The Galactic Center Gamma-Ray Excess and its Interpretations: A Status Report

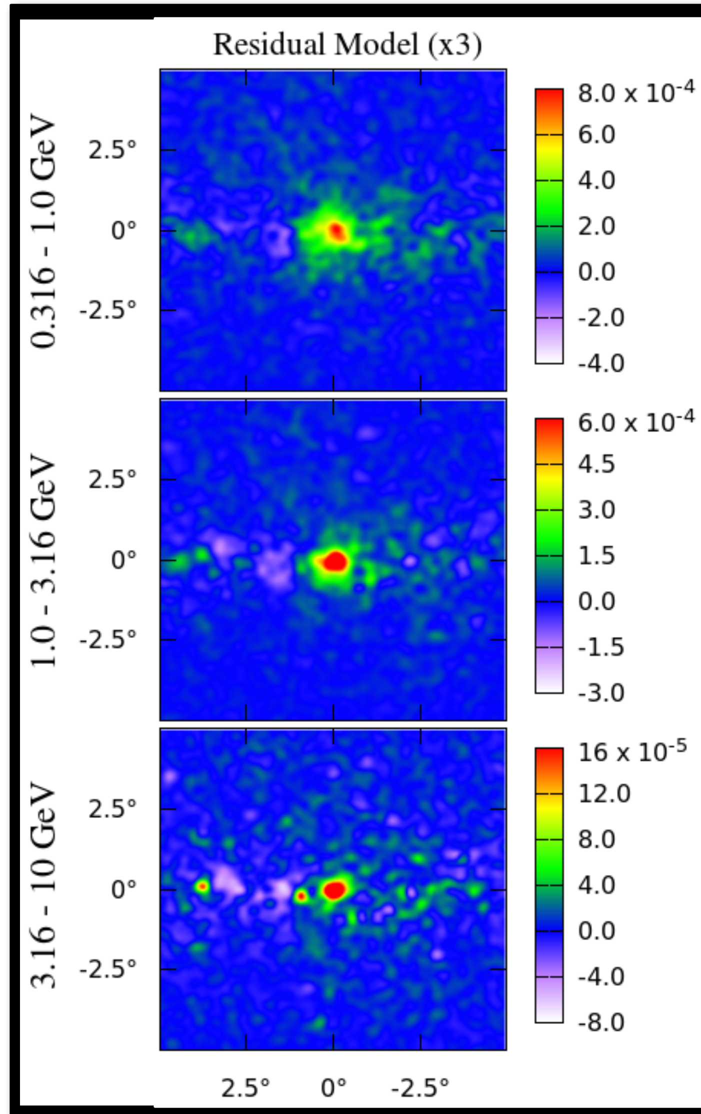
Dan Hooper – Fermilab and the University of Chicago

Identification of Dark Matter (IDM) 2018

July 26, 2018

The Galactic Center GeV Excess

- A bright and highly statistically significant excess of gamma-rays has been observed from the region surrounding the Galactic Center
- Although a consensus has formed regarding the basic features of this signal, its origin is still a topic of considerable debate

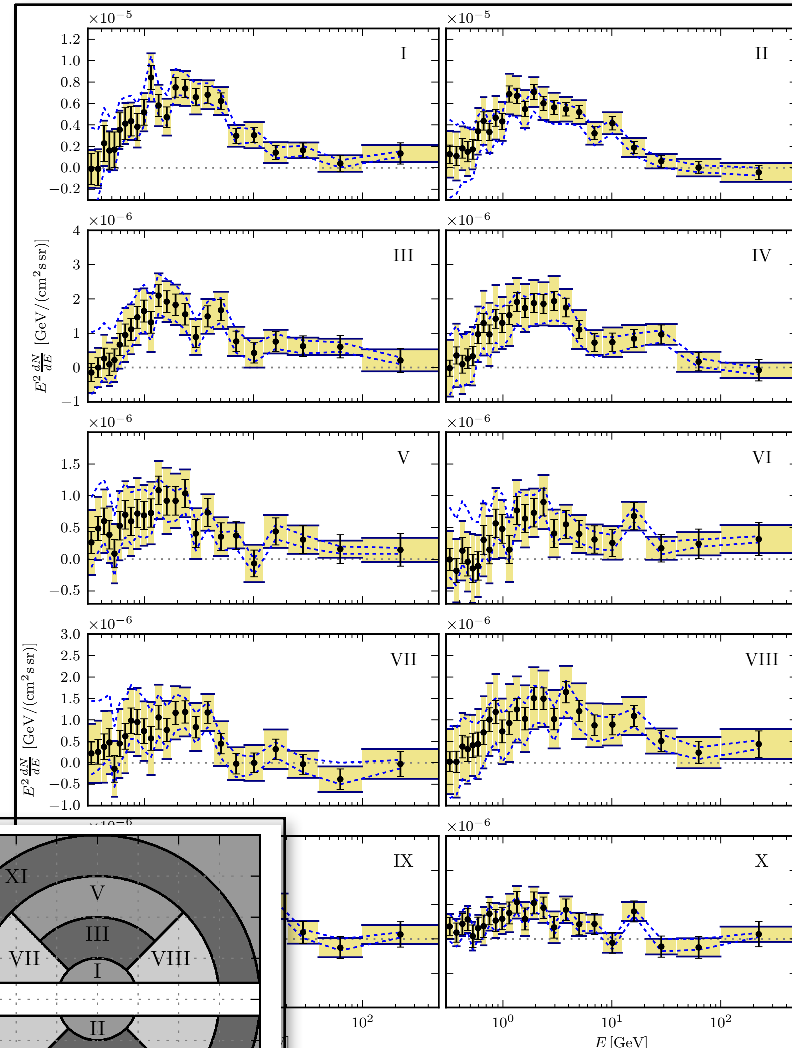


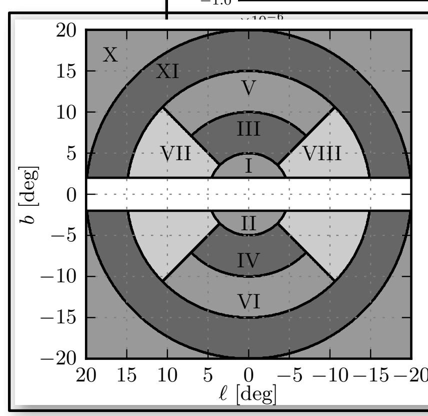
Among other references, see:
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

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

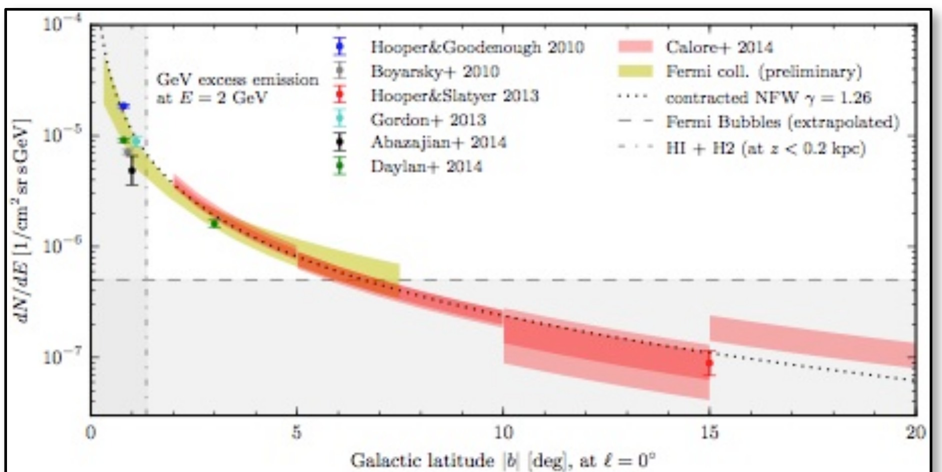




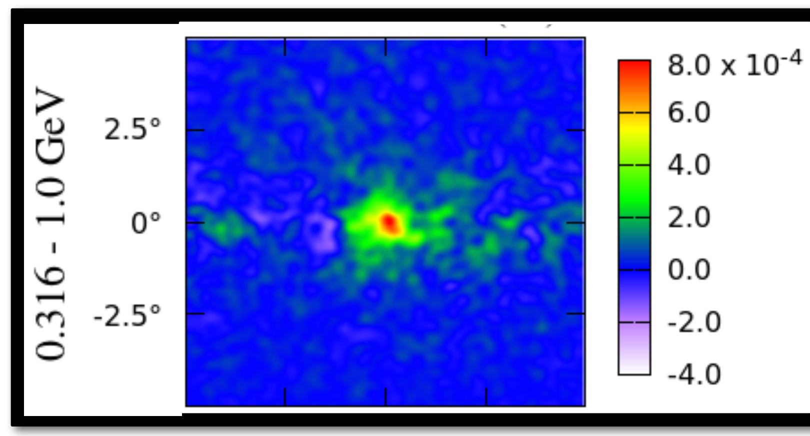
Calore, Cholis, Weniger; Calore, Cholis, McCabe, Weinger (2014); Escudero, Witte, DH, arXiv:1709.07002

Morphology

- The GeV excess exhibits approximate spherical symmetry about the Galactic Center (axis ratios within ~20% of unity), with a flux that falls as $\sim r^{-2.4}$ out to at least ~10°
- If interpreted as annihilating dark matter, this implies $\rho_{DM} \sim r^{-1.2}$ out to at least ~1.5 kpc, only slightly steeper than the canonical NFW profile



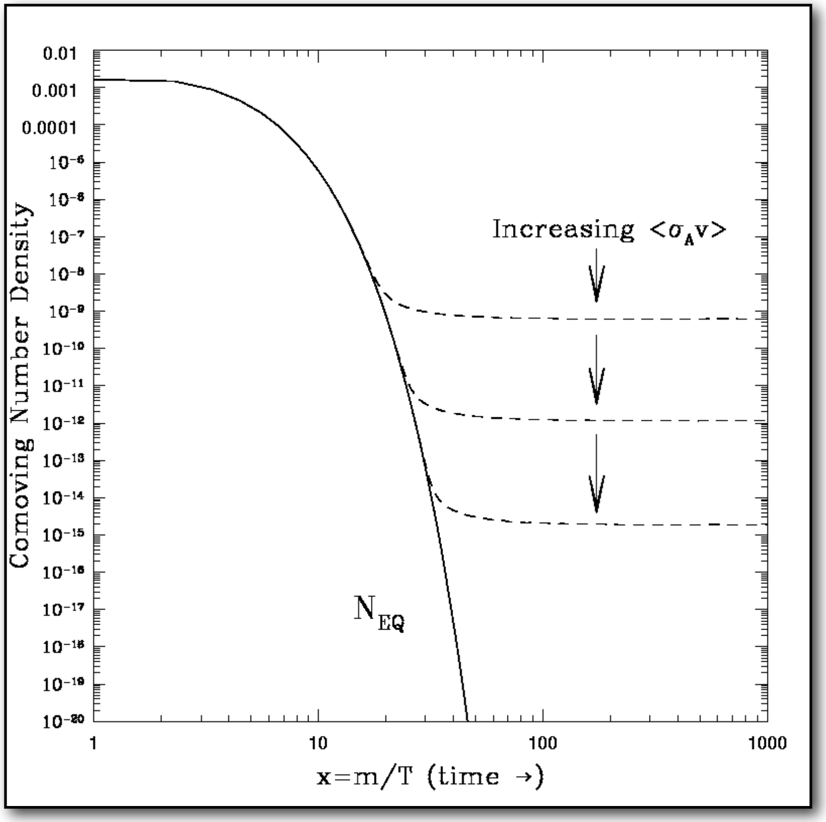
Calore, Cholis, Weniger (2014)



Daylan, et al. (2014)

