A Galactic Puzzle in Gamma Rays

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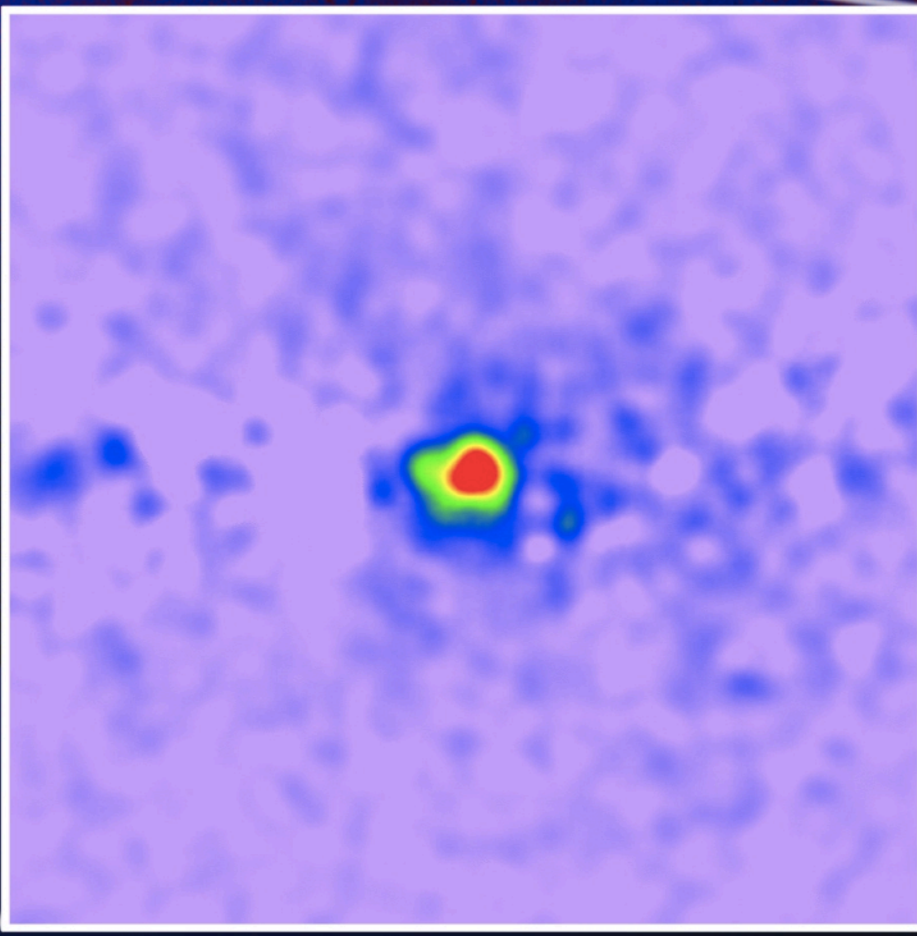
VP^3 Particle Physics Seminar
9 June 2020



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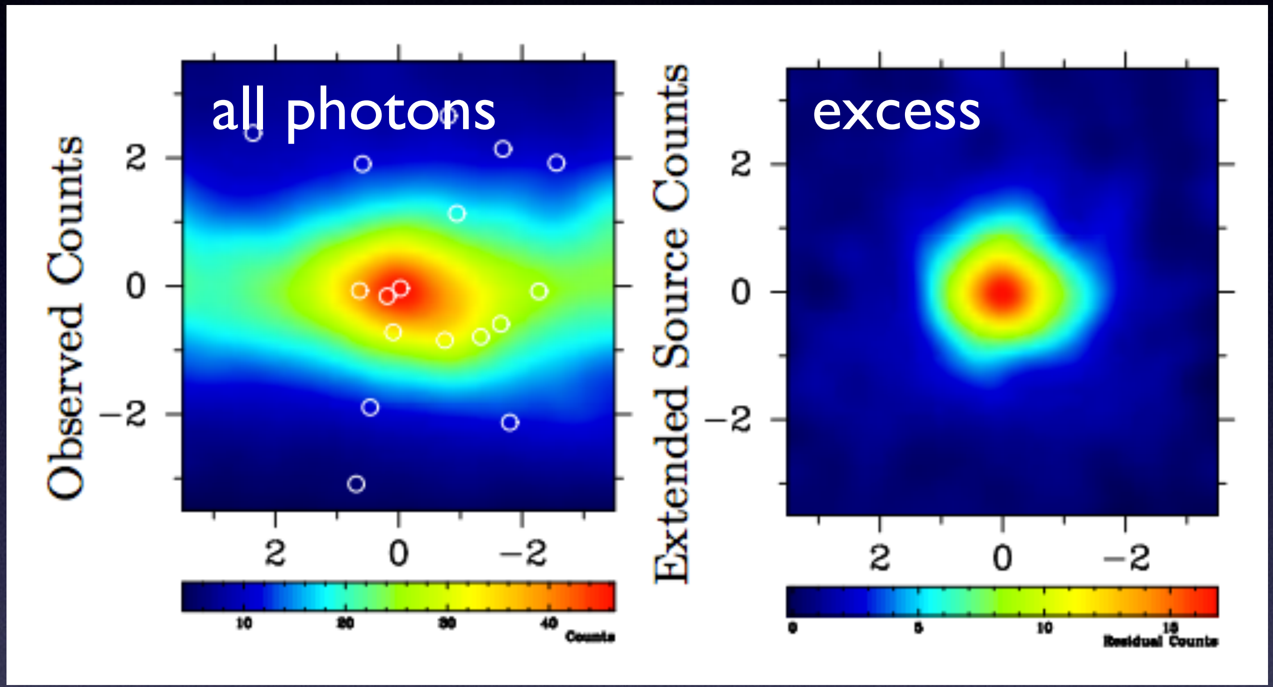
Outline

- History and properties of the Galactic center excess
- Possible interpretations as dark matter signal / new population of pulsars
- Have we found the pulsars?
- Systematic errors / dark matter (or another interpretation) strikes back?
- Summary and outlook

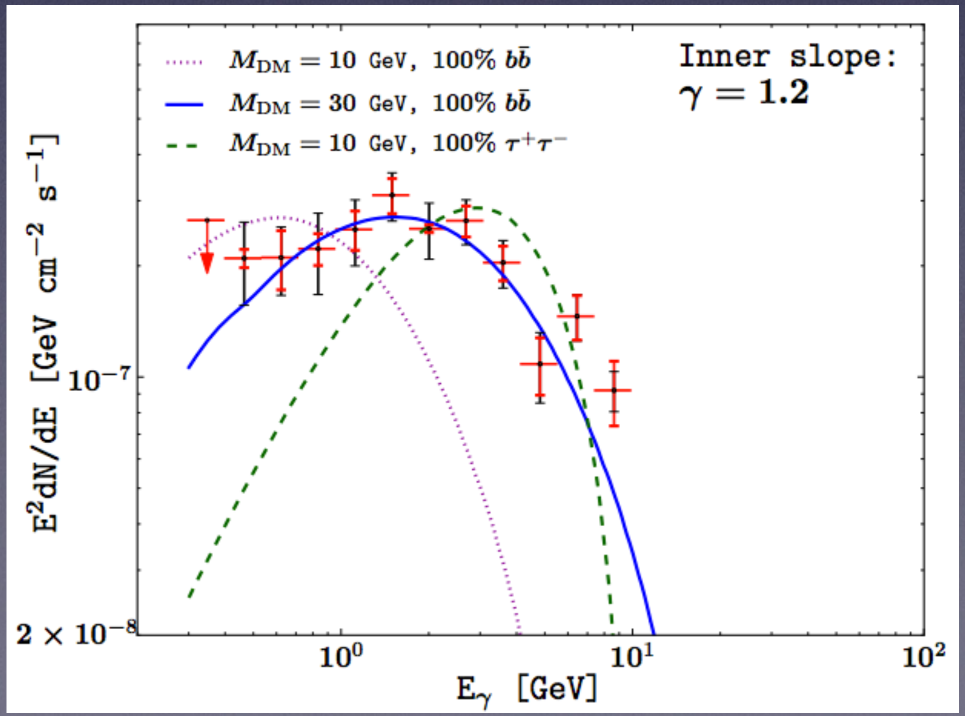
The Galactic Center Excess (GCE)

- 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

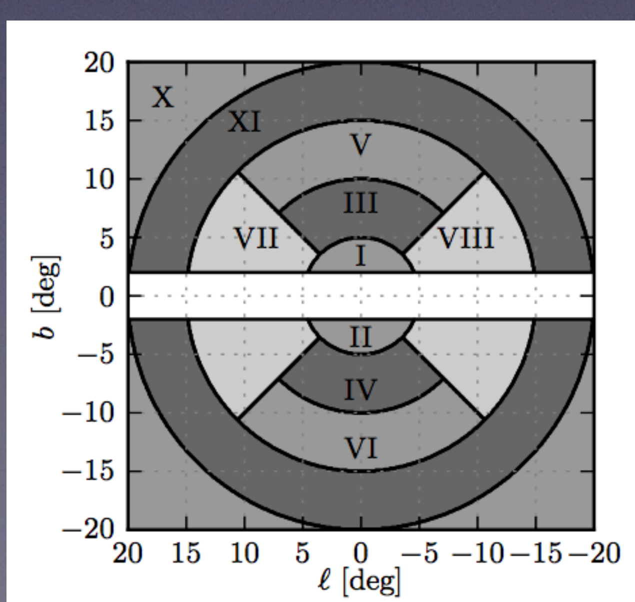


spectrum Gordon & Macias '13

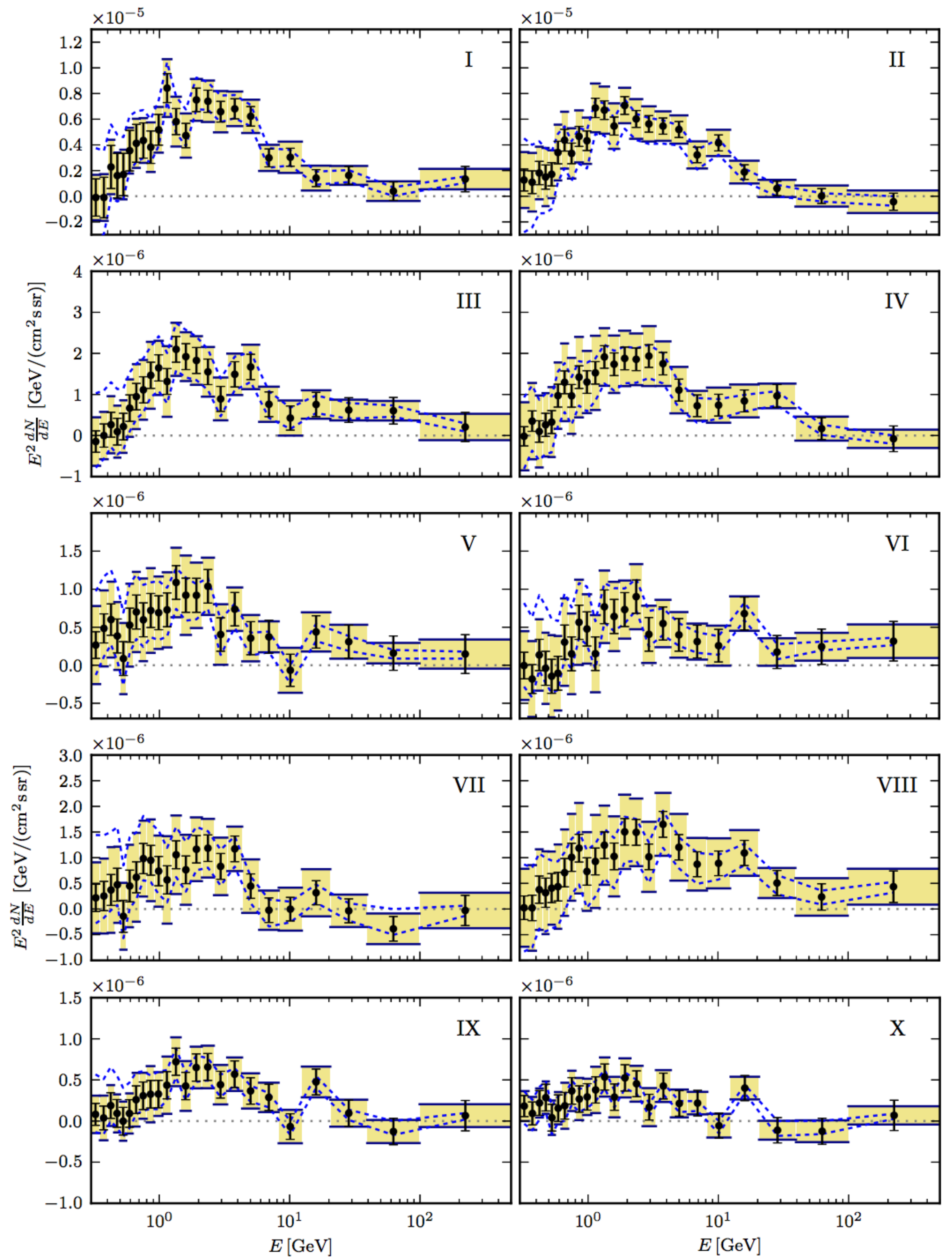


Properties

- Daylan, TRS et al '16 found that:
  - Photons peak around 1-3 GeV in energy
  - Excess is approximately symmetric around the GC, steeply peaked at GC. Later work showed it can also be well-described as Galactic-Bulge-like extended emission + central ~symmetric core, tracing stellar mass [Macias et al '18, Bartels et al '18, Macias et al '19, Abazajian et al '20].



