GCE UROP Summary

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Abstract

convention in astrophysics is to capitalize "Galactic" when referring to our Milky Way galaxy

We examine a millisecond pulsar model for the galactic center excess and extract predictions for the total number of pulsars in the galactic center, the number that can be resolved by the *Fermi* Gamma-ray space telescope, and the fraction of resolvable luminosity for four luminosity functions found in the literature. We compare the latter two extracted values to observations. We perform the analysis for two models of the telescope's sensitivity: a step function probability of detection, and a more detailed, position-dependent model. Results depend strongly on the sensitivity model used, but no luminosity functions analyzed differed from the observables by more than a factor of ten.

"space telescope" should have initial capital letters

1 Introduction

It's actually been detected in at the GC as well, |b|<2^\circ, we just often mask the Galactic plane to reduce backgrounds. For a paper you would make sure to cite the discovery paper and other key results here.

The Galactic Center GeV Excess (GCE) is an unexpected source of gamma radiation originating from the center of the Milky Way, detected recently by the *Fermi* Gamma-ray Space Telescope in the region $2° < |b| < 20°$ and $|\ell| < 20°$ [1]. Its origin is debated; the GCE holds potential to be the first evidence observed for dark matter annihilation, yet several studies have also shown that point sources such as millisecond pulsars (MSPs) may be responsible for the excess. add references

Previous work has interpreted this MSP model. Ref. [1] has proposed an exponentially damped power-law luminosity function

should be exp(-L/Lmax) right?

text subscripts in LaTeX are often wrapped in \text{} to stop them from being italicized by mathmode

$$\frac{dN}{dL} = L^{-\alpha} \exp\left(\frac{L}{L_{max}}\right) \left[\Gamma\left(1-\alpha, \frac{L_{min}}{L_{max}}\right) L_{max}^{1-\alpha}\right]^{-1}, \tag{1}$$

restricting the range of luminosities to $[L_{min}, \infty)$, where L_{min}, L_{max}, and α are free parameters. This reference found that $(1 \times 10^{29} \frac{\text{erg}}{\text{s}}, 1 \times 10^{35} \frac{\text{erg}}{\text{s}}, 1.94)$ reproduced observations. It assumed a step-function model of *Fermi*'s sensitivity, where all the MSPs with luminosity $L > L_{th}$ are observed and those with $L < L_{th}$ are not, where the threshold luminosity was fixed at $L_{th} = 10^{34} \frac{\text{erg}}{\text{s}}$. They find three million MSPs in the GCE.

I would probably reword to something like "They find that this luminosity function requires three million MSPs to explain the GCE". Would eventually be good to have a brief comment on the approximate number of MSPs expected in our Galaxy

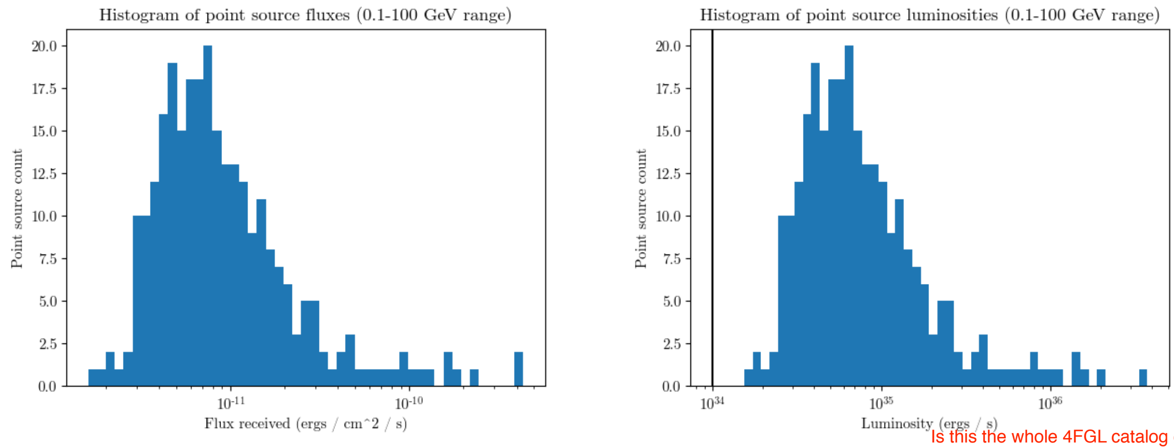
Ref. [2] proposes a luminosity function of

