Revisiting the Gamma-Ray Galactic Center Excess with Multi-Messenger Observations

Focus on recent work with:
IC, Zhong, McDermott, Surdutovich, PRD **105**, 103023 (2022)
(will mention other works with Tim Linden and Dan Hooper as well)

RICAP 2022
Ilias Cholis, 08/09/2022

The challenges of Indirect Searches for WIMPs

The Questions:

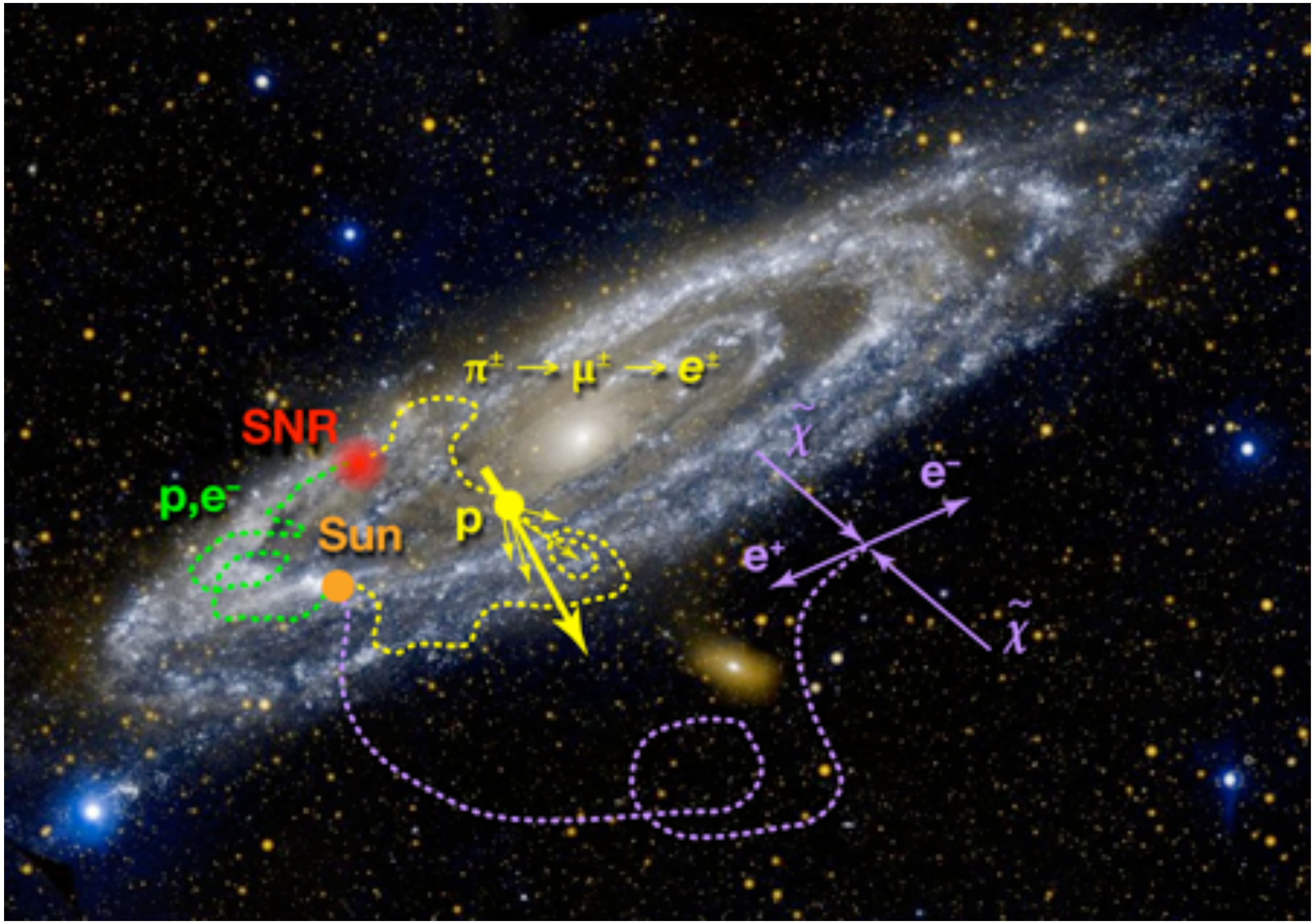
- Are we fully exploring the data? Is there a signal lurking within our observations?
- Do we have a good control of "systematics"? If Dark Matter is the Signal, do we understand the back-ground astrophysical uncertainties & astrophysical alternatives?

Will discuss

i) connection between cosmic rays and gamma rays in the and modeling the Milky Way

ii) using gamma ray observations to search for dark matter

A rough sketch of the Milky Way



With CR spectral measurements we can understand the properties of the Interstellar Medium (ISM), and probe sources of high energy cosmic rays (CRs) including dark matter that could give a signal in antimatter.

Modeling the ISM galactic production and propagation uncertainties for cosmic rays

$$\frac{\partial \psi(r,p,t)}{\partial t} = \underbrace{q(r,p,t)}_{\text{sources}} + \underbrace{\vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi)}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{\psi}{p^2}\right)\right]}_{\text{re-acceleration}} + \underbrace{\frac{\partial}{\partial p}\left[\frac{p}{3}(\vec{\nabla} \cdot \vec{V})\psi\right]}_{\text{convection}}$$

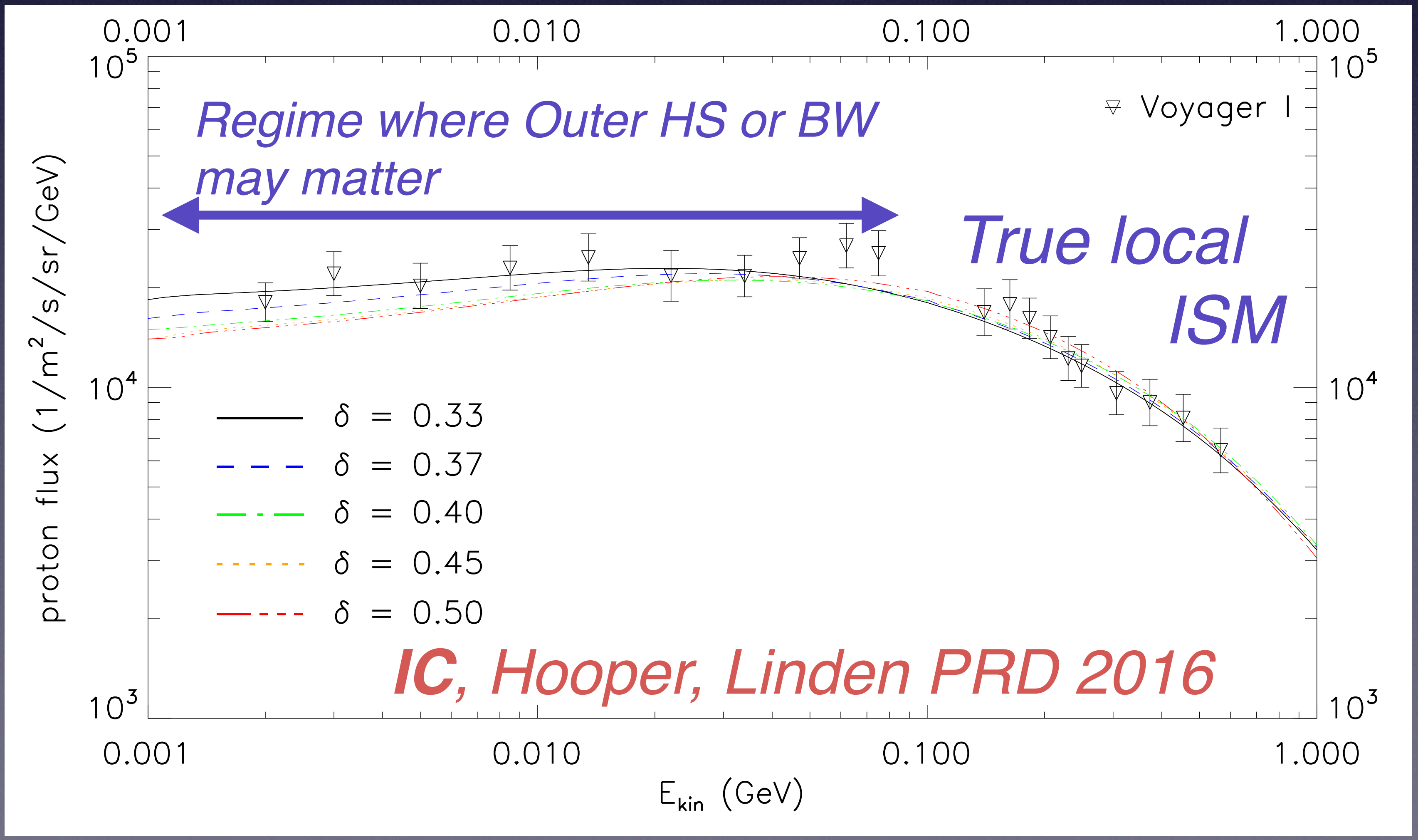
Modeling the ISM galactic production and propagation uncertainties for cosmic rays

$$\frac{\partial \psi(r,p,t)}{\partial t} = q(r,p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{\psi}{p^2}\right)\right] + \frac{\partial}{\partial p}\left[\frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]$$

sources — diffusion — re-acceleration — convection

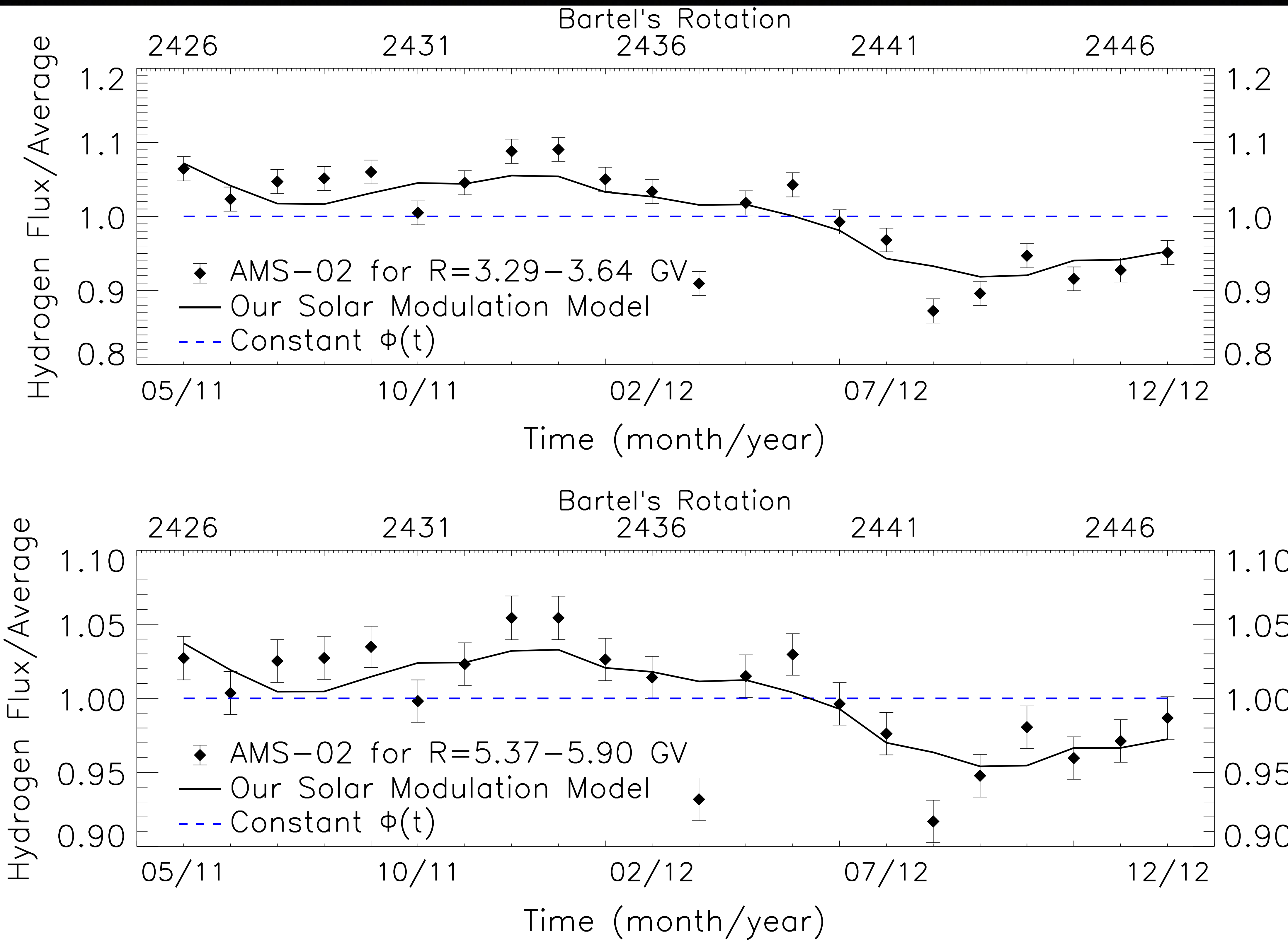
Voyager 1

Voyager 1 (ISM) proton flux:



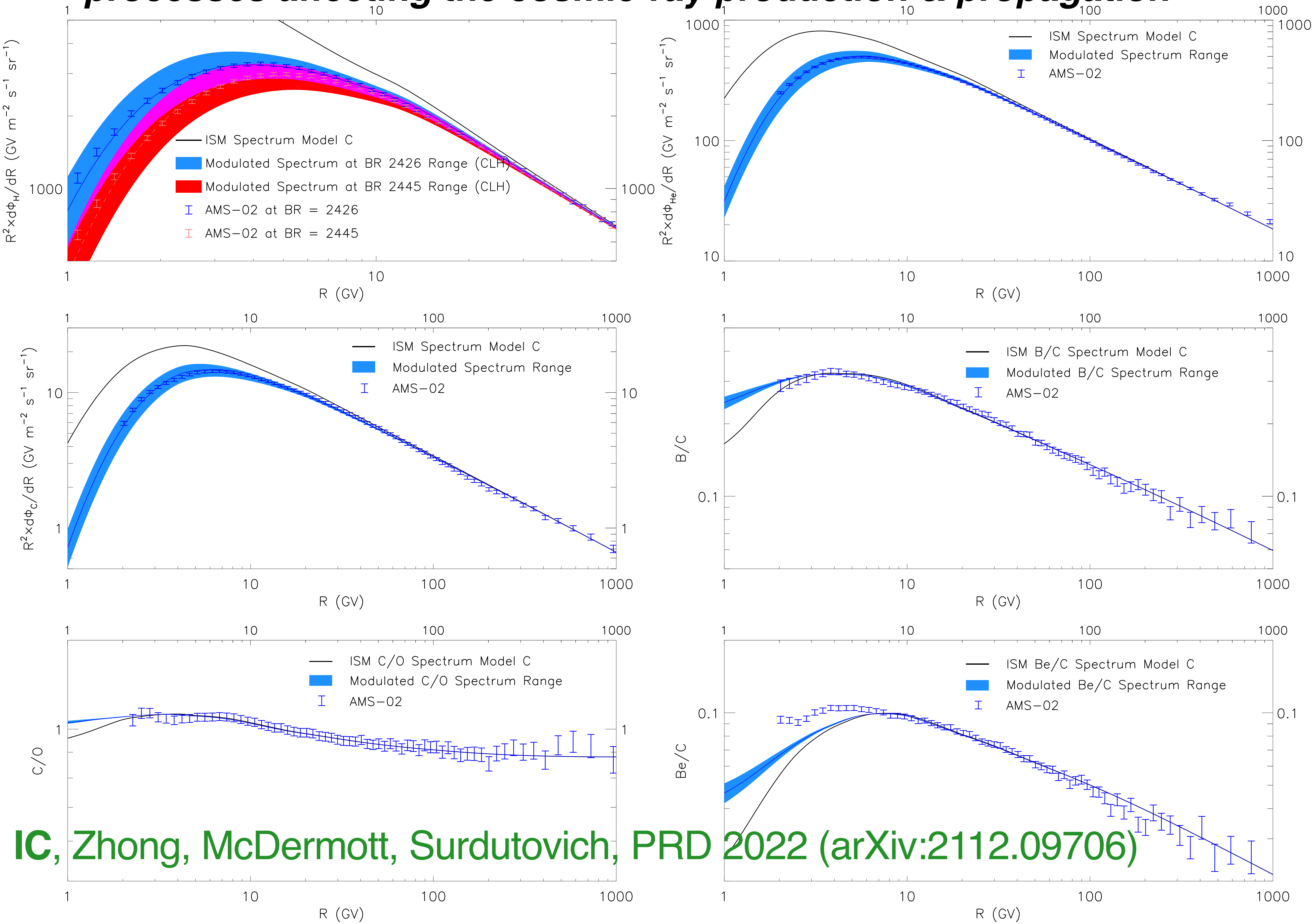
We use GALPROP a numerical solver build by Moskalenko, Strong et al. as a starting point and build several models that are in agreement with CR measurements

Cross-checking with the PROTON data that account for the majority of observed cosmic rays; monthly AND total (i.e ISM & Solar Modulation):



Constraining the form of the Modulation potential and the ISM p spectrum in a recursive manner. ***IC**, Linden, Hooper (arXiv:2007.00669)*

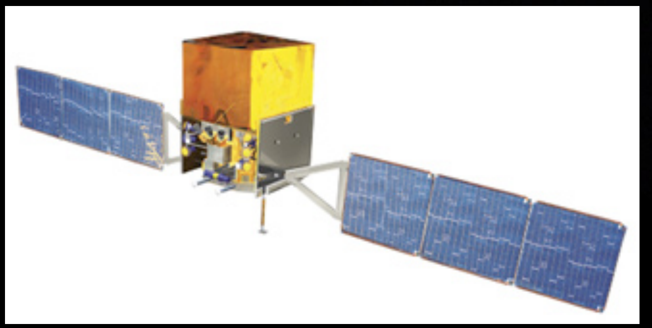
Repeating for multiple Cosmic-Ray species we can constrain the physical processes affecting the cosmic-ray production & propagation

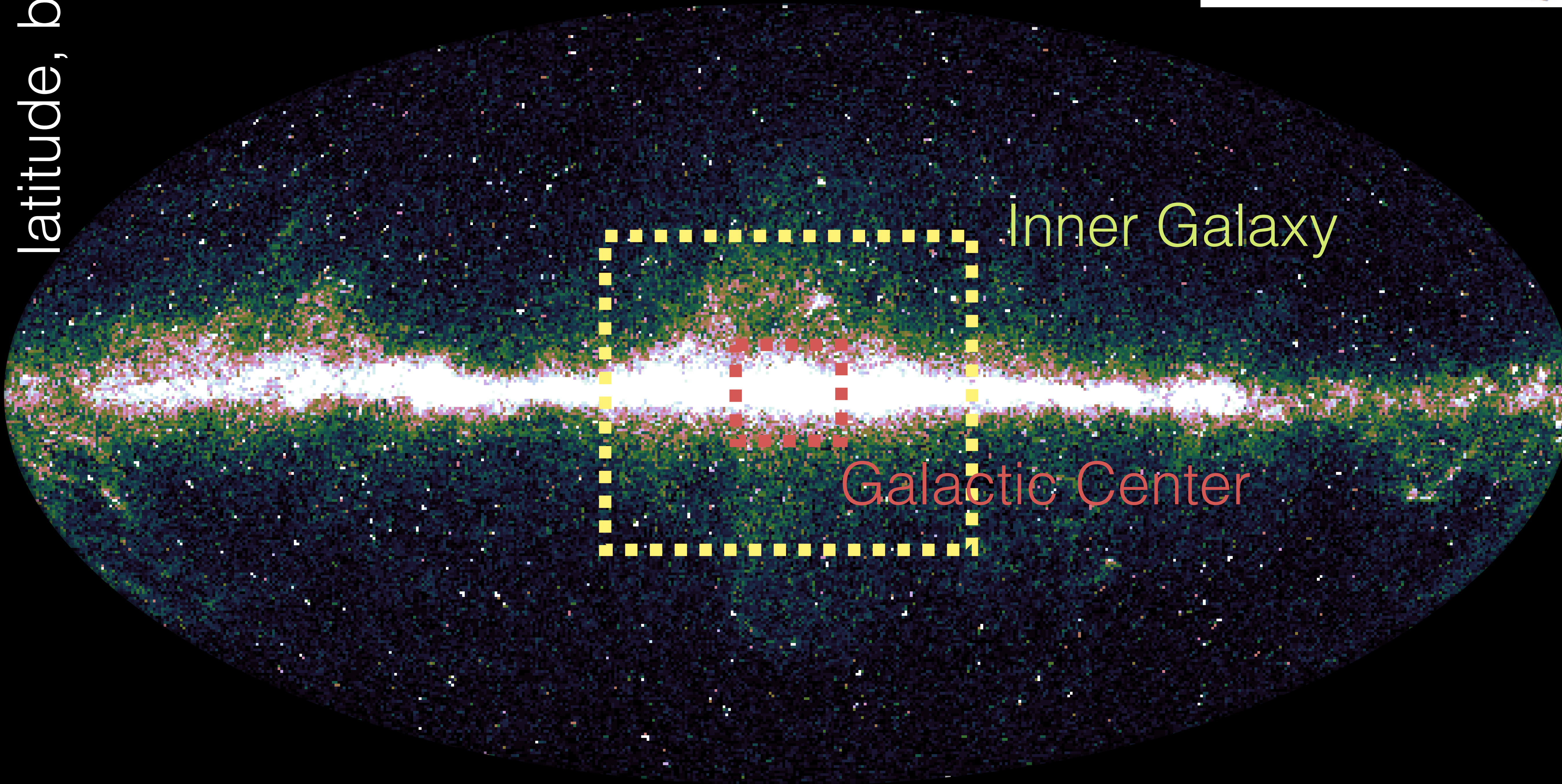


IC, Zhong, McDermott, Surdutovich, PRD 2022 (arXiv:2112.09706)

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY

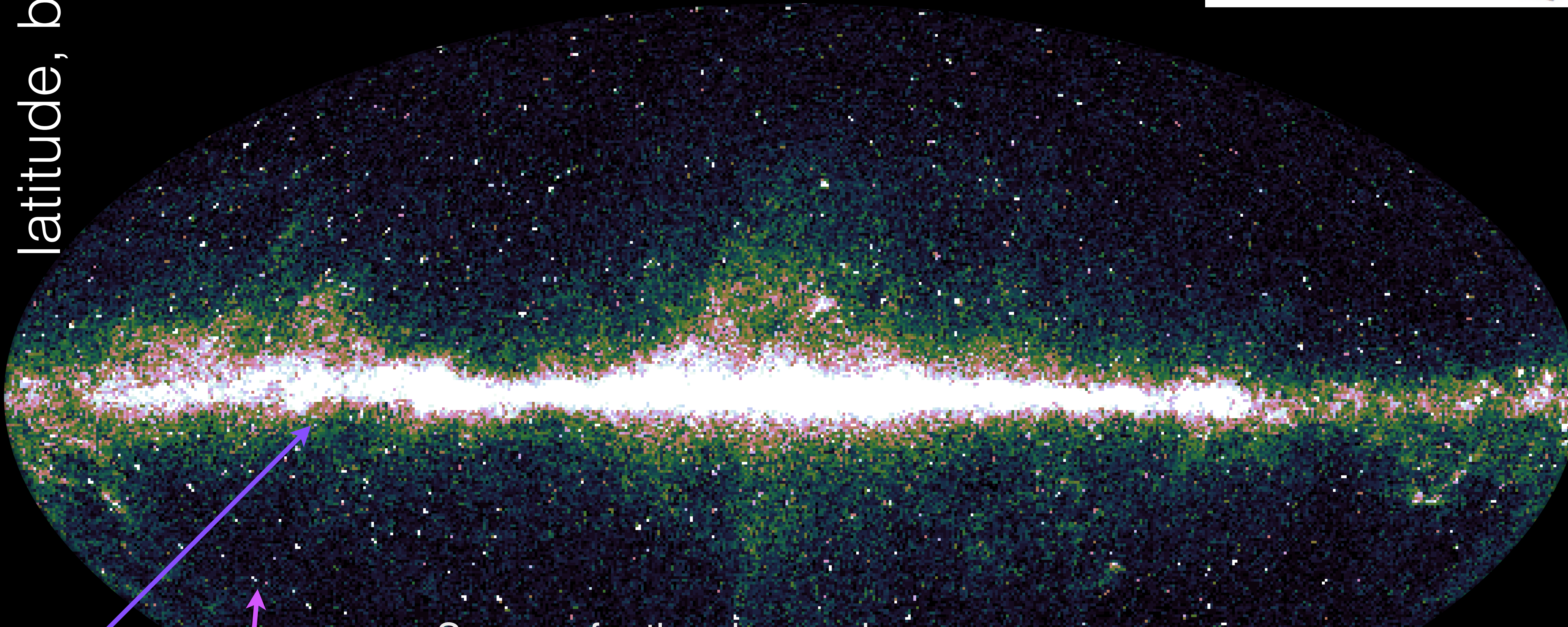




third dimension (not shown) — energy

latitude, b ⟶

The Fermi-LAT Gamma-ray SKY



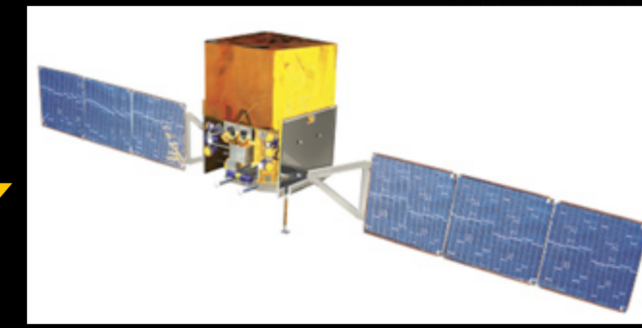
Sources for the observed gamma-rays are:

i)Galactic Diffuse Emission: decay of pi0s (and other mesons) from pp (NN) collisions in the ISM, bremsstrahlung radiation off CR e, Inverse Compton scattering: up-scattering of CMB and IR, optical photons from CR e

ii)from point sources (galactic or extra galactic)

