

PULSARS AND THE GALACTIC CENTER GAMMA-RAY EXCESS

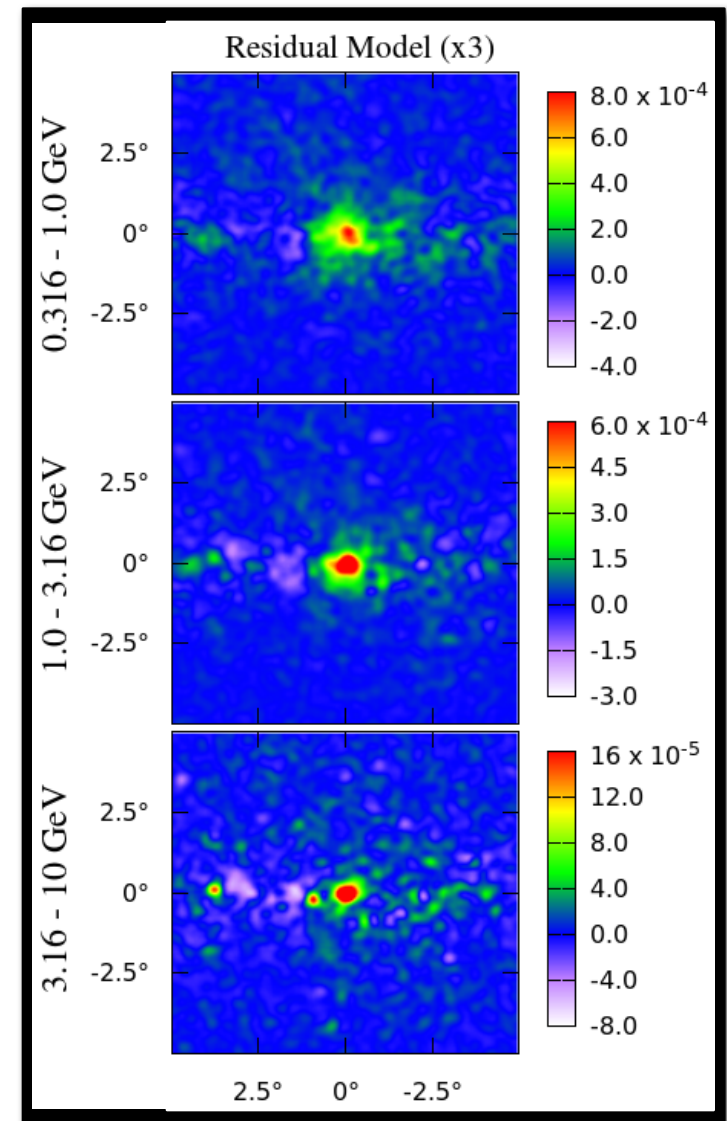
Dan Hooper – Fermilab and the University of Chicago
UCLA Dark Matter Meeting
February 22, 2018

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
- Spectrum, morphology and intensity are each consistent with annihilating dark matter
- The leading astrophysical explanation is a very large ($\sim 10^4$) population of centrally concentrated millisecond pulsars

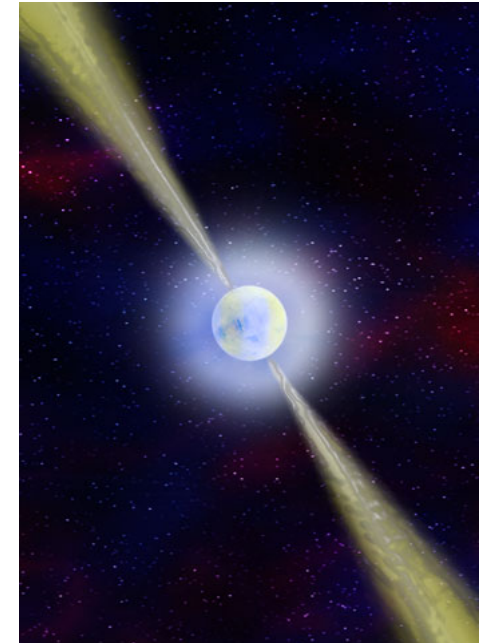
Among other references, see:

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)



Millisecond Pulsars and The Galactic Center Gamma-Ray Excess

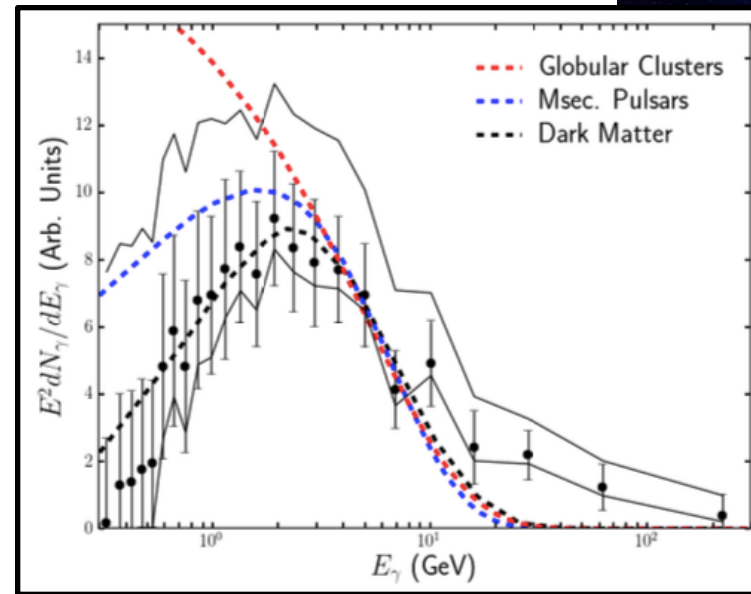
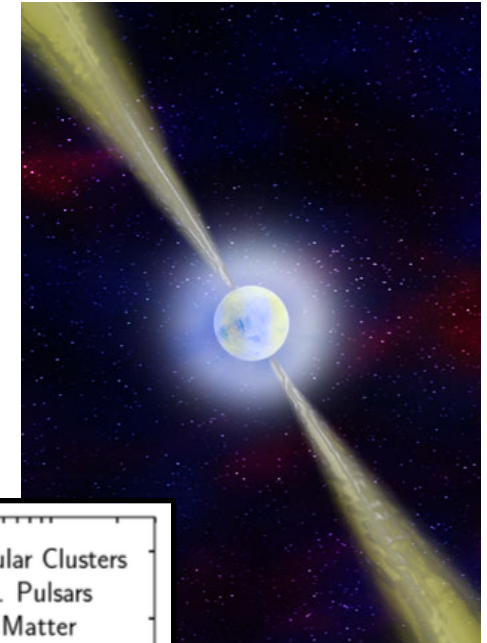
The Two Main Arguments in Favor of Pulsars:



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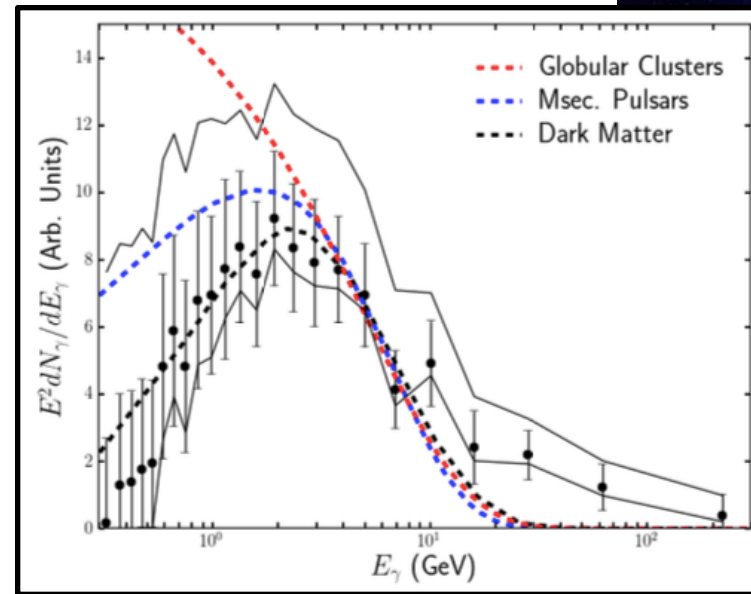
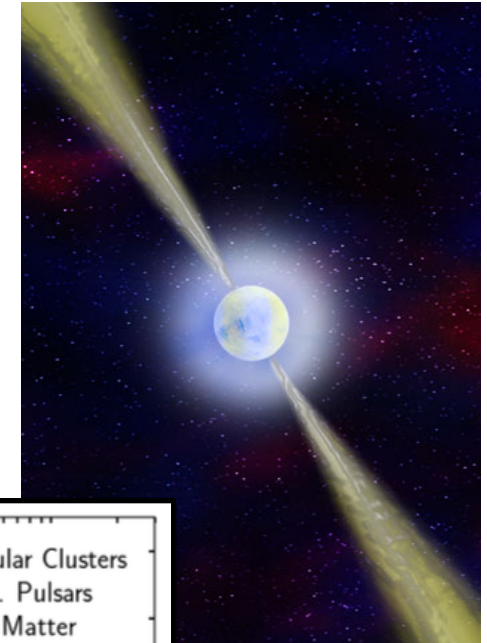
- The gamma-ray spectrum of observed pulsars



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



Evidence For Unresolved Point Sources?

- 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° 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

Evidence For Unresolved Point Sources?

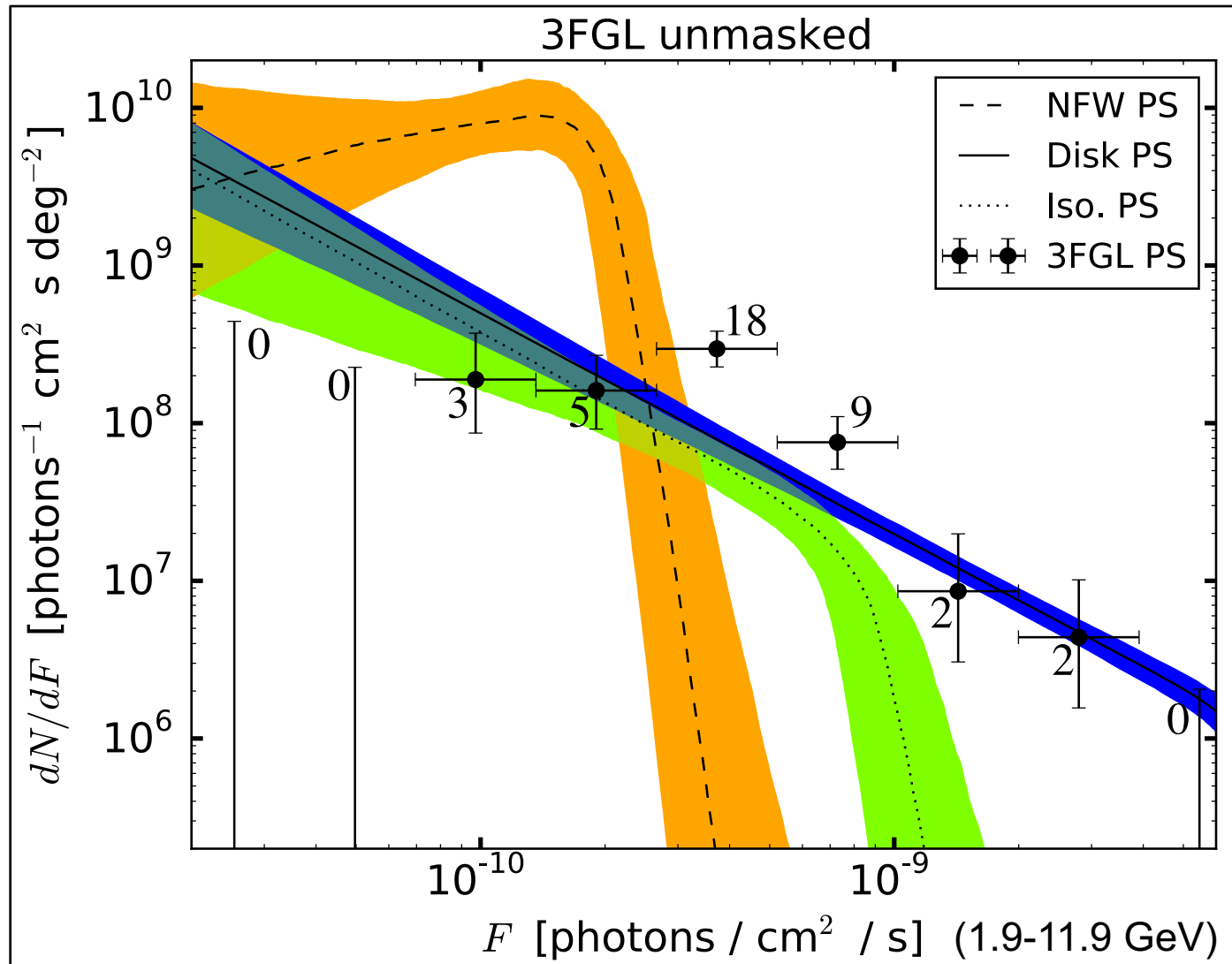
- A typical Fermi Inner Galaxy analysis might include the following spatial templates:
 - 1) Galactic diffuse emission
 - 2) Fermi Bubbles
 - 3) Isotropic background
 - 4) Dark matter annihilation (NFW, 1.25 slope)

