Dark Matter Strikes Back at the Galactic Center

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Based on arXiv:1904.08430 (accepted to PRL), with Rebecca Leane

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Outline

- Review of the Galactic Center excess (GCE) as a possible dark matter annihilation signal
- Intro/review on Non-Poissonian Template Fitting (NPTF) + evidence the GCE is comprised of point sources
- A proof-of-principle example of a possible bias to the NPTF method
- A consistency test in the real data
- Summary and outlook

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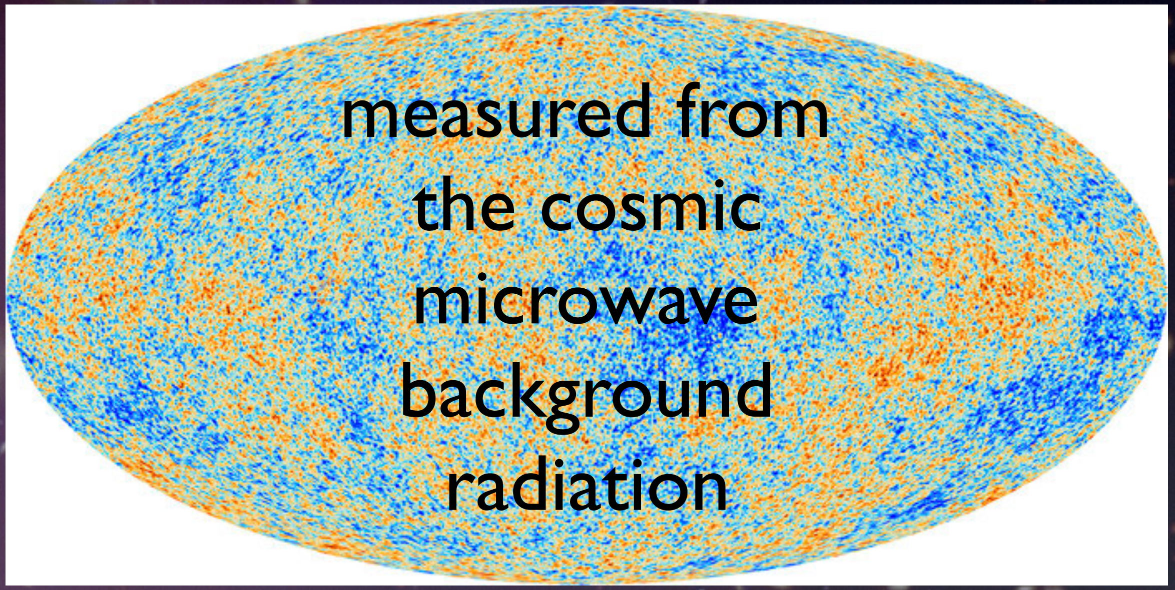

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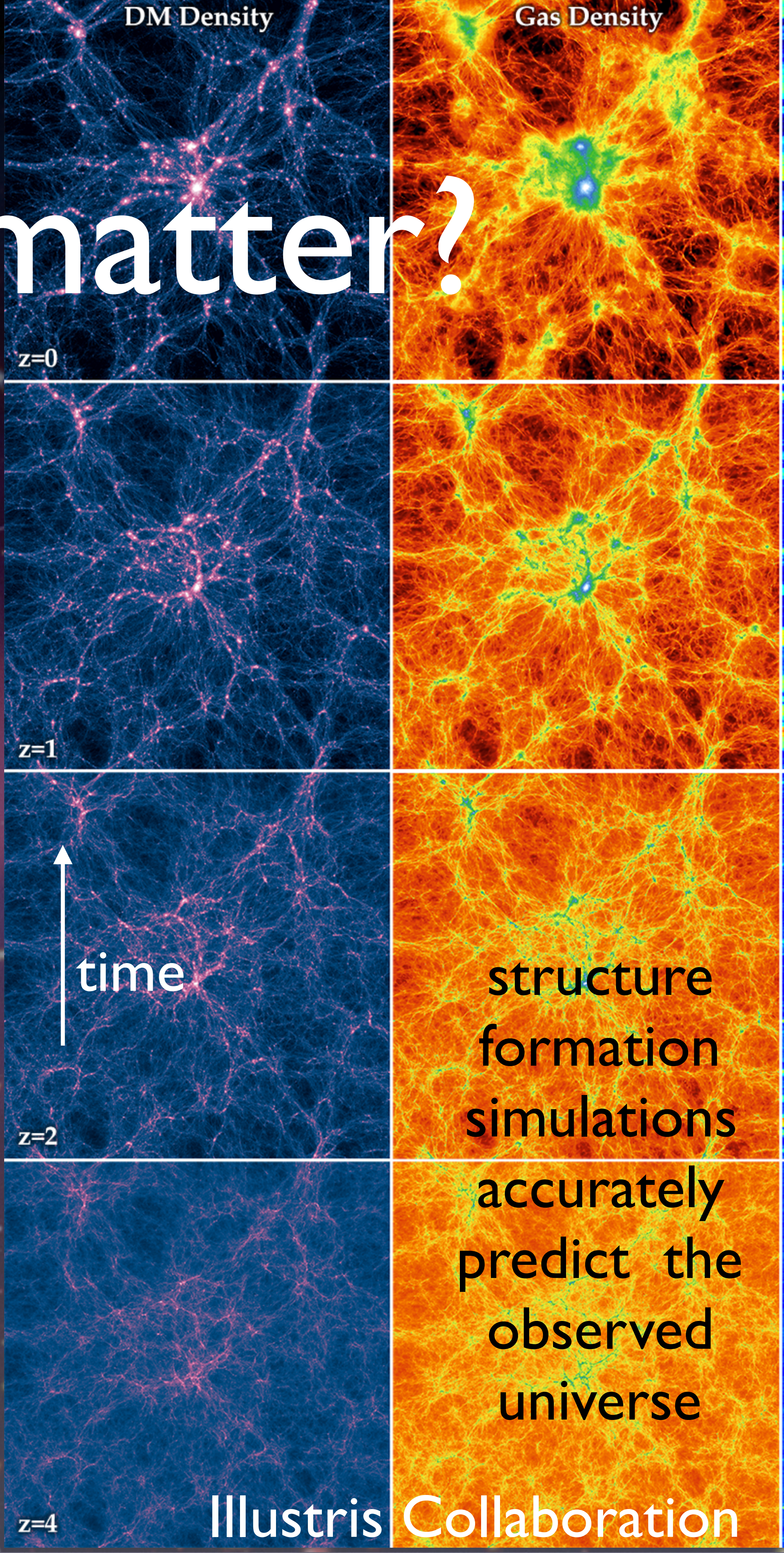

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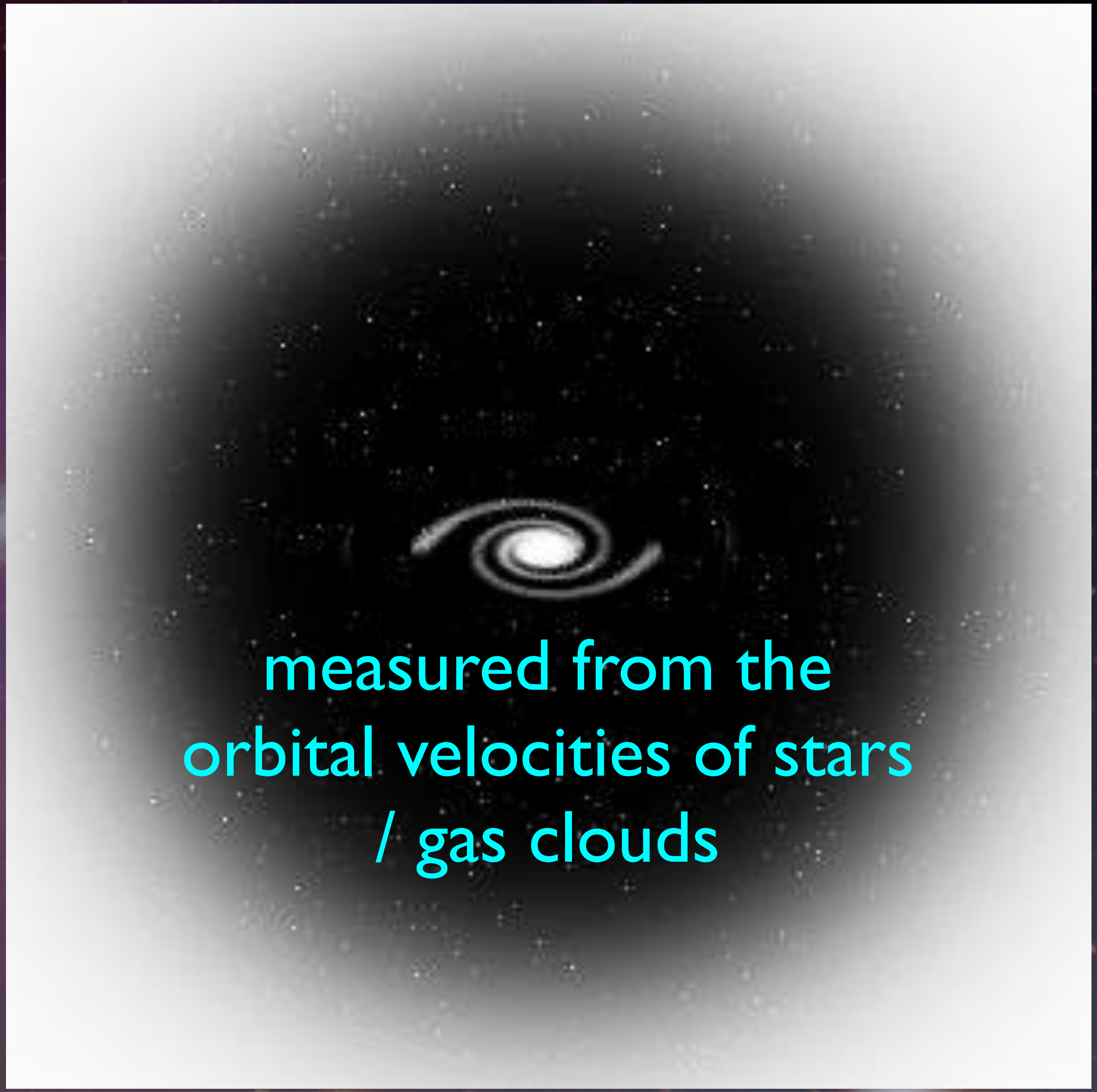

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- Interacts with other particles weakly or not at all (except by gravity).

