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

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Chung-Ang University Beyond the Standard Model Workshop

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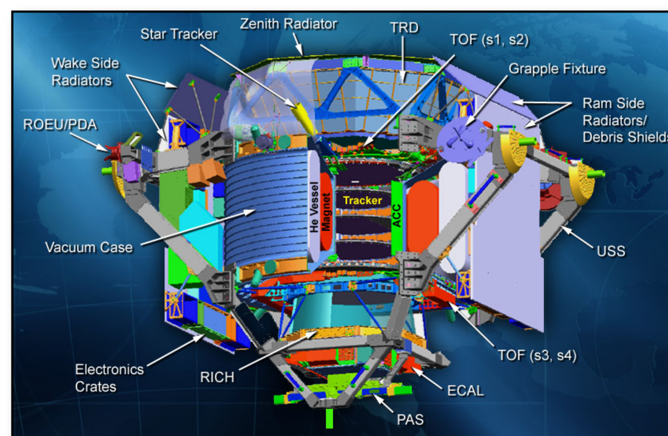
The Motivation for Indirect Searches

- To account for the observed dark matter abundance, a thermal relic must have an annihilation cross section (at freeze-out) of $\sigma v \sim 2\text{x}10^{-26}$ cm^3/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

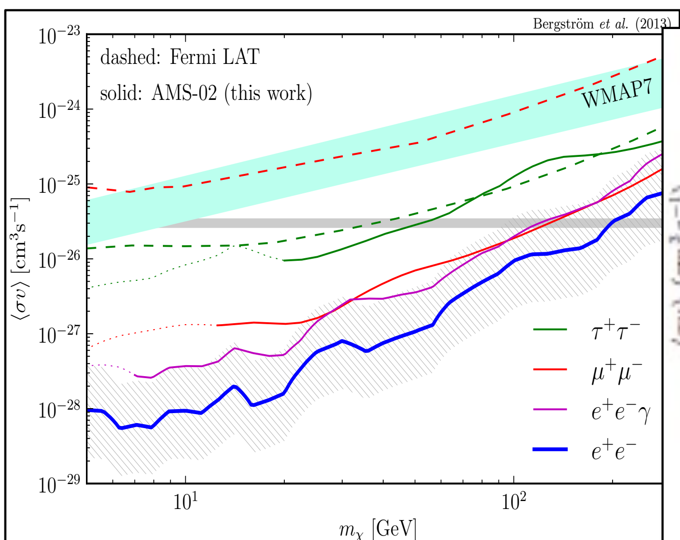
Fermi

AMS-02

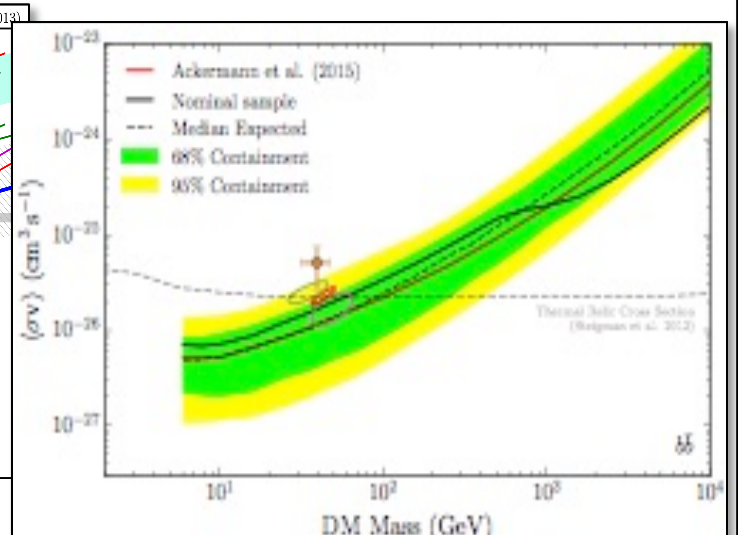


Constraints from Indirect Detection

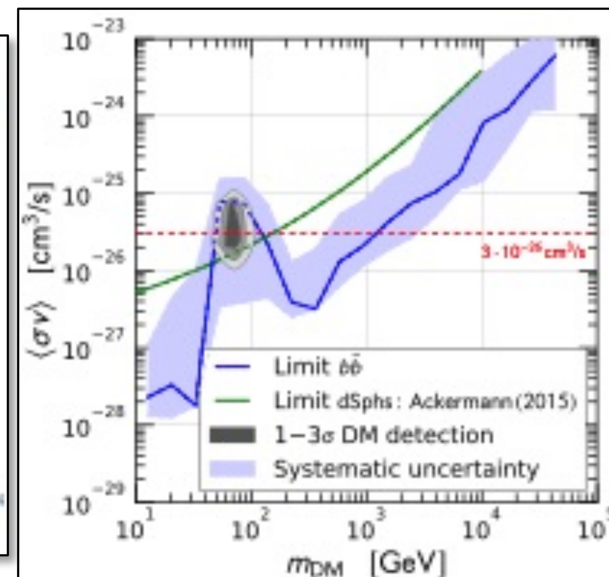
- A variety of gamma-ray strategies (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements from AMS, are currently sensitive to dark matter with the annihilation cross section predicted for a simple thermal relic, for masses up to $\mathcal{O}(100)$ GeV
- This program is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



Bergstrom, et al, arXiv:1306.3983



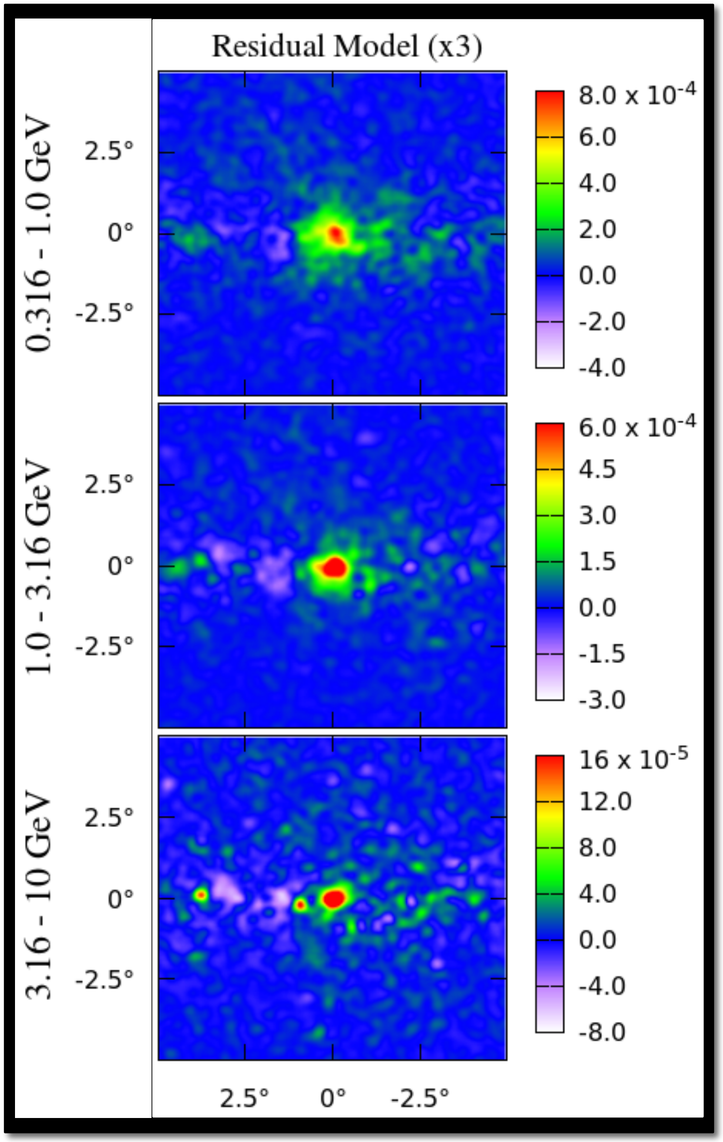
Fermi Collaboration, arXiv:1611.03184



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

The Galactic Center Gamma-Ray Excess

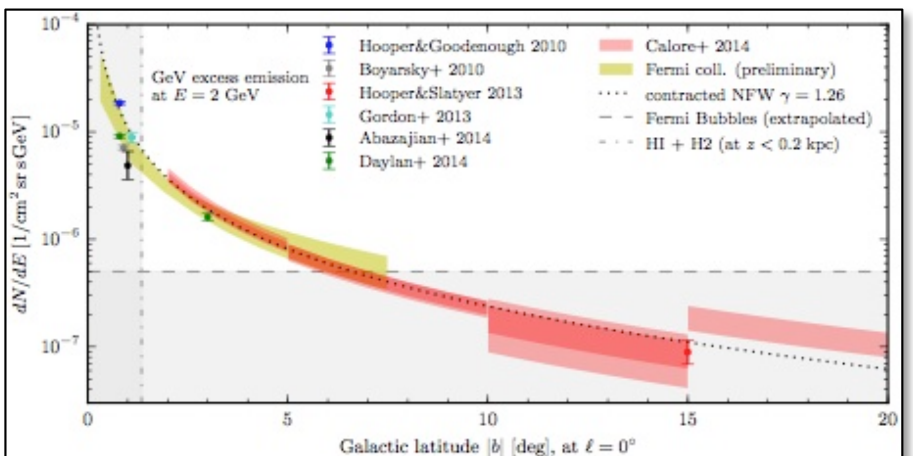
- A bright and highly statistically significant excess of gamma-rays has been observed from the region surrounding the Galactic Center
- This signal is difficult to explain with astrophysical sources or mechanisms, but is very much like the signal predicted from annihilating dark matter



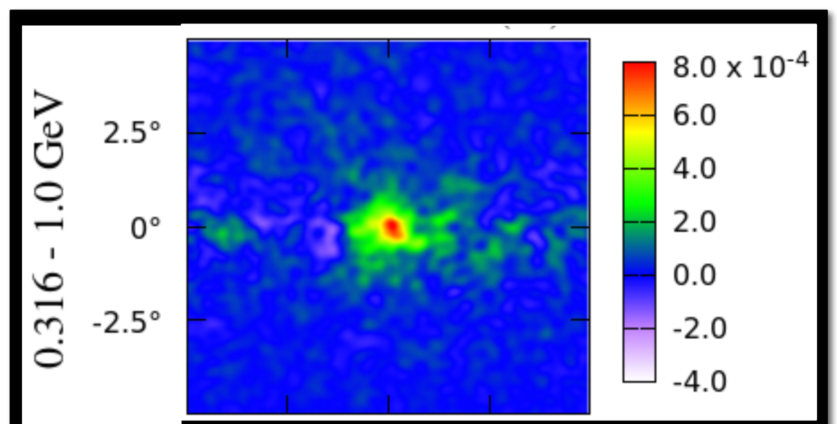
Among other references, see:
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

Morphology

- The GeV excess exhibits approximate spherical symmetry about the Galactic Center (axis ratios within ~20% of unity), with a flux that falls as ~r $^{-2.4}$ out to at least ~10°
- If interpreted as annihilating dark matter, this implies ρ_{DM} ~ r $^{-1.2}$ out to at least ~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)

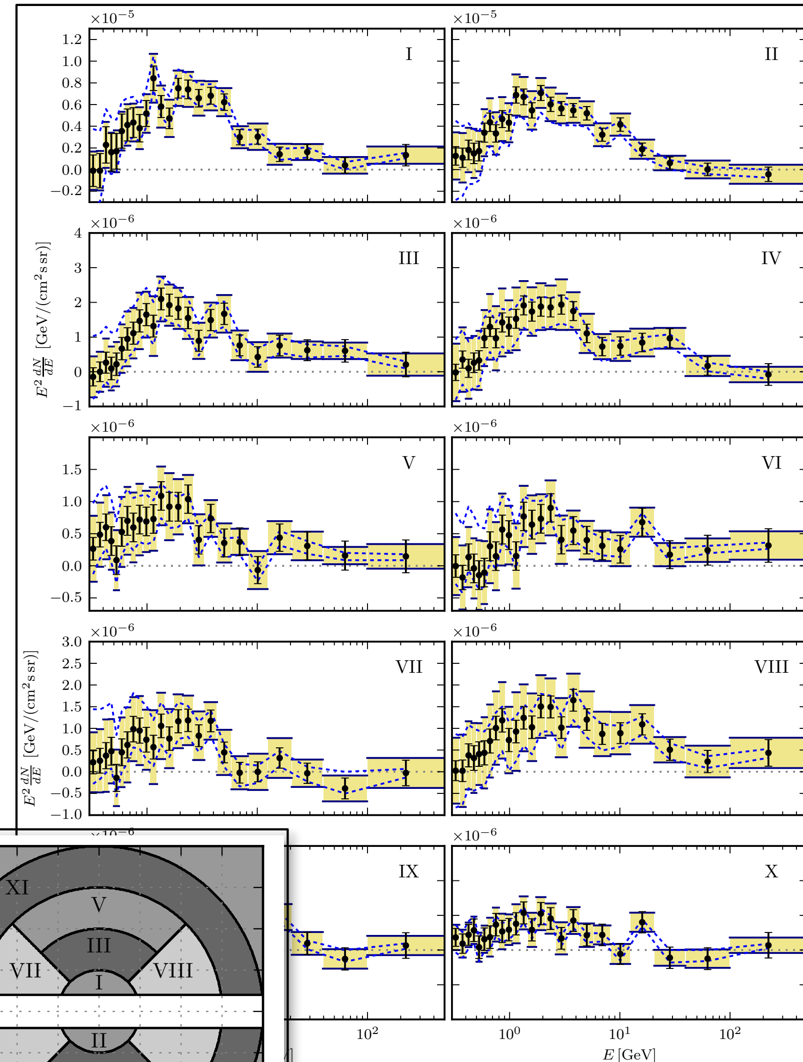


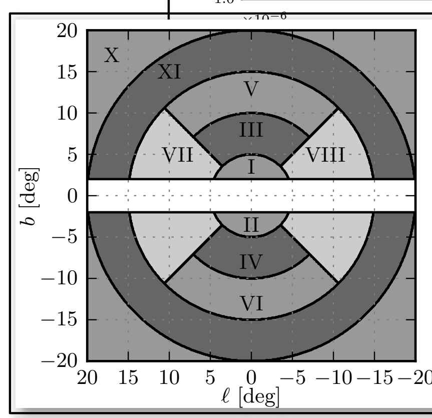
Daylan, et al. (2014)

Spectrum

- The spectrum of the excess is well fit by a ~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	$\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1})$	m_χ (GeV)	χ^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

