# Fermi Galactic Center Excess


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w/ Cholis, McDermott, Surdutovich, Hu, arXiv:2112.09706, 2401.02481, 2601.xxxxx


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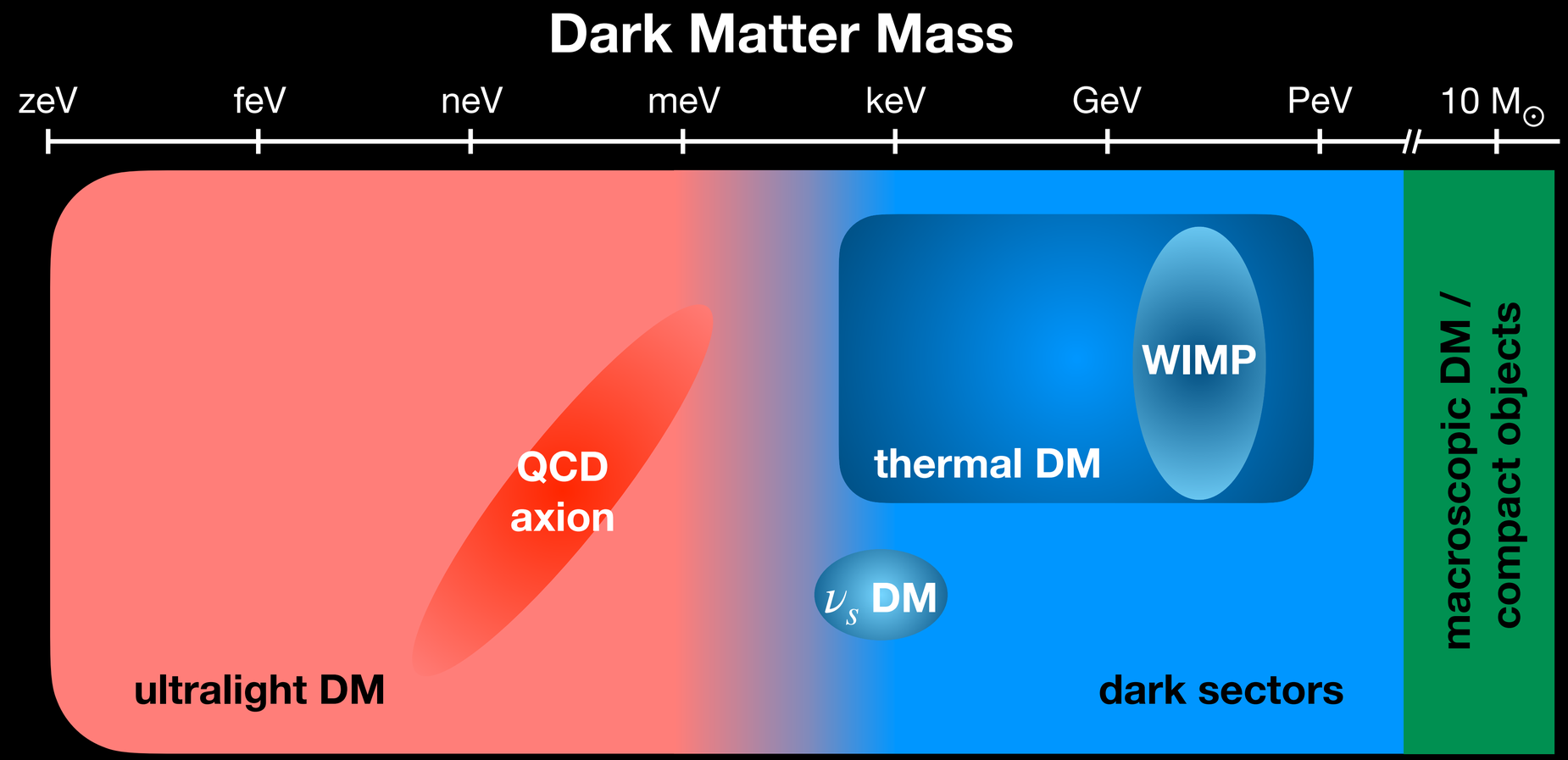
# Outline

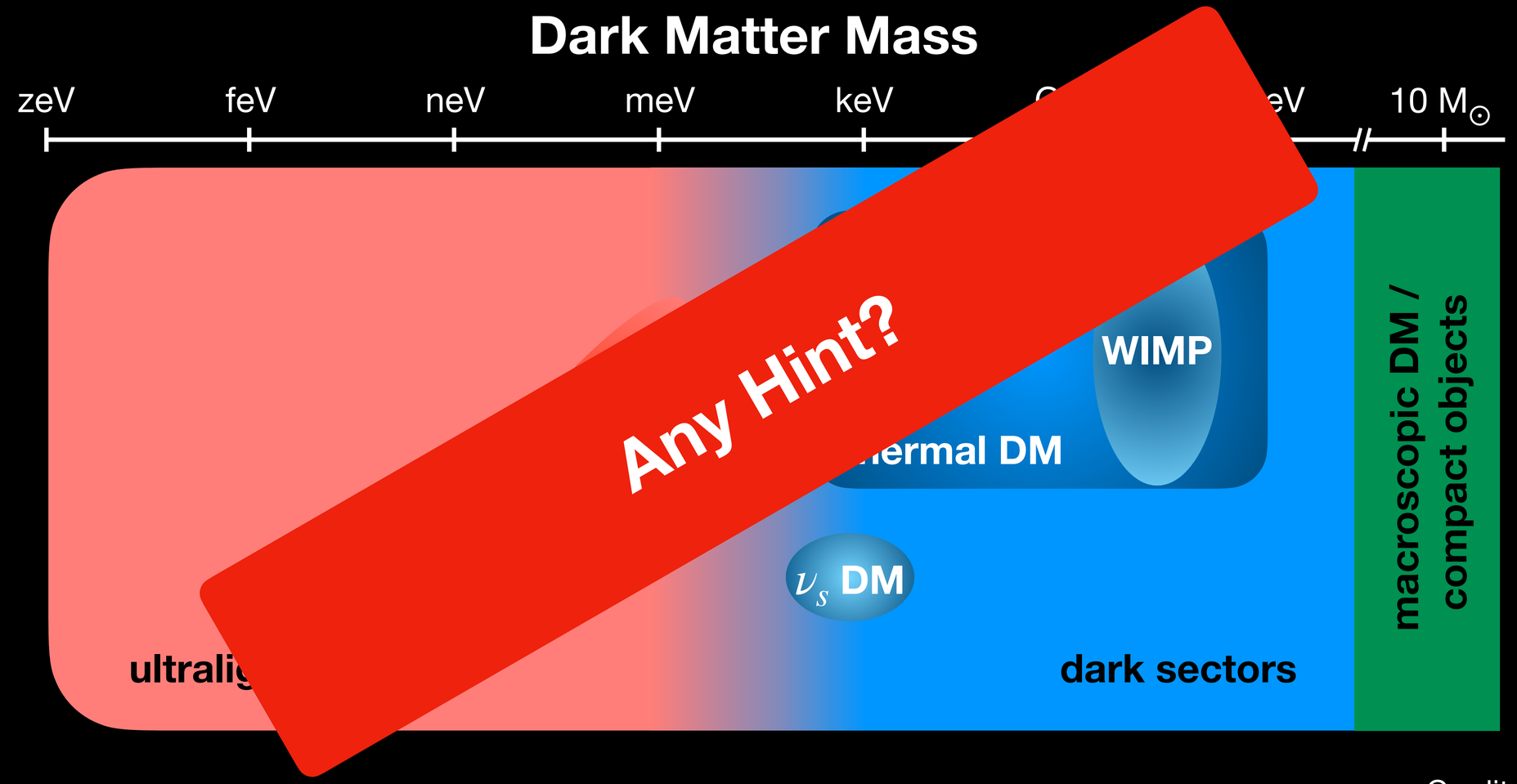
- Introduction
- Template fitting
- Morphology of the Galactic Center Excess (GCE)
- Comments on the 20 GeV halo excess
- Summary

# What is dark matter?



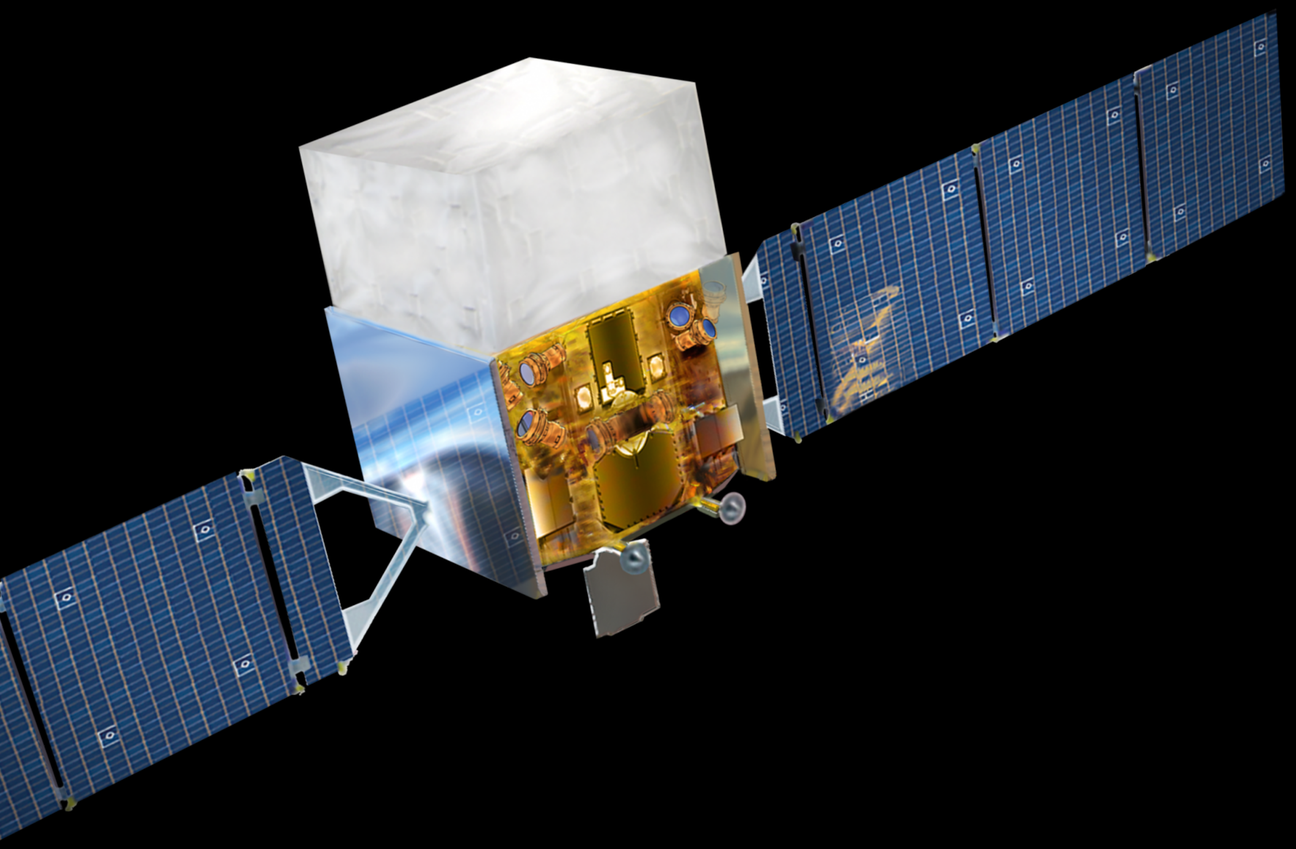

Credit: Snowmass report

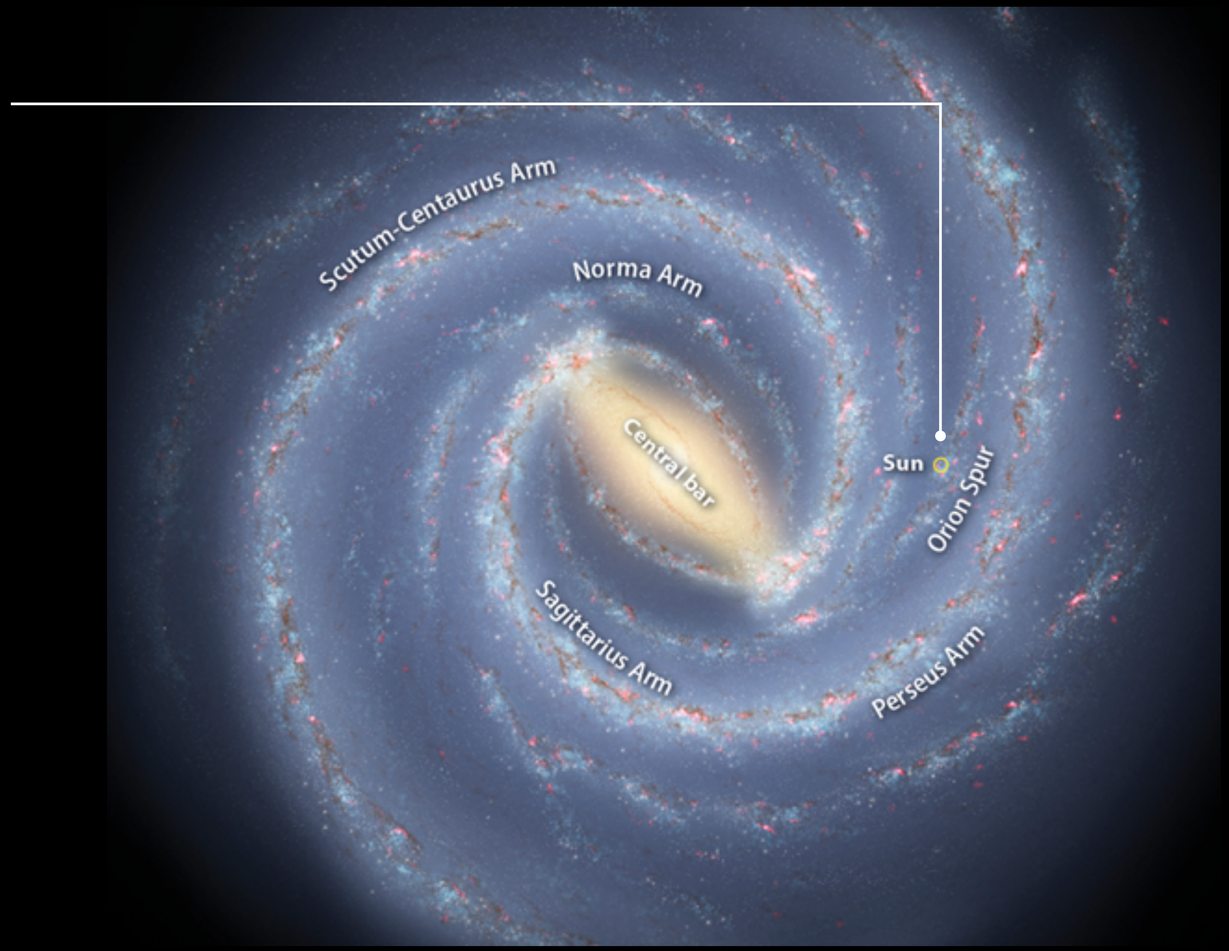
# What is dark matter?




