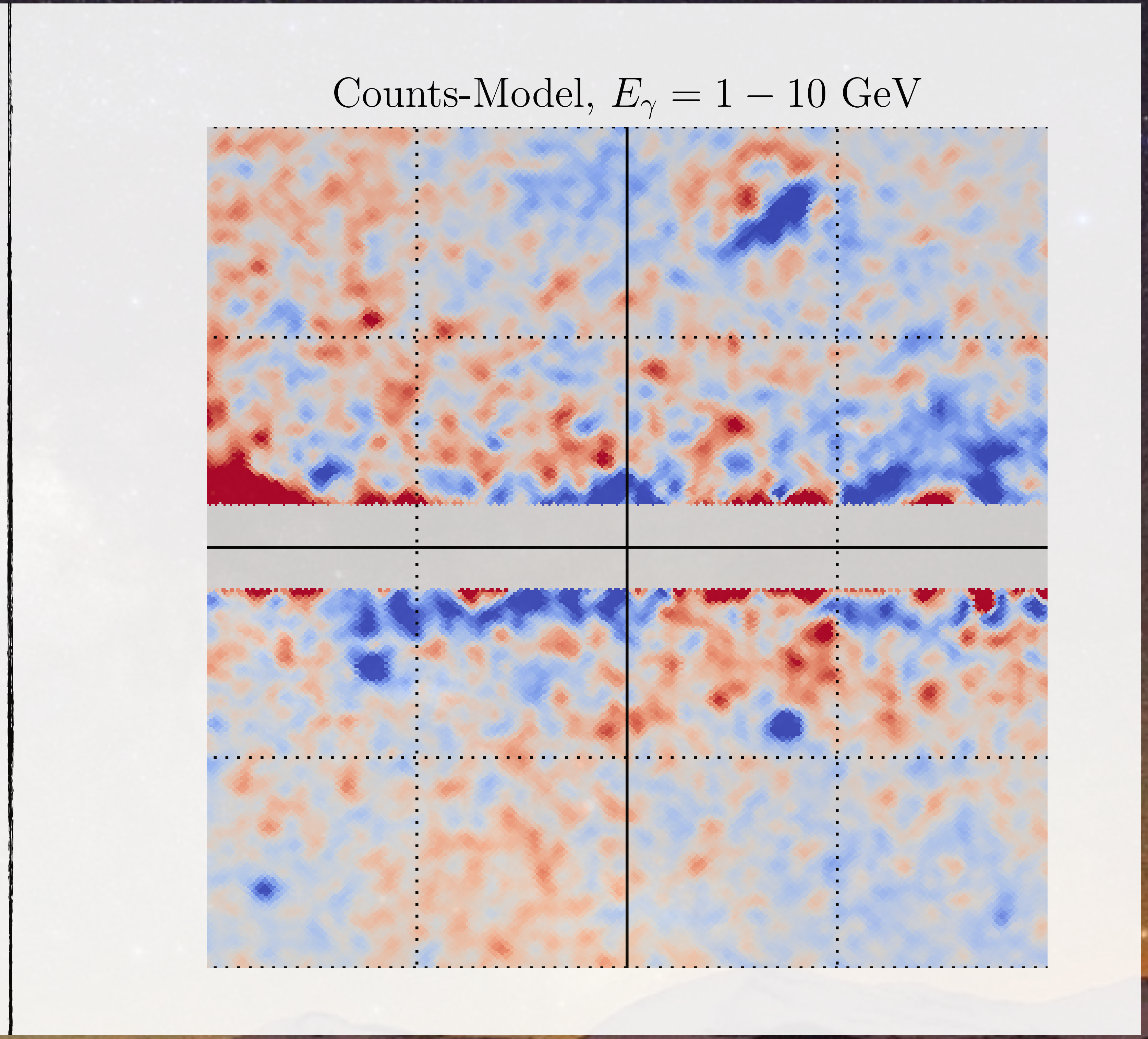
SPIKE vs DM

The residuals

ModelA+DM



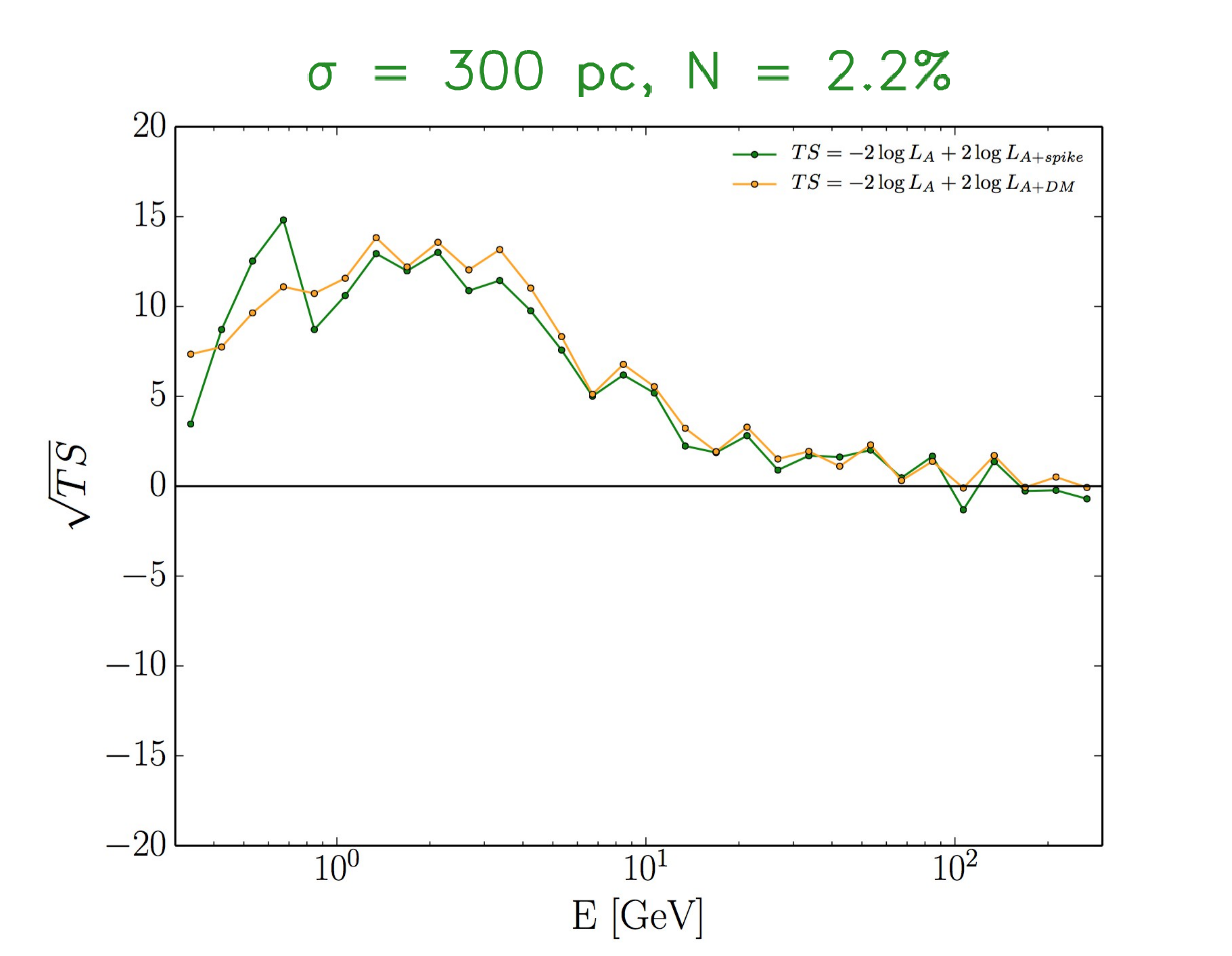
ModelA+spike



SPIKE vs DM

ModelA+DM

ModelA+spike



The likelihood

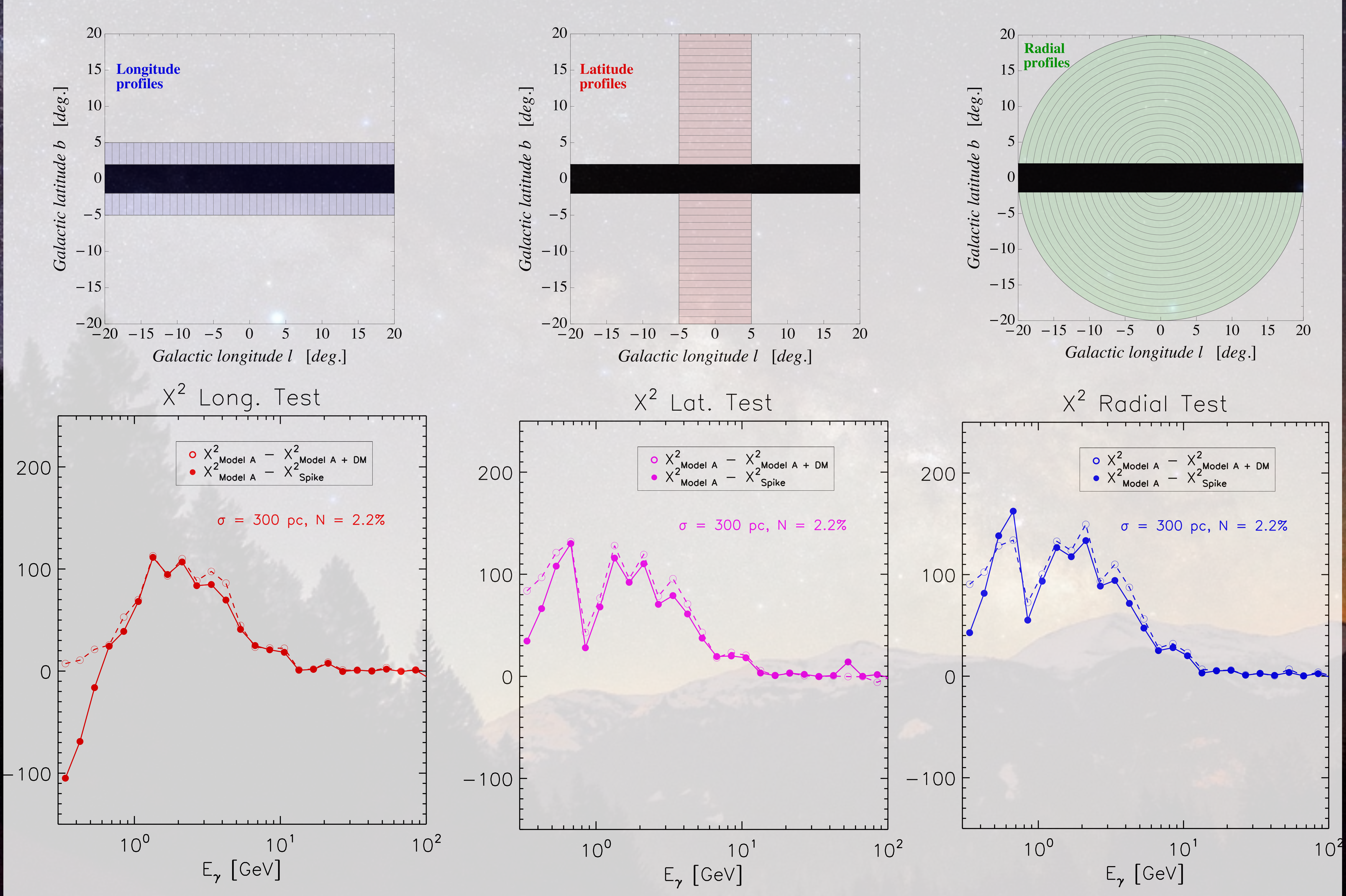
$$-2\ln(\mathcal{L}) = 2\sum_i (e_i - o_i \ln(e_i)) + 2\sum_i \ln(o_i!) + \chi^2_{ext}$$

