The Status of the Galactic Center Gamma-Ray Excess

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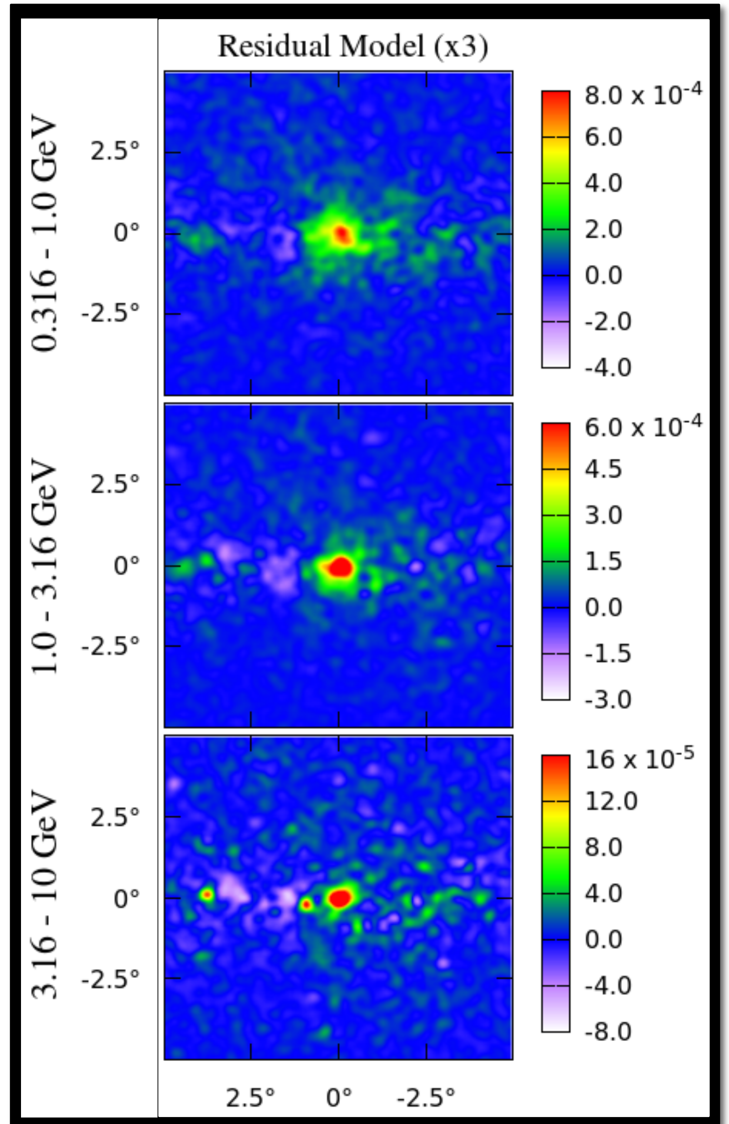
The Galactic Center Gamma-Ray Excess

- A bright and highly statistically significant excess of gamma-rays has been observed from the region surrounding the Galactic Center
- This signal is difficult to explain with astrophysical sources or mechanisms, but is very much like the signal long predicted from annihilating dark matter

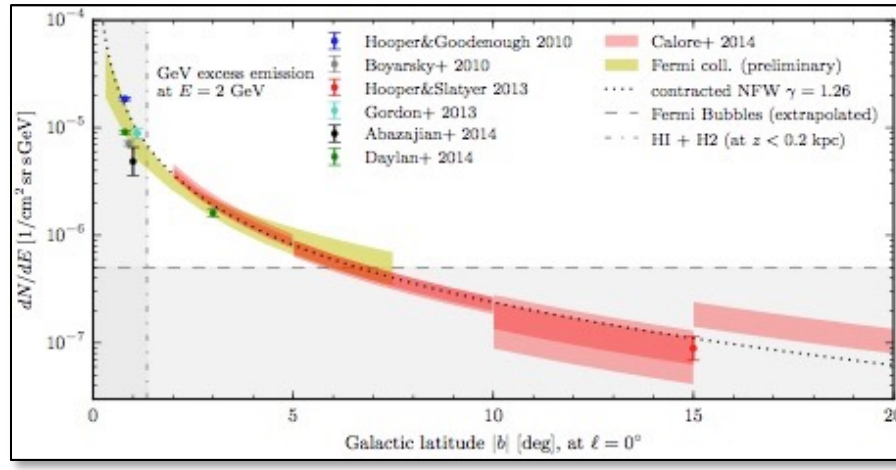


Among other references, see:
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
DH, Slatyer (2013)
Daylan, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

The Galactic Center Gamma-Ray Excess

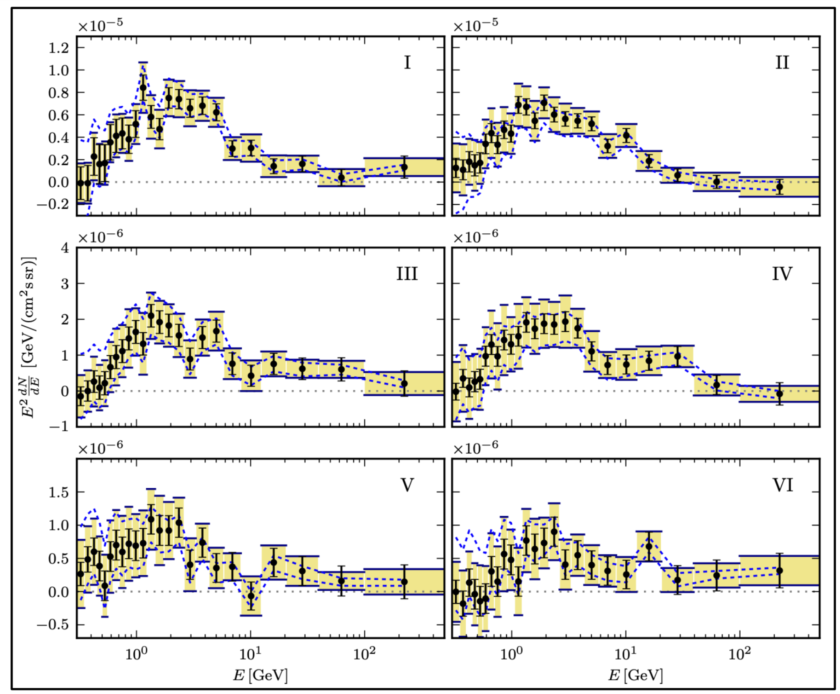
Morphology

- Approximate spherical symmetry about the Galactic Center, with a flux that falls as $\sim r^{-2.4}$ out to at least ~10-20°
- If from annihilating dark matter, this implies $\rho_{DM} \sim r^{-1.2}$ out to ~1.5-3 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



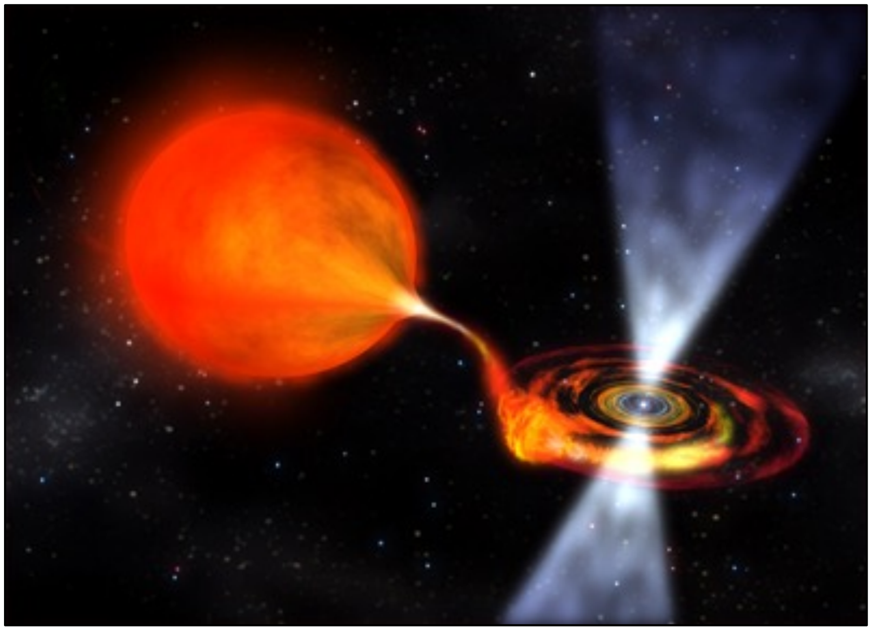
Intensity

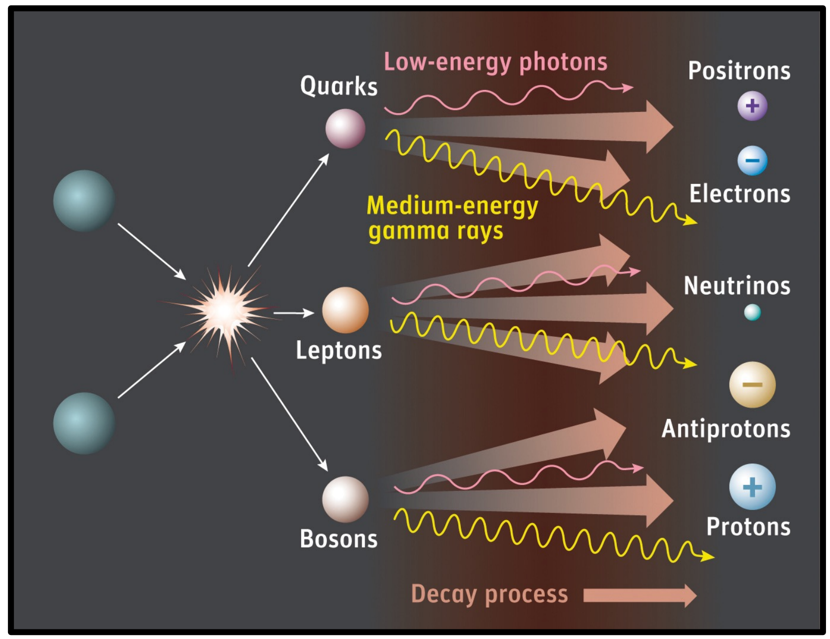
- To normalize the observed excess, the DM particles must annihilate with $\sigma v \sim 10^{-26}$ cm^3/s, approximately equal to the value required to obtain the measured DM abundance

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

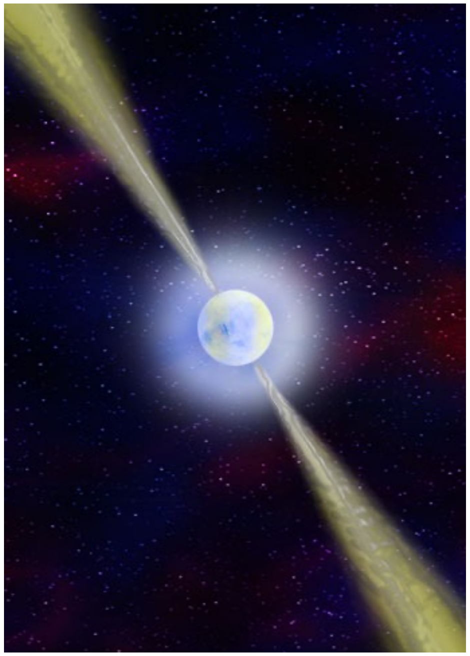
What Produces the Excess?