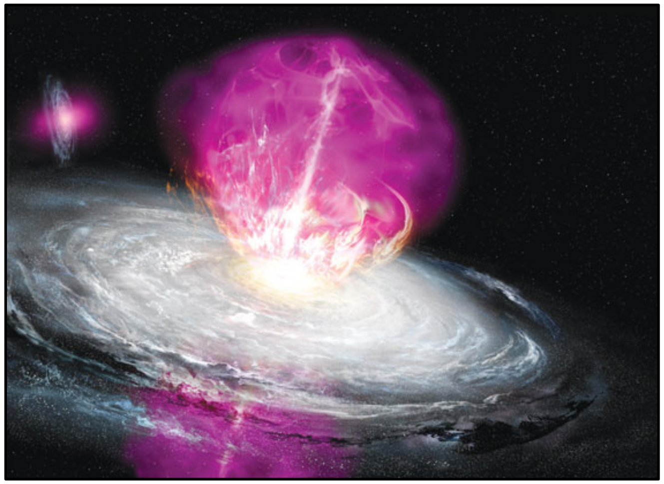
Intensity

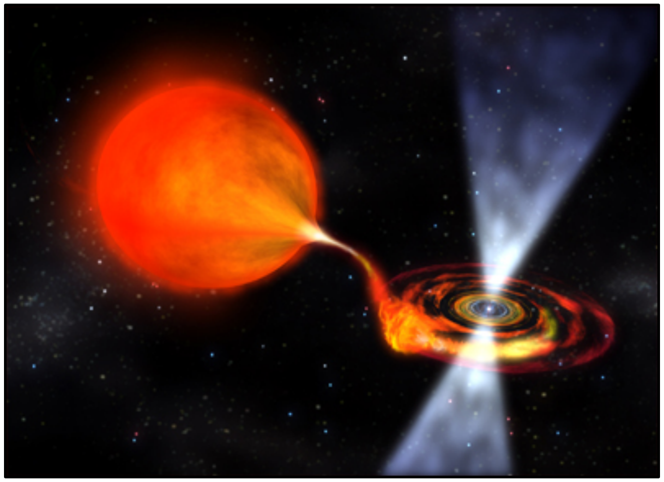
- To normalize the observed excess, the dark matter particles must annihilate with a cross section of $\sigma v \sim 10^{-26}$ cm^3/s
- This is approximately equal to the value of the cross section that is required to generate the measured dark matter abundance through thermal freeze-out in the early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

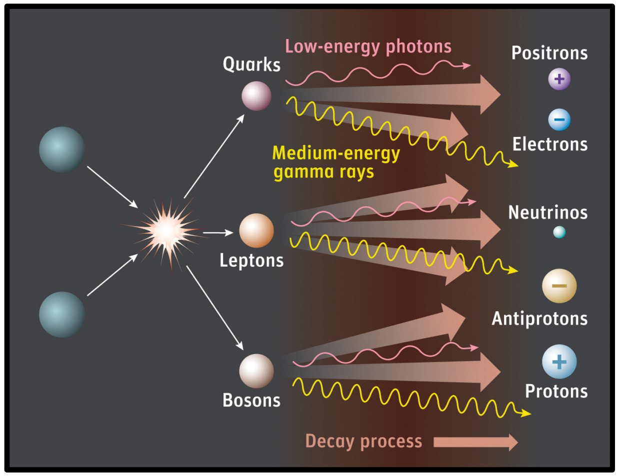


What Produces the Excess?

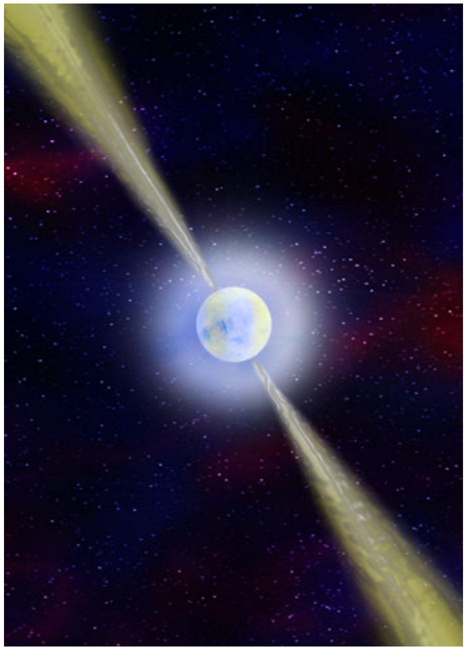
- A large population of centrally located millisecond pulsars?
- A recent outburst of cosmic rays?
- Annihilating dark matter?





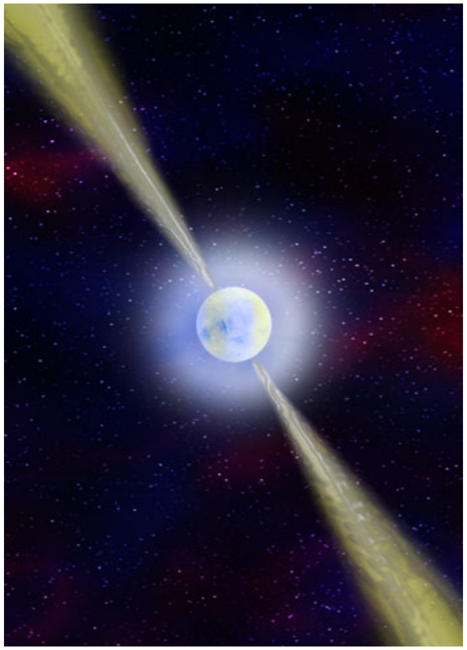


Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



The Two Main Arguments in Favor of Pulsars:

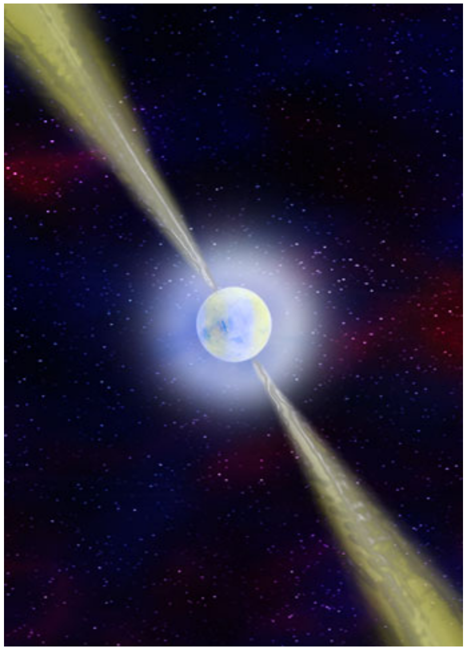
Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



The Two Main Arguments in Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



The Two Main Arguments in Favor of Pulsars:

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

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 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 γ-Rays

- A typical Fermi Inner Galaxy analysis might include the following spatial templates:
  1) Galactic diffuse emission
  2) Fermi Bubbles
  3) Isotropic background
  4) Dark matter annihilation (generalized NFW)

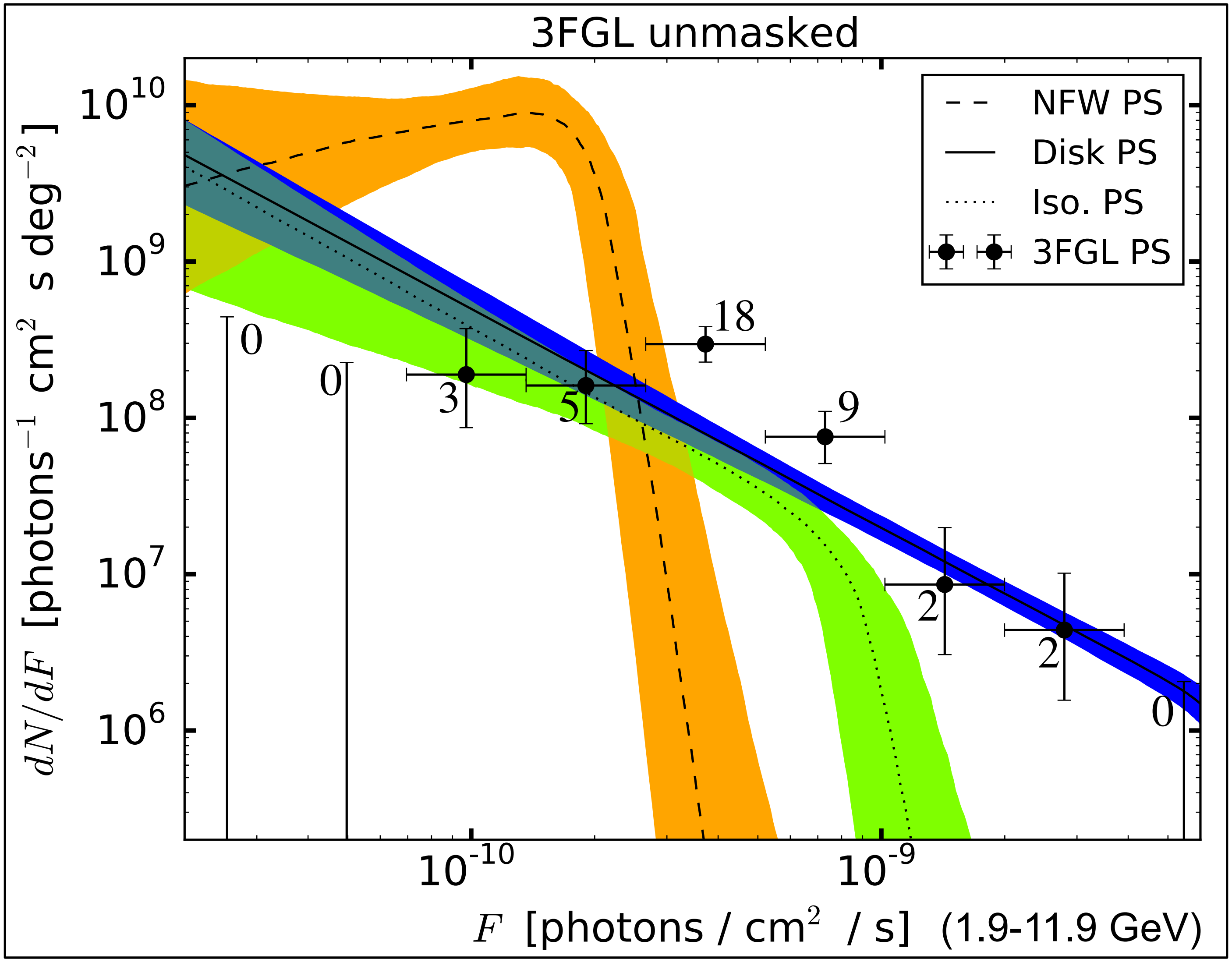
Small Scale Power Among Inner Galaxy γ-Rays

- A typical Fermi Inner Galaxy analysis might include the following spatial templates:
  1) Galactic diffuse emission
  2) Fermi Bubbles
  3) Isotropic background
  4) Dark matter annihilation (generalized NFW)

- Lee et al. add to this a number of non-Possionian 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

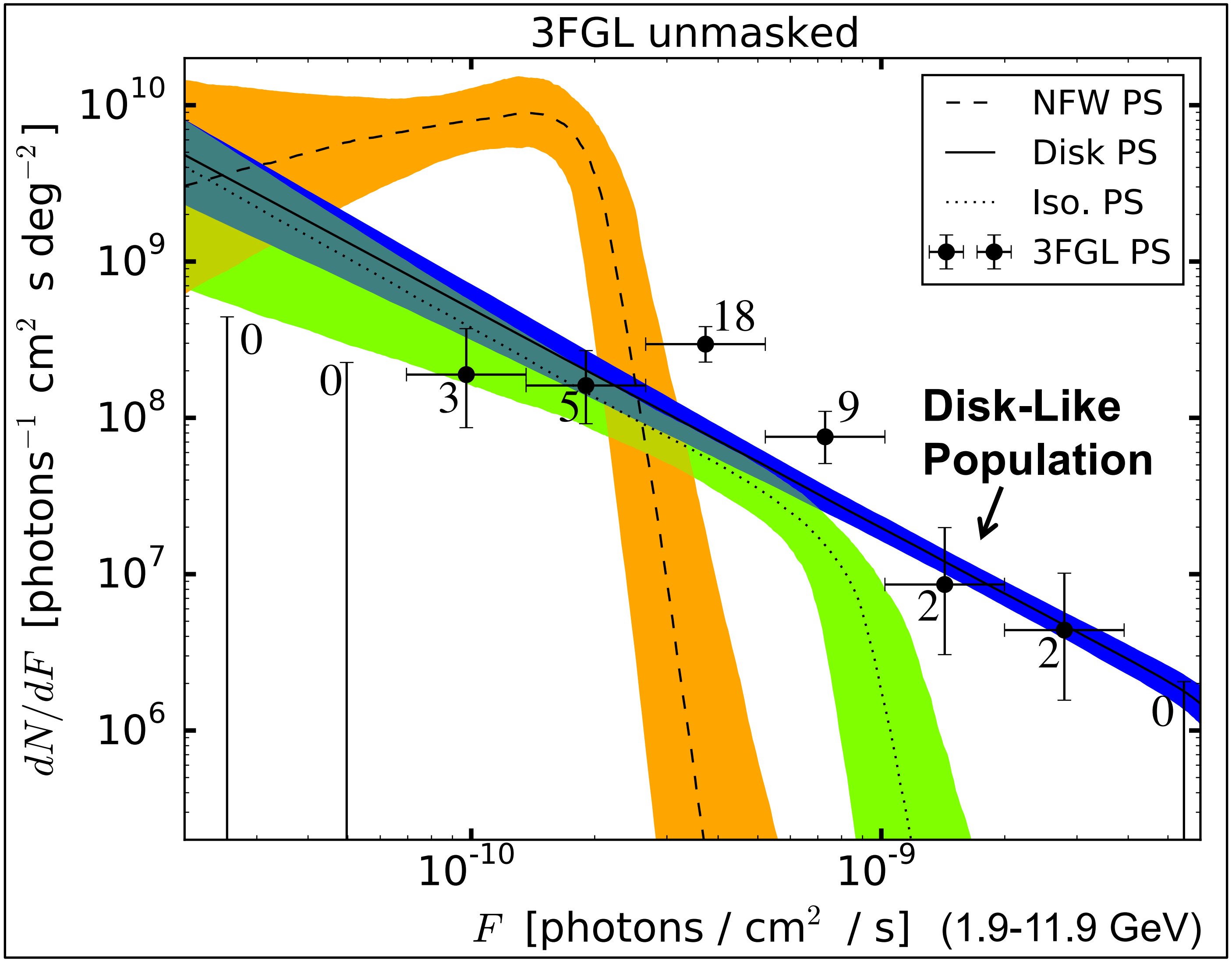
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124

