# *Challenges Facing Pulsar Interpretations of the Galactic Center Gamma-Ray Excess*

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Identification of Dark Matter Workshop, L'Aquila, Italy

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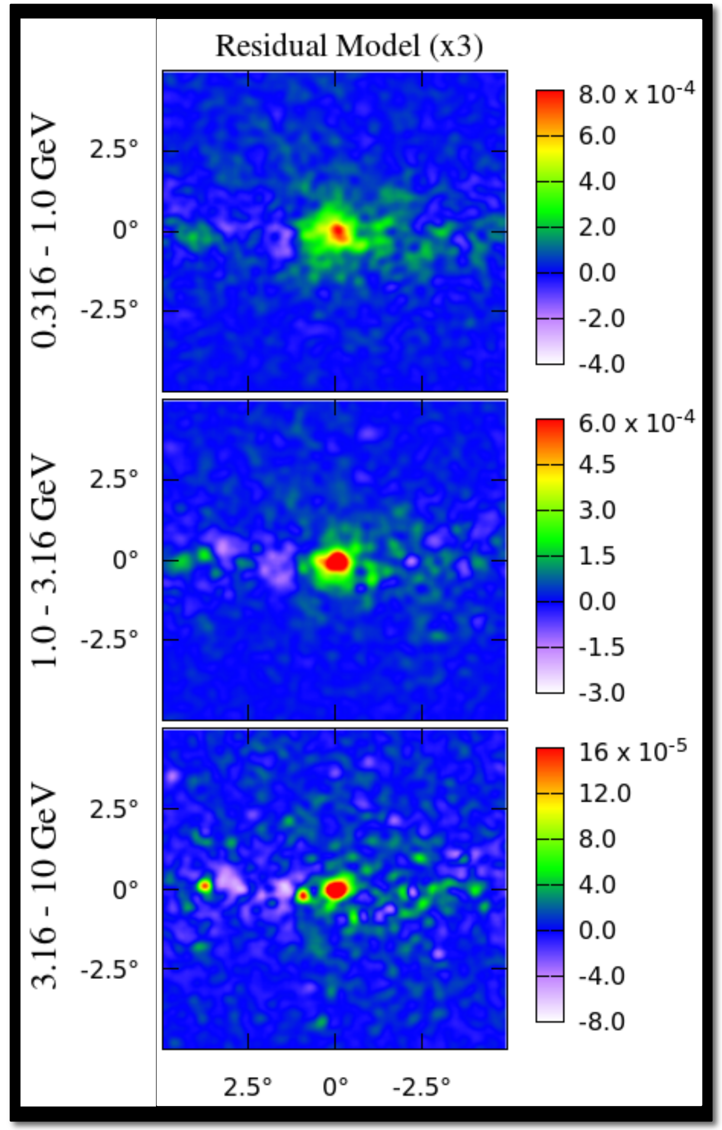
# The Galactic Center Gamma-Ray Excess

- The Fermi data contains an excess of GeV-scale emission from the direction of the Inner Galaxy, relative to *all models* of known astrophysical backgrounds
- This signal is bright and highly statistically significant – its existence is not in dispute
- It is very difficult to explain this signal with known astrophysical sources or mechanisms
- The observed characteristics of this signal are consistent with those expected from annihilating dark matter

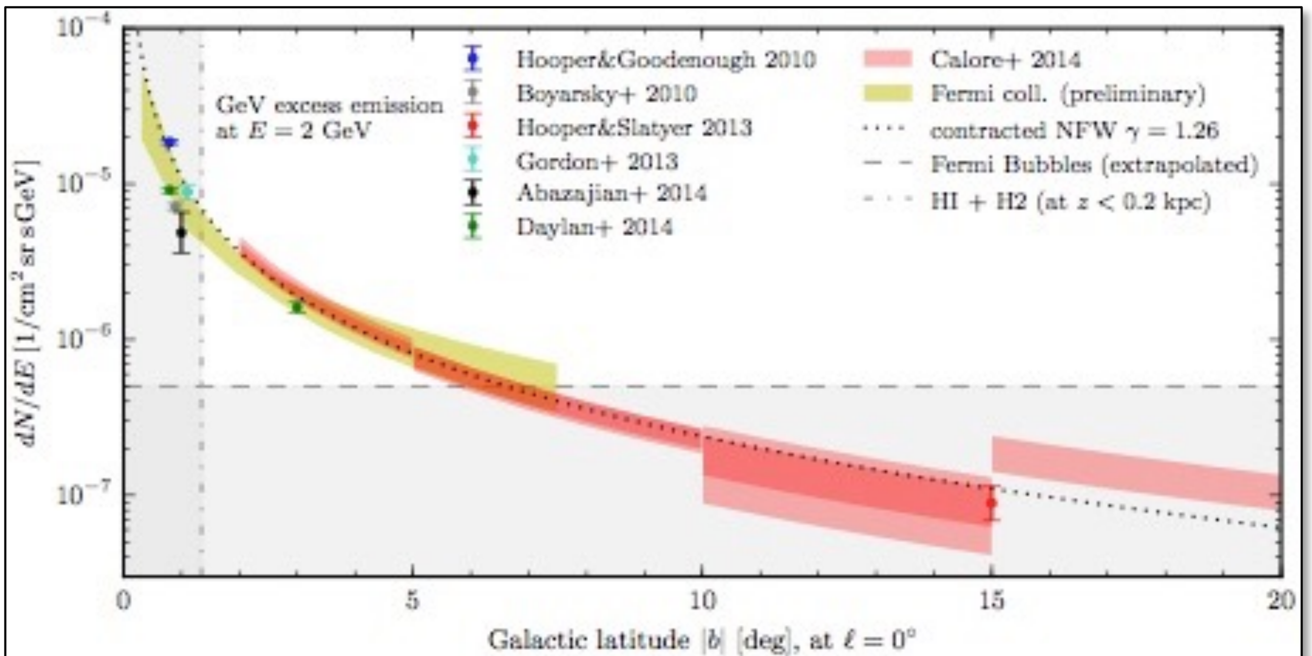
**Among other references, see:**
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, DH, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

**Fermi**



# Morphology

- The gamma-ray excess exhibits approximate spherical symmetry about the Galactic Center (axis ratios within ~20% of unity), with a flux that falls as ~$r^{-2.4}$ out to at least ~20°
- If interpreted as annihilating dark matter, this implies $\rho_{DM} \sim r^{-1.2}$ out to at least ~3 kpc, only slightly steeper than the canonical NFW profile

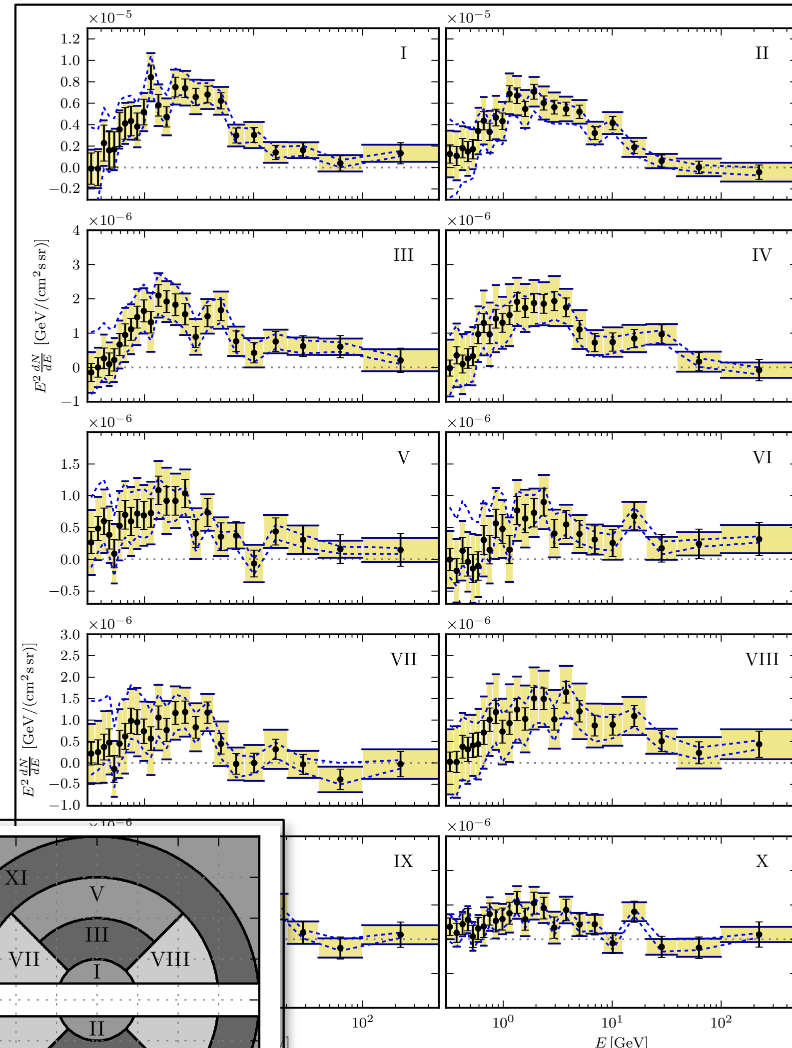


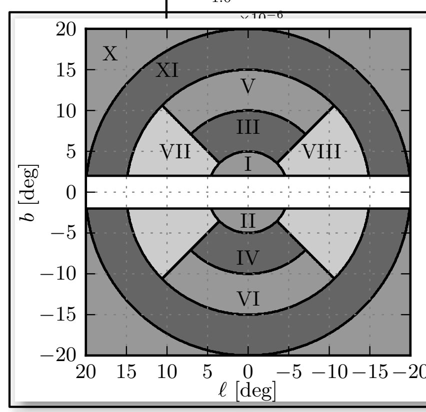

Calore, Cholis, Weniger (2014)

# Spectrum

- The spectrum of the excess is well fit by a ~20-65 GeV particle annihilating to quarks or gluons
- The shape of the spectrum is uniform across the Inner Galaxy

| Channel | $\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1})$ | $m_\chi$ (GeV) | $\chi^2_{\mathrm{min}}$ | $p$-value |
|---|---|---|---|---|
| $\bar{q}q$ | $0.83^{+0.15}_{-0.13}$ | $23.8^{+3.2}_{-2.6}$ | 26.7 | 0.22 |
| $\bar{c}c$ | $1.24^{+0.15}_{-0.15}$ | $38.2^{+4.7}_{-3.9}$ | 23.6 | 0.37 |
| $\bar{b}b$ | $1.75^{+0.28}_{-0.26}$ | $48.7^{+6.4}_{-5.2}$ | 23.9 | 0.35 |
| $gg$ | $2.16^{+0.35}_{-0.32}$ | $57.5^{+7.5}_{-6.3}$ | 24.5 | 0.32 |



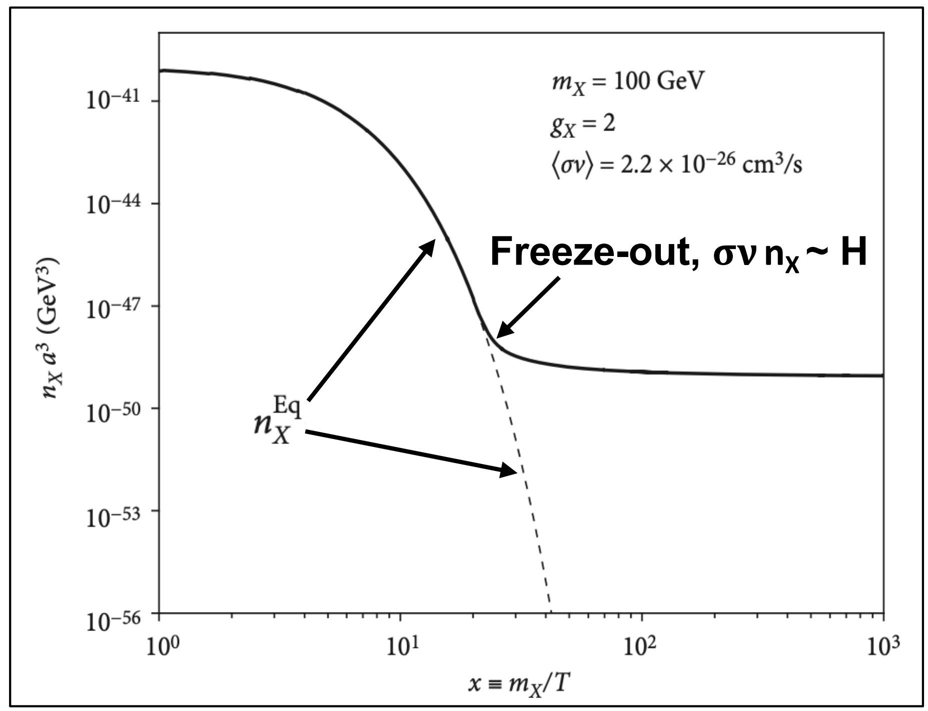




Calore, Cholis, Weniger; Calore, Cholis, McCabe, Weinger (2014); Escudero, Witte, DH, arXiv:1709.07002

