Current Constraints On Wimp Dark Matter

Recent results in collaboration with
Yi-Ming Zhong (KICP), Sam McDermott (Fermilab) & Patrick Fox (Fermilab), PRL 124, 231103, 2020 (arXiv:1911.12369)

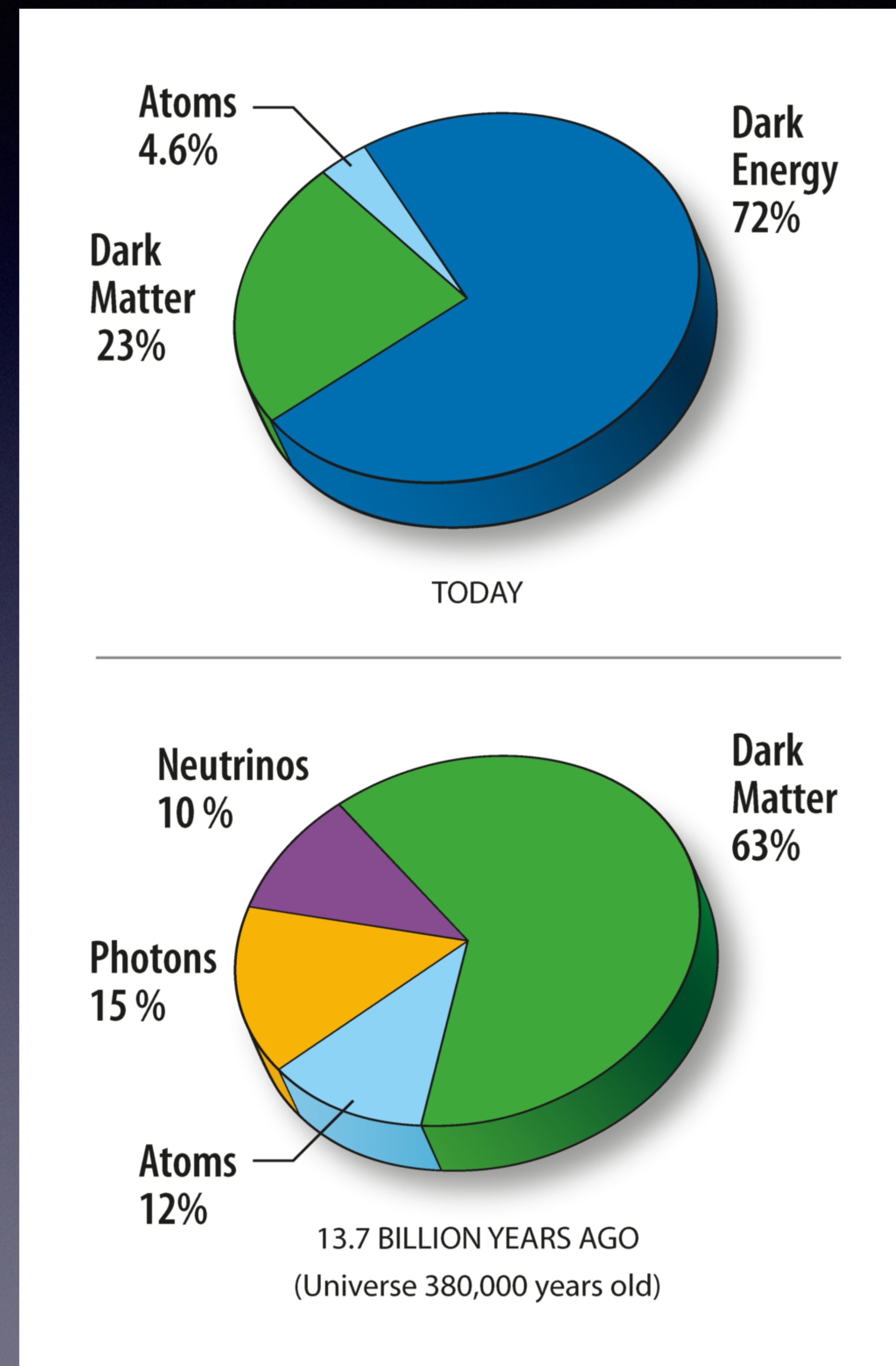
Also with, B. Balaji, F. Calore, G. Dobler, C. Evoli, D. Finkbeiner, D. Hooper, S. Lee, T. Linden, T. Slatyer, N. Weiner and C. Weniger

Fermi Symposium 2021

Ilias Cholis, 15/04/2021

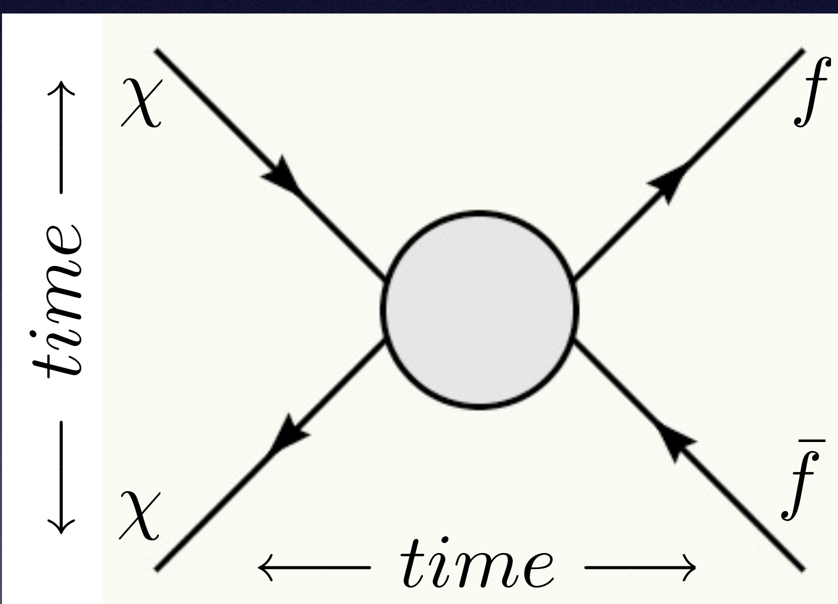
Why Dark Matter?

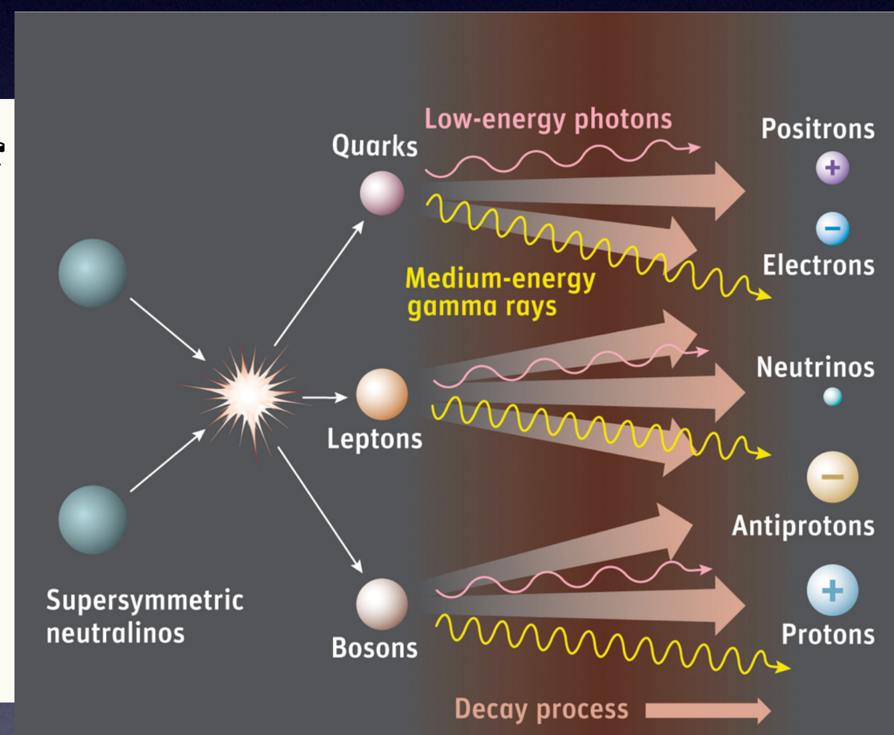
- *THERE IS A LOT OF "IT" (now and in the past history of the Universe)*
- *WE FIND EVIDENCE FOR "IT" IN MANY ASTROPHYSICAL SYSTEMS*
- *WE DO NOT KNOW WHAT "IT" IS.*



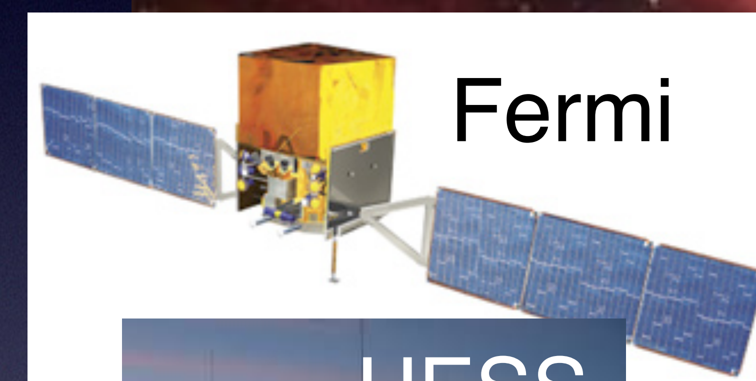
Searches for Particle Dark Matter

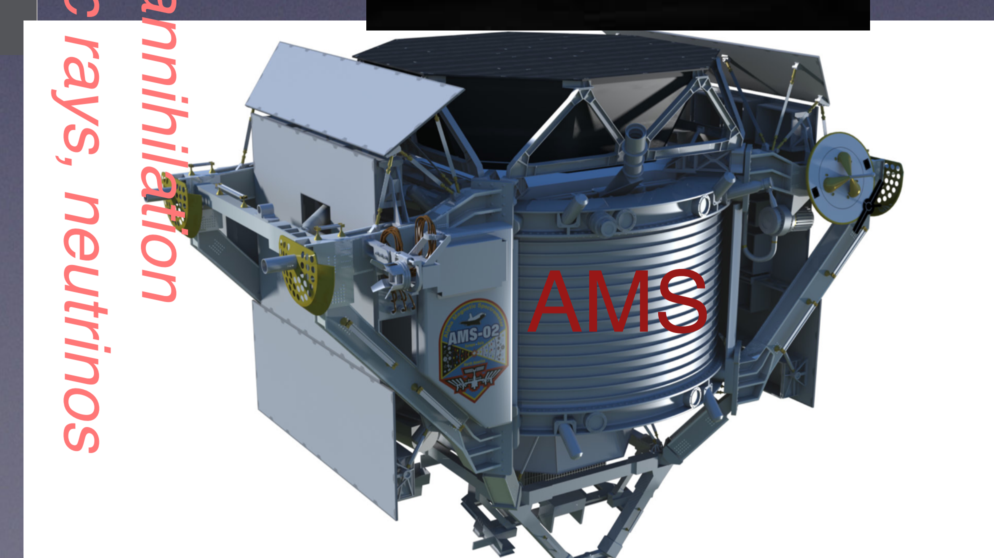
Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:



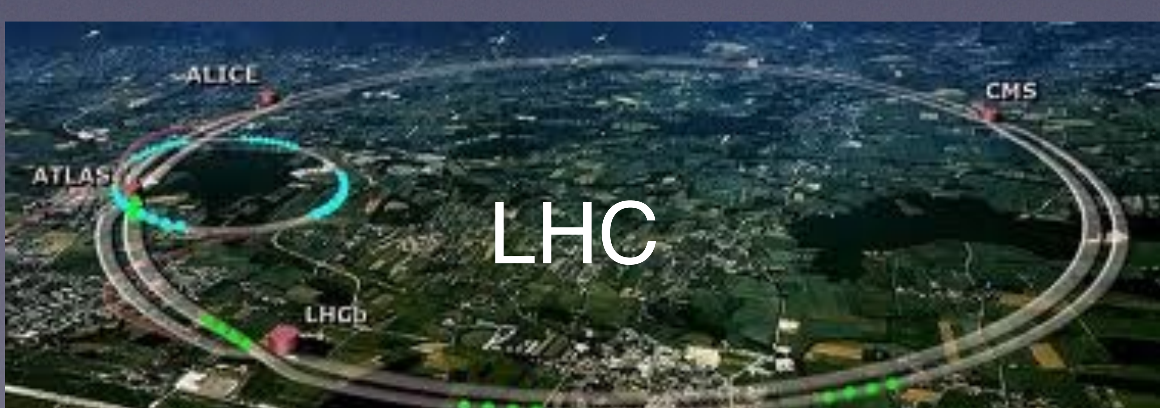


Indirect detection: annihilation into gamma-rays, cosmic rays, neutrinos



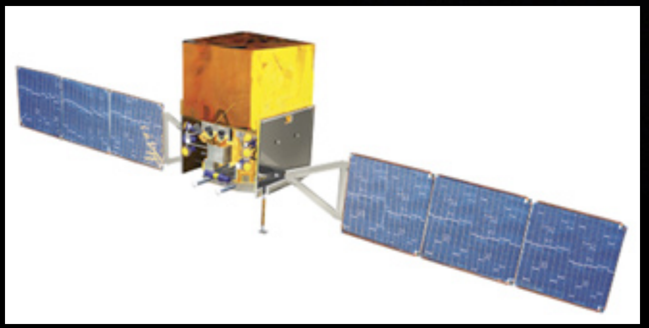


Dark matter production at colliders

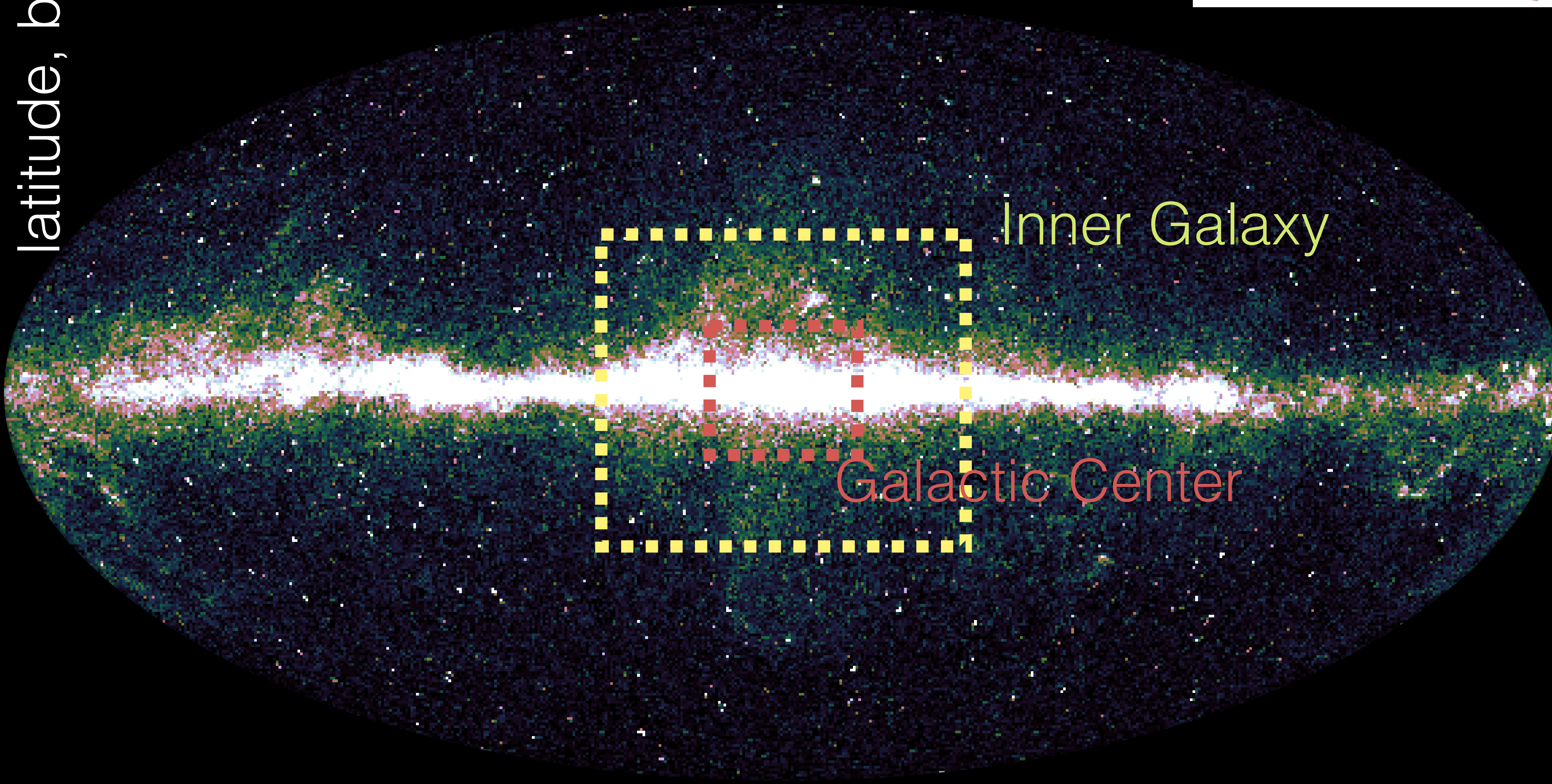


third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY



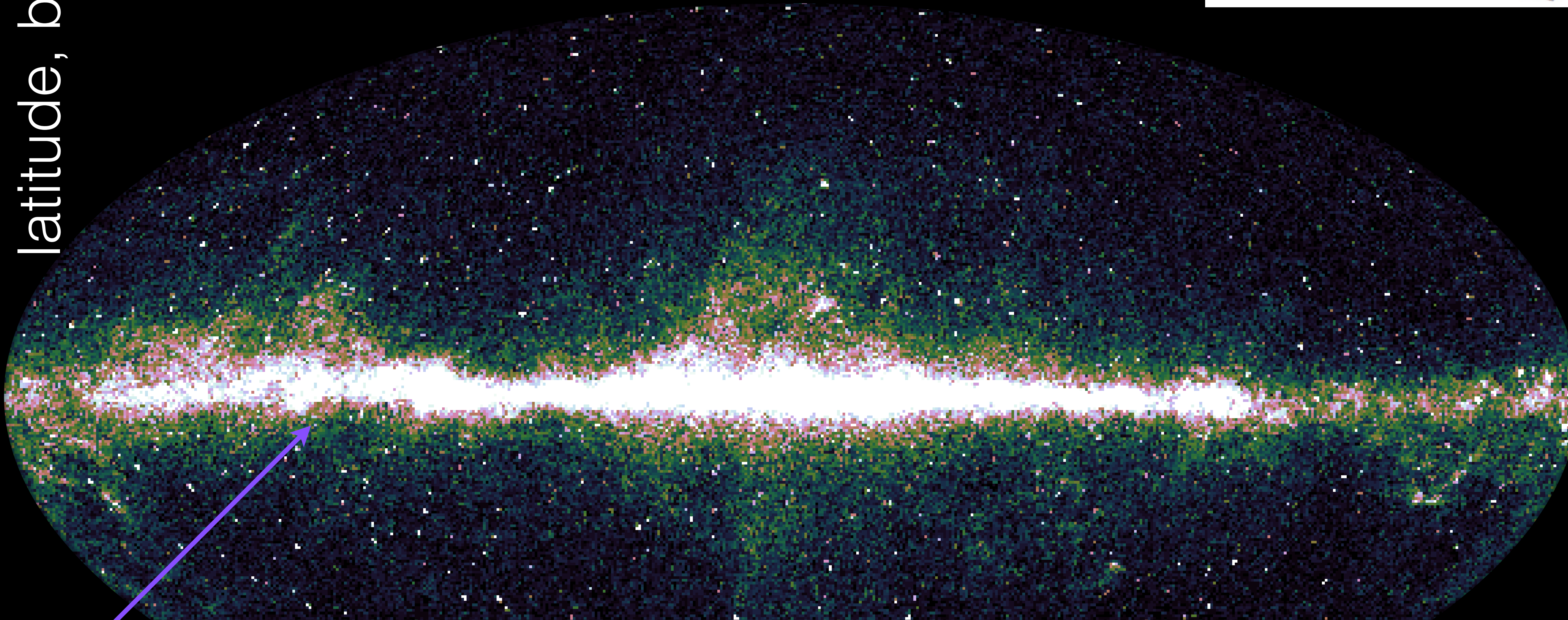
latitude, b ⟶



⟵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

third dimension (not shown) — energy

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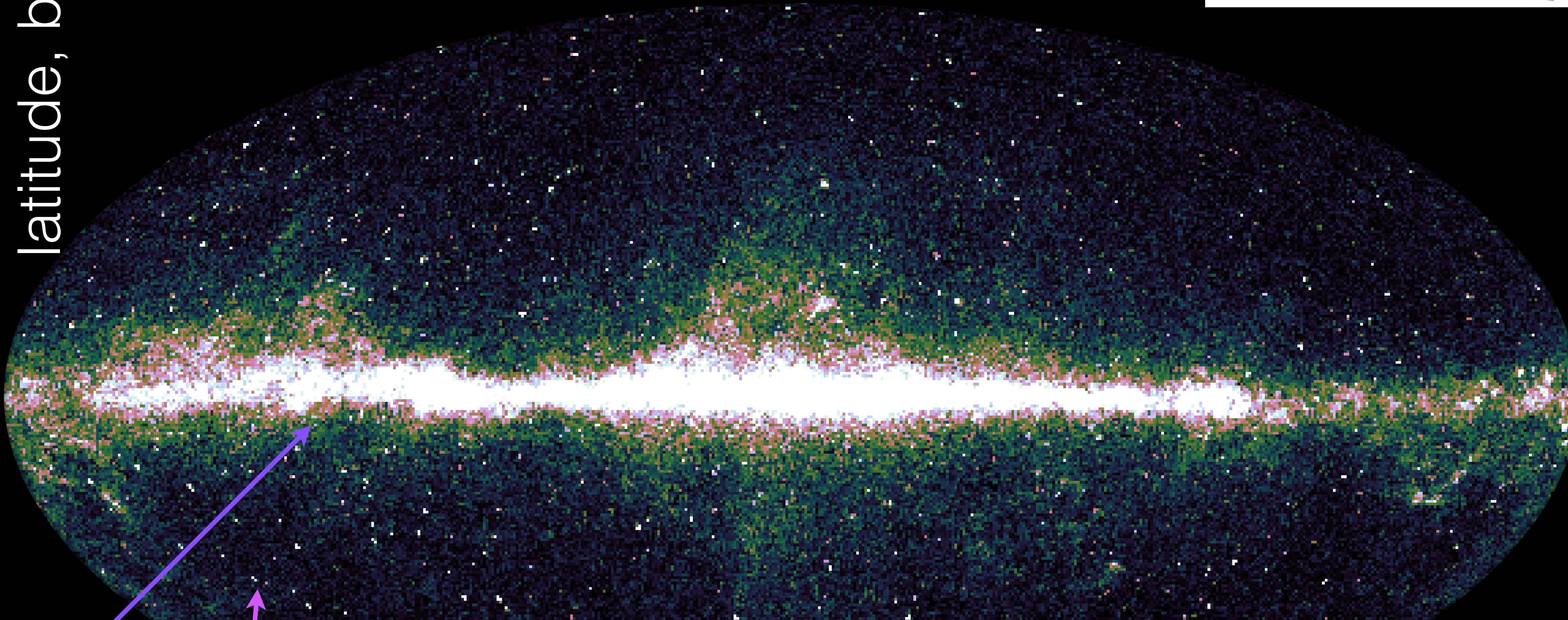