Plots taken from Calore, Cholis & Weniger '14

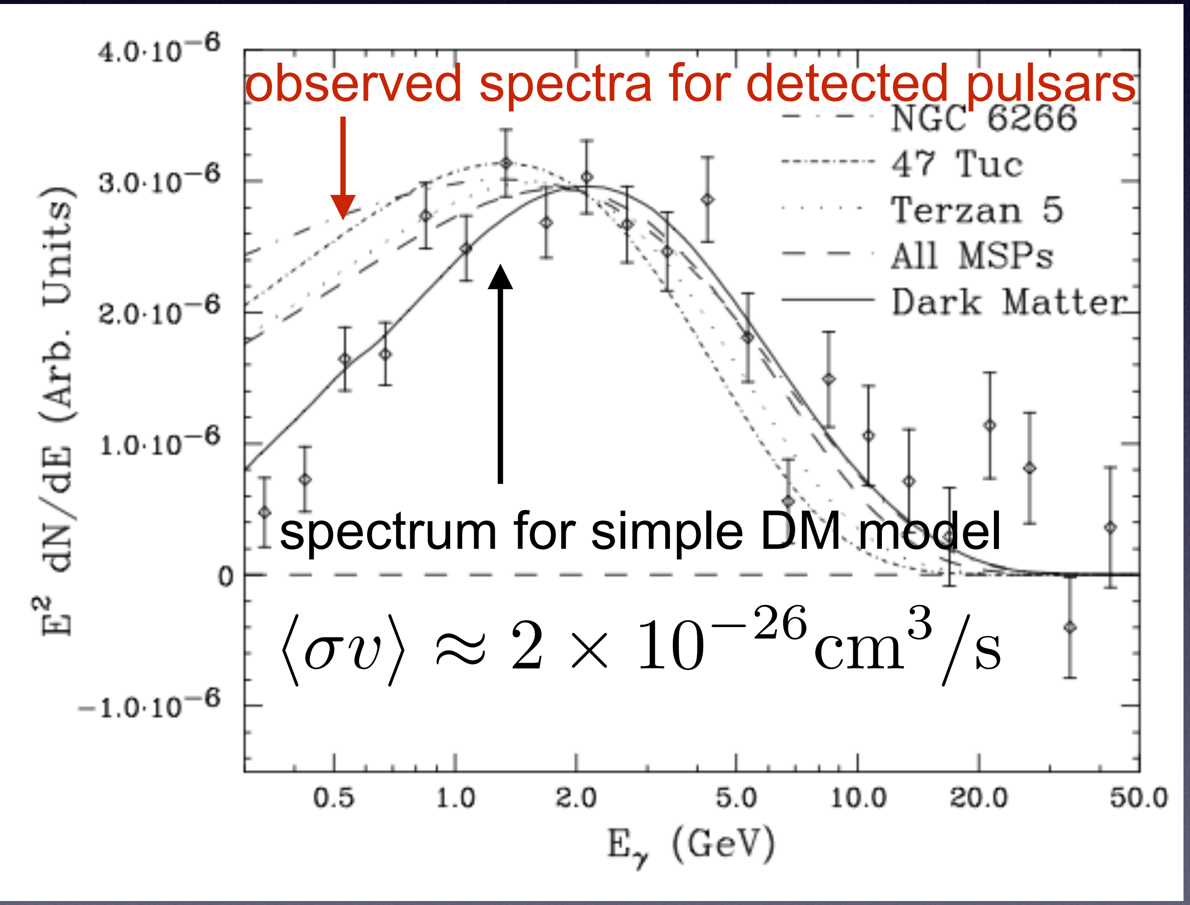


Hypotheses

- 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

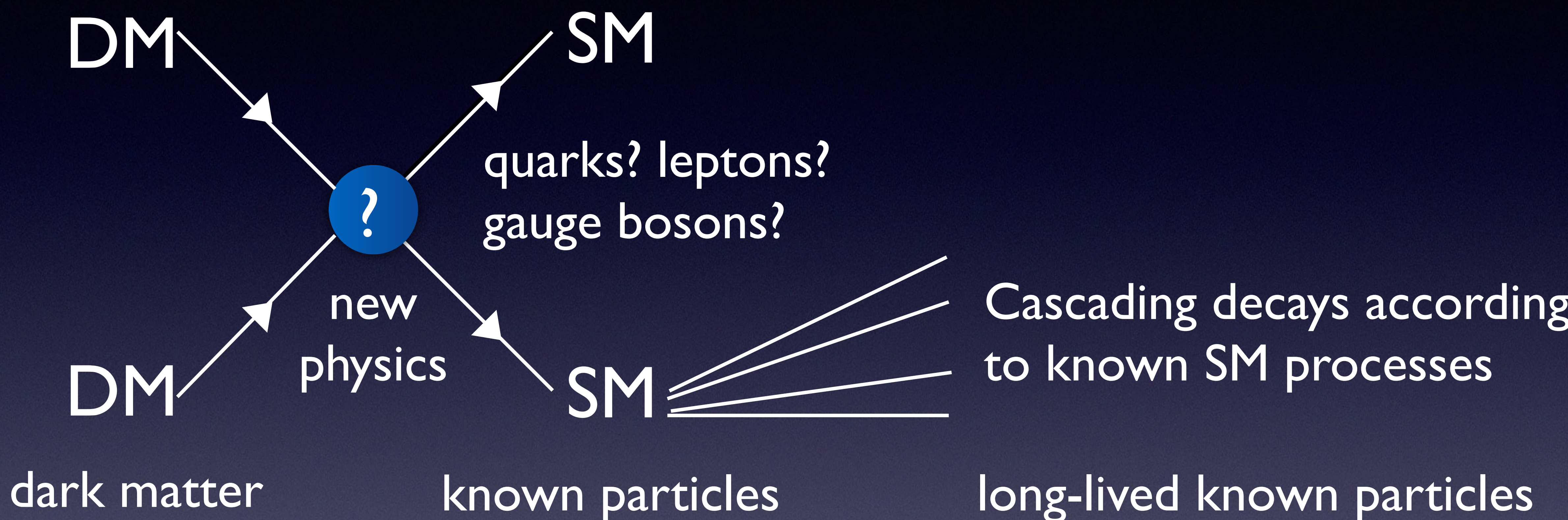
Particle theorist: 😕 Astrophysicist: 😀

DARK MATTER

Dark matter

- Roughly 80% of the matter in the universe is DARK - no electric charge, interacts at most very weakly with known particles.
- Multiple lines of evidence for this statement: rotation curves in galaxies, gravitational lensing of colliding galaxy clusters, imprints left on the cosmic microwave background, even the formation of galaxies.
- BUT - has only ever been detected by its gravitational interactions.
- No good candidates in known physics - one of our biggest clues to what might lie beyond the known.

Annihilation

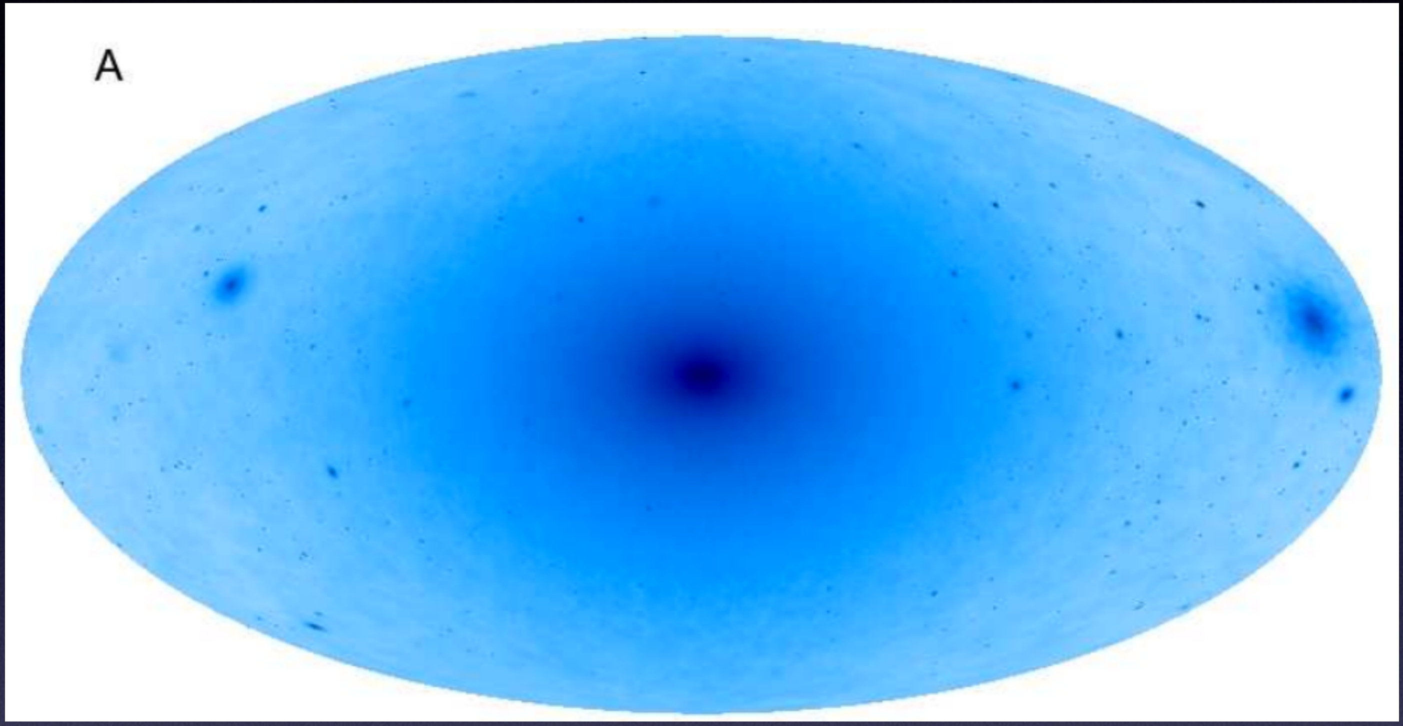


- One explanation for the observed abundance of DM is that most of it annihilated away in the early universe
- In such scenarios, the annihilation rate can be inferred from the present-day DM abundance, giving a cross section (“thermal relic cross-section”) of:

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

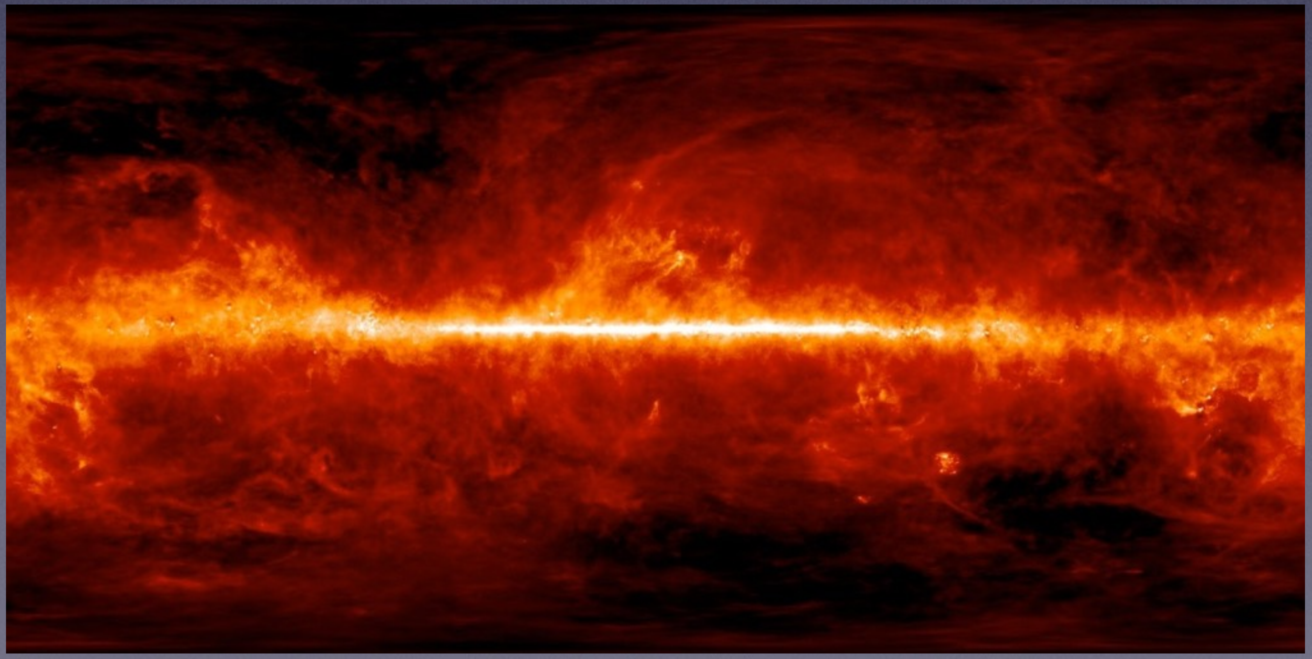
Features of a DM signal

- Spatial information:
  - Backgrounds: brightest near Galactic plane
  - Signal: should follow DM halo, more spherical
- Spectral information:
  - Backgrounds: mostly smooth and power-law-like
  - Signal: can be peaked, scale set by DM mass
- Galactic center generally has brightest predicted signal - albeit backgrounds also most challenging there.



