New Developments in the Galactic Center Gamma-Ray Excess

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with Cholis, Fox, McDermott, and Surdutovich

1) PRL 124 (2020), arXiv:1911.12369

2) PRD 105 (2022), arXiv:2112.09706

3) arXiv:2209.00006

King's College London, 11/23/2022

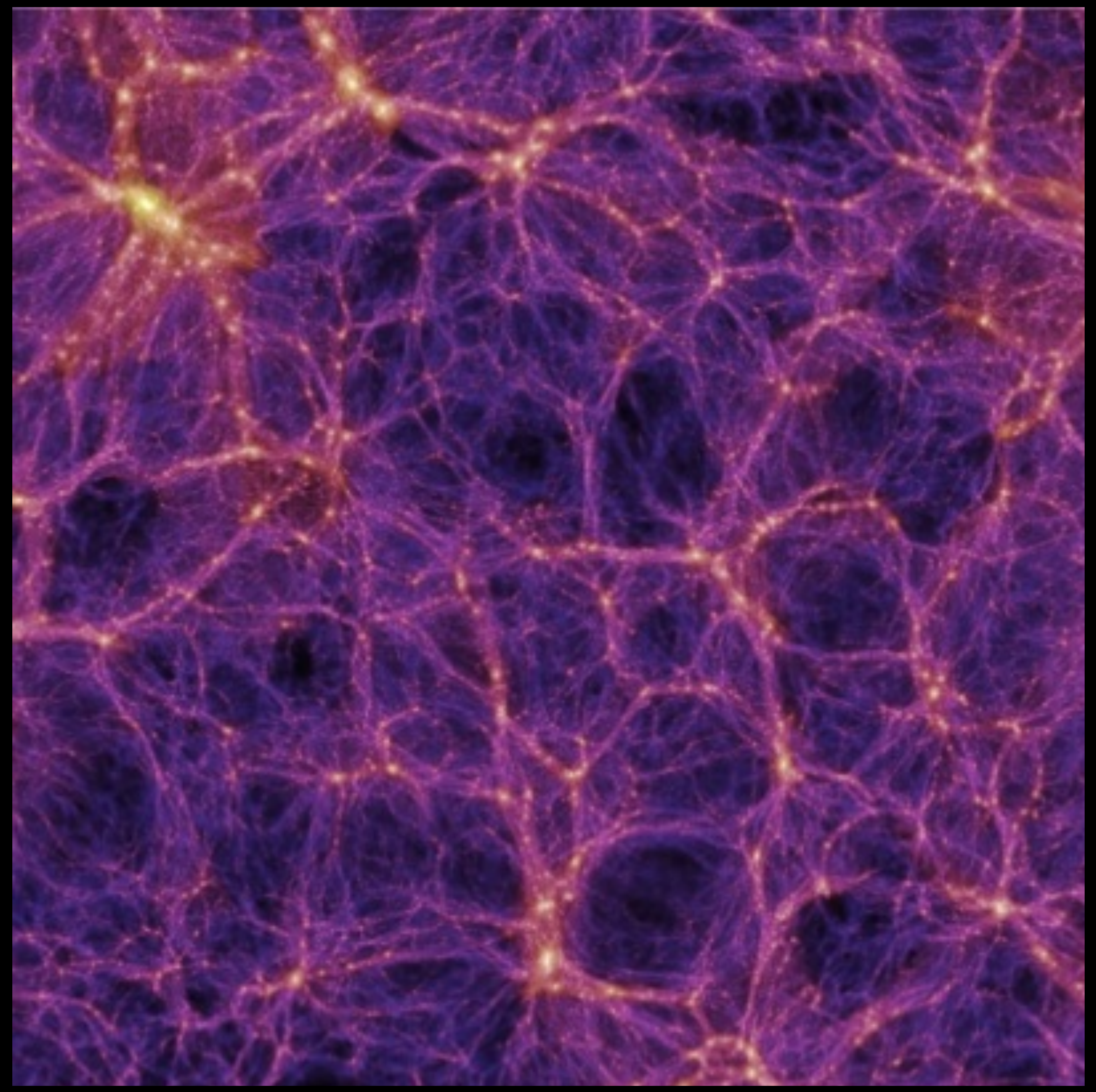
Outline

- Introduction
  - The Galactic Center γ-ray Excess (GCE)
  - What is the origin of the GCE?
- Testing the small-scale power of the GCE
- Revisiting the characteristics of the GCE w/ a new set of templates
- Summary

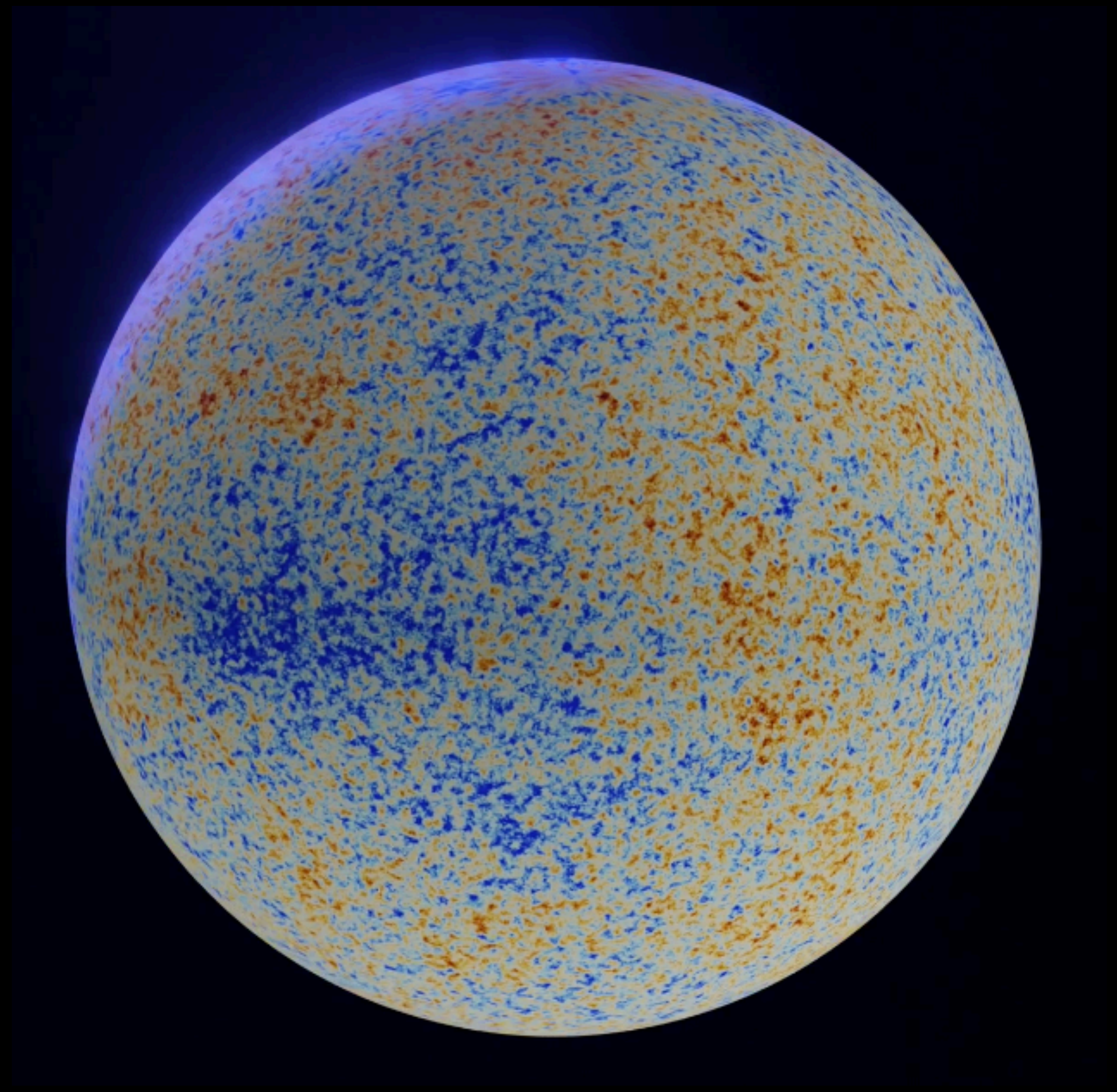
Introduction

Evidence for dark matter

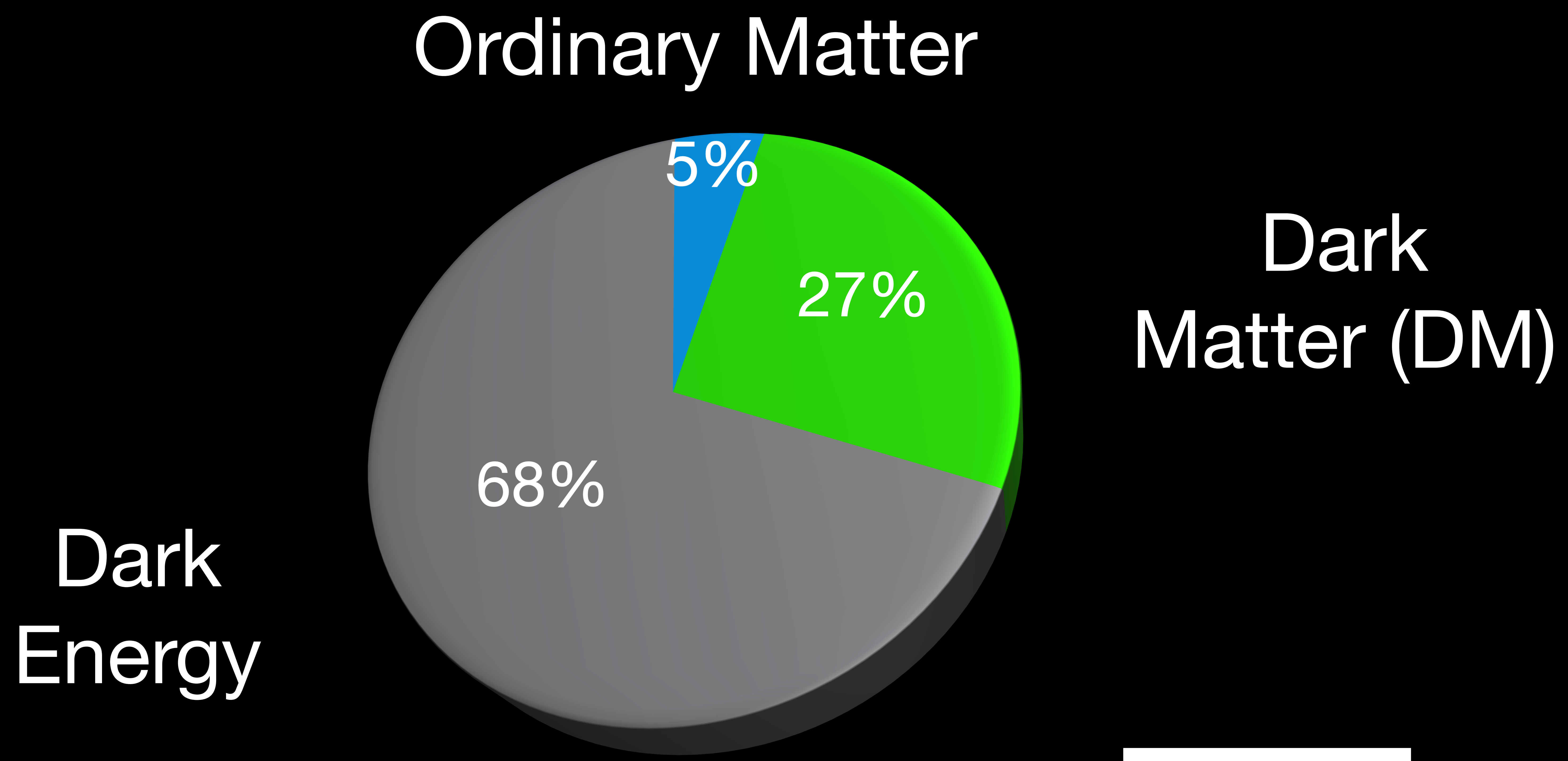
Bullet Cluster



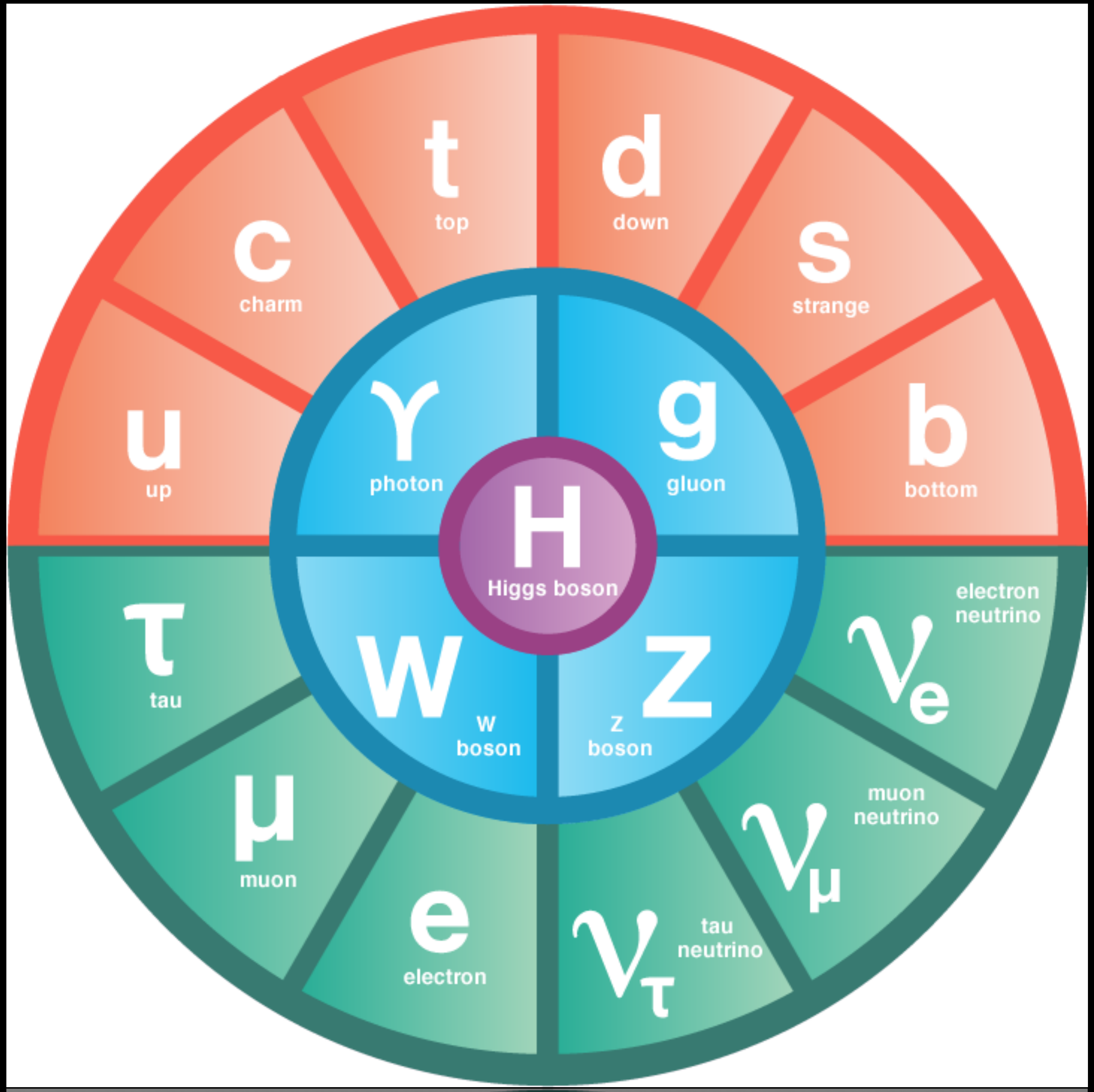
Large-Scale Structure



Cosmic Microwave Background



ΛCDM



Ordinary matter

Dark matter?

“Delve Deep, Search Wide.”

— Snowmass 2021

Astro bound

Ultralight dark matter (e.g. axion, dark photon)

Weakly interacting massive particles (WIMP)

Ultraheavy dark matter (e.g. black holes)

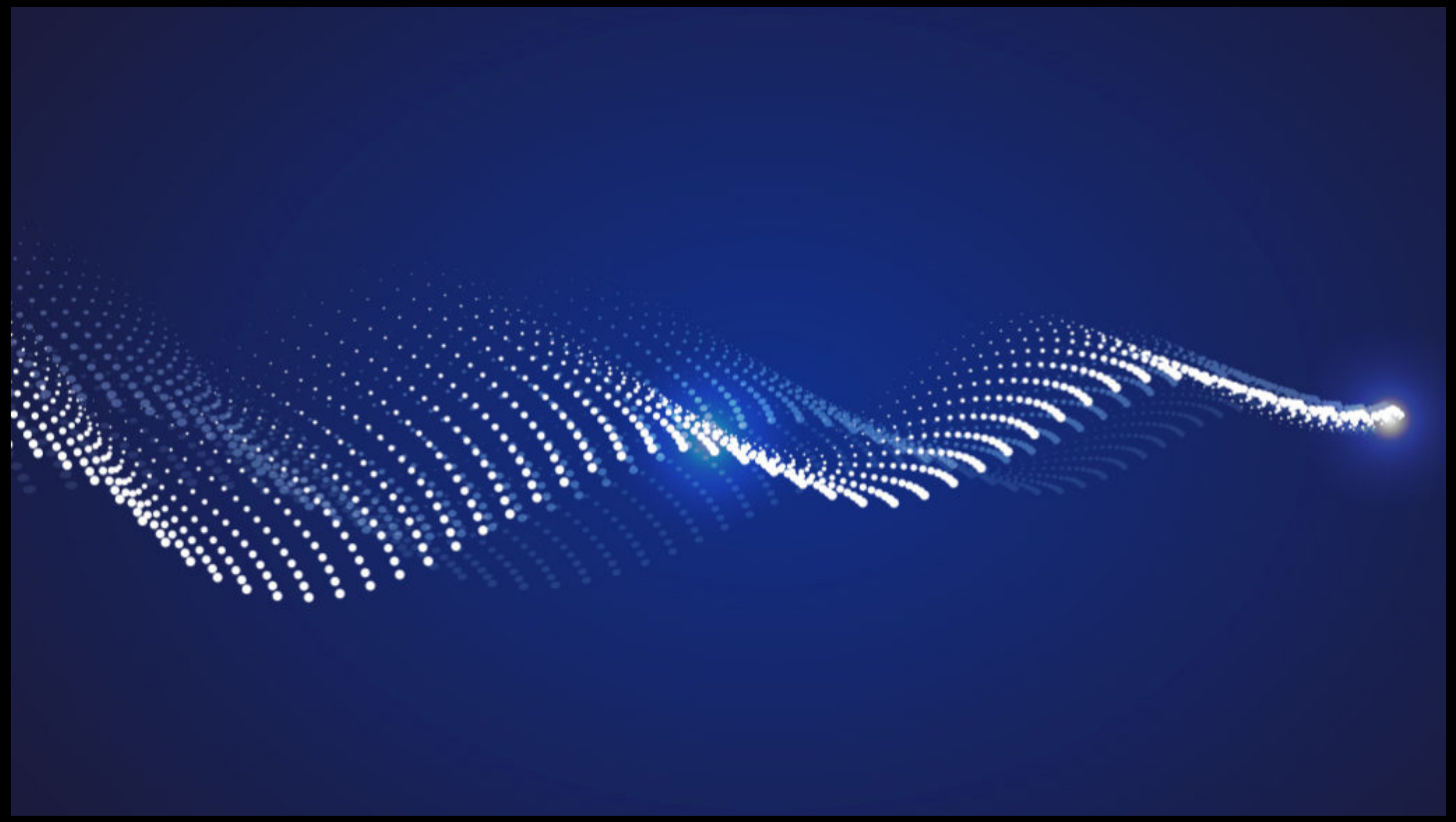
Astro bound

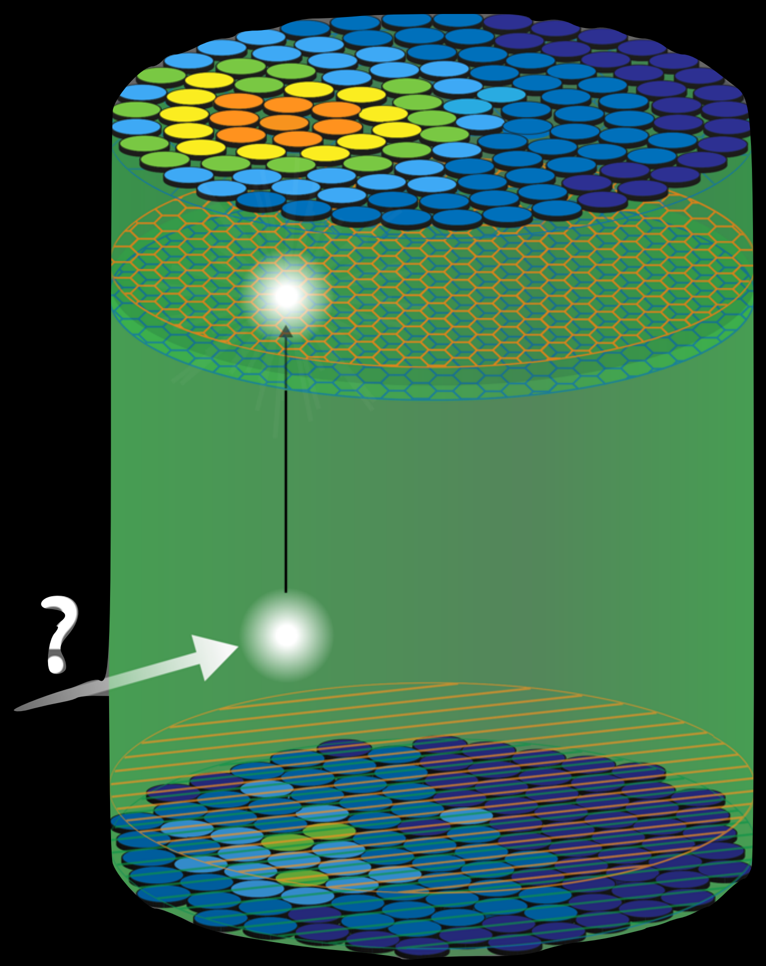
10^{-22} eV — 1 eV

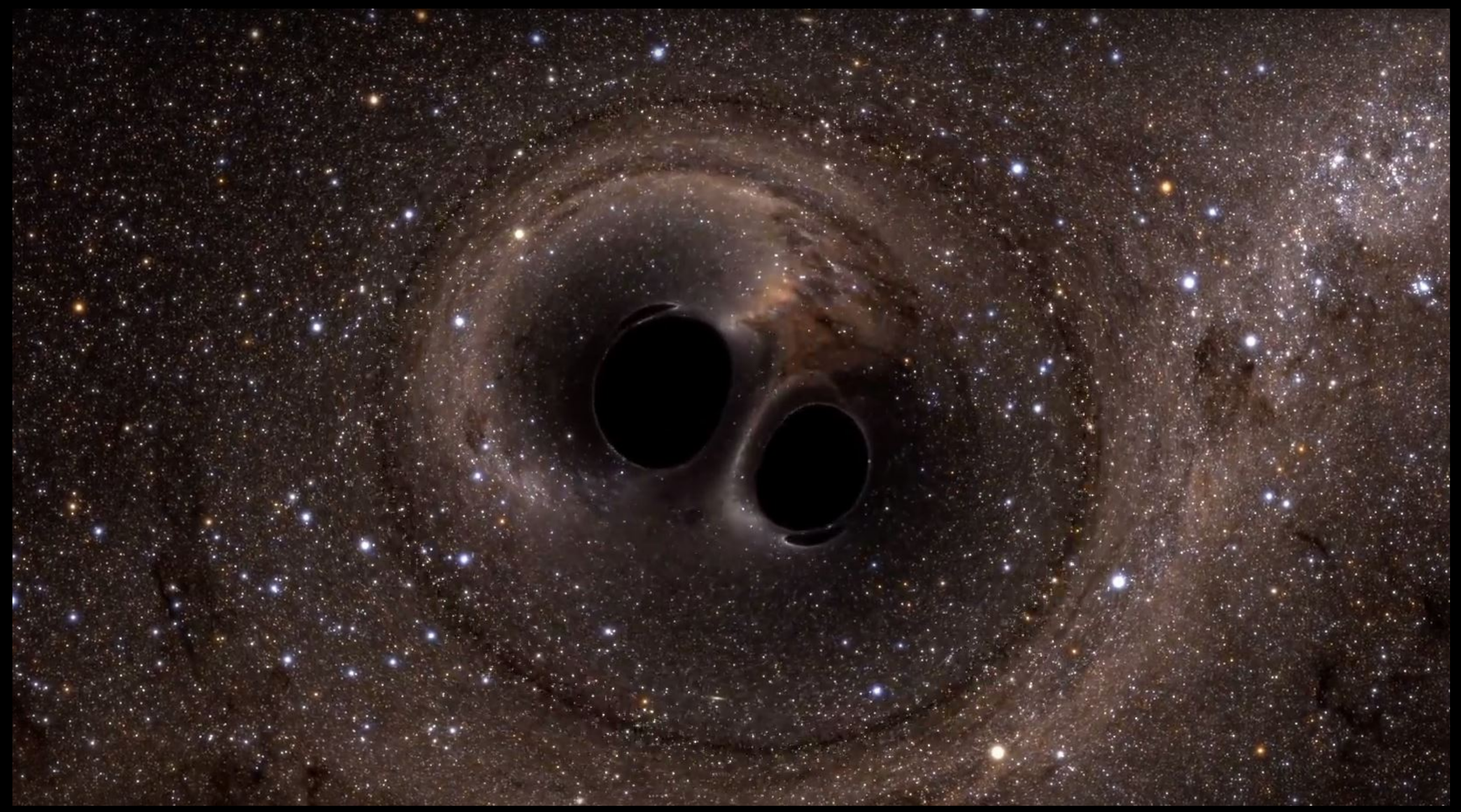
10^{9} eV — 10^{13} eV

10^{50} eV — 10^{53} eV

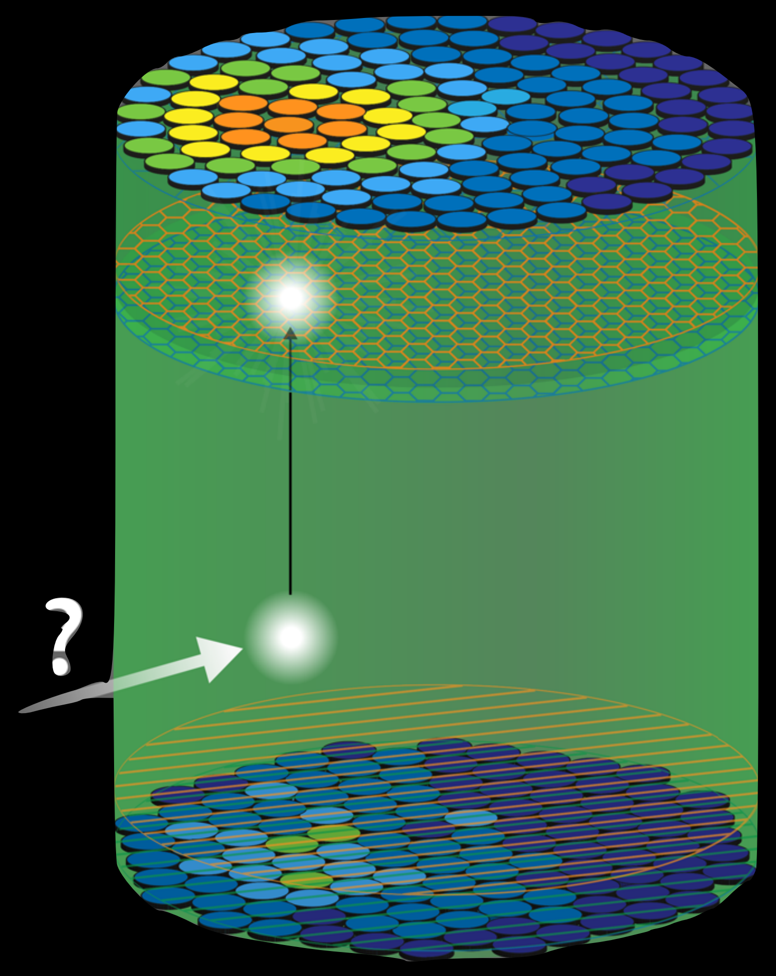
mass

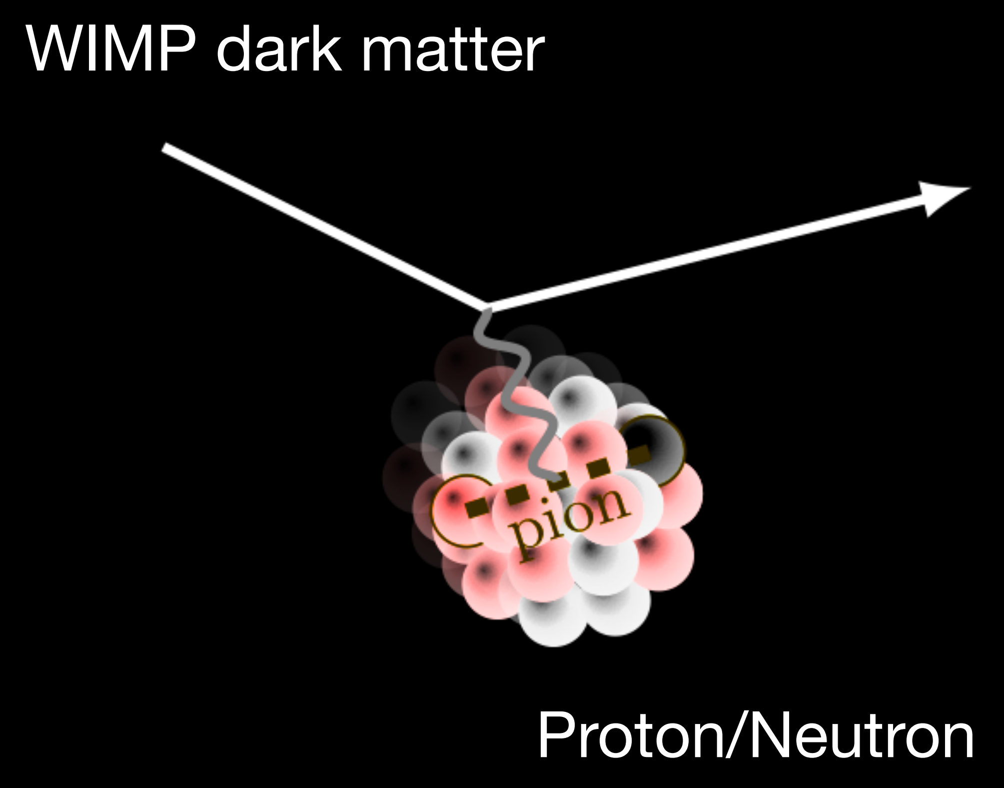






A key assumption

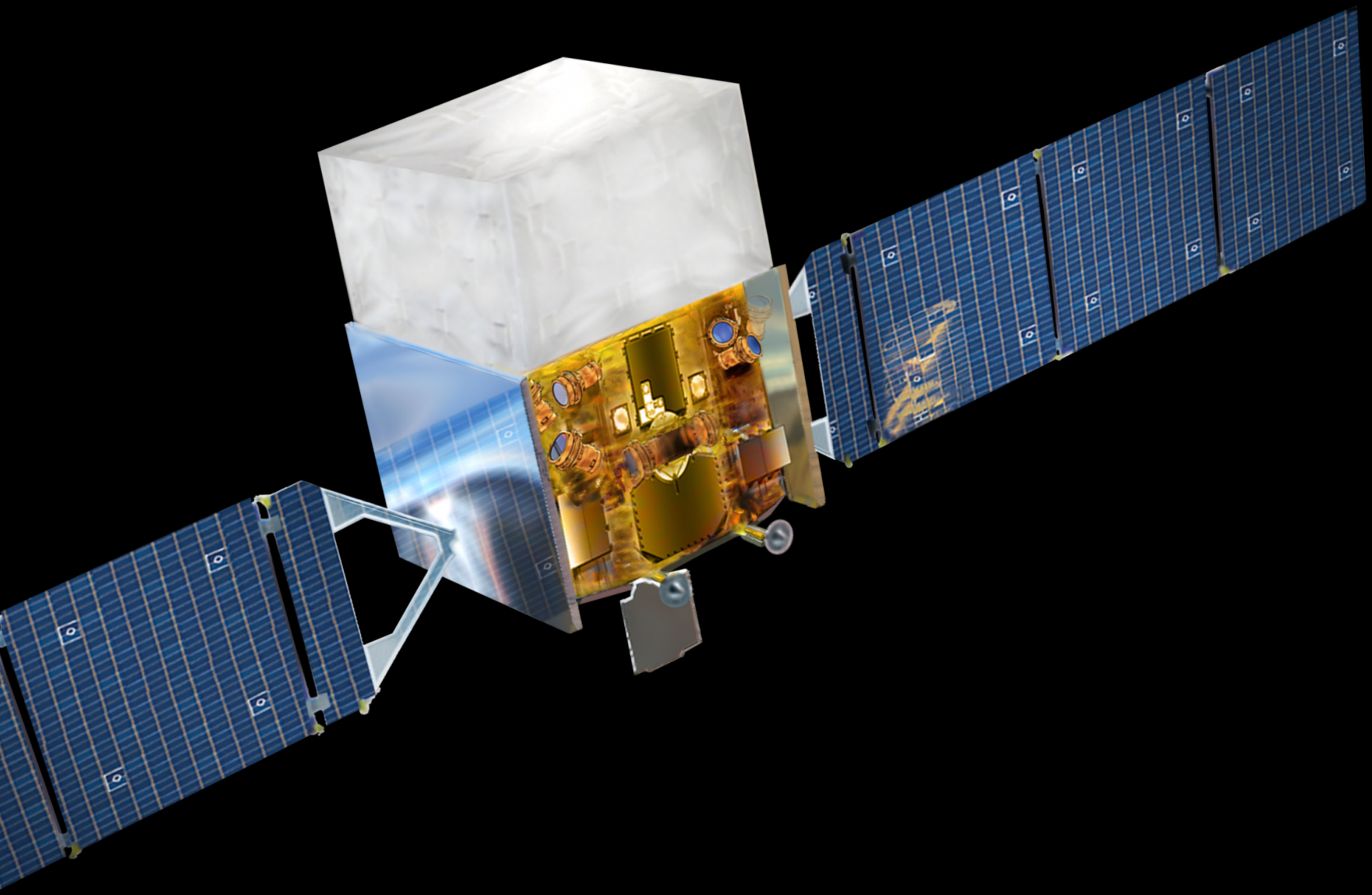




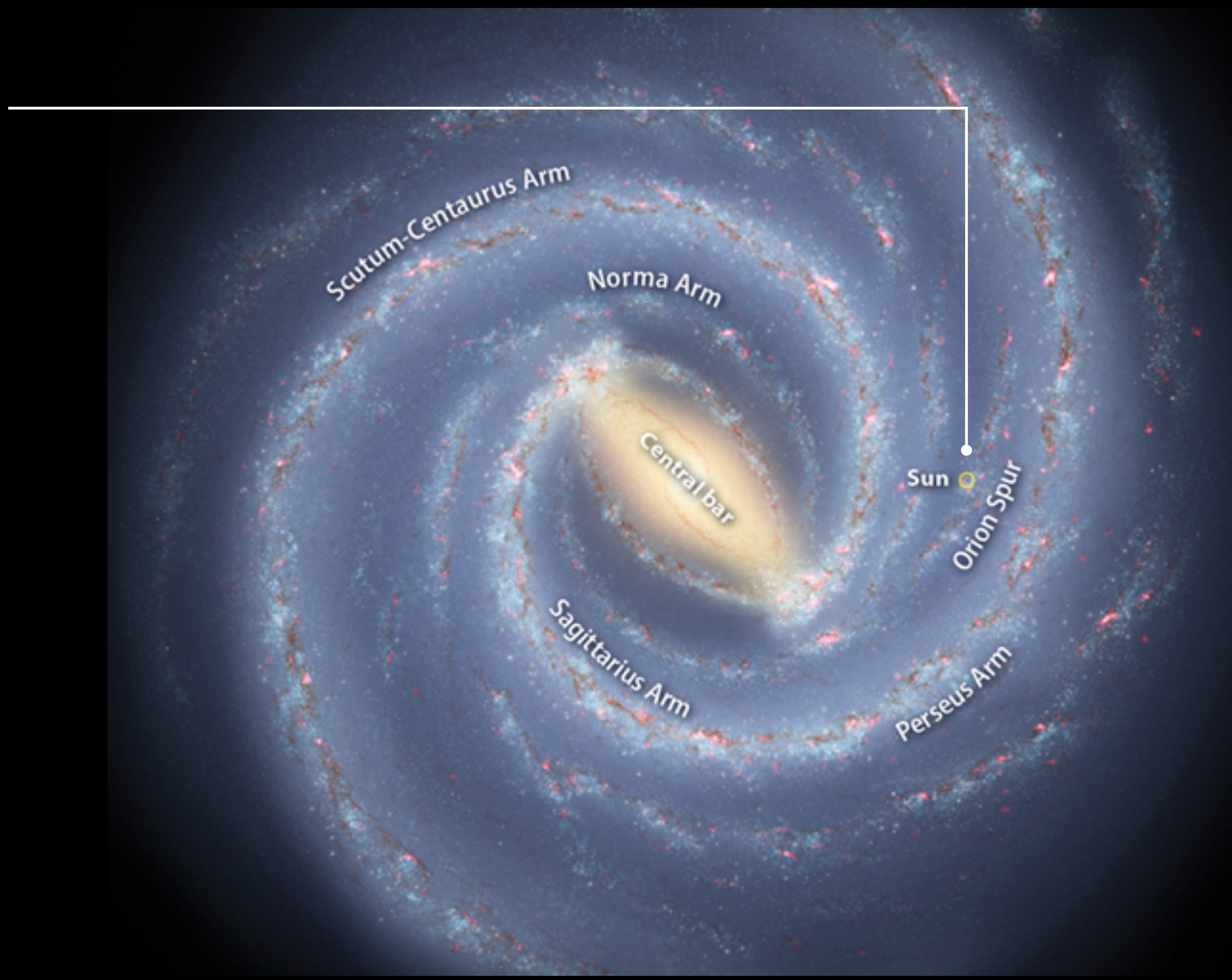
- Direct searches of dark matter often assumes that dark matter interacts with us besides the gravitational influence.
- Is this true?

Fermi-LAT satellite and the GCE

The Fermi Large Area Telescope (Fermi-LAT)

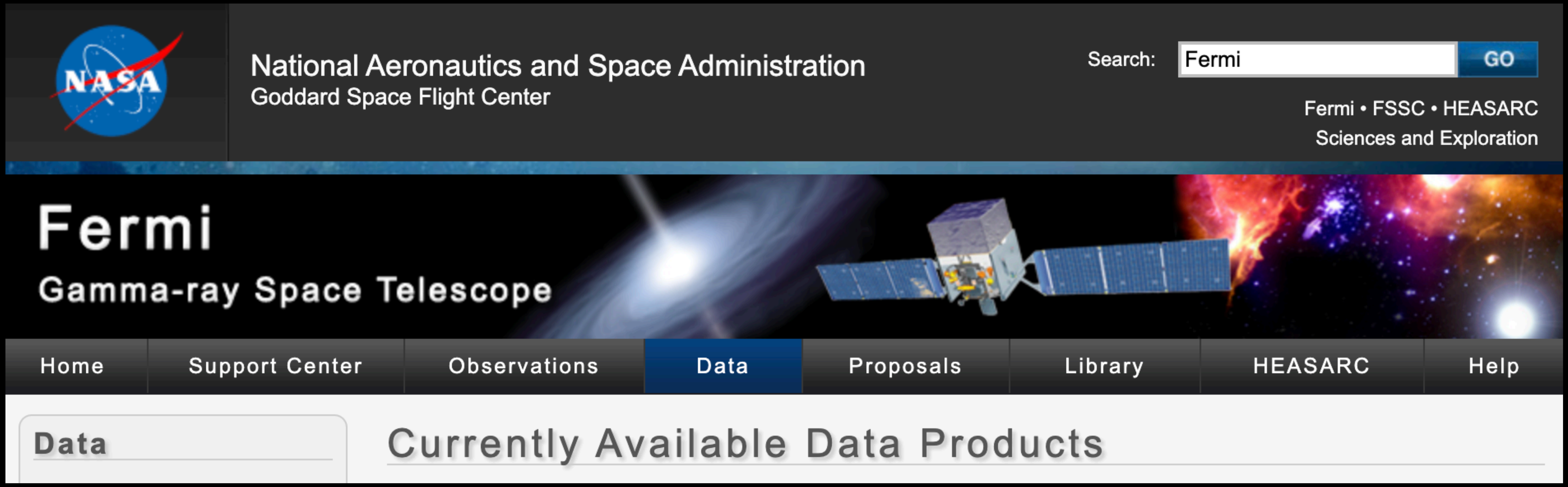


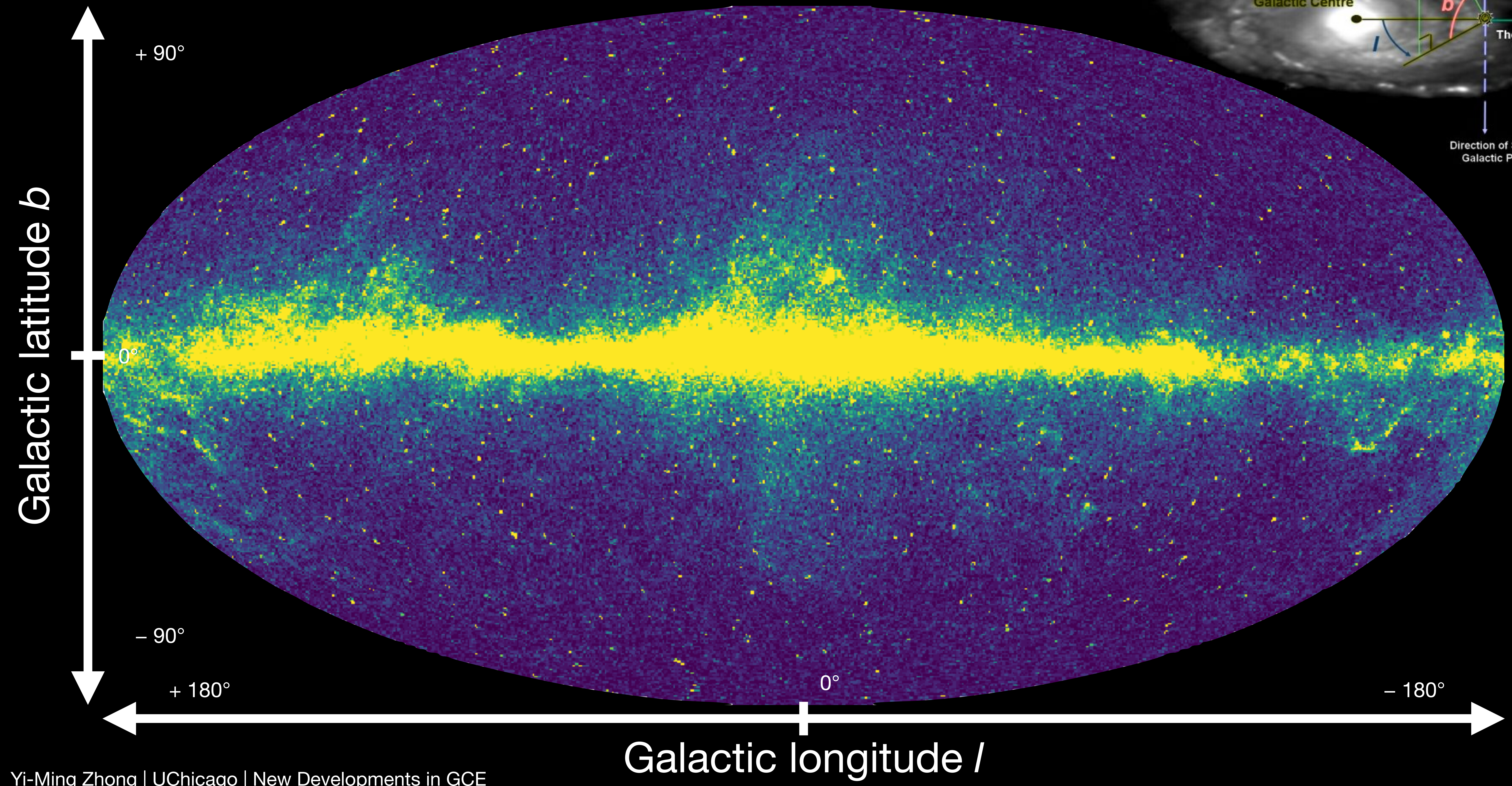
2008—present

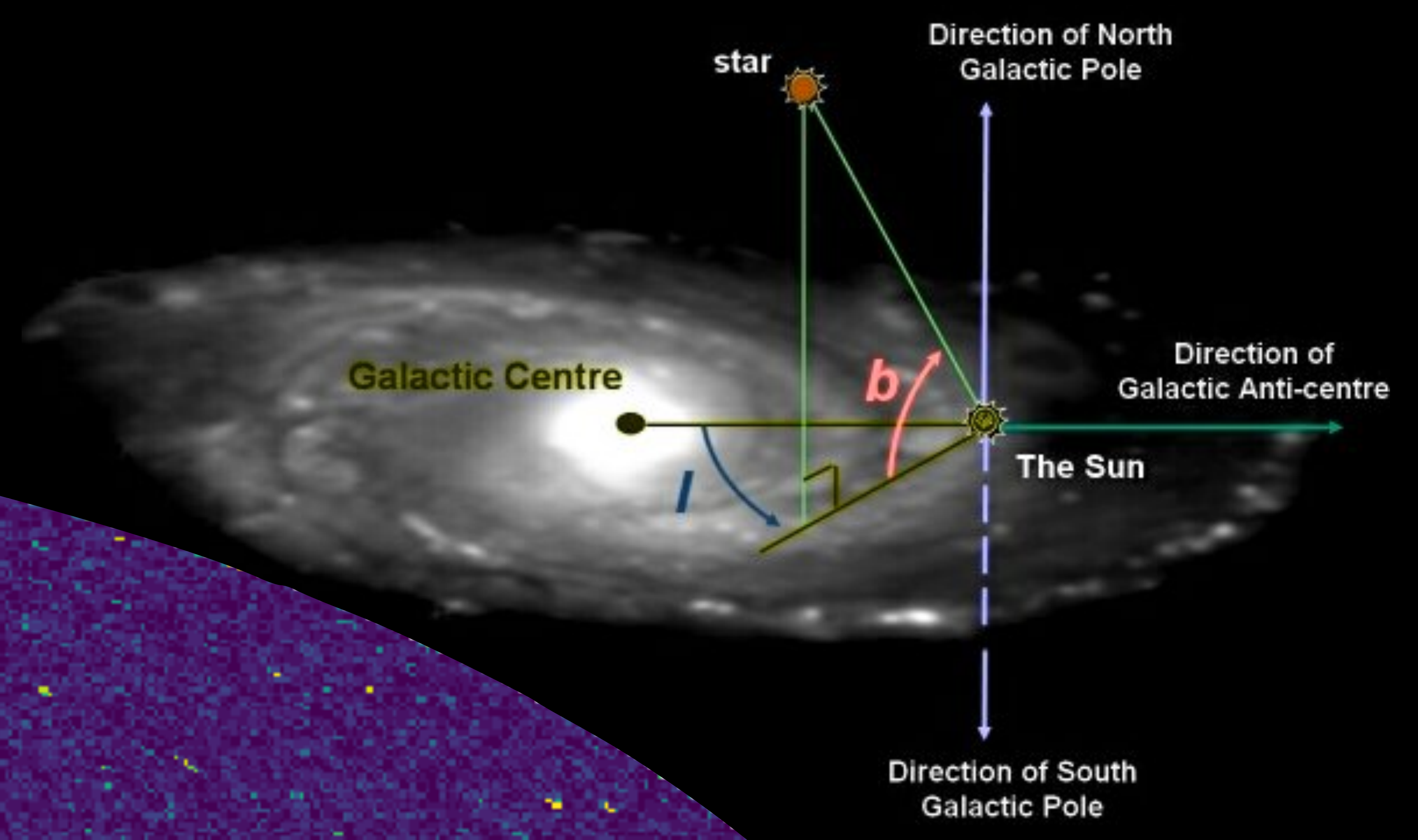


The Fermi Large Area Telescope (Fermi-LAT)