- 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
- Claims that the excess traces the Galactic Bulge/Bar

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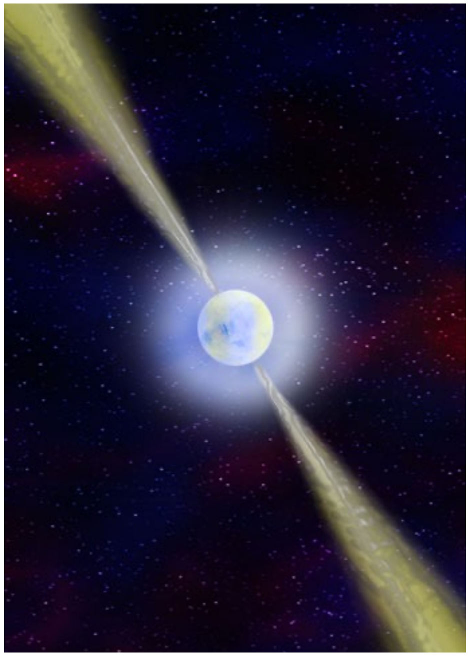

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Evidence of Unresolved Gamma-Ray Sources?

- 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 photon distribution within ~10° of the Galactic Center (masking within 2° of the Galactic Plane) is *clumpy*, potentially indicative of an unresolved point source population
- Bartels et al. reached a qualitatively similar conclusion employing a wavelet technique

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

Evidence of Unresolved Point Sources?

- 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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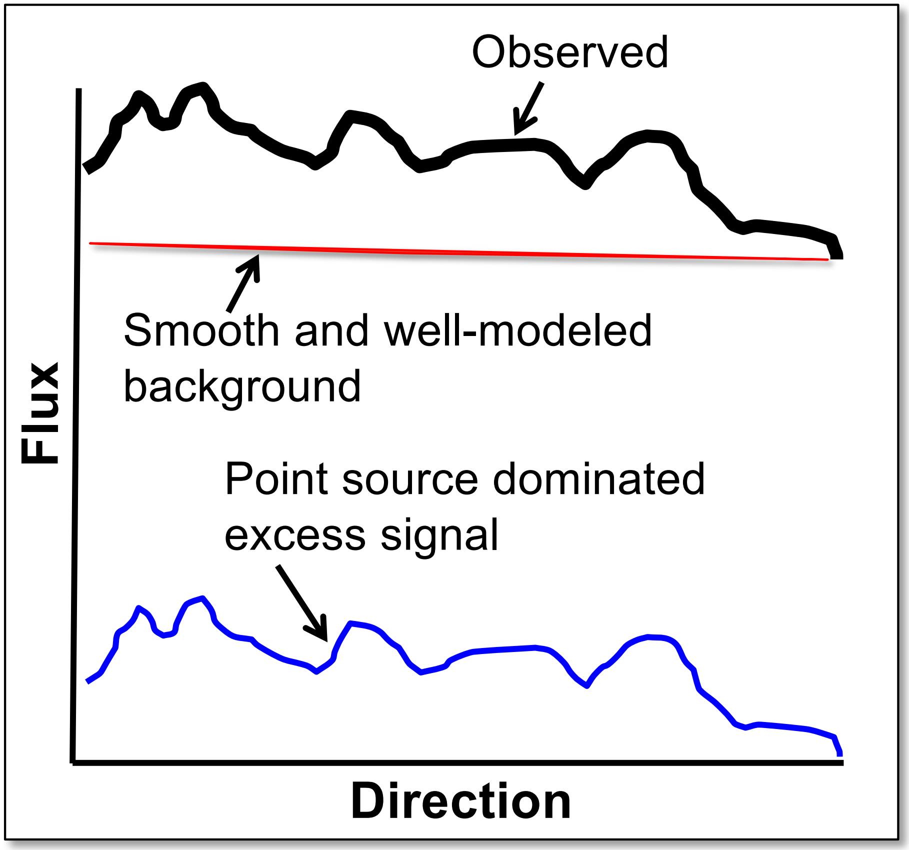

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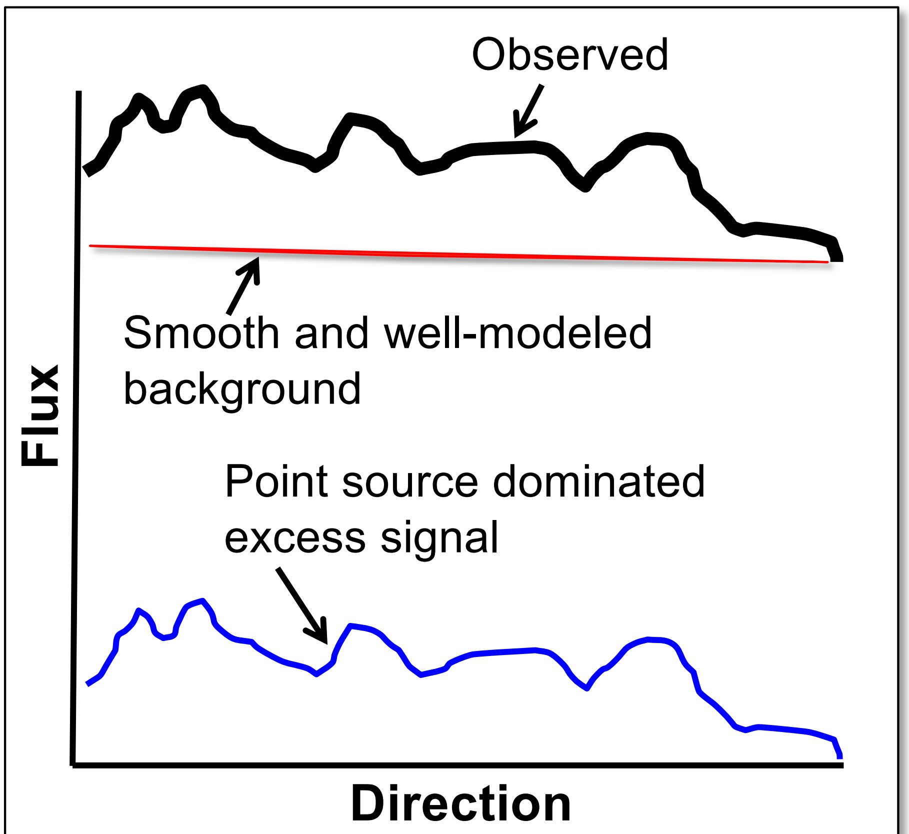

