A Status Update on the GeV Galactic Center Excess

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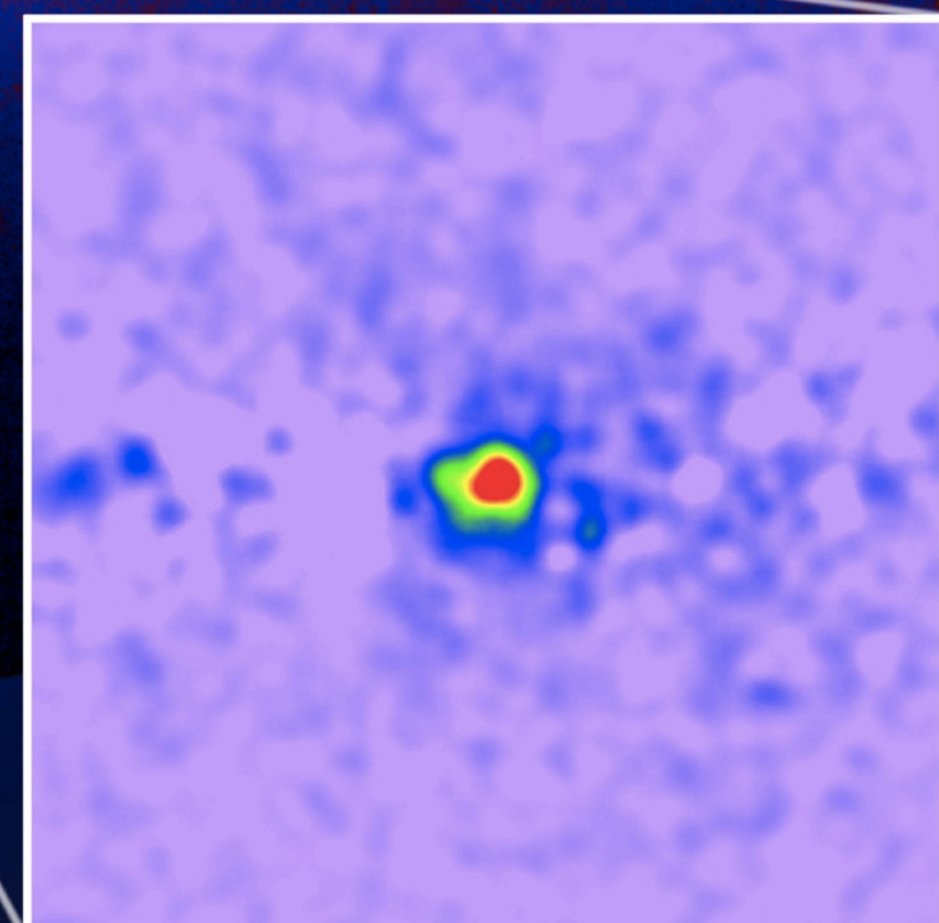

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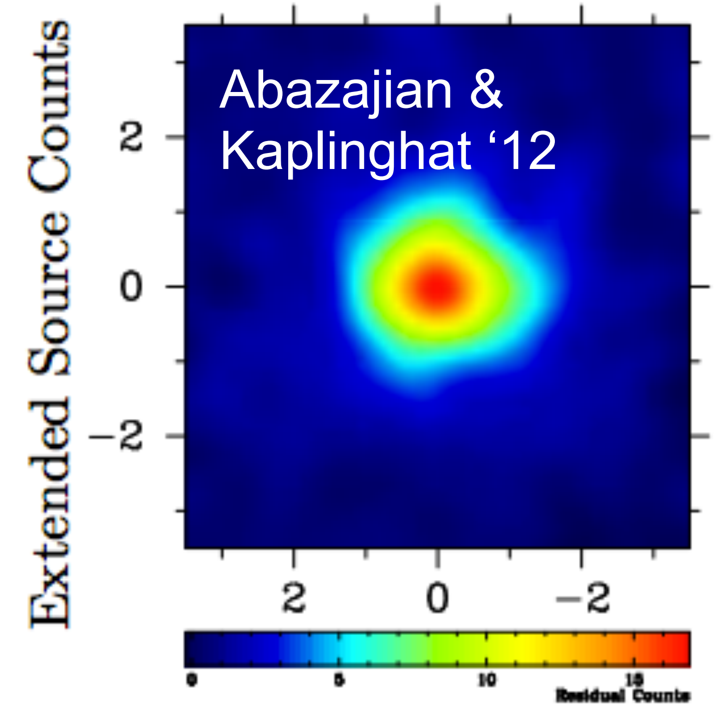
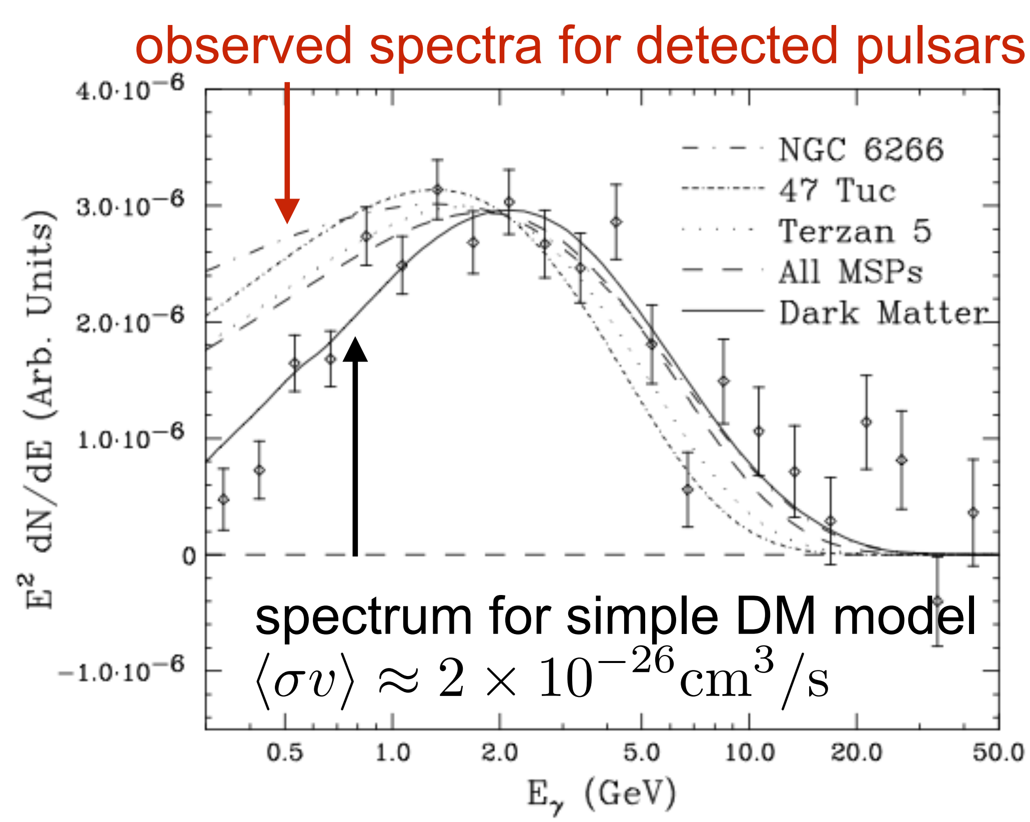
The GeV Galactic Center excess

- Excess of gamma-ray photons, peak energy ~1-3 GeV, in the region within ~10 degrees of the Galactic Center.
- Discovered by Goodenough & Hooper '09, confirmed by Fermi Collaboration in analysis of Ajello et al '16 (and many other groups in interim).
- Simplest dark matter (DM) explanation: thermal relic annihilating DM at a mass scale of O(10-100) GeV
- Leading non-DM explanation: population of pulsars below Fermi's point-source detection threshold





Daylan, TRS et al '16

Status of the GCE - a renewed controversy?

