OAKLAND UNIVERSITY

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)

TeV Particle Astrophysics
TeVPA 2022
August 8-12
Queen's University
Kingston, ON

TeVPA 2022
Ilias Cholis, 08/08/2022

The challenges of Indirect Searches for WIMPs

The Questions:

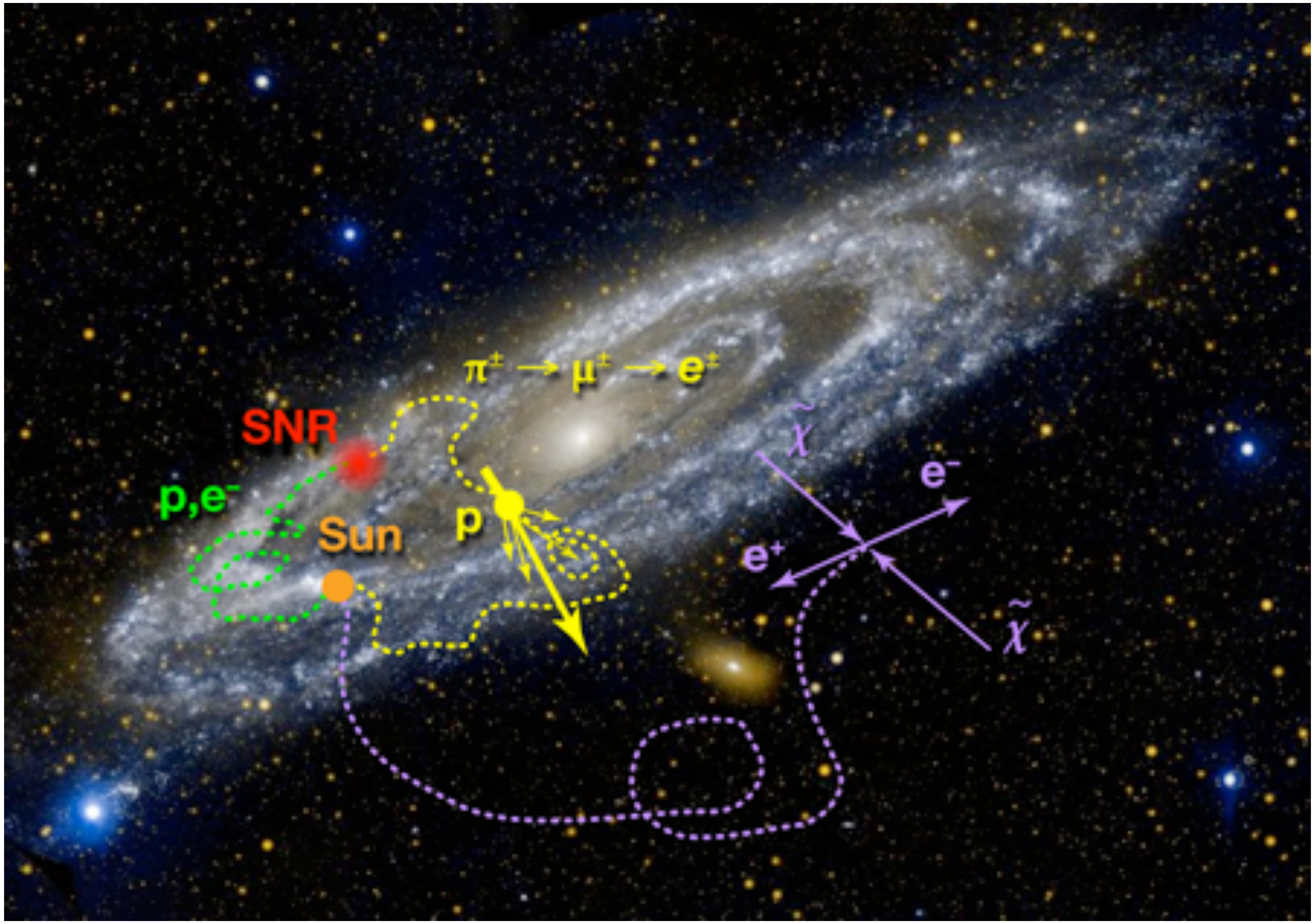
- Are we fully exploring the data? Is there a signal lurking within our observations?
- Do we have a good control of “systematics”? If Dark Matter is the Signal, do we understand the back-ground astrophysical uncertainties & astrophysical alternatives?

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

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

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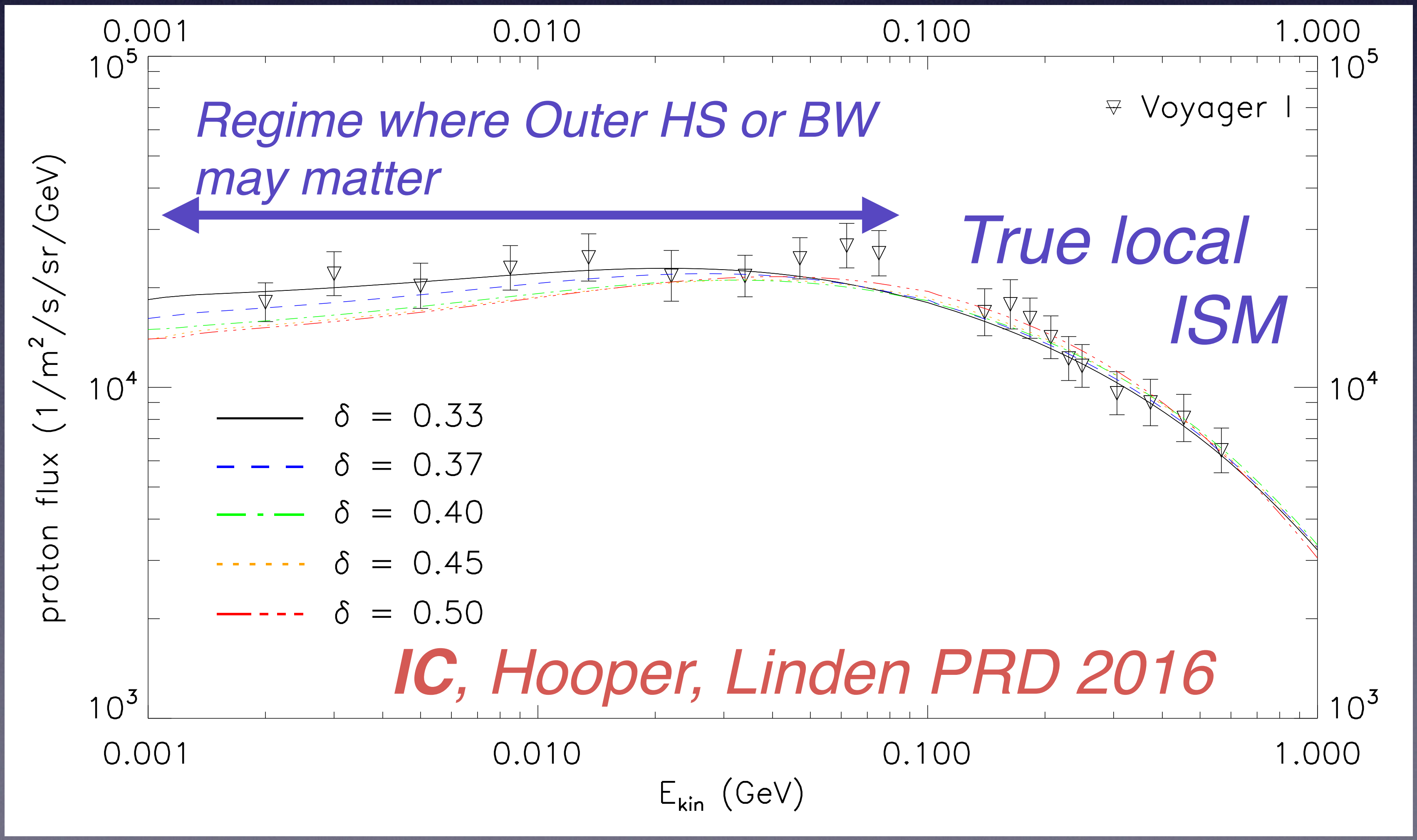
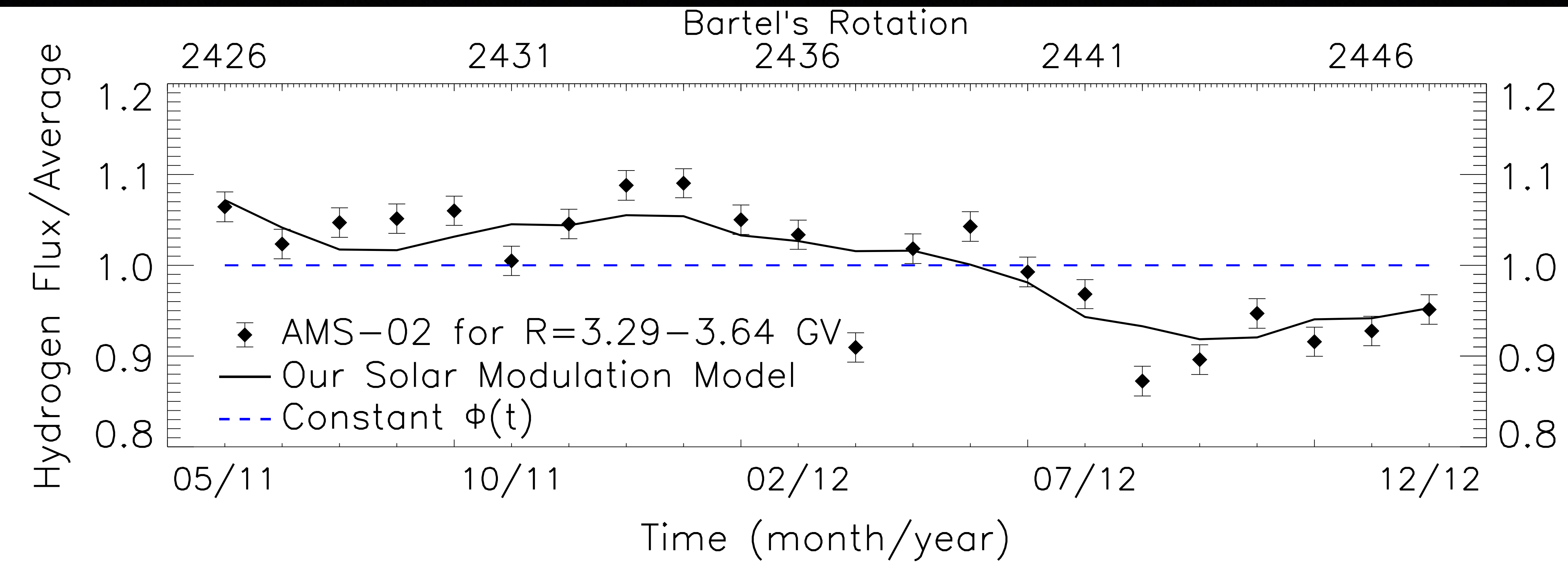
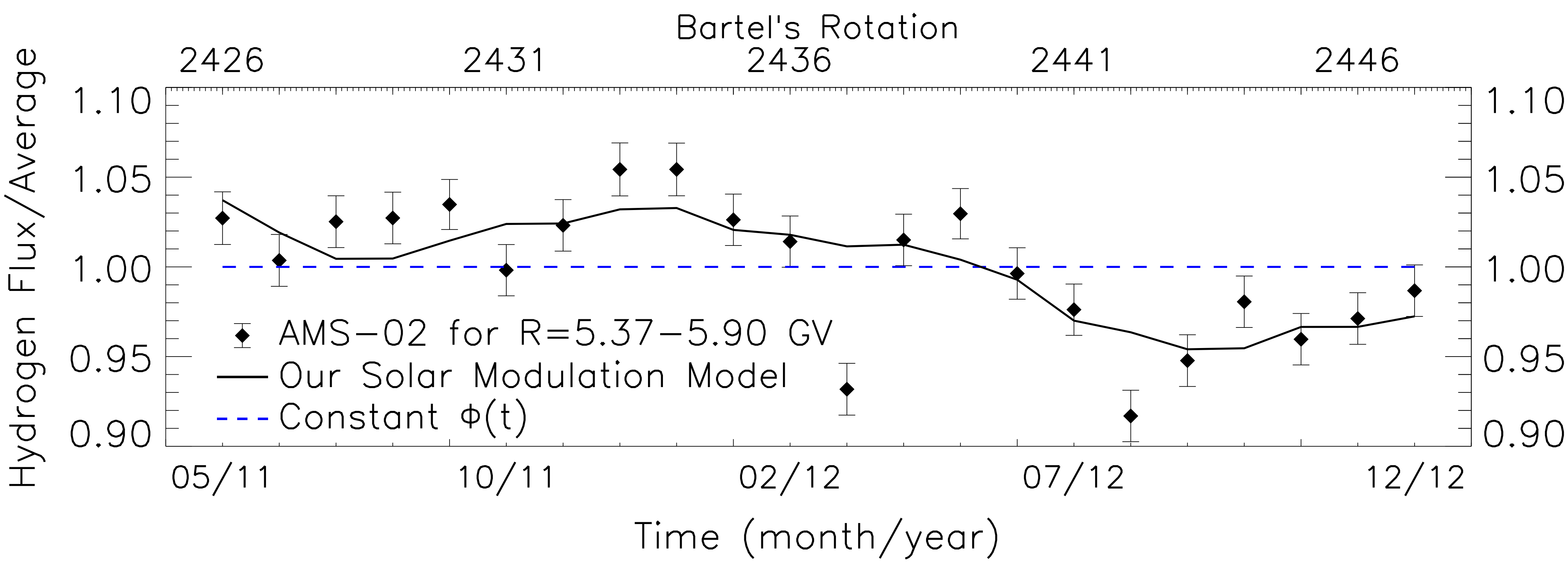
Voyager 1 (ISM) proton flux:



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

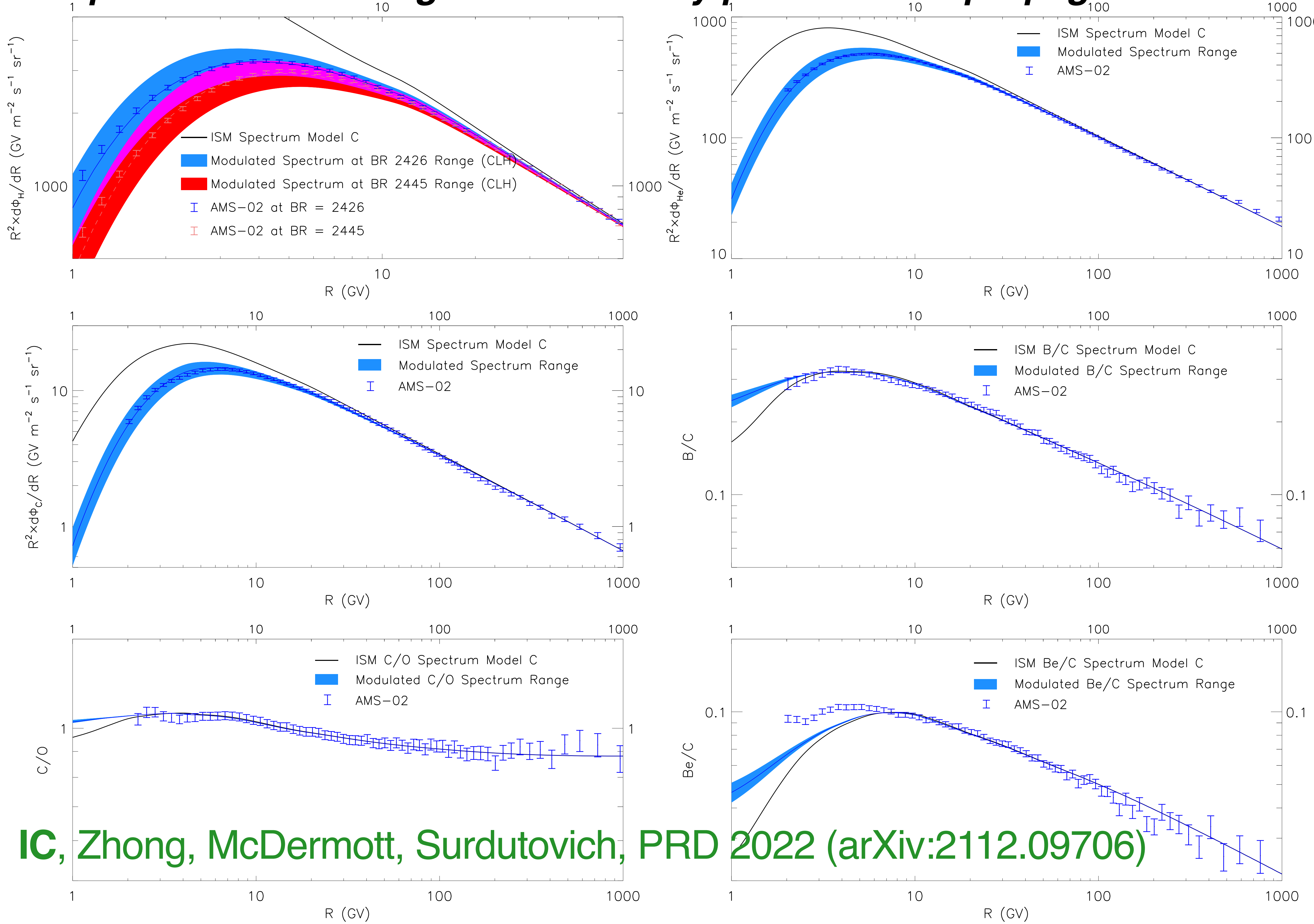
Cross-checking with the PROTON data that account for the majority of observed cosmic rays; monthly AND total (i.e ISM & Solar Modulation):





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

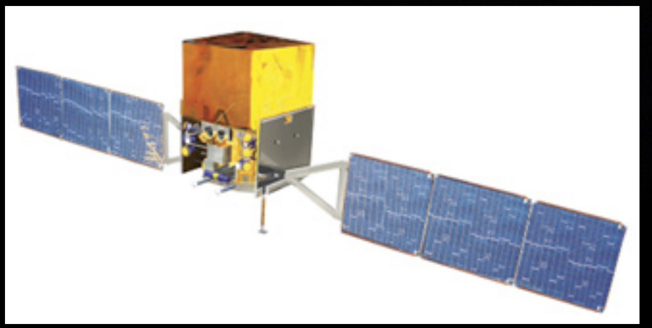
Repeating for multiple Cosmic-Ray species we can constrain the physical processes affecting the cosmic-ray production & propagation



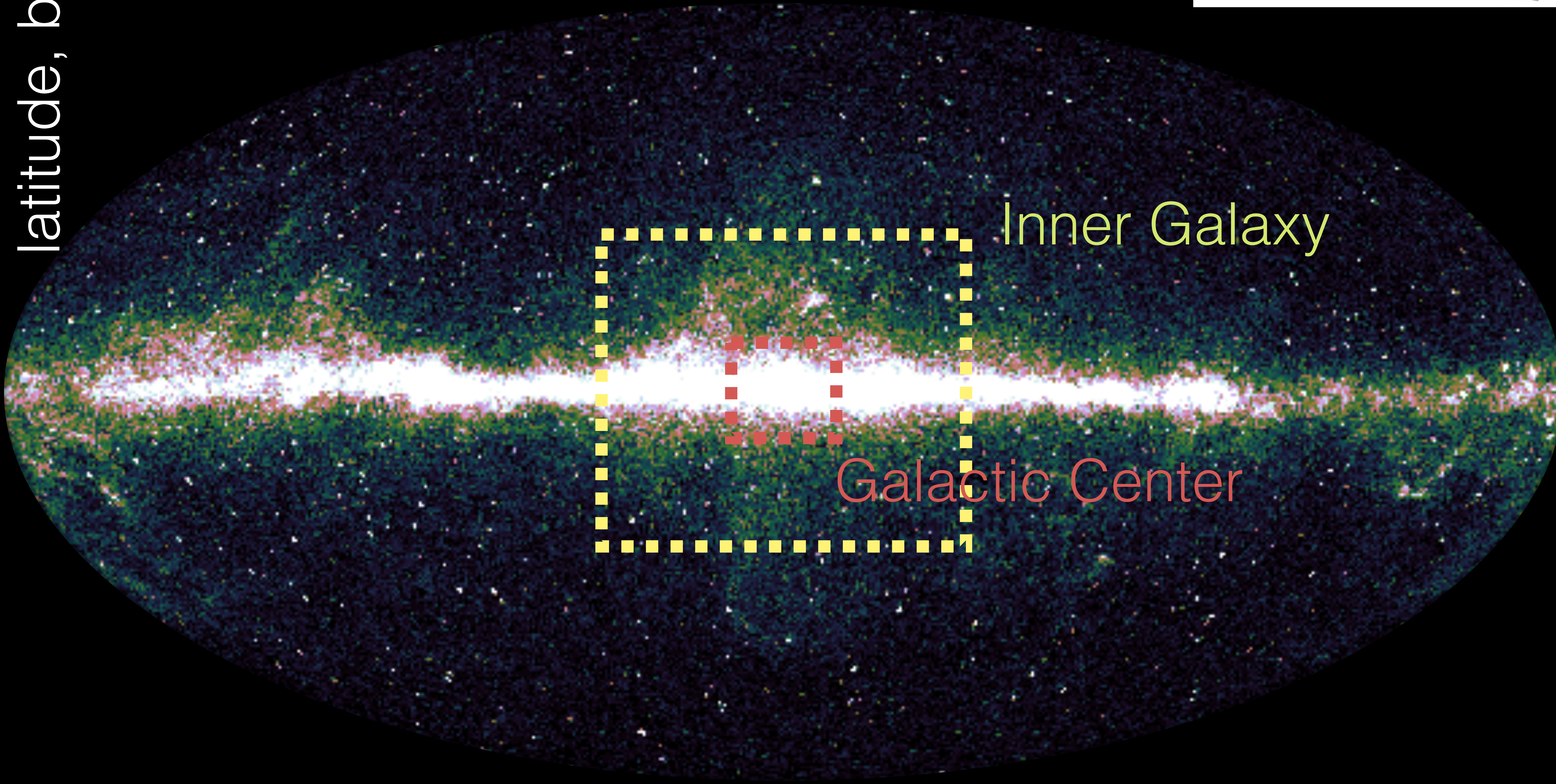
IC, Zhong, McDermott, Surdutovich, PRD 2022 (arXiv:2112.09706)

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY



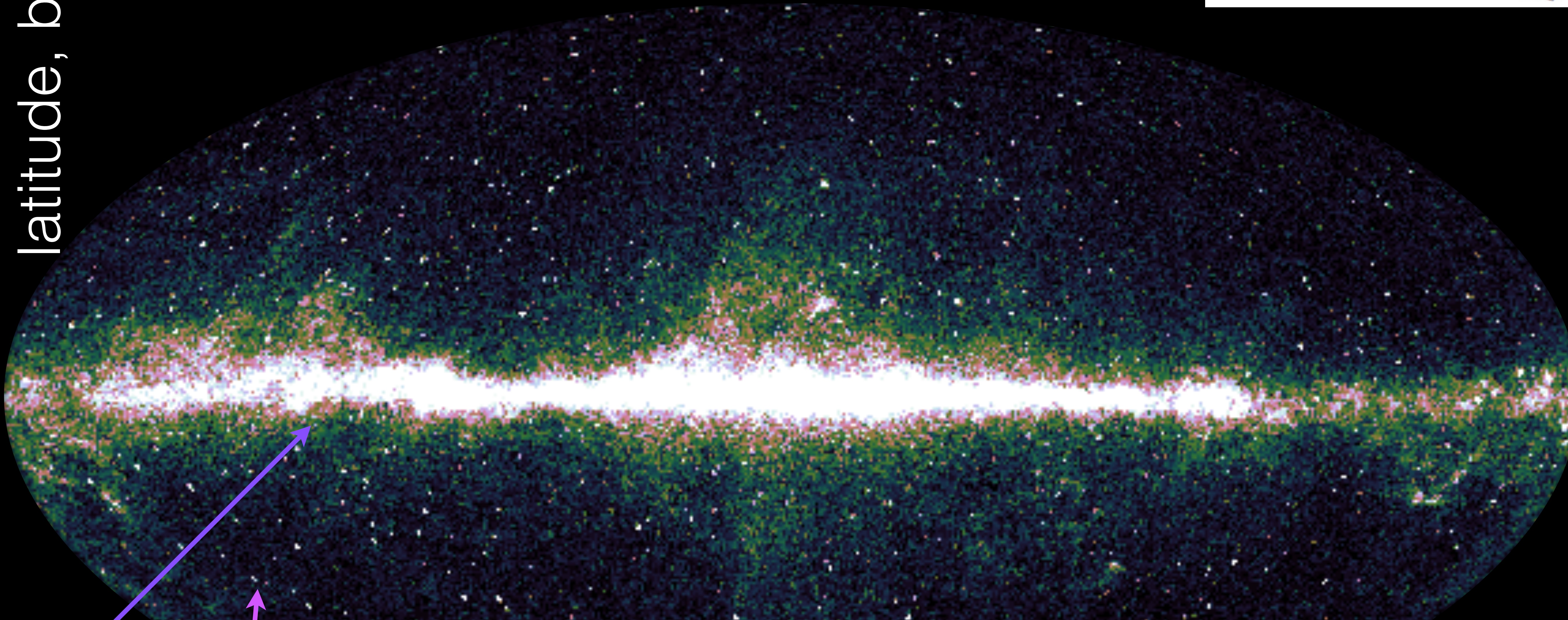
latitude, b ⟶



⟵ Galactic longitude, ℓ

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY



Sources for the observed gamma-rays are:

