Dark Matter Strikes Back at the Galactic Center

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TRIUMF WORKSHOP
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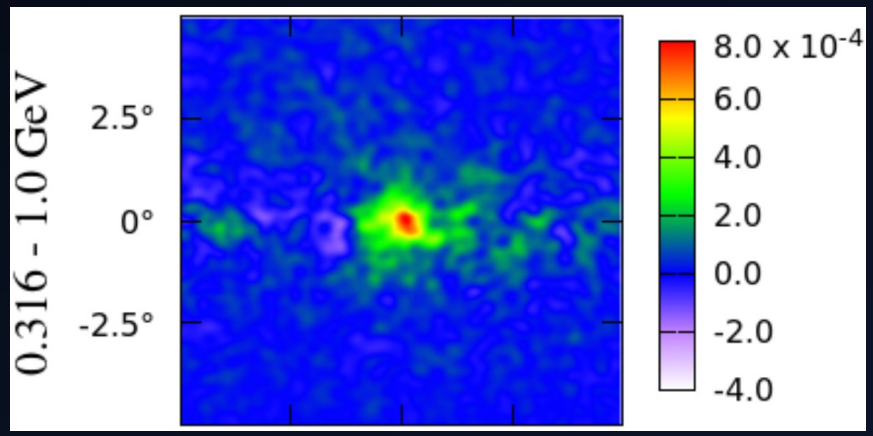
TO APPEAR, WITH TRACY SLATYER

Massachusetts Institute of Technology

THE GEV GALACTIC CENTER EXCESS

- Excess peaked at 1-3 GeV, highly significant
- First discovered in 2009
  - Goodenough+Hooper ‘09
- Found to extend out to 10 degrees
  - Hooper+Slatyer ‘13
- Spatially consistent with DM
  - Daylan et al ‘14, Calore et al ‘14
- If DM, first evidence of DM – SM interactions



Daylan et al ‘14

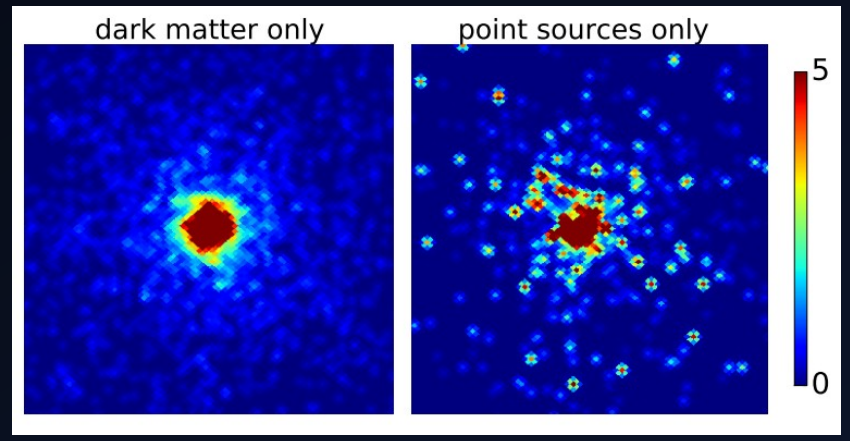
POINT SOURCES AS THE EXCESS

- Favored alternative: Point Sources!
- 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:

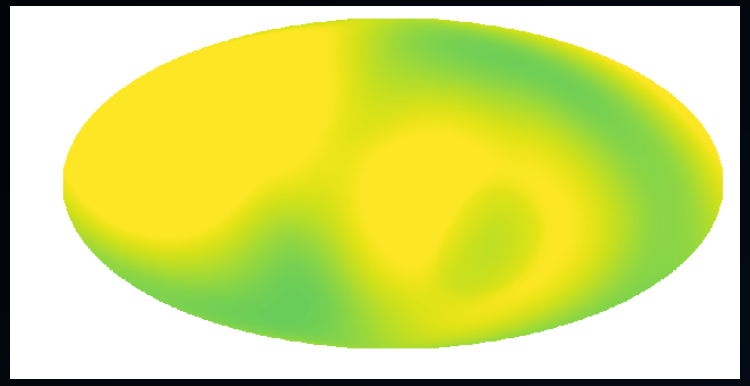
- DM: smooth continuous halo in the Galaxy
  - Follows Poisson statistics
- PS: individual sources, clumpy
  - Follows Non-Poisson statistics, complex to characterize



