



Revisiting the Galactic Center Excess in Gamma Rays 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)

PASCOS PARTICLES
STRINGS
COSMOLOGY
25-29 JULY 2022 - MPIK - HEIDELBERG - GERMANY

PASCOS 2022
Ilias Cholis, 26/07/2022

The challenges of Indirect Searches for WIMPs

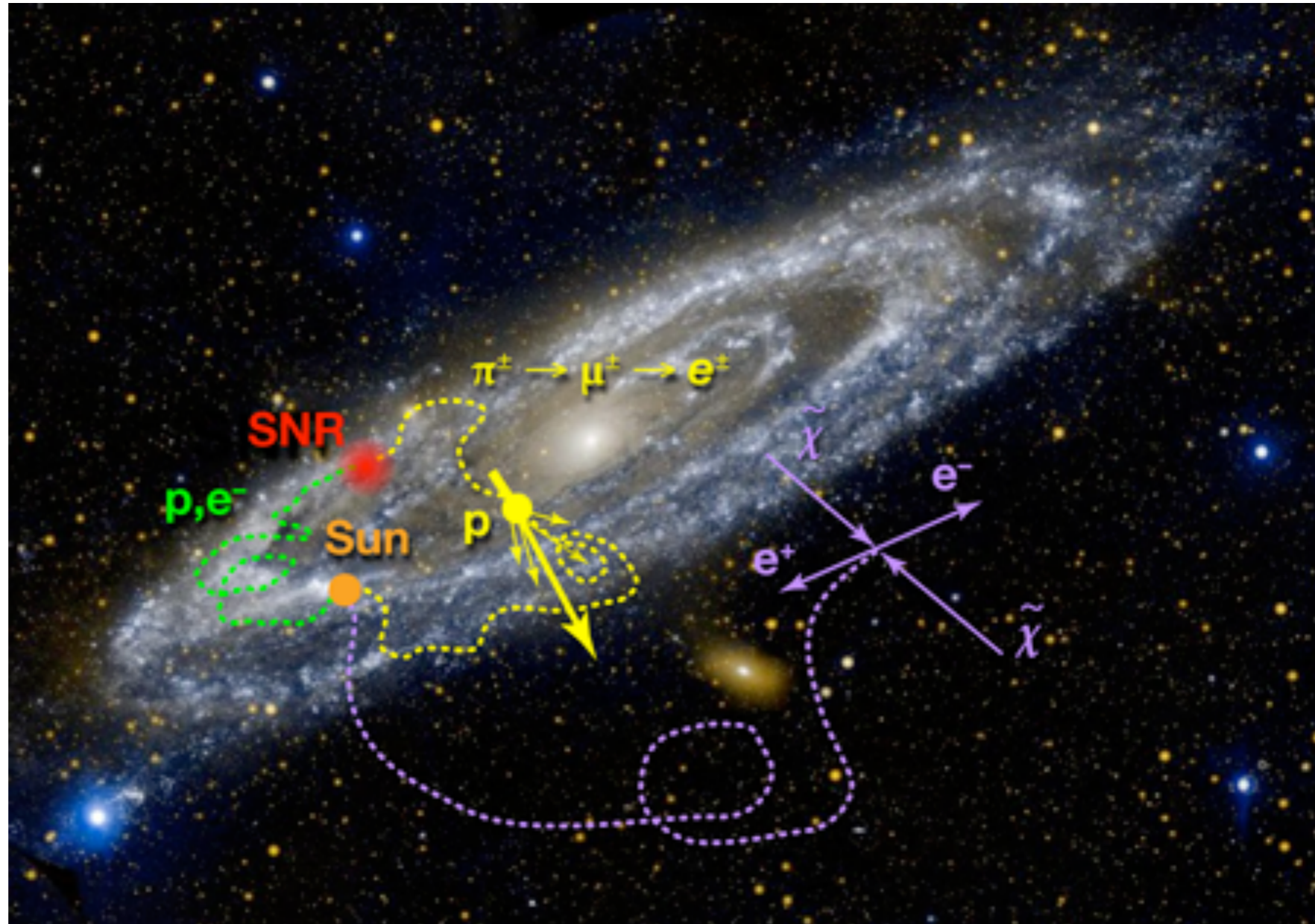
The Questions:

- 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 background 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

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

Voyager 1

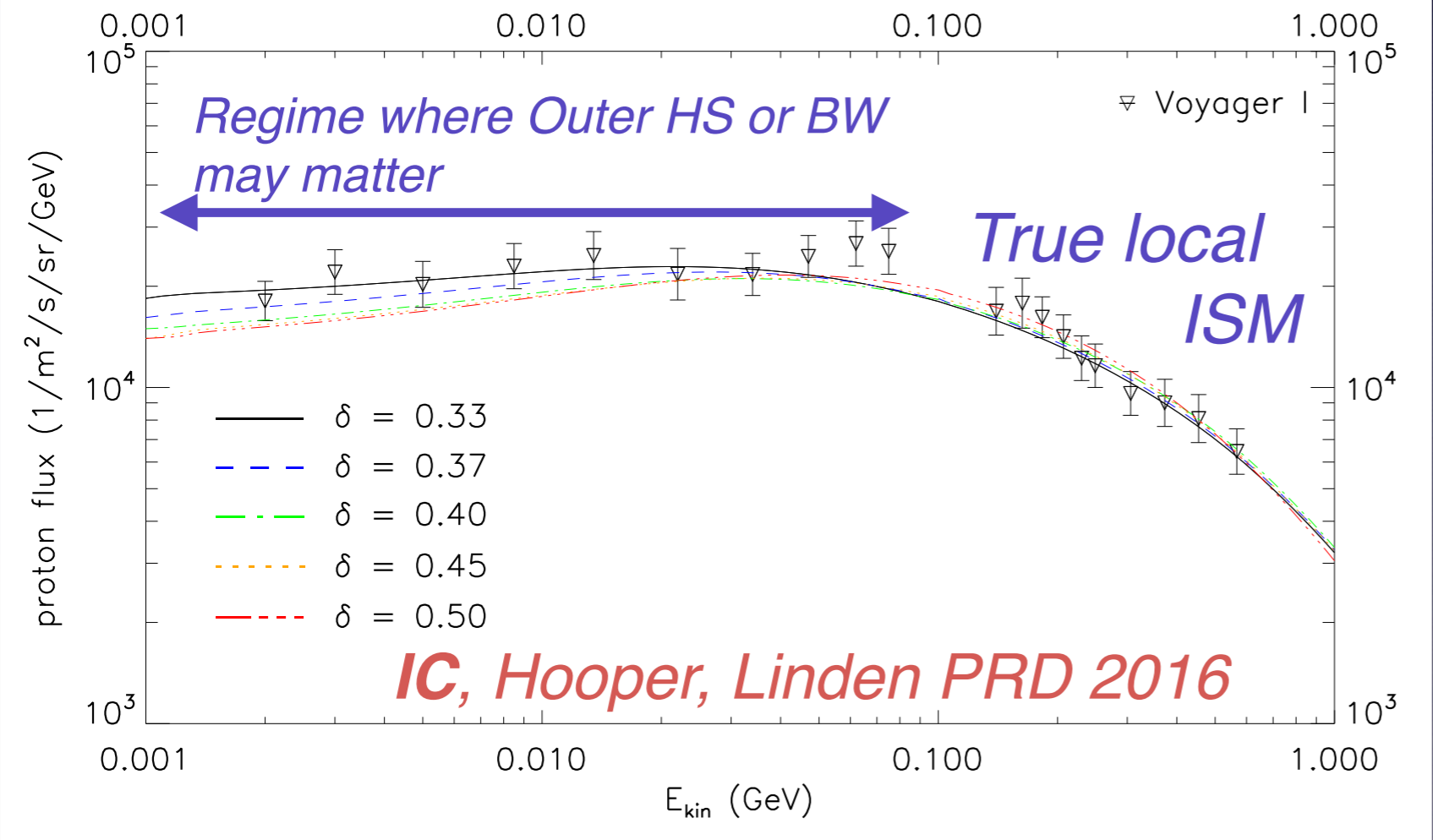


Modeling the ISM galactic production and propagation uncertainties for cosmic rays

$$\begin{aligned}
 \frac{\partial \psi(r, p, t)}{\partial t} &= \overset{\text{sources}}{q(r, p, t)} + \overset{\text{diffusion}}{\vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi)} \\
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 \end{aligned}$$

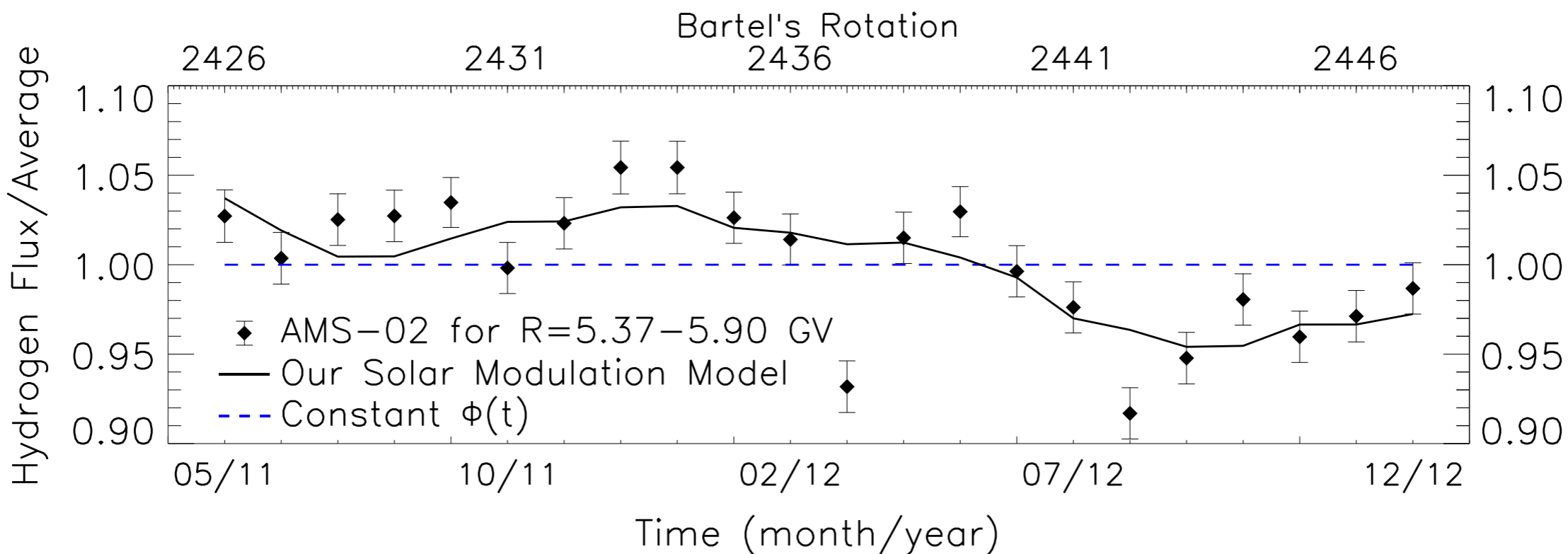
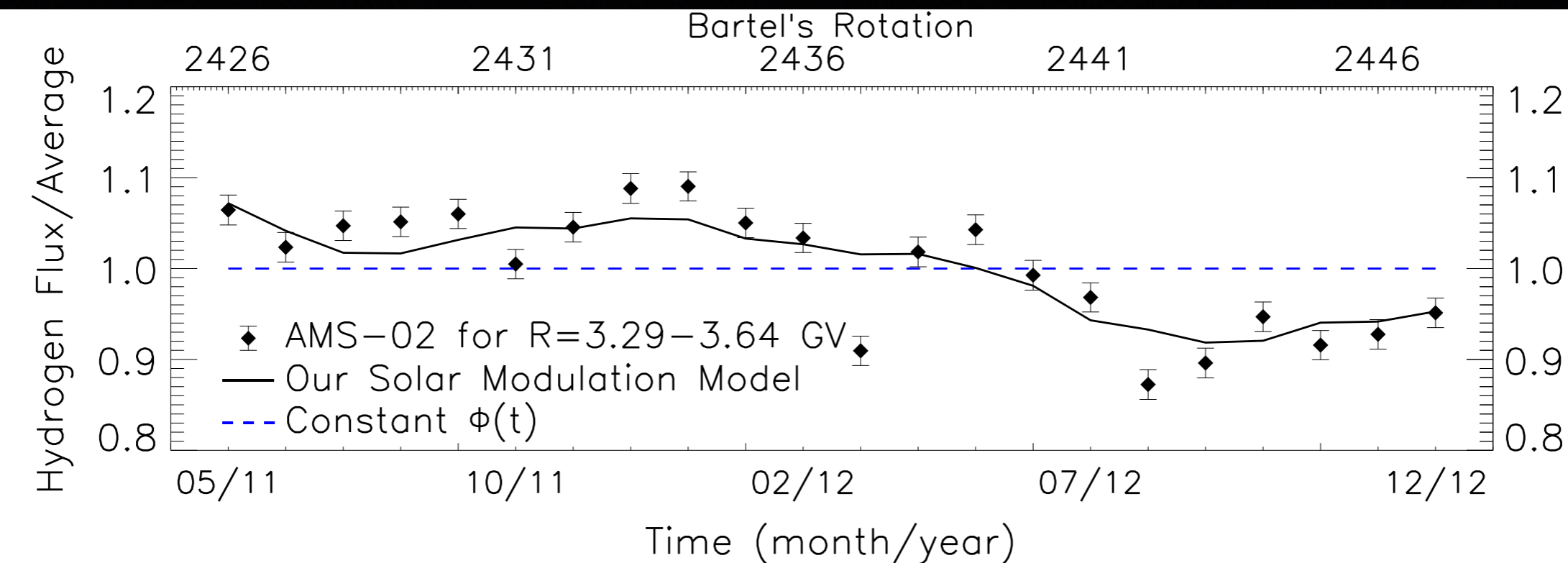


Voyager 1 (ISM) proton flux:



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

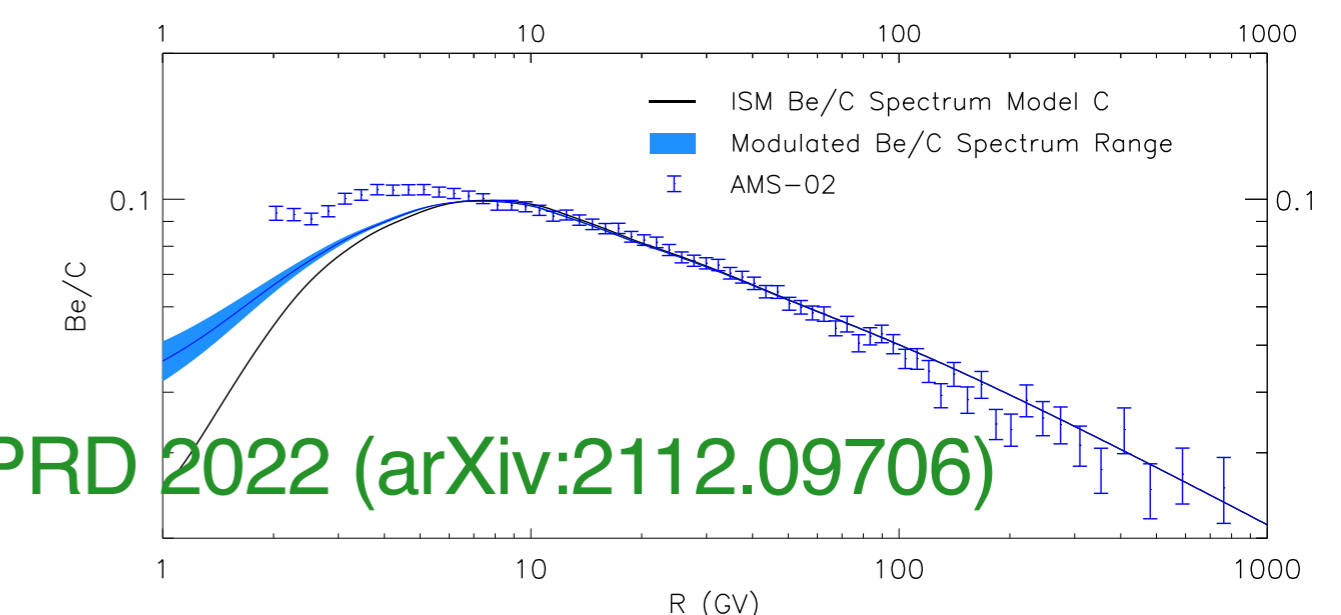
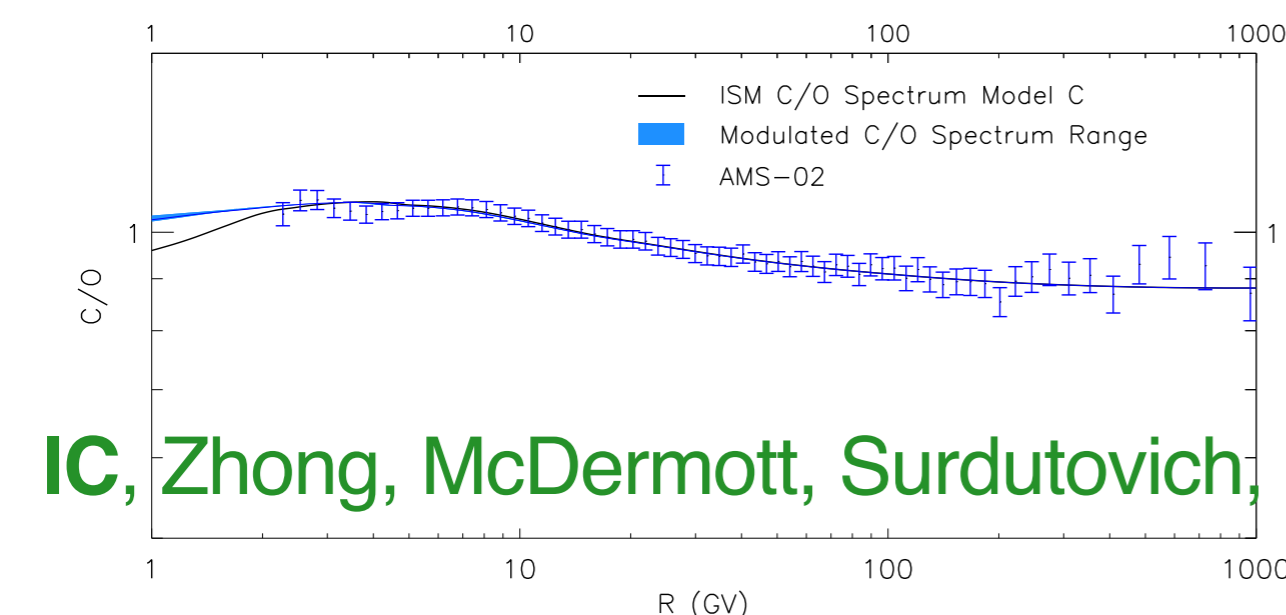
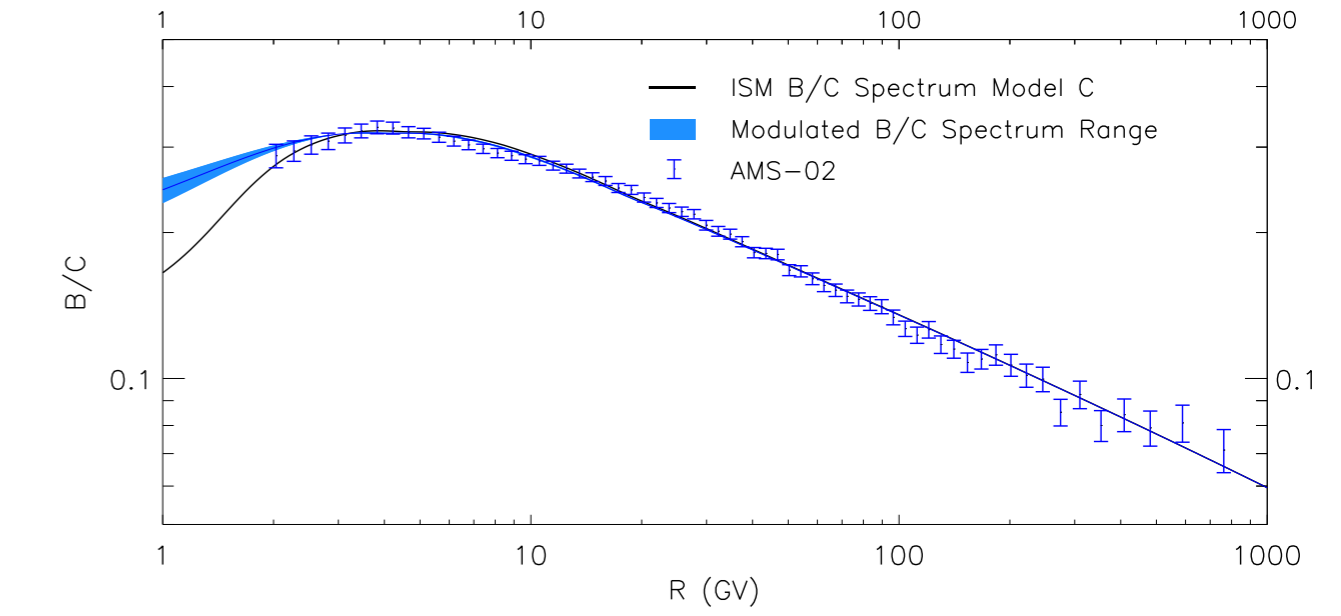
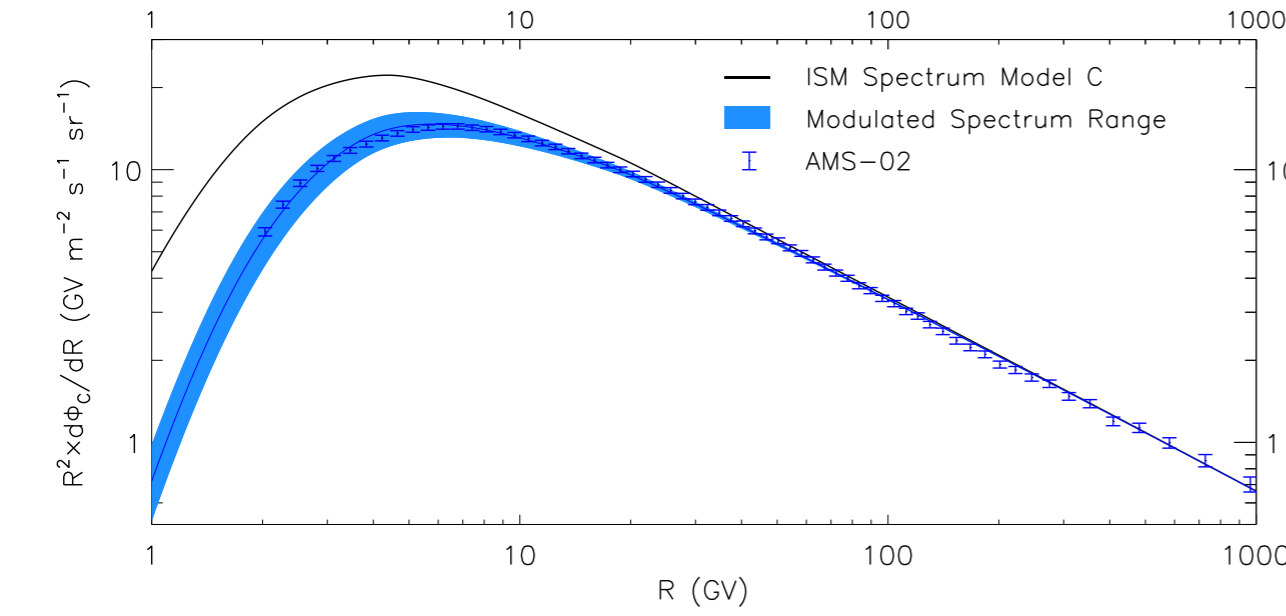
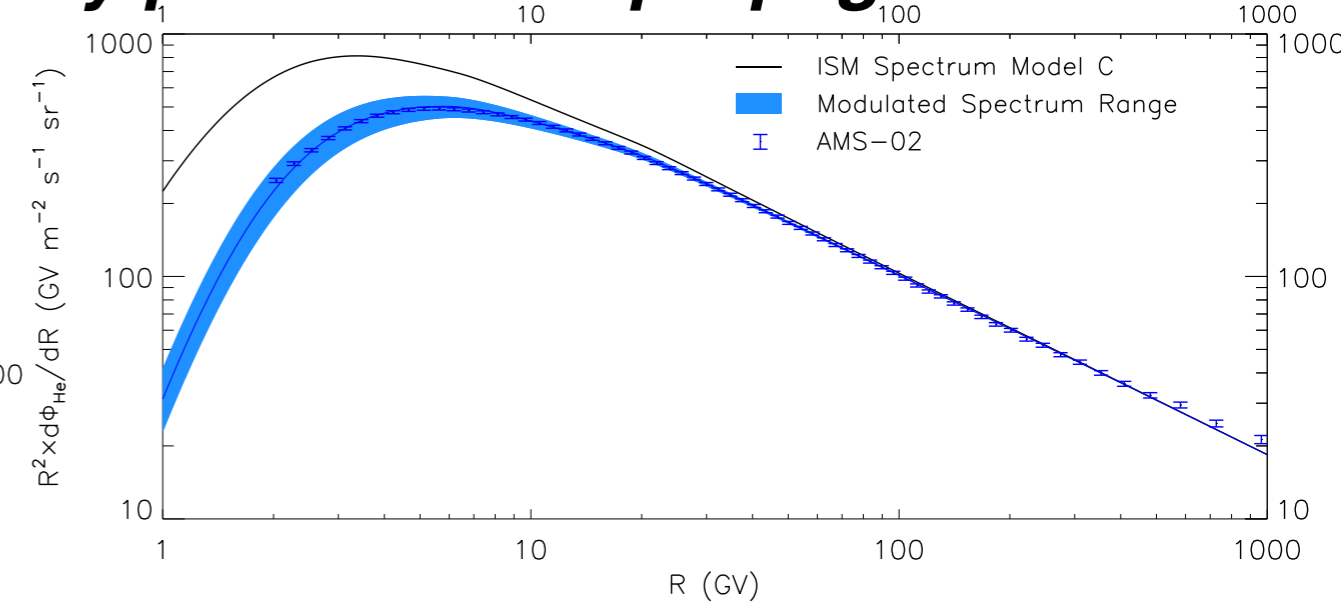
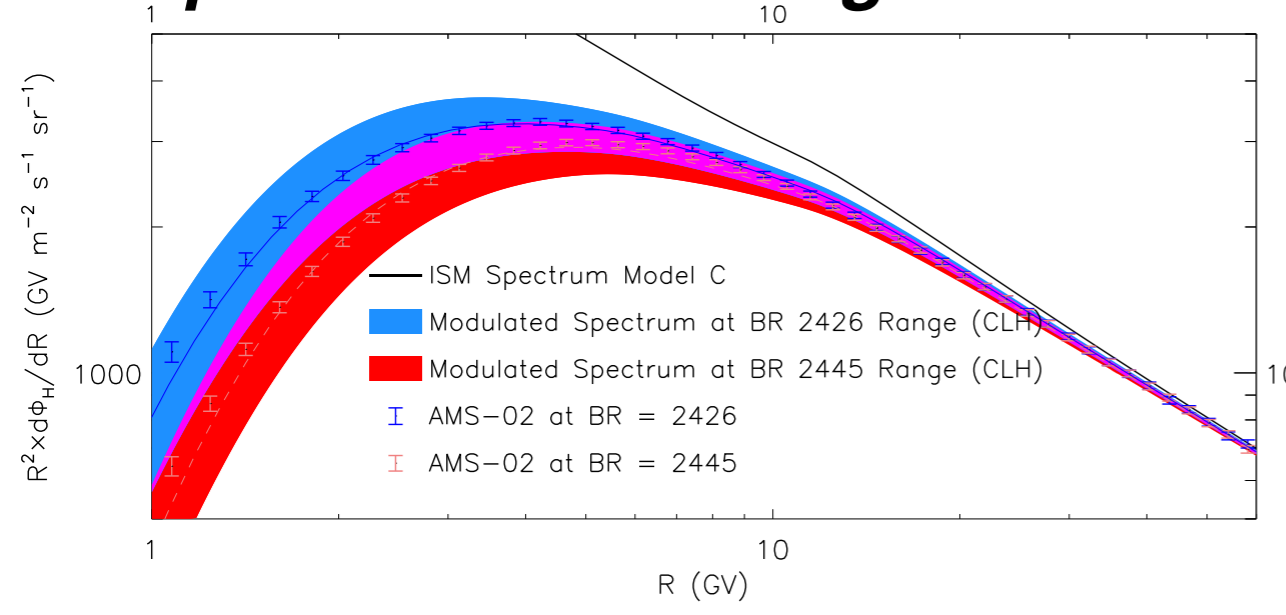
Cross-checking with the PROTON data that account for the majority of observed cosmic rays; monthly AND total (i.e ISM & Solar Modulation):



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



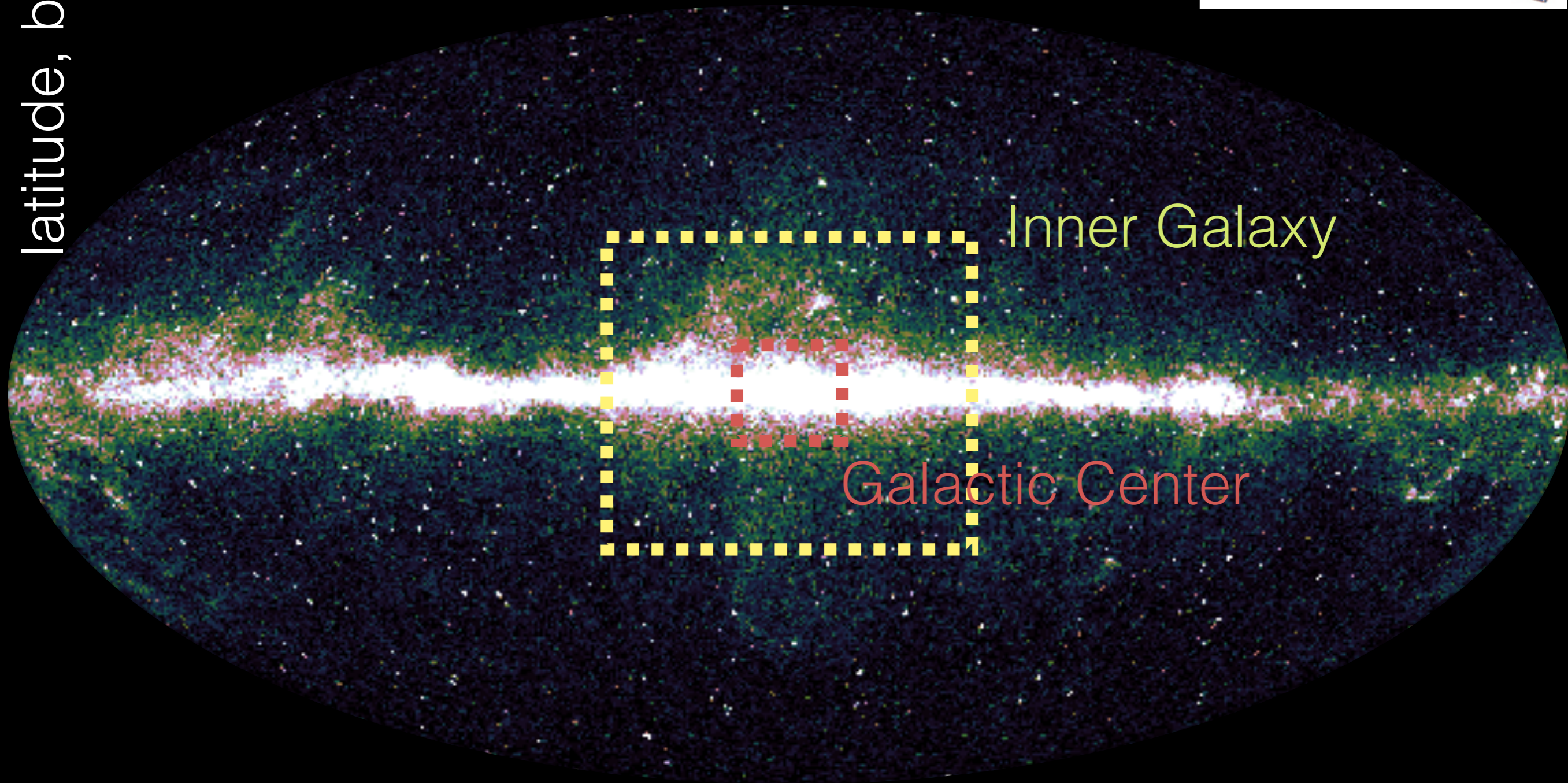
IC, Zhong, McDermott, Surdutovich, PRD 2022 (arXiv:2112.09706)