null results of
existing searches

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<u>We know it:</u>

<u>Open questions:</u>

- Consequently, CANNOT be explained by any known particles

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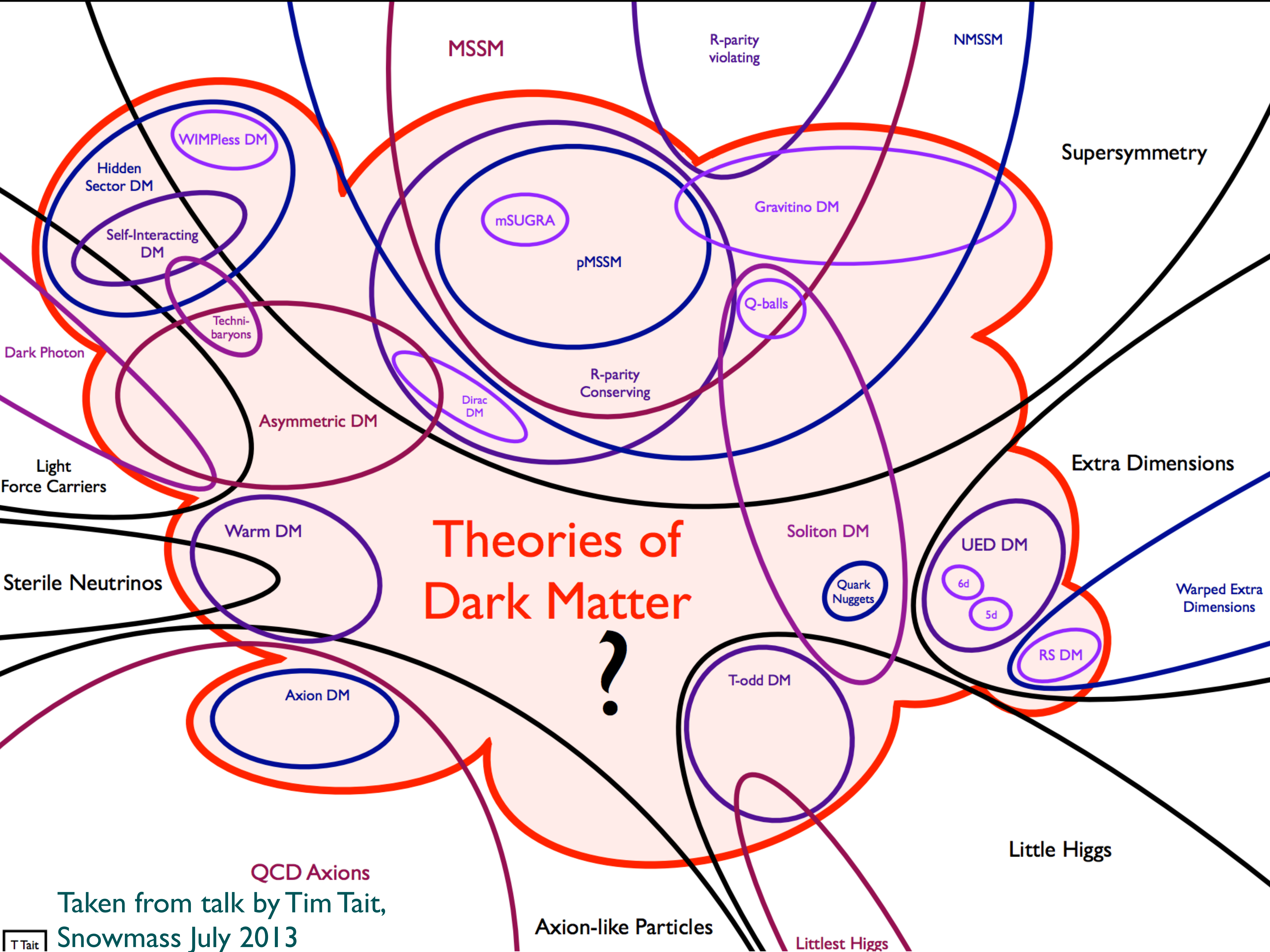
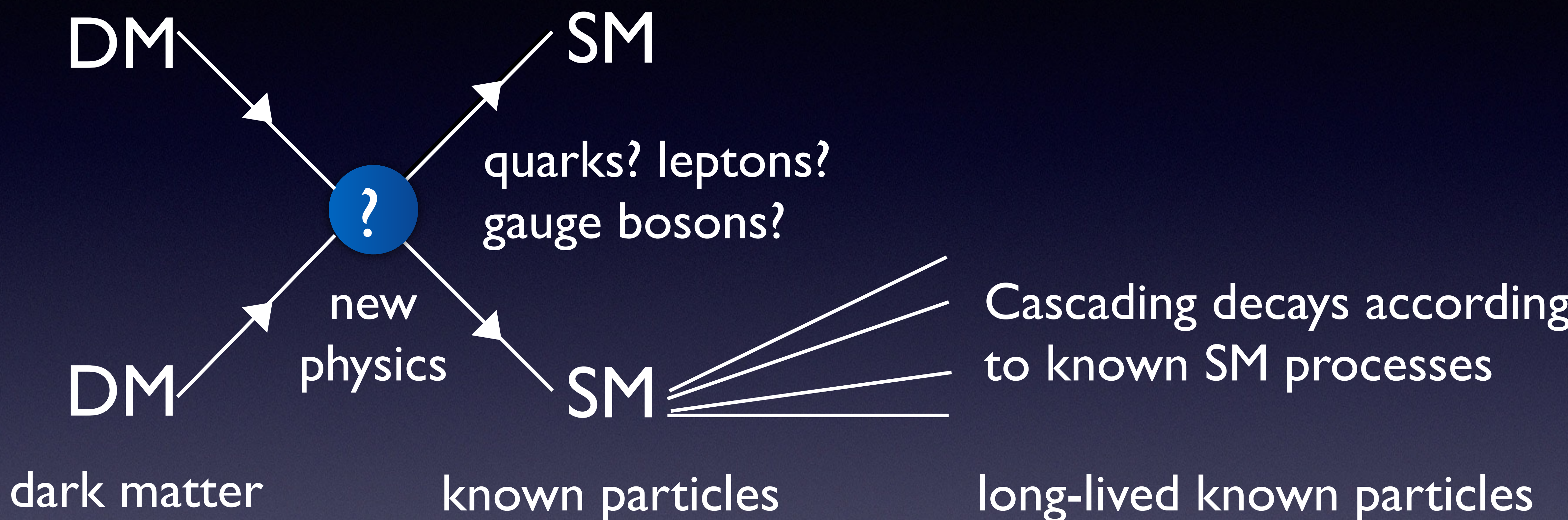
- and many more…



Taken from talk by Tim Tait, Snowmass July 2013

Annihilation



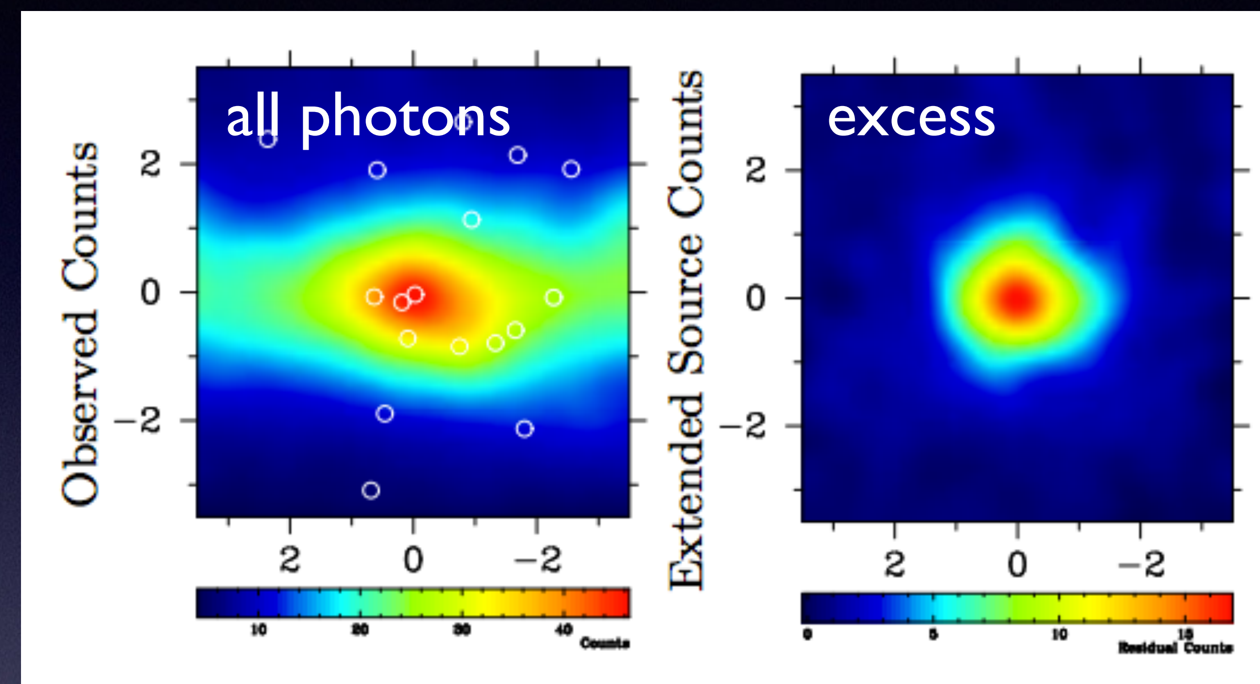
- One explanation for the observed abundance of DM is that most of it annihilated away in the early universe
- In such scenarios, the annihilation rate can be inferred from the present-day DM abundance, giving a cross section ("thermal relic cross-section") of:

$$\langle \sigma v \rangle \sim 2 - 3 \times 10^{-26} \mathrm{cm}^3/s \sim \pi\alpha^2/(100\mathrm{GeV})^2$$

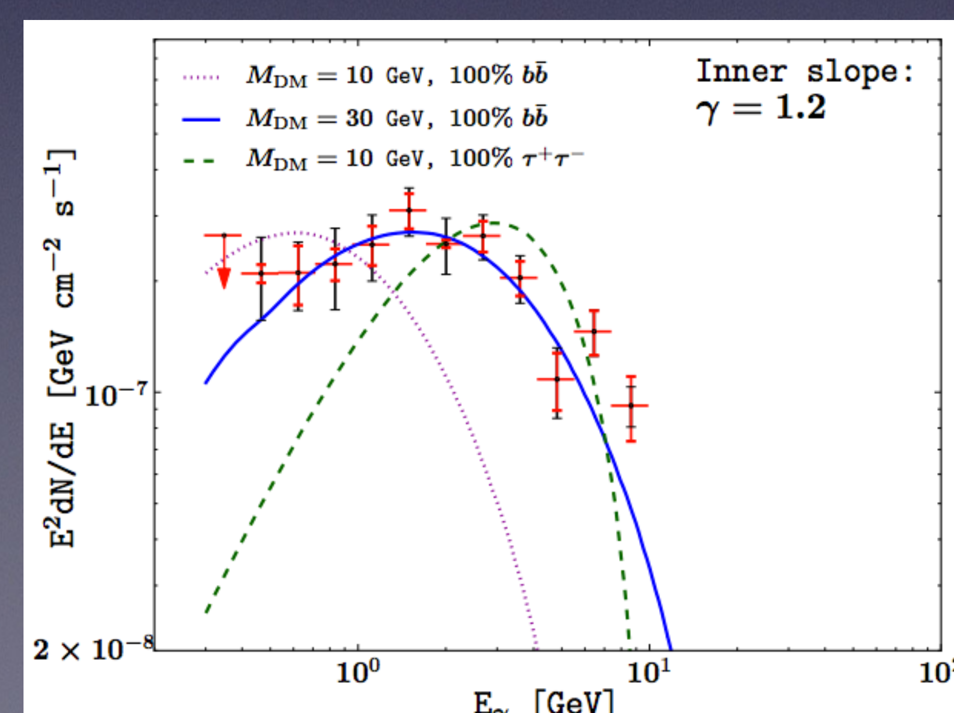
The Galactic Center Excess (GCE)

- Apparent new gamma-ray component found in Fermi Gamma-Ray Space Telescope public data
- Initial discovery '09 by Goodenough & Hooper, in the Galactic Center (GC)
- Discovered to extend outside the GC, into the inner Galaxy, by Hooper & TRS '13
- Confirmed by Fermi Collaboration in analysis of Ajello et al '16