Expected model counts (e_i) Fermi-LAT counts (o_i)

$$TS = -2\log\frac{\mathcal{L}_{reference\ model}}{\mathcal{L}_{alternative\ model}}$$

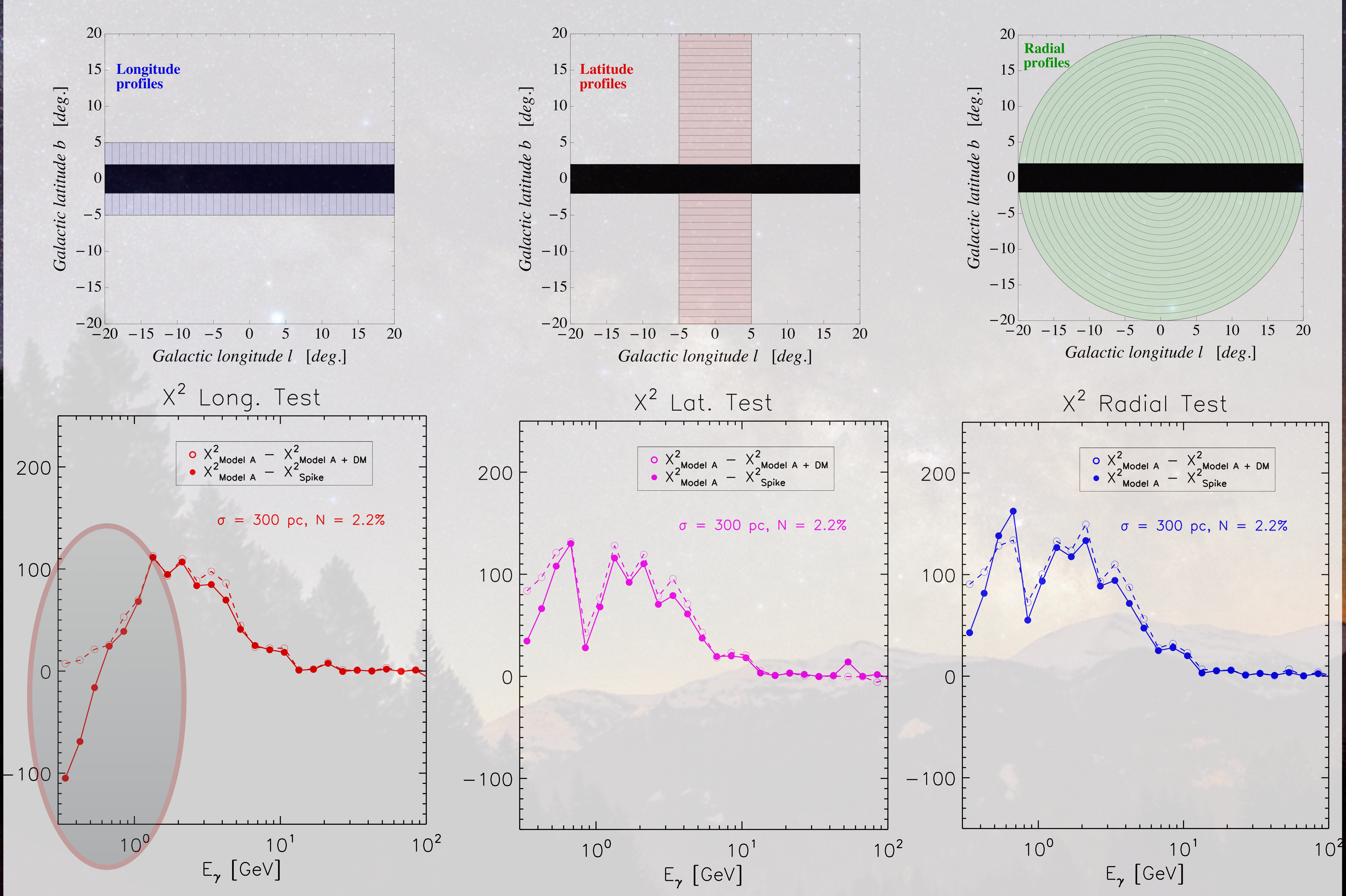
SPIKE vs DM

The profiles



A low-energy problem

The profiles



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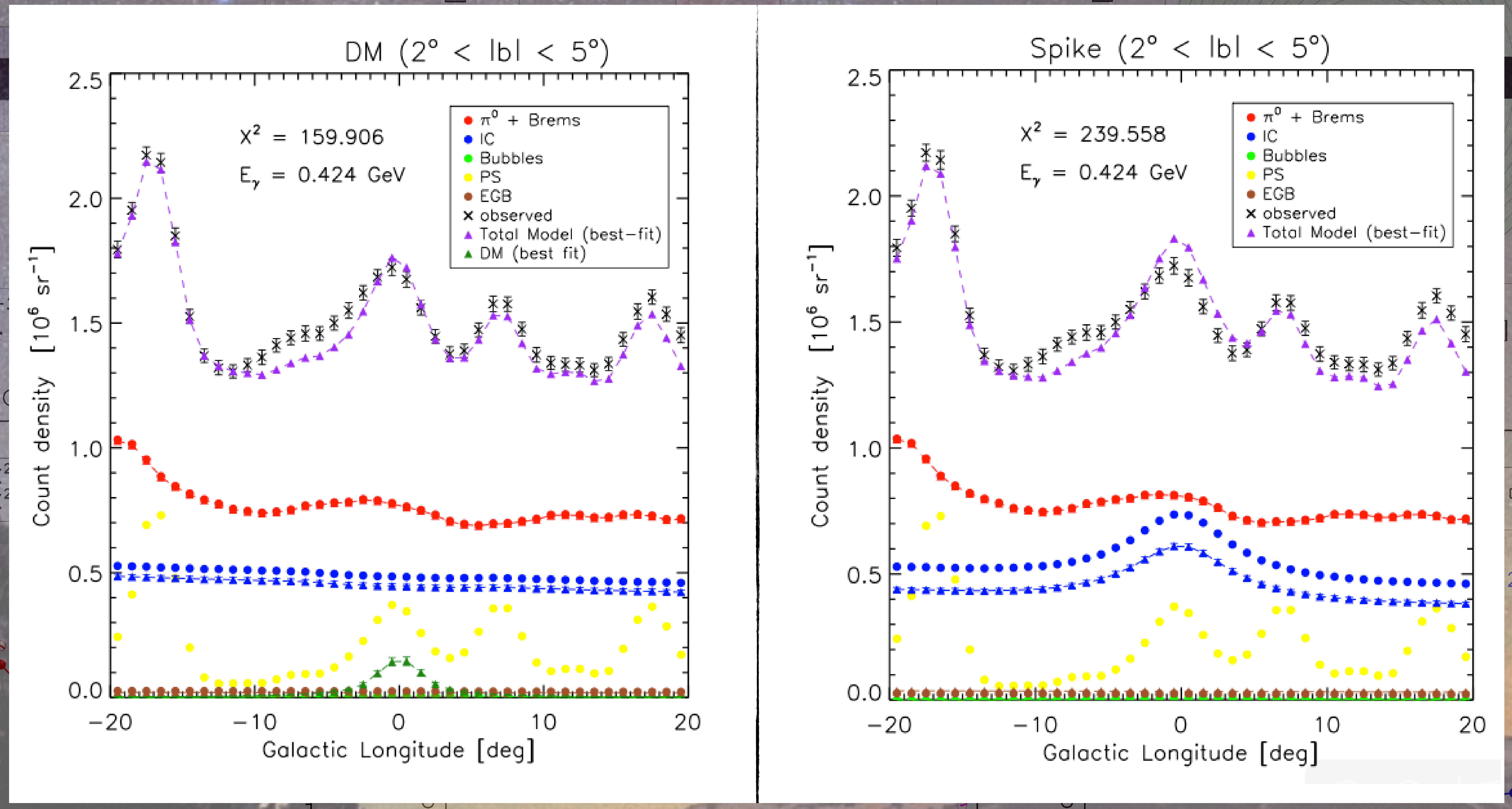
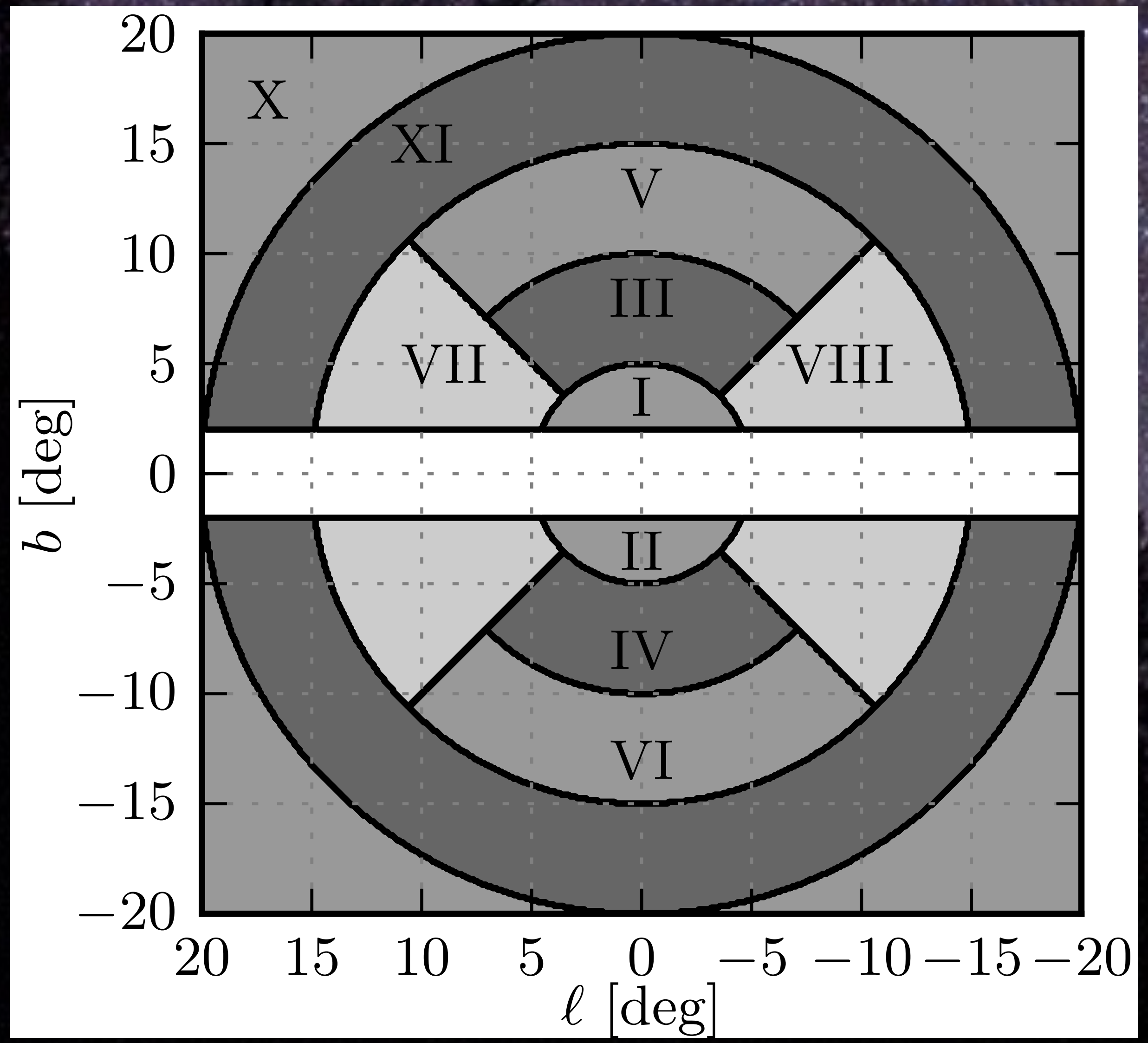


