New Developments in the Galactic Center Gamma-Ray Excess

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A New Mask for An Old Suspect
w/ McDermott, Cholis & Fox, PRL 124 (2020) 23, 231103

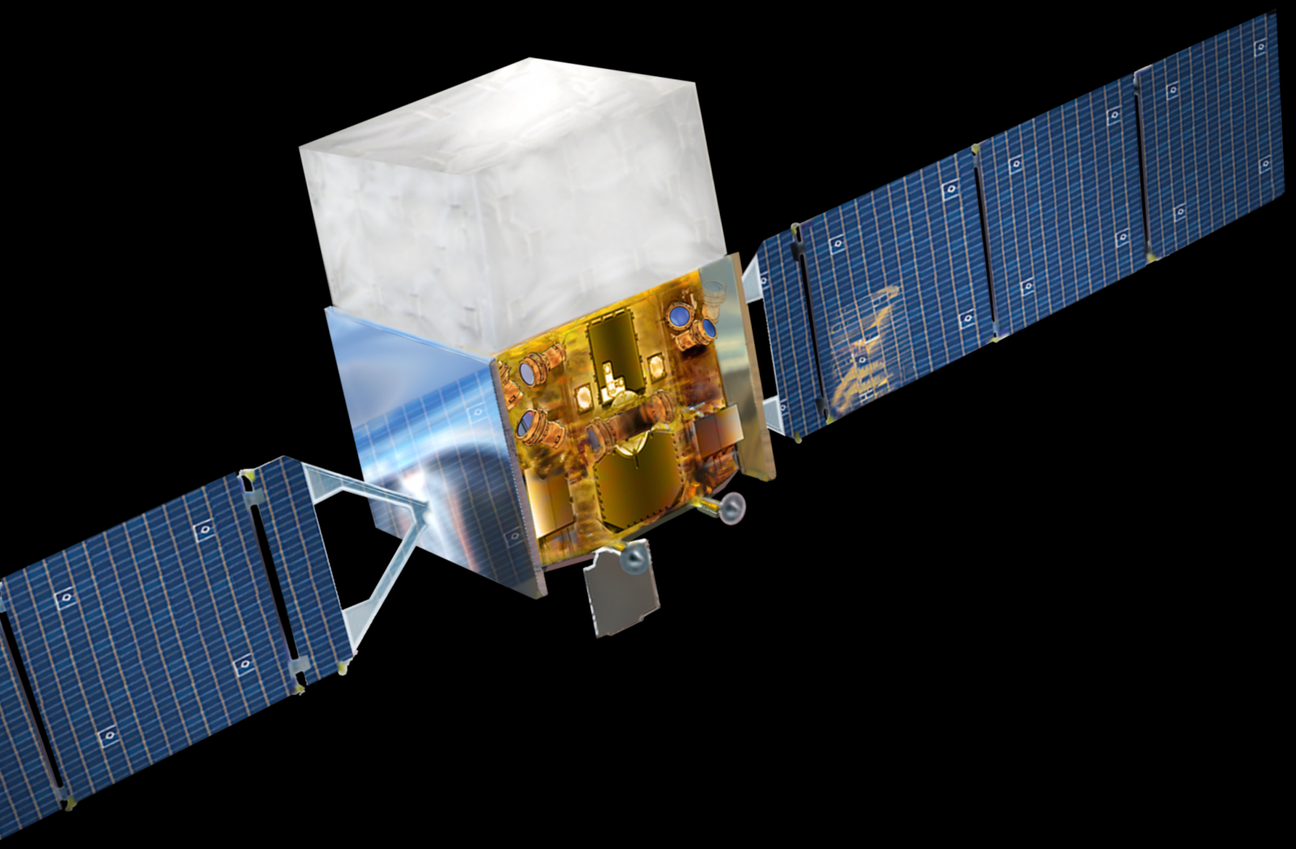
The Return of the Templates
w/ Cholis, McDermott & Surdutovich, arXiv:2112.09706, accepted by PRD

Pheno 2022, 05/09/2022

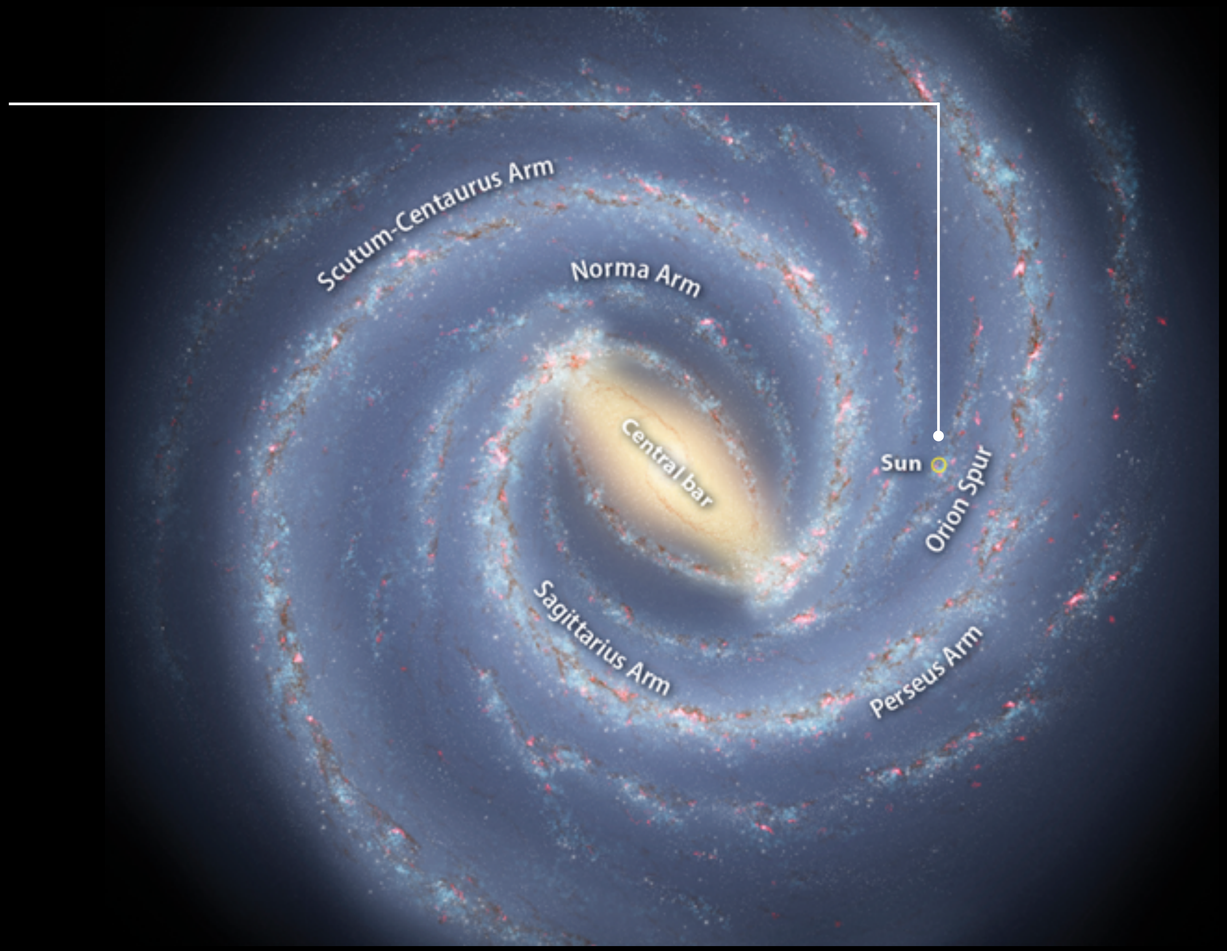
Outline

- Introduction
  - The Galactic Center γ-ray Excess (GCE)
  - Templates
- Developing a new set of templates
- Revisiting the characteristics of the GCE
- Summary

The Fermi Large Area Telescope (Fermi-LAT)

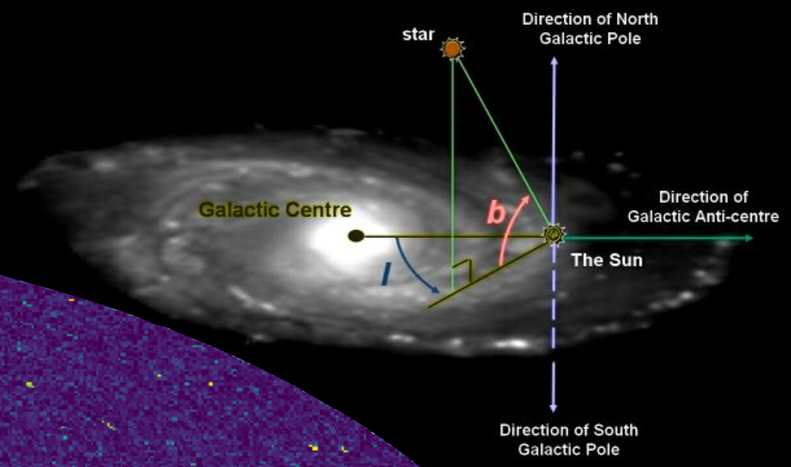


2008—present



Milky Way (top view)