spatial distribution   Abazajian & Kaplinghat '12

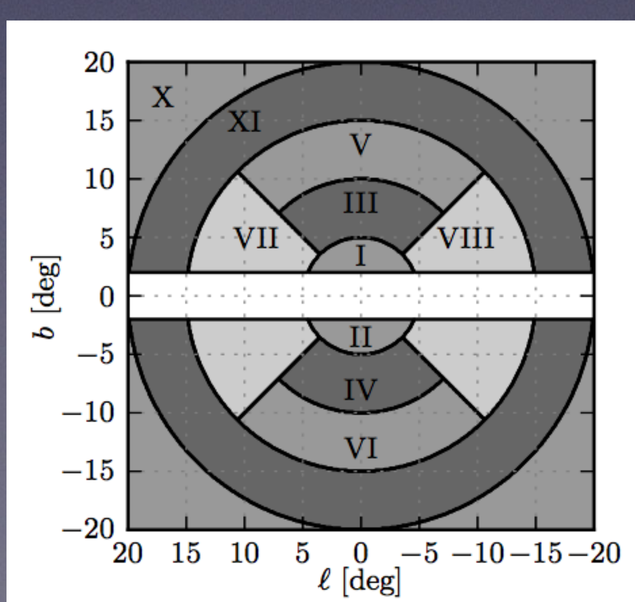


spectrum   Gordon & Macias '13

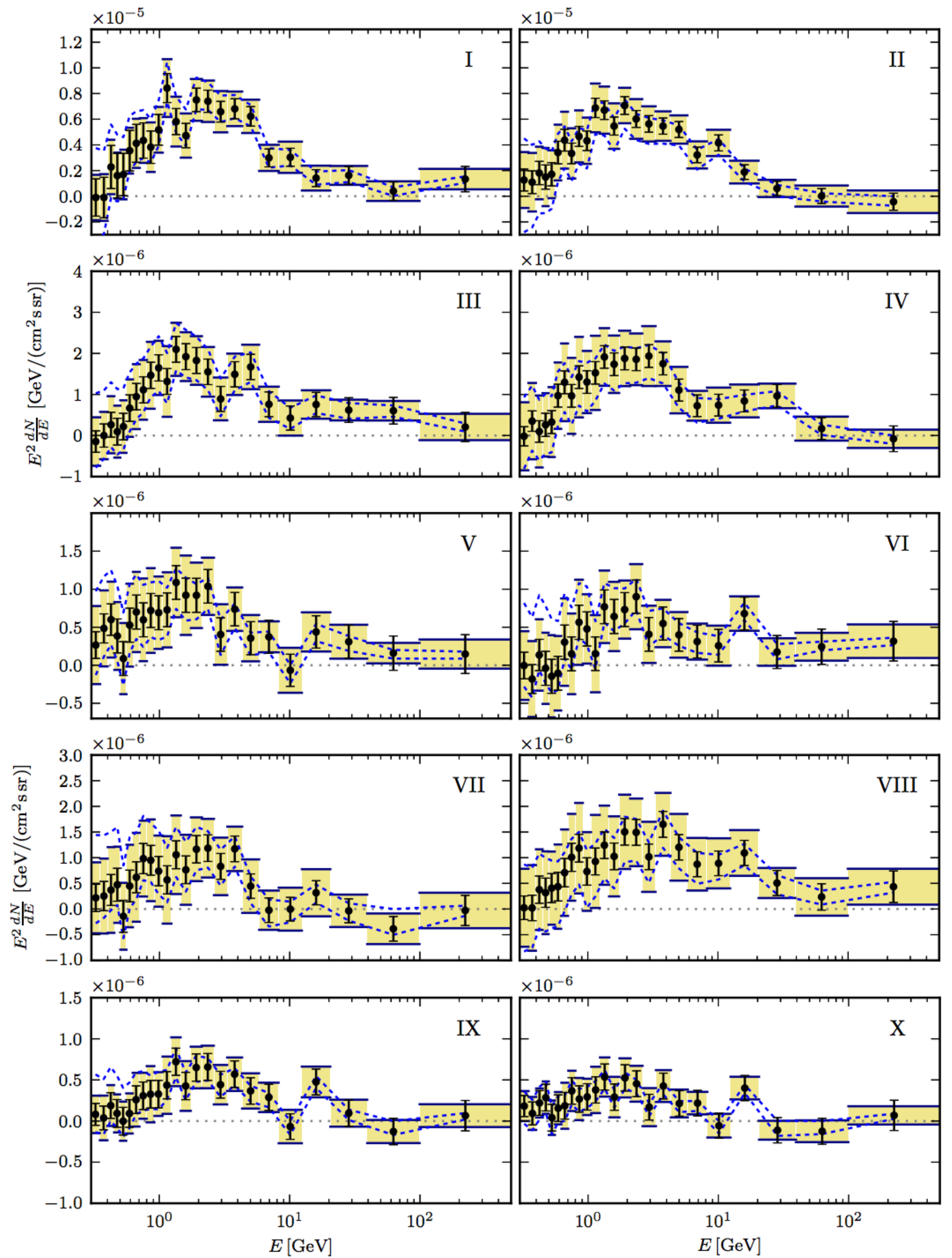


Properties

- Daylan, TRS et al ’16 found that:
  - Rate agrees well with expectations for thermal relic annihilating DM
  - Photons peak around 1-3 GeV in energy
  - Excess is approximately symmetric around the GC, steeply peaked at GC. Can also be well-described as Bulge-like extended emission + central symmetric core [Macias et al ’18, Bartels et al ’18].



Plots taken from Calore, Cholis & Weniger ‘14

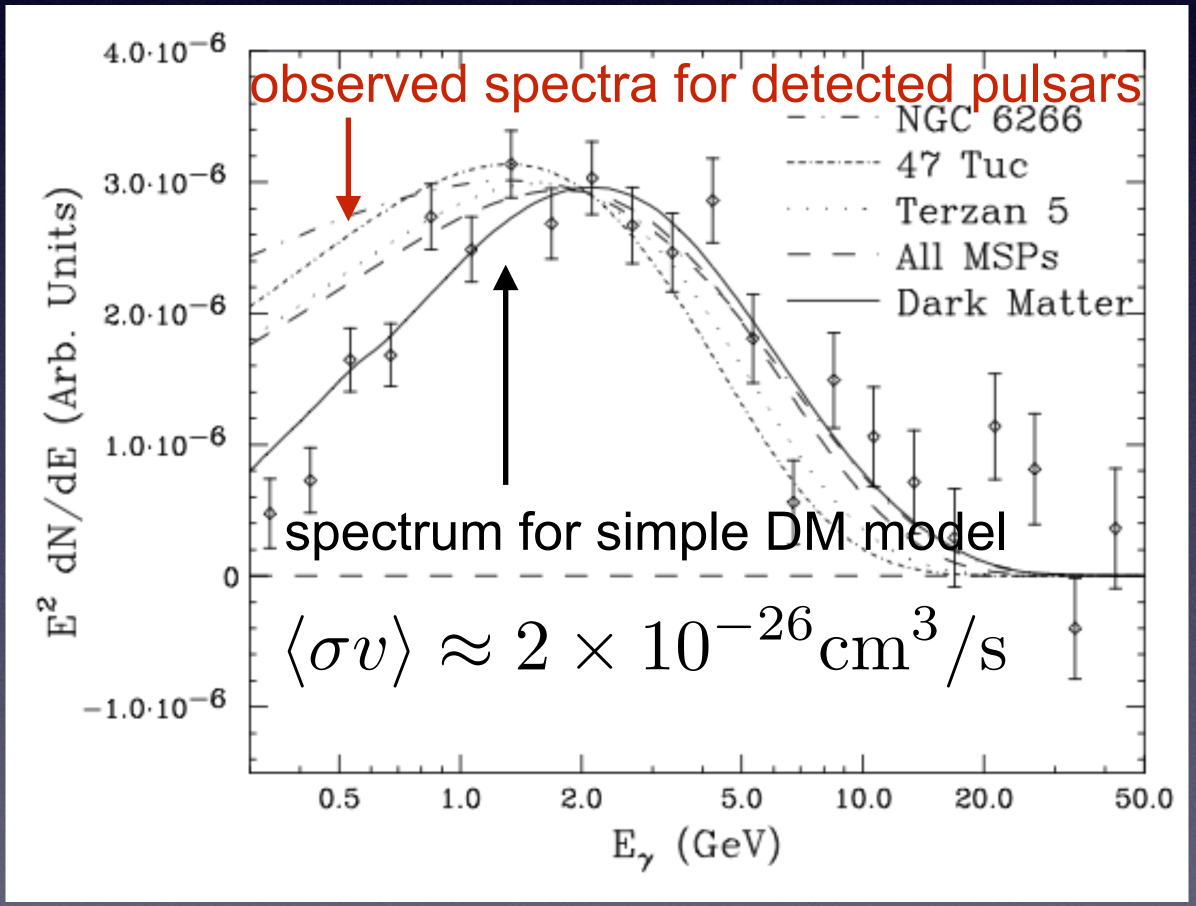


Hypotheses

- Dark matter annihilation.

Particle theorist: 😀

- "Conventional" astrophysics (i.e. not requiring physics beyond the Standard Model):
  - A new population of stars or other point sources - most discussed candidate is millisecond pulsars (MSPs), spinning neutron stars.
  - A new diffuse background - most discussed candidate is an outflow or burst from the Galactic Center.



Daylan, TRS et al '16

Particle theorist: 😕 Astrophysicist: 😀

of distinguishing hypotheses…

PULSAR WARS

A NEW HOPE

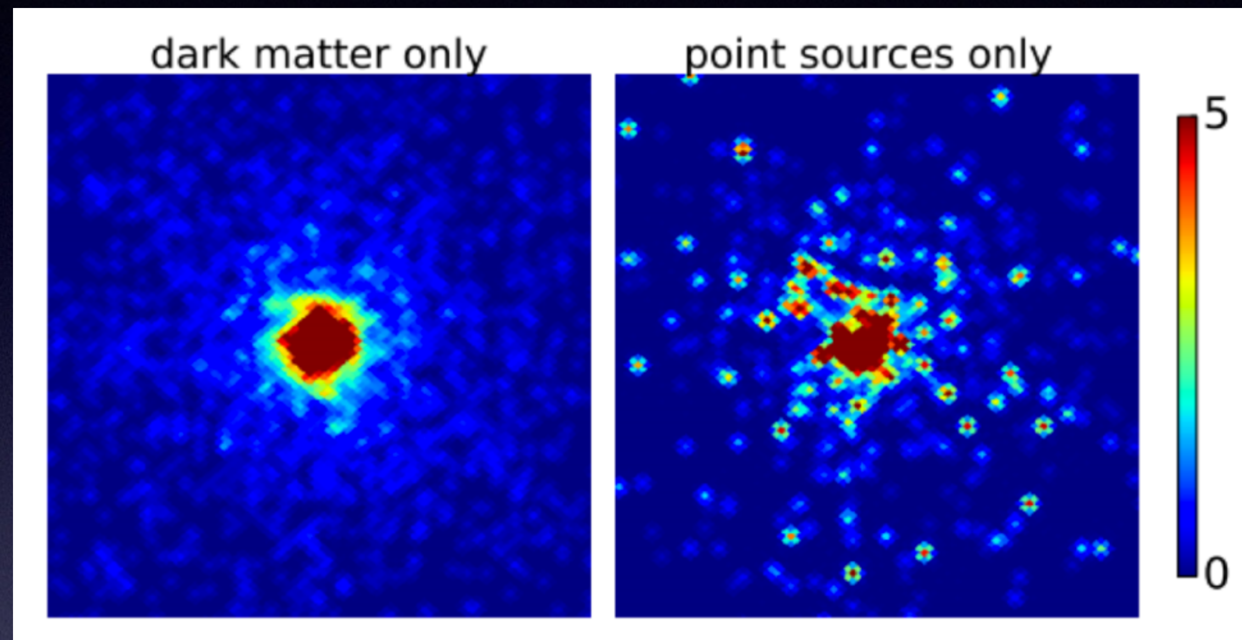
of distinguishing hypotheses…

Photon statistics

Lee, Lisanti, Safdi, TRS & Xue, PRL '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.
- If we are looking at dark matter (or another diffuse source, like an outflow), we expect a fairly smooth distribution.
- In the pulsar case, we might instead see many "hot spots" scattered over a fainter background.
- Related analysis by Bartels et al '16, using wavelet approach - found evidence for small-scale power in inner Galaxy, consistent with approach I will describe.

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

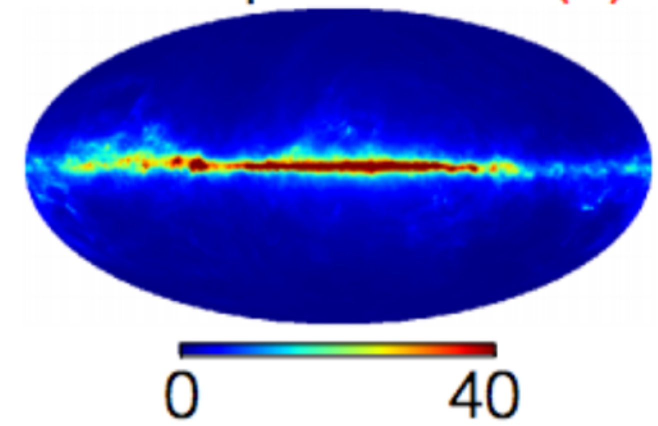
$P(0 \text{ photons}) \sim 0.9$, $P(12 \text{ photons}) \sim 0.1 \times 100^{12}\, e^{-100}/12! \sim 10^{-29}$, $P(100 \text{ photons}) \sim 4 \times 10^{-3}$

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

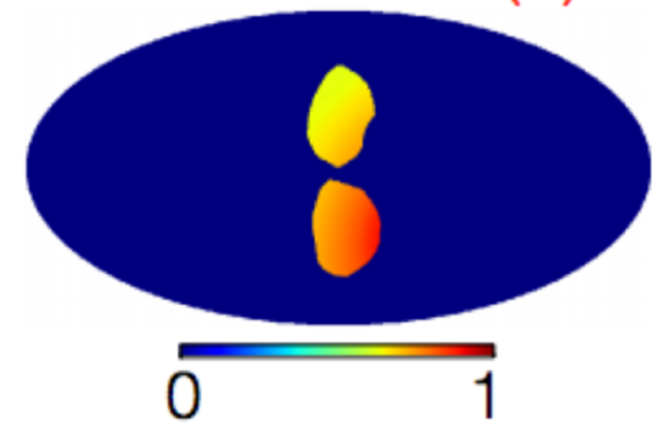
Template fitting

- 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

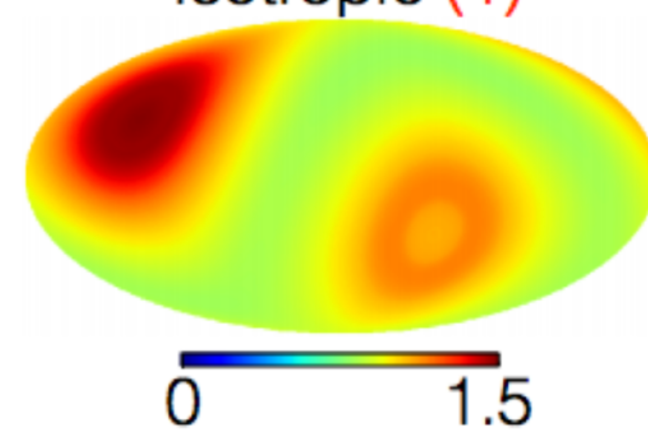
Fermi p6 diffuse (1)