Credit: Snowmass report

# The Fermi Large Area Telescope

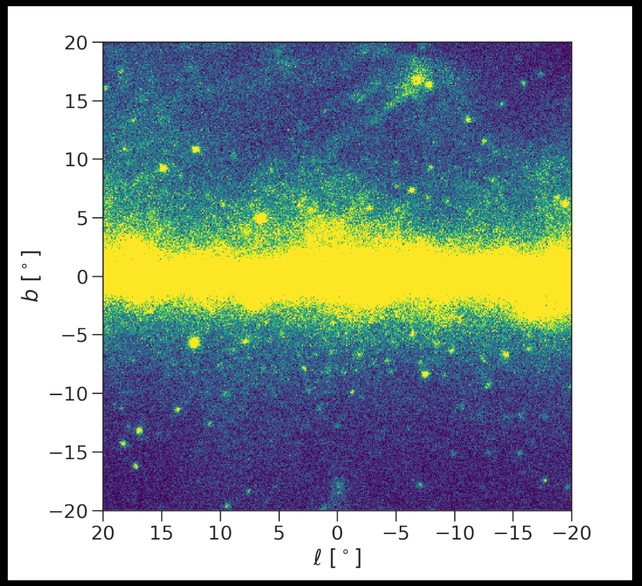


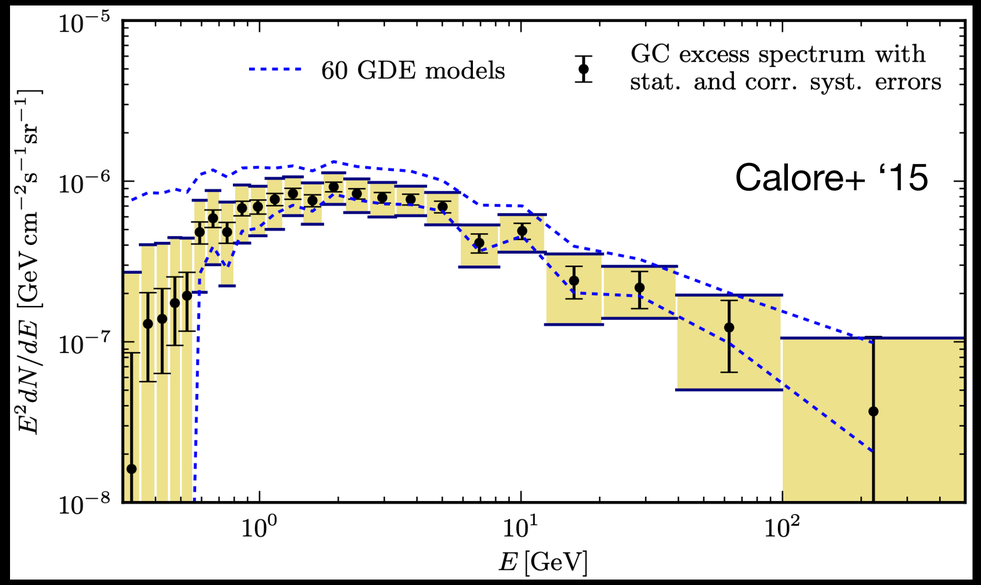



2008 to present

# The Galactic Center Excess

- Goodenough & Hooper ’09 found an excess of γ-ray photons, peaking around 1– 4 GeV, in the inner Galactic region.
- Later confirmed by the Fermi collaboration and other groups. Its existence is well established.
- Also confirmed by DAMPE (Shen+ ’25)

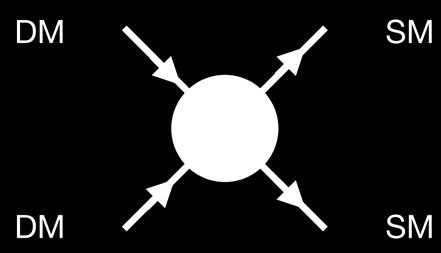



γ-ray energy spectrum

# If GCE comes from dark matter…

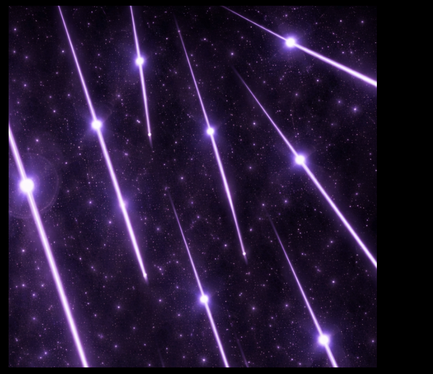
- First evidence that dark matter interacts with the ordinary matter.
- We could learn both dark matter mass and the interaction strength (WIMP particle).
- We could naturally explain the abundance of dark matter via thermal freeze-out.



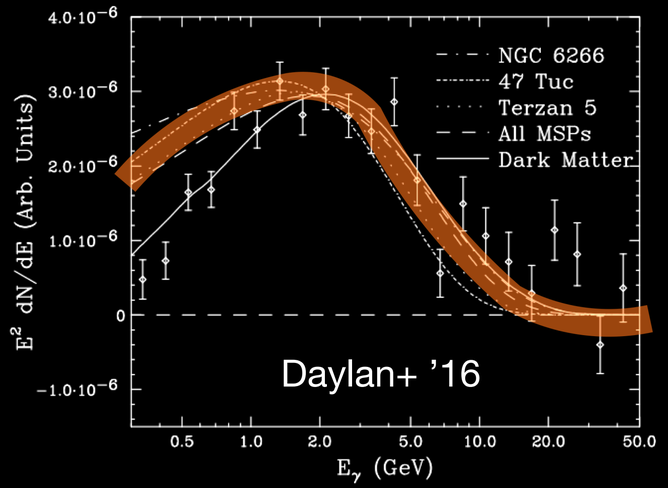

$m_\chi$ ~10-100 GeV

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

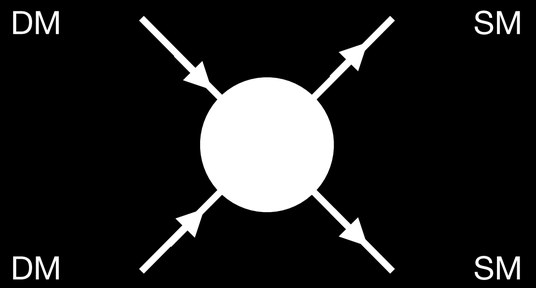
# Alternative explanation: pulsars

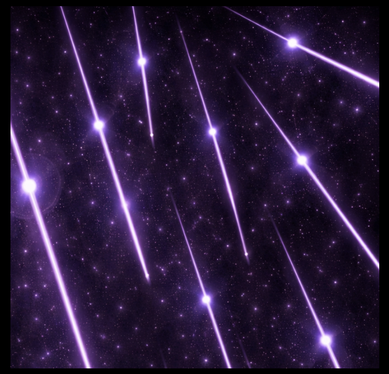


- Pulsars are rapidly spinning neutron stars.
- Among pulsars, millisecond pulsars have the correct spectra of the GCE.
- The GCE could be from a population of unresolved faint millisecond pulsars at the Galactic center.



# What are the sources of the GCE?

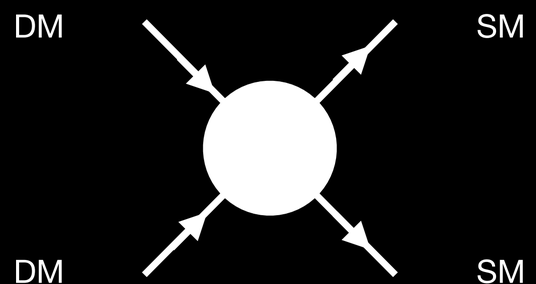


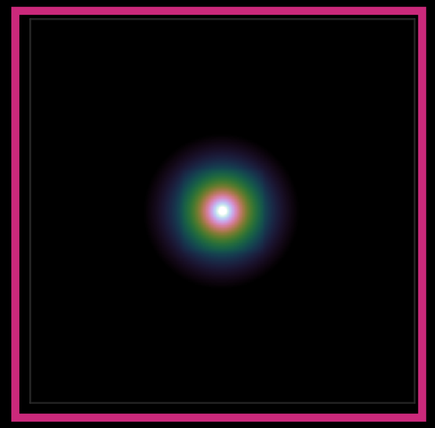



Dark matter annihilation

A new population of millisecond pulsars

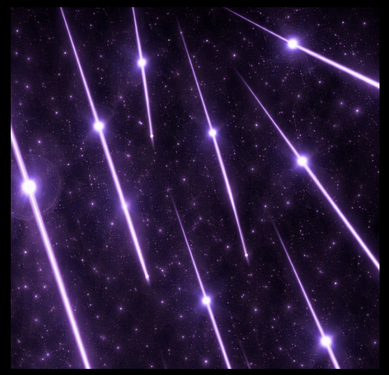
# Different small-scale powers



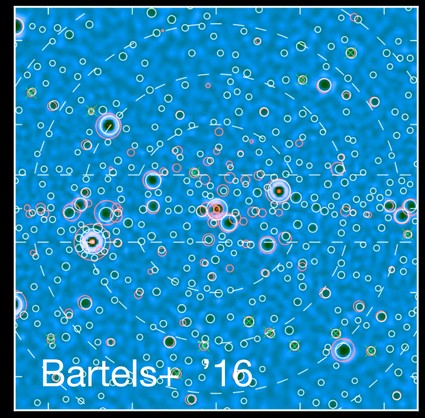



Smooth

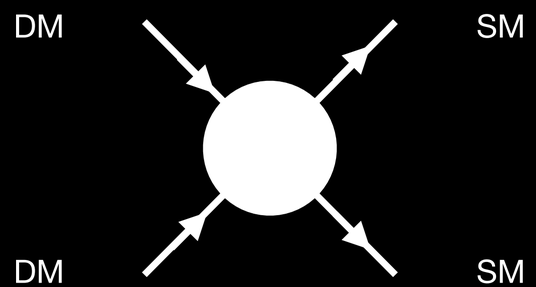
NPTF
Wavelet
1pPDF
CNN
...