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY



latitude, b ↑



Inner Galaxy

Galactic Center

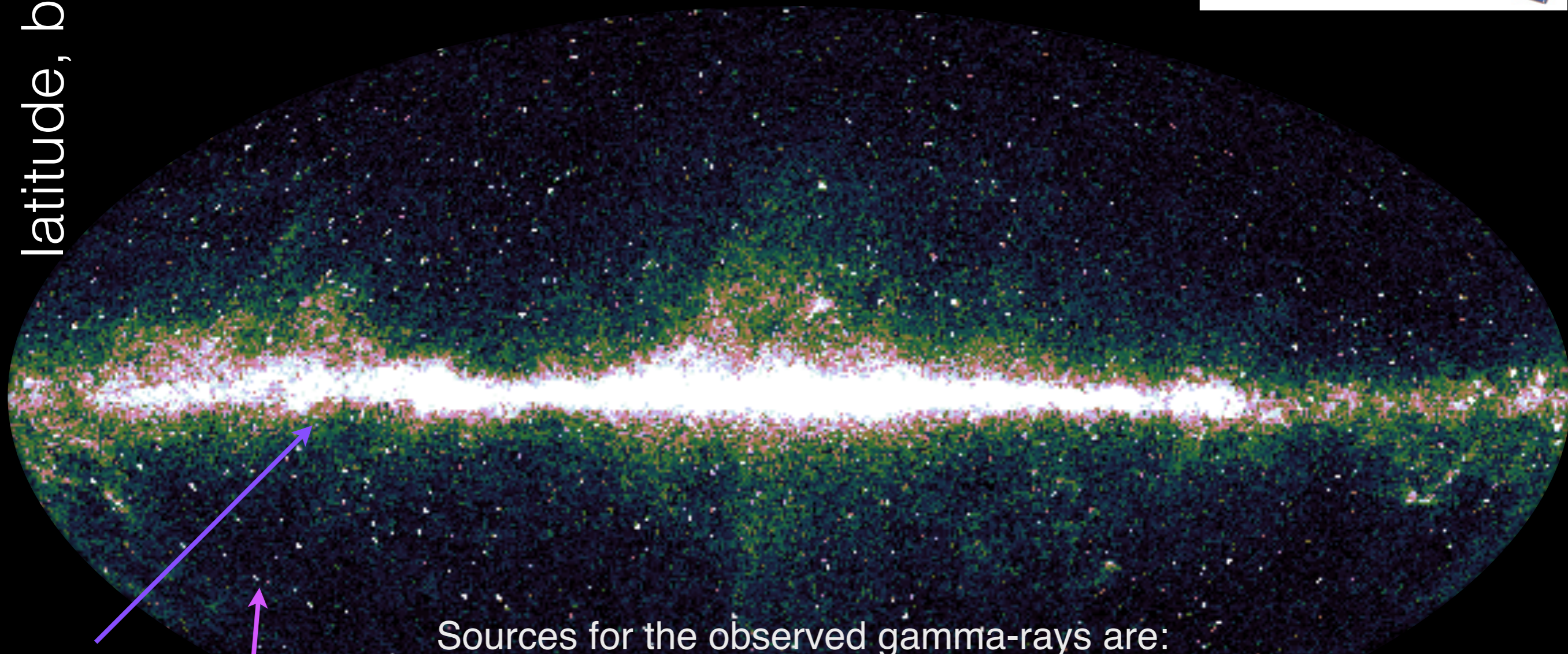
← Galactic longitude, l

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY



latitude, b ↑



Sources for the observed gamma-rays are:

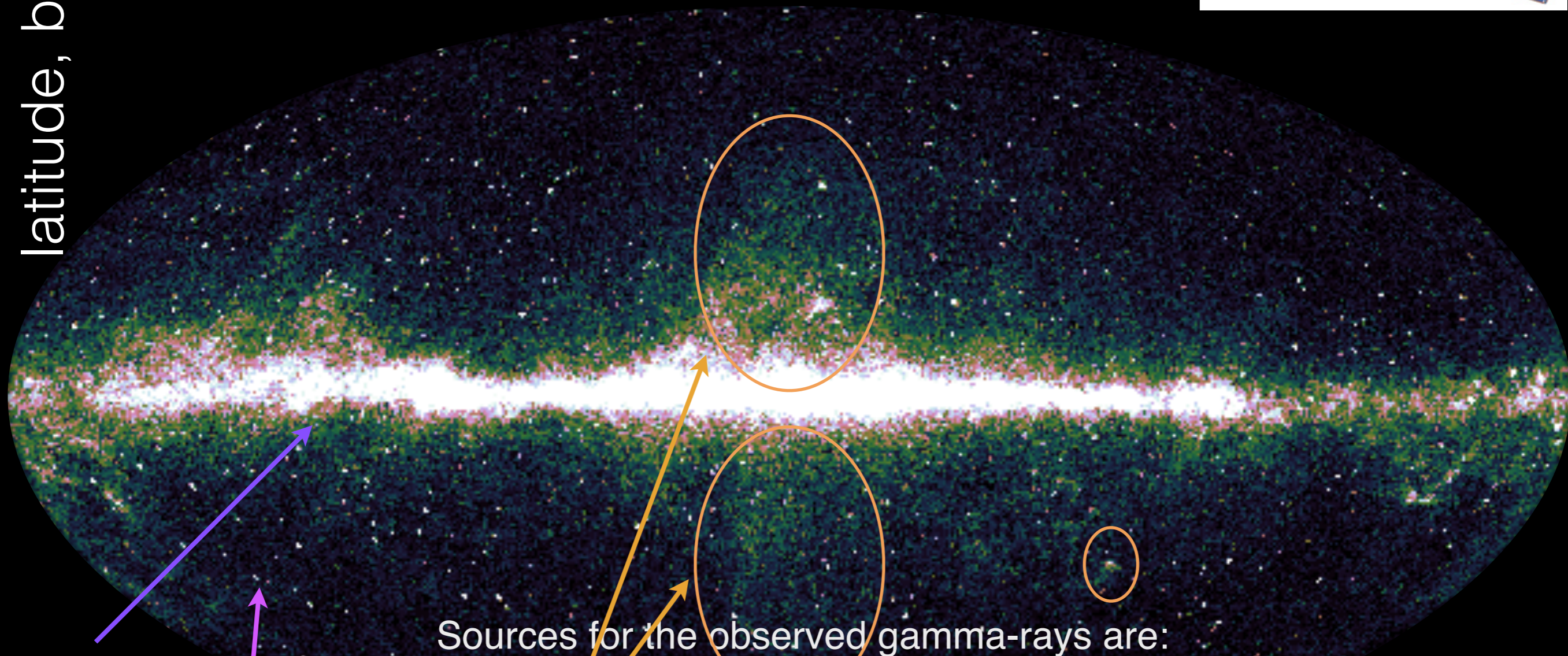
- i) **Galactic Diffuse Emission**: decay of π^0 s (and other mesons) from pp (NN) collisions in the ISM, **bremsstrahlung radiation** off CR e, **Inverse Compton scattering**: up-scattering of CMB and IR/optical photons from CR e
- ii) from **point sources** (galactic or extra galactic)
- iii) **Extragalactic Isotropic**

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY



latitude, b ↑



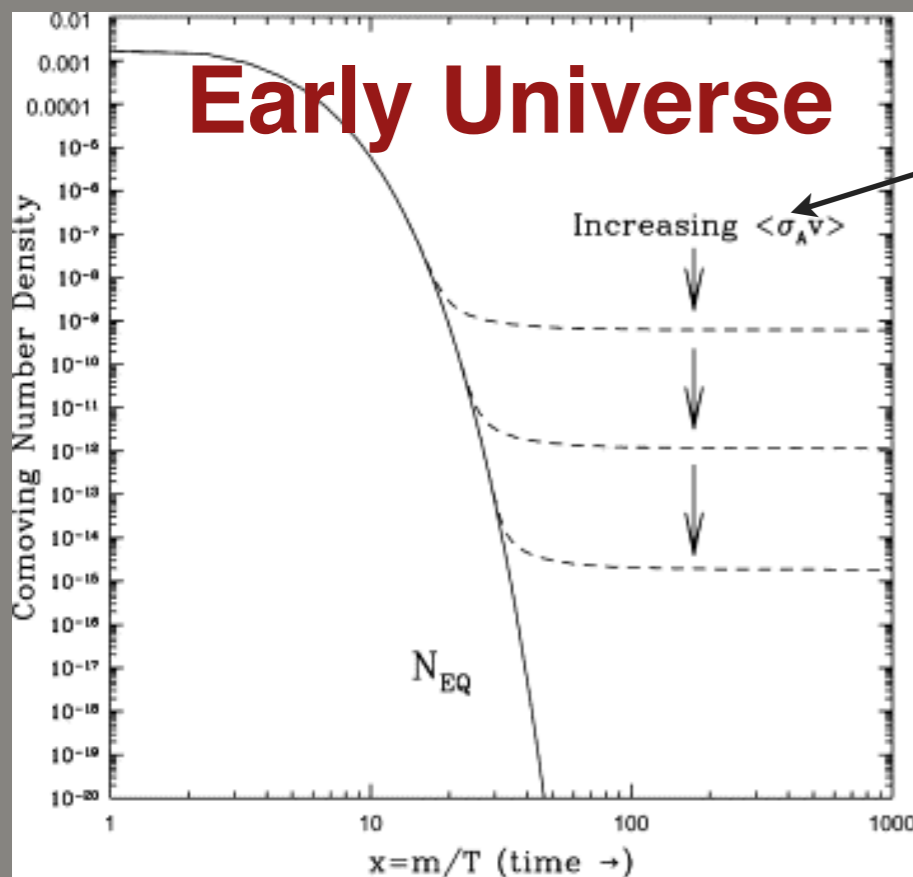
Sources for the observed gamma-rays are:

- i) **Galactic Diffuse Emission**: decay of π^0 s (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**
- iv) **“extended sources”** (Fermi Bubbles, Geminga, Vela ...)
- iv) **misidentified CRs** (isotropic due to diffusion of CRs in the Galaxy)

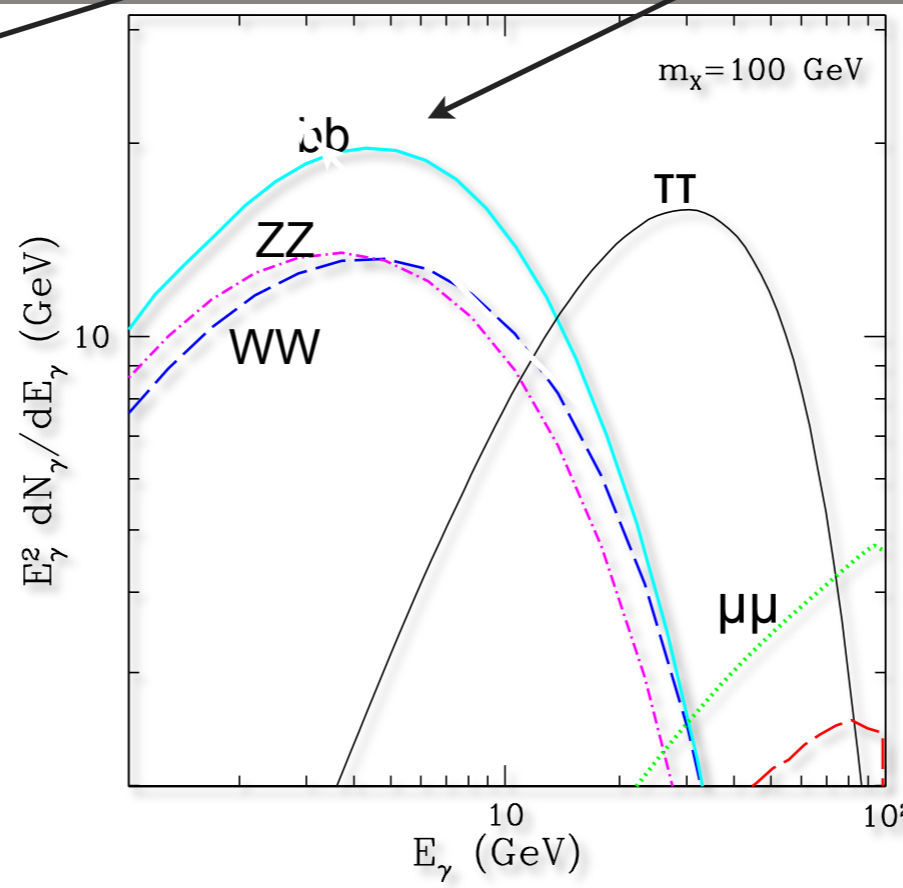
BUT ALSO the UNKNOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe:

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

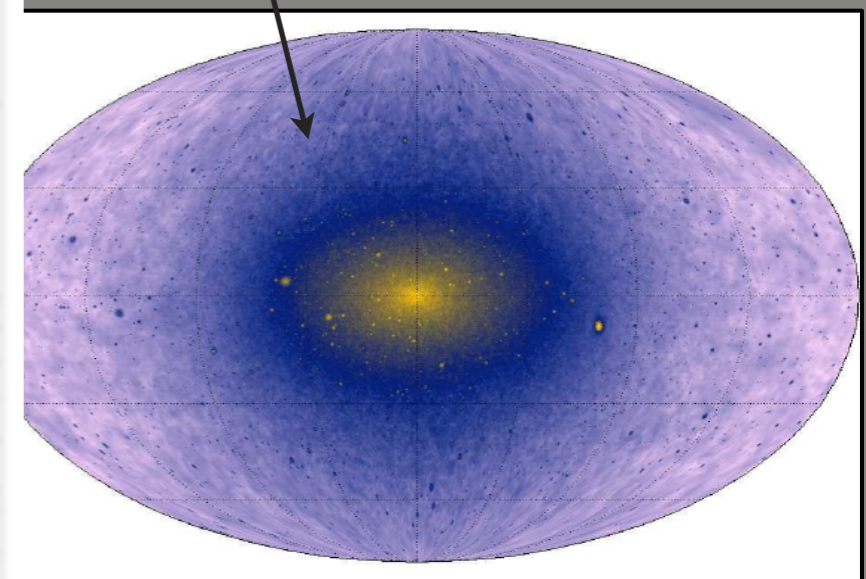


Steigman et al. 2012



Particle Physics

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

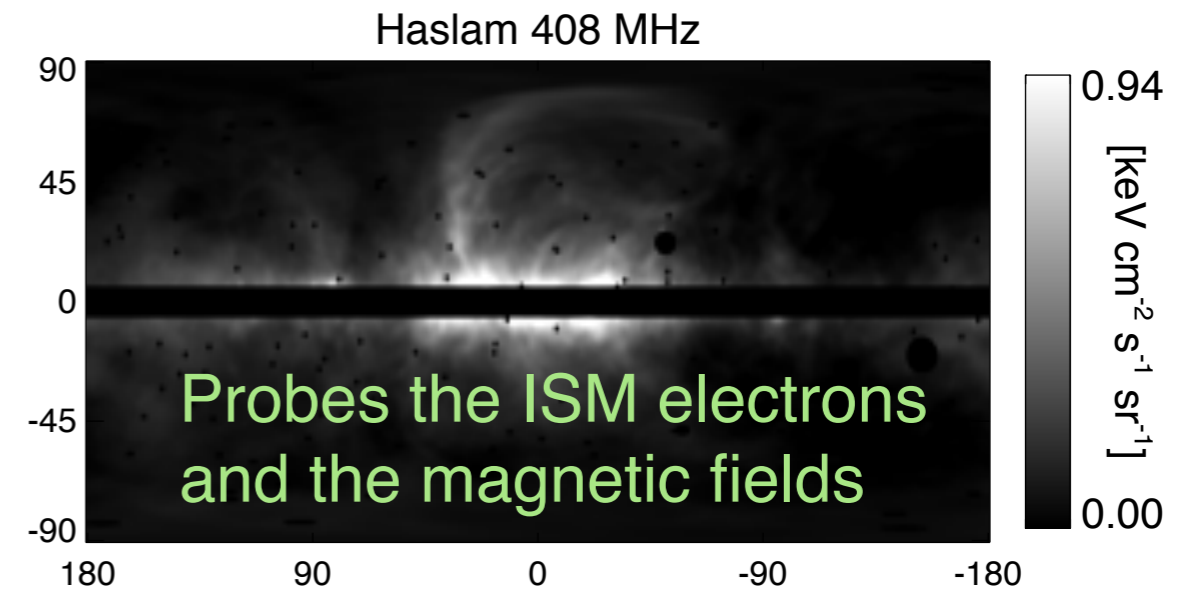
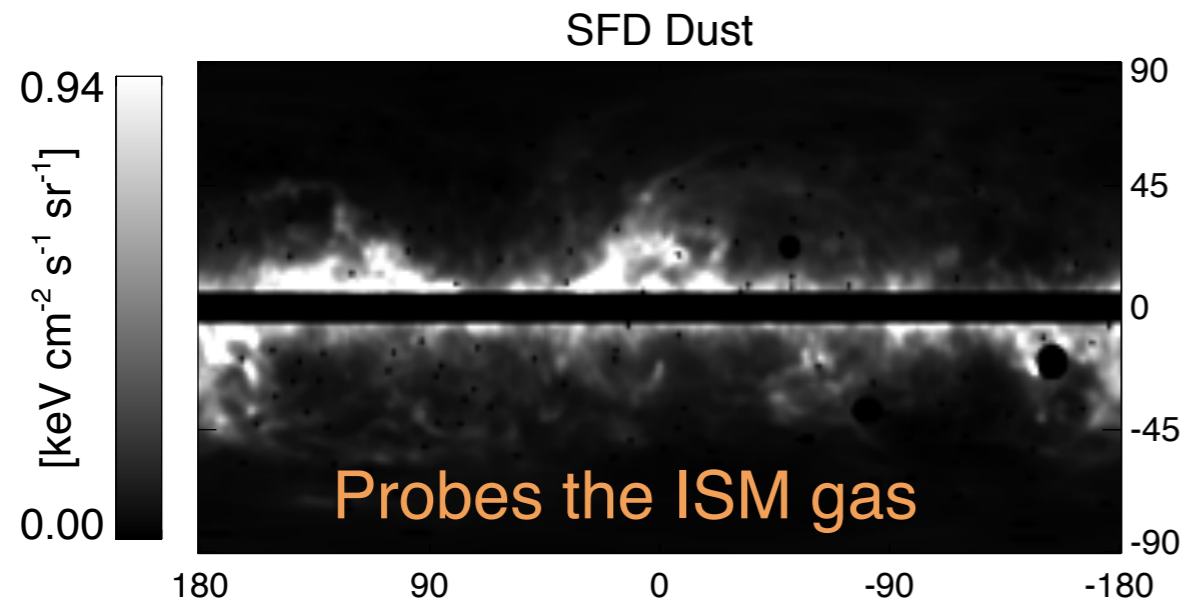


From Cosmological Simulations what we expect today

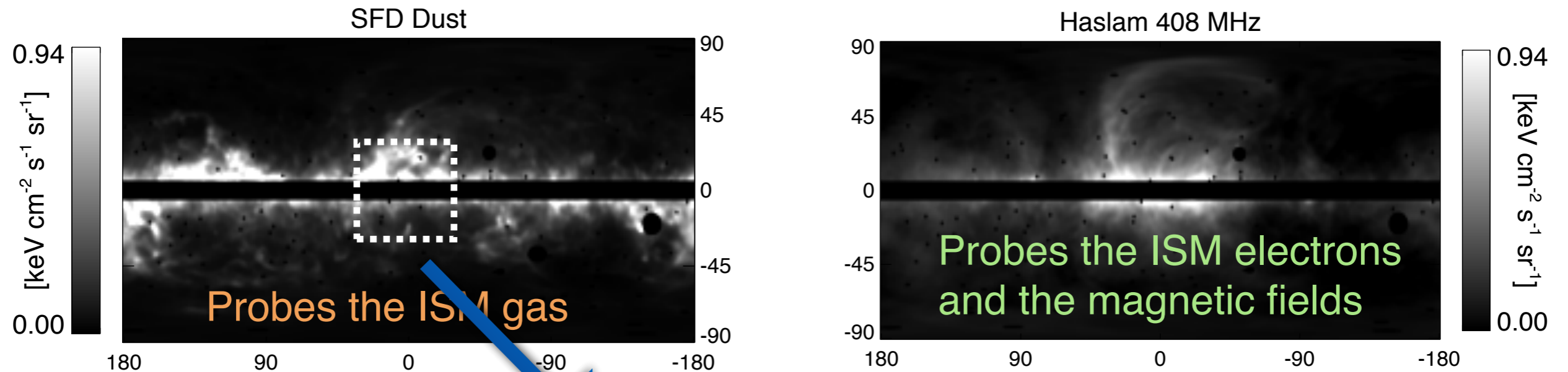
Springel et al. 2005,
Kuhlen et al. 2012,
Vera-Ciro et al. 2014

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

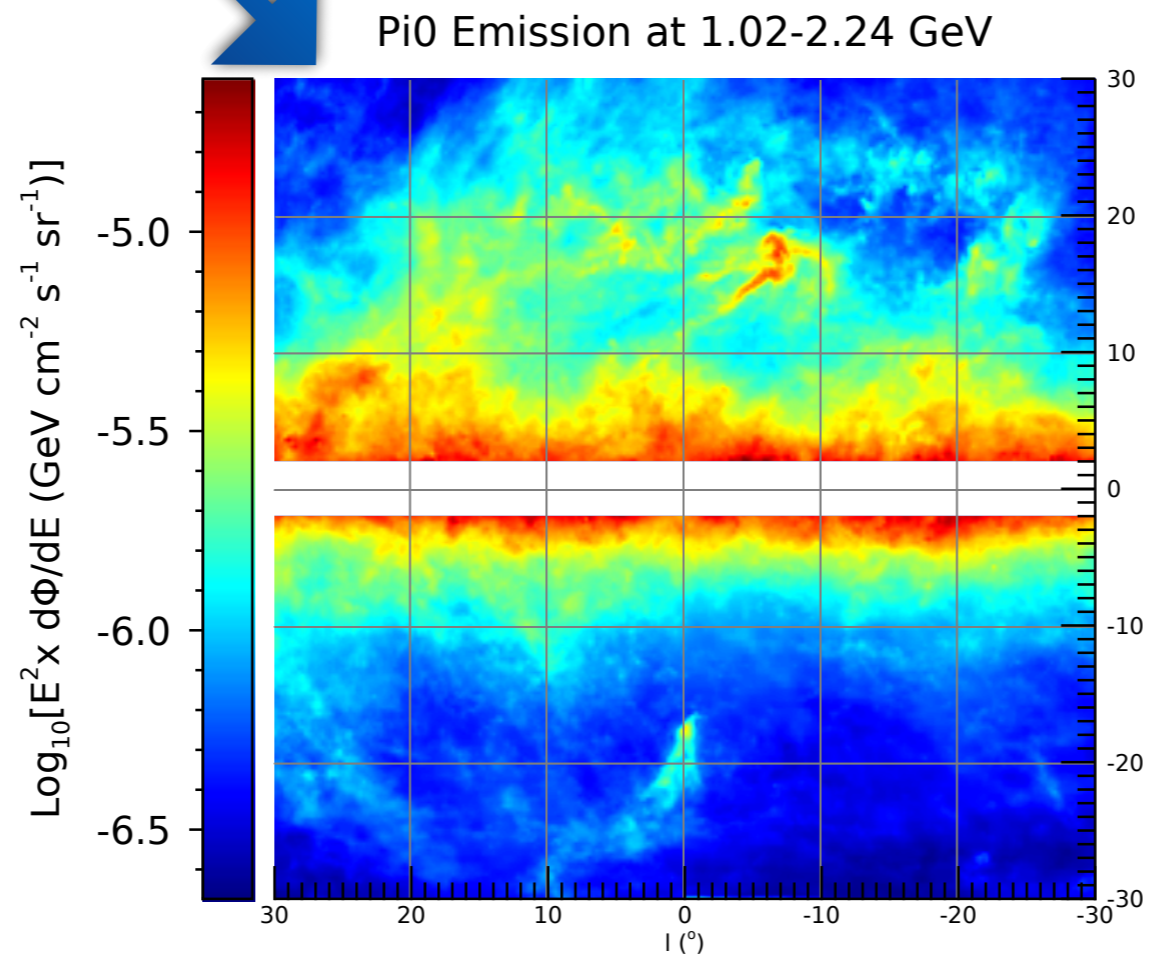


Using templates on Gamma-ray maps



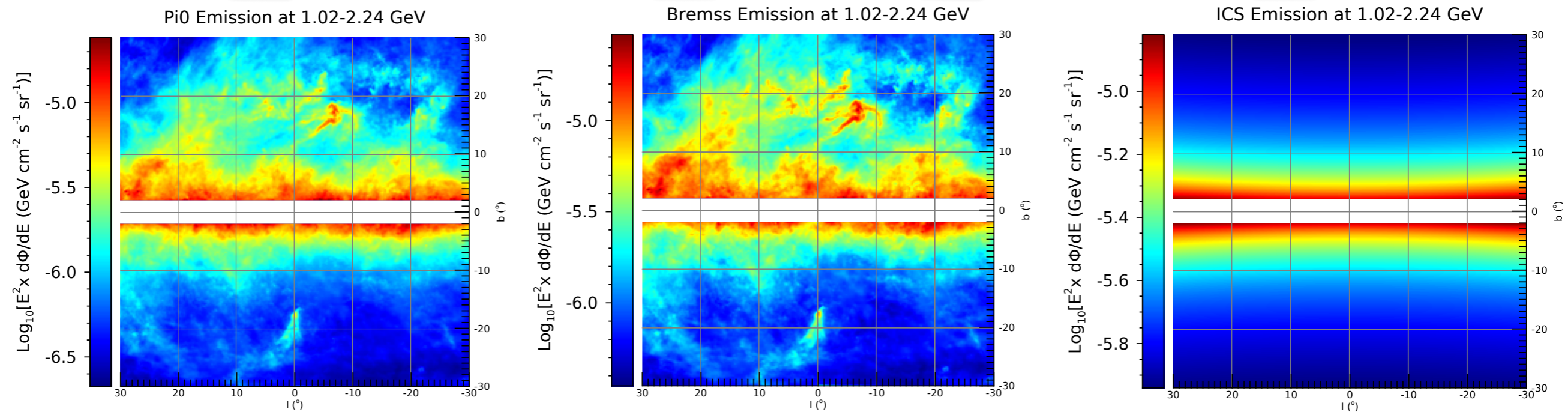
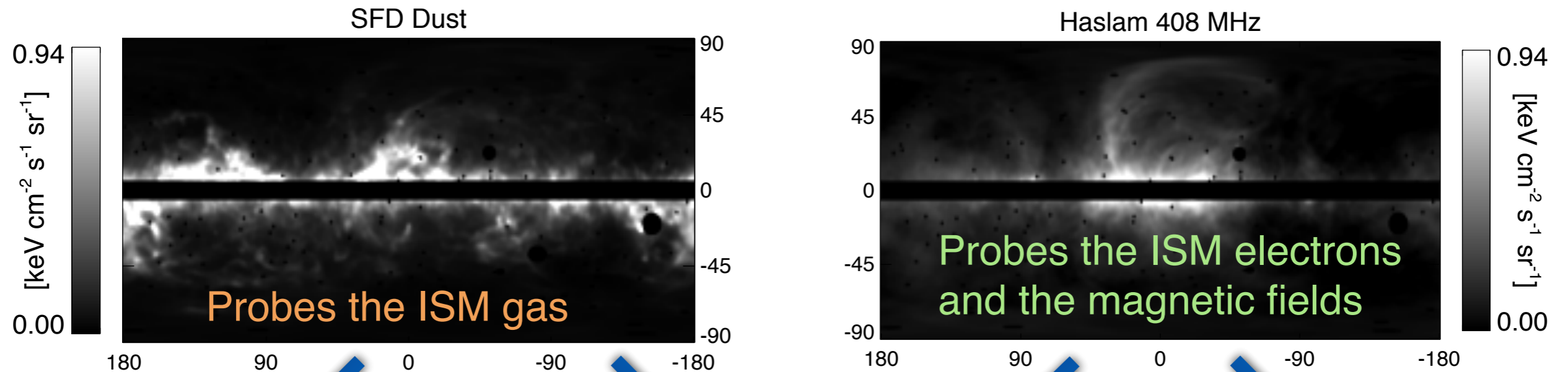
Adding ISM physics, cosmic-ray observations and running an array of Milky Way simulations

...