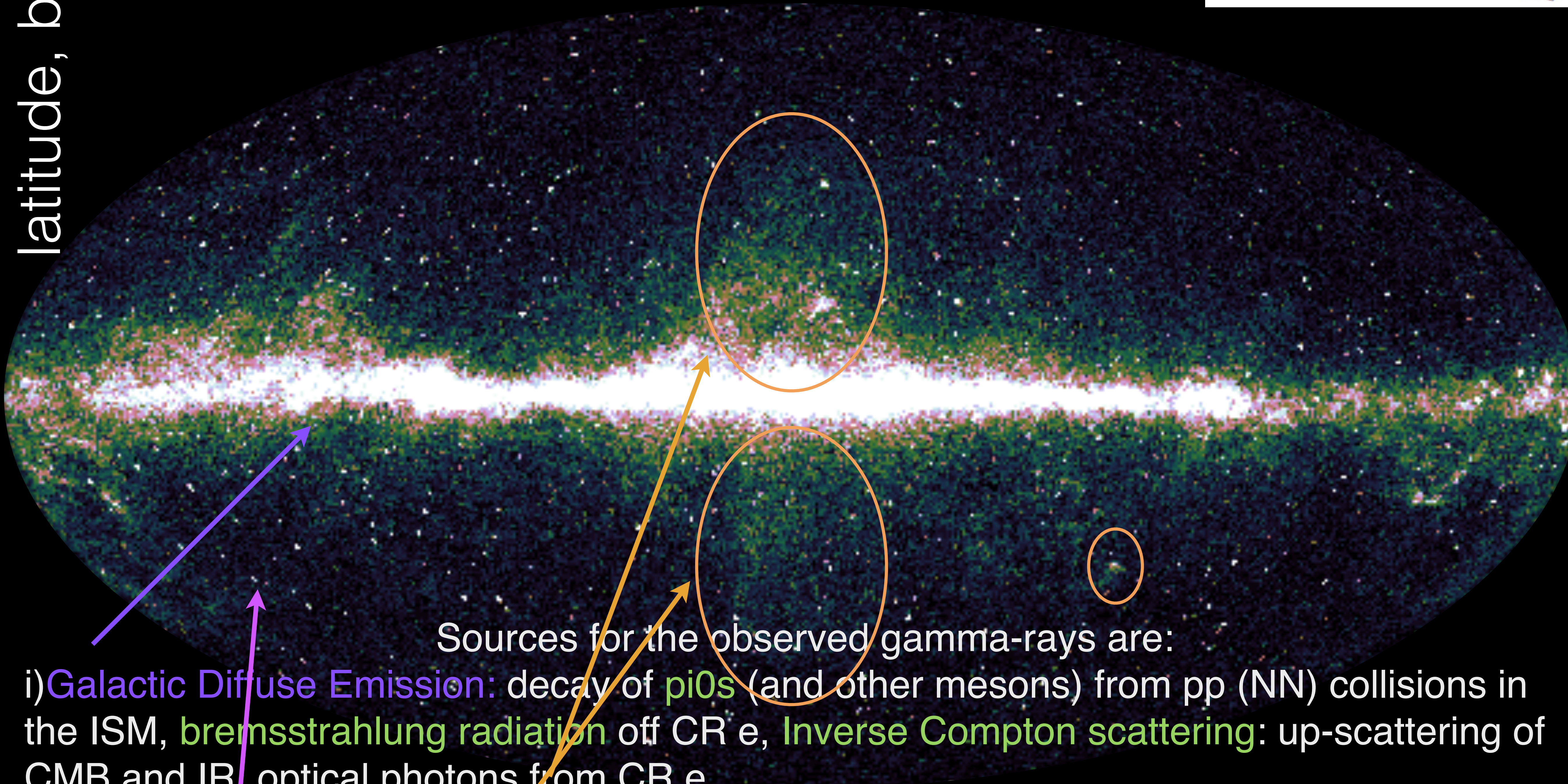
i)Galactic Diffuse Emission: decay of pi0s (and other mesons) from pp (NN) collisions in the ISM, bremsstrahlung radiation off CR e, Inverse Compton scattering: up-scattering of CMB and IR, optical photons from CR e

ii)from point sources (galactic or extra galactic)

iii)Extragalactic Isotropic

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY



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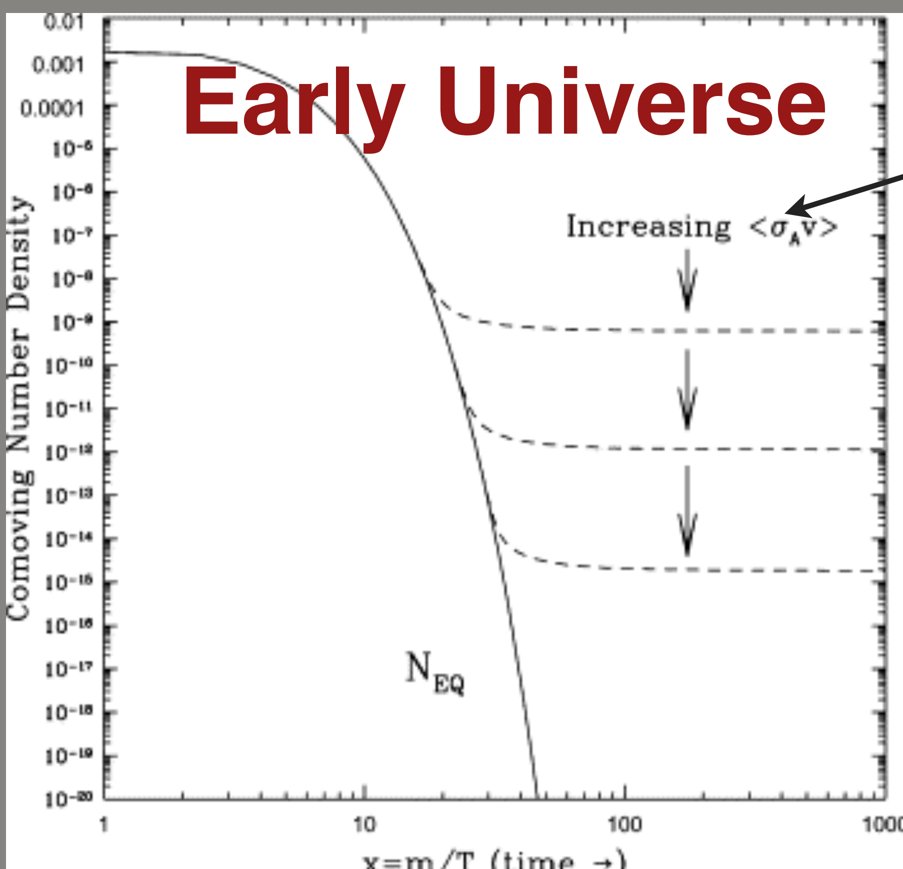
iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)

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

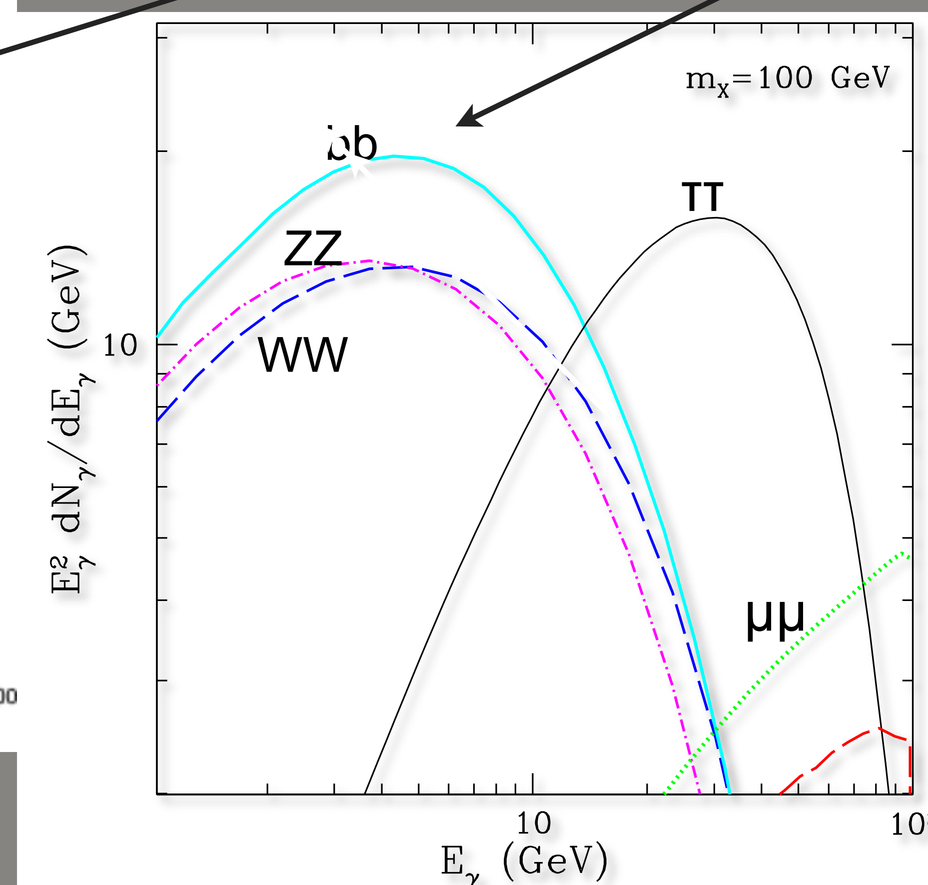
BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe:

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

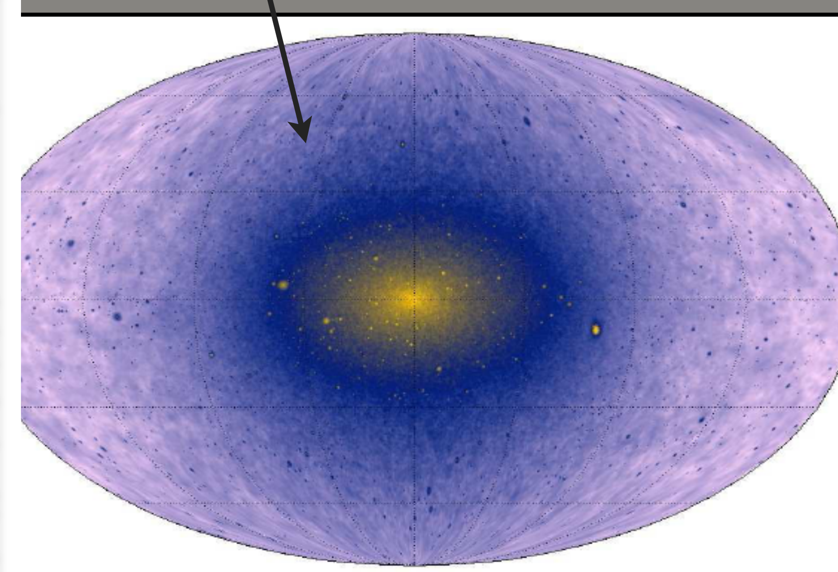


Steigman et al. 2012



Particle Physics

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

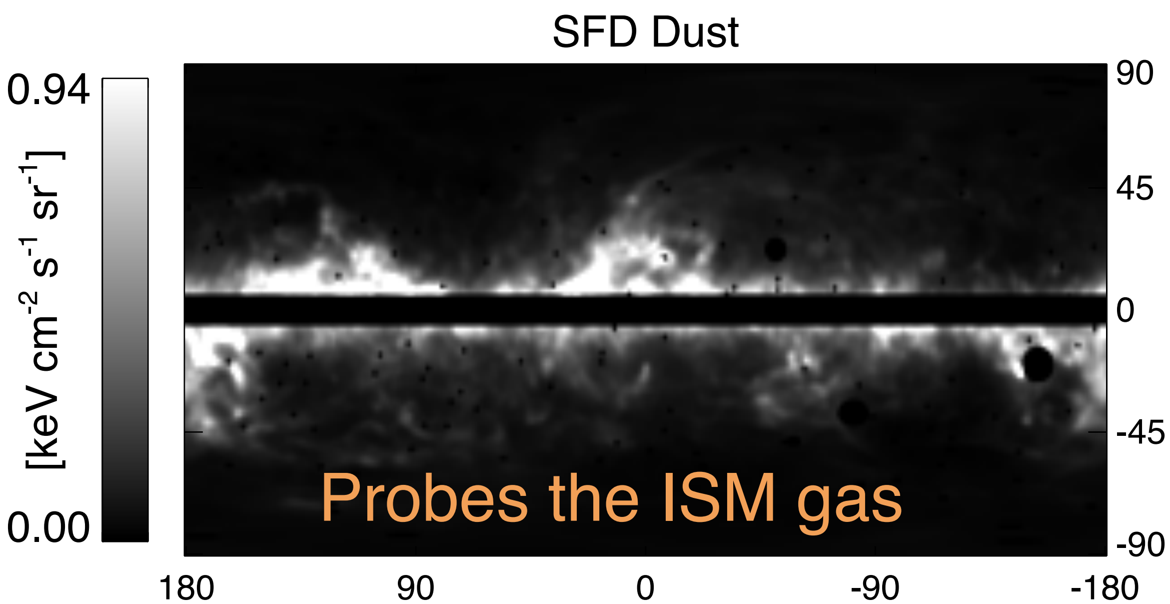


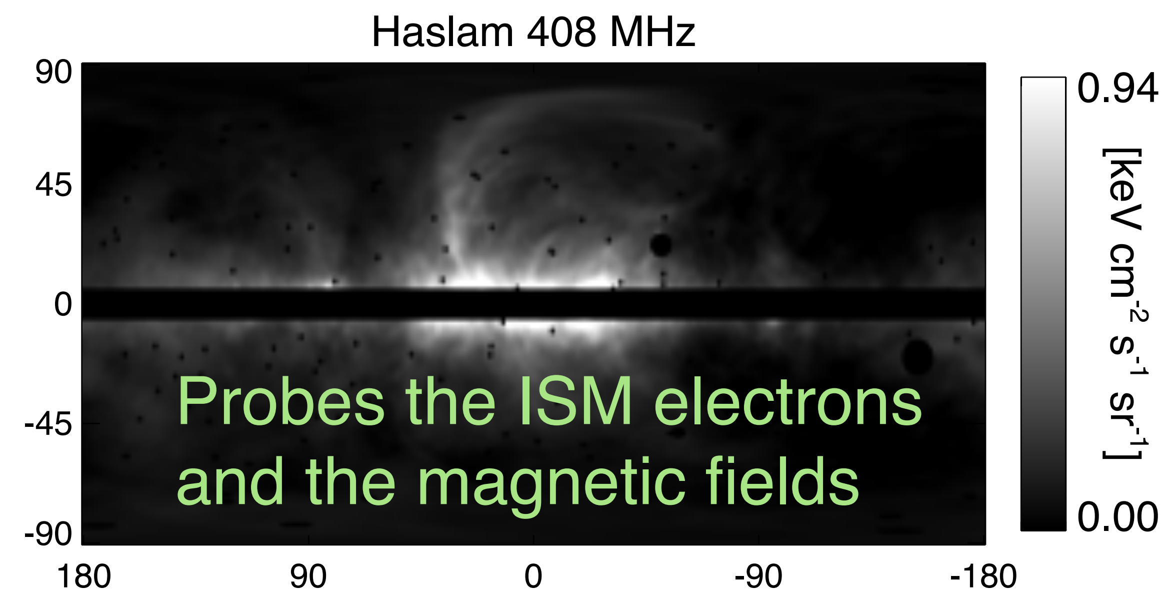
From Cosmological Simulations what we expect today

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

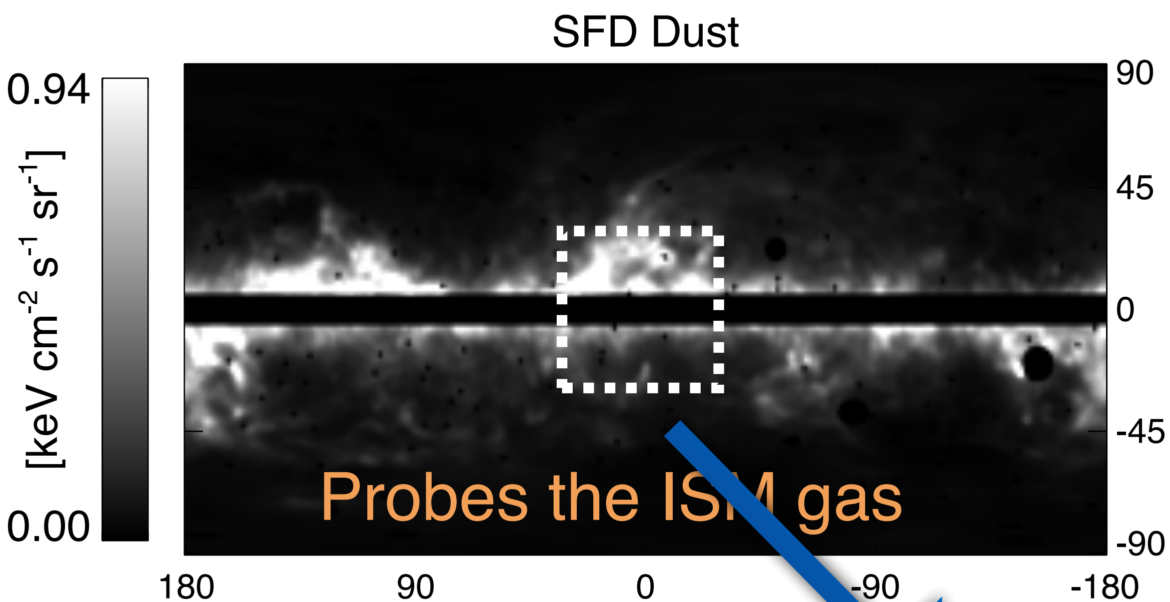
Using templates on Gamma-ray maps —> It's first use led to the discovery of the Fermi(Haze)-Bubbles

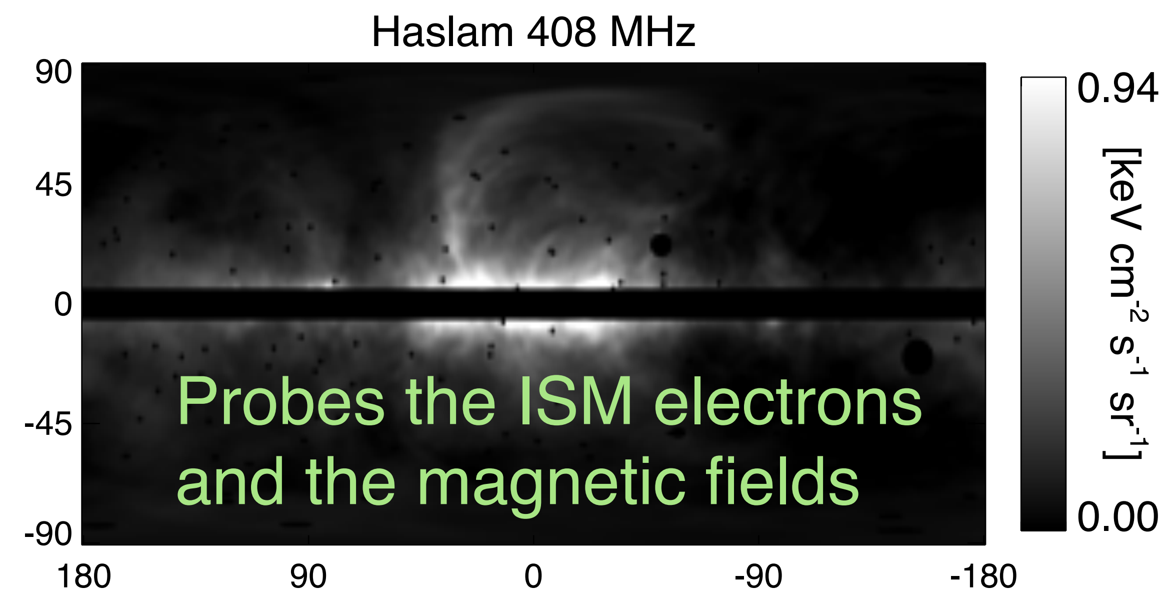
Dobler, Finkbeiner, **IC**, Slatyer, Weiner, ApJ, 2010