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



Galactic latitude b

+ 90°

0°

– 90°

x°

+ 180°

0°

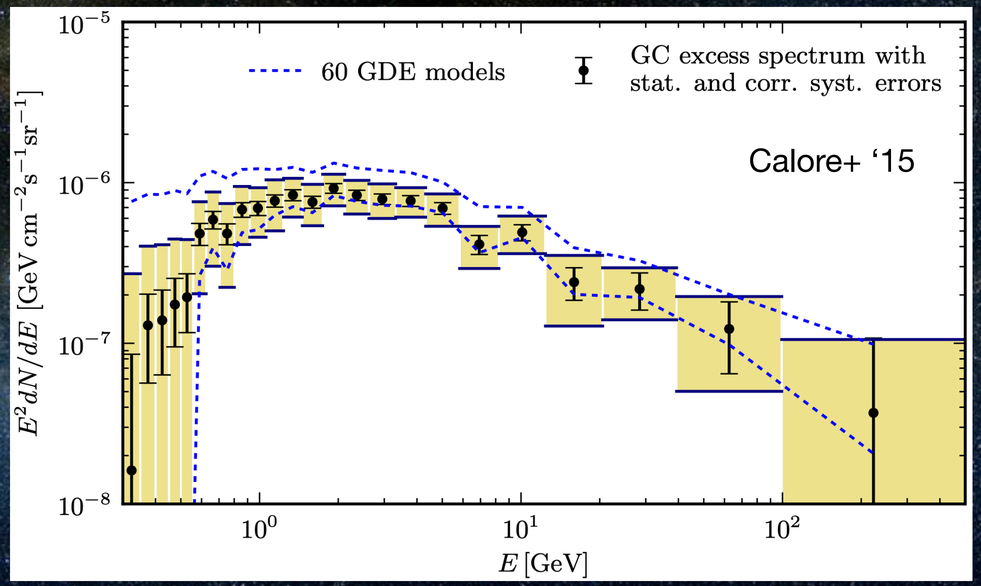
– 180°

Galactic longitude l

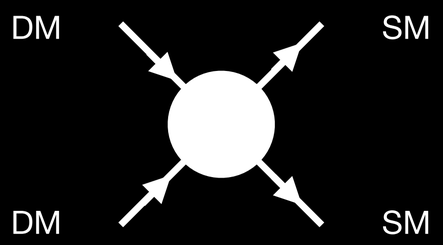
The excess

- 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



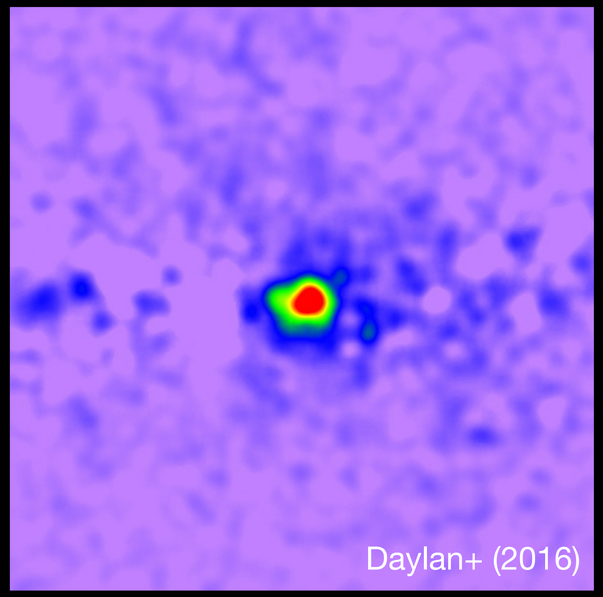
What is the origin of GCE?



Dark matter (WIMP) annihilation

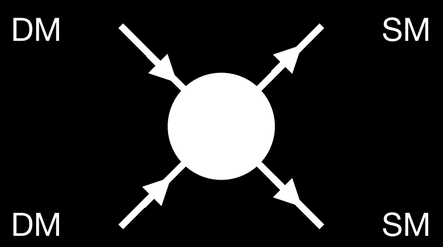
m_χ ~10-100 GeV

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



Daylan+ (2016)

What is the origin of GCE?



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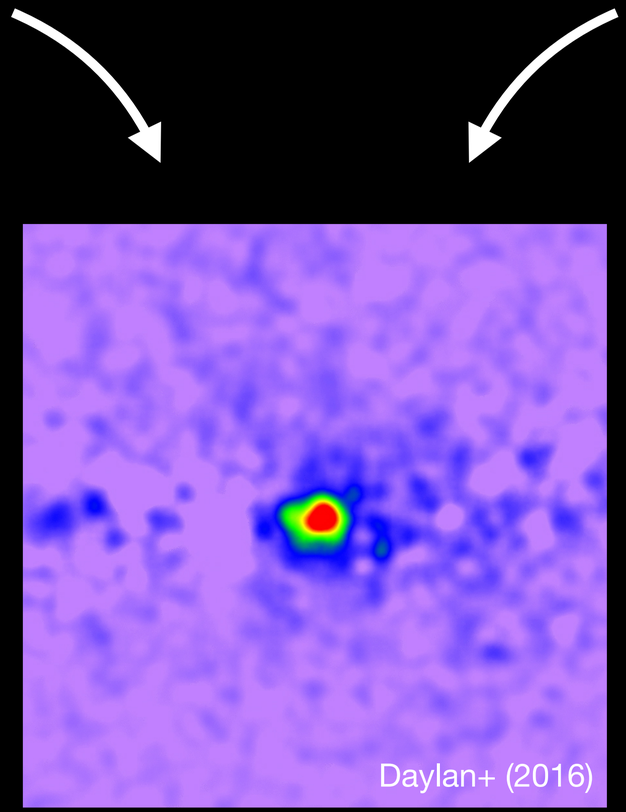
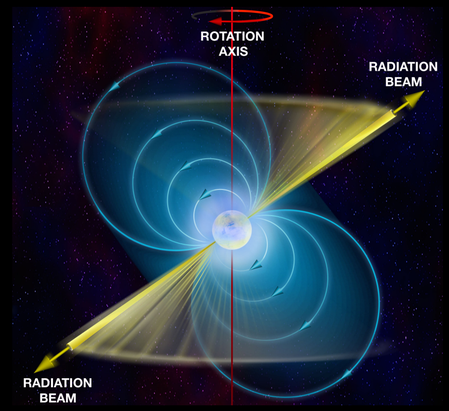




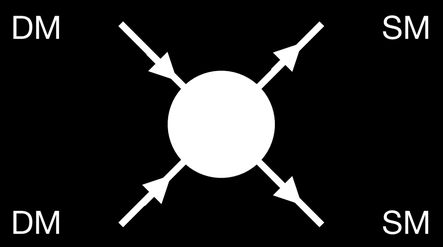
A new population of millisecond pulsars

m_χ ~10-100 GeV

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

Not yet been observed at GC

How to distinguish the two?



