OAKLAND UNIVERSITY

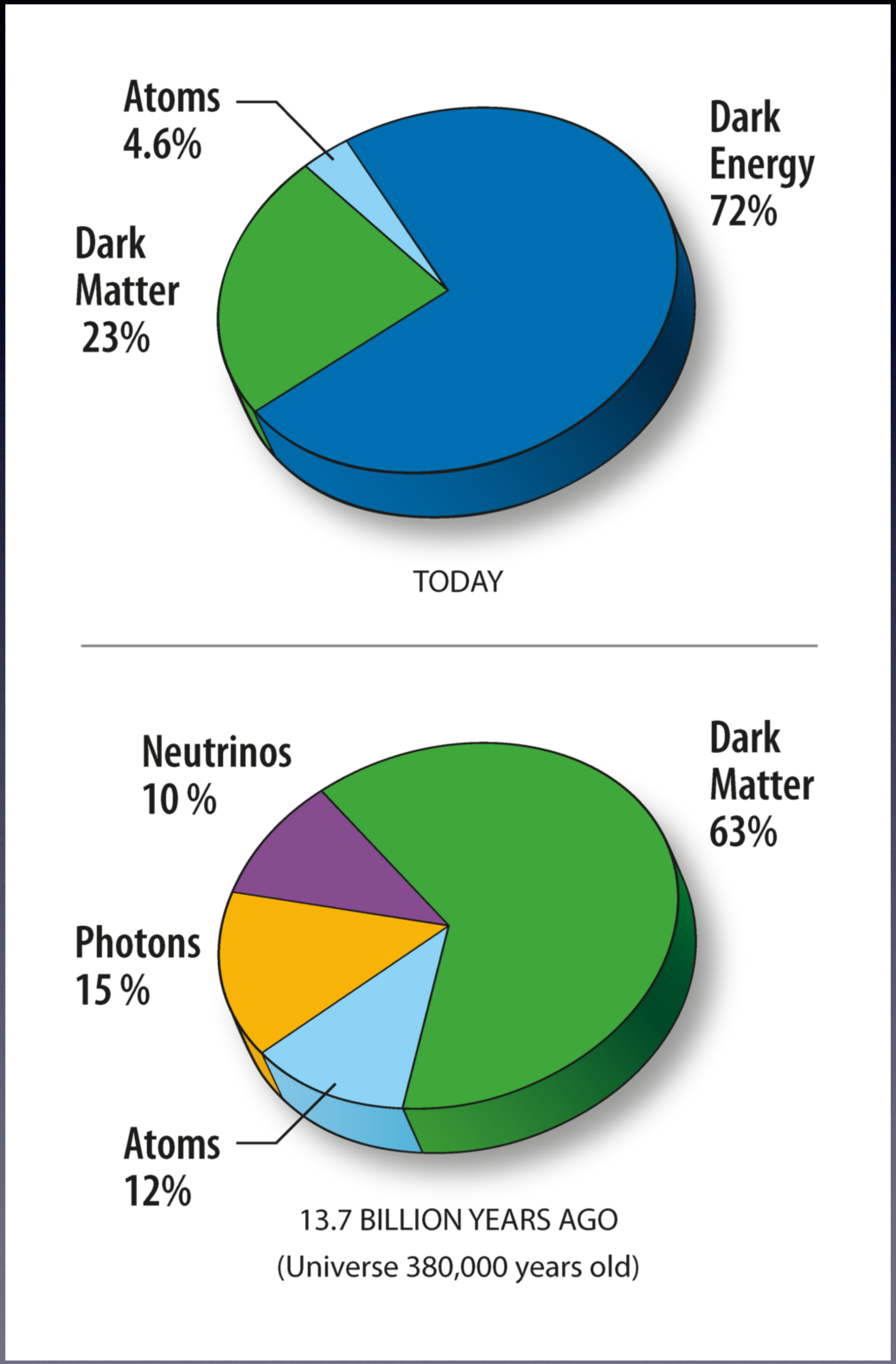
Searching for Dark Matter Signals from the Center of the Milky Way

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)

HEP2022
Ilias Cholis, 16/06/2022

Why Dark Matter?

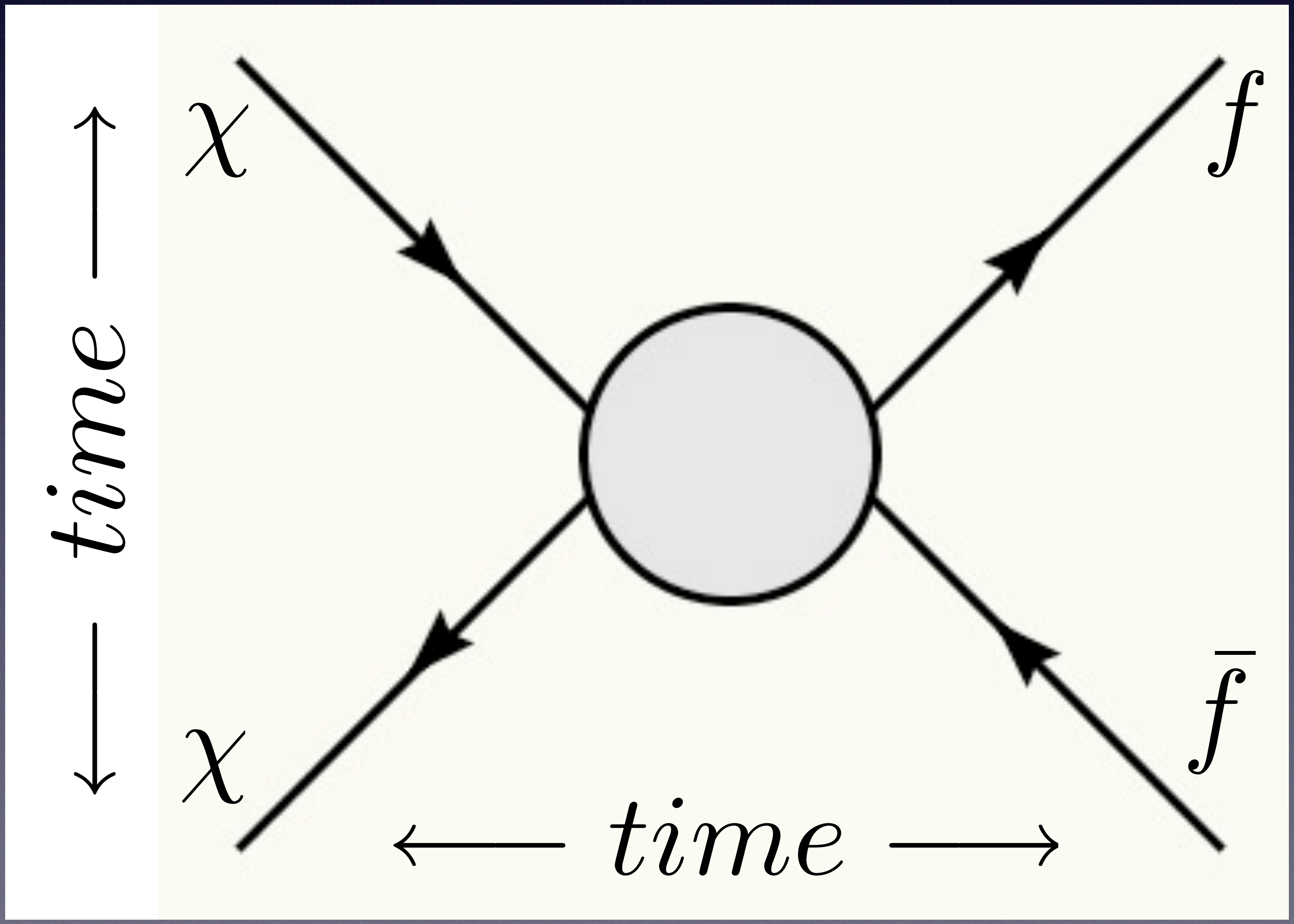
- THERE IS A LOT OF "IT" (now and in the past history of the Universe)
- WE FIND EVIDENCE FOR "IT" IN MANY ASTROPHYSICAL SYSTEMS
- WE DO NOT KNOW WHAT "IT" IS.



The significance of Dark Matter (DM): We are searching for new fundamental physics.

A class of DM models: Weakly Interacting Massive Particles (WIMP)

Searching for Interaction of DM with Known Physics



The challenges of Indirect Searches for WIMPs

The Questions:

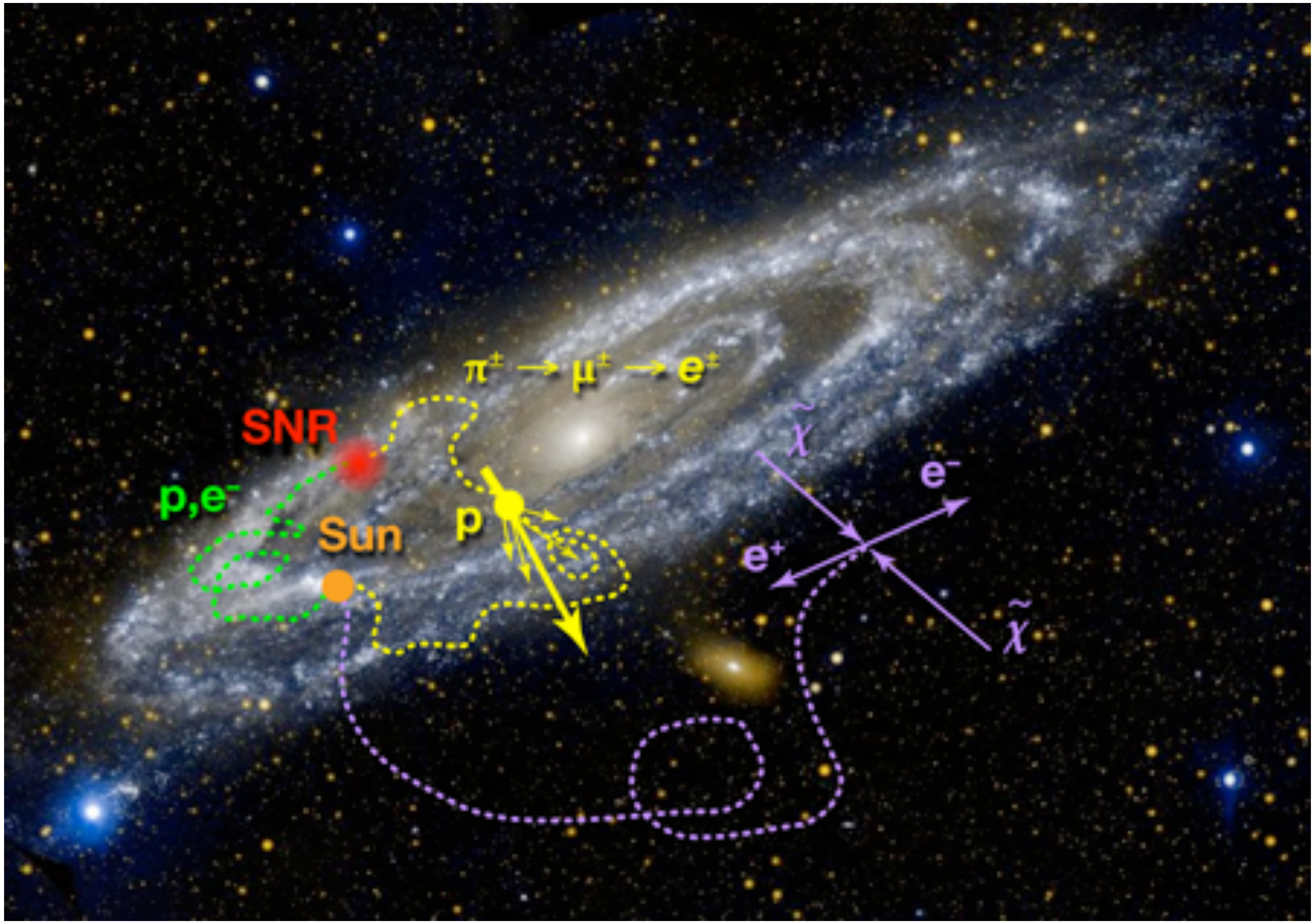
- Are we fully exploring the data? Is there a signal lurking within our observations?

- 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
iii) associations with antimatter cosmic rays

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.

The AMS-02 experiment on ISS

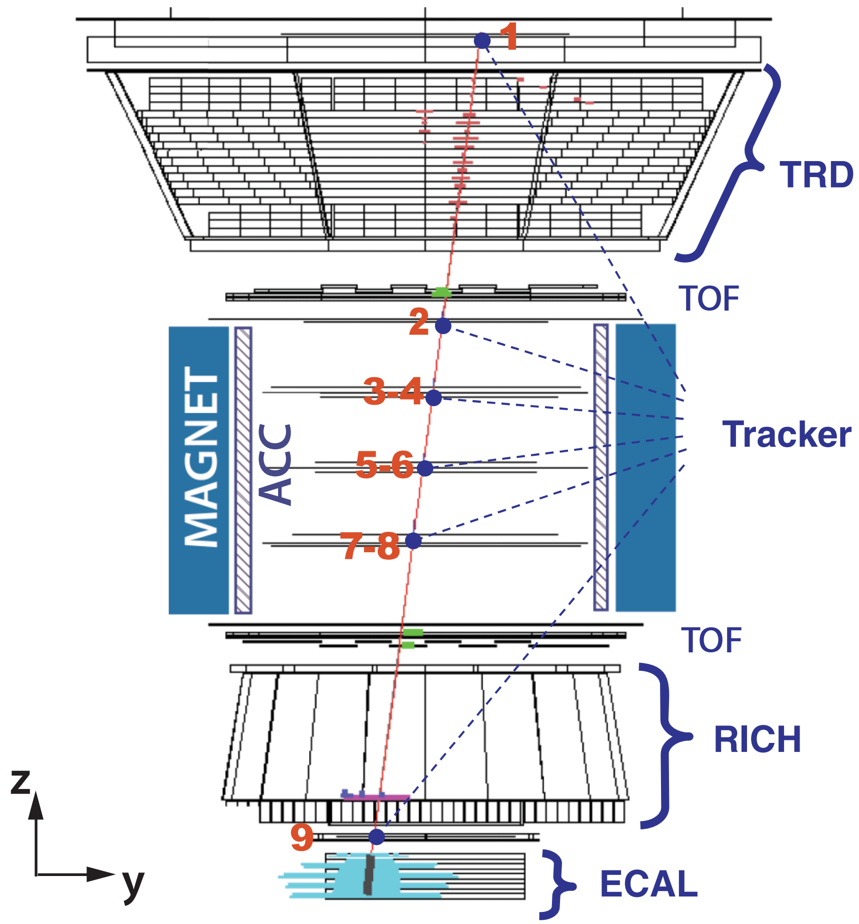
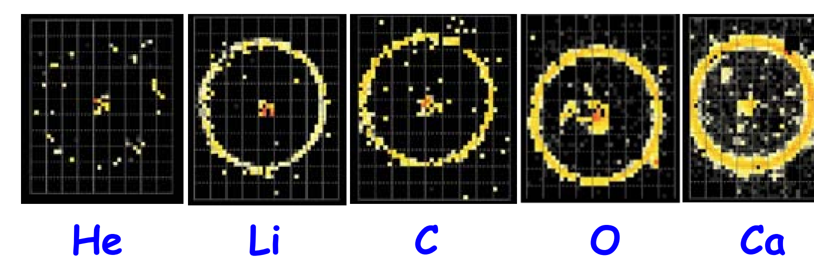
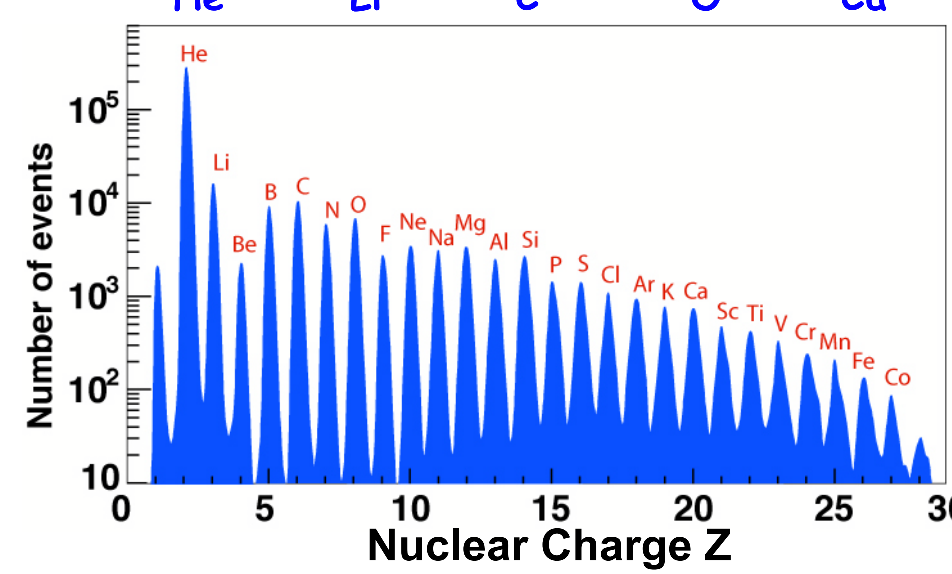


FIG. 1 (color). A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending (*y*-*z*) plane. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron. The TOF measures the charge and ensures that the particle is downward-going. 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





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

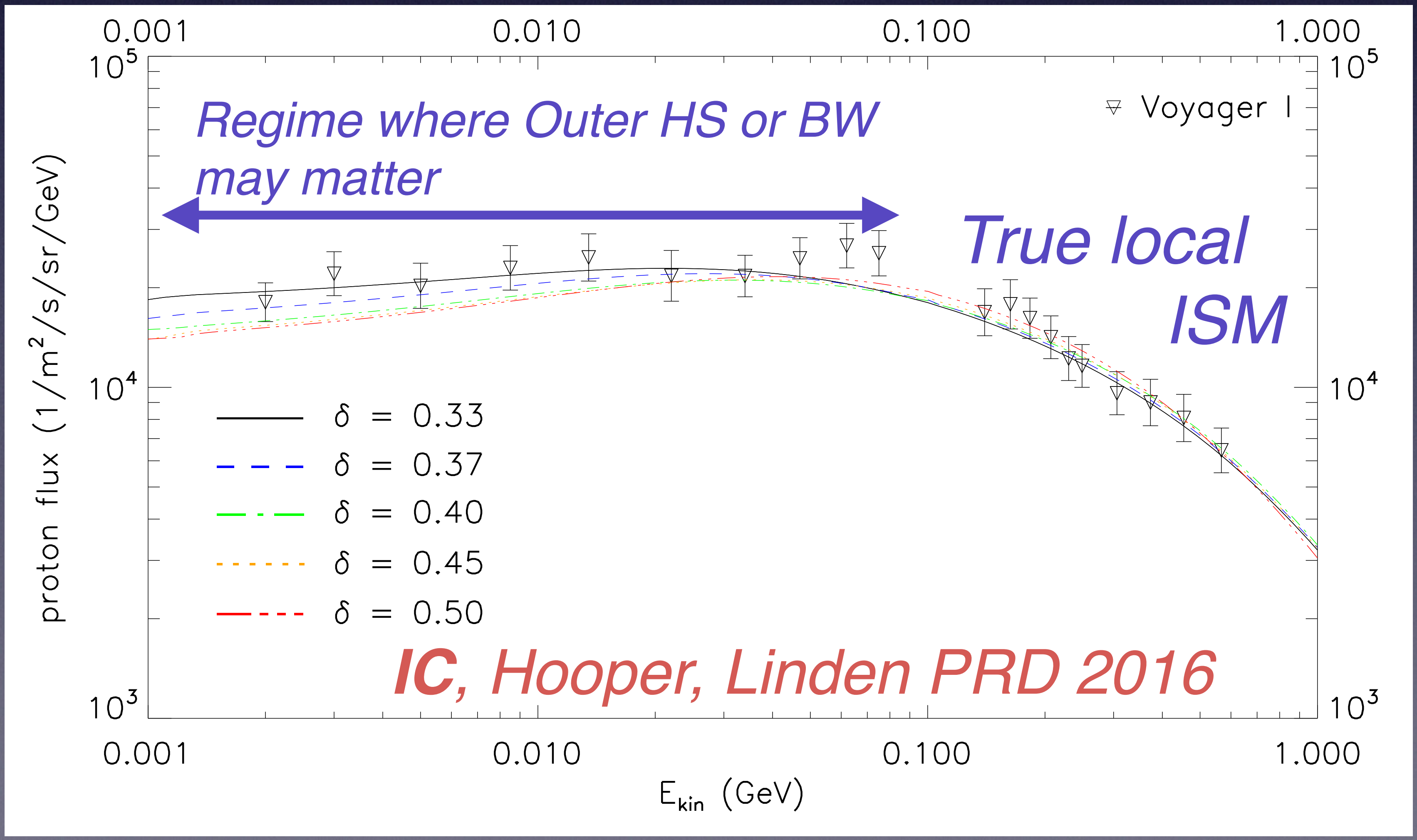
sources, *diffusion*

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

re-acceleration, *convection*

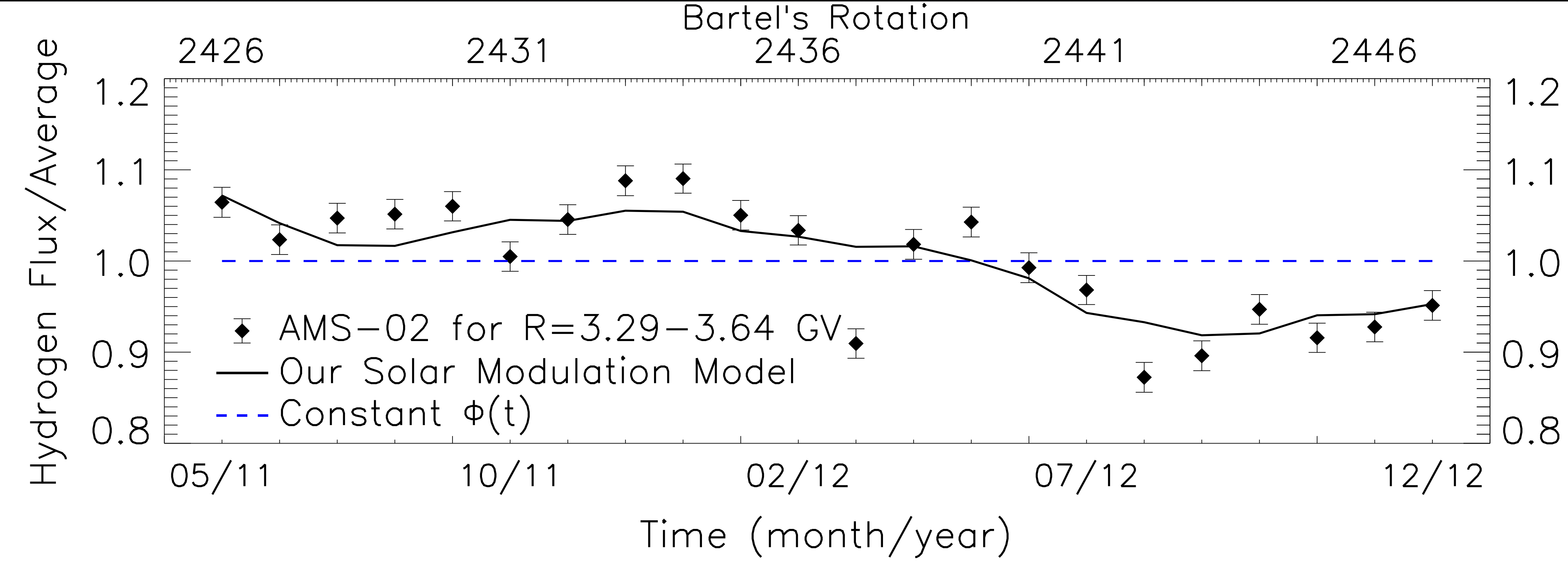
Voyager 1

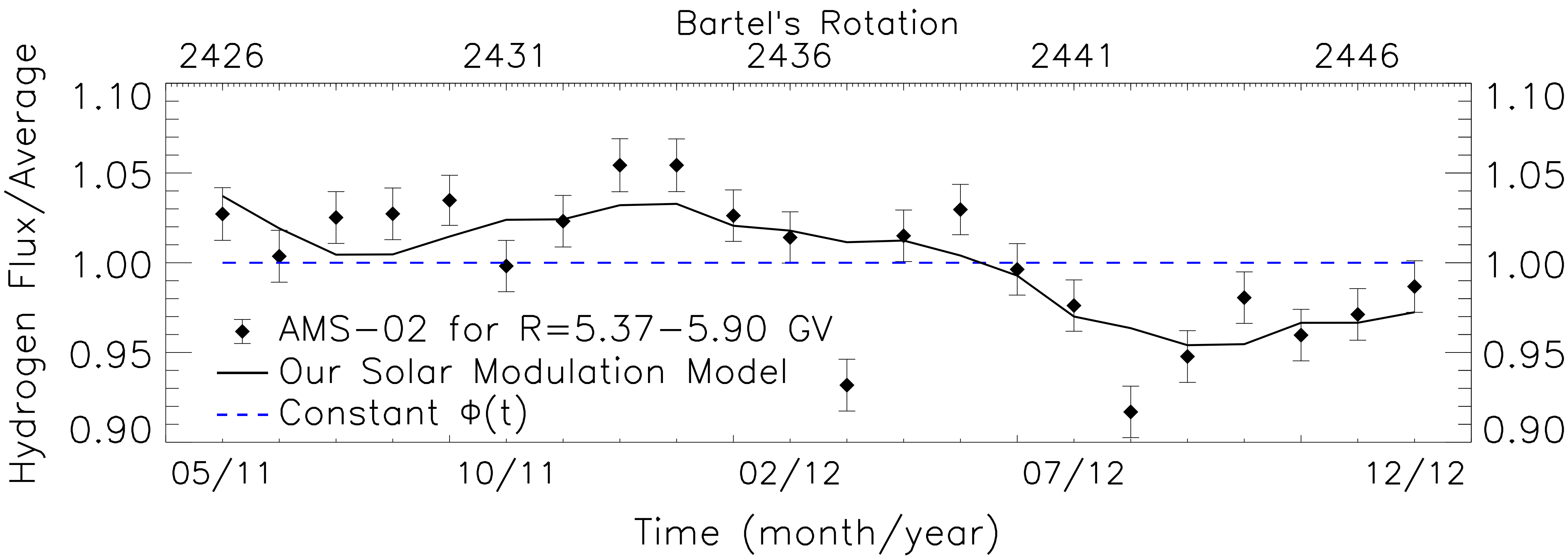
Voyager 1 (ISM) proton flux:



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

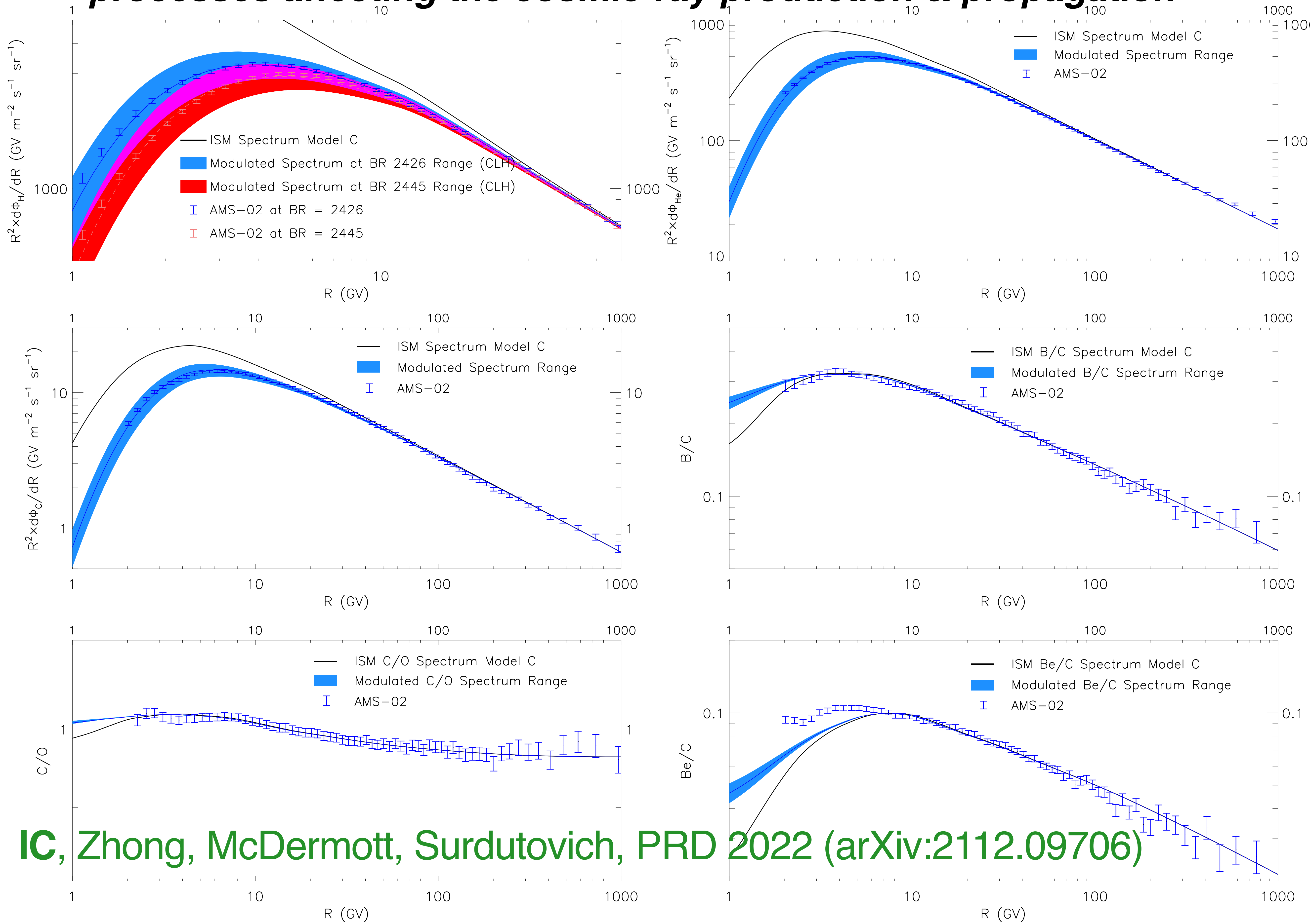
Cross-checking with the PROTON data that account for the majority of observed cosmic rays; monthly AND total (i.e ISM & Solar Modulation):





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

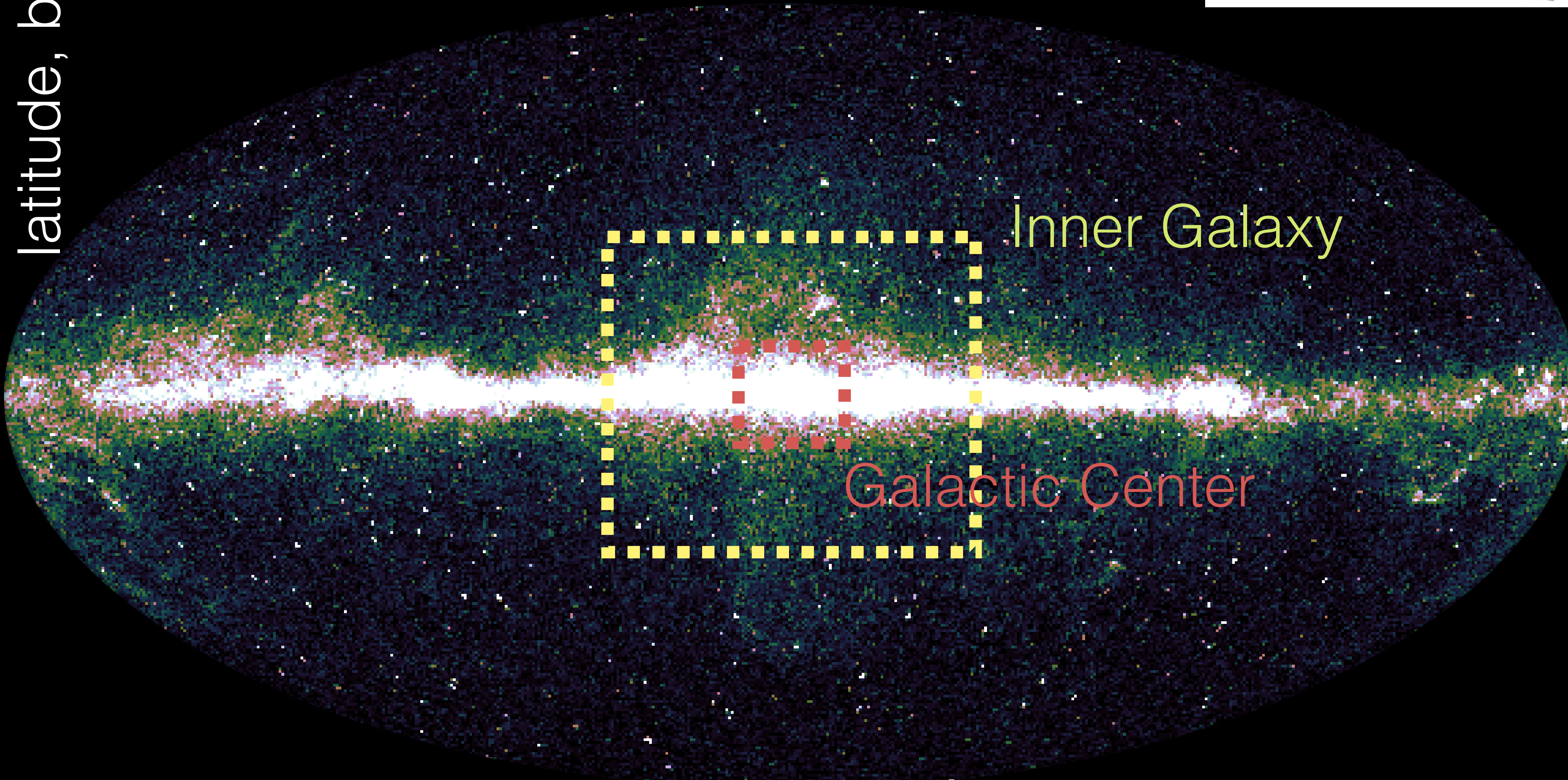
Repeating for multiple Cosmic-Ray species we can constrain the physical processes affecting the cosmic-ray production & propagation



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

third dimension (not shown) — energy

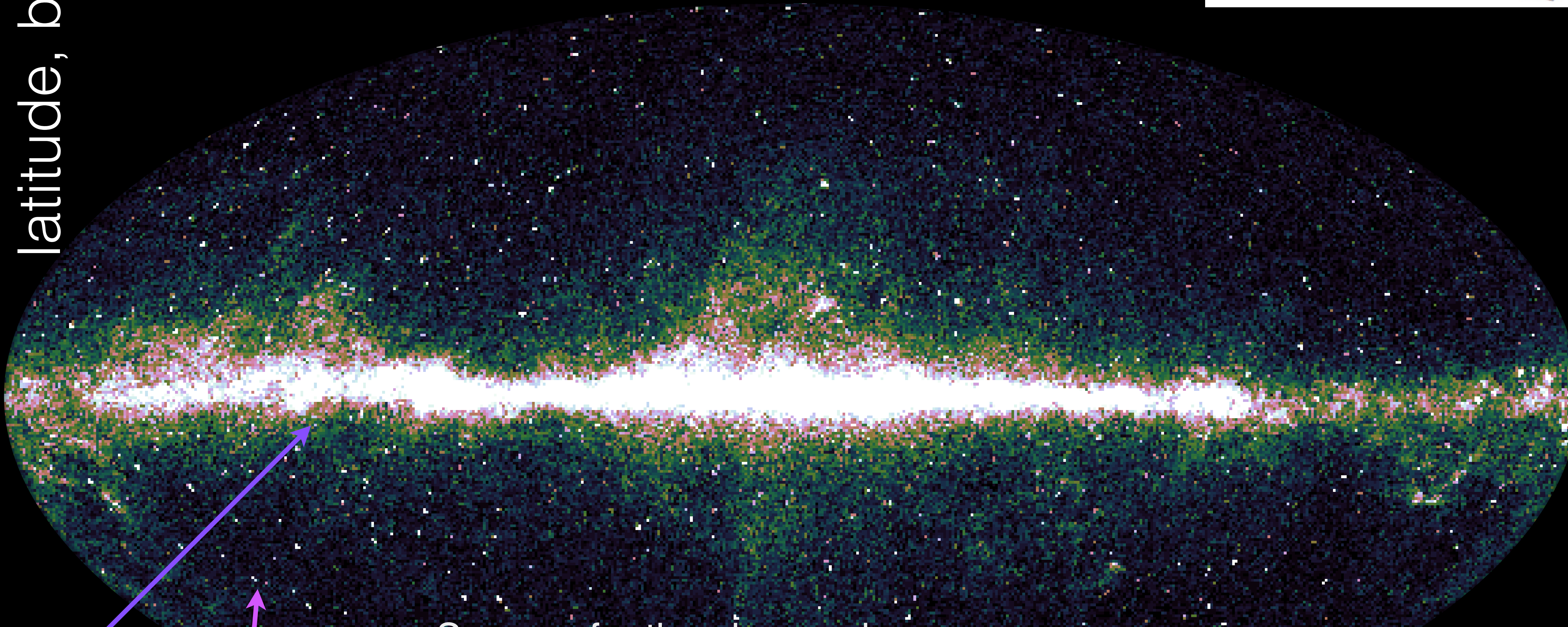
The Fermi-LAT Gamma-ray SKY



third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY

latitude, b ⟶



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

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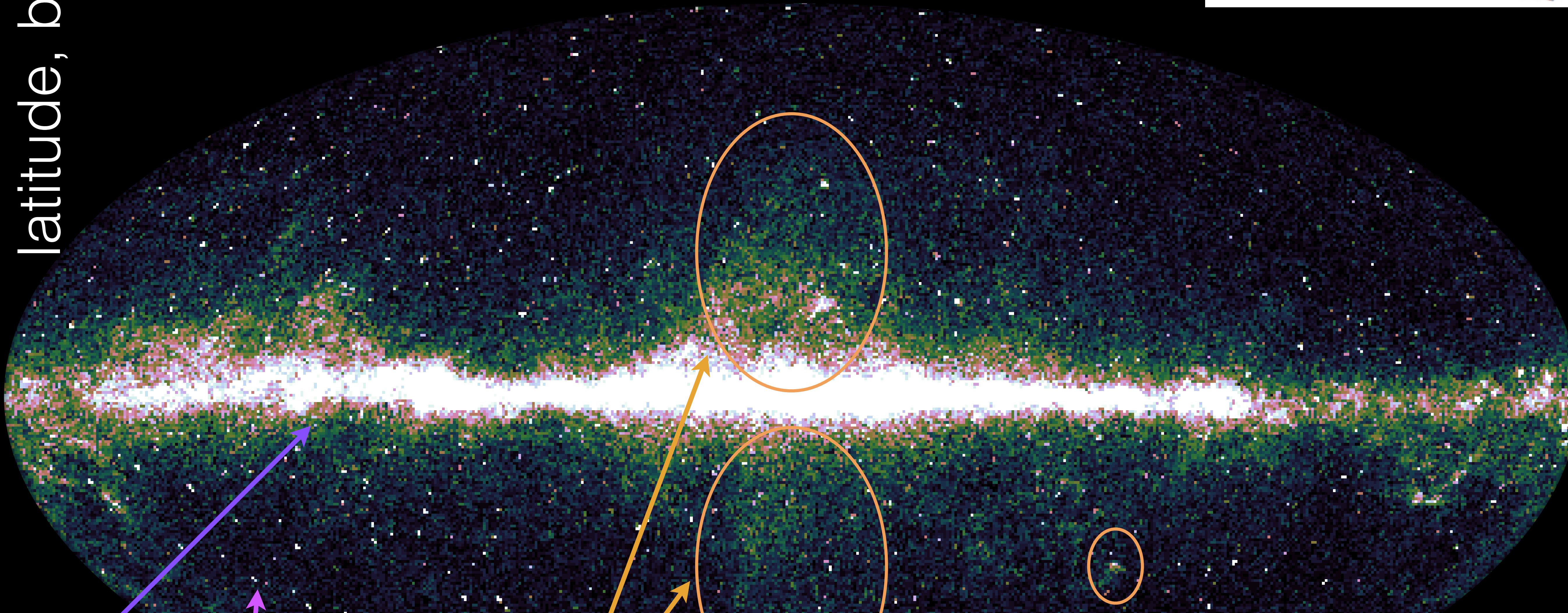

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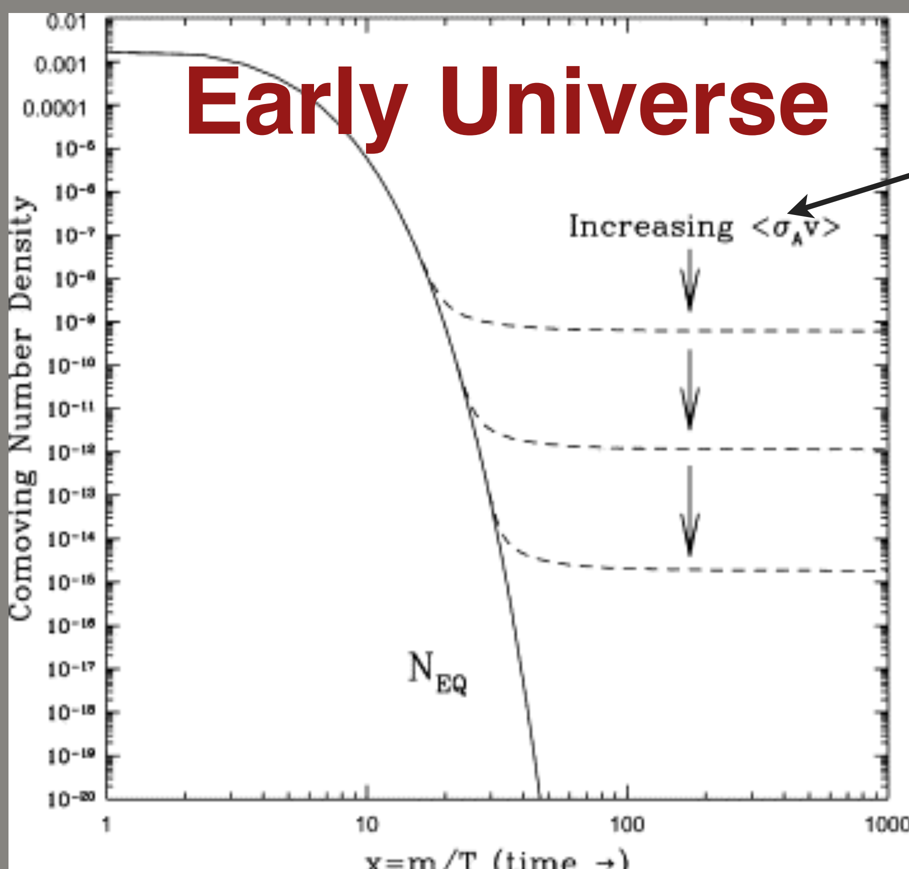
iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)