# Intensity

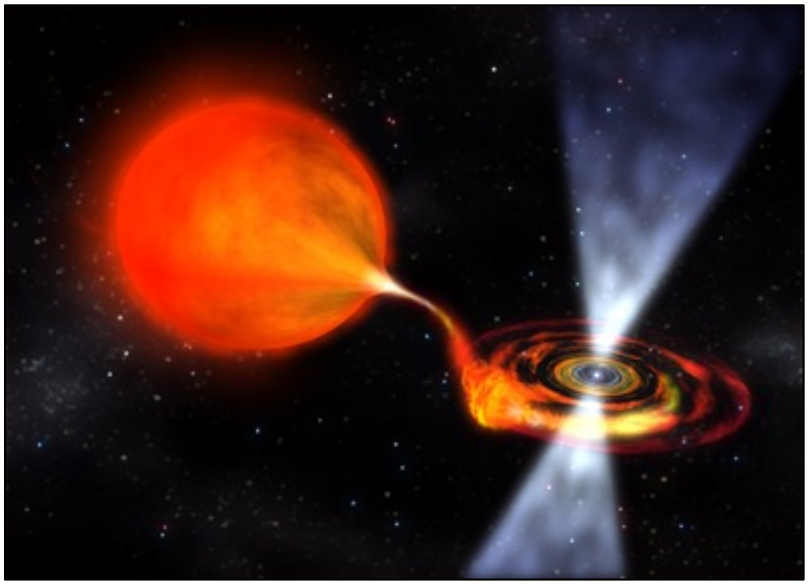
- To produce the observed intensity of the excess, the dark matter particles must annihilate with a cross section of $\sigma v \sim (1\text{-}2) \times 10^{-26}$ cm$^3$/s
- This is in remarkably good agreement with the value of the annihilation cross section that is required to generate the measured dark matter abundance through thermal freeze-out in the early universe

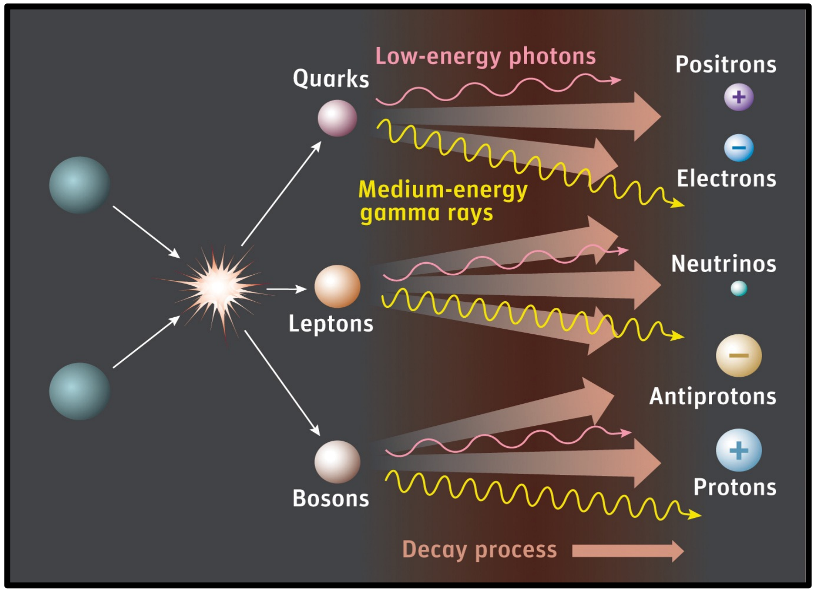
$$\Omega_X \sim 0.27 \times \left( \frac{2.2 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \right)$$



# What Produces the Galactic Center Excess?

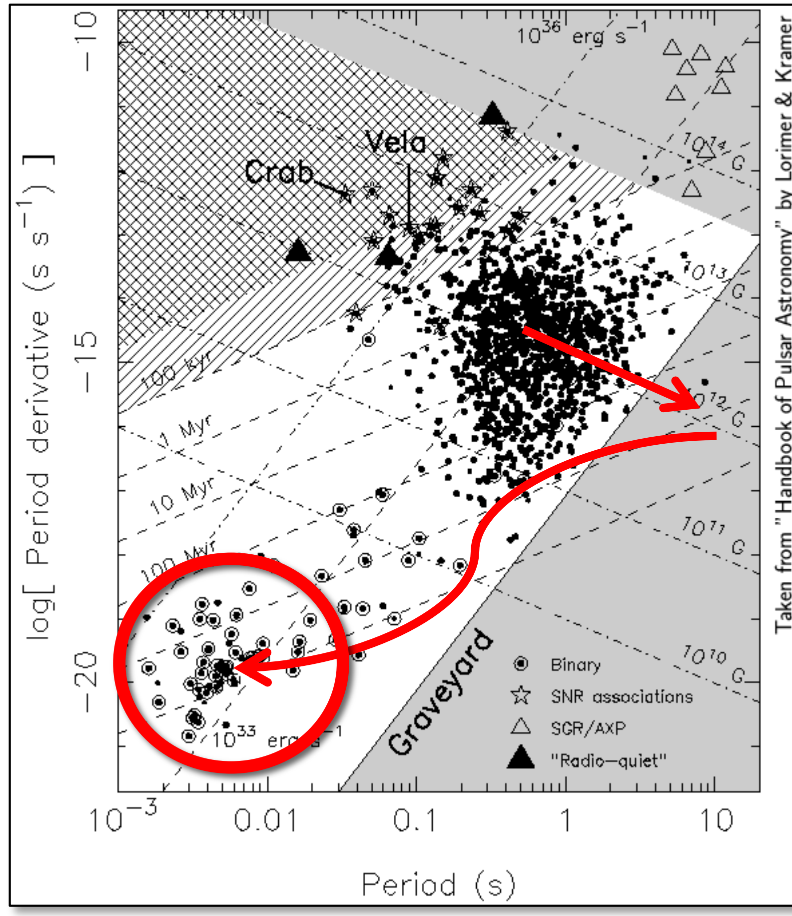
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?

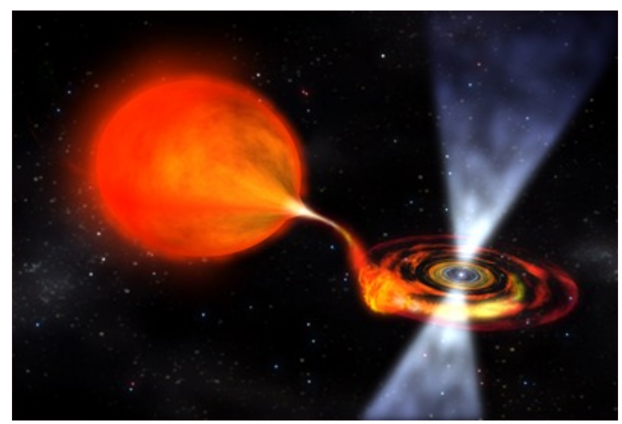




# Millisecond Pulsars

- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- Young pulsars exhibit periods on the order of ~1 second and slow down and become faint over ~$10^6$ -$10^8$ years
- Alternatively, accretion from a companion star can “spin-up” a neutron star to periods as fast as ~1.5 ms
- Such millisecond pulsars have low magnetic fields (~$10^8$-$10^9$ G) and thus spin down much more slowly than young pulsars, remaining bright for >$10^9$ years
- It seems plausible that large numbers of MSPs could exist near the Galactic Center



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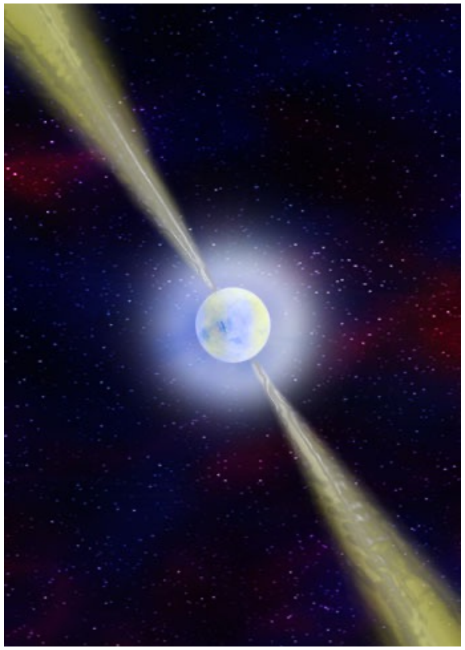

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- The gamma-ray spectrum of observed pulsars
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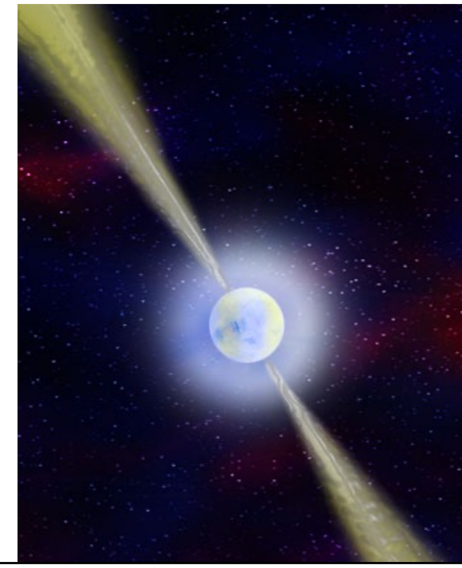

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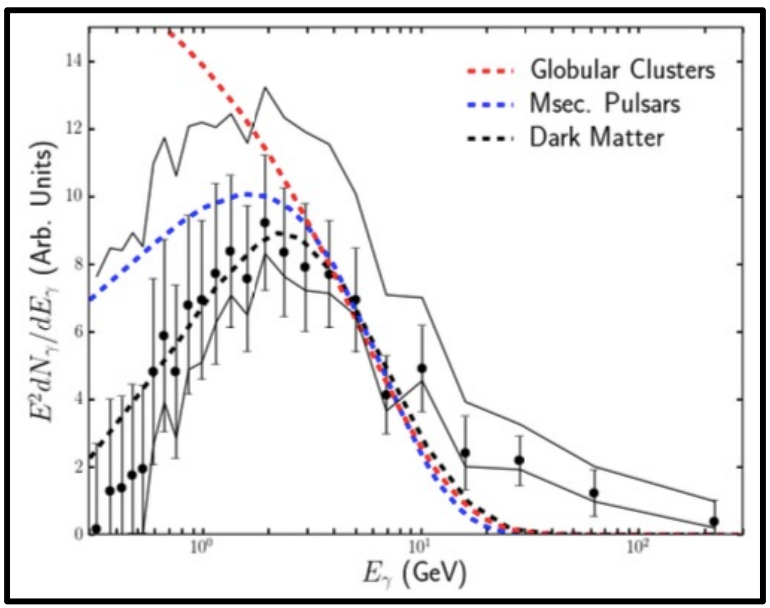
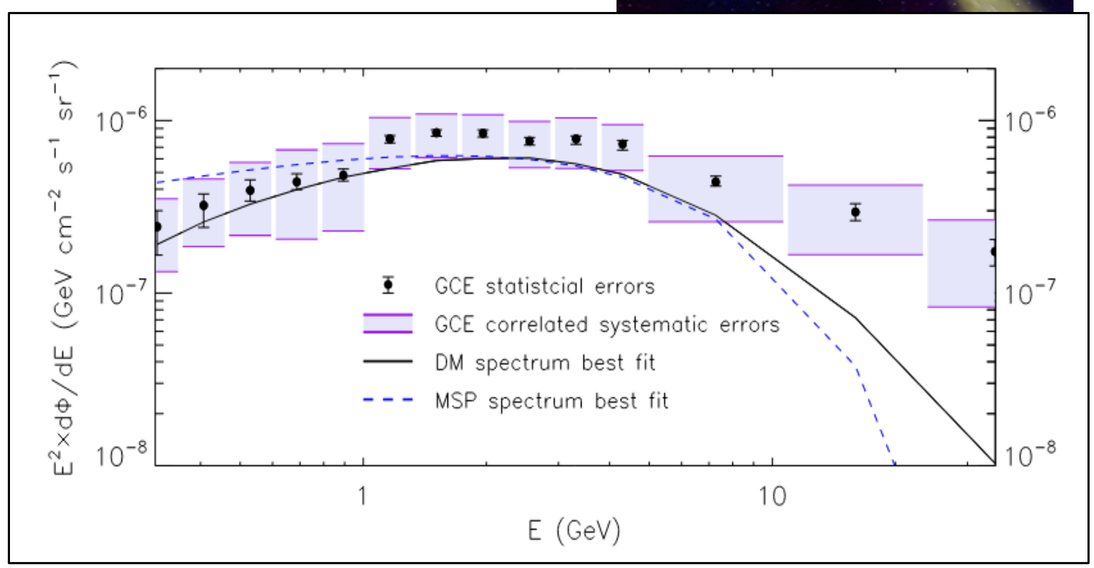