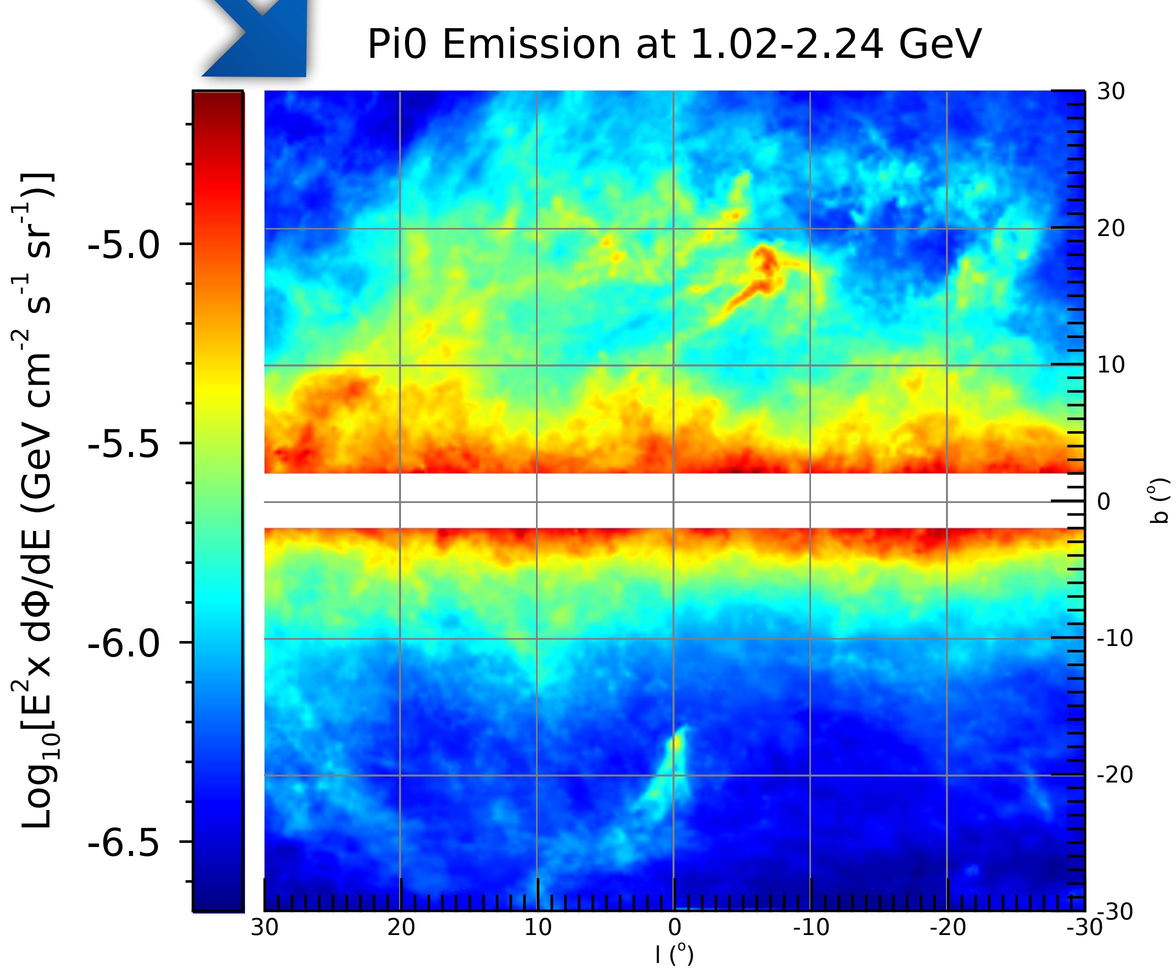


Using templates on Gamma-ray maps



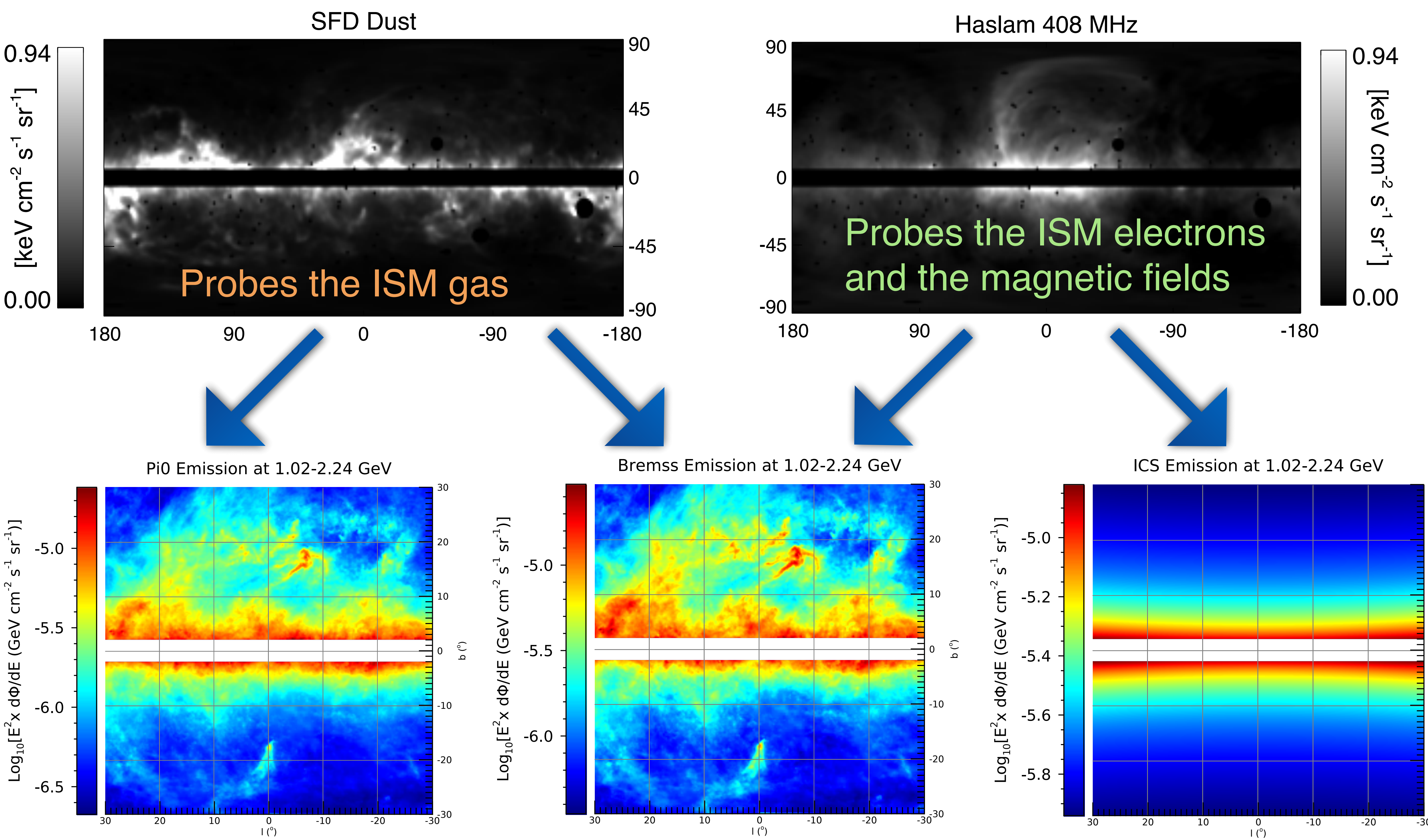


Adding ISM physics, cosmic-ray observations and running an array of Milky Way simulations …

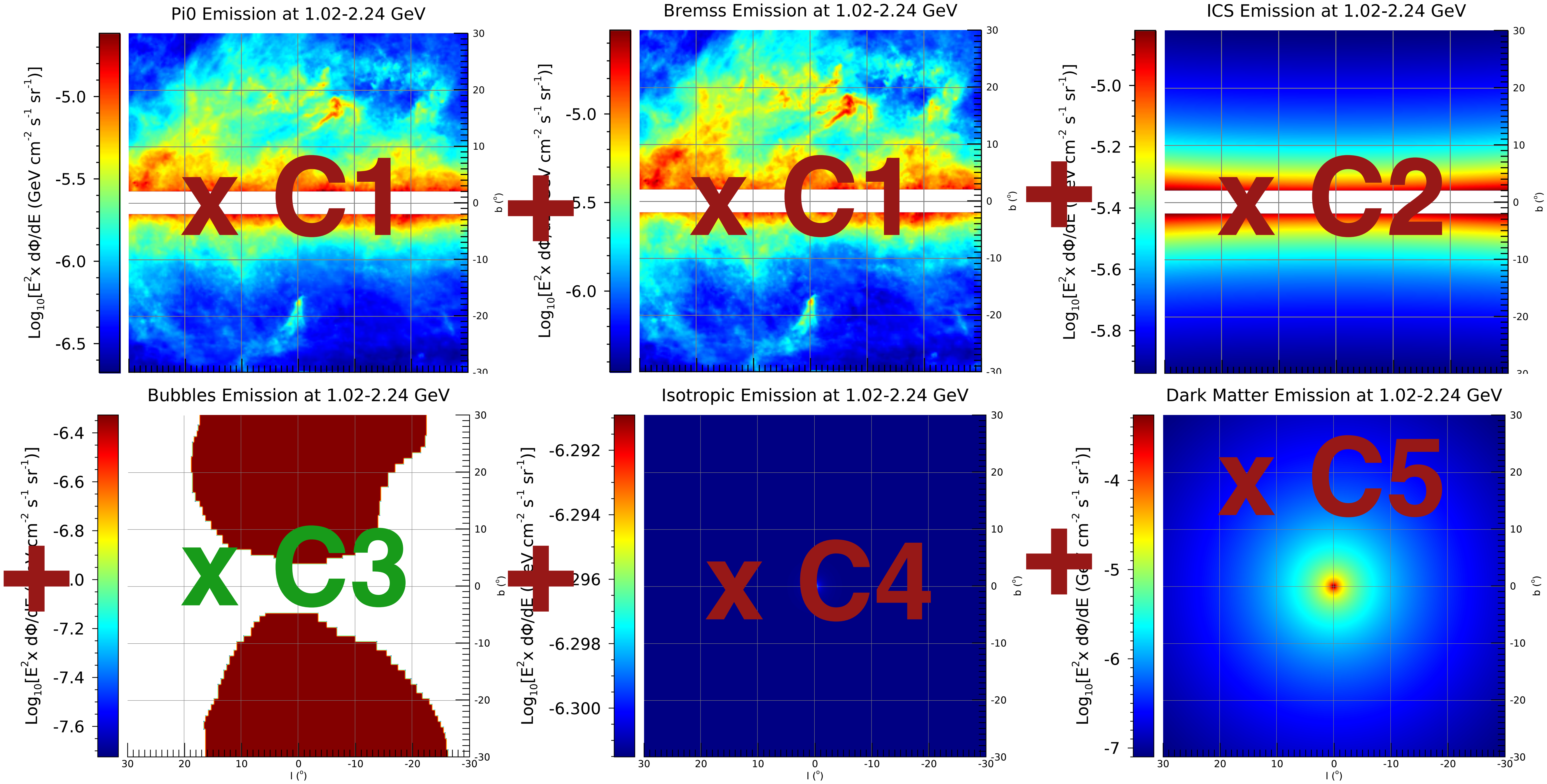


60 degrees in latitude

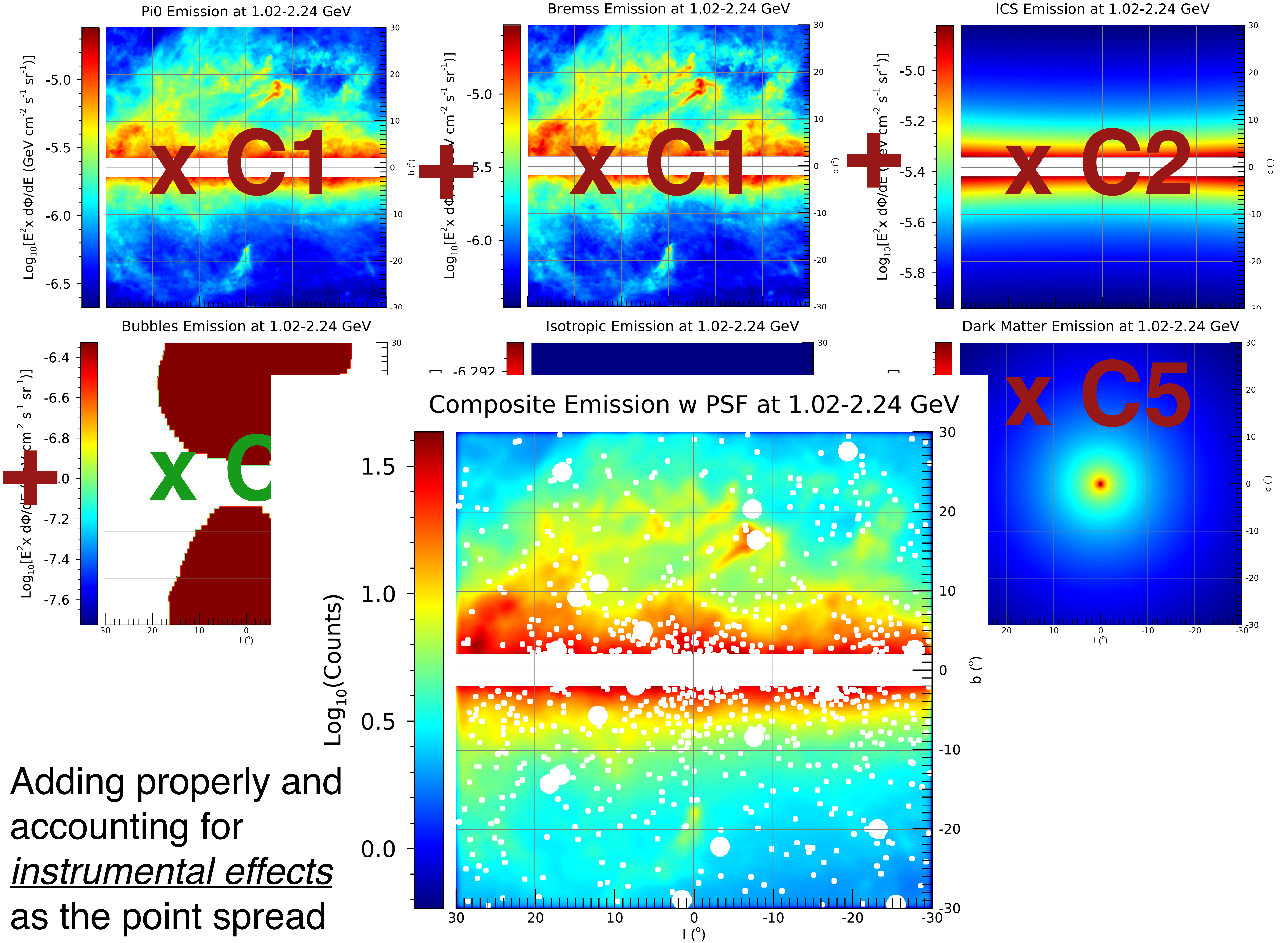
Using templates on Gamma-ray maps



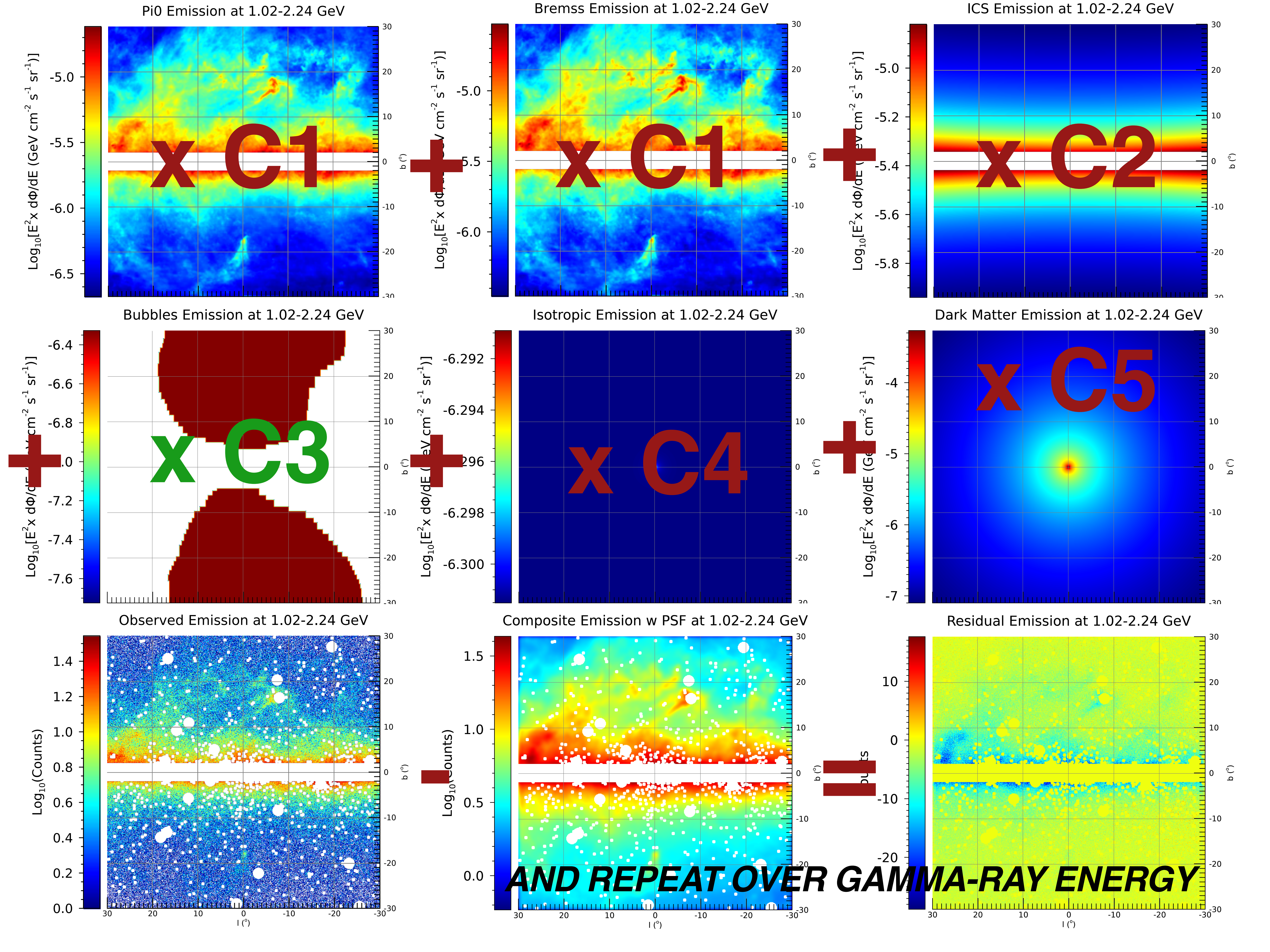
IC, Zhong, McDermott, Surdutovich, PRD 2022 (arXiv:2112.09706)



Pi0 Emission at 1.02-2.24 GeV
x C1
+
Bremss Emission at 1.02-2.24 GeV
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)]
b (°)
l (°)



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 C3
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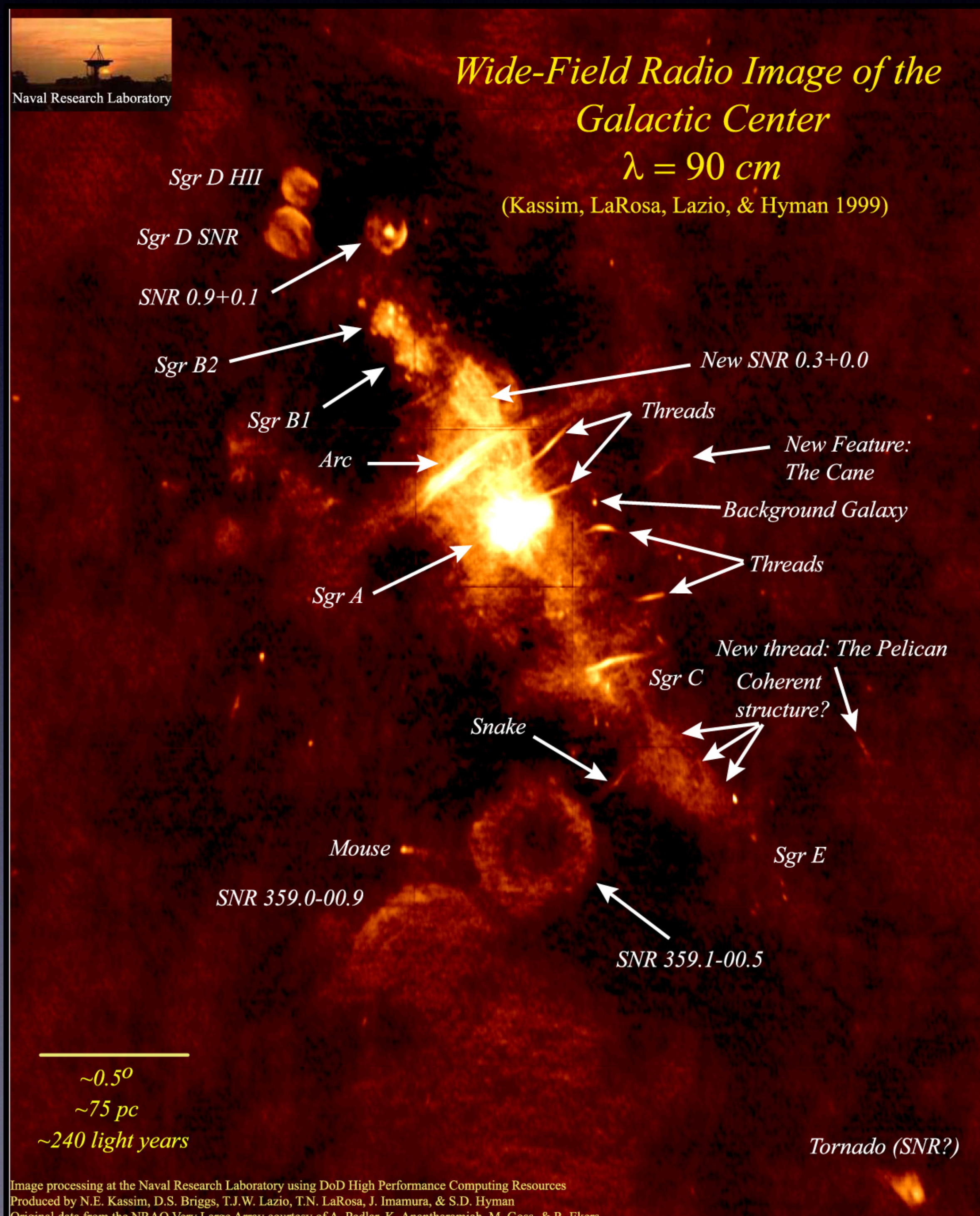
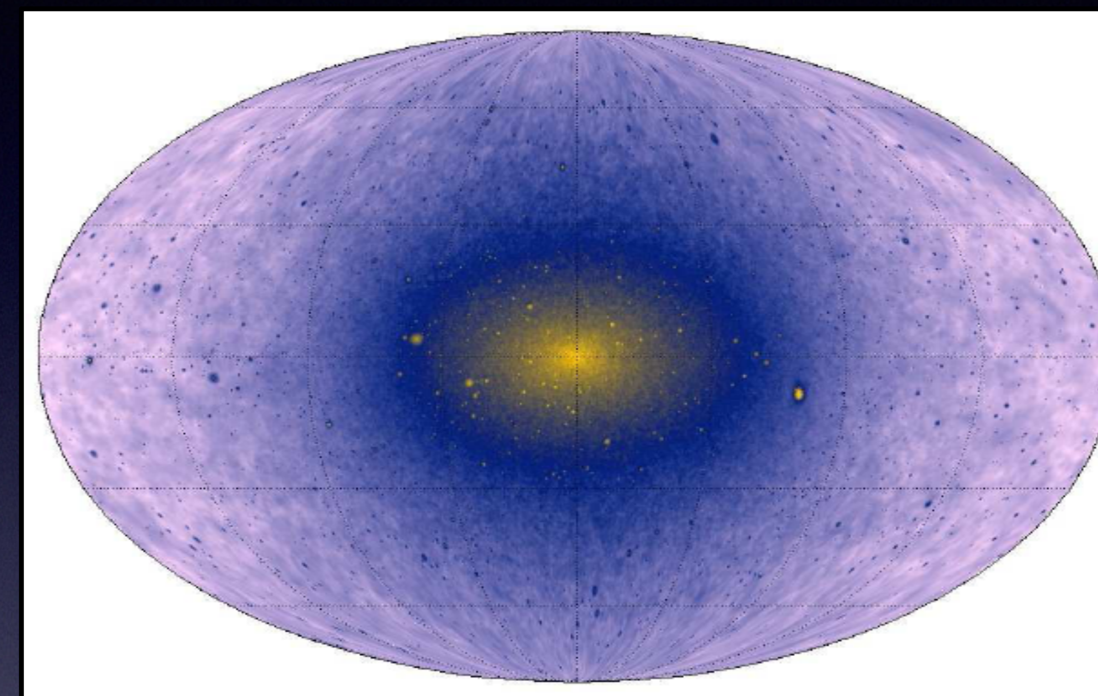
Isotropic Emission at 1.02-2.24 GeV
x C4
+
Dark Matter Emission at 1.02-2.24 GeV
x C5
Observed Emission at 1.02-2.24 GeV
-
Composite Emission w PSF at 1.02-2.24 GeV
=
Residual Emission at 1.02-2.24 GeV
AND REPEAT OVER GAMMA-RAY ENERGY
Log10[E2x dΦ/dE (GeV cm-2 s-1 sr-1)]
Log10(Counts)
b (°)
l (°)