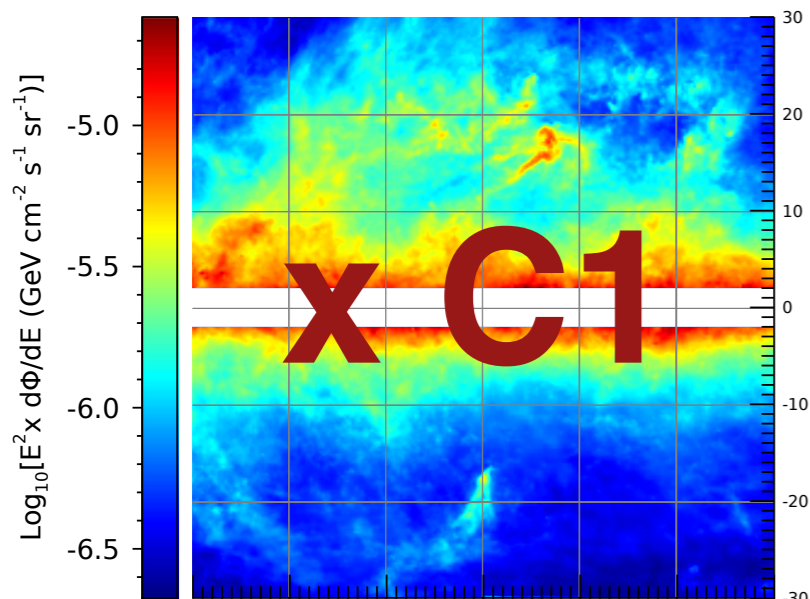


60 degrees in latitude

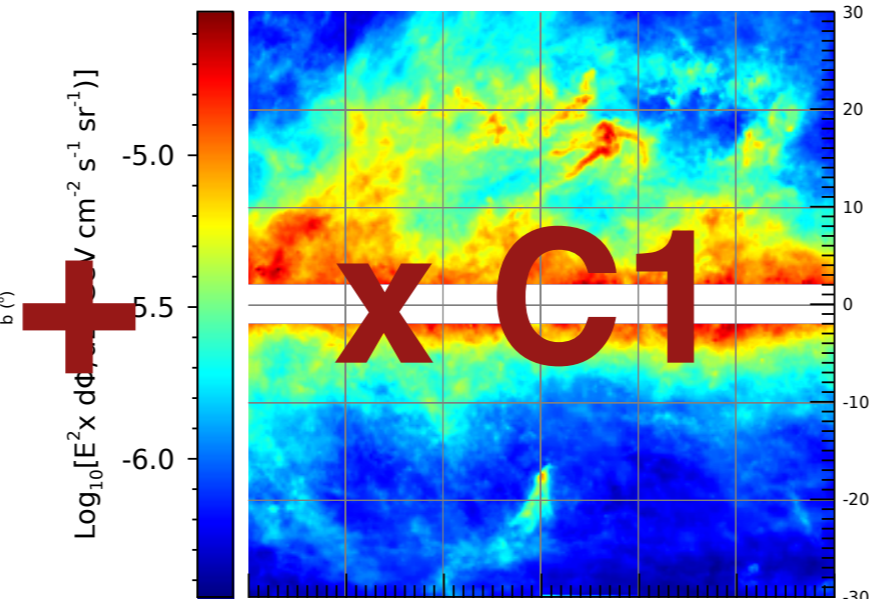
Using templates on Gamma-ray maps



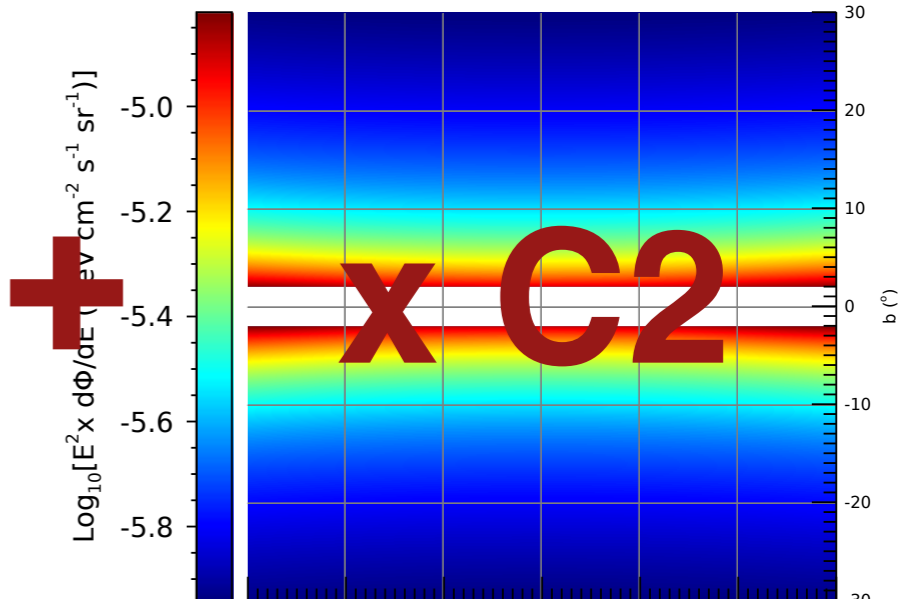
Pi0 Emission at 1.02-2.24 GeV



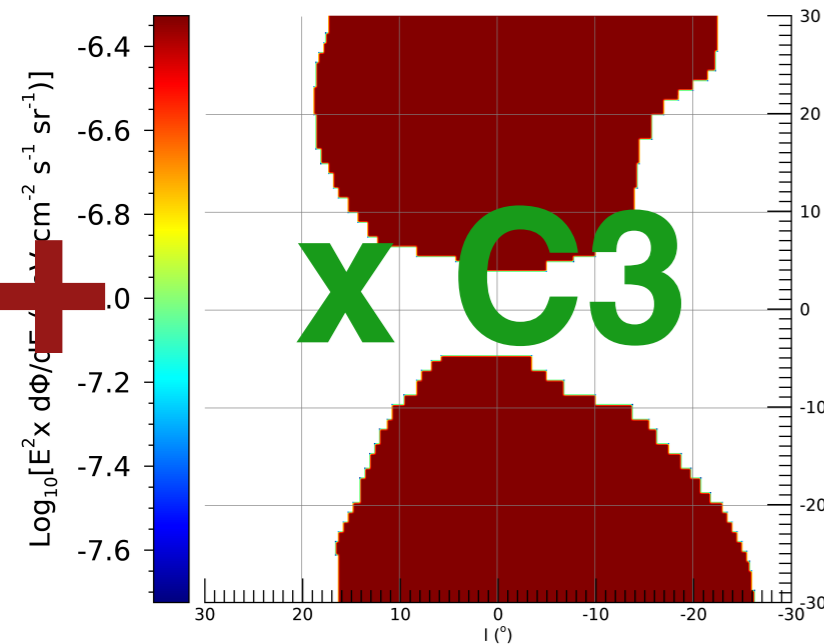
Bremss Emission at 1.02-2.24 GeV



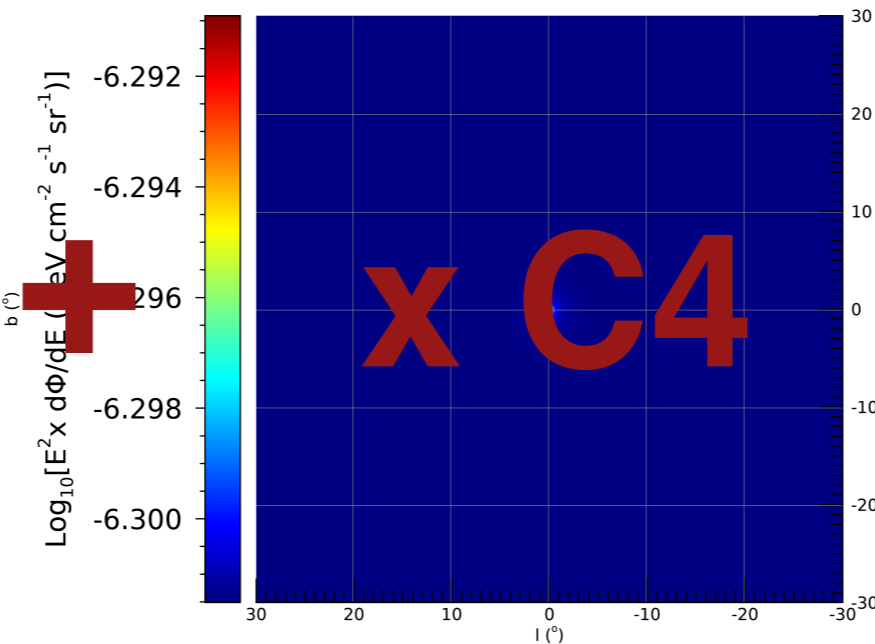
ICS Emission at 1.02-2.24 GeV



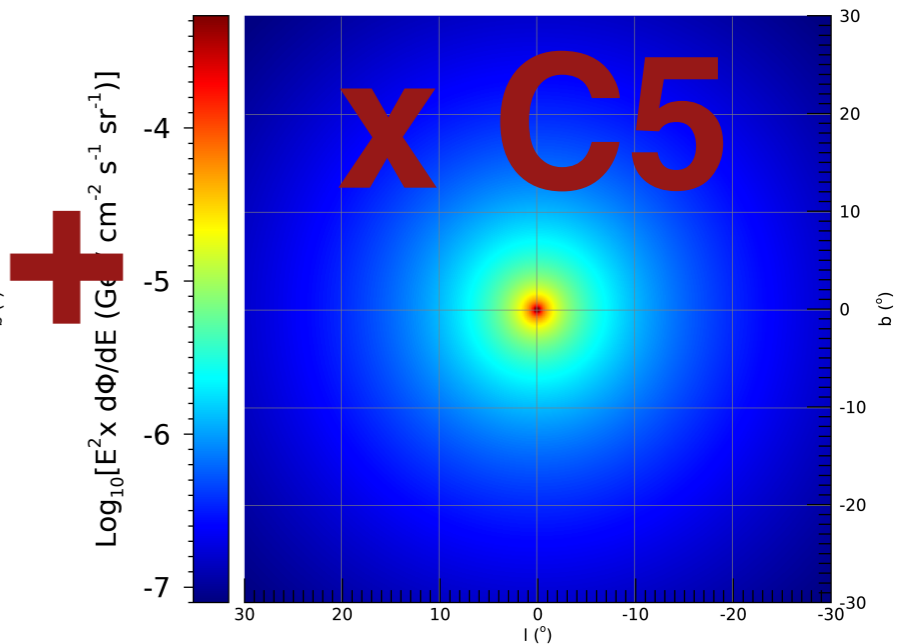
Bubbles Emission at 1.02-2.24 GeV



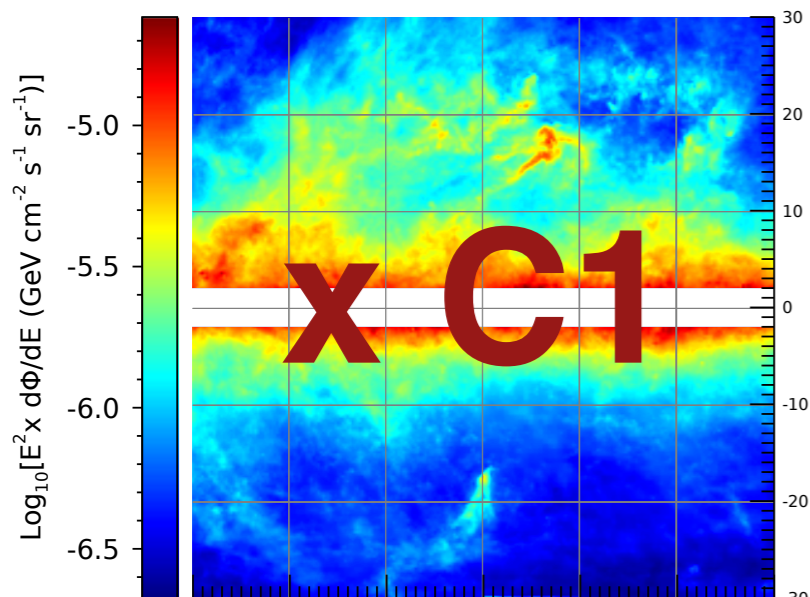
Isotropic Emission at 1.02-2.24 GeV



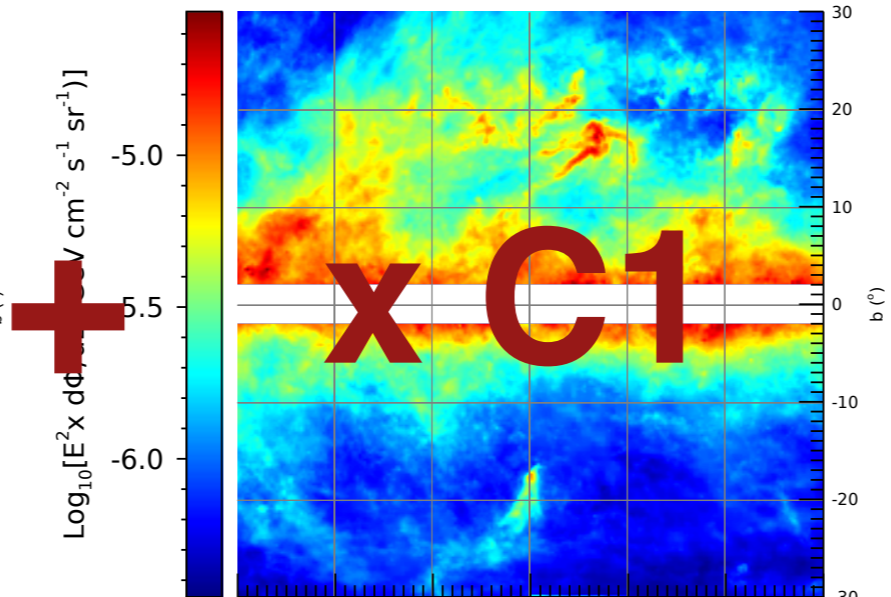
Dark Matter Emission at 1.02-2.24 GeV



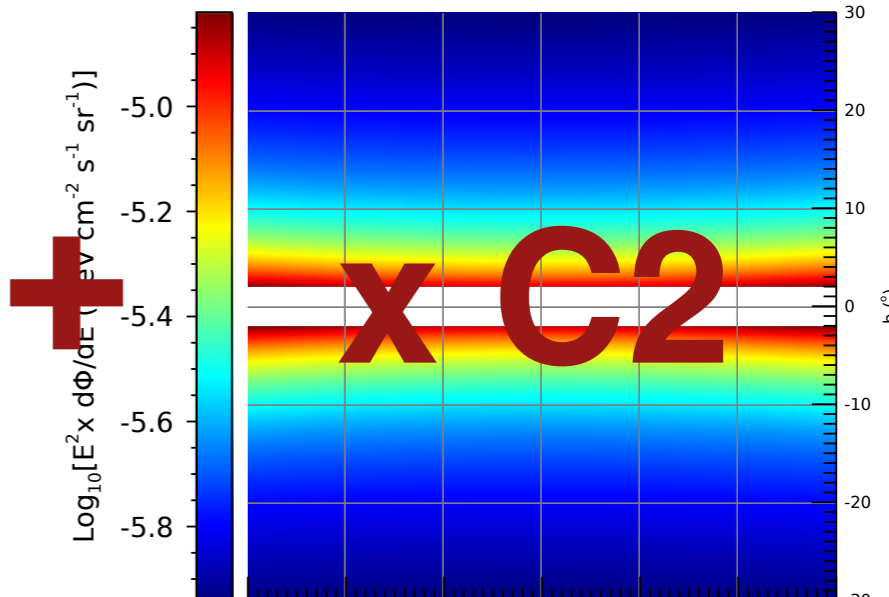
Pi0 Emission at 1.02-2.24 GeV



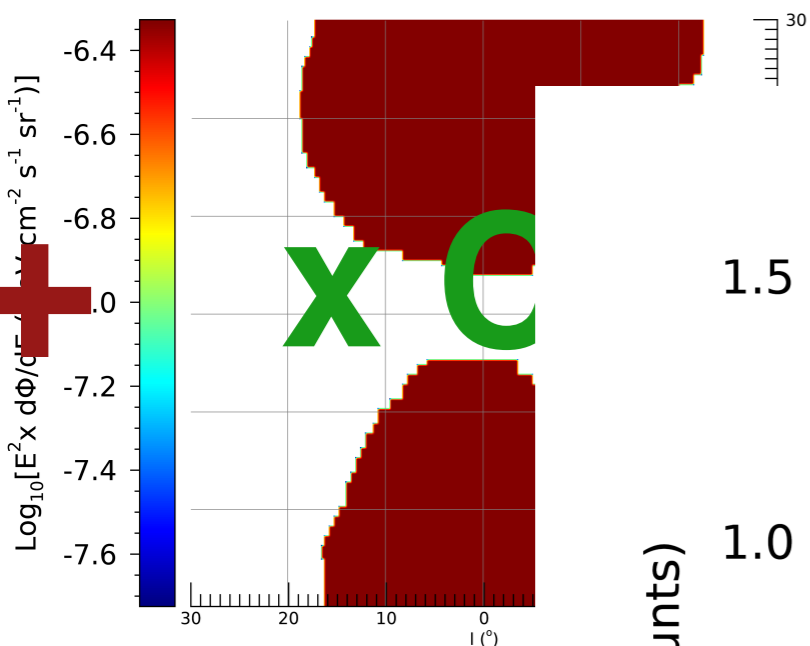
Brems Emission at 1.02-2.24 GeV



ICS Emission at 1.02-2.24 GeV



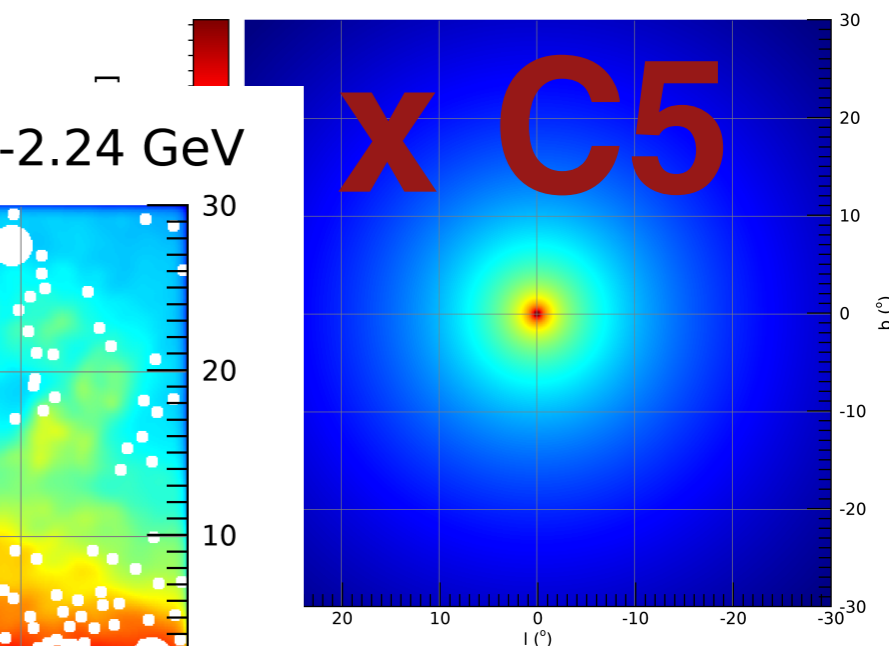
Bubbles Emission at 1.02-2.24 GeV



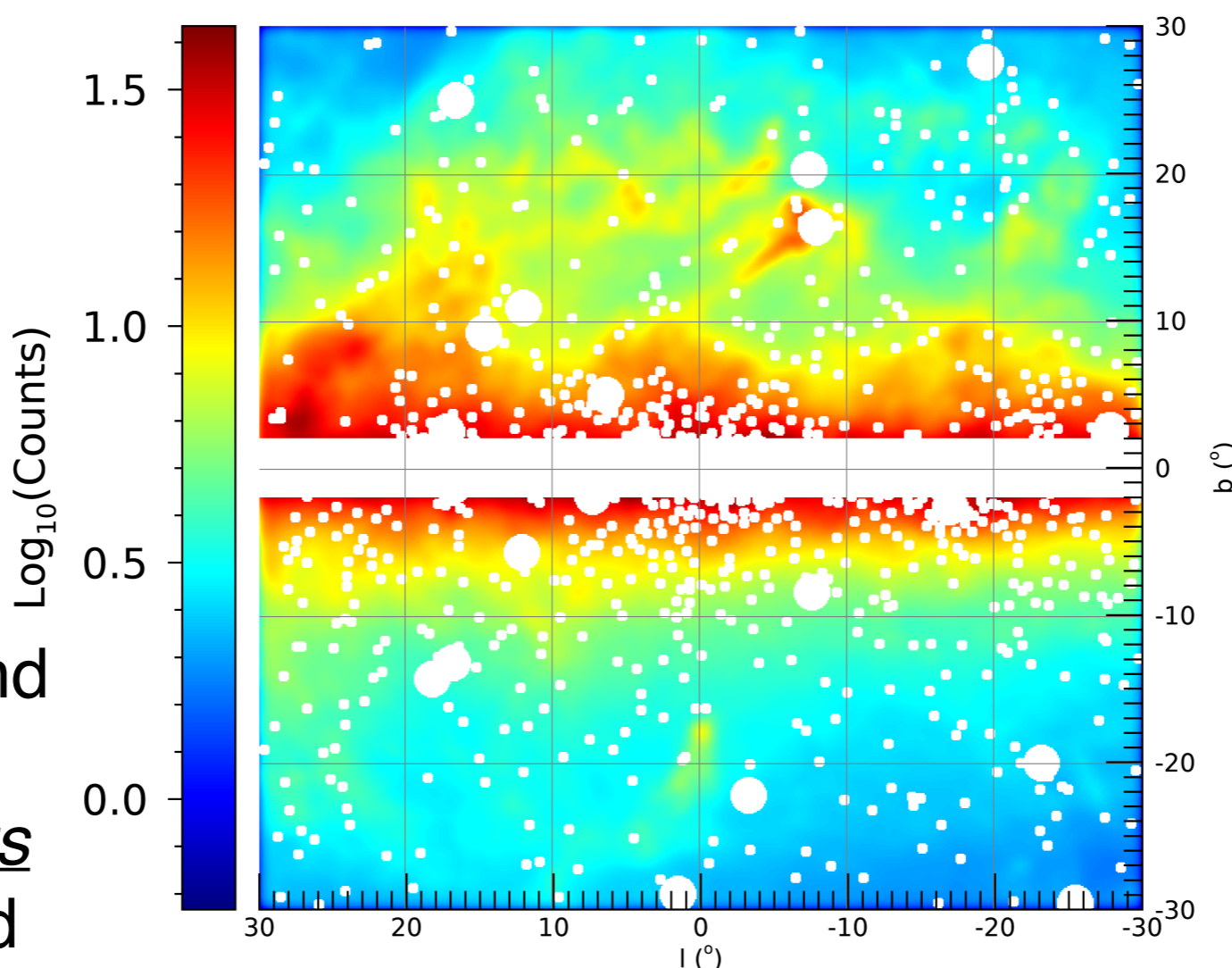
Isotropic Emission at 1.02-2.24 GeV



Dark Matter Emission at 1.02-2.24 GeV



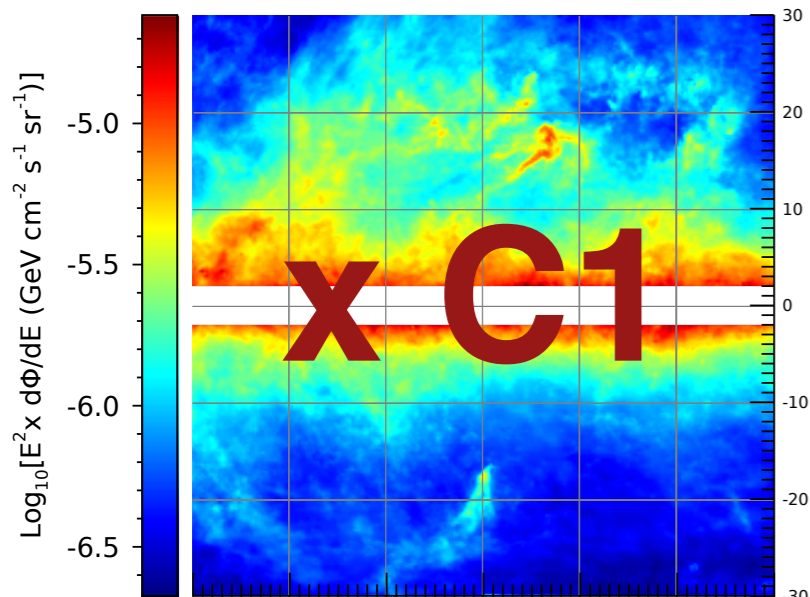
Composite Emission w PSF at 1.02-2.24 GeV



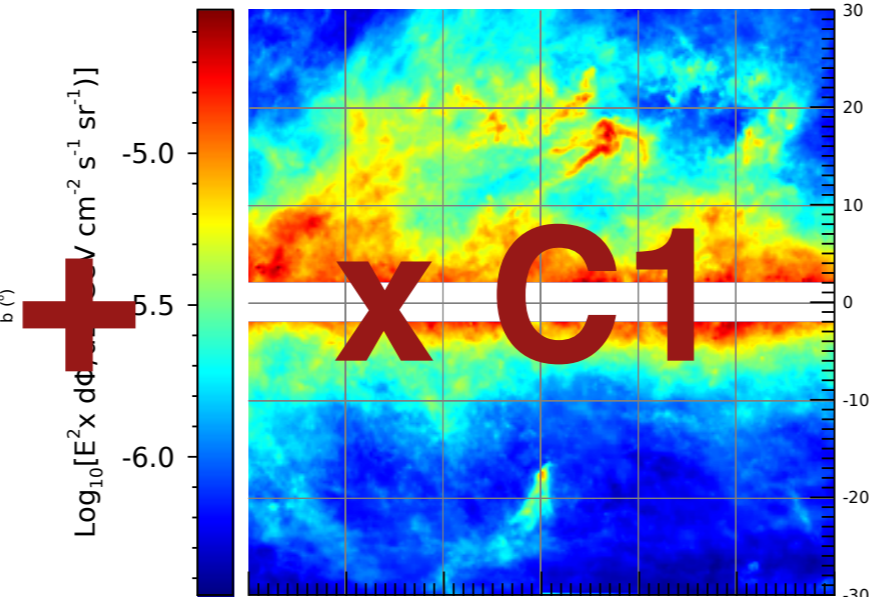
Adding properly and accounting for instrumental effects as the point spread

function and the non-uniform exposure (also masking-out bright point sources)