$$\frac{dN}{dL} = \frac{\log_{10} e}{\sigma\sqrt{2\pi}L} \exp\left(-\frac{(\log_{10} L - \log_{10} L_0)^2}{2\sigma^2}\right), \tag{2}$$

where L_0 and σ are free parameters. It fits this model to globular cluster data, yielding values $L_0 = 8.8 \times 10^{33} \frac{\text{erg}}{\text{s}}$ and $\sigma = 0.62$. It predicts thousands of MSPs to occupy the GCE.

Just to check, is Ref. [3]'s globular cluster MSP luminosity function very different from Ref [2], or is this just saying that GCE and globular clusters can be captured within the same model but with different parameters?

Ref. [3] proposes several more intricate luminosity functions derived from a model of the pulsars themselves. They fit the model to the observed GCE spectrum, and find that no properties of GCE MSPs are required to reproduce the excess that are not present in globular cluster MSPs. We use their luminosity function generated for the galactic disk. It closely resembles a log-normal luminosity function as in equation 2, where $L_0 = 1.61 \times 10^{32} \frac{\text{erg}}{\text{s}}$ and $\sigma = 0.700$.



Is this the whole 4FGL catalog or just those in the ROI?

Figure 1: *Left*: Distribution of fluxes observed per resolved point source in the 4FGL catalog. *Right*: Flux shown in *Left* converted to luminosity, assuming that all the point sources are located at the galactic center at $r_c = 8.5\,\mathrm{kpc}$. The black line is the $L_{th} = 1 \times 10^{34}\,\frac{\mathrm{erg}}{\mathrm{s}}$ sensitivity threshold used in ref. [1].

Finally, ref. [4] proposes a broken-power-law luminosity function of

$$\frac{dN}{dL} = \left(\frac{(1-n_1)(1-n_2)}{L_b(n_1-n_2)}\right)\begin{cases}(L/L_b)^{-n_1} & L < L_b \\ (L/L_b)^{-n_2} & L > L_b\end{cases} \tag{3}$$

where the free parameters n_1, n_2, and L_b were found via a Non-Poissonian Template Fitting model (NPTF) to be $(18.2, -0.66, 1.76 \times 10^{-10}\,\frac{\mathrm{photon}}{\mathrm{cm^2\,s}})$ for an NFW-distributed population of MSPs named NFW PS. The paper proposes a second luminosity function named Disk PS, which is unnormalizable except when a minimum luminosity of pulsars L_{min} is introduced. For the purpose of this paper, we set $L_{min} = 1 \times 10^{29}\,\frac{\mathrm{erg}}{\mathrm{s}}$, which is the same minimum pulsar luminosity used by ref. [1].

should explain what NFW means, and strictly the distribution is NFW^2 not NFW - you explain this later but maybe move it up

This UROP seeks to better understand the MSP model ~~to~~ for the GCE by extracting the total number of MSPs in the GCE (N), the number resolvable with *Fermi* (N_r), and the fraction of GCE luminosity emitted by resolved point sources (R_r). Observed values are $N_r \leq 47$ and $R_r \leq 0.2$ [1].

For the purposes of this summary, we will take the GCE spectrum to be between 0.1 and 100 GeV, as in [2]. We take the total luminosity to be $L_{GCE} = 6.756 \times 10^{36}\,\frac{\mathrm{erg}}{\mathrm{s}}$, which was obtained from ref. [1]'s value of $L_{GCE} = 6.37 \times 10^{36}\,\frac{\mathrm{erg}}{\mathrm{s}}$ for a range of 0.275 to 51.9 GeV, and extrapolating it using the power-law fit to the spectrum of the GCE produced in ref. [5]. Good, this is clear, thanks

2 Methods

We will use two models for *Fermi*'s sensitivity to generate predictions of N, N_r, and R_r for each luminosity model. The first is a step-function model like those used in [1, 2], and the second is a more detailed, position-dependent model.