The galactic center
A place to look for Dark Matter Annihilation

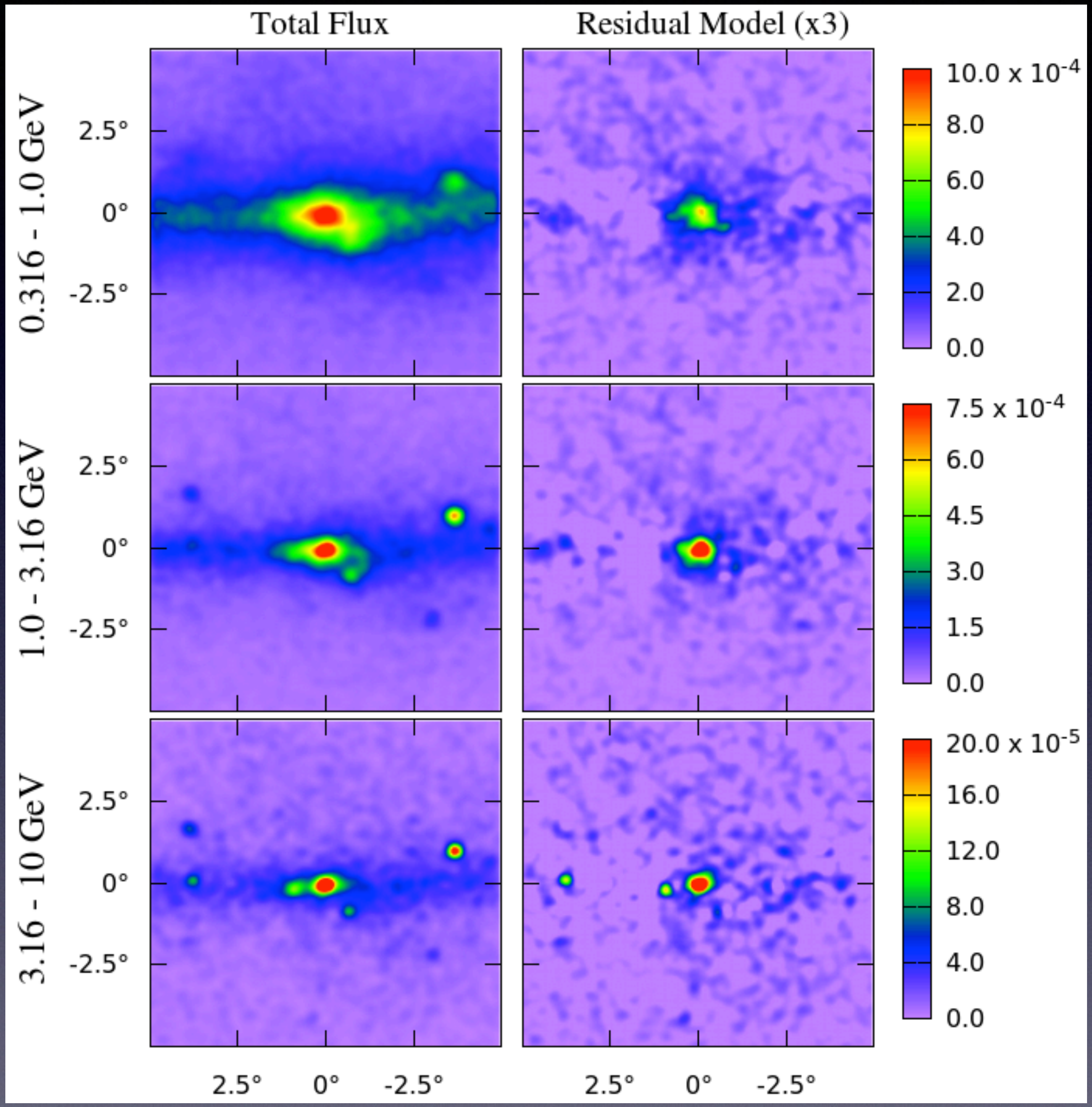




- The region of the galactic center is complex with large uncertainties.
- A DM annihilation signal peaks but also has significant uncertainties..
- Take advantage of multi-wavelength searches.

Looking for excesses in the galactic center

Using Templates:

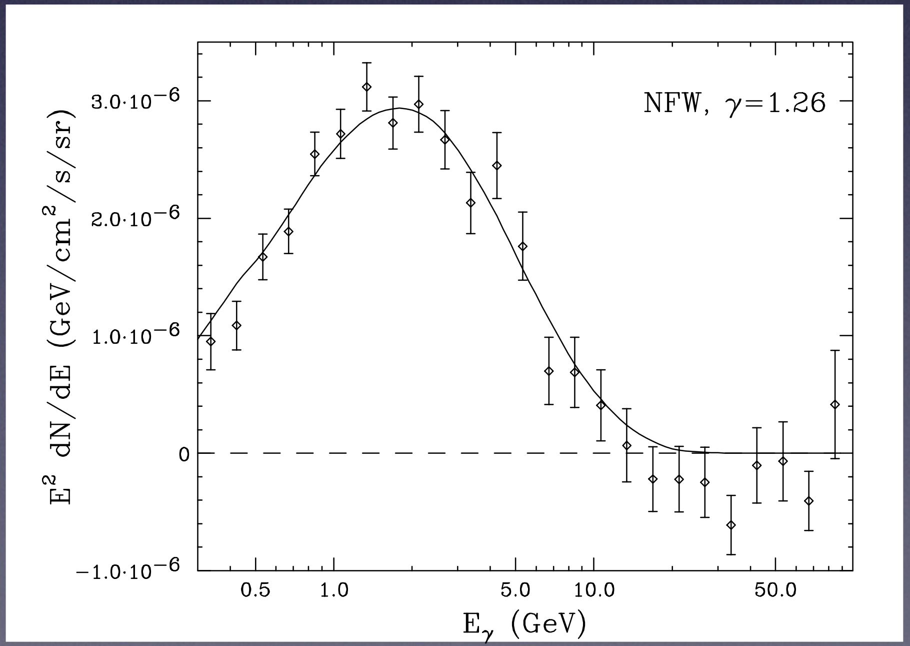


Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, PoDU 2015

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)***

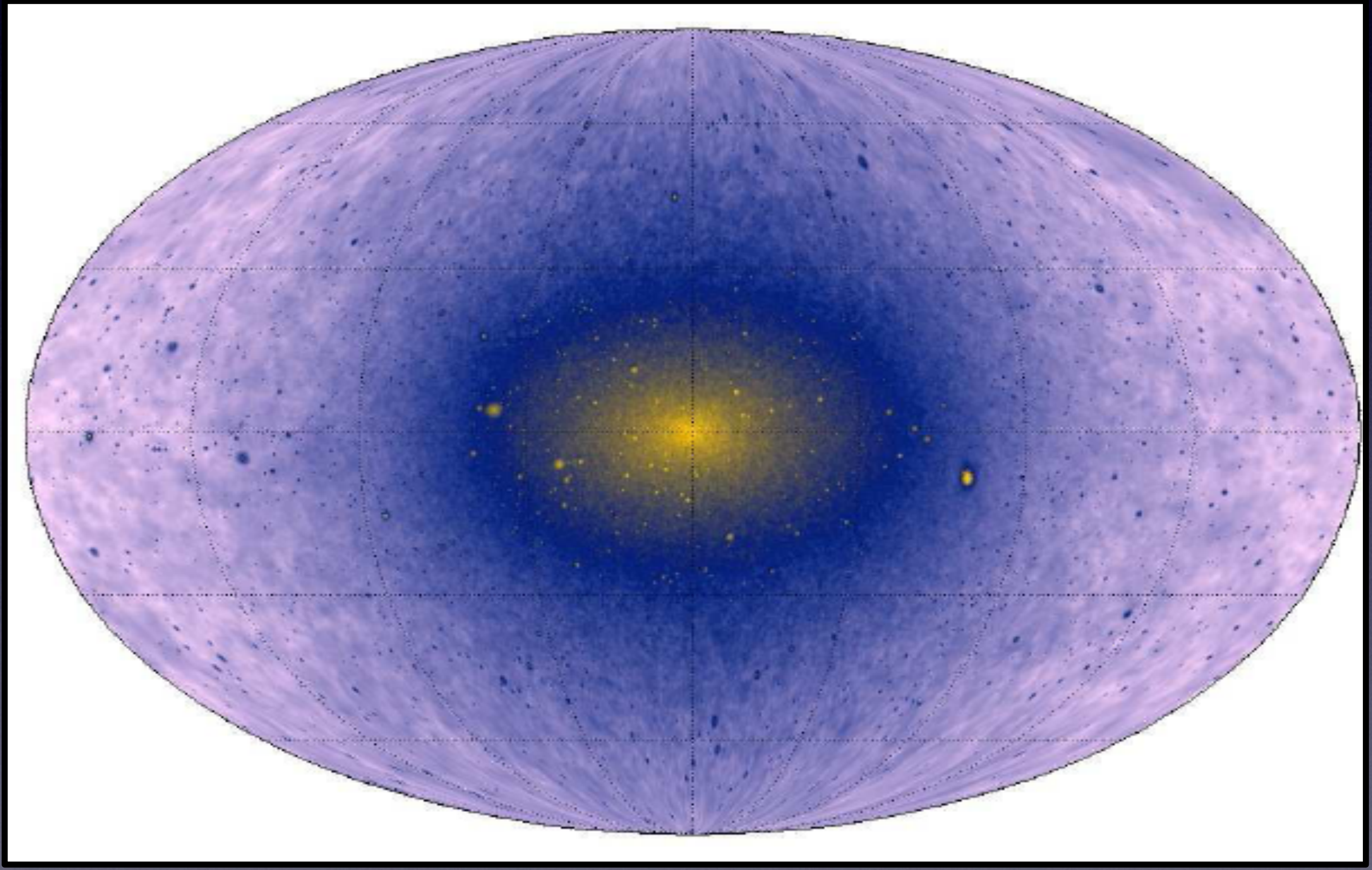


Also: Hooper & Goodenough PRL 2011, Abazajian JCAP 2011, Hooper & Linden PRD 2011, Gordon & Macias PRD 2014, Zhou et al. PRD 2015, Ajello et al. ApJ 2016

Going to High Latitudes (Inner Galaxy)

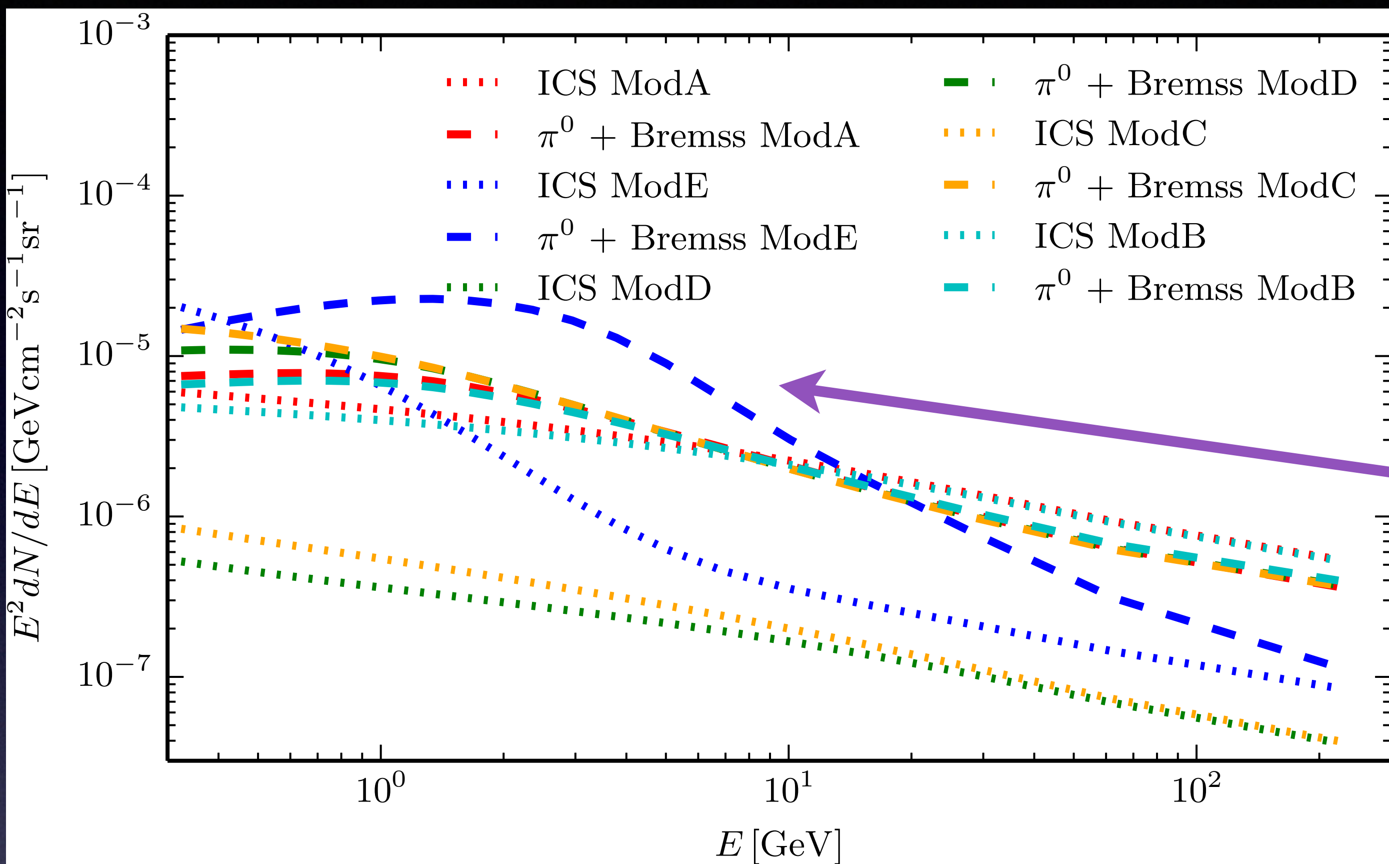
Advantages of looking further away from the center:

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

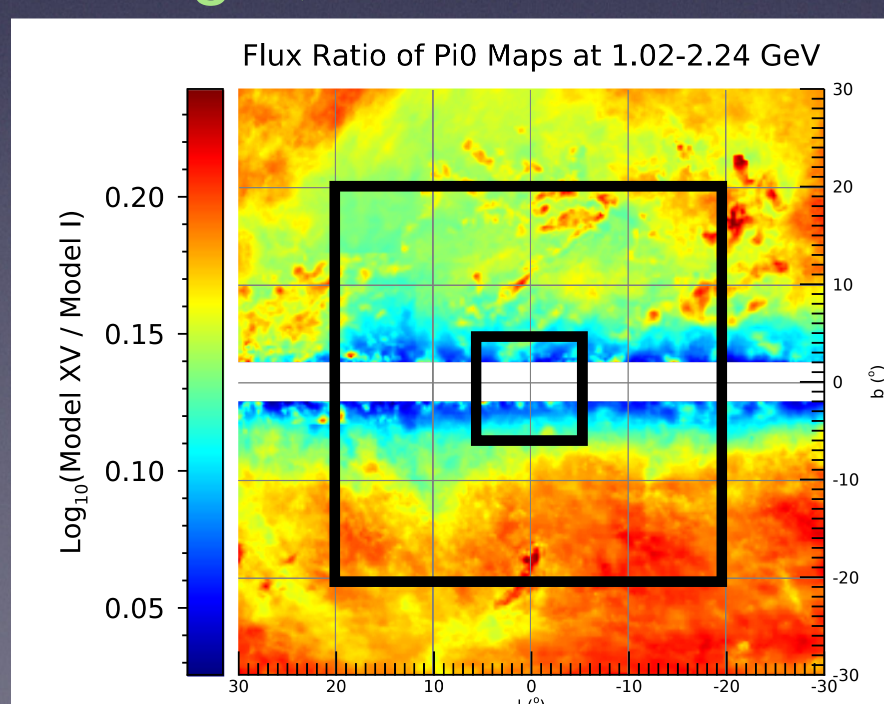


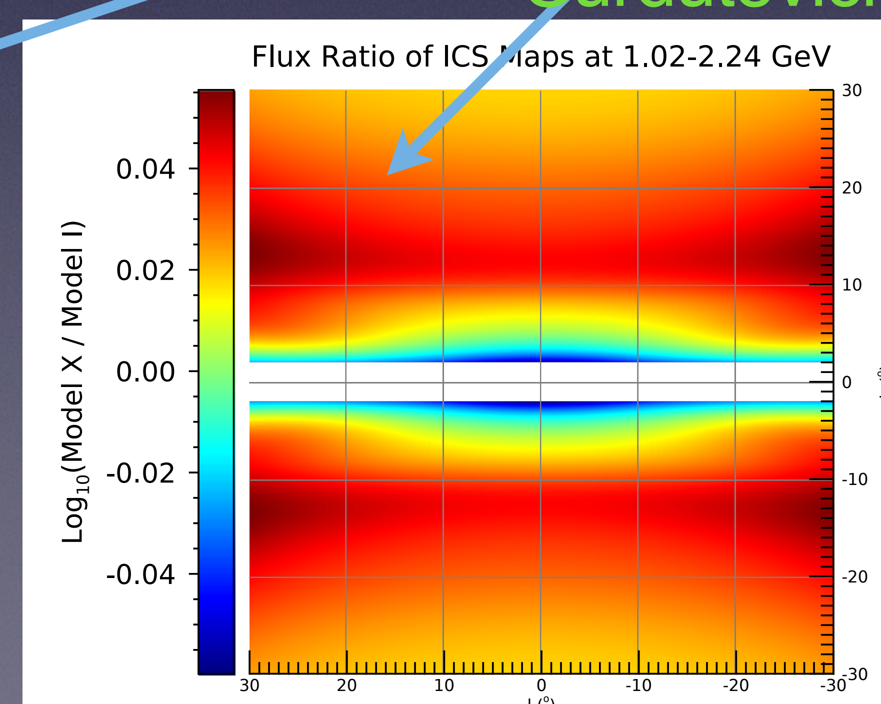
The exact astrophysics model assumptions can affect both the gamma-ray background spectrum and its morphology on the galactic sky.

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

IC, Zhong, McDermott, Surdutovich, PRD 2022

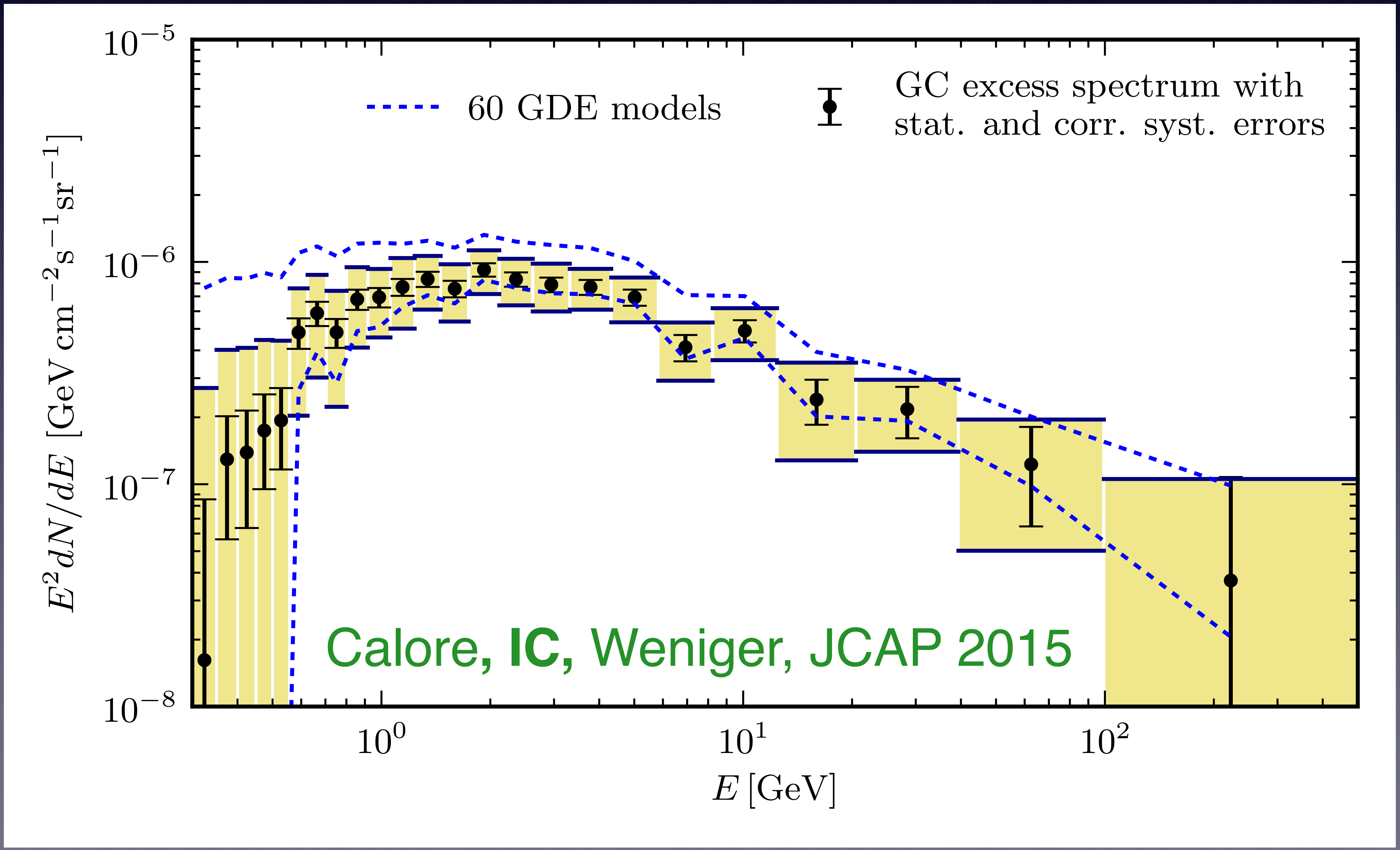
60 degrees in latitude





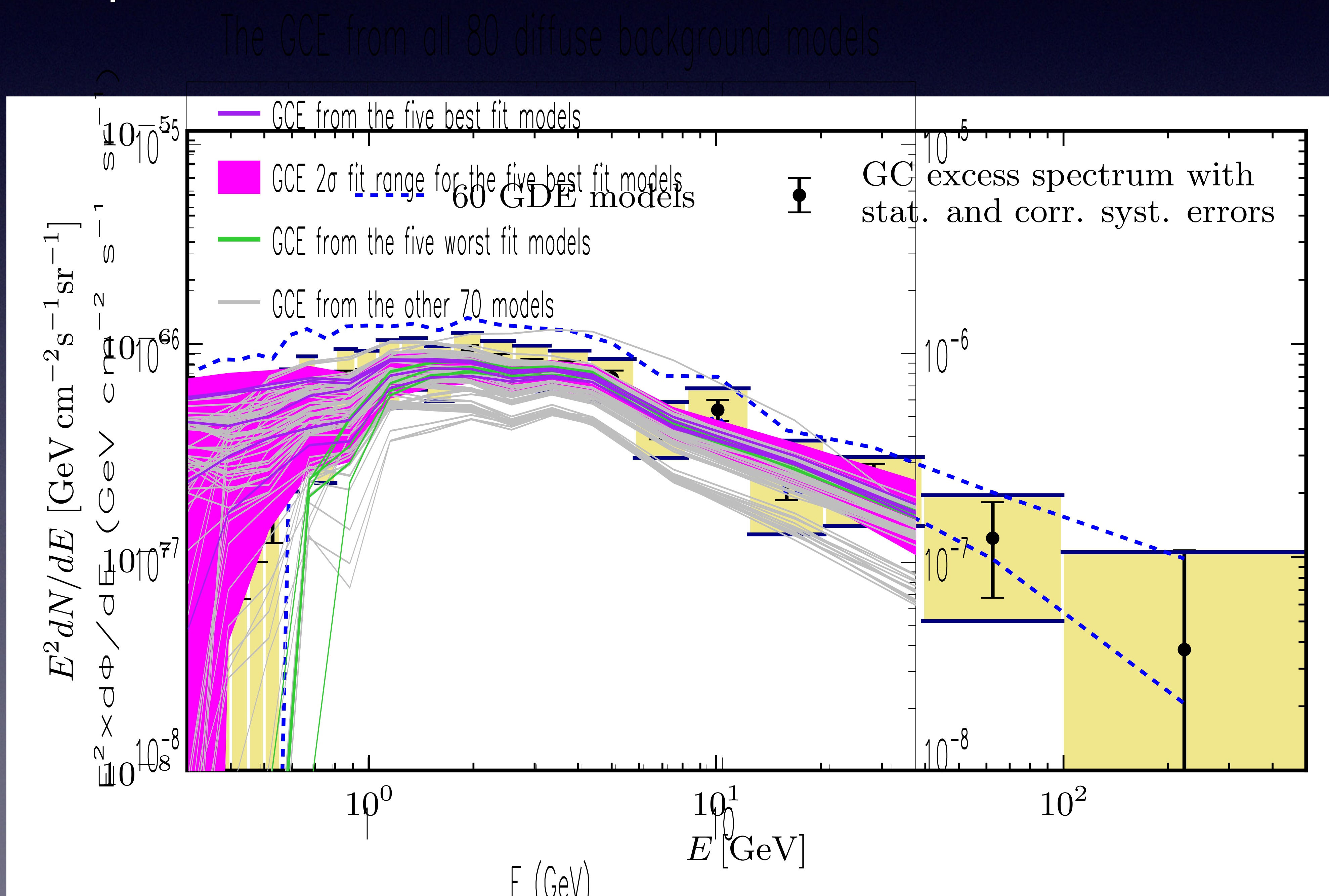
Accounting for the galactic diffuse emission uncertainties

