A Story of the Galactic Center Gamma-Ray Excess

Rebecca Leane
MIT Center For Theoretical Physics

MIT LNS Colloquium
February 3rd 2020

Massachusetts Institute of Technology

OUTLINE

- History and characteristics of the excess
- Arguments for dark matter vs. pulsars
  - How to tell the two hypotheses apart
- Recent controversies
- Ways forward

2008:
FERMI LAUNCHES

THE FERMI TELESCOPE

- Full-sky field of view,
  in low-Earth orbit (340 miles)

- Sensitive to gamma rays
  ~300 MeV to few TeV

- Publicly available data!

2009:
INNER GALAXY EXCESS FOUND

2009:
INNER GALAXY EXCESS FOUND

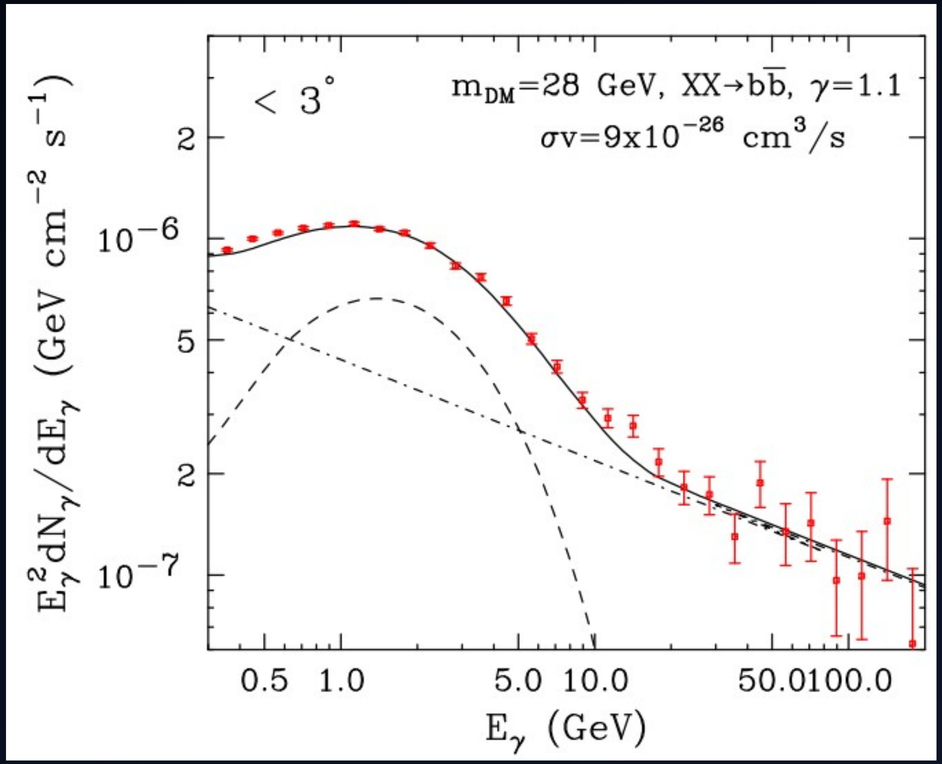
Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[3] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

THE GALACTIC CENTER GEV EXCESS

- Identified by Dan Hooper and Lisa Goodenough
- Highly significant bright excess in gamma rays
- Peaked at 1-3 GeV

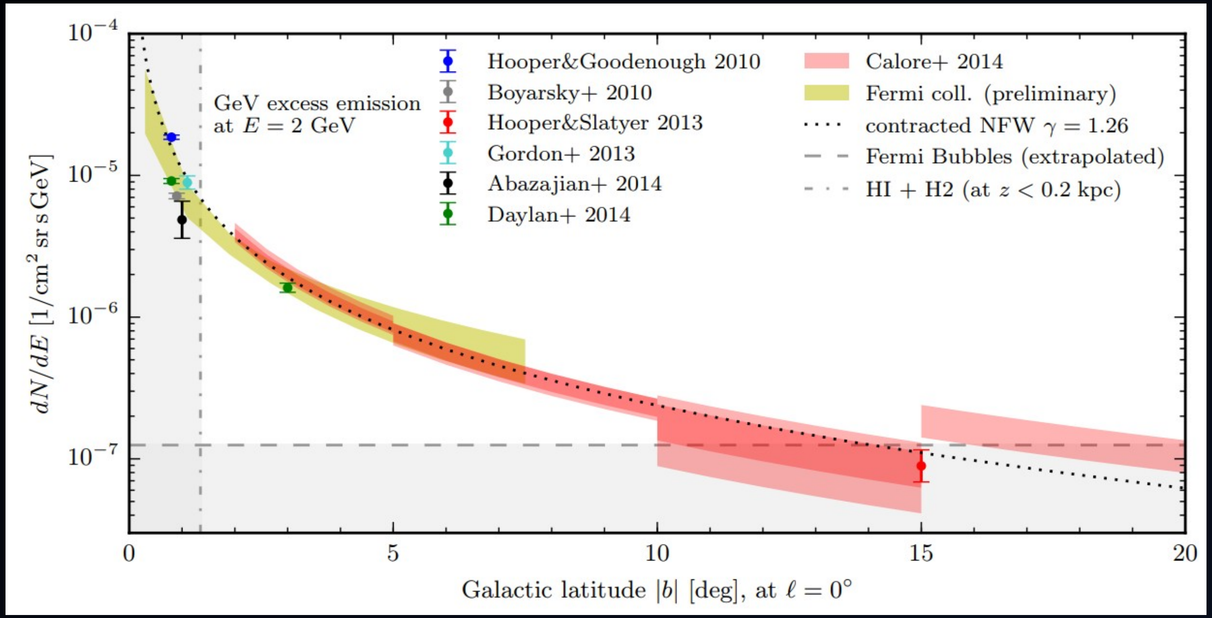


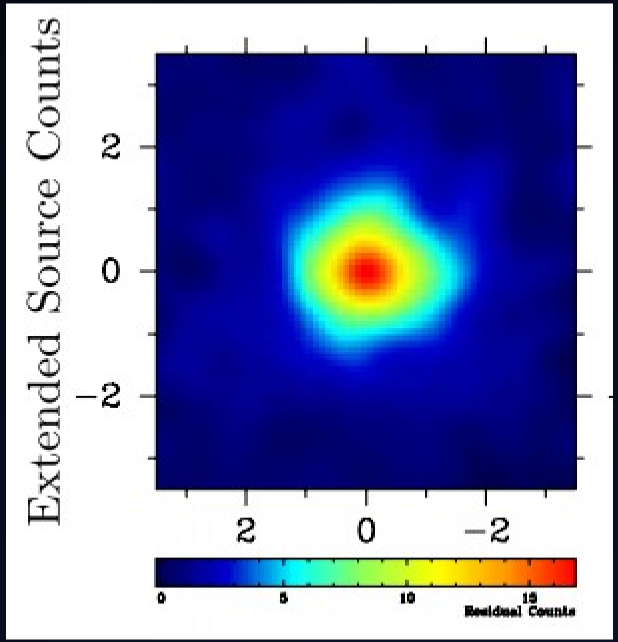
Goodenough+Hooper ‘09

2010-14:
CLUES OF ITS PROPERTIES

MORPHOLOGY

Calore et al ‘14





Abazajian+ Kaplinghat ‘12

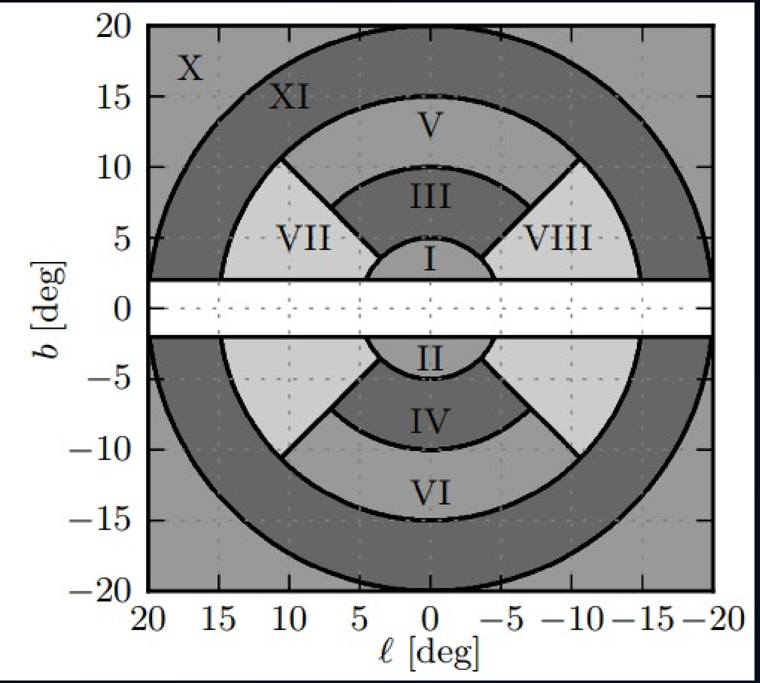
Spherically symmetric around Galactic Center

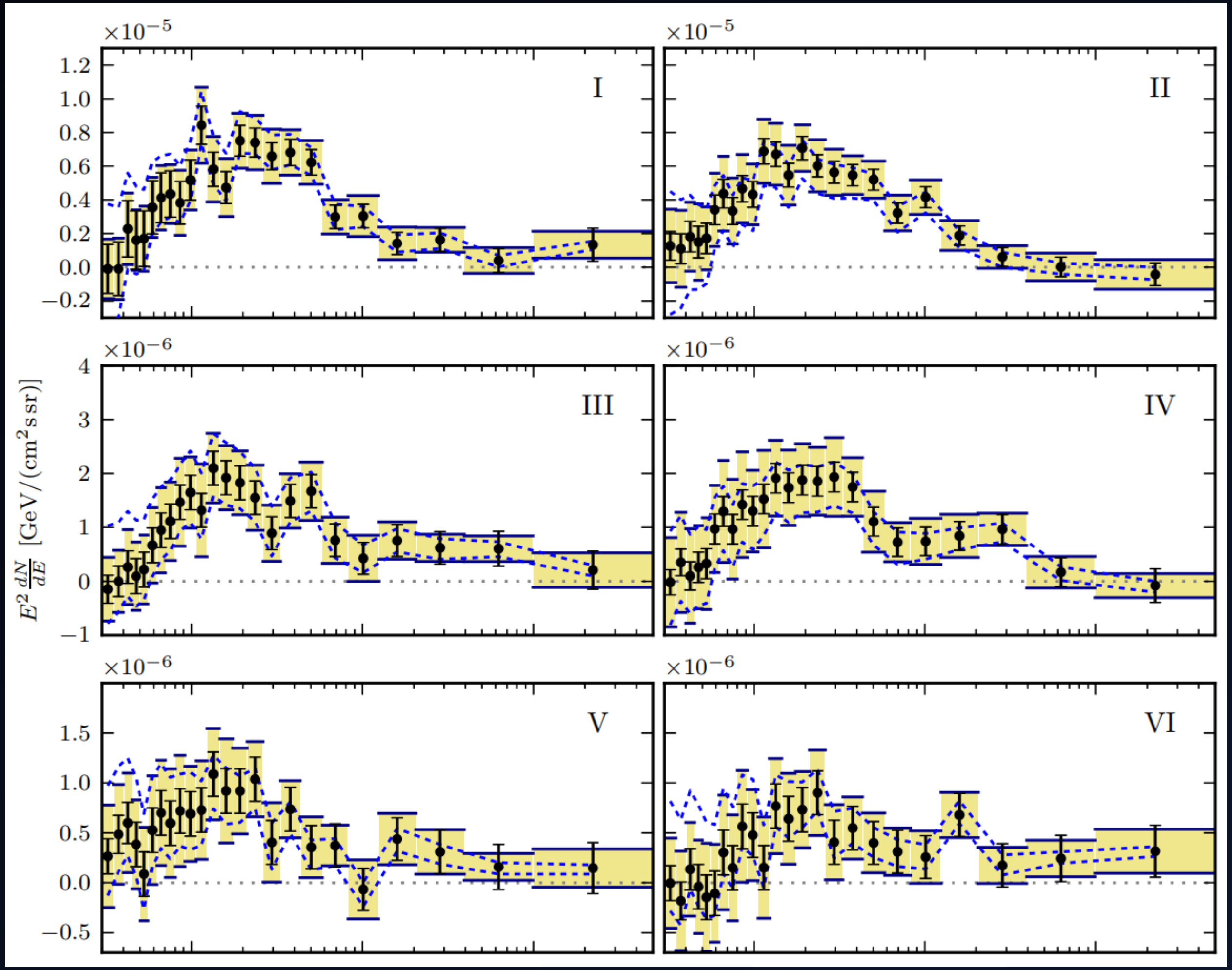
Scales like $r^{-2.4}$ extending out to around 10°, roughly fits standard dark matter (NFW) profile

Hooper+Slatyer ‘13

SPECTRUM

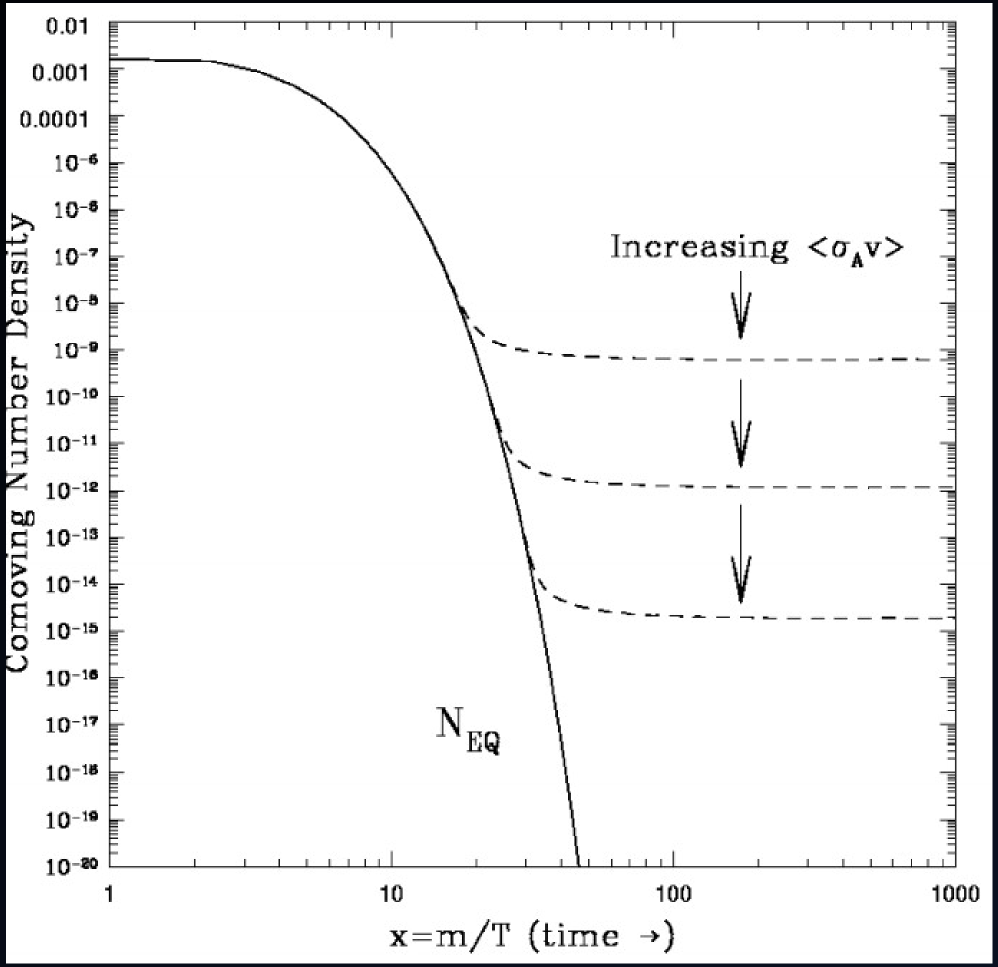
- Shape appears to be uniform throughout the Inner Galaxy





Calore et al '14

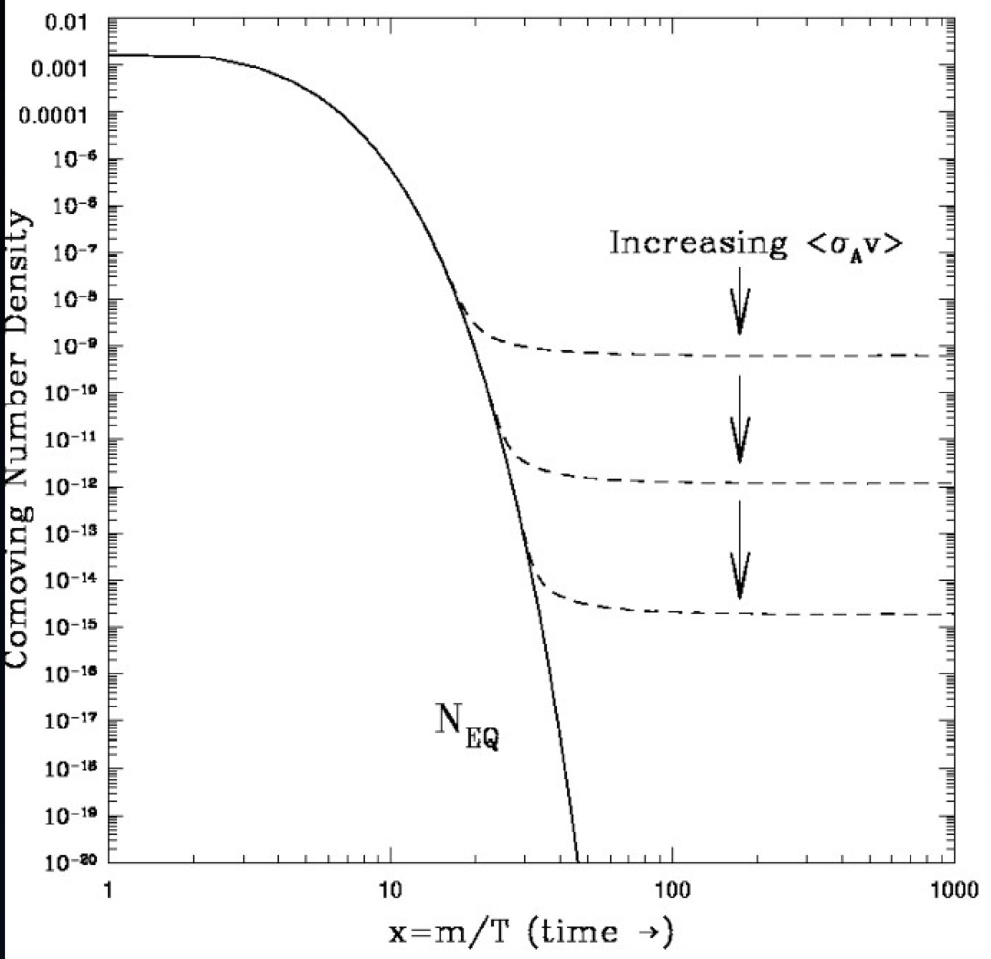
INTENSITY

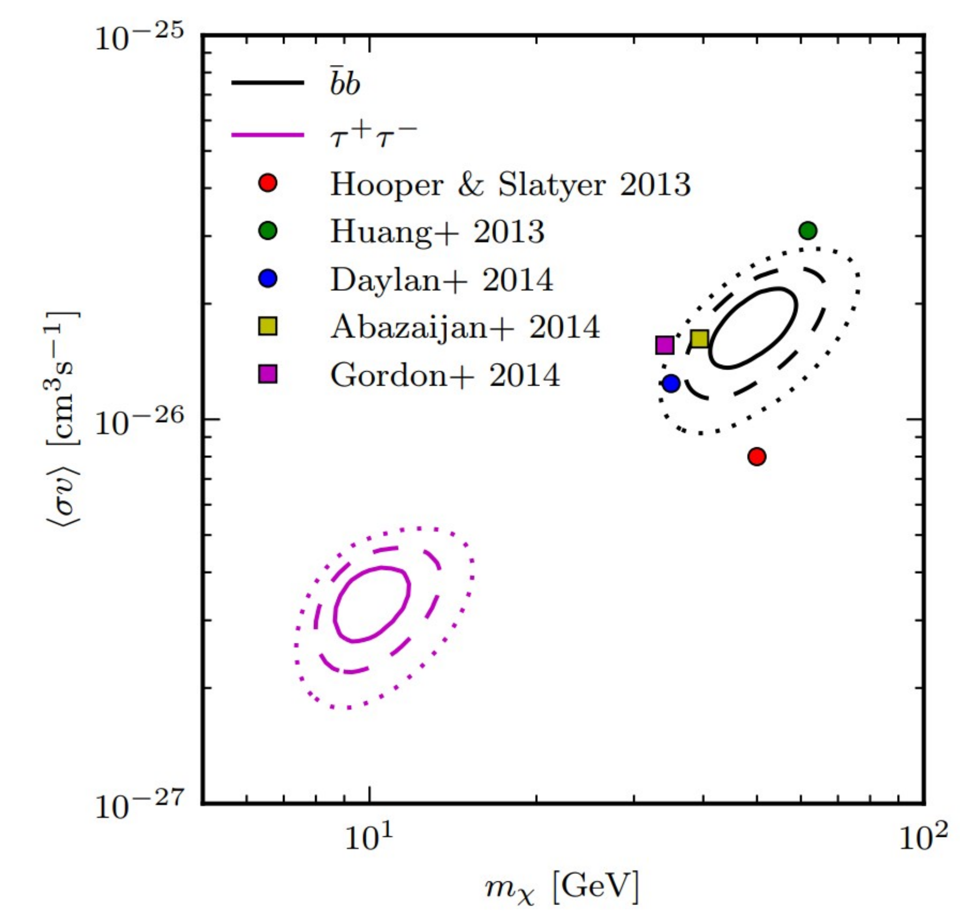


Comoving Number Density
x=m/T (time →)
Increasing <σ_Av>
N_{EQ}
0.01
0.001
0.0001
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
1
10
100
1000

DM
SM
DM
SM

INTENSITY





Calore et al '14

INTENSITY+SPECTRUM

Well fit by a ~20-60 GeV dark matter particle annihilating to hadronic final states

…with the intensity expected of thermal particle dark matter

Channel	$\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1})$	m_χ (GeV)	$\chi^2_{\min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055

Calore et al ‘14

SIGNAL OF ANNIHILATING DARK MATTER?

- Spatially consistent
  - approximately spherical
  - extending out of the center

- Intensity of thermal particle dark matter
  - can match thermal relic annihilation cross section

- Spectrum consistent: invariant with position and shape

If DM, first evidence of DM – SM interactions

2014:
A COMPELLING CASE FOR DARK MATTER

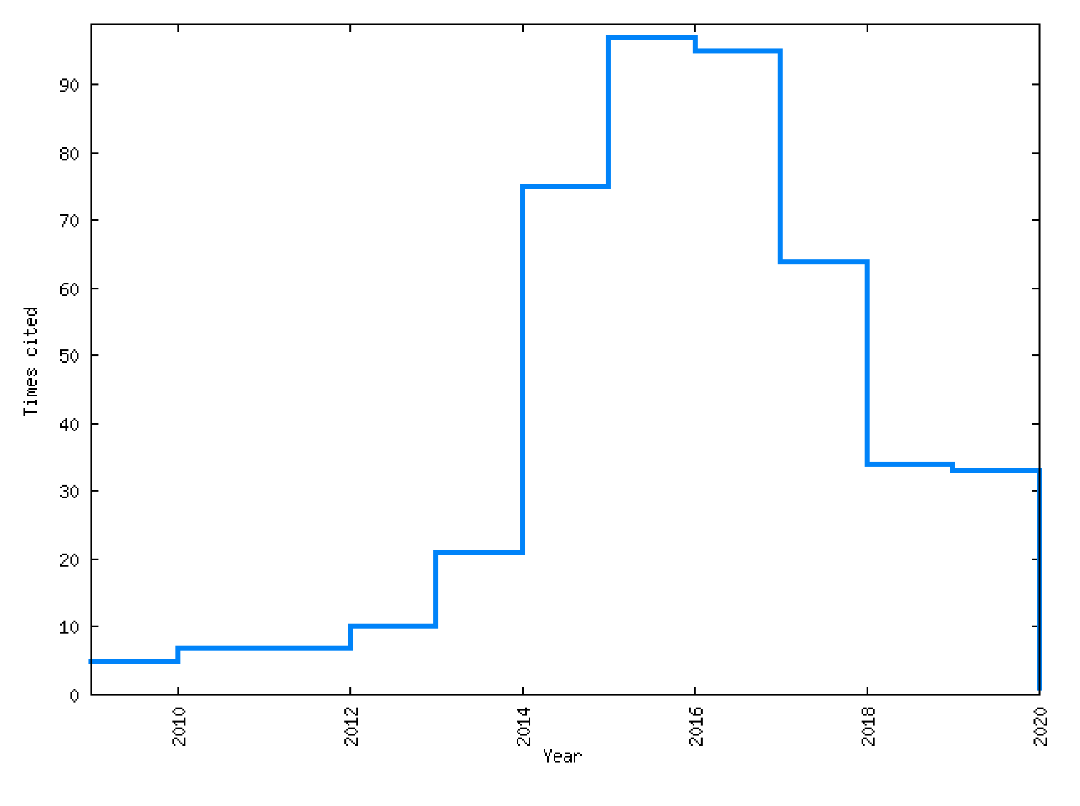
2014:
A COMPELLING CASE FOR DARK MATTER

The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

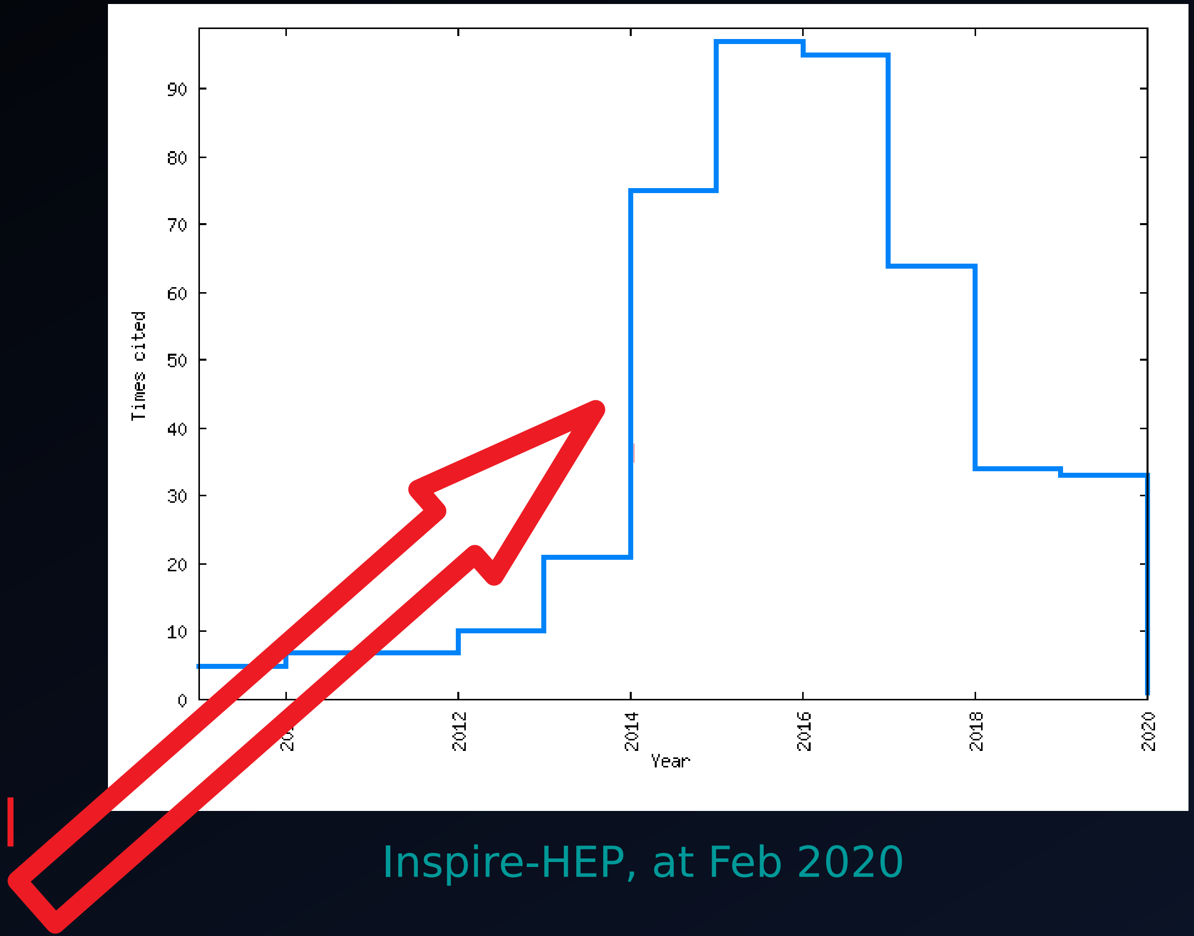
[1] *Department of Physics, Harvard University, Cambridge, MA*
[2] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA*
[3] *Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, IL*
[4] *University of Chicago, Department of Astronomy and Astrophysics, Chicago, IL*
[5] *University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL*
[6] *Center for Theoretical Physics, Massachusetts Institute of Technology, Boston, MA*
[7] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ*