signal? (DM sim)

background (gas)



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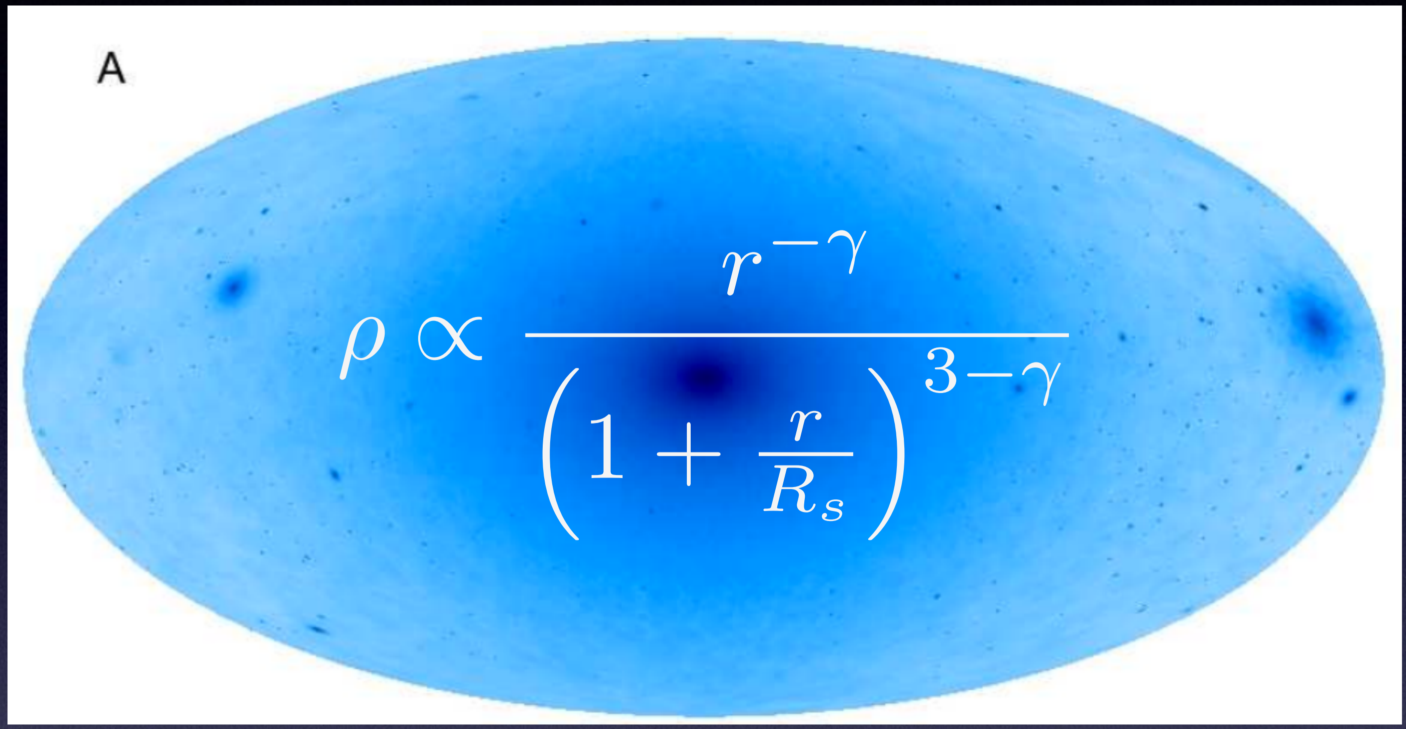

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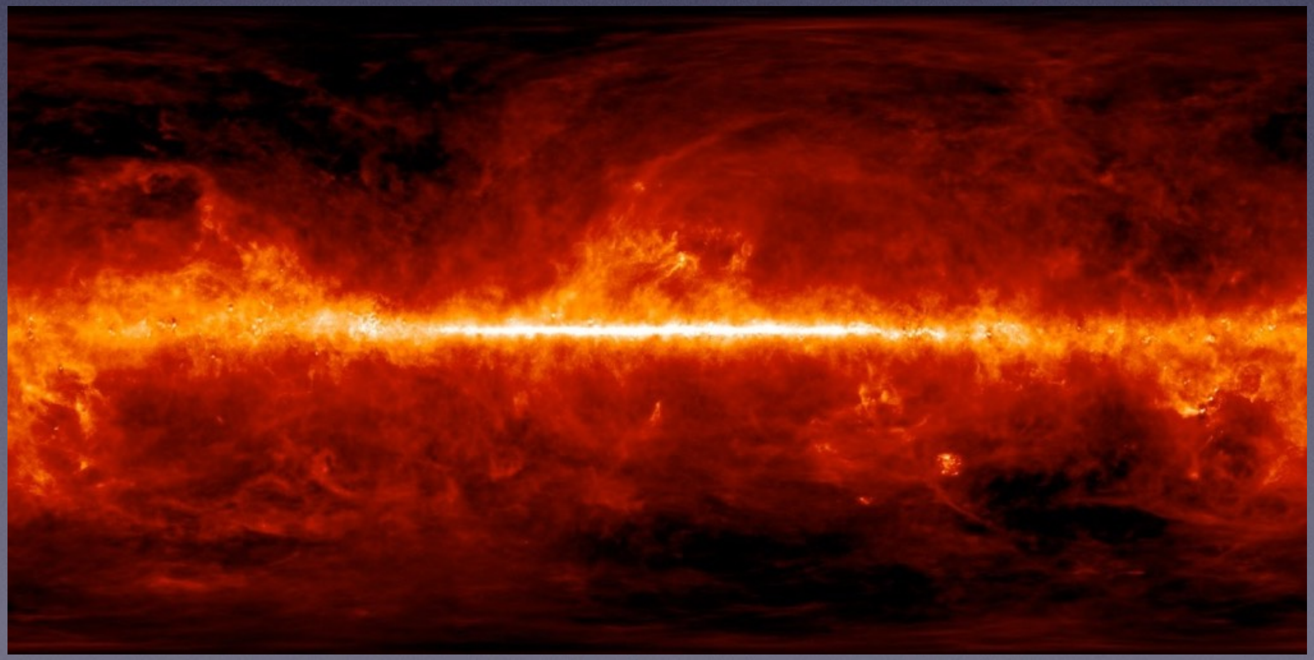


Dark matter annihilation

Naturally explains:

The invariance of the spectrum with position + shape of spectrum.

A ~spherical morphology for the signal (less so if it traces the stellar bulge).

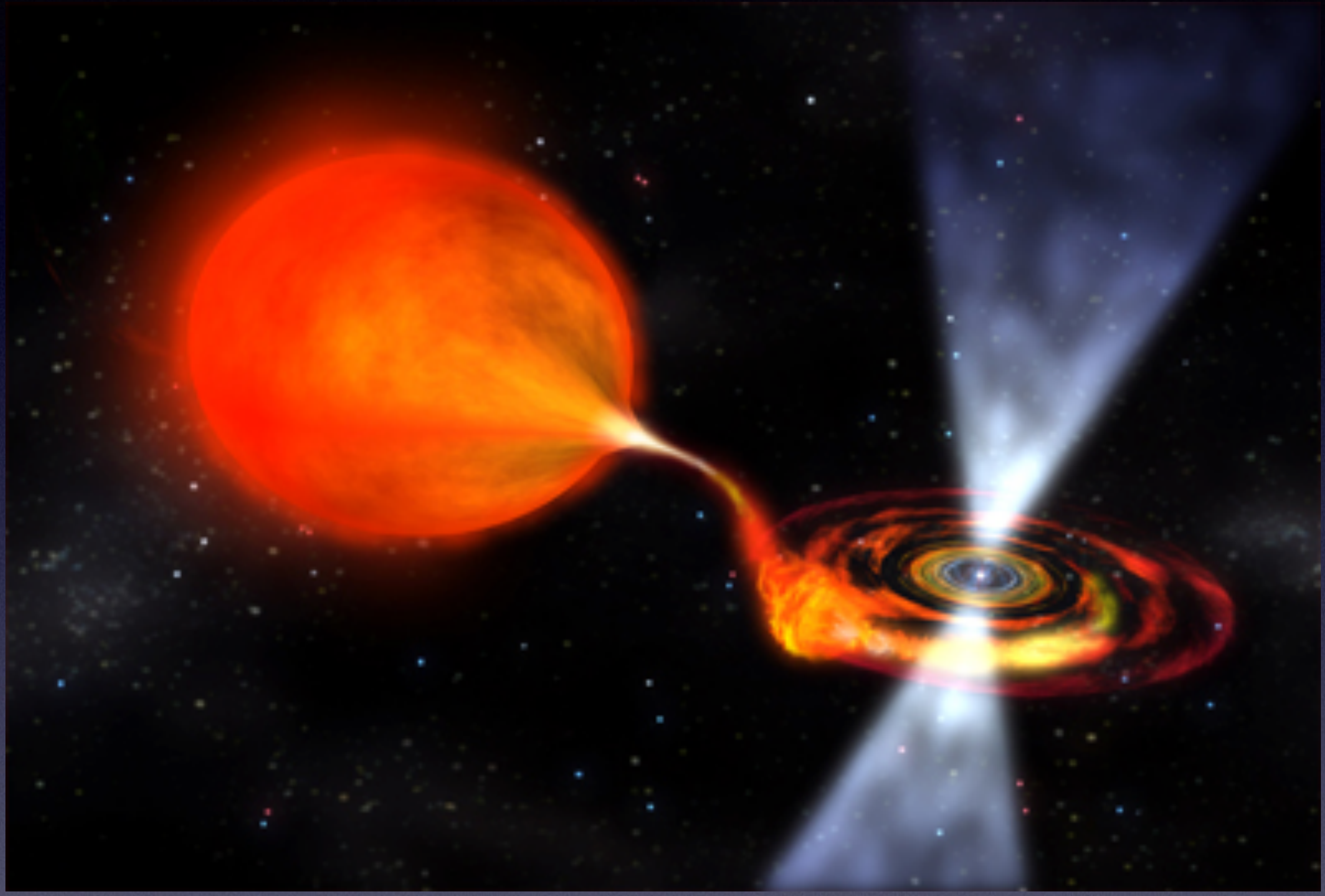
The profile: steeply peaked at the Galactic Center but extending out to at least 10 degrees, agrees well with (some, not all) simulations.

The rate: required annihilation cross section matches that required to explain observed dark matter abundance, in simple "thermal relic" scenario.

PULSARS

What is a pulsar?

- Rapidly rotating star, composed of ultradense neutrons, that emits a beam of radiation as it spins
- Can emit in radio, X-ray and gamma-ray wavelengths



- Millisecond pulsars are those with very short (millisecond) periods
  - They lose energy slowly - long lifetimes
  - Thought to be old pulsars that are spun up by accretion from a partner star

Pulsars

Naturally explains:

Spectrum: observed MSPs match excess well at energies above 1 GeV.

Can accommodate the observed morphology:

- MSPs originate from binary systems, can naturally explain steep slope of profile (and observed X-ray binaries in Andromeda have ~right profile).
- Globular cluster disruption could give rise to ~spherical distribution [Brandt & Kocsis '15].
- If morphology is confirmed to resemble stellar bulge rather than spherical halo (favored by latest background models), will strongly support stellar interpretation.