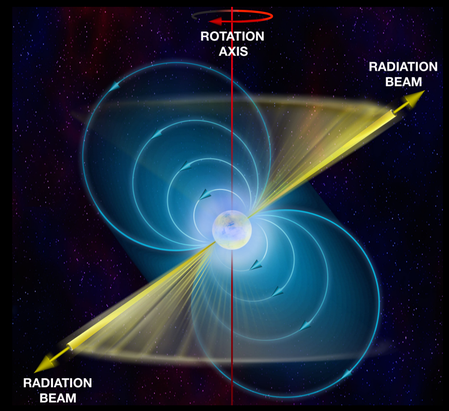
Dark matter (WIMP) annihilation

Spectrum

Morphism

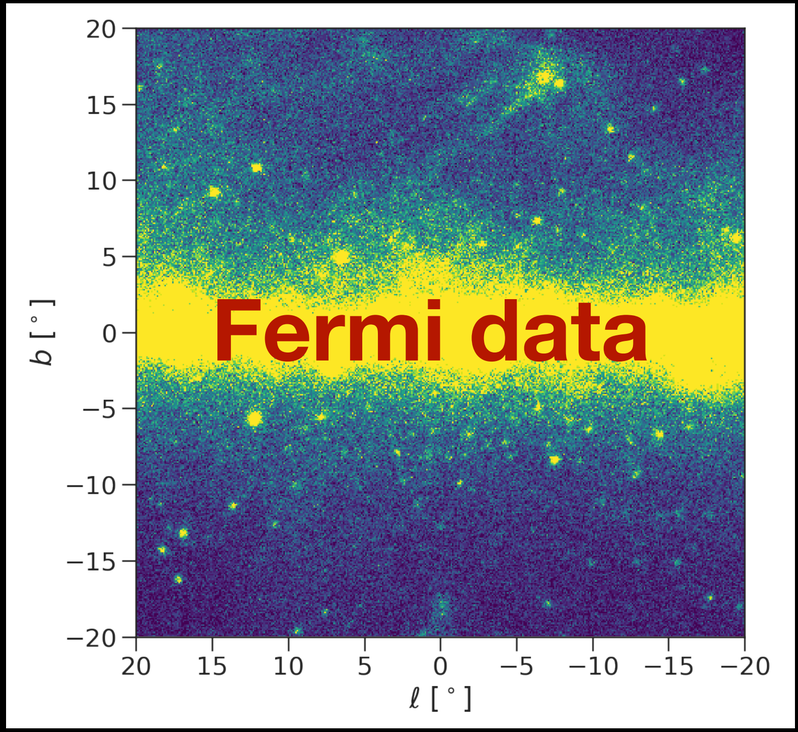
Small-scale power

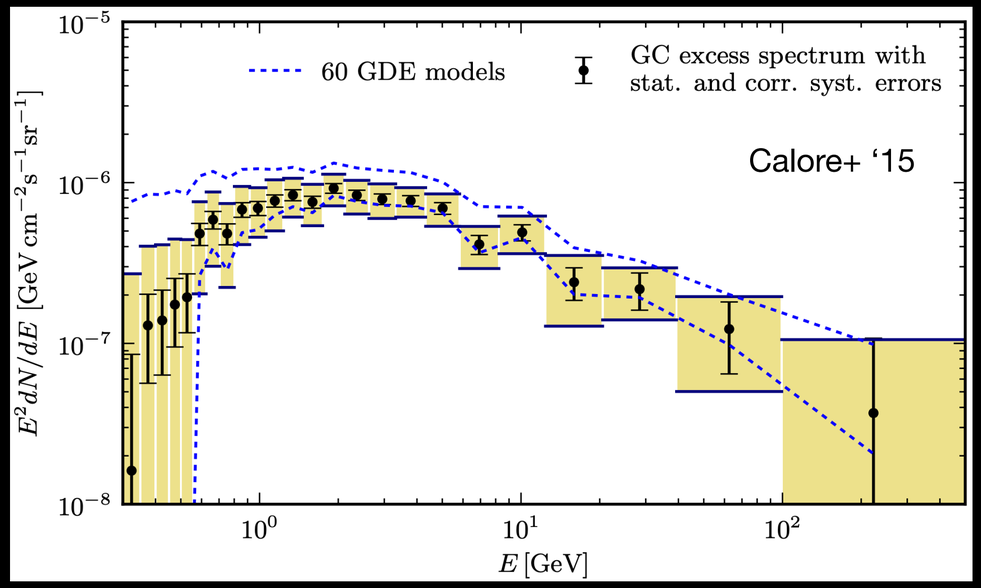
……



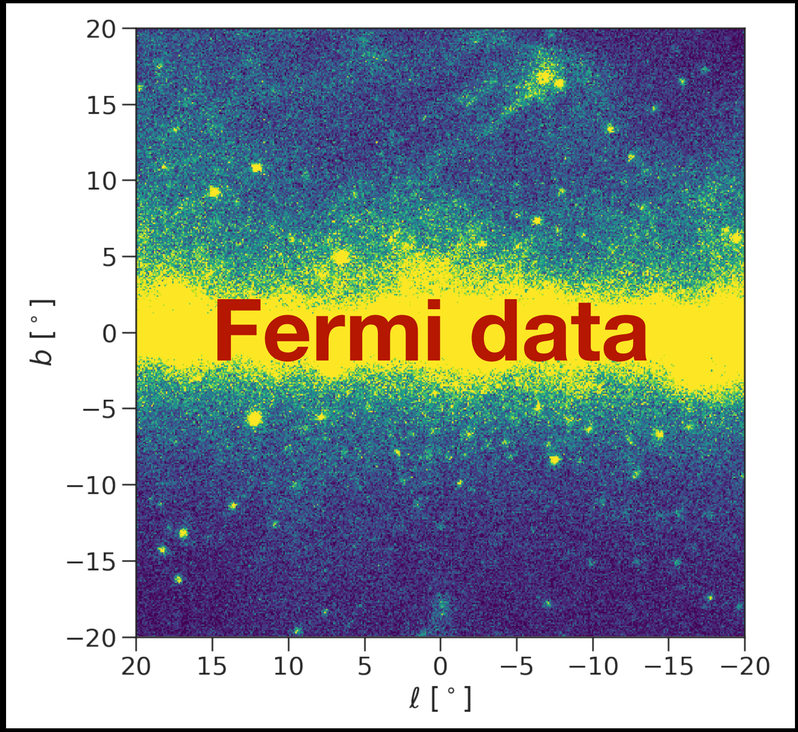
A new population of millisecond pulsars

Template fitting





Template fitting

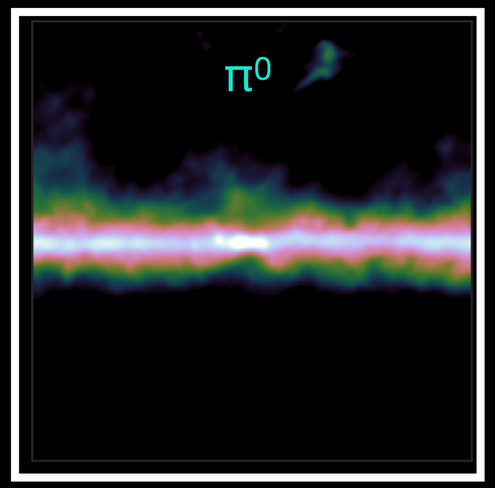


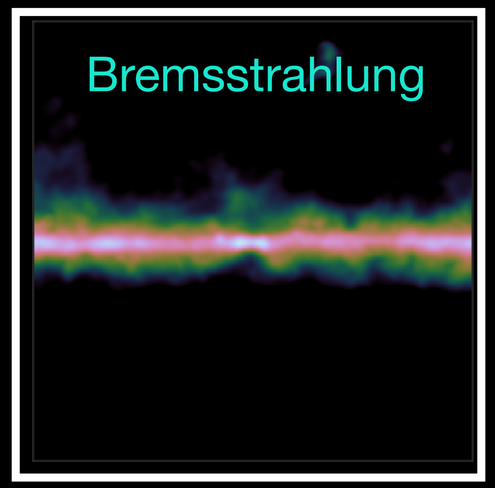
vs.