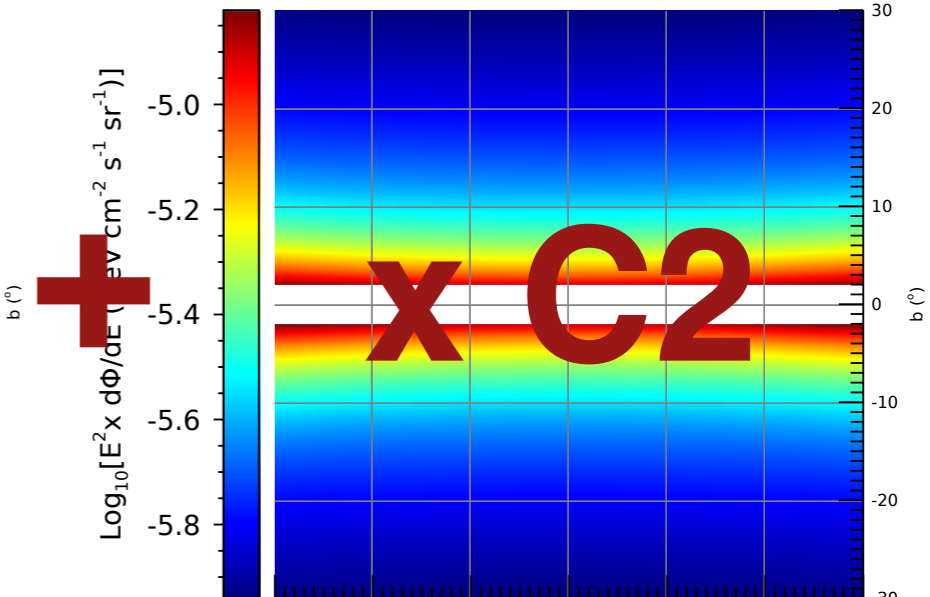
Pi0 Emission at 1.02-2.24 GeV



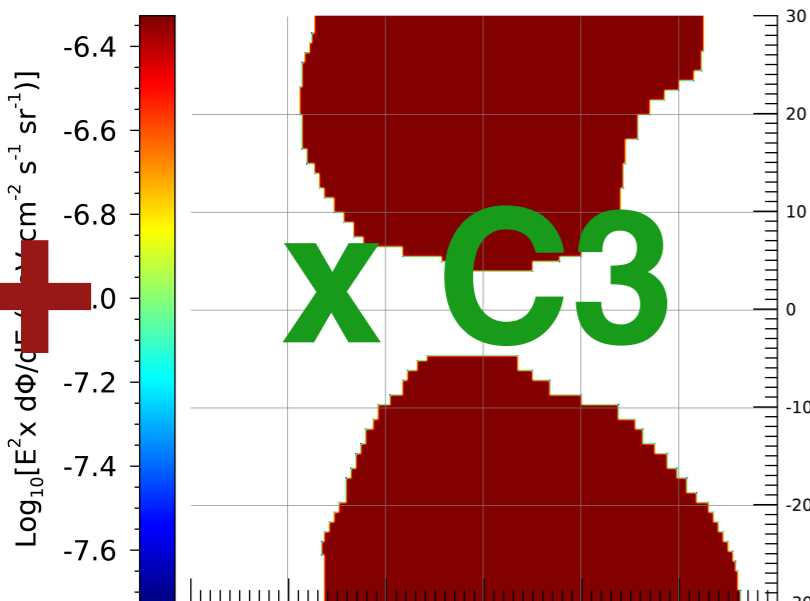
Bremss Emission at 1.02-2.24 GeV



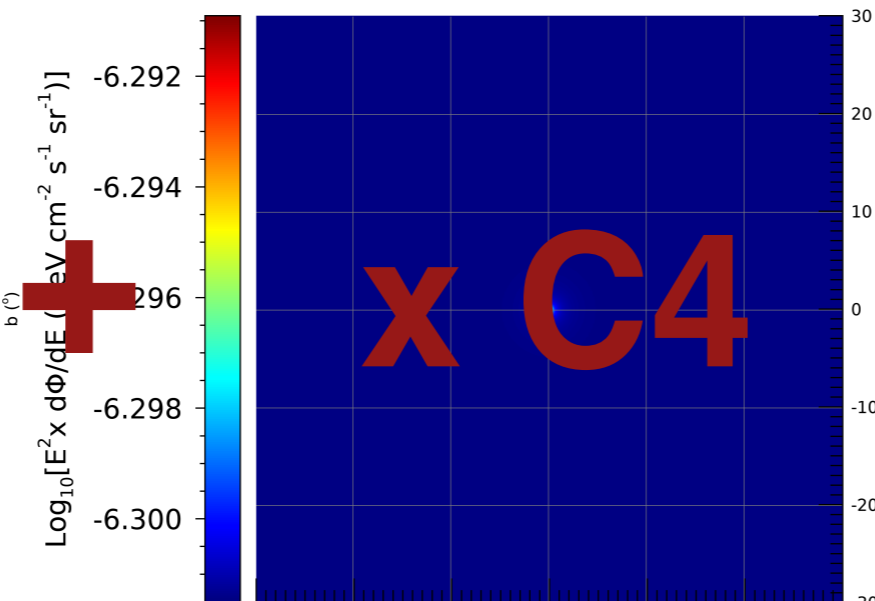
ICS Emission at 1.02-2.24 GeV



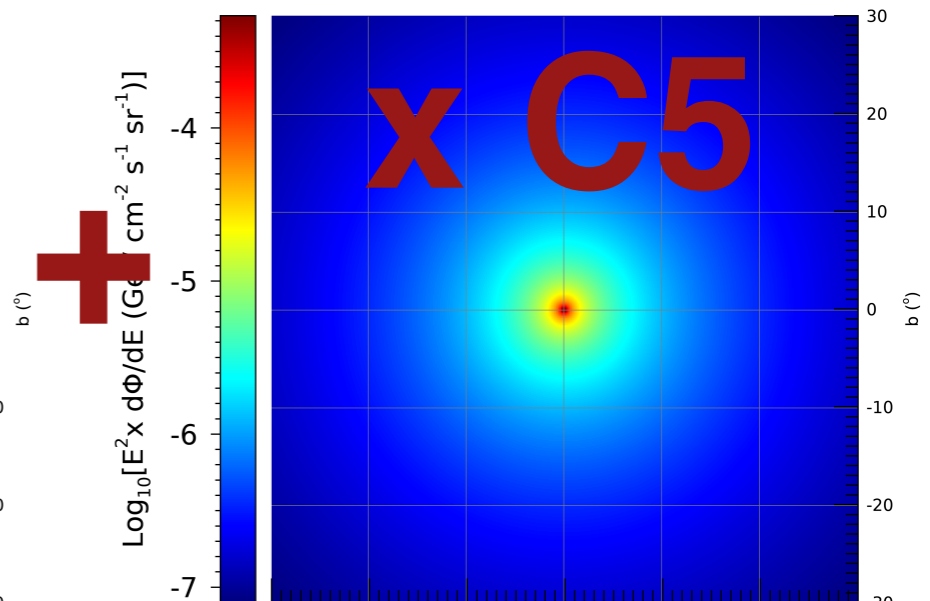
Bubbles Emission at 1.02-2.24 GeV



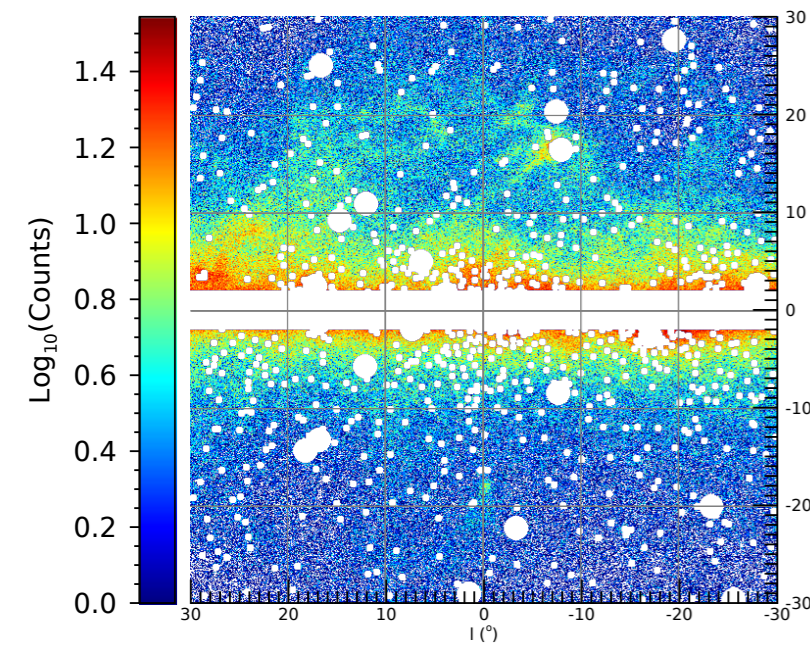
Isotropic Emission at 1.02-2.24 GeV



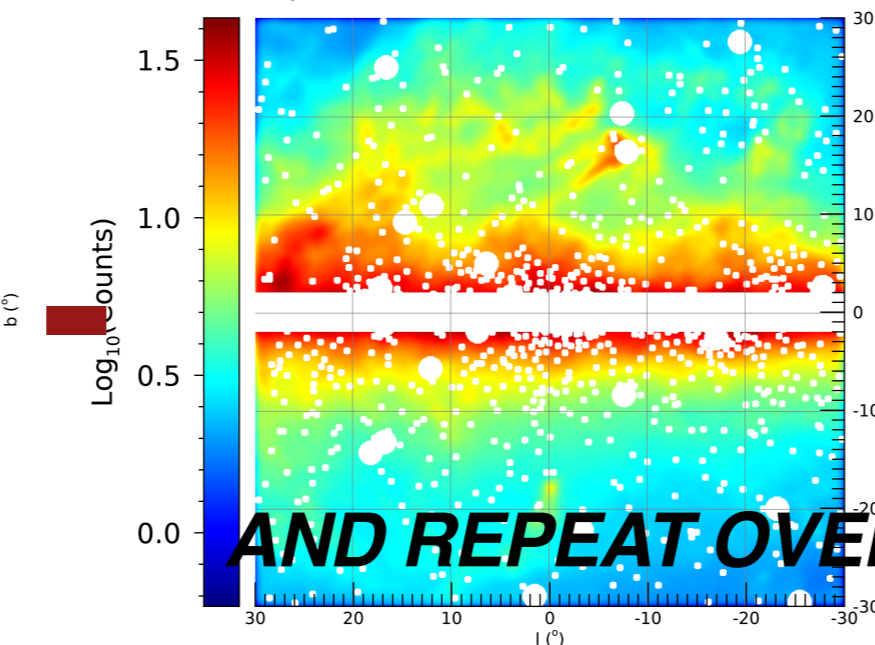
Dark Matter Emission at 1.02-2.24 GeV



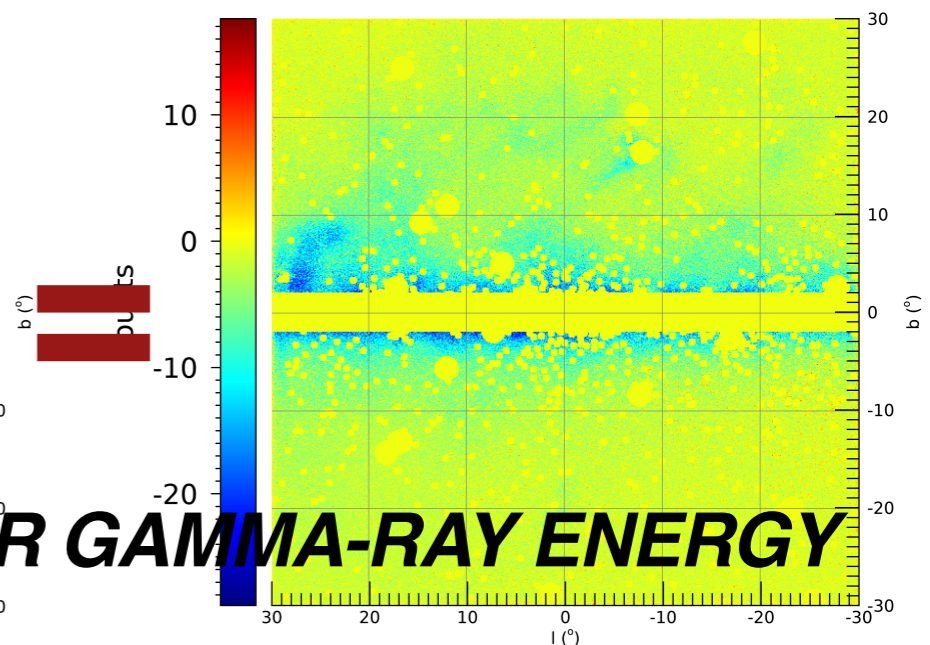
Observed Emission at 1.02-2.24 GeV



Composite Emission w PSF at 1.02-2.24 GeV



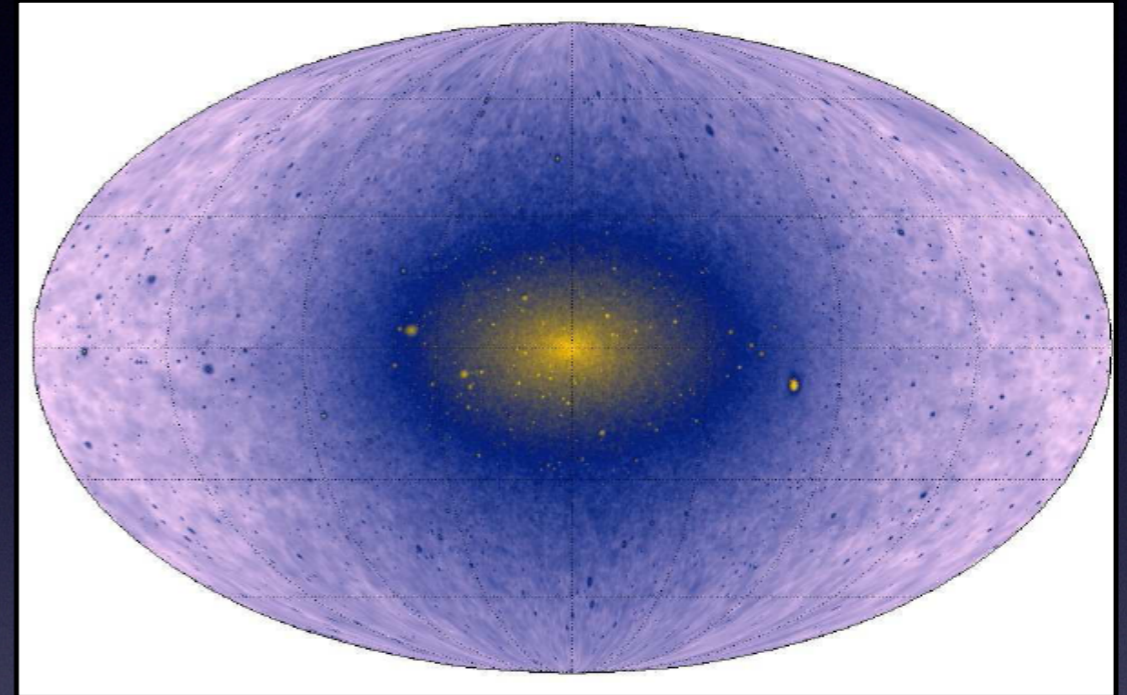
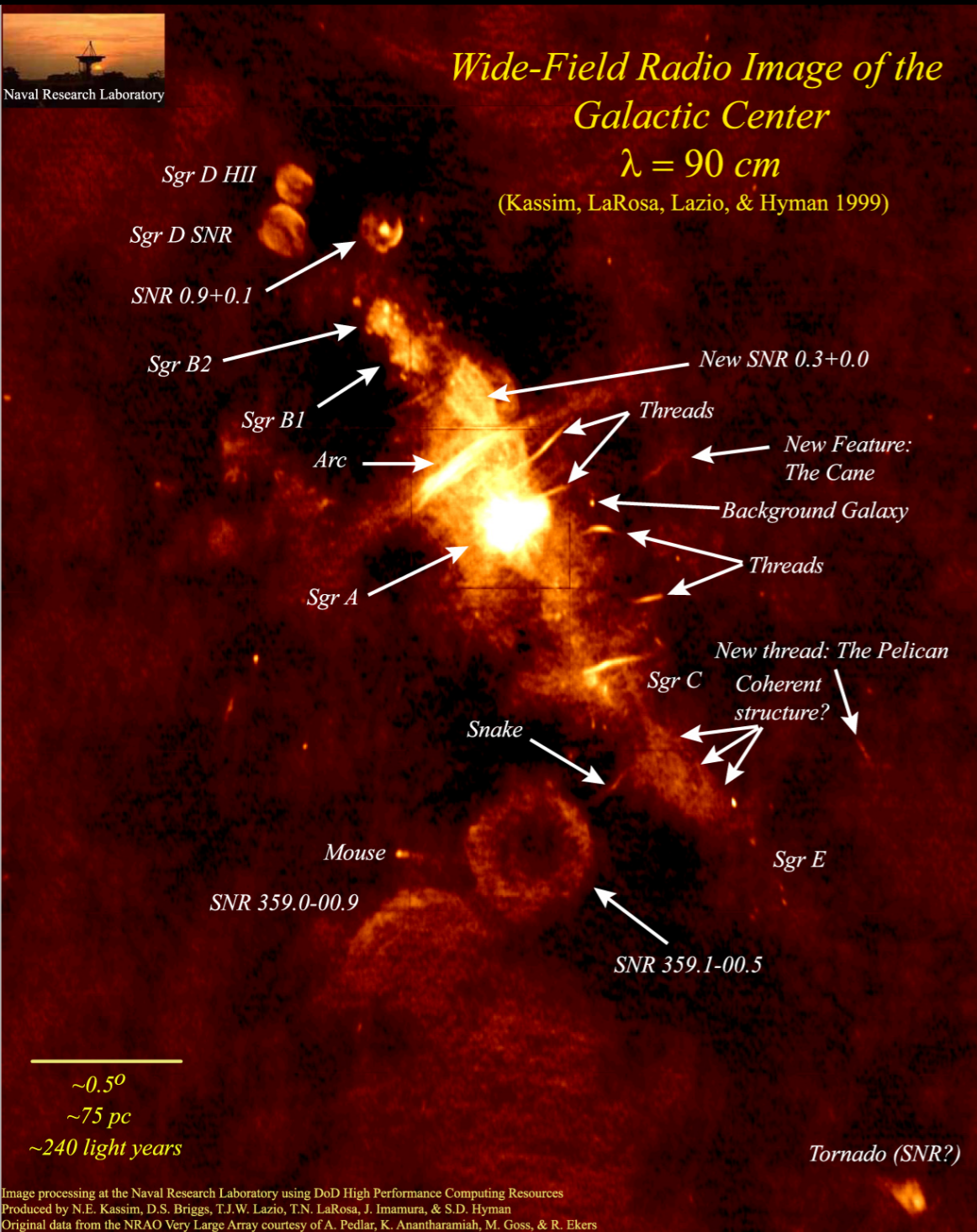
Residual Emission at 1.02-2.24 GeV



AND REPEAT OVER GAMMA-RAY ENERGY

The galactic center

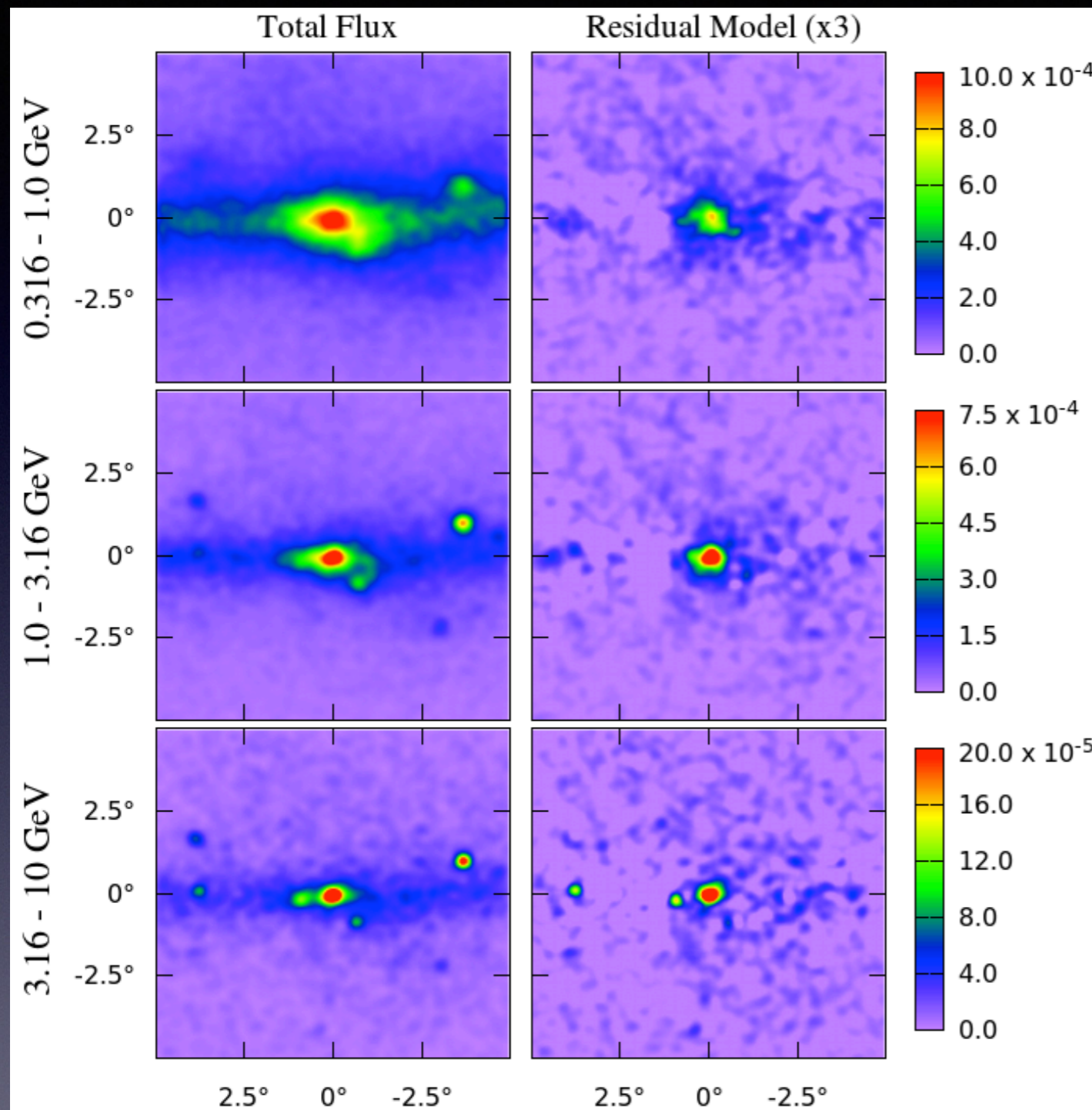
A place to look for Dark Matter Annihilation



- 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:

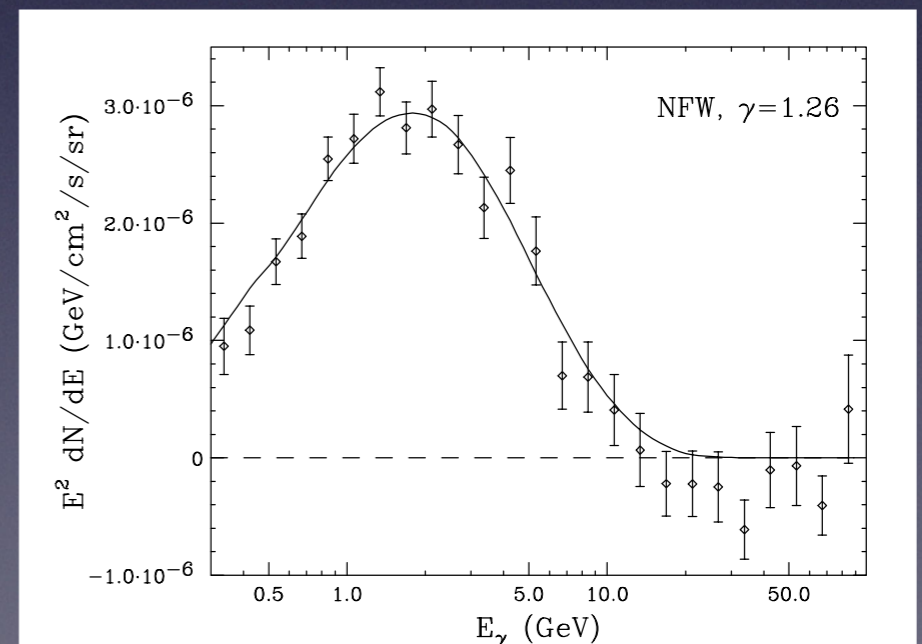


Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, PoDU 2015

Claim:

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

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

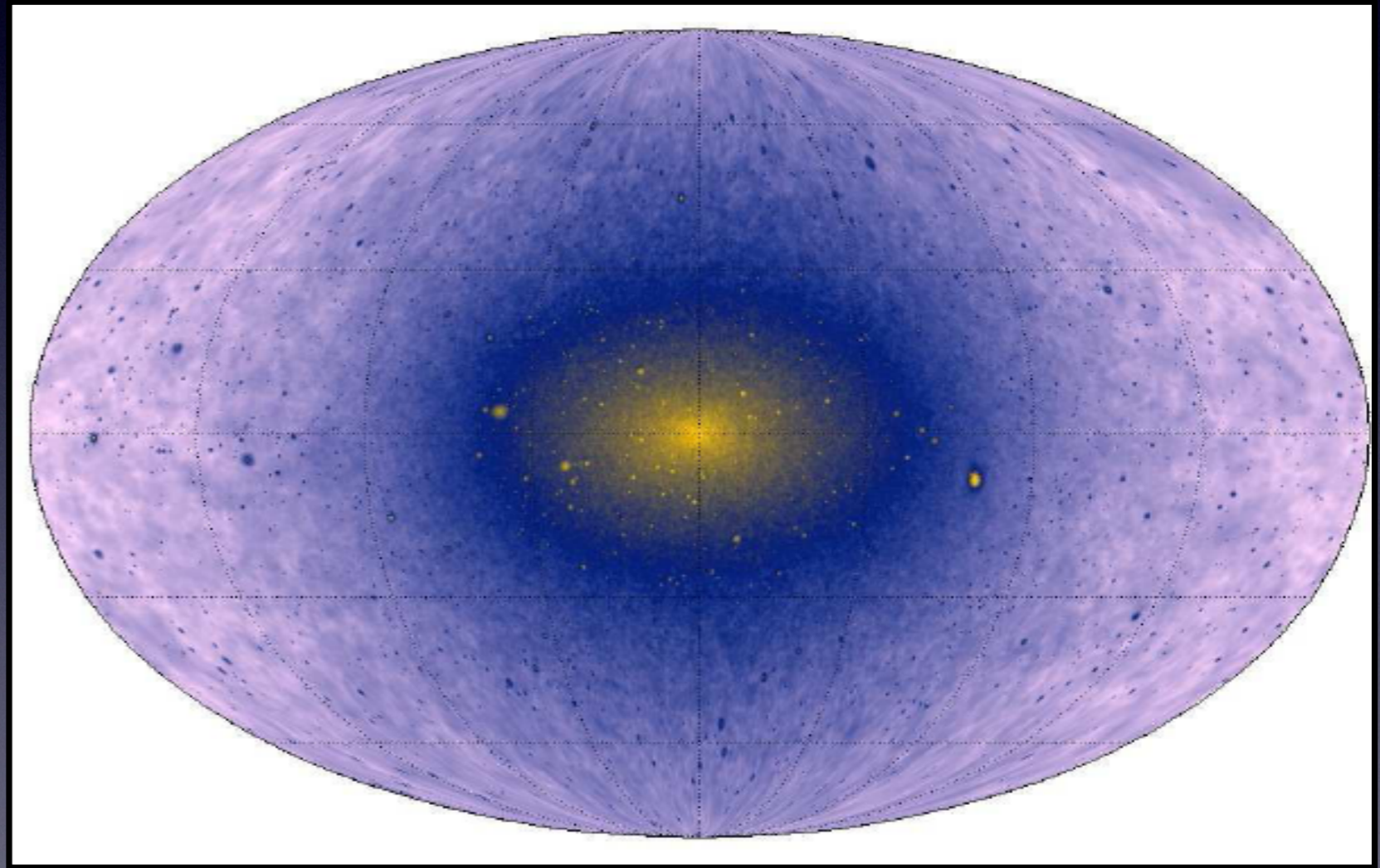


Also: Hooper & Goodenough PRL 2011, Abazajian JCAP 2011, Hooper & Linden PRD 2011, Gordon & Macias PRD 2014, Zhou et al. PRD 2015, Ajello et al. ApJ 2016

Going to High Latitudes (Inner Galaxy)

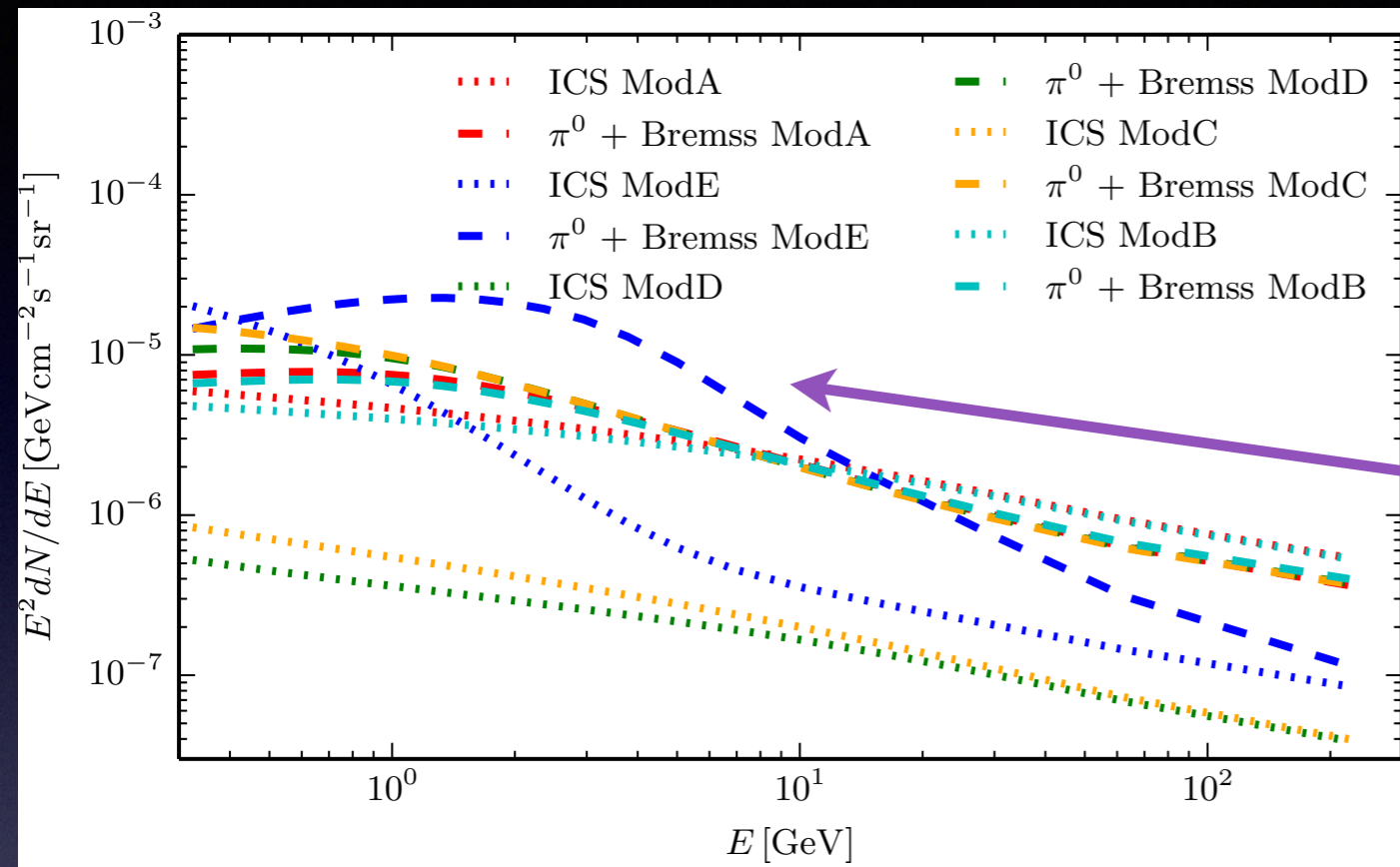
Advantages of looking further away from the center:

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

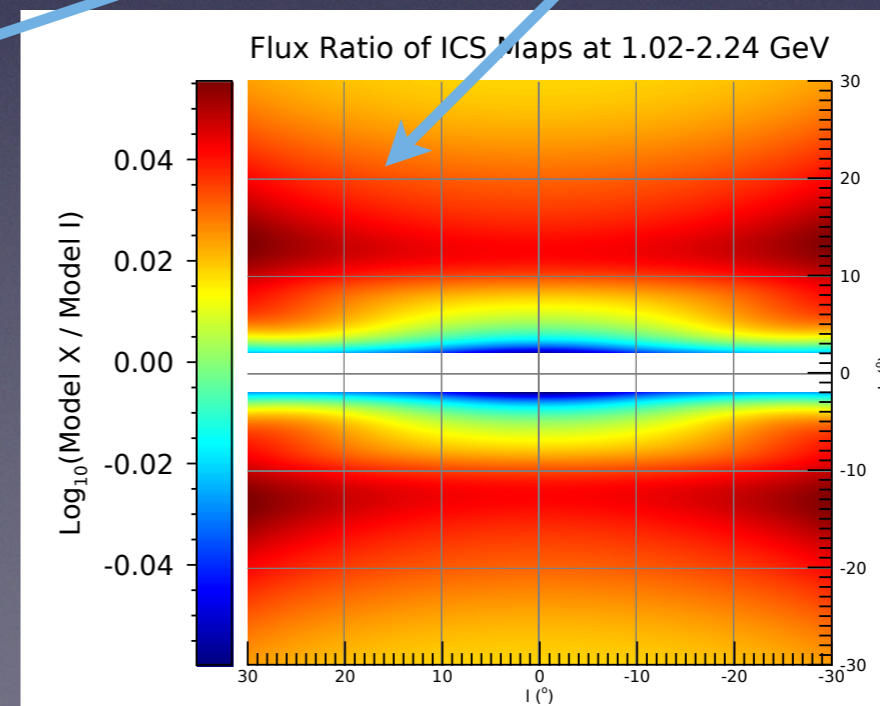
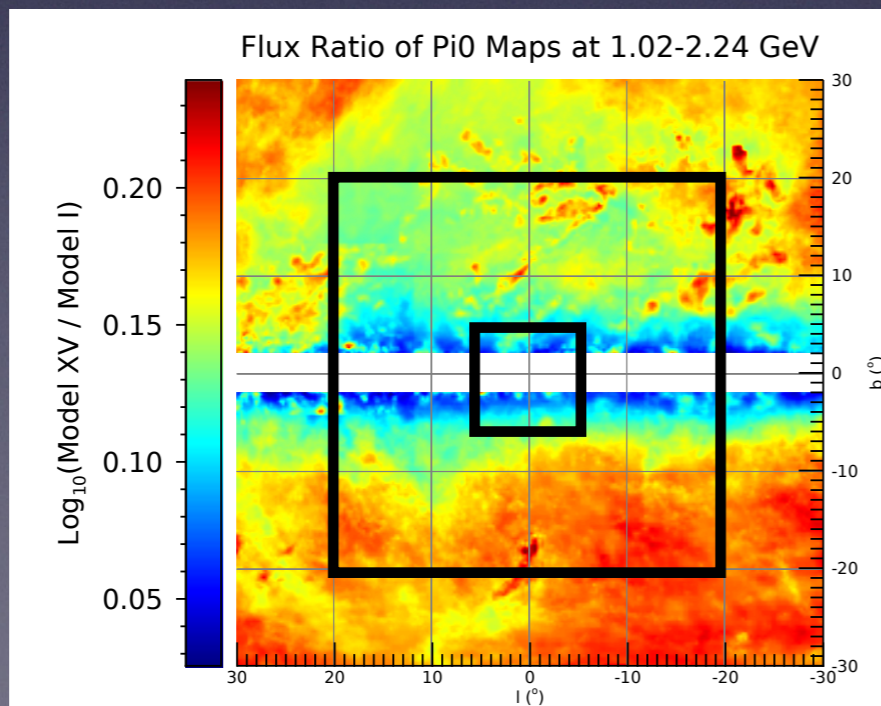


The exact **astrophysics model assumptions** can affect both the gamma-ray **background spectrum** and its **morphology** on the galactic sky.

Calore, IC, Weniger, JCAP 2015

IC, Zhong, McDermott, Surdutovich, PRD 2022

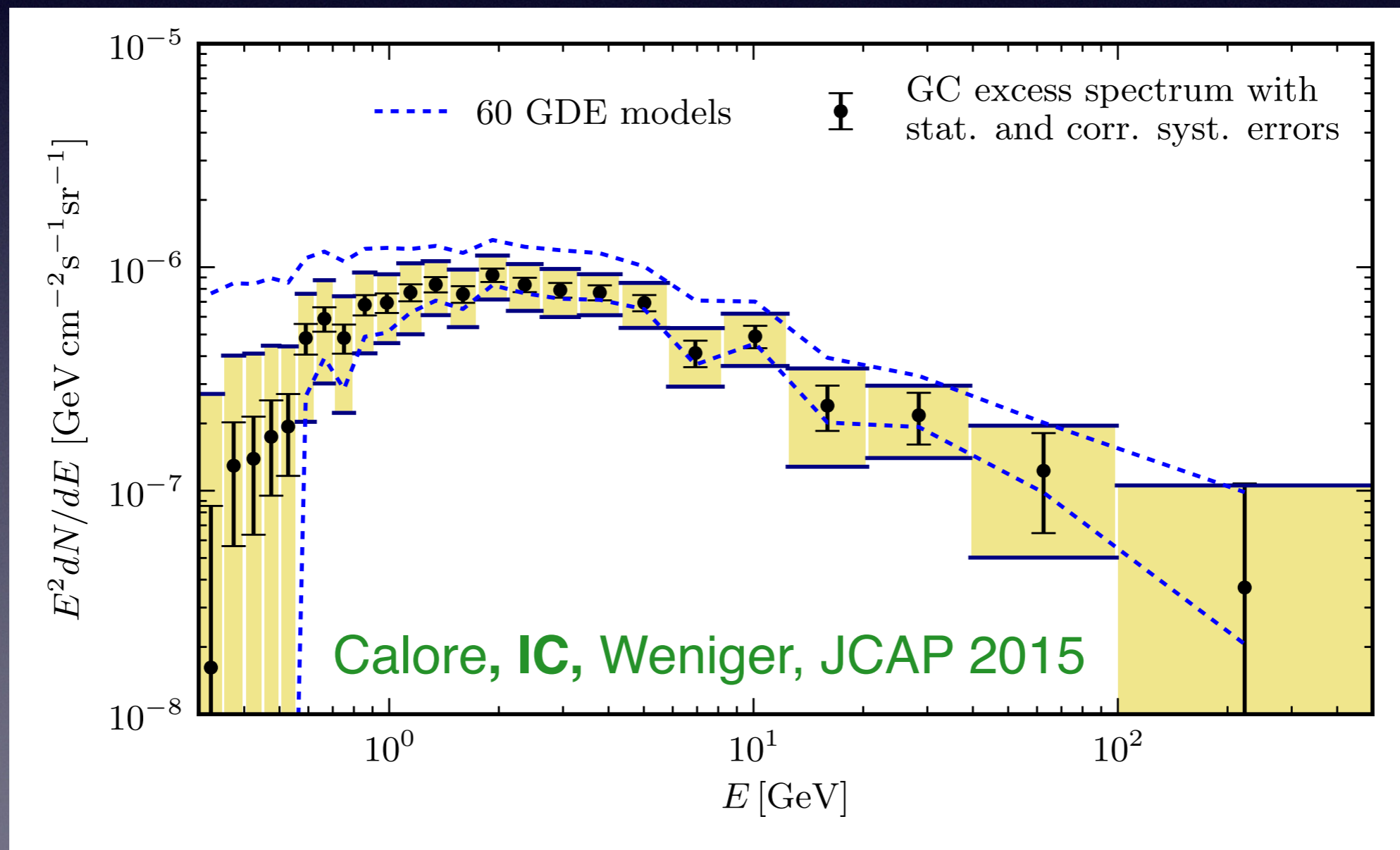
60 degrees in latitude



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!