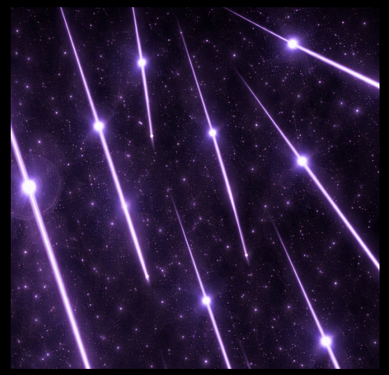


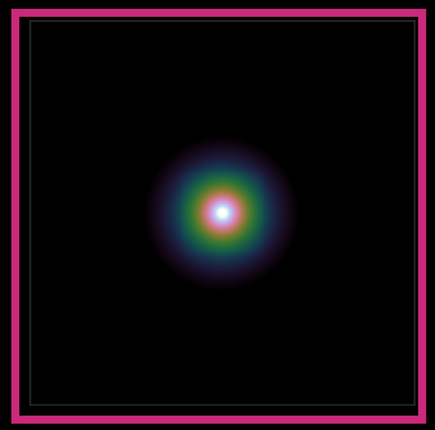
Clumpy



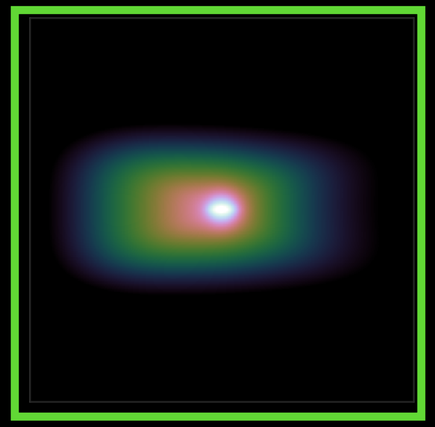
# Different morphologies





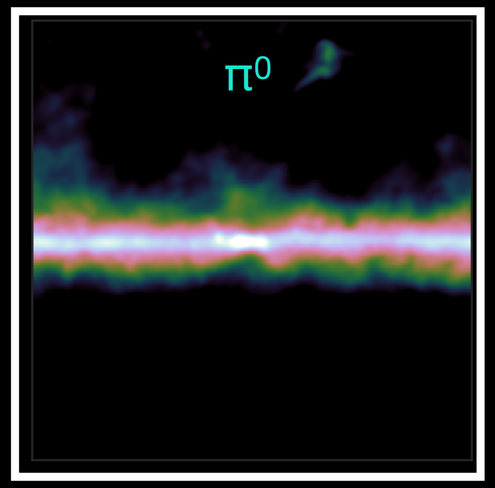
Spherical

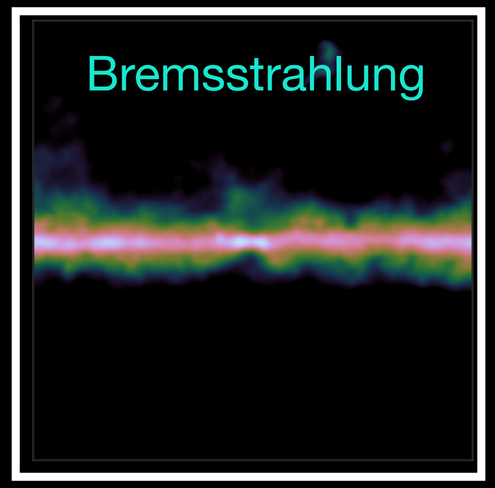


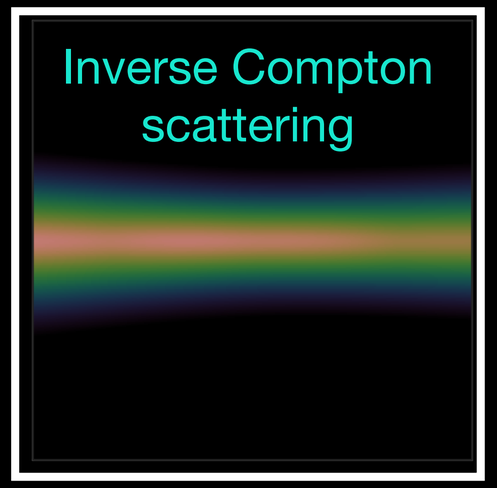
Boxy

X-shaped bulge
Boxy bulge
Boxy + Nuclear
F98
Coleman bulge
…

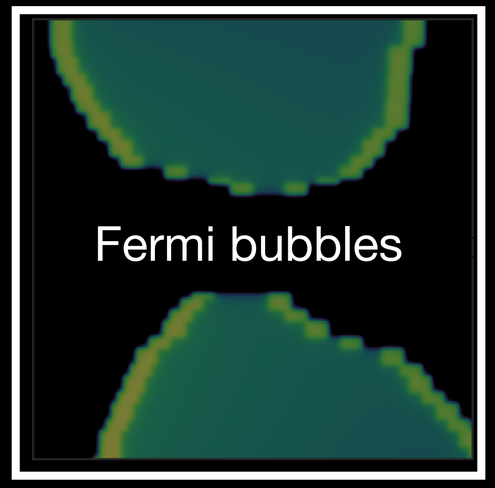
# Template fitting


$\pi^0$


Bremsstrahlung

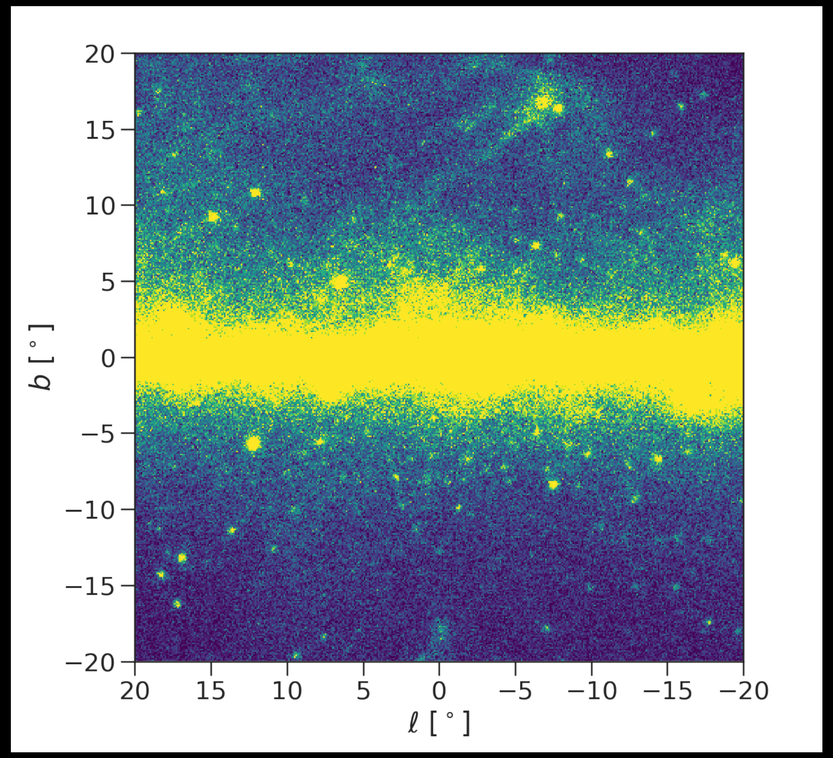

Inverse Compton scattering


Isotropic diffuse background


Fermi bubbles

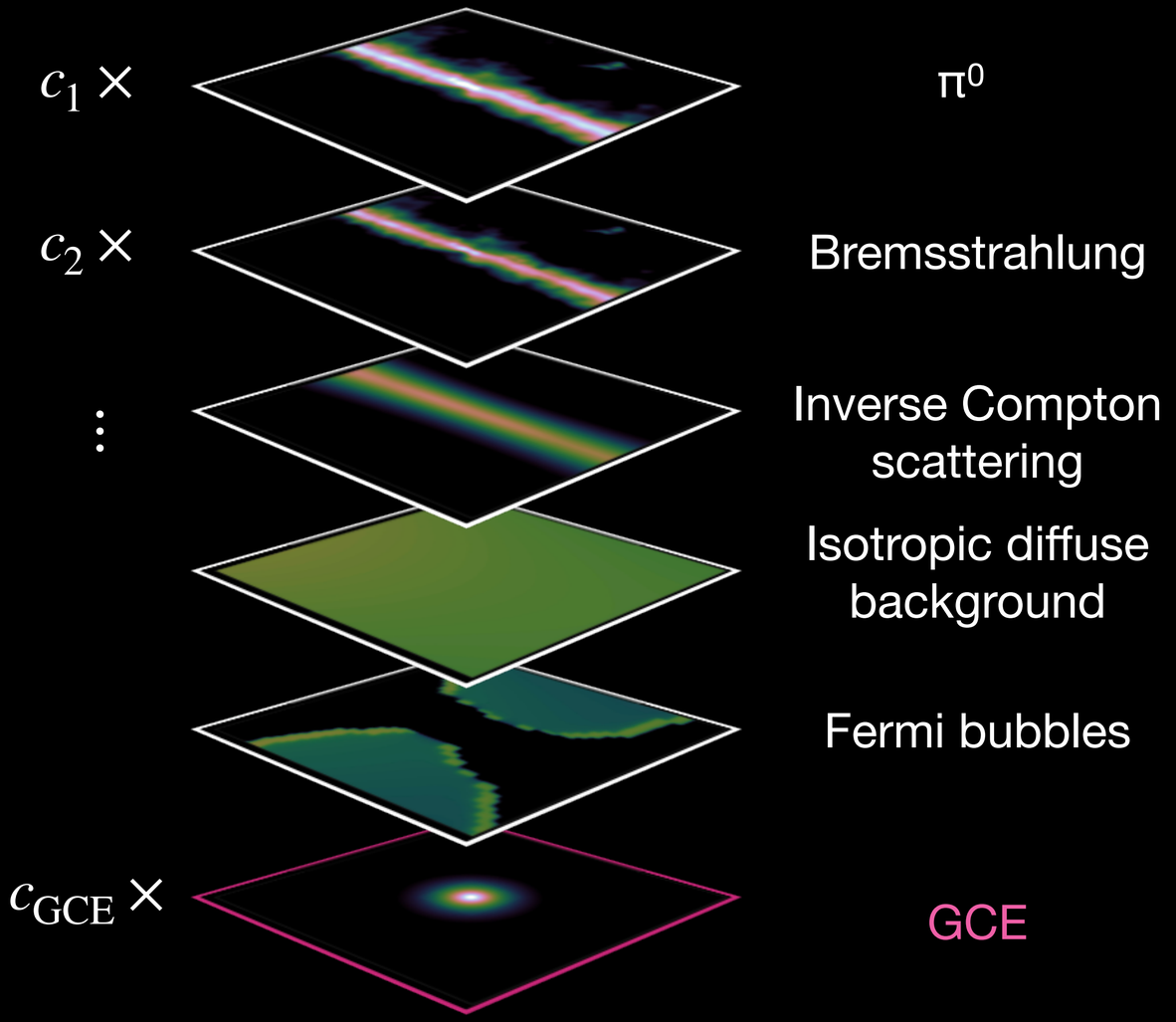

GCE

# Fermi data

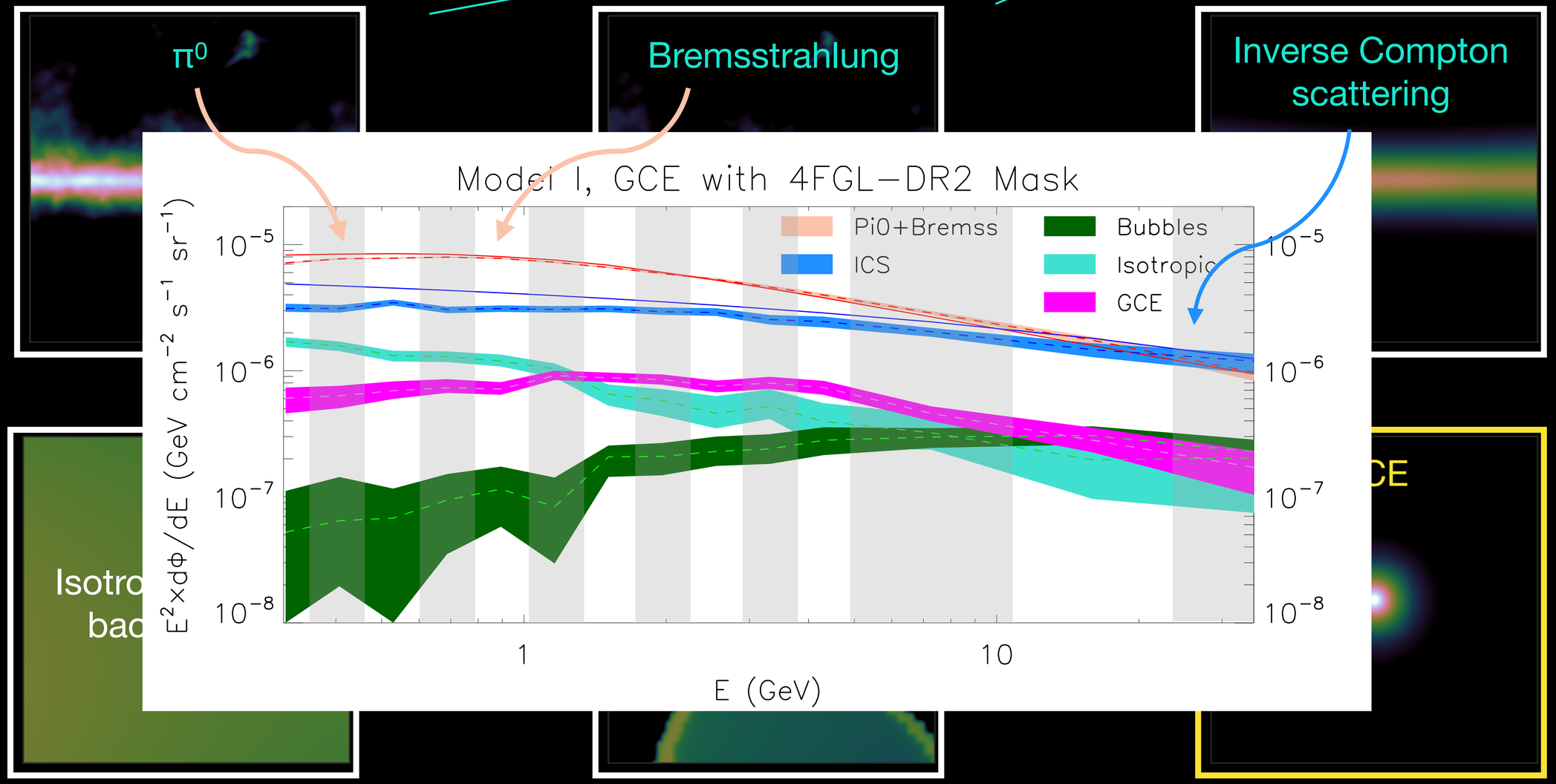



**vs.**

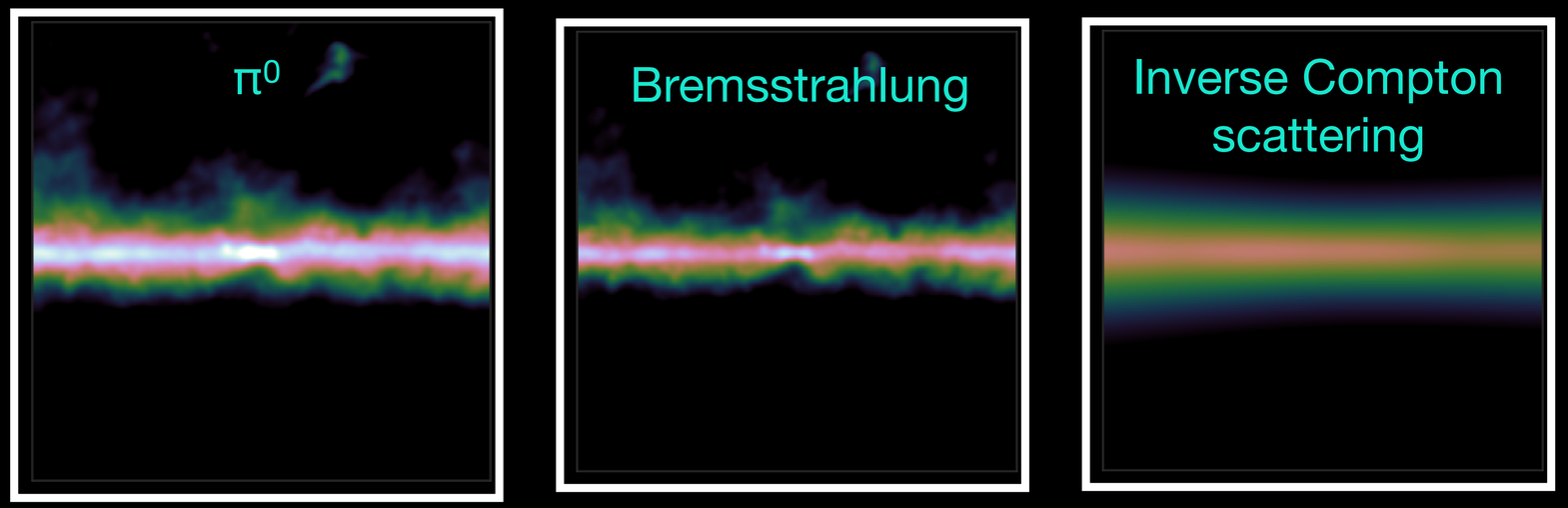
# *Weighted* sum over all background & GCE templates