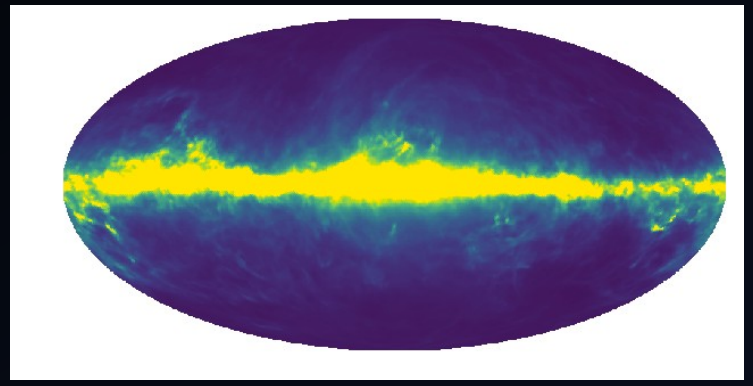
Lee+Lisanti+Safdi, ‘15

Drastically different predictions, orders of magnitude

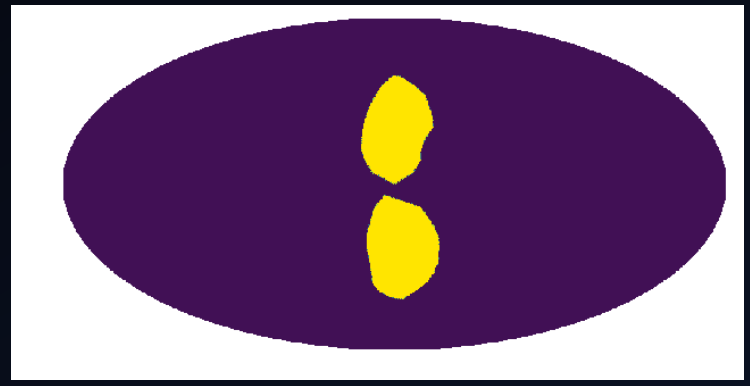
TEMPLATE FITTING



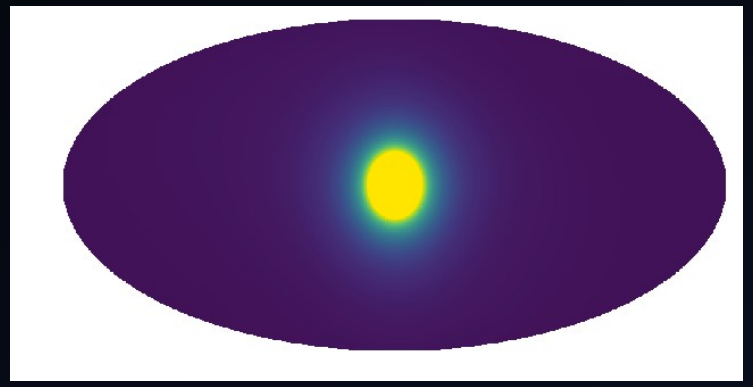
Isotropic



Diffuse



Bubbles



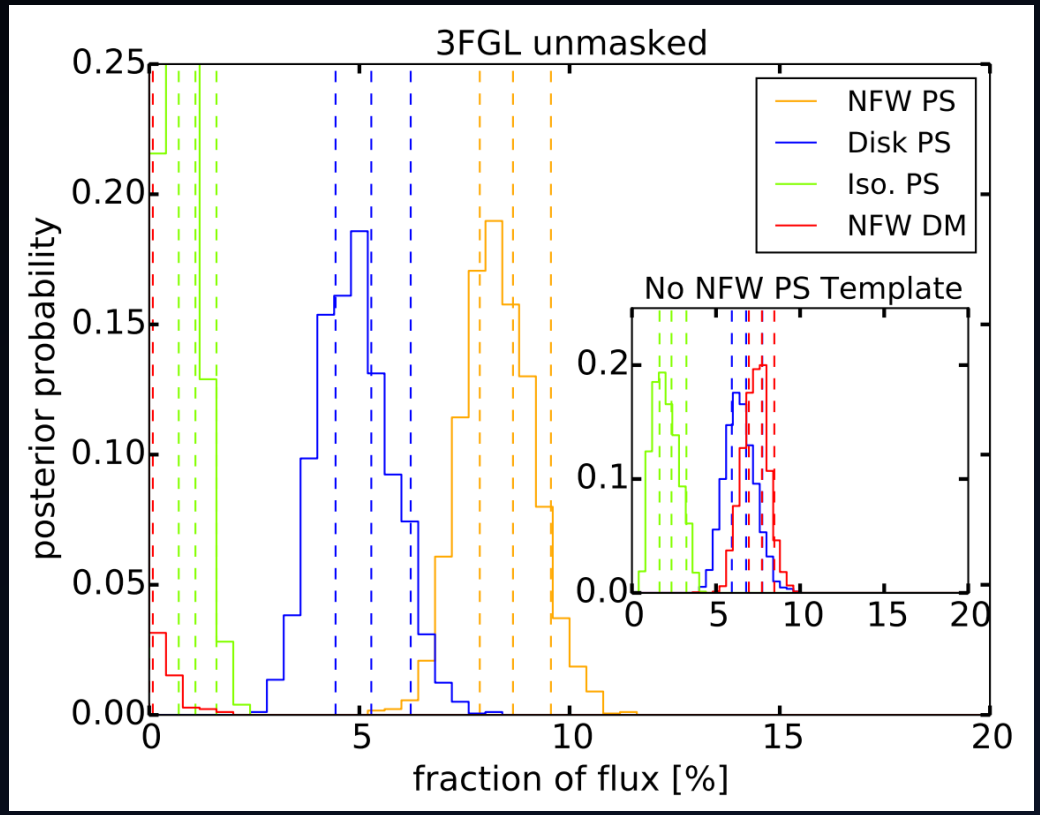
NFW

Assign statistics to each template.

Exploit different statistical predictions, along different spatial shapes

Distinguish the origin of the excess gamma rays.

PREFERENCE FOR POINT SOURCES AT THE GC



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

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

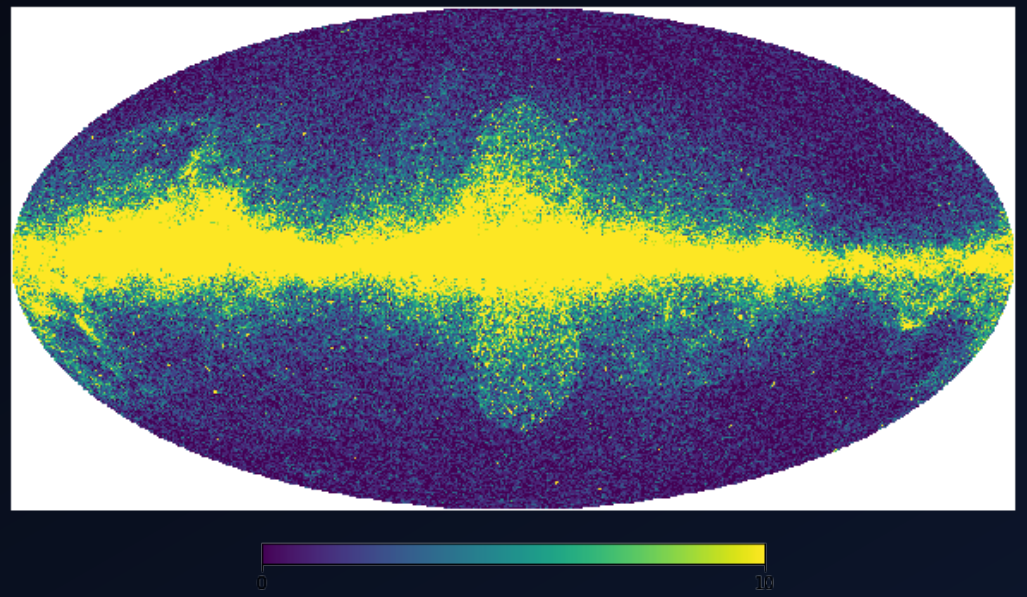
BIAS SEARCH USING SIMULATED DATA

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.



Analyze this data, with exactly the same templates.

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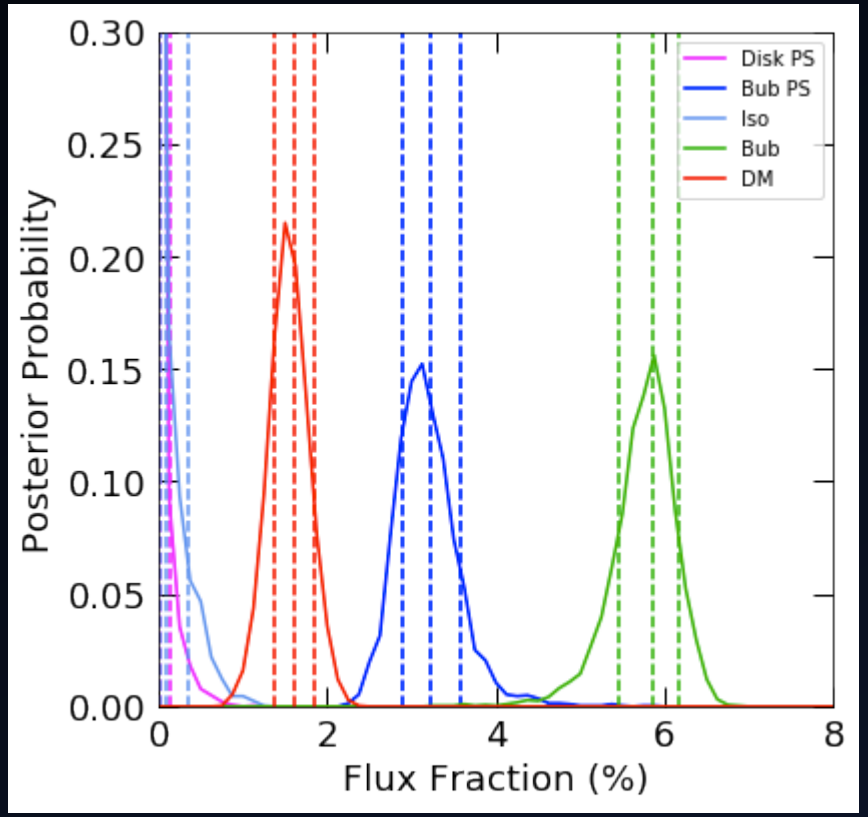
Return same normalizations.



