A status update on the Galactic Center GeV gamma-ray excess

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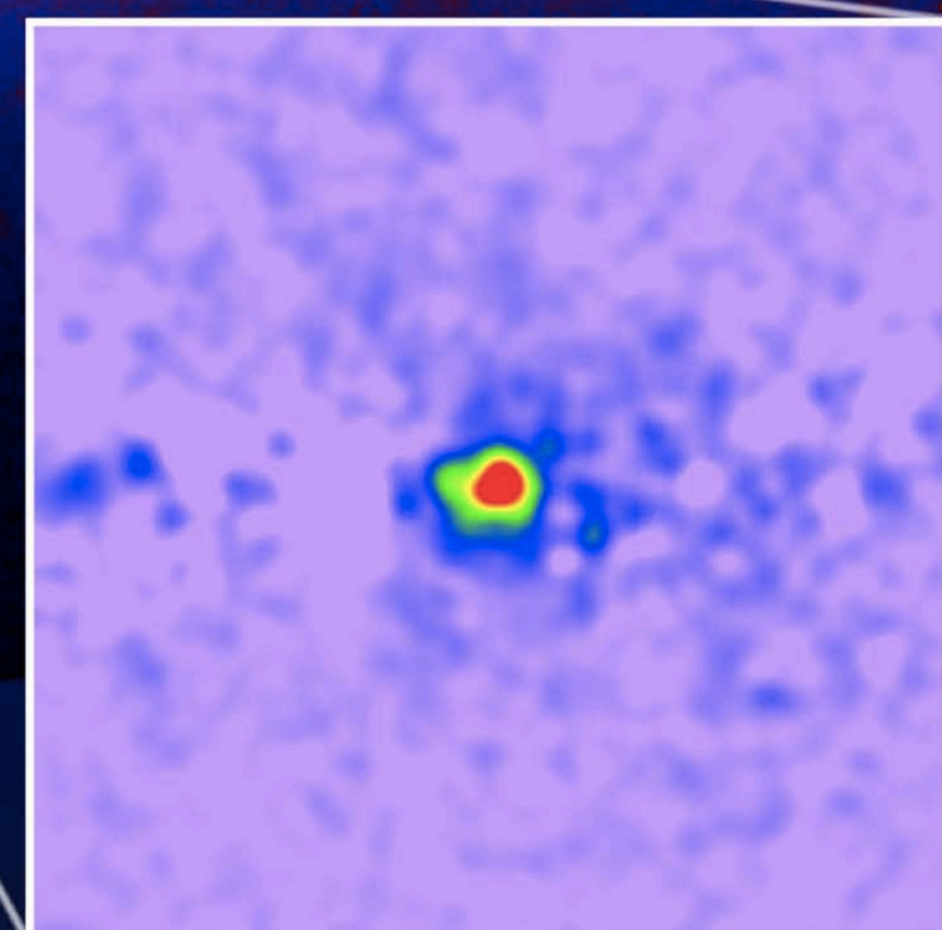

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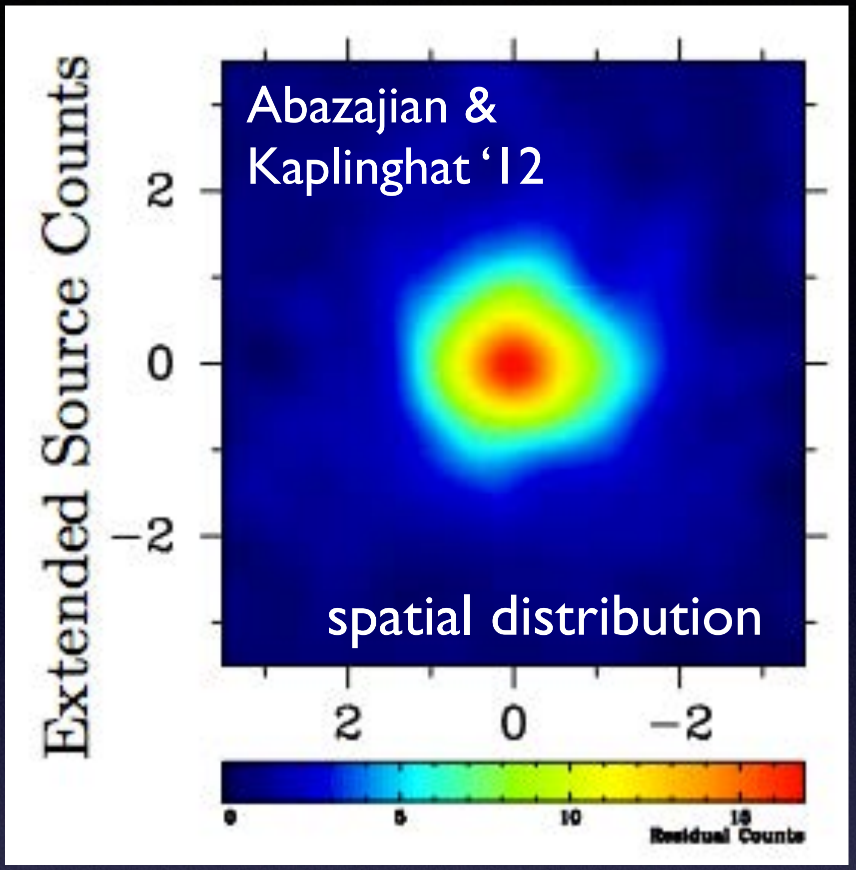
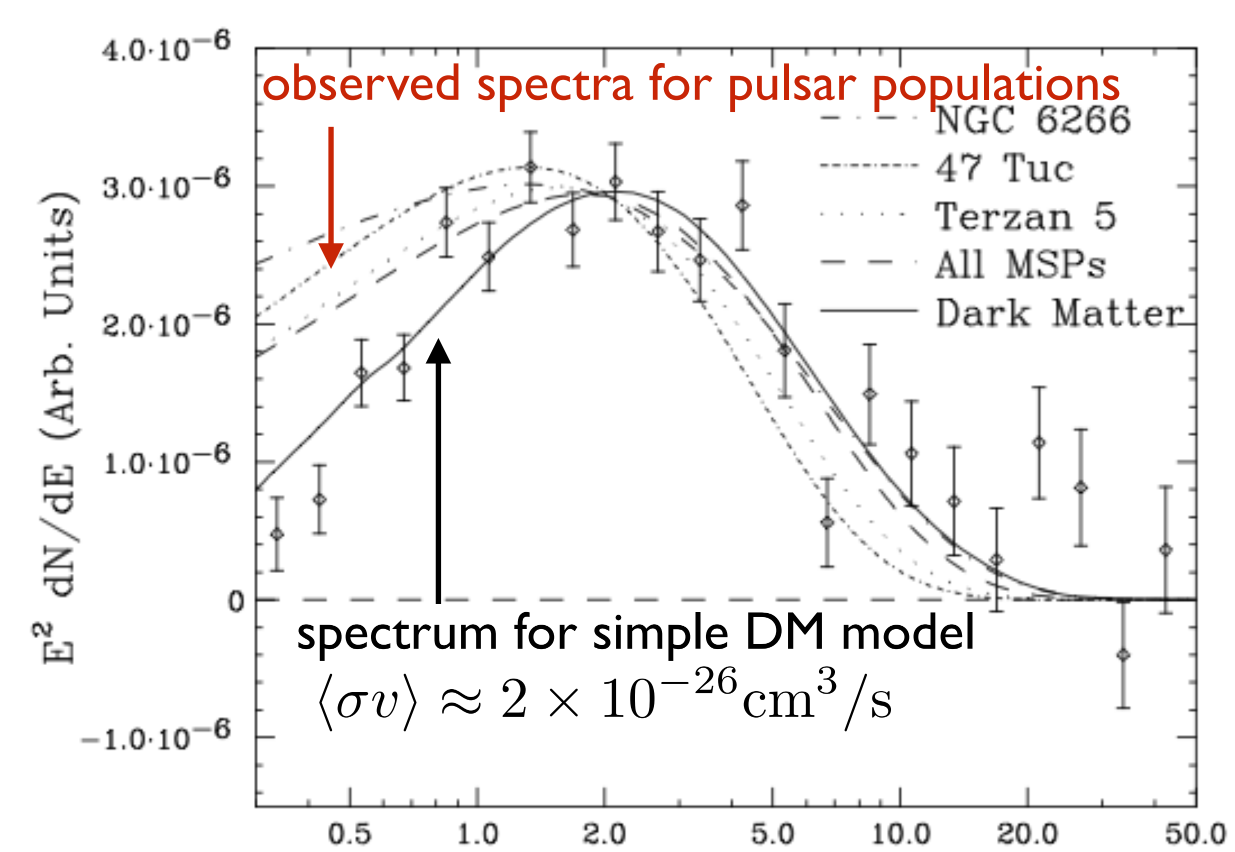
Outline