HOOPER+GOODENOUGH CITATIONS



Inspire-HEP, at Feb 2020

HOOPER+GOODENOUGH CITATIONS



Daylan et al comes out

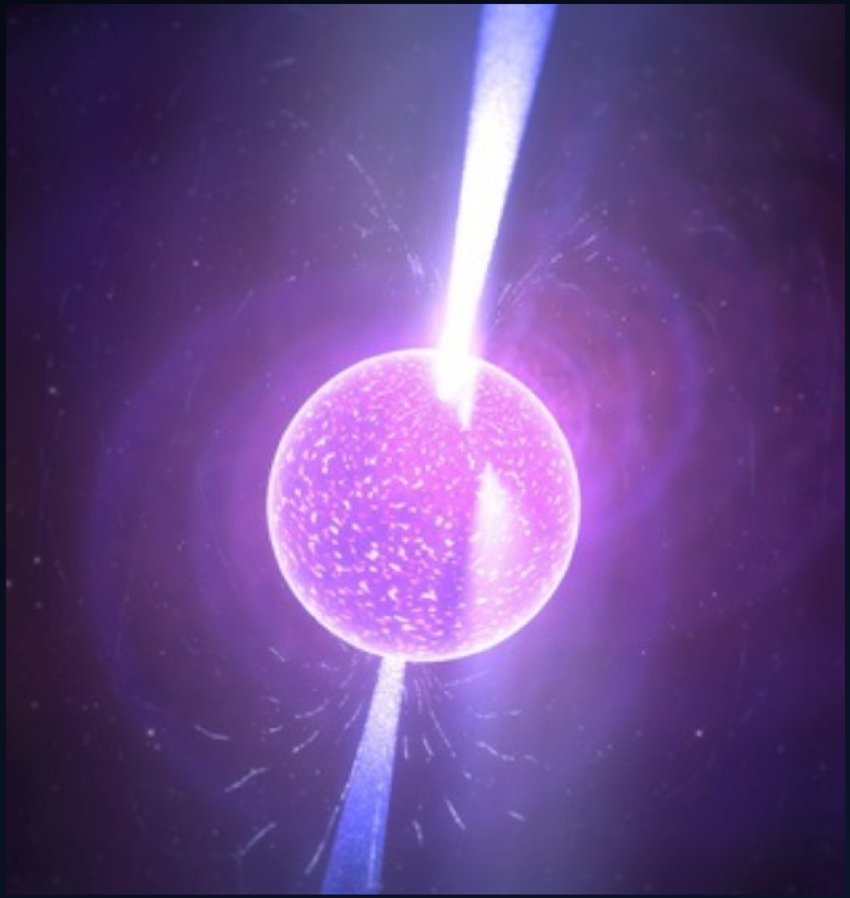
Inspire-HEP, at Feb 2020

2015

PULSARS AS THE EXCESS

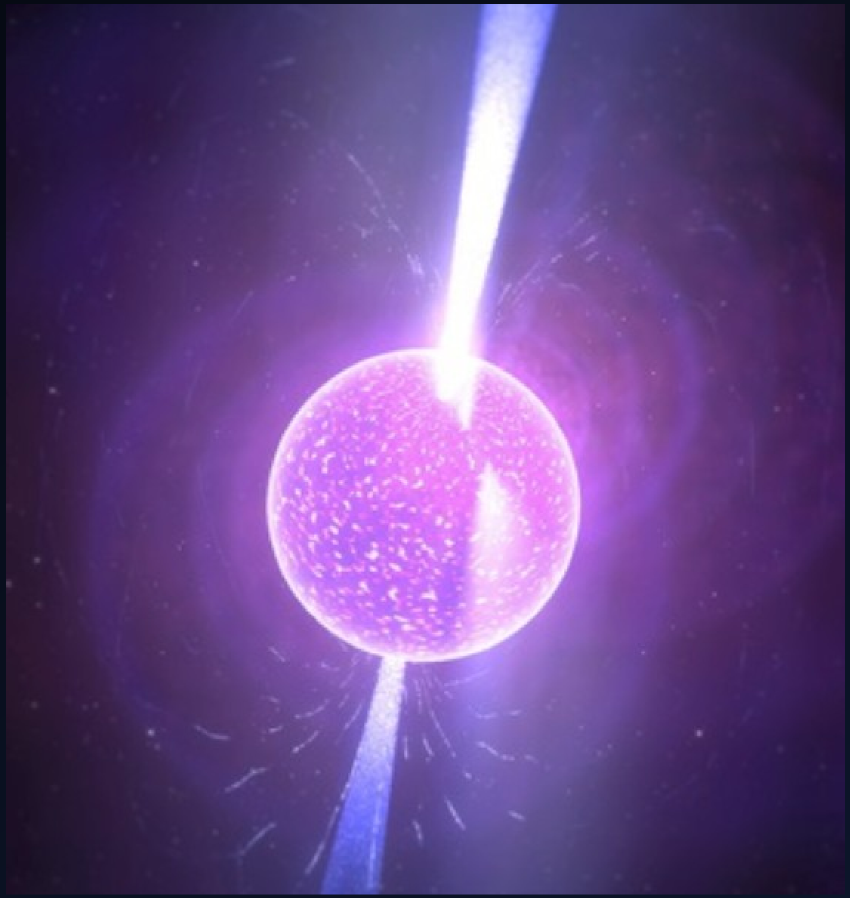
- Pulsars are old, rapidly spinning neutron stars

- Pulsars also match the gamma-ray energy spectrum



PULSARS AS THE EXCESS

- Pulsars are old, rapidly spinning neutron stars
- Pulsars also match the gamma-ray energy spectrum
- Pulsars appear as point sources to Fermi, which mean they have angular extent below detector thresholds



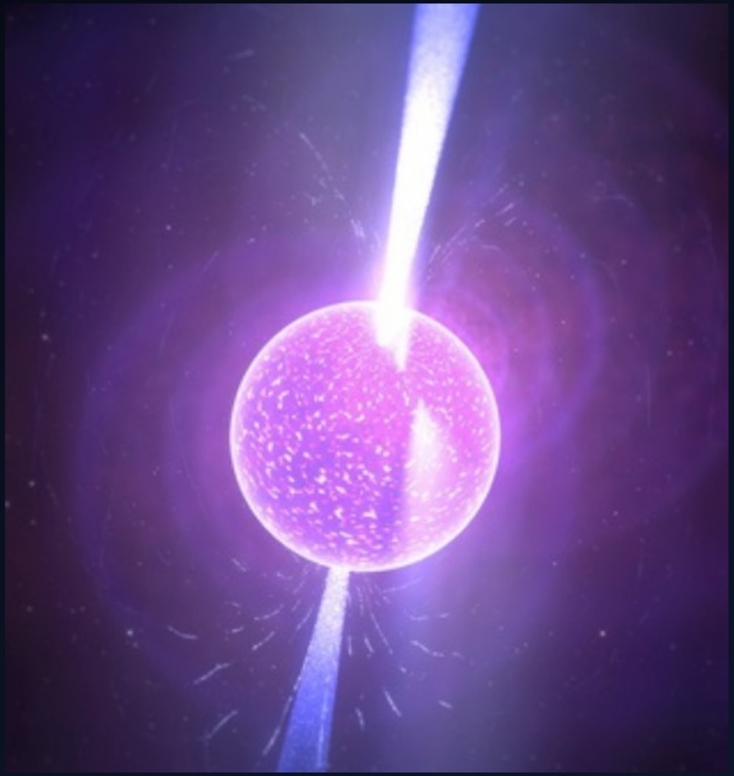
POINT SOURCES AS THE EXCESS

- Resolved Point Sources:

  Bright enough to be individually detected

- Unresolved Point Sources:

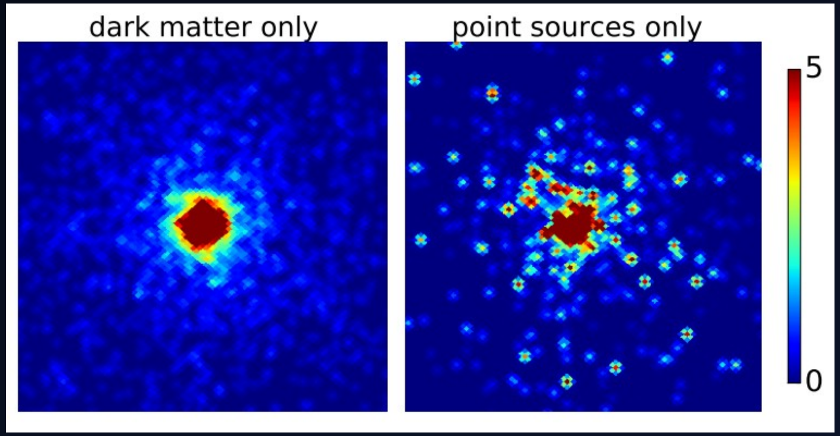
  Too dim to be individually detected, cannot be individually resolved, but collectively could explain GCE



DISTINGUISHING DM vs. POINT SOURCES

Counts of gamma rays from PS exhibit different statistical behavior compared to those from annihilating DM:

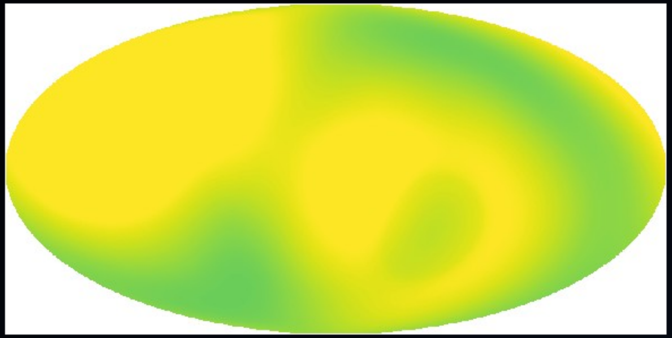
- DM: smooth continuous halo in the Galaxy
  - Follows Poisson statistics
- PS: individual sources, clumpy
  - Follows Non-Poisson statistics, complex to characterize



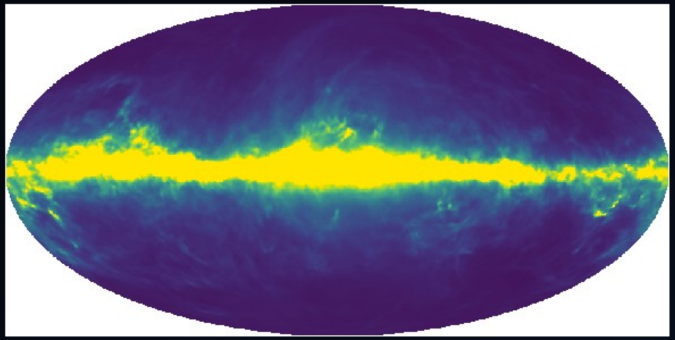
Lee+Lisanti+Safdi, ‘15

Drastically different predictions!

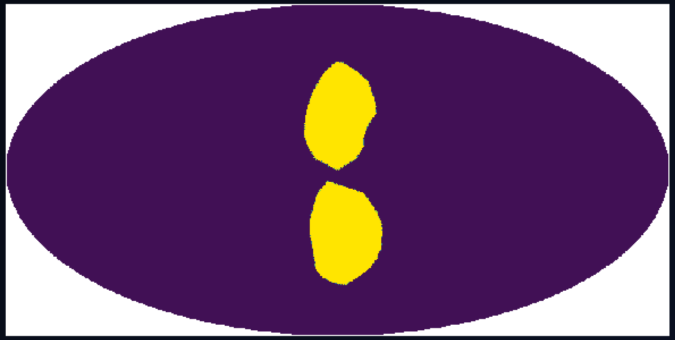
TEMPLATE FITTING



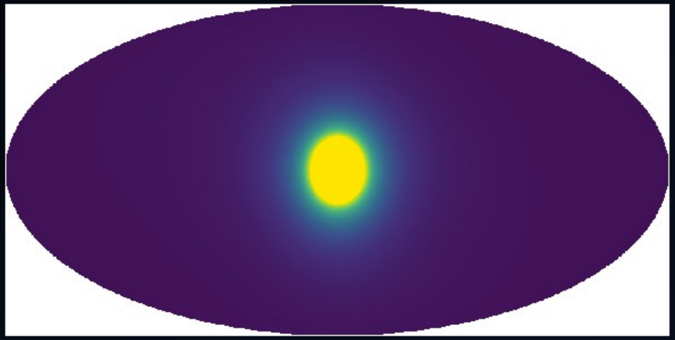
Isotropic



Diffuse



Bubbles



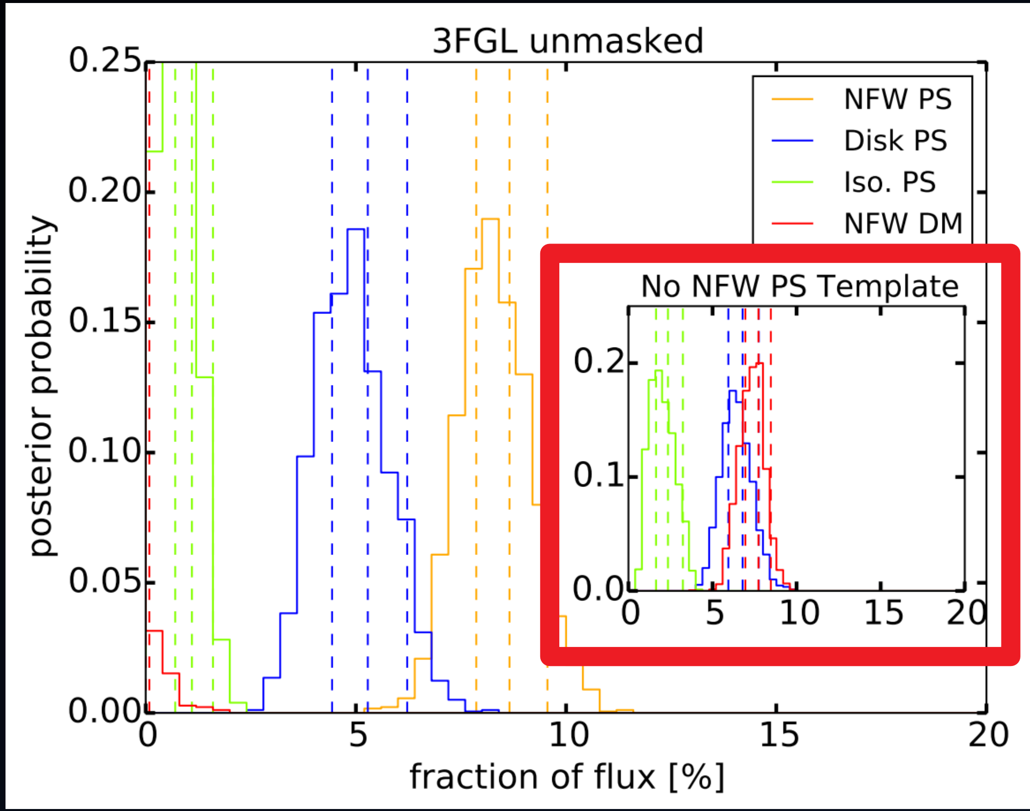
NFW

Assign statistics to each template.

Exploit different statistical predictions, along different spatial distributions

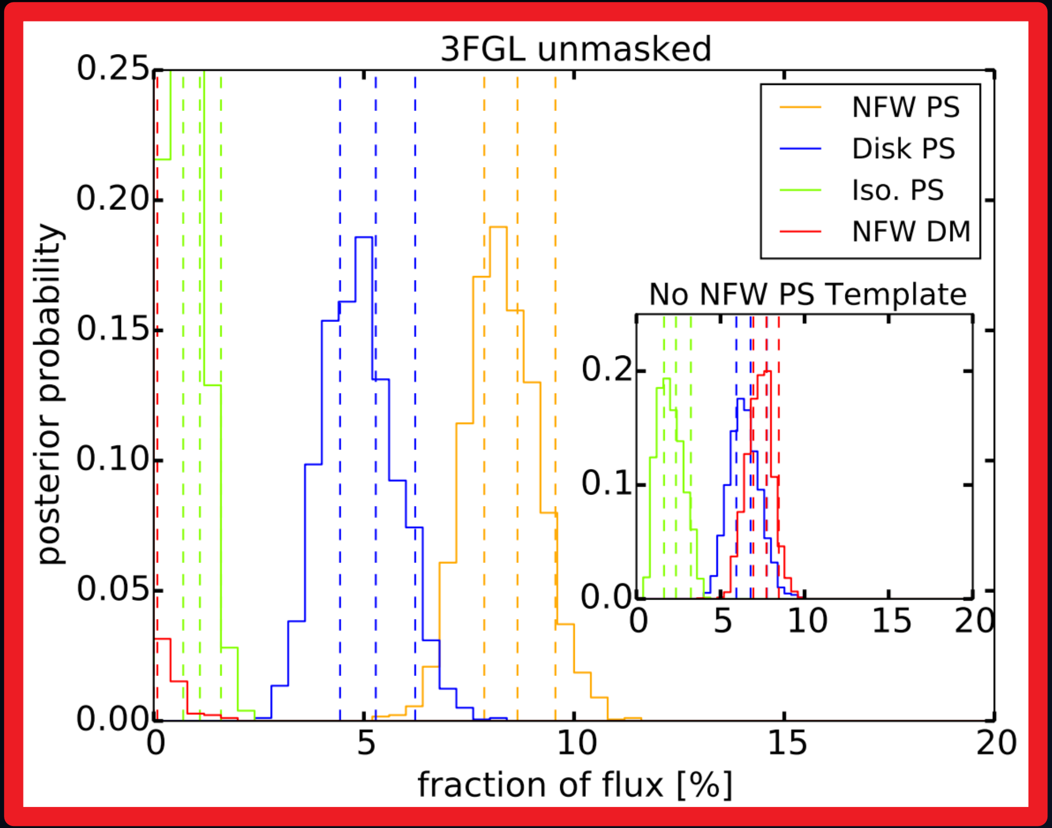
Distinguish the origin of the excess gamma rays.

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



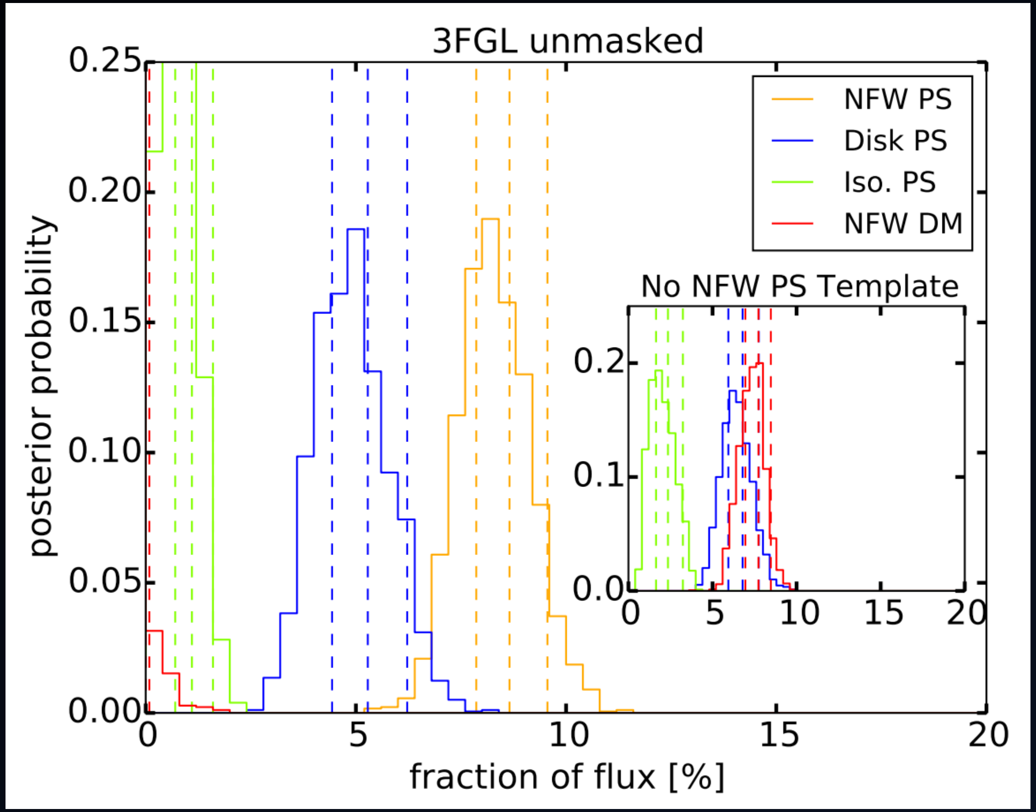
Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

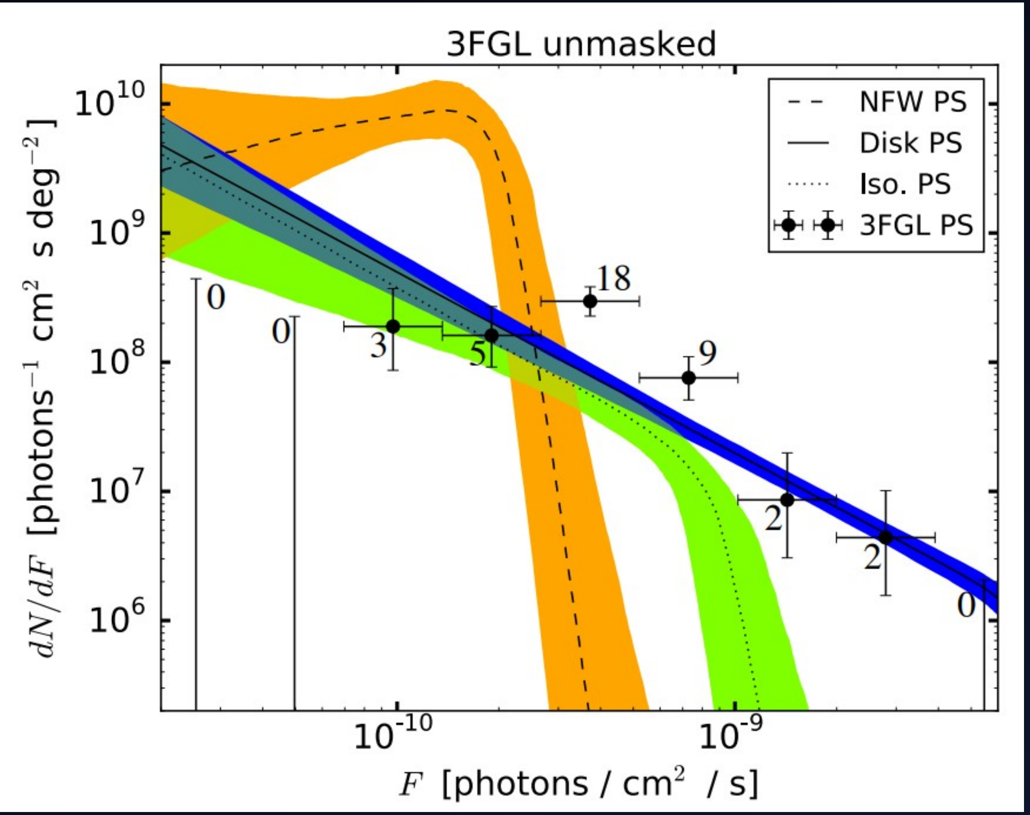
EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



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

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER

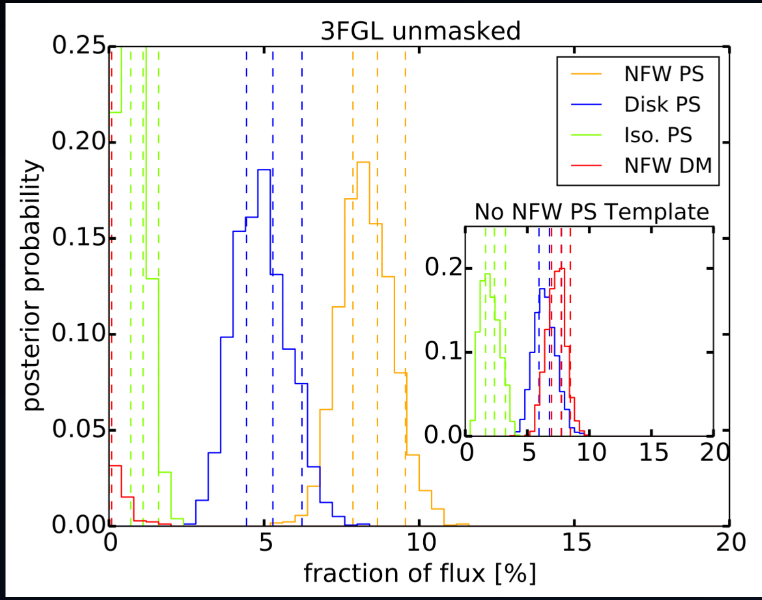




Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER

1.

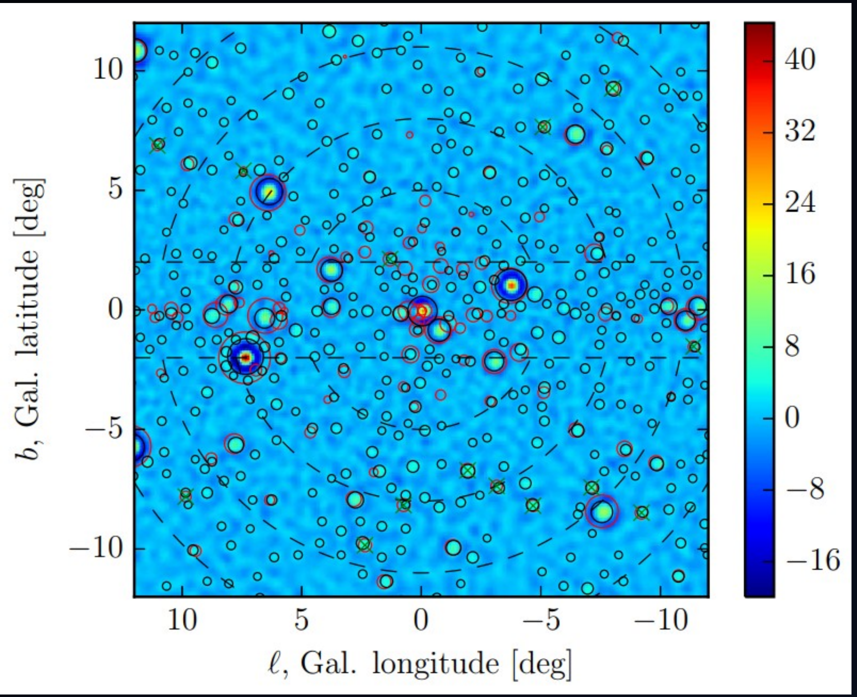


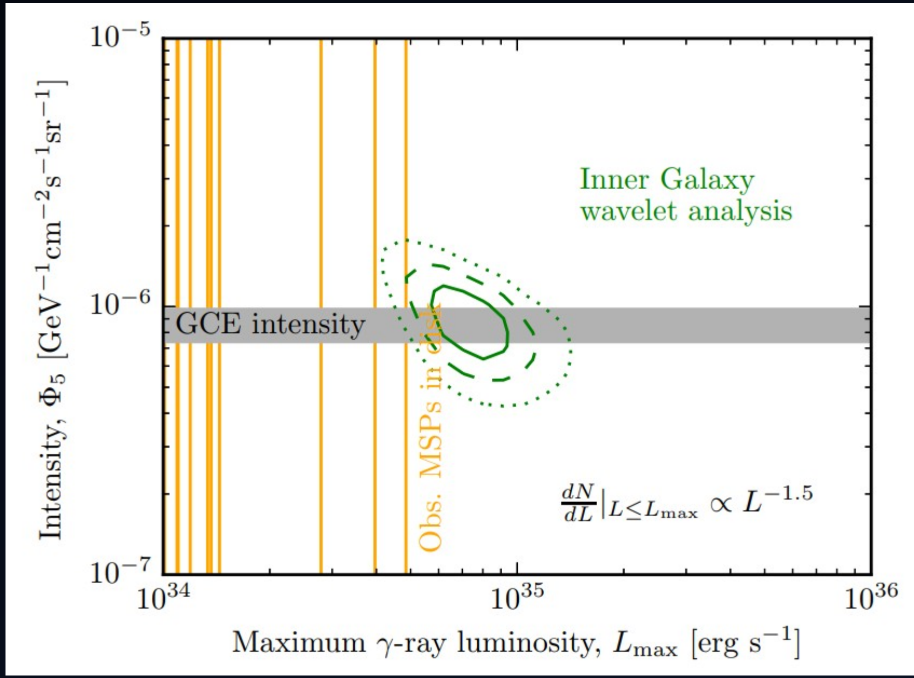
Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

2.

Also in 2015...

WAVELET METHOD: AGREEMENT



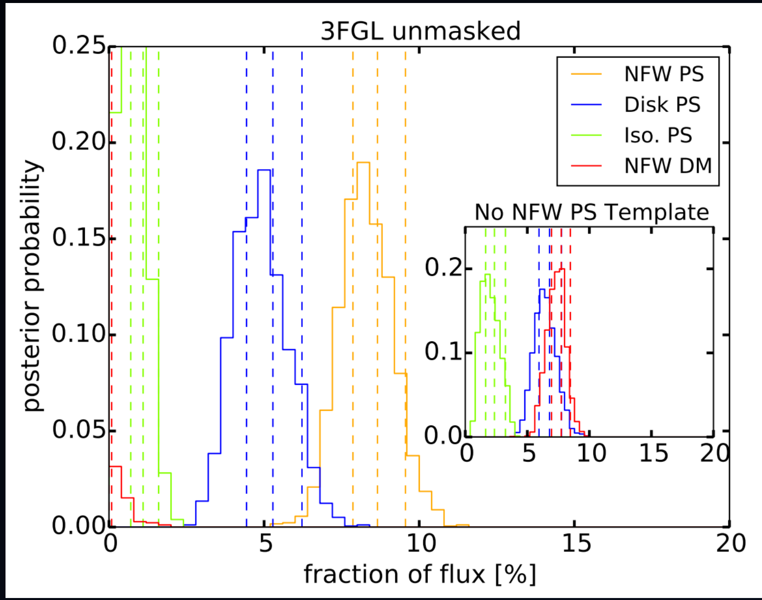


Detection of clustering of photons, consistent with a
new population of millisecond pulsars with the intensity of excess

Bartels, Krishnamurthy, Weniger (PRL ’15)

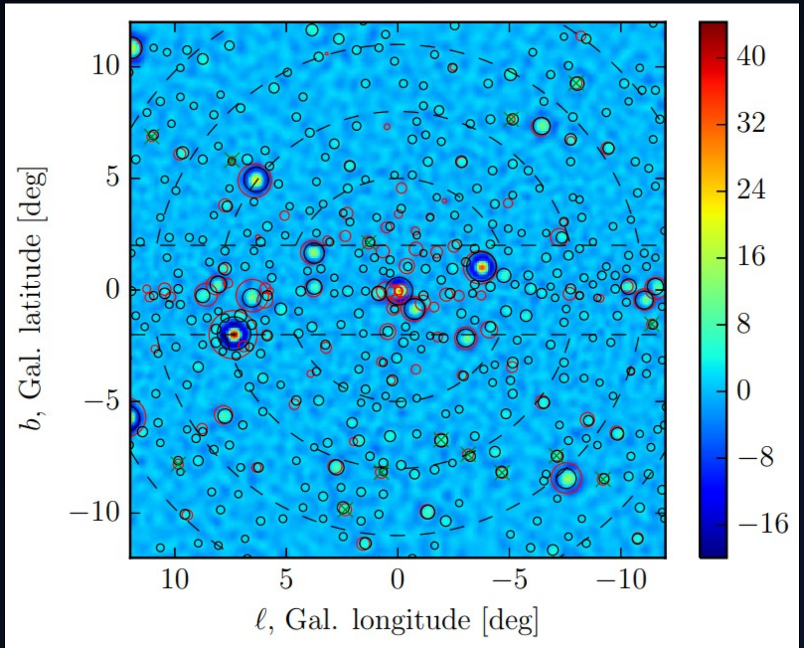
EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER

1.



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

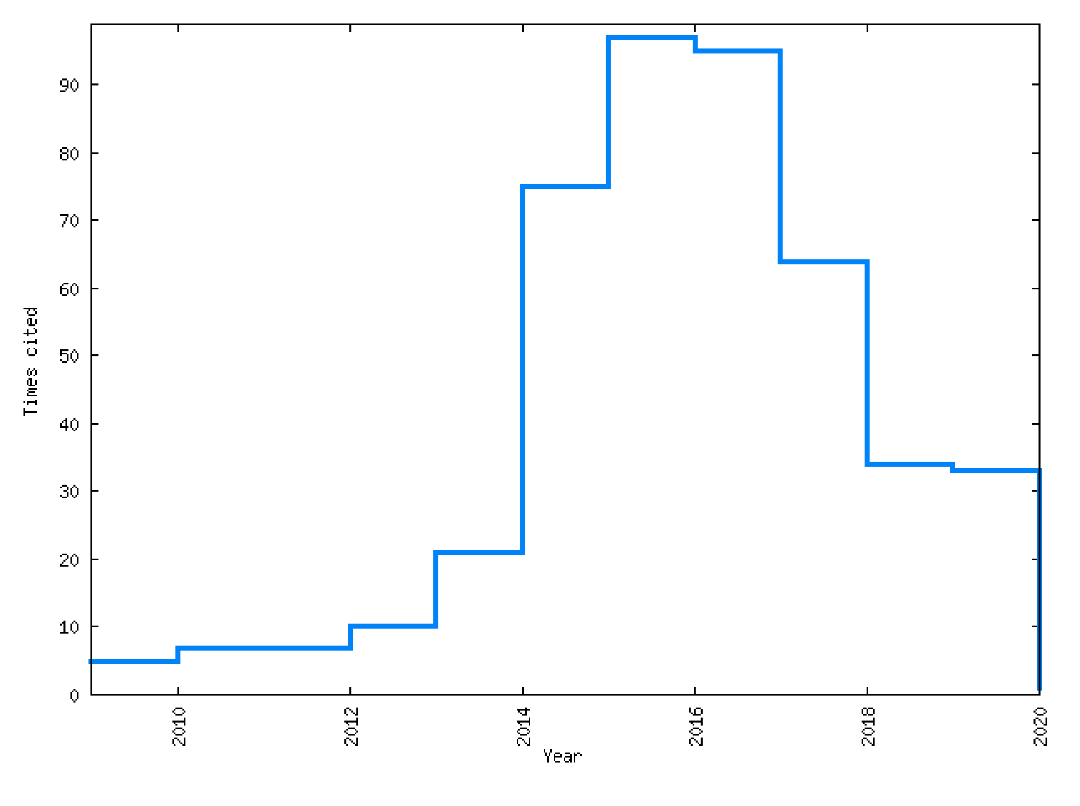
2.



