The Status of the Galactic Center Gamma-Ray Excess

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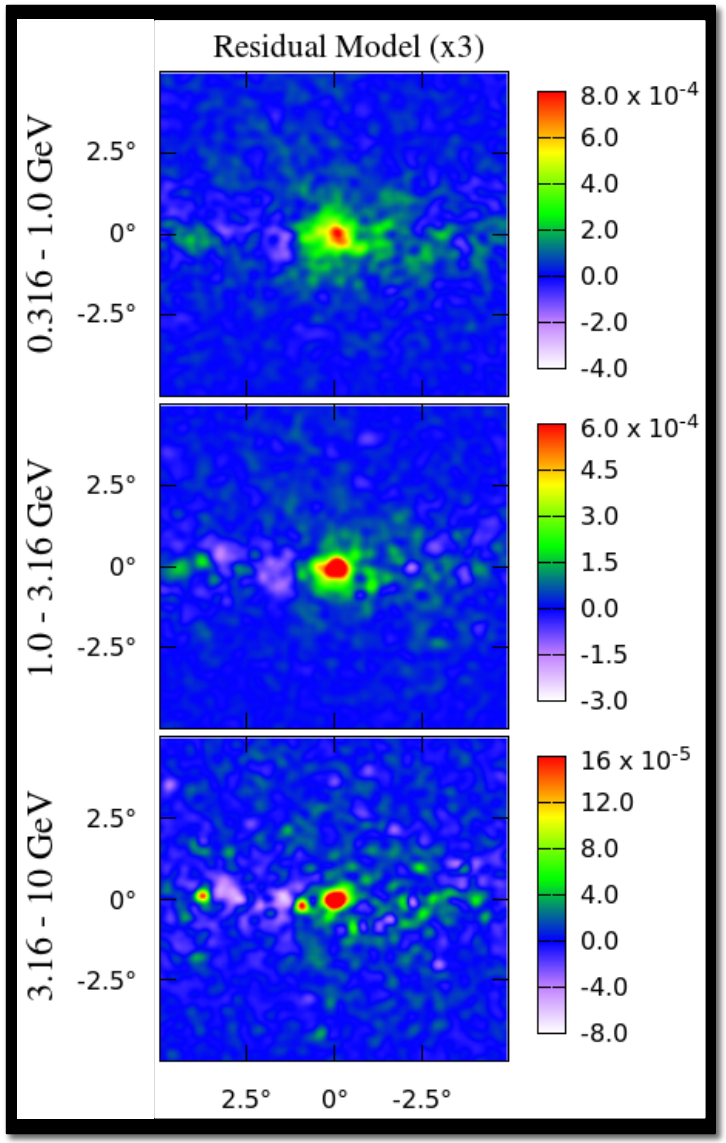
The Galactic Center Gamma-Ray Excess (aka the GeV Excess)

- Bright and highly statistically significant – the existence of this signal is not in dispute
- It has been difficult to explain this signal with known astrophysical sources or mechanisms
- The observed characteristics of this signal are consistent with those long predicted from annihilating dark matter



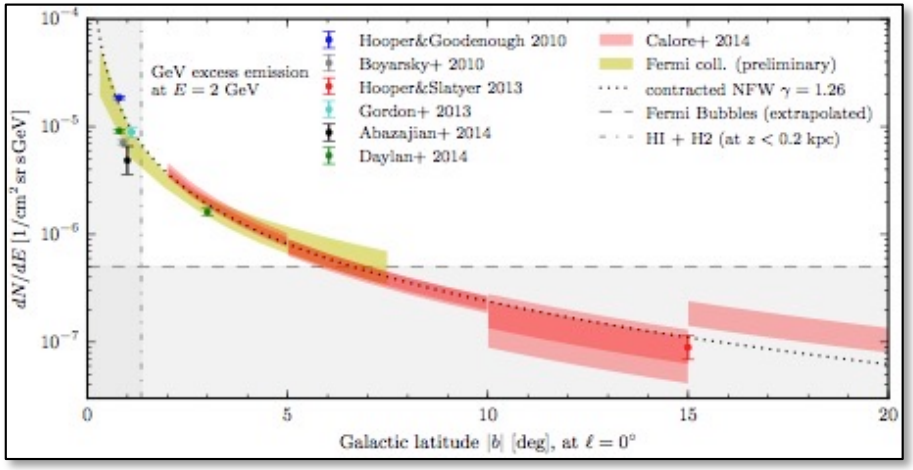
Fermi

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)

The Galactic Center Gamma-Ray Excess

Morphology

- Approximate spherical symmetry about the Galactic Center, with a flux that falls as ~$r^{-2.4}$ out to at least ~15-20°
- If from annihilating dark matter, this implies $\rho_{DM} \sim r^{-1.2}$ out to ~2-3 kpc, in good agreement with simulations

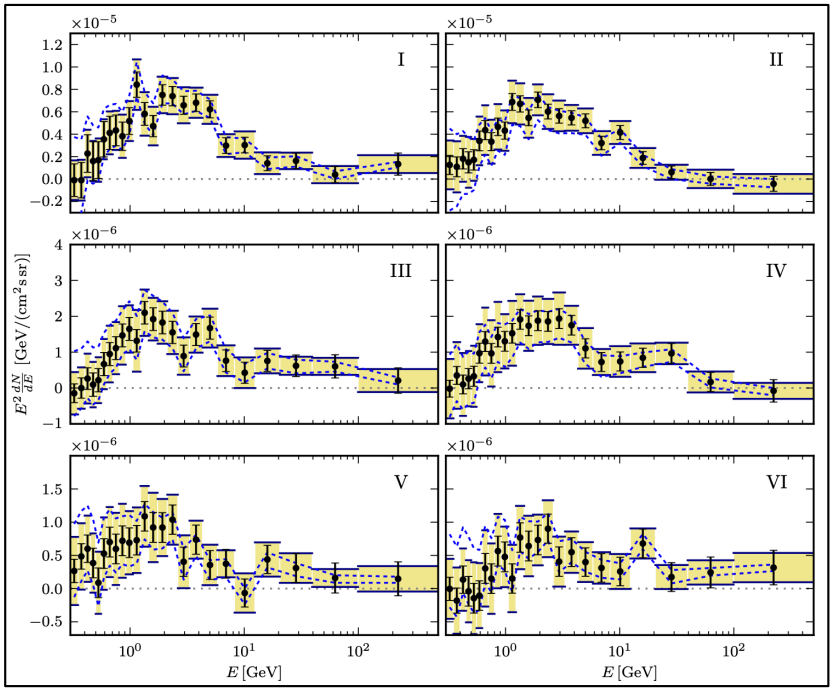


Spectrum

- Well fit by a ~40-60 GeV particle annihilating to quarks or gluons
- Uniform across the Inner Galaxy

Intensity

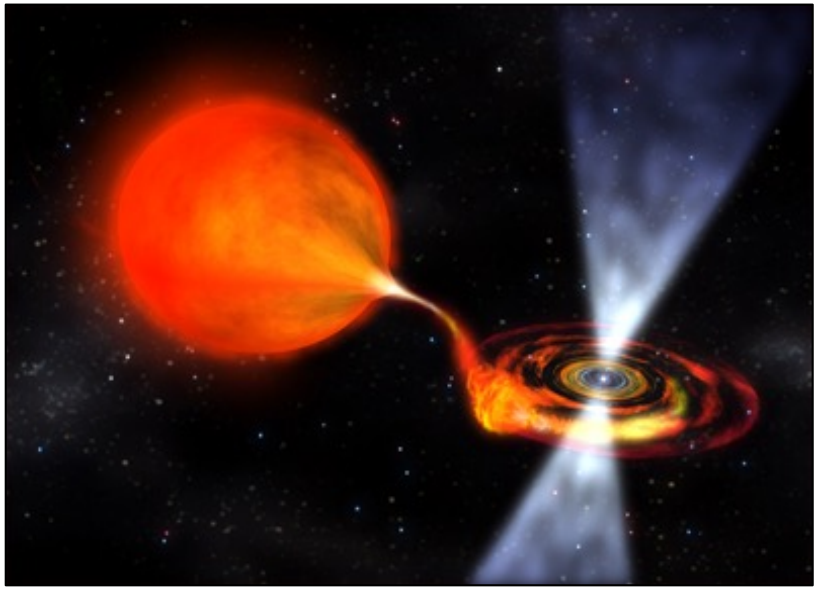
- To normalize the observed excess, the DM particles must annihilate with $\sigma v \sim 10^{-26}$ cm^3/s, approximately equal to the value required to obtain the measured DM abundance

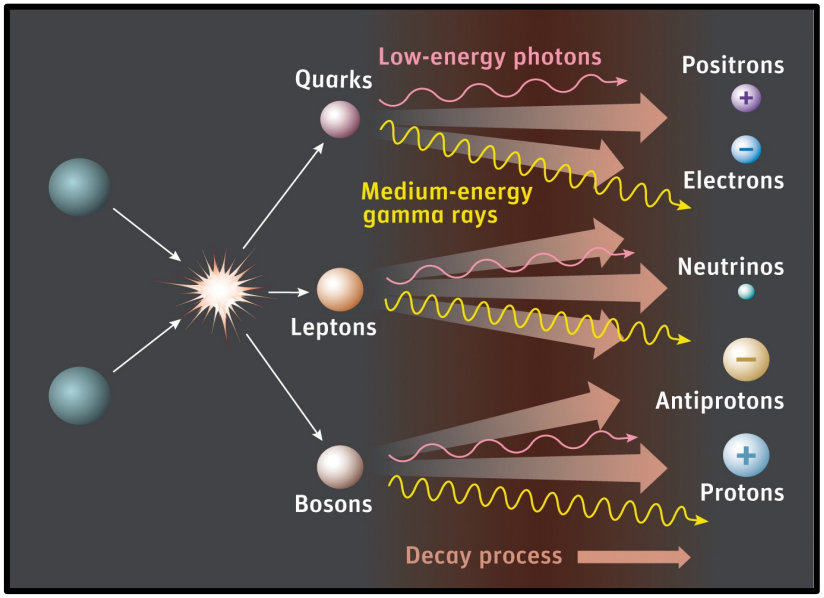


Cholis, Zhong, McDermott, Surdutovich (2021), Calore, Cholis, Weniger (2014)

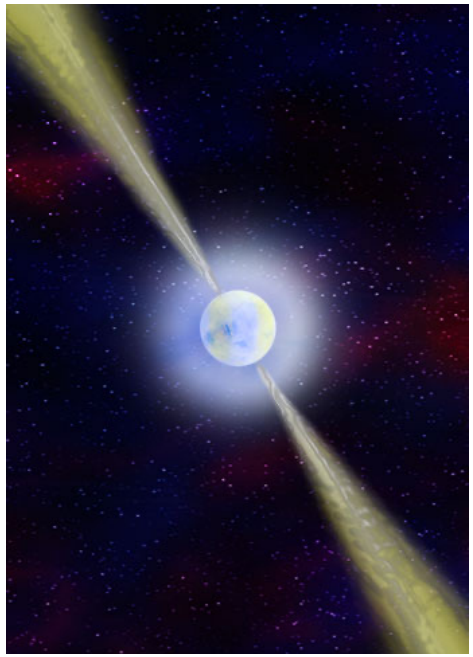
What Produces the Excess?