Small Scale Power Among Inner Galaxy γ-Rays



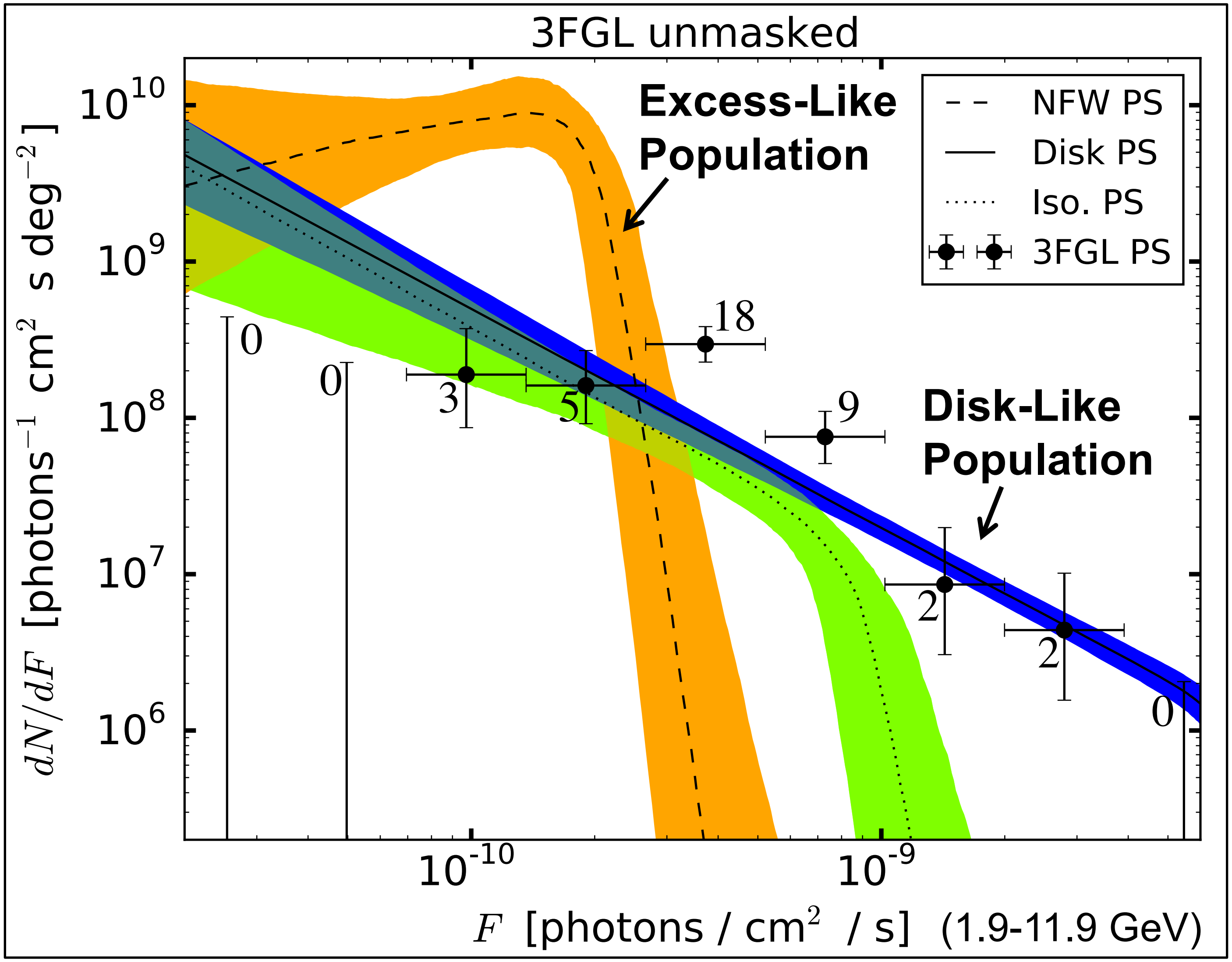
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124

Small Scale Power Among Inner Galaxy γ-Rays



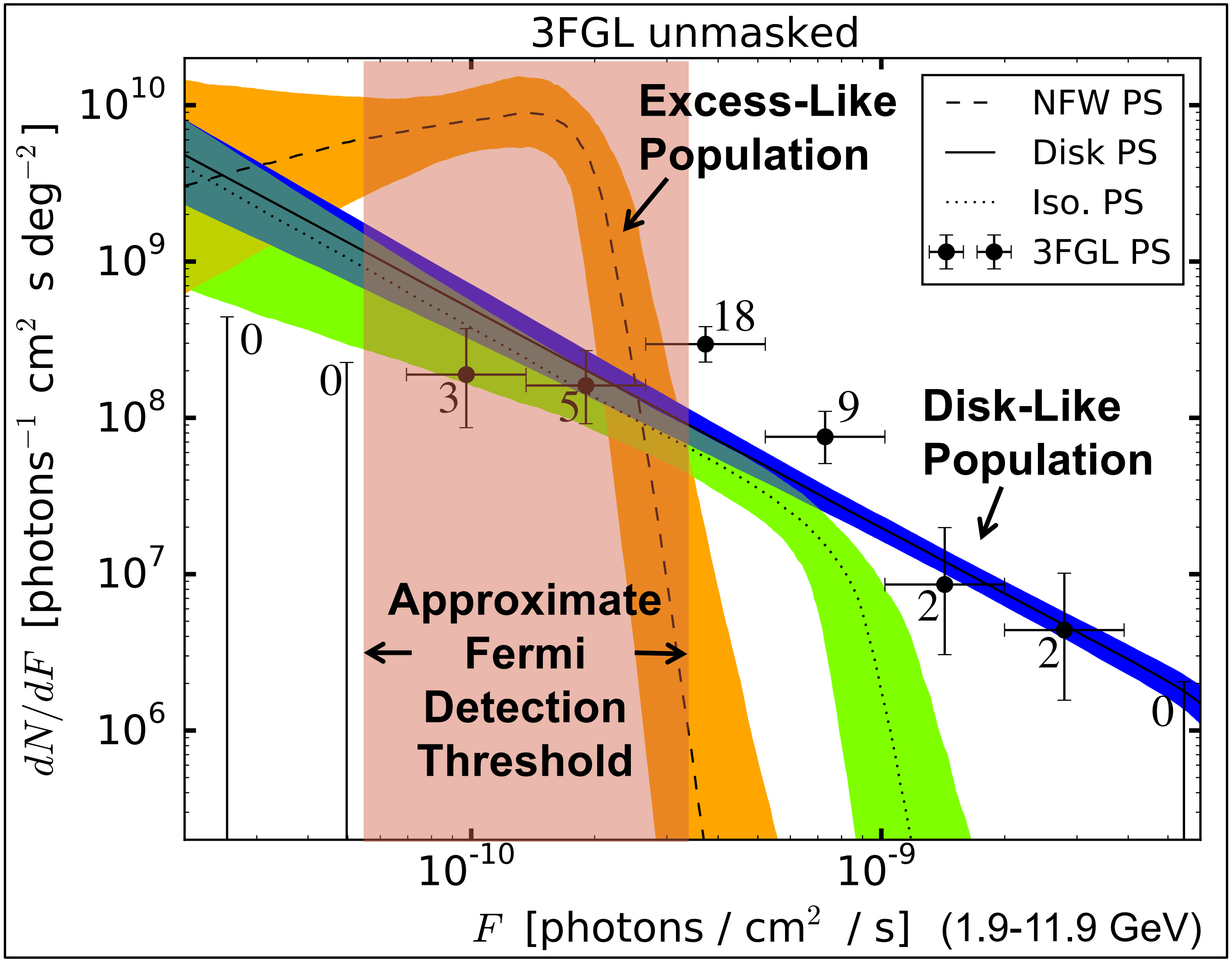
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124

Small Scale Power Among Inner Galaxy γ-Rays



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

Small Scale Power Among Inner Galaxy γ-Rays



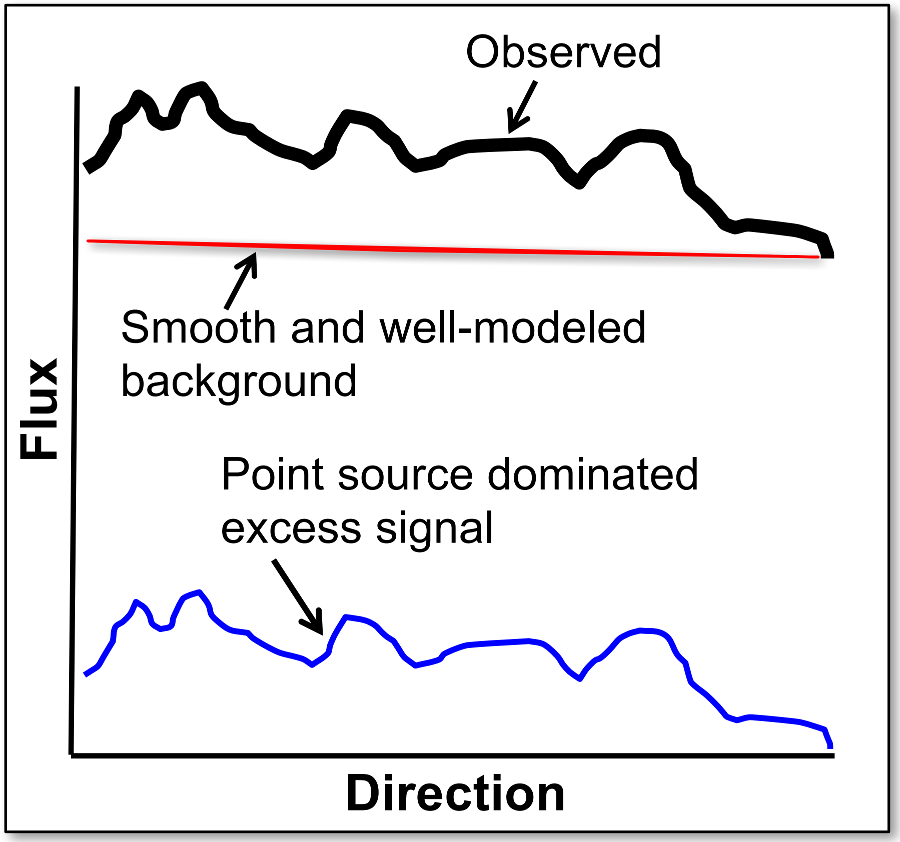
Bottom Line: A population of ~10³ points sources with luminosities just below Fermi's threshold could potentially account for the GeV Excess