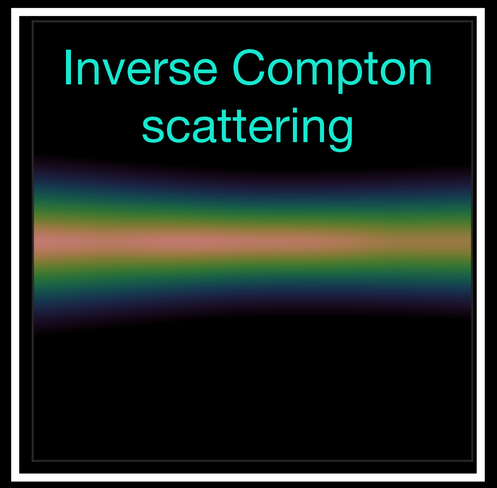
Sum of foregrounds & GCE templates

Do the comparison
energy-bin by energy-bin

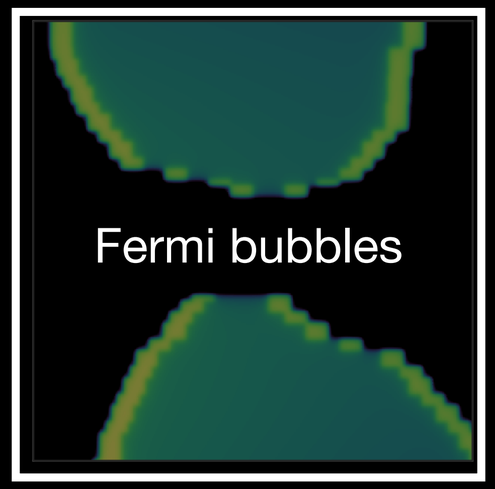
Templates


π^0


Bremsstrahlung

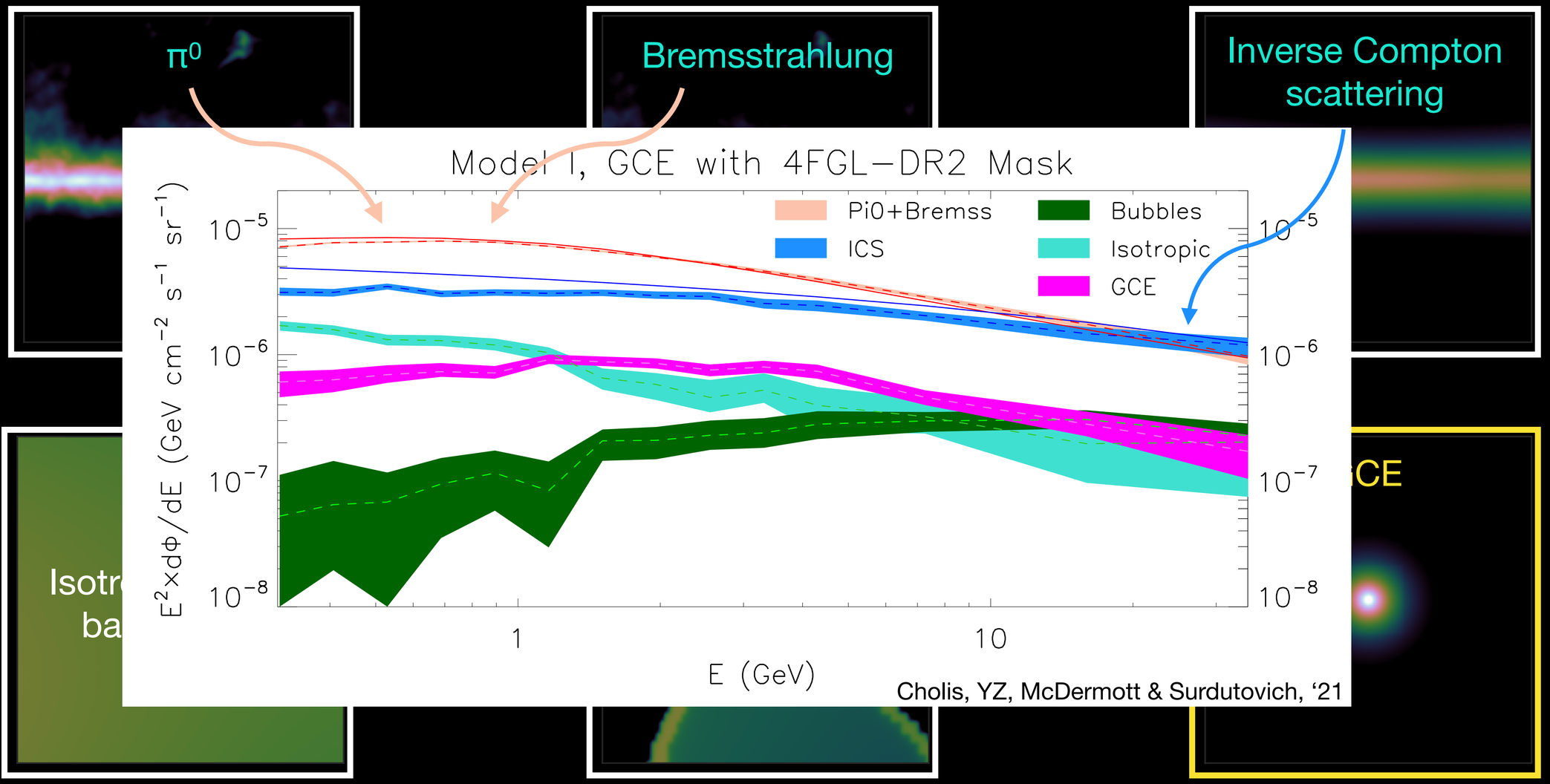

Inverse Compton scattering


Isotropic diffuse background


Fermi bubbles

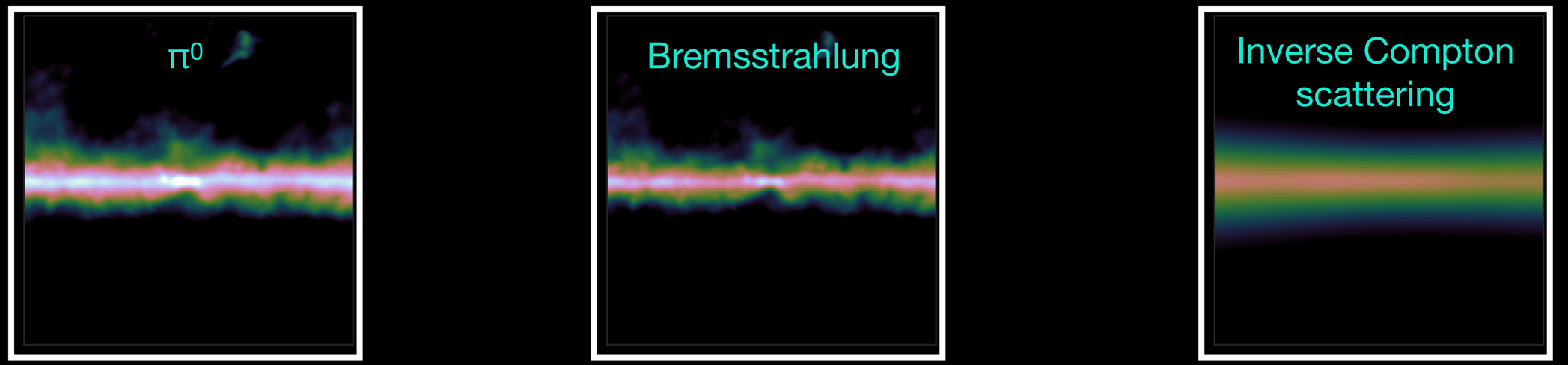

GCE

Templates



Cholis, YZ, McDermott & Surdutovich, ‘21

Templates



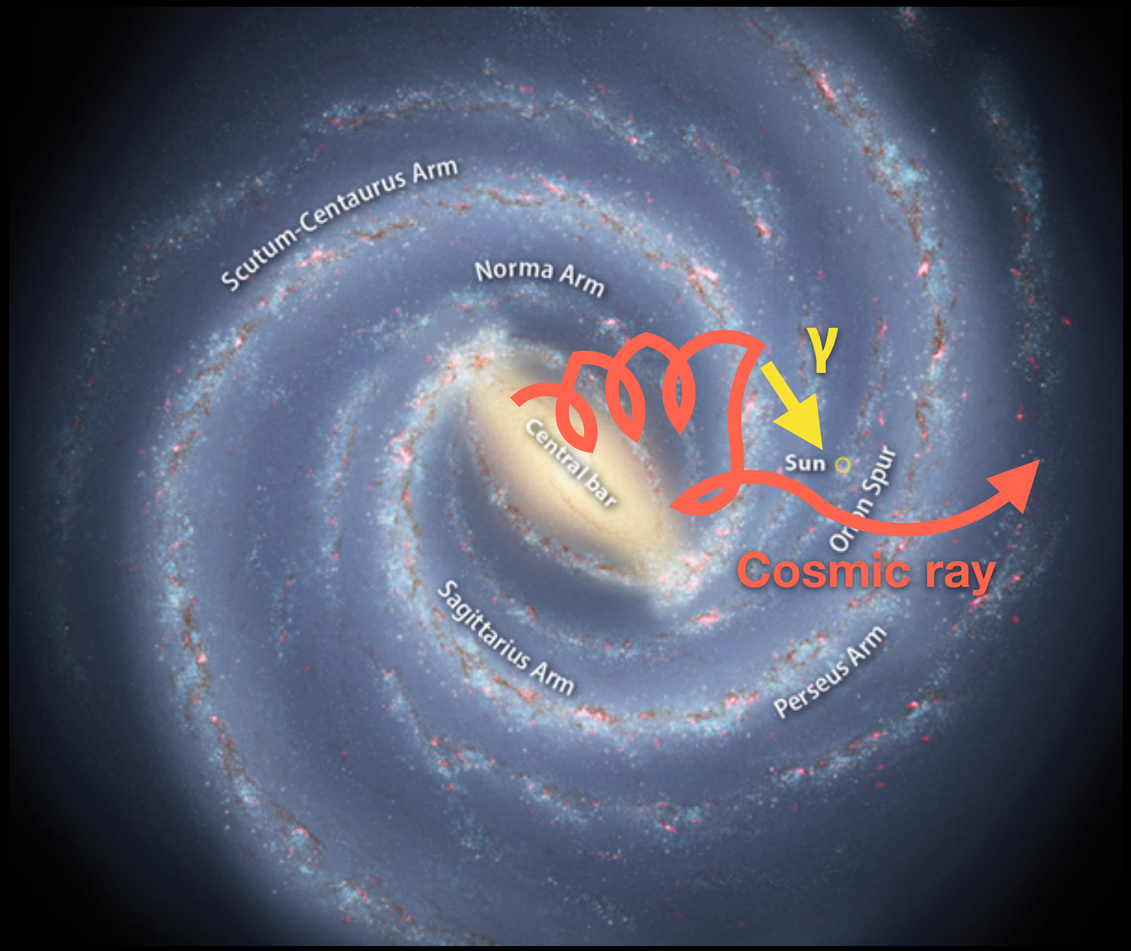
Galactic Diffuse γ-ray Emissions

- Dominate the γ-ray energy spectrum.
- Understanding them is important to understand the GCE origin.

Our work

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)

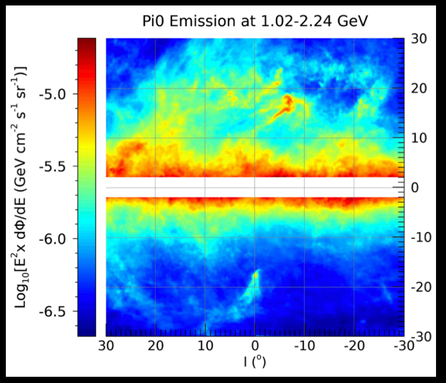
tune GALPROP parameter

5 calibrated CR models

Galactic environment

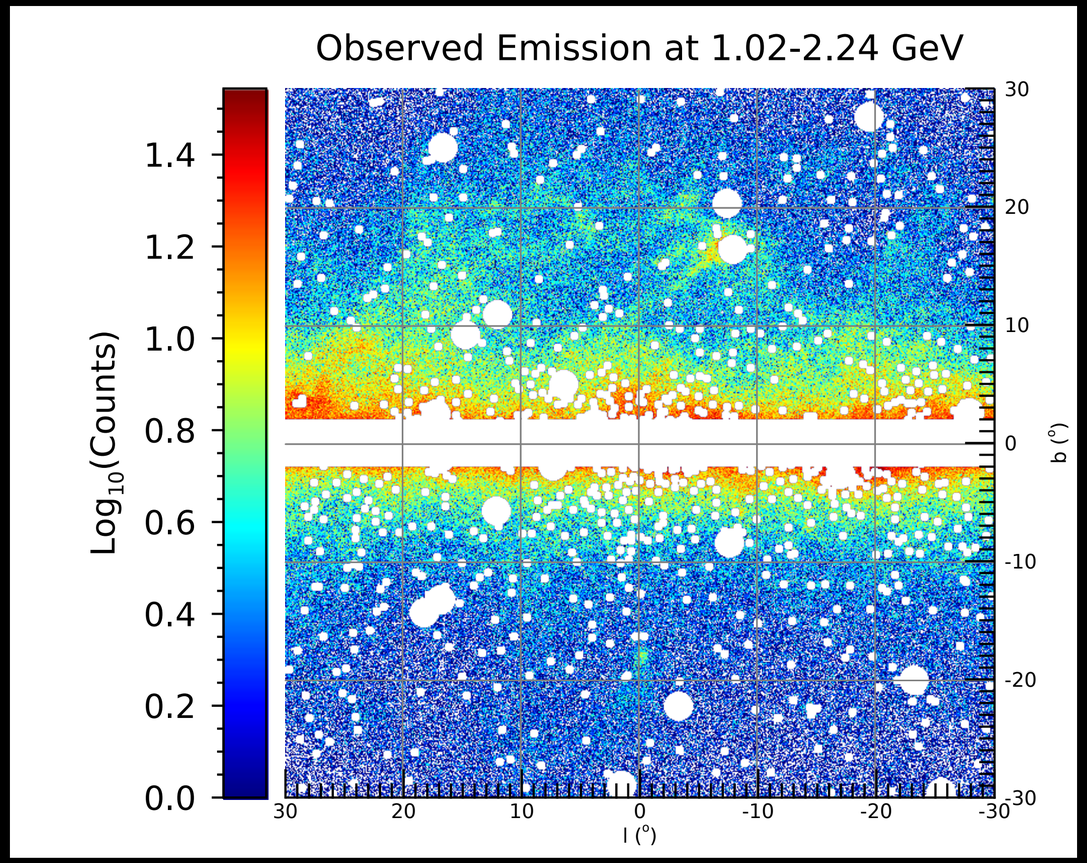
80 diffuse emission templates

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]