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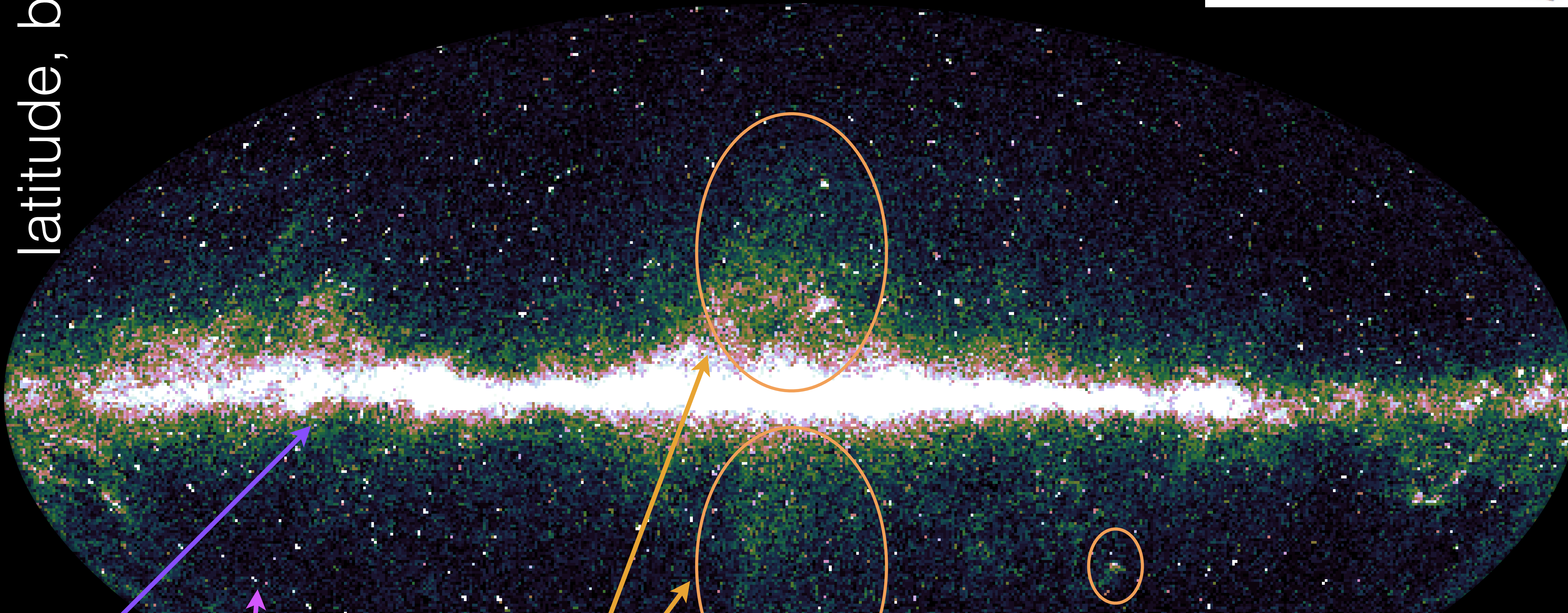
ii)from point sources (galactic or extra galactic)

iii)Extragalactic Isotropic

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY



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ii)from point sources (galactic or extra galactic)

iii)Extragalactic Isotropic

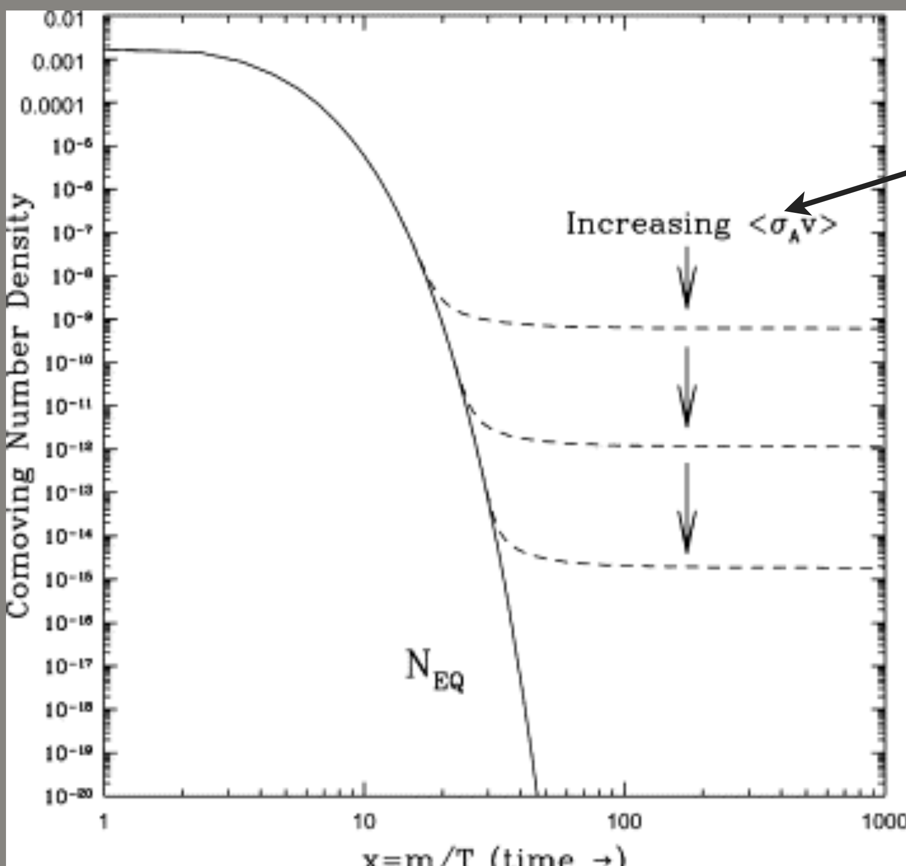
iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)

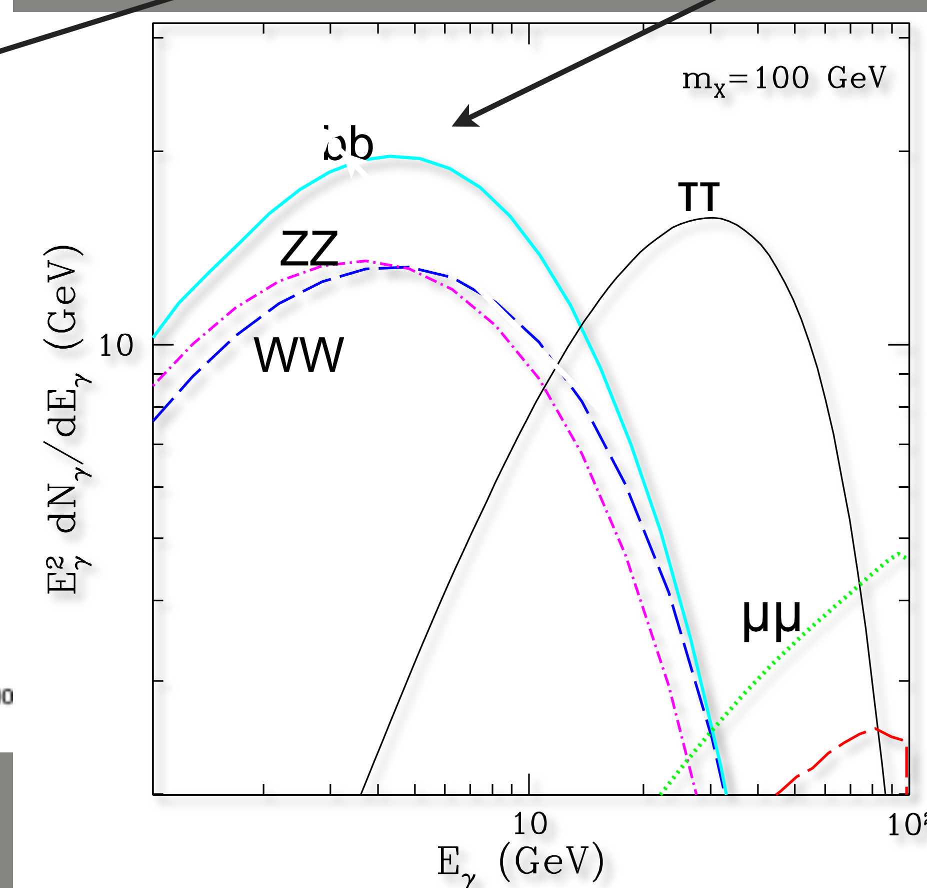
iv)misidentified CRs (isotropic due to diffusion of CRs in the Galaxy)

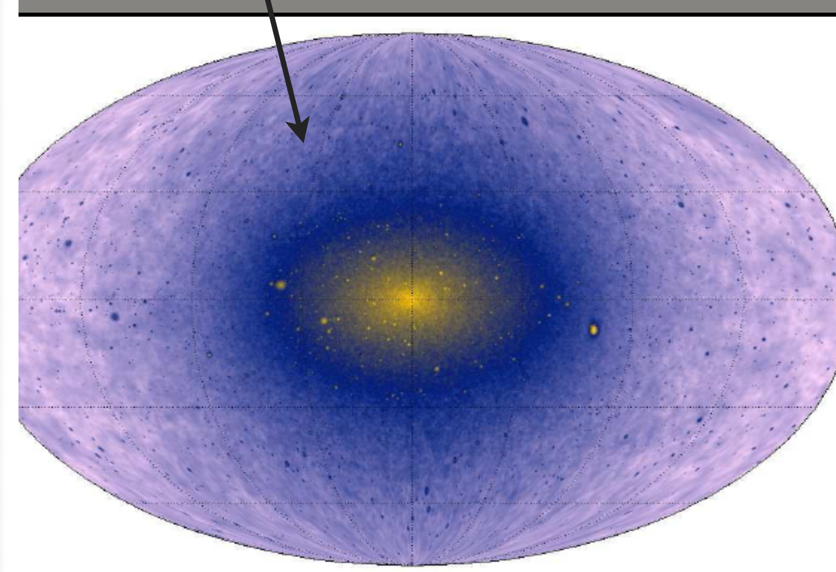
BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe:

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

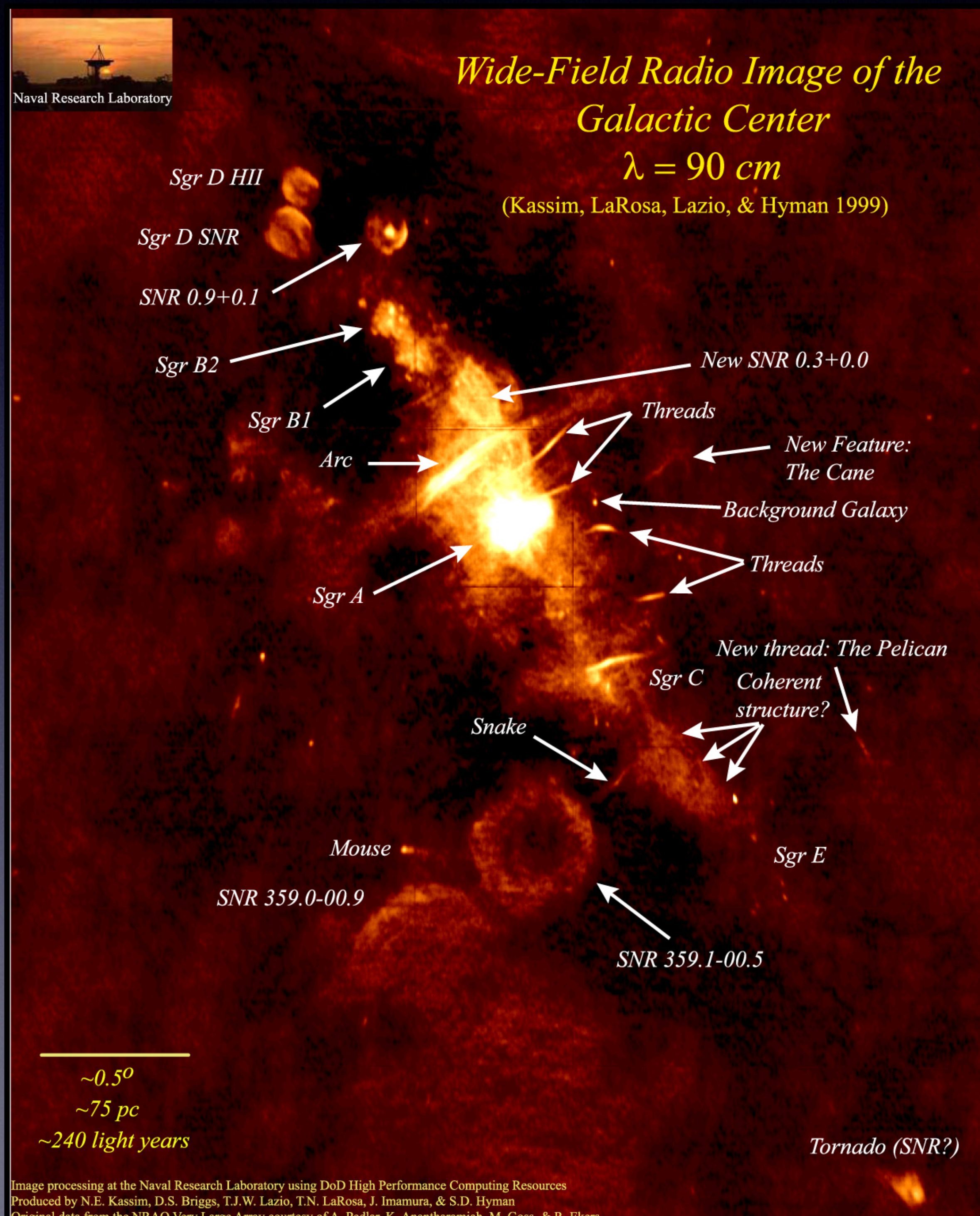


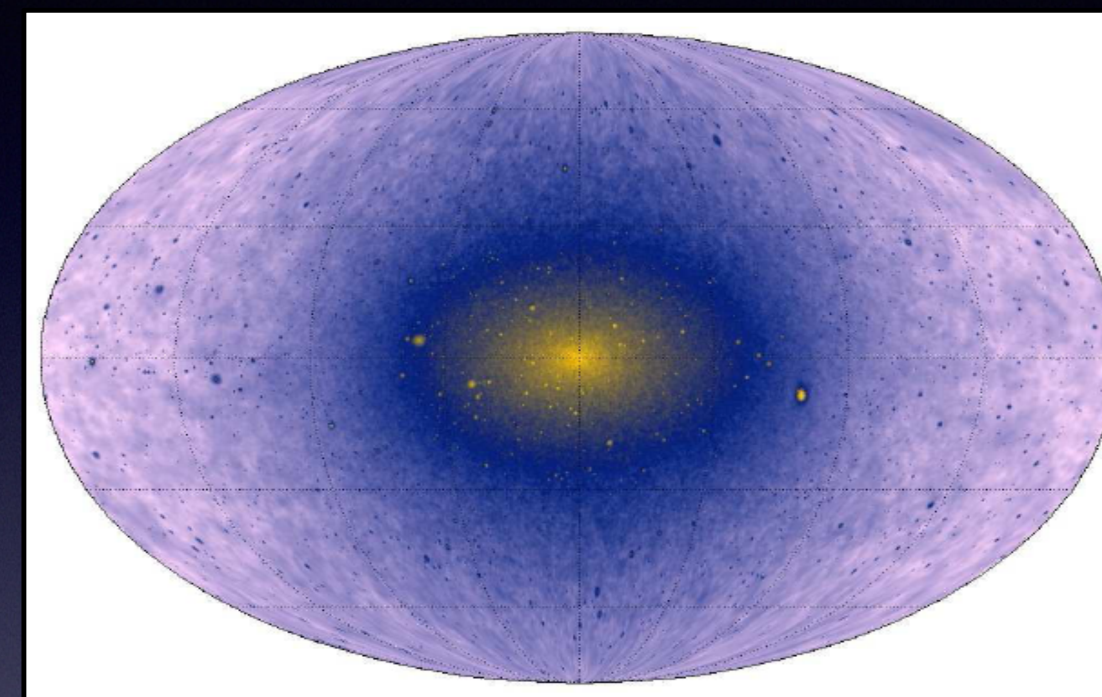




The Fermi galactic center excess. A possible signal of Dark Matter Annihilation?

One of the most likely targets is the Galactic Center

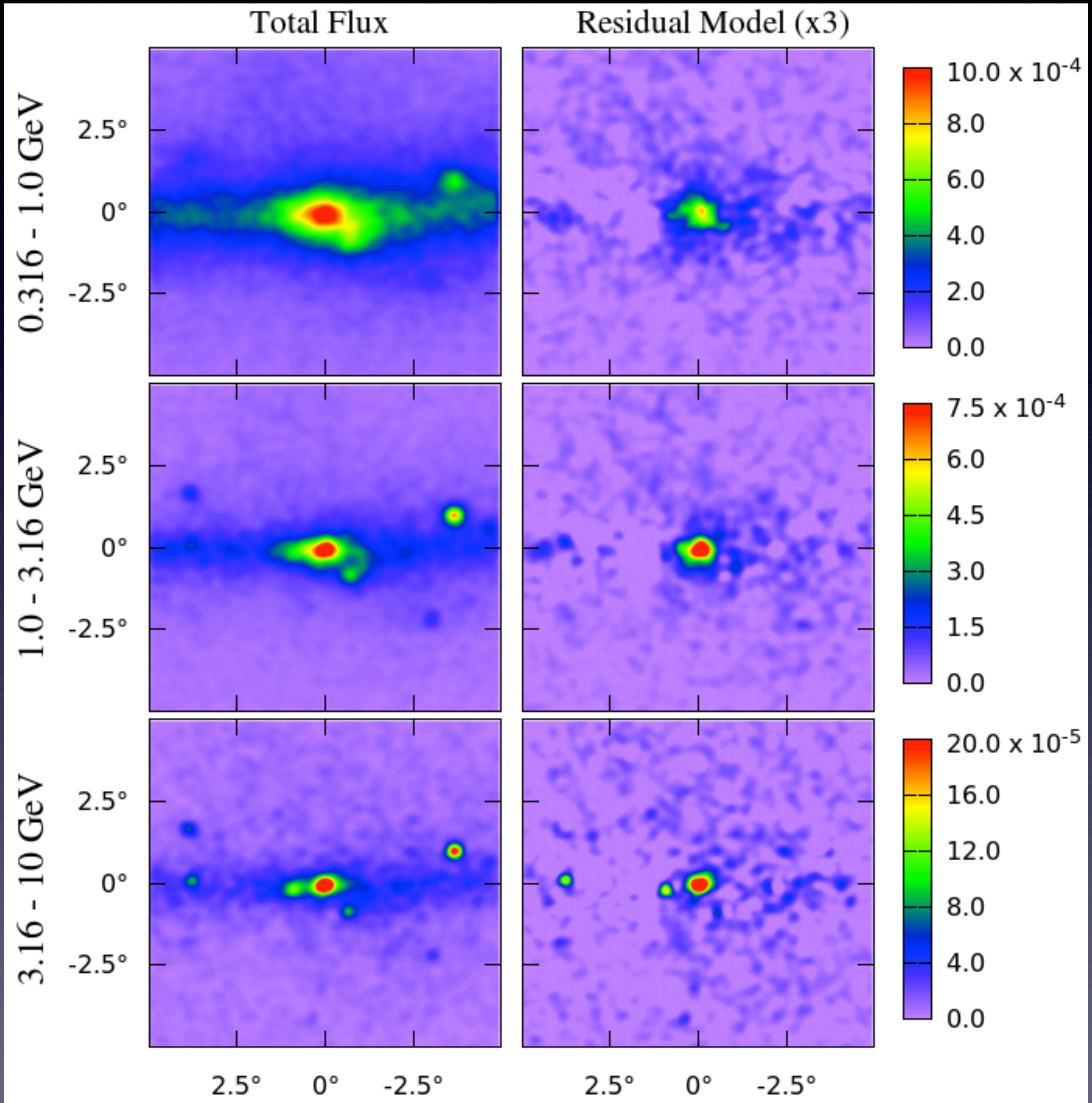




- The region of the galactic center is complex with large uncertainties.
- A DM annihilation signal peaks but also has significant uncertainties..
- Take advantage of multi-wavelength searches.

