The Status of the Galactic Center Gamma-Ray Excess

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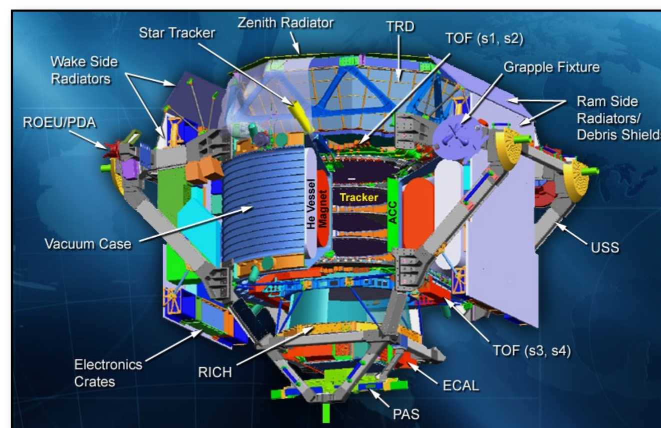
The Motivation for Indirect Searches

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

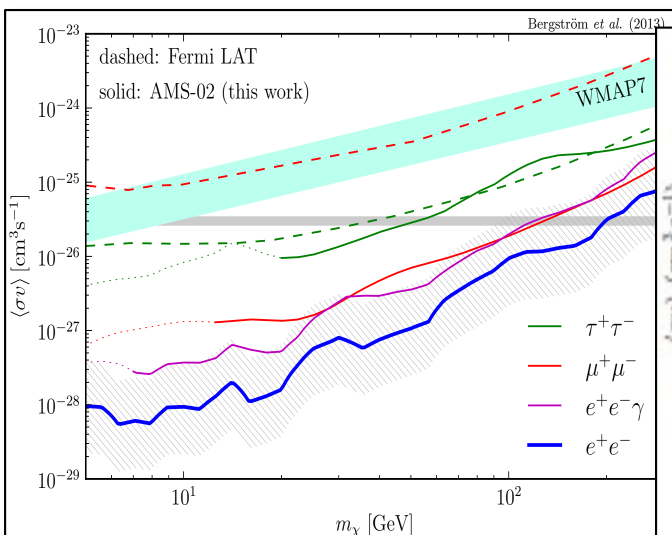
Fermi

AMS-02

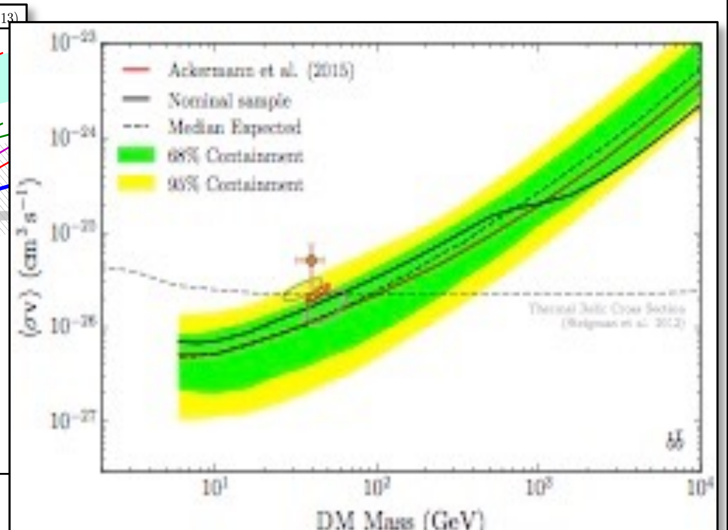


Constraints from Indirect Detection

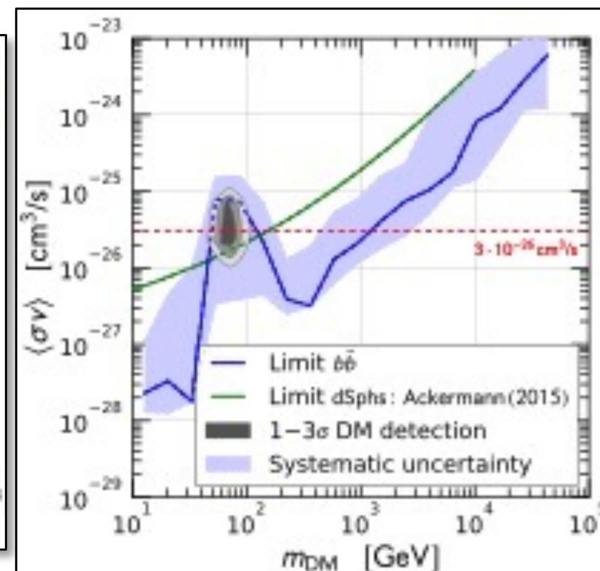
- A variety of gamma-ray strategies (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements from AMS, are currently sensitive to dark matter with the annihilation cross section predicted for a simple thermal relic, for masses up to $\sim\mathcal{O}(100)$ GeV
- This program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



Bergstrom, et al., arXiv:1306.3983



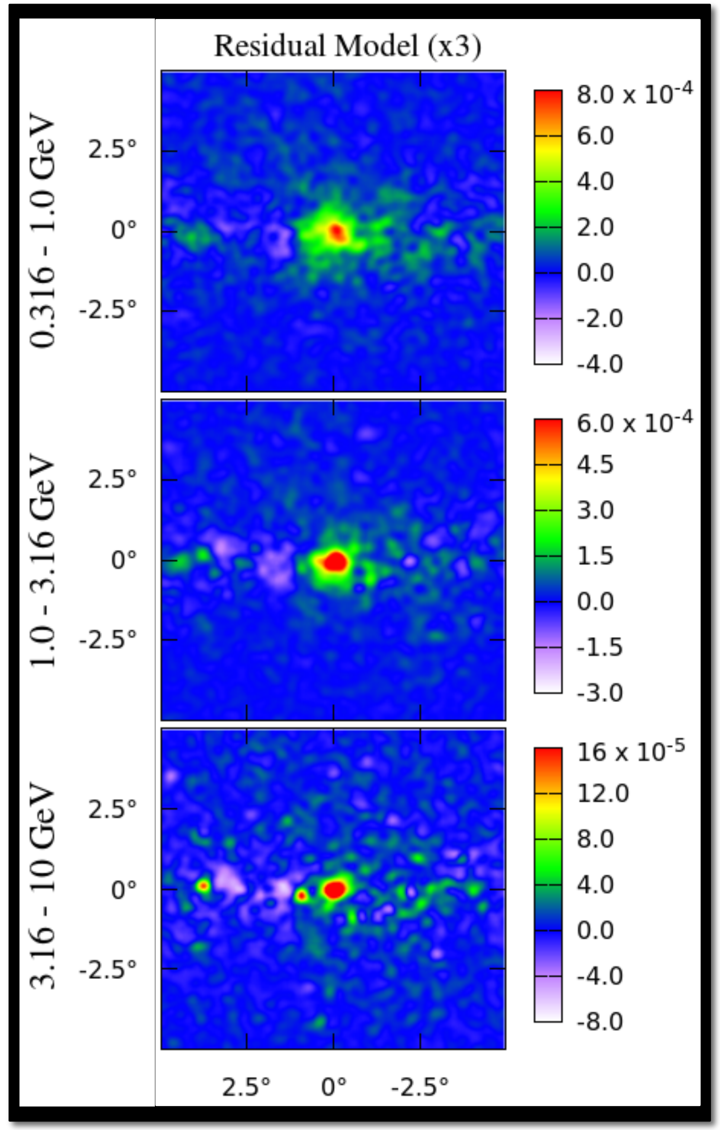
Fermi Collaboration, arXiv:1611.03184



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 long predicted from annihilating dark matter



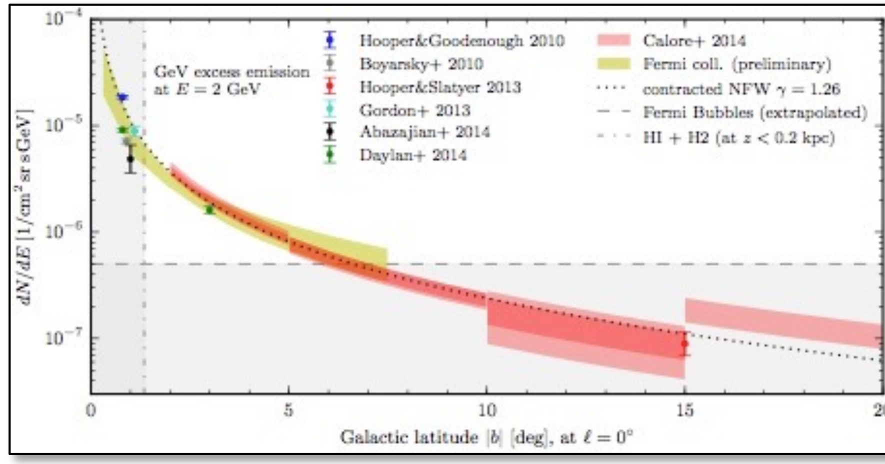
Among other references, see:

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)