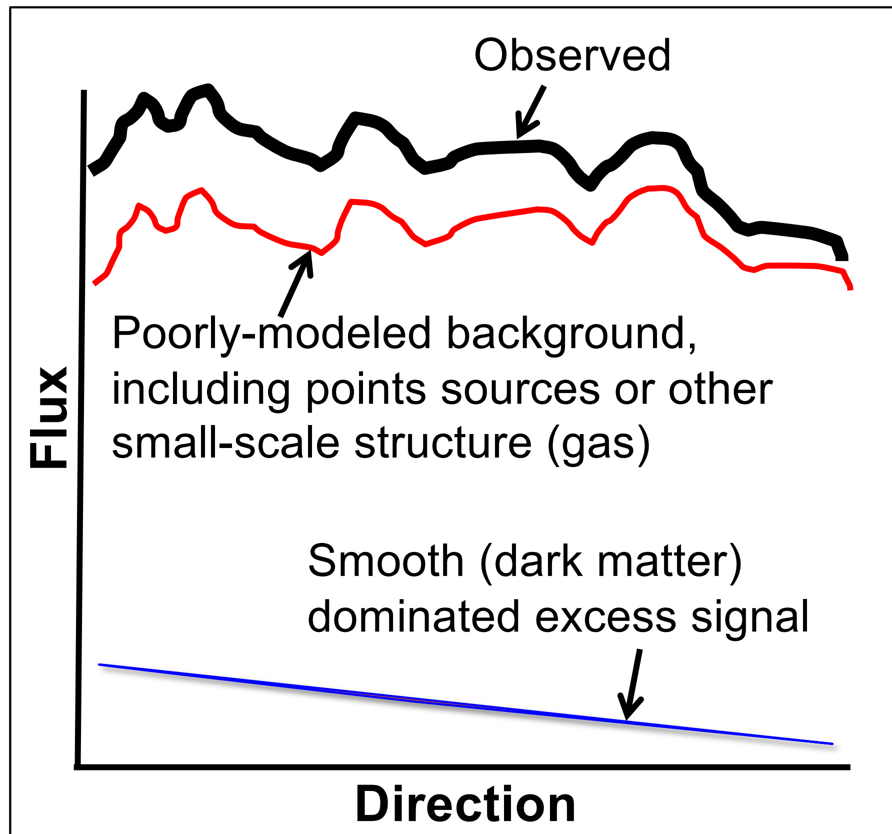

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

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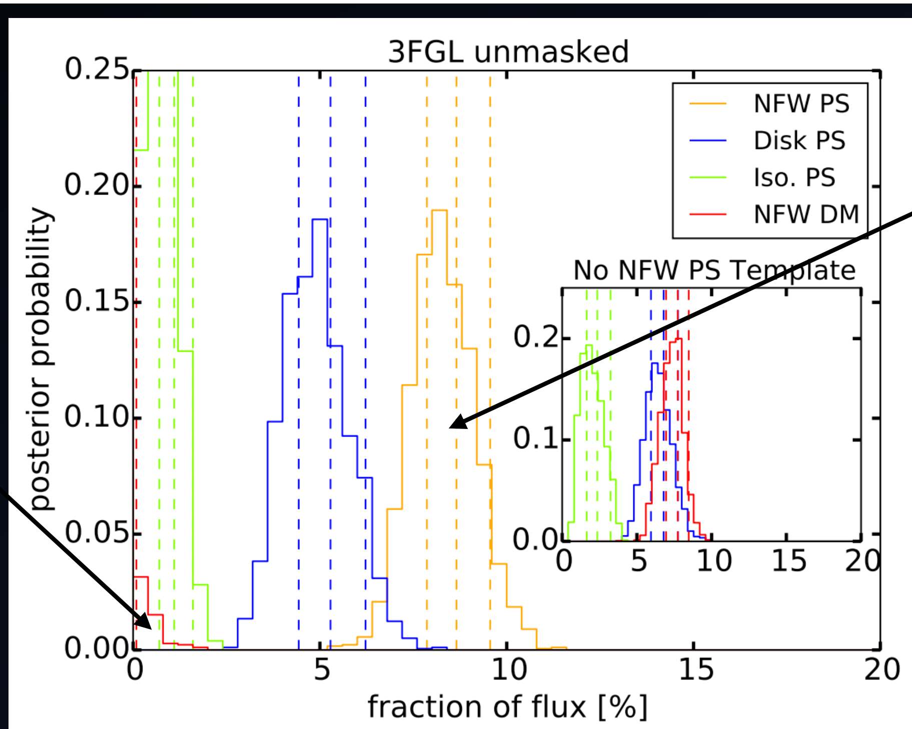
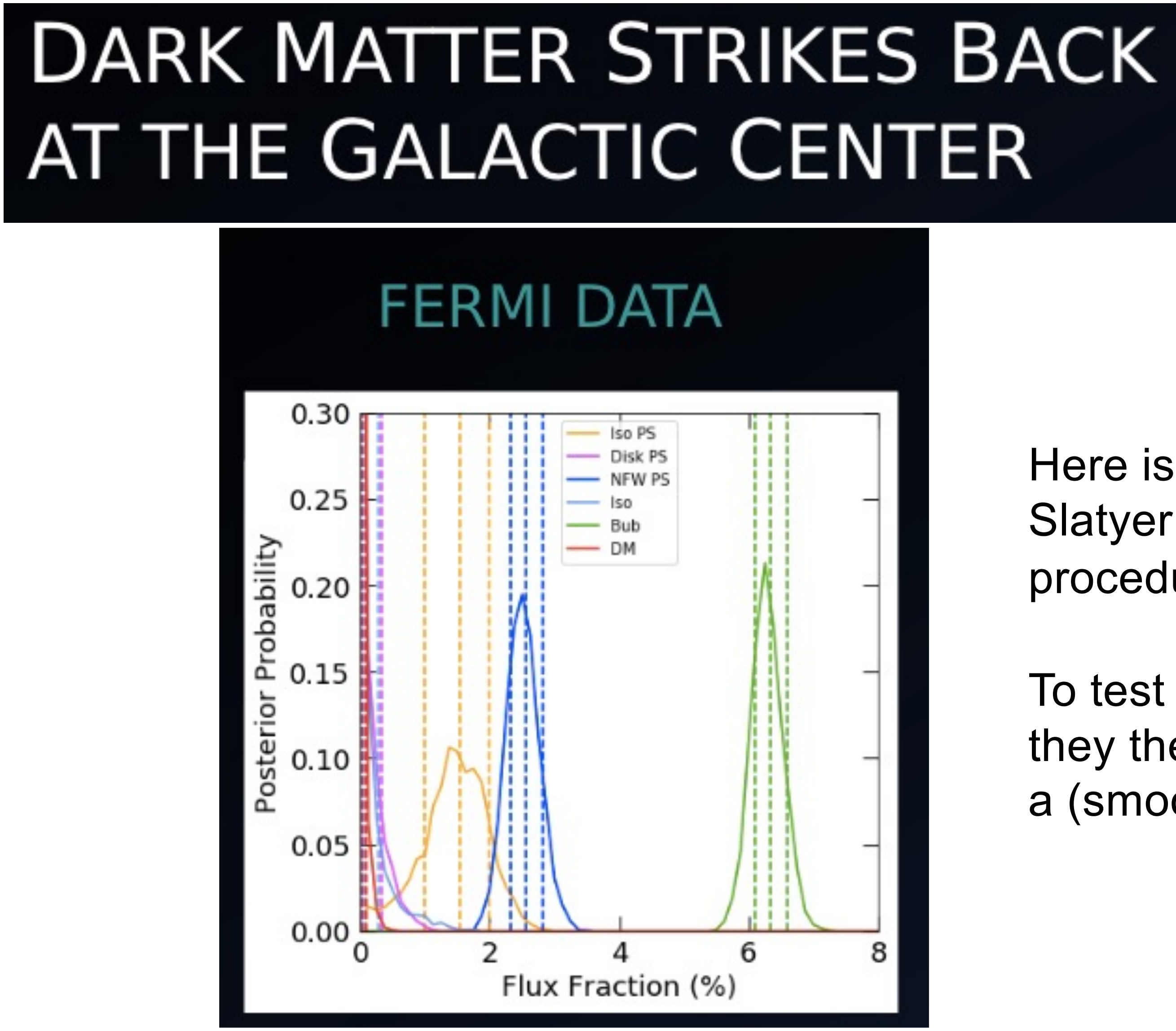
Evidence against any significant amount of dark matter annihilation



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

Evidence for NFW^2 Distributed Point Sources

To what extent could inadequate templates be biasing these results?



See Leane and Slatyer, arXiv:1904.08430

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

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

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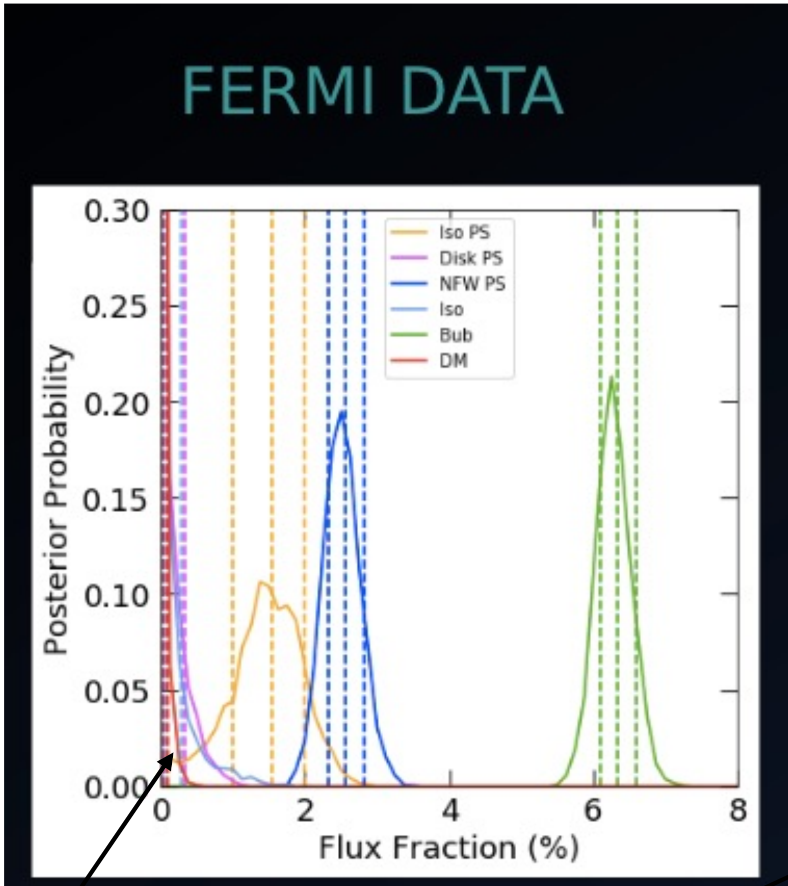
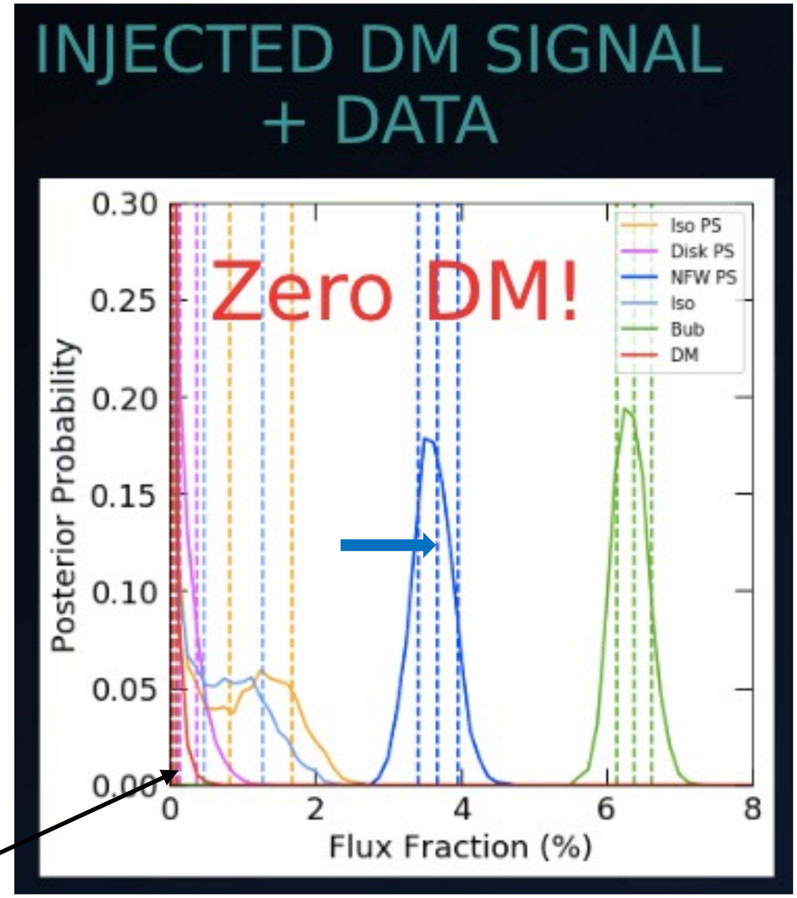
See Leane and Slatyer, arXiv:1904.08430