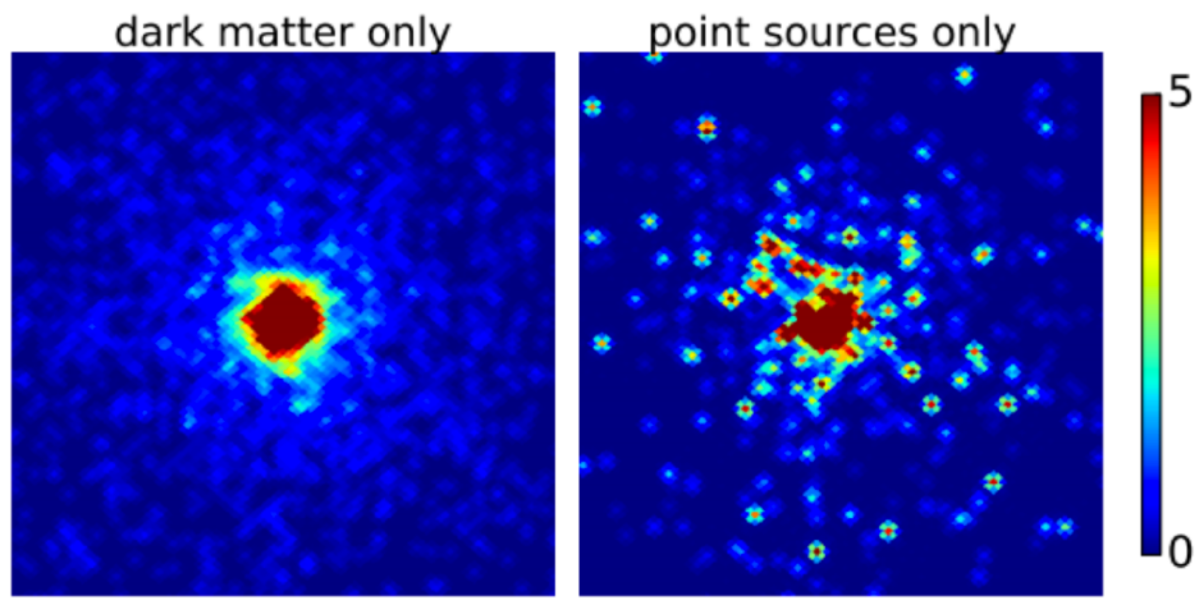
- Arguments against the DM explanation:
  - Spatial morphology of excess was originally characterized as spherical, but can also be described as boxy-bulge-like extended emission + central nuclear bulge component [Macias et al ’18, Bartels et al ’18, Macias et al ’19]. If the extended emission is robustly Bulge-like, suggests a stellar origin - but somewhat sensitive to background modeling.
  - Constraints from other searches - limits from dwarf galaxies are in some tension with DM explanation [e.g. Keeley et al ’18], but depends on Milky Way density determination.
  - Photon statistics.

Photon statistics

Lee, Lisanti, Safdi, TRS & Xue ’16

DM origin hypothesis

signal traces DM density squared, expected to be ~smooth near GC with subdominant small-scale structure



Pulsar origin hypothesis

signal originates from a collection of compact objects, each one a faint gamma-ray point source

- We may be able to distinguish between hypotheses by looking at clumpiness of the photons (see Malyshev & Hogg ’11; Lee, Lisanti & Safdi ’15).
- If we are looking at dark matter (or another diffuse source, like an outflow), we expect a fairly smooth distribution - fluctuations described by Poisson statistics.
- In the pulsar case, we might instead see many “hot spots” scattered over a fainter background - non-Poissonian fluctuations, higher variance.
- Related analysis by Bartels et al ’16, using wavelet approach - found evidence for small-scale power in inner Galaxy.

An example

I expect 10 photons per pixel, in some region of the sky. What is my probability of finding 0 photons? 12 photons? 100 photons?

Case 1: diffuse emission, Poissonian statistics

$P(12 \text{ photons}) = 10^{12} e^{-10}/12! \sim 0.1$
Likewise $P(0 \text{ photons}) \sim 5 \times 10^{-5}$, $P(100 \text{ photons}) \sim 5 \times 10^{-63}$

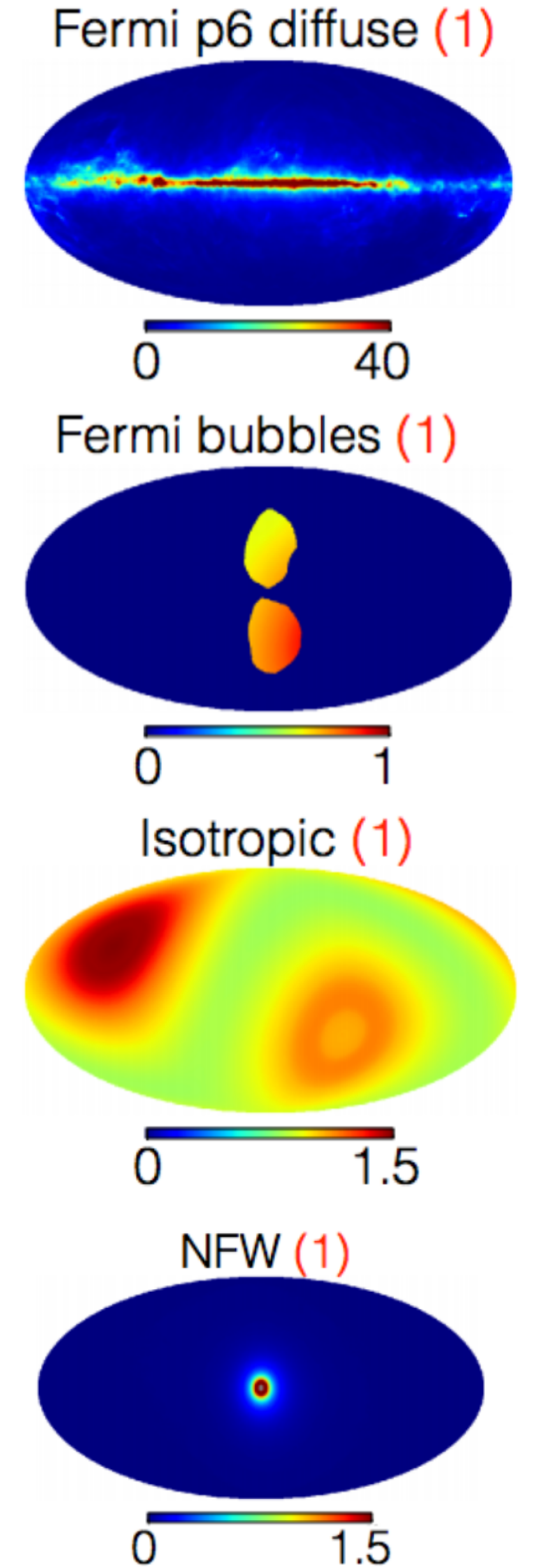
Case 2: population of rare sources.
Expect 100 photons/source, 0.1 sources/pixel - same expected mean # of photons