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





Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



Arguments in Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- Claims of small-scale power in the gamma-ray emission from the Inner Galaxy
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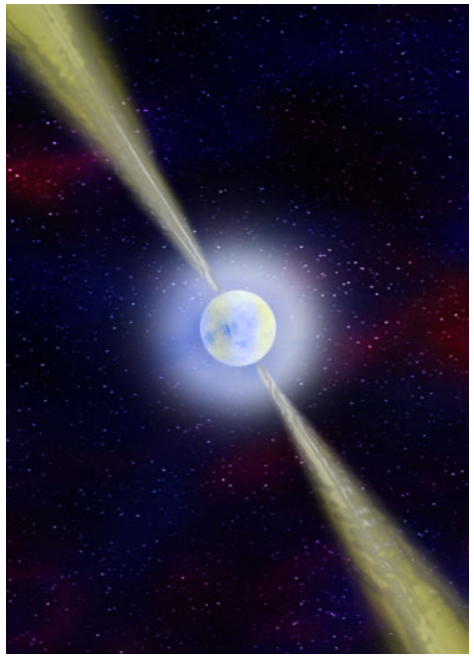

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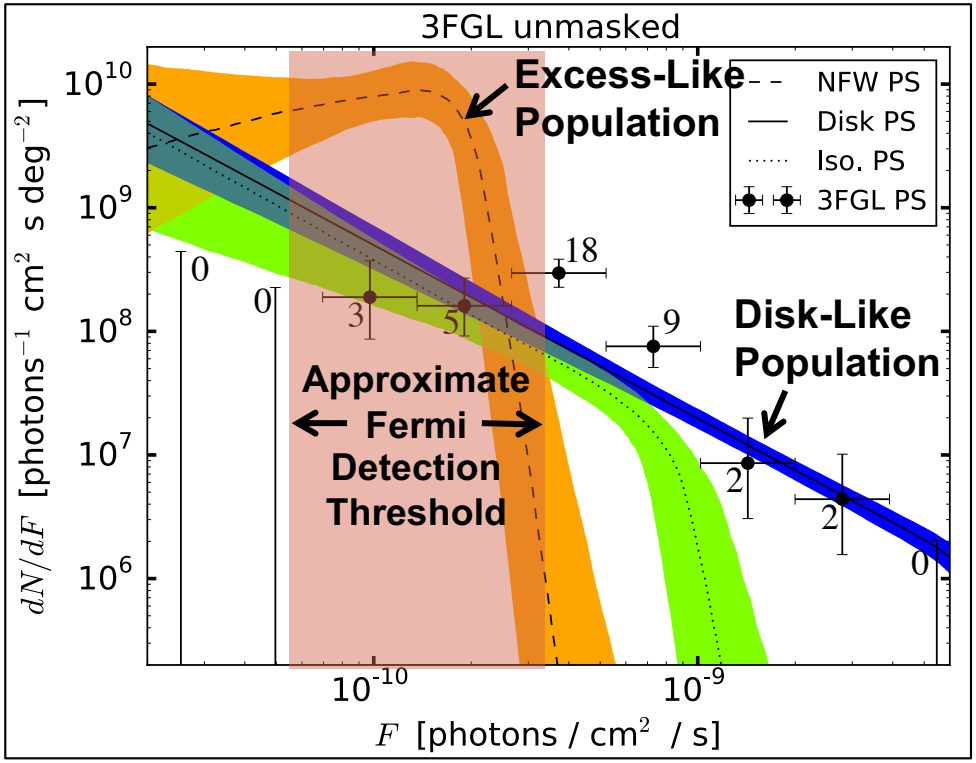
Evidence of Unresolved Gamma-Ray Sources?

- In 2015, two groups found that the ~GeV photons from the direction of the Inner Galaxy are more clustered than predicted from smooth backgrounds, suggesting that the GeV excess might be generated by a population of unresolved point sources
- Lee et al. used a non-Poissonian template technique to show that the gamma ray distribution near the Galactic Center is *clumpy*, potentially indicating that the GeV excess is being generated by ~10^3 unresolved point sources with fluxes near Fermi's detection threshold
- Bartels et al. reached a qualitatively similar conclusion employing a wavelet-based technique



Lee, Lisanti, Safdi, Slatyer & Xue
arXiv:1506.05124
Bartels, Krishnamurthy & Weniger
arXiv:1506.05104

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- It is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than are being modeled

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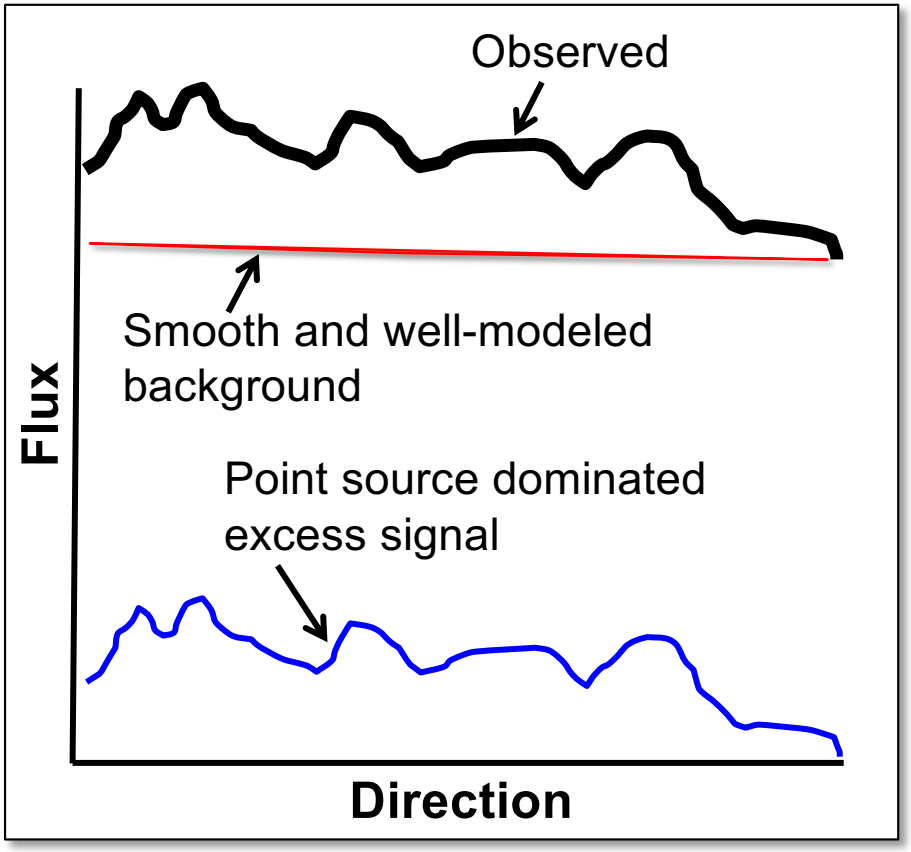

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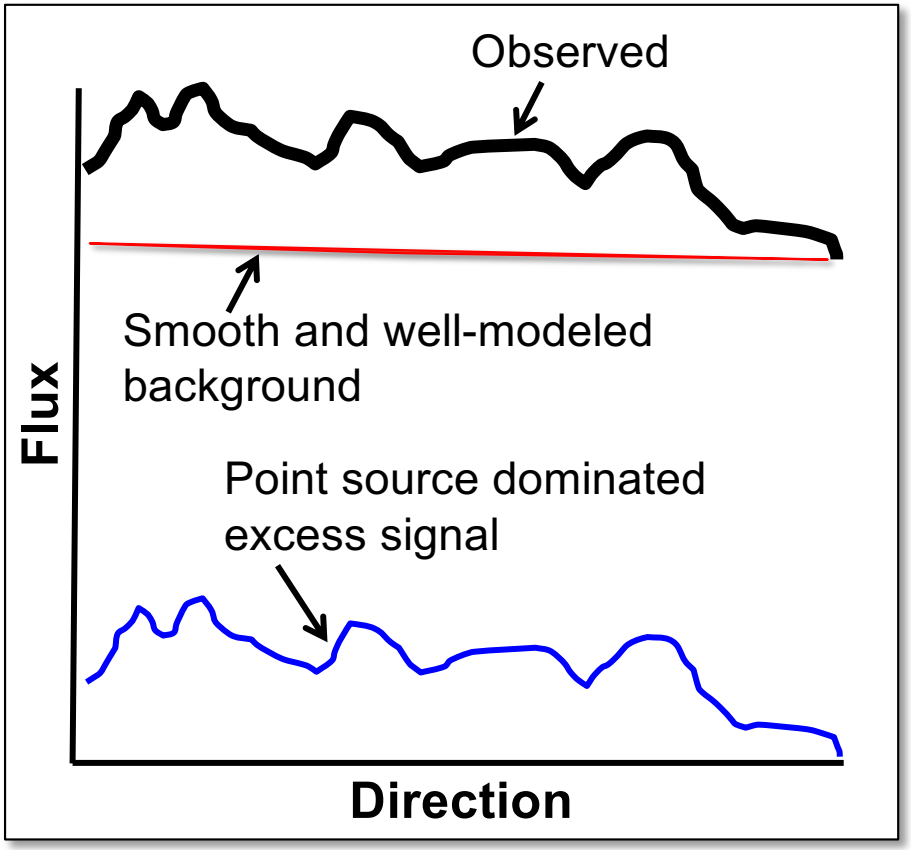
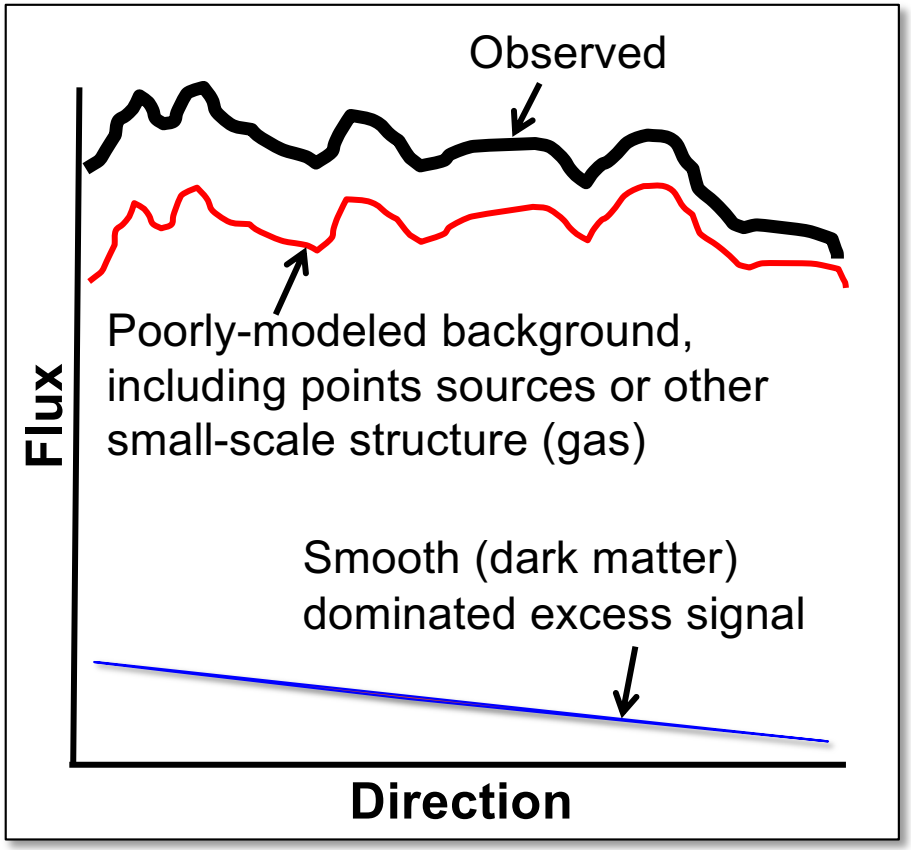