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

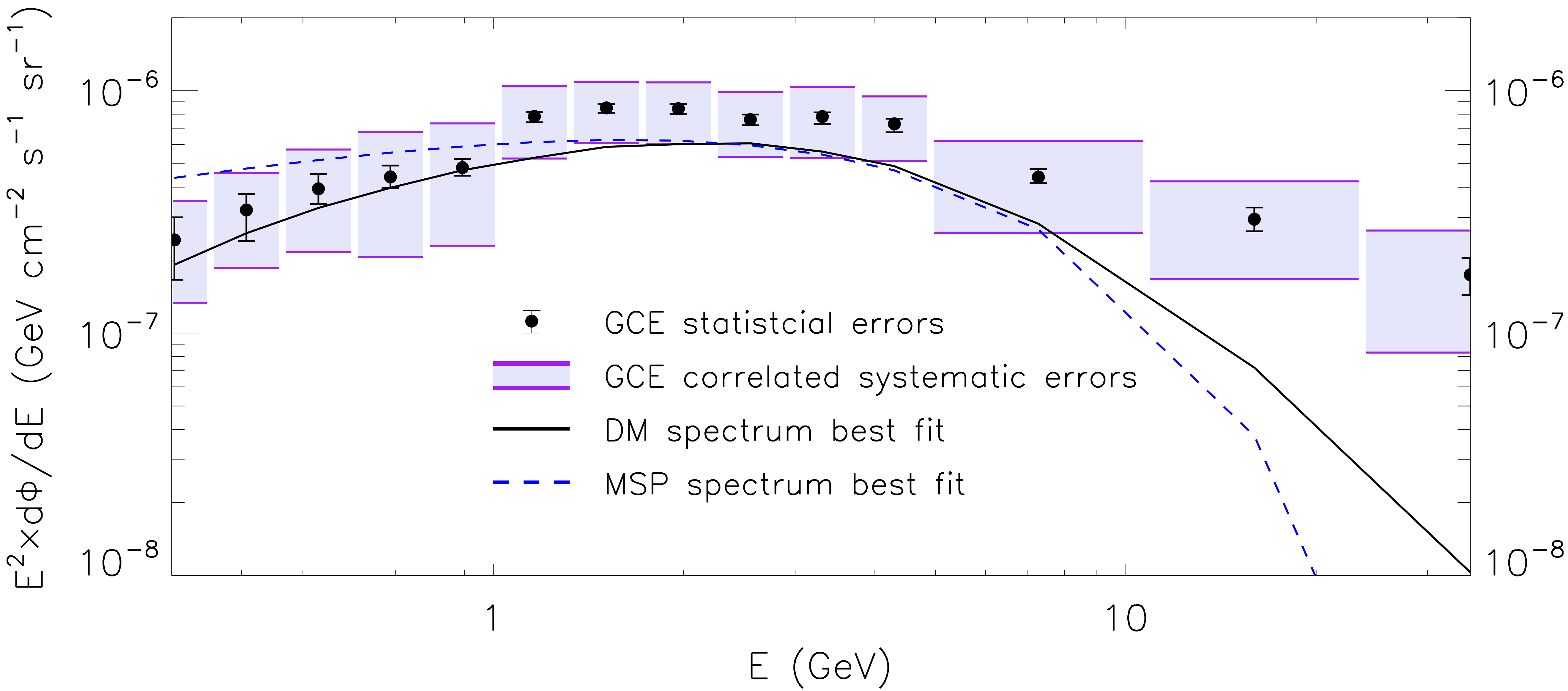
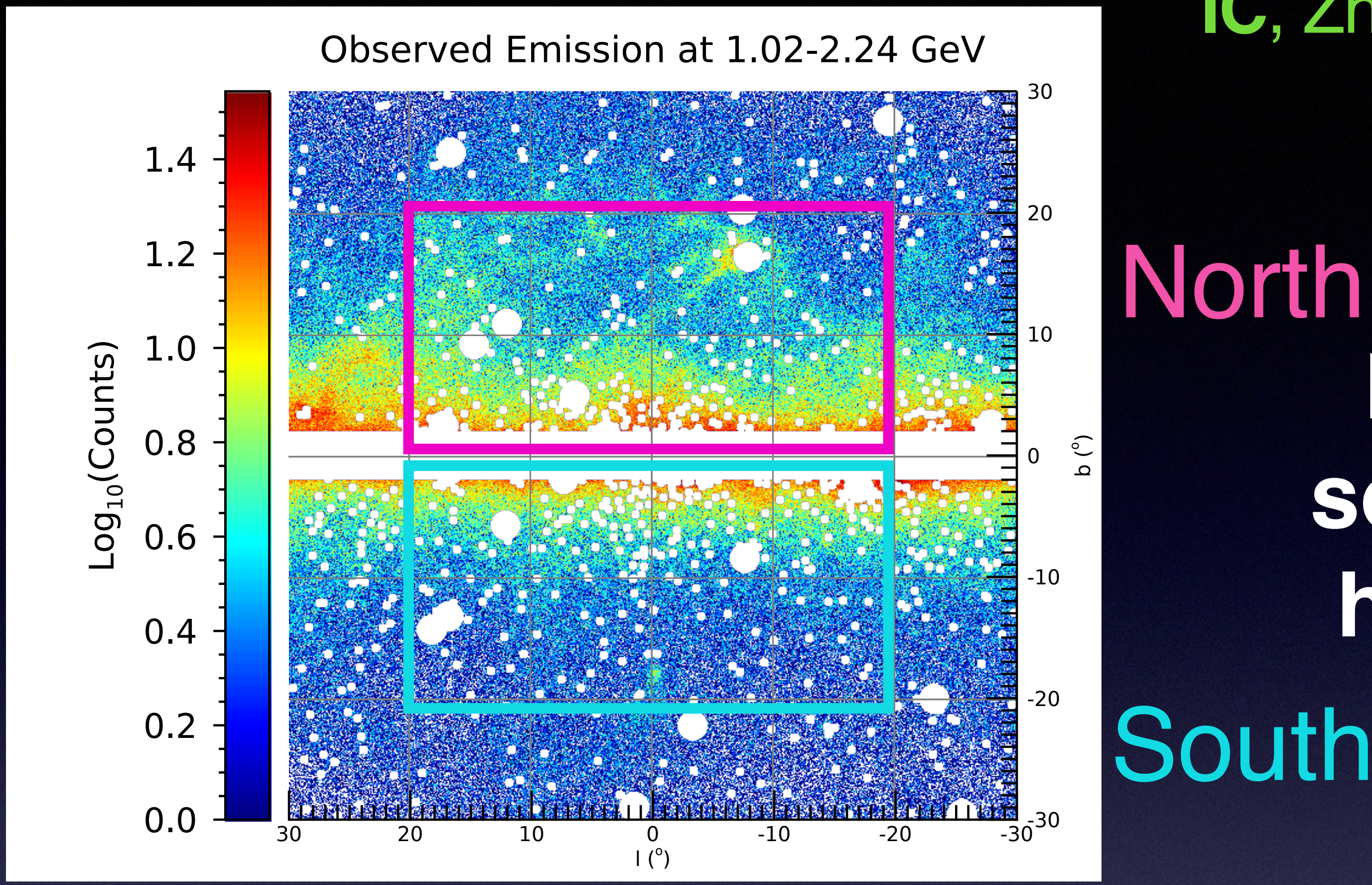


TABLE V. The first four principal components of the systematic uncertainty contribution to the covariance matrix, defined as in Eq. (16), in units of 10^{-7} GeV cm^{-2} s^{-1} sr^{-1}.

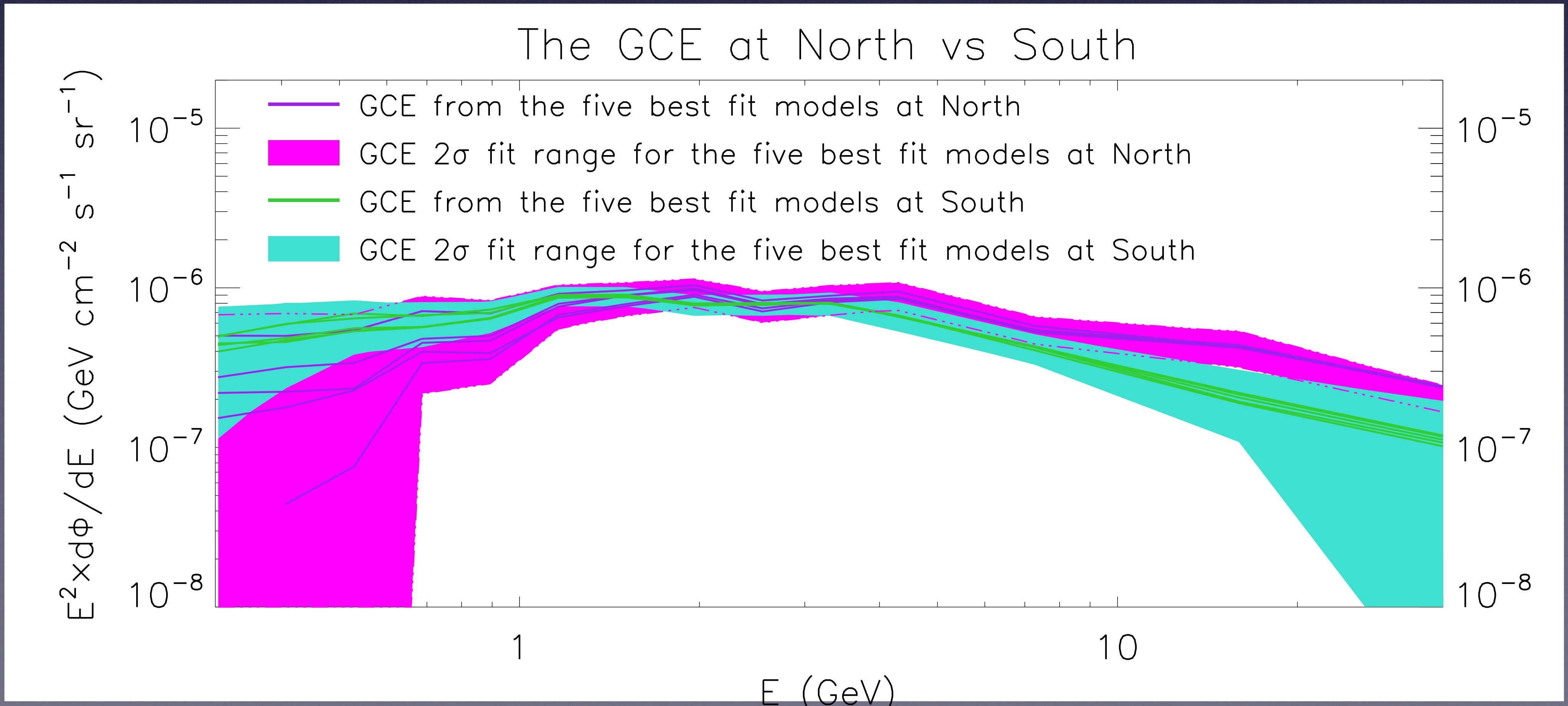
PC_i	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	Φ_6	Φ_7	Φ_8	Φ_9	Φ_{10}	Φ_{11}	Φ_{12}	Φ_{13}	Φ_{14}
PC_1	2.52	2.37	2.47	2.43	2.19	2.35	2.08	1.83	1.65	1.69	1.38	1.09	0.67	0.34
PC_2	−1.70	−1.07	−0.16	0.14	0.54	0.42	0.40	0.31	0.58	0.41	0.56	0.48	0.41	0.33
PC_3	0.27	0.06	−0.53	−0.22	−0.21	−0.18	−0.08	0.25	0.04	0.45	0.23	0.24	0.20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

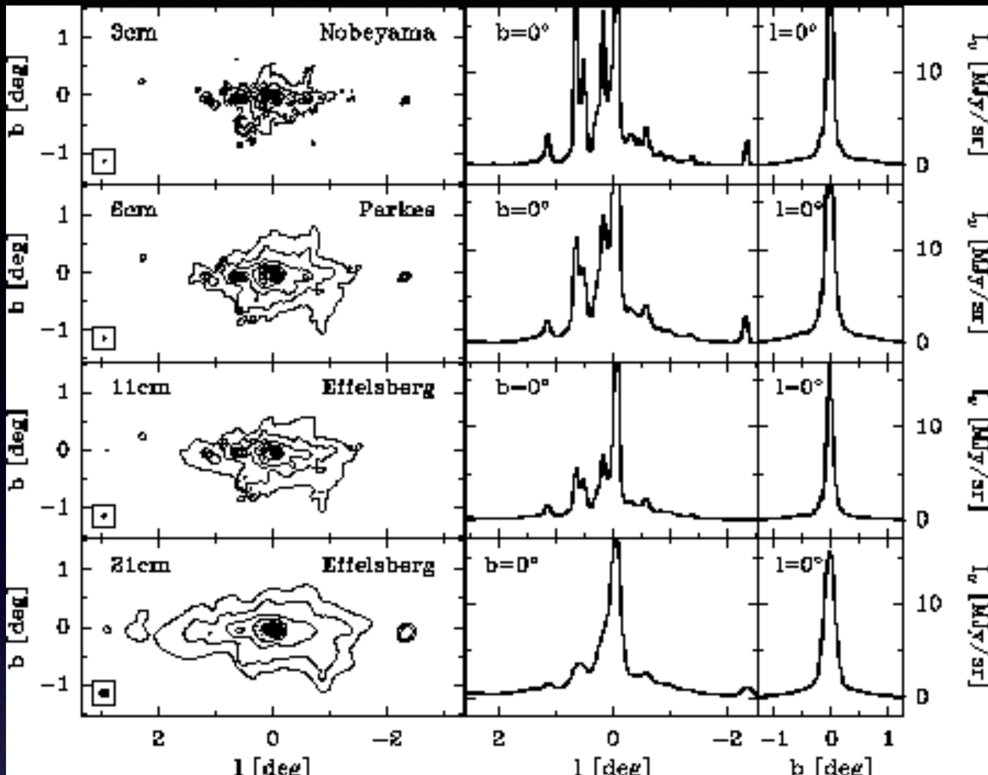
IC, Zhong, McDermott, Surdutovich, PRD 2022



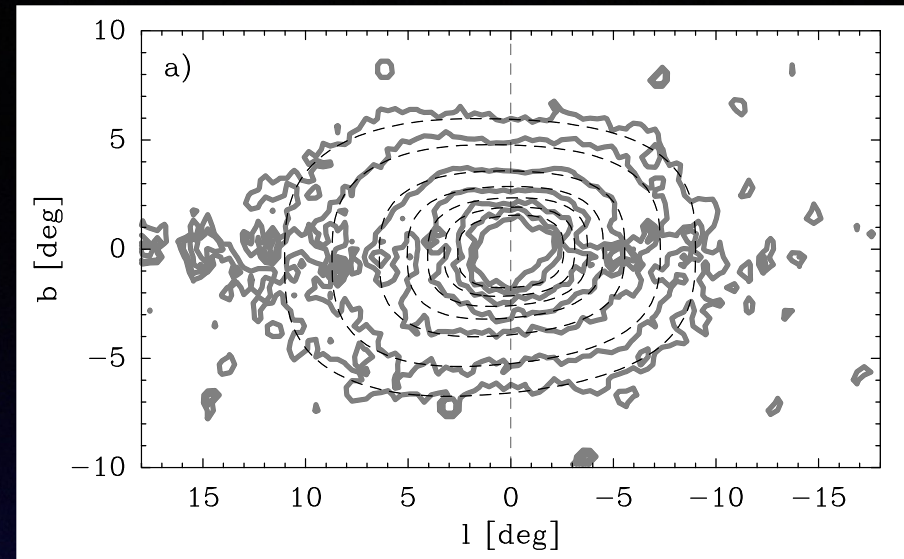
Roughly consistent between southern and northern galactic hemisphere as expected from dark matter