- History and properties of the Galactic center excess
- Possible interpretations as dark matter signal / new population of pulsars
- Status of studies of possibly distinguishing features:
  - morphology
  - granularity / photon statistics
  - counterpart signals
- Summary and outlook

The Galactic Center Excess (GCE)

- 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 DM explanation: thermal relic annihilating DM at a mass scale of O(10-100) GeV
- Leading non-DM explanation: population of pulsars (spinning neutron stars) below Fermi's point-source detection threshold





Daylan, TRS et al '16

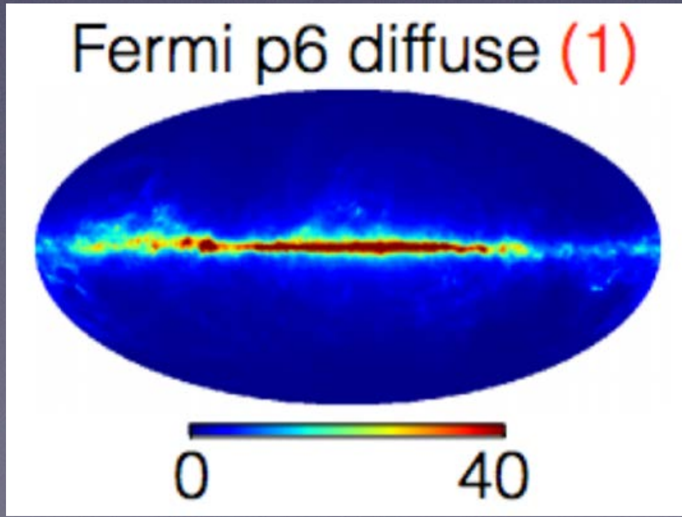
A first non-gravitational DM signal?

- Roughly 84% 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.
- No good candidates in physics we understand - one of our biggest clues to what might lie beyond known physics.
- In a broad class of scenarios, DM was once in thermal equilibrium with the Standard Model (SM) and was depleted through collisions producing SM particles, requiring an annihilation rate:

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

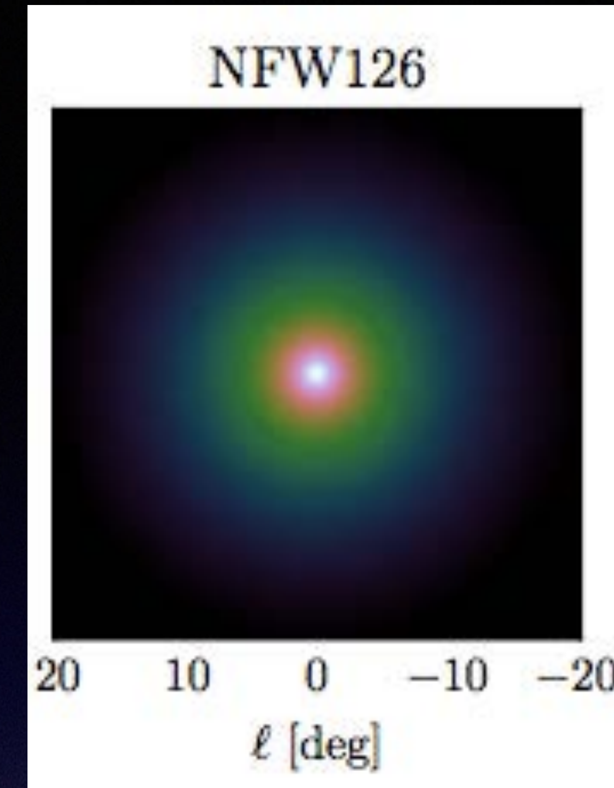
Distinguishing hypotheses in GC gamma rays

- Overall morphology:
  - we expect the inner region of the DM halo to be roughly spherically symmetric (modeled by modified Navarro-Frenk-White density profile, which is power-law-like close to the GC)
  - the pulsar distribution is more uncertain but could reasonably be either spherically symmetric [Brandt & Kocsis '15] or trace other Galactic stellar populations, e.g. the stellar bulge
- Granularity of the signal:
  - pulsars are point sources - if sufficiently bright, would lead to enhanced fluctuations in signal even if no pulsars are individually highly detectable
  - DM signal is expected to be smooth/diffuse
- Challenge: GCE sits on top of a bright, highly structured diffuse background from charged cosmic rays interacting with the gas/starlight.

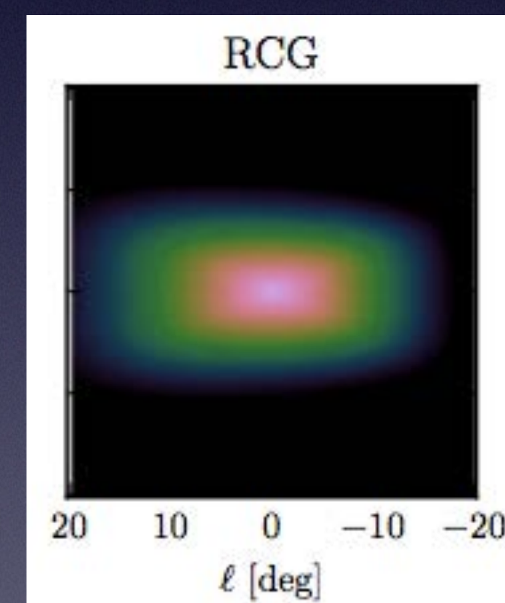


How is the GCE shaped?

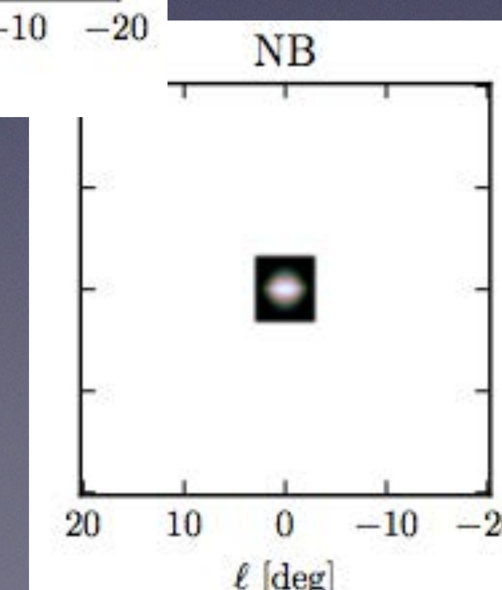
- Early studies (e.g. Daylan, TRS et al ’16, Cholis et al ’15): GCE appears to be roughly spherically symmetric
- Bartels et al ’18: use much more flexible background model (SkyFACT framework), finds morphology better described by boxy bulge + nuclear bulge once extra background dof are added
- Macias et al ’18, Macias et al ’19, Abazajian et al ’20, Pohl et al ’22: template-based method using hydrodynamical simulations to improve gas maps in inner Galaxy, find preference for bulge morphology
- di Mauro ’21, Cholis et al ’21: templates based on upgraded modeling of cosmic-ray propagation, find preference for NFW-like morphology
- McDermott et al ’22: compares background models from Cholis et al ’21 & Pohl et al '22, finds best overall fit = models of Cholis et al + NFW-like spherical GCE