For the first, step-function model, we assumed that all pulsars with luminosity $L < L_{th}$ were unresolvable, and all with $L > L_{th}$ were resolved, with threshold luminosity $L_{th} = 10^{34}\,\frac{\mathrm{erg}}{\mathrm{s}}$ as used in ref. [1]. A slightly higher value of L_{th} may be more accurate, as shown by the flux distribution of resolved point sources obtained from the 4FGL data release [6, 7]. See fig. 1.

For the second, position-dependent sensitivity model, we obtained a map of position-dependent thresholds given as flux values from the same source [6, 7] (see figure 2) and assumed that the MSPs are

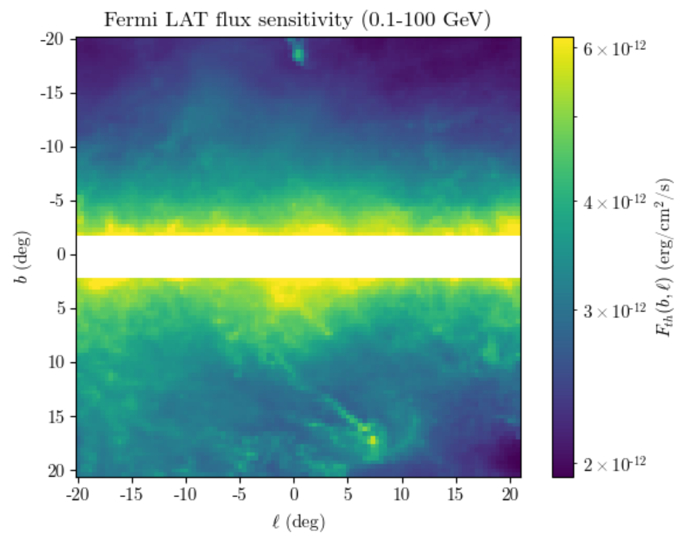


Figure 2: Position-dependent flux values per point source necessary in order to resolve the point source. A GCE location of $2° < |b| < 20°$, $|\ell| < 20°$ is shown.

distributed according to the square of an NFW profile of $\rho_{NFW} \propto (r/r_s)^{-\gamma}(1 + r/r_s)^{-3+\gamma}$ where $\gamma = 1.2$ and $r_s = 20\,\text{kpc}$. Using an arbitrary normalized luminosity function $P(L)$, the total number of pulsars in the GCE is given by

$$N = \int_{-20°}^{20°} \cos b db \int_{-20°}^{20°} d\ell \int_0^\infty s^2 ds A\rho_{NFW}^2(r). \tag{4}$$

where the third integral is taken along the line of sight, with $r^2 = r_c^2 + s^2 - 2r_c s \cos b \cos \ell$, where $r_c = 8.5\,\text{kpc}$ is the distance to the galactic center. Here, A is the constant of proportionality of ρ_{NFW}^2, which is fixed by setting the total flux of the GCE

$$F = \int_{-20°}^{20°} \cos b db \int_{-20°}^{20°} d\ell \int_0^\infty s^2 ds A\rho_{NFW}^2(r) \frac{1}{4\pi s^2} \int_{L_{min}}^{L_{max}} LP(L)dL. \tag{5}$$

equal to the observed value F_{GCE}. Then the number of resolved MSPs and resolved flux can be calculated respectively as

$$N_r = \int_{-20°}^{20°} \cos b db \int_{-20°}^{20°} d\ell \int_0^\infty s^2 ds A\rho_{NFW}^2(r) \int_{L_{th}(b,\ell)}^{L_{max}} P(L)dL. \tag{6}$$

$$F_r = \int_{-20°}^{20°} \cos b db \int_{-20°}^{20°} d\ell \int_0^\infty s^2 ds A\rho_{NFW}^2(r) \frac{1}{4\pi s^2} \int_{L_{th}(b,\ell)}^{L_{max}} LP(L)dL. \tag{7}$$