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

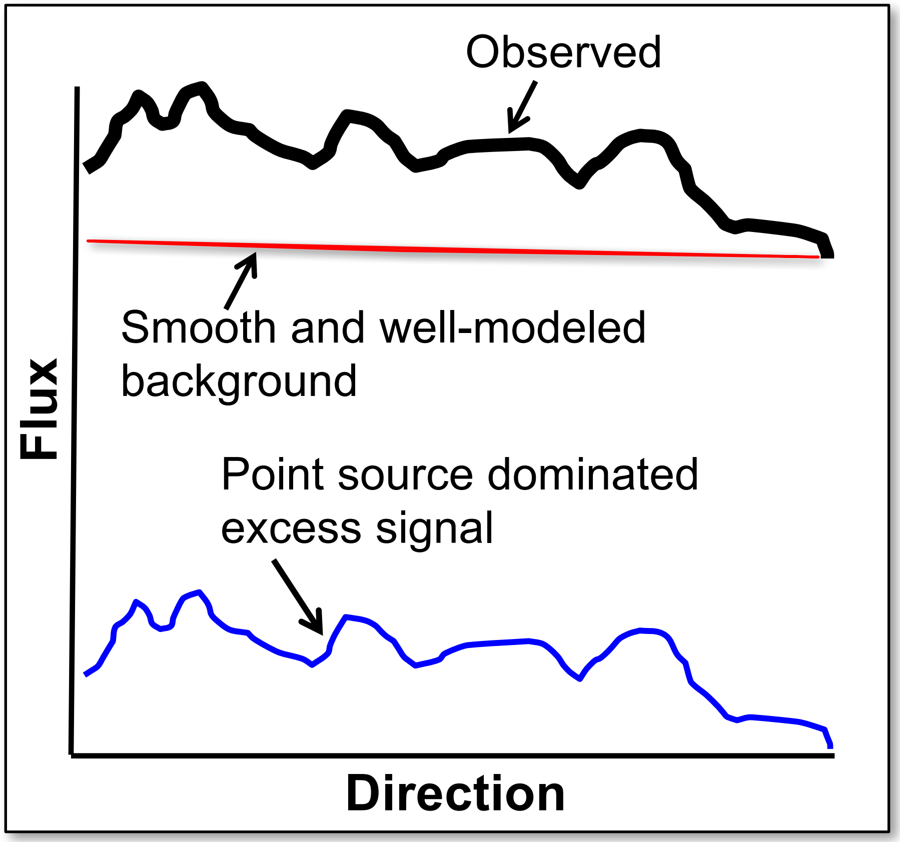
Evidence For Unresolved Point Sources?

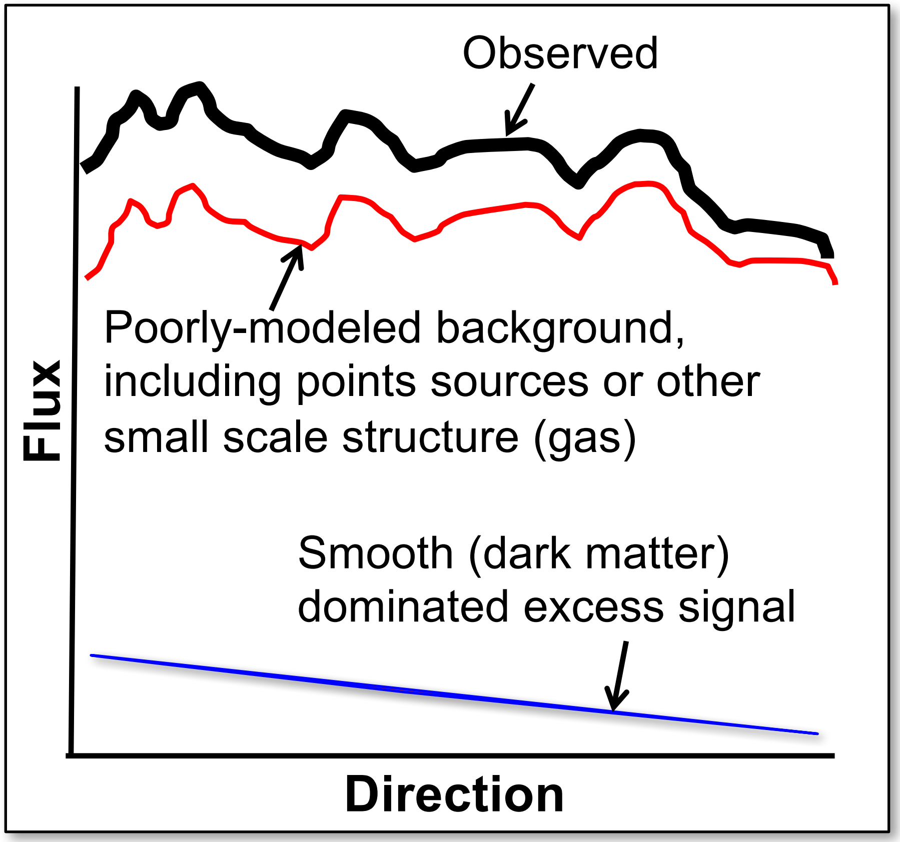
- It is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than are being modeled



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





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
- These clusters consist of only a few photons each, on top of large and imperfectly known backgrounds

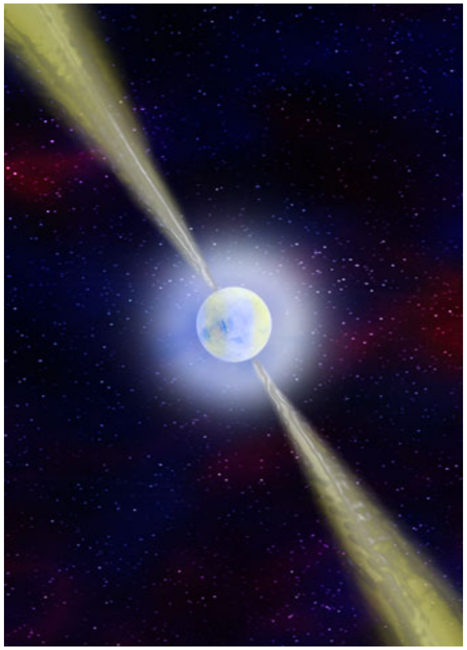
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

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
- These clusters consist of only a few photons each, on top of large and imperfectly known backgrounds
- Gamma-ray point source identification is difficult in the Galactic Center region – even for bright sources – and the contents of source catalogs depend strongly on how one treats diffuse backgrounds
(try comparing the contents of Fermi's 3FGL, 1FIG, 2FIG catalogs)

Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



The Two Main Arguments in Favor of Pulsars:

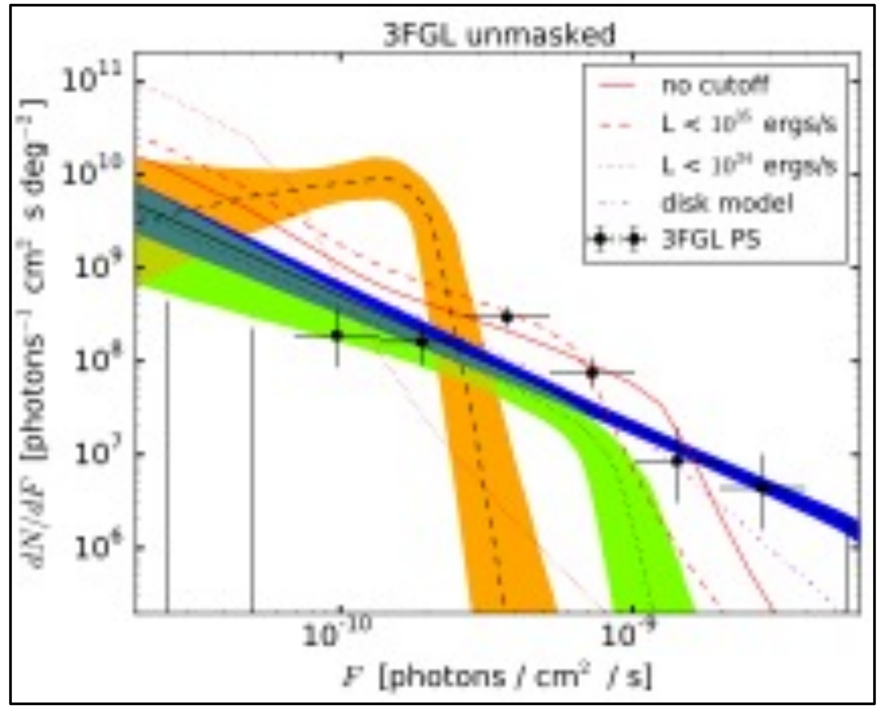
- The gamma-ray spectrum of observed pulsars
- Small-scale power in the gamma-ray emission from the Inner Galaxy

Arguments Against Pulsars:

- The measured luminosity function of gamma-ray pulsars
- The lack of low-mass X-ray binaries in the Inner Galaxy

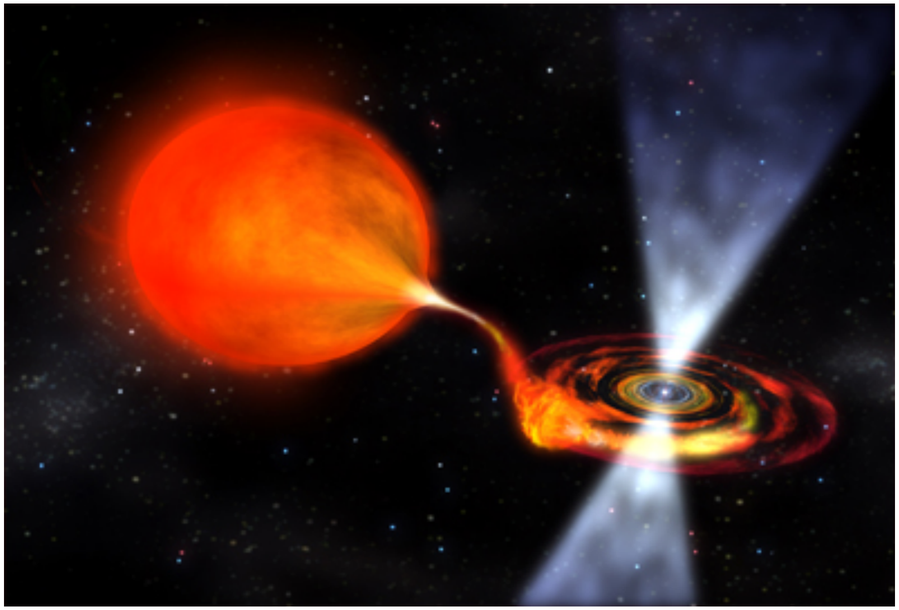
Comparison With The Measured MSP Luminosity Function

- It should be appreciated that the MSP populations observed in globular clusters and in the disk do *not* exhibit a luminosity function like that indicated by the analysis of Lee et al.
- The measured MSP luminosity function is very broad and extends over several orders of magnitude and up to at least ~10^{35} erg/s
- If the small scale power identified by these analyses does in fact originate from a population of MSPs, this is a very different population than those found in the disk of the Milky Way or in globular clusters



Millisecond Pulsars and Low-Mass X-Ray Binaries

- While a dead pulsar is being “spun-up” by a stellar companion to become a millisecond pulsar, it exists for a time as a low-mass X-ray binary (LMXB)
- We should expect the ratio of MSPs to LMXBs to be similar in the Inner Galaxy as in the Milky Way’s globular cluster population
- We can use the number of low-mass X-ray binaries in the Inner Galaxy to estimate the population of MSPs that is present there



Cholis, DH, Linden, JCAP, arXiv:1407.5625

Millisecond Pulsars and Low-Mass X-Ray Binaries In Globular Clusters

- We begin with the following sample of Milky Way globular clusters (selected for their large stellar encounter rates):
- As expected, most of of these have been detected by Fermi