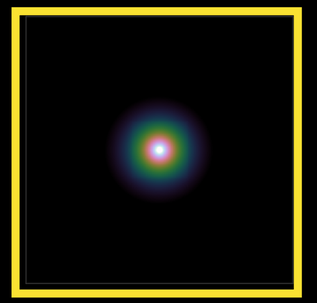


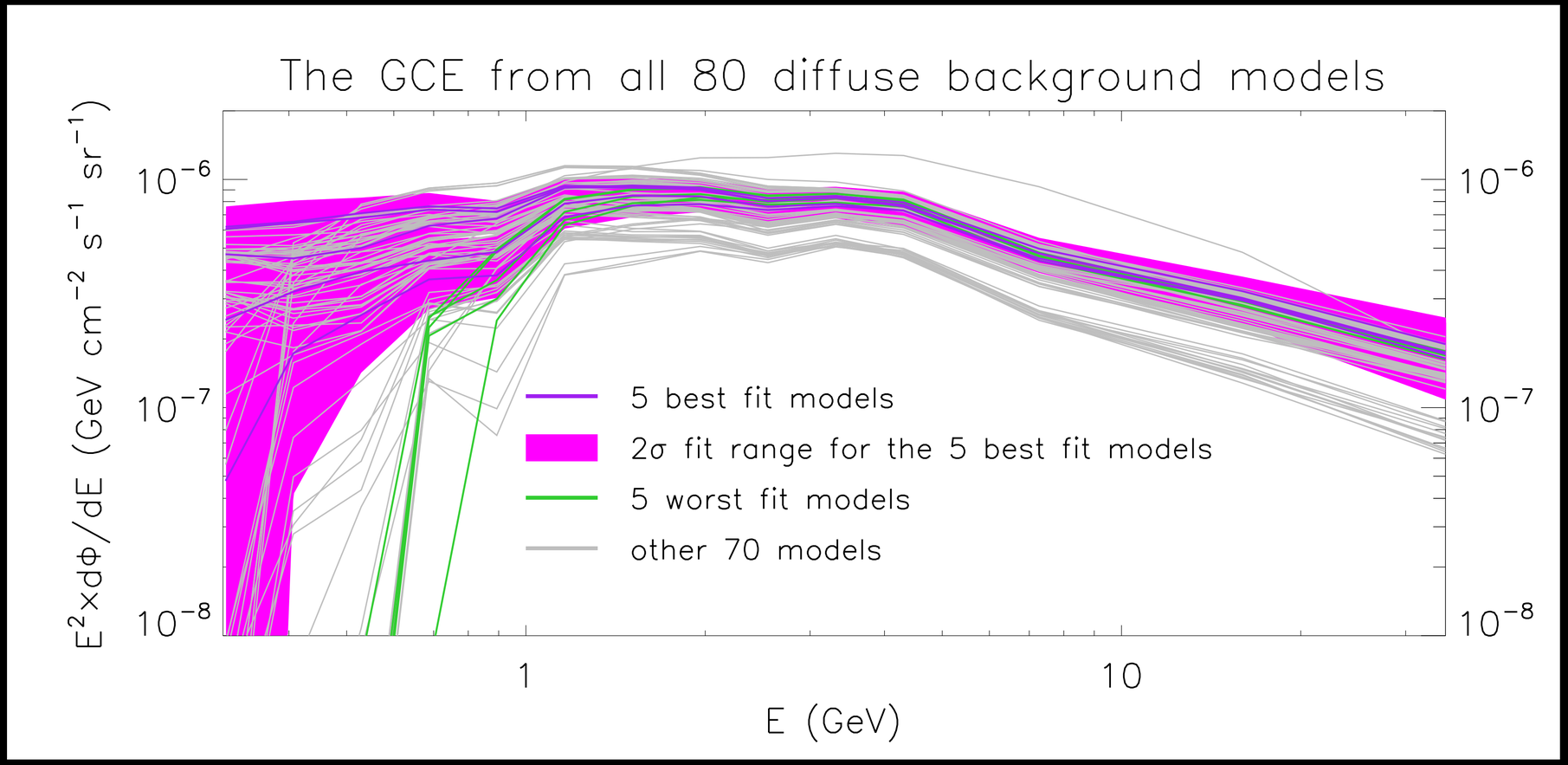
vs.

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

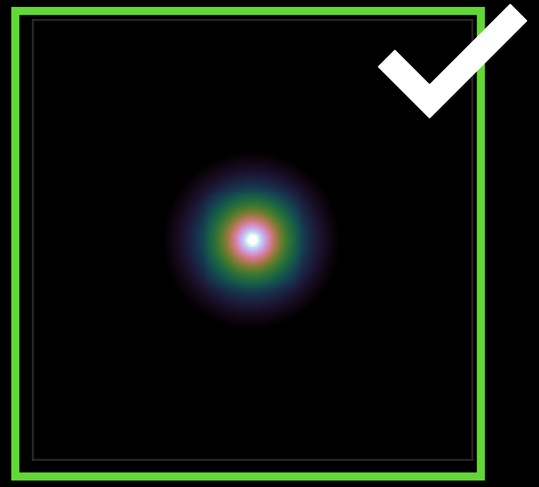
(Also masking the sources + disk)