PULSAR WARS

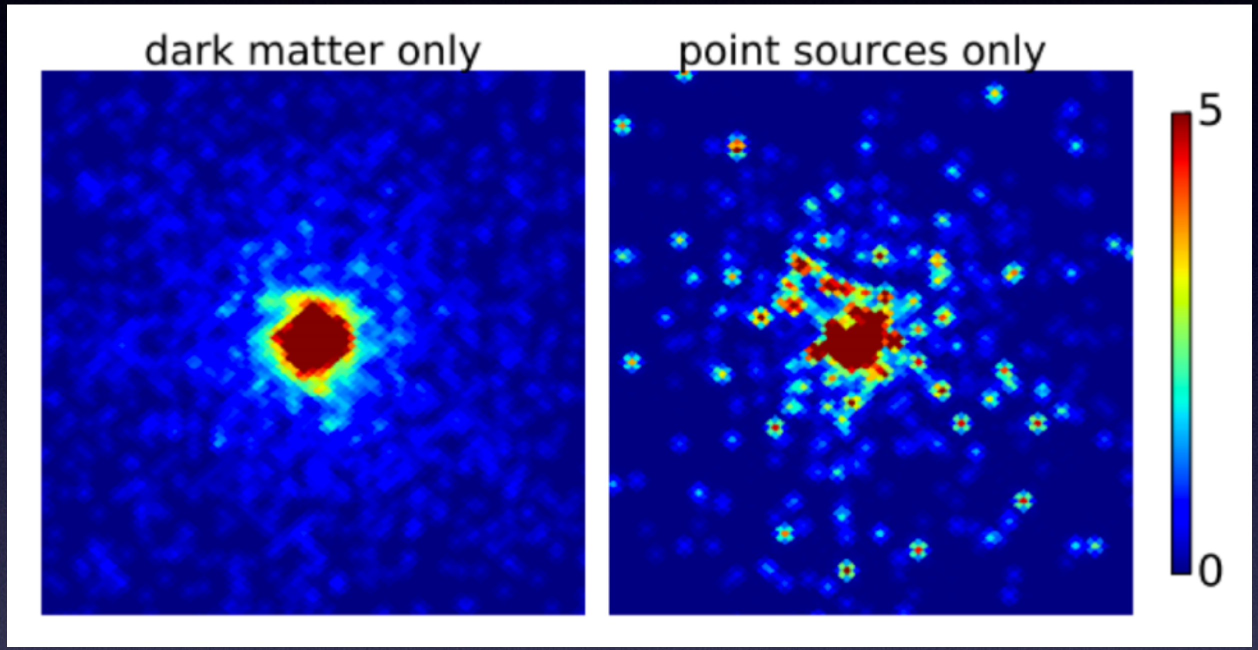
A NEW HOPE

of distinguishing hypotheses…

Deciphering the GCE with photon statistics

<u>DM origin hypothesis</u>

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



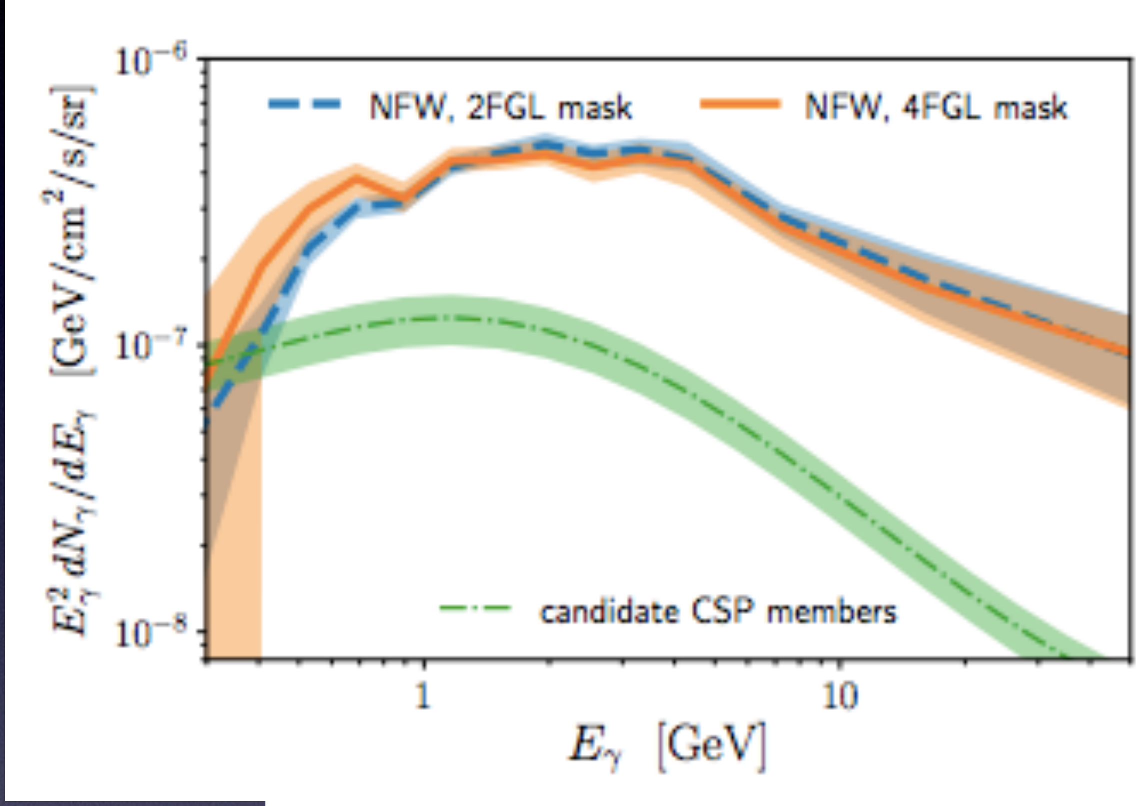
<u>Pulsar origin hypothesis</u>

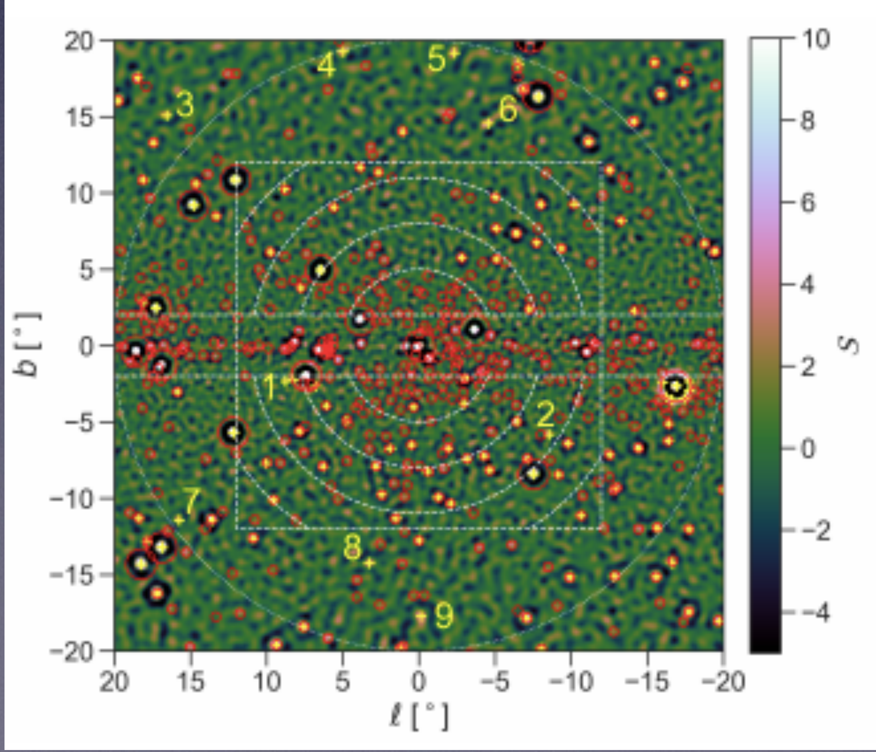
signal originates from a collection of compact objects, each one a faint gamma-ray point source

- Hope to distinguish between hypotheses by looking at granularity of the photon signal - presence or absence of "hot spots".
- Two main analyses in 2016, both claimed evidence for point source populations:
  - Exploiting non-Poissonian statistics of fluctuations from an unknown point source distribution [Malyshev & Hogg '11; Lee, Lisanti & Safdi '15; Lee, Lisanti, Safdi, TRS & Xue '16].
  - Using wavelet-based method to look for small-scale power above expectations from diffuse backgrounds [Bartels et al '16].

2020: wavelets → 4FGL

- 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 the GCE.
- Wavelet analysis thus essentially gives a subset of the 4FGL catalog.
- Masking 4FGL sources does not reduce GCE.
- Total emission from candidate GCE sources is a factor ~4-5 below GCE.
- Implies bulk of emission should be diffuse or originating from faint sources.





Statistics for point sources

Imagine 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 $P(0 \text{ photons}) \sim 5 \times 10^{-5}$, $P(100 \text{ photons}) \sim 5 \times 10^{-63}$

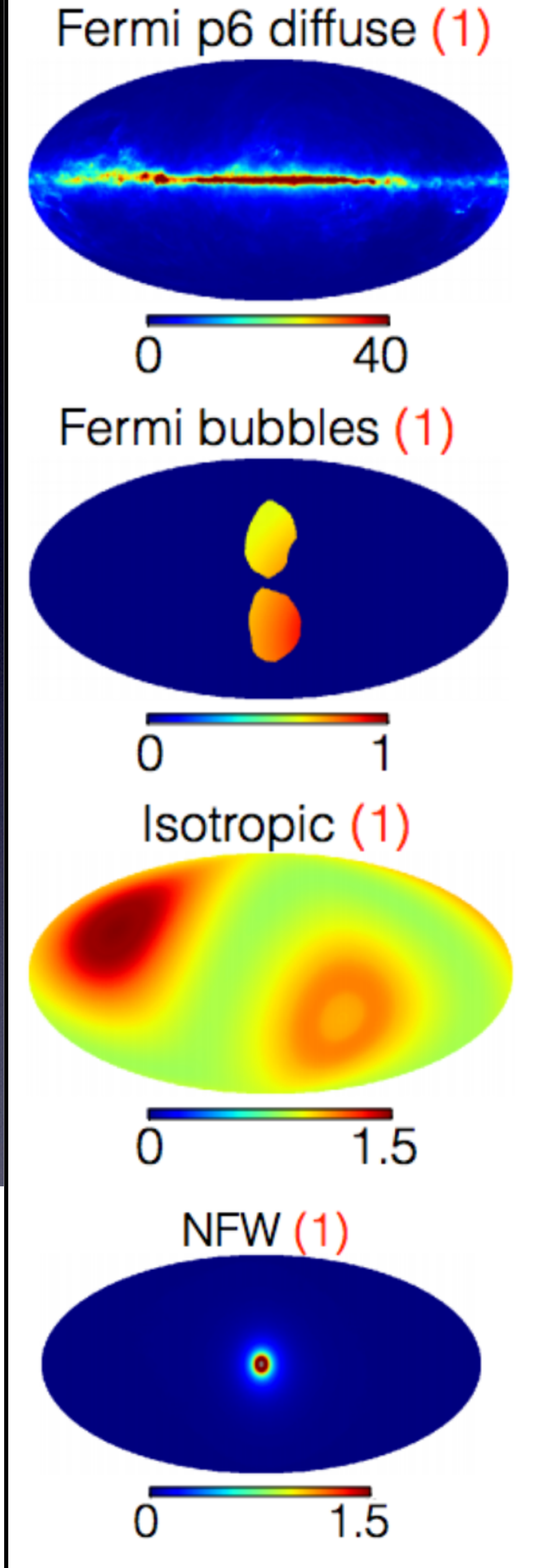
Case 2: population of rare sources.
Expect 100 photons/source, 0.1 sources/pixel - same expected mean # of photons