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

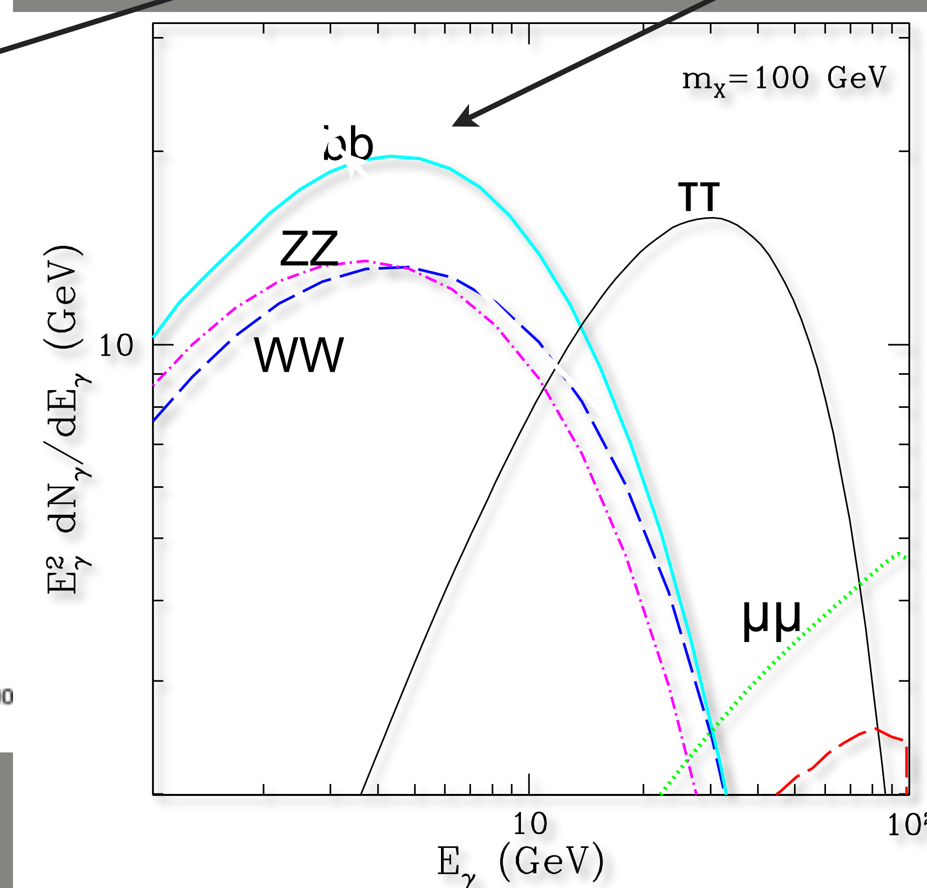
BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe:

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

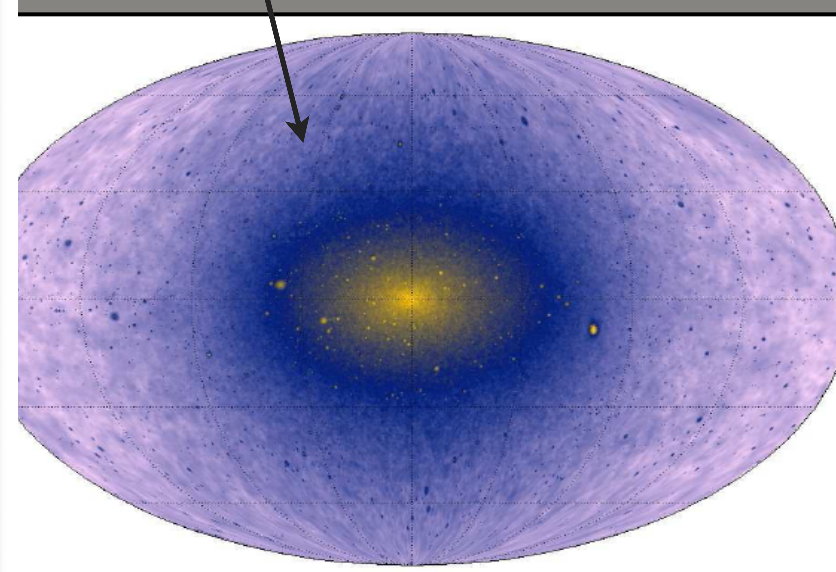


Steigman et al. 2012



Particle Physics

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

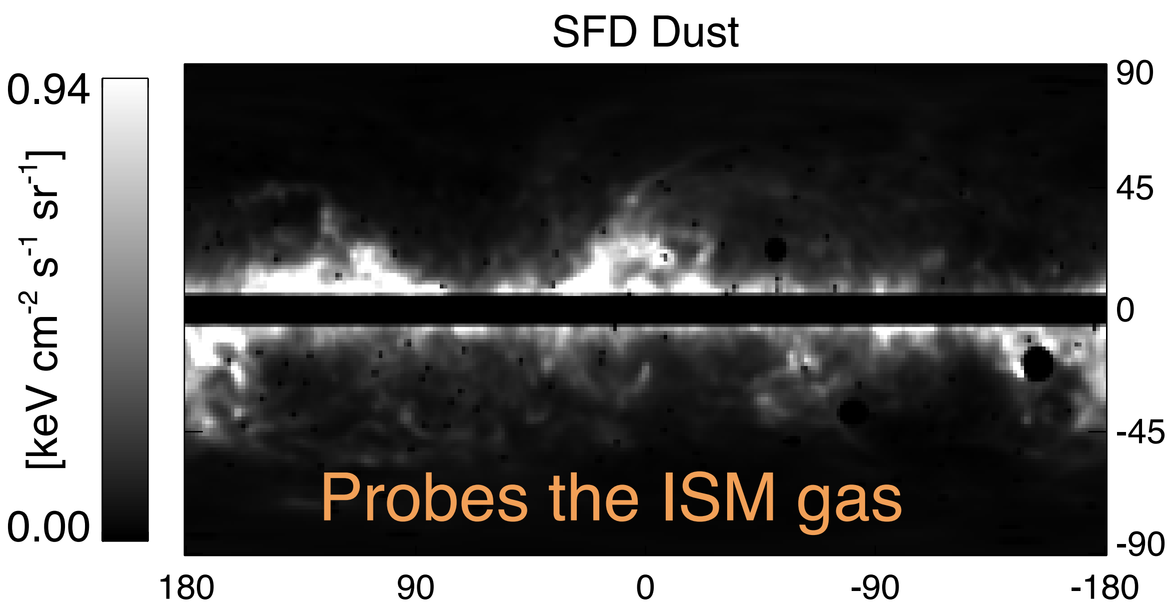


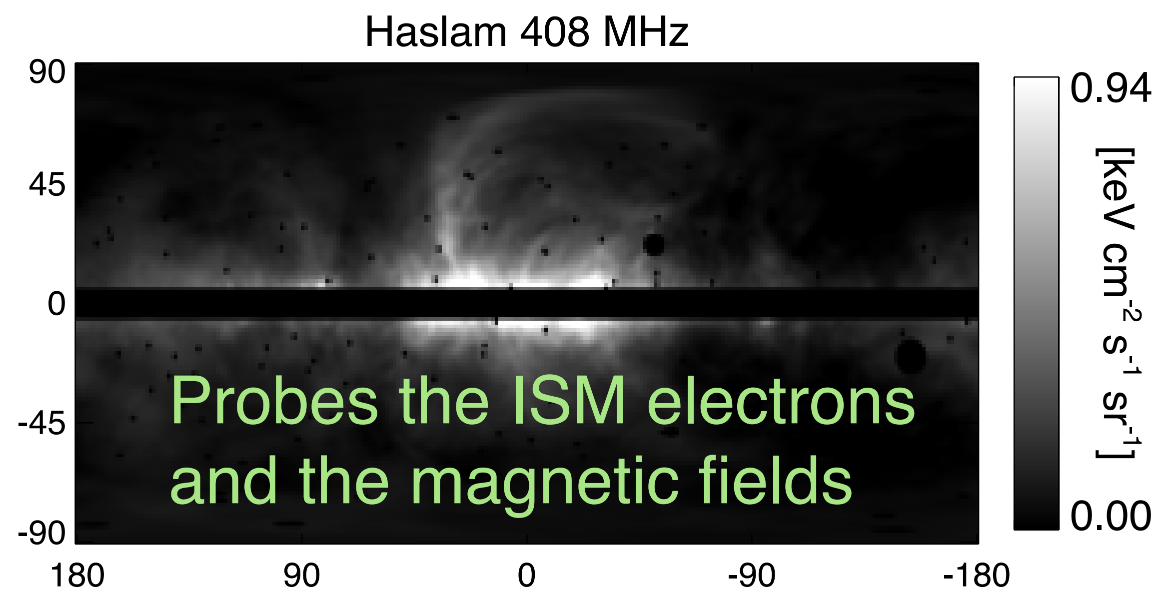
From Cosmological Simulations what we expect today

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

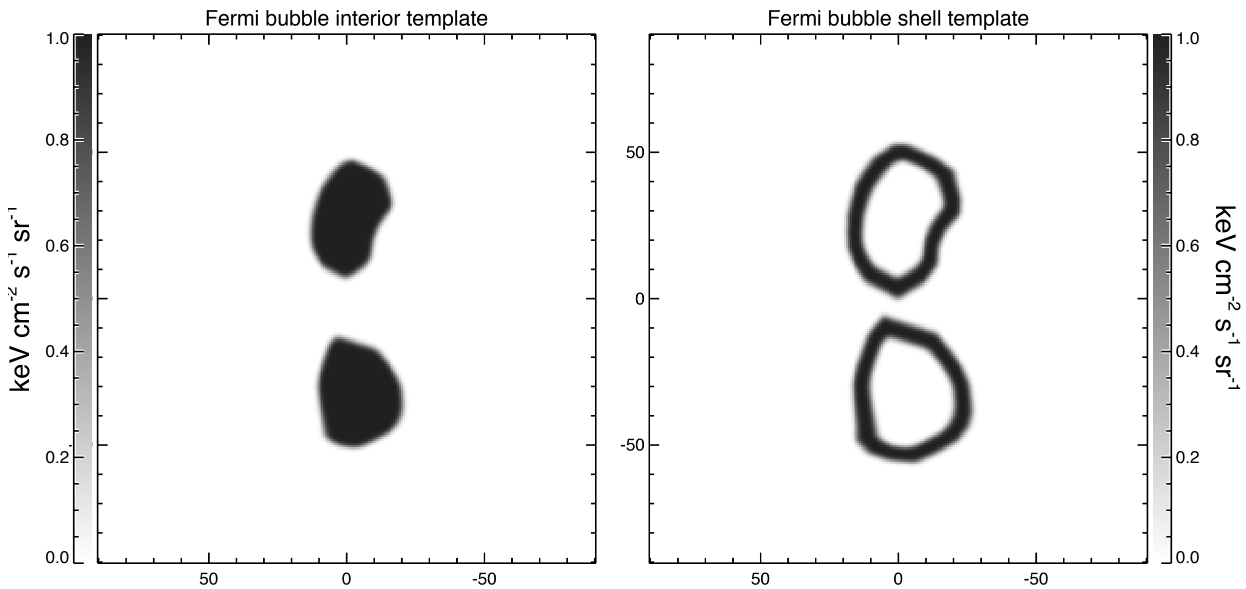
Dobler, Finkbeiner, **IC**, Slatyer, Weiner, ApJ, 2010





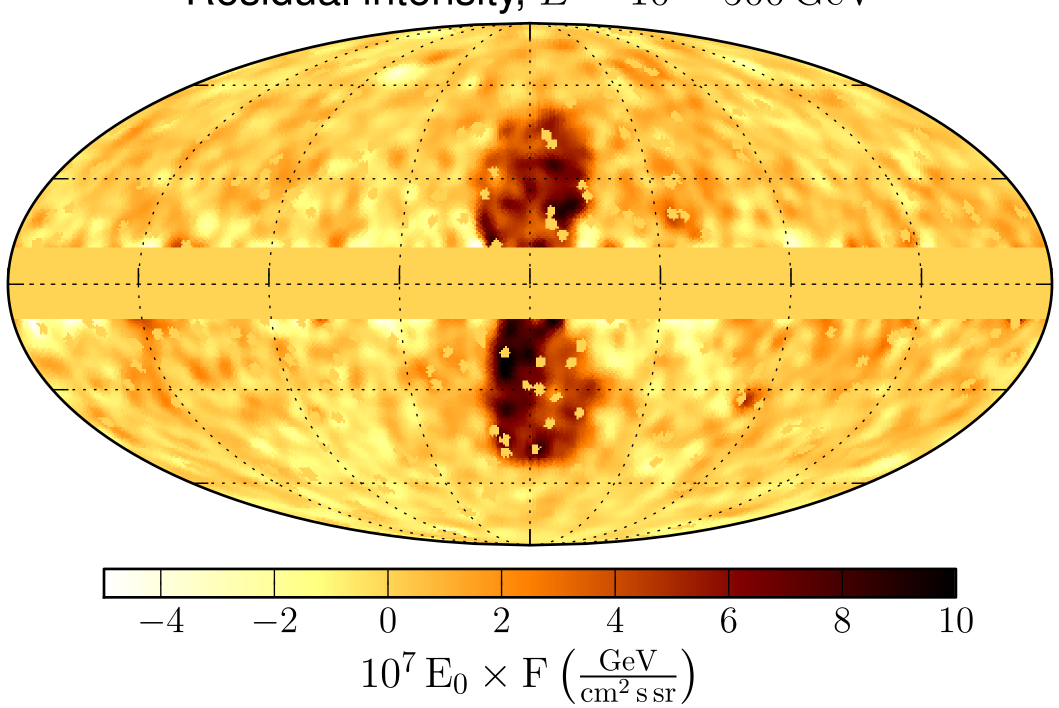
Fermi Bubbles

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



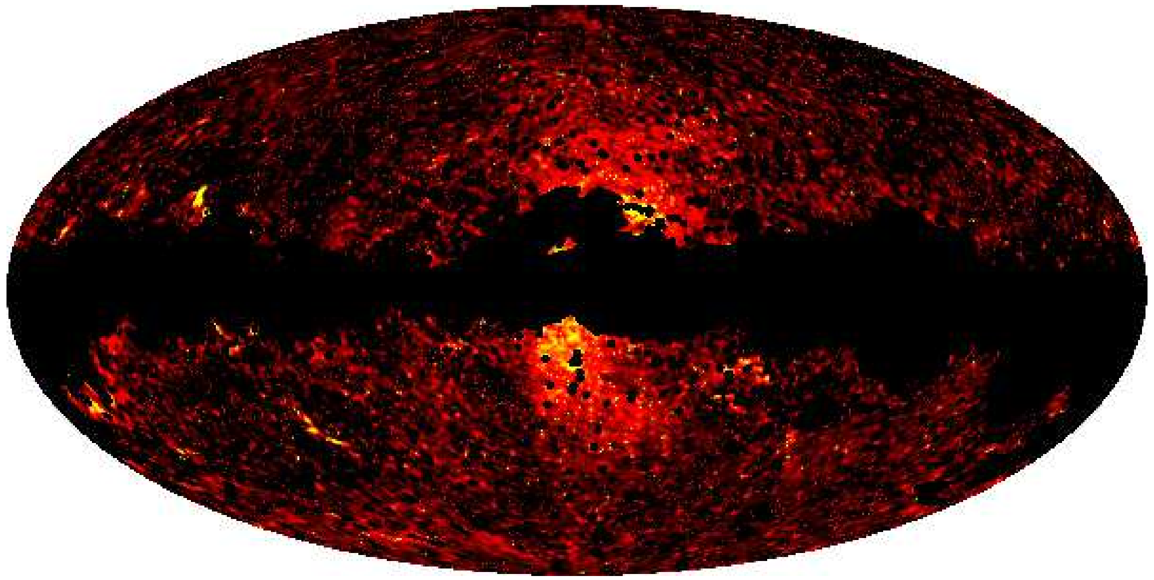
Discovery of edges on the emission.

Residual intensity, $E = 10 - 500\,\mathrm{GeV}$



Fermi-LAT Collaboration
Result ApJ 2014

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



Planck Coll. A&A 2013

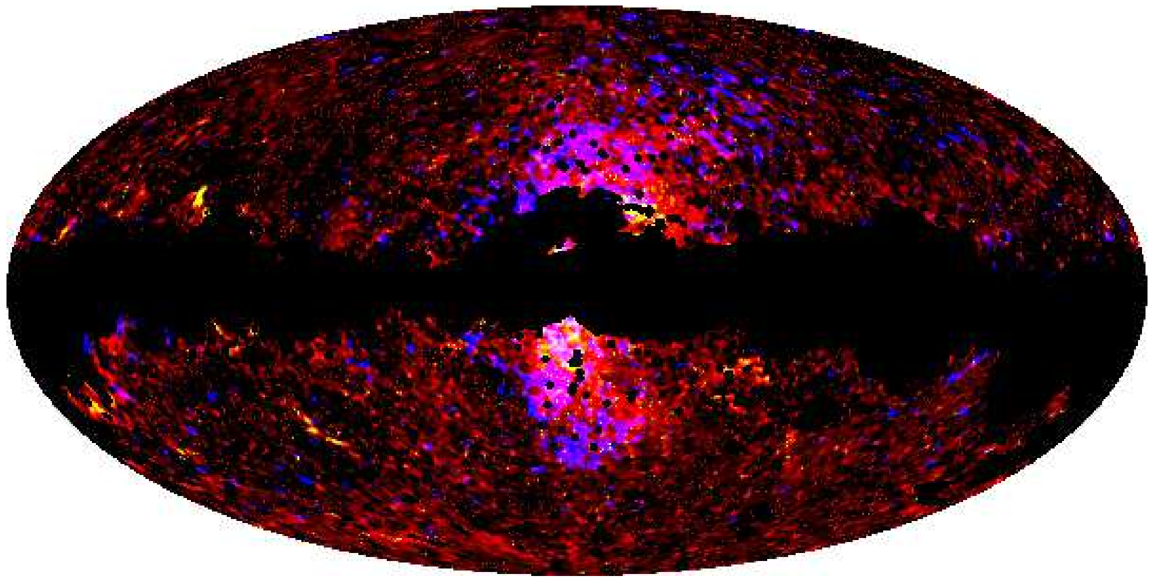
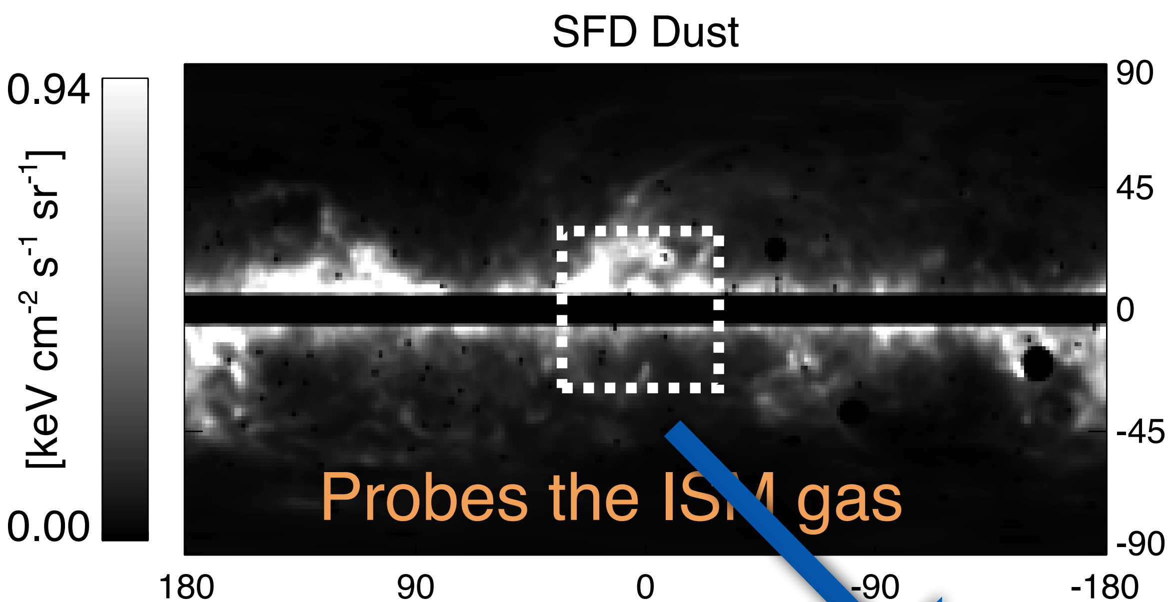
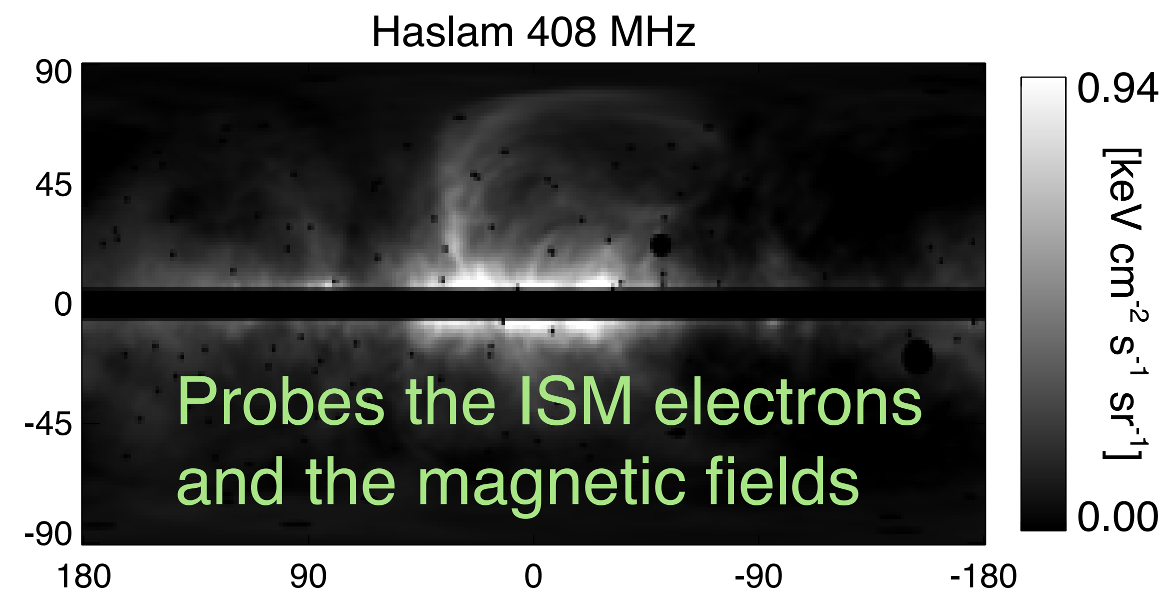


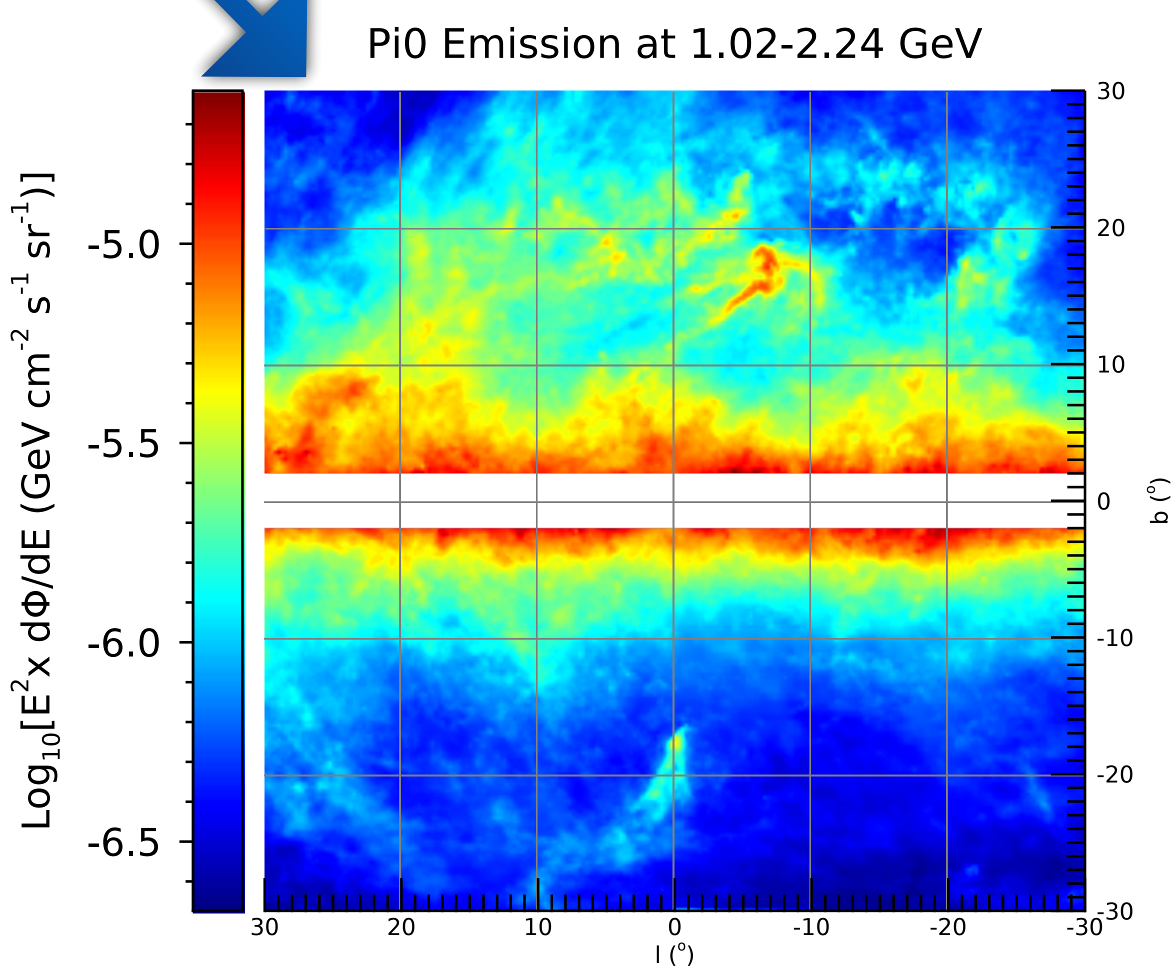
Fig. 9. *Top*: The microwave haze at *Planck* 30 GHz (red, $-12\,\mu$K < ΔT_{CMB} < 30 μK) and 44 GHz (yellow, 12 μK < ΔT_{CMB} < 40 μK). *Bottom*: The same but including the *Fermi* 2-5 GeV haze/bubbles of Dobler et al. (2010) (blue, 1.05 < intensity [keV cm^{-2} s^{-1} sr^{-1}] < 1.25; see their Fig.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

Using templates on Gamma-ray maps



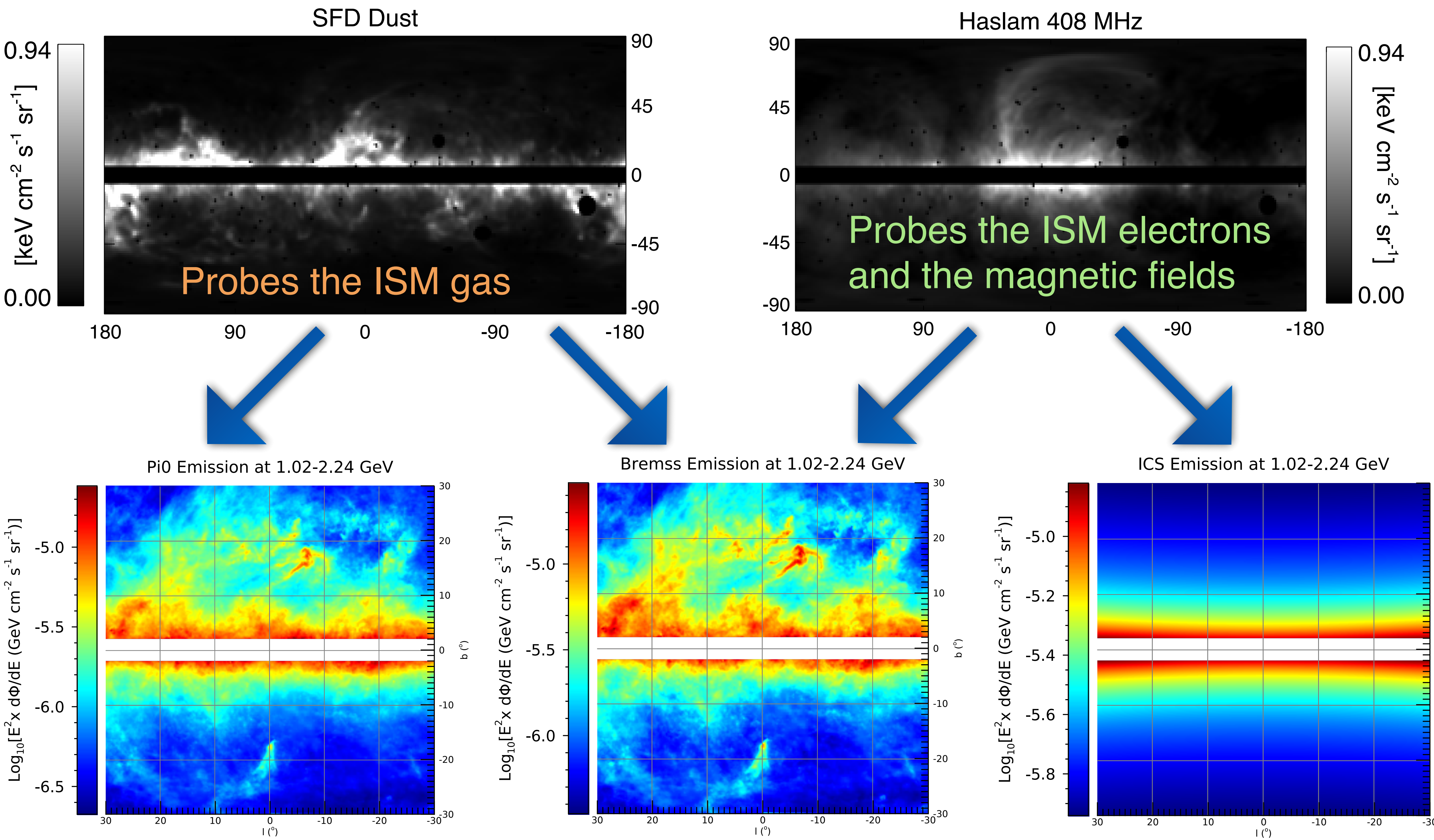


Adding ISM physics, cosmic-ray observations and running an array of Milky Way simulations …

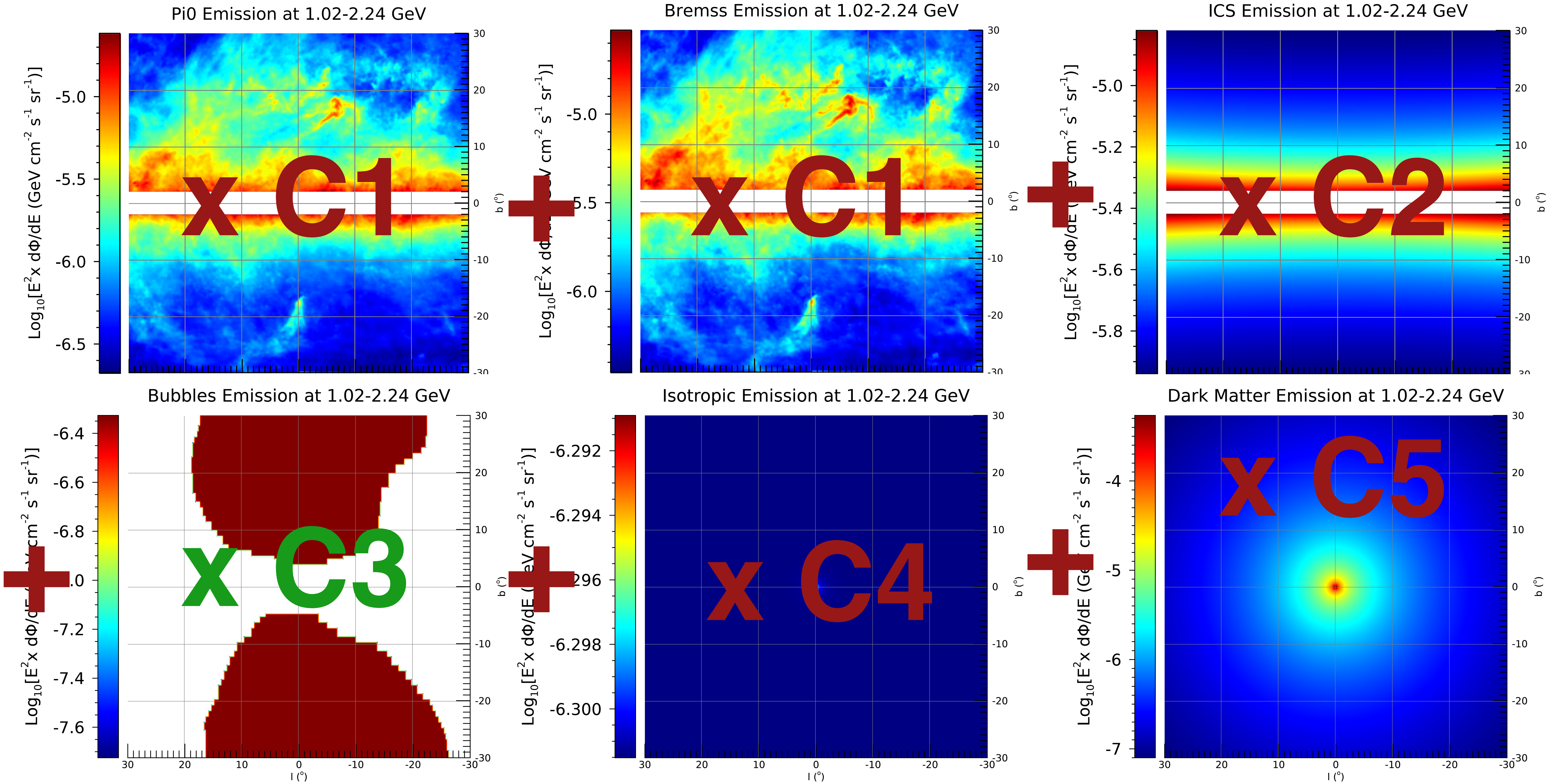


60 degrees in latitude

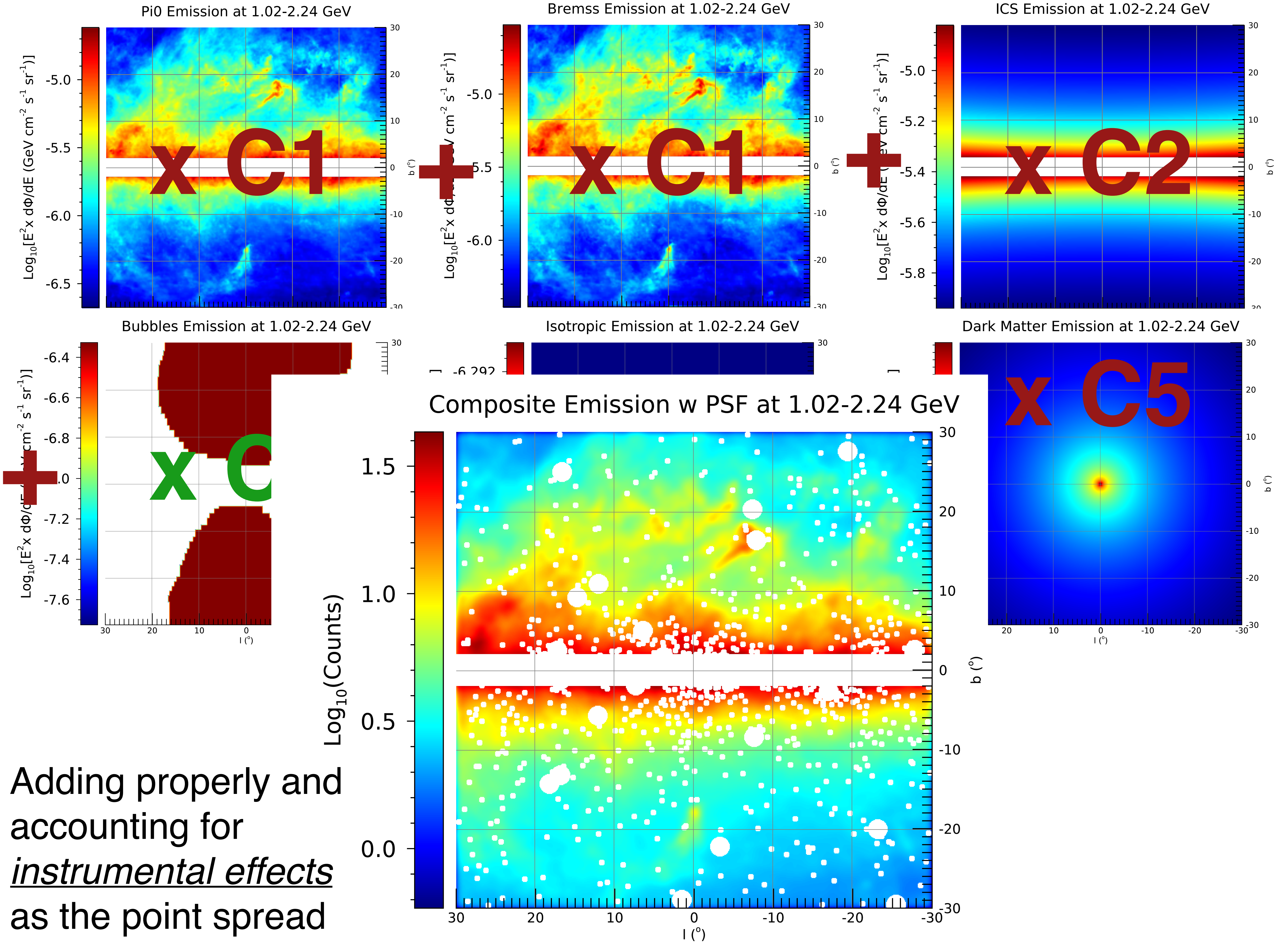
Using templates on Gamma-ray maps



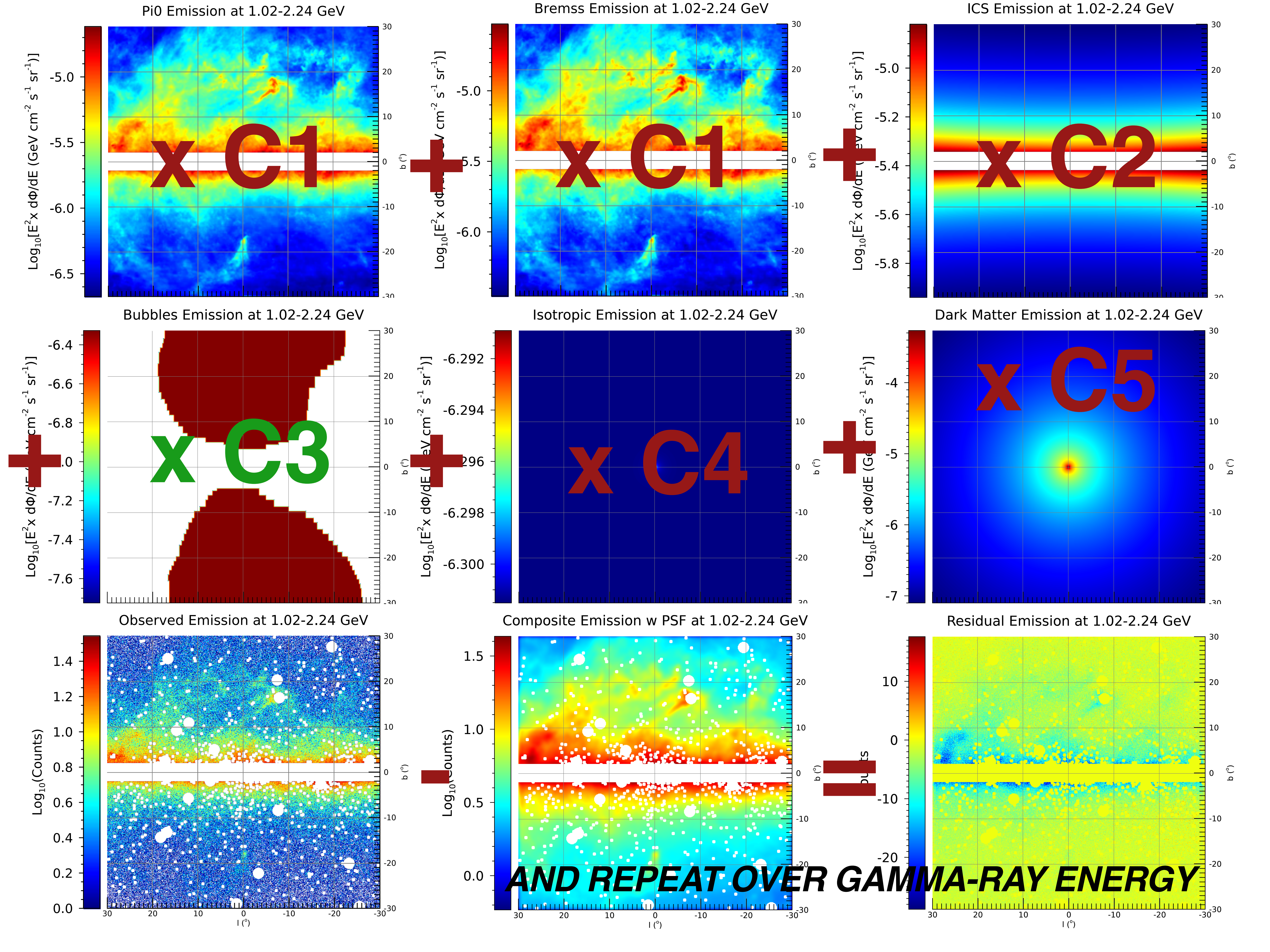
IC, Zhong, McDermott, Surdutovich, PRD 2022 (arXiv:2112.09706)



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)]
l (°)
b (°)