# Galactic Diffuse Emissions (GDE)



# New templates calibrated w/ cosmic-ray data




Cholis+ (+YZ) ’21

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

tune GALPROP

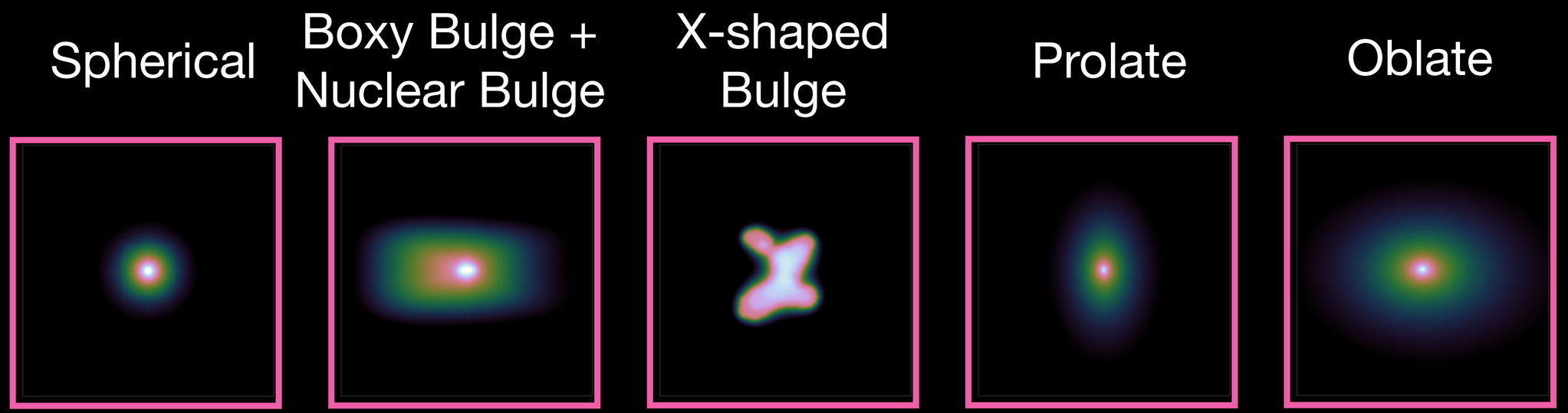
5 calibrated CR models

Galactic environment

80 GDE template sets

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

# Testing different GCE models

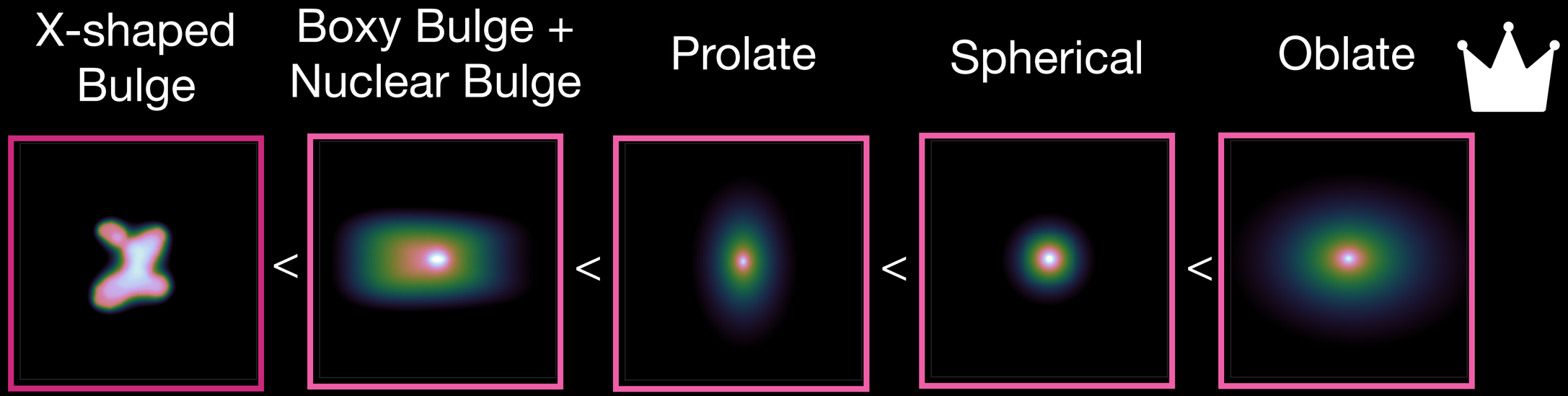



80 GDE template sets

Which model has the maximum log-likelihood?

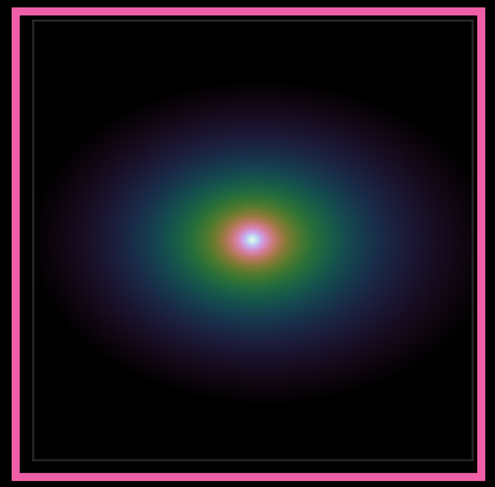
# Morphology of the GCE

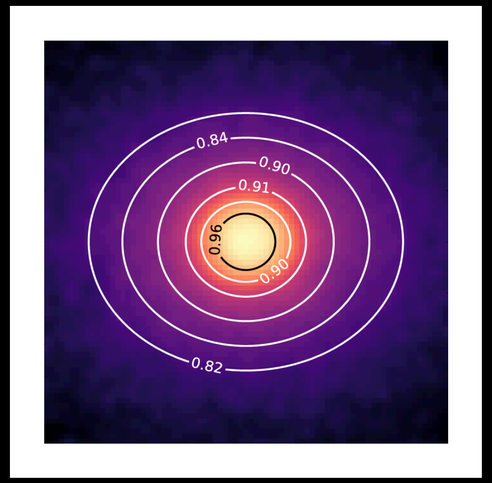
# Our earlier work Cholis+ ’21



# Why is the GCE oblate?

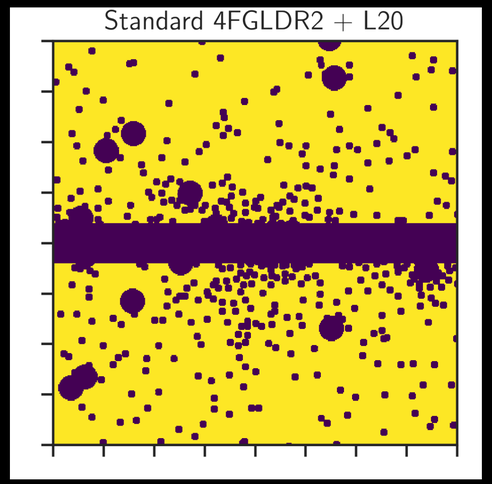
Oblate





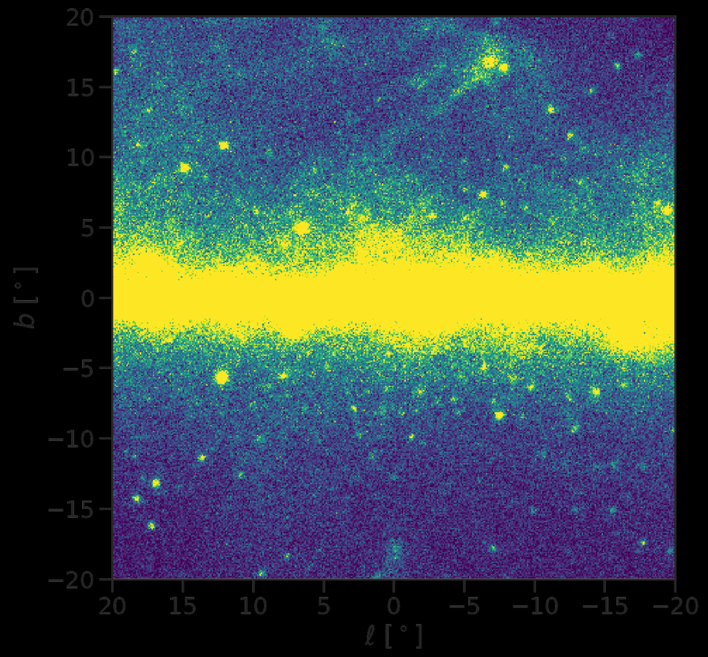

Adiabatic contraction

Grand & White ‘22



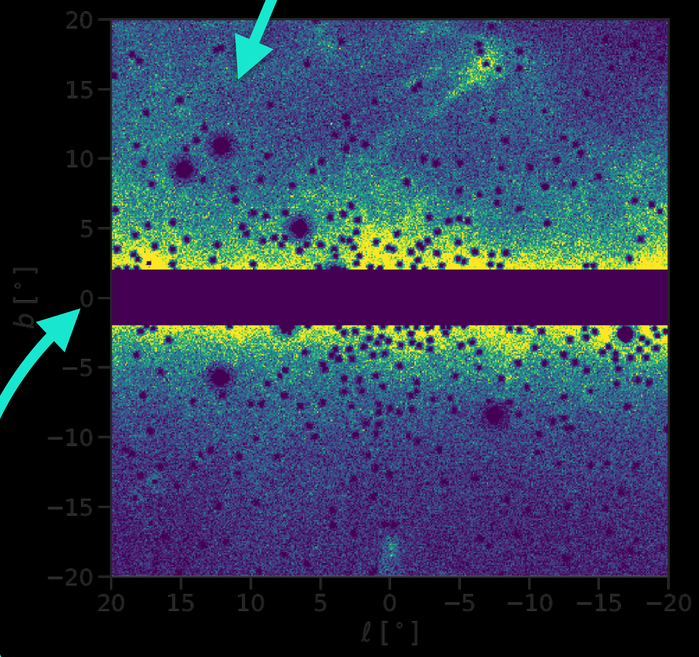

Masking bias?

Fermi data




Masking

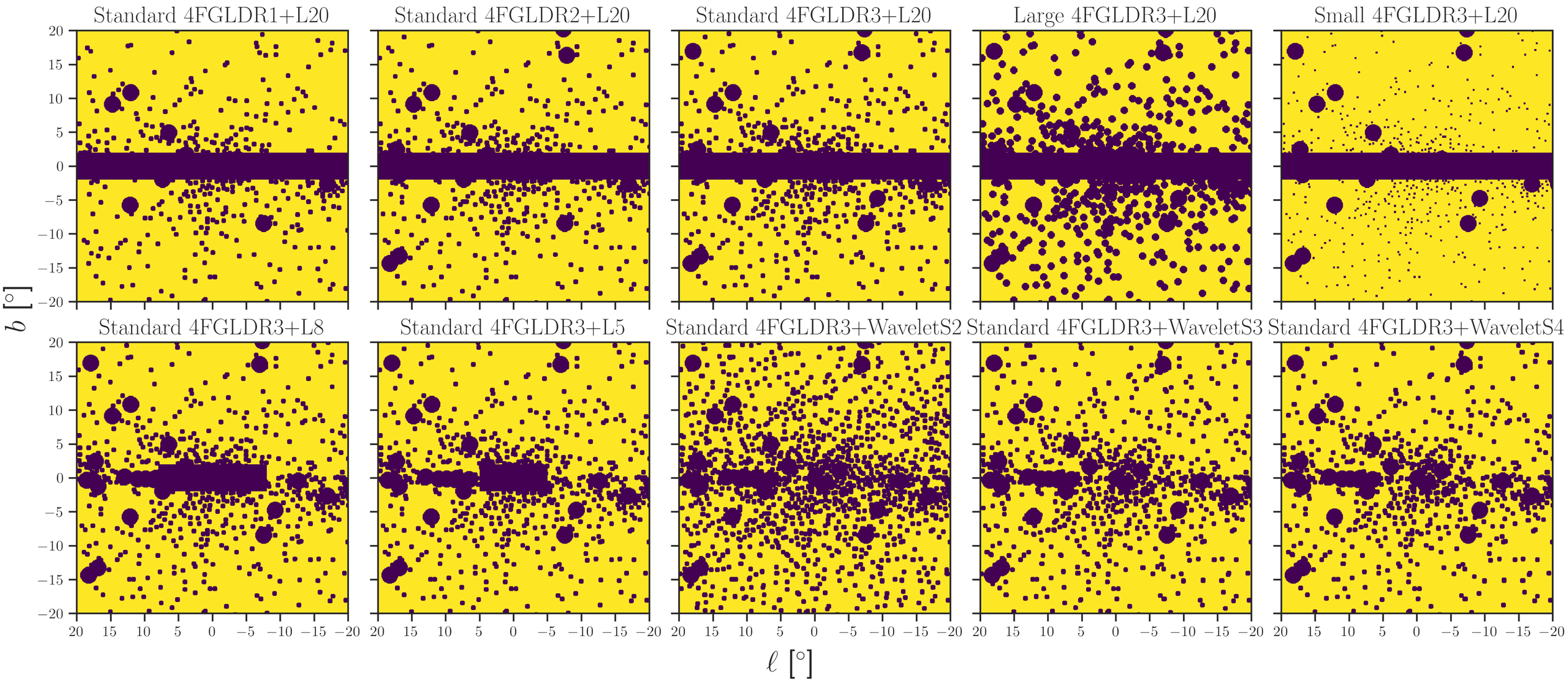
Removing point source regions




Fitting

Removing the Galactic disk region

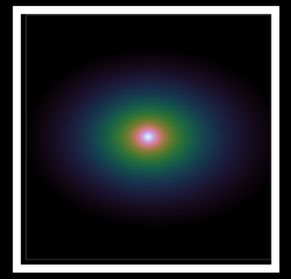
# Test GCE morphology against various masks