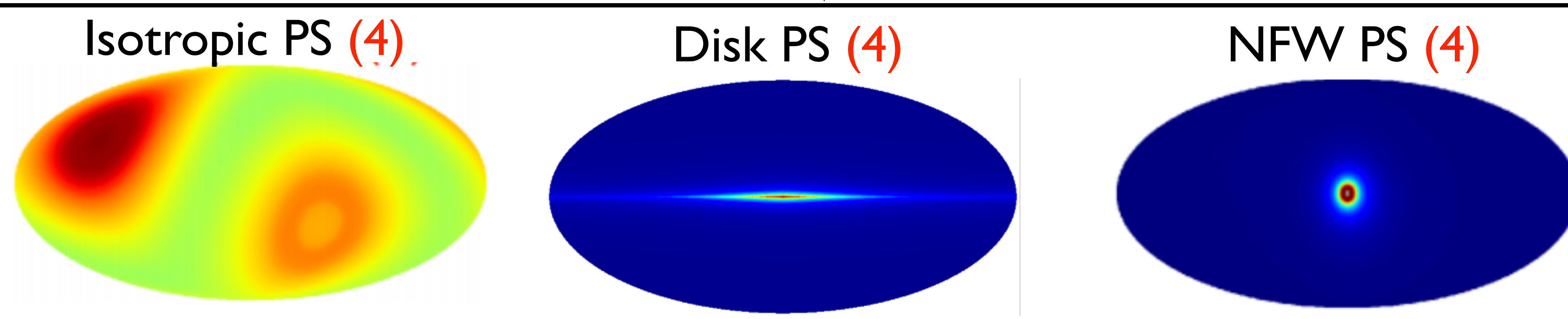
$P(0 \text{ photons}) \sim 0.9$, $P(12 \text{ photons}) \sim 0.1 \times 100^{12} e^{-100}/12! \sim 10^{-29}$,
$P(100 \text{ photons}) \sim 4 \times 10^{-3}$

(plus terms from multiple sources/pixel, which I am not including in this quick illustration)

Non-Poissonian template fitting

- Model sky (within some energy bin) as linear combination of spatial templates
- Evaluate P(data|model) as a function of template coefficients + other parameters - maximize P (frequentist), or use it to derive posterior probability distributions for the parameters (Bayesian).
- Templates may either have
  - Poissonian statistics
  - Point-source-like statistics - extra degrees of freedom describing number of sources as a function of brightness

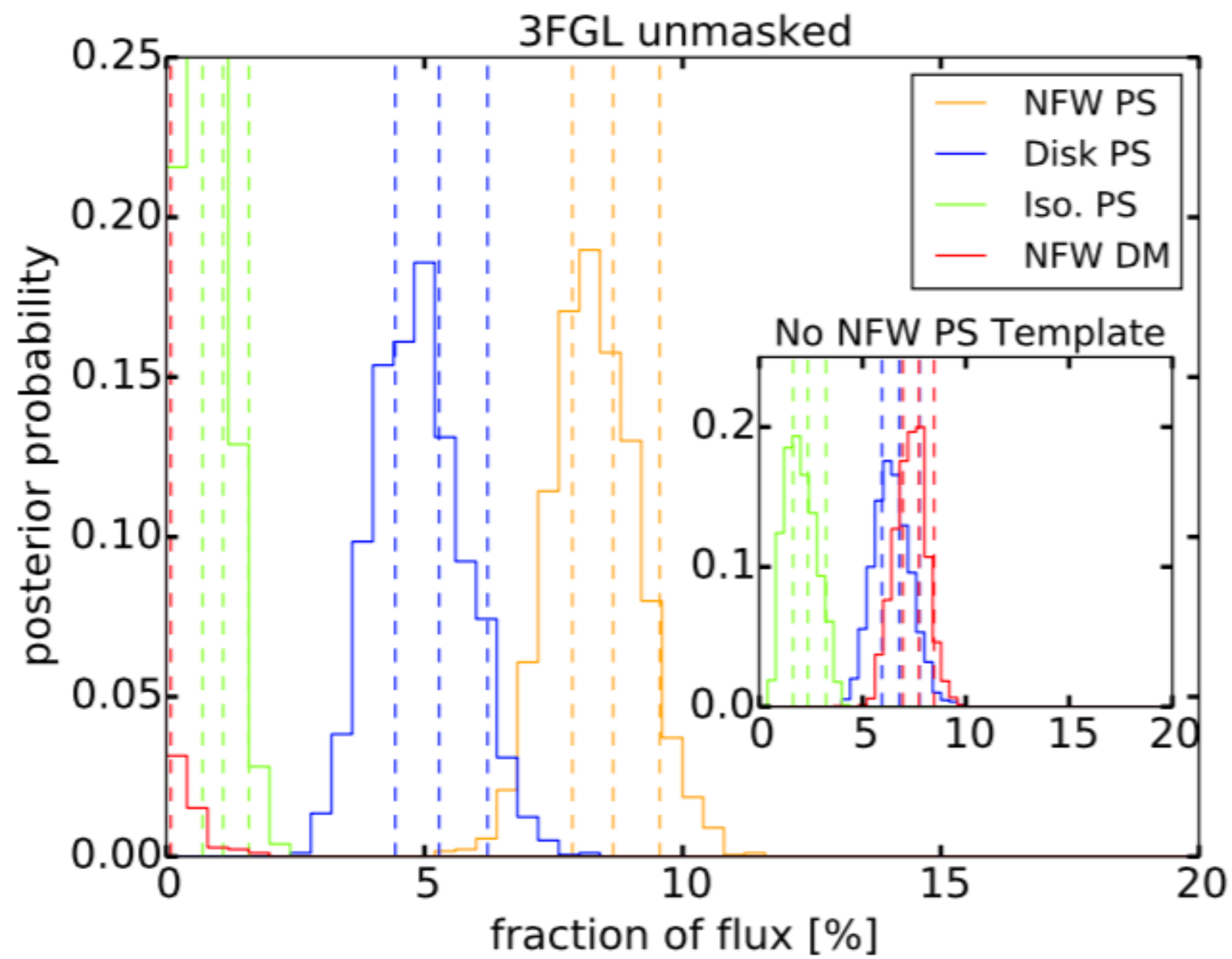




Point source templates

A preference for point sources

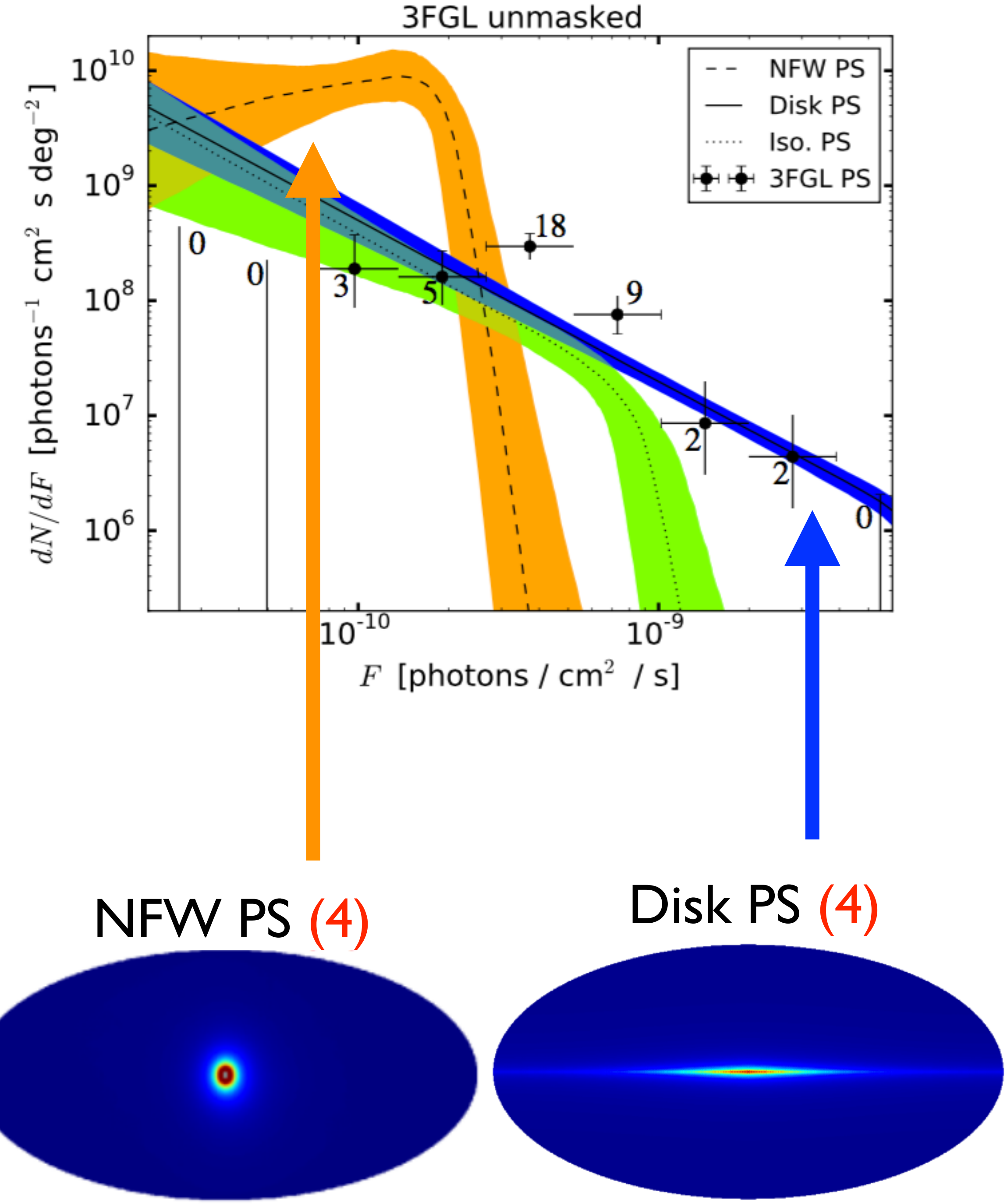
- Restrict to region within 30° of Galactic Center, mask plane at ±2°.
- Compare fit with and without point-source (PS) template peaked toward GC, “NFW PS”.
- In both cases there is a smooth “DM” template peaked toward GC, “NFW DM”.