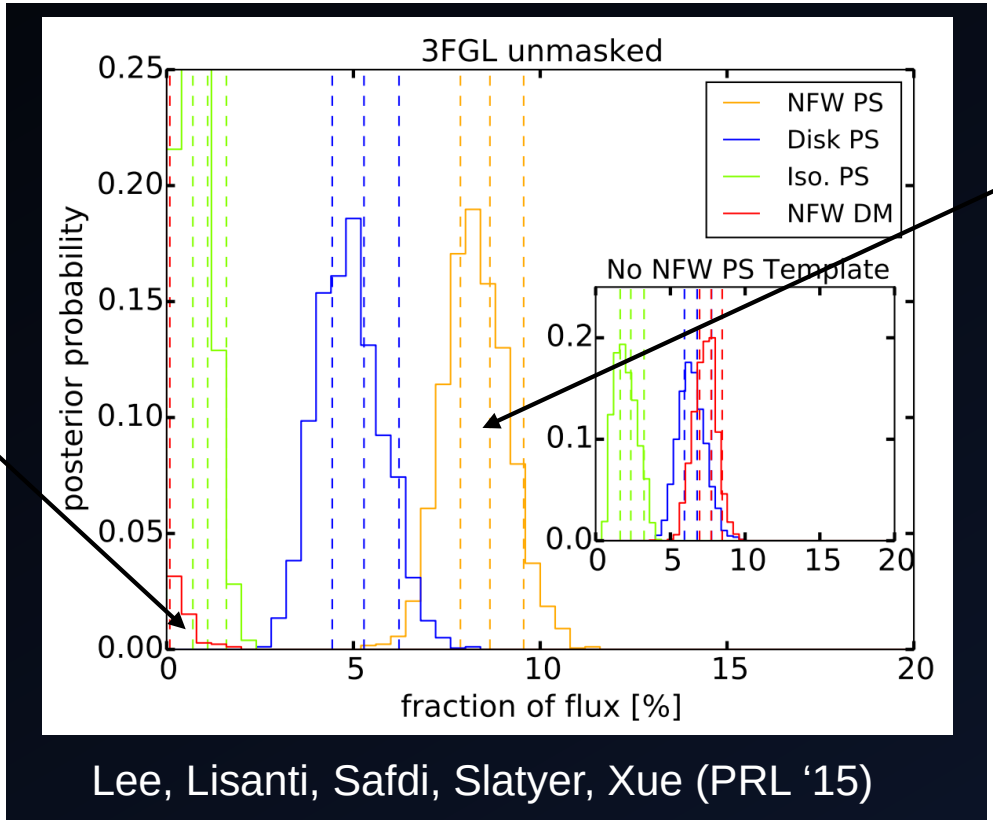
DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

Dark Matter Strikes Back at the Galactic Center

See Leane and Slatyer, arXiv:1904.08430

Evidence against any significant amount of dark matter annihilation



Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

Evidence for NFW^2 Distributed Point Sources

To what extent could inadequate templates be biasing these results?

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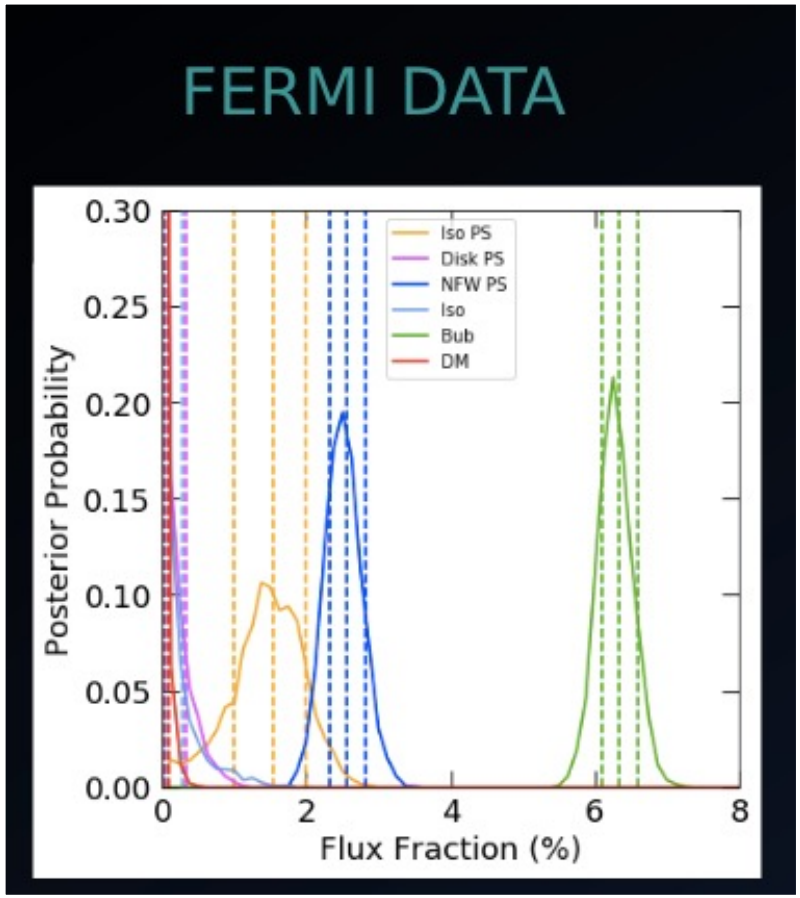
See Leane and Slatyer, arXiv:1904.08430

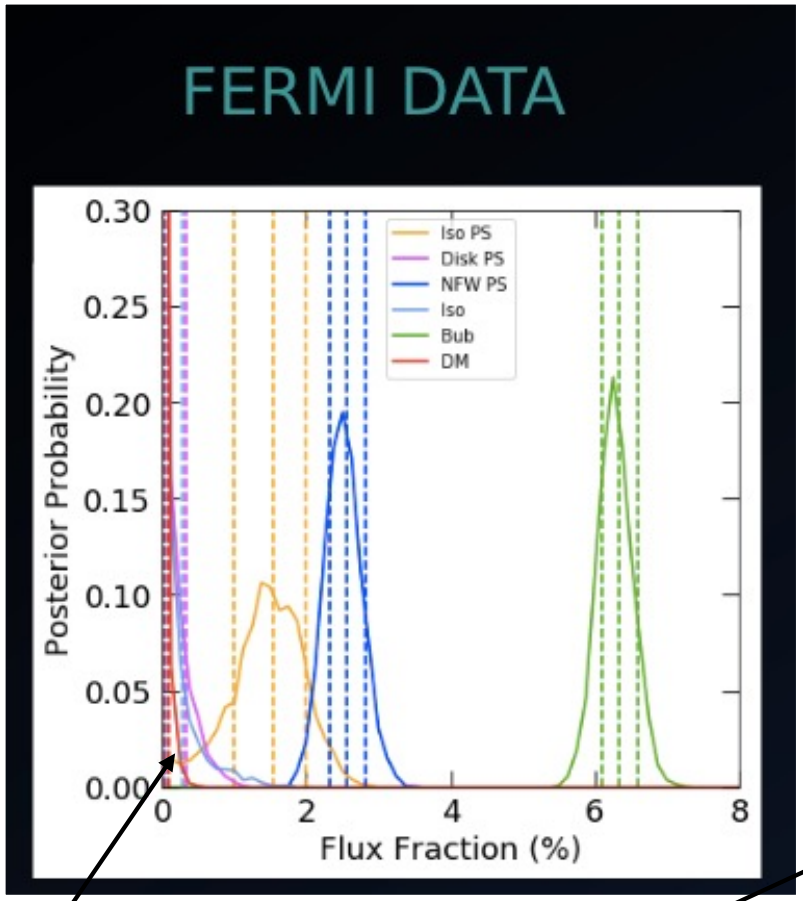


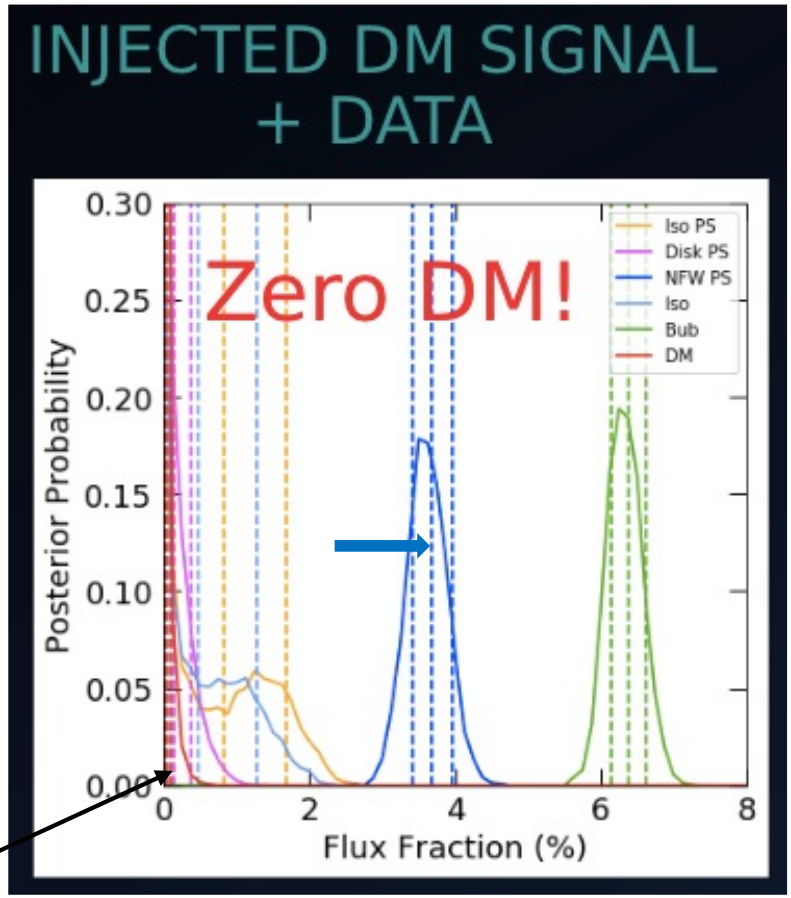
Here is the result that Leane and Slatyer obtain using the same procedure as Lee *et al.*