Cholis, DH, Linden (2014)




Cholis, Zhong, McDermott, Surdutovich (2021)

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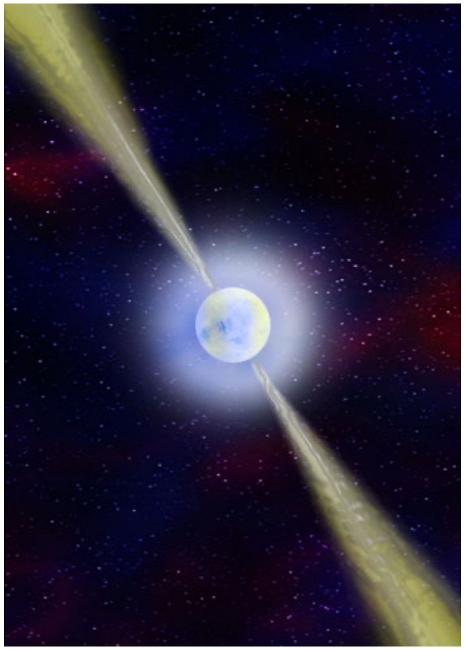

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# Evidence of Unresolved Gamma-Ray Sources?

- In 2015, two groups (Lee, *et al*., 1506.05124, Bartels *et al*., 1506.05104) found that the gamma rays from the Inner Galaxy are more clustered than expected from smooth backgrounds, suggesting that the excess might be generated by a population of unresolved gamma-ray point sources

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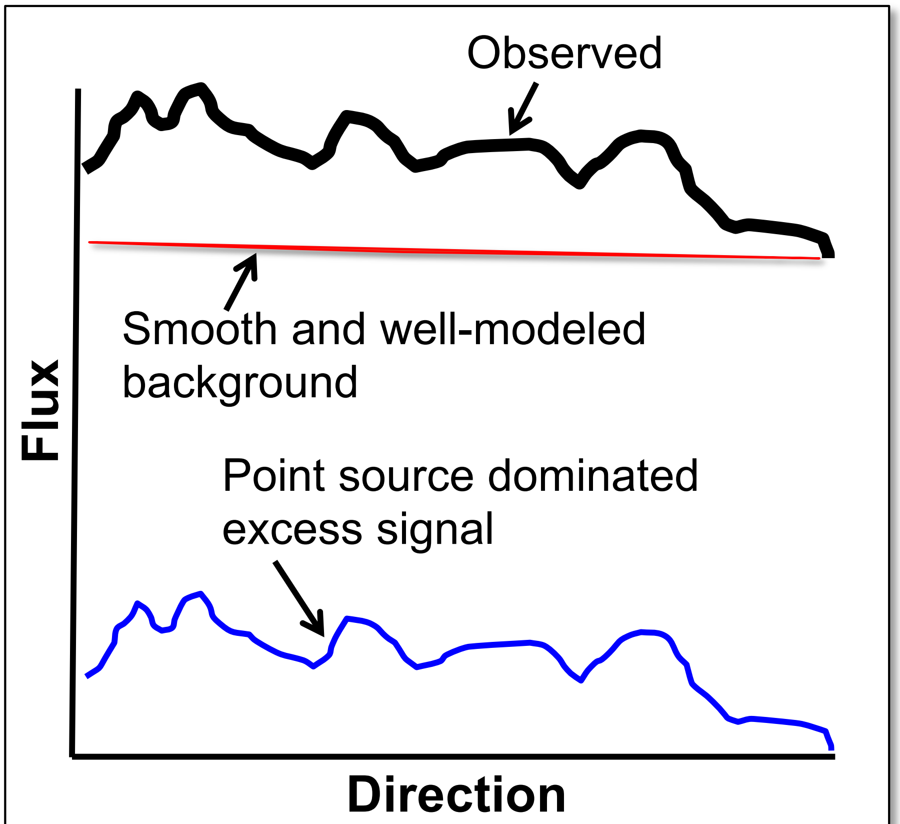

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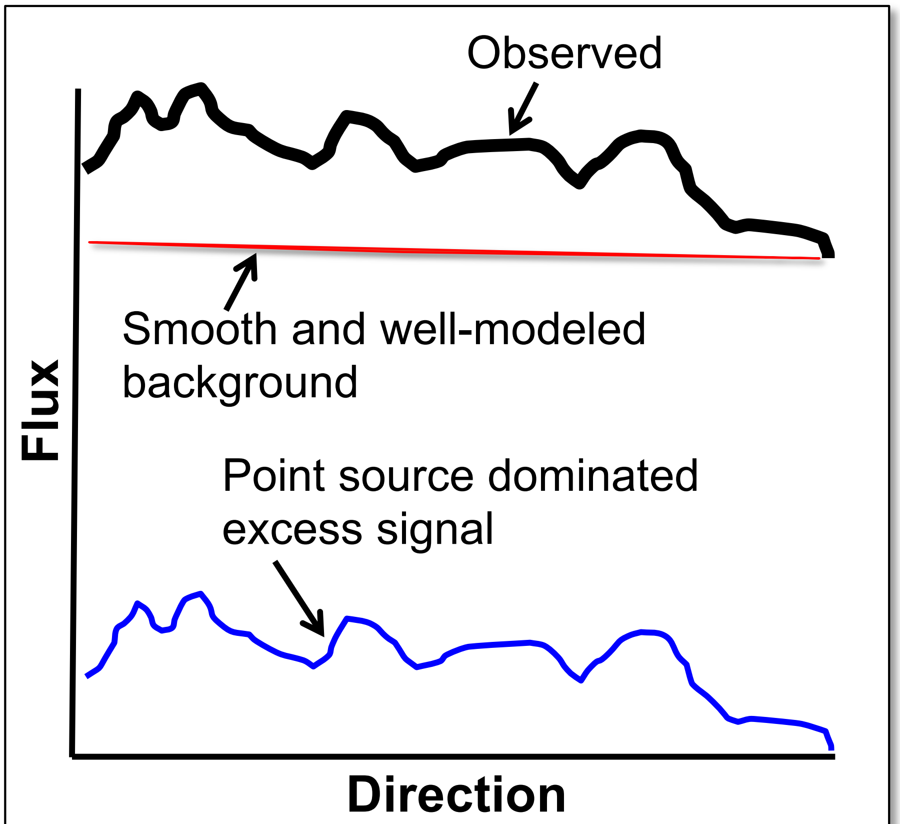


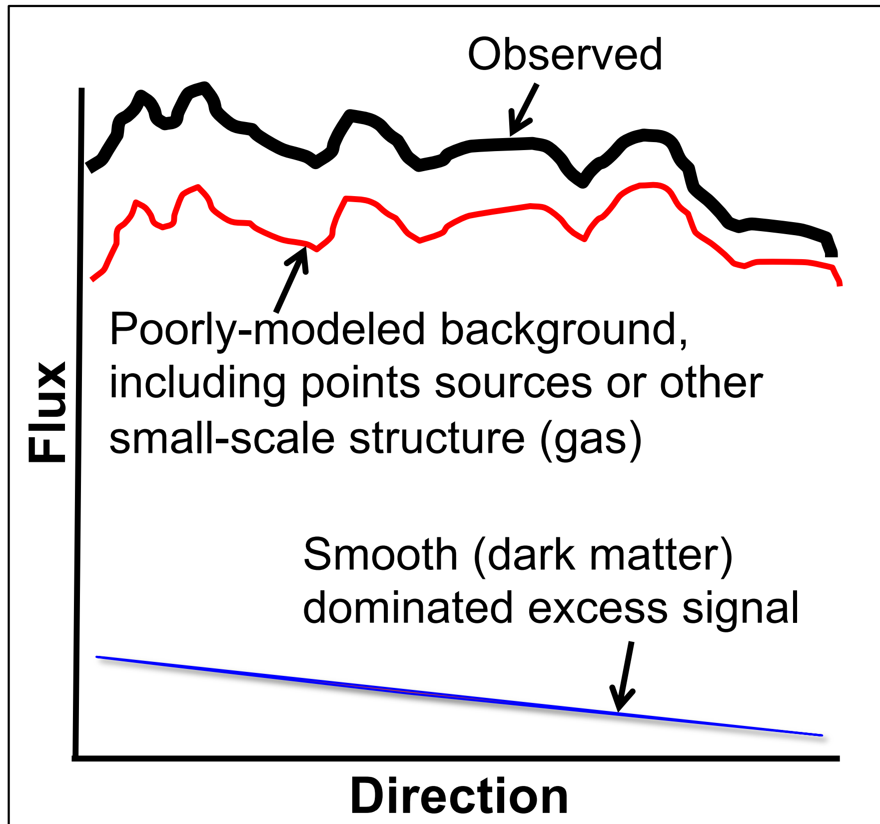

# DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

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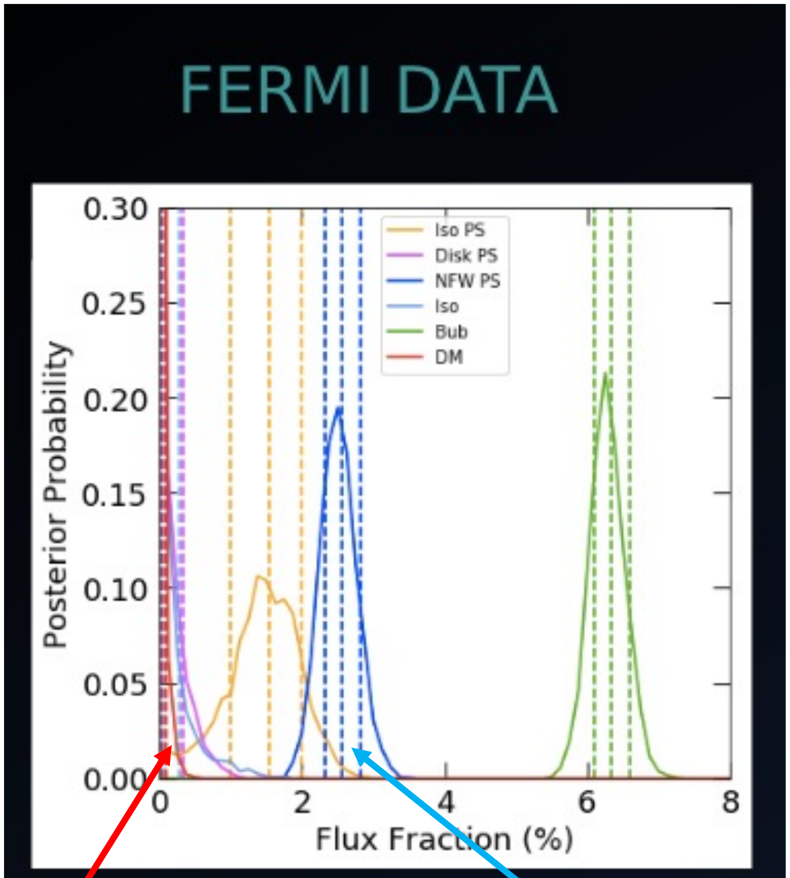