Looking for excesses in the inner galaxy

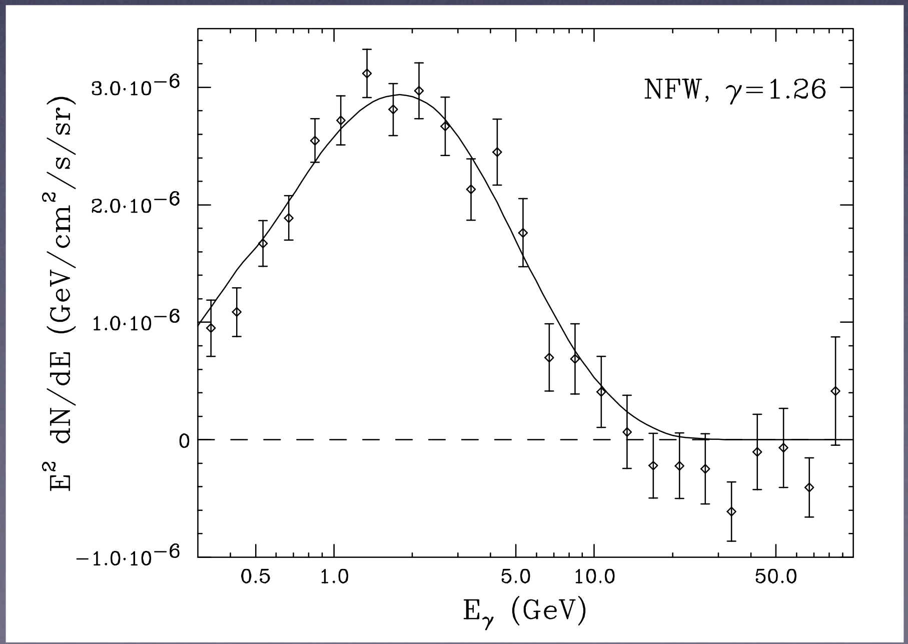
Using Templates:



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

Claim:

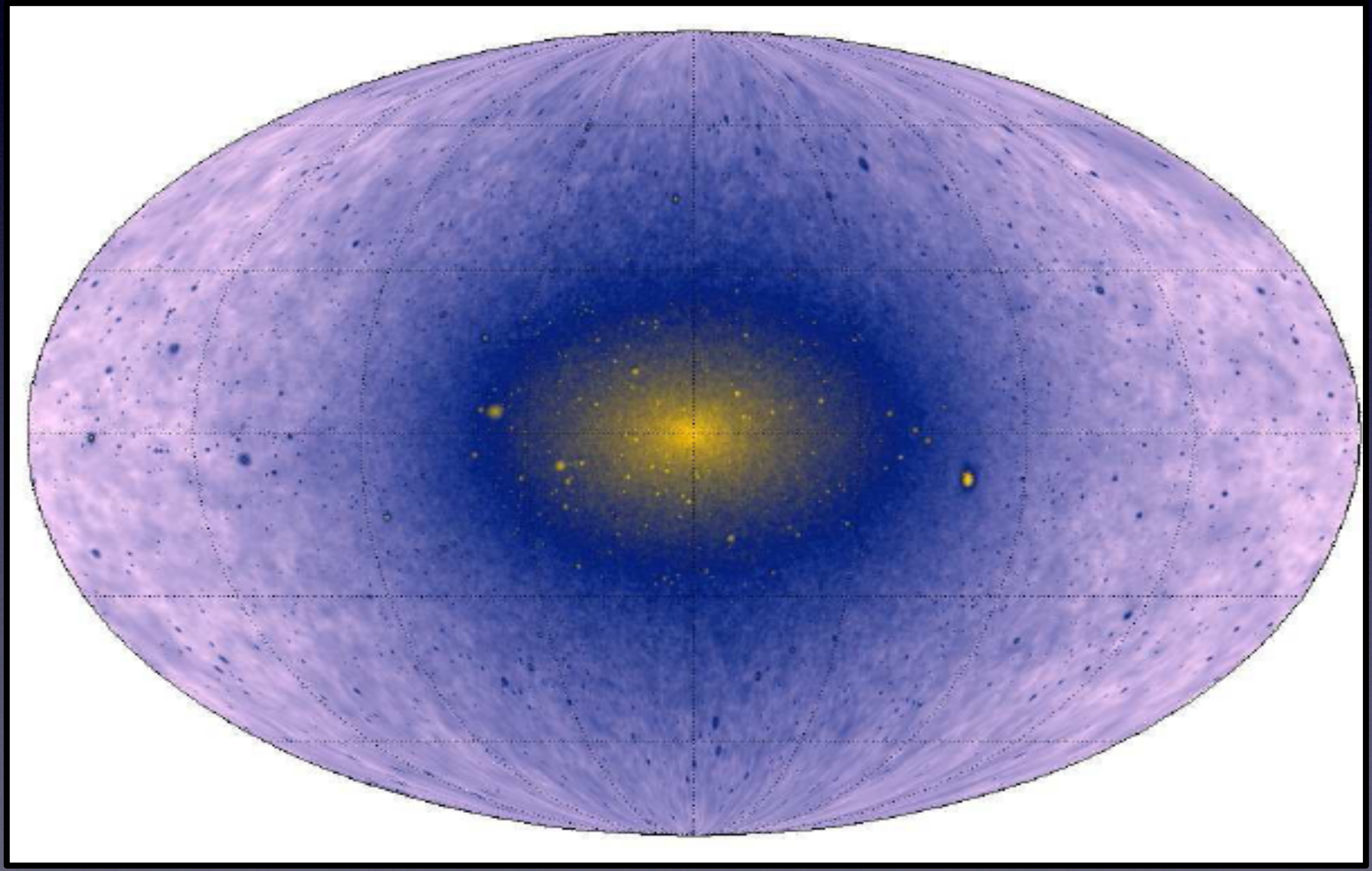
- A clear excess emission in the galactic center emerges
- Excess emission cuts-off at ~10 GeV (is in some dis-agreement with later findings)



Going to High Latitudes

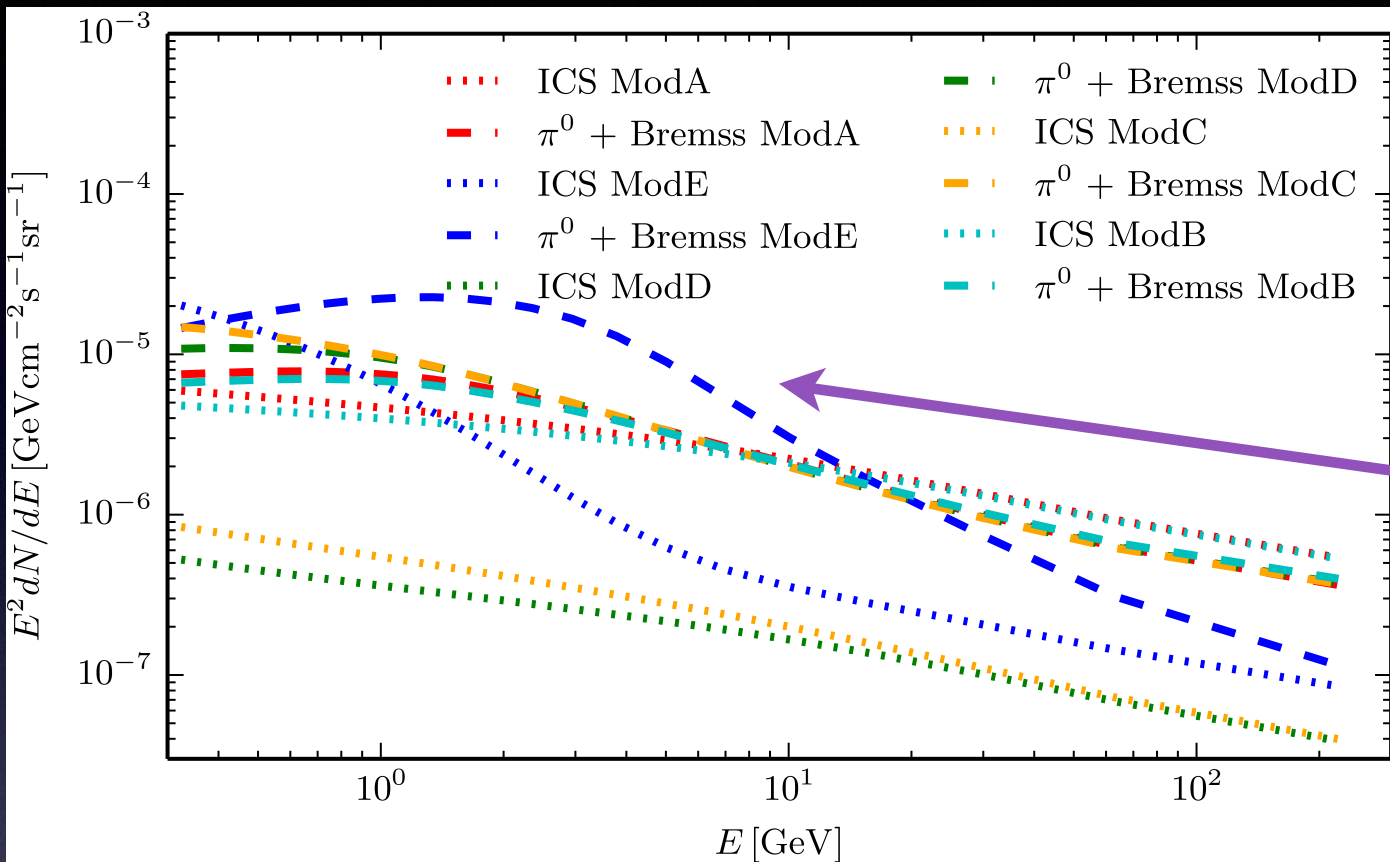
Advantages of looking further away from the center:

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.

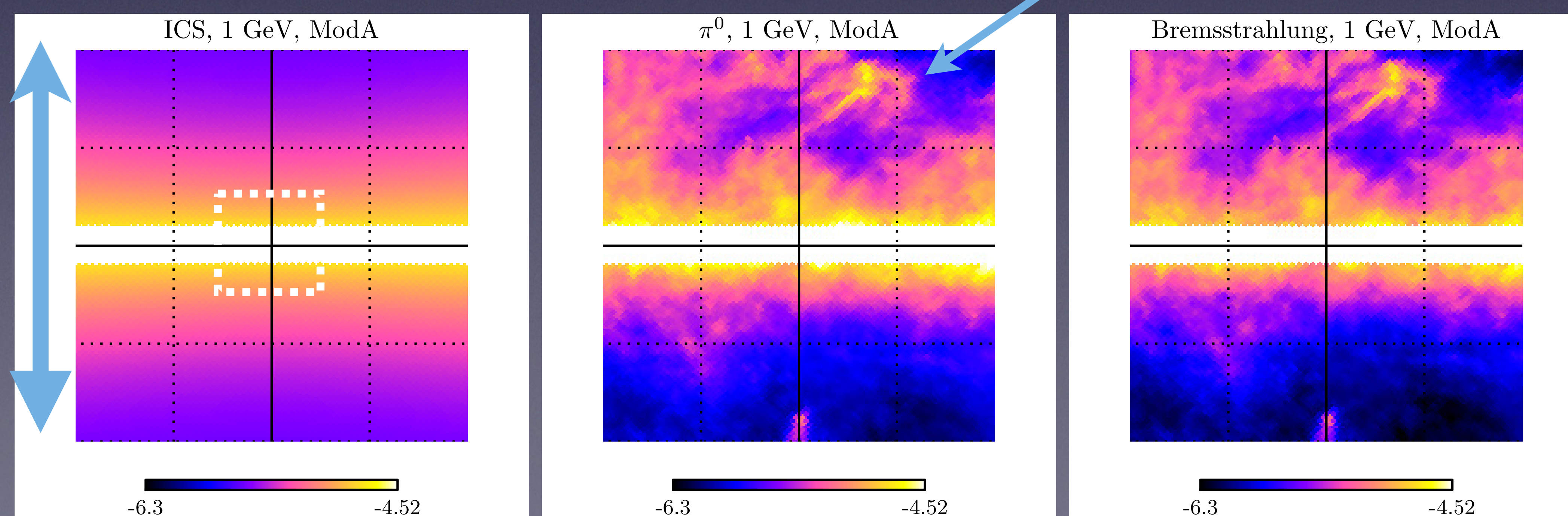
Modeling the background gamma-ray sky: Interplay with Cosmic-Rays & the ISM



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

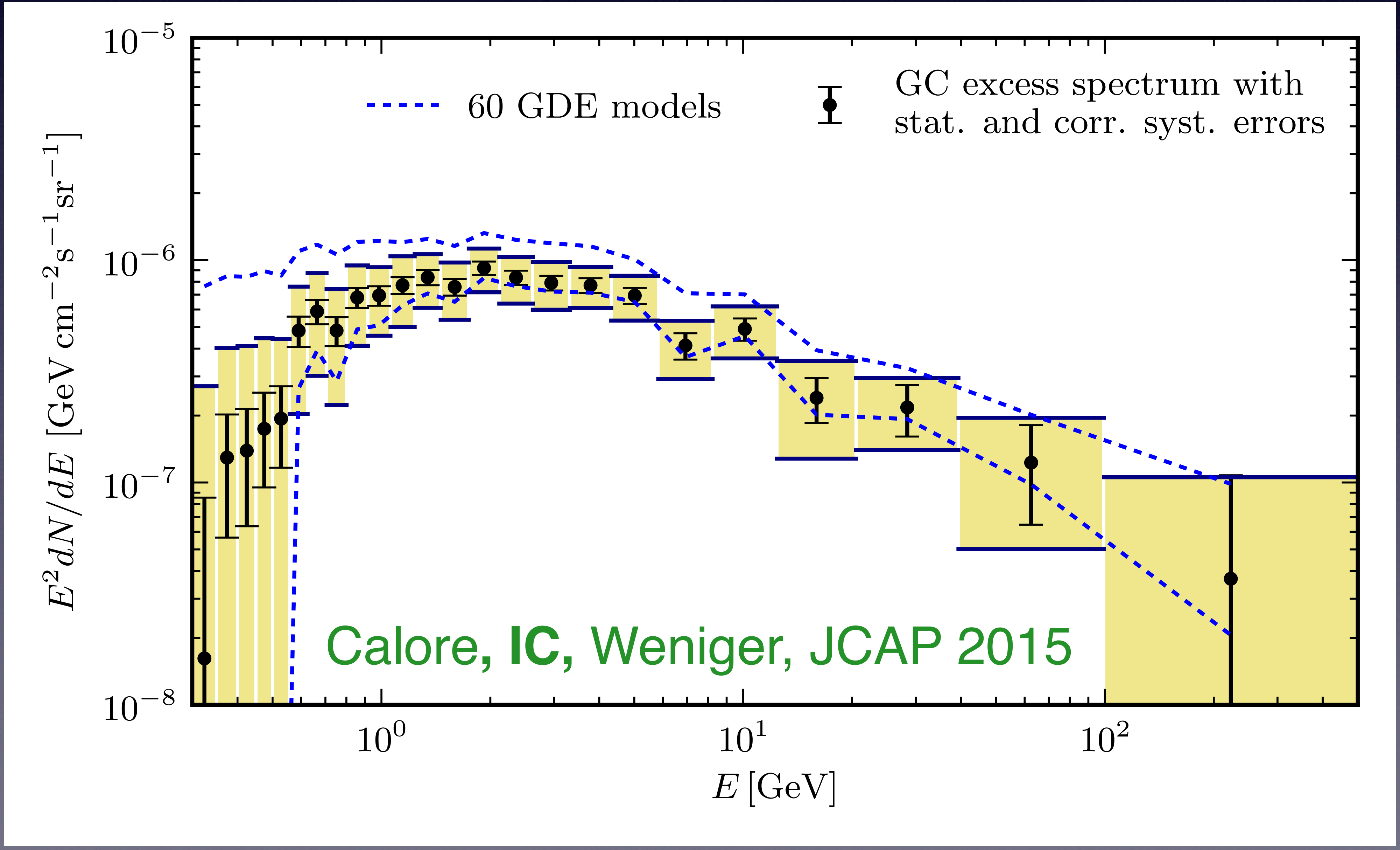
40 degrees in latitude



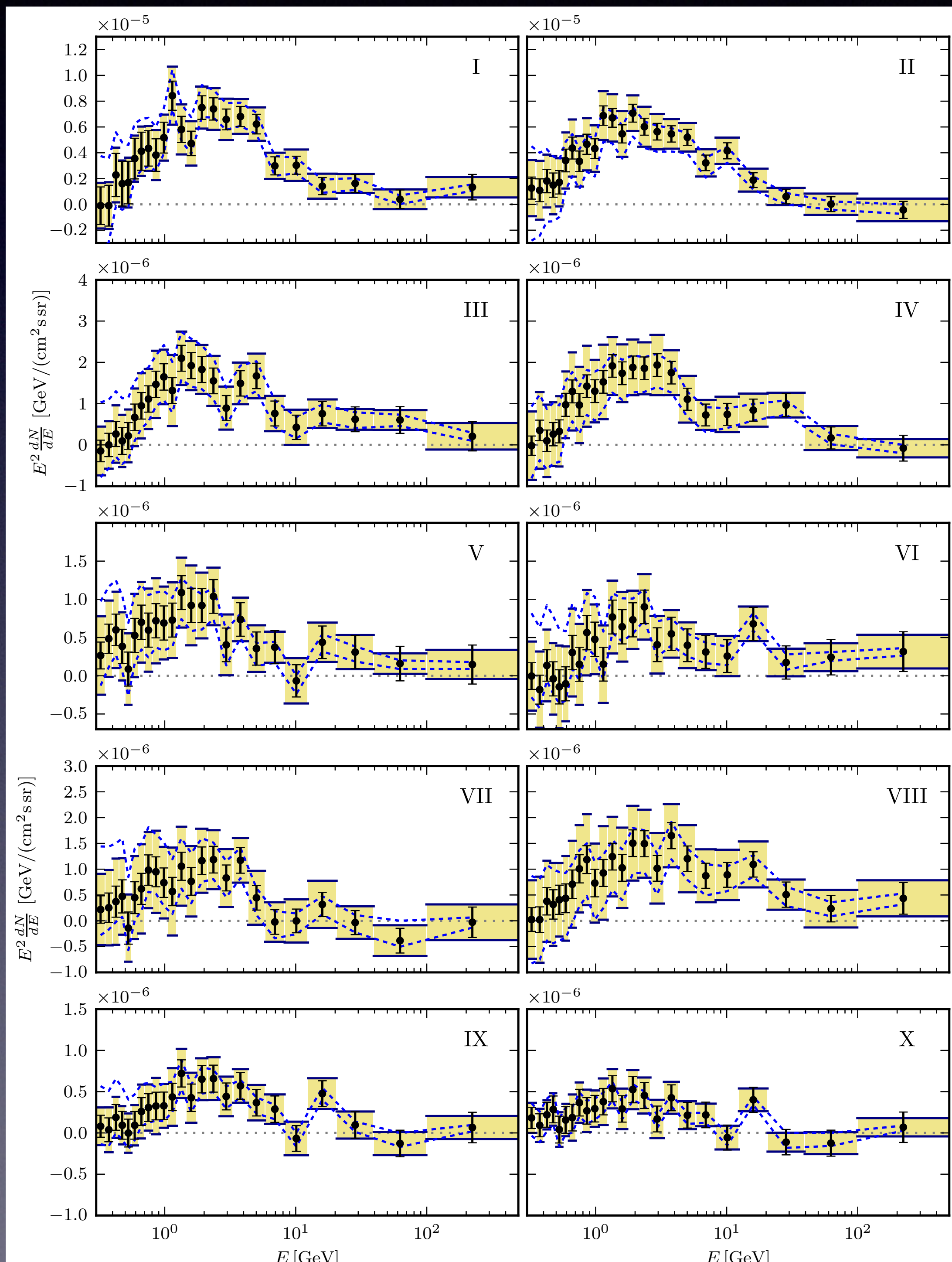
Accounting for the galactic diffuse emission uncertainties

We used 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 created our own (60) models—> 6660 different Templates!