The Galactic Center Gamma-Ray Excess

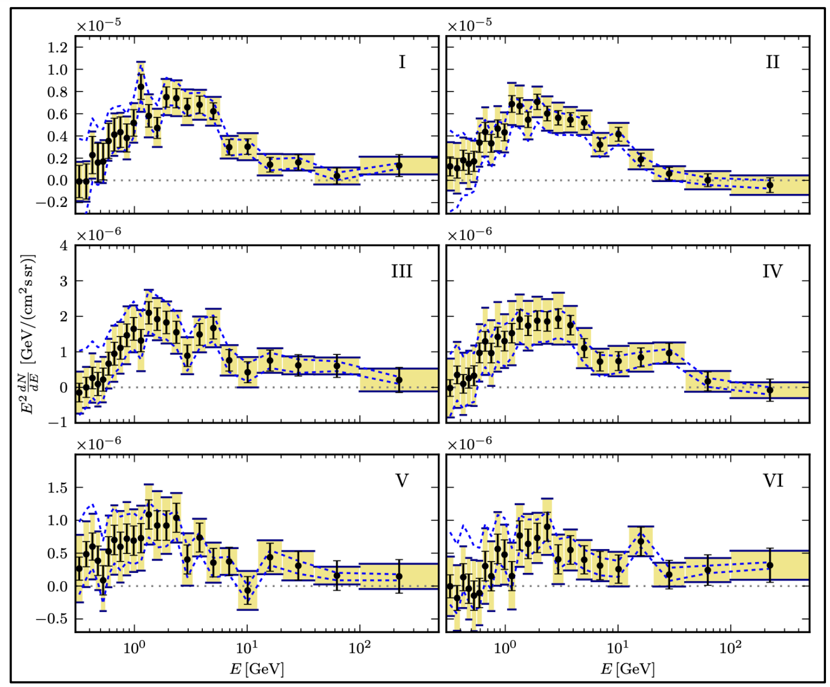
Morphology

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



Spectrum

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



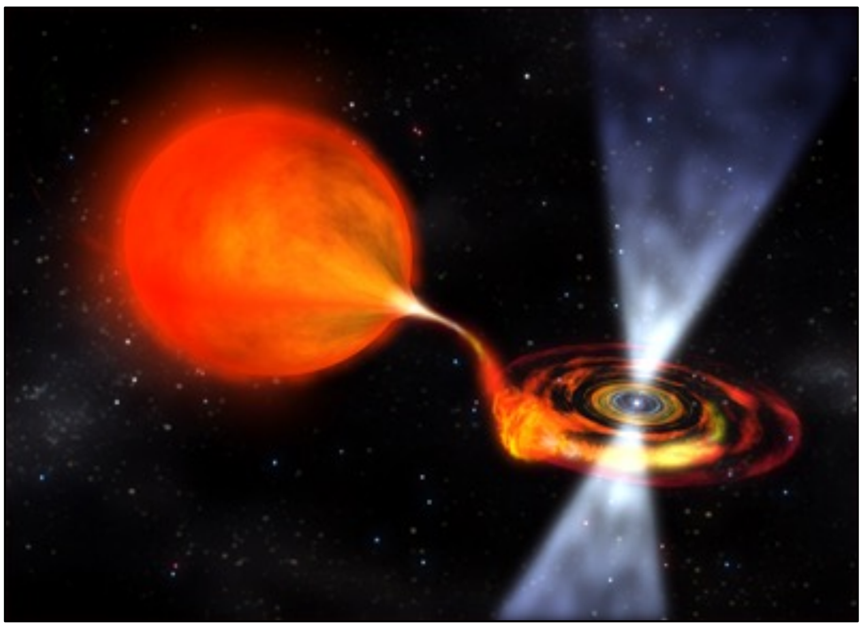
Intensity

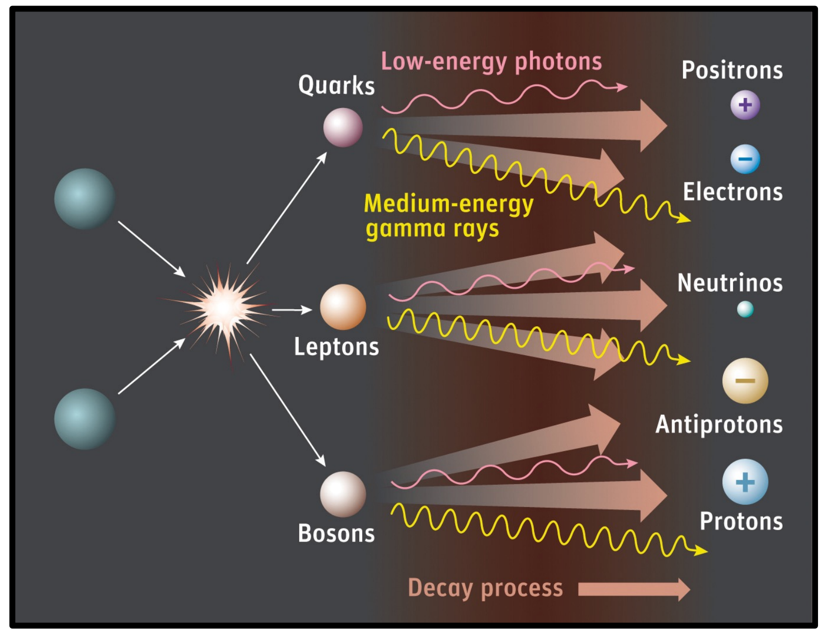
- To normalize the observed excess, the DM particles must annihilate with $\sigma v \sim 10^{-26}$ cm^3/s, approximately equal to the value required to obtain the measured DM abundance

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

What Produces the Excess?

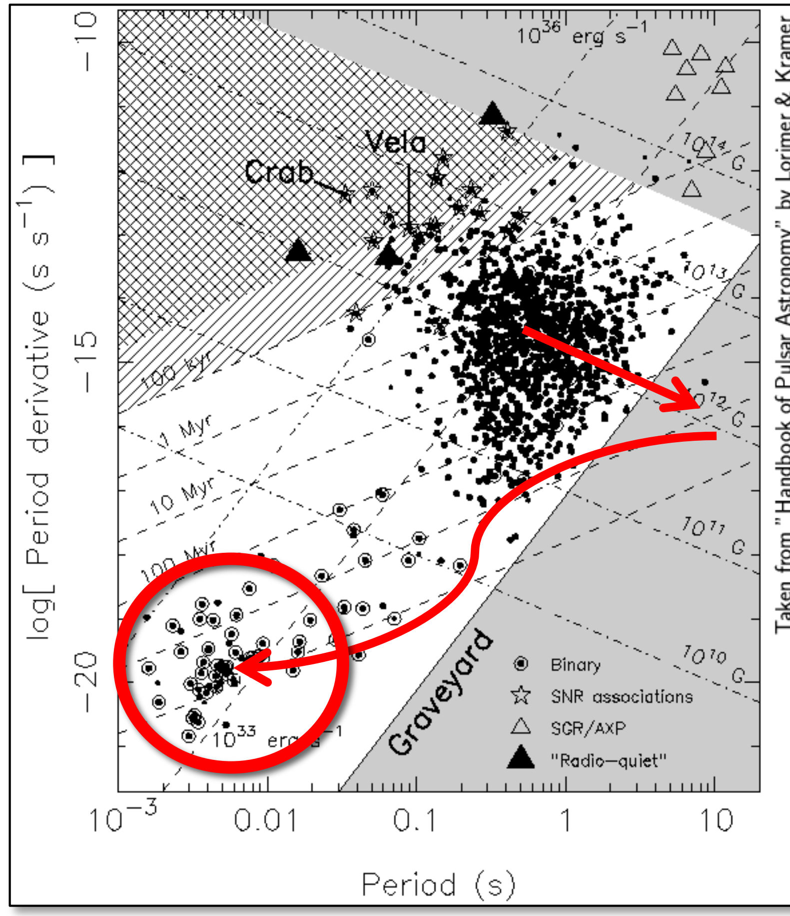
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?

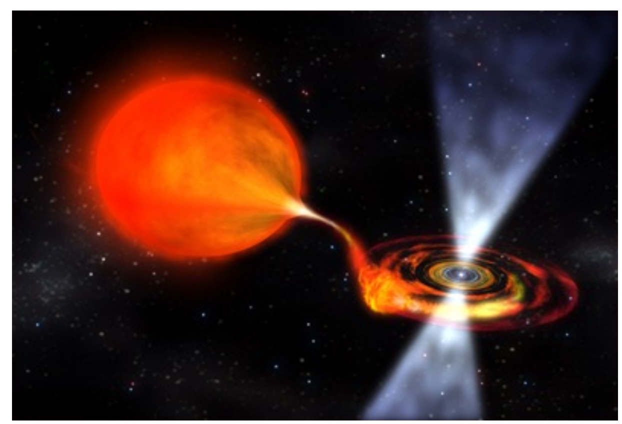




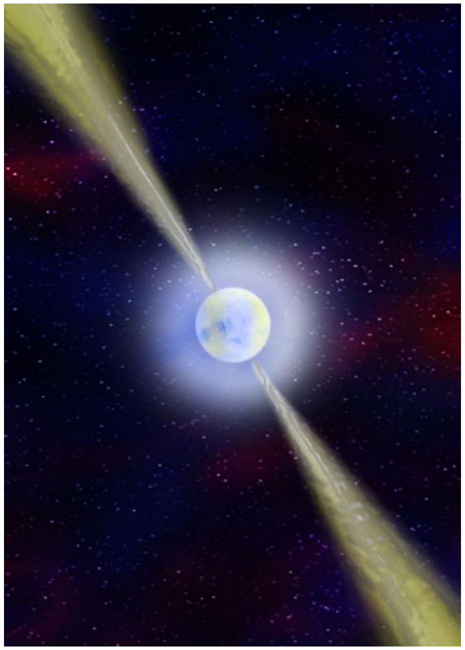
Millisecond Pulsars

- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- Young pulsars exhibit periods on the order of ~1 second and slow down and become faint over ~10^6 -10^8 years
- 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:

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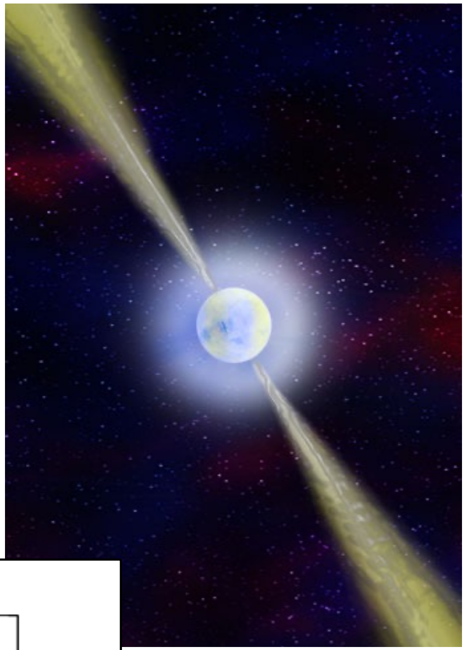

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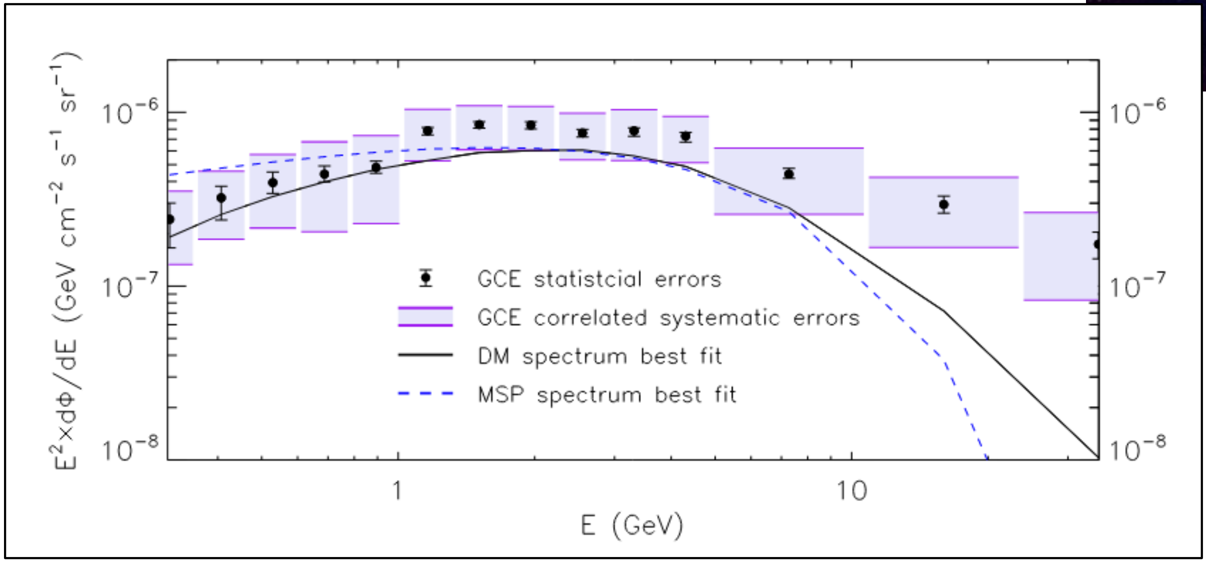

Cholis, Zhong, McDermott, Surdutovich (2021)

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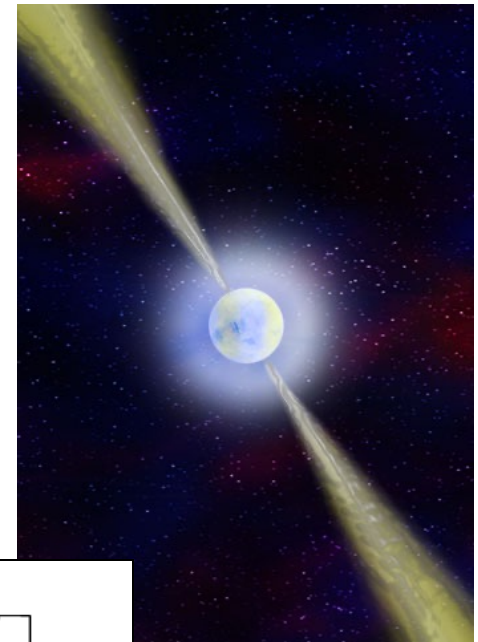

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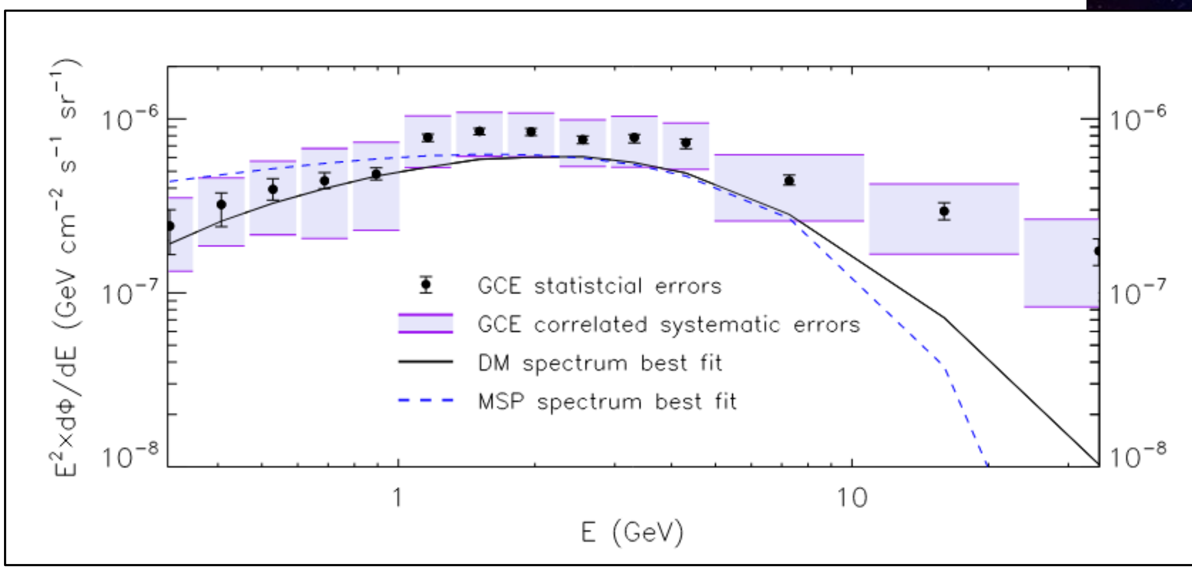

