

Title: Dark Matter Strikes Back at the Galactic Center

Speakers: Rebecca Leane

Series: Particle Physics

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Abstract: Statistical evidence has previously suggested that the Galactic Center GeV Excess (GCE) originates largely from point sources, and not from annihilating dark matter. In this talk, I will discuss the impact of unmodeled source populations on identifying the true origin of the GCE. In a proof-of-principle example with simulated data, I will demonstrate that unmodeled sources in the Fermi Bubbles can lead to a dark matter signal being misattributed to point sources. Furthermore, I will show there is striking behavior consistent with a mismodeling effect in the real Fermi data, finding that large artificial injected dark matter signals are completely misattributed to point sources. Consequently, I will conclude that dark matter may provide a dominant contribution to the GCE after all, and discuss future directions.

# DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

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PERIMETER INSTITUTE  
JUN 24<sup>th</sup> 2019

1904.08430 + WORK TO APPEAR,  
WITH TRACY SLATYER



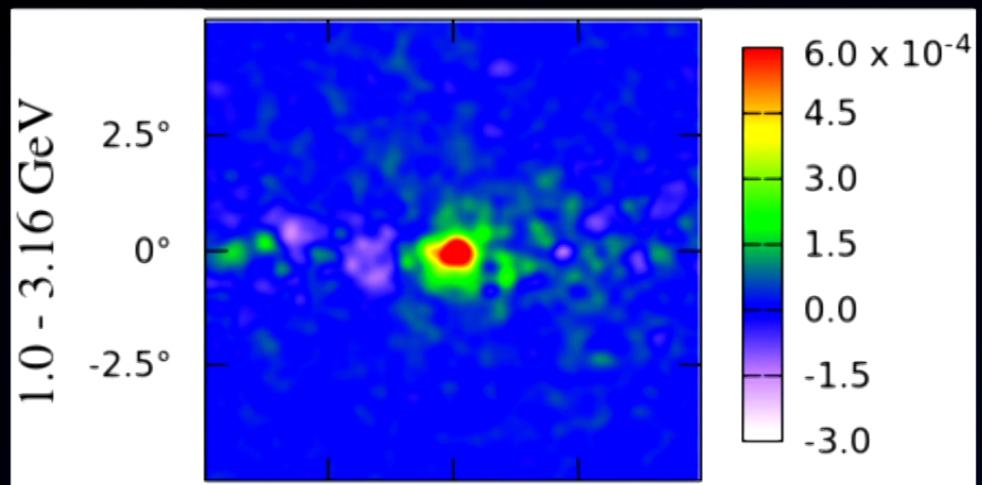
Massachusetts  
Institute of  
Technology

# THE GALACTIC CENTER GEV EXCESS

- Highly significant bright excess in gamma rays
- First discovered in 2009

Goodenough+Hooper '09

Origin still unknown!



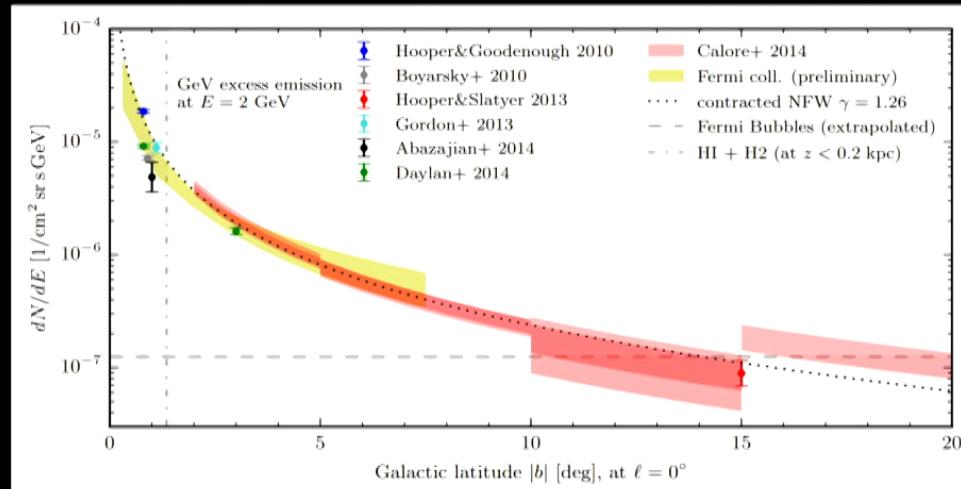
Daylan et al '14

Rebecca Leane

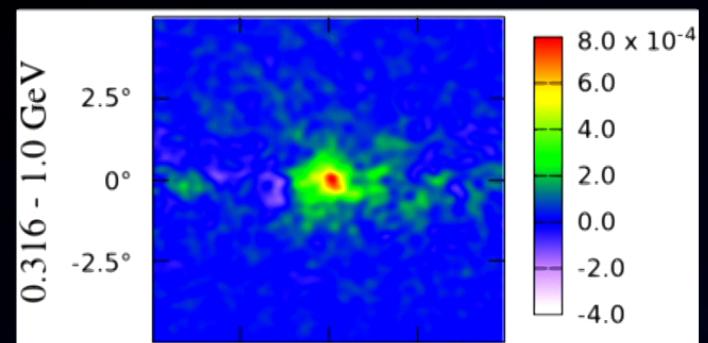


# MORPHOLOGY

Calore et al '14



Daylan et al '14



Spherically symmetric around GC

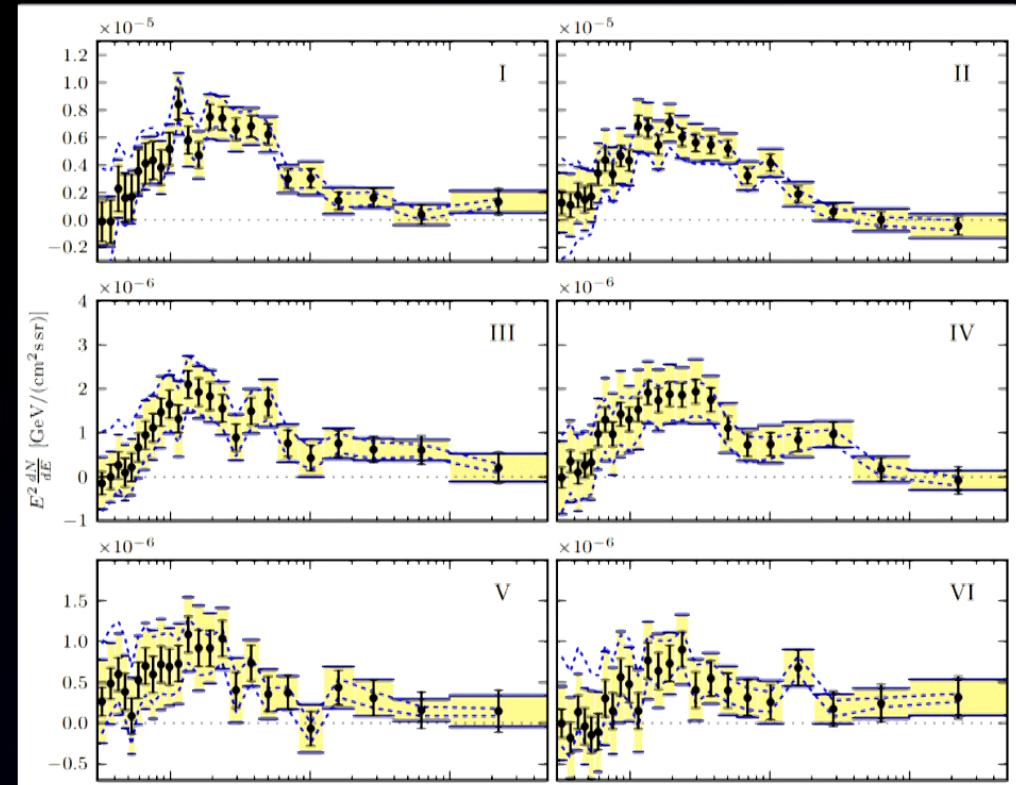
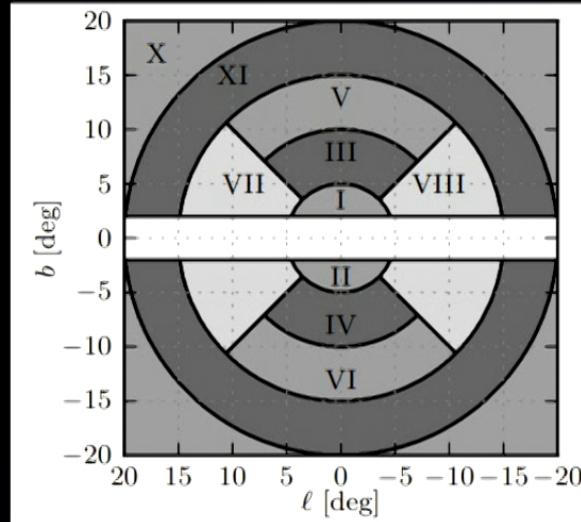
Scales like  $r^{-2.4}$  extending out to around  $10^\circ$ , fits  $\sim$ NFW profile

Hooper+ Slatyer '13

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# SPECTRUM



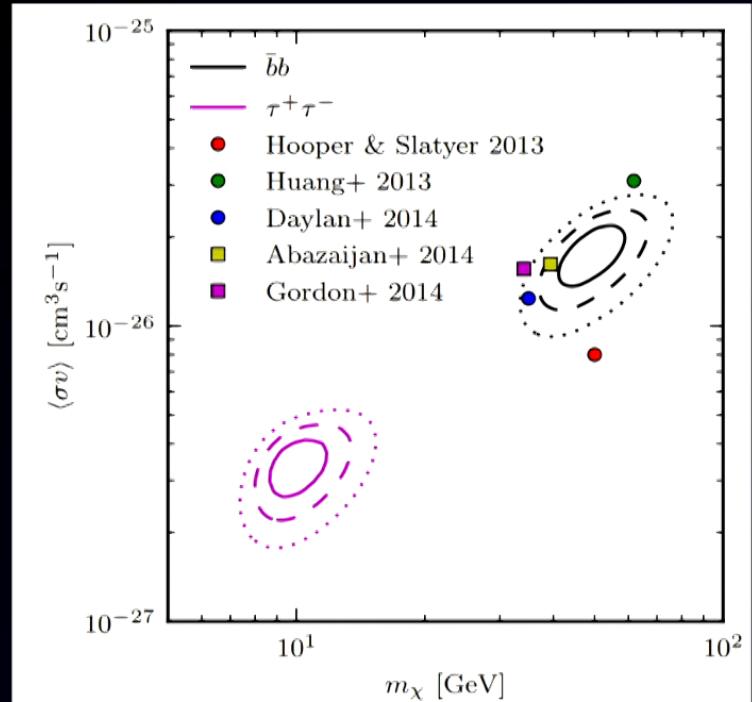
Calore et al '14

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# INTENSITY

Channel	$\langle \sigma v \rangle$ ( $10^{-26} \text{ cm}^3 \text{ s}^{-1}$ )	$m_\chi$ (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

