

# Dark Matter, Pulsars, and the Galactic Center Gamma-Ray Excess

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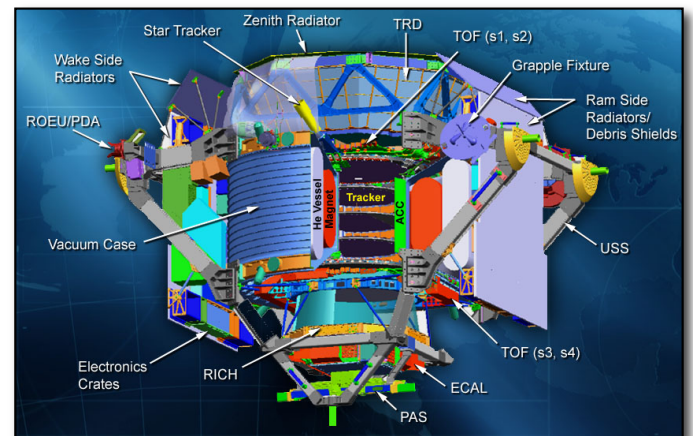
# The Motivation for Indirect Searches

- To account for the observed dark matter abundance, a thermal relic must have an annihilation cross section (at freeze-out) of  $\sigma v \sim 2 \times 10^{-26} \text{ cm}^3/\text{s}$
- Although many model-dependent factors can cause the dark matter to possess a somewhat lower or higher annihilation cross section today, most models predict current annihilation rates that are within an order of magnitude or so of this estimate
- Indirect detection experiments that are sensitive to dark matter annihilating at approximately this rate will be able to test a significant fraction of WIMP models

**Fermi**

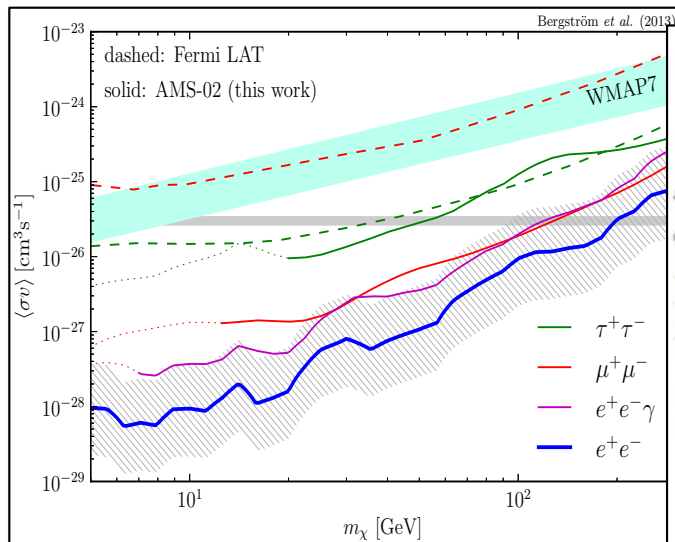


**AMS-02**

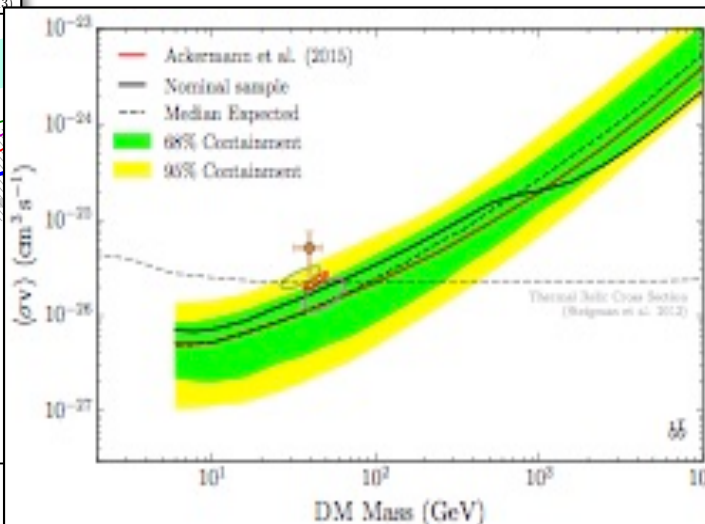


# Constraints from Indirect Detection

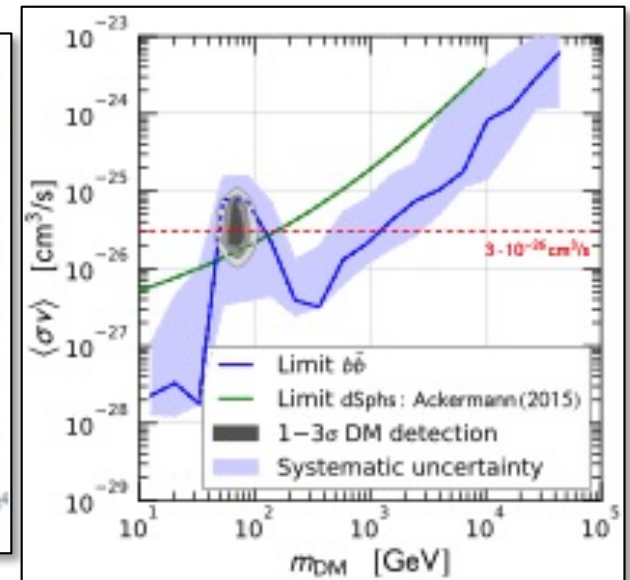
- A variety of gamma-ray strategies (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements from AMS, are currently sensitive to dark matter with the annihilation cross section predicted for a simple thermal relic, for masses up to  $\mathcal{O}(100)$  GeV
- This program is not a fishing expedition, but is testing a wide range of well-motivated dark matter models



Bergstrom, et al,  
arXiv:1306.3983



Fermi Collaboration,  
arXiv:1611.03184



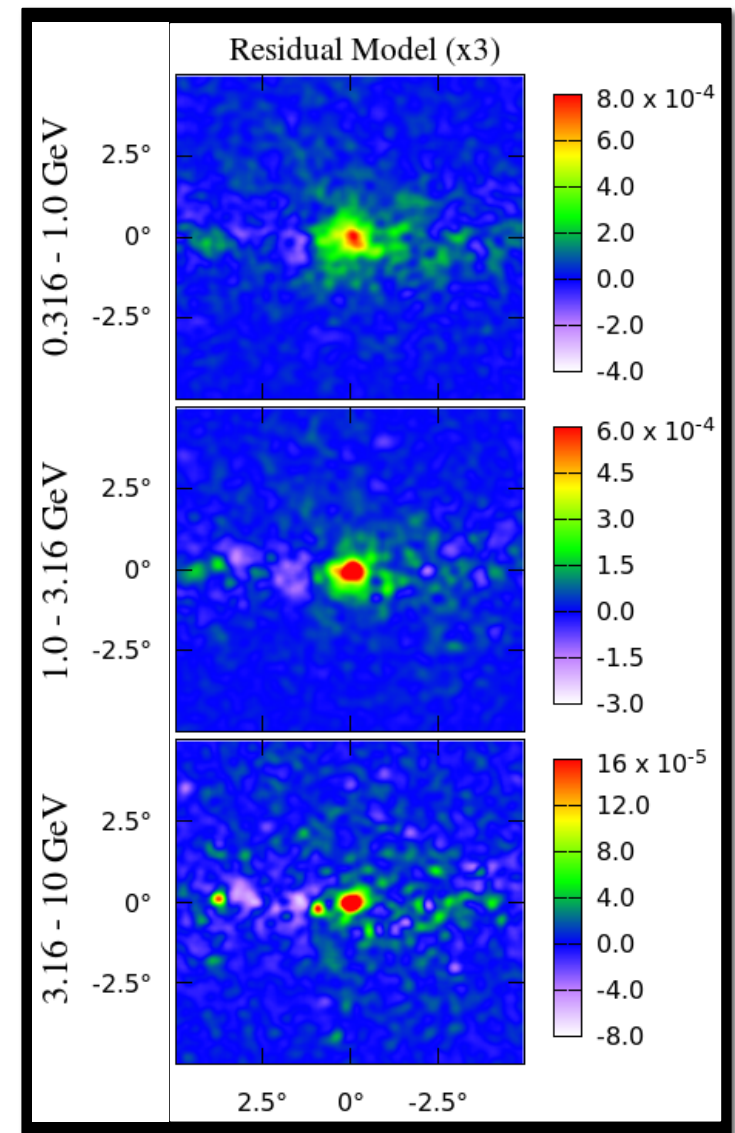
Cuoco, et al., arXiv:1610.03071  
Cui, et al. arXiv:1610.03840

# 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 predicted from annihilating dark matter

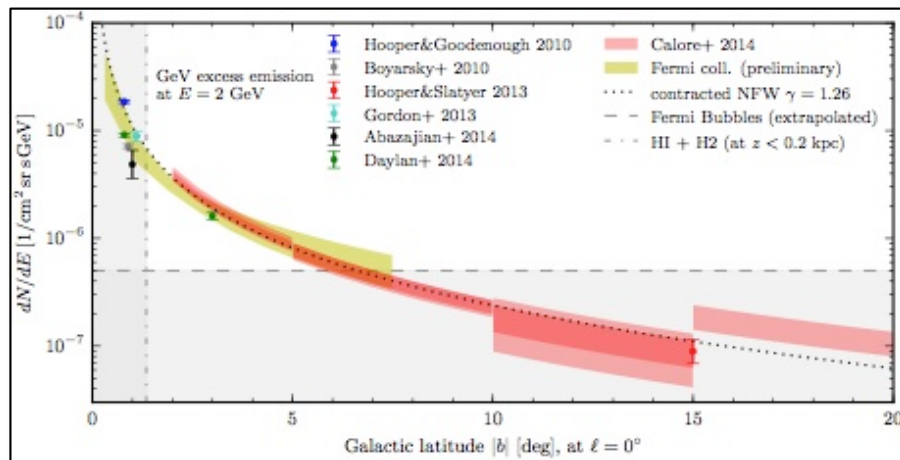
## Among other references, see:

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

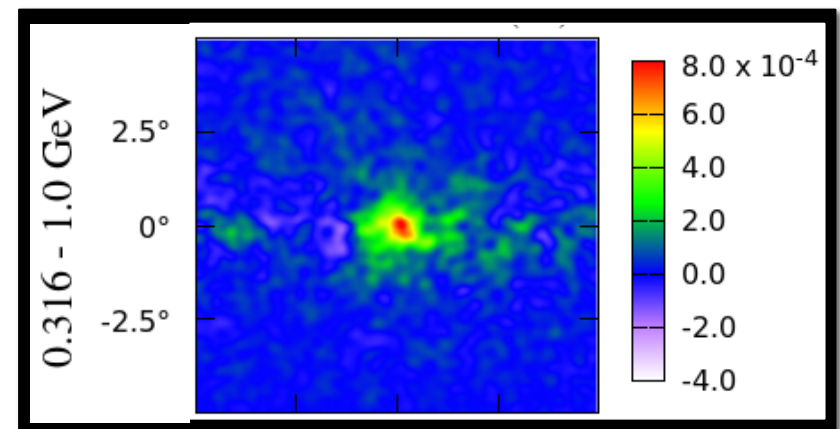


# Morphology

- The GeV excess exhibits approximate spherical symmetry about the Galactic Center (axis ratios within  $\sim 20\%$  of unity), with a flux that falls as  $\sim r^{-2.4}$  out to at least  $\sim 10^\circ$
- If interpreted as annihilating dark matter, this implies  $\rho_{\text{DM}} \sim r^{-1.2}$  out to at least  $\sim 1.5$  kpc, similar to and only slightly steeper than the canonical NFW profile
- Unlike stellar populations, we expect dark matter annihilation products to exhibit approximate spherical symmetry (see, for example, Bernal, Necib and Slatyer, arXiv:1606.00433)



Calore, Cholis, Weniger (2014)

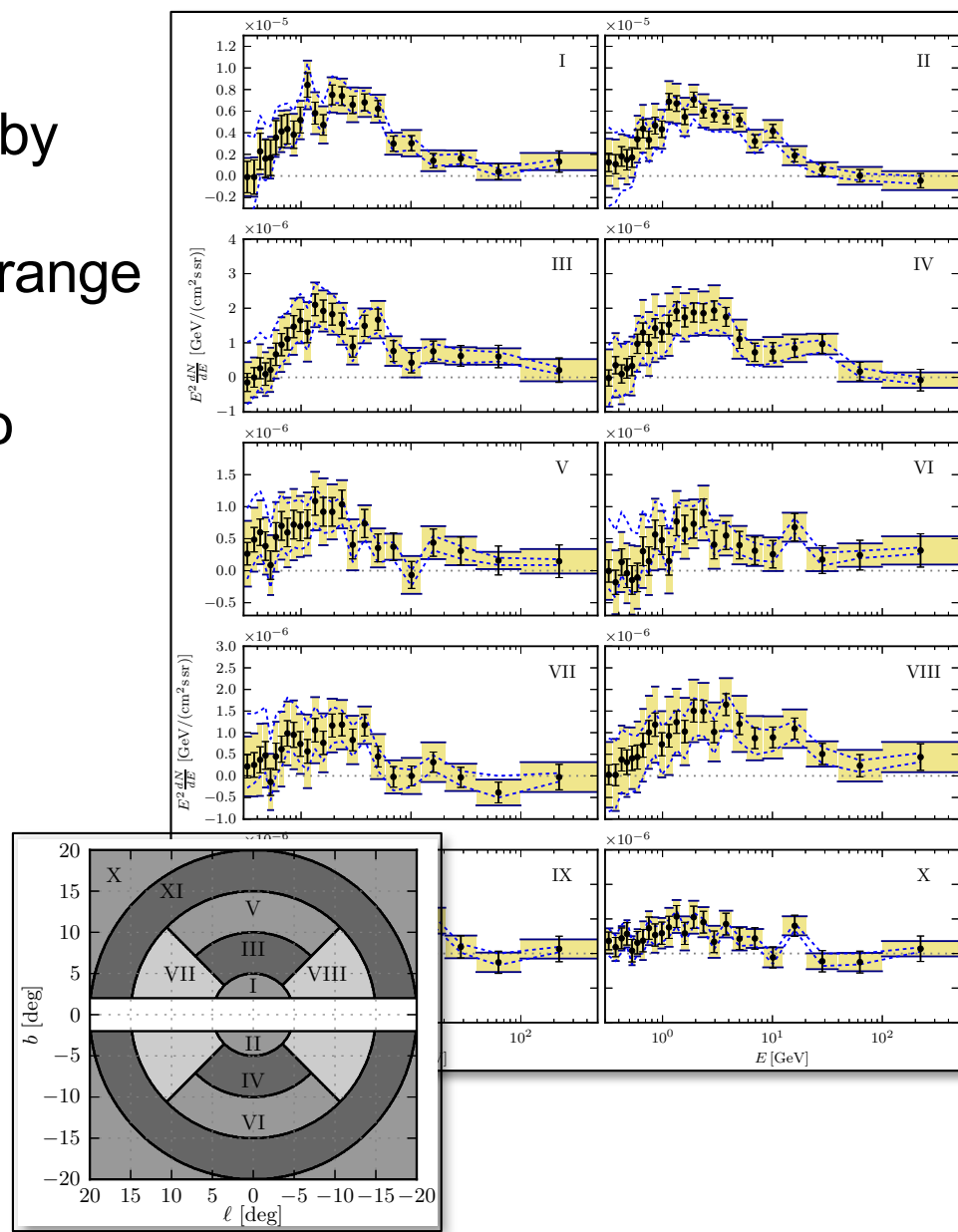


Daylan, et al. (2014)

