## Characterizing Unresolved Point-Source Populations in the Inner Galaxy

**Introduction.** — There has been an extensive debate in the literature over the origins of the Galactic Center Excess (GCE), an extended and roughly spherically symmetric gamma-ray source filling the region within $\sim 1.5$ kpc of the Galactic Center (GC), with energy spectrum peaking at $1-3$ GeV [1–3]. The leading hypotheses are a new population of unresolved gamma-ray pulsars – individually too faint to be detected at high confidence, but in aggregate yielding the excess – or alternatively a signal from annihilating dark matter (DM). The latter explanation, if confirmed, would be of extraordinary importance for our understanding of the Universe, as the first non-gravitational probe of the properties of DM and its interactions with visible particles.

Populations of unresolved point sources (PSs) can potentially be distinguished from diffuse backgrounds, including DM annihilation, via photon statistics [4, 5]. Qualitatively, a population of sufficiently-bright unresolved PSs will generally have a greater probability to generate pixels with a large number of counts (due to the presence of one or more sources) or a very small number of counts (due to an absence of sources), compared to an extended diffuse source with the same overall expected number of photons. "Template fitting" methods, where the sky is modeled as a linear combination of components with distinct spatial morphologies, can be adapted to incorporate these differences in statistical behavior. Within this "non-Poissonian template fitting" (NPTF) approach [4–6], different components are characterized by (1) their overall spatial morphology, (2) whether they represent diffuse emission or populations of point sources, and (3) in the case of point source populations, a source count function (describing the probability that a source has a certain brightness). The normalizations and source count functions of the various components can then be reconstructed from a likelihood analysis (although populations of very faint sources, producing only $0-1$ photons per source, cannot be distinguished from diffuse emission). The code package `NPTFit` [7] is a publicly available NPTF implementation, suitable for use on *Fermi*-LAT gamma-ray data, which we have previously used extensively, and will employ to perform the analyses proposed below.

The PI has previously applied NPTF methods to the public *Fermi*-LAT gamma-ray data from the inner Galaxy, finding evidence for an unresolved Galactic PS population that is not spatially correlated with the Galactic disk or captured by existing catalogs [6]. If modeled as a PS template with the spatial morphology of the GCE, this population has a best-fit normalization consistent with describing the entire GCE, in preference to a (diffuse) DM annihilation template. We reproduce this result in the left panel of Fig. **??**.

However, the PI and Co-I have work in preparation [8] that demonstrates explicitly, using simulated mock data, that under certain circumstances it is possible for a purely diffuse GCE (e.g. from DM annihilation) to be incorrectly reconstructed as entirely comprised of PSs. In particular, a large negative bias to the DM template coefficient can occur if there is an unresolved PS population in the inner Galaxy that is *not* spatially correlated with the GCE. An example is shown in the central panel of Fig. **??**, where the simulated data includes a purely diffuse GCE and a population of unresolved PSs correlated with the *Fermi* Bubbles; the NPTF pipeline correctly identifies a PS population, but the PSs are attributed to the GCE, and the diffuse part of the GCE is incorrectly inferred to be zero.

Furthermore, we show that when an artificial DM annihilation signal of comparable size to the GCE itself is injected into the real *Fermi*-LAT data, the NPTF method generically fails to recover it [8], as demonstrated in the right panel of Fig. **??**. This behavior is not found in mock data when the templates used in the fit match those employed to generate the data, but can be qualitatively reproduced if there is an unresolved PS population in the inner Galaxy that is not coincident with the GCE, and is not correctly modeled in the fit.

These initial results suggest that a better understanding of faint PS populations in the inner Galaxy is necessary in order to reconstruct the true properties of the GCE – in particular, whether it originates from a diffuse source (such as DM) or a PS population. Such populations can be highly detectable and have large effects on interpretation of the data, even if the individual sources cannot be resolved at high significance. In recent years there has been a great deal of work to understand the spatial morphology of both the GCE and gamma-ray backgrounds in the inner Galaxy; however, these analyses have not incorporated the photon-statistics information captured by NPTF methods.

We propose an expanded study of faint PS populations in the inner Galaxy region using NPTF tools, with the goal of determining their morphology and contributions to the GCE. We will incorporate recent improvements in modeling of various backgrounds into the NPTF pipeline, and explore their effects. We will study in detail the potential for greater sensitivity from using photon classes with higher statistics but worse angular resolution. The principal deliverable of our work will be a map of the spatial distribution and source-count function of inferred sub-threshold PS populations in the inner Galaxy, complementing *Fermi*-LAT Collaboration efforts to catalogue bright sources that can be individually detected.