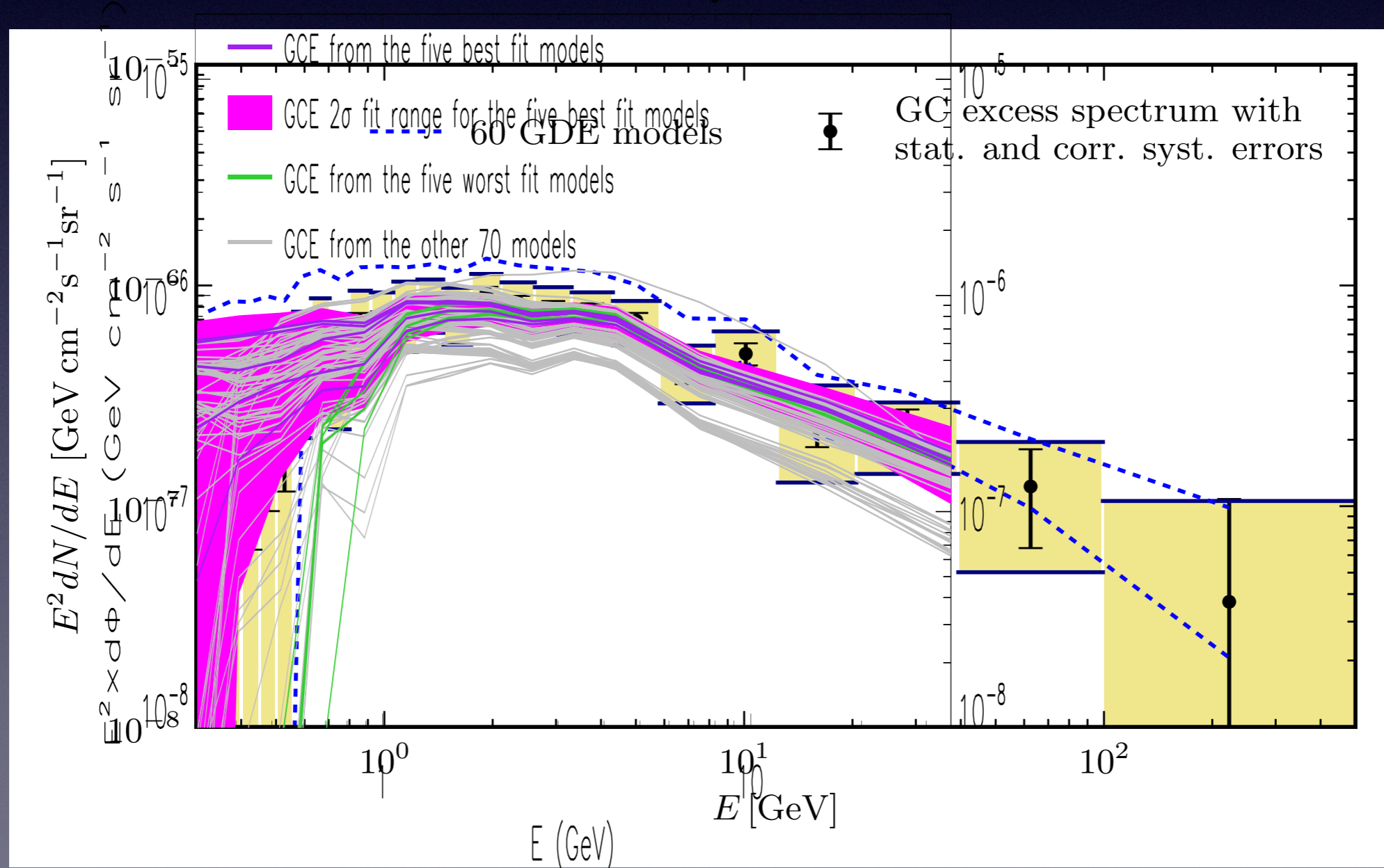
It turns out that it actually does not affect dramatically the excess spectrum:



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.

The GCE from all 80 diffuse background models



Maps, Astrophysical Models and Correlated Errors publicly available via Zenodo

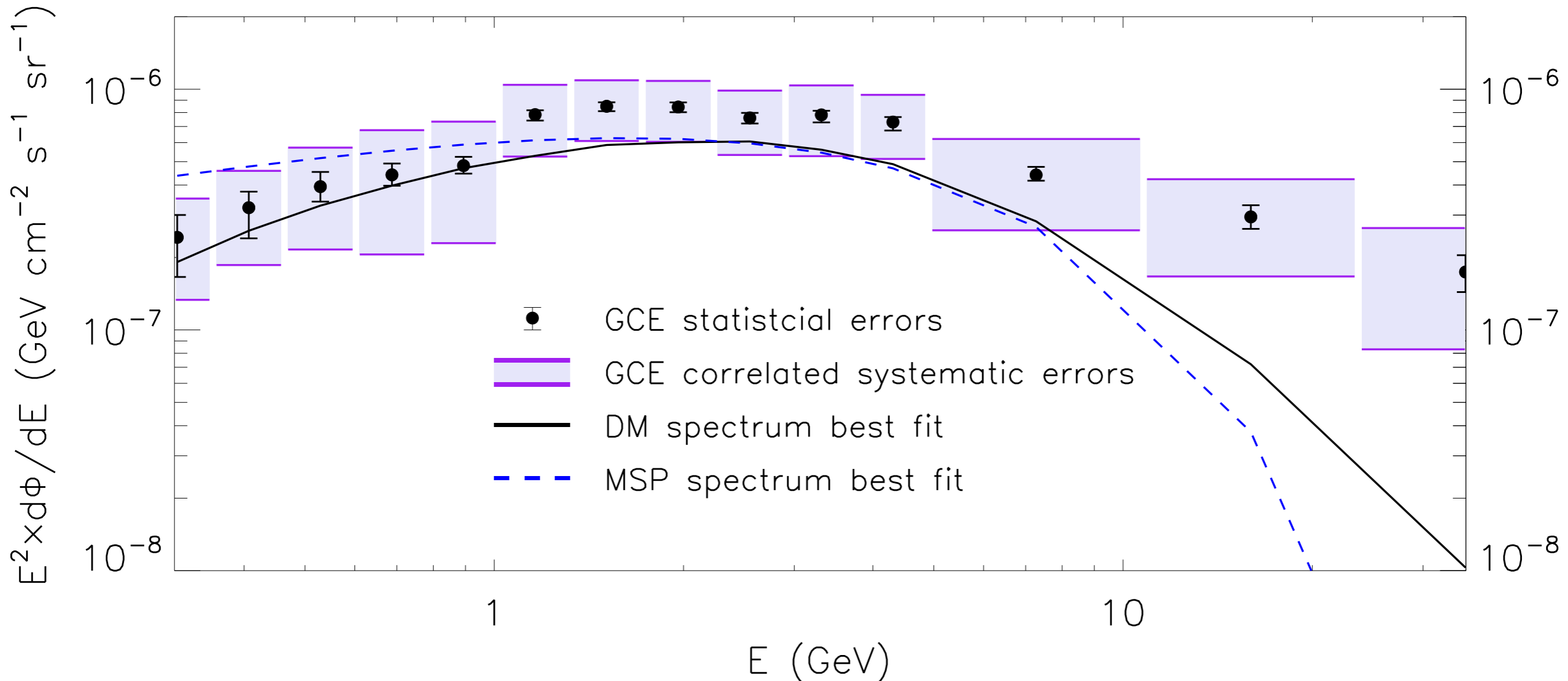
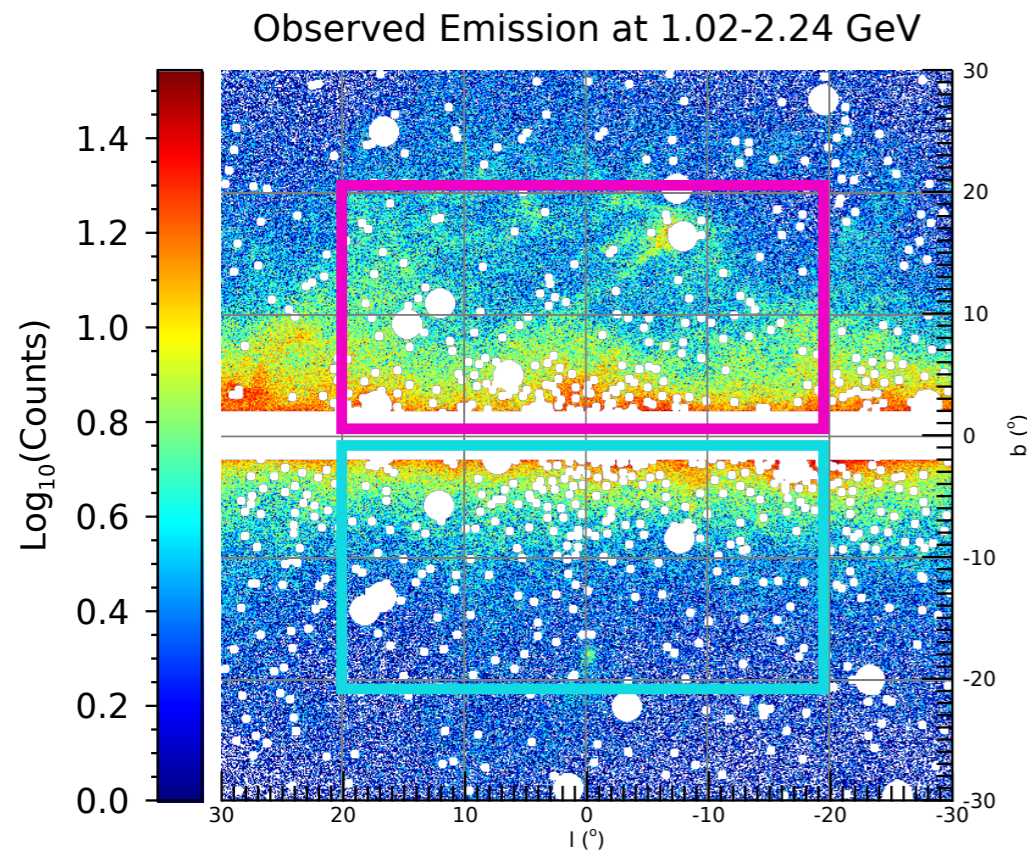


TABLE V. The first four principal components of the systematic uncertainty contribution to the covariance matrix, defined as in Eq. (16), in units of $10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

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?

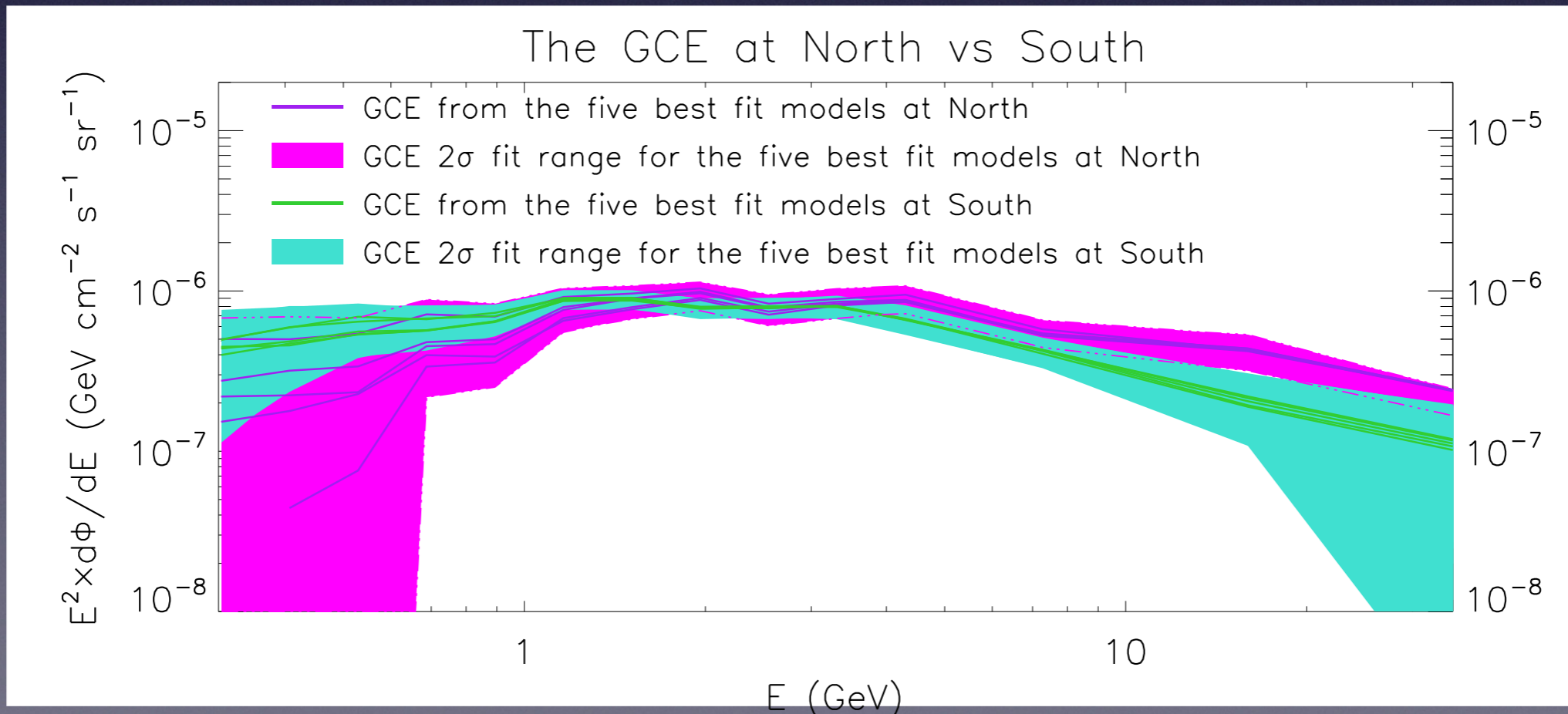
IC, Zhong, McDermott, Surdutovich, PRD 2022



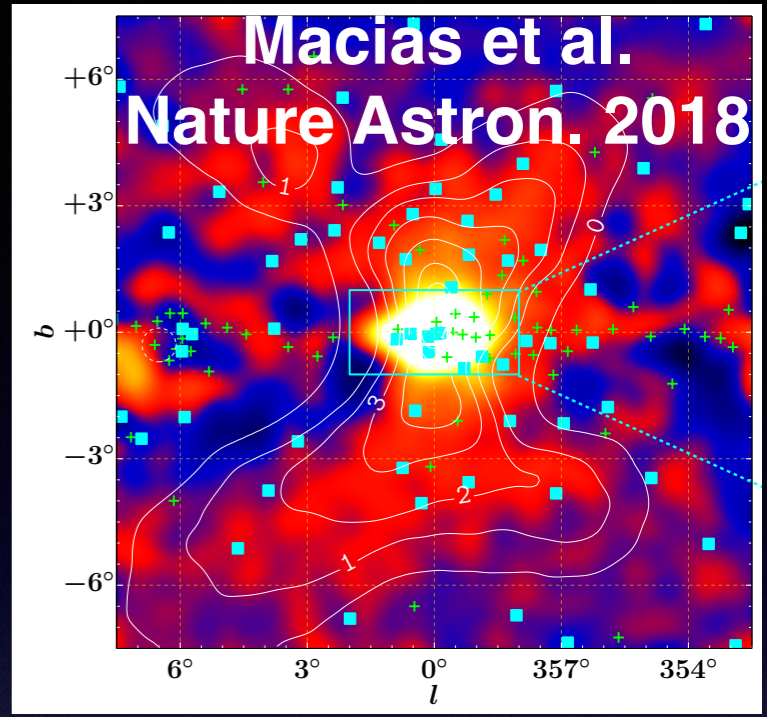
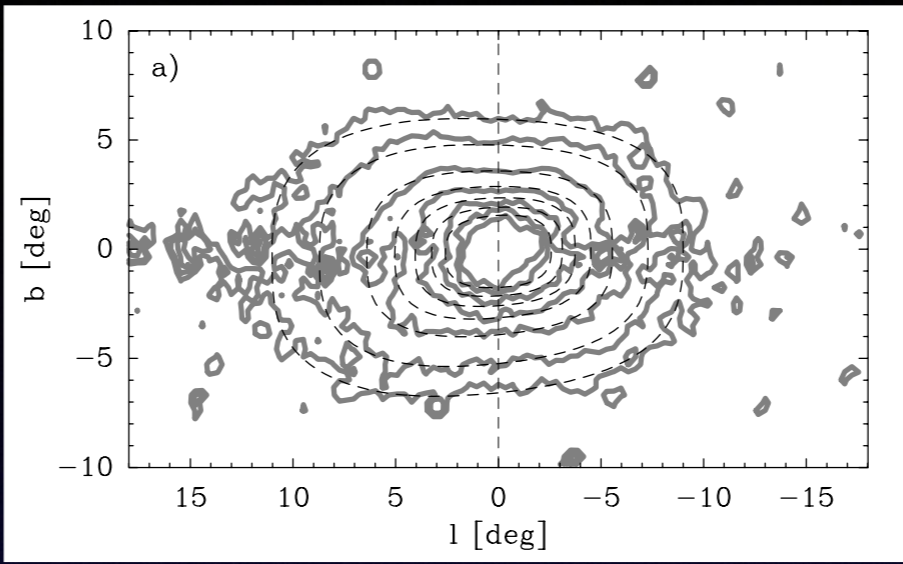
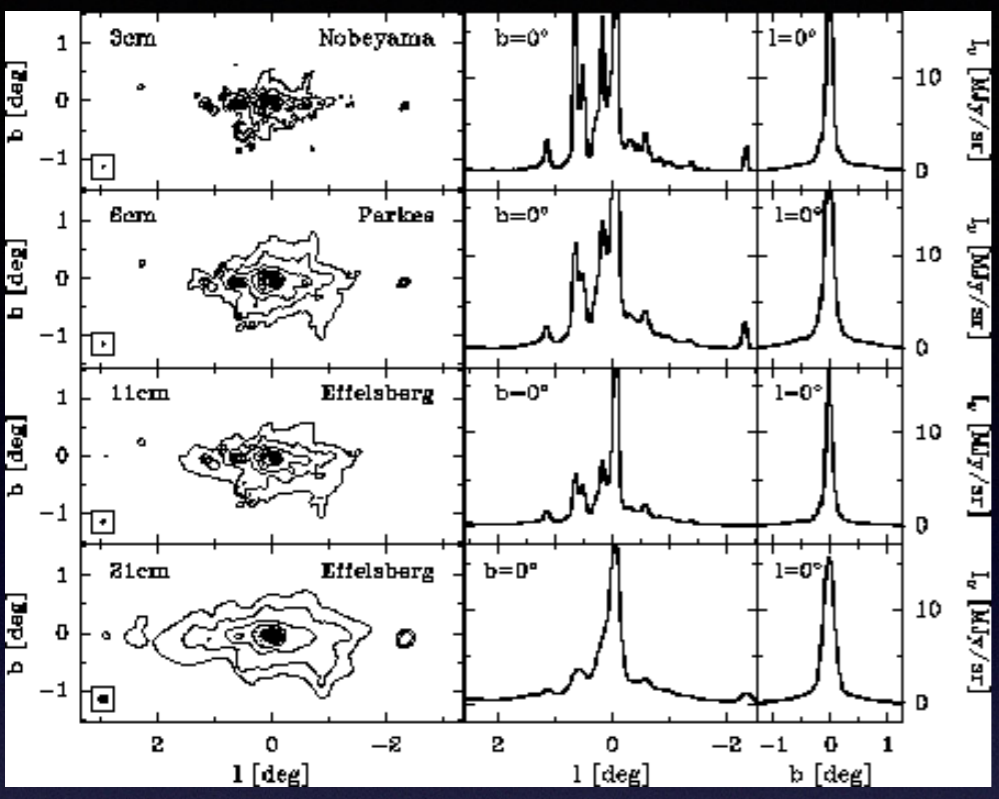
North

South

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



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

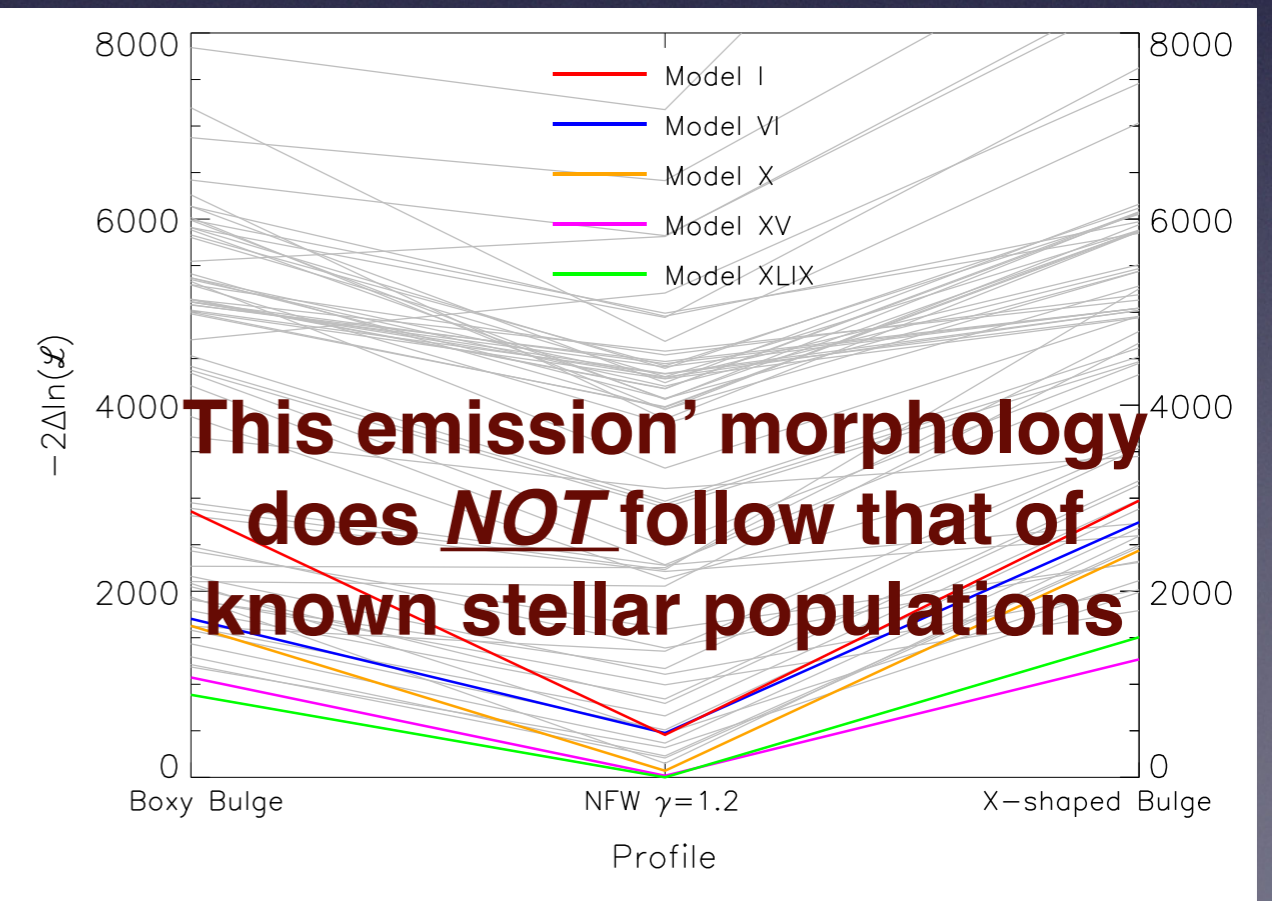
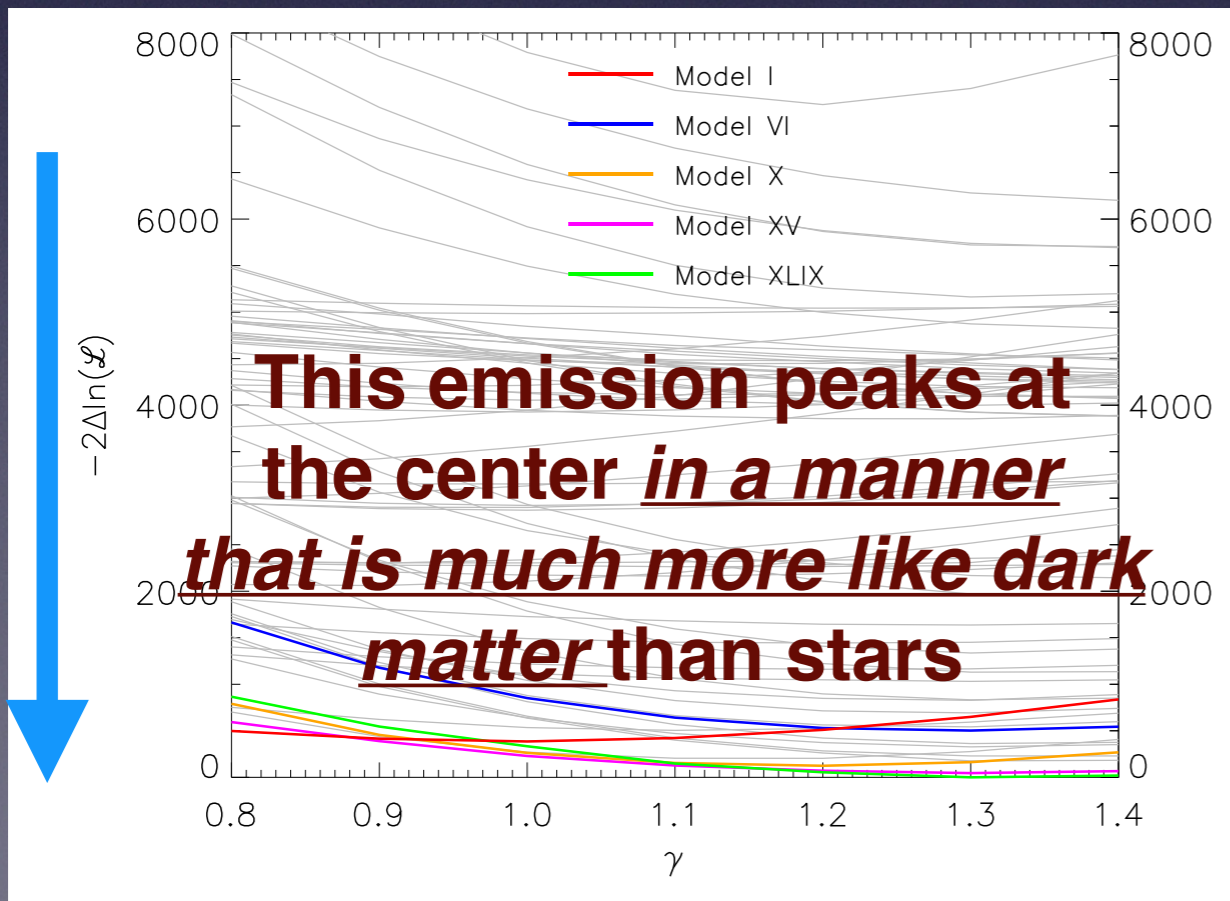


Boxy Bulge @ 2-5 μm

Launhardt et al. A&A 2002

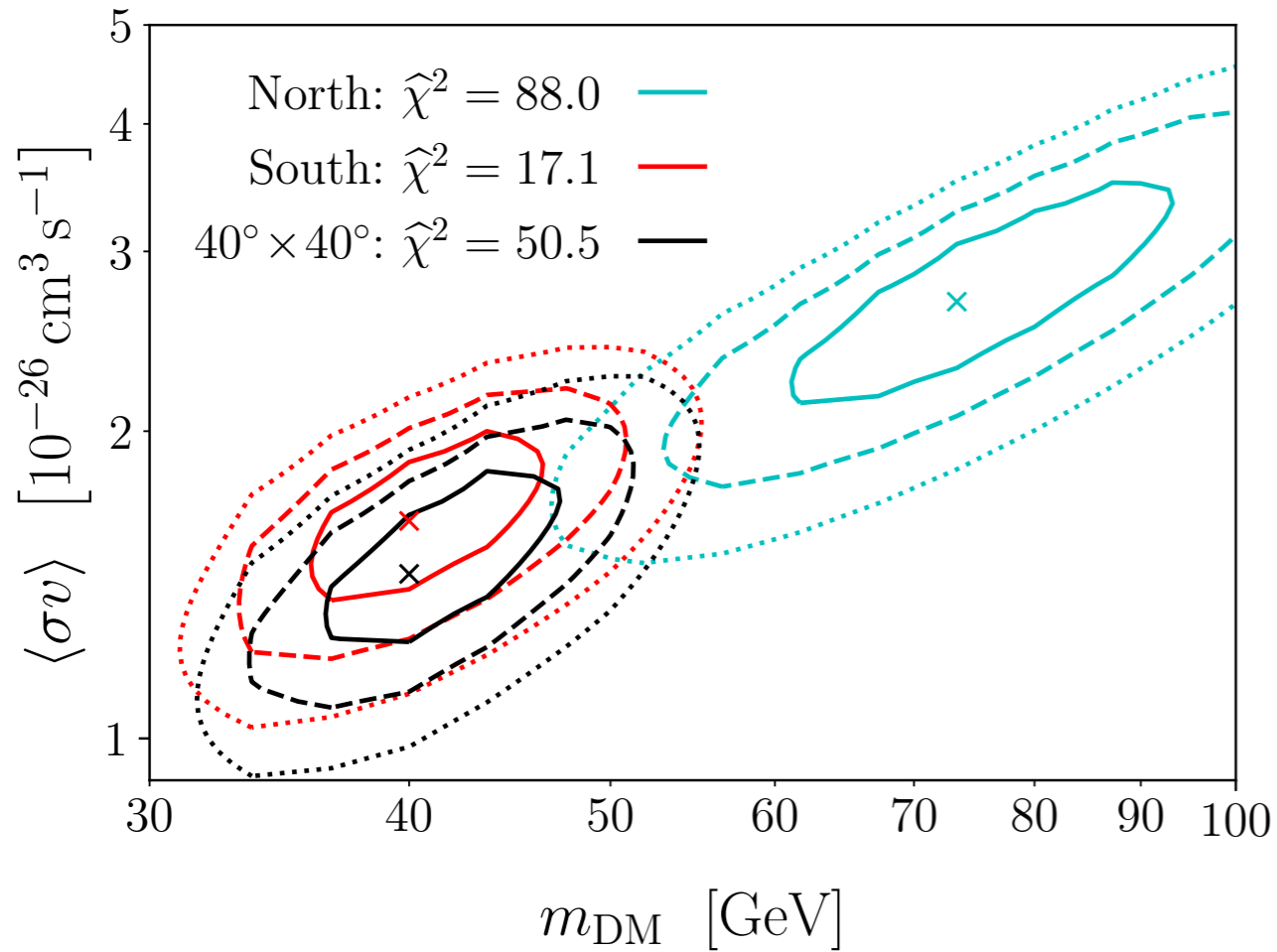
X-shaped Bulge @ "low" gamma-rays

Nuclear Bulge @ Radio



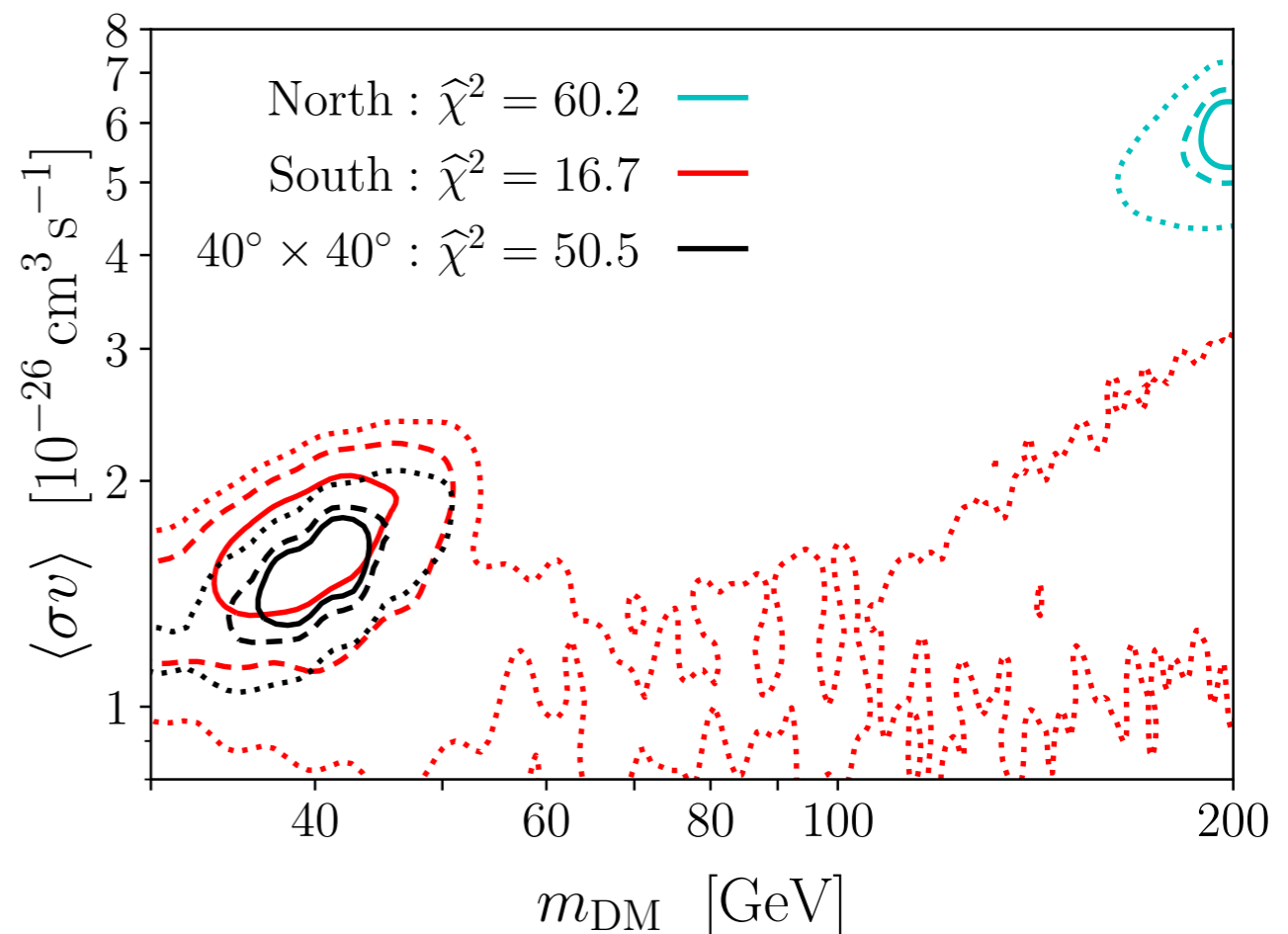
If this is a DM annihilation signal what do we learn about the particle physics?