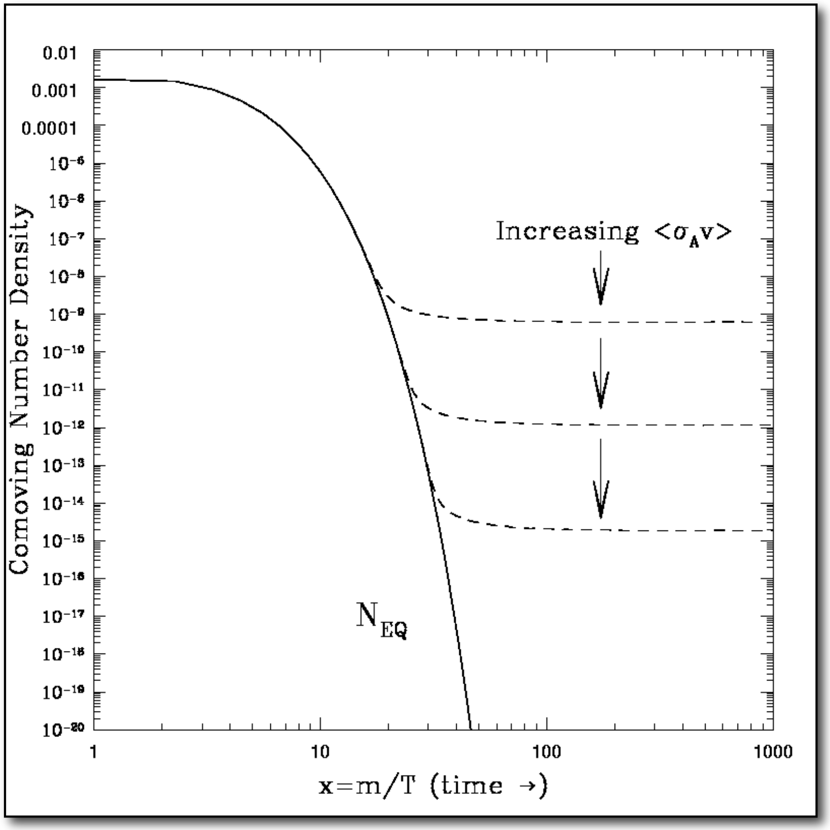




Calore, Cholis, Weniger; Calore, Cholis, McCabe, Weinger (2014); Escudero, Witte, DH, arXiv:1709.07002

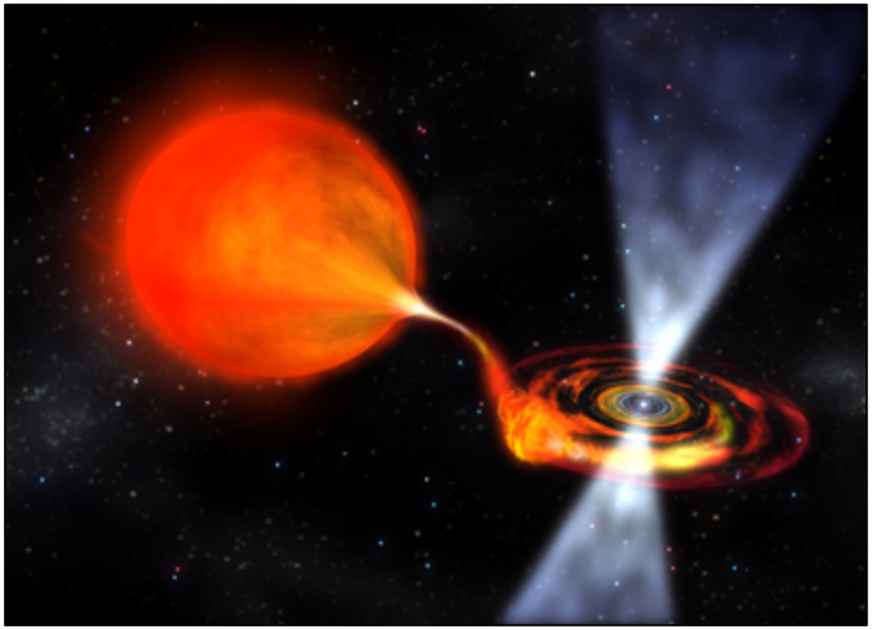
Intensity

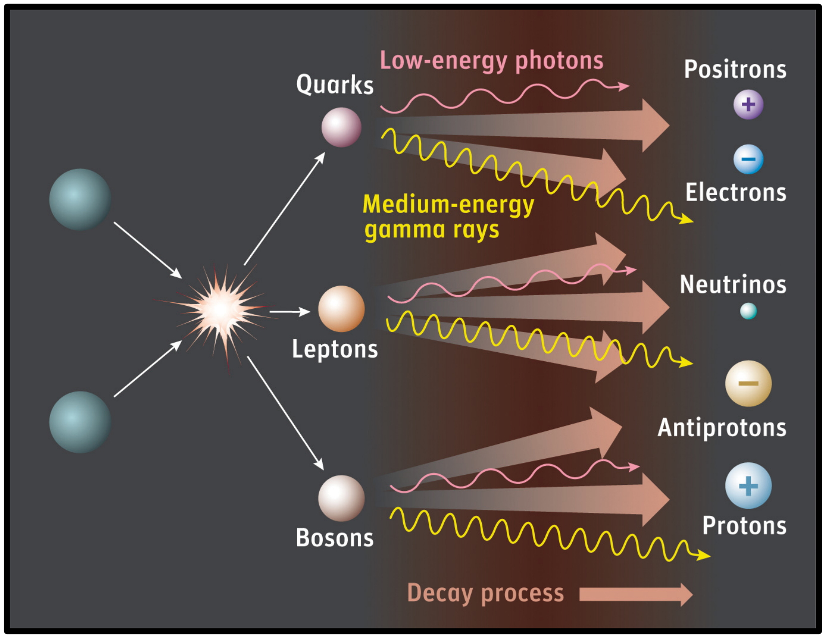
- To normalize the observed excess, the dark matter particles must annihilate with a cross section of $\sigma v \sim 10^{-26}$ cm^3/s
- This is approximately equal to the value of the cross section that is required to generate the measured dark matter abundance through thermal freeze-out in the early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



What Produces the Excess?

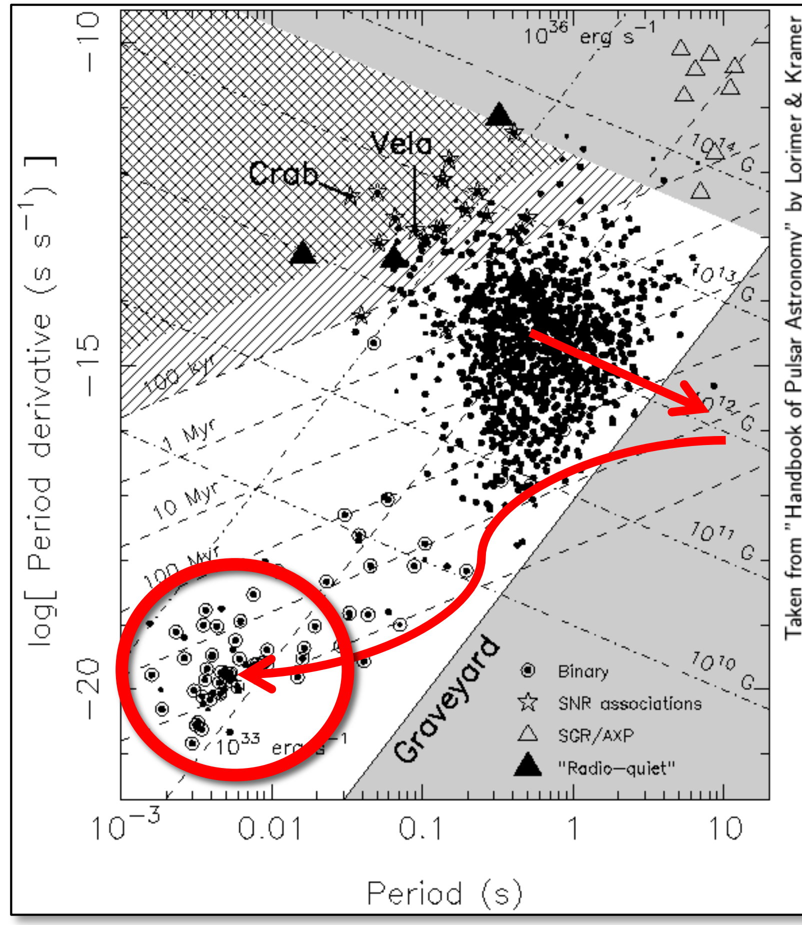
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?

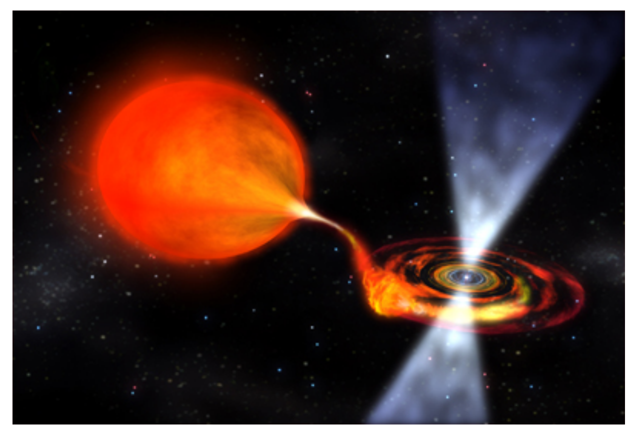




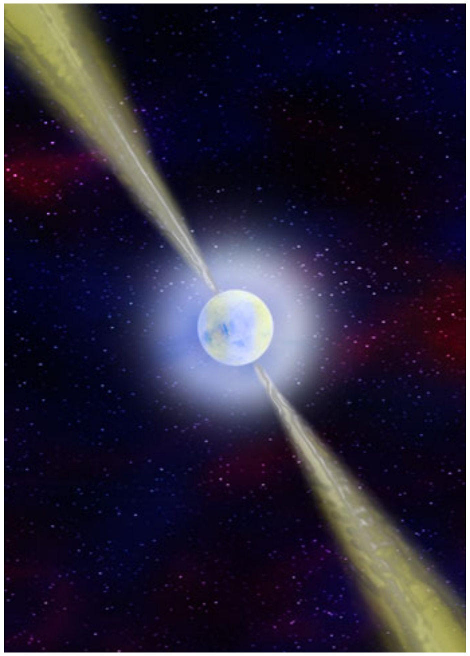
Millisecond Pulsars

- 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 ~1 second and slow down and become faint over ~10^6 -10^8 years
- Accretion from a companion star can "spin-up" a dead pulsar 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 gradually, remaining bright for >10^9 years
- It seems plausible that large numbers of MSPs could exist near the Galactic Center



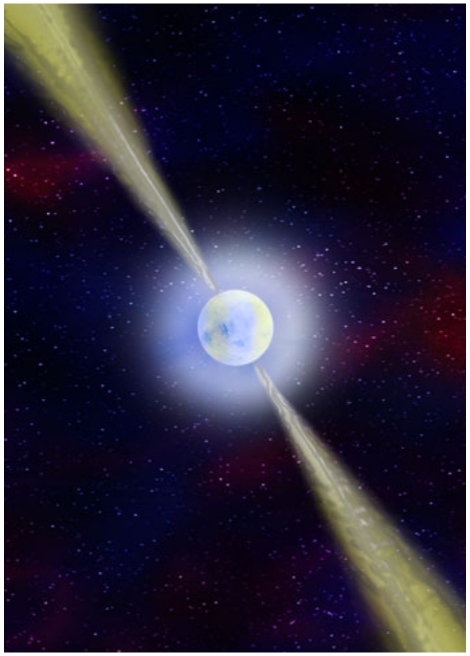


Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



Arguments in Favor of Pulsars:

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



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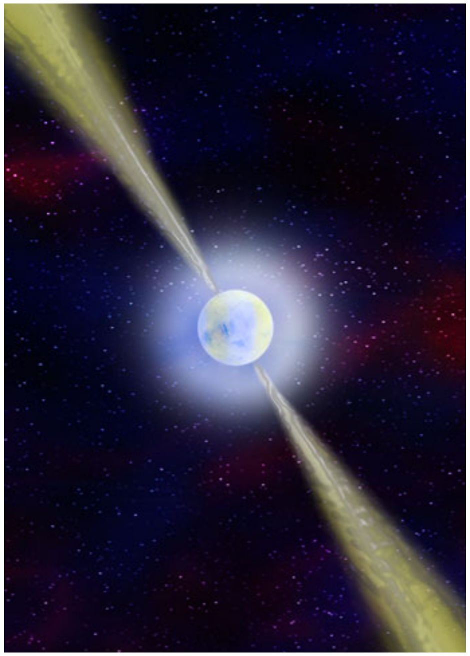

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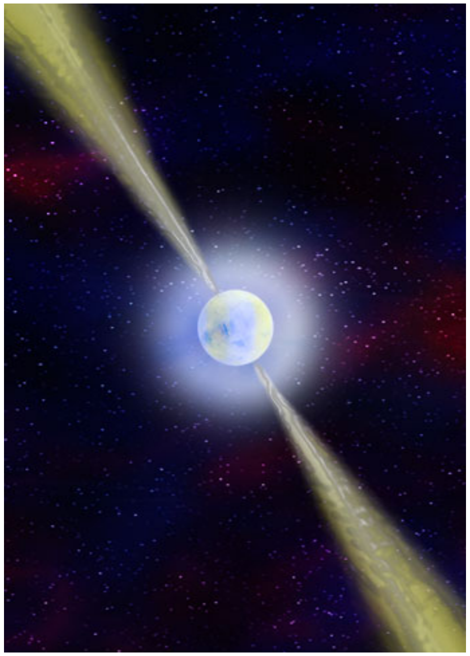

Arguments in Favor of Pulsars:

- 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 γ-Rays

- 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. reach a qualitatively similar conclusion employing a wavelet-based technique

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

Small Scale Power Among Inner Galaxy γ-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^2)

- 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^2 correlated point sources

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

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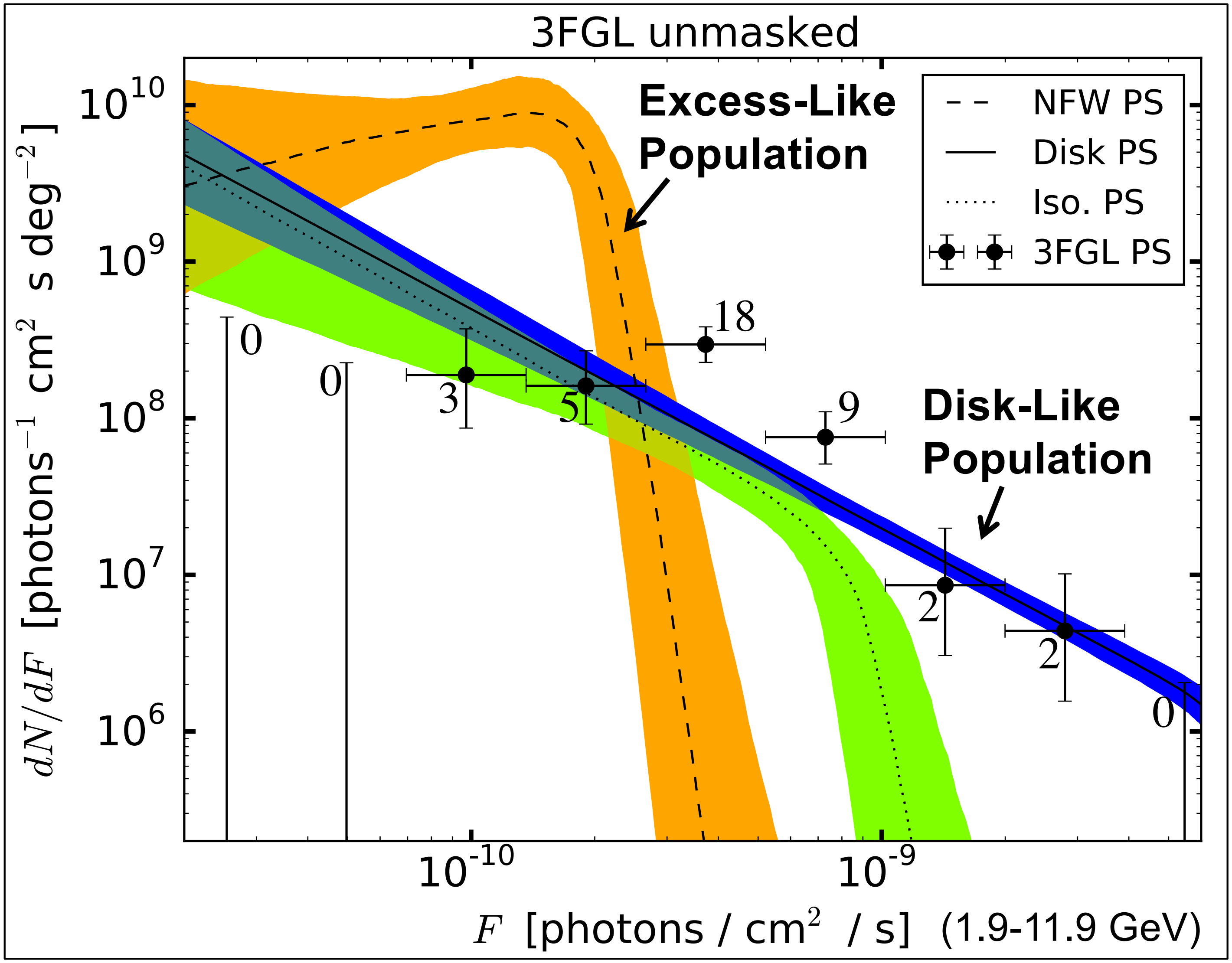