Cholis, Zhong, McDermott, Surdutovich (2021)

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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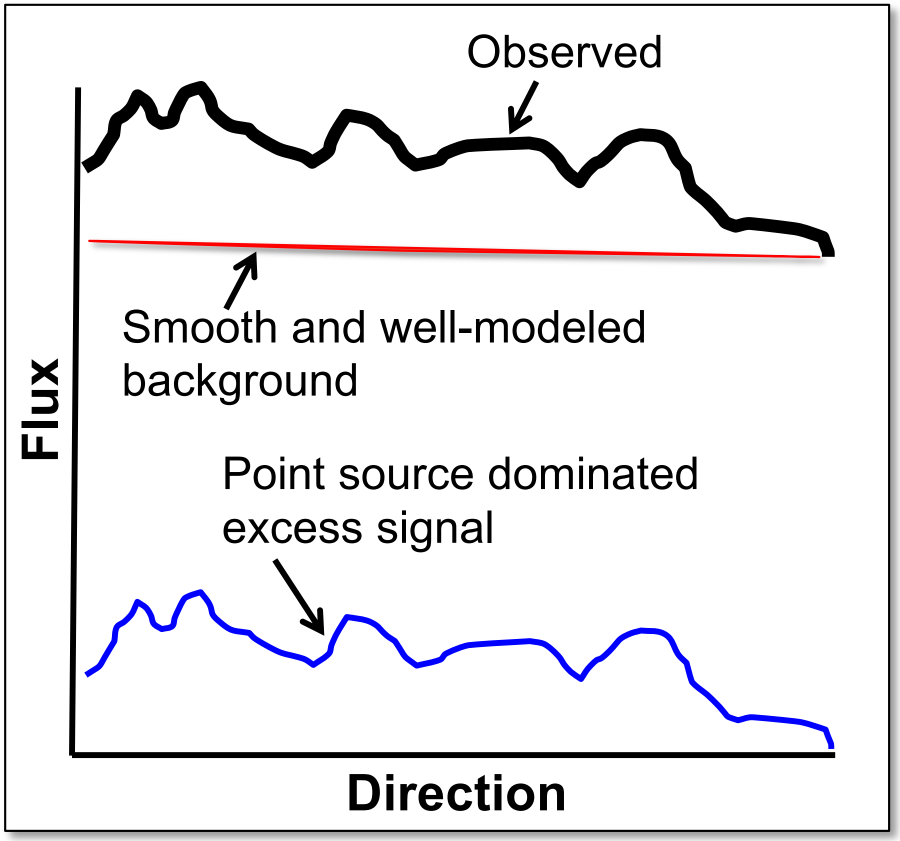

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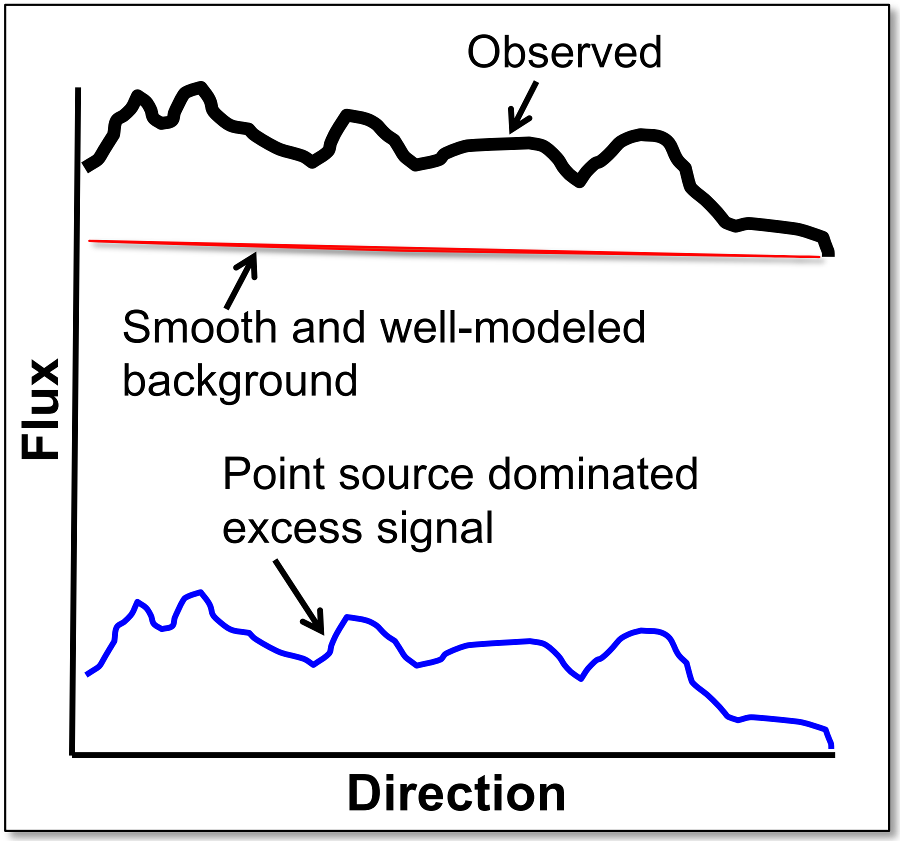

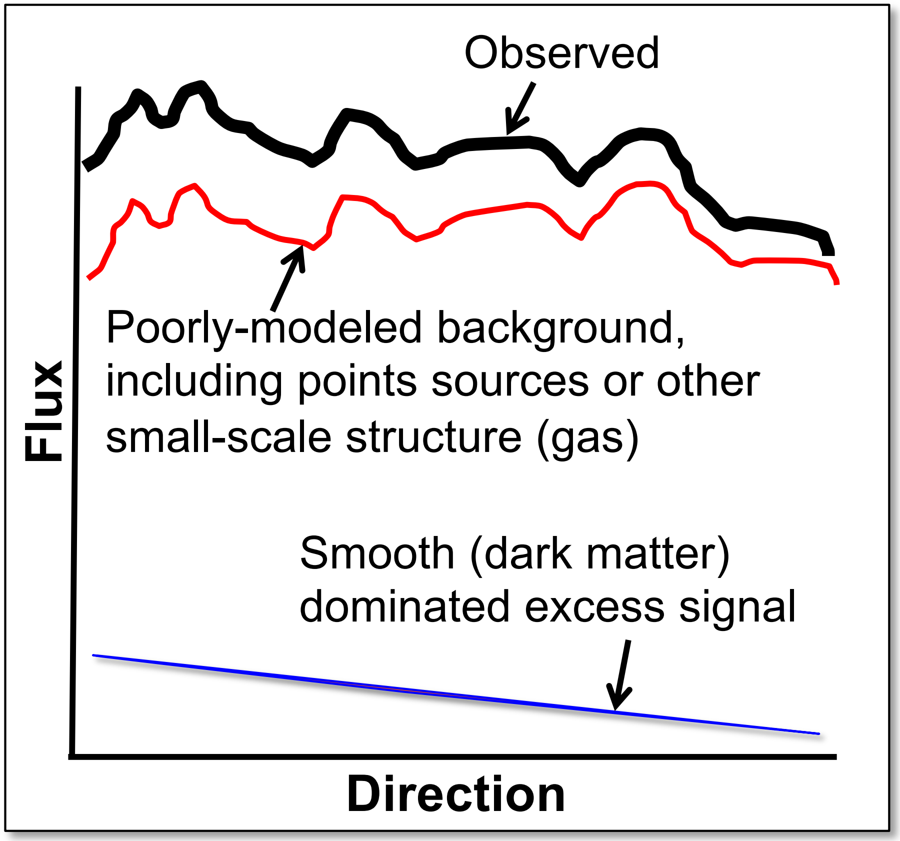

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

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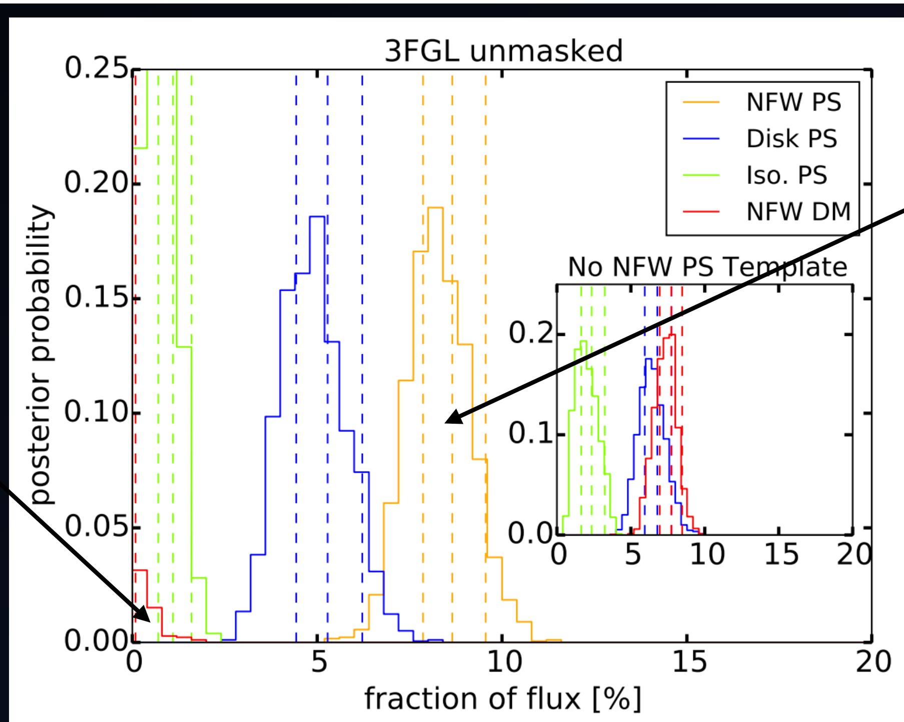
Evidence against any significant amount of dark matter annihilation



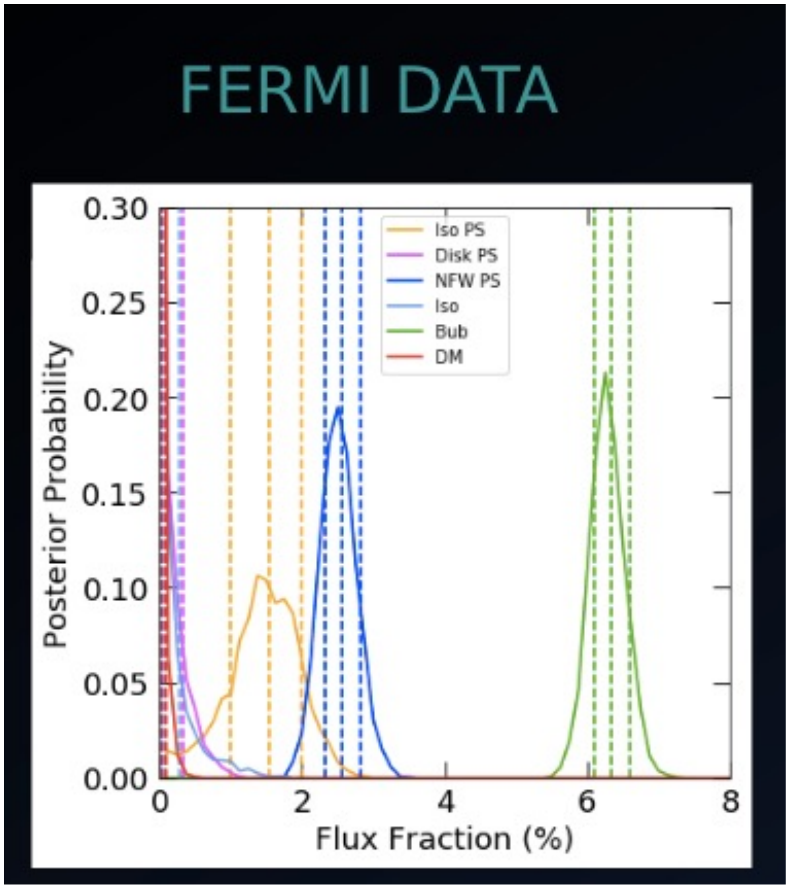
Lee, Lisanti, Safdi, Slatyer, Xue (PRL ‘15)

Evidence for NFW^2 Distributed Point Sources

To what extent could inadequate templates be biasing these results?