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

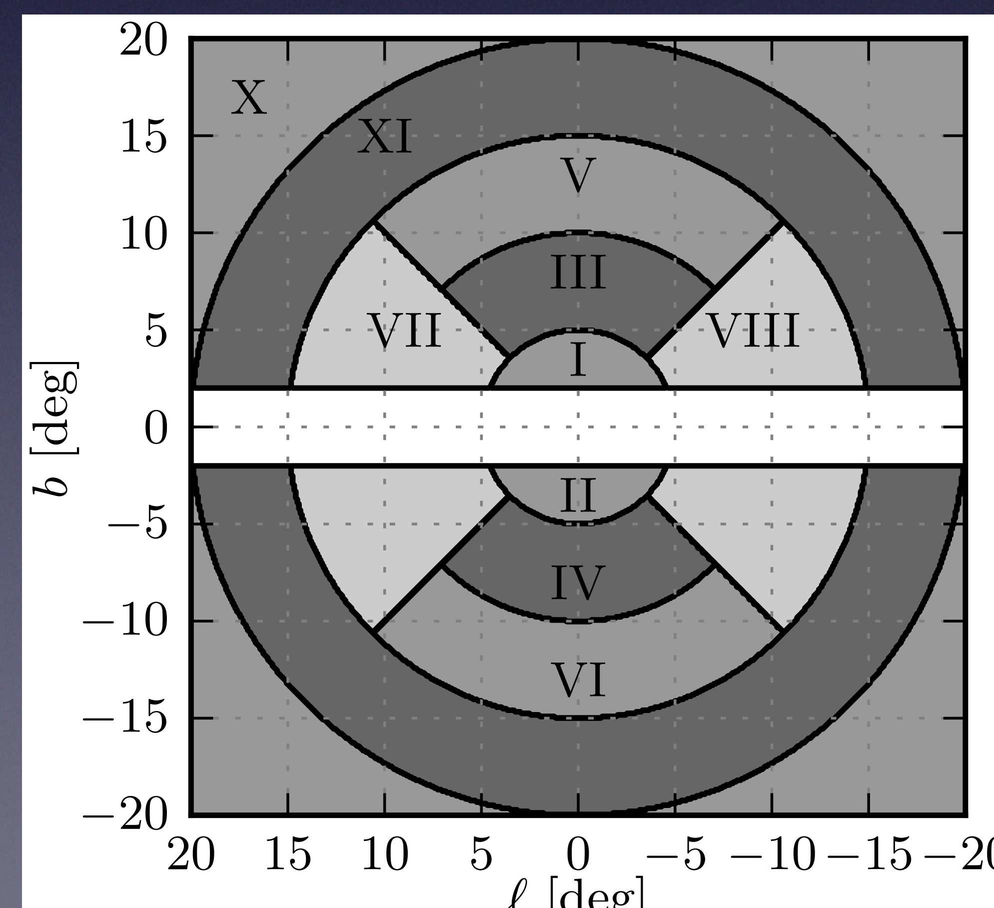


Robust to diffuse gamma-ray emission uncertainties



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

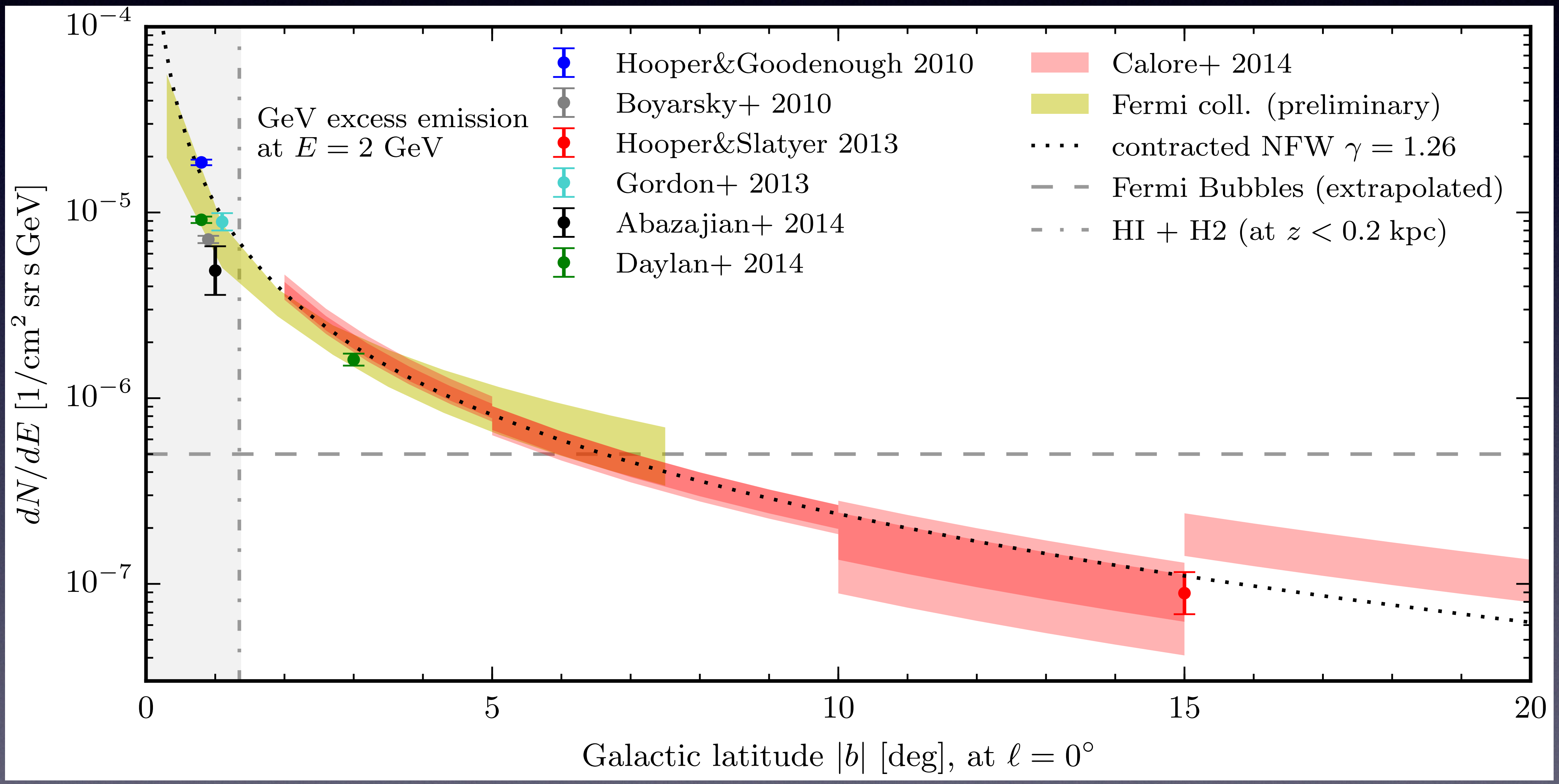
The GCE is present everywhere in the inner galaxy



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

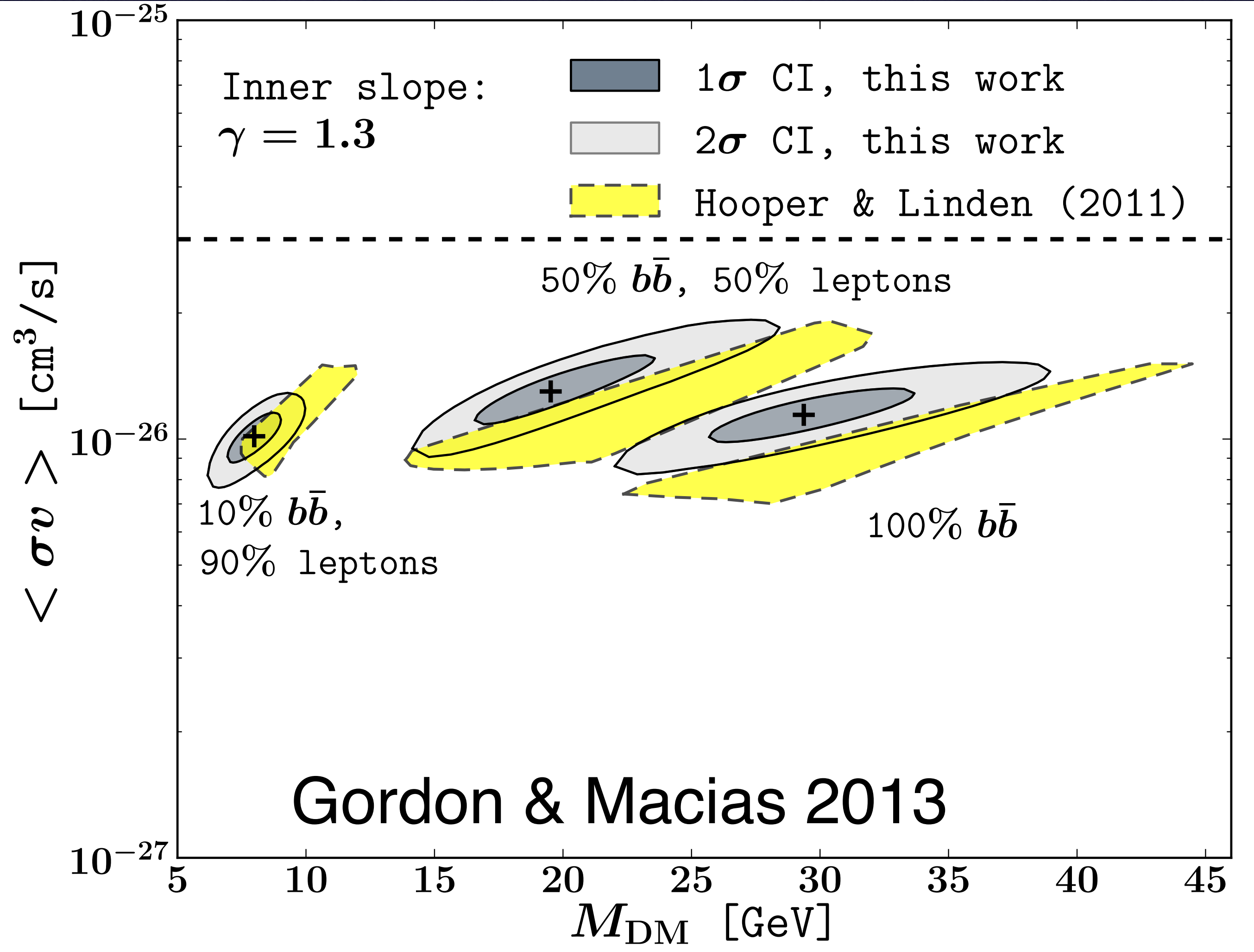


The excess signals from different analyses, agree within a factor of less than 2 in terms of total emission.

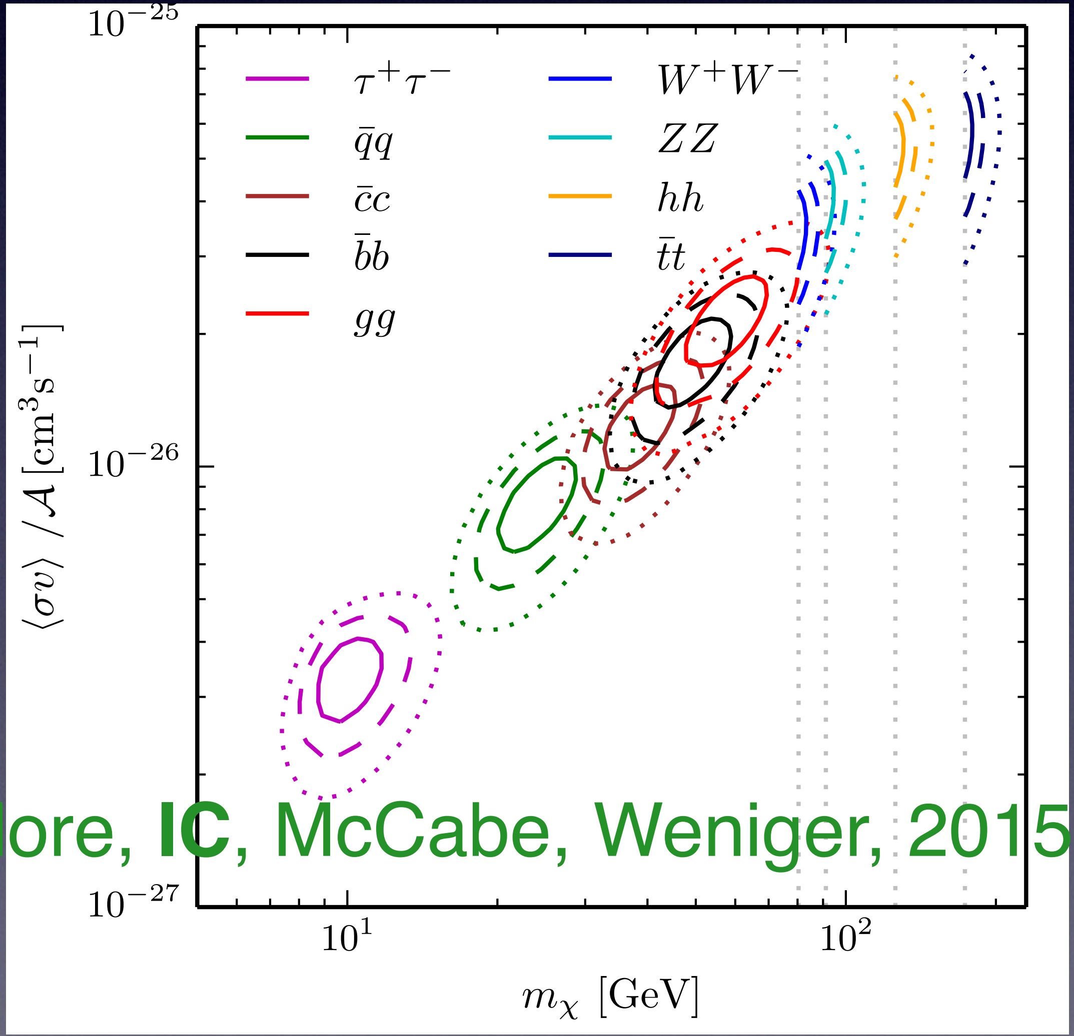
If this is a DM annihilation signal what do we learn about the particle physics?

The range of possibilities (phenomenologically) depends on properly taking into account the astrophysical (correlated) errors.

Without astro-errors:

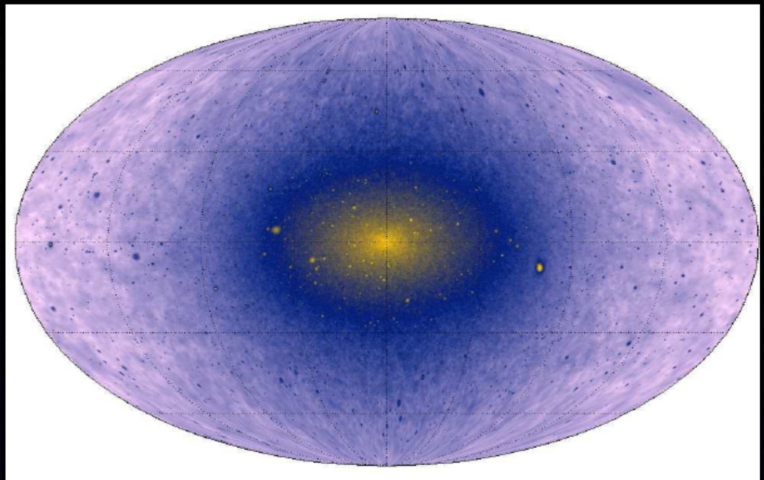


With astro-errors:



The mass range preferred is actually higher. Even though still light DM models can work.

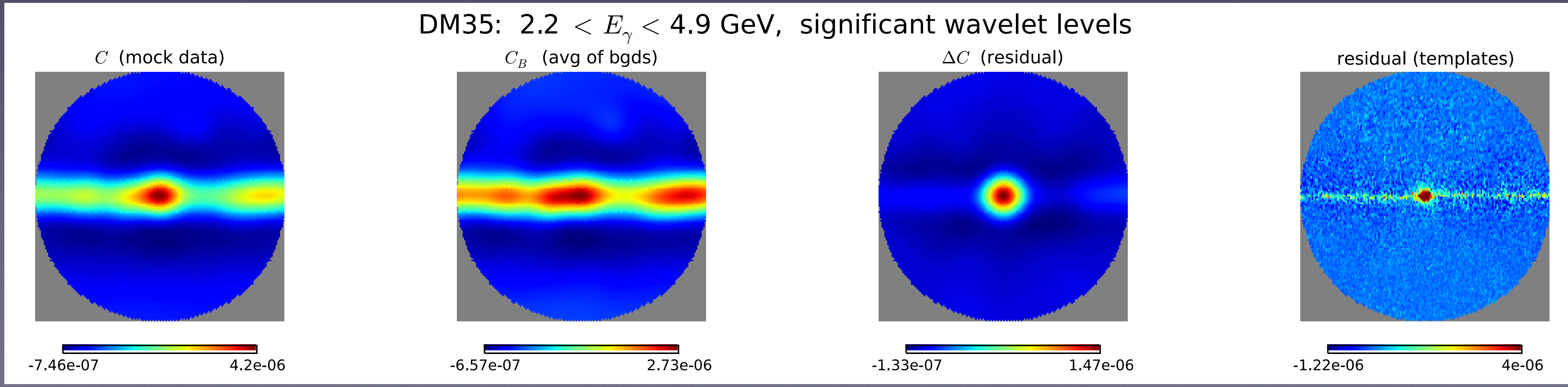
What else we do?



- Look in other directions of the sky (dwarf galaxies) & other DM probes/data
- Develop models for astrophysical predictive alternatives.
- Test them with more data and multi-wavelength approaches.
- Advance/Built theoretical tools to calculate, cosmic-rays and gamma-rays in the Milky-Way.
- Create new techniques of studying data.

Wavelet techniques McDermott, Fox, **IC**, Lee JCAP 2016

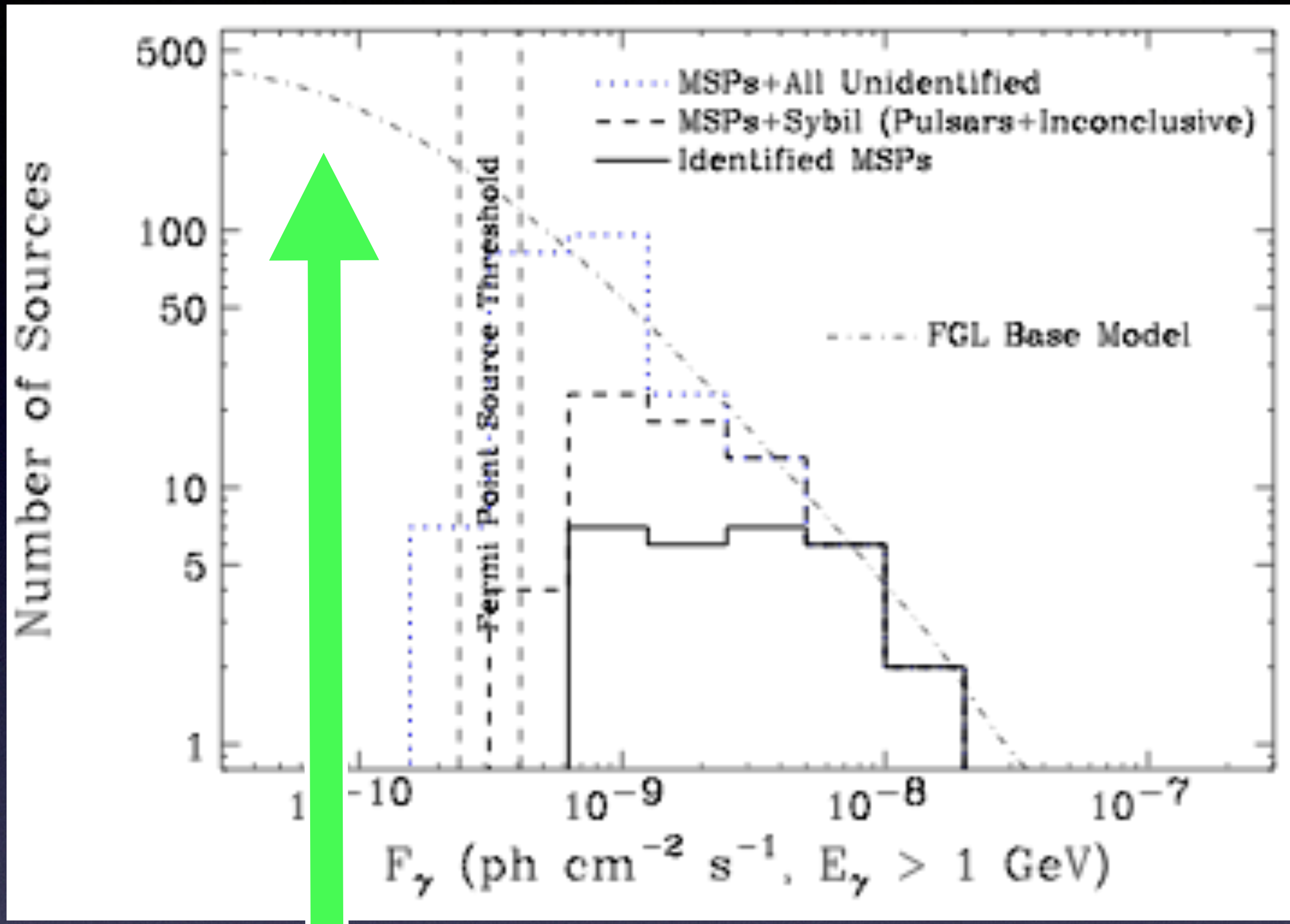
Balaji, **IC**, McDermott, Fox PRD 2018 Zhong, McDermott, **IC,** Fox PRL 2020



Alternative work related to the Galactic Center the GeV excess and it's interpretations

Millisecond Pulsars:

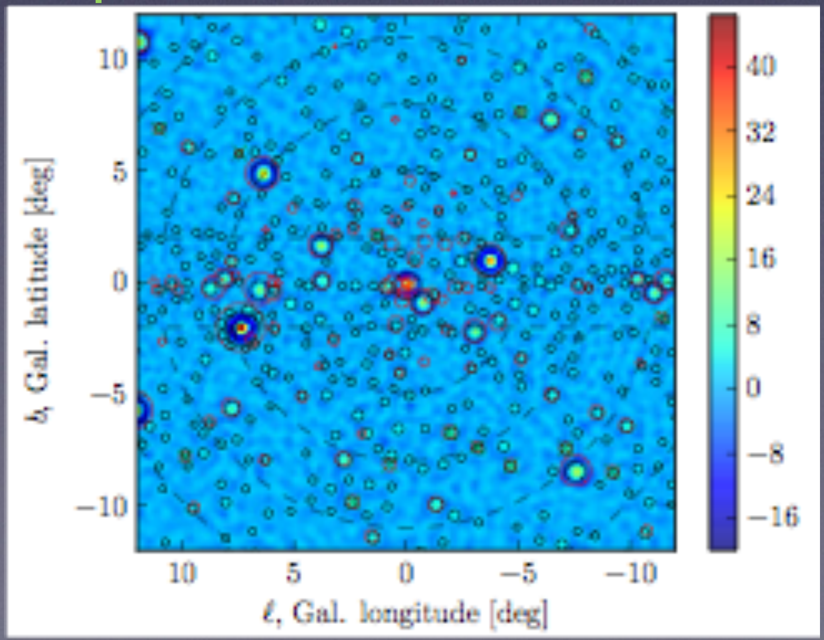
Hooper, IC, Linden, Siegal-Gaskins & Slatyer PRD 2013 (1305.0830), (<10% of total)
Calore, Di Mauro, Donato ApJ 2014 (1406.2706) (<10%)
IC, Hooper, Linden JCAP 2015 (1407.5625) NOT REALLY ABOVE 5deg
Calore, Di Mauro, Donato, Hessels, Weniger (1512.06825) MAYBE YES
Brandt, Cocsis ApJ 2015 YES BUT SPECIAL MSPs
O'Leary, Kistler, Kerr, Dexter 2016 PROBABLY



As reference we need 1-3x10^3 MSPs in the inner 2 kpc bellow threshold

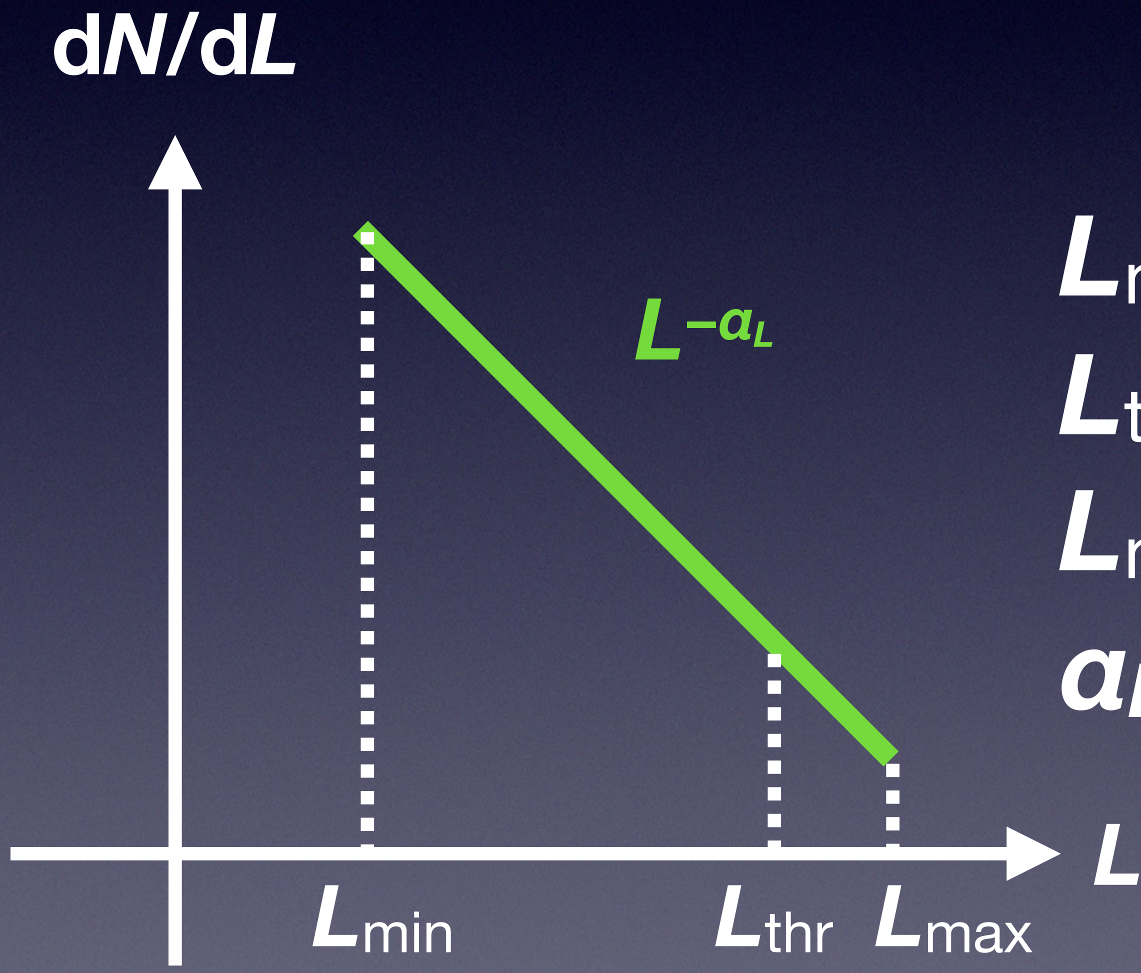
Sensitivity analyses on point-sources and astrophysics modeling:

Bartels, Krishnamurthi, Weniger PRL 2016
Lee, Lisanti, Safdi, Slatyer, Xue PRL 2016
Huang, Ensslin, Selig JPCS 2016.