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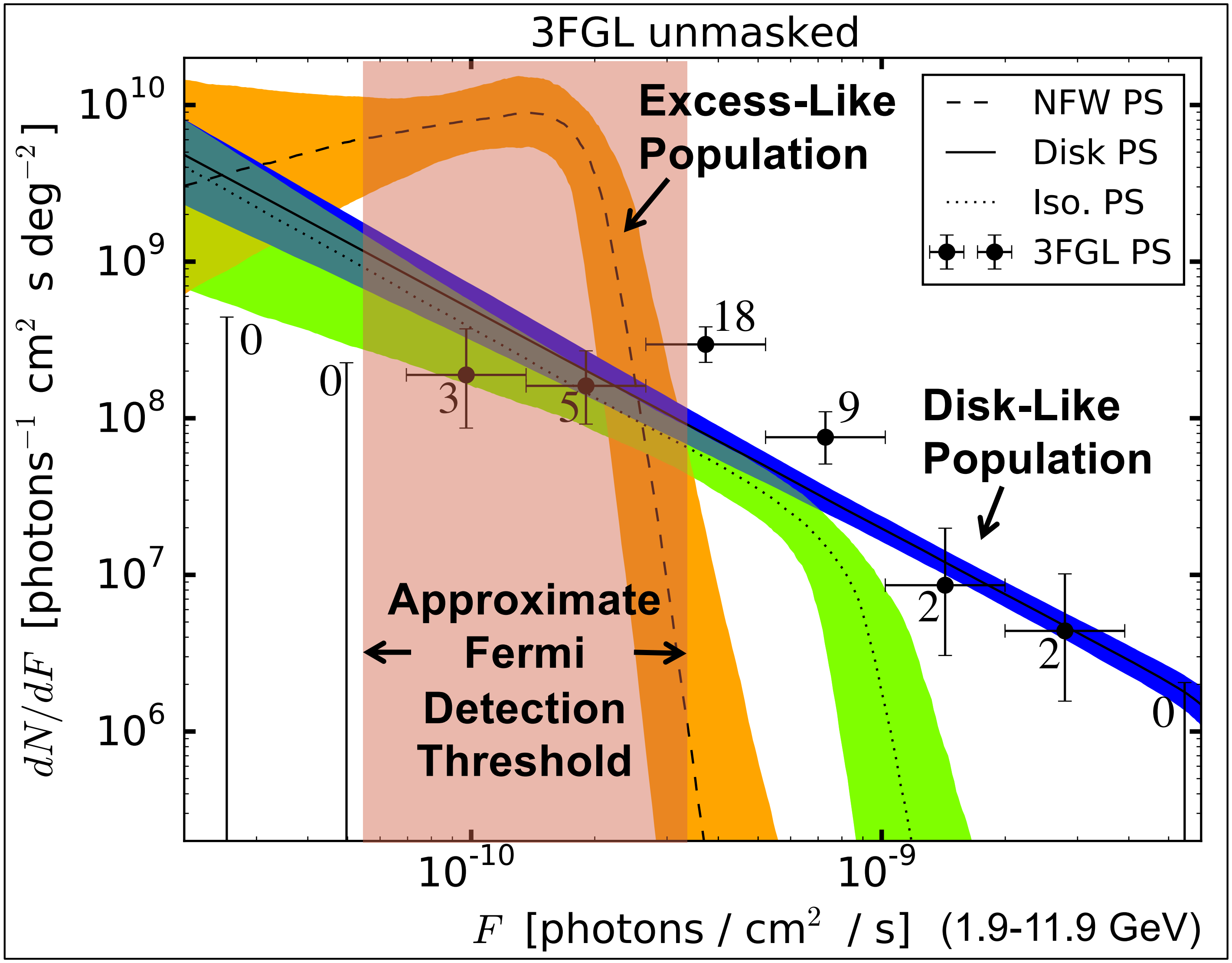

Bottom Line: A population of ~10^3 points sources with luminosities near Fermi's detection threshold could potentially account for the GeV Excess

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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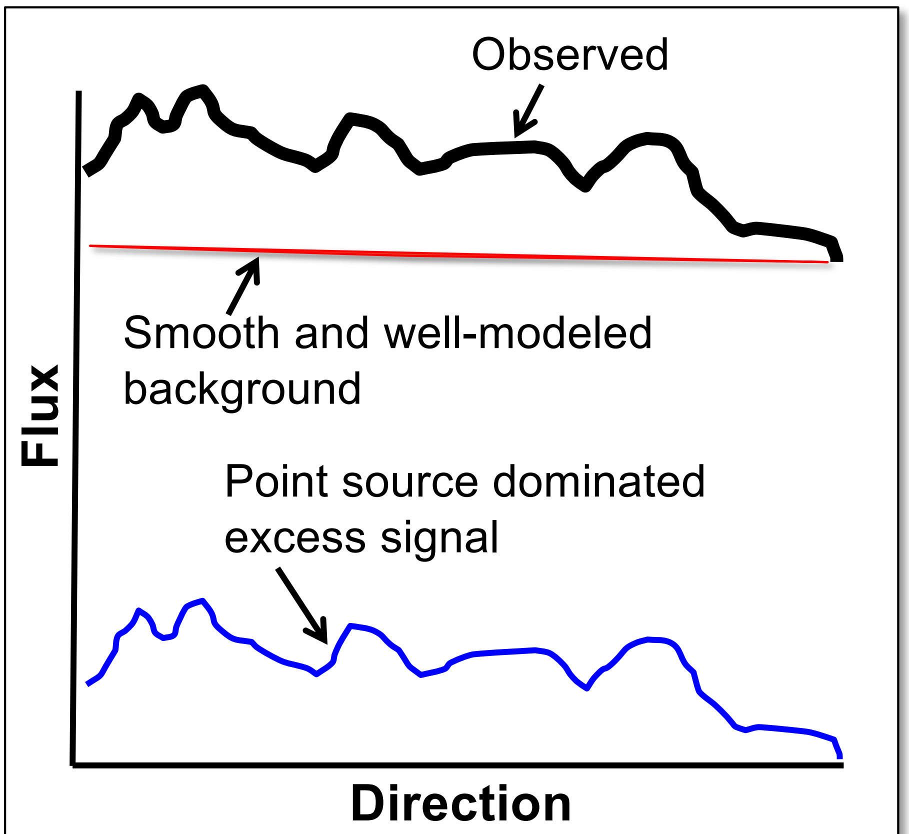

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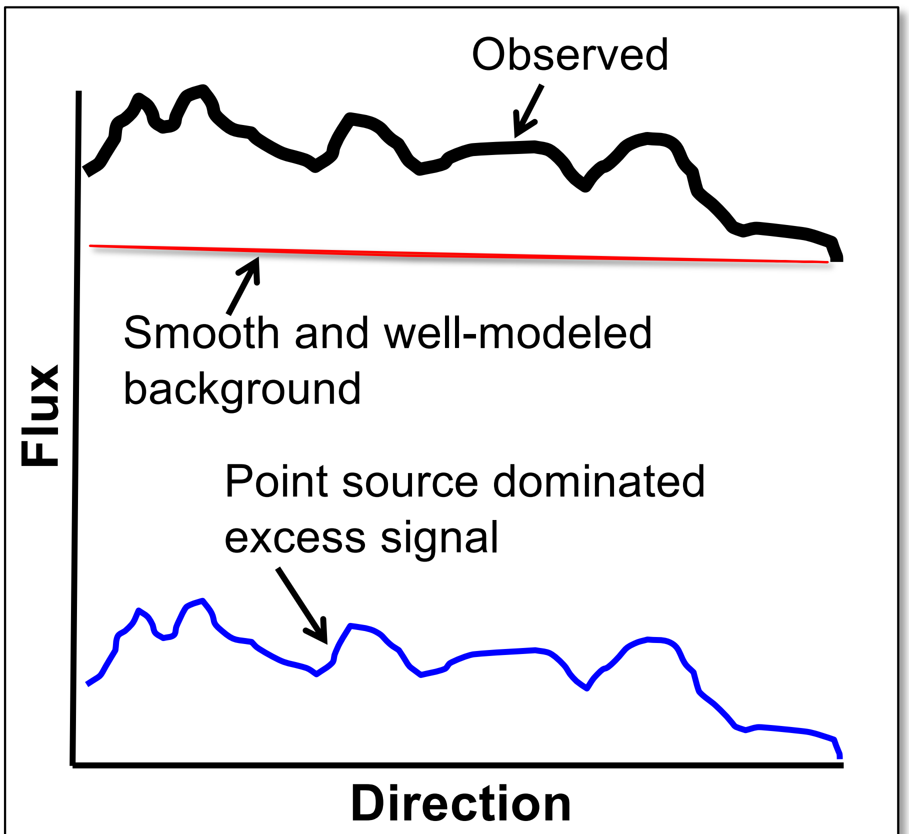
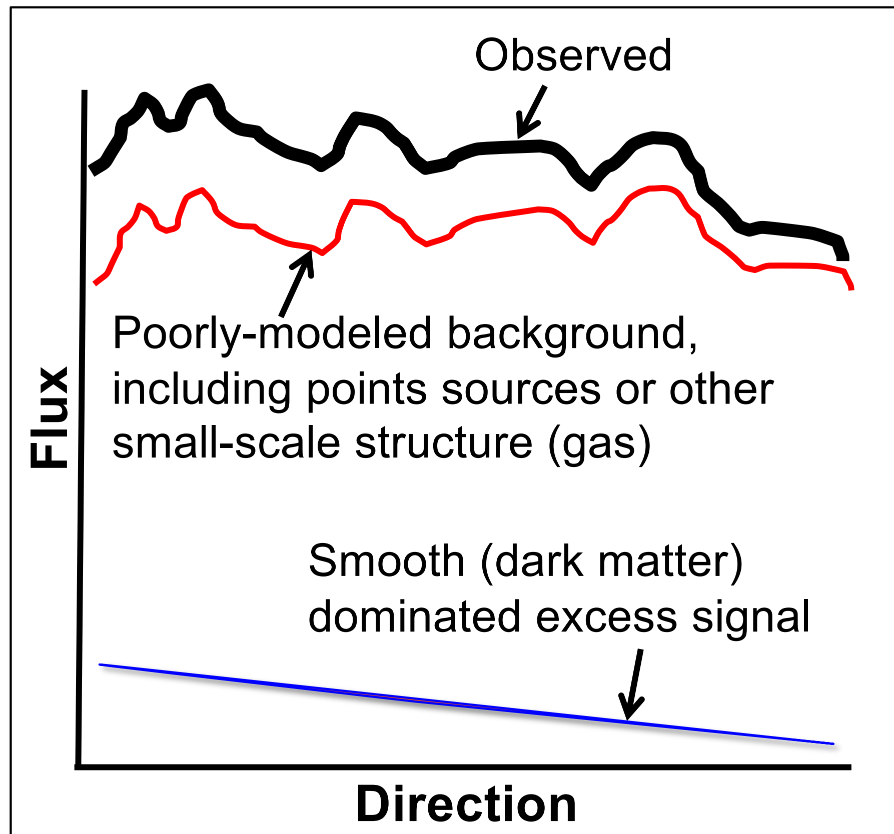




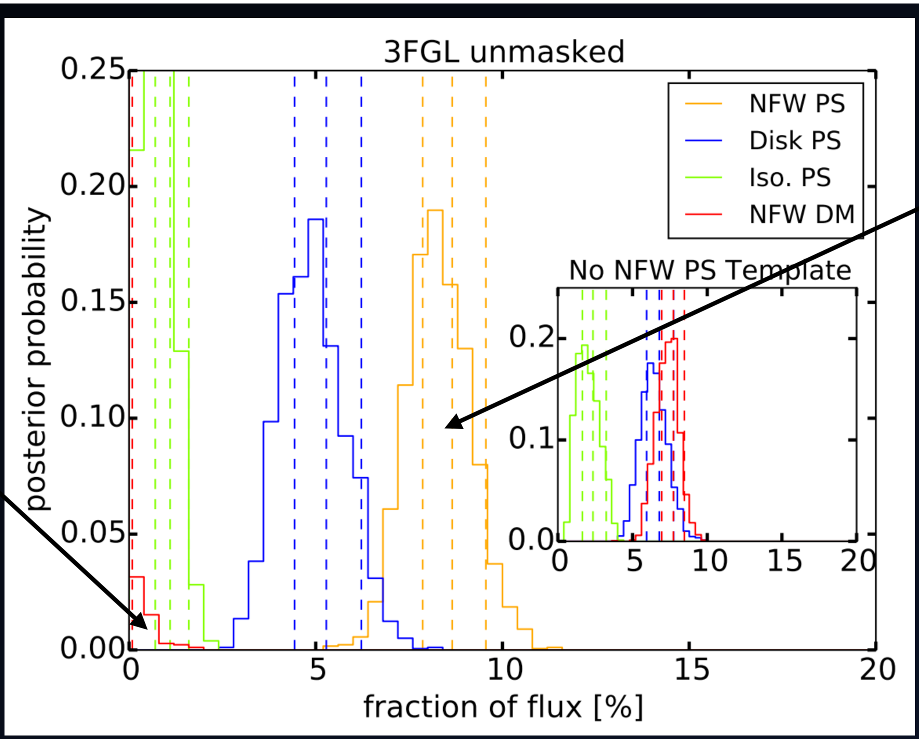
Dark Matter Strikes Back at the Galactic Center