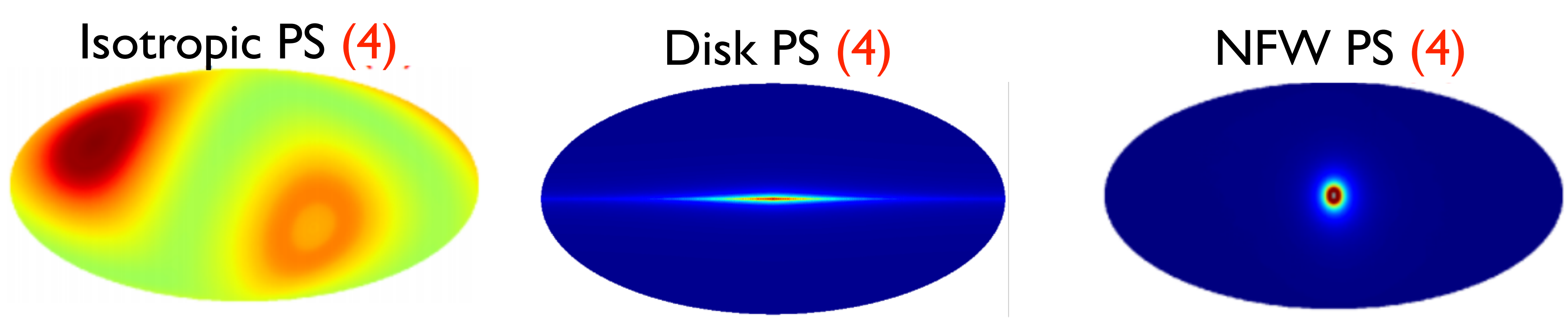
$P(0 \text{ photons}) \sim 0.9$, $P(12 \text{ photons}) \sim 0.1 \times 100^{12}\, e^{-100}/12! \sim 10^{-29}$,
$P(100 \text{ photons}) \sim 4 \times 10^{-3}$

(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

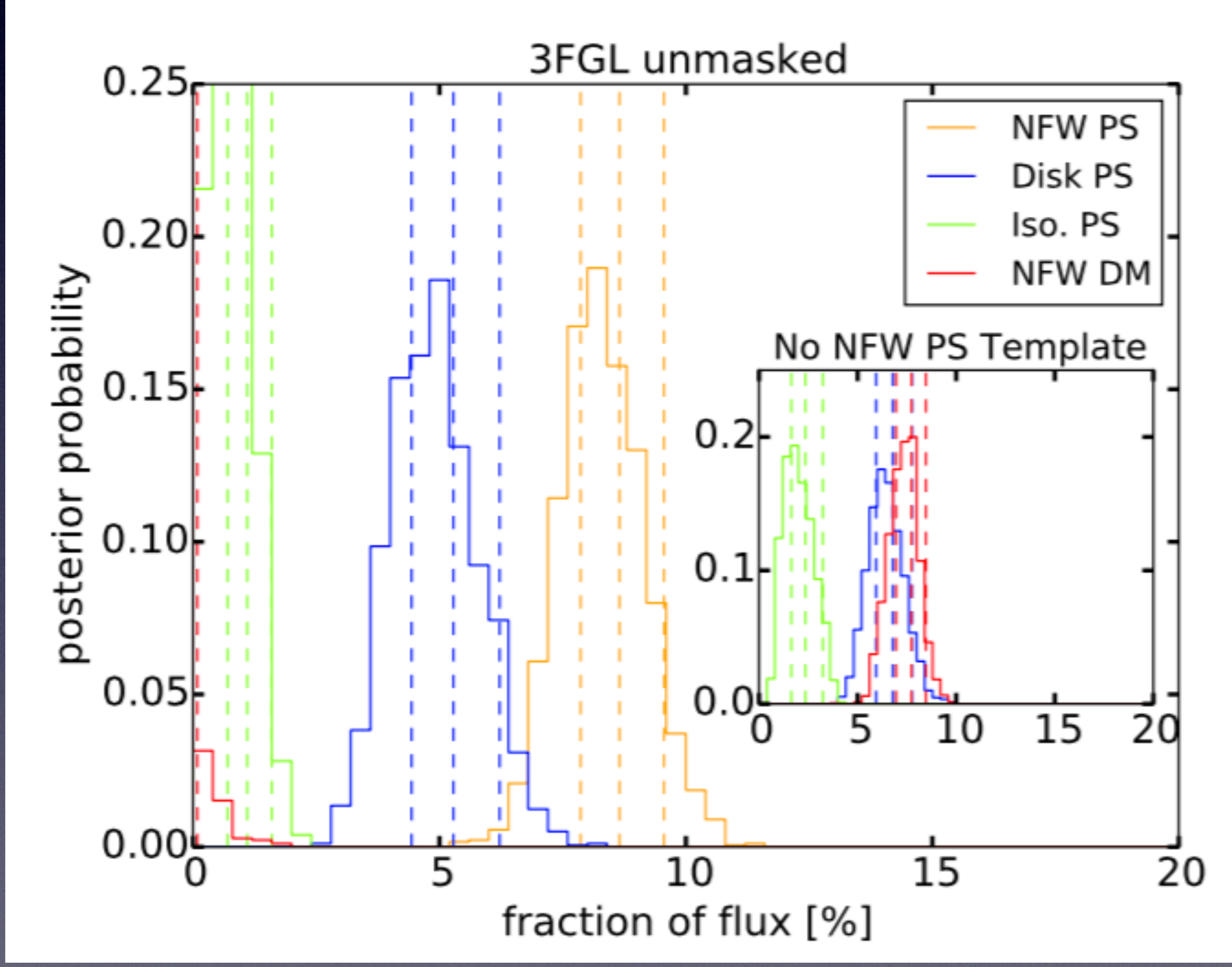




Point source templates

2016: 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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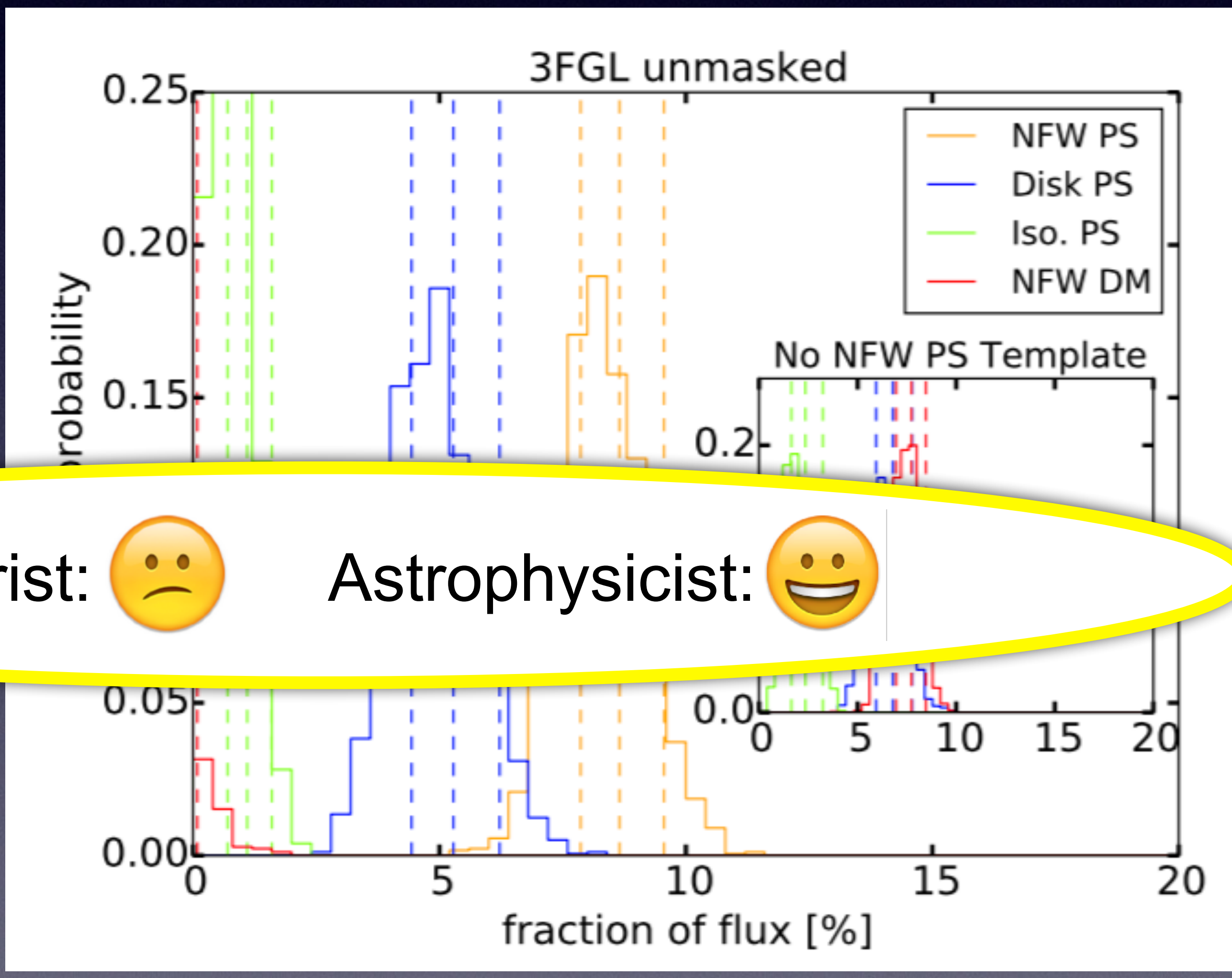
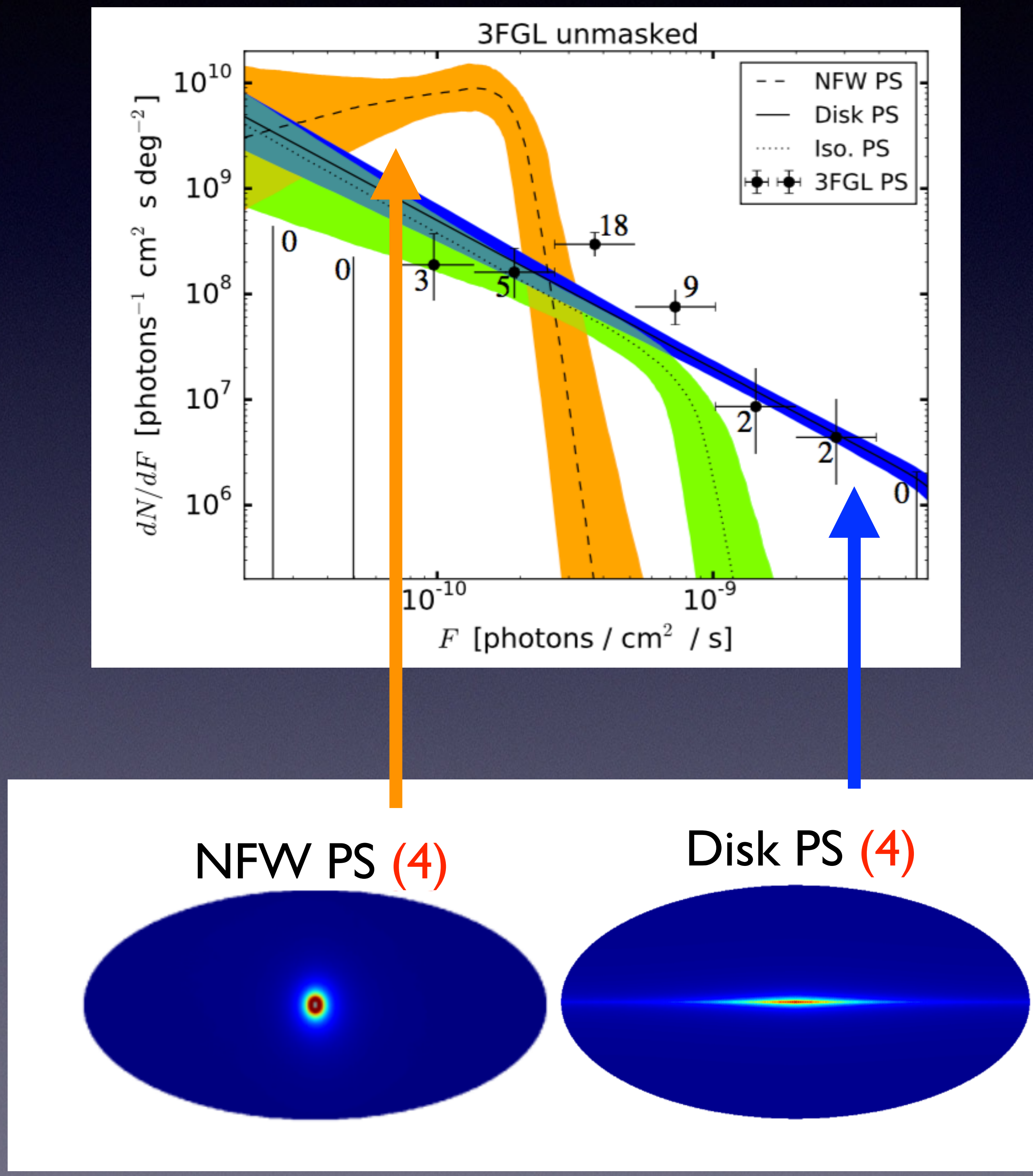


Particle theorist: 😕 Astrophysicist: 😀

Lee, TRS et al ’16

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
- This second point is a bit surprising… coincidence?