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

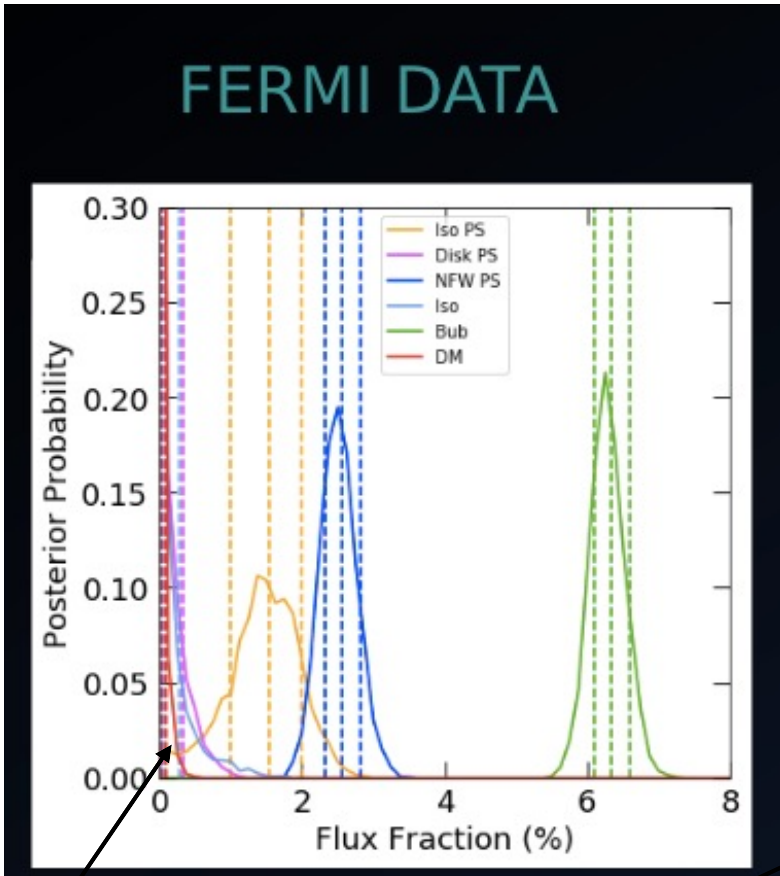


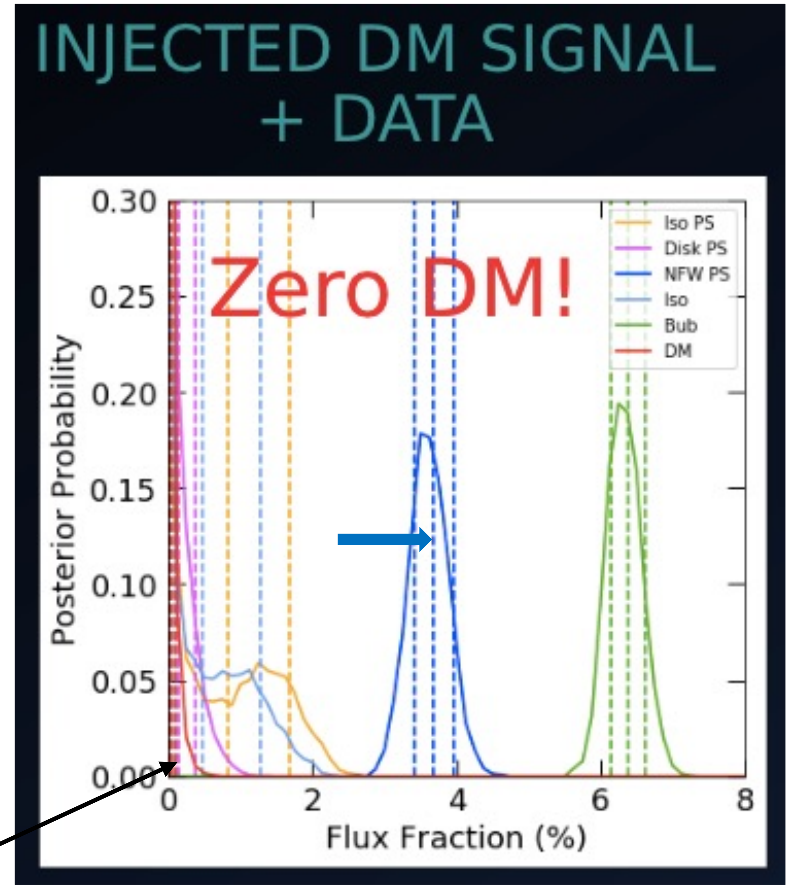
Here is the result that Leane and Slatyer get using the same procedure as Lee *et al.*

To test the reliability 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





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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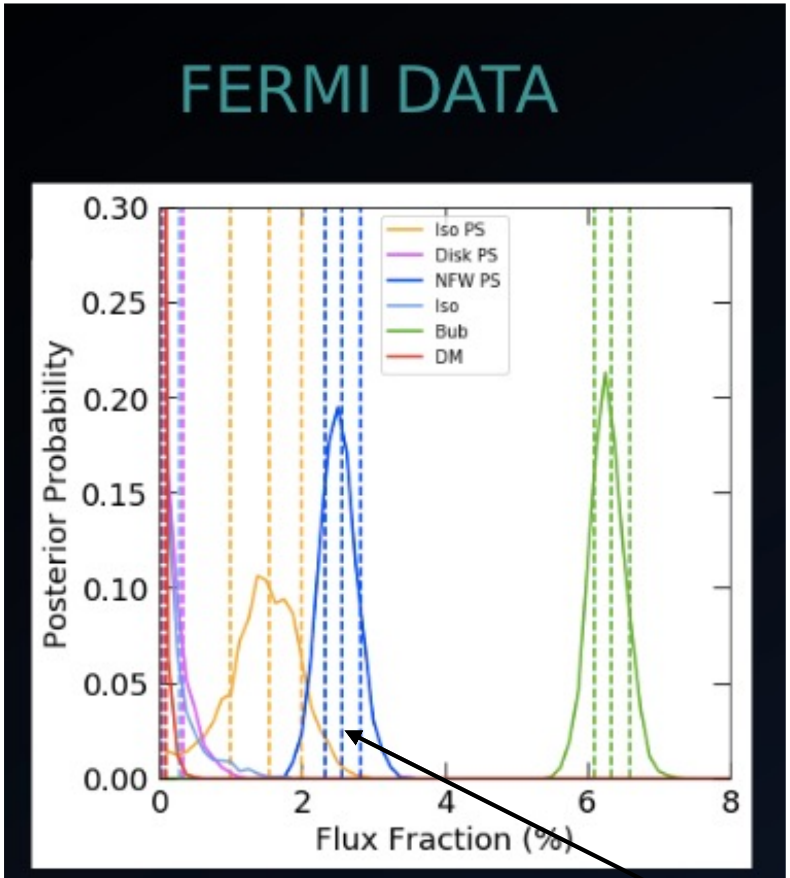

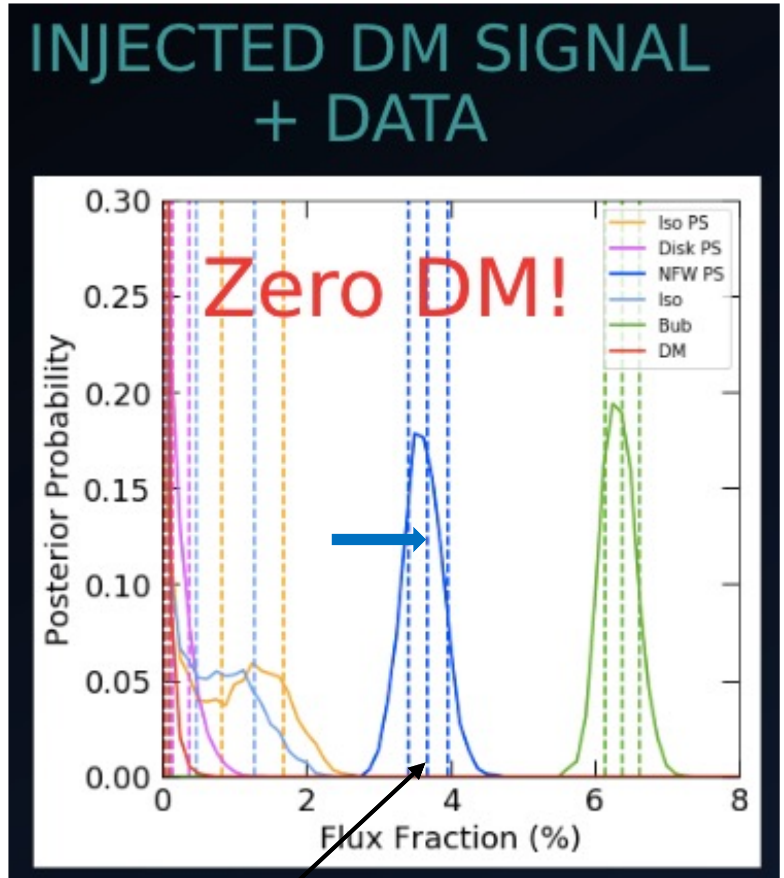

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Instead, the fit identifies the injected dark matter-like signal as originating from point sources

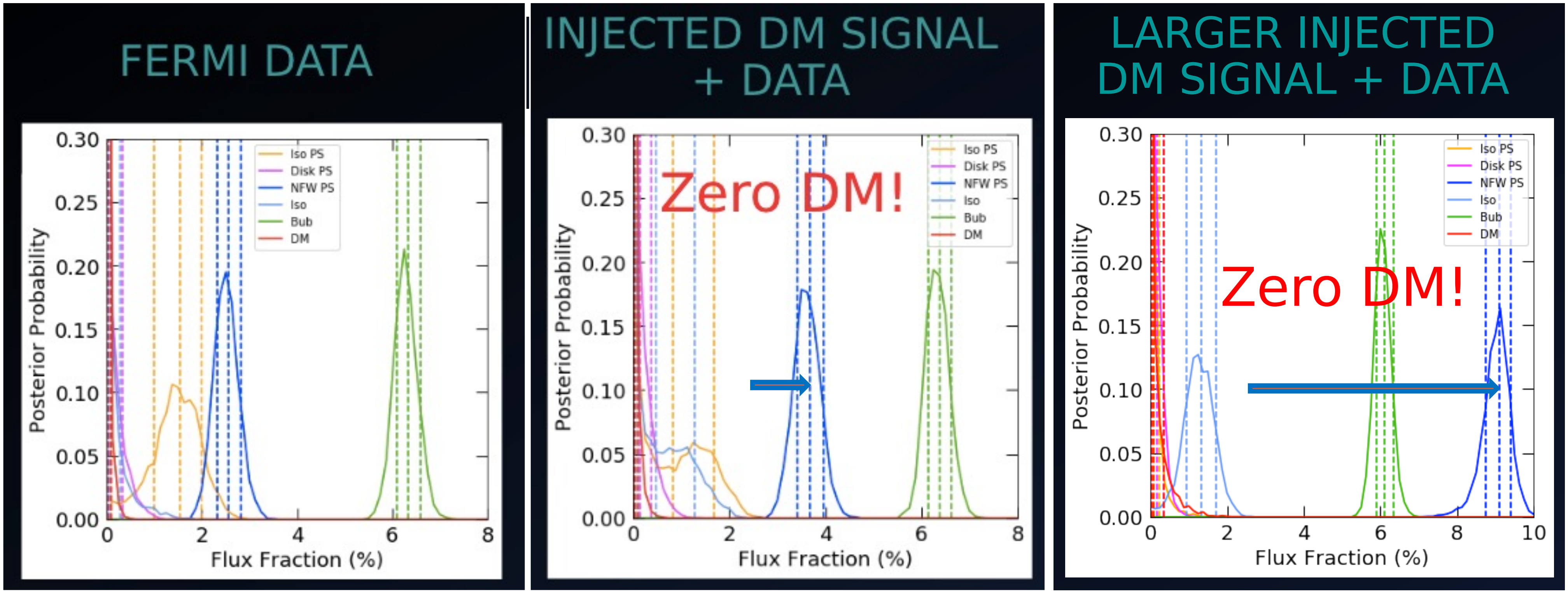
DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