Bartels, Krishnamurthy, Weniger (PRL ’15)

2016-2018:
REIGN OF THE PULSARS

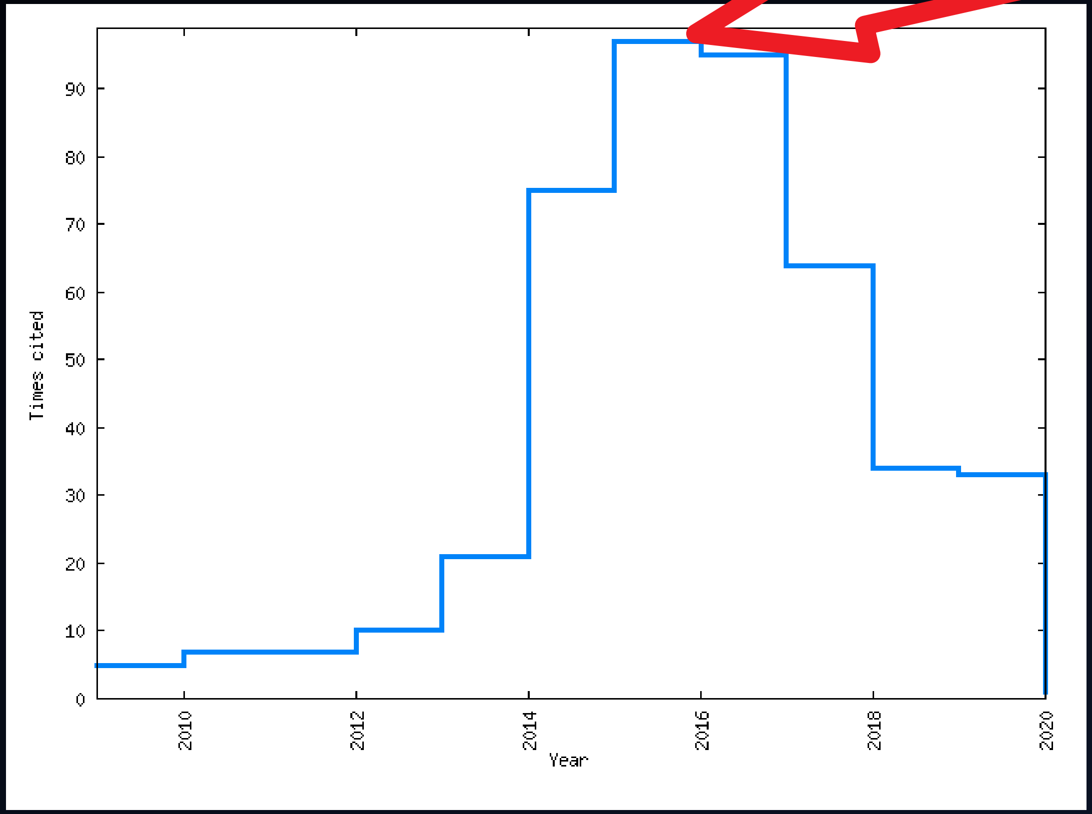
HOOPER+GOODENOUGH CITATIONS



Inspire-HEP, at Feb 2020

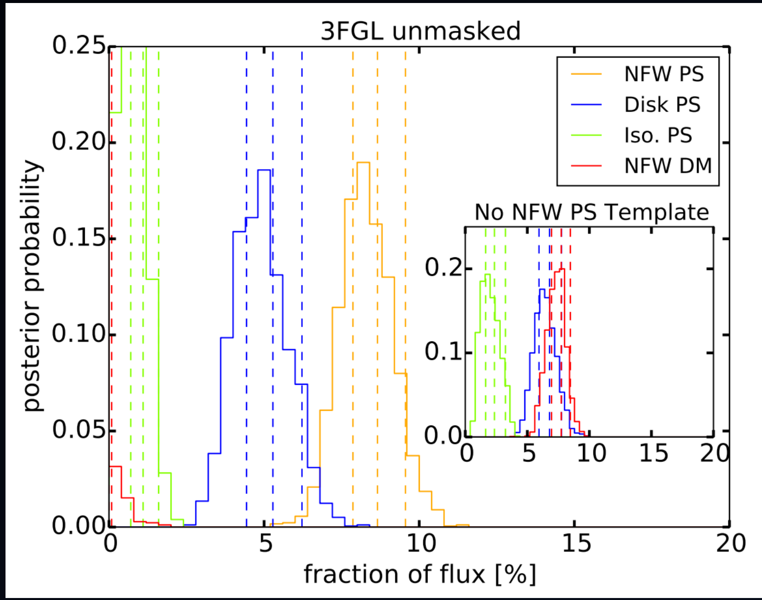
HOOPER+GOODENOUGH CITATIONS

Pulsar papers come out

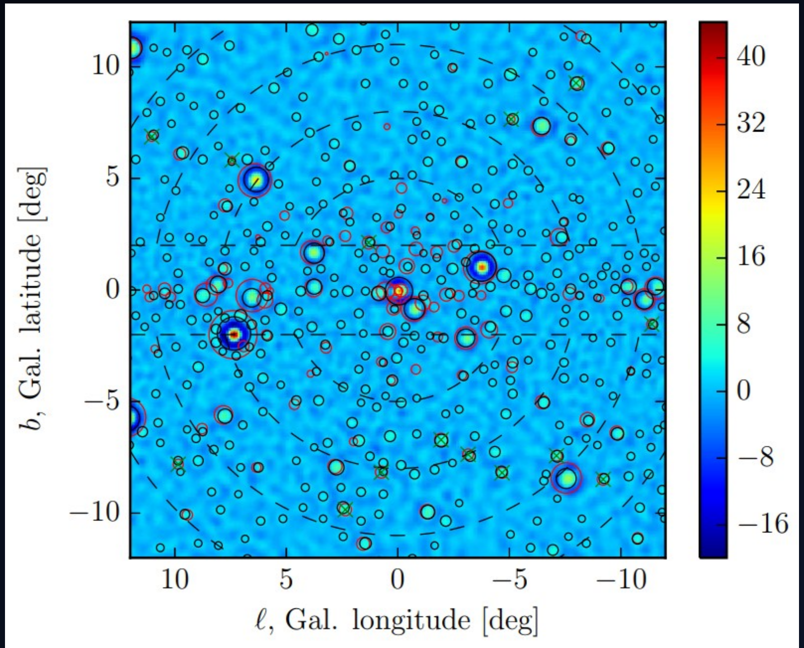


Inspire-HEP, at Feb 2020

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER

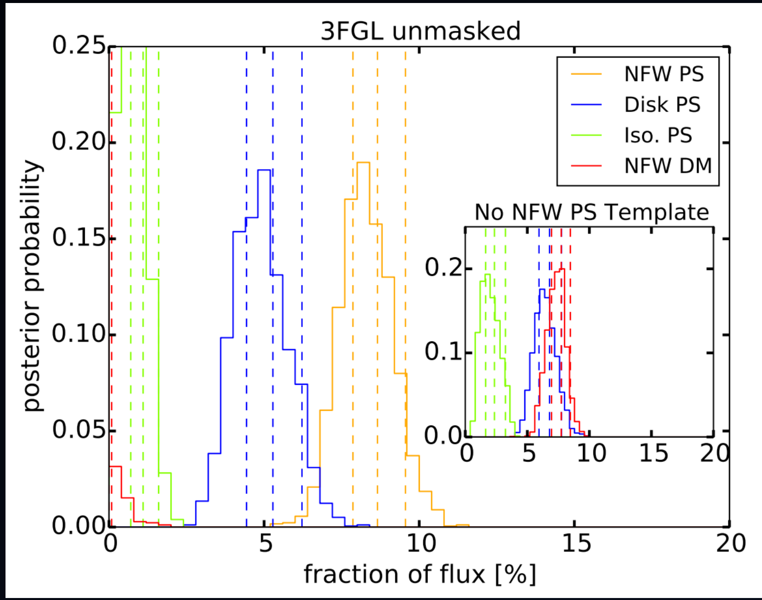


Lee, Lisanti, Safdi, Slatyer, Xue (PRL ‘15)

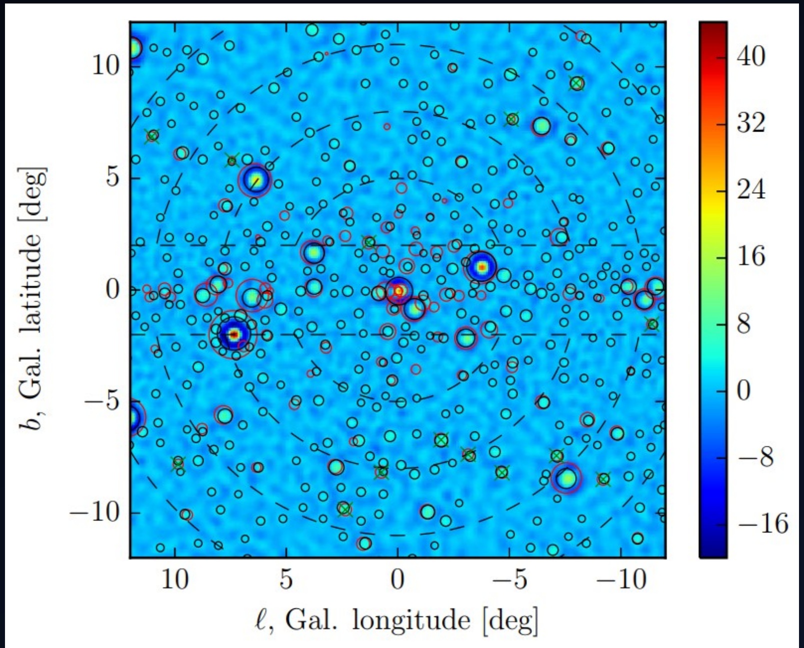


Bartels, Krishnamurthy, Weniger (PRL ’15)

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



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



Bartels, Krishnamurthy, Weniger (PRL '15)

2019

WHAT IS DRIVING THIS PREFERENCE?

If there are some point sources present,
but **not** following one of these templates, could this:

\+ **push up** the point source signal found with the current templates
and
\- **push down** the inferred dark matter signal?

RL+Slatyer (PRL '19)

WHAT IS DRIVING THIS PREFERENCE?

If there are some point sources present,
but **not** following one of these templates, could this:

+ **push up** the point source signal found with the current templates
and
- **push down** the inferred dark matter signal?

Investigate if a bias is possible:

1. In a simulated proof-of-principle scenario
2. In the real Fermi data

RL+Slatyer (PRL '19)

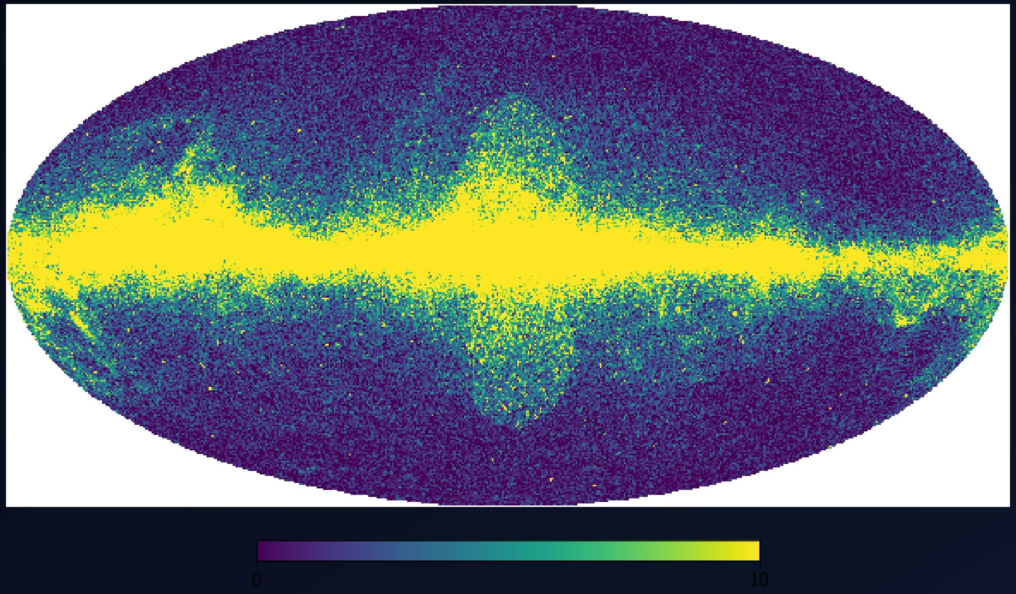
BIAS SEARCH USING SIMULATED DATA

Simulate:

- Point Sources: along the Galactic Disk and Bubbles

  Bubbles are the new ingredient, which we simulate as a possible source of bias

- Smooth emission: from isotropic+diffuse background, bubbles, and dark matter.

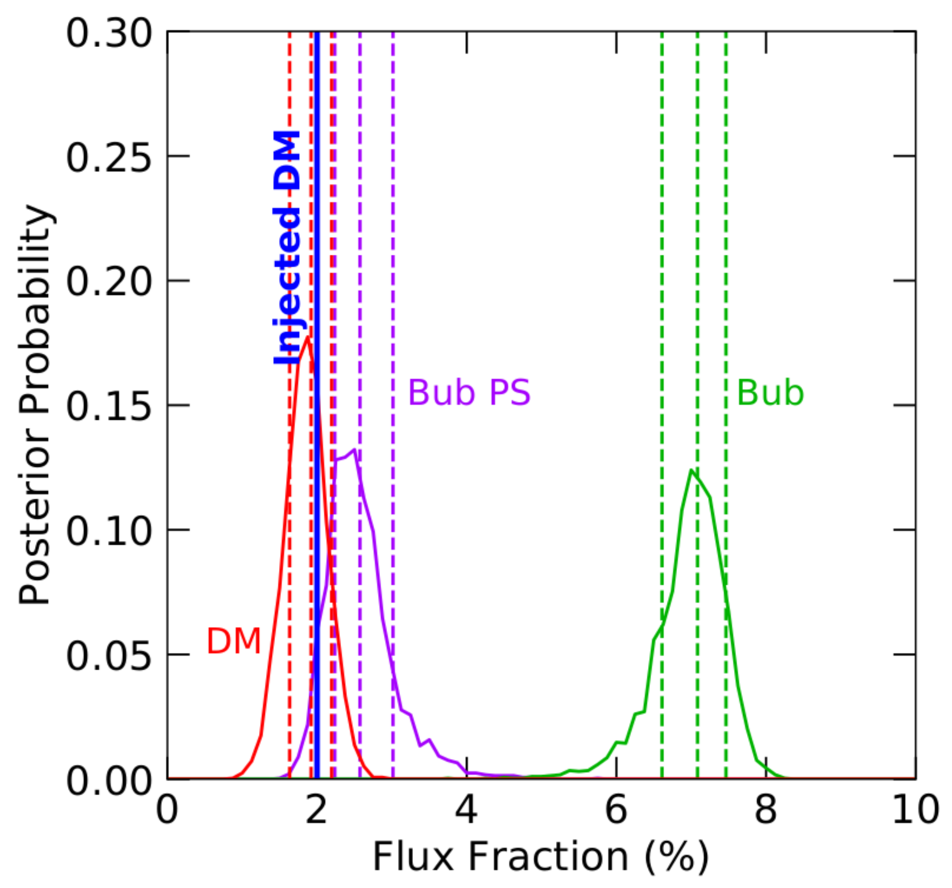


RL+Slatyer (PRL '19)

Analyze this data, with exactly the same templates.

Analyze this data, with exactly the same templates.

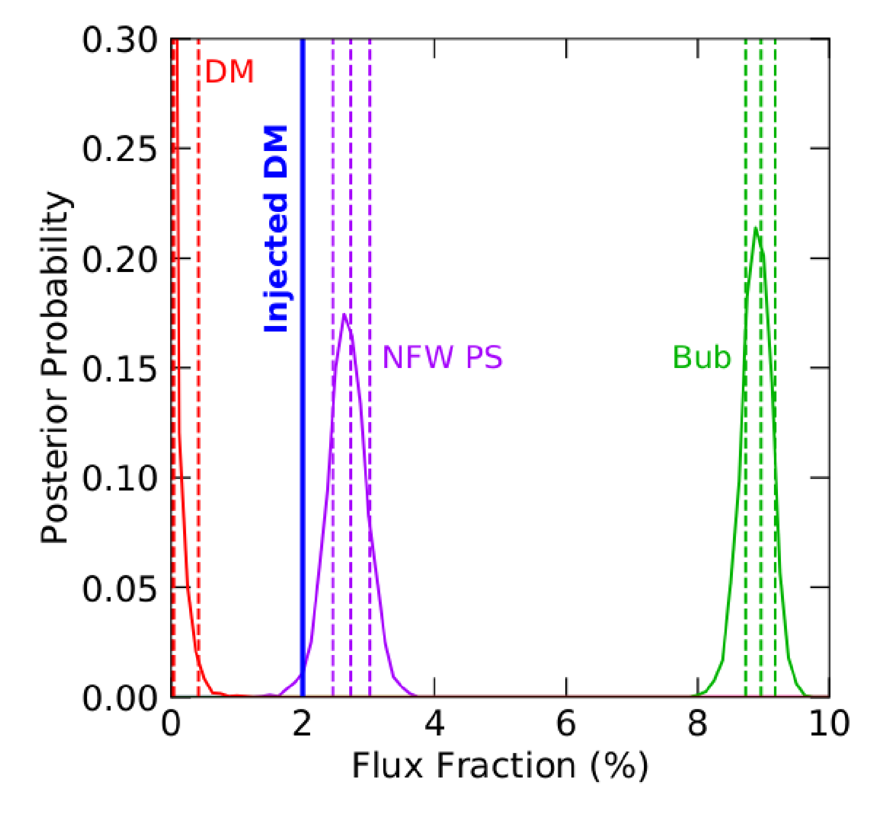
Return same normalizations.



RL+Slatyer (PRL '19)

What if we now instead analyze the data with NFW distributed PS instead of the PS bubbles?

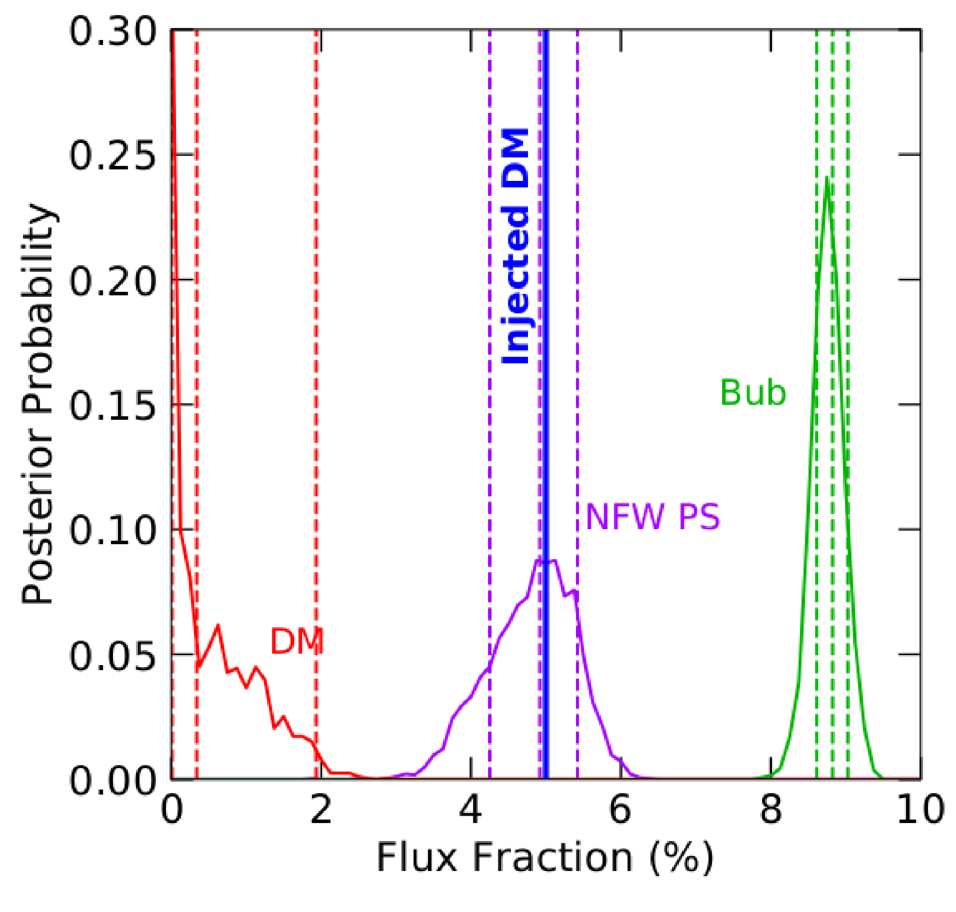
What if we now instead analyze the data with NFW distributed PS instead of the PS bubbles?



The dark matter signal is misattributed to point sources!

RL+Slatyer (PRL '19)

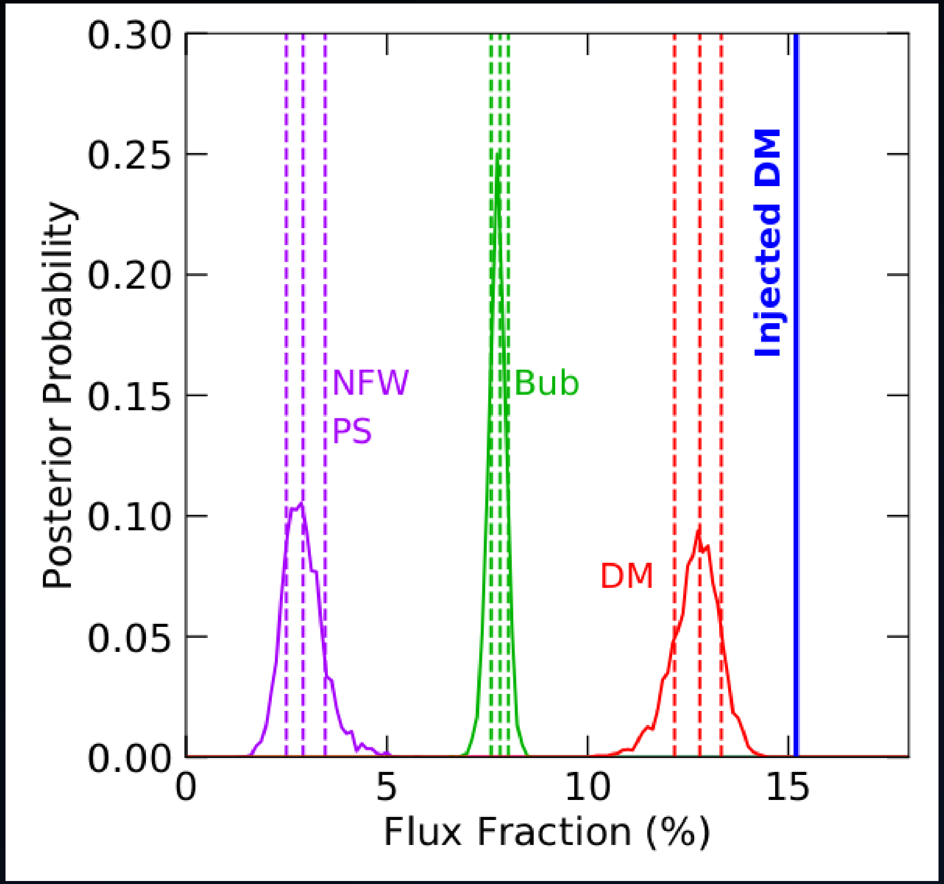
Add even more....



The dark matter signal is misattributed to point sources!

RL+Slatyer (PRL '19)

IS THERE A THRESHOLD IN SIMULATIONS?



Inject an order of magnitude more DM (~15%)

Takes this much to reconstruct DM, but still not all of it

RL+Slatyer (PRL '19)

EVIDENCE OF MISATTRIBUTED DM

- Cross talk between templates appears to be possible, when an unmodelled component is present
- Large Bayes factor preference for adding NFW PS, and pushing DM flux down, just like Lee at al ‘15 paper

…and in this case we KNOW dark matter is there!

RL+Slatyer (PRL ‘19)

ARE THERE BUBBLES POINT SOURCES?

- No evidence
- Serves as proof-of-principle example of mismodeling impact

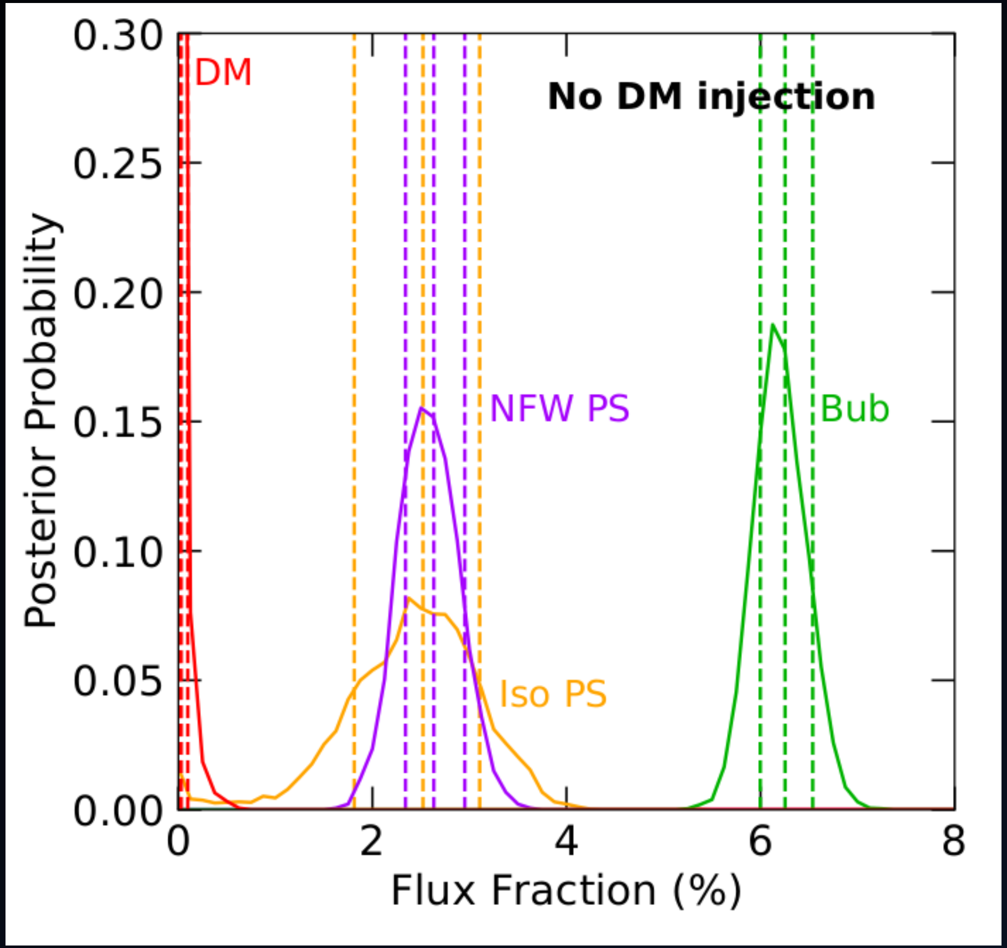
TESTING WITH THE REAL FERMI DATA

If this effect is present, template likely not saturated in its ability to absorb dark matter flux.

Inject a fake dark matter signal into the Fermi data.