Here is the result that Leane and Slatyer obtain using the same NPTF procedure as Lee *et al.*

The key question is to what extent inadequate astrophysical templates might be biasing these results

This technique finds that the excess emission comes almost entirely from faint **Point Sources**, and that almost none of the emission is smooth and **Dark Matter**-like

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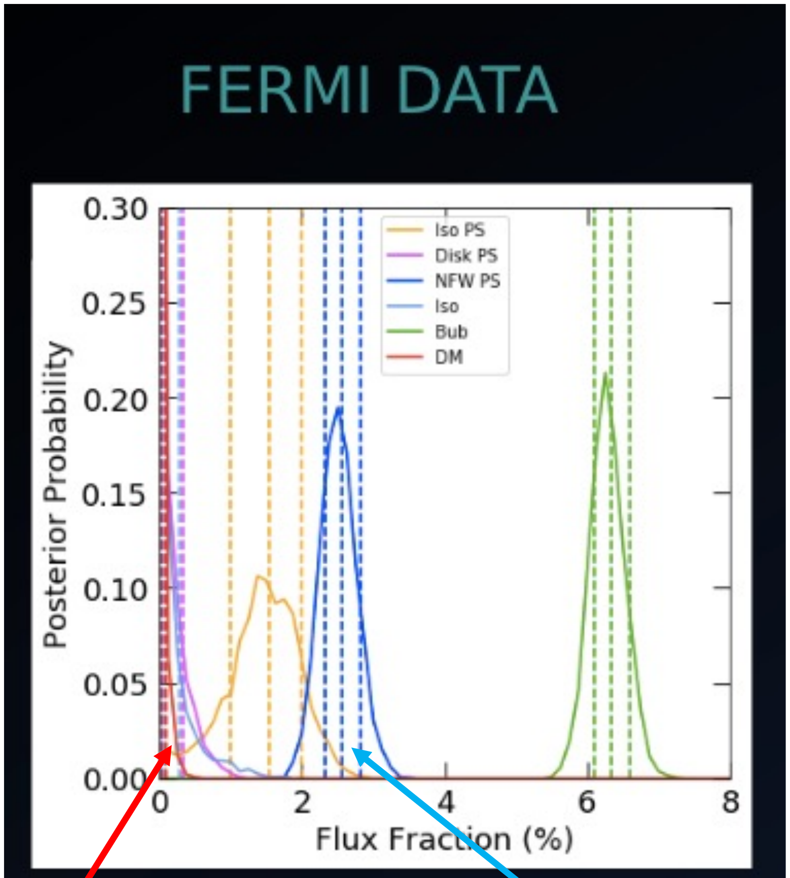


Here is the result that Leane and Slatyer obtain using the same NPTF procedure as Lee *et al.*

The key question is to what extent inadequate astrophysical templates might be biasing these results

To test the reliability of this result, they then *added* a (smooth) dark matter-like signal to the Fermi data

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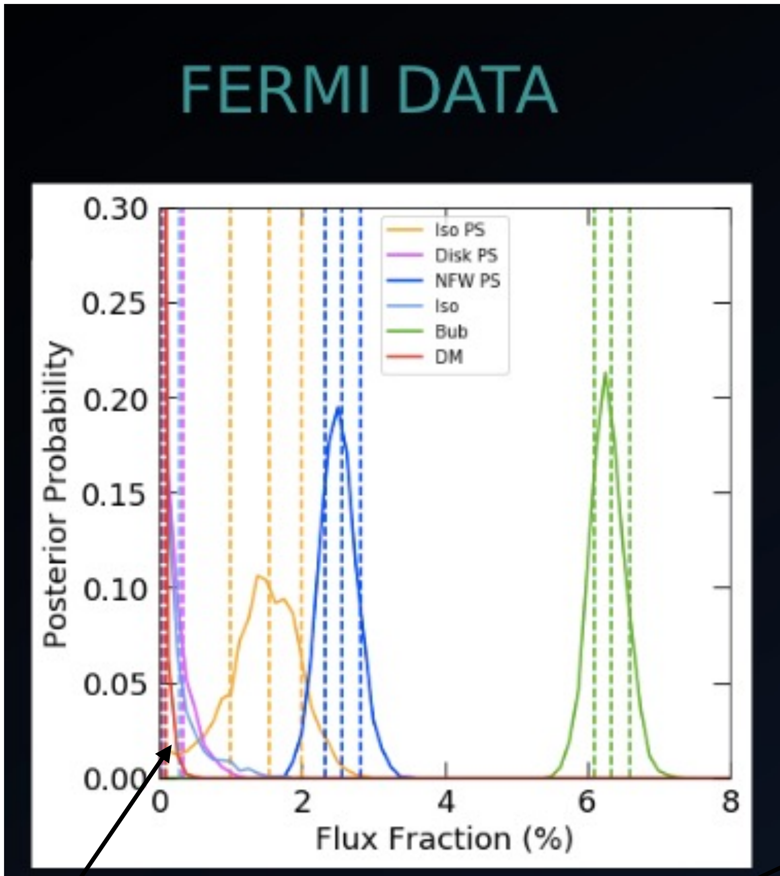


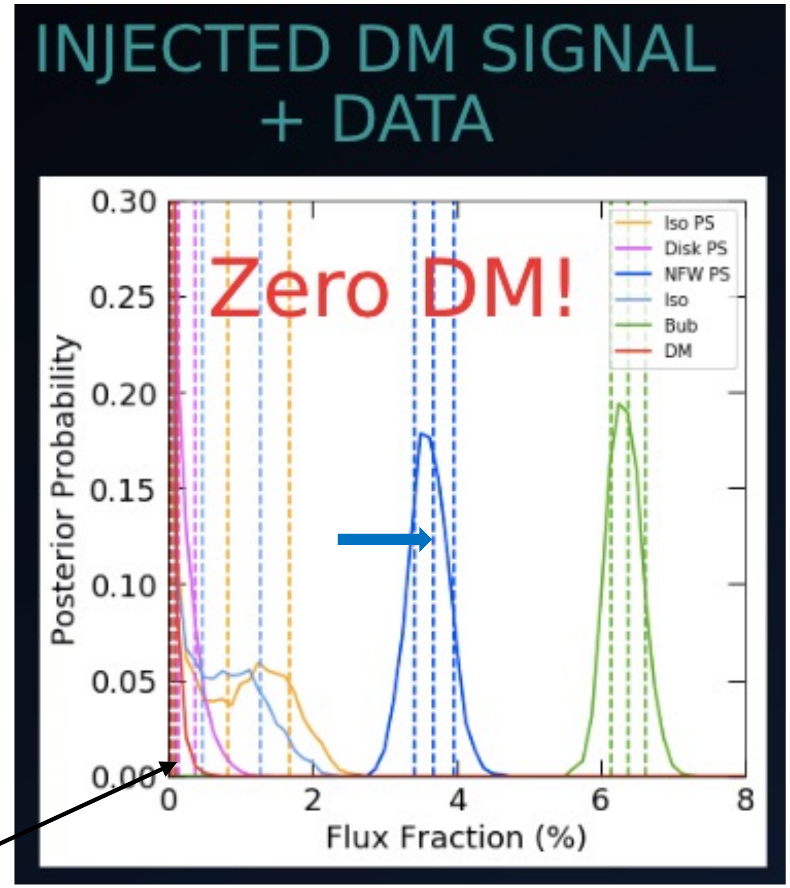


Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

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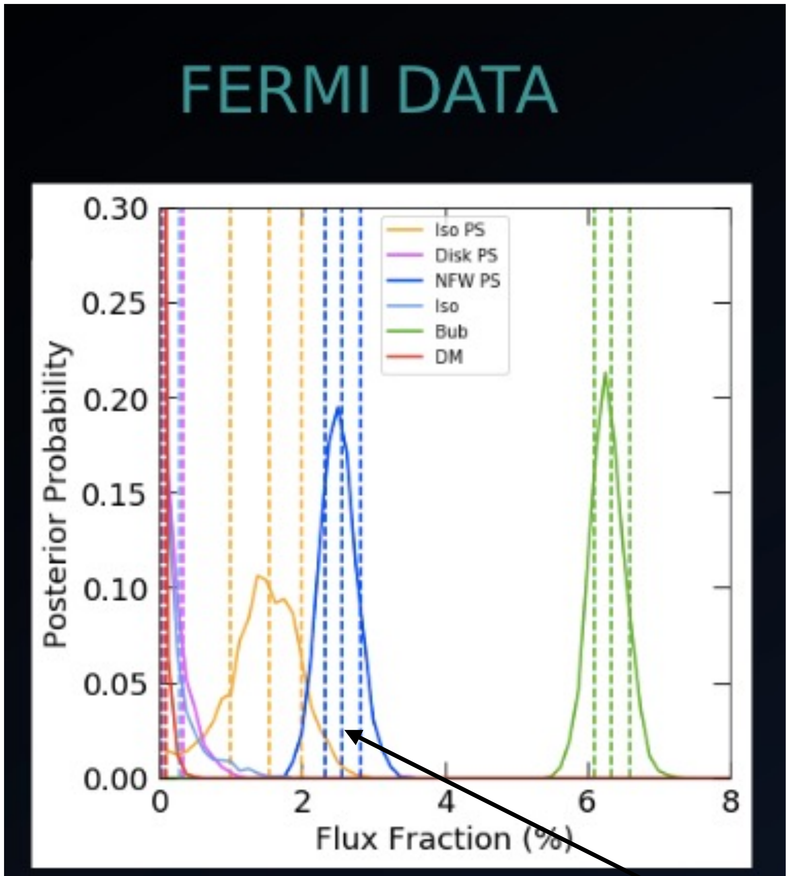


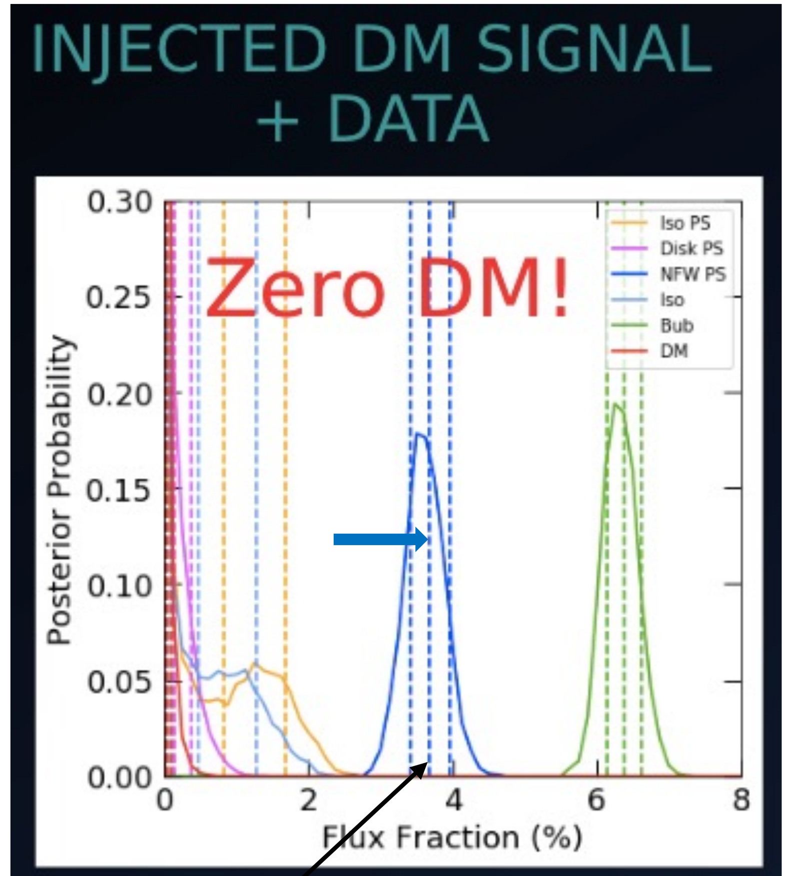


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Instead, the fit identifies the injected dark matter-like signal as originating from point sources