Globular Cluster	Flux (erg/cm^2/s)	Distance (kpc)	Stellar Encounter Rate	TS
NGC 104	$2.51^{+0.05}_{-0.06} \times 10^{-11}$	4.46	1.00	3995.9
NGC 362	$6.74^{+2.63}_{-2.46} \times 10^{-13}$	8.61	0.74	9.69
Palomar 2	$< 2.69 \times 10^{-13}$	27.11	0.93	0.0
NGC 6624	$1.14^{+0.10}_{-0.10} \times 10^{-11}$	7.91	1.15	455.8
NGC 1851	$9.05^{+2.92}_{-2.67} \times 10^{-13}$	12.1	1.53	14.4
NGC 5824	$< 4.78 \times 10^{-13}$	32.17	0.98	0.0
NGC 6093	$4.32^{+0.57}_{-0.53} \times 10^{-12}$	10.01	0.53	91.9
NGC 6266	$1.84^{+0.07}_{-0.10} \times 10^{-11}$	6.83	1.67	850.7
NGC 6284	$< 2.85 \times 10^{-13}$	15.29	0.67	0.0
NGC 6441	$1.00^{+0.09}_{-0.07} \times 10^{-11}$	11.6	2.30	210.9
NGC 6652	$4.84^{+0.51}_{-0.52} \times 10^{-12}$	10.0	0.70	128.3
NGC 7078/M15	$1.81^{+0.40}_{-0.39} \times 10^{-12}$	10.4	4.51	29.7
NGC 6440	$1.57^{+0.10}_{-0.11} \times 10^{-11}$	8.45	1.40	311.2
Terzan 6	$2.18^{+1.20}_{-0.90} \times 10^{-12}$	6.78	2.47	5.1
NGC 6388	$1.77^{+0.06}_{-0.09} \times 10^{-11}$	9.92	0.90	778.4
NGC 6626/M28	$1.95^{+0.13}_{-0.13} \times 10^{-11}$	5.52	0.65	749.8
Terzan 5	$6.61^{+0.17}_{-0.13} \times 10^{-11}$	5.98	6.80	2707.1
NGC 6293	$9.39^{+5.69}_{-5.45} \times 10^{-13}$	9.48	0.85	3.98
NGC 6681	$9.91^{+4.14}_{-3.86} \times 10^{-13}$	9.01	1.04	7.2
NGC 2808	$3.77^{+0.48}_{-0.48} \times 10^{-11}$	9.59	0.92	96.7
NGC 6715	$6.02^{+4.15}_{-3.77} \times 10^{-13}$	26.49	2.52	2.6
NGC 7089	$< 4.50 \times 10^{-13}$	11.56	0.52	0.0

Haggard, Heinke, DH, Linden, JCAP, arXiv:1701.02726

Millisecond Pulsars and Low-Mass X-Ray Binaries In Globular Clusters

- We begin with the following sample of Milky Way globular clusters (selected for their large stellar encounter rates):
- As expected, most of of these have been detected by Fermi
- This same collection of globular clusters contains the following list of bright LMXBs (those that would have been detected if they had been located in the Inner Galaxy)

Globular Cluster	Flux (erg/cm^2/s)	Distance (kpc)	Stellar Encounter Rate	TS
NGC 104	$2.51^{+0.05}_{-0.06} \times 10^{-11}$	4.46	1.00	3995.9
NGC 362	$6.74^{+2.63}_{-2.46} \times 10^{-13}$	8.61	0.74	9.69
Palomar 2	$< 2.69 \times 10^{-13}$	27.11	0.93	0.0
NGC 6624				
NGC 1851				
NGC 5824				
NGC 6093				
NGC 6266				
NGC 6284				
NGC 6441				
NGC 6652				
NGC 7078/M1				
NGC 6440				
Terzan 6				
NGC 6388				
NGC 6626/M2				
Terzan 5				
NGC 6293				
NGC 6681				
NGC 2808				
NGC 6715				
NGC 7089				

LMXB	Notes	Globular Cluster	References
4U 1820-30	P	NGC 6624	[69–71]
4U 0513-40	P	NGC 1851	[72–74]
4U 1746-37	P	NGC 6441	[69, 75, 76]
XB 1832-330	P	NGC 6652	[75, 77, 78]
M15 X-2	P	NGC 7078/M15	[79–81]
AC 211	P	NGC 7078/M15	[69, 80, 82]
SAX J1748.9-2021	T, XP	NGC 6440	[75, 83, 84]
GRS 1747-312	T	Terzan 6	[85–87]
Terzan 6 X-2	T	Terzan 6	[88]
IGR J17361-4441	T	NGC 6388	[89, 90]
IGR J18245-2542	T, XP	NGC 6626/M28	[91, 92]
EXO 1745-248	T	Terzan 5	[93, 94]
IGR J17480-2446	T	Terzan 5	[95–97]
Terzan 5 X-3	T	Terzan 5	[98]
MAXI J0911-635	T	NGC 2808	[99]

Haggard, Heinke, DH, Linden, JCAP, arXiv:1701.02726

Millisecond Pulsars and Low-Mass X-Ray Binaries In The Inner Galaxy

- Within 10° of the Galactic Center, the INTEGRAL General Reference Catalog contains 42 sources that are classified as an LMXB and 46 unclassified sources (which may or may not be LMXBs)
- To estimate the gamma-ray flux from MSPs in the Inner Galaxy, we compare the numbers of LMXBs in globular clusters to in the Inner Galaxy

- From this exercise, we conclude that no more than 8±3% (LMXBs) and 16±7% (LMXBs+unclassified) of the observed intensity of the GeV excess comes from millisecond pulsars

A MSP population capable of generating the observed GeV excess should be accompanied by ~500 bright LMXB, but only 42 (88) are actually observed

Haggard, Heinke, DH, Linden, JCAP, arXiv:1701.02726

Gamma-Ray Bright MSPs in The Inner Galaxy?

- The most direct way to prove that MSPs generate the GeV excess would be to detect a significant number of individual pulsars in the Inner Galaxy

Gamma-Ray Bright MSPs in The Inner Galaxy?

- The most direct way to prove that MSPs generate the GeV excess would be to detect a significant number of individual pulsars in the Inner Galaxy
- Last year, the Fermi Collaboration posted a paper which purported to present strong evidence (~7σ) for a large centrally located pulsar population

CHARACTERIZING THE POPULATION OF PULSARS IN THE GALACTIC BULGE WITH THE *FERMI* LARGE AREA TELESCOPE.

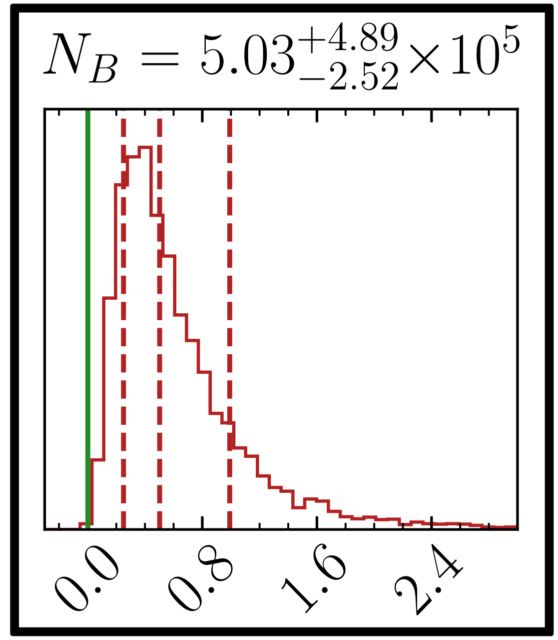
ABSTRACT

An excess of γ-ray emission from the Galactic Center (GC) region with respect to predictions based on a variety of interstellar emission models and γ-ray source catalogs has been found by many groups using data from the *Fermi* Large Area Telescope (LAT). Several interpretations of this excess have been invoked. In this paper we test the interpretation that the excess is caused by an unresolved population of γ-ray pulsars located in the Galactic bulge. We use cataloged LAT sources to derive criteria that efficiently select pulsars with very small contamination from blazars. We search for point sources in the inner $40^\circ \times 40^\circ$ region of the Galaxy, derive a list of approximately 400 sources, and apply pulsar selection criteria to extract pulsar candidates among our source list. We also derive the efficiency of these selection criteria for γ-ray pulsars as a function of source energy flux and location. We demonstrate that given the observed spatial and flux distribution of pulsar candidates, a model that includes a population with about 2.7 γ-ray pulsars in the Galactic disk (in our $40^\circ \times 40^\circ$ analysis region) for each pulsar in the Galactic bulge is preferred at the level of 7 standard deviations with respect to a disk-only model. The properties of these disk and bulge pulsar populations are consistent with the population of known γ-ray pulsars as well as with the spatial profile and energy spectrum of the GC excess. Finally, we show that the dark matter interpretation of the GC excess is strongly disfavored since a distribution of dark matter is not able to mimic the observed properties of the population of sources detected in our analysis.

Fermi Collaboration, arXiv:1705.00009v1

Evidence of a Central Pulsar Population?

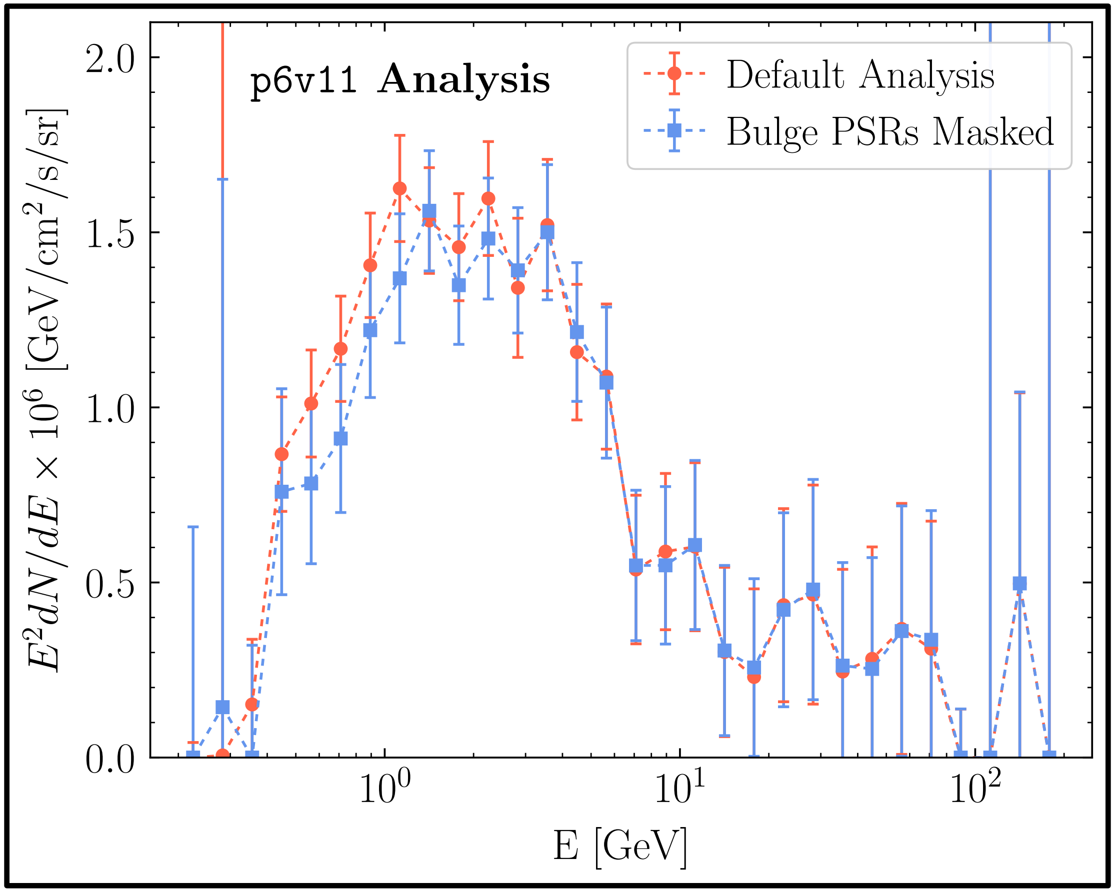
- In examining this paper, my collaborators and I found that we were unable to reproduce these results; our fit favored only a ~2**σ** preference for a central source component
- As a result of the ensuing discussions with the Fermi Collaboration, an error was identified in their code, and a replacement (v2) of their paper was posted in conjunction with our paper



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

Evidence of a Central Pulsar Population?

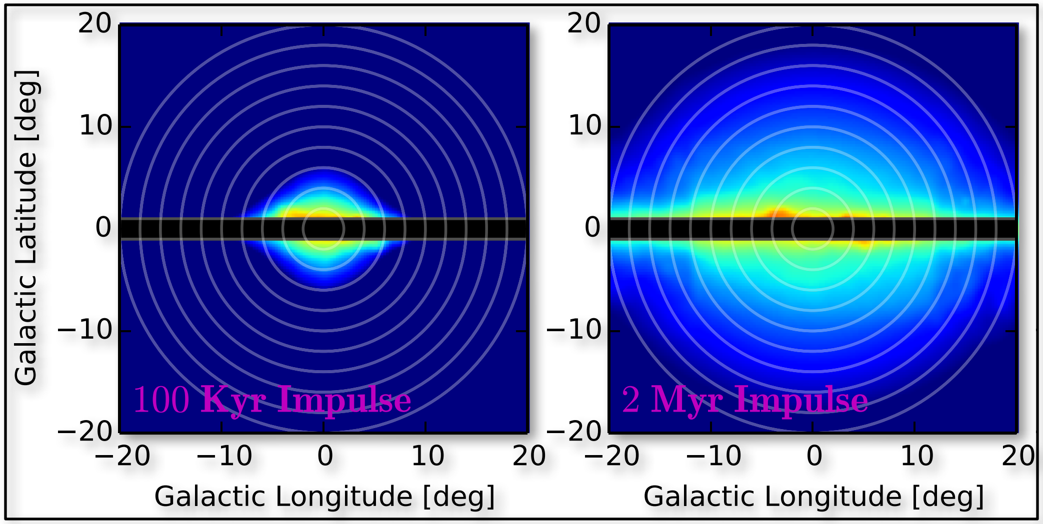
- In our paper, we also note that masking the pulsar candidate sources contained in the new Fermi catalog does *not* impact the characteristics of the excess; ***a negligible fraction of the excess emission originates from these sources***



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

A Series of Cosmic Ray Outbursts?