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

Dark Matter Strikes Back at the Galactic Center

See Leane and Slatyer, arXiv:1904.08430





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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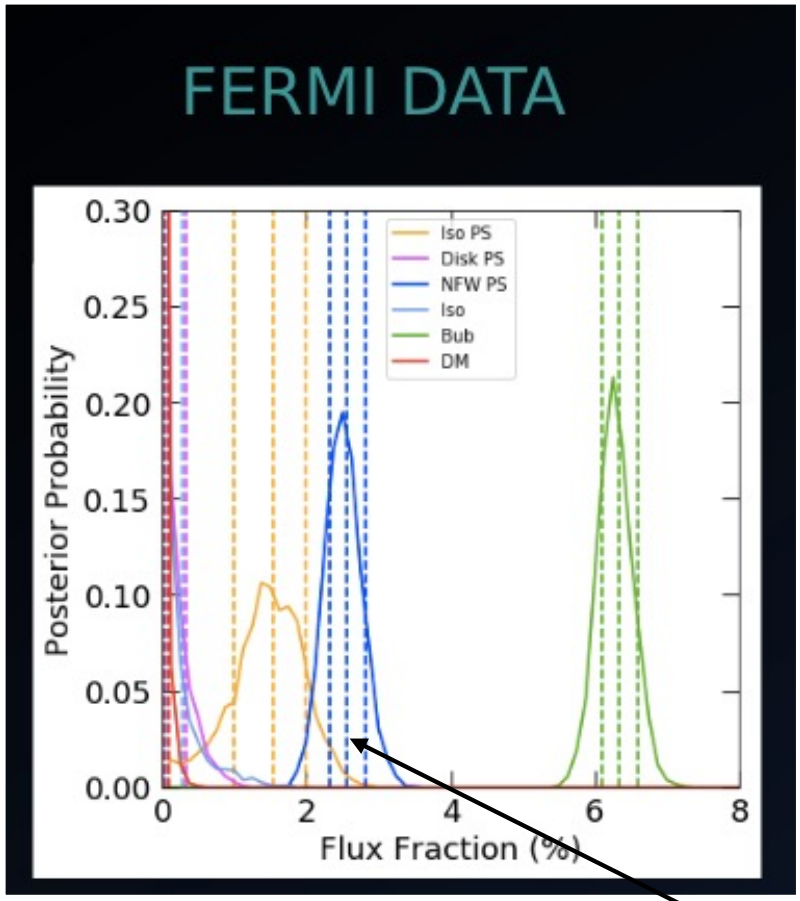
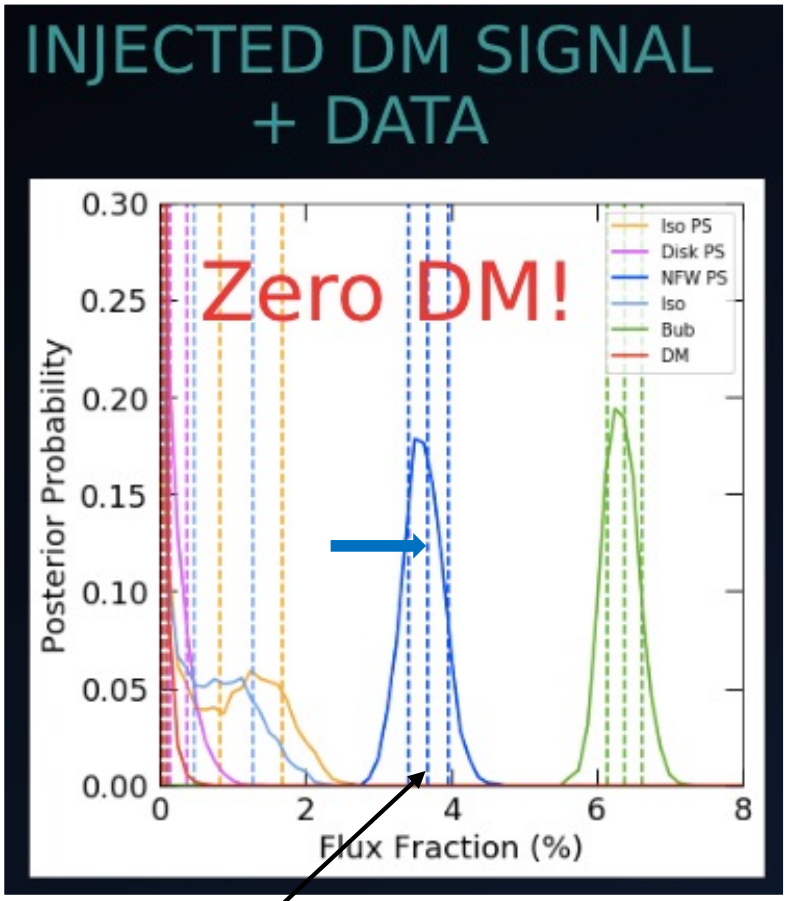




Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

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

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

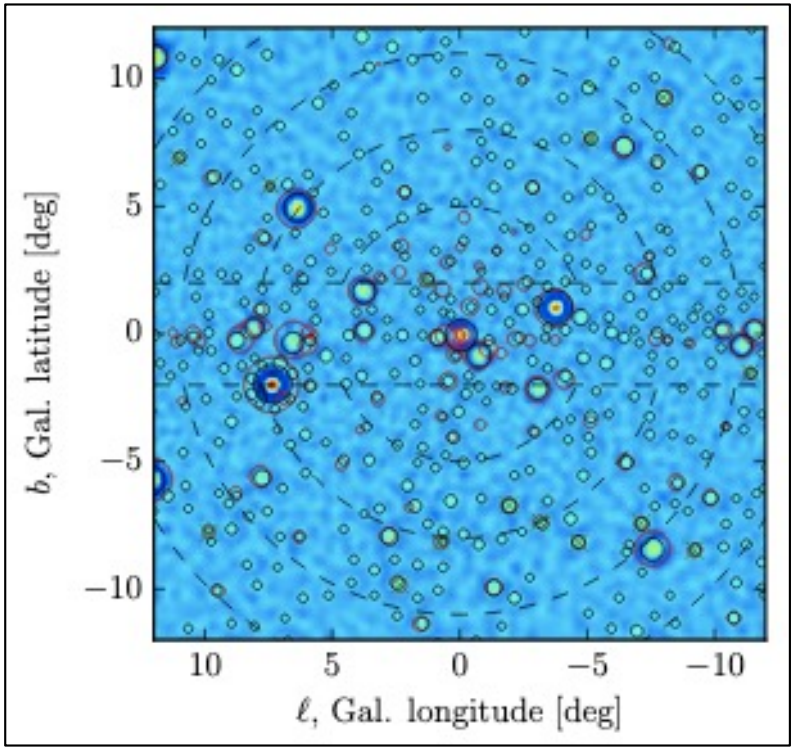
Bottom Line:

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 there is no evidence of this at this time

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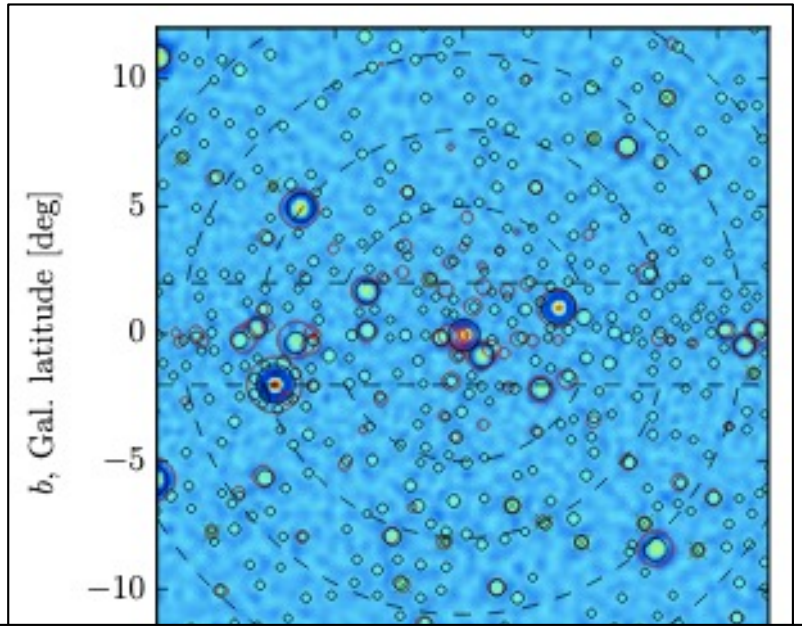
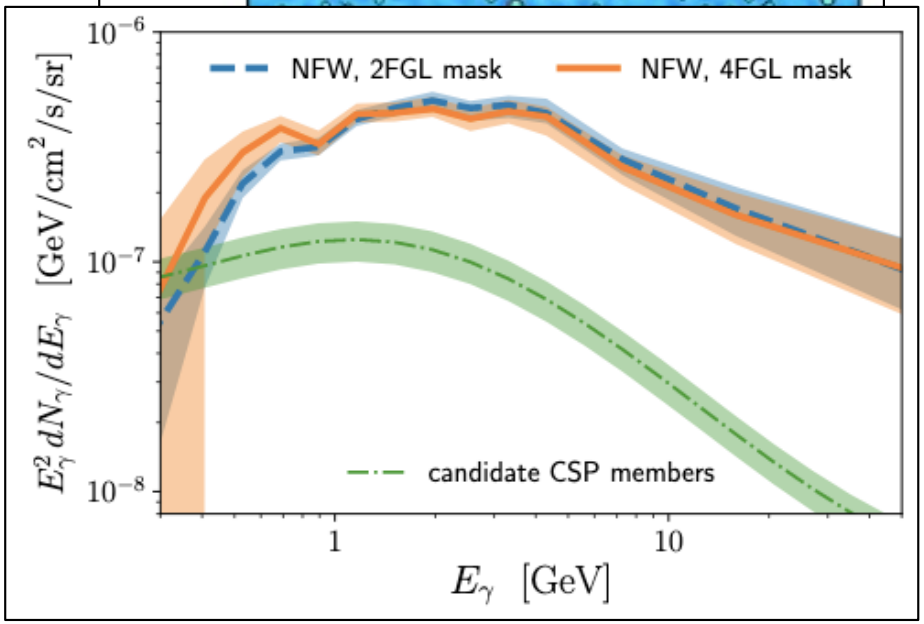
- Zhong, McDermott, Cholis, and Fox revisited this method, utilizing an updated gamma-ray source catalog (4FGL vs 3FGL)
- Using the 3FGL, Zhong *et al*. reproduced the results of Bartels *et al*.
- After accounting for the 4FGL sources, Zhong *et al*. find no evidence that the excess is produced by point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