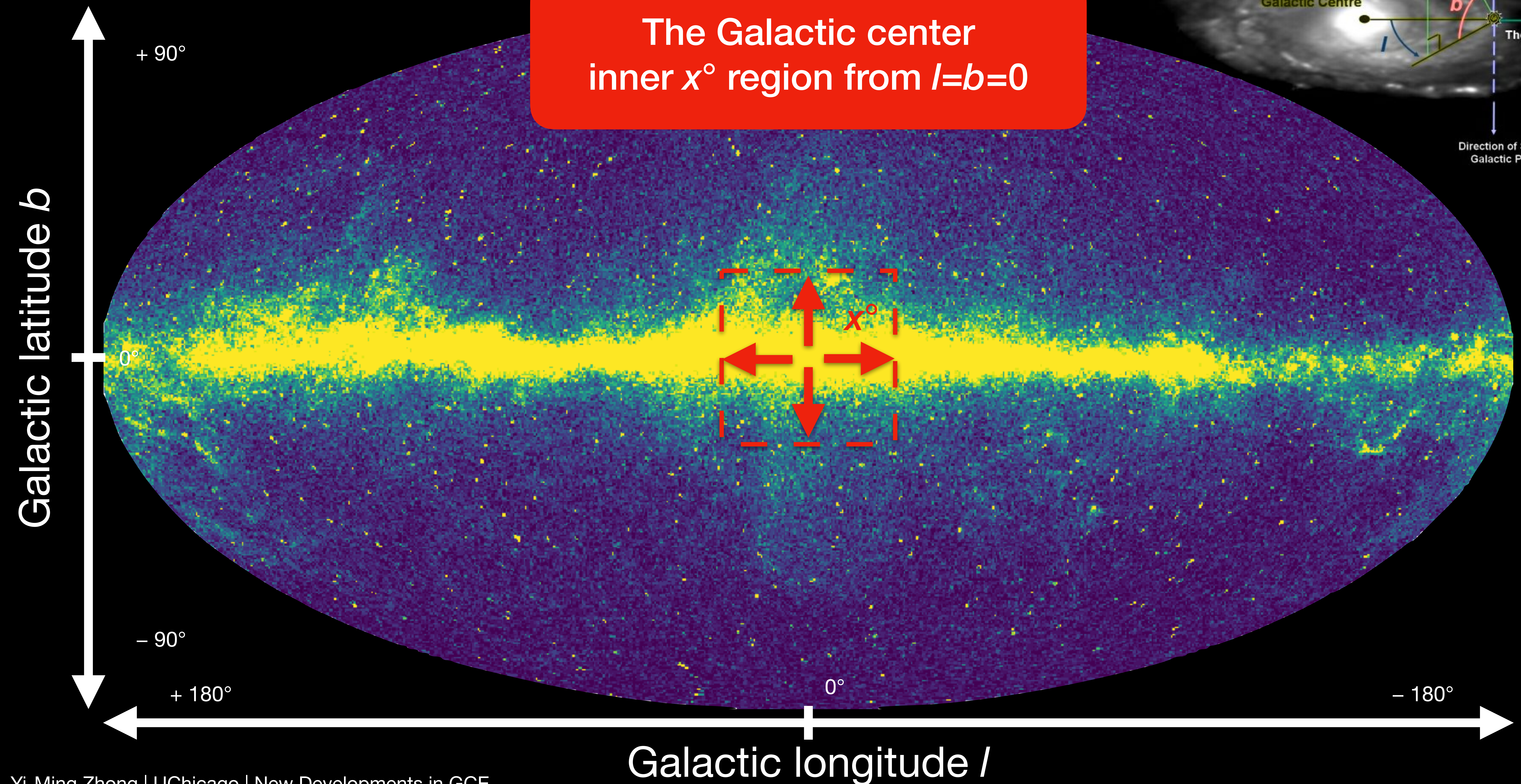
https://fermi.gsfc.nasa.gov/ssc/data/

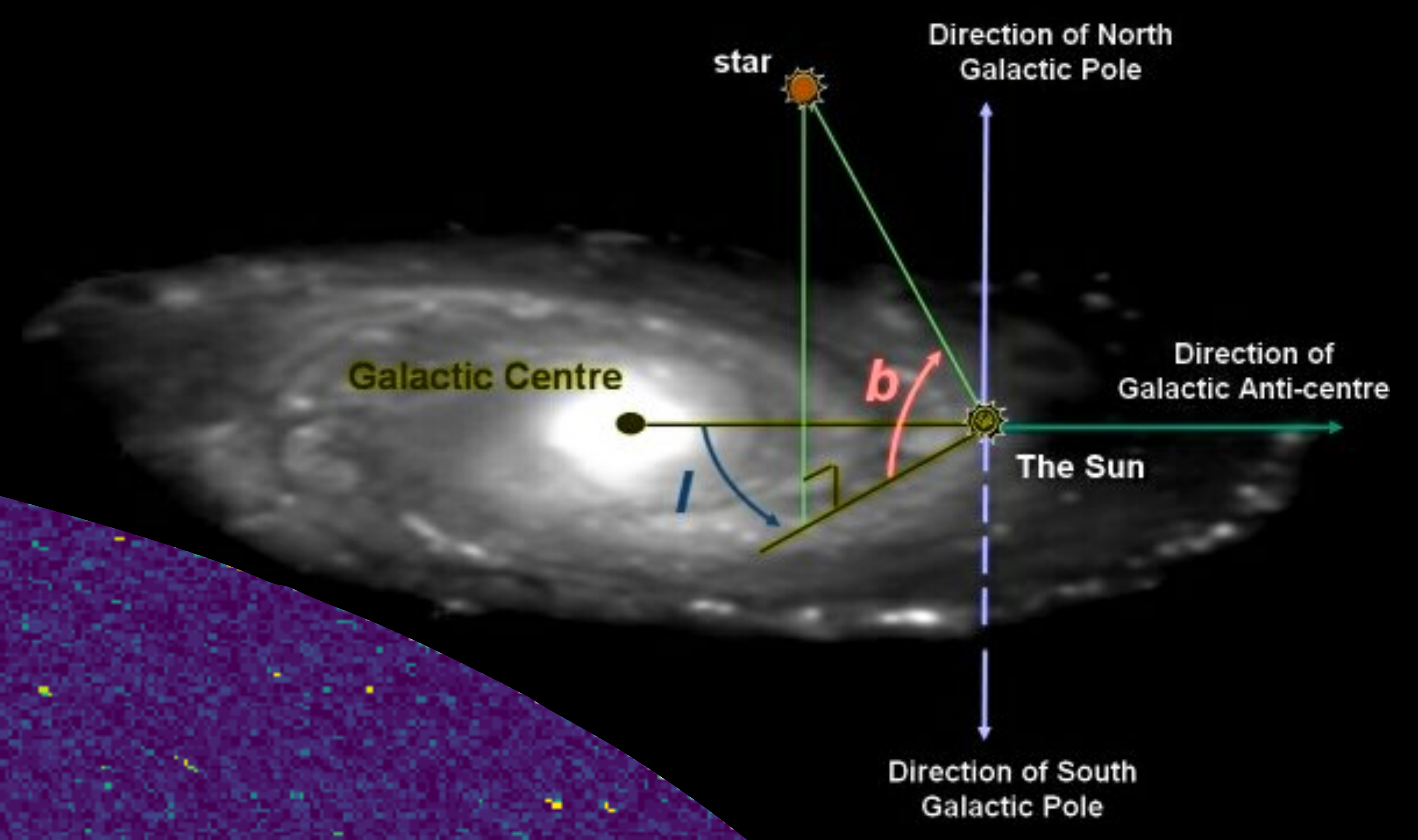



+ 90°
Galactic latitude *b*
0°
– 90°
+ 180°
0°
– 180°
Galactic longitude *l*


star
Direction of North Galactic Pole
Galactic Centre
b
Direction of Galactic Anti-centre
The Sun
l
Direction of South Galactic Pole

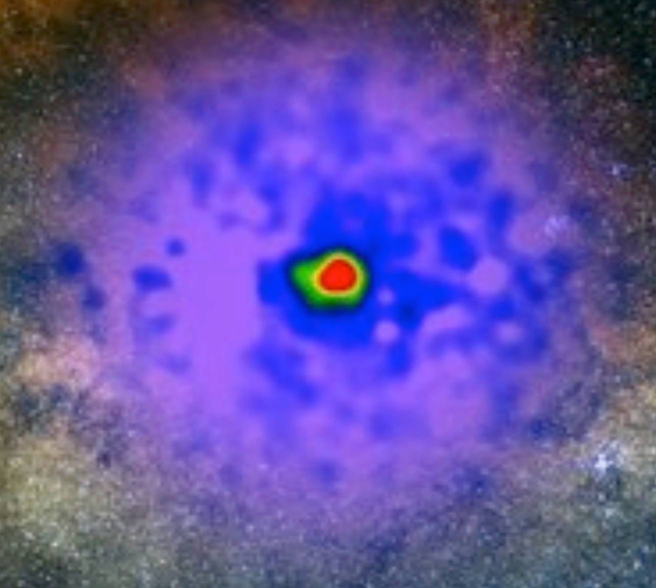
The Galactic center inner $x°$ region from $l=b=0$



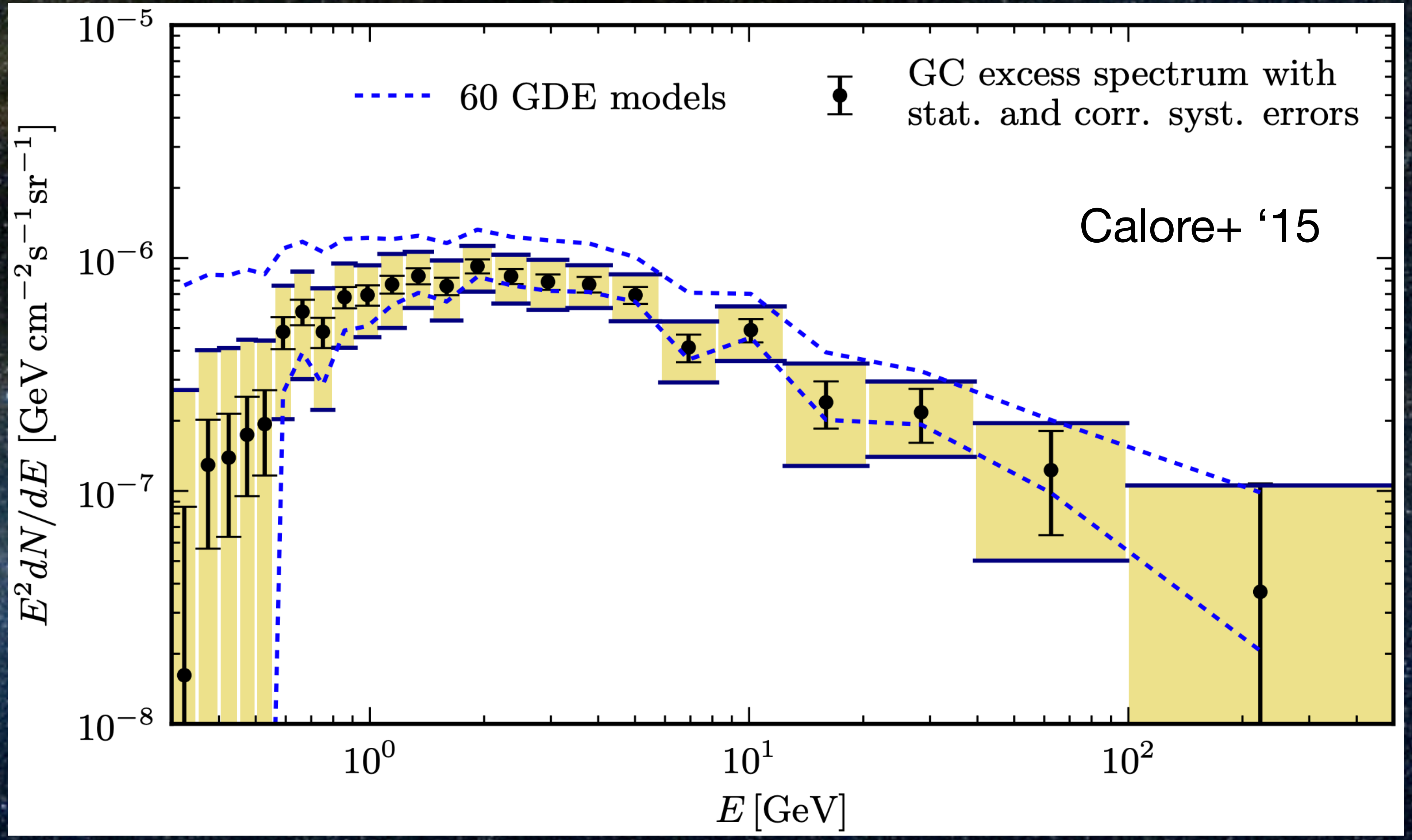


The excess

- Excess of γ-ray photos, peaked around 1– 4 GeV at ~inner 10° regions.
- Discovered by Goodenough & Hooper ’09. Later confirmed by Fermi-LAT collaboration (+ many other groups).

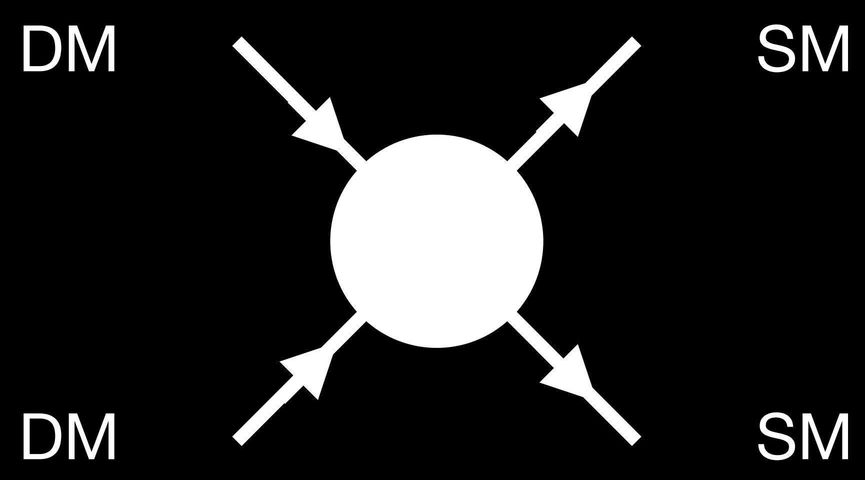


flux *N:* photons per area per sec per solid angle



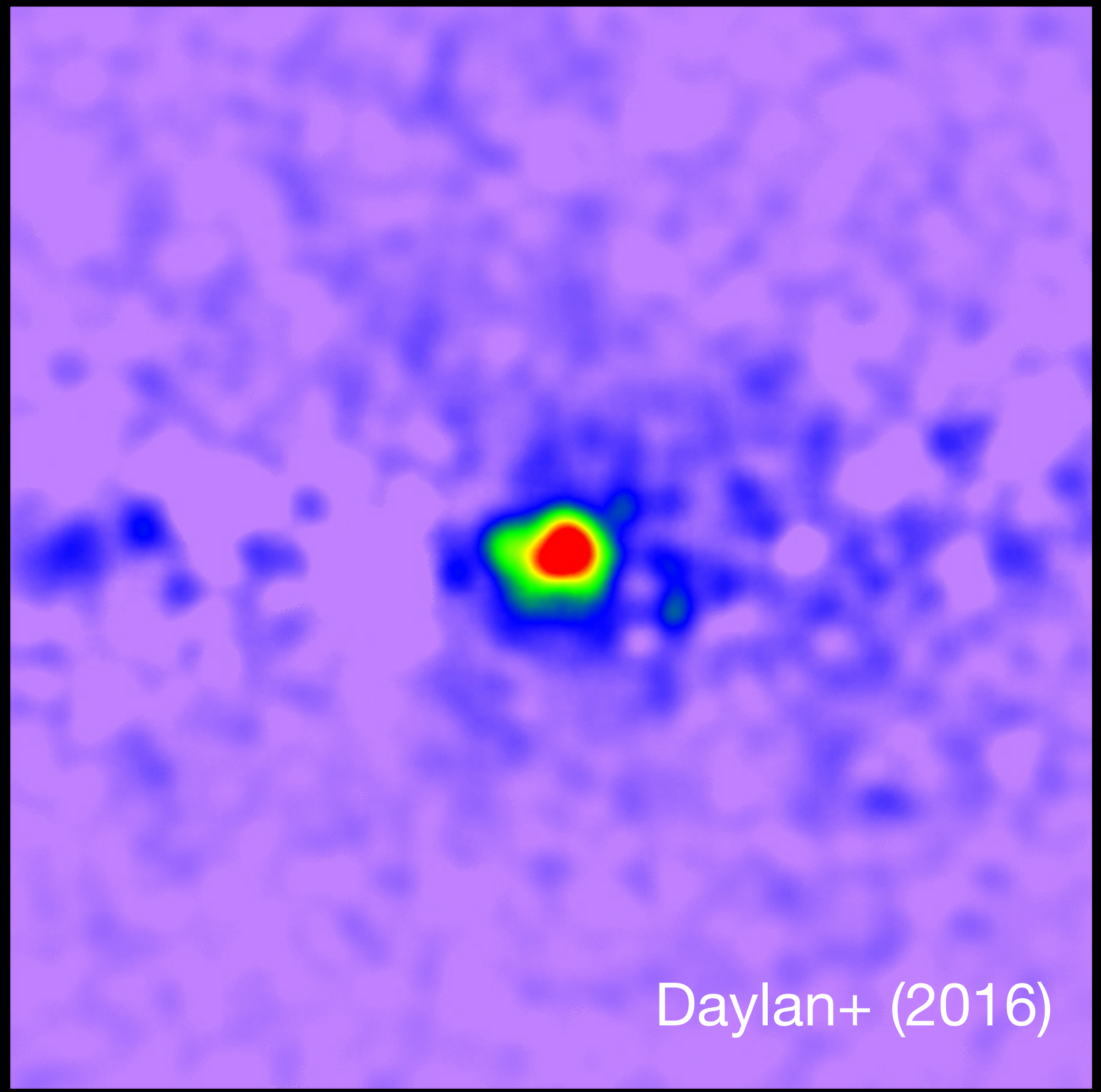
The GCE spectrum

If it comes from dark matter…



- First evidence for dark matter interacts with the ordinary matter.
- We could learn both dark matter mass and the interaction strength (WIMP particle).
- We could naturally explain the observed abundance of dark matter (thermal freezeout).

m_χ ~10-100 GeV
$\langle \sigma v \rangle \sim 10^{-26}$ cm^3/s


Daylan+ (2016)

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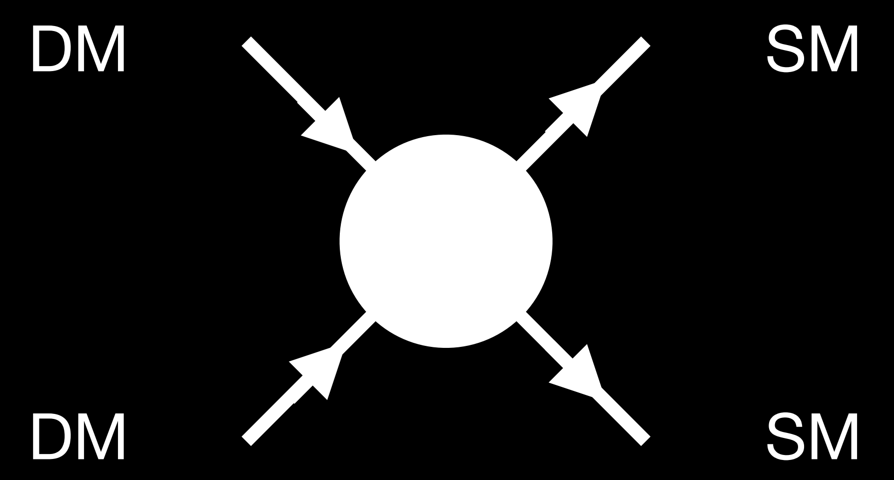

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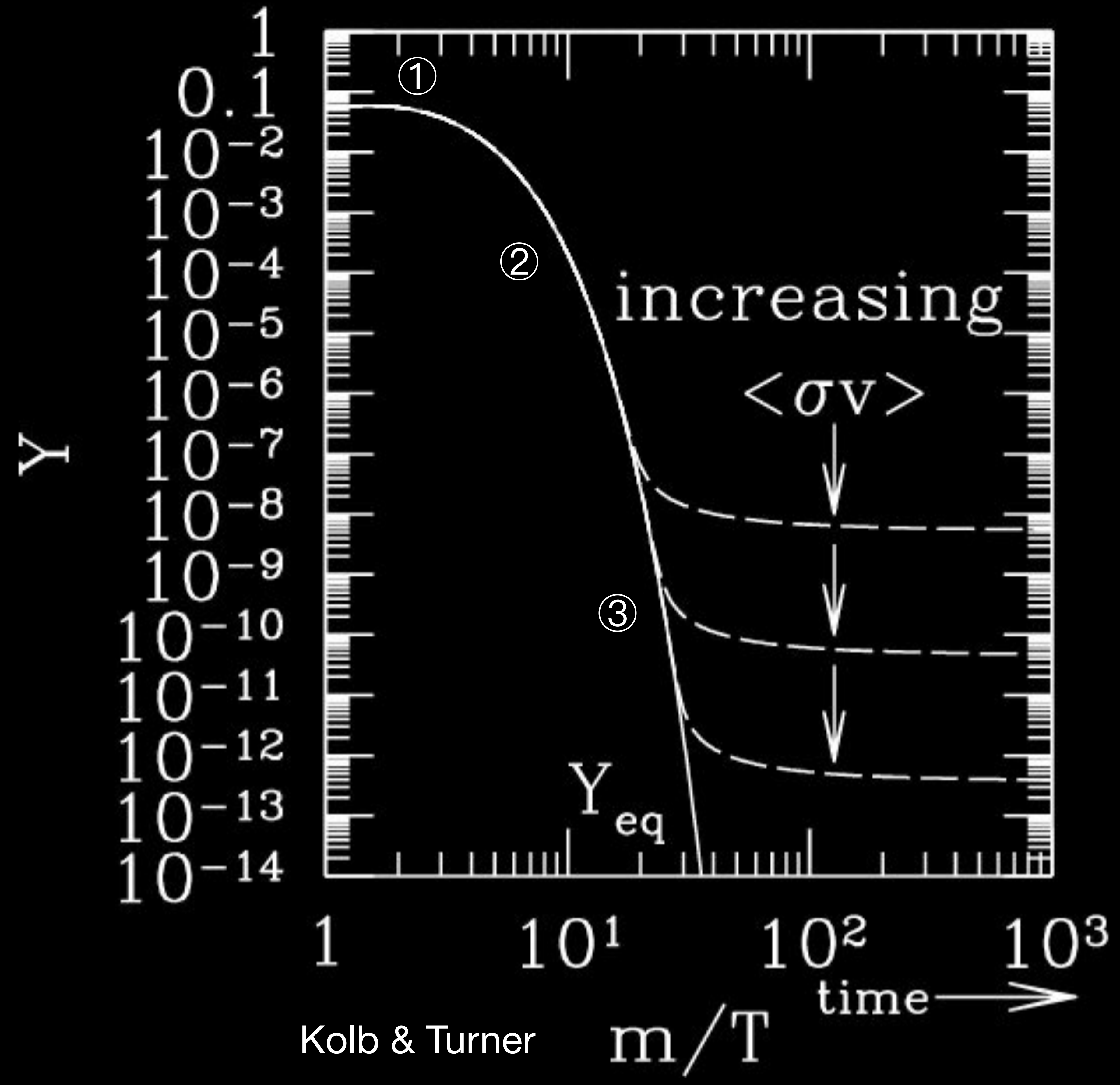
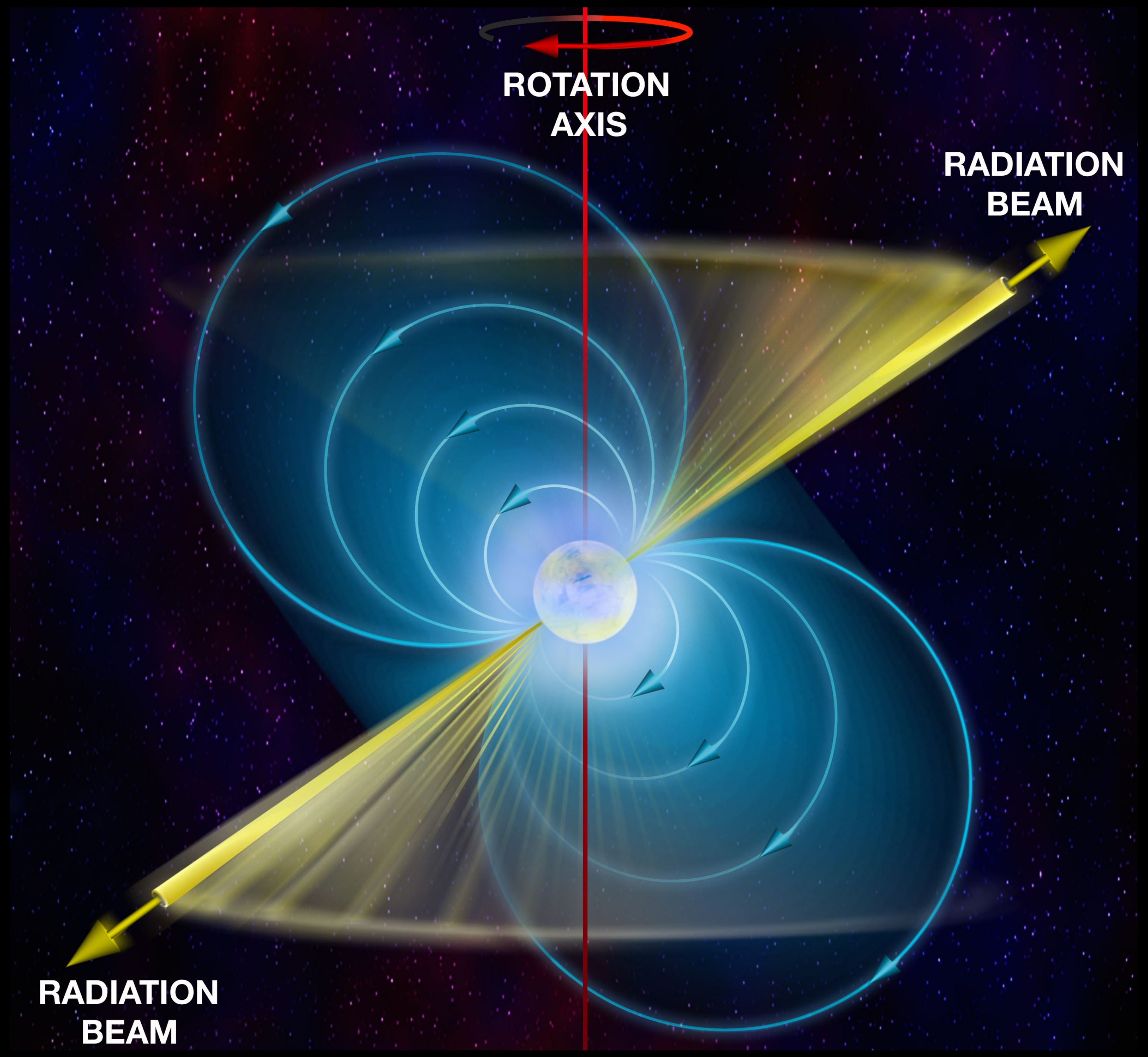


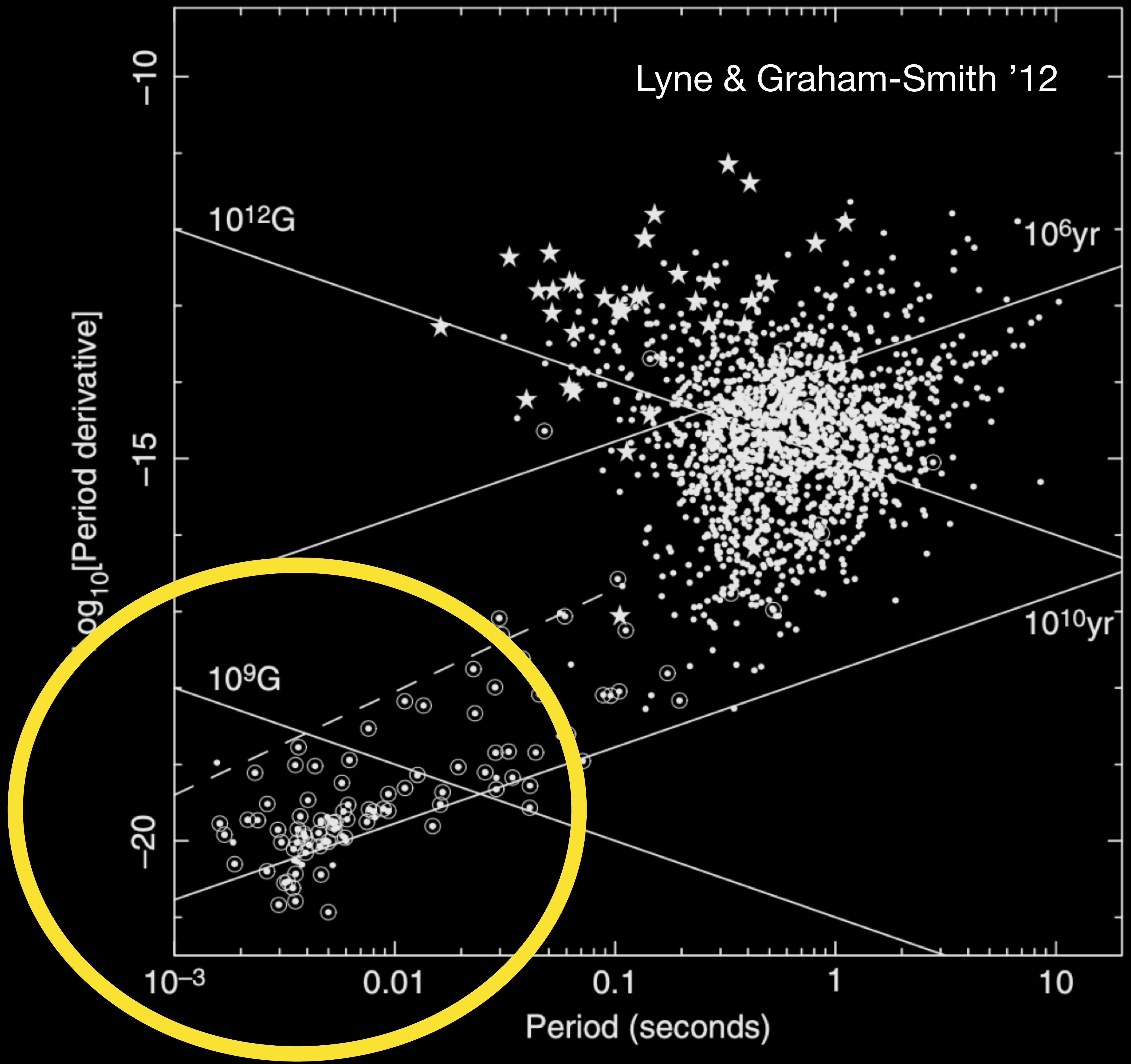
Kolb & Turner

Other explanation

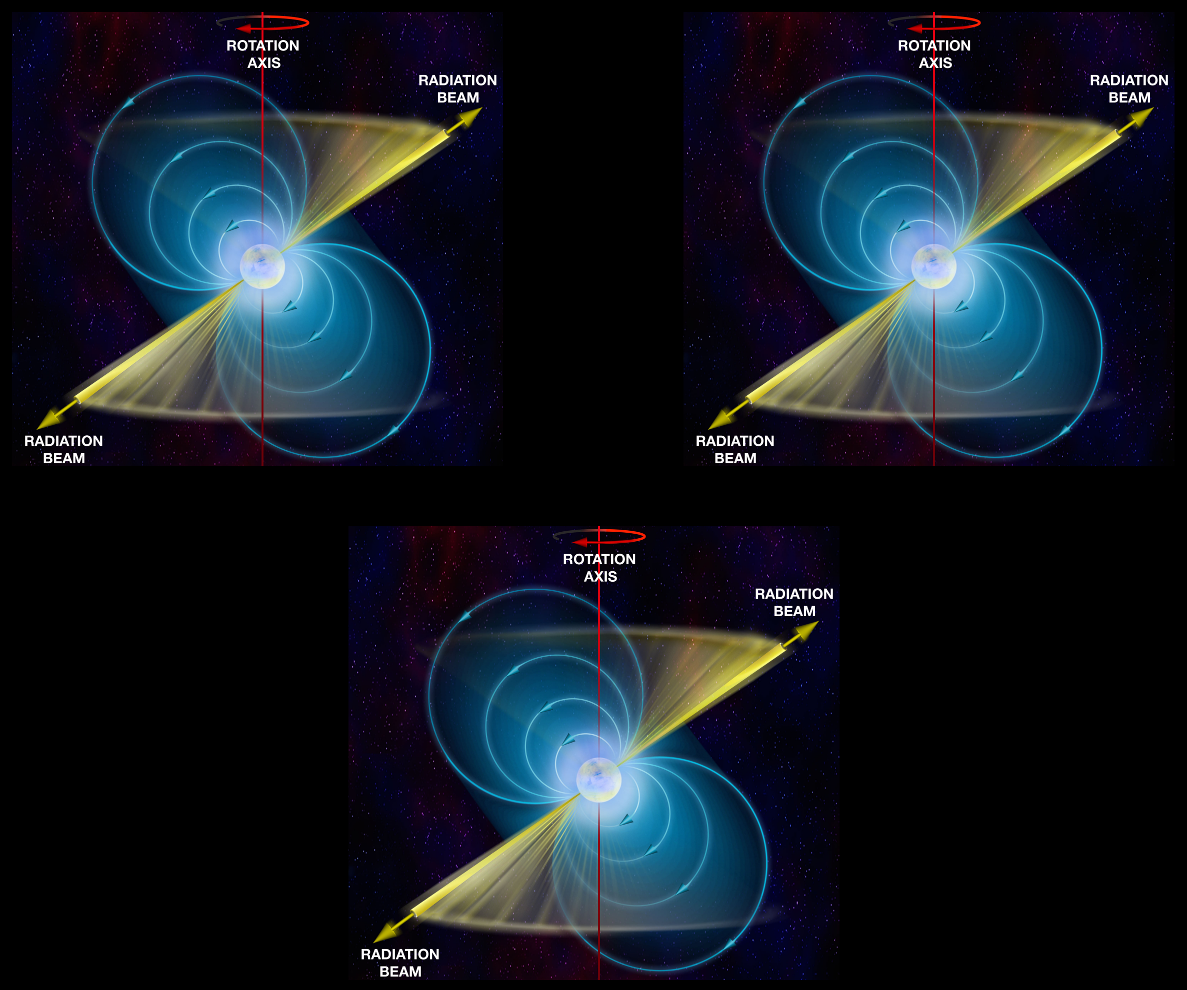
- Pulsars are rapidly spinning neutron stars.
- Classified by the period.



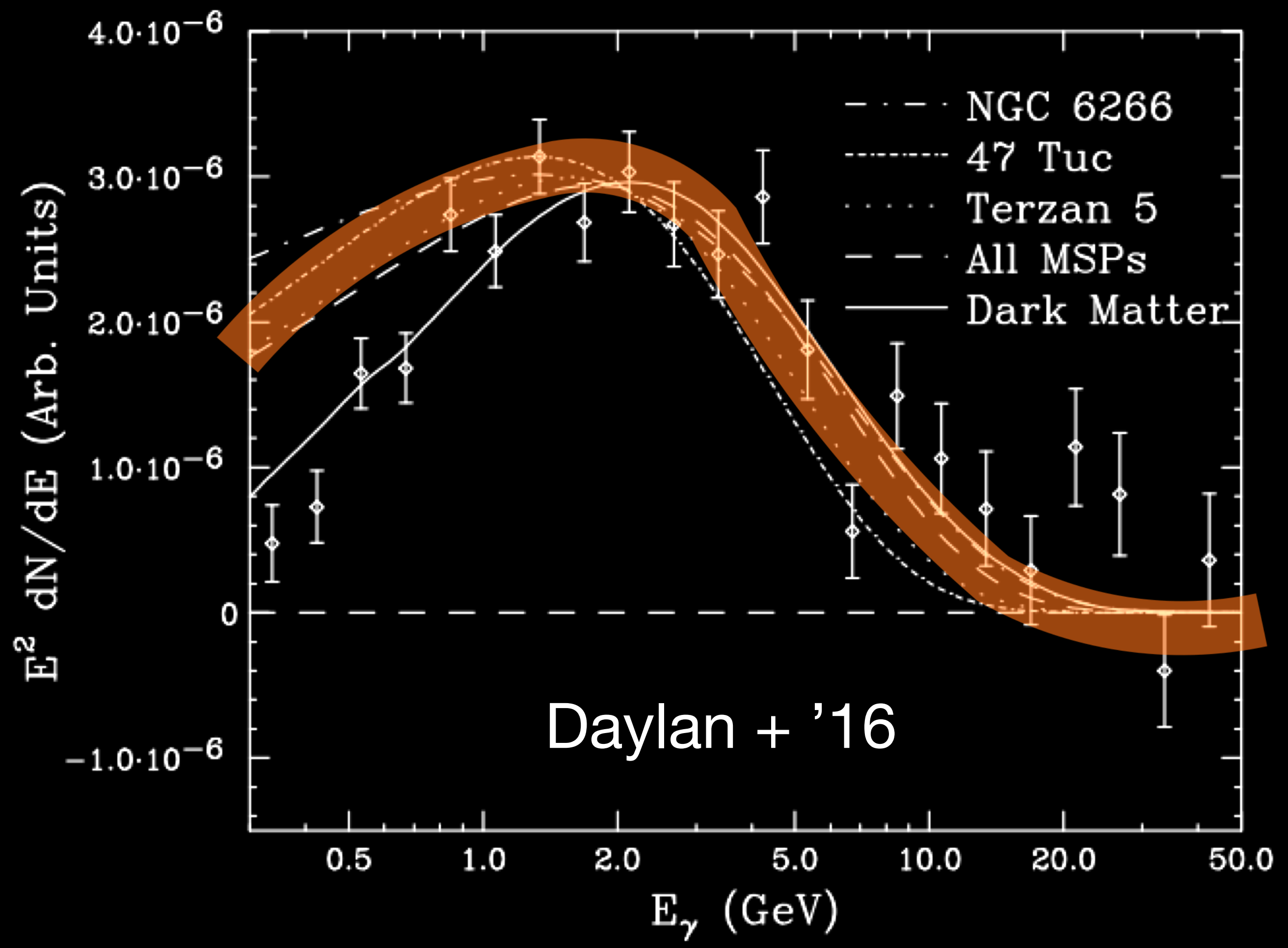
Credit: Bill Paxton

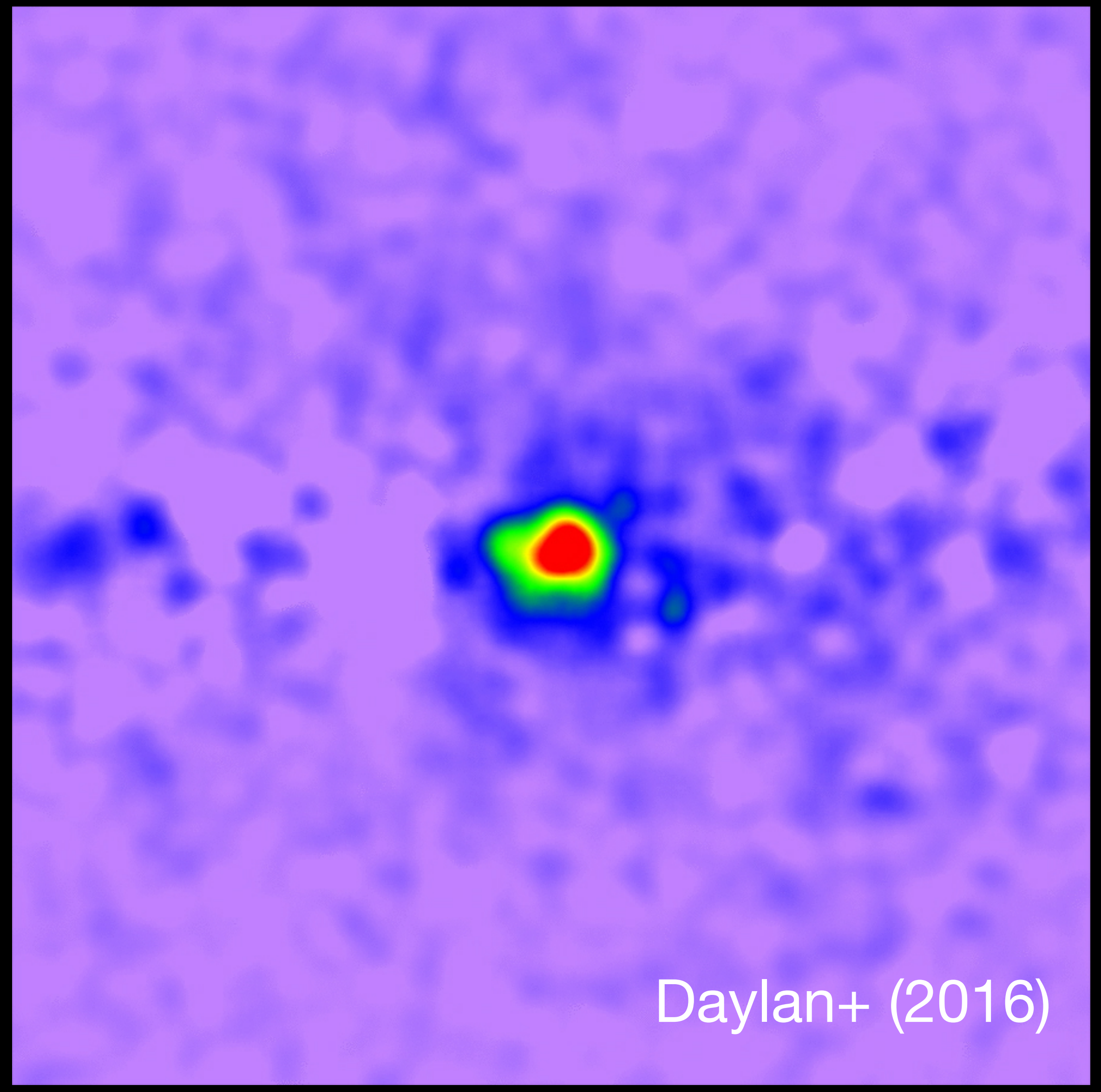


Other explanation

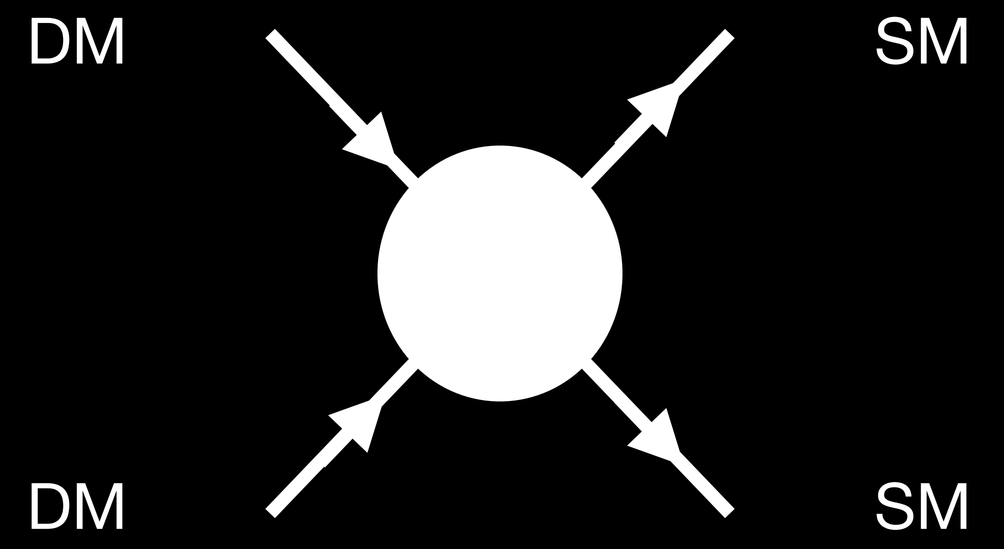


- Millisecond pulsars (MSPs), pulsars w/ period ~ milliseconds, give the correct spectra of the GCE.
- A new (not-yet-observed) population of millisecond pulsars at the GC could explain the GCE.




Daylan+ (2016)

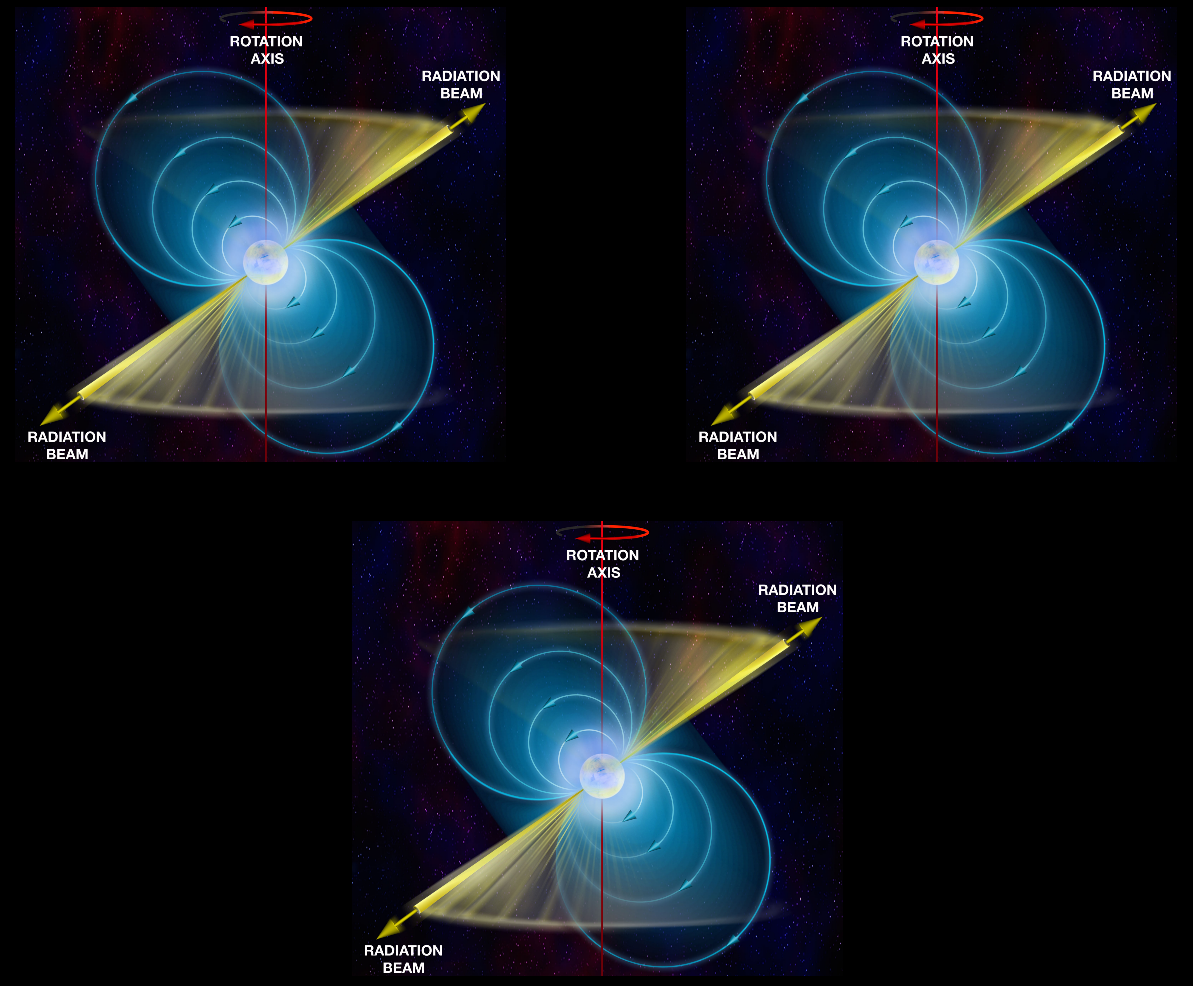
What is the origin of the GCE?