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



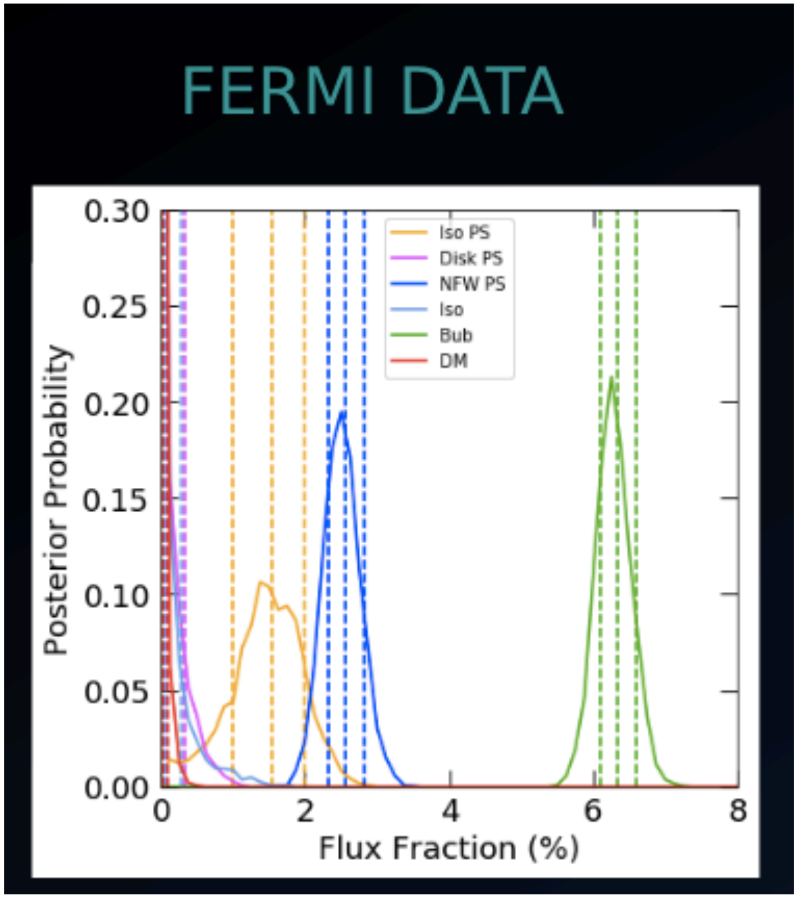
Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

Evidence for NFW^2 Distributed Point Sources

To what extent could inadequate templates be biasing these results?

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430



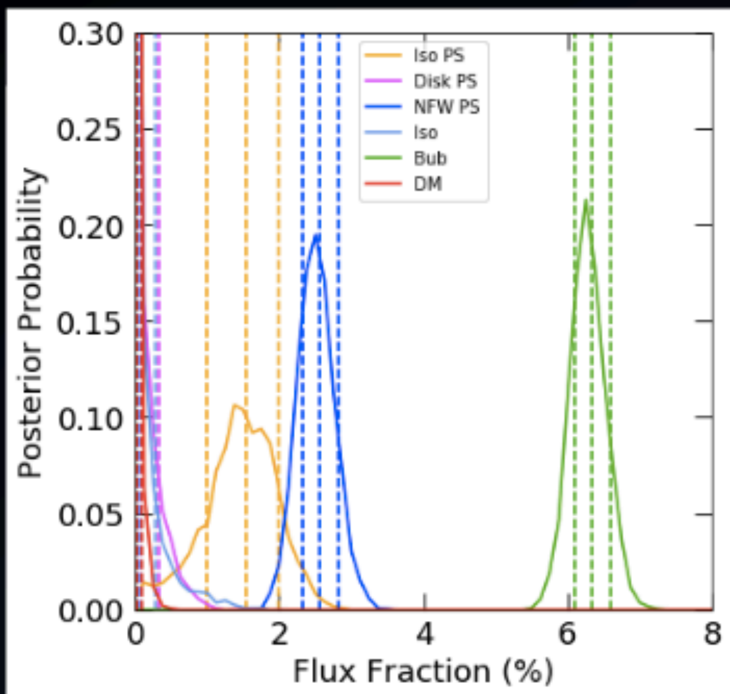
Here is the result that Leane and Slatyer get using the same procedure as Lee *et al.*

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

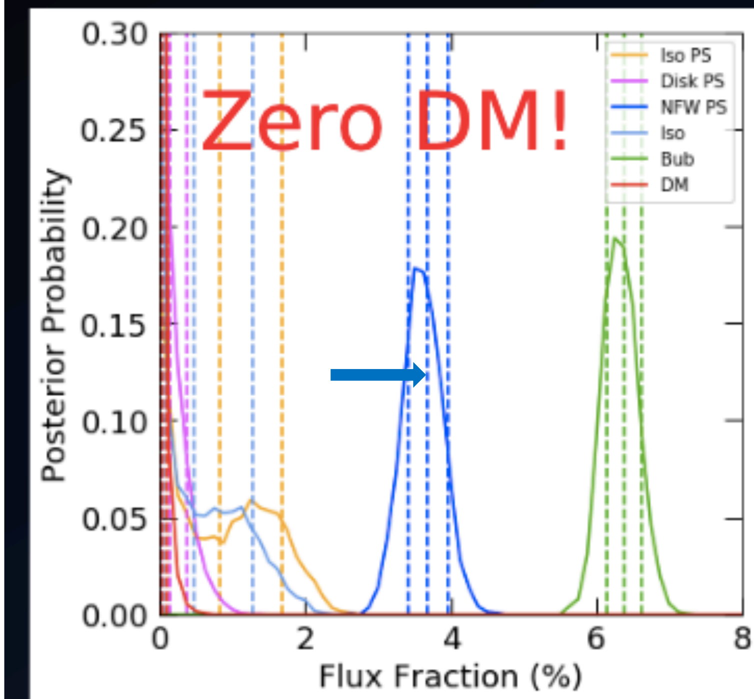
Dark Matter Strikes Back at the Galactic Center

See Leane and Slatyer, arXiv:1904.08430

FERMI DATA



INJECTED DM SIGNAL + DATA



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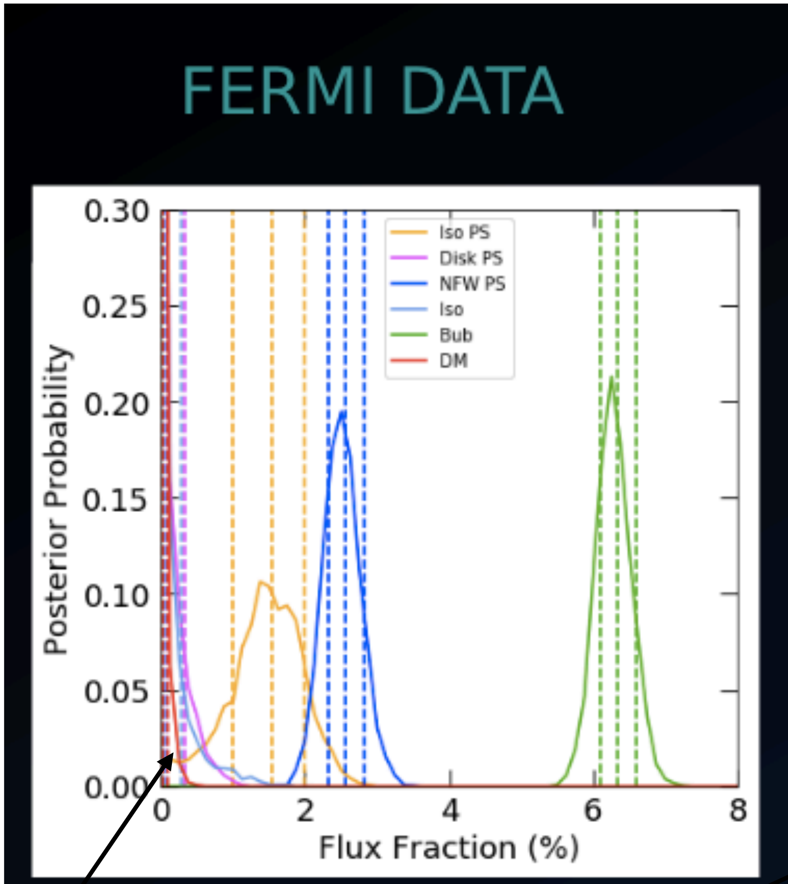

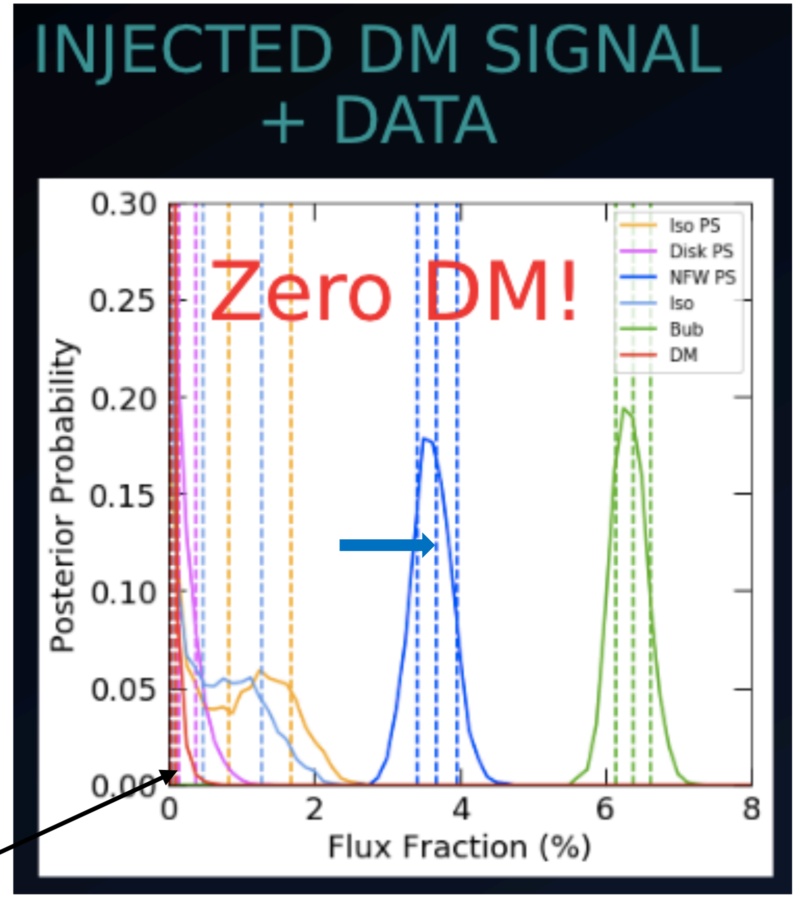

Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

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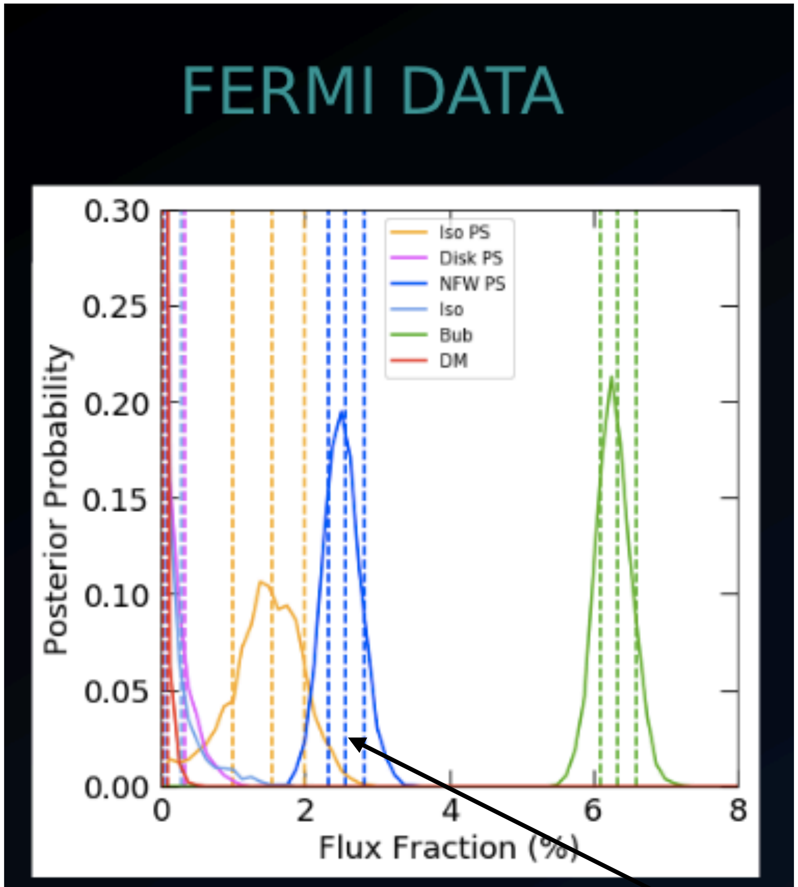

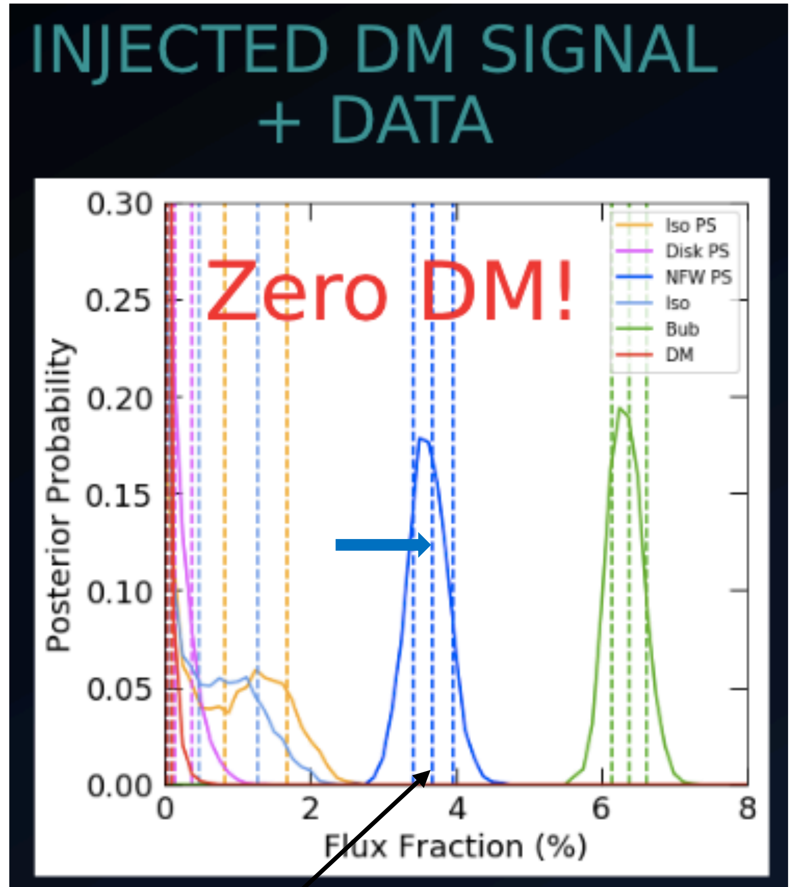

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Instead, the fit identifies the injected dark matter-like signal as originating from point sources