vs



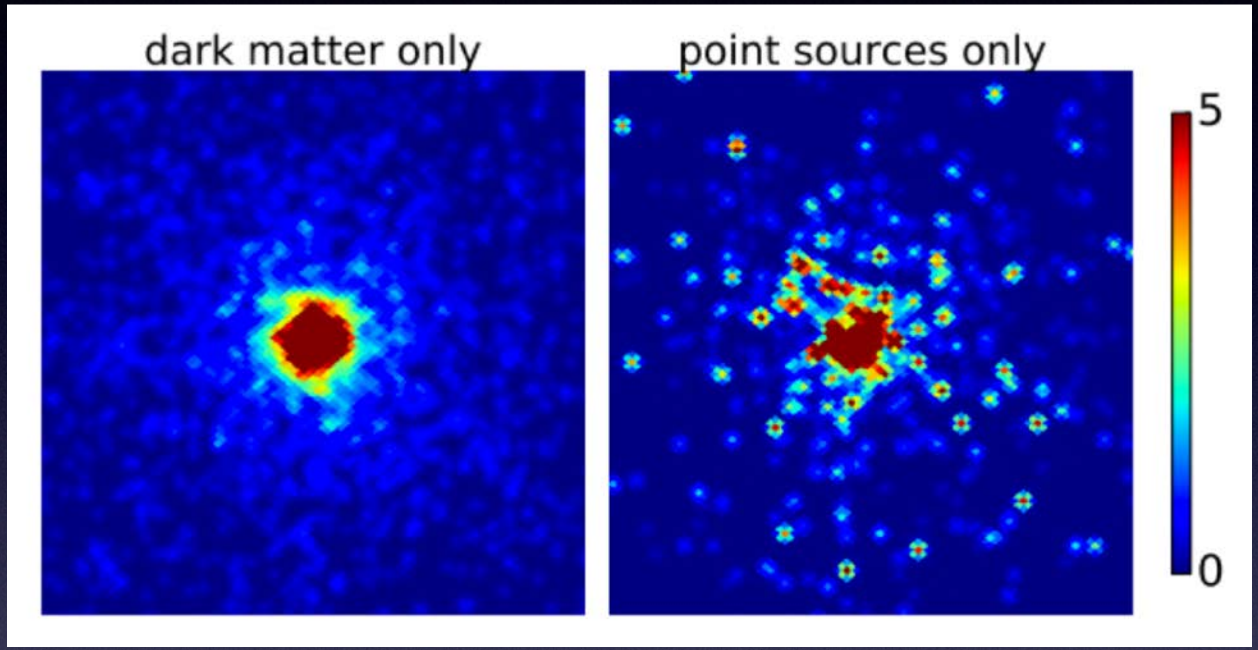
Bartels et al ‘18



Deciphering the GCE with photon statistics

DM origin hypothesis

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



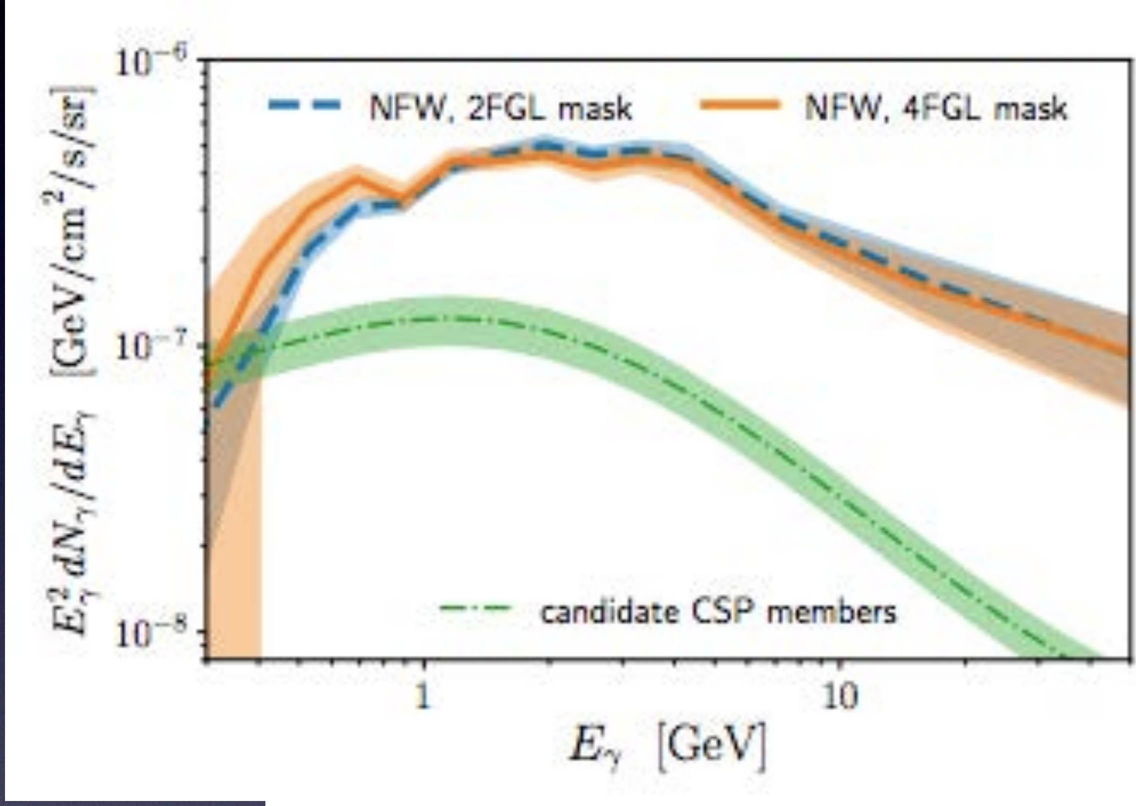
Pulsar origin hypothesis

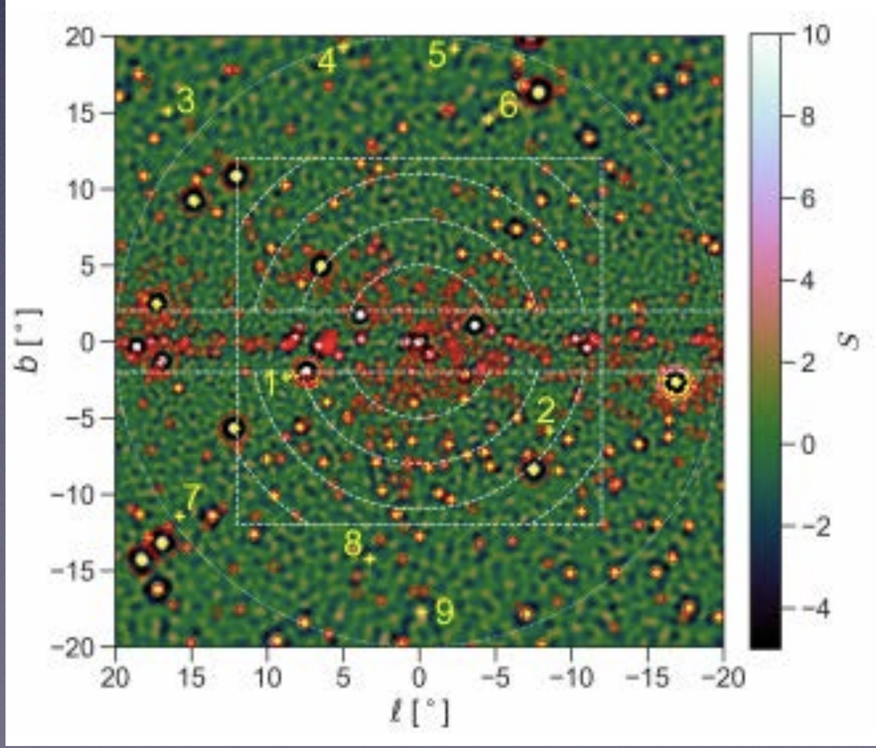
signal originates from a collection of compact objects, each one a faint gamma-ray point source