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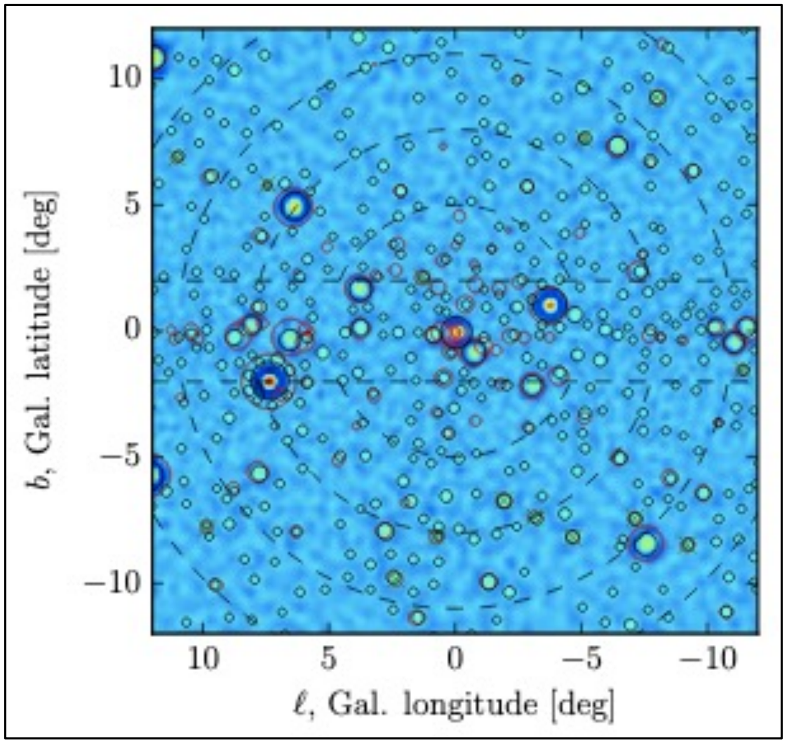
Bottom Line:

The non-Poissonian template fit is clearly **misattributing** the dark matter-like signal to point sources, demonstrating that the templates being used are **not adequate to describe the data**, strongly biasing the results of the fit

The excess could still be generated by a large number of faint point sources, but this kind of analysis does not provide any evidence of this

# Wavelet Analyses and GC Point Sources

- In 2015, Bartels *et al.* used a wavelet-based technique to identify what they called "strong support" for a millisecond pulsar interpretation of the gamma-ray excess




Bartels, Krishnamurthy, Weniger, arXiv:1506.05104
Zhong, McDermott, Cholis, Fox, arXiv:1911.12369

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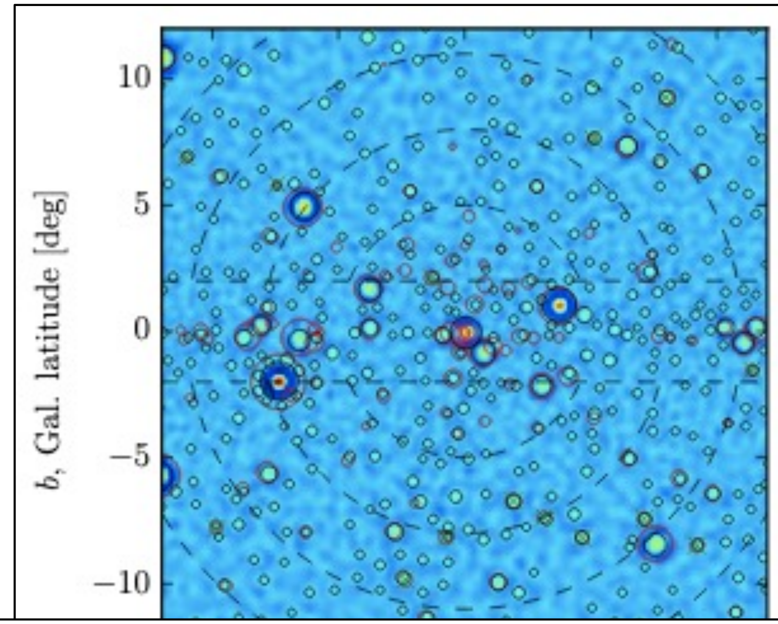
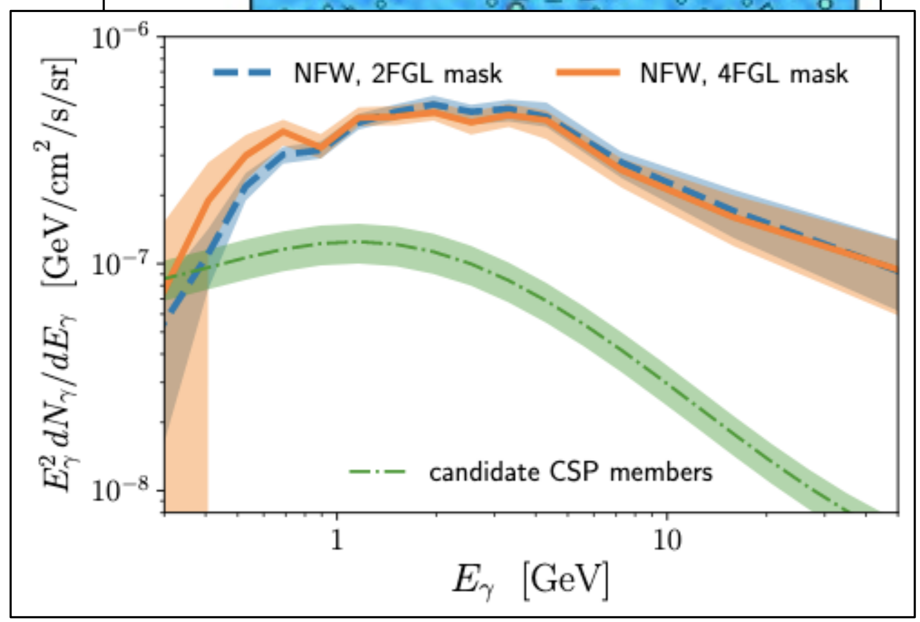
- More recently, Zhong, McDermott, Cholis and Fox revisited this method, utilizing an updated gamma-ray source catalog (4FGL vs 3FGL)
- Using the 3FGL, Zhong *et al*. reproduced the results of Bartels *et al*.
- After accounting for the 4FGL sources, Zhong *et al*. find no evidence that the excess is produced by point sources

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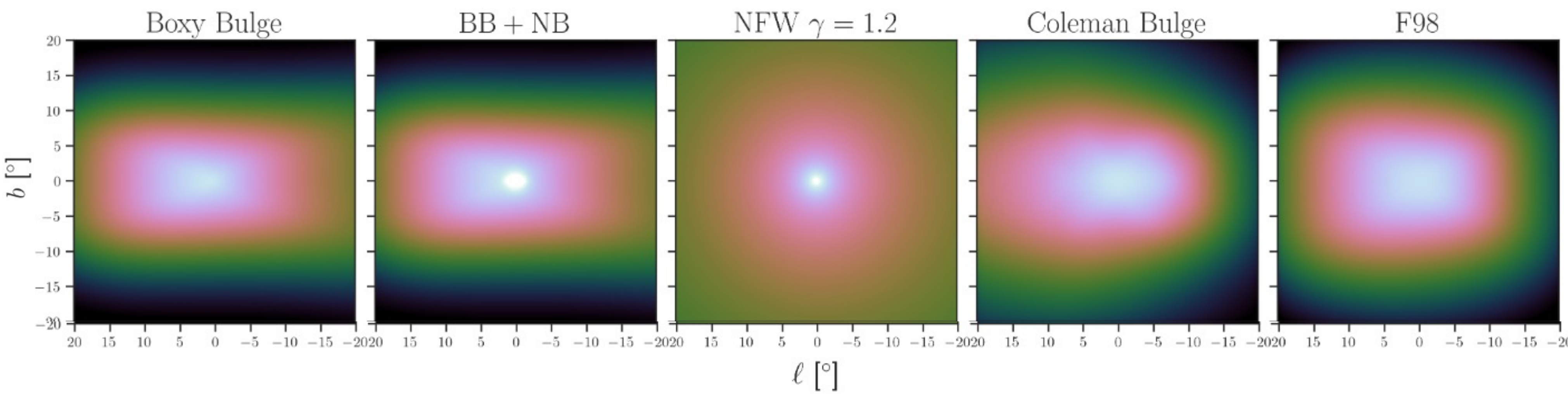
# Bulge/Bar-Like vs DM-Like Morphology

- An important test of the origin of the Galactic Center excess is to establish whether this signal is spherical and dark matter-like, or instead traces some combination of known stellar populations (*ie*., the Galactic Bulge and Bar)




- In papers by Macias *et al.* (arXiv:1611.06644, 1901.03822) and Bartels *et al.* (1711.04778), it was argued that the excess is better fit by spatial templates which trace stellar populations than by dark matter-like templates
- If confirmed, this would favor astrophysical interpretations of the gamma-ray excess

# Bulge/Bar-Like vs DM-Like Morphology

- Recent work, however, has not consistently reached the same conclusion
- Instead, it is now clear that the answer you get to this question depends strongly on choices/assumptions that you make in your analysis, including:

    1) The model that is used for the Galactic diffuse emission
    2) The regions of the sky that are included in the fit (*ie*., the mask)

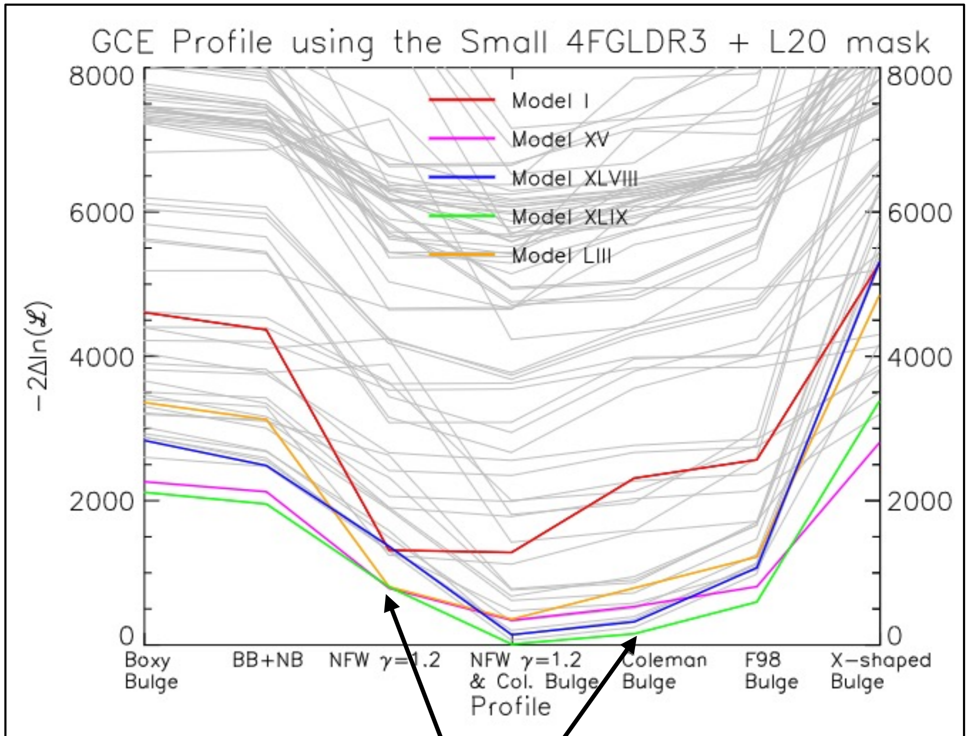
- For this reason, different groups, making different but seemingly reasonable analysis choices, reach different conclusions regarding the detailed morphology of the GCE