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



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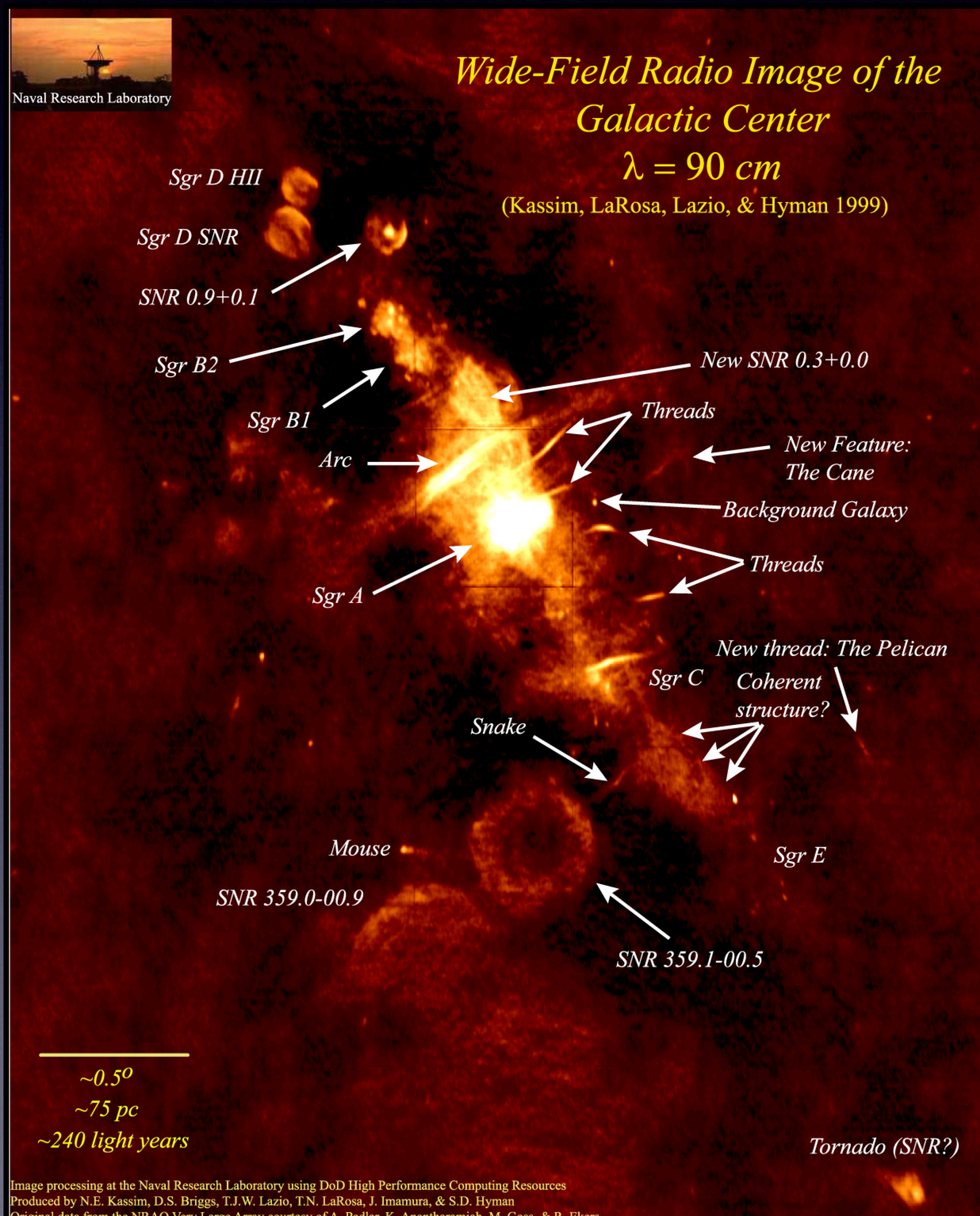
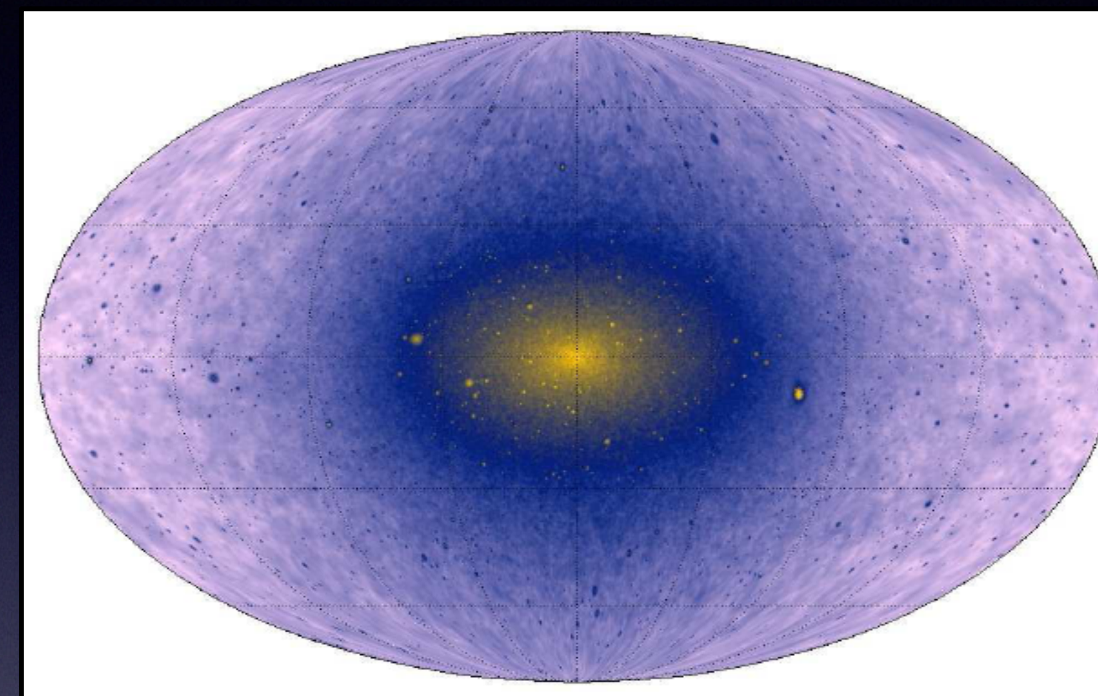
+
Bubbles Emission at 1.02-2.24 GeV
x C3
+
Isotropic Emission at 1.02-2.24 GeV
x C4
+
Dark Matter Emission at 1.02-2.24 GeV
x C5
Observed Emission at 1.02-2.24 GeV
-
Composite Emission w PSF at 1.02-2.24 GeV
=
Residual Emission at 1.02-2.24 GeV
AND REPEAT OVER GAMMA-RAY ENERGY
Log10[E2x dΦ/dE (GeV cm-2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

The galactic center
A place to look for Dark Matter Annihilation

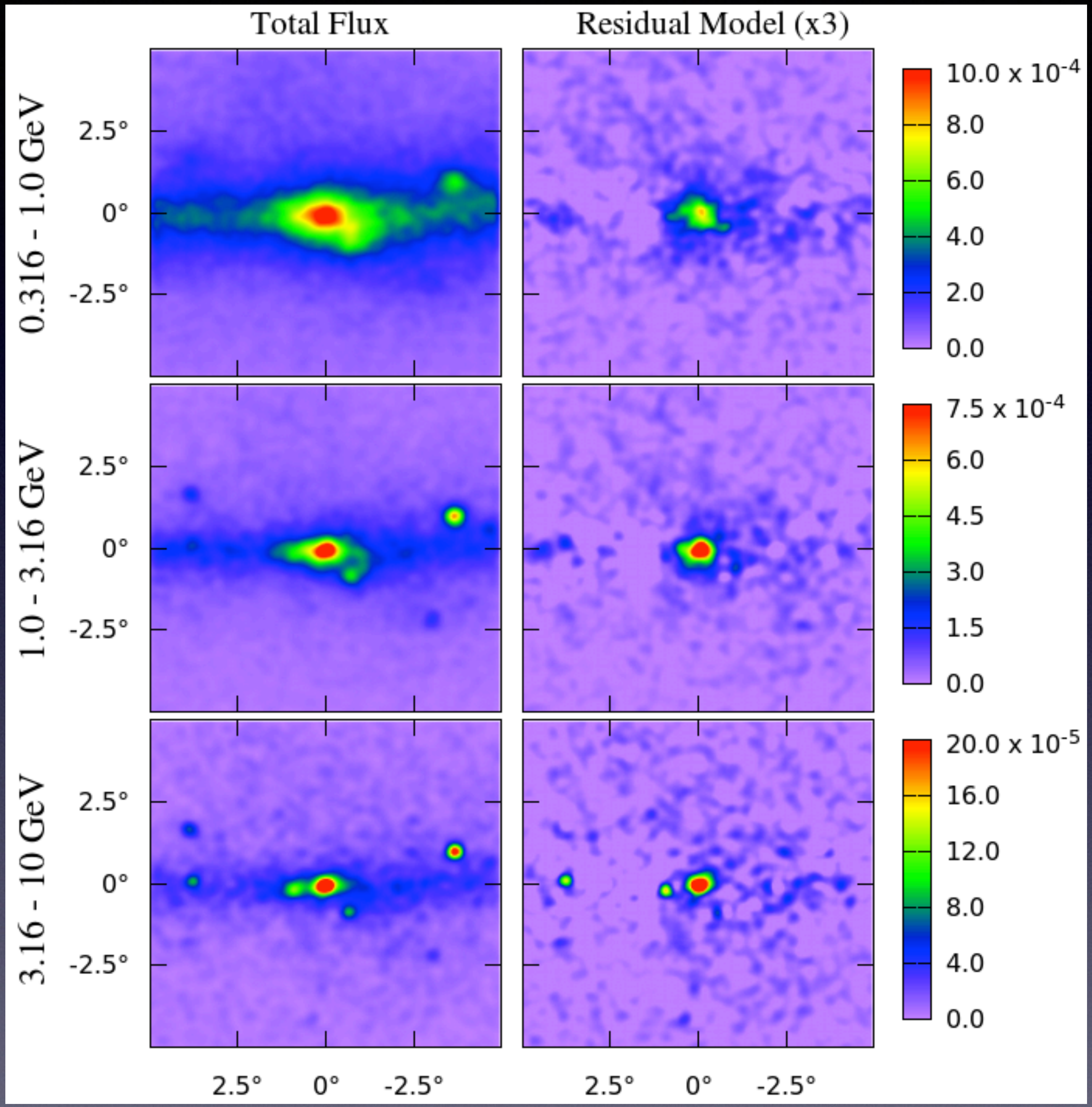




- The region of the galactic center is complex with large uncertainties.
- A DM annihilation signal peaks but also has significant uncertainties..
- Take advantage of multi-wavelength searches.

Looking for excesses in the galactic center

Using Templates:

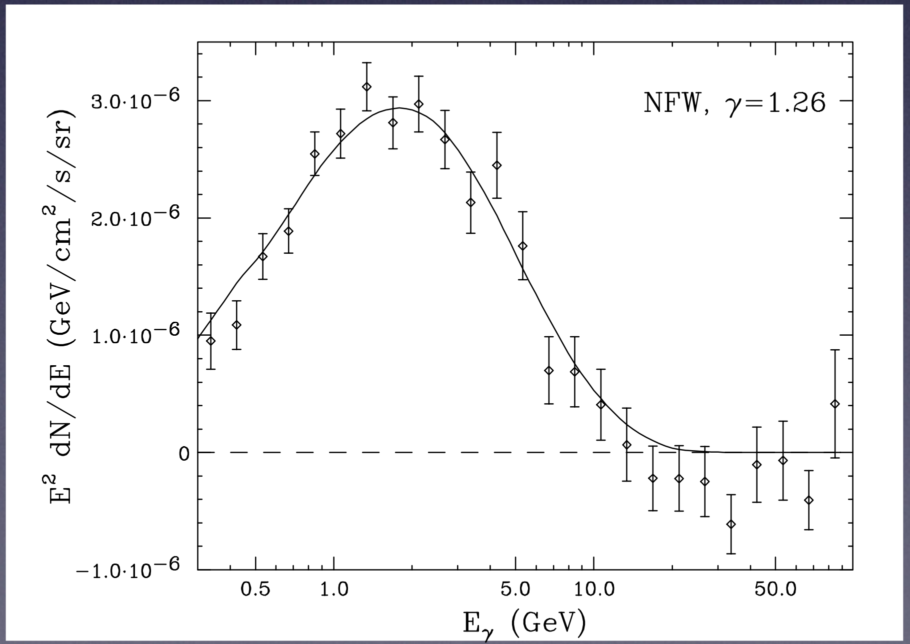


Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, PoDU 2015

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)***

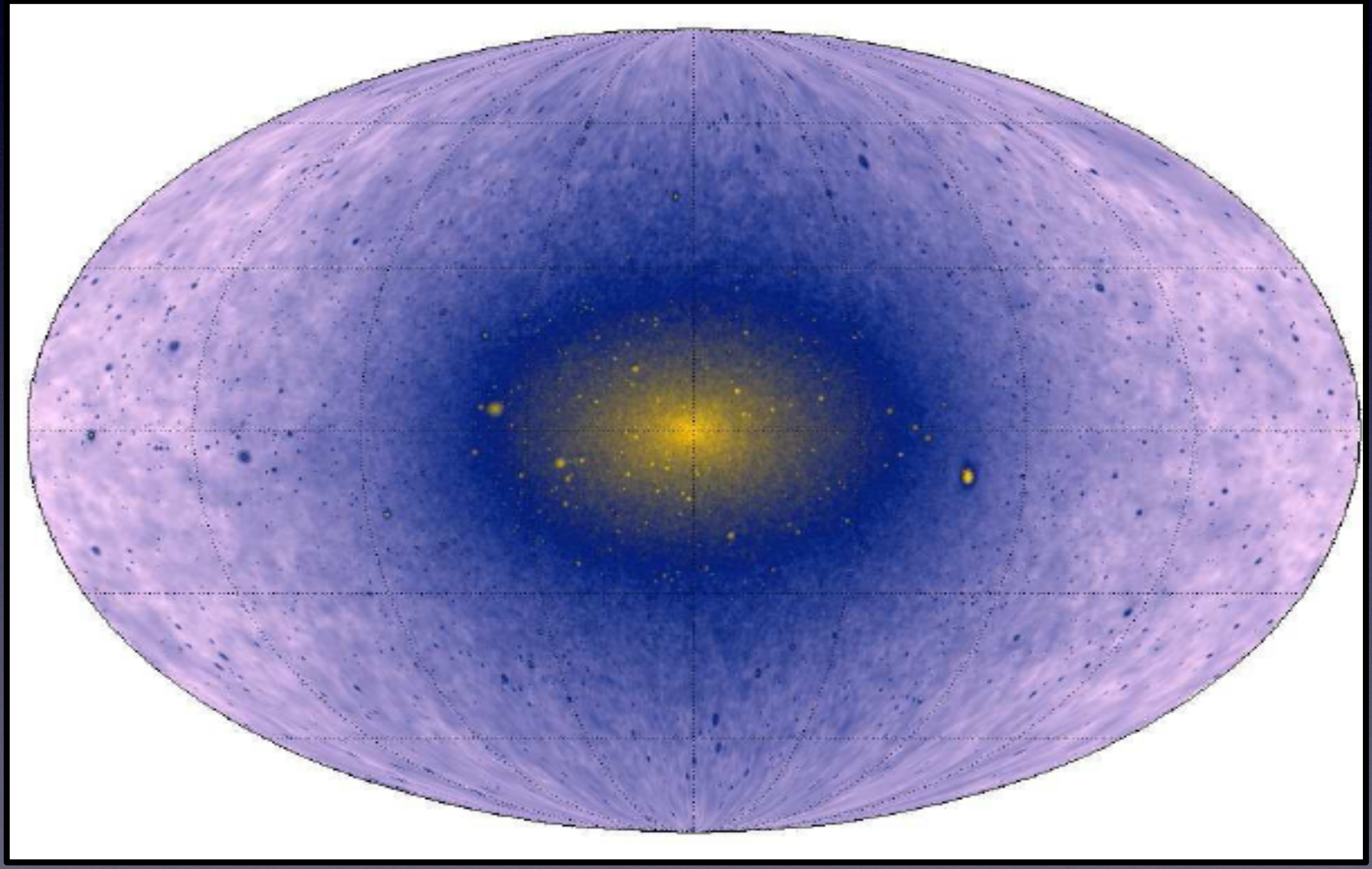


Also: Hooper & Goodenough PRL 2011, Abazajian JCAP 2011, Hooper & Linden PRD 2011, Gordon & Macias PRD 2014, Zhou et al. PRD 2015, Ajello et al. ApJ 2016

Going to High Latitudes (Inner Galaxy)

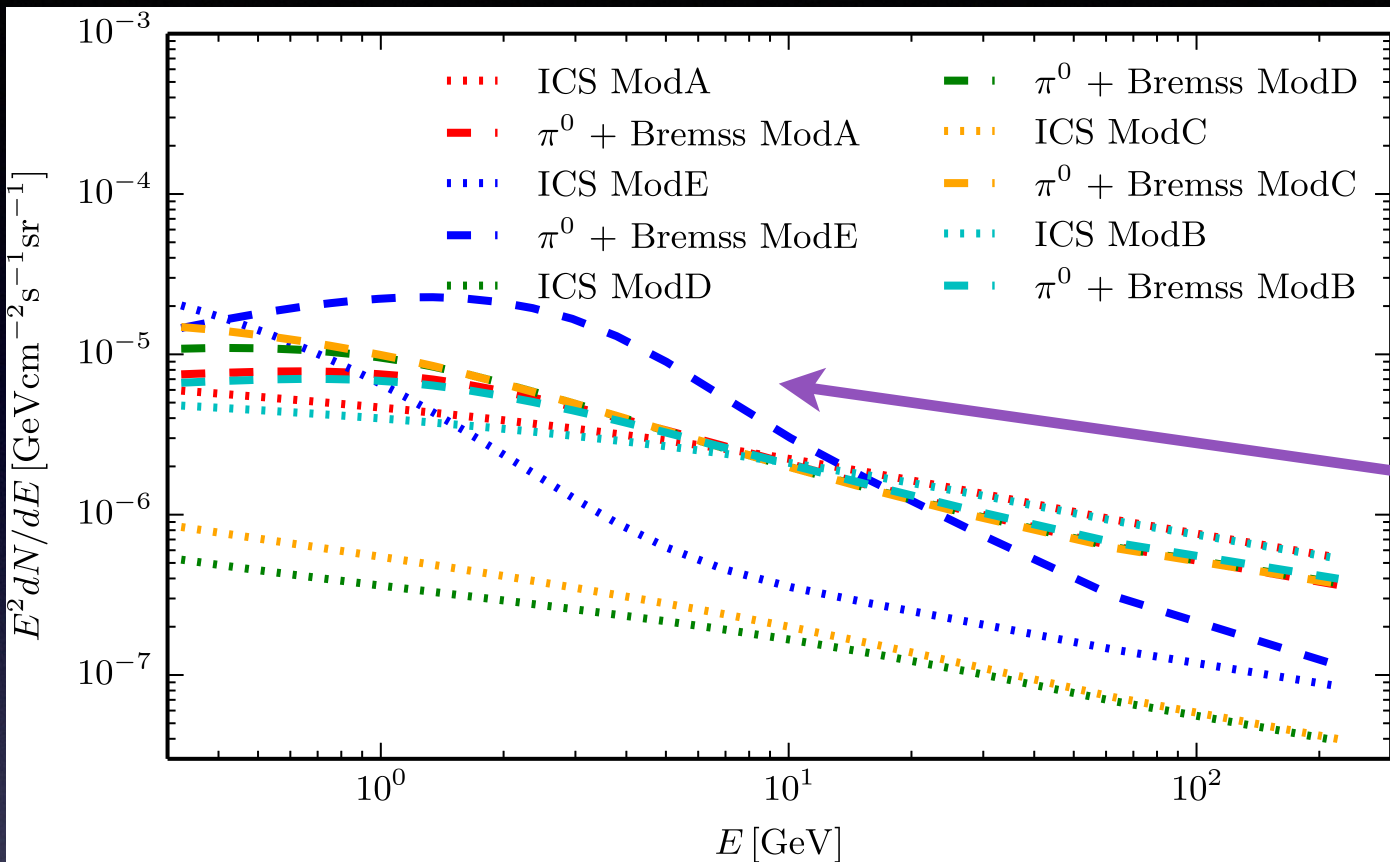
Advantages of looking further away from the center:

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

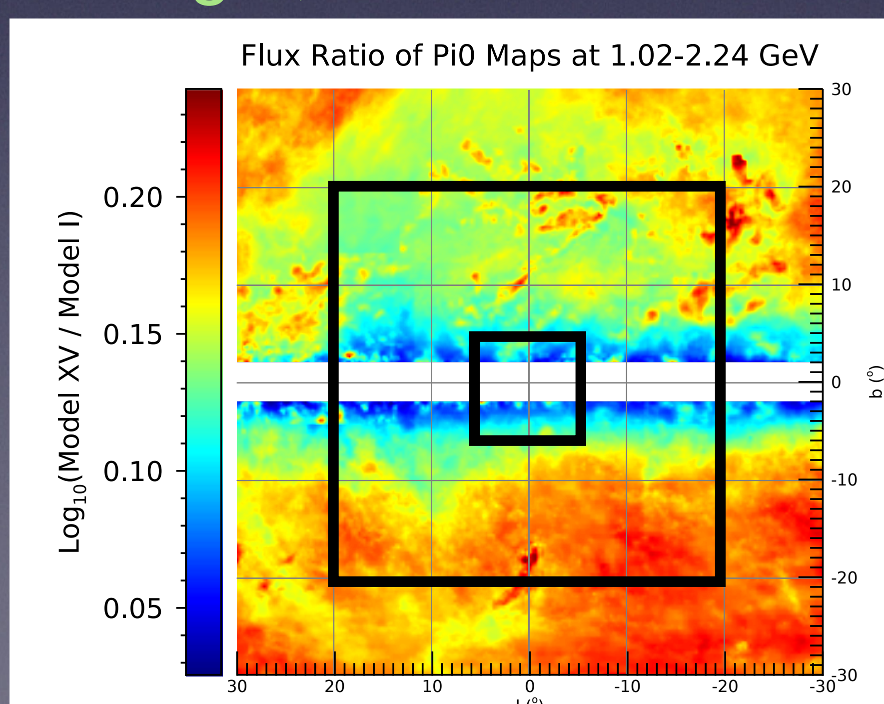


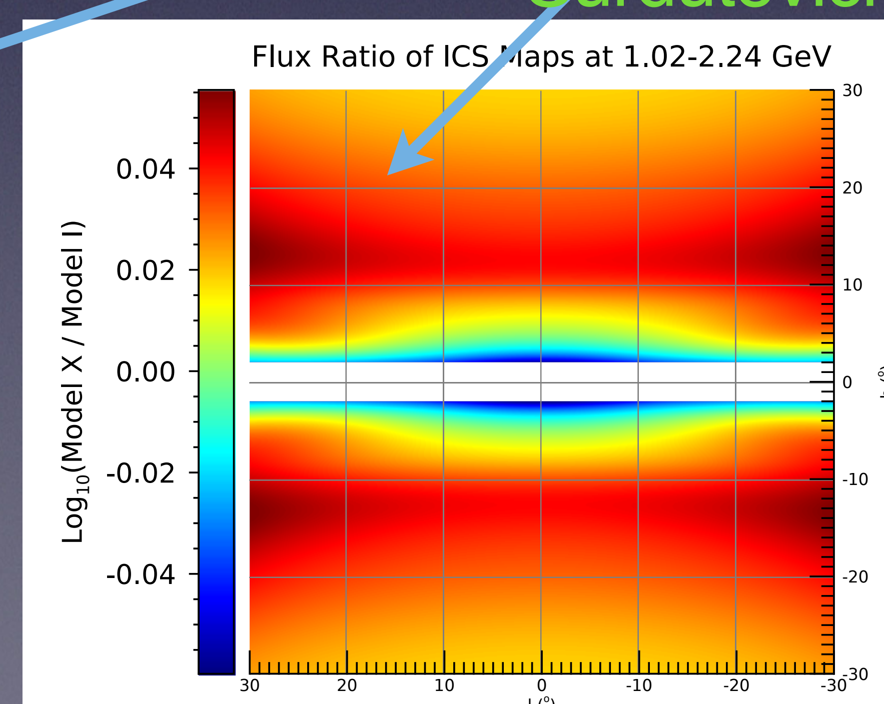
The exact astrophysics model assumptions can affect both the gamma-ray background spectrum and its morphology on the galactic sky.

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!

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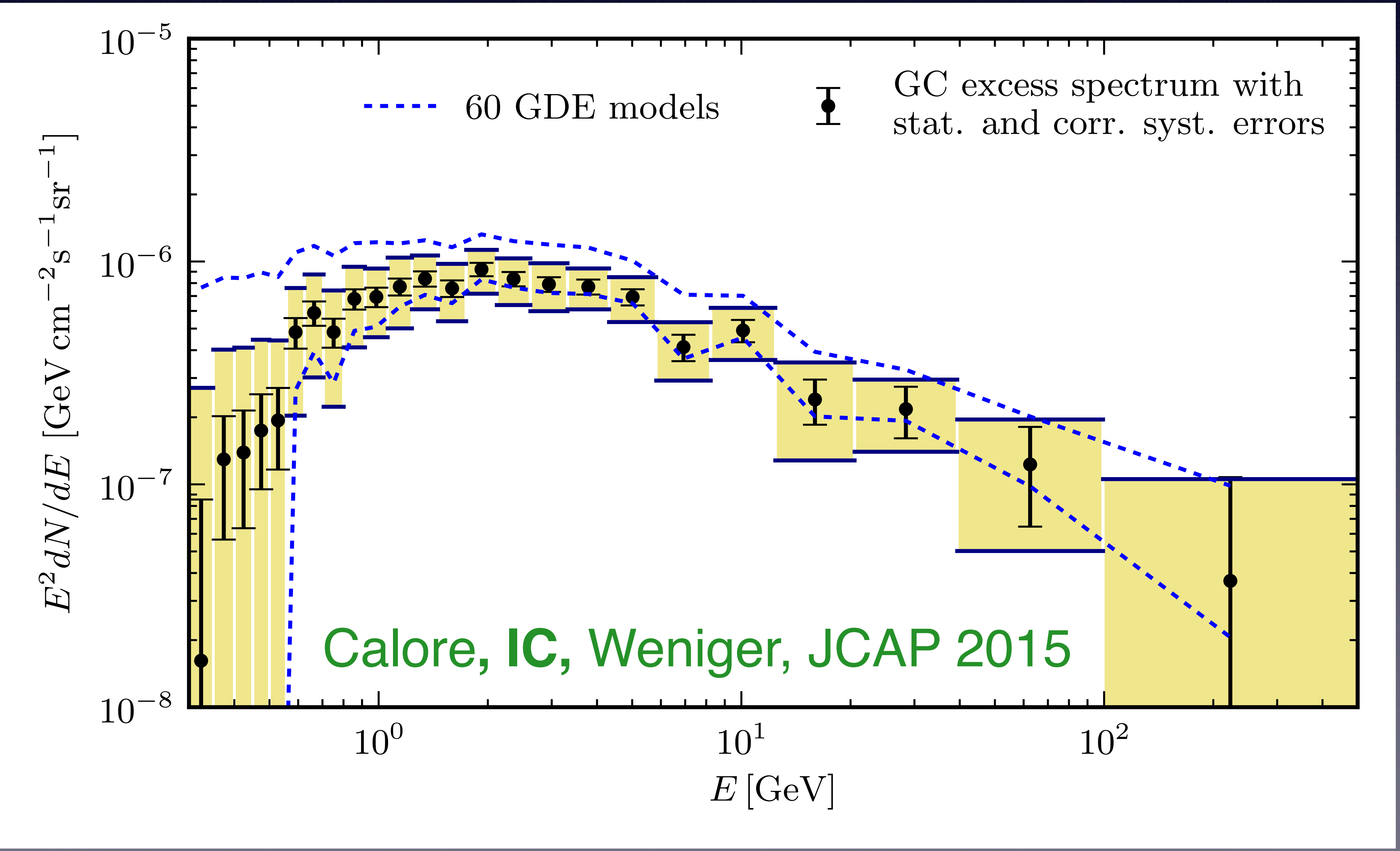
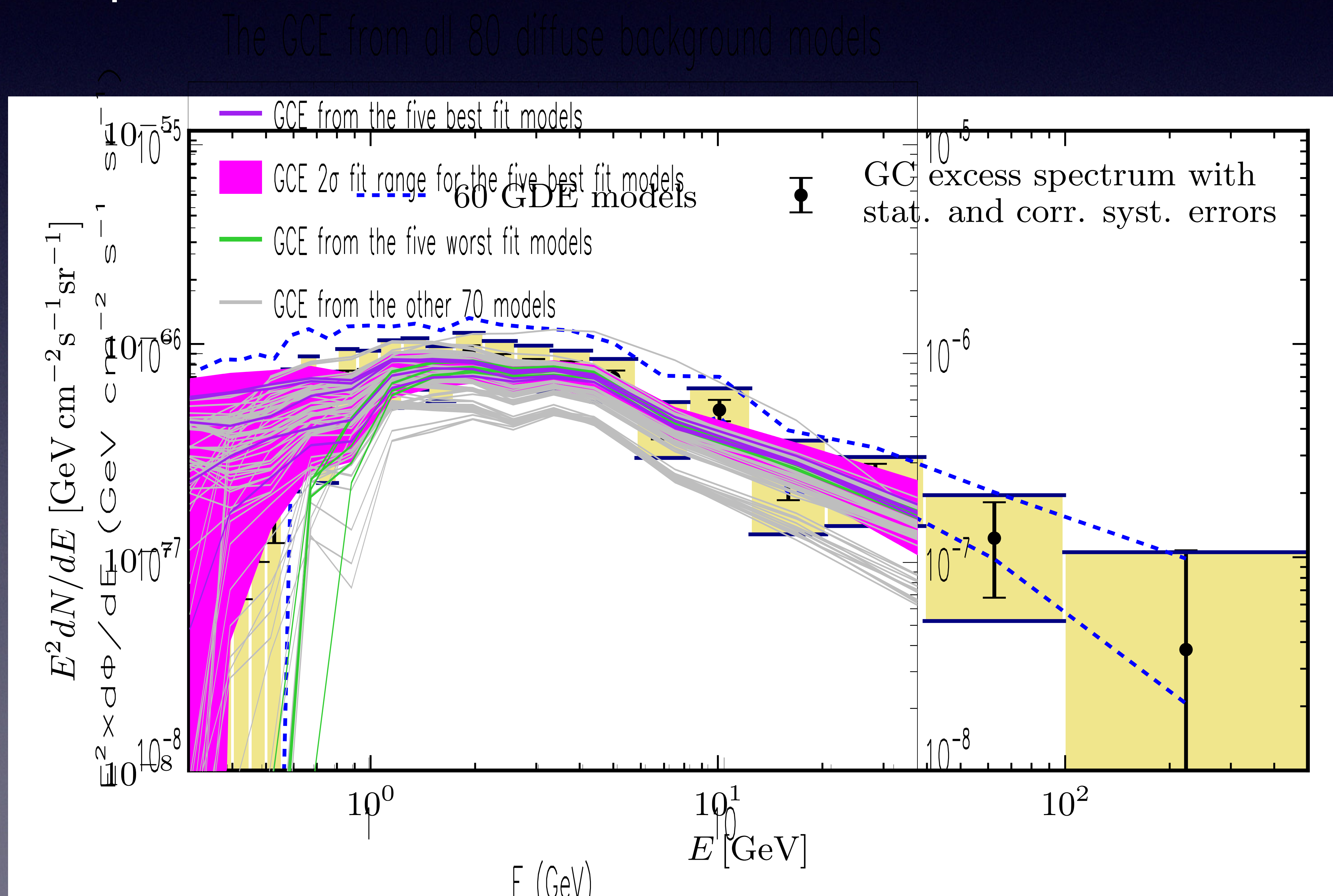
It turns out that it actually does not affect dramatically the excess spectrum:



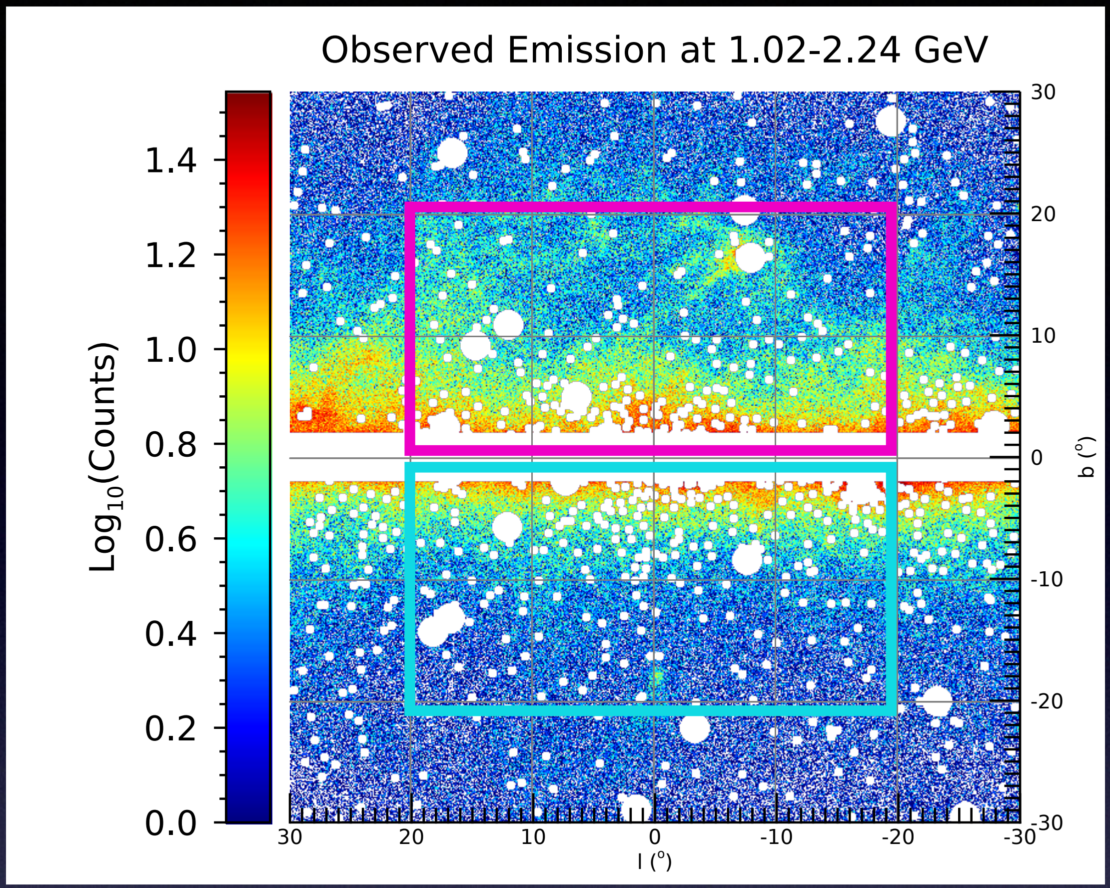
Accounting for the galactic diffuse emission uncertainties

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

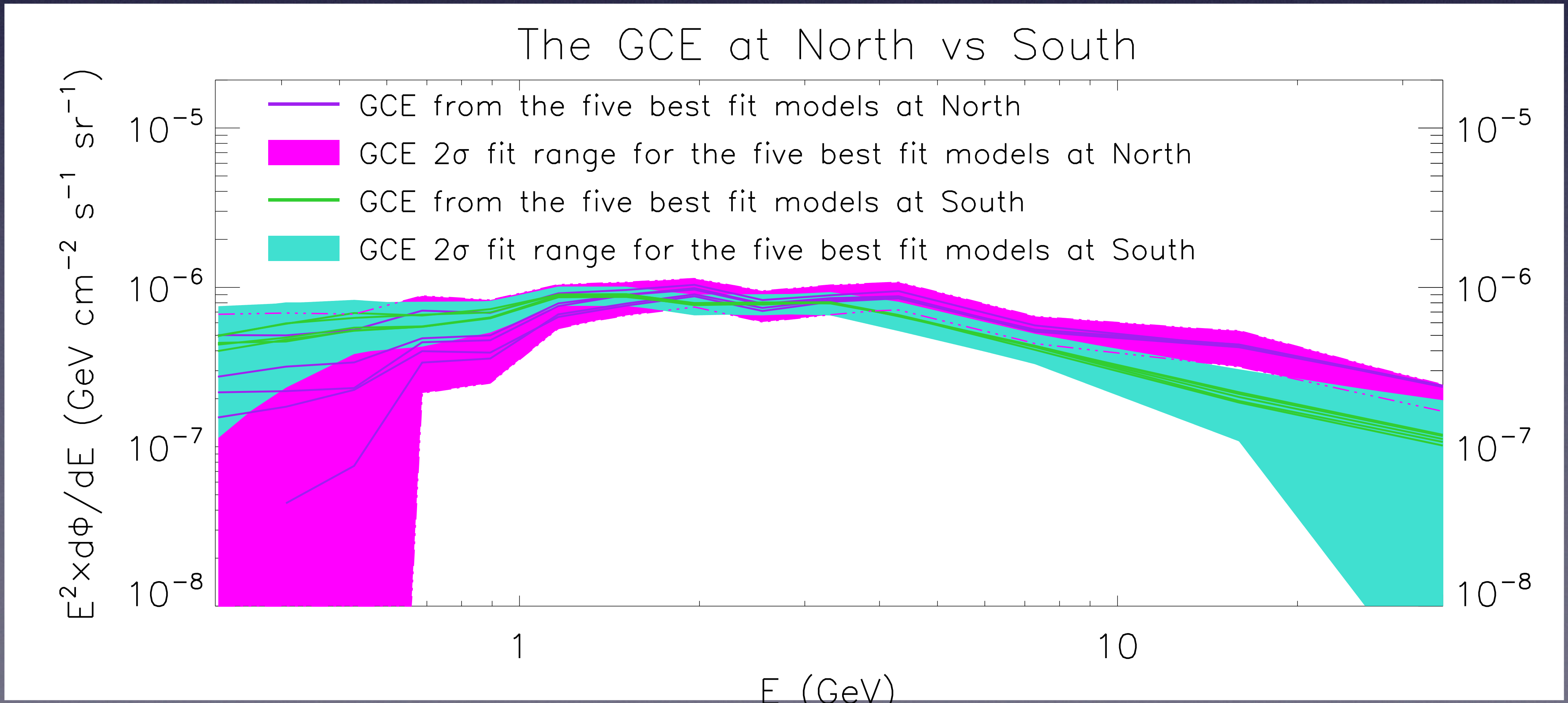
IC, Zhong, McDermott, Surdutovich, PRD 2022



North

South

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



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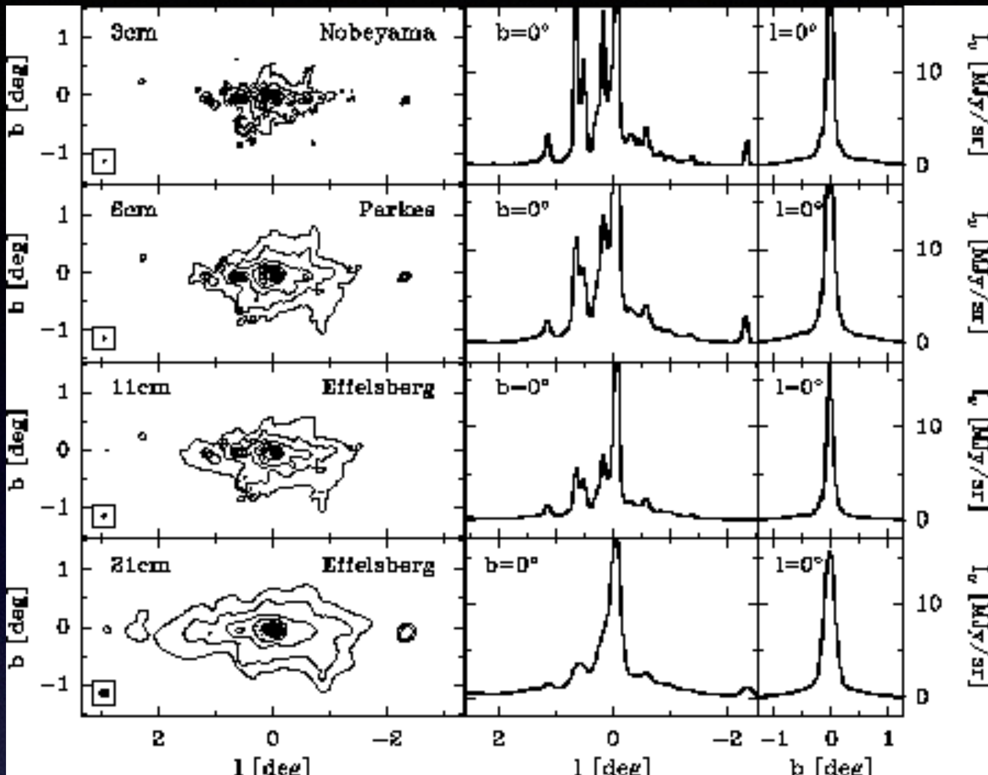
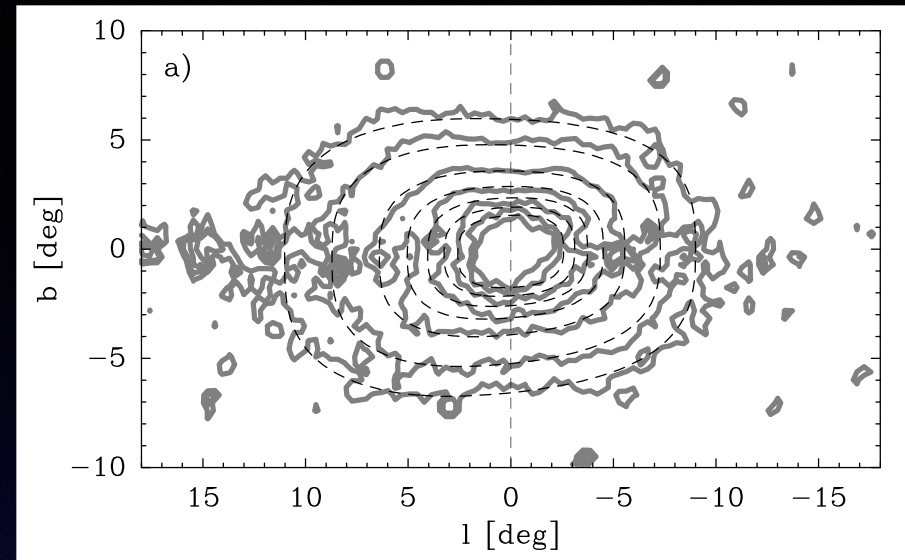
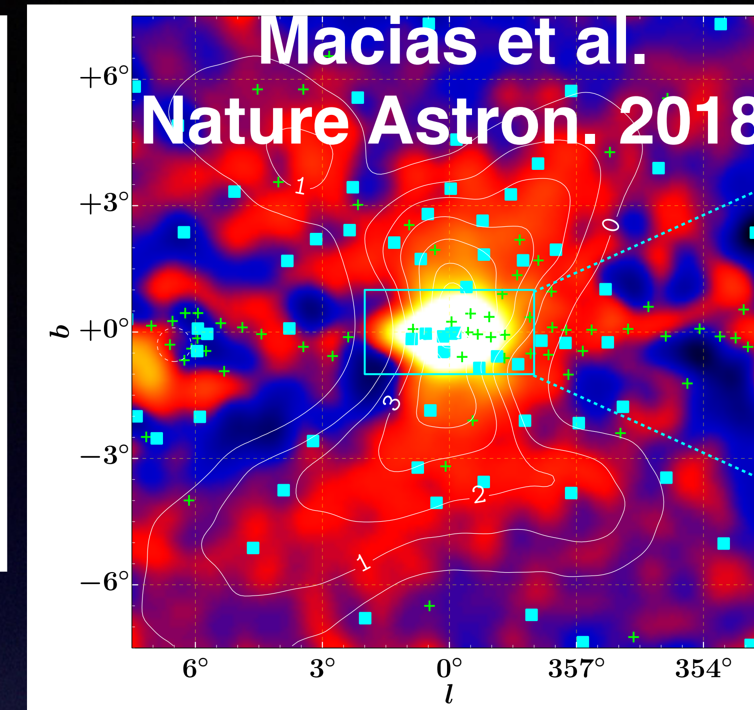