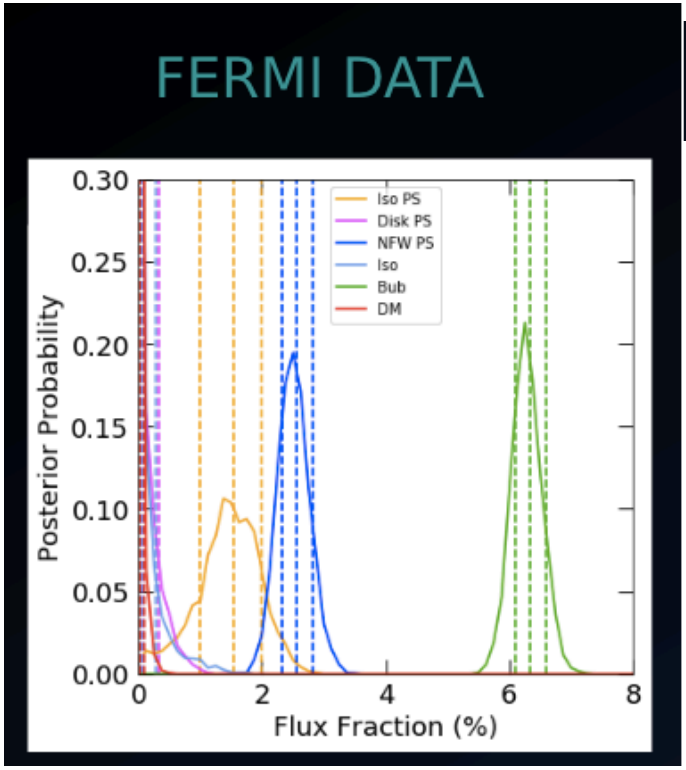
DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

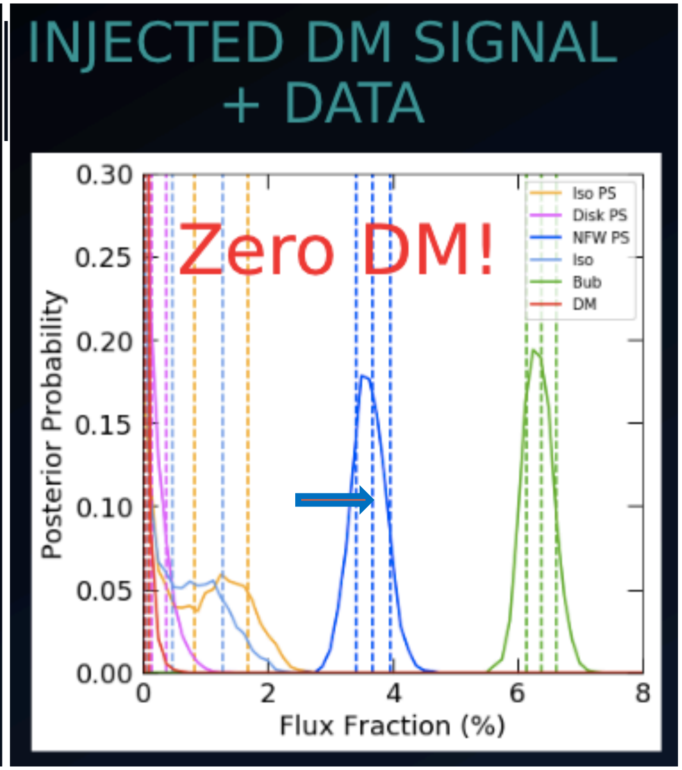
See Leane and Slatyer, arXiv:1904.08430

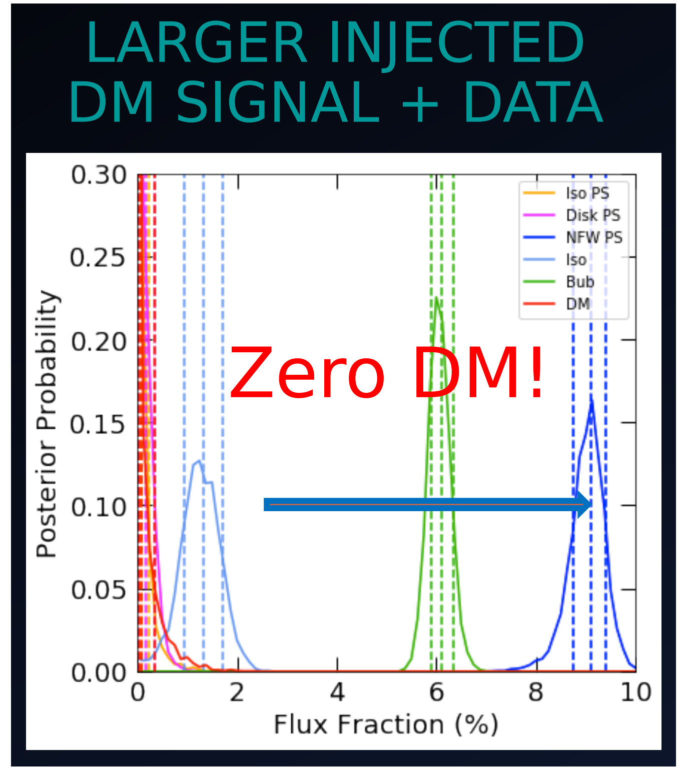
What happens if an even larger dark matter-like signal is added to the data?

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

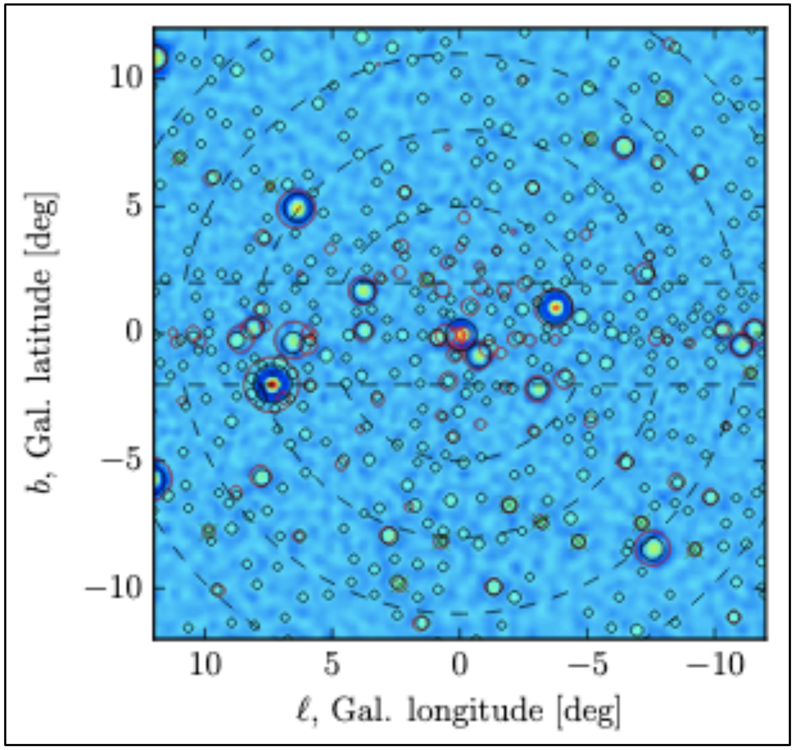
Bottom Line:

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

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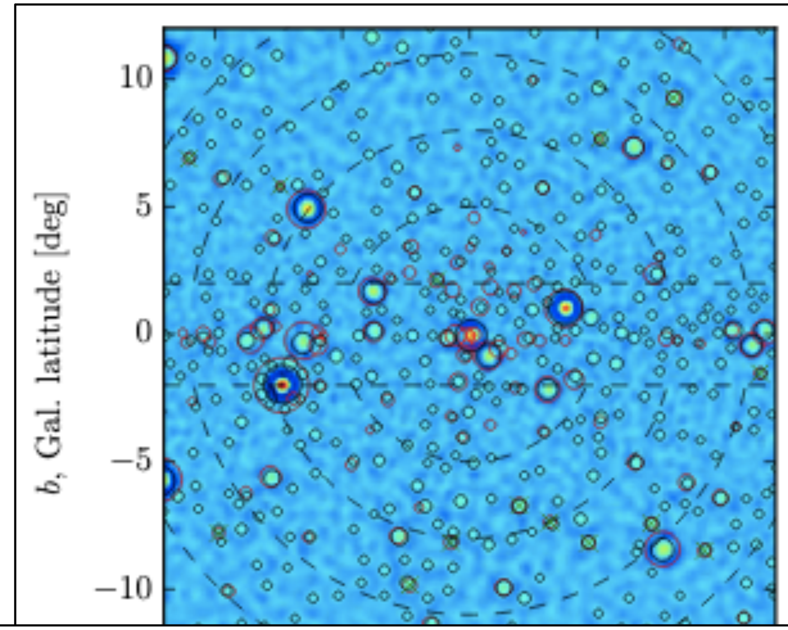
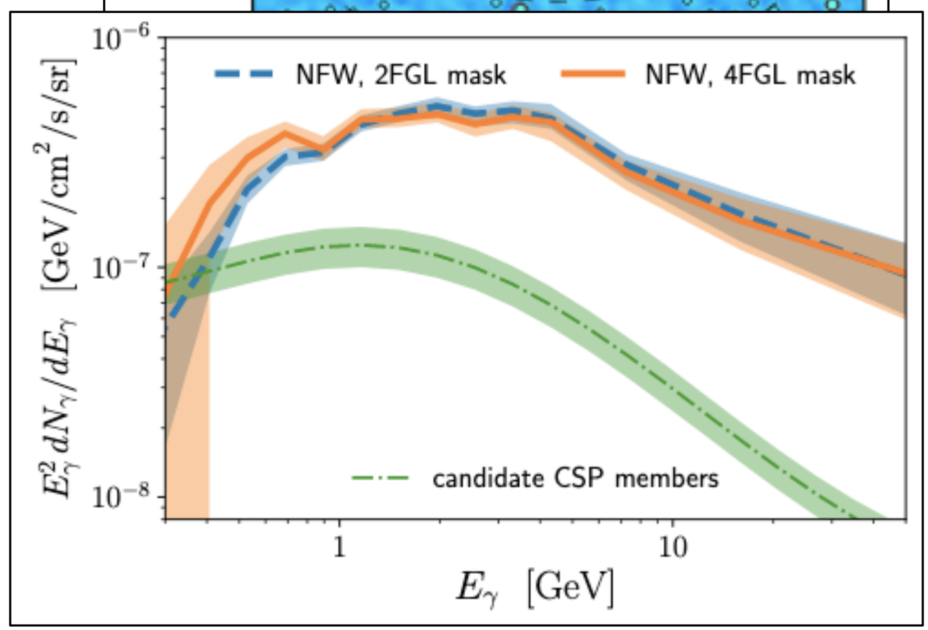
- More recently, Zhong, McDermott, Cholis and Fox revisited this method, utilizing an updated gamma-ray source catalog (4FGL vs 3FGL)
- Using the 3FGL, Zhong *et al*. reproduced the results of Bartels *et al*.
- After accounting for the 4FGL source, Zhong *et al*. find no evidence that the excess is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





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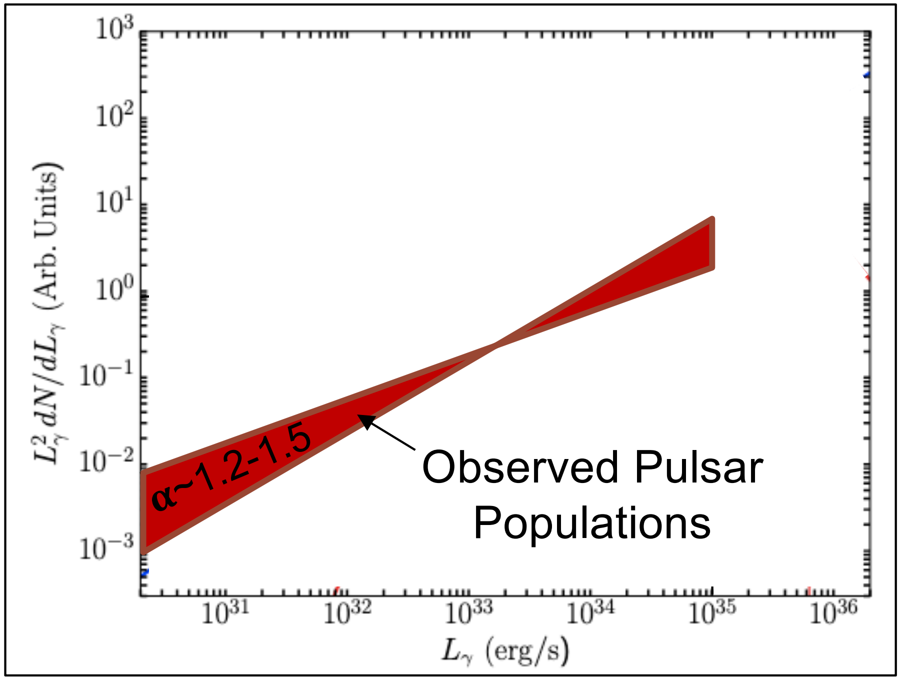
Tension with Pulsar Interpretations

- 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^2dN/dL units)
- If modeled as a power-law, $dN/dL \sim L^{-\alpha}$, such observations favor α~1.2-1.5 (for L_{max}~10^{35} erg/s)