The profiles

The spike slightly overshoots the data below 1 GeV

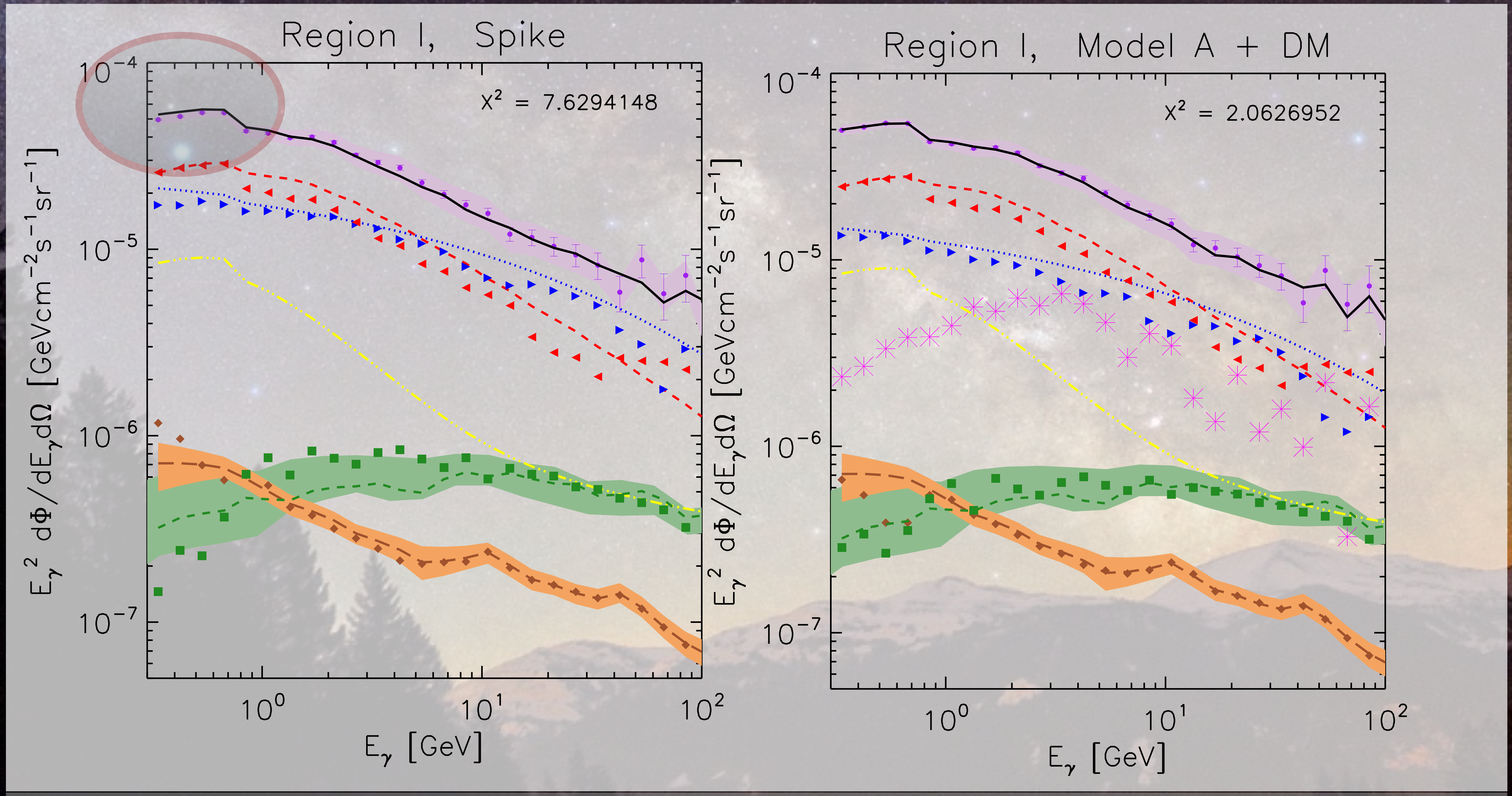
careful: low-energy physics is not totally under control.
Role of convective winds, role of anisotropic diffusion…