Rebecca Leane



# SIGNAL OF ANNIHILATING DARK MATTER?

- Spatially consistent: approximately spherical, extending out of the center
- Intensity of thermal WIMP DM: can match thermal relic annihilation cross section
- If DM, first evidence of DM – SM interactions

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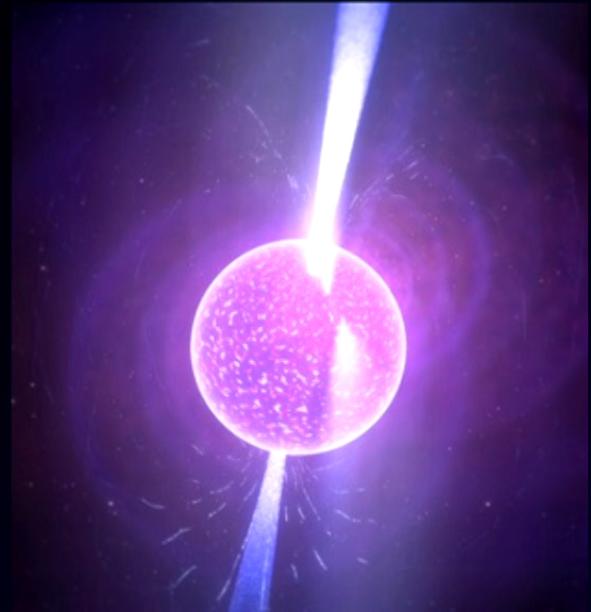


# POINT SOURCES AS THE EXCESS

- Favored alternative: millisecond pulsars!
- Separate studies find evidence for small scale power in GC  
Bartels et al '15, Lee et al '15
- MSPs also match the gamma ray spectrum

But why don't we see the low-mass x-ray binaries?

Cholis et al '14, Haggard et al '17

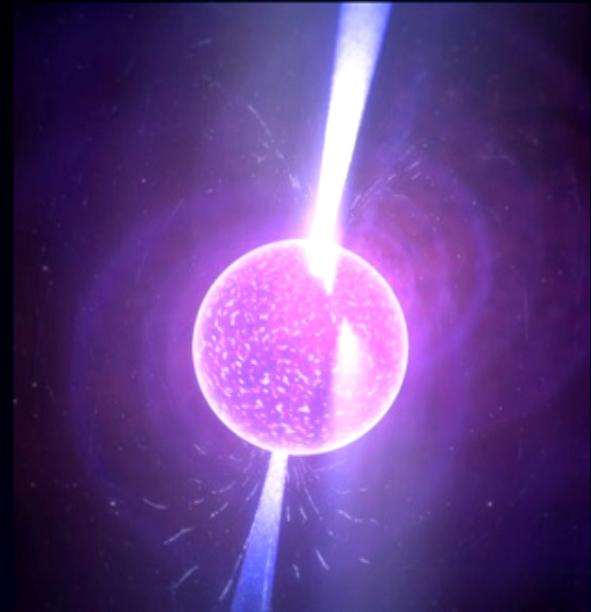


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# POINT SOURCES AS THE EXCESS

- 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



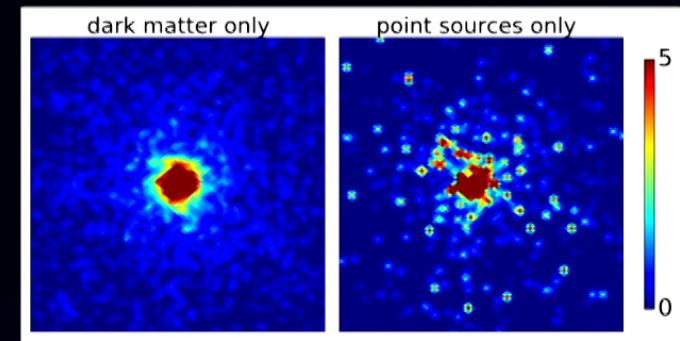
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# DISTINGUISHING DM vs. POINT SOURCES

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



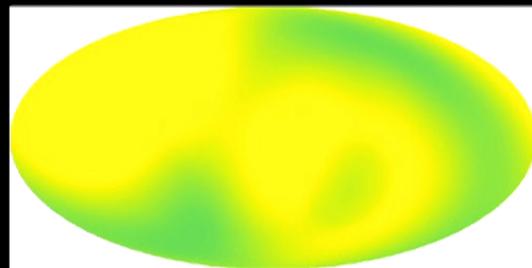
Lee+Lisanti+Safdi, '15

Drastically different predictions!

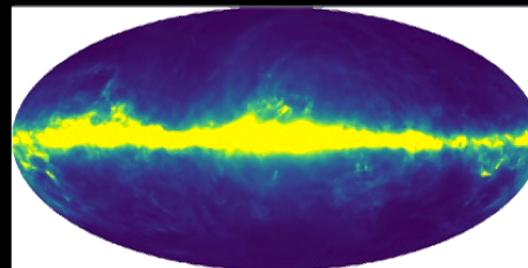
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# TEMPLATE FITTING



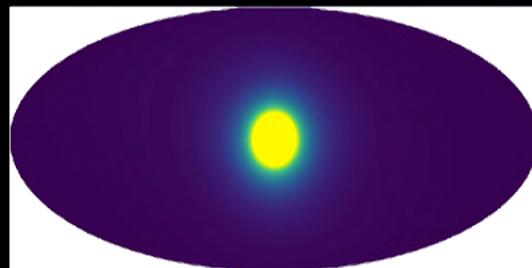
Isotropic



Diffuse



Bubbles



NFW

Assign statistics to each template.

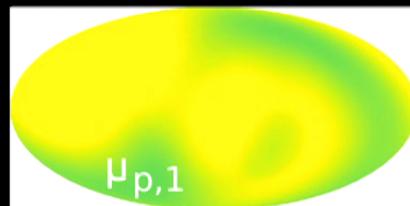
Exploit different statistical predictions, along different spatial distributions

Distinguish the origin of the excess gamma rays.

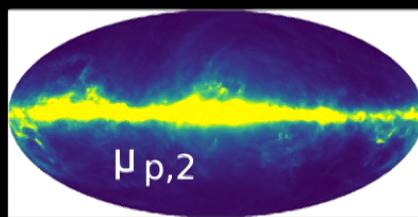
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# POISSON TEMPLATE FITTING



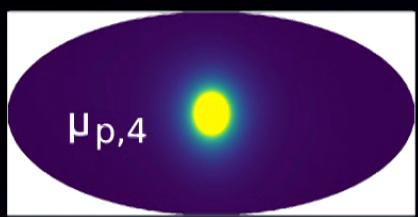
$\times \alpha_1$



$\times \alpha_2$



$\times \alpha_3$



$\times \alpha_4$

Prediction for each pixel

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

Likelihood per pixel is a Poisson distribution

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

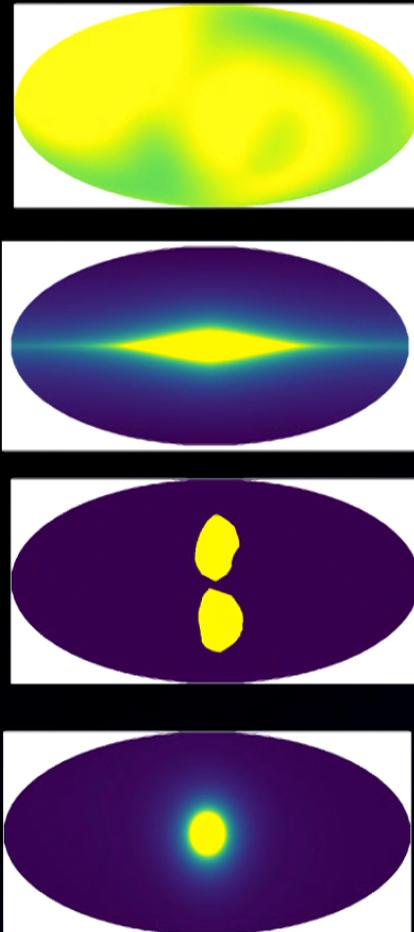
Total likelihood is given by product of Poisson likelihoods for each pixel

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

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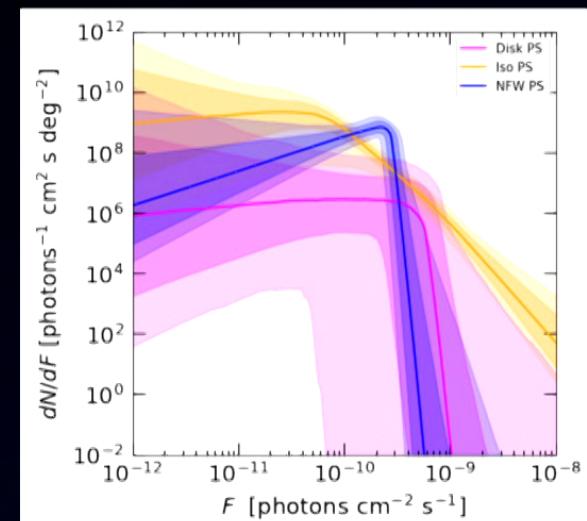
# NON-POISSON TEMPLATE FITTING



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  $n_1$  and  $n_2$ , and break  $S_b$



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# NON-POISSON TEMPLATE FITTING