A Central Source Population

How to characterize a Central Source Population?



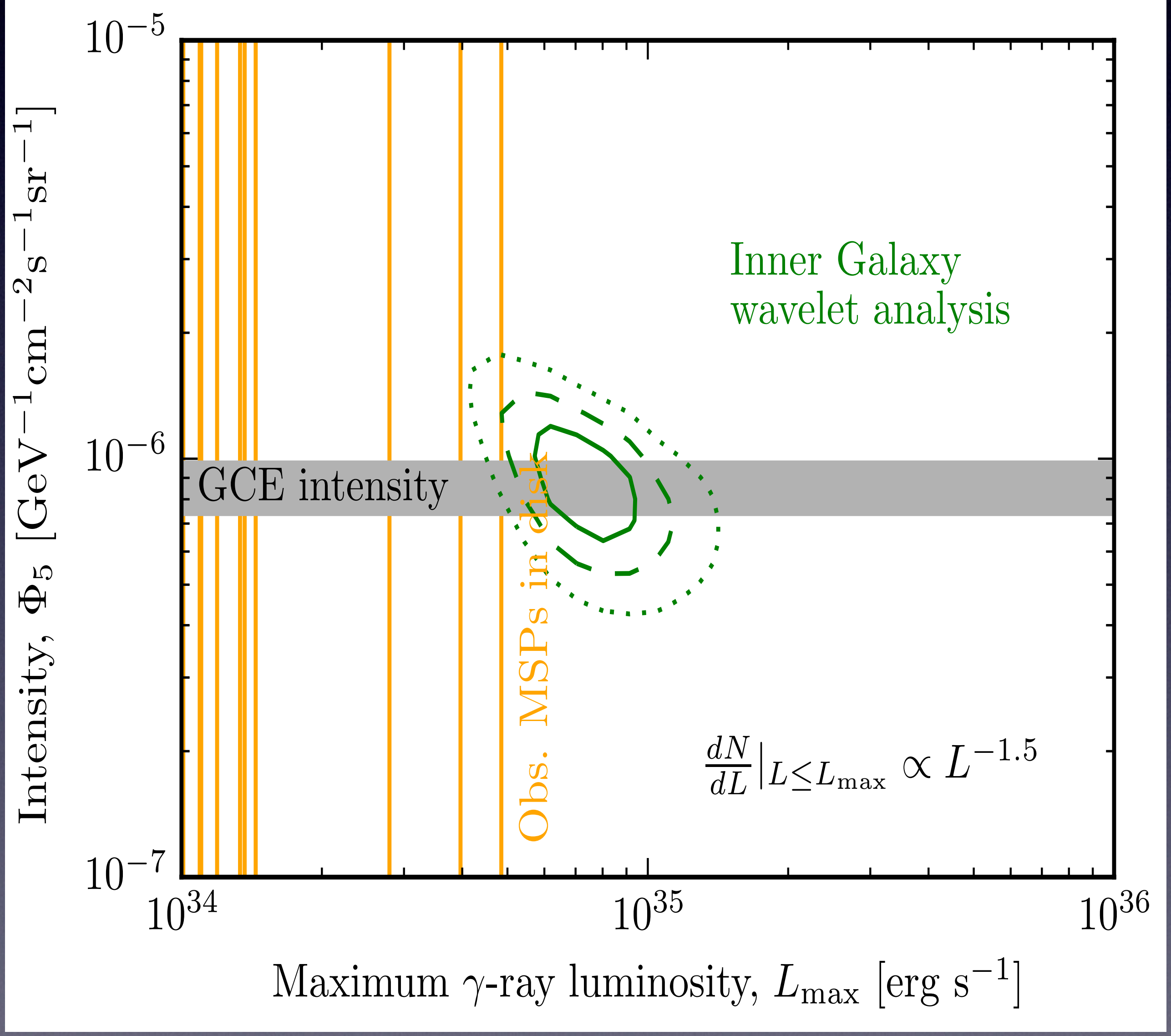
L_{min} → gamma-ray physics
L_{thr} → detection threshold
L_{max} → gamma-ray physics
α_L → theory prior

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, …

A simple Question: Can the CSP Be Bright Enough?

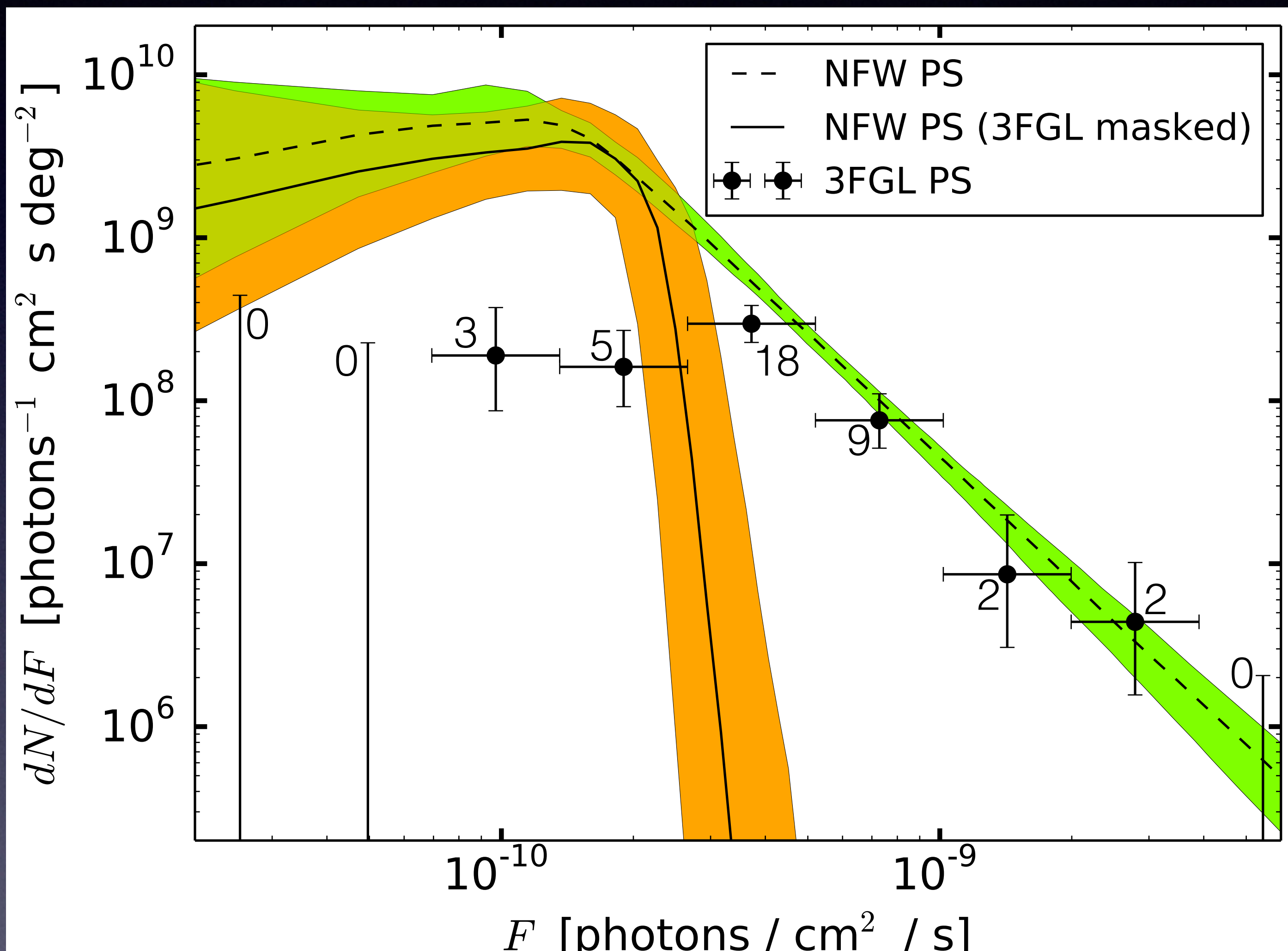
- Given an assumption about the "luminosity function" (the dependence of N_{PS} on L_{PS}), can ask if "point source-y" PSs are compatible with unresolved PSs accounting for the GCE
- Claim in 2015 was "yes" if the luminosity function had a power-law index α_L=1.5



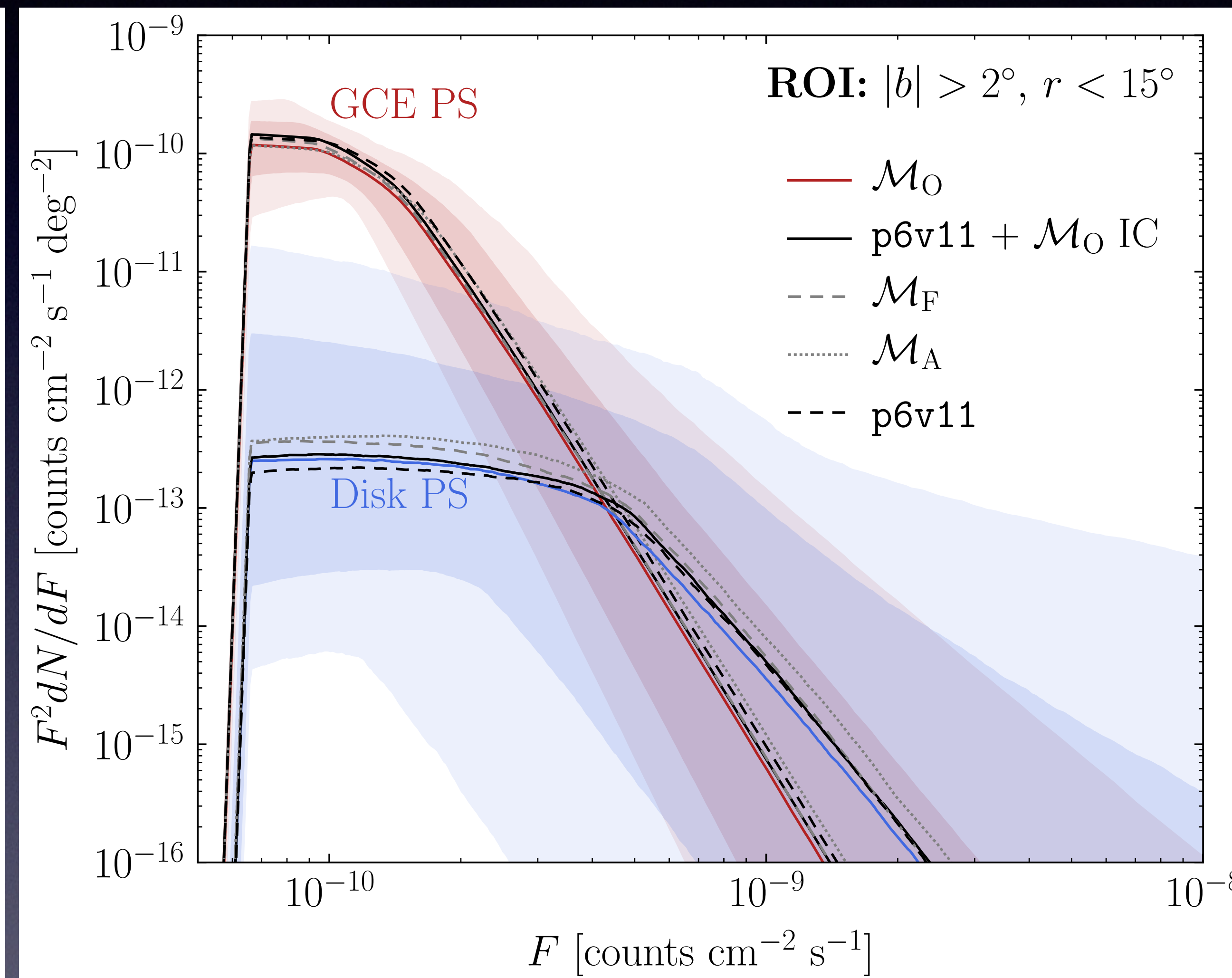
Bartels et al., **1506.05104**

Point Source Fit Update

Lee et al., **1506.05124**



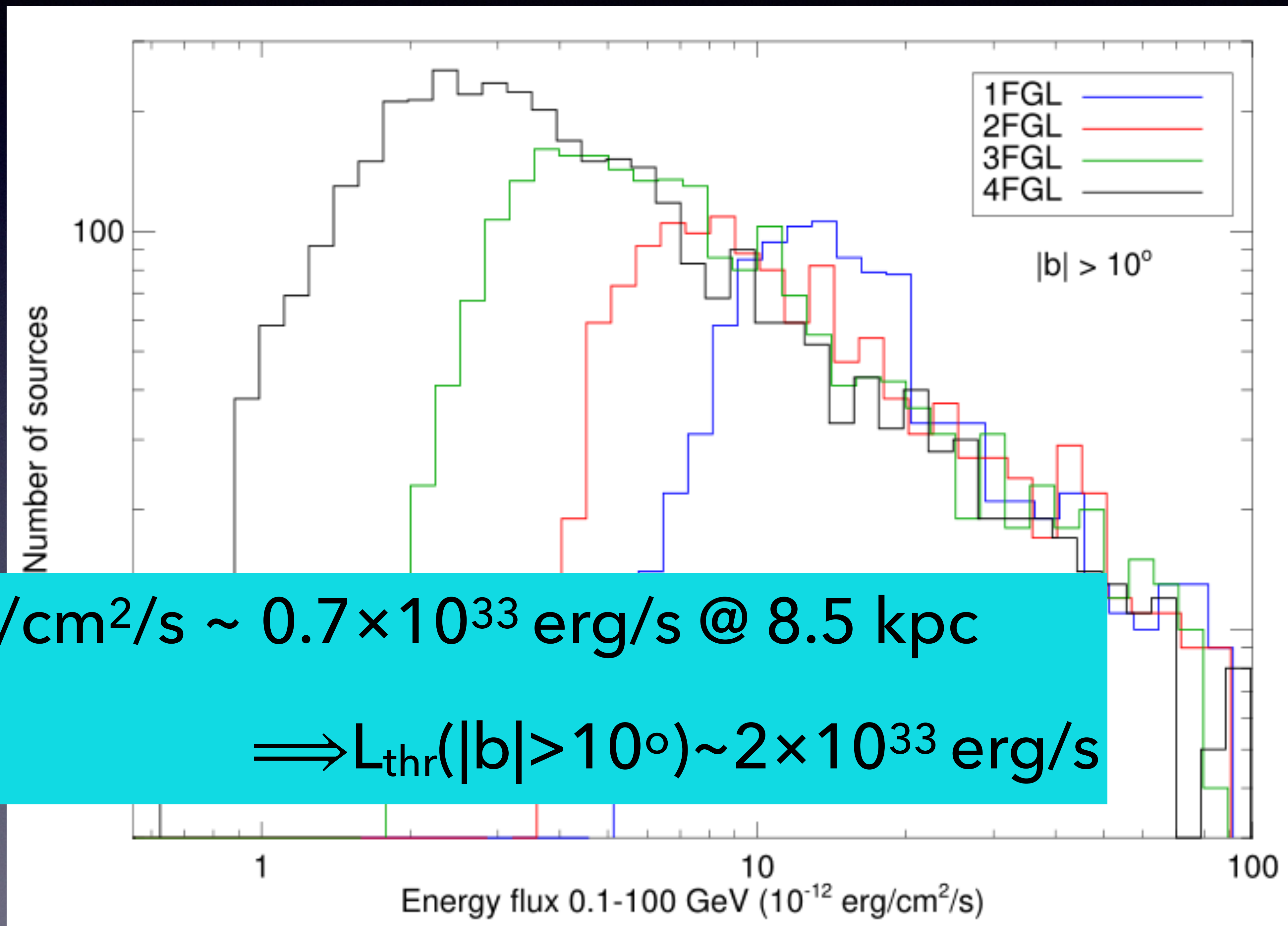
Buschmann et al., **2002.12373**



most of the brightness should have been just below the (ca. 2015) point source detection threshold

(time invariant statement)