- Although the existence of the excess is robust across a wide range of diffuse background models, non-steady state cosmic ray scenarios are more difficult to rule out – perhaps a recent series of burst-like events might be responsible?
- Hadronic scenarios predict a signal that is more disky than spherical; highly incompatible with the data
- Leptonic scenarios, however, are more difficult to rule out



Carlson, Profumo, PRD, arXiv:1405.7685,
Petrovic, Serpico, Zaharijas, arXiv:1405.7928

A Series of Cosmic Ray Outbursts?

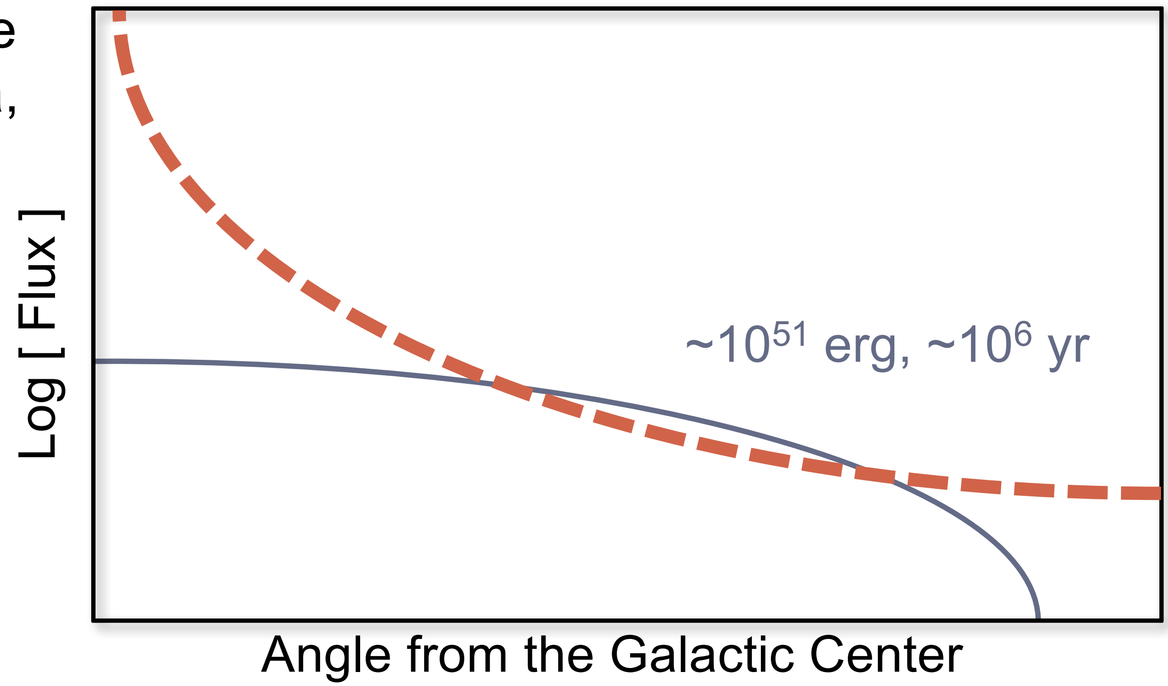
After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

A Series of Cosmic Ray Outbursts?

After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

1) The morphology from a given outburst is “convex”, whereas the data is “concave” – to fit the data, we need several outbursts, with highly tuned parameters

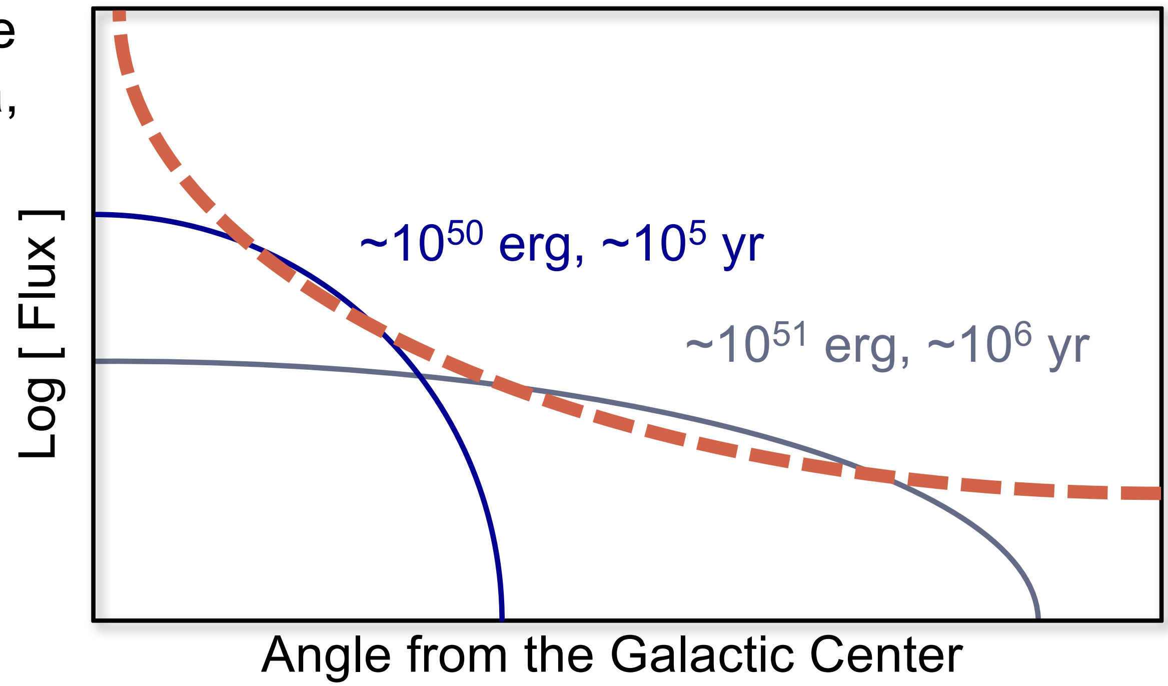


Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

A Series of Cosmic Ray Outbursts?

After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

1) The morphology from a given outburst is "convex", whereas the data is "concave" – to fit the data, we need several outbursts, with highly tuned parameters

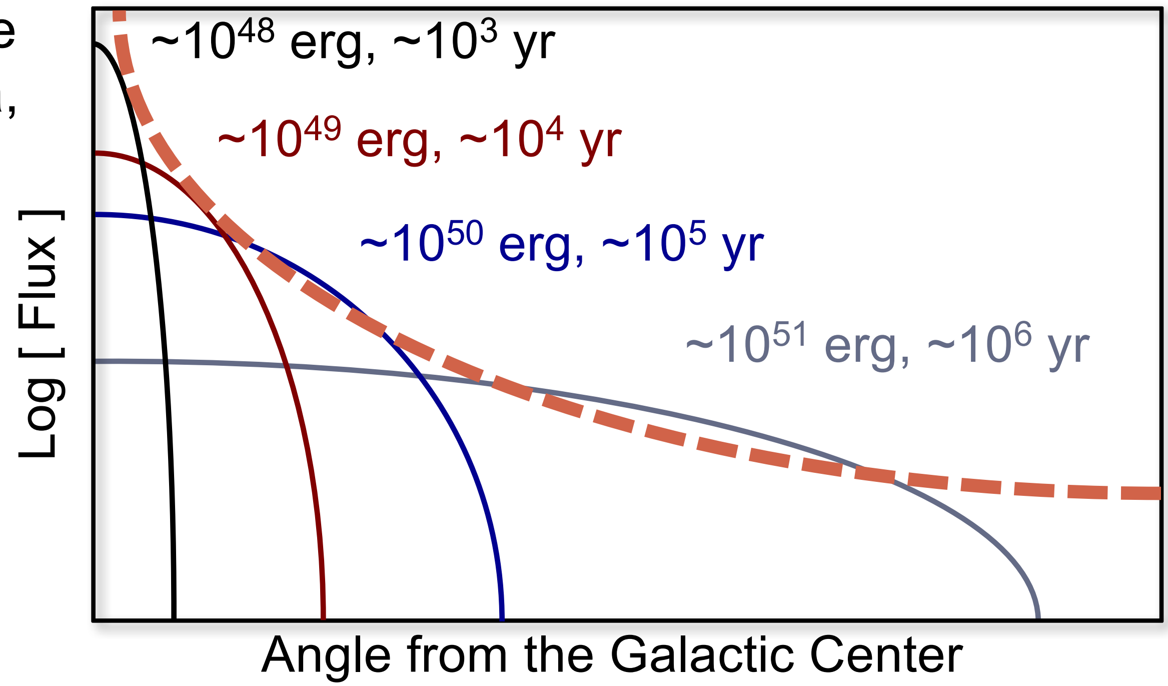


Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

A Series of Cosmic Ray Outbursts?

After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

1) The morphology from a given outburst is “convex”, whereas the data is “concave” – to fit the data, we need several outbursts, with highly tuned parameters



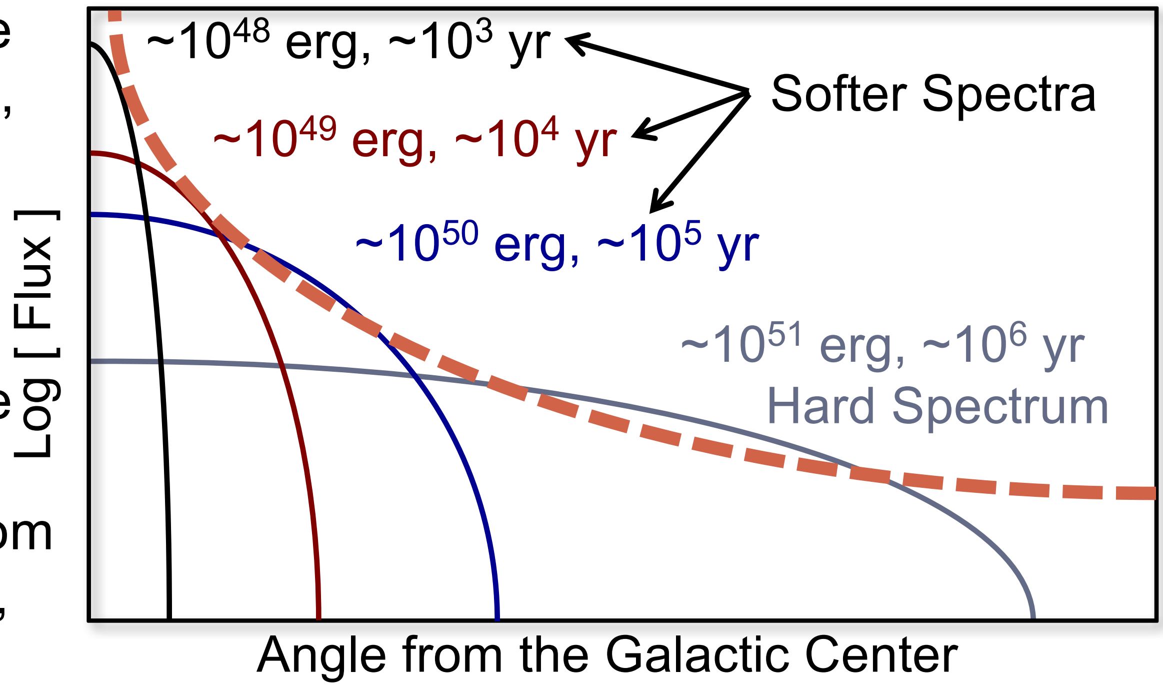
Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

A Series of Cosmic Ray Outbursts?

