Robustness of the Galactic Center Excess Morphology Against Masking

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New Opportunities for Particle Physics 2024, 21 July 2024

香港城市大學
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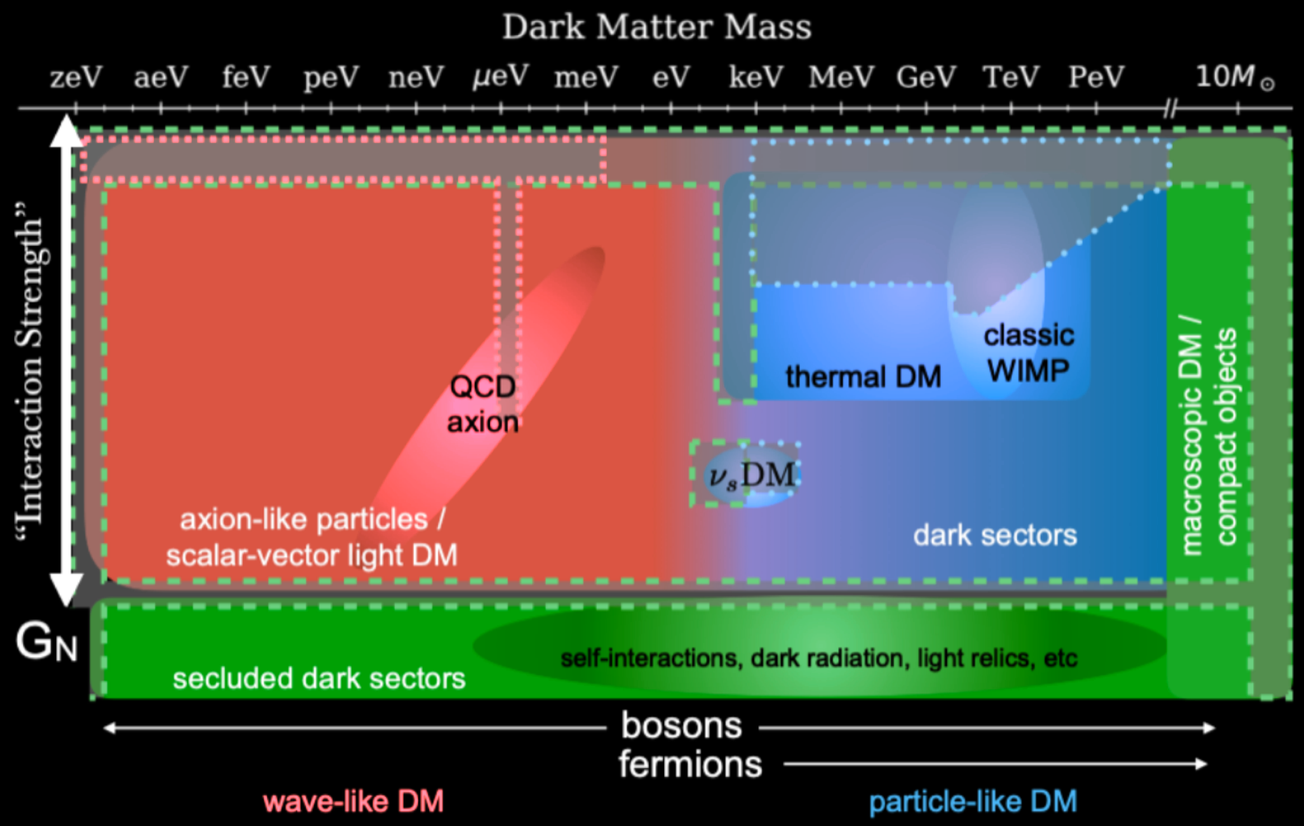
Outline

- Introduction
- The template fitting
- The characteristics of the GCE with a set of new templates
- Robustness of the Galactic Center Excess (GCE) morphology against masking
- Summary

What is dark matter?

Credit:

Credit: Snowmass report



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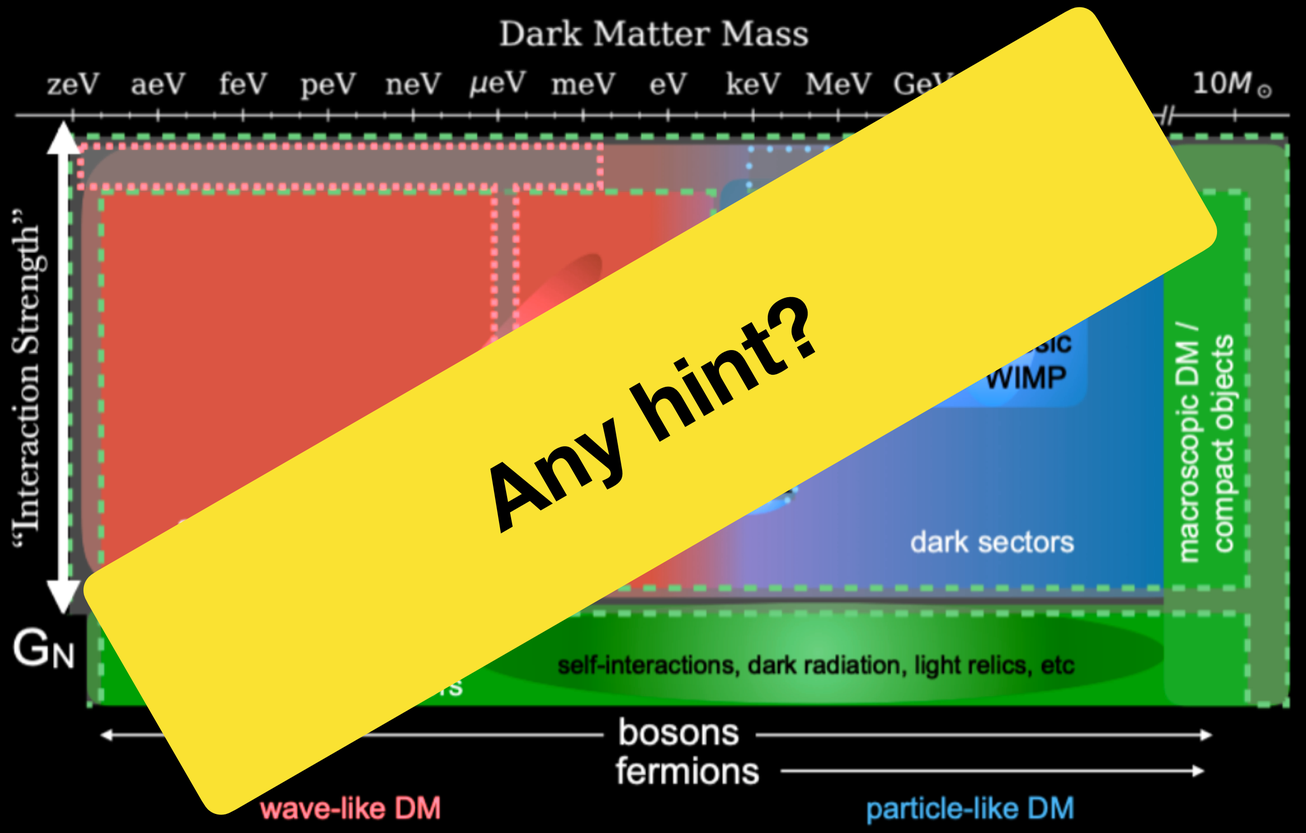
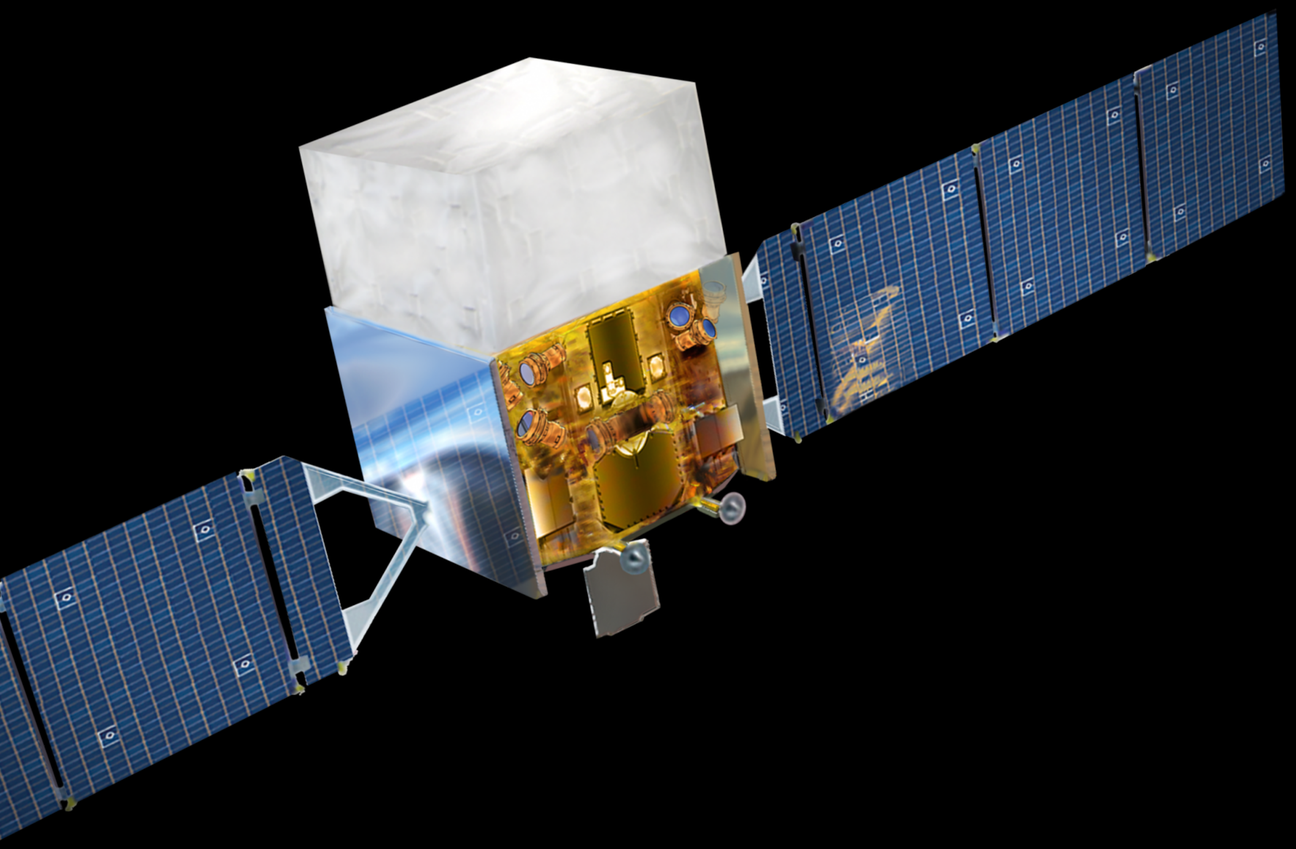
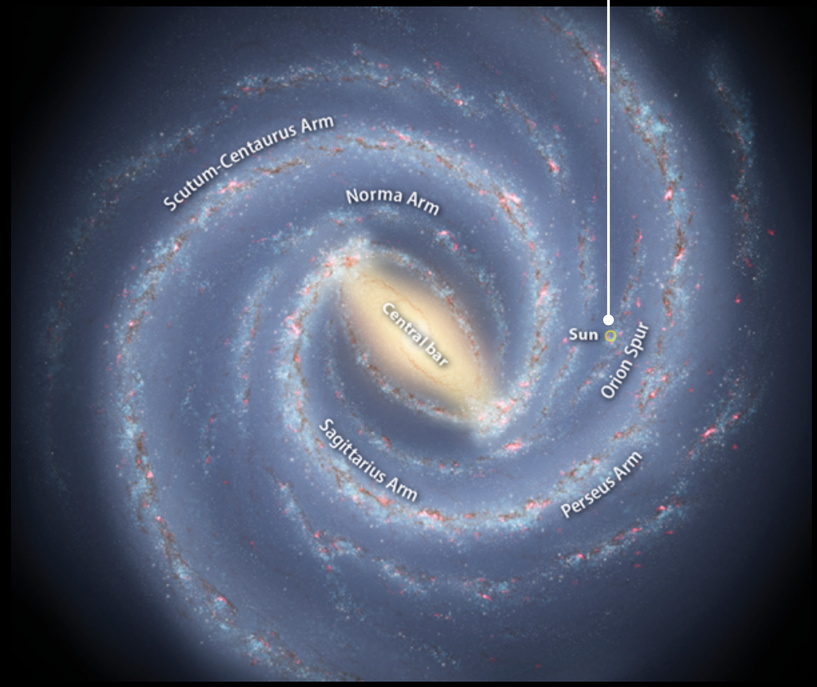
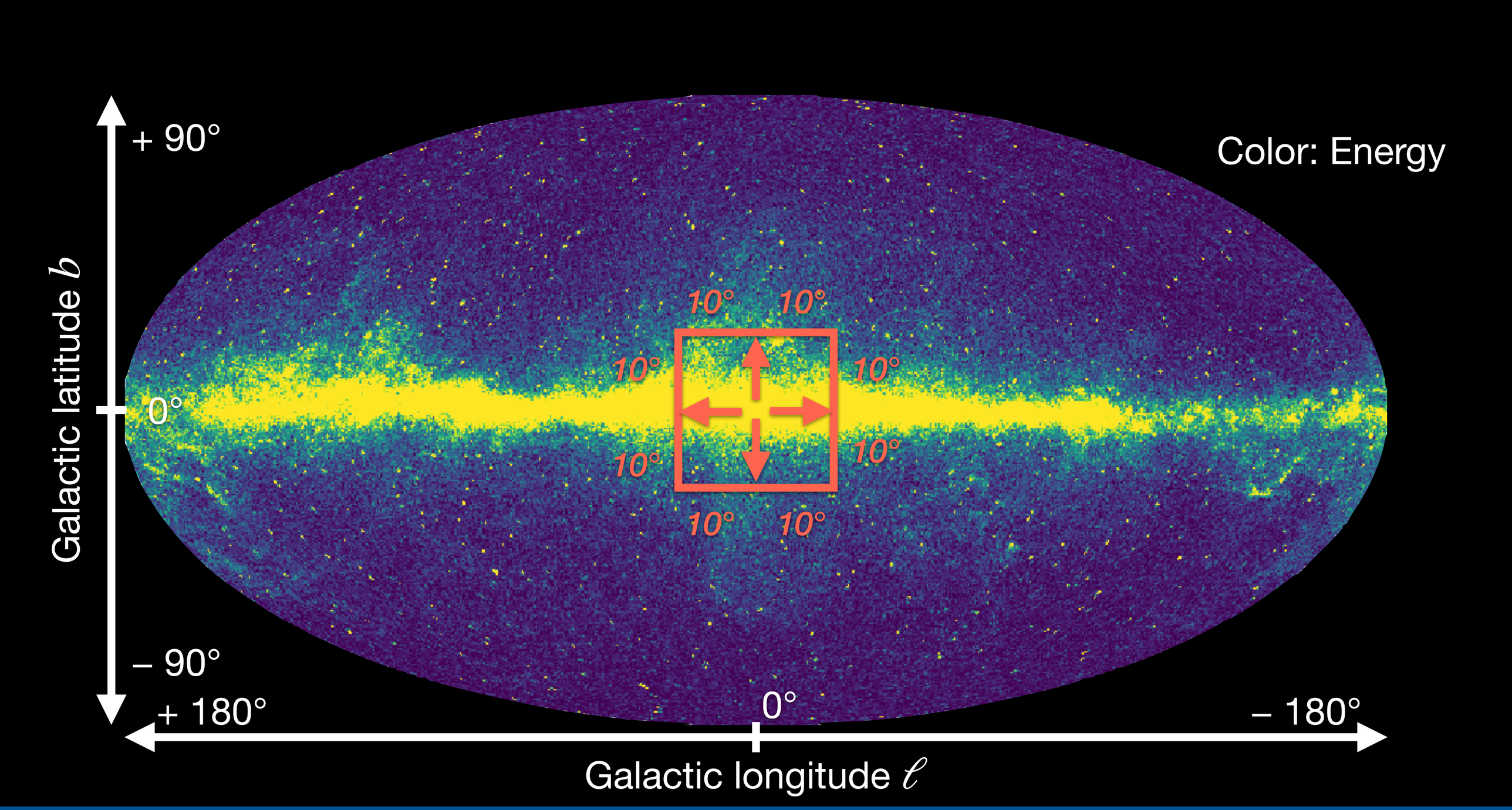


The Fermi Large Area Telescope



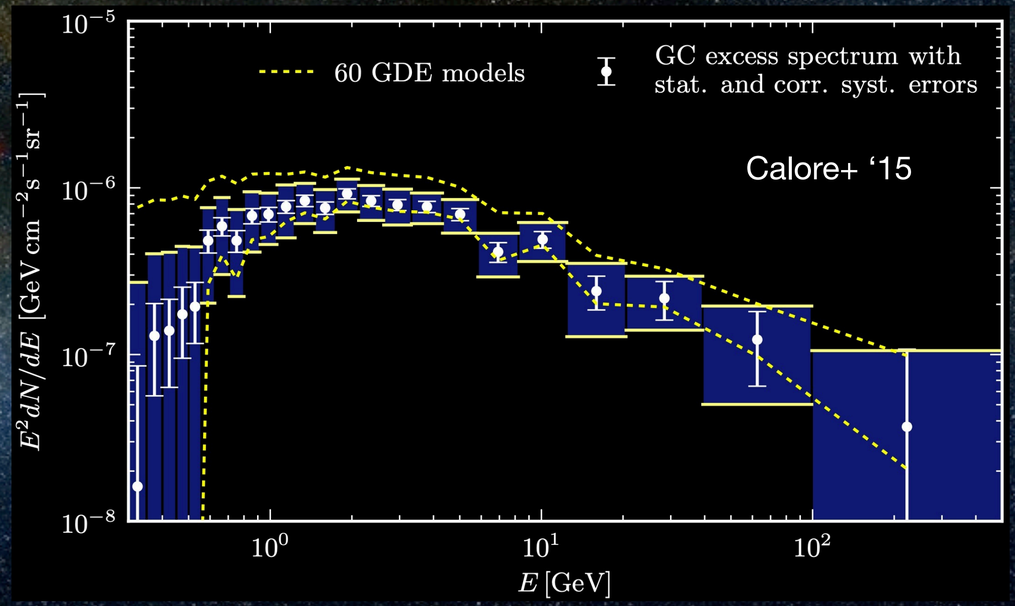


2008—today


Color: Energy
+ 90°
Galactic latitude b
0°
– 90°
+ 180°
0°
– 180°
Galactic longitude ℓ
10°
10°
10°
10°
10°
10°
10°
10°

The Galactic Center Excess

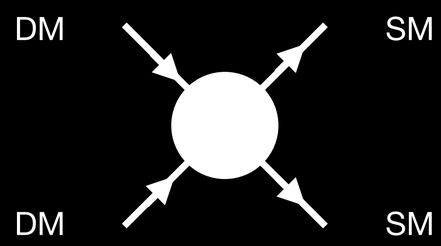
- Goodenough & Hooper (2009) found an excess of γ-ray photos, peaked around 1– 4 GeV, at inner ~10° regions.
- Later confirmed by Fermi-LAT collaboration and many other groups.



γ-ray energy spectrum

If GCE comes from dark matter…

- 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 abundance of dark matter (“WIMP Miracle”).

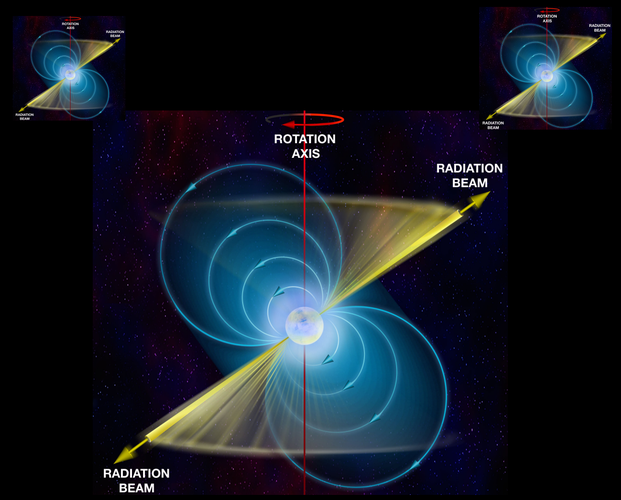


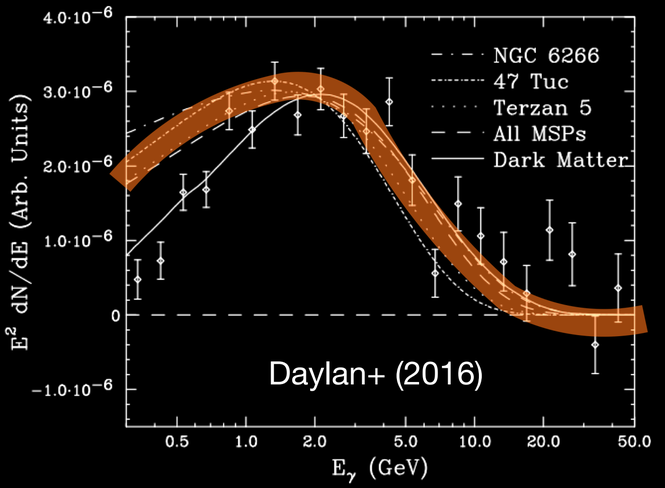
m_χ ~10-100 GeV

$\langle \sigma v \rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

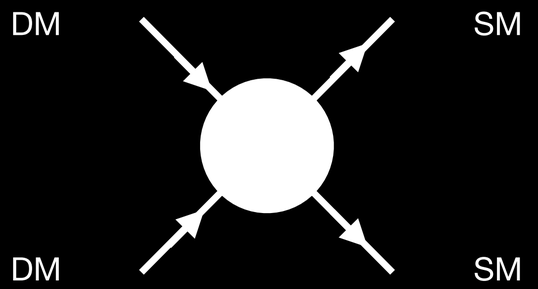
Other explanation — pulsars

- Pulsars are rapidly spinning neutron stars.
- Among pulsars, millisecond pulsars give the correct spectra of the GCE.
- Although we have not yet observed any millisecond pulsar at the Galactic center, the GCE could be from a population of faint millisecond pulsars there.

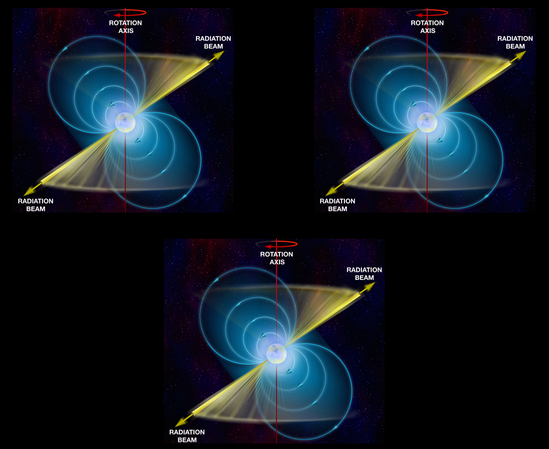




What is the origin of the GCE?