Leane & TRS, PRL ’19

Leane & TRS ‘20, arXiv:2002.12370, 2002.12371

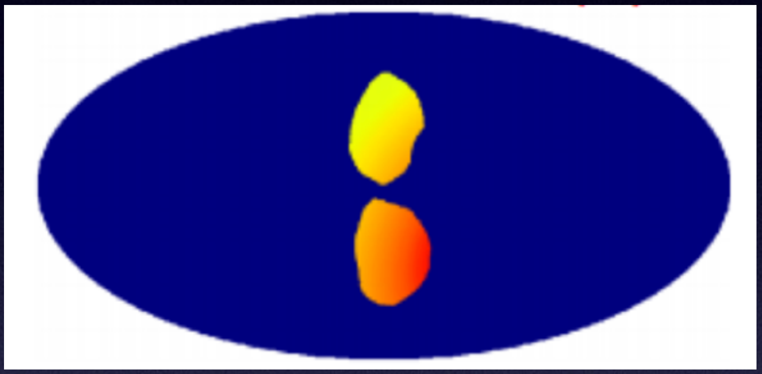
2019-2020: the NPTF and systematic errors

- If the diffuse background is mismodeled, could this mismodeling be absorbed into the PS template, leading to a spurious detection? (studied in 2016)
  - 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
- If unrelated PS populations are mismodeled, could we mistake that error for a GCE signal?
- What if the GCE <u>signal</u> is mismodeled - could we mistake an error in the template for a preference for point sources?

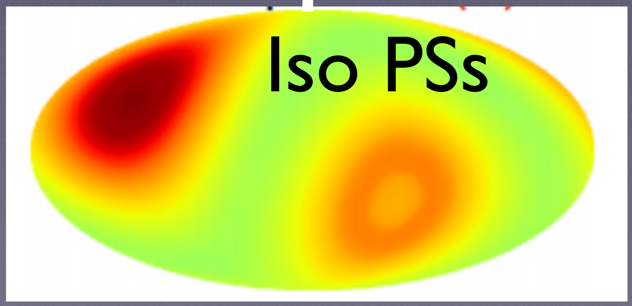
Effects of an unmodeled PS population

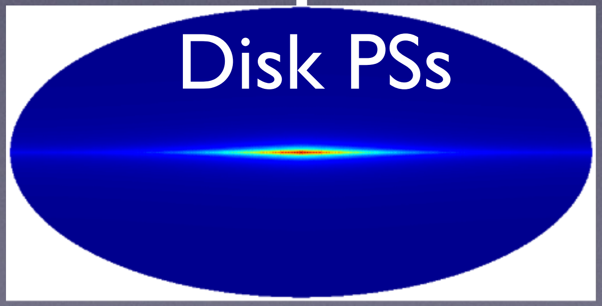
- Suppose there is a new PS population present, not well-described by disk + isotropic sources - e.g. PSs correlated with the Fermi Bubbles or (a subcomponent of) the Galactic bulge
- This population might drive up normalization of "NFW PS" template, to explain bright non-disk non-isotropic sources
-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

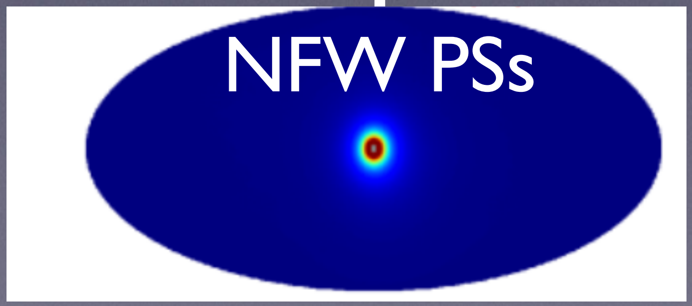
New PSs

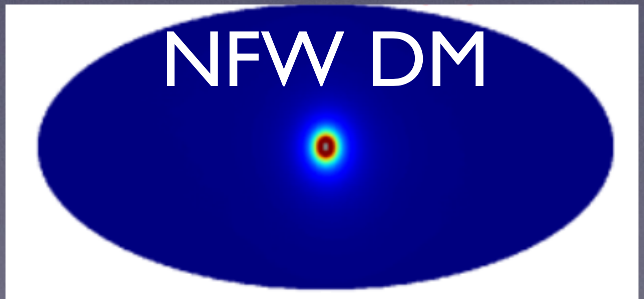


(Hypothetically) present in data, but not available as a (PS) template in fit



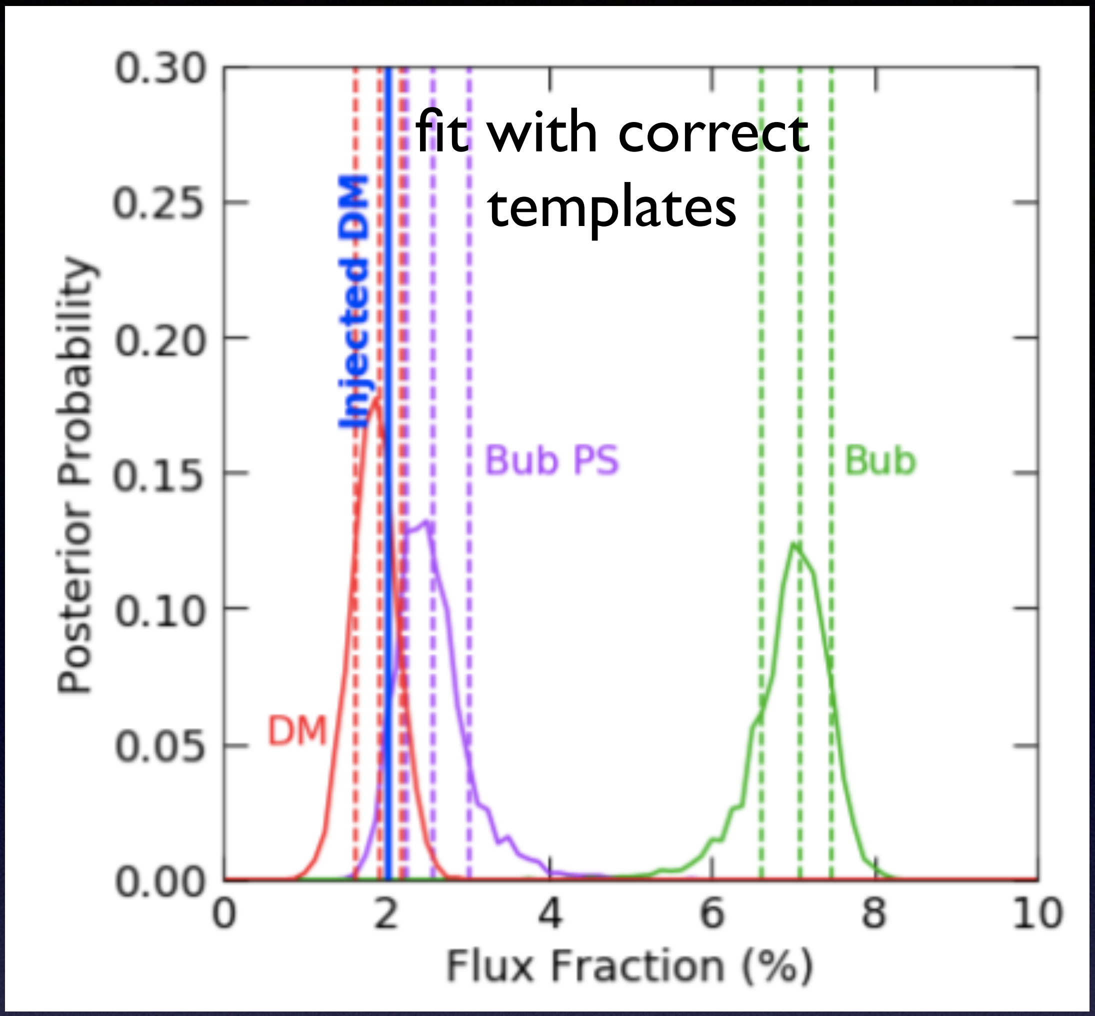


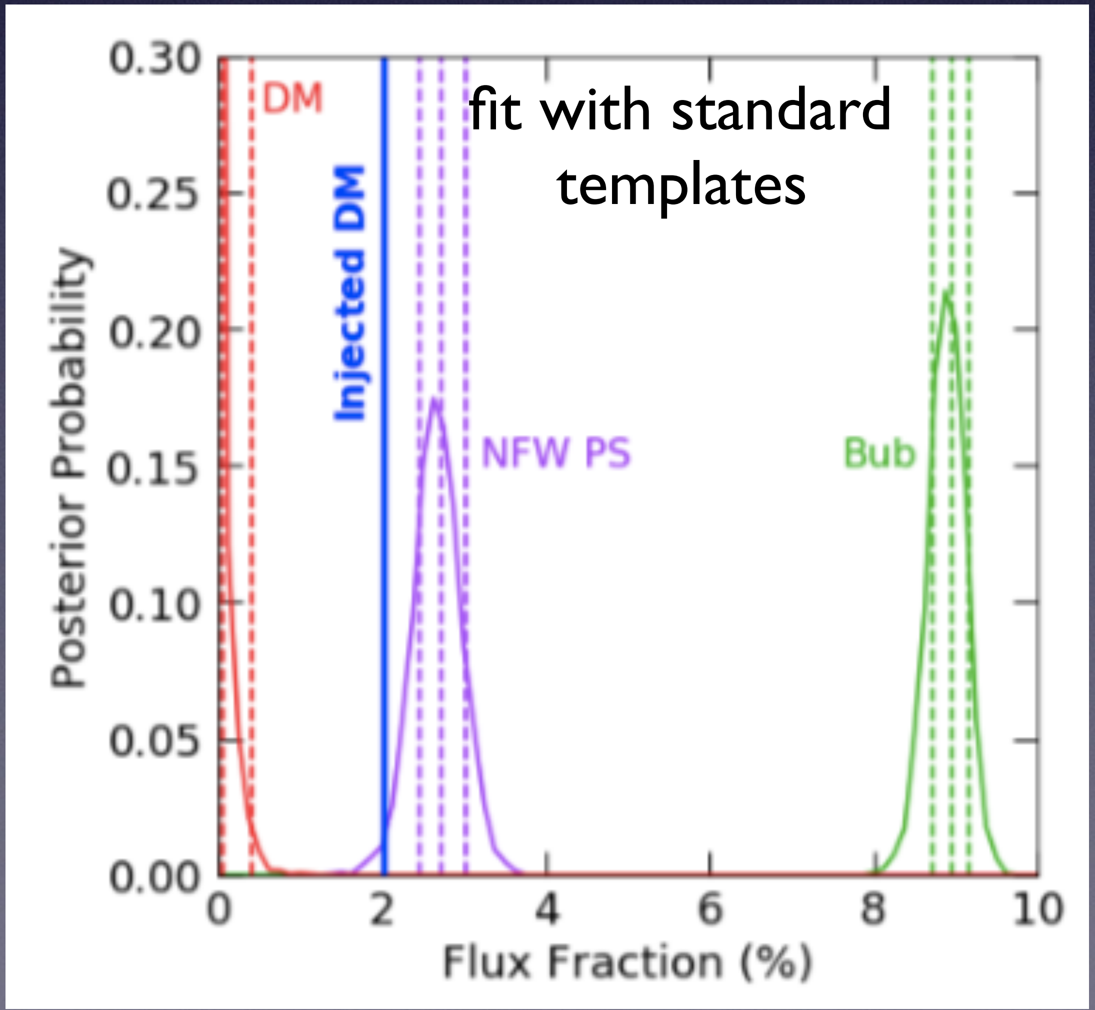




A mock-data example

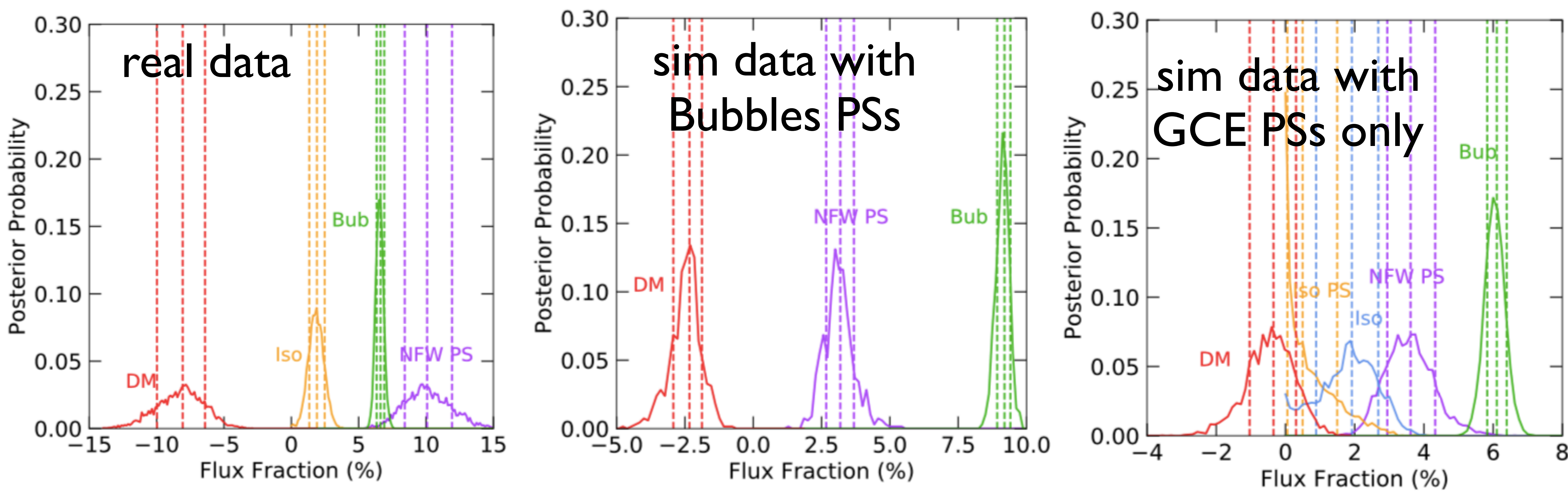
- Construct mock dataset using all standard templates (w/ best-fit values) except NFW PS, a GCE-like DM signal, and point sources spatially correlated with the Fermi Bubbles.
- Fit with same templates except replacing Bubbles-correlated PSs with GCE PSs.
- Result: fit prefers to assign all flux in GCE-like DM signal to GCE PS template, zero flux to DM template!
- That said we do not find a Bubbles PS population in the real data when we look - this is an example of what can happen if PSs are mismodeled