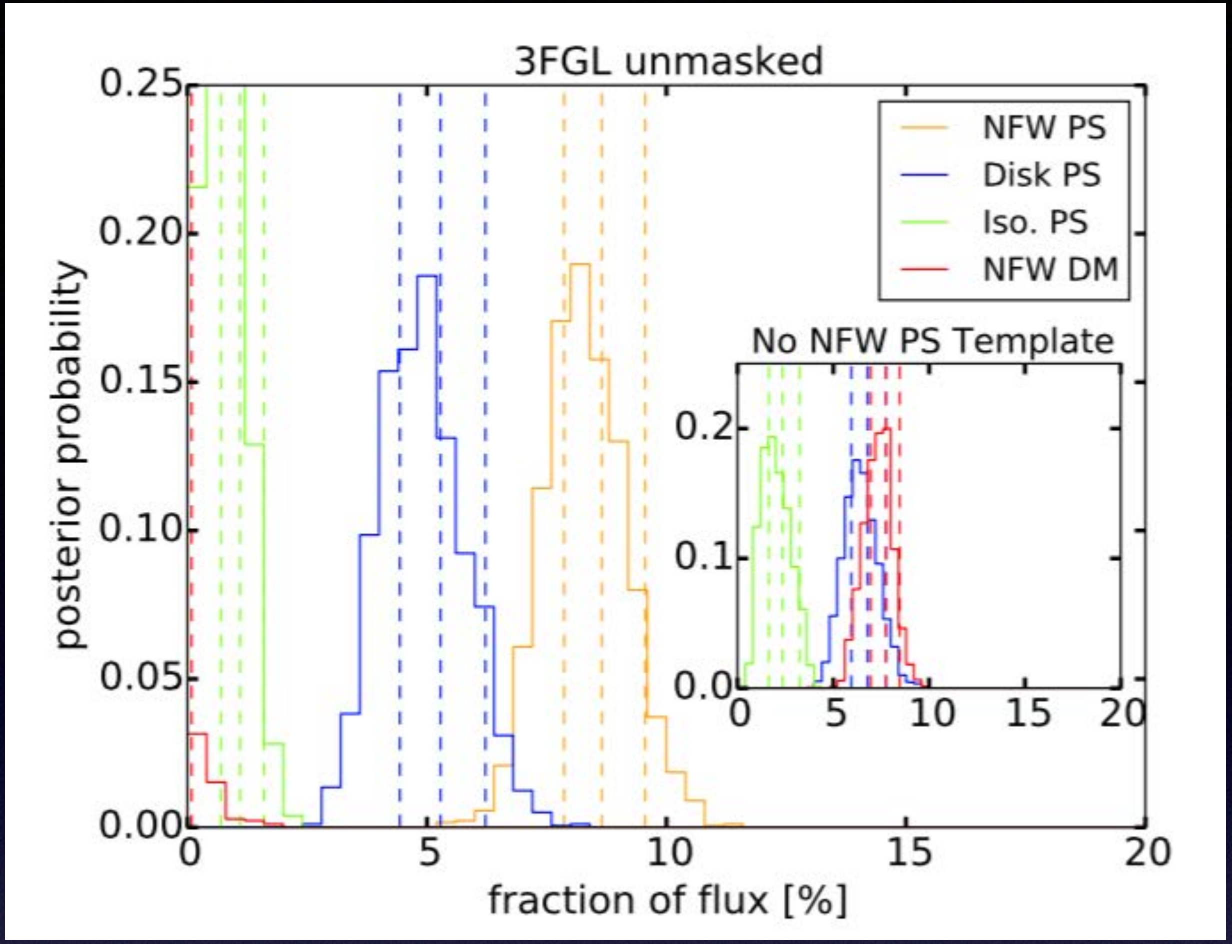
- Hope to distinguish between hypotheses by looking at granularity of the photon signal - presence or absence of "hot spots".
- Two main analyses in 2016, both claimed evidence for point source populations:
  - Exploiting non-Poissonian statistics of fluctuations from an unknown point source distribution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

2020: wavelets → 4FGL

- Zhong et al ’20 repeated wavelet analysis of Bartels et al ’16, but now comparing identified high-significance peaks to latest gamma-ray source catalog (4FGL).
- 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.





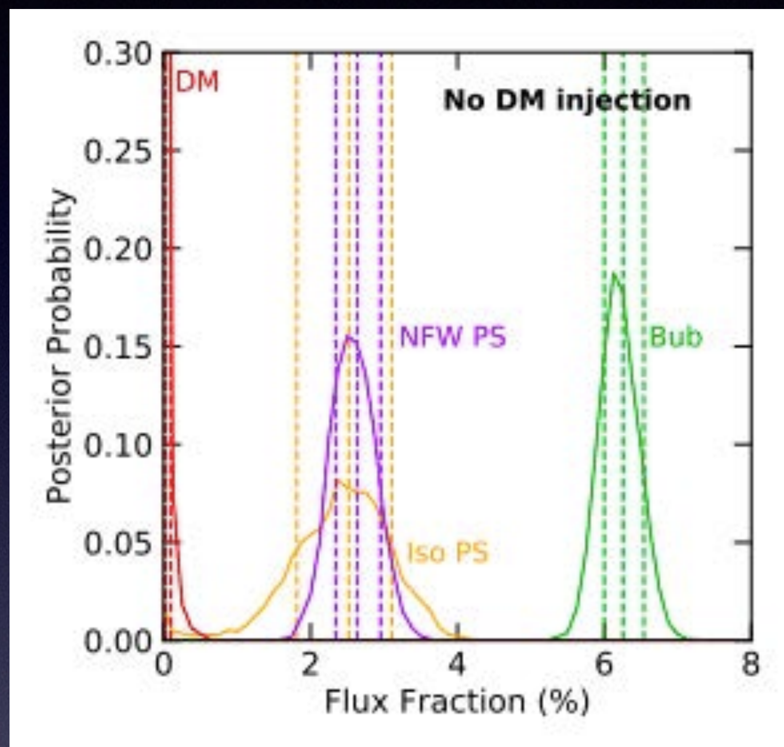


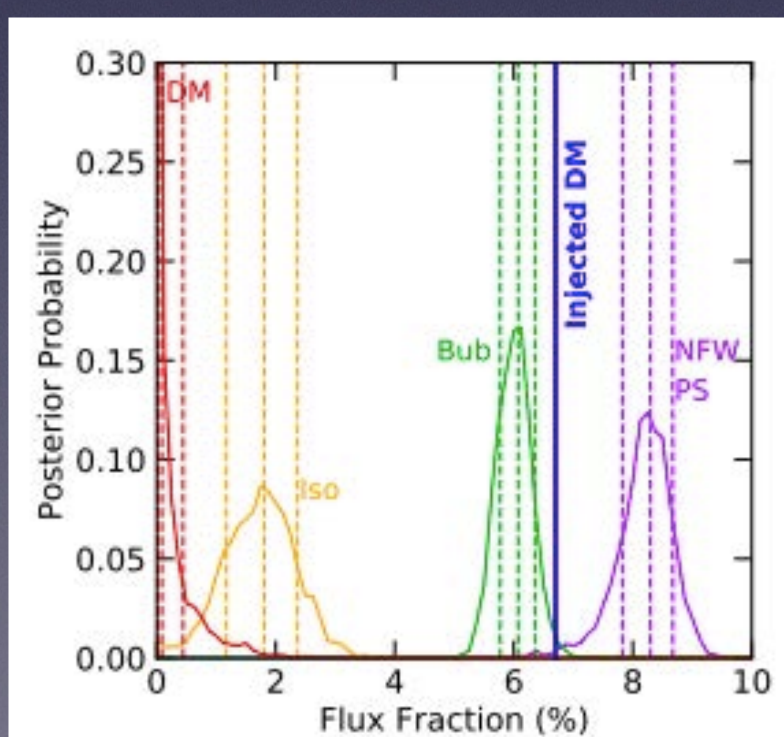
- Lee et al '16: fit shows a strong preference to assign all GCE flux to new PS population (Bayes factor in favor of model with PSs ~10^9)
- Suggests signal is composed of a relatively small number of just-below-threshold sources