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

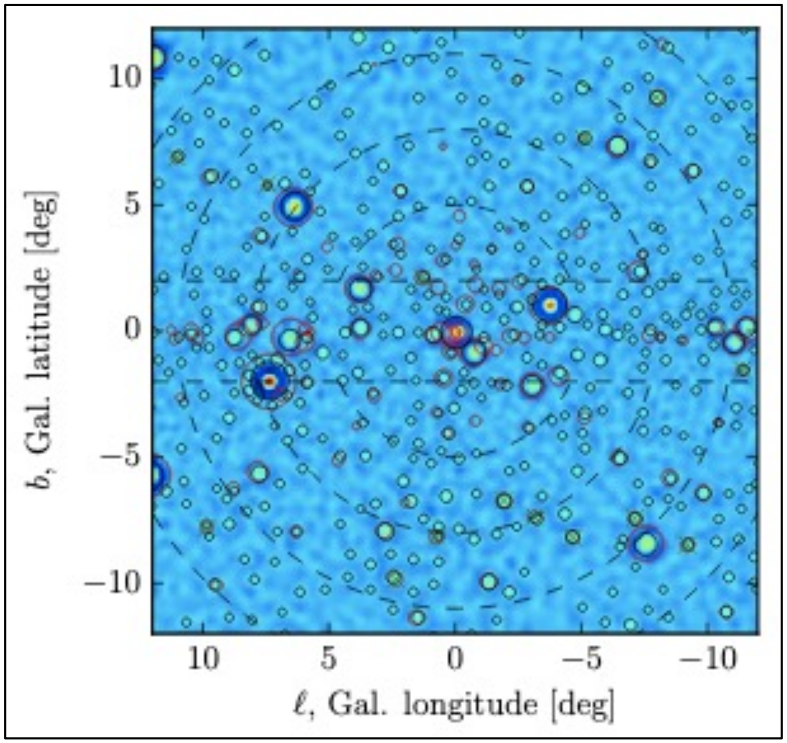
Bottom Line:

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

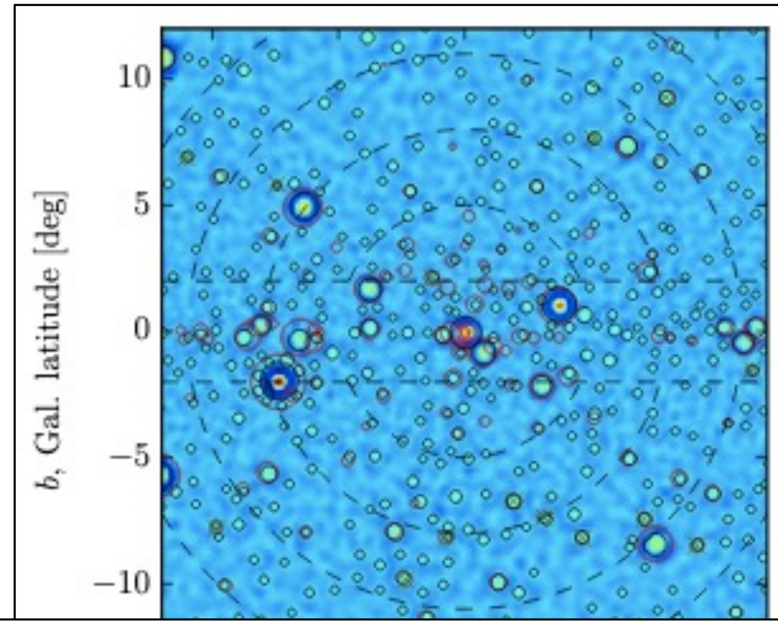
- In 2015, Bartels *et al.* used a wavelet-based technique to identify what they called "strong support" for a millisecond pulsar interpretation of the gamma-ray excess

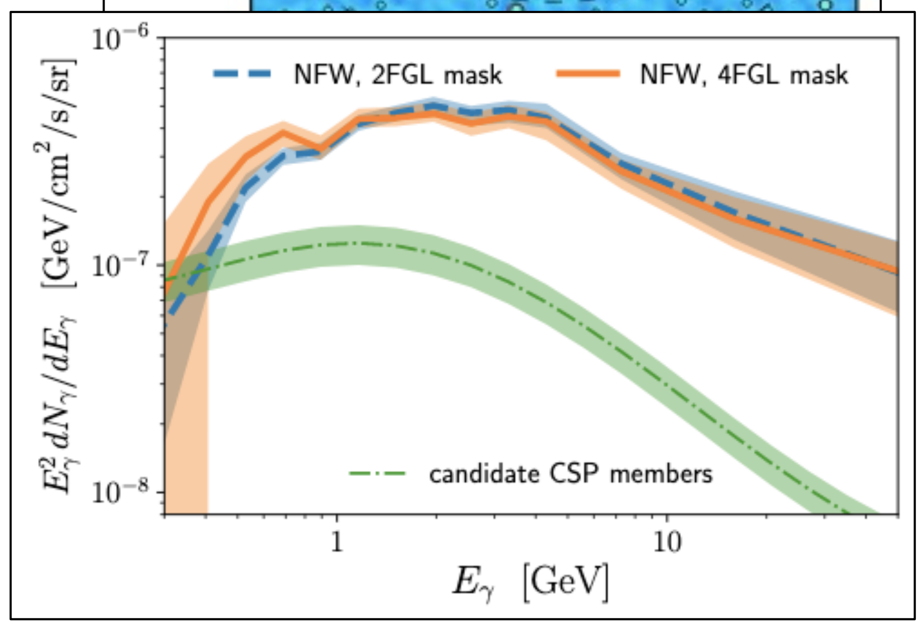


Bartels, Krishnamurthy, Weniger, arXiv:1506.05104
Zhong, McDermott, Cholis, Fox, arXiv:1911.12369

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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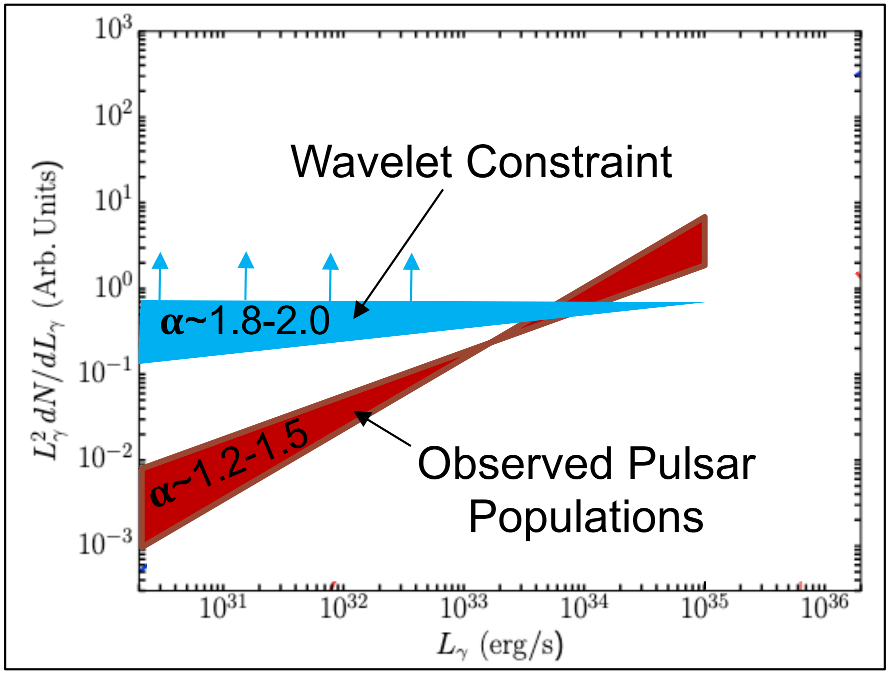
Tension with Pulsar Interpretations

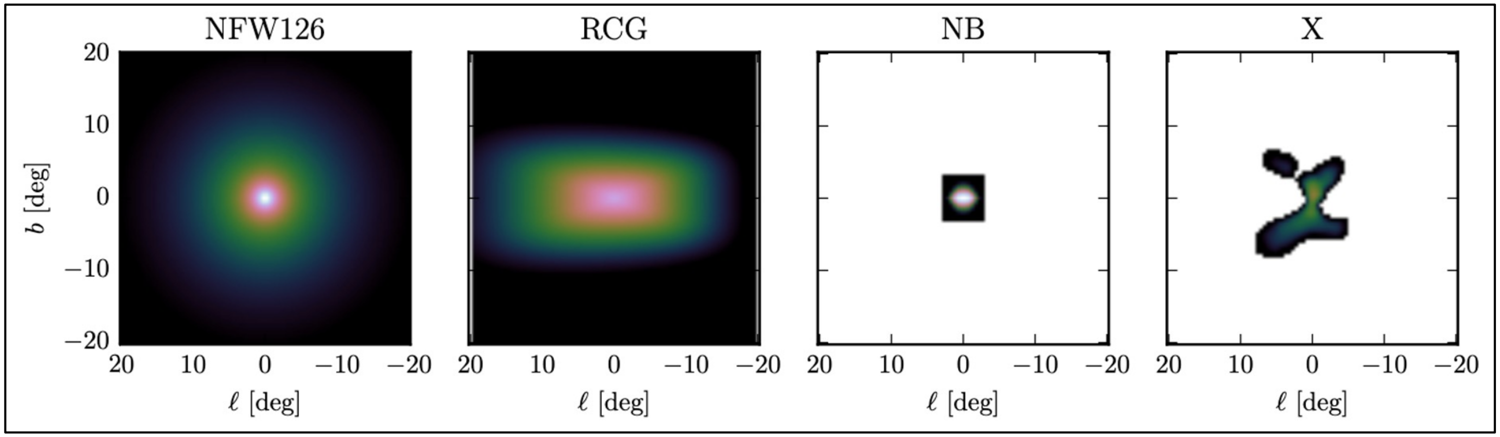
- The wavelet technique can be used to place constraints on the luminosity function of any point source population that could potentially be responsible for the Galactic Center excess
- Observed populations of millisecond pulsars (in the disk and in globular clusters) have luminosity functions that peak 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 α~1.2-1.5 (for $L_{max} \sim 10^{35}$ erg/s)
- 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 ~3x10^6 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

- 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)

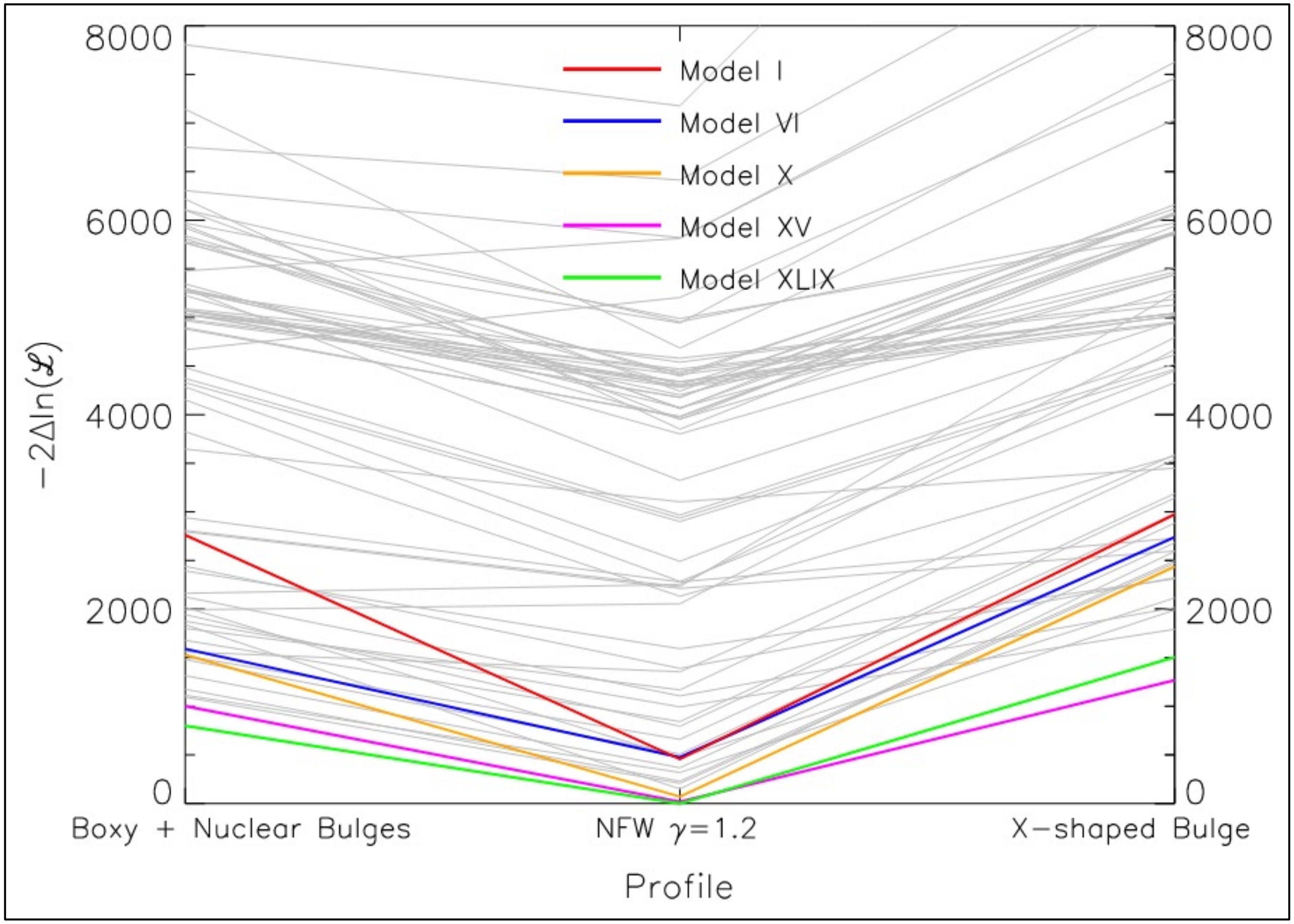


- In three papers (listed below), it was argued that the Fermi excess is better fit by spatial templates that trace stellar populations than dark matter-like templates, favoring MSP interpretations of the gamma-ray excess