Nuclear Bulge @ Radio



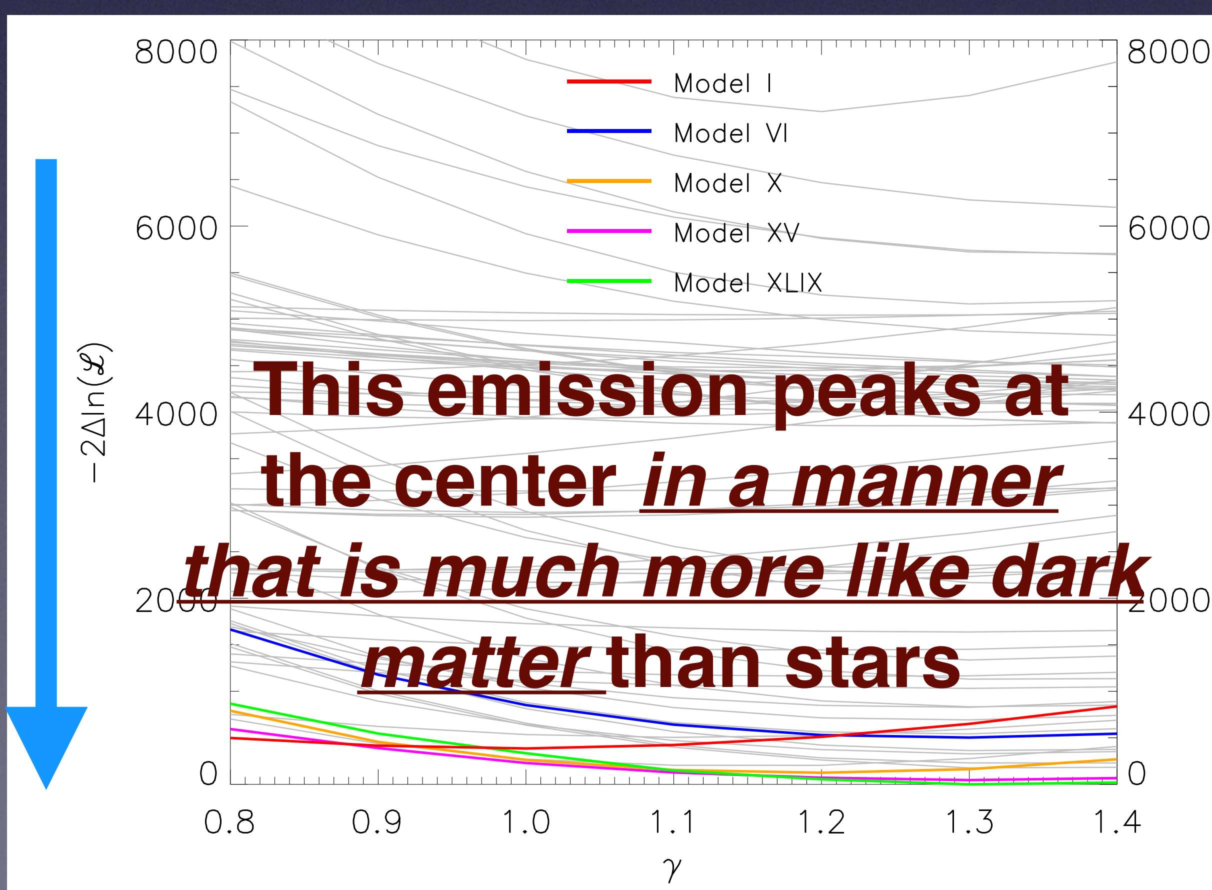
Boxy Bulge @ 2-5 µm

Launhardt et al. A&A 2002

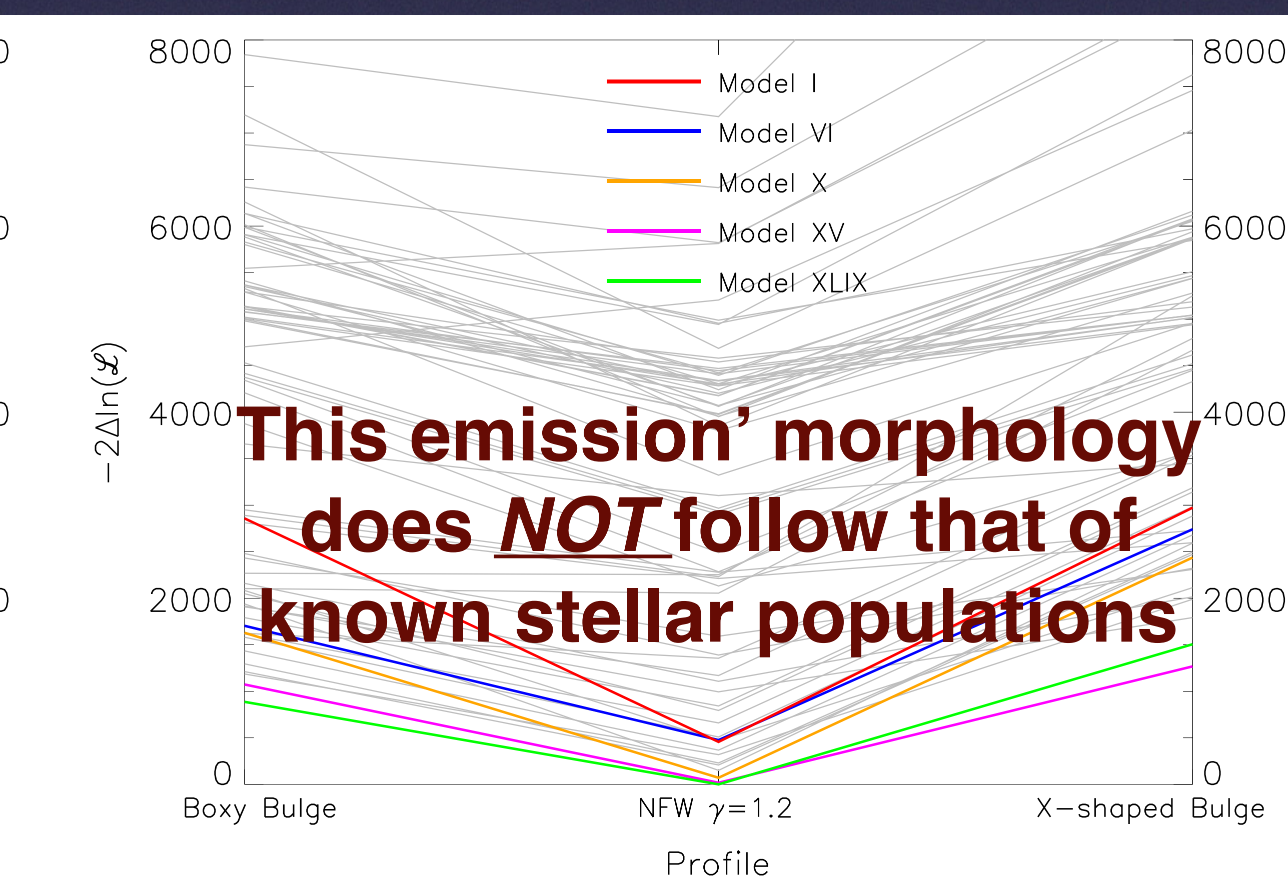


X-shaped Bulge @ "low" gamma-rays

Statistical Preference

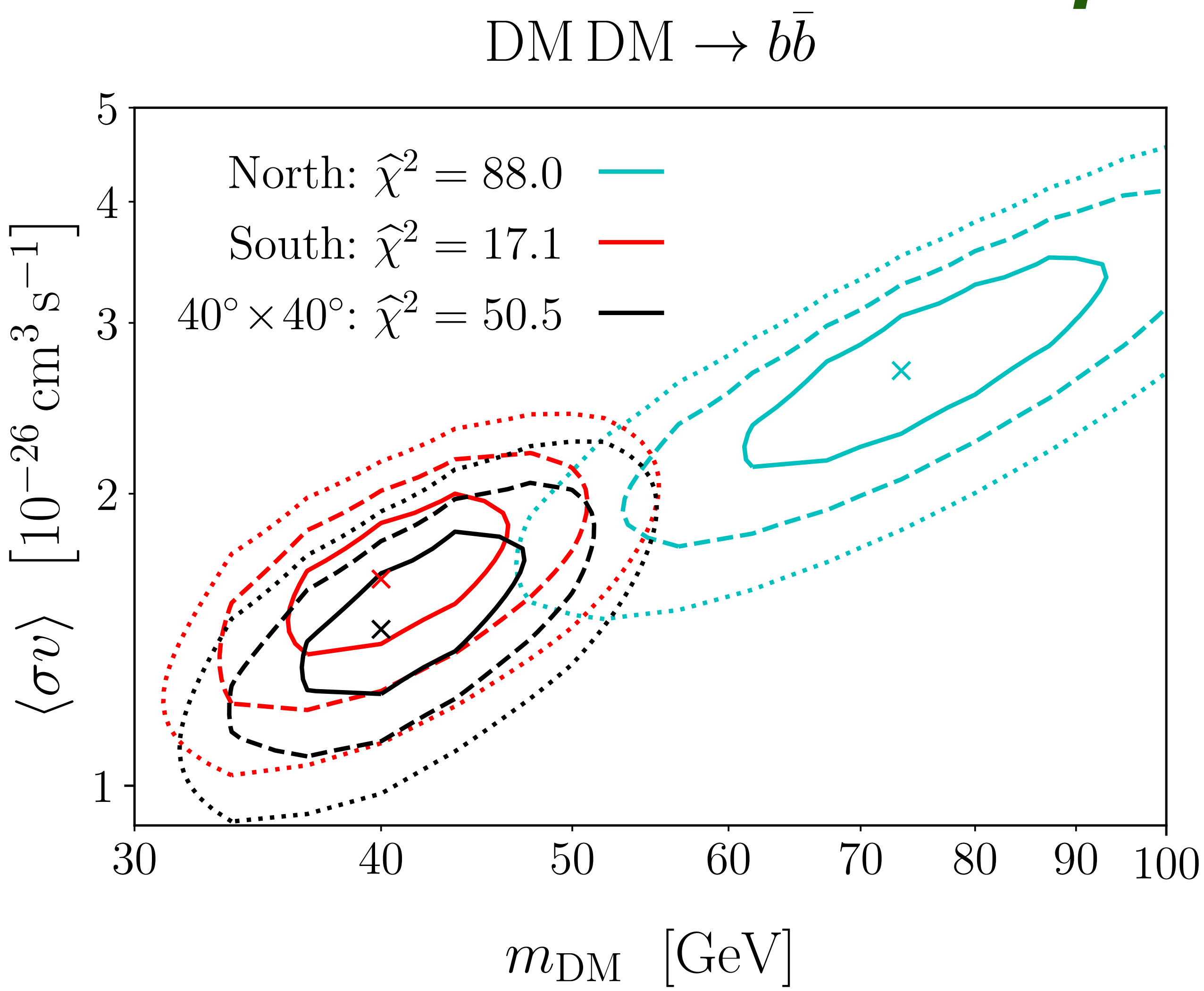


This emission peaks at the center *in a manner that is much more like dark matter* than stars

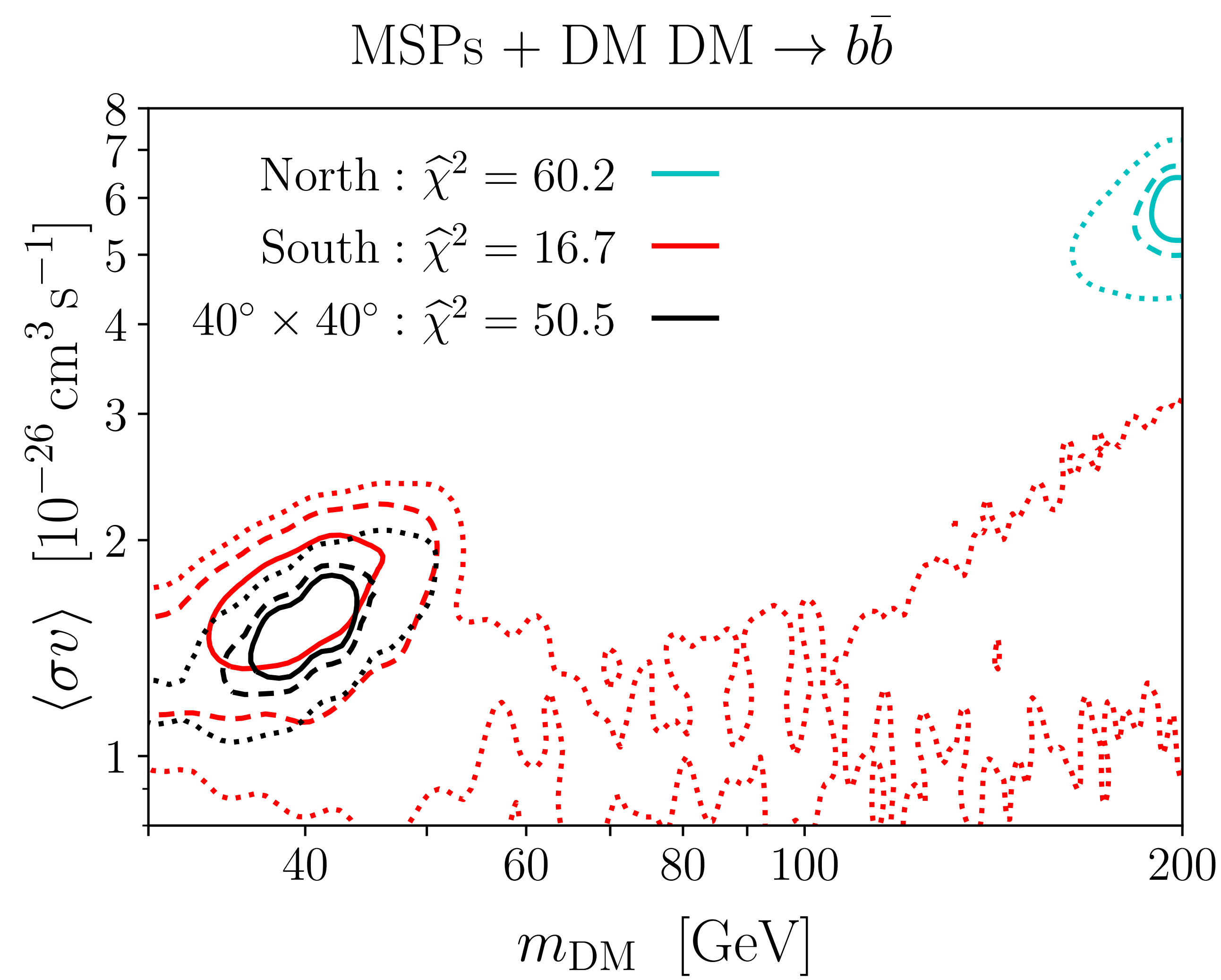


This emission' morphology does *NOT* follow that of known stellar populations

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

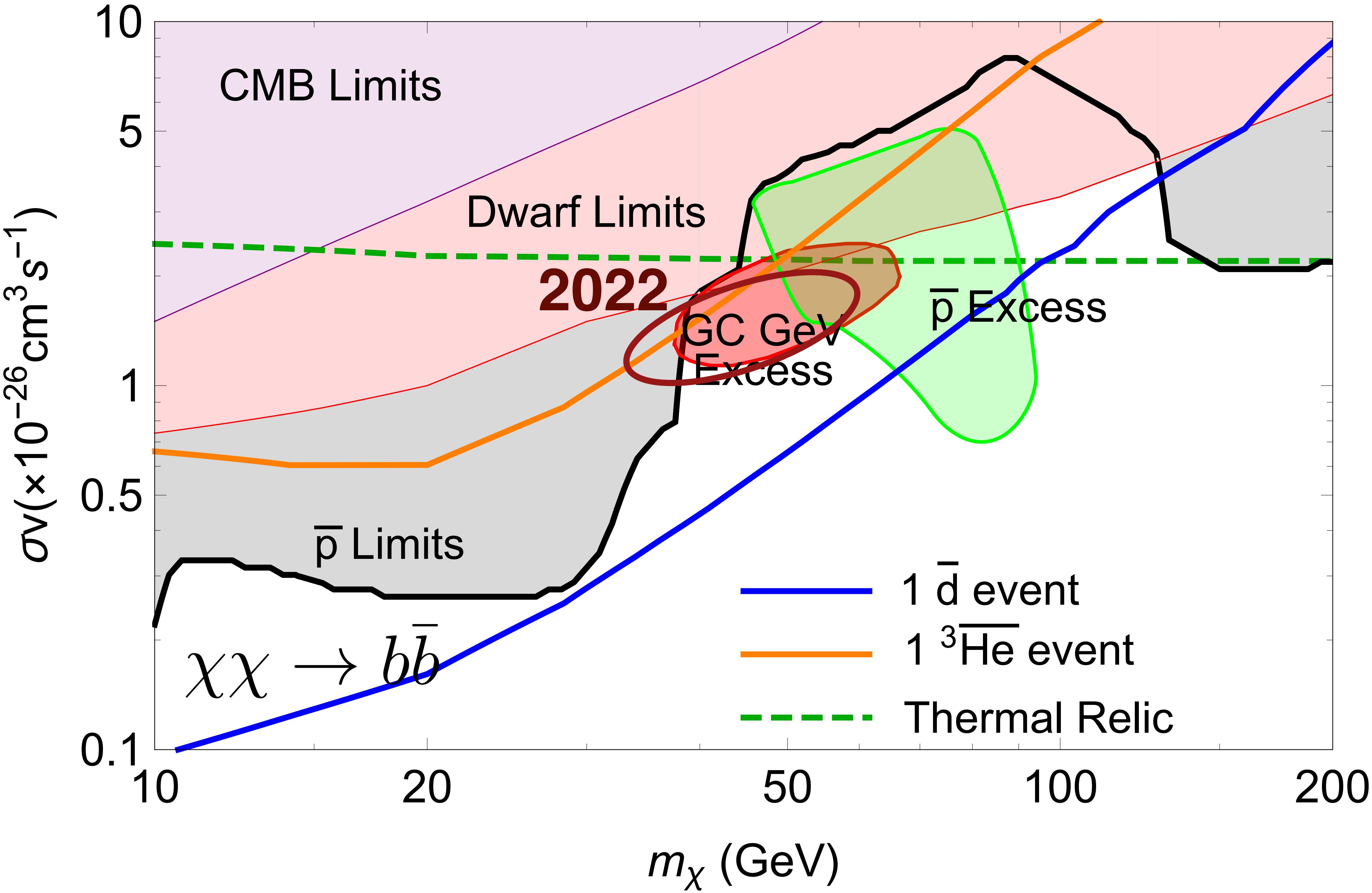


The mass range preferred very much within the WIMP range.



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)

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MSGC, NASA No. 80NSSC20M0124

Oakland University Research Fellowship

Department of Energy, DE-SC0022352

Thank you!

Extra

IC, Zhong, McDermott, Surdutovich, PRD 2022

Maps, Astrophysical Models and Correlated Errors publicly available via Zenodo

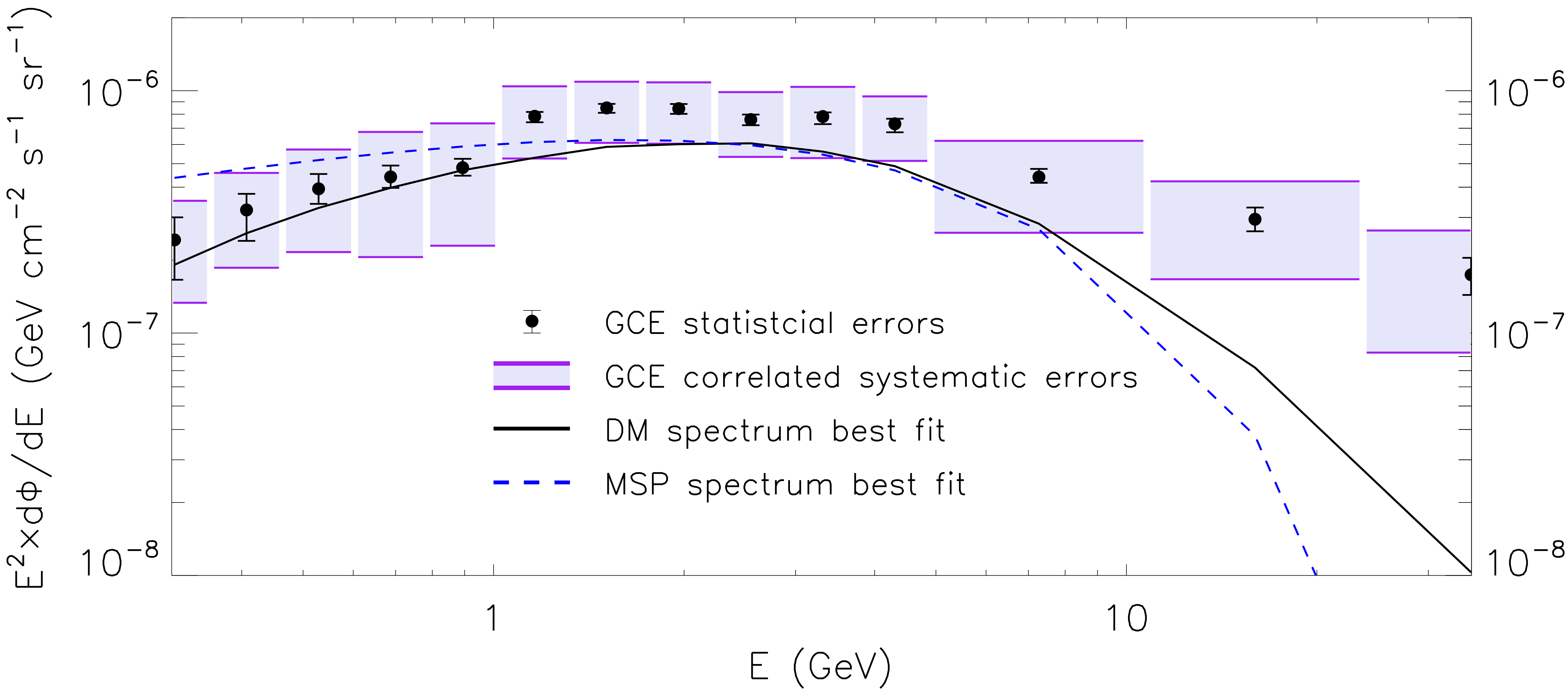
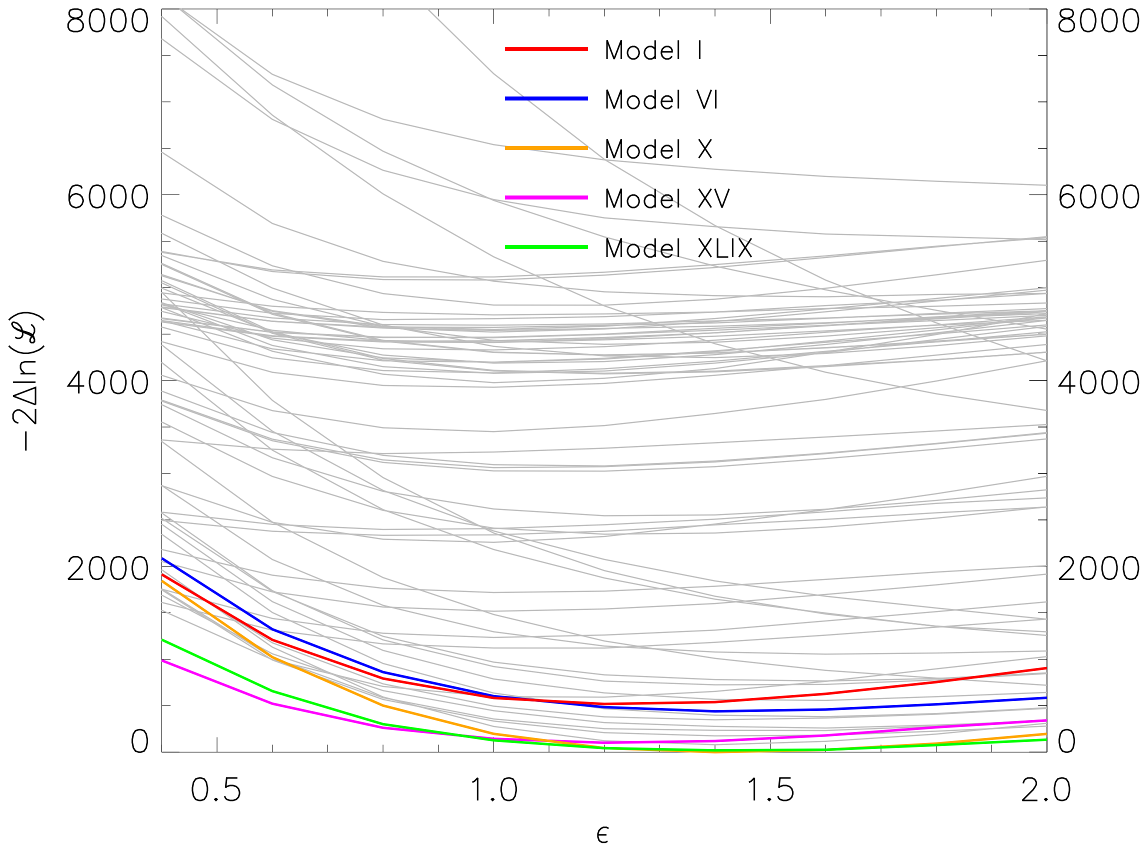
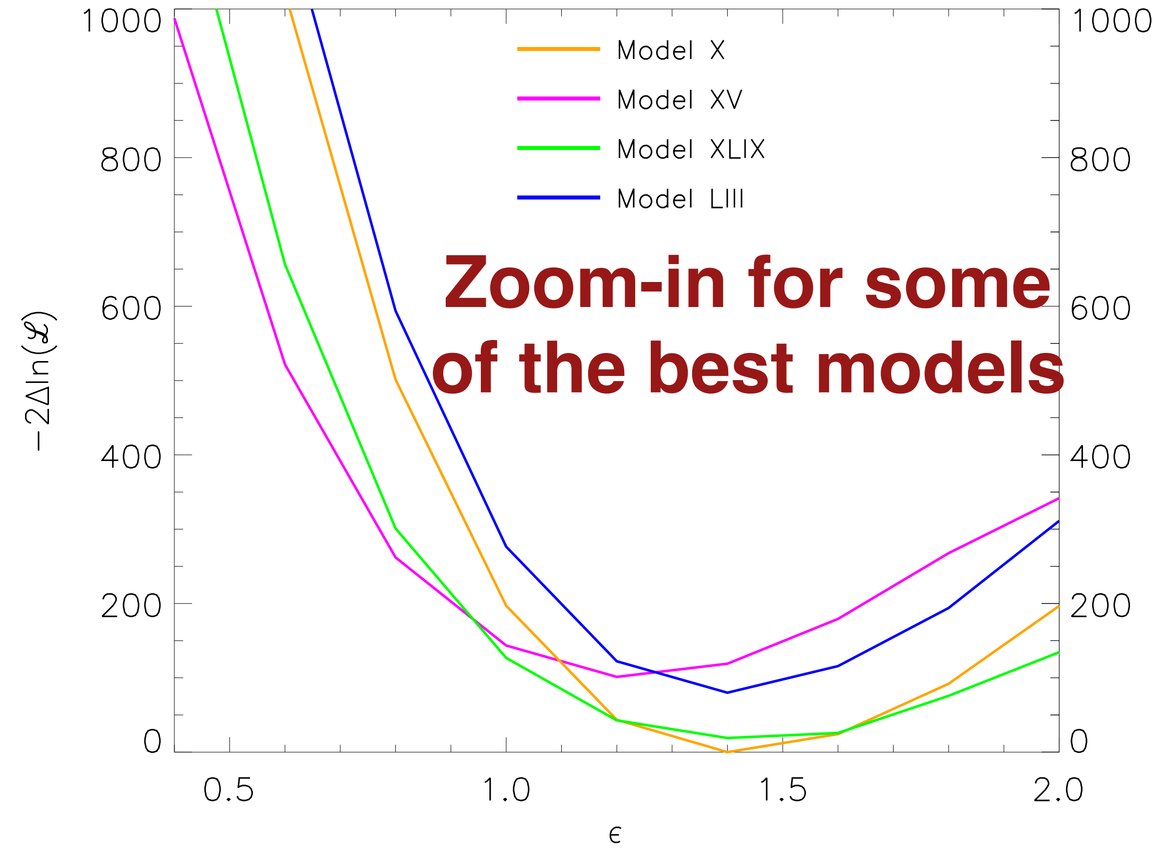


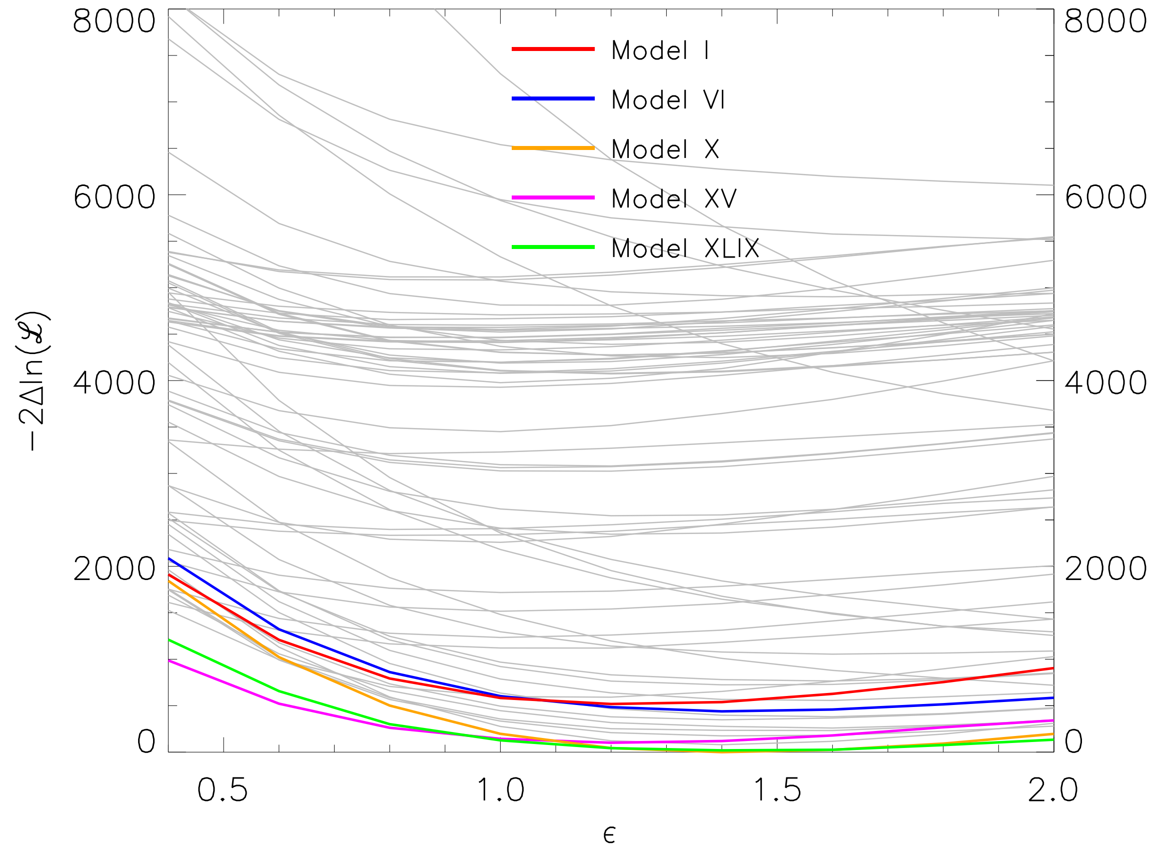
TABLE V. The first four principal components of the systematic uncertainty contribution to the covariance matrix, defined as in Eq. (16), in units of 10^{-7} GeV cm^{-2} s^{-1} sr^{-1}.

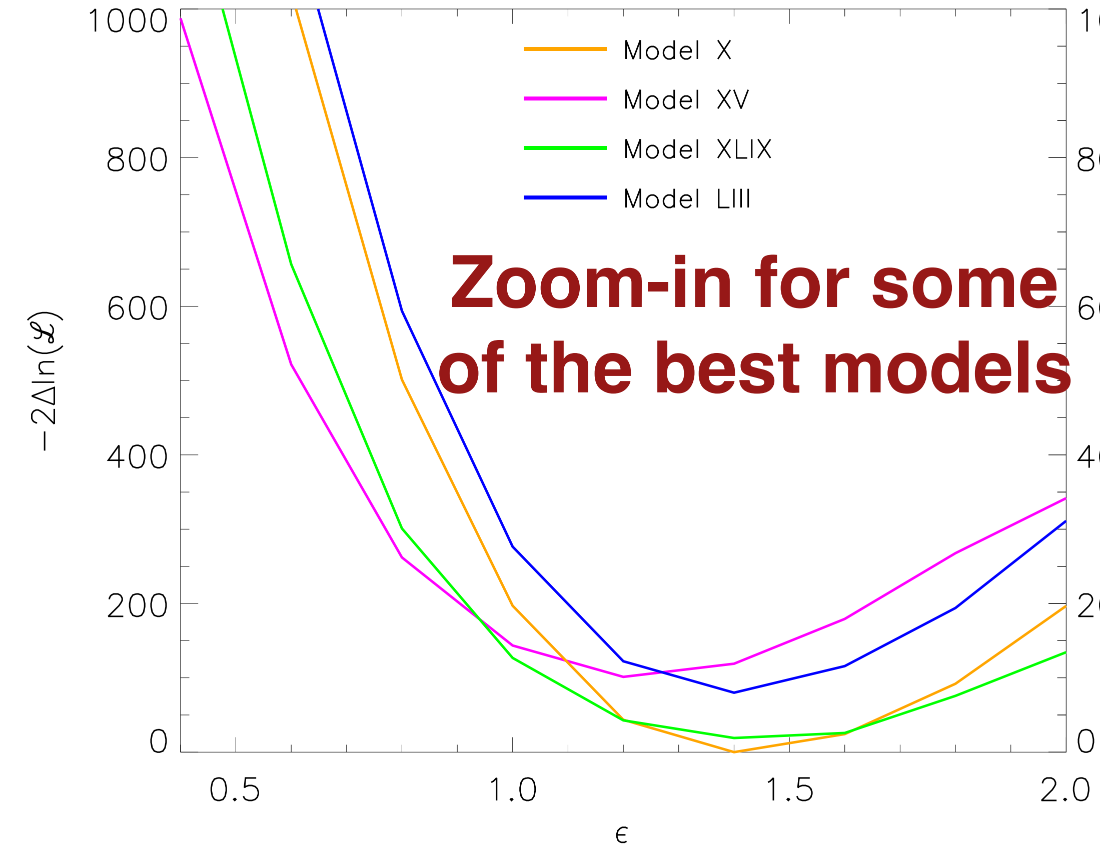
PC_i	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	Φ_6	Φ_7	Φ_8	Φ_9	Φ_{10}	Φ_{11}	Φ_{12}	Φ_{13}	Φ_{14}
PC_1	2.52	2.37	2.47	2.43	2.19	2.35	2.08	1.83	1.65	1.69	1.38	1.09	0.67	0.34
PC_2	−1.70	−1.07	−0.16	0.14	0.54	0.42	0.40	0.31	0.58	0.41	0.56	0.48	0.41	0.33
PC_3	0.27	0.06	−0.53	−0.22	−0.21	−0.18	−0.08	0.25	0.04	0.45	0.23	0.24	0.20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





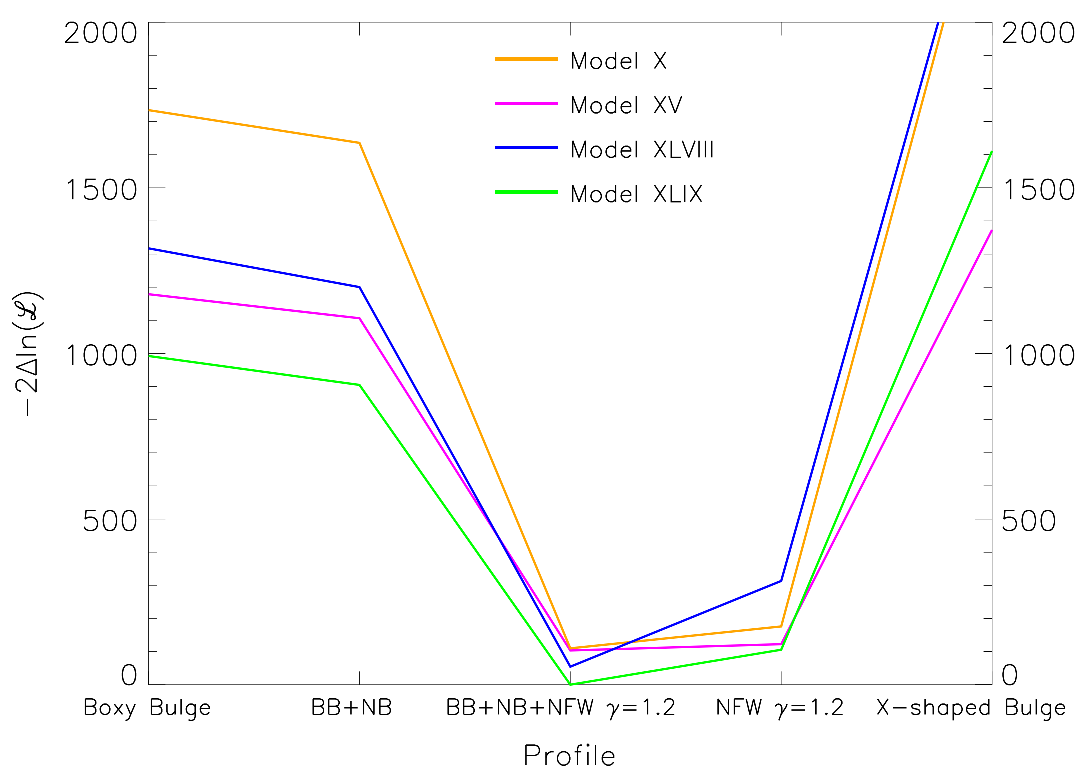
Results do not change substantively between 4FGL, 4FGL-DR2 (and also 4FGL-DR3) point source catalogues

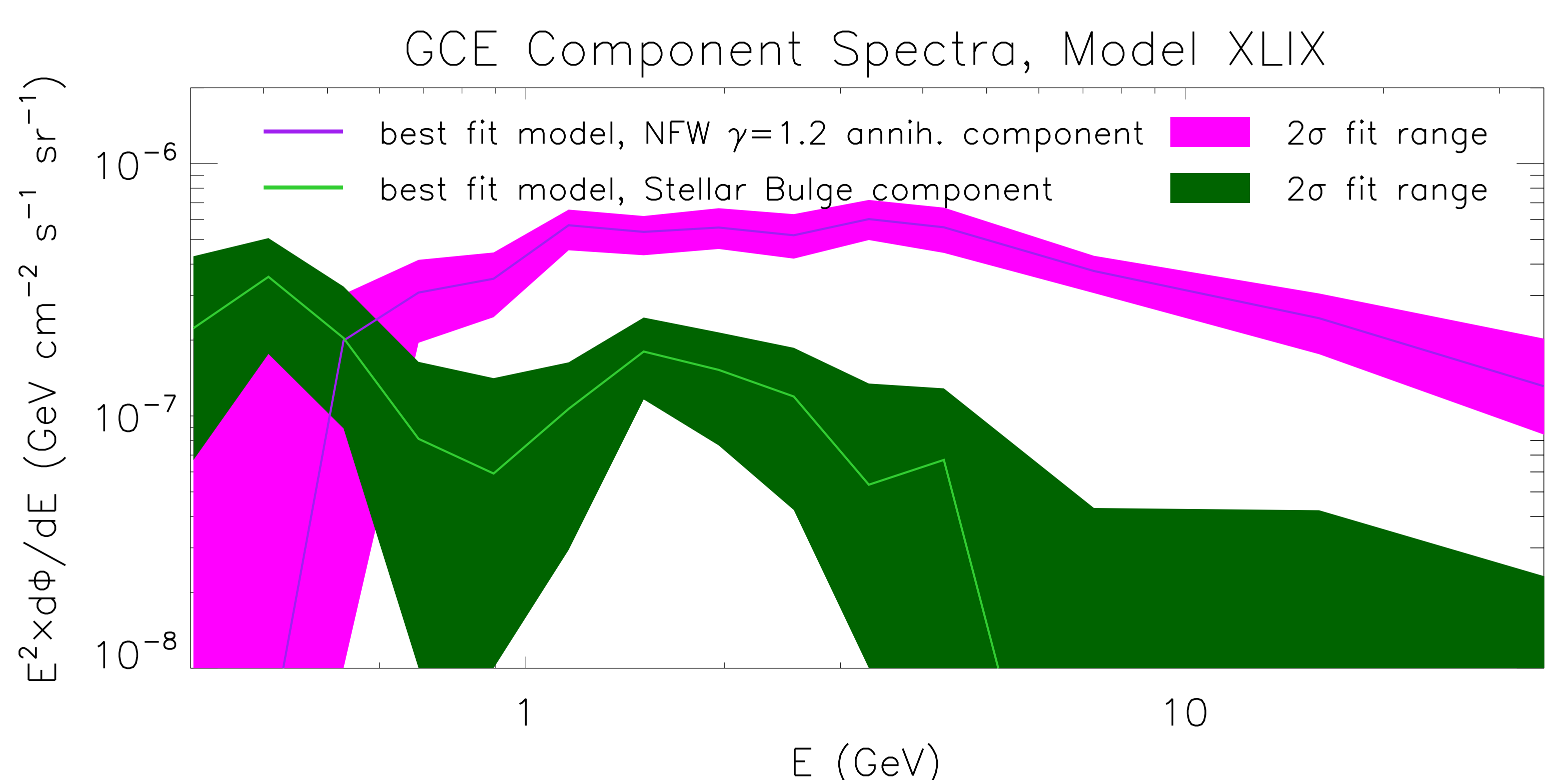




Results do not change substantively between 4FGL, 4FGL-DR2 (and also 4FGL-DR3) point source catalogues