- 2016 result: if “NFW PS” is absent, “NFW DM” template absorbs excess. If “NFW PS” is present, “NFW PS” absorbs full excess, drives “NFW DM” to zero.

Properties of the (apparent) sources

- Results suggest that known sources follow a disk-like distribution
- New sources appear to be different in two ways:
    - spherical distribution (vs disk-like)
    - characteristic brightness just below sensitivity threshold



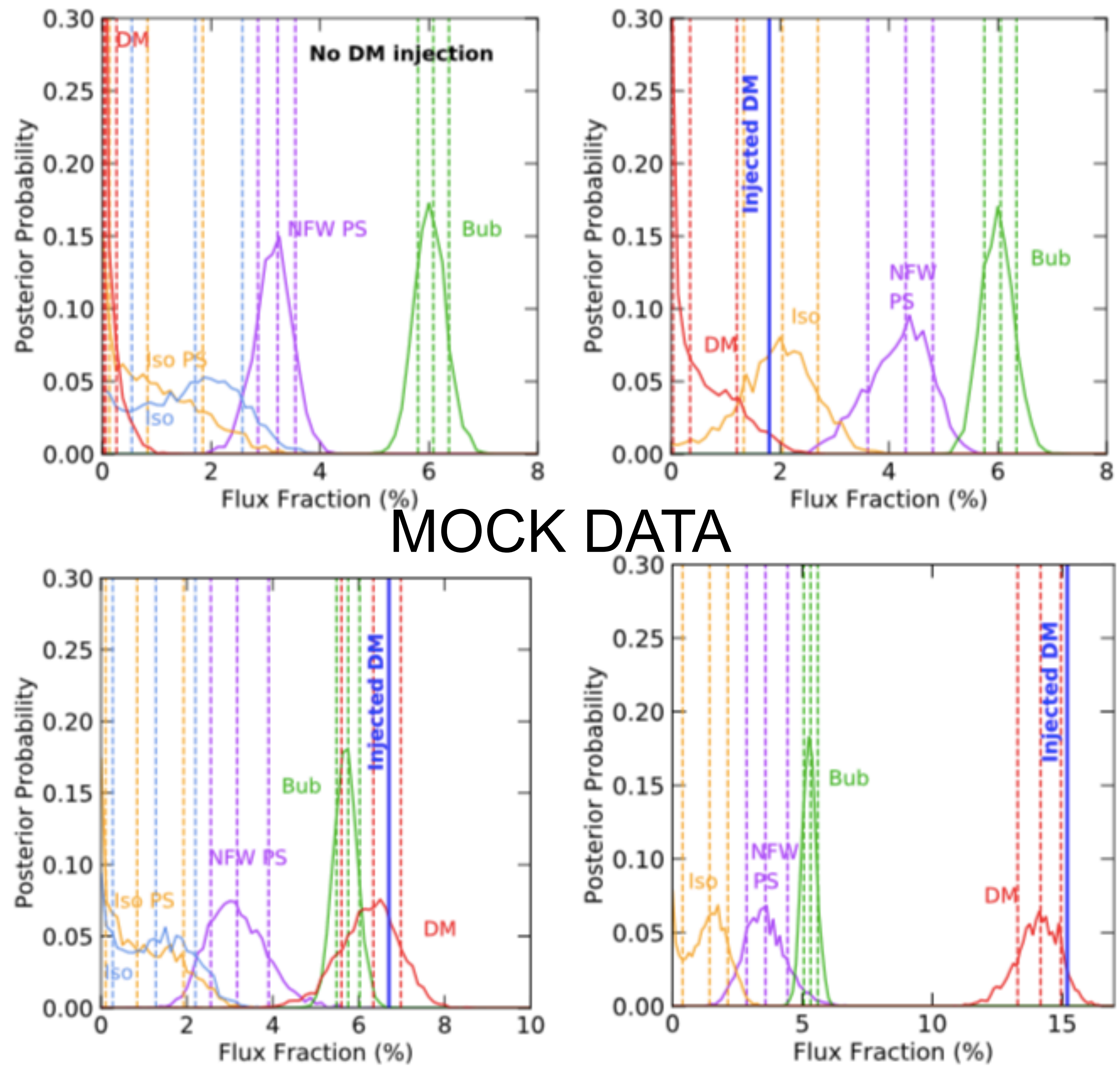
A new test for systematics

Leane & TRS '19

- In any template-based analysis, errors in the background templates can lead to misleading results for the signal templates.