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

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

**Non-Poisson** generating function:

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

**Poisson** generating function:

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

Expected number of m-photon sources is

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

SCF

PSF

probability seeing m photons  
when fS is expectation



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

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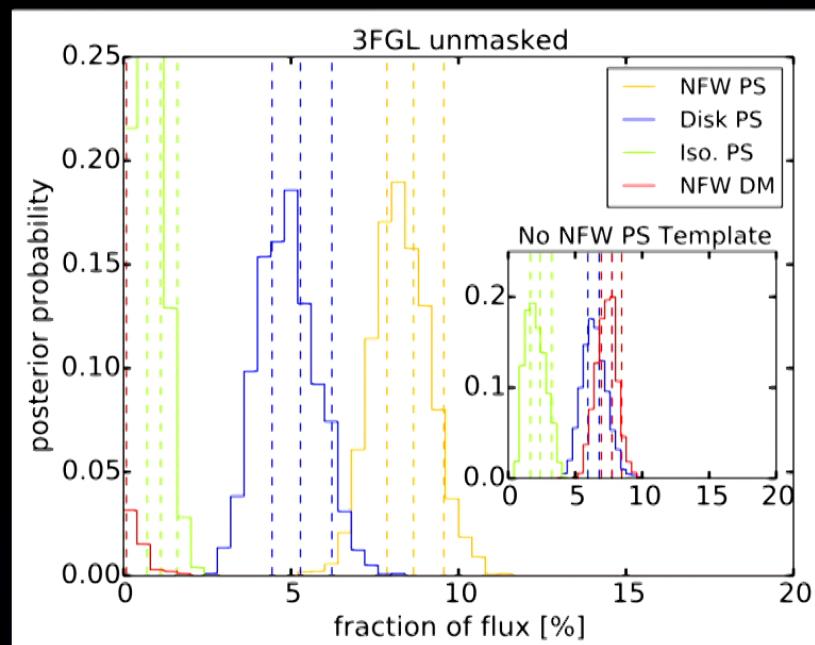
# NPTF TOOLS

- Analyze data using NPTFit  
(Mishra-Sharma, Rodd, Safdi '16)  
[github.com/bsafdi/NPTFit](https://github.com/bsafdi/NPTFit)
- Simulate NP data using NPTFit-Sim (Rodd+Toomey, in prog)  
[github.com/nrodd/NPTFit-Sim](https://github.com/nrodd/NPTFit-Sim)

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# PREFERENCE FOR POINT SOURCES AT THE GC

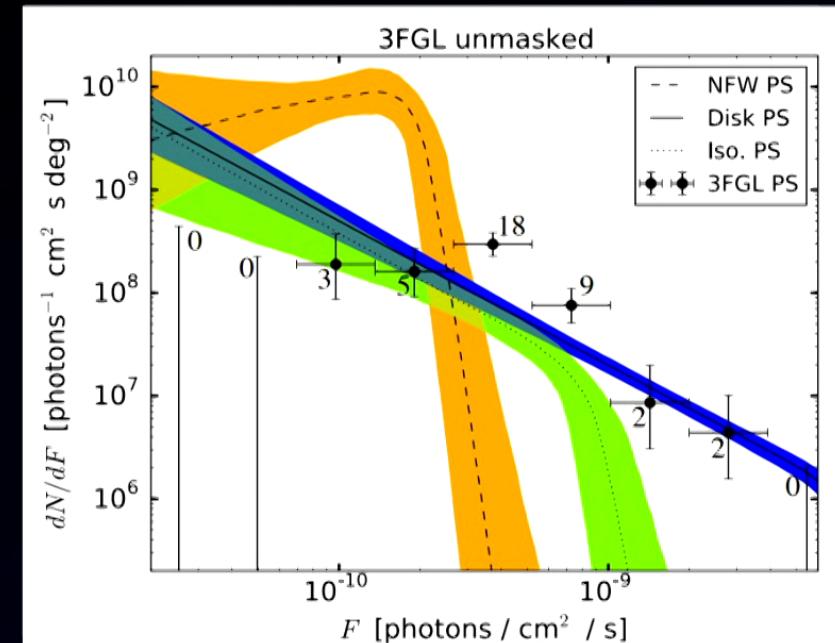
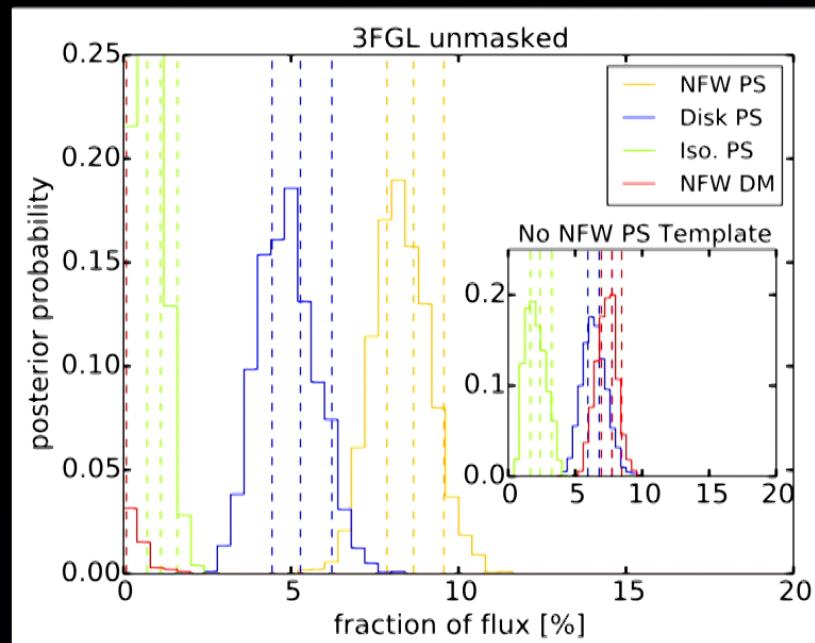


Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

Rebecca Leane



# PREFERENCE FOR POINT SOURCES AT THE GC



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

Rebecca Leane



# WHAT IS DRIVING THIS PREFERENCE?

Presence of some unmodelled source population could push up the NFW PS flux, and push down the inferred DM signal.

Investigate if a bias is possible:

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

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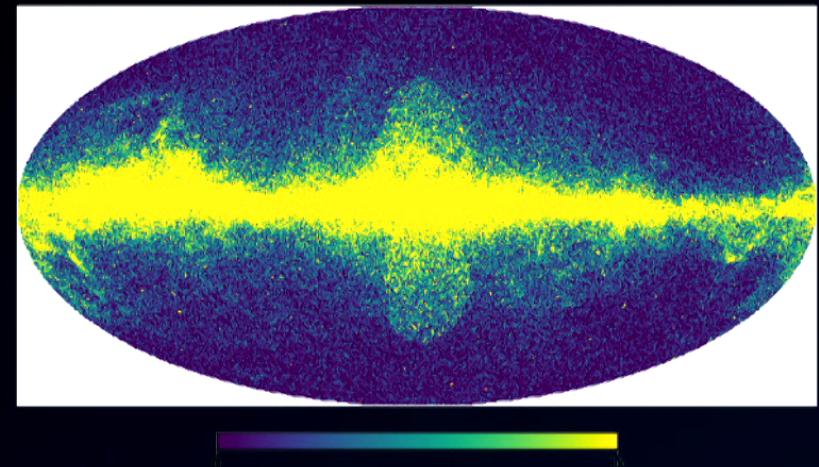
# BIAS SEARCH USING SIMULATED DATA

Simulate:

- **Point Sources:** along the Galactic Disk and Bubbles

Bubbles are the new ingredient, which we simulate as a possible source of bias  
(Potential gas clumps, Di Teodoro et al '18)

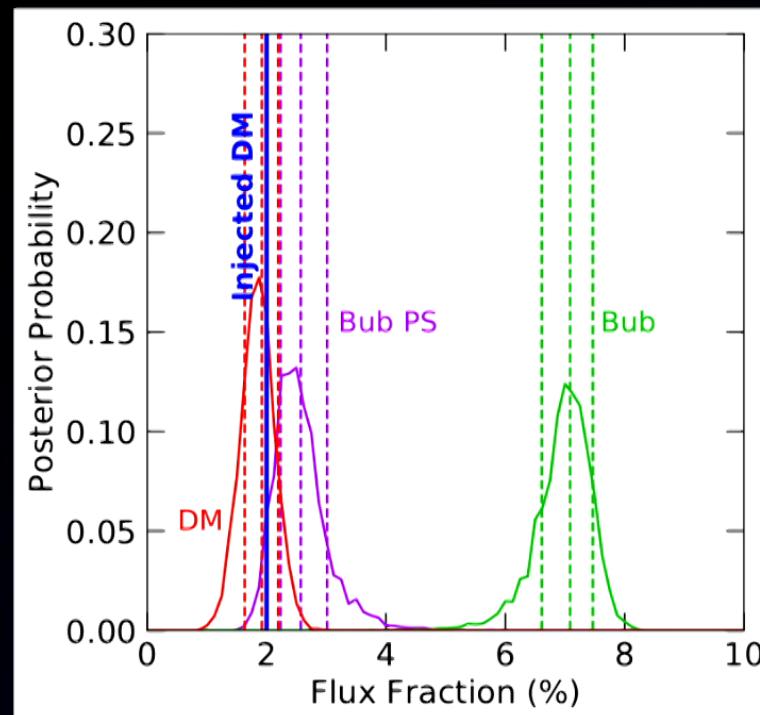
- **Smooth emission:** from isotropic+diffuse background, bubbles, and dark matter.



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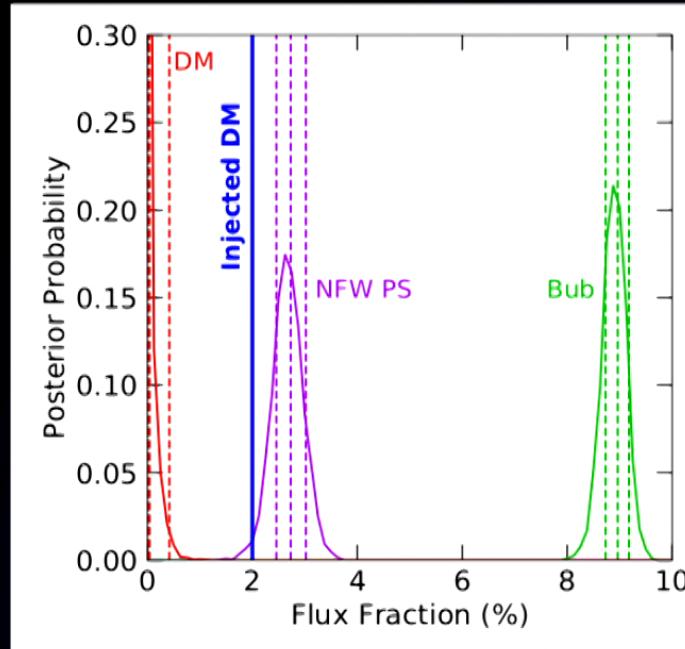
Analyze this data, with exactly the same templates.  
Return same normalizations.