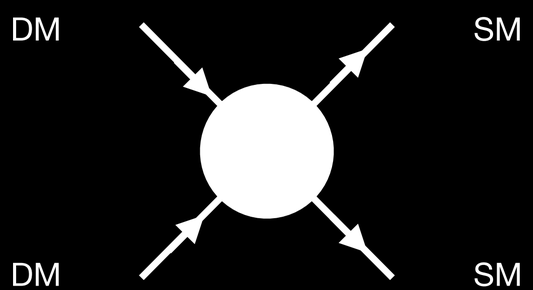


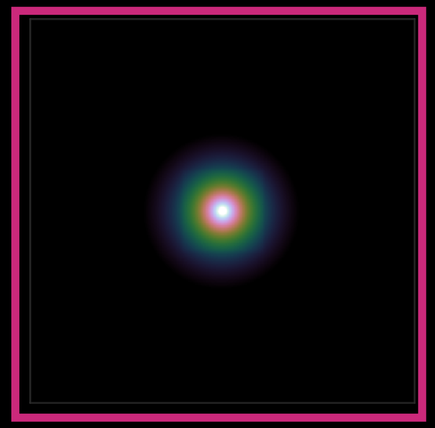
Dark matter annihilation



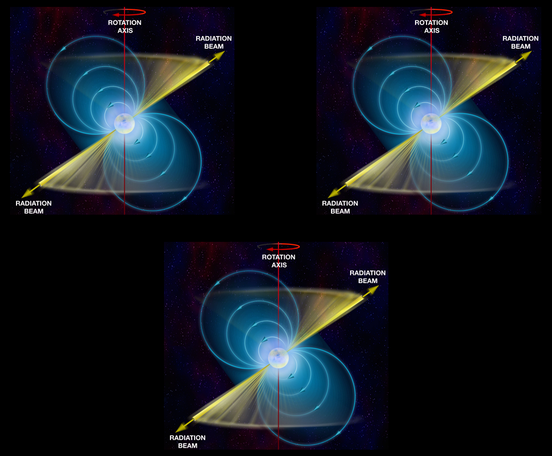
A new population of millisecond pulsars

Looking at the small-scale power

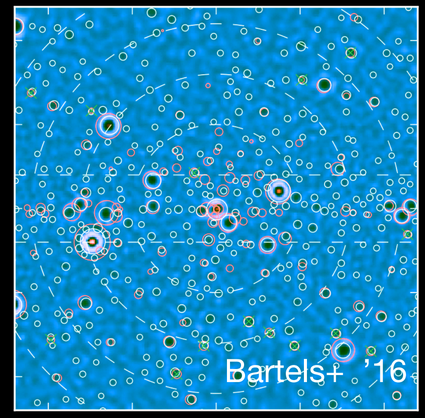




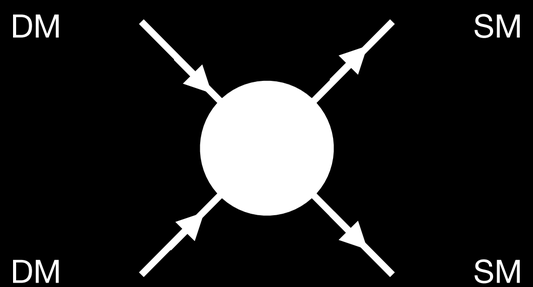
Smooth

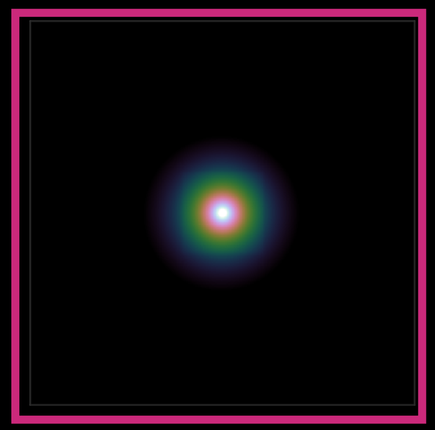


Clumpy

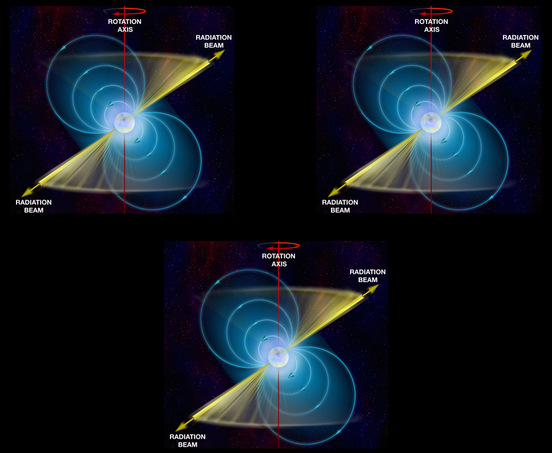


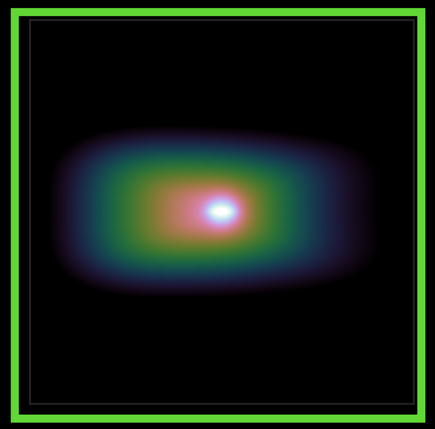
Looking at the morphism





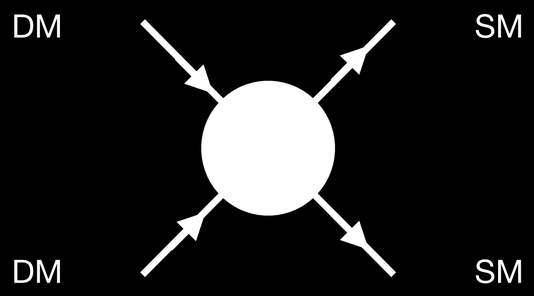
Spherical

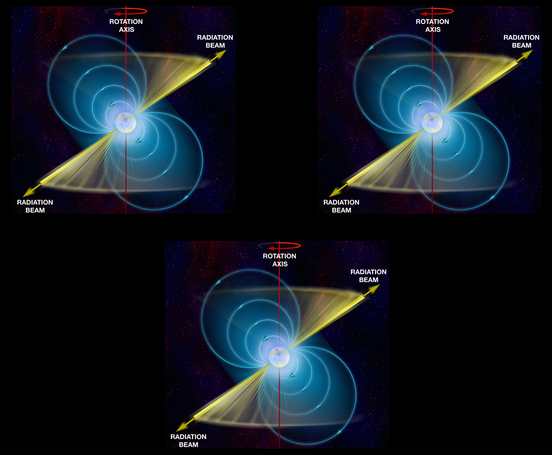




Boxy

The GCE status 2016—2018

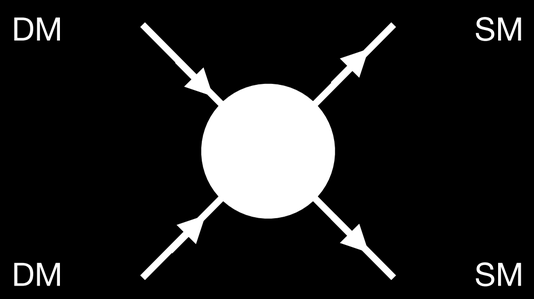


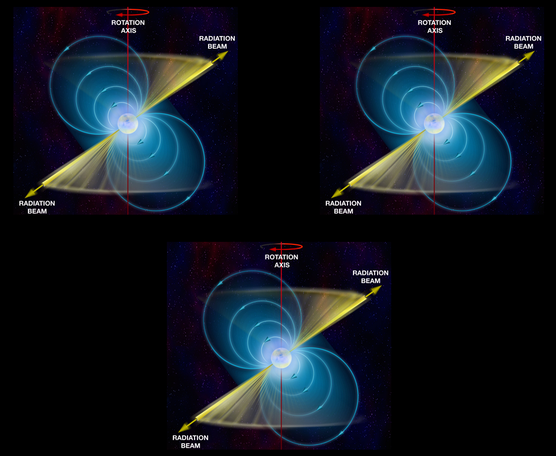


Small-Scale Power

Non-Poissonian Template Fitting: Lee+ ’16

The GCE status 2016—2018



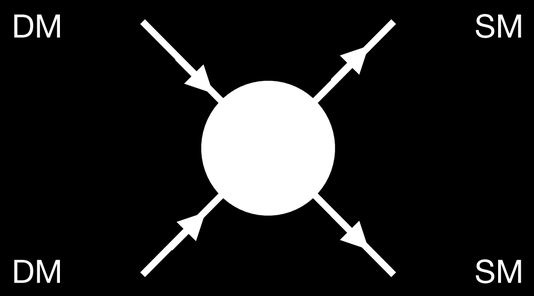


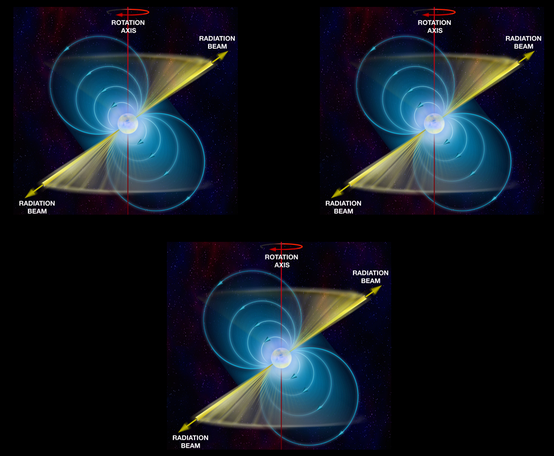
Small-Scale Power

Non-Poissonian Template Fitting: Lee+ ’16

Wavelet: Bartels+ ’16

The GCE status 2016—2018





Small-Scale Power

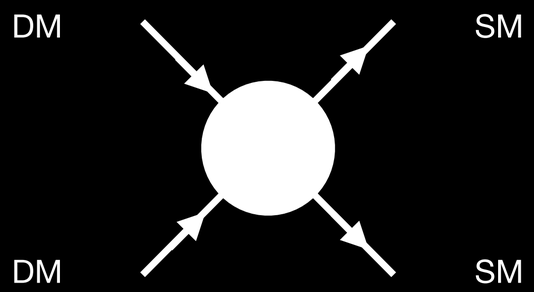
Non-Poissonian Template Fitting: Lee+ ’16

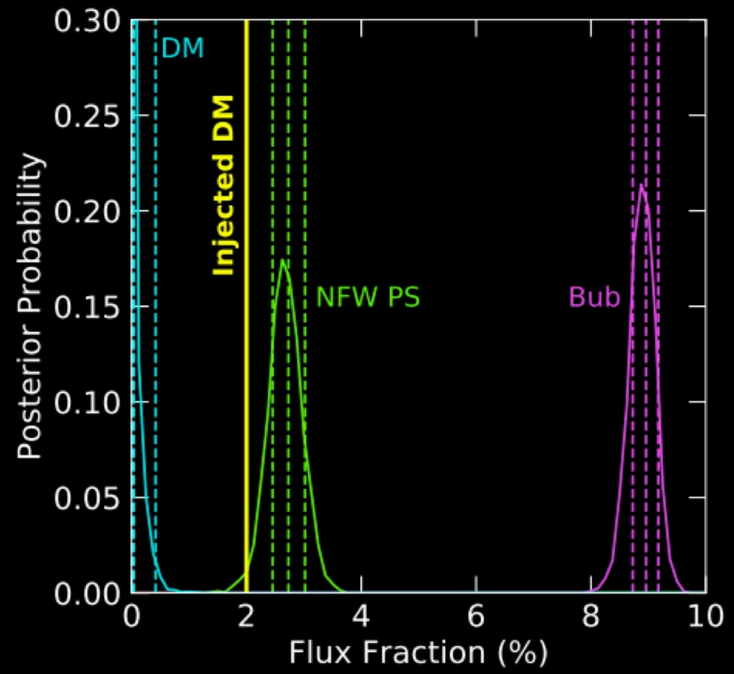
Wavelet: Bartels+ ’16

Morphism

Boxy Bulge: Macias+ ’16, ’17, Bartels+ ’17, Macias+ ’18

The GCE status after 2019





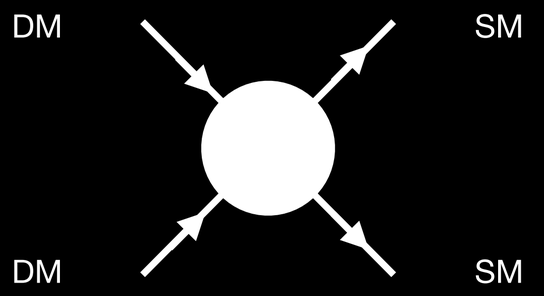
~~Non-Poissonian Template Fitting: Lee+ ’16~~

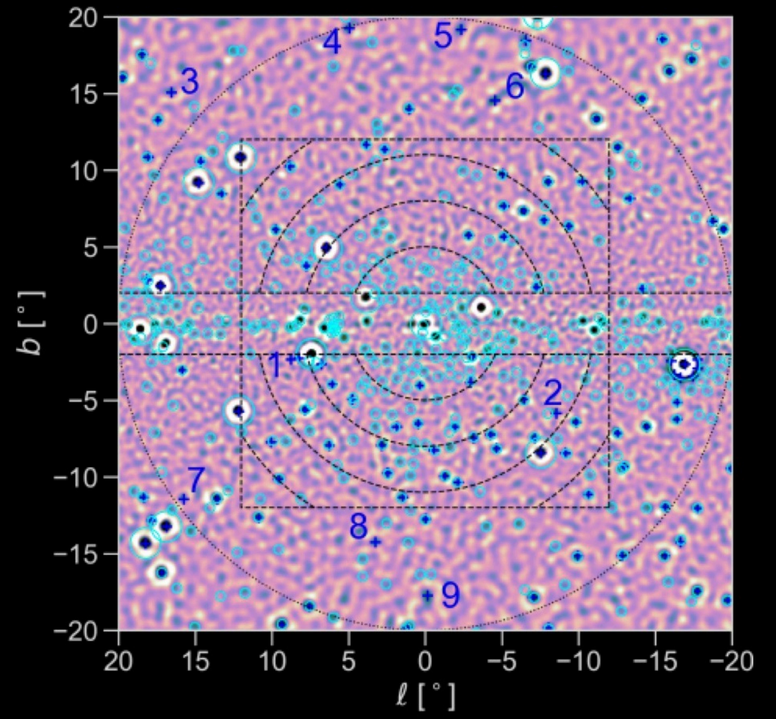
Wavelet: Bartels+ ’16

Boxy Bulge: Macias+ ’16, ’17, Bartels+ ’17, Macias+ ’18

Leane & Slatyer ’19, ’20, ’20, Chang+ ’19, Buschmann+ ’20,…

The GCE status after 2019





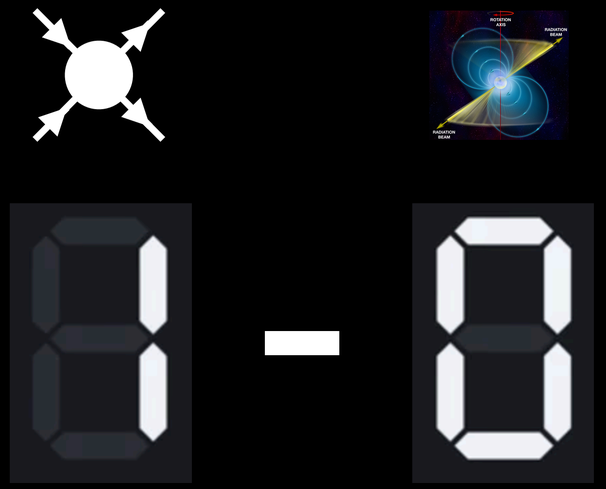
~~Non-Poissonian Template Fitting: Lee+ '16~~

~~Wavelet: Bartels+ '16~~

YZ, McDermott, Cholis & Fox '20

Boxy Bulge: Macias+ '16, '17, Bartels+ '17, Macias+ '18

The debate on the morphism



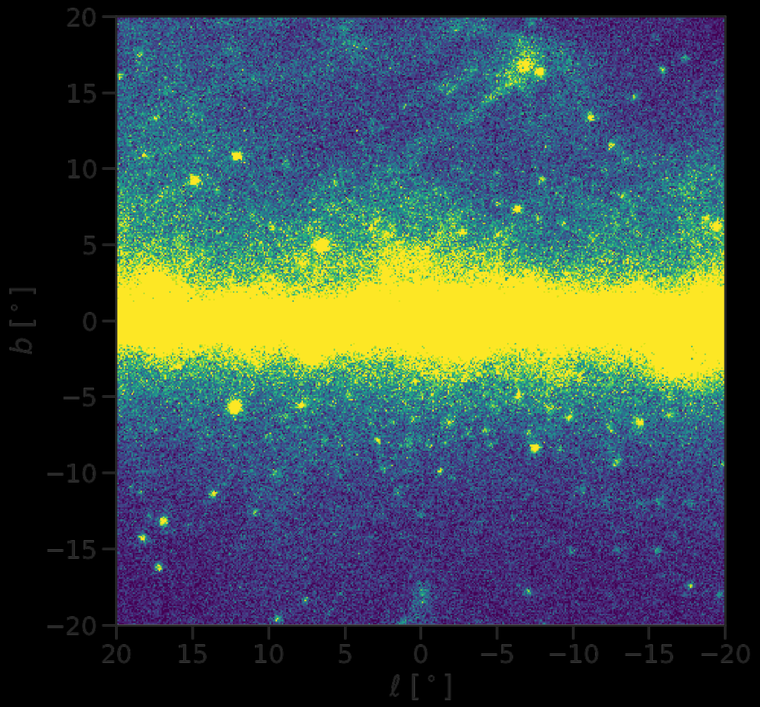
?

Spherical Shape:
Di Mauro ’20,
Cholis, YZ, McDermott &
Surdutovich ’21,
McDermott, YZ, Ilias ’22

Boxy Bulge:
Macias+ ’18, ’19,
Pohl+ ’20
Song+ ‘24

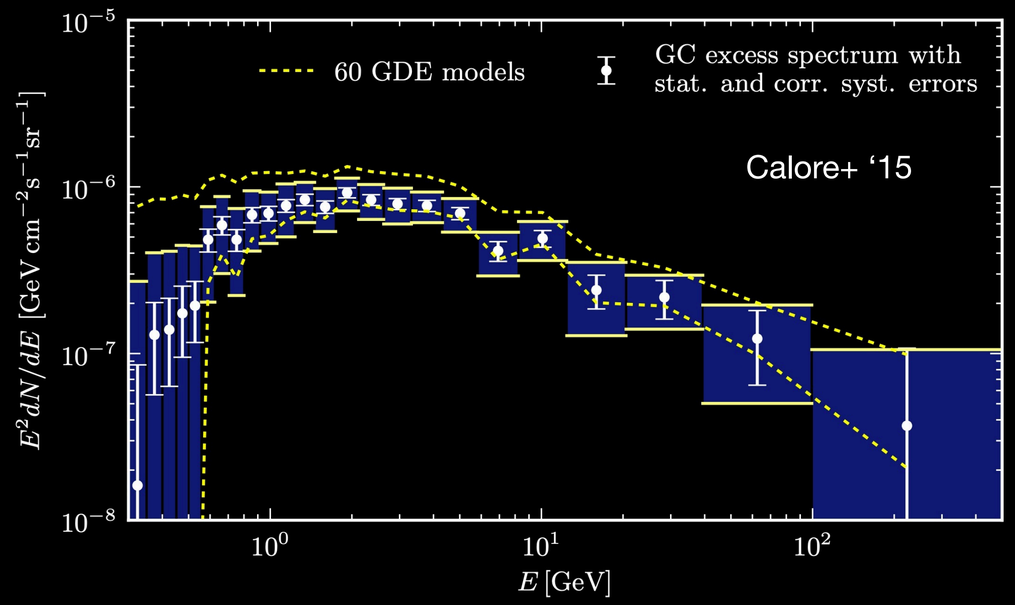
Template fitting

Fermi data

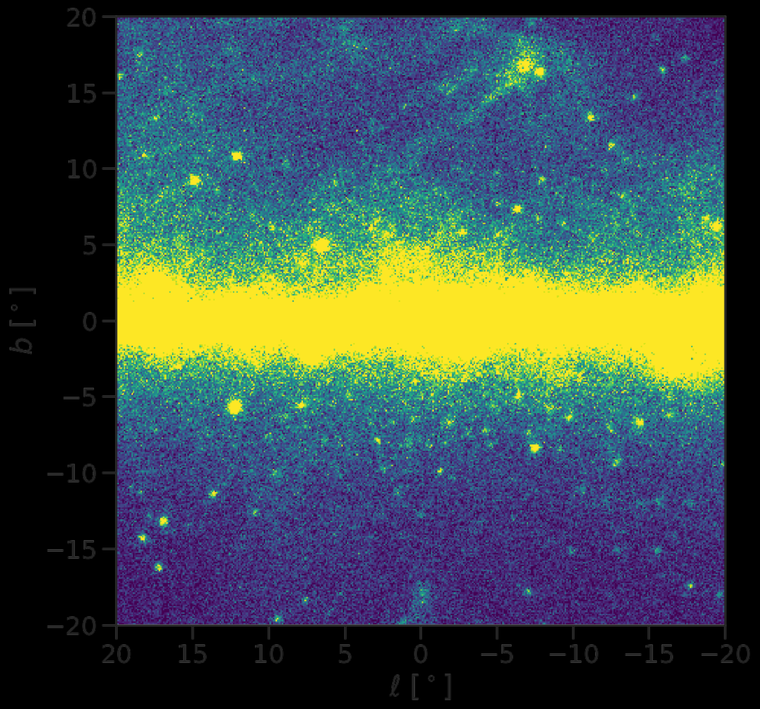


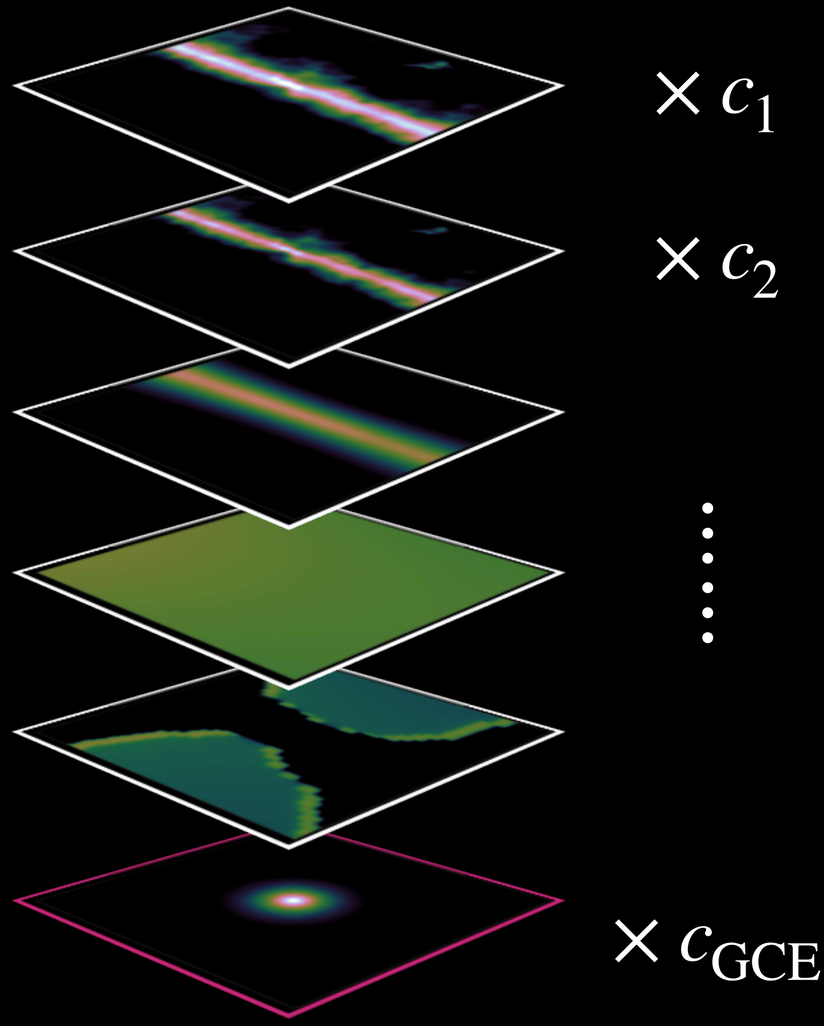
Template fitting

GCE spectrum



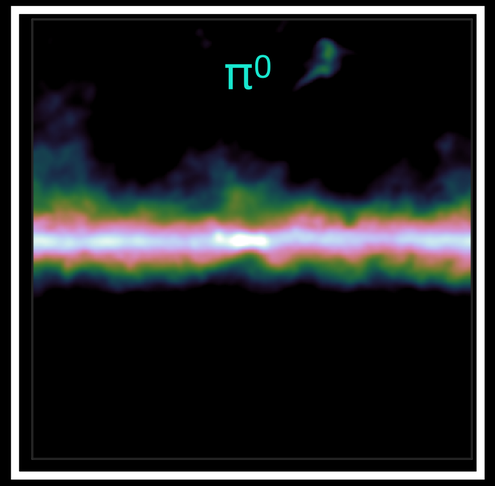
Fermi data **vs.** ***Weighted* sum over all background & GCE templates**