The 4FGL Catalog

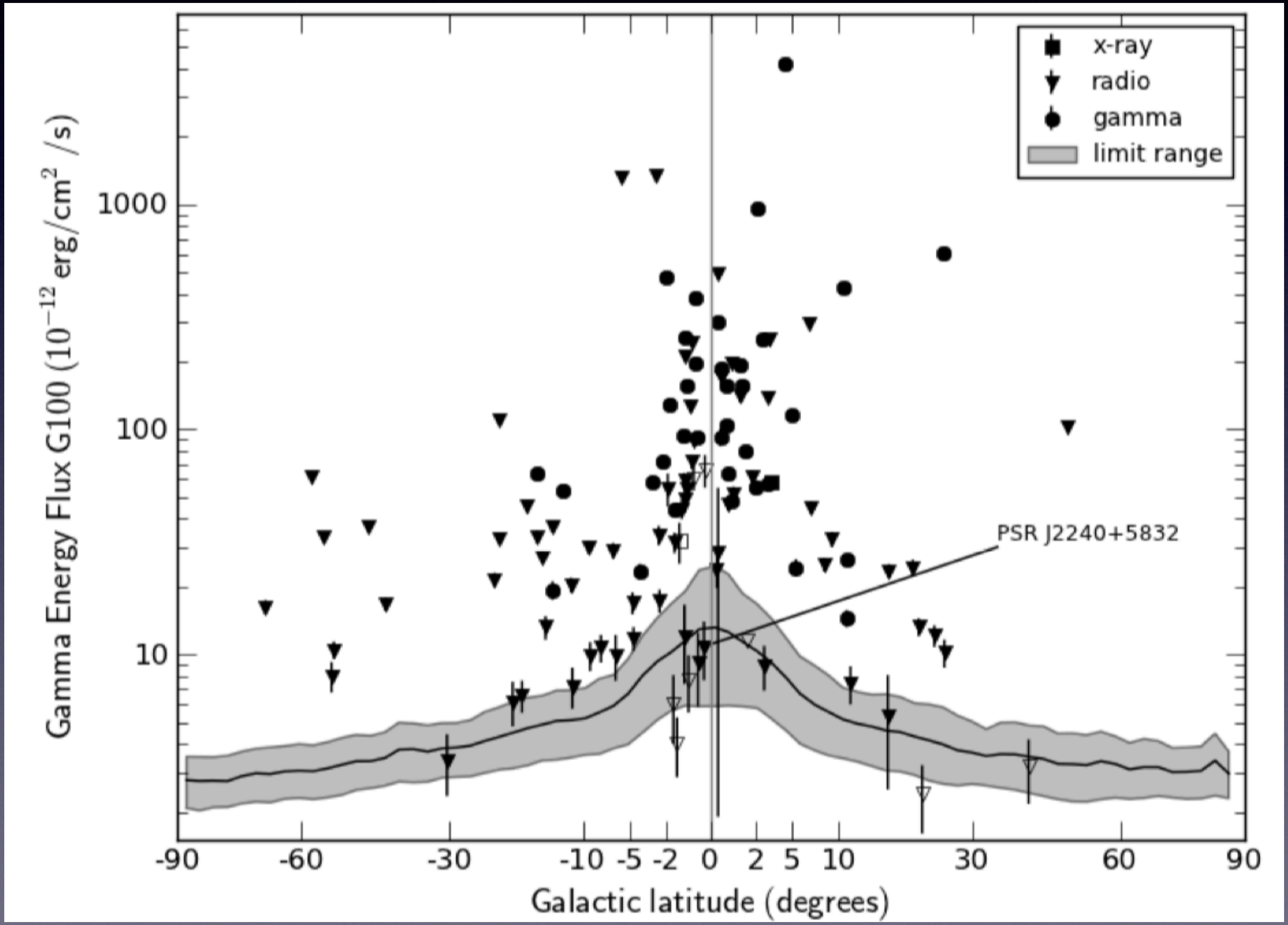


10^{-12} erg/cm^2/s ~ 0.7×10^{33} erg/s @ 8.5 kpc

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

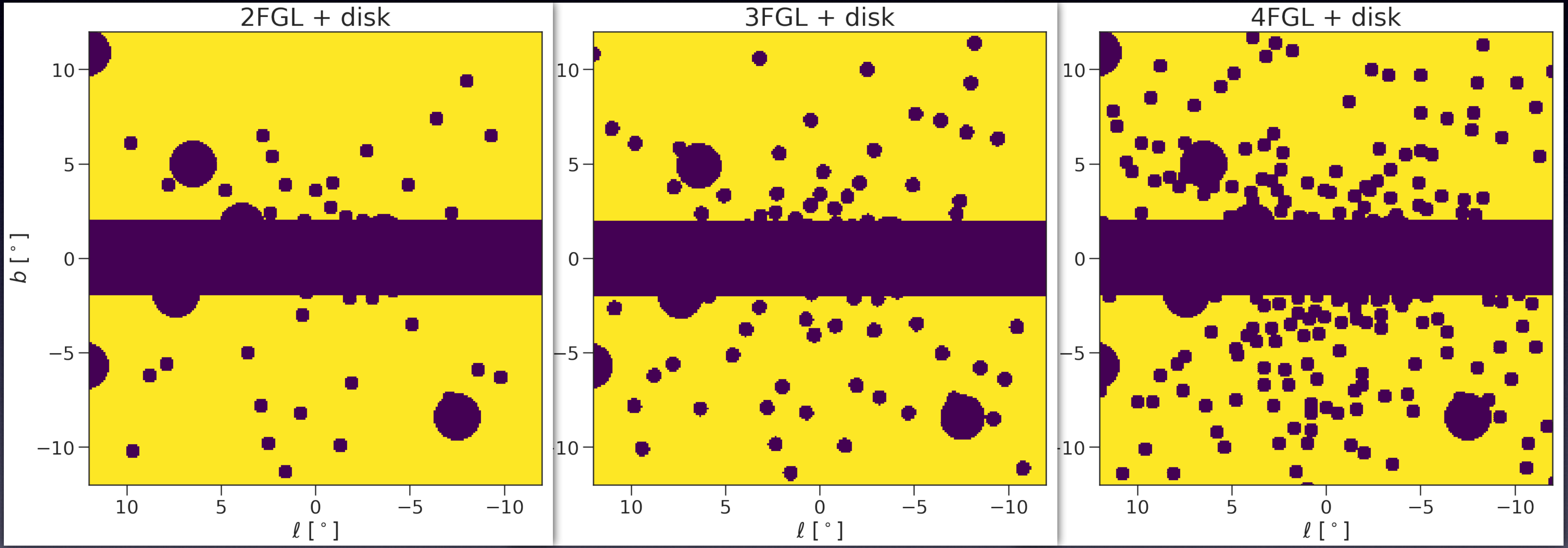
Abdollahi et al., **1902.10045**

b-dependence of detection



Abdo et al., **1305.4385**

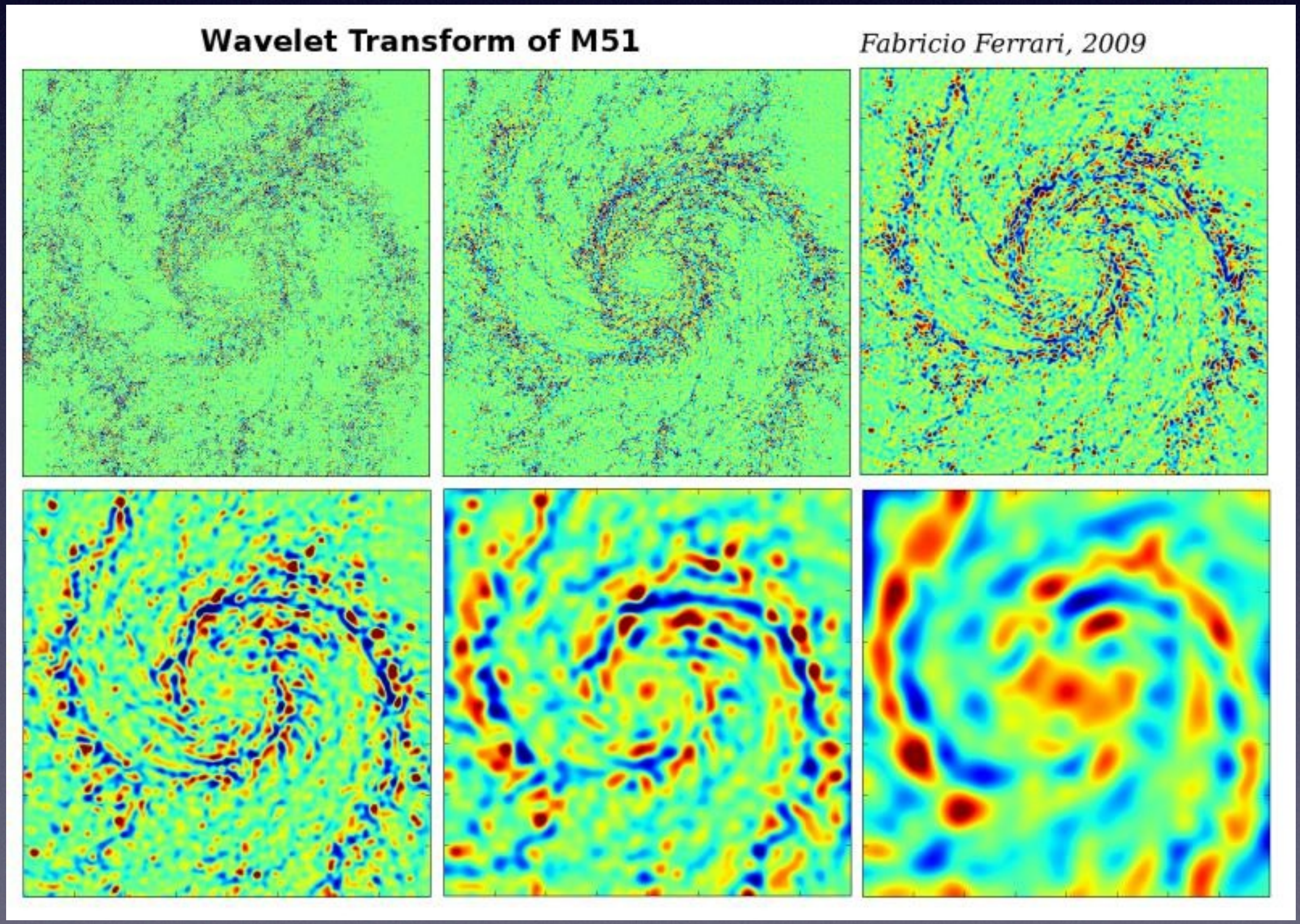
The Masks of different Fermi Catalogs (#FGL)



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

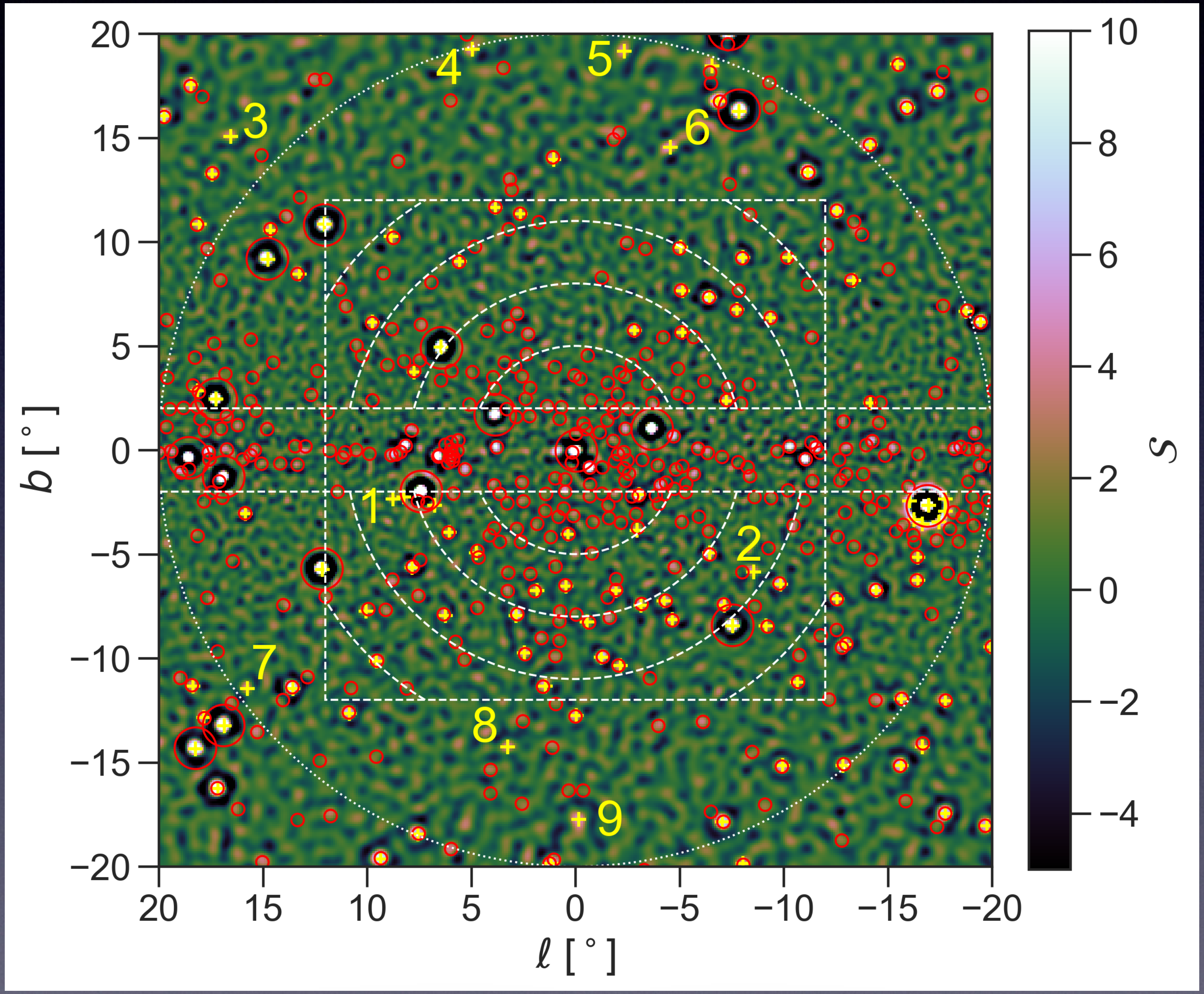


Different type of structures will have a different power at different levels of the deco-mposition (e.g. edges and other small scale structures vs larger scale variations).

Wavelets can find these different structures.

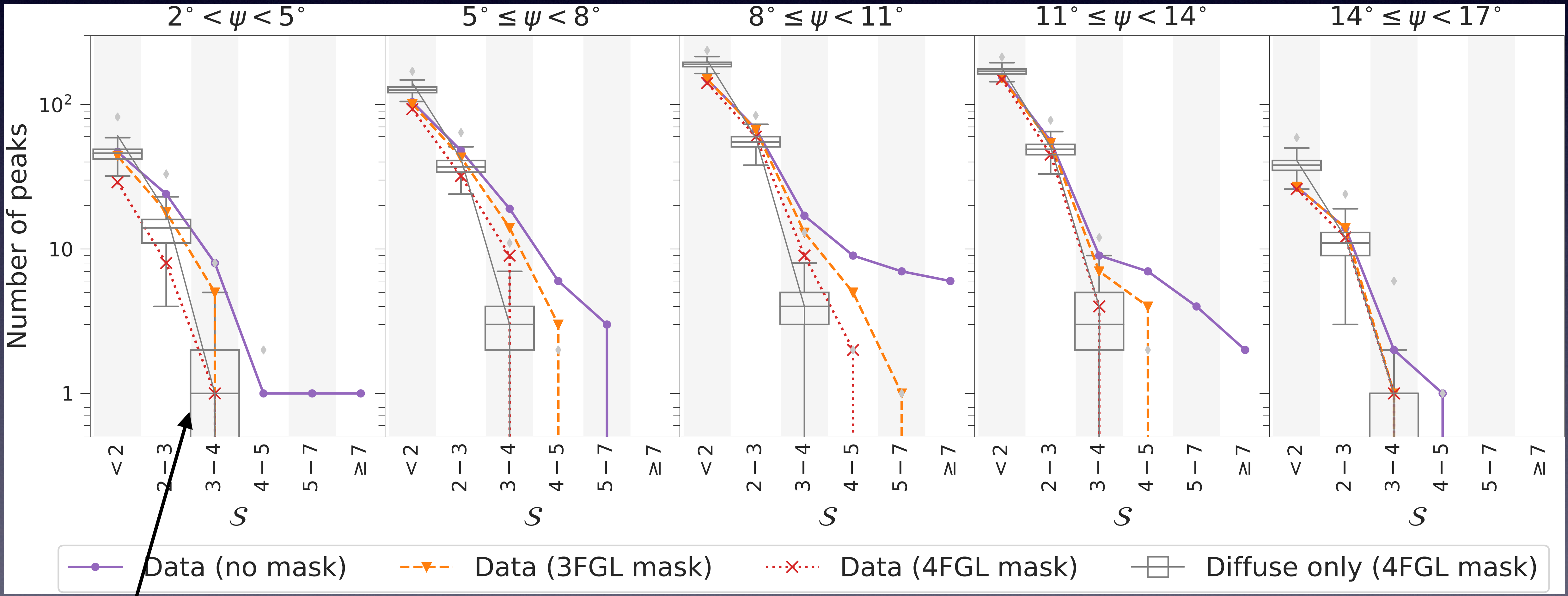
GCE: "Wavelet" Results

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



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

Counting "Wavelet" Peaks



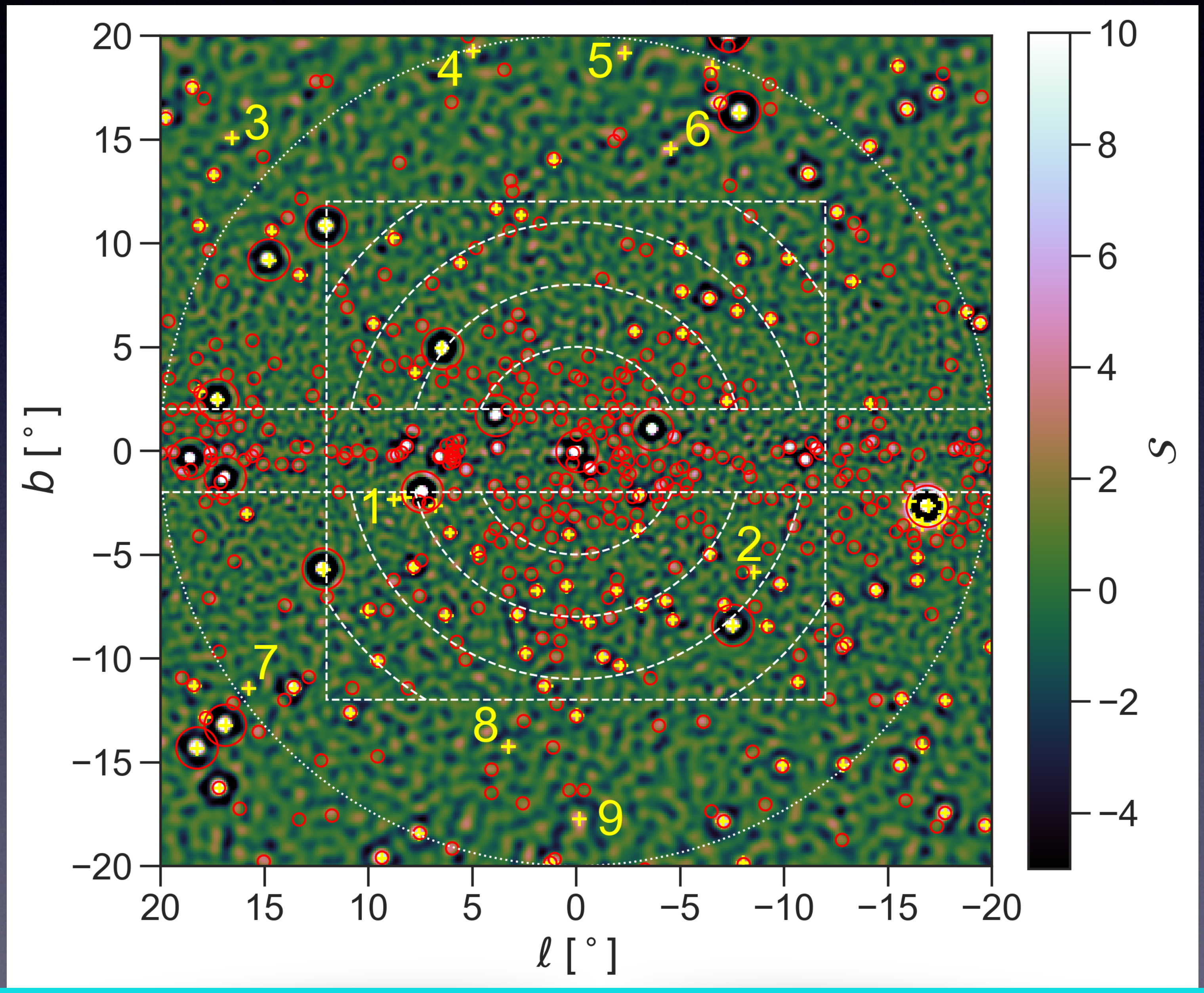
60 diffuse models × 100 trials

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

wavelet statistics change qualitatively with 4FGL!

High-S Sources

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

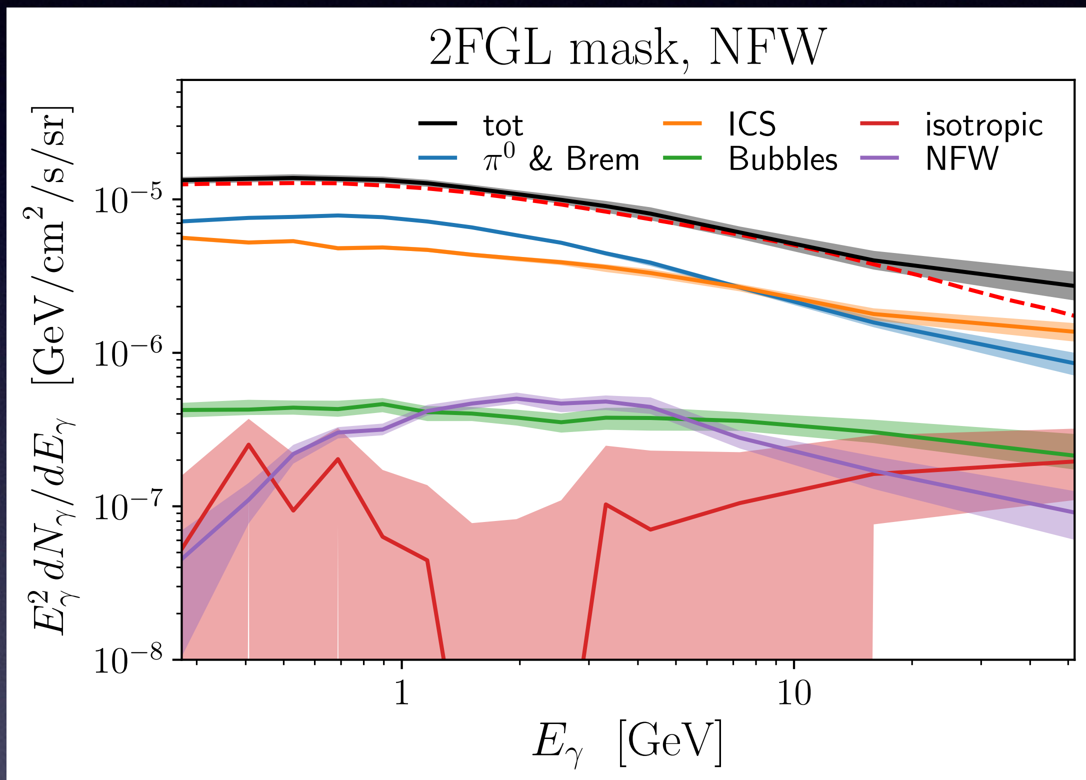


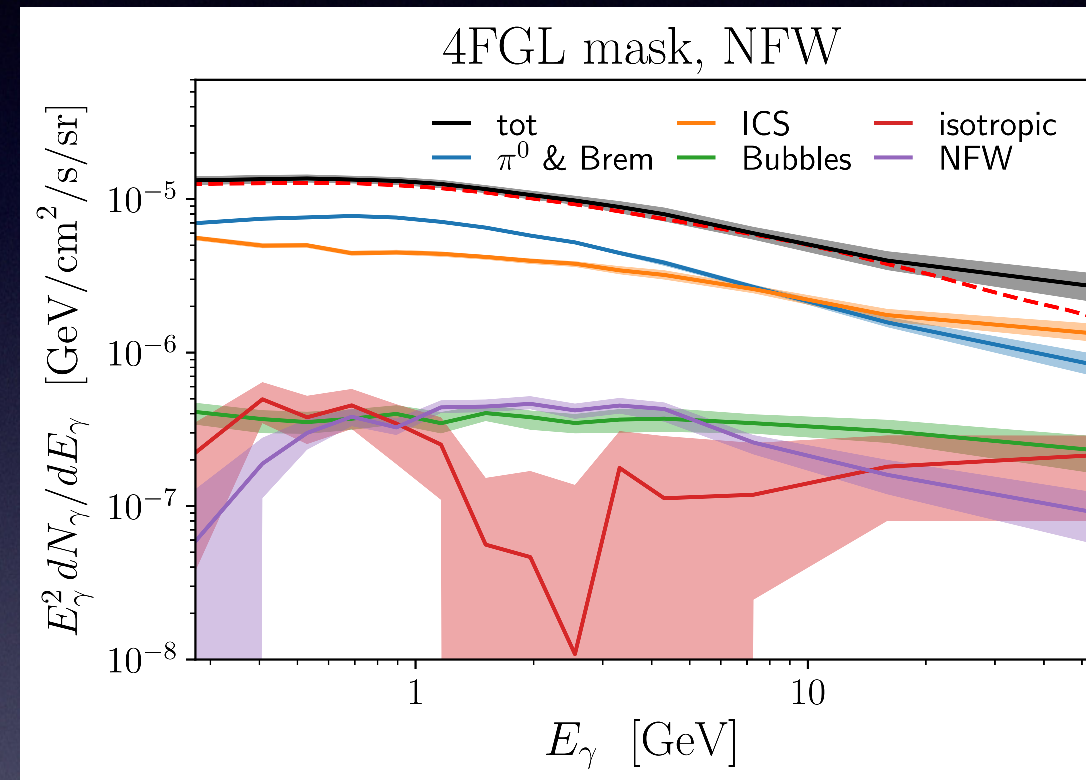
117 peaks (w/ S>4) ⊃ 109 peaks near 4FGL ⊃ 47 are unknown/unassociated

We have access to all of those spectra in 4FGL!