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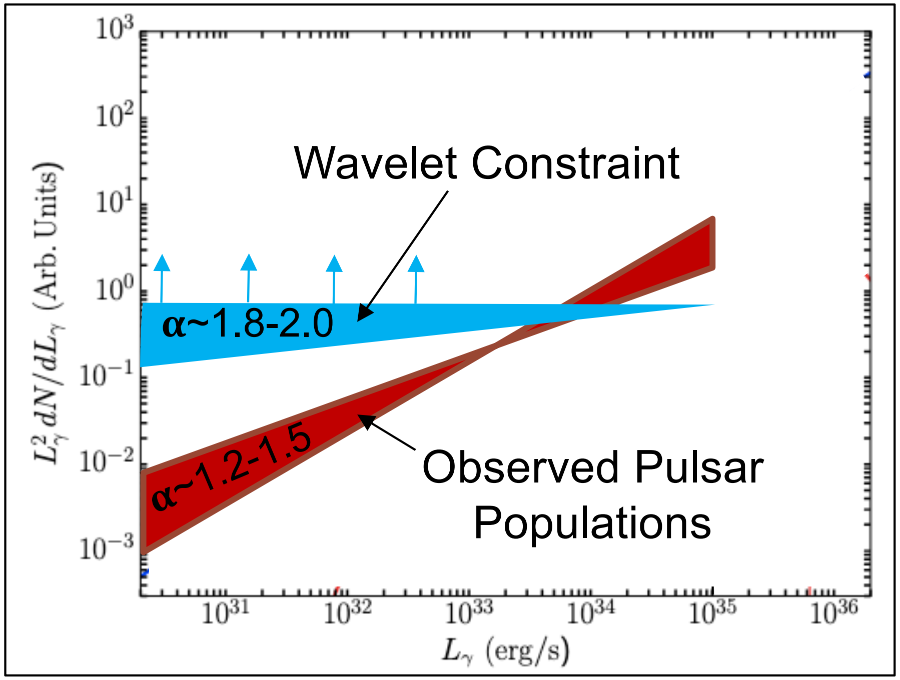
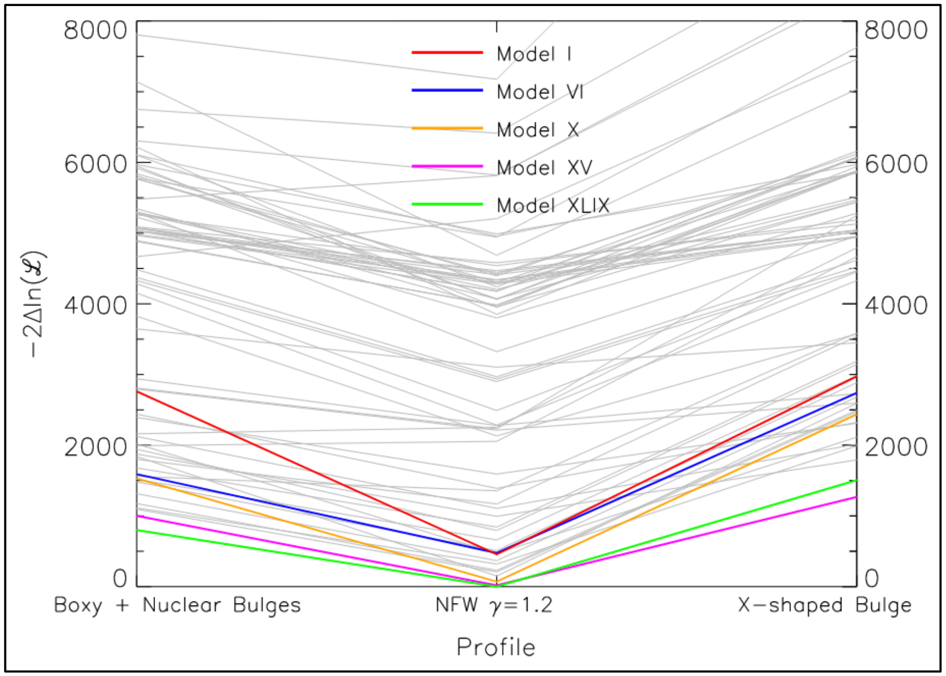
- If modeled as a power-law, $dN/dL \sim L^{-\alpha}$, such observations favor $\boldsymbol{\alpha}$~1.2-1.5 (for $L_{max} \sim 10^{35}$ erg/s)
- In contrast, the results of Zhong *et al*. constrain $\boldsymbol{\alpha}$ > 1.9, in strong contrast to observed pulsar populations
- Put another way, to explain the GC excess without dark matter would require ~3×10^6 pulsars with $L > 10^{29}$ erg/s
- No proposed pulsar population models predict anything close to so many pulsars in the Inner Galaxy



Zhong, McDermott, Cholis, Fox, arXiv:1911.12369

Bulge/Bar-Like vs DM-Like Morphology

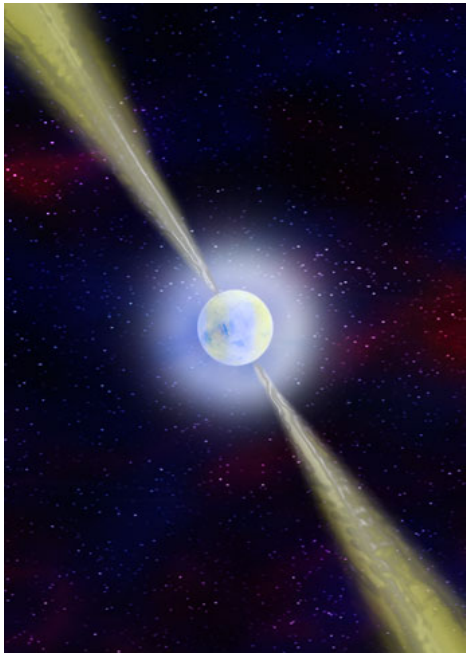
- In three papers (Macias *et al*. 2016, Bartels *et al.* 2017, Macias *et al*. 2017), the authors argued that the Fermi excess is better fit by a template that traces the stellar population of the Galactic Bulge and Bar than one that is dark matter-like, favoring MSP interpretations of the gamma-ray excess
- More recent work, however, has reached the opposite conclusion, finding a strong preference for a dark matter-like template (Di Mauro, arXiv:2101.04694; Cholis, Zhong, McDermott, Surdutovich, arXiv:2112.09706)
- The differences between these results seems likely to reflect the large systematic uncertainties that are associated with the choice of astrophysical templates



Cholis, et al. (2021)

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; Cholis, Zhong, McDermott, Surdutovich, arXiv:2112.09706

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



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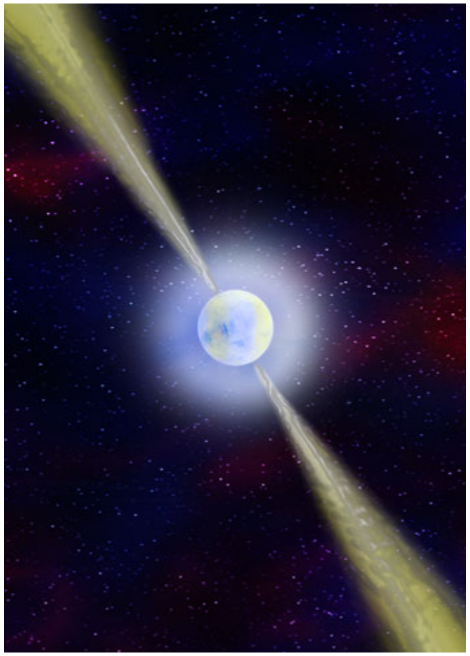

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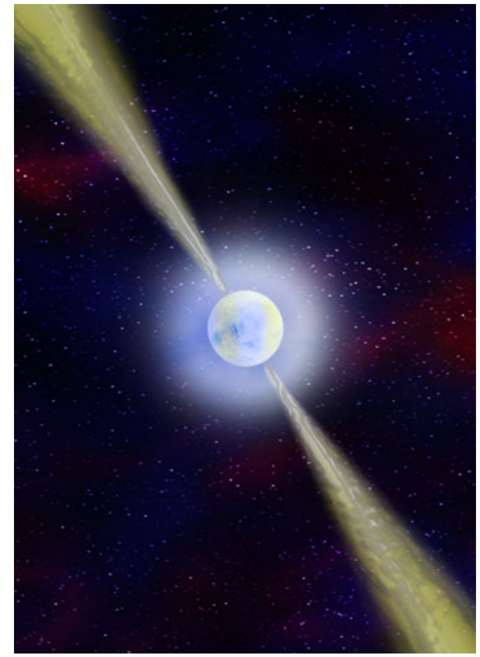
- Claims that th[illegible] trac[illegible]e Galactic Bulge/Bar

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 sm[illegible]le power i[illegible]he gamma-ray emission fr[illegible]n the In[illegible]Galaxy
- Claims that th[illegible]e Galactic Bulge/Bar

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

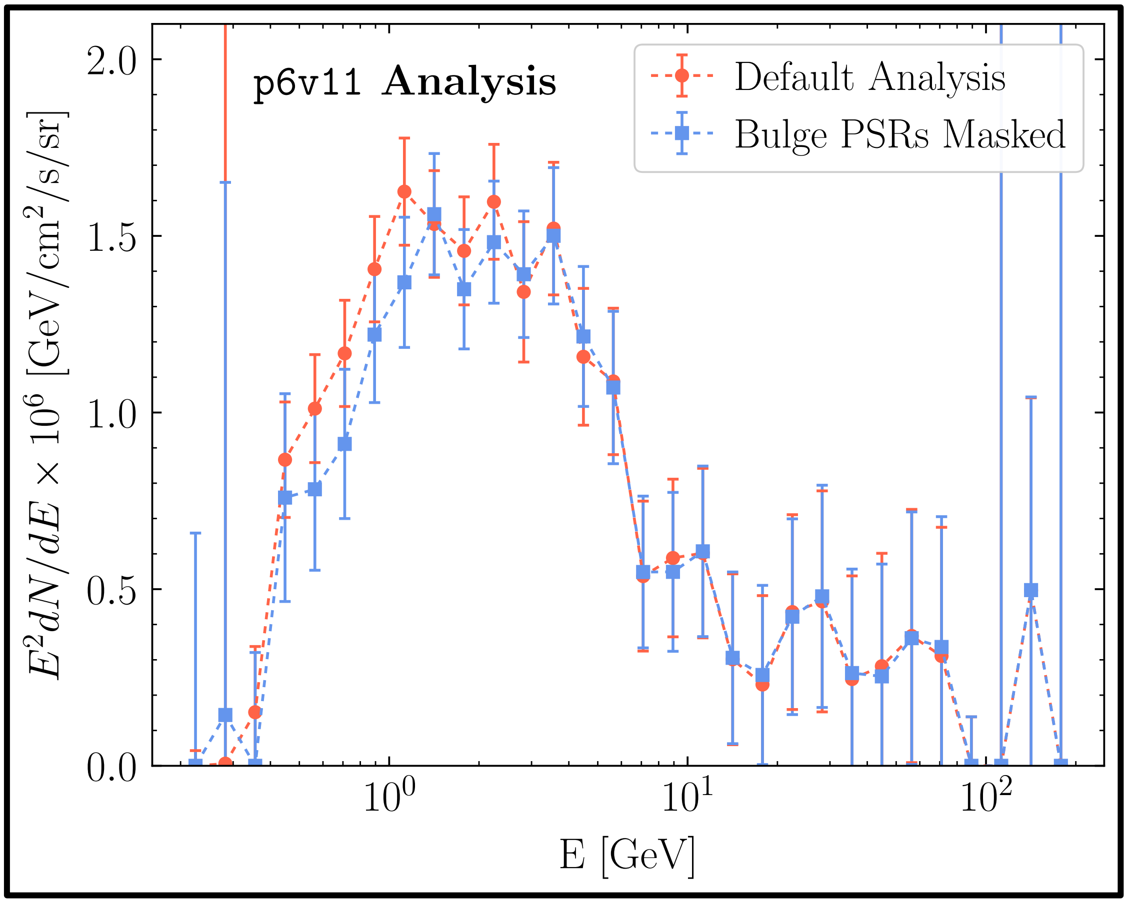
Gamma-Ray Bright MSPs in The Inner Galaxy?

- 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

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

Gamma-Ray Bright MSPs in The Inner Galaxy?

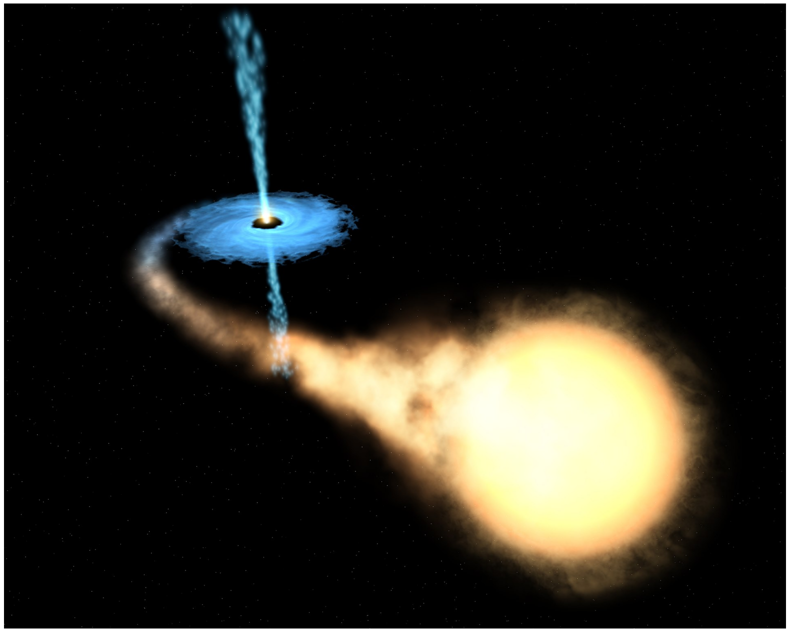
- Furthermore, known gamma-ray point sources do not appreciably contribute to the Galactic Center Excess; masking the pulsar candidate sources contained in various catalogs does *not* impact the characteristics of the excess



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

Searches for Bright Low-Mass X-Ray Binaries

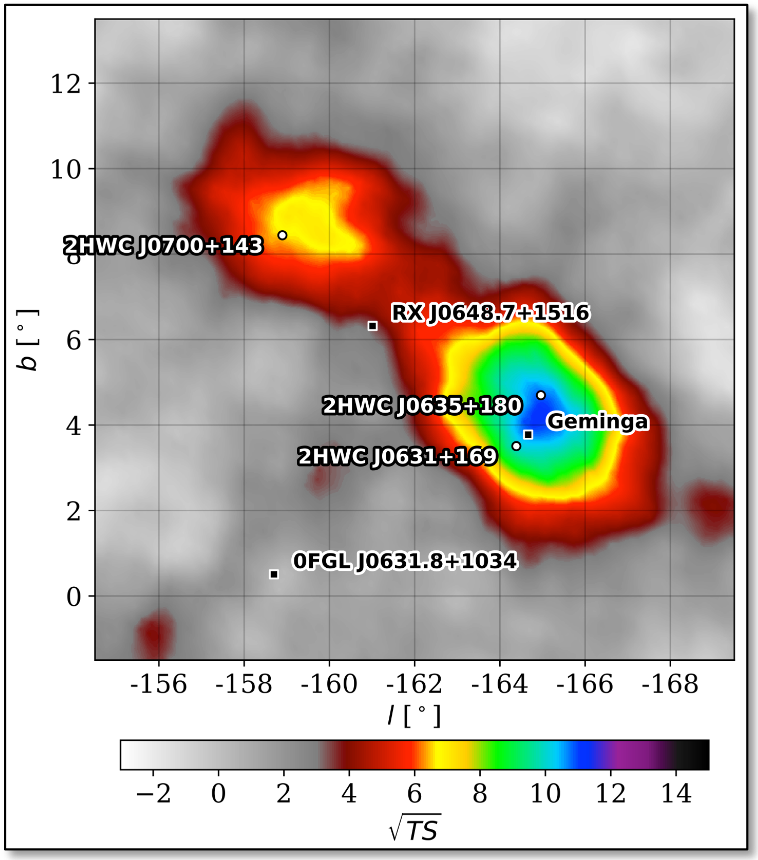
- Millisecond pulsars are formed when they are spun up by a binary companion; the precursors to MSPs are low-mass X-ray binaries (LMXBs)
- By measuring the ratio of the gamma-ray emission (from MSPs) to the number of bright LMXBs in globular clusters, and comparing this to the number of bright LMXBs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