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

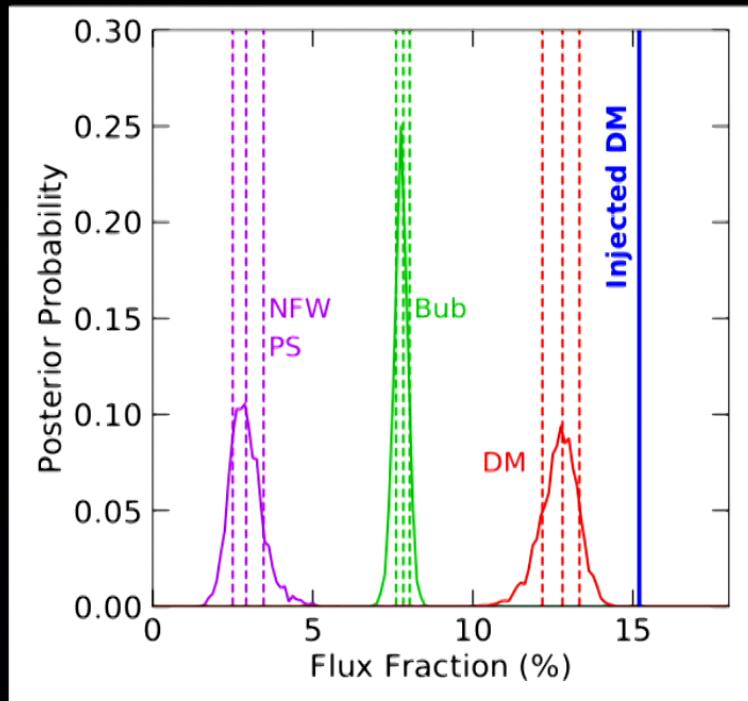


**The dark matter signal is misattributed to point sources!**

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# IS THERE A THRESHOLD IN SIMULATIONS?



Inject an order of magnitude more DM ( $\sim 15\%$ )

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

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# FIRST EVIDENCE OF MISATTRIBUTED DM

- Cross talk between templates appears to be possible, when an unmodelled component is present
- Behavior possible in masked and unmasked sky, different ROIs
- Large Bayes factor preference for adding NFW PS, and pushing DM flux down, just like Lee et al '15 paper

*...and in this case we KNOW dark matter is there!*

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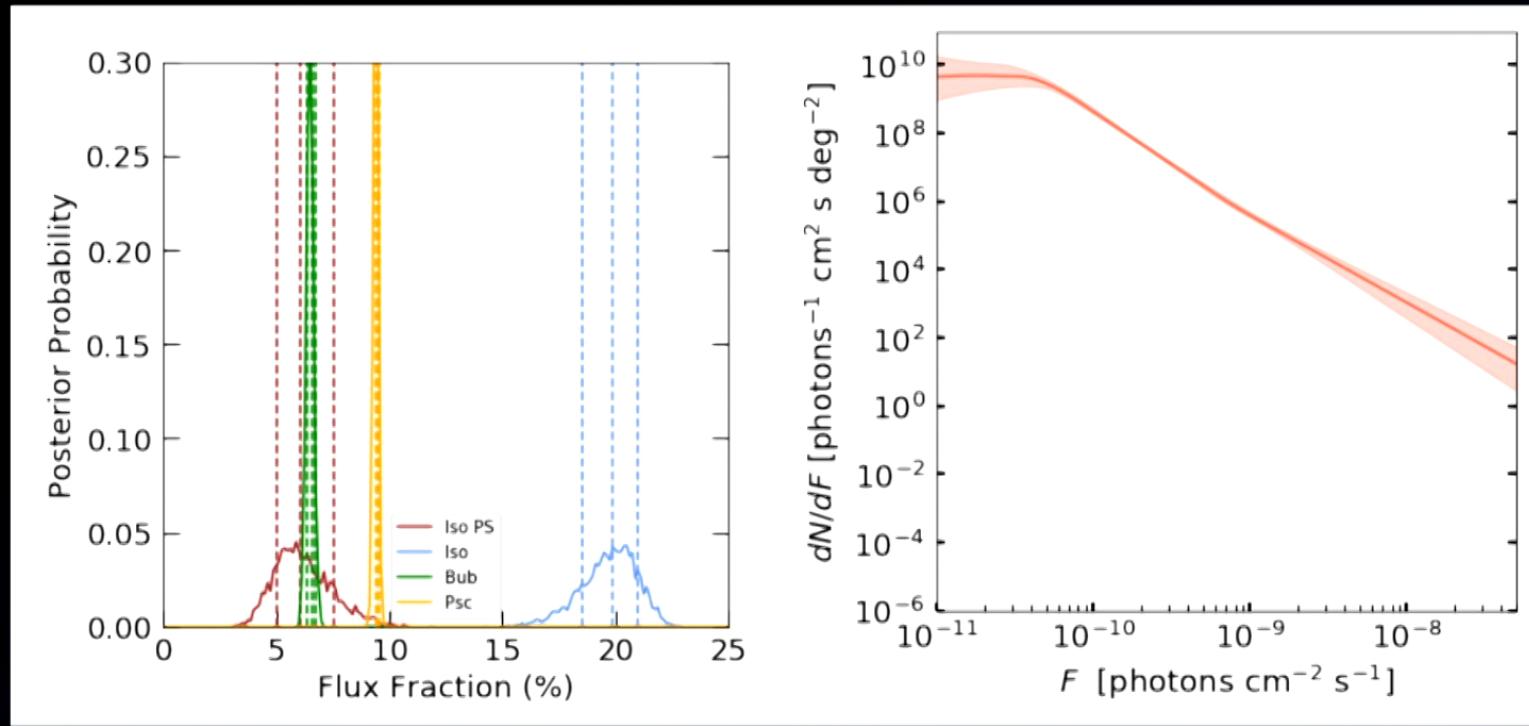
## ARE THERE PS ASSOCIATED WITH THE BUBBLES?

- Check several regions of sky: within longitudes of 20, 40, 60 deg, 2 or higher degrees masked through plane
- Analyze with and without PS in Fermi bubbles.
  - Include isotropic PS, disk PS at lower latitudes, plus poisson templates

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# EXAMINE WITHOUT BUBBLES PS

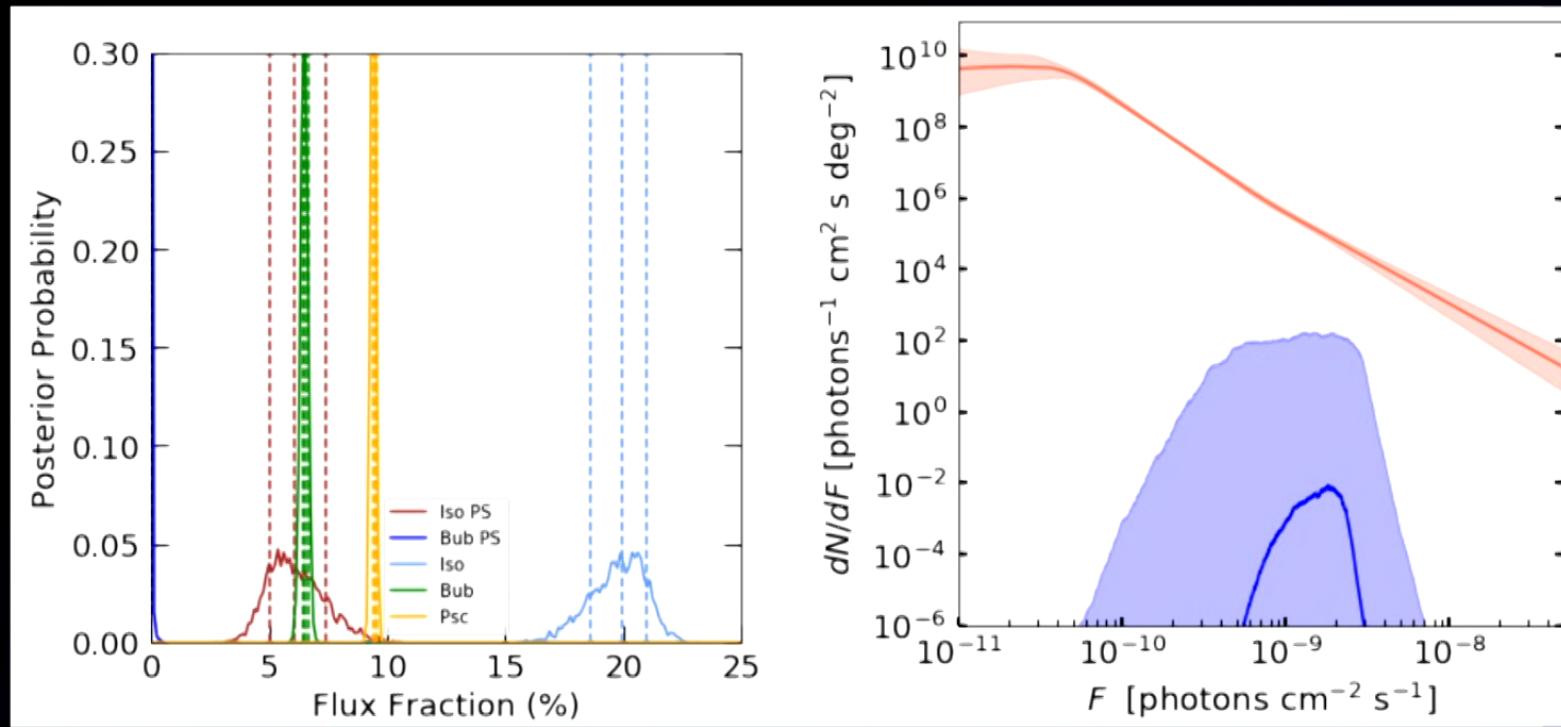


( $b > 20$  deg,  $|l| < 60$  deg)

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# ADD BUBBLES PS



( $b > 20$  deg,  $|l| < 60$  deg)

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## ARE THERE PS ASSOCIATED WITH THE BUBBLES?

See no meaningful change in Bayes factor.