# Spectrum

- The spectrum of the excess is well fit by a  $\sim 20$ -65 GeV particle annihilating to quarks or gluons (and also by a wide range of hidden sector dark matter models)
- The shape of the spectrum appears to be uniform across the Inner Galaxy

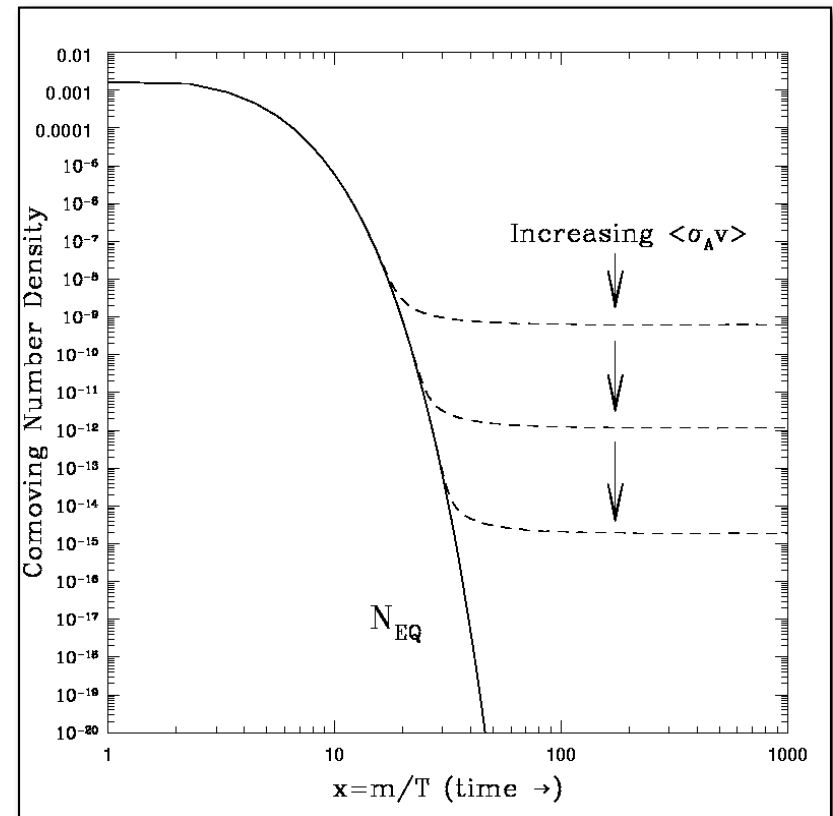
Channel	$\langle\sigma v\rangle$ ( $10^{-26} \text{ cm}^3 \text{ s}^{-1}$ )	$m_\chi$ (GeV)	$\chi^2_{\min}$	$p$ -value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$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

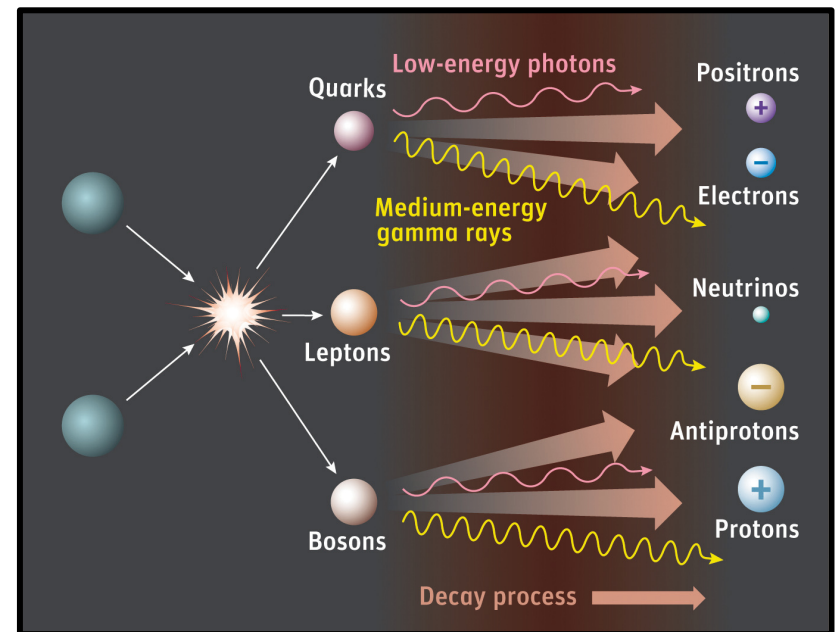
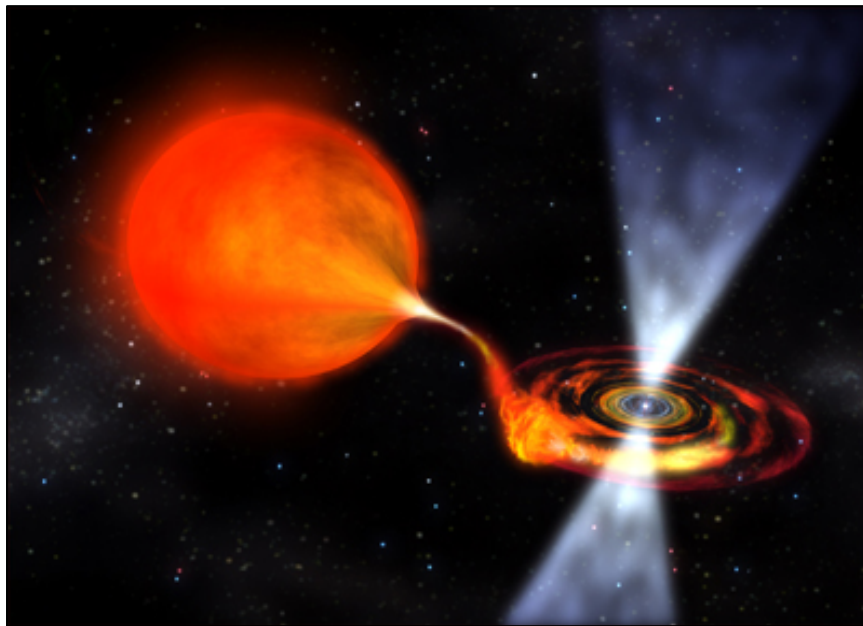
# Intensity

- To normalize the observed excess, the dark matter particles must annihilate with a cross section of  $\sigma v \sim 10^{-26} \text{ cm}^3/\text{s}$
- This is approximately equal to the value of the cross section that is required to generate the measured dark matter abundance through thermal freeze-out in the early universe



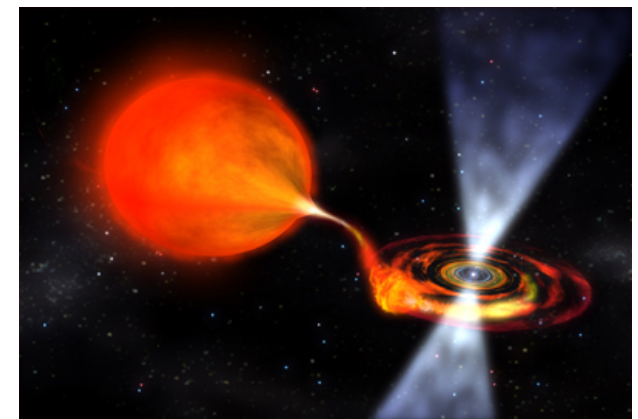
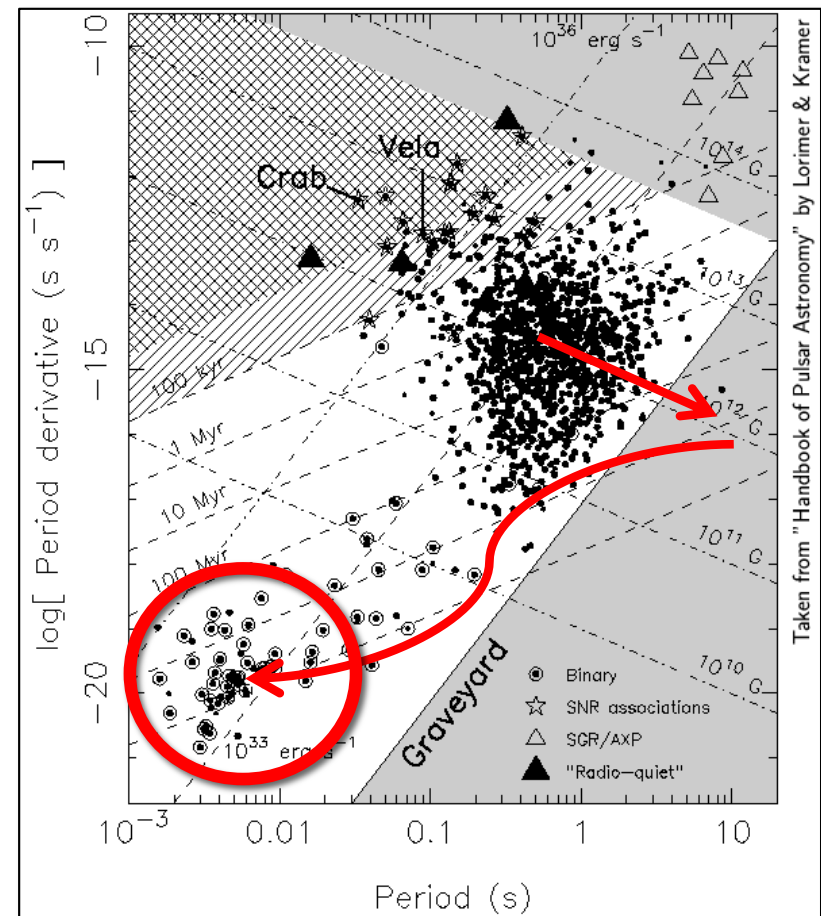
# What Produces the Excess?

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



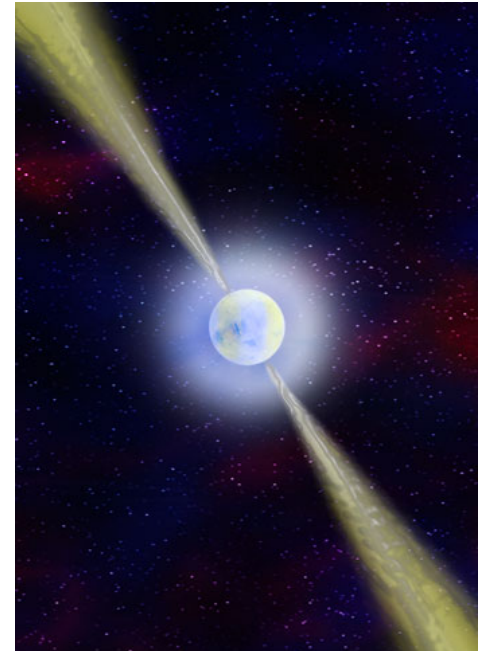
# Millisecond Pulsars

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



# Millisecond Pulsars and The Galactic Center Gamma-Ray Excess

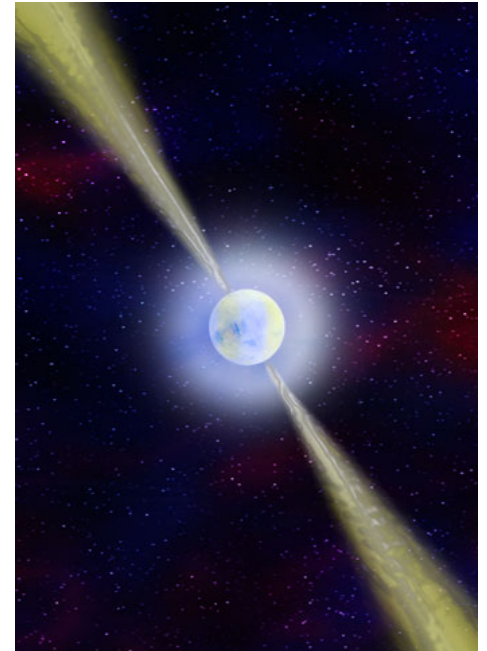
**Arguments in Favor of Pulsars:**



# Millisecond Pulsars and The Galactic Center Gamma-Ray Excess

## Arguments in Favor of Pulsars:

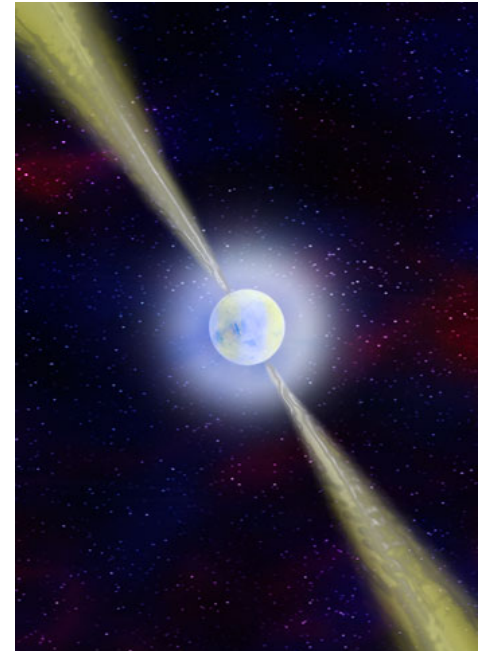
- The gamma-ray spectrum of observed pulsars