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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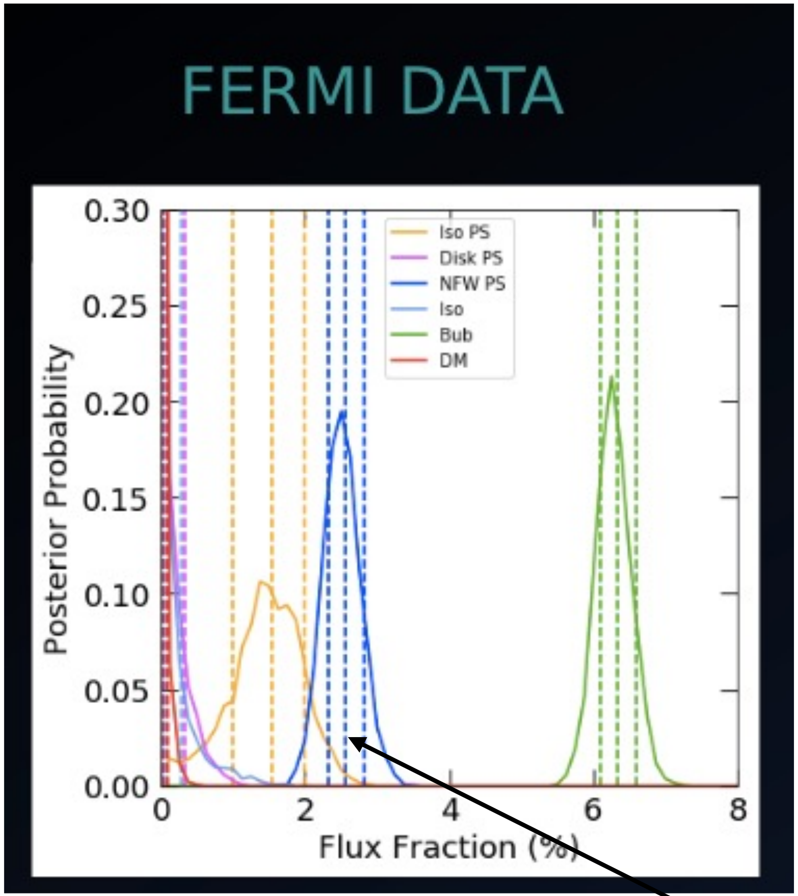
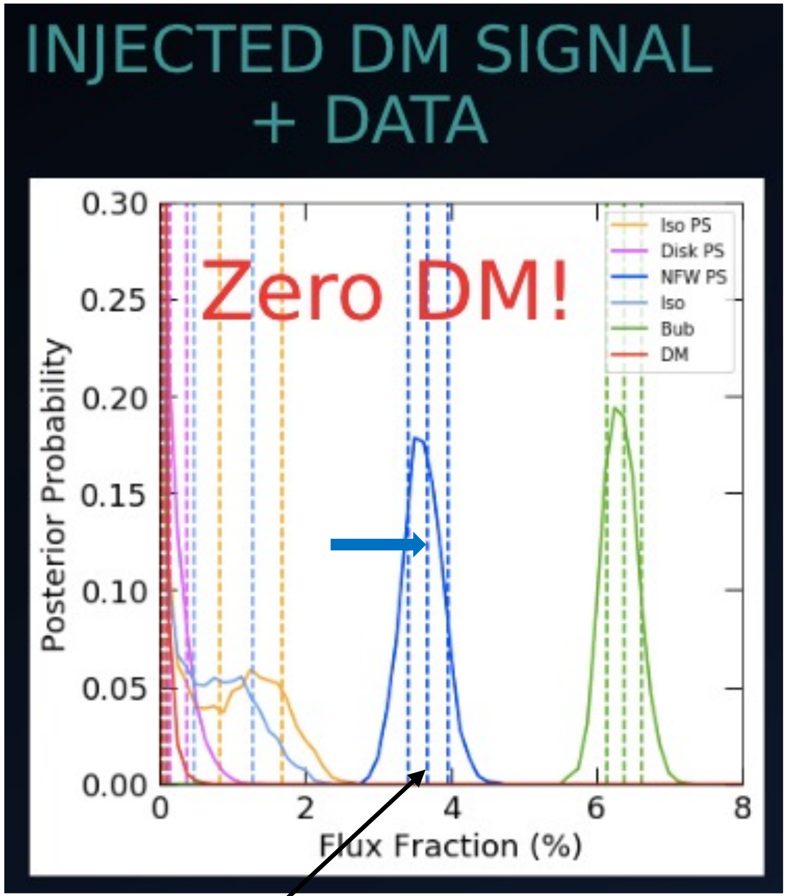




Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

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

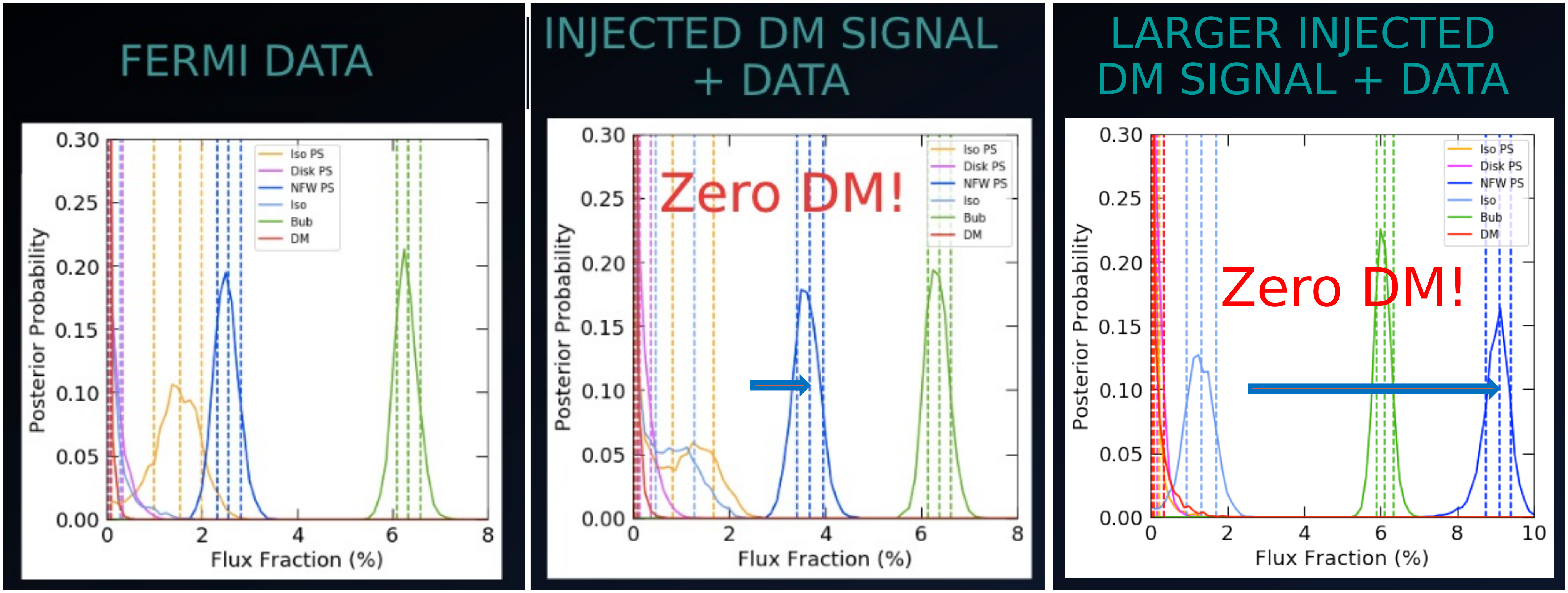
DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

What happens if an even larger dark matter-like signal is added to the data?

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430



Even very bright dark matter-like signals are misattributed to the point source templates!
(up to an order of magnitude larger than the intensity of the excess)

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

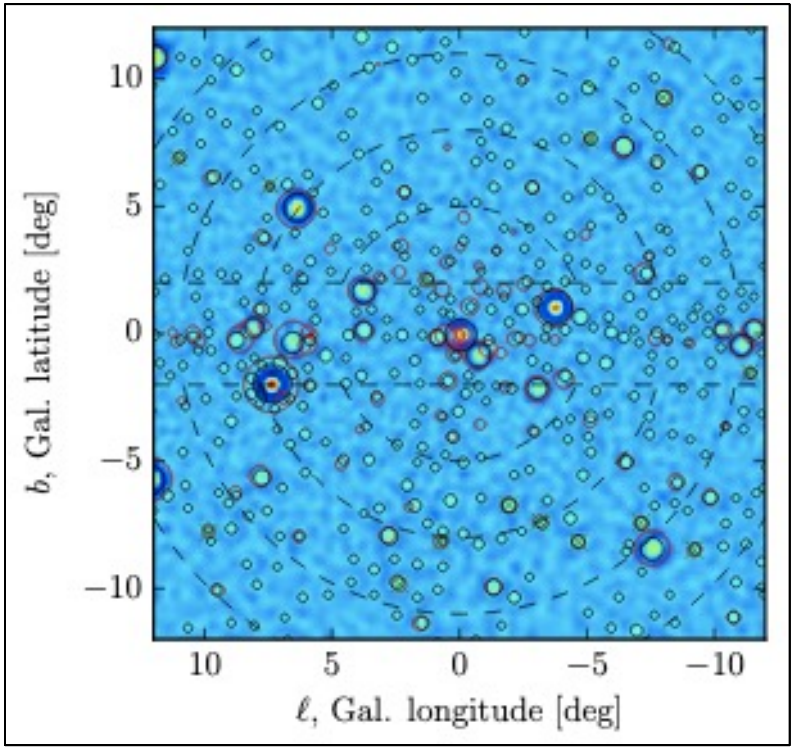
Bottom Line:

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

This method does ***not*** provide evidence for point sources over a dark matter interpretation of the excess

Wavelet Analyses and GC Point Sources

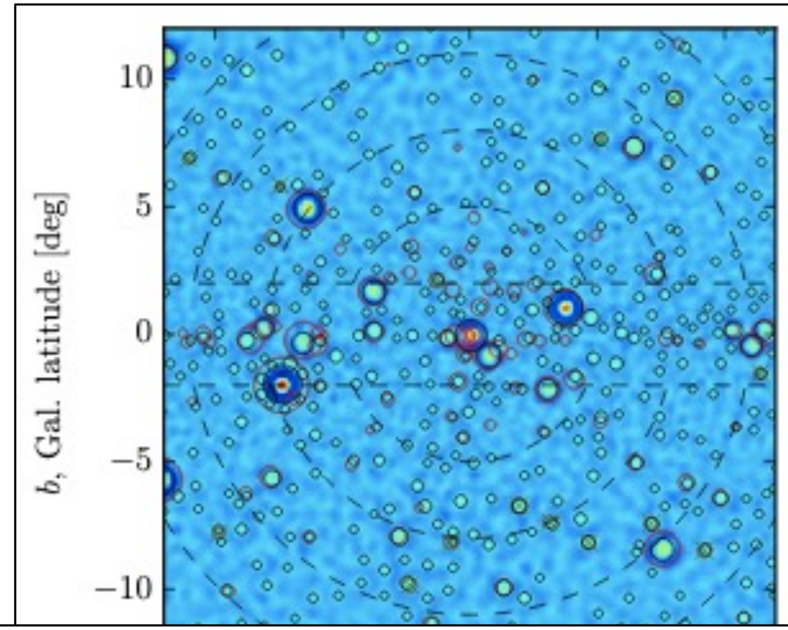
- In 2015, Bartels *et al.* used a wavelet-based technique to identify what they called "strong support" for a millisecond pulsar interpretation of the gamma-ray excess