Testing for biases

- While this exact problem does not seem to be occurring, it can give us clues on how to test for similar issues - in the mock-data example, the DM template doesn't just prefer a zero value, it would like to go negative
- Not physical - but we can allow this to happen, see if the fit is driven to unphysical region
- In real data we find the fit prefers a very negative DM coefficient - indication of some kind of mismodeling, could it hide a real DM signal?



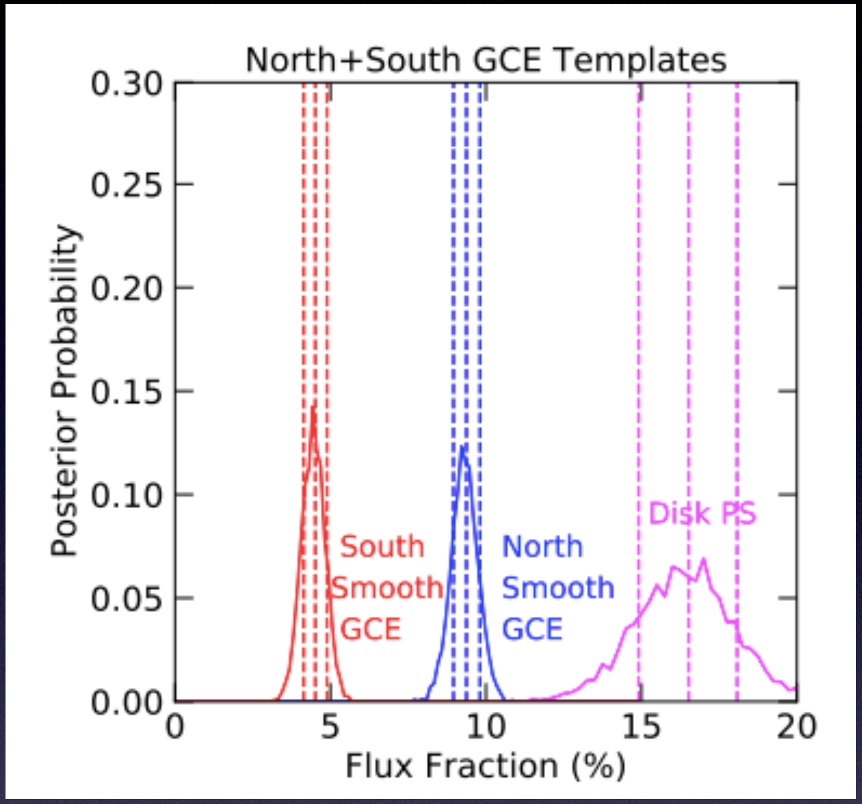
Improving the background model

- Galactic diffuse emission (from cosmic rays interacting with gas/starlight) is the largest background component, and not well-known to the level of noise, maybe it is responsible for the problem?
- Chang et al '19, Buschmann et al '20:
  - can quantitatively explain the observed preference for a negative flux by imperfections in the Galactic diffuse emission model
  - can construct newer models which do not prefer a (unphysical) negative coefficient for the smooth/DM component
  - with these models, there is still a preference for a PS population, albeit at lower significance (Bayes factor ~10^{3-4}, analogous to 3-4σ, vs ~6σ in 2016) and depending on the region-of-interest

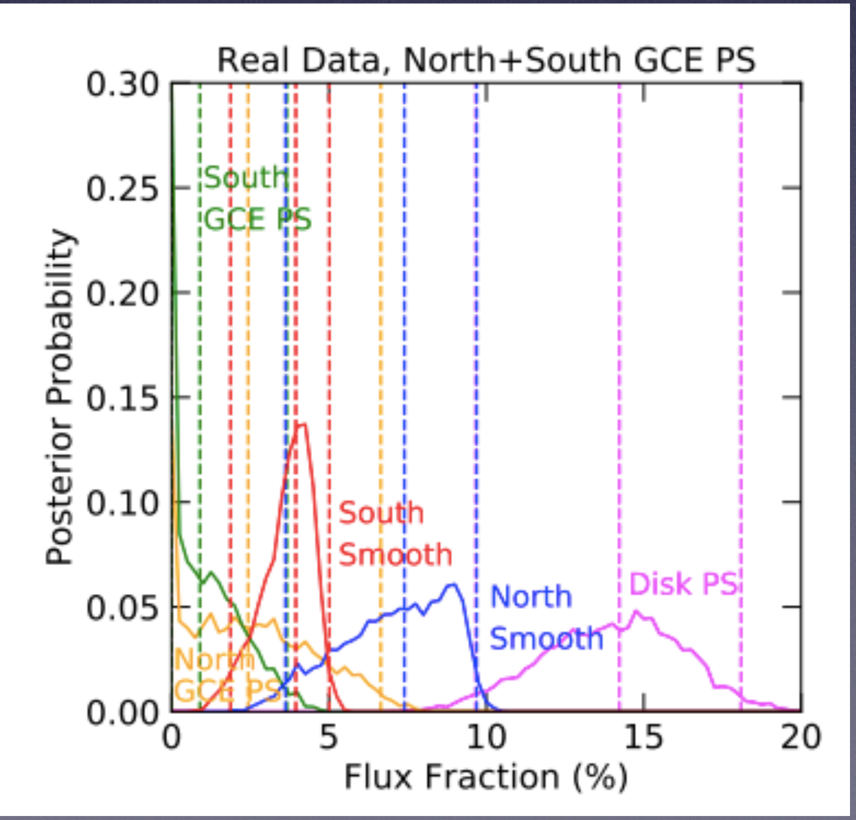
But what about the signal model?

- General idea: suppose the fit prefers a somewhat different spatial distribution for the signal than specified by the signal template
- Higher pixel-to-pixel variance for point-source population makes it easier to accommodate such differences
- The fit can prefer a point-source population based solely on this increased variance (i.e. inflating the error bars makes the fit better) - nothing to do with small-scale granularity
- Toy example: suppose I observe 2000 photons in one region and 1000 photons in another. If I know the underlying physics is the same in both regions, which can more easily explain my results? (1) statistical fluctuation of homogeneous smooth emission, or (2) point sources produce ~1000 photons each, there are three sources total?

Does this happen in the real data?

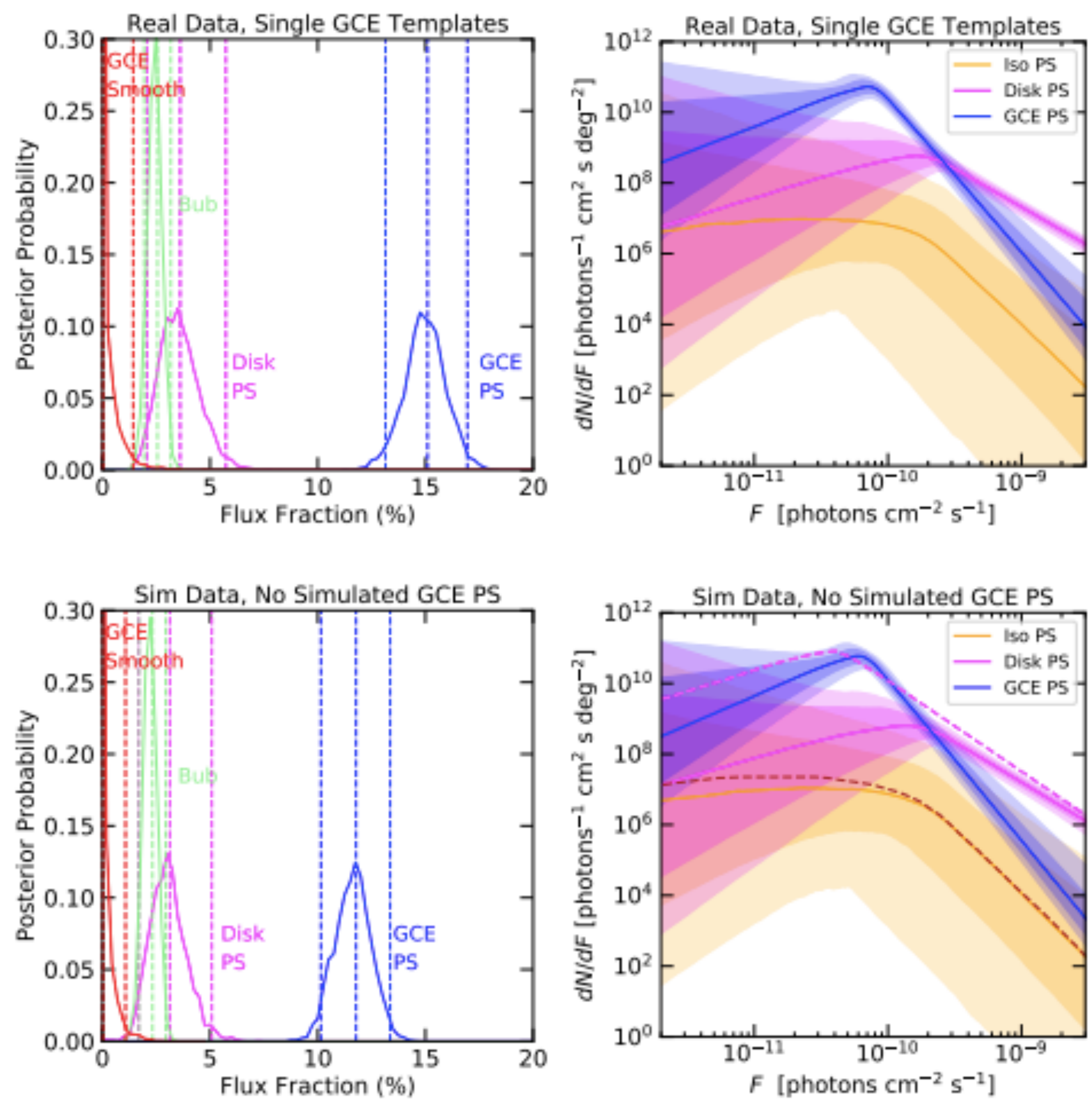


- Yes!
- We focused on a 10° radius region surrounding the GC
- In this region there is a clear mismatch between the standard template and the fit's preference - data prefers a north/south asymmetry (up to 2:1 depending on analysis choices)
- When we assume symmetric signal templates (standard analysis), point sources are initially strongly preferred (Bayes factor > 10^{15} with default background model).
- Once signal template is allowed to be asymmetric, preference for PSs drops to insignificance (BF~7).
- The preference for PSs (in this specific analysis) is really just a preference for N/S asymmetry!