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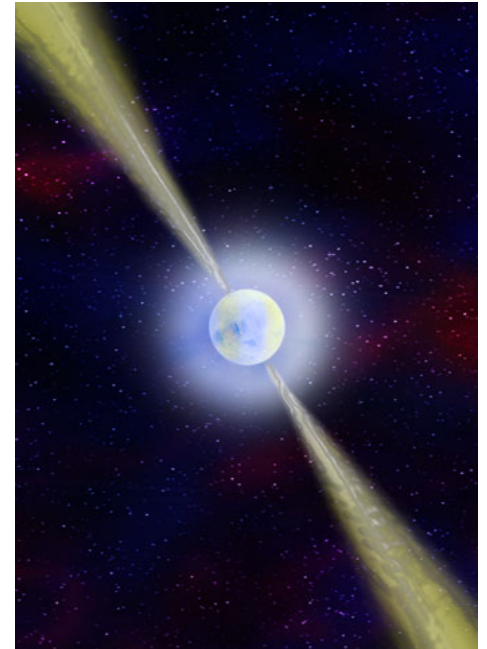
- The gamma-ray spectrum of observed pulsars
- Pulsars are known to exist



# Millisecond Pulsars and The Galactic Center Gamma-Ray Excess

## Arguments in Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- Pulsars are known to exist
- Claims of small-scale power in the gamma-ray emission from the Inner Galaxy
- Claims that the excess traces the Galactic Bulge/Bar



# Small Scale Power Among Inner Galaxy $\gamma$ -Rays

- In 2015, two groups found that the  $\sim$ 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  $\sim 10^\circ$  of the Galactic Center (masking within  $2^\circ$  of the Galactic Plane) is *clumpy*, potentially indicative of an unresolved point source population
- Bartels et al. reach a qualitatively similar conclusion employing a wavelet technique

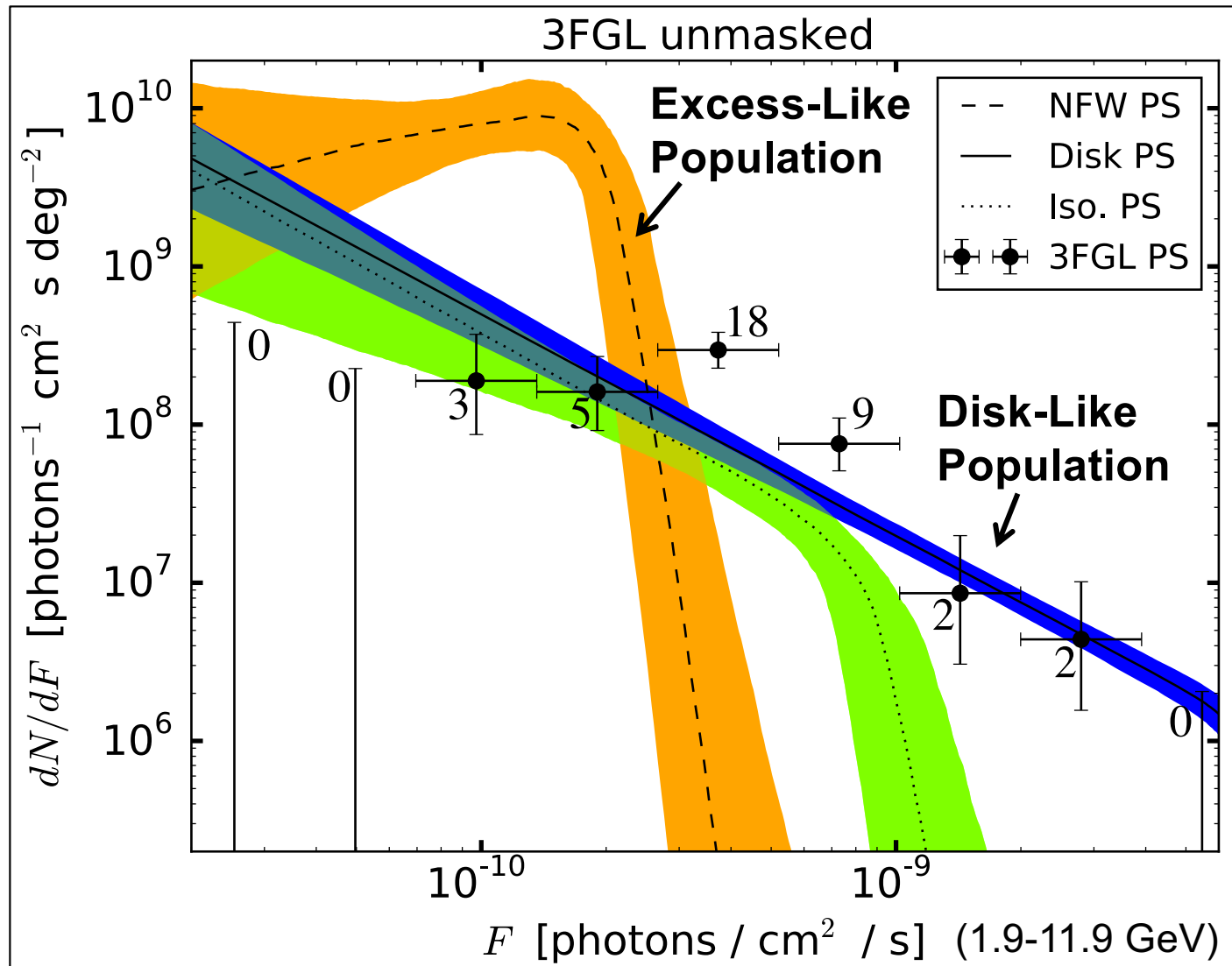
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124

Bartels, Krishnamurthy, Weniger, arXiv:1506.05104

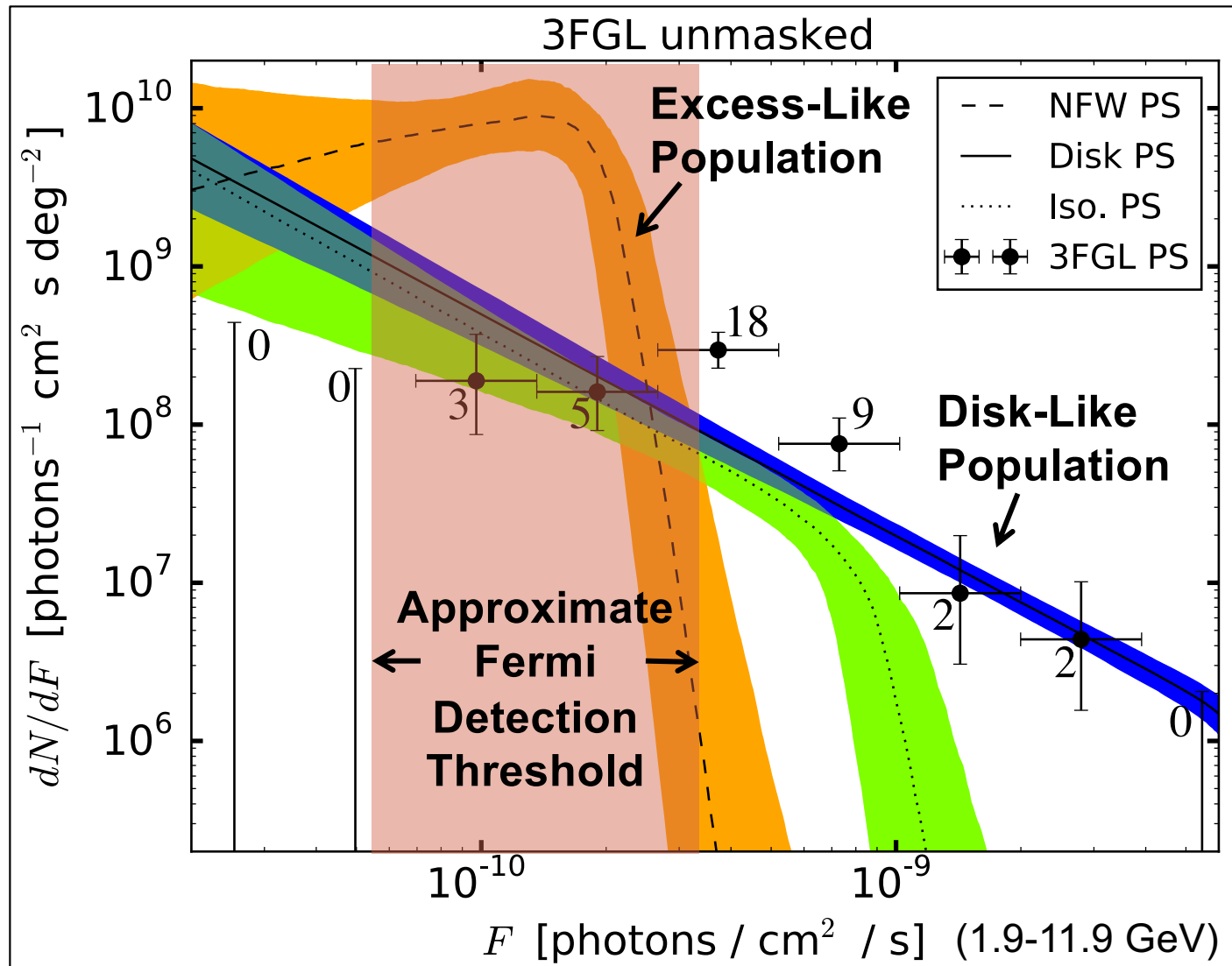
# Small Scale Power Among Inner Galaxy $\gamma$ -Rays

- A typical Fermi Inner Galaxy analysis might include the following set of spatial templates:
  - 1) Galactic diffuse emission
  - 2) Fermi Bubbles
  - 3) Isotropic background
  - 4) Known point sources
  - 5) Dark matter annihilation products (generalized NFW<sup>2</sup>)
  
- Lee *et al.* then add a number of non-Poissonian templates to model the distribution of unresolved point sources:
  - 5) Isotropically distributed point sources
  - 6) Disk-correlated point sources
  - 7) NFW<sup>2</sup> correlated point sources

# Small Scale Power Among Inner Galaxy $\gamma$ -Rays



# Small Scale Power Among Inner Galaxy $\gamma$ -Rays



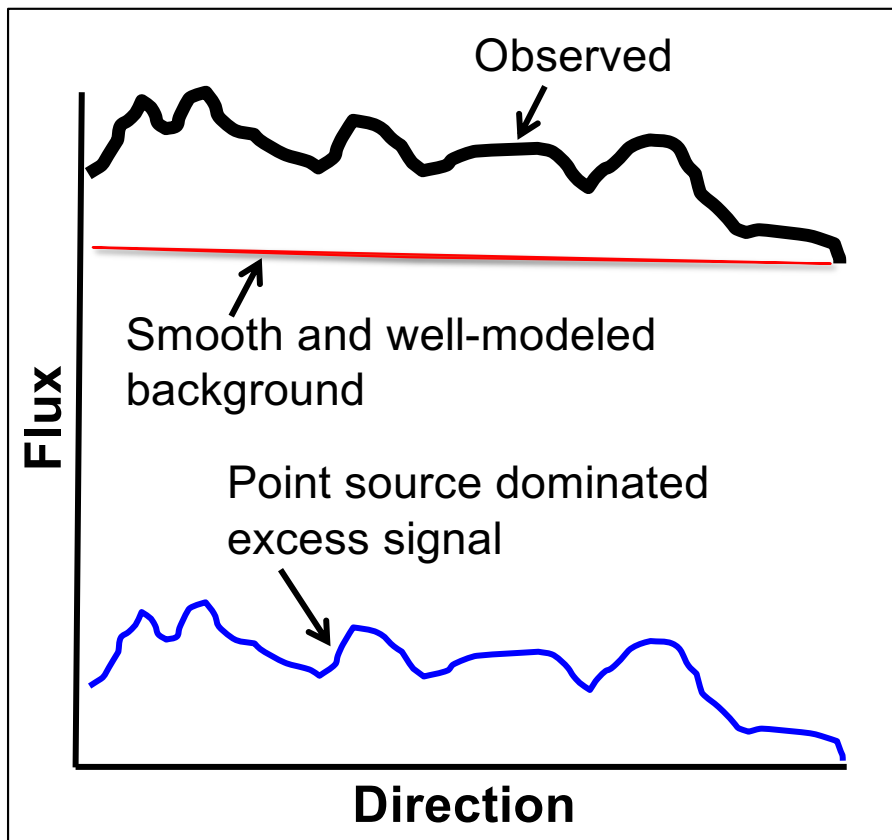
**Bottom Line:** A population of  $\sim 10^3$  point sources with luminosities near Fermi's detection threshold could potentially account for the GeV Excess