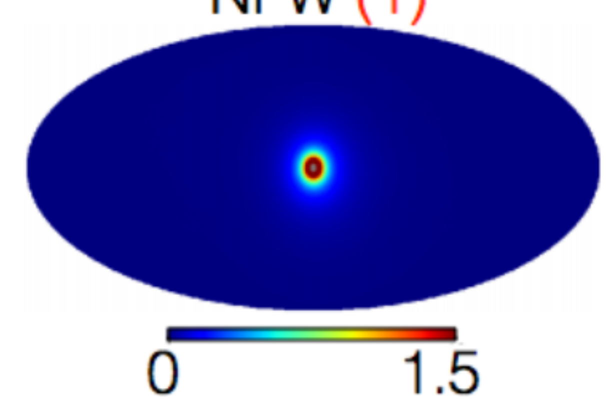
Fermi bubbles (1)



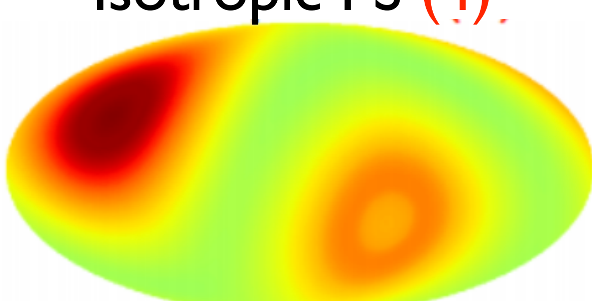
Isotropic (1)



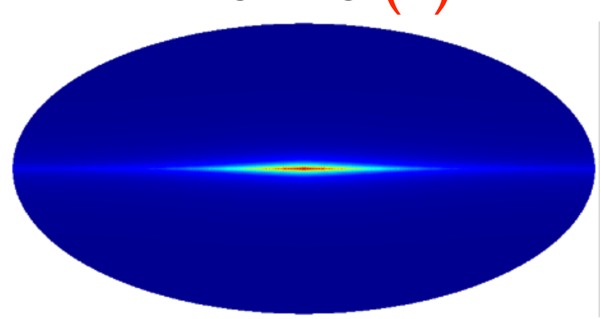
NFW (1)



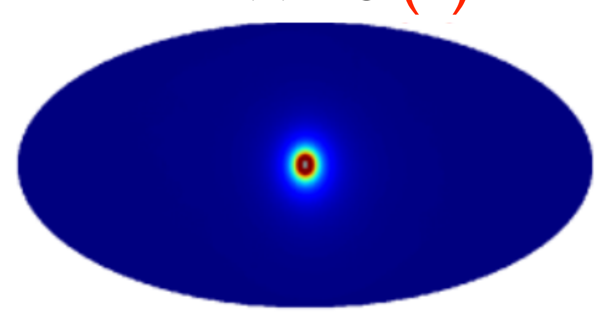
Isotropic PS (4)



Disk PS (4)



NFW PS (4)



Point source templates

Non-Poissonian statistics

Malyshev & Hogg '11; Lee, Lisanti & Safdi '15

- Easiest to recast probabilities in terms of generating functions:

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

probability for k counts in pixel p

- Then total generating function for sum of model components = product of component generating functions.

from Poissonian templates

$$\mathcal{P}^{(p)}(t) = \mathcal{D}^{(p)}(t)\mathcal{G}^{(p)}(t)$$

from non-Poissonian template

generating function for point source population

$$\sum_{k=0}^{\infty} P_k t^k = \exp\left[\sum_{m=1}^{\infty} x_m (t^m - 1)\right] \equiv \mathcal{G}(t)$$

expected number of m-photon sources

source count function

determined by Monte Carlo, accounts for finite angular resolution

$$x_m = \frac{\Omega_{\rm pix}}{4\pi}\int_0^\infty dS \frac{dN}{dS}(S) \int df\, \rho(f) \frac{(fS)^m}{m!} e^{-fS}$$

Statistics for a PS population are defined by source count function - # of sources with a given brightness.

The source count function

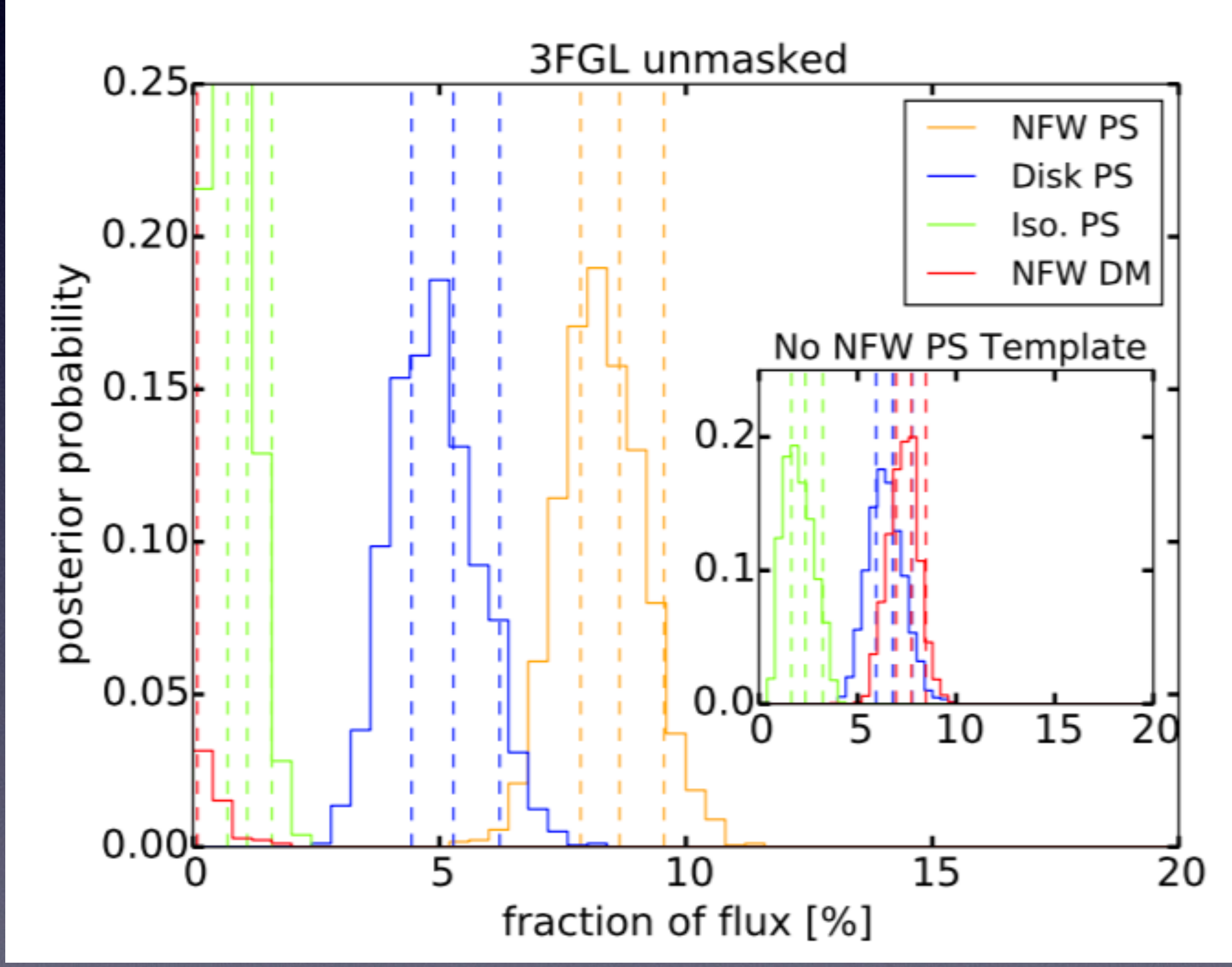
- By default we assume the source count function for all PS templates is a singly broken power law:

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

- Source count functions float independently for each PS template.
- Thus each PS template has 3 extra degrees of freedom, beyond the overall normalization parameterized by the spatial template.
- Source count function assumed constant over sky, only normalization is controlled by position (via spatial template).
- Restrict to a single broad energy bin (2-12 GeV) - no extraction of spectrum.

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".
- 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.



Lee, TRS et al '16

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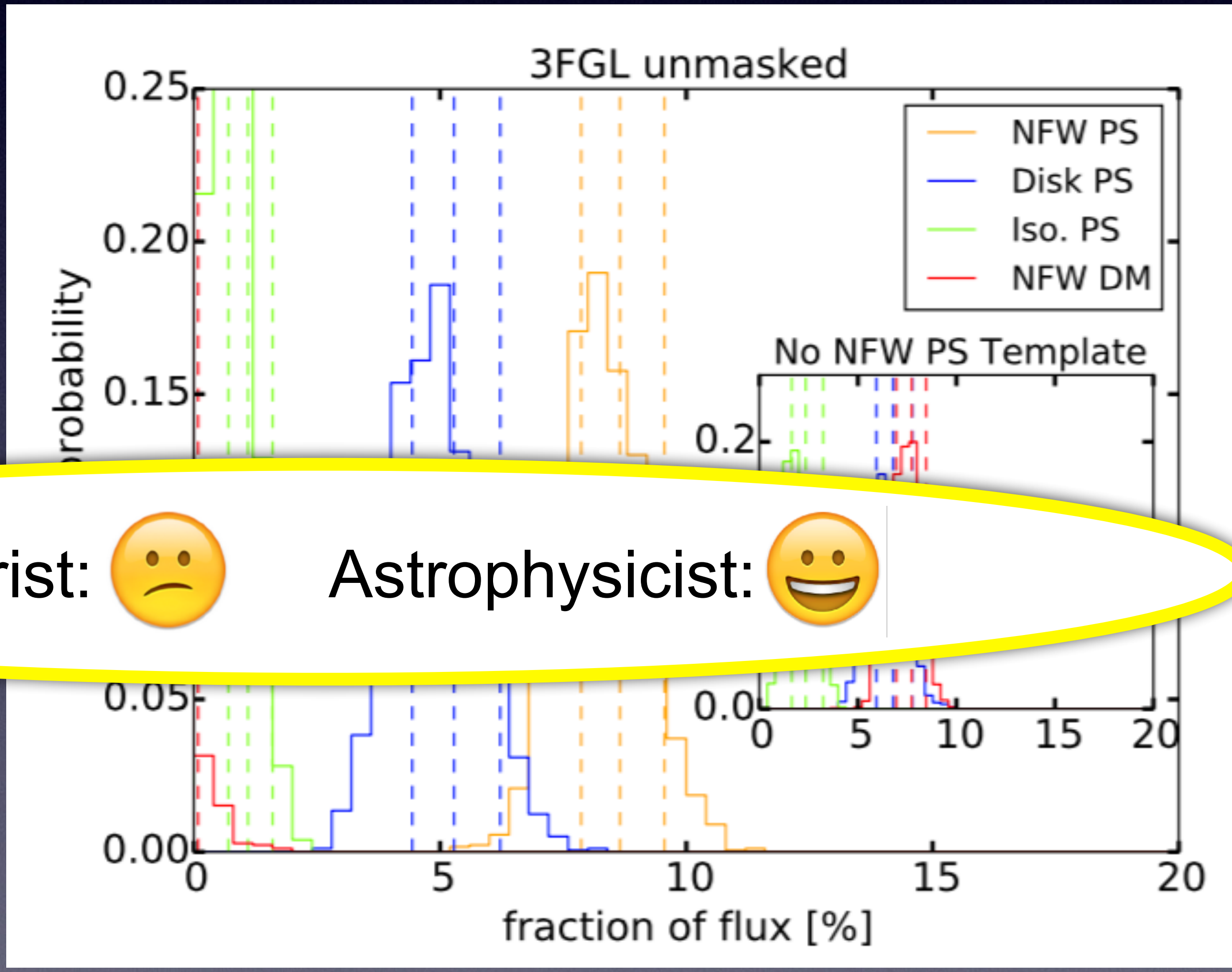


Particle theorist: 😕 Astrophysicist: 😀

Lee, TRS et al ’16

Model comparison

- We use the Bayes factor as our measure of statistical preference for the NFW PS template.
- Bayes factor = ratio of Bayesian evidences for the model with and without including NFW PS:

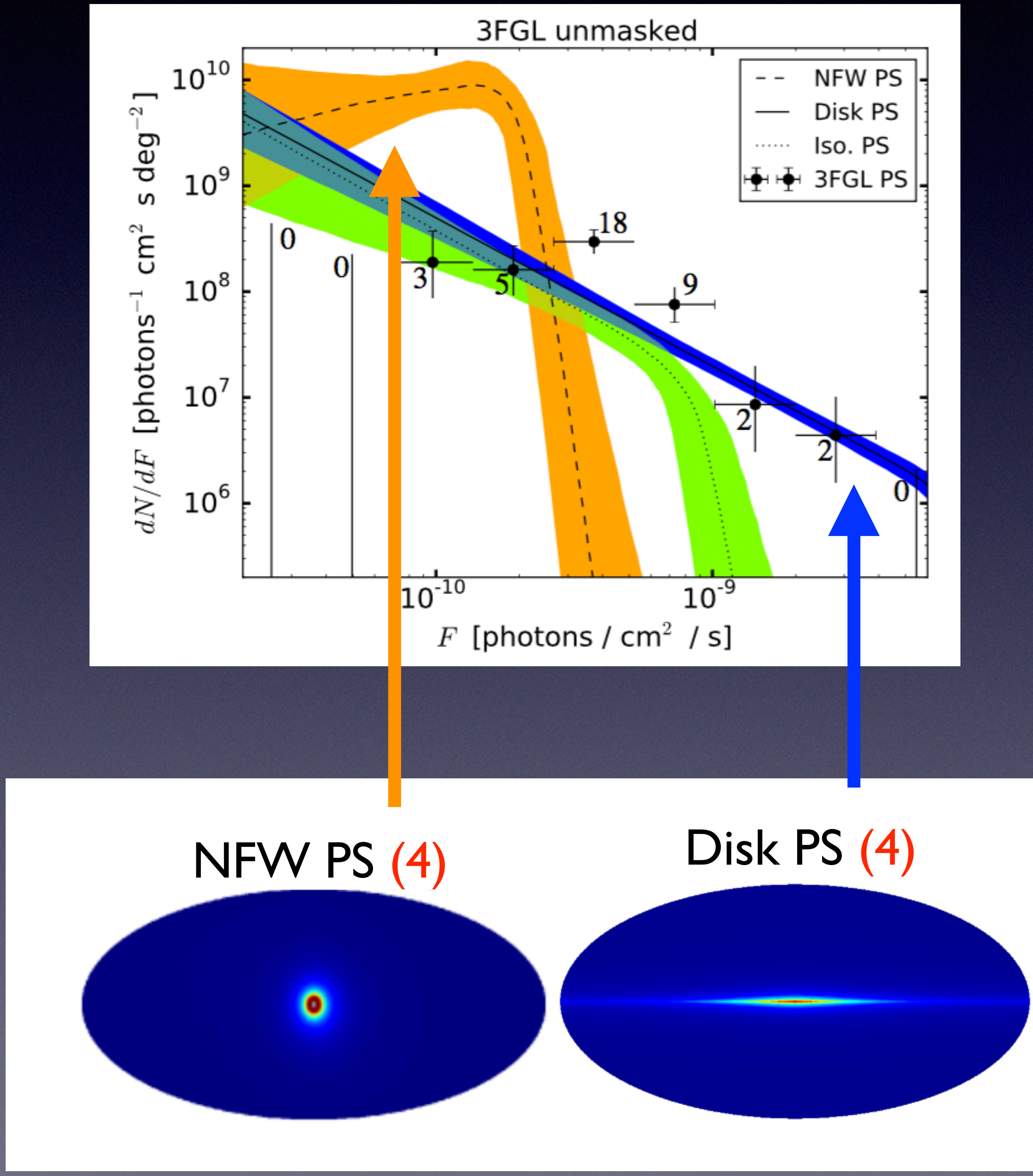
likelihood prior

$$B_{10} = \frac{P(d|\mathcal{M}_1)}{P(d|\mathcal{M}_0)} \qquad P(d|\mathcal{M}) = \int_{\Omega_M} d\theta \, P(d|\theta, \mathcal{M}) P(\theta|\mathcal{M})$$

- In our unmasked analysis, non-zero NFW PS contribution is preferred with a Bayes factor ~ 10^9. Strong statistical preference (but this number does not include systematics).
- Very rough frequentist analogy: Bayes factor ~ likelihood ratio (-correction for extra degrees of freedom), test statistic (TS) ~ 2 ln L ~ 2 ln(Bayes factor) ~ 41, number of sigma ~ $\sqrt{TS}$ ~ 6.4. (Or more simply, 1 - 10^{-9} CL ~ 6.1 sigma.)

Properties of the 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



STAR WARS™

THE EMPIRE STRIKES BACK

PULSAR

WARS™

DARK MATTER STRIKES BACK

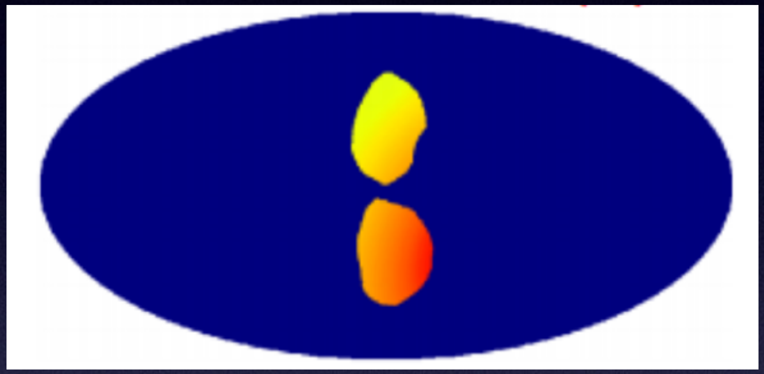
Possible biases in non-Poissonian template fitting

- If the diffuse background is mismodeled, could this mismodeling be absorbed into the PS template, leading to a spurious detection?
  - tested method in other regions with model/data discrepancies, didn't find strong preference for PSs
  - tested method in mock data built with one diffuse model and fitted with a different one, found biases to GCE PSs were modest
  - split the excess into different spatial regions with different diffuse emission (e.g. north/south), found consistent PS-population properties in all regions
- Wavelet-based methods (e.g. Bartels et al '16) do find evidence for small-scale power in the region of the GCE, beyond expectations from diffuse background - suggests <u>something</u> point-source-like is there.
- If the PS populations are mismodeled, could that bias the posterior distribution for the DM flux?

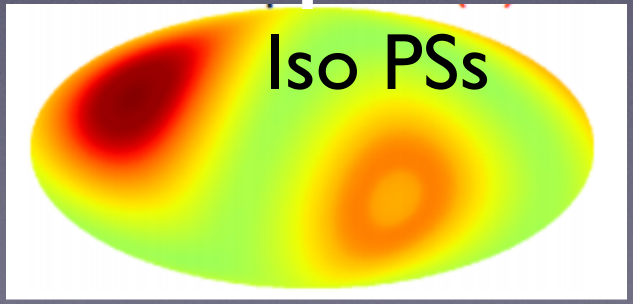
Effects of an unmodeled PS population

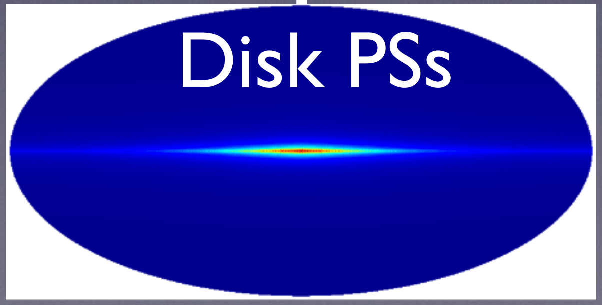
- Suppose there is a new PS population present, not well-described by disk + isotropic sources - e.g. PSs correlated with the Fermi Bubbles or (a subcomponent of) the Galactic bulge
- This population might drive up normalization of “NFW PS” template, to explain bright non-disk non-isotropic sources
- This in turn could drive “NFW DM” template normalization downward, to preserve total flux in the GCE