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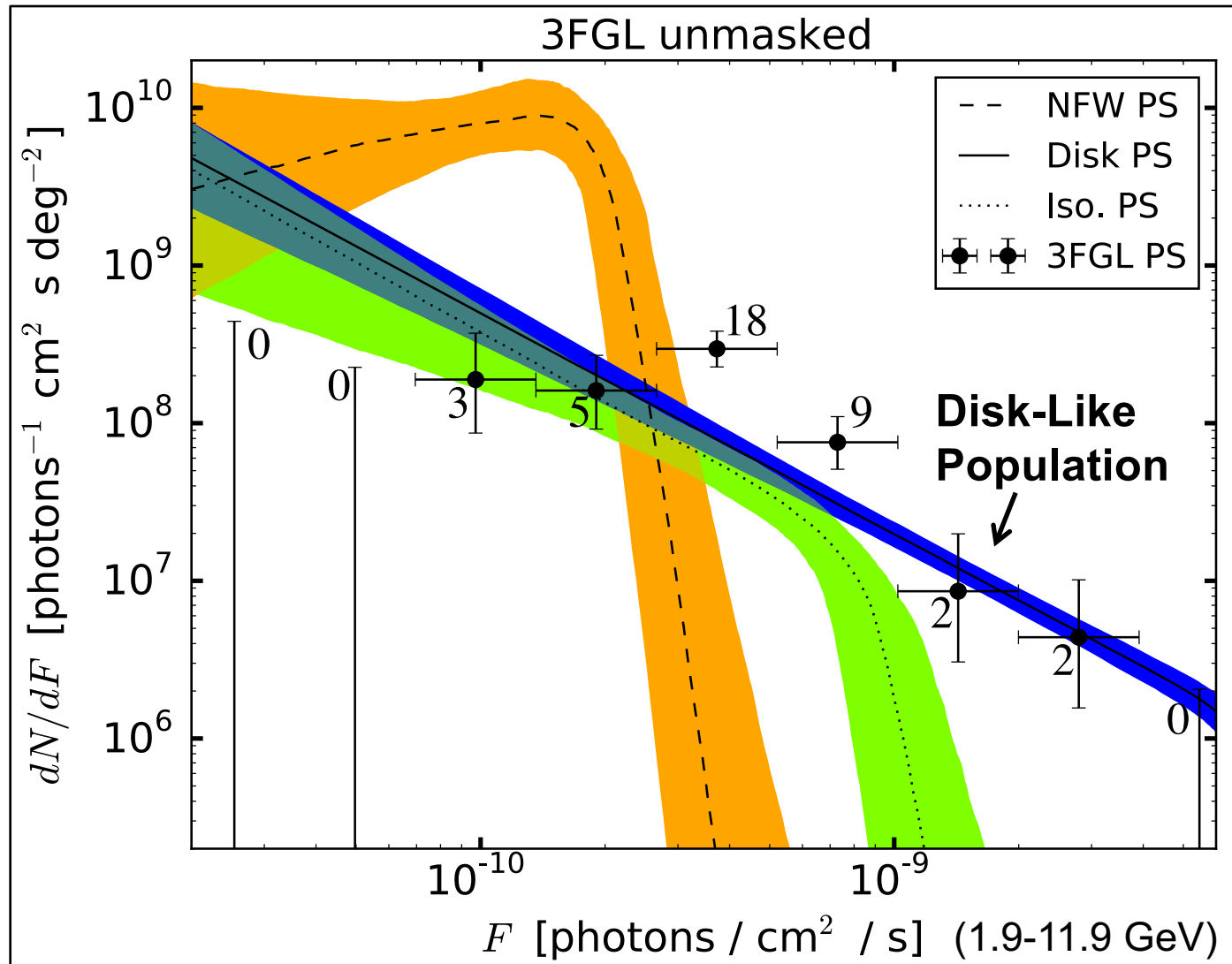
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 - 1) Galactic diffuse emission
 - 2) Fermi Bubbles
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 - 4) Dark matter annihilation (NFW, 1.25 slope)

- Lee et al. add to this a number of non-Poissonian templates to model the distribution of unresolved point sources:
 - 5) Isotropically distributed point sources
 - 6) Disk-correlated point sources ($R_s=0.3$ kpc)
 - 7) NFW² correlated point sources

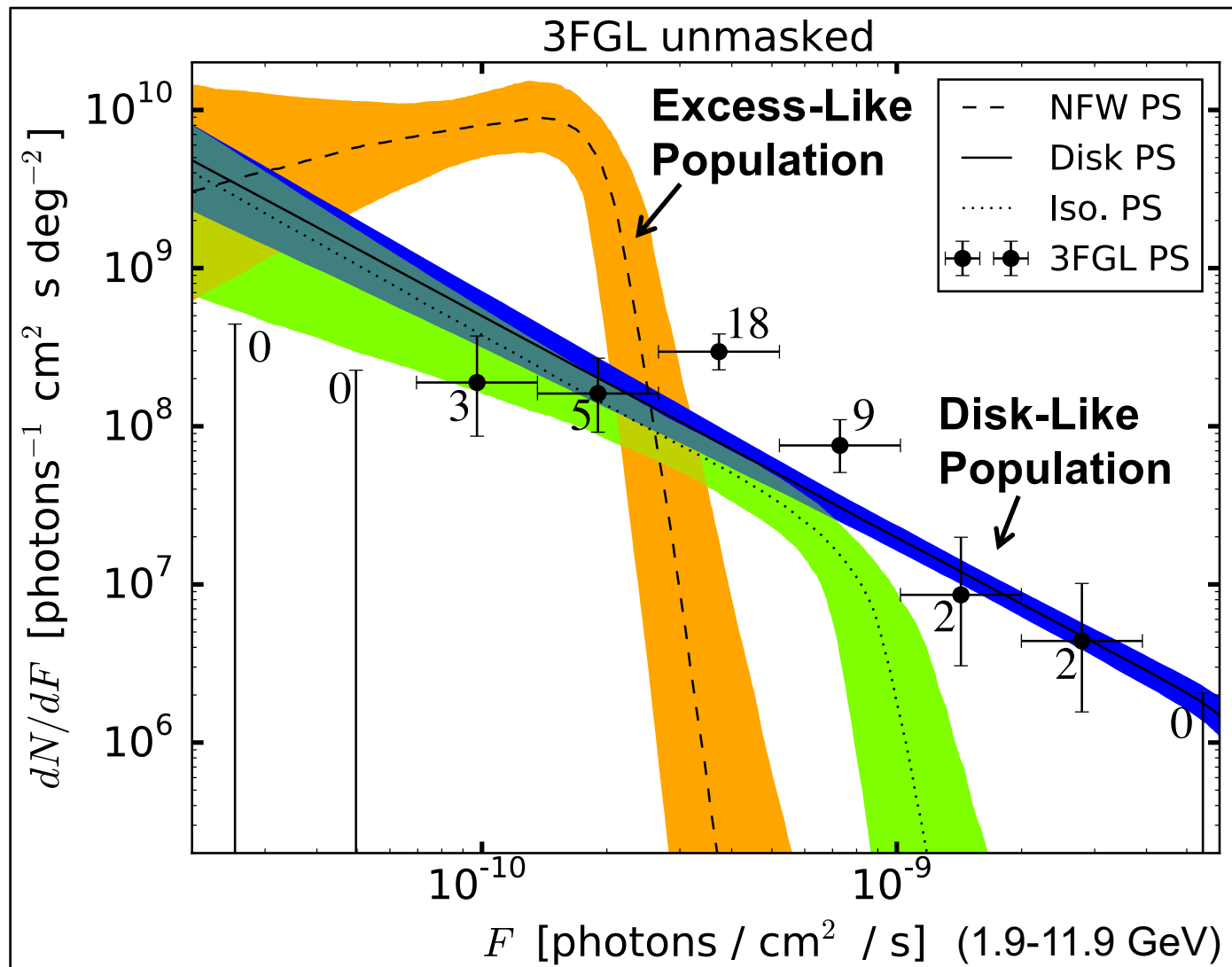
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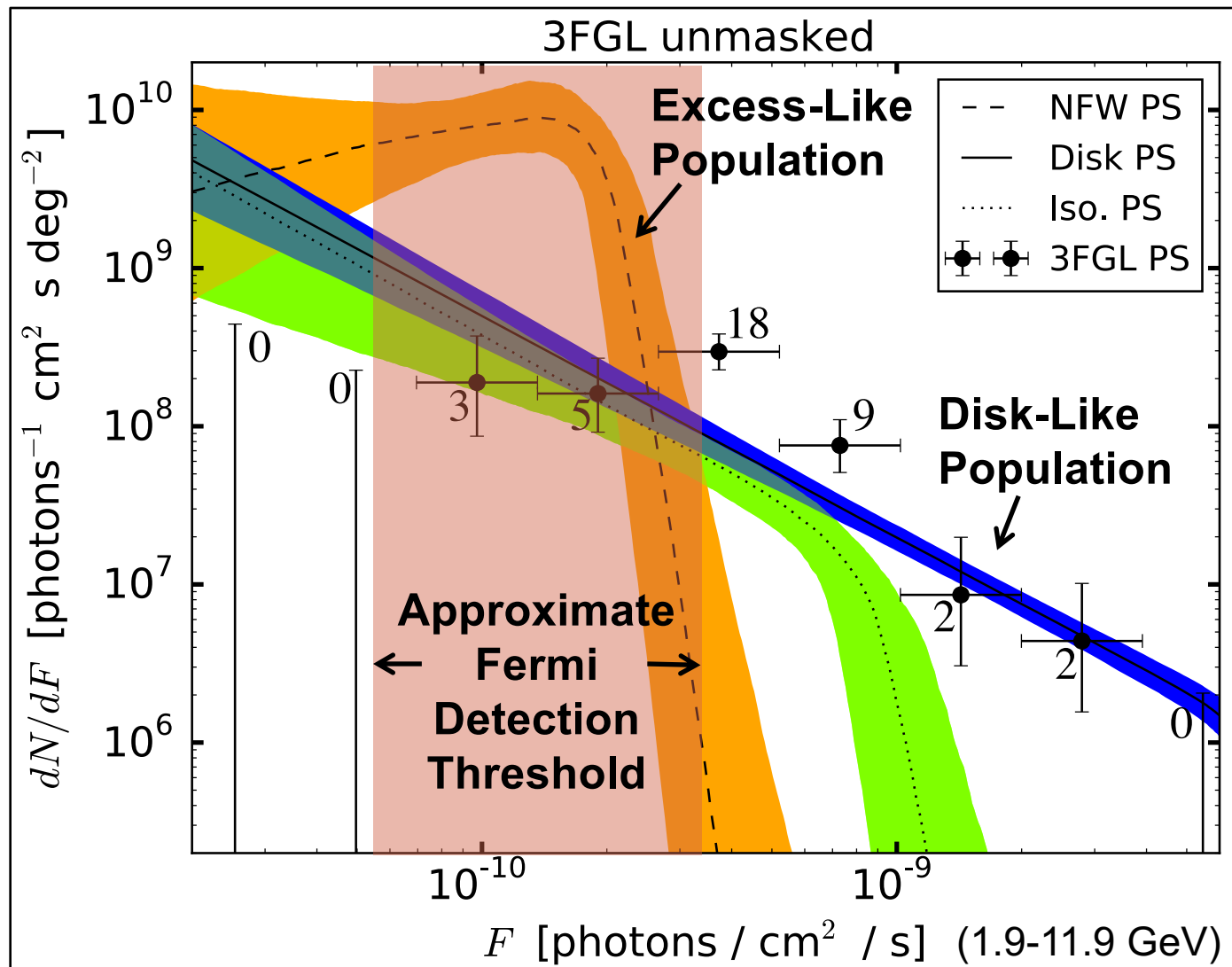