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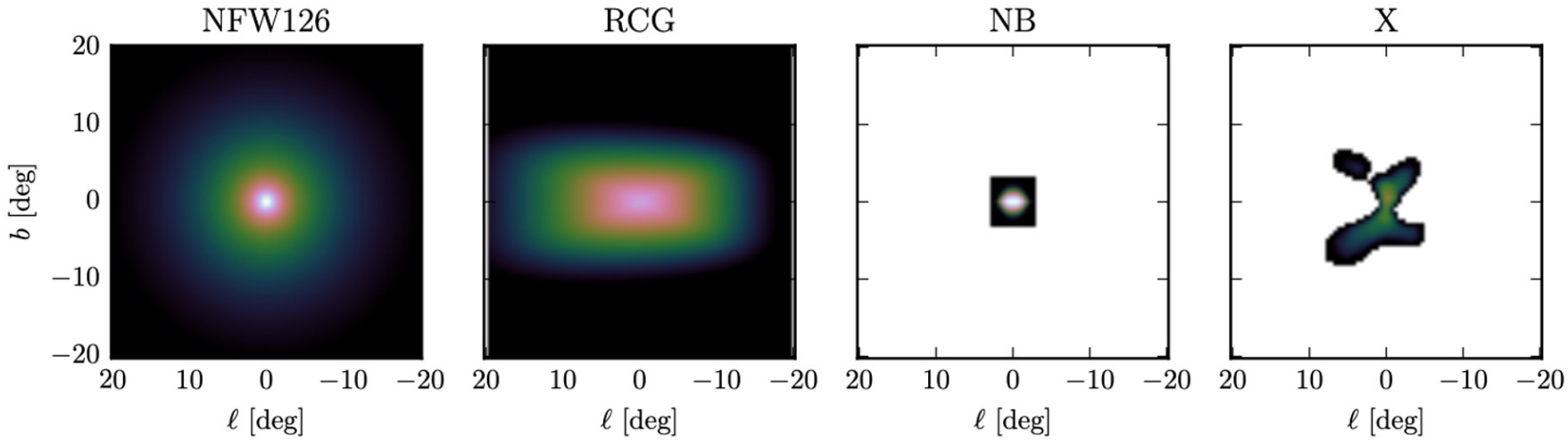
Bulge/Bar-Like vs DM-Like Morphology

- An important test of the GC excess' origin 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 the papers listed below, it was argued that the excess is better fit by spatial templates that trace stellar populations than by dark matter-like templates; if confirmed, this would favor MSP interpretations of the gamma-ray excess

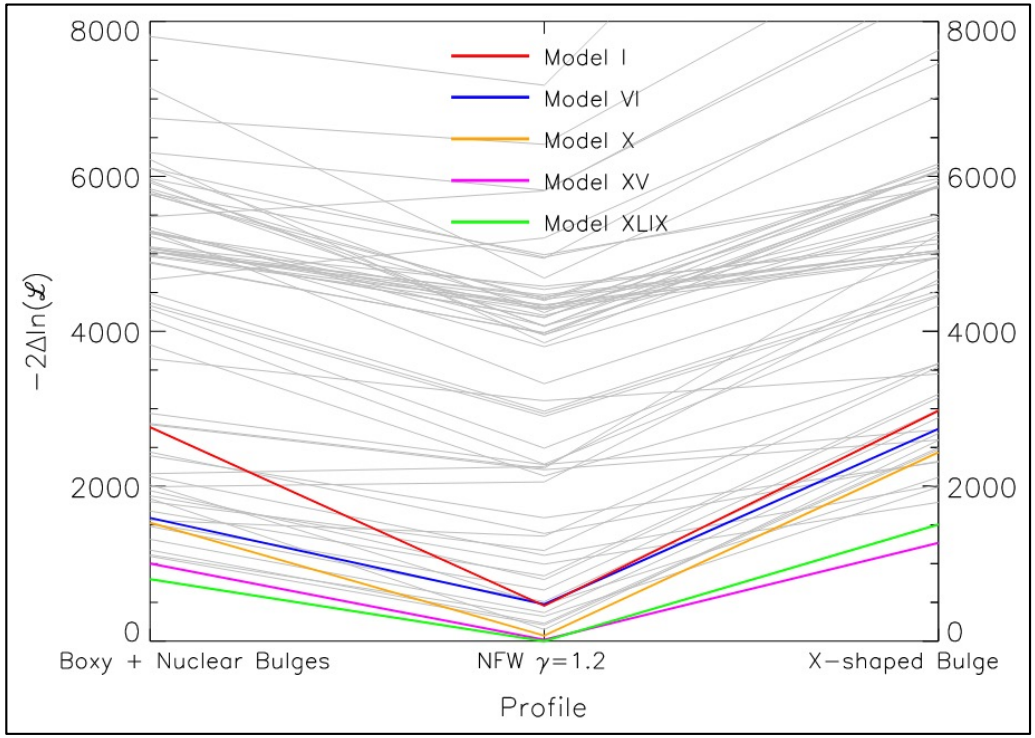
Macias, Gordan, Crocker, Coleman, Paterson, Horiuchi, Pohl, arXiv:1611.06644
Bartels, Storm, Weinger, Calore, arXiv:1711.04778
Macias, Horiuchi, Kaplinghat, Gordan, Crocker, Nataf, arXiv:1901.03822

Bulge/Bar-Like vs DM-Like Morphology

- More recent work has not confirmed these results, instead finding that dark matter-like templates are preferred
  (Cholis, Zhong, McDermott, 2112.09706; 2209.00006; Di Mauro, 2101.04694)
- What is going on here? Its not completely clear (at least to me)
- The differences, at least in part, seem to be related to the choice of astrophysical templates and bulge templates that are being considered

Bottom Line:

Different groups, making different (but seemingly reasonable) analysis choices, reach different conclusions regarding the detailed morphology of the Galactic Center Excess



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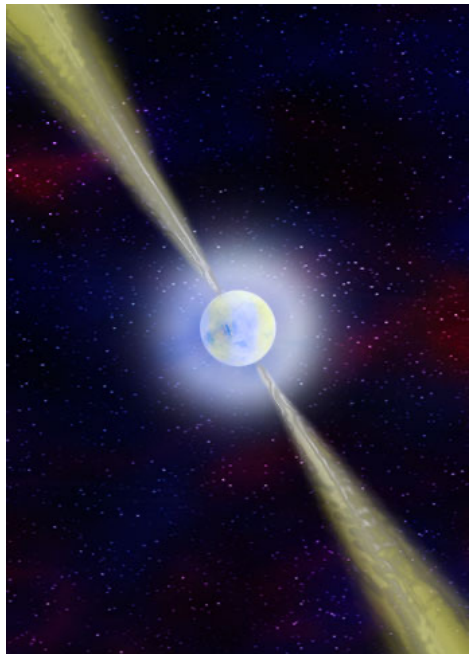

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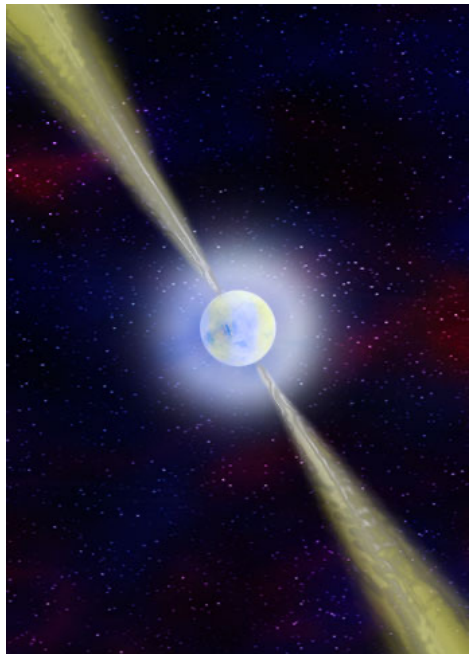

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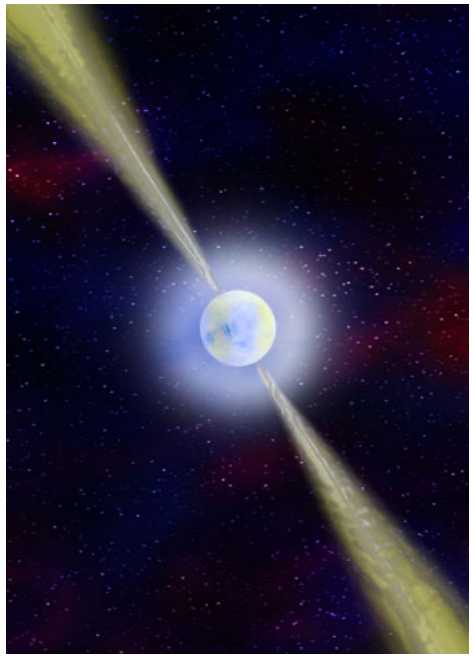

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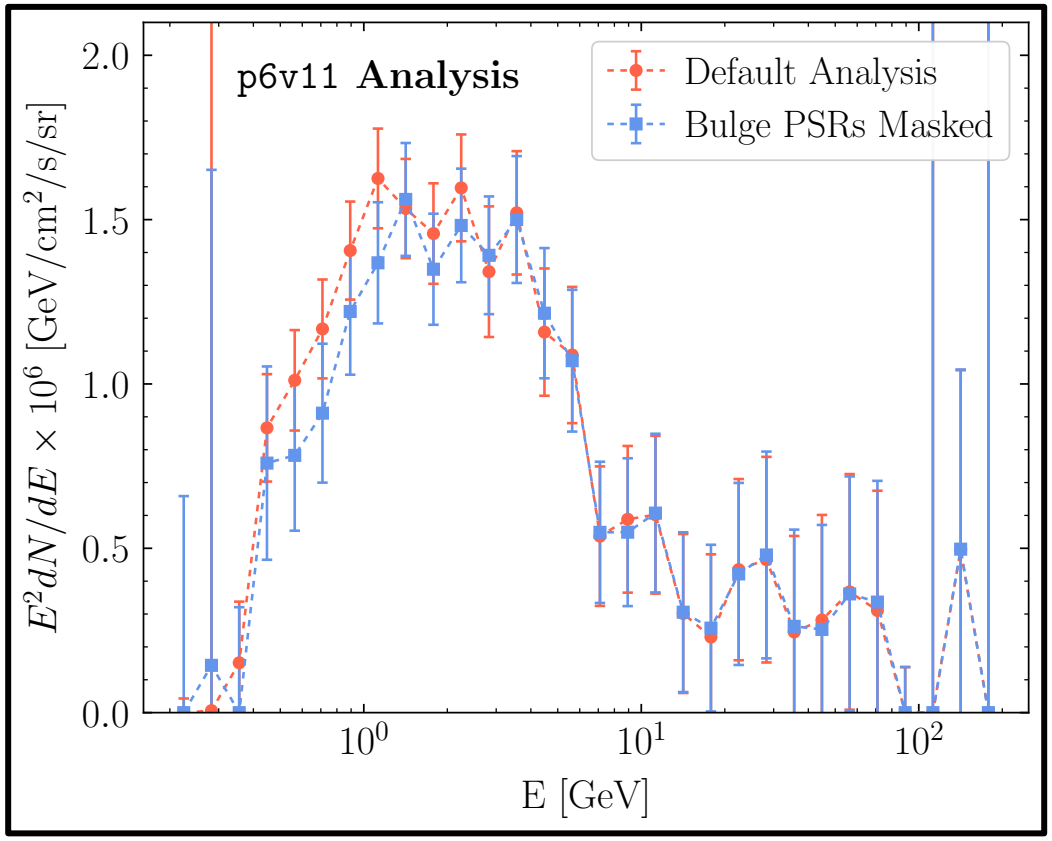
Arguments Against Pulsars:

- No millisecond pulsars have been detected in the Inner Galaxy, in tension with the measured luminosity function of gamma-ray pulsars
- The lack of low-mass X-ray binaries in the Inner Galaxy
- The relatively low luminosity of TeV-scale emission from the Inner Galaxy

Gamma-Ray Bright MSPs in The Inner Galaxy?