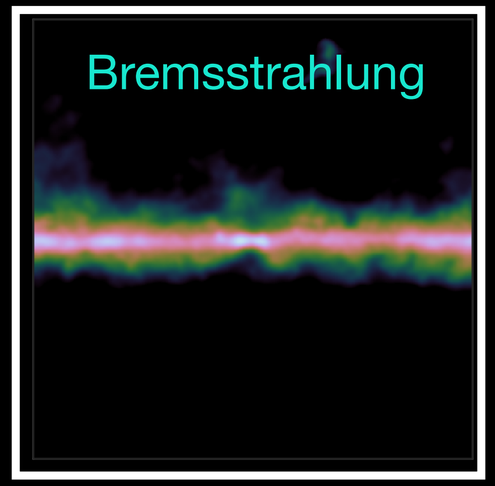


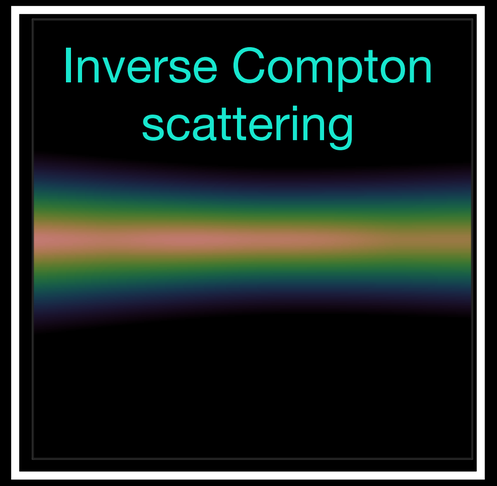


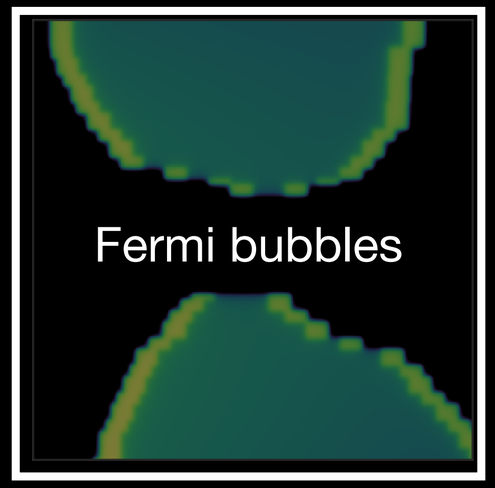
Templates

* Take one energy bin as an example

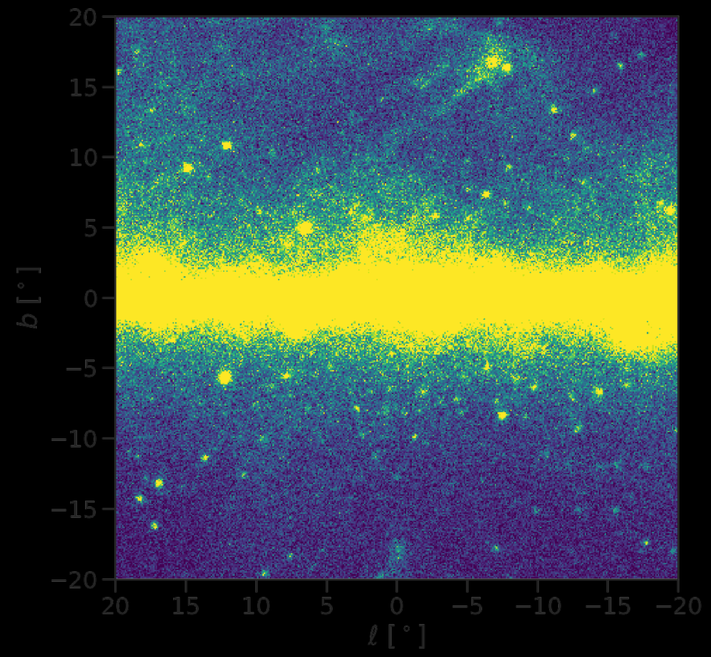






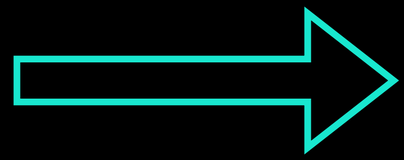


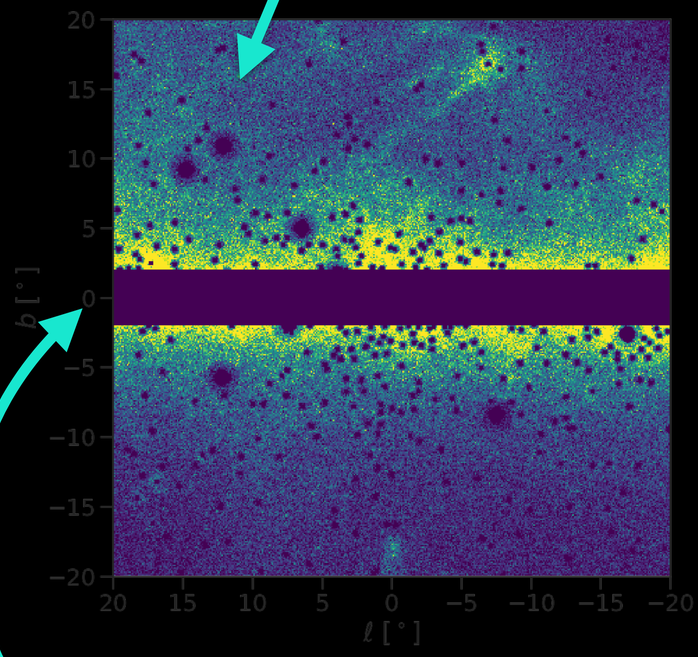
Fermi data



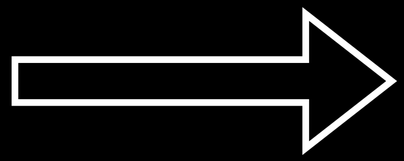
Removing point source regions

Masking





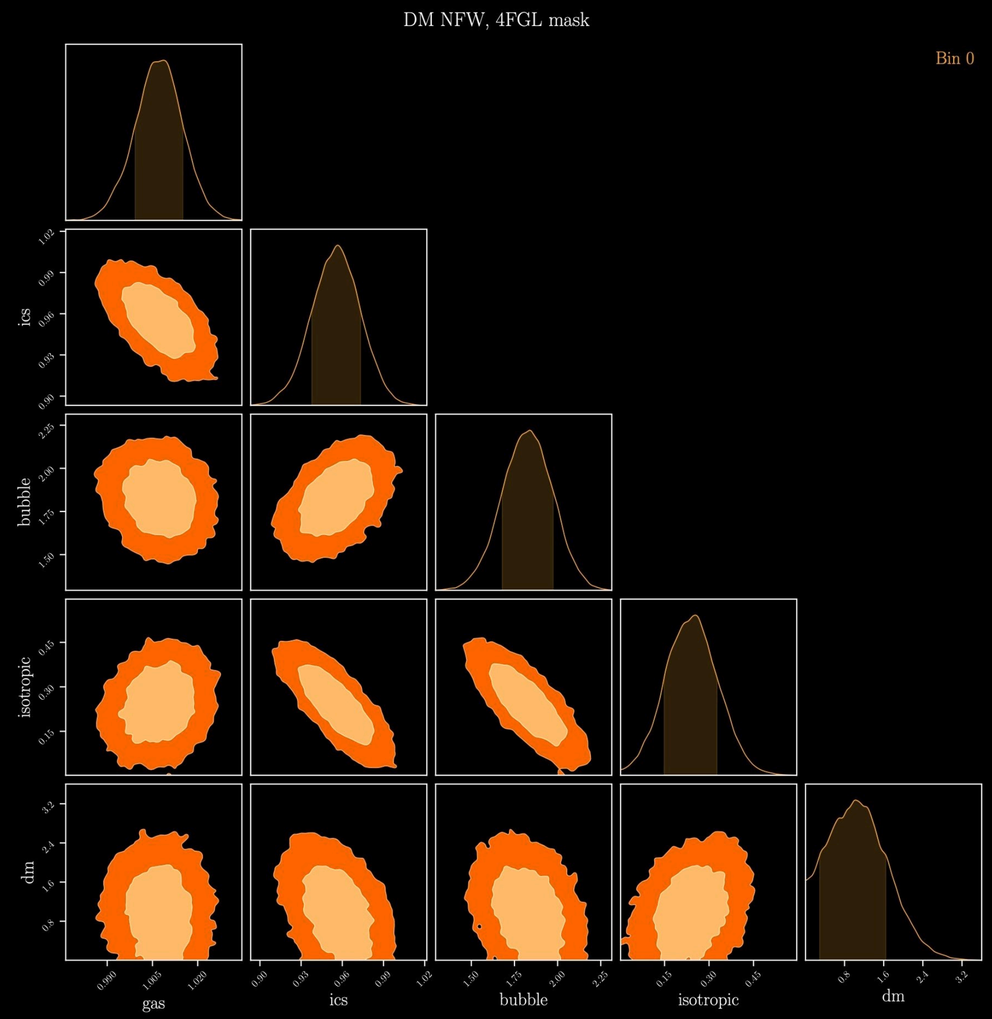
Fitting

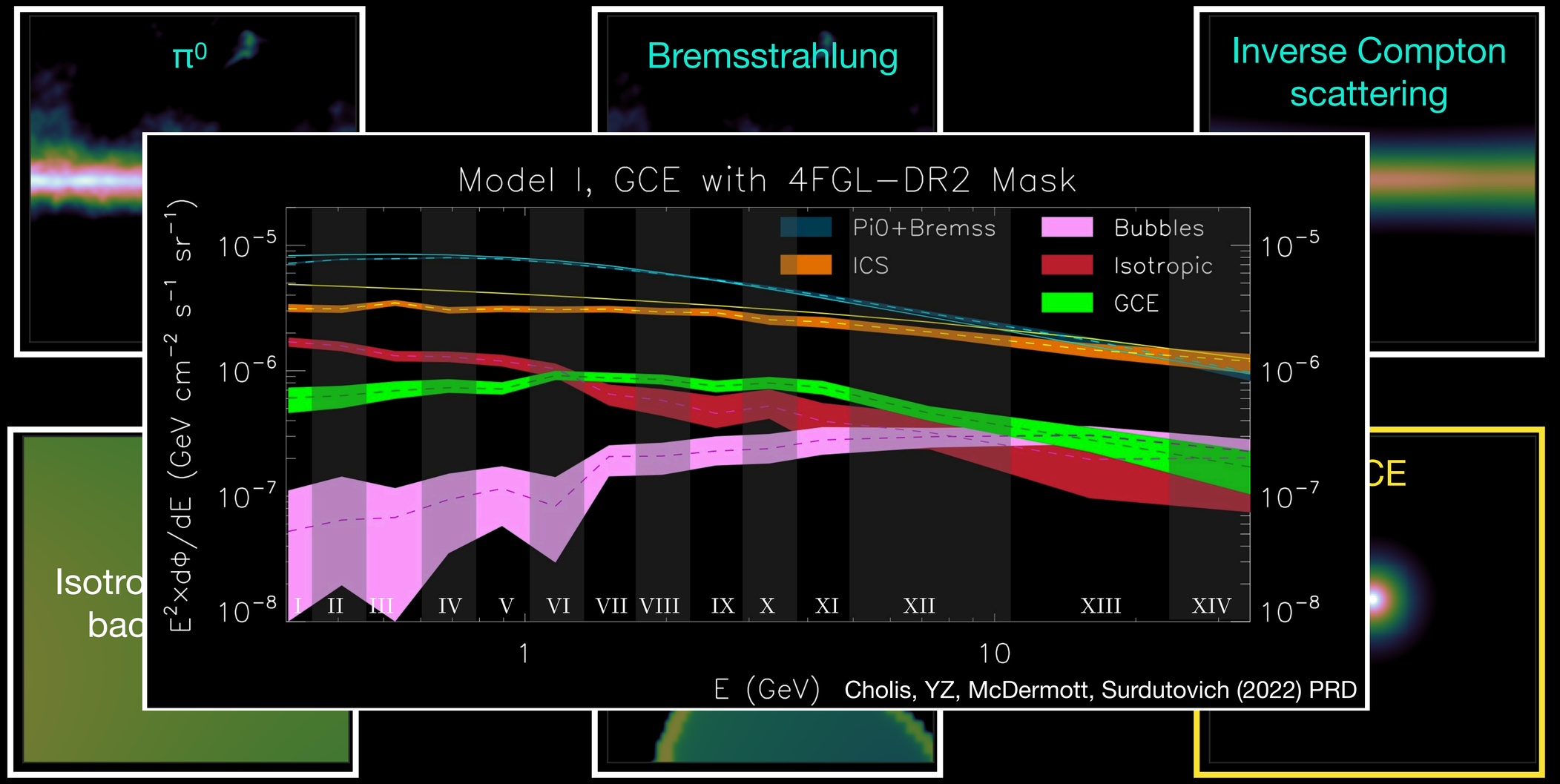


Removing the Galactic disk region

Fitting

- We split the Fermi data in 14 energy bins.
- We then perform the masking & fitting ***energy bin-by-energy bin***.
- For each energy bin, we run Markov chain Monte Carlo to get the statistics of the ***weights*** of the templates.




π0
Bremsstrahlung
Inverse Compton scattering
Isotro
bac
CE
Model I, GCE with 4FGL−DR2 Mask
Pi0+Bremss
ICS
Bubbles
Isotropic
GCE
$E^2 \times d\Phi/dE$ (GeV cm^{-2} s^{-1} sr^{-1})
10^{-5}
10^{-6}
10^{-7}
10^{-8}
I II III IV V VI VII VIII IX X XI XII XIII XIV
1
10
E (GeV)
Cholis, YZ, McDermott, Surdutovich (2022) PRD

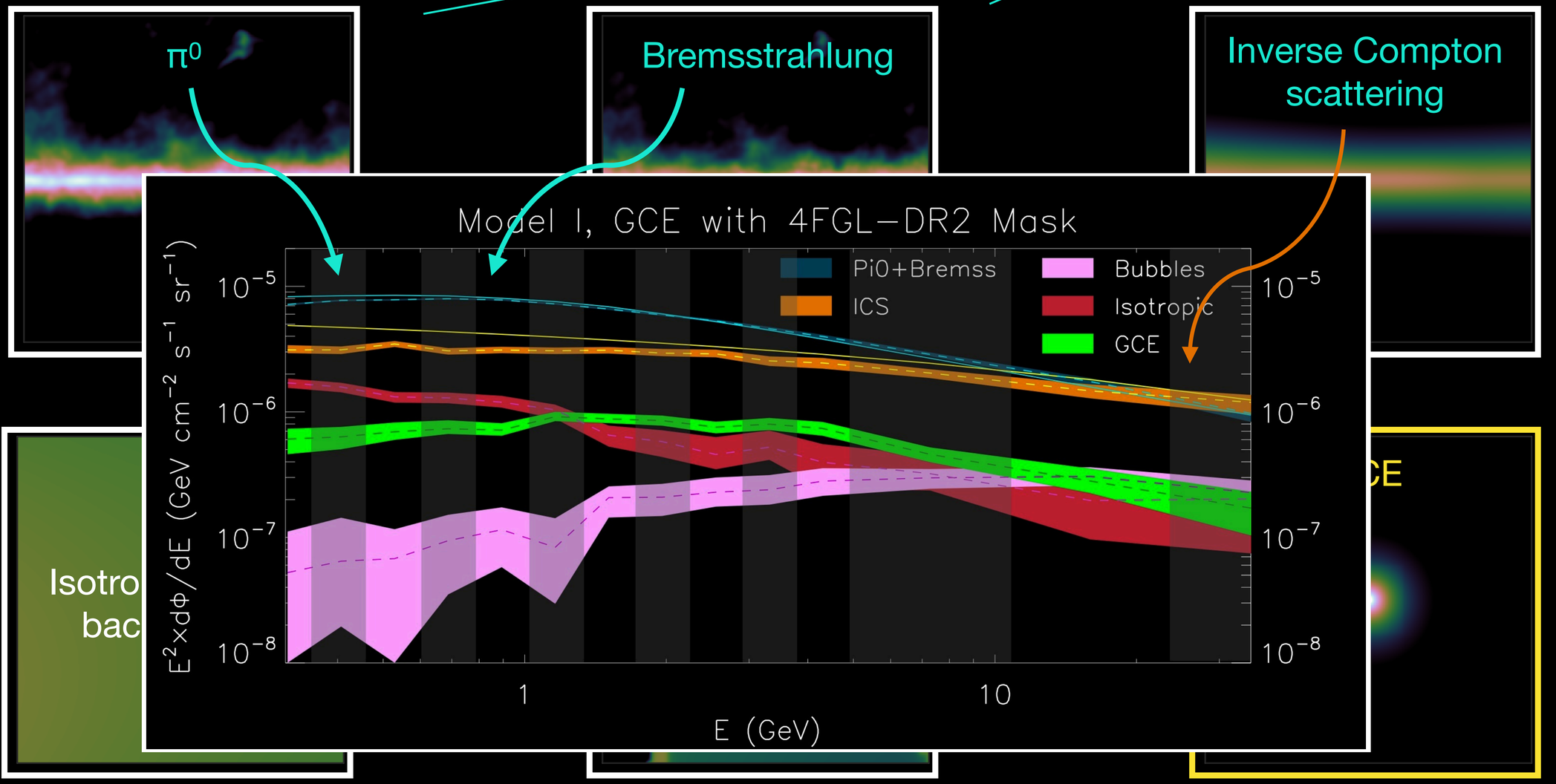
Testing GCE models

Template fitting

Which model has the best test statistics?

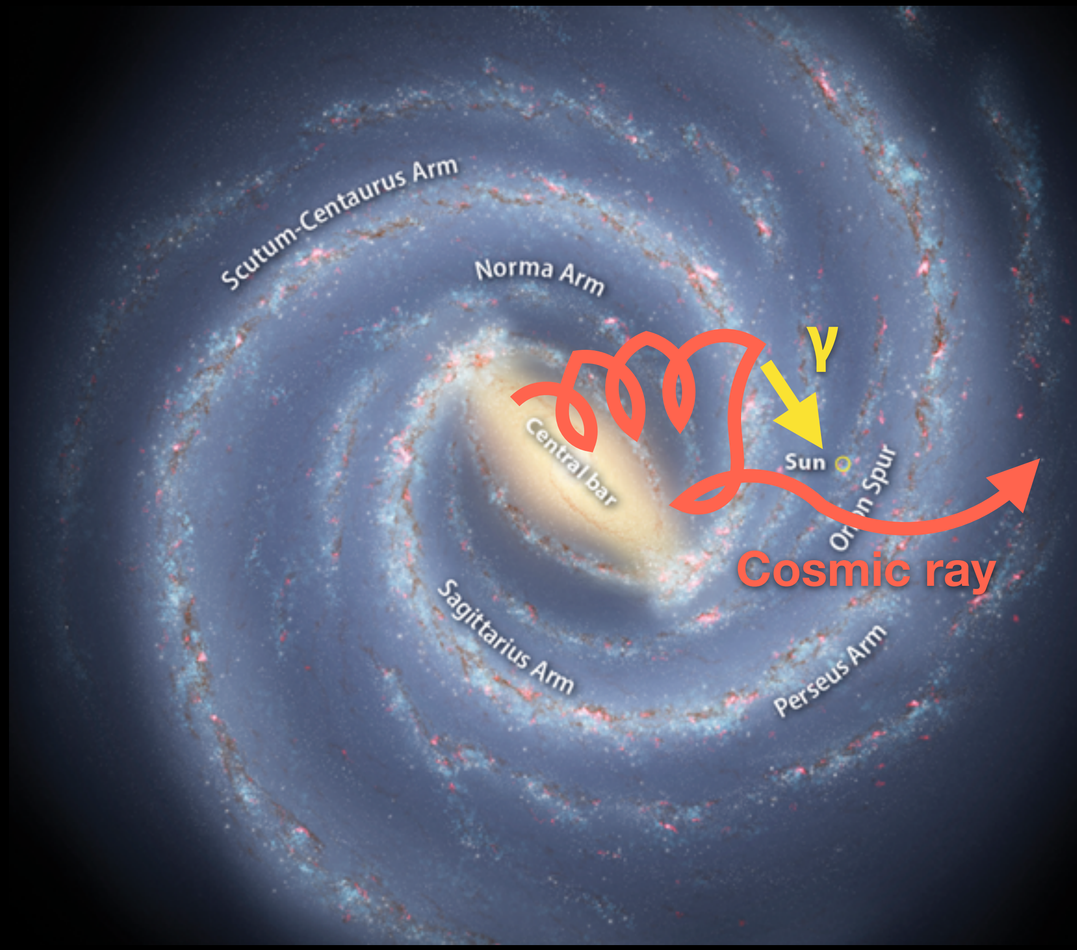
The characteristics of the GCE with a set of new templates

Galactic Diffuse γ-ray Emissions



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

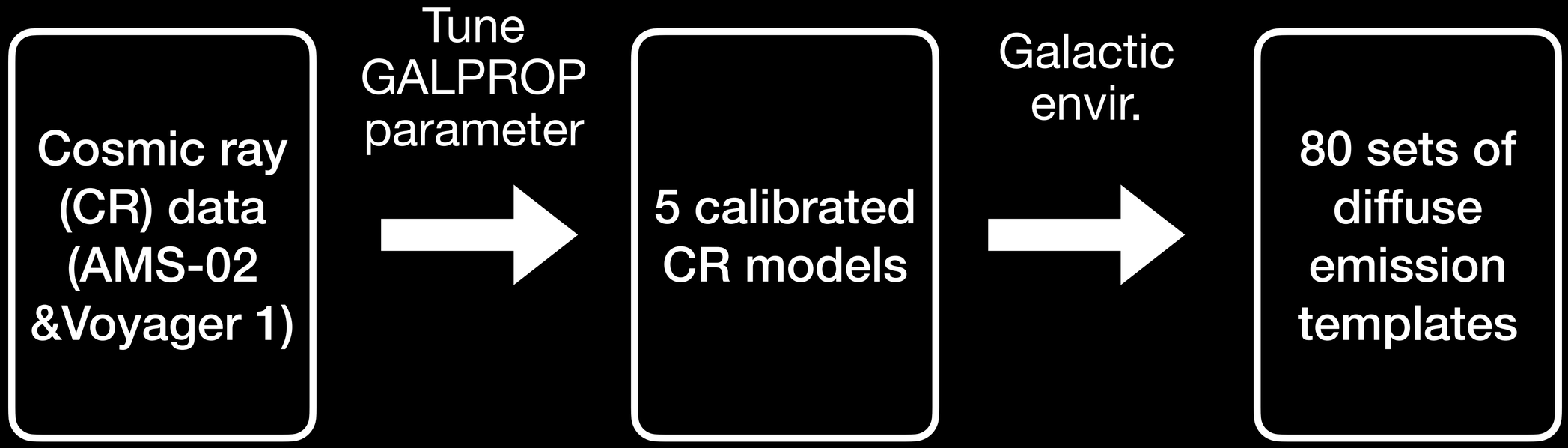
AMS-02

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

Voyager 1

CR proton outside the Heliosphere.