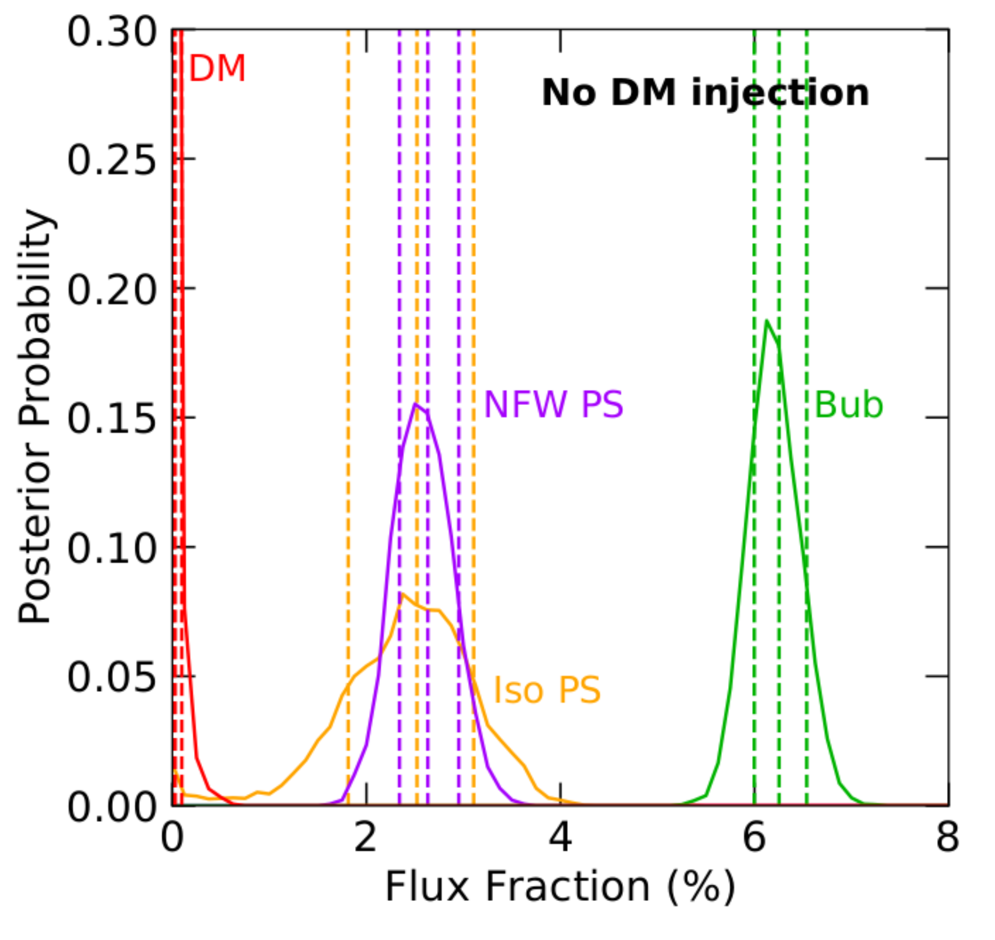
FERMI DATA

INJECTED DM SIGNAL + DATA

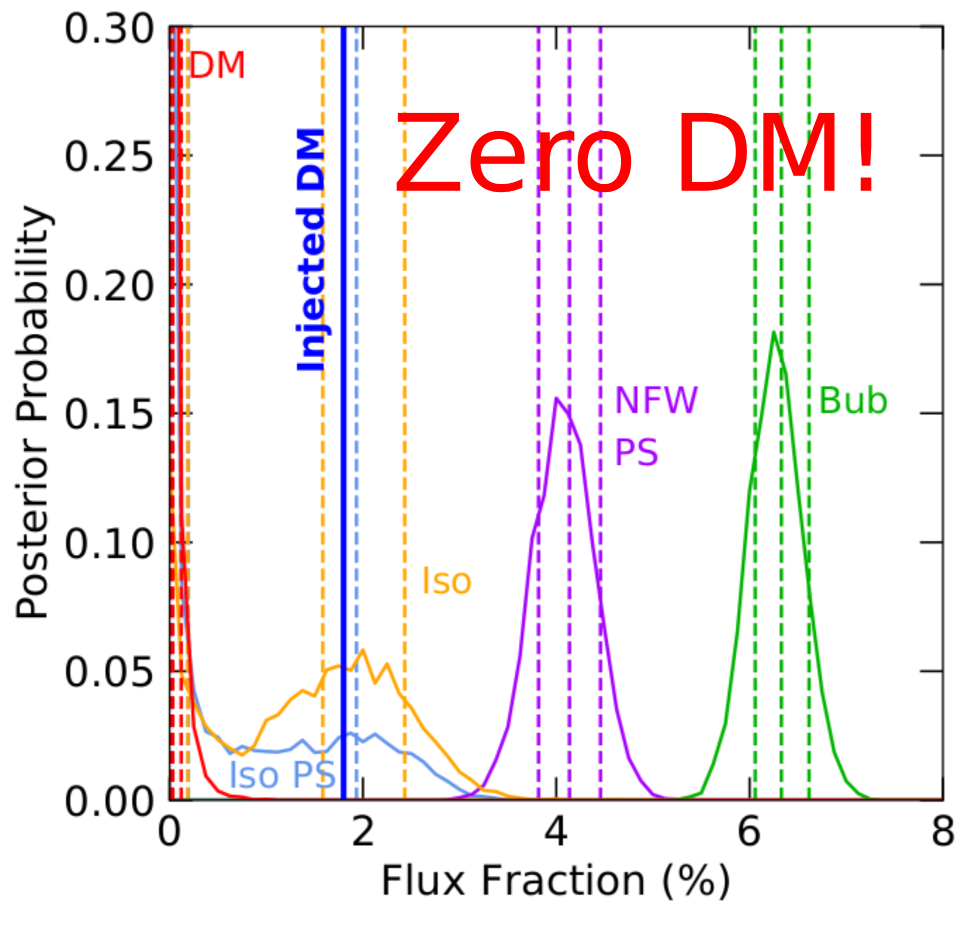


RL+Slatyer (PRL '19)

FERMI DATA



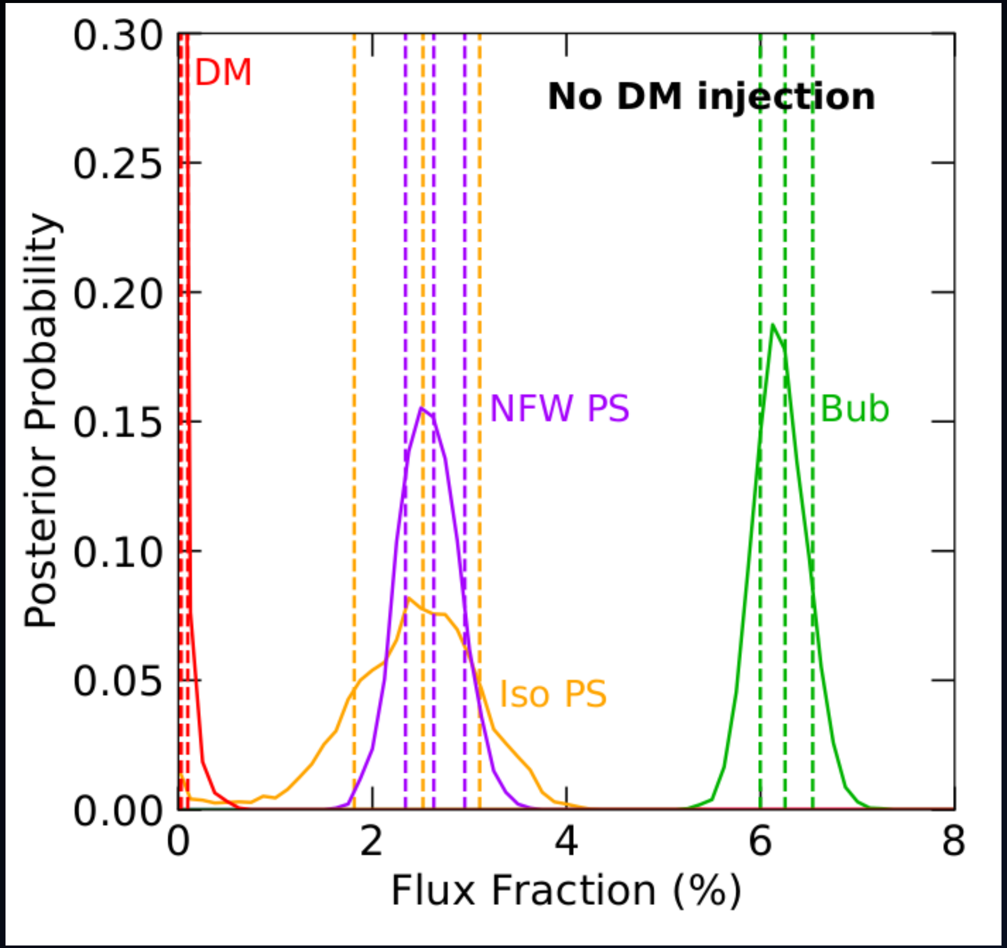
INJECTED DM SIGNAL + DATA



RL+Slatyer (PRL '19)

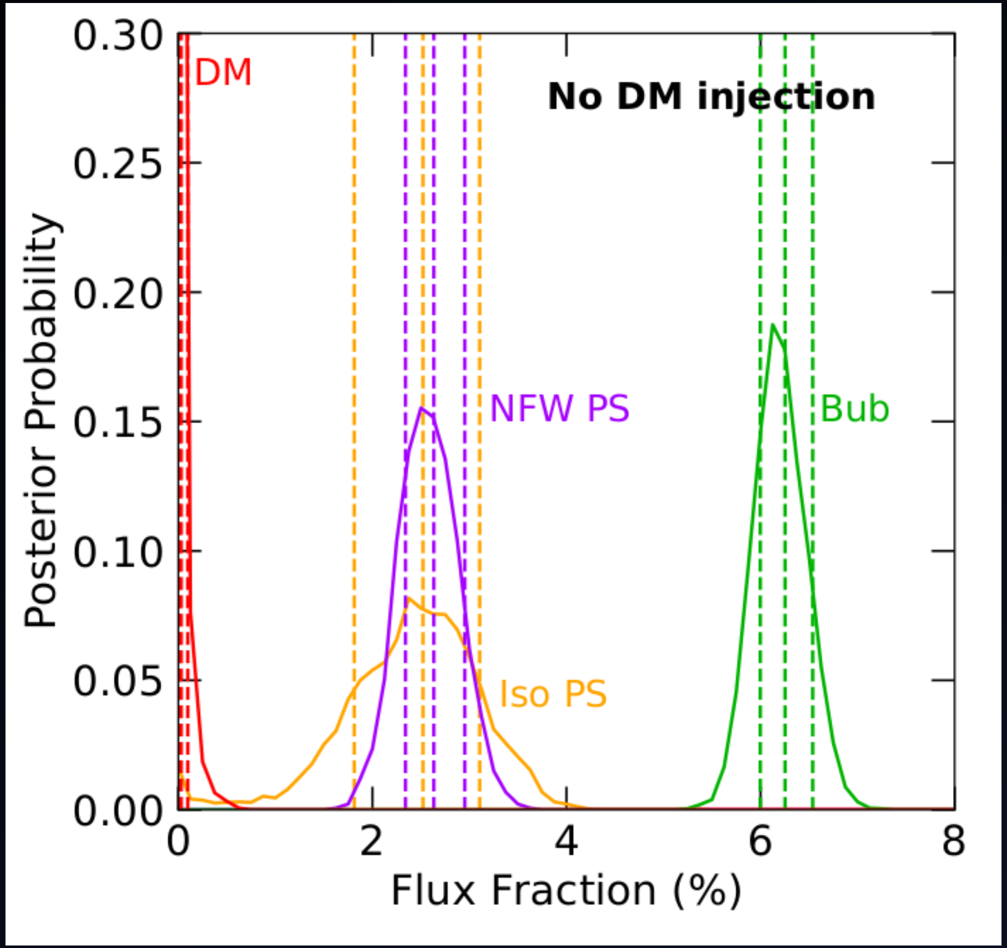
FERMI DATA

LARGER INJECTED DM SIGNAL + DATA

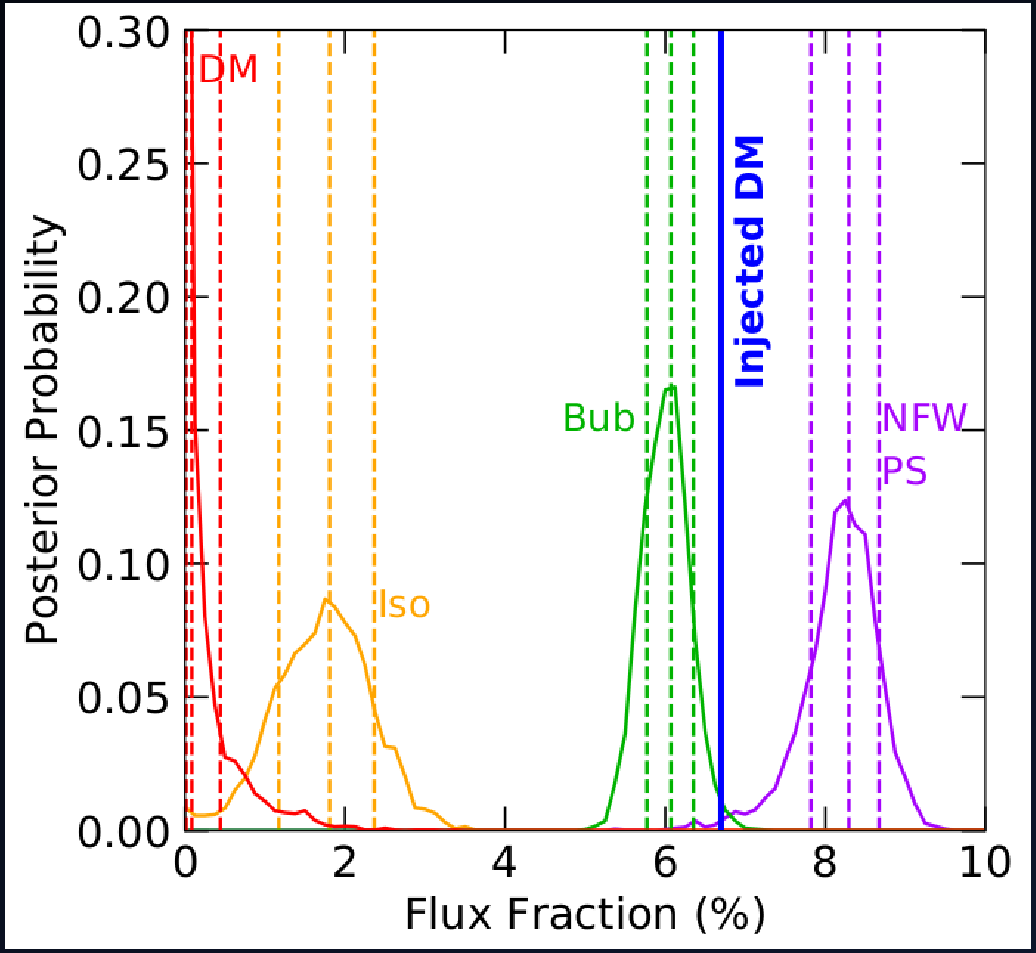


RL+Slatyer (PRL '19)

FERMI DATA



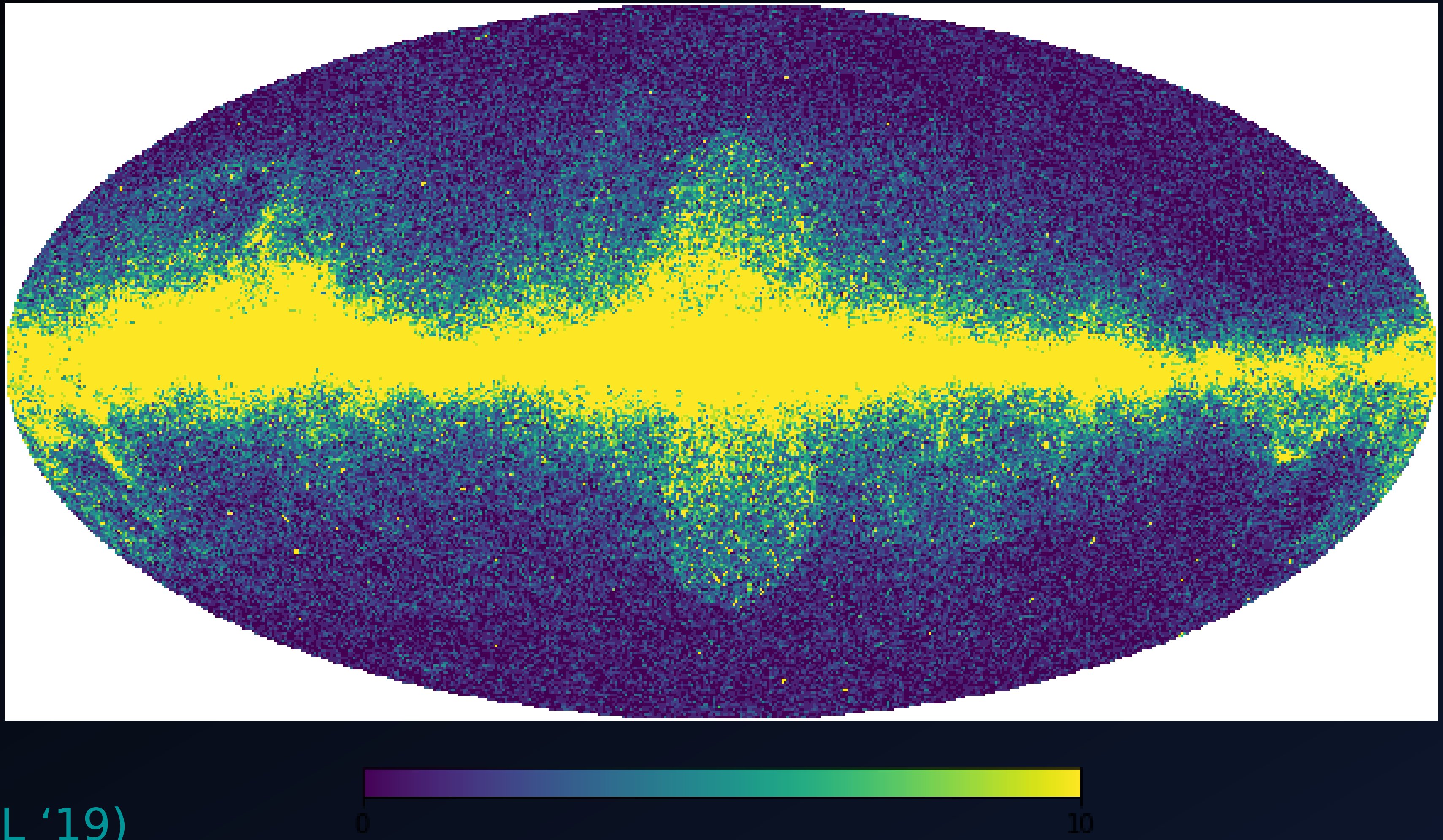
LARGER INJECTED DM SIGNAL + DATA



Zero DM!

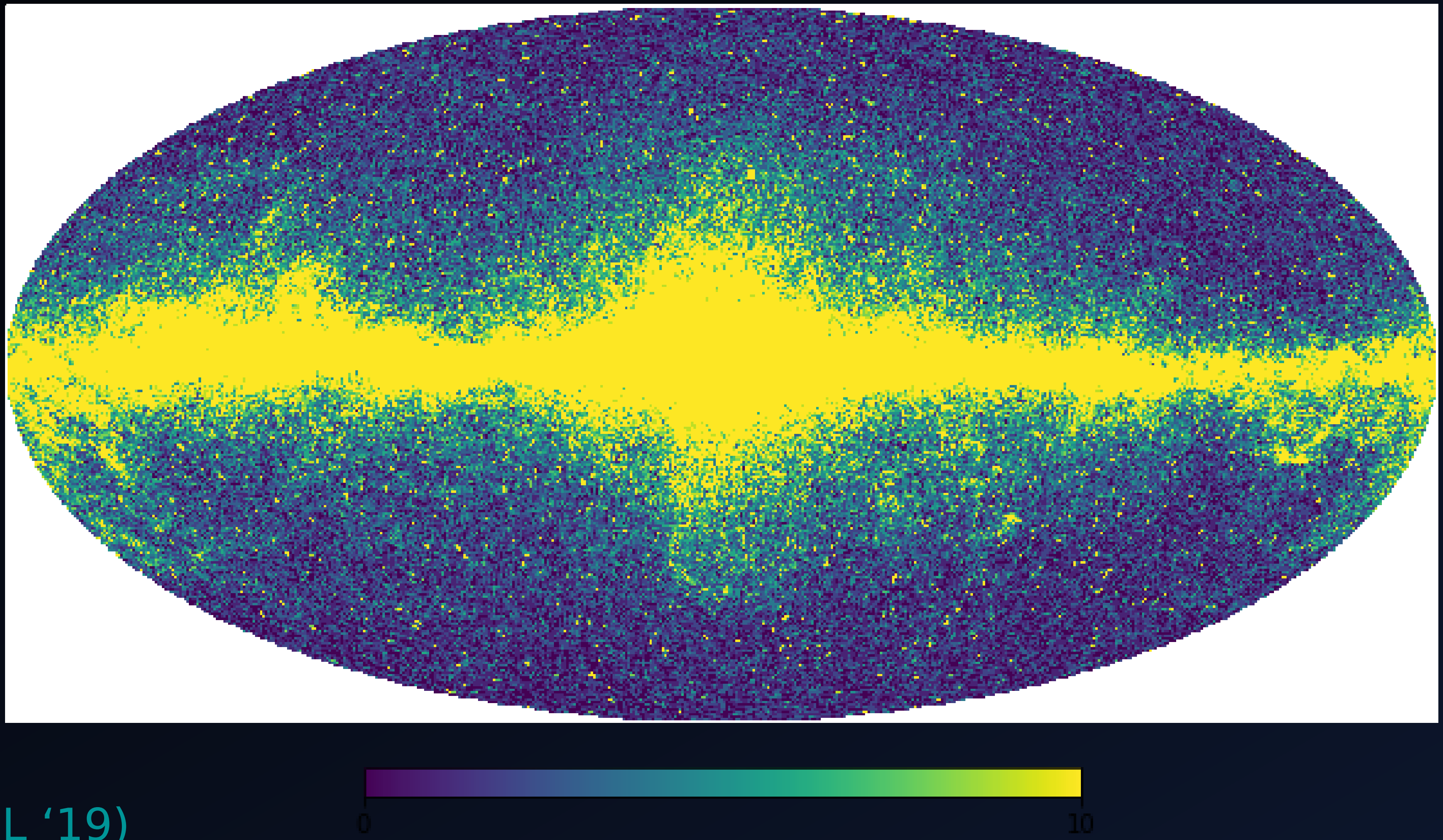
RL+Slatyer (PRL '19)

BOMBARD THE GALAXY!



RL+Slatyer (PRL ‘19)

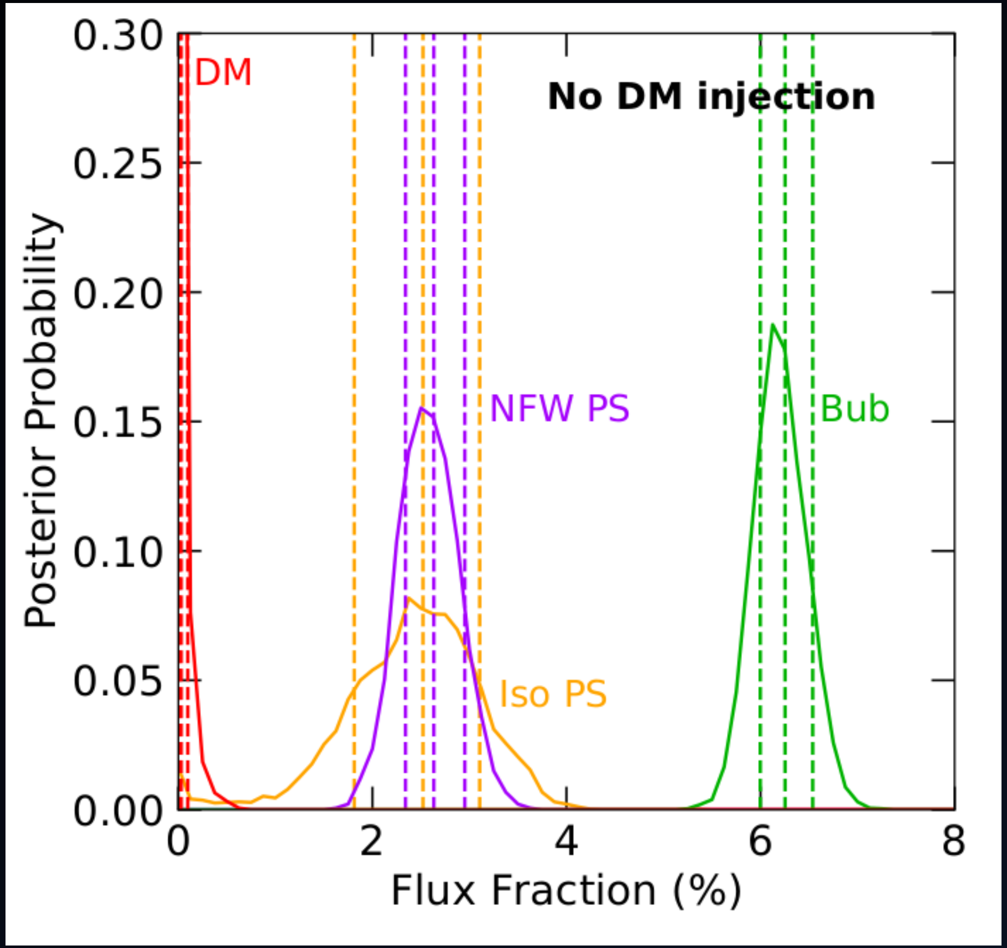
BOMBARD THE GALAXY!



RL+Slatyer (PRL '19)

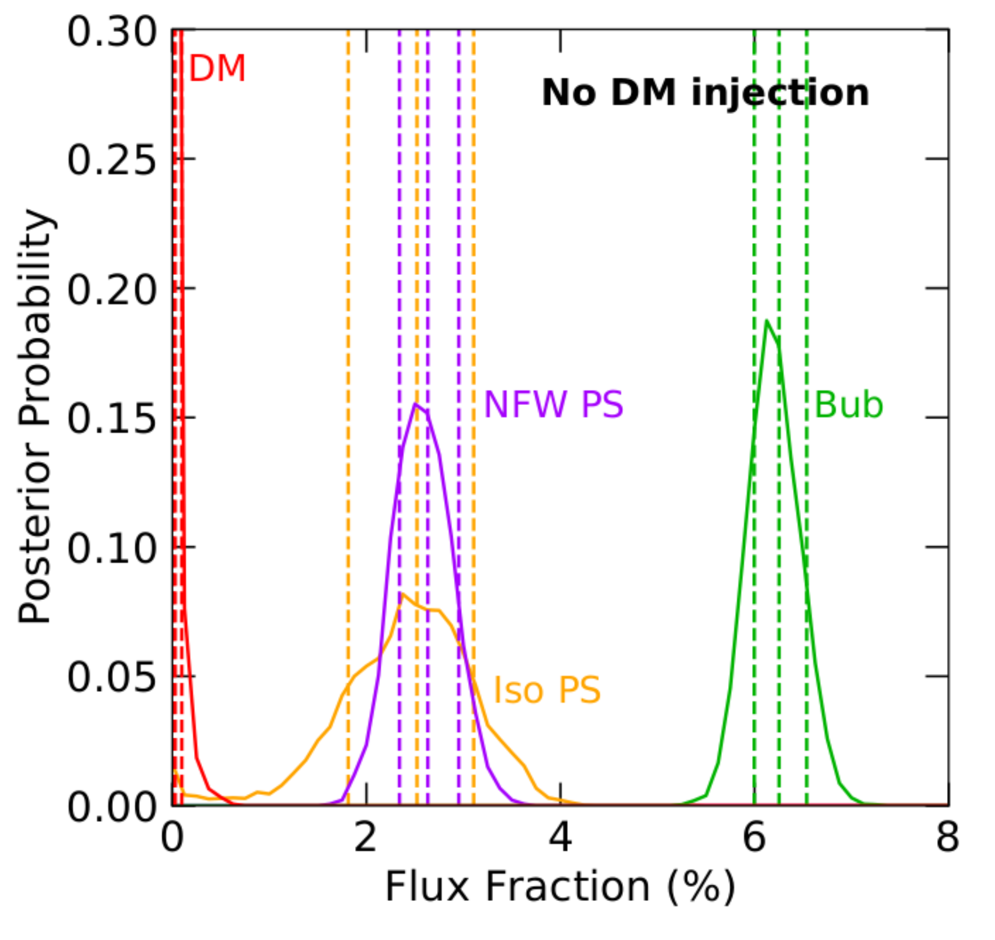
FERMI DATA

BOMBARDED DM SIGNAL + DATA

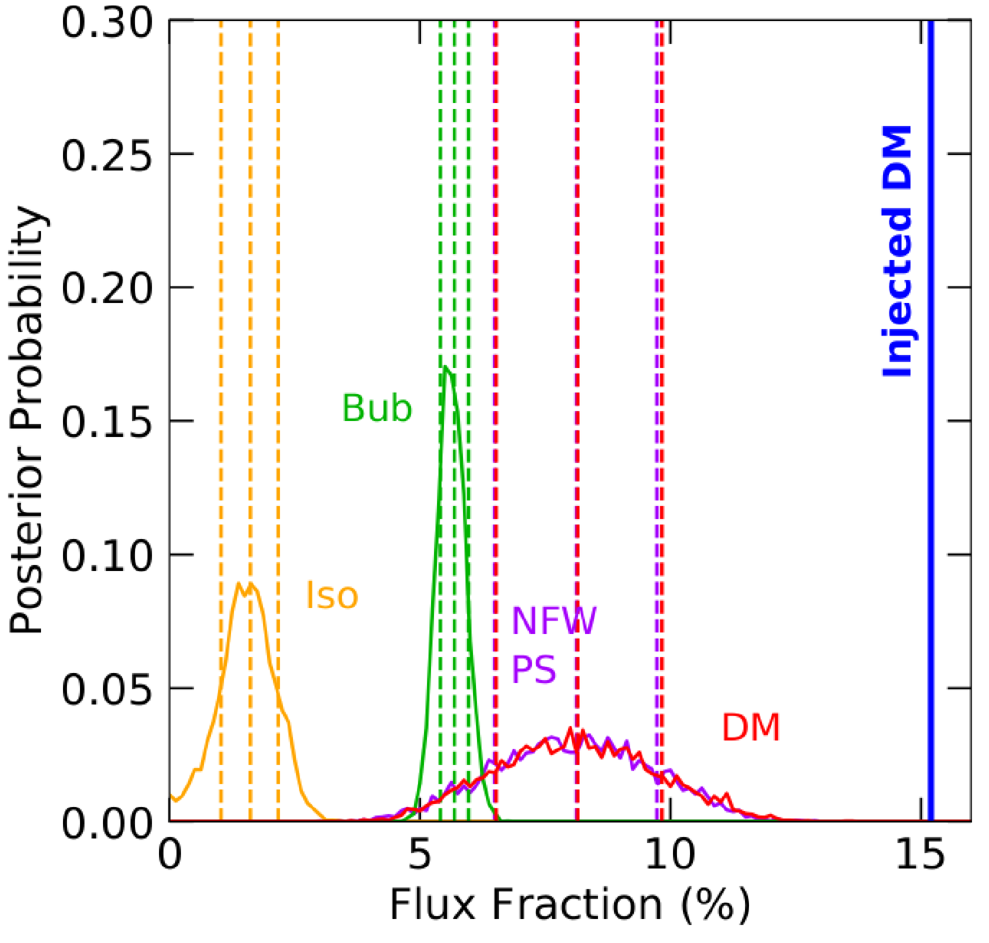


RL+Slatyer (PRL ‘19)

FERMI DATA



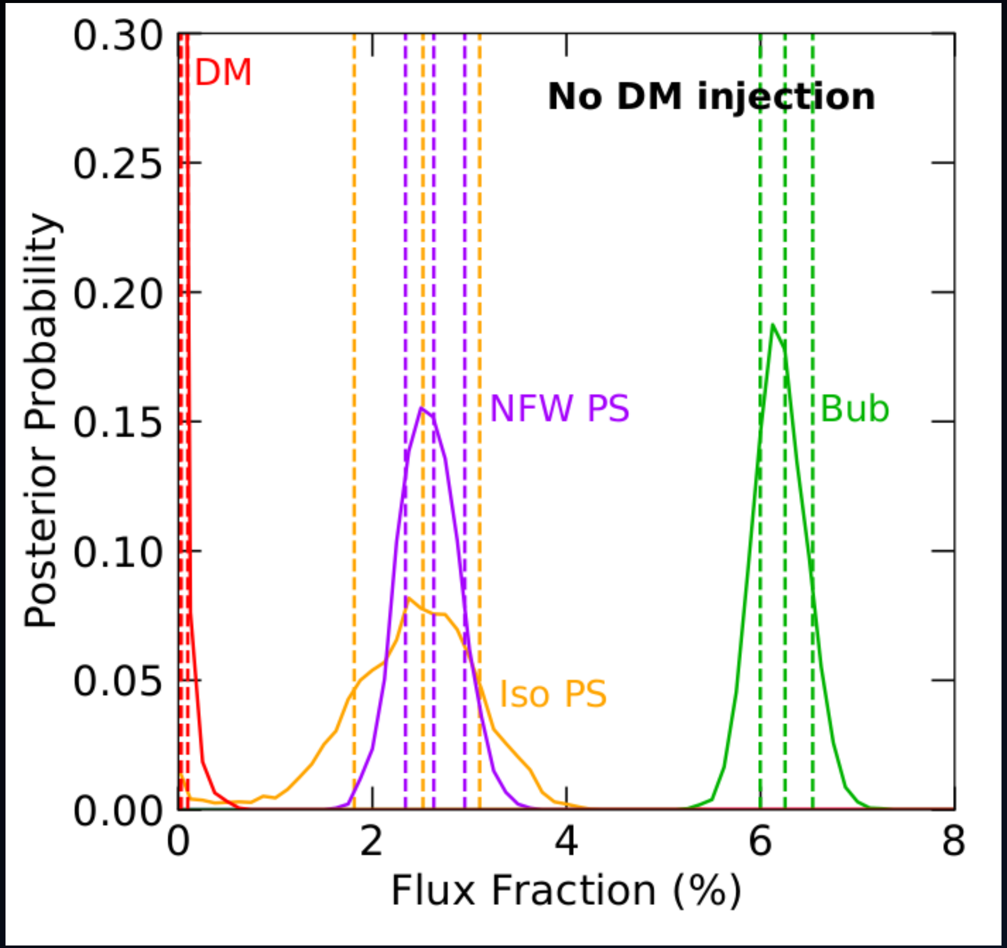
BOMBARDED DM SIGNAL + DATA

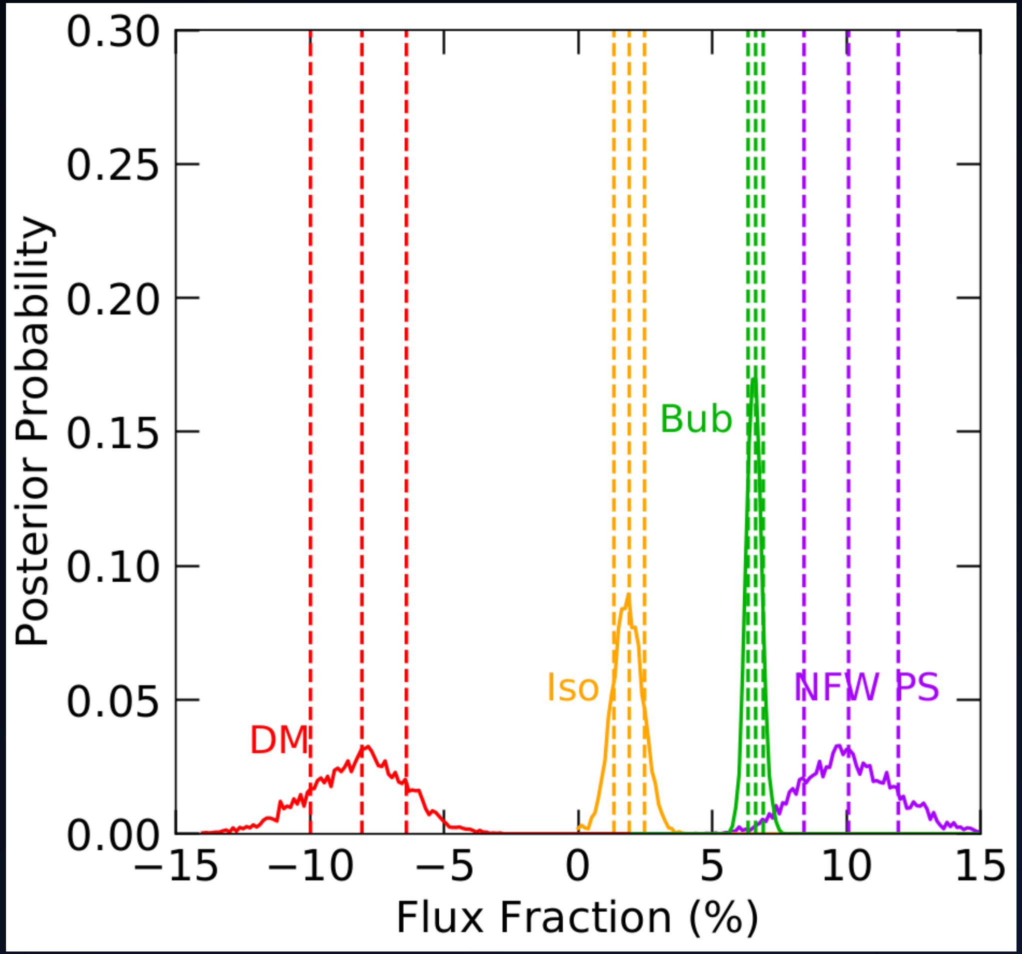


Finally, but low.