Clarify if you use this same prescription for position-independent sensitivity, just with constant F_th

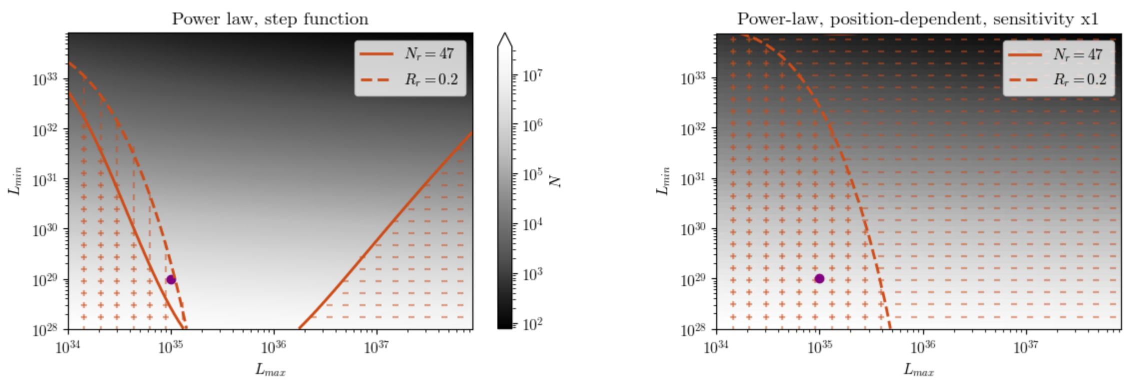
with the ratio of resolved flux to total flux being $R_r = F_r/F$. Note that L_{th} in the above equations was given by $L_{th}(b,\ell) = 4\pi s^2 F_{th}(b,\ell)$, where $F_{th}(b,\ell)$ was given in the sensitivity map (figure 2).

We calculated the observed flux of the GCE F_{GCE} from the observed luminosity L_{GCE} by assuming an NFW-distributed population of N MSPs, all with the same luminosity $L = L_{GCE}/N$, yielding a flux of

$$F_{GCE} = \frac{L_{GCE}}{4\pi} \left[\int_{-20°}^{20°} \cos b db \int_{-20°}^{20°} d\ell \int_0^\infty ds \rho_{NFW}^2(r)\right] \left[\int_{-20°}^{20°} \cos b db \int_{-20°}^{20°} d\ell \int_0^\infty s^2 ds \rho_{NFW}^2(r)\right]^{-1} \tag{8}$$

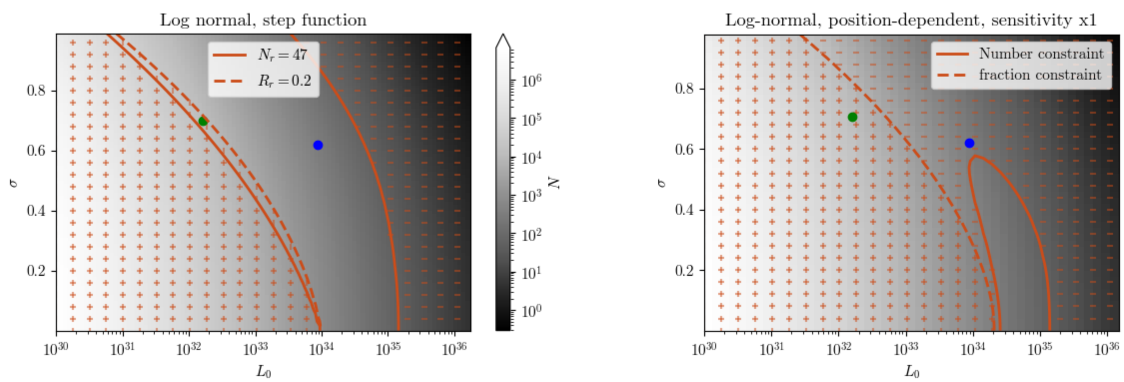
via equations 4 and 5. The calculated value for $L_{GCE} = 6.756 \times 10^{36}\,\frac{\text{erg}}{\text{s}}$ was $F_{GCE} = 7.631 \times 10^{-10}\,\frac{\text{erg}}{\text{cm}^2\,\text{s}}$.