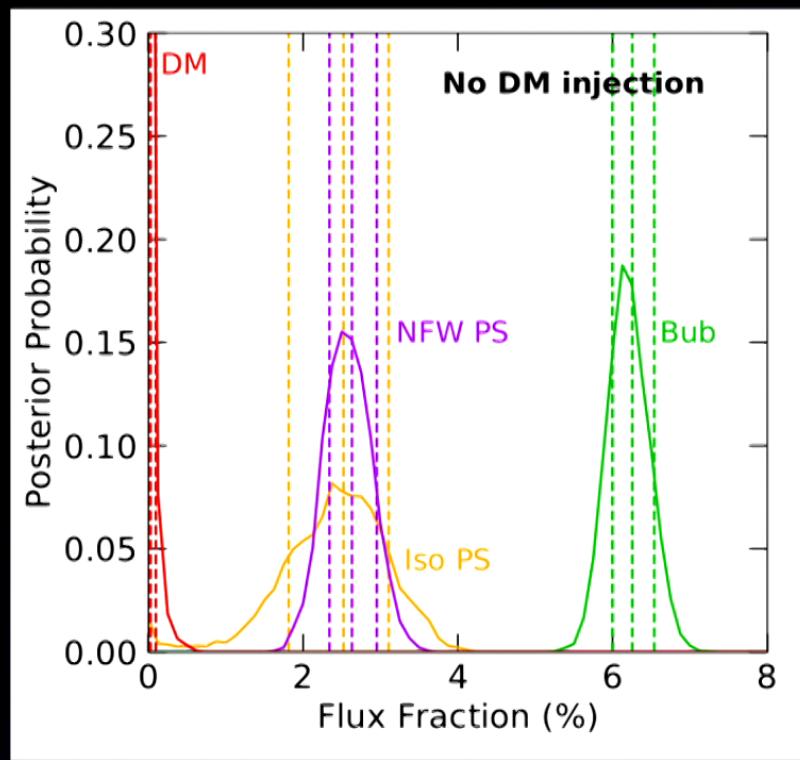
Find no evidence for point sources in the Fermi Bubbles.

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## FERMI DATA

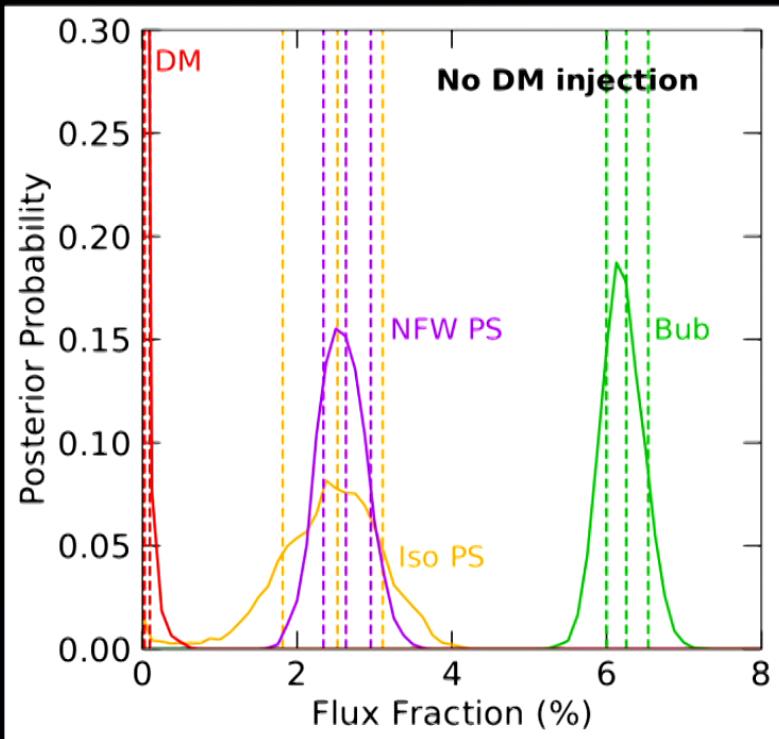
## INJECTED DM SIGNAL + DATA



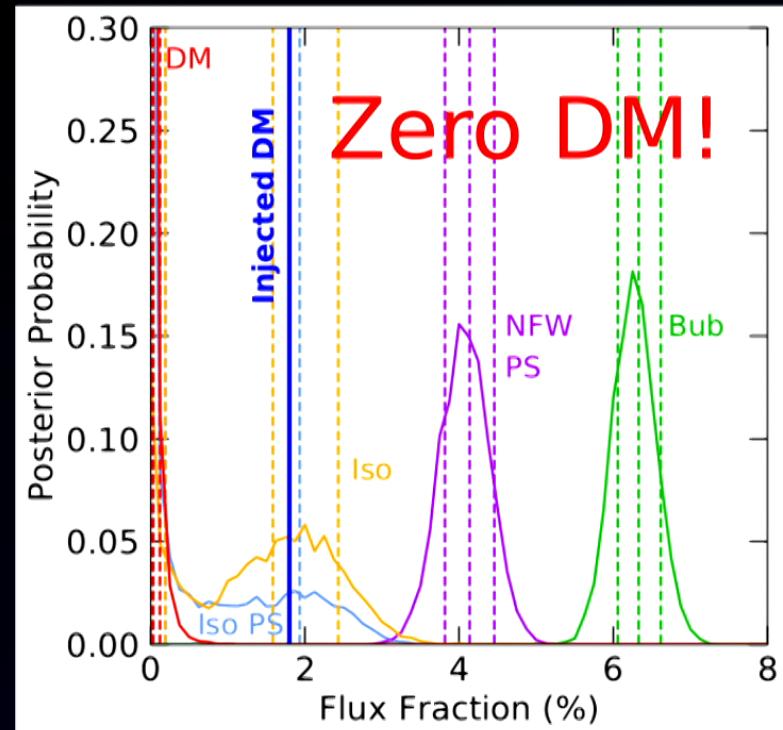
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## FERMI DATA



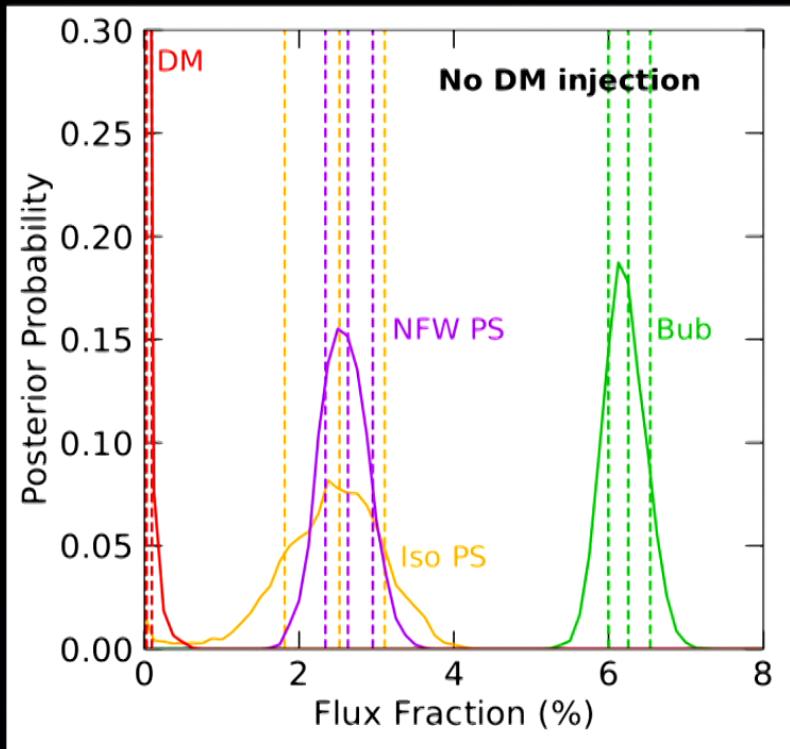
## INJECTED DM SIGNAL + DATA



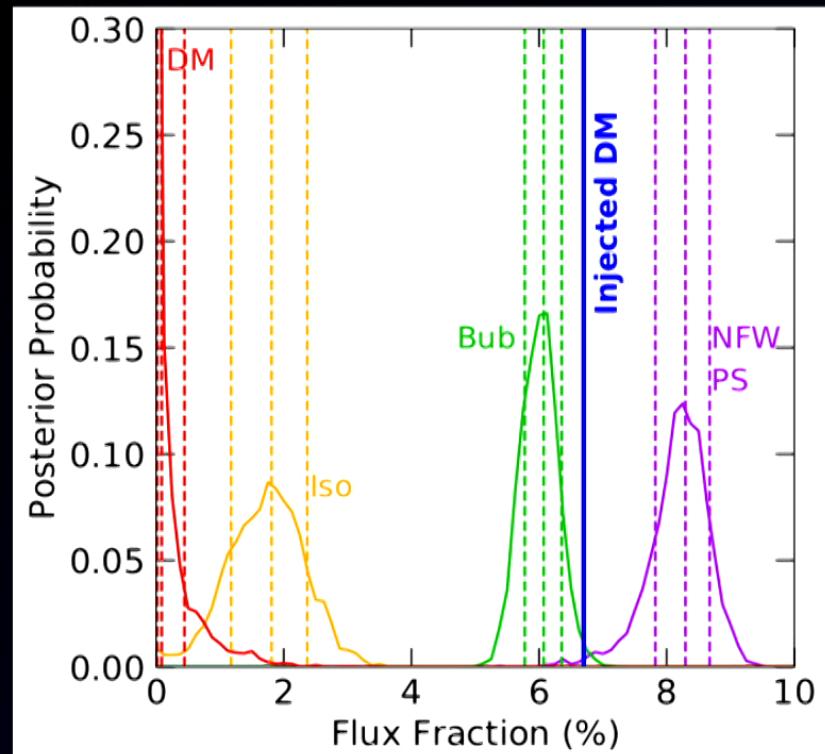
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## FERMI DATA