- Leane & TRS '19, Chang et al '19, Buschmann et al '20:
  - background models used in original analysis lead to significant bias against DM signal, reconstruct injected smooth signals as ensembles of point sources;
  - newer models can be created that do not have the same clear bias, evidence for PSs drops to Bayes factor ~10^3 (or may be lower, depending on priors)
- Leane & TRS '20a, b: even with perfect background models, an overly-rigid signal model can lead to a spurious preference for a PS population

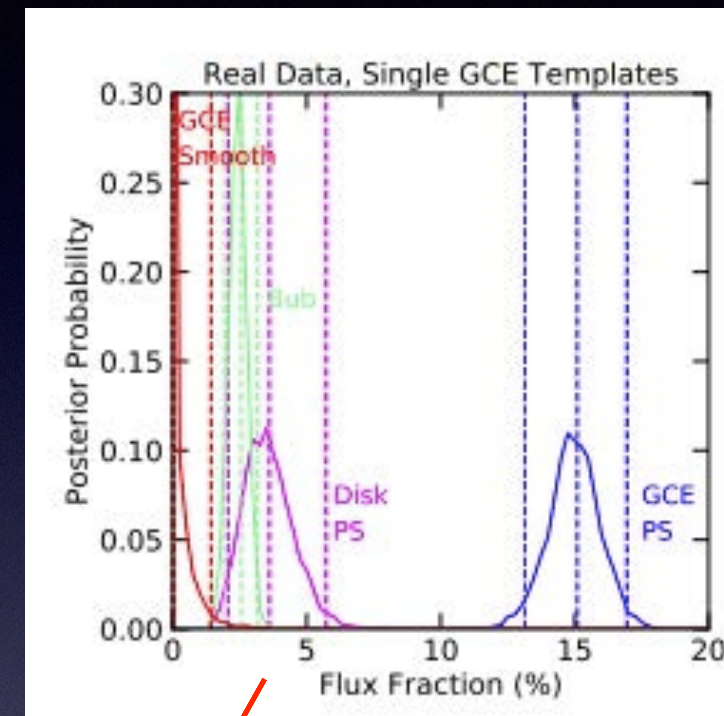
Biases favoring PSs

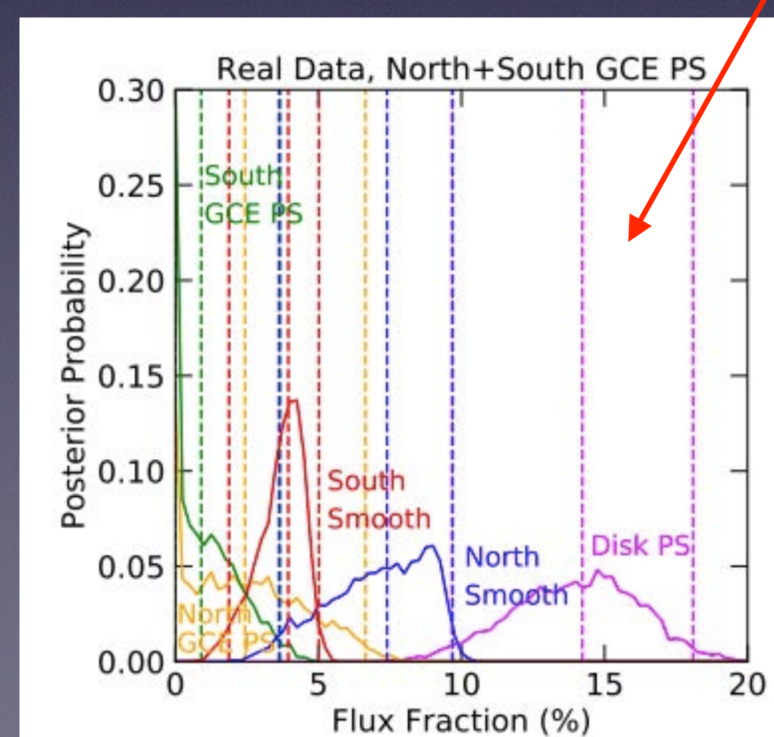
Example of diffuse background mismodeling creating/ enhancing PS preference - bias revealed by injection test





Example of how signal mismodeling can be confused for PSs - strong PS preference with default pipeline that goes away when GCE is allowed north/south asymmetry





(we can also simulate scenarios where smooth but asymmetric GCE gets reconstructed as PSs with the same properties as inferred from the real data)

Neural networks for the GCE

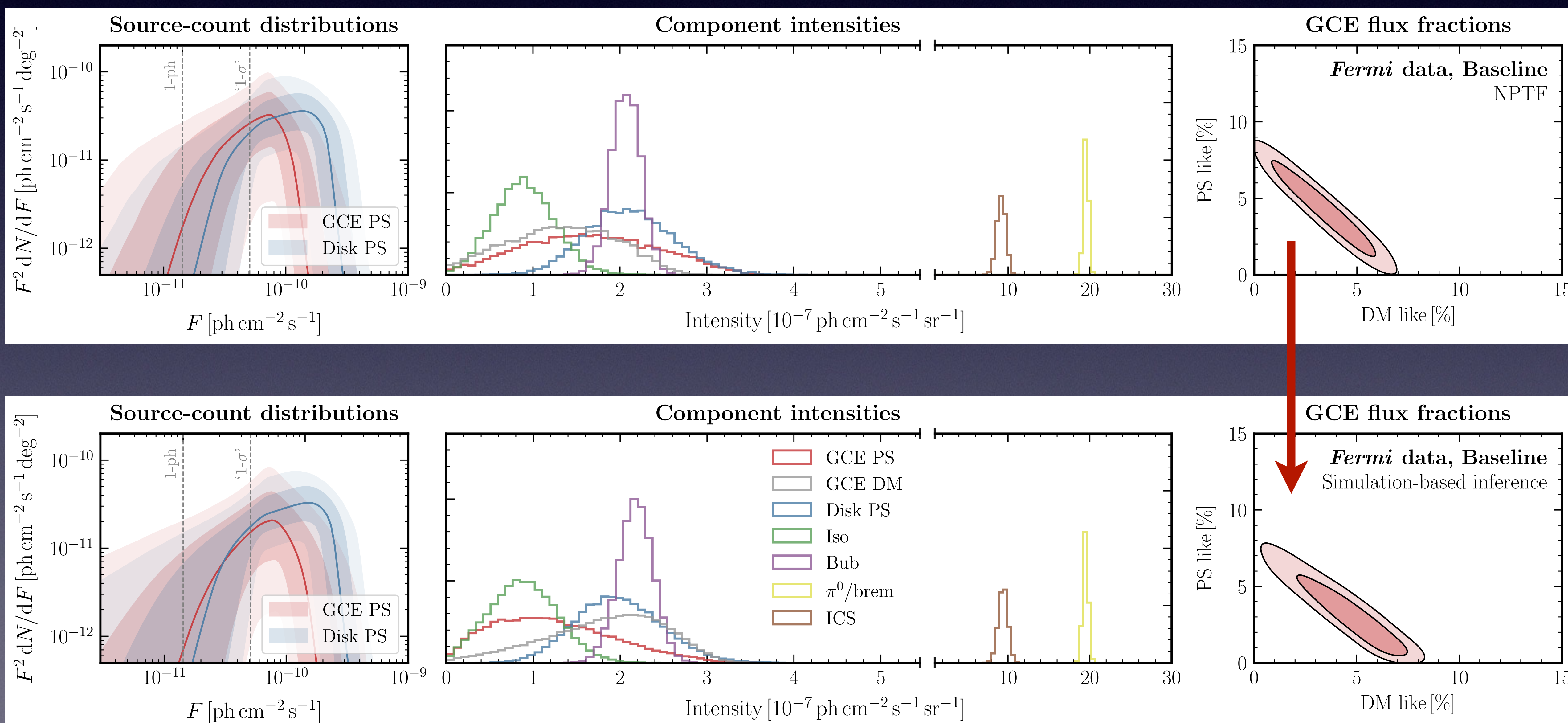
- General idea: train neural networks on simulations based on template models
  - seek to distinguish diffuse emission from source populations
  - capture information in multi-pixel structure not just single-pixel likelihoods
- Complementary methods by List et al (2020, 2021) (neural-network-based histogram regression) and Mishra-Sharma & Kranmer (2021) (normalizing flows).
- The most recent results from the first approach find the GCE should be <66% diffuse at 95% confidence; the second approach finds a PS fraction of 38^{+9}_{-19}%.
- In at least some cases, shown to be more robust to errors in the signal/background templates, although they still rely on templates for training