Checking the spectrum at different distances from the GC



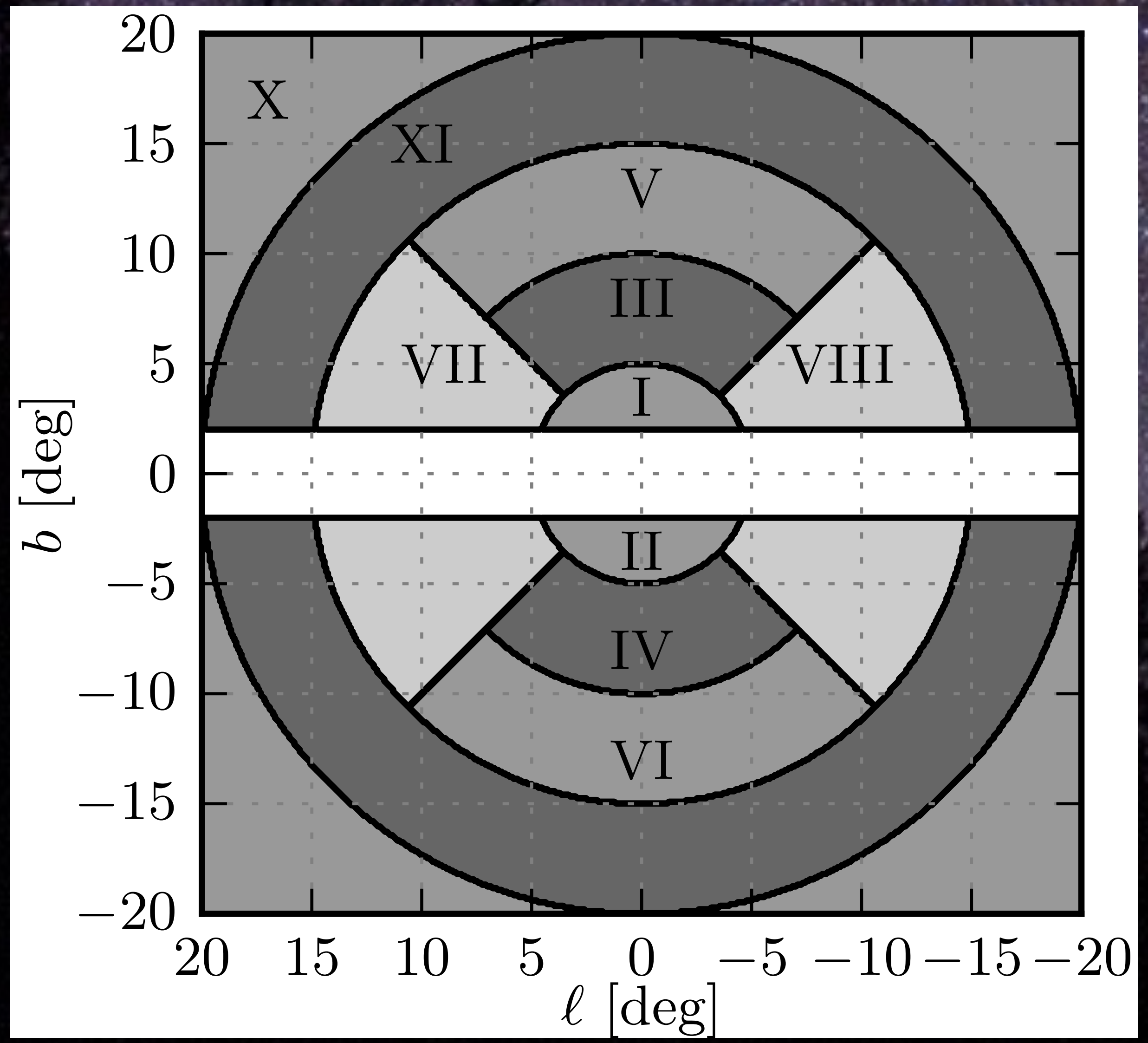
ModelA+spike

ModelA+DM



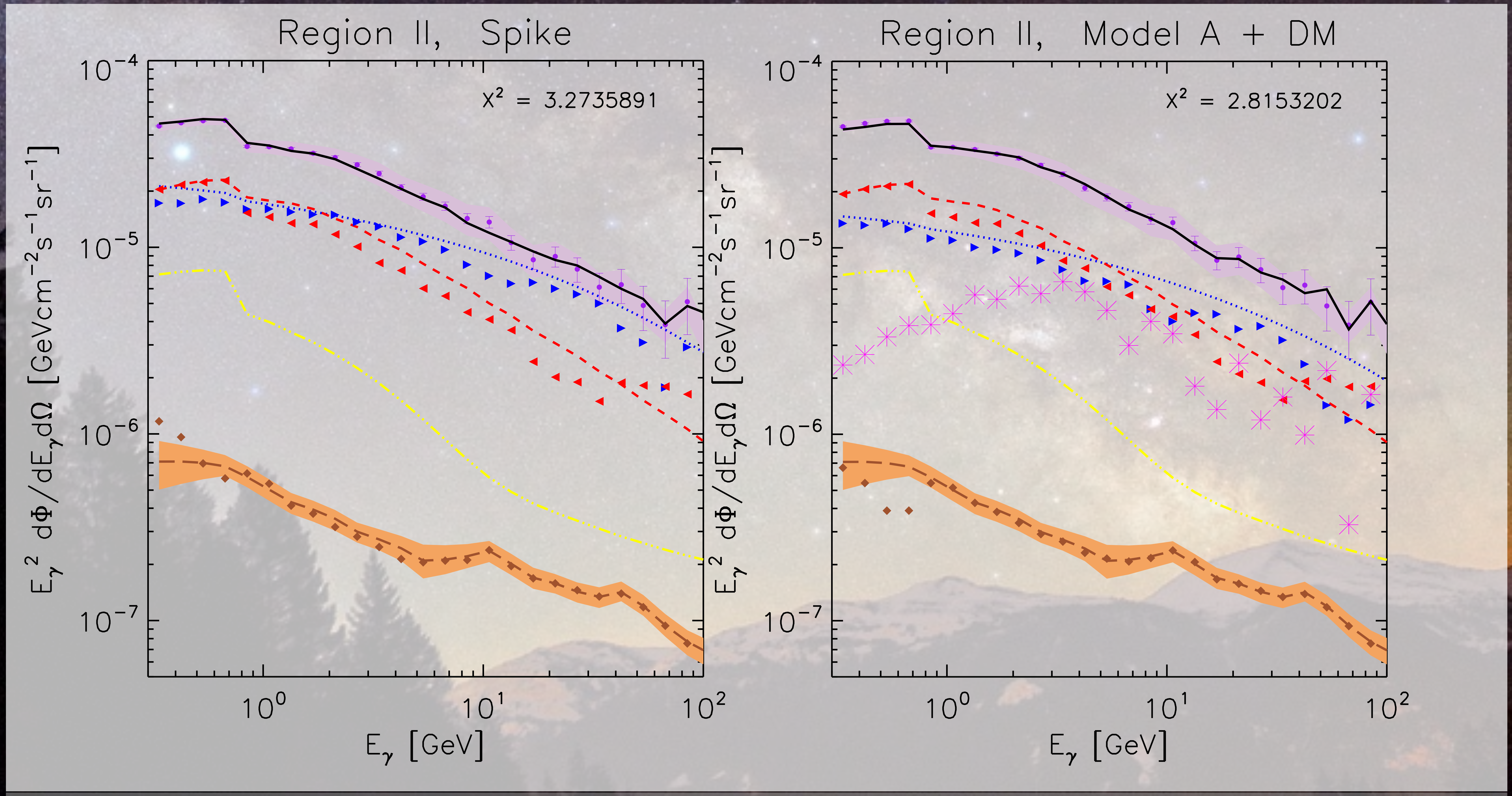
The slight low-energy problem pops up again

Checking the spectrum at different distances from the GC



ModelA+spike

ModelA+DM



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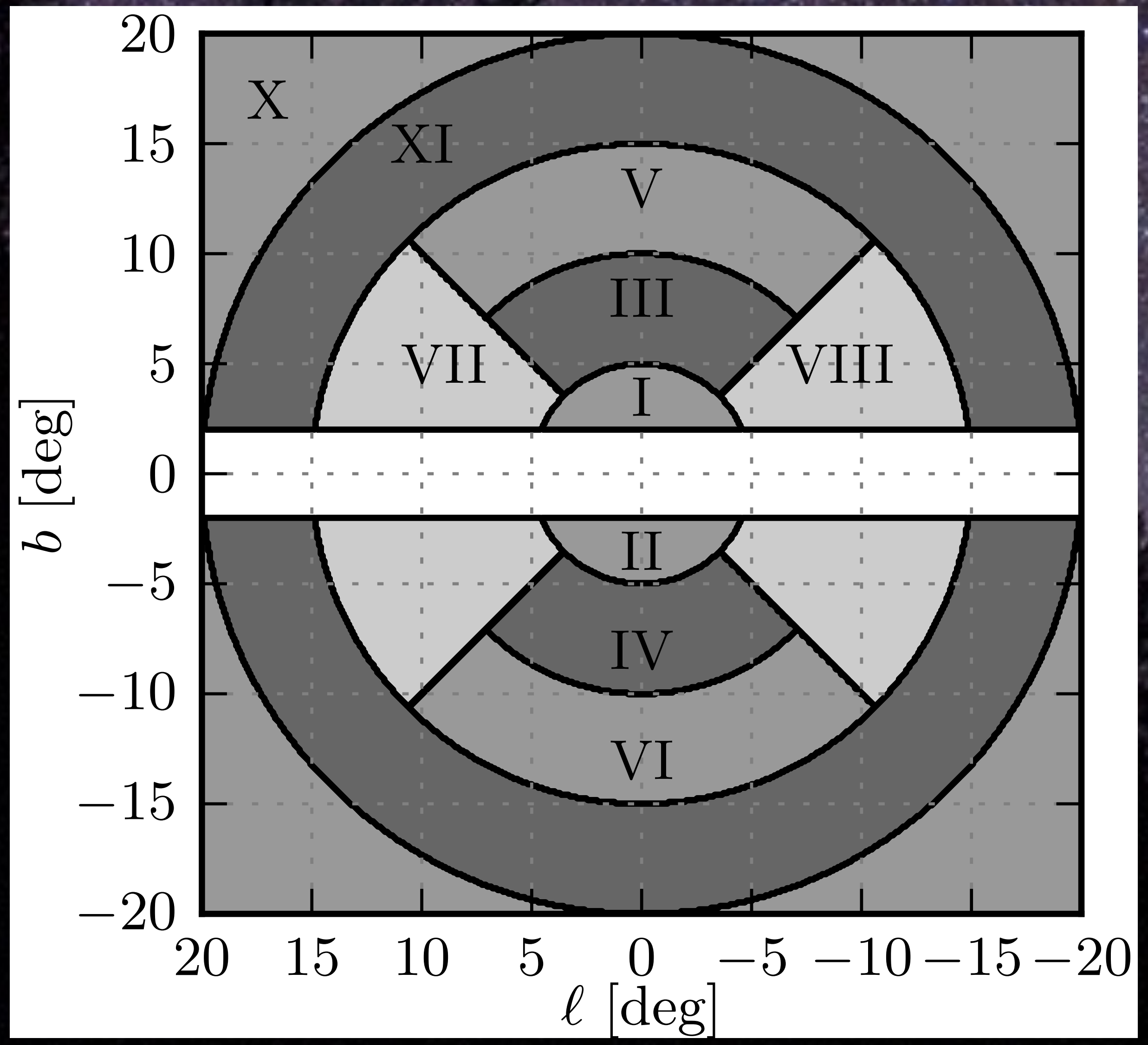
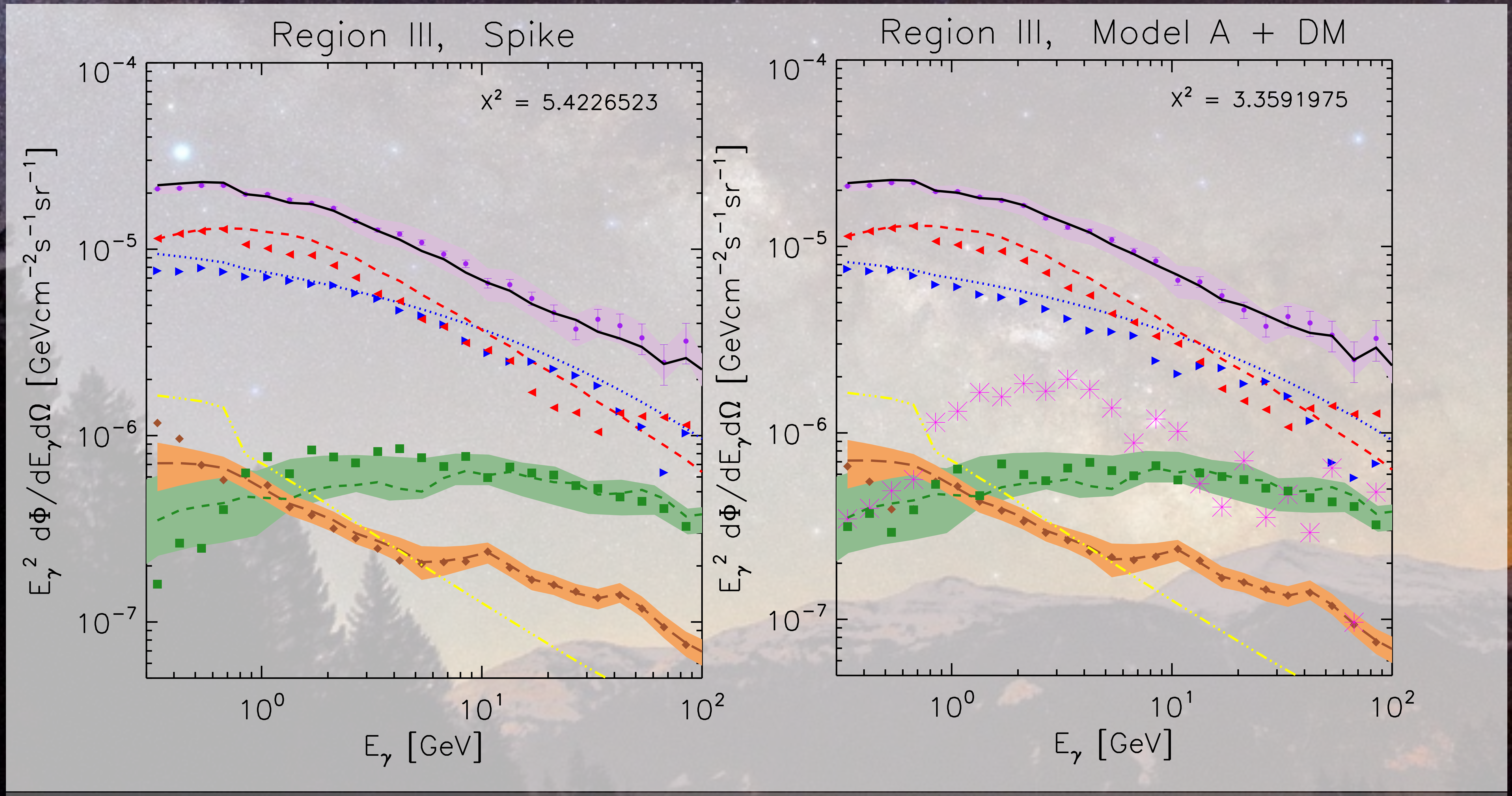