RL+Slatyer (PRL '19)

ALTERNATIVE TO INJECTION: GOING NEGATIVE





- Both simulated example and real data show similar behavior: significant preference against DM interpretation of the data

- A potential DM signal could be incorrectly discarded: due to the presence of a not yet discovered unresolved PS population, or another mismodelling effect

- *DM could substantially contribute to the GCE!*

2019:
DARK MATTER STRIKES BACK

Dark Matter Strikes Back at the Galactic Center

Rebecca K. Leane[1,*] and Tracy R. Slatyer[1,2,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*

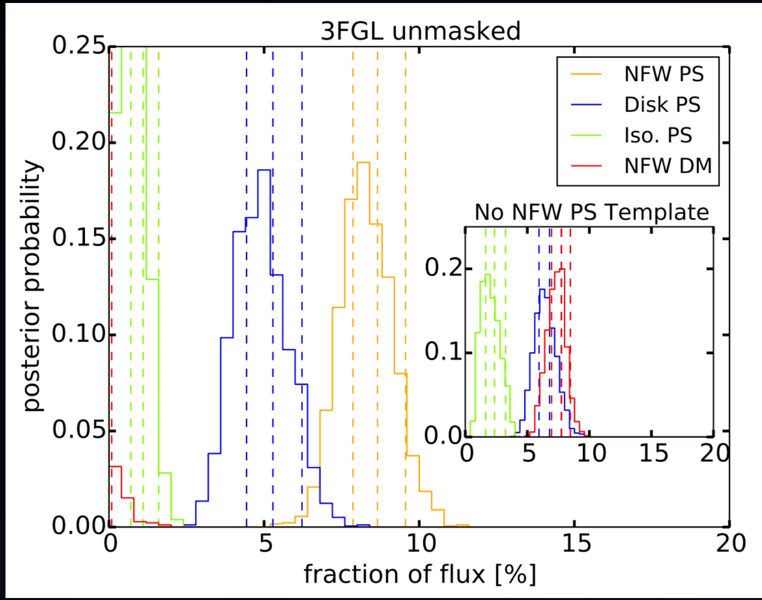
(Dated: April 19, 2019)

Daily Mail .com

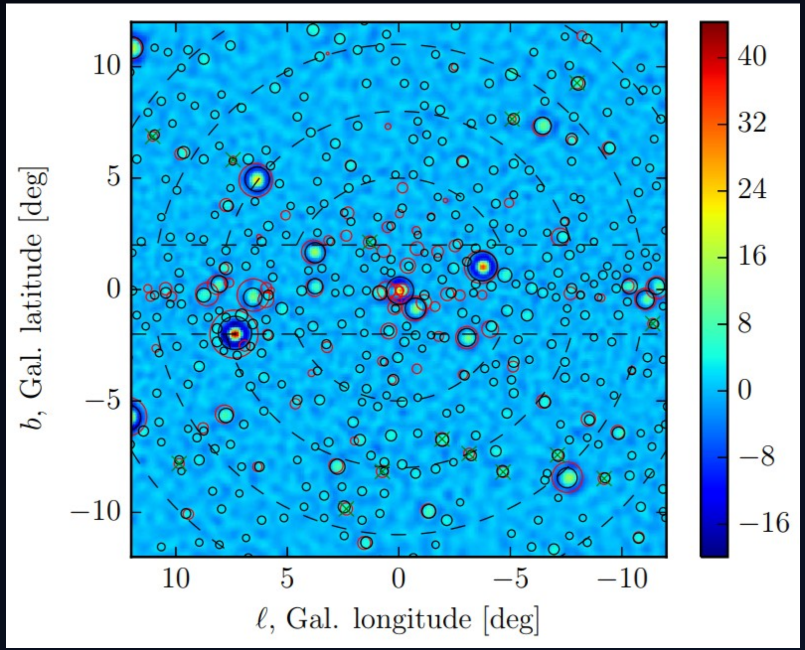
Mysterious gamma rays emanating from the center of our galaxy could be dark matter, scientists say

- Gamma rays coming from the center of the galaxy may be dark matter
- A new study has placed dark matter back in the discussion
- Previous research posited that gamma rays were caused by a pulsar
- Scientists say those calculations may have critical flaws

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER

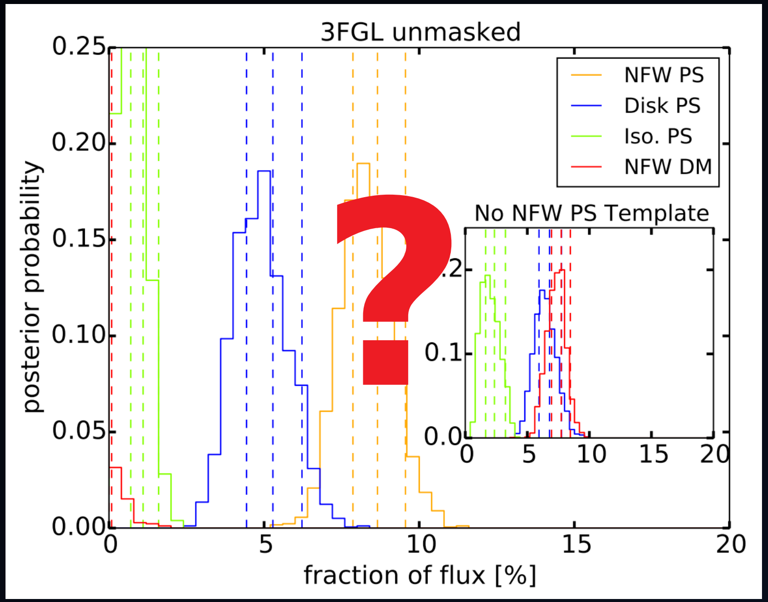


Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

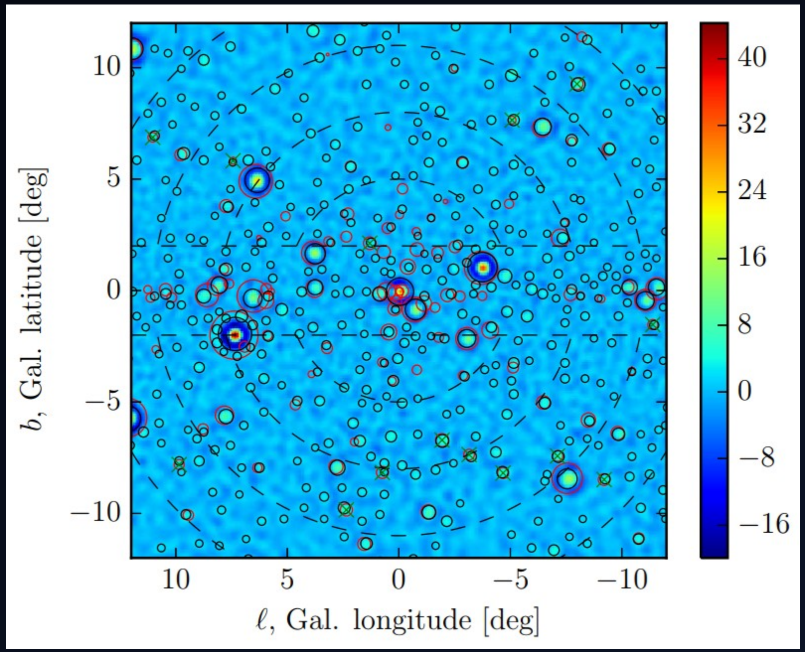


Bartels, Krishnamurthy, Weniger (PRL '15)

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



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

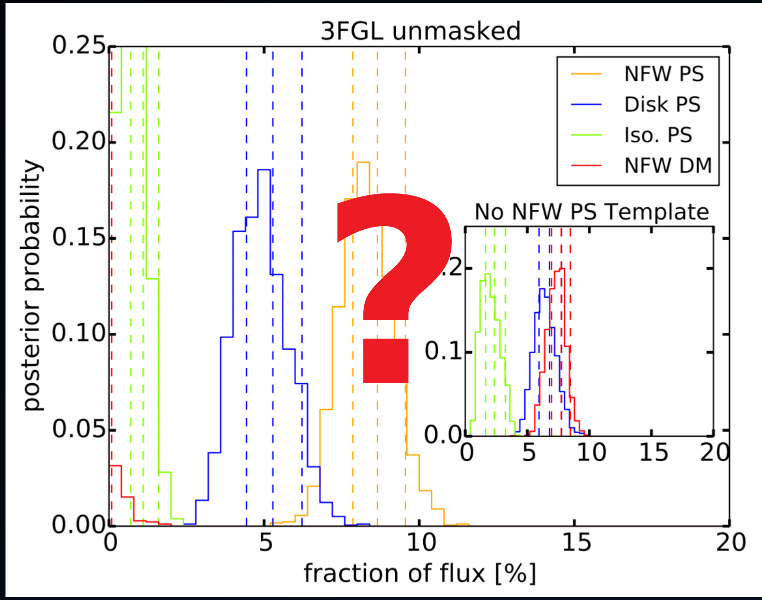


Bartels, Krishnamurthy, Weniger (PRL '15)

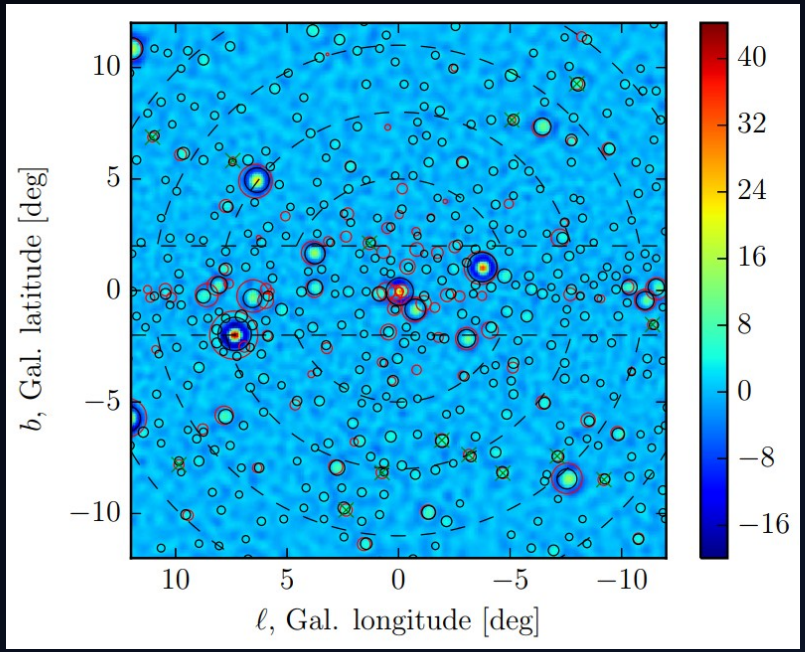
Challenged
RL+Slatyer (PRL '19)

Rebecca Leane

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



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



Bartels, Krishnamurthy, Weniger (PRL '15)

Challenged

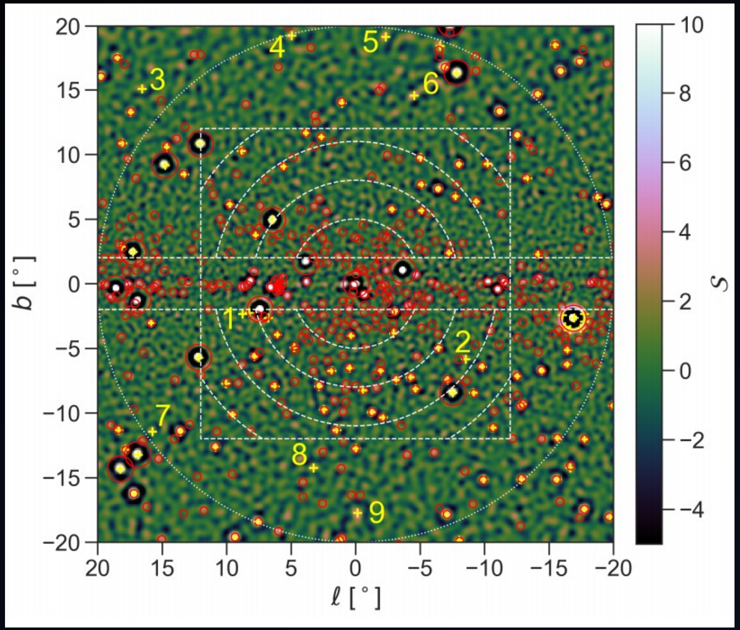
RL+Slatyer (PRL '19)

WAVELET METHOD RE-EVALUATION

Updated to mask out Fermi's new point source catalog.

WAVELET METHOD RE-EVALUATION

Updated to mask out Fermi's new point source catalog.

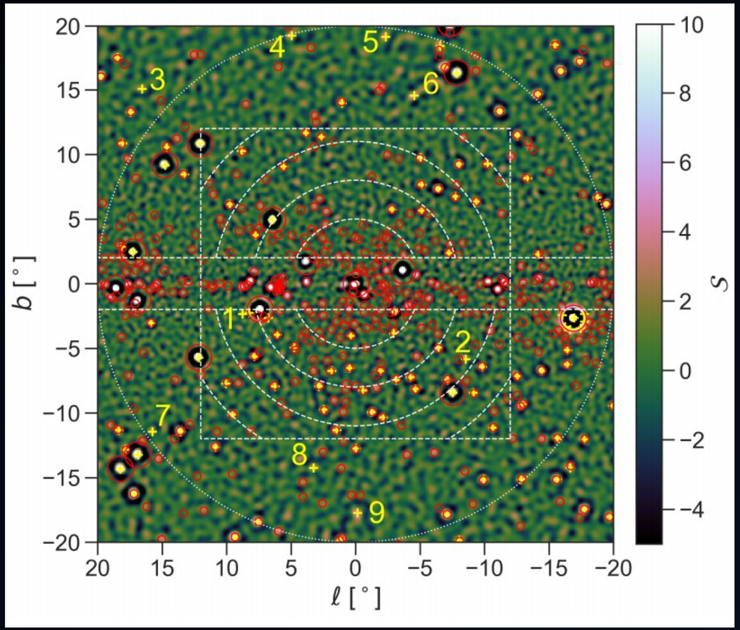


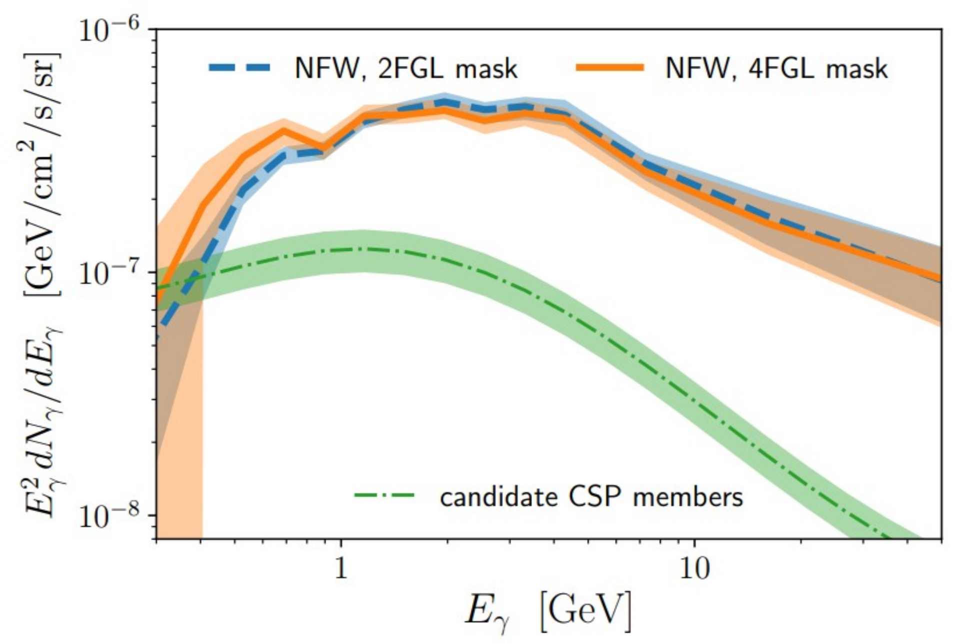
Turns out the 2015 paper correctly found point sources

Zhong, McDermott, Cholis, Fox '19

WAVELET METHOD RE-EVALUATION

Updated to mask out Fermi's new point source catalog.



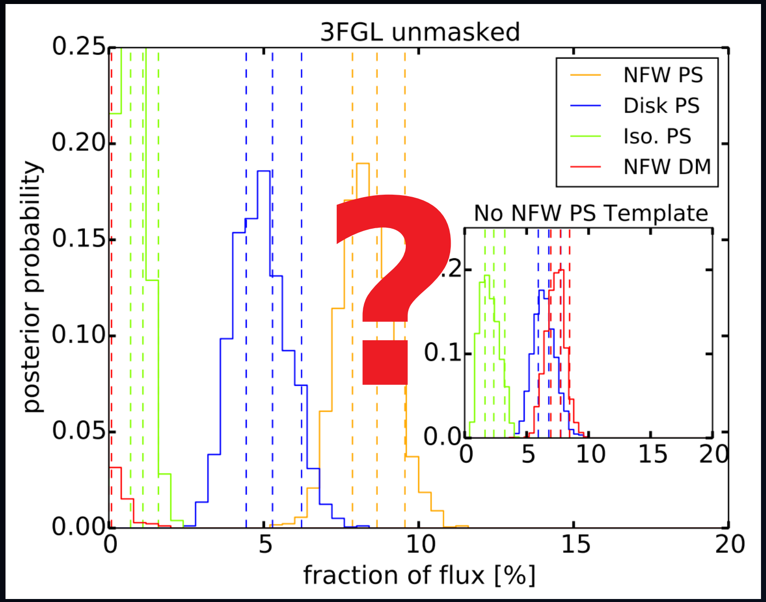


Turns out the 2015 paper correctly found point sources

...but **not** point sources that can explain the excess.

Zhong, McDermott, Cholis, Fox '19

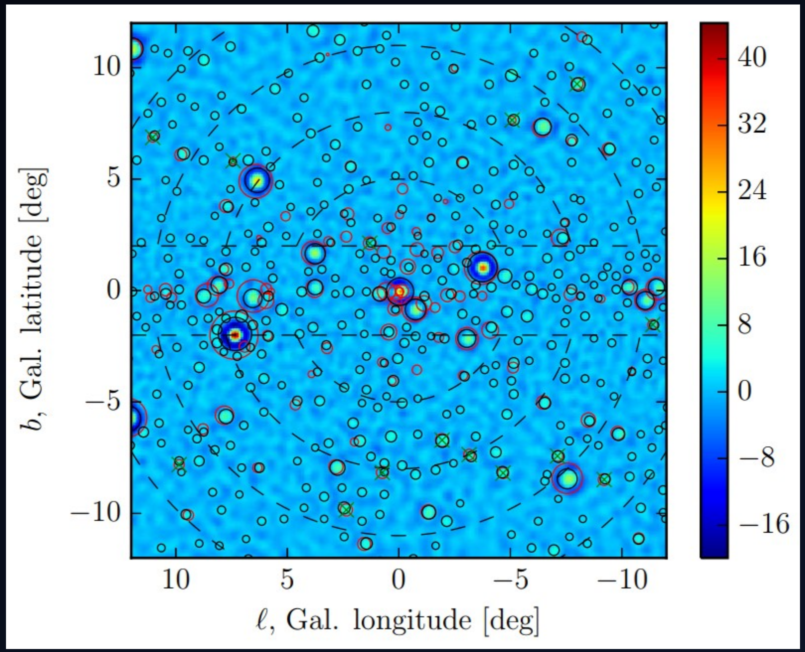
EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



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

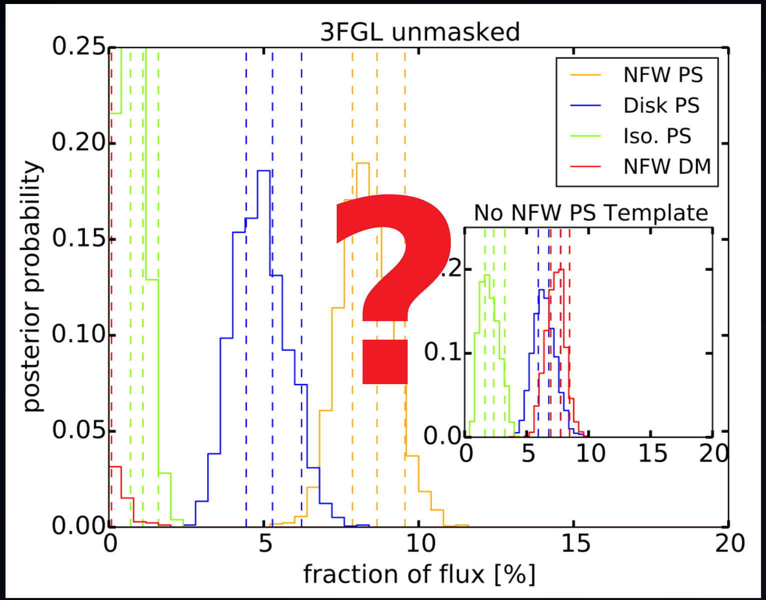
Challenged

RL+Slatyer (PRL '19)



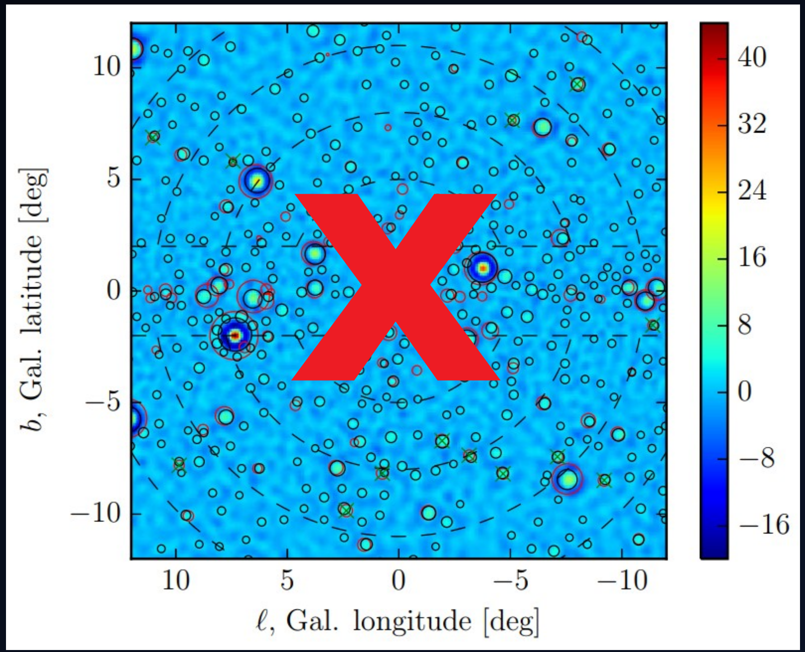
Bartels, Krishnamurthy, Weniger (PRL '15)

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



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

Challenged
RL+Slatyer (PRL '19)



Bartels, Krishnamurthy, Weniger (PRL '15)

Shown these point sources are not bulk of excess
Zhong, McDermott, Cholis, Fox '19

NOW

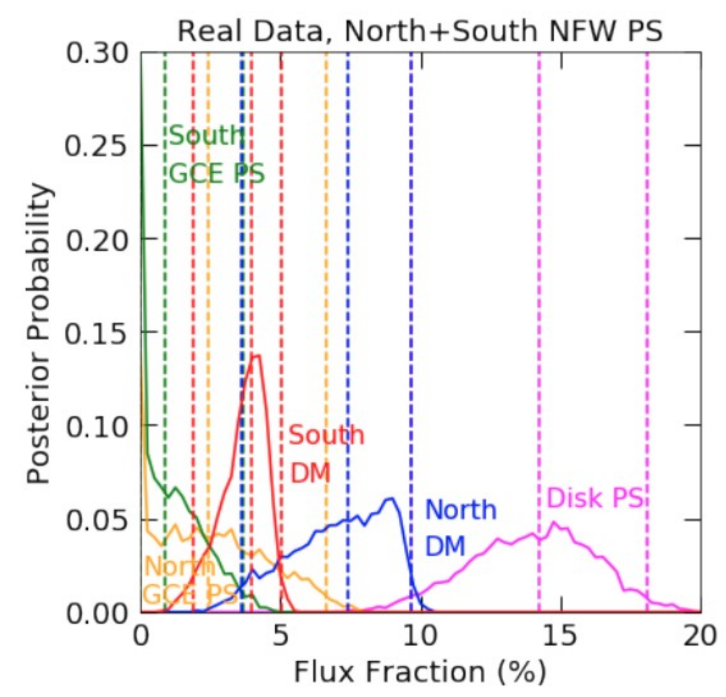
EFFECTS OF ADDITIONAL FREEDOM

- Break excess template into north and south pieces, let them float independently

RL+Slatyer (to appear)

EFFECTS OF ADDITIONAL FREEDOM

- Break excess template into north and south pieces, let them float independently



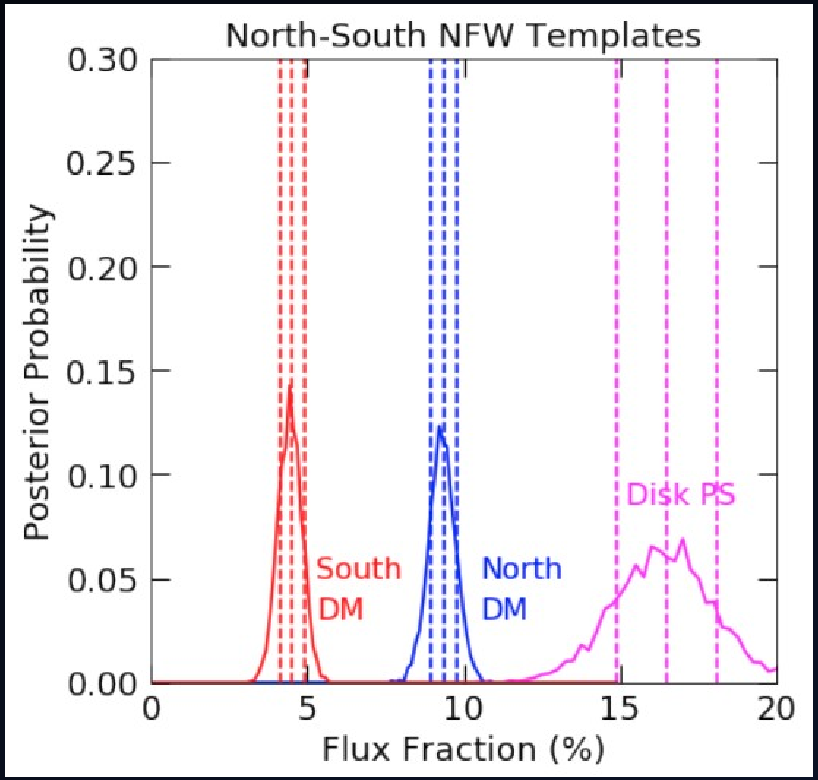
Preference for point sources:

Gone

RL+Slatyer (to appear)

THE DATA PREFERS THE FREEDOM

- Looking at only the smooth components

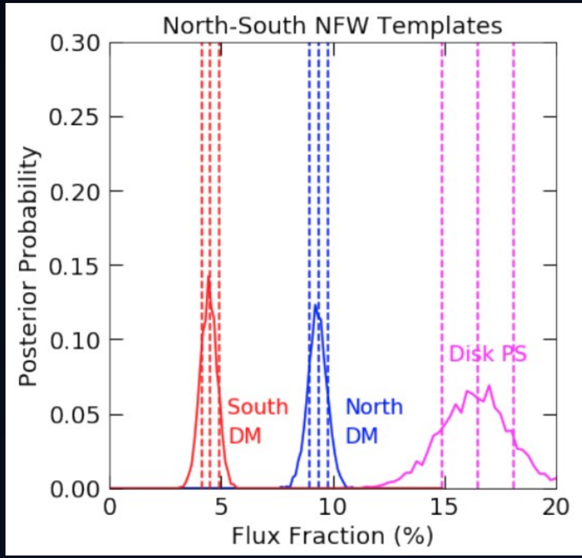


Data strongly prefer additional freedom, north/south asymmetry

RL+Slatyer (to appear)

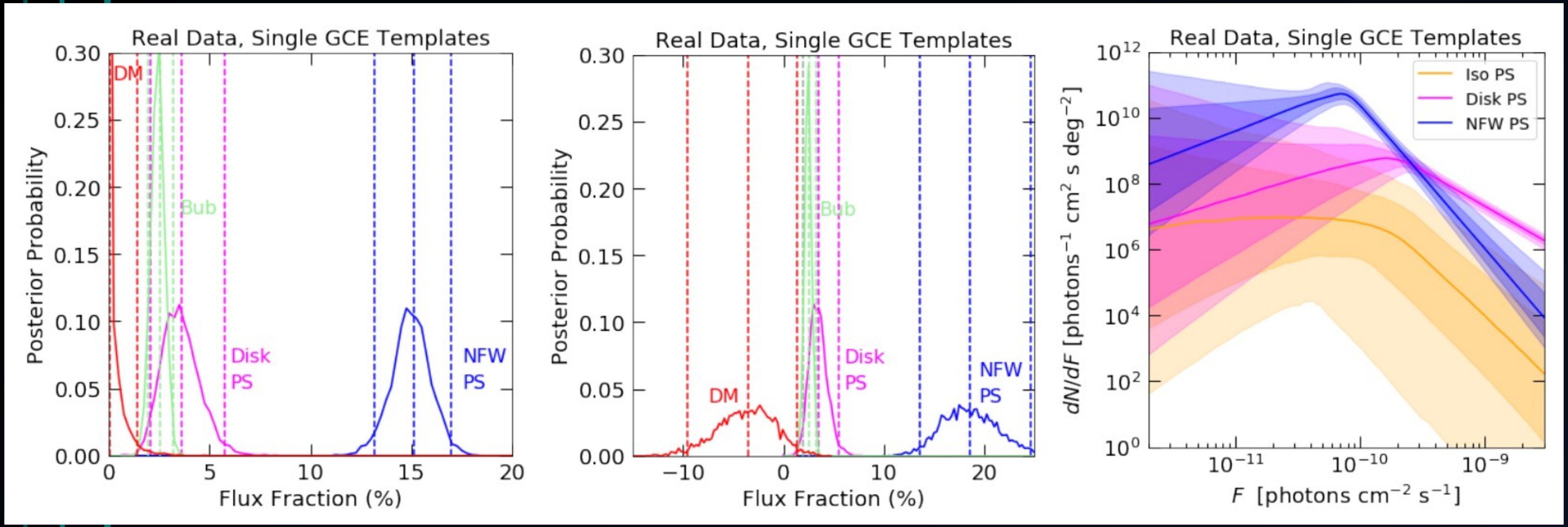
REPRODUCE IN SIMULATIONS?