# Evidence For 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

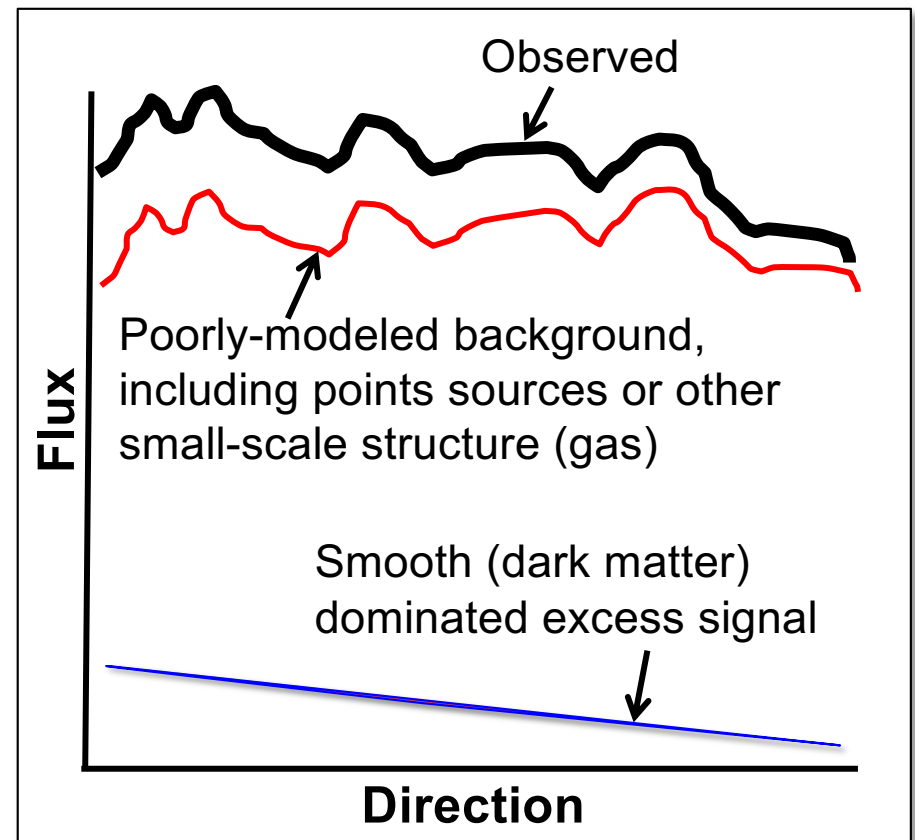
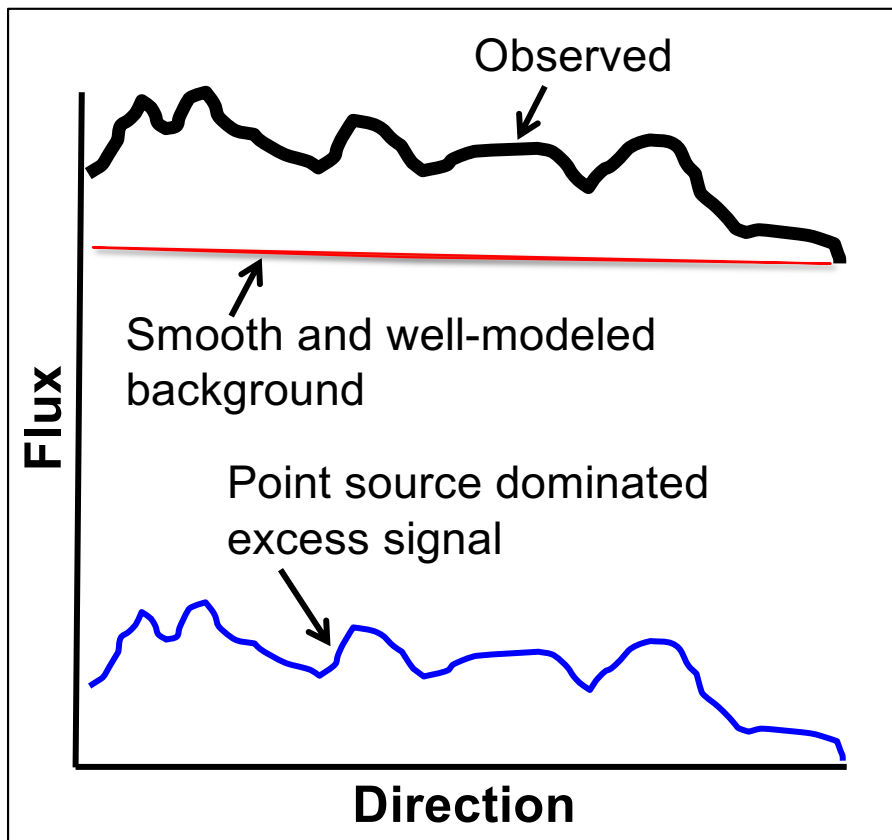
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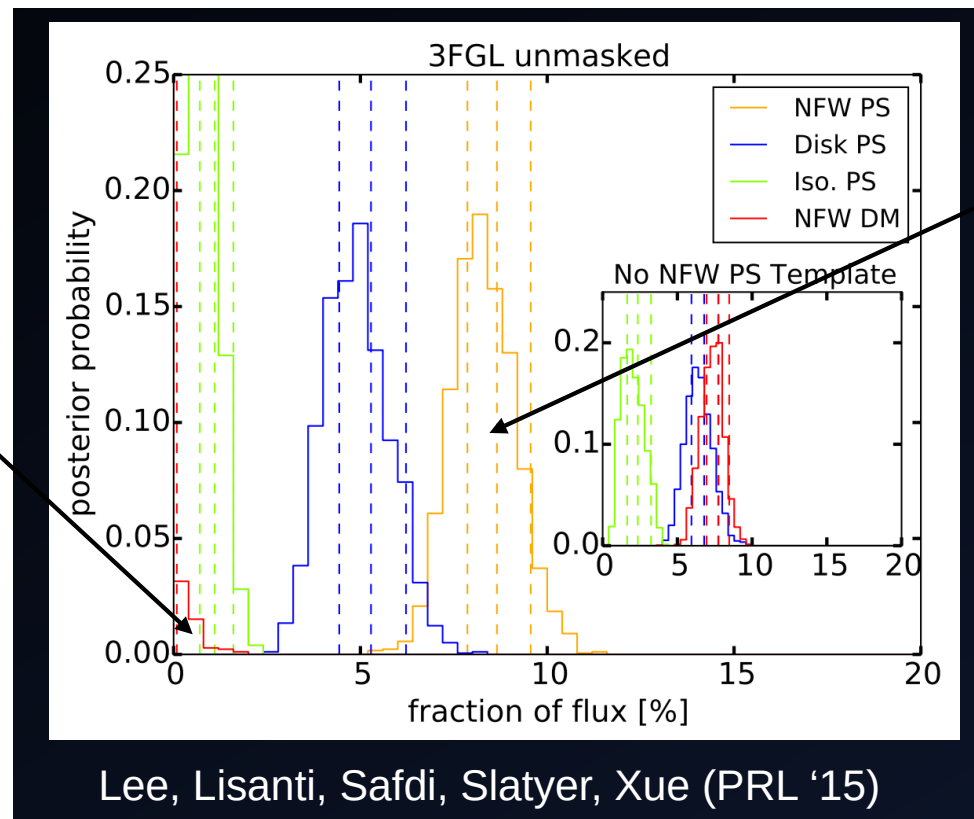
# DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer,  
arXiv:1904.08430

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See Leane and Slatyer,  
arXiv:1904.08430

Evidence against  
any significant  
amount of dark  
matter annihilation



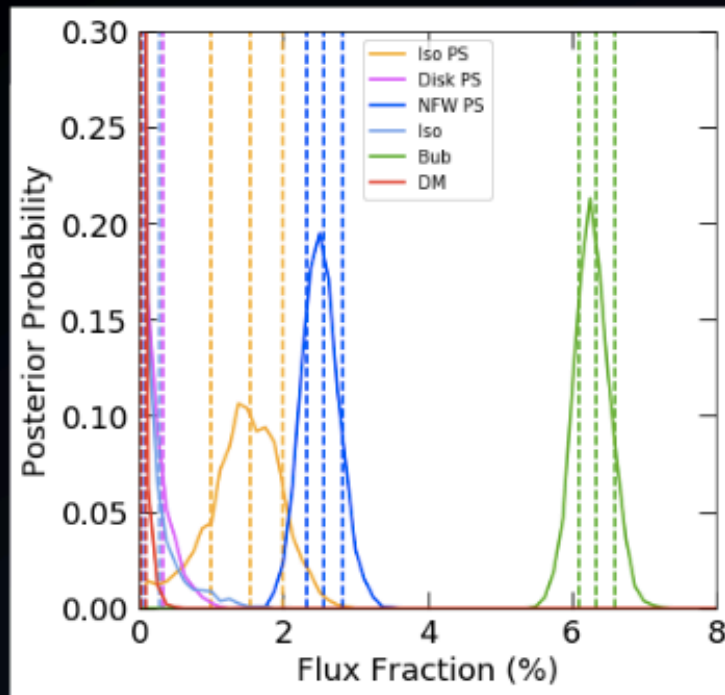
Evidence for  
NFW<sup>2</sup> Distributed  
Point Sources

*To what extent could inadequate templates be biasing these results?*

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See Leane and Slatyer,  
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## FERMI DATA



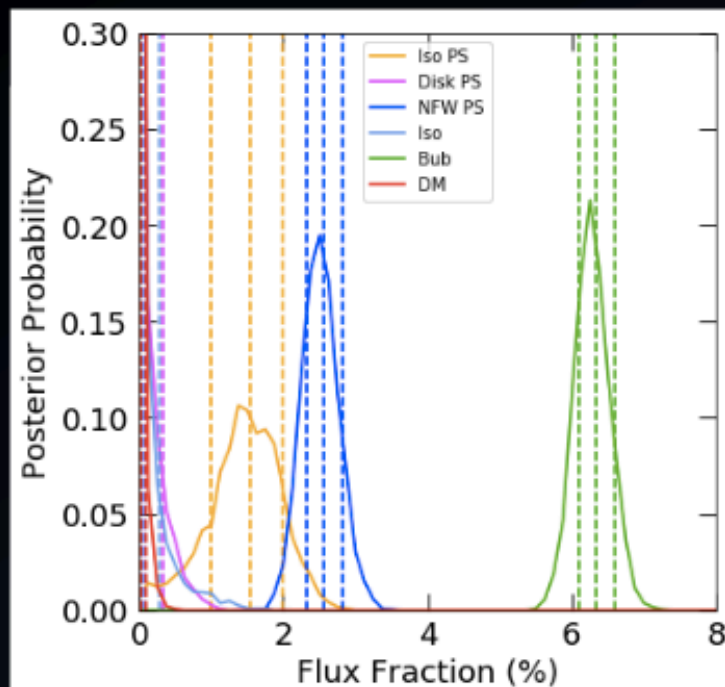
Here is the result that Leane and Slatyer get using the same procedure as Lee *et al.*

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

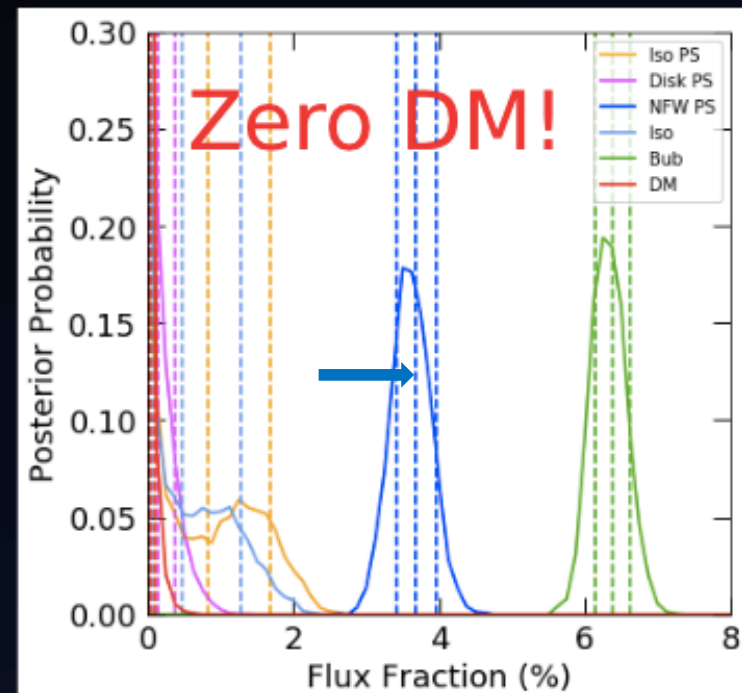
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## FERMI DATA