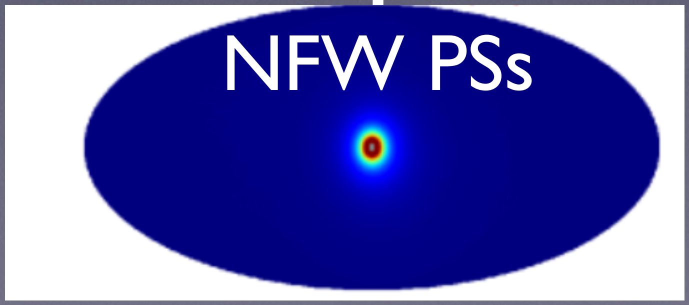
New PSs

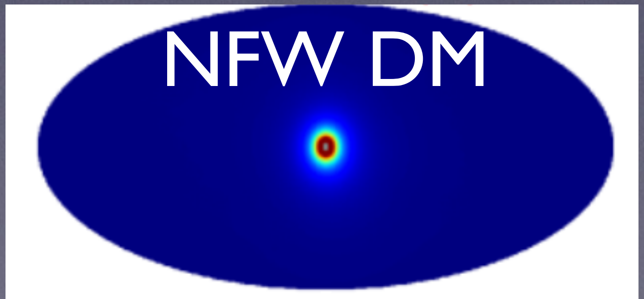


(Hypothetically) present in data, but not available as a (PS) template in fit







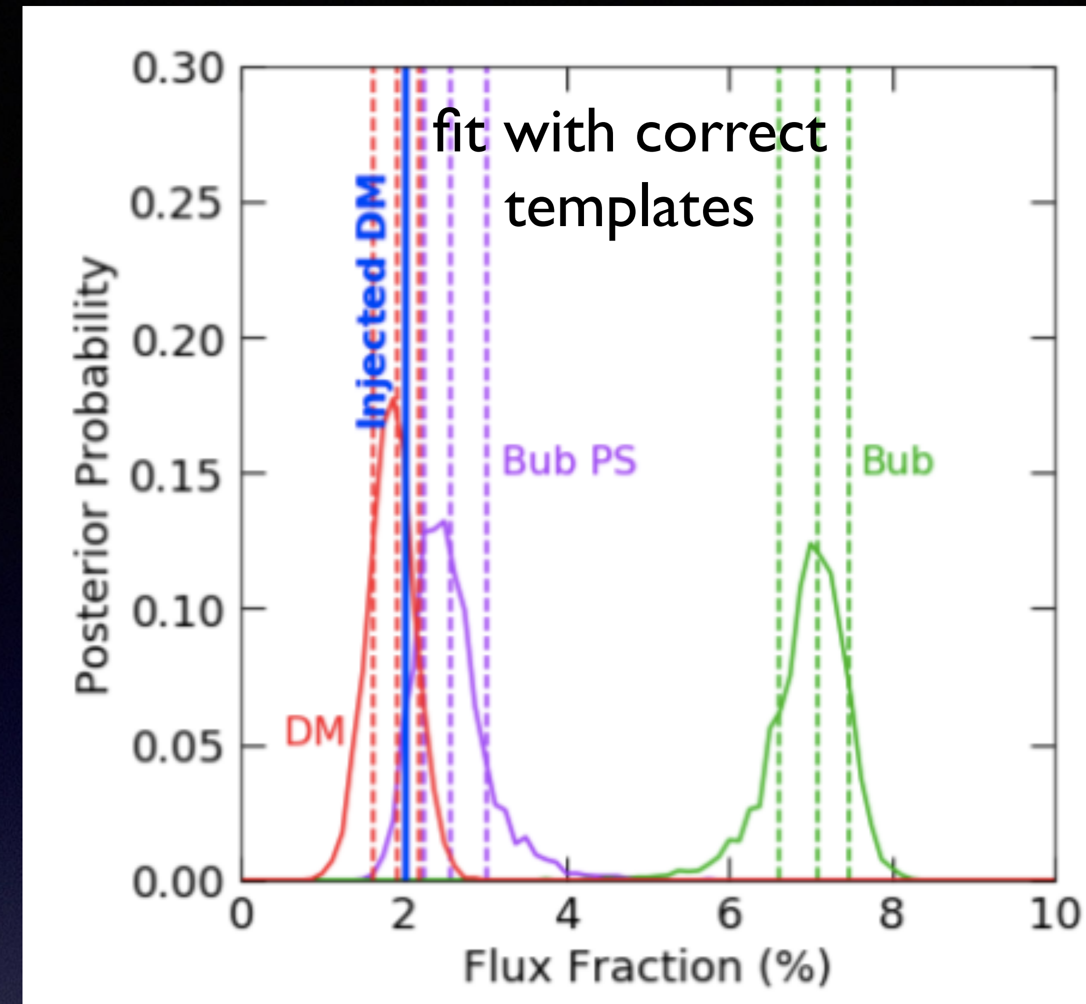


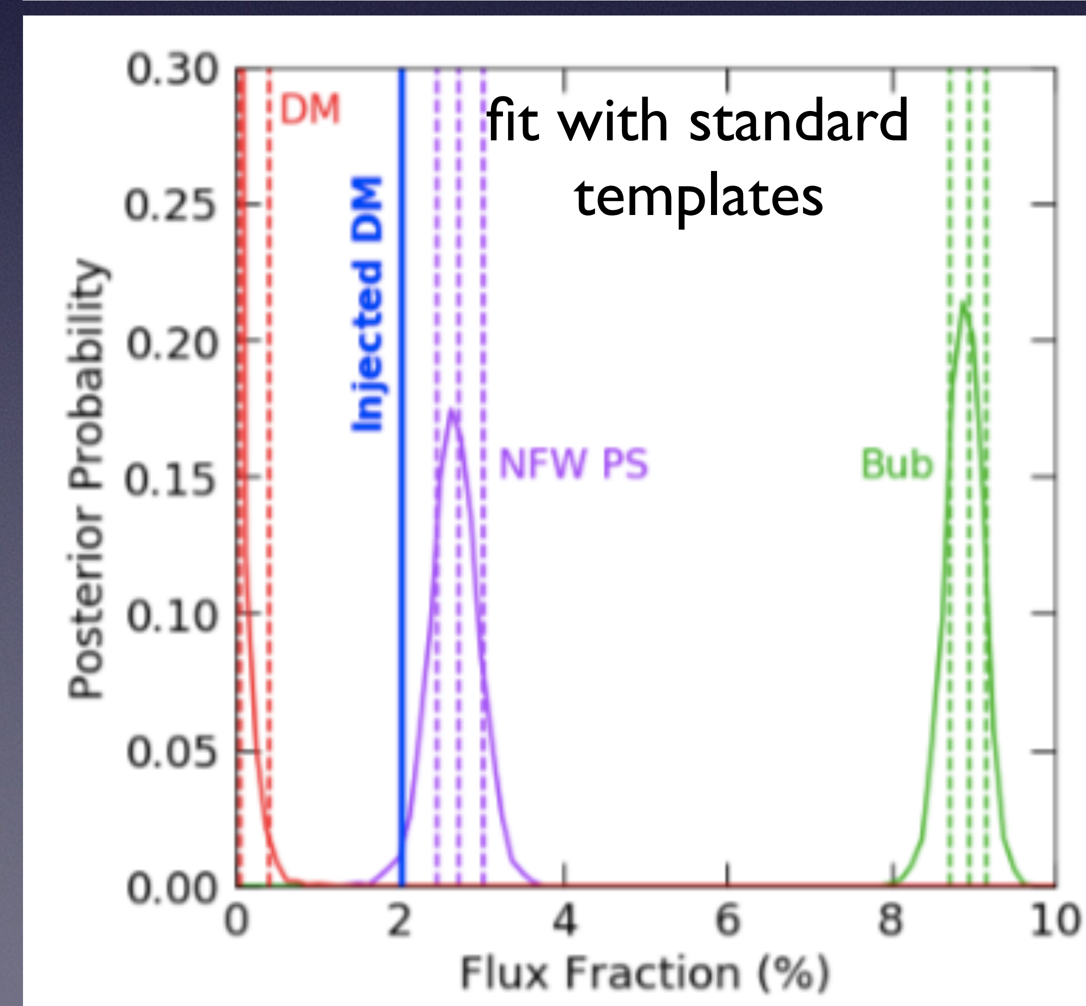
Analysis pipeline

- We use the public NPTFit package [Mishra-Sharma et al '17, https://github.com/bsafdi/NPTFit] to perform all fits.
- We use the default dataset from NPTFit, similar to Lee et al '16 - somewhat longer exposure, and a 2-20 GeV energy band.
- We mask known PSs in 3FGL (Fermi source catalog) at 99% containment radius (~0.8°).
- We simulate mock data using NPTFit-Sim [https://github.com/nickrodd/NPTFit-Sim]
- "Standard pipeline" for fits - template model contains (Poissonian) Galactic diffuse emission model + Fermi Bubbles + isotropic emission + NFW DM + (non-Poissonian) disk PSs + isotropic PSs + NFW PSs.

A mock-data example

- Construct mock dataset using all standard templates (w/ best-fit values) except NFW PS, a GCE-like DM signal, and point sources spatially correlated with the Fermi Bubbles.
- Fit with same templates except replacing Bubbles-correlated PSs with GCE PSs.
- <u>Result</u>: fit prefers to assign all flux in GCE-like DM signal to GCE PS template, <u>zero</u> flux to DM template!
- Consistent with behavior observed in real data.





Does the bias depend on mismodeling?

- Already noted by Lee et al '16 that in simulated data, when simulated GCE was 50% DM and 50% PSs, NPTF tended to return a result for the DM fraction biased low (this agrees with our new analysis).
- Lee et al '16: Bayes factor in favor of NFW PSs was $\sim 10^6$ in real data, $\sim 10^5$ in mock data with 100% NFW PSs, $\sim 10^2$ in sim data with 50-50.
- Our results for Bayes factor in favor of NFW PSs:

simulated, 100% PSs	simulated, 100% DM + Bubbles PSs	real data
$\sim 10^6$	$\sim 10^5$	$\sim 10^9$

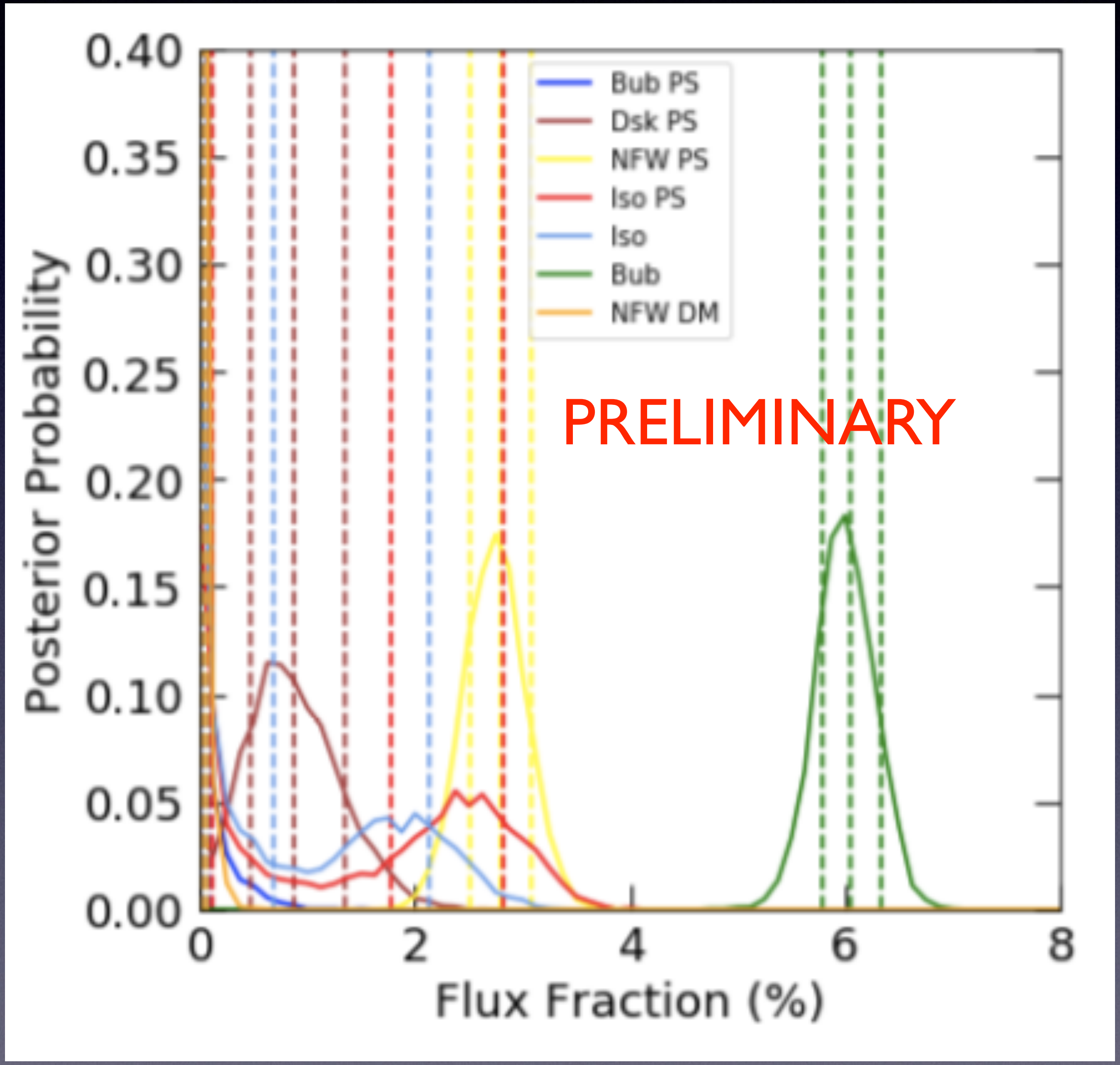
case with mismodeled PSs can yield large Bayes factors in favor of NFW PSs (even when GCE is 100% DM), comparable to case with only NFW PSs. (Caution though that templates for other PS populations are not identical in all analyses.)

Summary (mock data)

- If the templates do not adequately describe the data, template coefficients will in general be biased.
- PSs spatially correlated with the Fermi Bubbles provide an existence proof of a (hypothetical) population that would lead to a large negative bias in the DM template coefficient.
- Proof-of-principle example of a situation where:
  - the (mock) data contains a DM signal comprising ~100% of the GCE.
  - the fit concludes there is very little DM (consistent with zero).
  - there is a strong statistical preference for NFW PSs (in this case due to the fit misidentifying (real) PSs as a GCE population)

Does this occur in real data?

- We can try explicitly testing for other PS populations in the data, see if the GCE DM amplitude goes up
- Tested (preliminarily) with bubbles-correlated PSs - fit still prefers to assign GCE flux to NFW PS (or bulge PS) over NFW DM
- No positive detection of Bubbles PSs

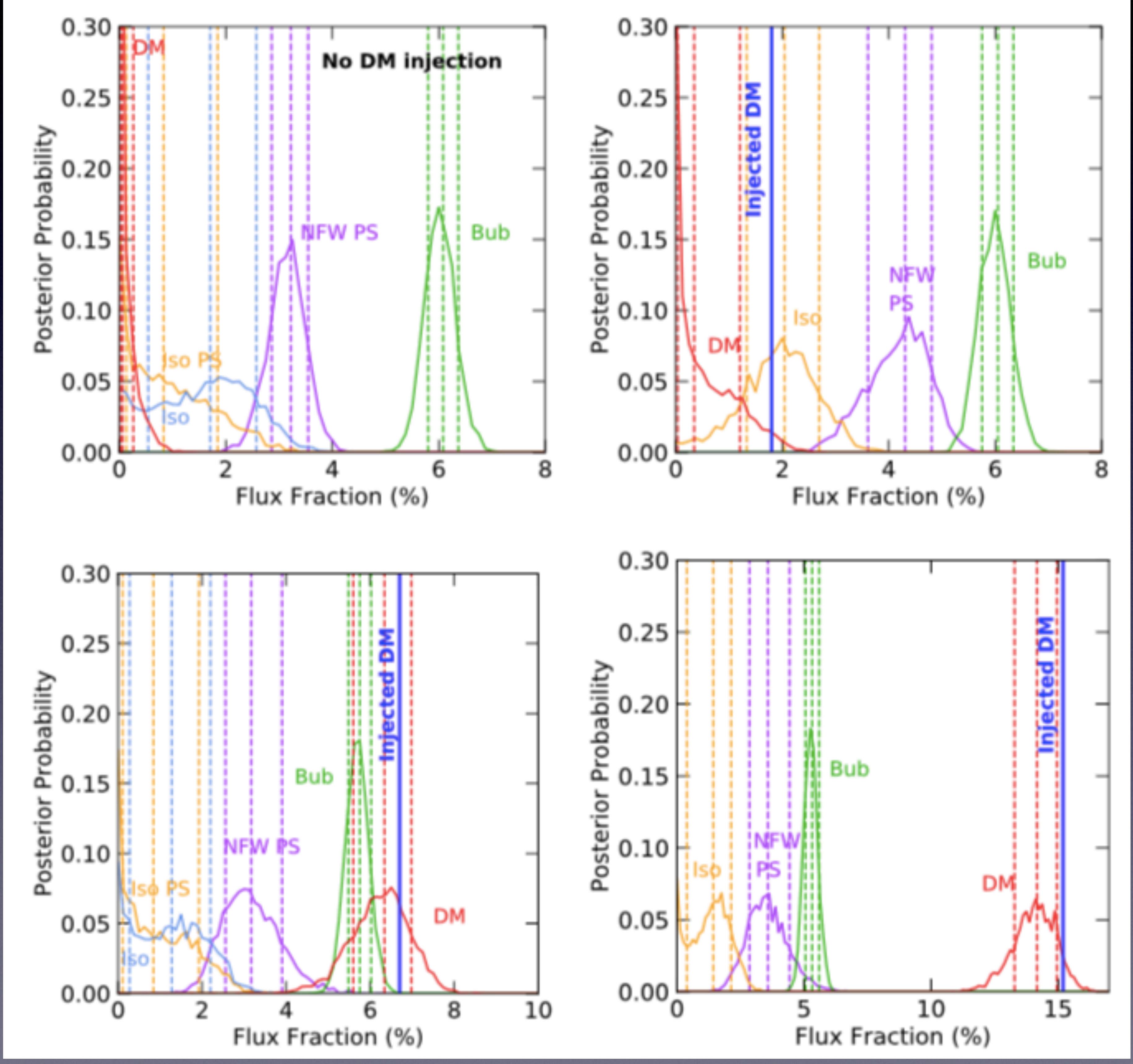


Does this occur in real data? (II)

- Alternative test (suggested by Tim Linden) that doesn't require knowing the PS distribution: inject additional simulated DM signal, see whether it is reconstructed correctly or not by the fit.
- If the data contains components not well-described by the templates in the fit, no reason for the resulting bias to be saturated in its ability to hide a DM signal.
- If a bias is present in the baseline case, we generically expect an extra simulated signal to also be biased. If there is no bias present, the injected signal should be reconstructed correctly.