OK, I think I understand a question you asked earlier now. This would be correct if both the flux and luminosity were measured within this ROI. If people are instead quoting the luminosity over the whole GCE (but the flux just in some 2D spatial window), then it would change the limits of integration for the luminosity integral in the denominator. So we'd need to check what they mean by the total GCE luminosity.



Have you tried scanning over alpha while fixing Lmin or Lmax? Also, is the point from (4) shown?

(a) Power law luminosity functions. The purple point is the configuration identified in ref. [1]: $L_{min} = 1 \times 10^{29}\ \frac{\text{erg}}{\text{s}}$, $L_{max} = 1 \times 10^{35}\ \frac{\text{erg}}{\text{s}}$.



I really like this way of depicting the allowed regions, much clearer

(b) Log normal luminosity functions. The blue point is the configuration identified in ref. [2]: $L_0 = 8.8 \times 10^{33}\ \frac{\text{erg}}{\text{s}}$, $\sigma = 0.62$, and the green point is a fit to the luminosity function found in ref. [3]: $L_0 = 1.61 \times 10^{32}\ \frac{\text{erg}}{\text{s}}$, $\sigma = 0.700$.

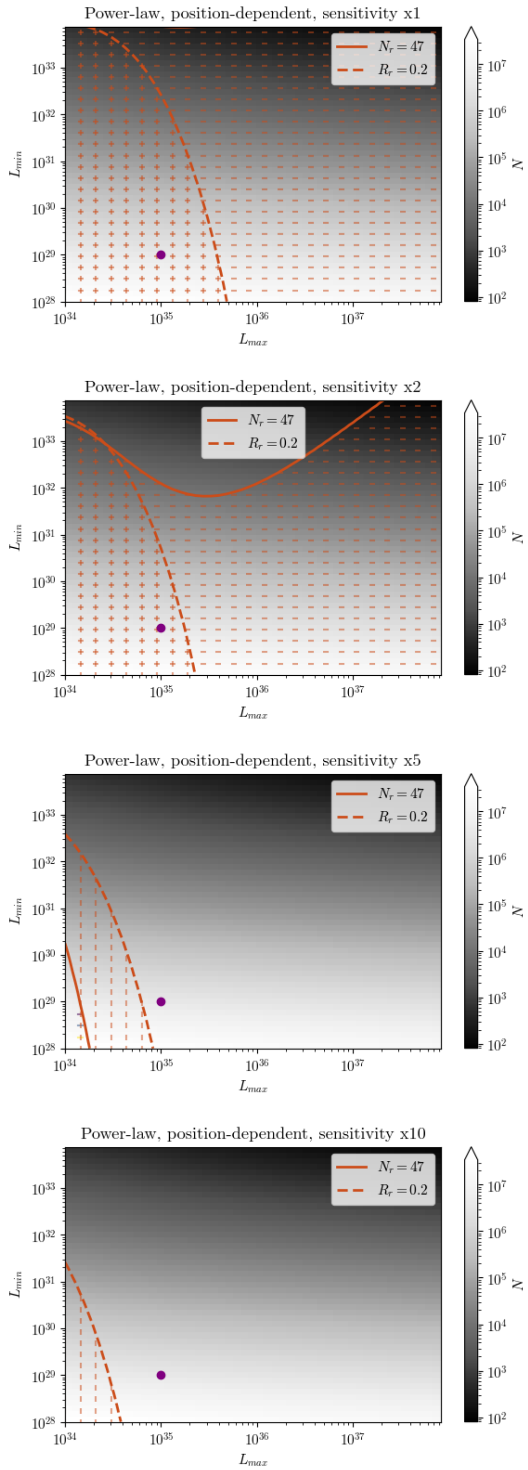
Figure 3: Predicted number of MSPs N plotted for different configurations of luminosity functions, with the $N_r = 47$ constraint and the $R_r = 0.2$ constraint superimposed. *Left*: The step-function sensitivity model was used, with $L_{th} = 10^{34}\ \frac{\text{erg}}{\text{s}}$. *Right*: The position-dependent sensitivity model was used. The - shading represents configurations that satisfy the number constraint $N_r < 47$, while the | shading represents those with $R_r < 0.2$. The + shading represents both.