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

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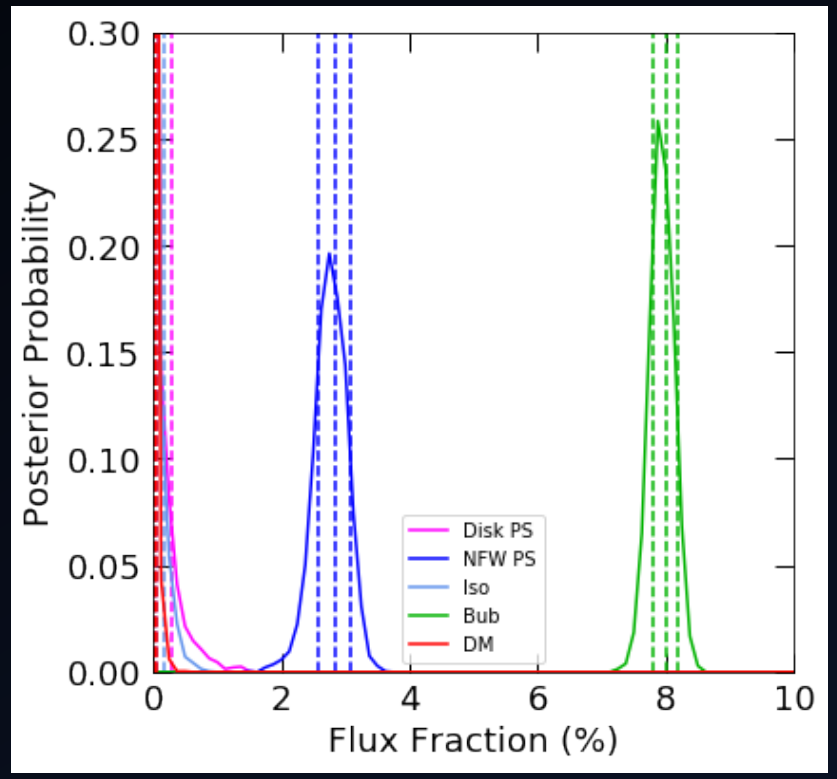
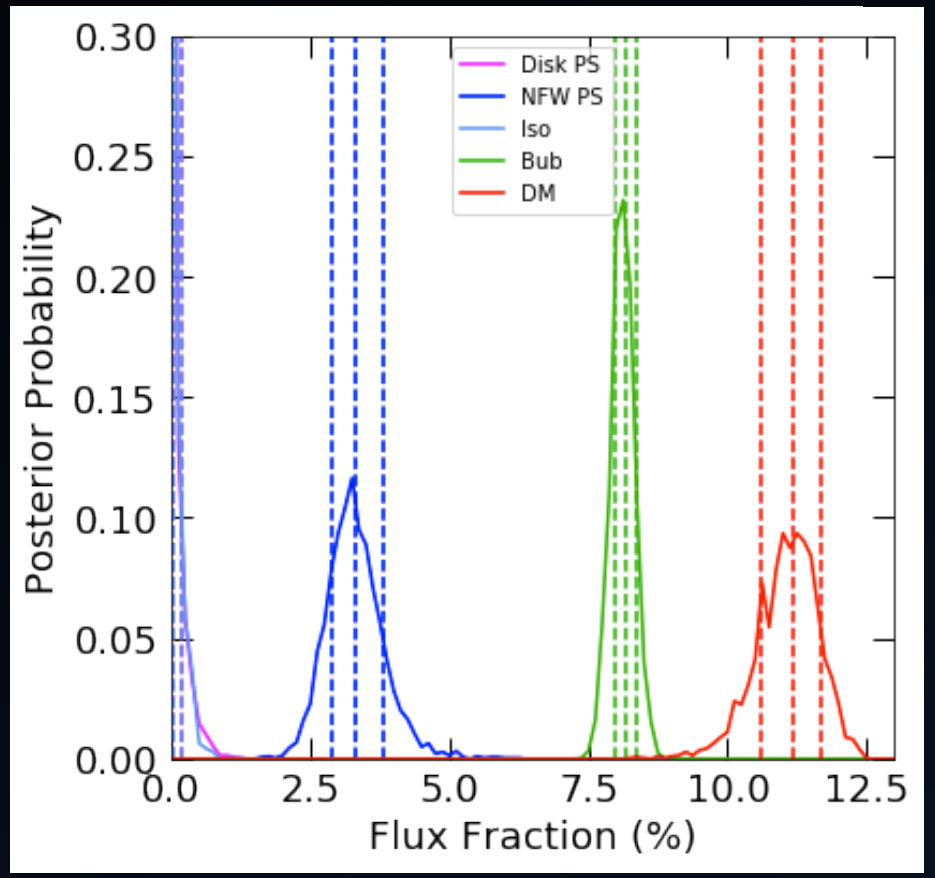


The dark matter signal is misattributed to point sources!

IS THERE A THRESHOLD IN SIMULATIONS?



Inject an order of magnitude more DM (~20%)

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

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 at al ‘15 paper

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

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

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
- See no meaningful change in Bayes factor

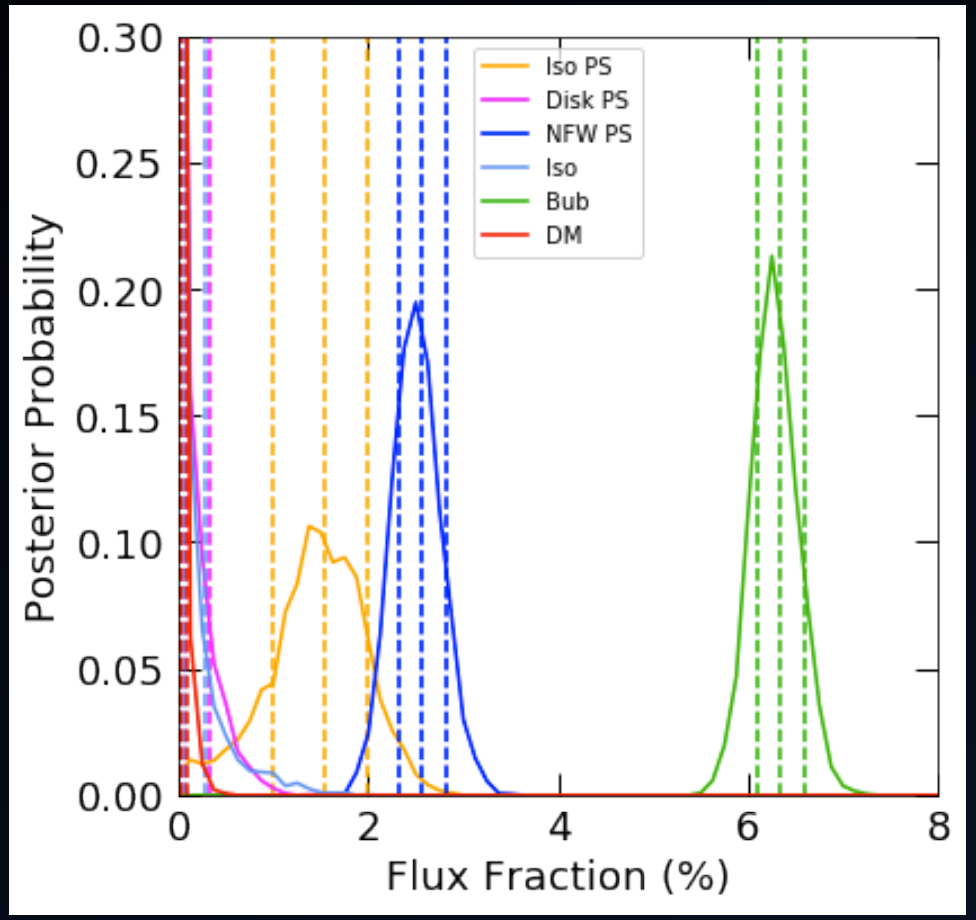
Find no evidence for point sources in the Fermi Bubbles.

TESTING WITH THE REAL FERMI DATA

Inject a fake dark matter signal into the Fermi data.

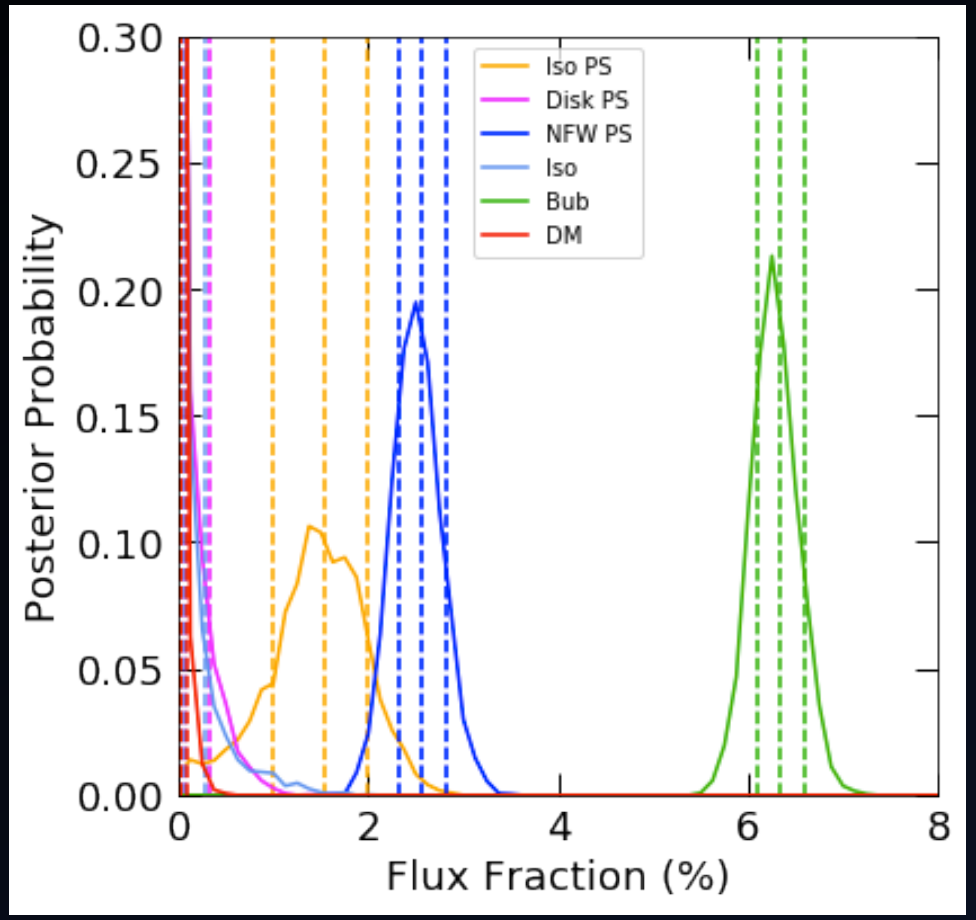
If this effect is present, template likely not saturated in its ability to absorb dark matter flux.