- Simulate the smooth asymmetry (best-fit to the data)



- Analyze it with one set of NFW point sources and NFW smooth, as per previous studies

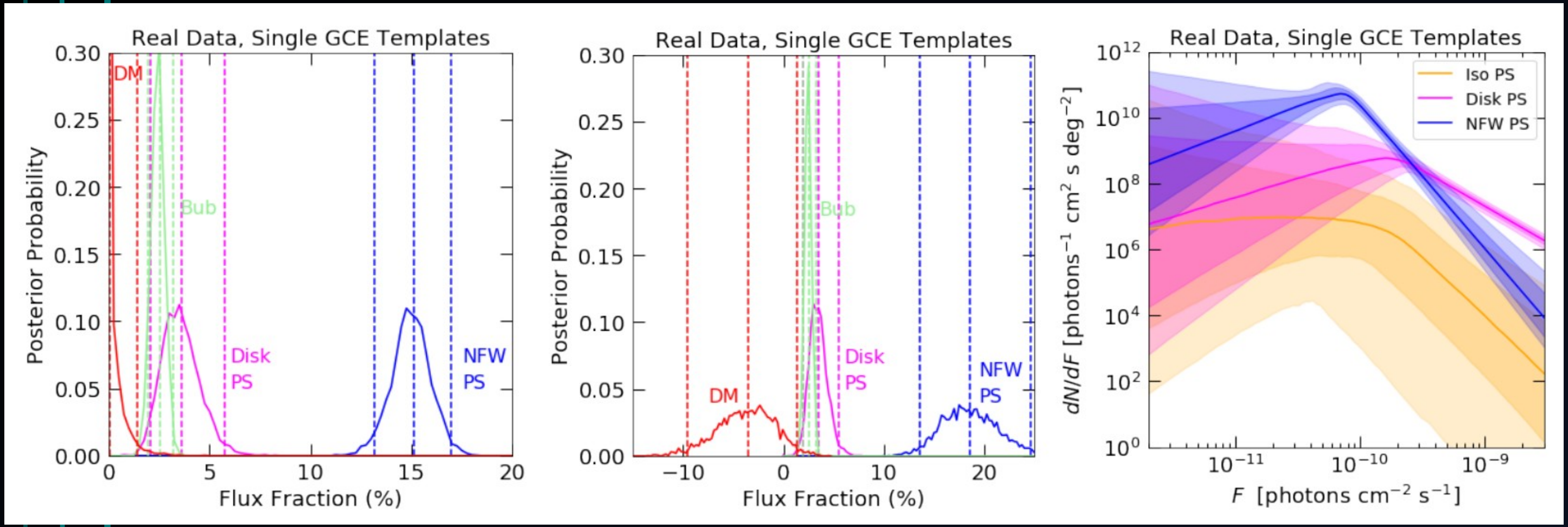
RL+Slatyer (to appear)



RL+Slatyer
(to appear)

Real data, one excess template

RL+Slatyer
(to appear)

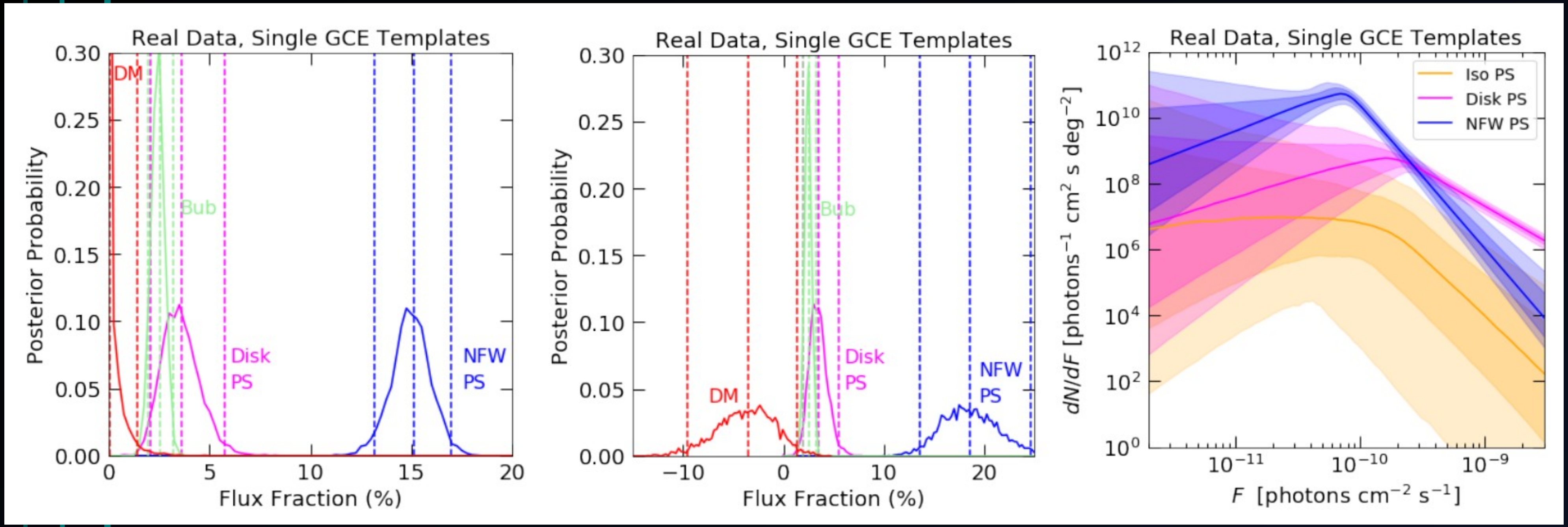


Real data, one excess template

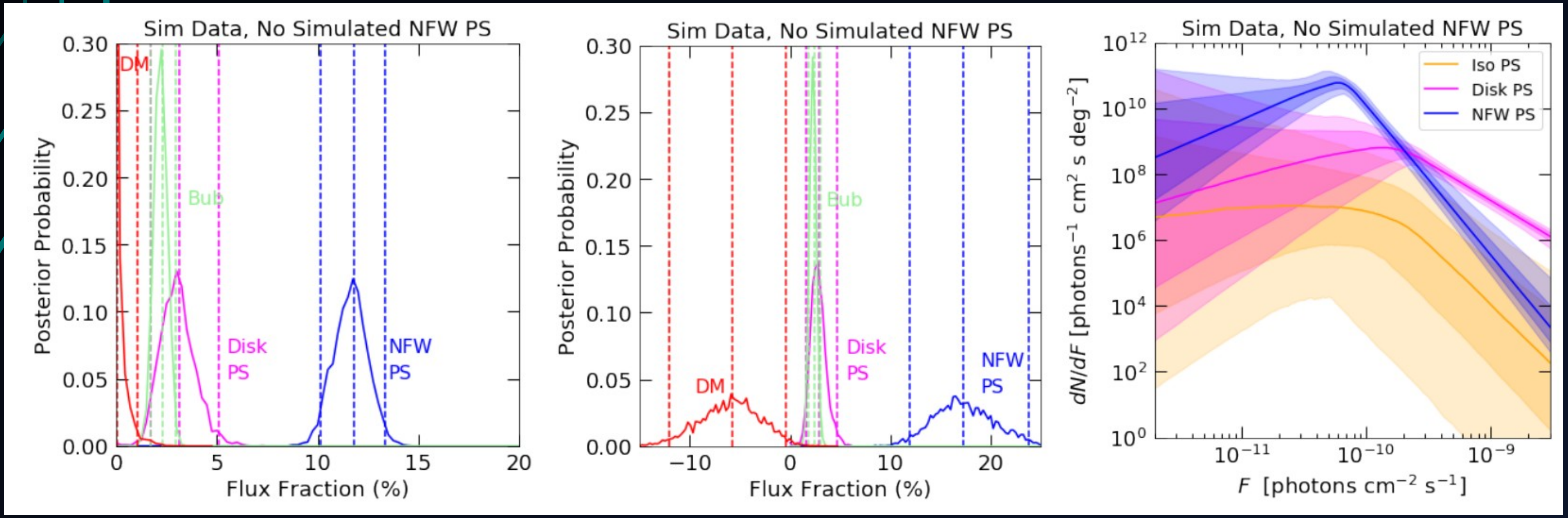
Simulated asymmetry, analyzed with one excess template

No simulated point sources

RL+Slatyer
(to appear)



Real data, one excess template



Simulated asymmetry, analyzed with one excess template

No simulated point sources

FAKE POINT SOURCES IN SIMULATIONS

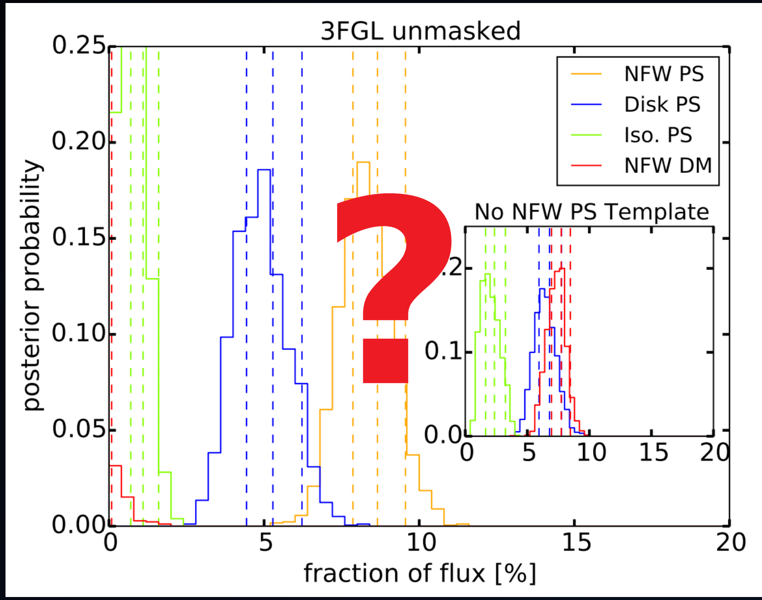
- We explicitly have shown that the point source evidence, from Non-Poissonian template fitting, is not currently robust

- Asymmetry maybe not intrinsic property of excess, but unmodeled asymmetry can produce spurious point sources

- Any variance larger than expected, due to mismodeling, can produce a spurious galactic center excess point source signal

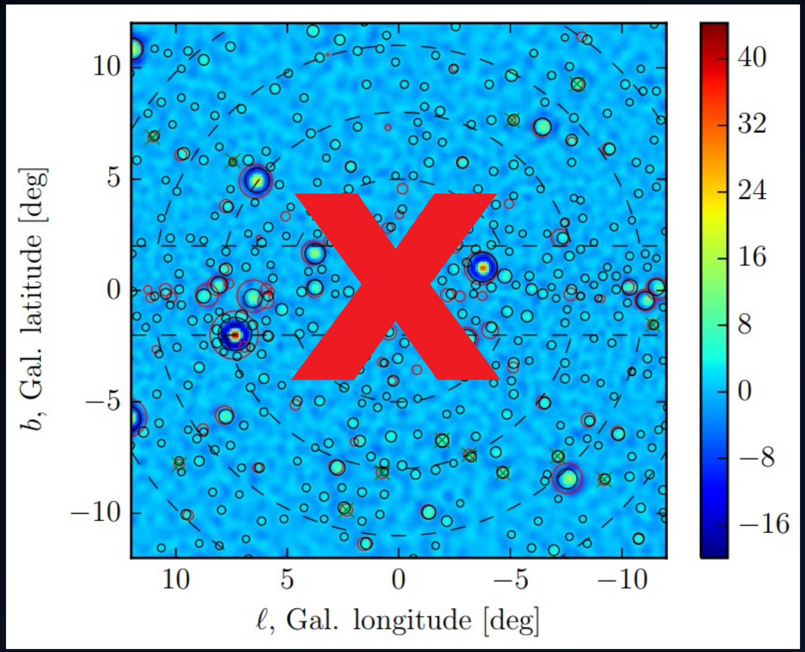
RL+Slatyer (to appear)

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



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

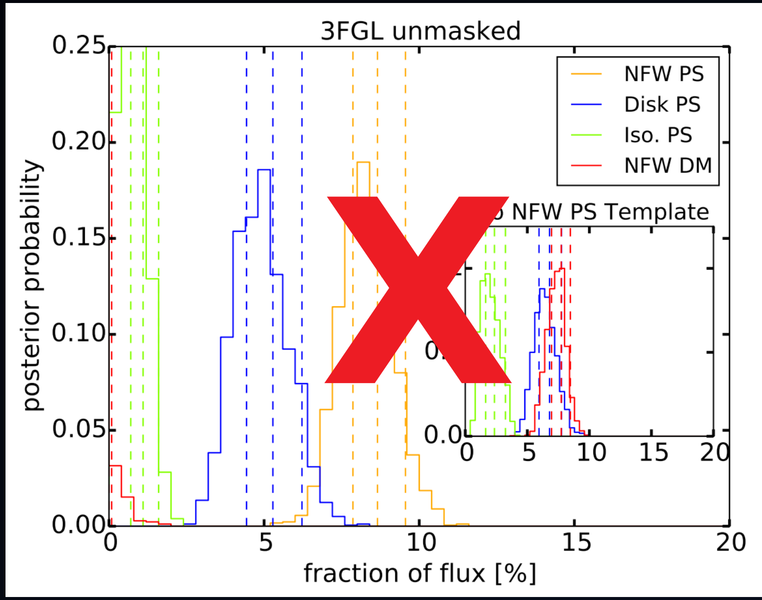
Challenged
RL+Slatyer (PRL '19)



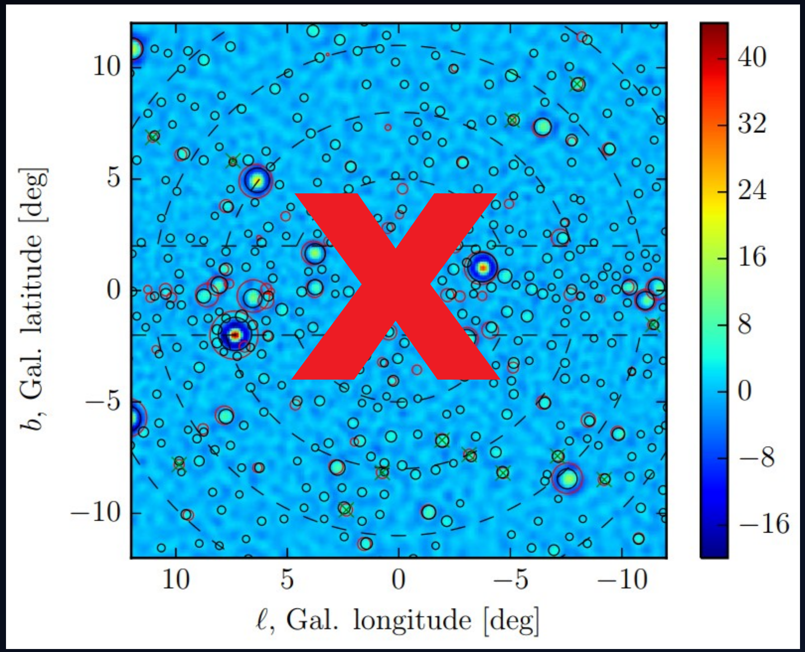
Bartels, Krishnamurthy, Weniger (PRL '15)

Shown these point sources are not bulk of excess
Zhong, McDermott, Cholis, Fox '19

EVIDENCE FOR POINT SOURCES AT THE GALACTIC CENTER



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



Bartels, Krishnamurthy, Weniger (PRL '15)

Challenged
RL+Slatyer (PRL '19)

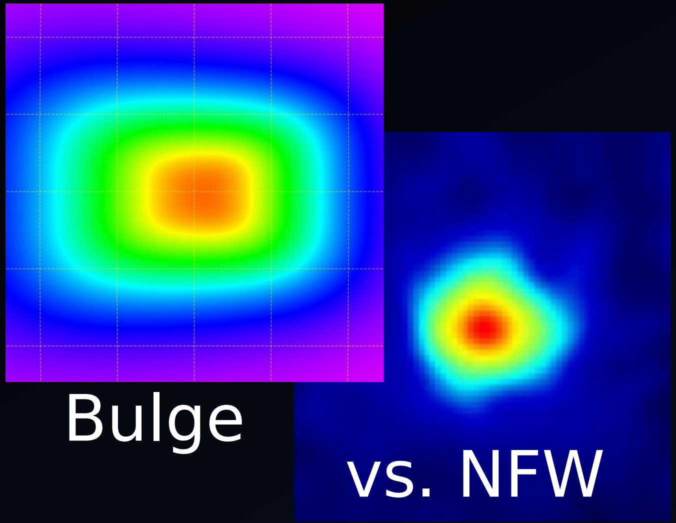
Shown these point sources are not bulk of excess
Zhong, McDermott, Cholis, Fox '19

Shown not currently robust
RL+Slatyer (to appear)

Rebecca Leane

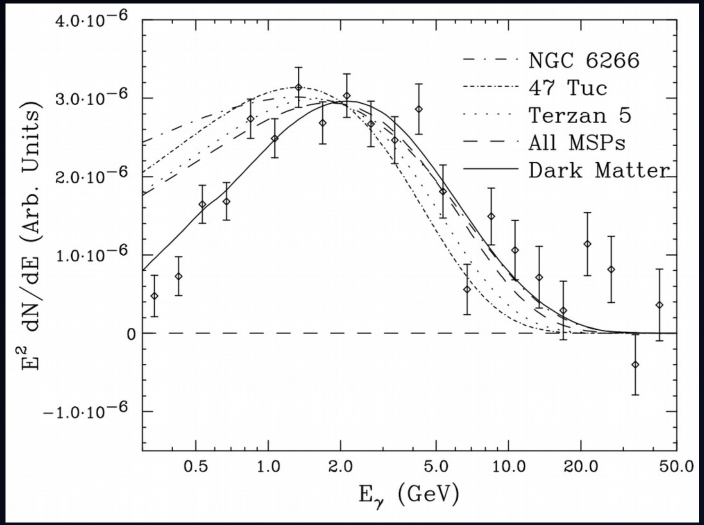
CURRENT PICTURE

Morphology



Not robustly known, but big implications

Energy Spectrum

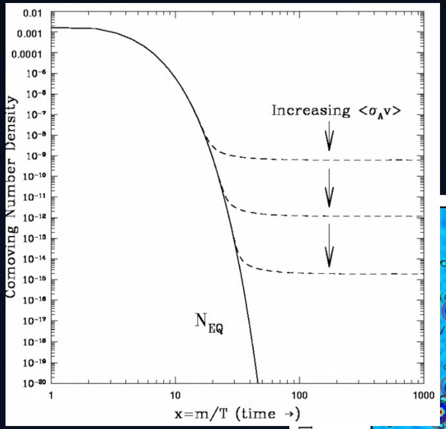


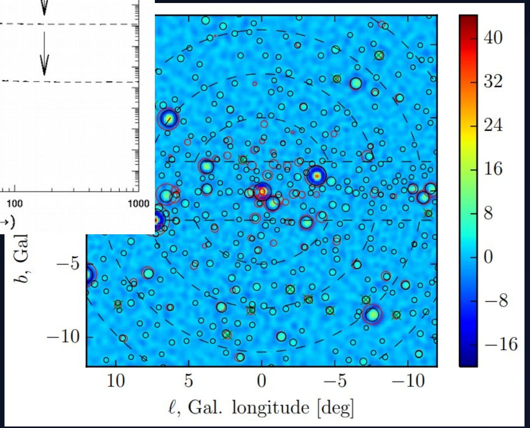
Comparable to millisecond pulsars

Can be well fit with DM annihilating to hadrons

Intensity

Well-explained by DM (Predicted by thermal relic cross section)

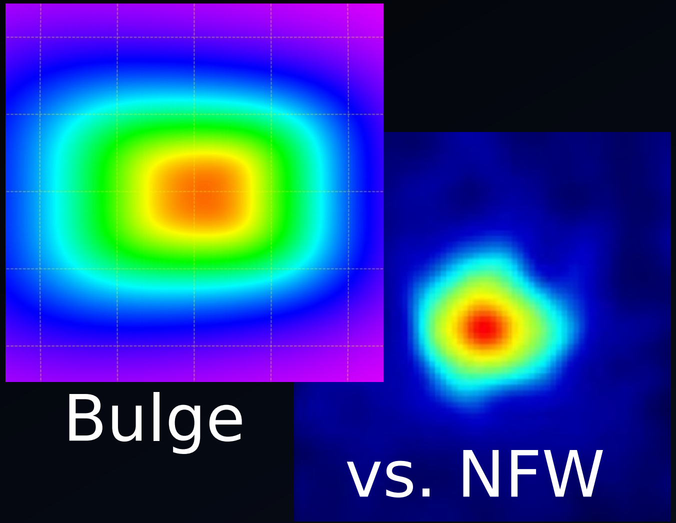




Tension for pulsars strong constraints on pulsar luminosity function

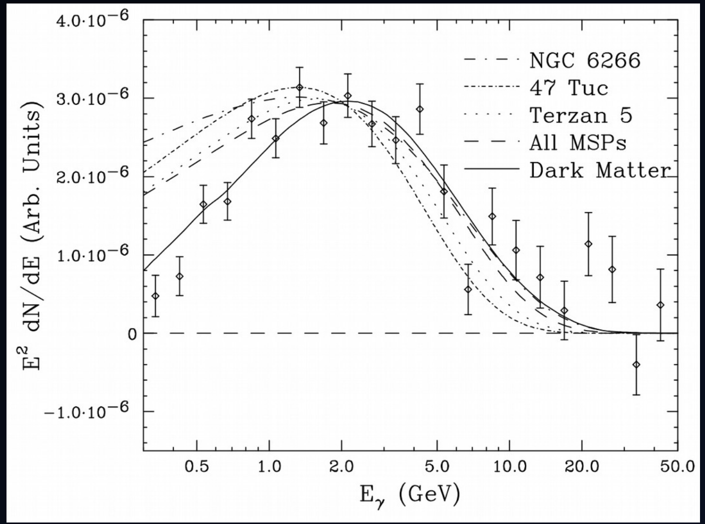
CURRENT PICTURE

Morphology



Not robustly known, but big implications

Energy Spectrum

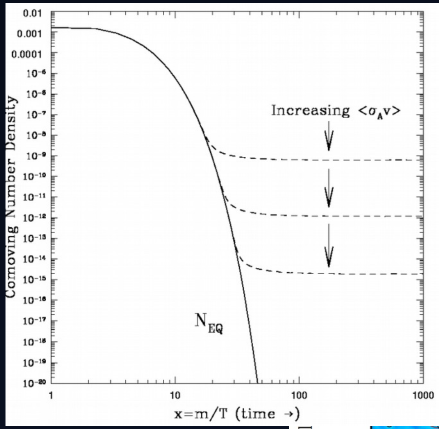


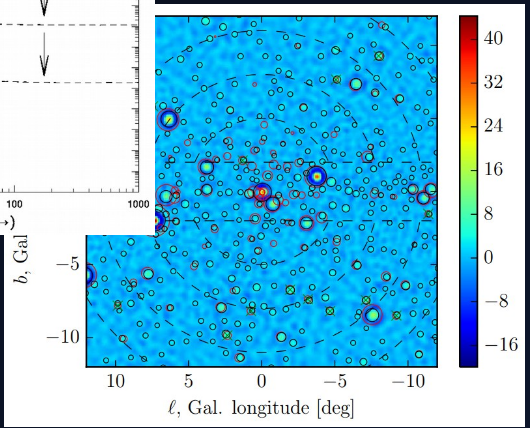
Comparable to millisecond pulsars

Can be well fit with DM annihilating to hadrons

Intensity

Well-explained by DM
(Predicted by thermal relic cross section)

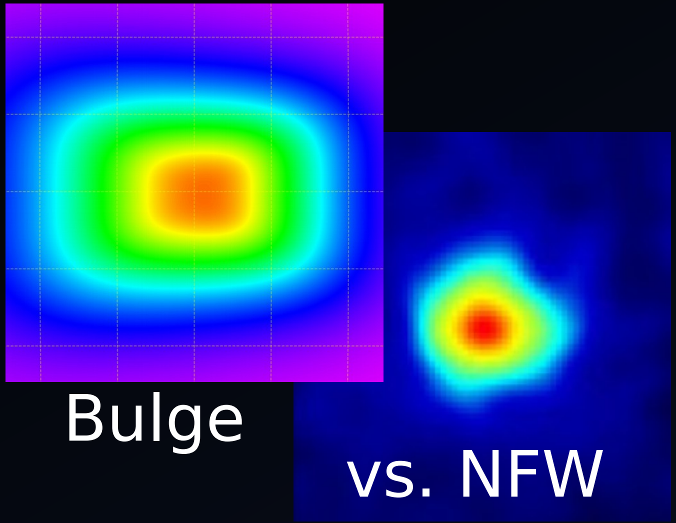




Tension for pulsars
strong constraints on pulsar luminosity function

CURRENT PICTURE

Morphology

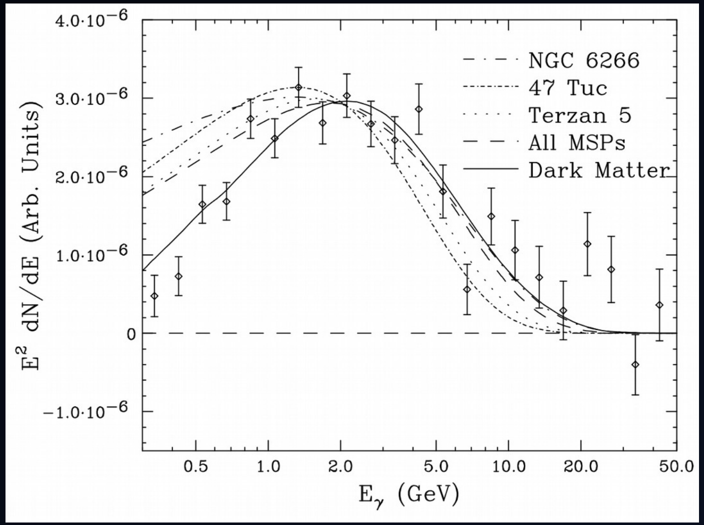


Bulge

vs. NFW

Not robustly known, but big implications

Energy Spectrum

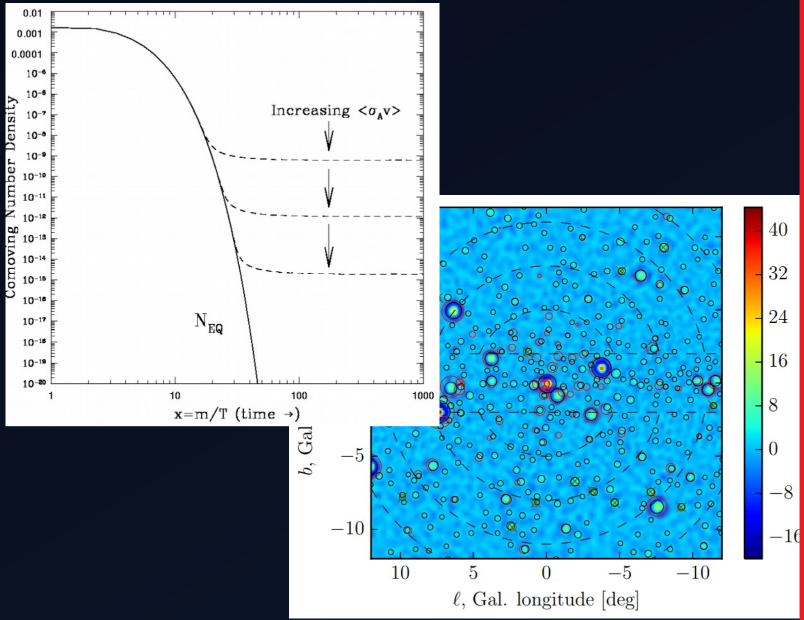


Comparable to millisecond pulsars

Can be well fit with DM annihilating to hadrons

Intensity

Well-explained by DM (Predicted by thermal relic cross section)



Tension for pulsars strong constraints on pulsar luminosity function

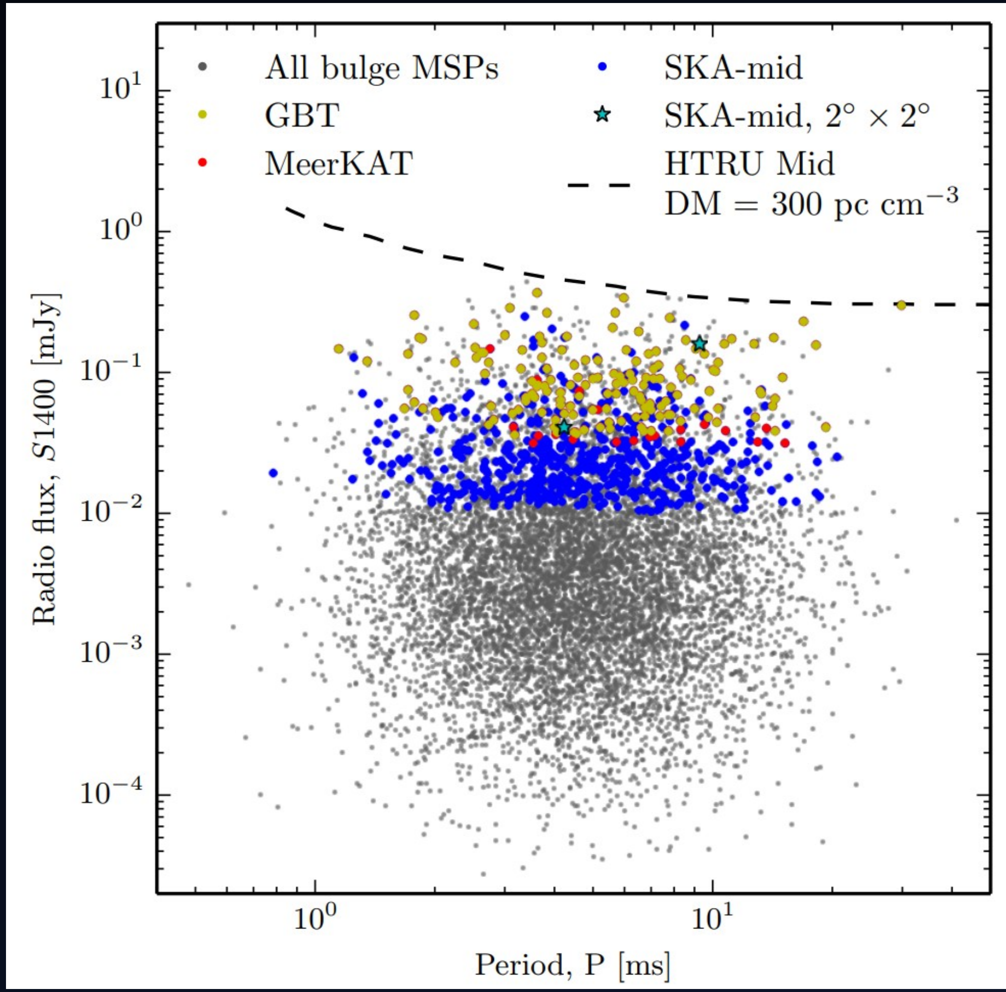
MOVING FORWARD:

DARK MATTER vs PULSARS

Rebecca Leane

PULSARS?