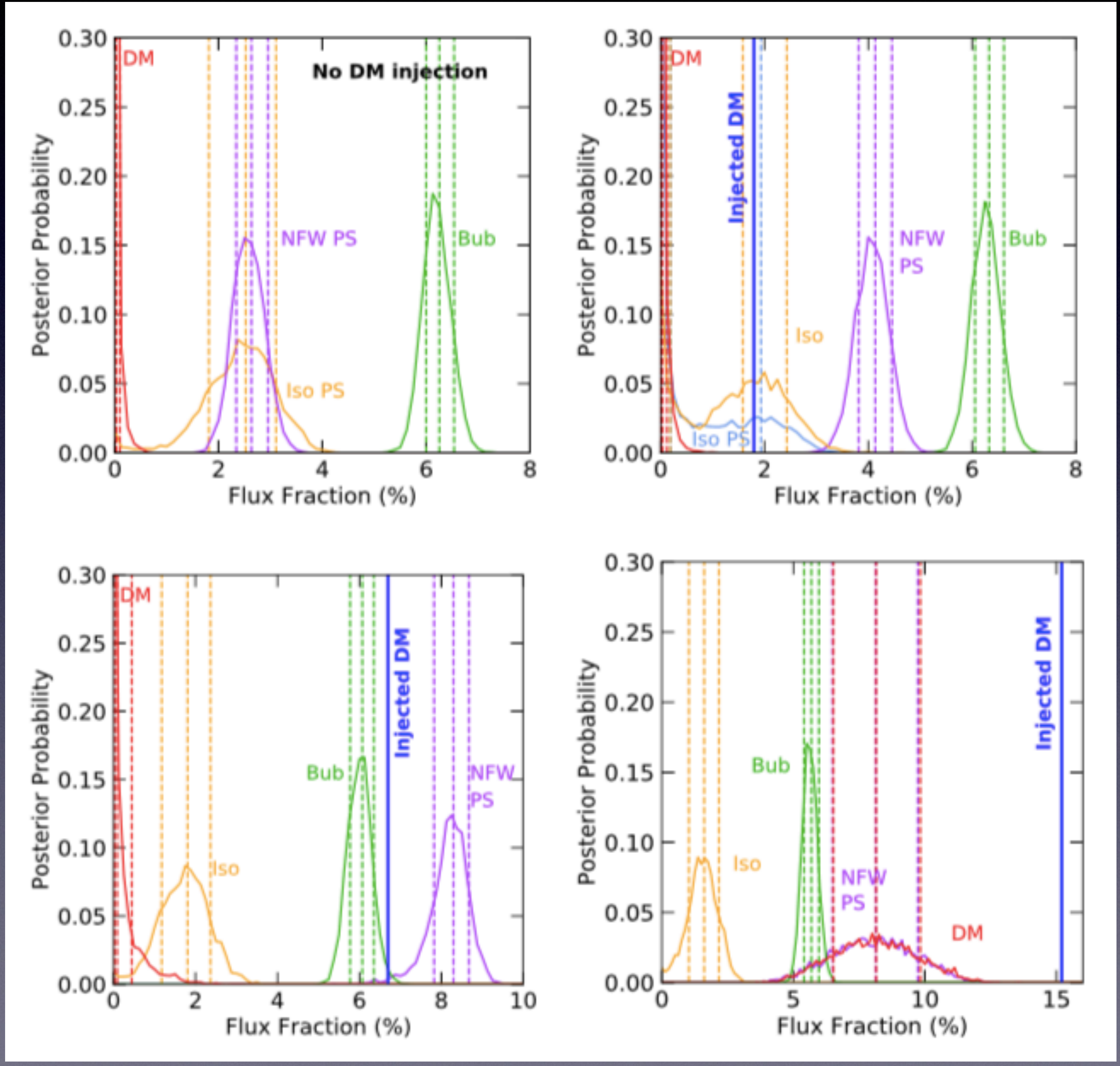
Injection test (simulated)

- Test first on simulated data based on best fit in standard pipeline (including NFW PSs)
- Inject DM signal at 0%, 1.8%, 6.7% and 15.2% of post-injection photon flux in ROI
- Run standard fit on mock data - injected DM signal is ~correctly reconstructed, NFW PS ~unchanged



Injection test (real data)

- Now take real Fermi data.
- Inject simulated DM signal at 0%, 1.7%, 6.7% and 15.2% of photon flux in ROI.
- Run standard fit on modified data - injected DM signal is forced to zero even at 6.7% injection, reconstructed as NFW PSs instead
- At 15.2% injection, DM signal is recovered (with large uncertainties)

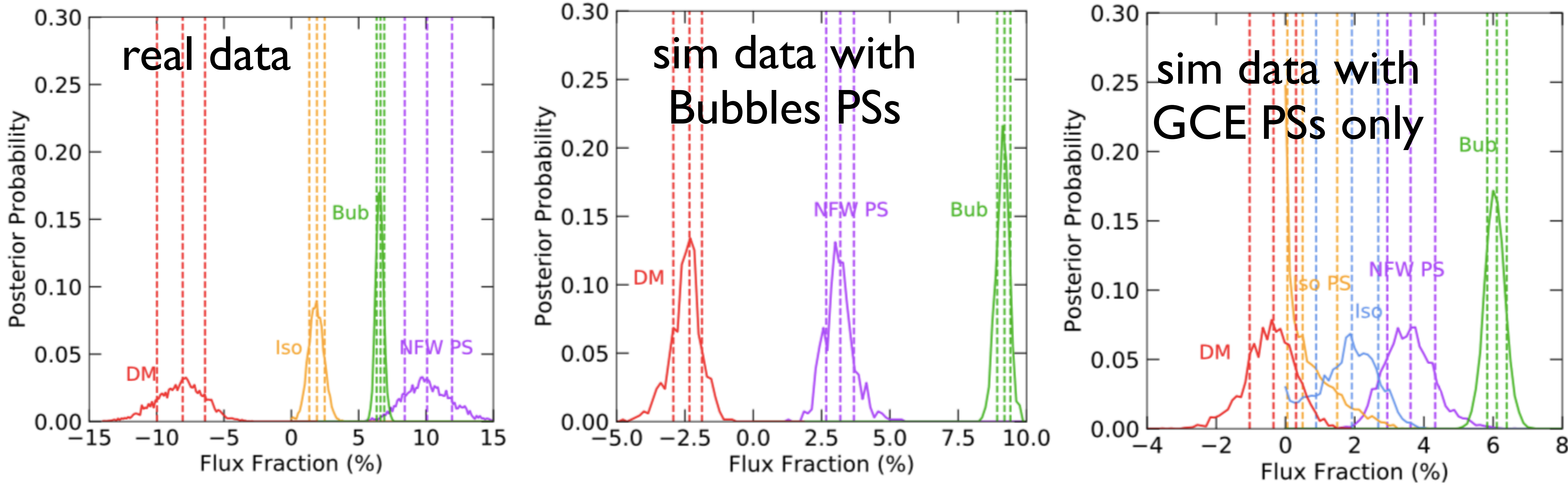


Summary (real data)

- By adding an extra simulated (GCE-like) DM signal to the real data, we can test whether a known DM component is reconstructed correctly
- We find that it is <u>not</u>, even when the injected component is several times larger than the GCE itself
- Suggests the existence of a bias in the analysis that could potentially hide a true DM signal
- In contrast, in simulated data containing NFW PSs and no NFW DM, the injected DM signal is recovered ~correctly (often 1-2 sigma low)

An alternative 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 - similar behavior in proof-of-principle (although not to the same degree), in simulated data with correct templates the posterior is typically skewed only slightly negative.



Implications for previous analyses

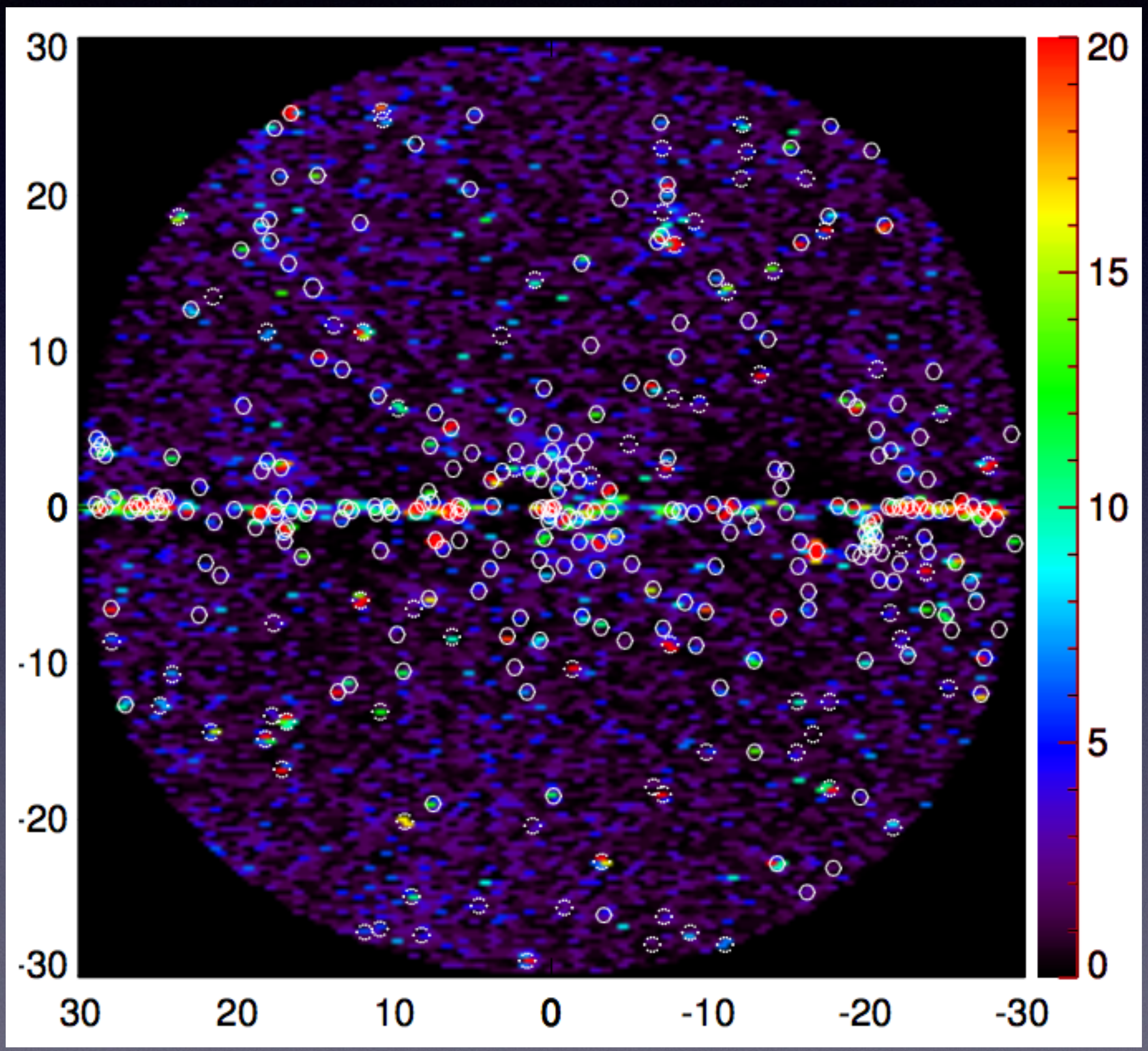
- If the preferred DM coefficient is negative but the prior forces it to be reconstructed as non-negative, then injecting extra DM will simply be absorbed by the "negative DM" component - we should expect failure of injection test.
- Different diffuse models could prefer quite different negative coefficients for DM, but standard analysis will then force DM coefficient to zero in all cases - result can look more stable to variations in diffuse models than it actually is.
- Likewise, the DM coefficient in different subregions (if allowed to float separately) could run negative to very different degrees - again, asymmetry masked by requiring DM coefficient > 0.
- Systematics that force the preferred DM coefficient outside the prior range can make the result look much more robust than it really is under various modifications to the analysis - all that is actually robust is that the analysis is finding the edge of the prior.

Where next?