Dark matter (WIMP) annihilation

Small-scale power

Morphism



A new population of millisecond pulsars

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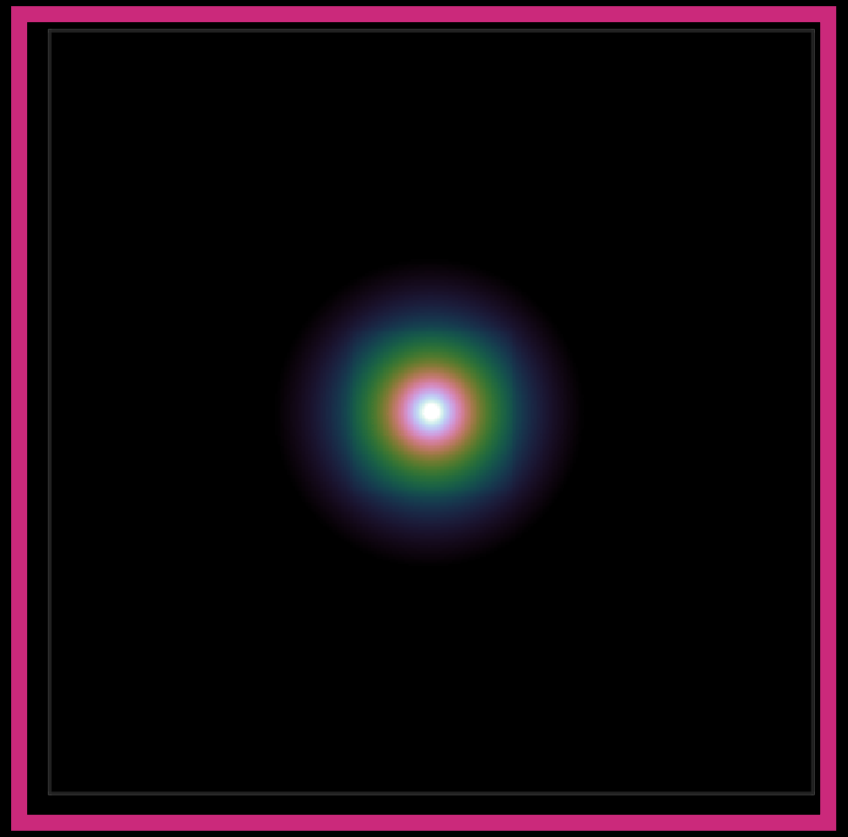

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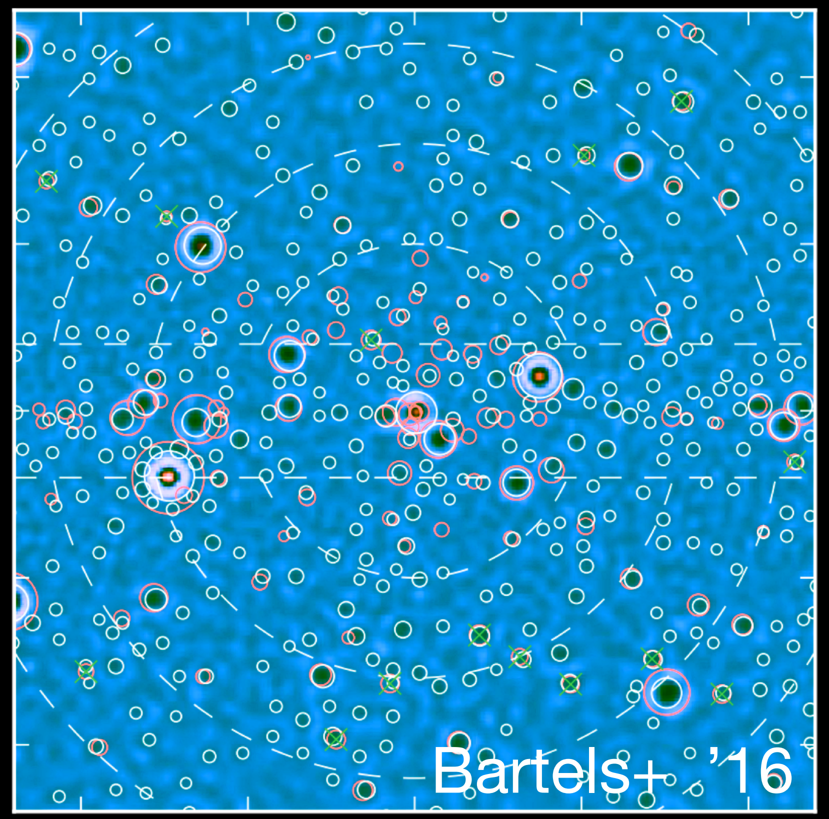

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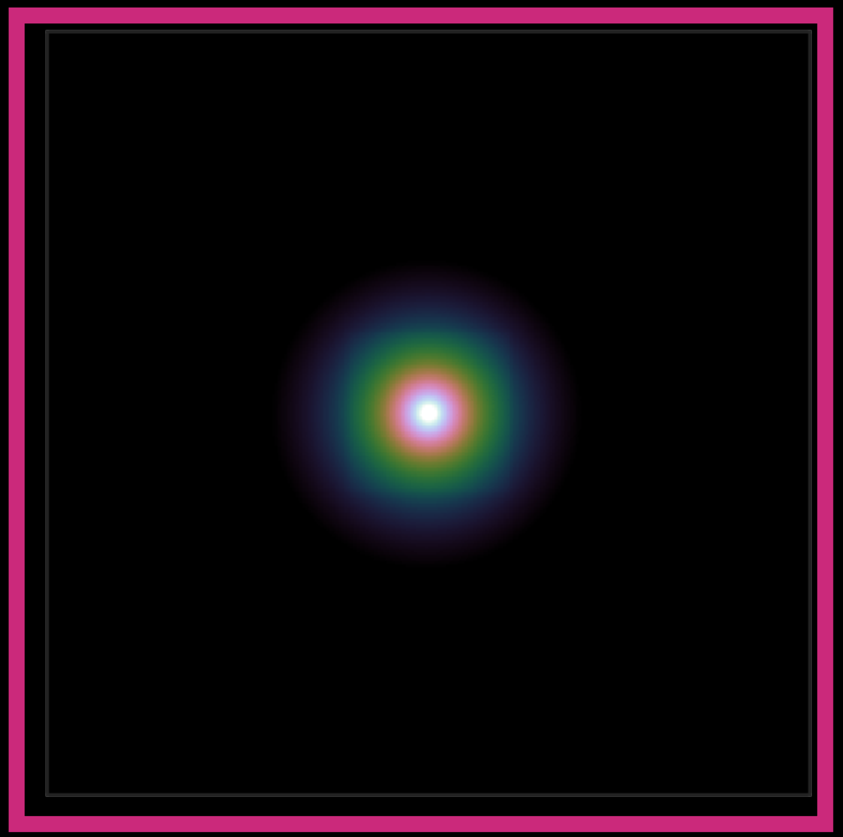

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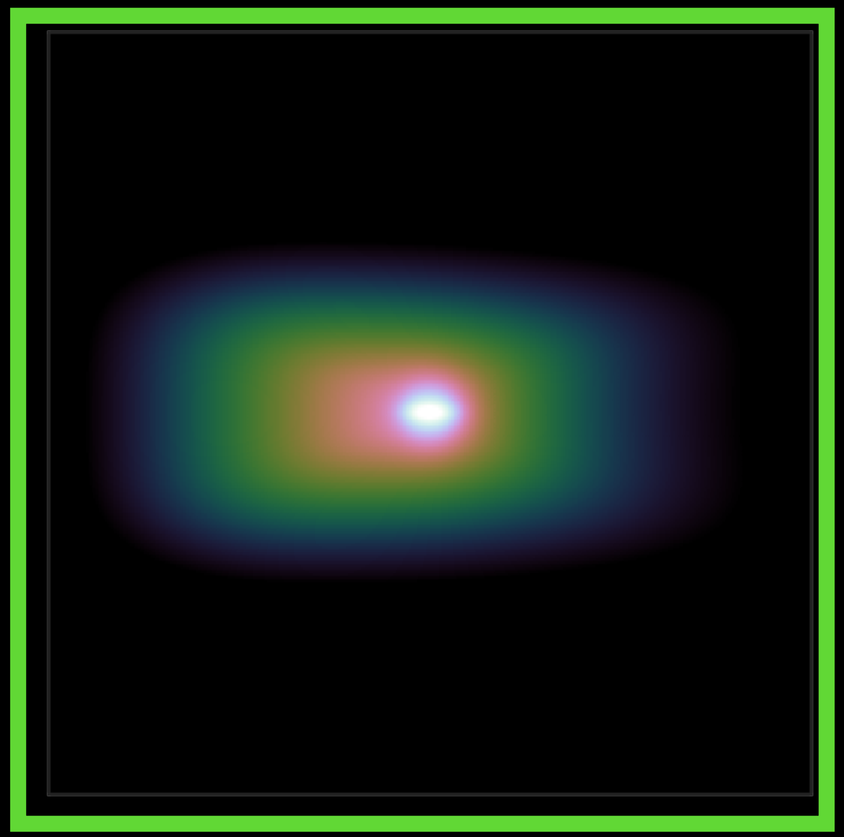
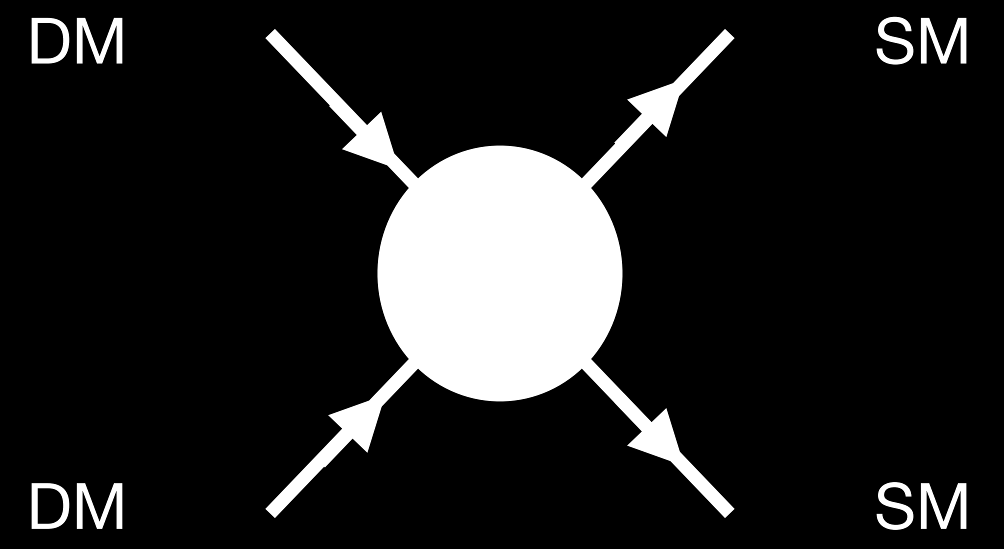


A new population of millisecond pulsars

The GCE status before 2019



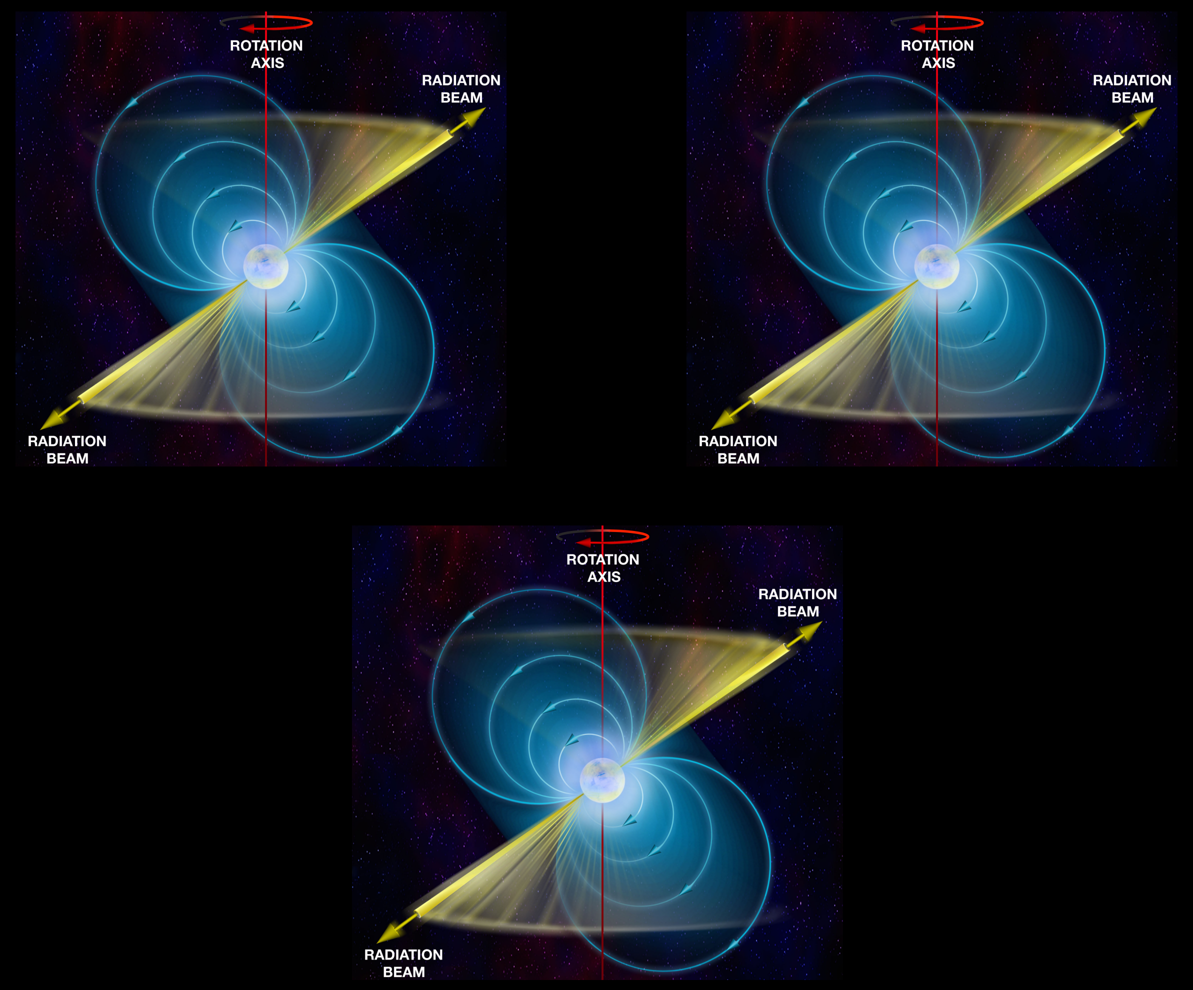
Dark matter (WIMP) annihilation

Small-scale power ✓

Bartels+ ’16, Lee+ ’16

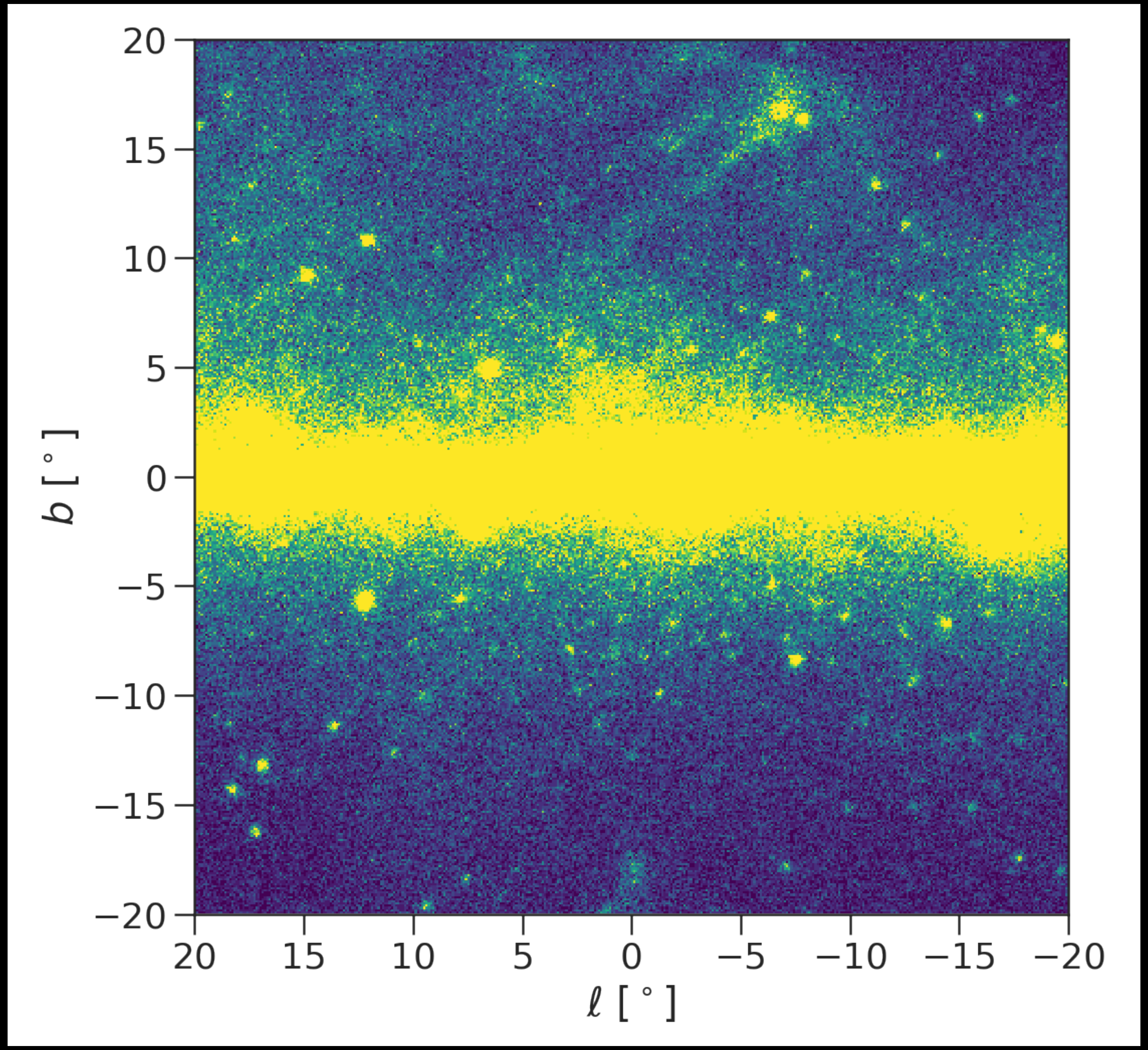
Morphism ✓

Macias+ ’16, ’17, Bartels+ ’17,
Macias+ ’18, ’19, Pohl+ ’20



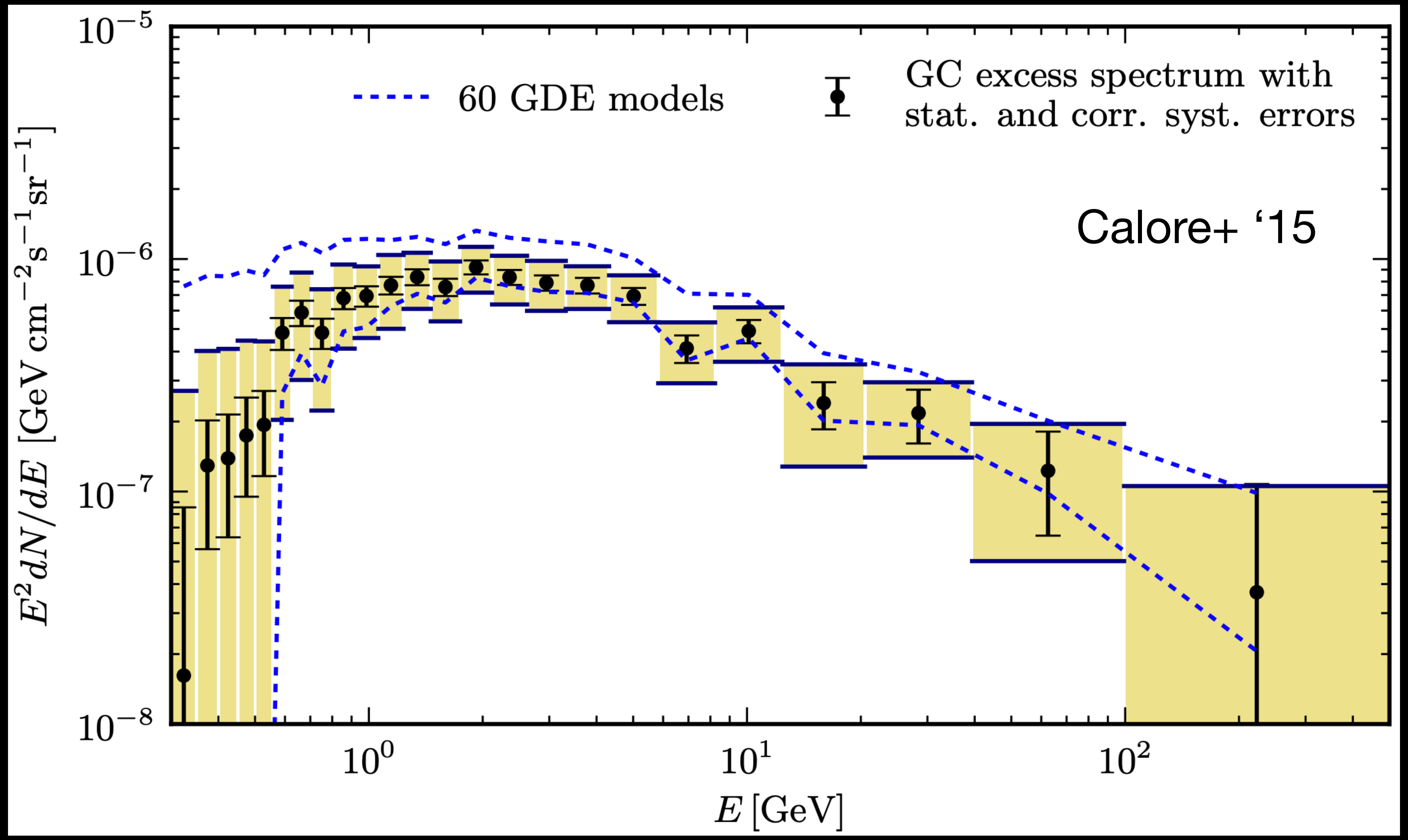
A new population of millisecond pulsars ✓

Fermi data

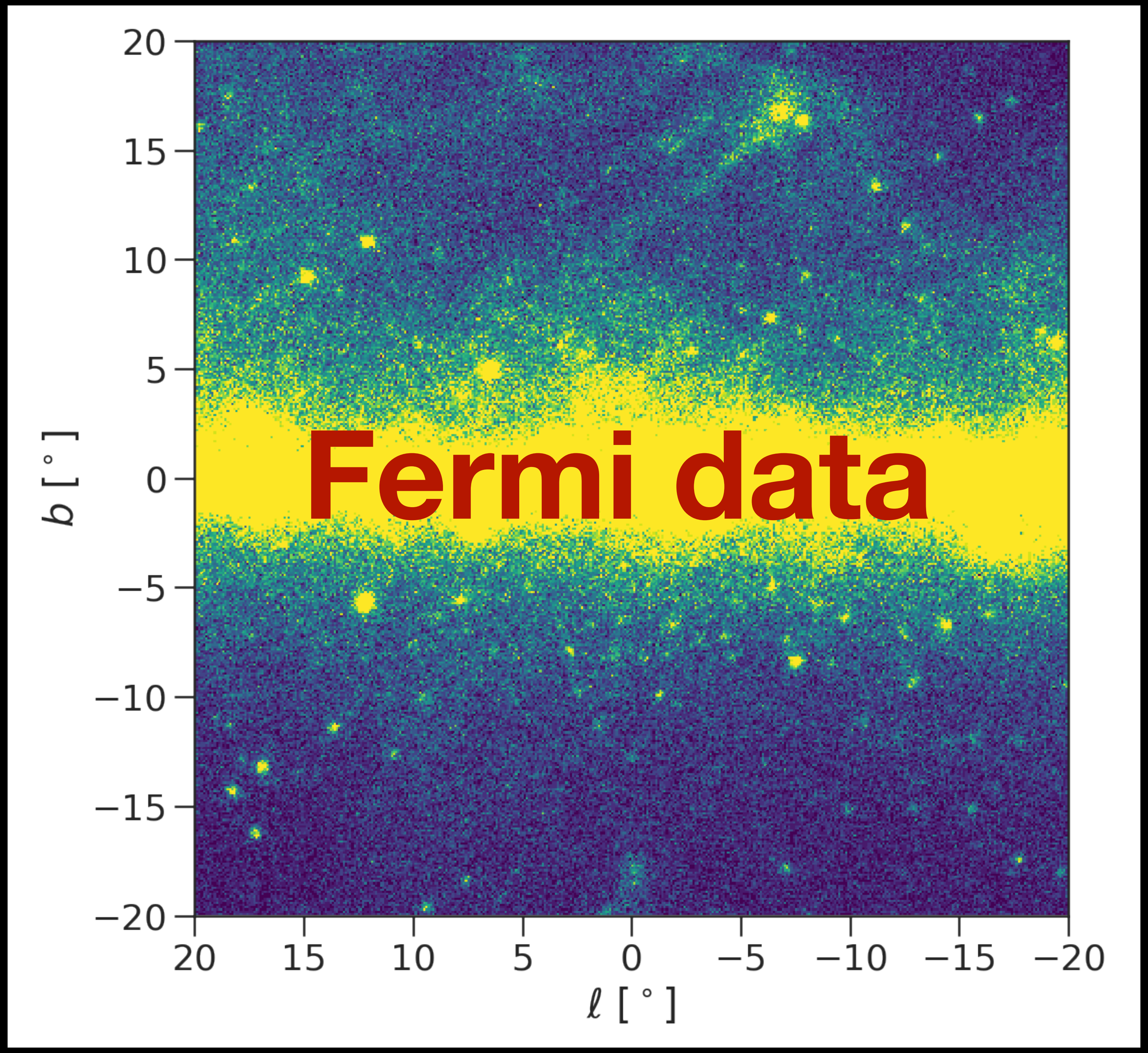


Template fitting

The GCE spectrum



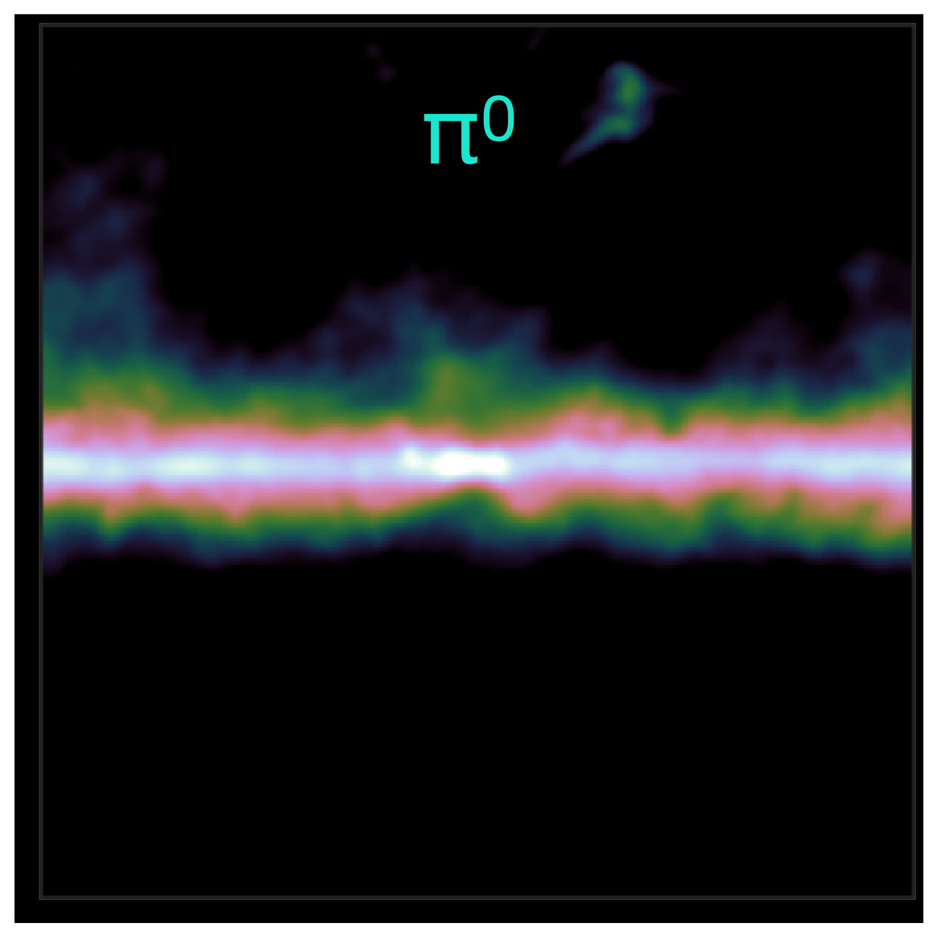
Template fitting

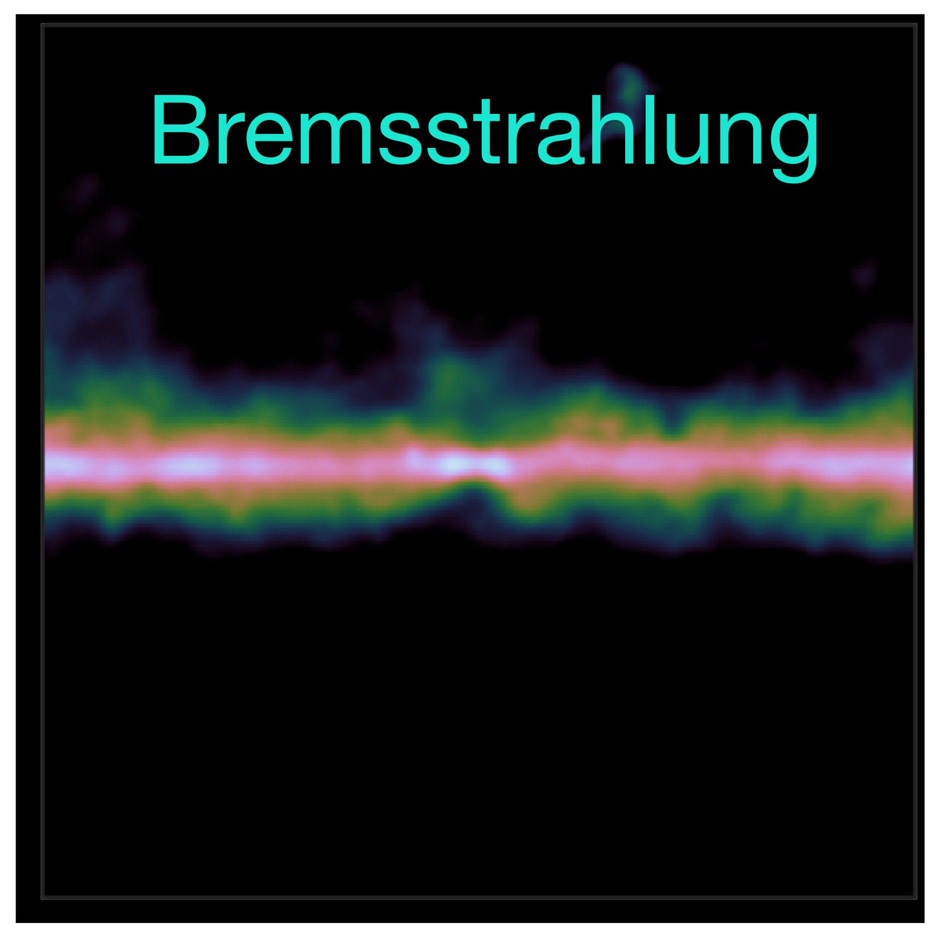


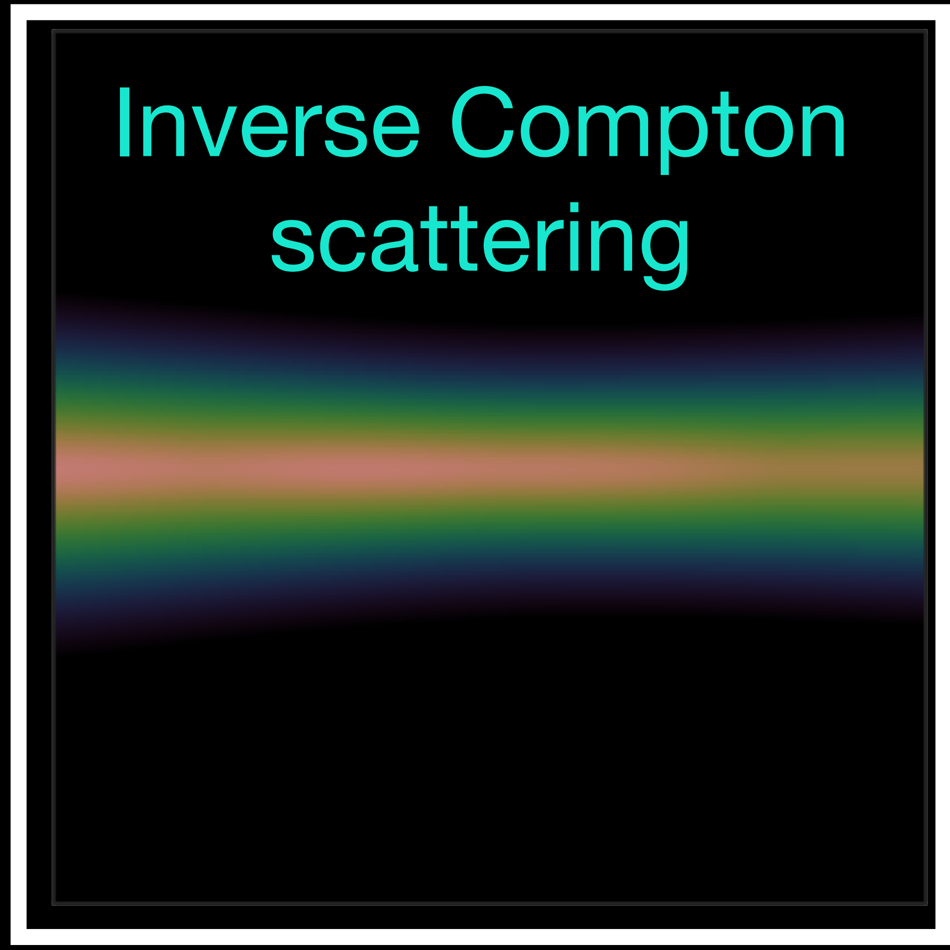
vs.

Sum of all foregrounds & GCE templates

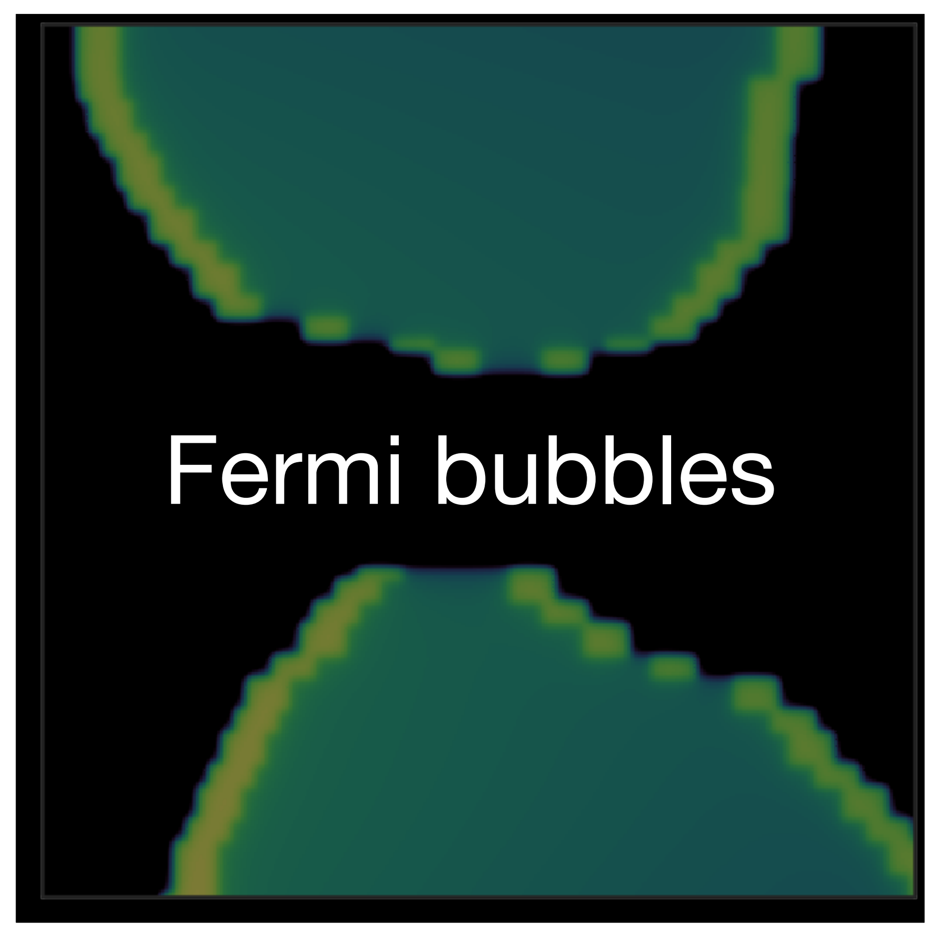
Templates


π^0


Bremsstrahlung


Inverse Compton
scattering


Isotropic diffuse
background


Fermi bubbles


GCE

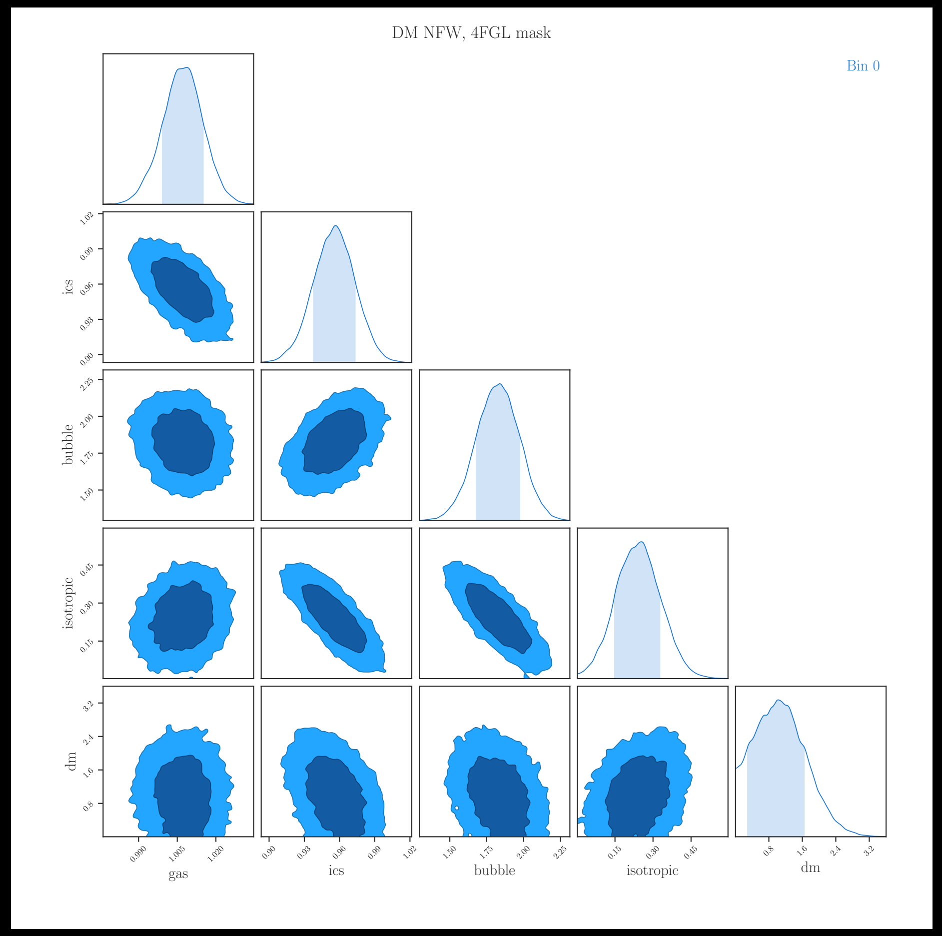
Fitting

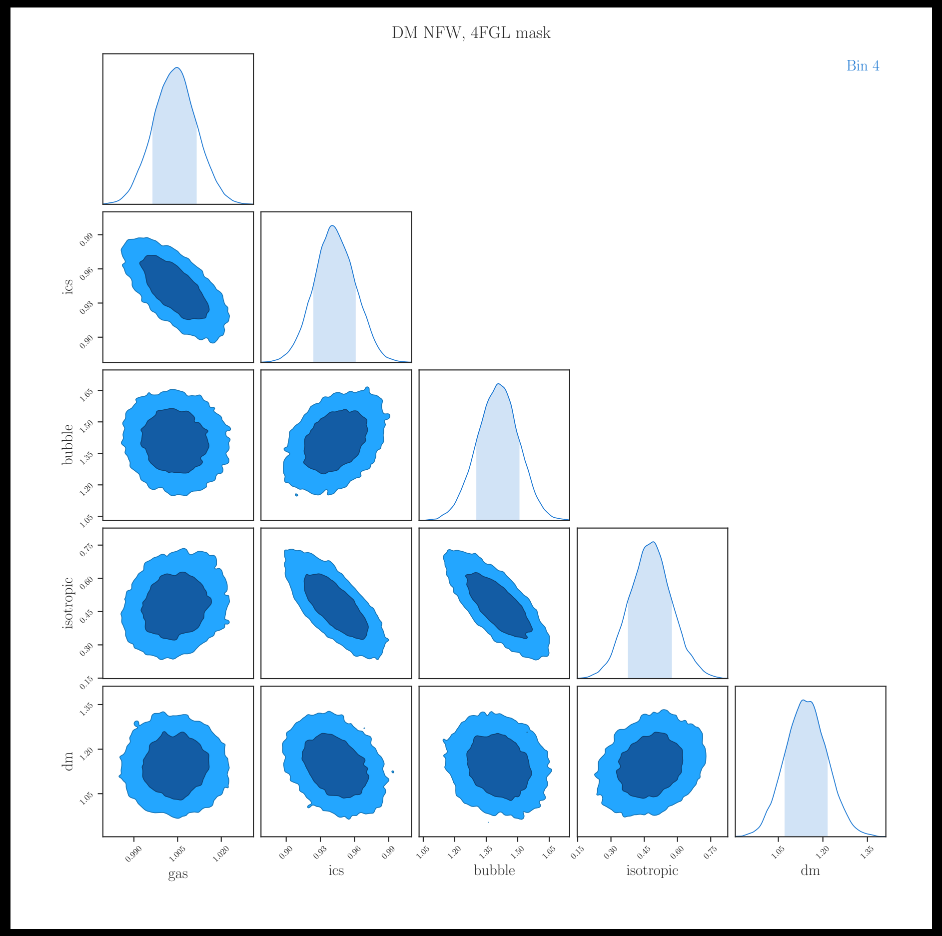
- Do the comparison energy-bin by energy-bin
- For each energy bin, we run MCMC to get the statistics of the weights of the templates