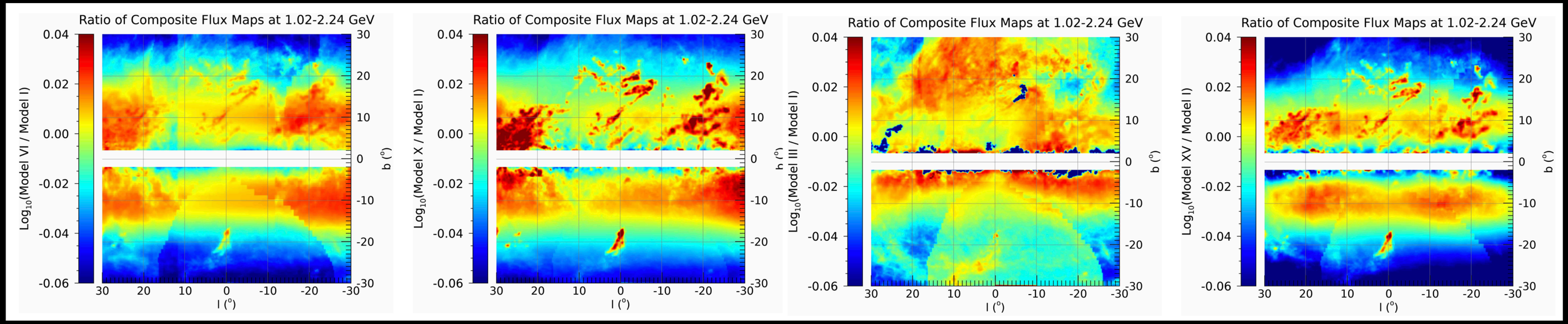
New templates calibrated w/ CR data



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

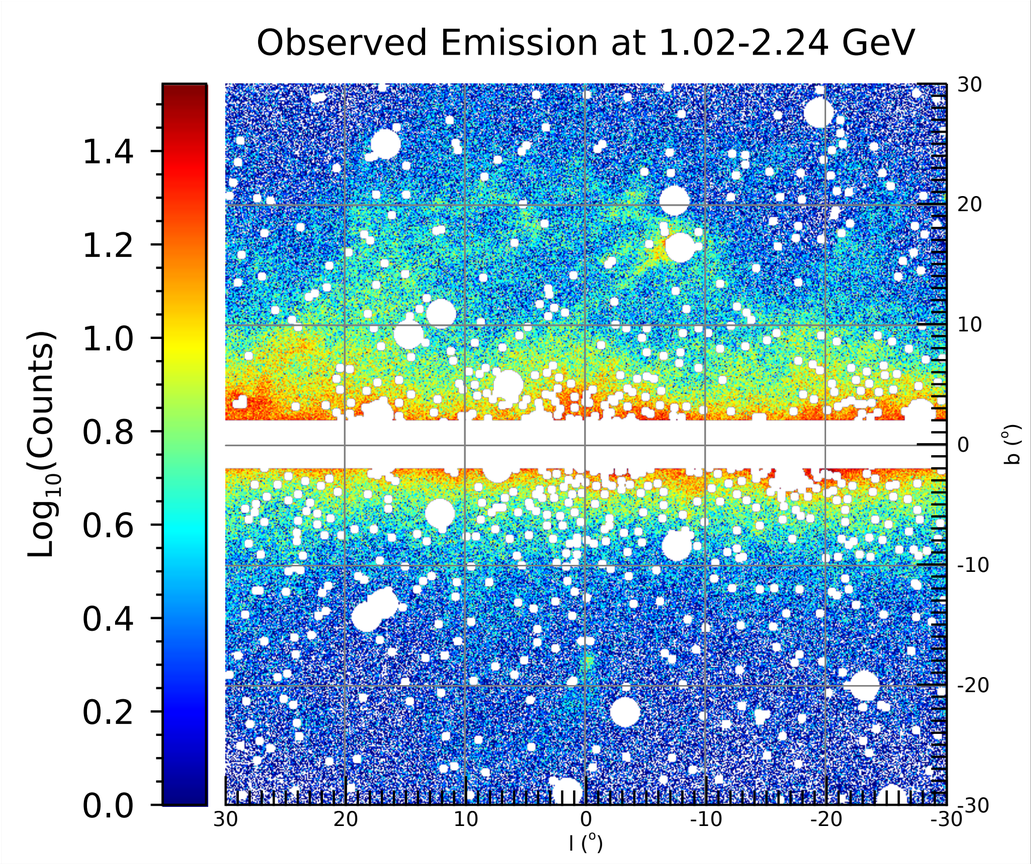
New templates calibrated w/ CR data

A diversity of templates



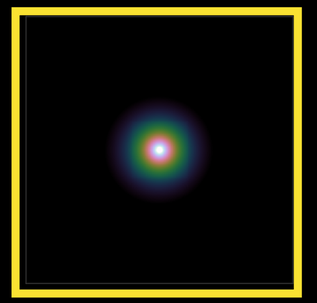
Model VI vs Model I | Model X vs Model I | Model III vs Model I | Model XV vs Model I

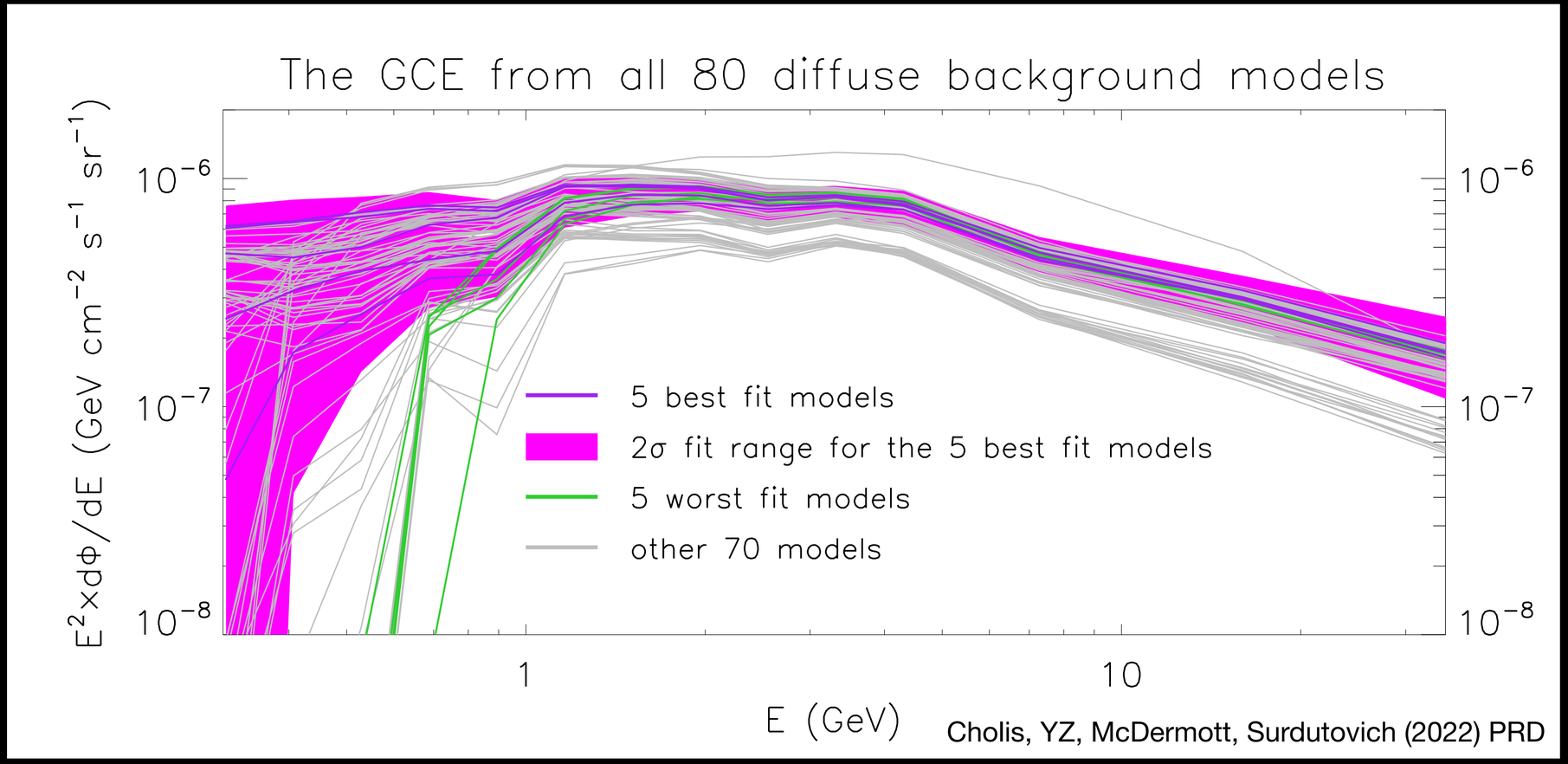
Template fitting



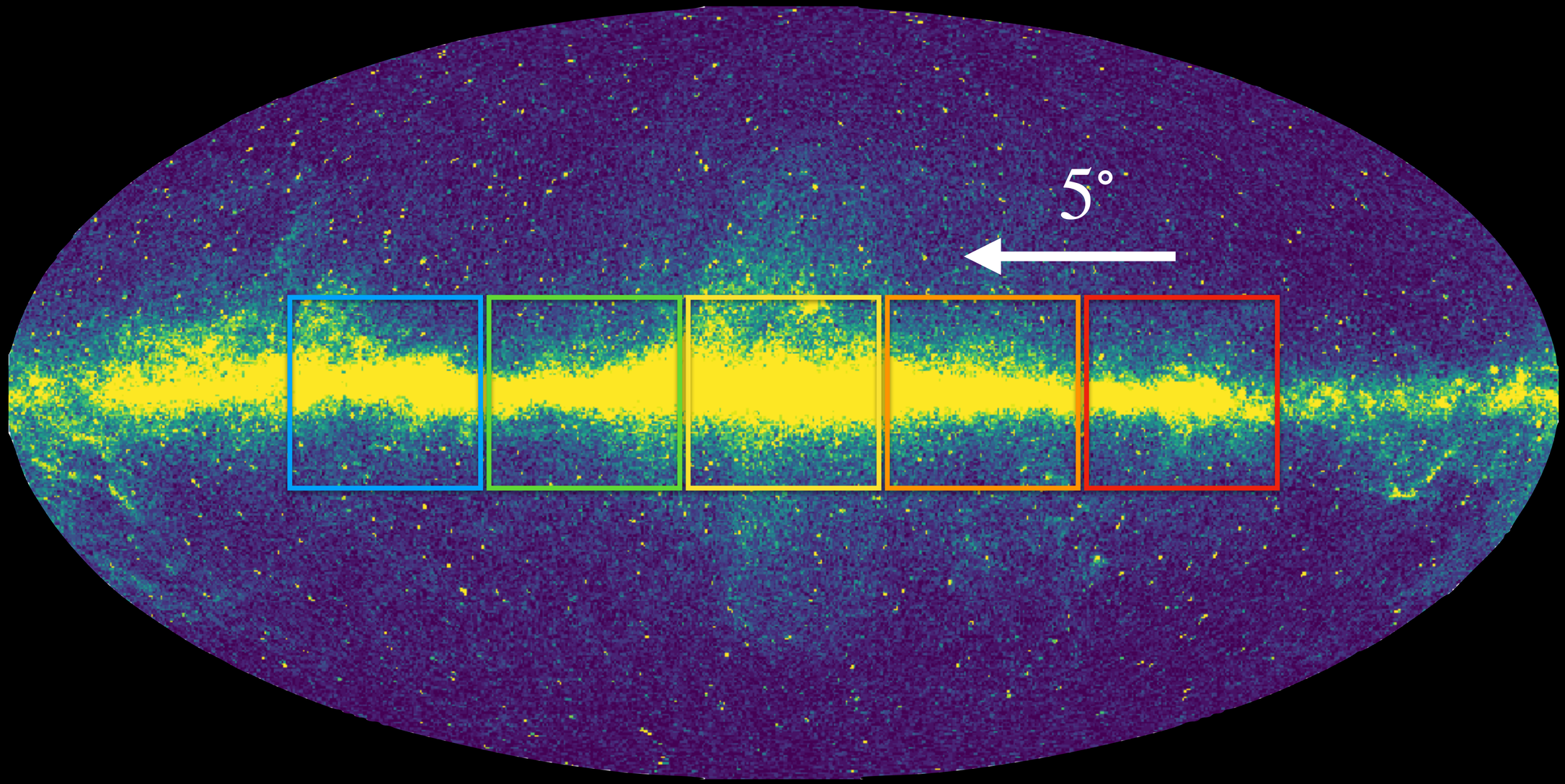
Fermi data [**12.5 years of obs.**] masking 4FGL-DR2 sources + disk [white regions]