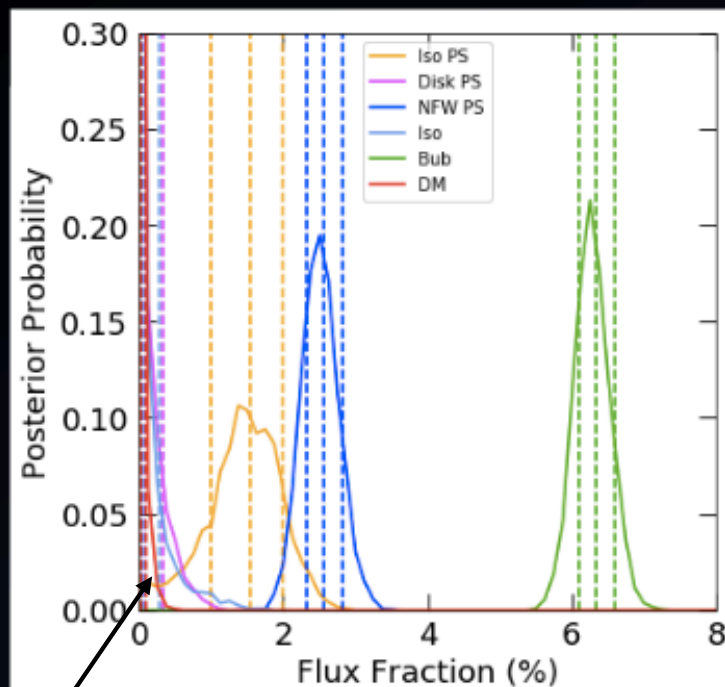
## INJECTED DM SIGNAL + DATA



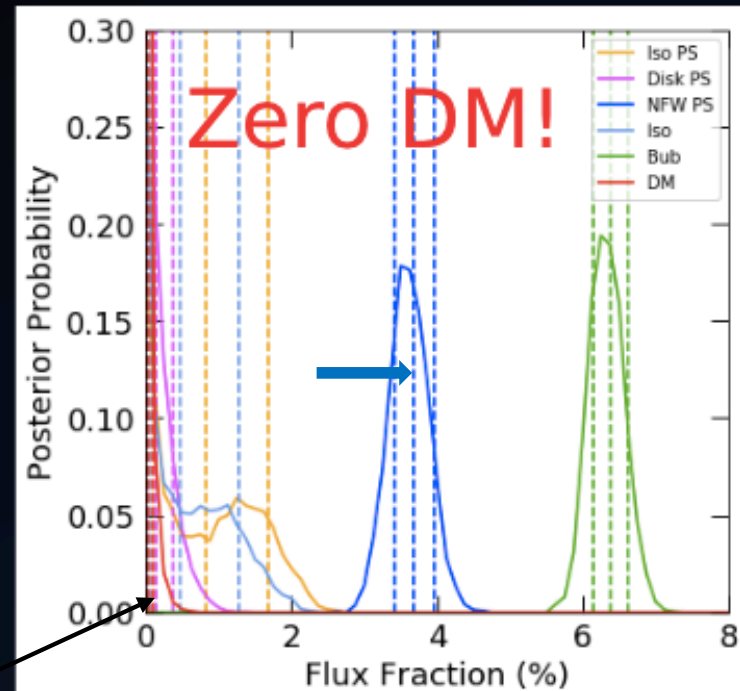
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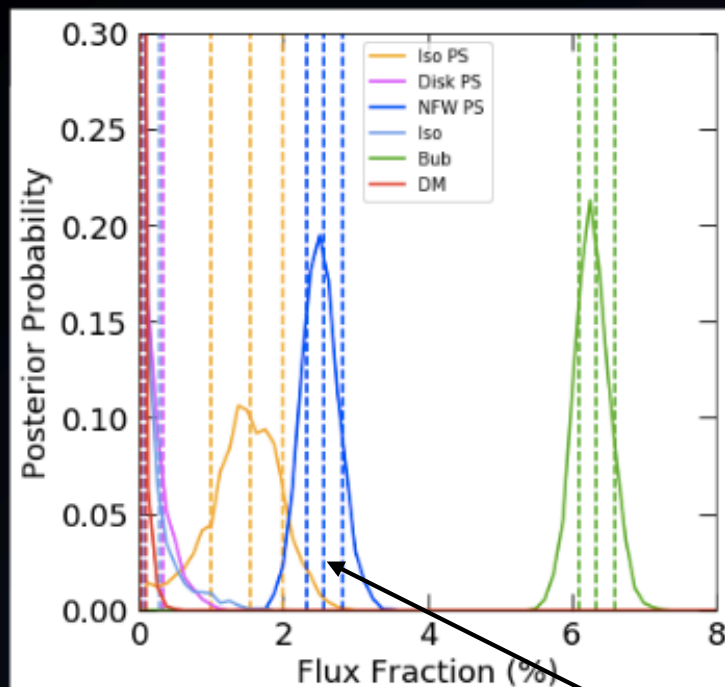


Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

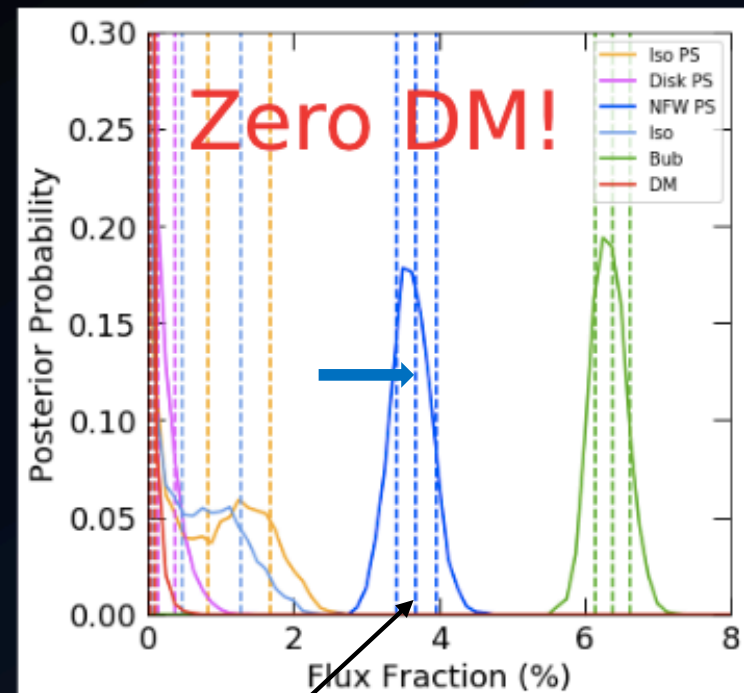
# DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer,  
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## FERMI DATA



## INJECTED DM SIGNAL + DATA



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

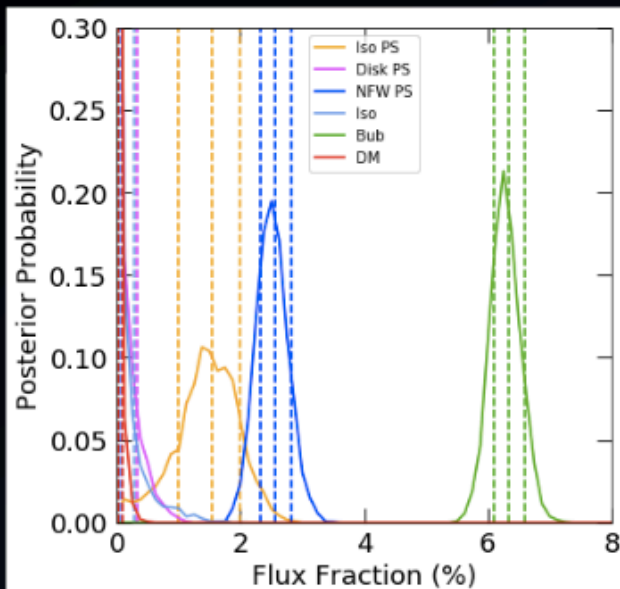
See Leane and Slatyer,  
arXiv:1904.08430

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

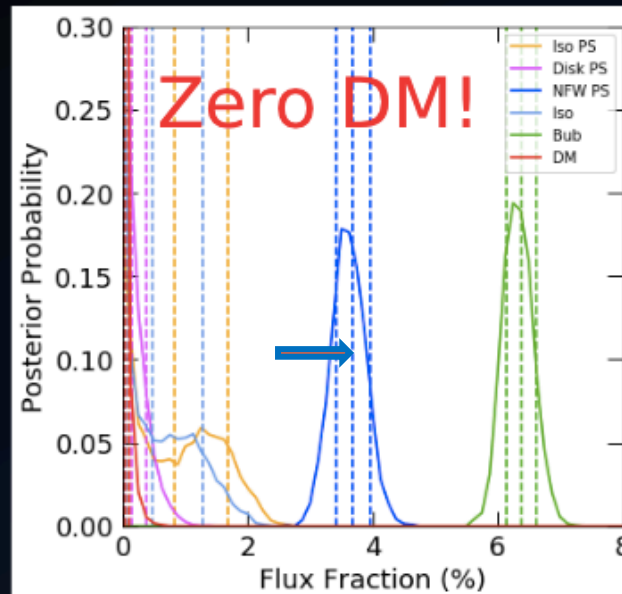
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arXiv:1904.08430

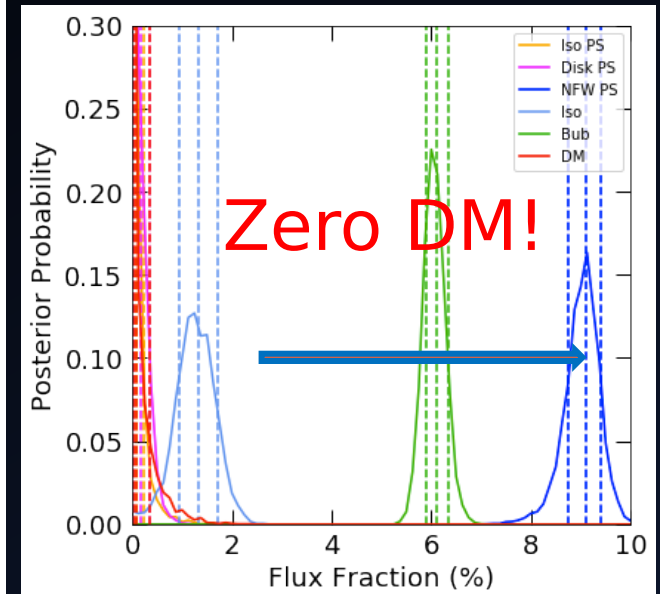
FERMI DATA



INJECTED DM SIGNAL + DATA



LARGER INJECTED DM SIGNAL + DATA



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

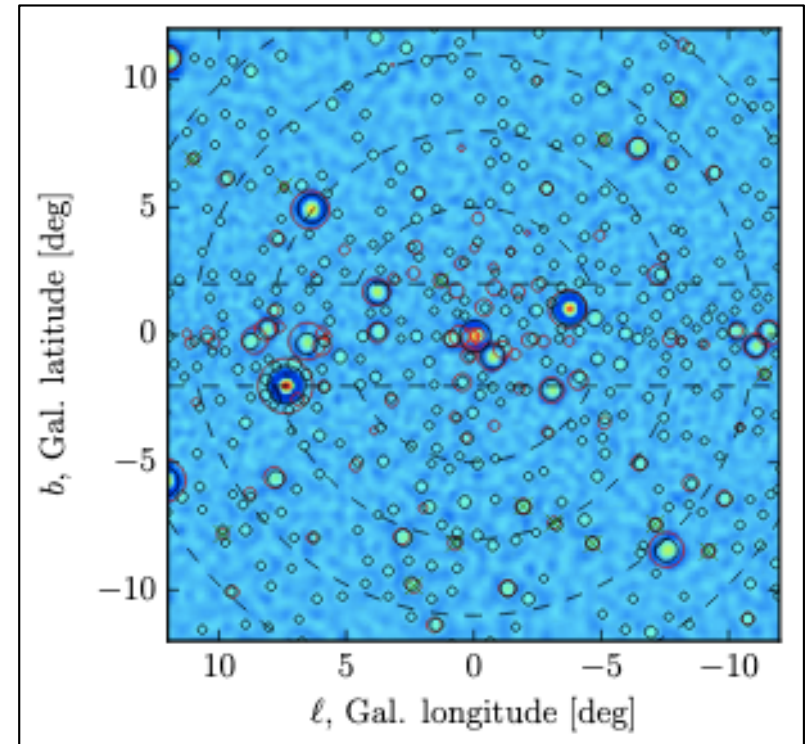
Bottom Line:

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

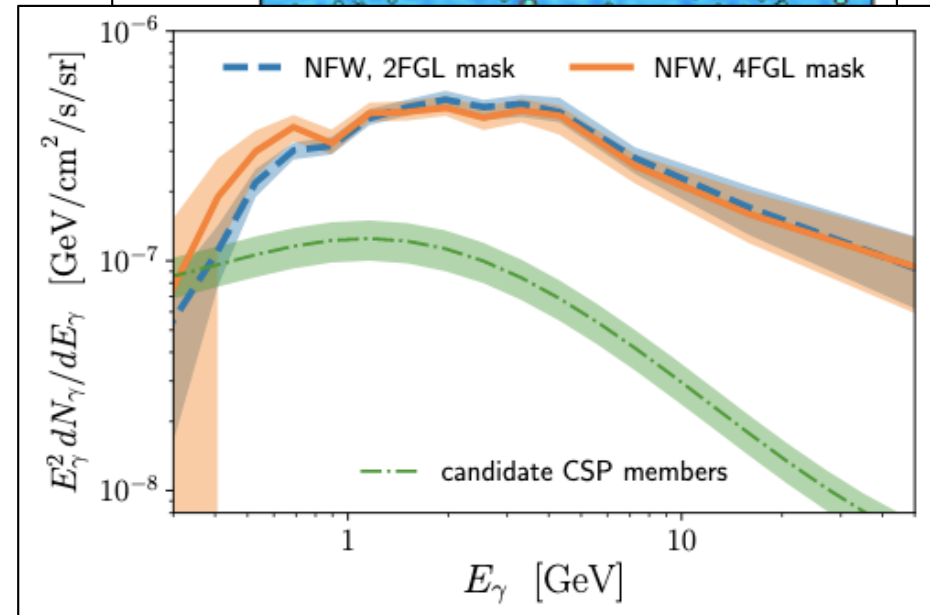
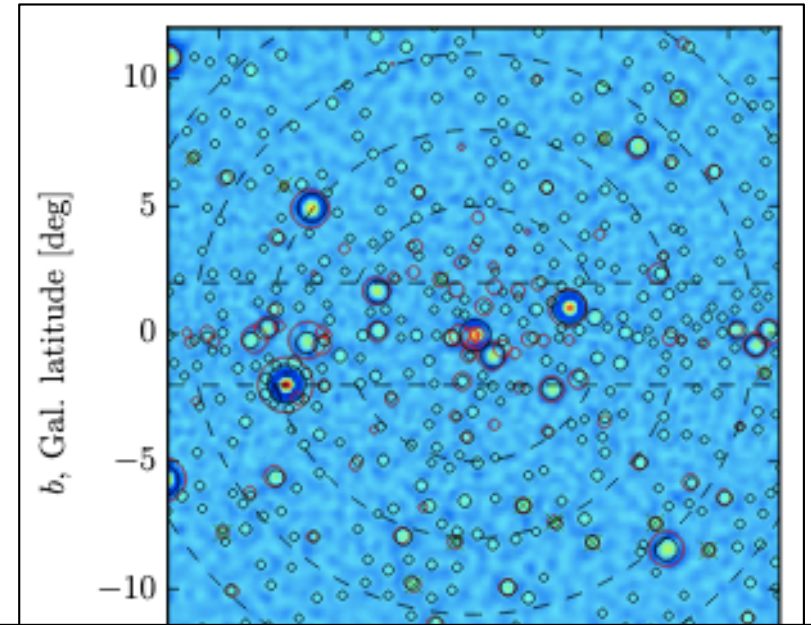
# Wavelet Analyses and GC Point Sources