NN methods (tentatively) still detect a hint of point sources

Plots provided by Siddharth Mishra-Sharma

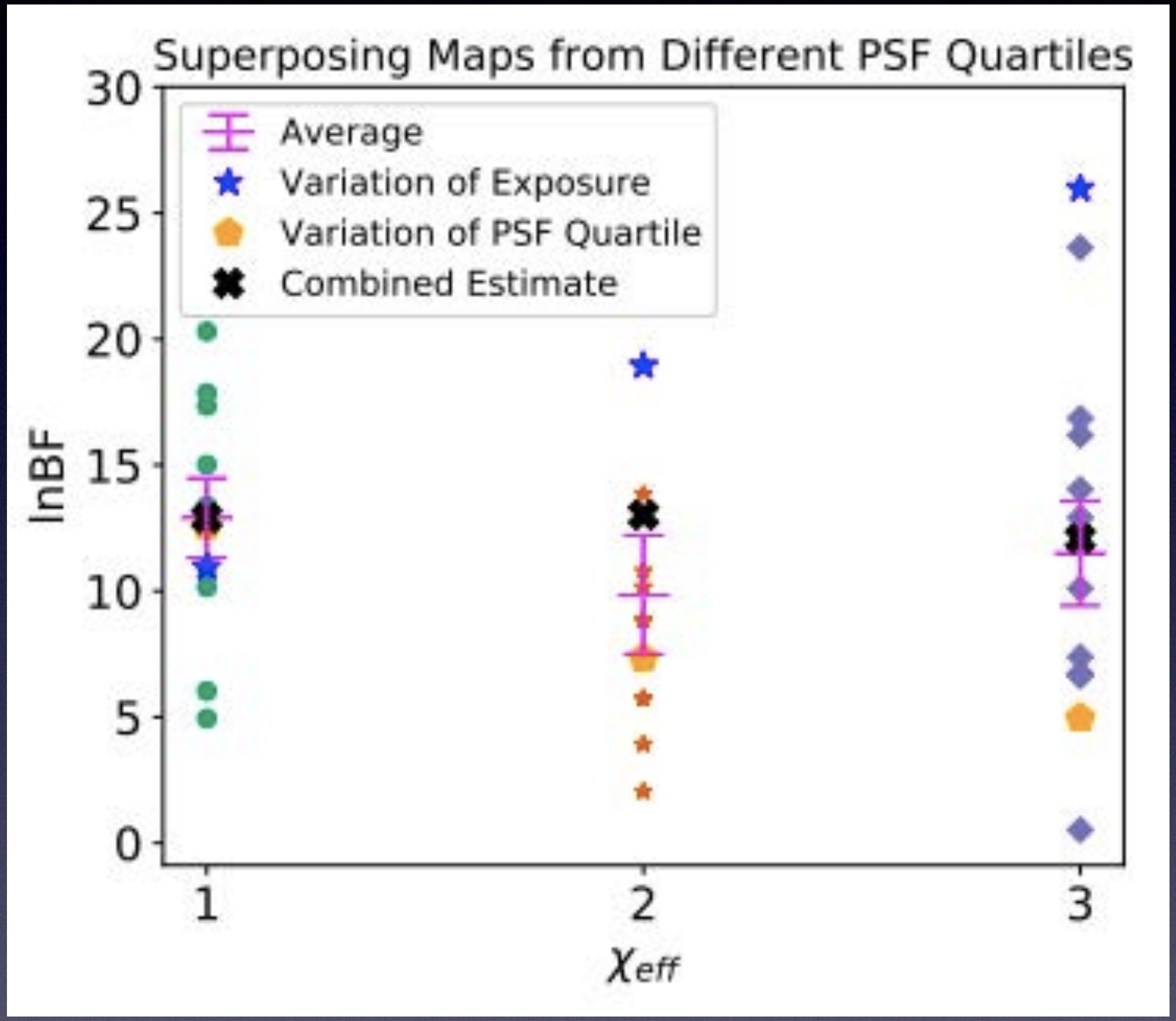
1-point PDF

Normalizing flows



How can we do better?