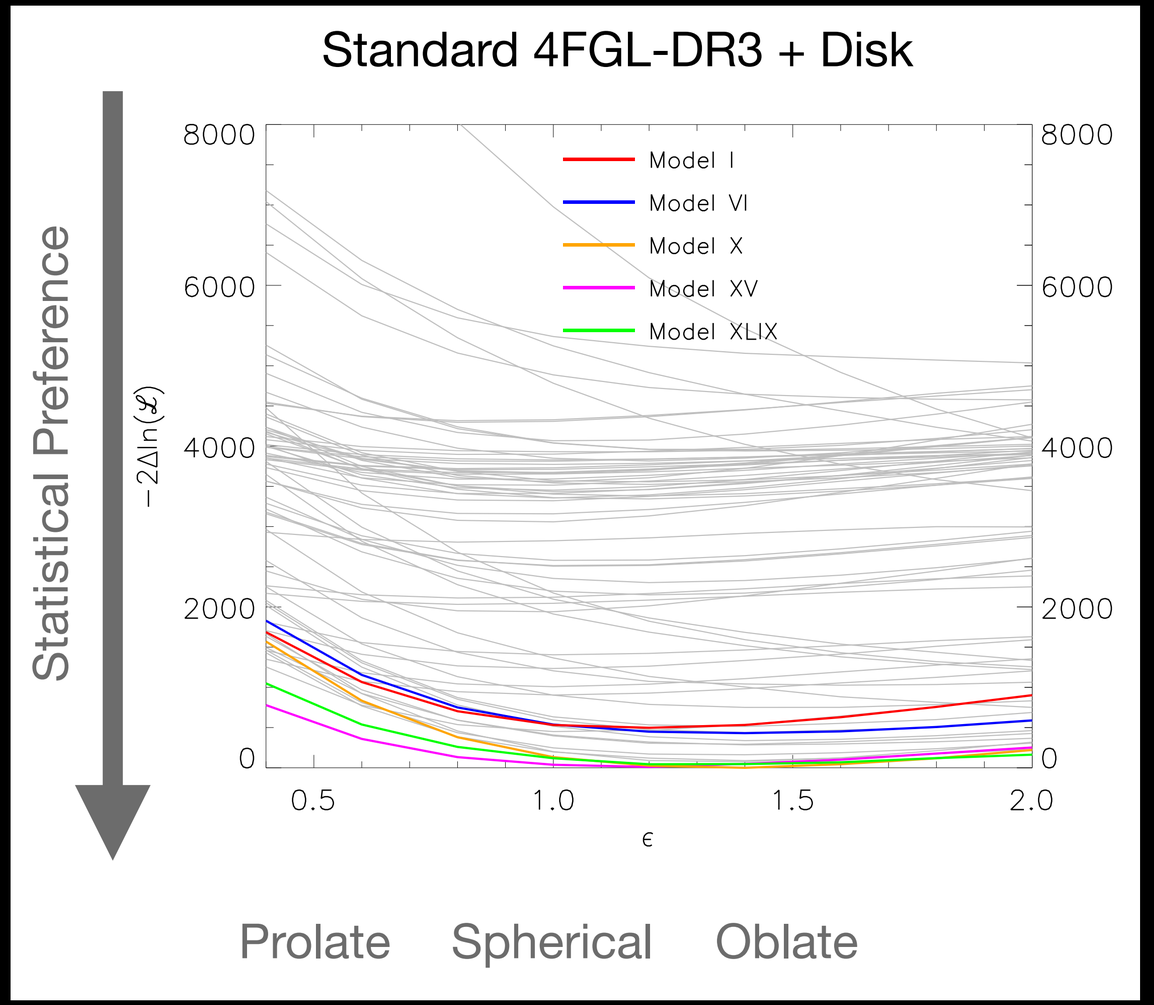
# GCE is oblate

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

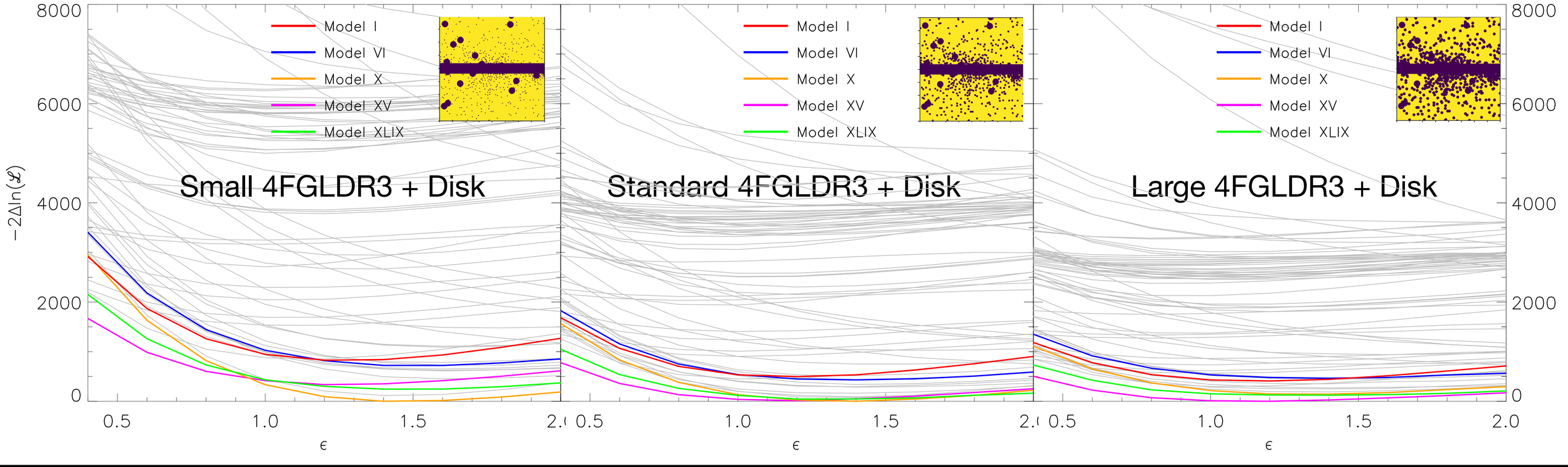
Open angle of GCE  Galactic coordinates



- The ellipticity of the GCE favors a value of $\epsilon$ between 1.0 and 1.4
- Results under 4FGL-DR3 mask are consistent with results under 4FGL-DR2 mask.



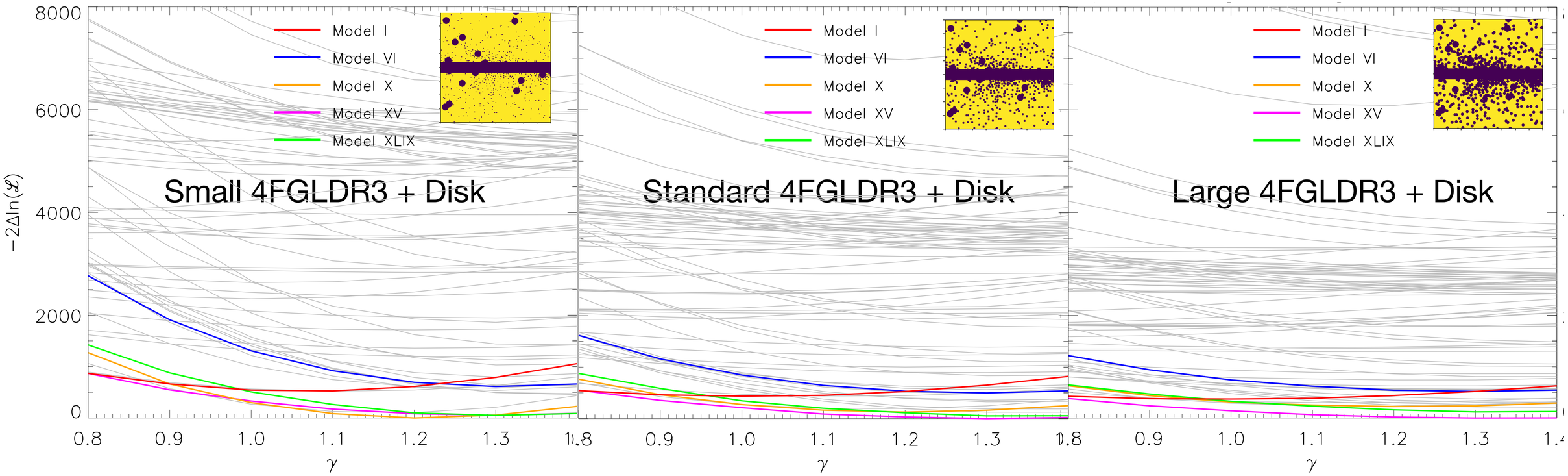
# The ellipticity of the GCE is robust




The GCE is oblate under various masks.

# The cuspiness of GCE is robust

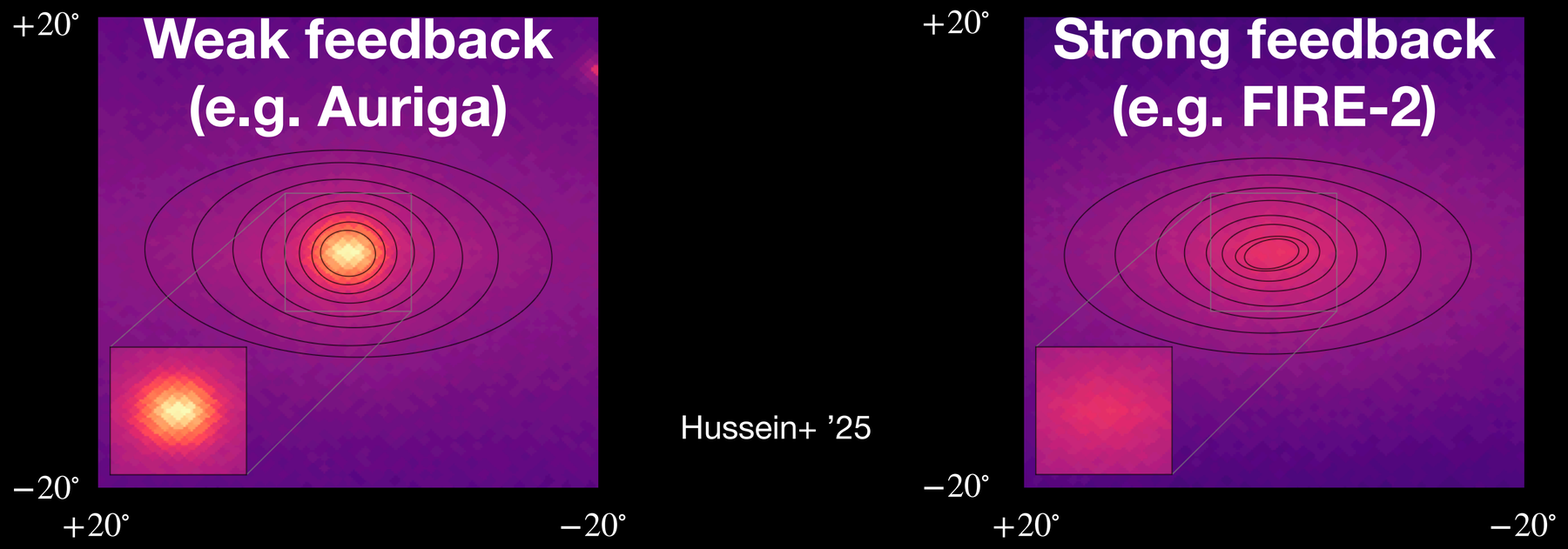
$$\rho(r) = \frac{\rho_0}{(r/r_c)^{\gamma}(1 + r/r_c)^{3-\gamma}}$$




The GCE is contracted in density under various masks.

# More to learn from the GCE morphology

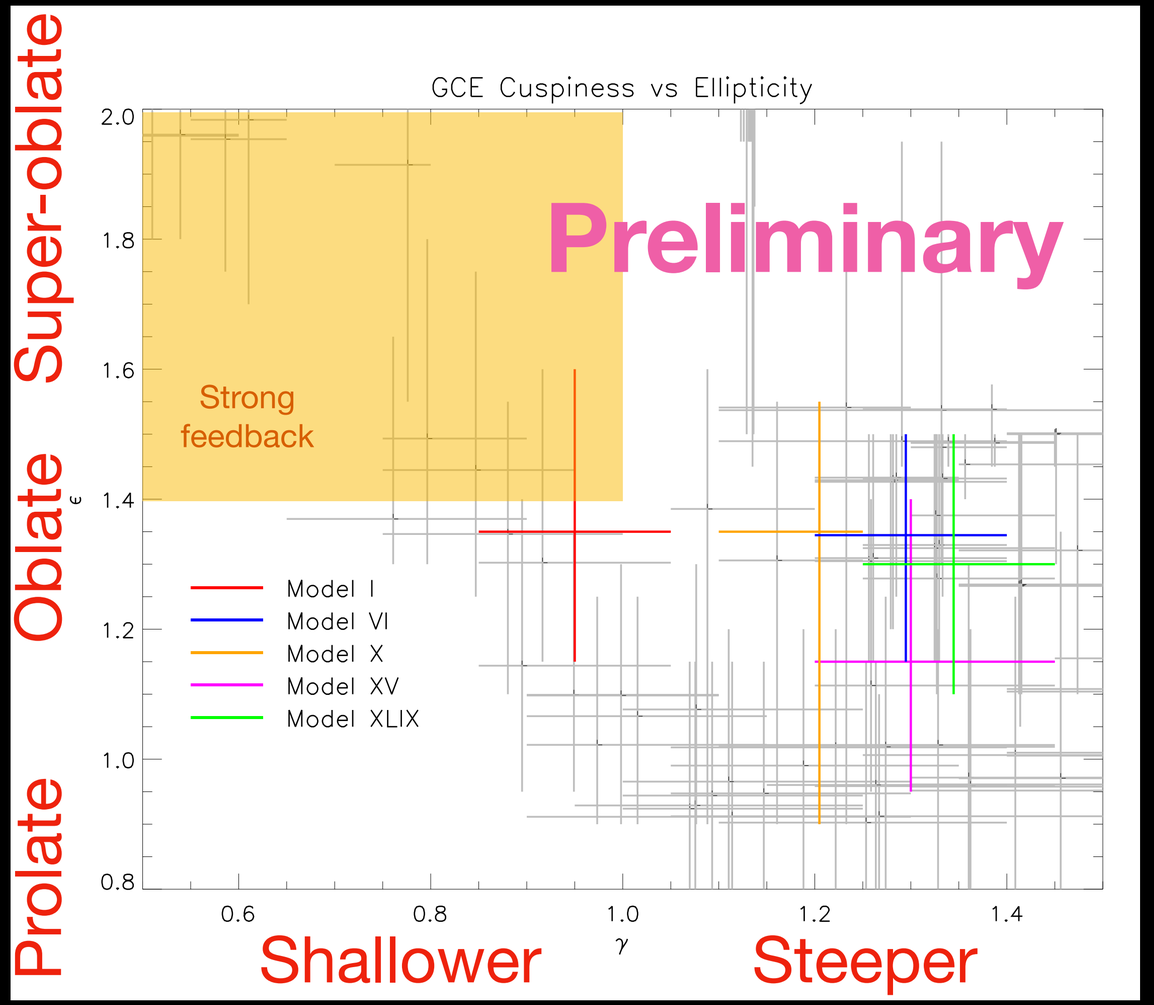
- Hussein+ ’25 finds strong dependence of the halo morphism on the baryonic feedback in DM+hydro cosmological simulations.
- A more oblate halo has a more flattened density profile.



# GCE is mildly oblate AND contracted

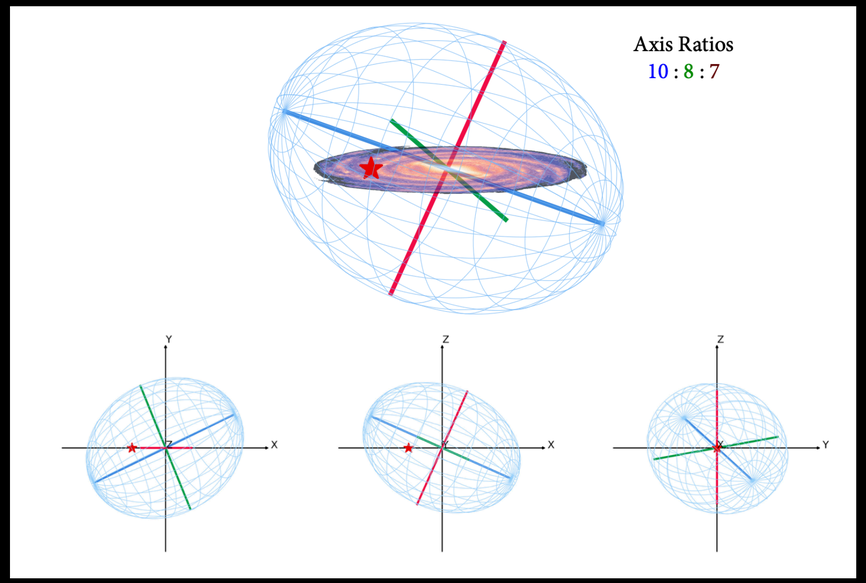
Leo Qiyuan Hu

- We fit the GCE with different combinations of ($\epsilon$, $\gamma$) under the 80 GDE template sets.
- We find that, for the best-fit GDE models, GCE prefers a contracted and a mildly oblate profiles.
- Not fall into the strong feedback region.