3 Results

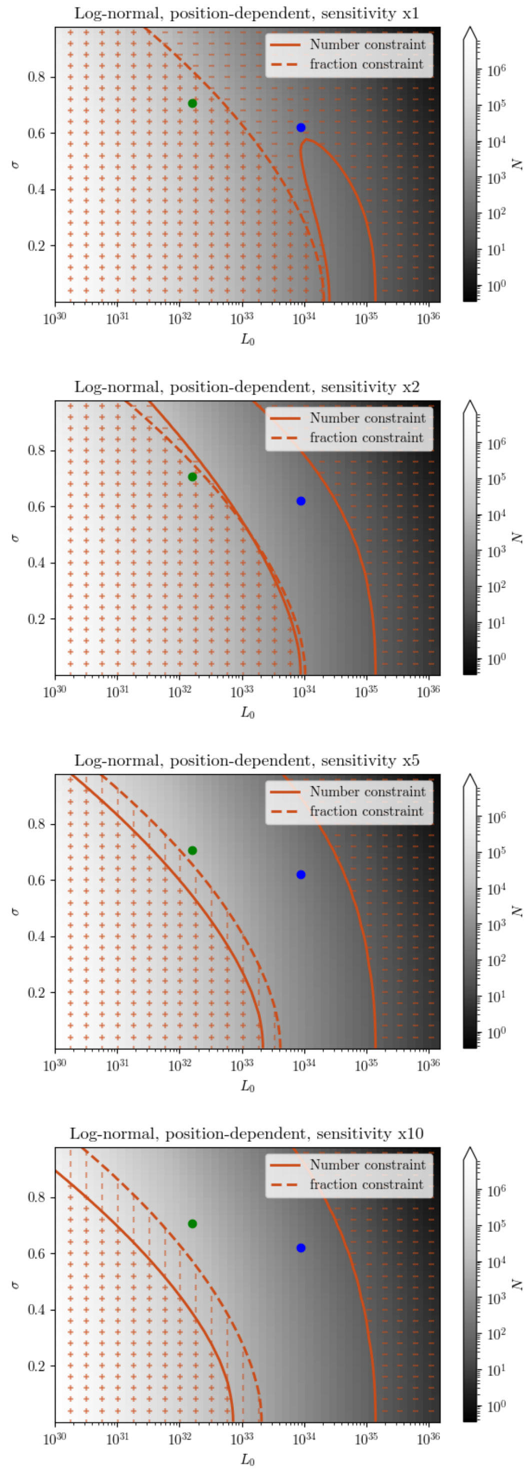
For each of the luminosity functions described above, we calculated N, N_r, and $R_r = F_r/F$ using both the step-function sensitivity model and the position-dependent model. Results are displayed in table 1.

Since the power-law and log-normal luminosity function models form a two-dimensional space of functions, parameterized by (L_{min}, L_{max}) and (L_0, σ) respectively (we keep $\alpha = 1.94$ for the power-law), we may display the predicted number of pulsars for all configurations, and superimpose the two observational constraints: $N_r = 47$ and $R_r = 0.2$. This is done using the step-function sensitivity model and the position-dependent sensitivity model in figure 3.

For the position-dependent sensitivity, we can easily simulate the power of a more advanced, next-generation gamma ray telescope by dividing the sensitivity per pixel provided by refs [6, 7] by some position-independent constant. This was done for a 2-, 5-, and 10-times improvement in sensitivity for both the power-law and the log-normal luminosity functions, and is shown in figure 4.