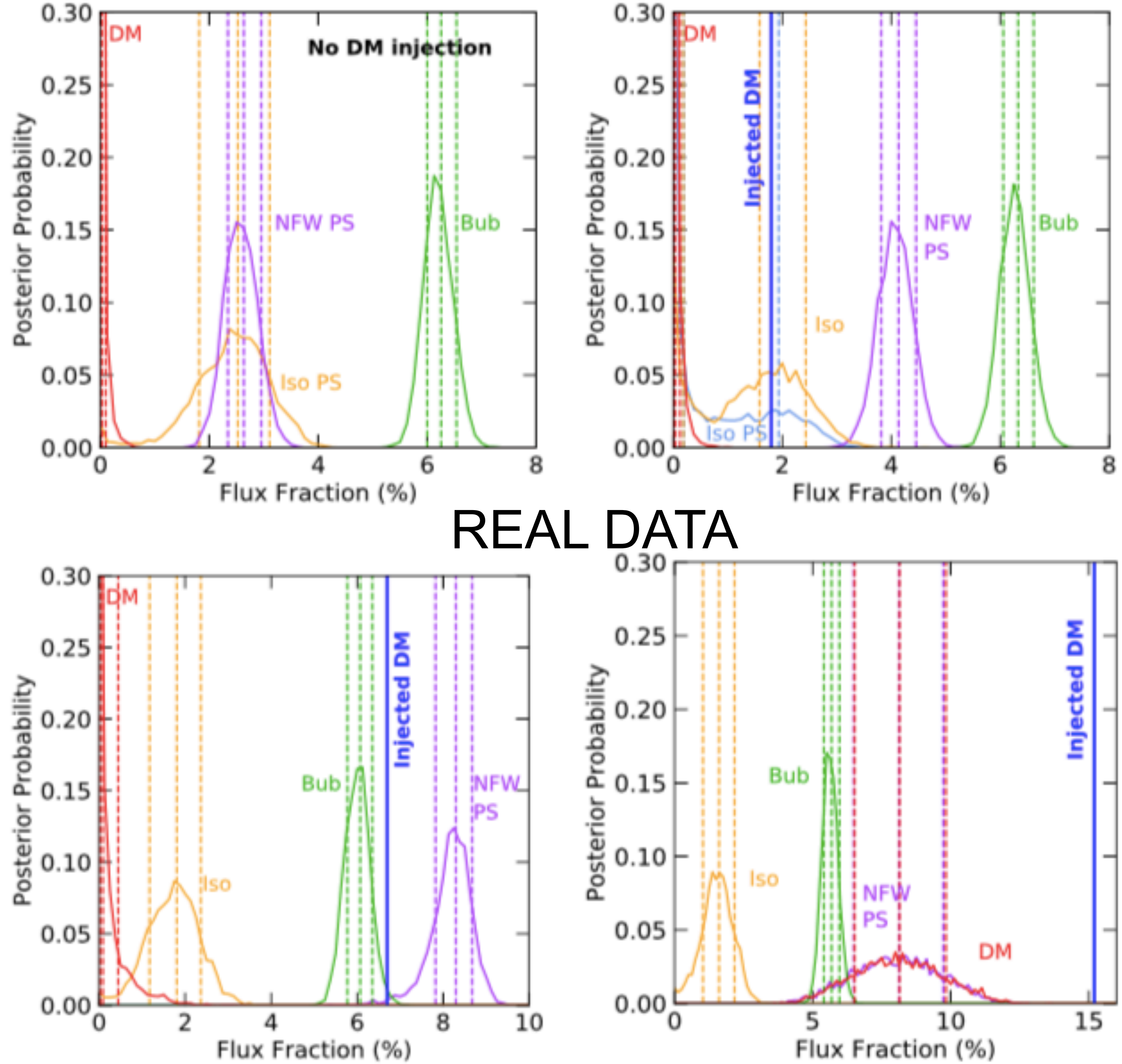
- One way to test for problems: inject simulated signal, check that pipeline can recover it.

- First perform test on simulated data - all templates are thus "correct" (GCE = point sources).



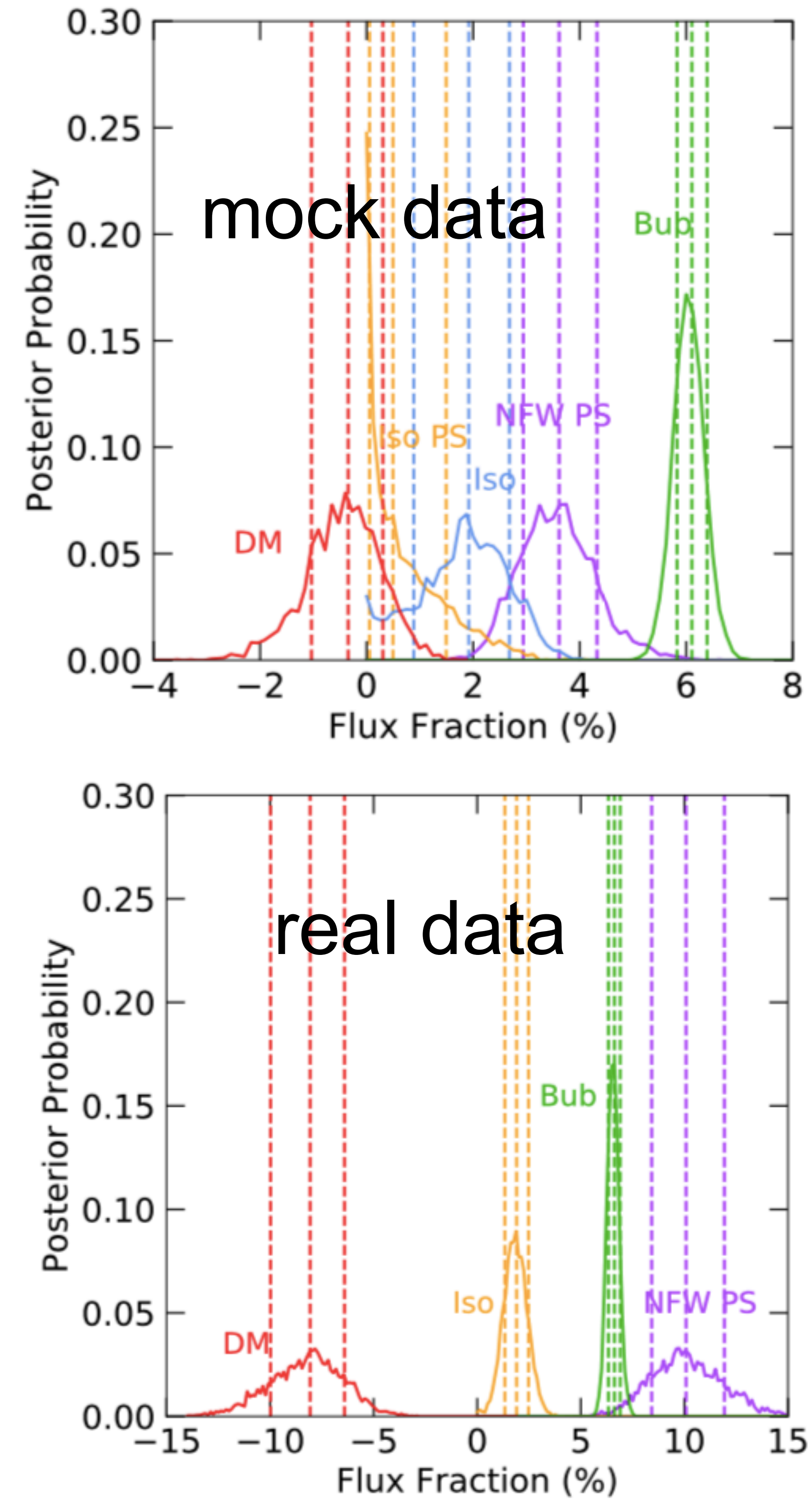
Dark matter strikes back?

- Injecting a simulated DM signal into real data, the signal is not correctly recovered.
- Even for injected DM signal ~5x larger than GCE, fit attributes signal to PSs.
- Indicates a discrepancy between simulated/real data - large enough to potentially hide a O(1) smooth contribution to GCE.
- But note: this does <u>not</u> mean the answer is DM, just that there's a systematic to understand (if we want to use this method to distinguish scenarios).



A complementary analysis

- Instead of injecting a fake DM signal, we can relax the prior on the DM template so its coefficient can run negative.
- Not physical, but allows us to test if the fit is driven into an unphysical region.
- In real data we find the fit prefers a very negative DM coefficient - in simulated data with correct templates the posterior is typically skewed only slightly negative.
- Work in progress by my group and others to understand and correct this behavior.



What could cause this?

- One possible cause of such a discrepancy would be if there is a new point-source population (<u>not</u> associated with the GCE) that we are not modeling correctly.