FERMI DATA



INJECTED DM SIGNAL + DATA

FERMI DATA



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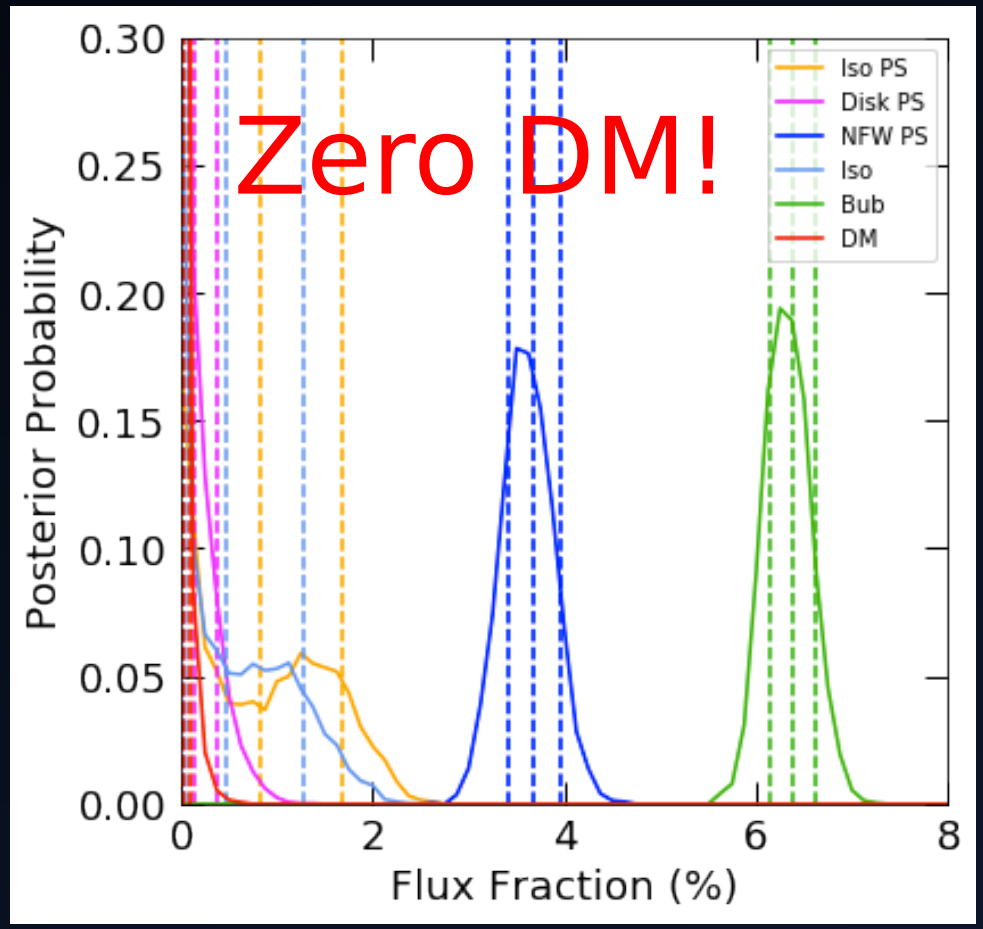

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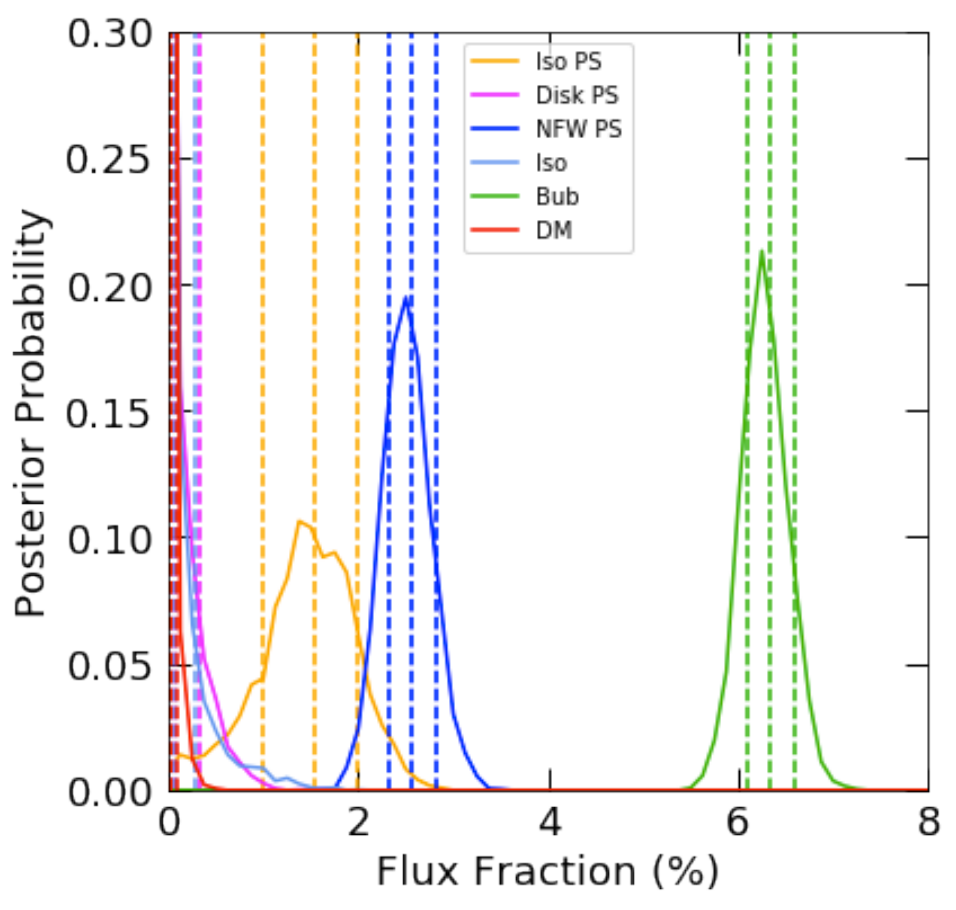
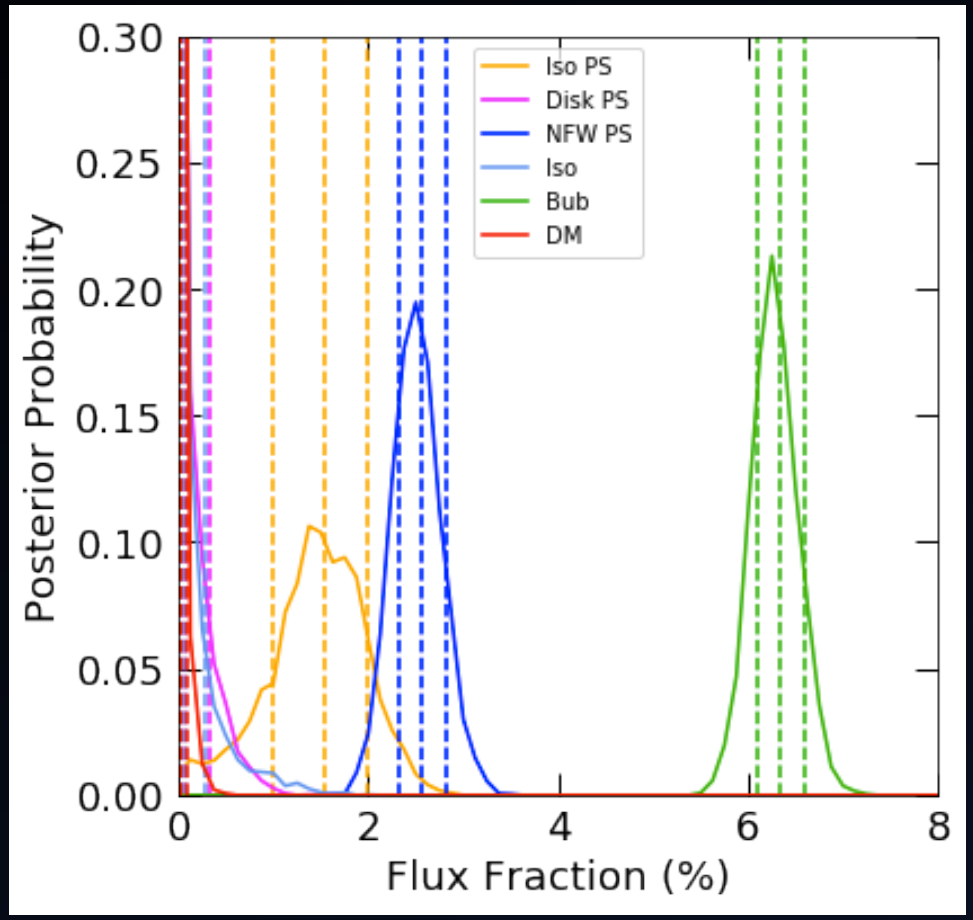