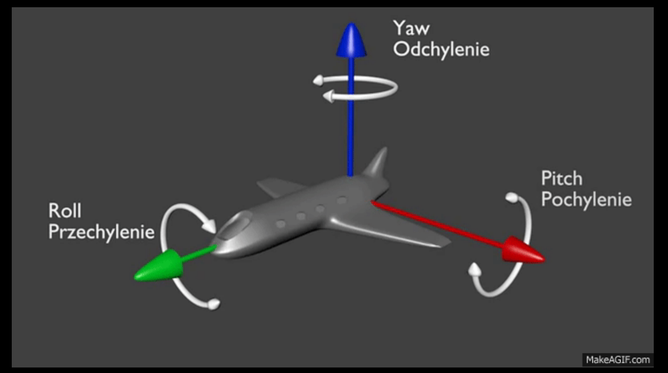


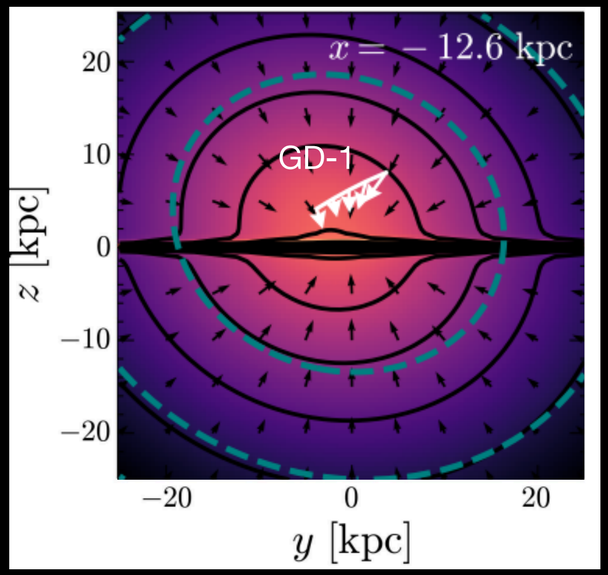
# The halo is triaxial and tilted

- Studies of stellar halo & stellar stream suggest that our Milk Way halo is not only triaxial but also tilted.
- Is it also true for the GC?




Han+ ‘22



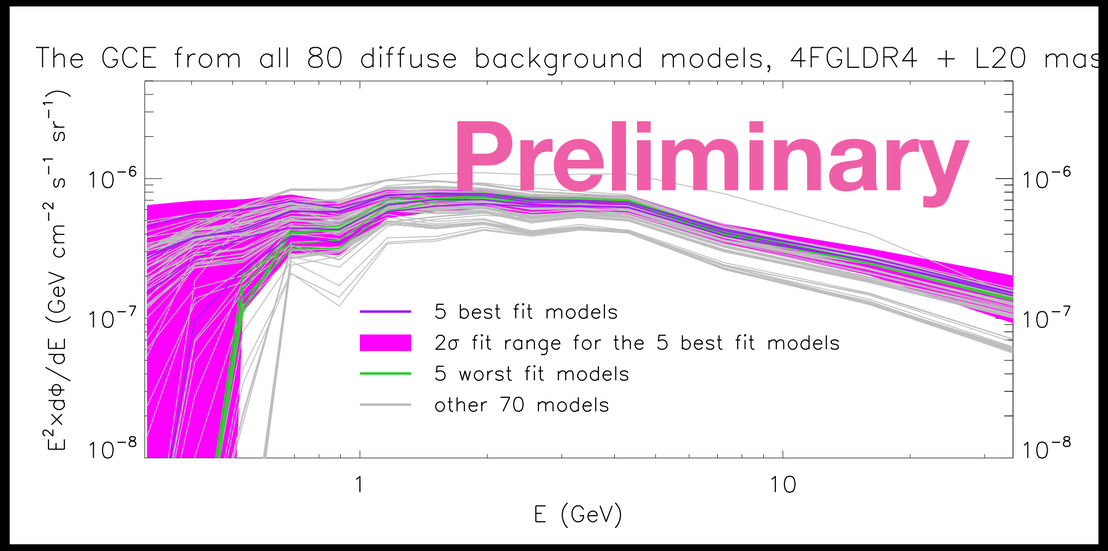

Nibauer & Bonaca ‘25

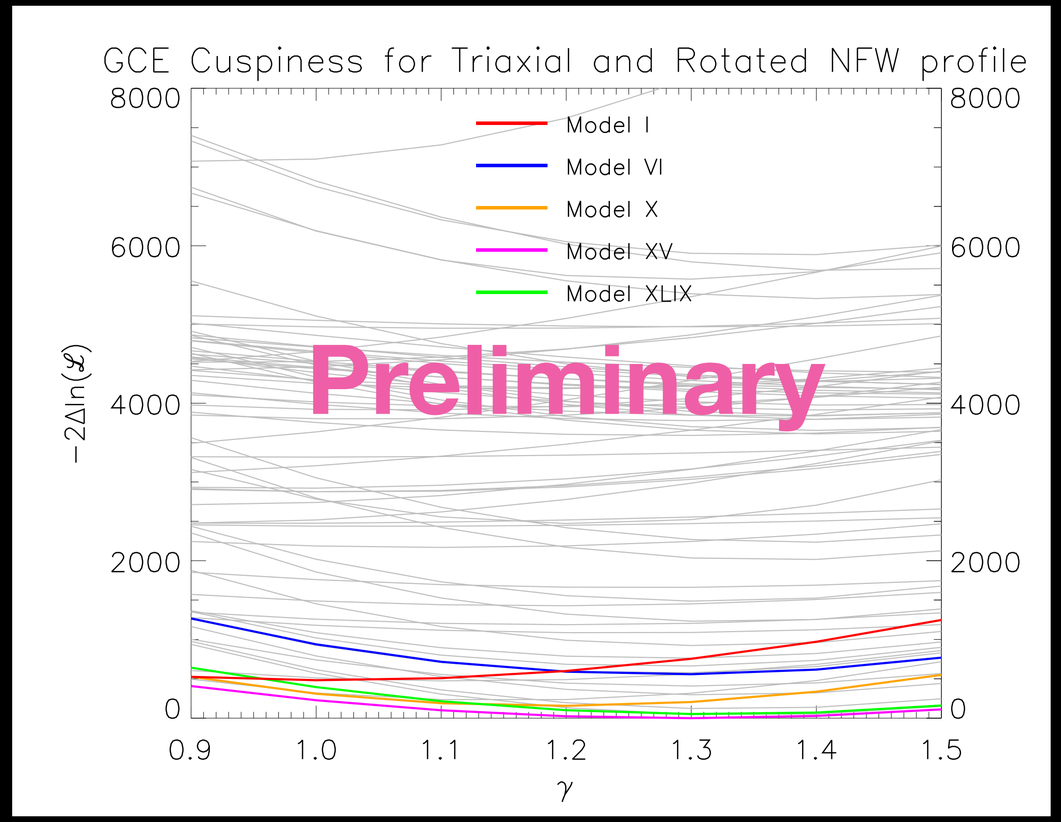
# Fit with a tilted GCE

Leo Qiyuan Hu

- Our fitting shows that GCE is insensitive to the proposed tilting by Han+ ’22.

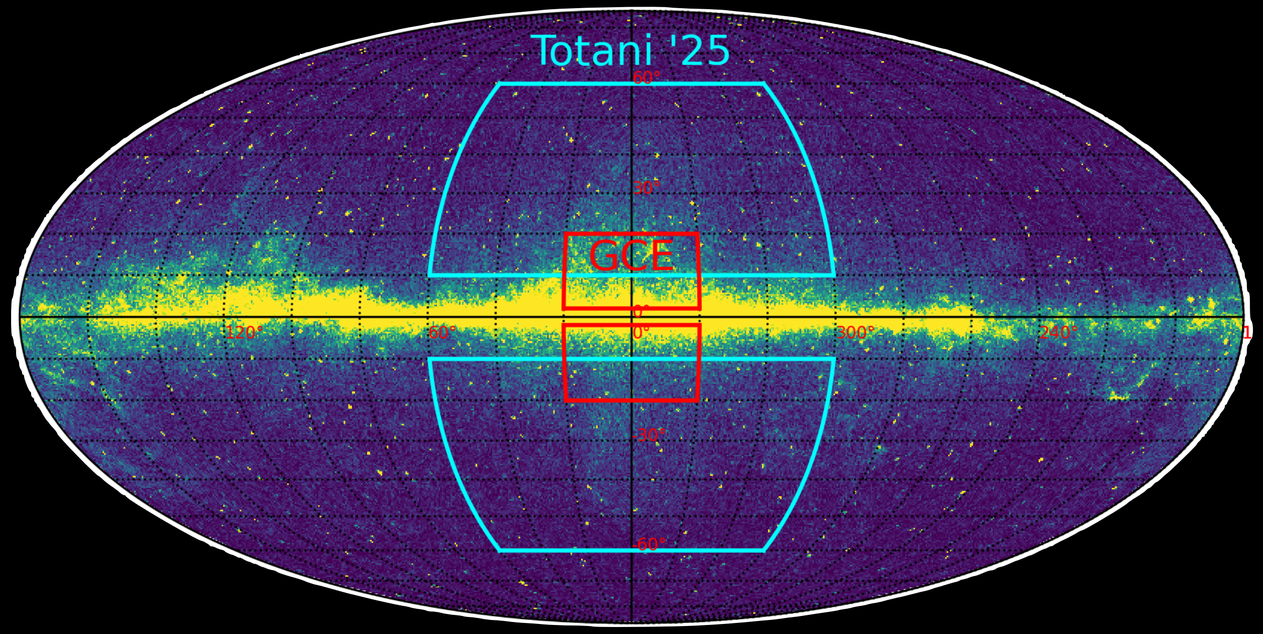
X : Y: Z = 10:8:7; Yaw by 24˚ and then pitch by 25˚.

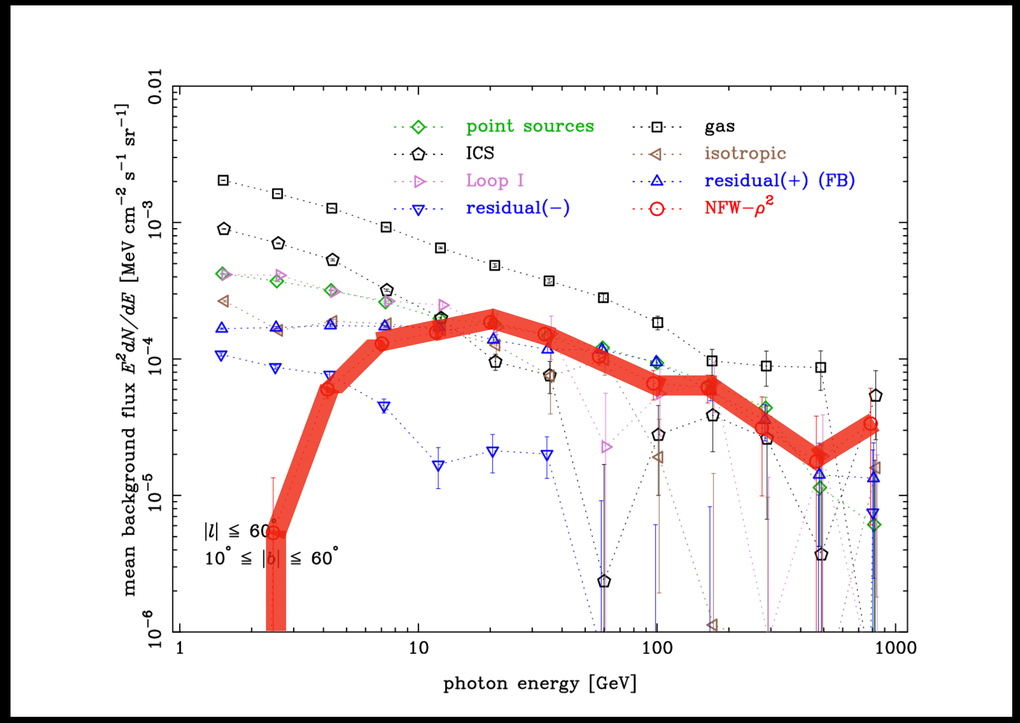


# Comments on the 20 GeV halo excess

- Totani ’25 searches the [-60°, 60°]² region with $|b| < 10^\circ$ excluded and claims to find a 20 GeV halo-like excess.
- Best fit by a NFW halo w/ $\chi\chi \to b\bar{b}$, $m_\chi \sim 500$ GeV, $\langle \sigma v \rangle \sim 5 \times 10^{-25}\,\mathrm{cm}^3/\mathrm{s}$
- GCE is absent.