DM DM $\rightarrow b\bar{b}$



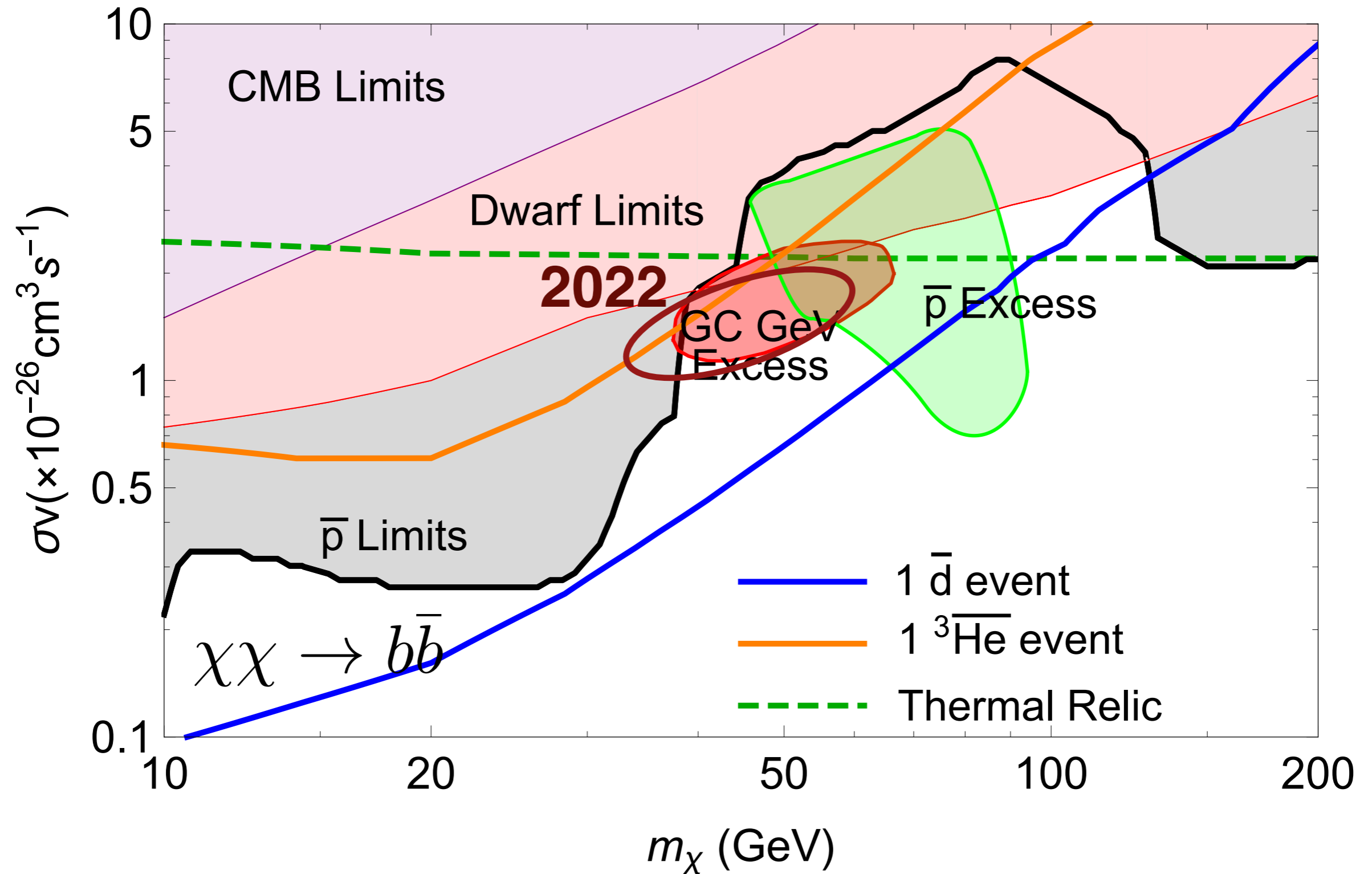
The mass range preferred very much within the WIMP range.

MSPs + DM DM $\rightarrow b\bar{b}$



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



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



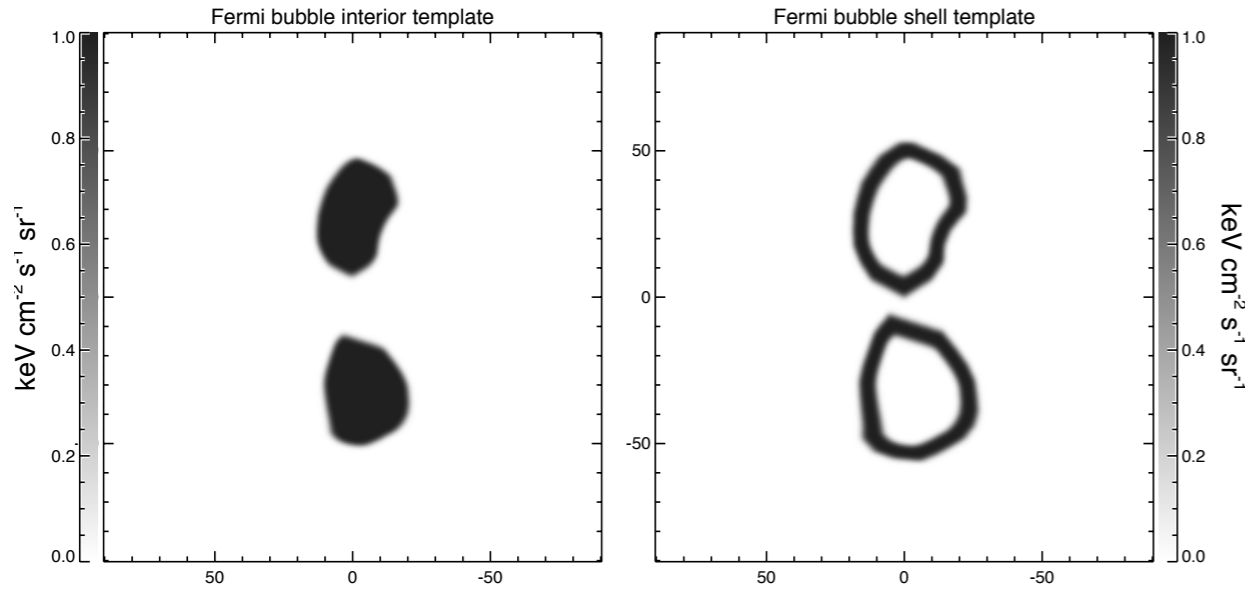
Thank you!

Extra

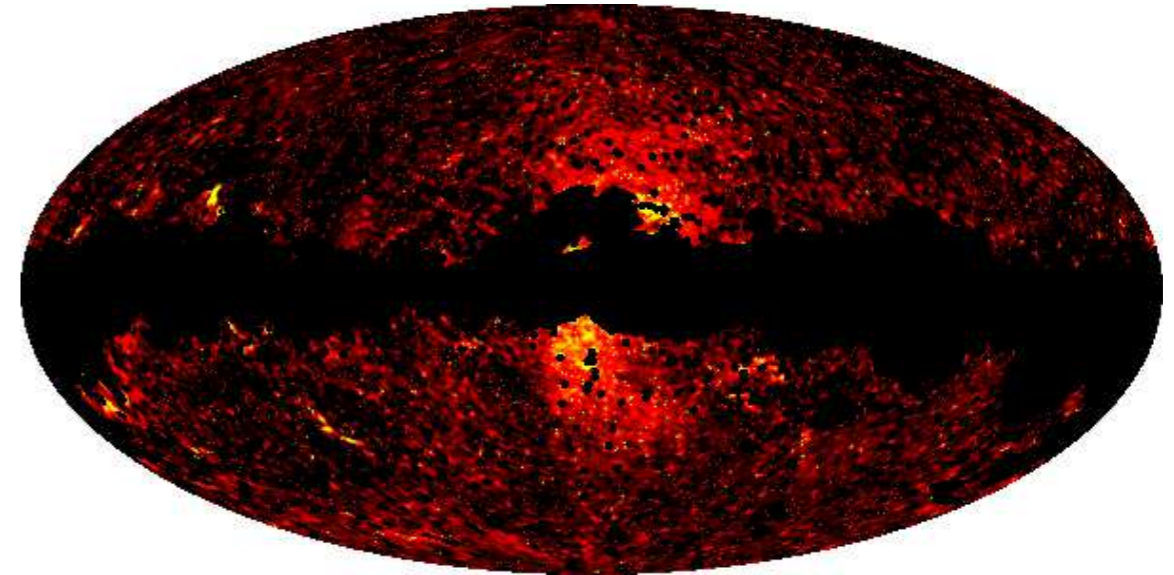
Fermi Bubbles

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

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



Planck



Discovery of **edges** on the emission.

Planck Coll. A&A 2013

Residual intensity, $E = 10 - 500$ GeV

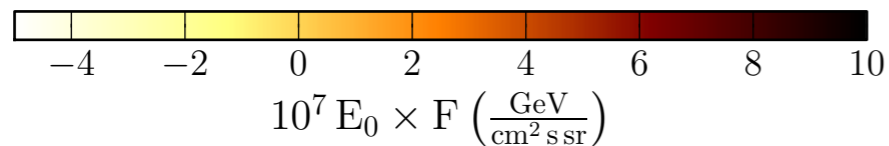
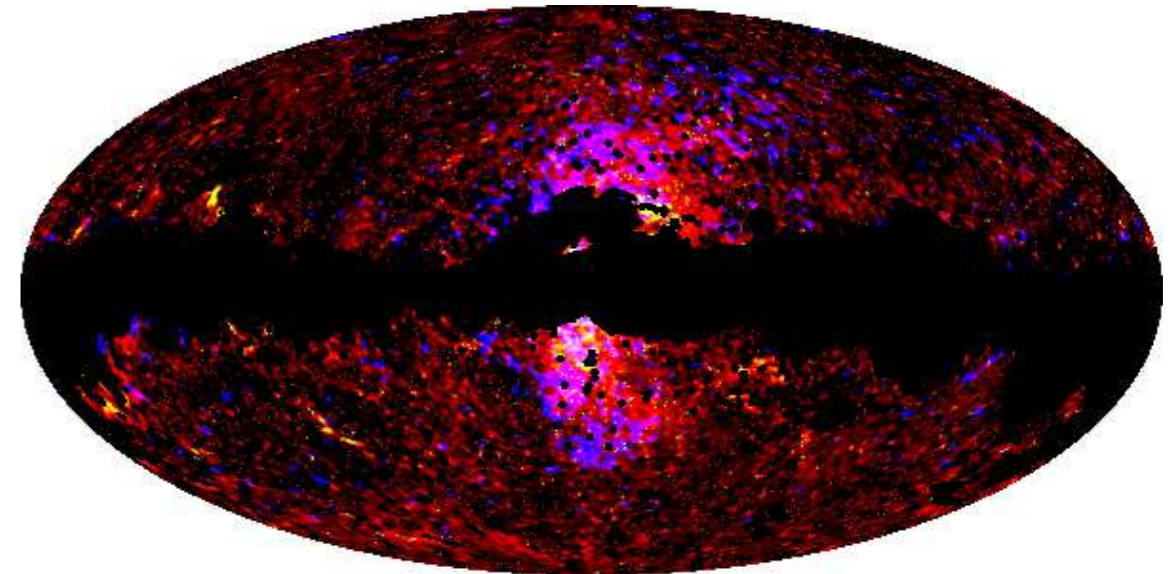
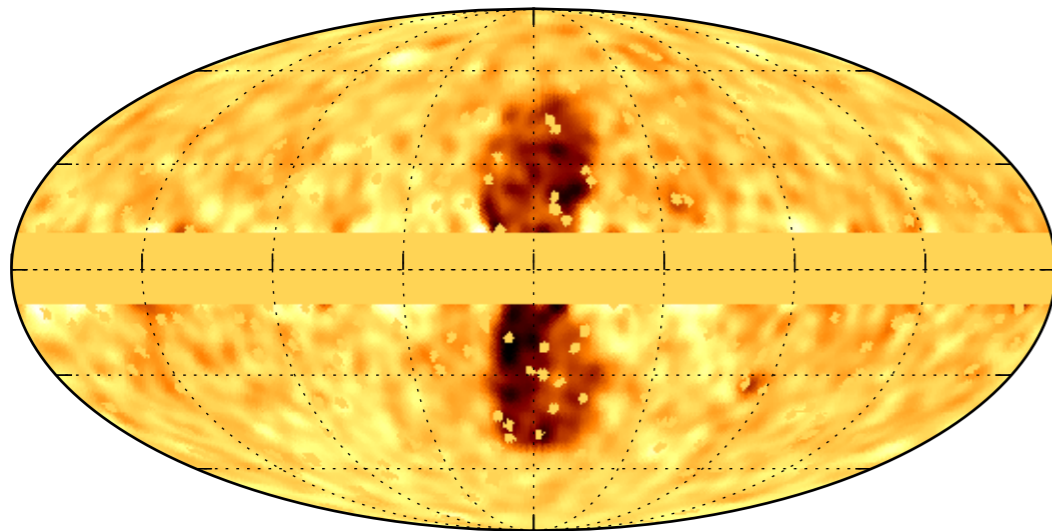
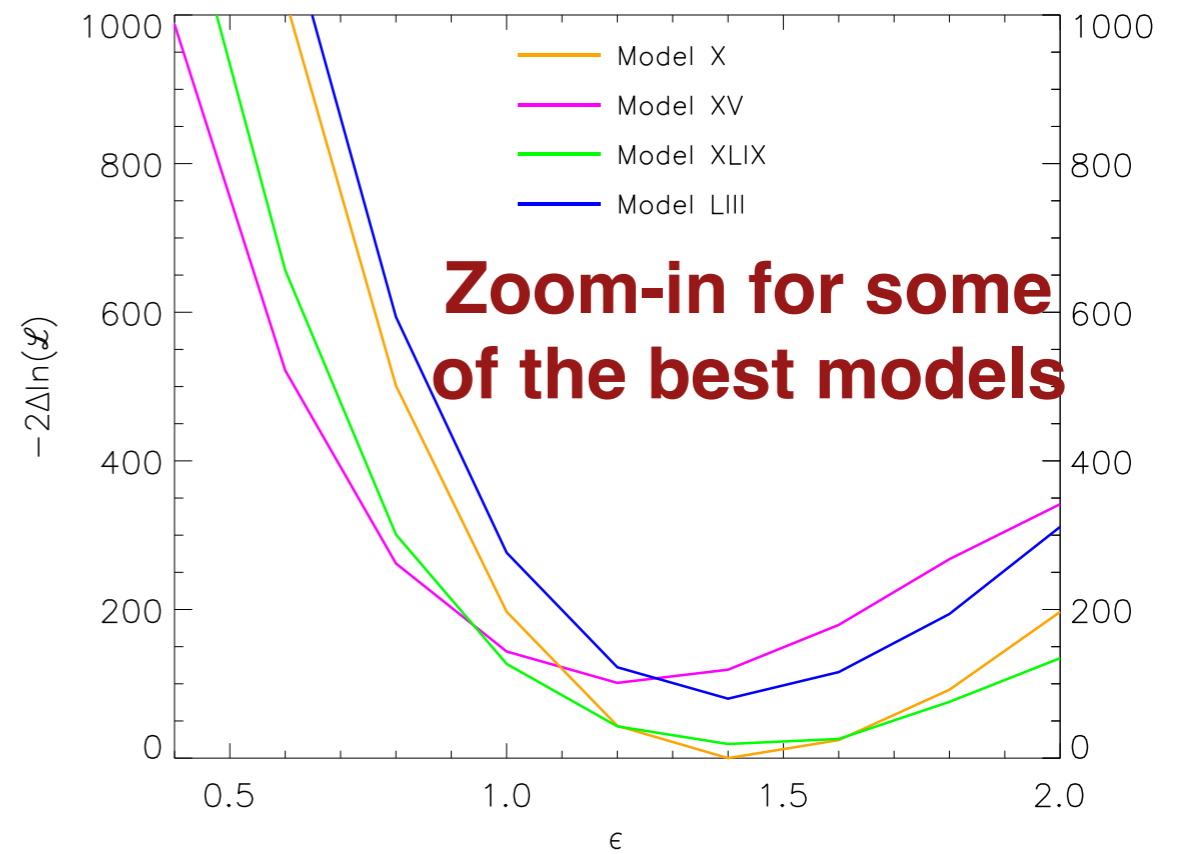
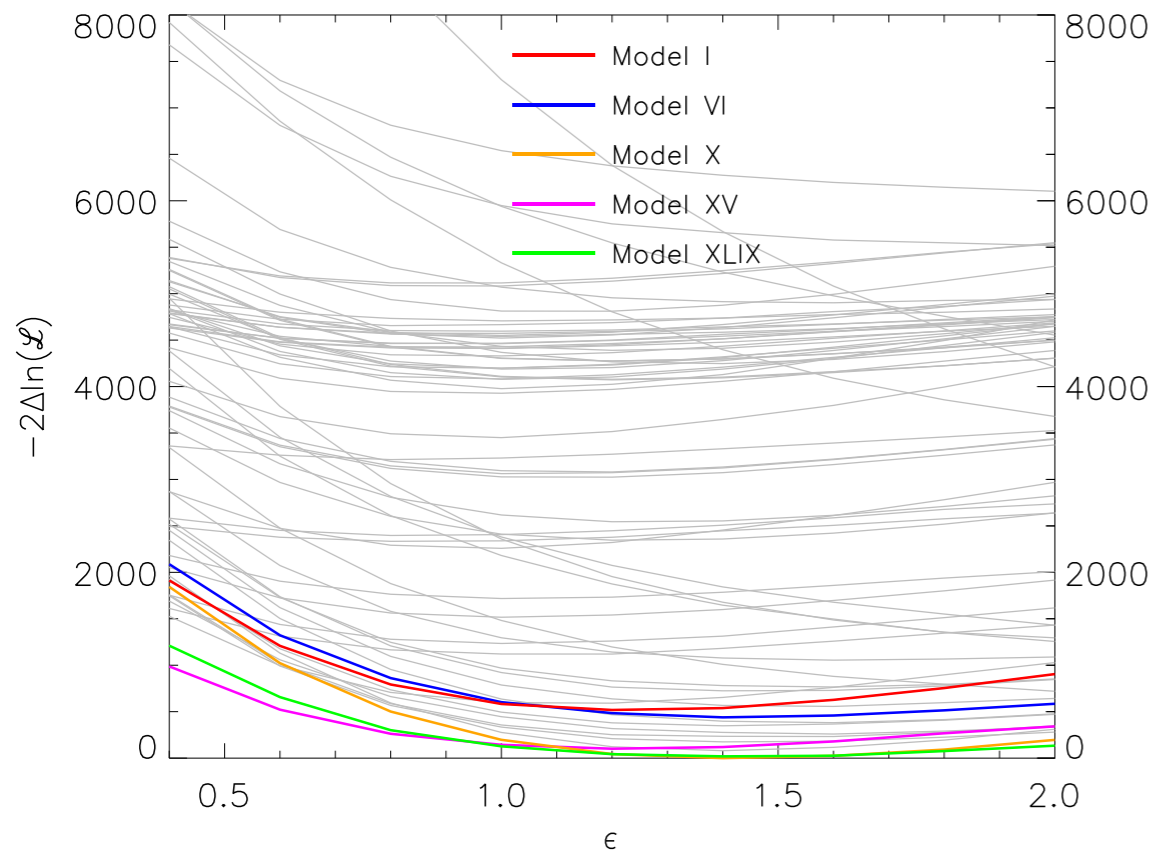
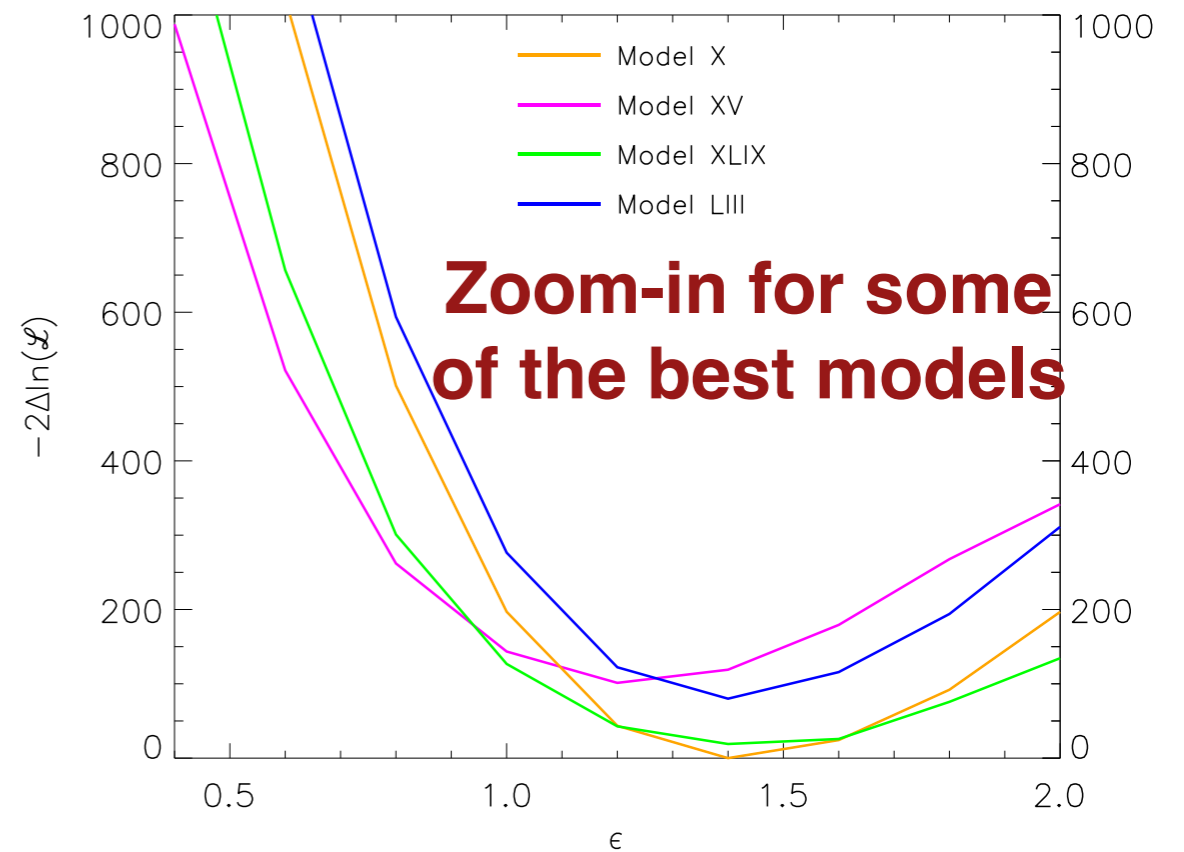
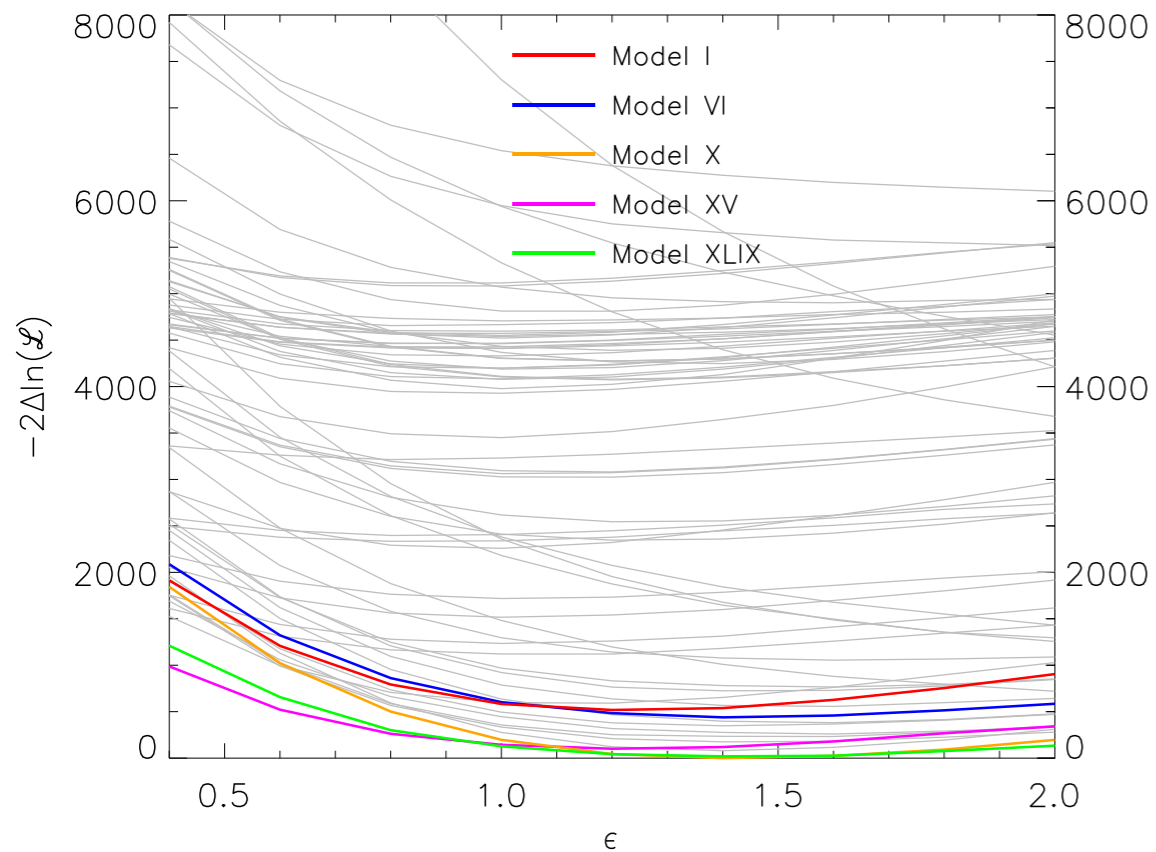


Fig.9. Top: The microwave haze at Planck 30 GHz (red, $-12 \mu\text{K} < \Delta T_{\text{CMB}} < 30 \mu\text{K}$) and 44 GHz (yellow, $12 \mu\text{K} < \Delta T_{\text{CMB}} < 40 \mu\text{K}$). Bottom: The same but including the Fermi 2-5 GeV haze/bubbles of [Dobler et al. \(2010\)](#) (blue, $1.05 < \text{intensity} [\text{keV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] < 1.25$; 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.