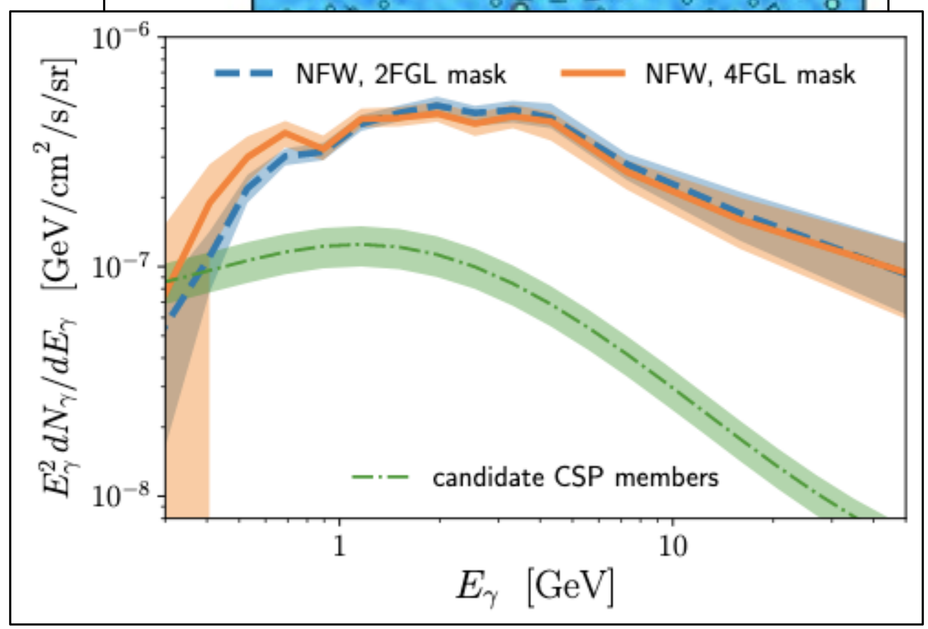


Bartels, Krishnamurthy, Weniger, arXiv:1506.05104
Zhong, McDermott, Cholis, Fox, arXiv:1911.12369

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
- 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





Bartels, Krishnamurthy, Weniger, arXiv:1506.05104
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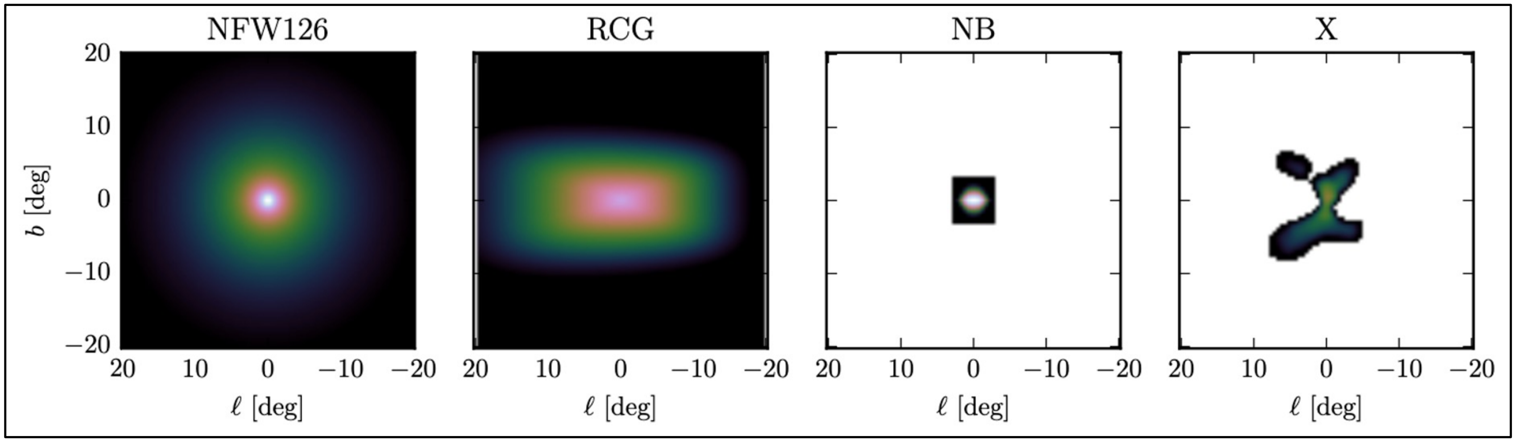
Bulge/Bar-Like vs DM-Like Morphology

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

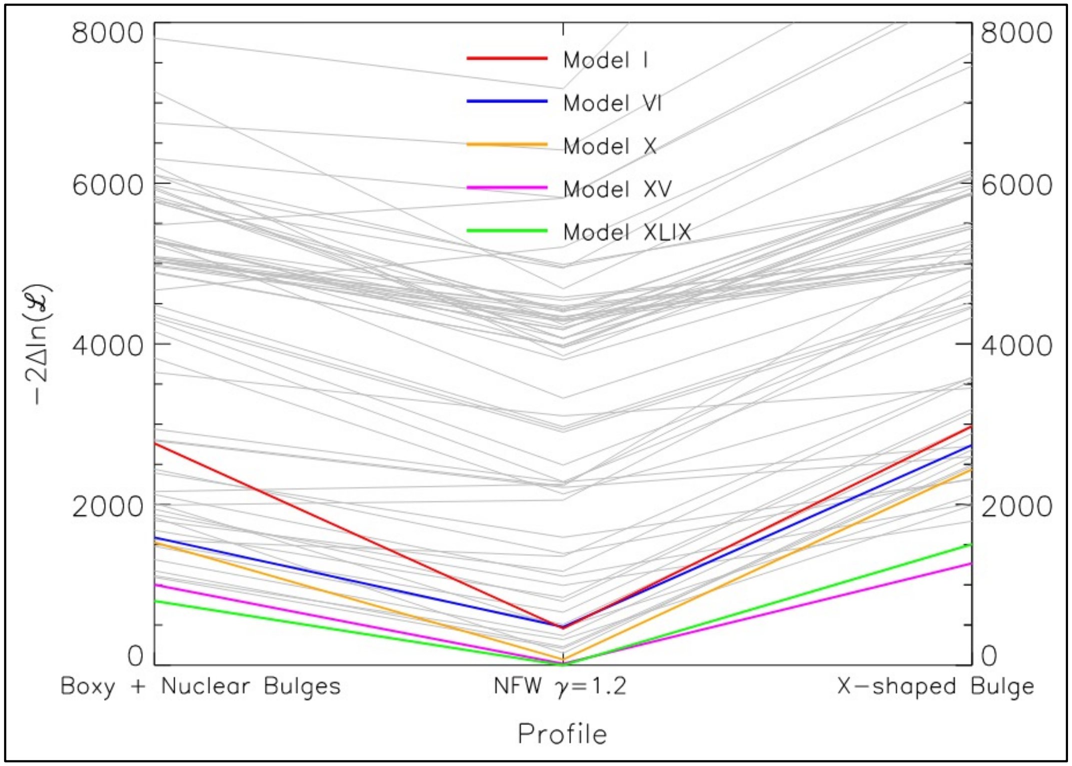


- In three papers (listed below), it was argued that the Fermi excess is better fit by spatial templates that trace stellar populations than dark matter-like templates, favoring MSP interpretations of the gamma-ray excess

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

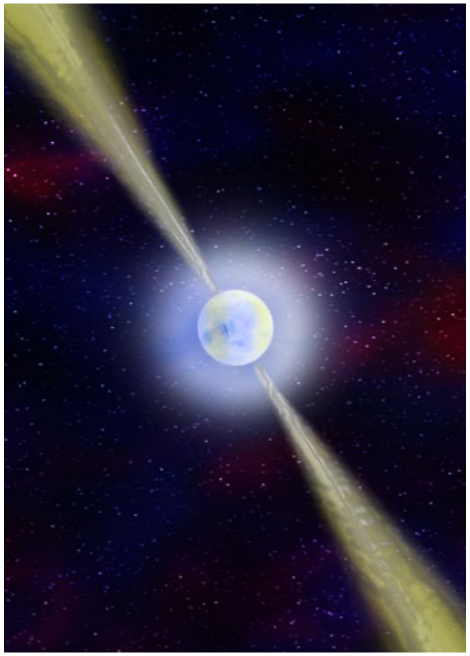
Bulge/Bar-Like vs DM-Like Morphology

- More recent work has not confirmed these results, but instead finds a strong statistical preference for dark matter-like templates
- The differences between these results could be indicative of systematic uncertainties associated with the choice of astrophysical templates, or might simply reflect a failure of the earlier analyses to identify the global minimum of the highly multi-dimensional parameter space
- Recent work has consistently favored a spherical morphology for this signal (and thus the DM hypothesis)



Cholis, Zhong, McDermott, Surdutovich (2021); see also Di Mauro, arXiv:2101.04694

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



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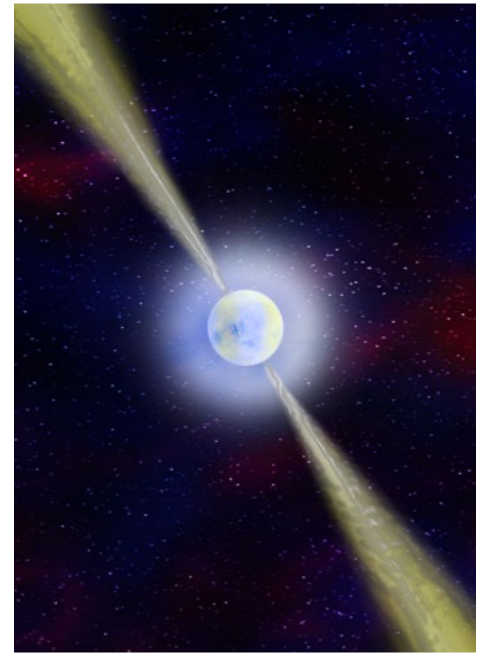