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

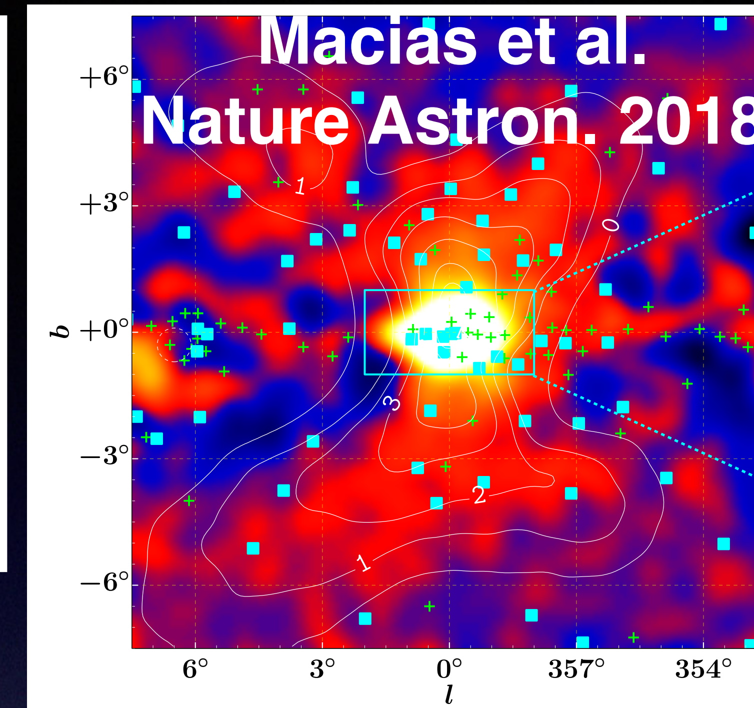


Nuclear Bulge @ Radio



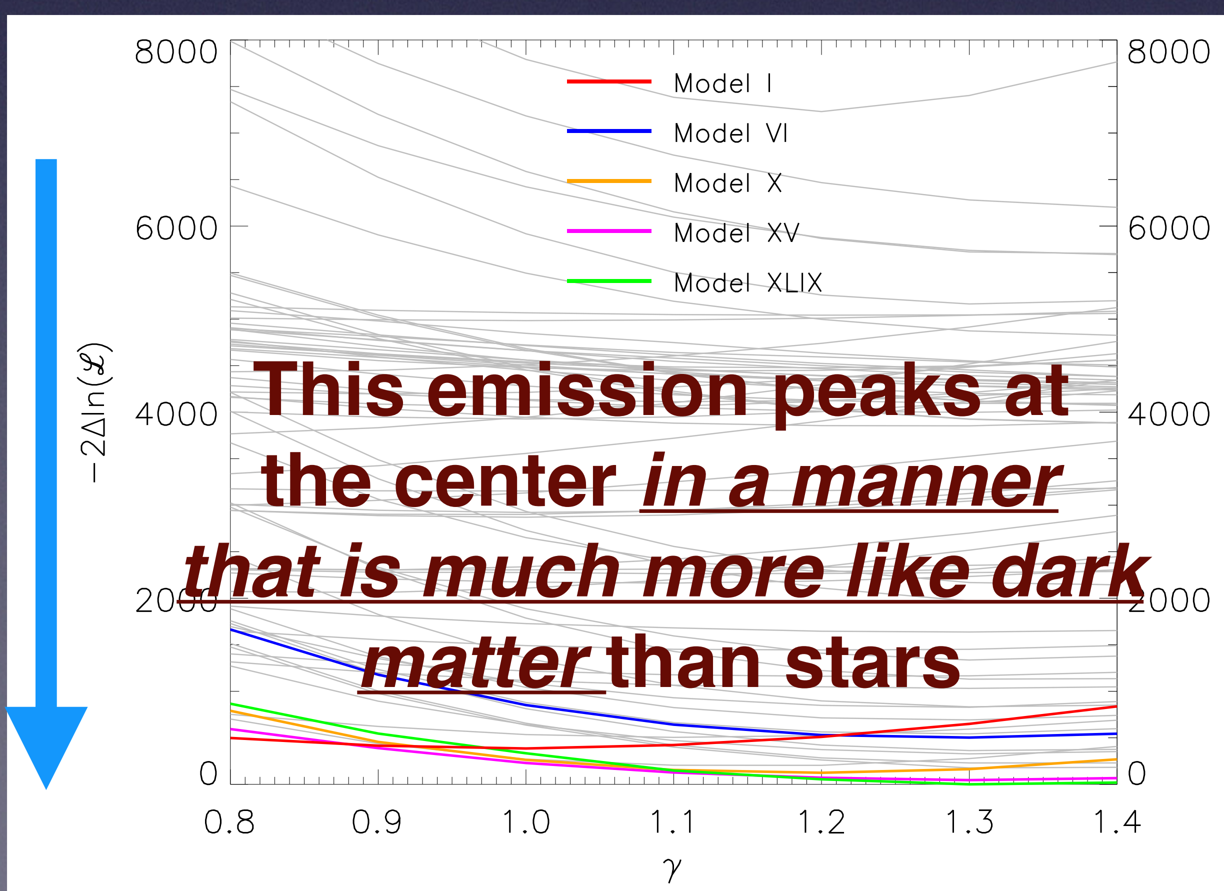
Boxy Bulge @ 2-5 µm

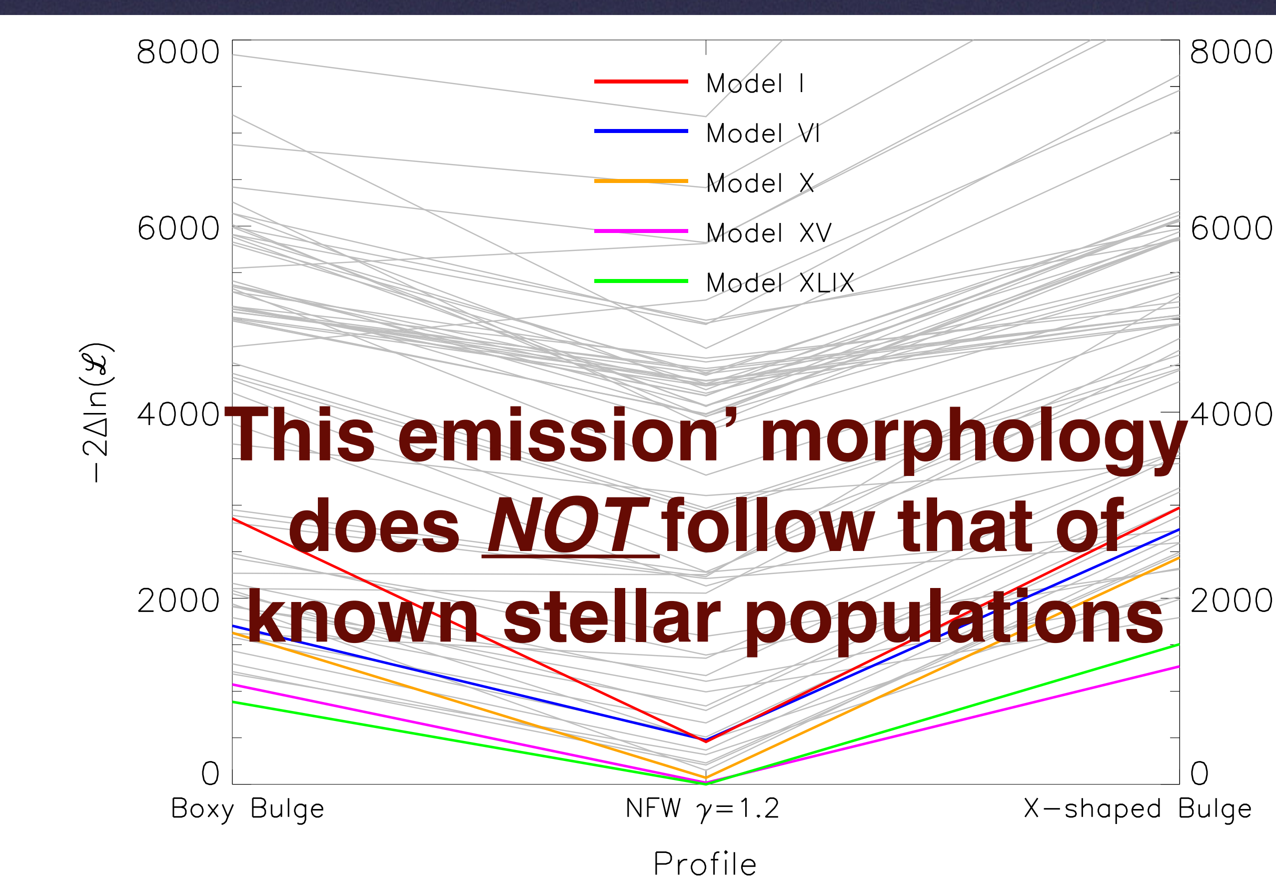
Launhardt et al. A&A 2002



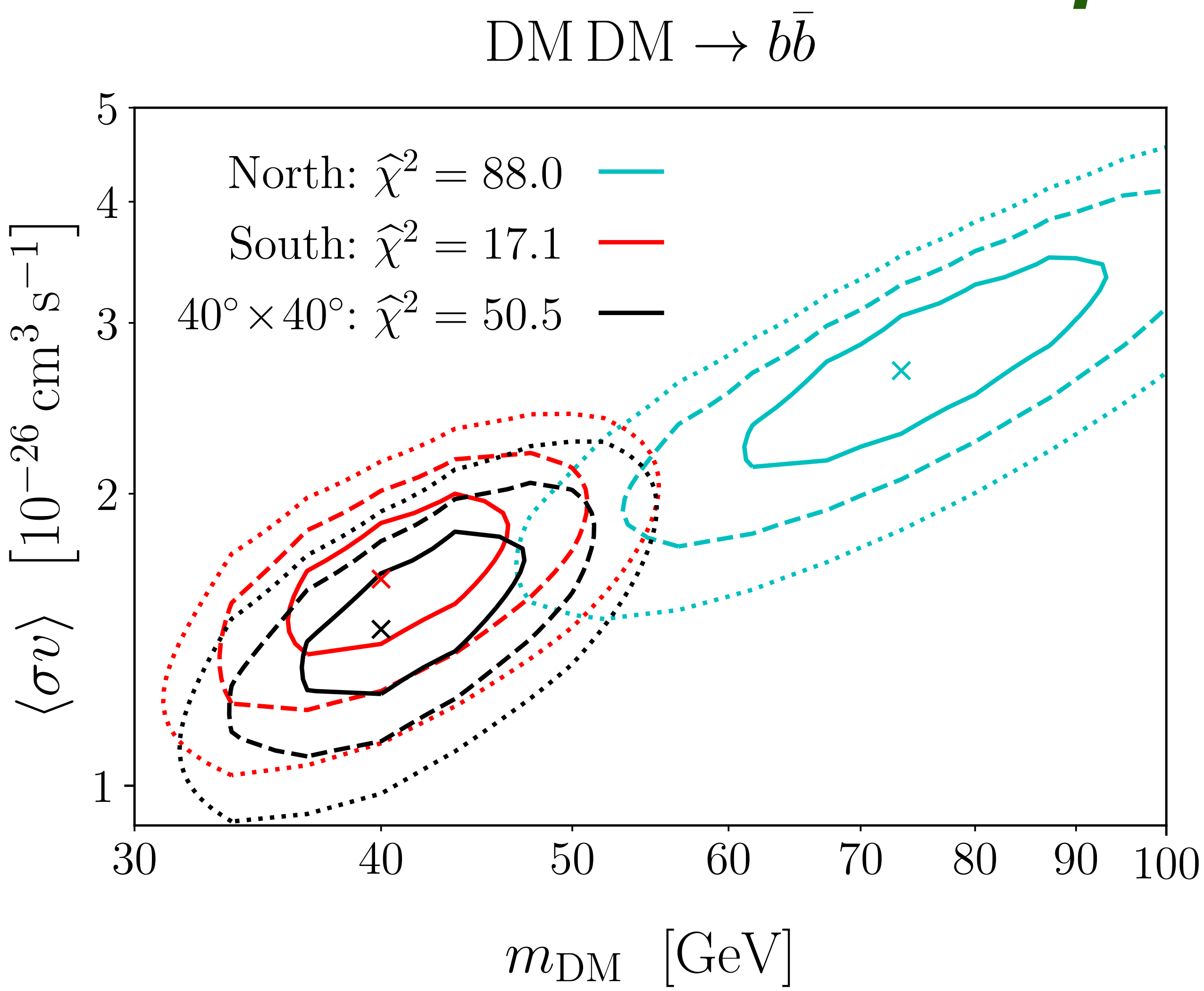
X-shaped Bulge @ "low" gamma-rays

Statistical Preference

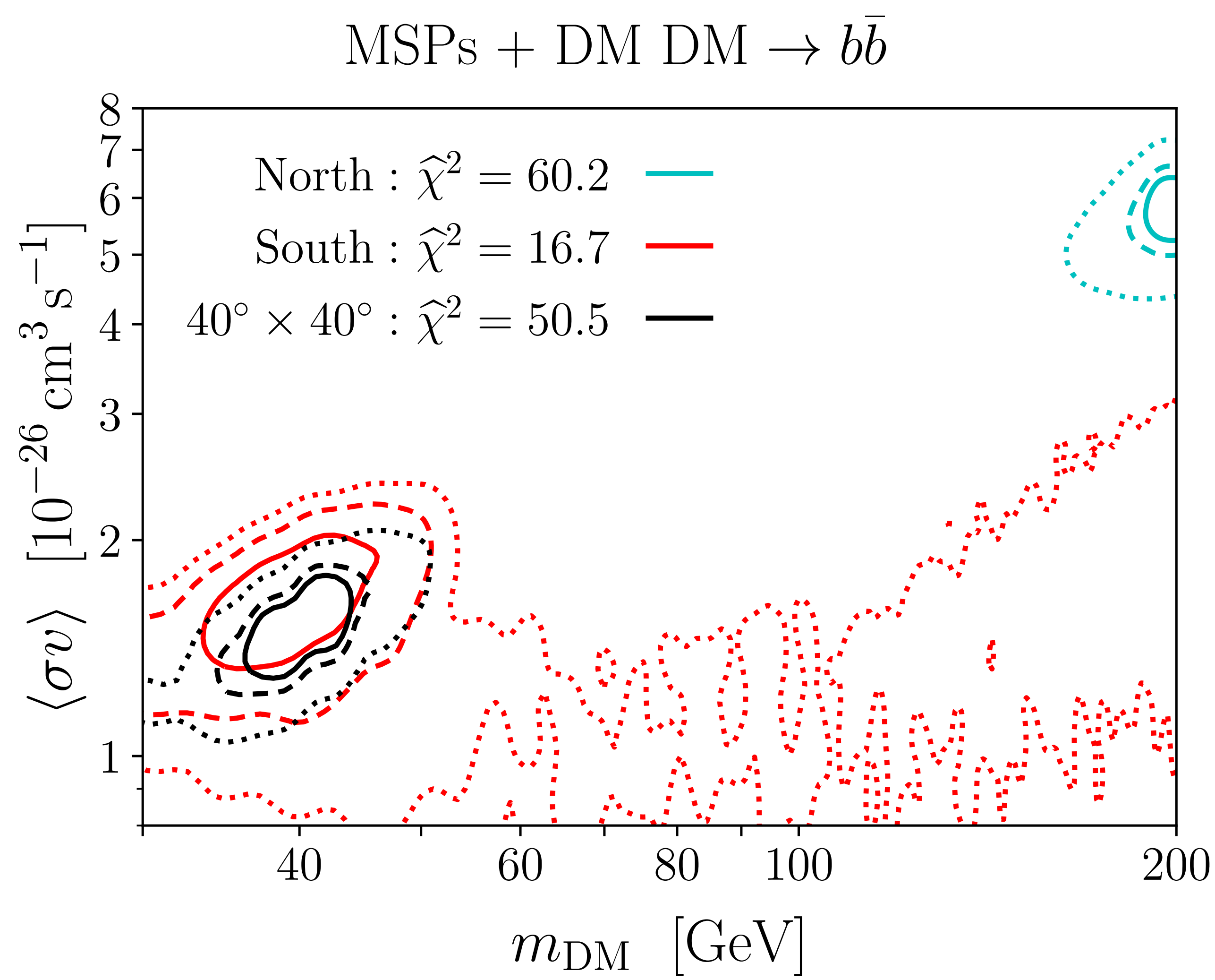




If this is a DM annihilation signal what do we learn about the particle physics?

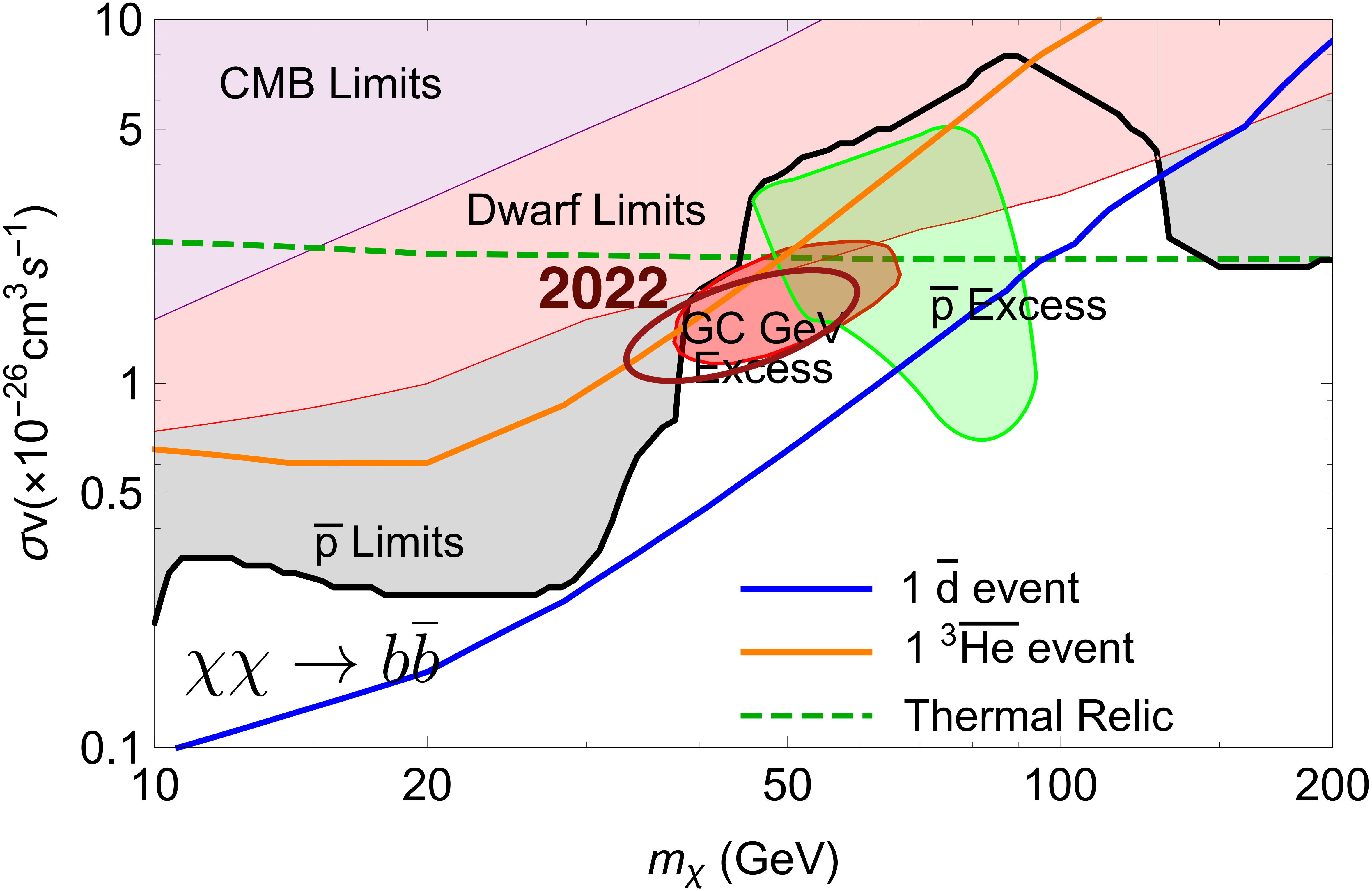


The mass range preferred very much within the WIMP range.



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

Acknowledgements

My Collaborators: Dan Hooper (Fermilab/U. Chicago), Tim Linden (U. Stockholm), Sam McDermott (Fermilab),Yi-Ming Zhong (KICP)

My Students: Jenna Bacon (OU), Iason Krommydas (NTUA), Ian McKinnon (OU), Osip Surdutovich (Carleton College)

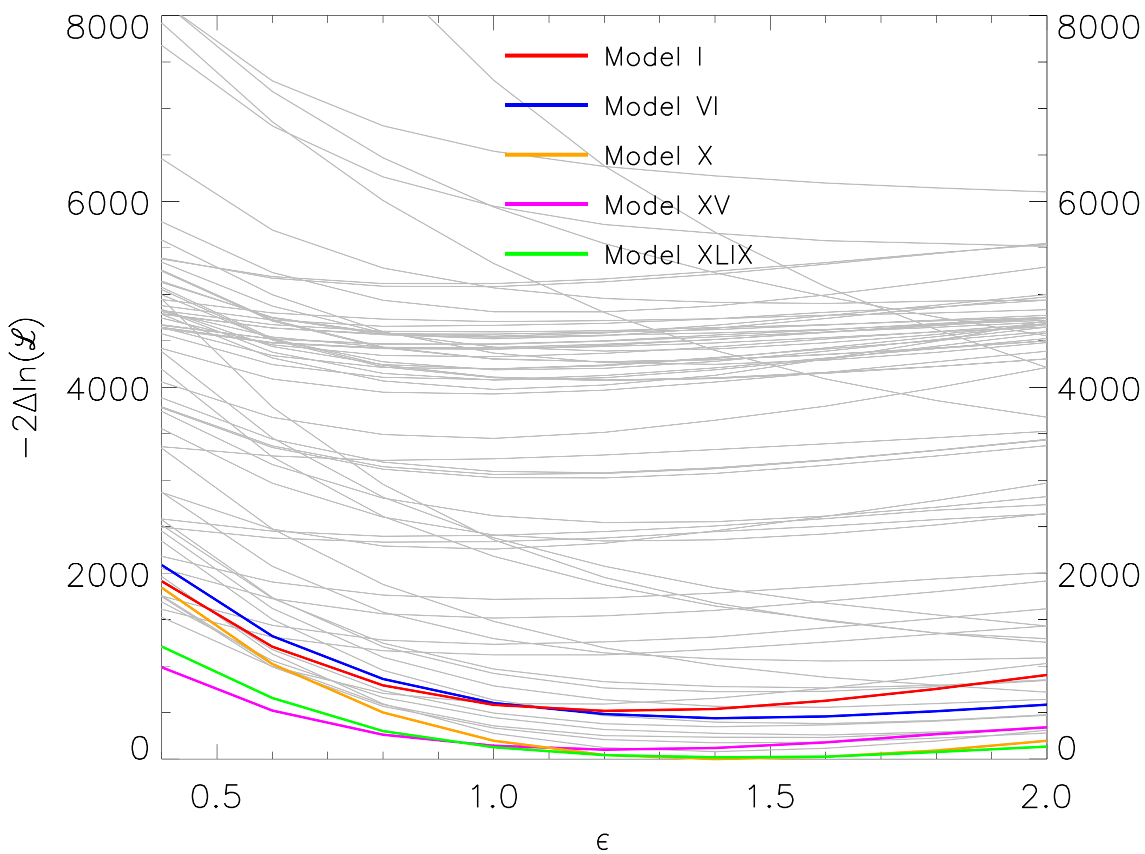
MSGC, NASA No. NNX15AJ20H
MSGC, NASA No. 80NSSC20M0124

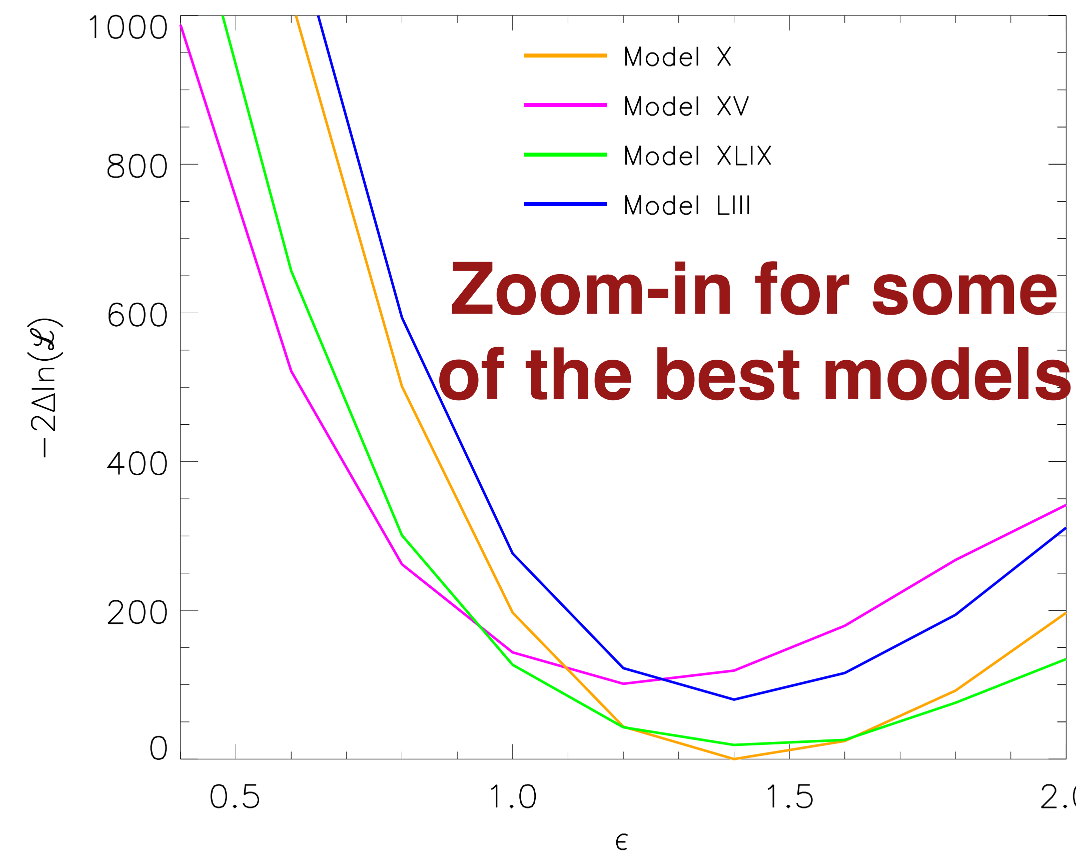
Oakland University Research Fellowship

Department of Energy, DE-SC0022352

Thank you!