Evidence For Unresolved Point Sources?



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

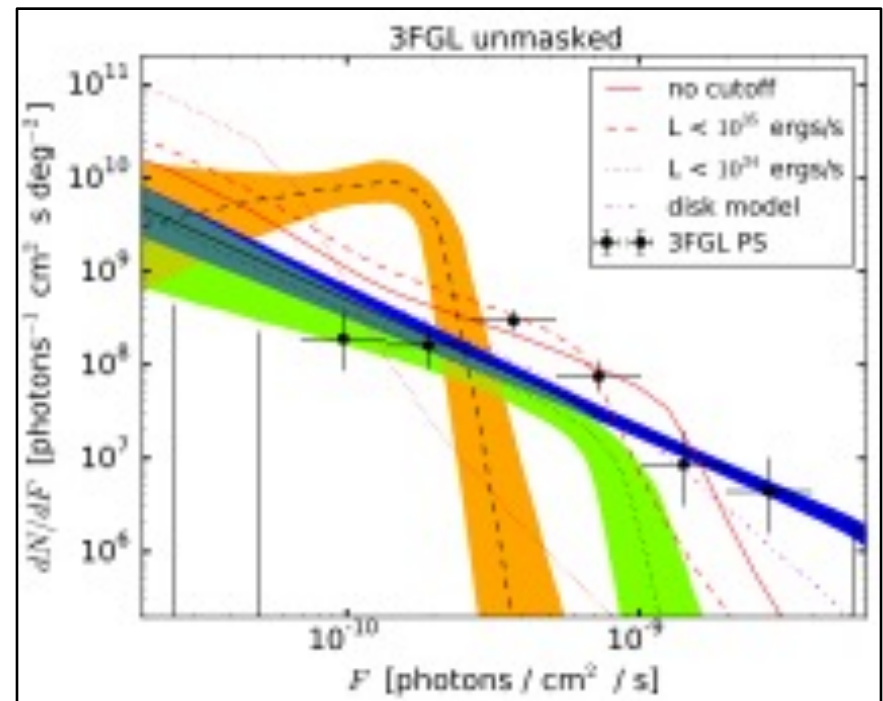
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Bottom Line: A population of $\sim 10^3$ points sources with luminosities just below Fermi's detection threshold could potentially account for the GeV Excess

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 $\sim 10^{35}$ erg/s (>0.1 GeV)
- 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

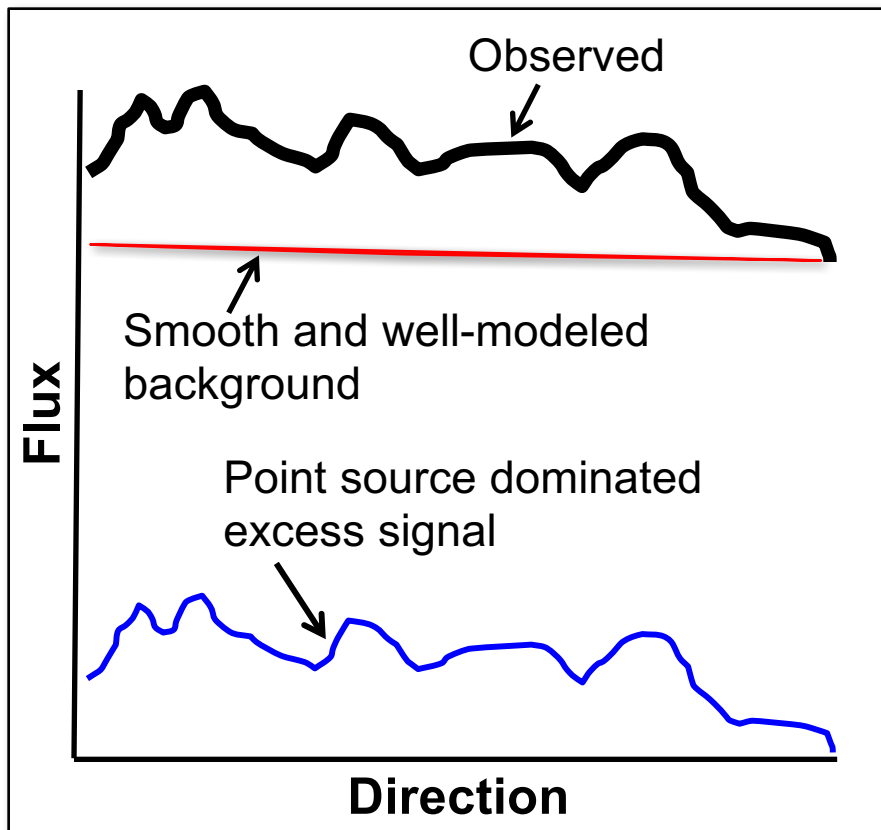


Evidence For Unresolved Point Sources?