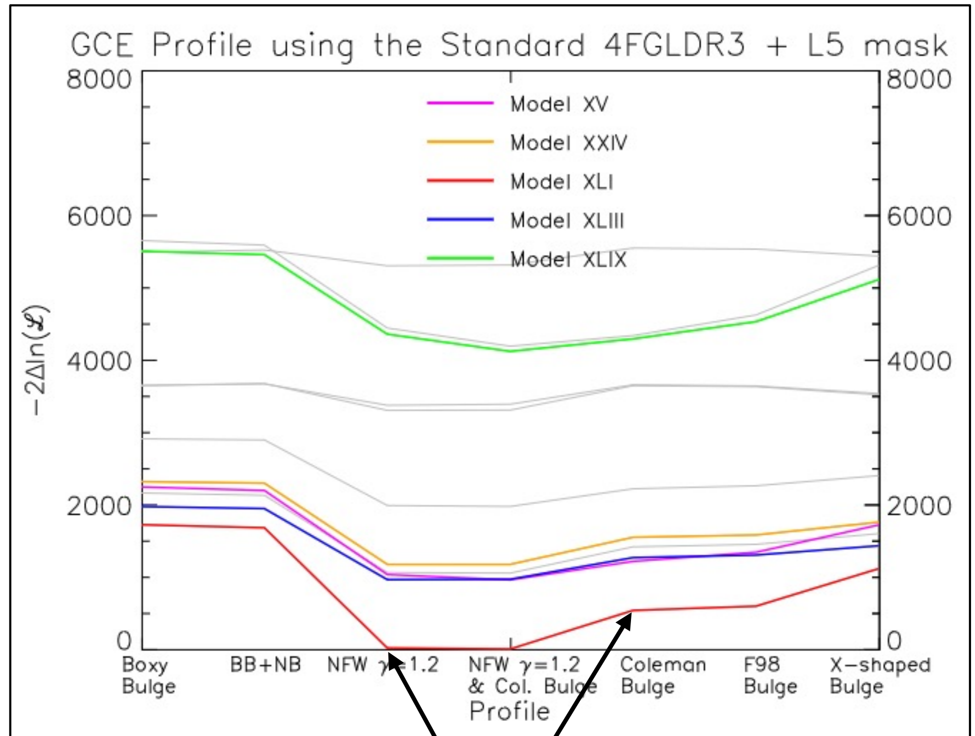
Zhong, Cholis, 2401.02481
McDermott *et al*., 2209.00006; 2112.09706
Di Mauro, 2101.04694

# Bulge/Bar-Like vs DM-Like Morphology

Zhong, Cholis, arXiv:2401.02481

Better Fit




For this choice of mask, the fits prefer some bulge models over dark matter models for the GCE

For other choices, the fits prefer dark matter models for the GCE

(see also McDermott *et al.*, 2209.00006; 2112.09706; Di Mauro, 2101.04694)

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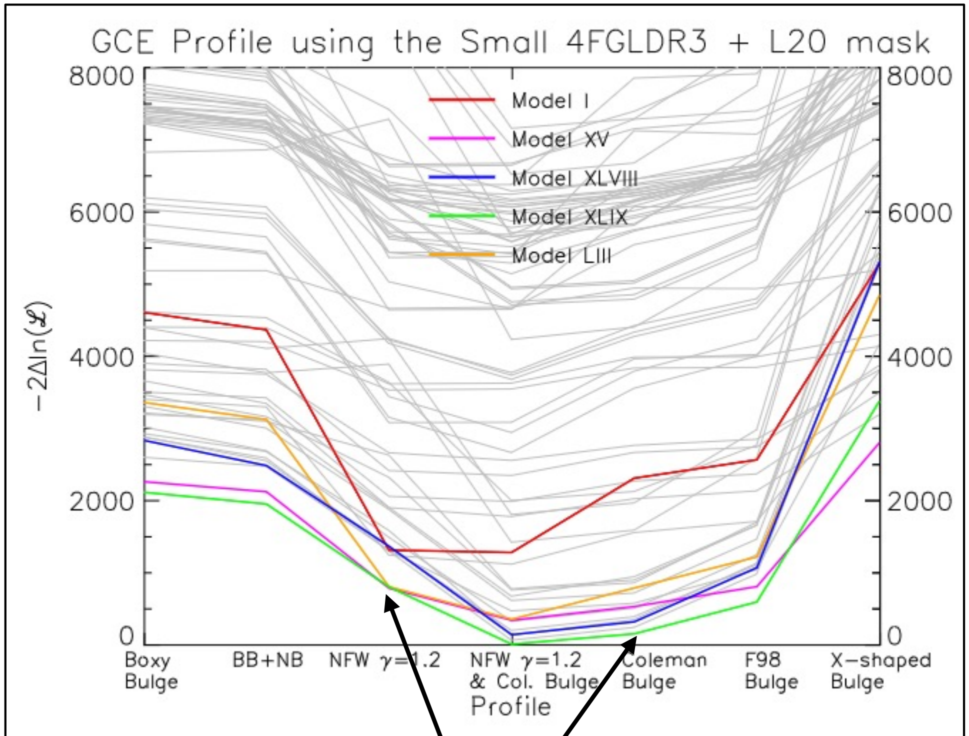


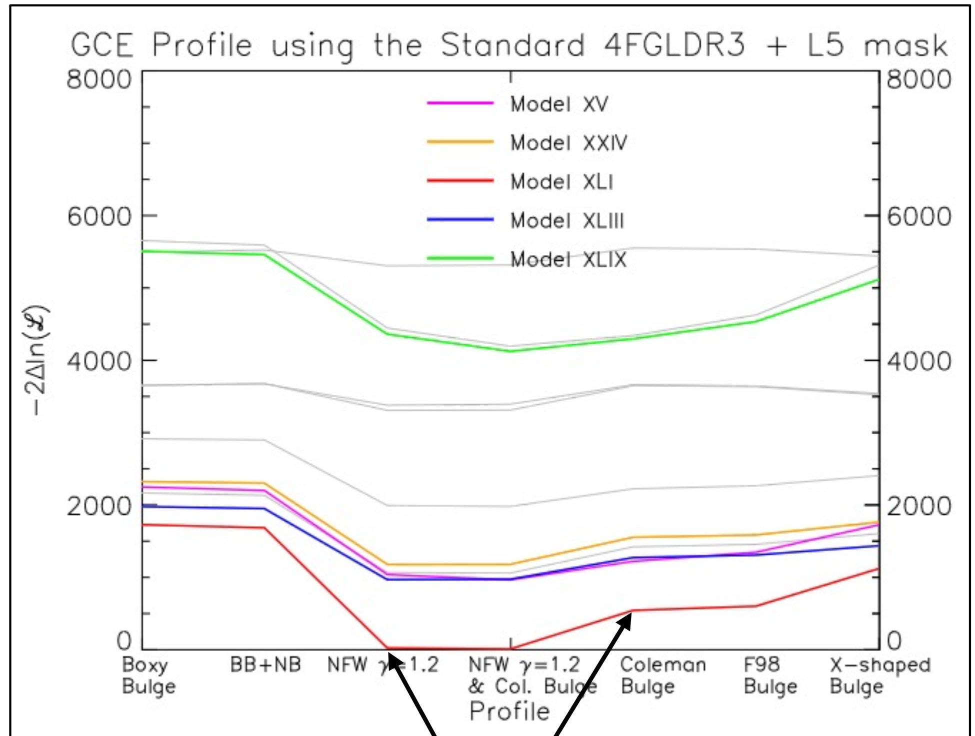


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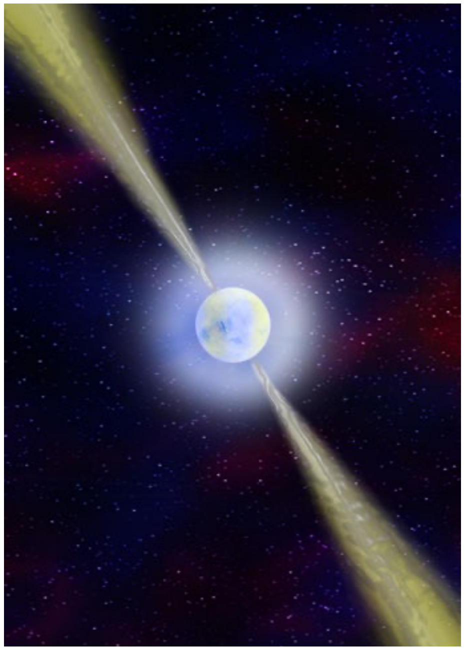
For other choices, the fits prefer dark matter models for the GCE

***Bottom Line: The detailed morphology of the GCE is systematic-limited; we can't currently differentiate between dark matter and bulge-like models***

(see also McDermott *et al.*, 2209.00006; 2112.09706; Di Mauro, 2101.04694)

# Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



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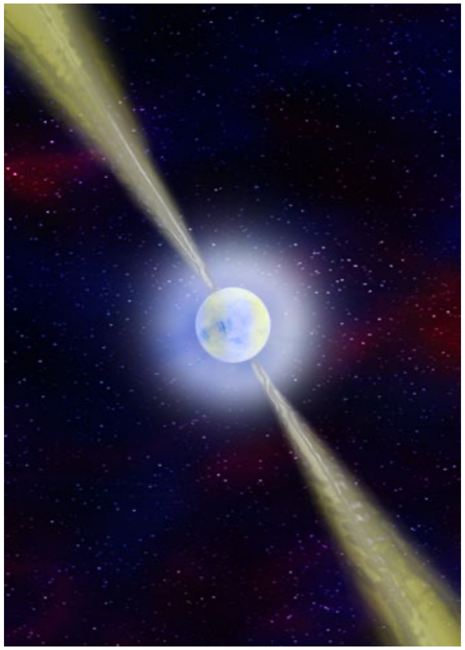

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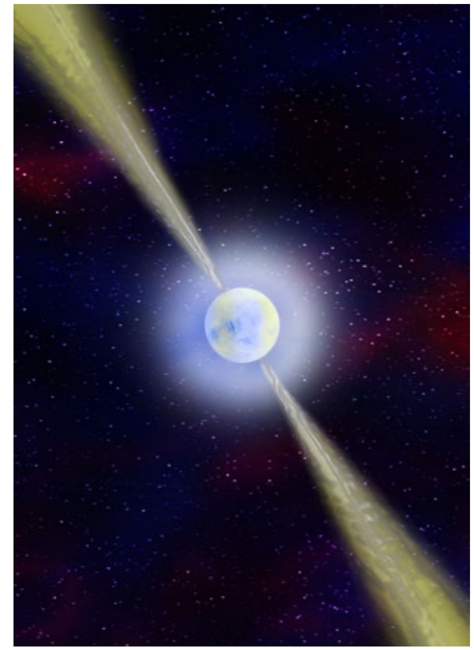

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**Arguments Against Pulsars:**

- The lack of pulsars detected in the Inner Galaxy
- The lack of low-mass X-ray binaries in the Inner Galaxy

# Why Don't We See More Pulsars in the Inner Galaxy?

- To date, Fermi has detected only three gamma-ray sources that could potentially be pulsars located within a few kpc of the Galactic Center (PSR J1747-4036, J1649-3012, J1833-3840)
- These three gamma-ray sources could be the first detected members of an Inner Galaxy pulsar population, but they could also easily be part of the Galactic Disk's pulsar population

# Why Don't We See More Pulsars in the Inner Galaxy?

- The Fermi Collaboration has recently released their Third Pulsar Catalog, which contains 179 MSPs from the Disk of the Milky Way
- Using the contents of this catalog, we were able to constrain the spatial distribution and luminosity function of these MSPs