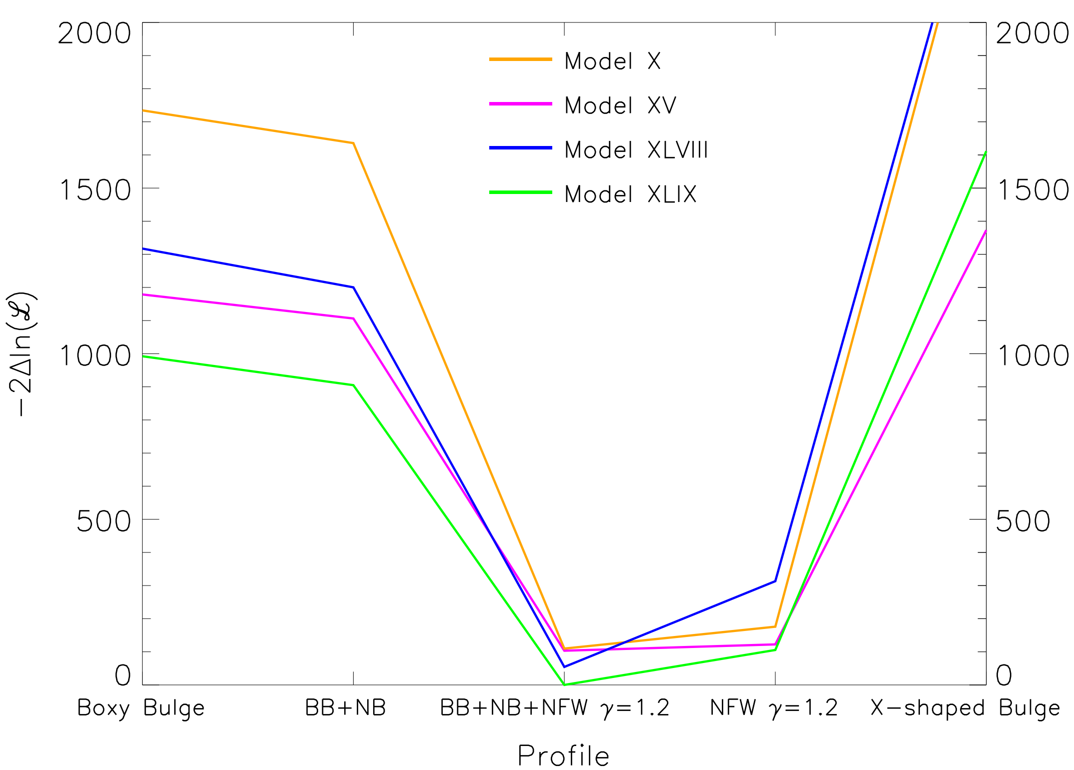
Extra

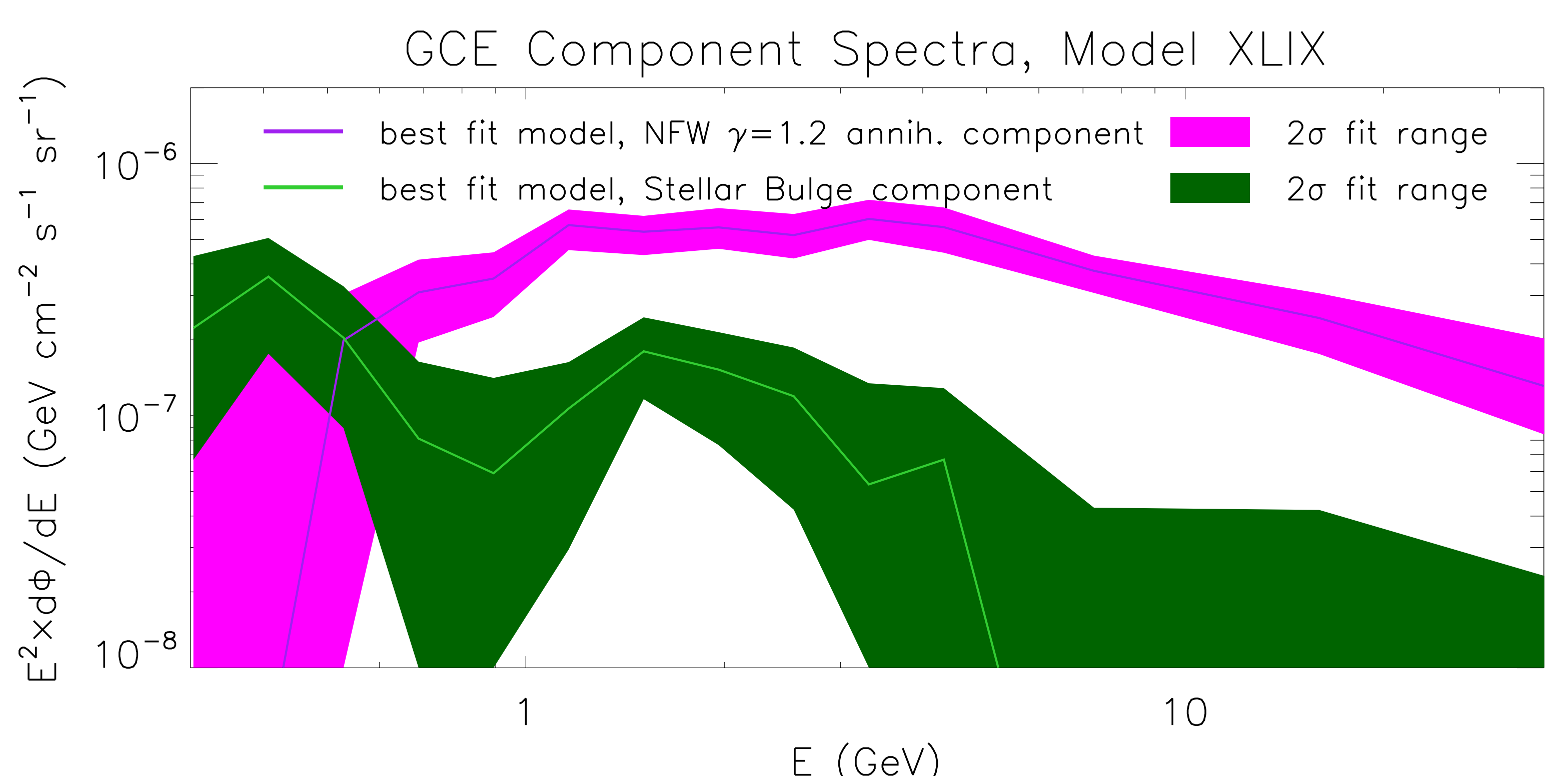


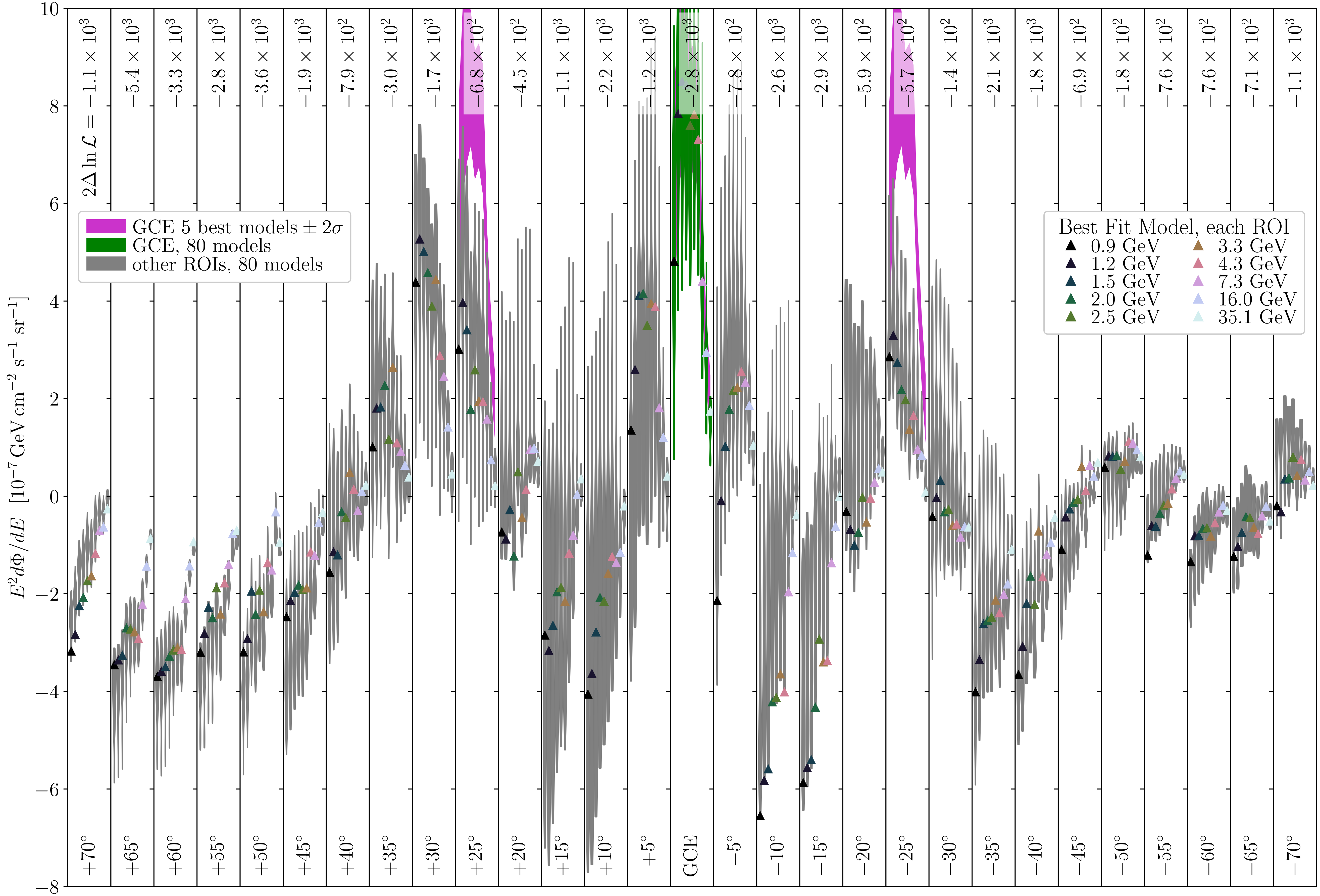


Results do not change substantively between 4FGL, 4FGL-DR2 (and also 4FGL-DR3) point source catalogues

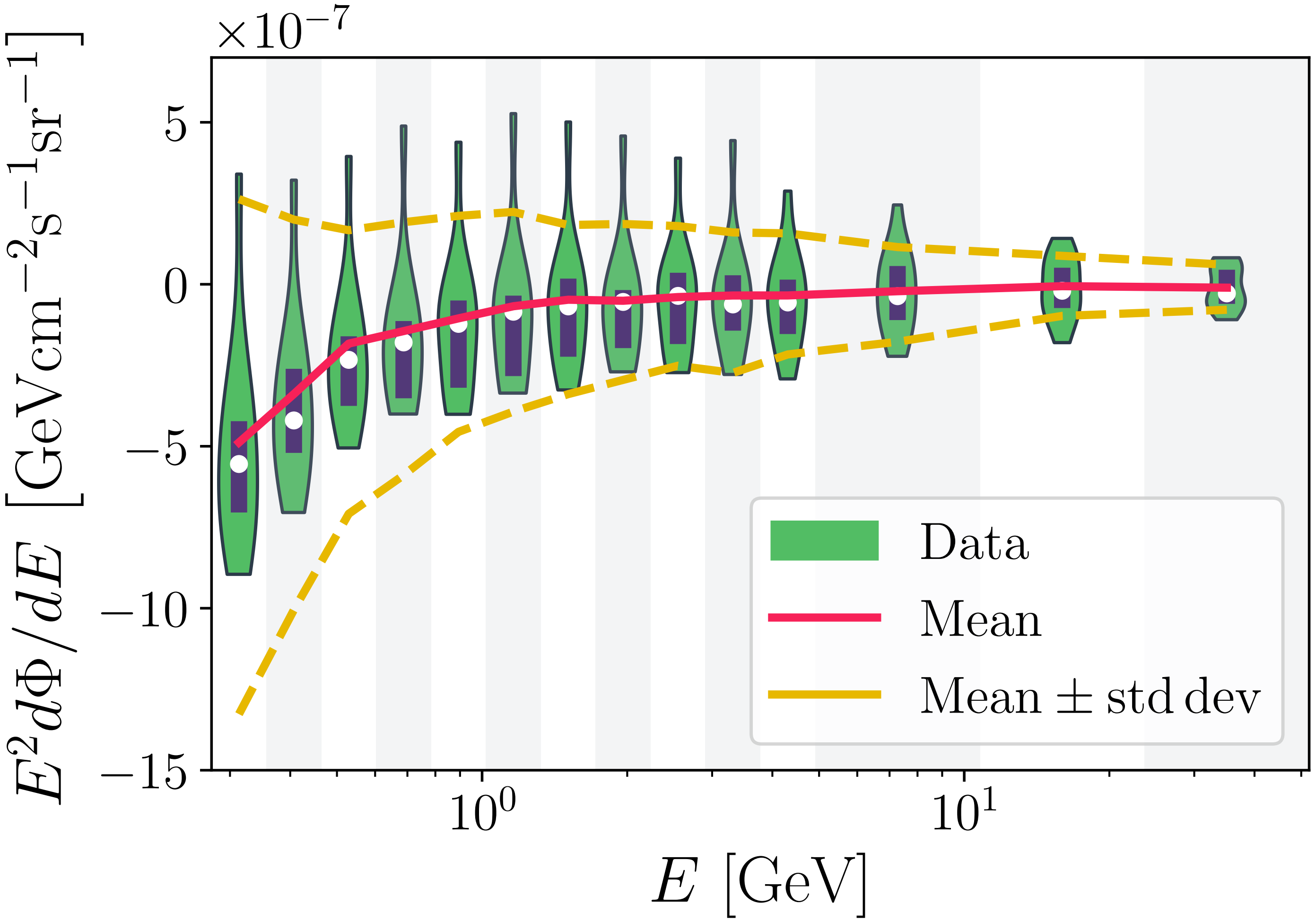
Even when we allow for an additional stellar bulge component (probing MSPs) component, we still get preference for a dominant cuspy NFW-like profile







GCE 5 best models ± 2σ
GCE, 80 models
other ROIs, 80 models
Best Fit Model, each ROI
0.9 GeV
1.2 GeV
1.5 GeV
2.0 GeV
2.5 GeV
3.3 GeV
4.3 GeV
7.3 GeV
16.0 GeV
35.1 GeV
$E^2 d\Phi/dE$ [10^{-7} GeV cm^{-2} s^{-1} sr^{-1}]
$2\Delta \ln \mathcal{L} = -1.1 \times 10^3$
-5.4×10^3
-3.3×10^3
-2.8×10^3
-3.6×10^3
-1.9×10^3
-7.9×10^2
-3.0×10^2
-1.7×10^3
-6.8×10^2
-4.5×10^2
-1.1×10^3
-2.2×10^3
-1.2×10^3
-2.8×10^3
-7.8×10^2
-2.6×10^3
-2.9×10^3
-5.9×10^2
-5.7×10^2
-1.4×10^2
-2.1×10^3
-1.8×10^3
-6.9×10^2
-1.8×10^2
-7.6×10^2
-7.6×10^2
-7.1×10^2
-1.1×10^3
+70° +65° +60° +55° +50° +45° +40° +35° +30° +25° +20° +15° +10° +5° GCE −5° −10° −15° −20° −25° −30° −35° −40° −45° −50° −55° −60° −65° −70°



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:

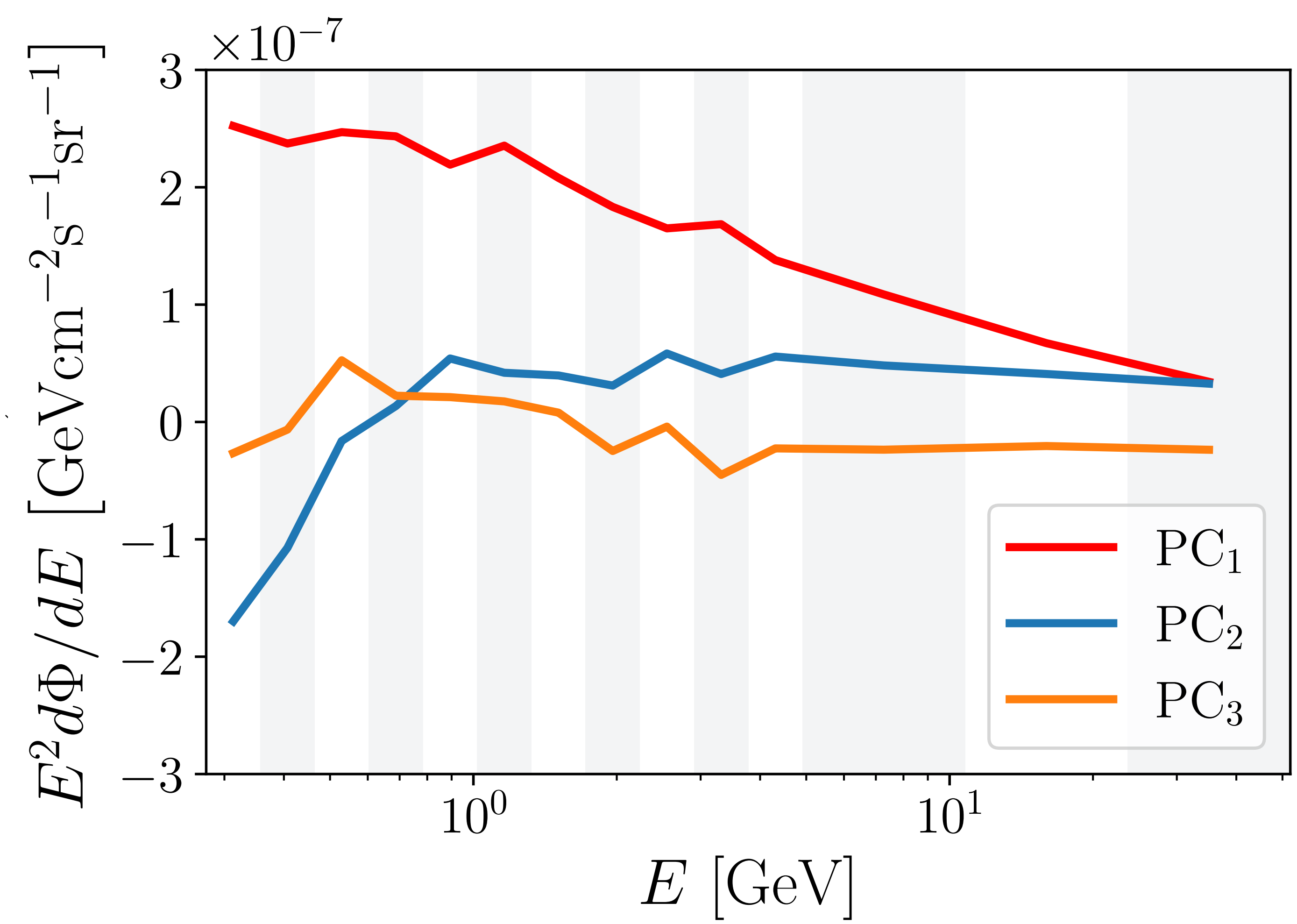
$$\Sigma_{jk,\mathrm{mod}} \simeq \Sigma^{\mathrm{trunc}}_{jk,\mathrm{mod}} \equiv \sum_{i=1}^{3} \mathrm{PC}^{\mathsf{T}}_{ij}\mathrm{PC}_{ik}$$

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:

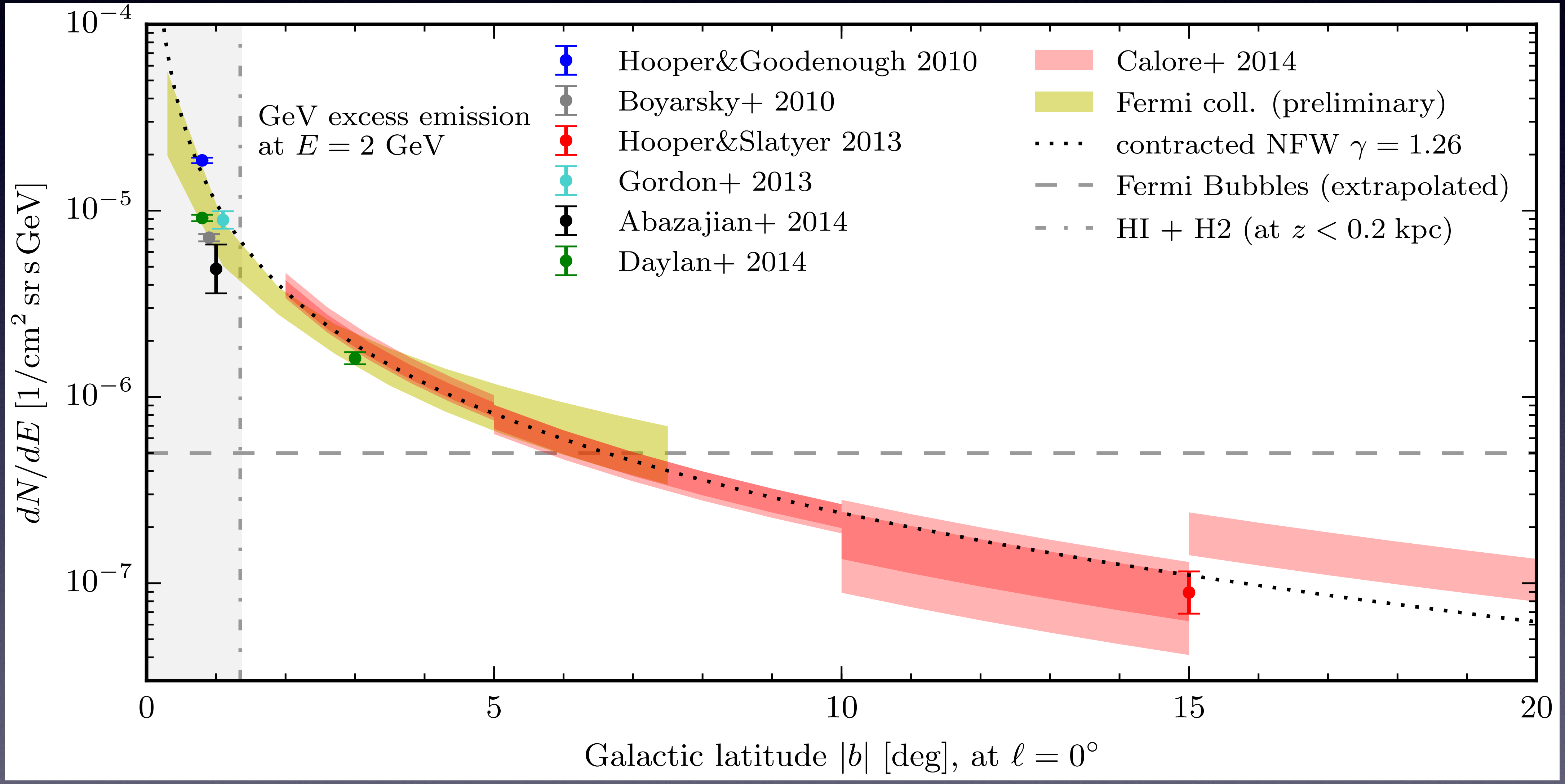
$$C_{ij} = \sigma_i^2 \delta_{ij} + \Sigma_{ij,\mathrm{mod}}$$



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

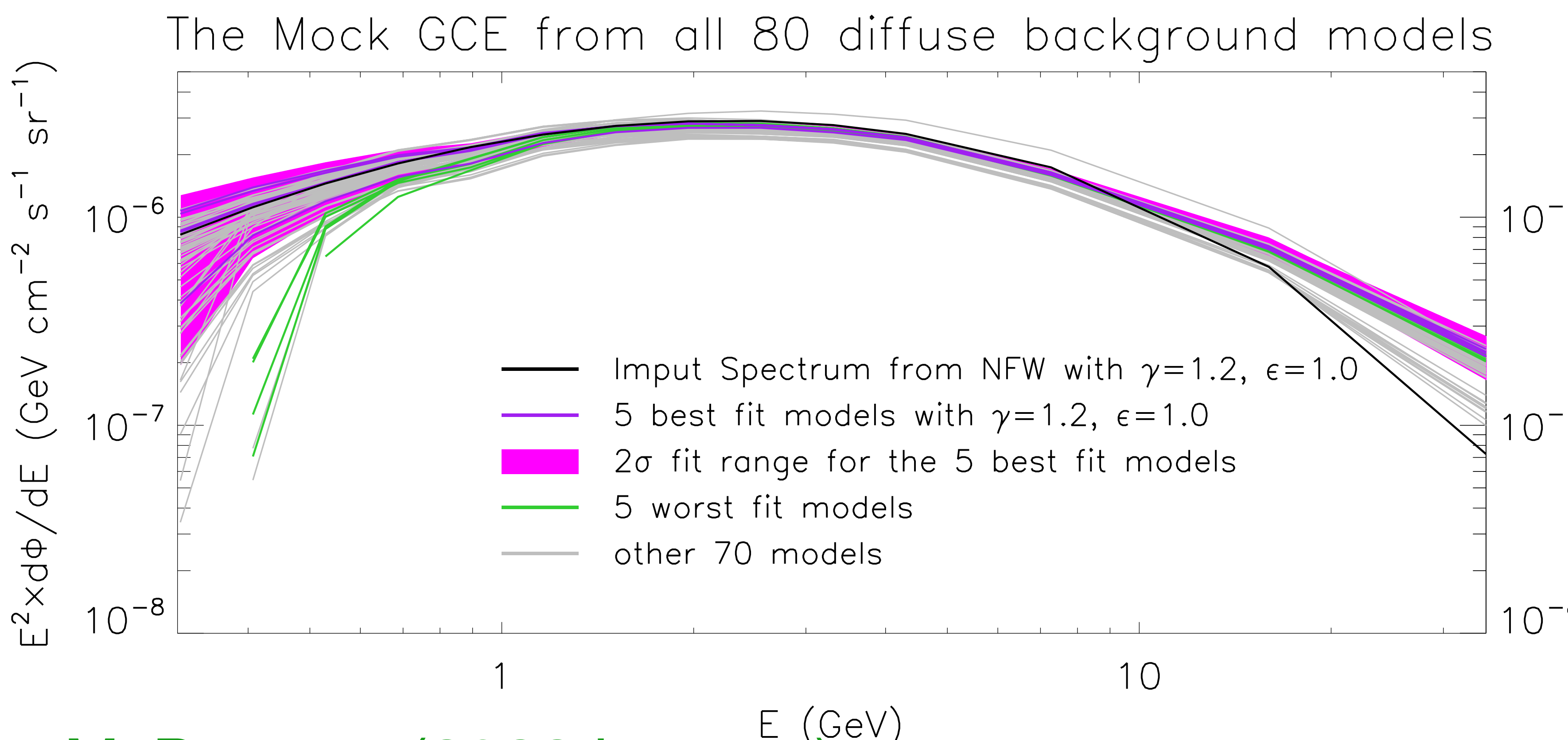
The flux associated to the excess emission at 2 GeV vs galactic latitude:

Calore, **IC,** McCabe, Weniger, PRD 2015

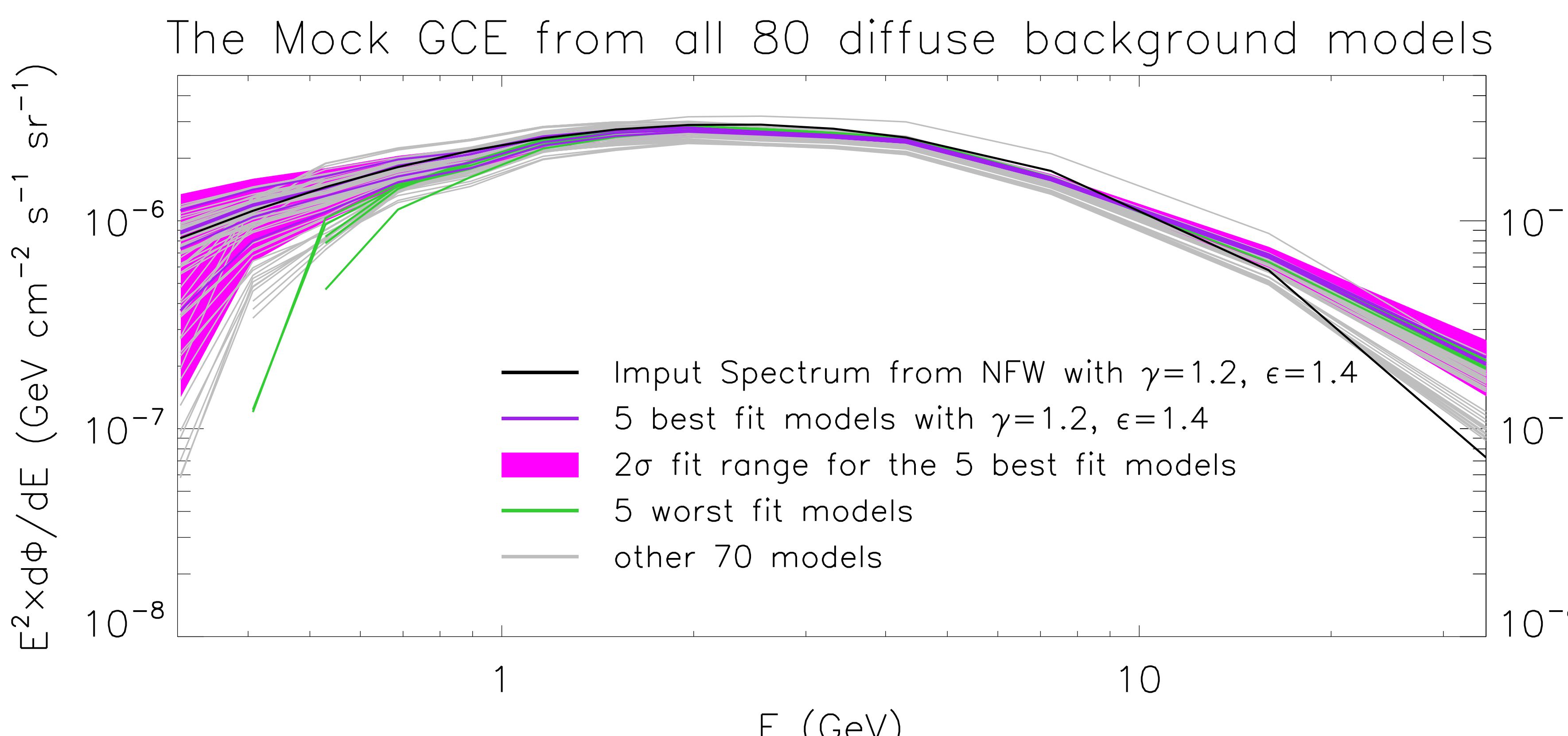


The excess signals from different analyses, agree within a factor of less than 2 in terms of total emission.