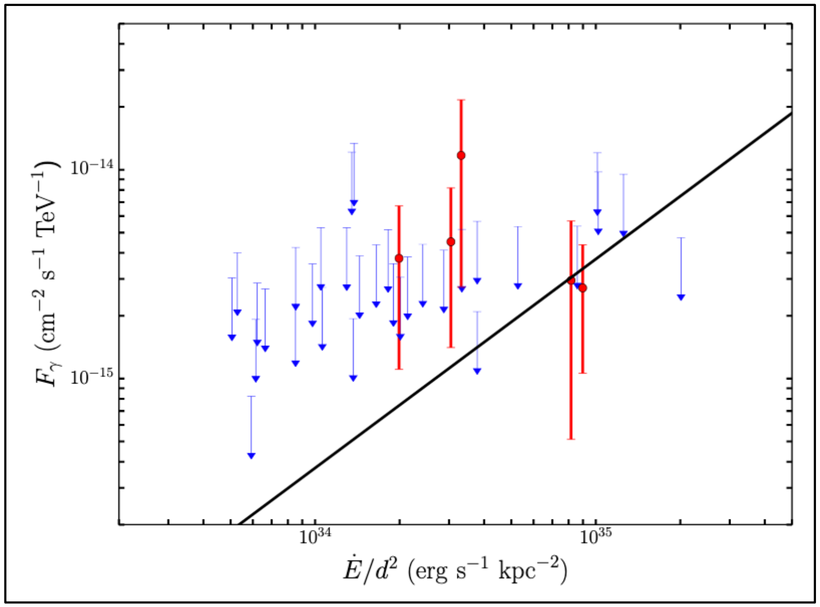


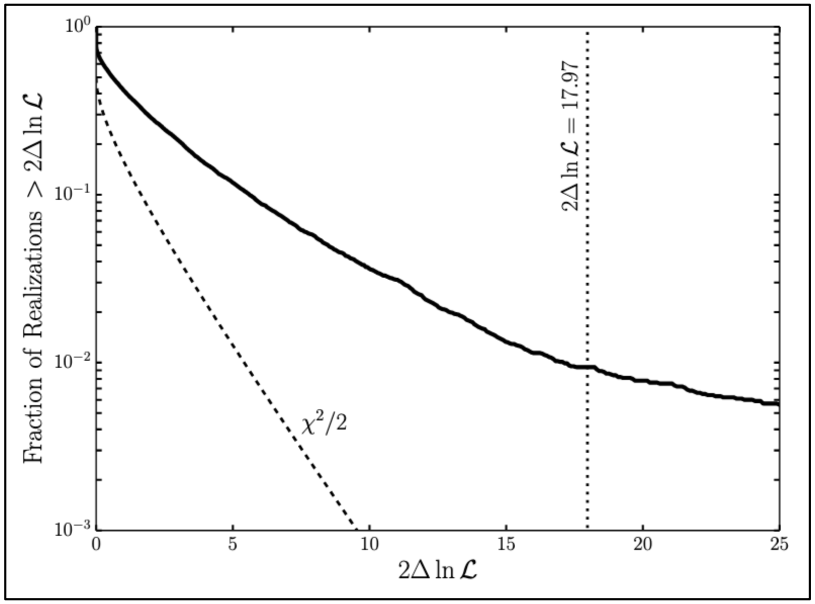
HAWC Collaboration, arXiv:1702.02992

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, $\eta_{MSP} = (0.39 - 1.08) \times \eta_{young}$

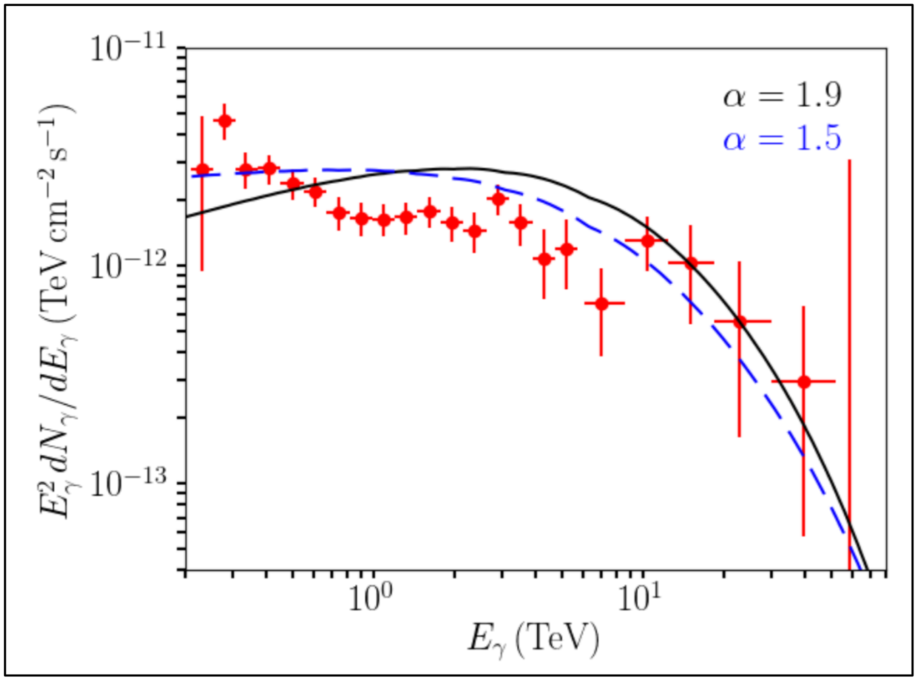




DH, Linden, arXiv:2104.00014 (1803.08046)

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 (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 the brightest TeV halos, or ruling out MSPs as the source of the GeV excess



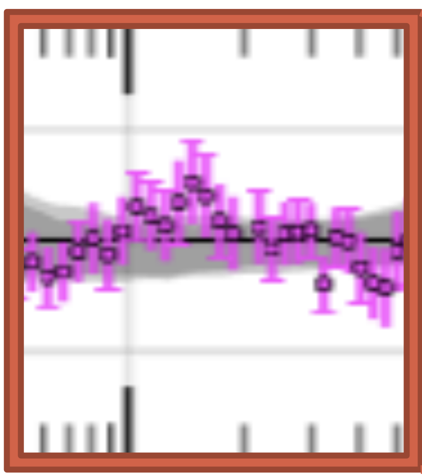
$0.2 - 0.5°$ annulus, $\eta_{MSP} = \eta_{young}$

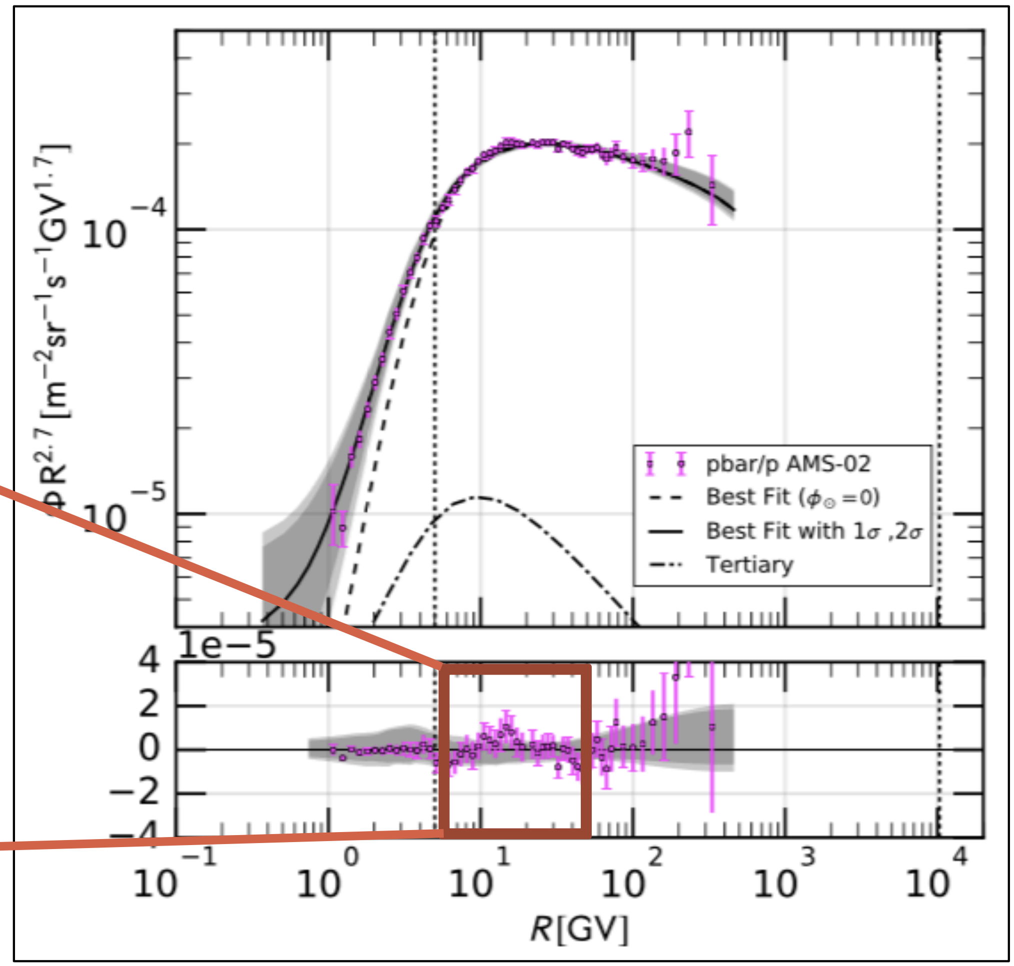
DH, Linden, arXiv:2104.00014 (1803.08046)

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 (~4.5**σ**)
- 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 ~40-70 GeV WIMP with a ~10^{-26} cm^3/s cross section





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

It's All About the Systematics

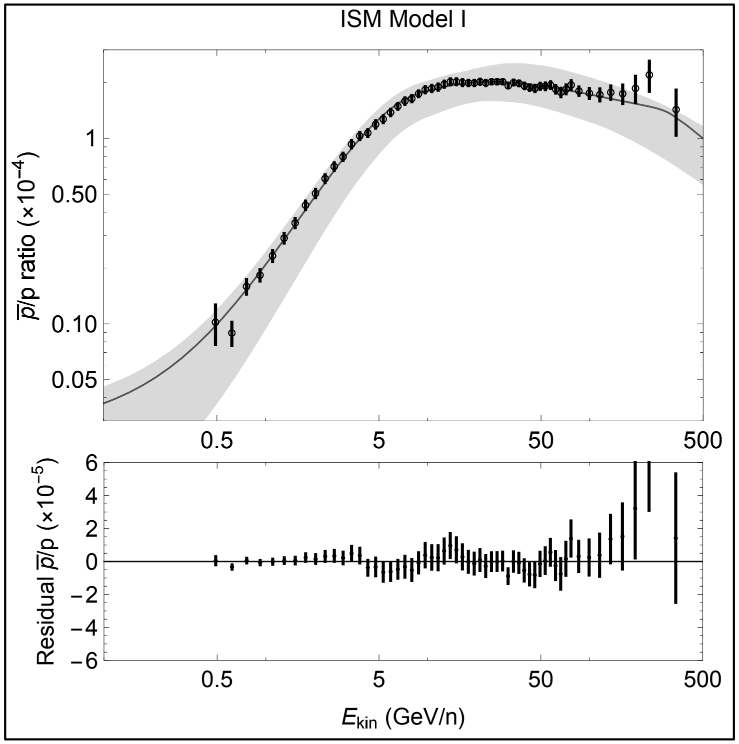
- The 2016 papers on the AMS antiproton excess received relatively little attention (roughly ~130 citations each), somewhat surprising for such a highly statistically significant and important result
- The skepticism of the community was the result of (perhaps reasonable) concerns pertaining to the difficult to quantify systematic uncertainties associated with:

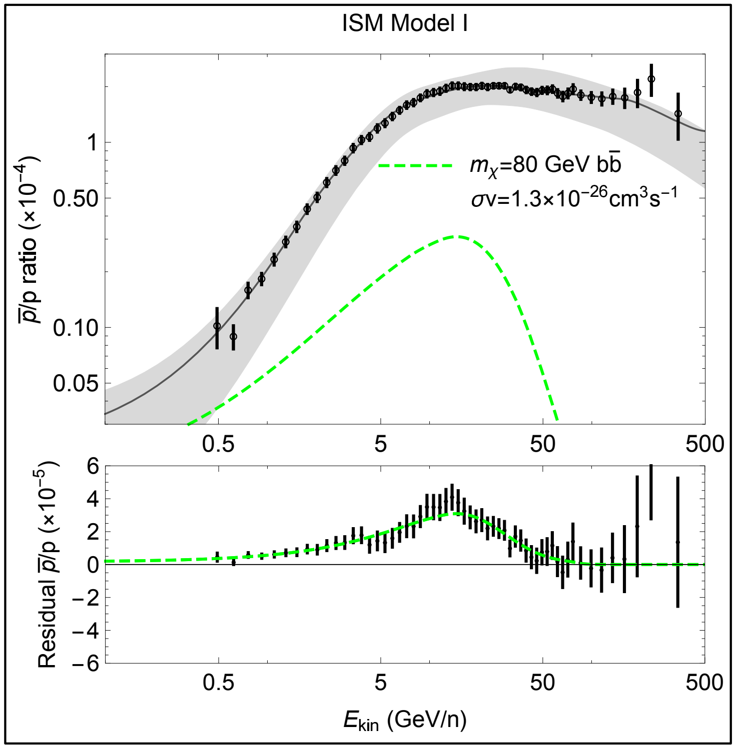
    1) Cosmic-ray injection and transport in the ISM (Cuoco *et al*., Cui *et al*.)

    2) The antiproton production cross section

    3) The impact of the solar wind (solar modulation)

The Cosmic-Ray Antiproton Excess



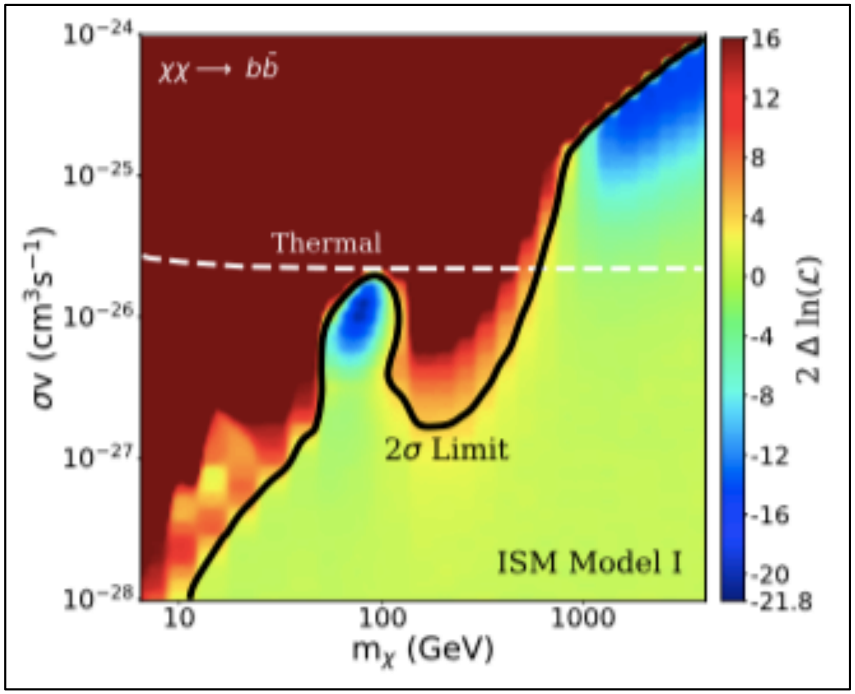


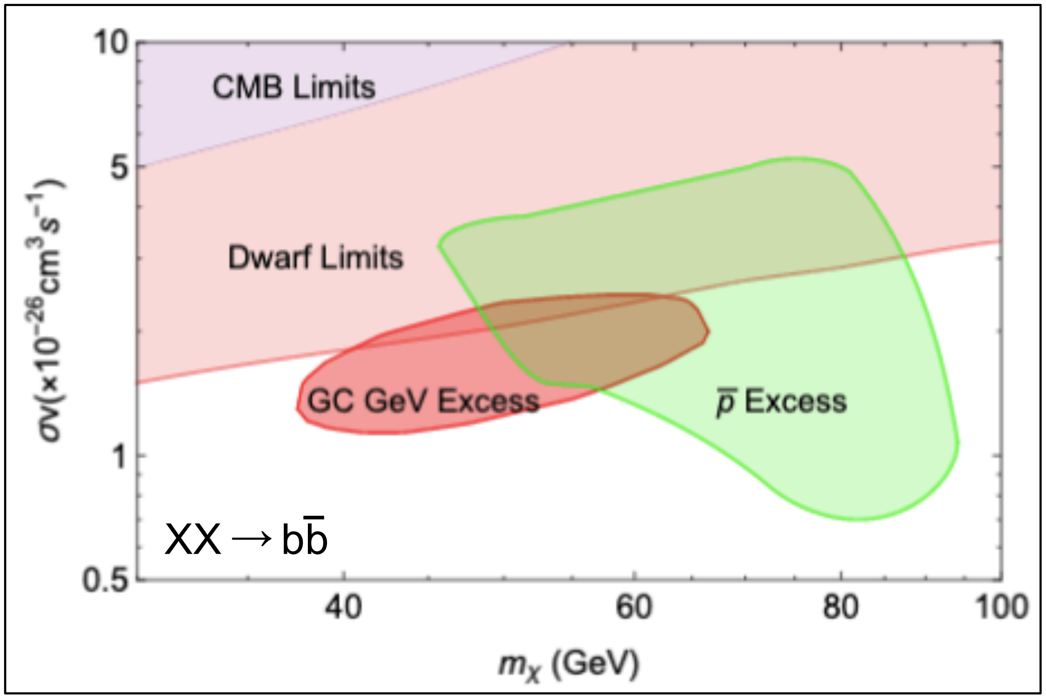
- Even after allowing for large systematic uncertainties associated with the antiproton production cross section and solar modulation, we find that the excess persists
- The fit consistently prefers a contribution from annihilating dark matter, at a level never less than 3.3σ