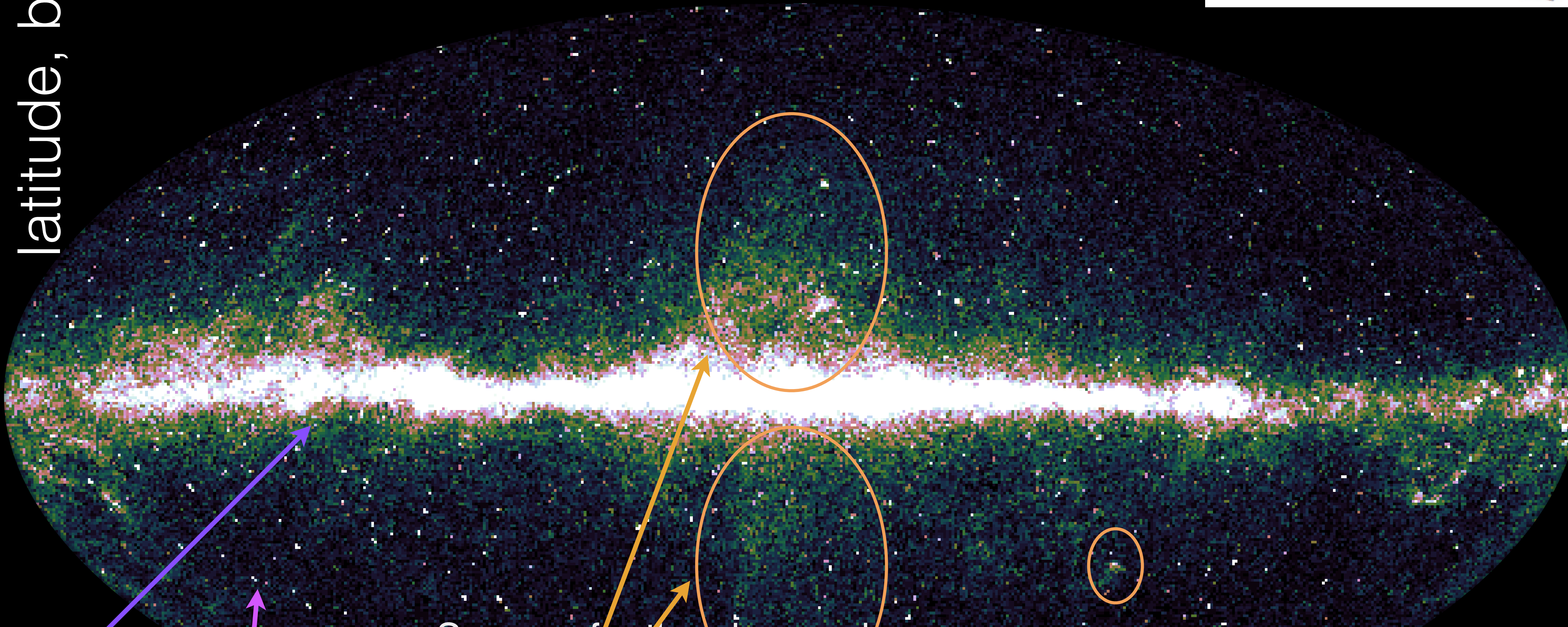
iii)Extragalactic Isotropic

third dimension (not shown) — energy



The Fermi-LAT Gamma-ray SKY

latitude, b ⟶



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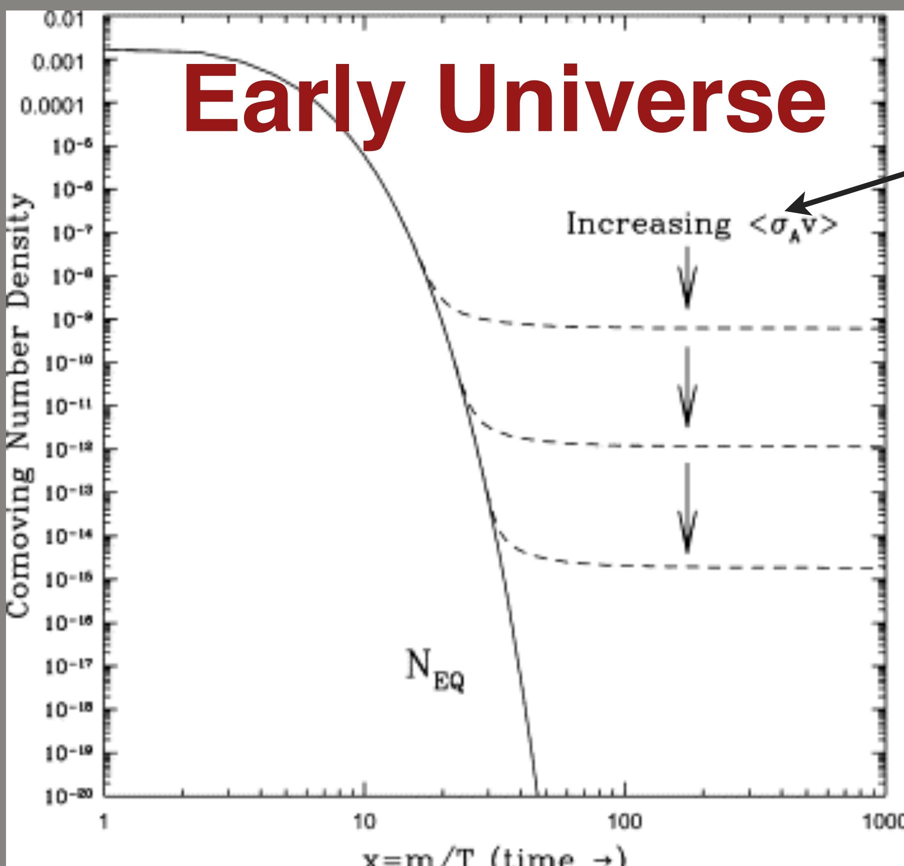
iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)

iv)misidentified CRs (isotropic due to diffusion of CRs in the Galaxy)

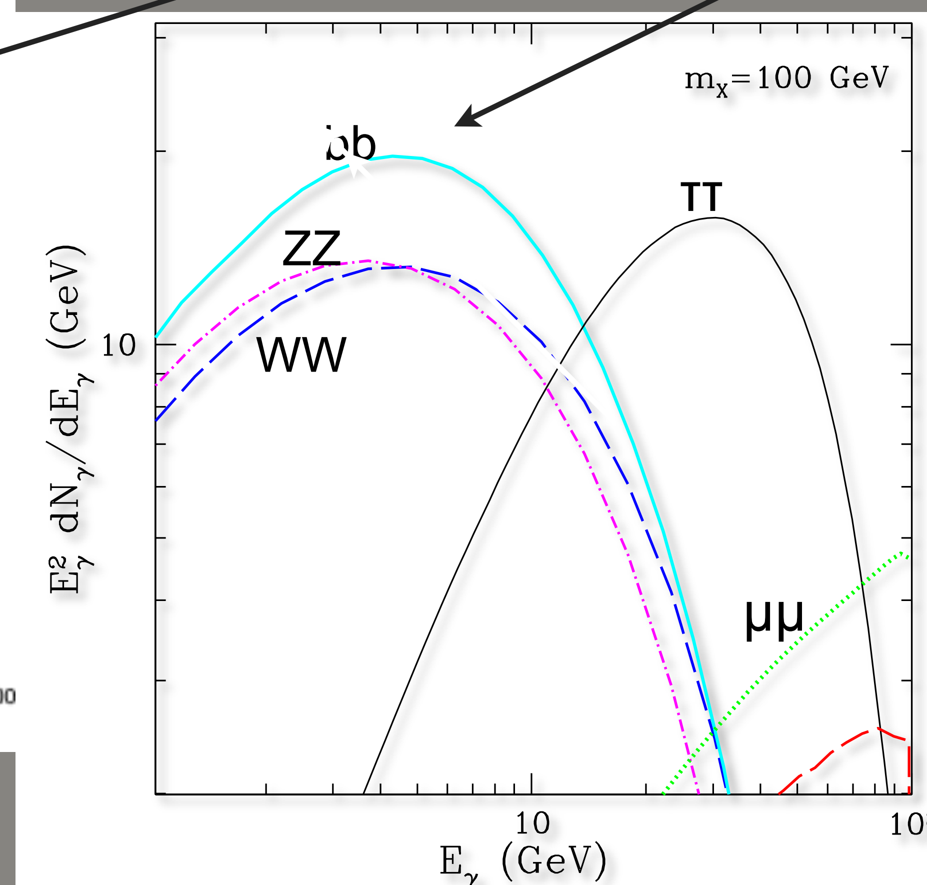
BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe:

$$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle\sigma v\rangle}{4\pi} \frac{dN_\gamma}{dE}_{DM} \frac{\rho^2_{DM}(l,\Omega)}{2\,m_\chi^2} dl\, d\Omega$$

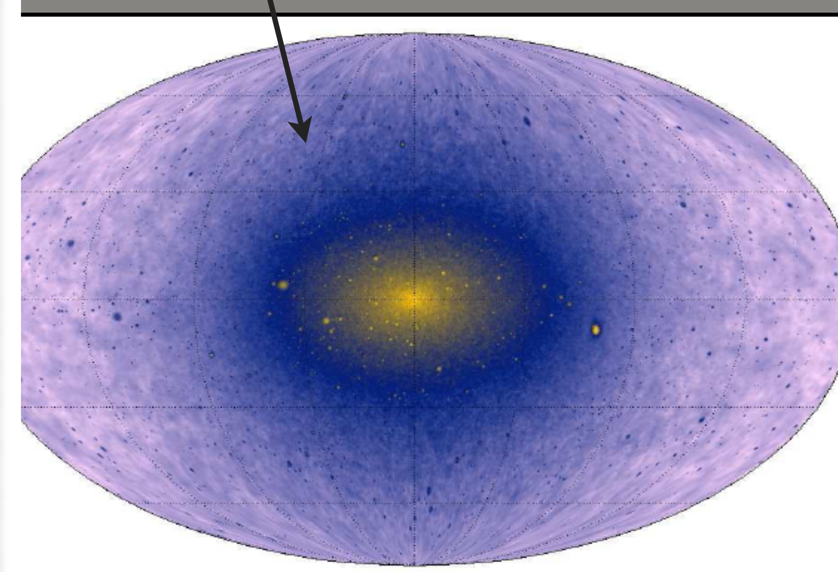


Steigman et al. 2012



Particle Physics

PYTHIA: Sjostrand et al. 2006 & 2007
HERWIG: Corcella et al. 2001

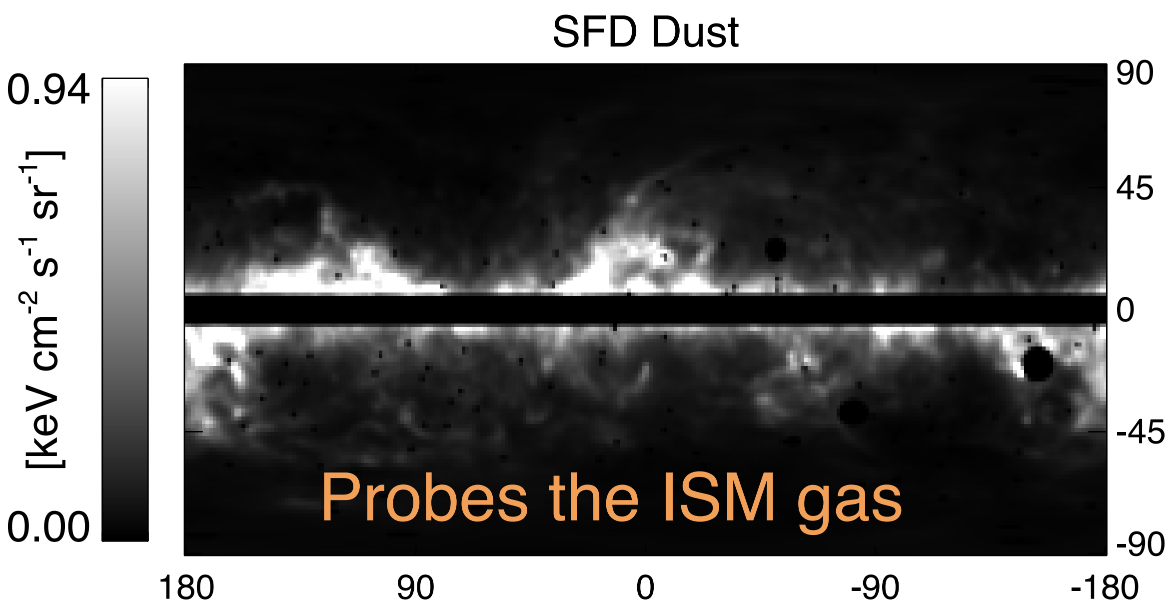


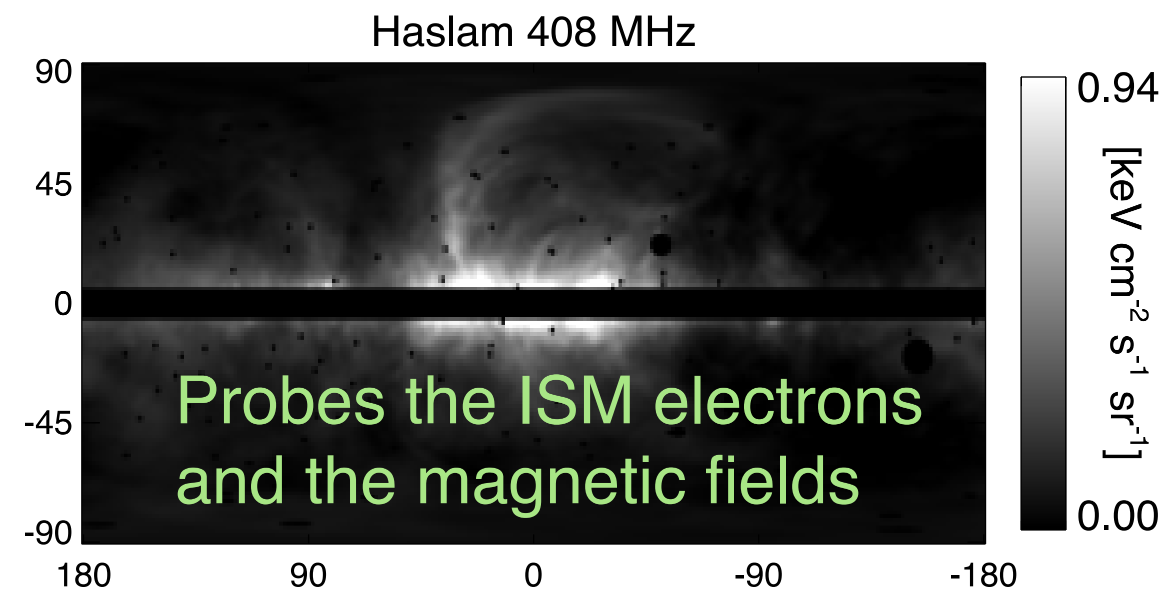
From Cosmological Simulations what we expect today

Springel et al. 2005,
Kuhlen et al. 2012,
Vera-Ciro et al. 2014

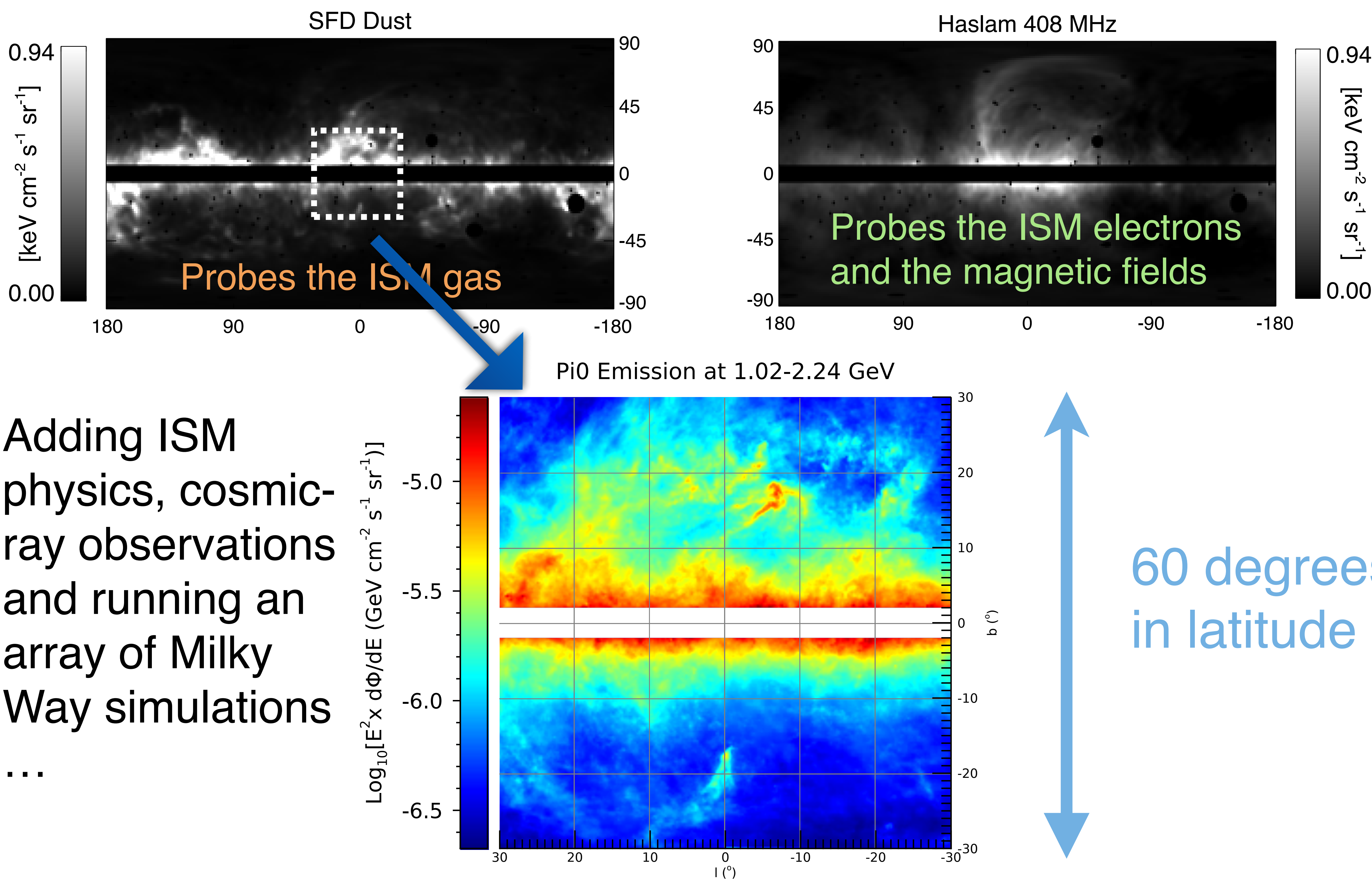
Using templates on Gamma-ray maps —> It's first use led to the discovery of the Fermi(Haze)-Bubbles

Dobler, Finkbeiner, **IC**, Slatyer, Weiner, ApJ, 2010





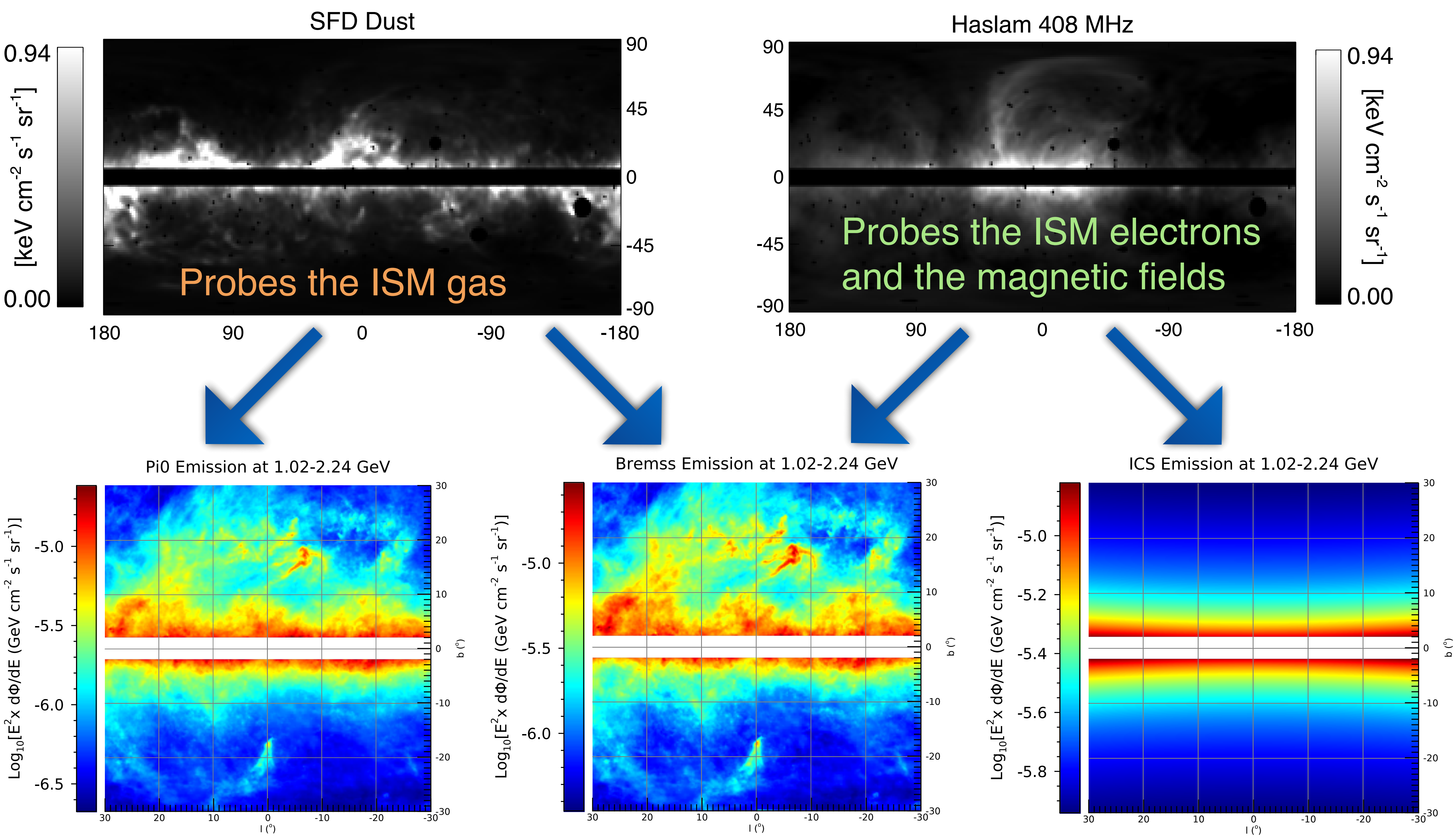
Using templates on Gamma-ray maps



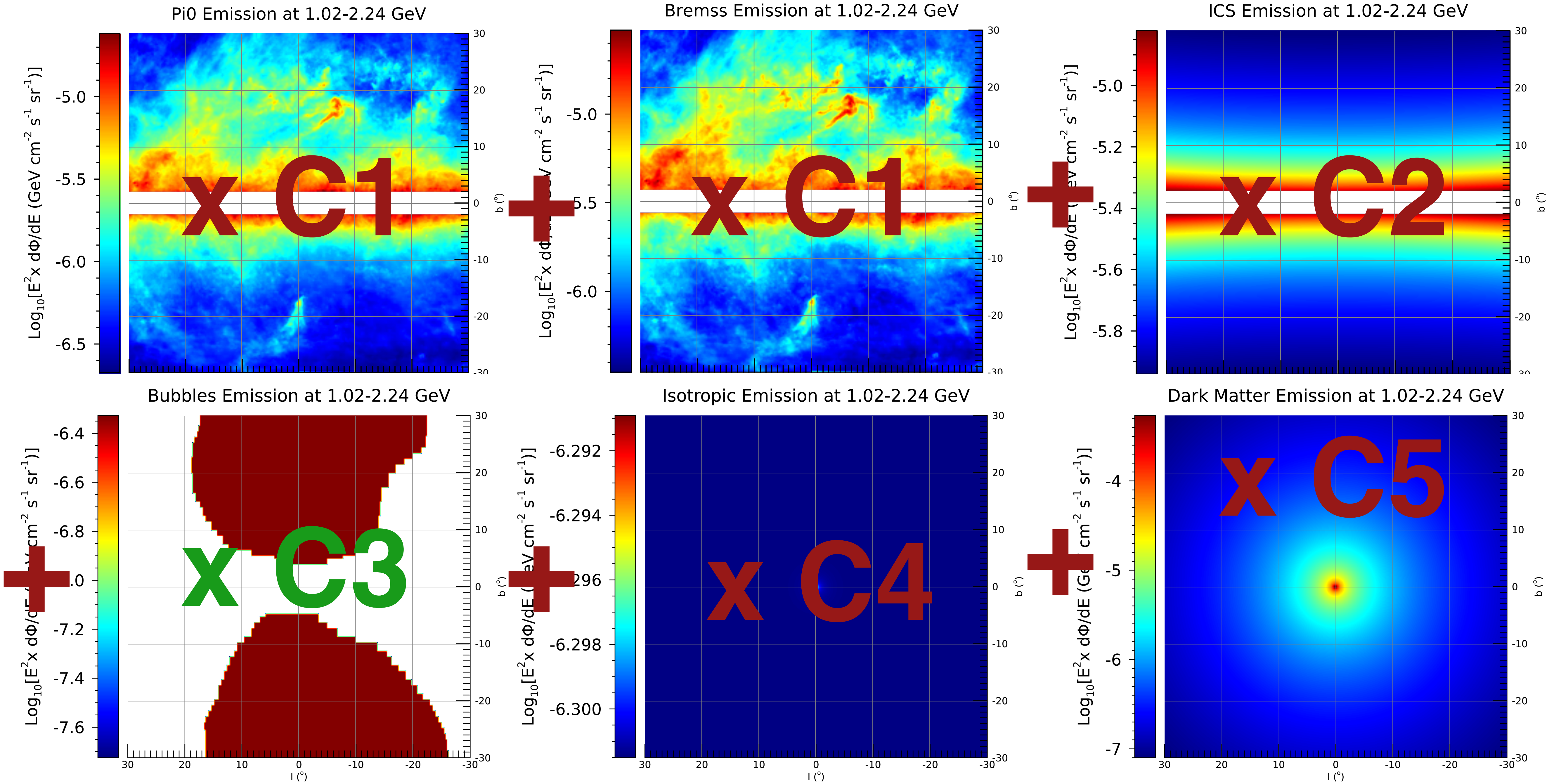
Adding ISM physics, cosmic-ray observations and running an array of Milky Way simulations …

60 degrees in latitude

Using templates on Gamma-ray maps



IC, Zhong, McDermott, Surdutovich, PRD 2022 (arXiv:2112.09706)