Comparison with simulations

- We can see (and quantitatively explain) this effect in simulations
- Simulate smooth GCE with asymmetry, fit as linear combination of symmetric smooth template + symmetric PS template
- The observed behavior matches what we see (for the same fit) in the real data very closely, although in the simulations we <u>know</u> the PS population isn't real



One example realization

Comparison with simulations

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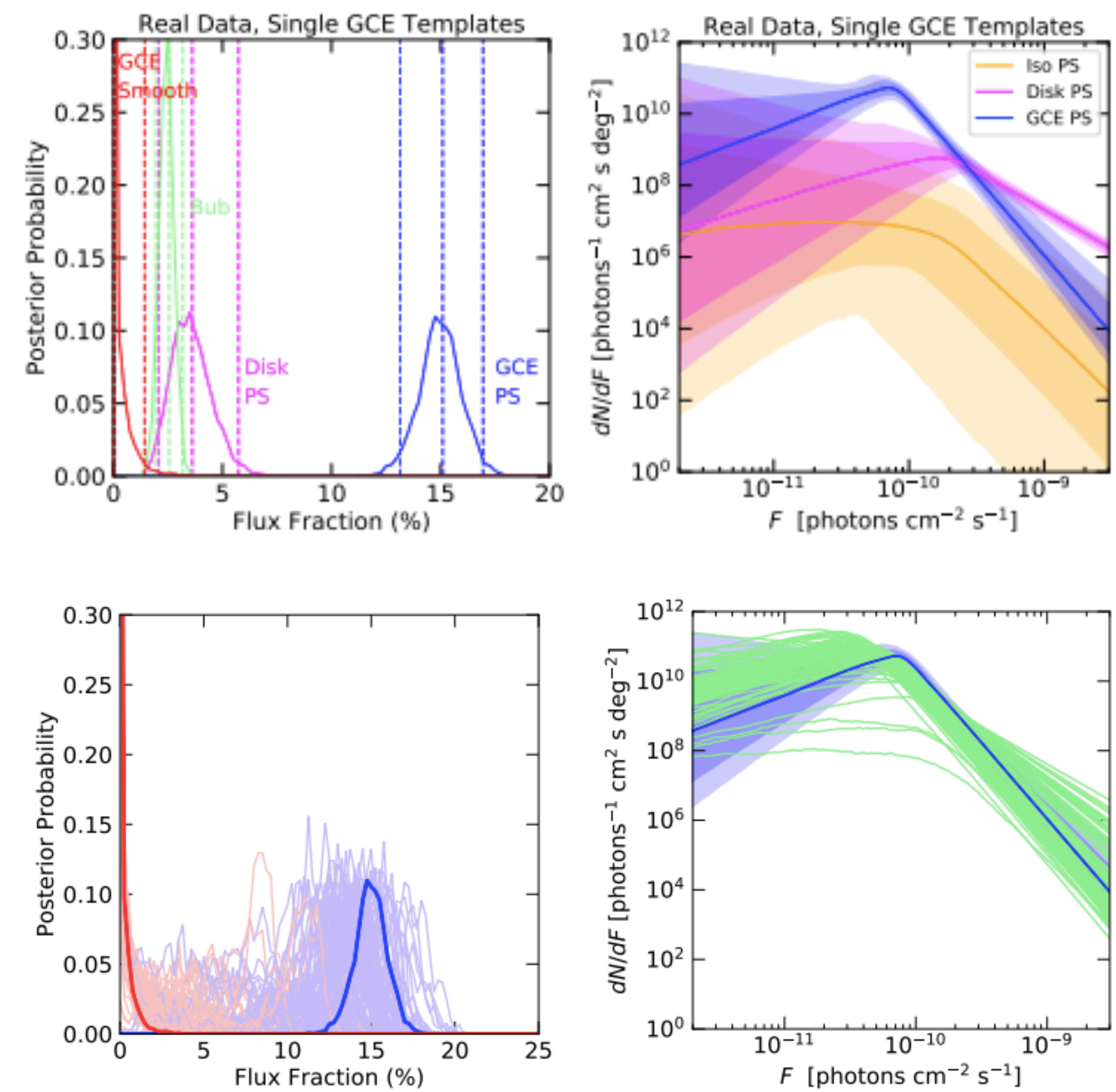
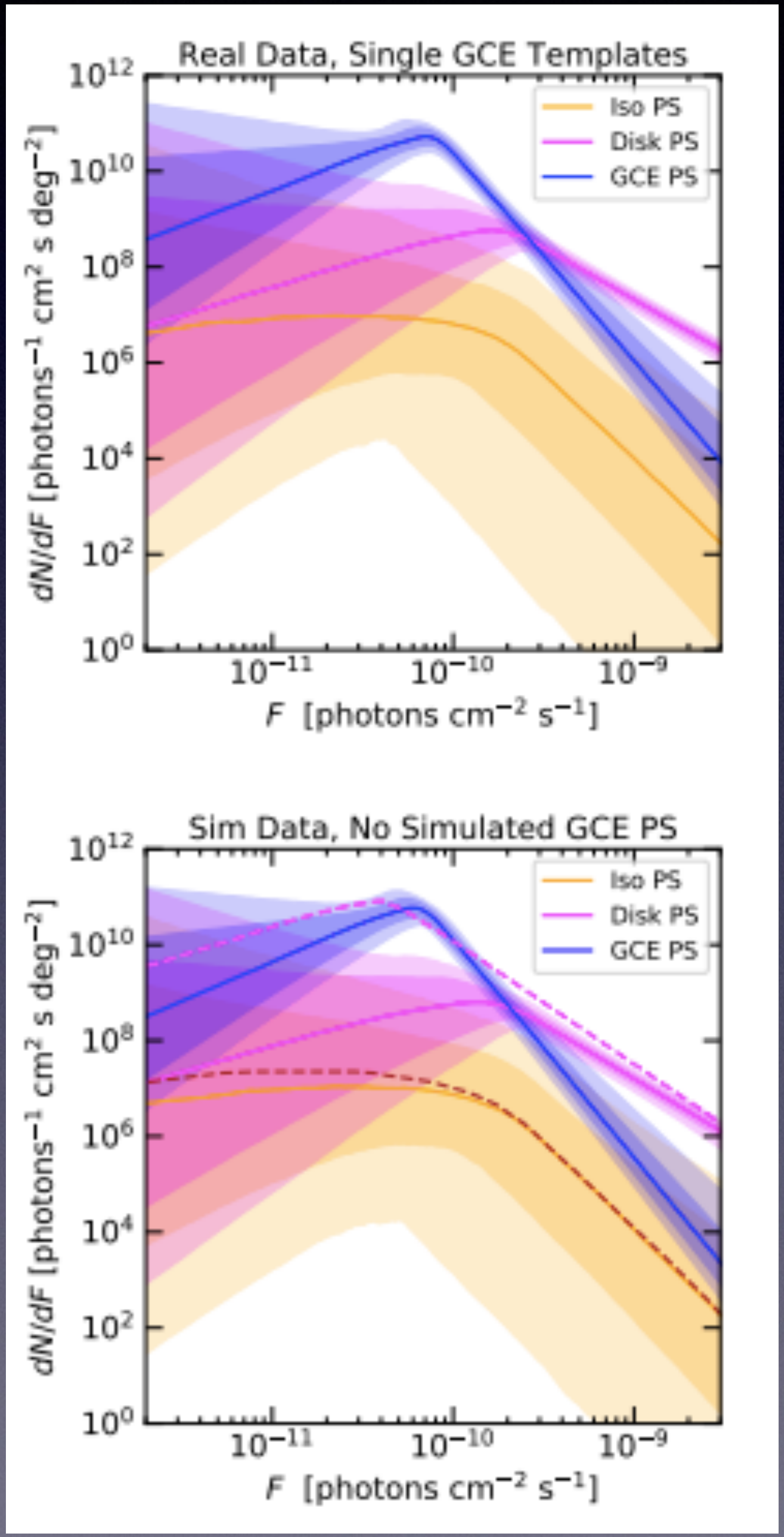


100 realizations

Properties of the (fake) sources

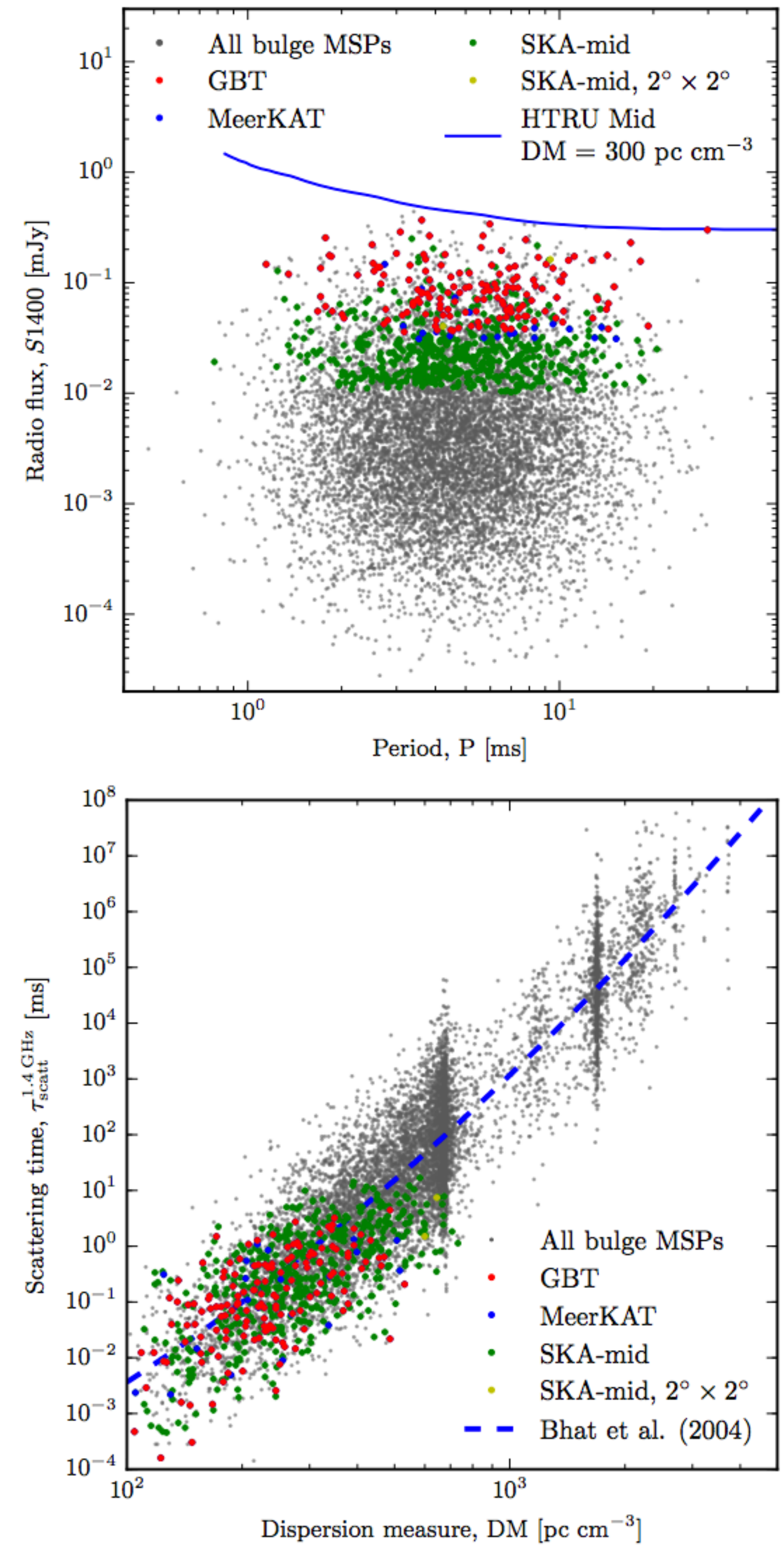
- Recall we said previously that it was surprising the sources peaked right below the detection threshold, and the source # fell off rapidly at higher fluxes
- A range of NPTF analyses have found very similar behavior - seems stable
- Now we see this behavior is also exactly what we get in simulations with no GCE PSs but a mismodeled smooth signal
- Reason for caution about apparent PS populations with similar brightness distribution in other NPTF analyses



So is the GCE asymmetric?

- A robust detection of N/S asymmetry would be very interesting - and imply the GCE is probably <u>not</u> dark matter
- But not so fast - we find whether or not the asymmetry is present is sensitive to systematic effects (e.g. choice of background model, choice of fit region)
- Our argument is just that <u>if</u> there is a mismatch between the signal model and the shape preferred by the fit (with N/S asymmetry as one example), <u>then</u> it can give a very convincing-looking but spurious preference for point sources
- Reason for caution in all NPTF analyses - especially if inferred source count function looks like expectations for spurious PSs

- Gamma-ray systematic uncertainties seem hard…
- But 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 combination of a population of point sources (PSs) and a smooth diffuse component, non-Poissonian template fitting methods initially found a strong preference for most/all of the GCE to be attributed to the PSs.
- BUT we have recently shown that searches for Galactic Center Excess (GCE)-correlated PS populations can obtain spurious detections due to signal mis-modeling, at high apparent significance, with properties closely matching previous claims of detected PS populations.
- We do not claim to exclude PS-based scenarios for the GCE - a true PS population could be hiding beneath these systematic effects - but advise against discarding non-PS models for the GCE on these grounds.