LARGER INJECTED DM SIGNAL + DATA

FERMI DATA



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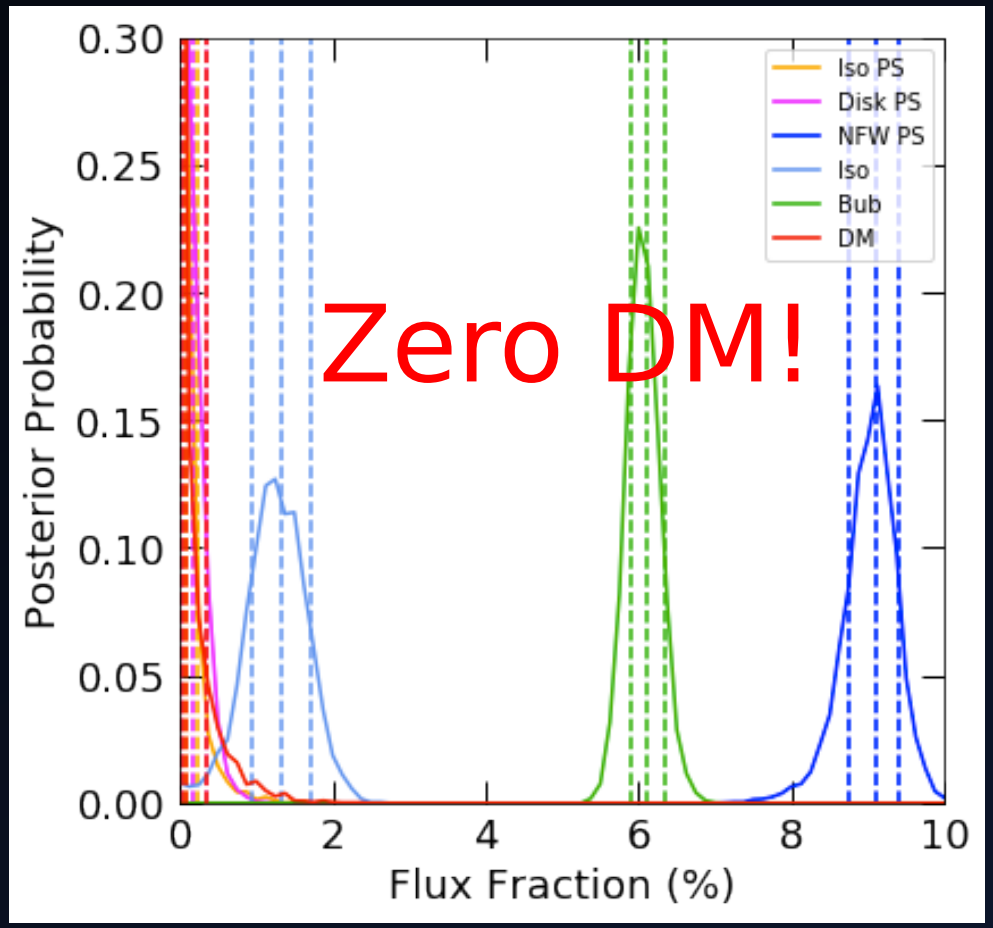
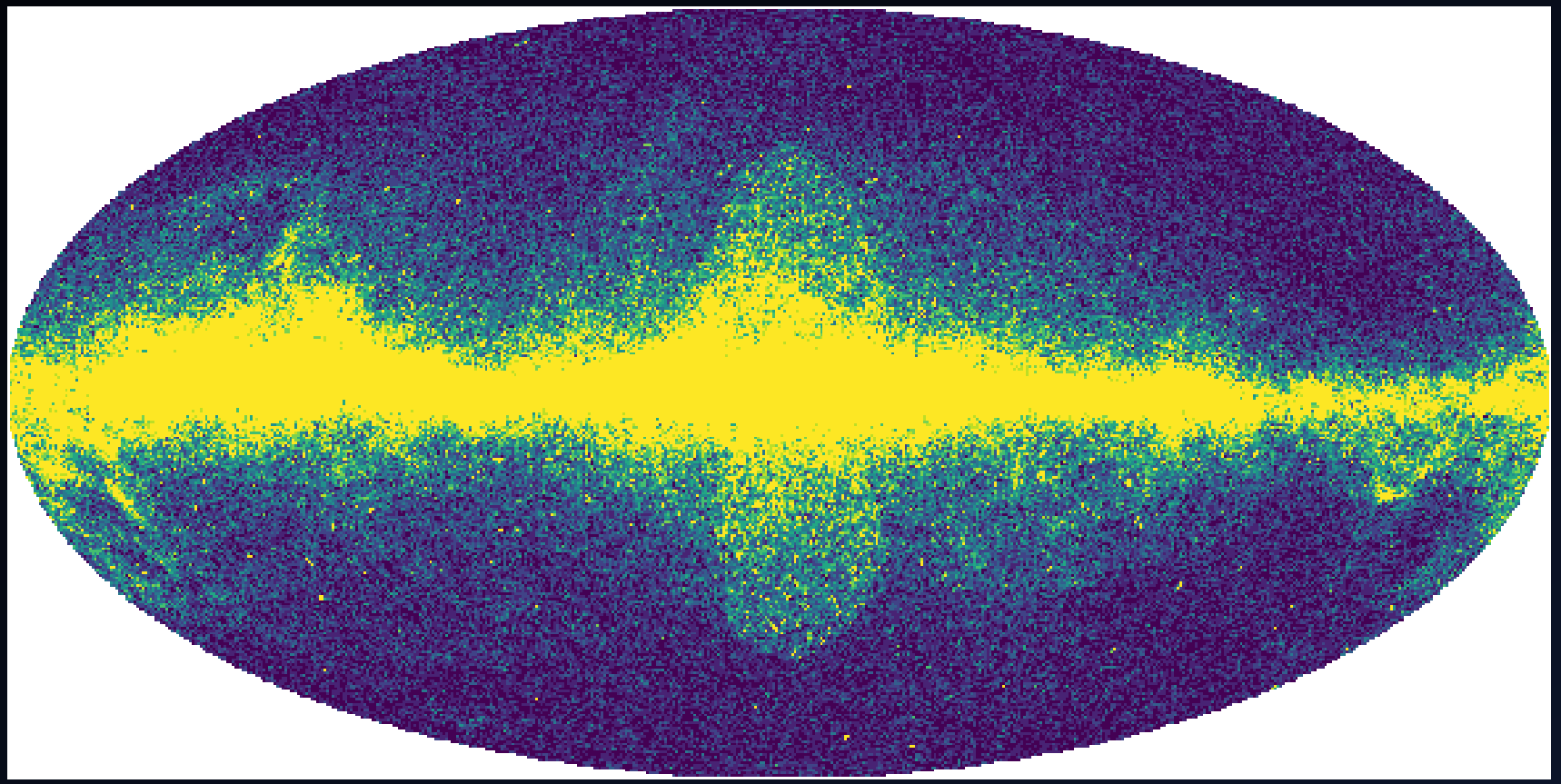


BOMBARD THE GALAXY!