**Proposed work.** — *Model-Independent Analysis of PSs Within the GCE.* Firstly, we will attempt to model-independently determine which spatial regions drive the preference for PSs within the GCE. A recent analysis using wavelet techniques [9] has claimed that while there is excess small-scale power within the GCE, it is localized to particular subregions of the inner Galaxy. We will test this claim in the NPTF context by subdividing the GCE template to match the subregions of Ref. [9], and letting the template normalization and source count function vary independently between these subregions. If some limited set of these subregions drives the preference for PSs found in Ref. [6], one would expect to see the inferred source-count function and flux associated to PSs vary between subregions. Even if PSs are present in all subregions, this test could reveal a spatial gradient in the source count function, and/or a spatial distribution of PSs that differs from that of the GCE. Either could serve as inputs to an improved and more flexible analysis of the GCE.

*Tests for Physically Motivated PS Populations.* In addition to the model-independent analysis, we will test for PS populations associated with known physical features of the inner Galaxy, which could either contribute to the GCE or serve as backgrounds to it. For example, it has been suggested in the literature that the morphology of the GCE may correlate with features in the stellar bulge [10, 11], and there are hints that the *Fermi* Bubbles may contain small dense gas clouds that could potentially source small-scale power in gamma rays [12]. We will test for PS populations following these spatial distributions, both in addition to and as a replacement for the previously-used GCE template (which is spherically symmetric and has a power-law dependence on distance from the GC). In the case of the *Fermi* Bubbles, we will subdivide the Bubbles by latitude and examine whether there is a preference for PSs in any latitude band of the Bubbles.

If variation in the GCE PS population is detected, and/or there is significant evidence for unresolved PS populations associated with the stellar Bulge or the *Fermi* Bubbles, we will add one or more extra templates to incorporate this variation into our template-fitting procedure. We will then test for whether there is any preference for a smooth DM component in addition to the PS populations, and we will repeat the injection test described in the introduction, to determine whether this improved pipeline can successfully reconstruct injected diffuse signals.

*Determining the Optimal Dataset.* In the presence of many independently-varying components, statistical uncertainties will increase, making it increasingly important to exploit as much of the *Fermi*-LAT data as possible. To date, most NPTF analyses in the inner Galaxy have been performed with `ULTRACLEANVETO` data, retaining only the top quartile of the data in angular resolution, and discarding photons below 2 GeV, in order to optimize angular resolution and reduce possible systematic effects from cosmic-ray contamination (although a limited study using `SOURCE`-class data and three of the four PSF quartiles, focusing on high energies, was performed by the PI in Ref. [13]). There is thus great potential to increase the statistical power of the analysis by retaining a larger fraction of gamma rays.

We will study the sensitivity of the NPTF method as a function of photon statistics and angular resolution, to attempt to optimize the cuts on minimum energy, angular resolution, and analysis class. Our approach will be to create simulated data for a range of different normalizations and angular resolutions corresponding to the `SOURCE` through `ULTRACLEANVETO` analysis classes, while also varying the number of included PSF quartiles. We will also vary the low-energy cutoff in our simulations, down to 1 GeV. Within each simulation category, we will analyze the realizations with the NPTF pipeline, and determine which dataset is expected to yield the highest significance for faint PS populations.

This analysis will be valuable for any subsequent NPTF studies in the inner Galaxy, but we will first apply it to the tests described above, repeating them using the optimal dataset. We will validate our results against those obtained previously, including testing whether the uncertainties have decreased as expected from simulations.

*Modeling Diffuse Emission Systematics.* Diffuse backgrounds, from cosmic rays interacting with the gas and starlight, are the largest source of photons in the inner Galaxy, and systematics in their modeling can significantly affect the reconstructed properties of the GCE (e.g. [3]). Previous NPTF studies have tested the effect of using a range of models for the Galactic diffuse emission, and found little impact [6], but the true Galactic diffuse emission may not lie within the space of models that have been tested. If time permits, we will test the impact of changing the modeling of the *Fermi* Bubbles and Galactic diffuse emission, using templates derived in Ref. [3] and elsewhere. In particular, we will test in simulated data whether using an incorrect diffuse model can cause the NPTF pipeline to fail to correctly reconstruct an injected DM signal, as is observed in real data.

**Timeline and Summary.** — We will prioritize the first two tasks listed above, which we expect to be completed within the first six months of the project period. The combination of these two analyses will provide a map of regions with unresolved PS populations in the inner Galaxy, including either a detection or an upper limit for unresolved PSs spatially associated with the stellar Bulge and *Fermi* Bubbles. By the end of the project period, we expect to produce an improved version of this map with higher statistics, as well as guidance on the optimal analysis choices for studying the inner Galaxy with NPTF methods. We will also provide at least an initial analysis of the impact of changing the templates for diffuse backgrounds, although this aspect of the project has broad scope and may continue beyond the funding period. This research, if funded, will provide an important new characterization of faint PS populations in the inner Galaxy, with the potential to greatly enhance our understanding of the GCE and its origins.

**Management Plan.** — The requested funds will support CO-I Leane to work on this project for 0.5 FTE, at a total cost of $\$70,000$. PI Slatyer will contribute expertise and guidance at no cost.

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