- To be clear, no millisecond pulsars have been detected in the Inner Galaxy
- Furthermore, known gamma-ray point sources do *not* appreciably contribute to the Galactic Center Excess; masking the pulsar candidate sources contained in various catalogs does *not* impact the characteristics of the excess



Bartels, DH, Linden, Mishra-Sharma, Rodd, Safdi, Slatyer, arXiv:1710.10266

Tension with Pulsar Interpretations

- Observed MSP populations (in the disk, globular clusters) have luminosity functions which peak near $L_\gamma \sim 10^{34}$ erg/s (in L^2dN/dL units)
- If the excess is produced by MPSs with a similar luminosity function, ~10^2 MSPs should have already been detected

Luminosity function	N_r	R_r	$N_{\rm GCE}$
Wavelet 1	31	0.11	8.5×10^6
Wavelet 2	98	0.38	2.2×10^5
GLC	124	0.72	670
GCE	20	0.059	3.5×10^4
AIC	12	0.039	3.6×10^5
NPTF	111	0.26	970
Disk	30	0.13	2.6×10^4

(a) Standard sensitivity model

Bottom Line:

As few as ~3×10^4 MSPs could potentially generate the GCE, but this would require a luminosity function that sharply peaks only slightly below Fermi's current point source threshold ($L_\gamma \sim 10^{32}$-10^{33} erg/s)

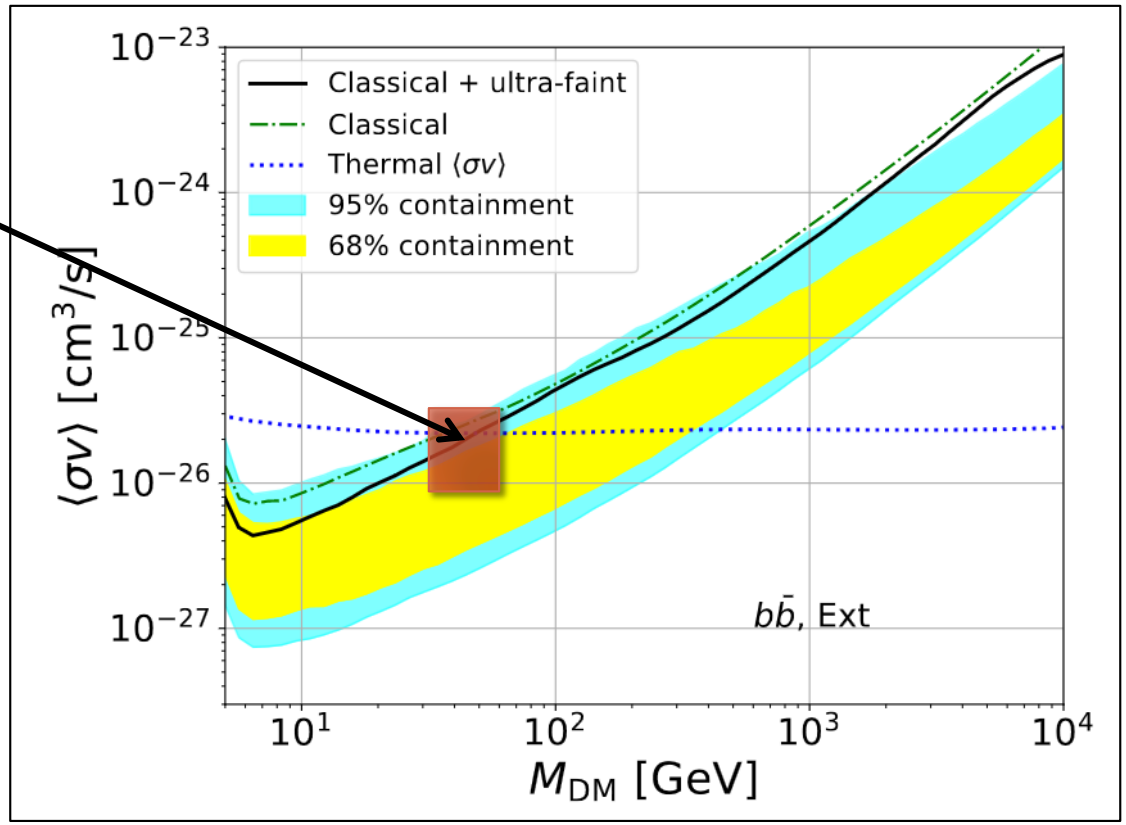
Zhong, McDermott, Cholis, Fox, arXiv:1911.12369; Dinsmore, Slatyer, arXiv:2112.09699; List, Rodd, Lewis, arXiv:2107.09070, Mishra-Sharma, Cranmer, arXiv:2110.06931

If the Galactic Center Excess is the result of annihilating dark matter, where else would we expect to see evidence of this process?

Fermi Observations of Dwarf Galaxies

- Current Fermi dwarf constraints are based on observations of several dozen dwarf galaxies, including many that were discovered by DES and other recent surveys
- Although these constraints are currently compatible with dark matter interpretations of the Galactic Center excess, even modest improvements in sensitivity would shed significant light on this interpretation

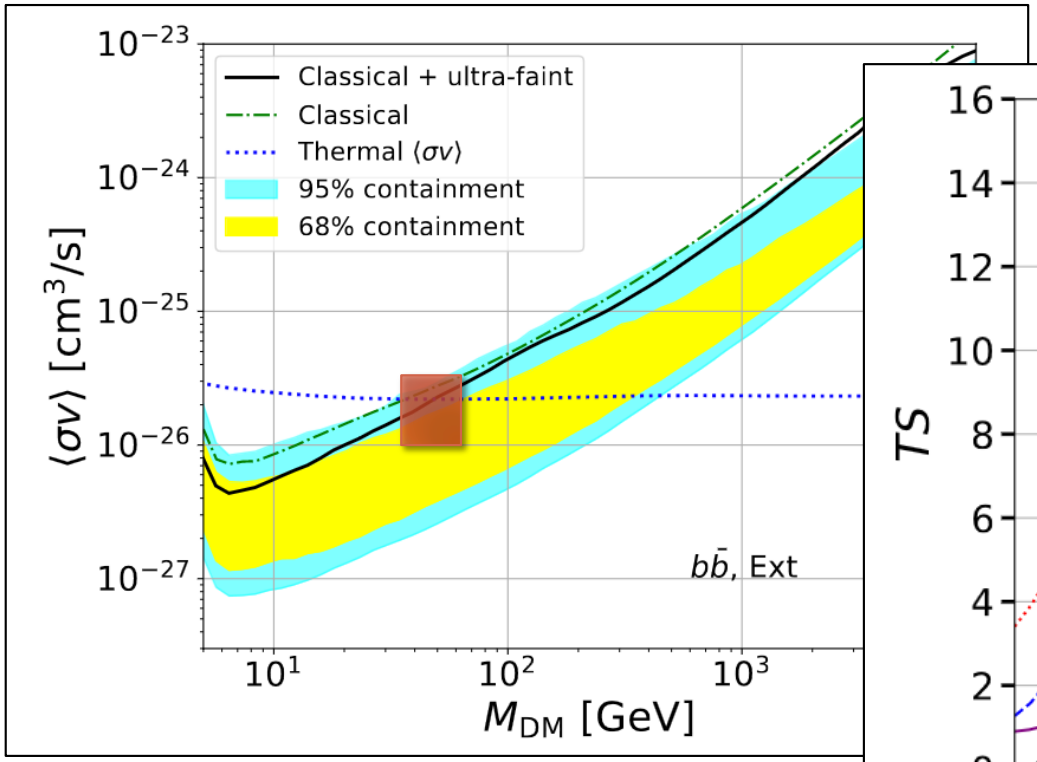
Region favored by the GCE



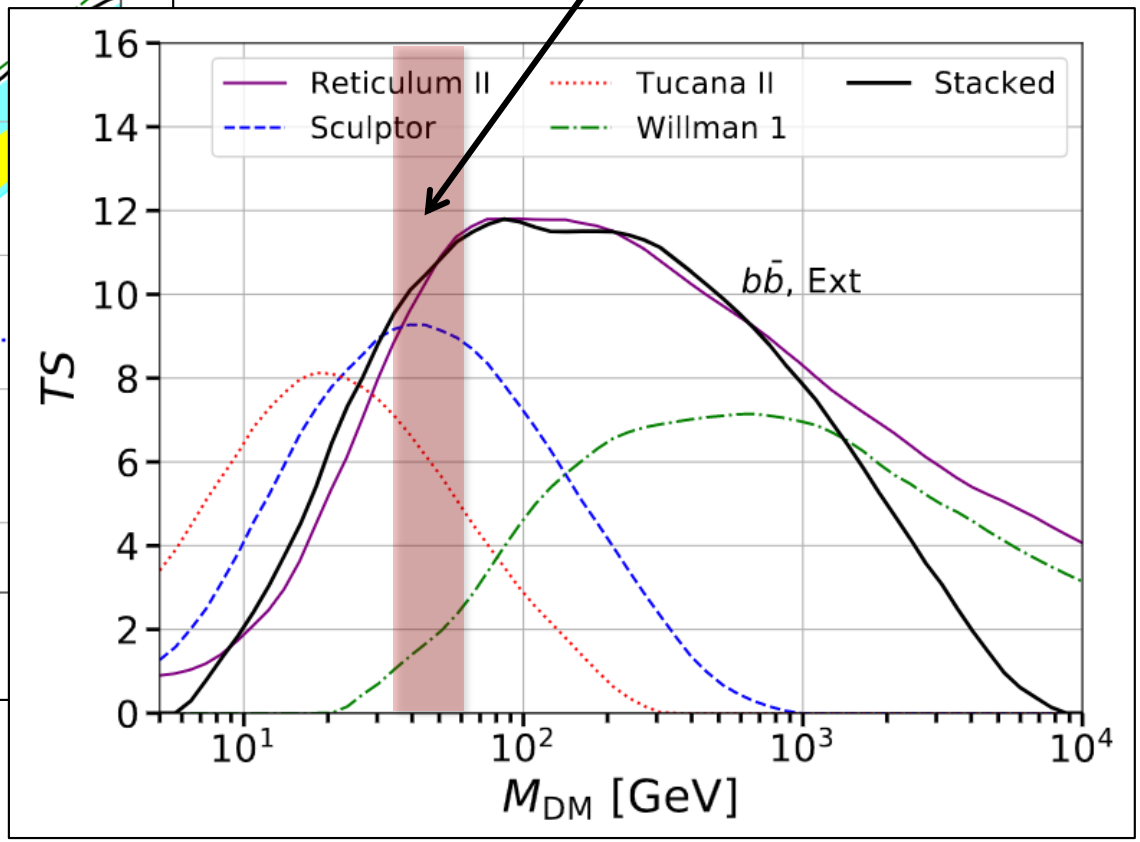
Di Mauro, Stref, Calore, arXiv:2212.06805 (see also, Fermi Collaboration, arXiv:1611.03184)