The GCE is still there



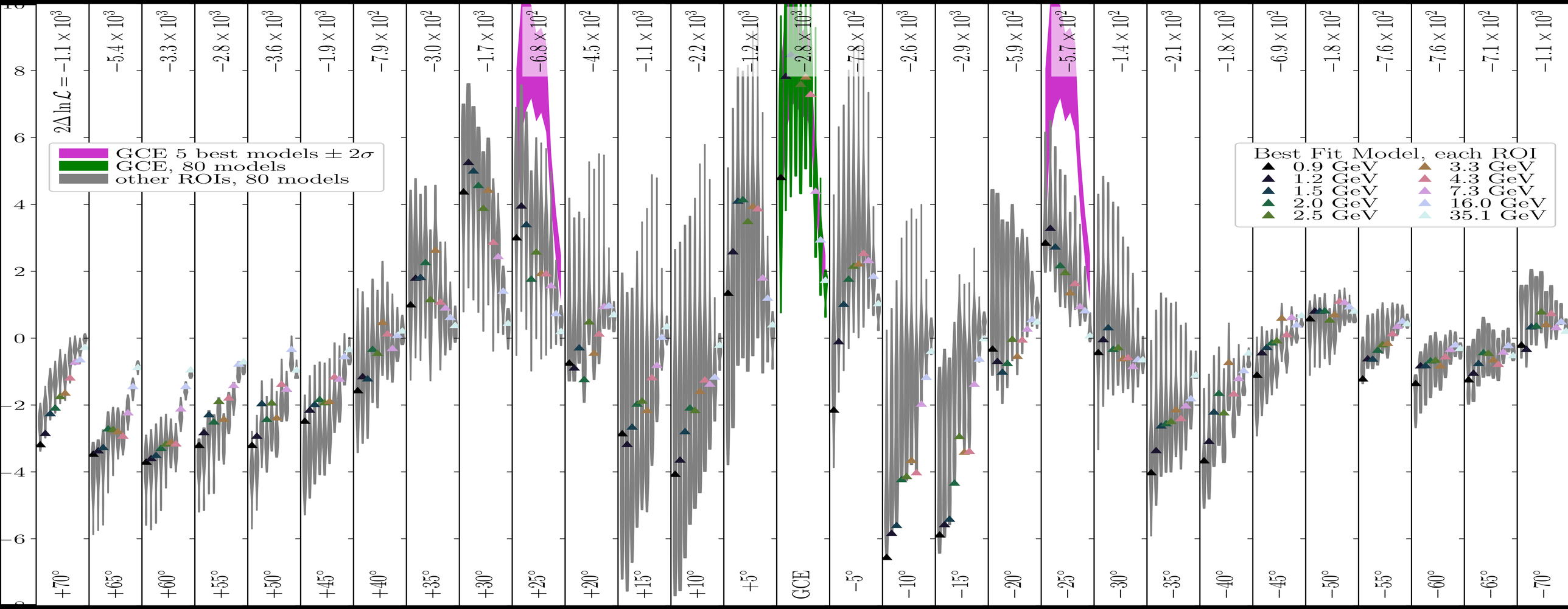


Translated regions-of-interest



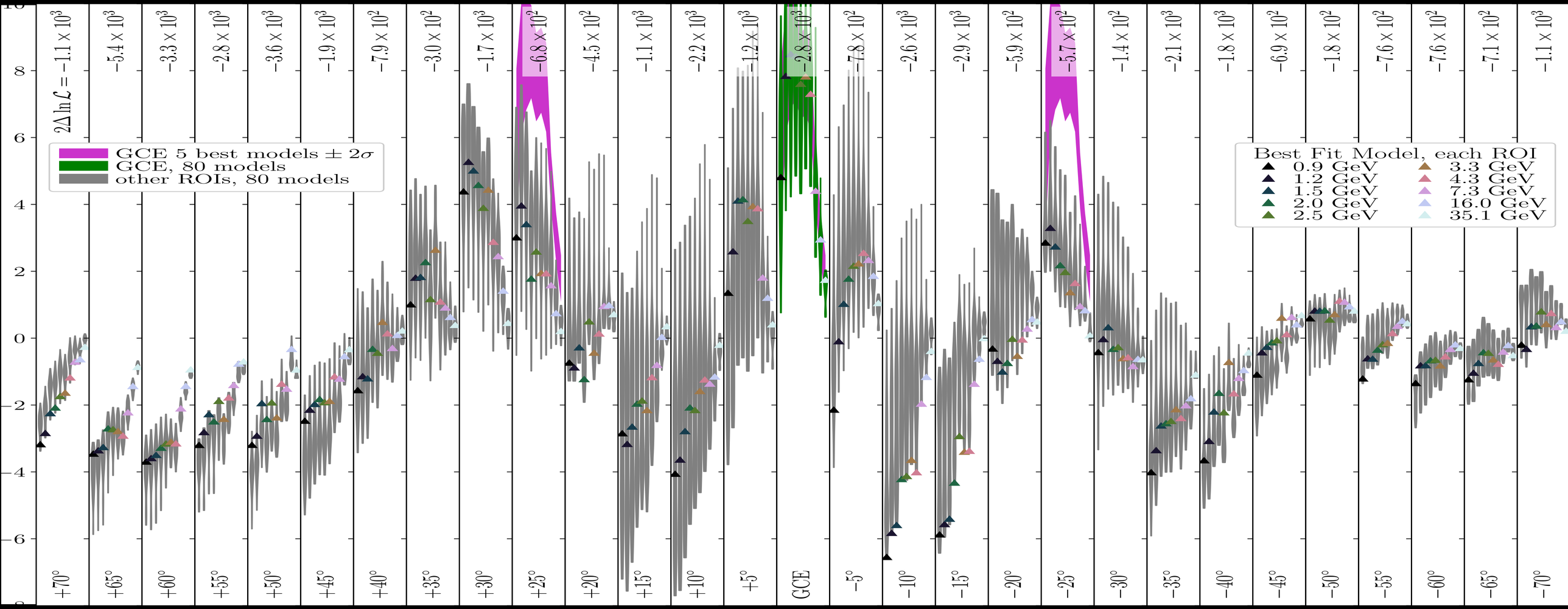
The residue across the sky

X: E
Y: $E^2 d\Phi/dE$



GCE is unique: brighter & harder

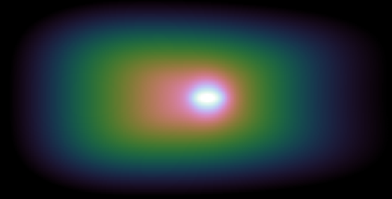
X: E
Y: $E^2 d\Phi/dE$



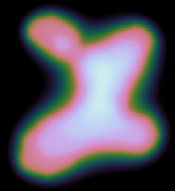
On the morphism of GCE

Spherical

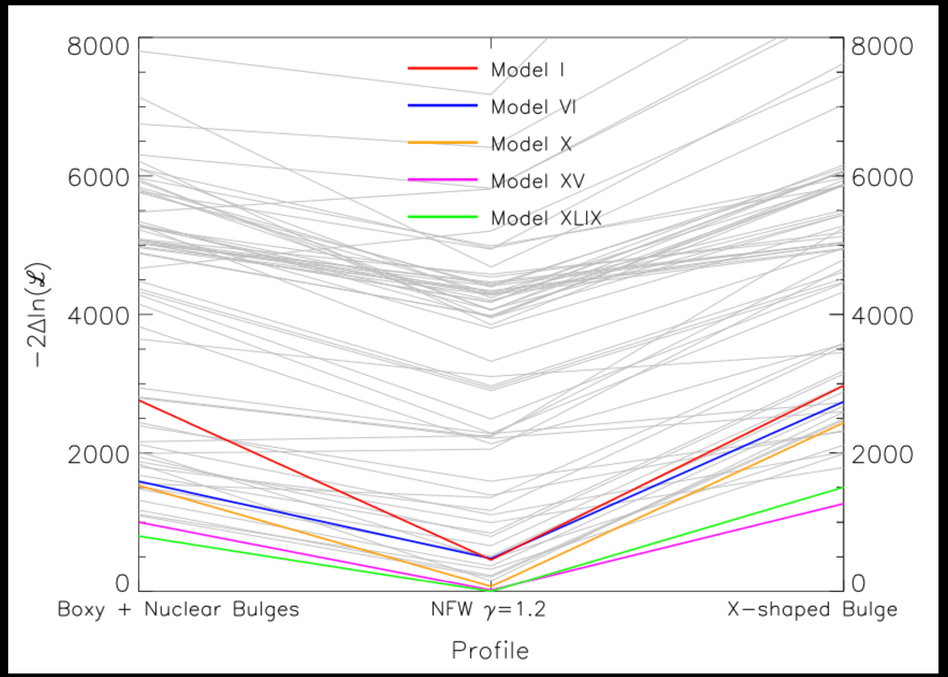
Boxy + Nuclear Bulges



X-shape Bulge

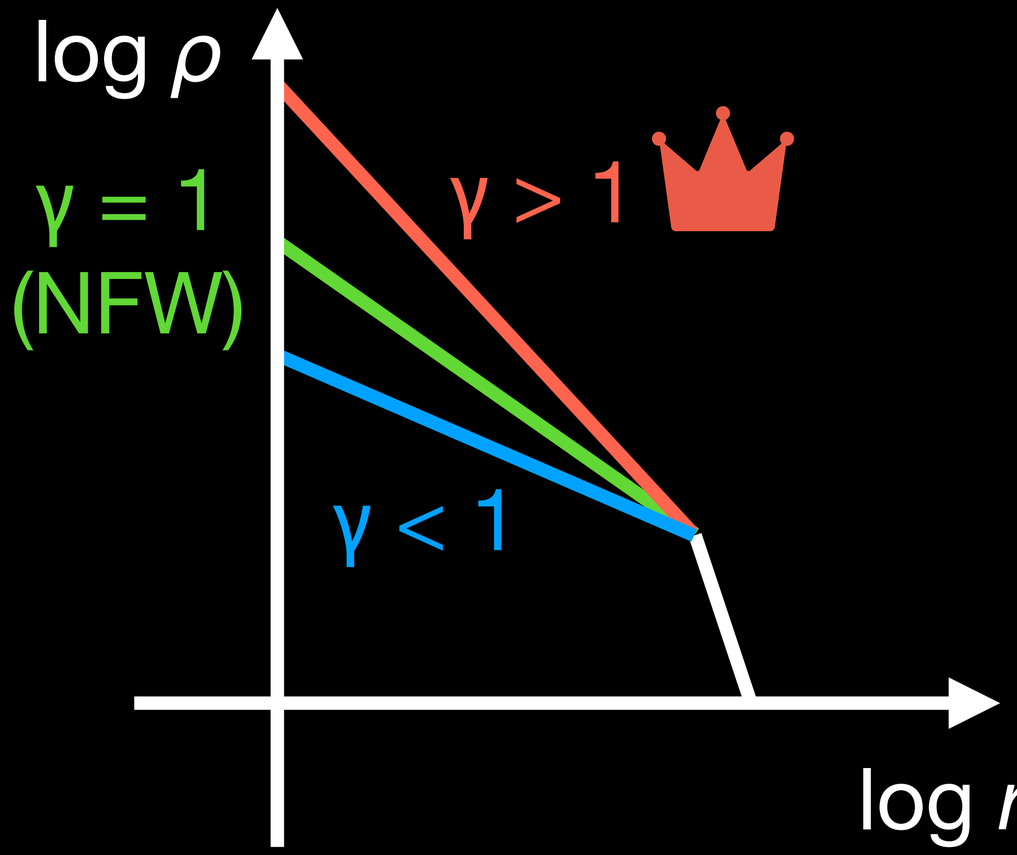


Statistical Preference

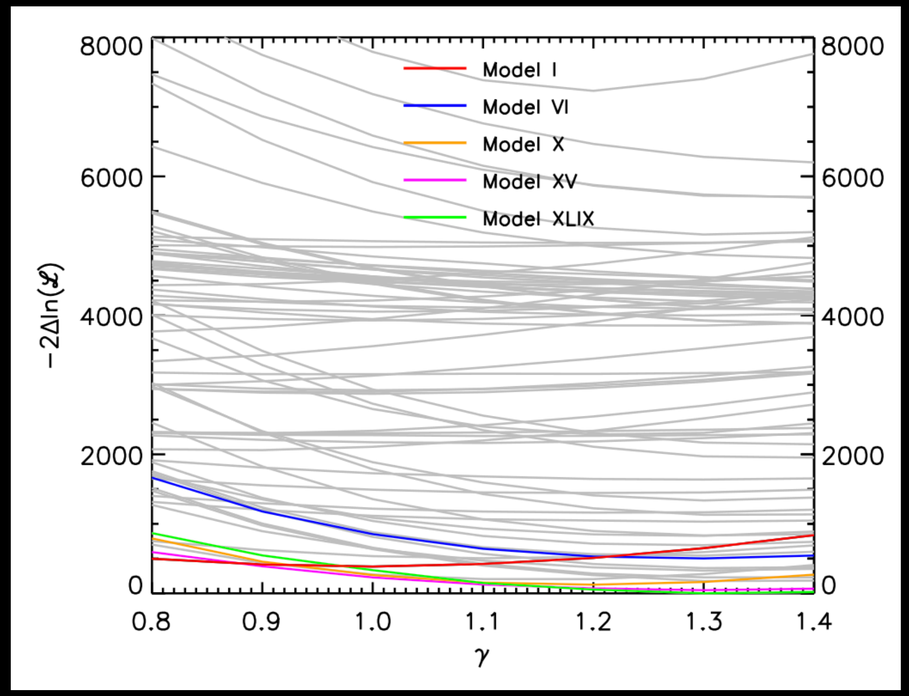


Prefers a round shape

On the cuspiness of GCE

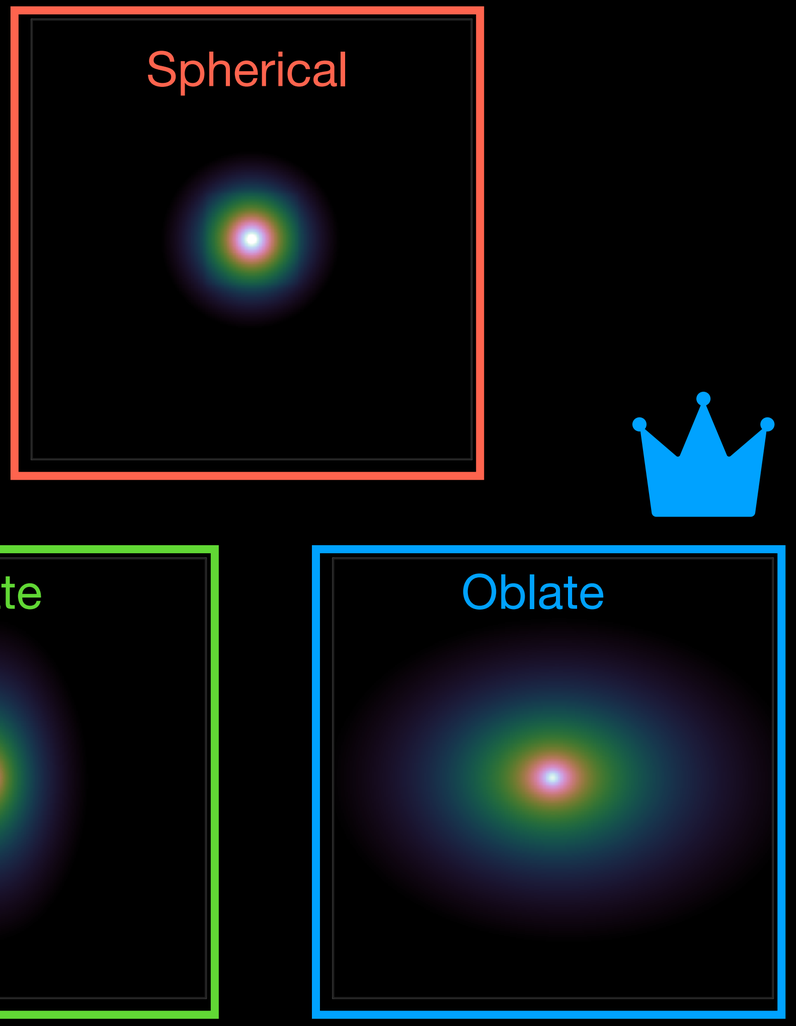


Statistical Preference



Prefer slightly contracted density profile

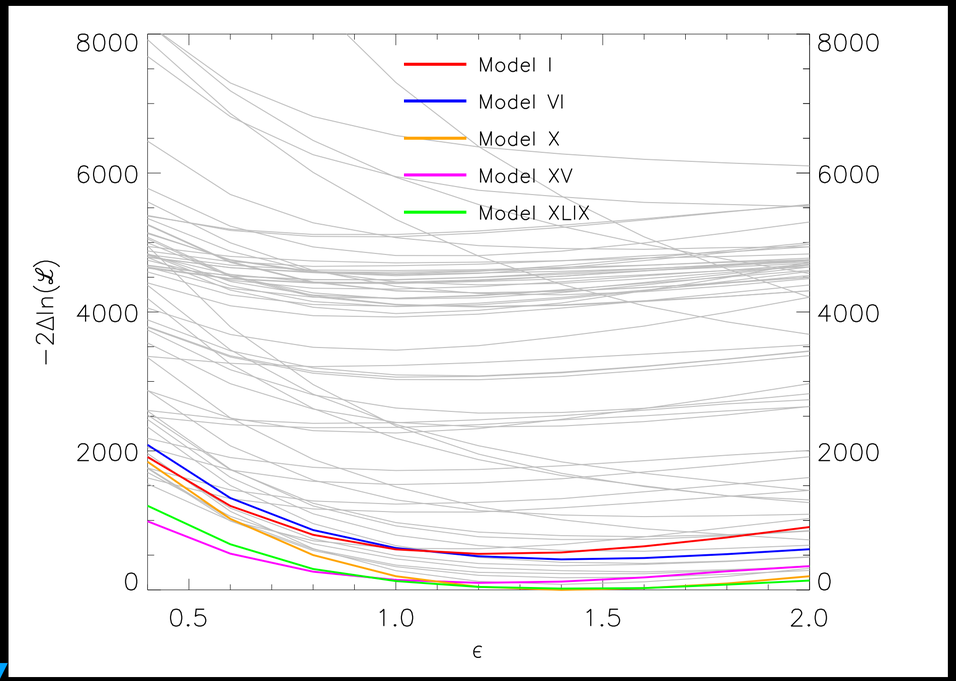
On the ellipticity of GCE



$$\cos(\psi) = \cos(b)\cos(\ell/\epsilon)$$

Opening angle from GC Latitude Longitude/ϵ

Statistical Preference

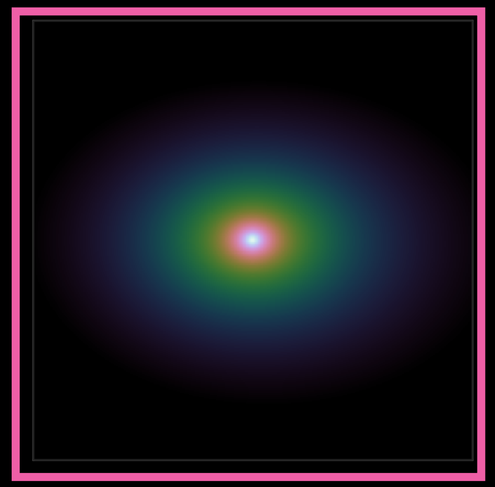


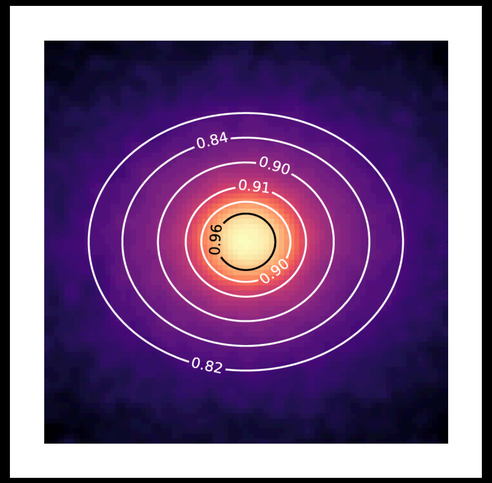
Approximately spherical
Prefer slightly oblate shape

Robustness of the Galactic Center Excess morphology against masking

Q1: Why is the GCE oblate?

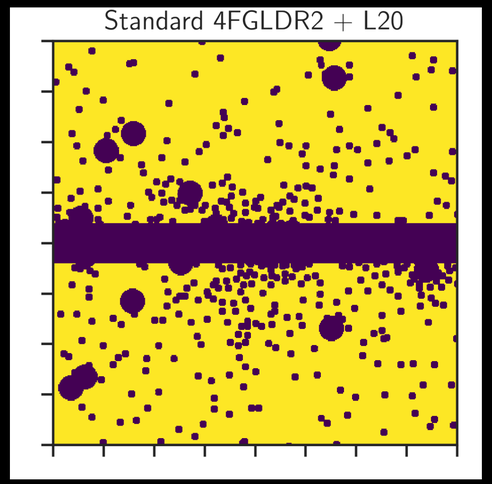
Oblate





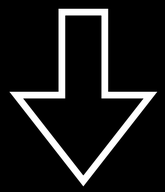
Baryonic contraction

Simulation from Grand & White ‘22

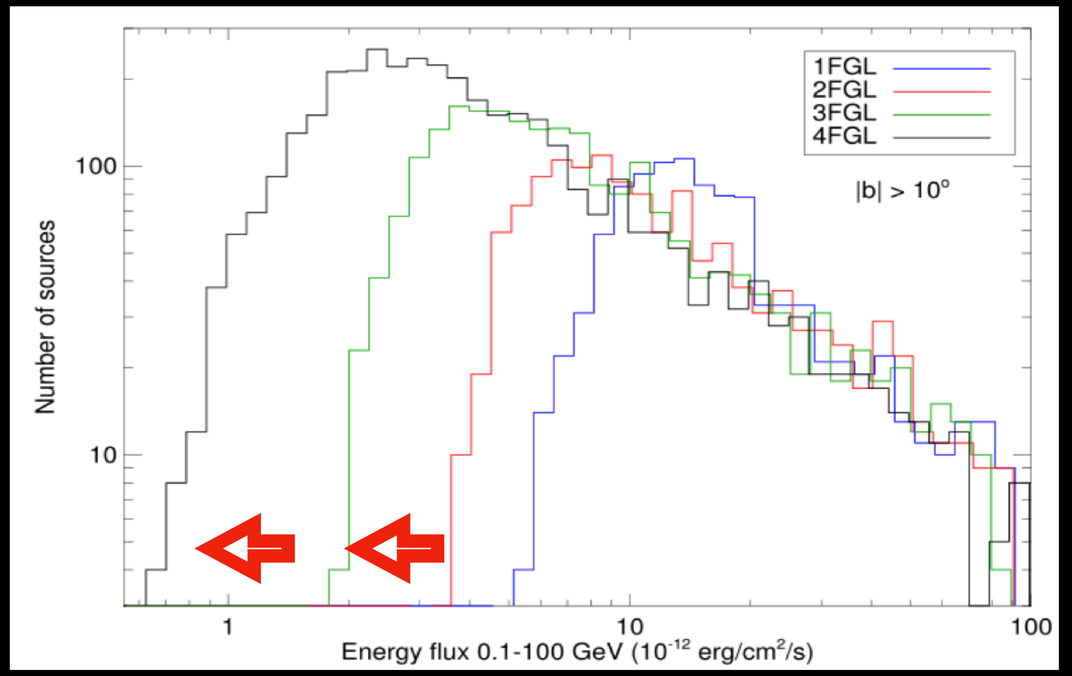


Masking bias?

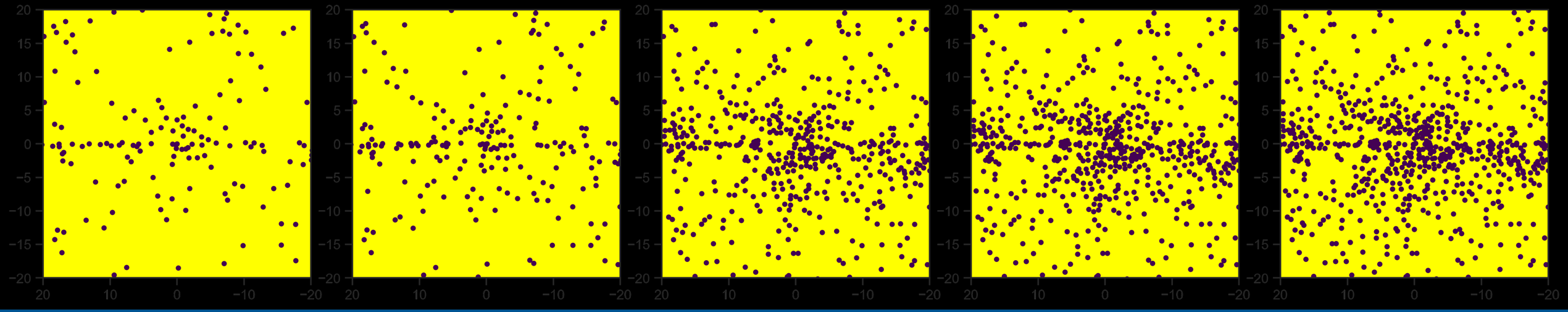
Q1: Why is the GCE oblate?



Q2: Are the GCE properties robust against masks?

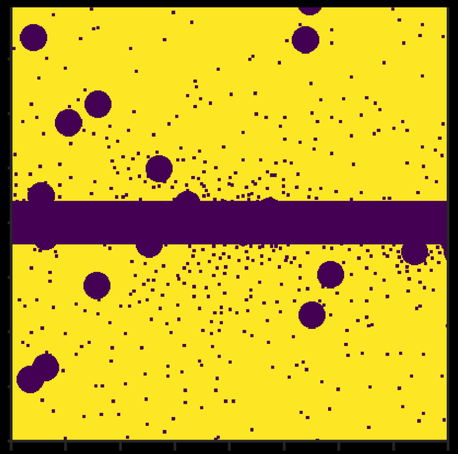


2FGL (2011) 3FGL (2015) 4FGLDR1 (2019) 4FGLDR2 (2020) 4FGLDR3 (2022)

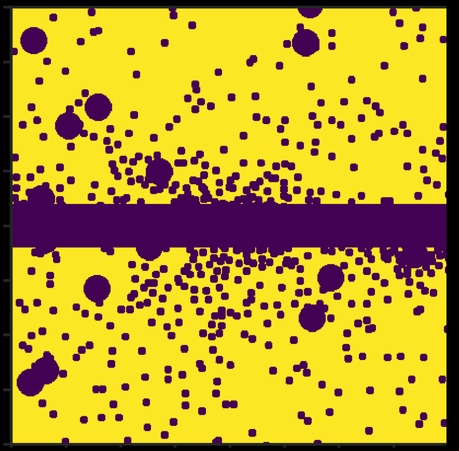


New masks

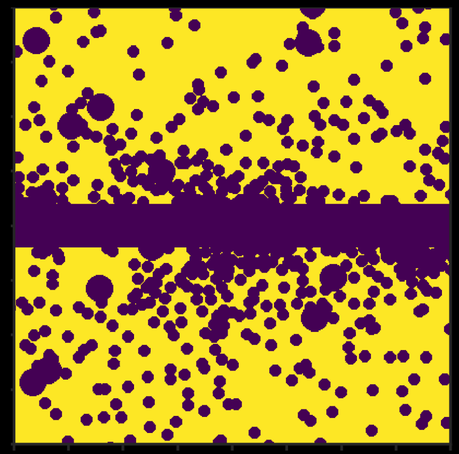
Smaller pt source mask



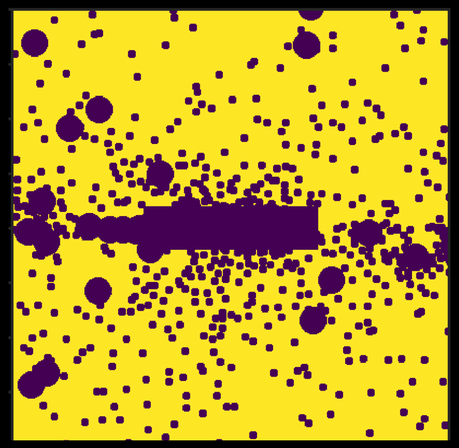
Standard mask

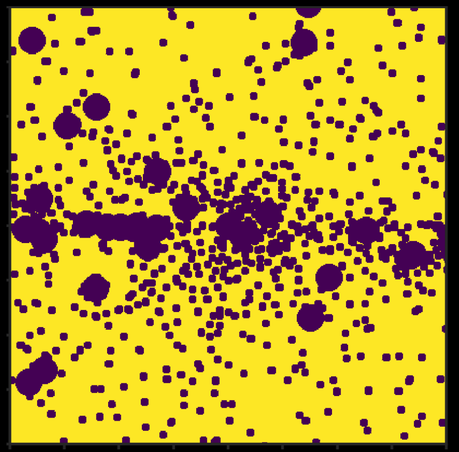


Larger pt source mask



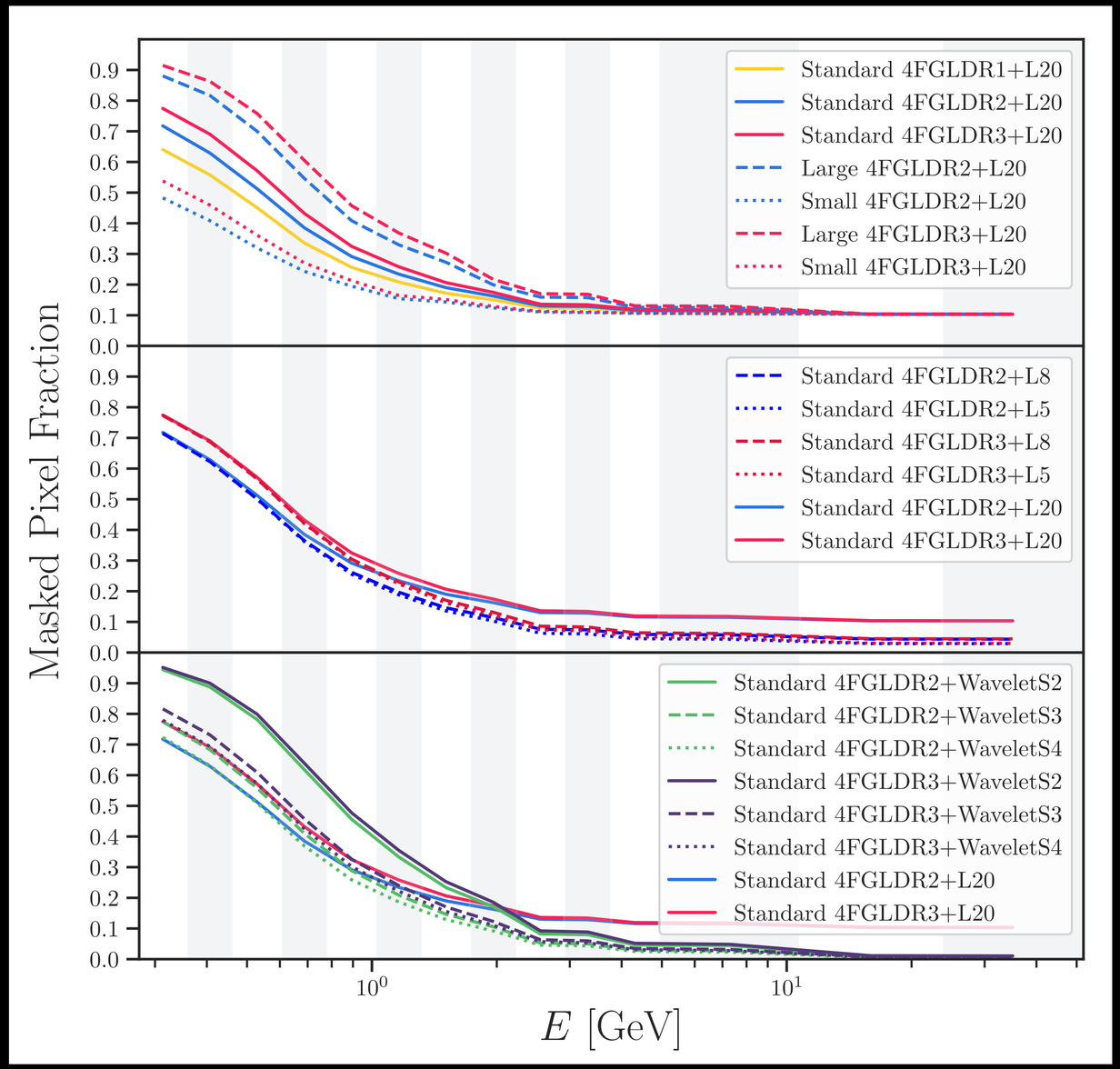
Shorter disk mask





No disk mask; use wavelet peaks instead

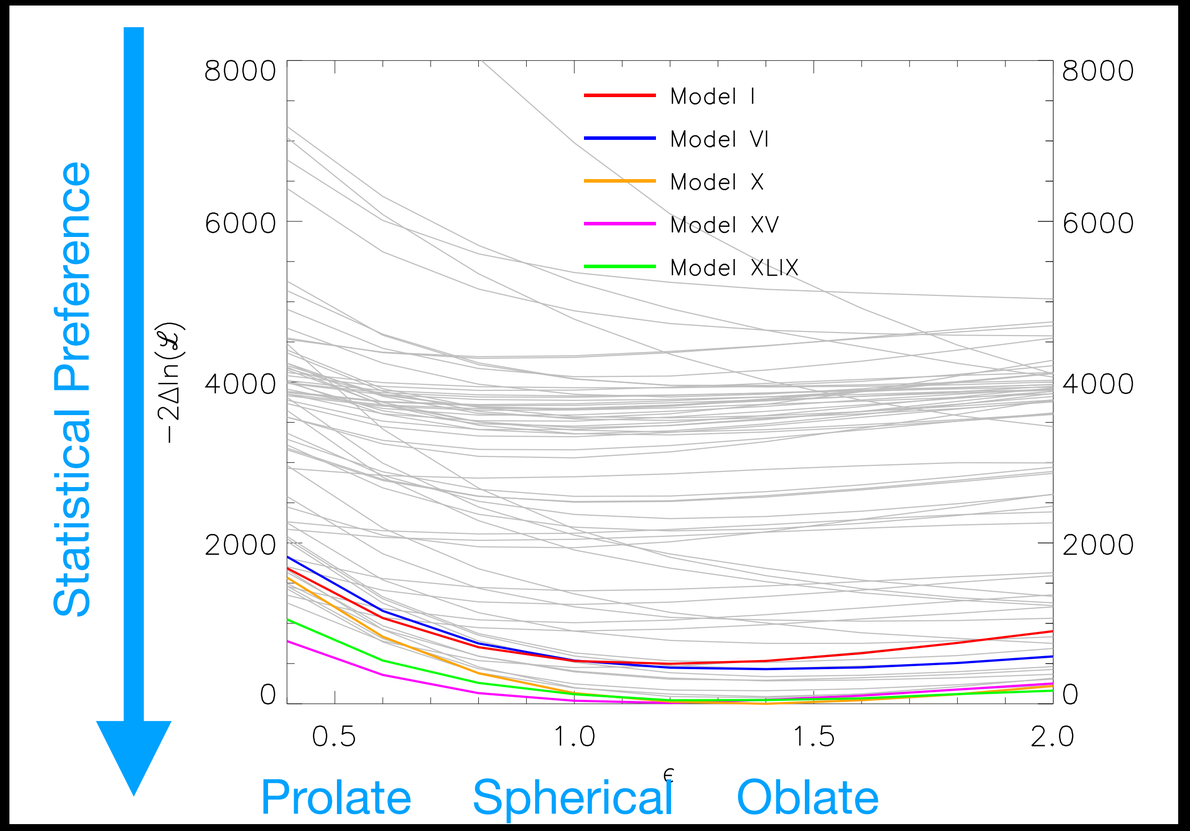
Masked pixel fraction for different masks



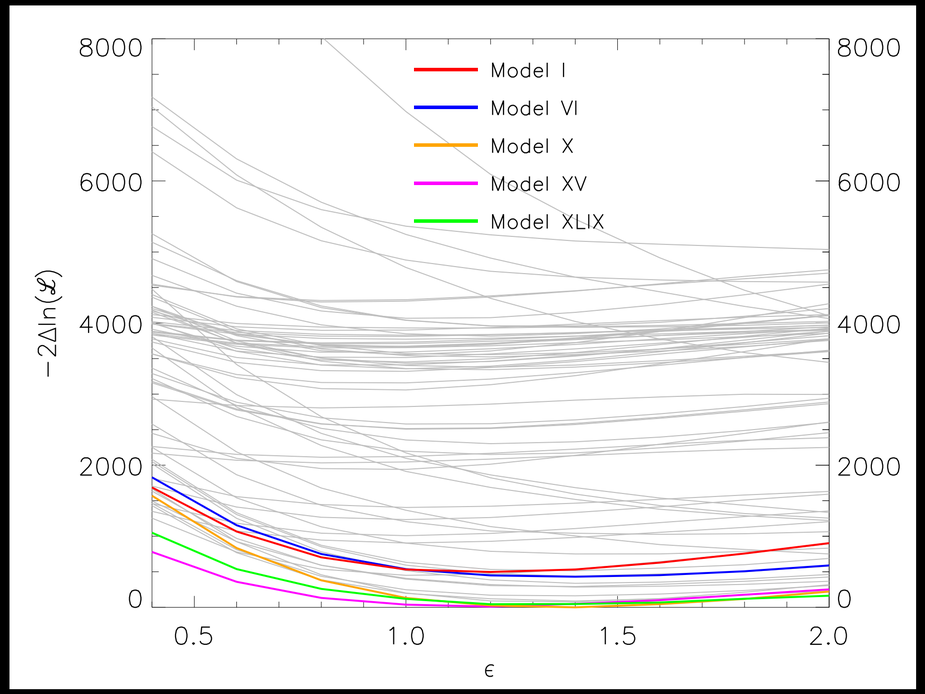
The ellipticity of the GCE is robust

- The ellipticity of the GCE prefers a value of ϵ between 1.0 to 1.4.
- The result, obtained with the masking of 4FGLDR3 sources, is consistent with our previous findings where 4FGLDR2 sources were masked.