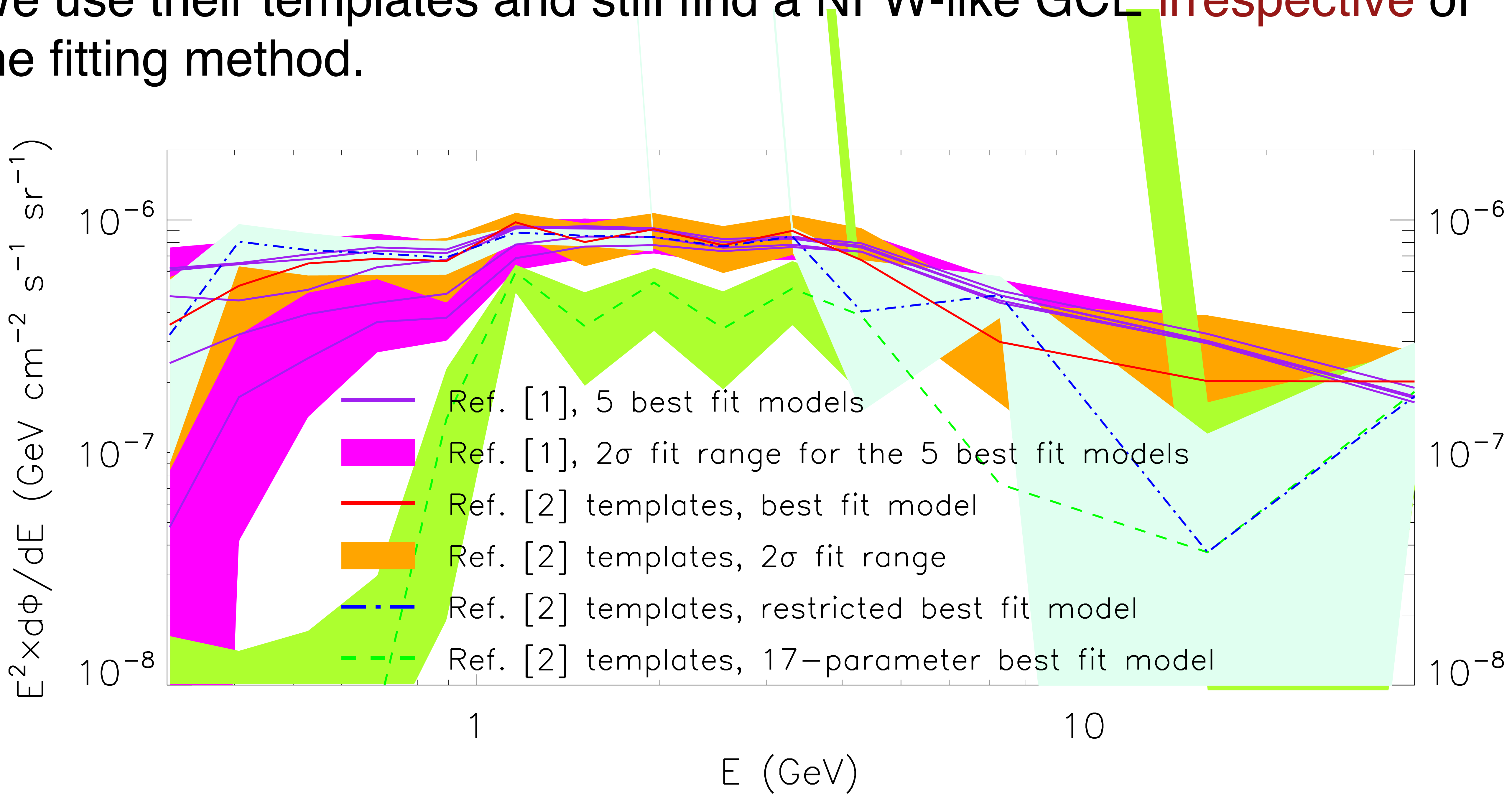
Even when we allow for an additional stellar bulge component (probing MSPs) component, we still get preference for a dominant cuspy NFW-like profile





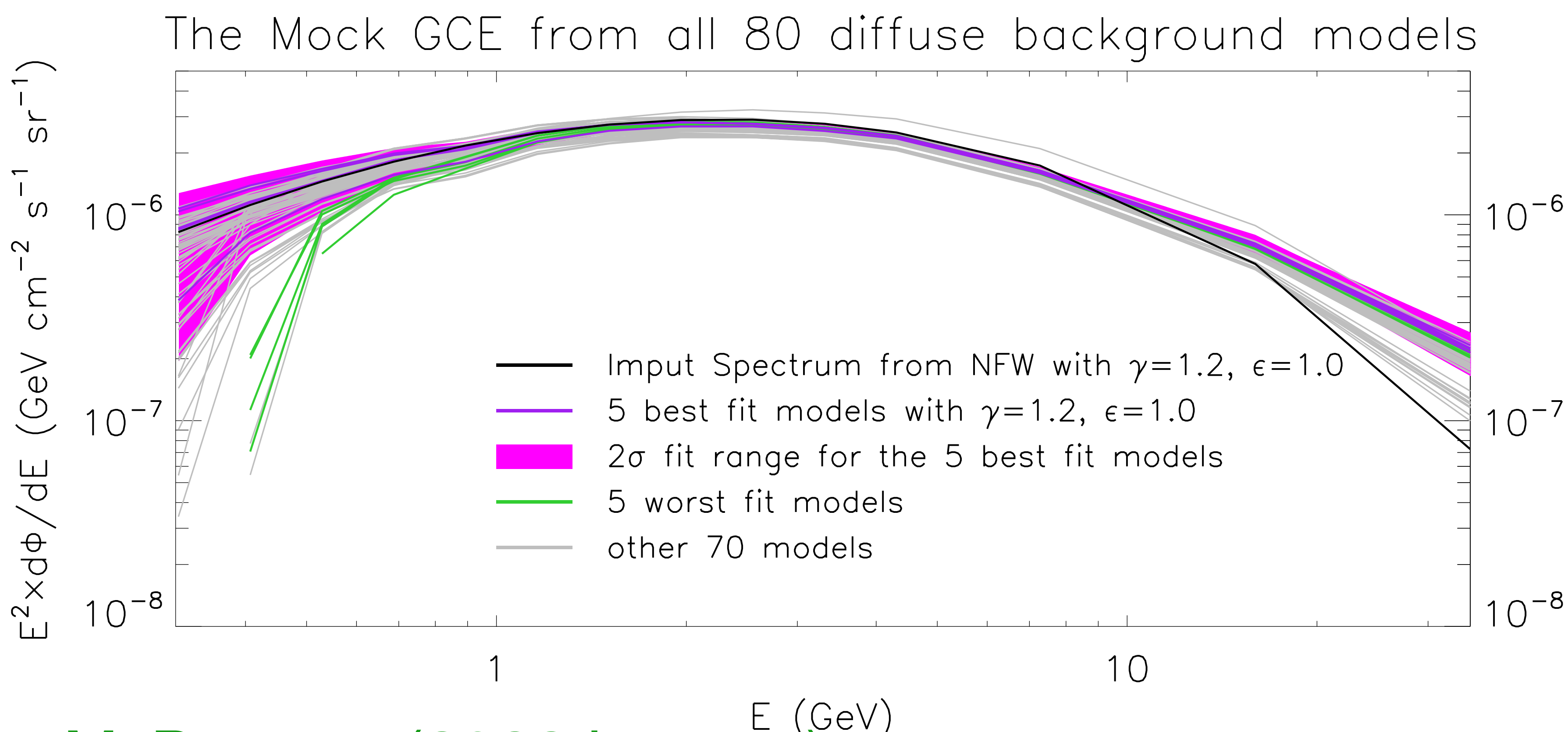
Ongoing Preliminary:

Comparison with Abazajian et al. 2020 results.
We use their templates and still find a NFW-like GCE irrespective of the fitting method.

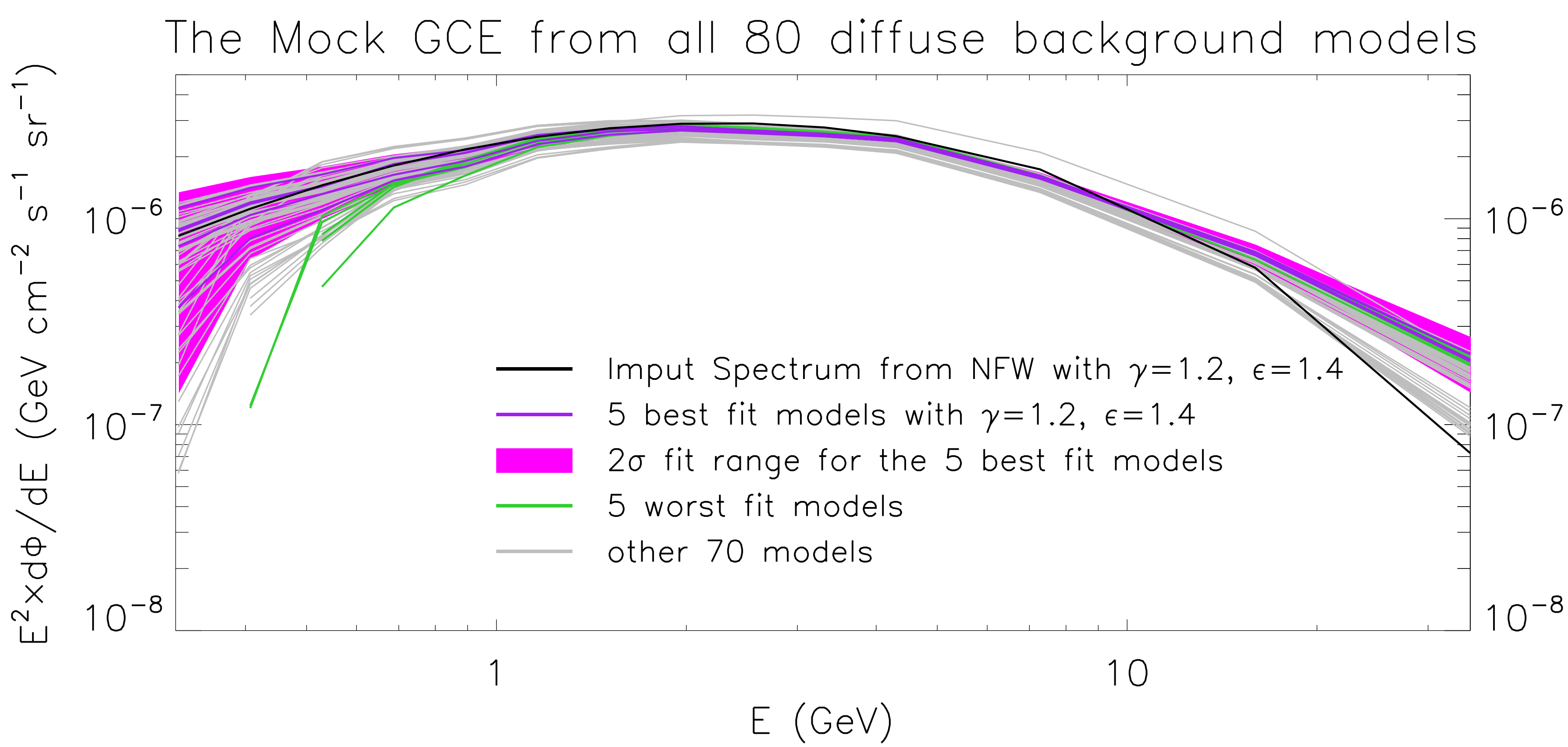


McDermott, Zhong, Cholis (2022 in prep.)

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

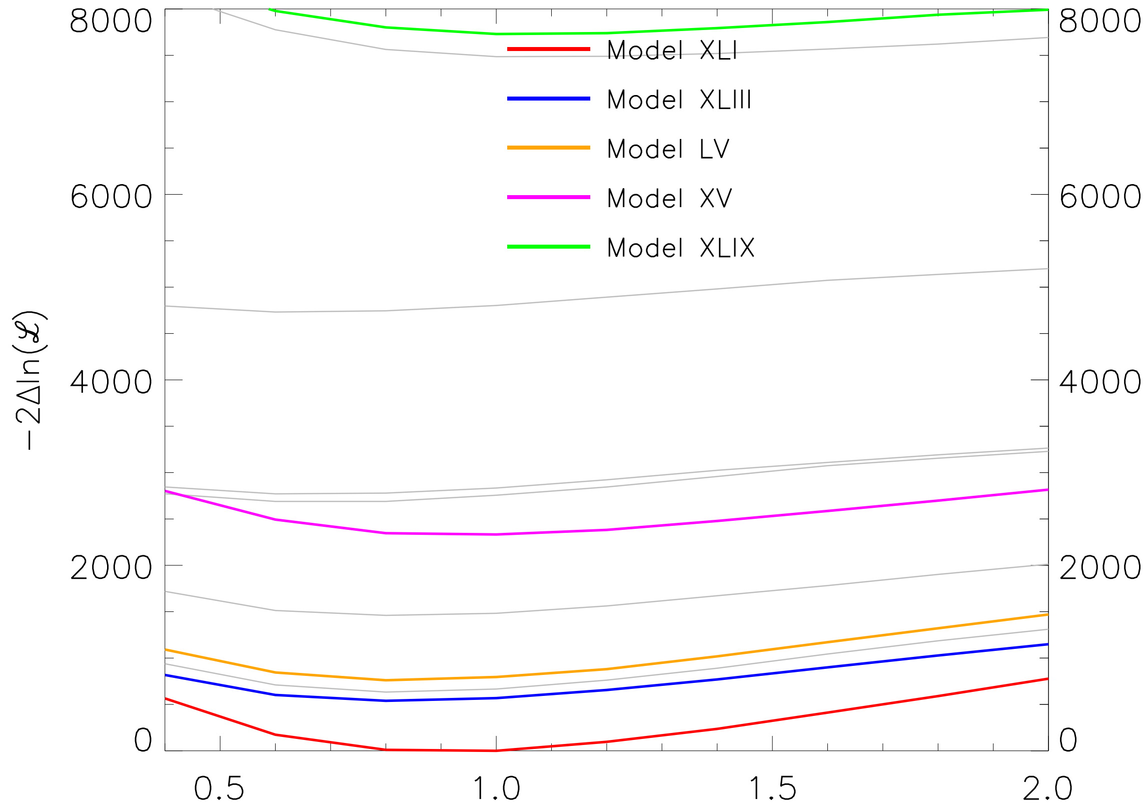


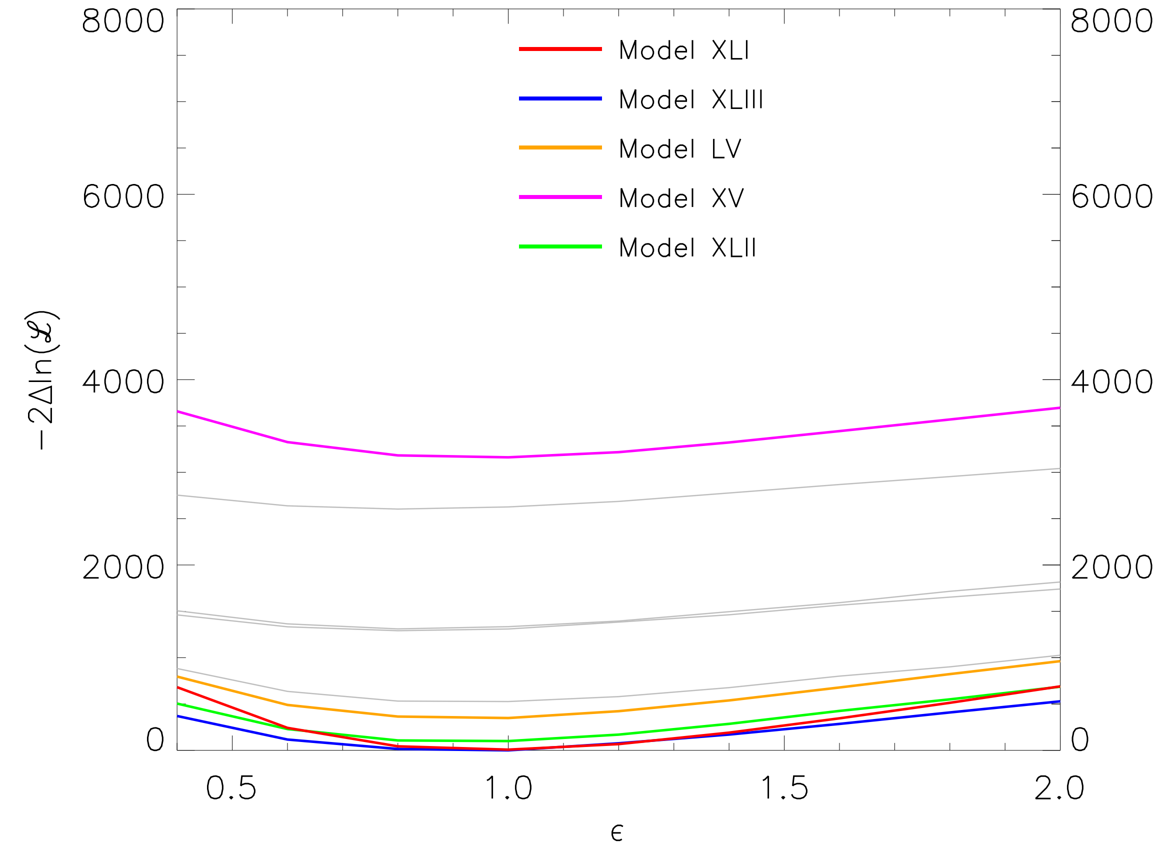
Zhong, Cholis, McDermott (2022 in prep.)



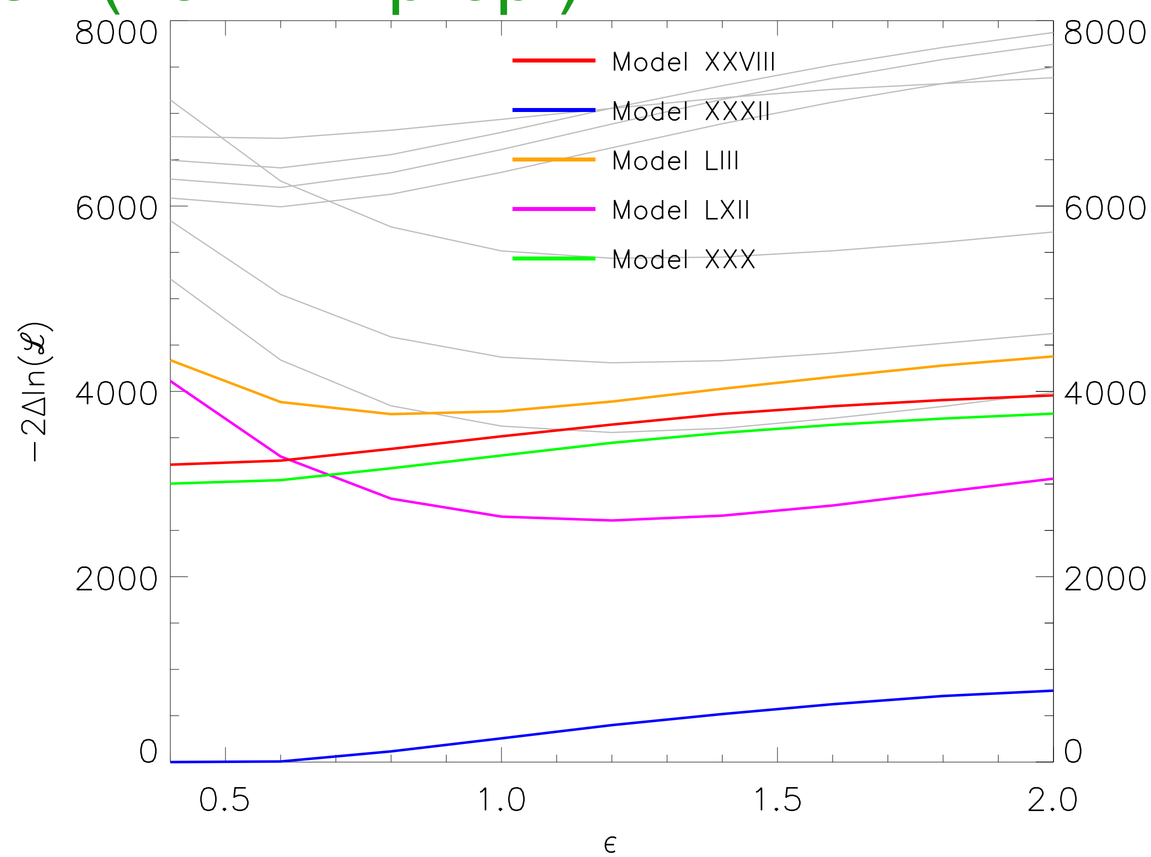
Ongoing Preliminary:

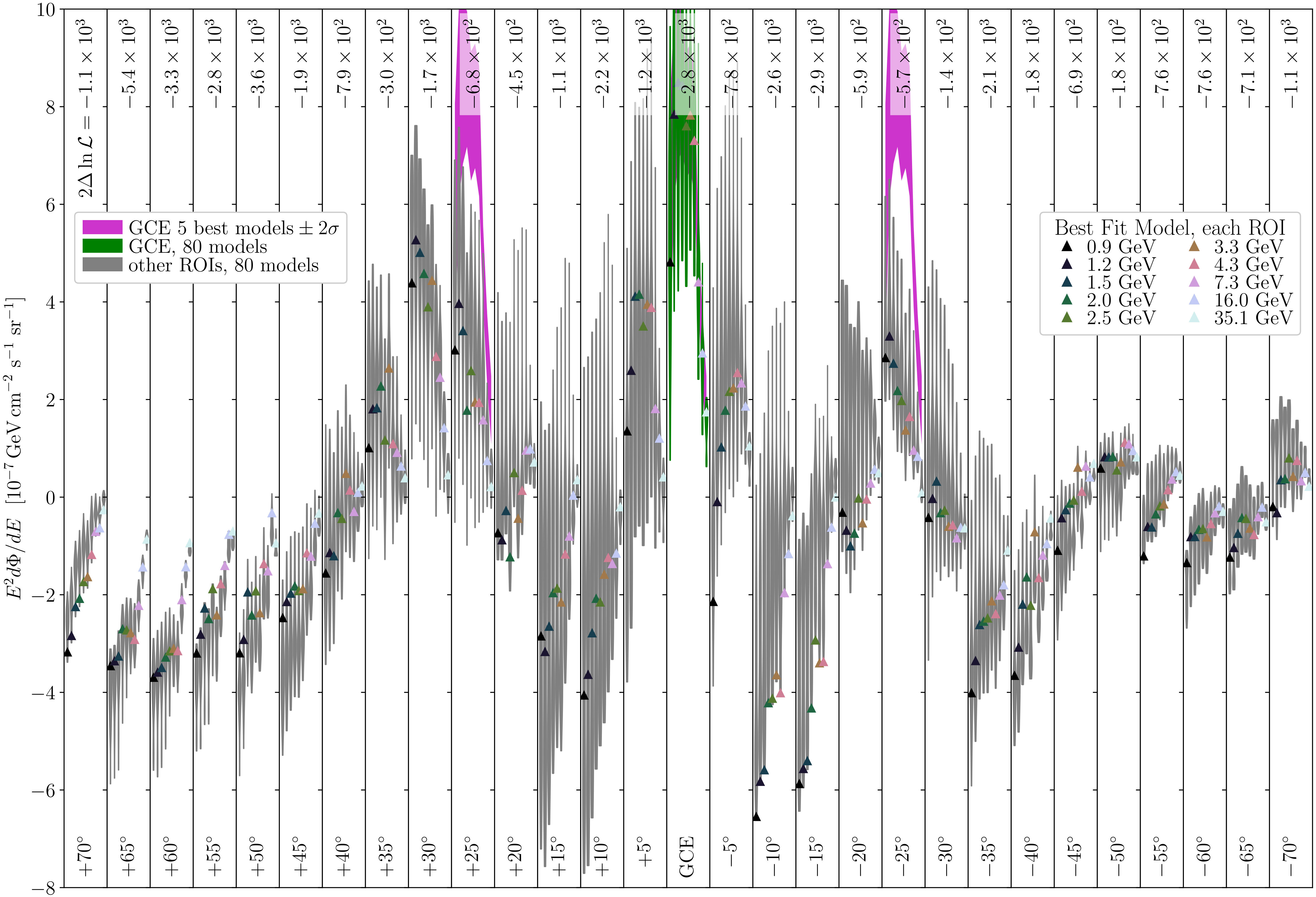
Further Tests on the GCE morphology with Alternative Wavelet based Masks:



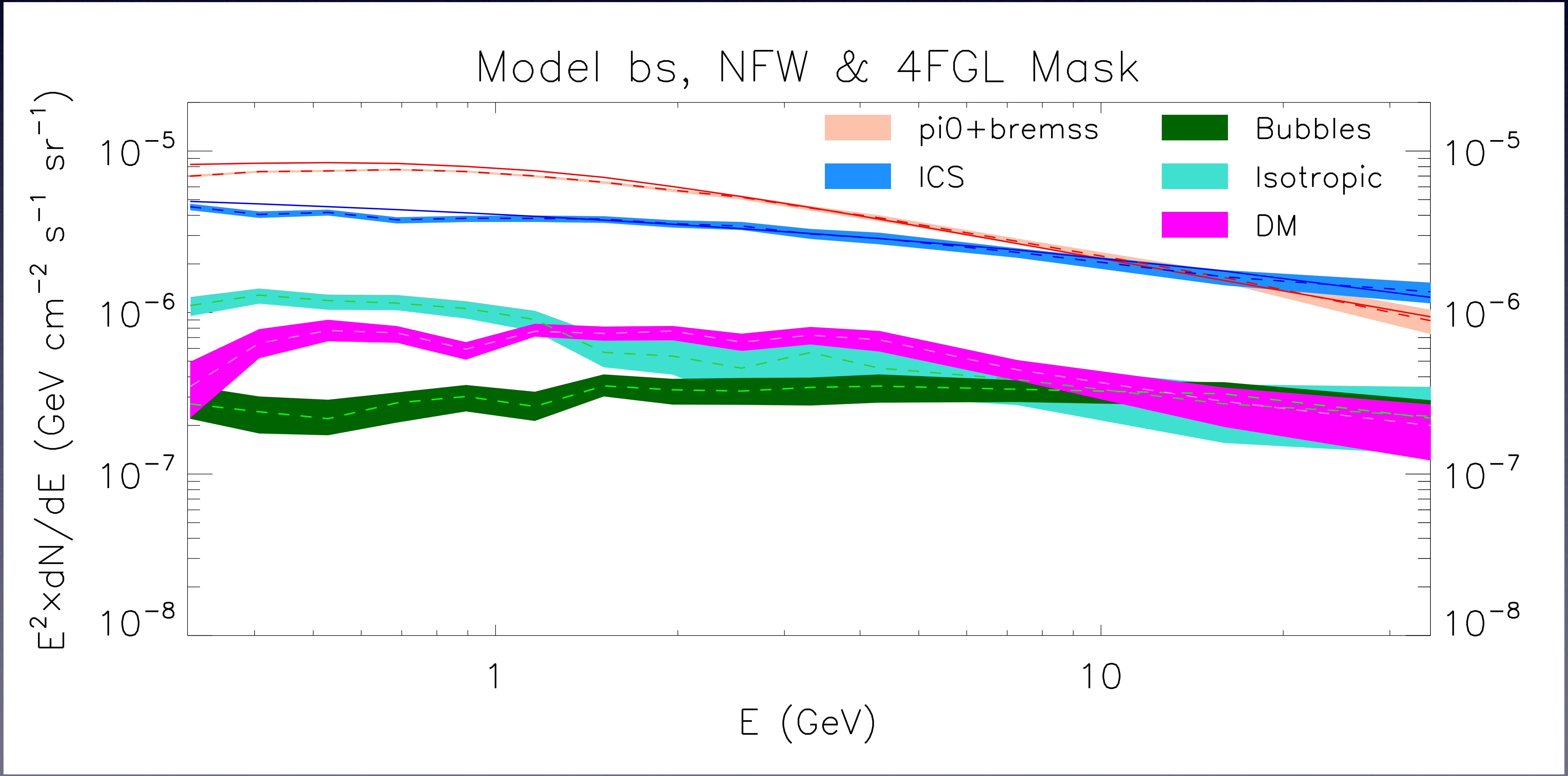


Zhong, Cholis, McDermott (2022 in prep.)

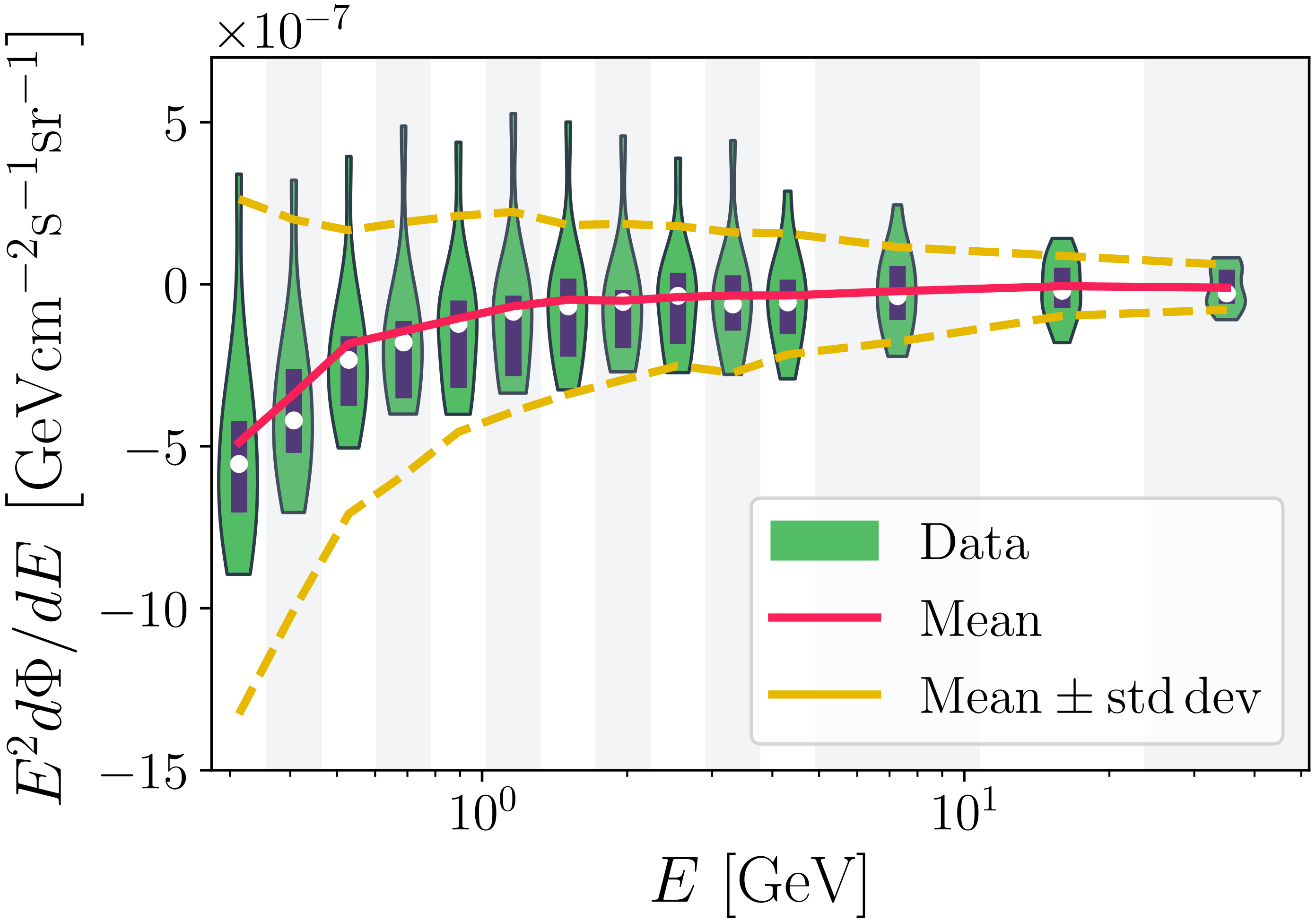




GCE 5 best models $\pm 2\sigma$
GCE, 80 models
other ROIs, 80 models
Best Fit Model, each ROI
0.9 GeV
1.2 GeV
1.5 GeV
2.0 GeV
2.5 GeV
3.3 GeV
4.3 GeV
7.3 GeV
16.0 GeV
35.1 GeV
$E^2 d\Phi/dE\ [10^{-7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}]$
$2\Delta\ln\mathcal{L} = -1.1\times10^3$
-5.4×10^3
-3.3×10^3
-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°
10
8
6
4
2
0
−2
−4
−6
−8



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



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:

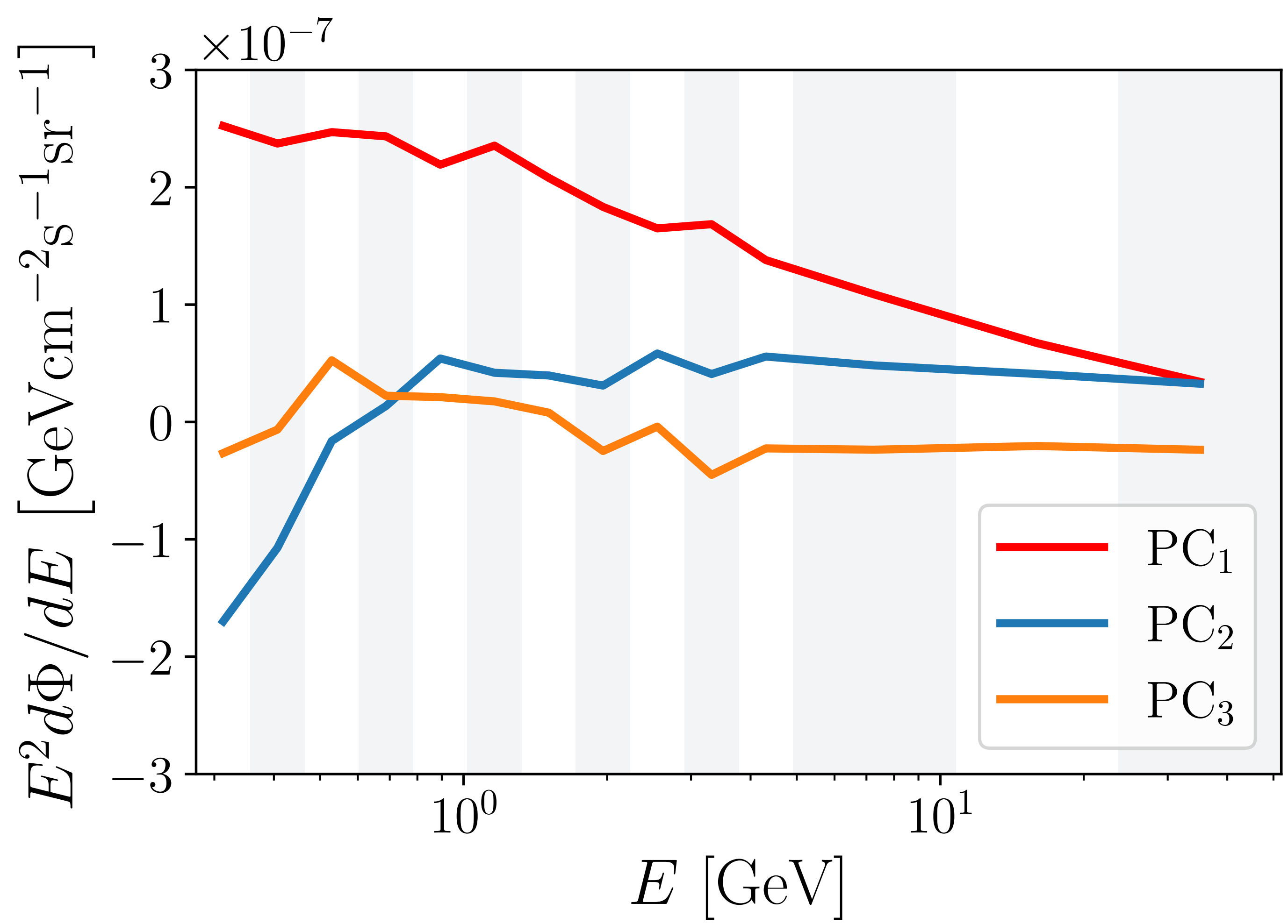
$$\Sigma_{jk,\mathrm{mod}} \simeq \Sigma^{\mathrm{trunc}}_{jk,\mathrm{mod}} \equiv \sum_{i=1}^{3} \mathrm{PC}^{\mathsf{T}}_{ij}\mathrm{PC}_{ik}$$

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:

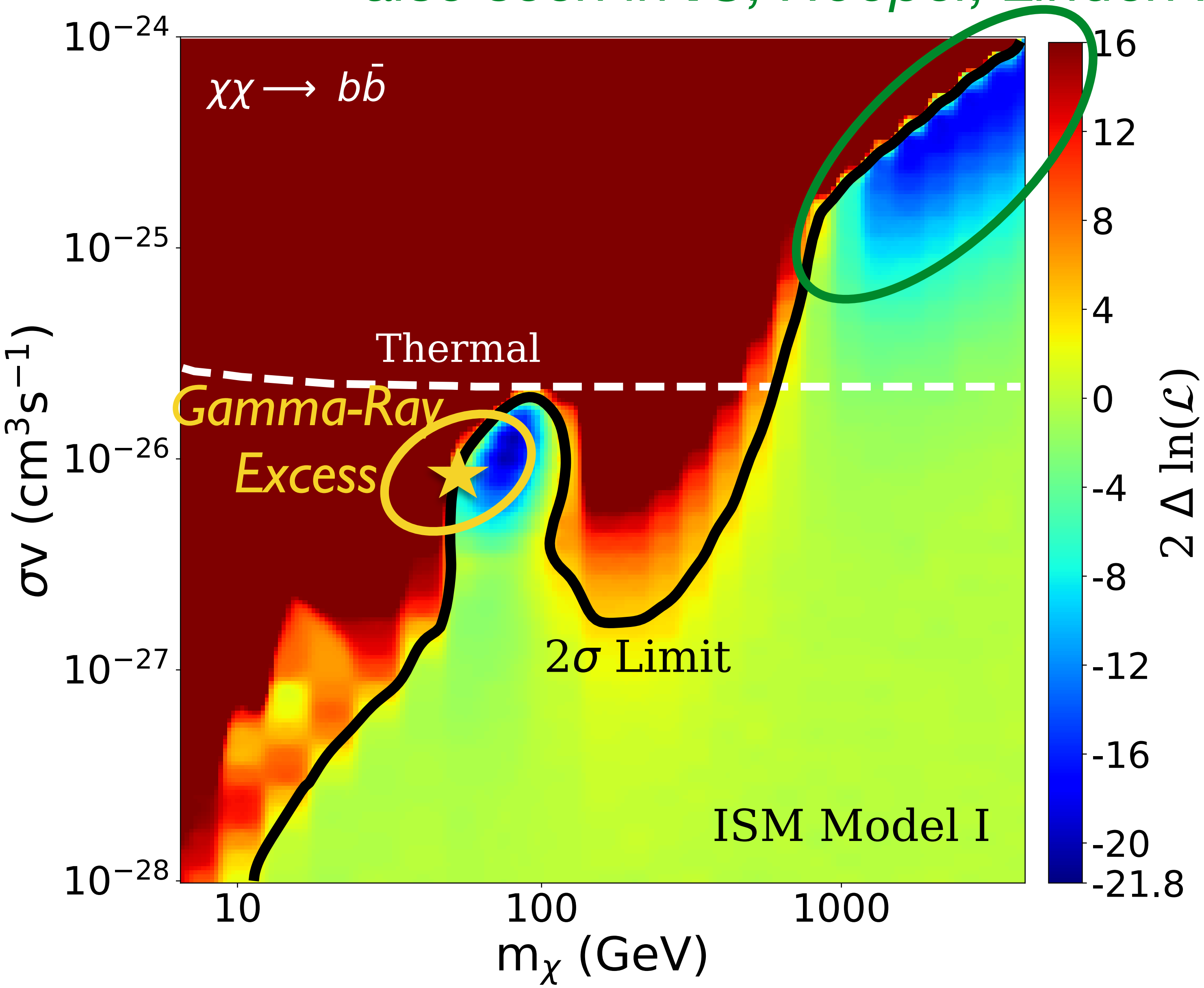
$$C_{ij} = \sigma_i^2 \delta_{ij} + \Sigma_{ij,\mathrm{mod}}$$