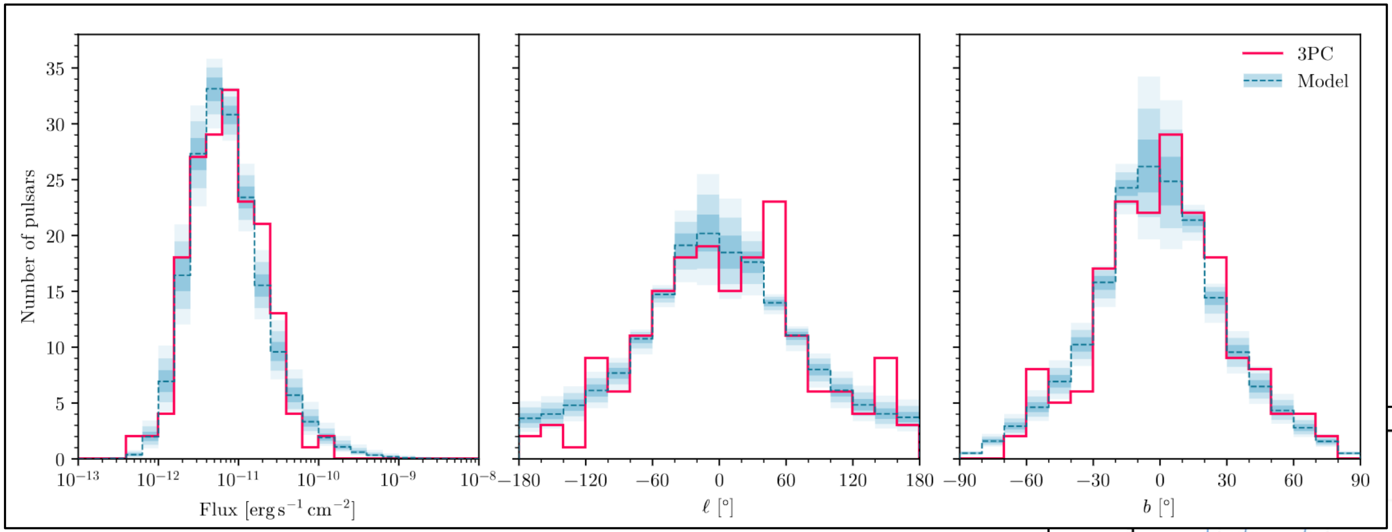
**The Third *Fermi* Large Area Telescope Catalog of Gamma-ray Pulsars**

FERMI-LAT COLLABORATION

Holst, DH, arXiv:2403.00978

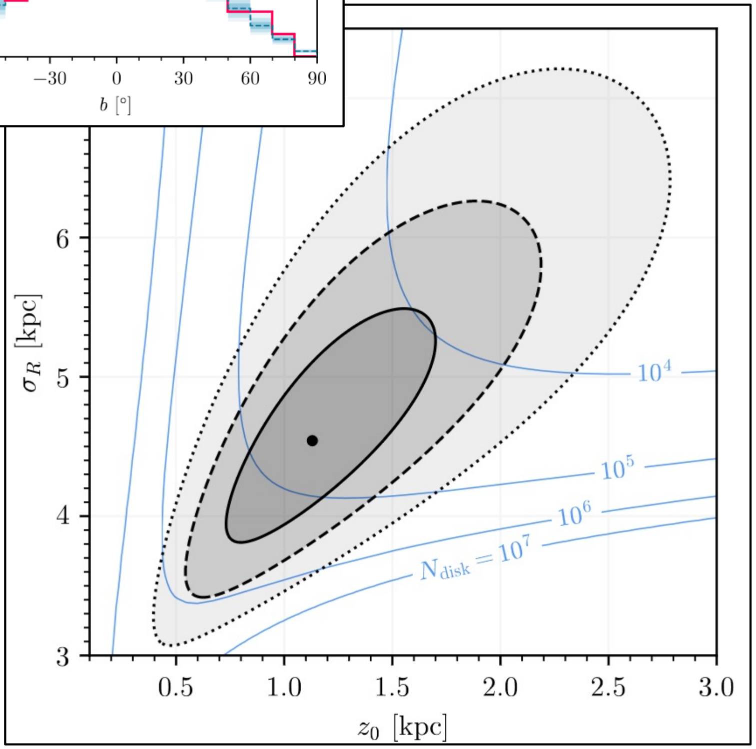
# Why Don't We See More Pulsars in the Inner Galaxy?

- Our results fit the the 3PC catalog data quite well




- The spatial distributions favored by our analysis are consistent with expectations from radio data

$$n_{\rm MSP} \propto e^{-|z|/z_0}\, e^{-r^2/2\sigma_R^2}$$




Holst, DH, arXiv:2403.00978

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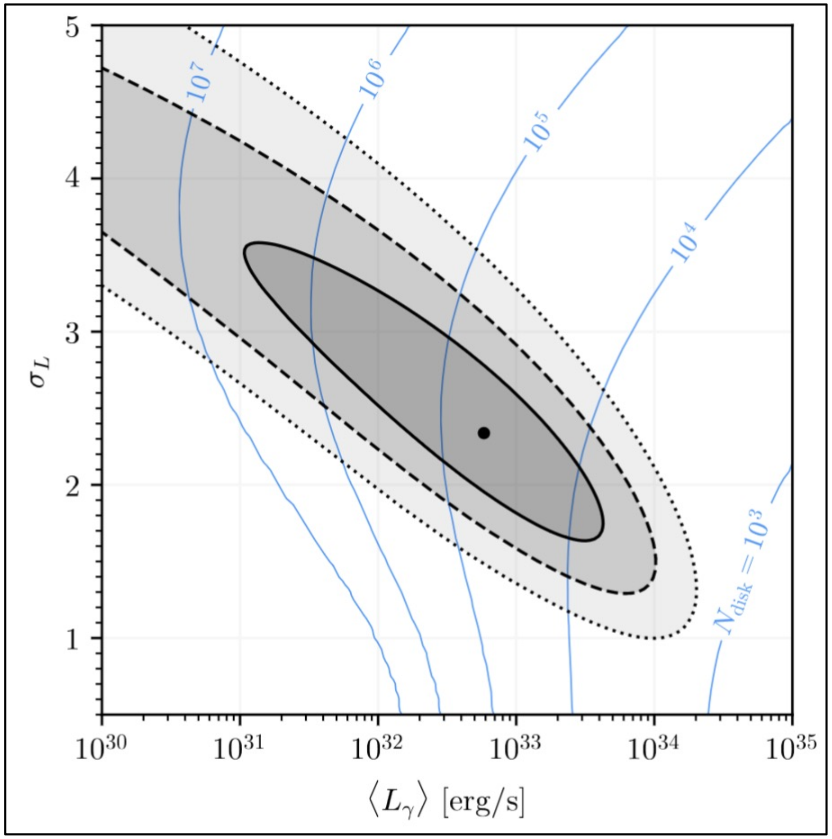
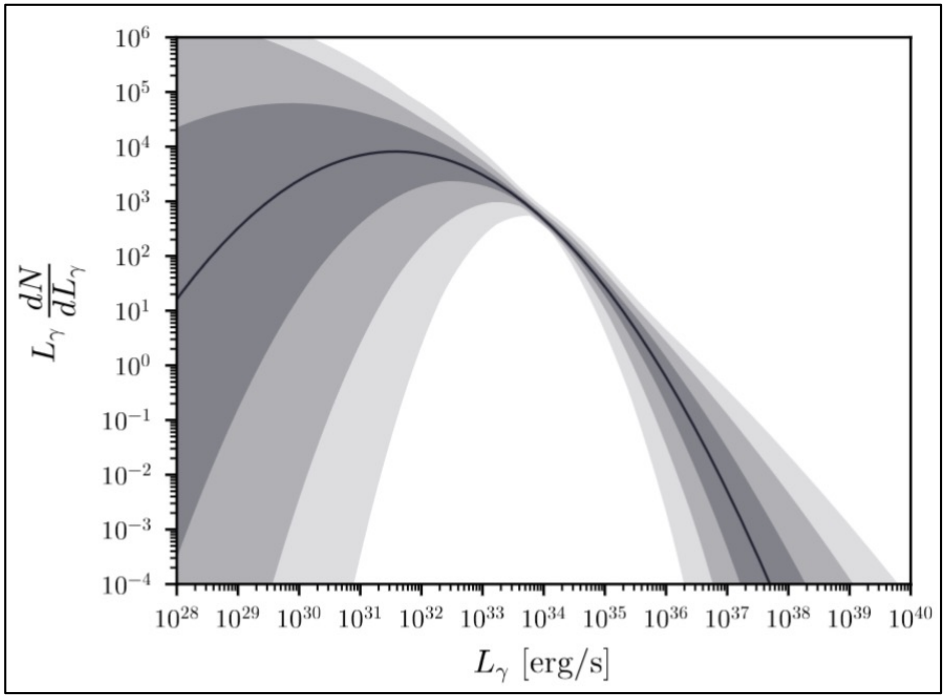
- The gamma-ray luminosity function favored by our analysis peaks at around $\mathrm{L}_\gamma \sim 10^{31} - 10^{32}$ erg/s and requires a total of $N_{Disk} \sim 10^5$ MSPs in the Milky Way's Disk



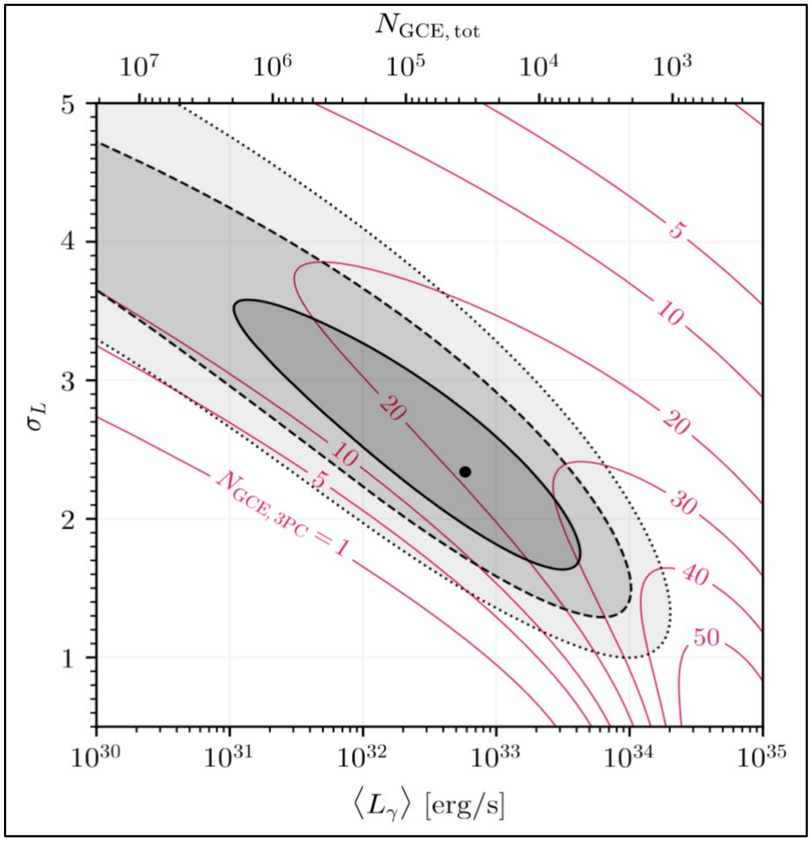




$$\frac{dN}{dL_\gamma} \propto \frac{1}{L_\gamma} \exp\left( - \frac{(\ln L_\gamma - \ln L_0)^2}{2\sigma_L^2} \right)$$

Holst, DH, arXiv:2403.00978

# Why Don't We See More Pulsars in the Inner Galaxy?

- We then used our determination of the MSP luminosity function to estimate how many pulsars Fermi should have already detected in the Inner Galaxy, assuming that pulsars are responsible for the Galactic Center excess
- If the gamma-ray excess is produced by pulsars with this same luminosity function, then Fermi should have already detected ~20 pulsars in the Inner Galaxy (instead of only 3)




(See also Dinsmore & Slatyer, 2112.09699; List, et al., 2107.09070; Mishra-Sharma & Cranmer, 2110.06931; Zhong, et al., 1911.12369)