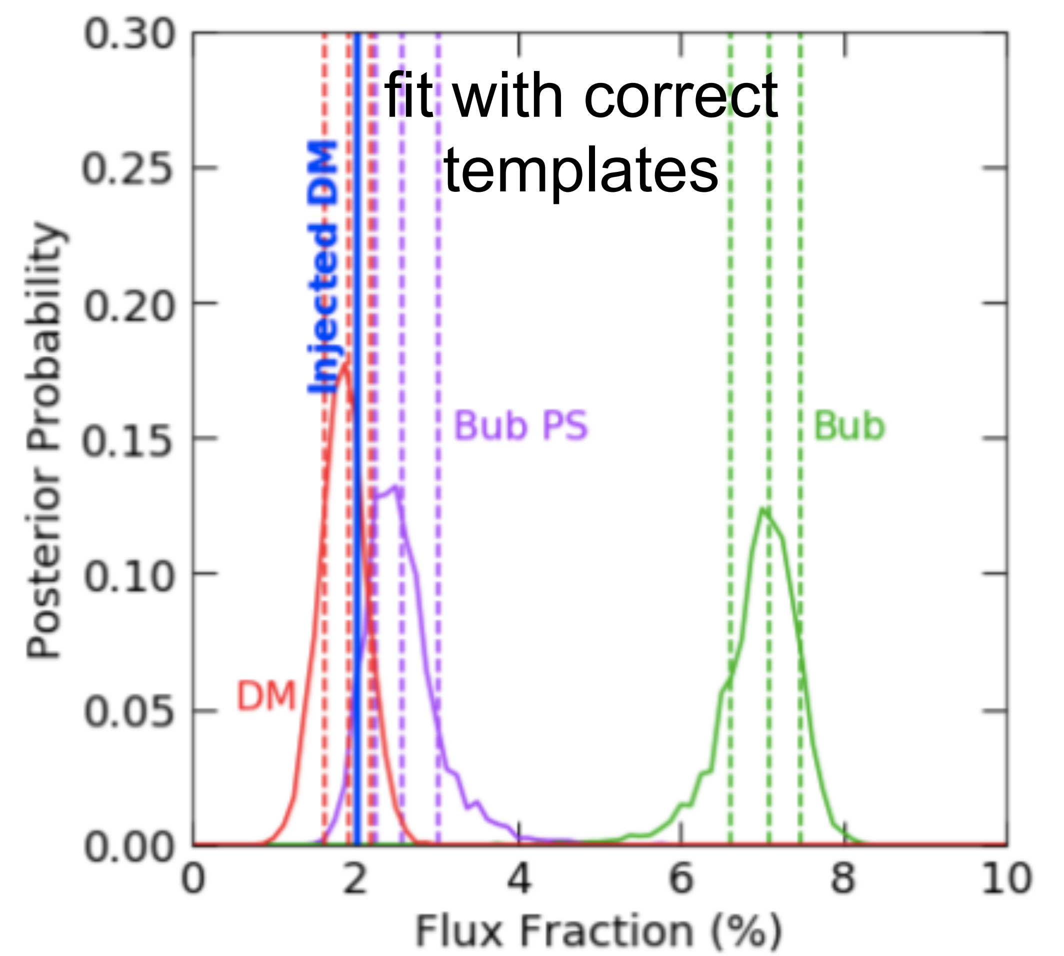
- Simple example as a demonstration (not the actual answer): suppose there were point sources in the base of the Fermi Bubbles (e.g. small dense gas clumps illuminated by cosmic-ray flux through the Bubbles).

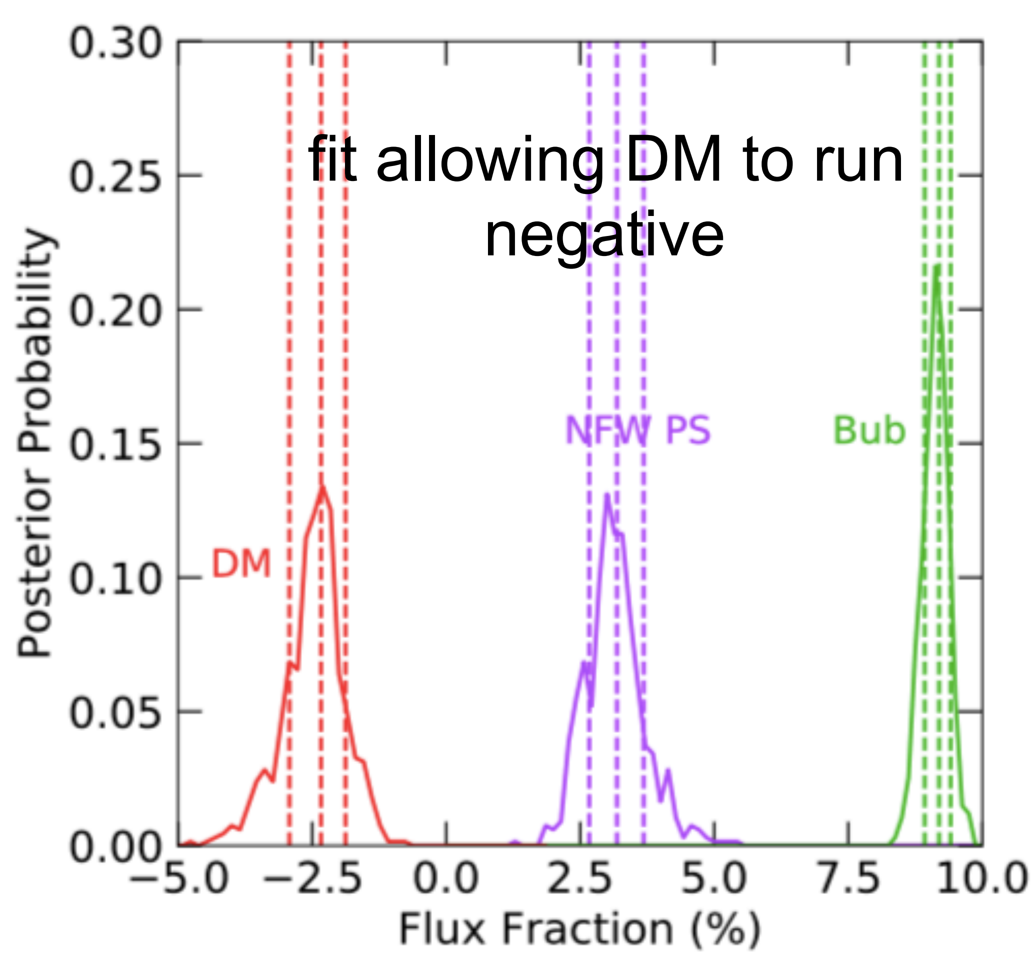
- No template in the fit can perfectly describe this population. To try to explain it, the fit could assign these PSs to the GCE, driving down the DM component to maintain the correct total GCE flux.

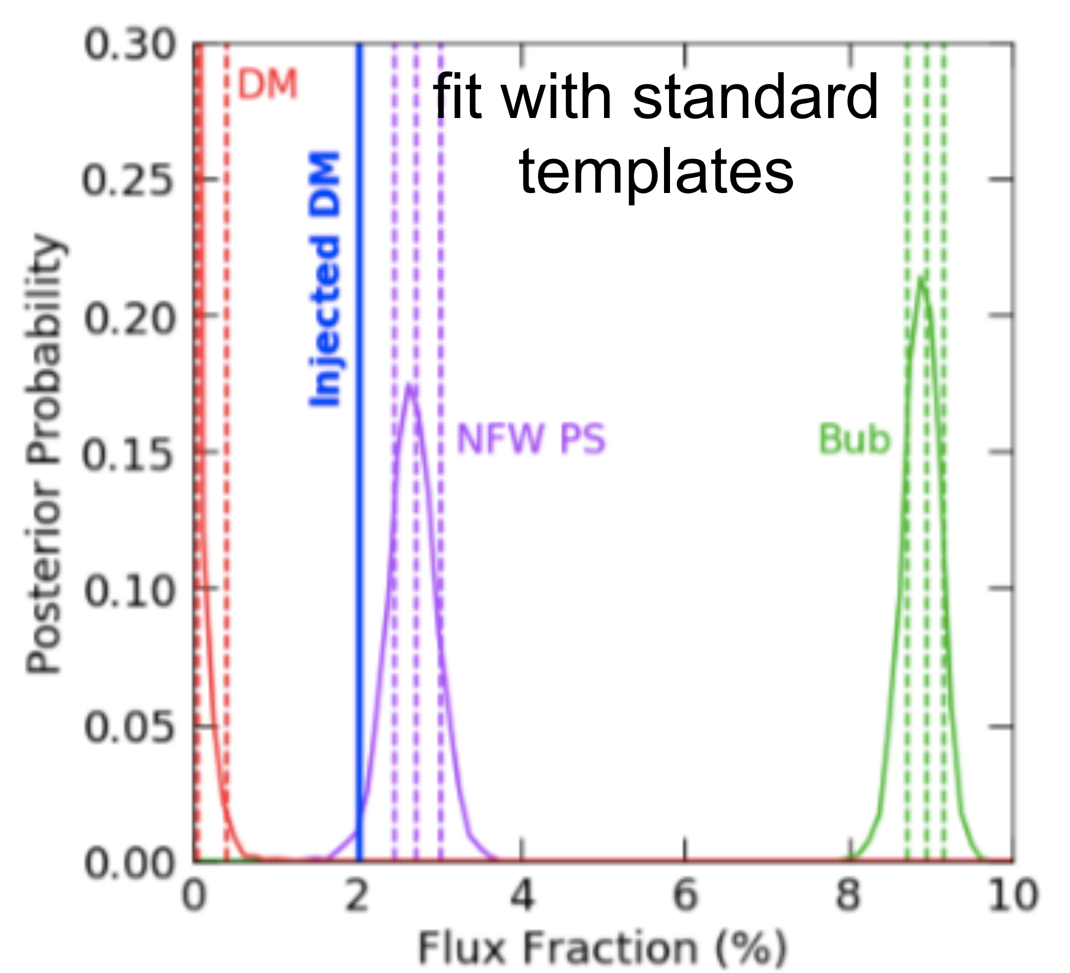
- We demonstrated this scenario can indeed lead to a failure of the injection test, similar to what is observed in real data.