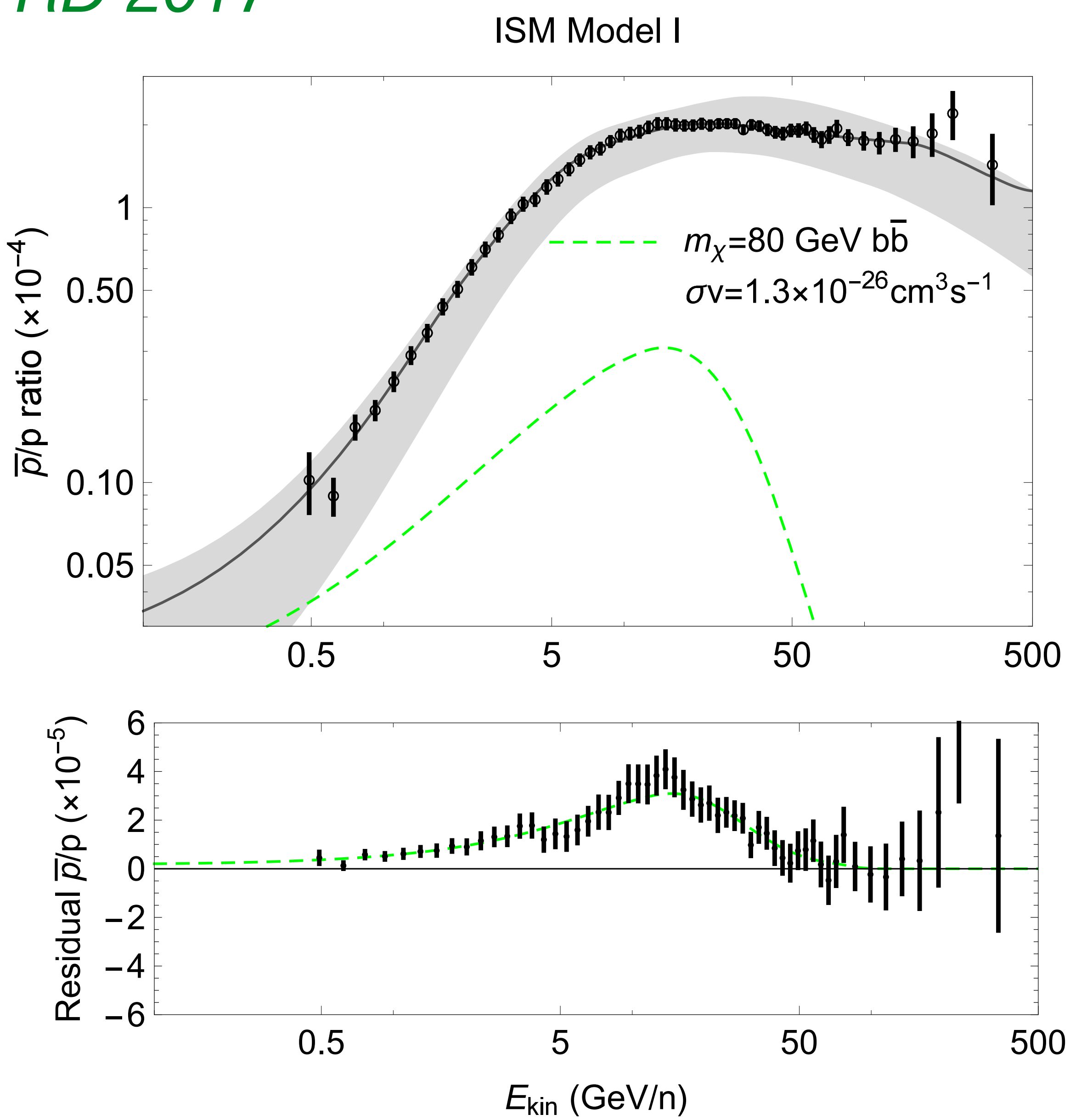


Looking at the antiproton to proton ratio find an the excess at~3 sigma

Supernova,

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





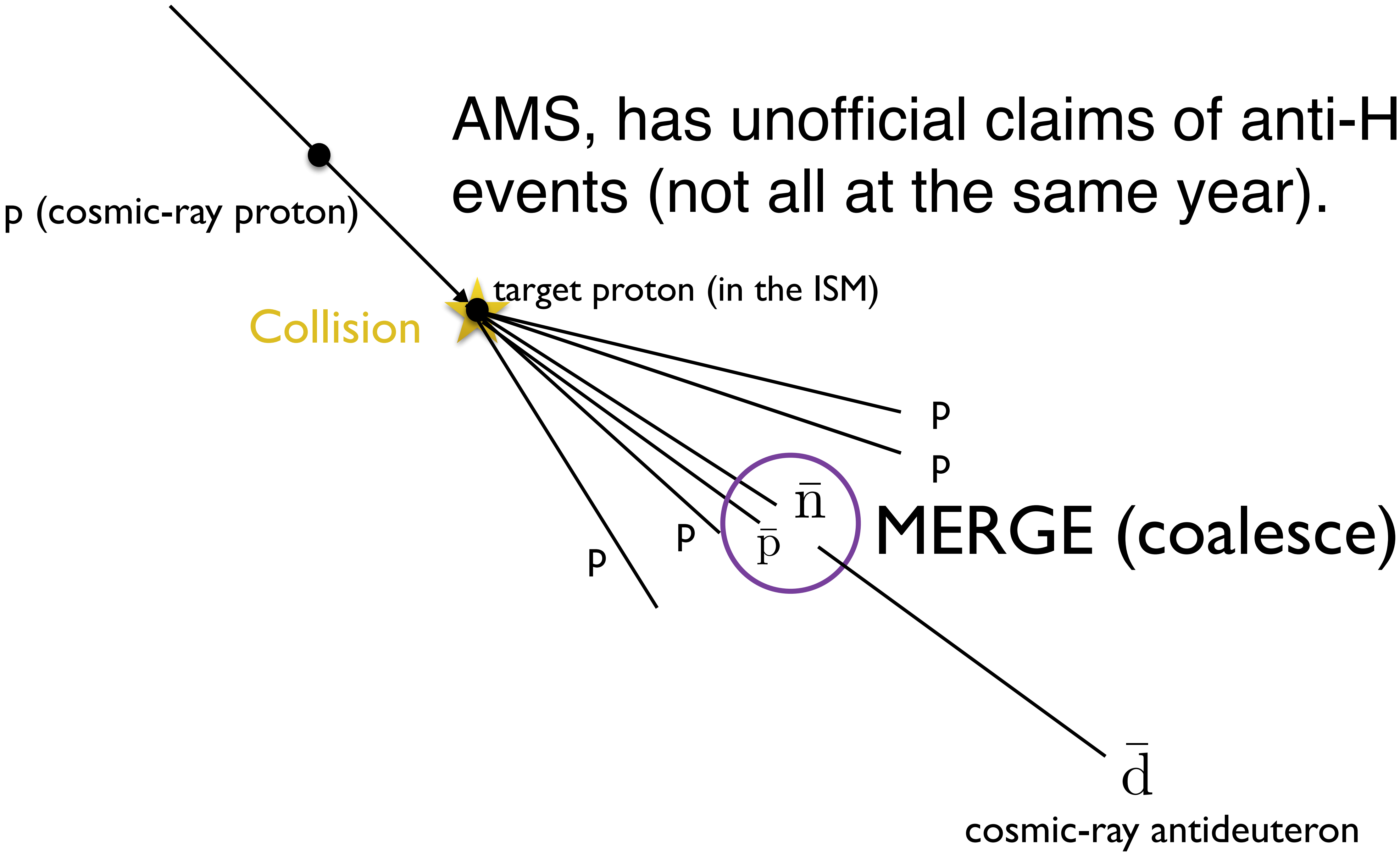
IC, Tim Linden, Dan Hooper PRD 2019

See also A. Cuoco et al. PRD 2019

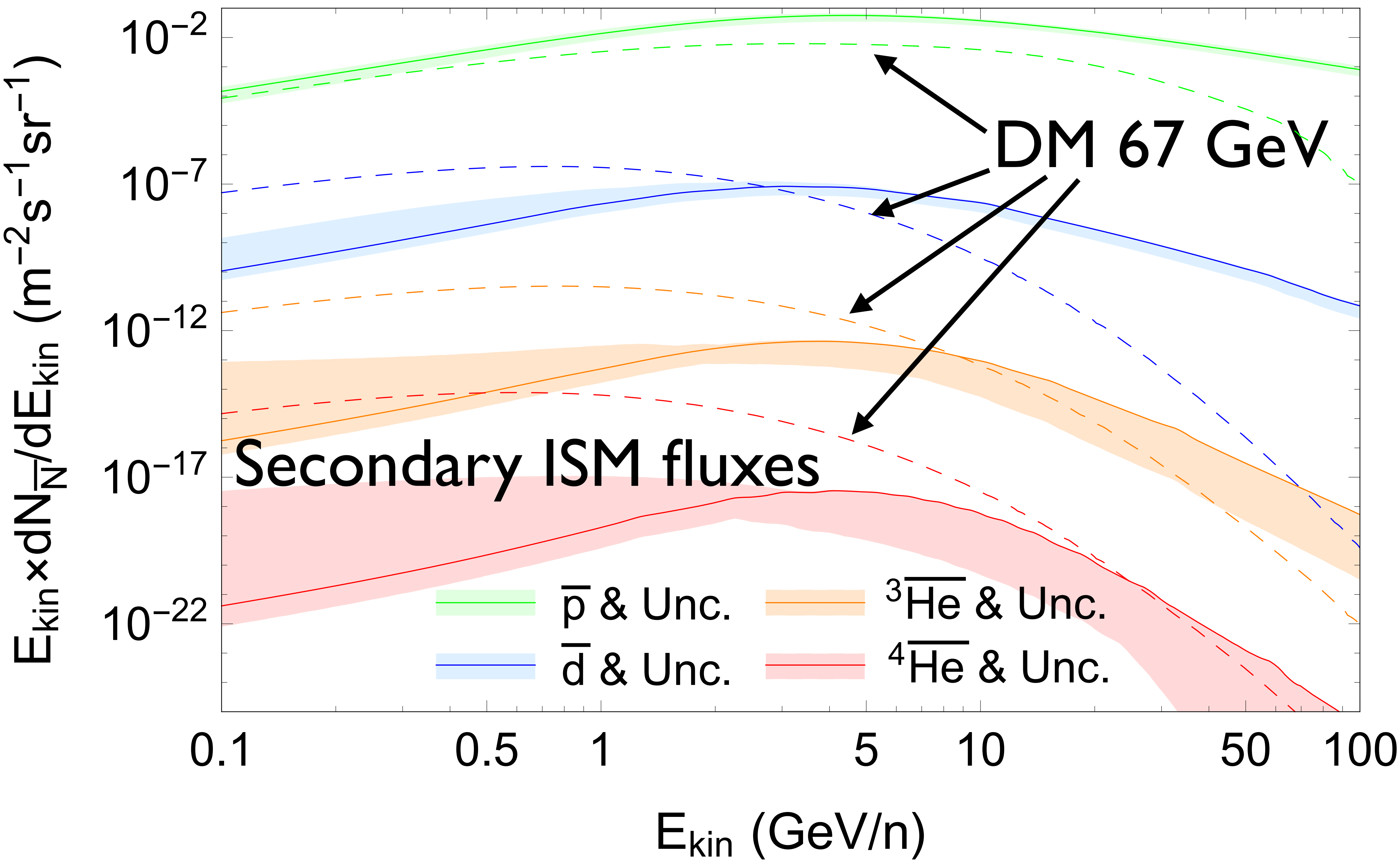
Earlier results: Cuoco et al. PLR 2017,Cui et al. PRL 2017

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

PHYSICAL REVIEW D **105,** 023015 (2022)

And a little extra positrons….

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

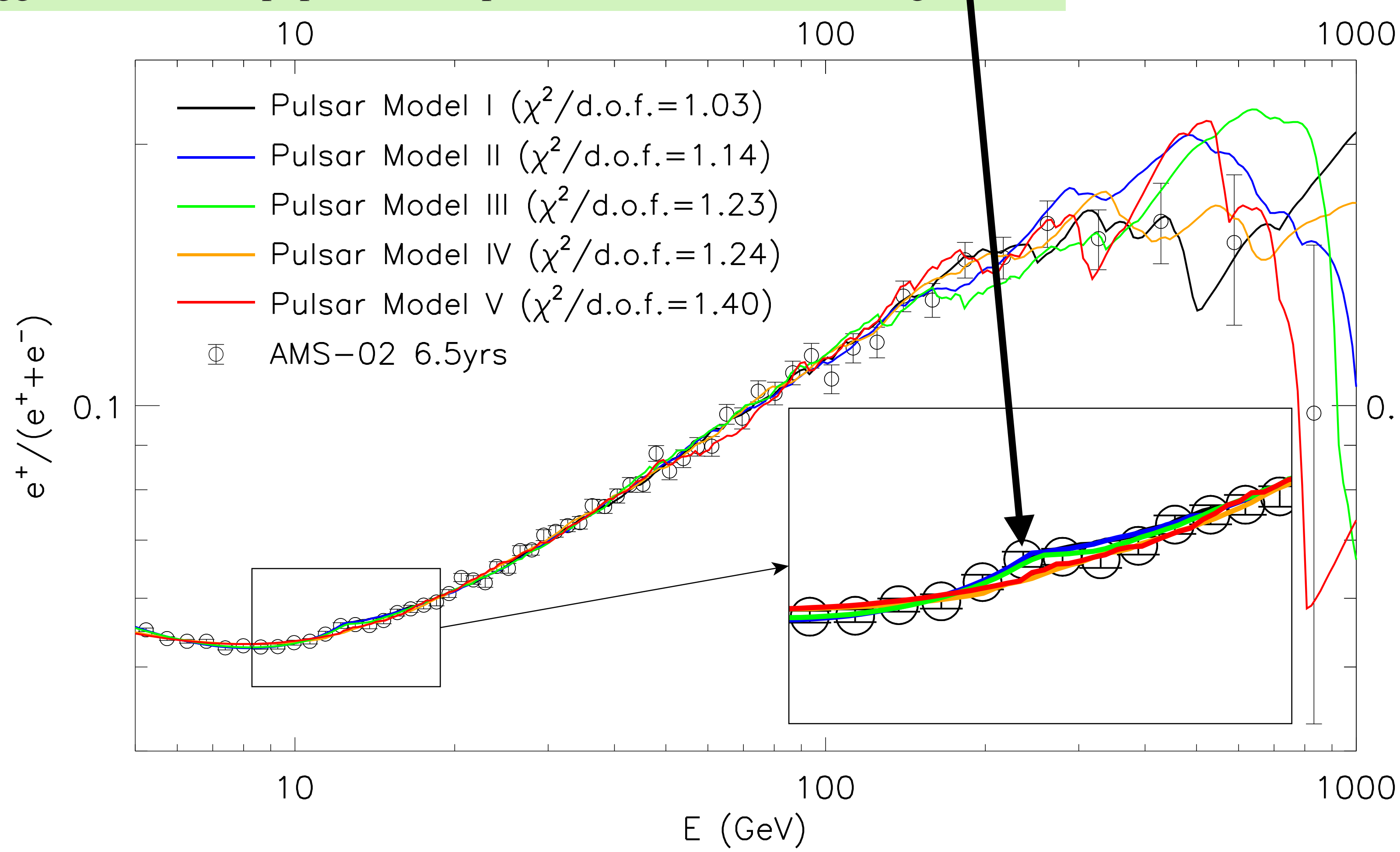
Ilias Cholis[1*] and Iason Krommydas[2†]

[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*

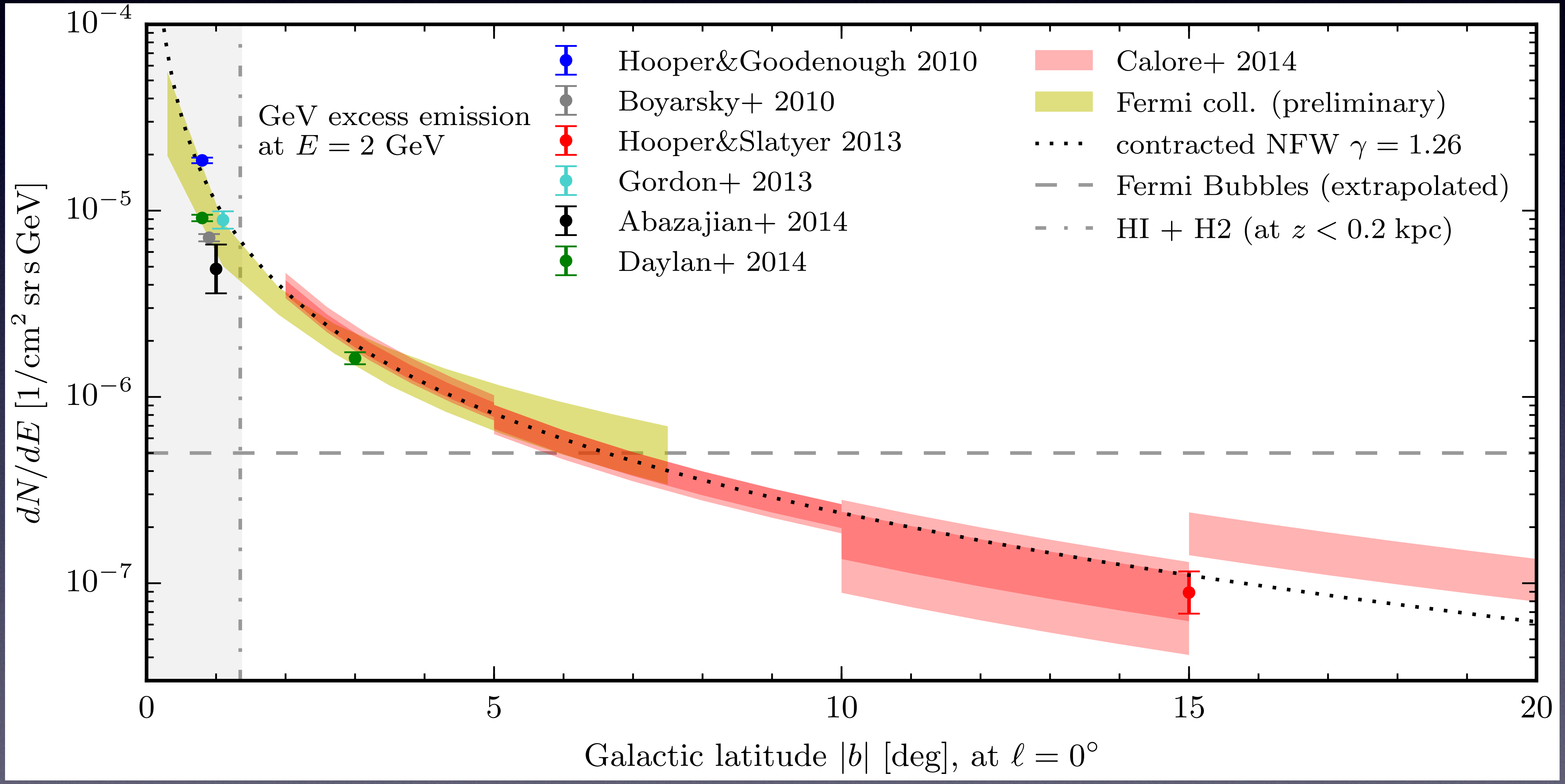
and likely release $O(10\%)$ of their rotational energy to cosmic rays in the ISM. Finally, we find at ≃12 GeV positrons a spectral feature that suggests a new subpopulation of positron sources contributing at these energies.



The 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:

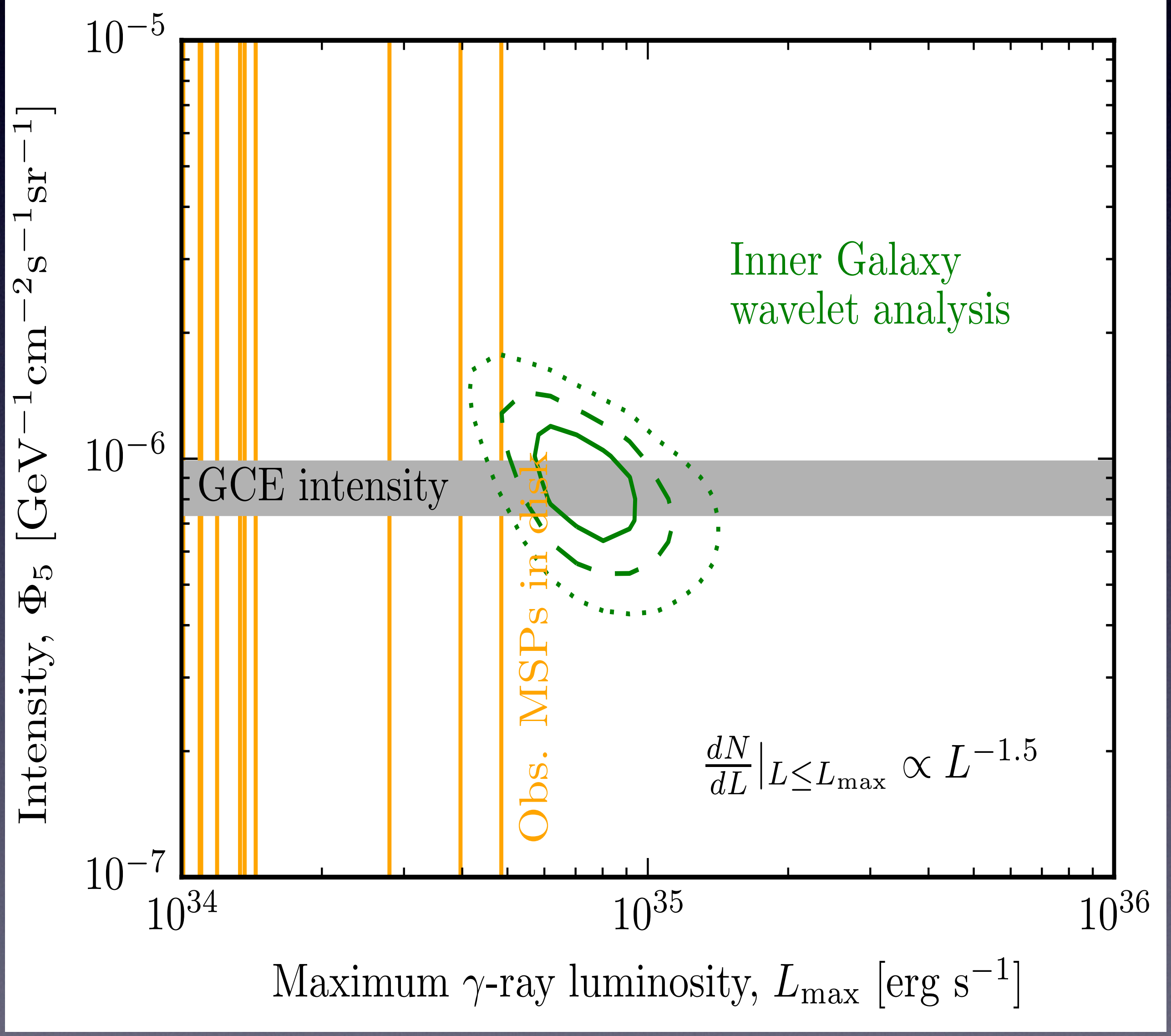
Calore, **IC,** McCabe, Weniger, PRD 2015



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

A simple Question: Can the CSP Be Bright Enough?

- Given an assumption about the "luminosity function" (the dependence of N_{PS} on L_{PS}), can ask if "point source-y" PSs are compatible with unresolved PSs accounting for the GCE
- Claim in 2015 was "yes" if the luminosity function had a power-law index α_L=1.5

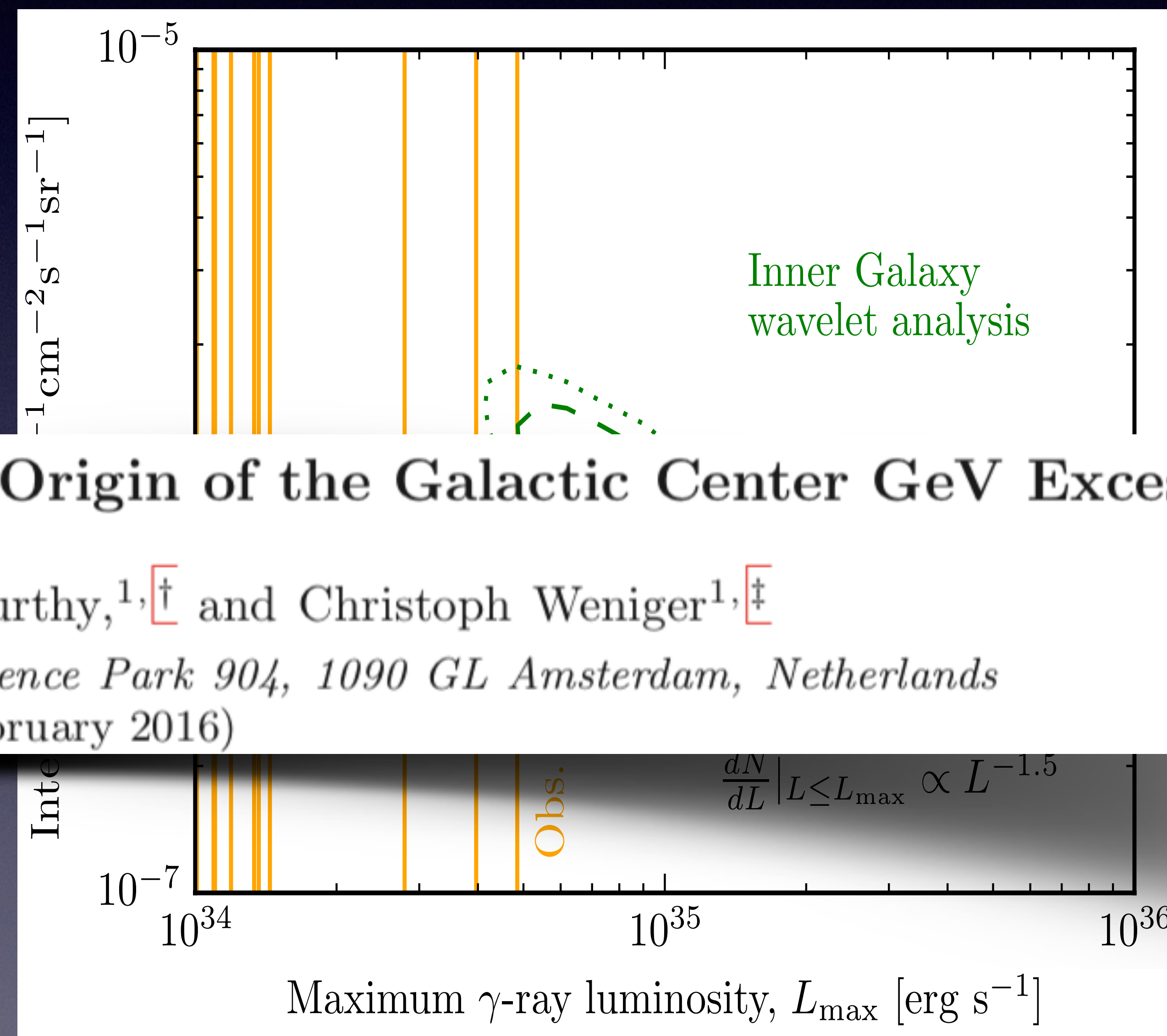


Bartels et al., **1506.05104**

An alternative Millisecond pulsars (recycled pulsars)

- Given an assumption about the "luminosity function" (the dependence of N_{PS} on L_{PS}), can ask if "point source-y" PSs

  luminosity function had a power-law index α_L=1.5



Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

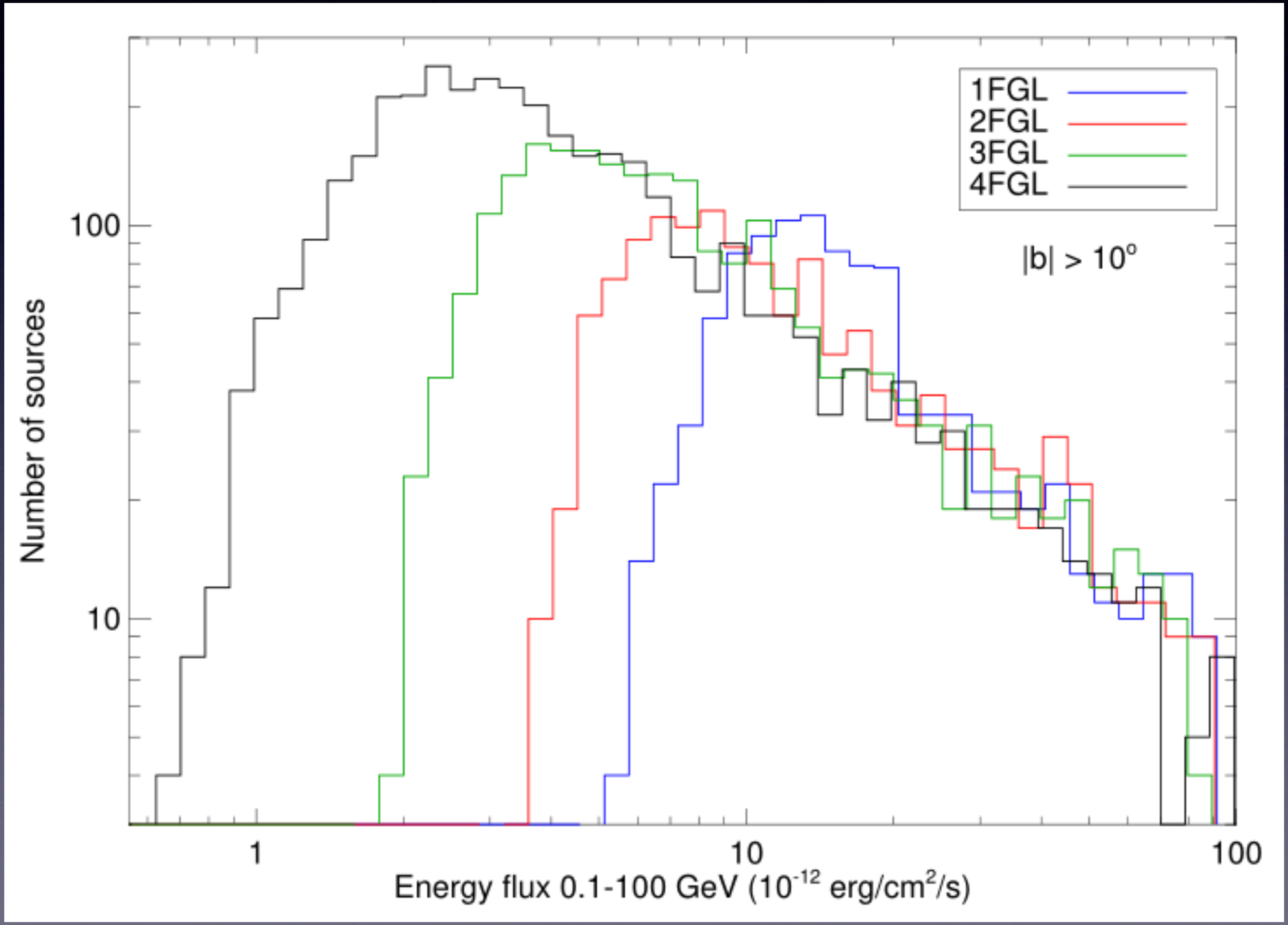
Richard Bartels,[1,*] Suraj Krishnamurthy,[1,†] and Christoph Weniger[1,‡]

[1] *GRAPPA Institute, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, Netherlands*

(Dated: 4 February 2016)

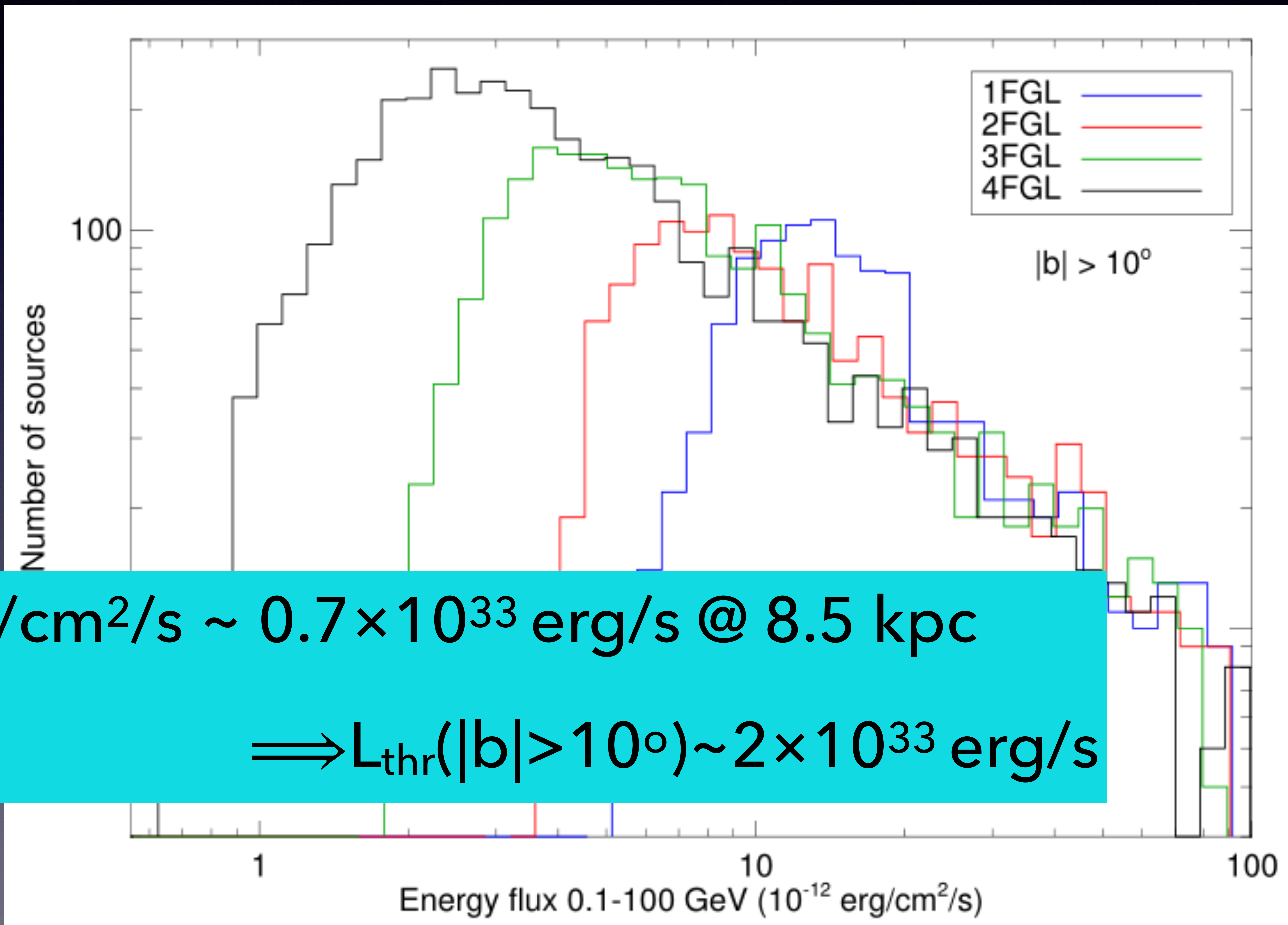
Bartels et al., **1506.05104**

The 4FGL Catalog



Abdollahi et al., **1902.10045**

The 4FGL Catalog

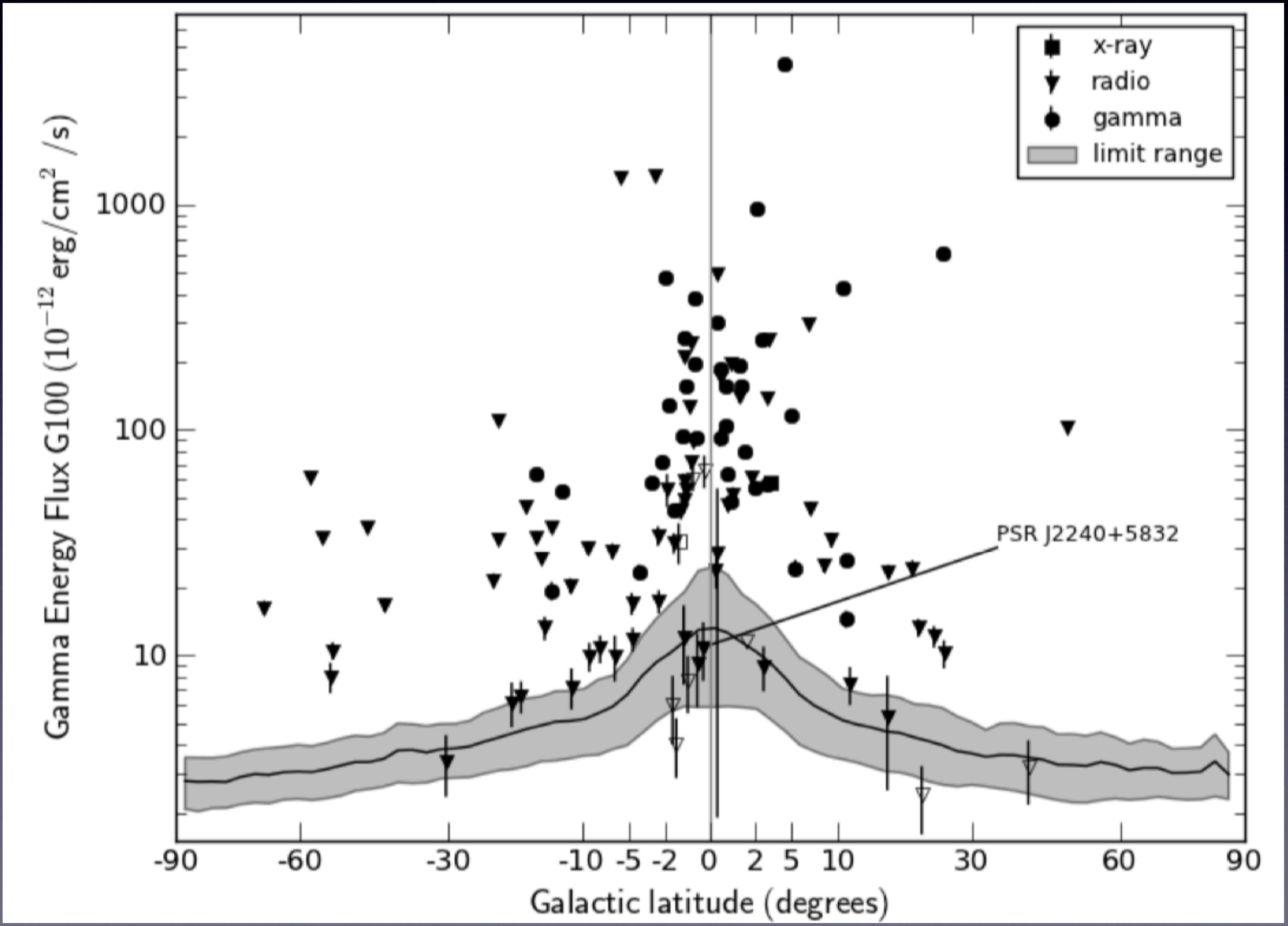


10^{-12} erg/cm^2/s ~ 0.7×10^{33} erg/s @ 8.5 kpc

$\Longrightarrow L_{thr}(|b|>10^{\circ}) \sim 2\times10^{33}$ erg/s

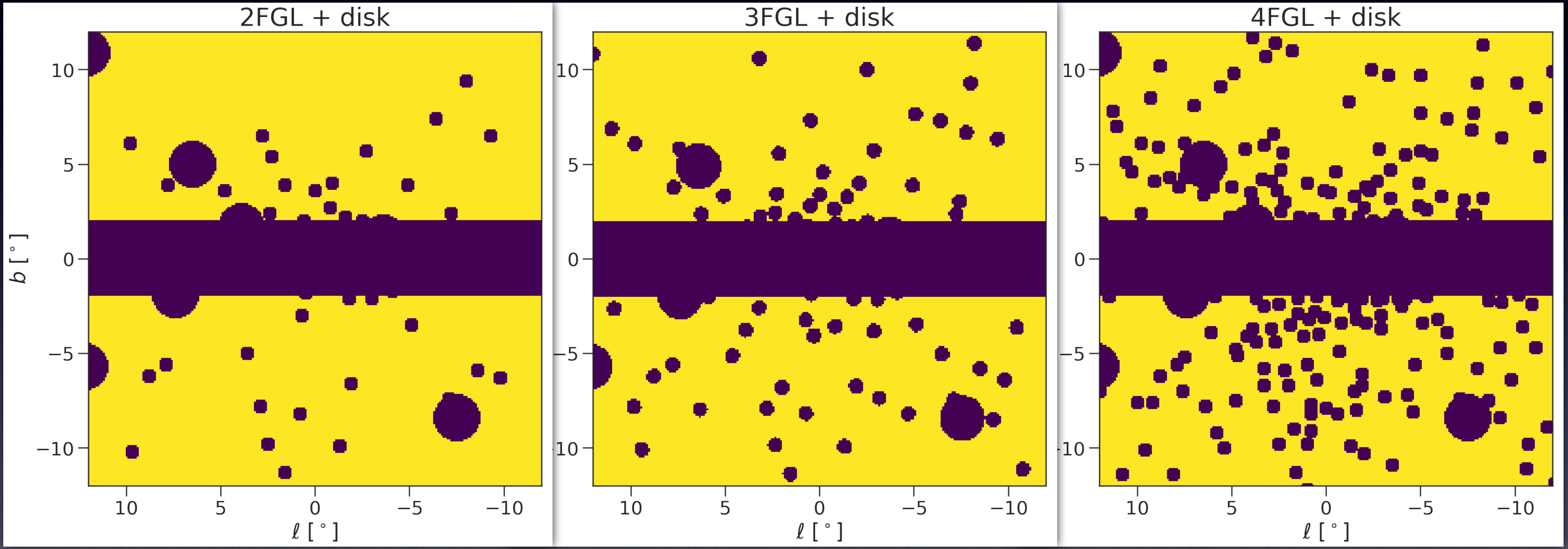
Abdollahi et al., **1902.10045**

b-dependence of detection



Abdo et al., **1305.4385**

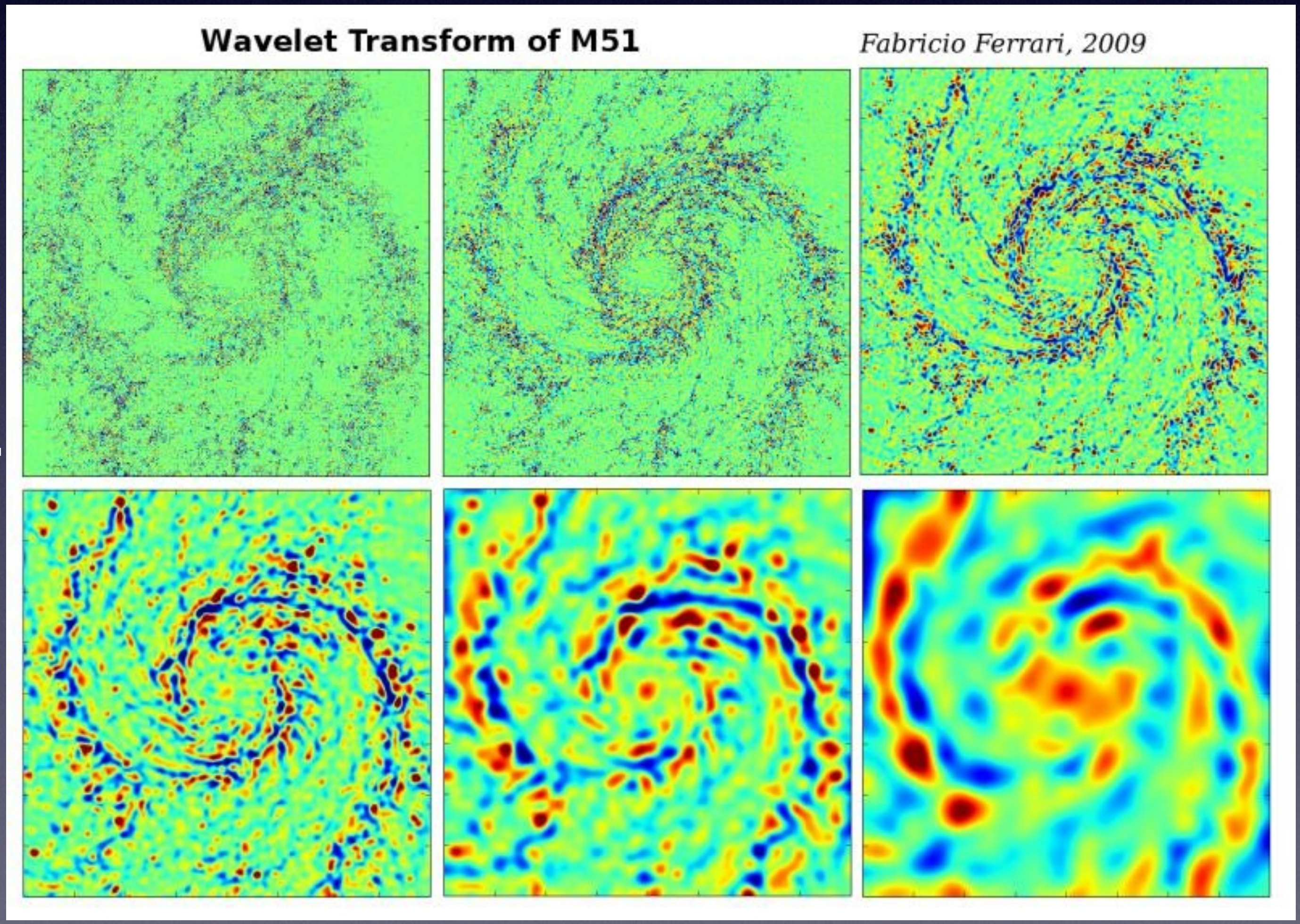
The Masks of different Fermi Catalogs (#FGL)



What are wavelets?