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

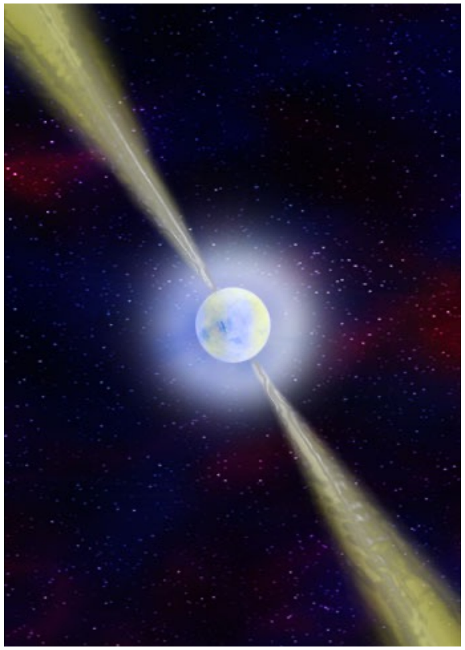
Bulge/Bar-Like vs DM-Like Morphology

- Recent work has not confirmed these results, but instead finds a strong statistical preference for dark matter-like templates



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

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



Arguments in Favor of Pulsars:

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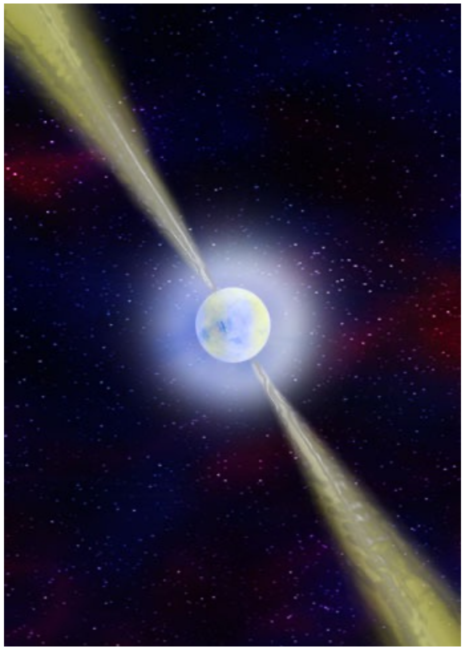

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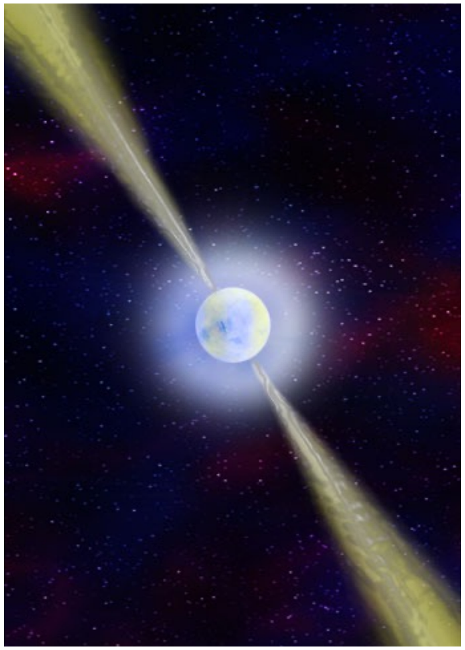

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Arguments Against Pulsars:

- 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 the TeV-scale emission from the Inner Galaxy

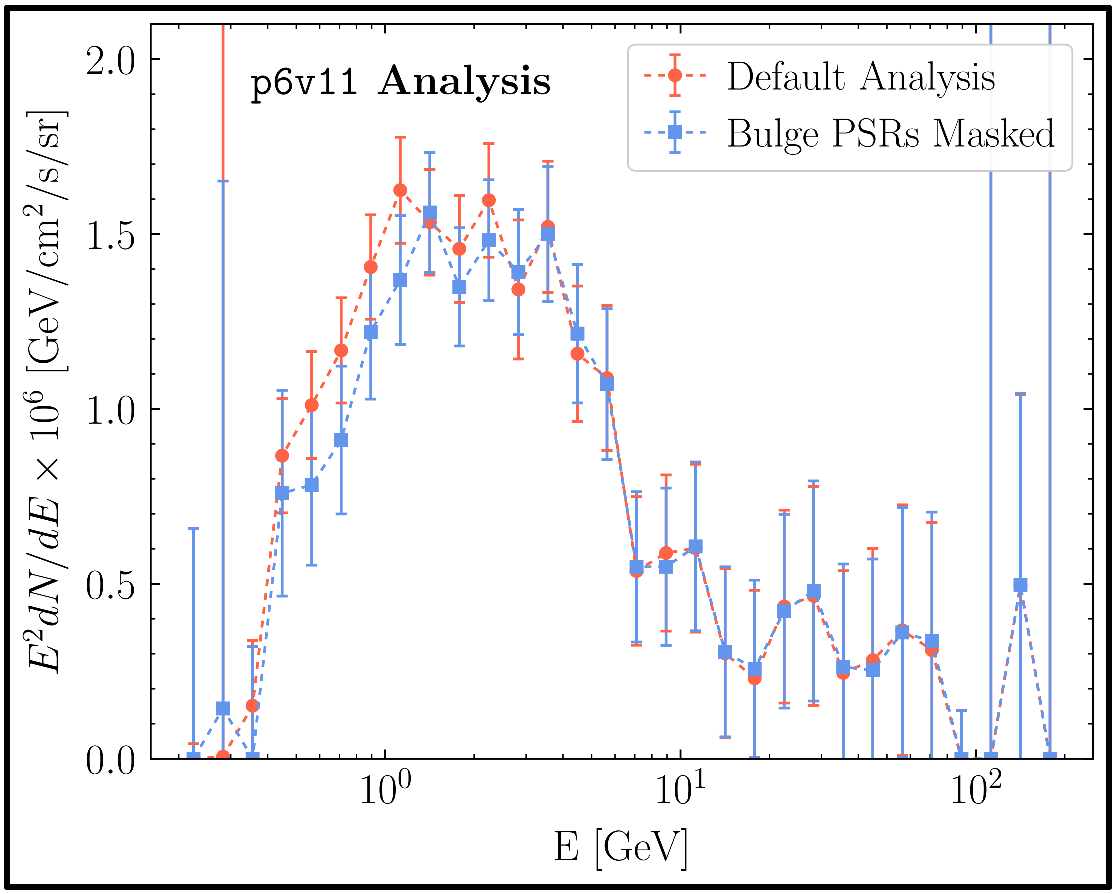
Gamma-Ray Bright MSPs in The Inner Galaxy?

- 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?

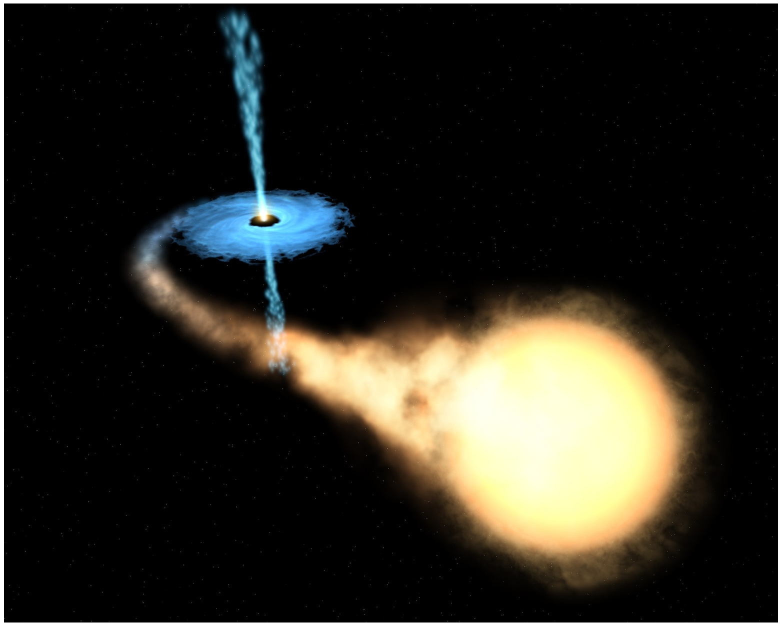
- Furthermore, known gamma-ray point sources do not appreciably contribute to the Galactic Center Excess; masking the pulsar candidate sources contained in various catalogs does *not* impact the characteristics of the excess



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

Searches for Bright Low-Mass X-Ray Binaries

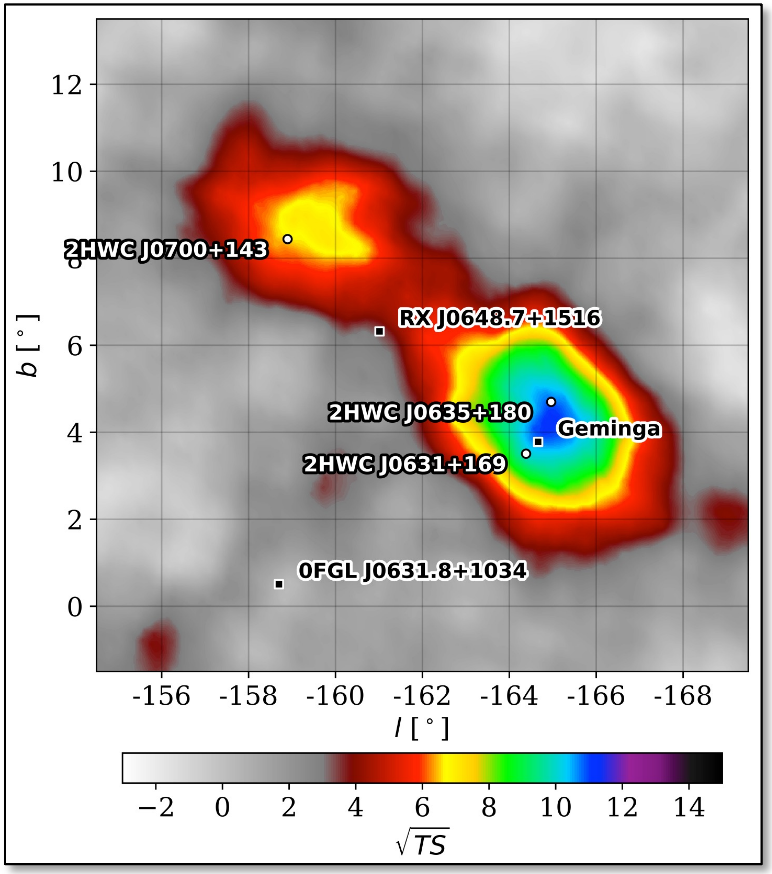
- Millisecond pulsars are formed when they are spun up by a binary companion; the precursors to MSPs are low-mass X-ray binaries (LMXBs)
- By measuring the ratio of the gamma-ray emission (from MSPs) to the number of bright LMXBs in globular clusters, and comparing this to the number of bright LMXBs 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 ~10^3 LMXBs; but they actually detected only 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
- 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