Fermi-LAT Collaboration
Result ApJ 2014

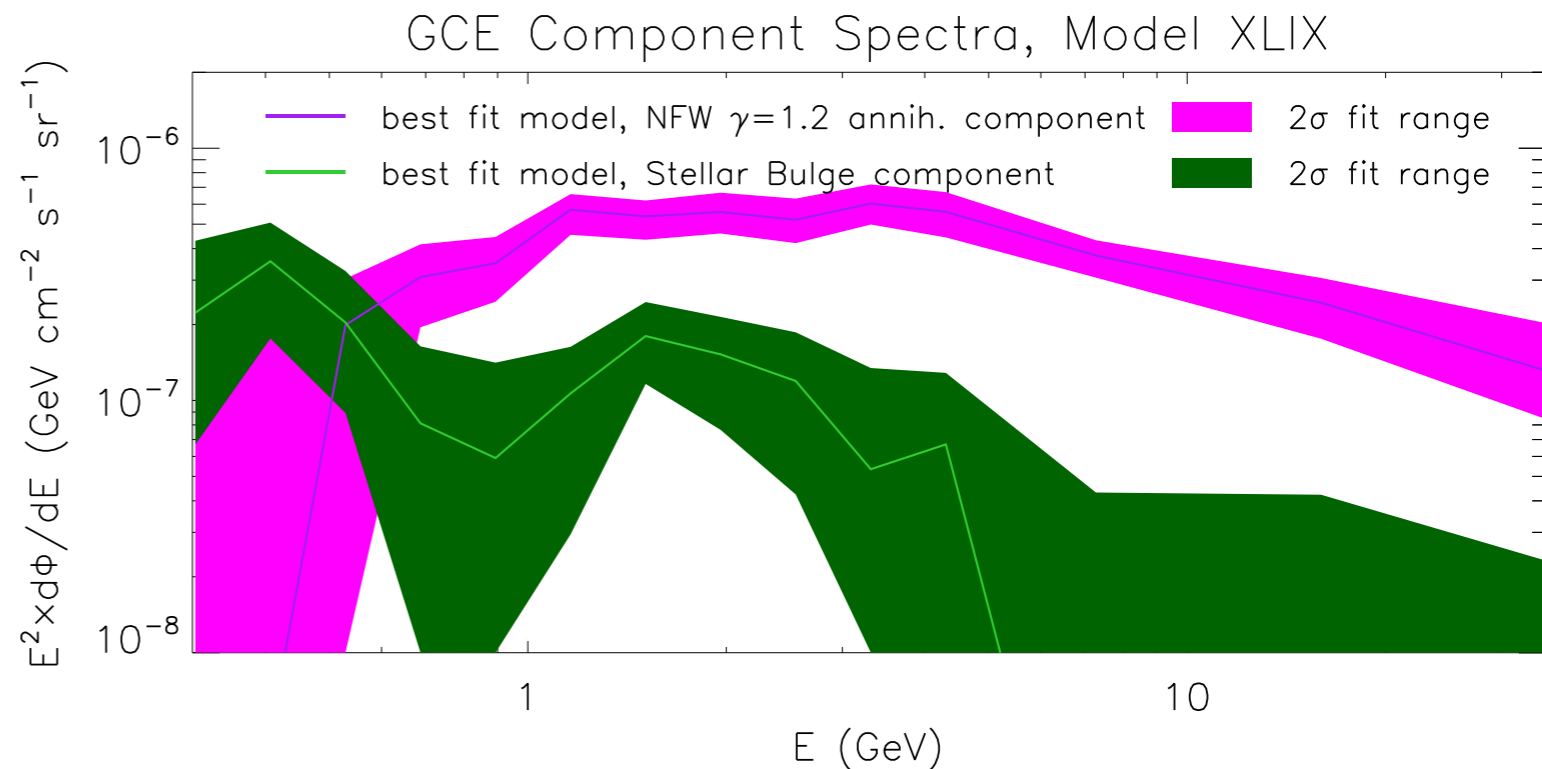
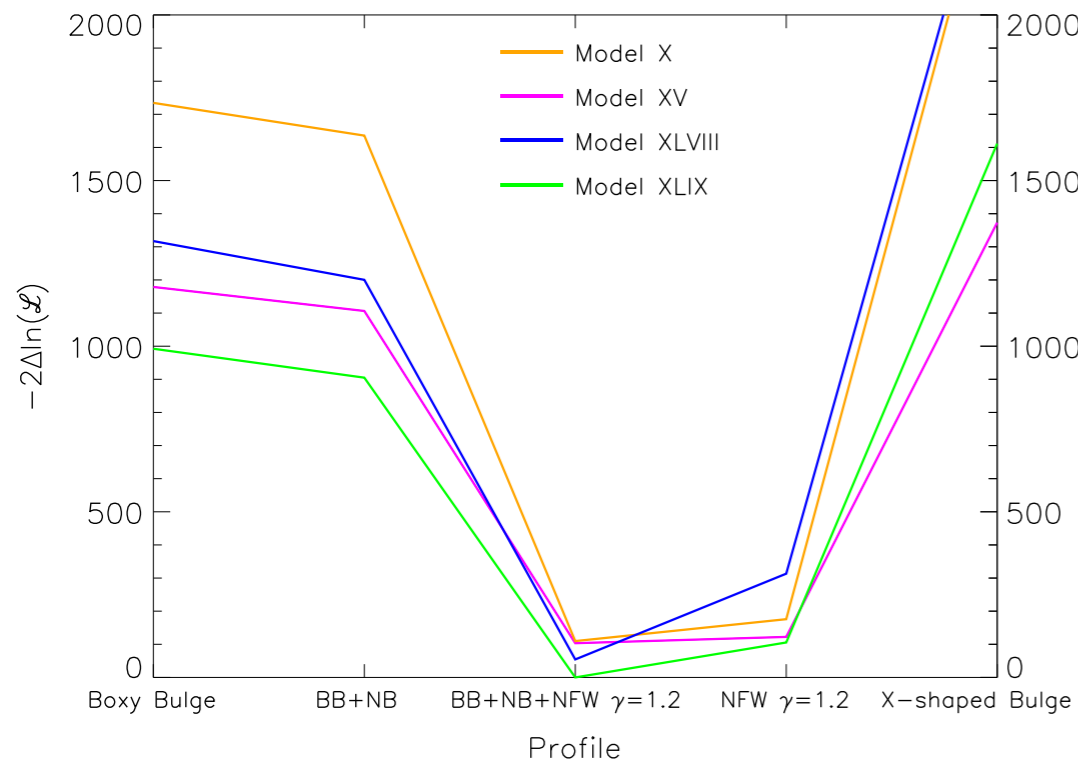


Results do not change substantively between 4FGL, 4FGL-DR2 (and also 4FGL-DR3) point source catalogues



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

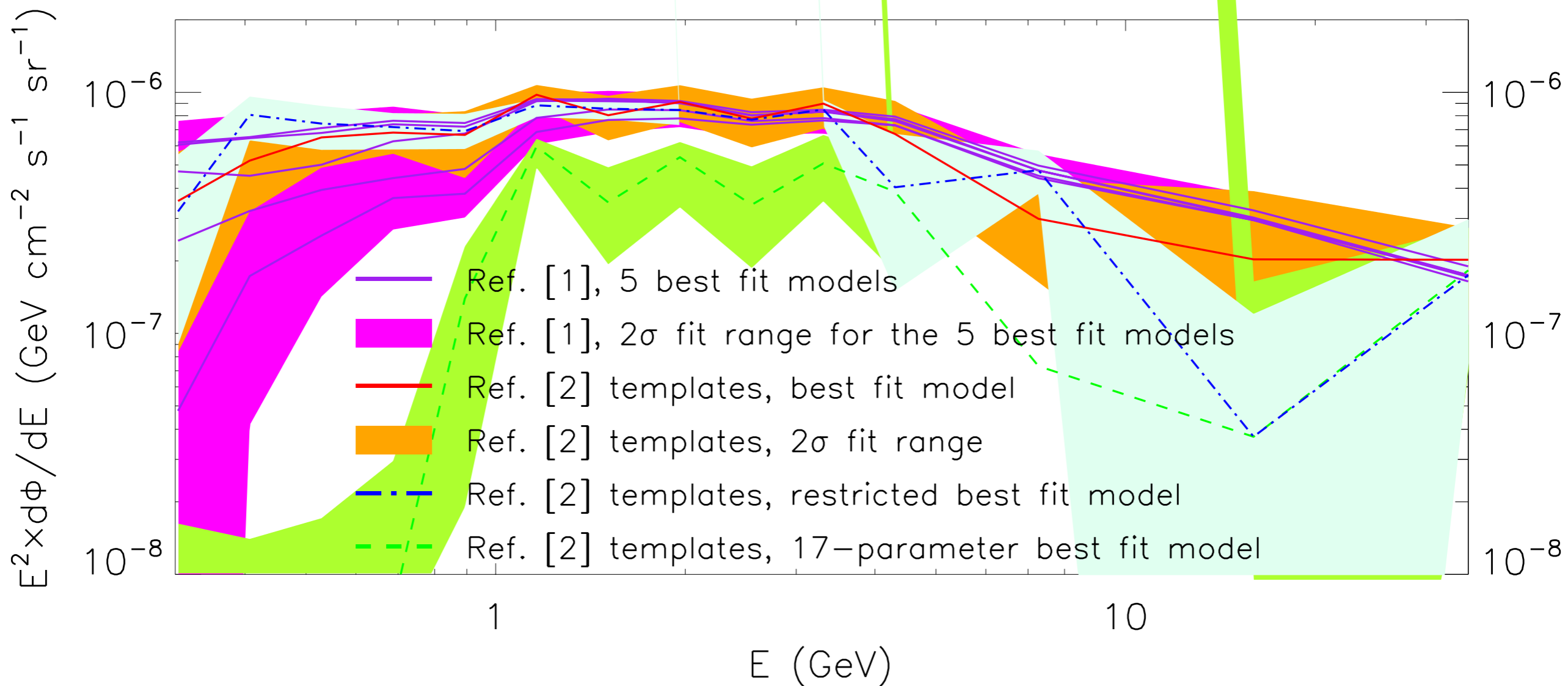
Even when we allow for an additional **stellar bulge component** (probing MSPs) component, we still get **preference for a dominant cuspy NFW-like profile**



Ongoing Preliminary:

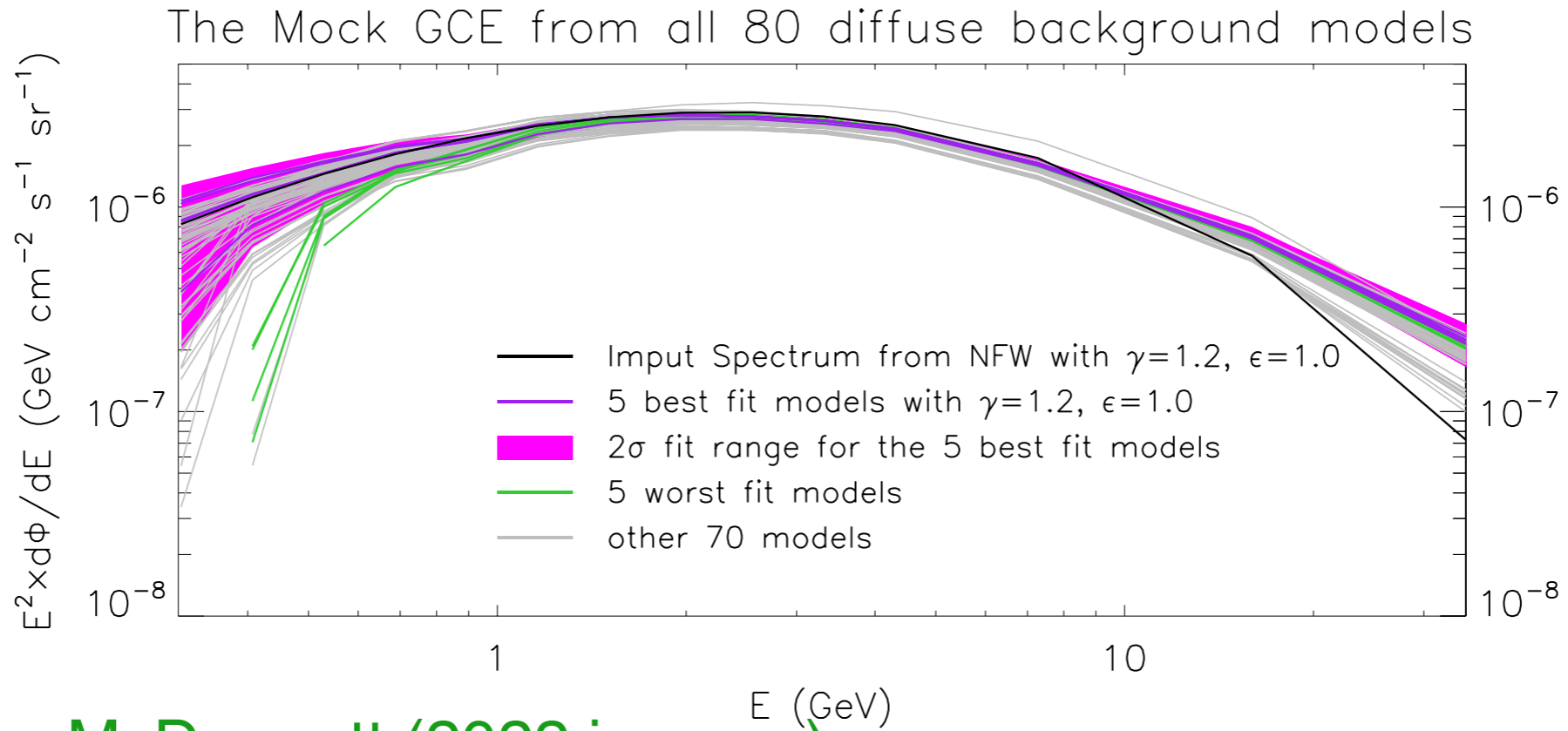
Comparison with Abazajian et al. 2020 results.

We use their templates and still find a NFW-like GCE **irrespective** of the fitting method.

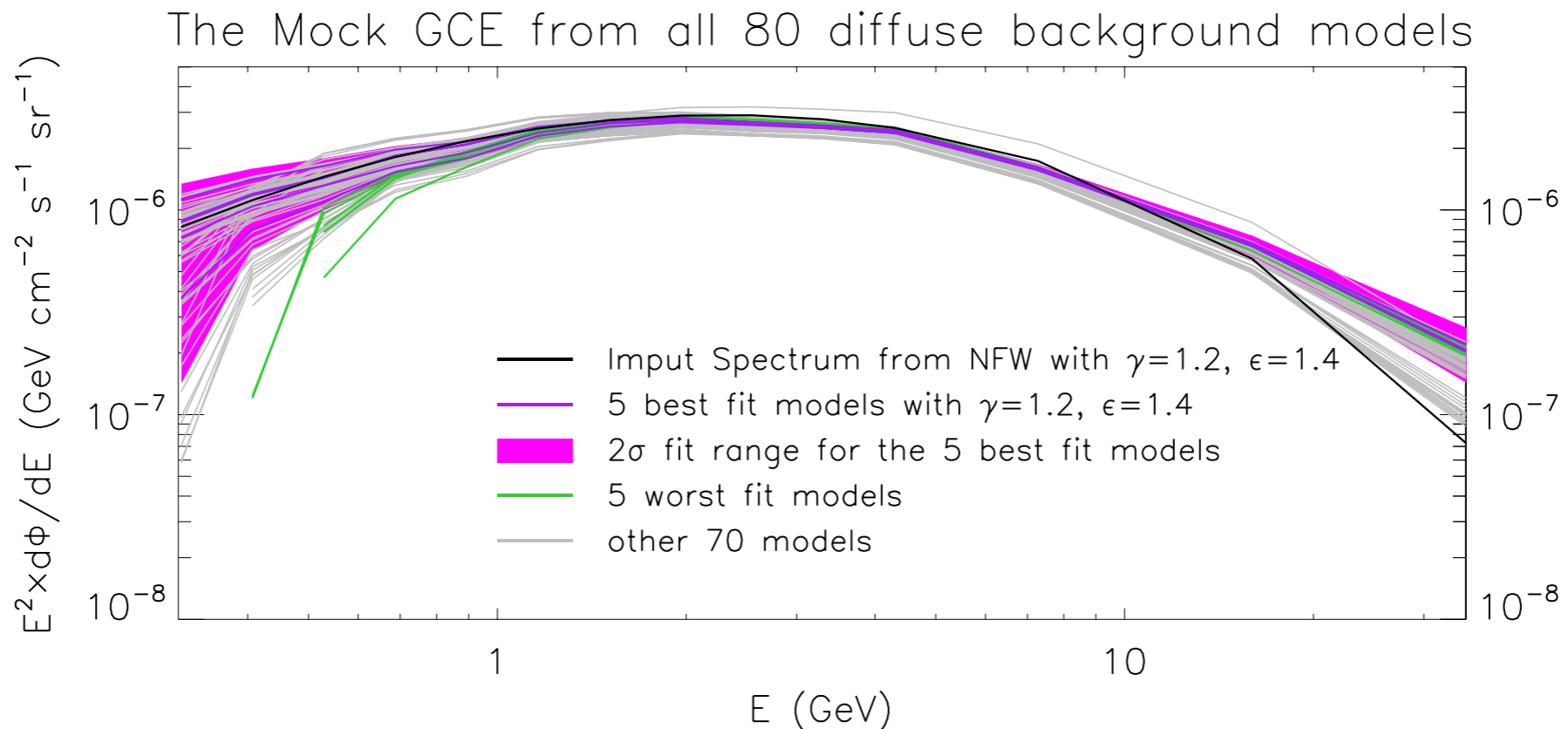


Ongoing Preliminary:

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

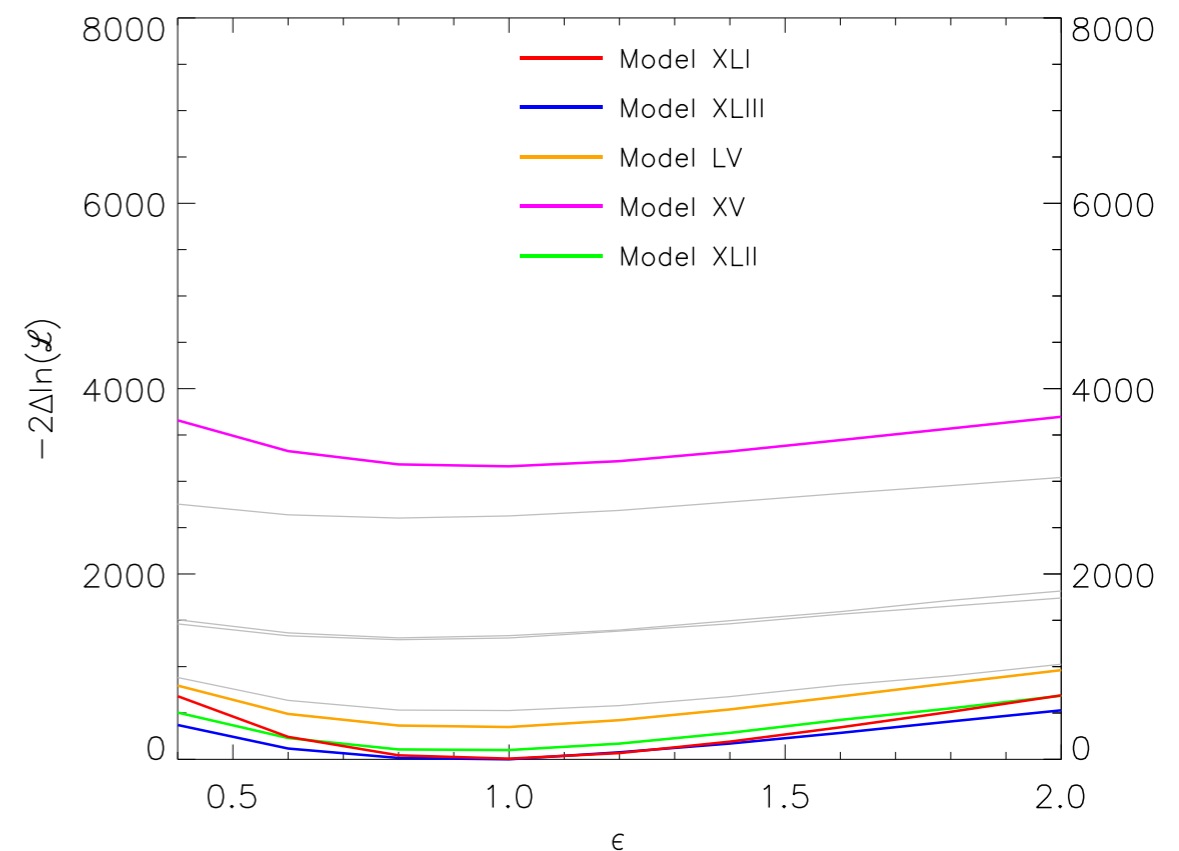
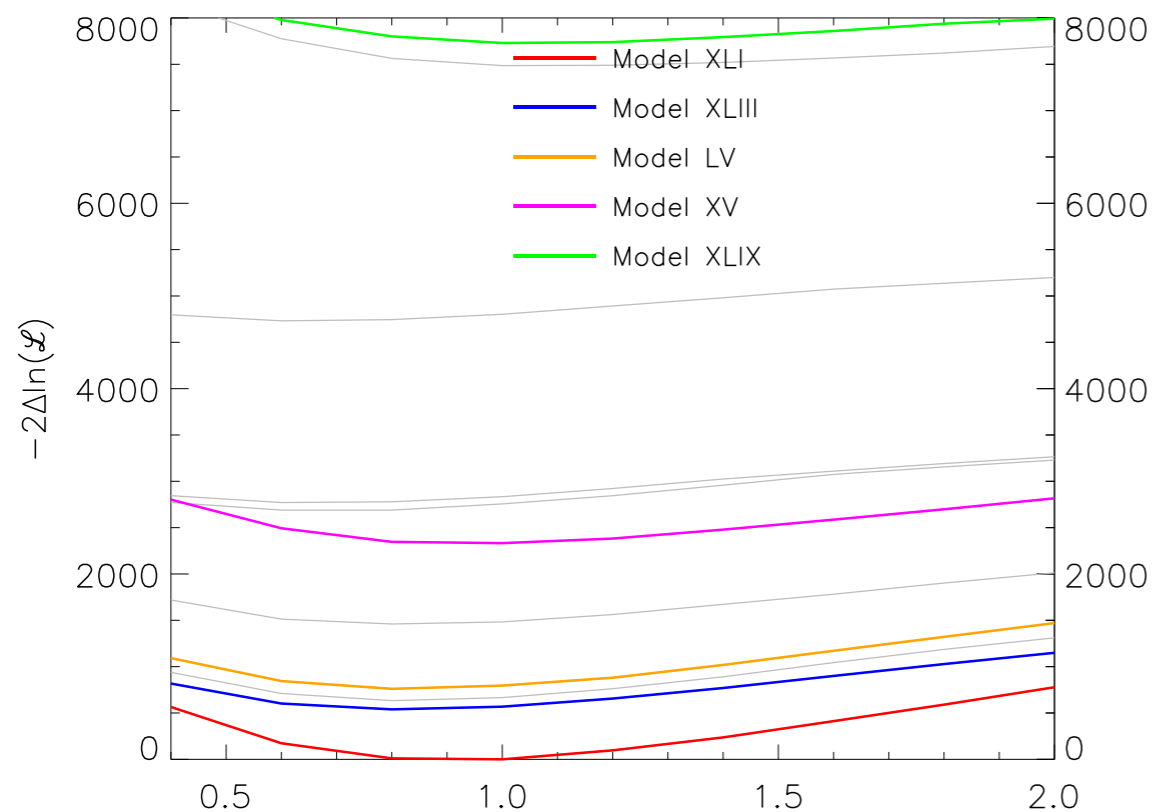


Zhong, Cholis, McDermott (2022 in prep.)

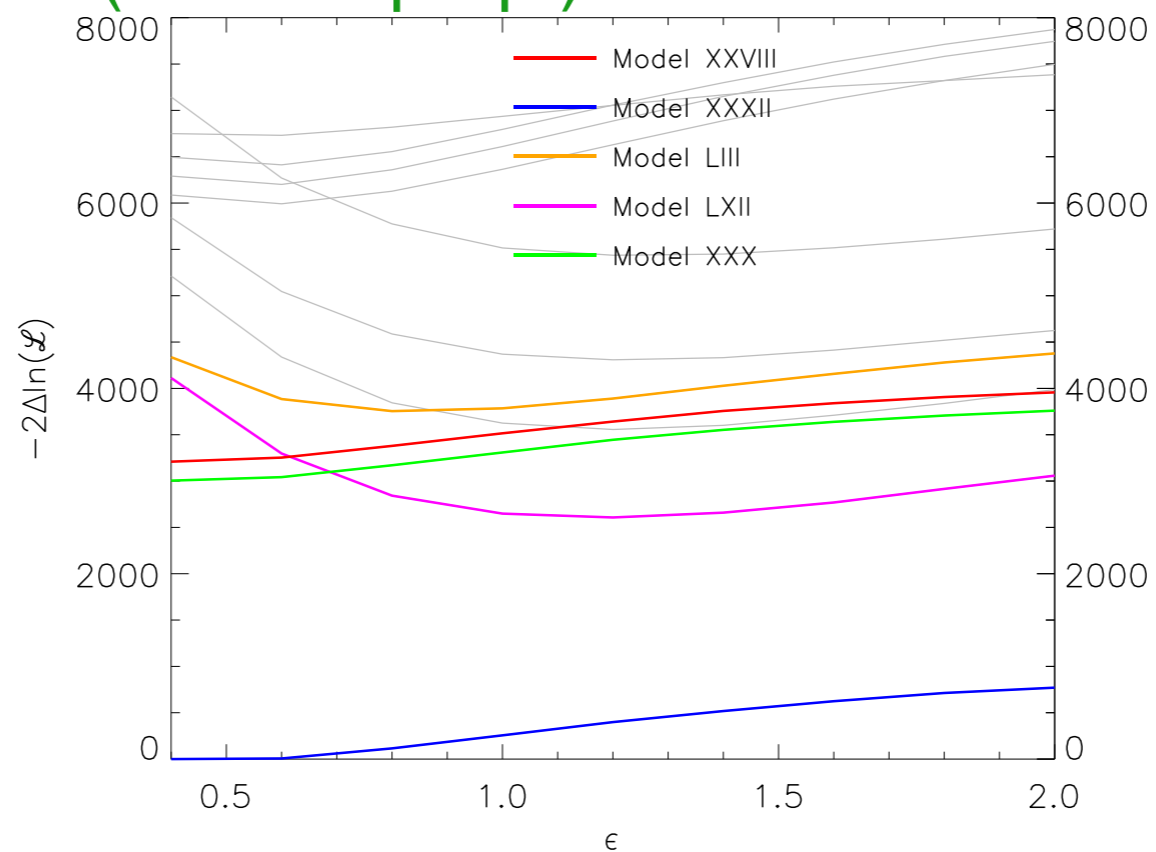


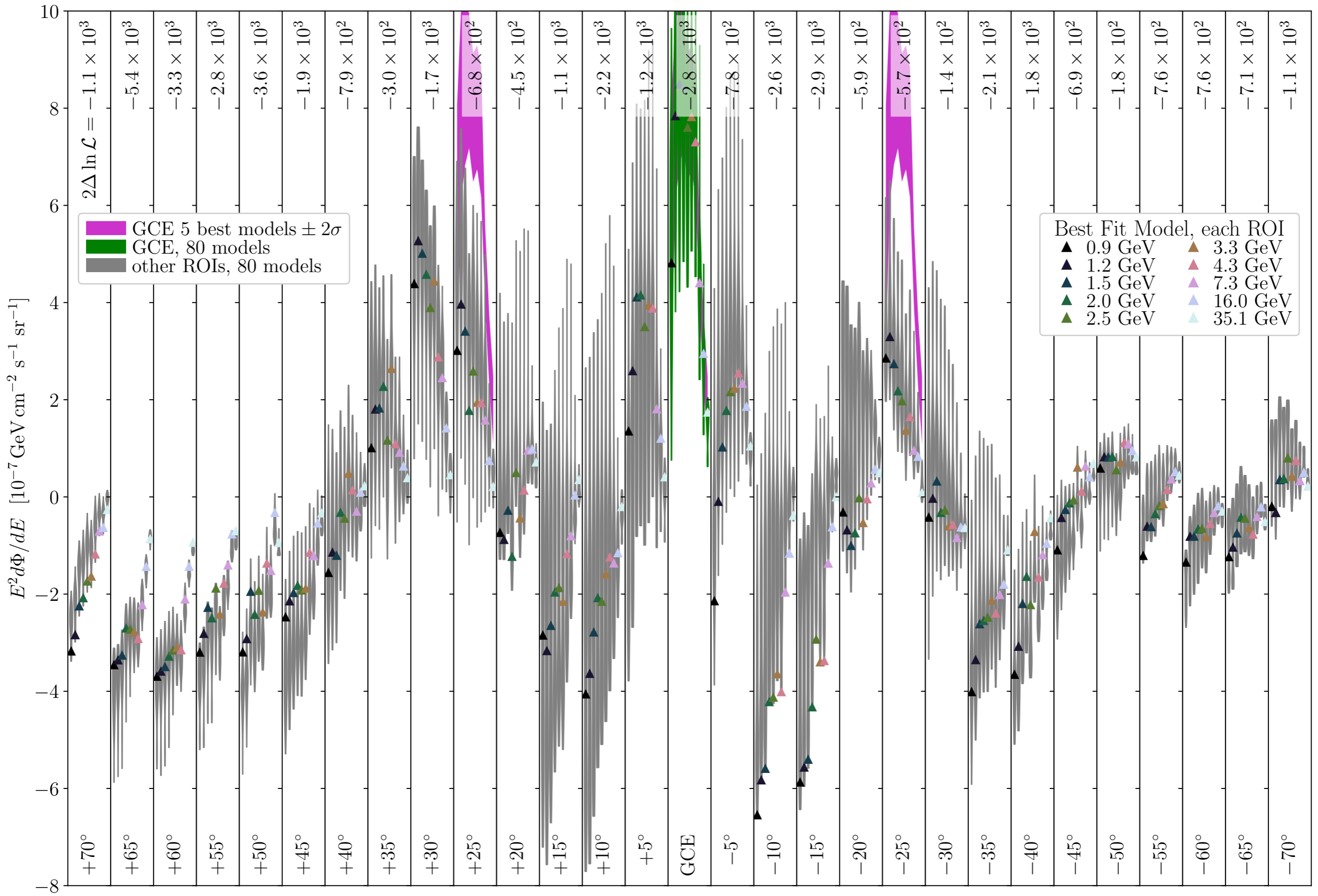
Ongoing Preliminary:

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

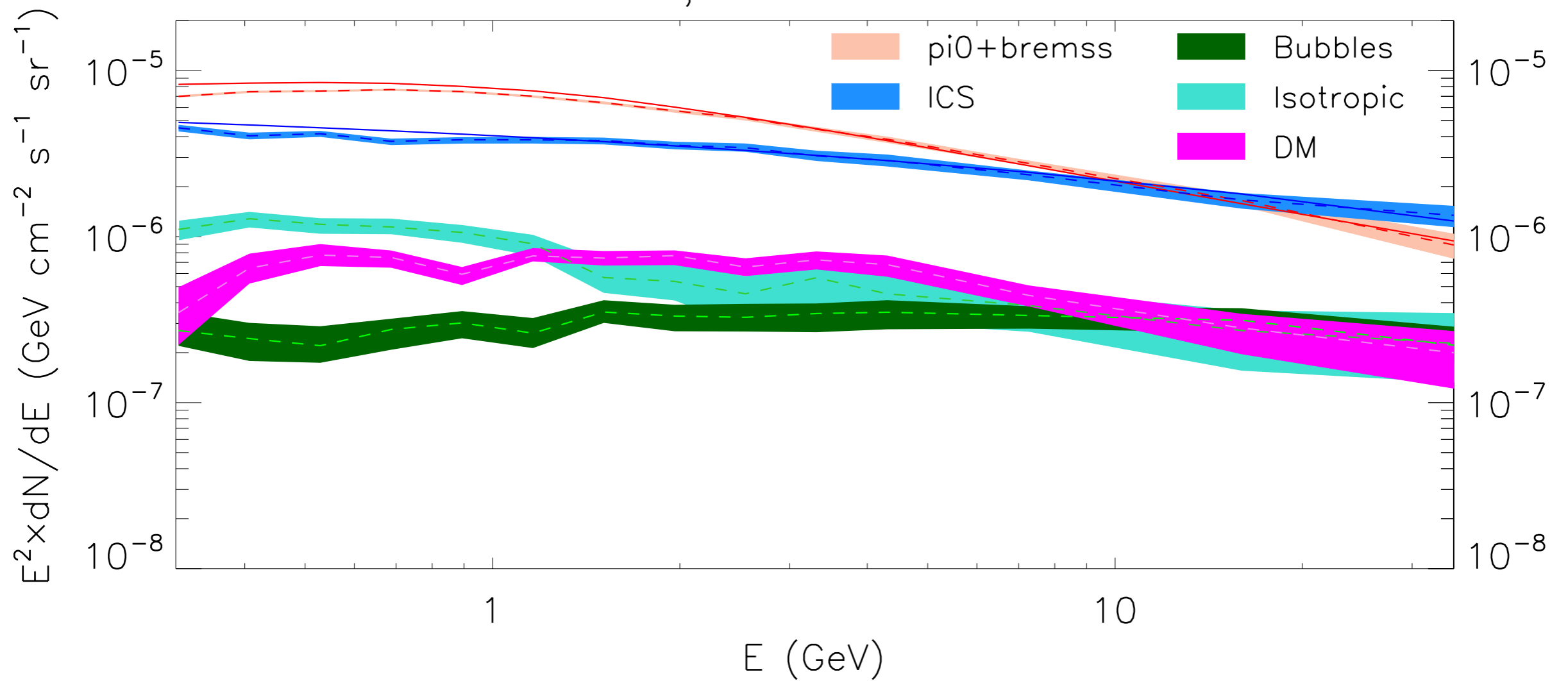


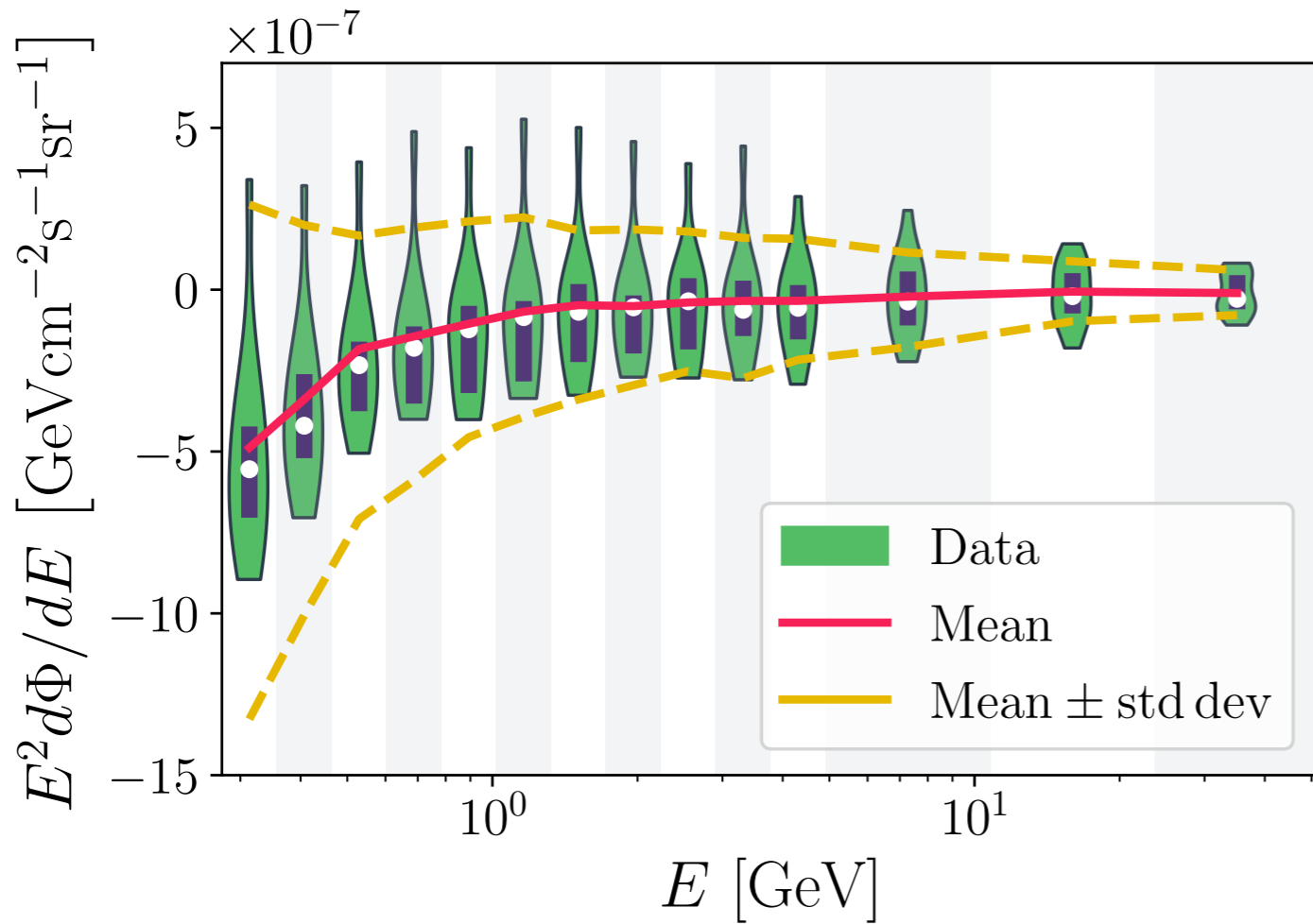
Zhong, Cholis, McDermott (2022 in prep.)