- More generally speaking, 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

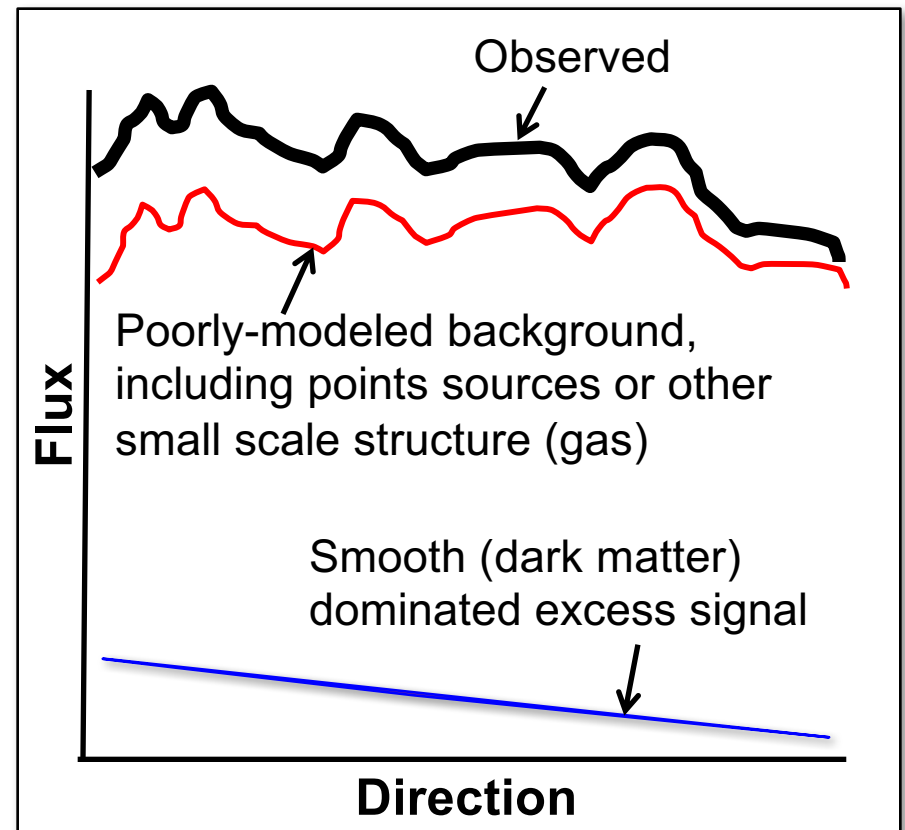
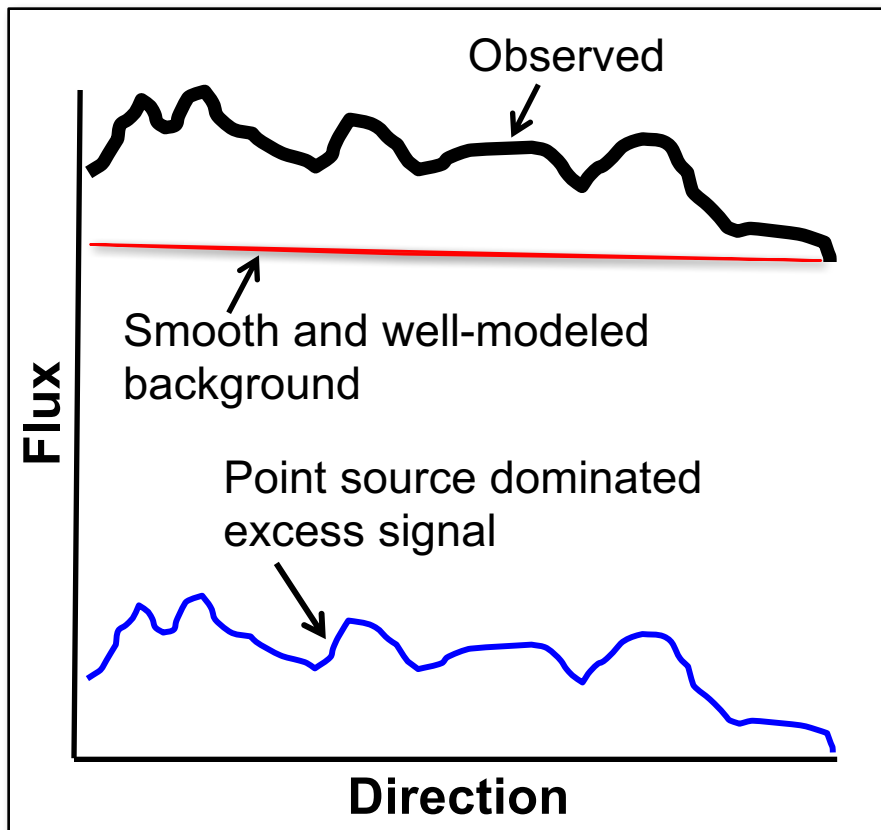
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- Keep in mind that these clusters consist of only a few photons each, on top of large and imperfectly known backgrounds

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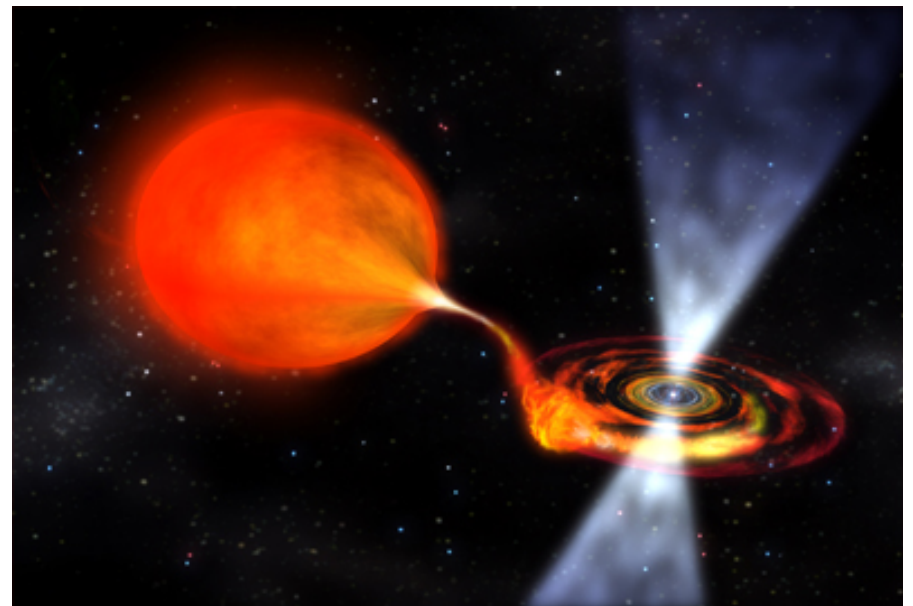
- More generally speaking, it is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than are being modeled
- Keep in mind that these clusters consist of only a few photons each, on top of large and imperfectly known backgrounds
- 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 (to convince yourself of this, compare 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 Low-Mass X-Ray Binaries

- We can also use the number of low-mass X-ray binaries in the Inner Galaxy to estimate or constrain the population of MSPs that is present
- 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