After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

1) The morphology from a given outburst is “convex”, whereas the data is “concave” – to fit the data, we need several outbursts, with highly tuned parameters

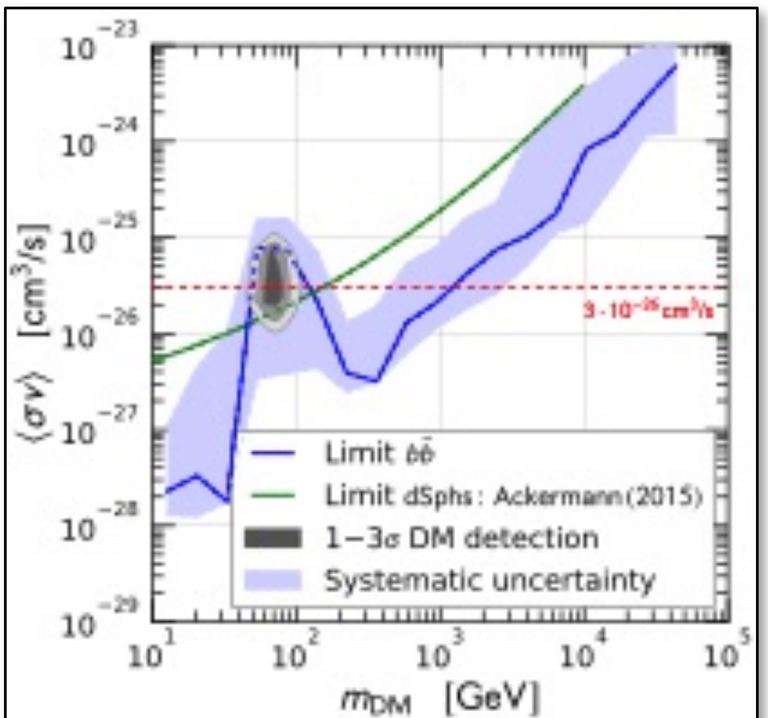
2) The gamma-ray spectrum is approximately uniform across the Inner Galaxy, but energy losses should lead to softer emission from the outer regions – to fit the data, we need the older outbursts to inject electrons with higher energies than more recent outbursts



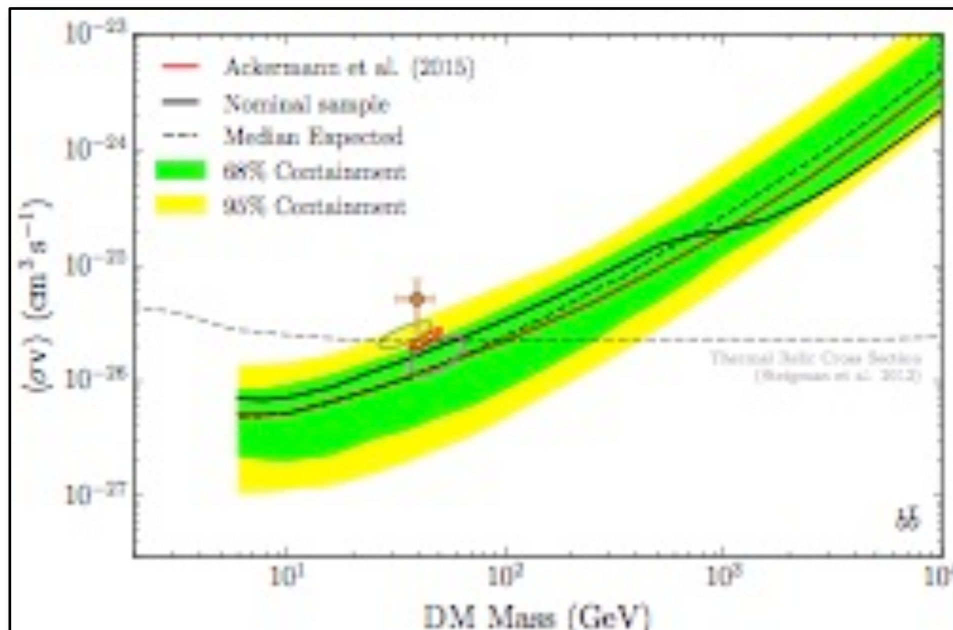
Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

Testing Dark Matter Interpretations

- Searches for gamma rays from dwarf galaxies with Fermi and measurements of the cosmic-ray antiproton spectrum by AMS, are moderately sensitive to dark matter with the characteristics needed to account for the observed gamma-ray excess



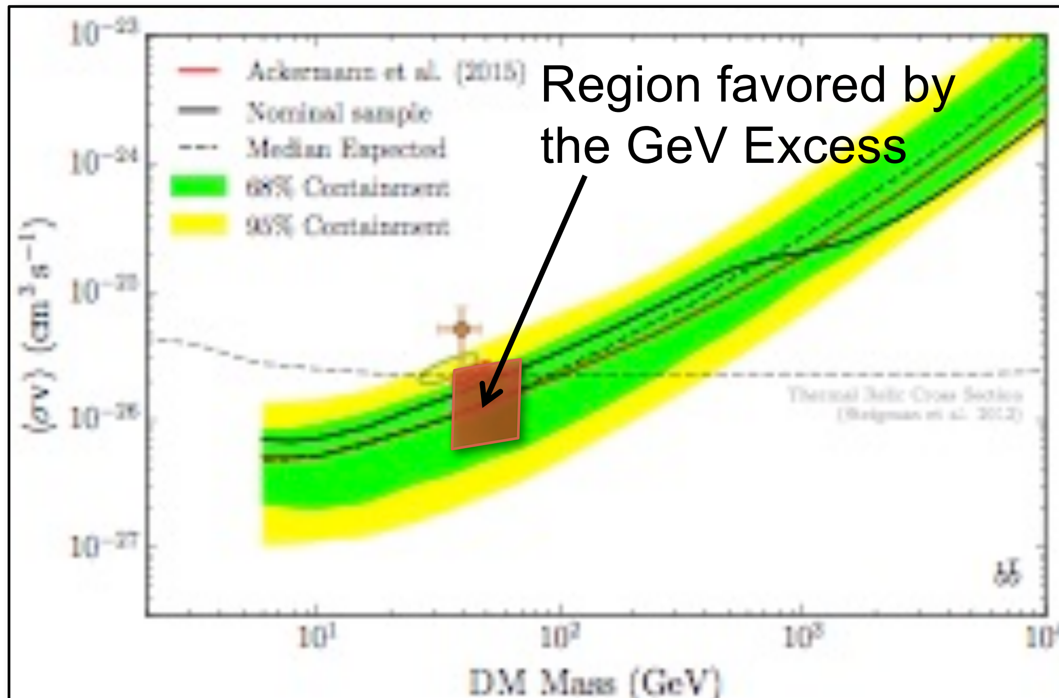
Cuoco, et al., arXiv:1610.03071
Cui, et al. arXiv:1610.03840



Fermi Collaboration, arXiv:1611.03184

Fermi Observations of Dwarf Galaxies

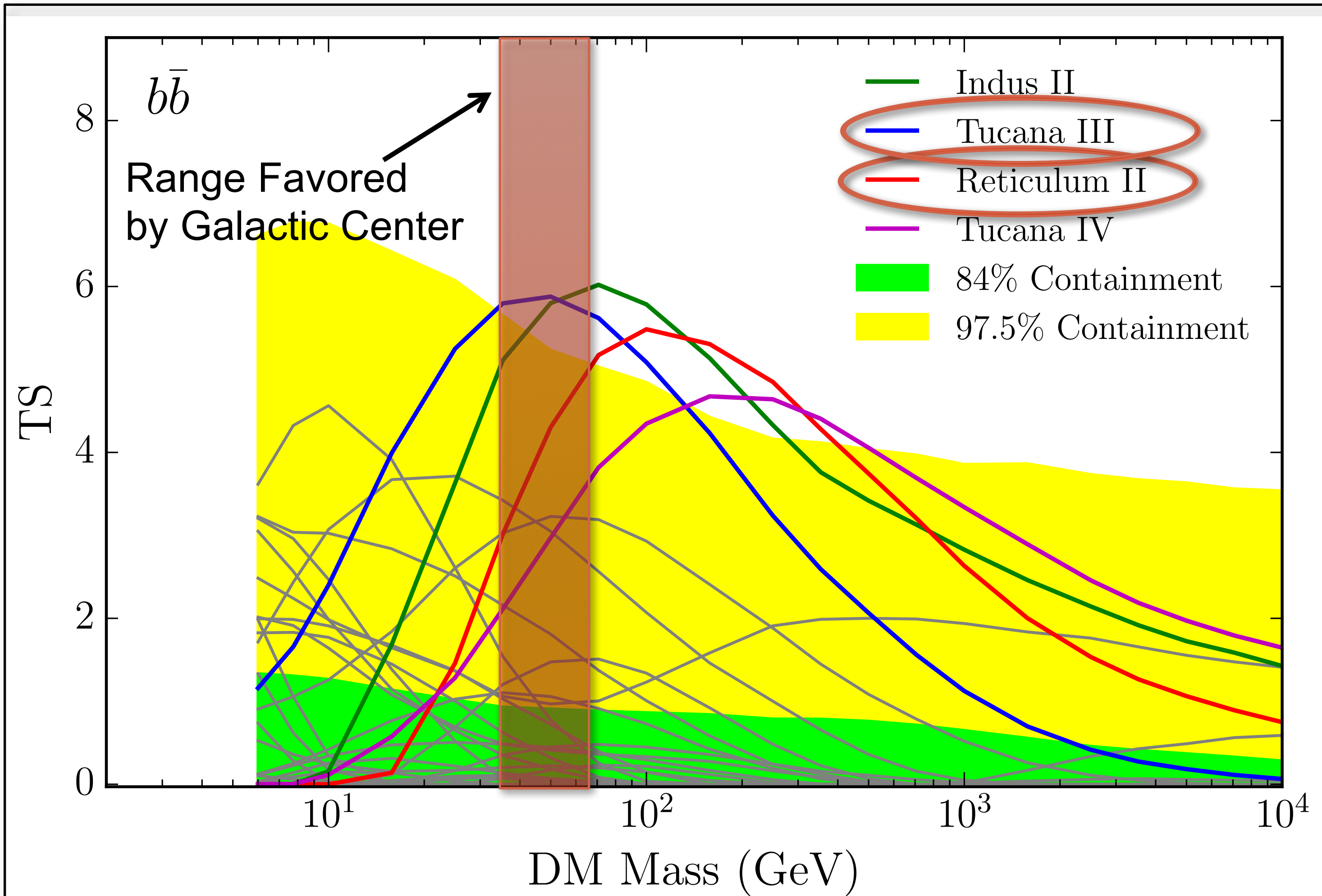
- Current Fermi dwarf constraints are based on stacks of many dwarf candidates, aided by recent discoveries by DES and other surveys
- At this time, these constraints are compatible with dark matter interpretations of the Galactic Center excess
- That being said, if the Galactic Center signal is coming from annihilating dark matter, one should expect gamma rays to be detected from dwarfs soon
- Particularly exciting are Reticulum II, Tucana III and Cetus II which are each nearby (~25-30 kpc) and represent attractive targets for dark matter searches



Fermi Collaboration, arXiv:1611.03184
(see also 1503.02641)