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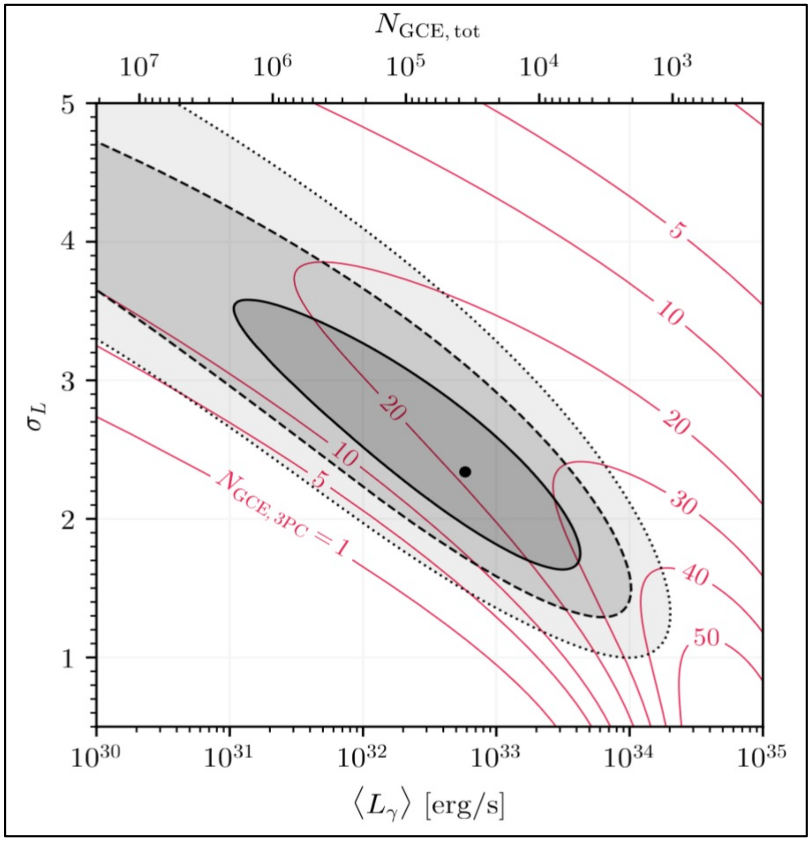
# Why Don't We See More Pulsars in the Inner Galaxy?

- We then used our determination of the MSP luminosity function to estimate how many pulsars Fermi should have already detected in the Inner Galaxy, assuming that pulsars are responsible for the Galactic Center excess
- If the gamma-ray excess is produced by pulsars with this same luminosity function, then Fermi should have already detected ~20 pulsars in the Inner Galaxy (instead of only 3)




One of the following must be true:

- Pulsars produce less than 39% of the gamma-ray excess
- The MSPs in the Inner Galaxy are at least ~5 times less luminous than pulsars in the Galactic Disk

(the later option would require >200,000 MSPs in the Inner Galaxy)

Holst, DH, arXiv:2403.00978

(See also Dinsmore & Slatyer, 2112.09699; List, et al., 2107.09070; Mishra-Sharma & Cranmer, 2110.06931; Zhong, et al., 1911.12369)

# Why Don't We See More Low-Mass X-Ray Binaries?

- Millisecond pulsars are formed when they are spun up by a binary companion; the precursors to MSPs are low-mass X-ray binaries (LMXBs)
- By measuring the ratio of the gamma-ray emission (from MSPs) to the number of bright LMXBs in globular clusters, and comparing this to the number of bright LMXBs in the Inner Galaxy, we can estimate the number of MSPs in the Inner Galaxy

Measure

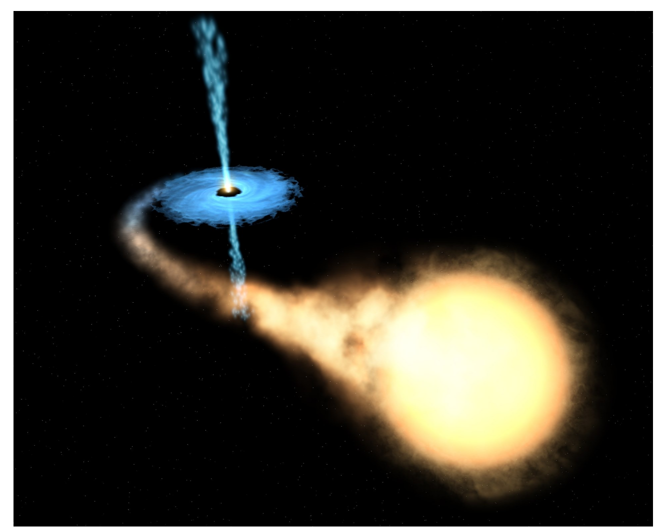
Infer

$$\frac{F_\gamma}{N_{\mathrm{LMXB}}}\Big|_{\text{Globular Clusters}} = \frac{F_\gamma}{N_{\mathrm{LMXB}}}\Big|_{\text{Inner Galaxy}}$$

Measure

Measure

- This procedure finds that only 4-11% of the gamma-ray excess is attributable to MSPs
- If the entire excess was from MSPs, INTEGRAL should have detected ~$10^3$ LMXBs in the Inner Galaxy; they actually detected 42



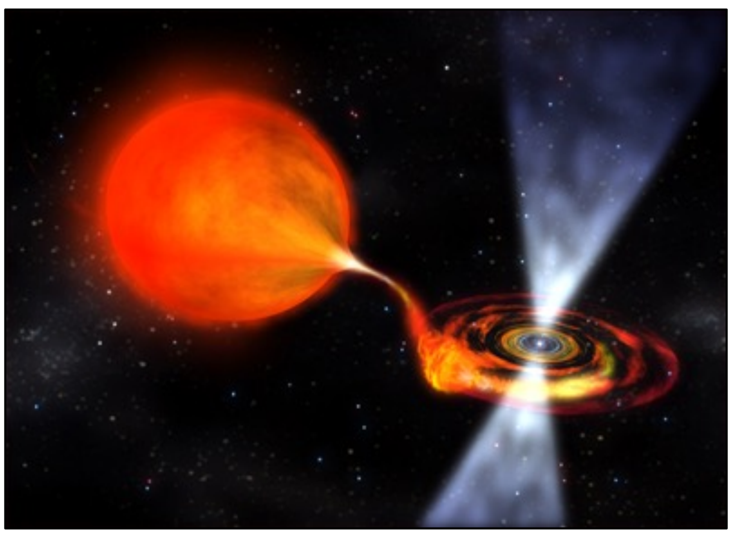
Haggard, Heinke, DH, Linden, arXiv:1701.02726
(see also Cholis, DH, Linden, arXiv:1407.5625)

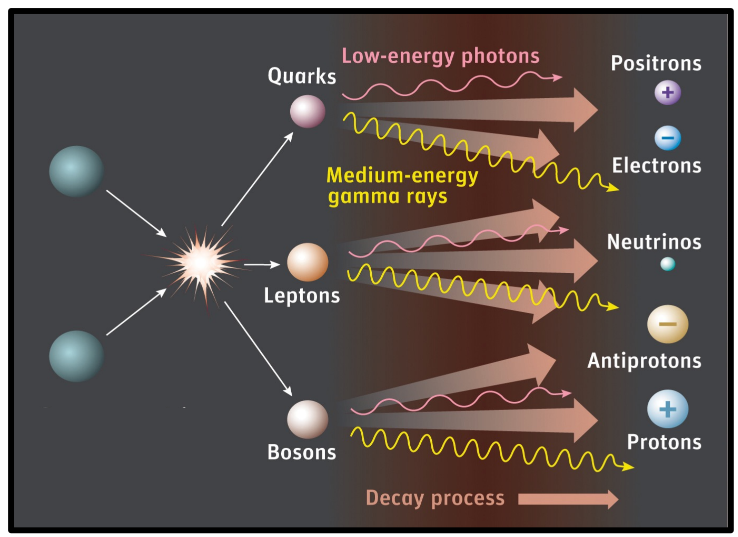
# What Produces the Galactic Center Excess?

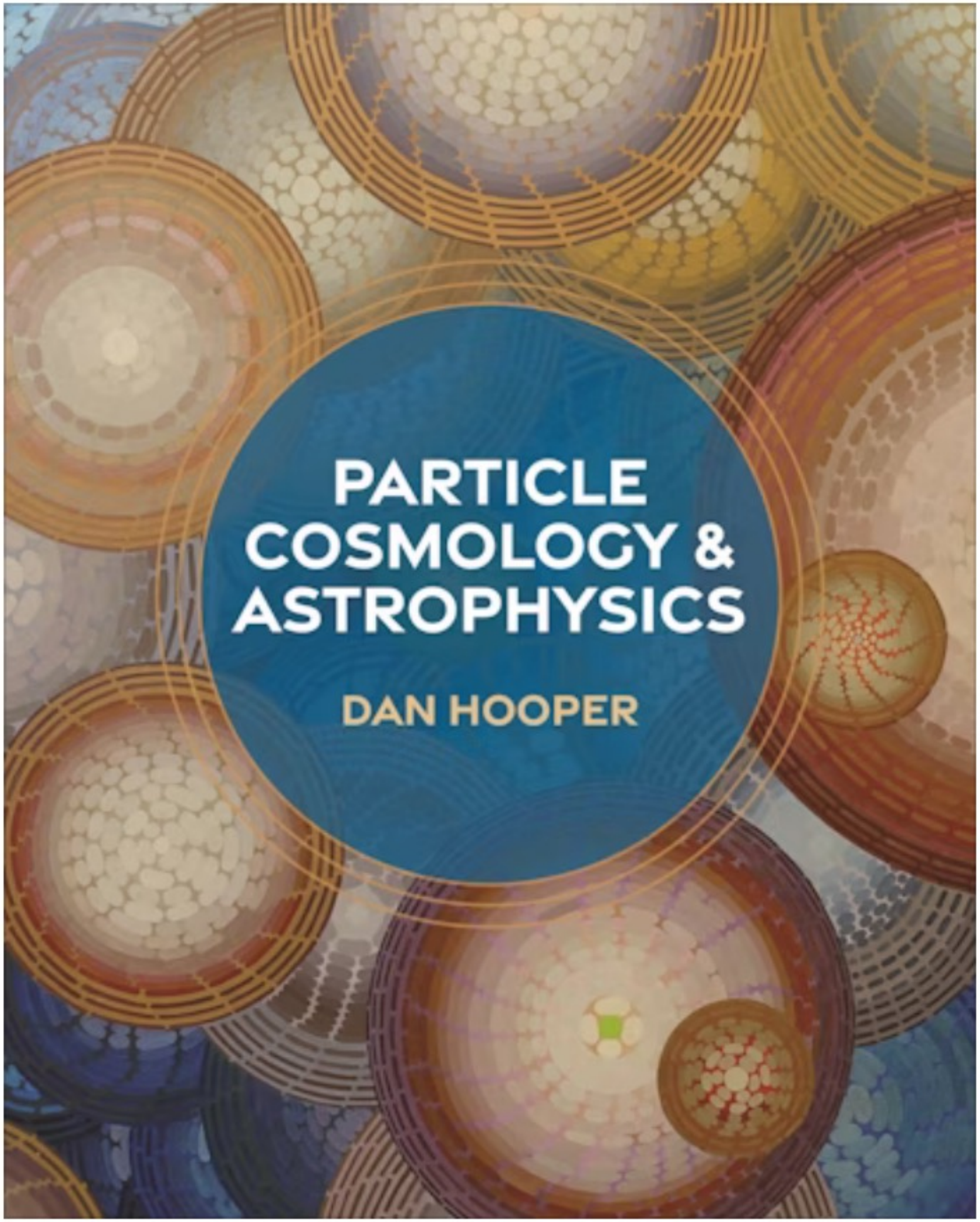
Bottom Line:

The measured spectrum, morphology, and intensity of the Galactic Center Gamma-Ray Excess each agree well with the predictions of annihilating dark matter in the form of a ~50 GeV thermal relic

The excess could be generated by pulsars, but this would require a very large and exotic population of low-luminosity millisecond pulsars, with few accompanying low-mass X-ray binaries



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