Fermi Observations of Dwarf Galaxies

- Small excesses have been observed from several dwarf galaxies (Reticulum II, Tucana II, Sculptor, and Willman 1)
- The combination of this data favors the presence of a GCE-like WIMP at a level of TS~10-12 (corresponding to a local significance of ~3σ)



GCE-Favored Region



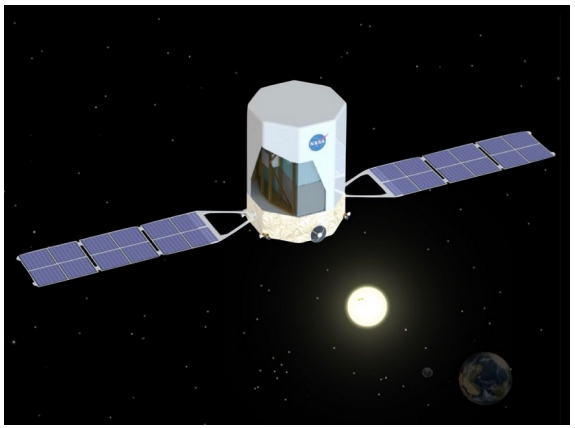
Di Mauro, Stref, Calore, arXiv:2212.06805

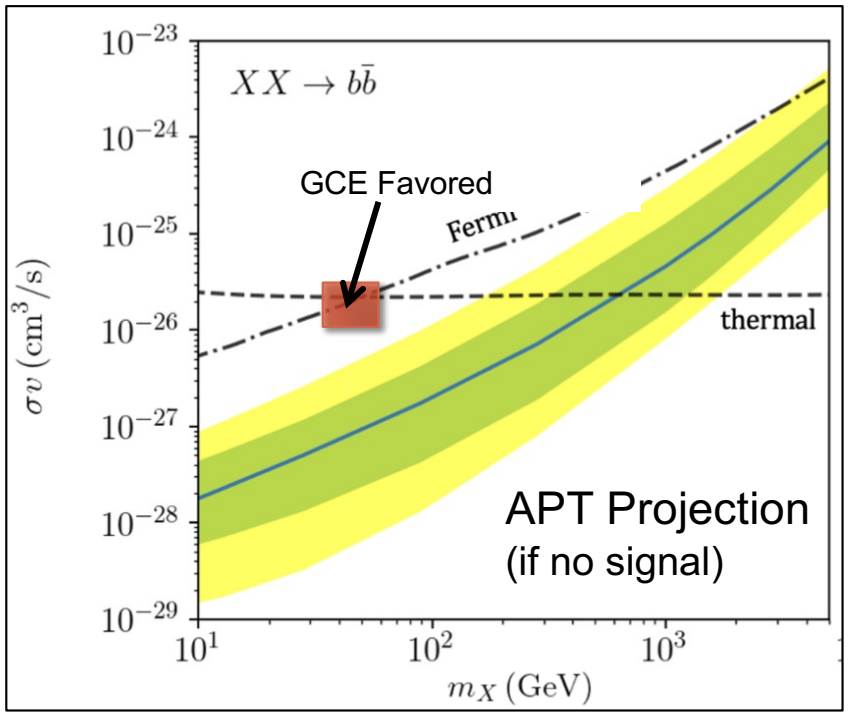
Dwarf Galaxies in the Rubin Era

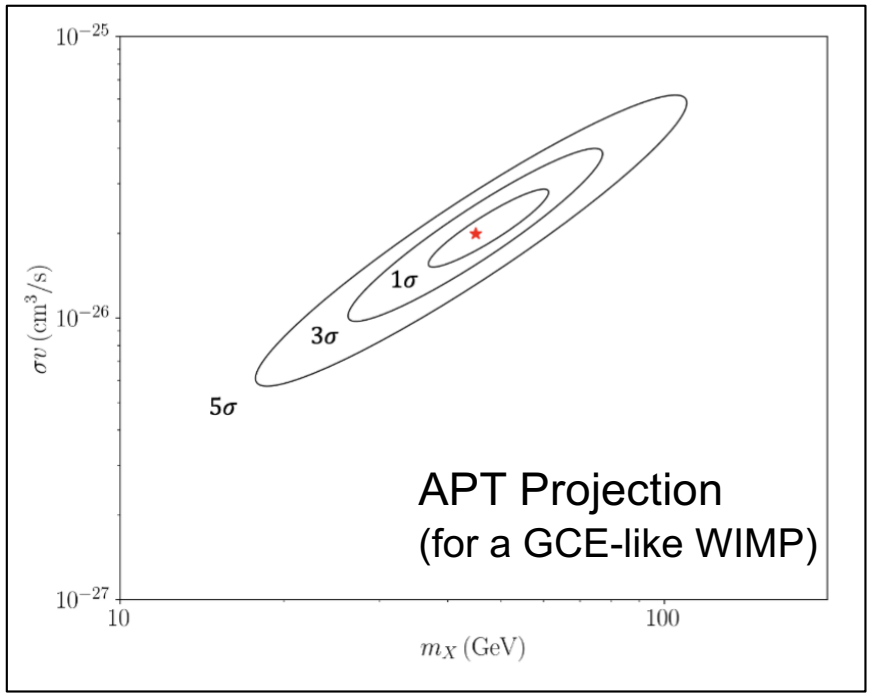
- The Rubin Observatory (first light in 2024!) is expected to discover ~150-250 new Milky Way dwarf galaxies (compared to ~50 at present)
- Once these new dwarfs are discovered, we can use already existing Fermi data to look for gamma-ray signals from annihilating dark matter
- With Rubin, Fermi's sensitivity to dark matter annihilation in dwarf galaxies could plausibly increase by a factor of ~2-3, finally enabling us to test much (perhaps all?) of parameter space favored by the Galactic Center excess

Beyond Fermi

- Dark matter searches using gamma rays from dwarf galaxies are limited by statistics; their sensitivity could be dramatically improved by larger telescopes
- As an example, consider the projected sensitivity of the proposed Advanced Particle-astrophysics Telescope (APT):



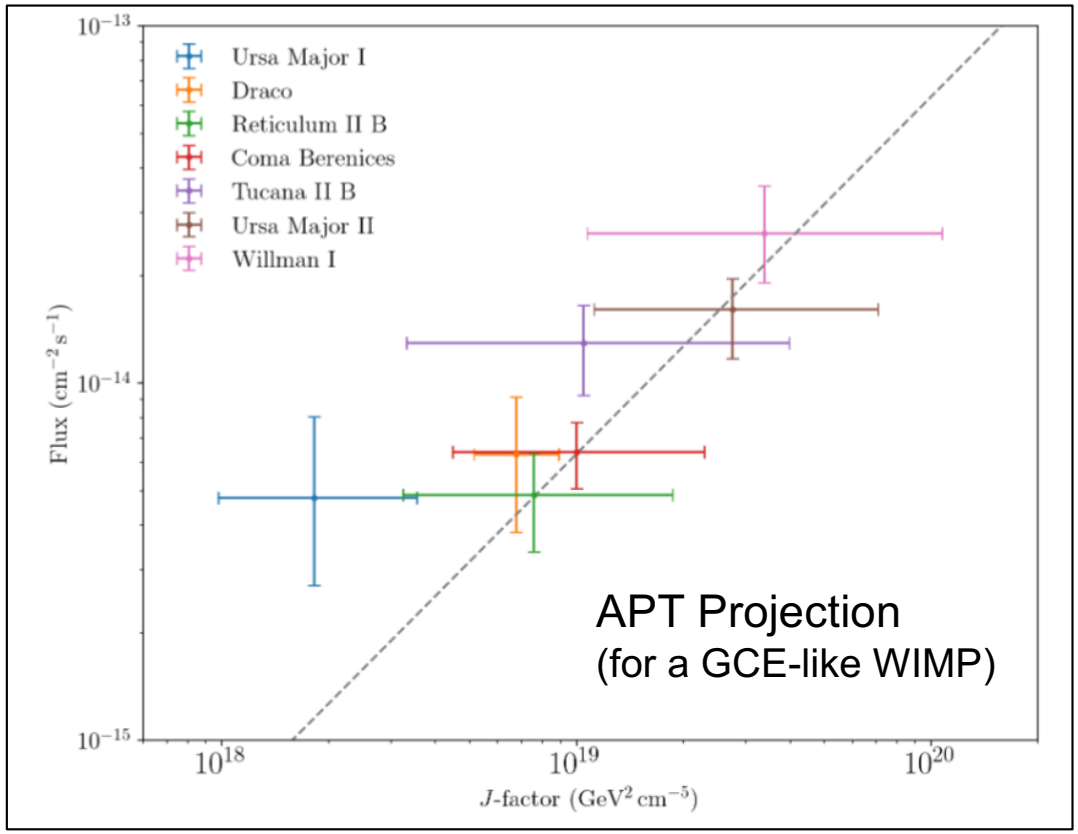




F. Xu and DH, arXiv:2308.XXXXX

Beyond Fermi

- Dark matter annihilation signals from dwarf galaxies will be proportional to their independently measured J-factors; No astrophysical backgrounds will have this scaling!
- For a GCE-like WIMP, APT will detect gamma rays from several dwarfs, and will be able to clearly establish whether this proportionality holds
- If this scaling is observed, it would be an unambiguous signature of annihilating dark matter – a smoking gun