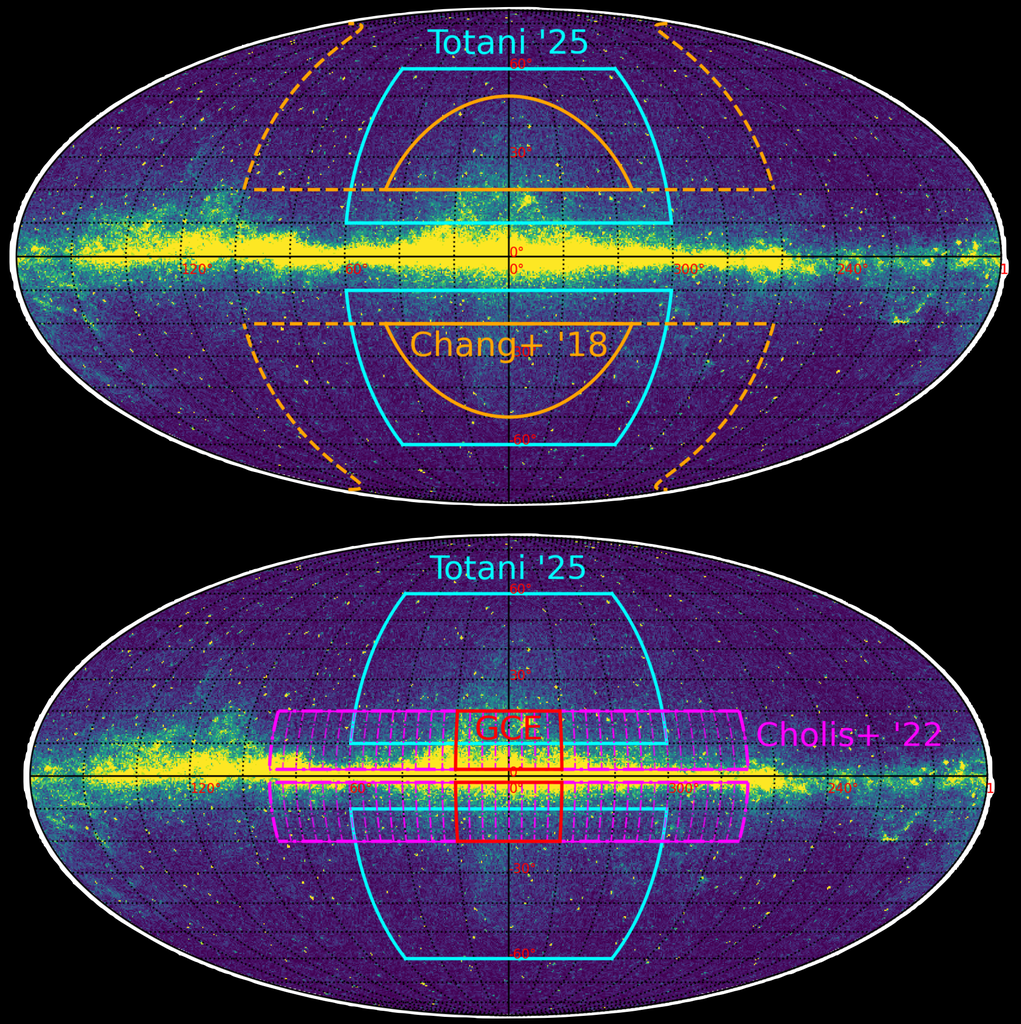


# I. Earlier studies do not see the 20 GeV excess.

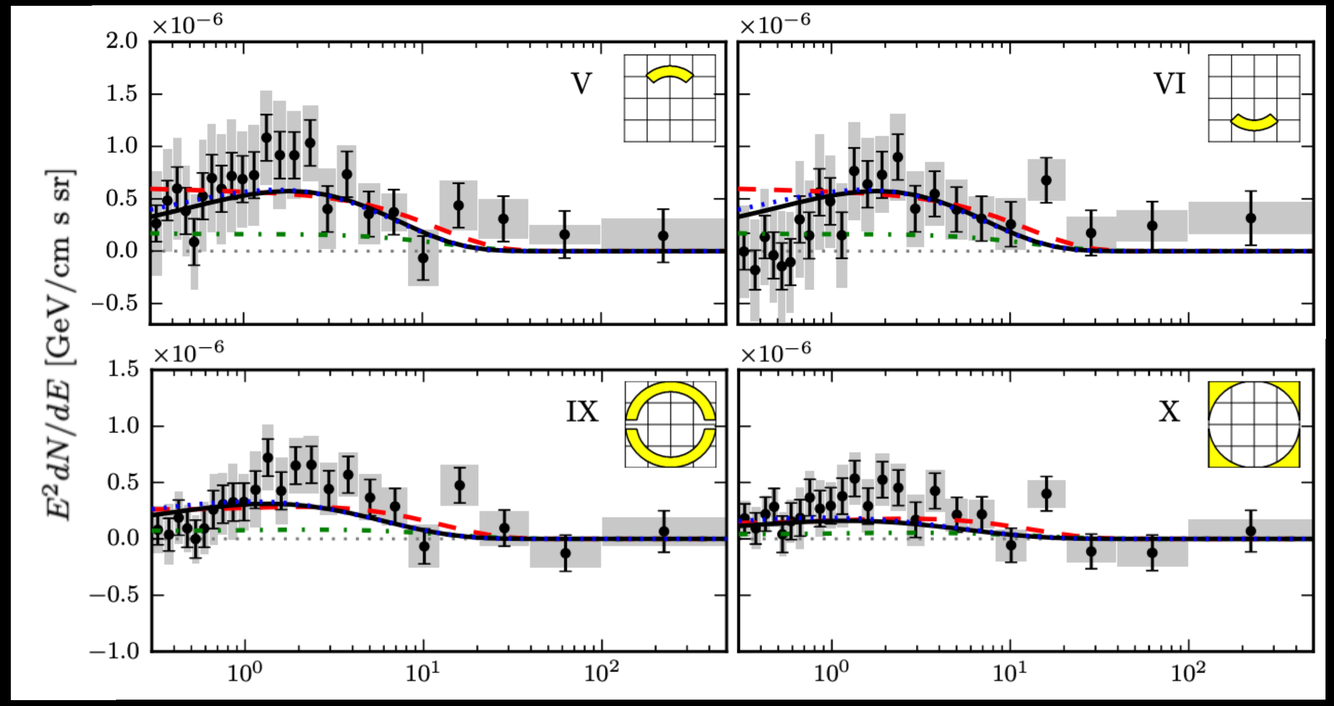
1. Chang+ ’18 searches for $r \equiv \sqrt{\ell^2 + b^2} < 50^\circ$ and $r < 100^\circ$ w/ $|b| < 20^\circ$ excluded. No 20 GeV excess is found.

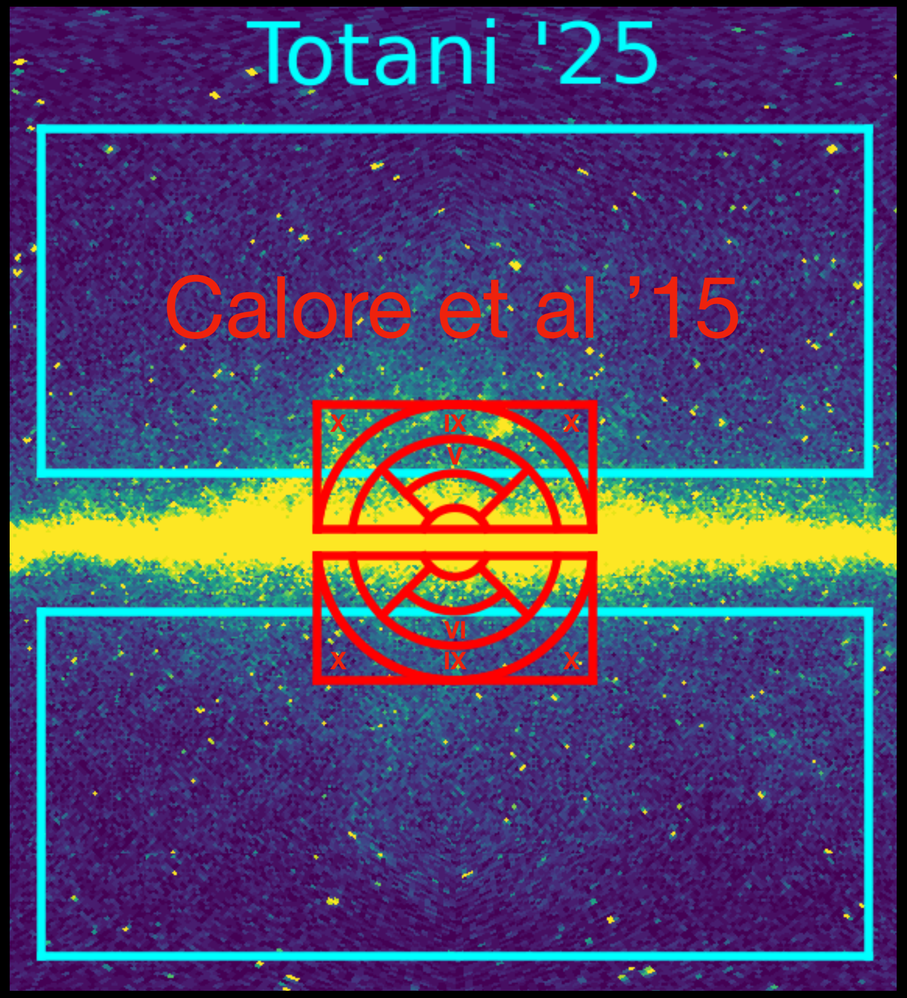
2. Cholis+ (+YZ) ’21 performed a moving-window search for [-20˚, 20˚]$^2$ centered on $\ell = 70^\circ, \cdots, -70^\circ$. No 20 GeV excess is found.



# II. Earlier studies do see the GCE.

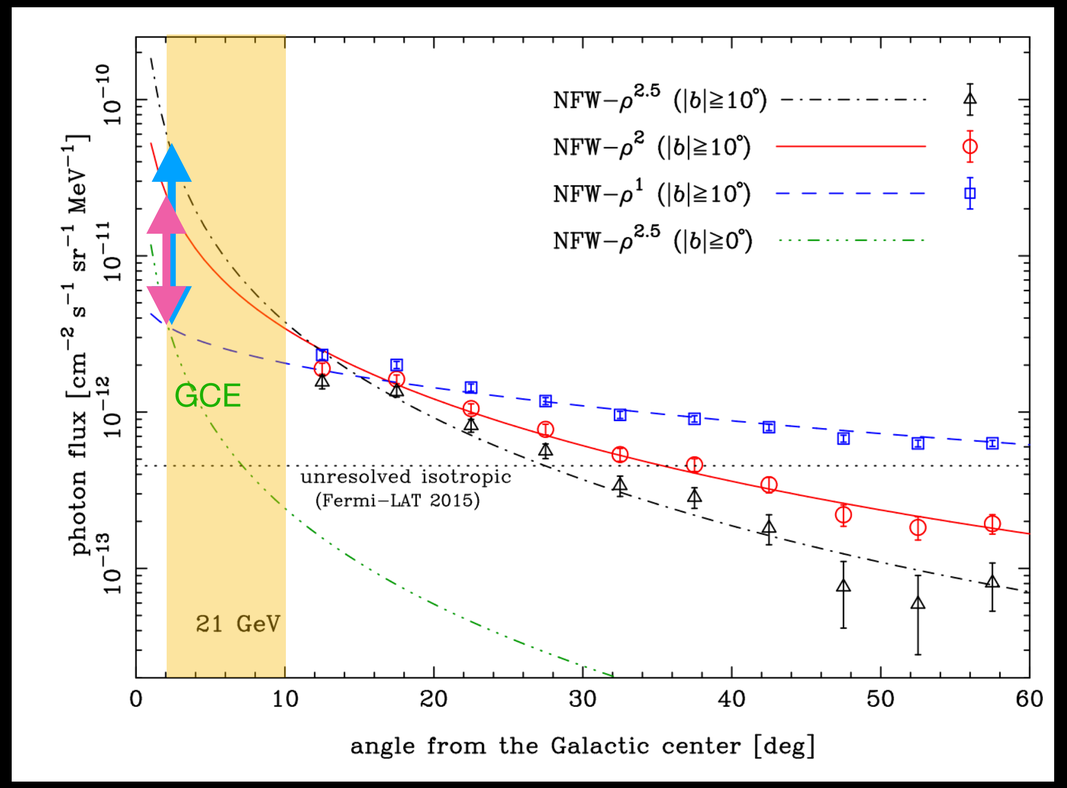
- GCE has been observed at $|b| > 10^{\circ}$, see, e.g., Calore+ ’15:



# III. The halo excess is too bright at the GC.

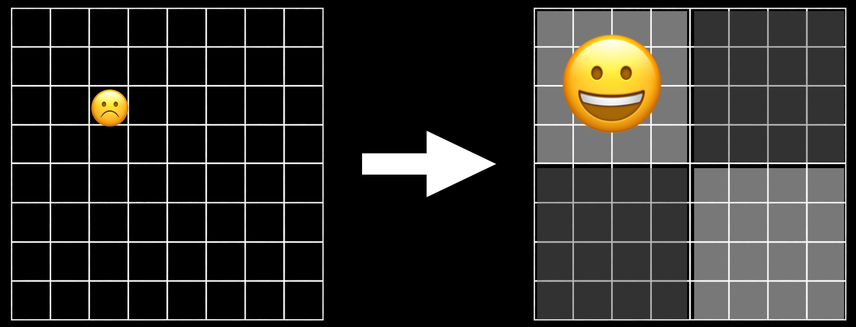
- The 20 GeV halo excess should become even brighter if its profile follows (g)NFW.
- Totani ’25 finds it is a factor of ~7 (~140) brighter than GCE if the density follows $\rho \propto r^{-1}$ ($\rho \propto r^{-1.25}$).
- DM distribution needs to be shallower than NFW when approaches the GC.
- In tension with GCE fitting (cuspier than NFW).
  => New physics? Mass segregation?



# Other comments

IV. Pixel binning could allow the negative residue template to become more significant.

V. More tests on the morphology are needed.

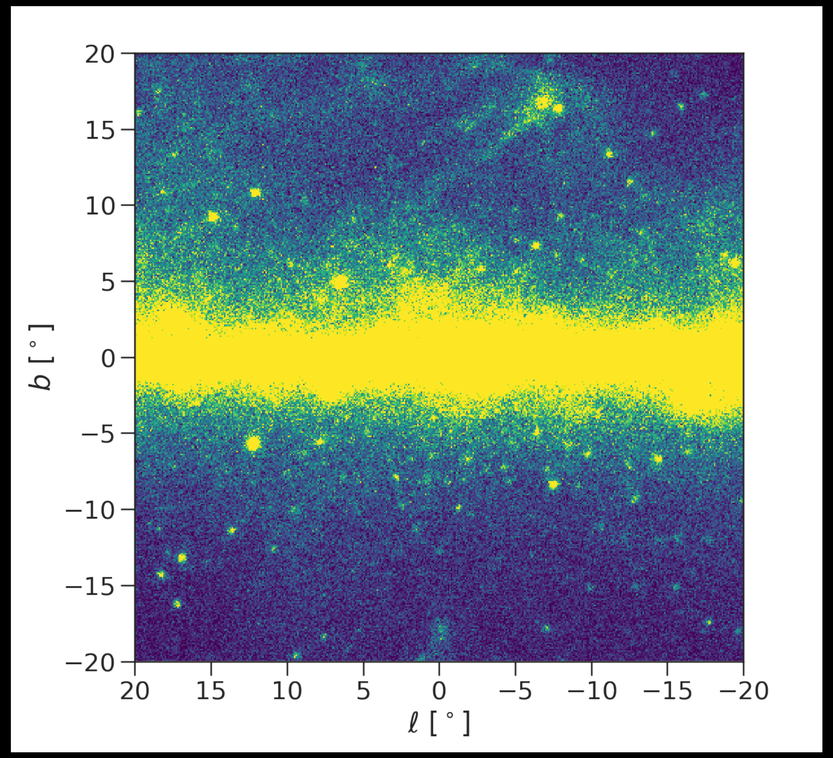


# Summary

- The GCE is one of the most intriguing discoveries from the Fermi telescope.
- Its origin remains actively debated.
- GCE is mildly oblate AND contracted. The morphology is robust against masking and tilting of the triaxial halo.
- More tests are needed to understand the 20 GeV halo excess.