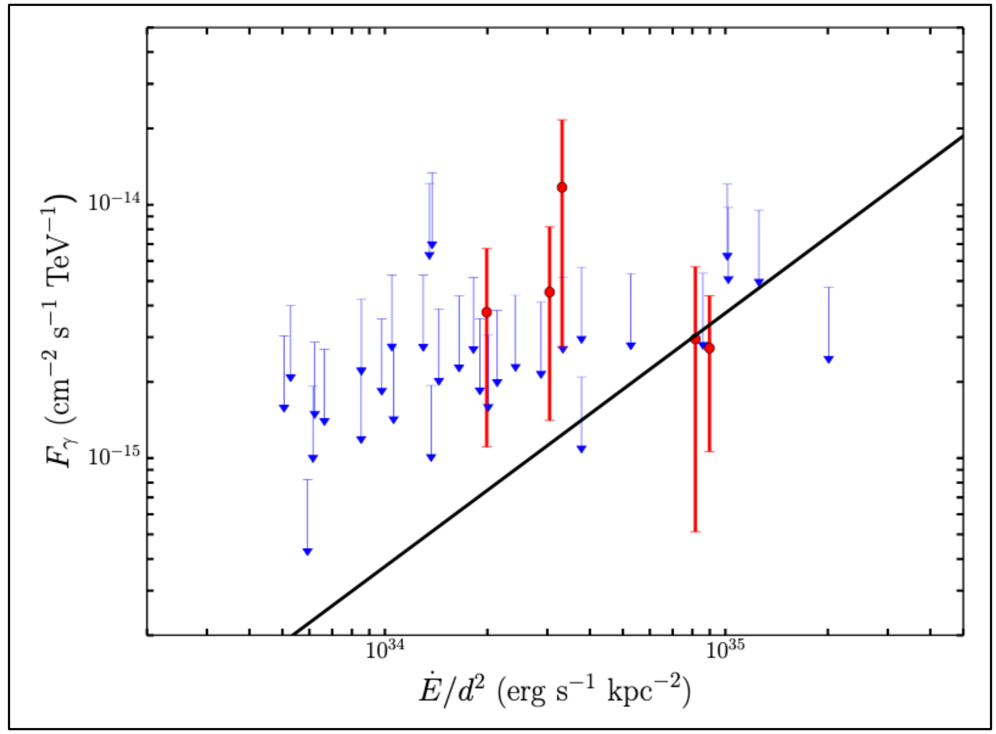


HAWC Collaboration, arXiv:1702.02992

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

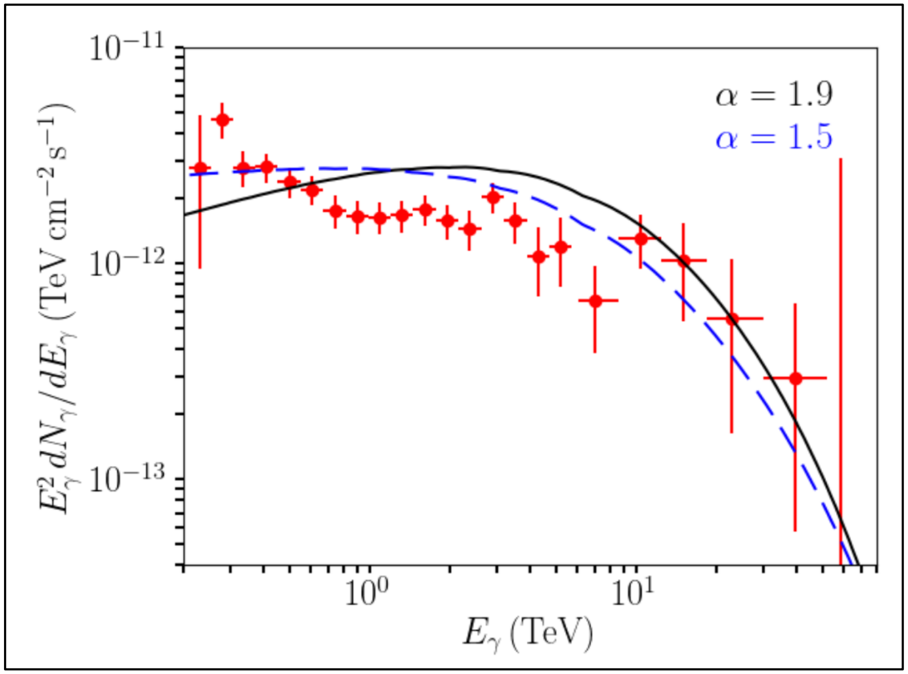
- Until recently, it was unknown whether MSPs have TeV halos (although theorists generally expected that they would)
- Using publicly available HAWC data from the directions of 37 high-spindown power MSPs, we found ~3$\boldsymbol{\sigma}$ evidence that these sources produce multi-TeV emission (after calibrating to random blank sky locations)
- MSPs appear to produce TeV halos with an efficiency that is similar to that observed among younger pulsars, $\eta_{MSP} = (0.39 - 1.08) \times \eta_{young}$



DH, Linden, arXiv:2104.00014

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 bright TeV-scale emission that traces the morphology of the GeV excess, or ruling out MSPs as the source of the GeV excess



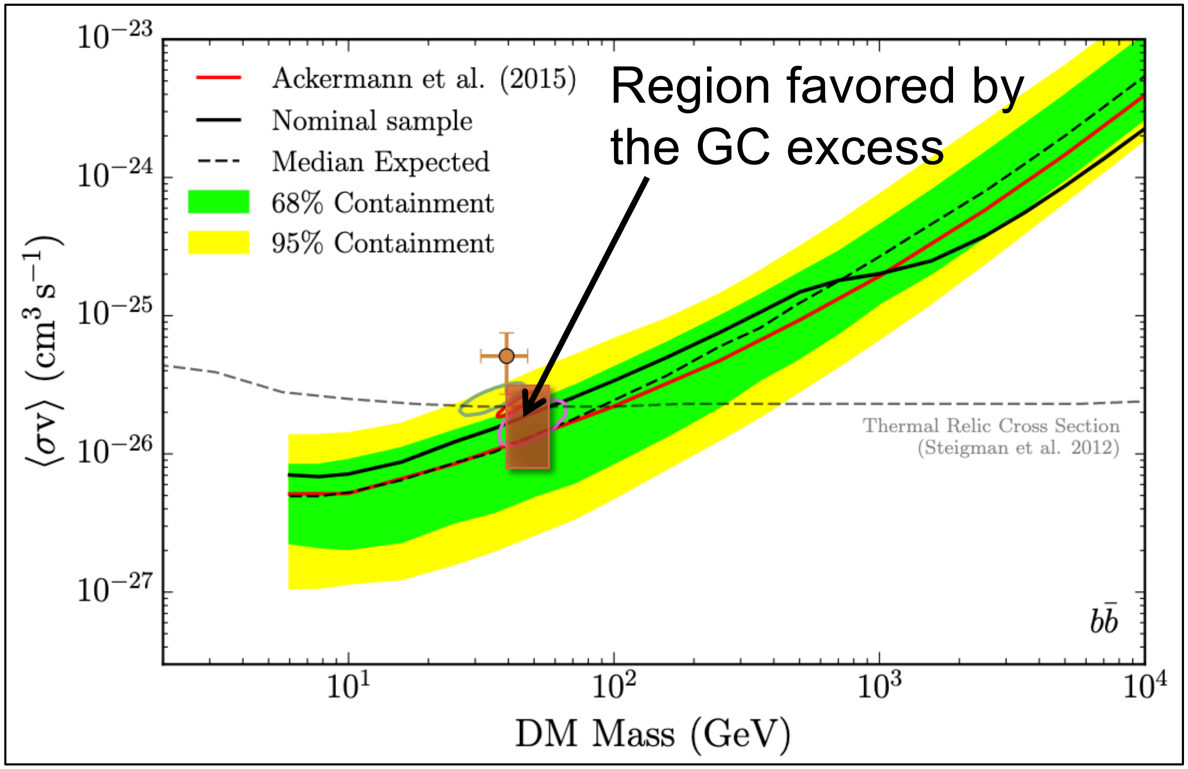
$0.2 - 0.5°$ annulus, $\eta_{MSP} = \eta_{young}$

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?

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



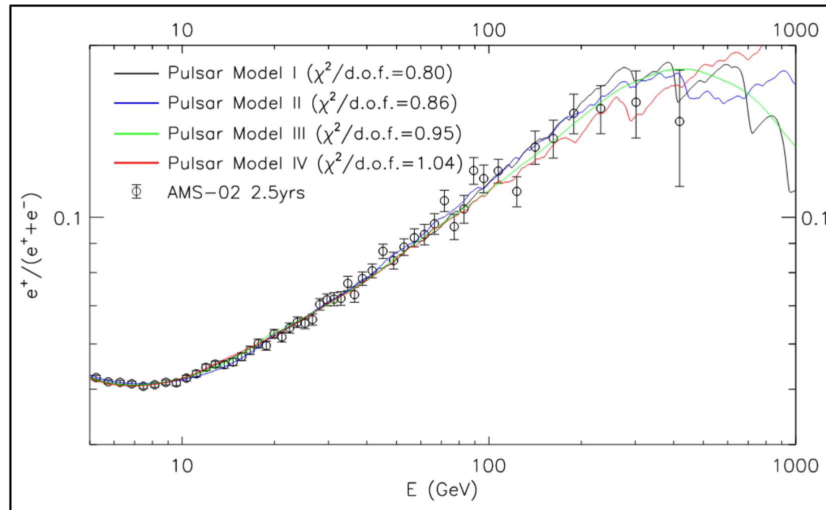
Fermi Collaboration, arXiv:1611.03184

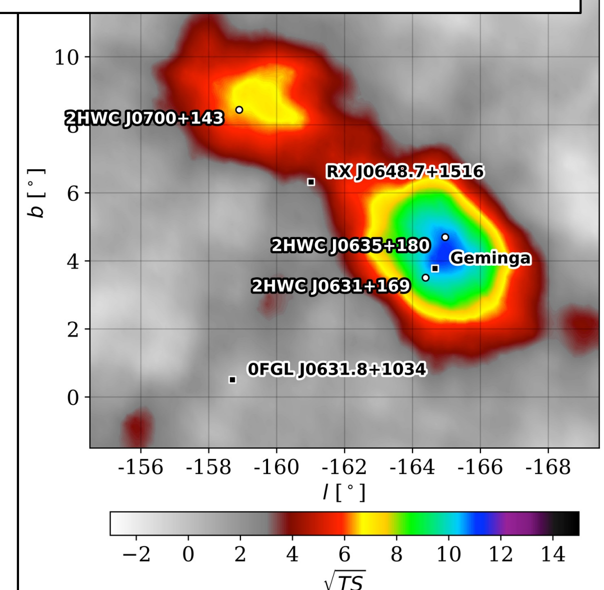
Dwarf Galaxies in the Rubin Era

- The Rubin Observatory (first light in 2023!) 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 of parameter space favored by the Galactic Center excess

Dark Matter Searches Using Cosmic-Ray Anti-Nuclei

- While most astrophysical processes generate far more matter than antimatter, dark matter annihilation (in most models) produces equal fluxes of particles and antiparticles
- Searches for excess antimatter (positrons, antiprotons, anti-nuclei) in the cosmic-ray spectrum can be a powerful probe of DM annihilation in the halo of the Milky Way
- An excess of cosmic-ray positrons generated a great deal of interest in this context, but it is now reasonably clear that these particles originate from nearby TeV halos associated with young and middle-aged pulsars (DH et al, arXiv:1702.08436)