(a) Power law luminosity functions



(b) Log normal luminosity functions

This is really interesting! It's interesting that which constraint dominates varies with sensitivity (although I think that makes sense).

Figure 4: Predicted number of MSPs over the space of power-law and log-normal luminosity functions, and different sensitivities of the telescope, with current observational constraints superimposed.

Using the position-dependent sensitivity model, the predicted number of pulsars is largely unchanged as expected, but the observational constraints differ greatly from the step-function sensitivity model.

Luminosity function	N	N_r	R_r
Observations	-	47	0.2
Ref. [1]: Power-law	3.54×10^6	50.0	0.193
Ref. [2]: Log-normal	277	129	0.910
Ref. [3]: Custom	8.76×10^3	54.5	0.355
Ref. [3]: Log-normal fit	1.14×10^4	59.7	0.171
Ref. [4]: Broken power-law, NFW PS	1.23×10^3	4.41	6.94×10^{-3}
Ref. [4]: Broken power-law, Disk PS	1.21×10^4	92.1	0.880

(a) Results for a step-function sensitivity model with $L_{th} = 10^{34} \, \frac{\text{erg}}{\text{s}}$

I don't understand why the broken power-law NFW PS gives a larger fraction above threshold with the position-dependent threshold (which is generally higher) - check this?

Also surprised by the huge difference between Ref. 3 custom and log-normal fit in R_r given that N_r is pretty similar

Also the number of pulsars needed for the NFW PS is higher (by a factor of a few) than found in 1506.05124; double-check the energy window conversion and ROI have been treated correctly

Finally, we should include the delta-function estimate you did early on, about the absolute minimum number of pulsars needed to explain the GCE consistent with constraints

Luminosity function	N	N_r	R_r
Observations	-	47	0.2
Ref. [1]: Power-law	3.42×10^6	10.2	0.101
Ref. [2]: Log-normal	268	44.8	0.692
Ref. [3]: Custom	8.48×10^3	9.66	0.266
Ref. [3]: Log-normal fit	1.11×10^4	7.76	0.0648
Ref. [4]: Broken power-law, NFW PS	1.19×10^3	4.06	0.0283
Ref. [4]: Broken power-law, Disk PS	1.17×10^4	42.1	0.751

(b) Results for a position-dependent sensitivity function

Table 1: Predictions for N, the total number of MSPs required to make up the GCE; N_r, the number of resolvable MSPs; and R_r, the fraction of luminosity that comes from resolved sources. The luminosity functions used are those proposed by the various references cited. For the final luminosity function, a cutoff value of $L_{min} = 1 \times 10^{29} \, \frac{\text{erg}}{\text{s}}$ was used so that the function would be normalizable. The observed values are discussed in ref. [1].

4 Conclusion

An excess of gamma rays in the galactic center suggests an undiscovered population of millisecond pulsars. Several luminosity functions found in the literature were examined for the number of MSPs they predict to inhabit the galactic center; the result depends strongly on the type of luminosity function used. Luminosity functions fit to globular clusters, not GCE data, tend not to reproduce observational values of the number of resolved pulsars and the fraction of GCE luminosity emitted from them.

A more detailed sensitivity model was applied to these luminosity functions, and the result was found to drastically alter the predicted number of resolvable pulsars and the fraction of luminosity emitted from them.

Potential future steps include to predict the observables attainable assuming a higher sensitivity, to simulate a next generation gamma ray telescope, or extending the analysis to search for complementary radio wave signals from MSPs.

References

[1] Y. Zhong, S. McDermott, I. Cholis, P. Fox. "A New Mask for An Old Suspect: Testing the Sensitivity of the Galactic Center Excess to the Point Source Mask." arXiv:1911.12369v (2019).

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[7] S. Abdollahi et al. "*Fermi* Large Area Telescope Fourth Source Catalog" *ApJS* (2020).