Rebecca Leane

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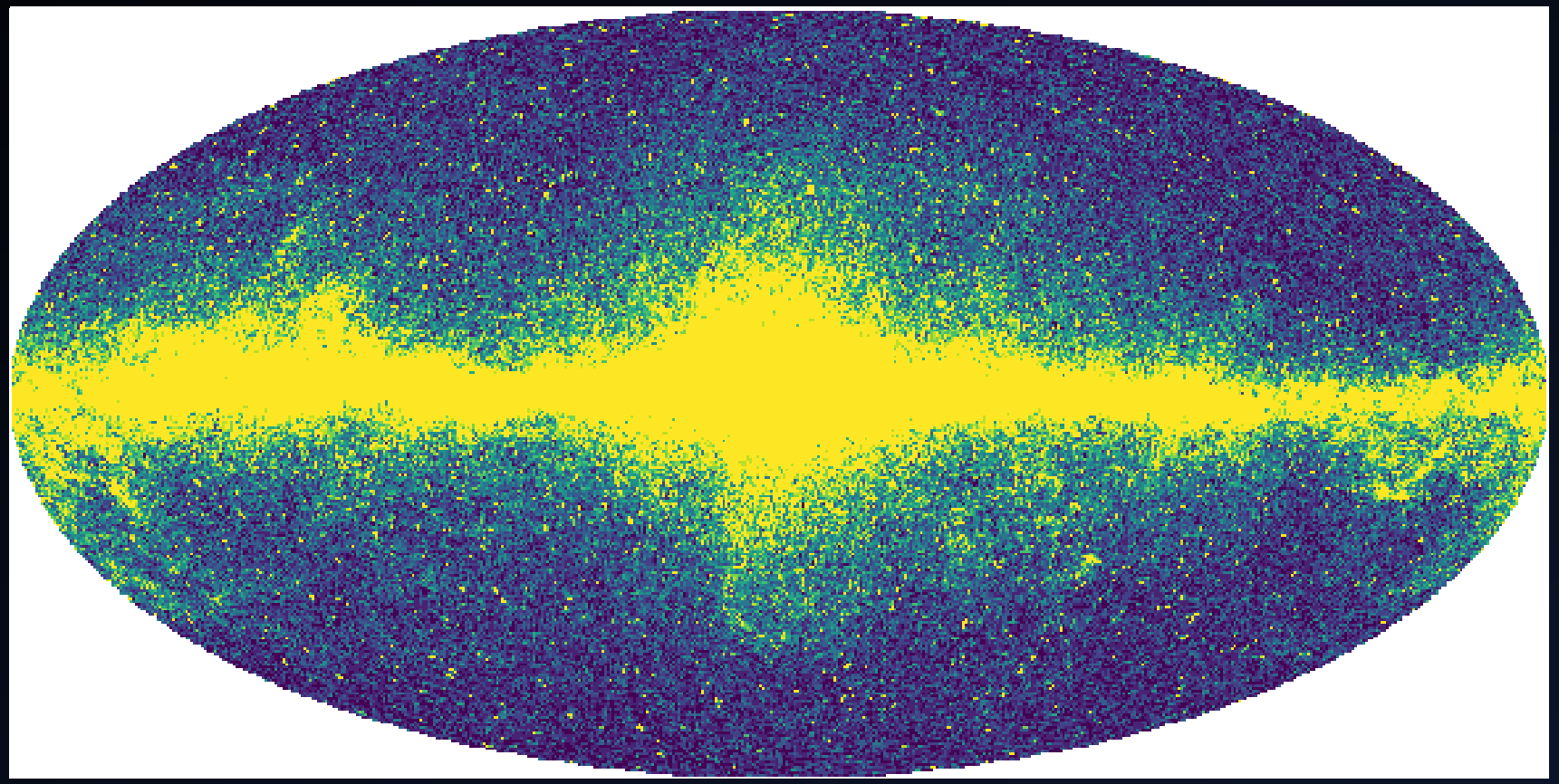

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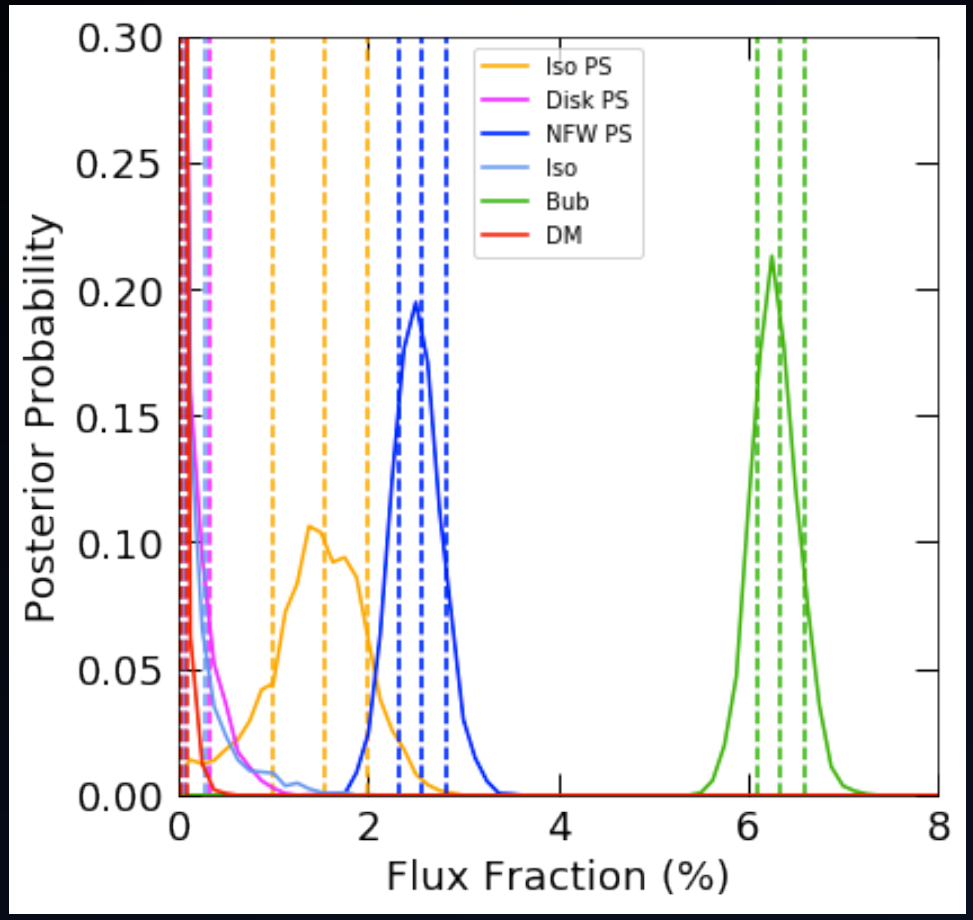
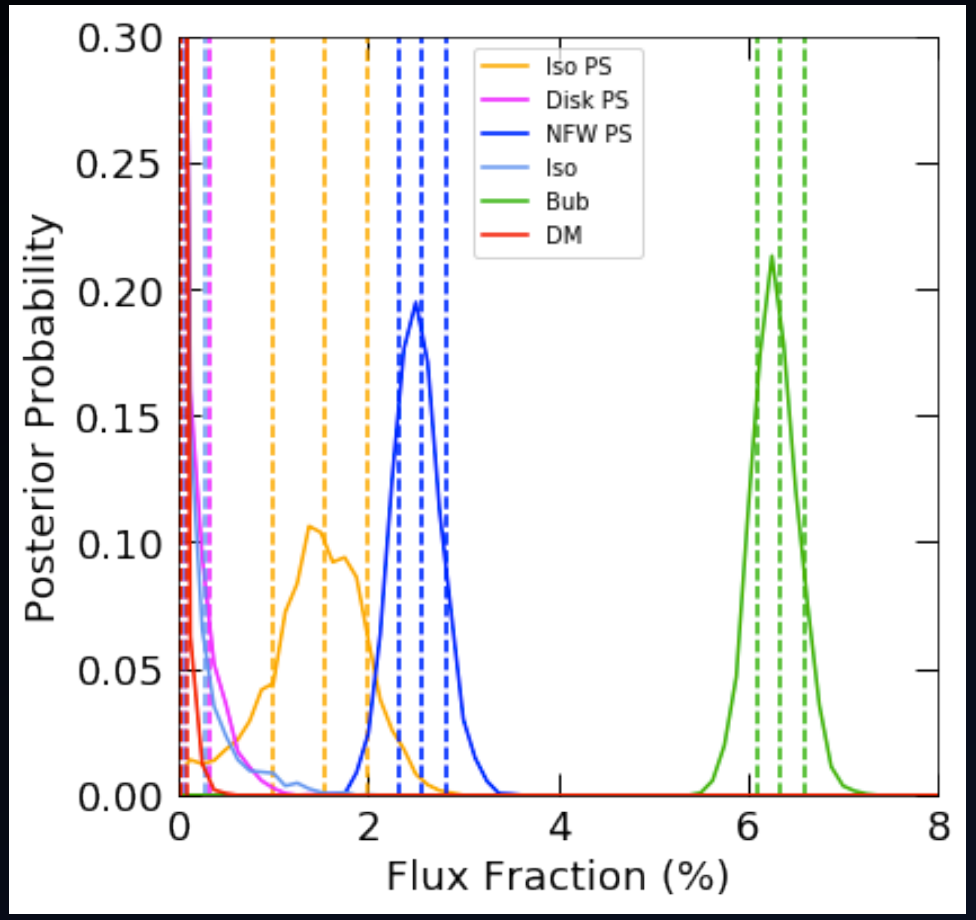
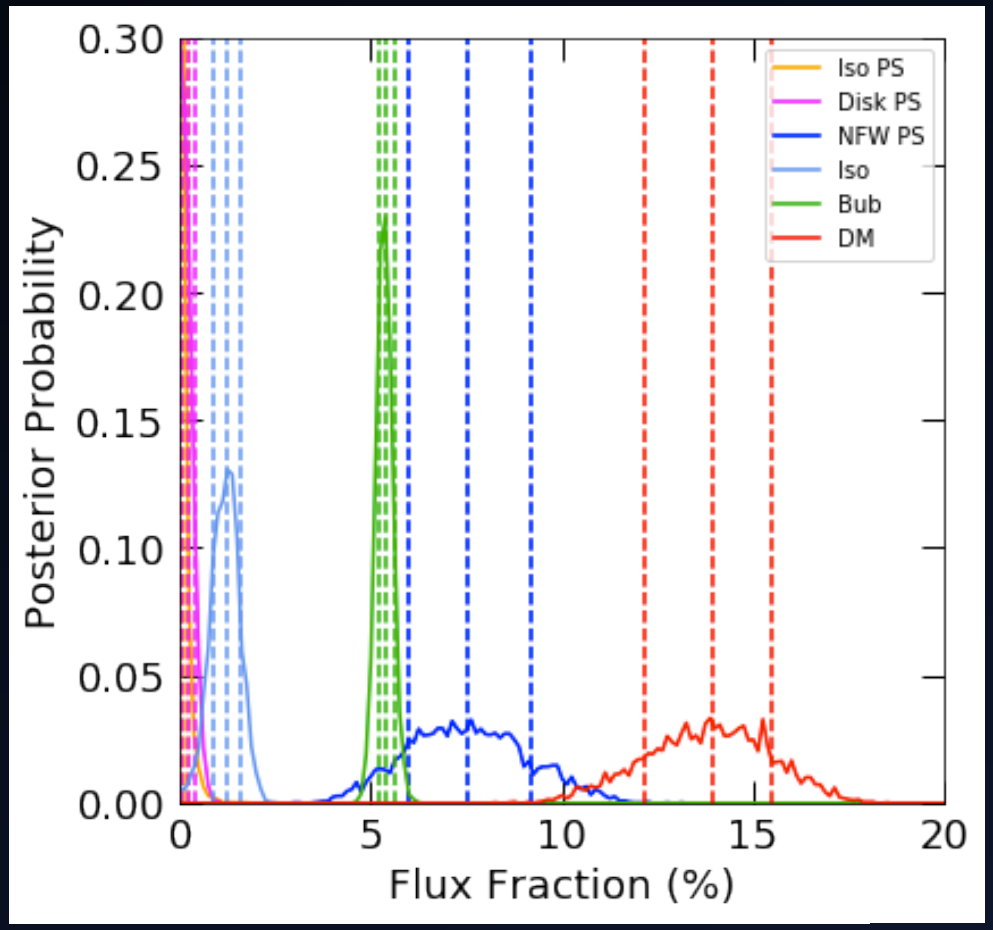