The GCE is still there

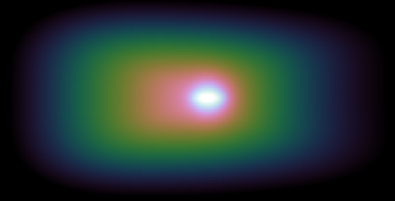




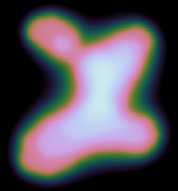
Test the morphism of GCE

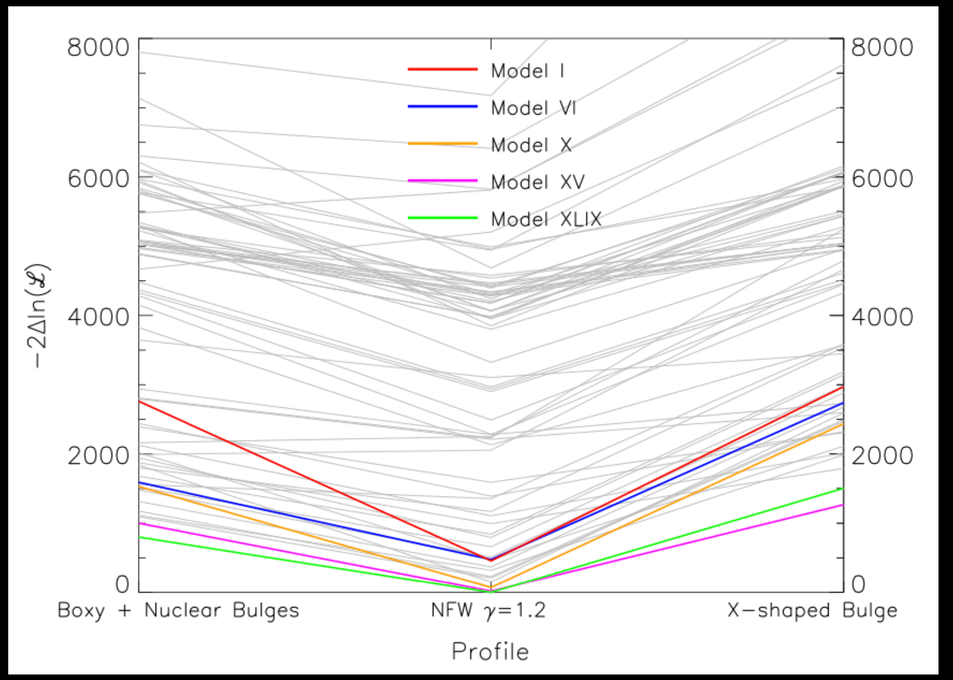


Boxy + Nuclear Bulges



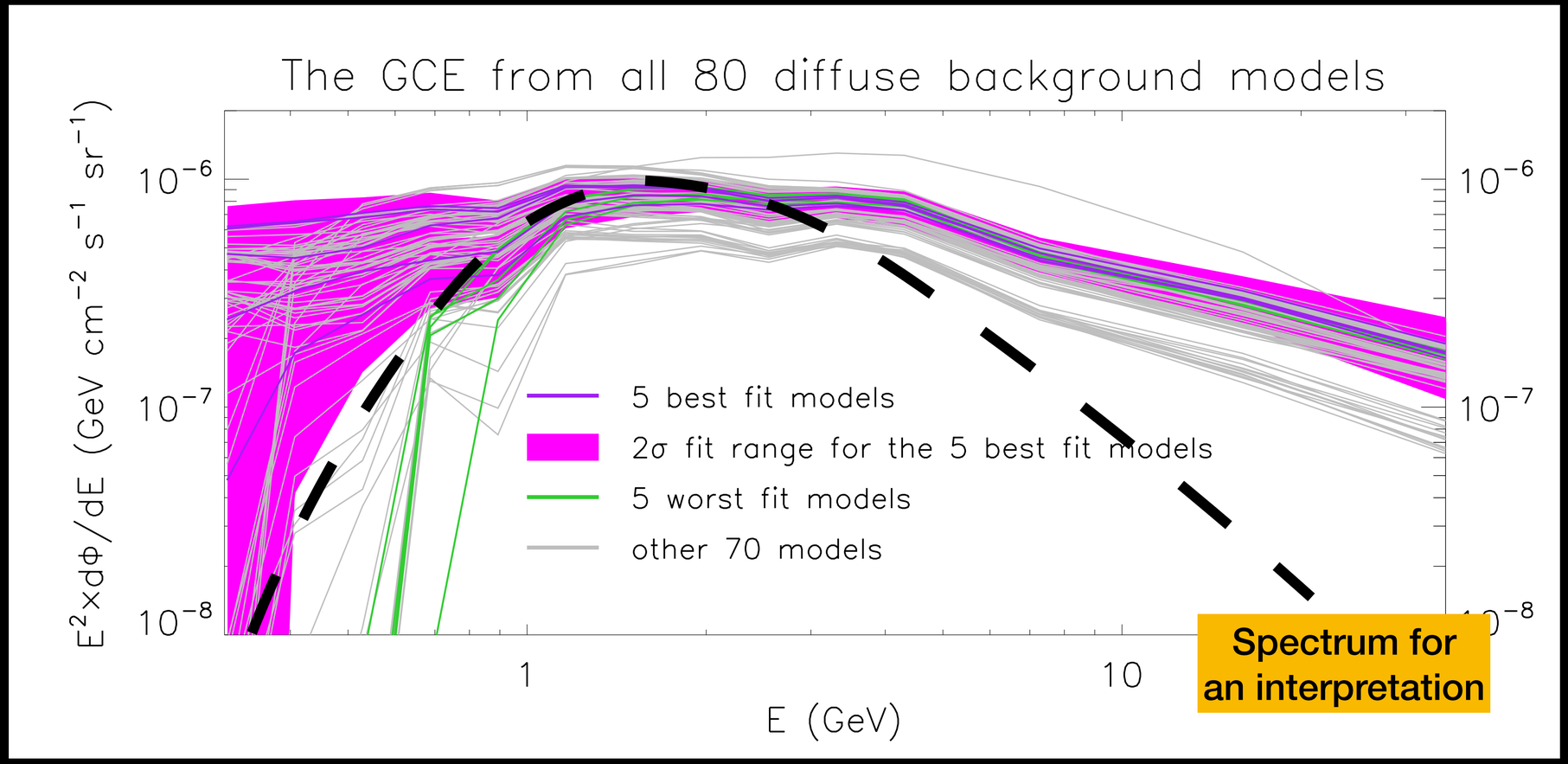
X-shape Bulge





Prefer round shape

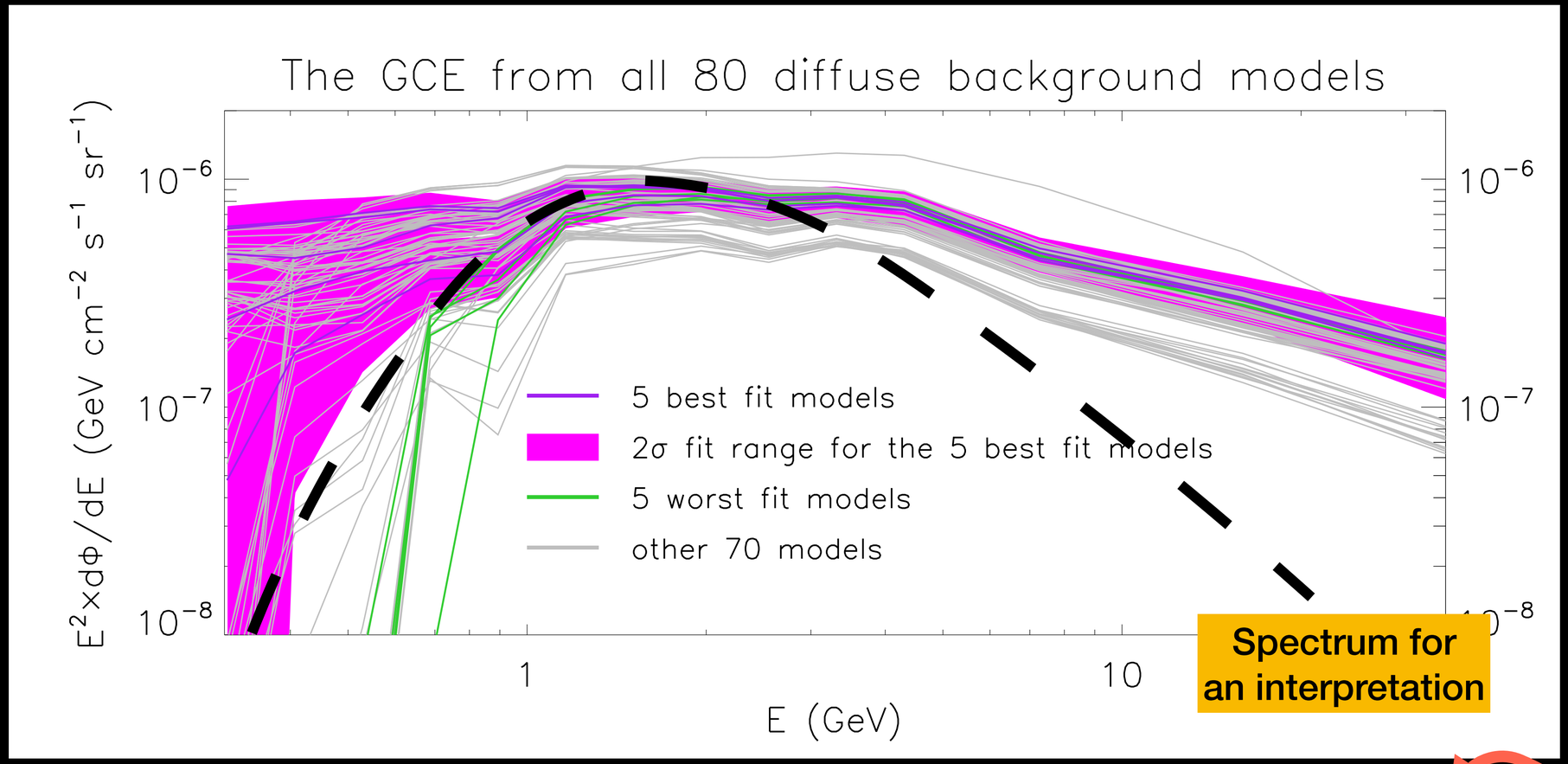
Ready for interpretation?



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

Ready for interpretation?

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



Stat. + Sys.

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

WIMP or Millisecond pulsars?

- 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.

Model	$\widehat{\chi}^2$/dof	$\hat{p}$-value	ROI
MSPs	76.6/13	$< 10^{-6}$	$40^\circ \times 40^\circ$
	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}	$40^\circ \times 40^\circ$
	17.1/12	0.15	southern sky
	88.0/12	$< 10^{-6}$	northern sky

WIMP or Millisecond pulsars?

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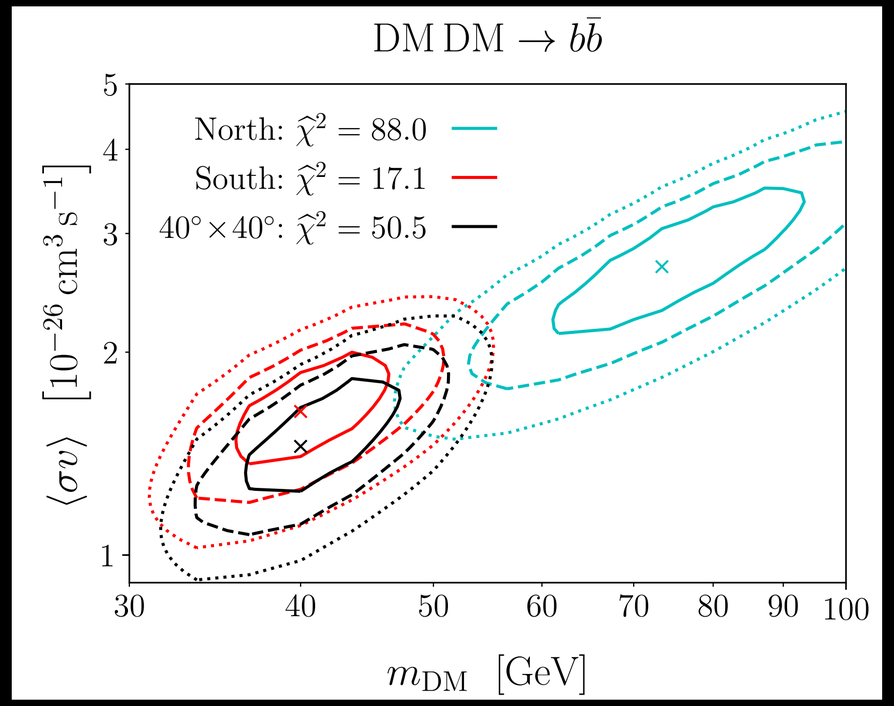


Summary

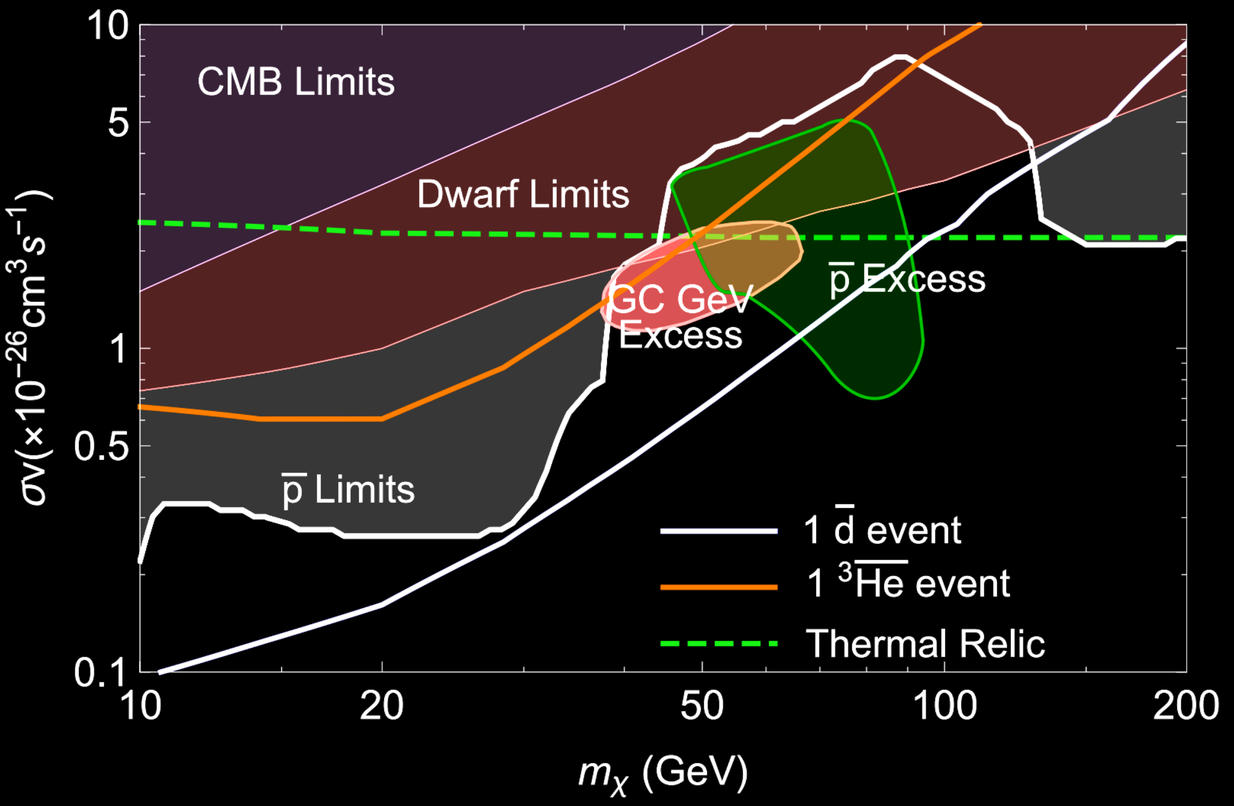
- The GCE remains one of the most intriguing discoveries from Fermi telescope.
- With the new diffuse emission templates calibrated w/ CR data, the characteristics of the GCE remains mostly unchanged.
- We find a high-energy tail at higher significance than previously reported, which favors the DM interpretation over millisecond pulsars.