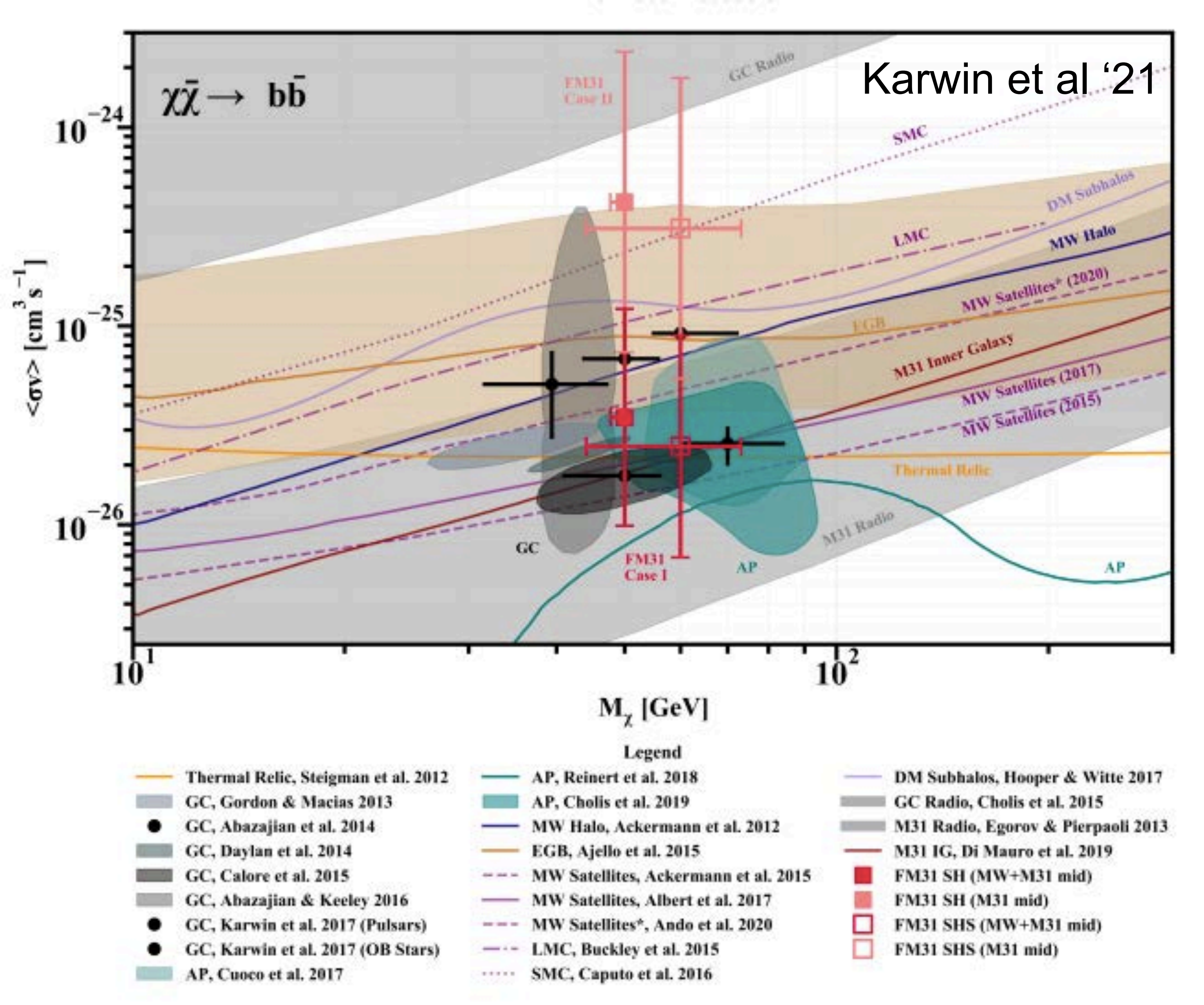
- Currently NN and NPTF methods discard the vast majority of the dataset - throwing out all photons below 2 GeV + also roughly 80% of photons >2 GeV (due to quality cuts)
- Bariuan & TRS '22: in naive/baseline NPTF method, relaxing cuts does not lead to gain in expected significance, due to worse angular resolution
- May be able to do better via simulation-based inference, avoiding assumption of a single angular resolution



- Simulation-based inference may also facilitate use of energy information
- Work in progress to use ML-based methods to better quantify uncertainties, understand degeneracy between modeling of different background/signal components

DM counterpart signals?

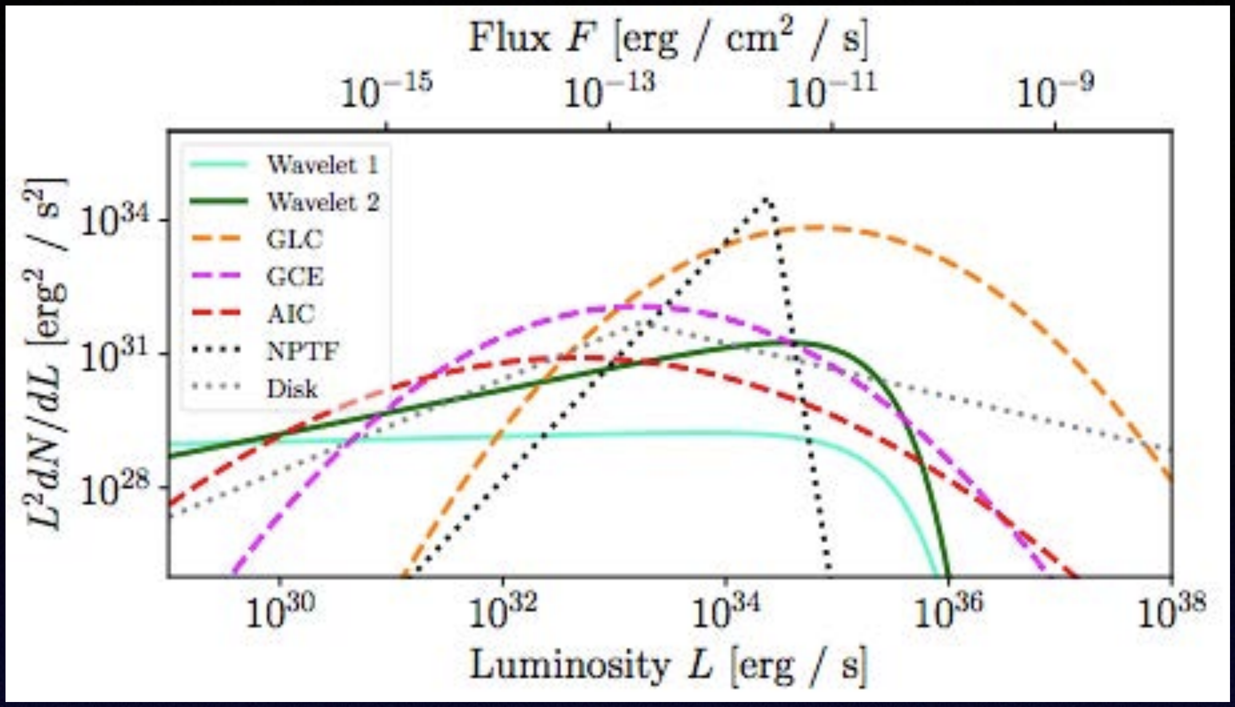
- The most model-independent limit would come from gamma-ray counterpart searches in other systems
- Cleanest are dwarf satellite galaxies - but sensitivity is not quite good enough for exclusion
- Depends on uncertainties in DM density in dwarfs - newer studies, e.g. Alvarez ’20, find weaker constraints than older limits, e.g. Keeley et al ’18
- Possible strong constraints from antiprotons and M31 radio - but there are claims of counterparts in those channels (and updates to M31 work give weaker limits, Egorov ‘22)