ModelA+spike **ModelA+DM**



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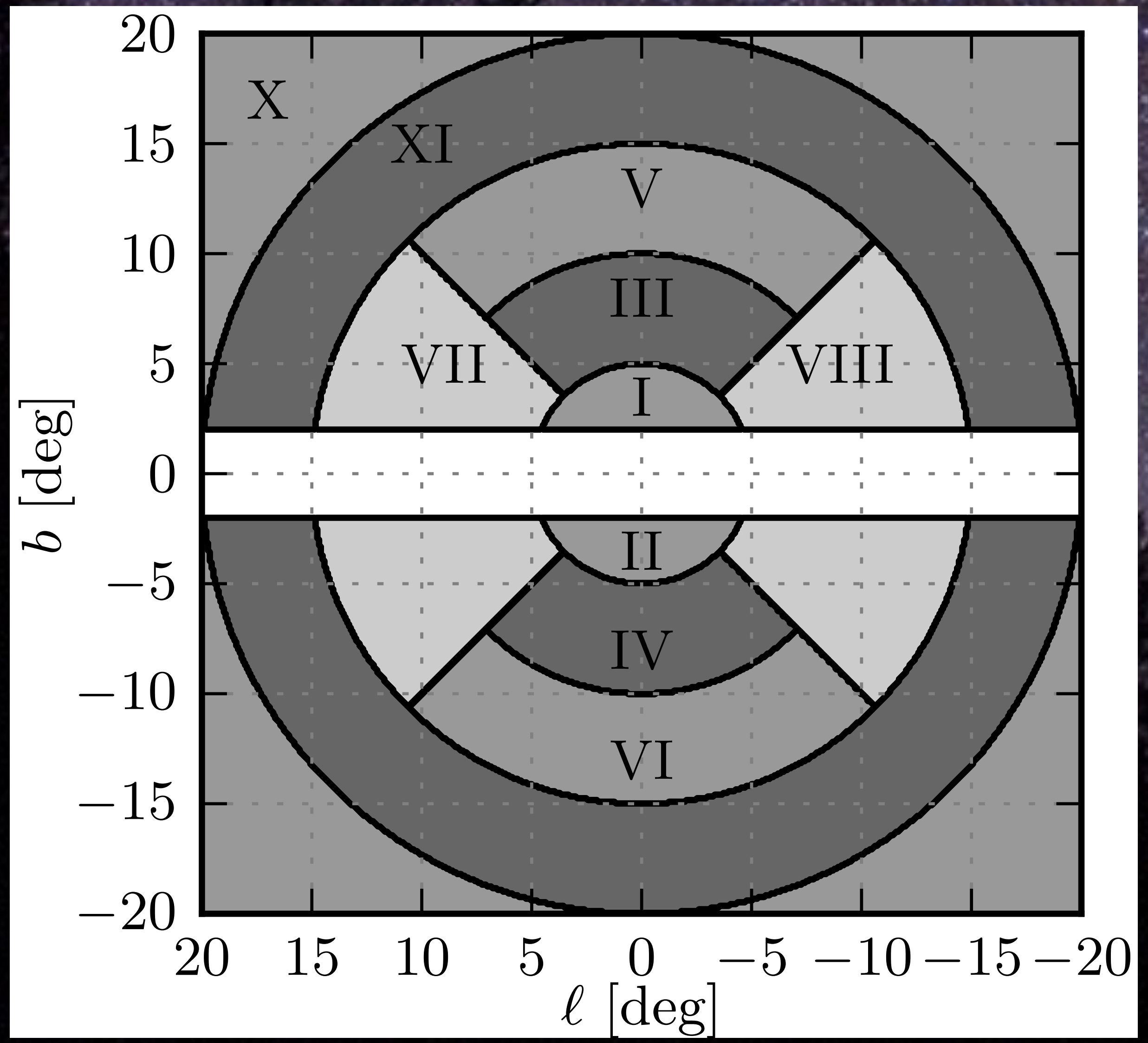

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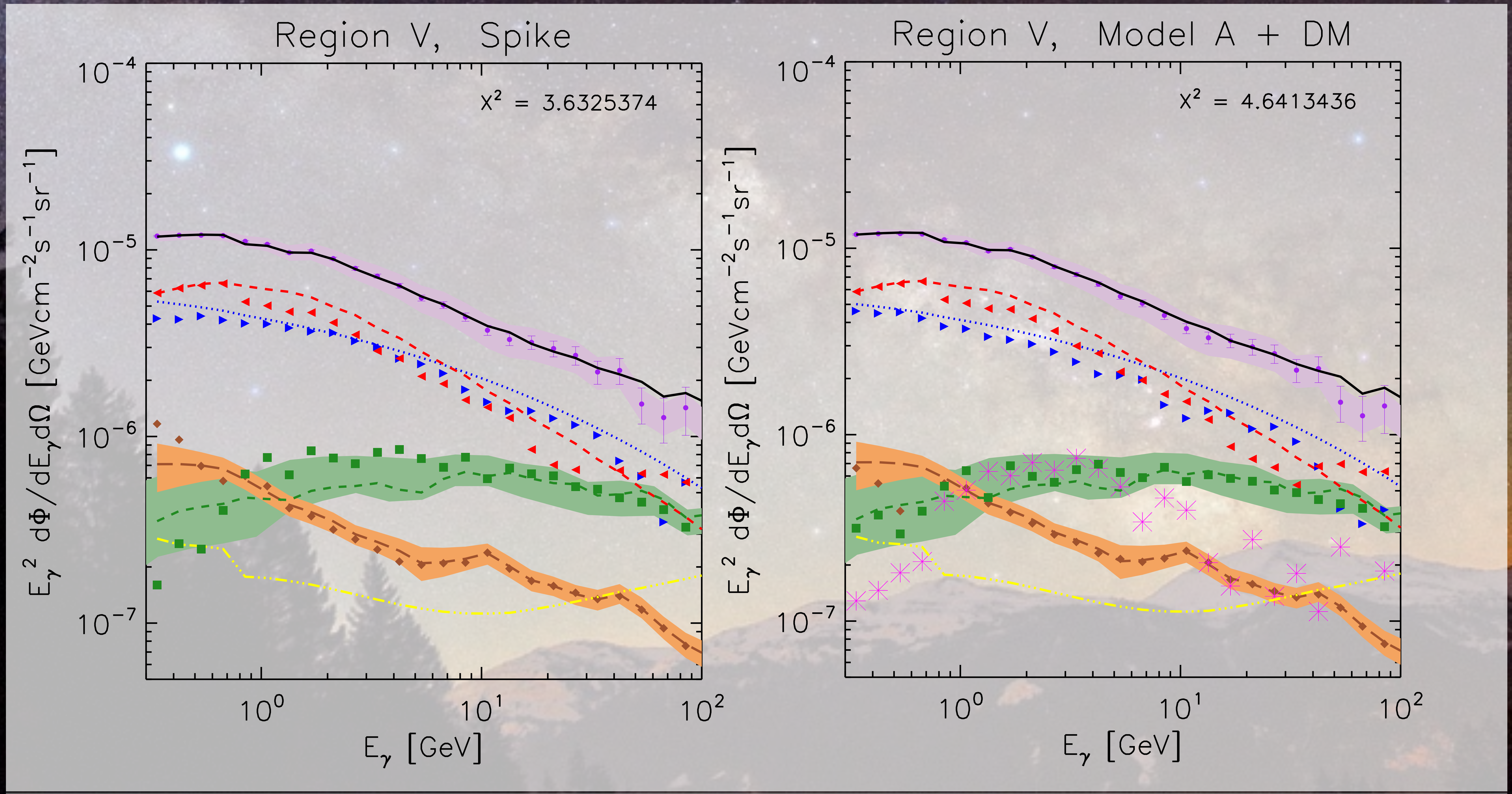