https://zenodo.org/record/5787376

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

Source catalog

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

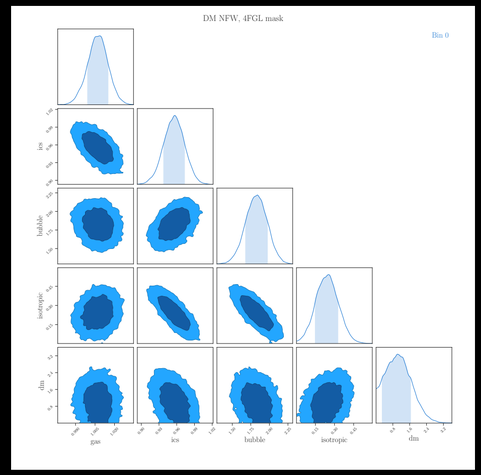
Template fitting

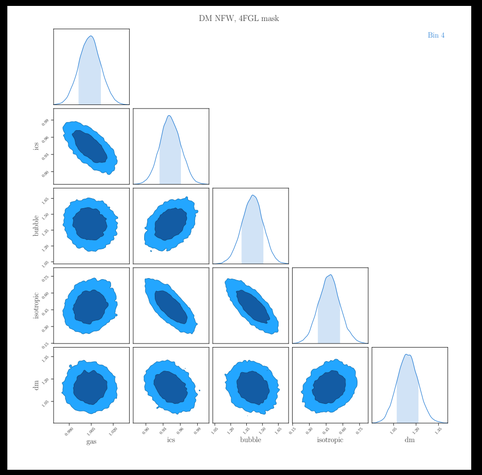
- We consider the Fermi data for 14 energy bins from 0.275 GeV to 51.9 GeV
- For each energy bin, we run MCMC to get the statistics of the weights of the templates

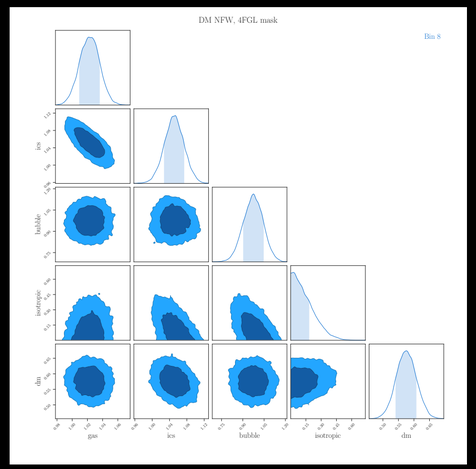
Weighted sum of templates

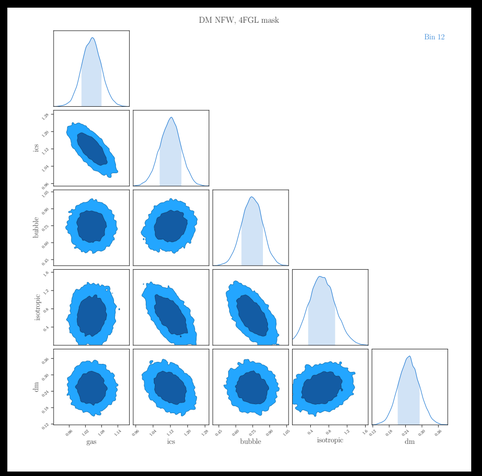
$$-2\ln\mathcal{L} = 2\sum_{\text{pix}}[C + \ln D! - D\ln C] + \chi^2_{\text{ext}}$$

Fermi data

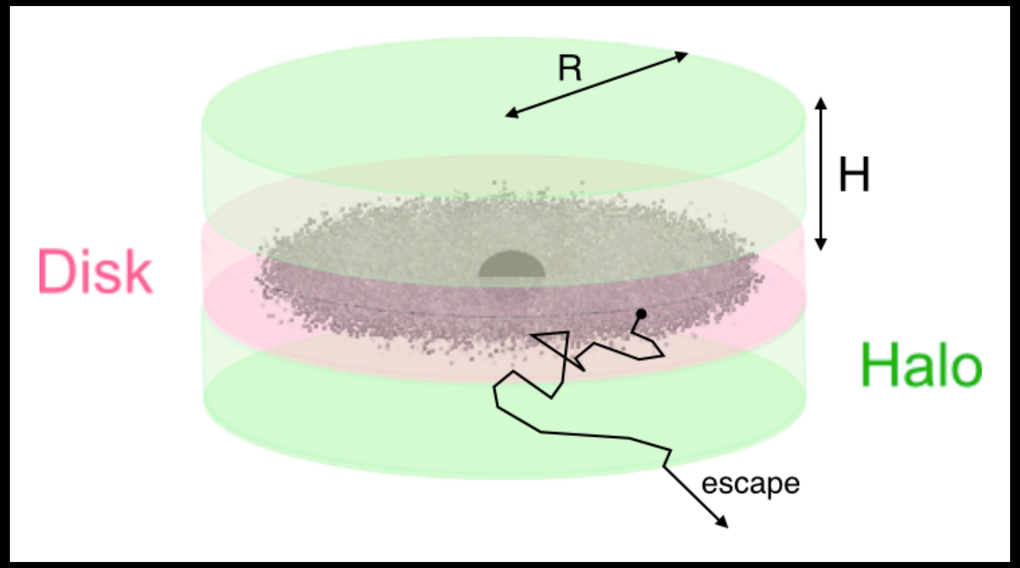






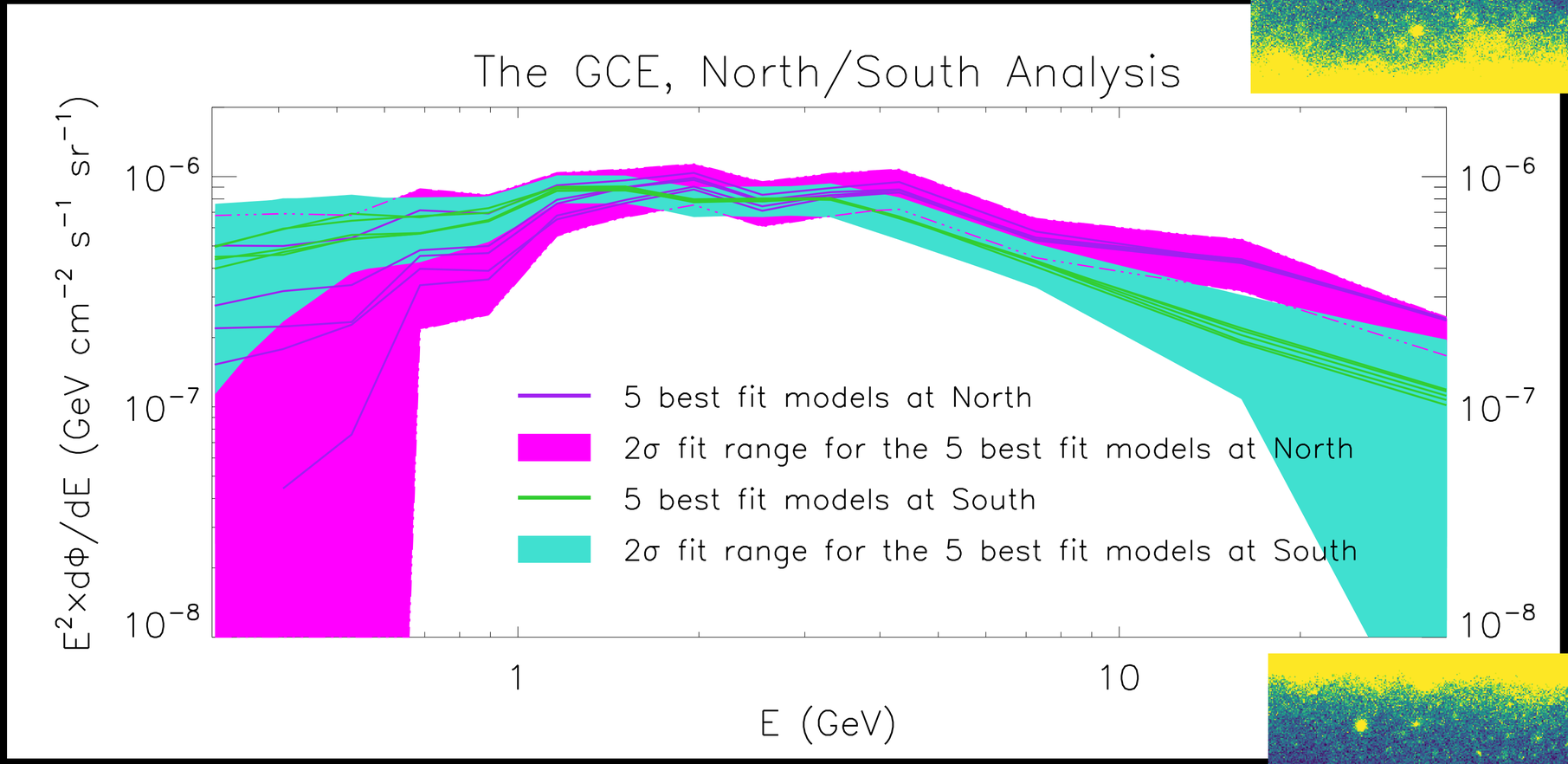


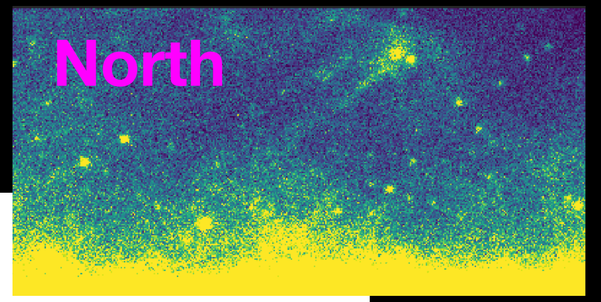
GALPROP (leaky-Box model)