- 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



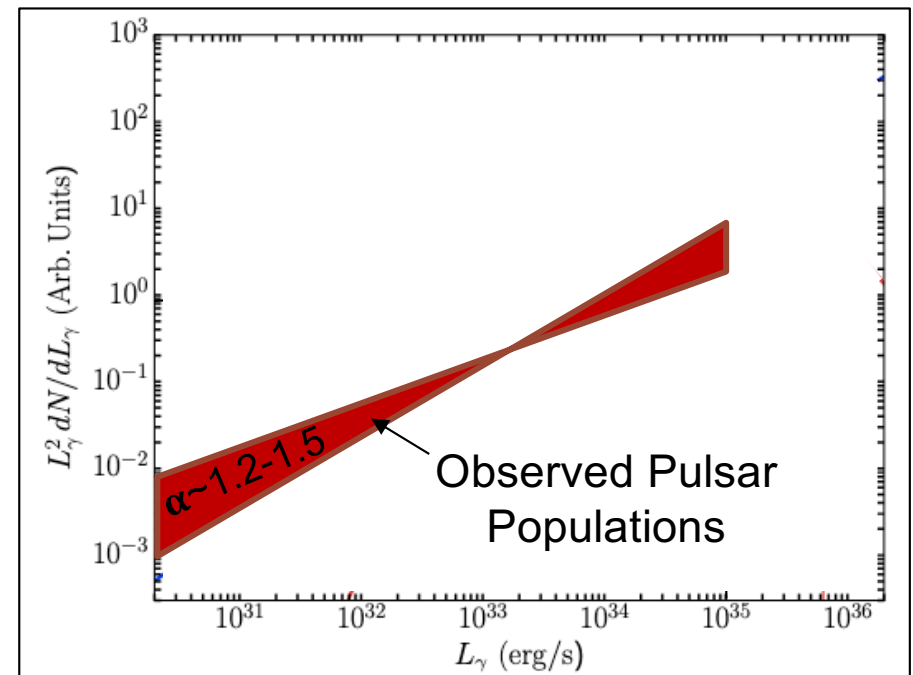
# Wavelet Analyses and GC Point Sources

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- 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 source, Zhong *et al.* find no evidence that the excess is produced by point sources



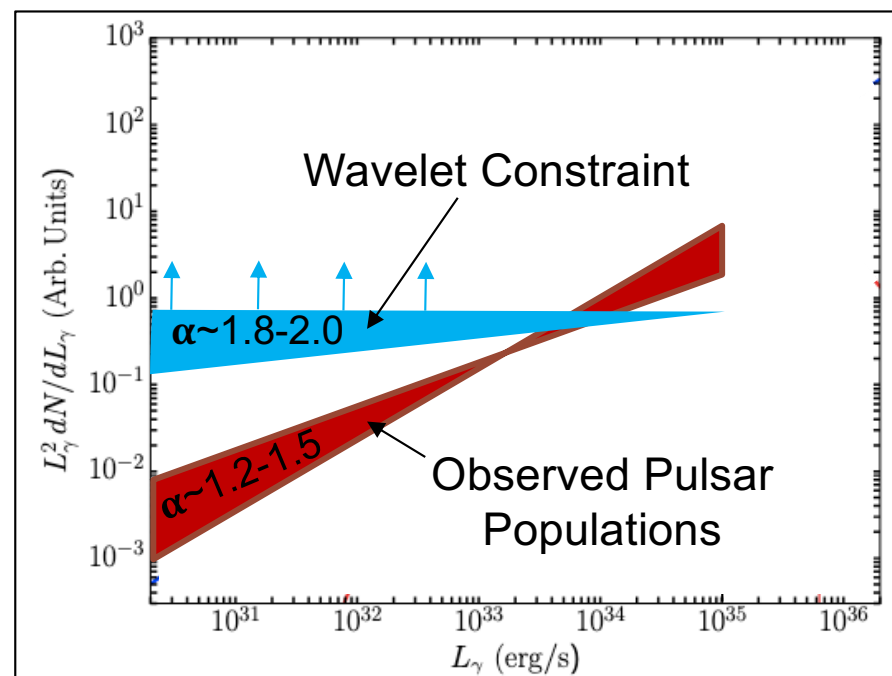
# Tension with Pulsar Interpretations

- Furthermore, the wavelet technique can be used to place stringent constraints on the luminosity function of any point source population that could potentially be responsible for the Galactic Center excess
- Observed populations of millisecond pulsars (in the disk and in globular clusters) have luminosity functions that peak near  $L_\gamma \sim 10^{34}$ - $10^{35}$  erg/s (in  $L^2 dN/dL$  units)
- If modeled as a power-law,  $dN/dL \sim L^{-\alpha}$ , such observations favor  $\alpha \sim 1.2$ - $1.5$  (for  $L_{\text{max}} \sim 10^{35}$  erg/s)



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- In contrast, the results of Zhong *et al.* constrain  $\alpha > 1.9$ , in strong contrast to observed pulsar populations
- Put another way, to explain the GC excess without dark matter would require  $\sim 3 \times 10^6$  pulsars with  $L > 10^{29}$  erg/s
- No proposed pulsar population models predict anything close to so many pulsars in the Inner Galaxy



# Bulge/Bar-Like vs DM-Like Morphology

- In three recent papers (Macias *et al.* 2016, Bartels *et al.* 2017, Macias *et al.* 2017), it has been argued that the Fermi excess is better fit by a template that traces the stellar population of the Galactic Bulge and Bar than one that is DM-like, favoring MSP interpretations of the gamma-ray excess
- This result, however, is highly sensitive to the choice of templates that are adopted (the recent analysis of Di Mauro 2021, for example, reaches the opposite conclusion, preferring a spherical morphology for the excess)
- The systematic uncertainties associated with the choice of templates are large, and could explain the variation that is found between these different studies
- The data cannot be said to robustly prefer a bulge/bar-like or dark matter-like morphology at this time

Macias, Gordan, Crocker, Coleman, Paterson, Horiuchi, Pohl, arXiv:1611.06644

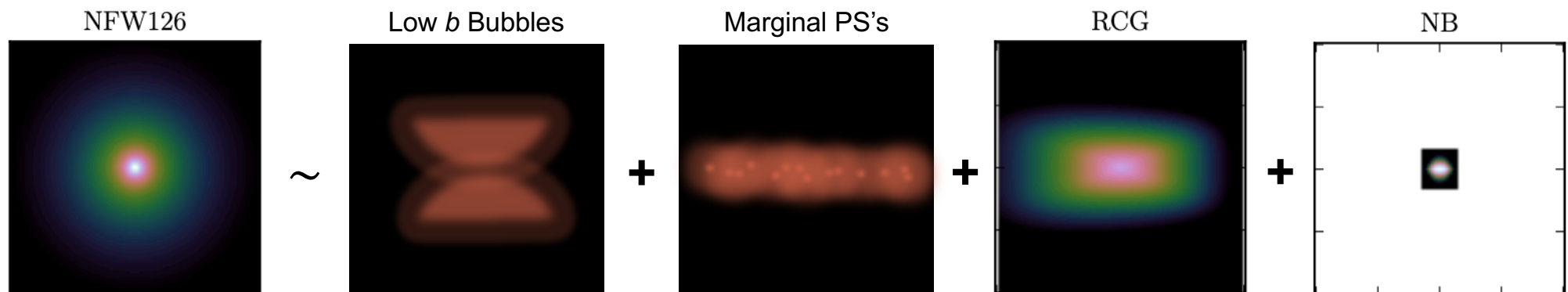
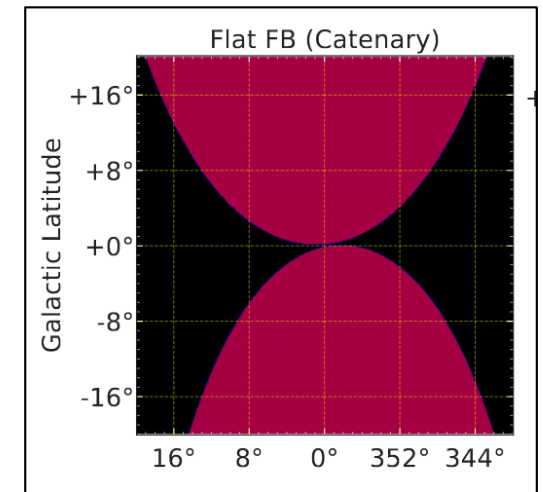
Bartels, Storm, Weinger, Calore, arXiv:1711.04778

Macias, Horiuchi, Kaplinghat, Gordan, Crocker, Nataf, arXiv:1901.03822

Di Mauro, arXiv:2101.04694

# Bulge/Bar-Like vs DM-Like Morphology

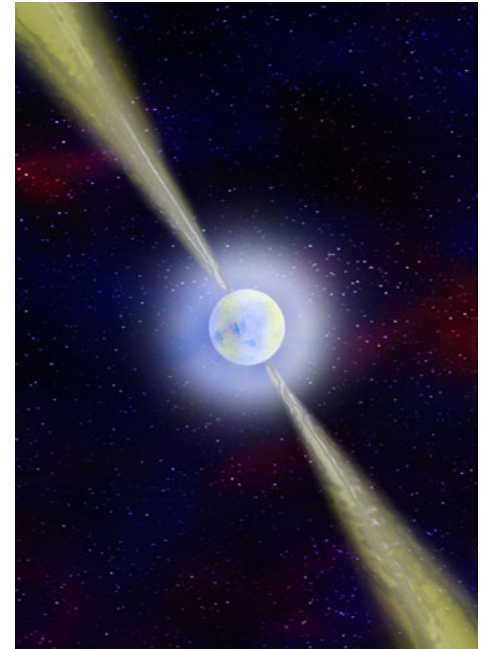
- The way in which we model the Fermi Bubbles can non-negligibly impact the inferred morphology of the excess
- The Bubbles are usually taken to be of uniform brightness, with well-defined edges; near the Galactic Plane, this is highly uncertain and poorly constrained
- There are also several dozen point source candidates in this region of the sky, most of which are clustered along the Galactic Plane; which of these are “real” depends on the templates used
- It would be easy for imperfections in these templates to cause a spherical excess to look bulge-like (or vice versa)



# Millisecond Pulsars and The Galactic Center Gamma-Ray Excess

## Arguments in Favor of Pulsars:

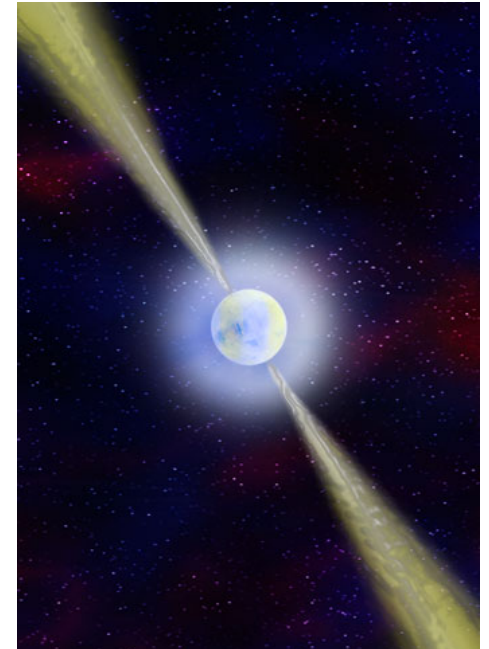
- The gamma-ray spectrum of observed pulsars
- Pulsars are known to exist
- Claims of small-scale power in the gamma-ray emission from the Inner Galaxy
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## Arguments Against Pulsars:

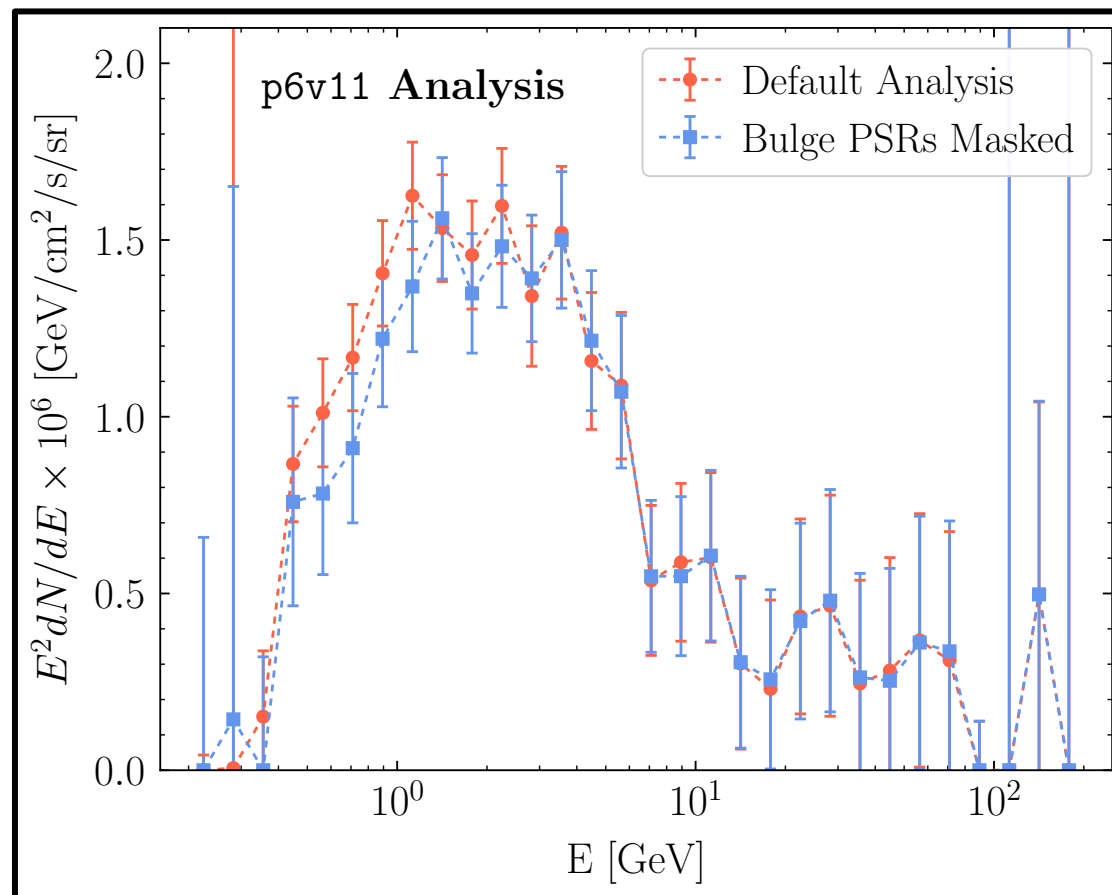
- No millisecond pulsars have been detected in the Inner Galaxy
- The measured luminosity function of gamma-ray pulsars
- The lack of low-mass X-ray binaries in the Inner Galaxy
- The relatively low luminosity of the TeV-scale emission from the Inner Galaxy

# 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

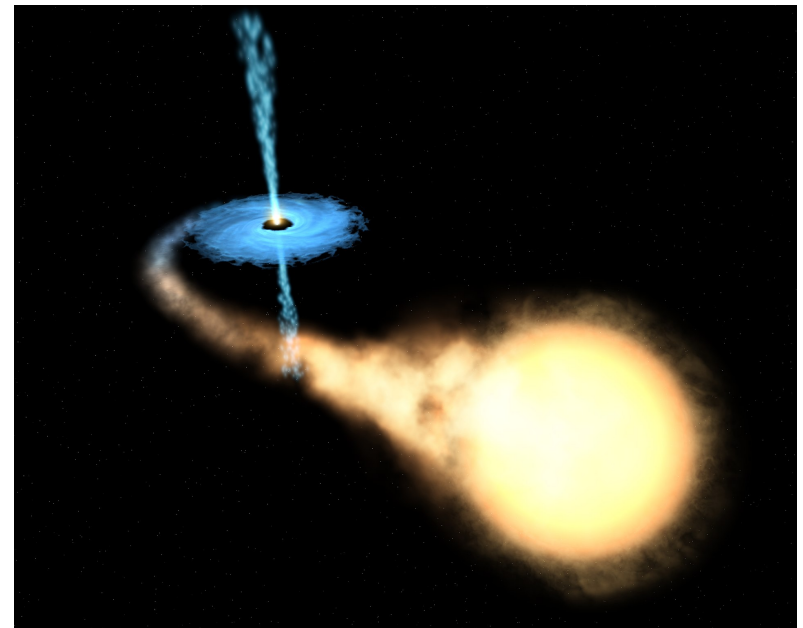
# Gamma-Ray Bright MSPs in The Inner Galaxy?