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 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

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

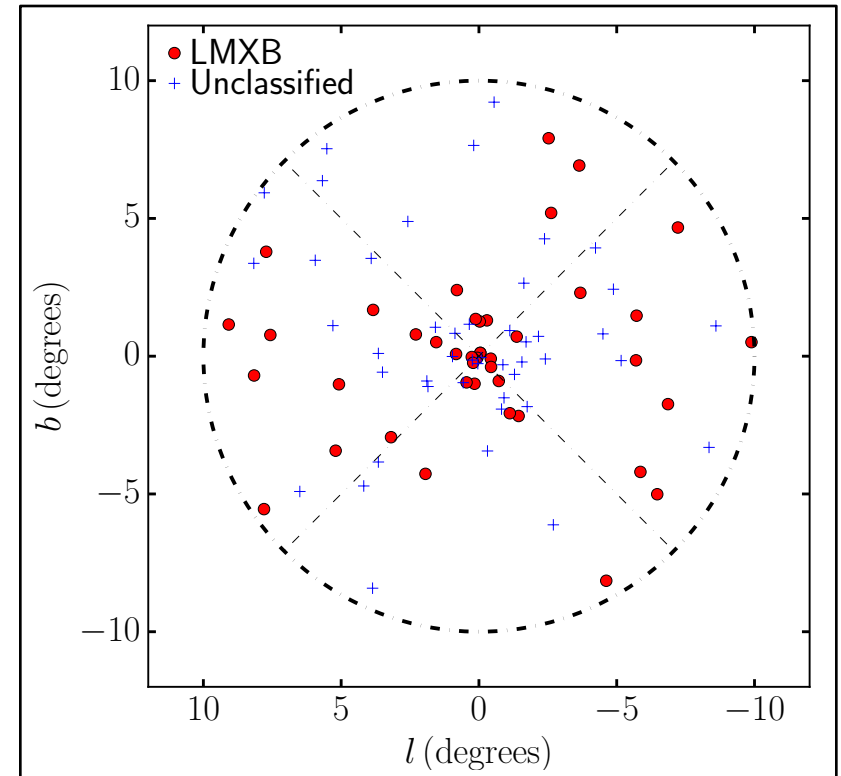
- We begin with the following sample of Milky Way globular clusters (selected for their large stellar encounter rates):
- As expected, most of these have been detected by Fermi
- This same collection of globular clusters contains the following list of bright LMXBs ($>10^{36}$ erg/s for a week or more between 2003-2016)
- This criteria is intended to identify those LMXBs that we are confident would have been detected if they had been located in the Inner Galaxy
- We now have the GeV flux from MSPs per bright LMXB

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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]

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

- To characterize the LMXB population in the Inner Galaxy, we utilize the INTEGRAL General Reference Catalog
- Within 10° of the Galactic Center, this catalog contains 42 sources classified as an LMXB and 46 unclassified sources (which may or may not be LMXBs)
- Some of these sources ($\sim 1/3$) are part of a disk population; the remainder could be associated with a population of MSPs responsible for the GeV excess



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

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:

$$L_{\gamma}^{\text{IG}} = L_{\gamma}^{\text{clusters}} \times \left(\frac{N_{\text{LMXB}}^{\text{IG}}}{N_{\text{LMXB}}} \right)$$

This exercise yields the following:

$$L_{\gamma}^{\text{IG}} = (2.09_{-0.71}^{+0.86}) \times 10^{36} \text{ erg/s}, \quad \text{Only Sources Classified as LMXBs}$$

$$L_{\gamma}^{\text{IG}} = (4.38_{-1.48}^{+1.79}) \times 10^{36} \text{ erg/s}, \quad \text{Including All Unclassified Sources}$$

This corresponds to $11 \pm 4\%$ (LMXBs) or $22 \pm 9\%$ (LMXBs+unclassified) of the observed intensity of the GeV excess

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

This calculation, however, likely overestimates the gamma-ray flux from MSPs in the Inner Galaxy for at least two reasons:

- 1) Our threshold of $L_x=10^{36}$ erg/s for LMXBs in globular clusters likely includes sources that would *not* have been detected in the Inner Galaxy
- 2) Our calculation assumes that none of the gamma-ray emission from central MSPs will come from resolved sources (those in the 3FGL catalog):
 - Adopting a reasonable MSP luminosity function, we estimate that ~30-50% of the total gamma-ray flux from MSPs in the Inner Galaxy should come from individually resolvable sources
 - When this is taken into account, we estimate that MSPs are responsible for between $8\pm 3\%$ (LMXBs) and $16\pm 7\%$ (LMXBs+unclassified) of the observed intensity of the GeV excess

In summary, we find that a MSP population that is capable of generating the observed GeV excess should be accompanied by ~500 bright LMXB, but only 42 (88) are actually observed

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
- In May, the Fermi Collaboration posted a paper which purported to present strong evidence ($\sim 7\sigma$) for a large centrally located pulsar population

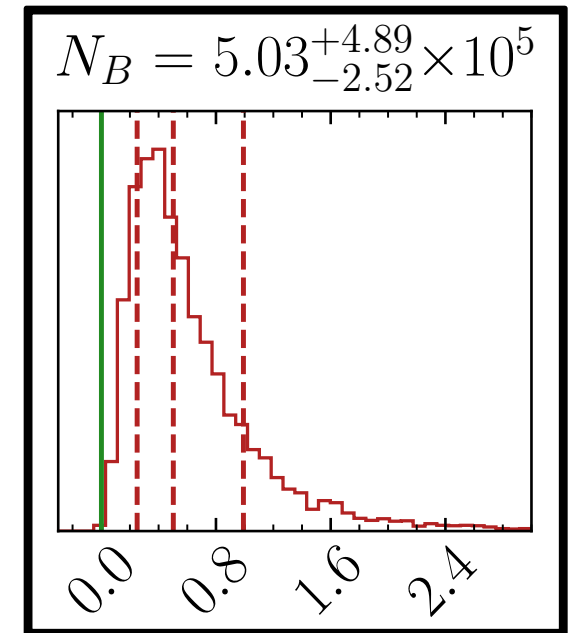
CHARACTERIZING THE POPULATION OF PULSARS IN THE GALACTIC BULGE WITH THE *FERMI* LARGE AREA TELESCOPE.

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.