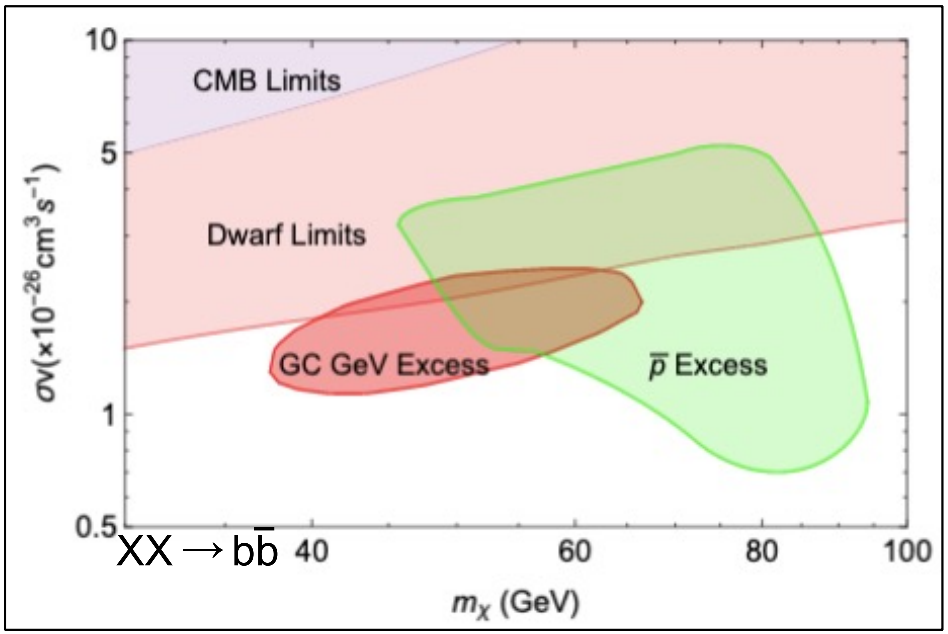


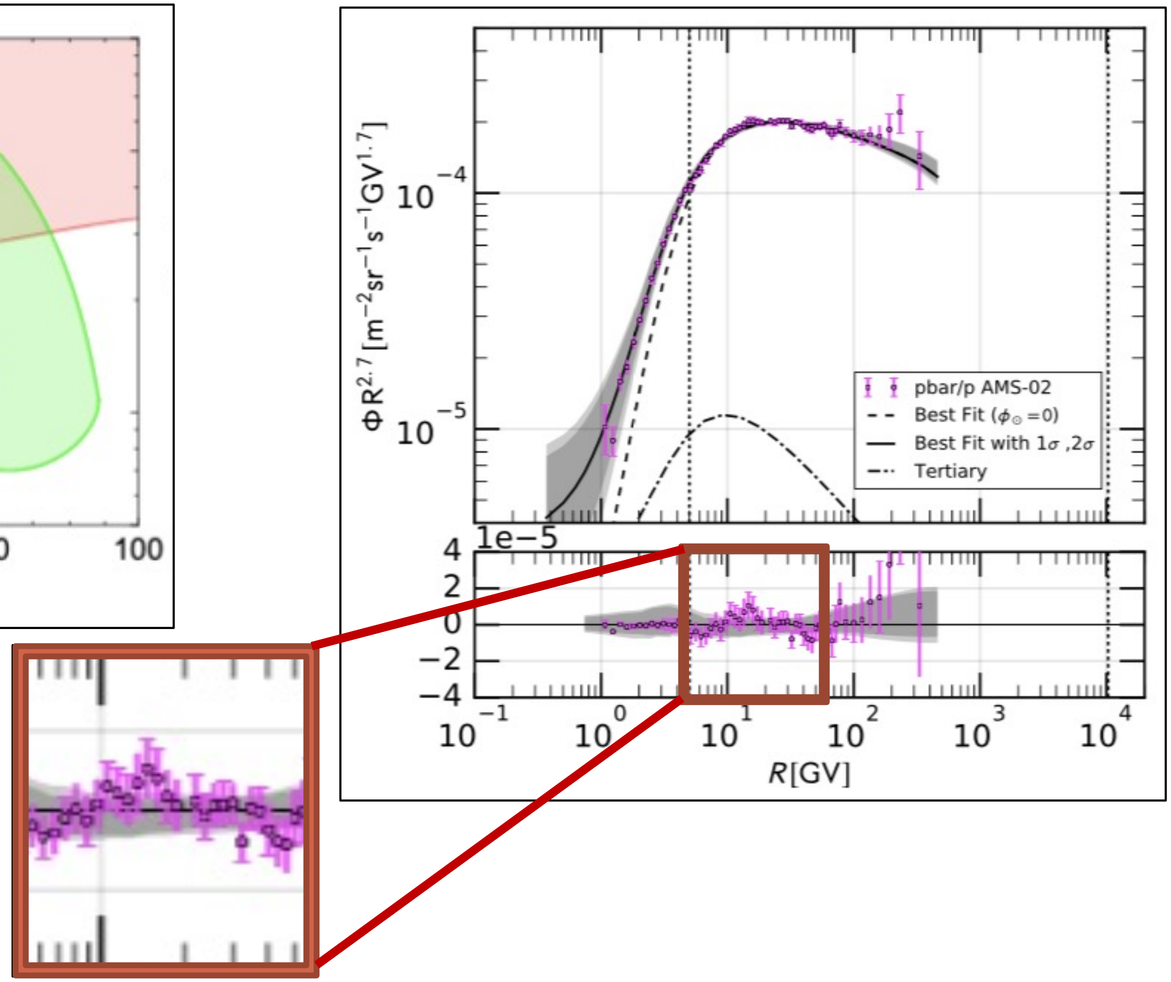


Cholis et al., arXiv:1807.05230;
HAWC Collaboration, arXiv:1702.02992

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**σ** (Cuoco, et al., Cui, et al.)
- This excess is well fit by a ~40-100 GeV WIMP with a σv ~ $2x10^{-26}$ cm^3/s – a good match to the Galactic Center gamma-ray excess!

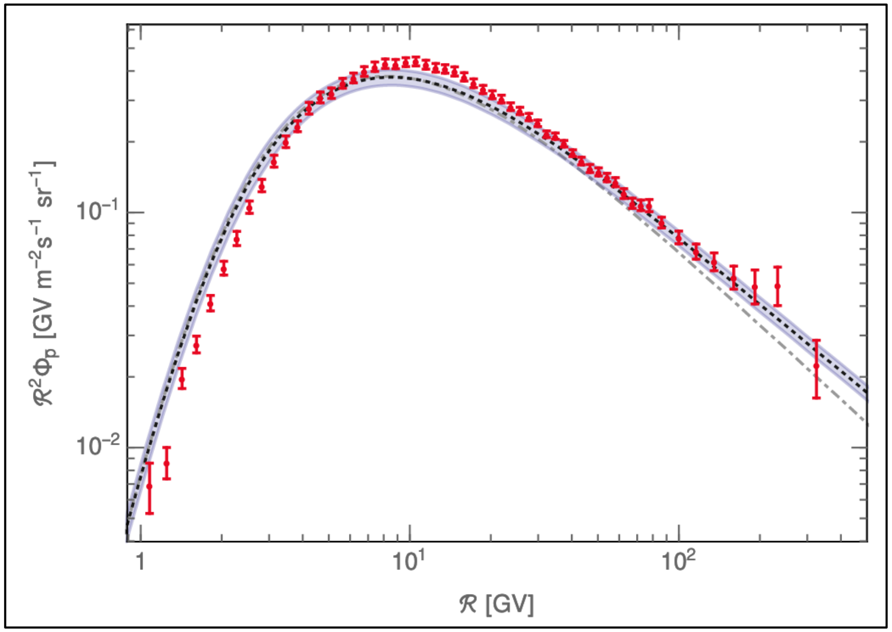




Cuoco et al., arXiv:1610.03071
Cui et al., arXiv:1610.03840
Cholis, DH, Linden, arXiv:1903.02549
Cuoco et al., arXiv:1903.01472
Reinert, Winkler, arXiv:1712.00002

The Cosmic-Ray Antiproton Excess

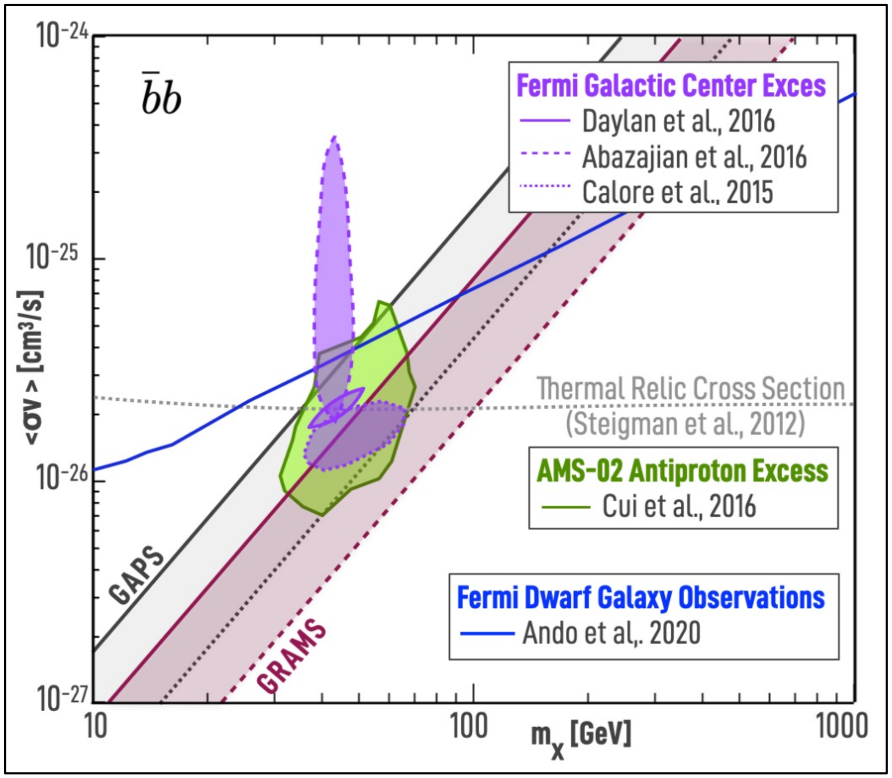
- Although suggestive, many of us in the cosmic-ray community are somewhat skeptical of the anti-proton excess, driven in large part by concerns pertaining to the uncertainties associated with the antiproton production cross section
- To convince us that this excess is real, it is imperative that laboratory measurements of this cross section be improved



M. Winkler, arXiv:1701.04866

Cosmic-Ray Anti-Nuclei

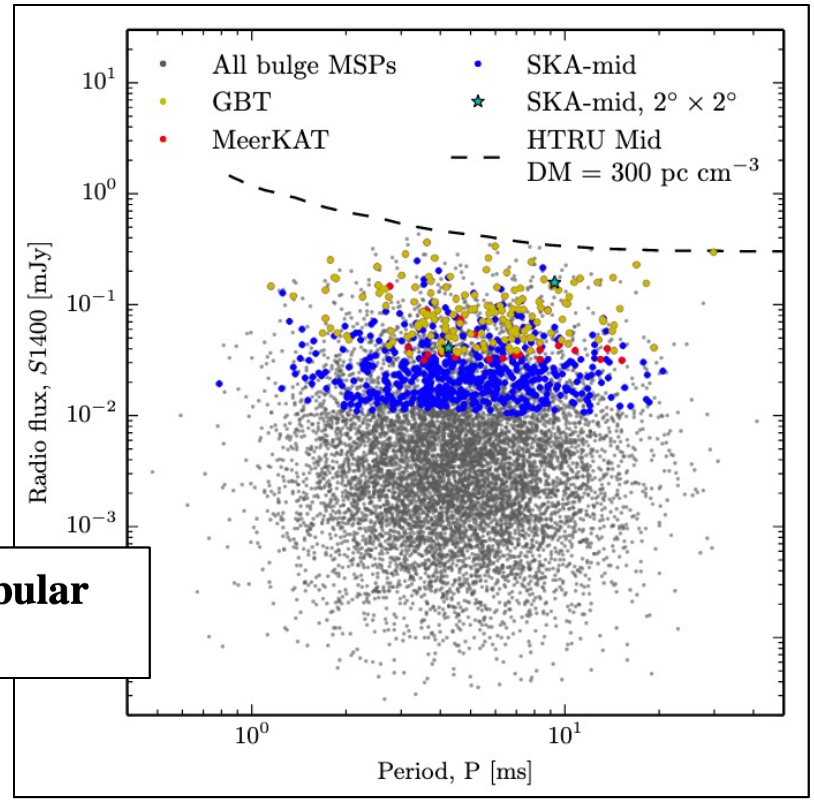
- Searches for cosmic-ray anti-deuterons and anti-helium nuclei are also going to be very exciting in the years ahead
- GAPS (General Anti-Particle Spectrometer), GRAMS (Gamma-Ray and Anti-Matter Survey), and AMS are each projected to be sensitive to the dark matter parameter space favored by the Galactic Center excess
- The first balloon flight for GAPS is scheduled for early 2023
- We could hear more from AMS on this subject at anytime



Leane et al., arXiv:2203.06859

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

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 $\sim\mathcal{O}(100)$ GeV; this program is 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
- Recent studies have found that the morphology of this signal is consistent with 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