Pi0 Emission at 1.02-2.24 GeV
x C1
+
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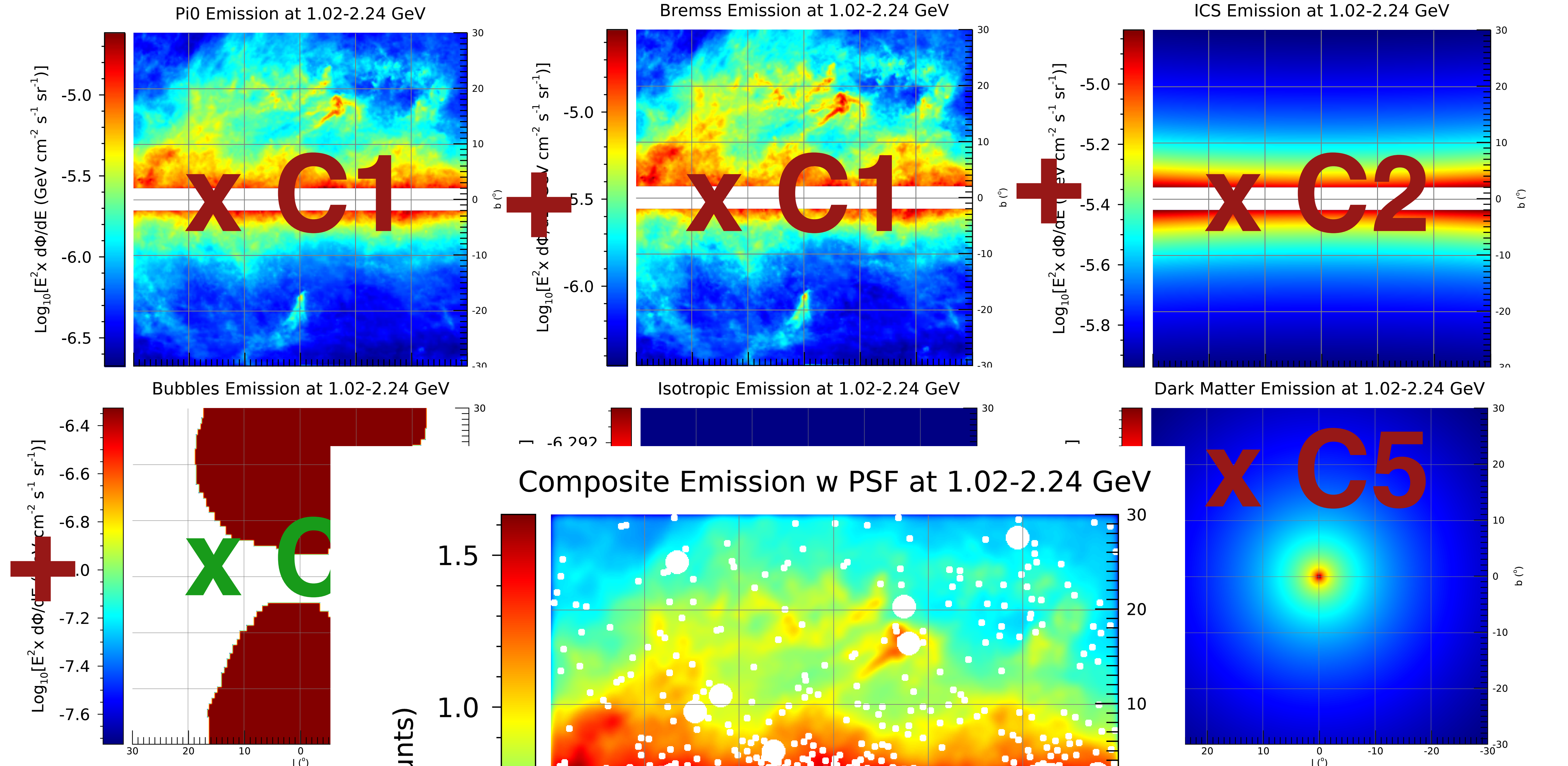
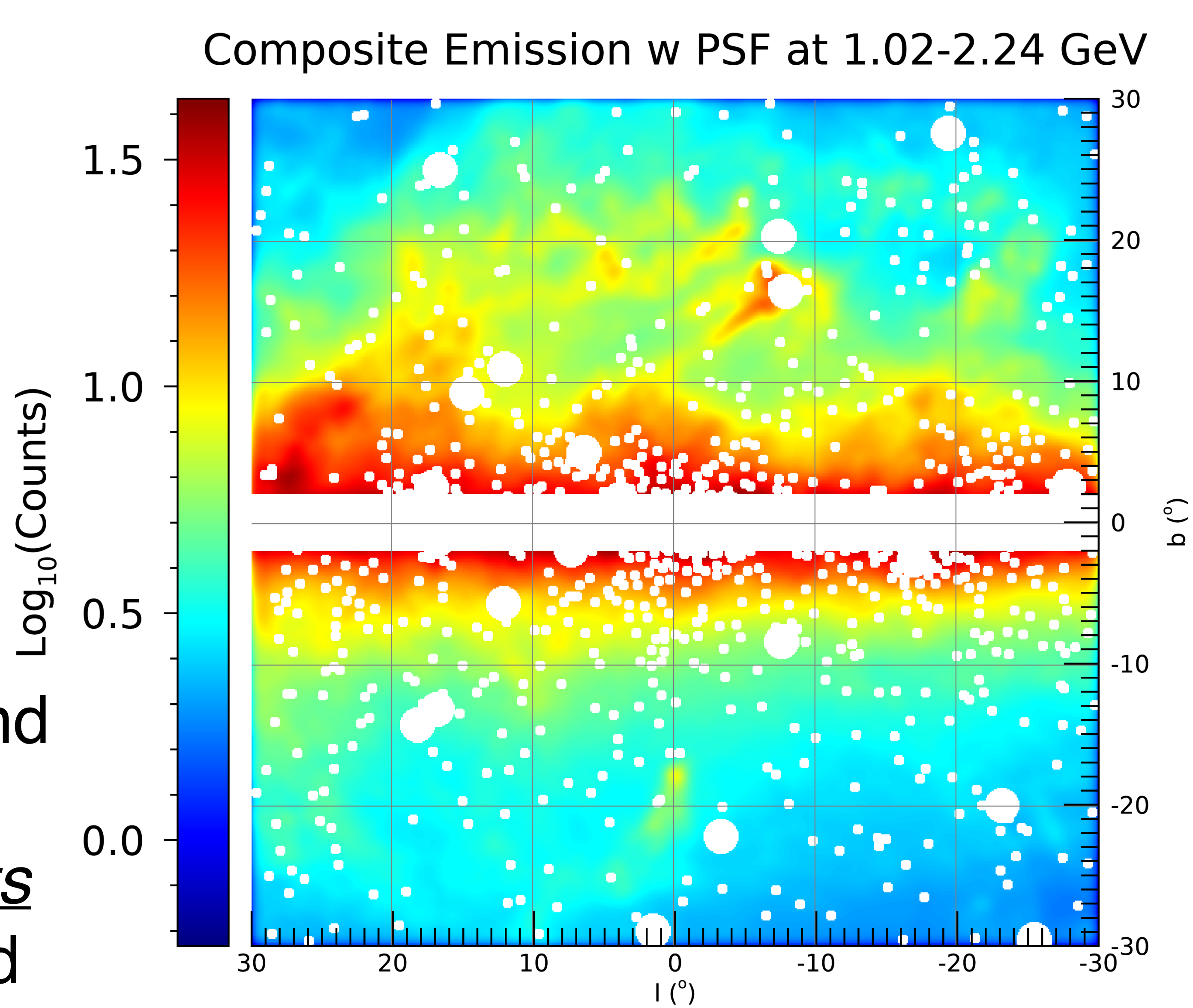
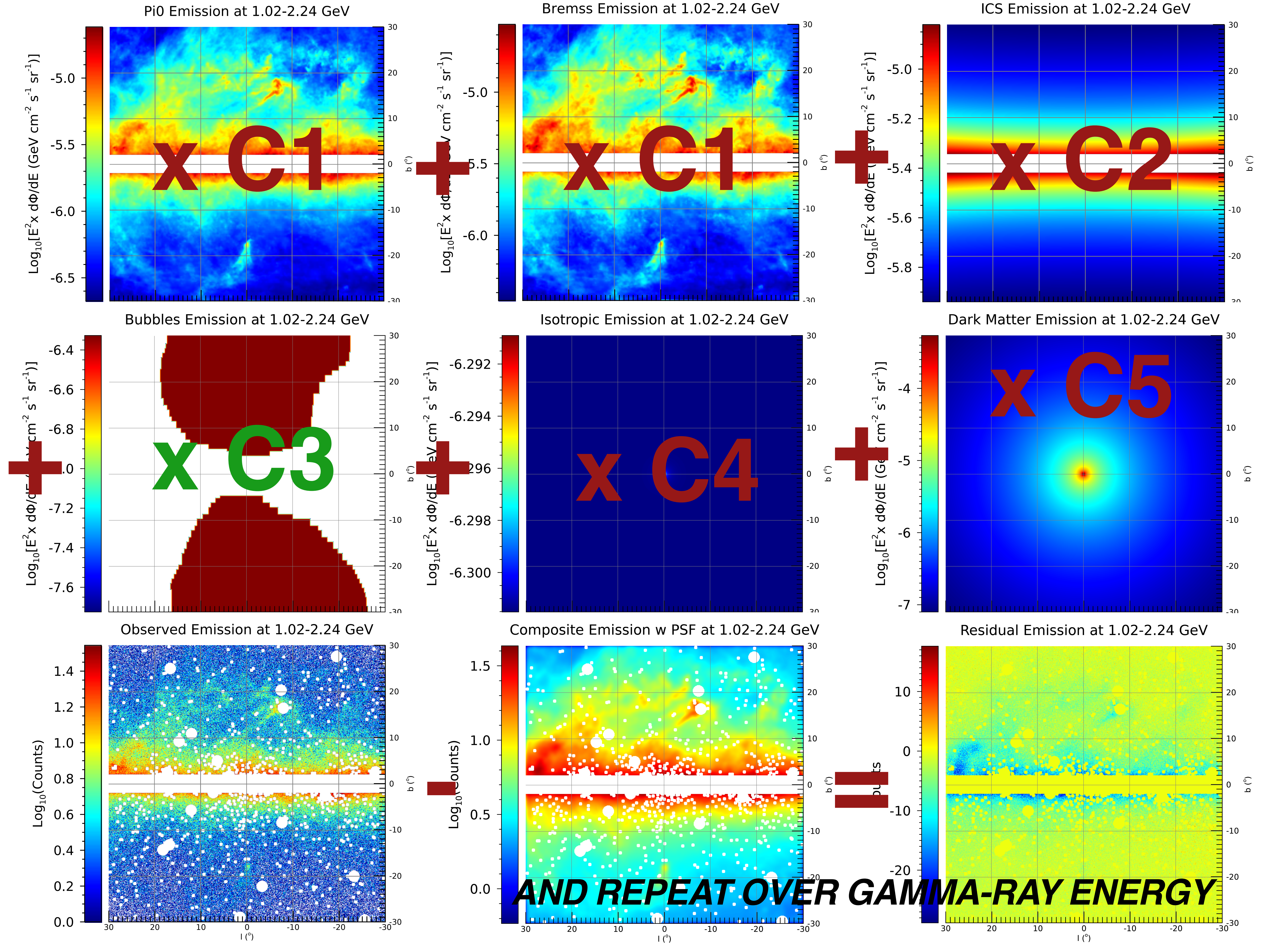
x C1
+
ICS Emission at 1.02-2.24 GeV
x C2
Bubbles Emission at 1.02-2.24 GeV
+
x C3
+
Isotropic Emission at 1.02-2.24 GeV
x C4
+
Dark Matter Emission at 1.02-2.24 GeV
x C5
Log10[E2x dΦ/dE (GeV cm-2 s-1 sr-1)]
l (°)
b (°)





Adding properly and accounting for *instrumental effects* as the point spread function and the non-uniform exposure (also masking-out bright point sources)



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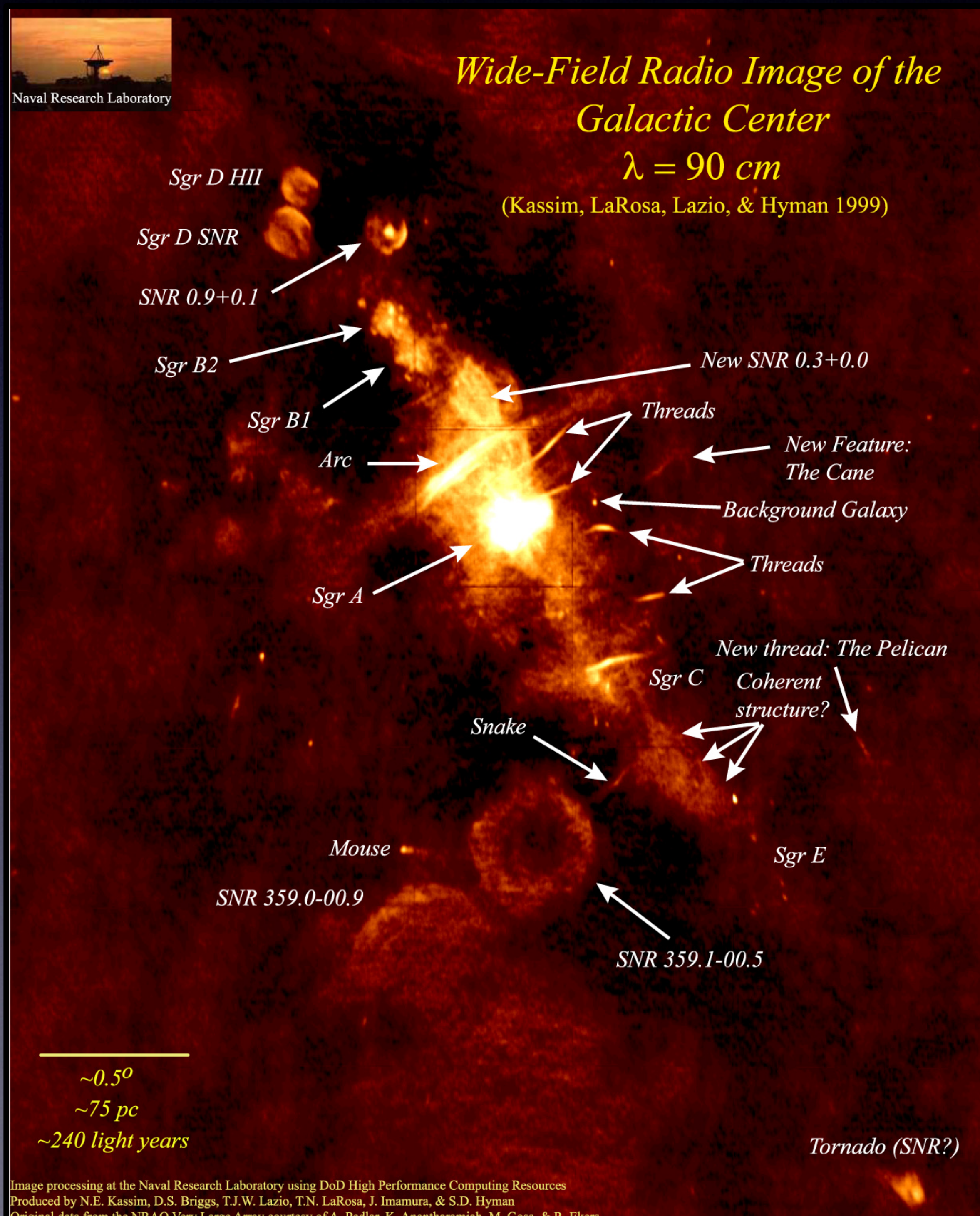
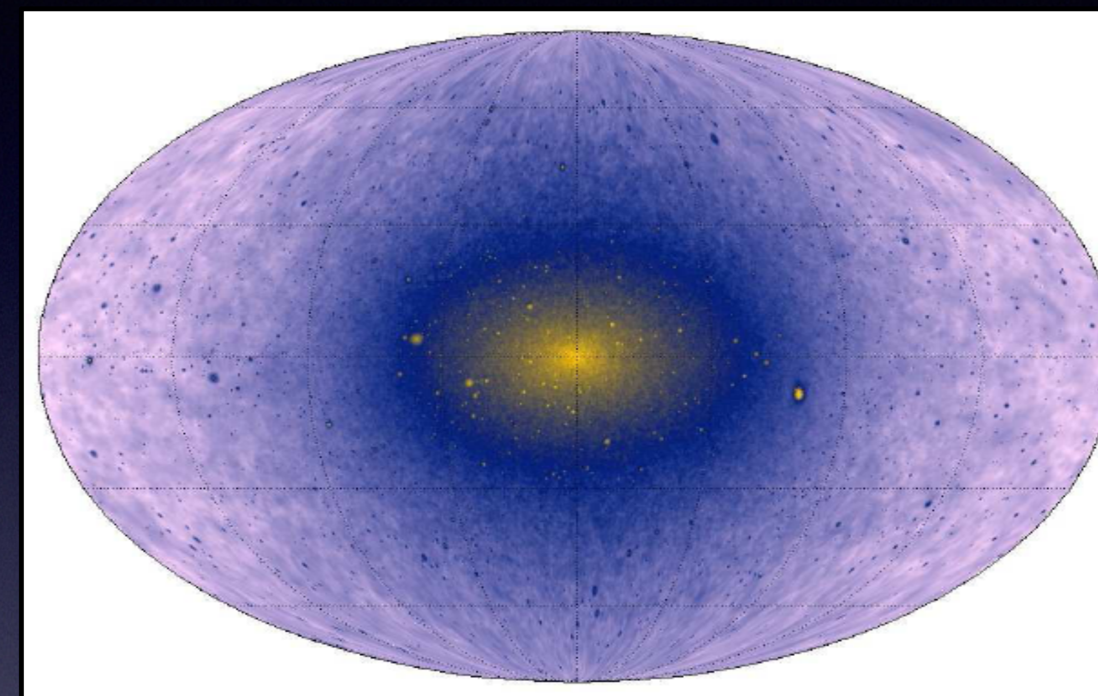
x C4
+
Dark Matter Emission at 1.02-2.24 GeV
x C5
Observed Emission at 1.02-2.24 GeV
-
Composite Emission w PSF at 1.02-2.24 GeV
=
Residual Emission at 1.02-2.24 GeV
AND REPEAT OVER GAMMA-RAY ENERGY
Log10[E2x dΦ/dE (GeV cm-2 s-1 sr-1)]
Log10(Counts)
l (°)
b (°)

The galactic center
A place to look for Dark Matter Annihilation

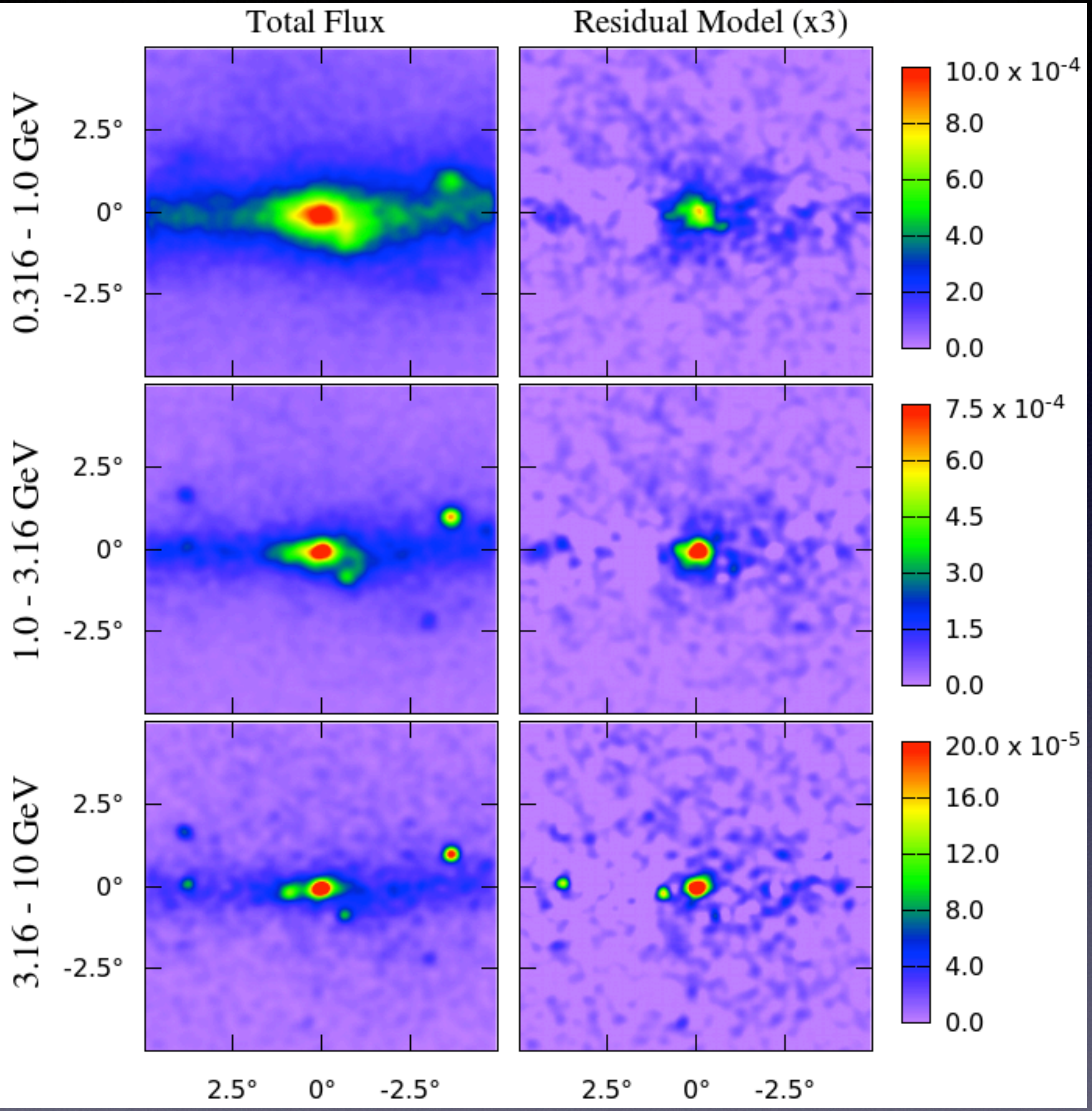




- The region of the galactic center is complex with large uncertainties.
- A DM annihilation signal peaks but also has significant uncertainties..
- Take advantage of multi-wavelength searches.

Looking for excesses in the galactic center

Using Templates:

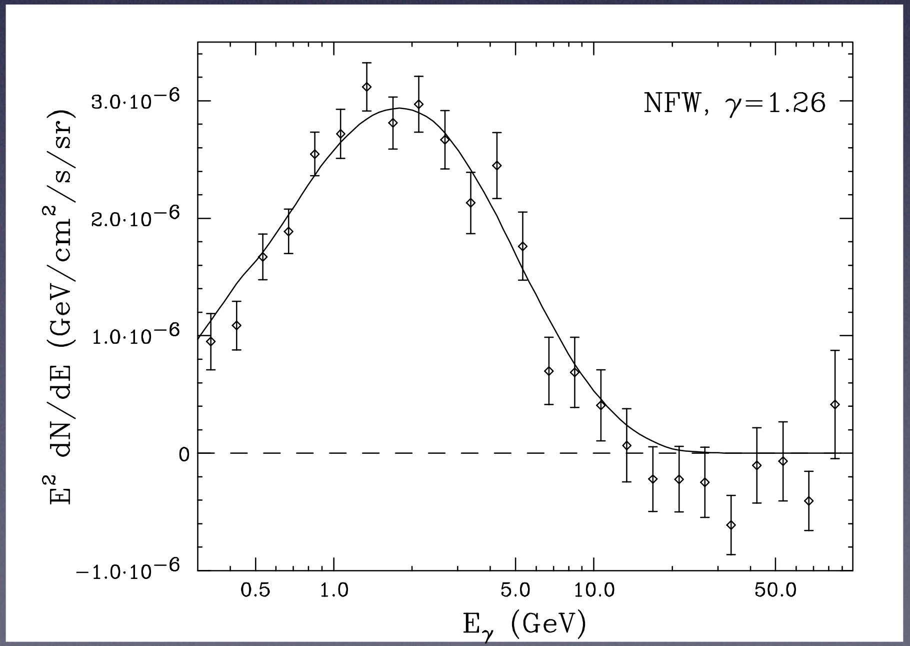


Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, PoDU 2015

Claim:

- A clear excess emission in the galactic center emerges
- Excess emission cuts-off at ~10 GeV (is in some dis-agreement with later findings)

Will call this excess emission the ***Galactic Center Excess (GCE)***

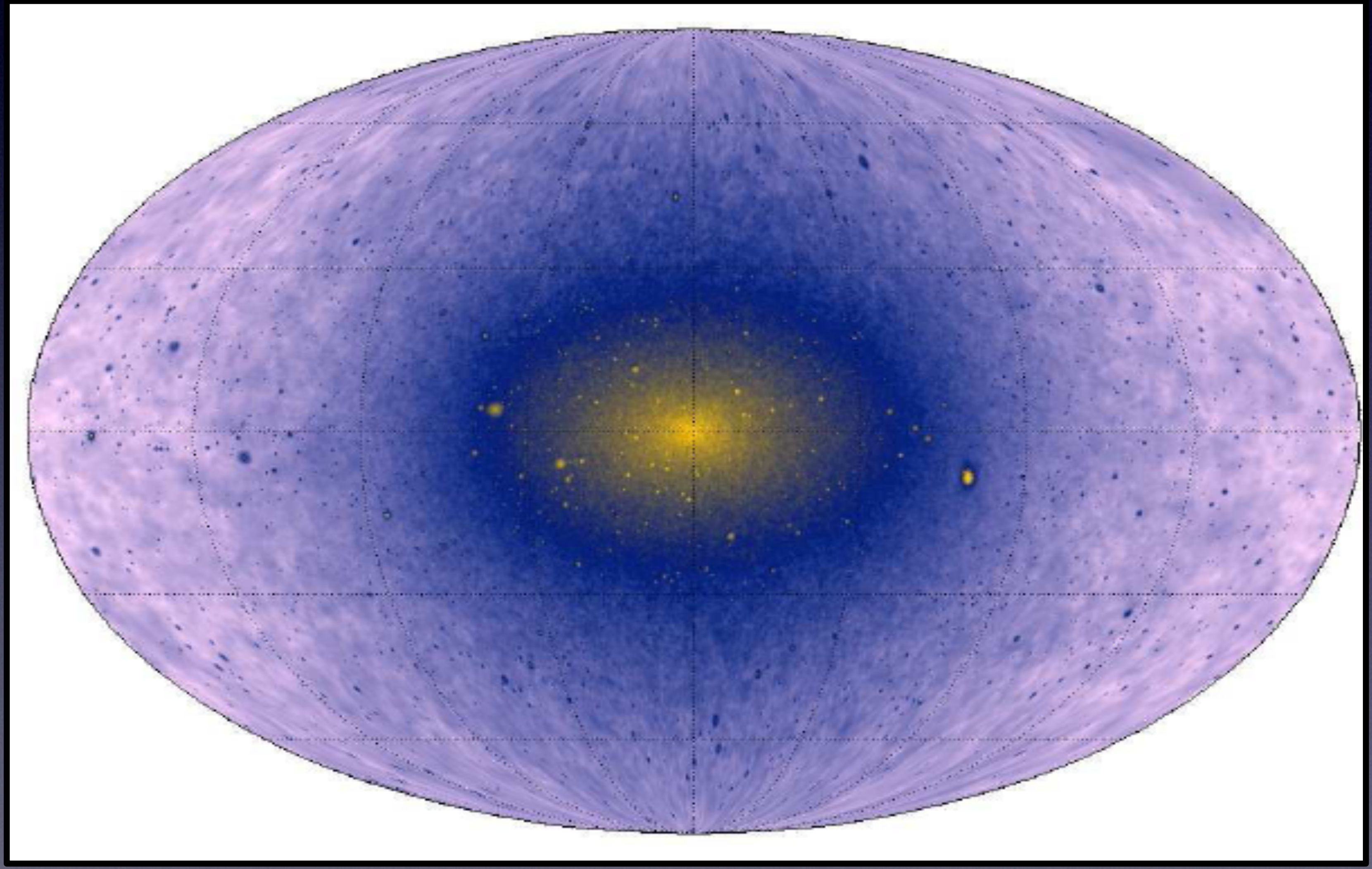


Also: Hooper & Goodenough PRL 2011, Abazajian JCAP 2011, Hooper & Linden PRD 2011, Gordon & Macias PRD 2014, Zhou et al. PRD 2015, Ajello et al. ApJ 2016

Going to High Latitudes (Inner Galaxy)

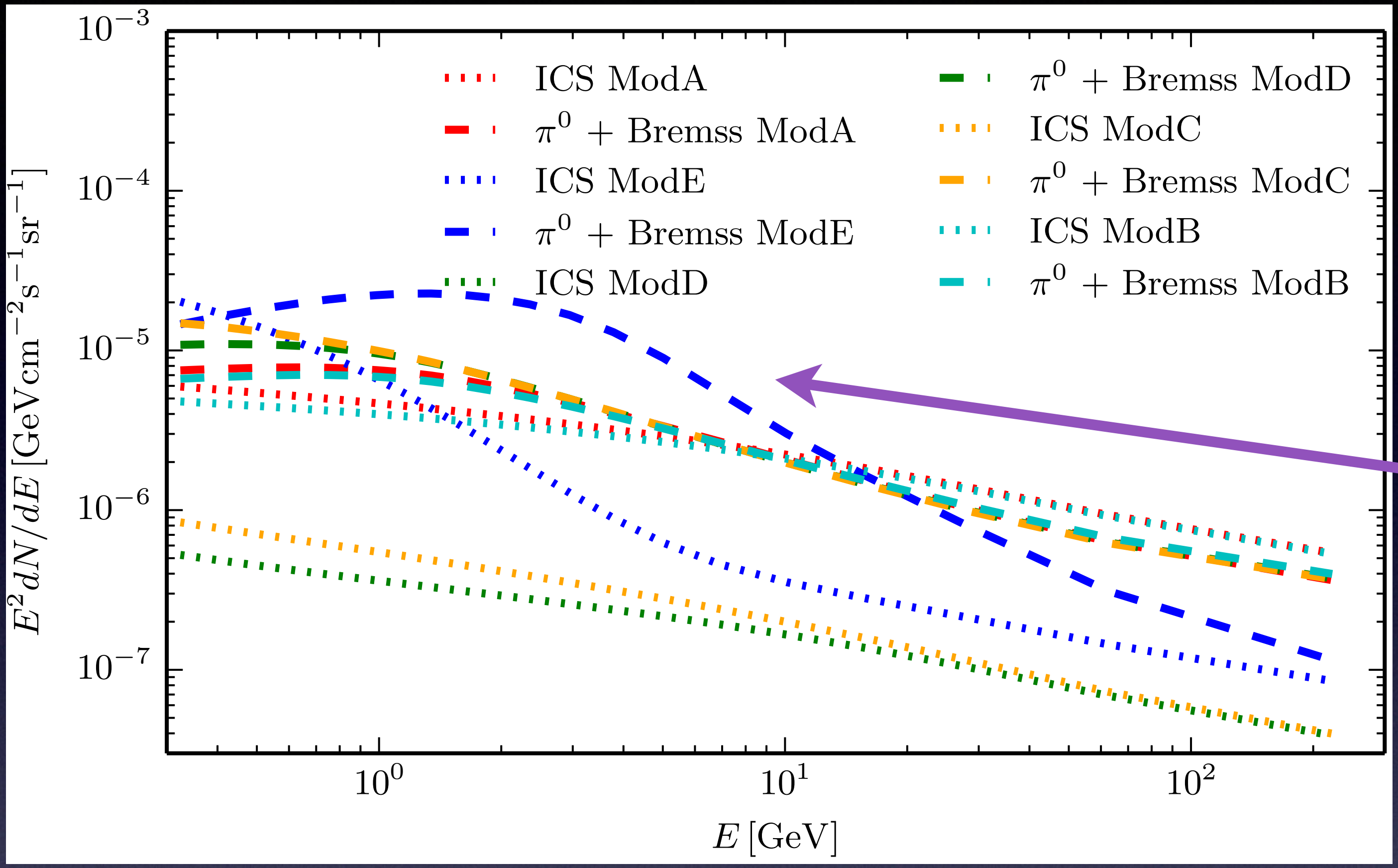
Advantages of looking further away from the center:

i)For a DM signal, you now have a prediction on the spectrum and its normalization based on the DM distribution.



ii) Different region on the galactic sky suffers from different uncertainties in the background gamma-ray flux.