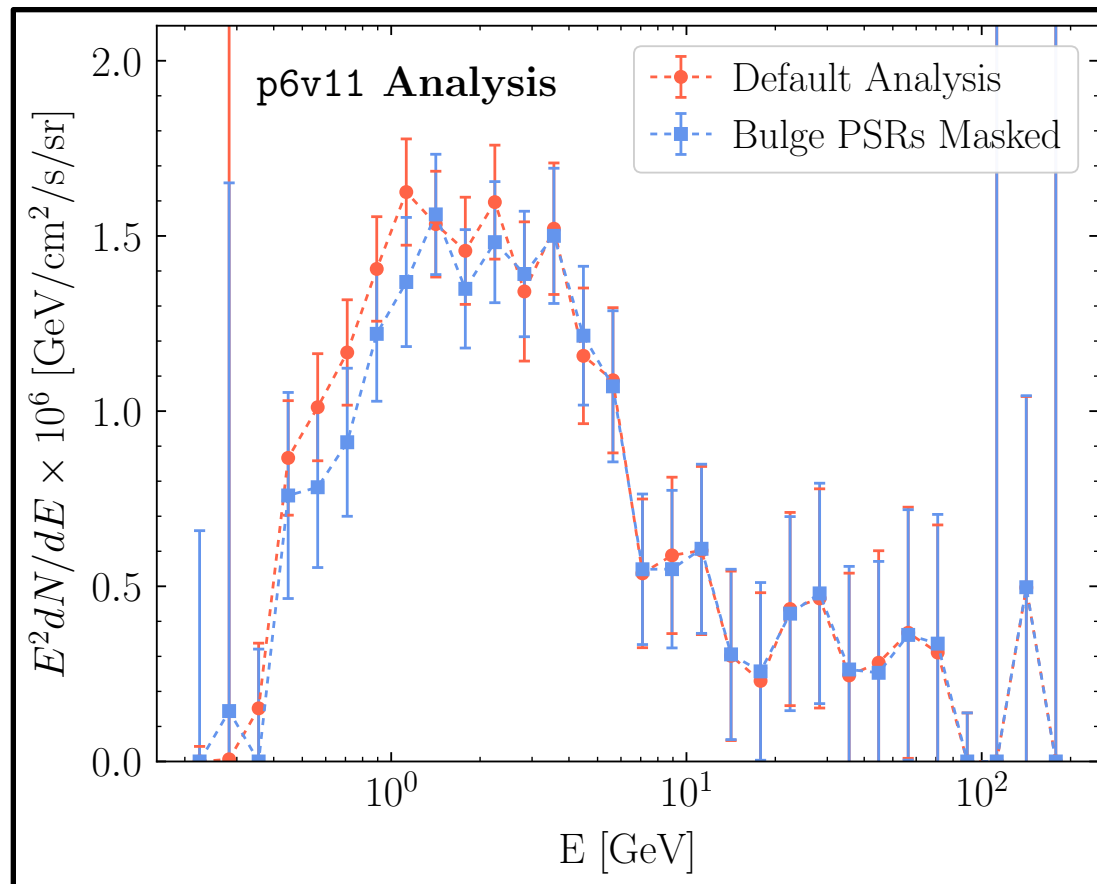
Evidence of a Central Pulsar Population?

- In examining this paper, my collaborators and I found that we were unable to reproduce these results; our fit favored only a $\sim 2\sigma$ 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



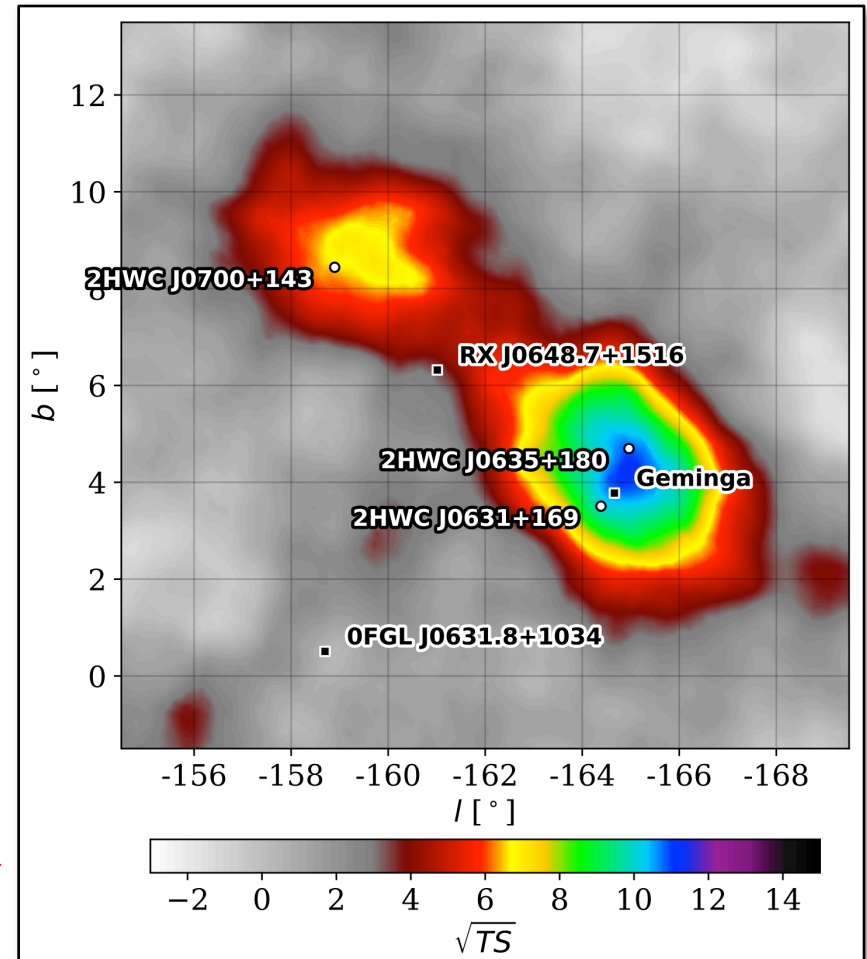
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- In our paper, we also note that masking the pulsar candidate sources contained in the new Fermi catalog does *not* impact the characteristics of the excess; **a negligible fraction of the excess emission originates from these sources**



The TeV Halos of Pulsars

- The HAWC Collaboration has recently reported spatially extended ($\sim 2^\circ$ radius) multi-TeV emission from the Geminga and Monogem pulsars
- 16 out of 39 of the sources in the 2HWC catalog are potentially associated with known pulsars
- 6 out of 11 of the known young pulsars in HAWC's field-of-view with the highest spindown flux, have potential associations with the HAWC sources
- **All indications are that most (if not all) young pulsars are surrounded by TeV halos**



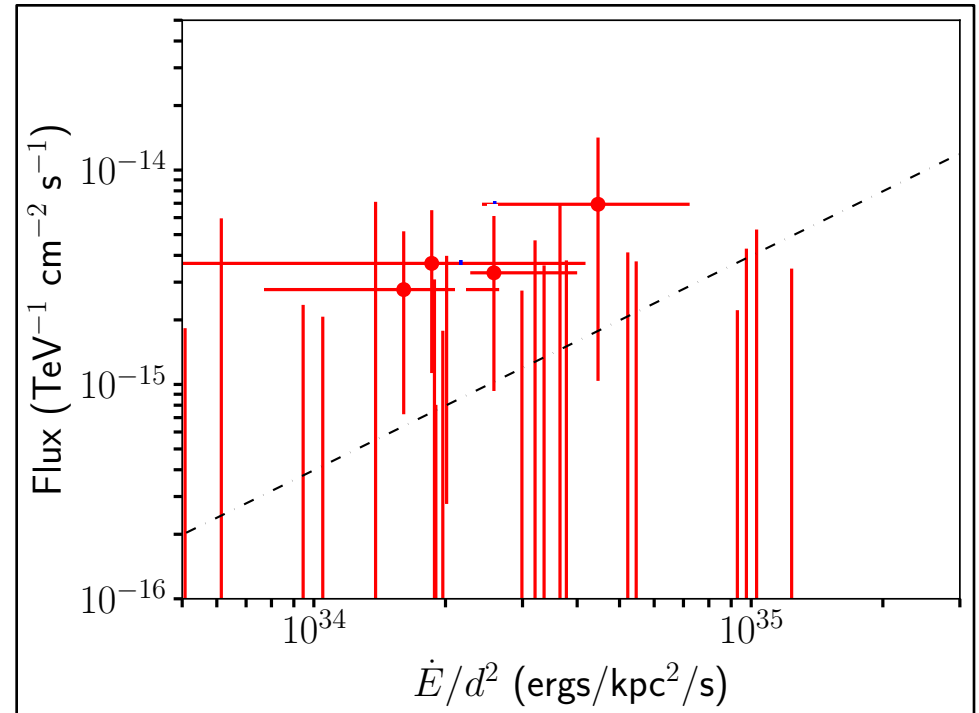
HAWC arXiv:1702.02992, 1711.06223

DH et al. arXiv:1702.08436

Linden, et al. arXiv:1703.09704

Do Millisecond Pulsars Have TeV Halos?