# Backup

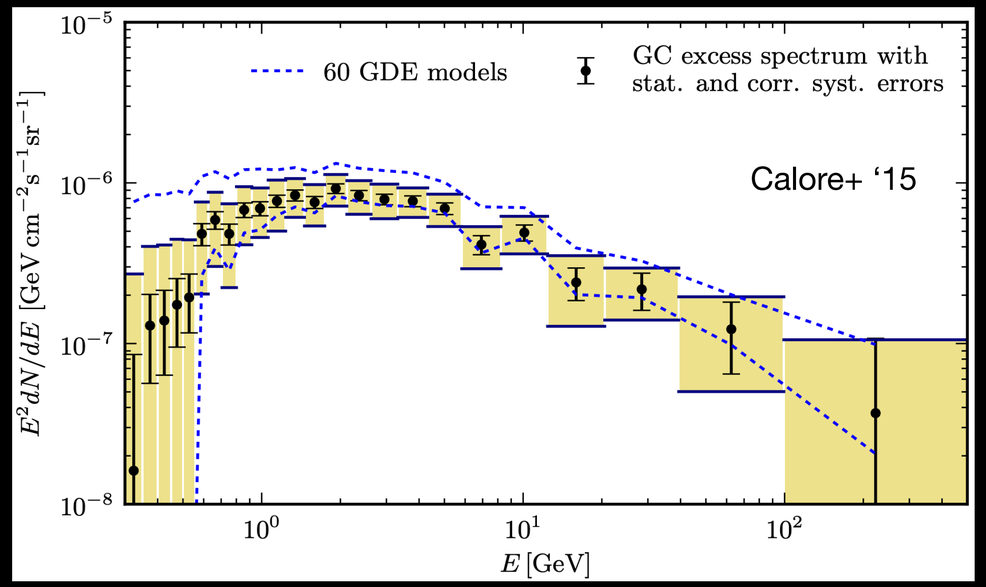
# Fermi data




Color: photon counts

**Template fitting**

# GCE spectrum



# 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?

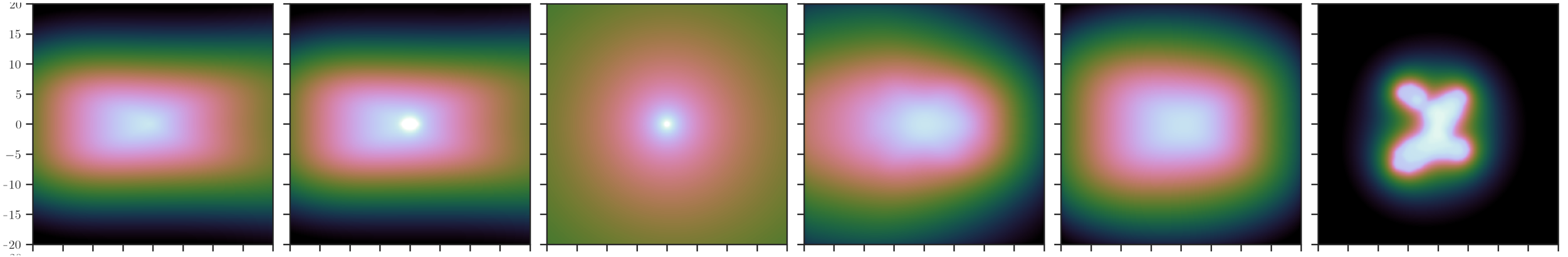
Weighted sum of templates

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

Fermi data

# Testing more GCE models

Dark matter annihilation




Boxy Bulge

Boxy Bulge + Nuclear Bulge

Coleman Bulge

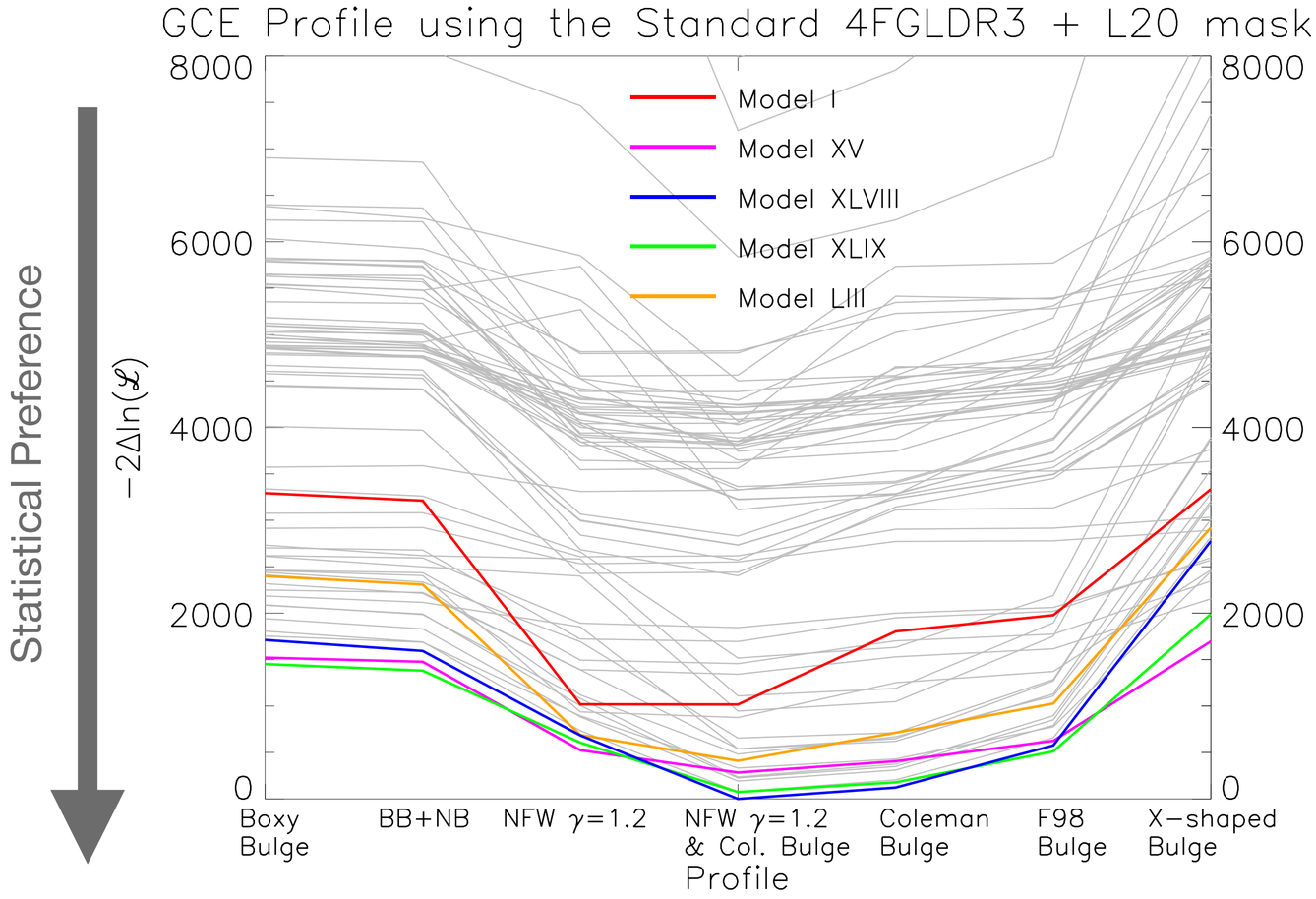
F98

X-shaped Bulge

(The point spread function are applied)

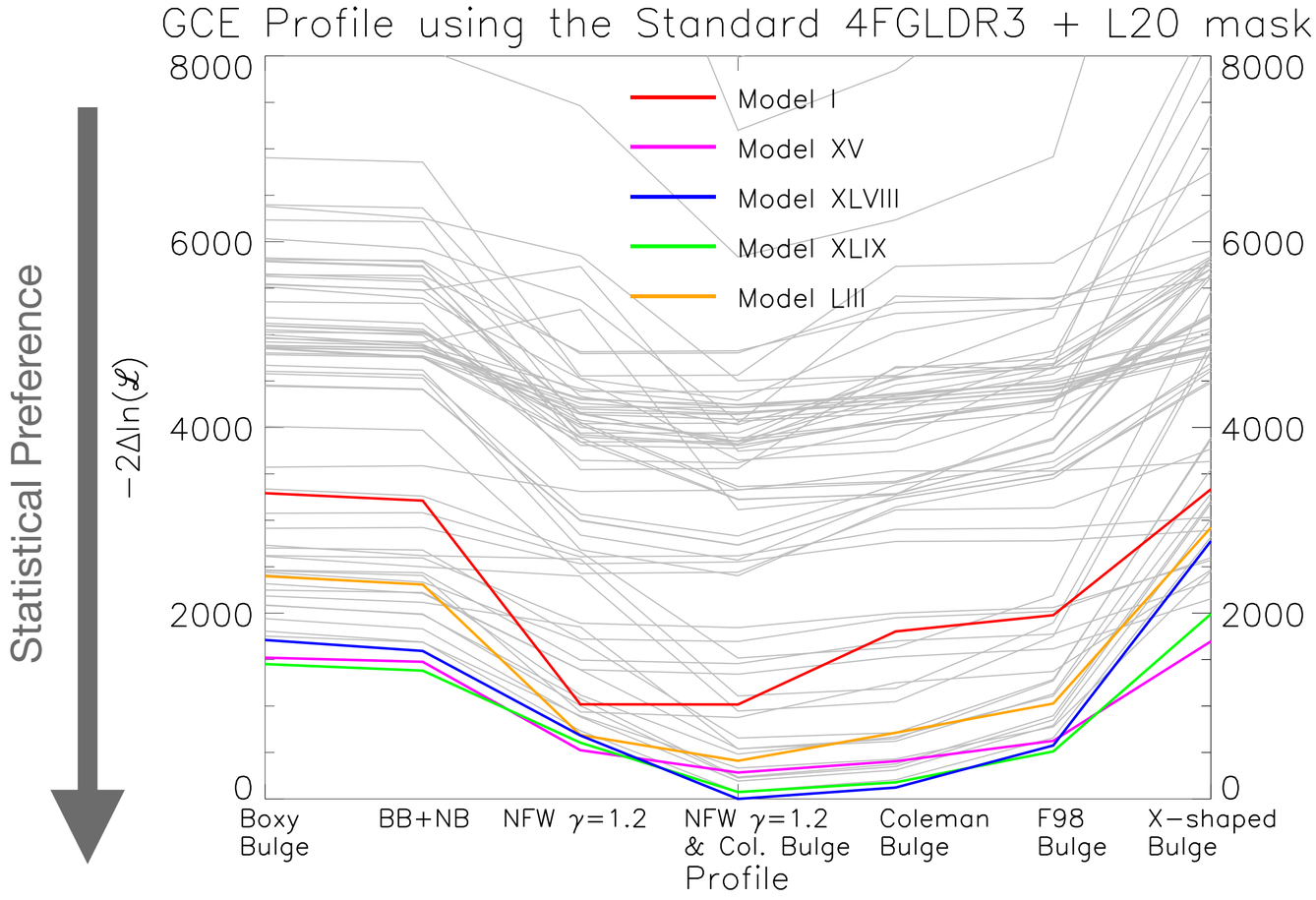
# Coleman bulge or dark matter annihilation?

- **It is background dependent.**
  - For ***some*** best-fit background models:
    Coleman Bulge > Dark matter annihilation
  - For ***other*** best-fit background models:
    Dark matter annihilation > Coleman Bulge



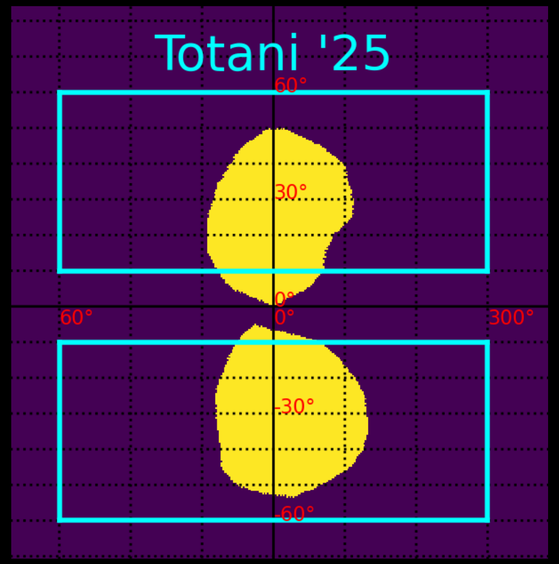
# Dark matter & millisecond pulsars

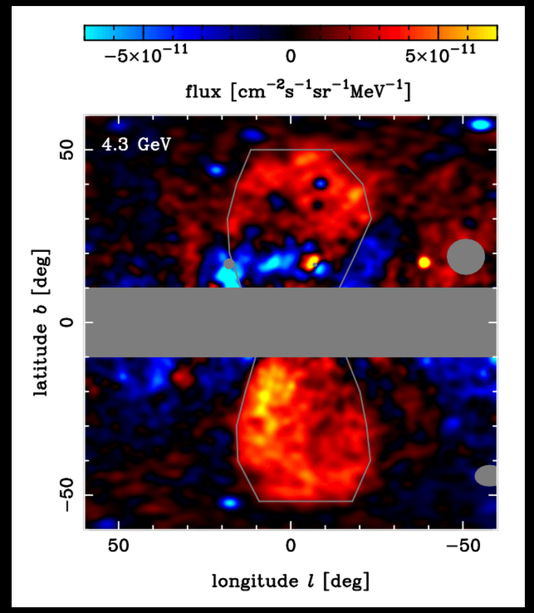
- Overall, The combination of Dark matter annihilation and Coleman Bulge provides a better fit than each component alone.
- We should expect some MSPs contribution for GCE.
- Let's examine the spectra of both components in the "NFW γ=1.2 & Coleman Bulge".



# Flat bubbles vs. structured bubbles

- Chang+ ’18 and Cholis+ (+YZ) ’21 use flat bubbles.
- Totani ’25 uses structured bubbles (1) adding the positive residue to flat bubbles to make one template (2) making the negative residue an independent template.



# Flat bubbles vs. structured bubbles

- Totani ’25 shows (1) with flat bubbles only, there is no excess (2) keep the flat bubbles, add the negative residue template, the 20 GeV excess emerged. (3) replace the flat bubbles with flat + positive templates, the excess does not change much.