Model bs, NFW & 4FGL Mask





The covariance matrix:

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

Its truncated version:

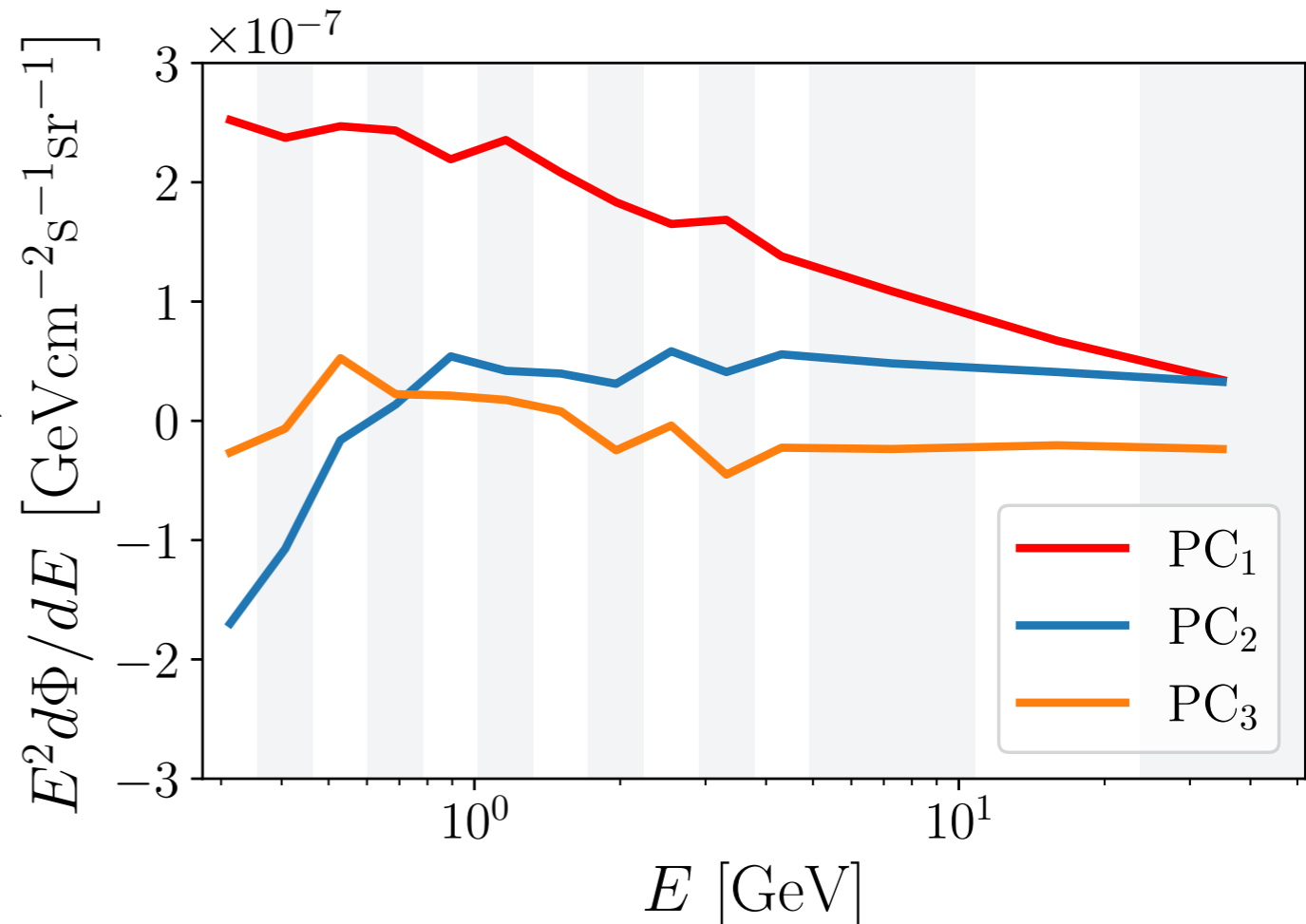
$$\Sigma_{jk,\text{mod}} \simeq \Sigma_{jk,\text{mod}}^{\text{trunc}} \equiv \sum_{i=1}^3 \text{PC}_{ij}^T \text{PC}_{ik}$$

The formal fit:

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

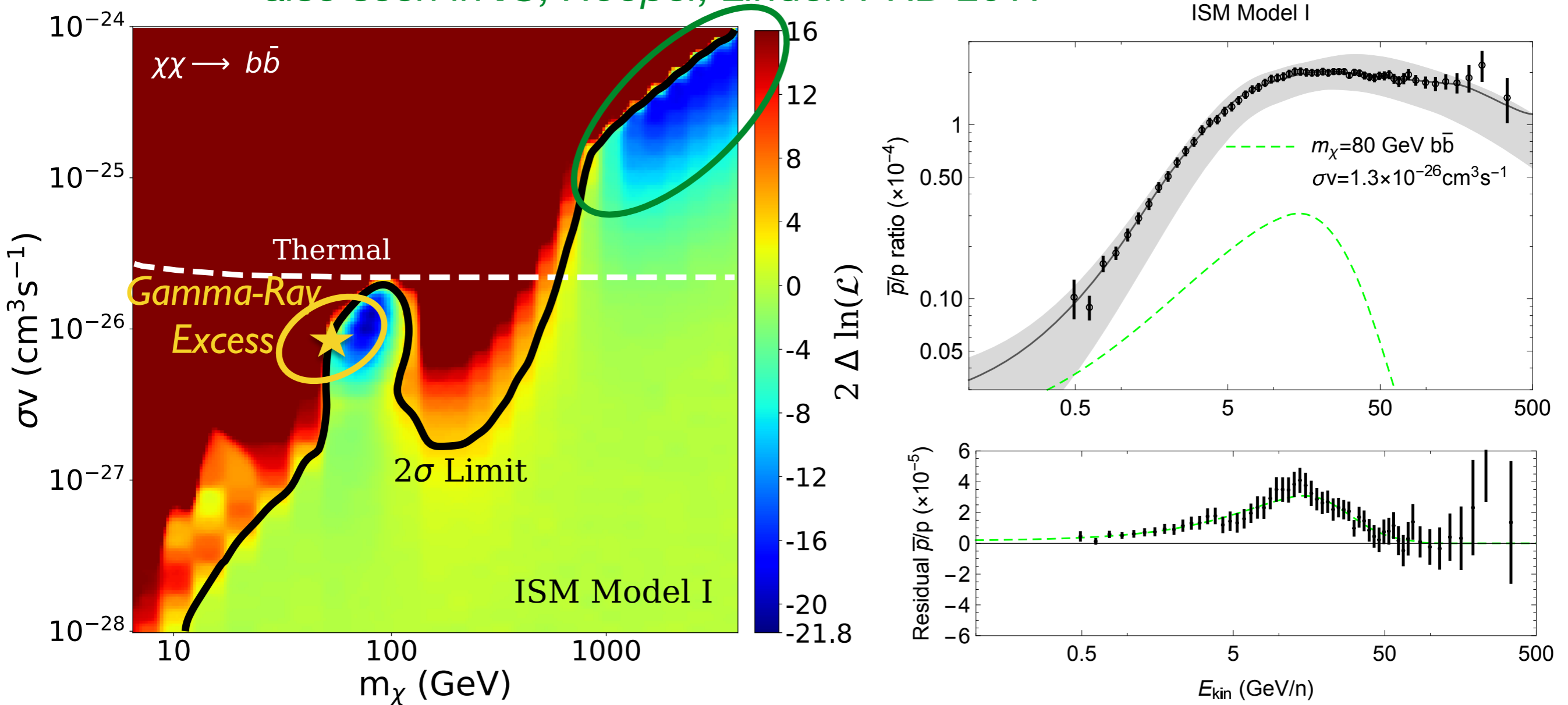
Where:

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



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

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



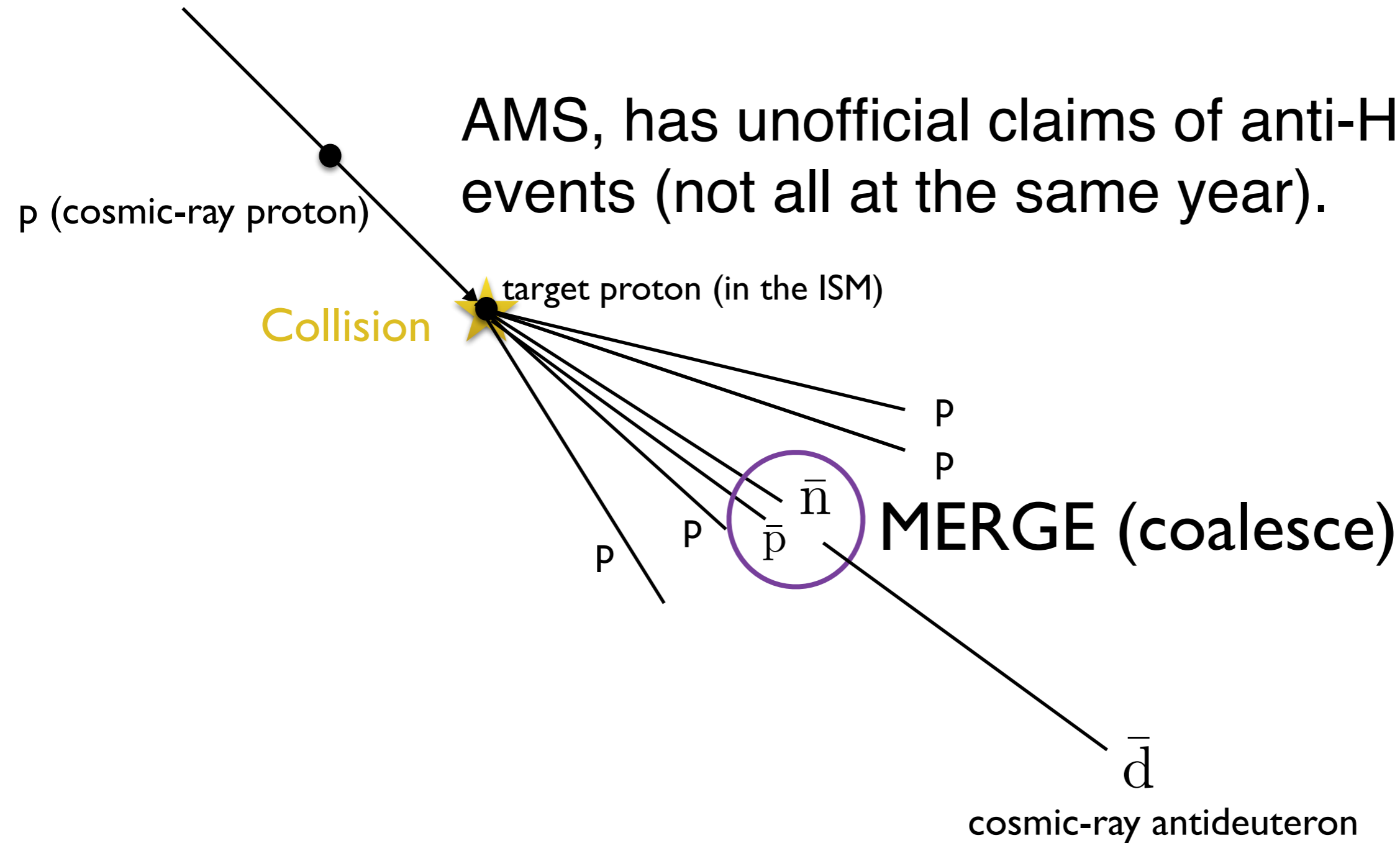
IC, Tim Linden, Dan Hooper PRD 2019

See also A. Cuoco et al. PRD 2019

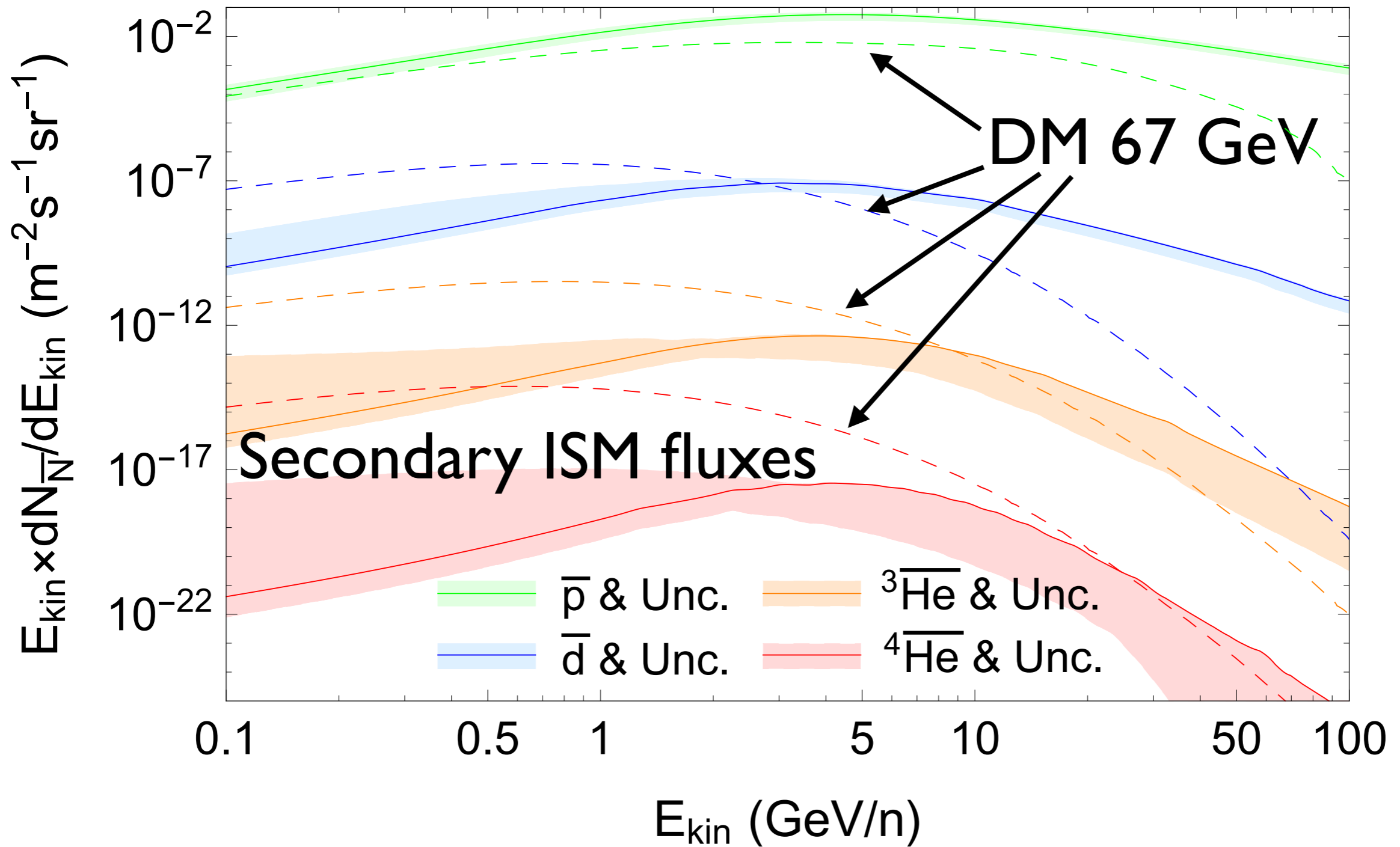
Earlier results: Cuoco et al. PLR 2017, Cui et al. PRL 2017

How about heavier nuclei?

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



Antimatter flux Uncertainties



And a little extra positrons....

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

Ilias Cholis^{1*} and Iason Krommydas^{2†}

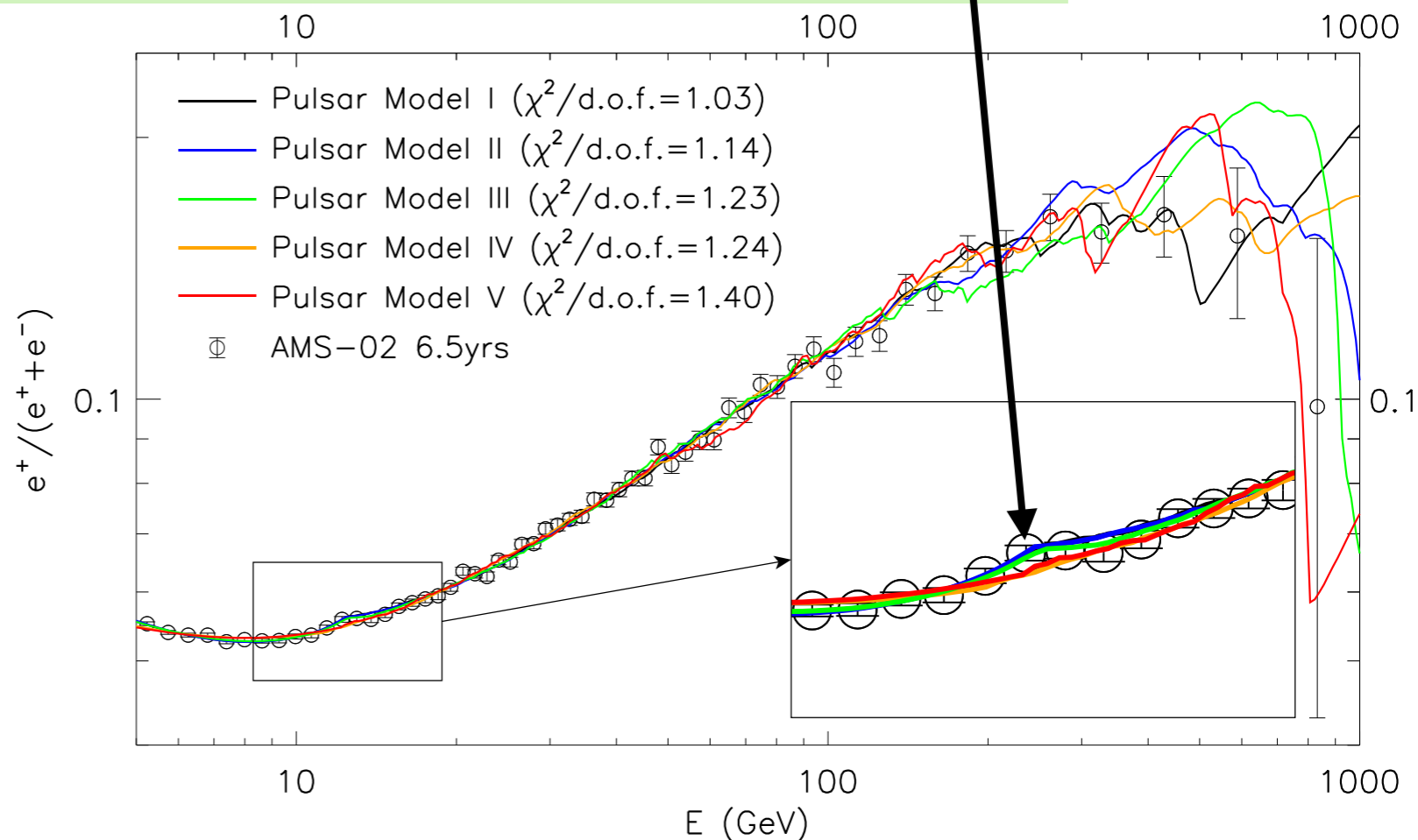
¹*Department of Physics, Oakland University, Rochester, Michigan 48309, USA*

²*Physics Division, National Technical University of Athens, Zografou, Athens 15780, Greece*

 (Received 19 November 2021; accepted 4 January 2022; published 14 January 2022)

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.



The AMS-02 experiment on ISS

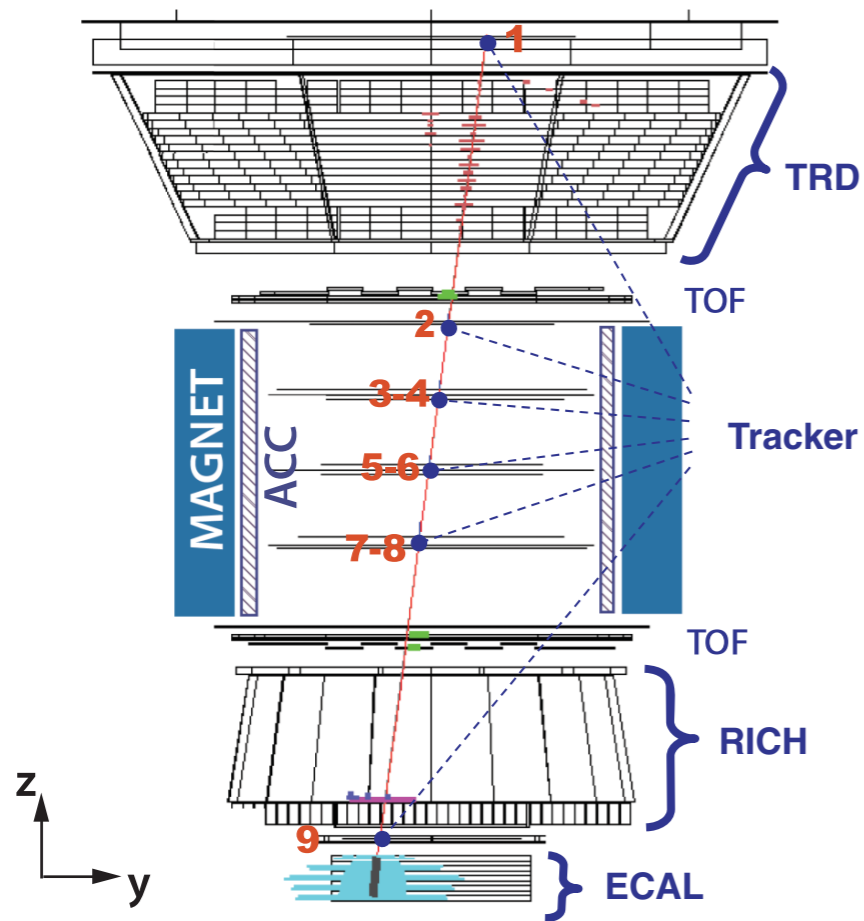
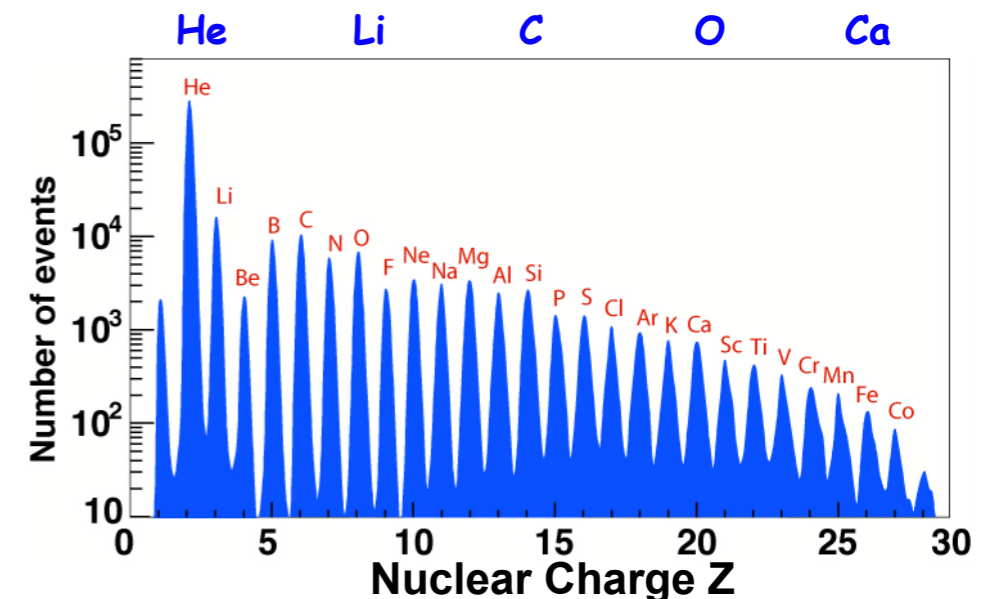
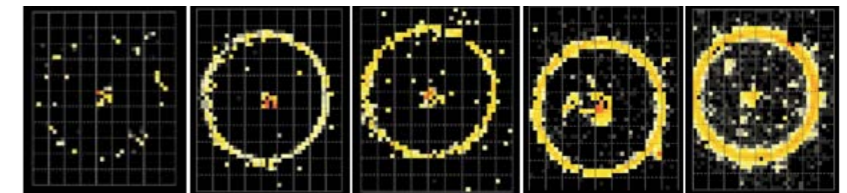


FIG. 1 (color). A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending (y - z) plane. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron. The TOF measures the charge and ensures that the particle is downward-going. The RICH independently measures the charge and velocity. The ECAL measures the 3D shower profile, independently identifies the particle as an electron, and measures its energy. An electron is identified by (i) an electron signal in the TRD, (ii) an electron signal in the ECAL, and (iii) the matching of the ECAL shower energy and the momentum measured with the tracker and magnet.

*Lunched on May 2011, will collect data for 20 yrs.
Measuring all CR nuclei species up to Ni.*

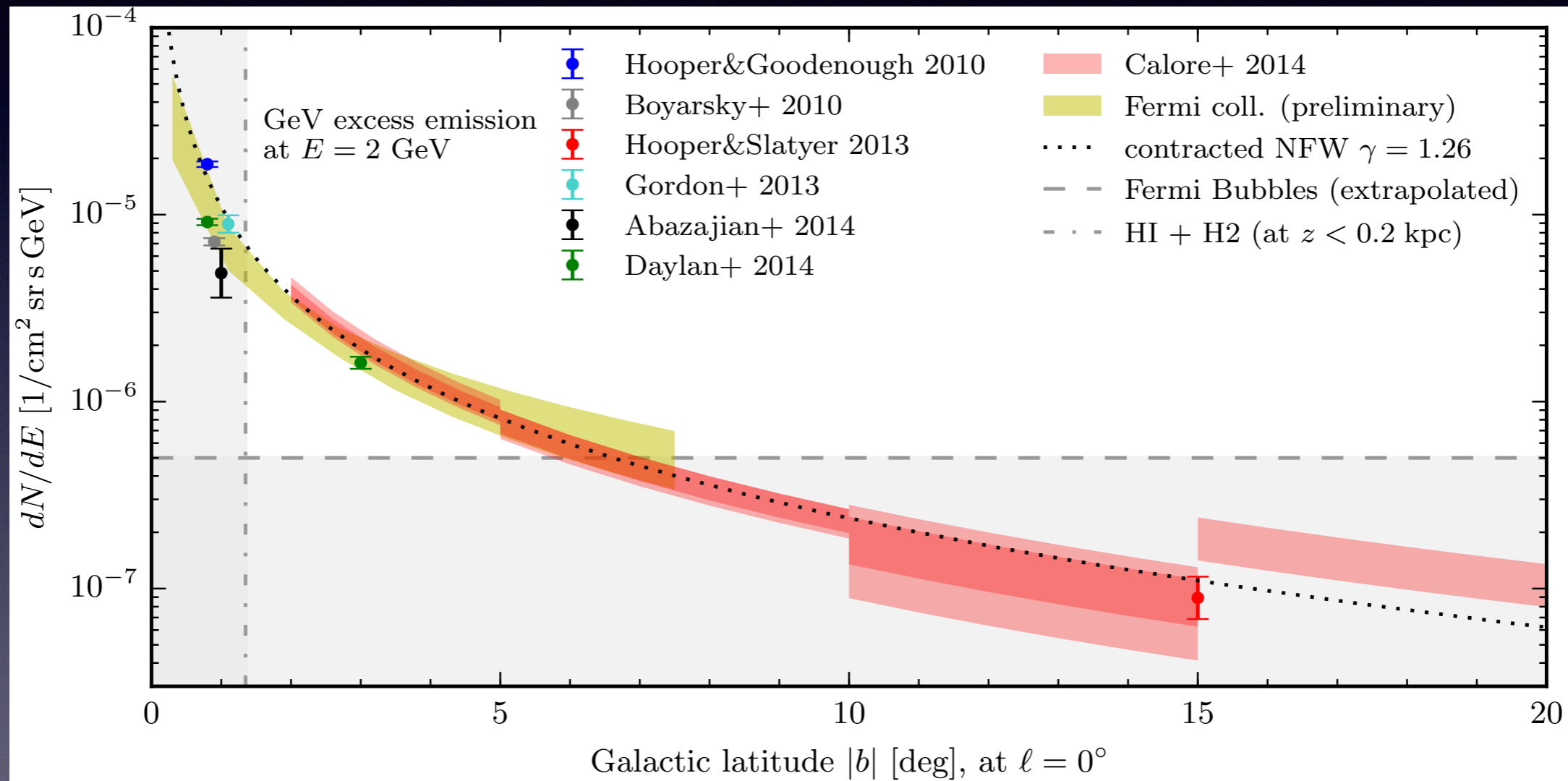
*positron fraction,
positrons, electrons
spectra,
antiproton/proton
anti-nuclei?
B/C, Be10/Be9*



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.