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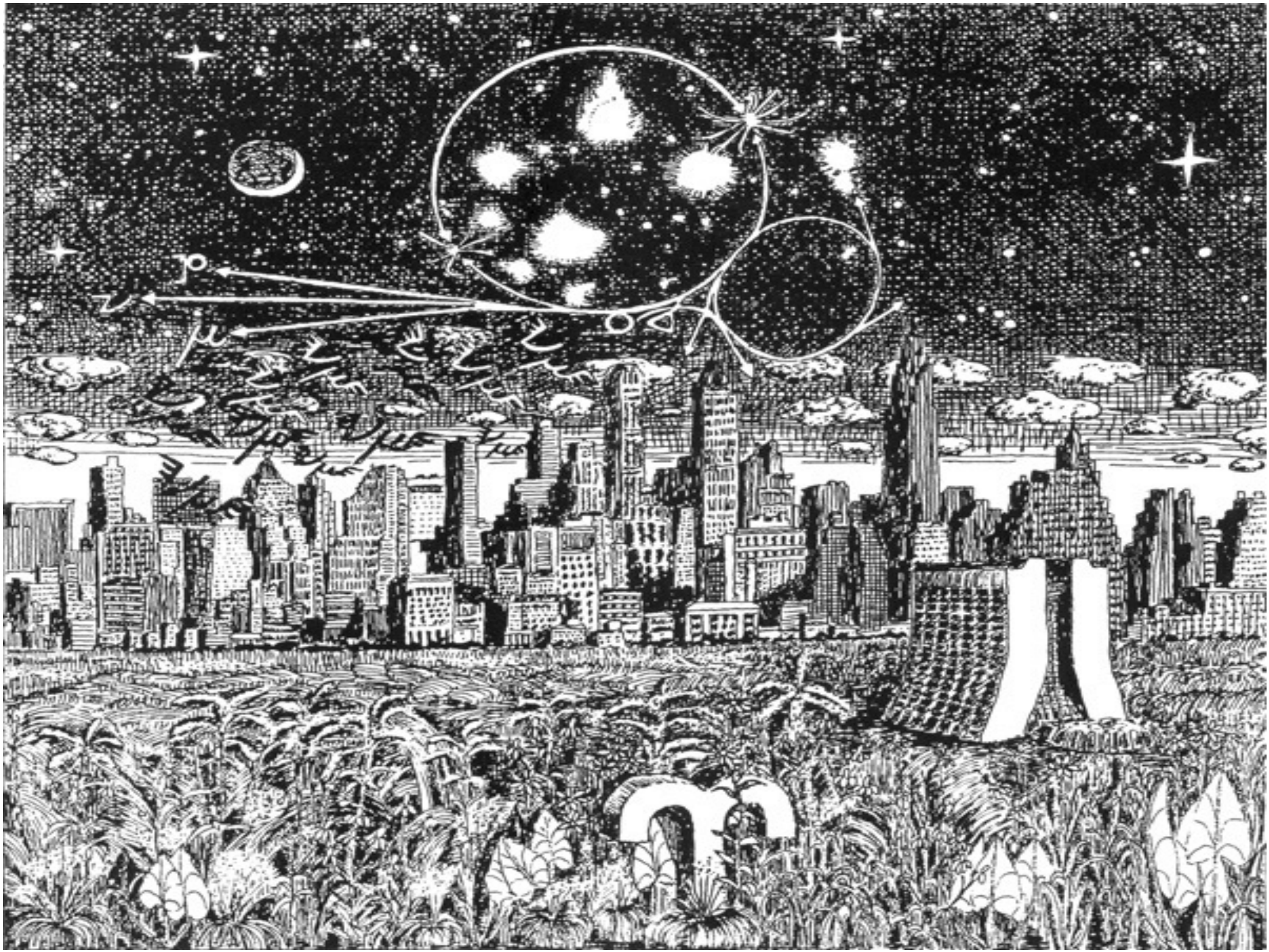
Summary

- The Galactic Center's GeV excess remains compelling: highly statistically significant, robust, extended, spherical, and not easily explained with known or proposed astrophysics
- Earlier arguments claiming that this excess is generated by near threshold point sources have not held up to scrutiny
- Recent studies have found that the morphology of this signal is consistent with that expected from annihilating dark matter
- Arguments based on the number of gamma-ray bright MSPs, bright LMXBs, and diffuse TeV emission each disfavor MSPs as the source of this emission
- Gamma-ray observations of dwarf galaxies with future large-acceptance telescopes could provide a critical test of this signal's origin

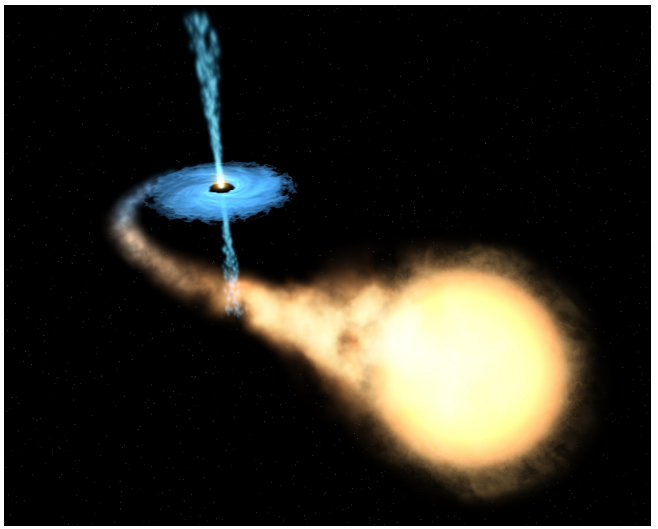


Searches for Bright Low-Mass X-Ray Binaries

- 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, Measure: $\left.\frac{F_\gamma}{N_{\rm LMXB}}\right|_{\rm Globular\ Clusters} = \left.\frac{F_\gamma}{N_{\rm LMXB}}\right|_{\rm Inner\ Galaxy}$ — Infer, Measure

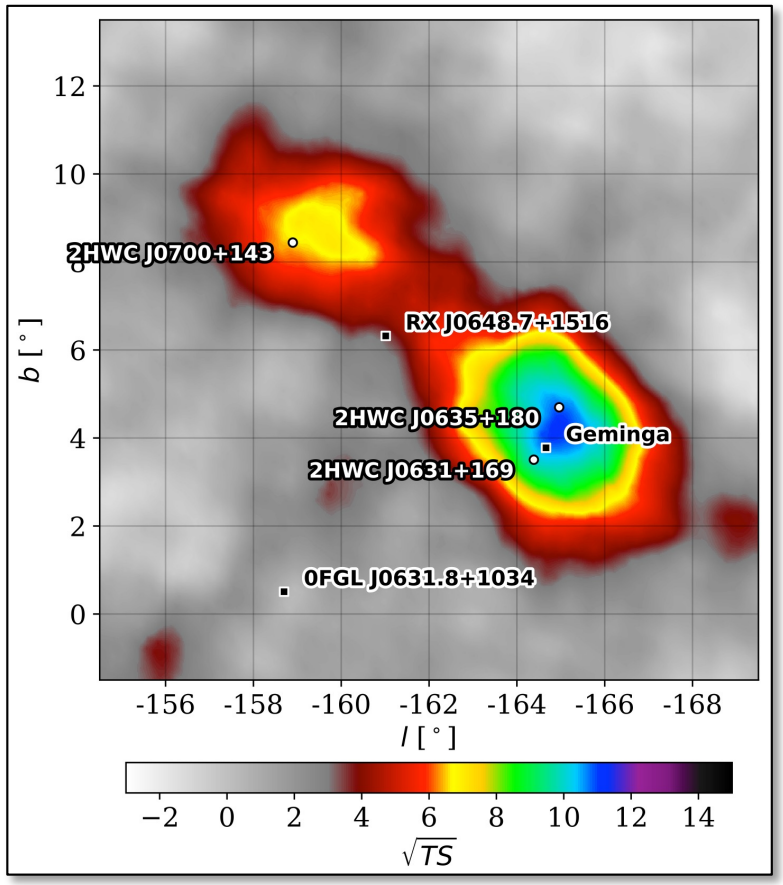
- This procedure finds that only 4-11% of the gamma-ray excess is attributable to MSPs
- If the entire excess was from MSPs, INTEGRAL should have detected ~10^3 LMXBs in the Inner Galaxy; they actually detected 42



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

Millisecond Pulsars and TeV Halos

- Observations by the HAWC and LHAASO telescopes have shown that young/middle-aged pulsars are universally surrounded by bright, spatially-extended, multi-TeV emitting regions, known as “TeV Halos”
- This emission is produced through the inverse Compton scattering of very high-energy electrons and positrons
- Approximately ~10% of the spindown power of young pulsars goes into the acceleration of these particles
- HAWC data suggest (~3σ) that MSPs produce TeV halos with a similar efficiency as young pulsars

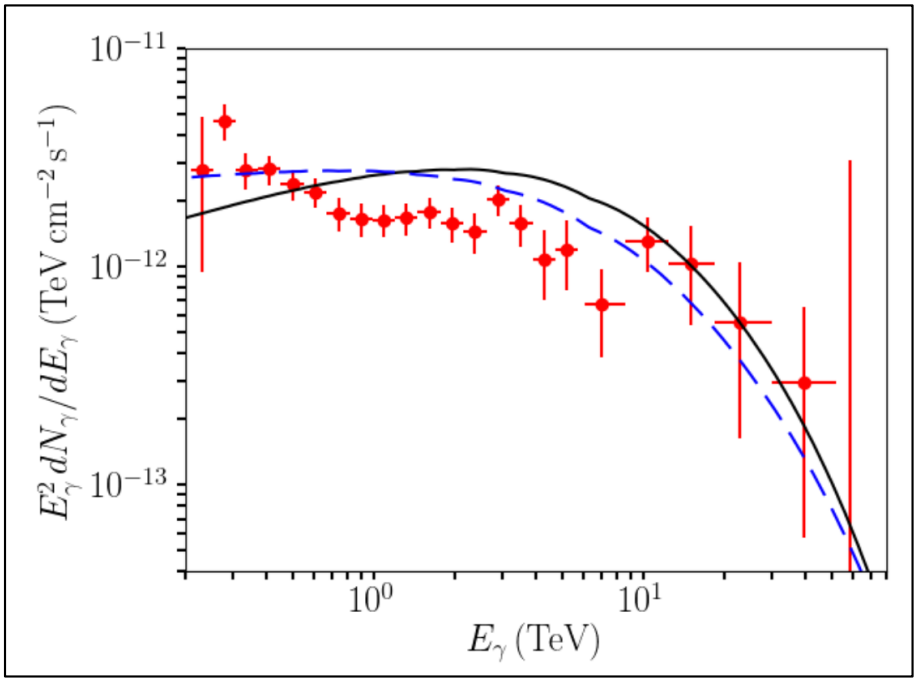


HAWC Collaboration, arXiv:1702.02992

DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436
Linden, et al, arXiv:1703.09704
Sudoh, Linden, DH, arXiv:2101.11026
DH, Linden, arXiv:2104.00014

Millisecond Pulsars and TeV Halos

- If MSPs do generate the GeV excess, their TeV halos should also approximately saturate (or exceed) the TeV-scale emission that is observed from this region by HESS
- Unrealistically, this would leave no room for other sources of TeV emission (π^0, ICS, brems, *etc.*)
- We could relax the TeV constraints by increasing the B-fields, but this would result in more radio emission than is observed
- CTA should be able to significantly clarify this situation, either identifying bright TeV-scale emission that traces the morphology of the GeV excess, or ruling out MSPs as the source of the GeV excess



$0.2 - 0.5°$ annulus, $\eta_{MSP} = \eta_{young}$

Keith, DH, Linden, arXiv:2212.08080,
DH, Linden, arXiv:2104.00014 (1803.08046)