GCE: Template Fit Results

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



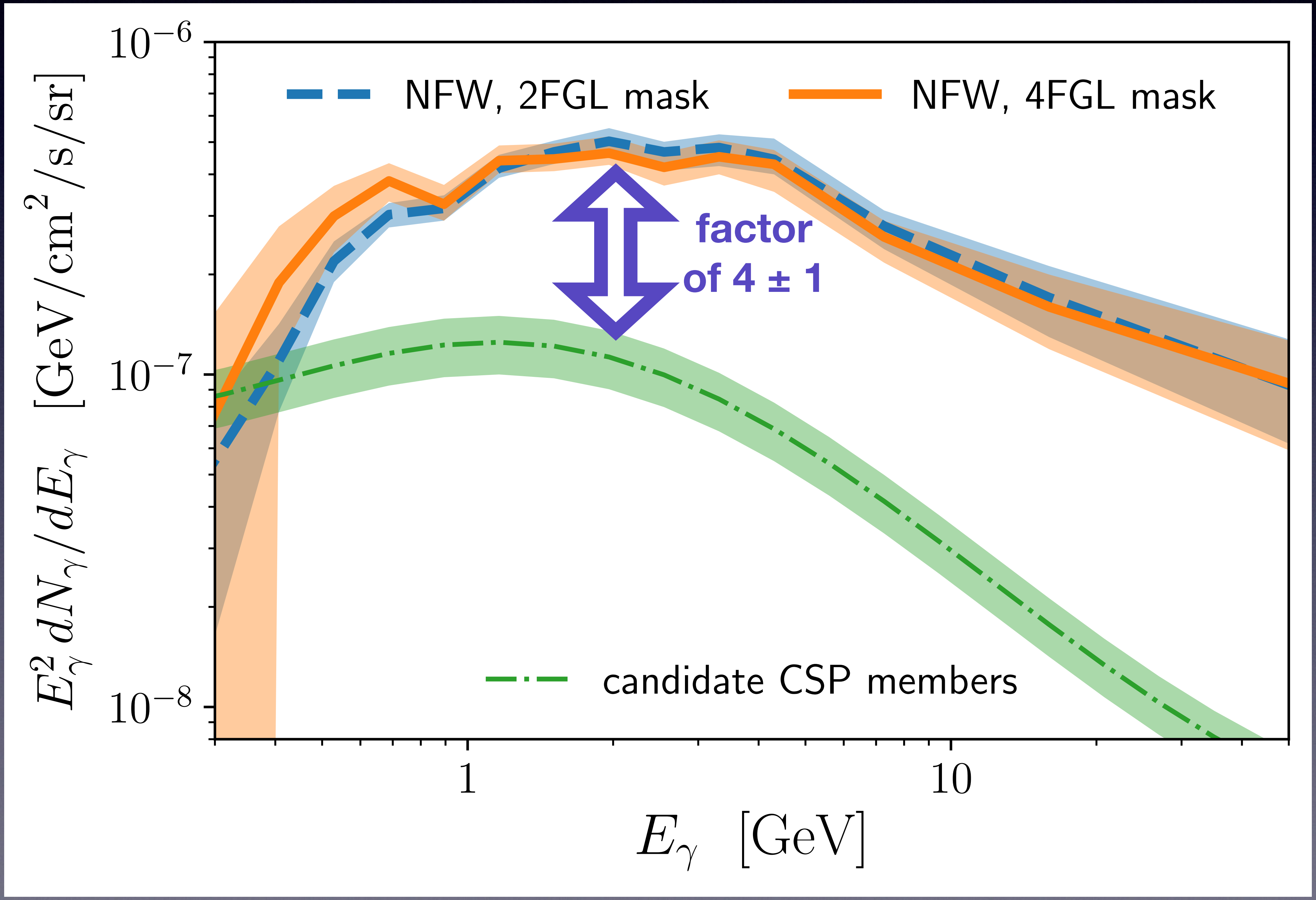


preference slightly smaller (fewer photons)

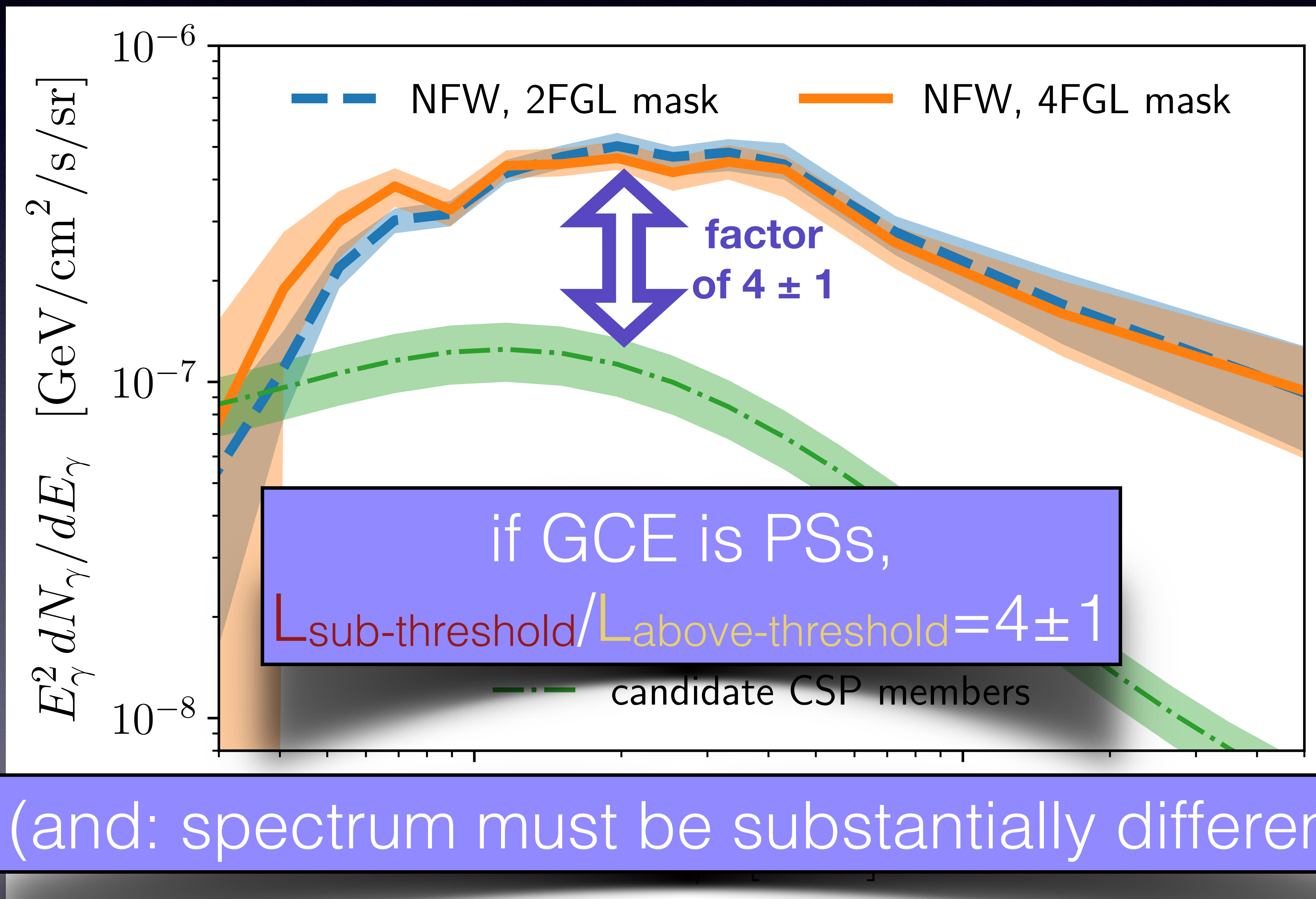
TABLE I. Difference in $-2\ln\lambda$ (lower numbers are better) at the best fit points of each model, summed over energy bins, compared to our best fit for each mask.

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

Compare Spectra



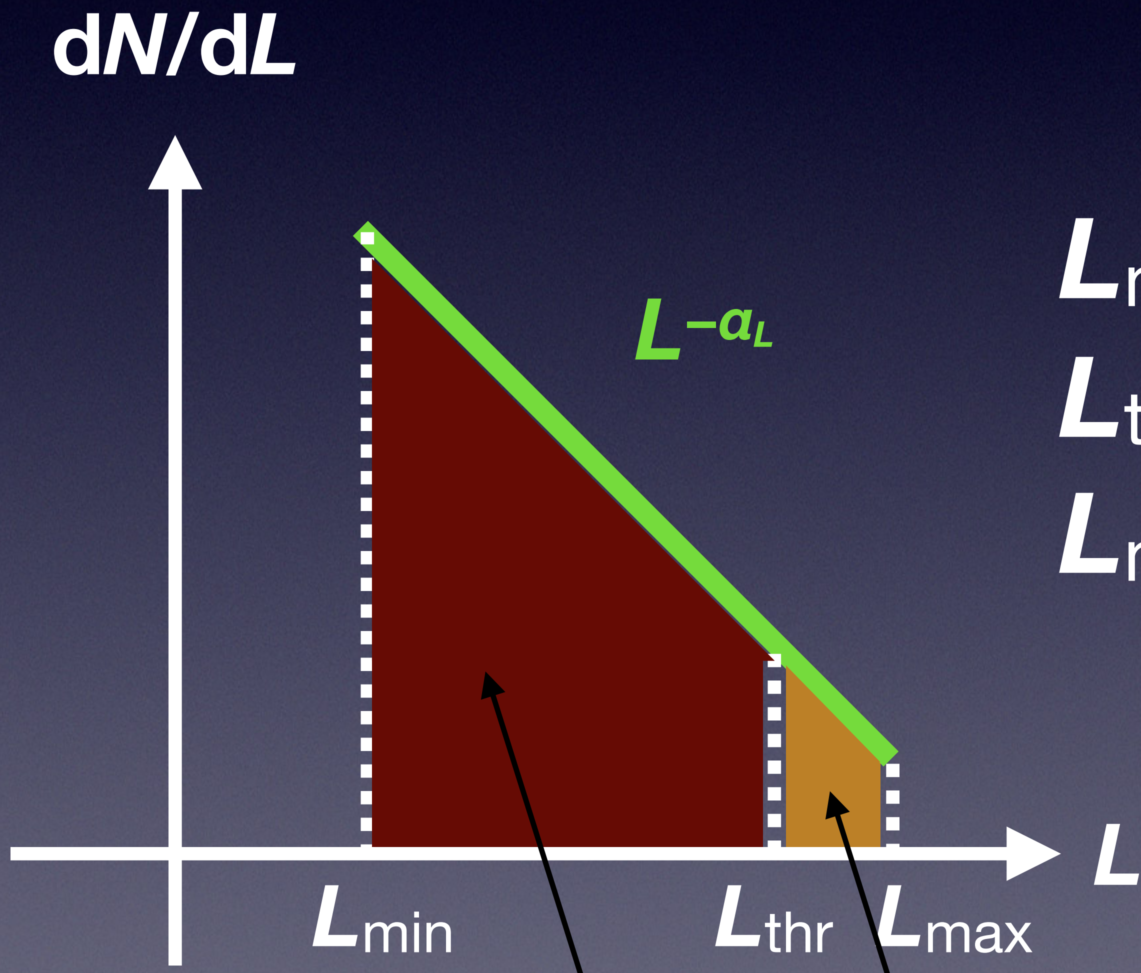
Implications for GCE



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

(and: spectrum must be substantially different)

Luminosity Function



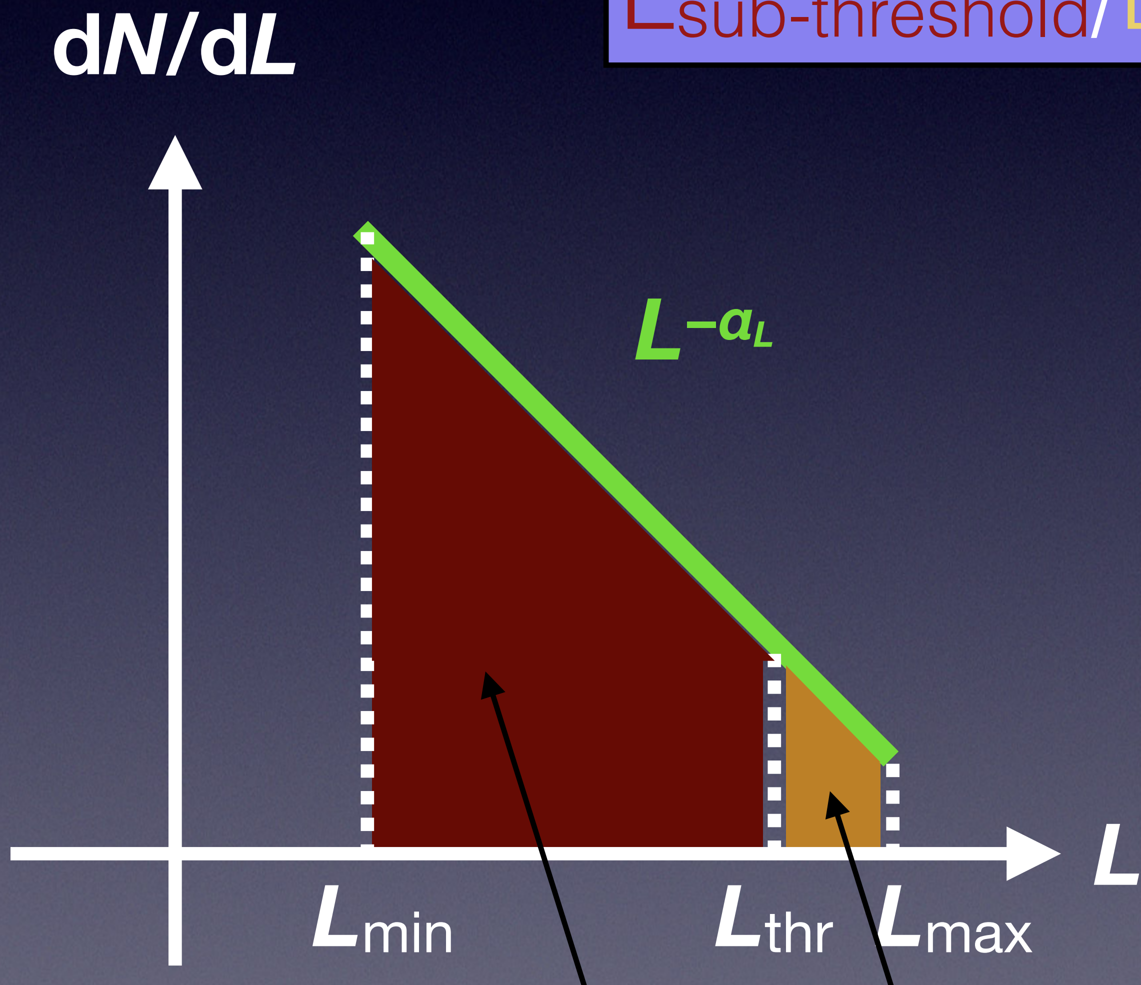
L_{min} → gamma-ray physics
L_{thr} → detection threshold
L_{max} → gamma-ray physics

$\int_{<thr} L\ dN/dL\ dL$ “= 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
$\Longrightarrow \alpha_L \rightarrow 1.95 \pm 0.05$
$N_{sub} \rightarrow (3.5 \pm 1.7)*10^6$

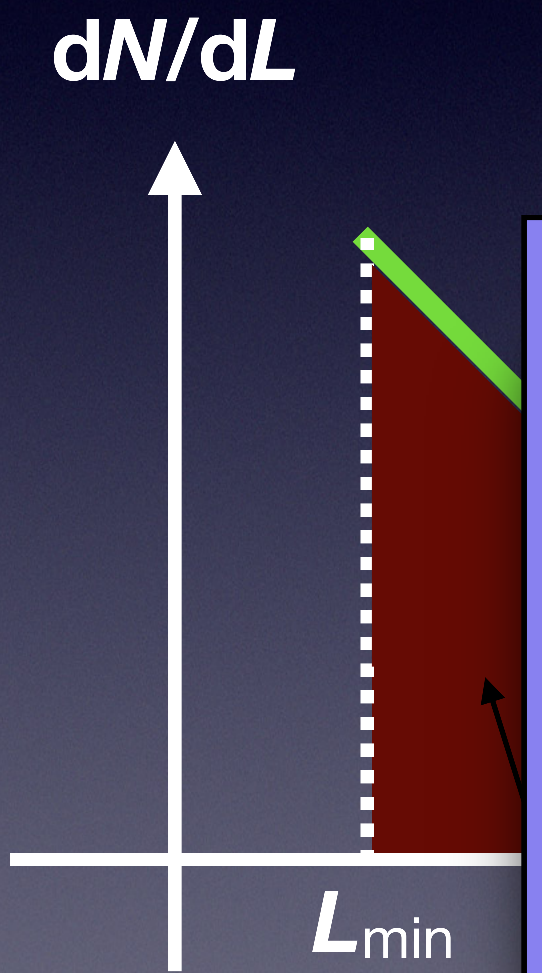
(compare to $N_{vis} \sim 47$)

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

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

Luminosity Function

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



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

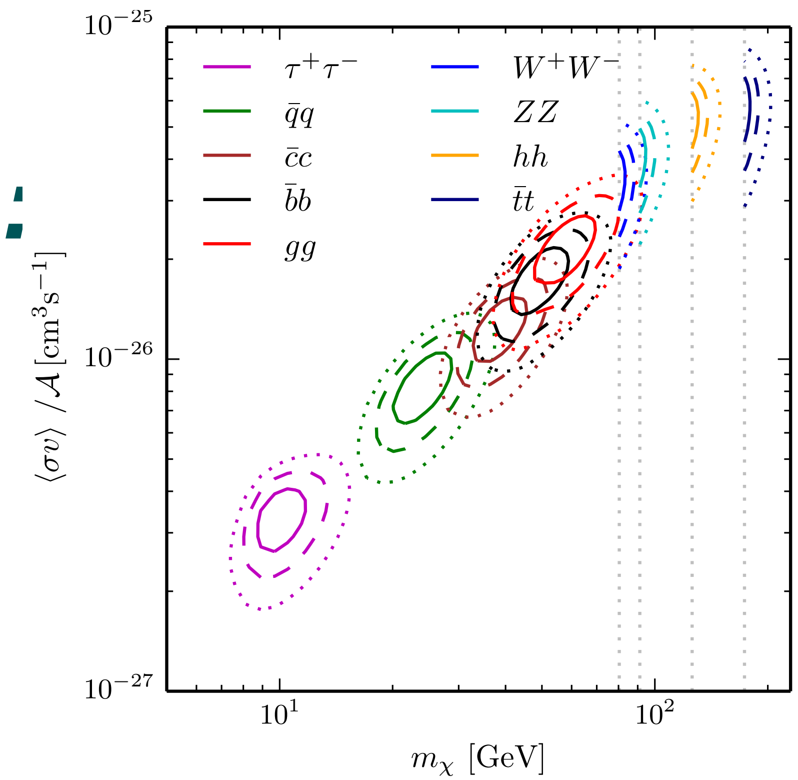
.05

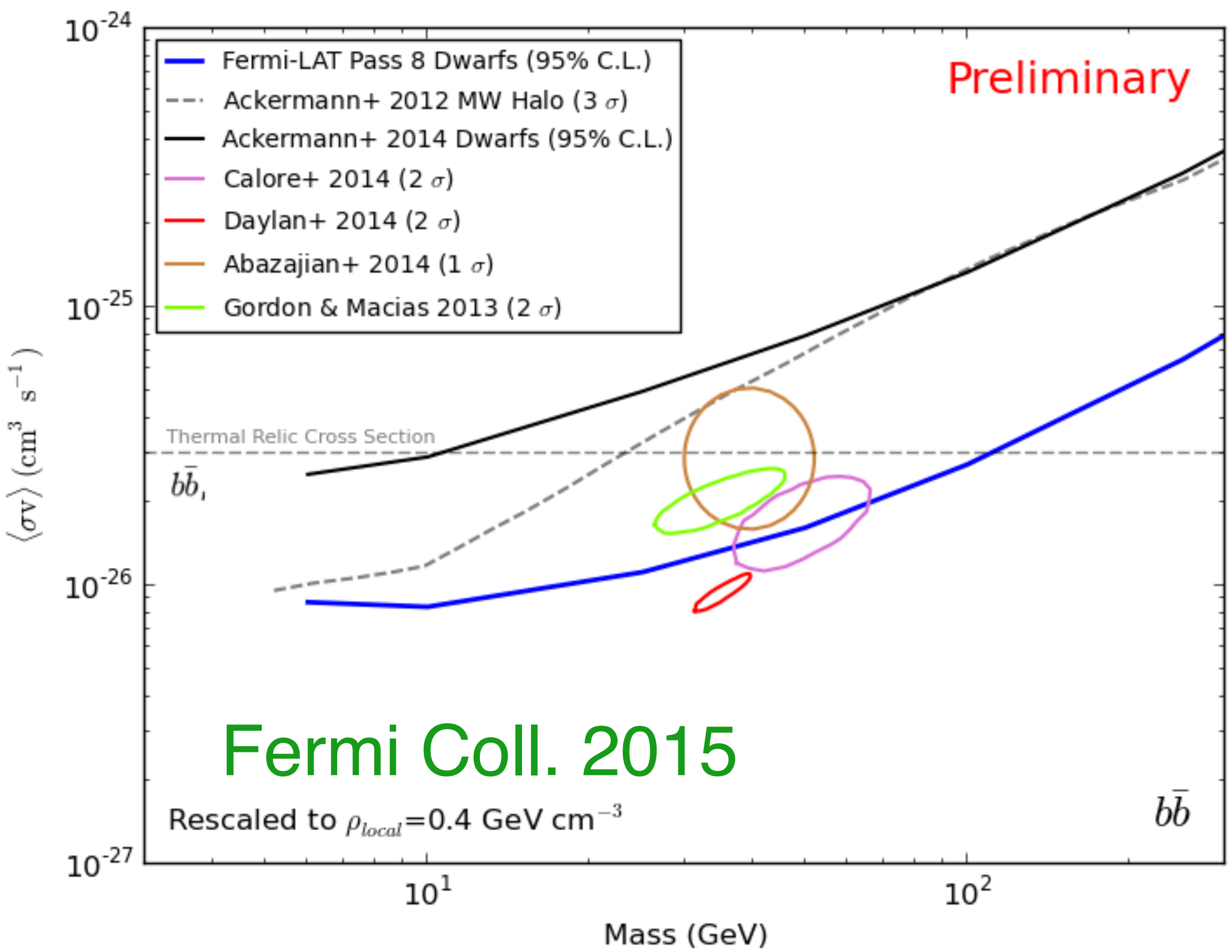
, diverges!)