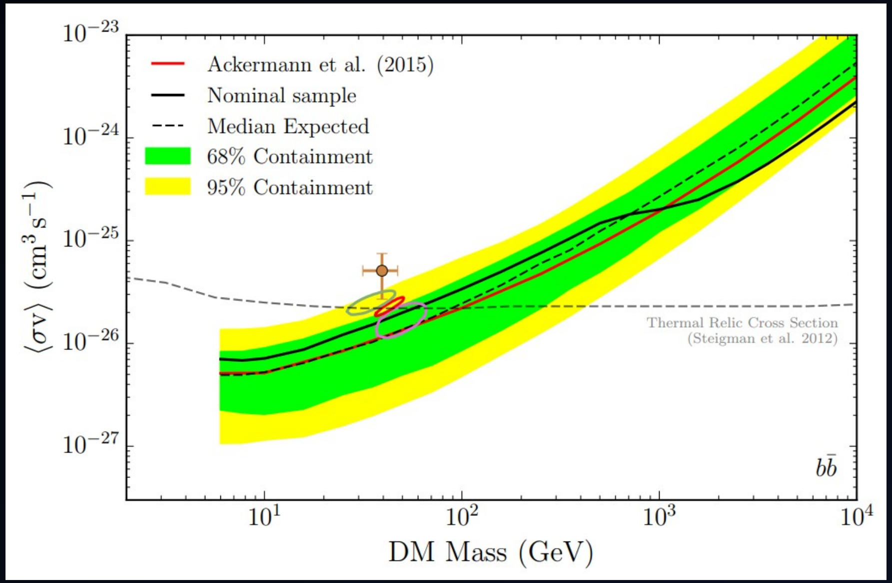
- Future detection of radio emission from pulsars by MeerKat and SKA



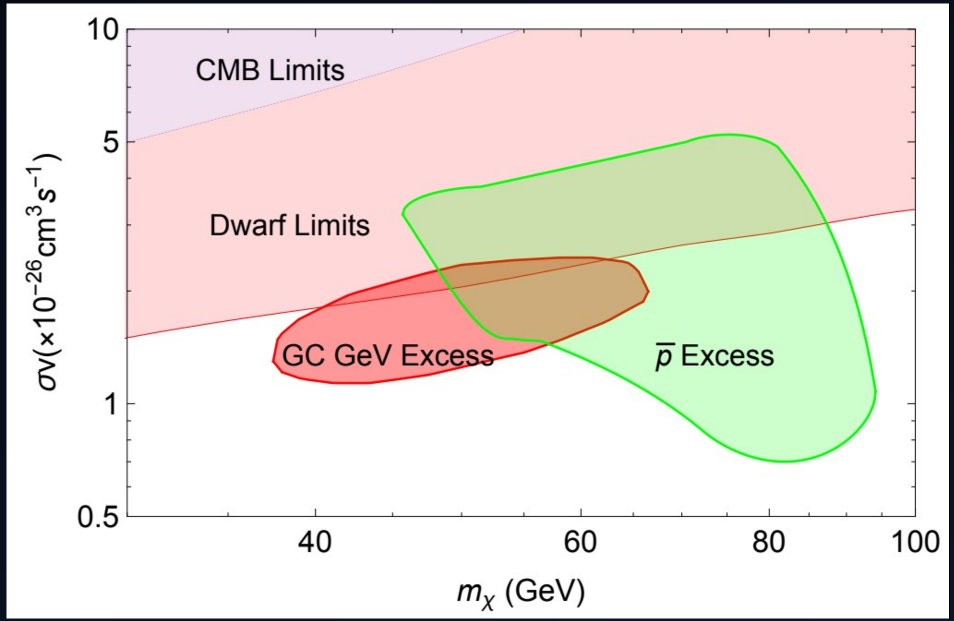
Calore et al 1512.06825

DARK MATTER?

- Dwarf spheroidal observations, want to see consistent signal
- Antiproton excess overlaps?



Ackermann et al 1611.03184

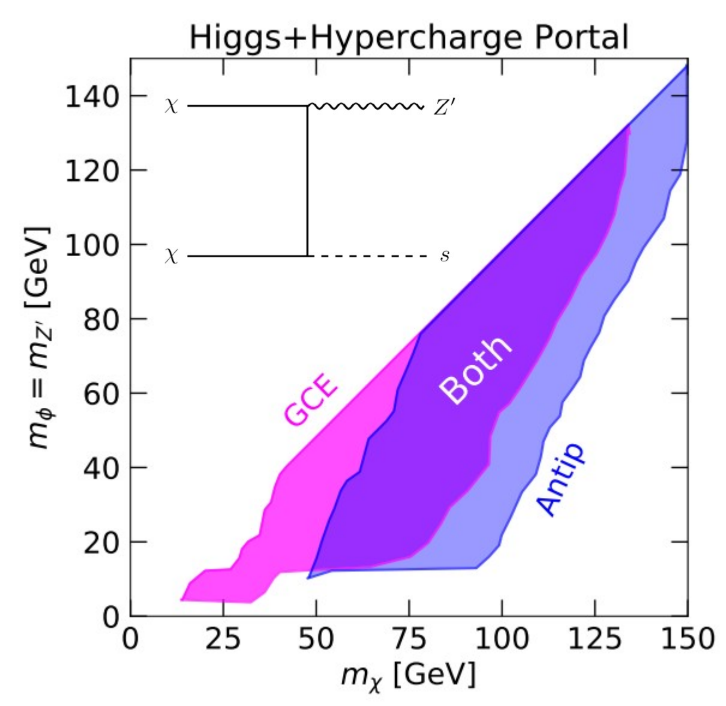


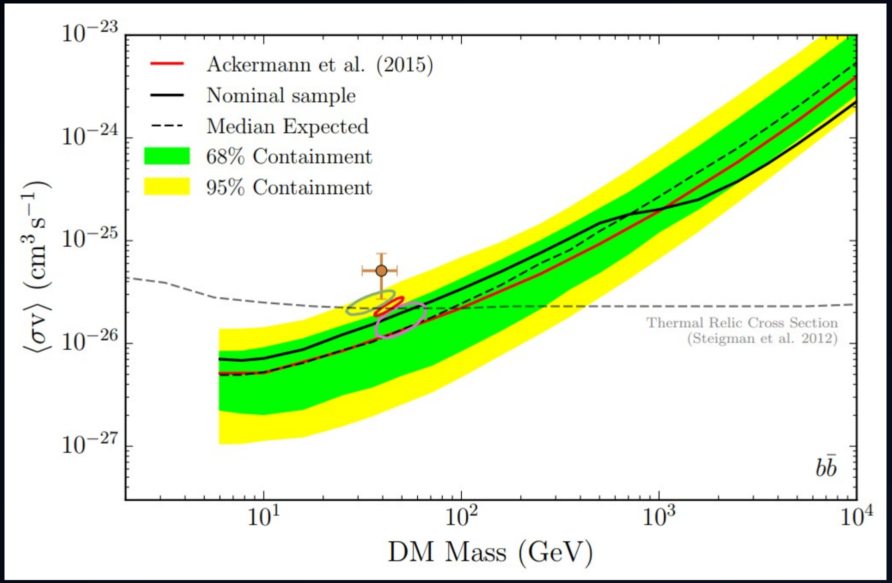
Cholis et al 1903.02549

DARK MATTER?

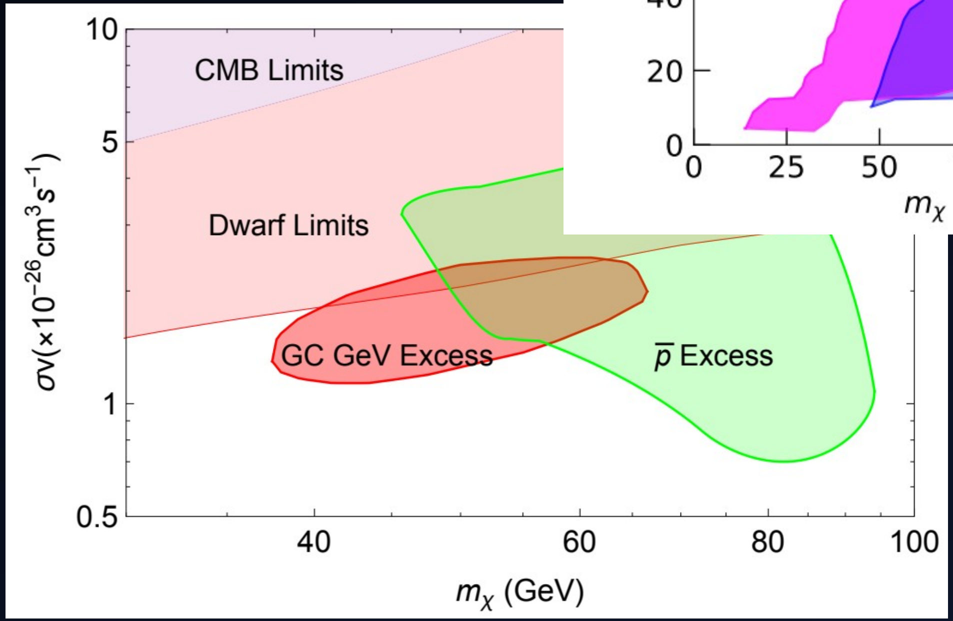
Hooper, **RL**, Tsai, Wegsman, Witte ‘19

- Dwarf spheroidal observations, want to see consistent signal
- Antiproton excess overlaps?
- Can be accommodated by fairly minimal models





Ackermann et al 1611.03184



Cholis et al 1903.02549

SUMMARY

- Excess firmly detected, signal origin is unknown – controversial signal!
- Tested if mismodeling can bias non-Poissionian methods
- Simulated proof-of-principle: DM signal is misattributed to point sources
- Real Fermi data: Injected DM misattributed to point sources!
  - Dark matter could provide dominant contribution to the excess?

SUMMARY

- Excess firmly detected, signal origin is unknown – controversial signal!
- Tested if mismodeling can bias non-Poissionian methods
- Simulated proof-of-principle: DM signal is misattributed to point sources
- Real Fermi data: Injected DM misattributed to point sources!
  - Dark matter could provide dominant contribution to the excess?
- Preference for asymmetry in the excess itself
  - If asymmetry not allowed, can force a positive DM signal negative
- Updated with asymmetry, lose evidence for point sources, get smooth signal!
- Spurious point source signals can arise from mismodeling

SUMMARY

- Excess firmly detected, signal origin is unknown – controversial signal!
- Tested if mismodeling can bias non-Poissionian methods
- Simulated proof-of-principle: DM signal is misattributed to point sources
- Real Fermi data: Injected DM misattributed to point sources!
  - Dark matter could provide dominant contribution to the excess?
- Preference for asymmetry in the excess itself
  - If asymmetry not allowed, can force a positive DM signal negative
- Updated with asymmetry, lose evidence for point sources, get smooth signal!
- Spurious point source signals can arise from mismodeling
- Previous 2015 point source evidence could be from spurious signals, not robust

SUMMARY

- Excess firmly detected, signal origin is unknown – controversial signal!
- Tested if mismodeling can bias non-Poissionian methods
- Simulated proof-of-principle: DM signal is misattributed to point sources
- Real Fermi data: Injected DM misattributed to point sources!
  - Dark matter could provide dominant contribution to the excess?
- Preference for asymmetry in the excess itself
  - If asymmetry not allowed, can force a positive DM signal negative
- Updated with asymmetry, lose evidence for point sources, get smooth signal!
- Spurious point source signals can arise from mismodeling
- Previous 2015 point source evidence could be from spurious signals, not robust
  - Signal looks consistent with being smooth

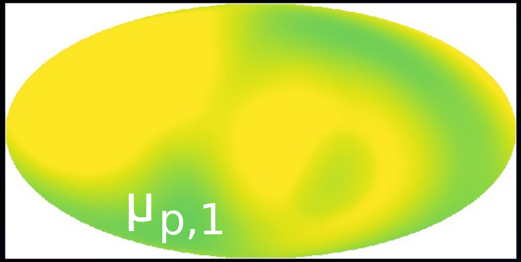
The story continues...

EXTRA SLIDES

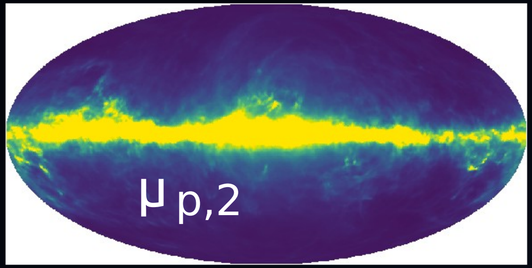
FUTURE STUDIES

- Better models:
  - Test well-motivated point source populations
  - Improved diffuse models, effects of perturbing diffuse models
- Understanding the method:
  - Systematics under perfect modeling (Chang et al ‘19)
  - Mitigating the issues

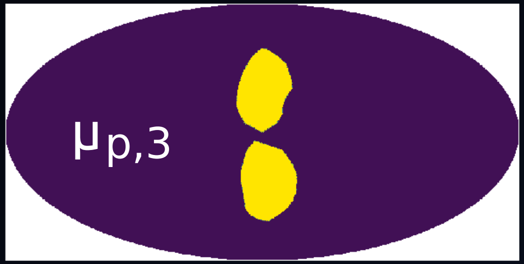
POISSON TEMPLATE FITTING



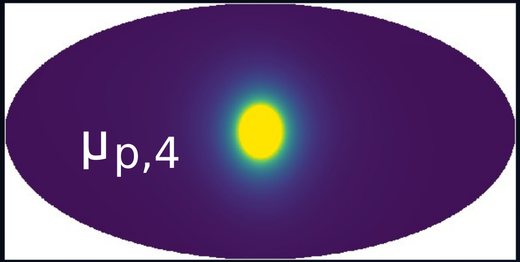
$\times\, \alpha_1$



$\times\, \alpha_2$



$\times\, \alpha_3$



$\times\, \alpha_4$

Prediction for each pixel

$$\mu_p = \sum_{\ell} \alpha_\ell \, \mu_{p,\ell}$$

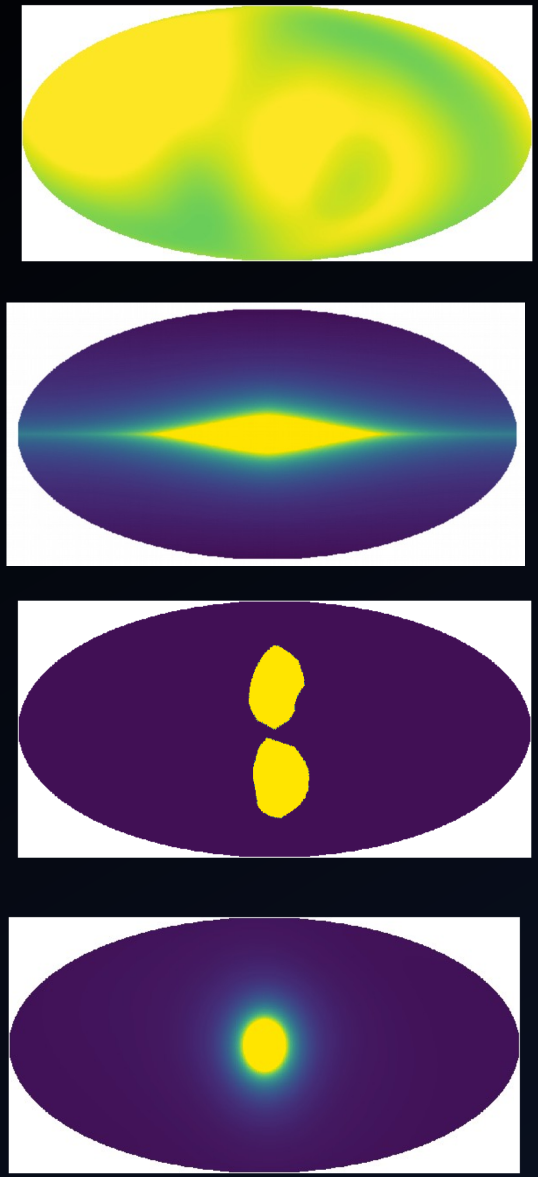
Likelihood per pixel is a Poisson distribution

$$p^{(p)}_{n_p}(\boldsymbol{\theta}) = \frac{\mu_p^{n_p}(\boldsymbol{\theta})}{n_p!} e^{-\mu_p(\boldsymbol{\theta})}$$

Total likelihood is given by product of Poisson likelihoods for each pixel

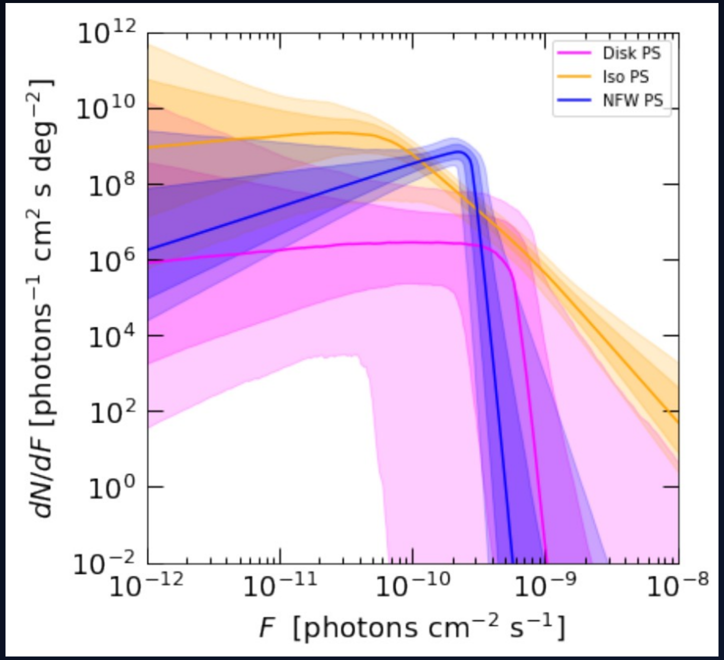
$$p(d|\boldsymbol{\theta}, \mathcal{M}) = \prod_p p^{(p)}_{n_p}(\boldsymbol{\theta})$$

NON-POISSON TEMPLATE FITTING



Photon count distribution has an additional dependence on a pixel-dependent PS source-count distribution. This can be modelled by a broken power law:

$$\frac{dN_p(S)}{dS} = A_p \begin{cases} \left(\frac{S}{S_b}\right)^{-n_1} & S \geq S_b \\ \left(\frac{S}{S_b}\right)^{-n_2} & S < S_b \end{cases}$$



3 additional degrees of freedom:
indices n1 and n2, and break Sb

NON-POISSON TEMPLATE FITTING

Predictions for each pixel in terms of generating functions, incorporates both Poisson and non-Poisson templates.

$$P_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}(t)}{dt^k}\bigg|_{t=0}$$

Poisson generating function:

$$\mathcal{P}_\ell^{(p)}(t) = e^{\mu_{p,\ell}(t-1)}$$

Non-Poisson generating function:

$$\mathcal{P}_{\rm NP}(t;\boldsymbol{\theta}) = \prod_p \exp\left[\sum_{m=1}^{\infty} x_{p,m}(\boldsymbol{\theta})(t^m - 1)\right]$$

Expected number of m-photon sources is

$$x_{p,m}(\boldsymbol{\theta}) = \underbrace{\int_0^\infty dS \frac{dN_p}{dS}(S;\boldsymbol{\theta})}_{\text{SCF}} \underbrace{\int_0^1 df \rho(f)}_{\text{PSF}} \frac{(fS)^m}{m!} e^{-fS}$$

probability seeing m photons when fS is expectation

Malyshev+Hogg '11
Lee+Lisanti+Safdi '15

M
n
By

Mysterious gamma rays emanating from the center of our galaxy could be dark matter, scientists say

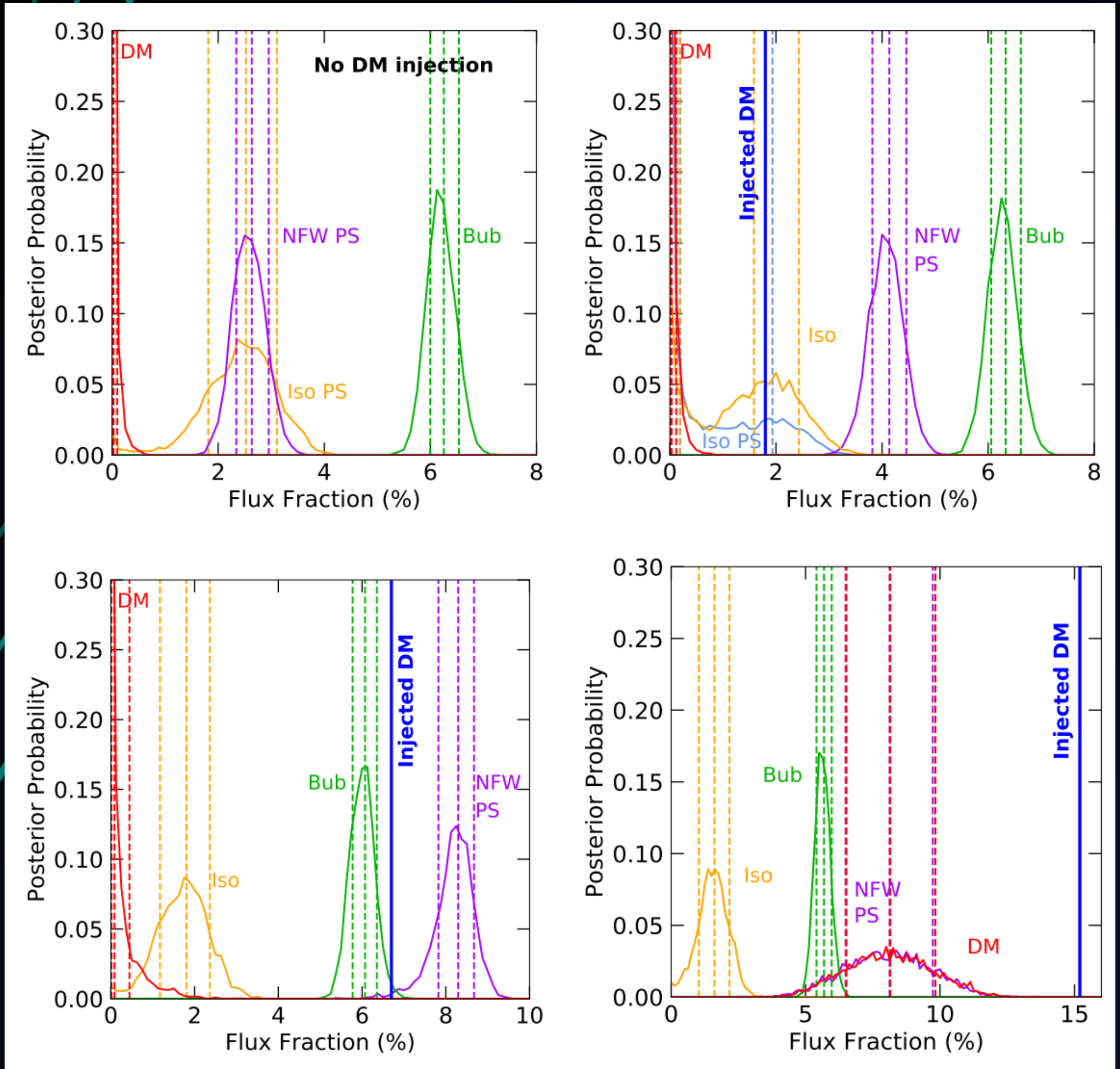
- Gamma rays coming from the center of the galaxy may be dark matter
- A new study has placed dark matter back in the discussion
- Previous research posited that gamma rays were caused by a pulsar
- Scientists say those calculations may have critical flaws

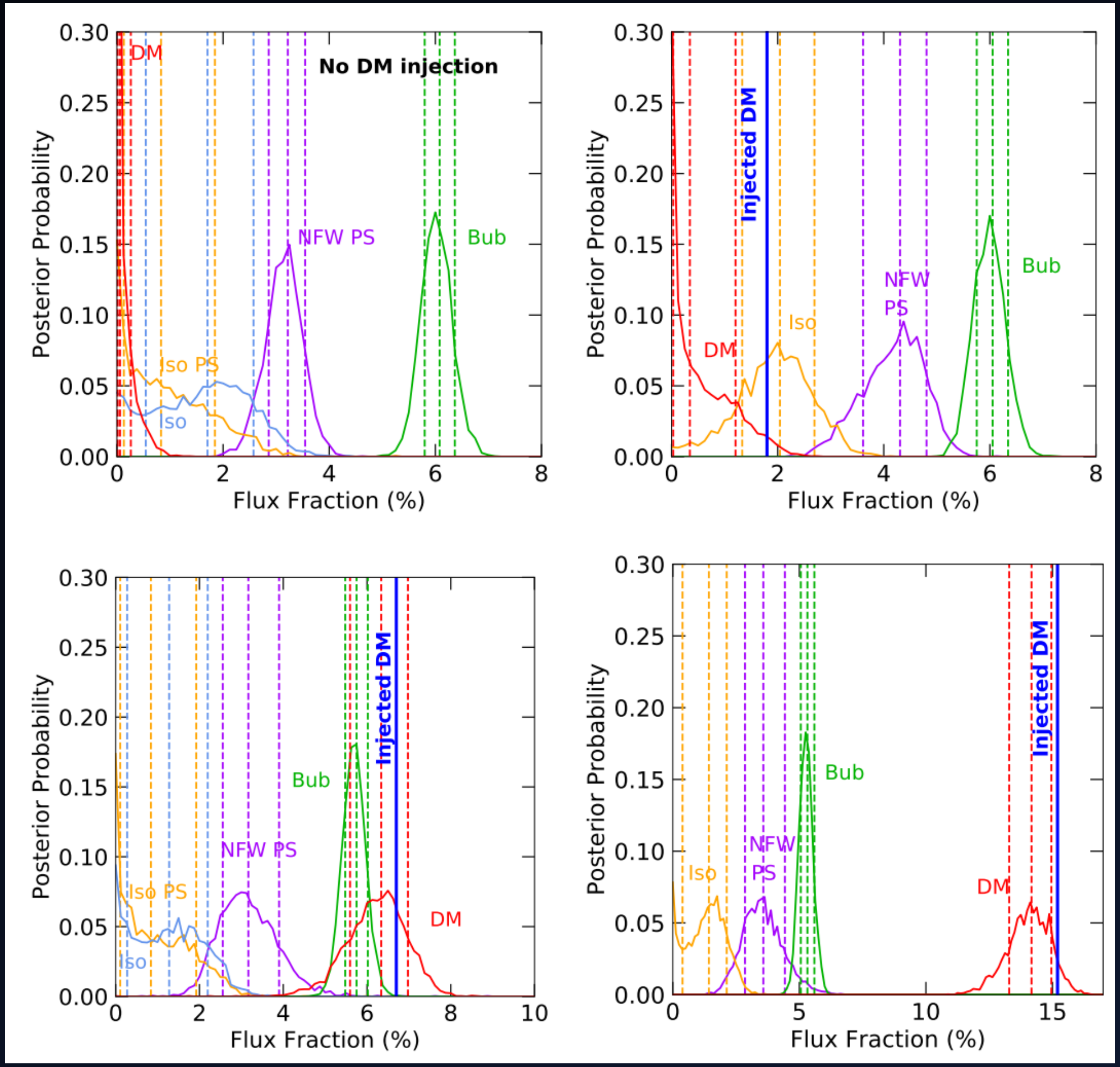
NPTF TOOLS

- Analyze data using NPTFit
  (Mishra-Sharma, Rodd, Safdi ‘16)
  github.com/bsafdi/NPTFit

- Simulate NP data using NPTFit-Sim (Rodd, Toomey)
  github.com/nrodd/NPTFit-Sim

REAL DATA vs SIMULATED DATA

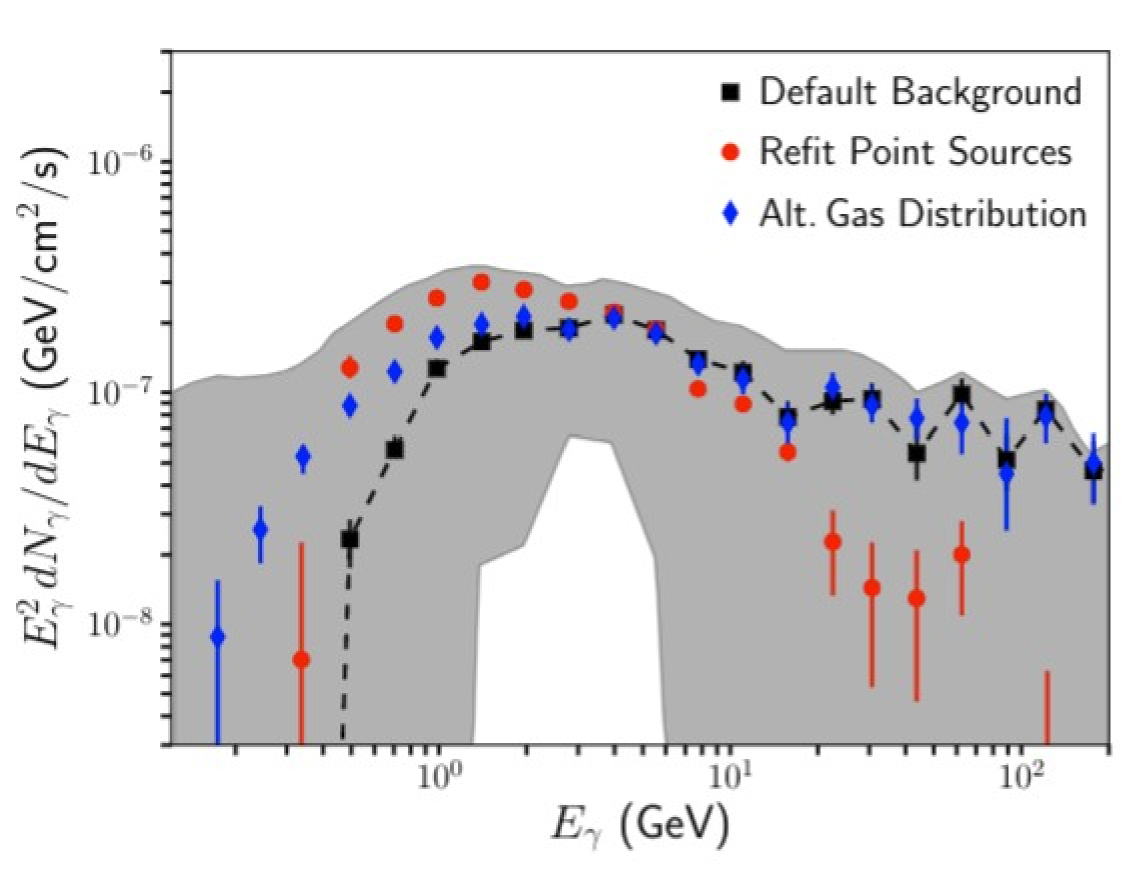




THEORY IDEAS?