BOMBARDED DM SIGNAL + DATA

FERMI DATA



BOMBARDED DM SIGNAL + DATA



Finally, but low.

- Both simulated and real data show same behavior, finding in all cases a significant Bayes factor against a DM interpretation of the data.
- This supports a DM signal being incorrectly discarded due to the presence of a not yet discovered unresolved PS population
- If DM is contributing to the GC, an apparent (incorrect) zero flux result is potentially only arising due to some unmodelled source population.
- *DM can substantially contribute to the GCE!*

FURTHER DIAGNOSTICS

- All simulations return true values when given correct templates
- Mixed GCE simulation recovered ok
- Check 100 DM signal injections, all give comparable result
- Holds for varied diffuse models, and several templates

SUMMARY

- GCE firmly detected, generation unknown
- Simulated data was used to examine if unaccounted for PS populations can bias NPTF methods
- Simulated DM signal is misattributed to PSs by the NPTF, in a sim including unmodelled sources in the Fermi Bubbles
- Find no evidence for PS correlated with the Fermi Bubbles
- Injecting DM signal into real Fermi data: confirms possible effect!

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EXTRA SLIDES

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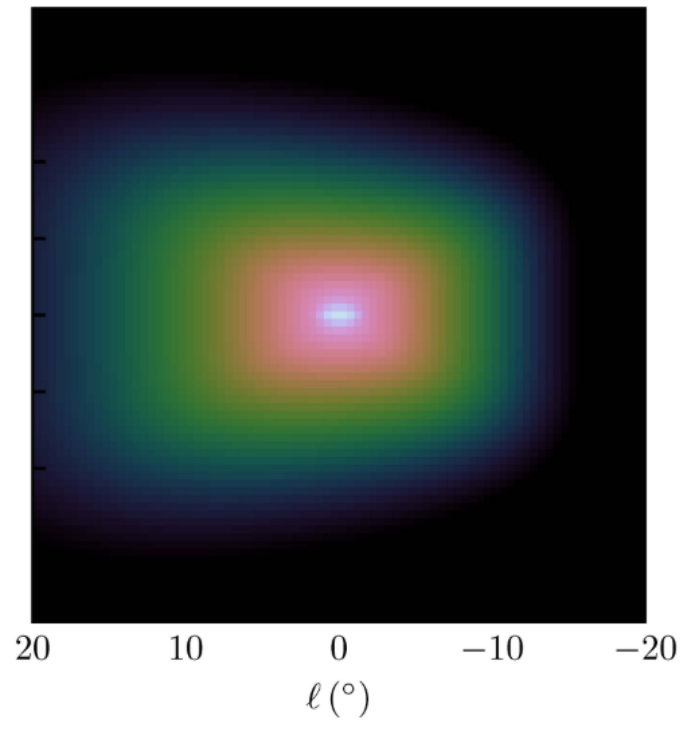
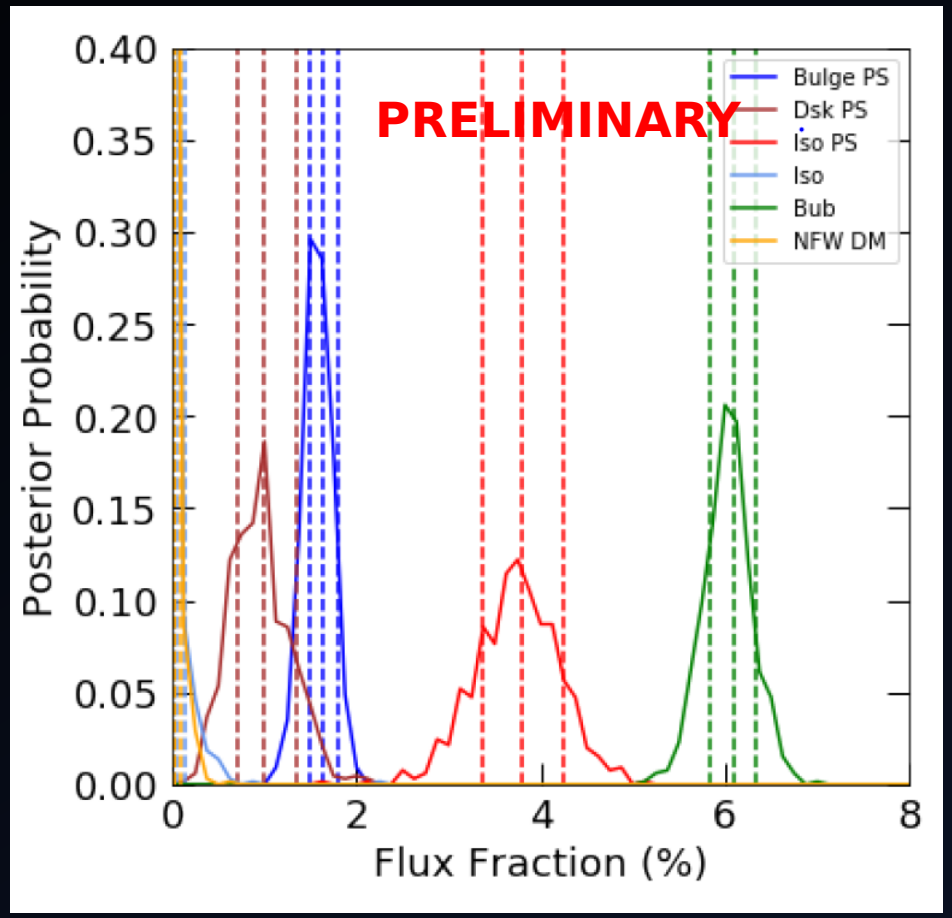
WHAT ABOUT THE BOXY BULGE?