- Its an open question whether MSPs are also surrounded by TeV Halos
- Using the HAWC online tool (data.hawc-observatory.org), we tested this hypothesis using the 24 most promising MSPs (highest spindown flux, not located near other HAWC sources)
- From among these 24 sources, 4 yield $TS > 4.3$
- This has a chance probability of 0.13%, corresponding to a significance of 3.2σ
- ***This suggests that MSPs produce TeV Halos with an efficiency roughly equal to that of Geminga and Monogem***

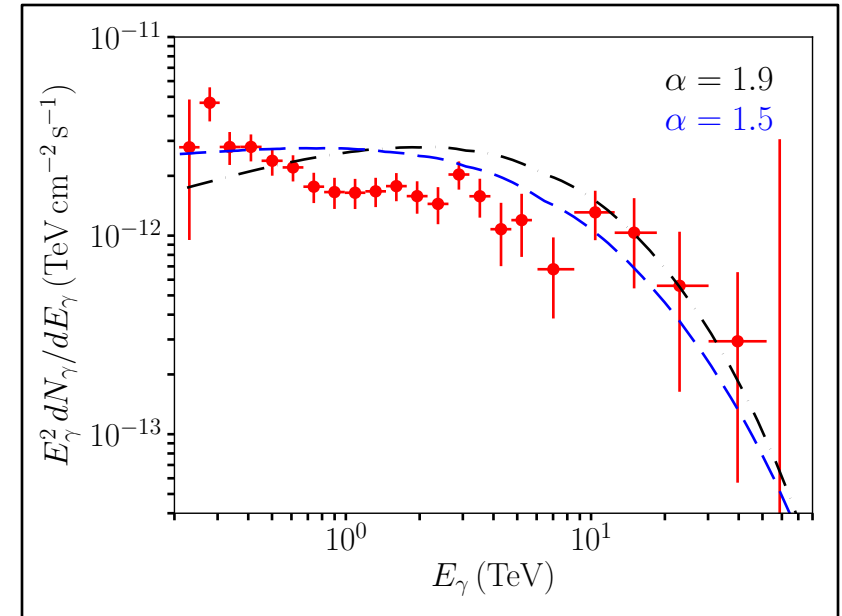


TeV Halos In the Inner Galaxy

- If the presence of TeV halos around MSPs is confirmed, this would provide us with a new way to independently estimate the number of MSPs that are present in the Inner Galaxy

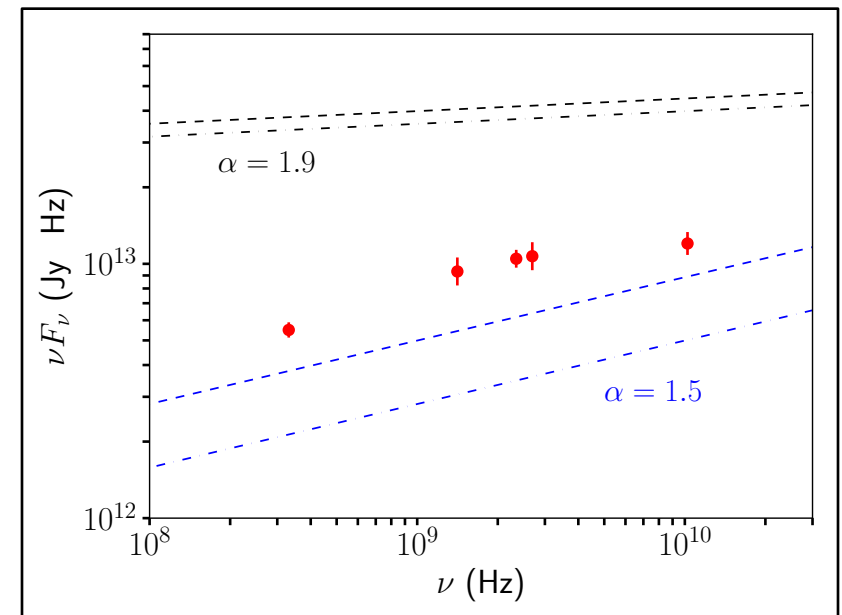
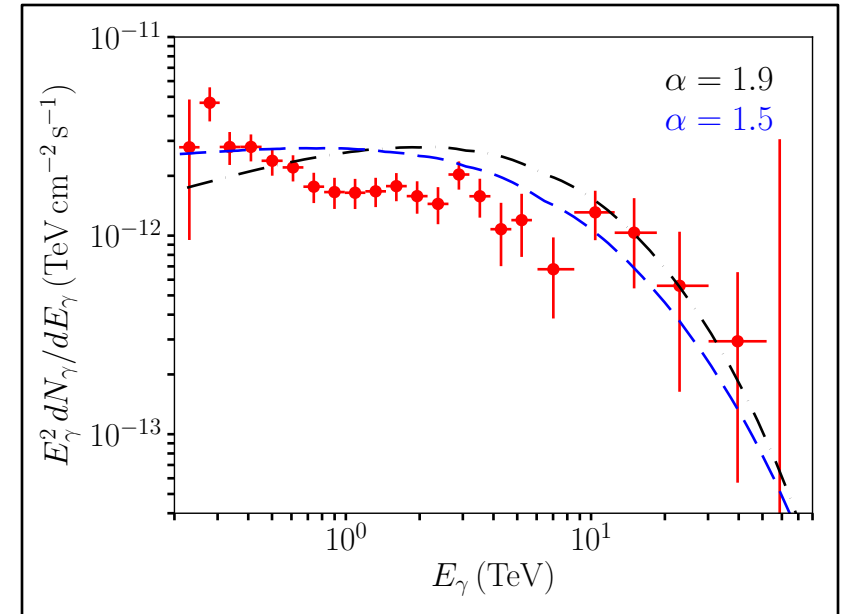
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- If MSPs are responsible for the GeV excess, we estimate that their TeV halos will approximately saturate the emission from the Inner Galaxy observed by HESS
- If most of the energy in these TeV halos instead goes into synchrotron (due to large magnetic fields), radio measurements from the region will instead be approximately saturated
- This is rich area for future study



Summary

- In my opinion, MSPs could be responsible for the GeV excess observed from the Galactic Center; they remain the most plausible astrophysical explanation for this signal
- If this is the case, however, this population of MSPs must be quite different from those observed in the disk of the Milky Way, or in the Milky Way's globular cluster population
- The luminosity function of such a population must peak strongly just below Fermi's detection threshold ($L \sim 2 \times 10^{34}$ erg/s); the observed populations exhibit a wide range of luminosities, from below 10^{32} to above 10^{35} erg/s
- Such a pulsar population must be accompanied by ~ 10 times fewer LMXBs than MSPs in globular clusters
- If the MSPs in this population are surrounded by TeV halos (as suggested by HAWC), this emission will approximately saturate the TeV *and* GHz emission observed from the Inner Galaxy, leaving little room for other astrophysical contributions