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

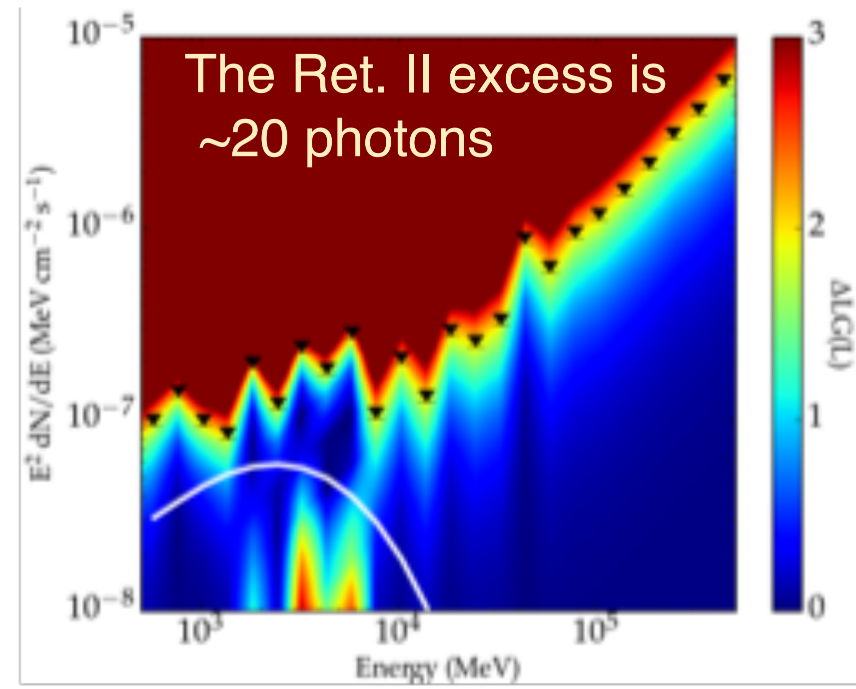
$\int_{>thr}$ L dN/dL dL = stacked spectra

A signal of Dark Matter has to show up in more than one places:

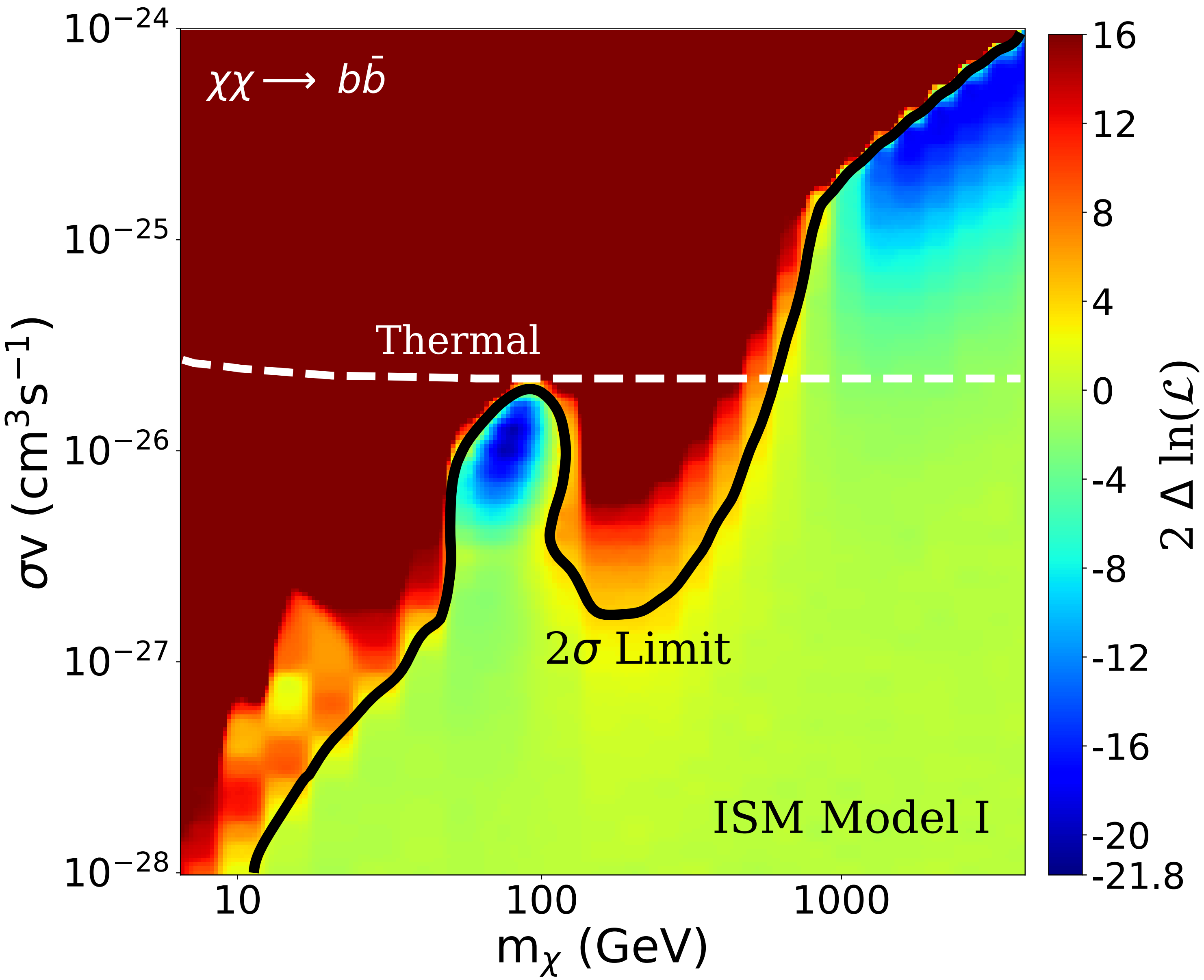


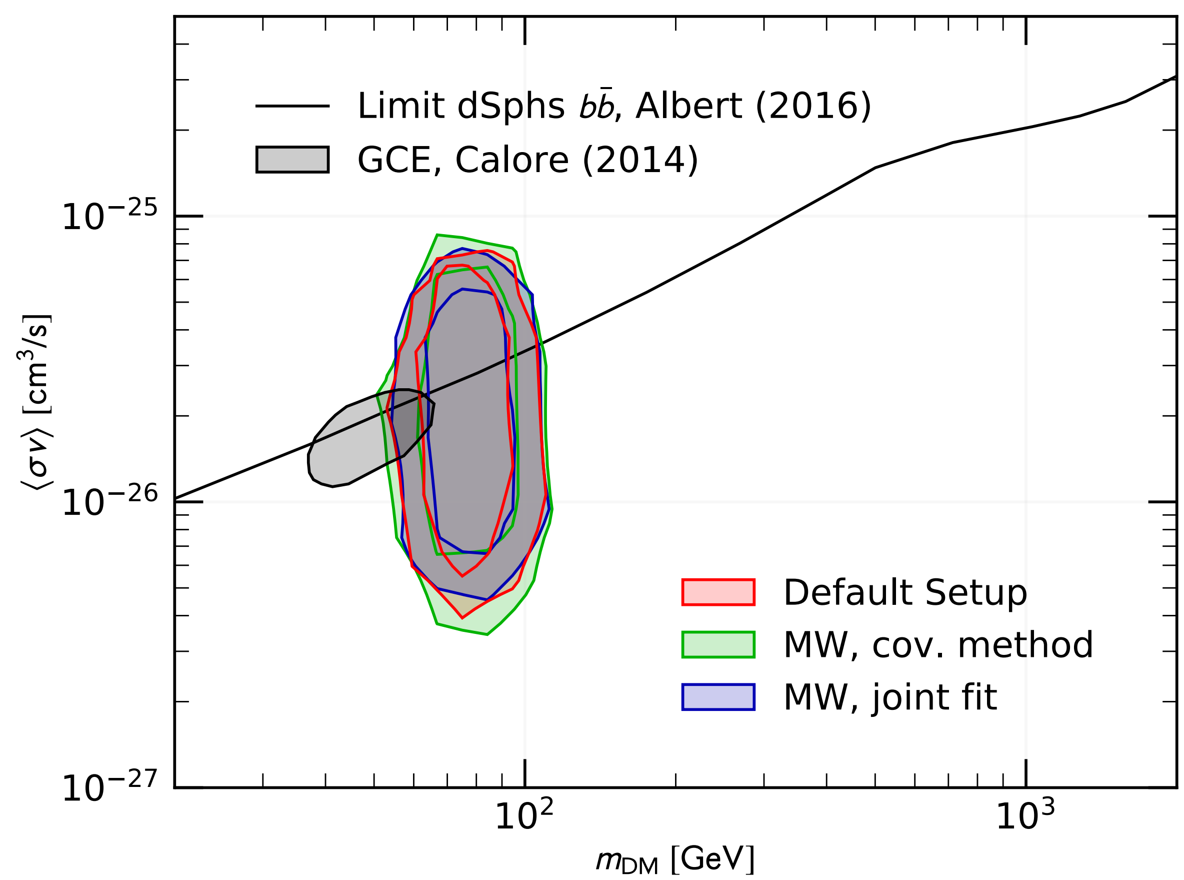


Geringer-Sameth et al. 2015



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

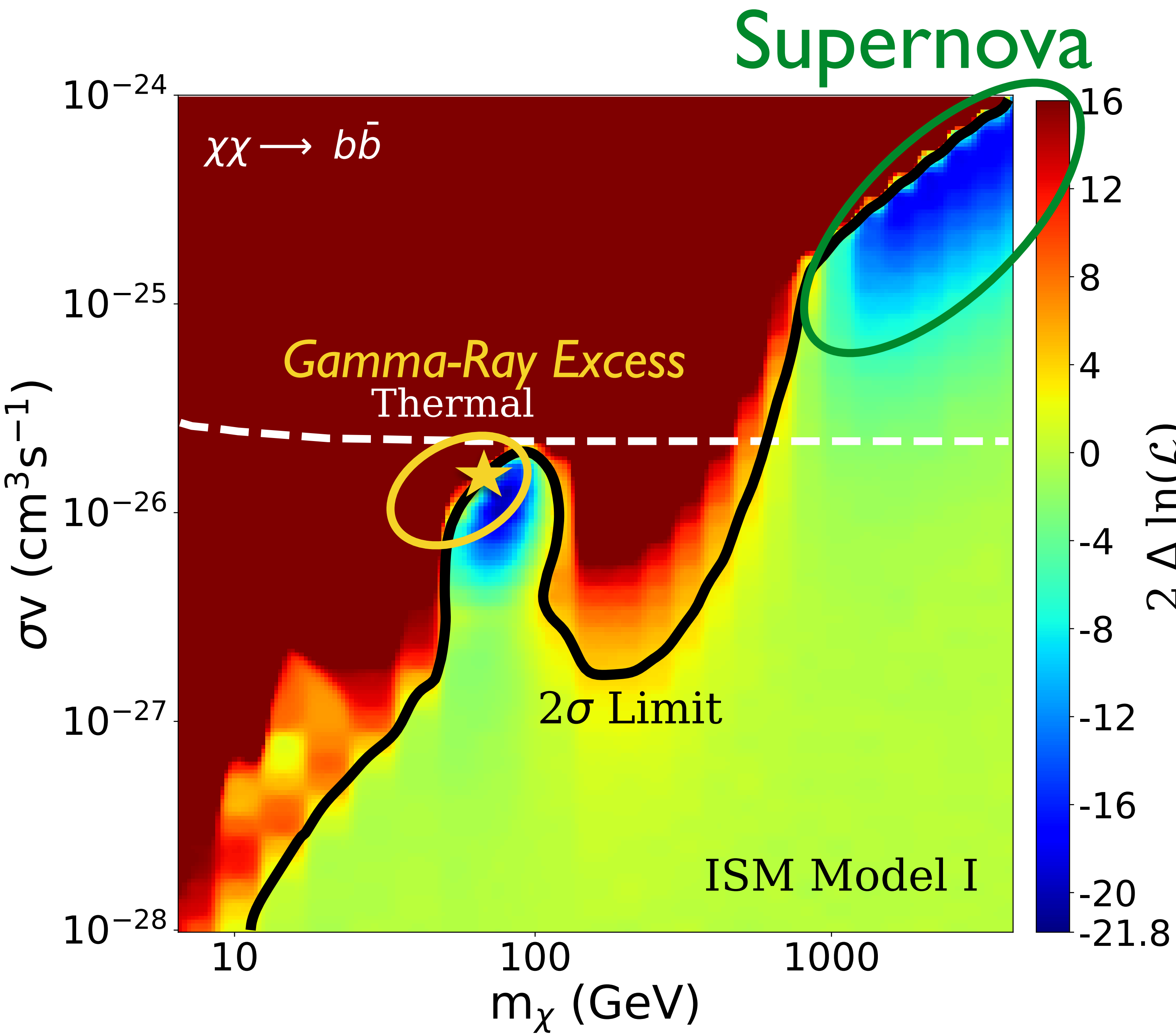


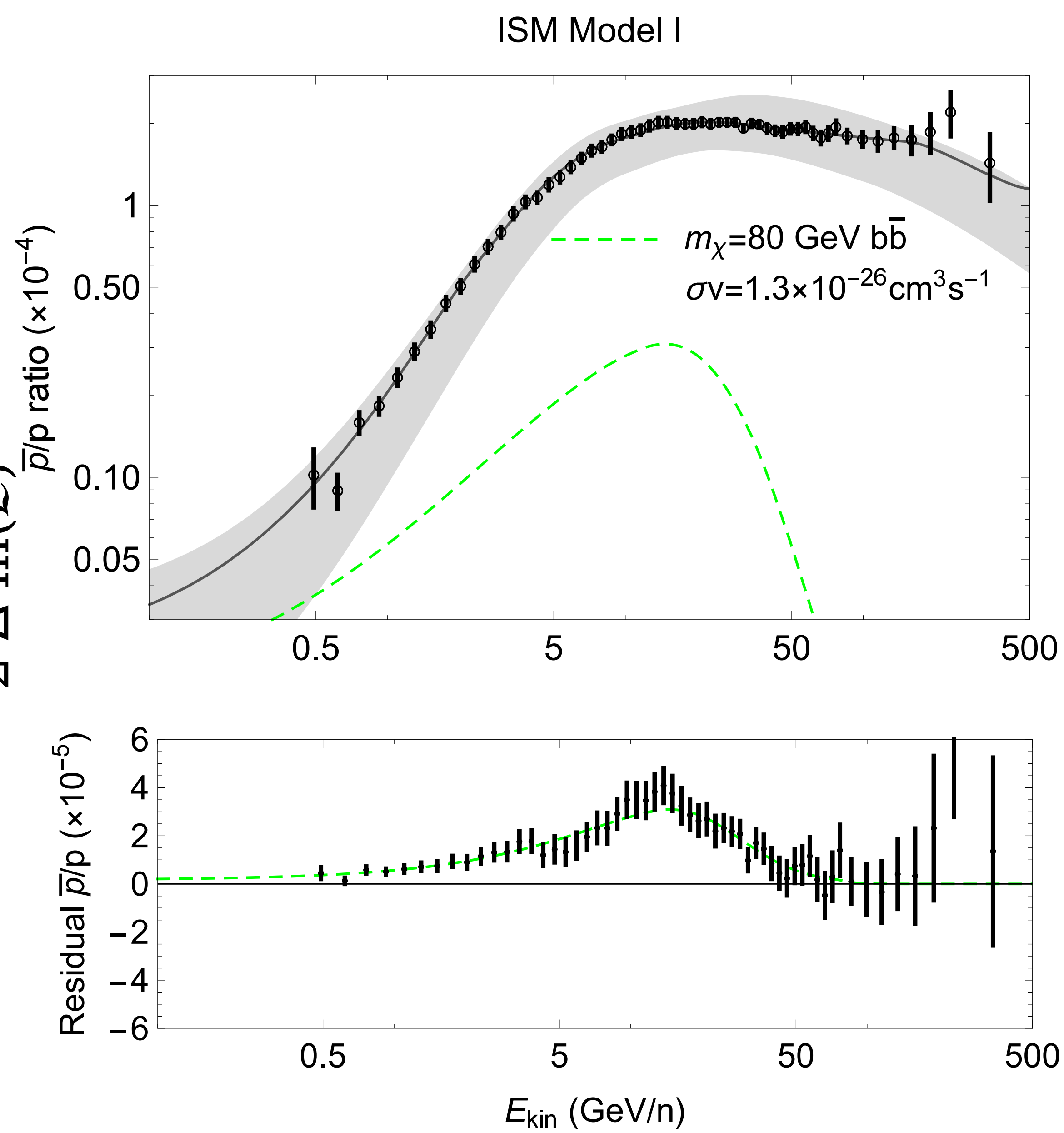


A. Cuoco et al. PRD 2019

***IC**, Tim Linden, Dan Hooper PRD 2019*

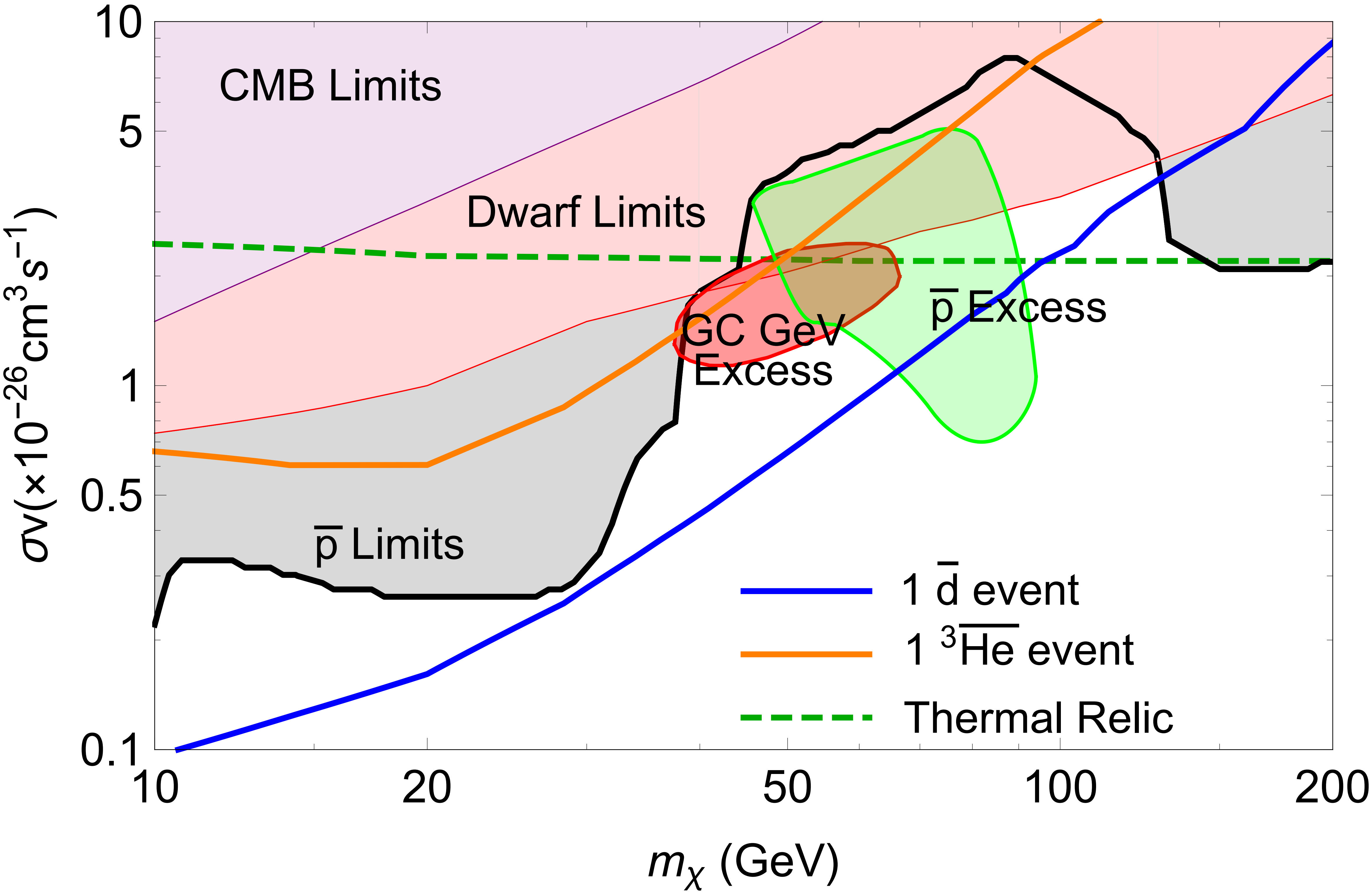
Looking at the antiproton to proton ratio find an the excess at~3 sigma





IC, Tim Linden, Dan Hooper
PRD 2019

Combining all Indirect DM searches



IC, Linden, Hooper PRD 2020

Thank you!