Proof-of-principle example: plots

- This example behaves similarly to the real data, but is not as extreme
- The real data does not appear to contain Bubbles-correlated PSs





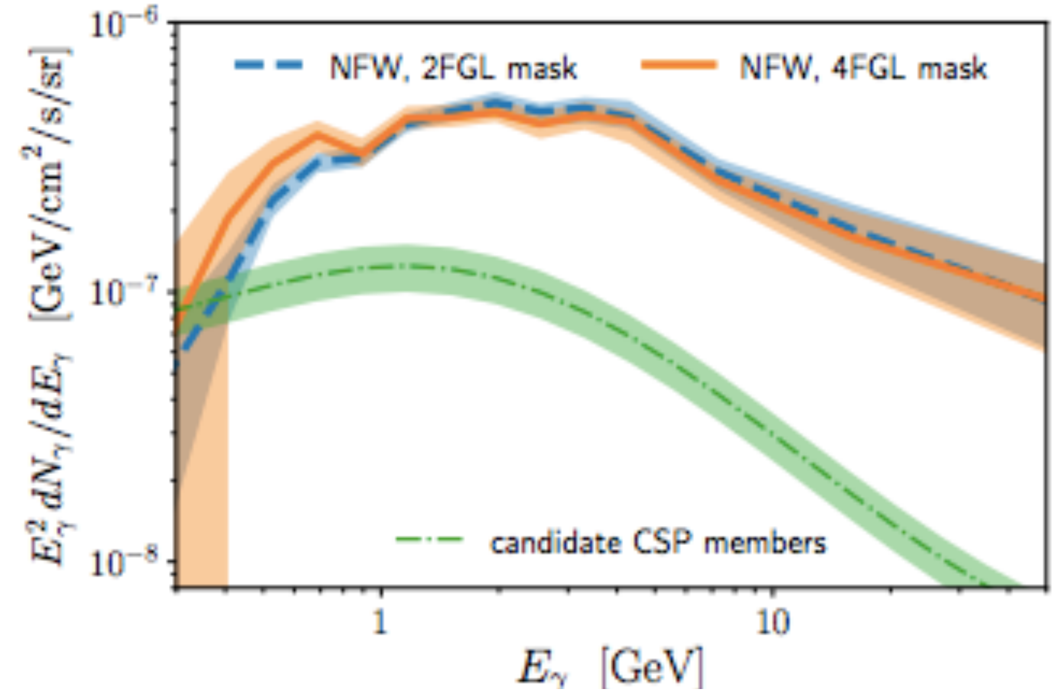


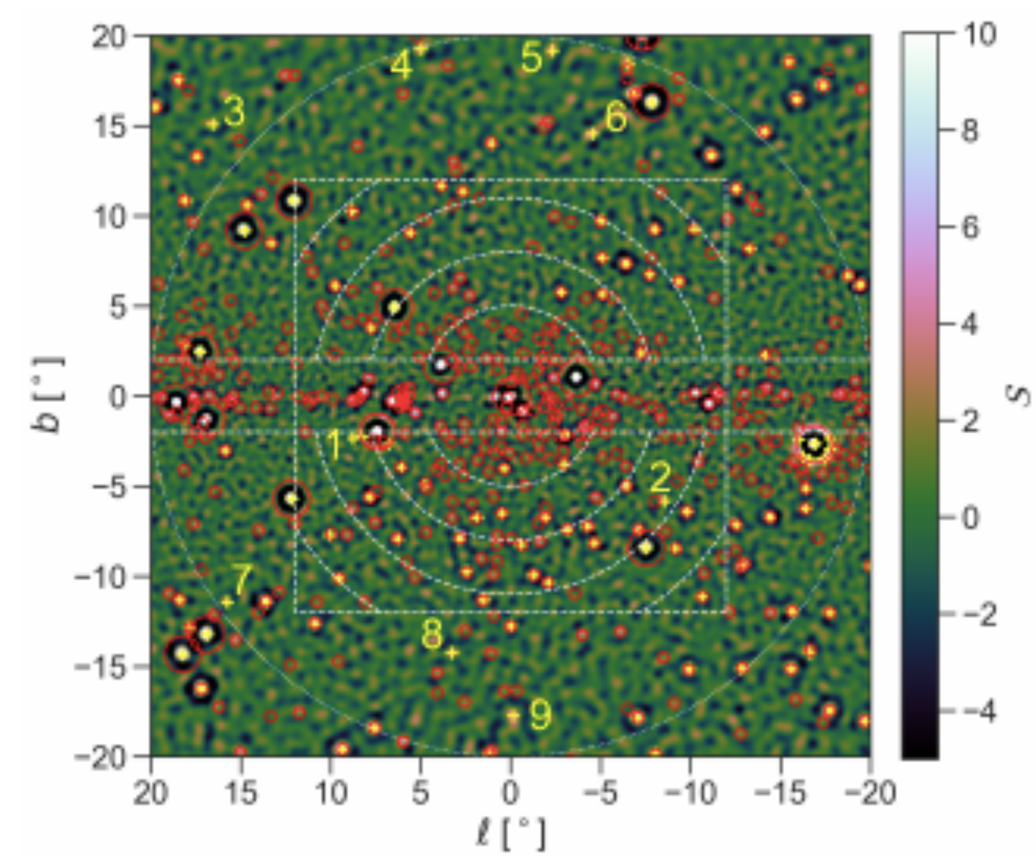
Other possible causes

- Chang et al [arXiv:1908.10874] demonstrate:
    - if the underlying source count function (SCF) is fairly soft (many faint PSs), then the NPTF can reconstruct a too-hard SCF, and furthermore injected signals may be reconstructed incorrectly.
    - this particular source of bias usually does not badly affect the bright end of the SCF - might trust detection of bright PSs, but not limit on smooth component.
    - does not (at least at this stage) seem to quantitatively explain degree to which injection test is failed - plausible to absorb O(GCE) injected signals, but in real data much larger injections are mis-reconstructed.
- [work in progress, preliminary] Mismodeling of the diffuse background/signal templates appears to allow for a spurious detection of point sources (similar to results in real data) even when *no* sources are present - even bright end of SCF not always robust.