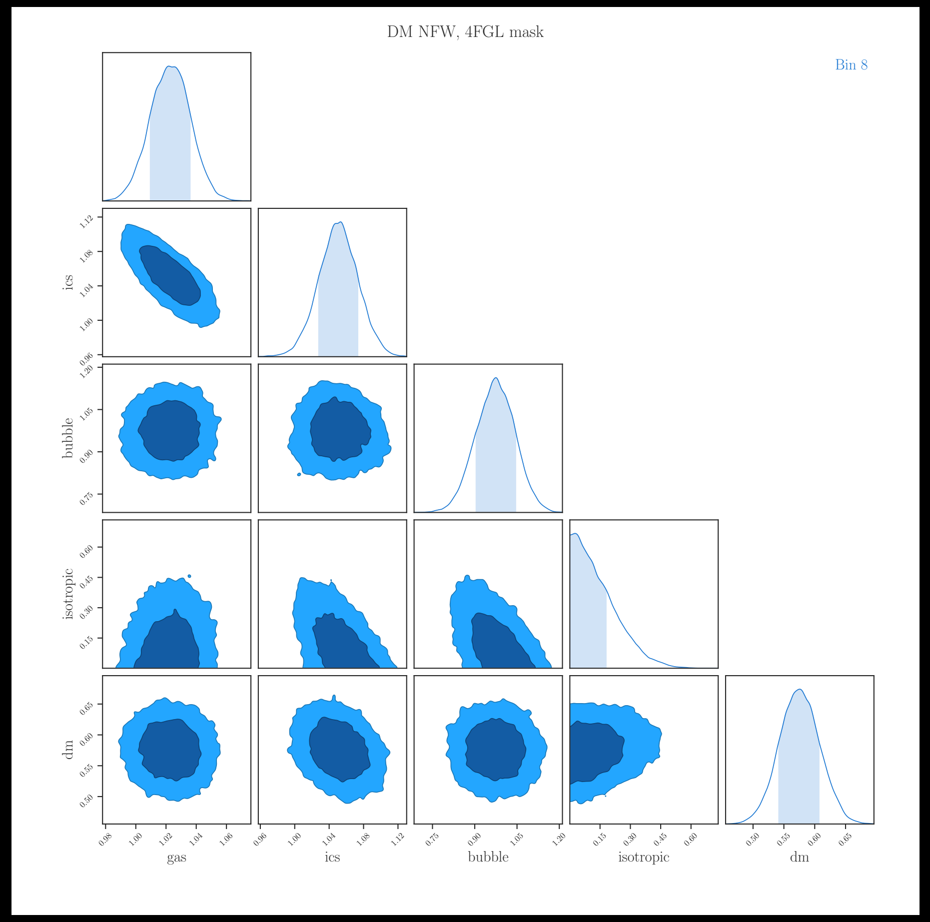
Weighted sum of templates

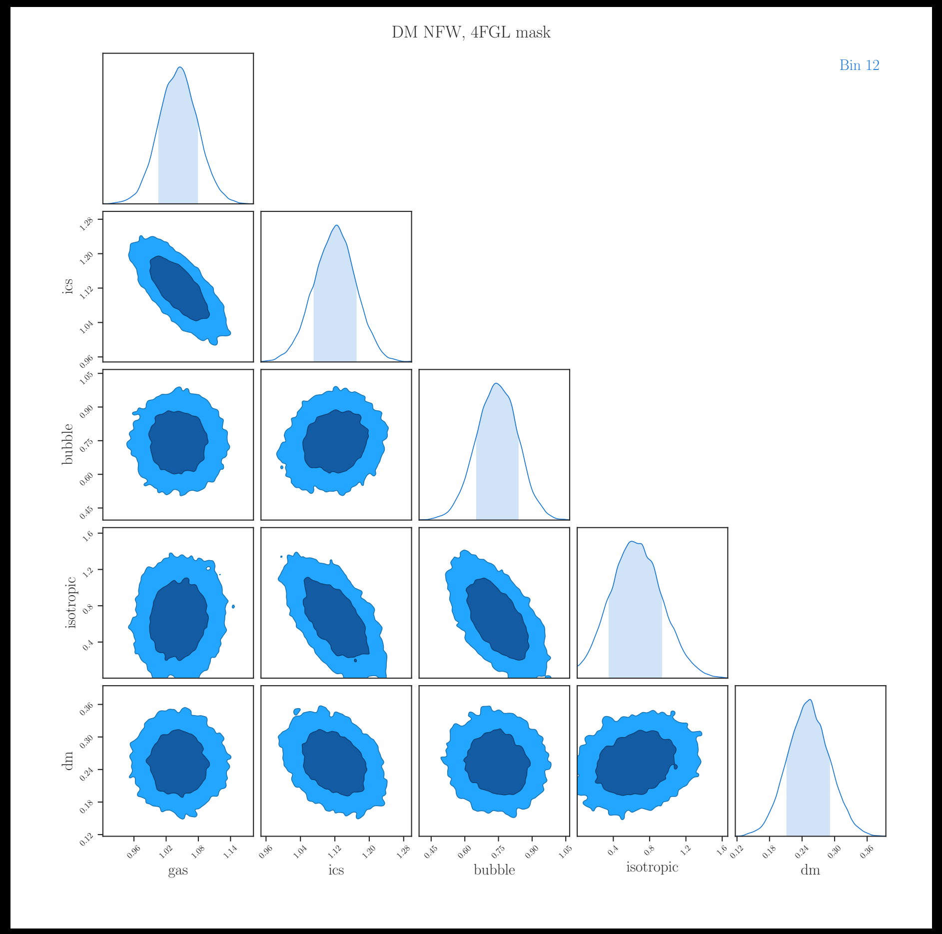
$$-2\ln\lambda = 2\sum_{\text{pixcels}}\left[C + \ln D! - D\ln C\right] + \chi^2_{\text{ext}}$$

Fermi data

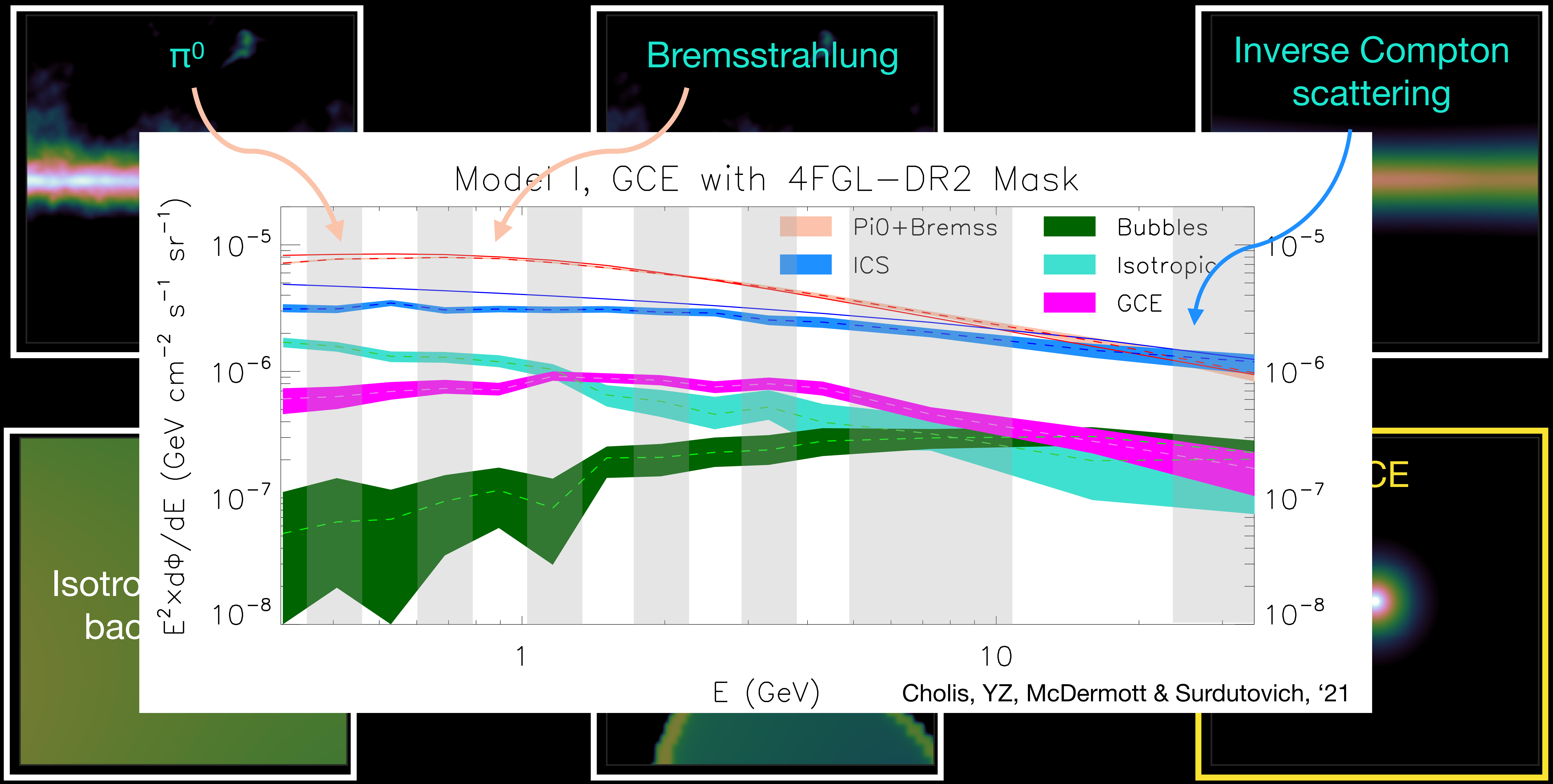




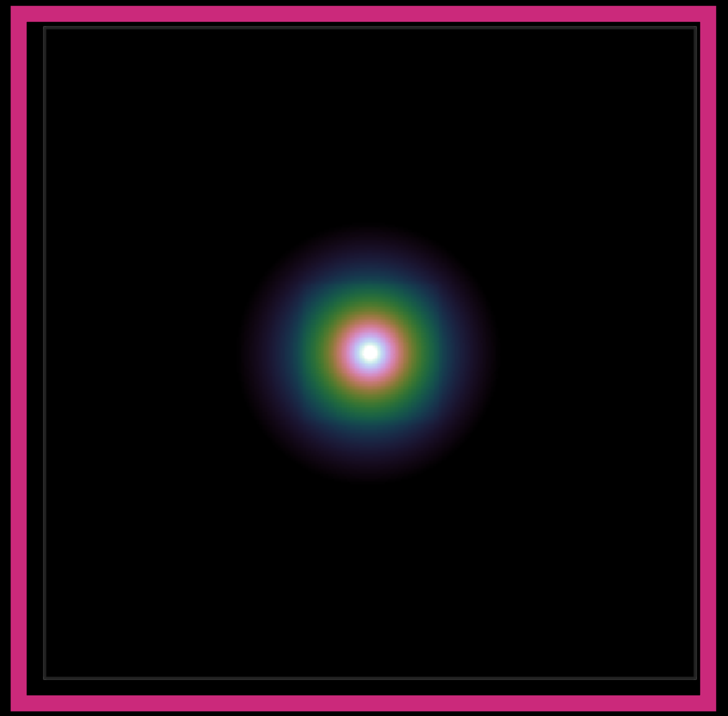


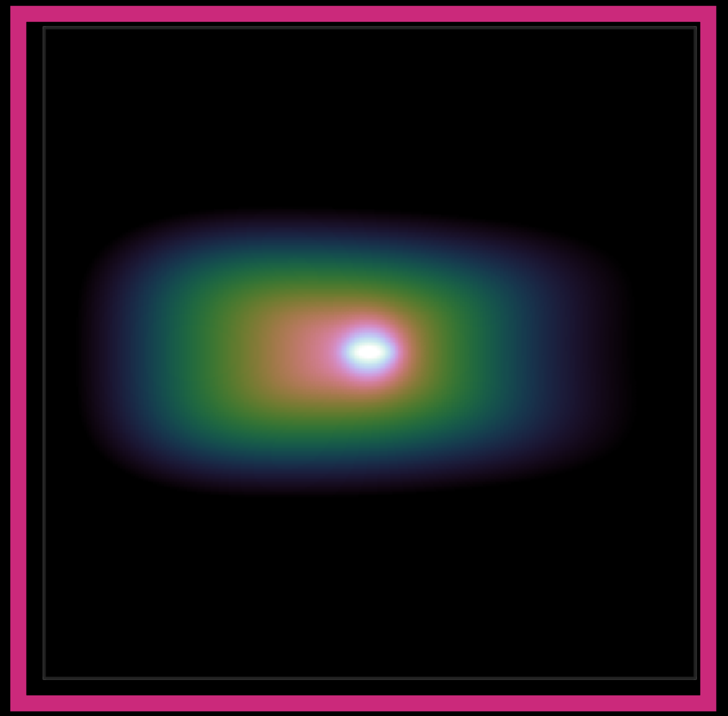


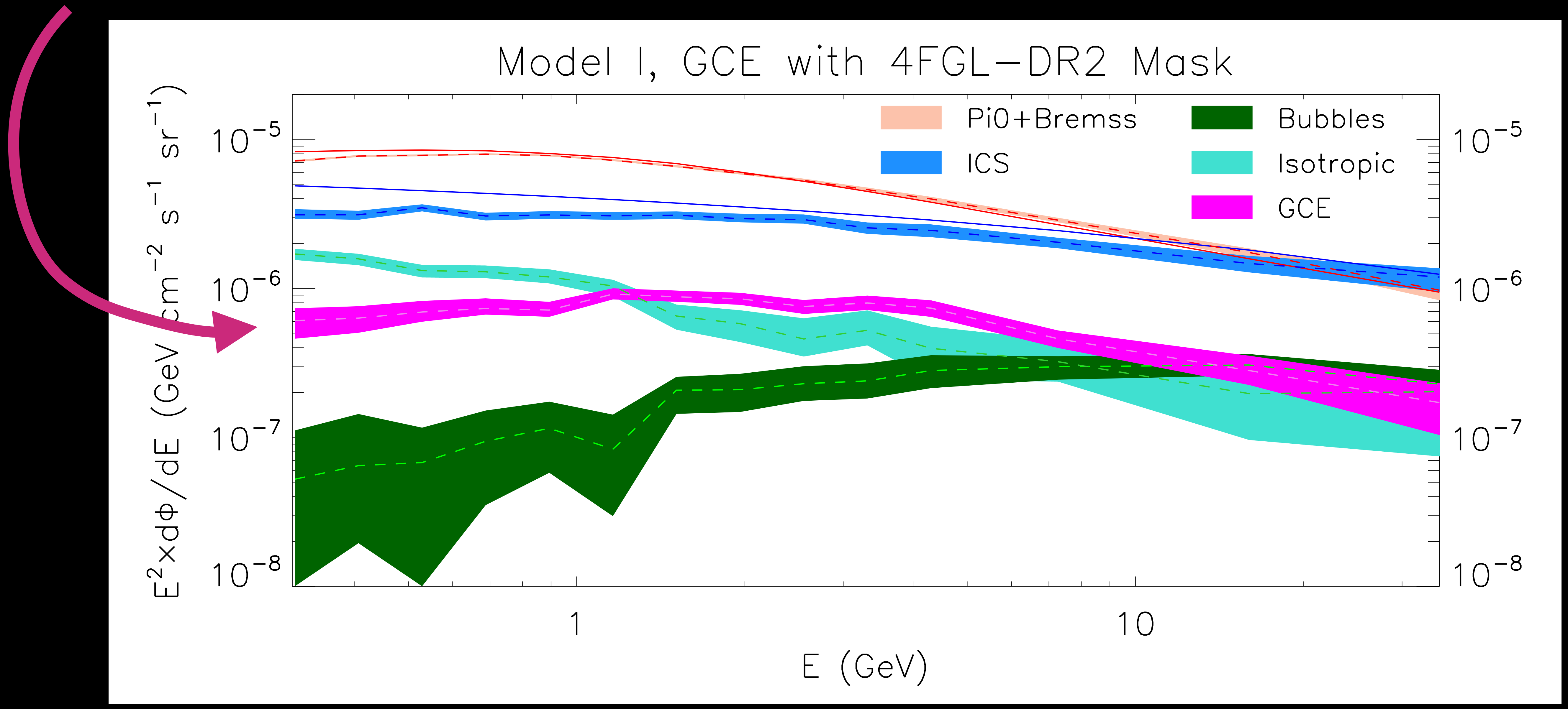
Template fitting



Test GCE hypothesis



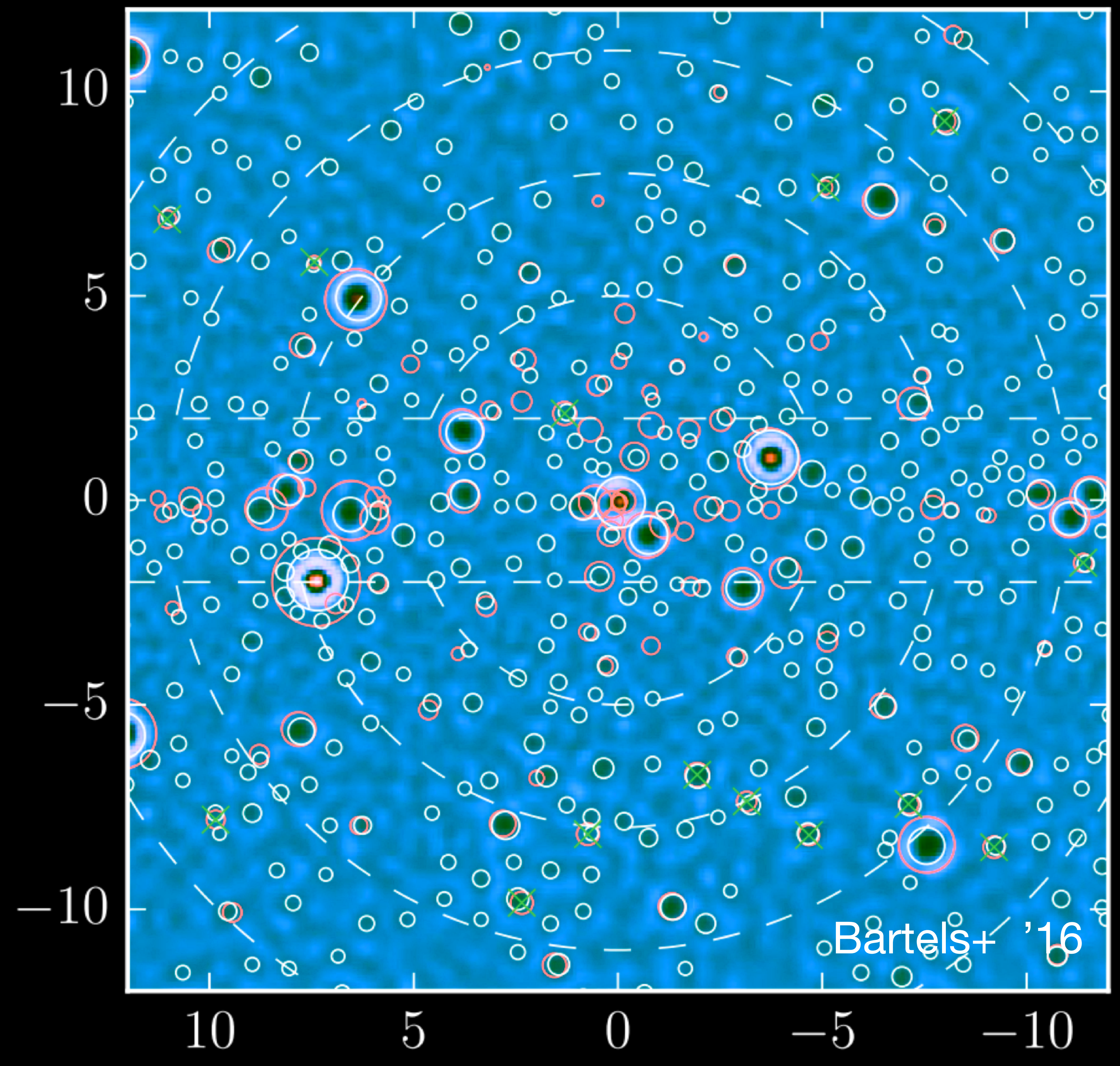




Testing the small-scale power of the GCE

The small-scale power

- At the small scale (resolution scale), γ-ray emissions from MSPs is clumpy but those from WIMP is smooth.
- Important to distinguish the two origins.
- Bartels+ '16 [Wavelet] and Lee+ '16 [Non-Poisson template fitting] both found GCE is clumpy.



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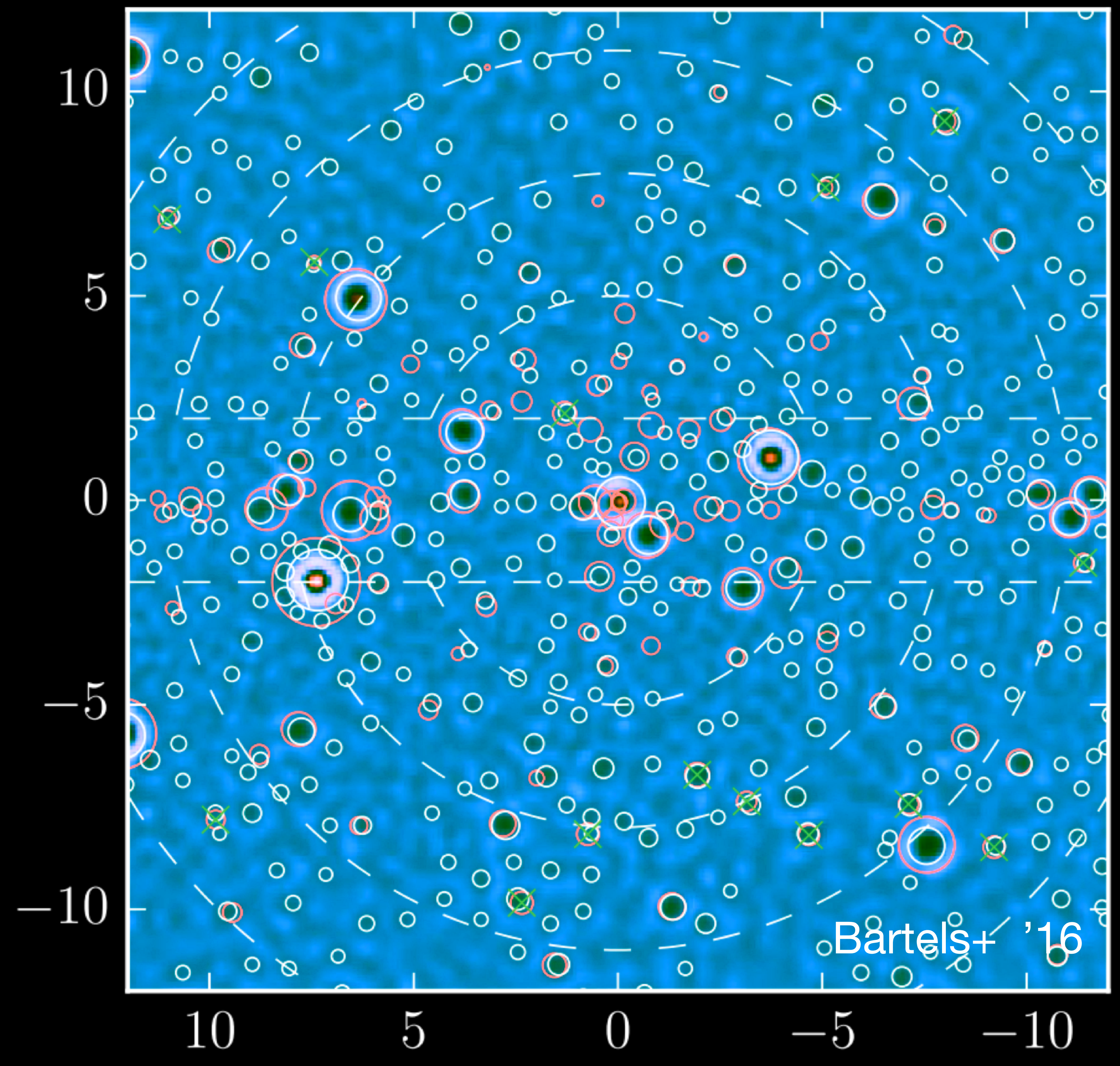


Is the GCE origin settled?

New data released in 2019

- Fermi-LAT collaboration released the 4th point source catalog in early 2019. (Abdollahi+ ’19)

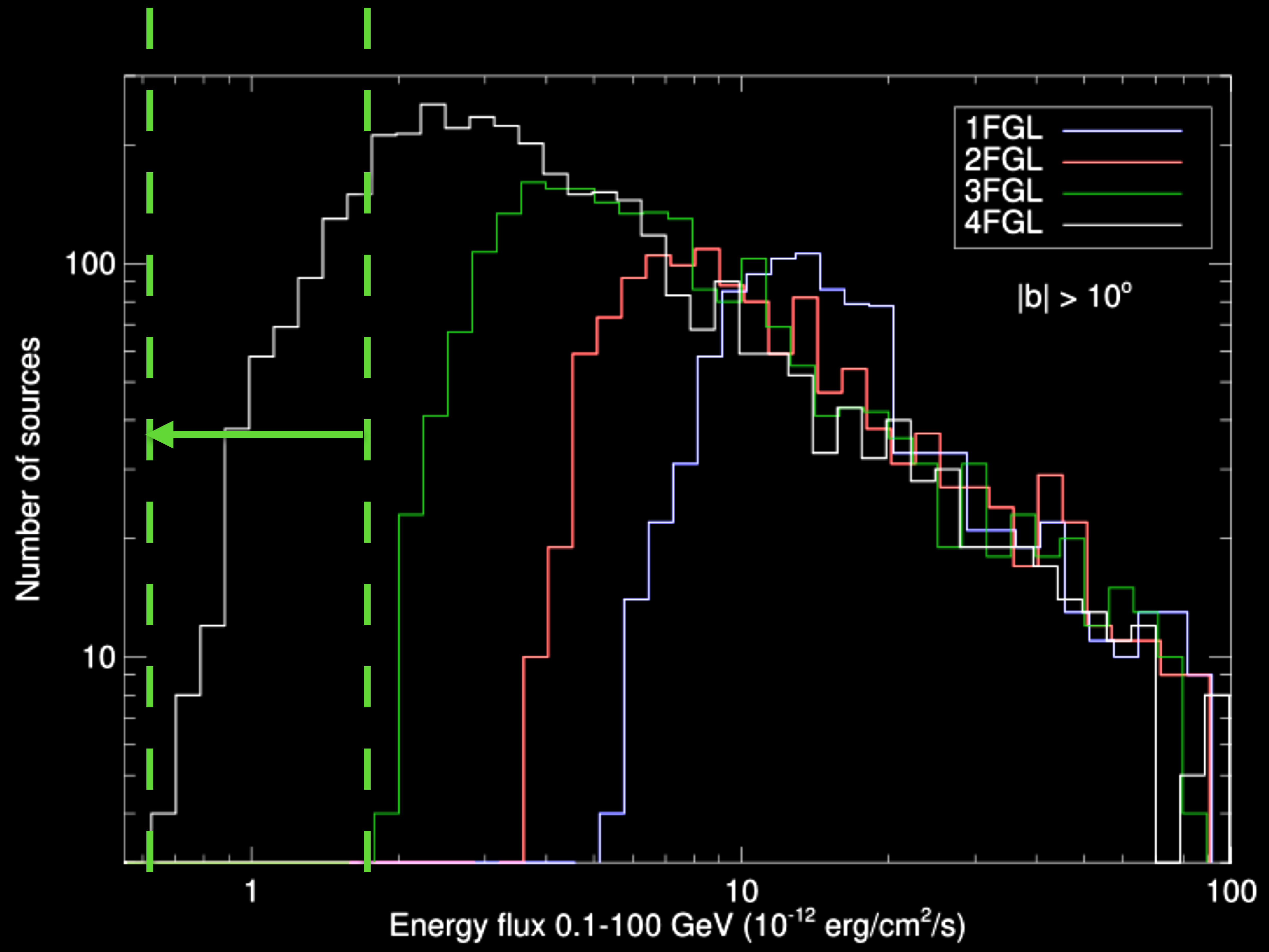
A new point source catalog: 4FGL

- Fermi-LAT collaboration released the 4th point source catalog in early 2019.
(Abdollahi+ ’19)

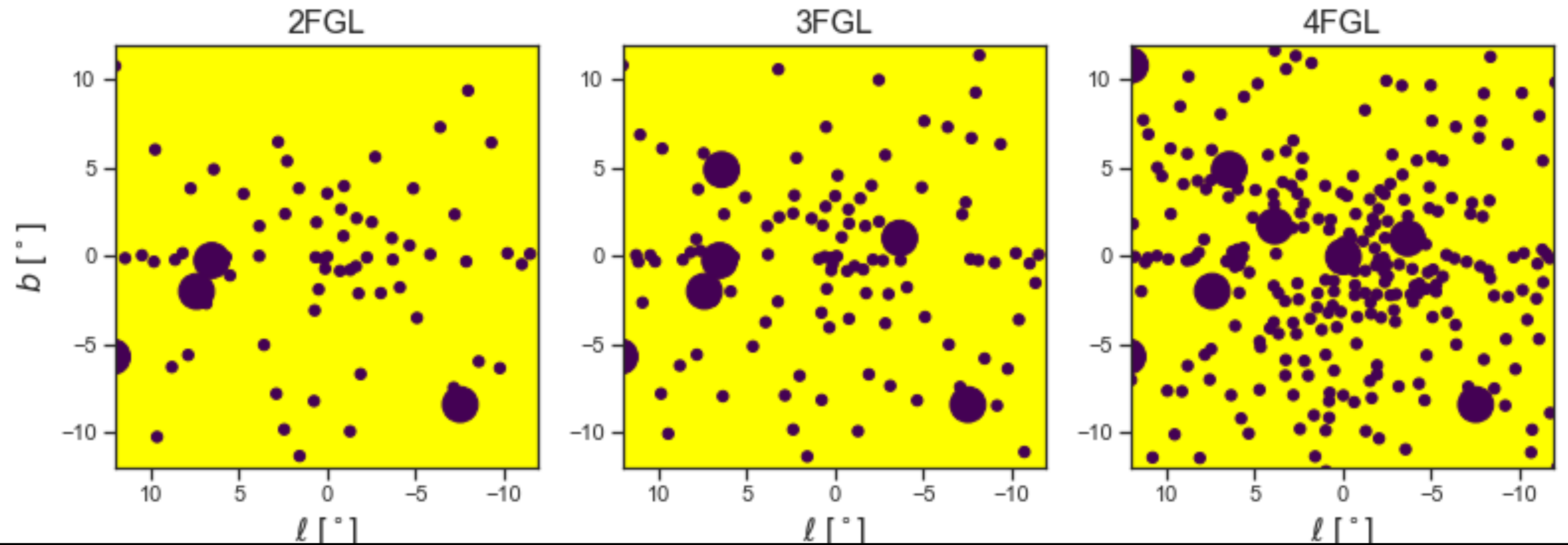
Catalog	Exposure	Date released
1FGL	1 year	2010
2FGL	2 year	2011
3FGL	4 year	2015
4FGL	8 year	2019

4FGL

- Classification, location, and spectrum information for all the point sources
- Compare to earlier catalogs:
    - More exposure
    - Lower energy flux threshold



More sources are identified



12° around the Galactic center

Given the newly released data

1. Is GCE still there?

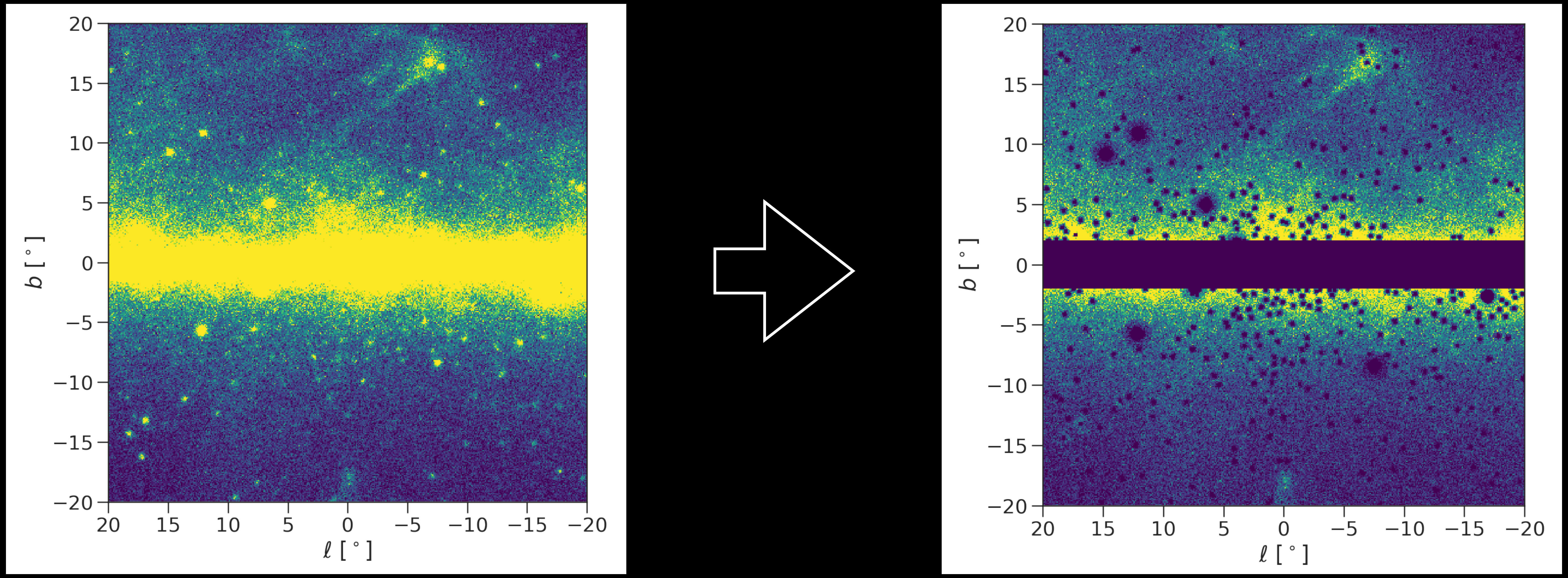
2. Are MSPs still in favor in small-scale power analysis?

1

Is GCE still there?

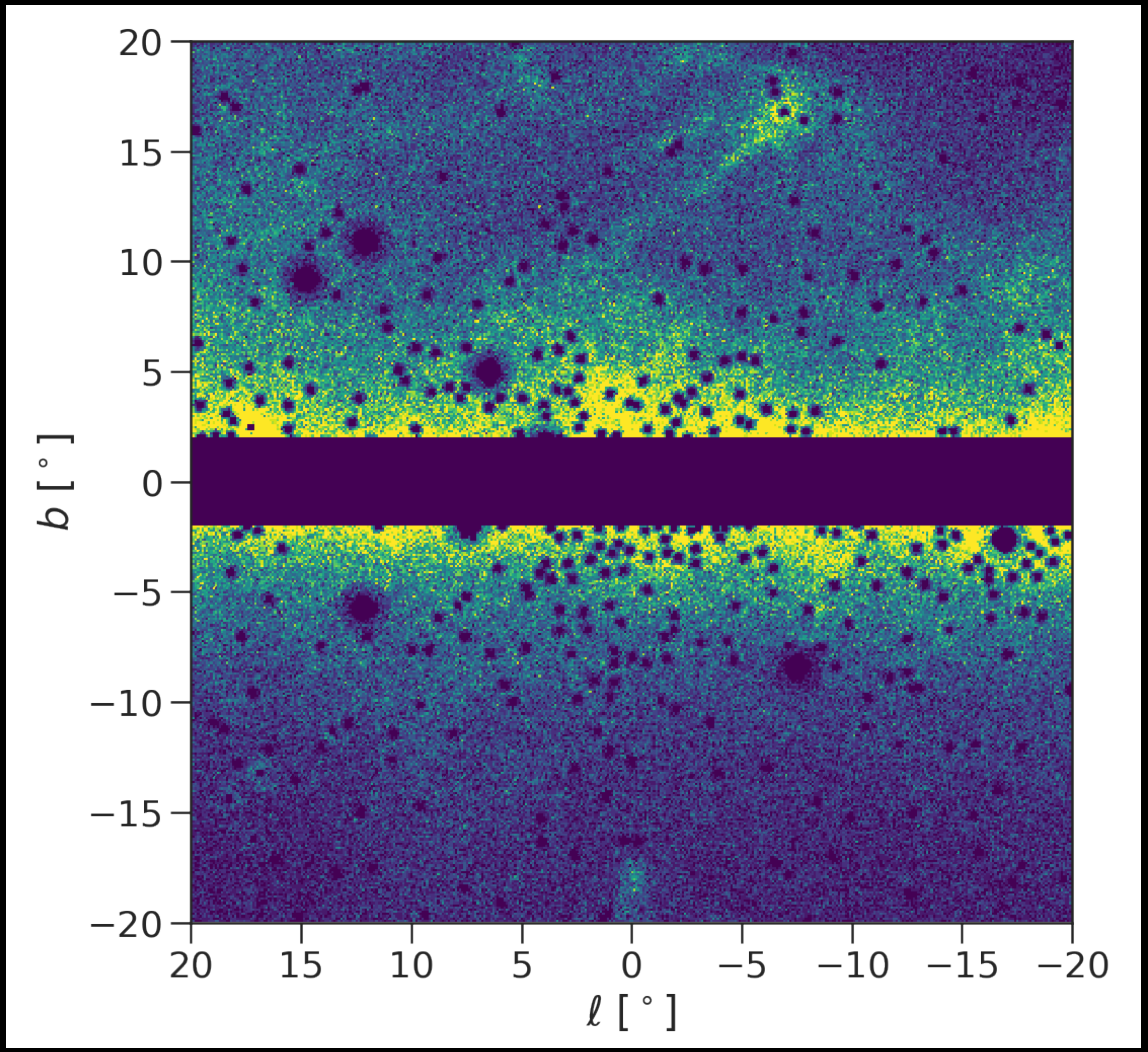
4FGL & the GCE energy spectrum

- To study the GCE spectrum, the pt sources (and the Galactic disk) are usually masked out because they are difficult to model.
- Is there still a GCE after masking out 4FGL point sources?



Template fitting

Fermi data [**11 years of obs.**]
masking 4FGL + disk

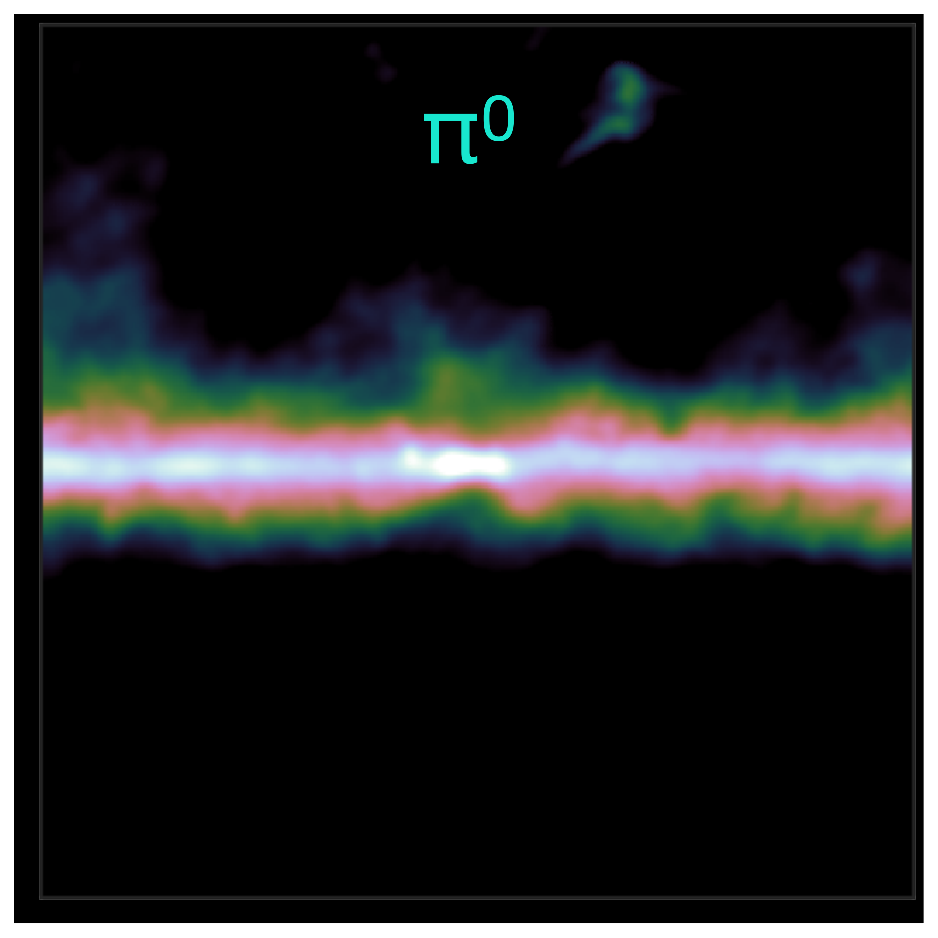


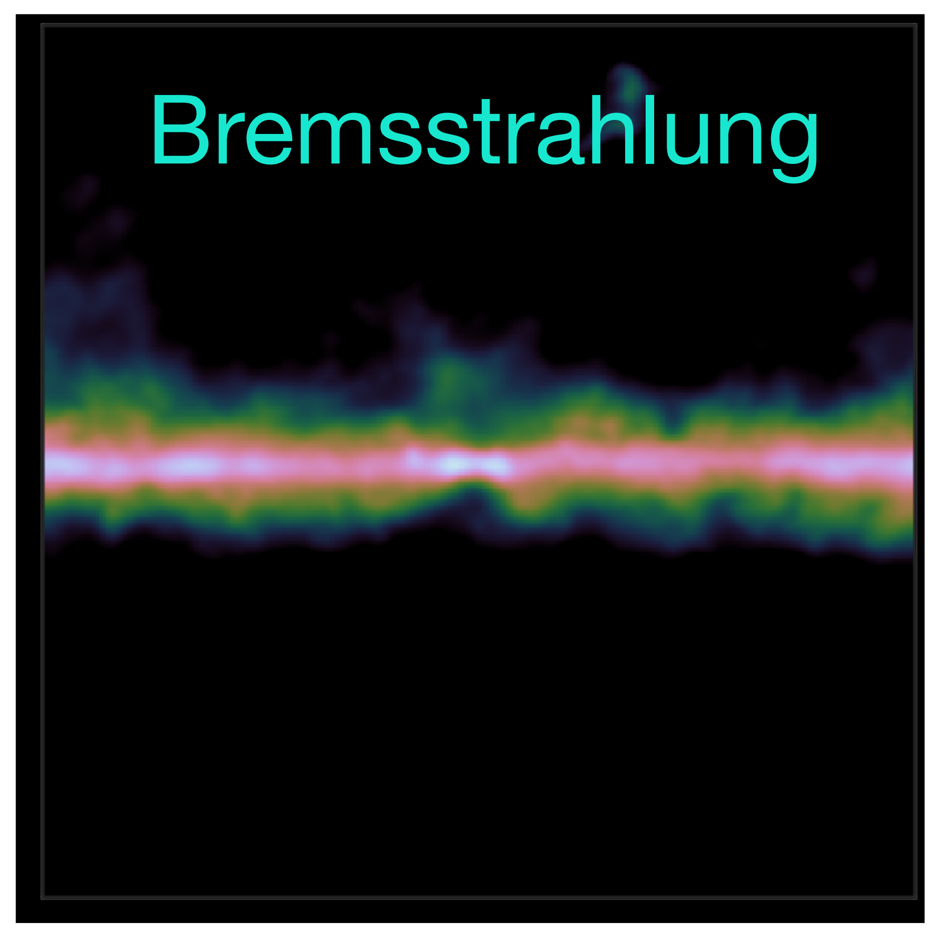
vs.