Modeling the background gamma-ray sky: Interplay with Cosmic-Rays & the ISM

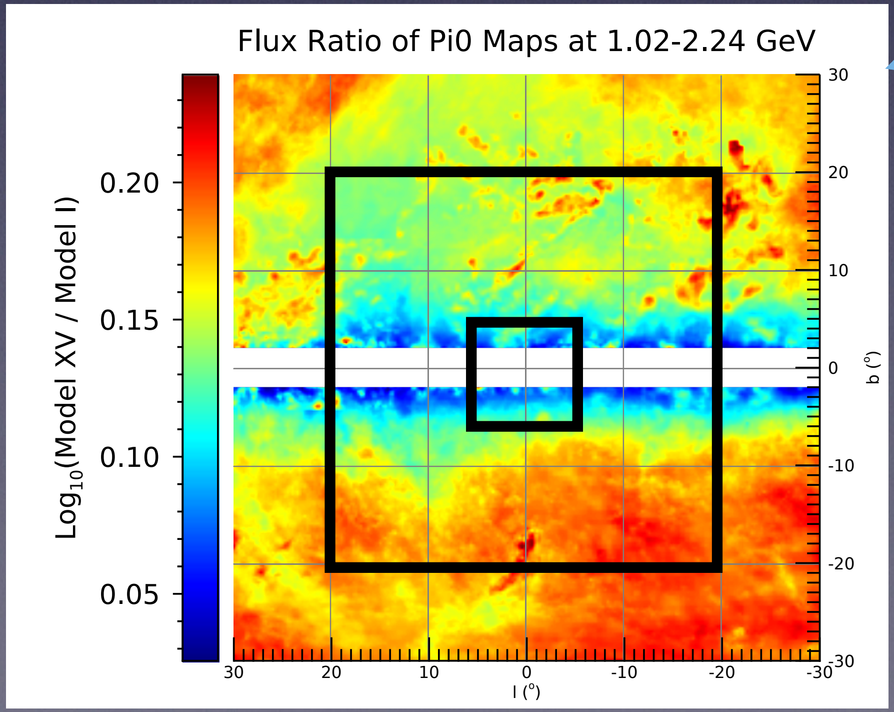


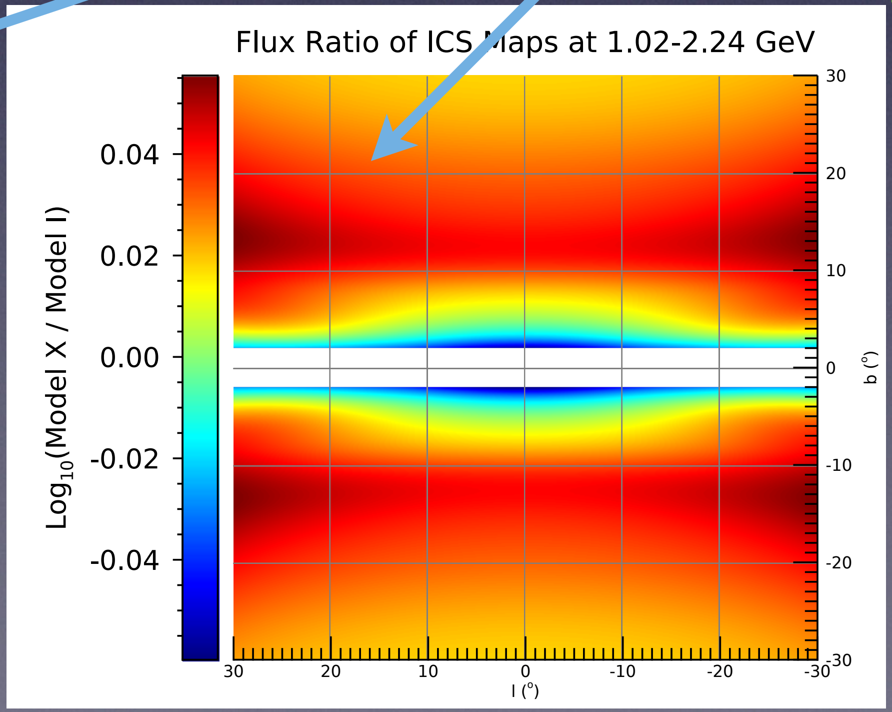
The exact astrophysics model assumptions can affect both the gamma-ray background spectrum and its morphology on the galactic sky.

Calore, **IC,** Weniger, JCAP 2015

IC, Zhong, McDermott, Surdutovich, PRD 2022

60 degrees in latitude

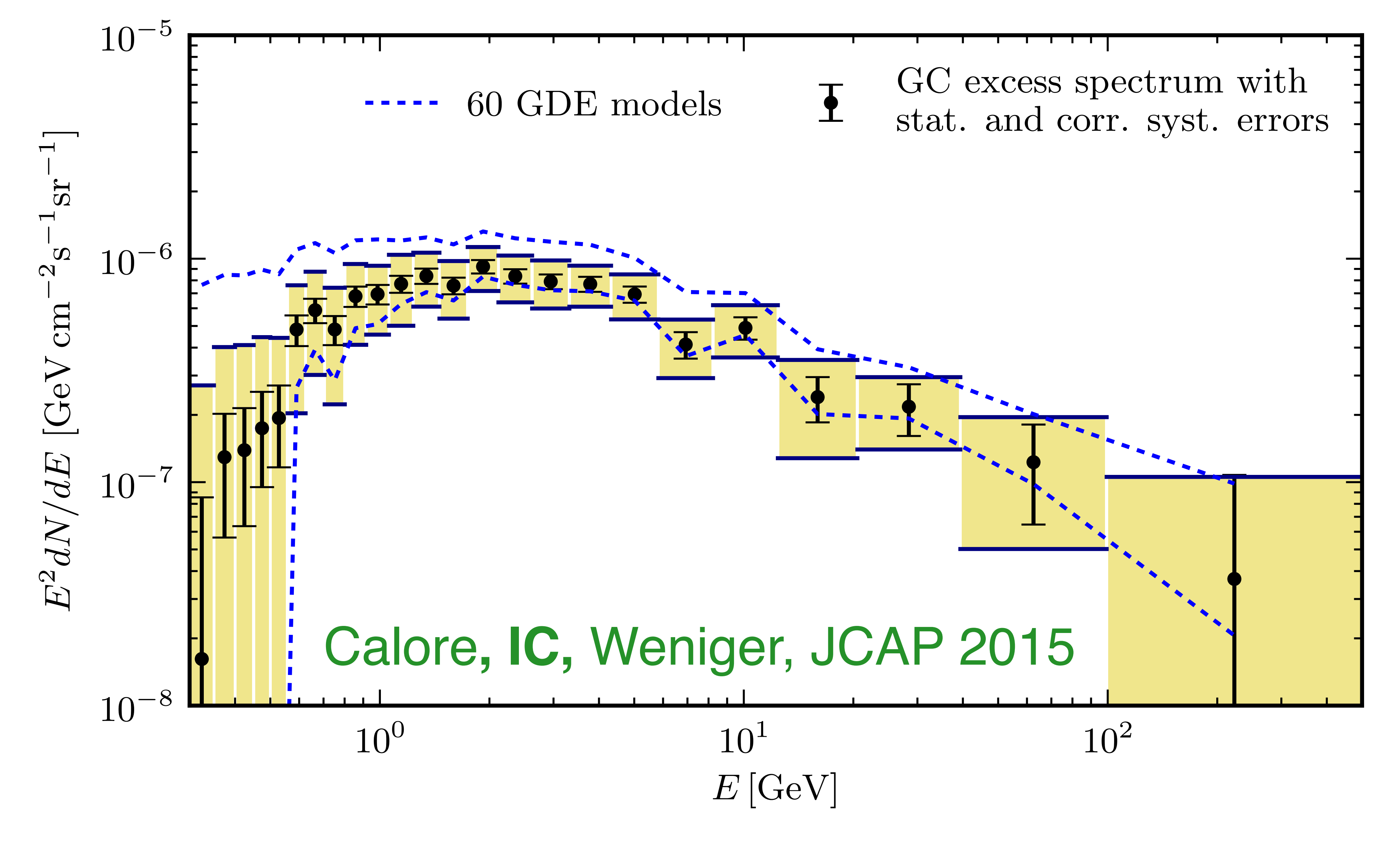




Accounting for the galactic diffuse emission uncertainties

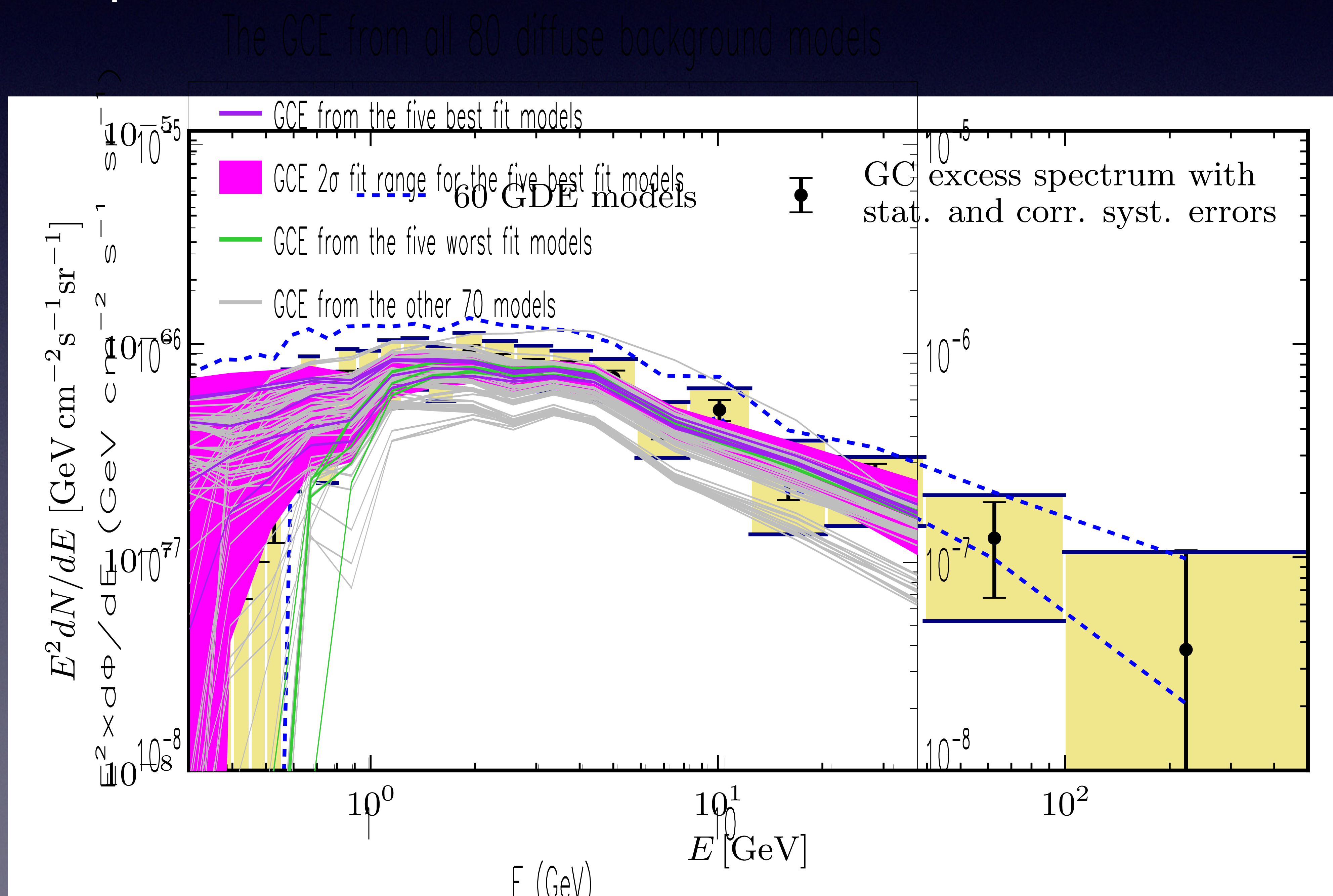
We use models, accounting for uncertainties related to the diffusion of CRs, the presence of convective winds, diffusive re-acceleration, energy losses, CR injection sources, gas and other interstellar medium properties. From the existing literature and in 2015 we created our own (60) models—> 6660 different Templates!

It turns out that it actually does not affect dramatically the excess spectrum:



Accounting for the galactic diffuse emission uncertainties

We use models, accounting for uncertainties related to the diffusion of CRs, the presence of convective winds, diffusive re-acceleration, energy losses, CR injection sources, gas and other interstellar medium properties. To account for new observations in 2020-2021 we created and tested 45K high resolution templates.



IC, Zhong, McDermott, Surdutovich, PRD 2022

Maps, Astrophysical Models and Correlated Errors publicly available via Zenodo

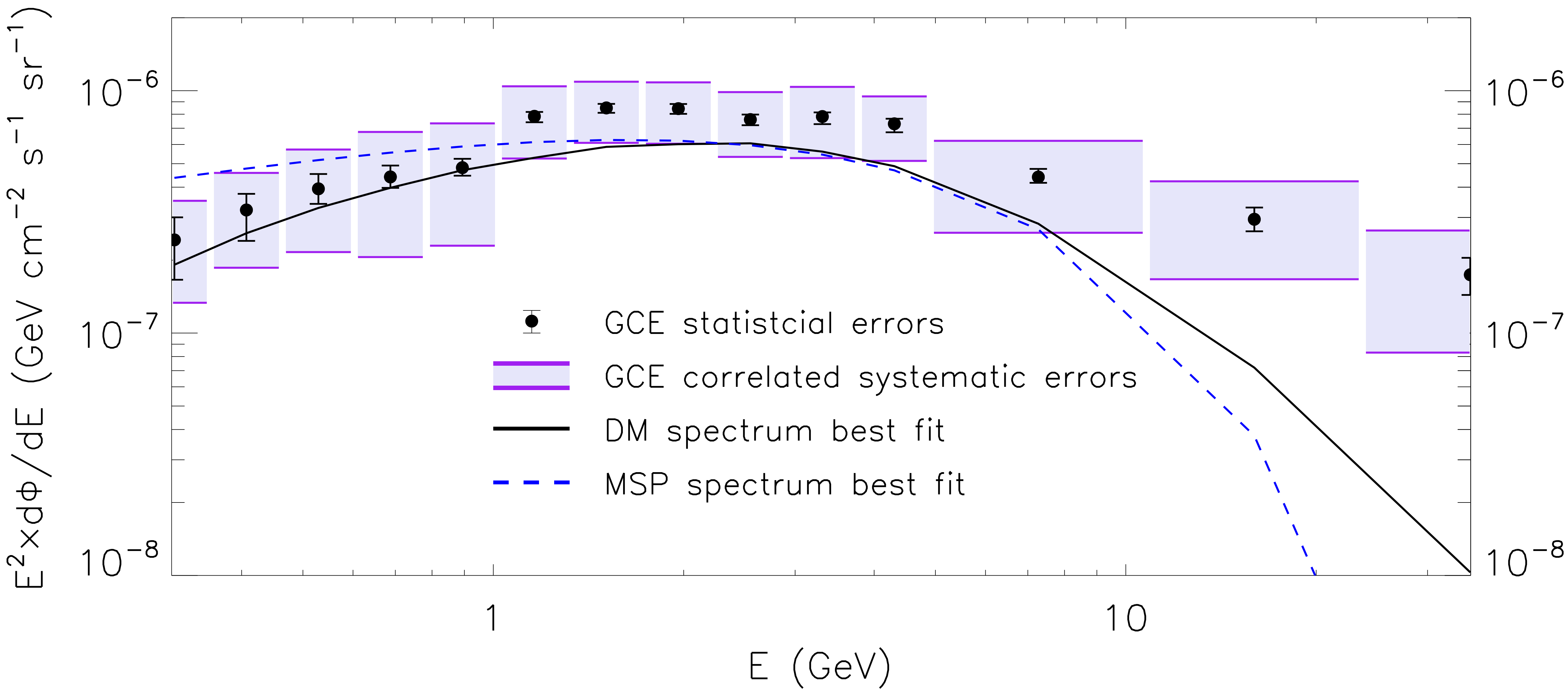
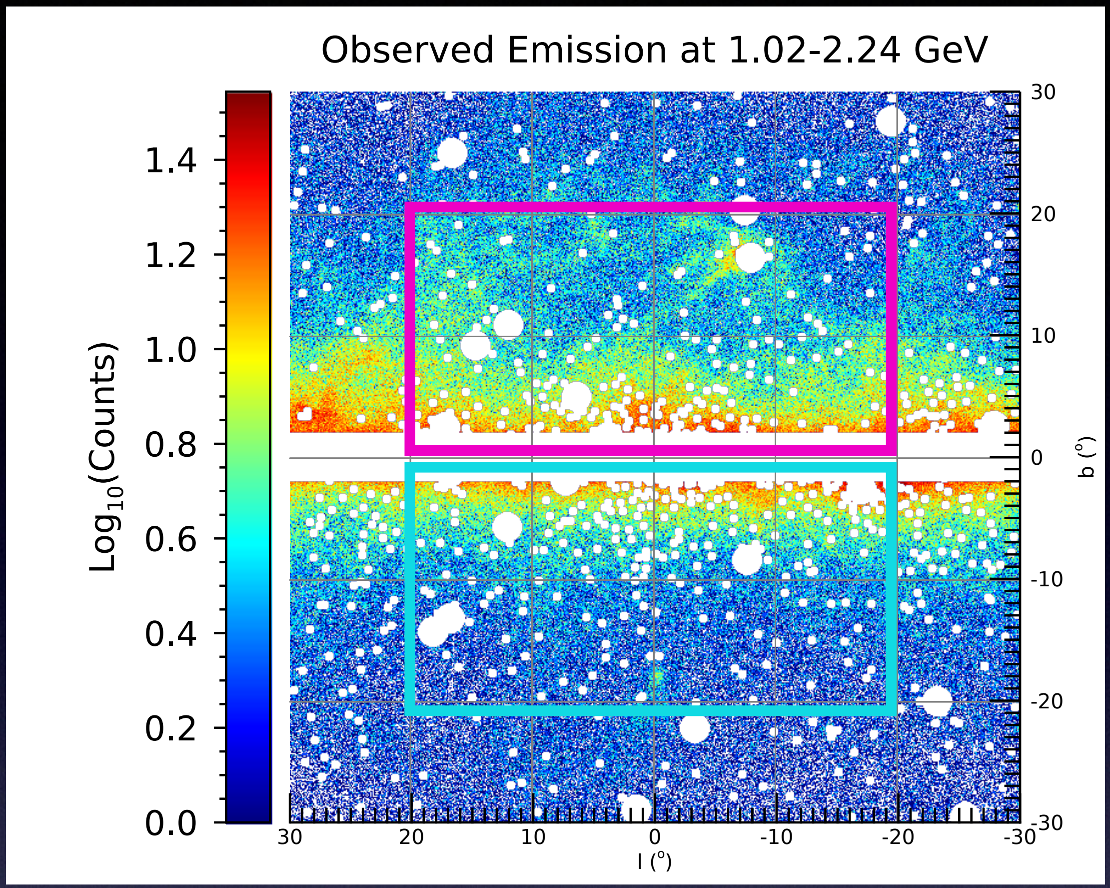


TABLE V. The first four principal components of the systematic uncertainty contribution to the covariance matrix, defined as in Eq. (16), in units of 10^{-7} GeV cm^{-2} s^{-1} sr^{-1}.

PC_i	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	Φ_6	Φ_7	Φ_8	Φ_9	Φ_{10}	Φ_{11}	Φ_{12}	Φ_{13}	Φ_{14}
PC_1	2.52	2.37	2.47	2.43	2.19	2.35	2.08	1.83	1.65	1.69	1.38	1.09	0.67	0.34
PC_2	−1.70	−1.07	−0.16	0.14	0.54	0.42	0.40	0.31	0.58	0.41	0.56	0.48	0.41	0.33
PC_3	0.27	0.06	−0.53	−0.22	−0.21	−0.18	−0.08	0.25	0.04	0.45	0.23	0.24	0.20	0.24
PC_4	0.20	−0.15	0.15	−0.14	0.06	−0.04	−0.04	−0.27	0.08	−0.25	0.11	0.25	0.27	0.17

The profile for the GCE. Does it look like a DM signal?

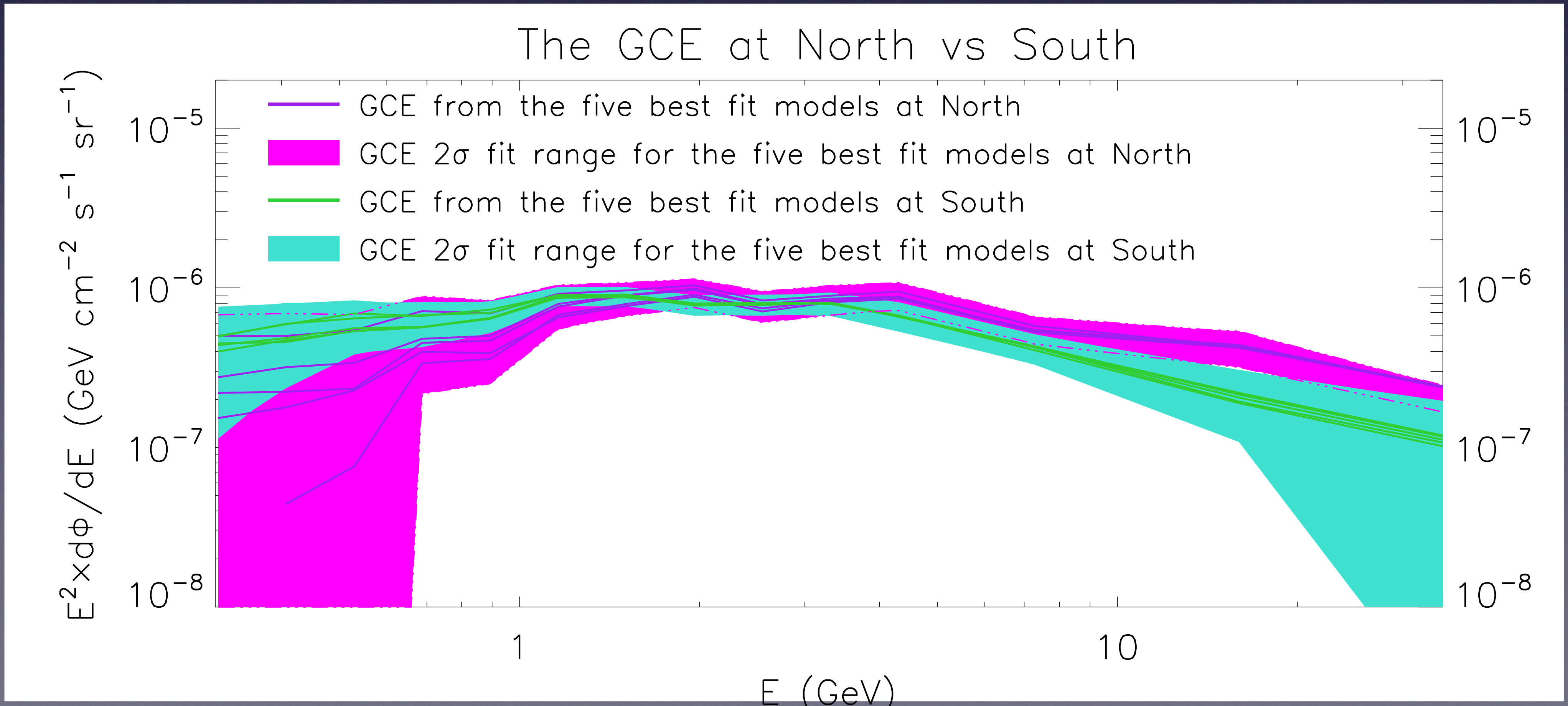
IC, Zhong, McDermott, Surdutovich, PRD 2022



North

South

Roughly consistent between southern and northern galactic hemisphere as expected from dark matter



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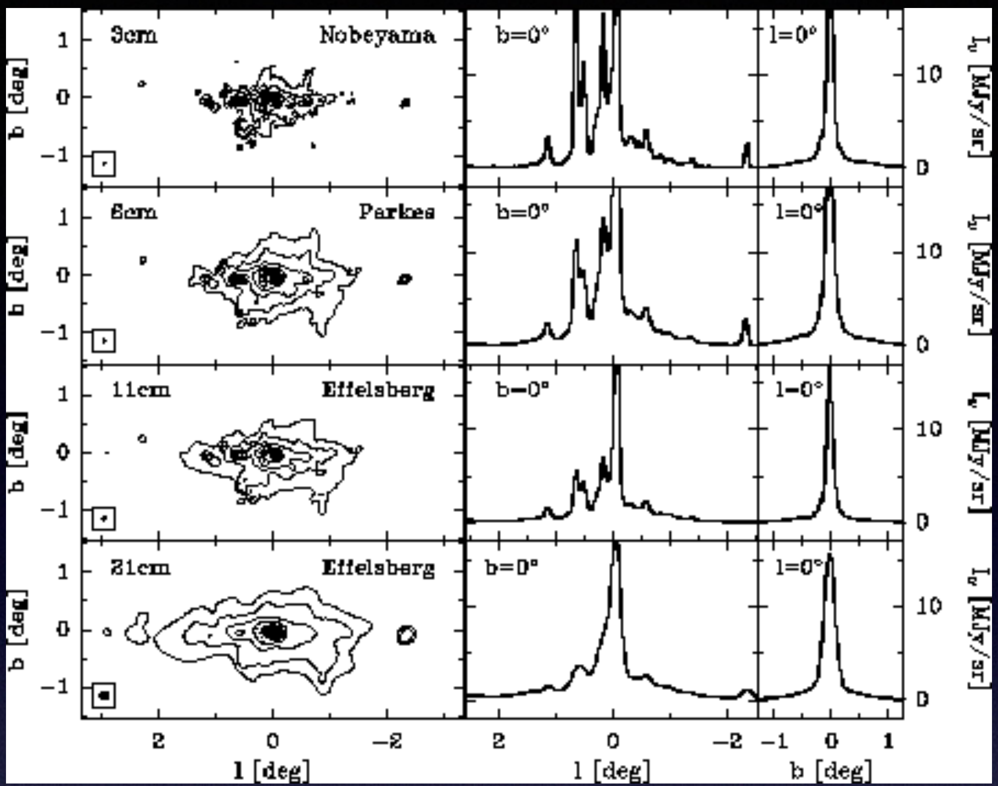
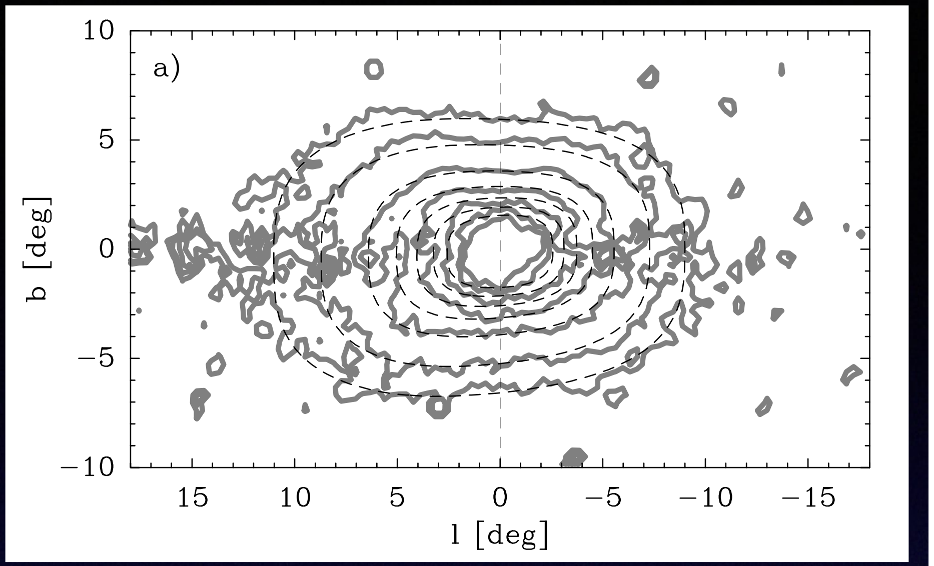
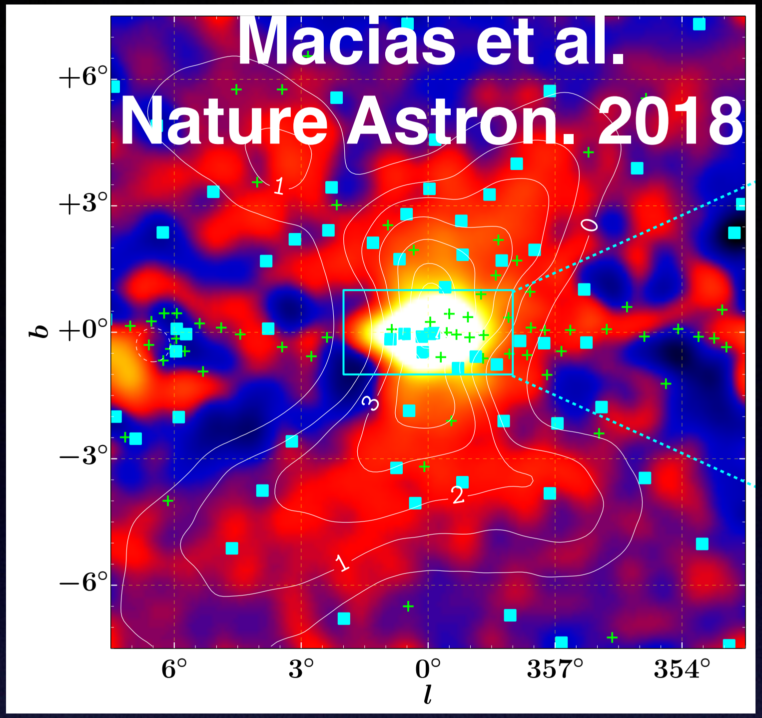