Alternative methods

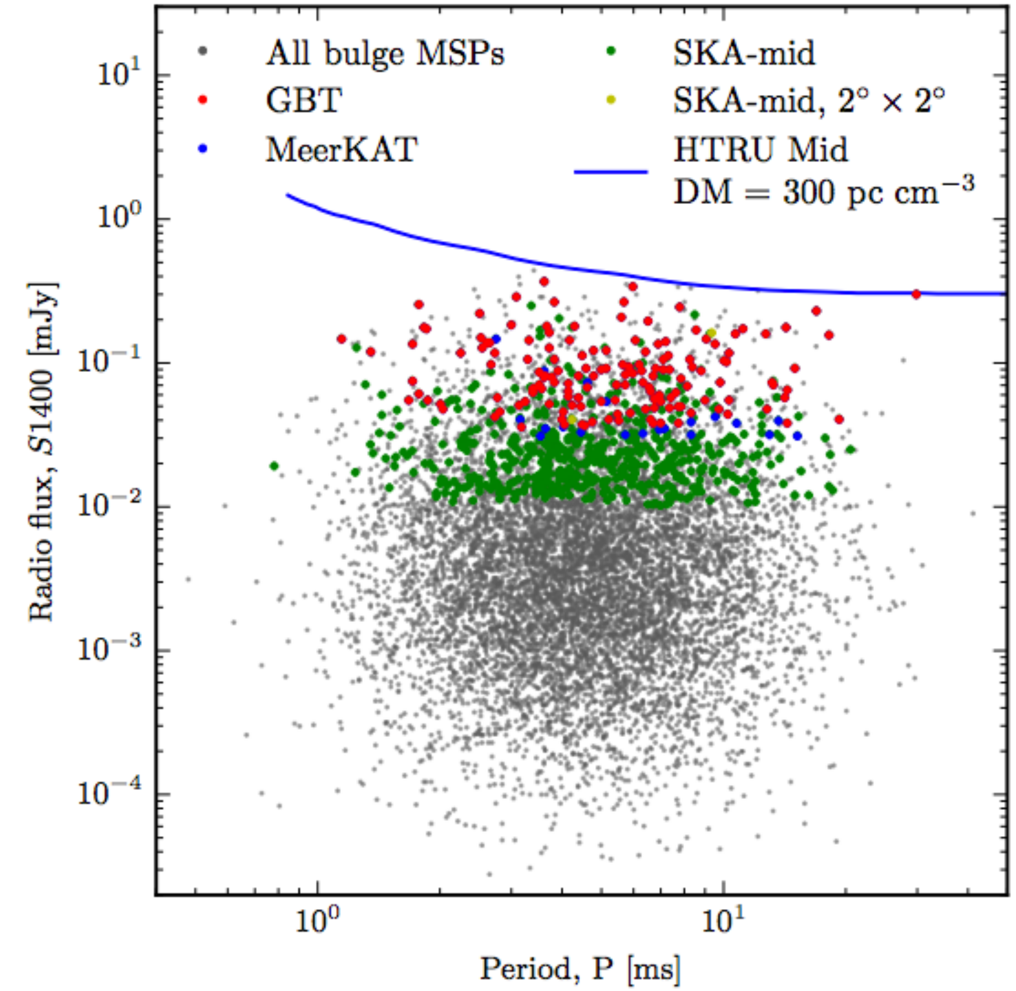
- Can also try to look for individual faint sources directly.
- Recent analysis repeats wavelet analysis of Bartels et al '16, but now compares identified high-significance peaks to latest gamma-ray source catalog (4FGL) [Zhong et al 1911.12369].
- Of 115 peaks, 107 are near a source; 40 of these are potential members of a central GCE population (identified as Galactic pulsars, or unidentified/unassociated).
- Masking 4FGL sources does not reduce GCE.
- Total emission from candidate central-pop sources is a factor ~4-5 below GCE.
- Implies bulk of emission should be diffuse or originating from faint sources.

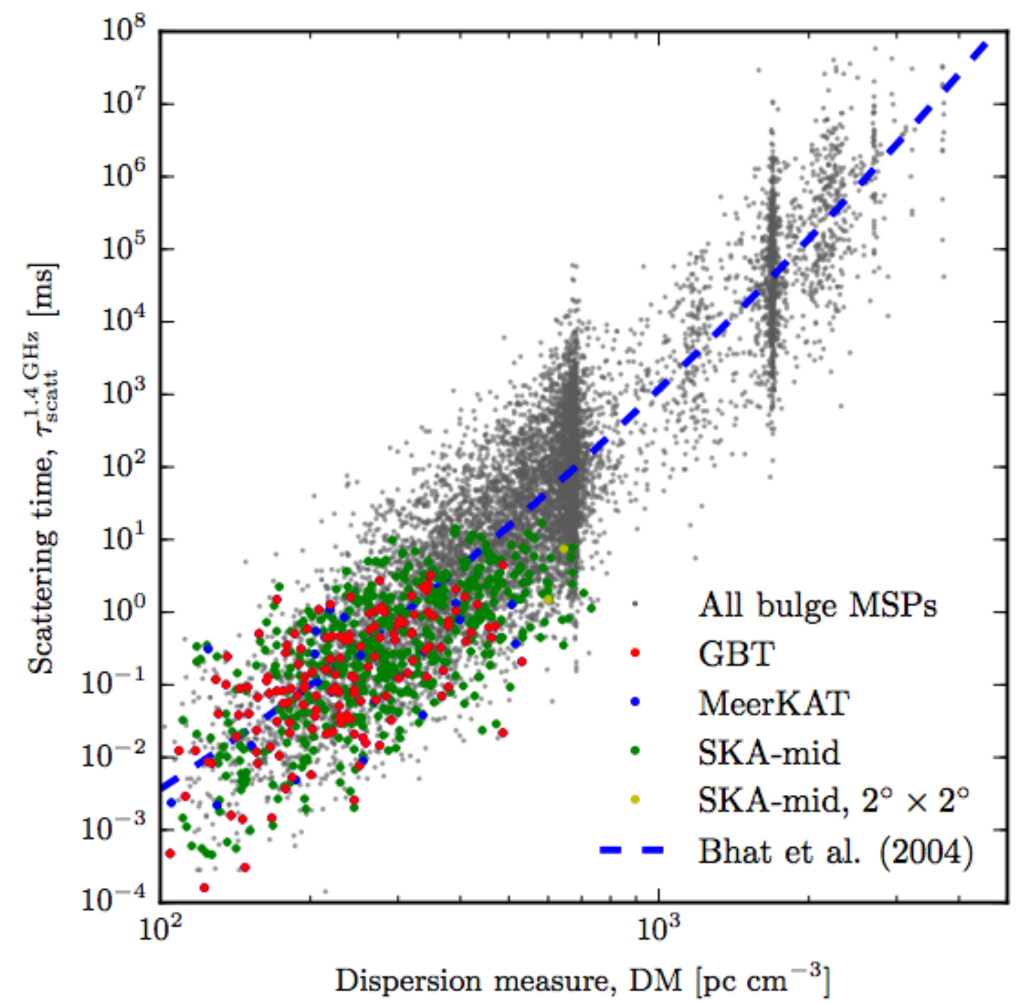




Beyond gamma rays

- If the GCE actually is from pulsars, could potentially be probed by radio or X-ray telescopes.
- Calore et al ’16: MeerKAT could see 10s of pulsars from this population (once fully operational), SKA hundreds.





Summary

- The Galactic Center Excess (GCE) is a robust feature of the central region of the Milky Way; leading explanations are a population of millisecond pulsars or an exotic signal from annihilating dark matter.
- Modeling the GCE as a linear combination of a population of point sources (PSs) and a smooth diffuse component, non-Poissonian template fitting methods initially found a strong preference for the bulk of the GCE to be attributed to the PSs.
- However, we have tested the effect of injecting an additional smooth DM signal into the real data, and found even quite large injected DM signals are attributed to the GCE PS template by the NPTF pipeline.
- Previous arguments that the Galactic Center excess cannot be DM (or other diffuse sources) due to photon statistics may be premature - need to understand systematics from (mis)modeling of backgrounds to make this claim robust.