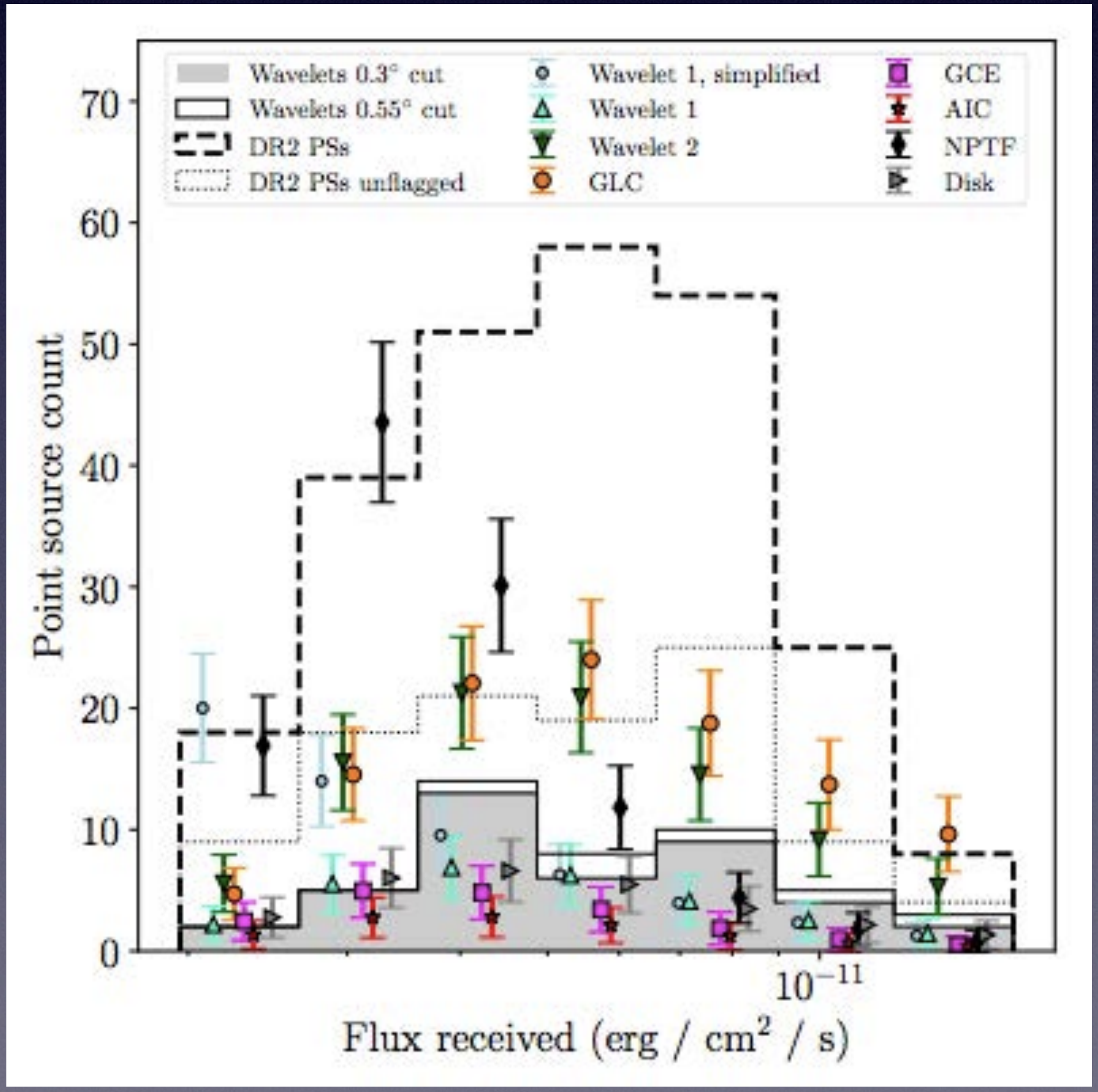
How plausible are pulsars?

- There has been considerable debate in the literature about the plausibility of the pulsar interpretation
- If many very faint sources are required, explaining how these are produced or accumulate in the inner Galaxy could be challenging
- A key question is the expected luminosity function - how many bright (potentially detectable) sources should be visible, compared to the number of fainter sources?
- Zhong et al '20 quoted an estimate of $\sim 3 \times 10^6$ pulsars to explain the whole excess, mostly very faint
- Earlier NPTF studies (e.g. Lee et al '16) found a preference for all sources to be ~at threshold, needing only O(1000) total

How many pulsars are needed?



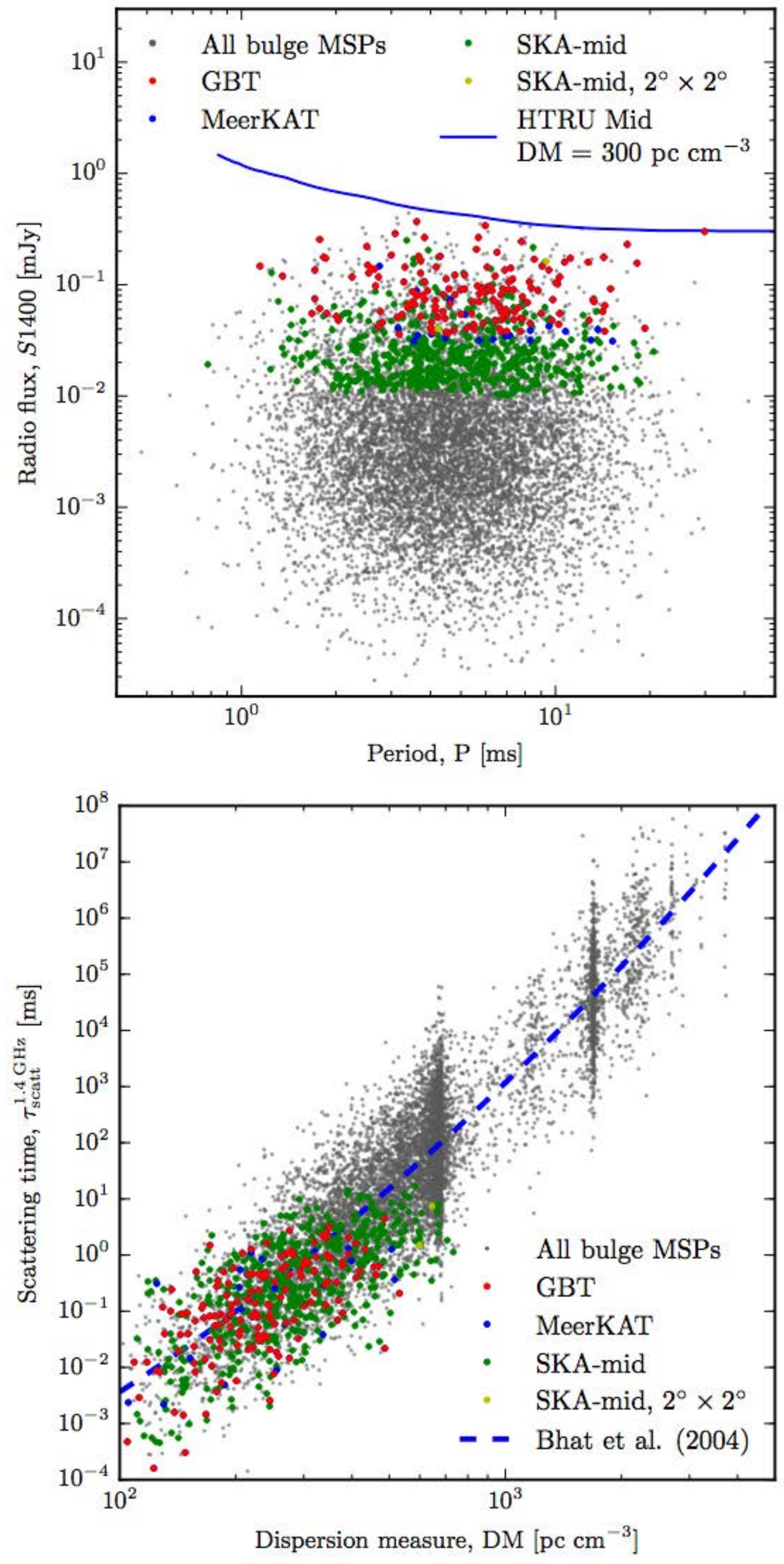
- We considered a range of luminosity functions from the literature
- Found there are simple luminosity functions predicting O(10,000) point sources and very few detected high-significance sources
- Original NPTF luminosity function seems in tension with data (newer background models prefer fainter sources)
- Improving sensitivity down to the one-photon level predicts resolving at least 30% of the excess for all our benchmarks (relevant for NN indication of O(30%) PS component?)



Dinsmore & TRS '22

Multiwavelength pulsar signals?

- Typically pulsars also emit in radio and X-ray (where we have better angular resolution) - for radio in particular, much larger expected # of photons, possibility to detect pulsations
- Could aim to cross-correlate detected pulsars in this region with gamma rays
- In radio, MeerKAT could see 10s of pulsars from this population, SKA hundreds [Calore et al '16]
- Berteaud et al '21 identifies X-ray sources for multiwavelength followup using Chandra data.



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 with more sophisticated methods & background modeling, that preference is now quite mild (~2 sigma detection of a PS component).
- The detailed morphology extracted for the GCE, which could help distinguish hypotheses, is quite sensitive to the choice of background model.
- Active work is in progress to improve both analysis methods for inner Galaxy gamma-rays and searches for counterparts at other wavelengths/locations.