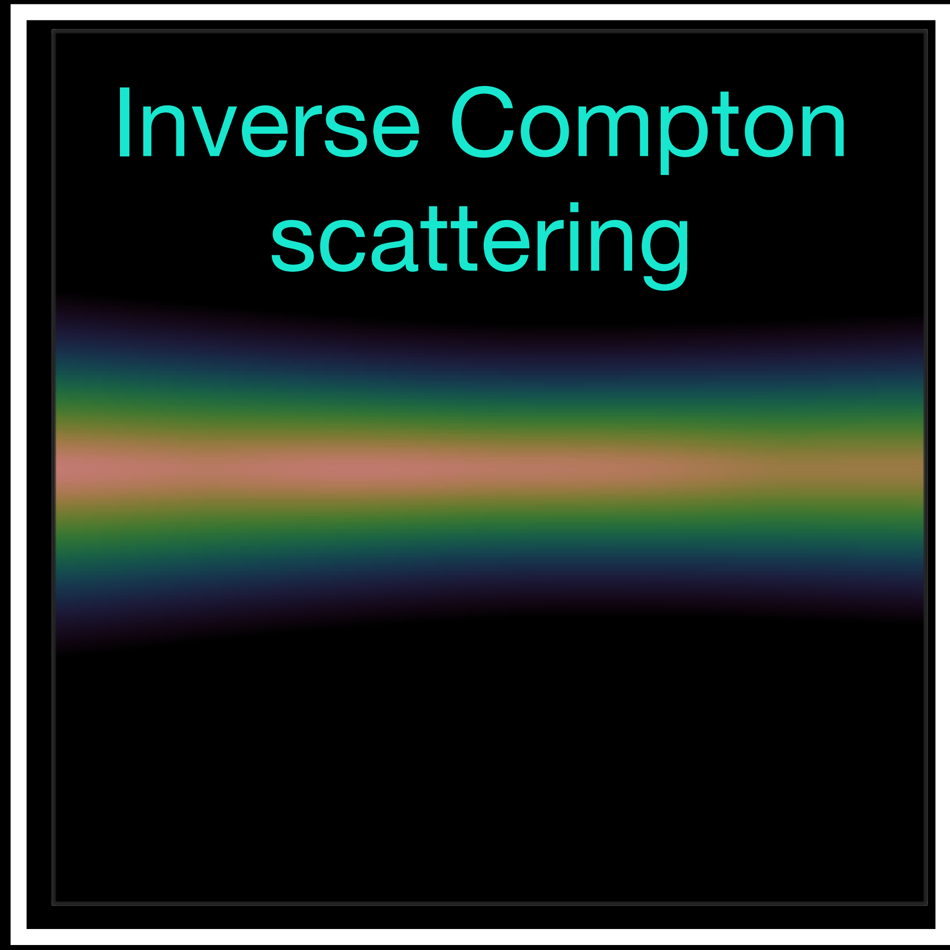
Templates for foregrounds
+
Template for GCE

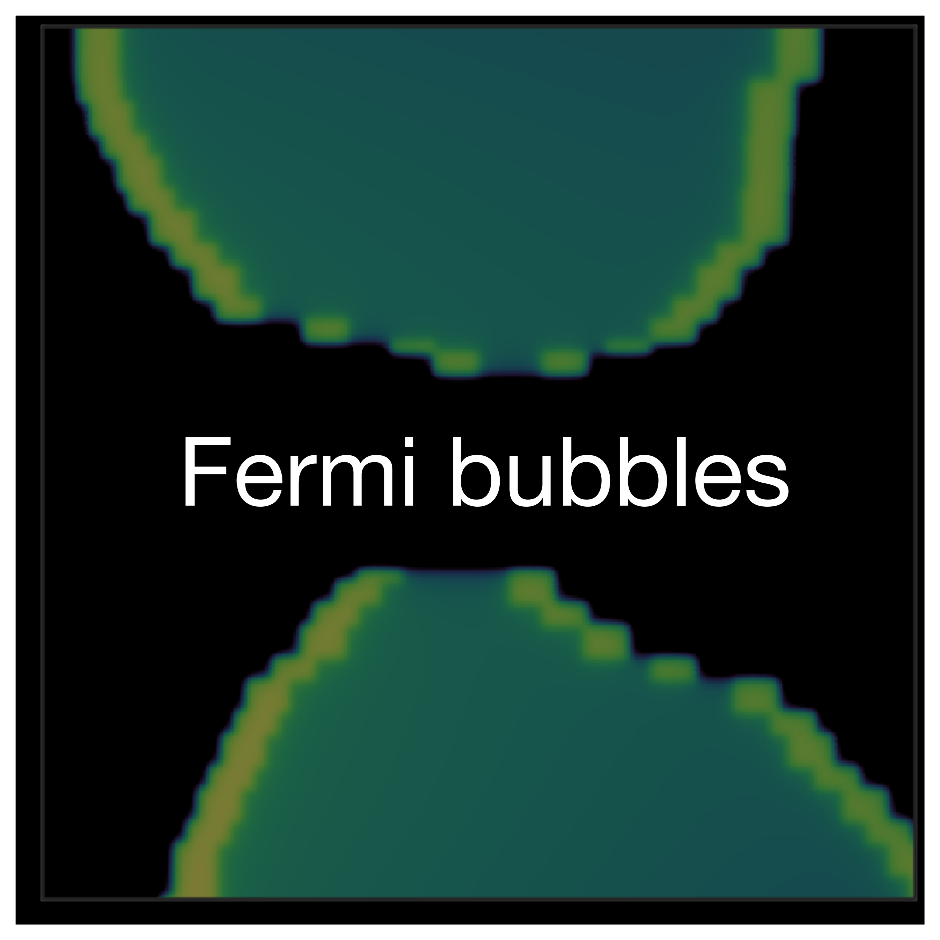
Templates

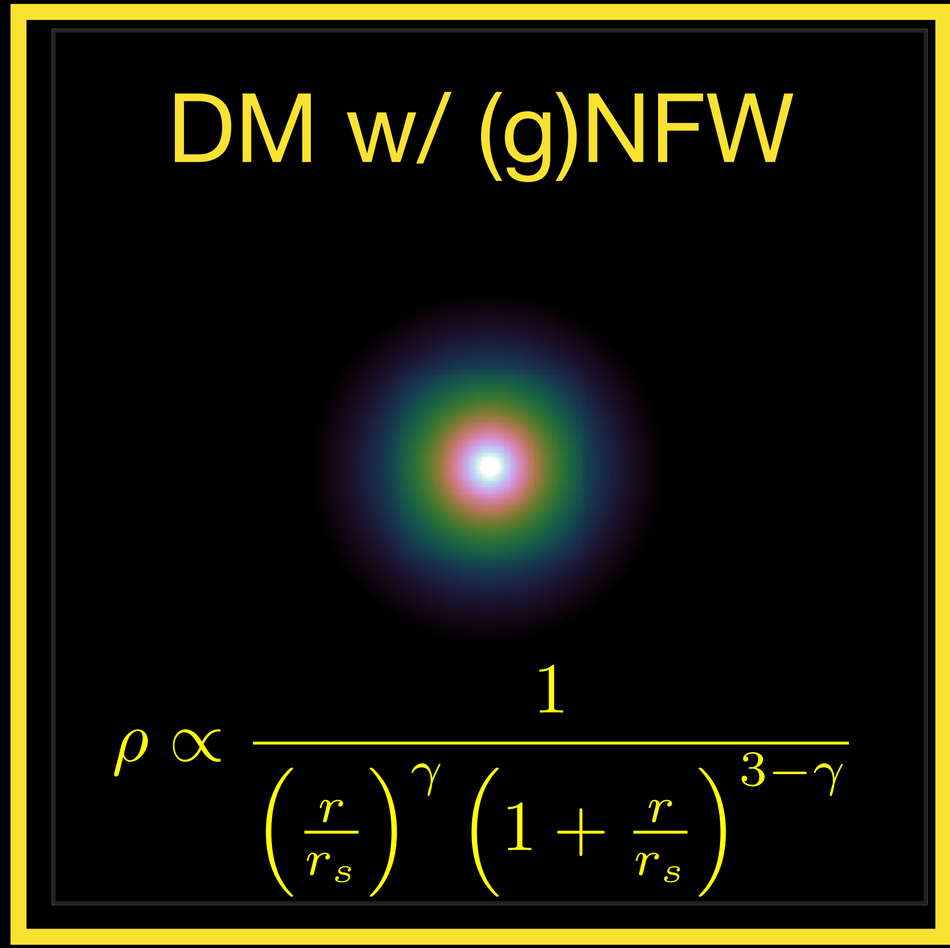
Use Model A from Calore+ '15
for the diffuse γ-ray emission



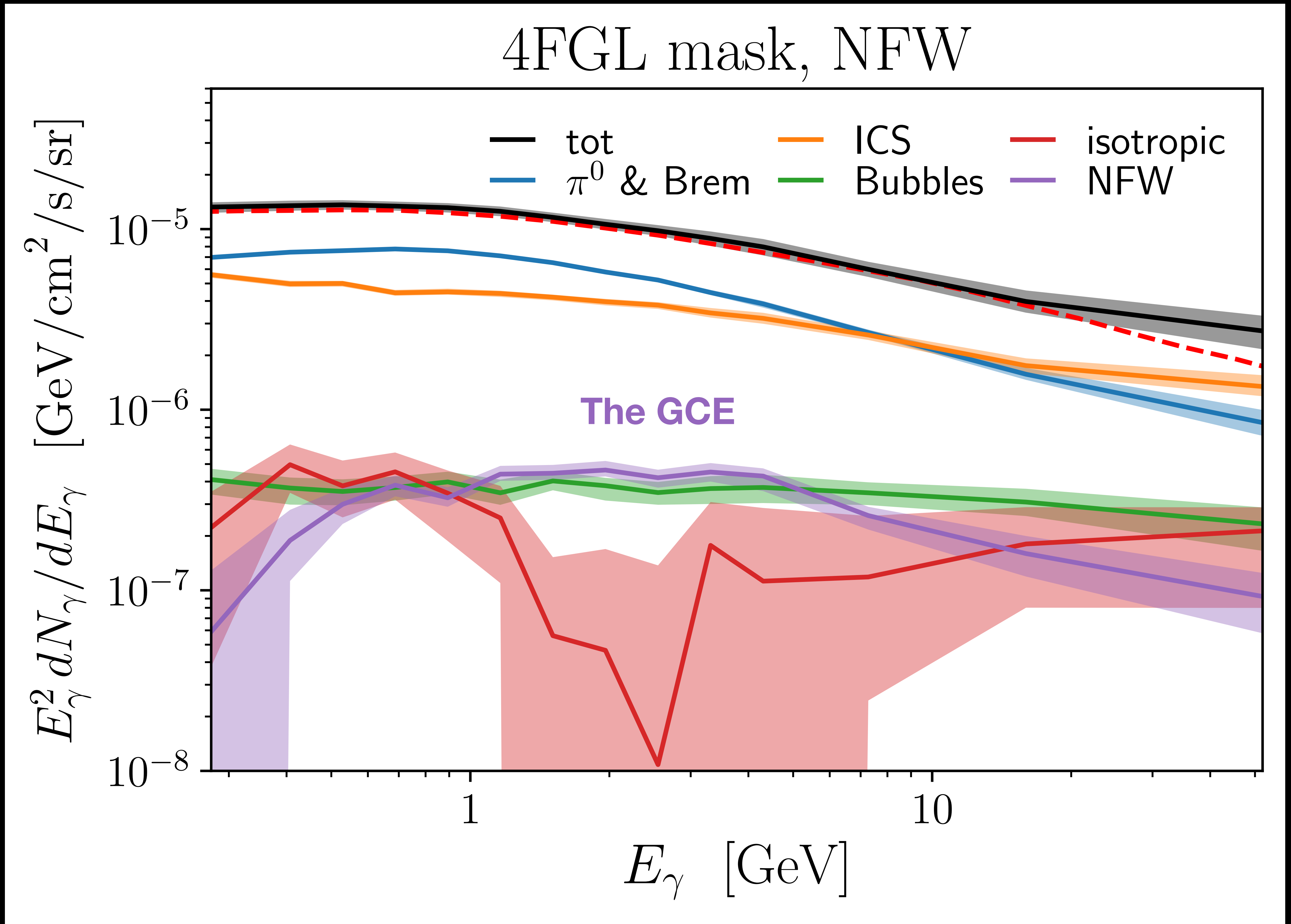








The GCE is still there



$$\rho \propto \frac{1}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2} \qquad \rho \propto \frac{1}{\left(\frac{r}{r_s}\right)^{1.2}\left(1+\frac{r}{r_s}\right)^{1.8}}$$

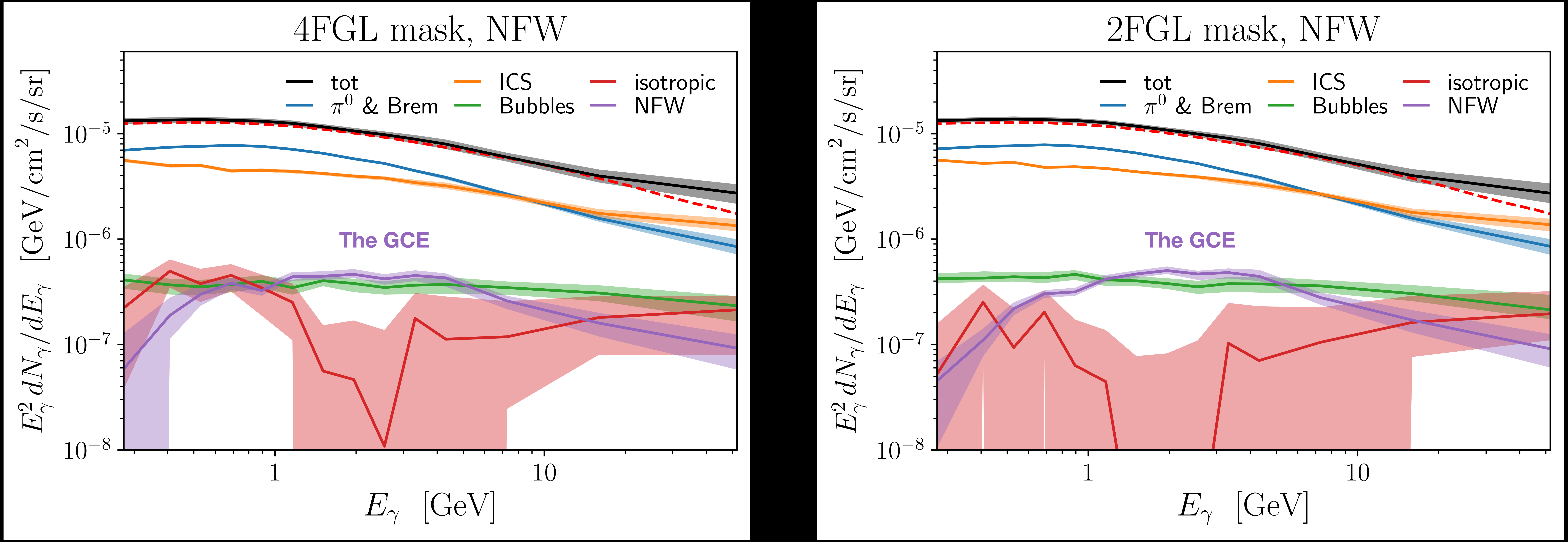
TABLE I. Difference in $-2\ln\lambda$ (lower numbers are better) at the best fit points of each model, summed over energy bins, compared to our best fit for each mask.

Type of Mask	NFW	gNFW	no excess
2FGL	0	476	5430
4FGL	0	368	3600

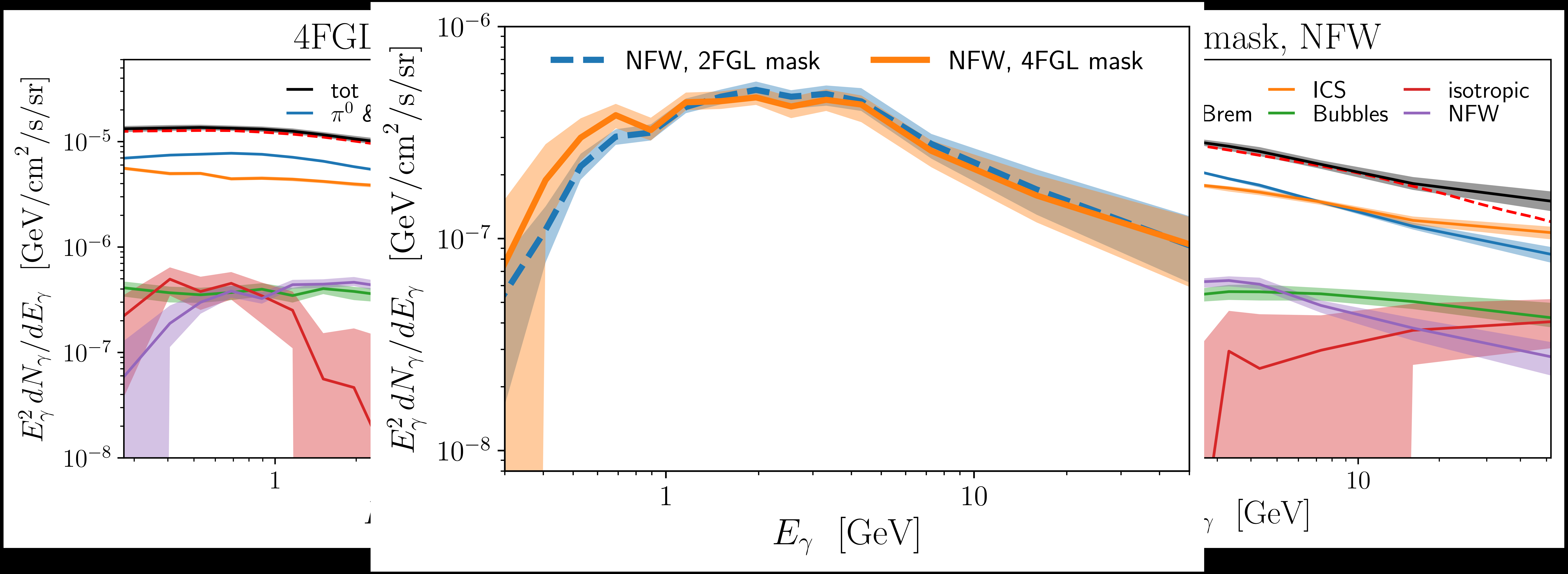
Less positive
⇒ Better fit

Best fit

The GCE spectrum is almost unchanged



The GCE spectrum is almost unchanged

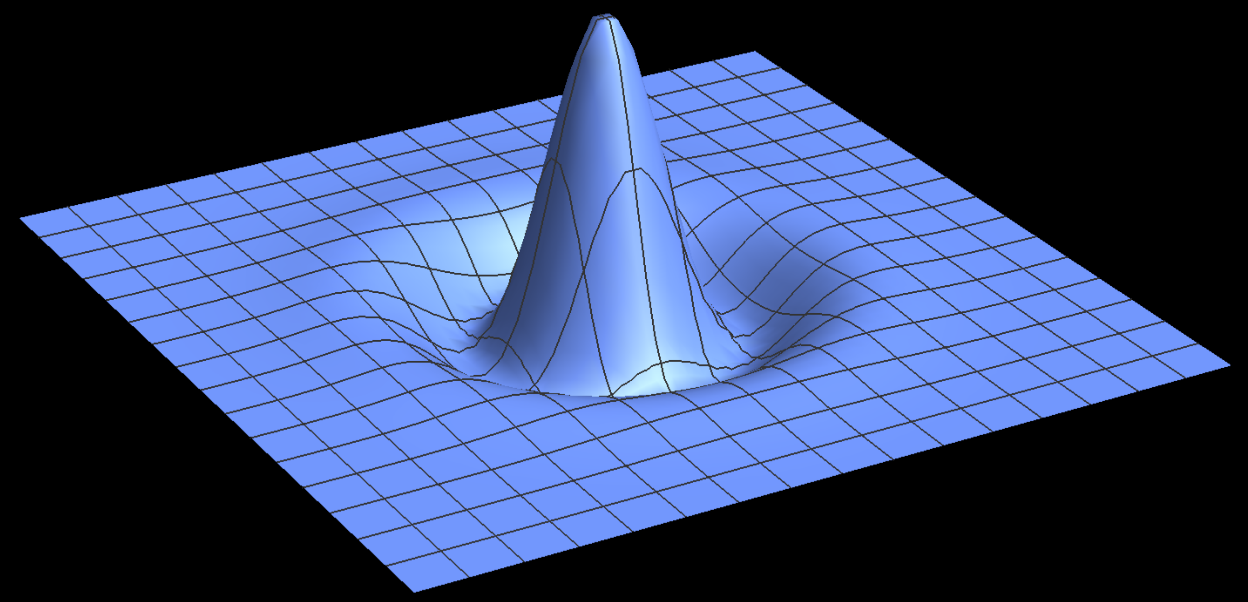


2

Are MSPs still in favor in small-scale power analysis?

2D continuous wavelet

- Decompose signal in terms of wavelets that has special scaling properties
- Effective method to decompose information to different scales
- Used in the analysis of solar astronomy, Cosmic Microwave Background, GCE, etc.
- 2D continuous wavelet ⇒ an effective match-filter

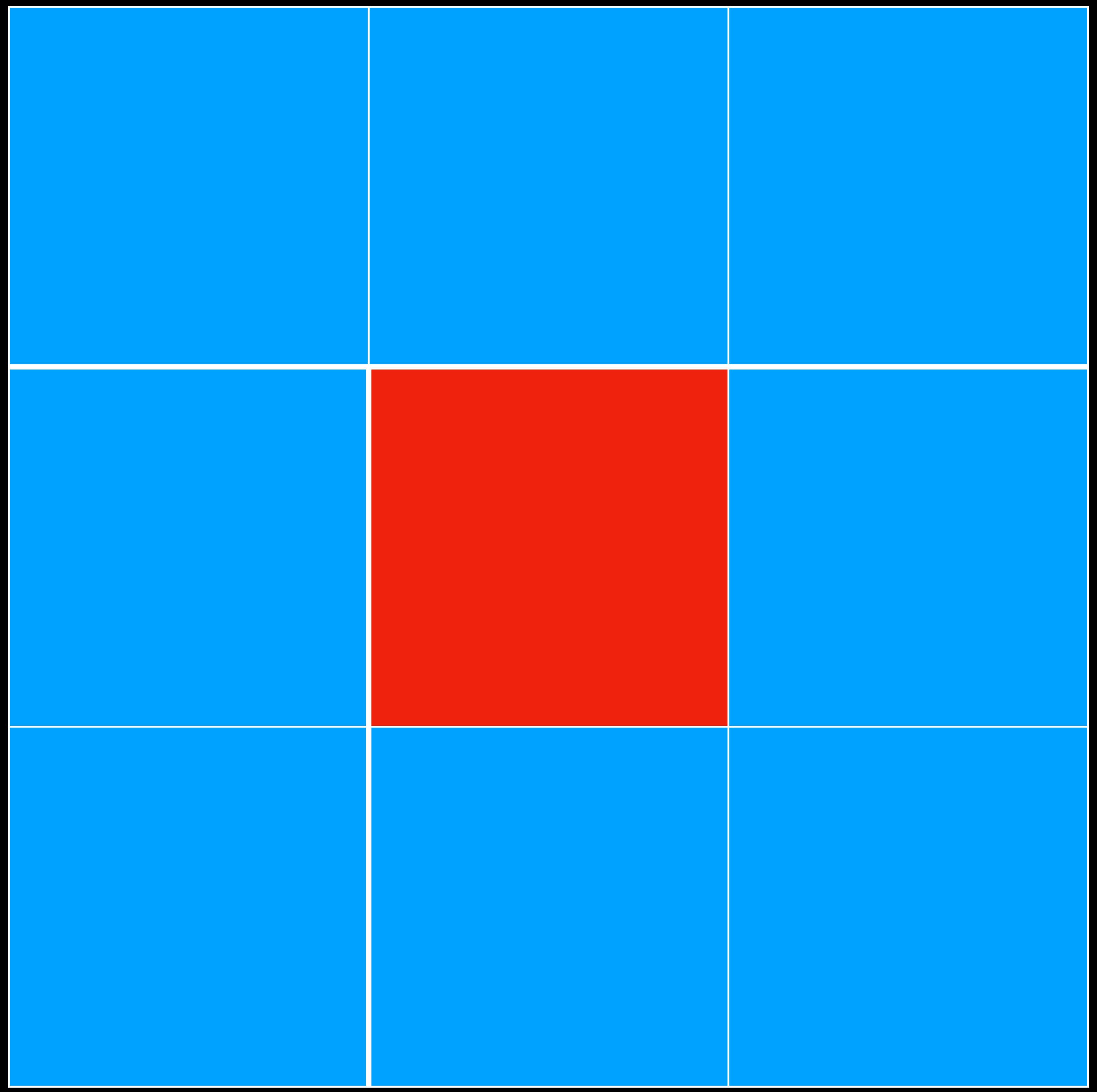


Antoine+ ’19, Balaji+ ‘18

What is a matched filter?

Δ

Laplacian operator



Testing the small-scale power w/ wavelet

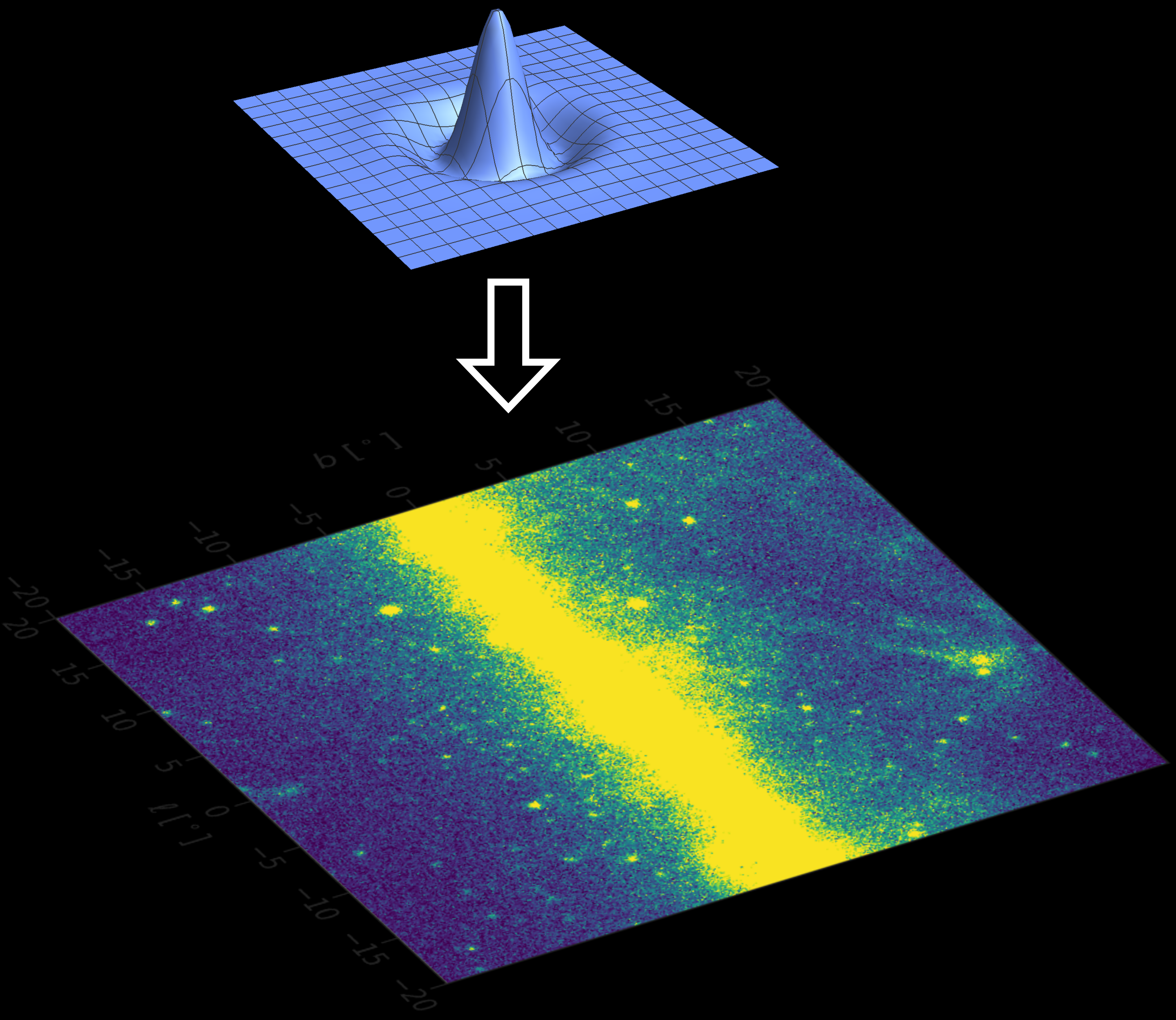
2nd member of the
Mexican Hat Wavelet Family (*M*₂)

$$\Delta^2 e^{-\frac{r^2}{2\sigma^2}}$$

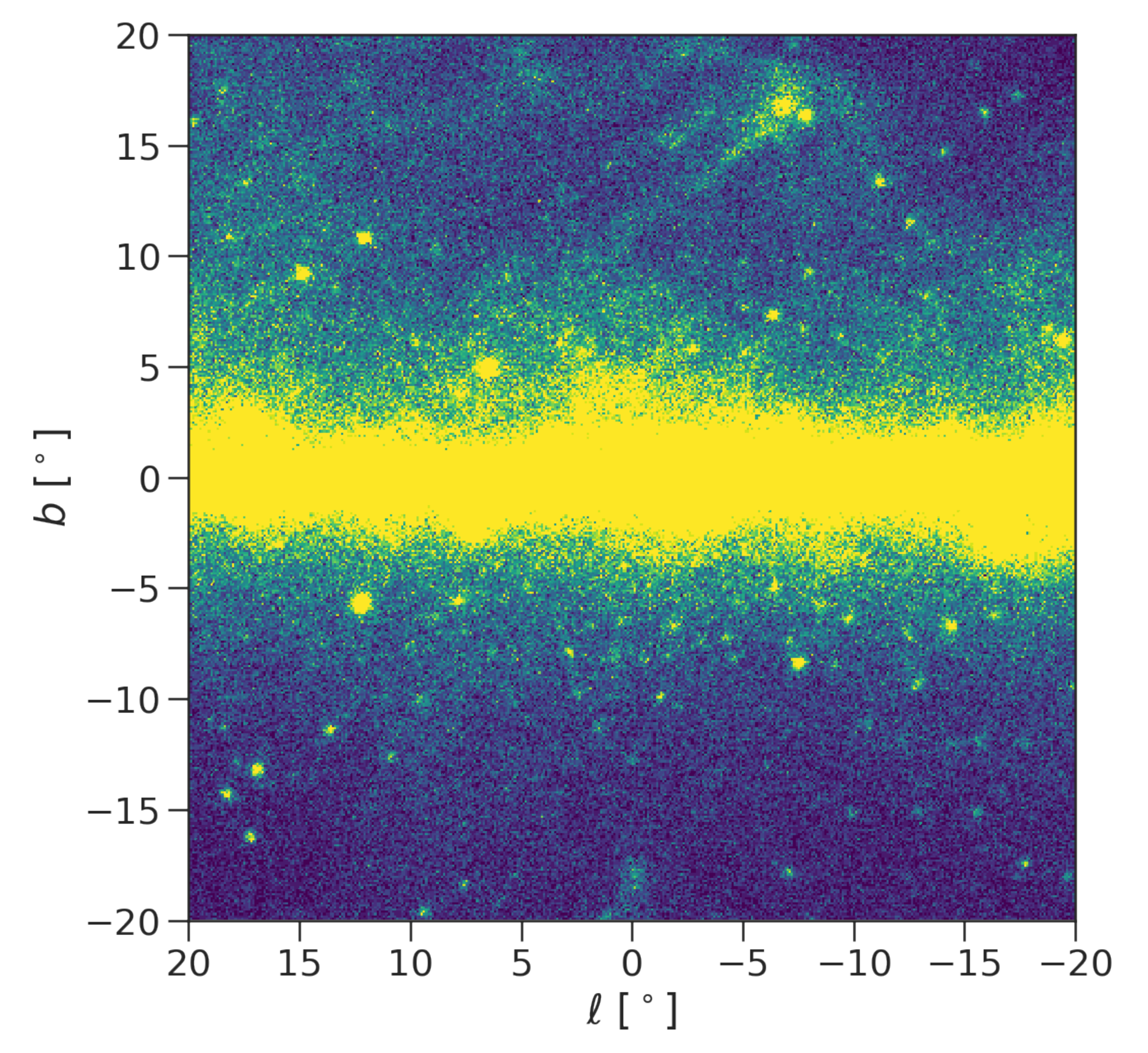
← Pixel distance

← Tele. resolution

Fermi data around the peak energy
of GCE (*C*)

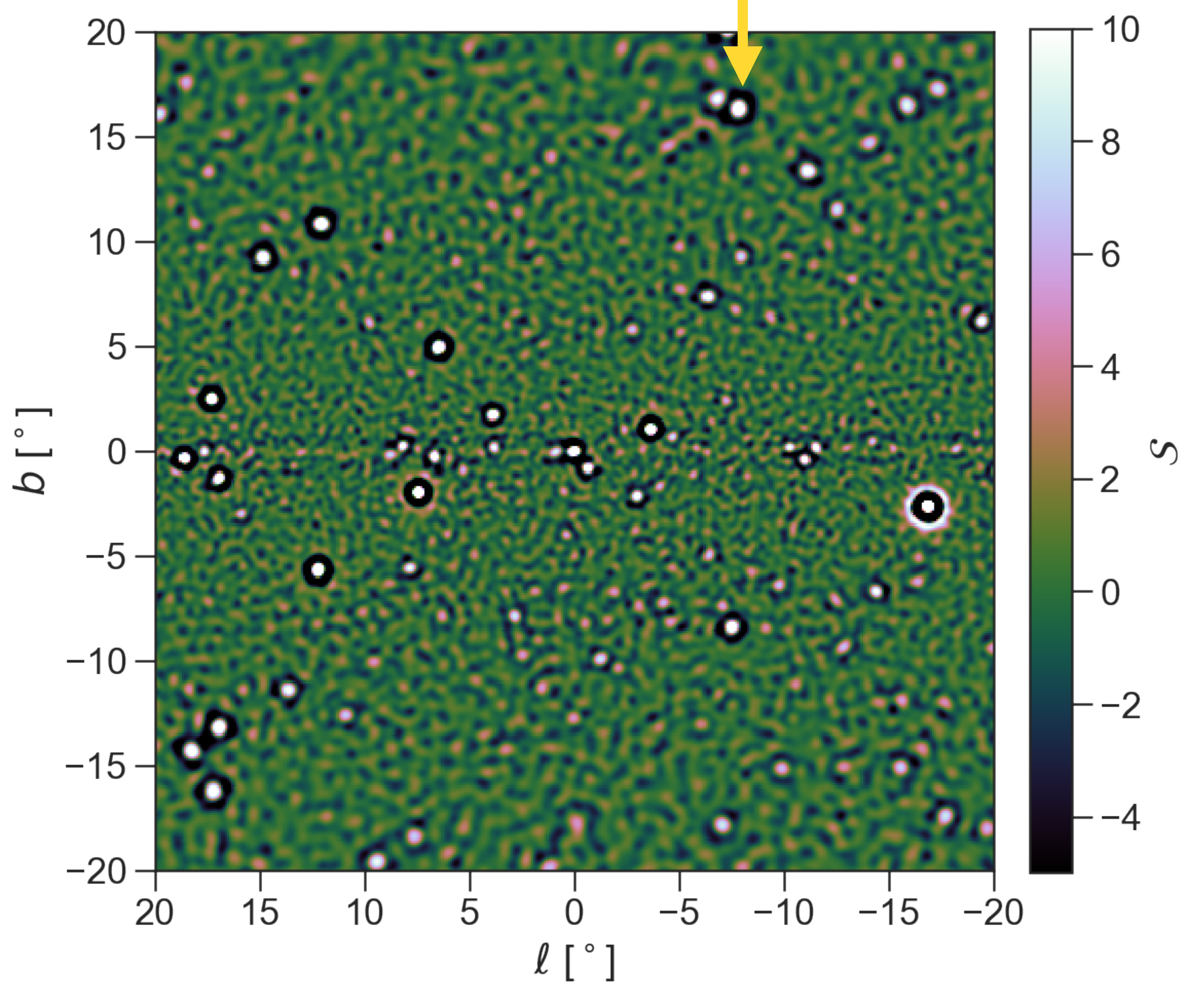


GC under wavelet



$$\mathcal{S} = \frac{M_2 \circledast \mathcal{C}}{\sqrt{M_2^2 \circledast \mathcal{C}}}$$

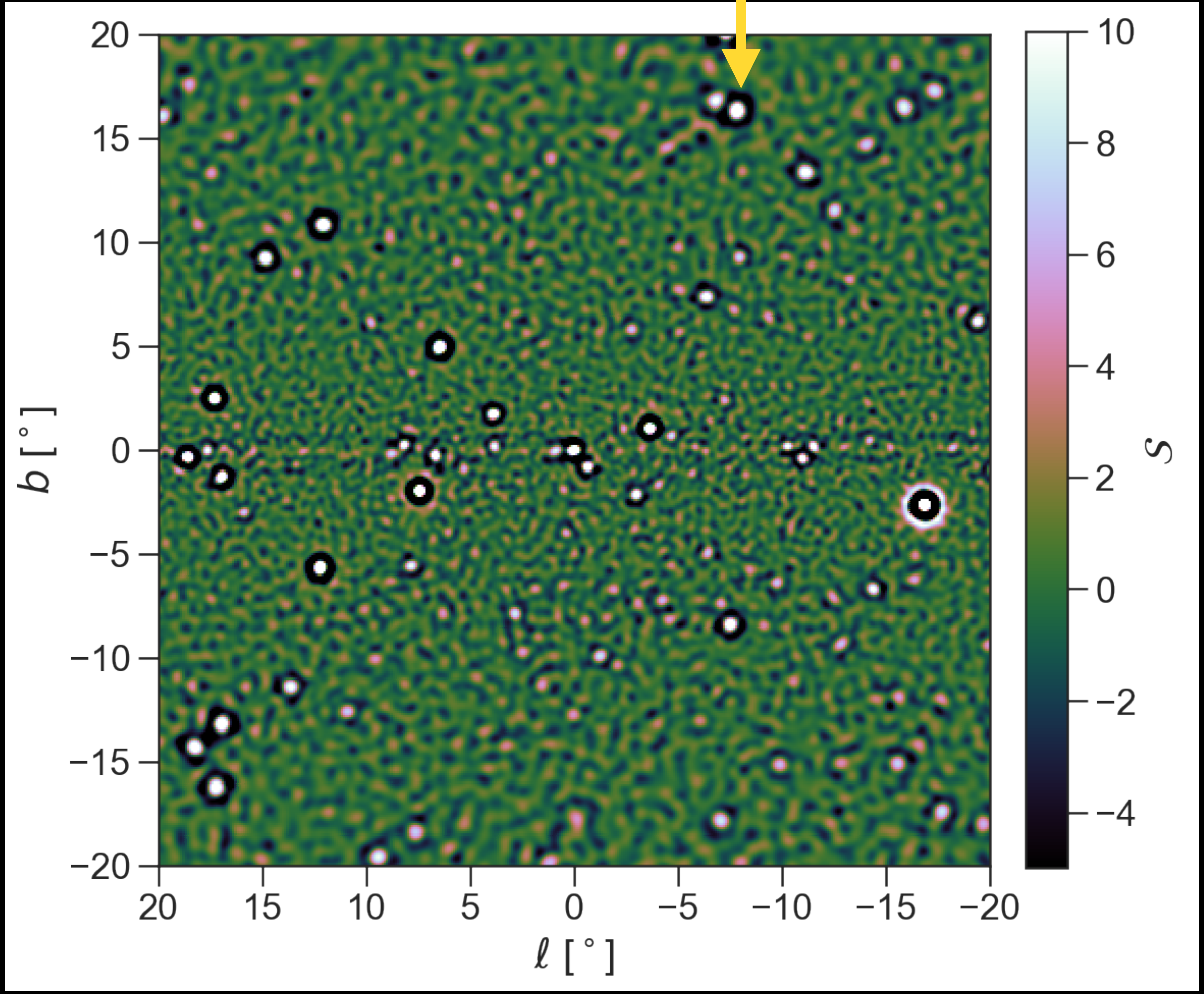
Peak



GC under wavelet

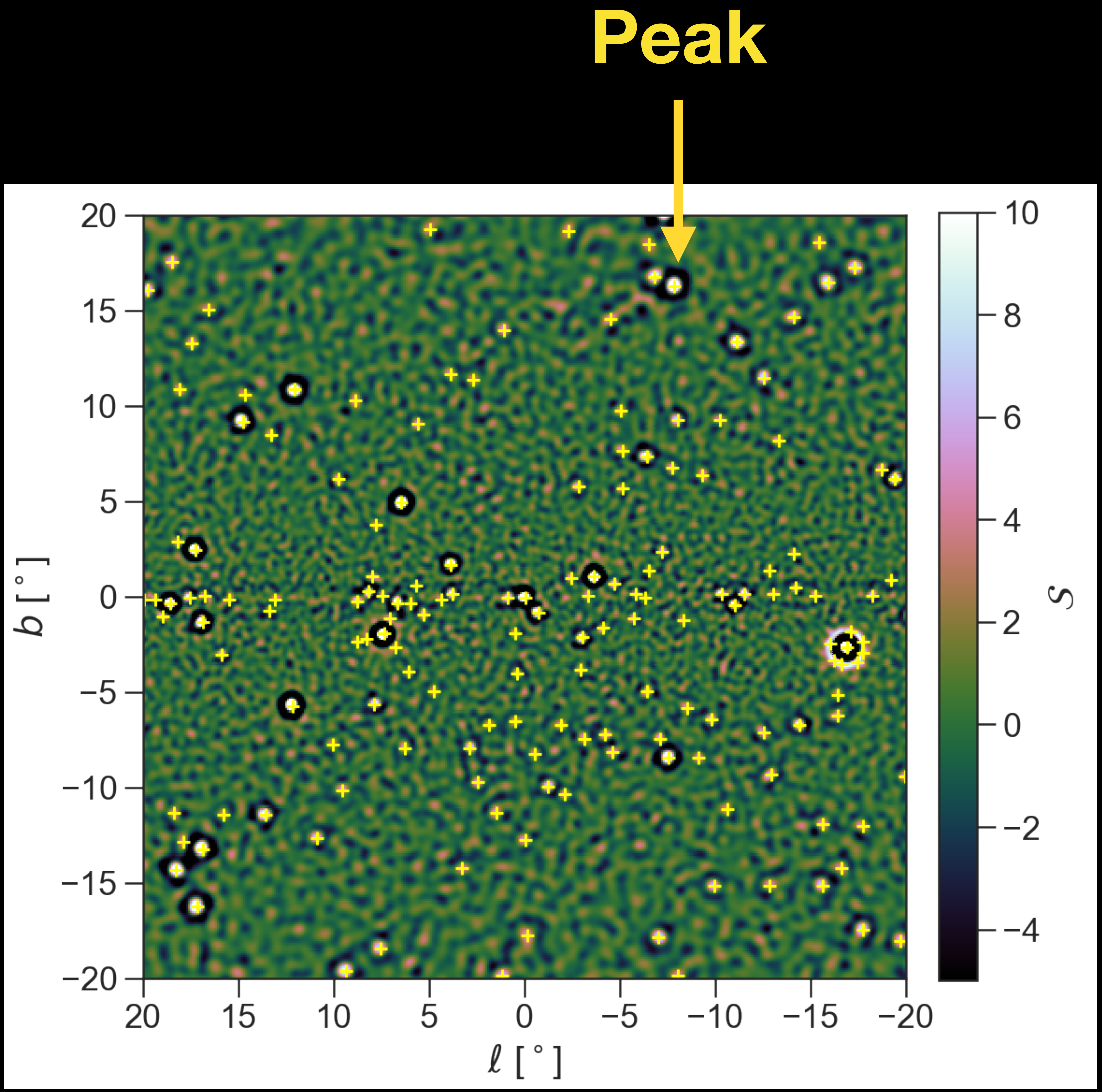
- By testing the templates, we found many of the peaks are from diffused emission foreground.
- But we found peaks with S > 4 (white colored) cannot be produced by the diffuse γ-ray emission.

Peak



GC under wavelet

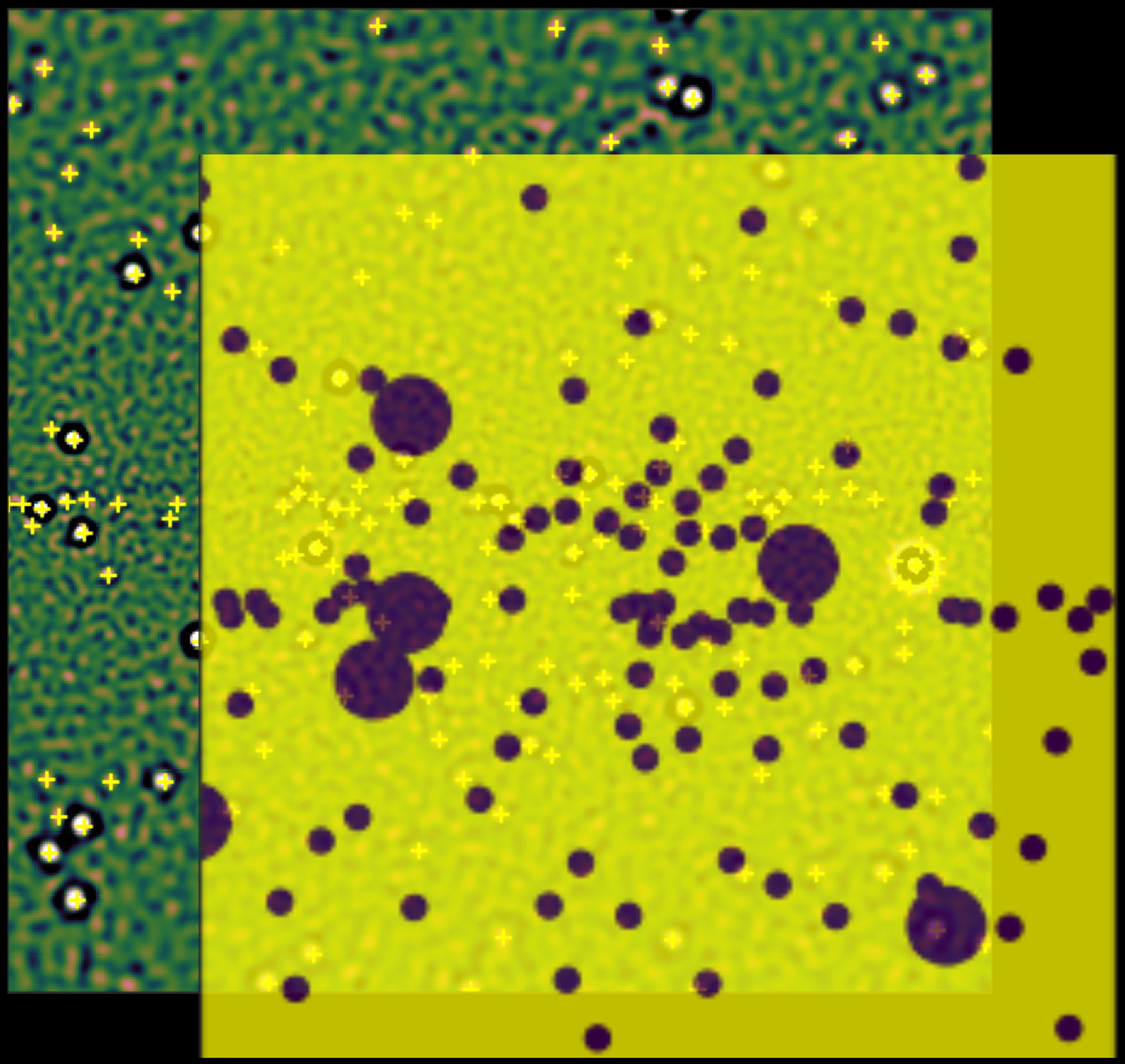
- There are 117 peaks with S > 4 (marked w/ yellow cross).
- What are those peaks?



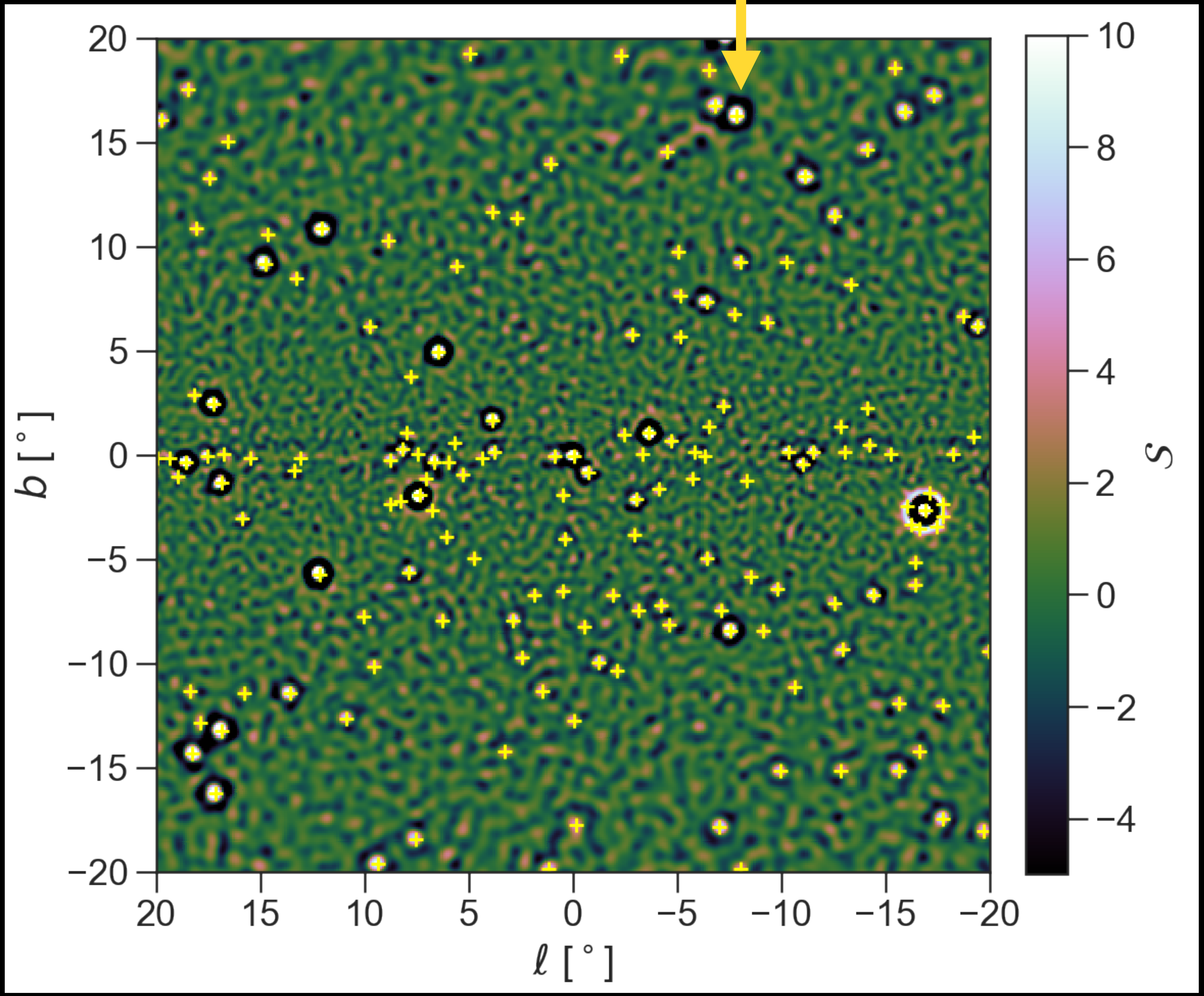
What are those peaks w/ high S?

Peak

- Bartels+ ’16 thought they are all millisecond pulsars.