Nuclear Bulge @ Radio



Boxy Bulge @ 2-5 μm

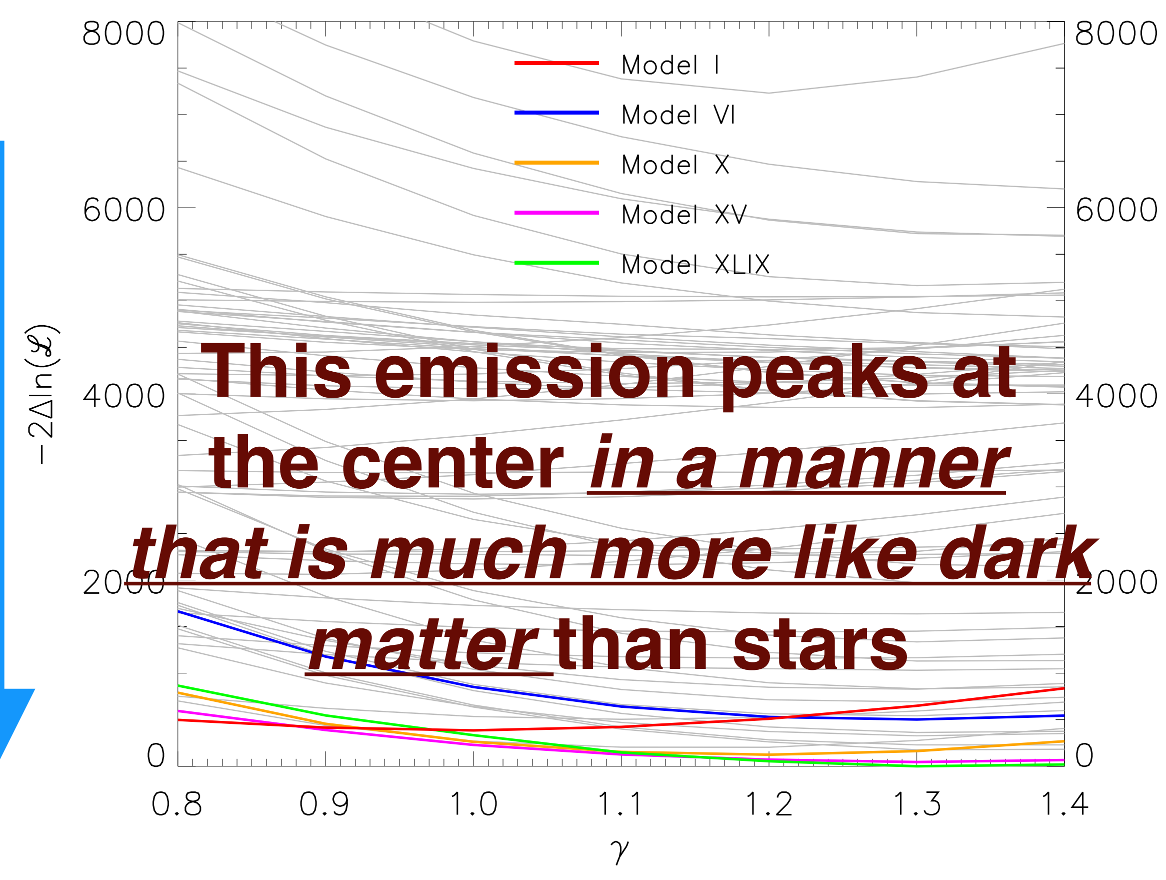
Launhardt et al. A&A 2002



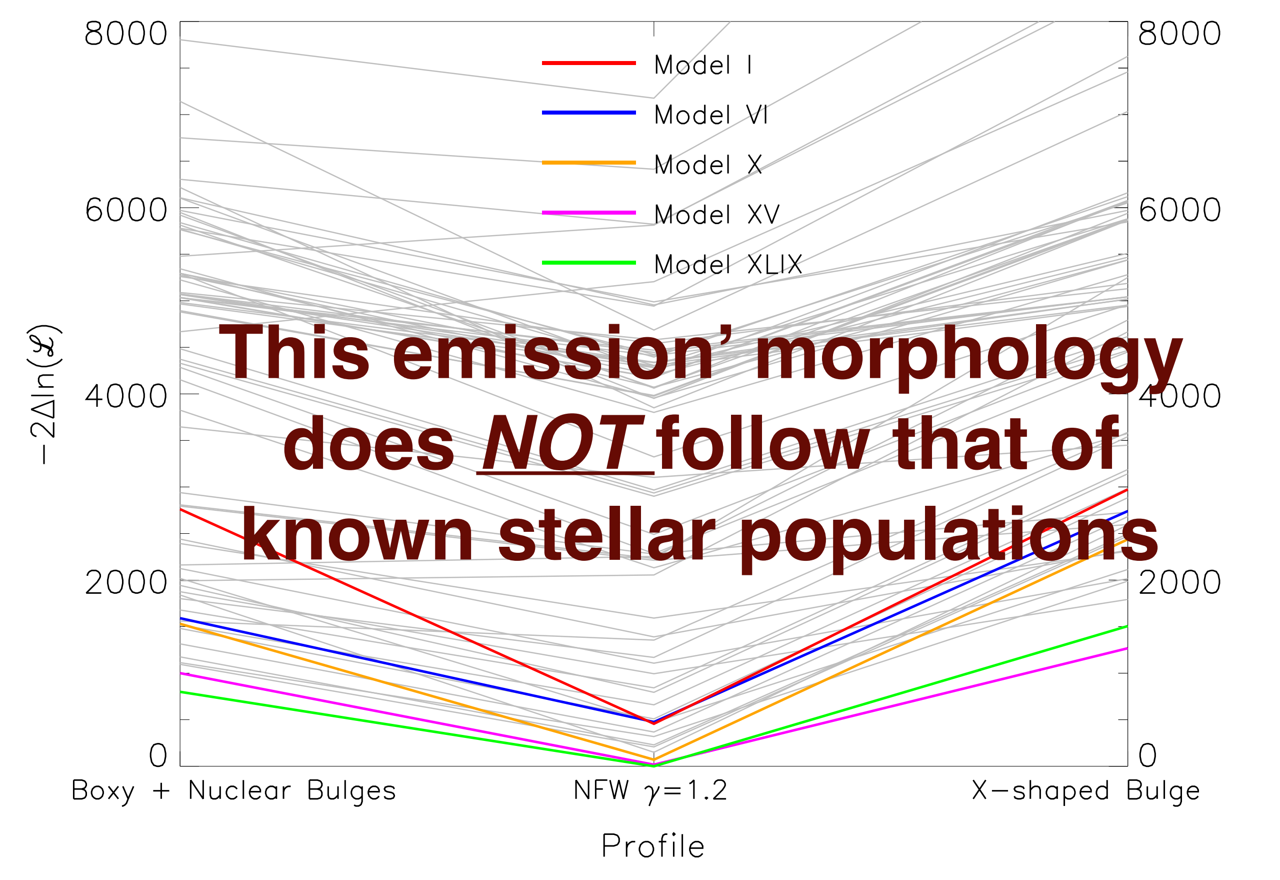
X-shaped Bulge @ "low" gamma-rays

IC, Zhong, McDermott, Surdutovich, PRD 2022

Statistical Preference



This emission peaks at the center *in a manner that is much more like dark matter* than stars



This emission' morphology does *NOT* follow that of known stellar populations

The background assumptions on the galactic diffuse emission affect the derived conclusions on the GCE.

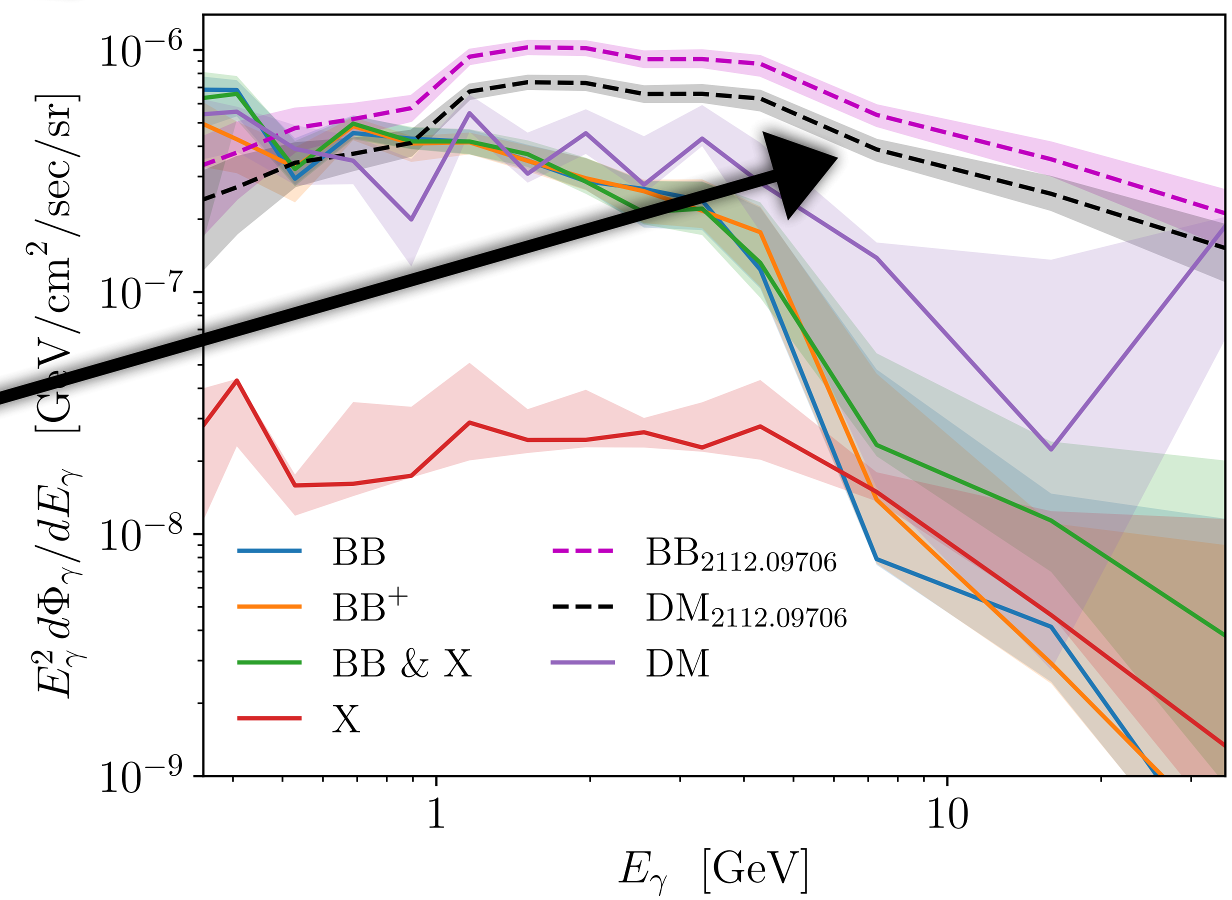
McDermott, Zhong, **IC** (arXiv:2209.00006)

Comparing astrophysically motived templates (IC et al. 2022) vs ring-based templates (Pohl et al. 2022).

TABLE I. Comparison of models of the GCE. The first six results, generated in this work, rely on the ring-based method of [23] to describe astrophysical emission. The final three results utilize templates from [15].

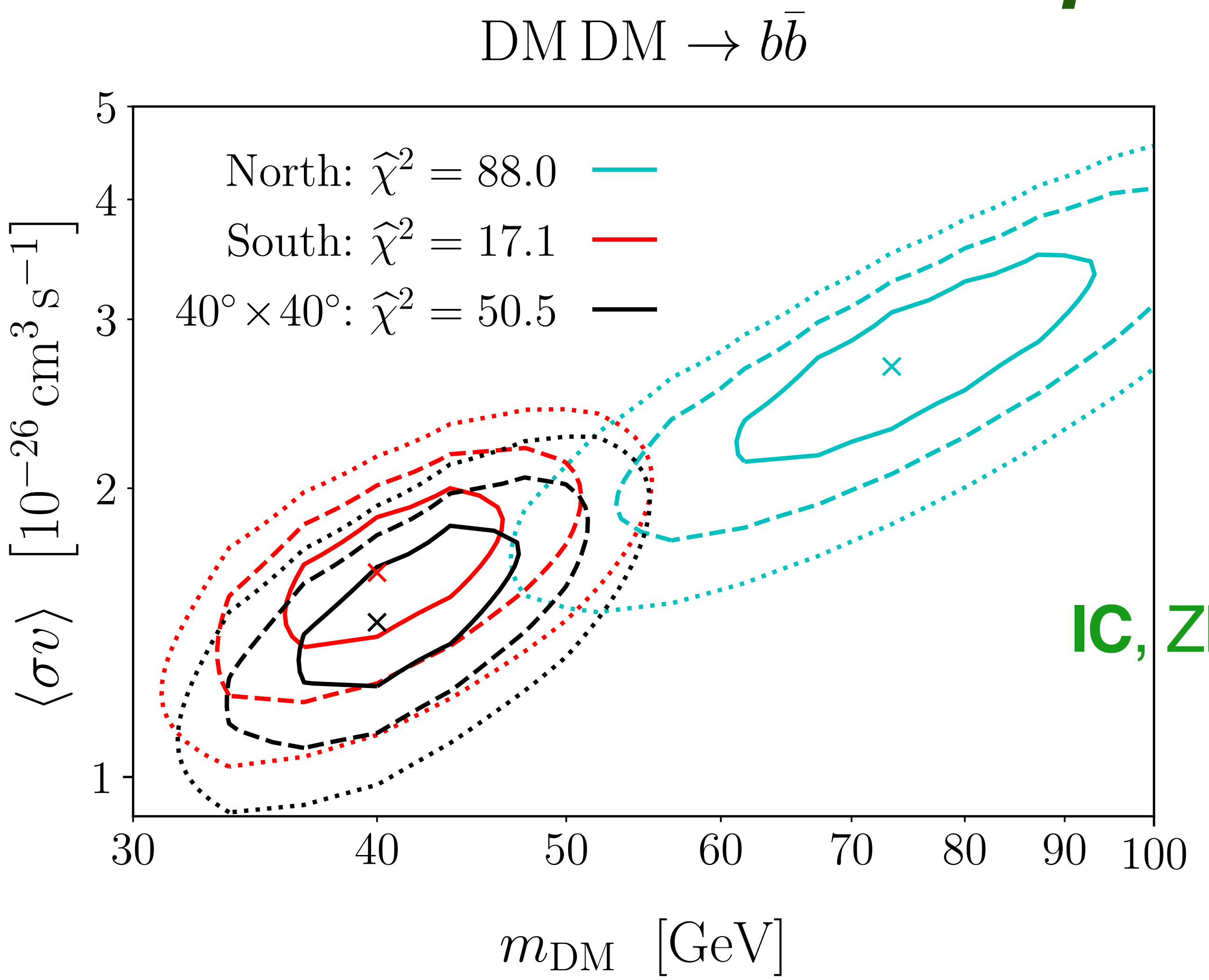
Excess Model	Bgd. Templates	$-2\Delta\ln\mathcal{L}$	$\Delta\ln\mathcal{B}$
No Excess	rings [23]	0	0
X-Shaped Bulge	rings [23]	+30	−190
Dark Matter	rings [23]	−237	+12
Boxy & X-Shaped Bulges	rings [23]	−634	+178
Boxy Bulge	rings [23]	−724	+228
Boxy Bulge "plus"	rings [23]	−765	+311
No Excess	astrophysical [15]	−4539	+2933
Boxy Bulge	astrophysical [15]	−6398	+3814
Dark Matter	astrophysical [15]	−7288	+4268

The statistically best models give preference for a more spherical GCE morphology



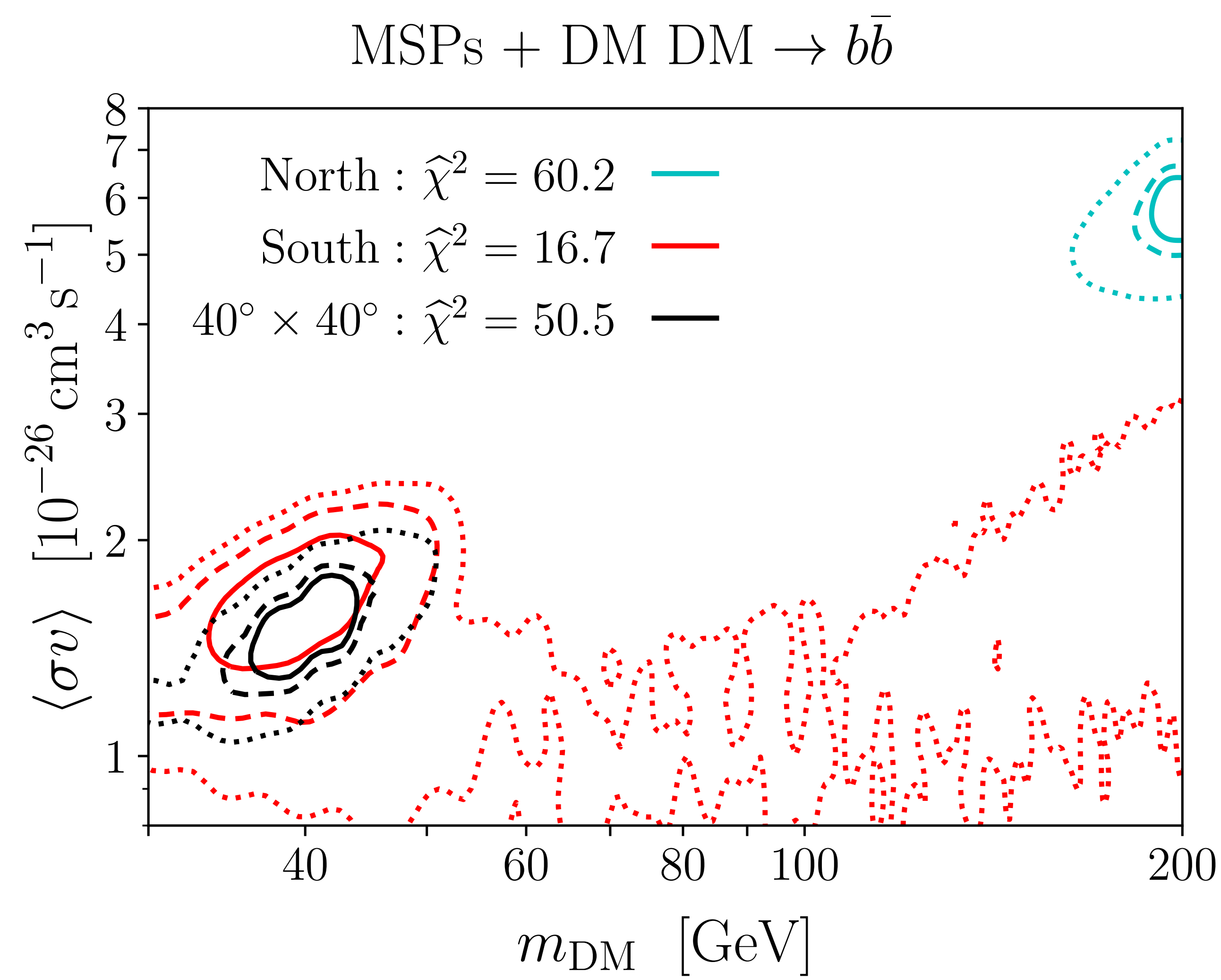
And also a preference for a harder GCE spectrum at higher energies (and also a smoother spectrum).

If this is a DM annihilation signal what do we learn about the particle physics?



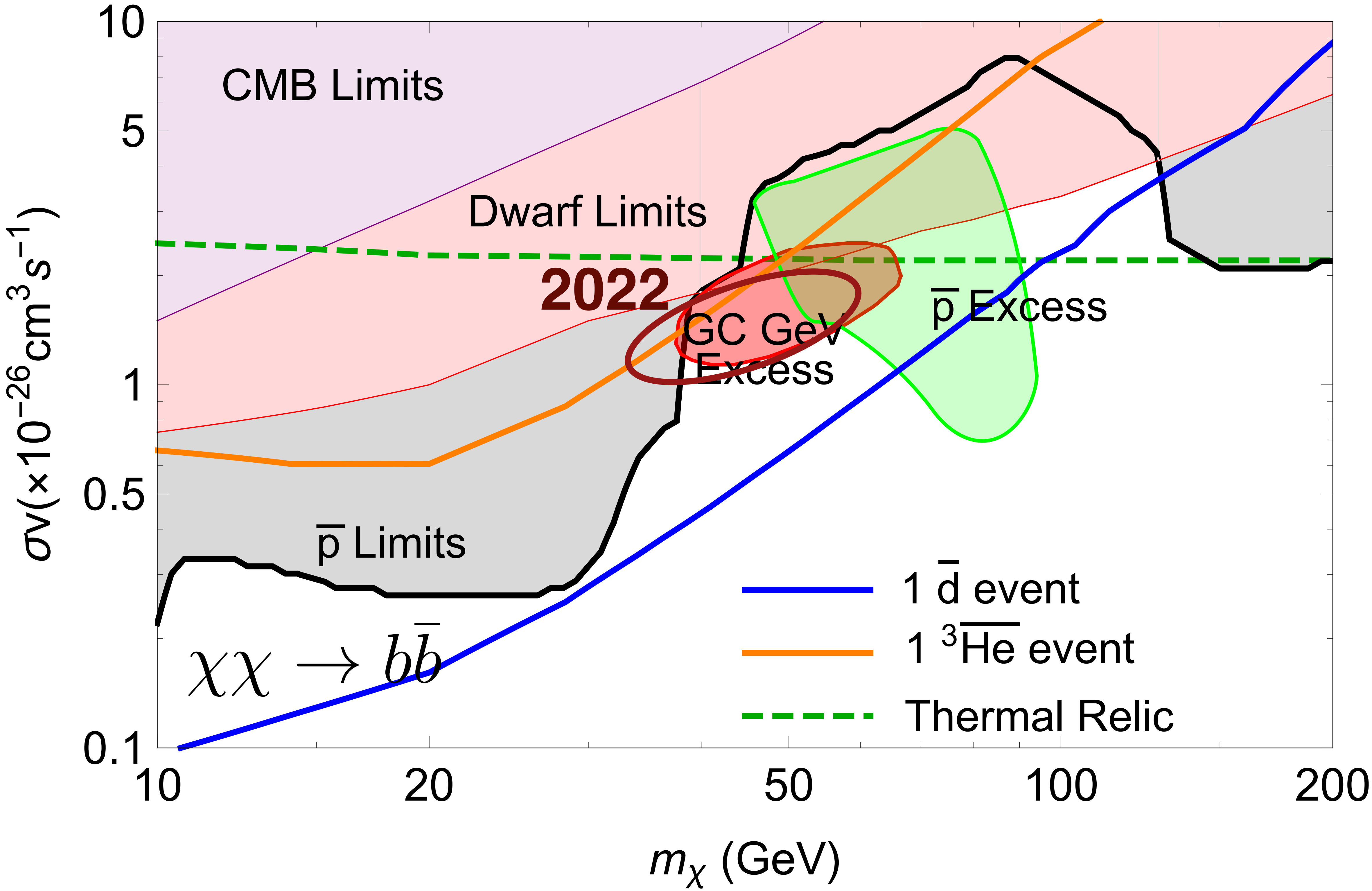
The mass range preferred very much within the WIMP range.

IC, Zhong, McDermott, Surdutovich, PRD 2022



Adding an MSP component affects the fits on the more “dirty” (more galactic gas) Northern Hemisphere, but the Southern Hemisphere and the overall Inner Galaxy fit are fairly unaffected.

Combining all Indirect DM searches



IC, Linden, Hooper PRD 2020

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MSGC, NASA No. NNX15AJ20H
MSGC, NASA No. 80NSSC20M0124

Oakland University Research Fellowship

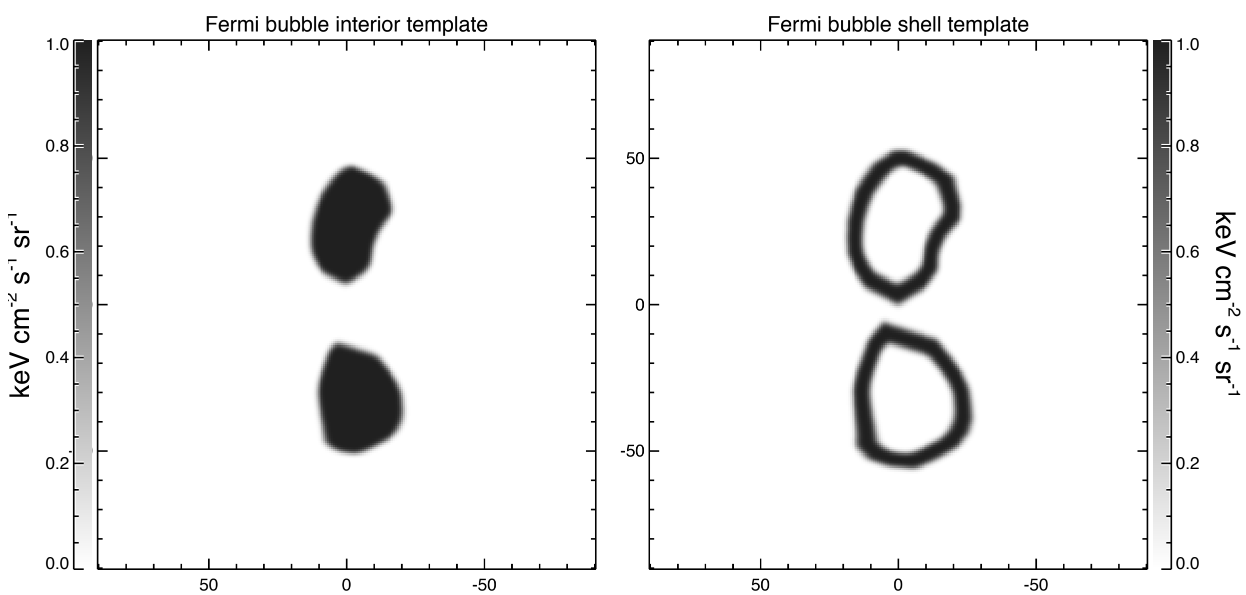
Department of Energy, DE-SC0022352

Thank you!