## LARGER INJECTED DM SIGNAL + DATA

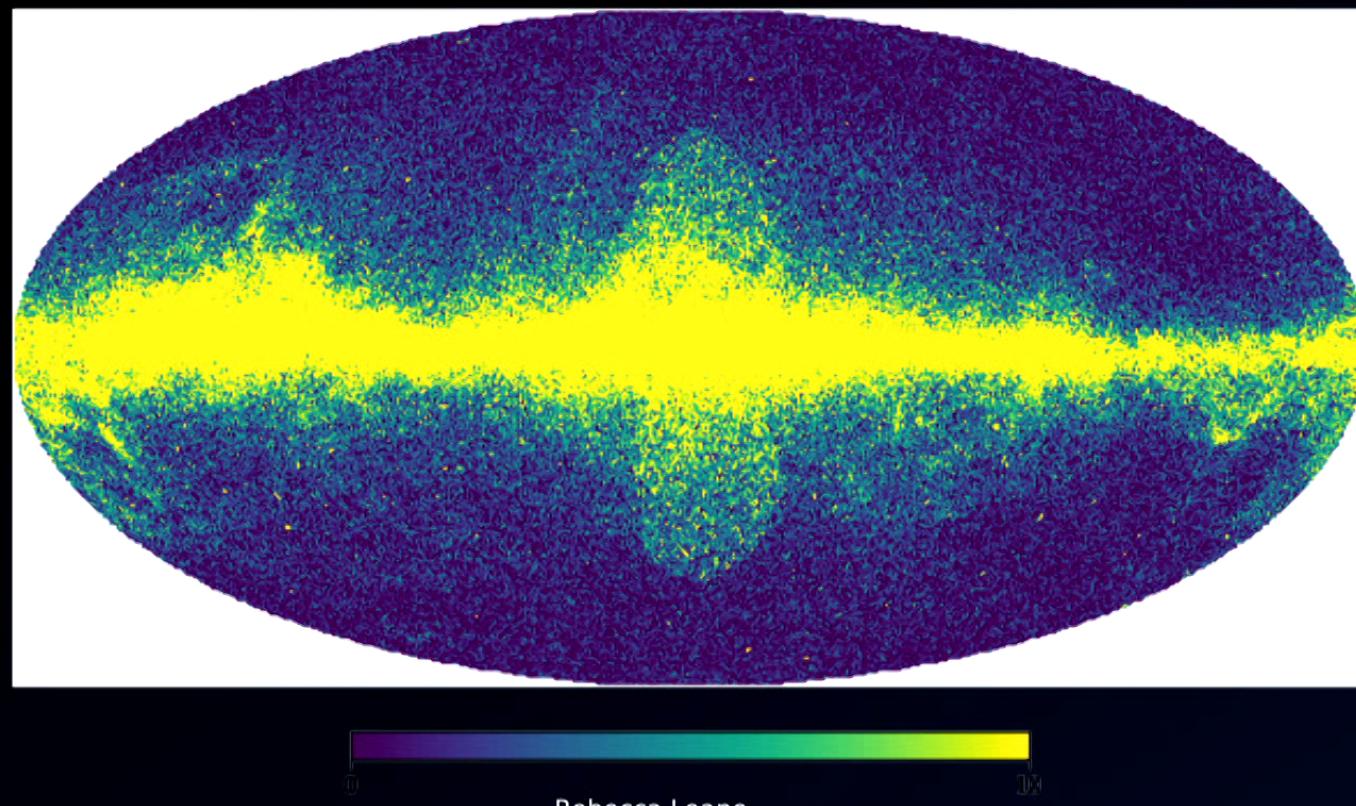


Zero DM!

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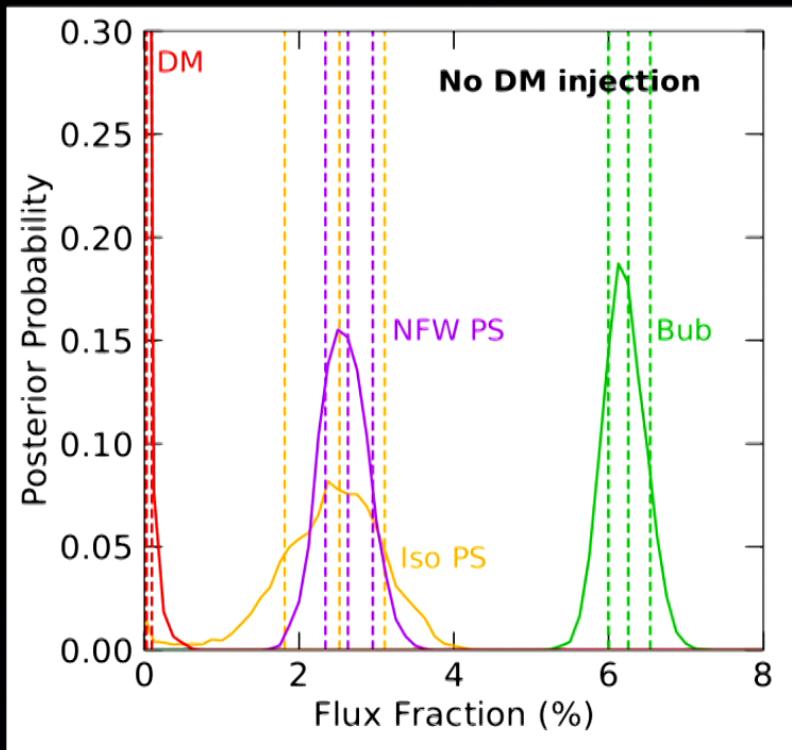


# BOMBARD THE GALAXY!

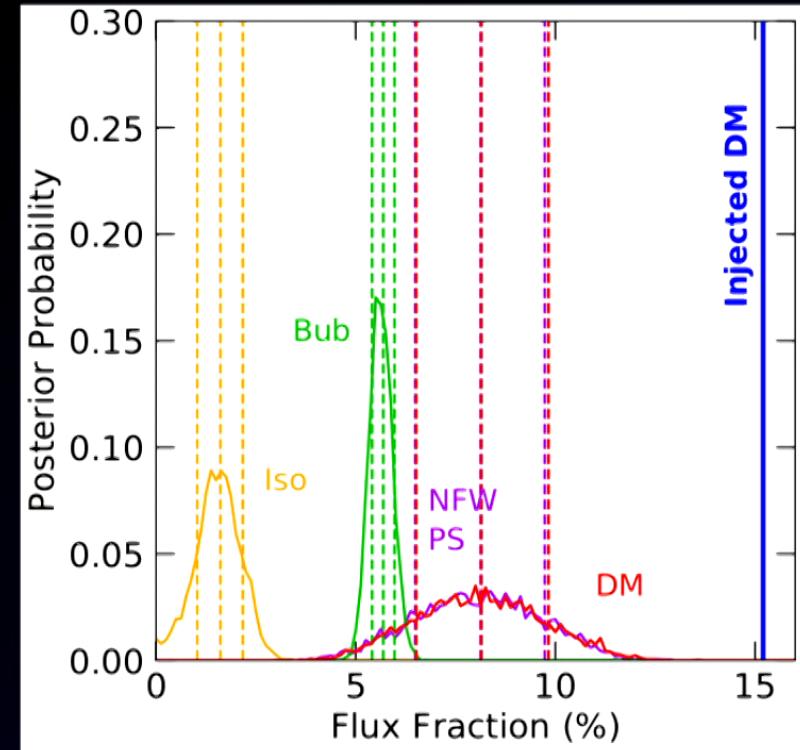


MIT

## FERMI DATA



## BOMBARDED DM SIGNAL + DATA

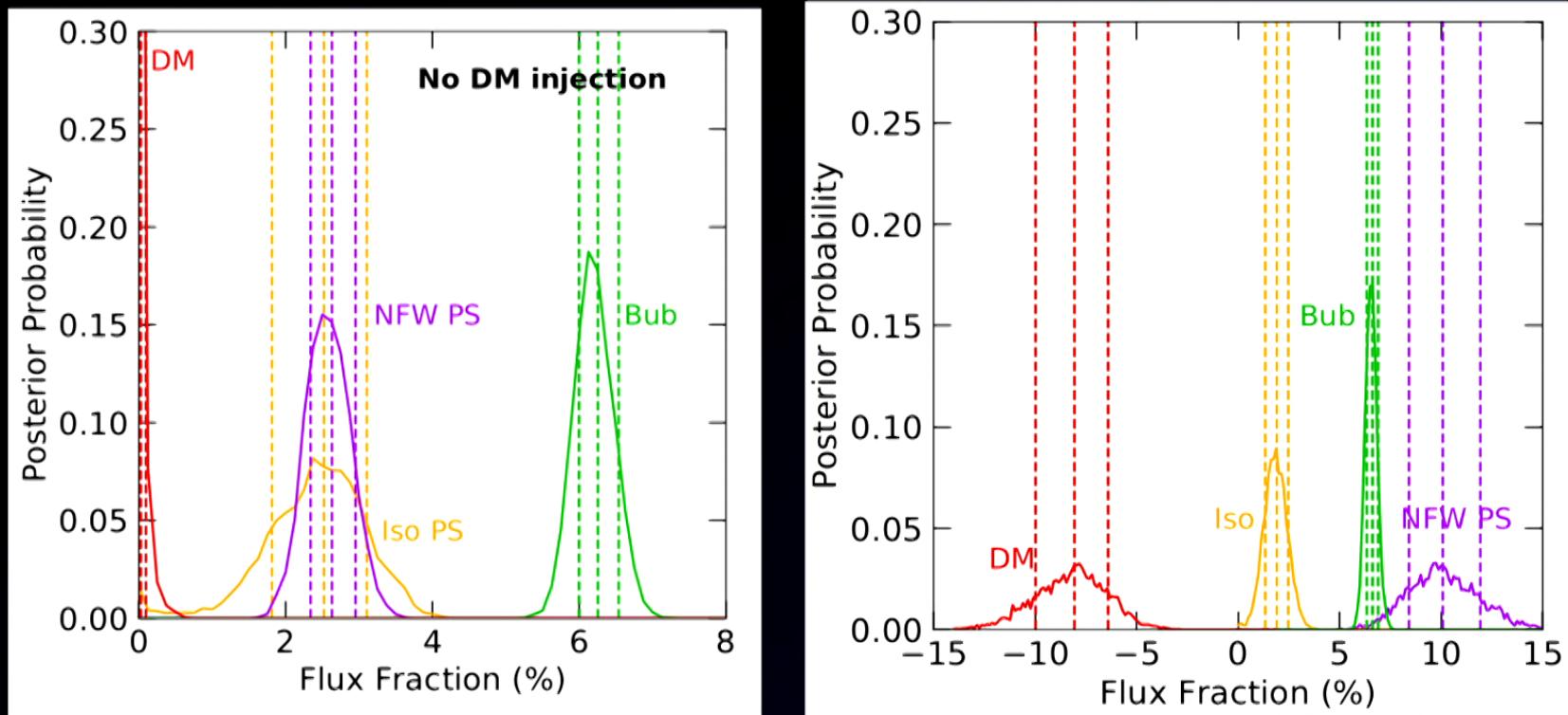


Finally, but low.