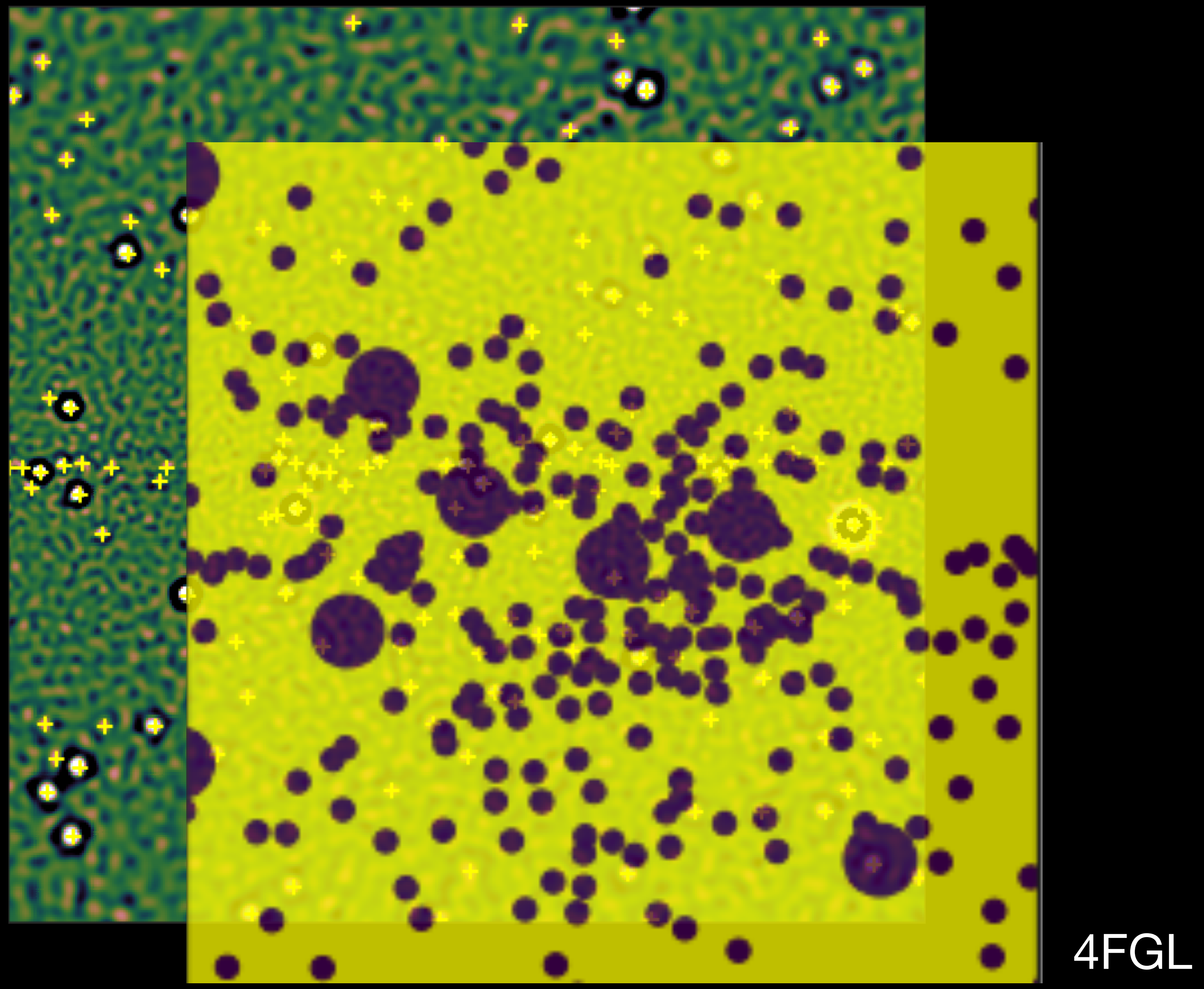


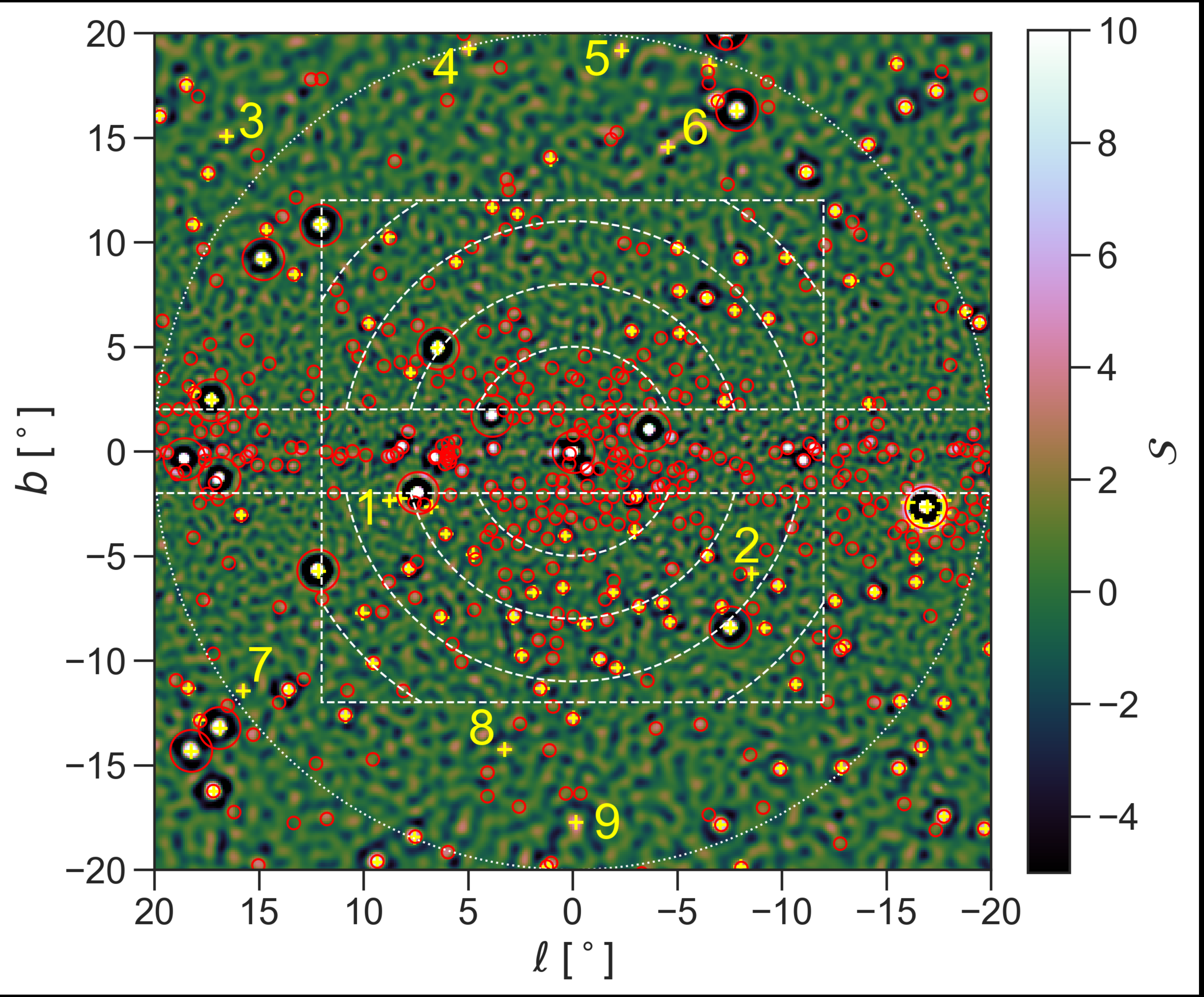
3FGL



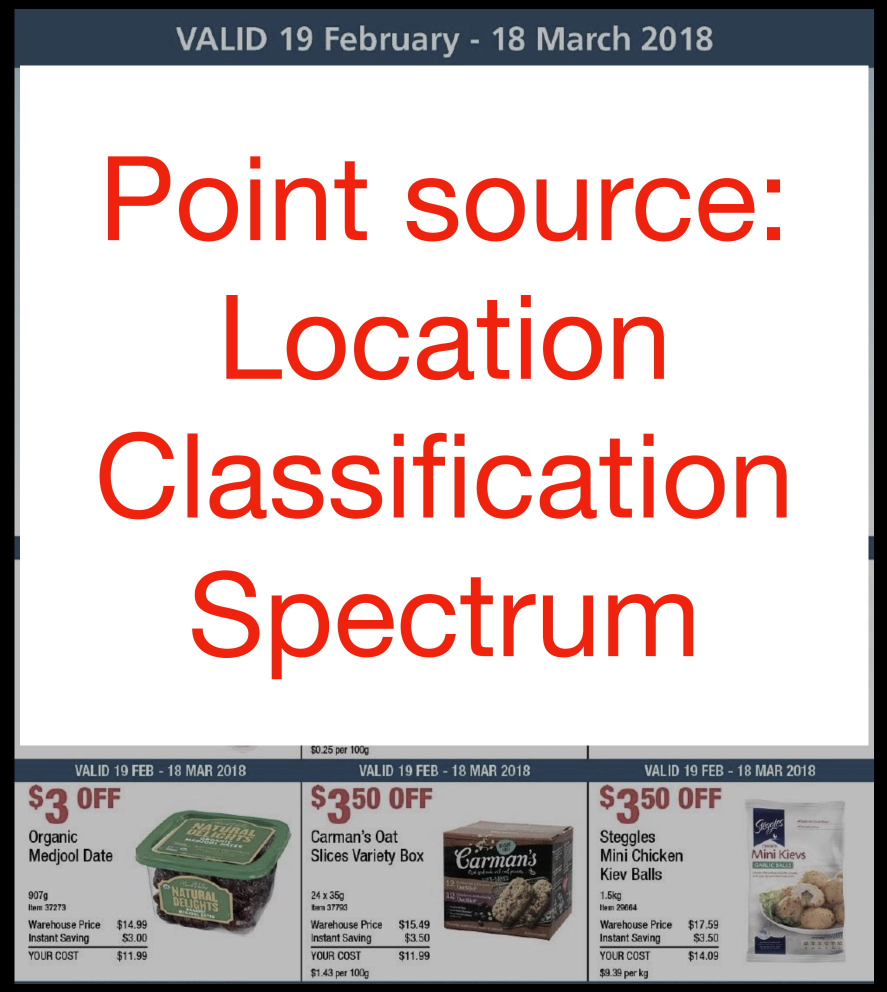
What are those peaks with high S?

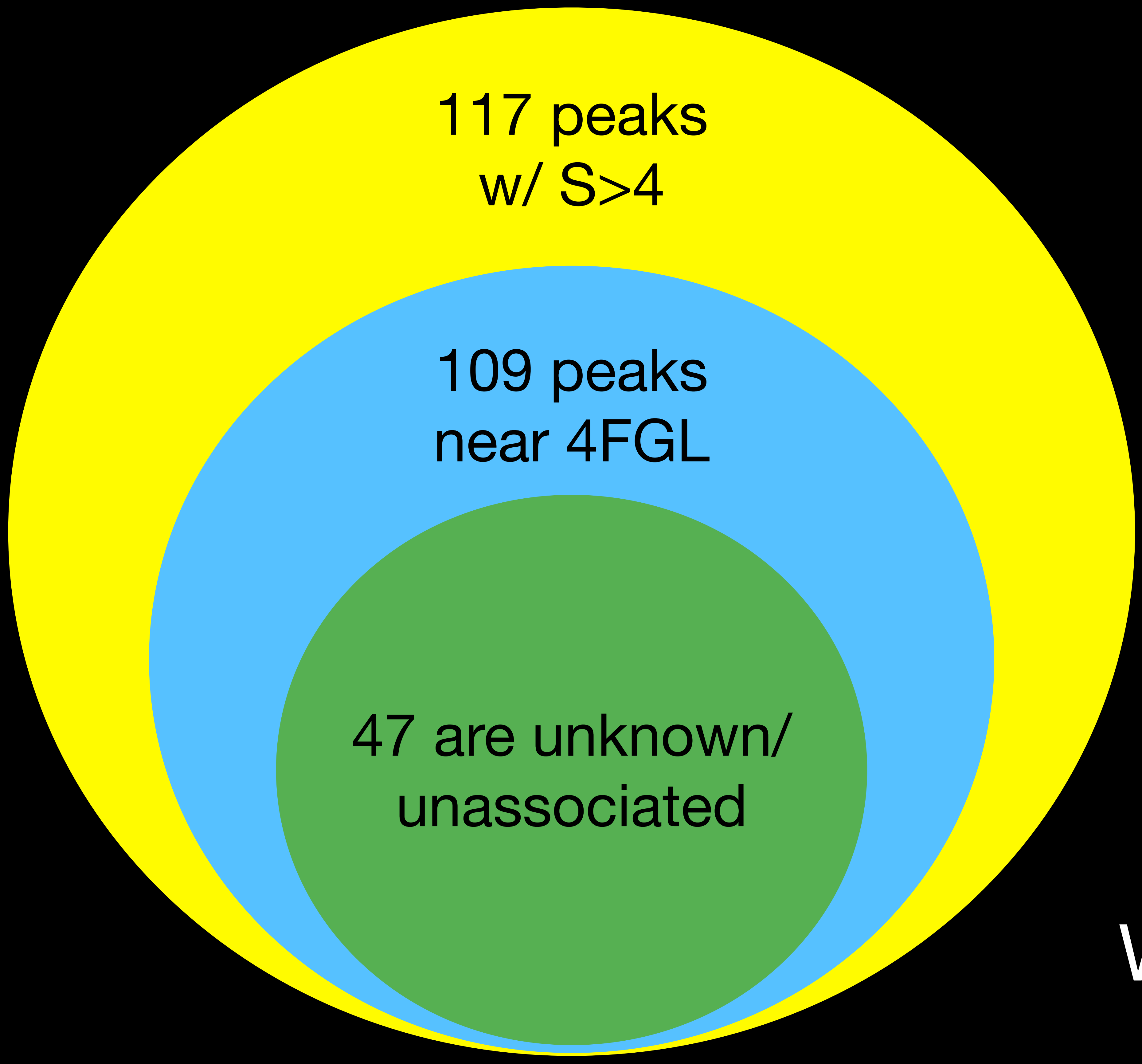
- We found most of peaks w/ S>4 are associated w/ pt sources in the 4FGL catalog (red circles).





What are those peaks with high S?



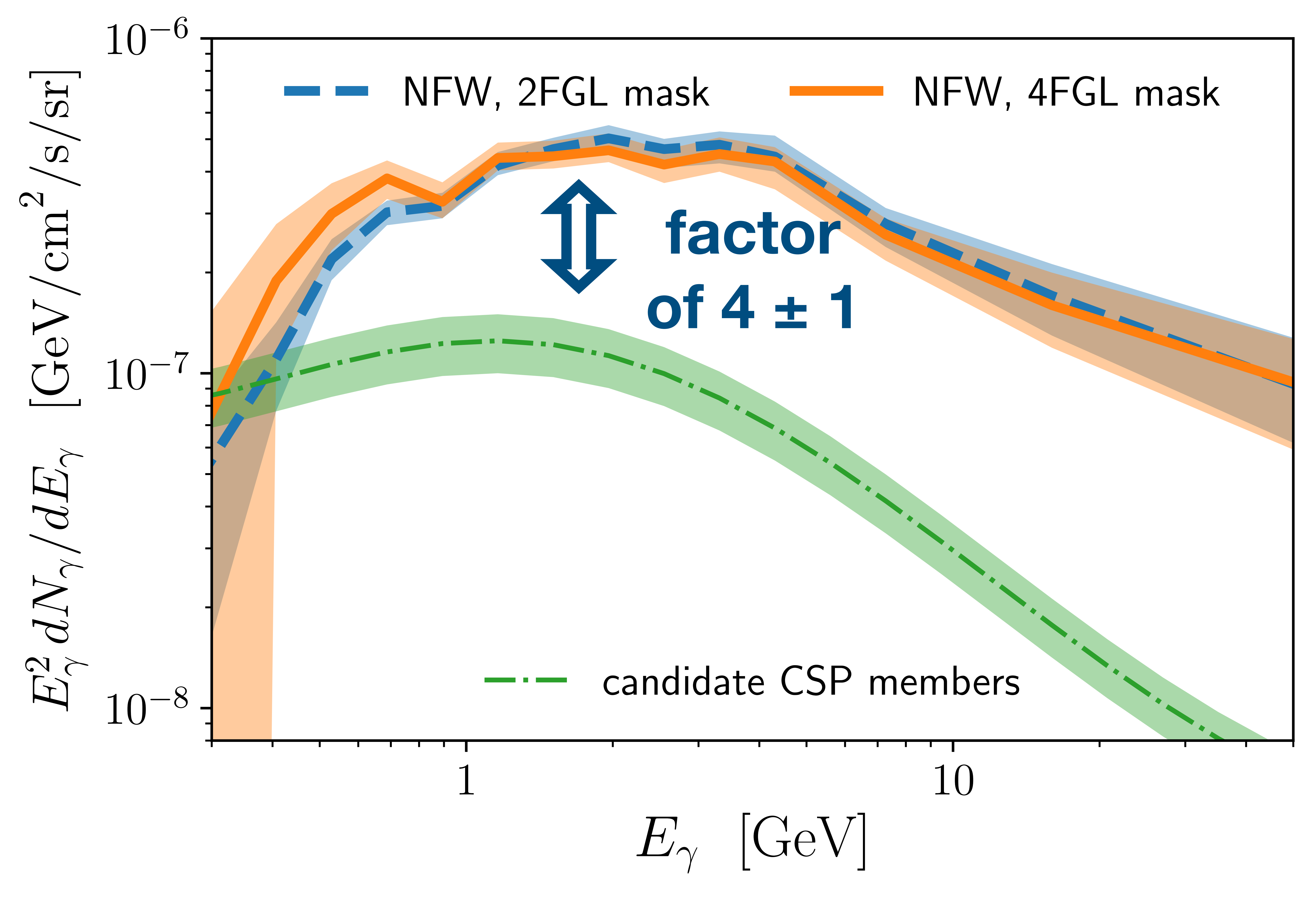


We have access to all of those spectra in 4FGL!

Stacked spectra of the unknown pt sources

- Bright source contribute little to the GCE
- Need large contributions from sub-detection-threshold pt sources

$L_{\text{sub-thr}} / L_{\text{above-thr}} = 4 \pm 1$

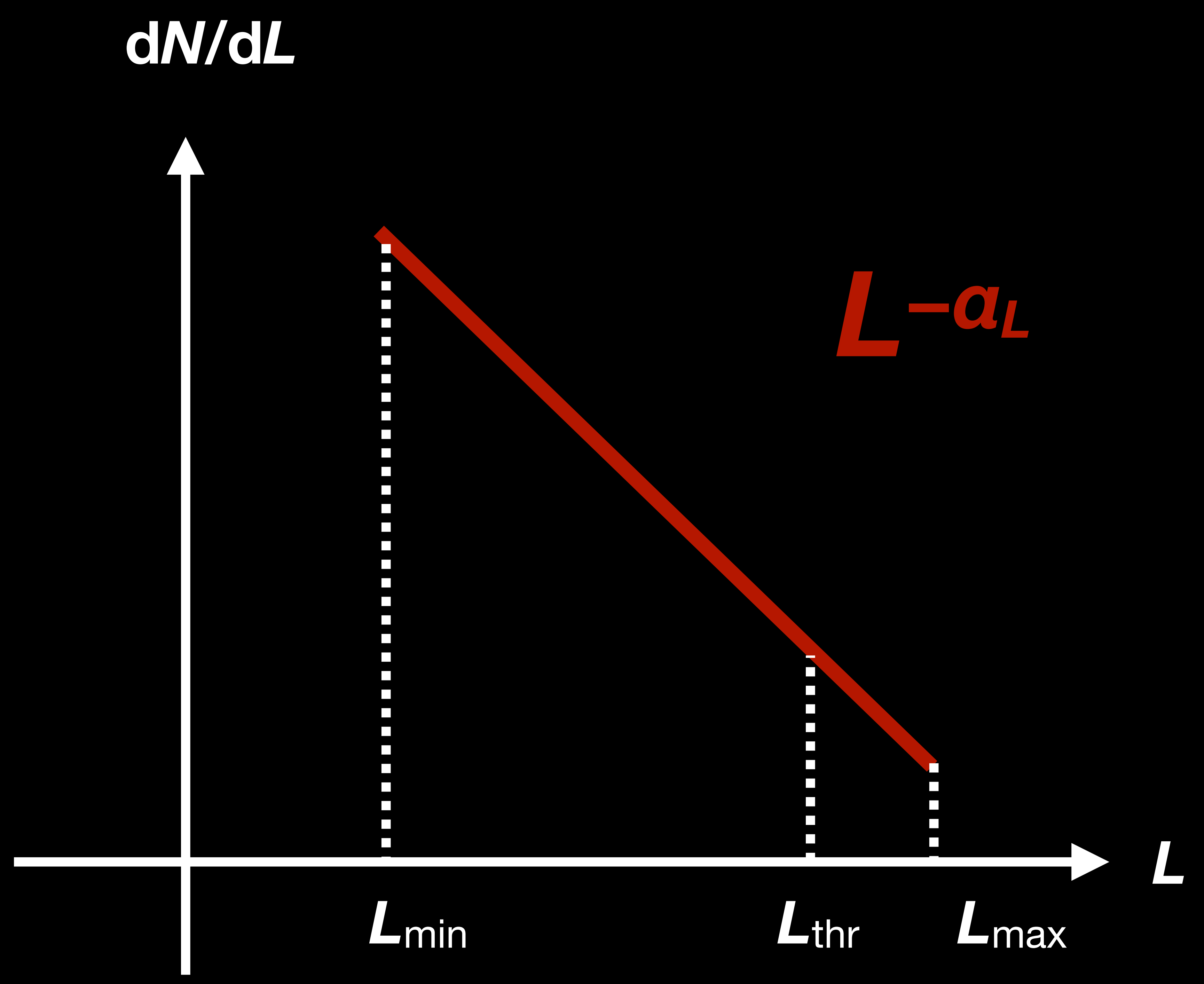


Constraining the luminosity functions

L_{min}: cosmic ray

L_{thr}: detection threshold

L_{max}: cosmic ray



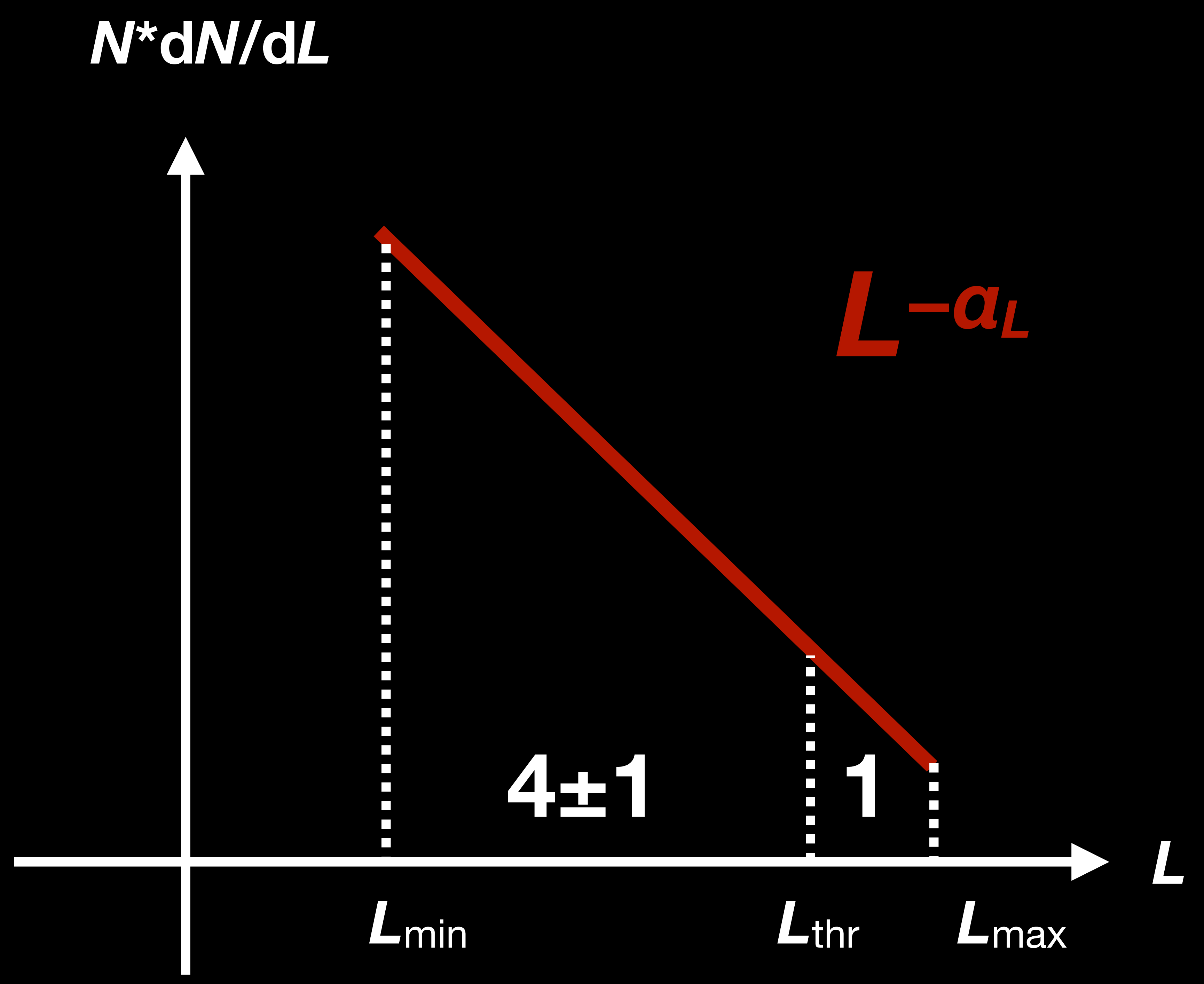
Constraining the luminosity functions

$L_{\rm min} \sim 10^{29}$ erg/s

$L_{\rm thr} \sim 10^{34}$ erg/s

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

$\Rightarrow \alpha_L \sim 1.96 \pm 0.04$

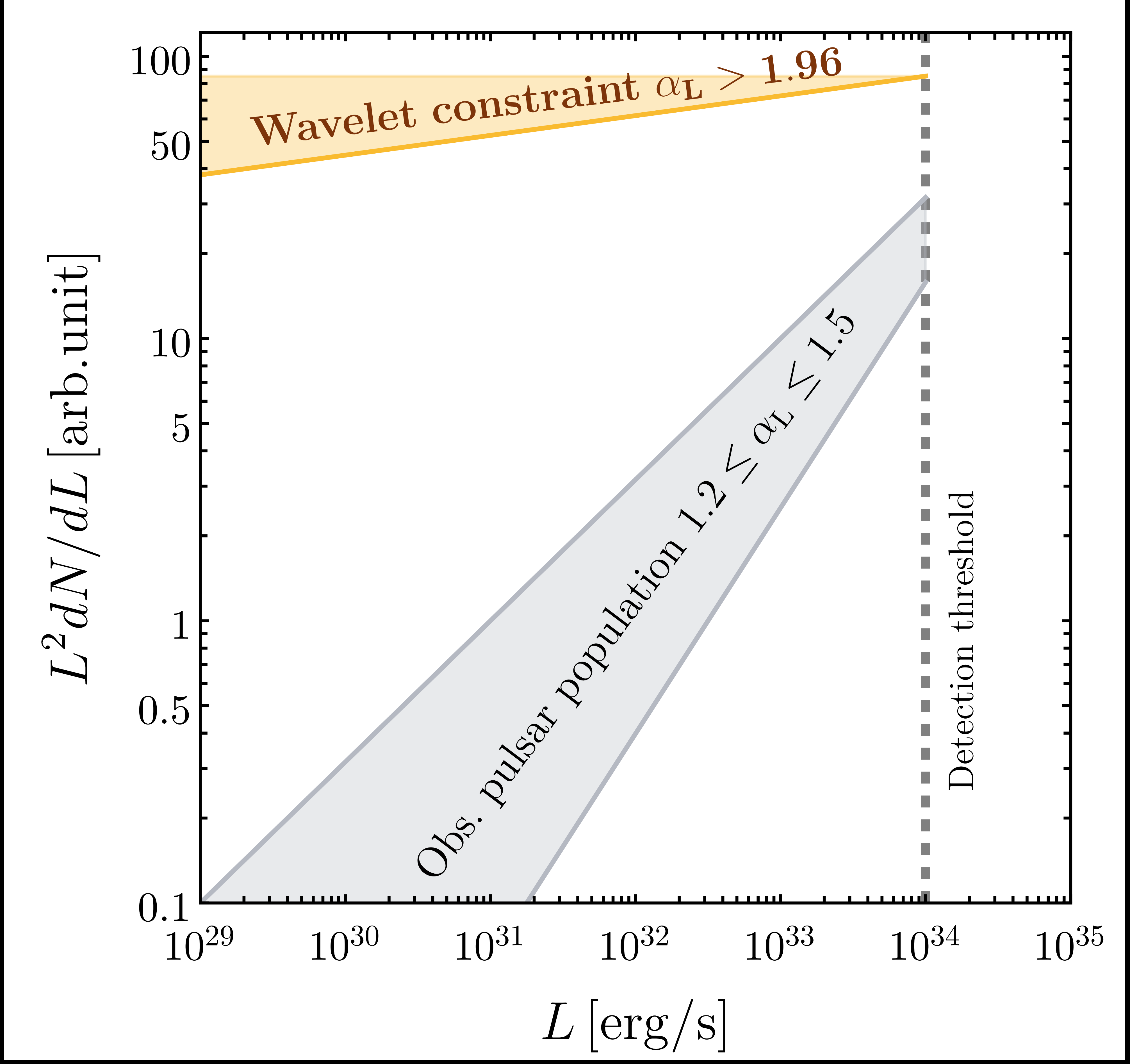


Constraining the luminosity function of MSPs

- The luminosity function of observed pulsars, modeled as a power-law $dN/dL \sim L^{-\alpha_L}$, favors $1.2 \leq \boldsymbol{\alpha_L} \leq 1.5$.

Strong ‘06, Cimpoeas ‘06, Venter+ ’14, Petrovic+ ’14, Cholis+ ‘14

- We found $\boldsymbol{\alpha_L} > 1.96 \pm 0.04$ are needed to explain the GCE. A big contrast with observed pulsar populations.

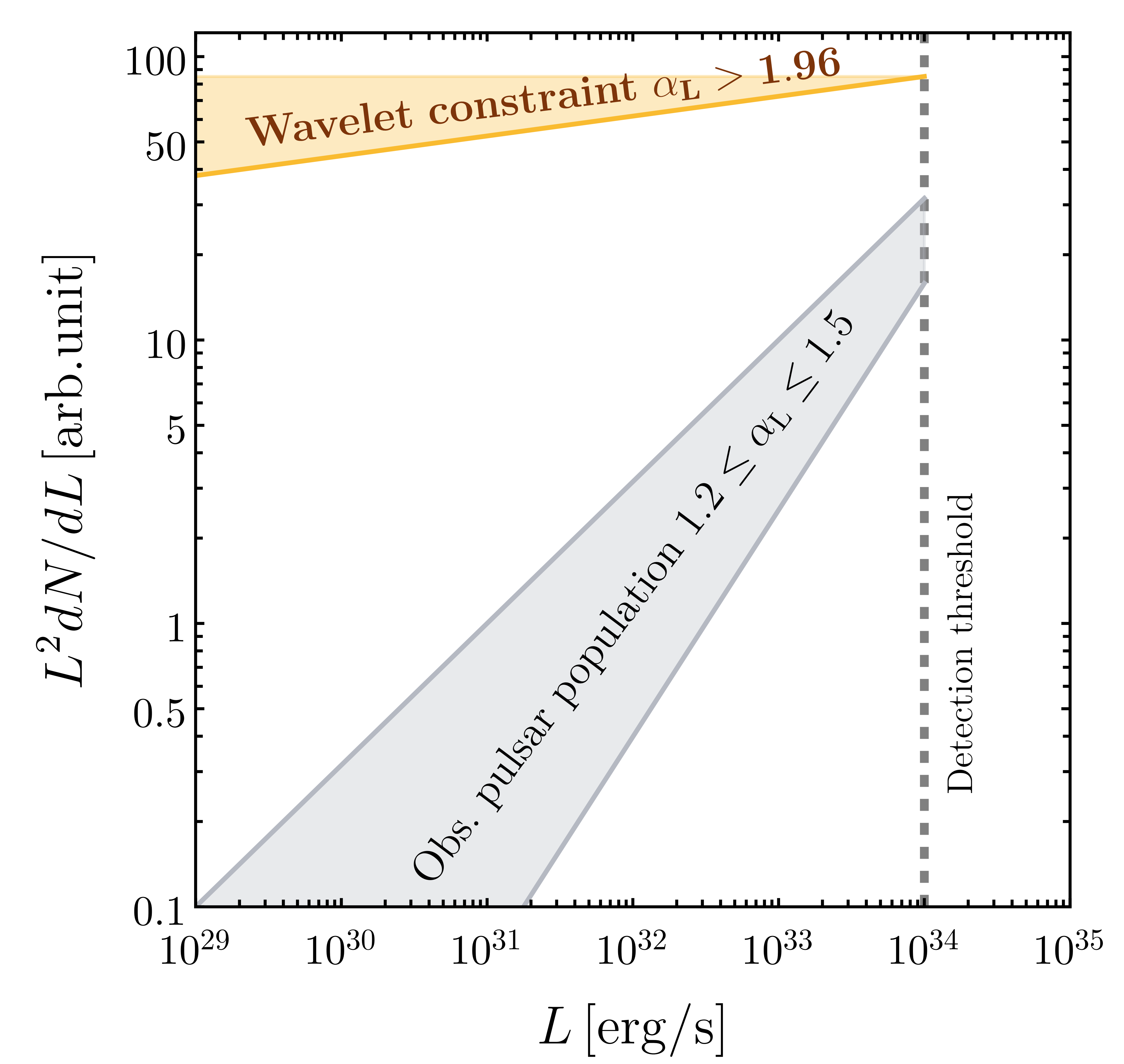


Constraining the luminosity function of MSPs

- α_L ~ 1.96 ± 0.04 ⇒

  O(million) of MSPs (w/ $L > 10^{29}$ erg/s) are needed to explain the GCE.

- **MSPs are unlikely to explain the GCE.**

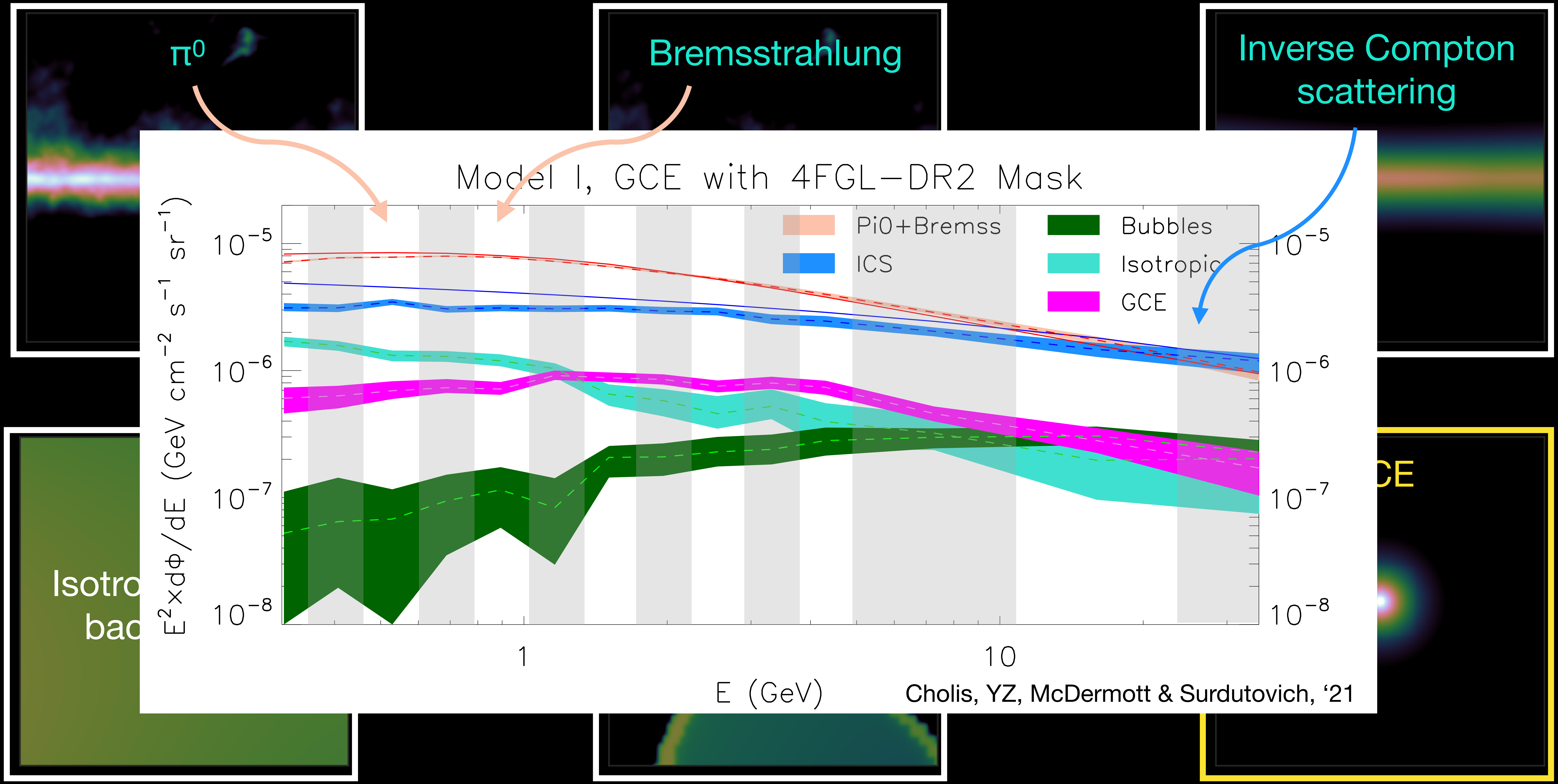


Constraining the luminosity function of MSPs

- Dinsmore & Slatyer ’21 tested luminosity functions w/ broken-power-laws.
- # of MSPs varies from O(1,000) to O(100,000).
- To reach O(1,000), a peaked luminosity function located at high luminosity is needed.

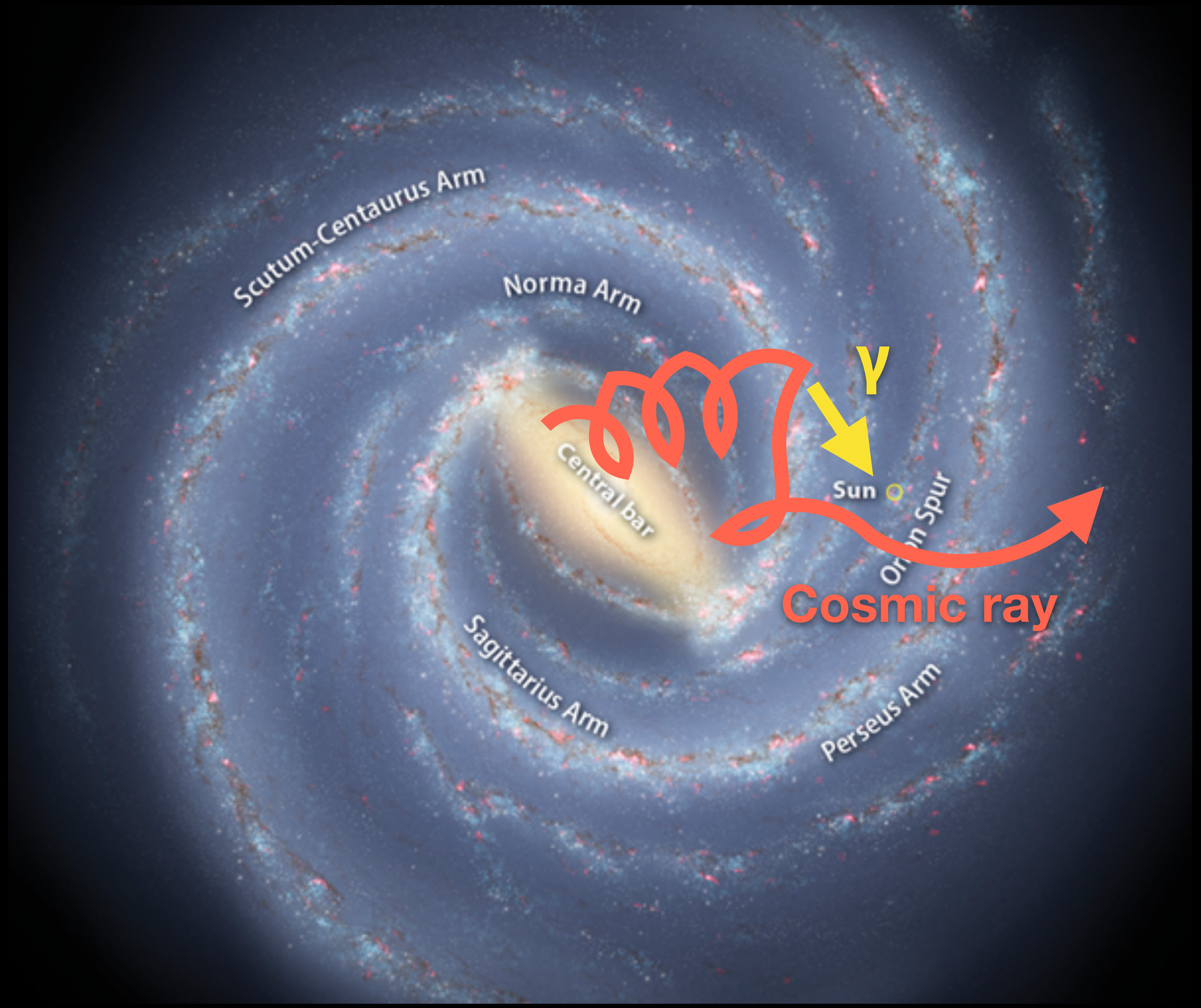
Revisiting the characteristics of the GCE w/ a new set of templates

Diffuse γ-ray emission are important



Modeling the diffused γ-ray emission

- Two steps:
  1. Propagation of the cosmic ray (CR)
  2. γ-ray produced from the cosmic rays interacting w/ interstellar medium (ISM)
- Need to control systematic uncertainties well. Observations of CR could help.



CR observation

AMS-02

CR hydrogen (H), helium (He), carbon (C), beryllium (Be), boron (B), and oxygen (O) near earth.

Voyager 1

CR proton outside the Heliosphere.

New templates calibrated w/ CR data

CR data
(AMS-02: 6 yr
Voyager 1: 3 yr)

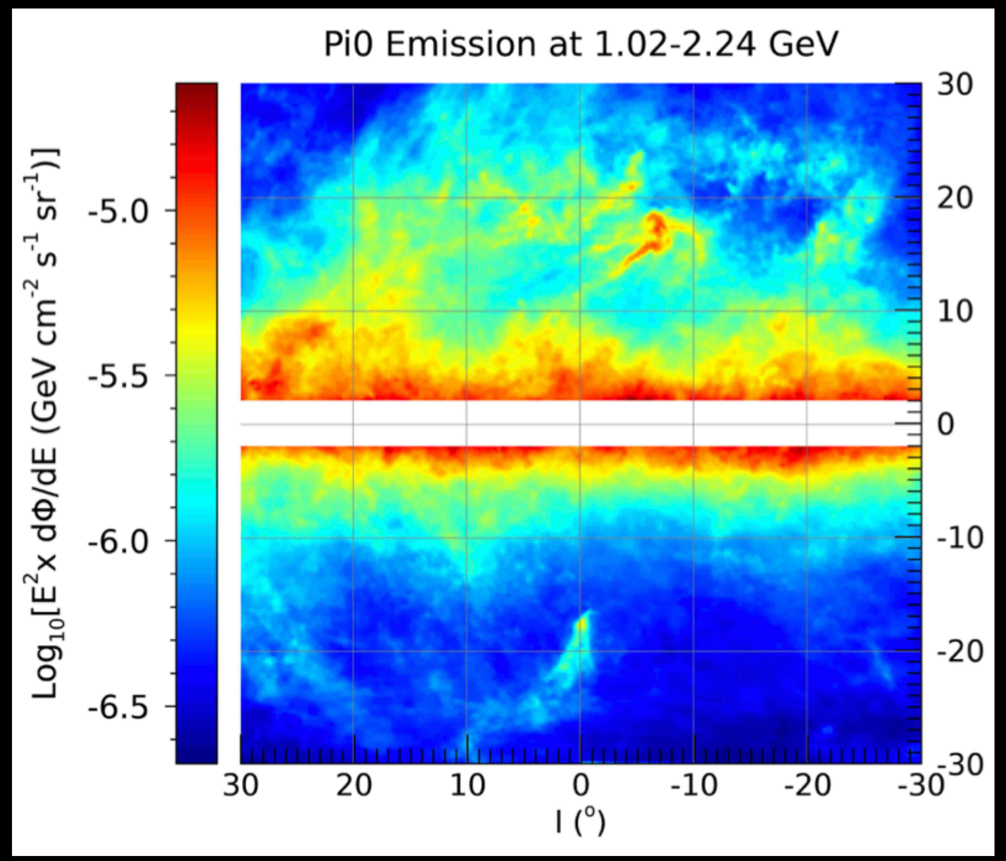
→ tune GALPROP parameter →

5 calibrated
CR models

→ Galactic environment →

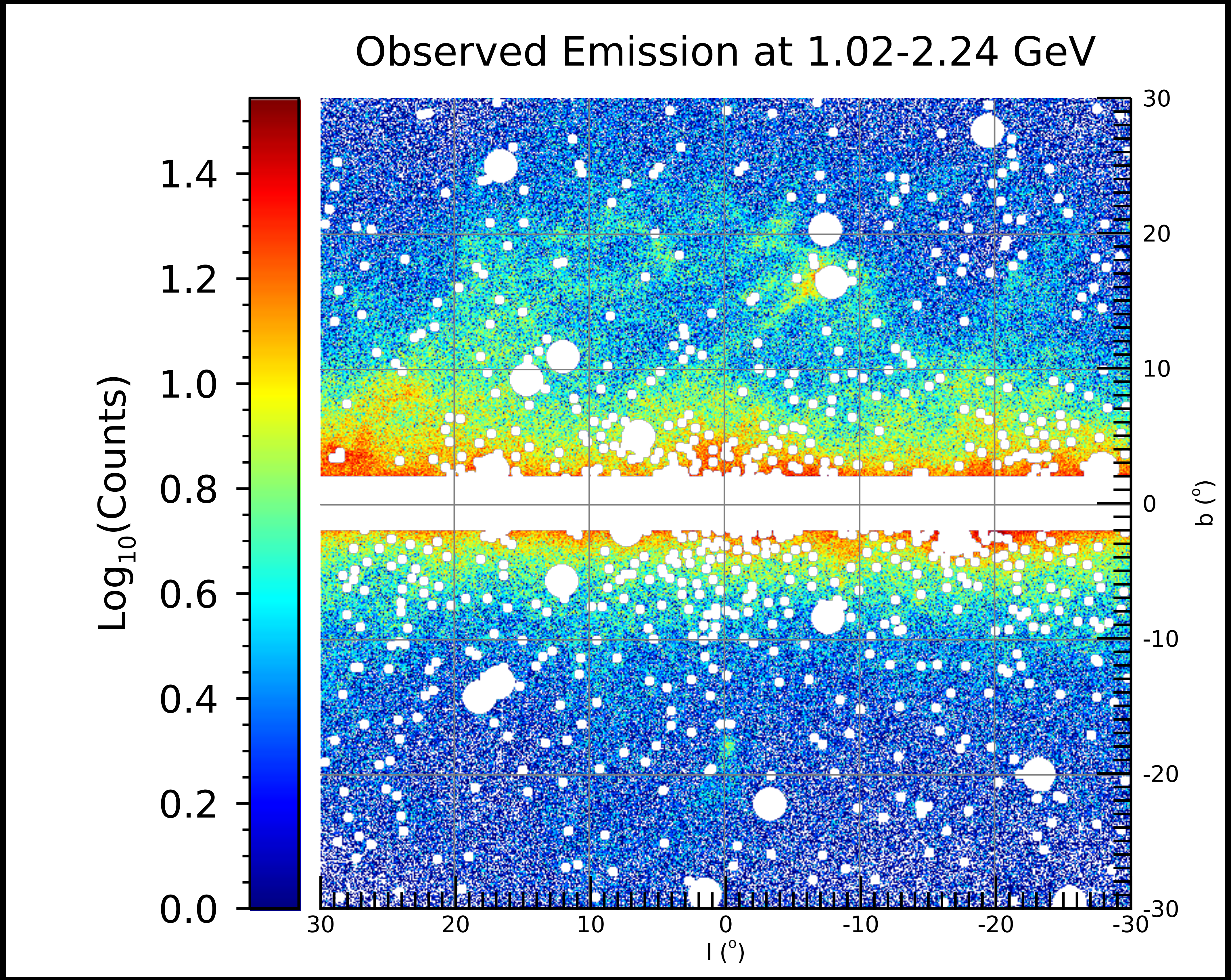
80 diffuse
emission
templates

All templates are publicly available at
https://zenodo.org/record/5787376



Template fitting

Fermi data [**12.5 years of obs.**]
masking 4FGL-DR2 sources + disk [white regions]

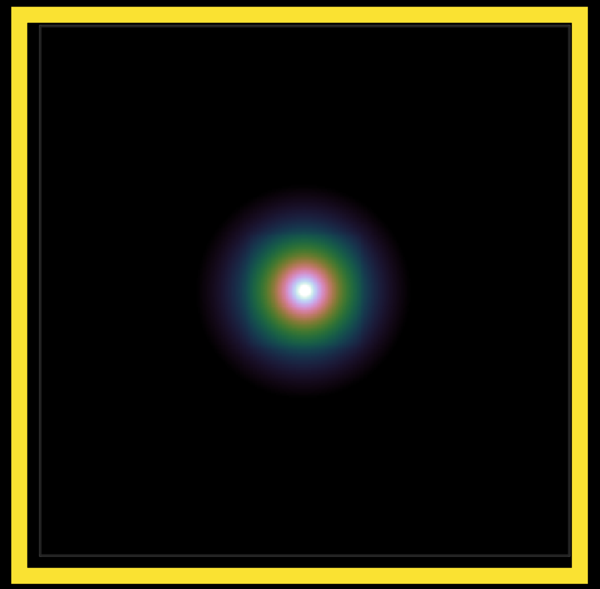


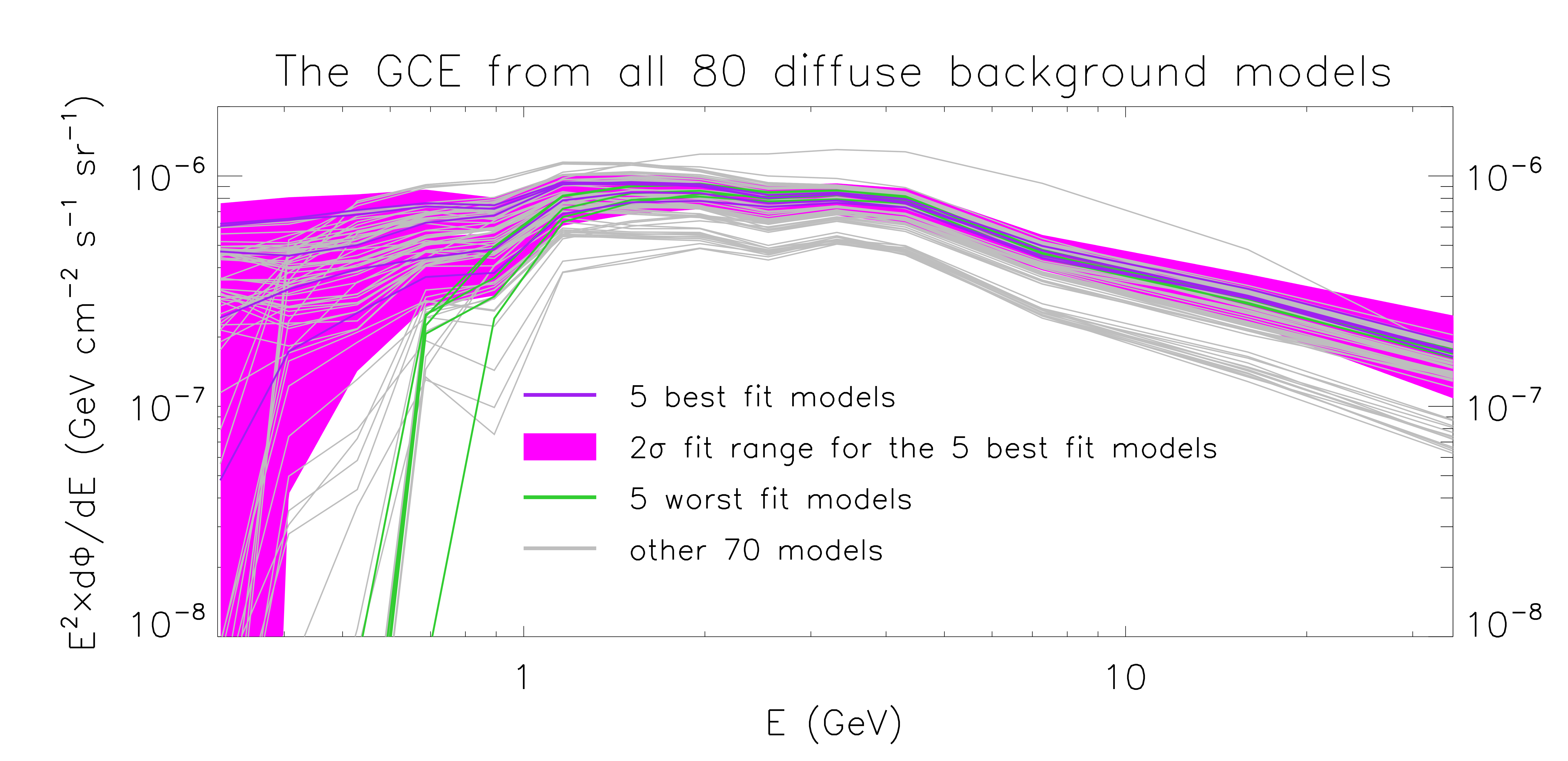
vs.