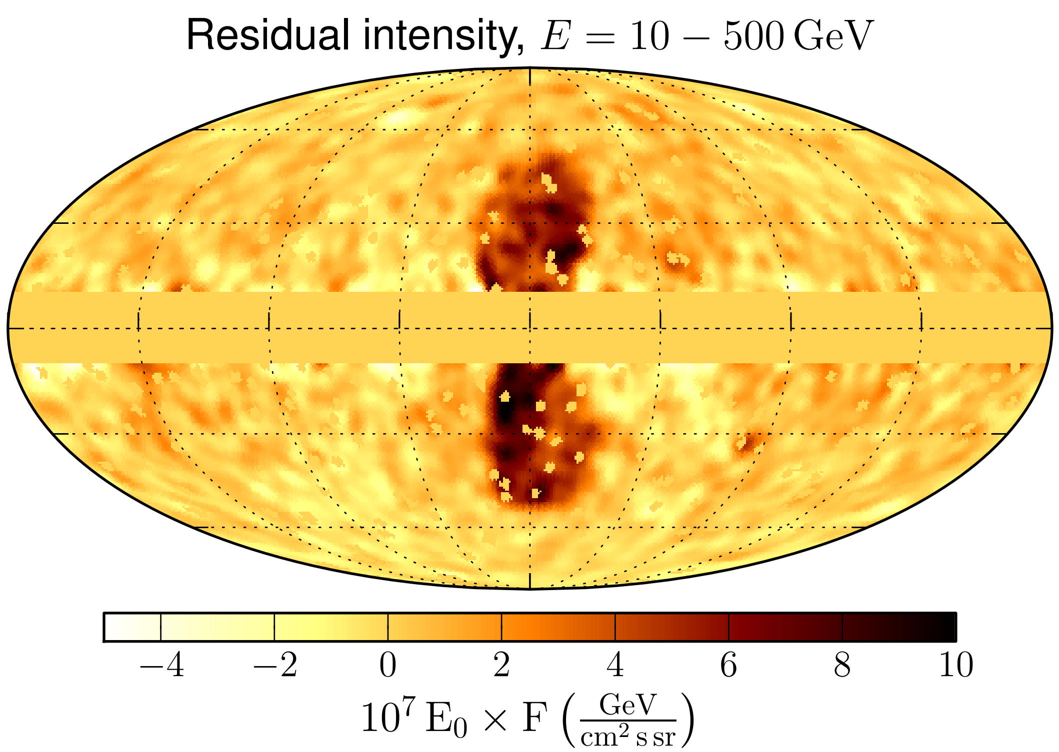
Extra

Fermi Bubbles

Su, Slatyer, Finkbeiner ApJ 724, 1044 (2010)

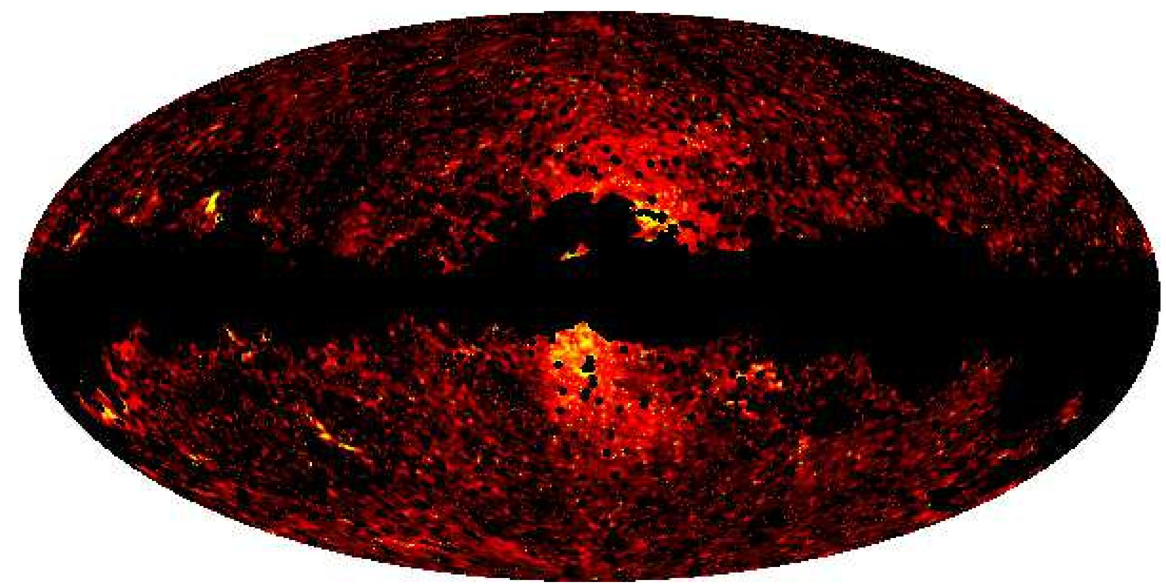


Discovery of edges on the emission.



Fermi-LAT Collaboration Result ApJ 2014

Planck* intermediate results. IX. Detection of the Galactic haze with *Planck



Planck Coll. A&A 2013

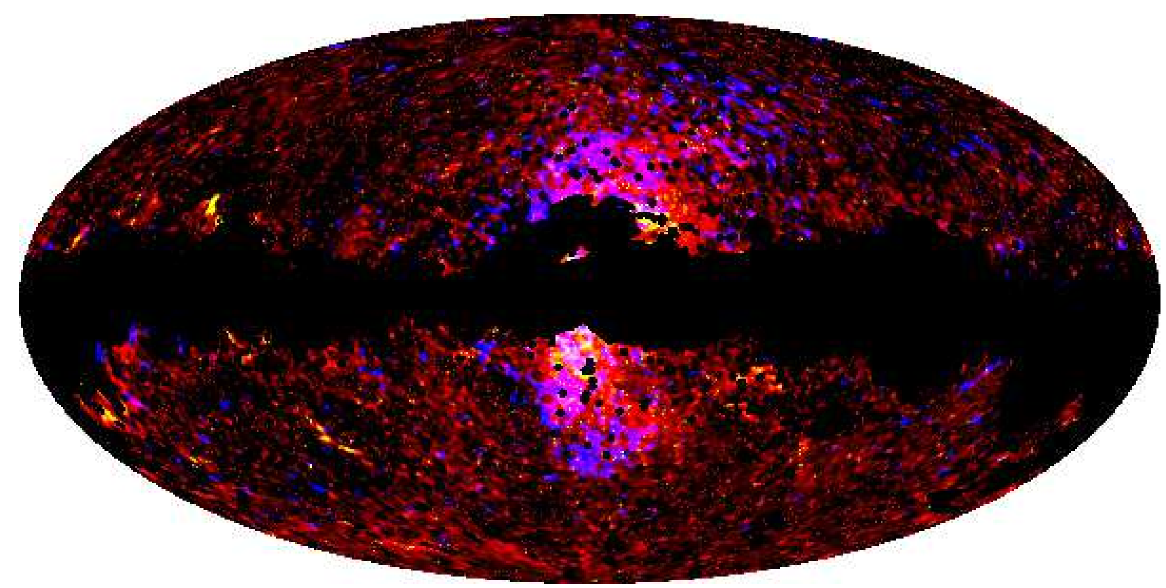
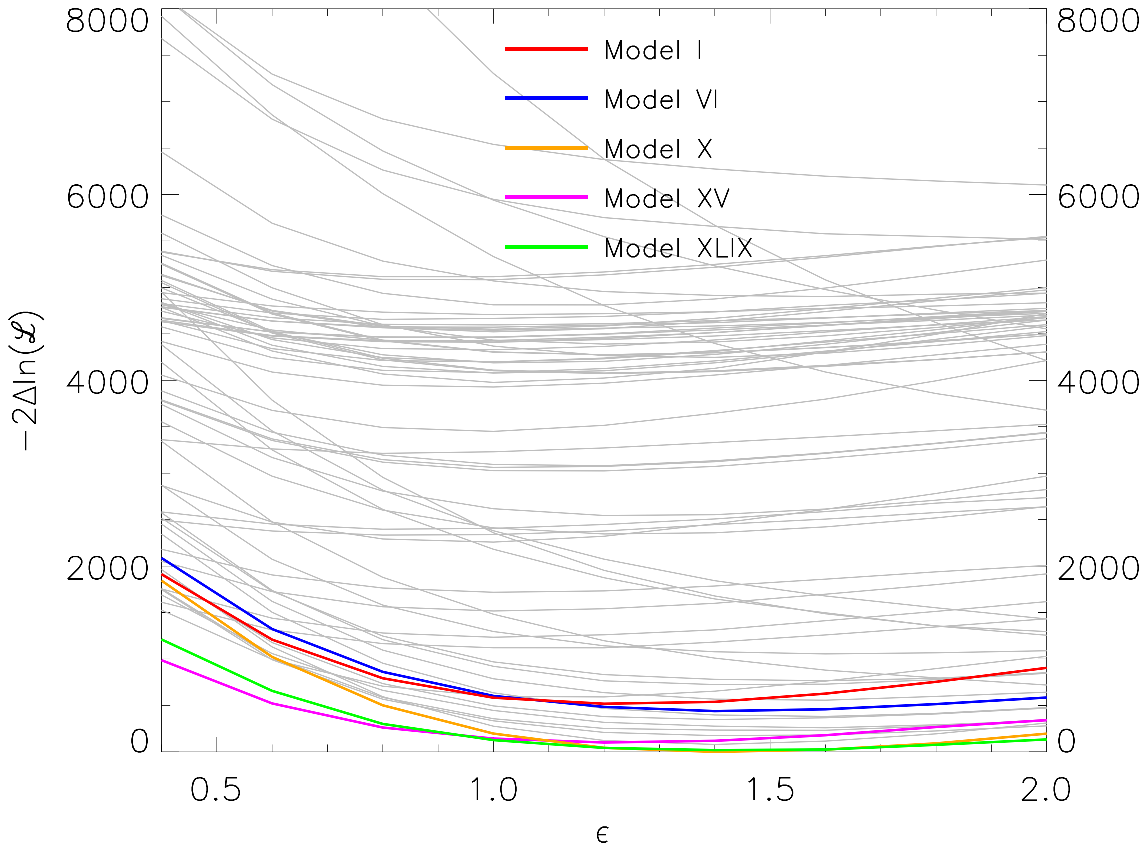
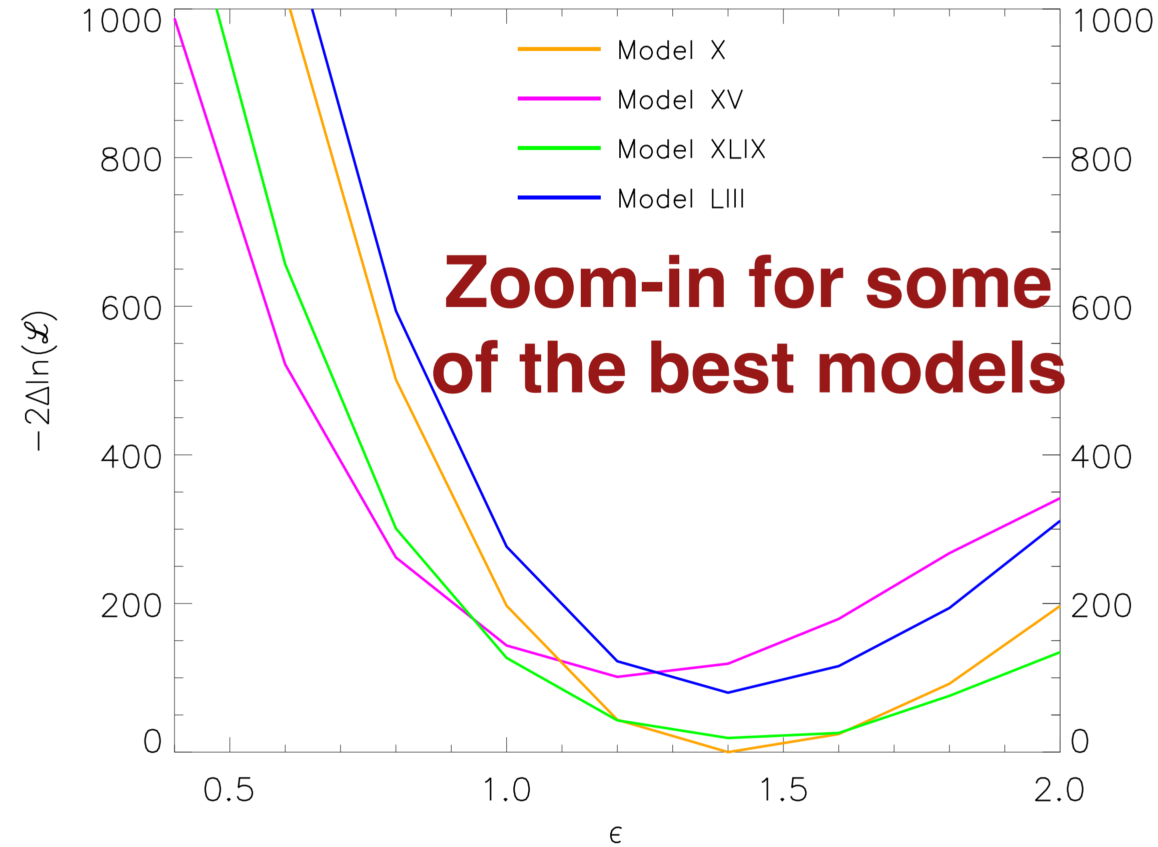
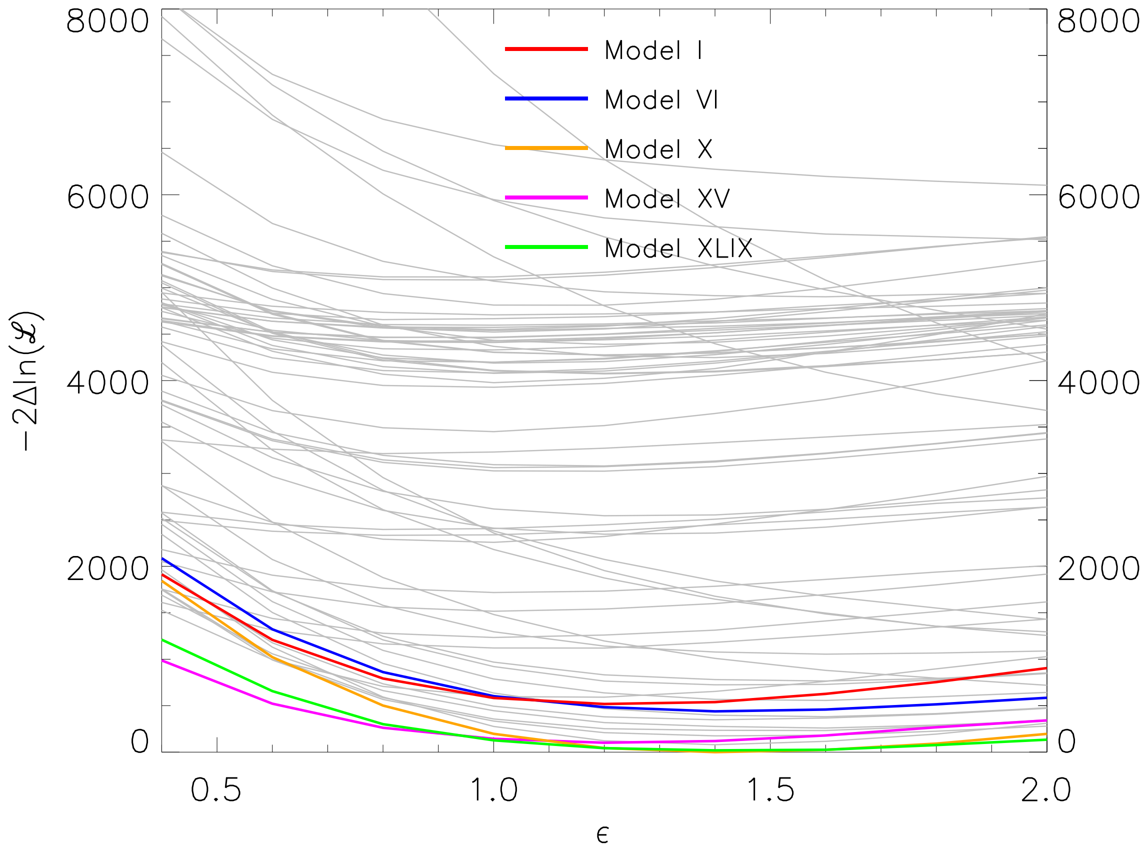


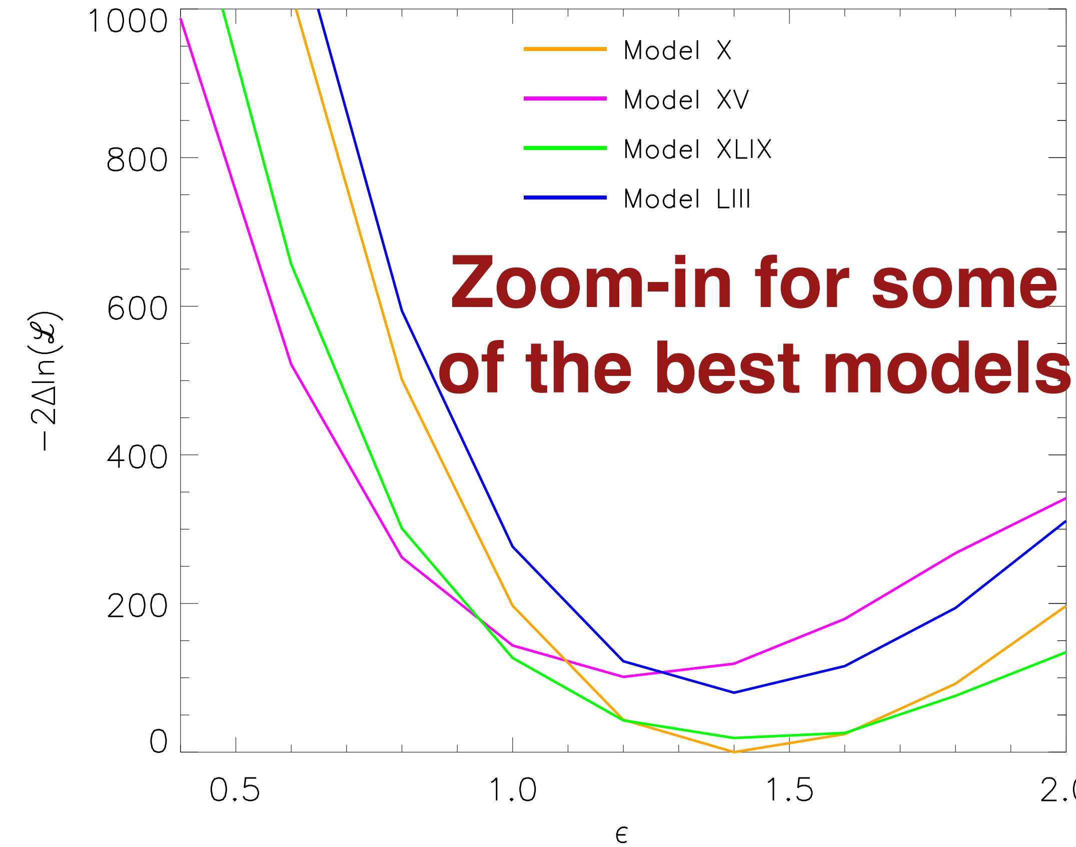
Fig. 9. *Top*: The microwave haze at *Planck* 30 GHz (red, $-12\,\mu\mathrm{K} < \Delta T_{\mathrm{CMB}} < 30\,\mu\mathrm{K}$) and 44 GHz (yellow, $12\,\mu\mathrm{K} < \Delta T_{\mathrm{CMB}} < 40\,\mu\mathrm{K}$). *Bottom*: The same but including the *Fermi* 2-5 GeV haze/bubbles of Dobler et al. (2010) (blue, $1.05 <$ intensity [keV cm^{-2} s^{-1} sr^{-1}] < 1.25; see their Fig. 11). The spatial correspondence between the two is excellent, particularly at low southern Galactic latitude, suggesting that this is a multi-wavelength view of the same underlying physical mechanism.





Results do not change substantively between 4FGL, 4FGL-DR2 (and also 4FGL-DR3) point source catalogues

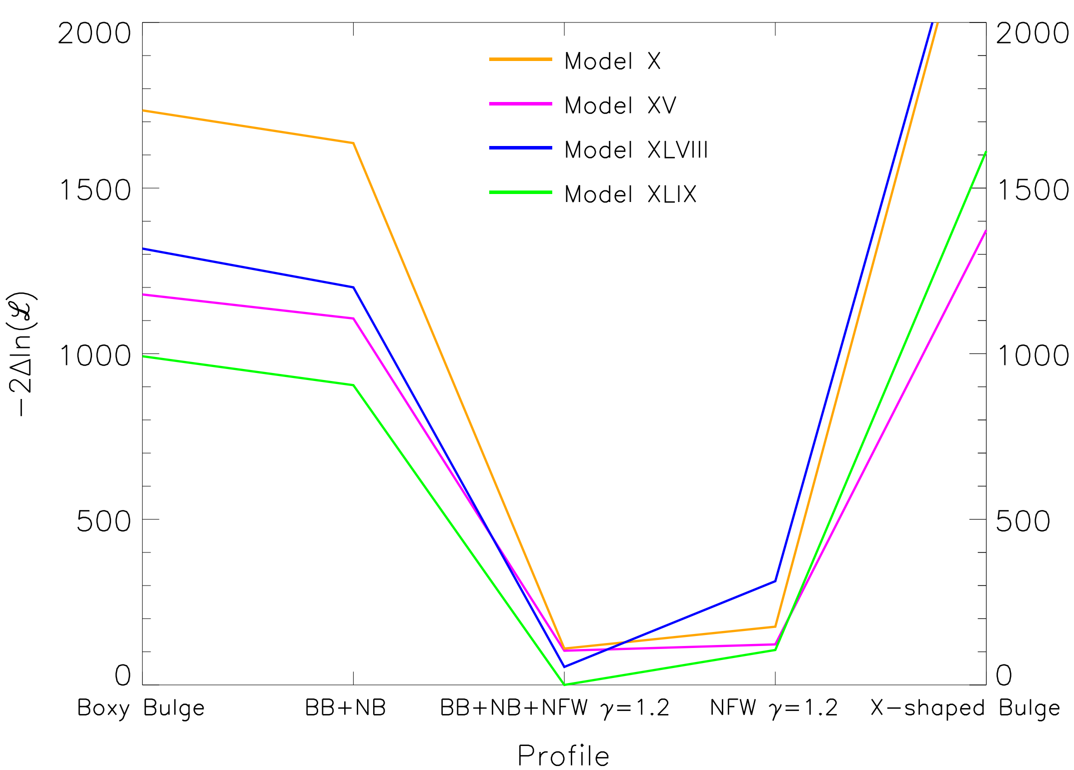


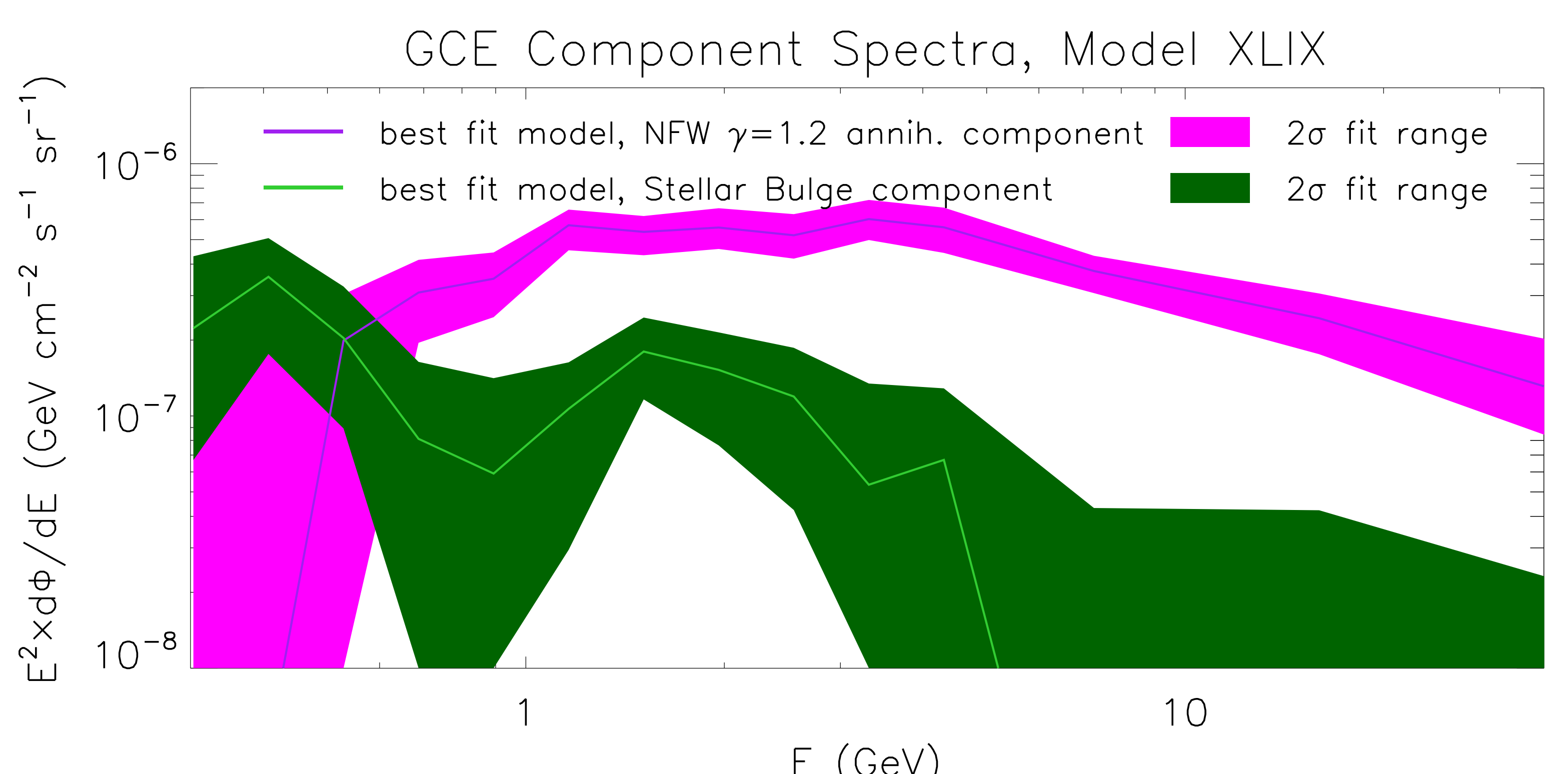


Results do not change substantively between 4FGL, 4FGL-DR2 (and also 4FGL-DR3) point source catalogues

IC, Zhong, McDermott, Surdutovich, PRD 2022

Even when we allow for an additional stellar bulge component (probing MSPs) component, we still get preference for a dominant cuspy NFW-like profile





McDermott, Zhong, **IC** (arXiv:2209.00006)

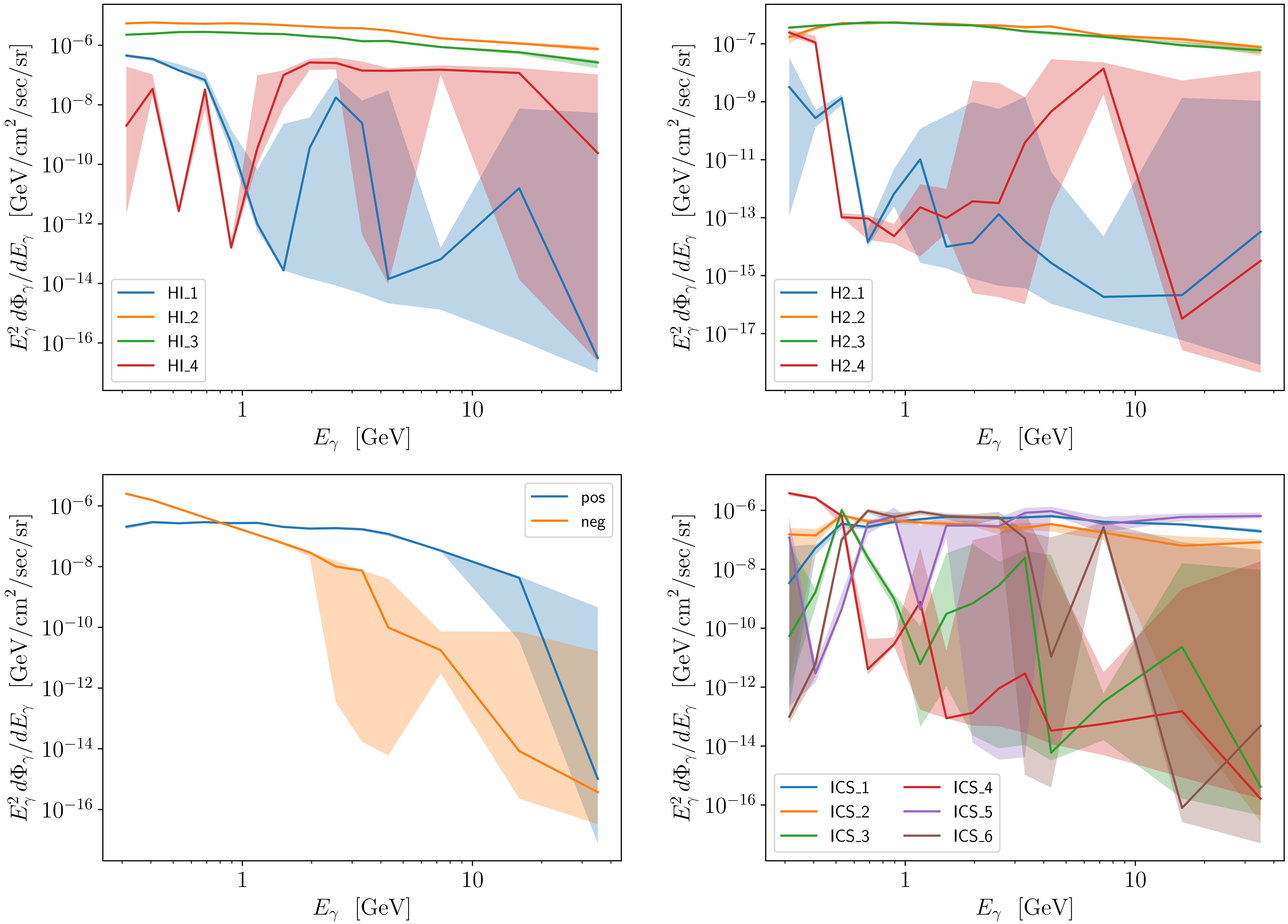


FIG. 3. Best-fit spectra and 95% credible intervals of the flux of the ring-based templates that were fit alongside the boxy bulge excess template. For the negative residual component, we show its absolute value in the lower left panel.