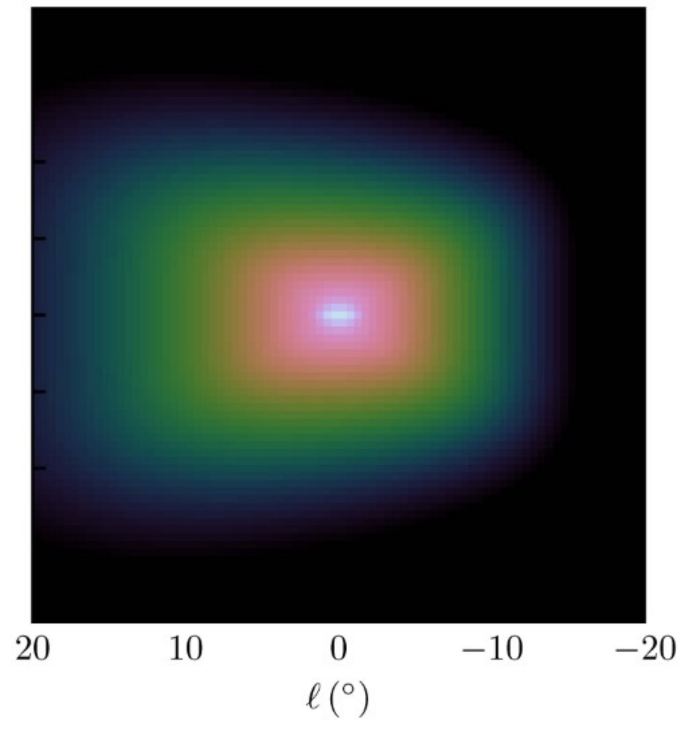
- Looking in individual ROIs
- Better understanding diffuse models
- Studying individual energy bins
- Complementary methods: SKYFACT, wavelet technique

DM	Mediator		Annihilation Products				
			$\bar{f}+f$	$\overline{N_R}+N_R$	$\phi_1+\phi_2$	$Z'_1+Z'_2$	$\phi+Z'$
spin-1/2	s-chan	spin-0	$\Gamma_{\mathrm{DM}}\otimes\Gamma_f$: $P\otimes P$ $P\otimes S$	$\Gamma_{\mathrm{DM}}\otimes\Gamma_{N_R}$: $P\otimes P$ $P\otimes S$	Γ_{DM}: P	No	No
spin-1/2	s-chan	spin-1	$\Gamma_{\mathrm{DM}}\otimes\Gamma_f$: $V\otimes V$ $V\otimes A$ $A\otimes A^*$	$\Gamma_{\mathrm{DM}}\otimes\Gamma_{N_R}$: $V\otimes V$ $V\otimes A$ $A\otimes A$	Γ_{DM}: V	Γ_{DM}: $V+A$	Γ_{DM}: V A
spin-1/2	t-chan	spin-1/2	-	-	$\Gamma_{\phi_1}\otimes\Gamma_{\phi_2}$: $S\otimes P$	$\Gamma_{Z'_1}\otimes\Gamma_{Z'_2}$: $V\otimes V$ $V\otimes A$ $A\otimes A$	$\Gamma_{\phi}\otimes\Gamma_{Z'}$: $S\otimes V$ $P\otimes V$
spin-1/2	t-chan	spin-0	Yes*	Yes	-	-	-
spin-1/2	t-chan	spin-1	-	-	-	-	-
spin-0	s-chan	spin-0	Γ_f: $S+P$	Γ_{N_R}: $S+P$	Yes	Yes	No
spin-0	s-chan	spin-1	No	No	Yes	Yes	No
spin-0	t-chan	spin-0	-	-	Yes	Yes	No
spin-0	t-chan	spin-1/2	Γ_f: $S+P$	Γ_{N_R}: $S+P$	-	-	-
spin-0	t-chan	spin-1	-	-	No	Yes	Yes
spin-1	s-chan	spin-0	Γ_f: S, P	Γ_f: S,P	Yes	Yes	Yes
spin-1	s-chan	spin-1	Γ_f: V ,A	Γ_f: V ,A	No	Yes	Yes
spin-1	t-chan	spin-0	-	-	Yes	Yes	No
spin-1	t-chan	spin-1	-	-	Yes	Yes	Yes
spin-1	t-chan	spin-1/2	V, A	V, A	-	-	-



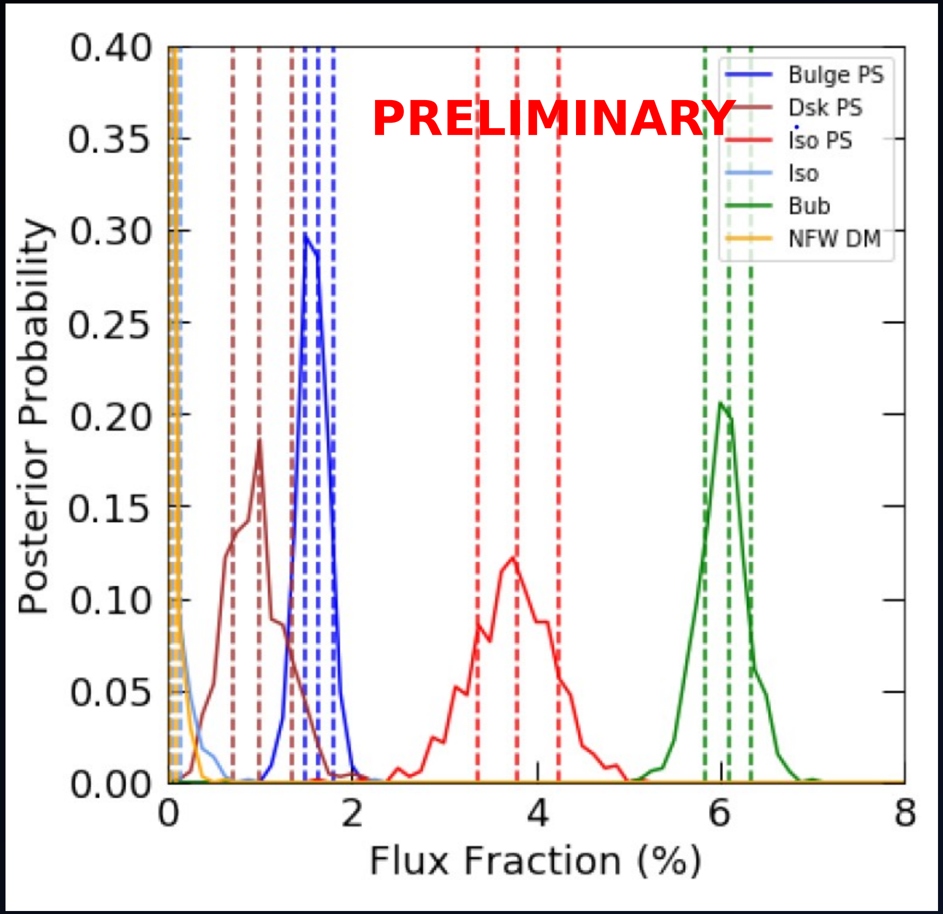
Default Background
Refit Point Sources
Alt. Gas Distribution
$E_\gamma^2 dN_\gamma/dE_\gamma$ (GeV/cm^2/s)
10^{-6}
10^{-7}
10^{-8}
10^0
10^1
10^2
E_γ (GeV)

WHAT ABOUT THE BOXY BULGE?



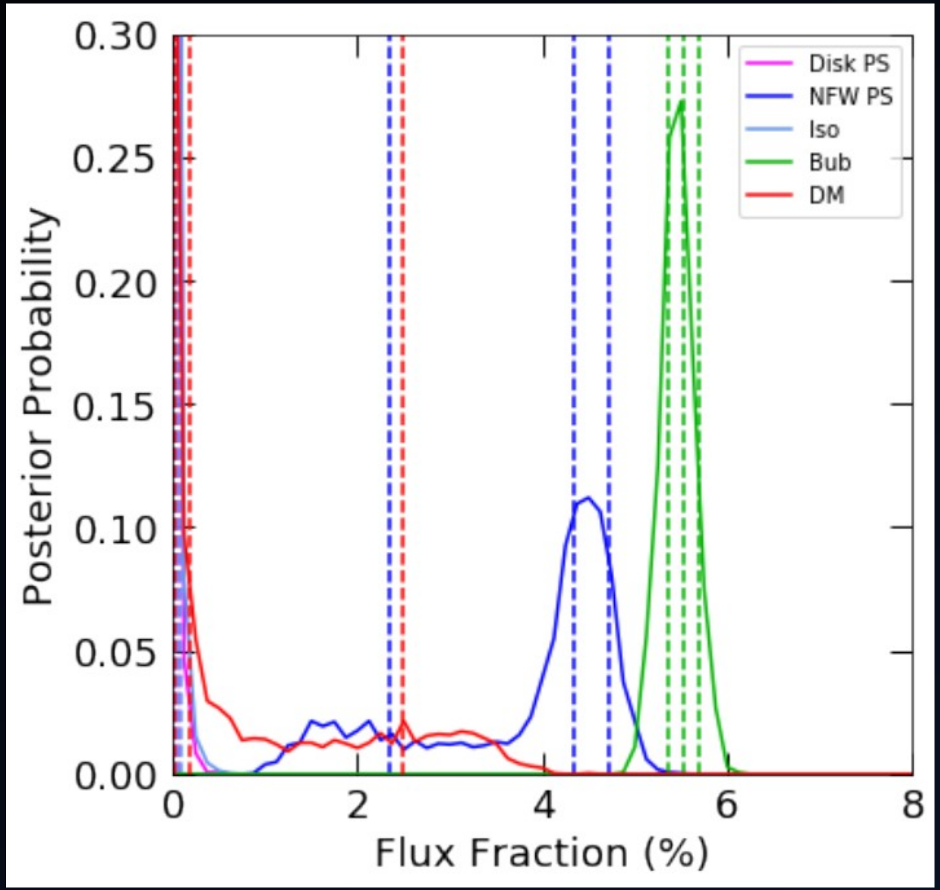
- Population of stars at the GC
- Unmodelled candidate could impact interpretation of the data

BOXY BULGE CAN EXPLAIN GCE



- Find evidence for PS associated with the Boxy Bulge!
- Can do just as well as NFW PS. Beats in some cases.

…BUT CAN'T BIAS THE NPTF



In simulated data, successfully recover the DM component when Bulge emission is simulated, and is analyzed with NFW PS.

VARYING THE DIFFUSE MODEL

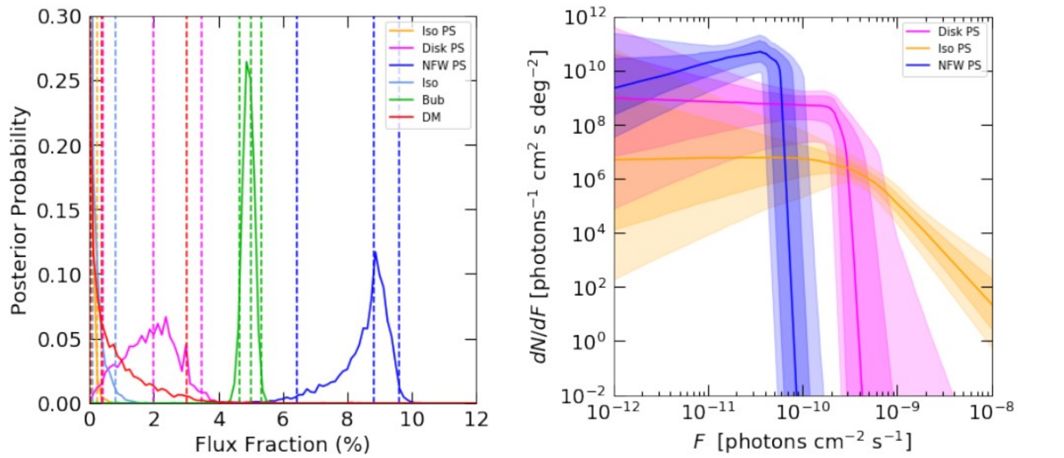


Figure 15. Same as Fig. 8, but replacing the Pass 6 *Fermi* diffuse model with the diffuse Model A from Ref. [7], and injecting a DM flux making up $\sim 4.5\%$ of the gamma-ray sky.

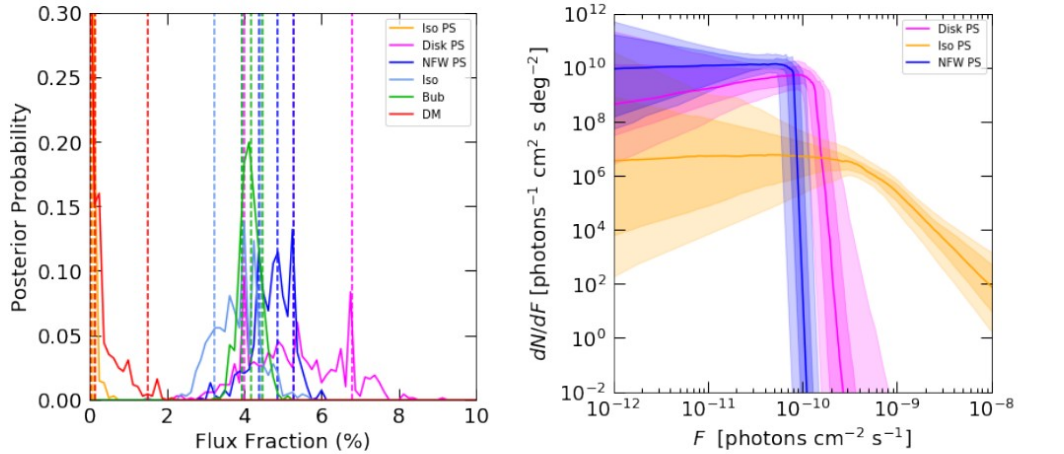


Figure 16. Same as Fig. 8, but replacing the Pass 6 *Fermi* diffuse model with the diffuse Model F from Ref. [7], and injecting a DM flux making up $\sim 2.8\%$ of the gamma-ray sky.

Simulated Data, 3FGL Masked						
Simulation	**Injected DM Flux**	**Analysis Templates**	**DM Flux (95%)**	**Bayes Factor**		
Bubbles PS	$\sim 1.5\%$	Same as simulated	$[1.2, 2.1]\ \%$	$\sim 10^{39}$		$\sim 10^{49}$
Disk PS		Same but Bubbles PS $\to$ NFW PS	$[0.0, 0.2]\ \%$ **DEFICIT**		$\sim 10^{9}$	
NFW DM		Same but no Bubbles PS	$[0.0, 0.9]\ \%$			
Bubbles PS	$\sim 12.5\%$	Same as simulated	$[11.8, 12.8]\ \%$	$\sim 10^{19}$		$\sim 10^{27}$
Disk PS		Same but Bubbles PS $\to$ NFW PS	$[8.8, 10.8]\ \%$ **DEFICIT**		$\sim 10^{8}$	
NFW DM		Same but no Bubbles PS	$[11.1, 12.2]\ \%$			
Bulge PS	$\sim 1.5\%$	Same as simulated	$[0.4, 2.5]\ \%$	$\sim 10^{18}$		$\sim 10^{29}$
Disk PS		Same but Bulge PS $\to$ NFW PS	$[0.0, 3.5]\ \%$		$\sim 10^{10}$	
NFW DM		Same but no Bulge PS	$[3.9, 5.0]\ \%$			

<table>
<tr><th colspan="6">Real Data, 3FGL Masked</th></tr>
<tr><th>Injected DM Flux</th><th>Analysis Templates</th><th>DM Flux (95%)</th><th colspan="3">Bayes Factor</th></tr>
<tr><td rowspan="2">None</td><td>Disk PS + Iso PS
Diffuse + Iso P + Bub P + DM</td><td>$[\,0.8, 1.9\,]$ %</td><td colspan="3" rowspan="2">$\sim 10^{13}$</td></tr>
<tr><td>Disk PS + Iso PS + NFW PS
Diffuse + Iso P + Bub P+ DM</td><td>$[\,0.0, 0.2\,]$ %</td></tr>
<tr><td rowspan="3">$\sim 1.5\%$</td><td>Disk PS + Iso PS
Diffuse + Iso P + Bub P + DM</td><td>$[\,2.2, 3.3\,]$ %</td><td rowspan="2">$\sim 10^{16}$</td><td></td><td></td></tr>
<tr><td>Disk PS + Iso PS + NFW PS
Diffuse + Iso P + Bub P + DM</td><td>$[\,0.0, 0.3\,]$ %
DEFICIT</td><td rowspan="2">$\sim 10^{3}$</td><td></td></tr>
<tr><td>Disk PS + Iso PS + NFW PS
Diffuse + Iso P + Bub P + Fixed DM</td><td>Fixed at injection value ($\sim 1.5\%$)</td><td></td><td>$\sim 10^{13}$</td></tr>
<tr><td rowspan="2">$\sim 8\%$</td><td>Disk PS + Iso PS
Diffuse + Iso P + Bub P + DM</td><td>$[\,8.2, 9.3\,]$ %</td><td colspan="3" rowspan="2">$\sim 10^{23}$</td></tr>
<tr><td>Disk PS + Iso PS + NFW PS
Diffuse + Iso P + Bub P + DM</td><td>$[\,0.0, 0.9\,]$ %
DEFICIT</td></tr>
<tr><td rowspan="2">$\sim 20\%$</td><td>Disk PS + Iso PS
Diffuse + Iso P + Bub P + DM</td><td>$[\,20.6, 21.7\,]$ %</td><td colspan="3" rowspan="2">$\sim 10^{12}$</td></tr>
<tr><td>Disk PS + Iso PS + NFW PS
Diffuse + Iso P + Bub P + DM</td><td>$[\,11.2, 17.2\,]$ %
DEFICIT</td></tr>
</table>

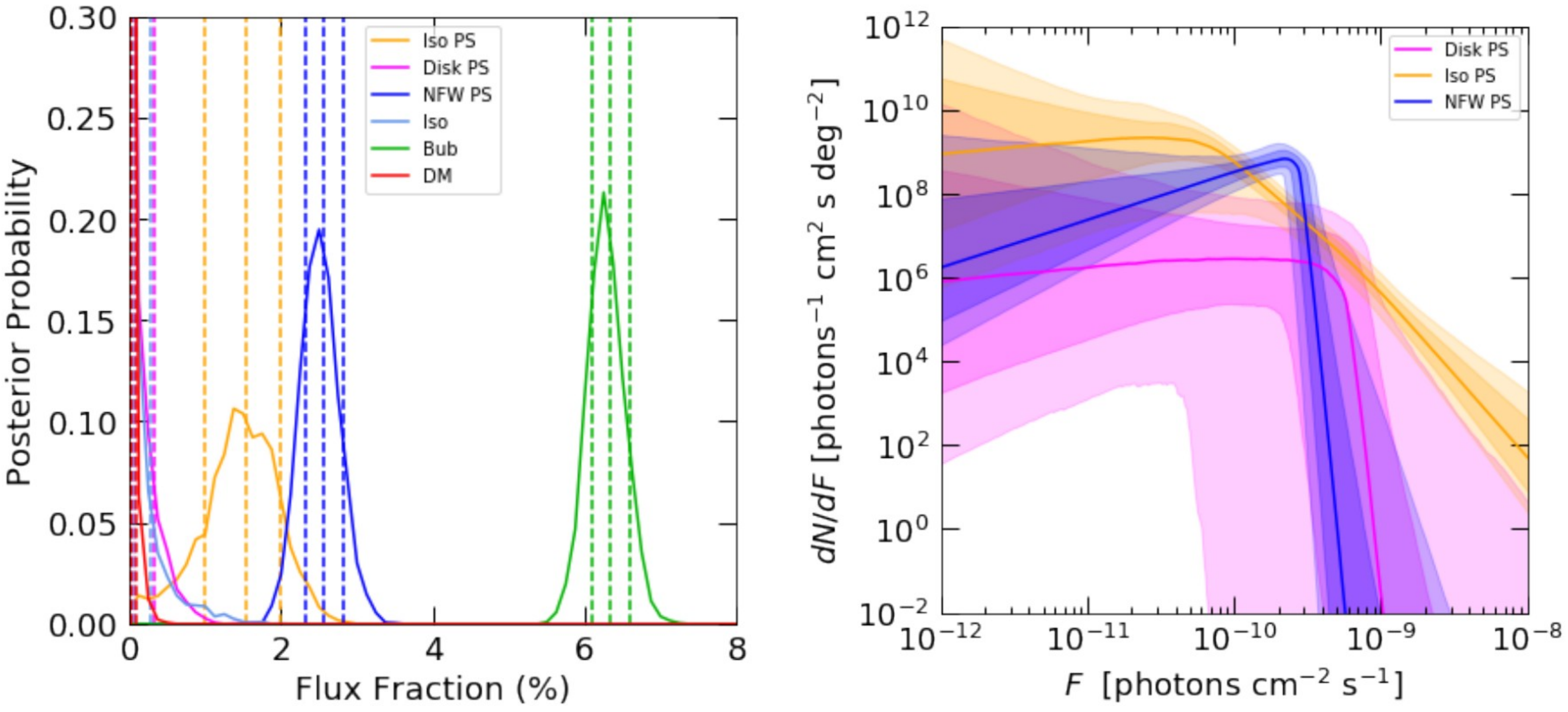


Figure 7. Inner Galaxy (masked) results for analysis of the real *Fermi* data without any added simulated DM signal. **Left:** Flux posteriors when analyzed with NFW PS, Disk PS, Isotropic PS, and Poisson NFW DM, Bubbles, Isotropic and Diffuse backgrounds. **Right:** Luminosity functions for this scenario for NFW PS, Disk PS, and Isotropic PS.

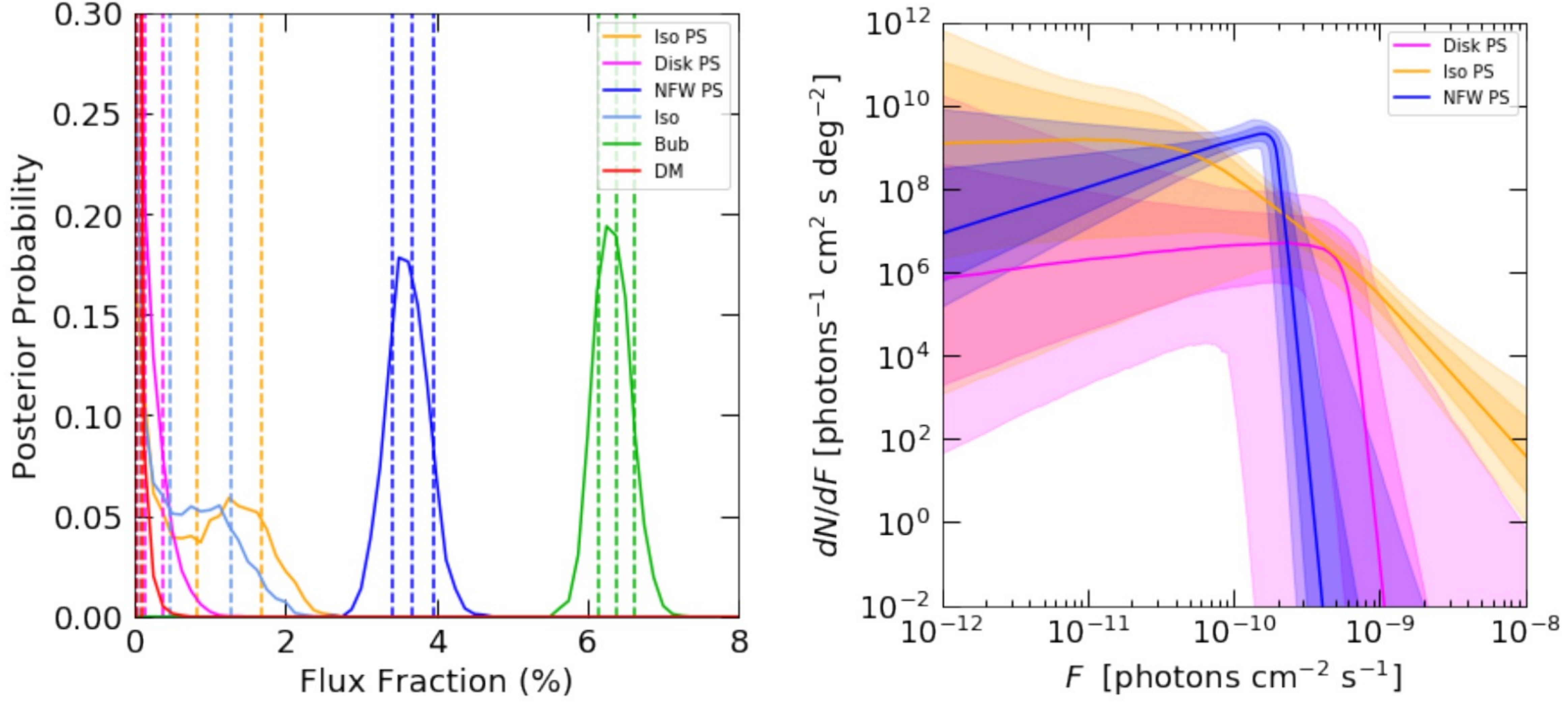


Figure 8. Inner Galaxy (masked) results for the case where fake DM signal (flux $\sim 1.5\%$ of sky) is injected into the *Fermi* data. **Left:** Flux posteriors when analyzed with NFW PS, Disk PS, Isotropic PS, and Poisson NFW DM, Bubbles, Isotropic and Diffuse backgrounds. **Right:** Luminosity functions for this scenario for NFW PS, Disk PS, and Isotropic PS.

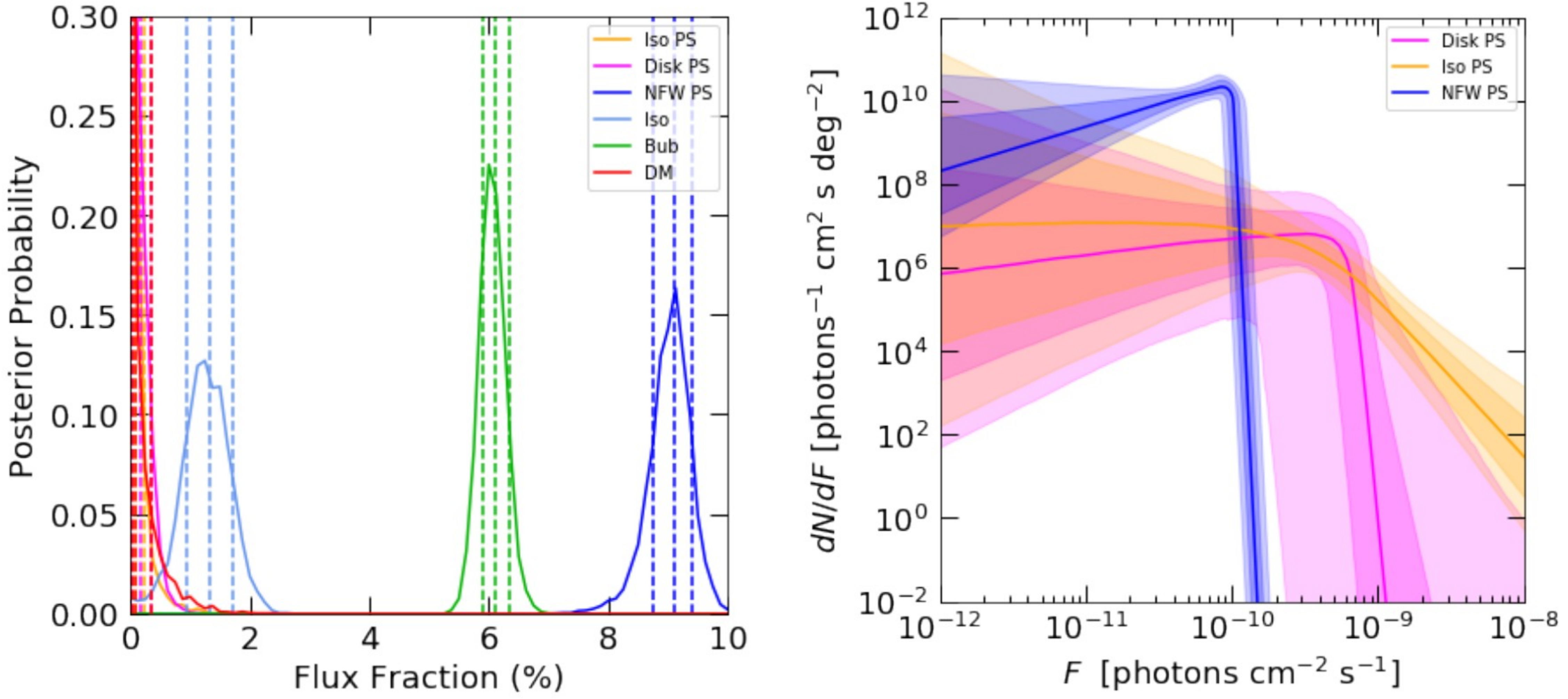


Figure 10. Inner Galaxy (masked) results for the case where fake DM signal with a larger normalization (flux $\sim 8\%$ of sky) is injected into the *Fermi* data. **Left:** Flux posteriors when analyzed with NFW PS, Disk PS, Isotropic PS, and Poisson NFW DM, Bubbles, Isotropic and Diffuse backgrounds. **Right:** Luminosity functions for this scenario for NFW PS, Disk PS, and Isotropic PS.

EXCESS CANDIDATES

- Pulsars
  - Matching gamma-ray spectrum
  - Small scale power in inner Galaxy gamma-ray emission
  - BUT why don’t we see the low-mass X-ray binaries in the Inner Galaxy?
  - AND luminosity function of pulsars doesn’t match Lee at al (2015)
    - Population of MSPs would have to be different to those in disk of the Milky Way or globular clusters
- Cosmic Outbursts
- Annihilating DM?

DIFFUSE TEMPLATE

Diffuse gamma-ray emission in Milky Way

= Gas density x CR proton density

+ gas density x CR electron density

+ photon density x CR electron density

Use Fermi diffuse model, p6v11