New templates for the diffuse emission
+
Templates for isotropic & Fermi bubbles
+
Template for GCE

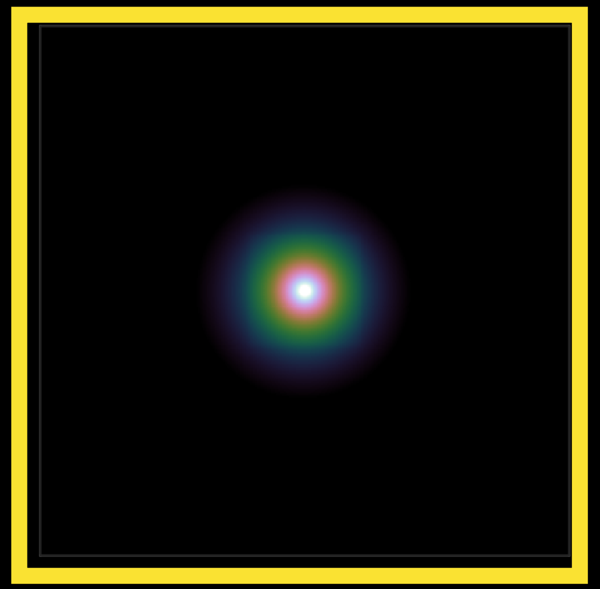
(Also masking the sources + disk)

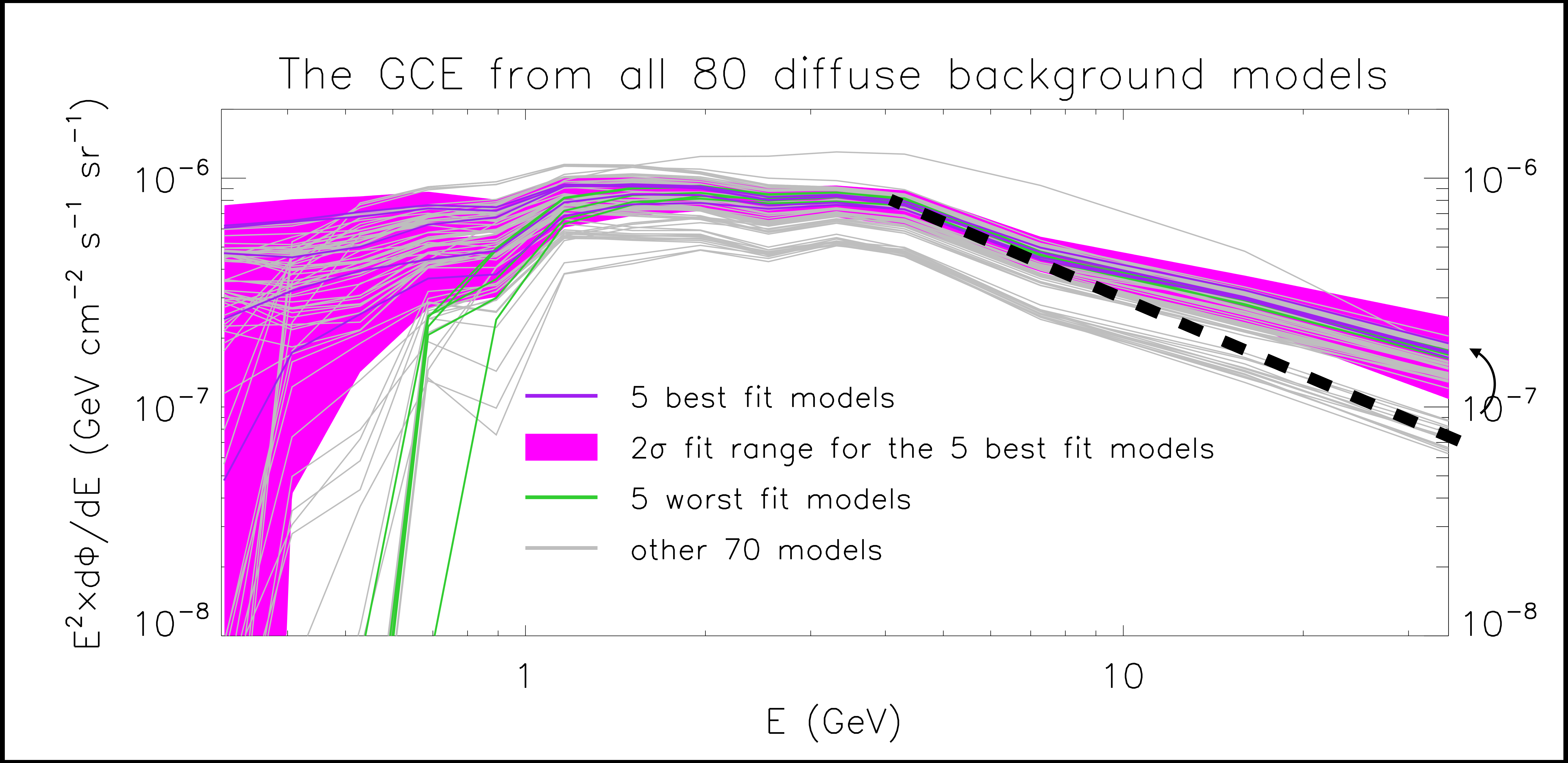
The GCE is still there





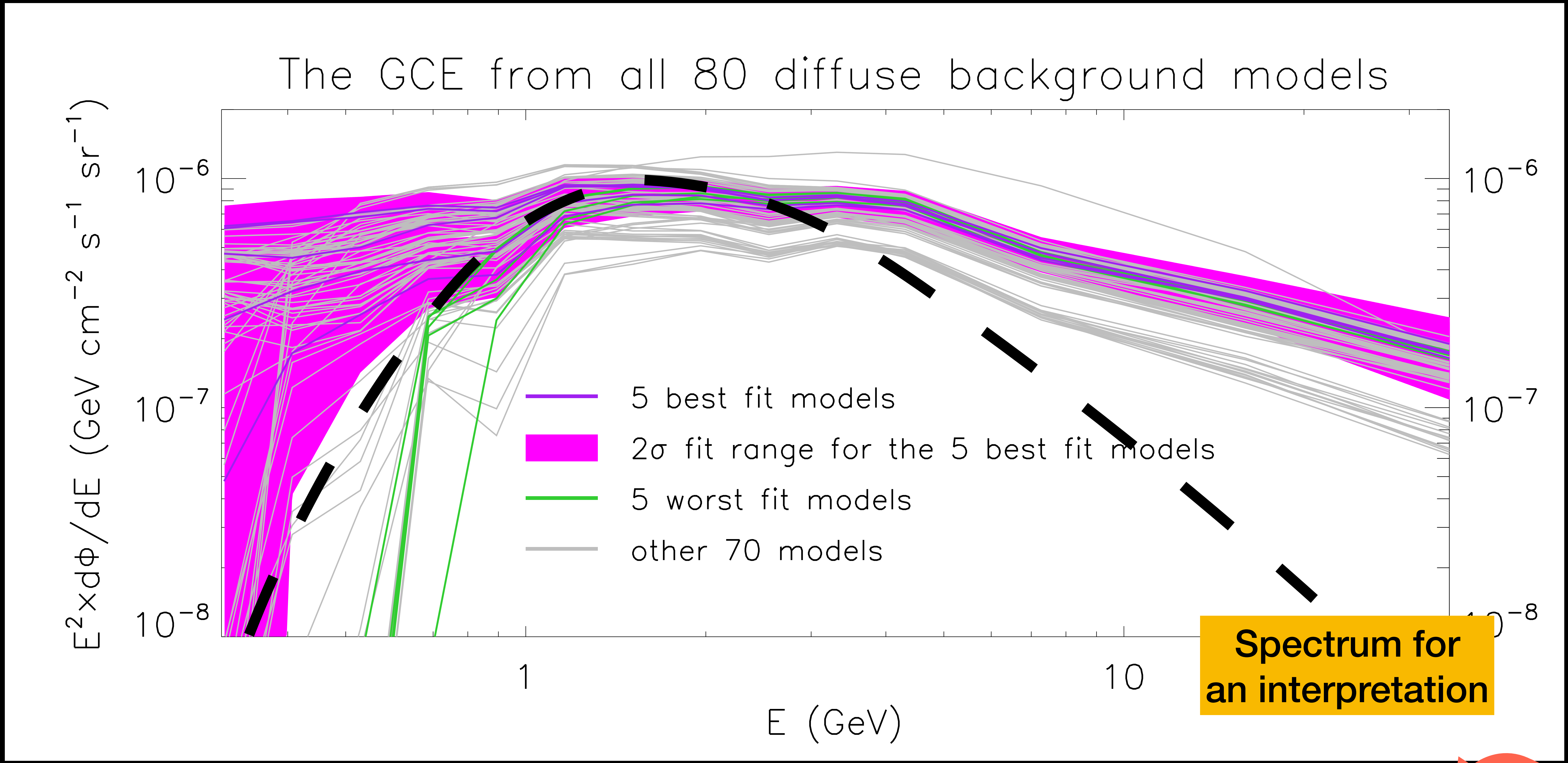
What is new? Harder energy tail





Ready for interpretation?

available at https://zenodo.org/record/5787376



Stat. + Sys.

$$\chi^2 = \sum_{i,j}^{\text{energy bins}} (\mathrm{GCE}_i - \mathrm{Interp}_i)\, \boxed{C_{ij}^{-1}}\, (\mathrm{GCE}_j - \mathrm{Interp}_j)$$

WIMP or MSPs?

- For WIMP, we consider, e.g.,

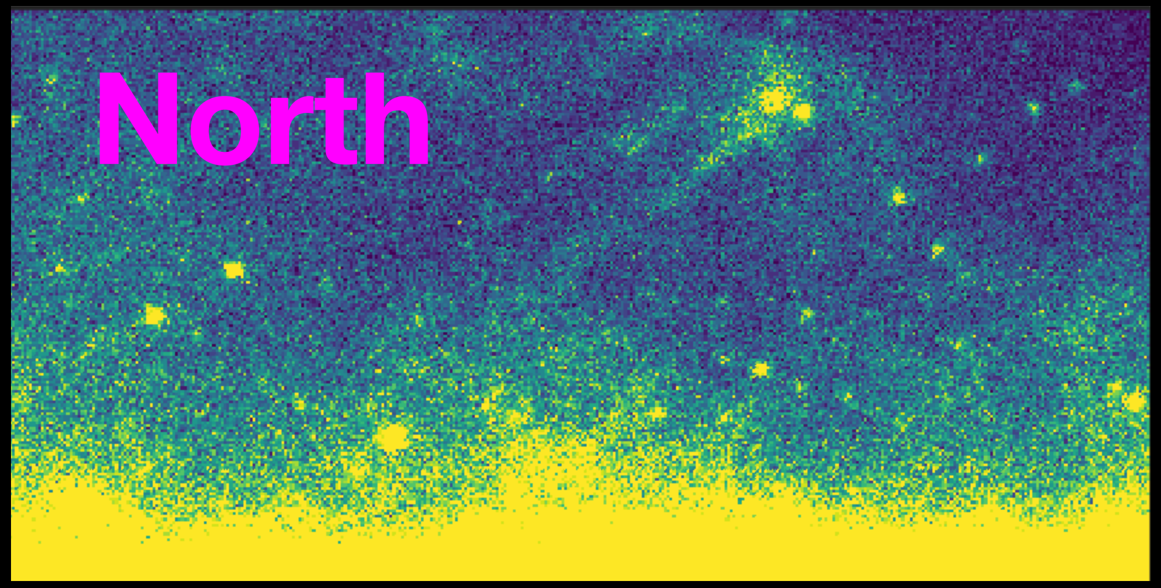
$$\mathrm{DM}\,\mathrm{DM} \to b\bar{b}$$

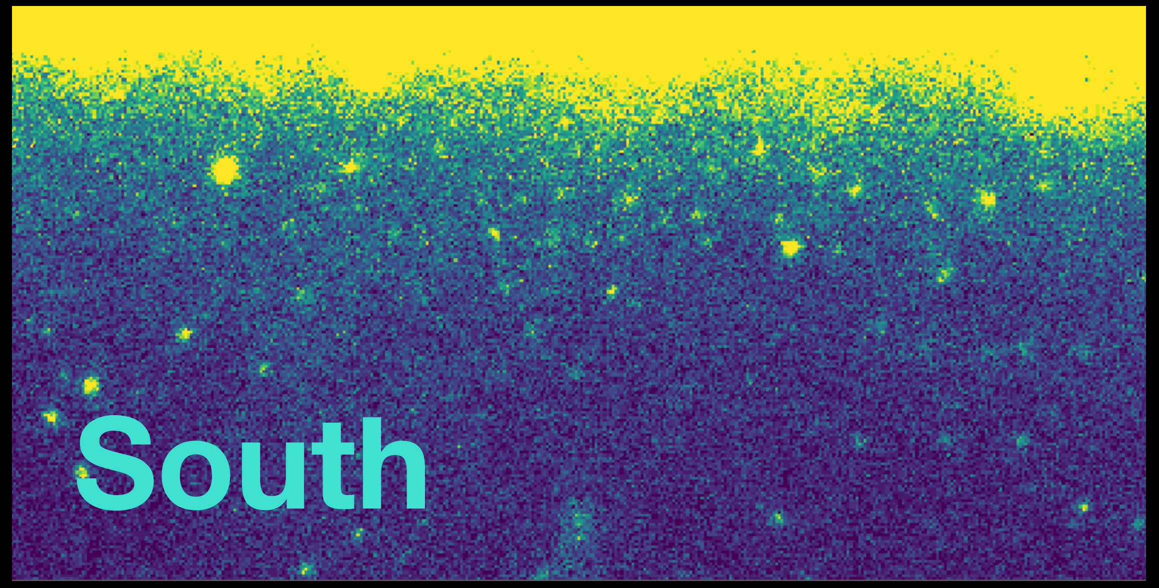
- For millisecond pulsars, we consider spectrum from known pulsars (Ploeg+ '18, Cholis+ '14).

- We found millisecond pulsar cannot fit the hard high-energy tail well. WIMP wins.

Less positive
⇒ Better fit

Model	$\widehat{\chi}^2/\mathrm{dof}$	$\hat{p}$-value	ROI
MSPs	$76.6/13$	$< 10^{-6}$	$40° \times 40°$
	$34.5/13$	1.0×10^{-3}	southern sky
	$194.5/13$	$< 10^{-6}$	northern sky
DM DM $\to b\bar{b}$	$50.5/12$	1.1×10^{-6}	$40° \times 40°$
	$17.1/12$	0.15	southern sky
	$88.0/12$	$< 10^{-6}$	northern sky





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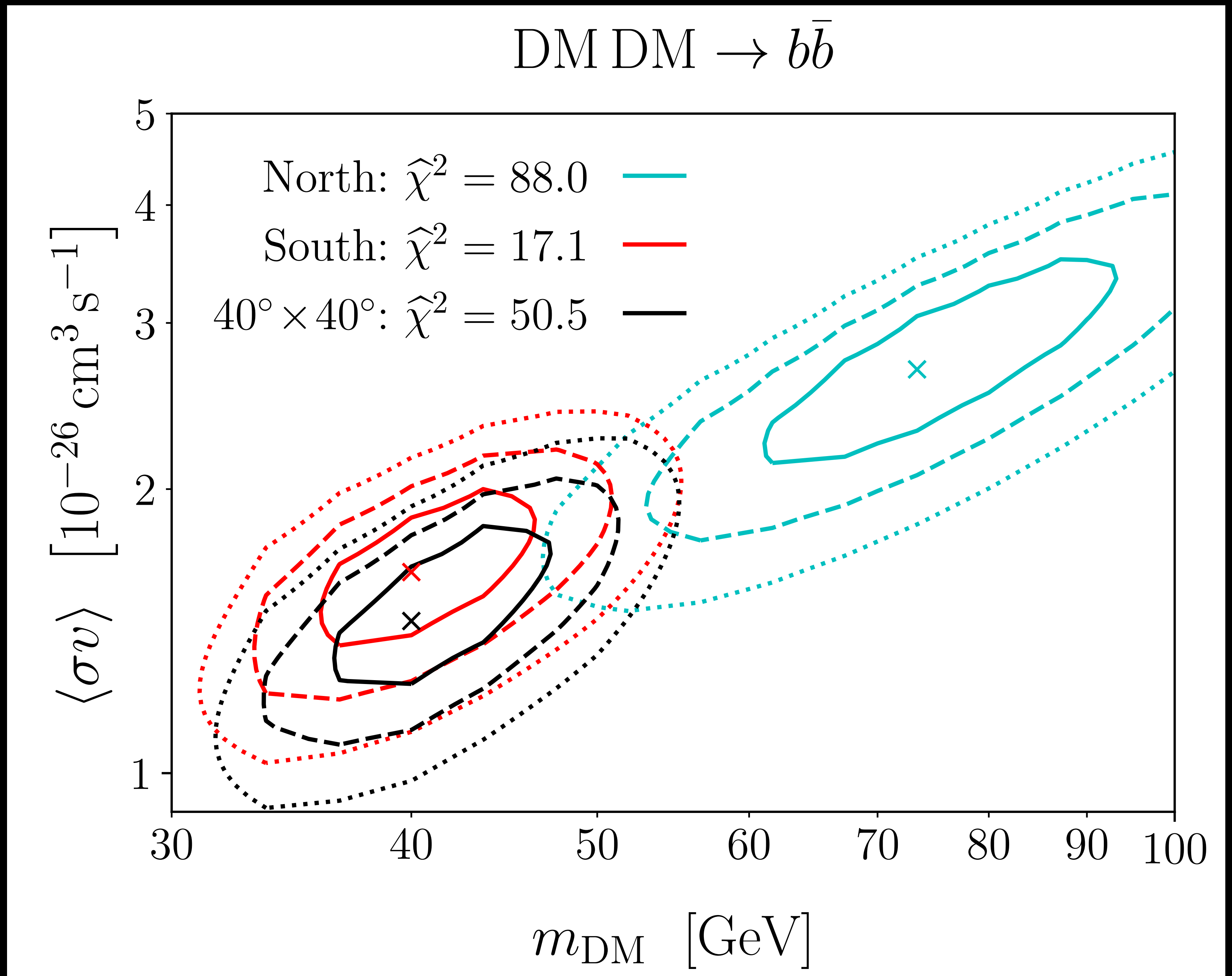
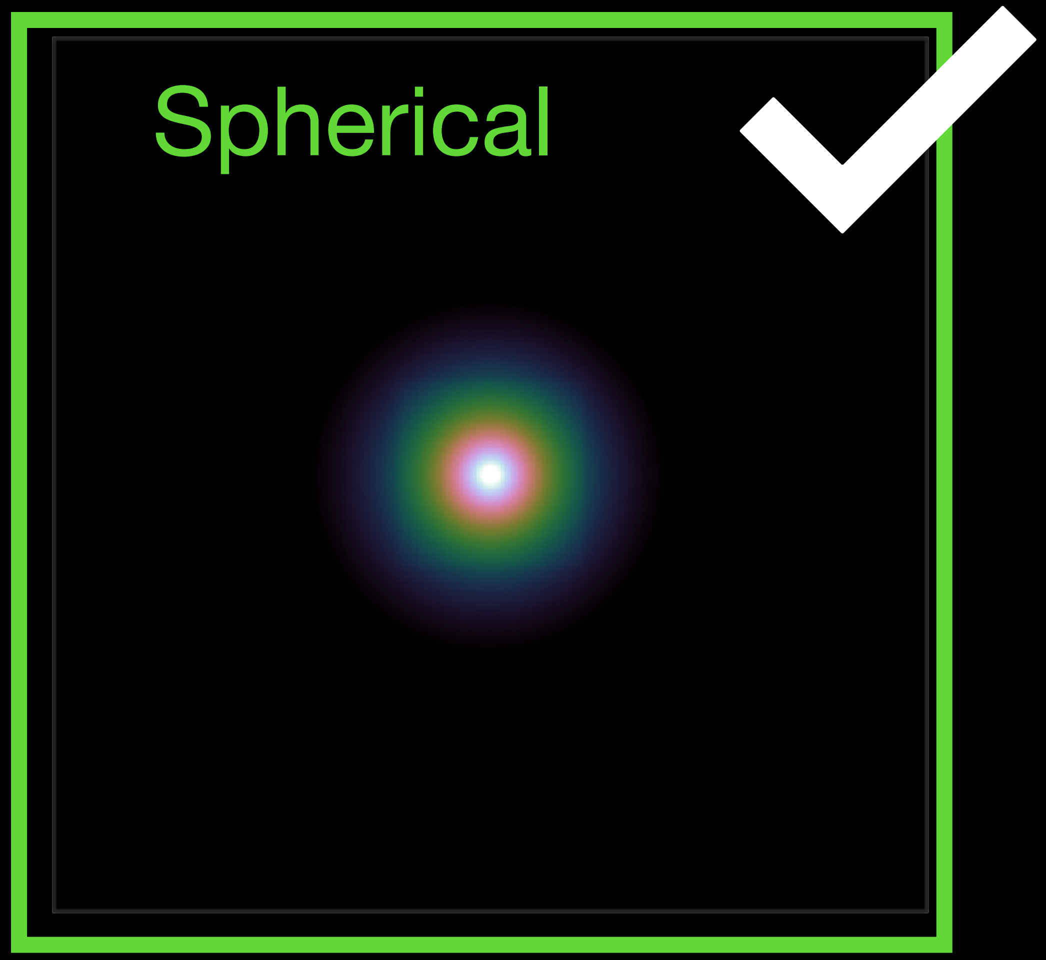
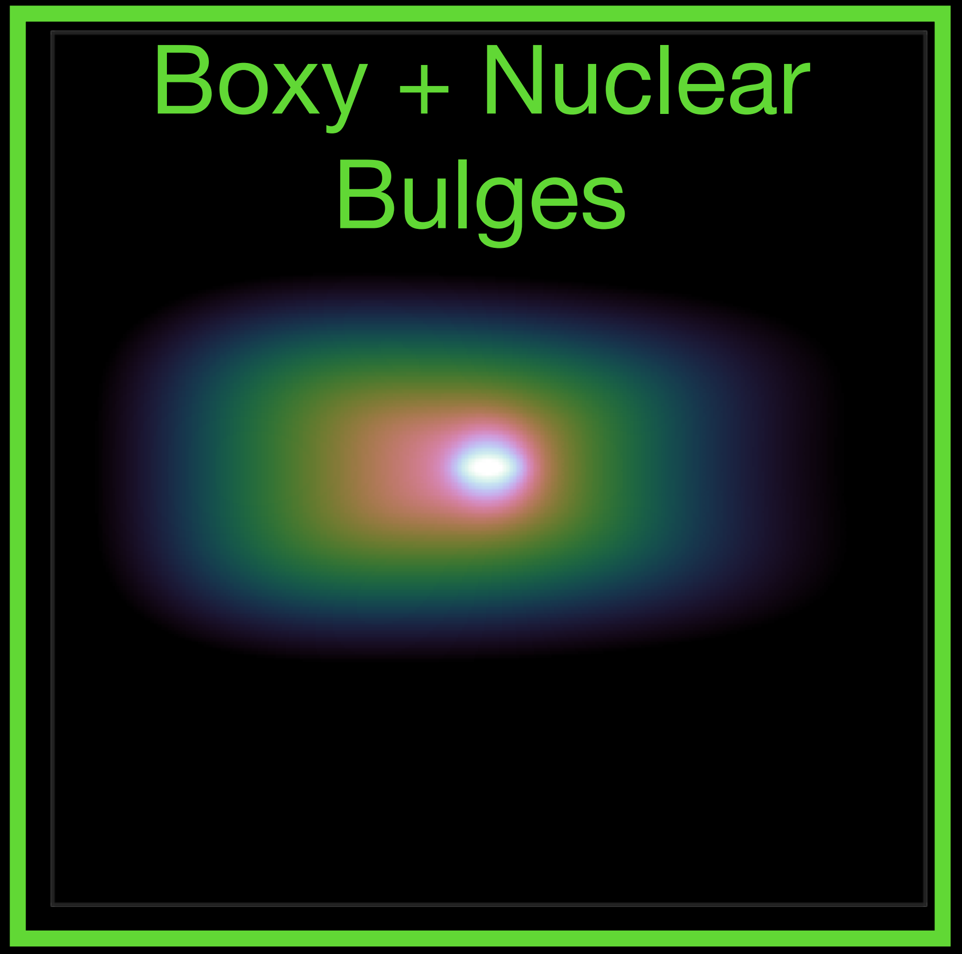
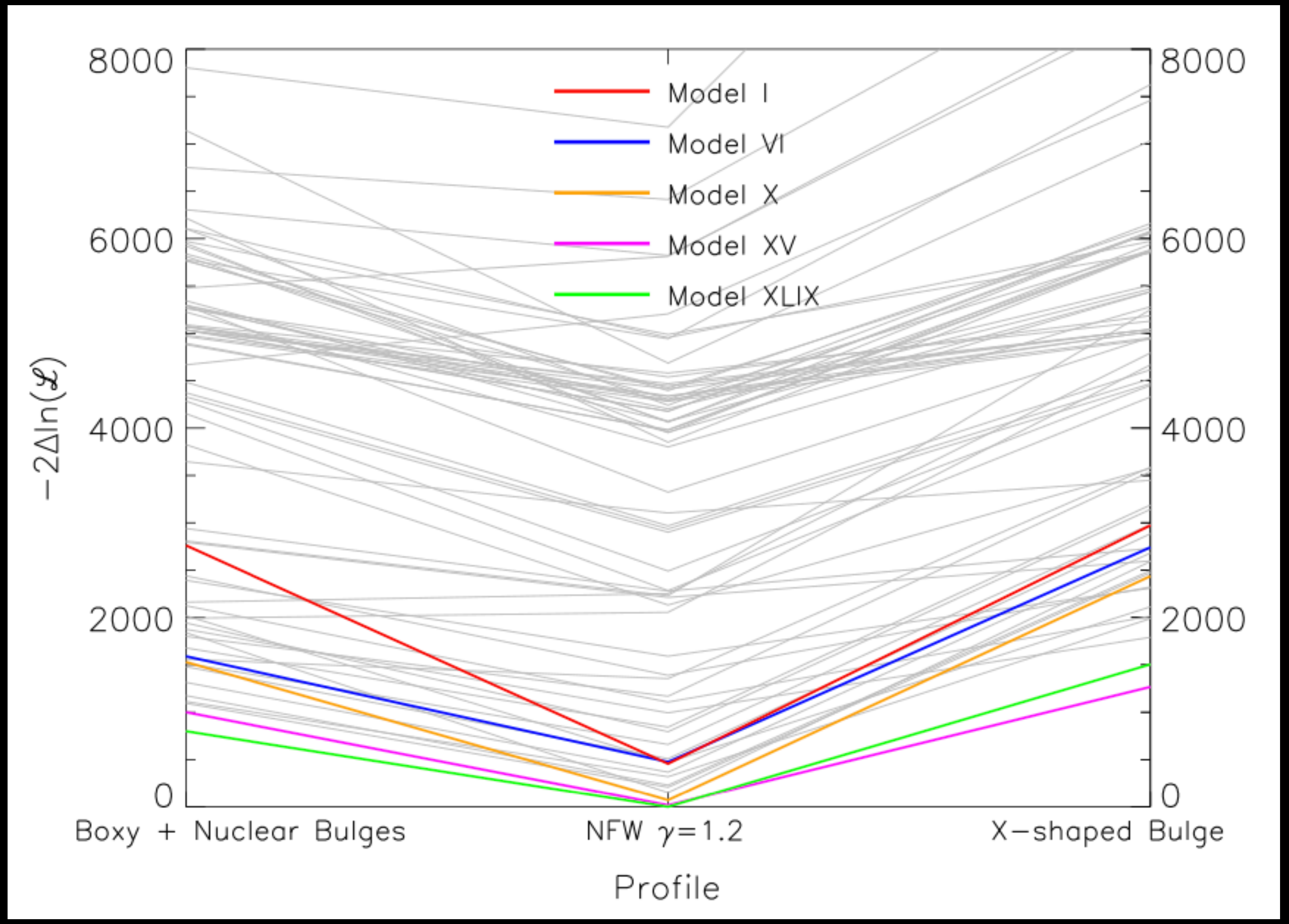


The GCE is spherical



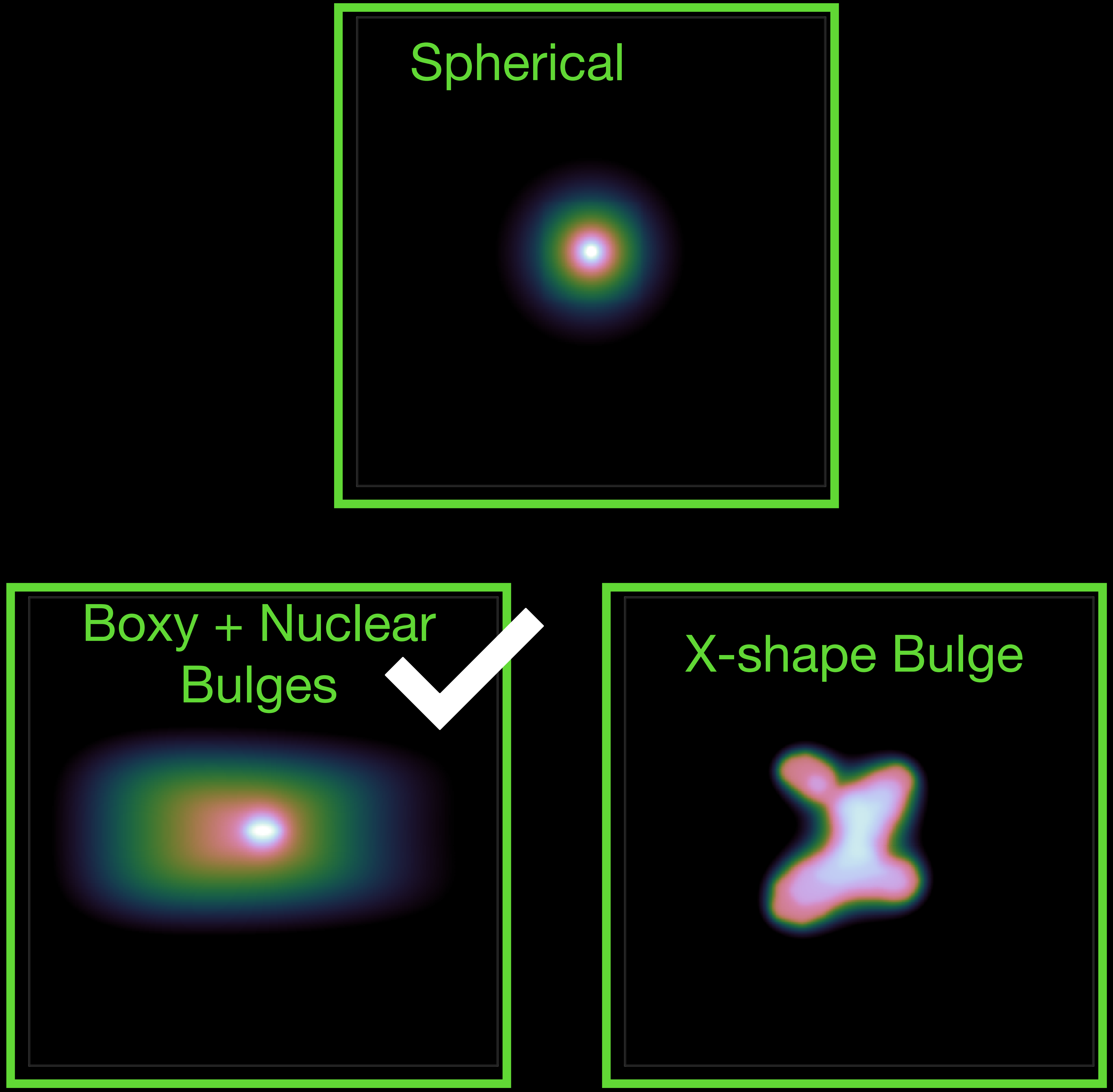




Prefer round shape

A debate

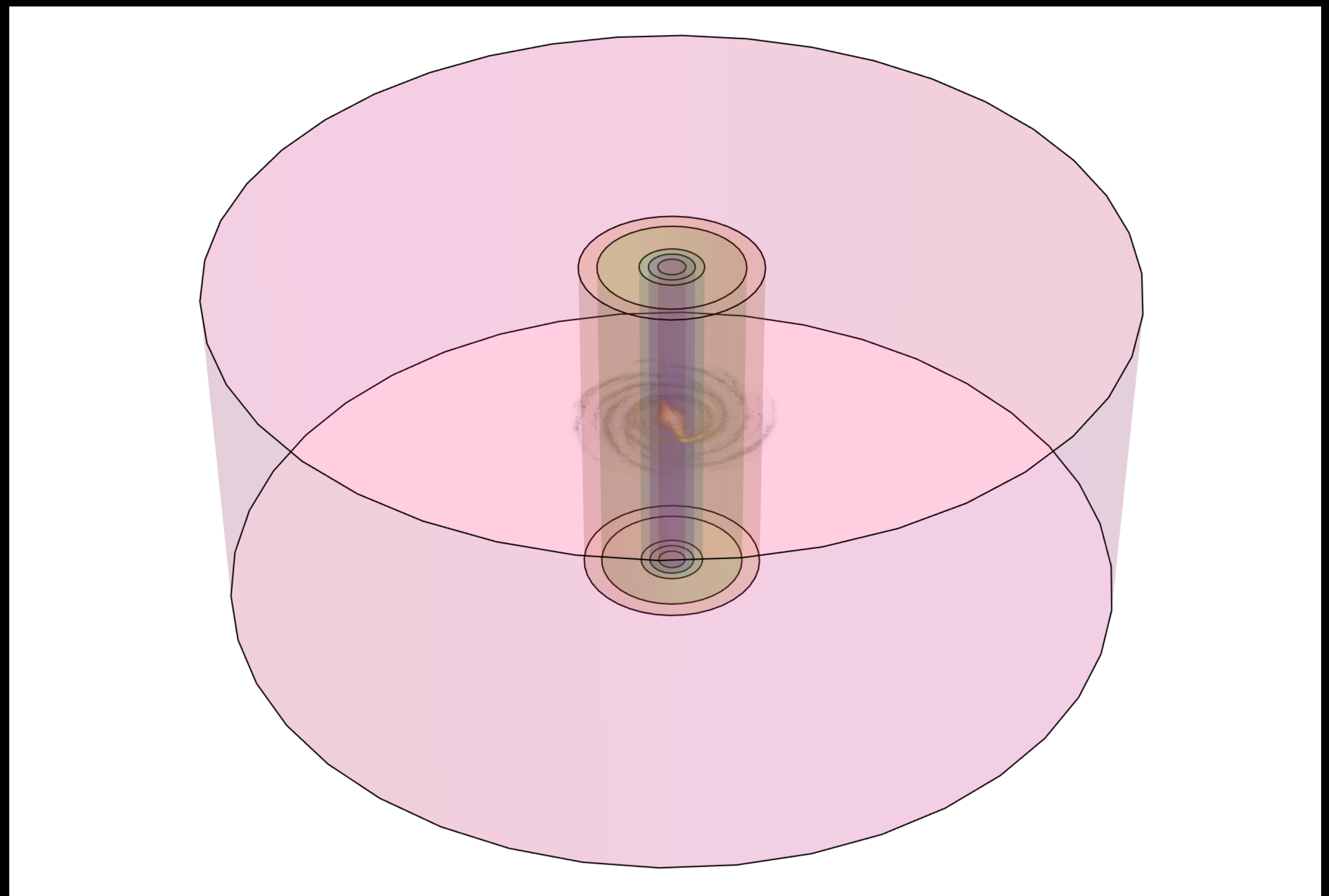
Earlier results



- Macias+ ’18, ’19, and Pohl+ ’20 claim the GCE is boxy instead of spherical.

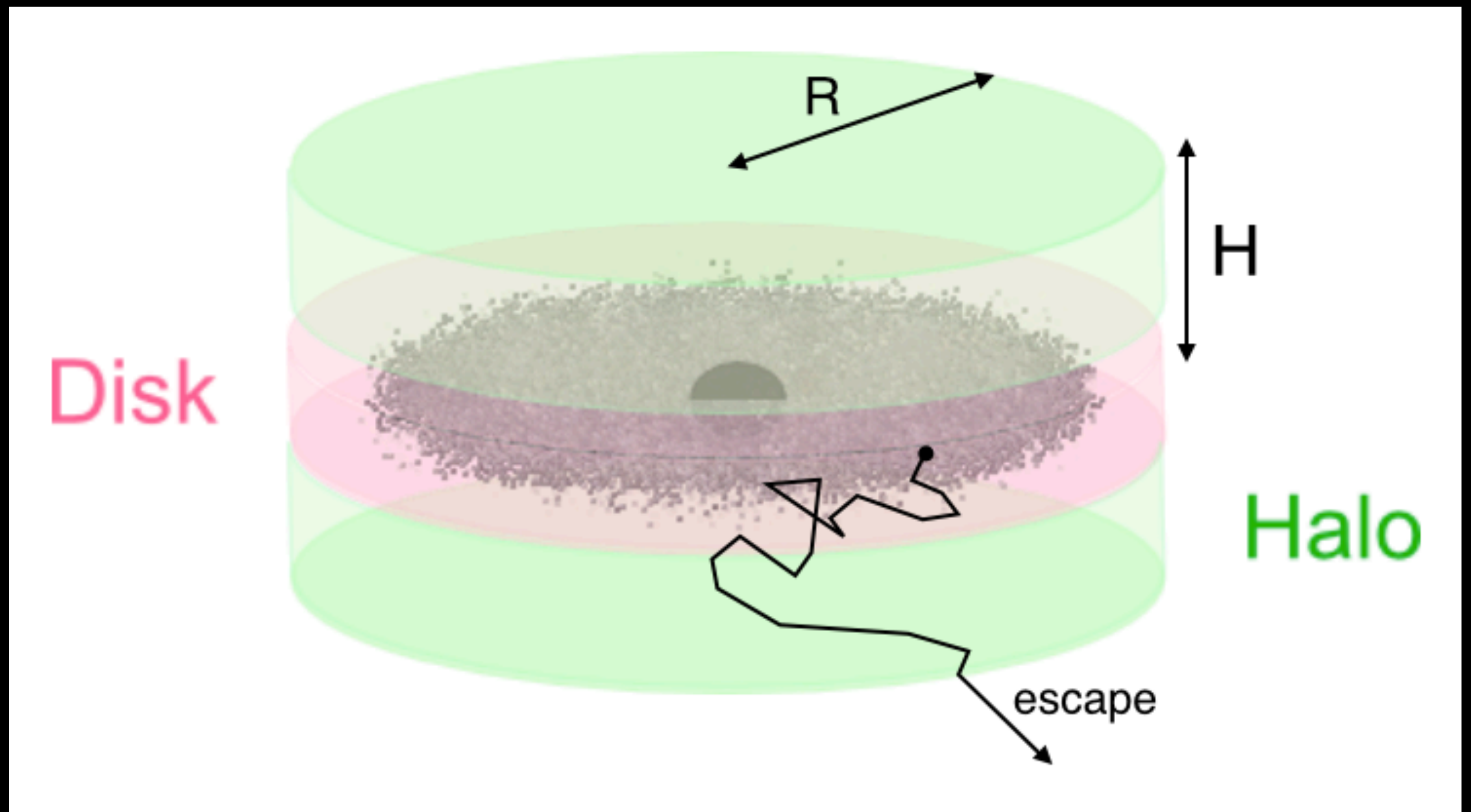
Differences in the templates

- Macias+ ’18, ’19, and Pohl+ ’20 use ring-based templates w/ a total of 19 templates.



HI ring 1, HI ring 2, HI ring 3, HI ring 4, H2 ring 1, H2 ring 2, H3 ring 3, H2 ring4, ICS ring 1, ICS ring 2, ICS ring 3, ICS ring 4, ICS ring 5, ICS ring 6, Pos Res, Neg Res, Fermi bubbles, Isotropic, GCE

- We use an astrophysical motivated leaky-box model w/ a total of 6 templates.