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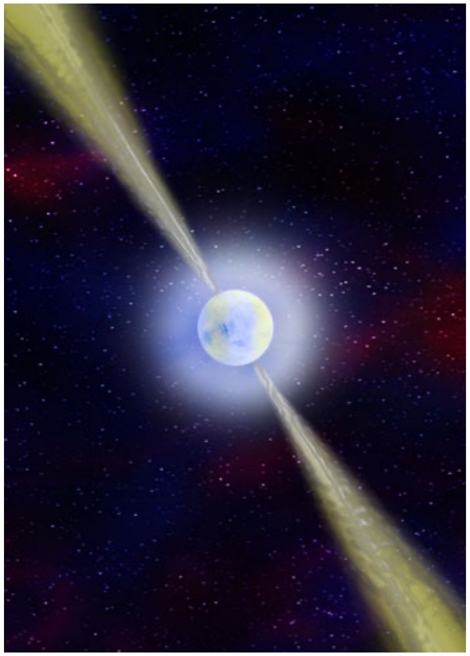

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Arguments Against Pulsars:

- 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 lack of bright TeV-scale emission from the Inner Galaxy

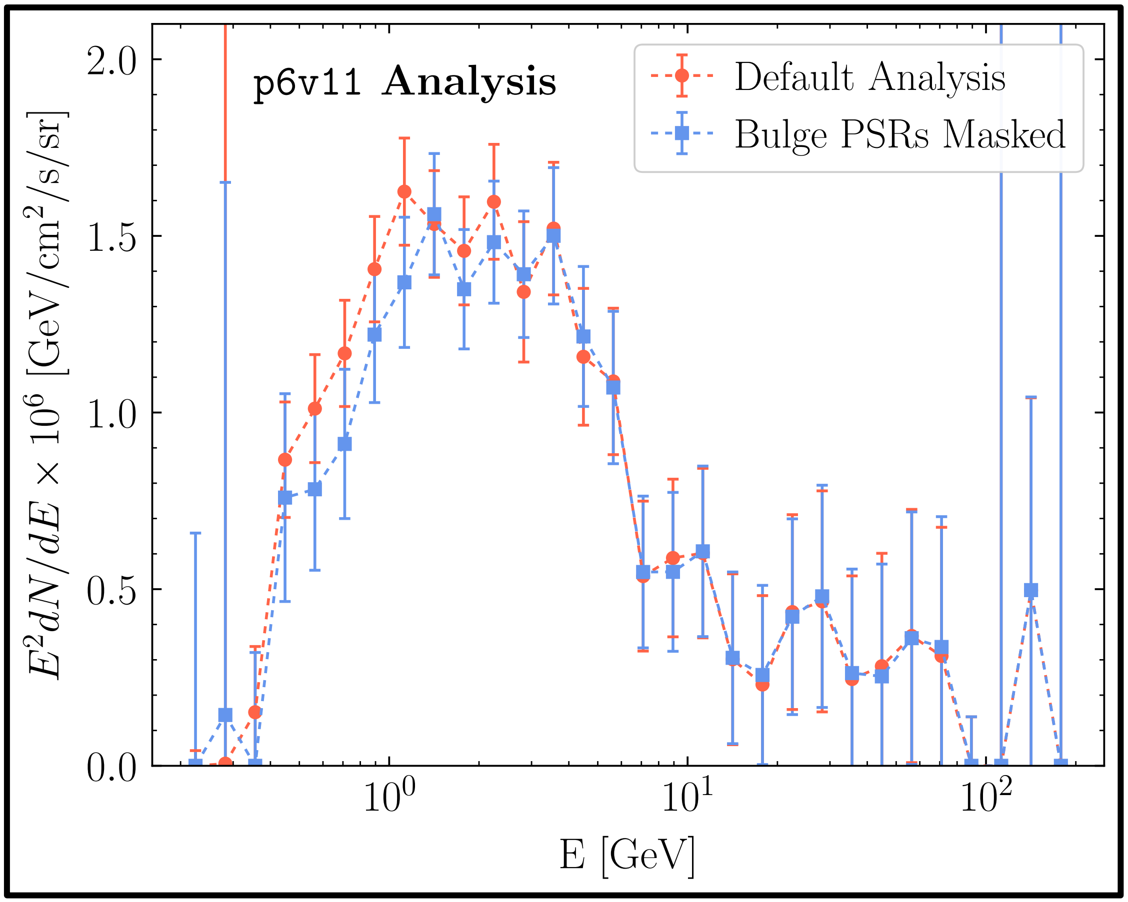
Gamma-Ray Bright MSPs in The Inner Galaxy?

- To be clear, no millisecond pulsars have been detected in the Inner Galaxy
- Ploeg, Gordan, Crocker and Macias (2008.10821) argued that the MSPs J1747-4036, J1811-2405, J1855-1436 are likely part of an Inner Galaxy population, but the distances to these pulsars had already been measured, confirming that they are not

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

Gamma-Ray Bright MSPs 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 $L_\gamma \sim 10^{34}$-10^{35} erg/s (in $L^2 dN/dL$ units)
- If the excess is produced by MPSs with a similar luminosity function, ~10^2 MSPs should have already been detected
- If the luminosity function is modeled as a power-law, ~3×10^6 pulsars (with $L>10^{29}$ erg/s) would be needed to explain the excess; no proposed pulsar population model predict anything close to so many pulsars in the Inner Galaxy
- As few as ~10^4-10^5 MSPs could generate this signal, but this would require a luminosity function that peaks only slightly below Fermi's current point source threshold ($L_\gamma \sim 10^{32}$-10^{33} erg/s)

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

Zhong, McDermott, Cholis, Fox, arXiv:1911.12369; Dinsmore, Slatyer, arXiv:2112.09699

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

Infer

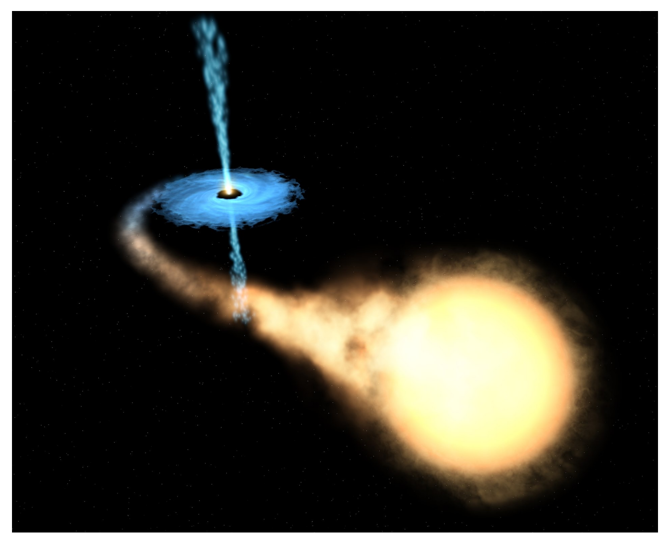
Measure

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

Measure

Measure

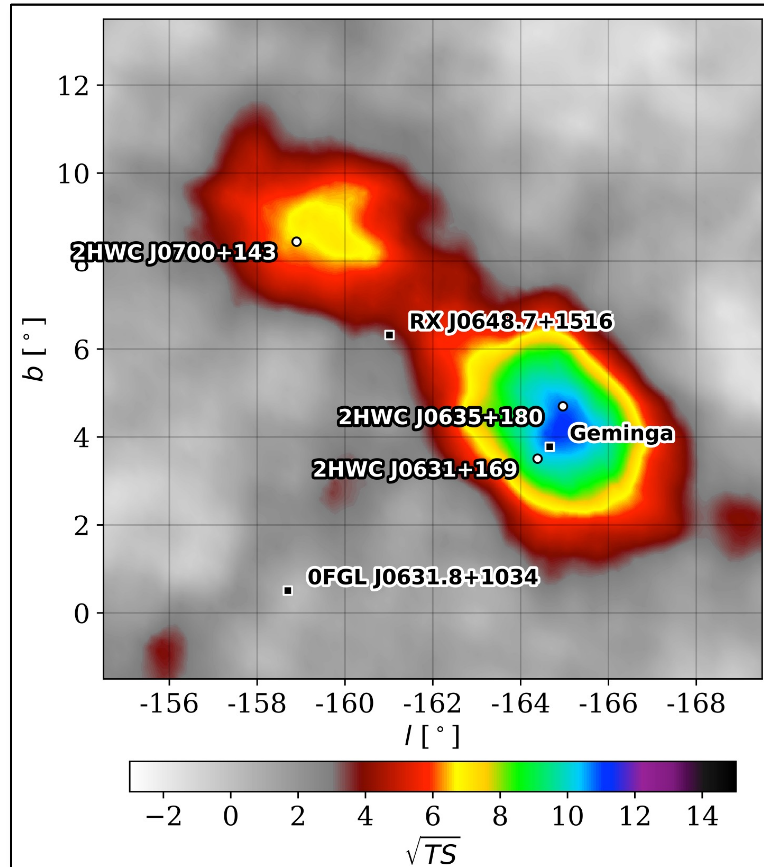
- This procedure finds that only 4-11% of the gamma-ray excess is attributable to MSPs
- If the entire excess was from MSPs, INTEGRAL should have detected ~10^3 LMXBs; they actually detected 42



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

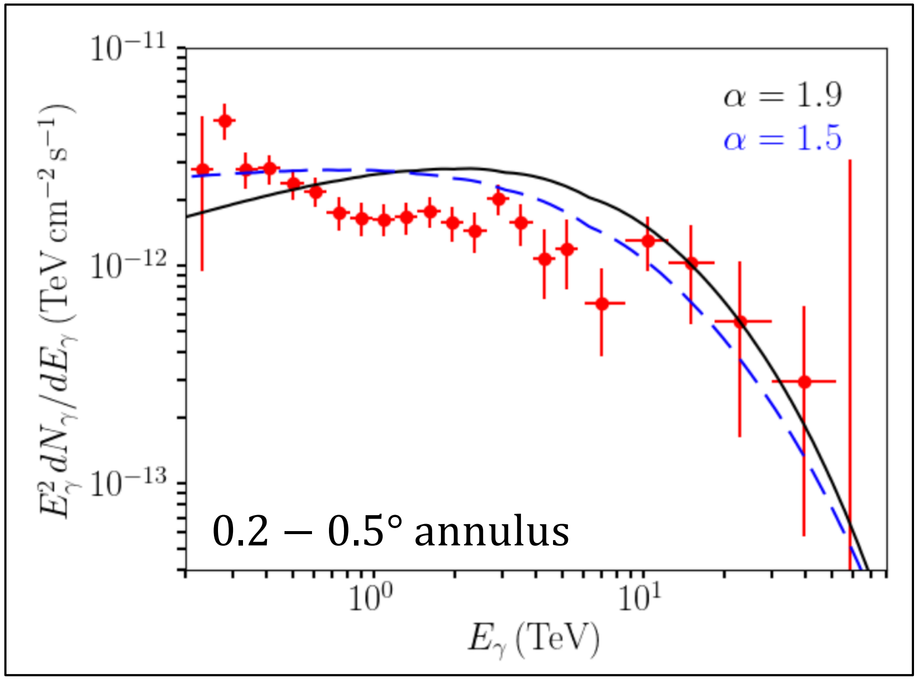


HAWC Collaboration, arXiv:1702.02992

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 generate the GeV excess, their TeV halos should (slightly) exceed the TeV-scale emission observed from the Inner Galaxy by HESS; this would leave no room for other sources of TeV-emission (π^0, ICS, brems, *etc.*)
- We could relax these 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