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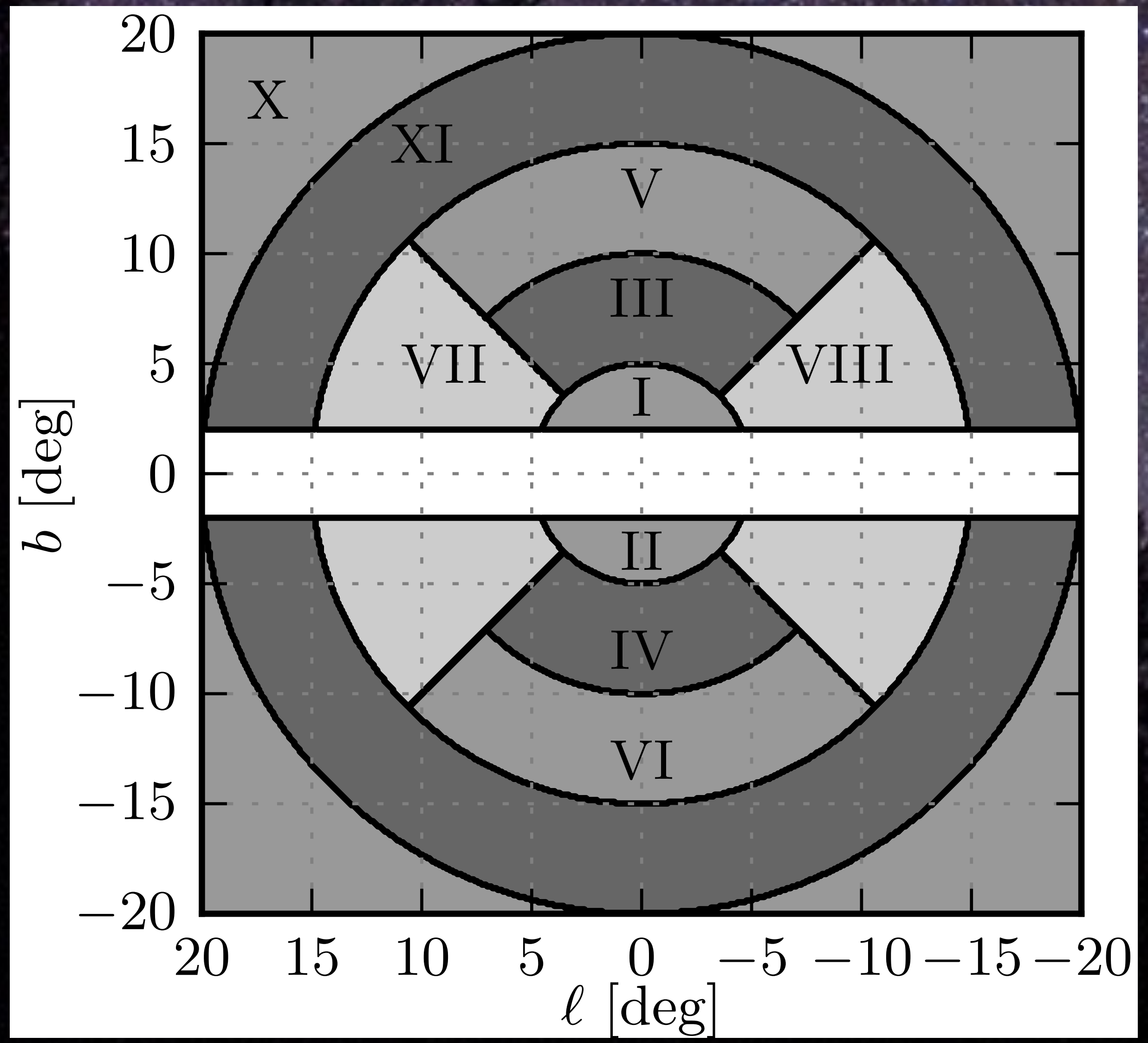
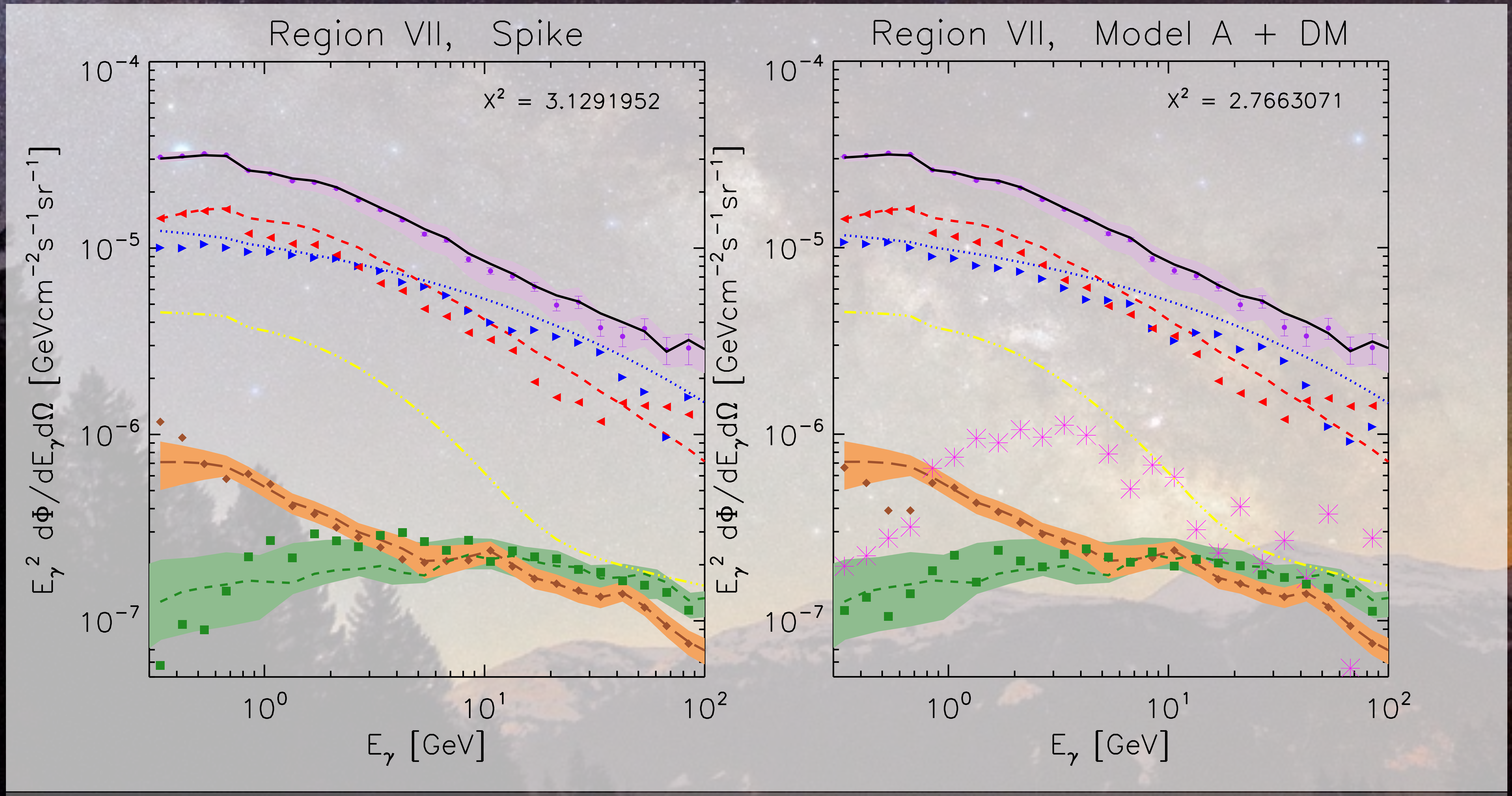
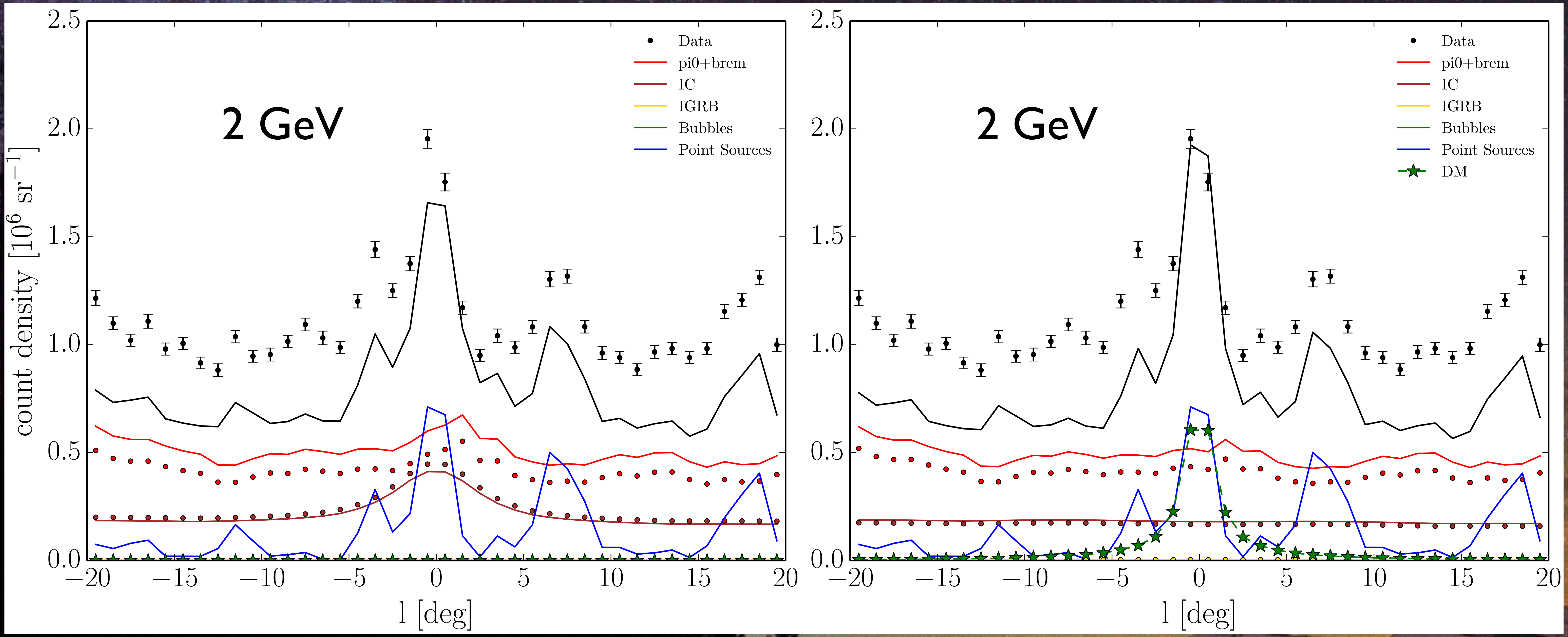