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 ~45-95 GeV dark matter particles with a cross section of σv ~(0.7-5)x10^{-26} cm^3/s (for $b\bar{b}$)
- For m_χ~50-70 GeV and σv ~(1.4-2.4)x10^{-26} cm^3/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)

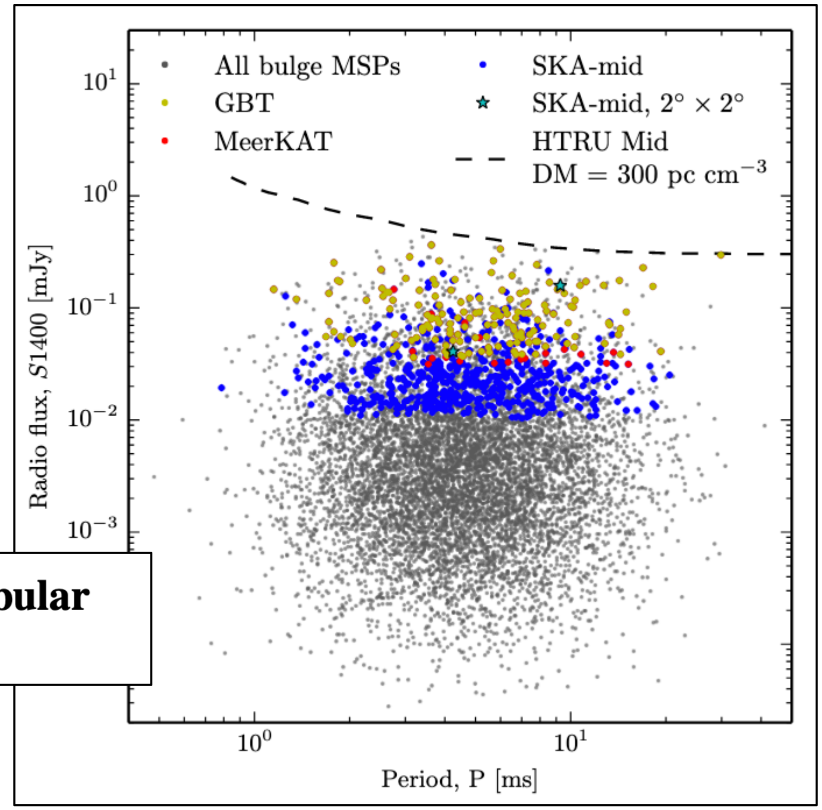




Looking Forward: Radio Searches for Inner Galaxy MSPs

- If MSPs generate the GeV excess, future deep radio surveys should be able to detect the pulsed radio emission from these objects
- After ~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 they recently announced their first MSP discoveries (far from Inner Galaxy), arXiv:2103.04800

Eight new millisecond pulsars from the first MeerKAT globular cluster census

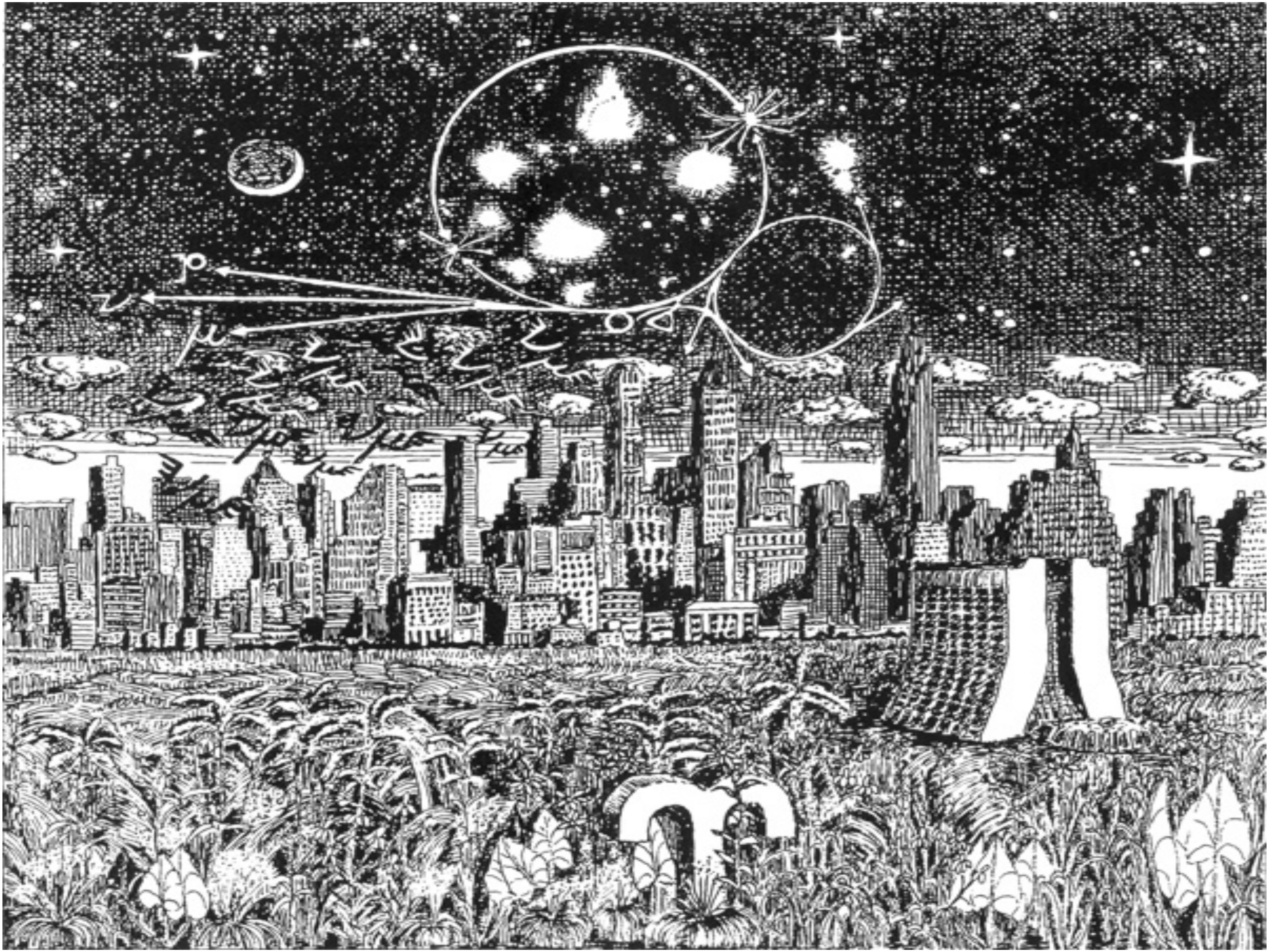


- First light for SKA is projected for 2027

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

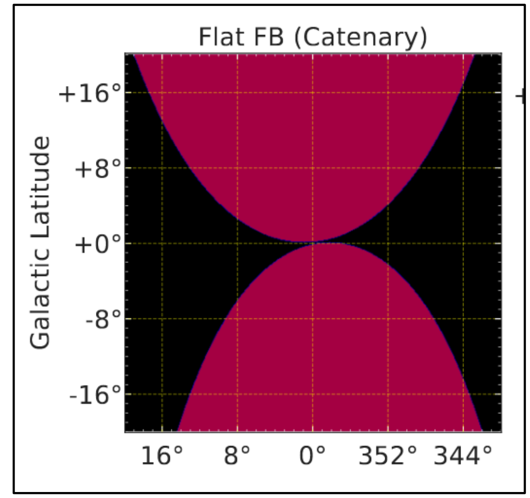
Summary

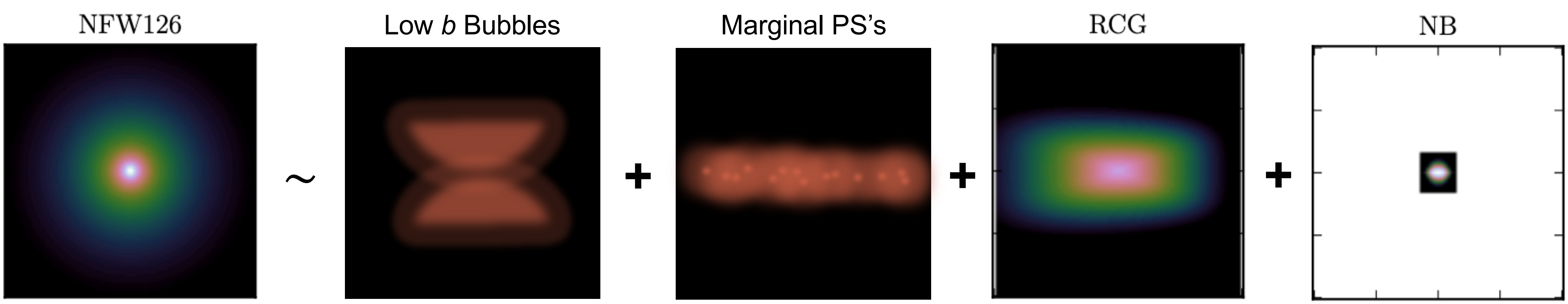
- Indirect searches using gamma rays and cosmic rays are currently testing the range of annihilation cross sections that are predicted for a thermal relic, for masses up to ~100 GeV
- Along with the direct detection program, these telescopes and detectors are actively testing the WIMP paradigm
- The 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



Bulge/Bar-Like vs DM-Like Morphology

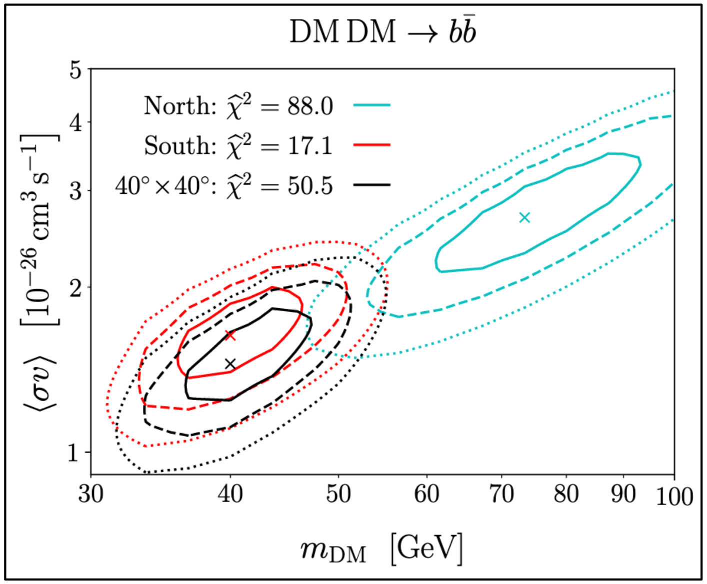
- The way in which we model the Fermi Bubbles can non-negligibly impact the inferred morphology of the excess
- The Bubbles are usually taken to be of uniform brightness, with well-defined edges; near the Galactic Plane, this is highly uncertain and poorly constrained
- There are also several dozen point 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)

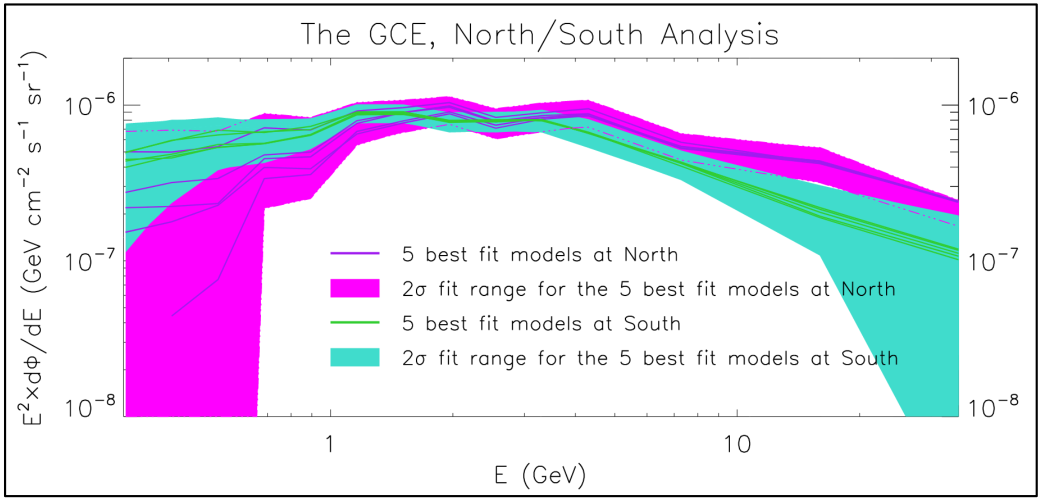




Does the GCE Have a North-South Asymmetry?

- Using standard templates, the answer seems to be "yes"
- The GCE has a more pronounced high-energy tail in the northern half of the dataset, which is likely to be the consequence of imperfections in the astrophysical templates
- In light of this, it is probably wise to rely on the southern analysis to derive constraints on dark matter parameters, etc.





Leane, Slatyer, arXiv:1904.08430, 2002.12370,
Cholis, Zhong, McDermott, Surdutovich, arXiv:2112.09706