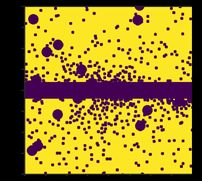
Standard 4FGLDR3 + Disk

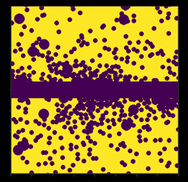


The ellipticity of the GCE is robust

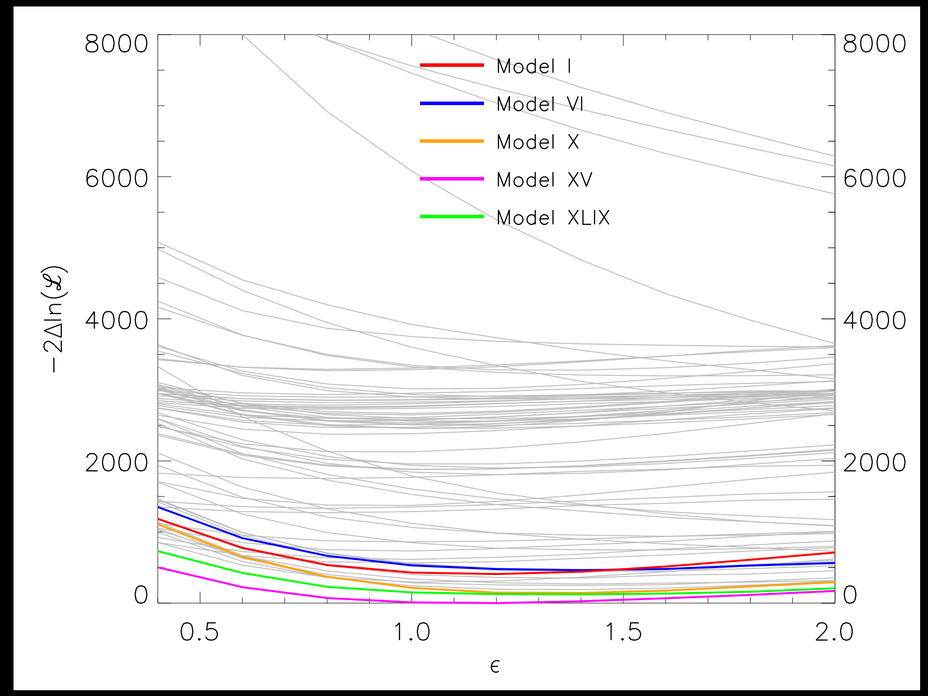


Standard 4FGLDR3 + Disk

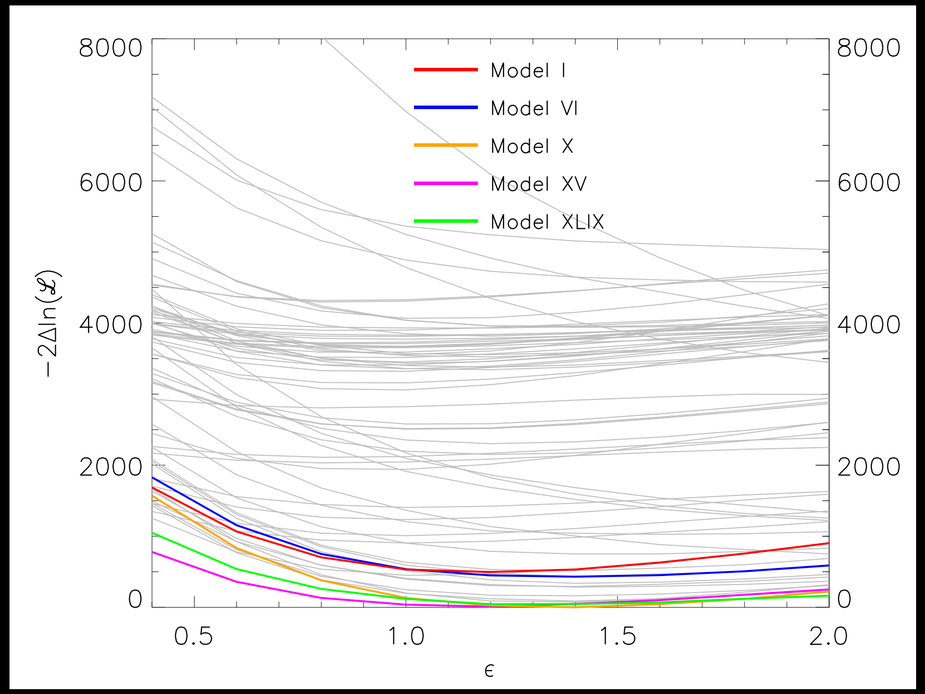




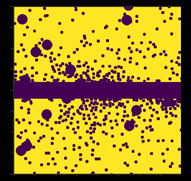
Large 4FGLDR3 + Disk

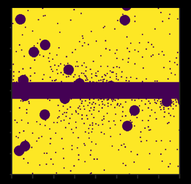


The ellipticity of the GCE is robust

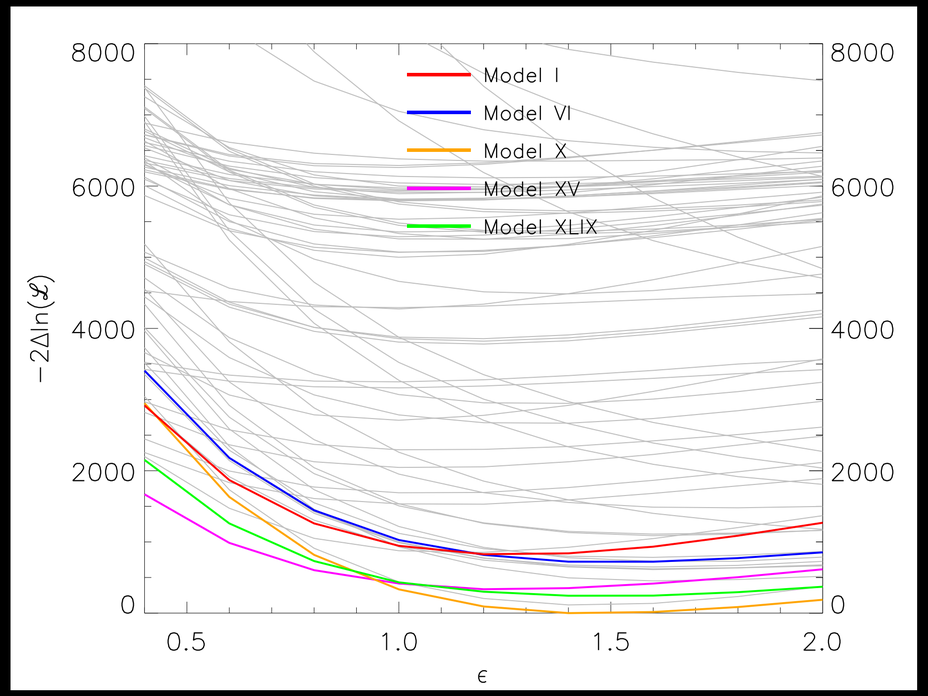


Standard 4FGLDR3 + Disk





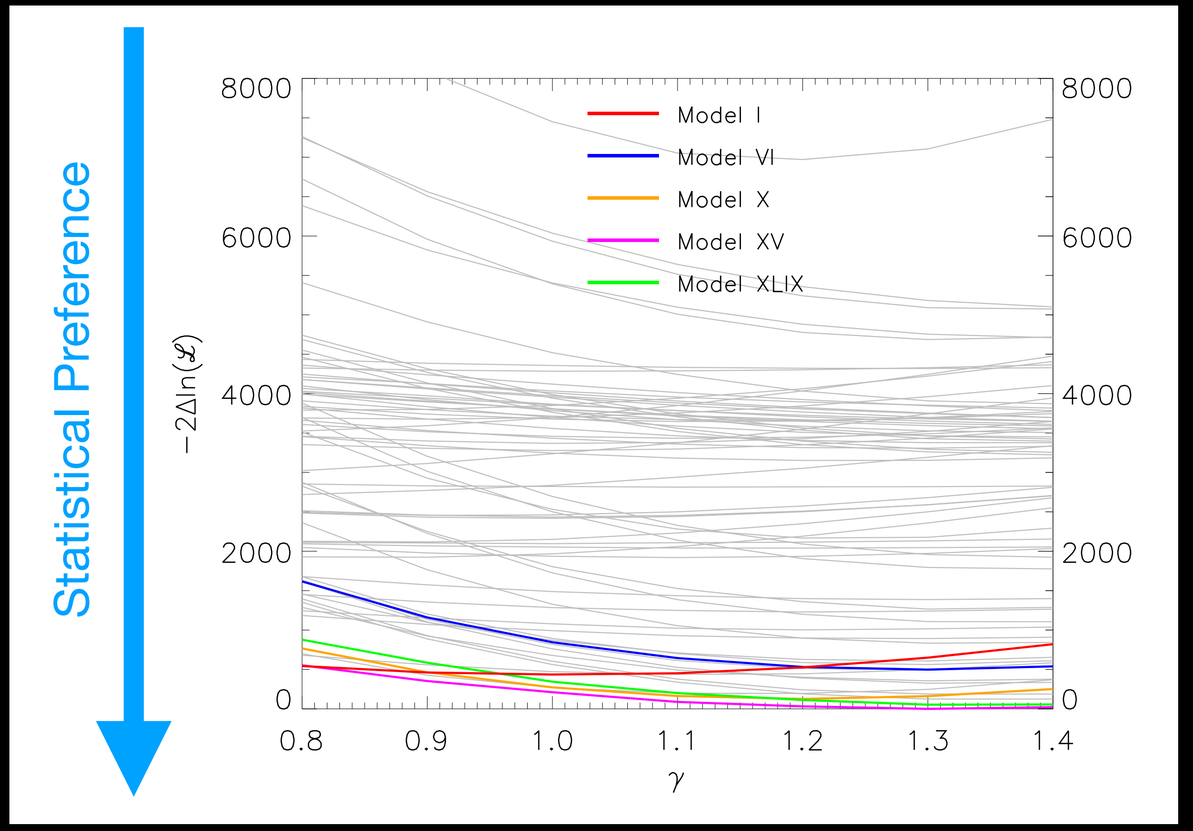
Small 4FGLDR3 + Disk



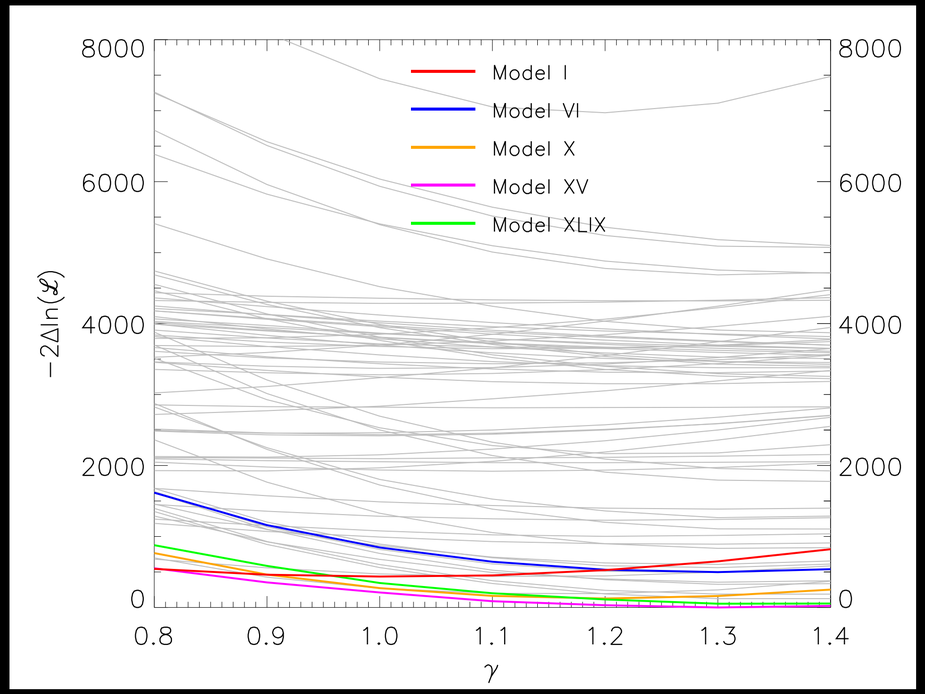
The cuspiness of the GCE is robust

- The cuspiness of the GCE prefers a value of $\gamma = 1.2$.
- Consistent with our earlier results.

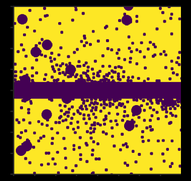
Standard 4FGLDR3 + Disk

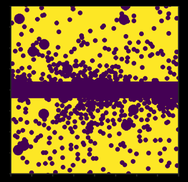


The cuspiness of the GCE is robust

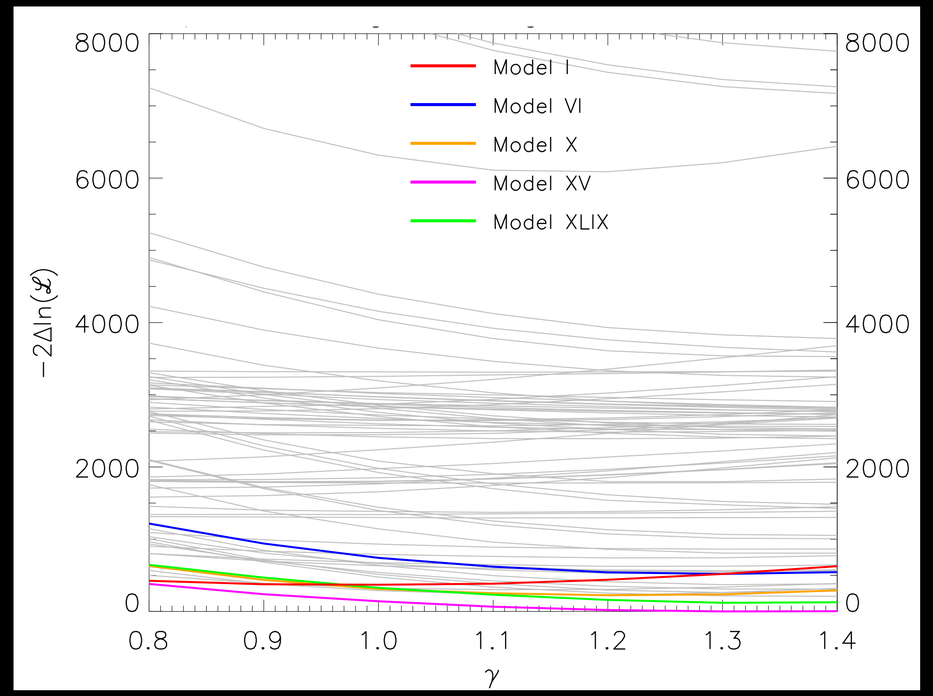


Standard 4FGLDR3 + Disk

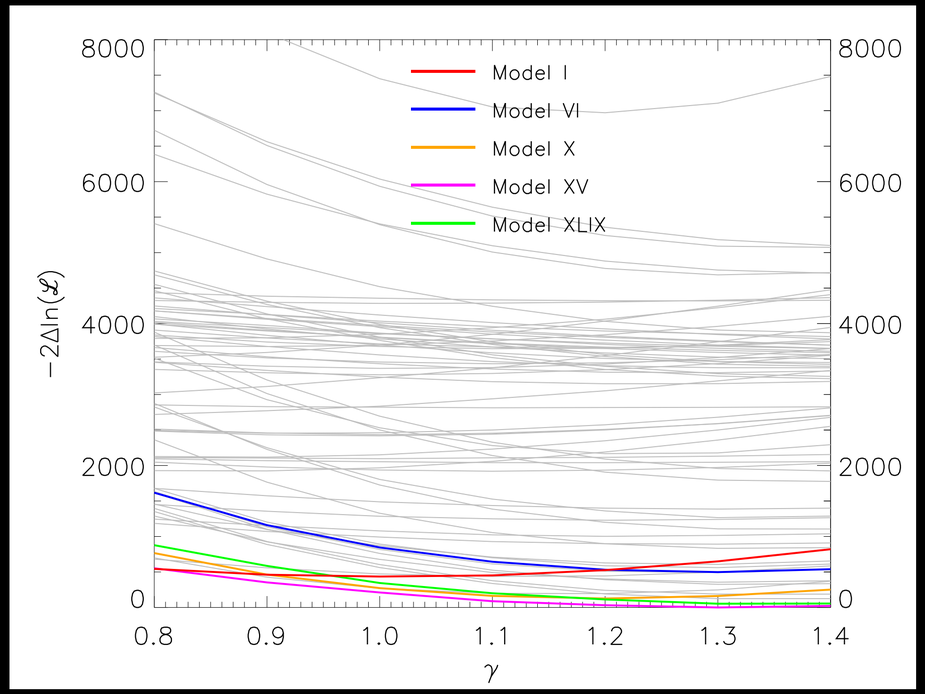




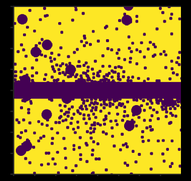
Large 4FGLDR3 + Disk

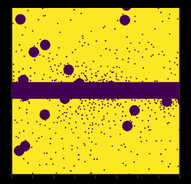


The cuspiness of the GCE is robust

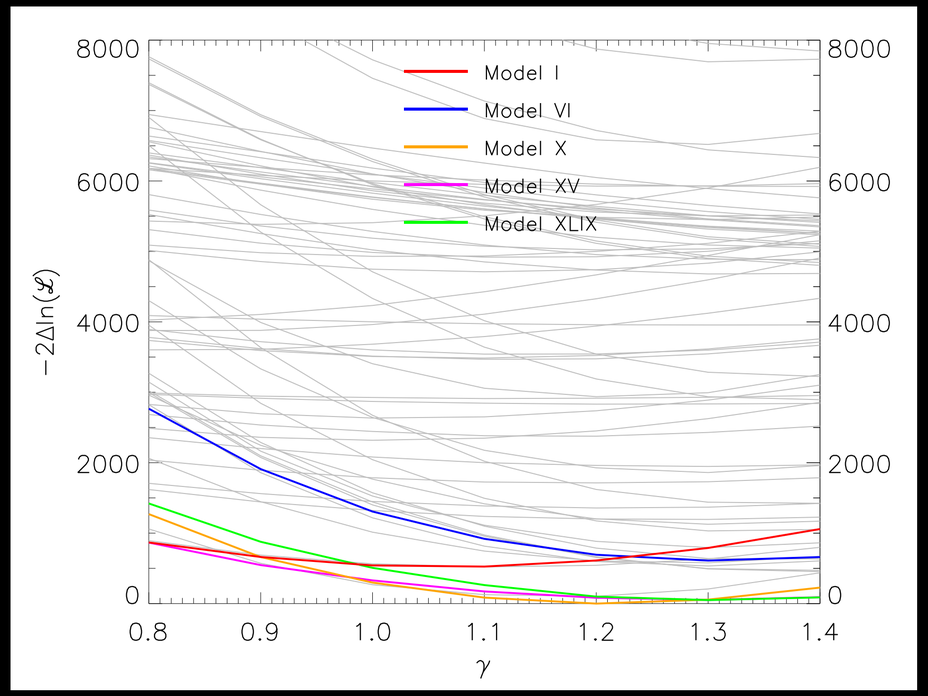


Standard 4FGLDR3 + Disk

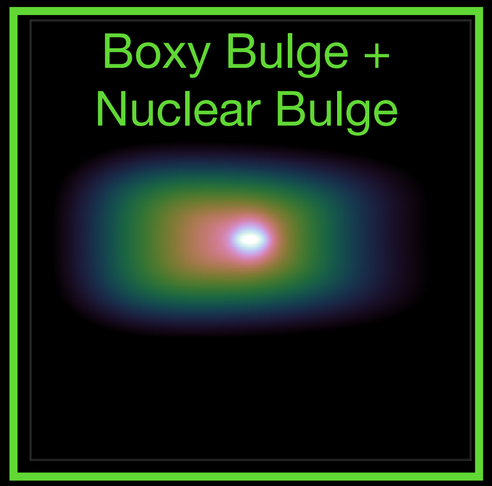


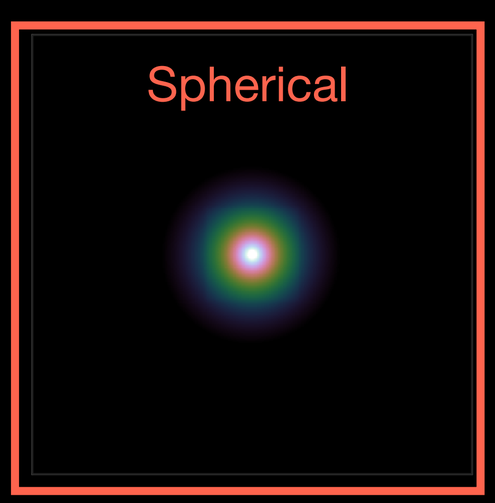


Small 4FGLDR3 + Disk



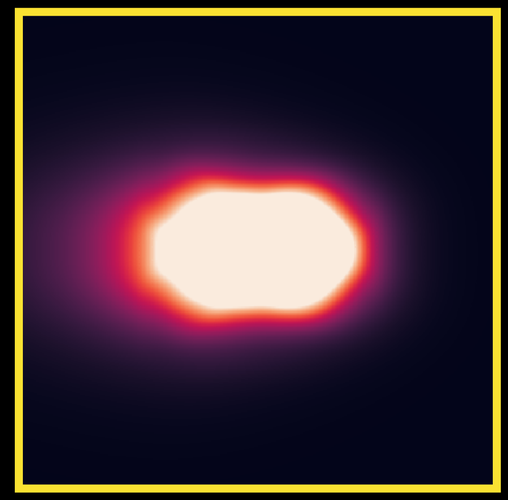
Q3: A new stellar bulge?





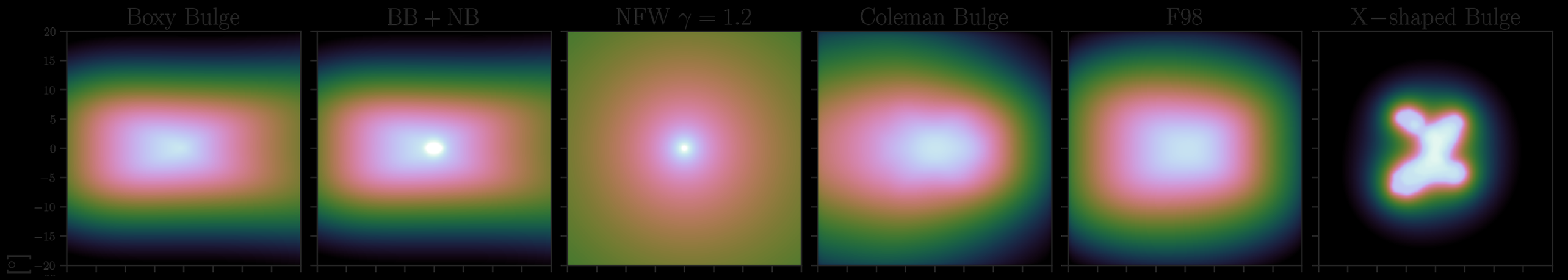
A new bulge profile from Coleman+ ’20. It is based on the red clump stars from the VVV survey