Wavelets have been used in image compression (JPEG), de-noising, fast signal identification, even in HEP data

Allow analysis of data in both time/space and frequency space

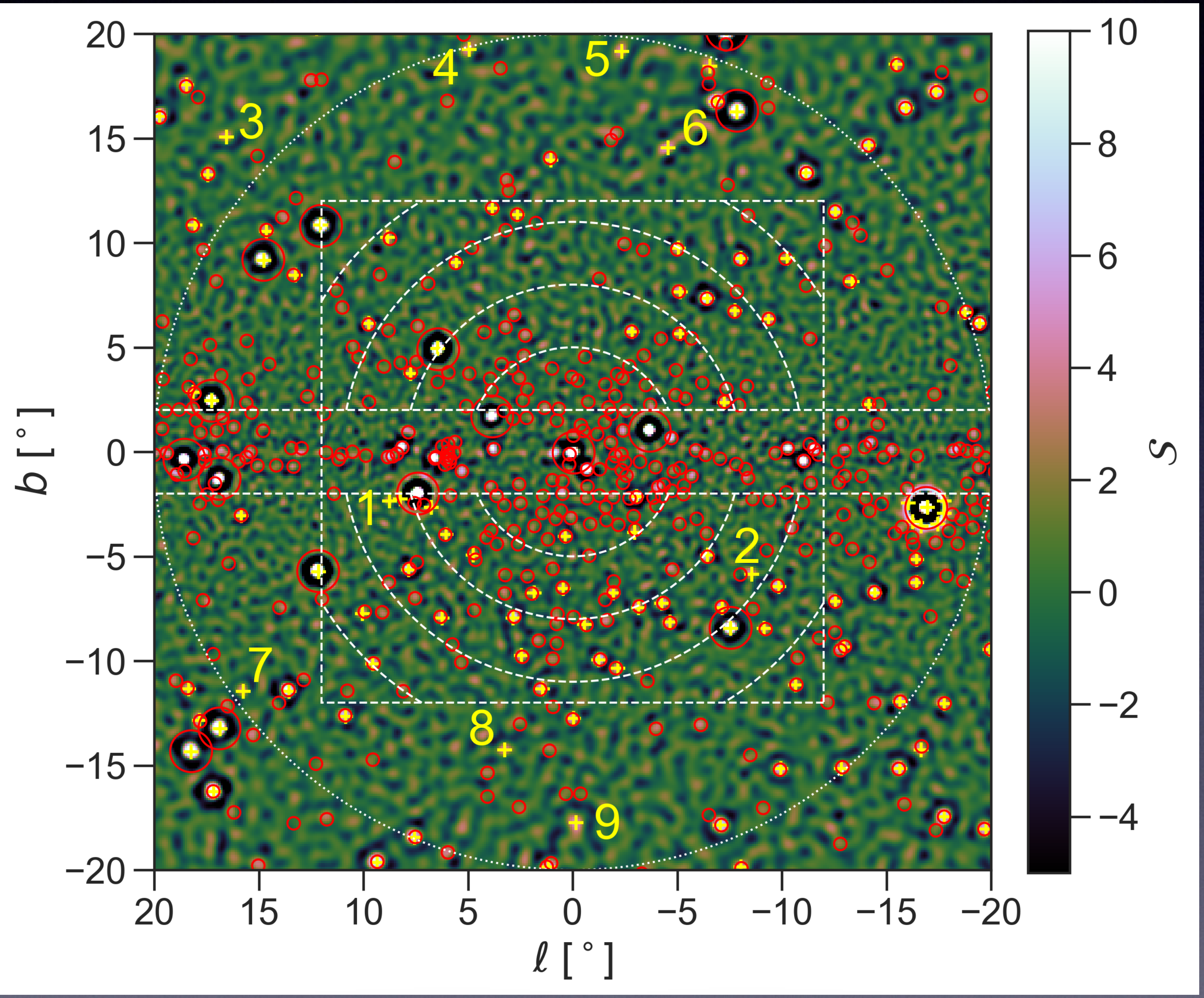


Different type of structures will have a different power at different levels of the decom-position (e.g. edges and other small scale structures vs larger scale variations).

Wavelets can find these different structures.

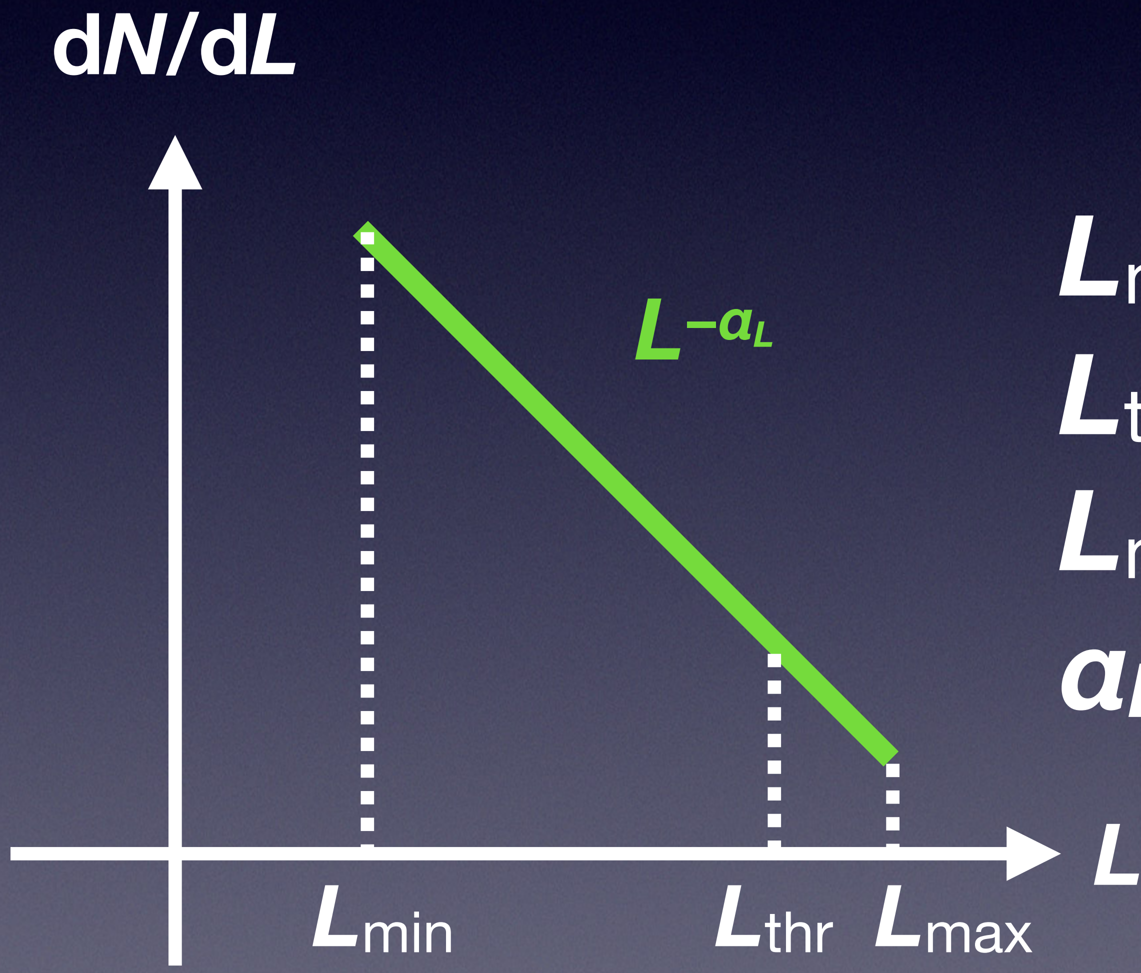
GCE: “Wavelet” search for point-like gamma-ray sources

Zhong, McDermott, **IC**, Fox, PRL 2020 (1911.12369)



117 peaks (w/ *S*>4) ⊃ 109 peaks near 4FGL

How to characterize a Central Source Population?



L_{min} → gamma-ray physics

L_{thr} → detection threshold

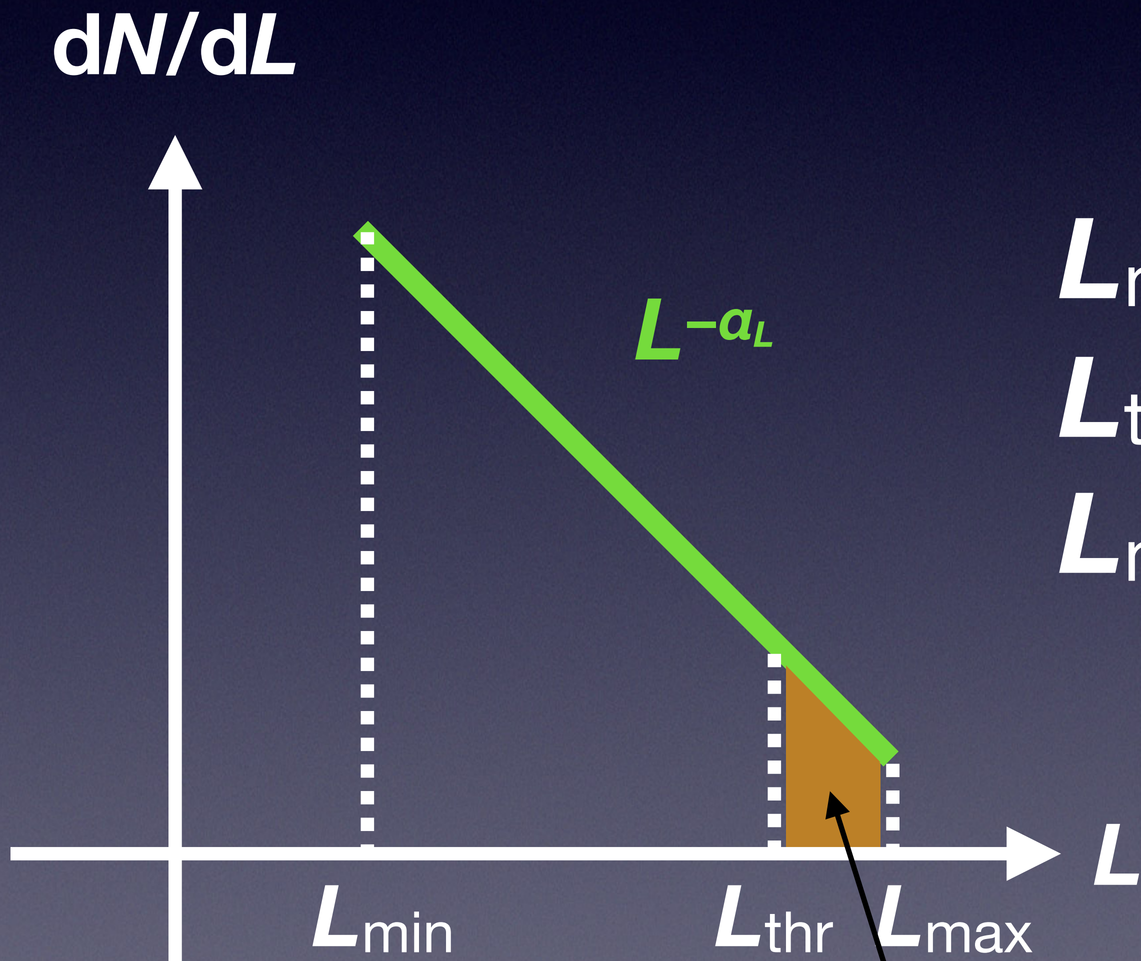
L_{max} → gamma-ray physics

α_L → theory prior

Prior peaked at $\alpha_L \sim 1$; strong preference for $\alpha_L \leq 1.5$ (various arguments)

0609359, 0610649, 1407.5583, 1411.0559, 1411.2980, …

Luminosity Function



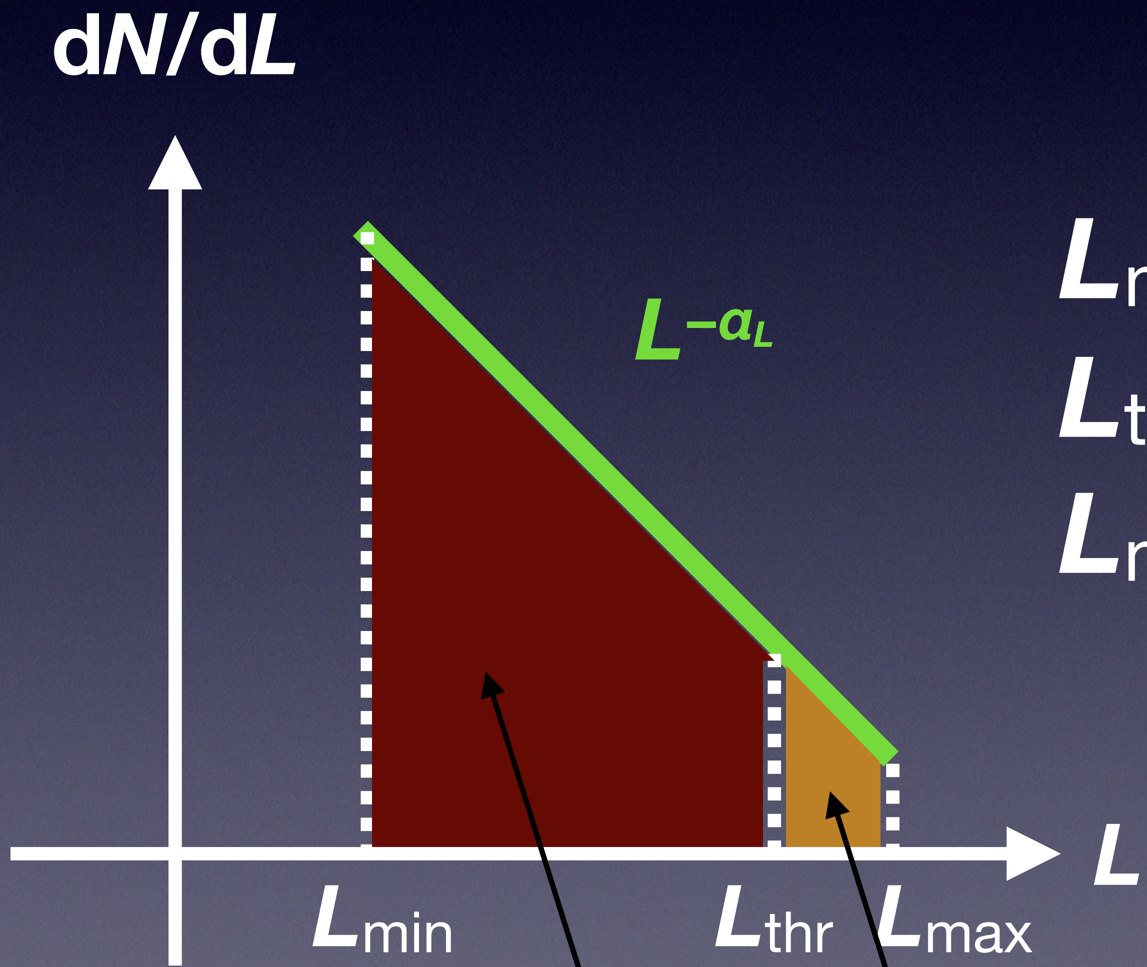
L_{min} → gamma-ray physics

L_{thr} → detection threshold

L_{max} → gamma-ray physics

$\int_{>thr} L \, dN/dL \, dL$ = stacked spectra

Luminosity Function



L_{min} → gamma-ray physics

L_{thr} → detection threshold

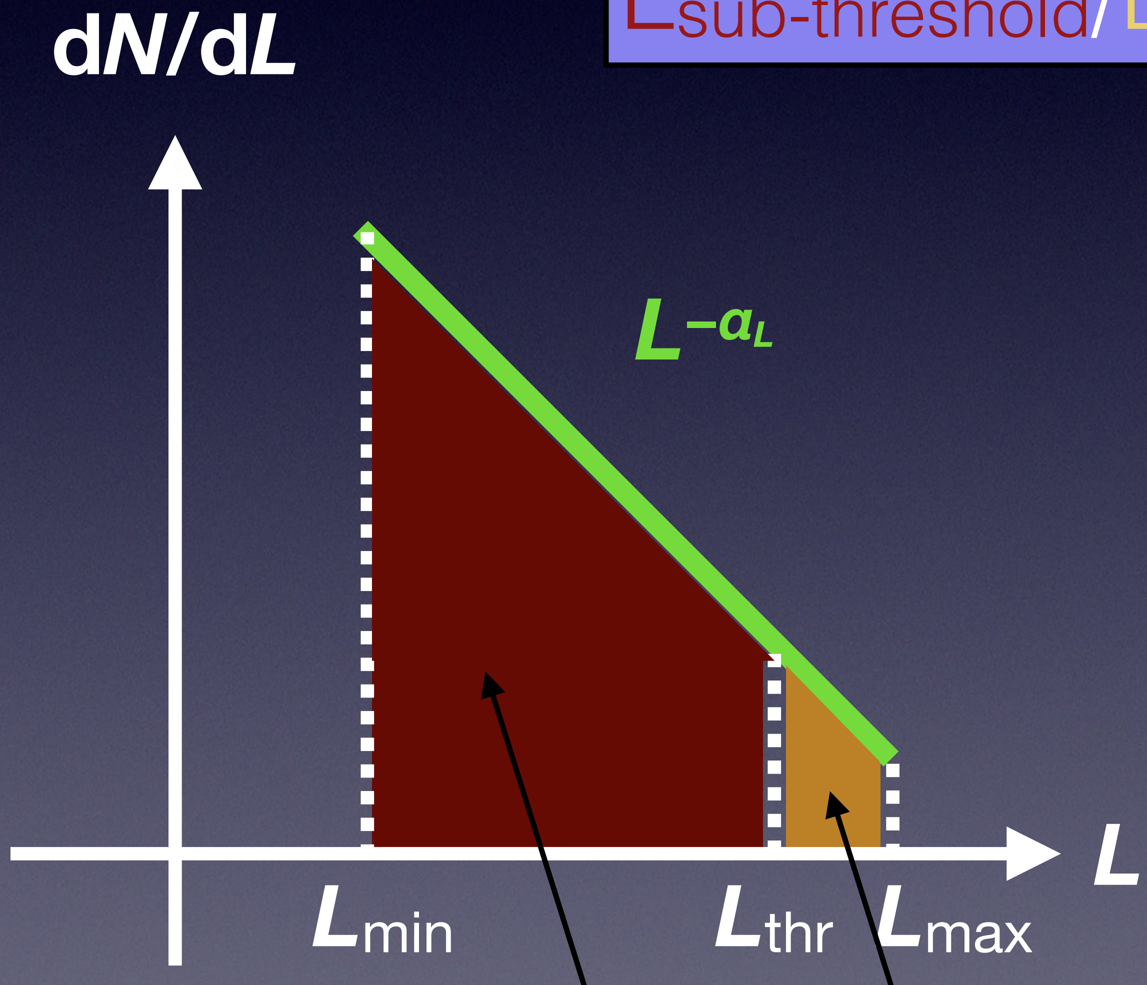
L_{max} → gamma-ray physics

$\int_{<thr}$ L dN/dL dL "= GCE"

$\int_{>thr}$ L dN/dL dL = stacked spectra

Luminosity Function

if GCE is PSs,
$L_{sub\text{-}threshold}/L_{above\text{-}threshold} = 4 \pm 1$



$L_{min} \rightarrow 10^{29}$ erg/s
$L_{thr} \rightarrow 10^{34}$ erg/s
$L_{max} \rightarrow 10^{35}$ erg/s
$\Longrightarrow \alpha_L \rightarrow 1.95 \pm 0.05$
$N_{sub} \rightarrow (3.5 \pm 1.7)*10^6$

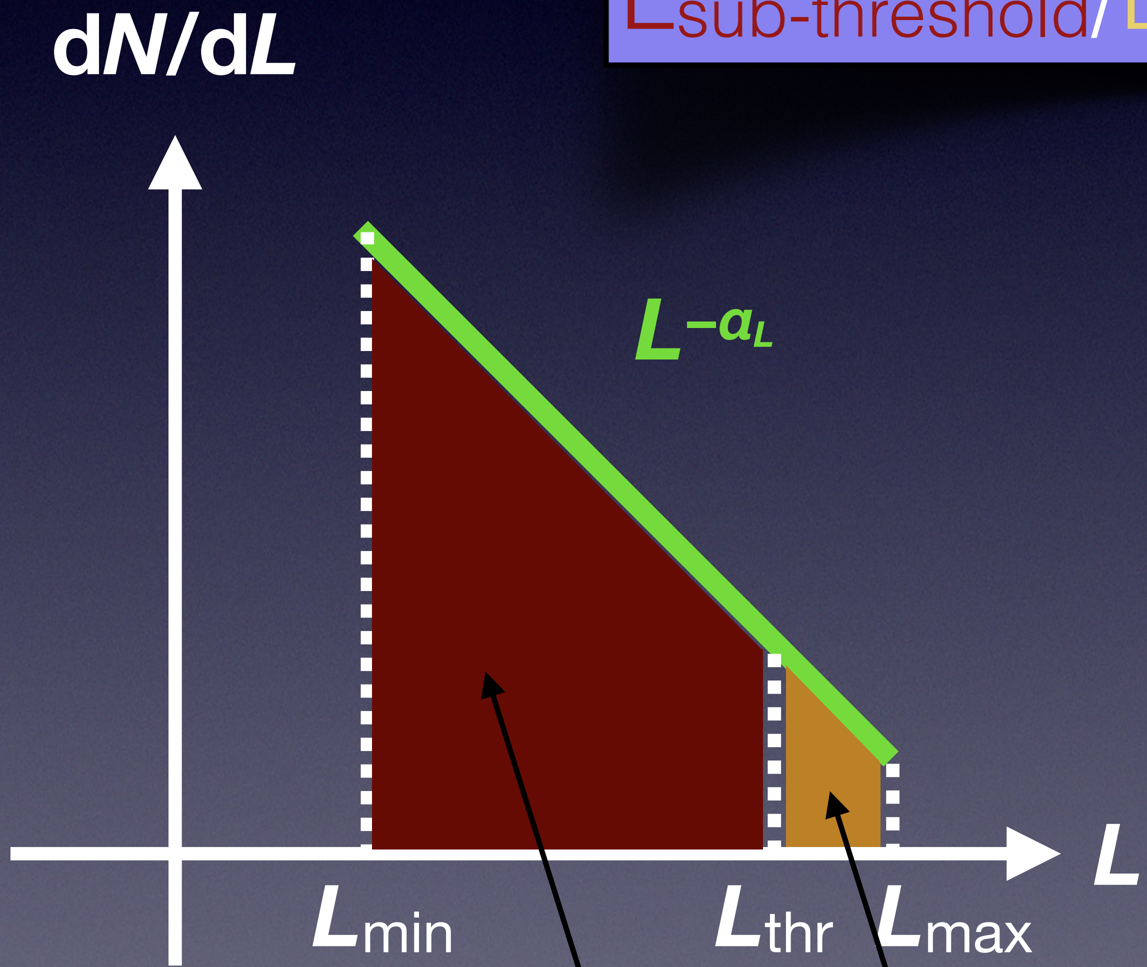
(compare to N_{vis} ~ 47)

$\int_{<thr} L\ dN/dL\ dL$ "= GCE"

$\int_{>thr} L\ dN/dL\ dL$ = stacked spectra

Luminosity Function?

if GCE is PSs,
$L_{\text{sub-threshold}}/L_{\text{above-threshold}}=4\pm1$



$L_{min} \rightarrow 0$

$L_{thr} \rightarrow 3\times10^{34}$ erg/s

$L_{max} \rightarrow 10^{35}$ erg/s

$\Longrightarrow \alpha_L \rightarrow 1.8 \pm 0.05$

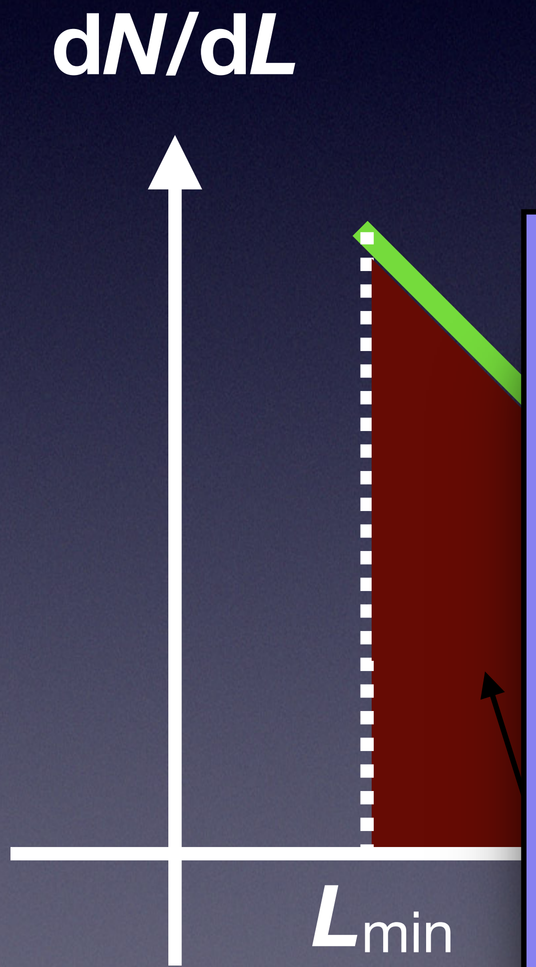
(N_{sub} diverges)

$\int_{<thr} L\ dN/dL\ dL$ "= GCE"

$\int_{>thr} L\ dN/dL\ dL$ = stacked spectra

Luminosity Function

if GCE is PSs,
$L_{\text{sub-threshold}}/L_{\text{above-threshold}}=4\pm1$



bottom line: $\alpha_L<1.5$ is strongly disfavored under any reasonable set of assumptions

$\Longrightarrow$

the GCE is not a large population of MSPs

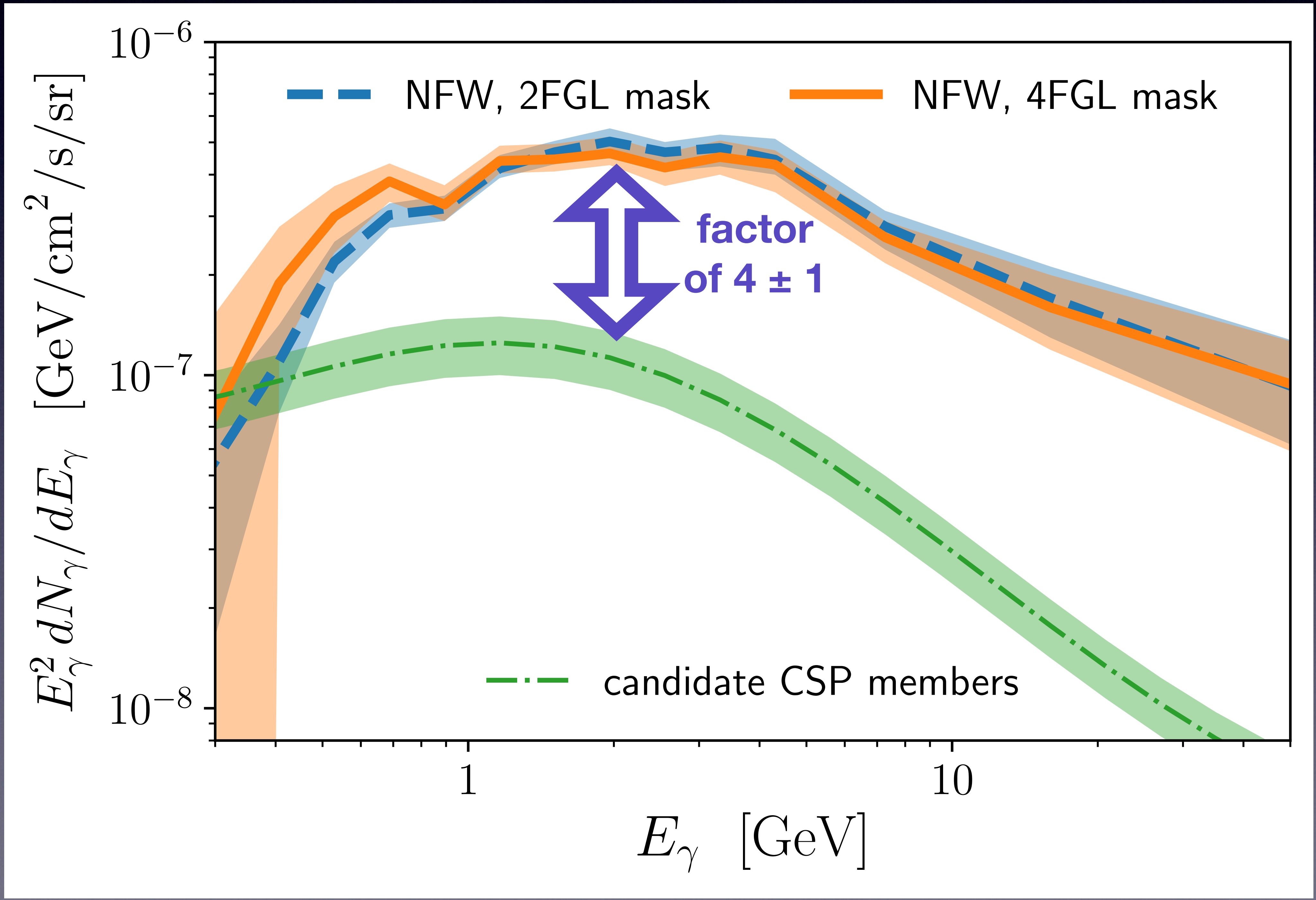
g/s
/s
.05
, diverges!)

$\int_{<thr} L\ dN/dL\ dL$ "= GCE"

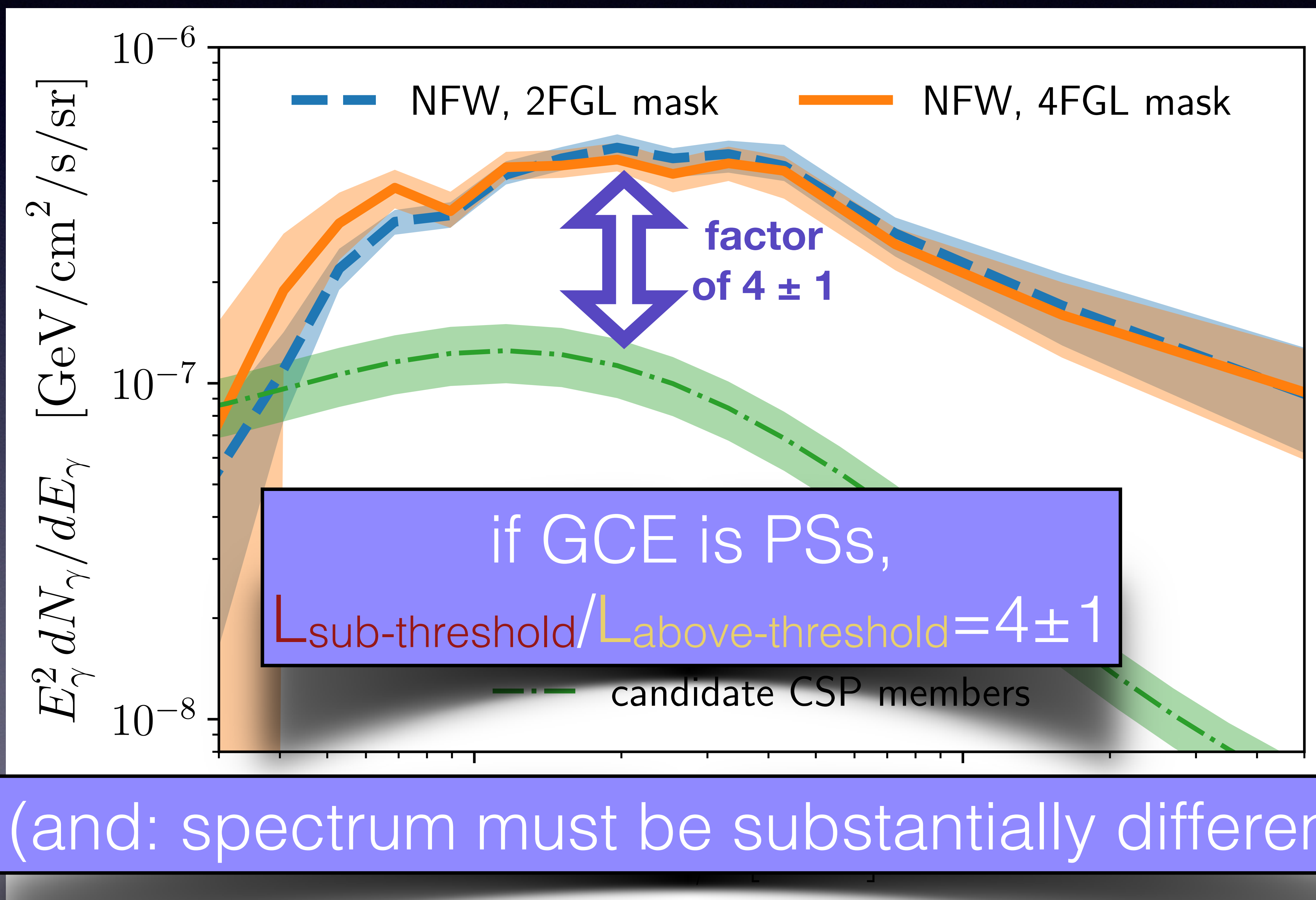
$\int_{>thr} L\ dN/dL\ dL$ = stacked spectra

Compare Spectra

Zhong, McDermott, **IC**, Fox, PRL 2020 (1911.12369)



Implications for GCE



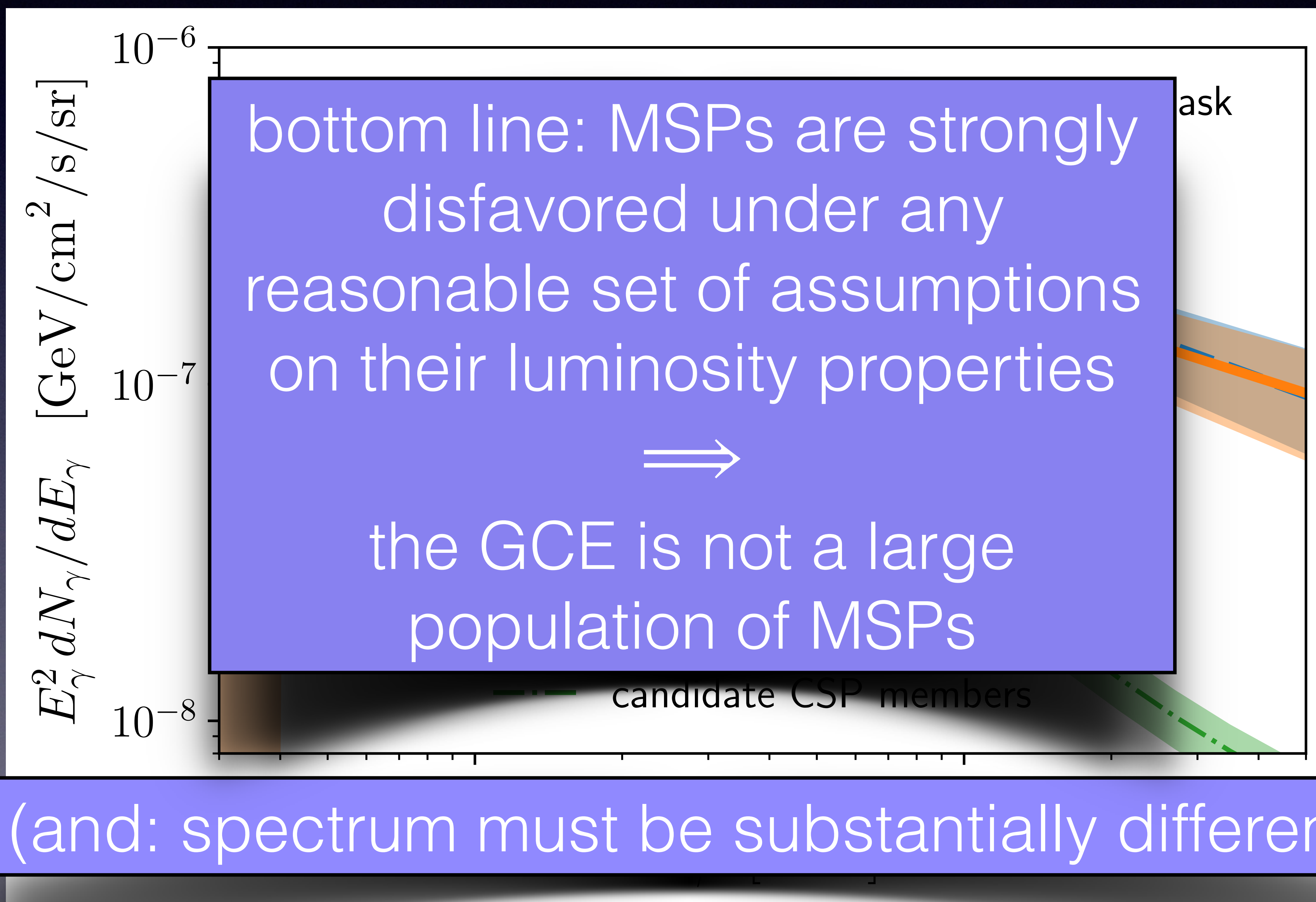
if GCE is PSs, $L_{sub\text{-}threshold}/L_{above\text{-}threshold}=4\pm1$

(and: spectrum must be substantially different)

Implications for GCE

Zhong, McDermott, **IC**, Fox, PRL 2020 (1911.12369)

Leane & Slatyer PRD 2020



bottom line: MSPs are strongly disfavored under any reasonable set of assumptions on their luminosity properties

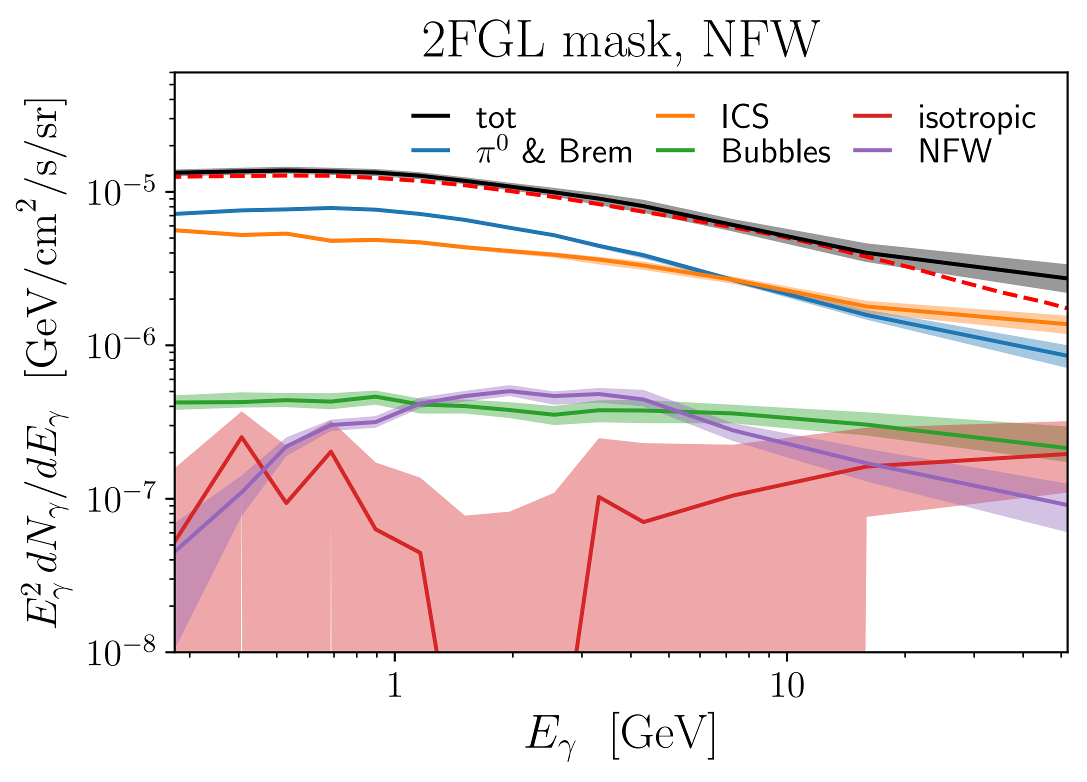
$\Longrightarrow$

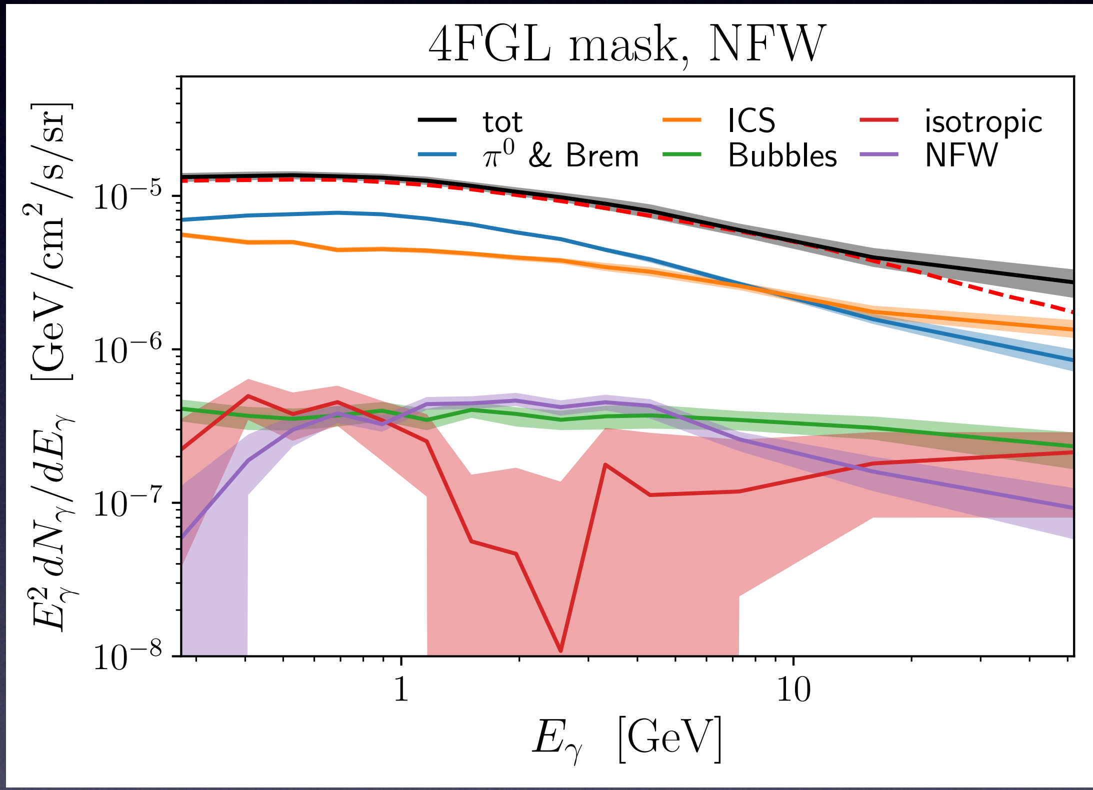
the GCE is not a large population of MSPs

(and: spectrum must be substantially different)

GCE: Template Fit Results

Zhong, McDermott, **IC**, Fox, PRL 2020



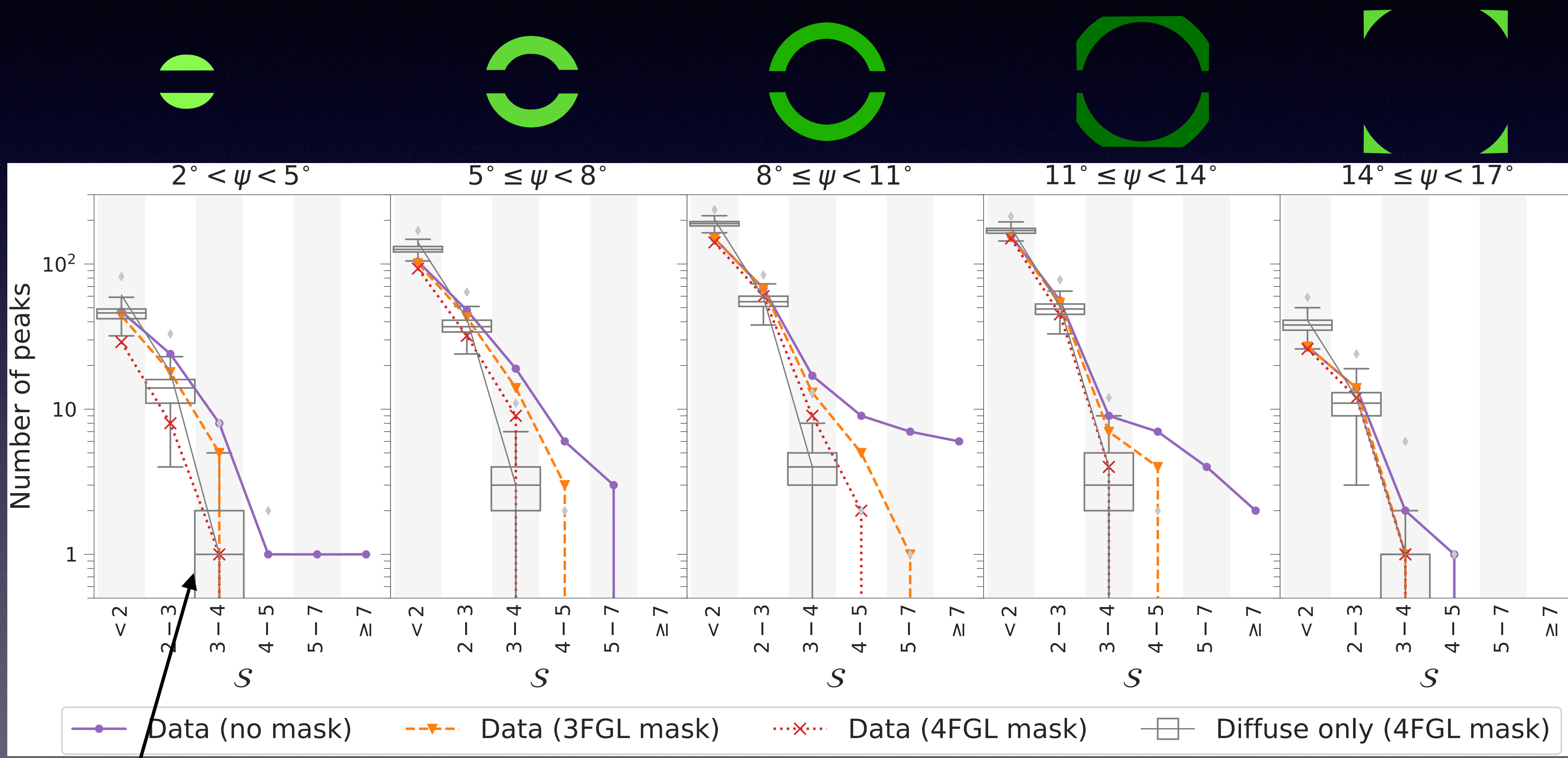


preference slightly smaller (fewer photons)

TABLE I. Difference in $-2\ln\lambda$ (lower numbers are better) at the best fit points of each model, summed over energy bins, compared to our best fit for each mask.