ModelA+spike

ModelA+DM



Unmasking the Galactic plane

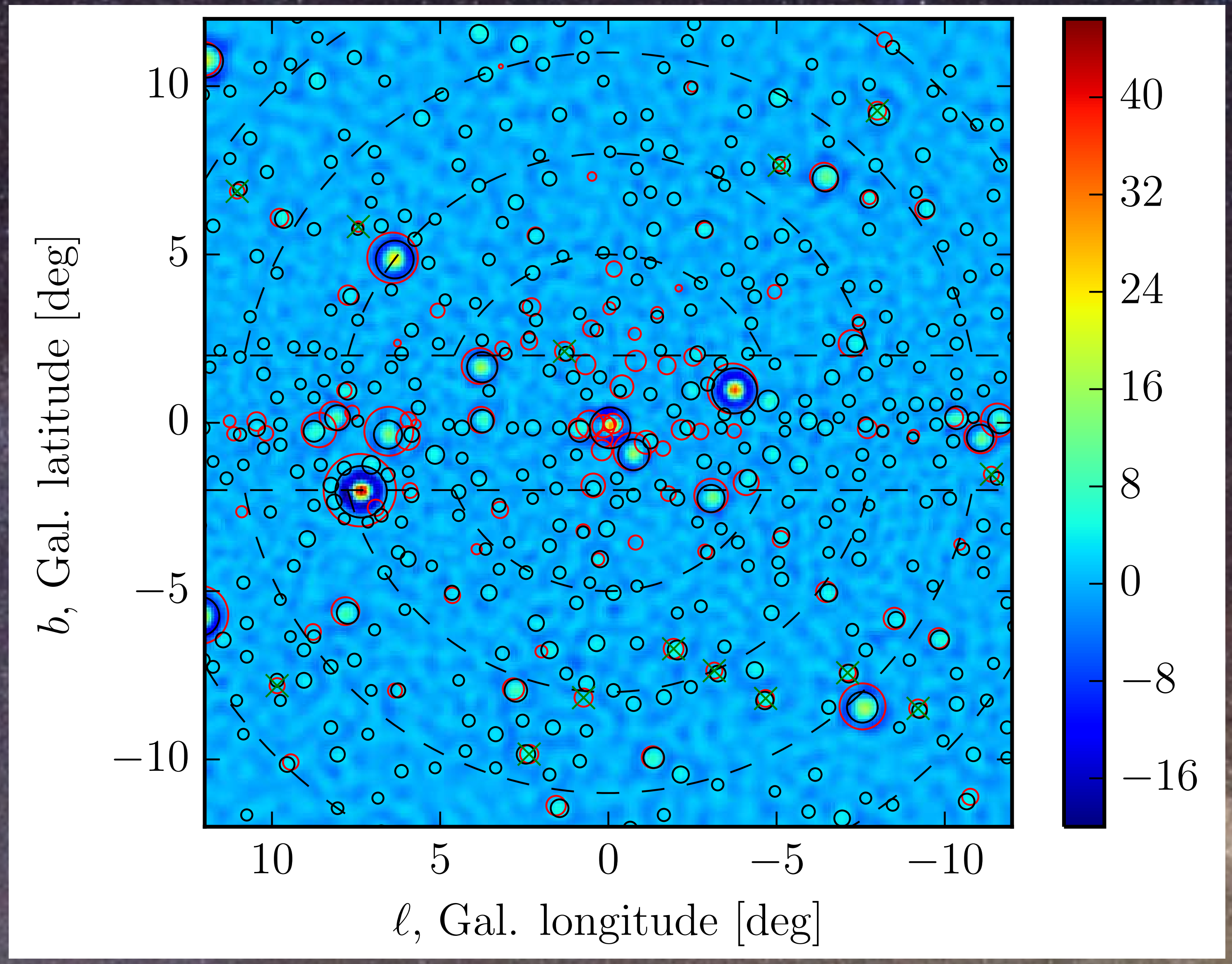


ModelA+spike **ModelA+DM**

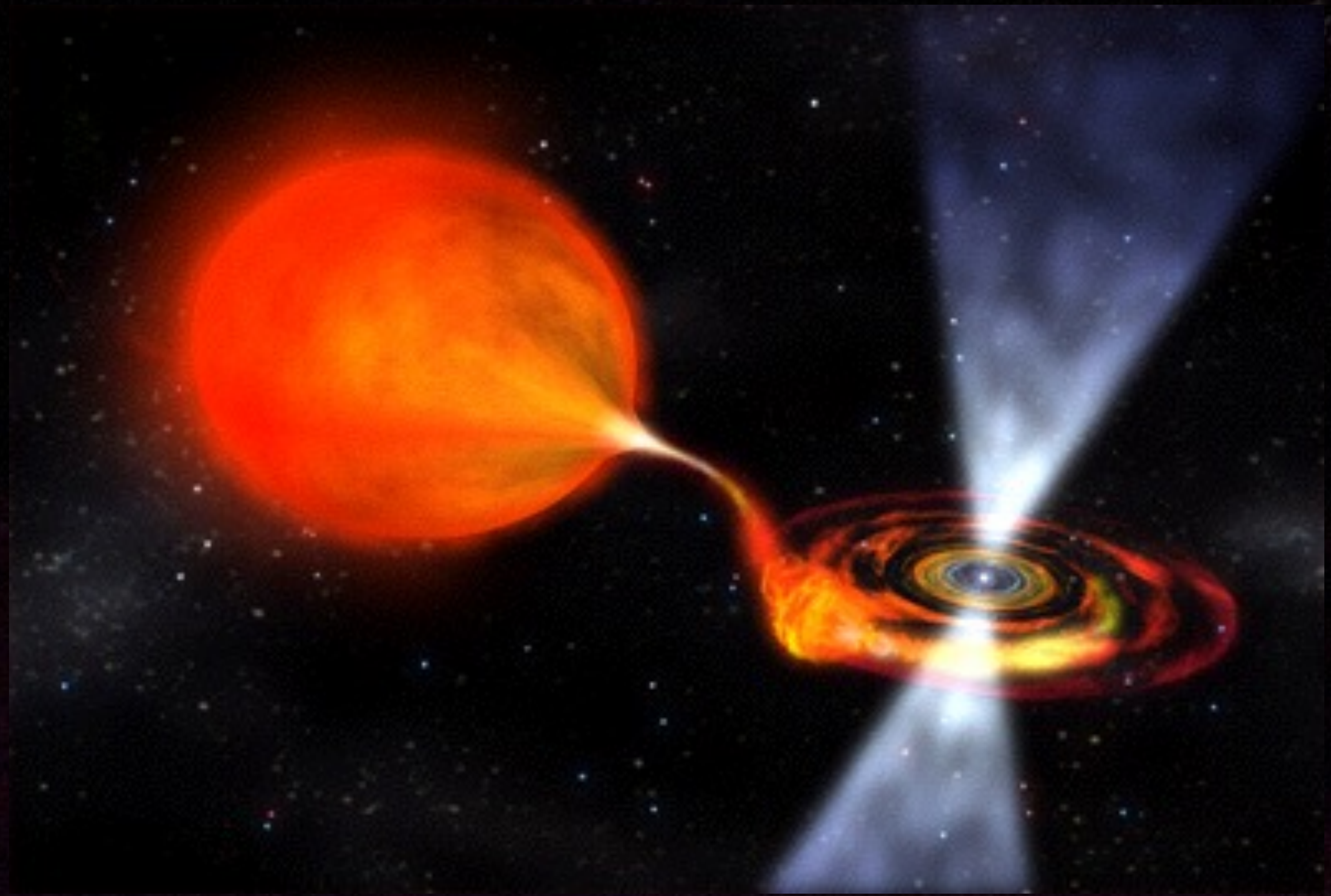
Figure 1: *Longitude profile of ModelA+spike (left) and ModelA+DM (right, along the Galactic plane for an energy bin centered at 2 GeV, after performing the template fitting described in the paper. Data and models are averaged in the latitude window* $|b| < 2°$.

The role of millisecond pulsars. Hybrid scenarios?

There is a growing evidence for a dominant contribution from a population of millisecond pulsars at least at ~1 GeV where the excess is peaked [see e.g. the recent analyses in Lee at al. 2015, Bartels et al. 2015]



SNR of the wavelet transform of γ-rays with energies in the range 1–4 GeV, from arXiv: 1506.05104



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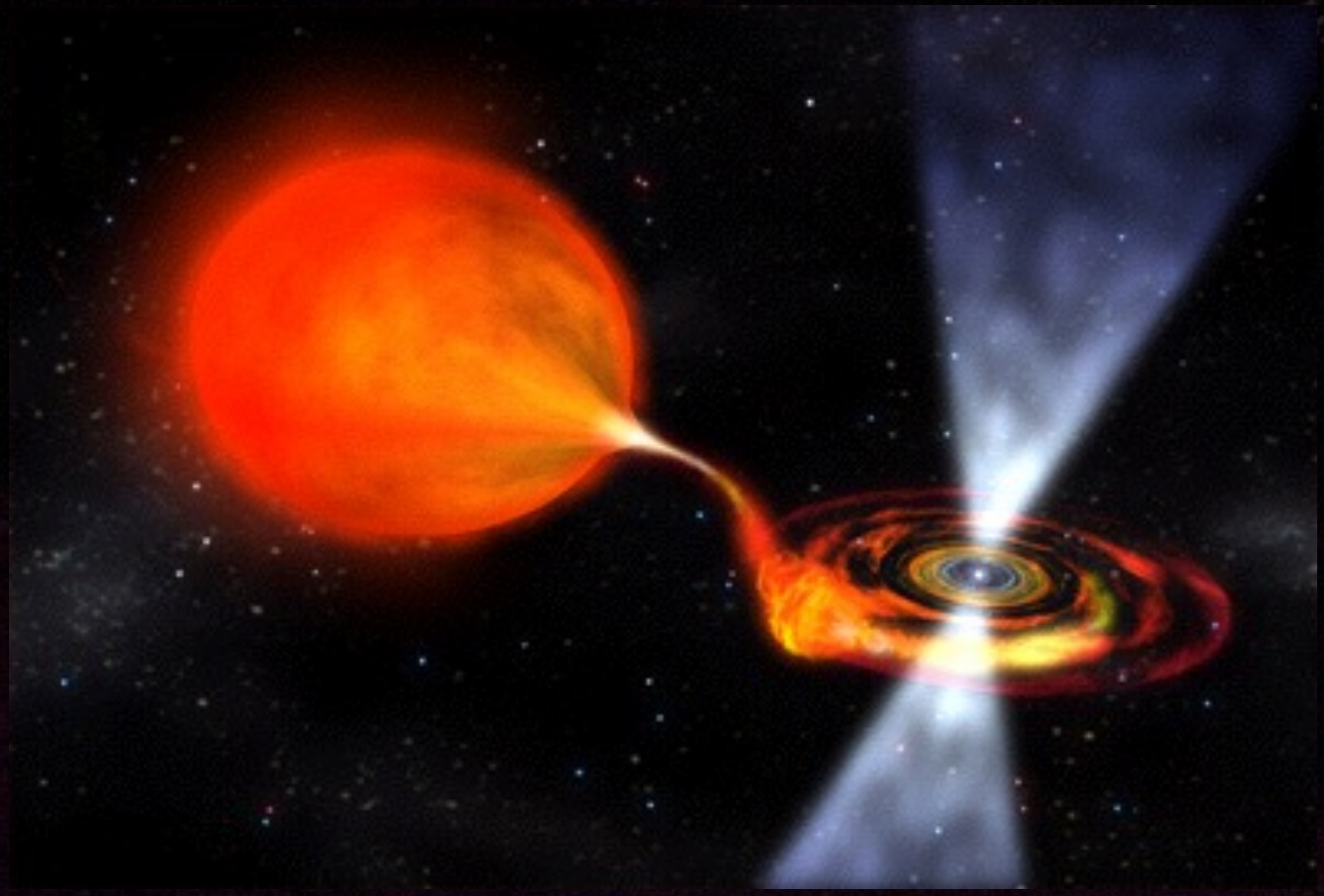


It would be interesting to extend the wavelet analysis reported in 1506.05104 to lower energies.

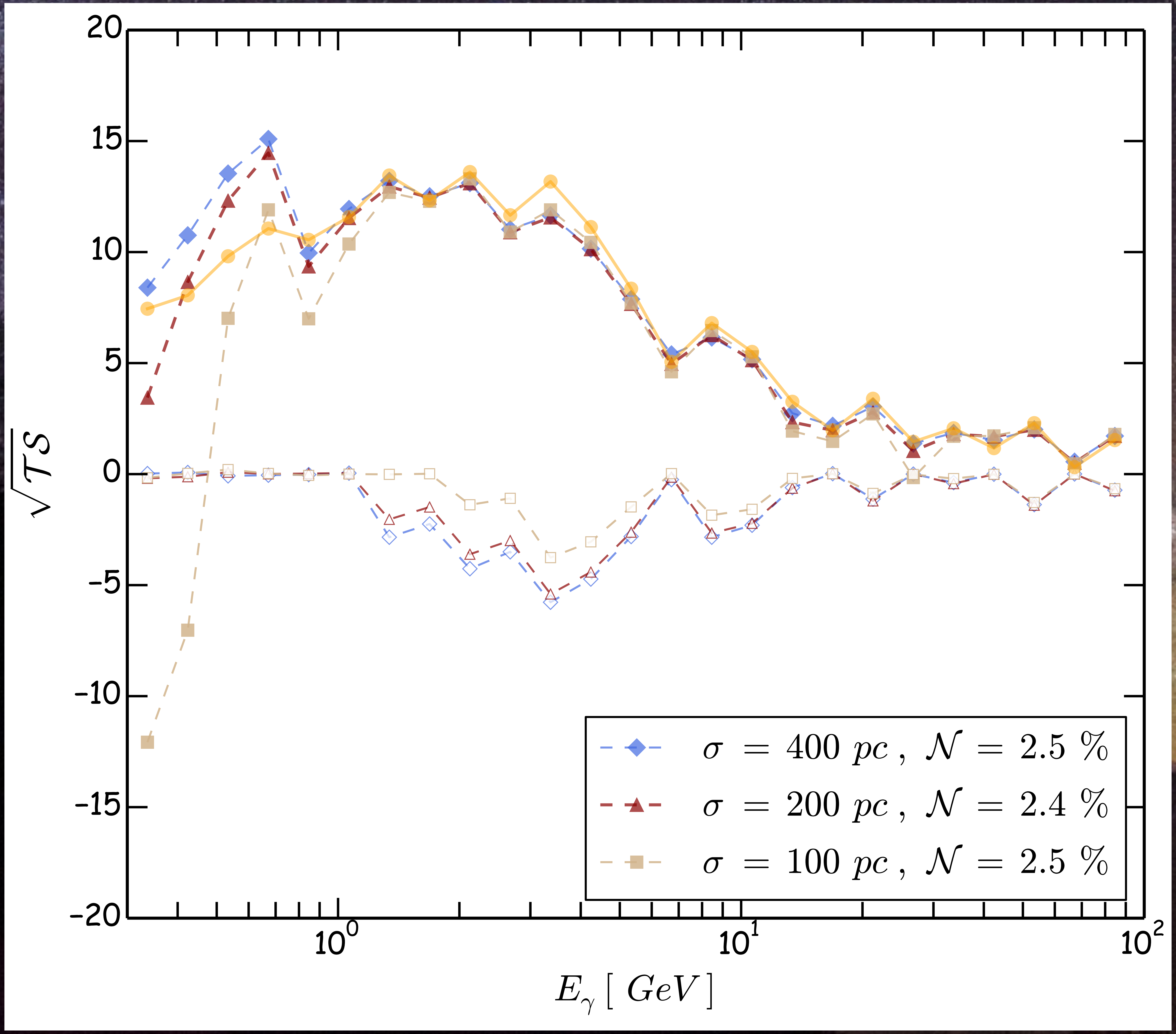
Given the low-energy problems of the "spike model", an hybrid scenario may be viable?