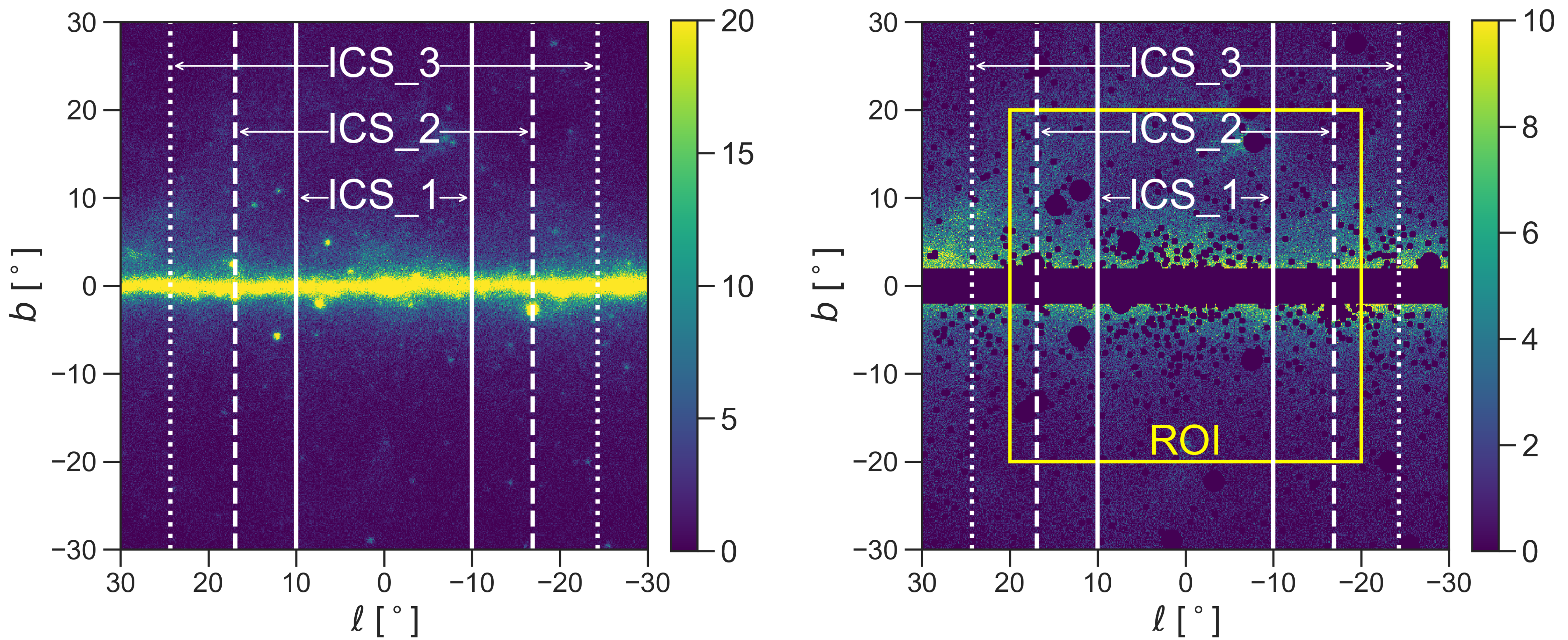
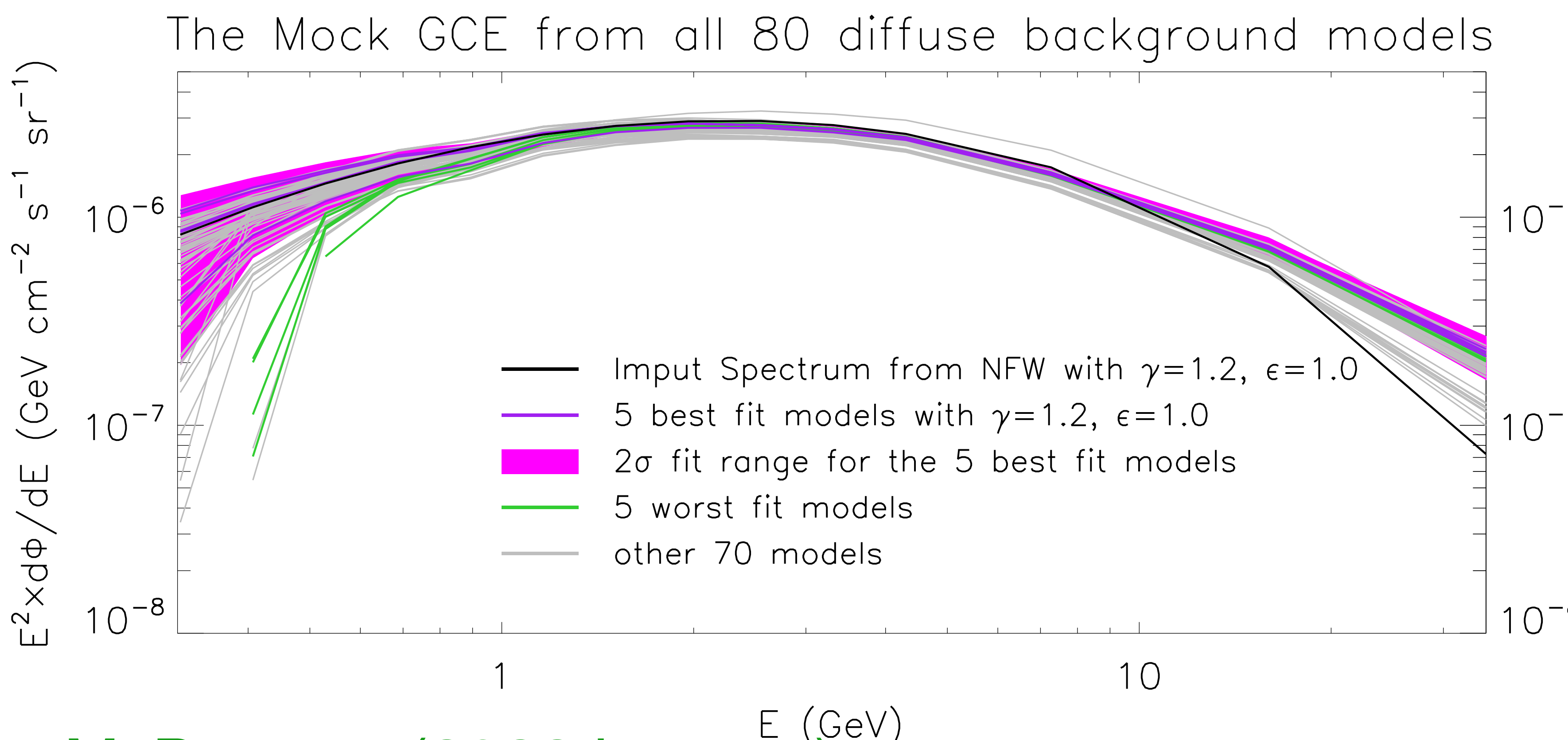


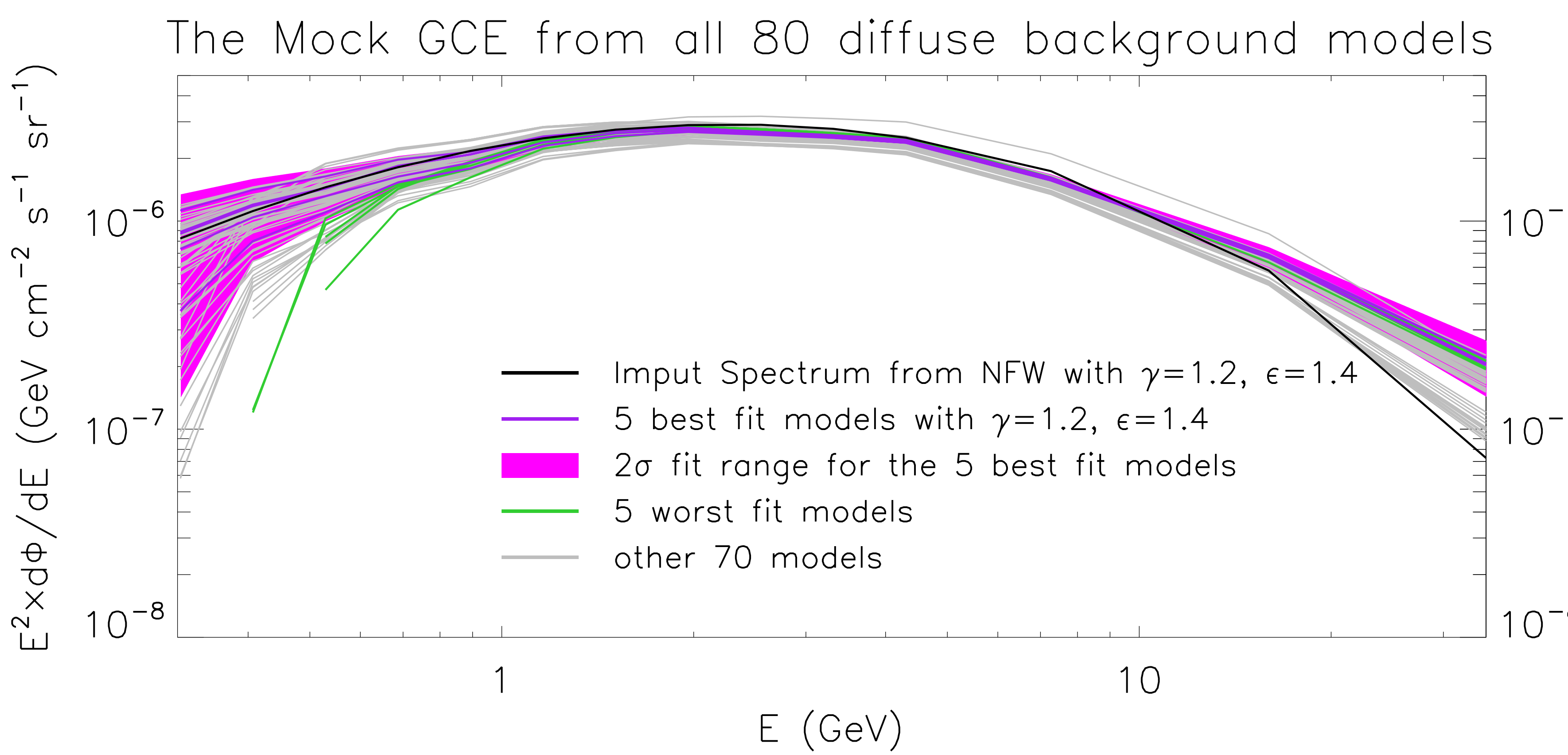
FIG. 2. Photons passing our cuts with energy $1.02\,\mathrm{GeV} < E_\gamma < 1.32\,\mathrm{GeV}$, without (left) and with (right) the mask that we use for our data. For illustration purposes, we show the boundaries of the ICS_1, ICS_2, and ICS_3 rings that vary independently in our fits. In the right panel, we show the region of interest in which we perform our fits.

McDermott, Zhong, **IC** (arXiv:2209.00006)

Ongoing Preliminary:
Further Tests of injected Mock Maps versus what we recover from the fits:

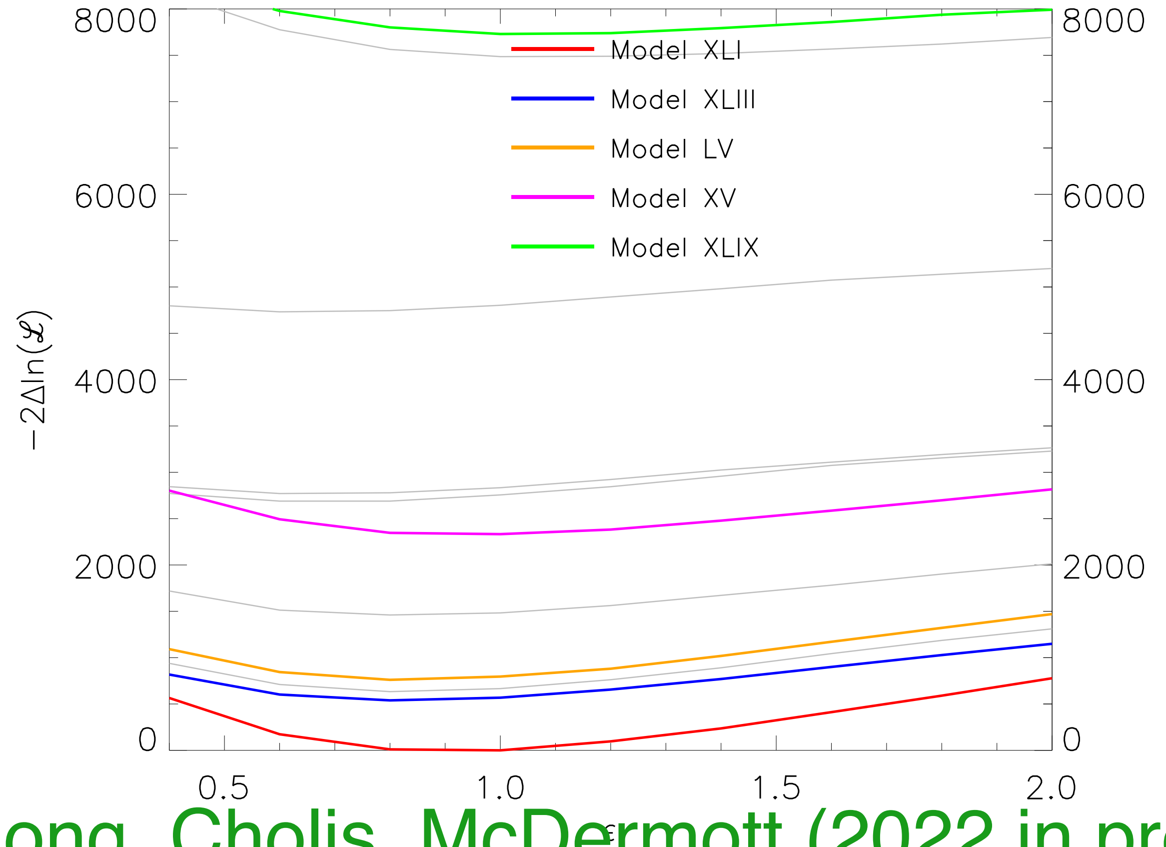


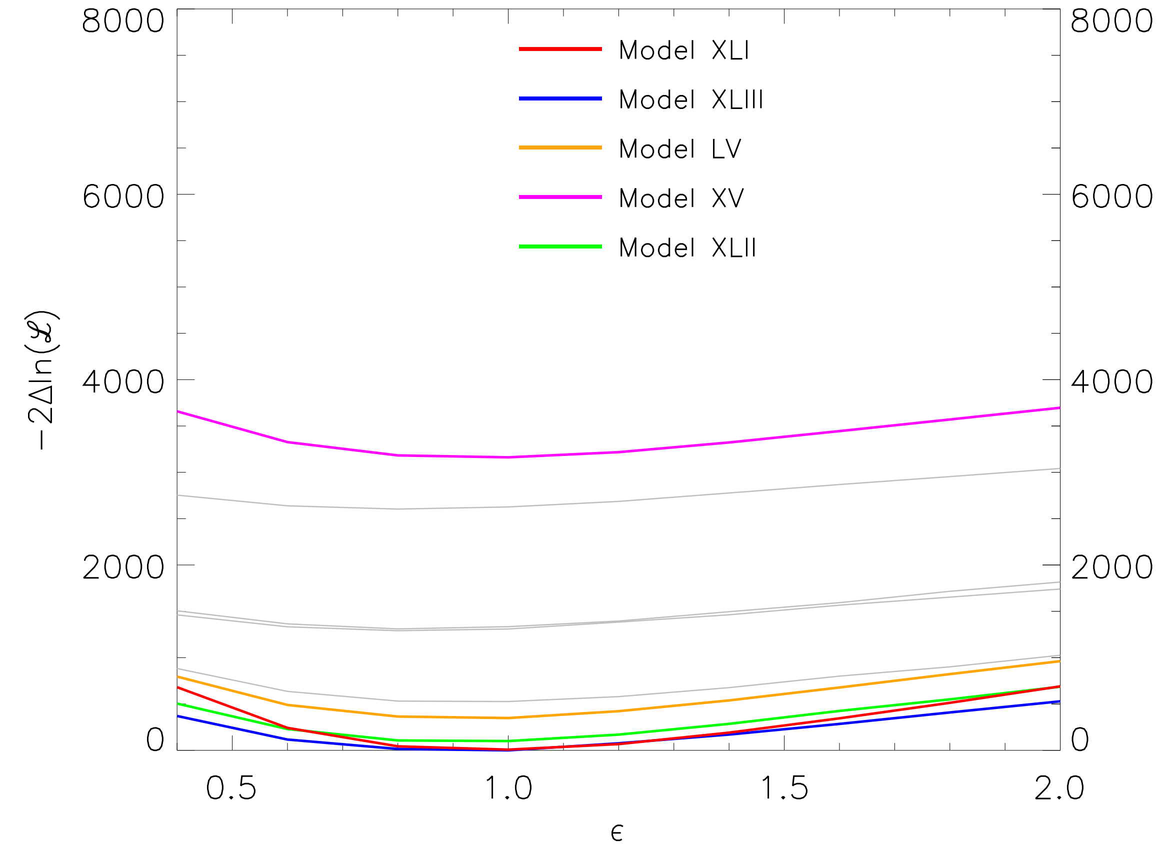
Zhong, Cholis, McDermott (2022 in prep.)



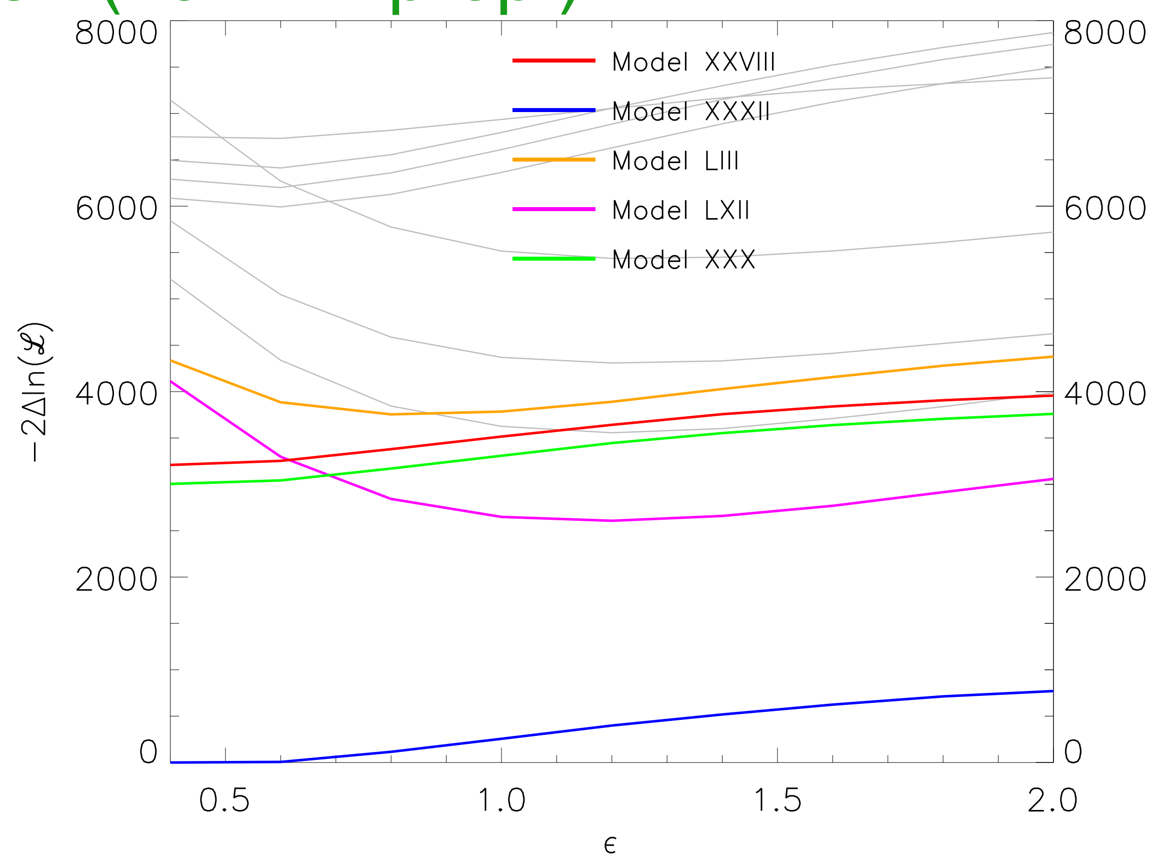
Ongoing Preliminary:

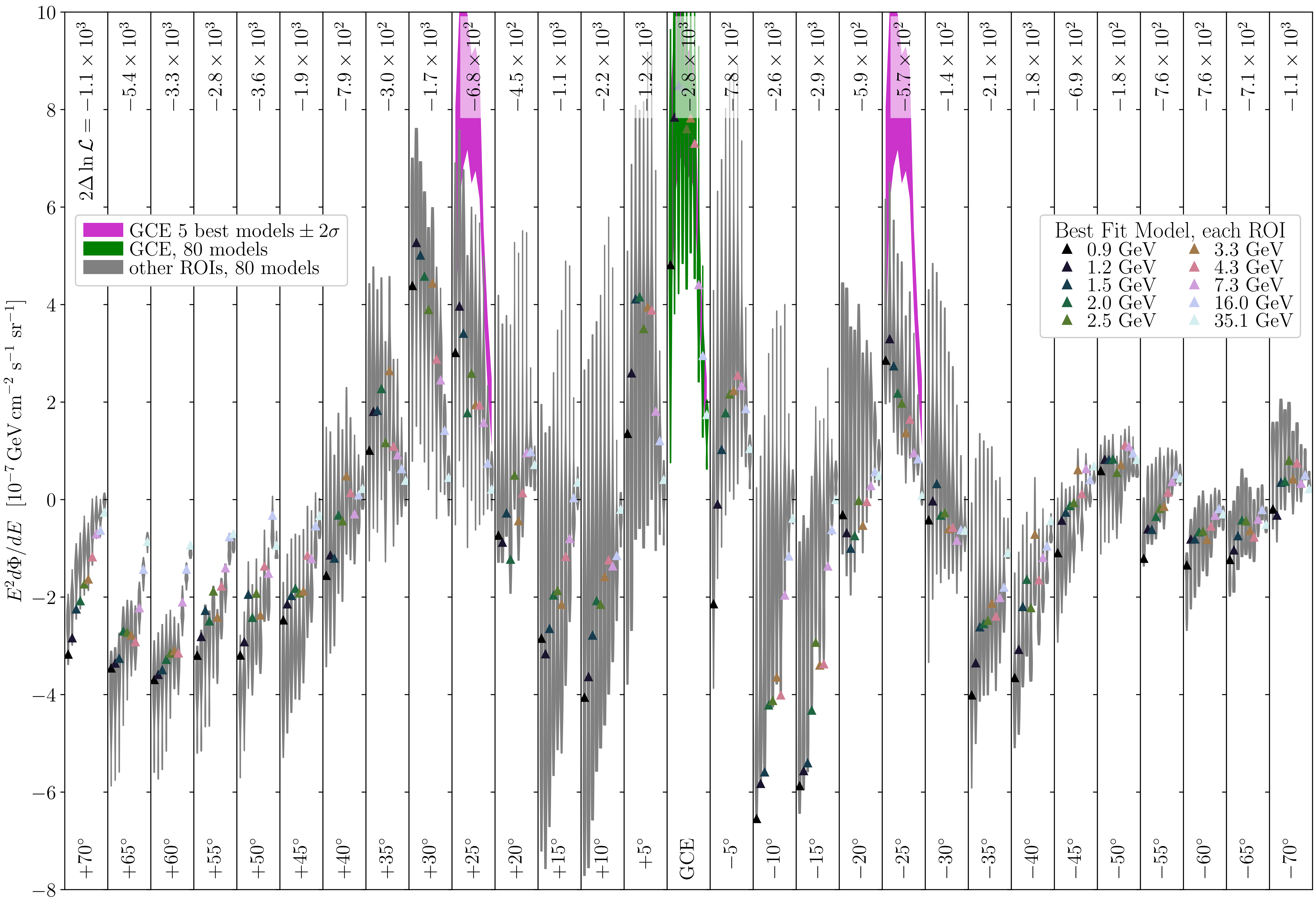
Further Tests on the GCE morphology with Alternative Wavelet based Masks:





Zhong, Cholis, McDermott (2022 in prep.)