Follow-up studies in gamma rays

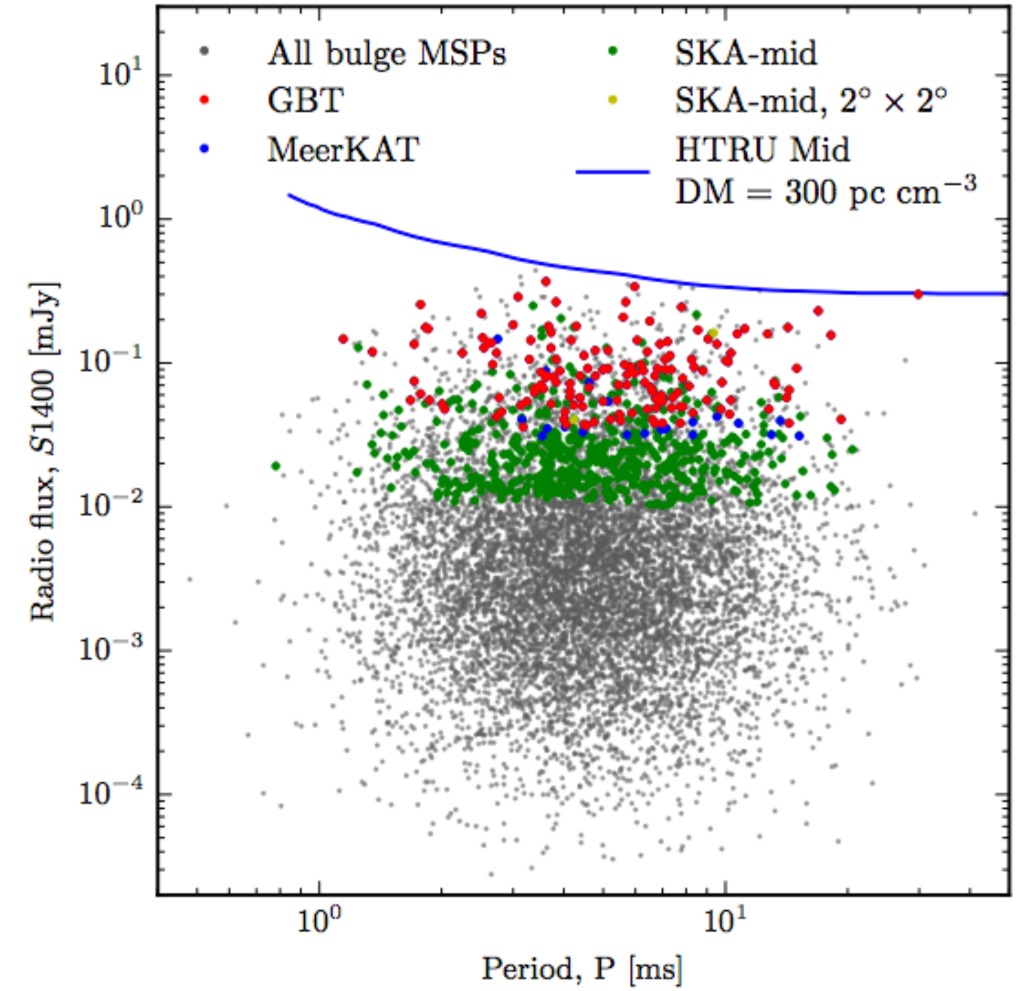
- Subdividing the signal template, allowing extra freedom in smooth and PS contributions
- Testing well-motivated PS population models
- Inclusion of extra data by relaxing cuts on angular resolution, cosmic-ray rejection
- Exploring sensitivity of analysis to perturbing the diffuse model at different angular scales
- Other groups are exploring systematic biases in NPTF even when all templates are correct (see Chang et al '19), effects of varying the diffuse model, effects of varying the region of interest, effects of adding extra freedom to background models…
- Goals: understand causes for what we see and ways to mitigate it, determine robustness of results in the presence of possible systematic errors

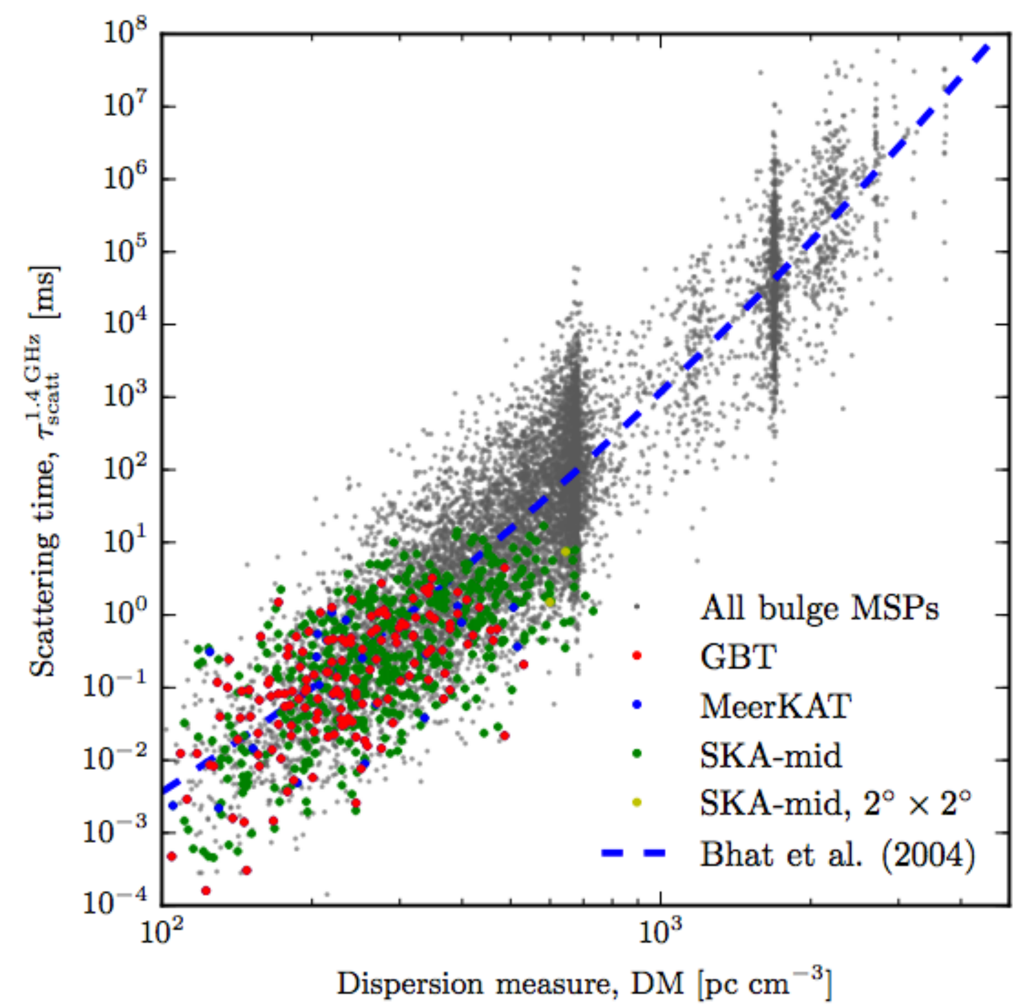
Where are the sources?



- From Lee et al '16: bright spots correspond to "hot pixels", relative to model with no point sources
- May hint at source locations
- White circles = known sources
- Detecting pulsars or other gamma-ray sources in the inner Galaxy could reveal origin of GCE
- Could do so directly (if distribution matches GCE) or indirectly, by better characterizing PS backgrounds
- Potentially complementary technique: probabilistic cataloguing of faint sources [Daylan et al '17].

- 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.





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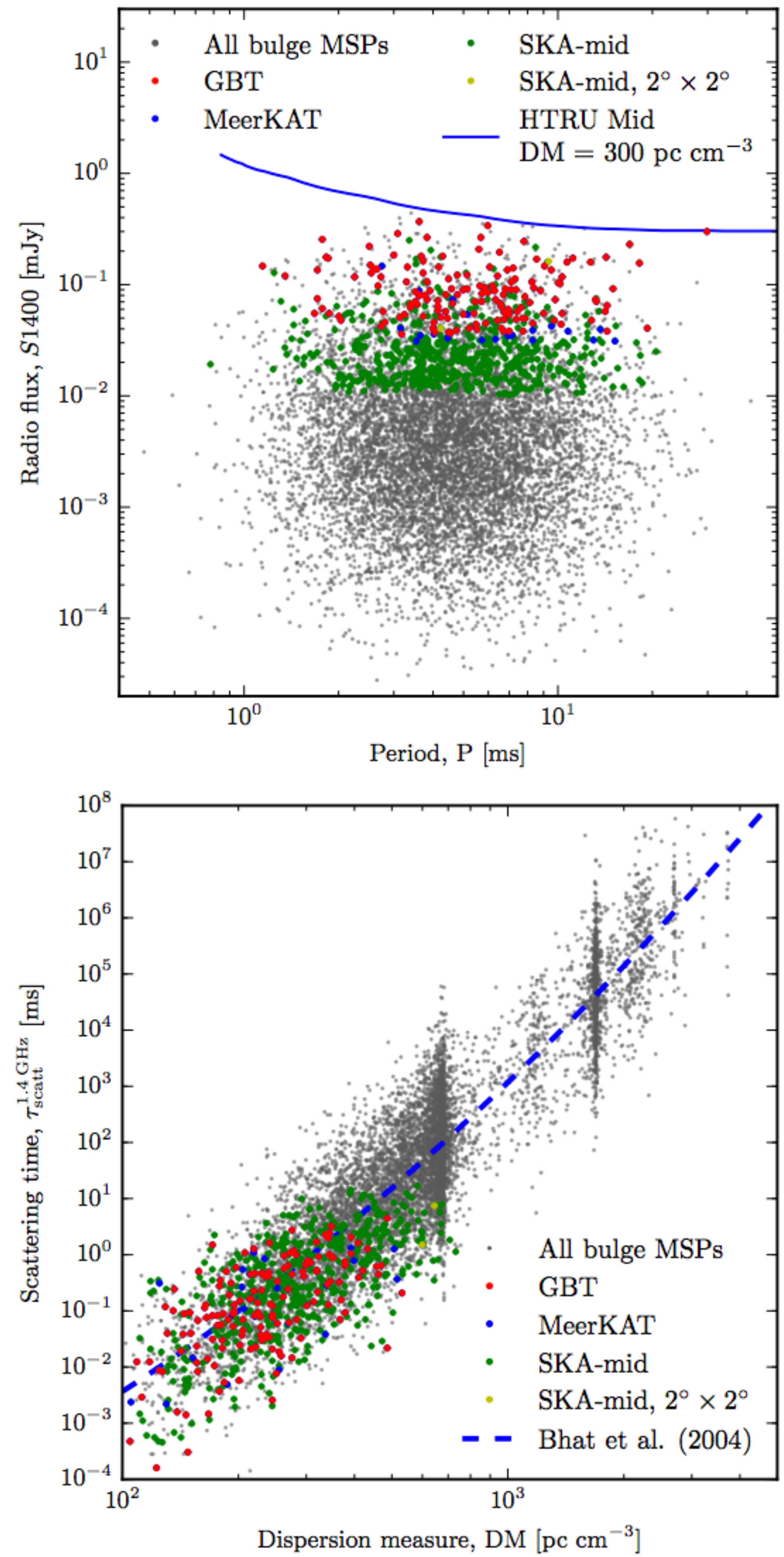

Conclusions

- Non-Poissonian template fitting (NPTF) techniques indicate the presence of a population of unresolved PSs in the inner Galaxy, not associated with the Galactic disk.
- Modeling the GCE as a linear combination of a population of such PSs and a smooth diffuse component, there is 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.
- We have demonstrated in mock data that the presence of a spatially distinct, unmodeled population of unresolved PSs can lead to an apparent strong preference for GCE PSs, even if the GCE consists entirely of DM.
- Previous arguments that the Galactic Center excess cannot be DM due to photon statistics may be premature - need to understand systematics from (mis)modeling of backgrounds to make this claim robust.

Other arguments against a DM origin

- Wavelet analyses suggest presence of at least some PSs in this region, not consistent with solely a disk population, with abundance of the right order of magnitude that their fainter counterparts could generate the GCE [e.g. Bartels et al '16] - Occam's razor.
- Studies of the morphology of the excess suggest it becomes less spherical further from the GCE, & stellar-bulge-motivated templates can provide better fits [e.g. Macias et al '18, Bartels et al '18, Macias et al '19]. This behavior would strongly support a stellar origin - but does depend on background modeling + spatial tails of excess.

Explanations for failure of injection test

- Chang et al [arXiv:1908.10874] make the argument that if the underlying source count function is fairly soft (many faint PSs) then:
  - the NPTF will often still reconstruct a (wrong) hard SCF
  - additional injected DM signals can naturally be reconstructed incorrectly in this case
  - the presence of at least some point sources is quite robust to this particular systematic error - unlikely to be a spurious detection if this is the sole problem
- 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
- Probably need other systematic errors as well - not obvious if near-threshold PSs are also robust to these systematics