DH, Linden, arXiv:2104.00014 (1803.08046)

Looking Forward

Dwarf Galaxies

- Although current Fermi dwarf constraints are compatible with DM interpretations of the GC excess, even modest improvements in sensitivity would shed significant light on this interpretation
- The Rubin Observatory (first light in 2023!) is expected to discover ~150-250 new Milky Way dwarf galaxies (compared to ~50 at present)

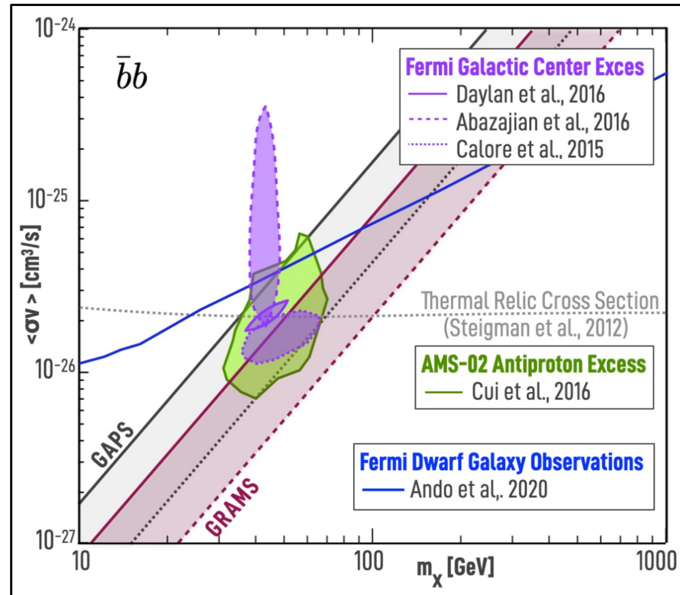
Cosmic-Ray Anti-Nuclei

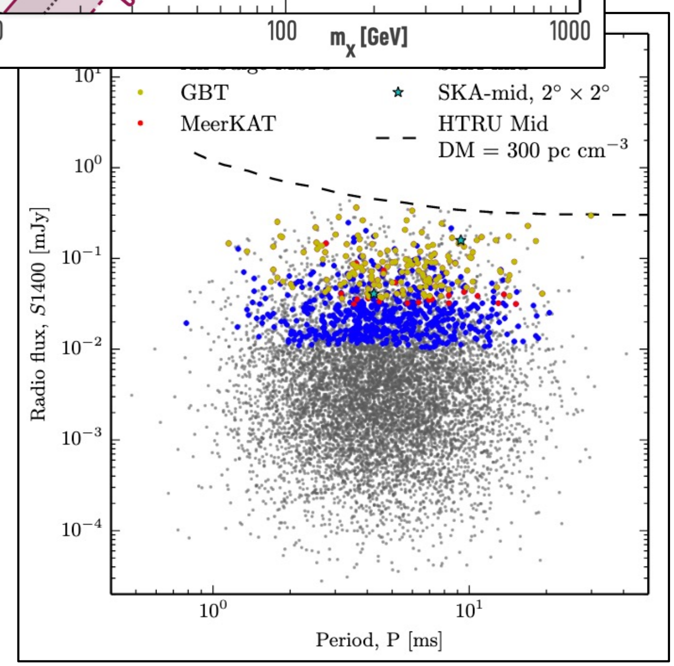
- A possible antiproton excess has been identified in the AMS data; a good match to DM models favored by the GC
- Antideuteron/antihelium searches by AMS and GAPS should be sensitive to these scenarios

Radio Searches for Inner Galaxy MSPs

- If MSPs generate the GeV excess, future deep radio surveys should be able to detect the pulsed radio emission from these objects

Leane et al., arXiv:2203.06859

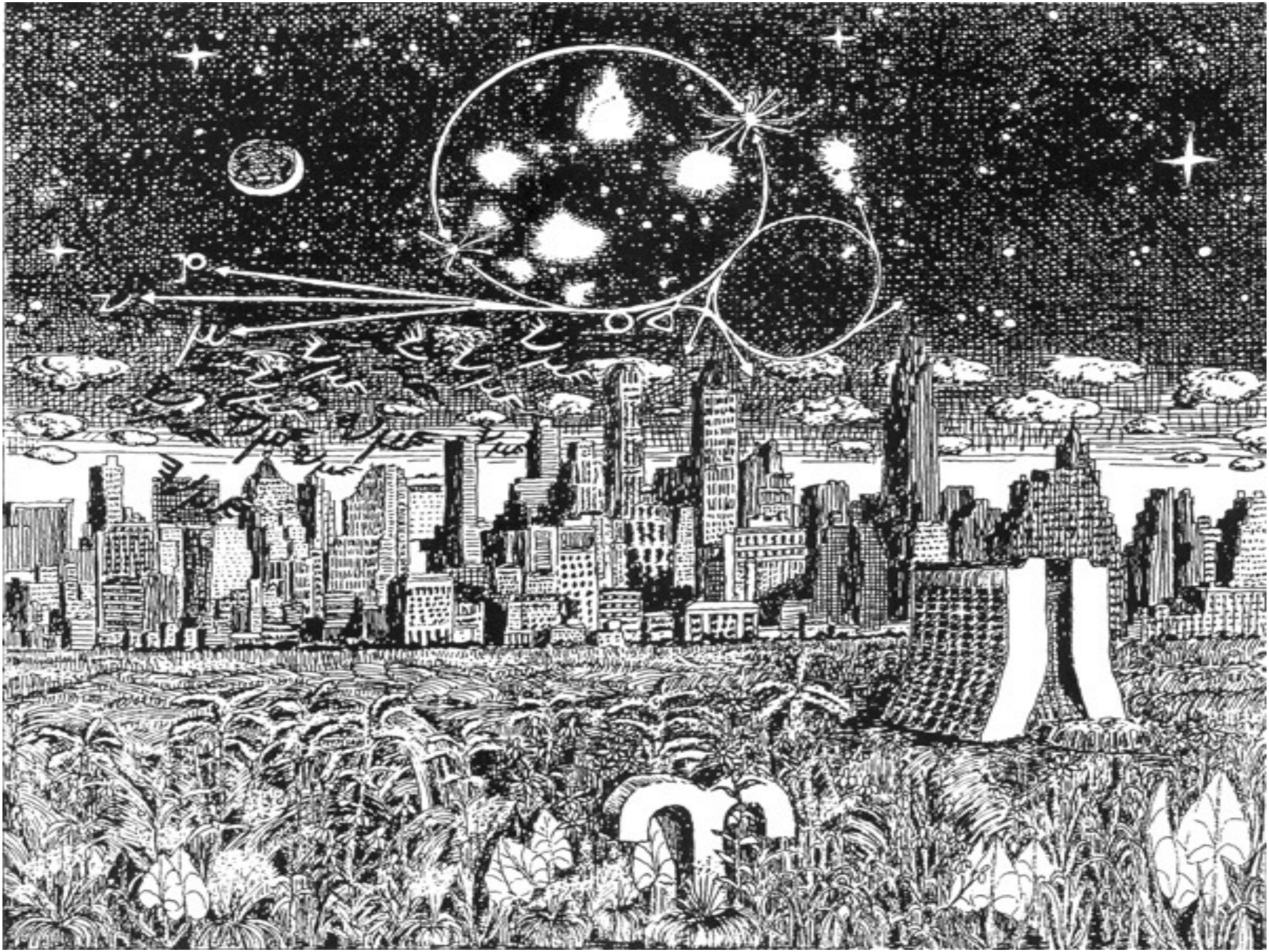




Calore, et al., arXiv:1512.06825

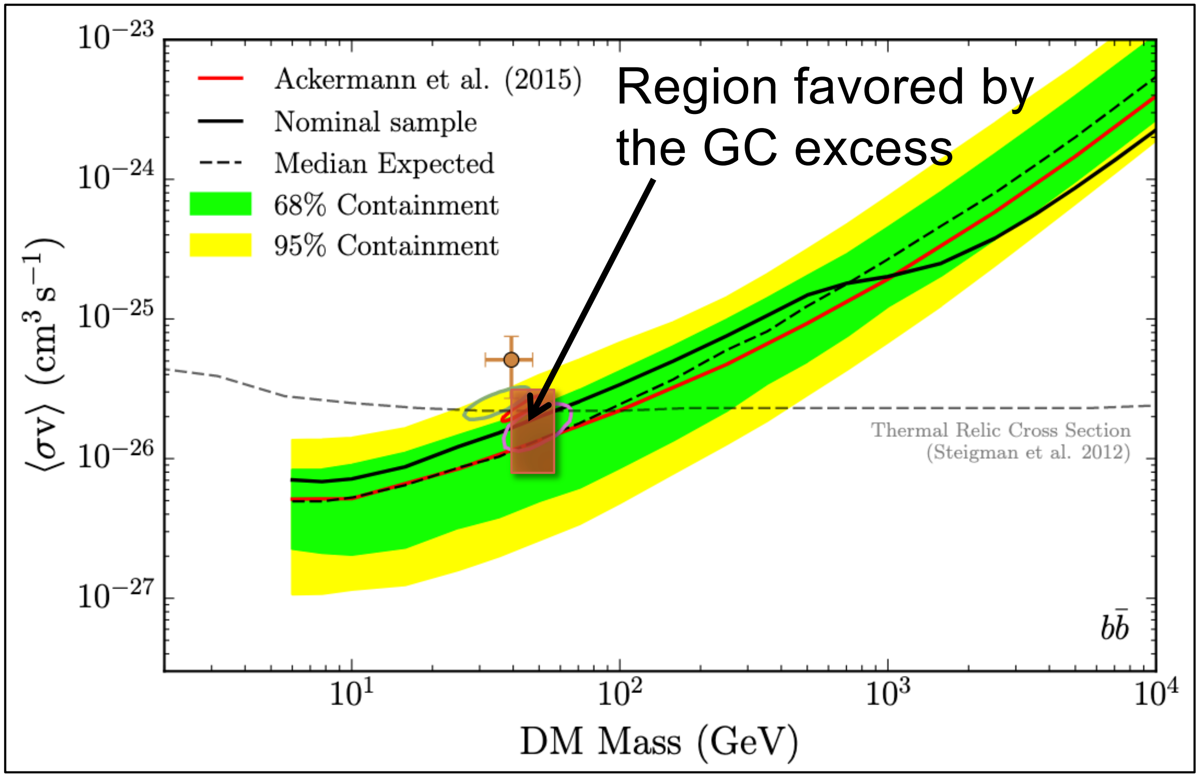
Summary

- The Galactic Center's GeV excess remains compelling: highly statistically significant, robust, extended, spherical, and not easily explained with known or proposed astrophysics
- Earlier NPTF-based and wavelet-based 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 arising from annihilating dark matter, and does not trace the Galaxy's bulge/bar
- 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
- Future gamma-ray and radio observations, as well as measurements of antimatter in the cosmic ray spectrum, will be provide critical tests to definitively establish the origin of this signal