- 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



# Searches for Bright Low-Mass X-Ray Binaries

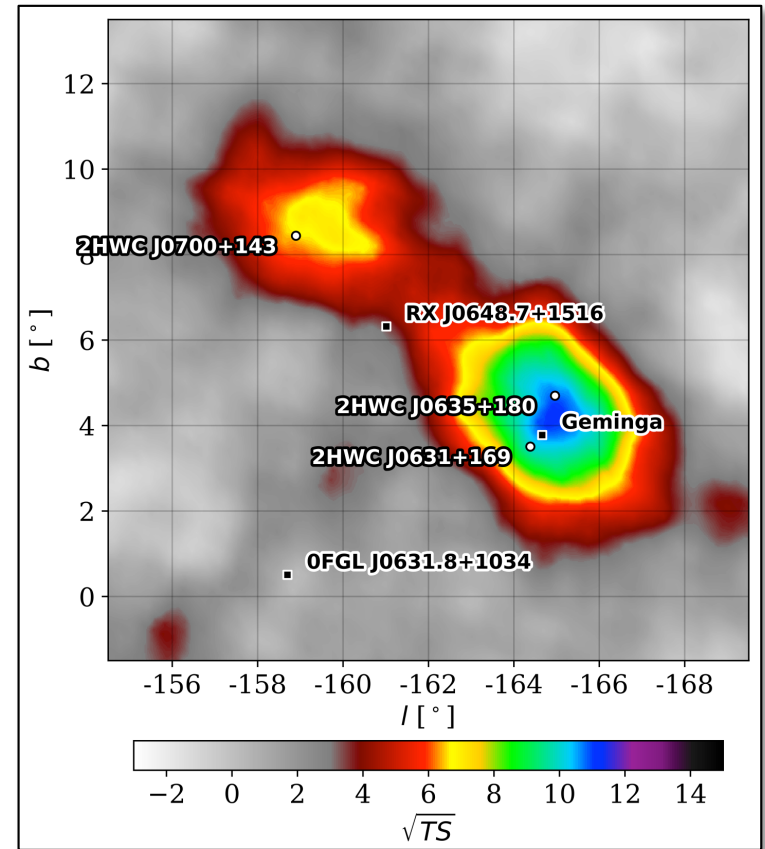
- Millisecond pulsars are formed when they are spun up by a binary companion; the precursors to MSPs are low-mass X-ray binaries (LMXBs)
- By measuring the ratio of the gamma-ray emission (from MSPs) to the number of bright LMXBs in globular clusters, and comparing this to the number of bright LMXBs in the Inner Galaxy, we can estimate the number of MSPs in the Inner Galaxy
- 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  $\sim 10^3$  LMXBs, but they actually detected 42
- Under our most conservative assumptions (assuming that all bright X-ray sources are LMXBs), we still find that less than 23% of the excess can originate from MSPs



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

# Millisecond Pulsars and TeV Halos

- Observations by the HAWC telescope 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  $\sim 10\%$  of the spindown power of young pulsars goes into the acceleration of these particles
- If MSPs also produce TeV halos with a similar efficiency, we could use the TeV-scale emission observed from the Inner Galaxy to constrain their abundance

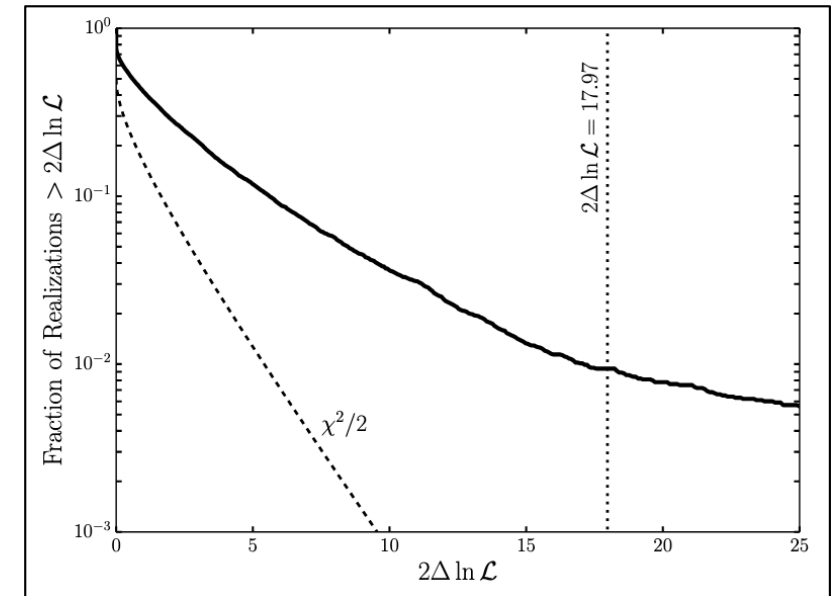
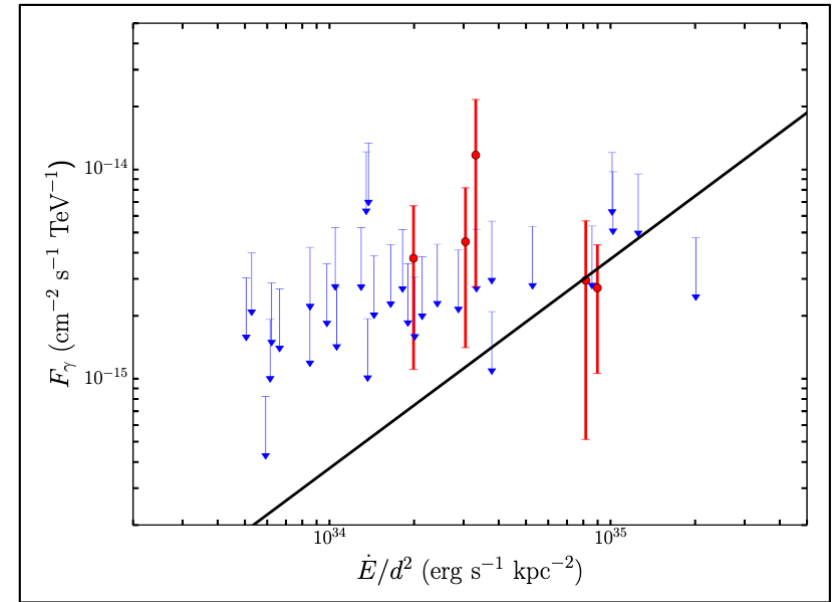


HAWC Collaboration, arXiv:1702.02992

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

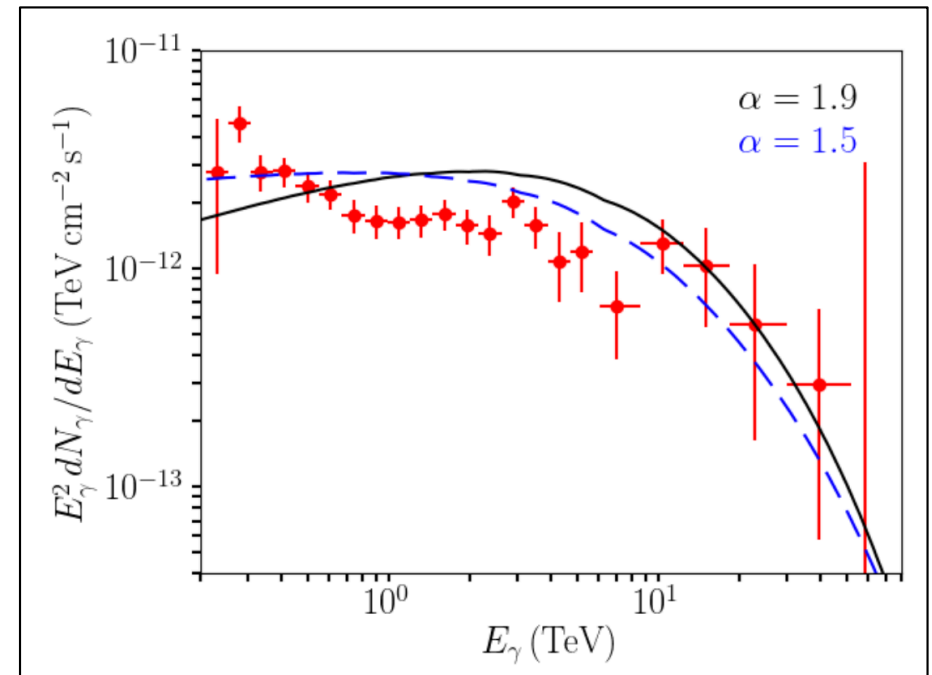
# Millisecond Pulsars and TeV Halos

- Until recently, it was unknown whether MSPs have TeV halos (although theorists expected that they would)
- In a recent study, we used the publicly available HAWC data from the directions of 37 high-spindown power MSPs, finding evidence that these sources produce multi-TeV emission at a level of  $(2\Delta \ln \mathcal{L})^{1/2} = 4.24$
- Less than 1% of control group (blank sky) realizations yielded as much statistical significance
- MSPs appear to produce TeV halos with a similar efficiency to younger pulsars,  $\eta_{MSP} = (0.39 - 1.08) \times \eta_{young}$



# Millisecond Pulsars and TeV Halos

- If MSPs do generate the GeV excess, they 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 ( $\pi^0$ , 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 the brightest TeV halos, or ruling out MSPs as the source of the GeV excess

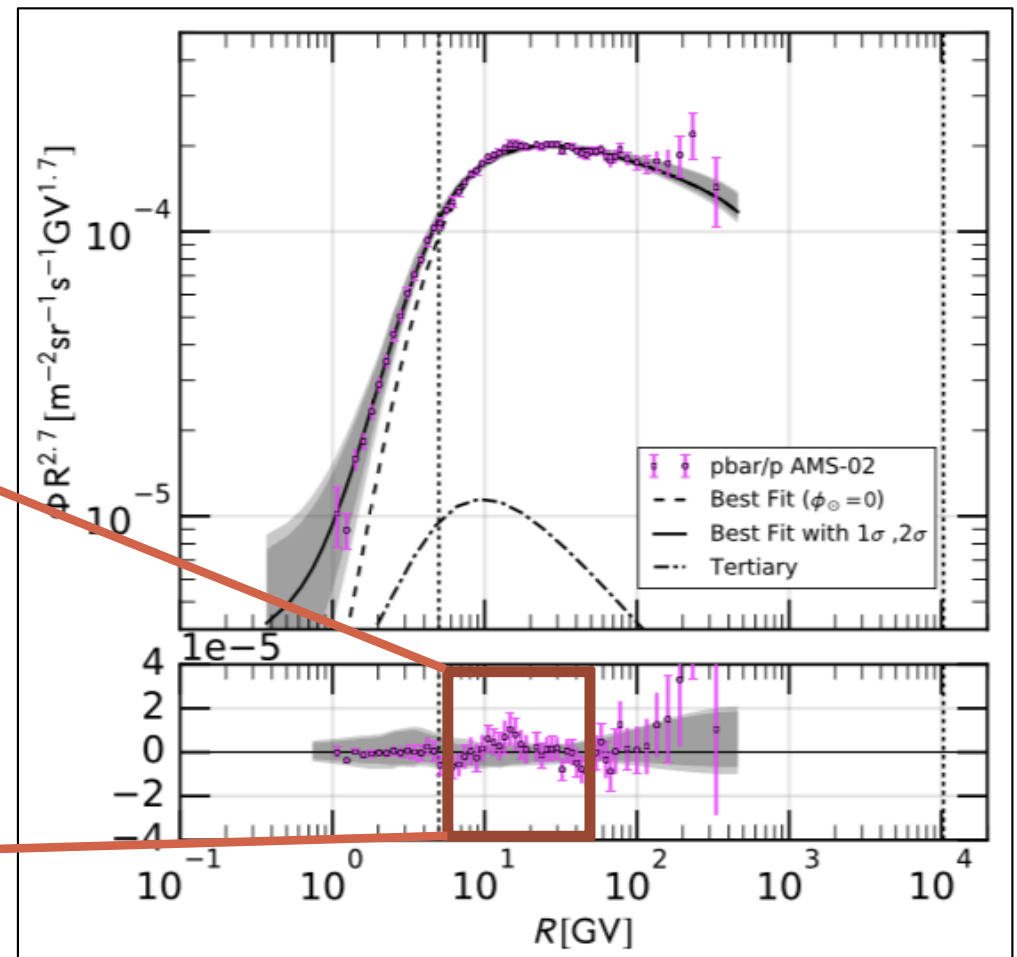
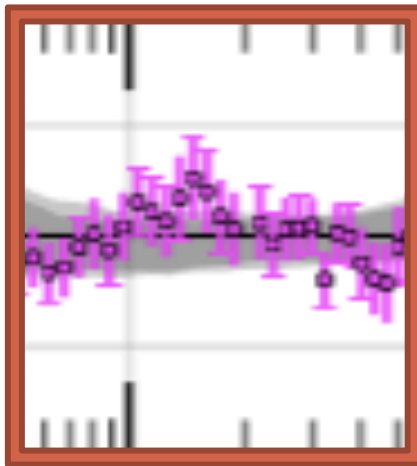