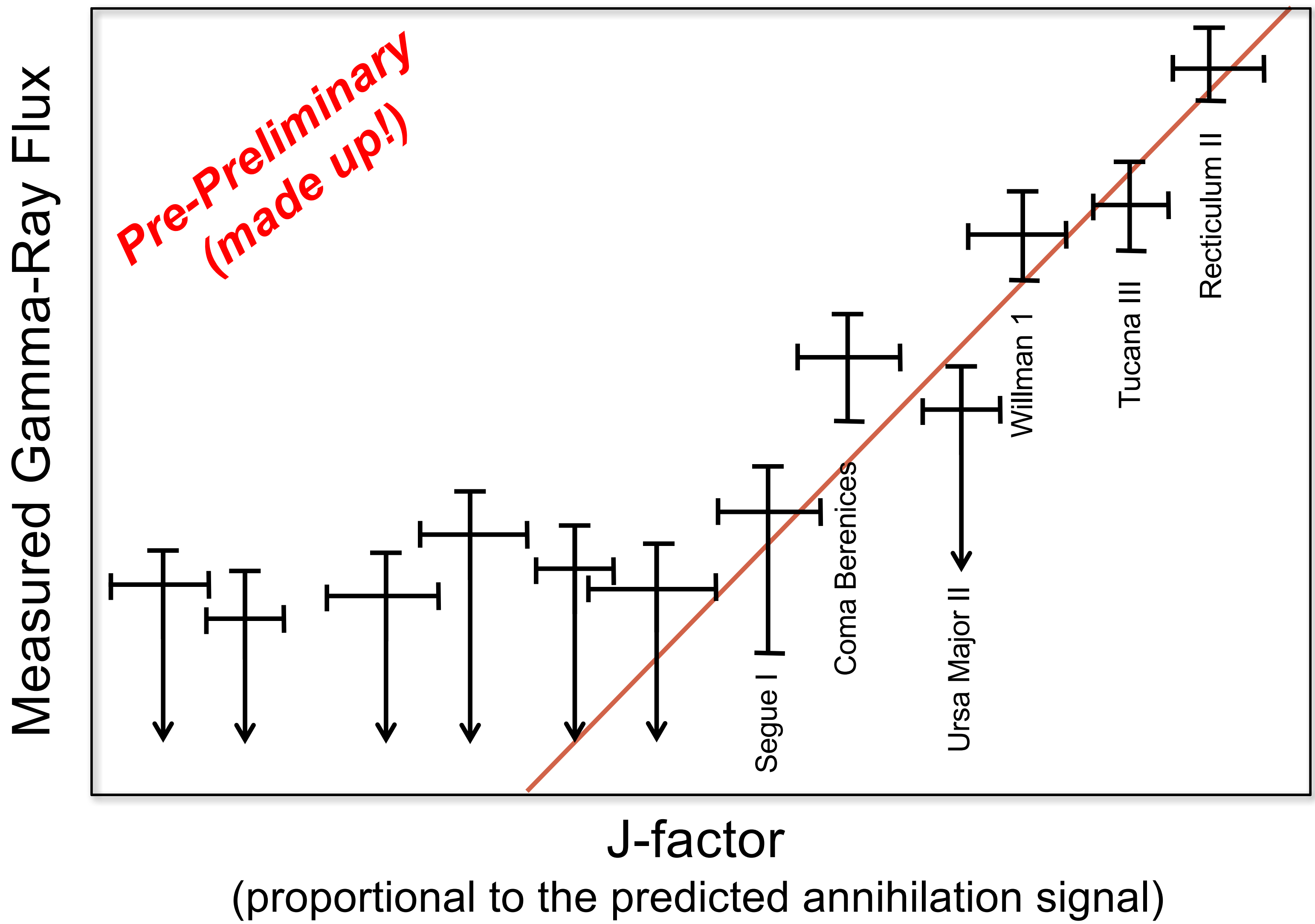
Fermi's Observations of Dwarf Galaxies

- In 2015, three groups reported an excess from the newly discovered Reticulum II, with a significance of 2.4-3.2σ (Geringer-Sameth et al. Drlica-Wagner, et al, DH & Linden)



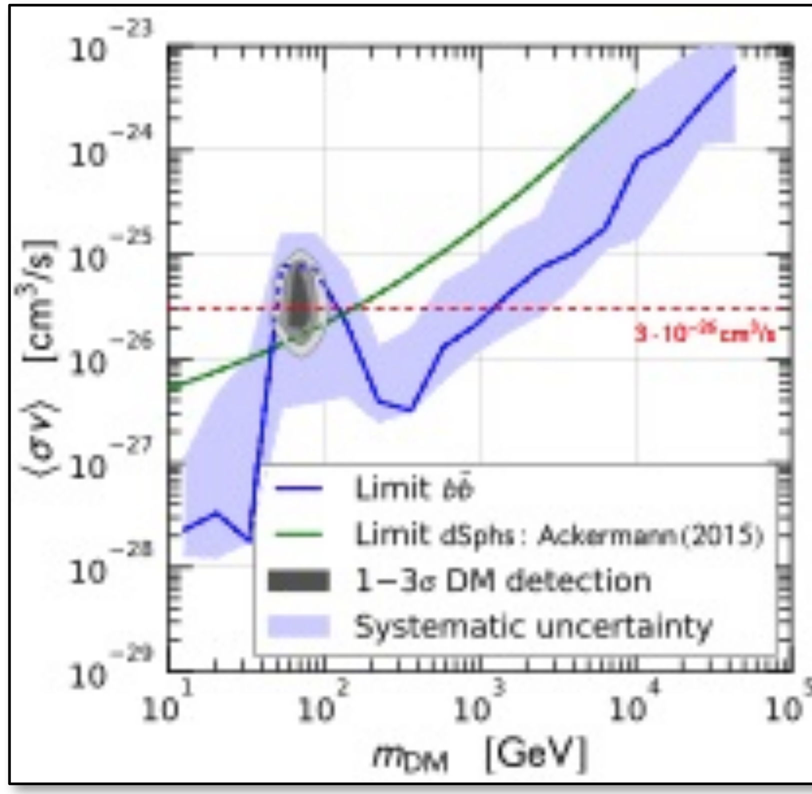
Fermi Collaboration, arXiv:1611.03184

The plot I see in my dreams…



Annihilating Dark Matter And Cosmic-Ray Antiprotons

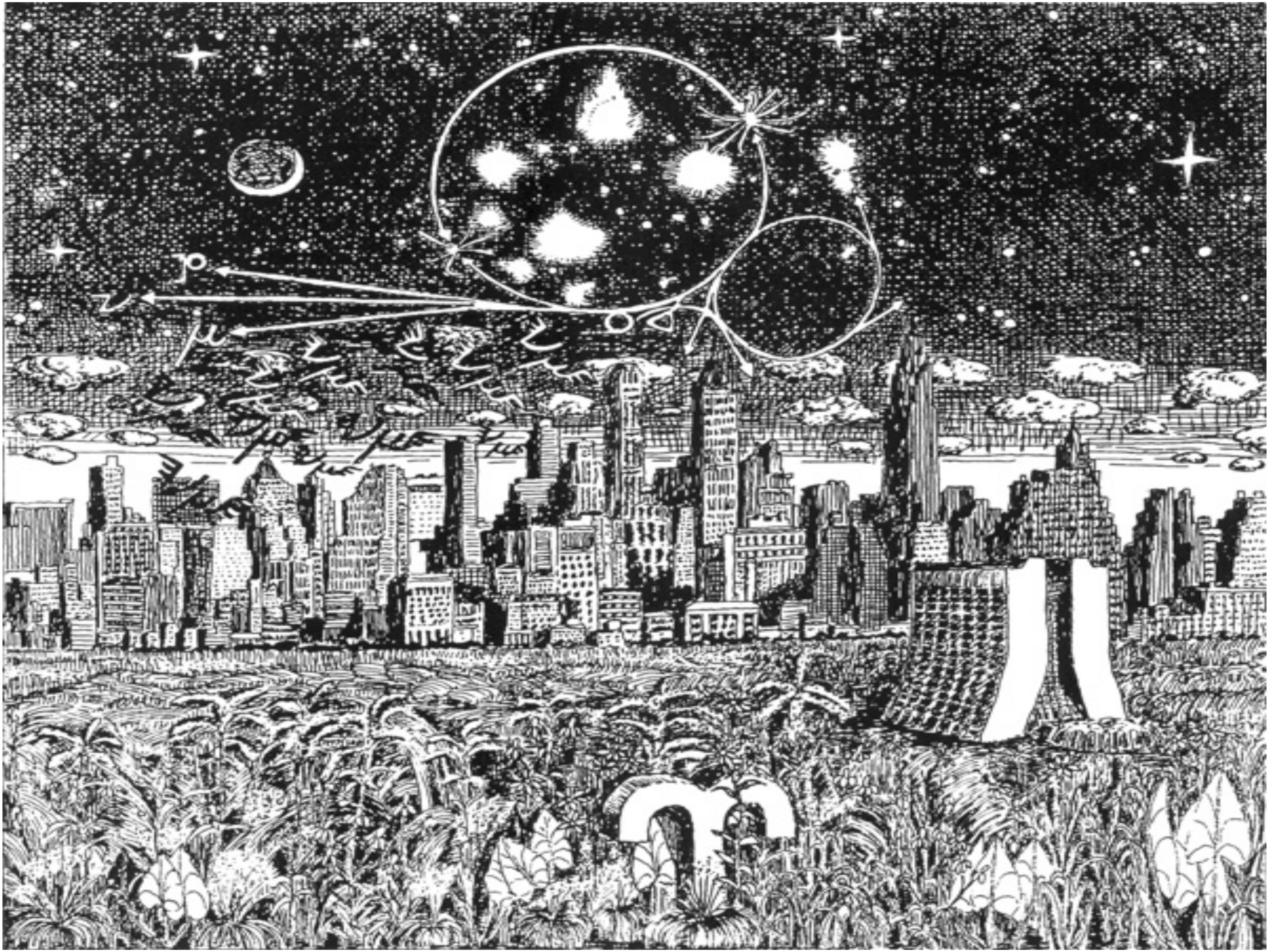
- In the AMS antiproton spectrum, there is a small excess (relative to standard secondary production) at R~10-20 GV
- This is quite statistically significant (~4.5σ), but systematics associated with the antiproton production cross section and the effects of solar modulation are difficult to quantify
- The excess is well fit by a ~50-90 GeV dark matter particle with an annihilation cross section of ~10^{-26} cm^3/s (for bb), in good agreement with the Galactic Center excess



Cuoco, et al., arXiv:1610.03071
Cui, et al., arXiv:1610.03840
Reinert, Winkler, arXiv:1712.00002
Cui, et al., arXiv:1803.02163

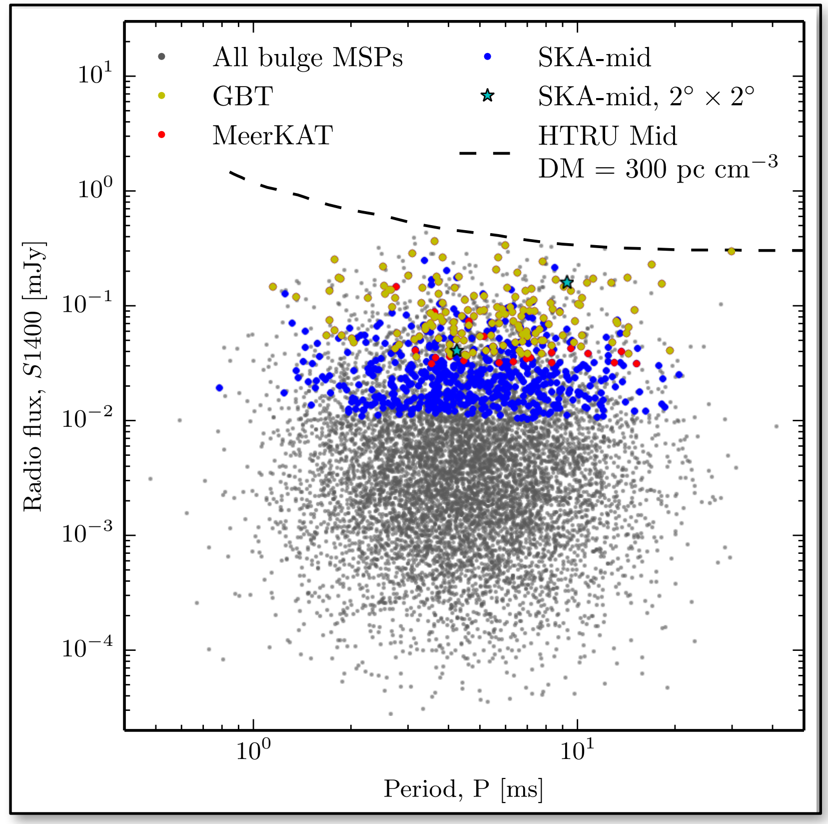
Summary

- The Galactic Center's GeV excess remains compelling: highly statistically significant, robust, extended, and difficult to explain with known or proposed astrophysics
- Although millisecond pulsars could be responsible for this gamma-ray excess, the Inner Galaxy population would have to be quite different from those observed in the disk of the Milky Way and in the Milky Way's globular cluster population (strongly peaked luminosity function, accompanied by fewer LMXBs)
- Gamma-ray (and radio) searches for millisecond pulsars in the Inner Galaxy have not yet found any evidence for such sources; sub-threshold searches have yielded results that are open to multiple interpretations
- The modest excesses observed from dwarf galaxies and in the cosmic-ray antiproton spectrum are suggestive


p
ν
μ

Millisecond Pulsars and Next Generation Radio Telescopes

- Although no radio MSPs have been detected in the Inner Galaxy (in mild tension with pulsar interpretations of the gamma-ray excess), upcoming large-area surveys (utilizing MeerKAT, and later SKA) are expected to detect ***dozens*** to ***hundreds*** of MSPs if they are, in fact, responsible for the excess
- This seems like a reasonably clear and straightforward path to test the hypothesis that MSPs are responsible for the gamma-ray excess



Calore, et al. arXiv:1512.06825