Fermi Observations of Dwarf Galaxies

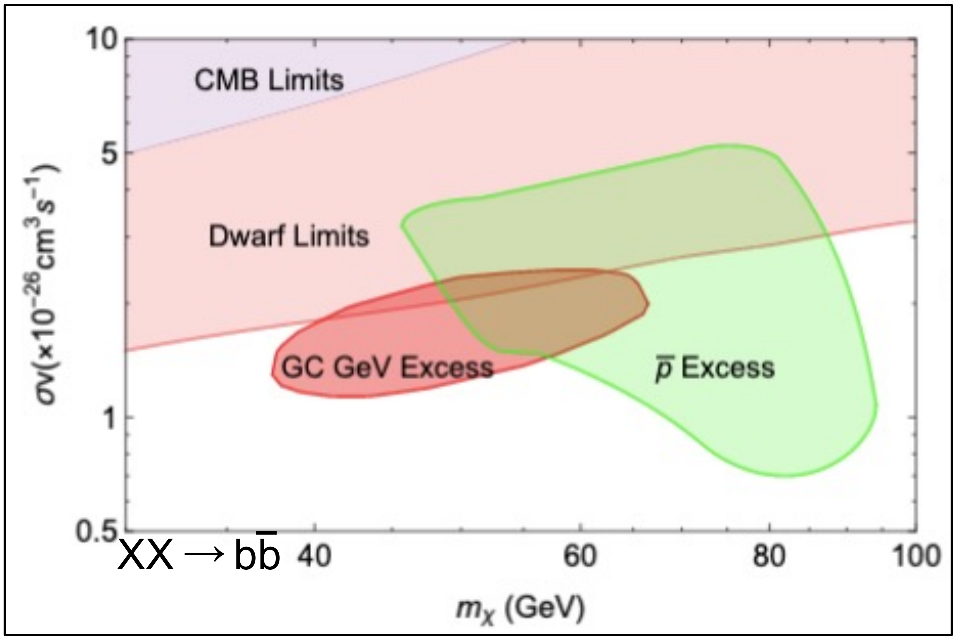
- Current Fermi dwarf constraints are based on observations of several dozen dwarf galaxies, including many that were discovered by DES and other recent surveys
- Although these constraints are currently compatible with dark matter interpretations of the Galactic Center excess, even modest improvements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

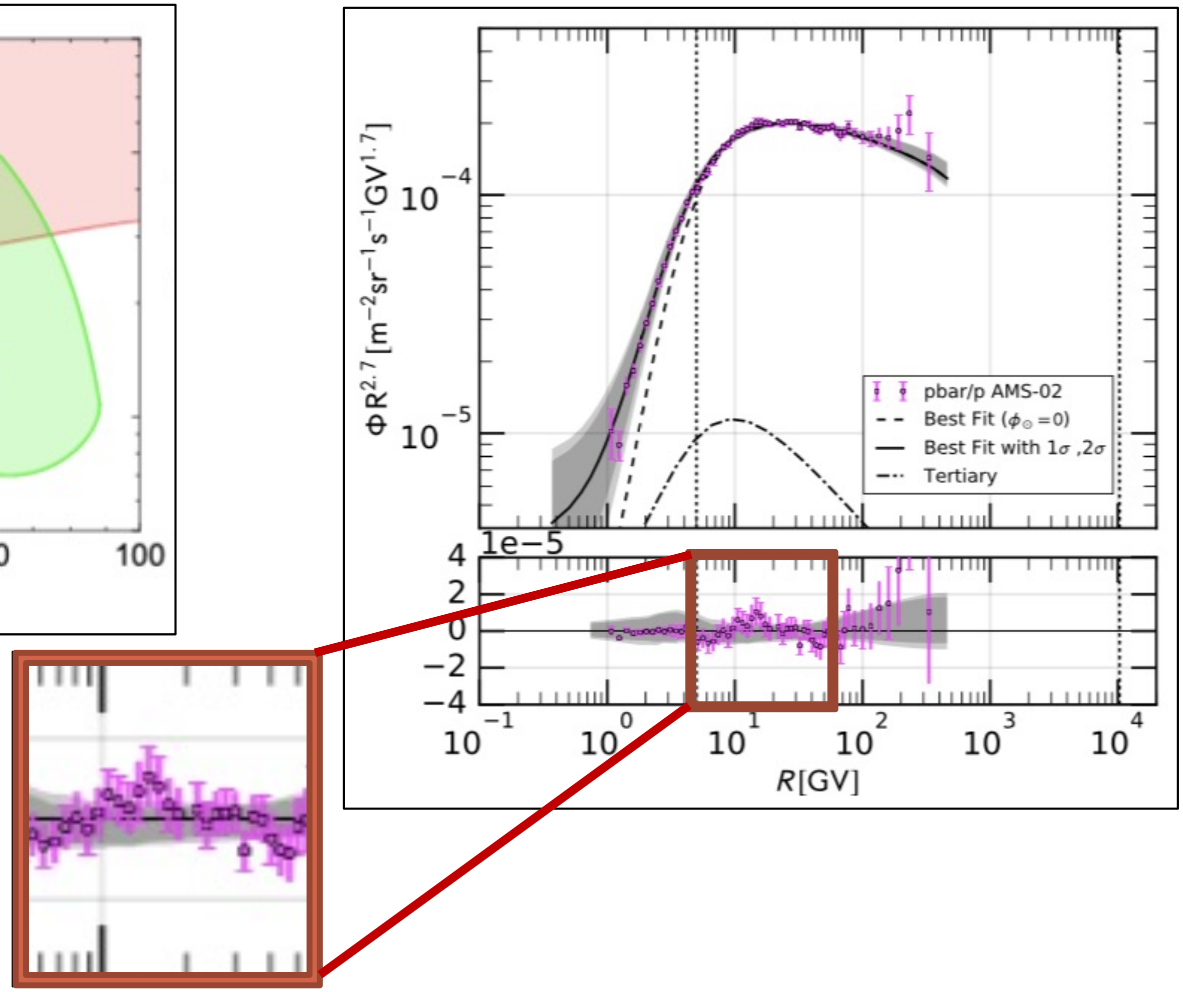


Fermi Collaboration, arXiv:1611.03184

The Cosmic-Ray Antiproton Excess

- There is a small excess of ~10-20 GeV cosmic-ray antiprotons in the AMS data, which at face value is quite statistically significant, ~4.5$\boldsymbol{\sigma}$ (Cuoco, et al., Cui, et al.)
- This excess is well fit by a ~40-100 GeV WIMP with a σv ~ 2×10^{-26} cm^3/s – a good match to the Galactic Center gamma-ray excess!





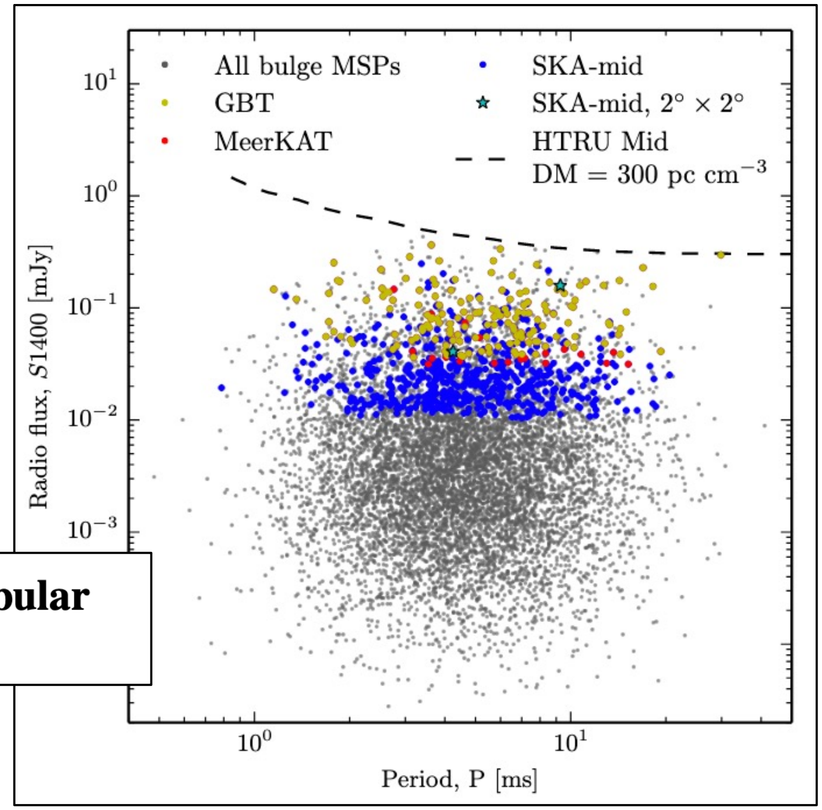
Cuoco et al., arXiv:1610.03071
Cui et al., arXiv:1610.03840
Cholis, DH, Linden, arXiv:1903.02549
Cuoco et al., arXiv:1903.01472
Reinert, Winkler, arXiv:1712.00002

Radio Searches for Inner Galaxy MSPs

- If MSPs generate the GeV excess, future deep radio surveys should be able to detect the pulsed radio emission from these objects
- After ~10^2 hours of observation, Green Bank should detect ~1-2 Inner Galaxy MSPs
- Dozens should be detectable with MeerKAT (after a similar exposure)
- Hundreds should be detectable with SKA

- MeerKAT was commissions in 2016, and has already announced their first MSP discoveries (far from Inner Galaxy), arXiv:2103.04800

Eight new millisecond pulsars from the first MeerKAT globular cluster census



- First light for SKA is projected for 2027

Calore, Di Mauro, Donato, Hessels, Weniger, arXiv:1512.06825