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

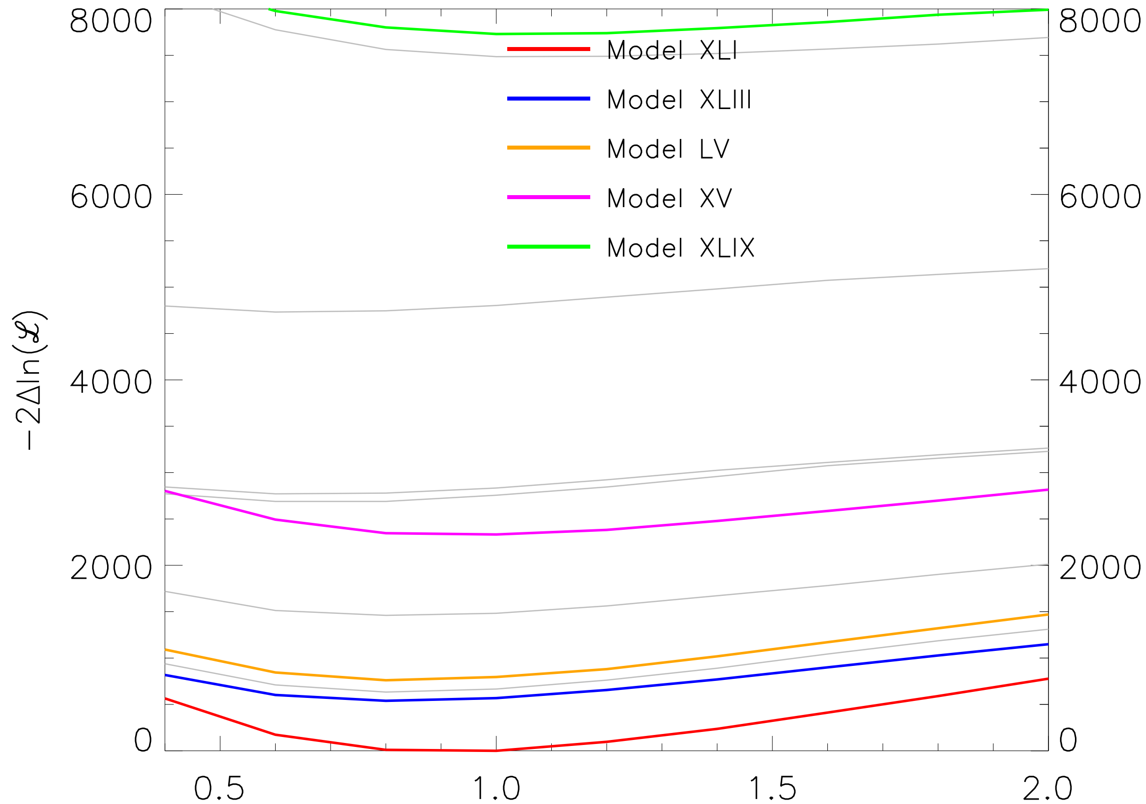


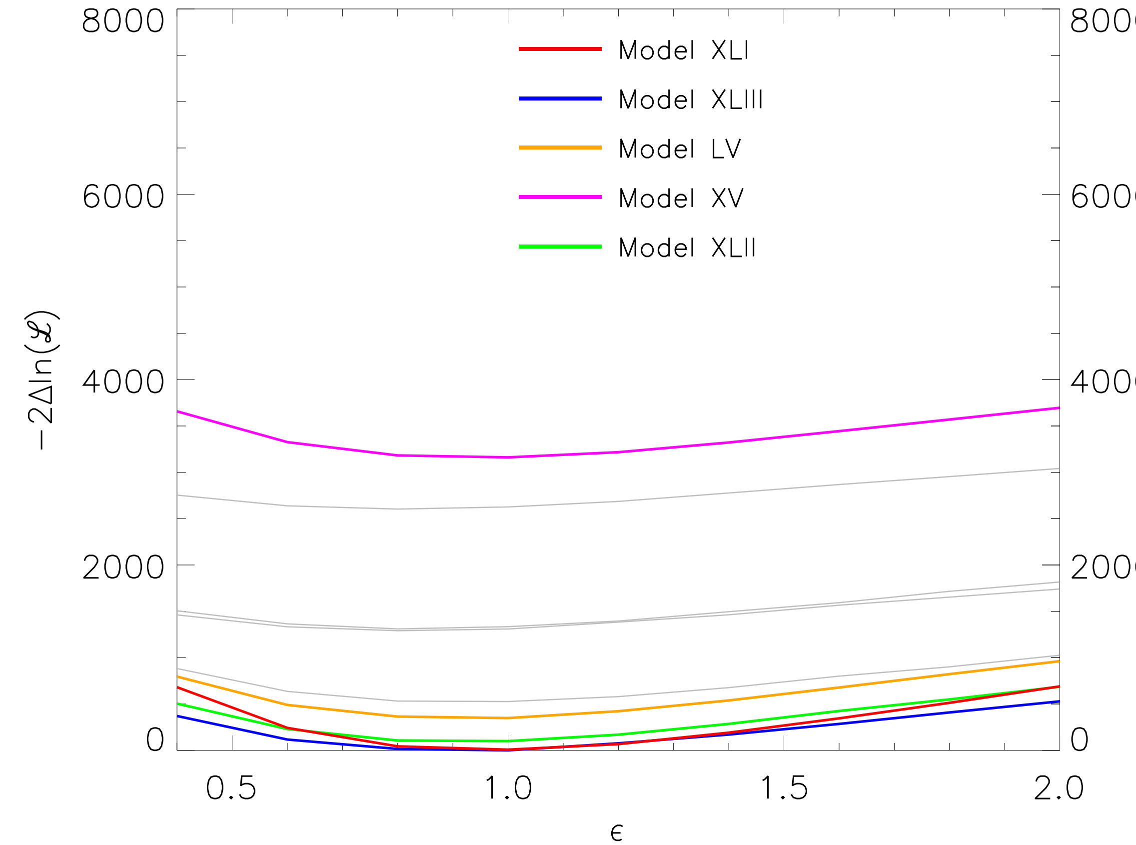
Zhong, Cholis, McDermott (2022 in prep.)



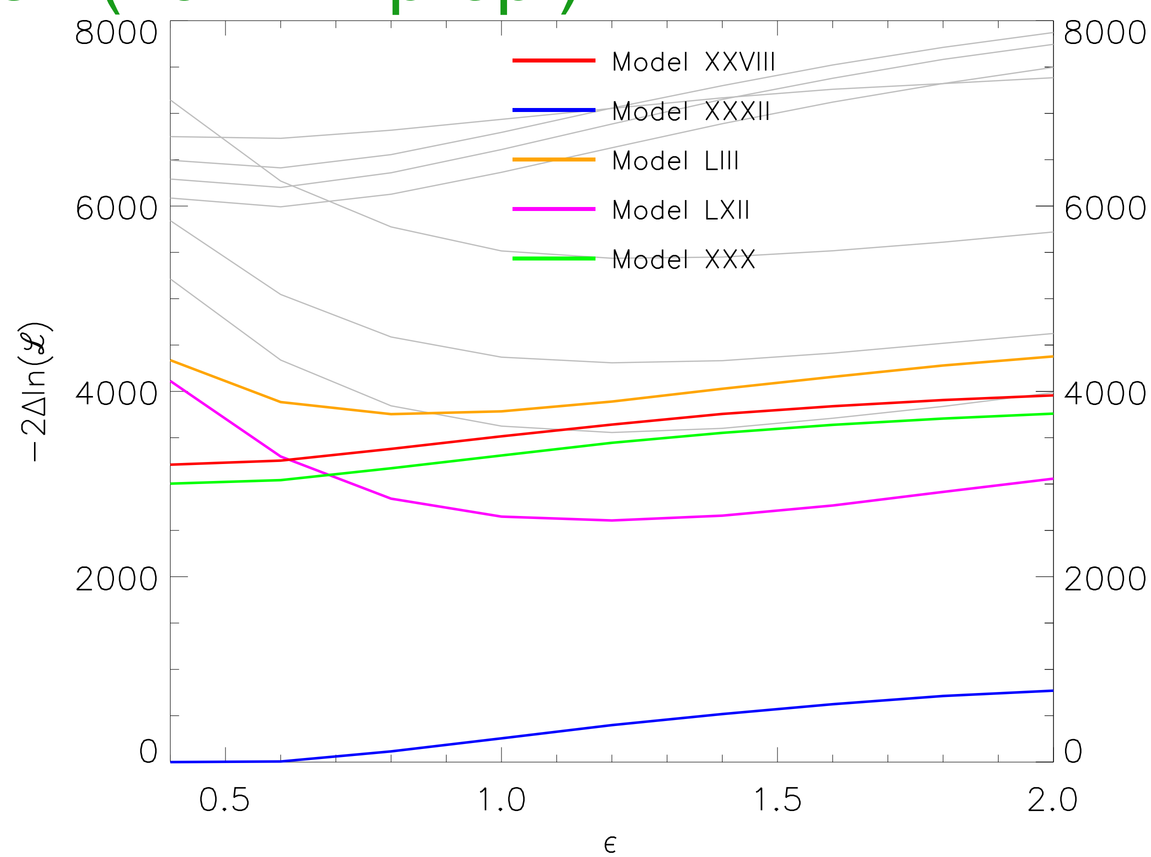
Ongoing Preliminary:

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





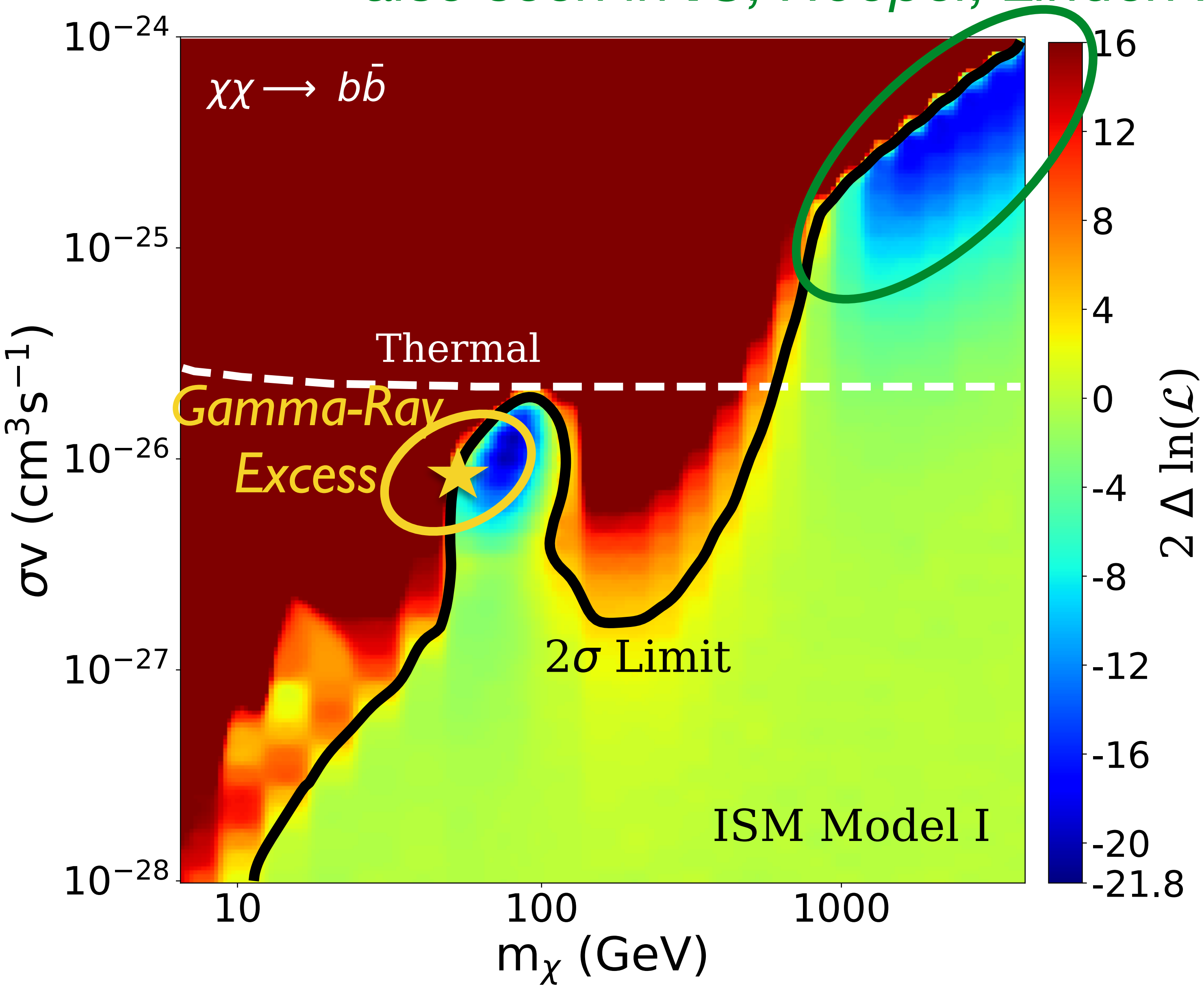
Zhong, Cholis, McDermott (2022 in prep.)

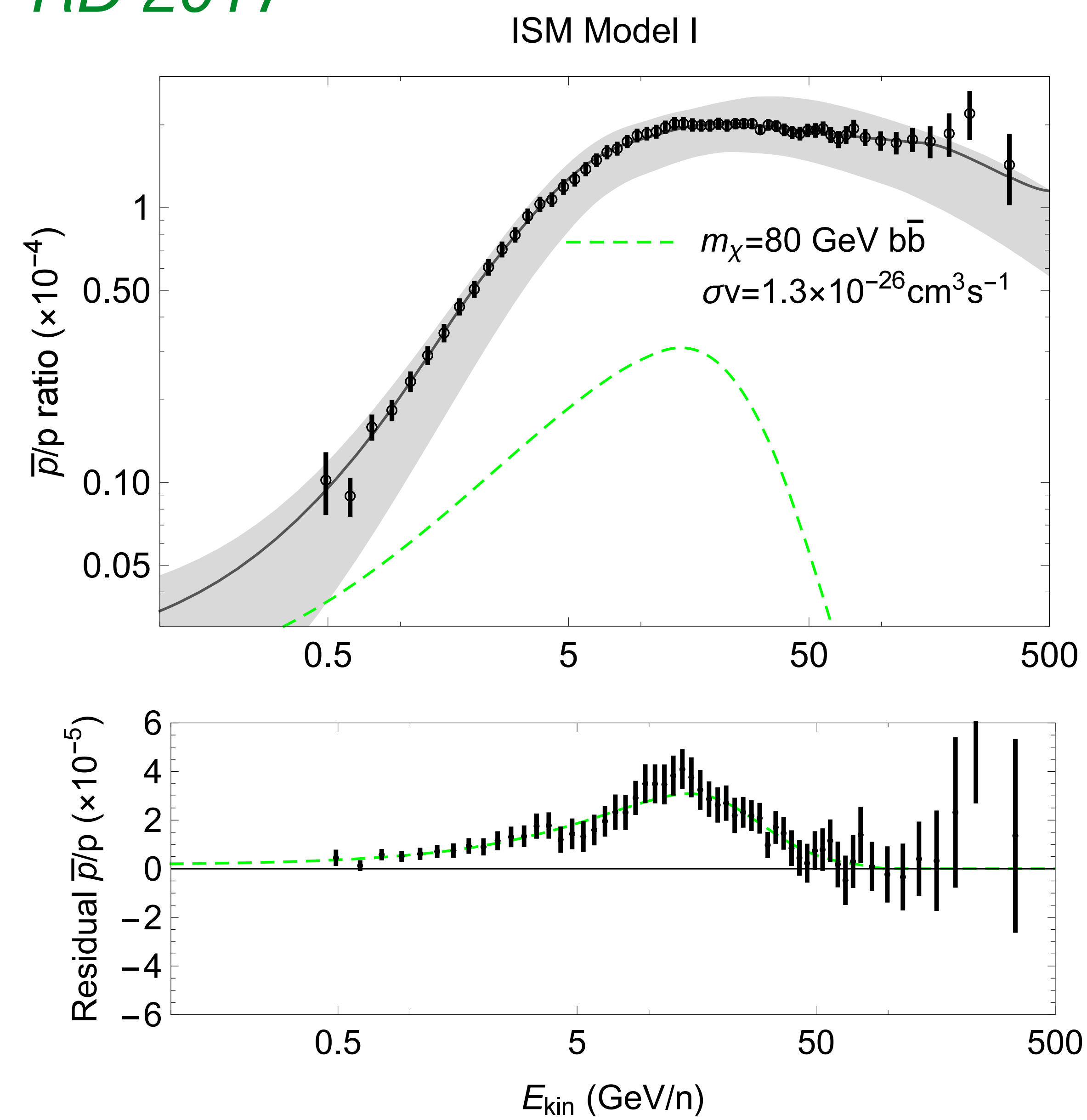


Looking at the antiproton to proton ratio find an the excess at~3 sigma

Supernova,

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



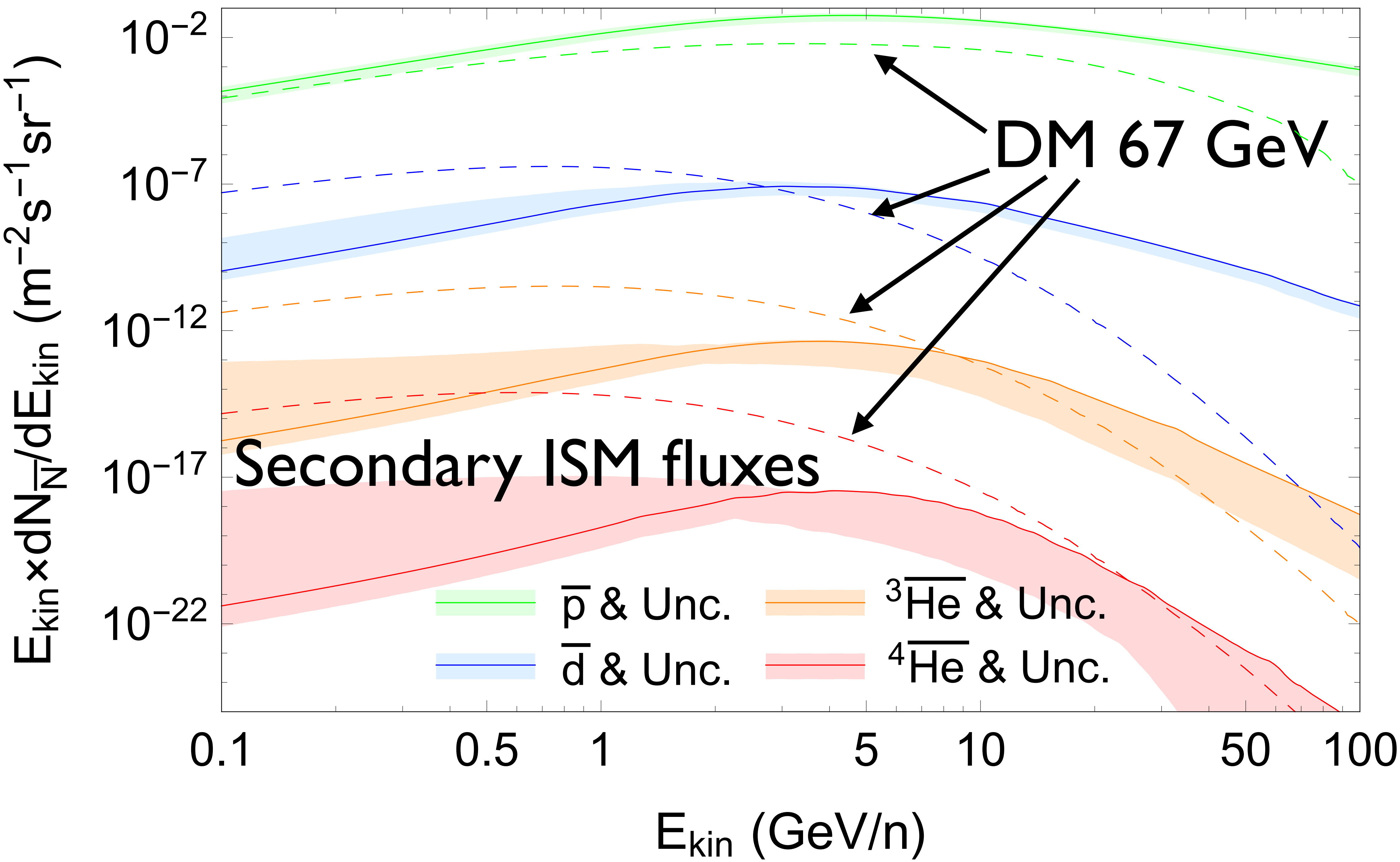


IC, Tim Linden, Dan Hooper PRD 2019

See also A. Cuoco et al. PRD 2019

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

Antimatter flux Uncertainties



IC, Linden, Hooper PRD 2020