Coleman Bulge



Testing more GCE models

Dark matter annihilation



Boxy Bulge

Boxy Bulge + Nuclear Bulge

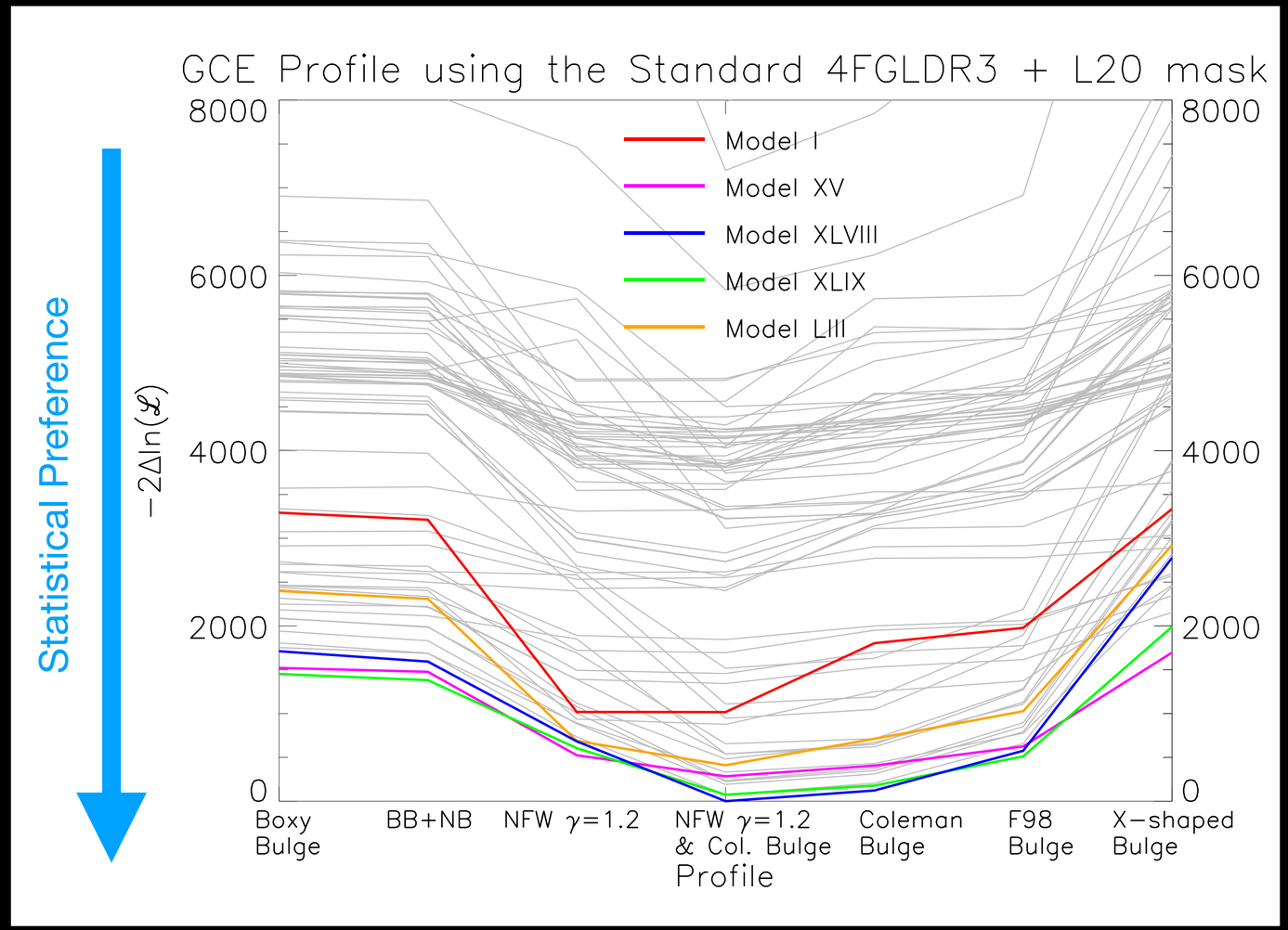
Coleman Bulge

F98

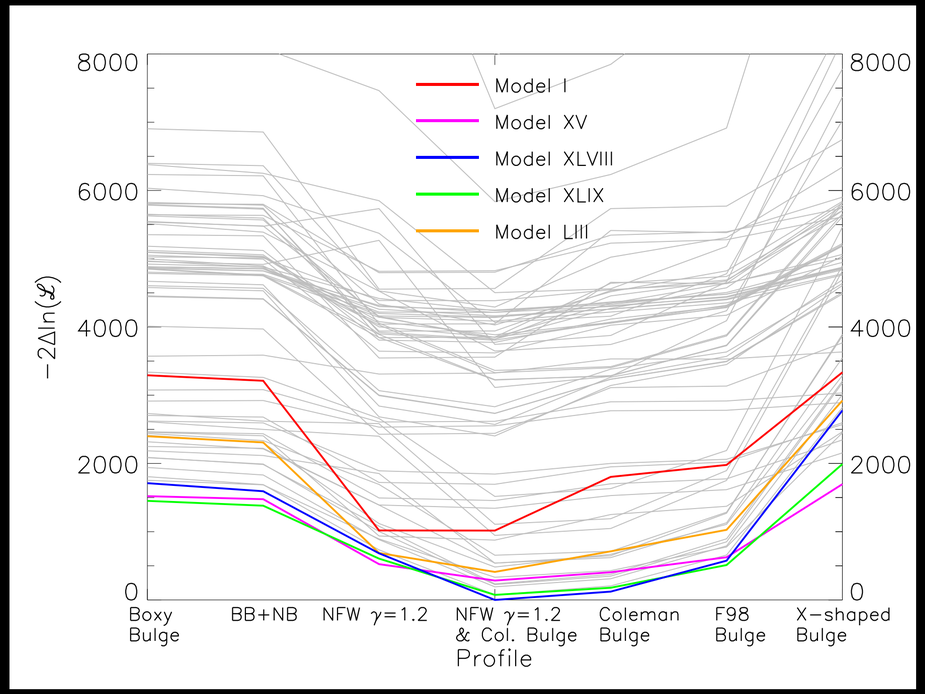
X-shaped Bulge

Coleman bulge or dark matter annihilation?

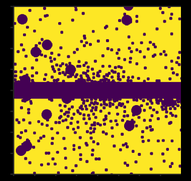
- Preference ranking:
  - For ***some*** best-fit background models:
    - Coleman Bulge > Dark matter annihilation
  - For ***other*** best-fit background models:
    - Dark matter annihilation > Coleman Bulge

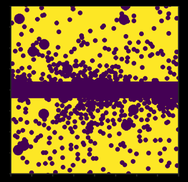


The shape of the GCE are robust

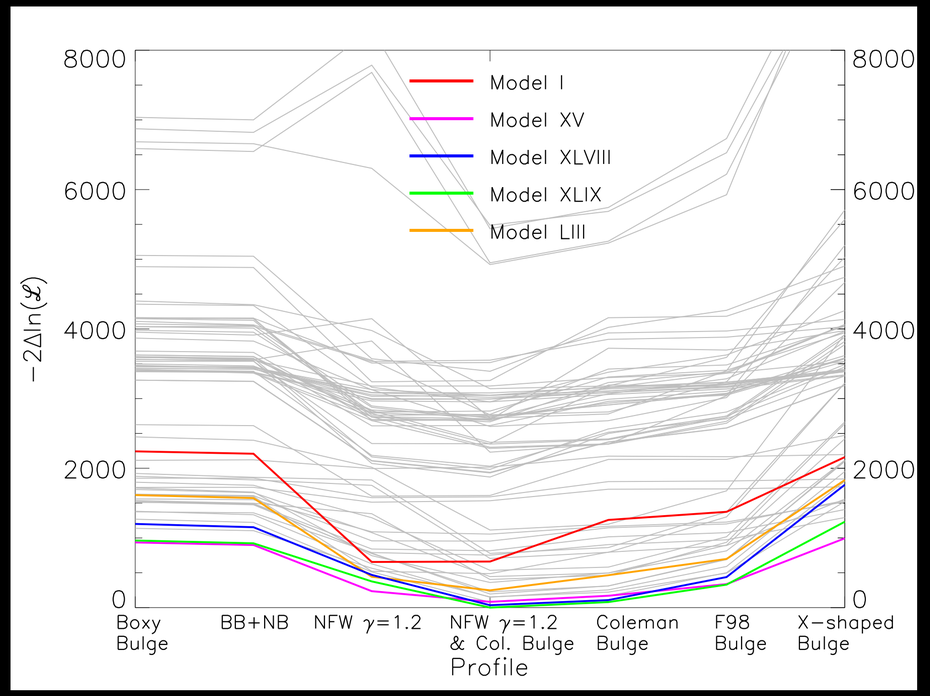


Standard 4FGLDR3 + Disk

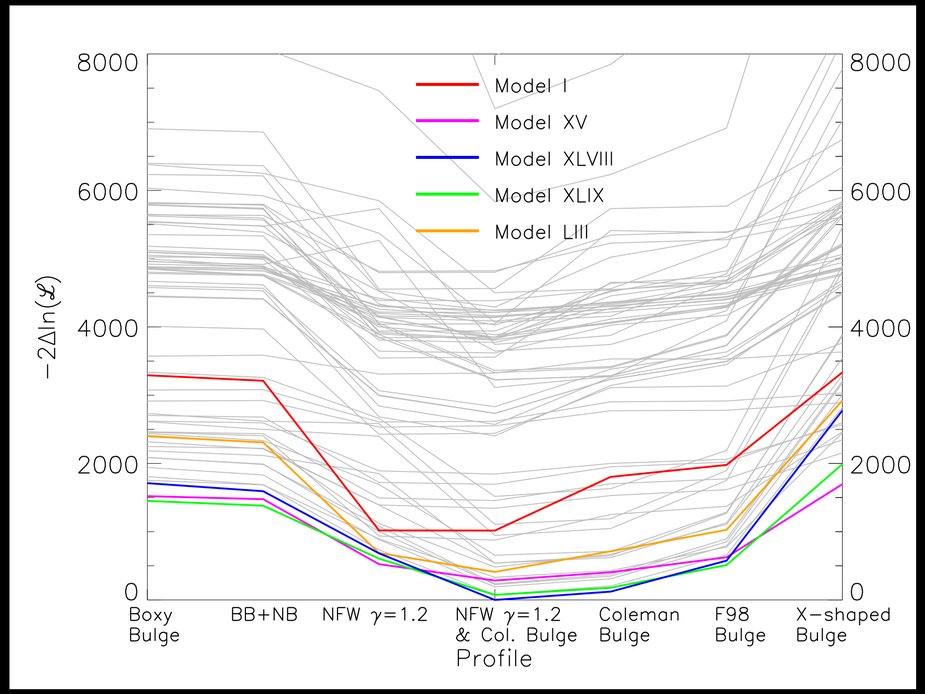




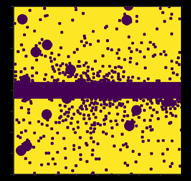
Large 4FGLDR3 + Disk

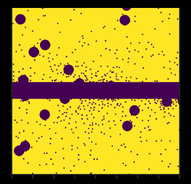


The shape of the GCE are robust

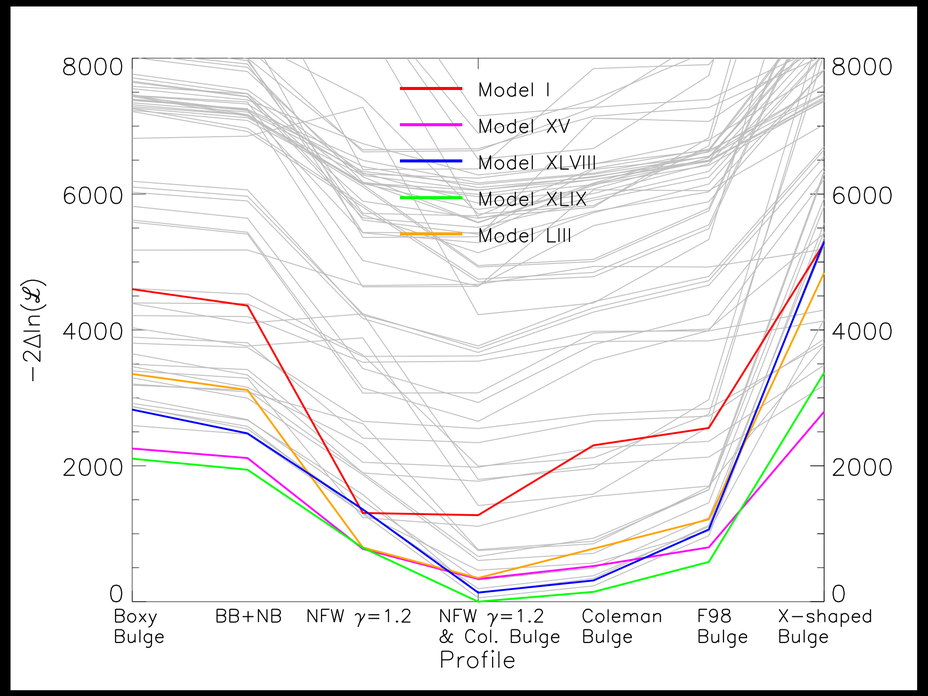


Standard 4FGLDR3 + Disk





Small 4FGLDR3 + Disk



Two components?

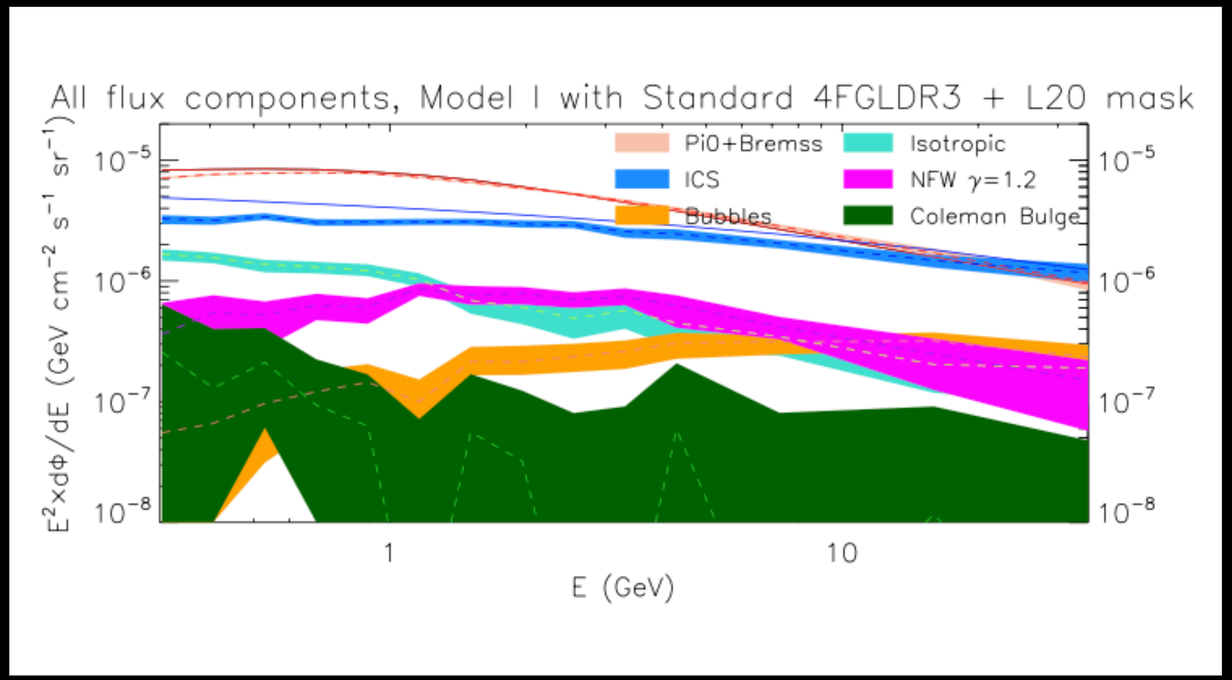
- Almost for all the models, Dark matter annihilation & Coleman Bulge > Dark matter annihilation or Coleman Bulge only.
- We should expect some MSPs contribution for GCE and should look into the spectra for the two components of “Dark matter annihilation + Coleman Bulge”.

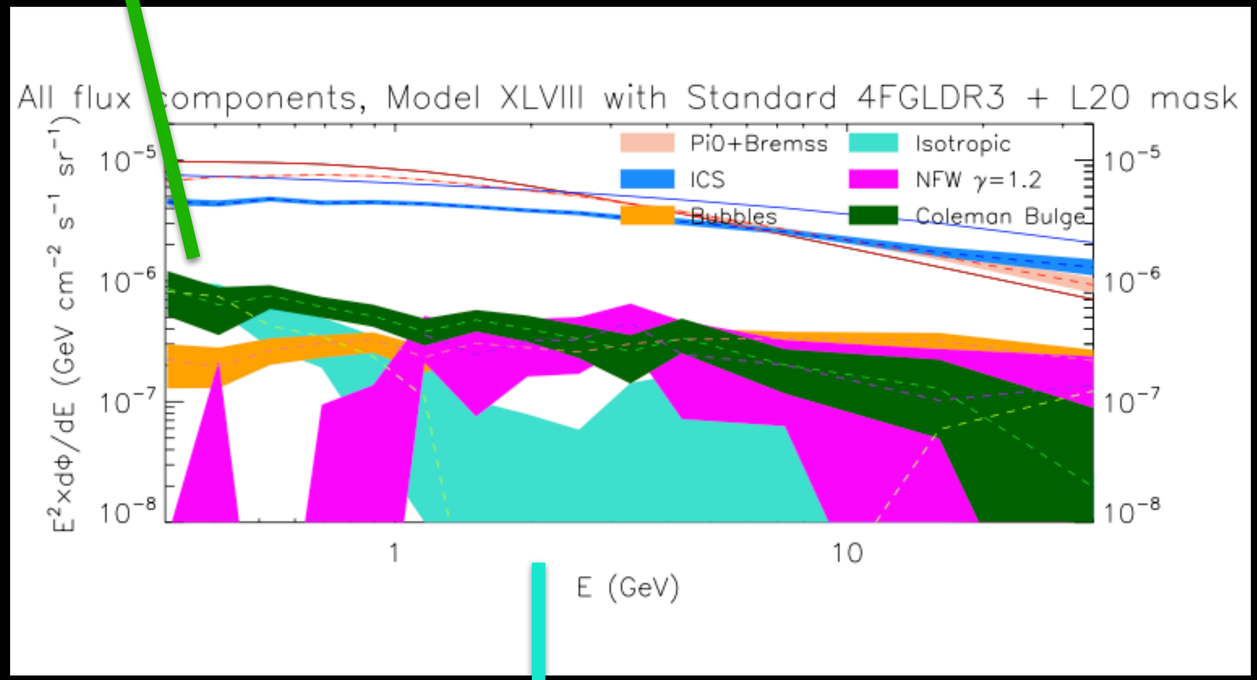
The spectrum

Do not represent MSPs' spectrum

Dark matter annihilation dominates GCE

Coleman Bulge dominates GCE





The unexpected dip of the isotropic spectrum

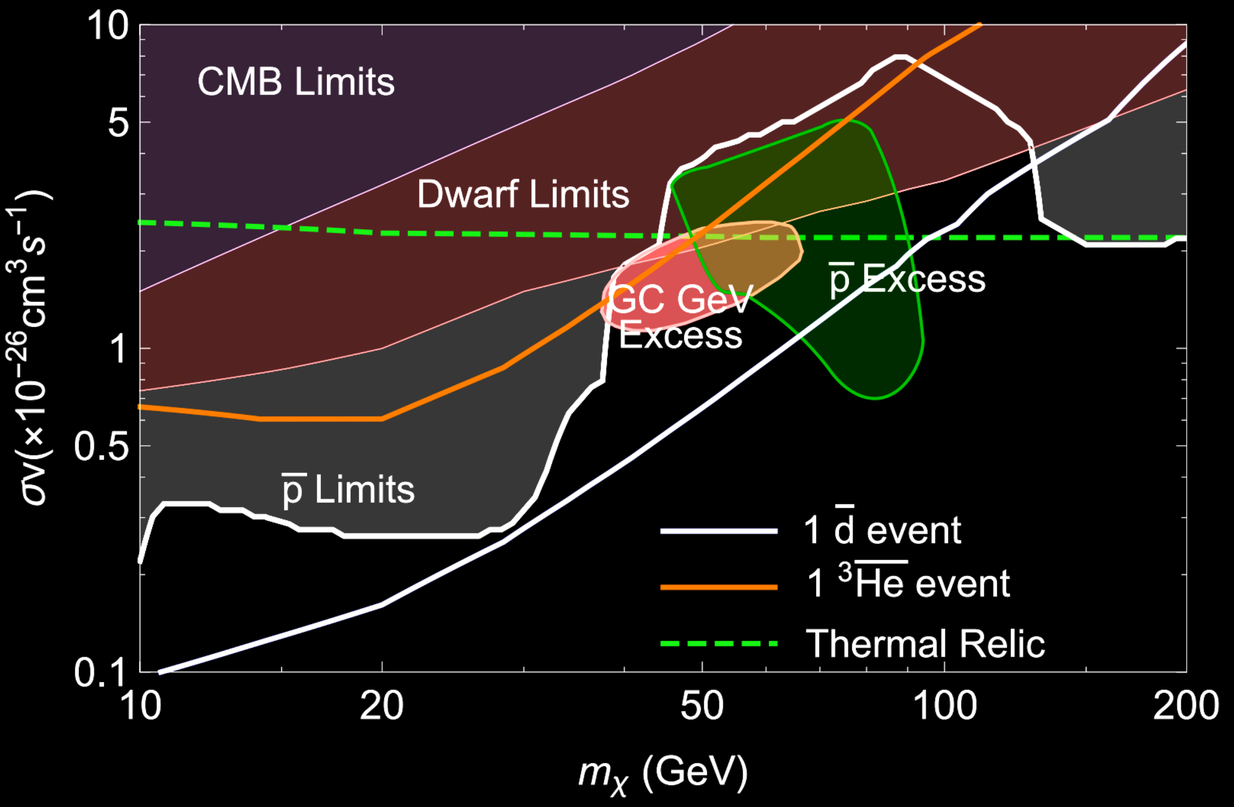
Summary

- The GCE is one of the most intriguing discoveries from the Fermi telescope, with its nature still under active debate.
- The characteristics of the GCE remain consistent despite changes in the masking areas, especially with the expansion due to the inclusion of new point sources.
- The morphology of the GCE, in relation to millisecond pulsars (MSPs), is dependent on the background model and requires further study.

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

More mathematically speaking

$$C = c_{\rm gas}\Phi_{\rm Pi0} + c_{\rm ICS}\Phi_{\rm ICS} + ... + c_{\rm GCE}\Phi_{\rm GCE}$$

Weighted sum of templates

$$D = \text{Fermi Data}$$

What are the weights maximize the log-likelihood?

Weighted sum of templates

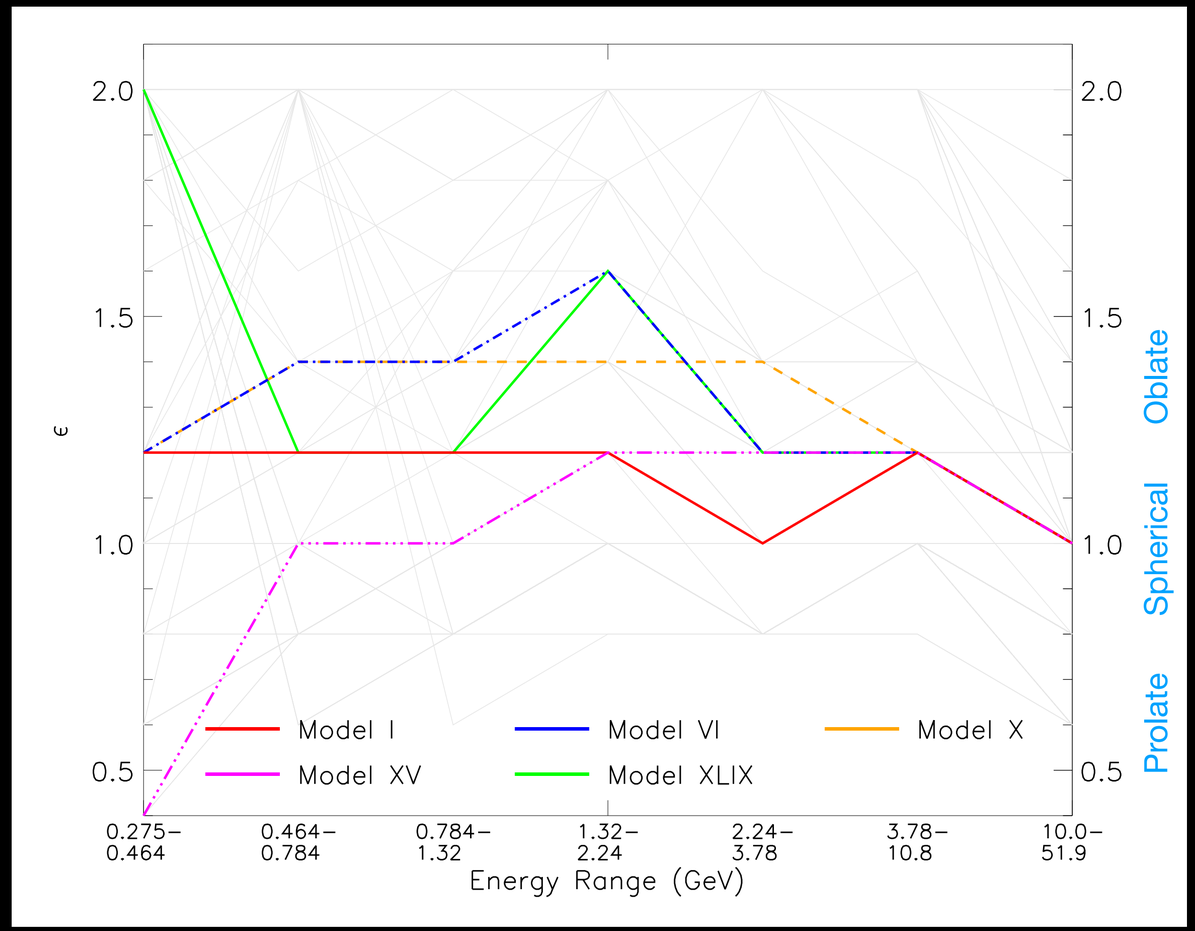
$$\ln \mathcal{L} = \sum_{\rm pixcels} \ln\left(\frac{C^D e^{-C}}{D!}\right) - \frac{1}{2}\chi^2_{\rm ext}$$

Fermi data

Energy-dependence of the ellipticity

- For energies > 3 GeV, the GCE shows approximate sphericity across best-fit background models.
- The property remains robust across various masks.