Pion0, Brems, ICS, Fermi bubbles, Isotropic, GCE

Apple-to-apple comparison

McDermott, YZ, Ilias ‘22

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

More negative ⇒ better fit

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

Fits based on Pohl+ ’20’s templates

Fits based on our templates

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Fits based on Pohl+ '20's templates

Fits based on our templates

Our diffuse model provides a better fit if no excess

Apple-to-apple comparison

McDermott, YZ, Ilias '22

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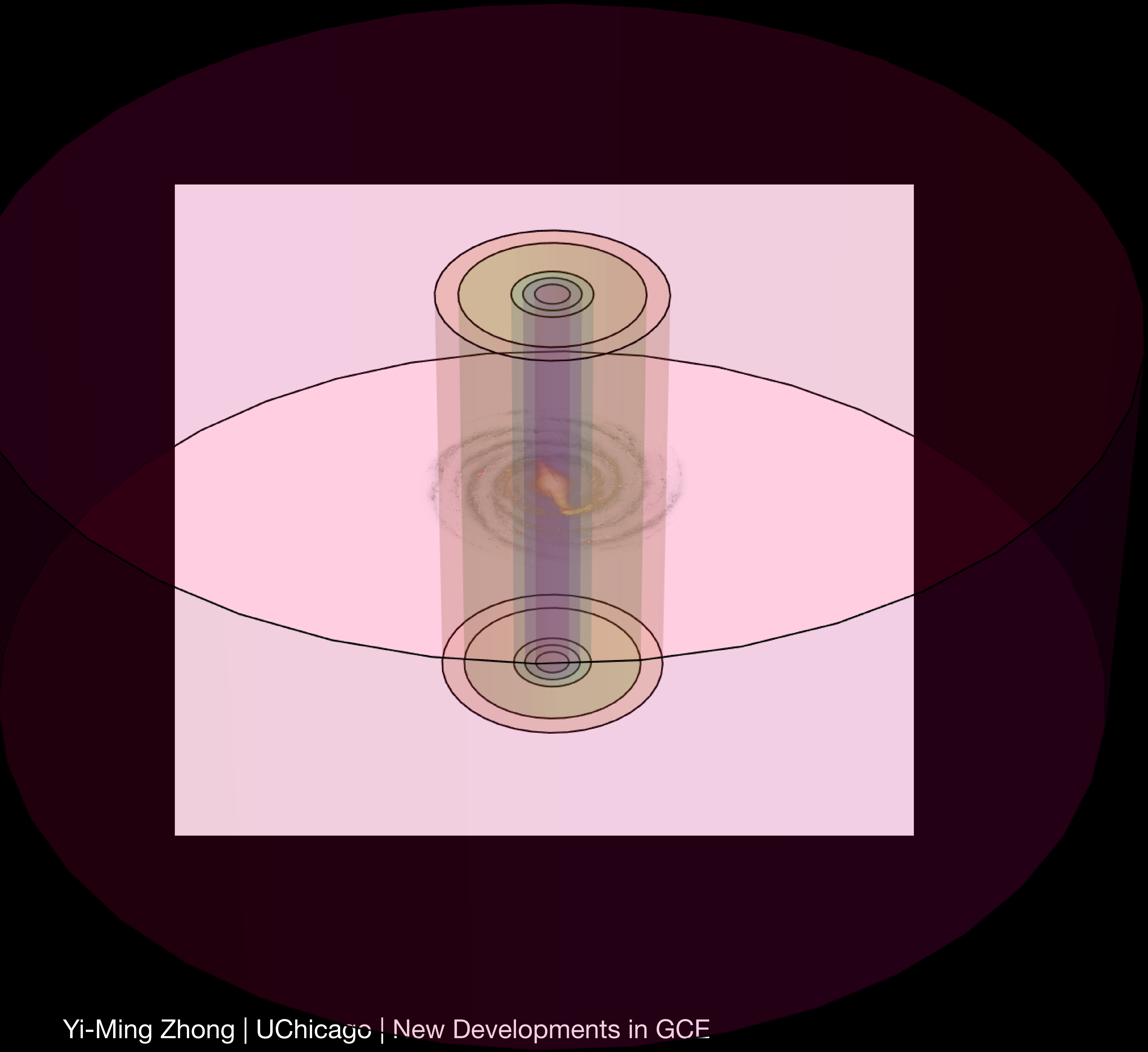
Fits based on Pohl+ '20's templates

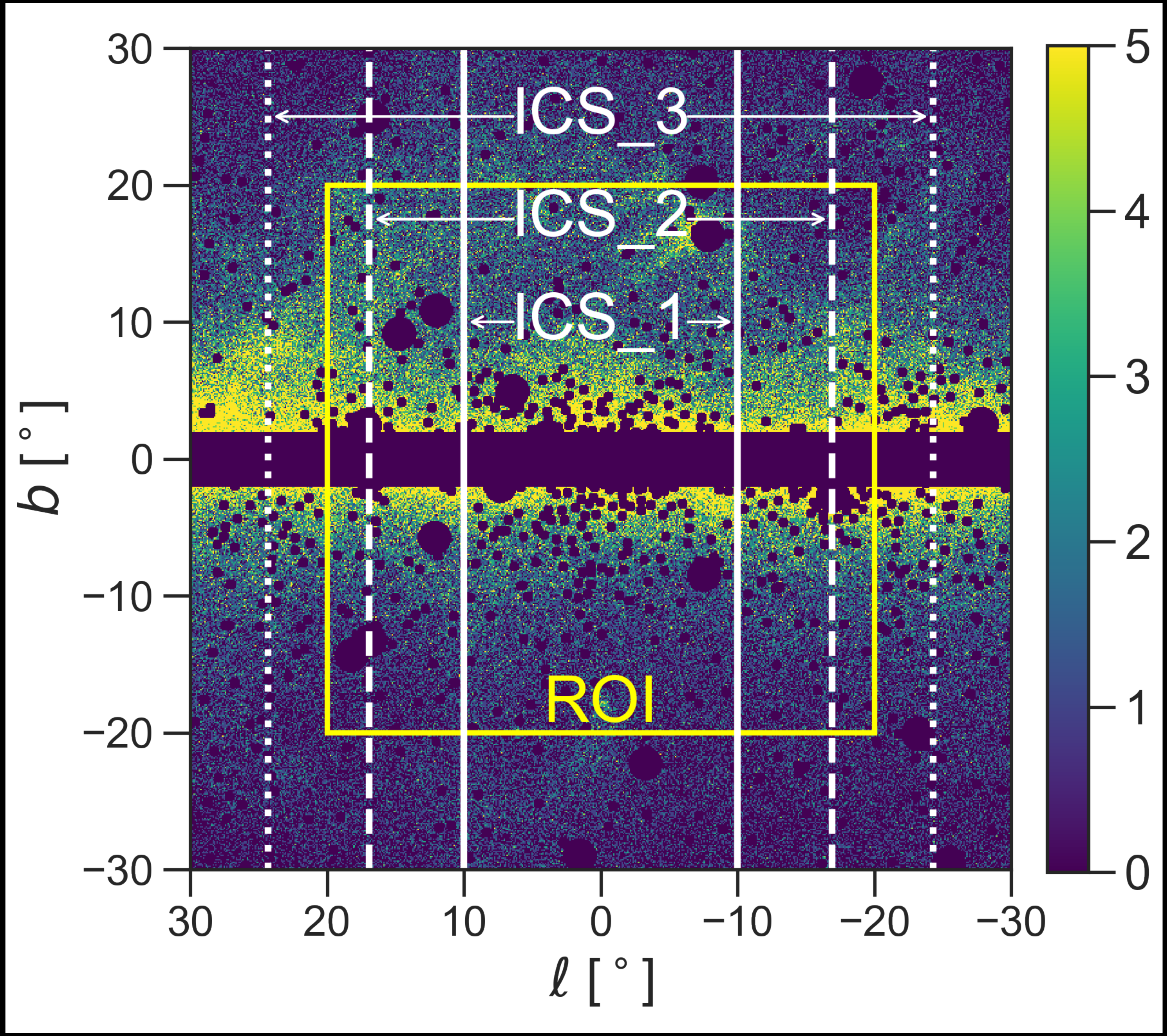
Fits based on our templates

Best fit from Pohl+ '20's templates

Best fit from our templates is better than the best fit from Pohl+ '20

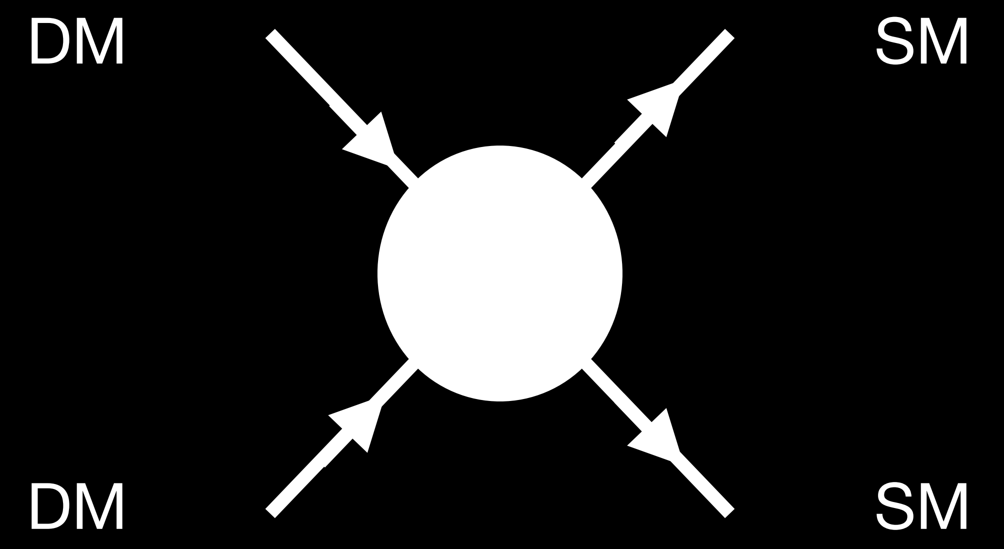
Possible reason for the boxy GCE?





Summary

The GCE status before 2019



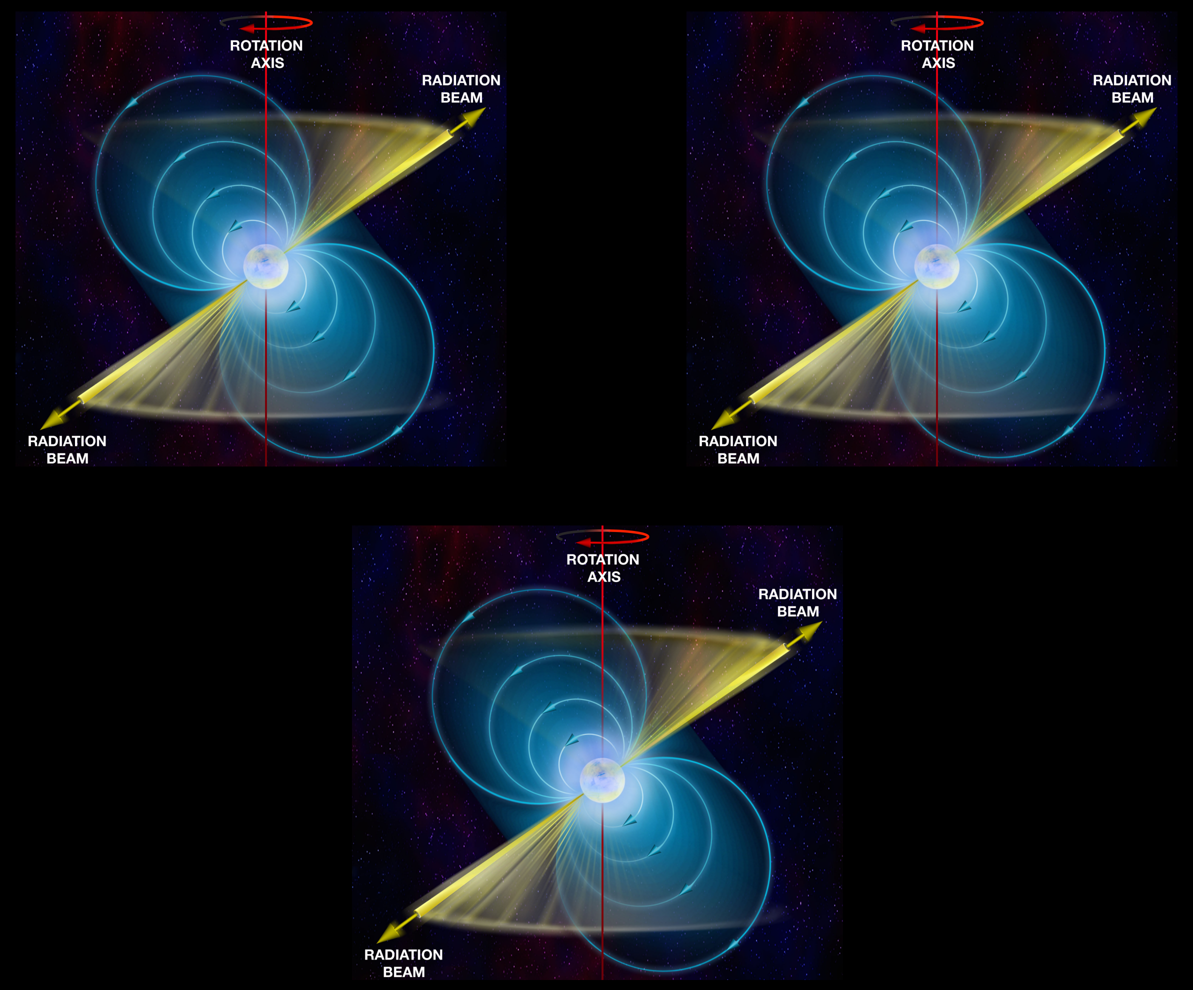
Dark matter (WIMP) annihilation

Small-scale power

Bartels+ ’16, Lee+ ’16

Morphism

Macias+ ’16, ’17, Bartels+ ’17,
Macias+ ’18, ’19, Pohl+ ’20



A new population of millisecond pulsars

The GCE status at 2022

- Arguments no-longer in favor of MSPs:
  - The point sources found by wavelet methods are mostly known sources.
  - The luminosity functions of MSPs at GC need to be very different than observed MSPs.

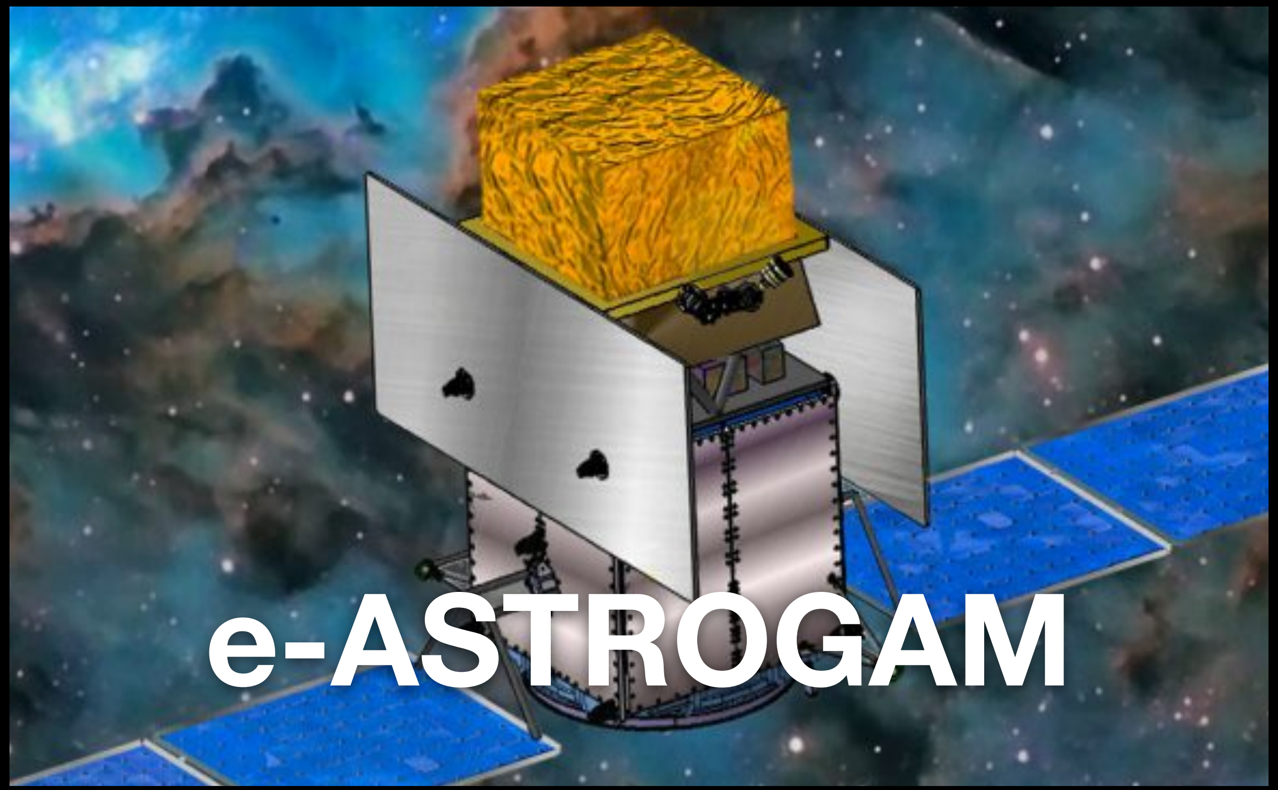
    YZ, McDermott, Cholis & Fox ‘20
  - The NPTF methods are template-sensitive.

    Leane & Slatyer ’19, ’20, ’20, Chang+ ’19, Buschmann+ ’20
  - The morphism prefers the spherical shape.

    Di Mauro ’20, YZ, Cholis, McDermott & Surdutovich ’21, McDermott, YZ, Ilias ‘22

The GCE remains intriguing

γ-ray
@ other wavelengths



Pulsar candidates
@ other wavelengths

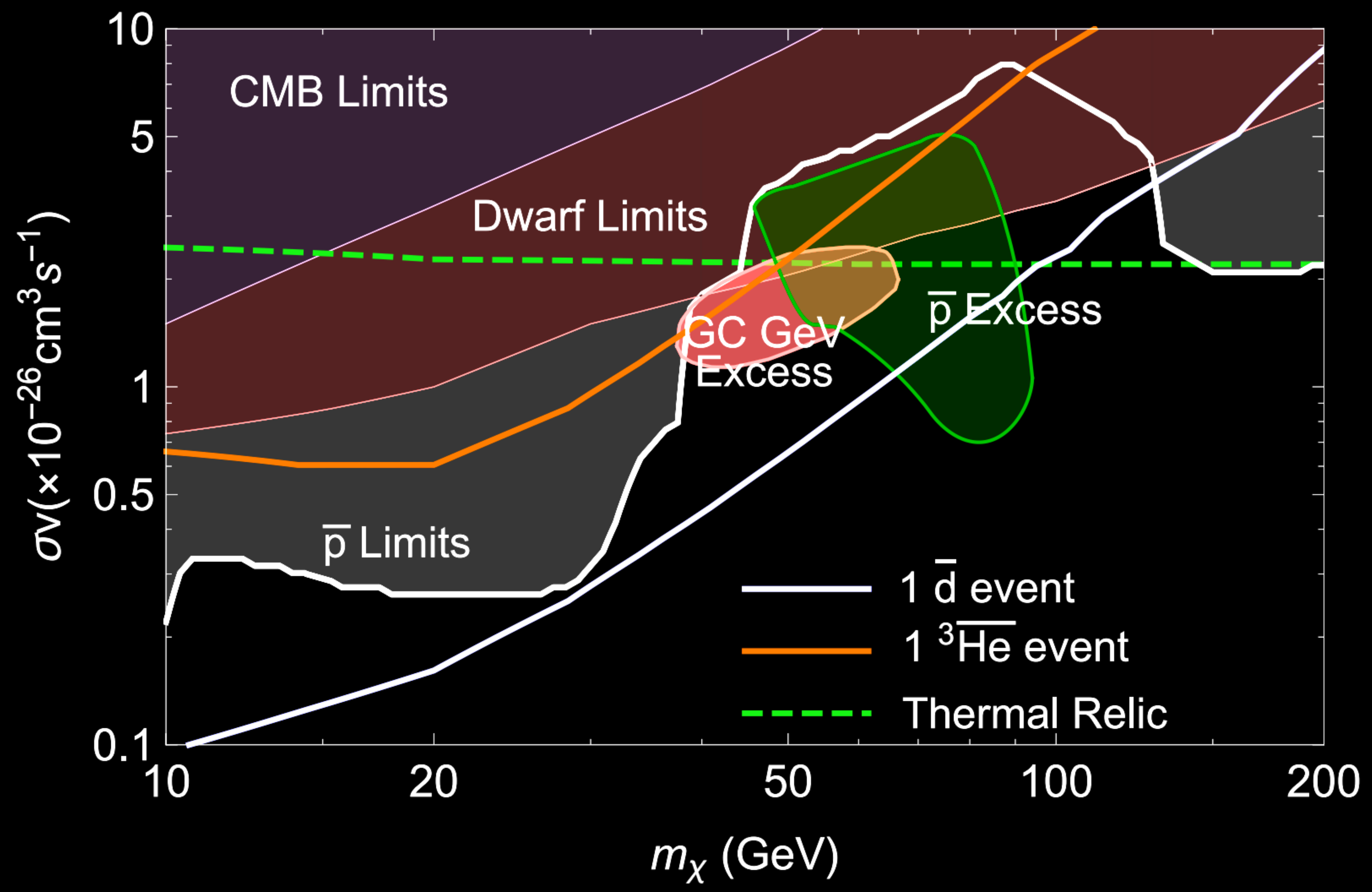
Cosmic ray

Let’s combine all the inputs to understand it.

Backup

Current status for WIMP

- No γ-ray excess observed in dwarf galaxies [tension w/ GCE is dominated by J-factor uncertainties].
- The parameter space still exists

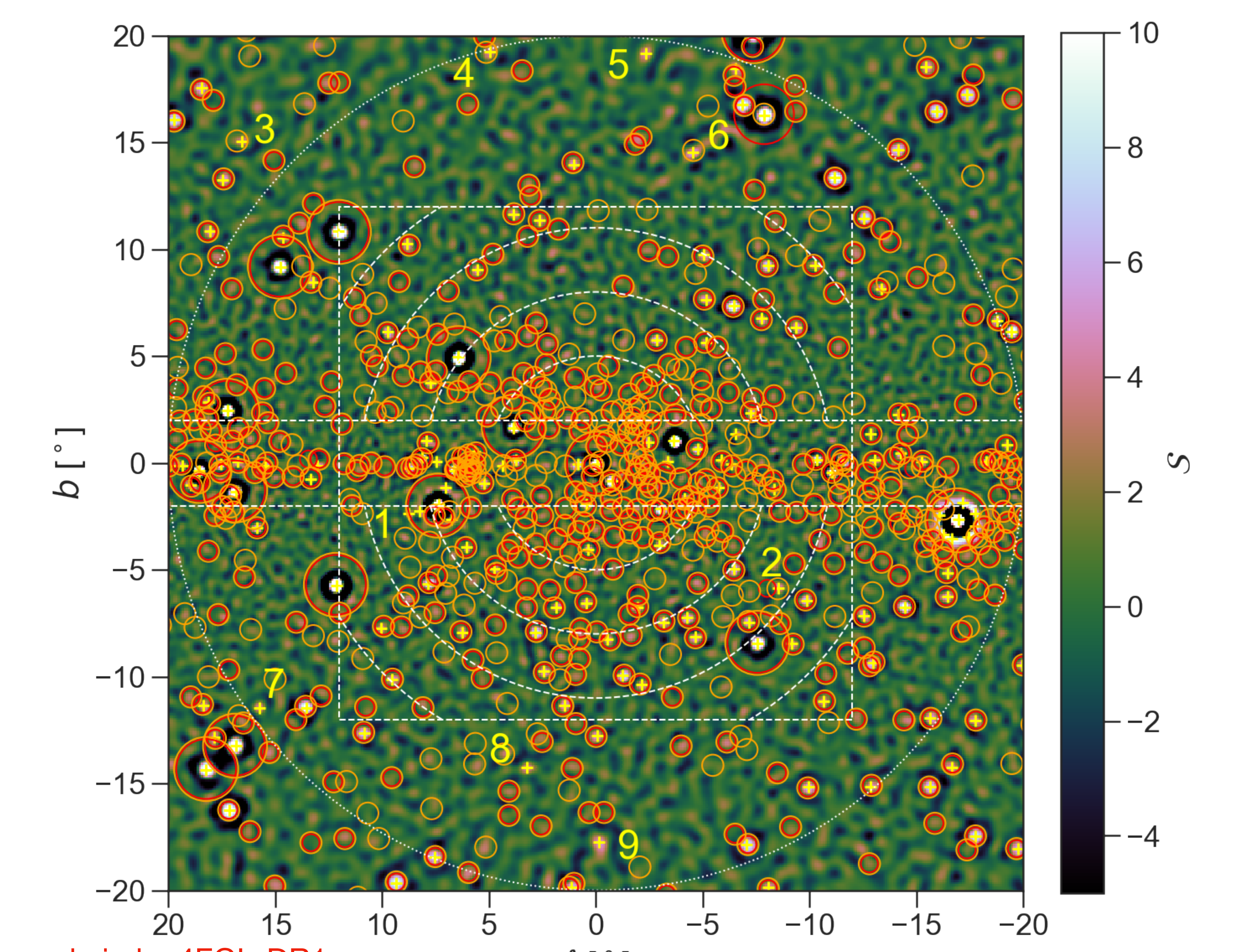


Cholis+, '20

A side note: wavelets are useful to find pt source

Catalog	Exposure	Date released
1FGL	1 year	2010
2FGL	2 year	2011
3FGL	4 year	2015
4FGL-DR1	8 year	2019
4FGL-DR2	10 year	2020
4FGL-DR3	12 year	2022

#2, #3, #4, #6 got confirmed in 4FGL-DR2/DR3



red circle: 4FGL-DR1,
orange circle: 4FGL-DR3

A side note: wavelets are useful to find pt source

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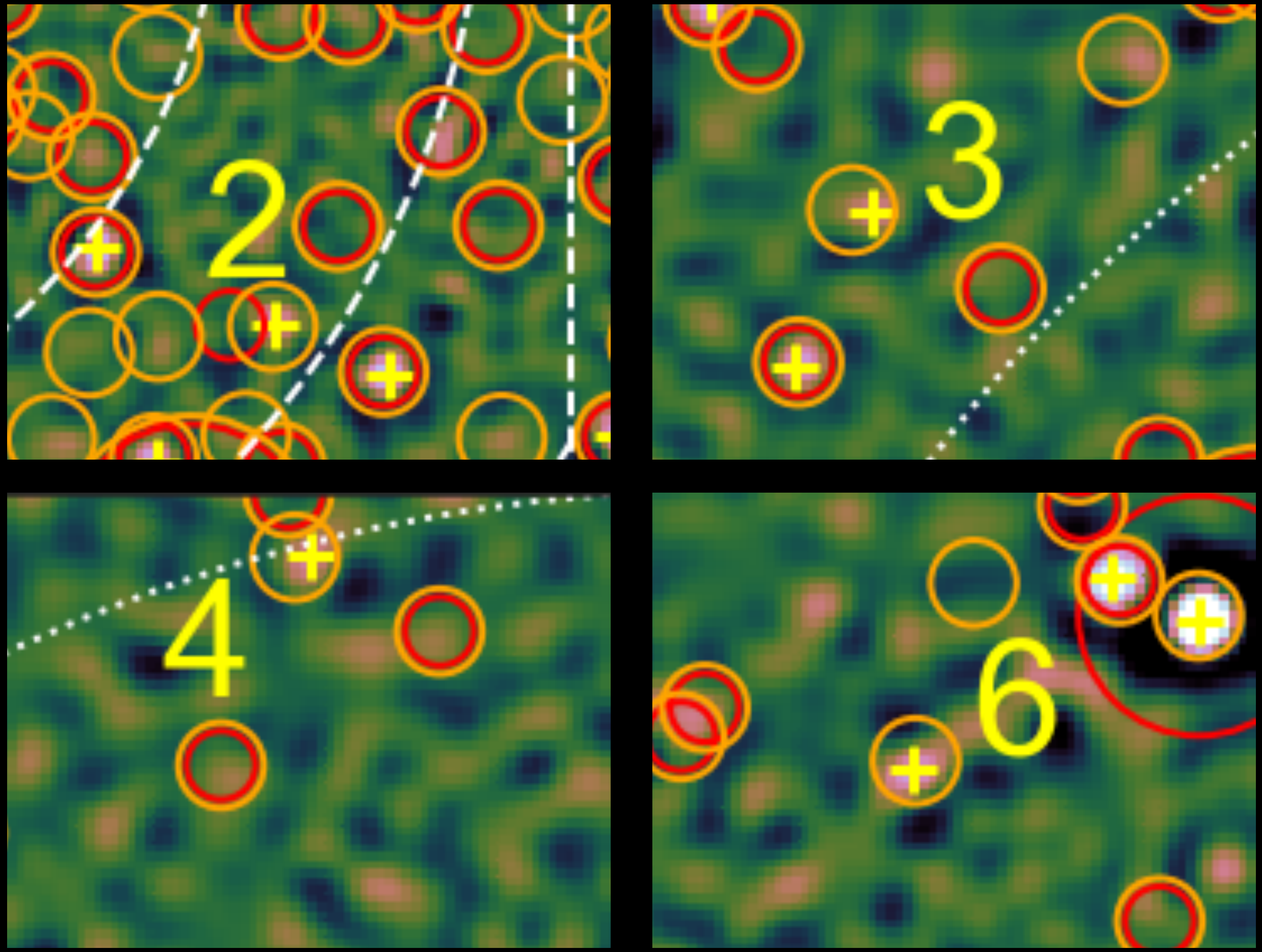
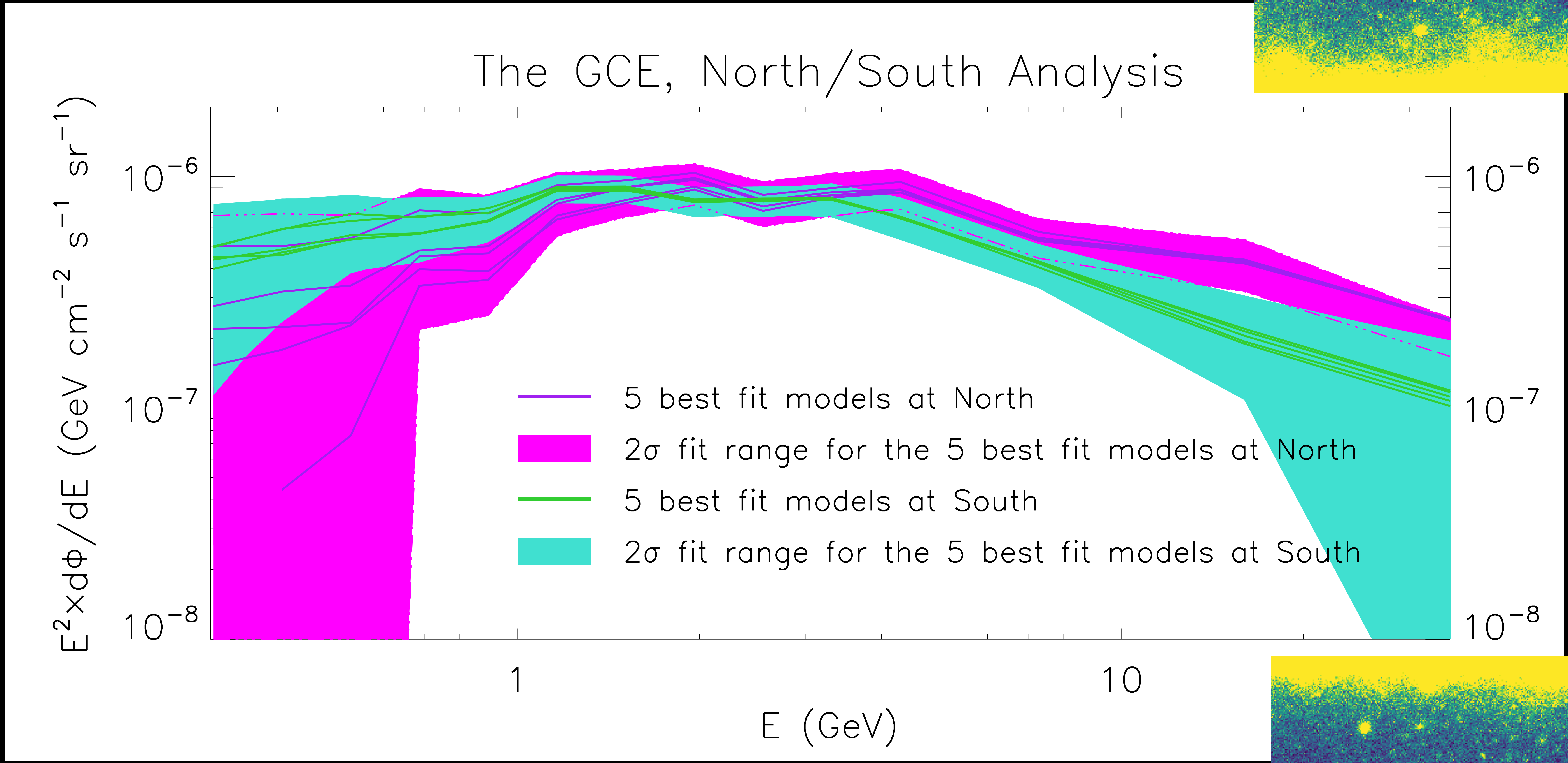
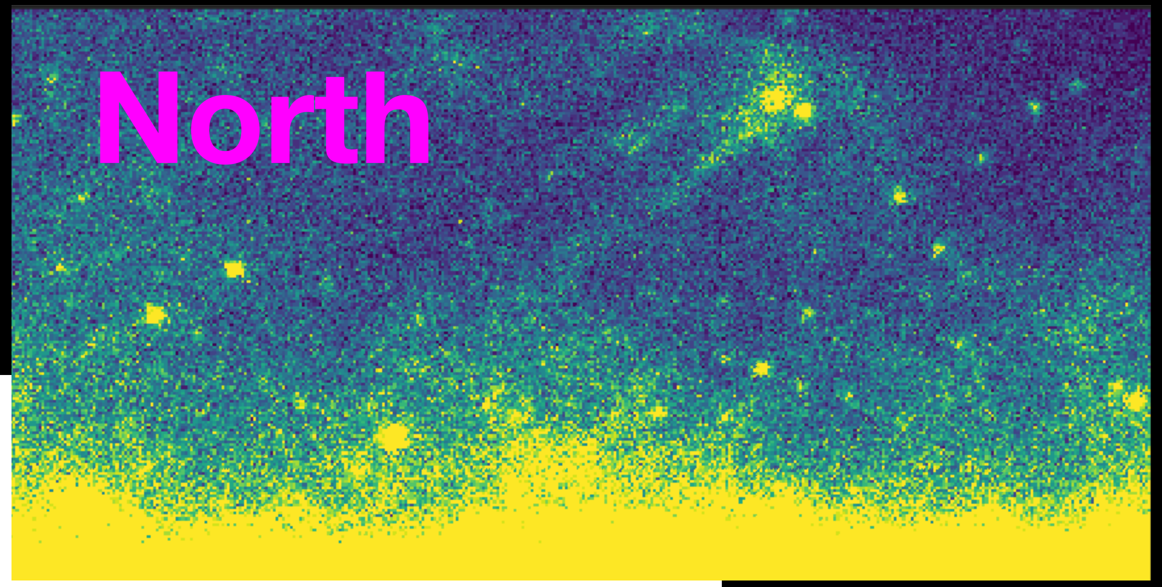
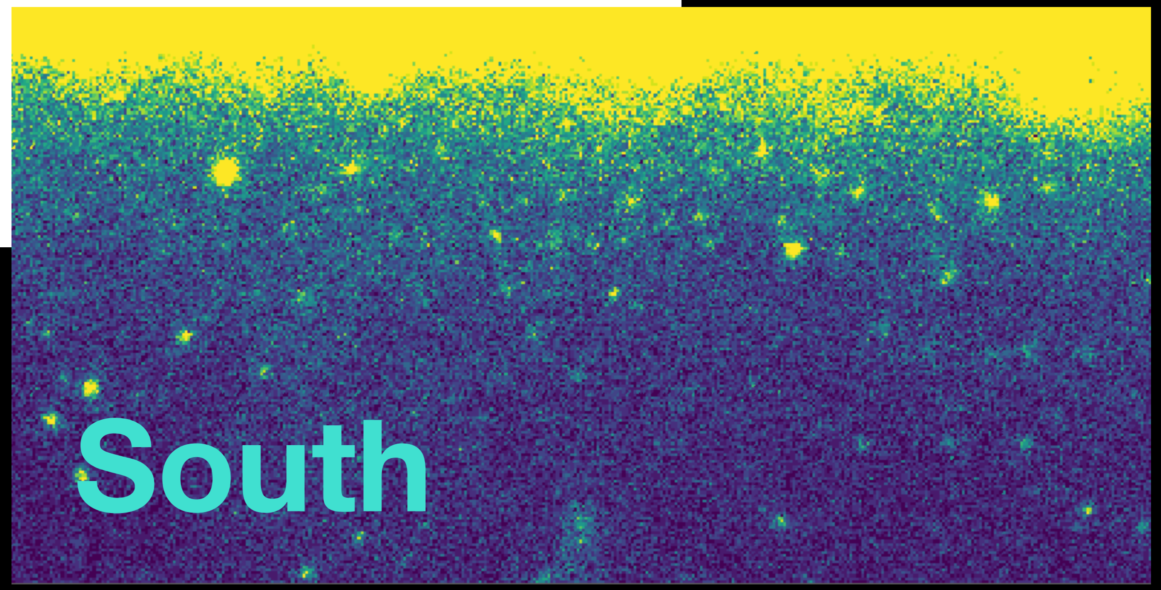


red circle: 4FGL-DR1
orange circle: 4FGL-DR3

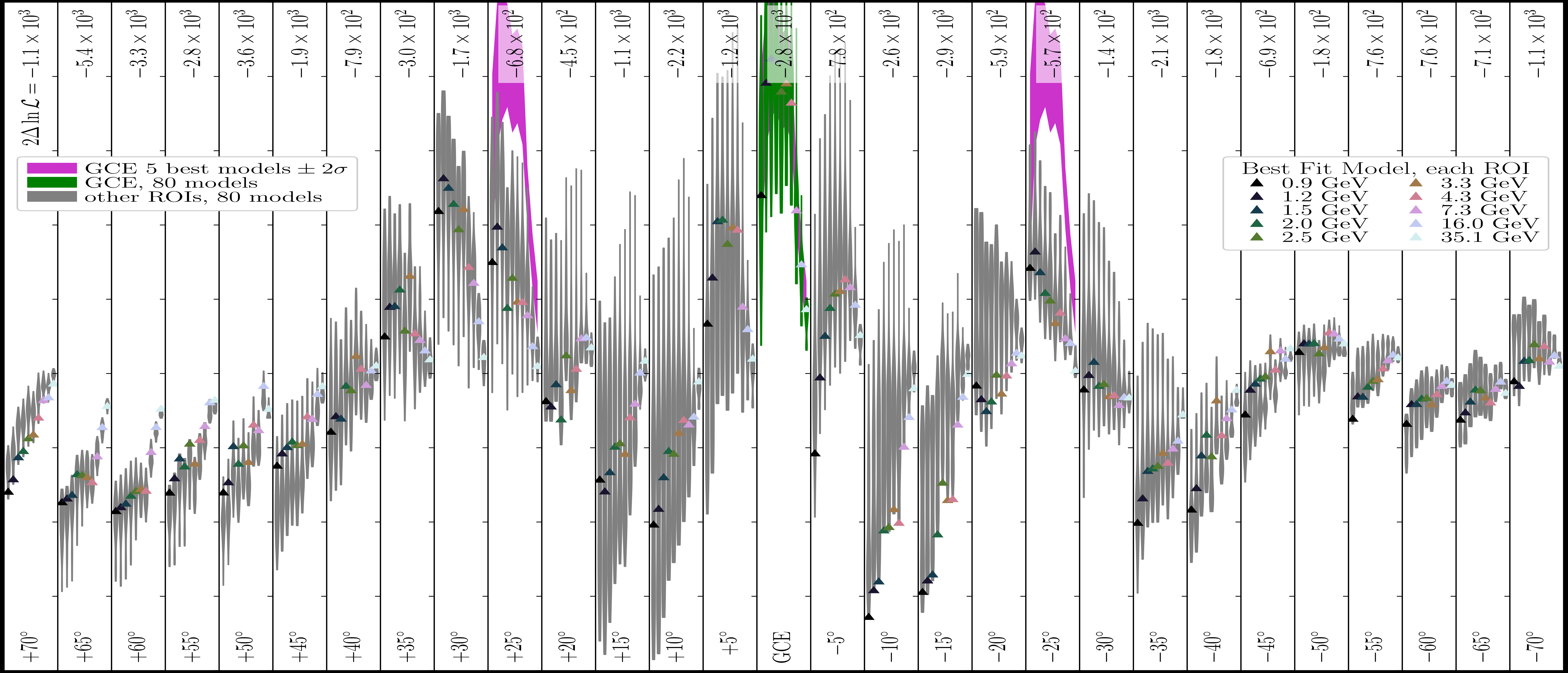
Northern vs southern sky





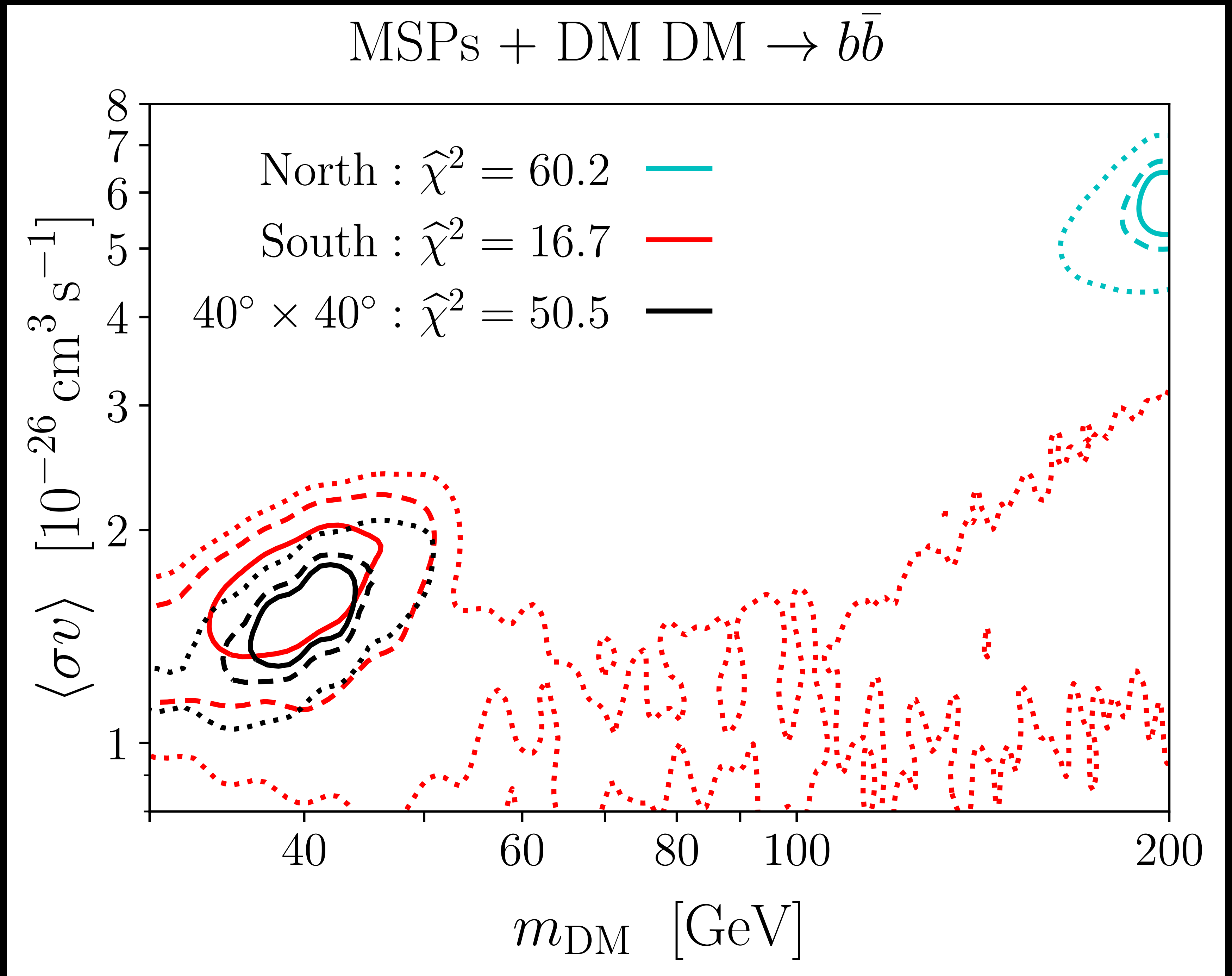


Fit for 22 translated regions-of-interest (ROI)

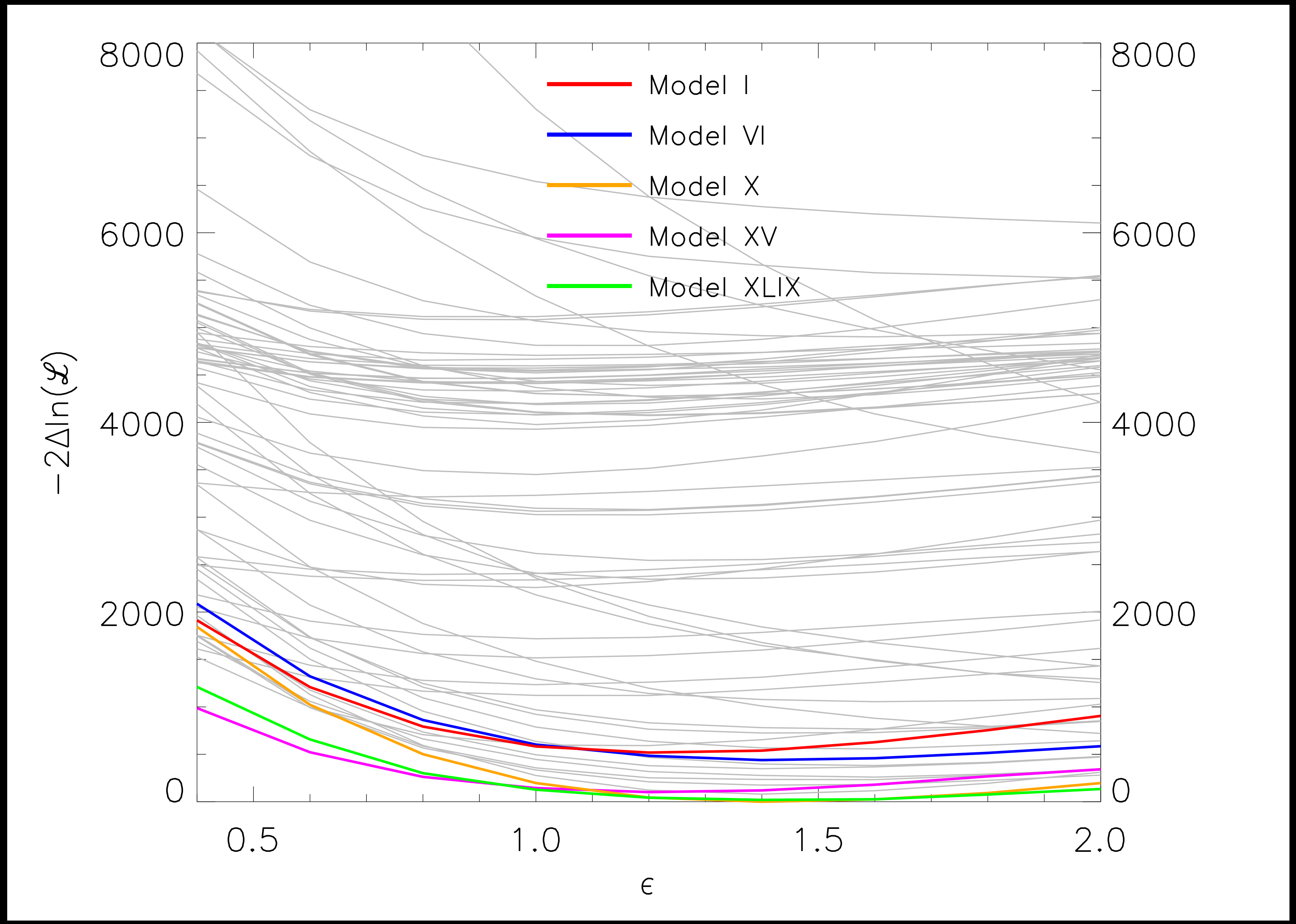


WIMP + MSPs for northern sky?

Model	$\widehat{\chi}^2$/dof	$\hat{p}$-value	ROI
MSPs	76.6/13	$< 10^{-6}$	$40° \times 40°$
	34.5/13	1.0×10^{-3}	southern sky
	194.5/13	$< 10^{-6}$	northern sky
DM DM $\to b\bar{b}$	50.5/12	1.1×10^{-6}	$40° \times 40°$
	17.1/12	0.15	southern sky
	88.0/12	$< 10^{-6}$	northern sky
MSPs+DM DM $\to b\bar{b}$	50.5/11	$< 10^{-6}$	$40° \times 40°$
	16.7/11	0.12	southern sky
	60.2/11	$< 10^{-6}$	northern sky



Test the morphism of GCE



Prefer slightly oblate shape