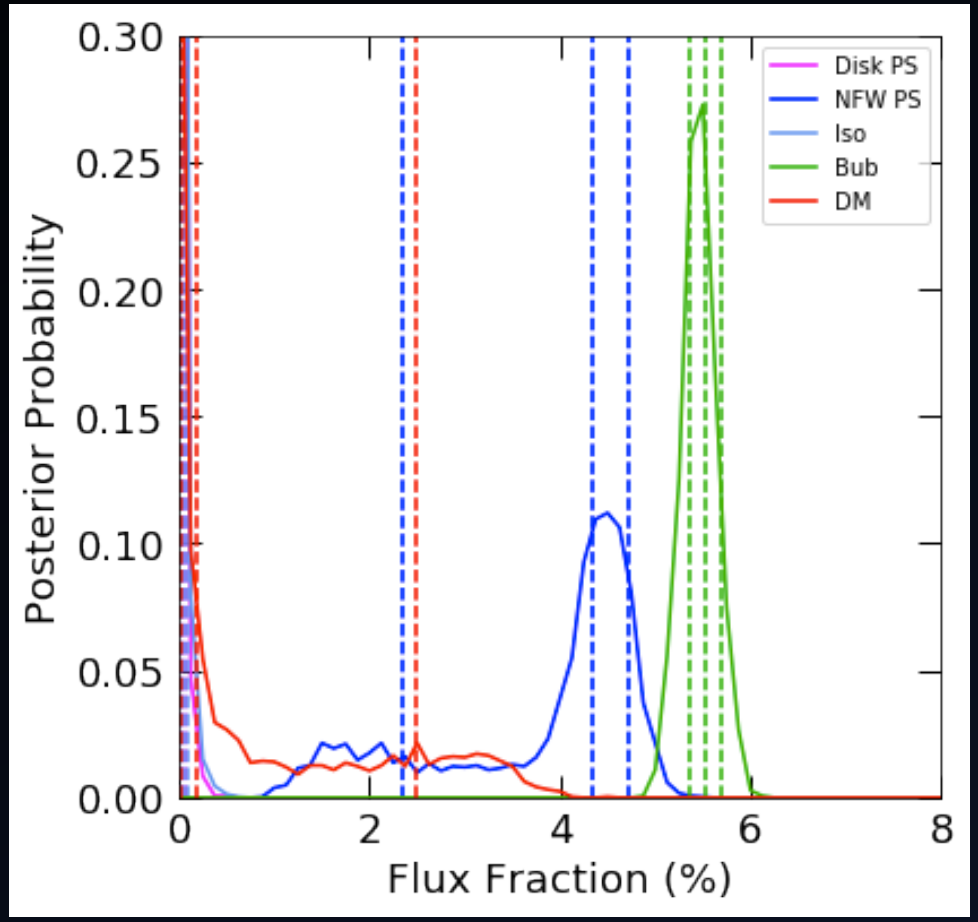
- Population of stars at the GC
- Unmodelled candidate could impact interpretation of the data

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

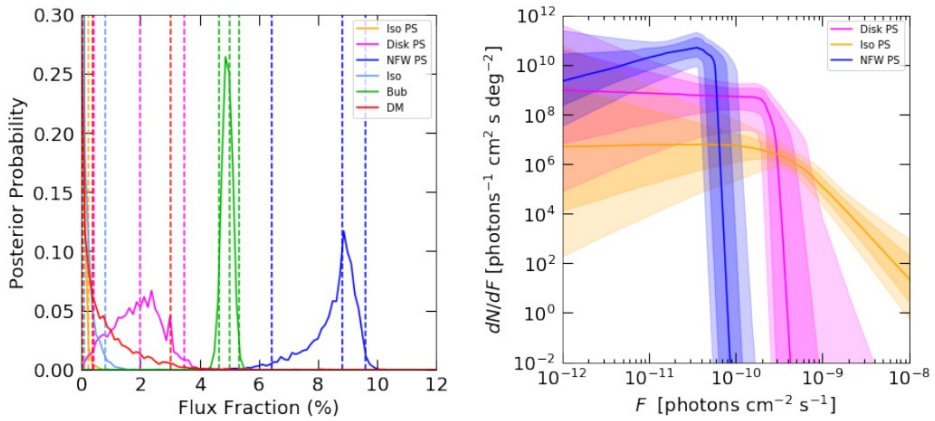


Figure 15. Same as Fig. 8, but replacing the `Pass 6` *Fermi* diffuse model with the diffuse Model A from Ref. [7], and injecting a DM flux making up $\sim 4.5\%$ of the gamma-ray sky.

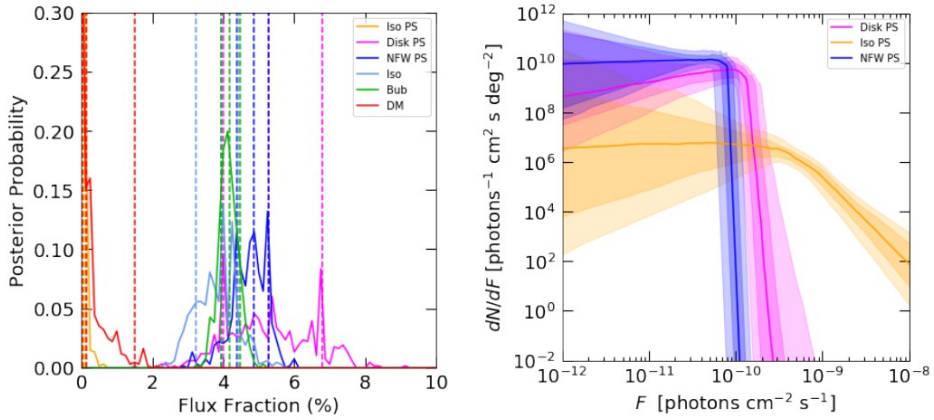


Figure 16. Same as Fig. 8, but replacing the `Pass 6` *Fermi* diffuse model with the diffuse Model F from Ref. [7], and injecting a DM flux making up $\sim 2.8\%$ of the gamma-ray sky.

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 $\rightarrow$ 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 $\rightarrow$ 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 $\rightarrow$ NFW PS	$[0.0, 3.5]$ %		$\sim 10^{10}$	
NFW DM		Same but no Bulge PS	$[3.9, 5.0]$ %			

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

NPTF TOOLS

- Analyze data using NPTFit package (Mishra-Sharma, Rodd, Safdi 1612.03173)
  github.com/bsafdi/NPTFit

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

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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?

GCE MORPHOLOGY

- Spherically symmetric around GC (axis ratios within 20% of unity)
- Scales $r^{-2.4}$ extending out to around 10°
- DM annihilation interpretation implies $r^{-2.4}$ out to at least about 1.5 kpc

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

POISSON vs NON-POISSON TEMPLATE FITTING

- For smooth emission, likelihood is given by product of poisson likelihoods for each pixel
- For point sources, relationship between no. of photons observed and mean no. of photons is not poisson.
  - Probability of source(s) present in pixel
  - Probability source(s) producing certain no. of photons

    (See Malyshev+Hogg (2011), Lee+Listanti+Safdi (2015))
- Look for PS populations distributed along same templates (Lee at al (2015))