Type of Mask	NFW	gNFW	no excess
2FGL	-	476	5430
4FGL	-	368	3600

Counting “Wavelet” Peaks



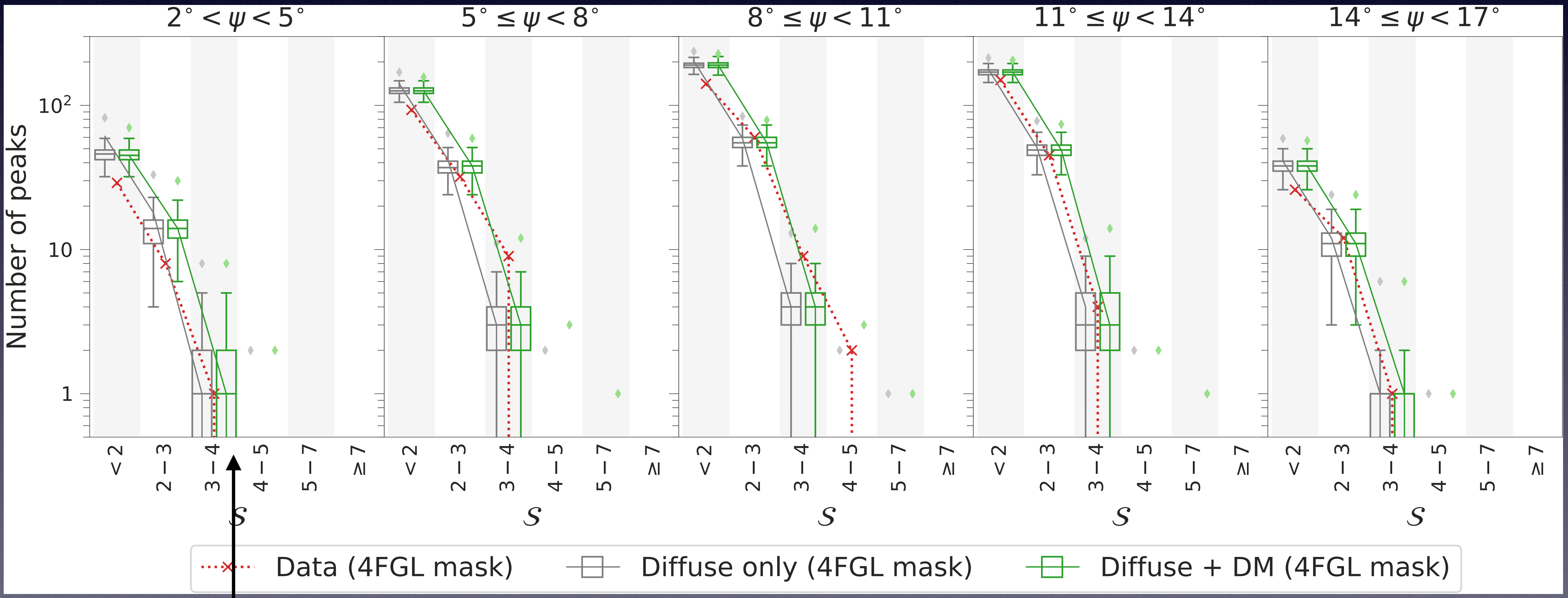
60 diffuse models × 100 trials

Zhong, McDermott, **IC**, Fox, PRL 2020

wavelet statistics change qualitatively with 4FGL!

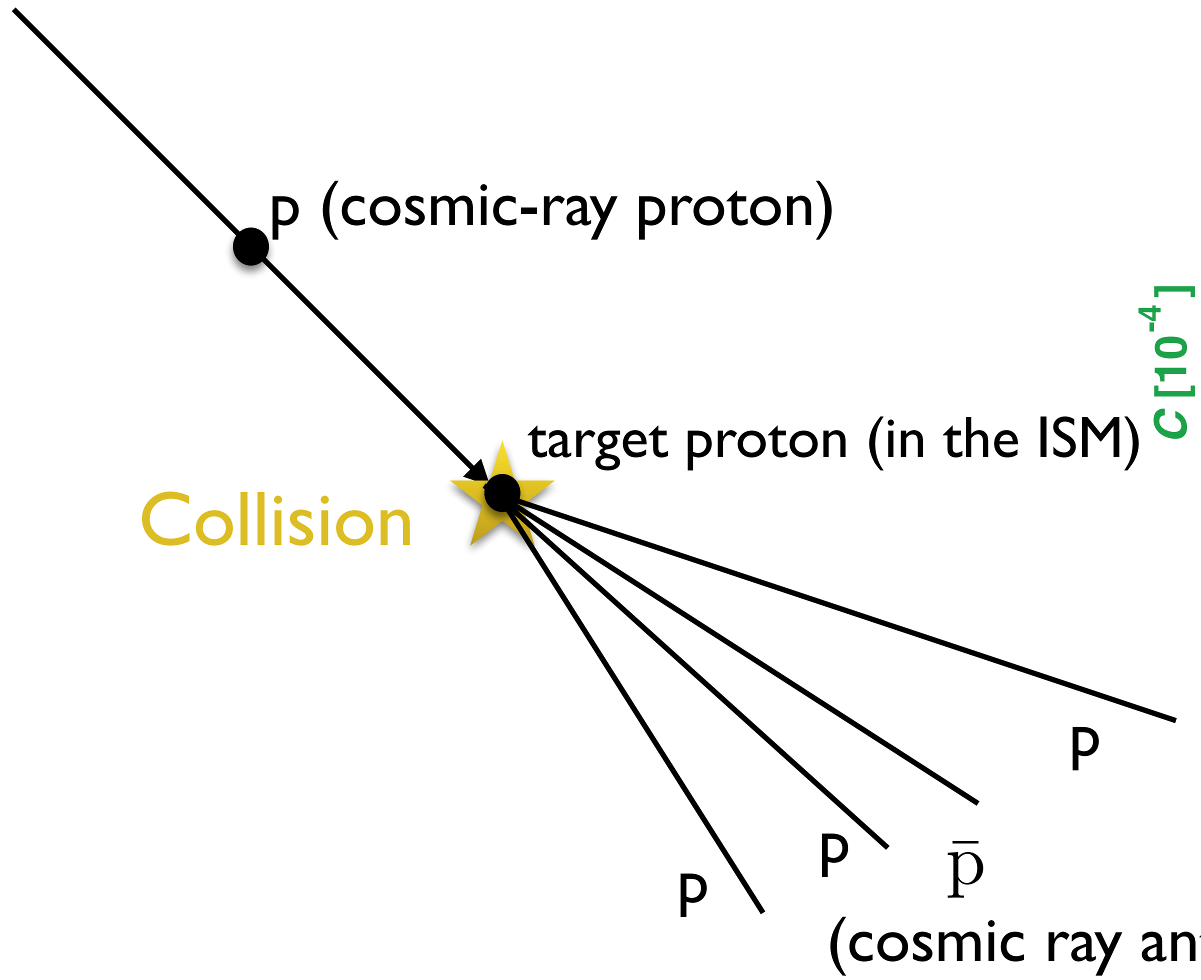
DM or Cosmic-Ray Burst activity still work

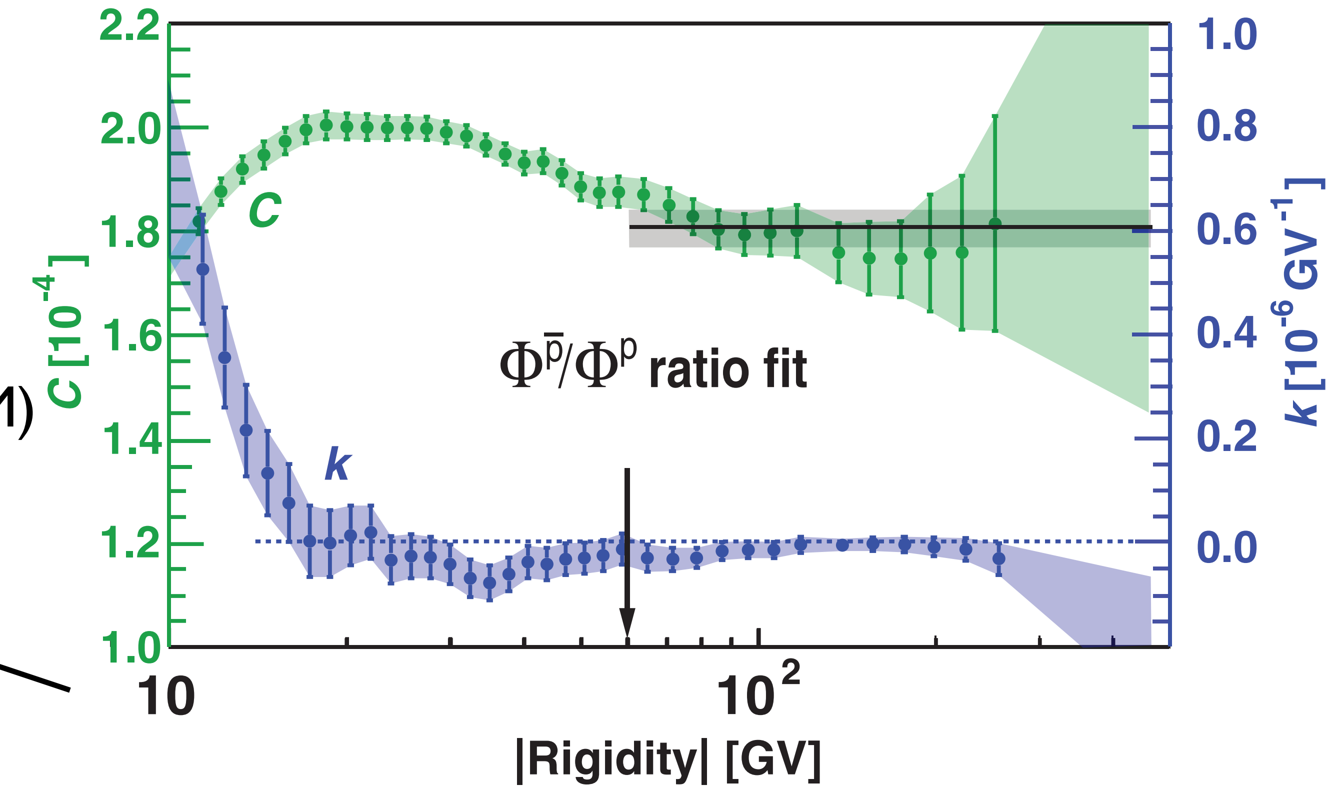
No additional small-scale structure,
so it looks just as good as diffuse-only



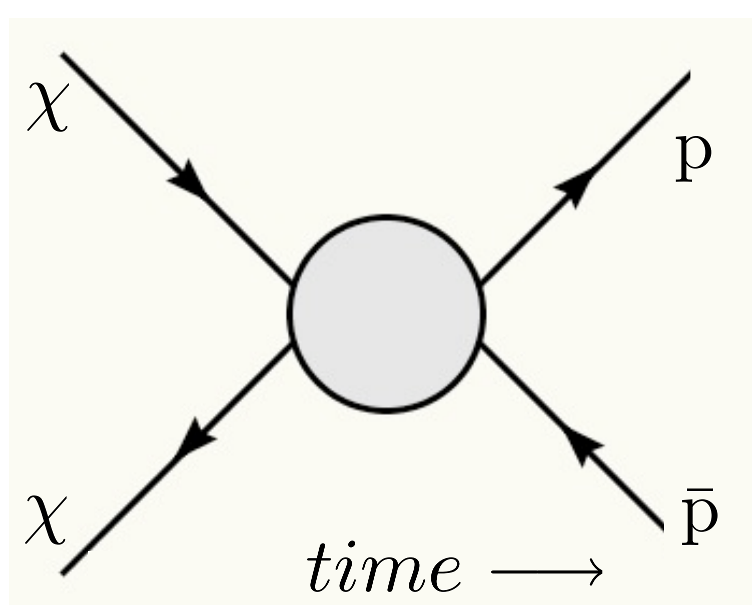
3 DM models × 60 diffuse models × 100 trials

AMS-02 pbar/p ratio and Dark Matter





AMS Coll. PRL.117.091103 (2016)



Could we have an additional contribution?

What about the Antiproton to Proton Ratio Uncertainties?

Antiprotons background uncertainties are very large.

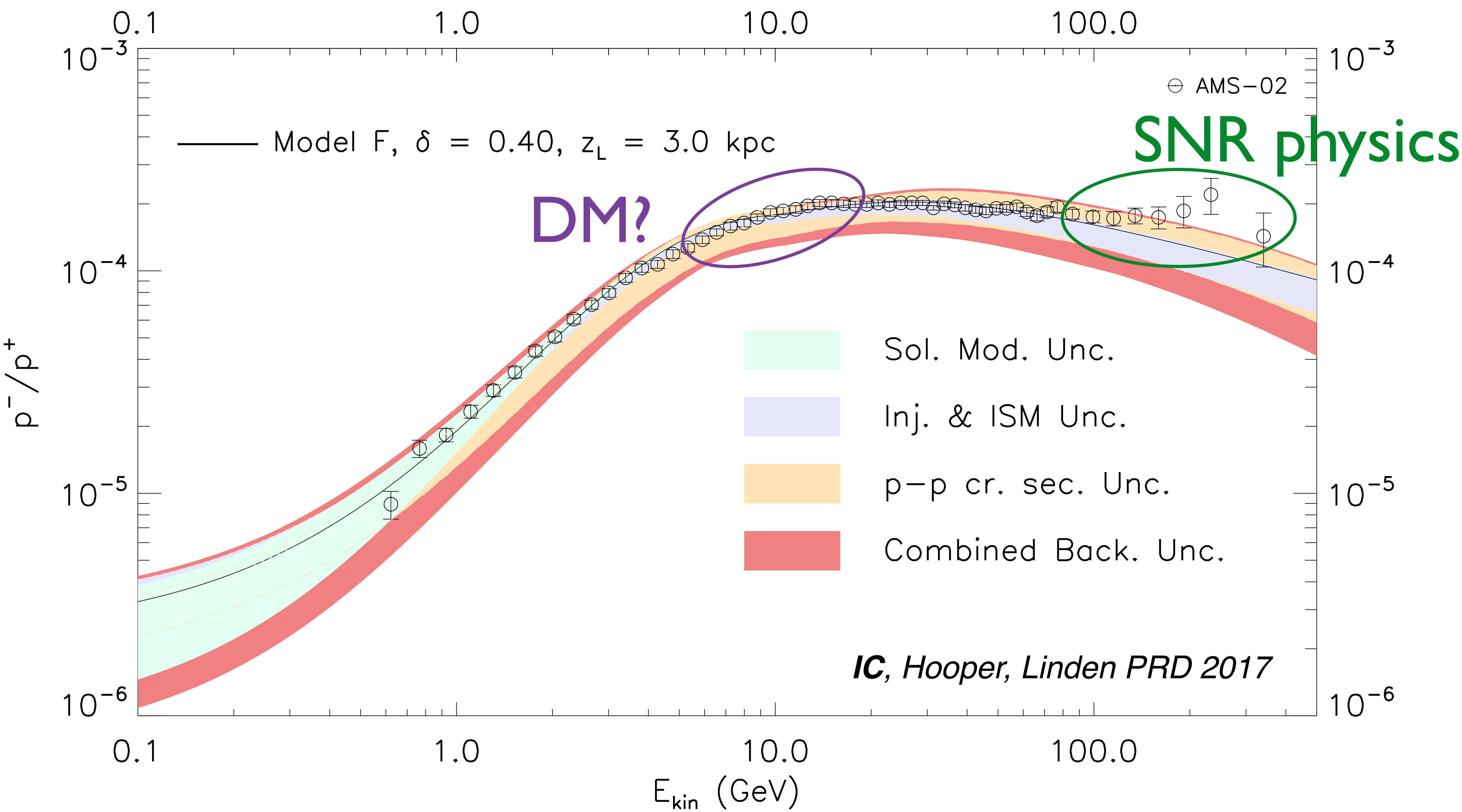
They are associated with:

i) the antiproton production cross-section from CR protons and heavier nuclei collisions with the ISM gas

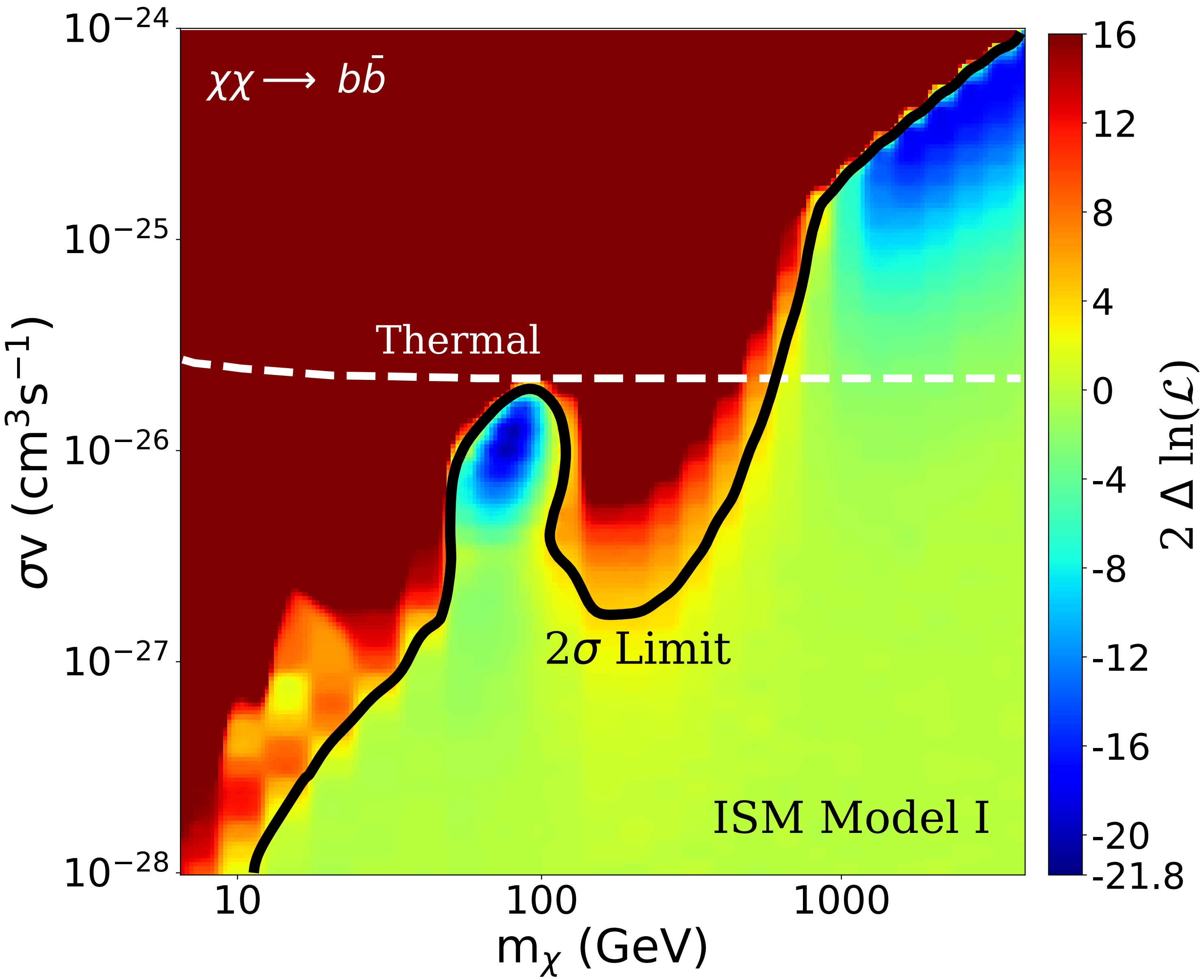
ii) the propagation of CRs through the ISM

iii) Solar Modulation (the propagation of CRs through the Heliosphere)

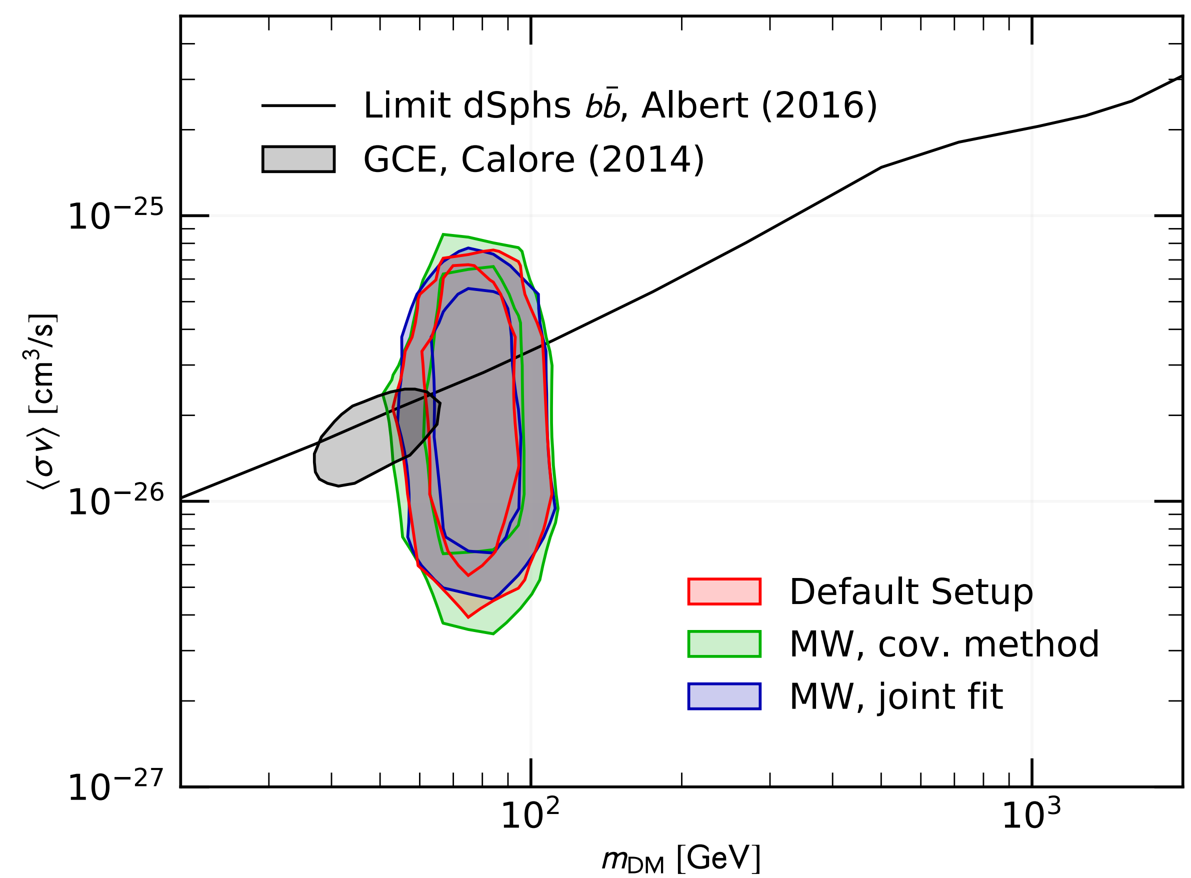
Combining all uncertainties together and marginalizing over them:



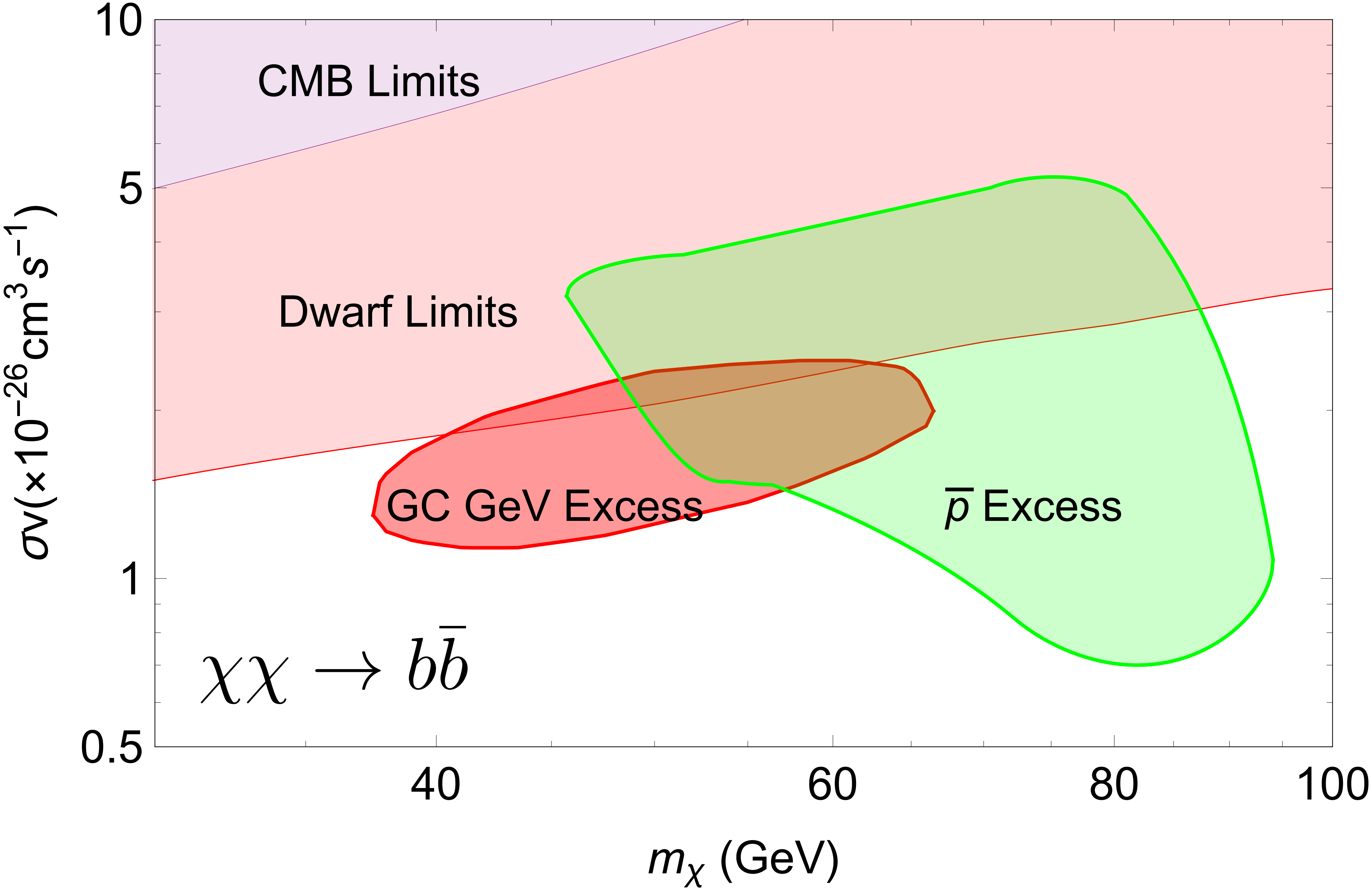
Looking at the antiproton to proton ratio find an the excess at~3 sigma



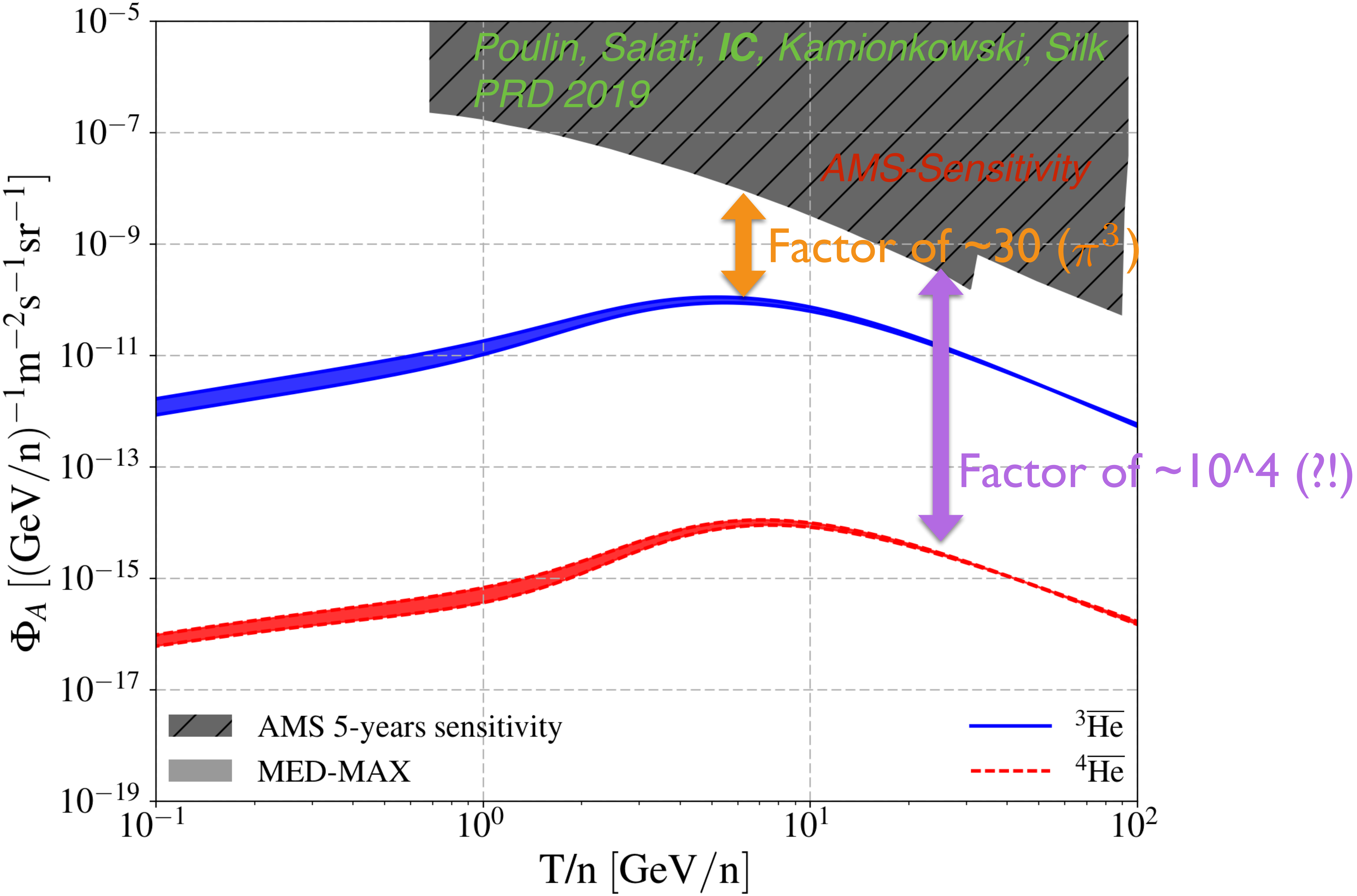
IC, Tim Linden, Dan Hooper PRD 2019



A. Cuoco et al. PRD 2019

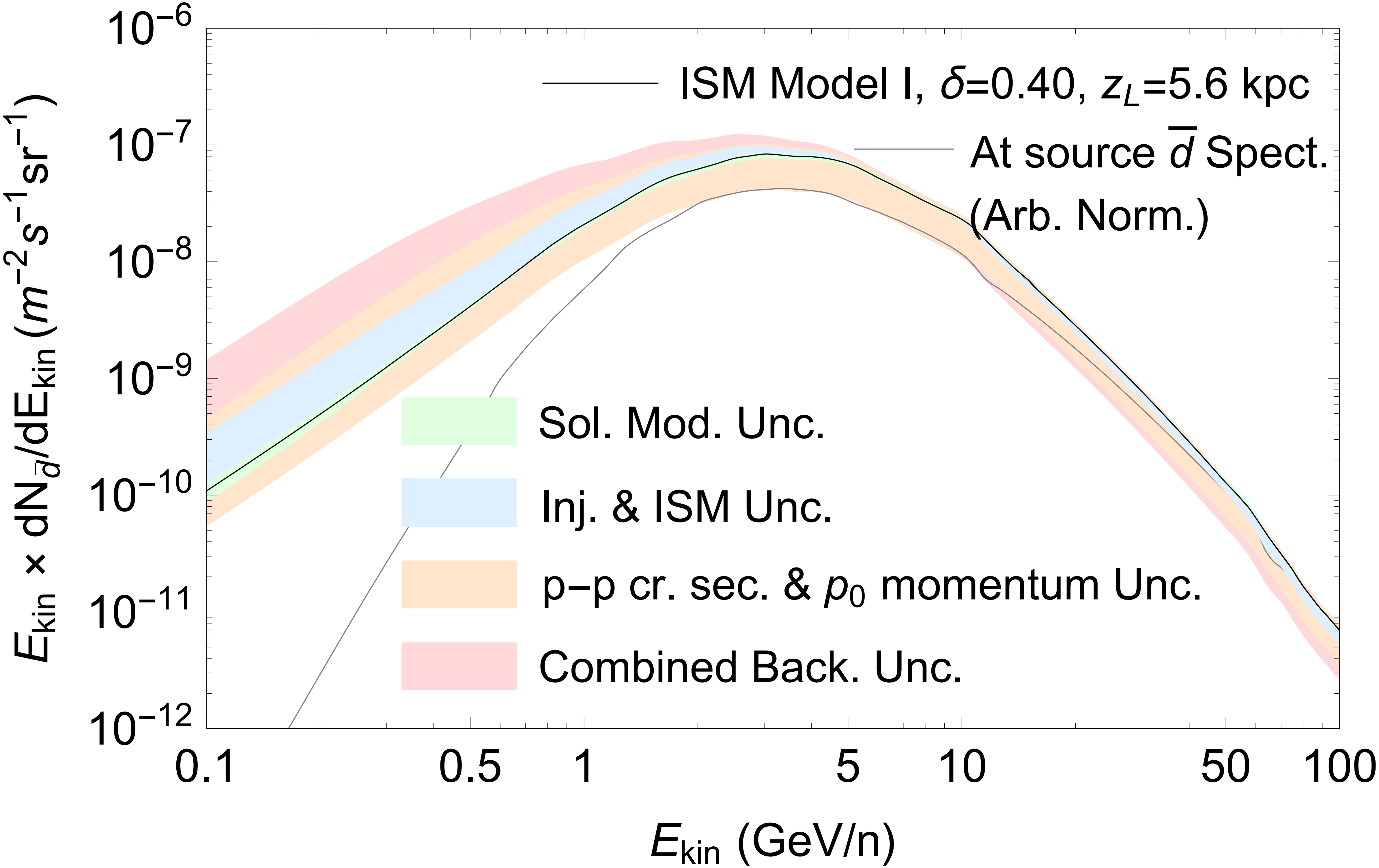


***IC**, Linden, Hooper PRD 2019*

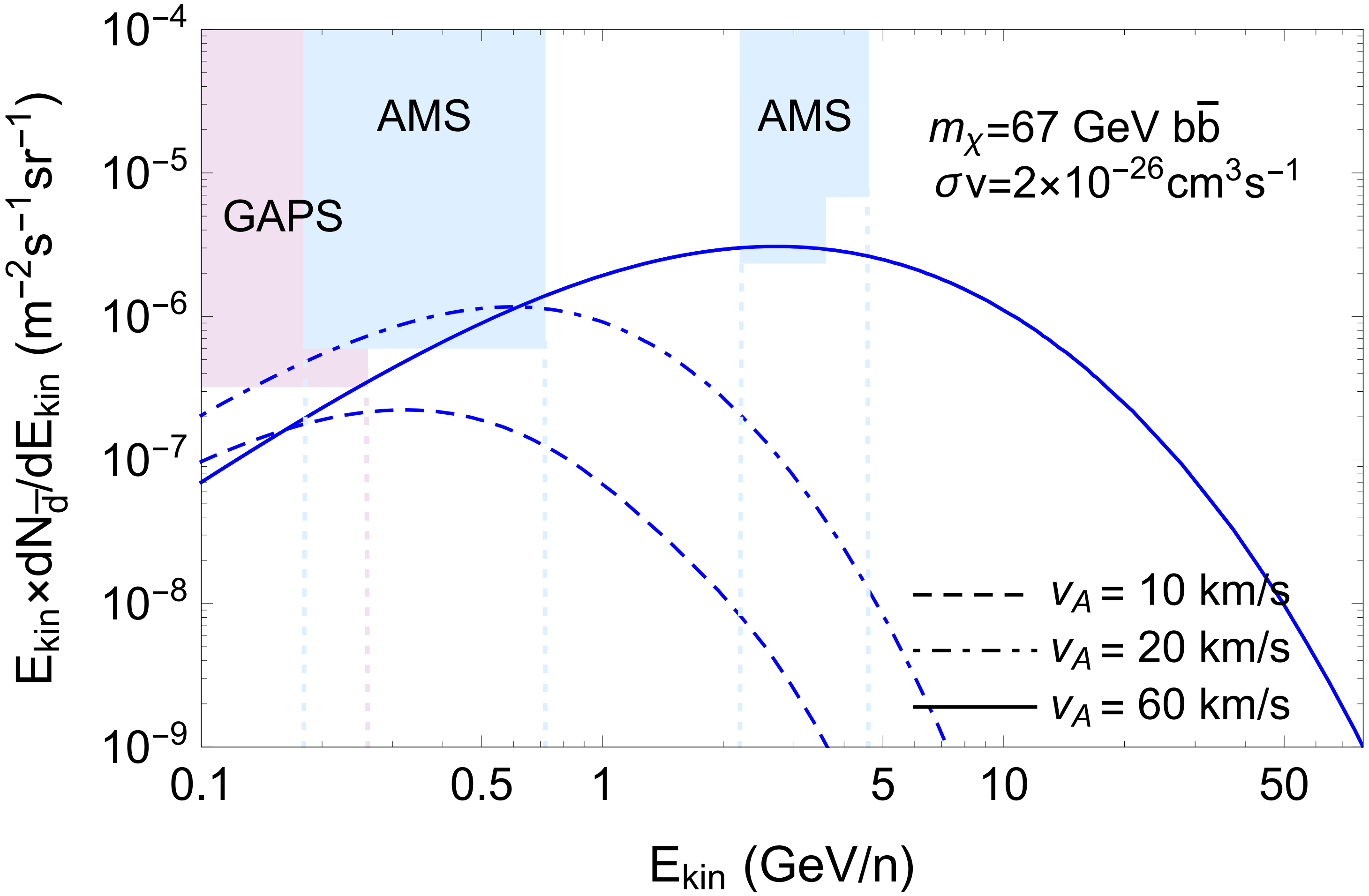


There is an unexpected amplitude on the flux of anti-He

Anti-deuterons Uncertainties



***IC**, Linden, Hooper PRD 2020*



Diffusive re-acceleration in regions of high turbulence can reshape antimatter cosmic-ray spectra from energies where instruments can not detect them to energies where AMS02 and future GAPS can.

__IC__, Linden, Hooper
PRD 2020