$0.2 - 0.5^\circ$  annulus,  $\eta_{\text{MSP}} = \eta_{\text{young}}$

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

# The Cosmic-Ray Antiproton Excess

- An excess of cosmic-ray antiprotons was pointed out in 2016 by two independent groups (Cuoco, Krämer, Korsmeier and Cui, Yuan, Tsai, Fan)
- Both papers identified a small, but statistically significant excess ( $\sim 4.5\sigma$ )
- These papers made it clear that out-of-the-box GALPROP models could not explain the antiproton spectrum measured by AMS
- Well fit by a  $\sim 40$ -70 GeV WIMP with a  $\sim 10^{-26}$  cm<sup>3</sup>/s cross section

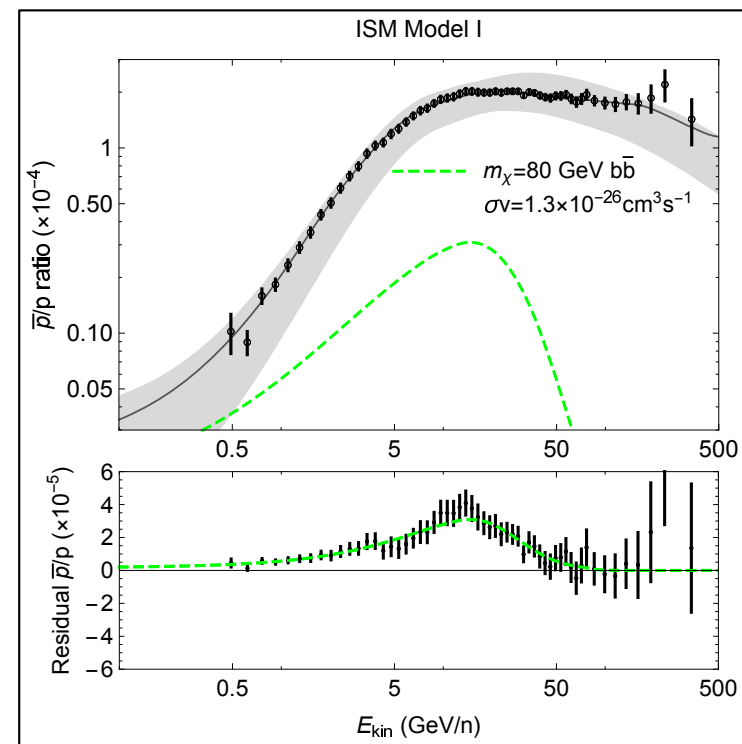
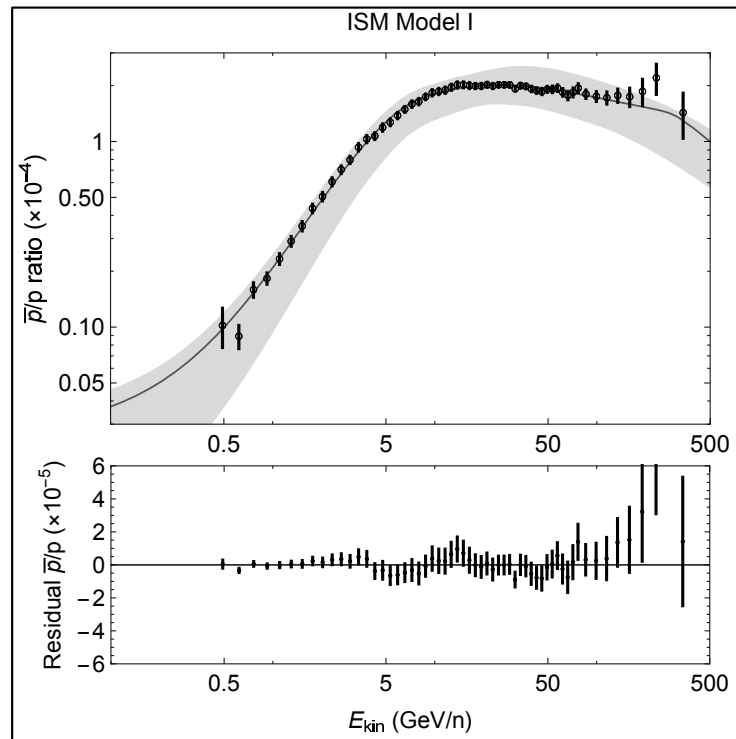


Cuoco et al., arXiv:1610.03071  
 Cui et al., arXiv:1610.03840

# It's All About the Systematics

- The 2016 papers on the AMS antiproton excess received relatively little attention (roughly ~130 citations each), somewhat surprising for such a highly statistically significant and important result
- The skepticism of the community was the result of (perhaps reasonable) concerns pertaining to the difficulty to quantify systematic uncertainties associated with:
  - 1) Cosmic-ray injection and transport in the ISM (Cuoco *et al.*, Cui *et al.*)
  - 2) The antiproton production cross section
  - 3) The impact of the solar wind (solar modulation)

# The Cosmic-Ray Antiproton Excess

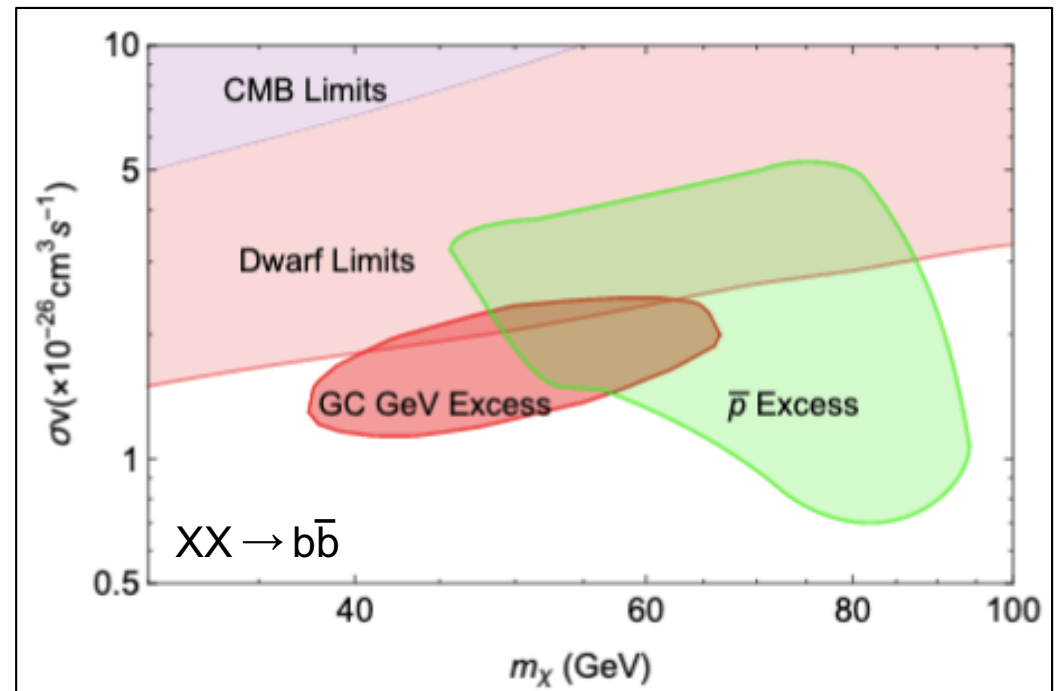
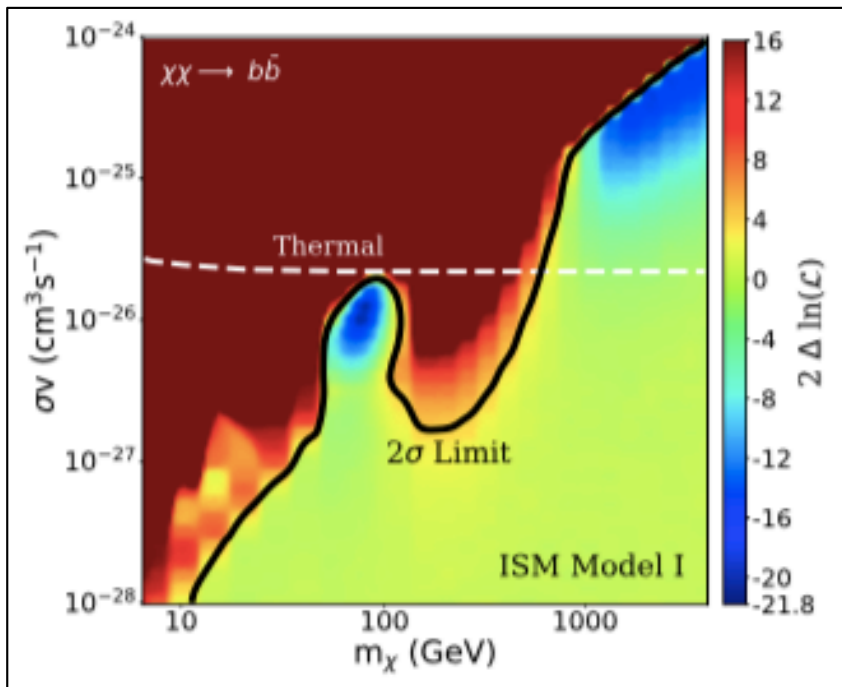


- Even after allowing for large systematic uncertainties associated with the antiproton production cross section and solar modulation, we find that the excess persists
- The fit consistently prefers a contribution from annihilating dark matter, at a level never less than  $3.3\sigma$

Cholis, DH and Linden, arXiv:1903.02549;  
 see also, Cuoco et al. arXiv:1903.01472,  
 Reinert, Winkler, arXiv:1712.00002

# Implications For Dark Matter

- Marginalizing over all of the free parameters in our fit, we find that the antiproton excess could potentially be generated by  $\sim 45\text{-}95$  GeV dark matter particles with a cross section of  $\sigma v \sim (0.7\text{-}5) \times 10^{-26} \text{ cm}^3/\text{s}$  (for  $b\bar{b}$ )
- For  $m_\chi \sim 50\text{-}70$  GeV and  $\sigma v \sim (1.4\text{-}2.4) \times 10^{-26} \text{ cm}^3/\text{s}$ , we can simultaneously account for the gamma-ray **and** antiproton excesses
- Searches for cosmic ray anti-deuterons and anti-helium could help to clarify (the first GAPS flight is scheduled for late 2022)

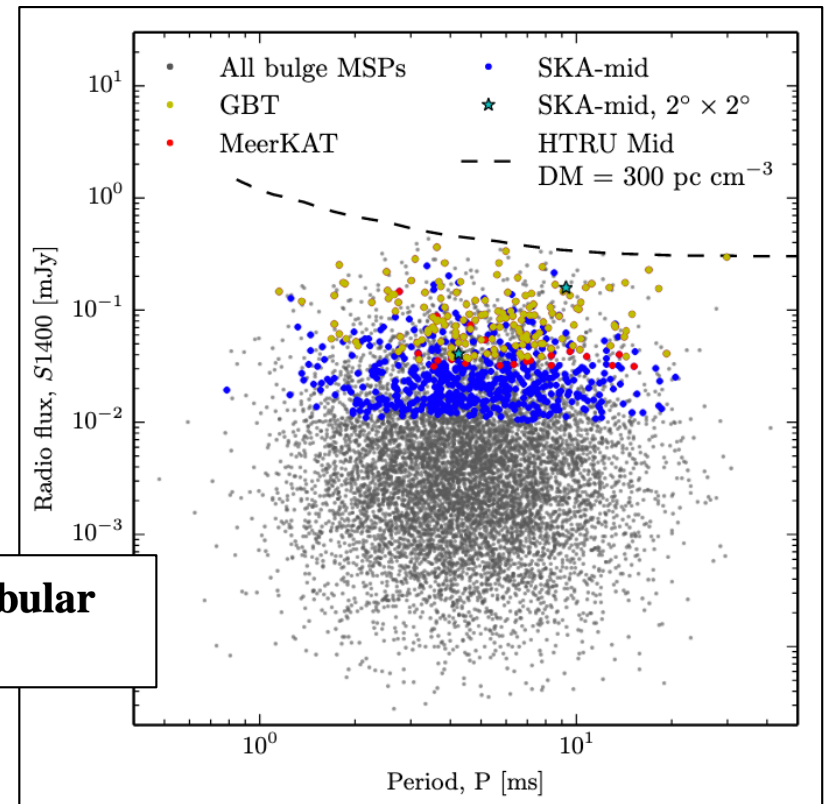


# Looking Forward: Radio Searches for Inner Galaxy MSPs

- If MSPs generate the GeV excess, future deep radio surveys should be able to detect the pulsed radio emission from these objects
- After  $\sim 10^2$  hours of observation, Green Bank should detect  $\sim 1$ -2 Inner Galaxy MSPs
- Dozens should be detectable with MeerKAT (after a similar exposure)
- Hundreds should be detectable with SKA
- MeerKAT was commissioned in 2016, and they recently announced their first MSP discoveries (far from Inner Galaxy), [arXiv:2103.04800](https://arxiv.org/abs/2103.04800)

**Eight new millisecond pulsars from the first MeerKAT globular cluster census**

- First light for SKA is projected for 2027



# Summary

- Indirect searches using gamma rays and cosmic rays are currently testing the range of annihilation cross sections that are predicted for a thermal relic, for masses up to  $\sim 100$  GeV
- Along with the direct detection program, these telescopes and detectors are actively testing the WIMP paradigm
- 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
- Arguments based on the number of gamma-ray bright MSPs, bright LMXBs, and diffuse TeV emission each disfavor MSPs as the main source of this emission (non-standard MSP populations are more difficult to assess)
- Future gamma-ray and radio observations, as well as measurements of antimatter in the cosmic ray spectrum, will provide critical tests to definitively establish the origin of this signal