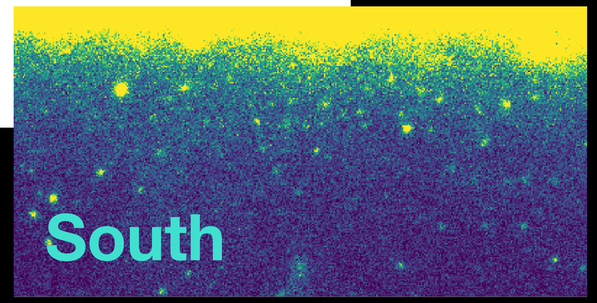


credit: J. Aguilar

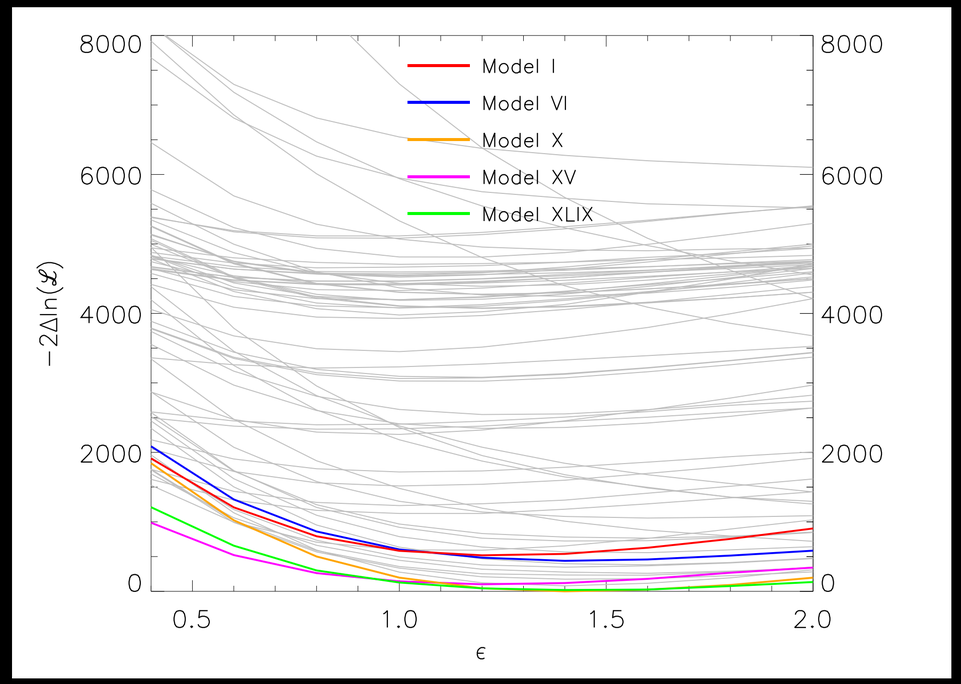
Northern vs southern sky



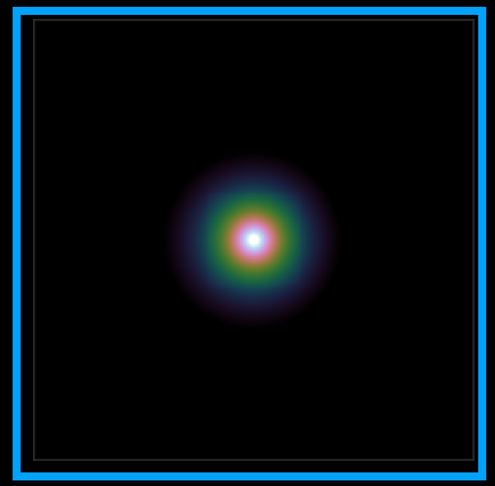


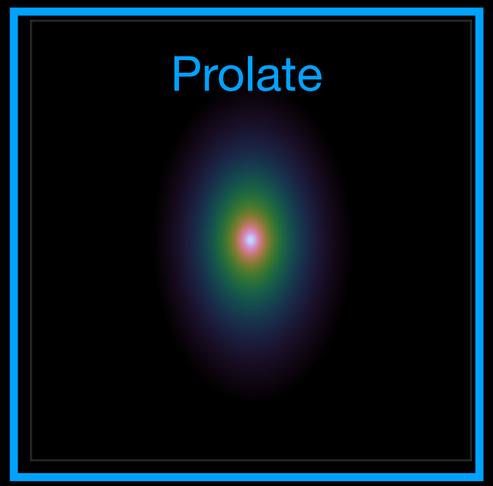


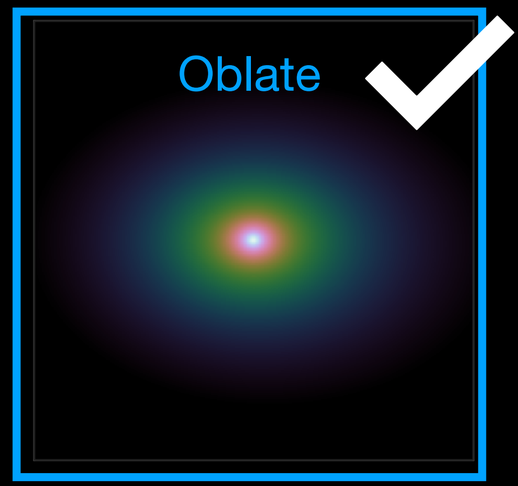
Test the morphism of GCE



Prefer slightly oblate shape

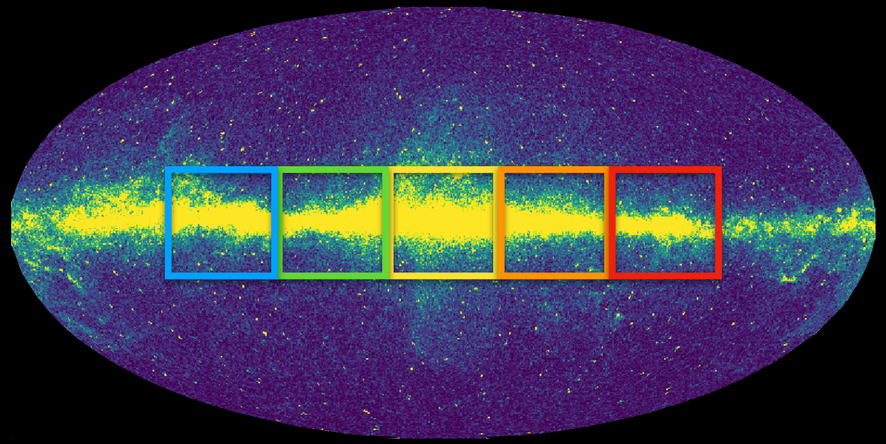






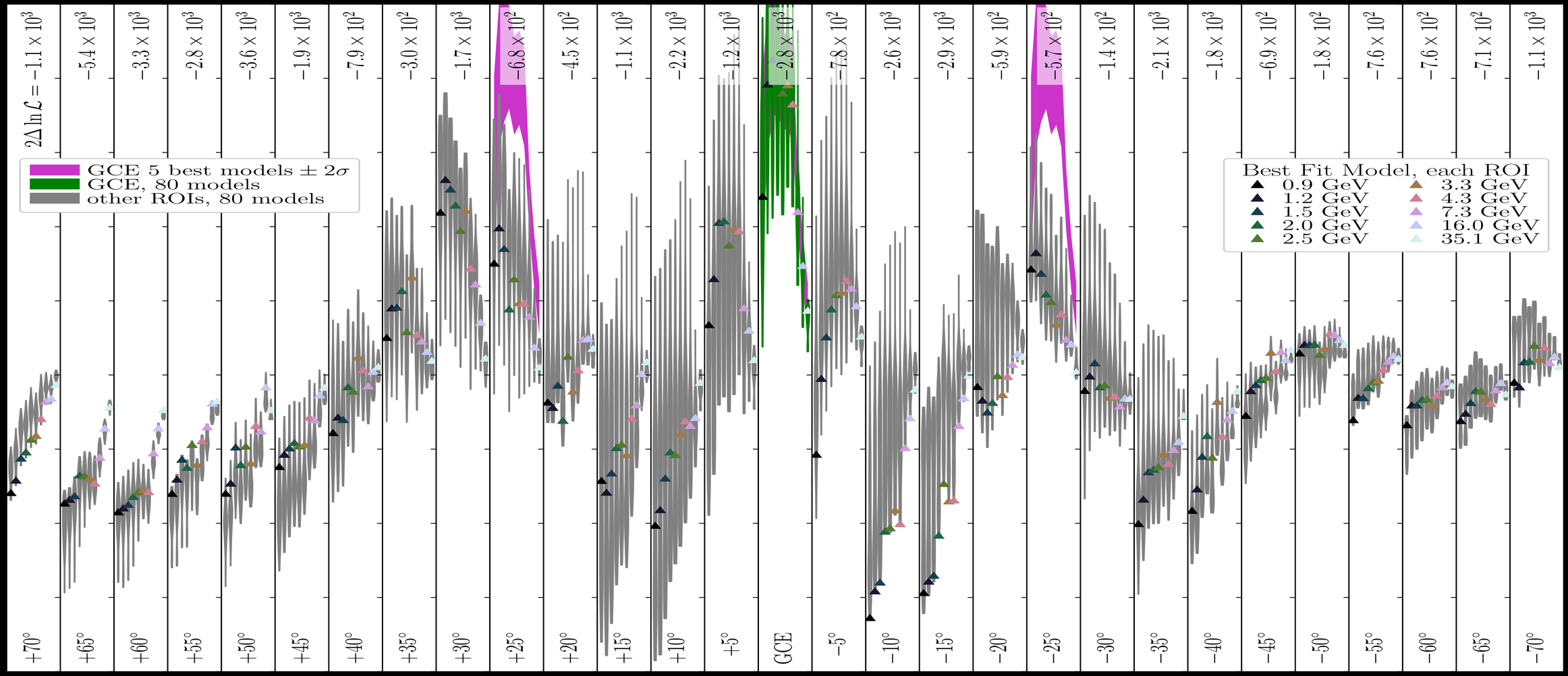
Covariance matrix for the GCE spectrum

- We perform the GCE analysis for 22 different region of interest along the Galactic disk and use observed residues to estimate systematics.
- The final covariance matrix (sys.) is available at https://zenodo.org/record/5787376



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

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



WIMP + MSPs for northern sky?

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	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}	$40^\circ \times 40^\circ$
	17.1/12	0.15	southern sky
	88.0/12	$< 10^{-6}$	northern sky
MSPs+DM DM $\to b\bar{b}$	50.5/11	$< 10^{-6}$	$40^\circ \times 40^\circ$
	16.7/11	0.12	southern sky
	60.2/11	$< 10^{-6}$	northern sky