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# ALTERNATIVE TO INJECTION: GOING NEGATIVE



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- Both simulated example and real data show similar behavior, finding in all cases a significant Bayes factor 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
- Upper bounds on DM annihilation can be badly mis-estimated
- *DM could substantially contribute to the GCE!*

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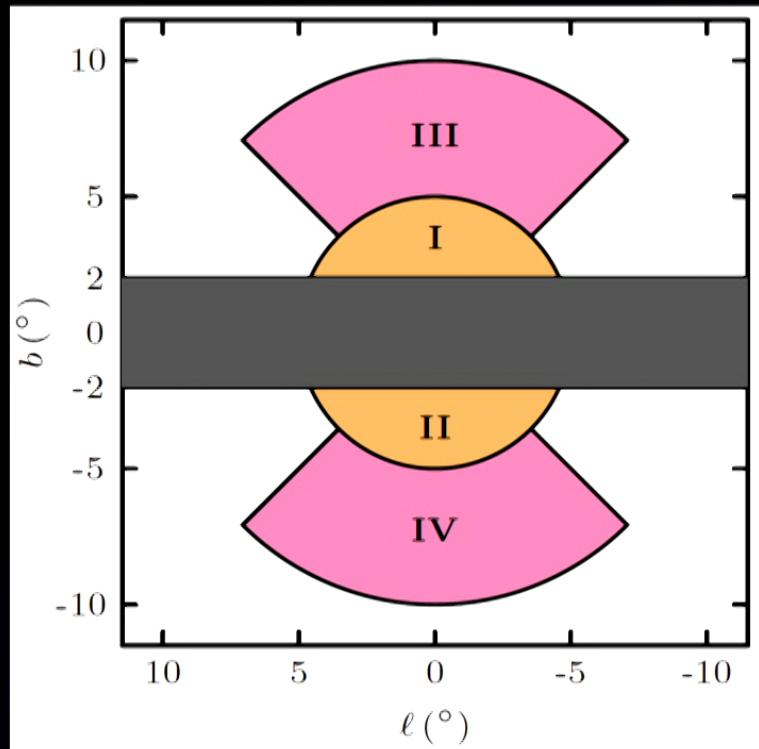
# SOME FURTHER INVESTIGATION

- Try bias test with some other well motivated point-source populations
- Break sky into different regions of interest, check if a particular region is causing this

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# POINT SOURCES IN DIFFERENT REGIONS?

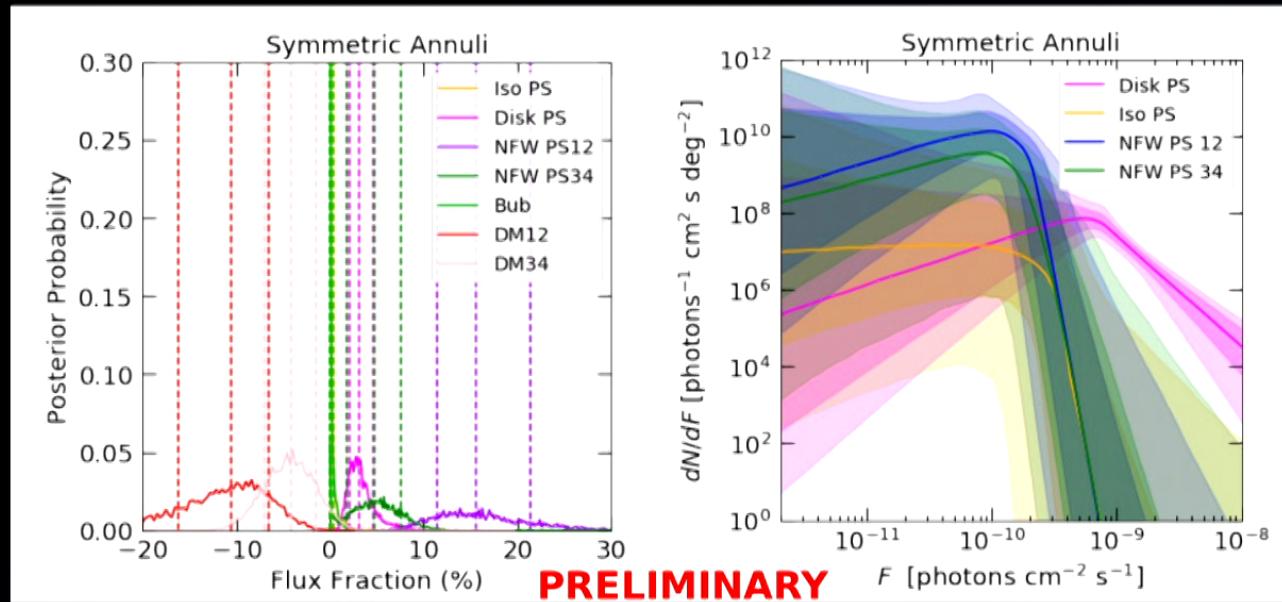


- Recently found smooth emission preference for  $b > 5\text{deg}$   
Balaji, Cholis, Fox, McDermott '18
- Annulus study, regions: 2-5, 5-10 deg of GC
- Also consistent with regions from earlier studies  
Calore, Cholis, Weniger '14

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# SYMMETRIC IN HEMISPHERES

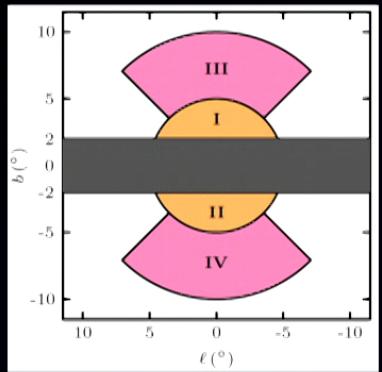
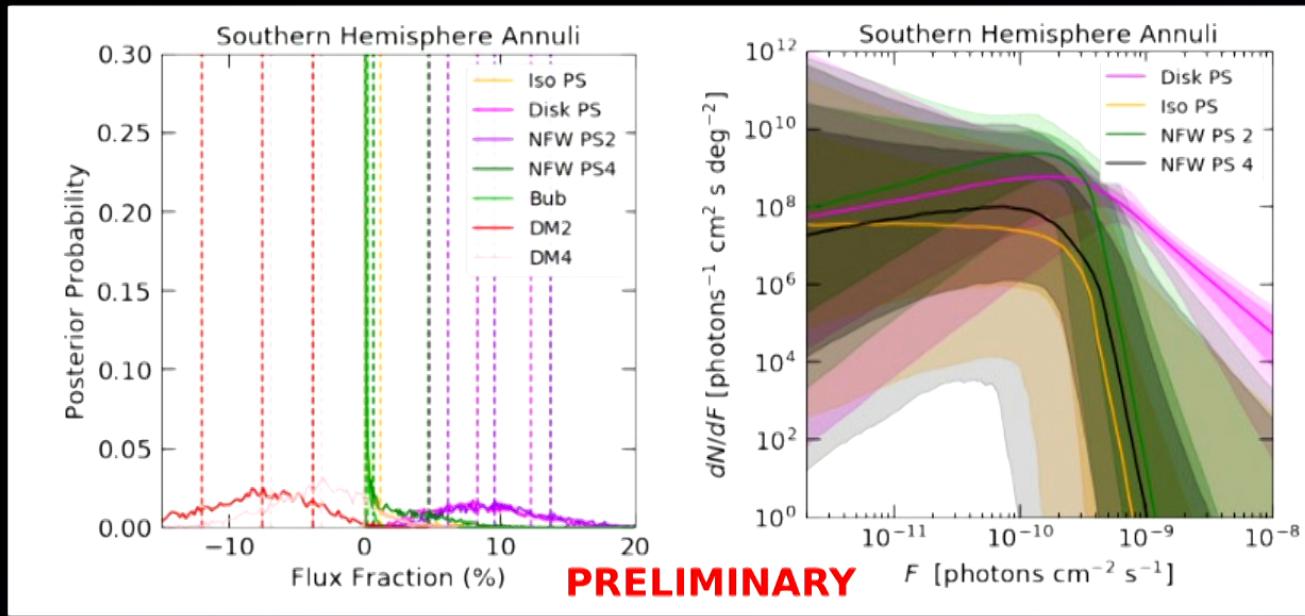


Mismodelling effect in both regions

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# SOUTHERN HEMISPHERE

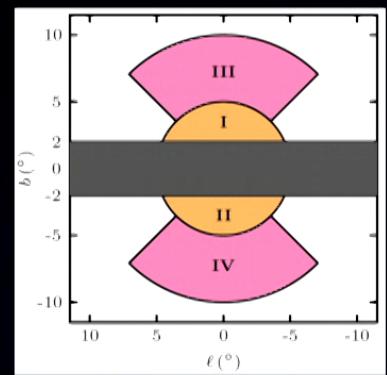
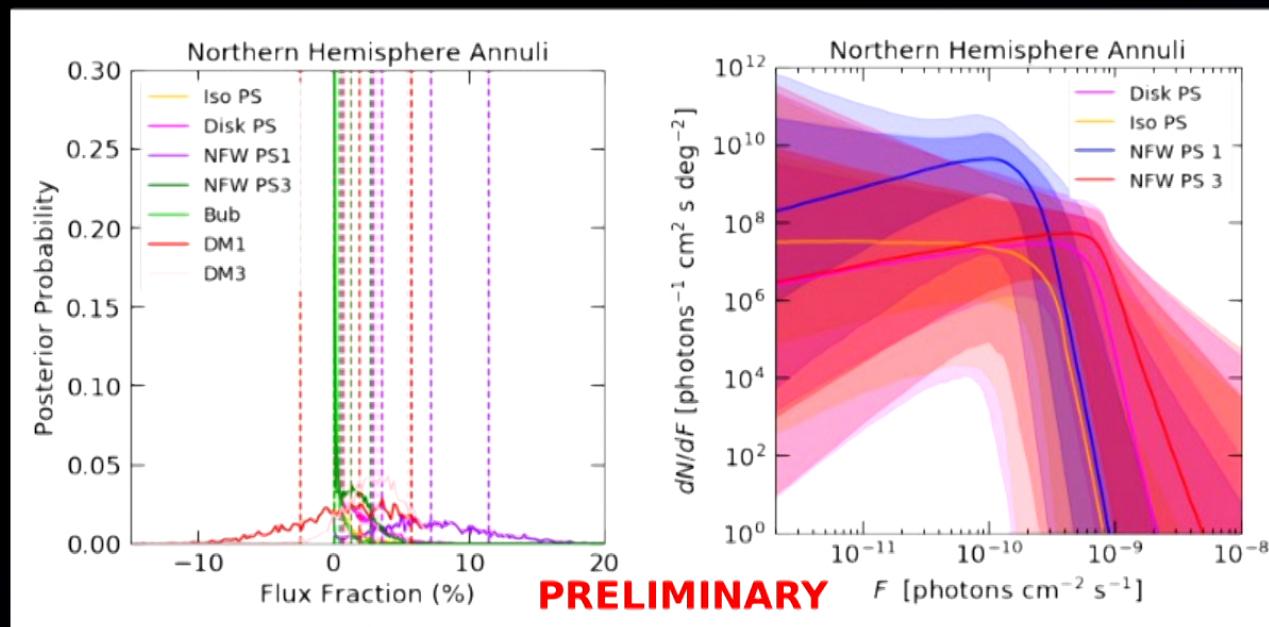


Deeply negative – culprit?