Standard 4FGLDR3 + Disk



McDermott et al., arXiv:2209.00006v3

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]	−16	−115
Dark Matter	ring-based [23]	−542	+251
Boxy & X-Shaped Bulges	ring-based [23]	−350	+119
Boxy Bulge	ring-based [23]	−414	+142
Boxy Bulge "plus"	ring-based [23]	−466	+156
Boxy Bulge "plus" & DM	ring-based [23]	−734	+351
No Excess	astrophysical [15]	+1805	−50
Boxy Bulge	astrophysical [15]	−53	+835
Boxy Bulge "plus"	astrophysical [15]	−132	+875
Dark Matter	astrophysical [15]	−943	+1290
Boxy Bulge "plus" & DM	astrophysical [15]	−1056	+1320

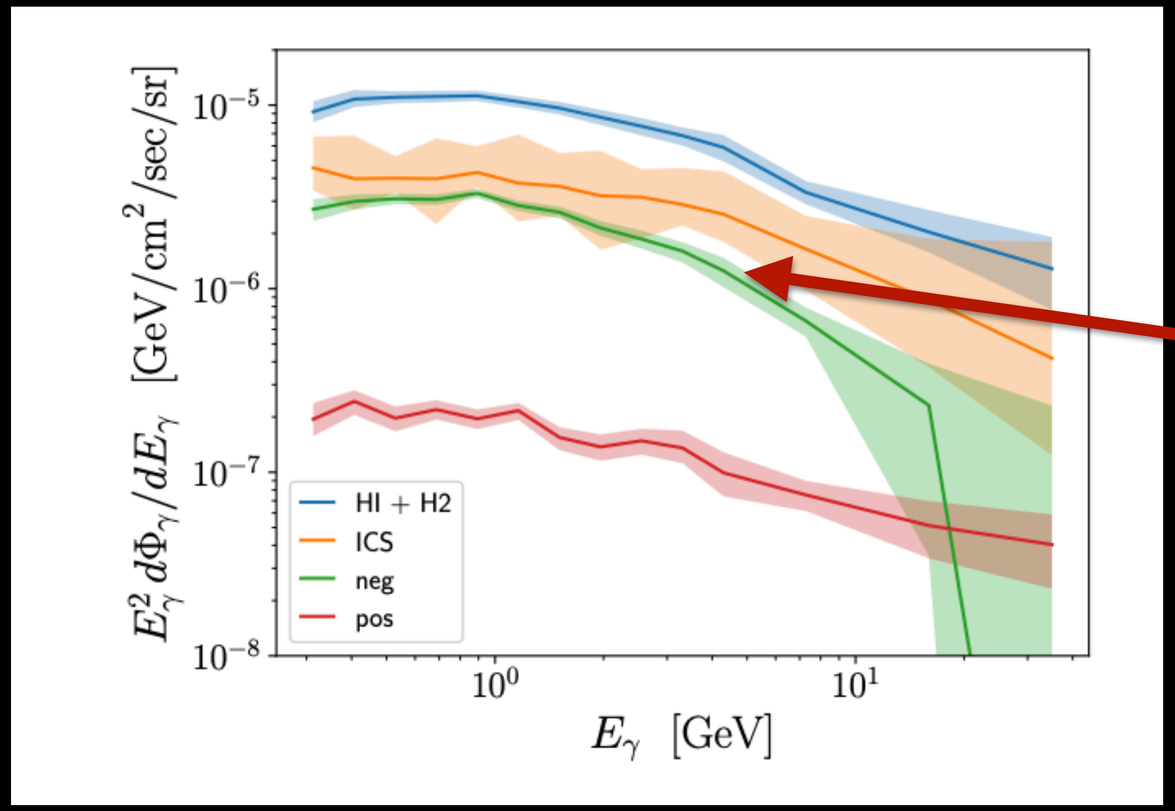
Song et al., arXiv:2402.05449v1

Baseline Model	Additional source	$-2\ln\mathcal{L}$	TS	$\ln\mathcal{H}$	$\ln\mathcal{B}\equiv\Delta$
ring-based	none	3750994	0	−1876462	0
ring-based	BB (gcepy)	3750592	402	−1876297	165
ring-based	F98	3750570	424	−1876302	160
ring-based	Cao13	3750560	434	−1876276	186
ring-based	gNFW^2	3750433	561	−1876232	230
ring-based	Coleman20	3750333	661	−1876144	318
GALPROP$_{7p}$	none	3752798	0	−1876678	0
GALPROP$_{8t}$	BB (gcepy)	3750941	1857	−1875793	885
GALPROP$_{8t}$	gNFW^2	3750051	2747	−1875340	1338
GALPROP$_{8t}$	Cao13	3750582	2216	−1875613	1065
GALPROP$_{8t}$	F98	3749924	2874	−1875286	1392
GALPROP$_{8t}$	Coleman20	3749563	3235	−1875108	1570

Excess Model	Bgd. Templates	-2Δ ln L (McDermott et al)	-2Δ ln L (Song et al)	Δ ln B (McDermott et al)	Δ ln B (Song et al)
No Excess	Ring-based	0	0	0	0
Dark Matter	Ring-based	-542	-561	+251	+230
Boxy Bulge	Ring-based	-414	-402	+142	+165
Boxy Bulge “Plus”	Ring-based	-466		+156	
Coleman20	Ring-based		-661		+318
Cao13	Ring-based		-434		+186
F98	Ring-based		-424		+160
X-Shape Bulge	Ring-based	-16		-115	
Boxy Bulge “plus” & DM	Ring-based	-734		+351	
Boxy & X-Shaped Bulge	Ring-based	-350		+119	
No Excess	Astrophysical (another model)	+1805	+1804	-50	-216
Dark Matter	Astrophysical	-943	-943	+1290	+1122
Boxy Bulge	Astrophysical	-53	-53	+835	+669
Boxy Bulge “Plus”	Astrophysical	-132		+875	
Coleman20	Astrophysical		-1431		+1354
Cao13	Astrophysical		-412		+849
F98	Astrophysical		-1070		+1176
Boxy Bulge “plus” & DM	Astrophysical	-1056		+1320	

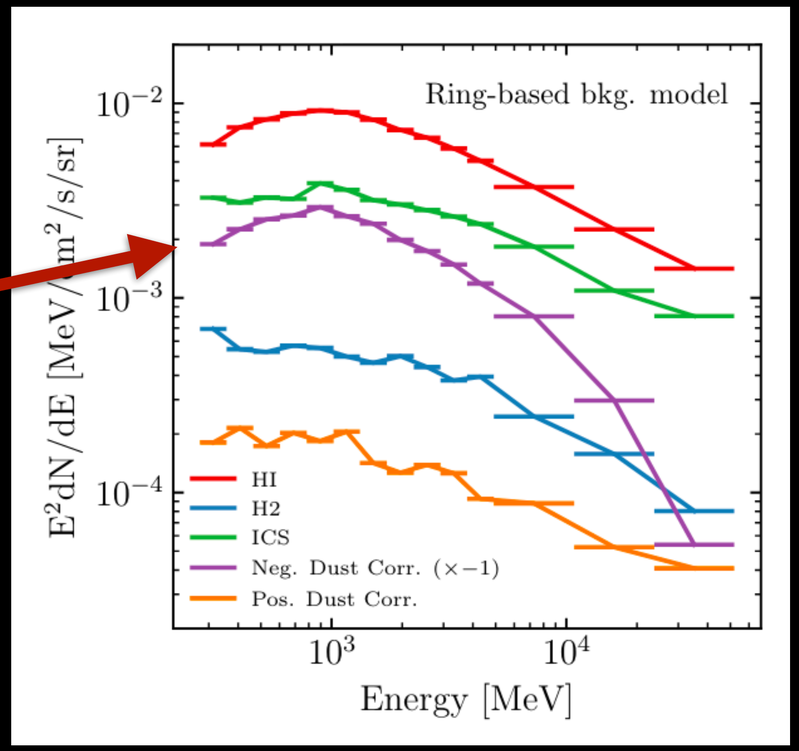
Compare

McDermott et al., arXiv:2209.00006v3

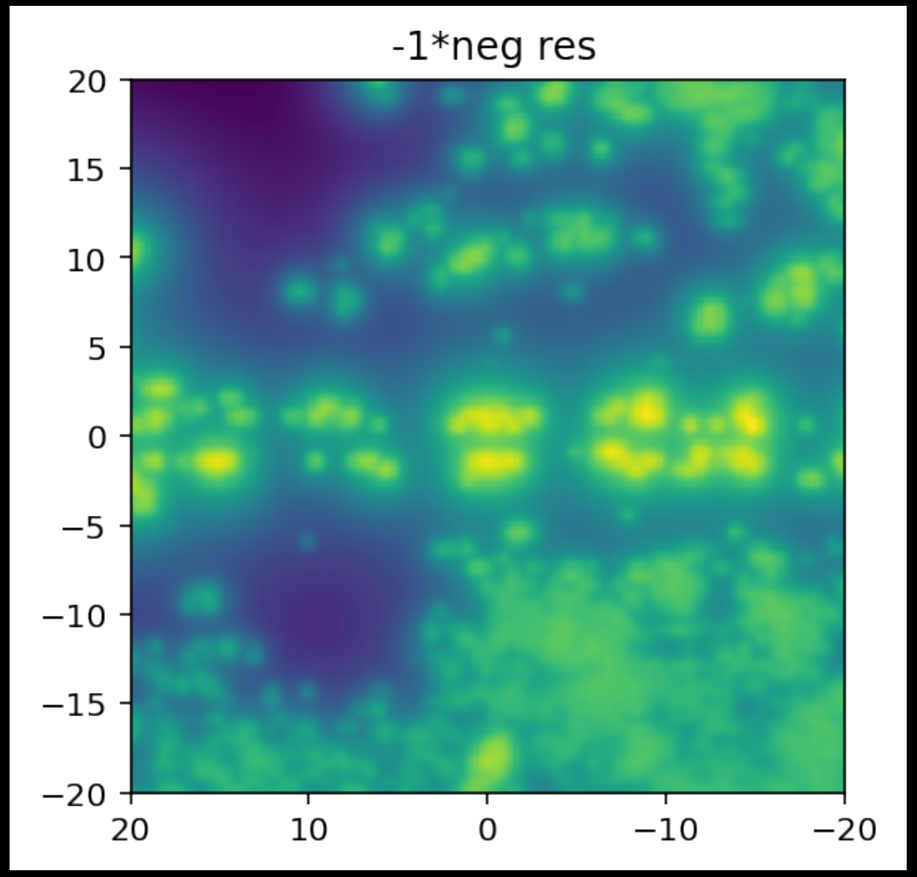


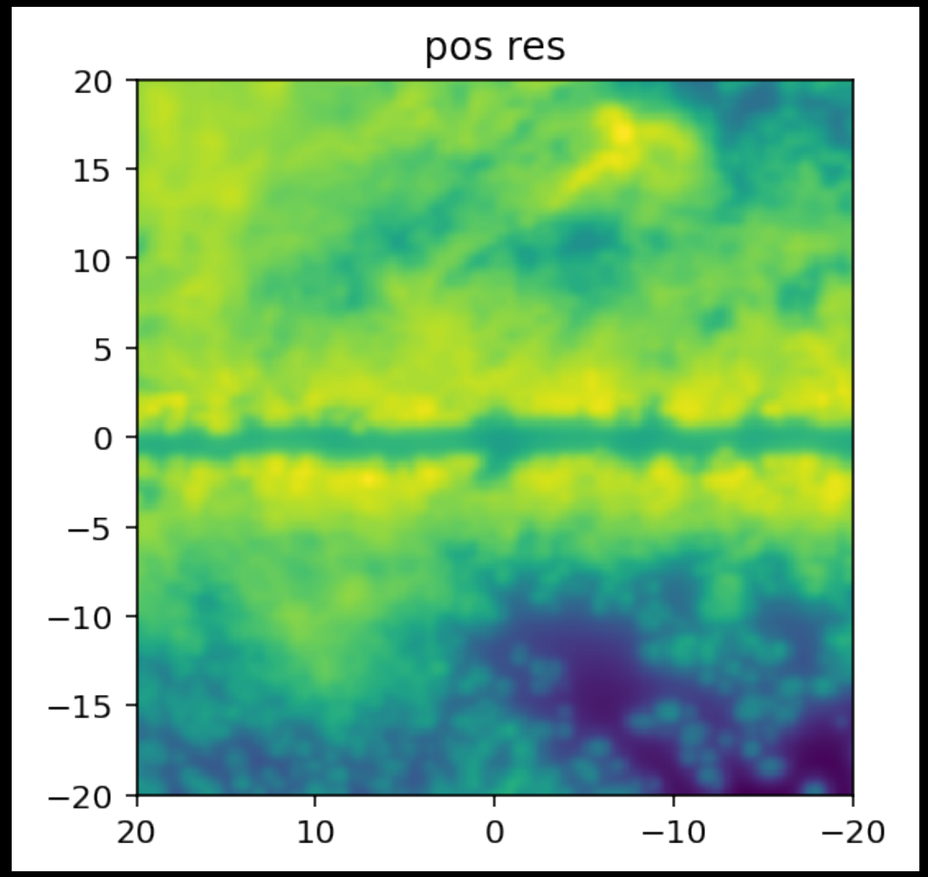
Large corrections from the negative residue

Song et al., arXiv:2402.05449v1

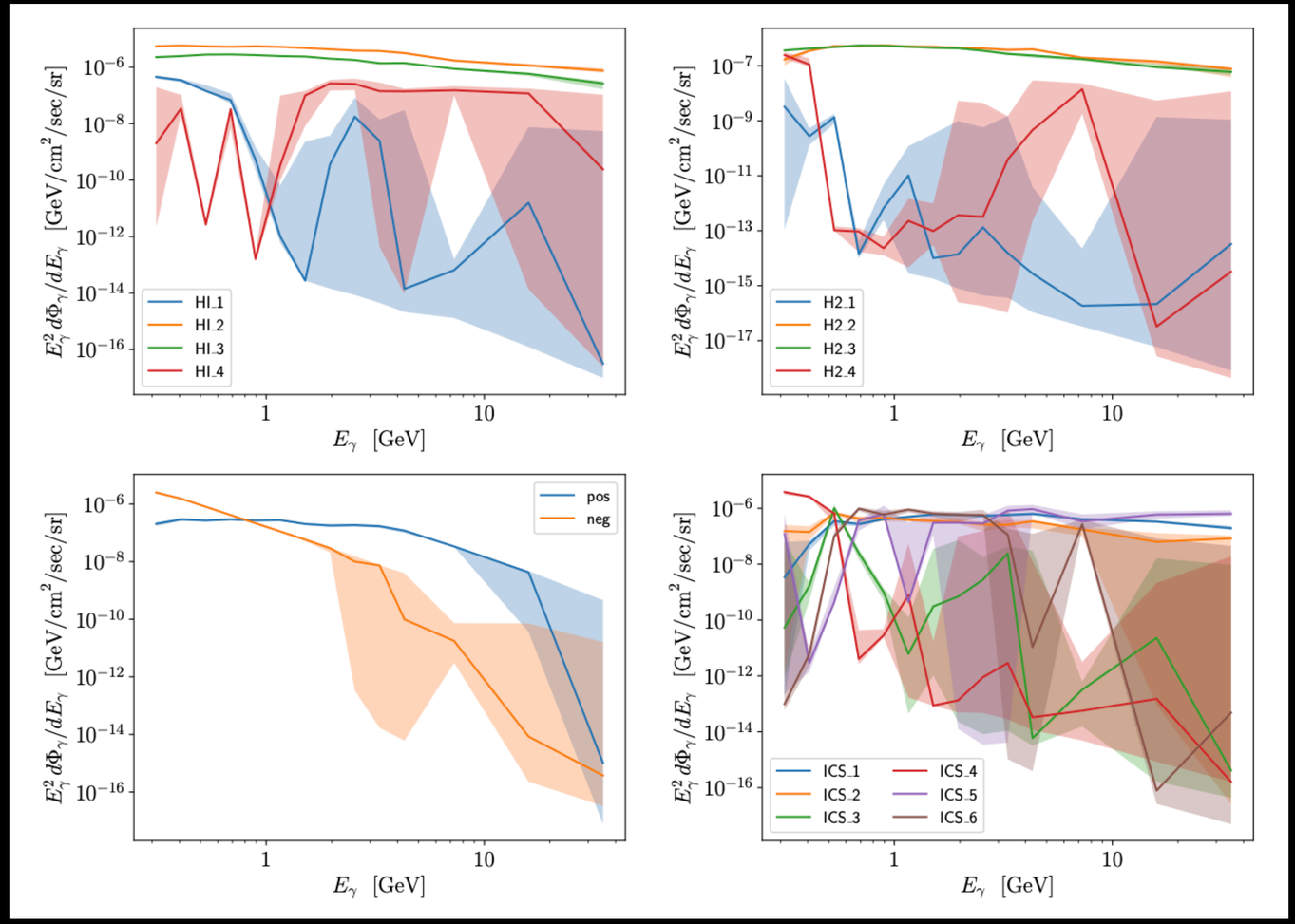


Residue templates used in Pohl et al. (2020)

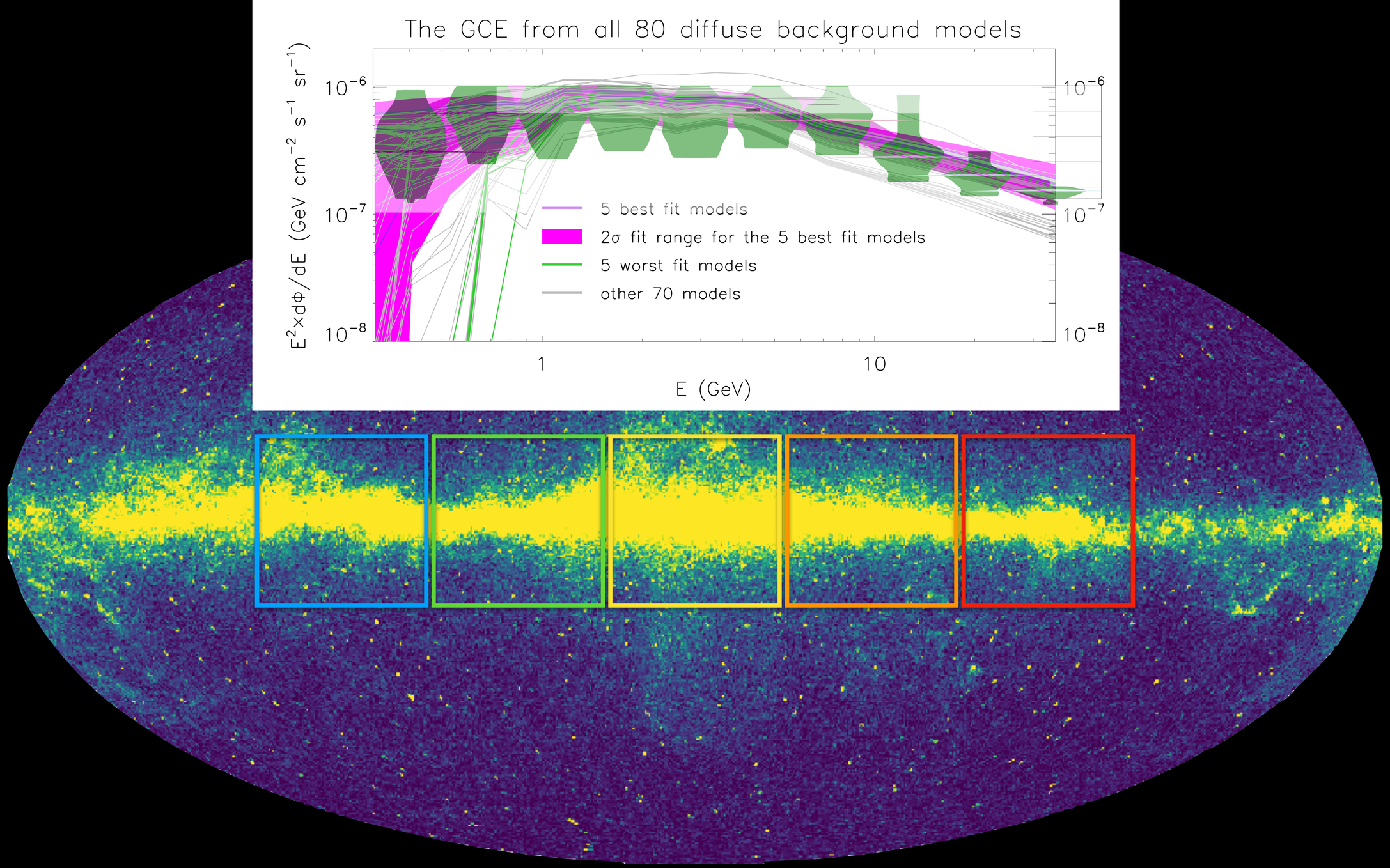


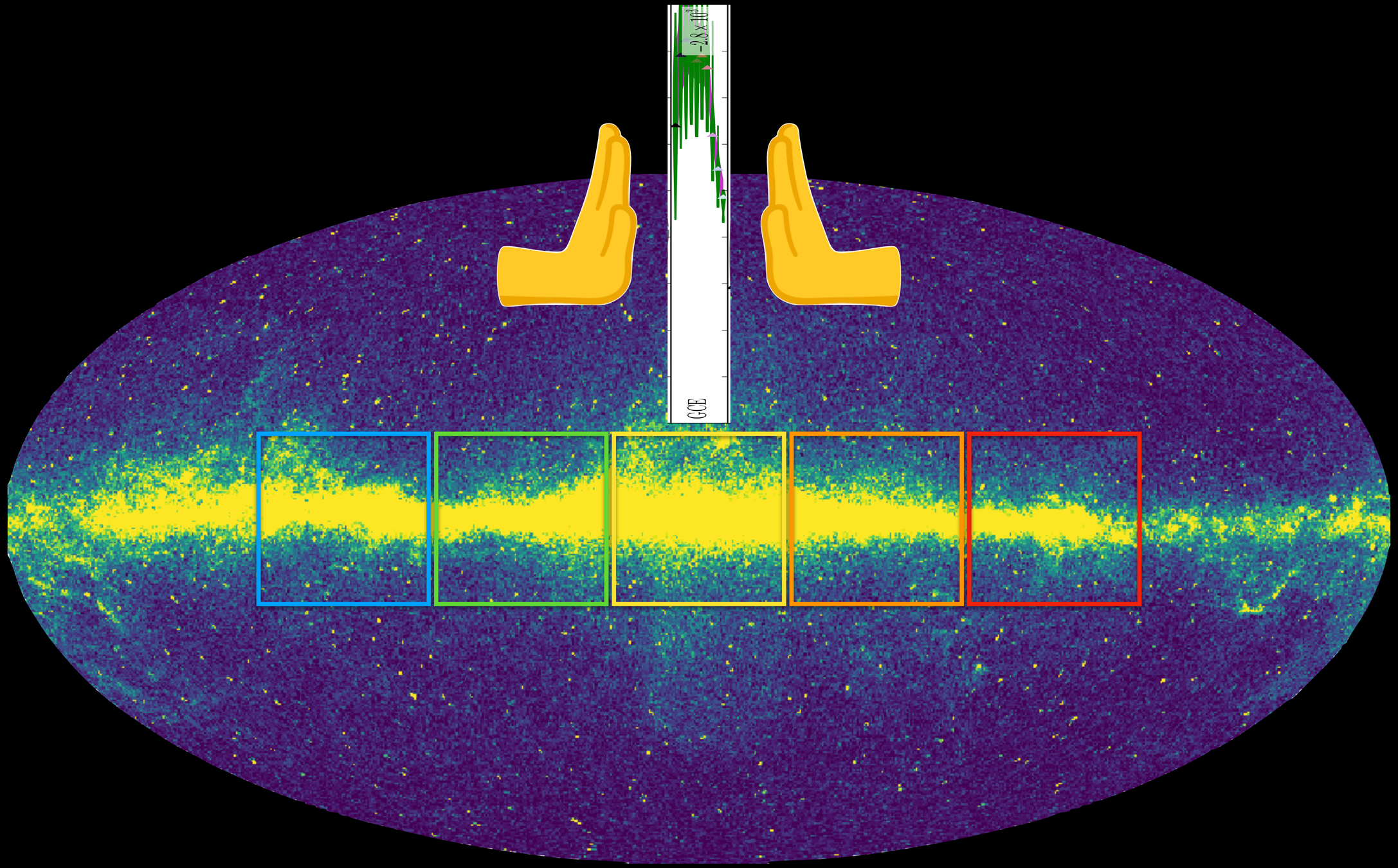


Spectra from ring-based templates



McDermott et al., arXiv:2209.00006v3


The GCE from all 80 diffuse background models
$E^2 \times d\Phi/dE$ (GeV cm^{-2} s^{-1} sr^{-1})
10^{-6}
10^{-7}
10^{-8}
1
10
E (GeV)
5 best fit models
2σ fit range for the 5 best fit models
5 worst fit models
other 70 models


2.8 x 10^3
GCE