Both millisecond pulsars and ordinary CR sources are there! the relative contribution is still to be determined!

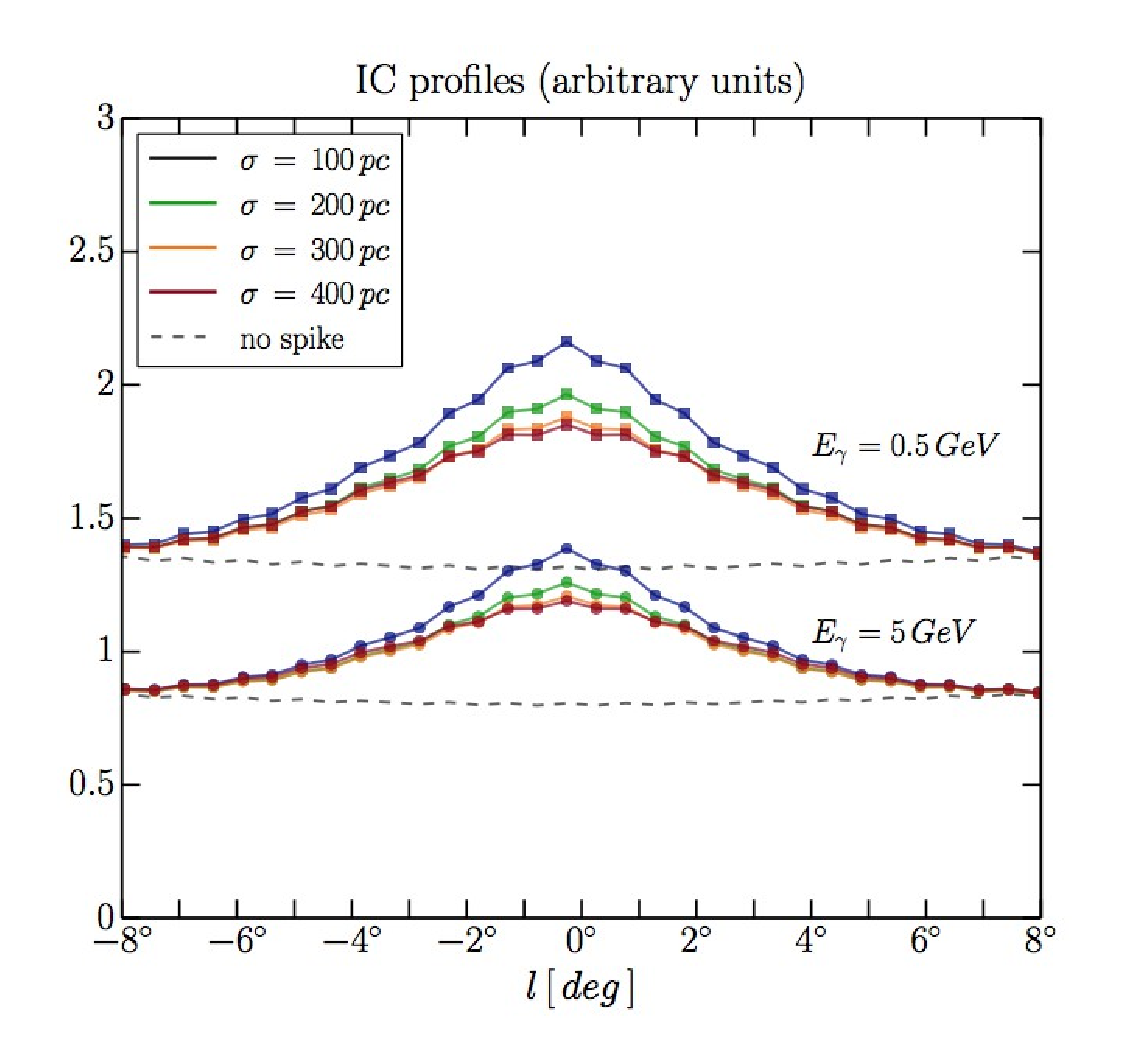
Final remarks

- It is natural to consider CR propagation models where the CR source term does not drop to 0 in the GC region.
- We showed a phenomenological model with a ordinary CR source peaked at the GC, whose energy budge compatible with astronomical observation (1% os the total SFR should be confined in the inner 2-300 pc)
- We computed hadronic and leptonic propagation consistently with DRAGON, and the corresponding gamm ray emission
- The usual template-fitting machinery does not show a clear evidence of a GC excess anymore
- Our scenario performs as well as the DM scenario, still there are problems at low energy
- The first energy bins (< 1 GeV) are very delicate. The low-energy CR diffusion is not totally under contro (non linear feedbacks, anisotropic diffusion, convective winds…)
- It is diffucult to analyze the impact of these ingredients in this framework.
- Both CR sources and millisecond pulsars are there. CR physics is complicated.It is not unnatural to consid slightly more complicated hybrid scenarios.

Backup slide: Spike extension



Backup slide: IC emission from the spike



Backup slide: is the DM signal so spiky?

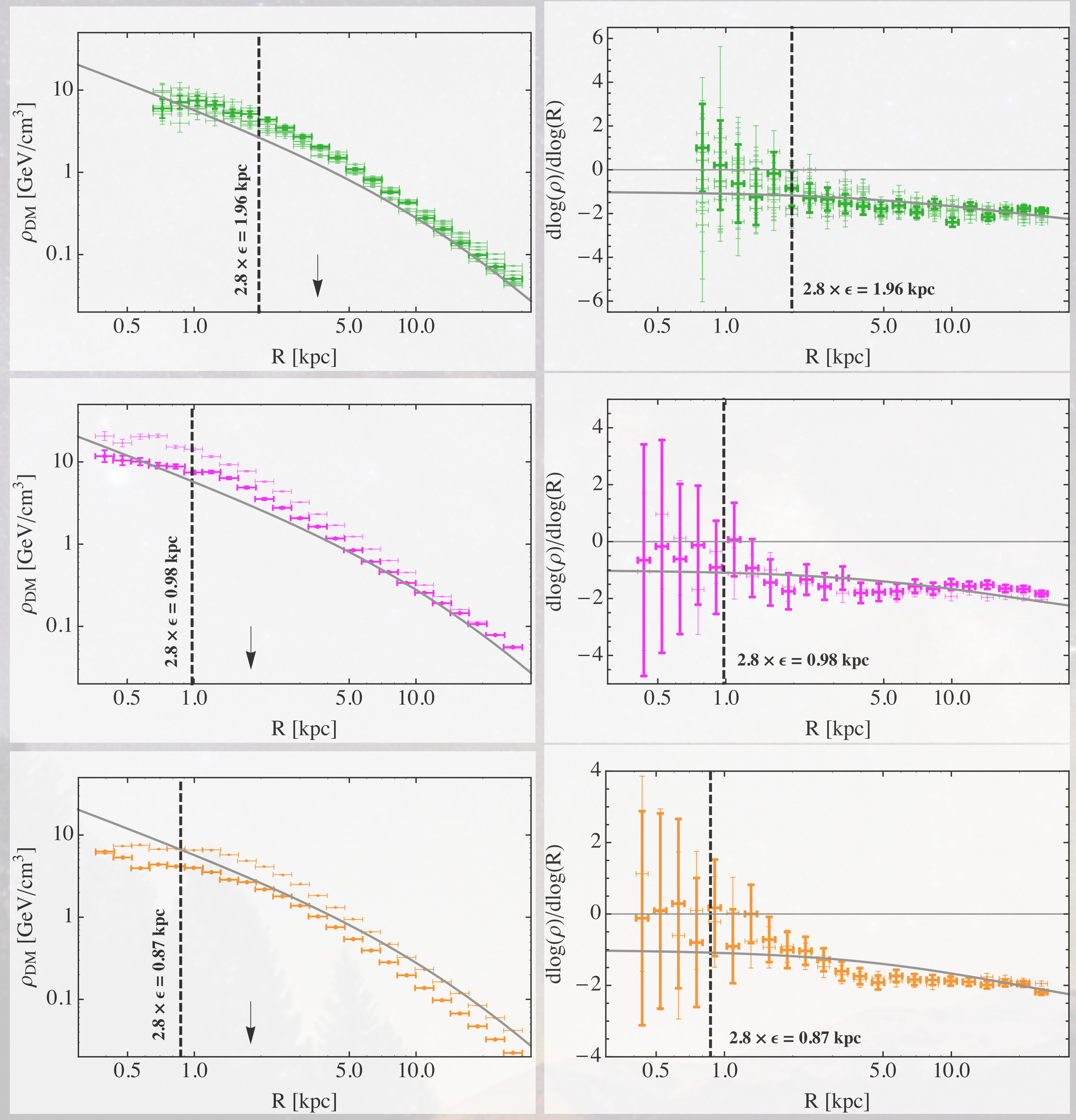


Figure 6. DM density profiles (*left* panels) and the radial change of the local logarithmic slopes (*right* panels) of the selected MW-like galaxies in the EAGLE IR (*top*), EAGLE HR (*middle*) and APOSTLE IR (*bottom*) runs. The *thick grey line* represents the prediction for an NFW profile with $r_s = 20$ kpc and local DM density $\rho_\odot = 0.4$ GeV/cm^3 (as commonly assumed in DM indirect detection studies). In all panels the effective resolution of the simulation is shown by the *dashed black line*, while the *black arrows* on the left panels indicate the convergence radii of 3.6 kpc (EAGLE IR) and 1.8 kpc (EAGLE HR and APOSTLE IR) as discussed in the text.