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# NORTHERN HEMISPHERE

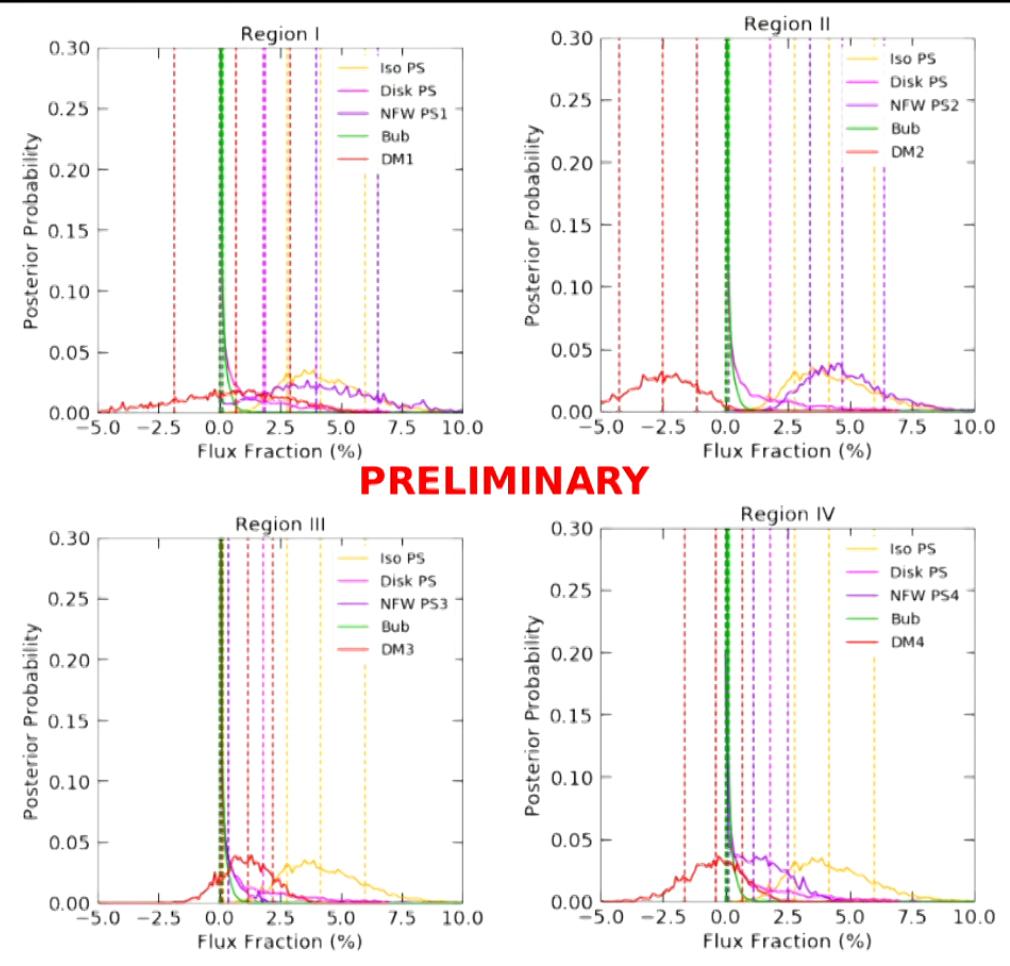


DM? Same region as Balaji et al '18 ...

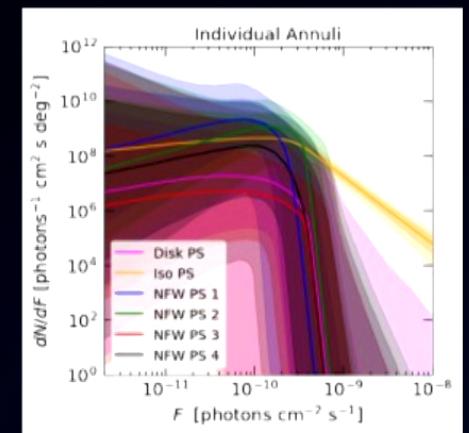
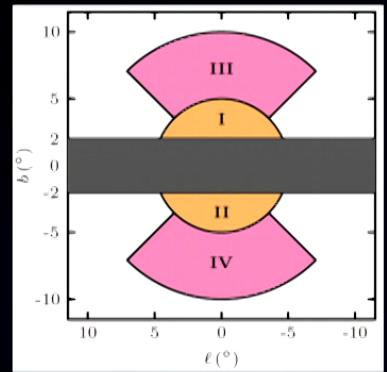
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ALL



PRELIMINARY



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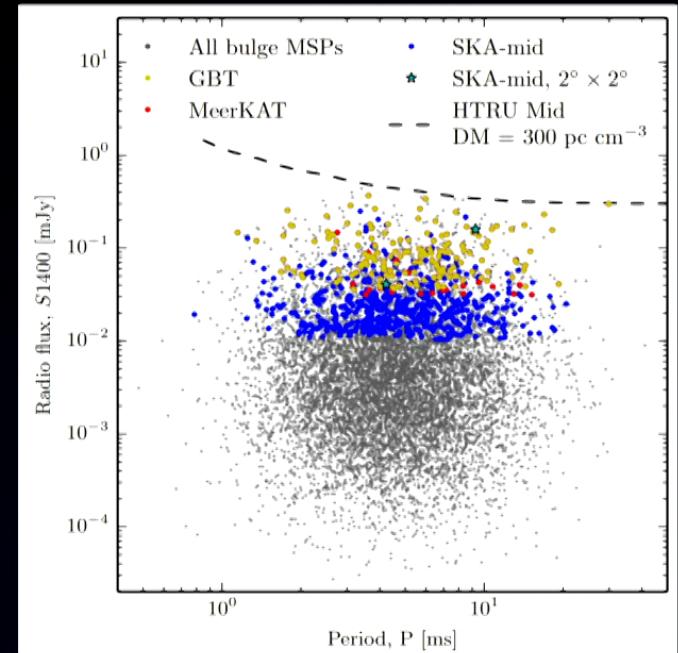
# MOVING FORWARD: DARK MATTER VS PULSARS

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# PULSARS?

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



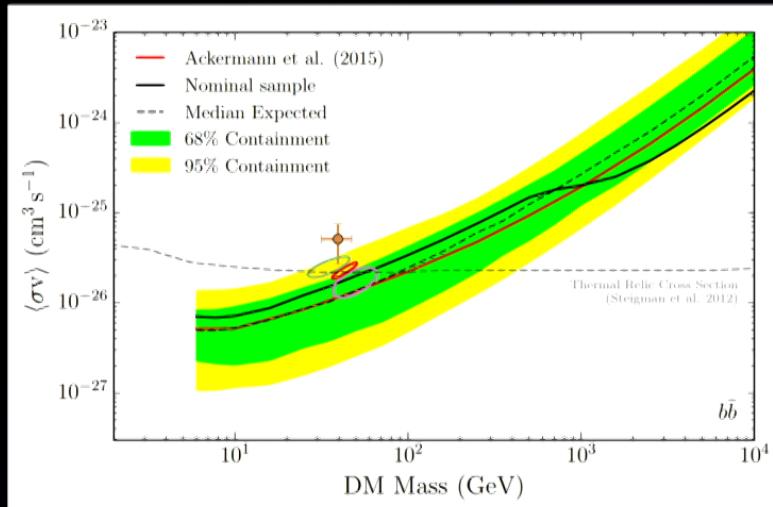
Calore et al 1512.06825

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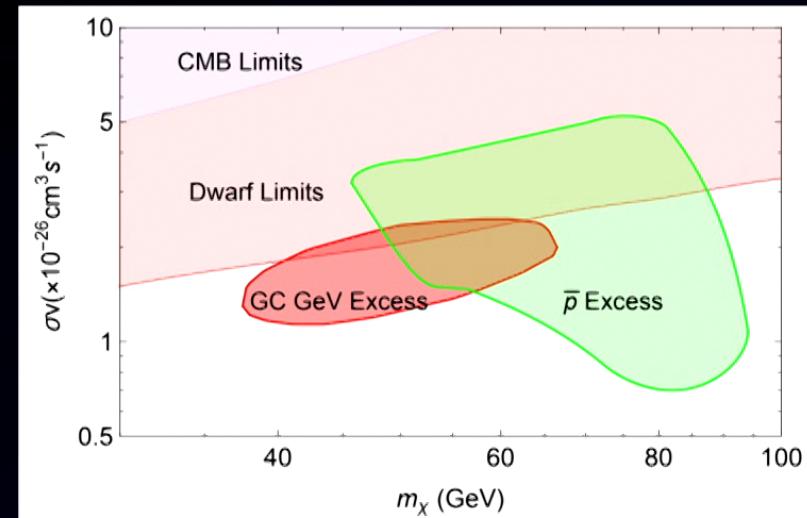


# DARK MATTER?

- Dwarf spheroidal observations, want to see consistent signal



Ackermann et al 1611.03184



Cholis et al 1903.02549

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# THEORY IDEAS?

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

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# SUMMARY

- GCE firmly detected, generation unknown
- Tested if unaccounted for PS populations can bias NPTF methods, in both simulated proof-of-principle, and real data
- Simulated proof-of-principle: signal is misattributed to PSs by the NPTF, in a sim including unmodelled sources in the Fermi Bubbles
  - No evidence for PS correlated with the Fermi Bubbles
  - Evidence for PS in the Boxy Bulge, but doesn't bias DM interpretation
- Real Fermi data: Injected DM misattributed to point sources!  
Dark matter can provide dominant contribution to the GCE!

Rebecca Leane