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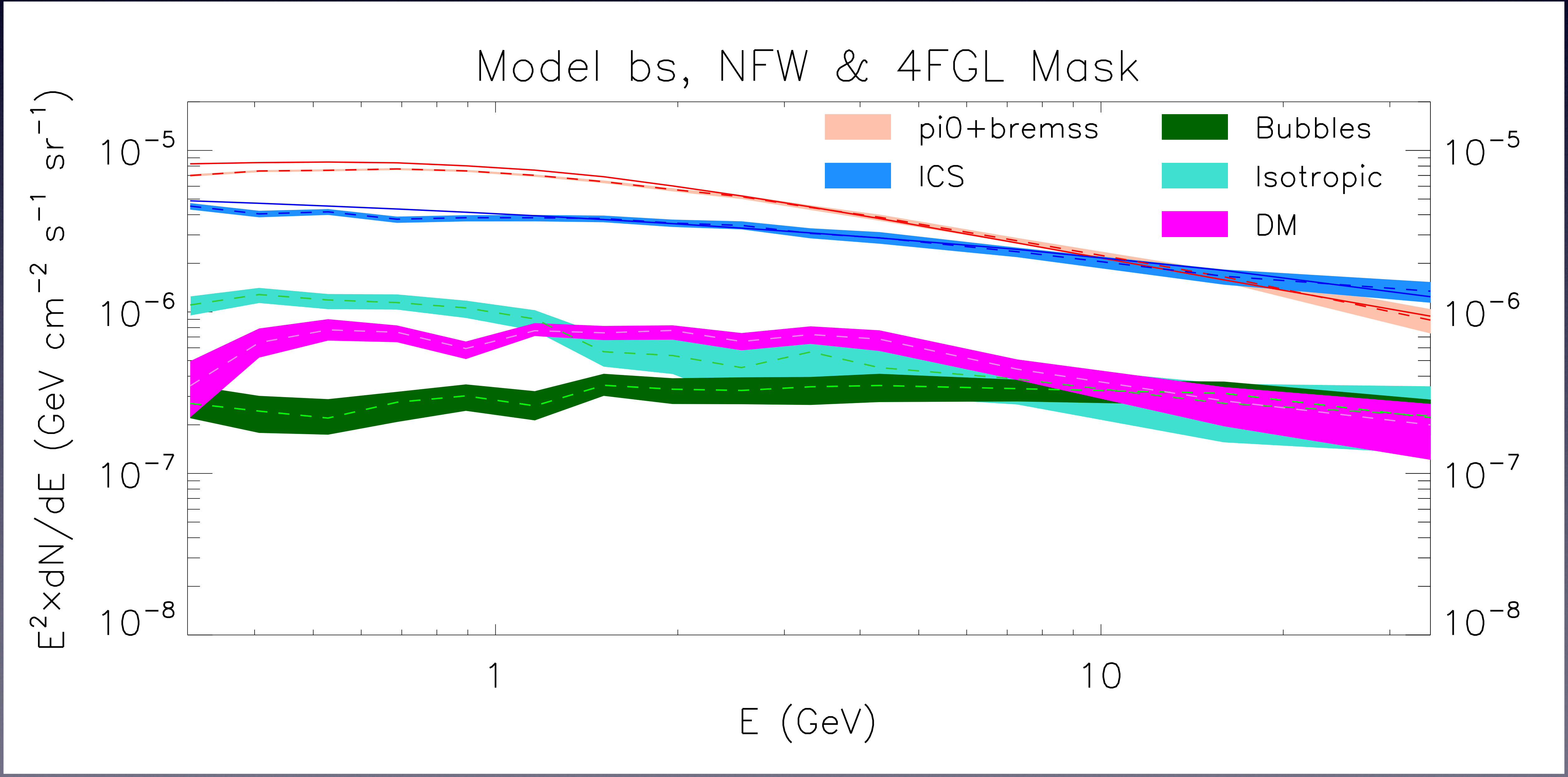
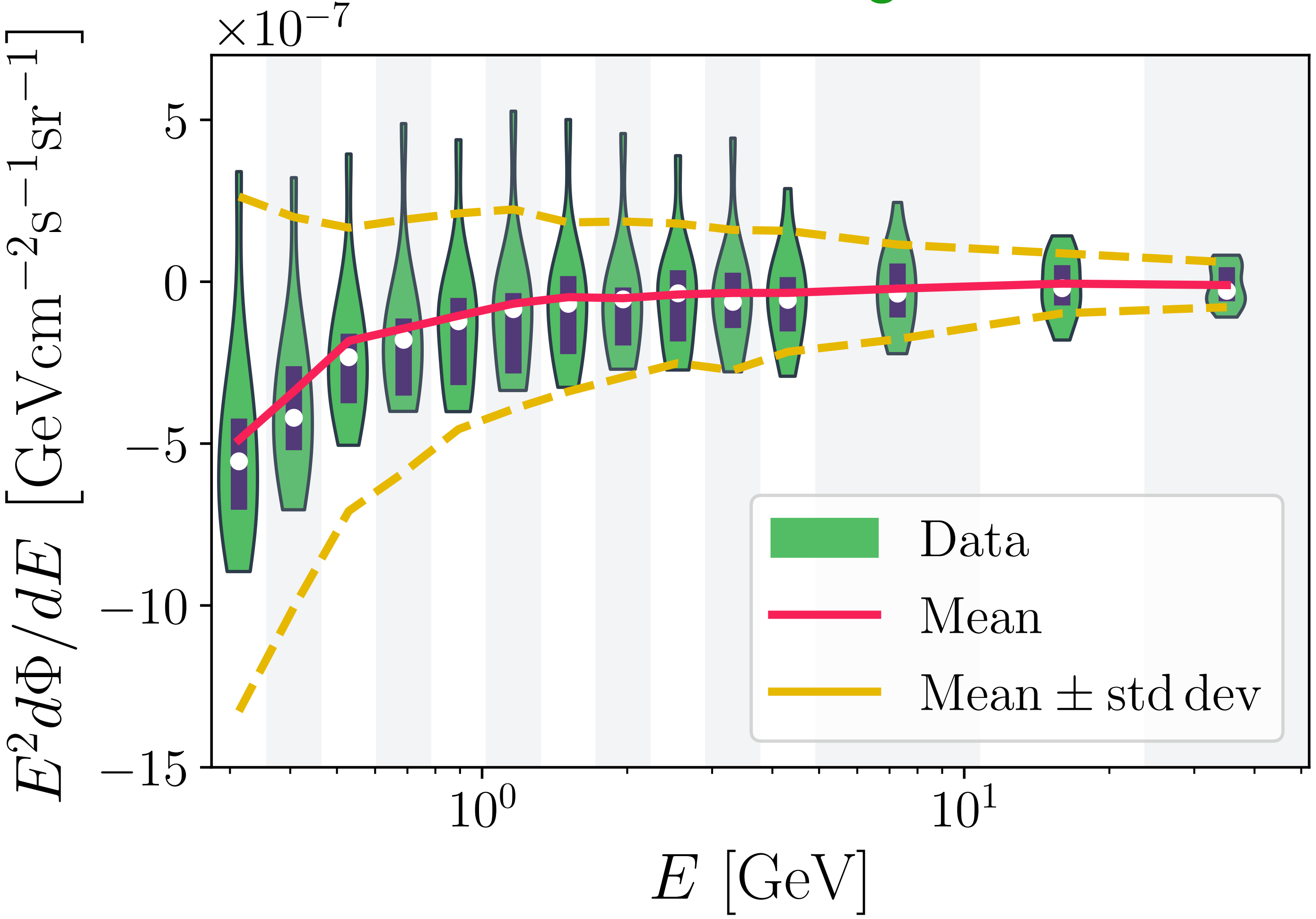


Model bs, NFW & 4FGL Mask
pi0+bremss
ICS
Bubbles
Isotropic
DM
$E^2 \times dN/dE$ (GeV cm^{-2} s^{-1} sr^{-1})
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
10
E (GeV)

IC, Zhong, McDermott, Surdutovich, PRD 2022



The covariance matrix:

$$\Sigma_{ij,\mathrm{mod}} = \left\langle E^4 \frac{d\Phi}{dE_i}\frac{d\Phi}{dE_j}\right\rangle - \left\langle E^2 \frac{d\Phi}{dE_i}\right\rangle \left\langle E^2 \frac{d\Phi}{dE_j}\right\rangle$$

Its truncated version:

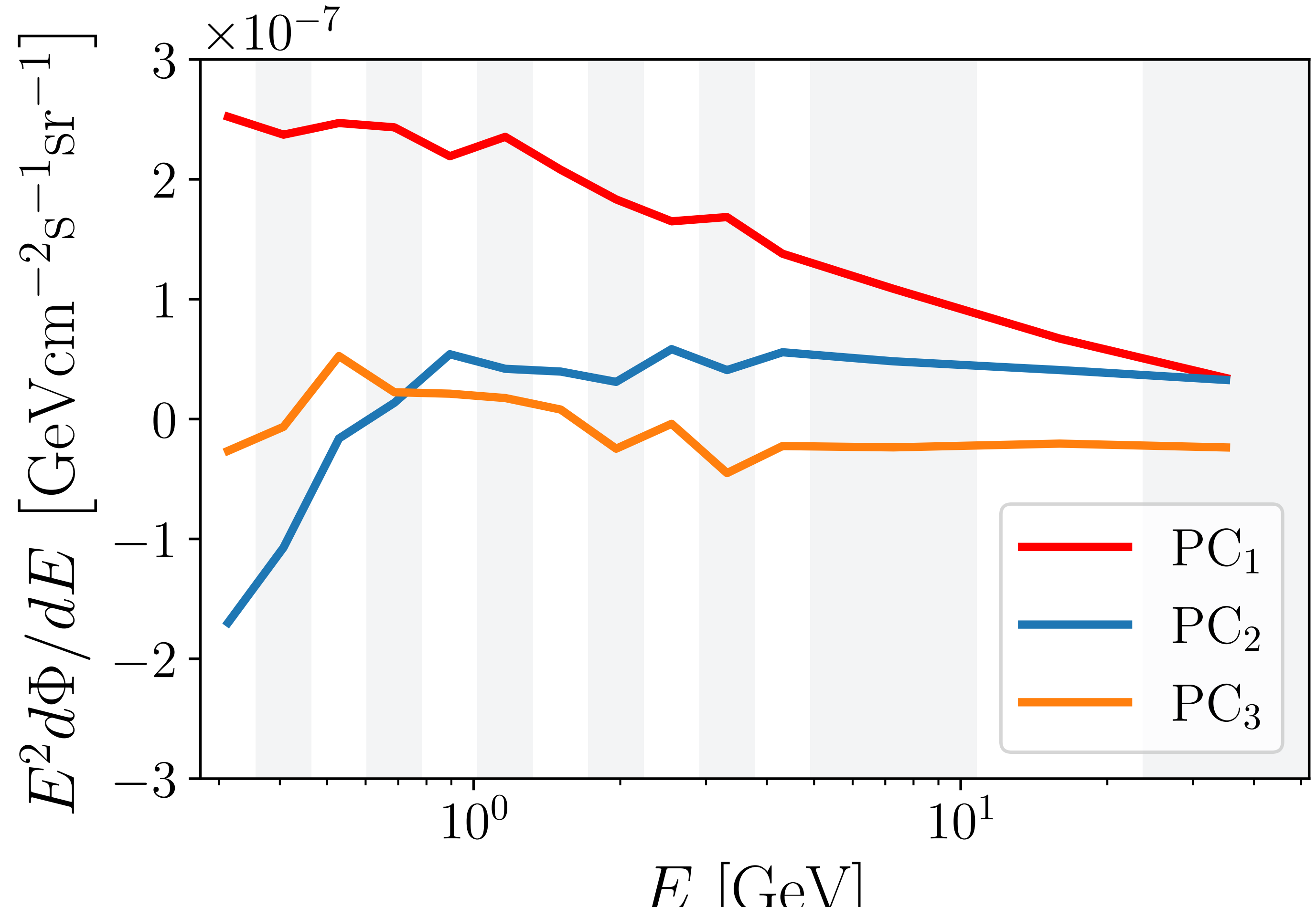
$$\Sigma_{jk,\mathrm{mod}} \simeq \Sigma^{\mathrm{trunc}}_{jk,\mathrm{mod}} \equiv \sum_{i=1}^{3} \mathrm{PC}^{\mathsf{T}}_{ij}\mathrm{PC}_{ik}$$

The formal fit:

$$\chi^2 = \sum_{ij}\left(\mathrm{GCE}_i - \sum_k f_{ik}(\theta_k)\right) C^{-1}_{ij} \left(\mathrm{GCE}_j - \sum_\ell f_{j\ell}(\theta_\ell)\right)$$

Where:

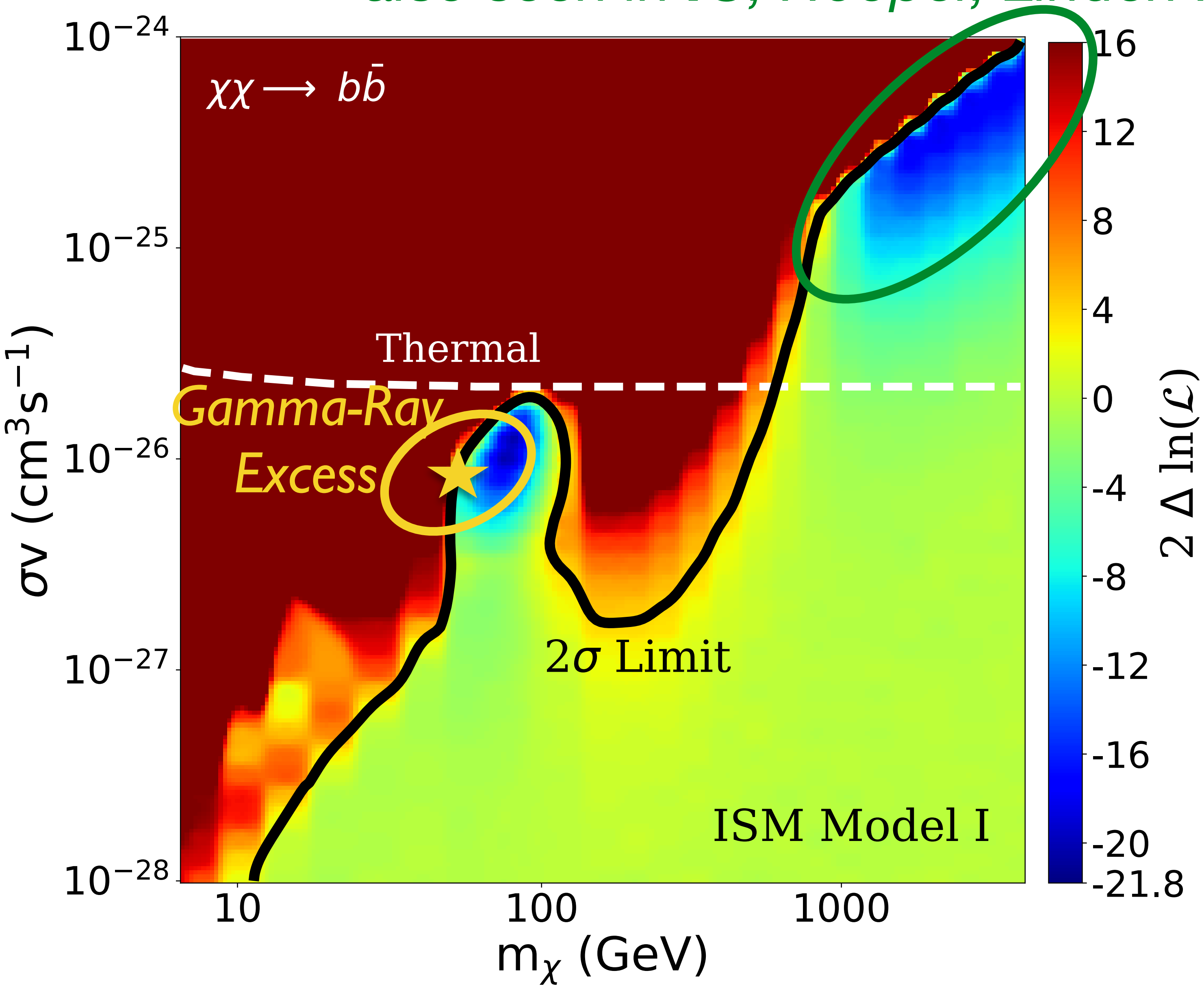
$$C_{ij} = \sigma_i^2 \delta_{ij} + \Sigma_{ij,\mathrm{mod}}$$

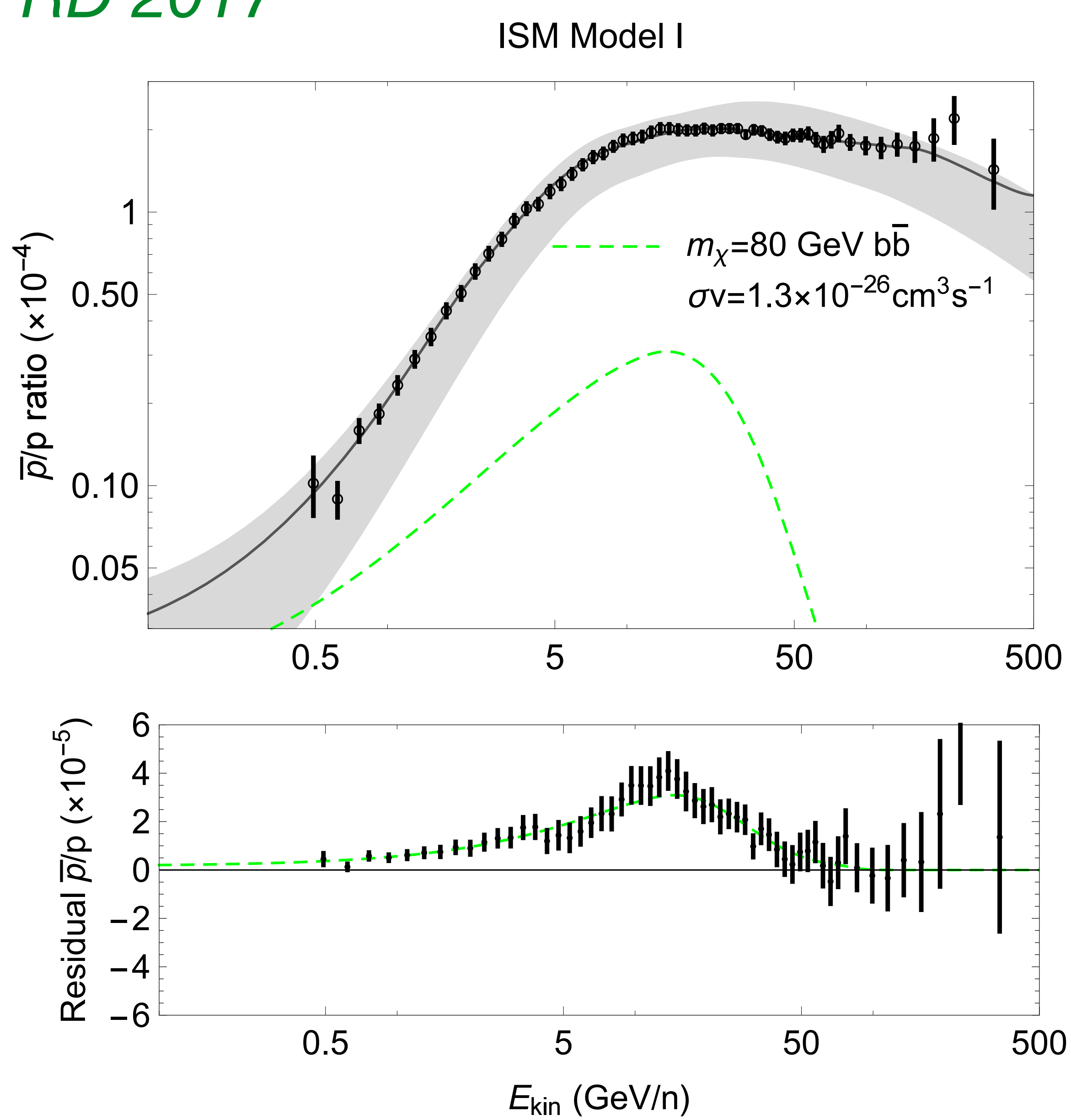


Looking at the antiproton to proton ratio find an the excess at~3 sigma

Supernova,

*also seen in **IC**, Hooper, Linden PRD 2017*





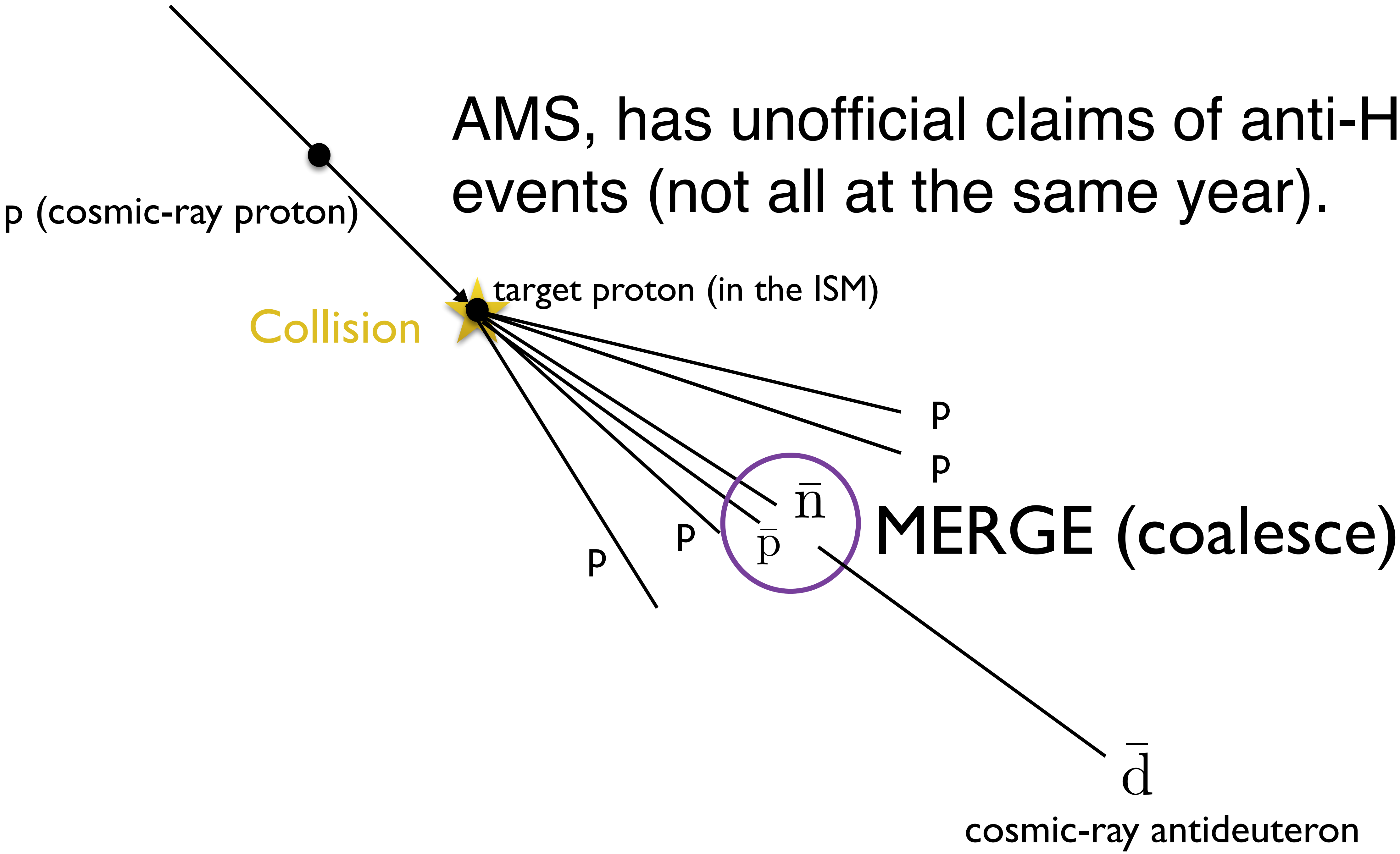
IC, Tim Linden, Dan Hooper PRD 2019

See also A. Cuoco et al. PRD 2019

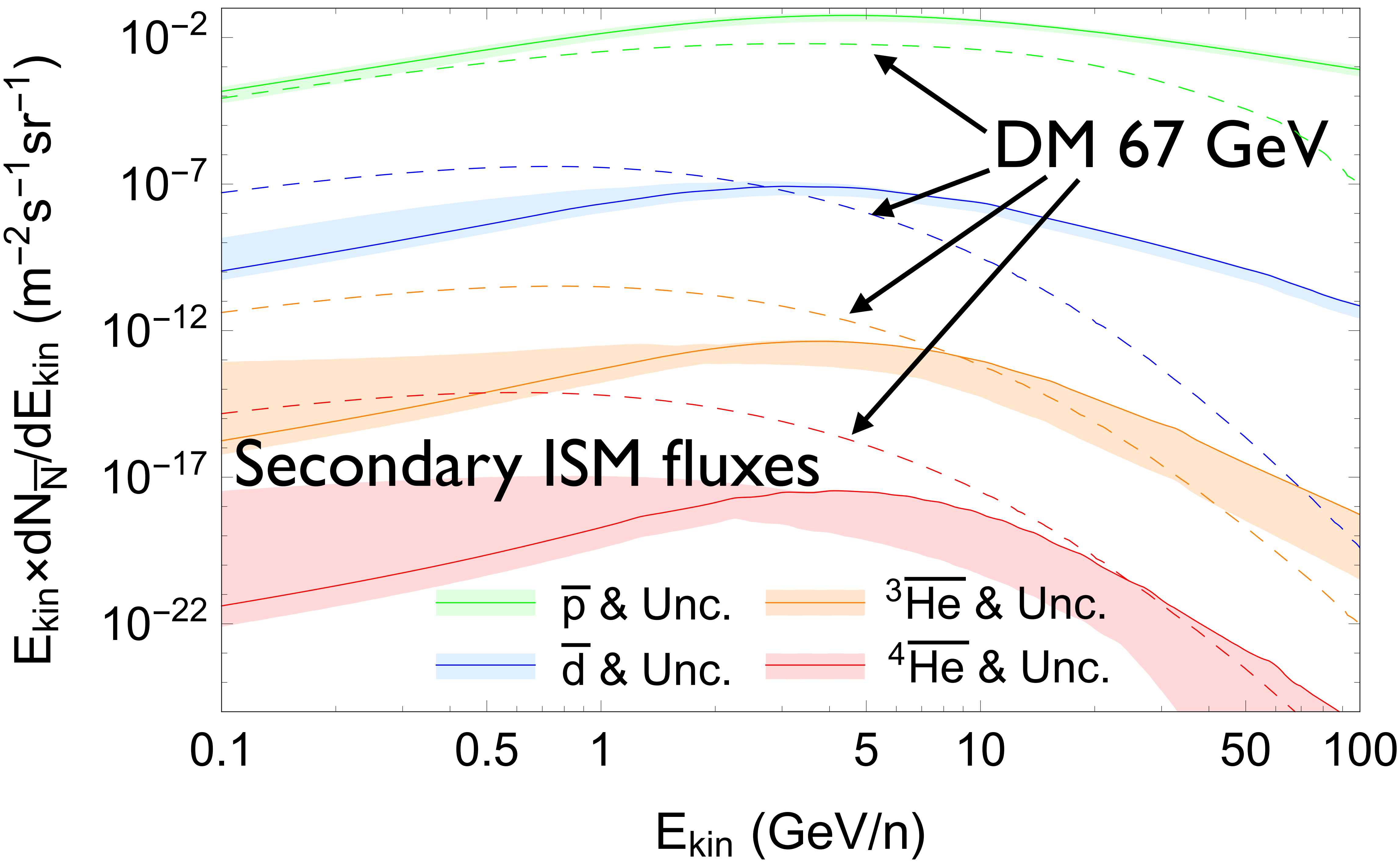
Earlier results: Cuoco et al. PLR 2017,Cui et al. PRL 2017

How about heavier nuclei?

AMS, has unofficial claims of anti-He CR events (not all at the same year).



Antimatter flux Uncertainties



IC, Linden, Hooper PRD 2020

And a little extra positrons….

Utilizing cosmic-ray positron and electron observations to probe the averaged properties of Milky Way pulsars

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Pulsars have long been studied in the electromagnetic spectrum. Their environments are rich in high-energy cosmic-ray electrons and positrons likely enriching the interstellar medium (ISM) with such particles. In this work we use recent cosmic-ray observations from the *AMS-02*, *CALET*, and *DAMPE*

and likely release $O(10\%)$ of their rotational energy to cosmic rays in the ISM. Finally, we find at ≃12 GeV positrons a spectral feature that suggests a new subpopulation of positron sources contributing at these energies.