Comment on ”Understanding the γ-ray emission from the globular cluster 47 Tuc: evidence for dark matter?”

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In a recent paper Ref. [1] analyzed the spectral properties of the globular cluster 47 Tucanae (47 Tuc) using 9 years of Fermi-LAT data. Ref. [1] argues that the emission from 47 Tuc cannot be explained by millisecond pulsars (MSPs) alone because of a significant discrepancy between the MSP spectral properties and those of 47 Tuc. It is argued that there is a significant (> 5σ) preference for a two source scenario. The second component could be from the annihilation of dark matter in a density spike surrounding the intermediate-mass black hole candidate in 47 Tuc. In this paper we argue that the claimed discrepancy arises because Ref. [1] uses a stacked MSP spectrum to model the emission from MSPs in 47 Tuc which is insufficient to account for the uncertainties in the spectrum of the MSPs in 47 Tuc. Contrary to the claims in Ref. [1], we show that the significance of an additional dark matter component is < 2σ when sample variance in the spectrum of a population of MSPs is accounted for. The spectrum of 47 Tuc is compatible with that of a population of MSPs similar to the disk population.

I. INTRODUCTION

Globular clusters (GCs) are old (∼ 10 Gyr) systems typically hosting a sizable population of millisecond pulsars (MSPs). γ-ray emission from GCs is expected to be dominated by their MSP population [2]. For certain GCs the γ-ray emission can receive a large contribution from only one or a few pulsars [3,5]. On the other hand, for 47 Tuc the γ-ray emission appears to arise from a larger number of MSPs [6].

In a recent paper, Ref. [1] analyzed the γ-ray emission from 47 Tuc using 9 years of Fermi-LAT data. The obtained spectrum of 47 Tuc is then compared to the stacked MSP spectrum from Ref. [7]. It is argued that the stacked MSP spectrum provides a poor fit to the data and a second emission component is required. Ref. [1] then includes a dark matter (DM) signal, χχ → bb, which could arise from annihilation of dark matter in a density spike around the candidate intermediate-mass black hole present in 47 Tuc[1]. The combined DM + MSP model significantly improves the fit to the spectrum of 47 Tuc by a ∆TS = 40 compared to stacked MSPs only. This discrepancy between the observed spectrum of 47 Tuc and that of stacked MSPs is then interpreted as possible evidence for DM within a globular cluster [1]. It is pointed out by Ref. [1] that since the stacked spectrum of MSPs is determined from observations of local MSPs, the conclusions could be altered if the spectral properties of MSPs in 47 Tuc differ from those of the local population. However, based on the comparison of disk and GC MSPs at other wavelengths the authors deem this unlikely [1,6,8,9].

In this paper, we show that the spectrum of 47 Tuc is well explained by a population of MSPs with similar properties to the MSPs in the disk, contrary to the conclusions of Ref. [1]. Our argument relies on the fact that the stacked MSPs spectrum used by Ref. [1] does not adequately represent the uncertainty in the spectrum of the MSP population in 47 Tuc. When these uncertainties are accounted for the significance of the need for a second emission component drops drastically. Consequently, there is no discrepancy between the spectrum of 47 Tuc and that of a population of MSPs, and thus no potential evidence for dark matter.

II. METHODS

We wish to assess the probability of obtaining data as extreme of more extreme as that observed when considering the MSP only hypothesis. In this way we can assess whether there is a significant hint of a DM signal in the γ-ray spectrum of 47 Tuc. For this purpose, we simulate 10^4 mock γ-ray spectra representative of 47 Tuc assuming all emission arises from MSPs. For consistency with Ref. [1] we assume that the characteristics of the MSPs in 47 Tuc are similar to those in the Galactic disk. First, we sample MSPs until we saturate the luminosity of 47 Tuc (L47Tuc = (6.45 ± 0.19) × 10^{34} erg s^{-1}) from 0.1–100 GeV (note that the luminosity of 47 Tuc is comparable to that of the brightest MSPs). Luminosities are drawn randomly from the best-fit lognormal luminosity function for disk MSPs obtained by Ref. [10], \( dN/L \propto L^{-1} \exp \left[ - \frac{(\log_{10} L - \log_{10} L_0)^2}{2\sigma_L^2} \right] \), with \( \sigma_L = 0.63 \) and \( L_0 = 4.1 \times 10^{32} \text{erg s}^{-1} \) [11]. We then assign each MSP a spectrum, which is sampled with replacement from the spectra of the 39 MSPs in the second Fermi-LAT catalog of γ-ray pulsars (2PC) [12].
For maximum consistency we use the spectra as derived by Ref. [7]. We note that there is no obvious correlation between the γ-ray spectra and the MSP luminosity, justifying our choice to sample spectra and luminosities independently. However, for completeness we mention that assigning to each spectrum the corresponding luminosity from the 2PC (determined using distance proxies as in Ref. [10]), rather than a random luminosity, does not alter the results discussed below.

After having created $10^4$ representative γ-ray spectra of the MSP population in 47 Tuc we fit these mock spectra with (i) the stacked MSP spectrum from Ref. [7], and (ii) including an additional dark matter spectrum corresponding to a 34 GeV particle annihilating into $b\bar{b}$ [13]. This analysis is similar to what has been performed by [1] on the true spectrum of 47 Tuc. Our mock data, representing random MSP populations that could be present in 47 Tuc, allows us to study how likely it is that we find a preference for a DM component when fitting this population with the stacked MSP spectrum from Ref. [7]. In order to test by how much an additional DM component improves the fit over a stacked MSP spectrum only, we perform a Gaussian likelihood analysis minimizing the $\chi^2$ test statistic: 

$$\chi^2 = \sum_{i}^{N}(\mu_{i} - E^2 dN/dE|_{i,M,C})^2/\sigma_{i}^2.$$  

Here the data points $(dN/dE|_{i,M,C})$ come from our Monte-Carlo realizations of MSP populations and the errors ($\sigma_i$) are chosen such that the fractional errors are identical to those in Fig. 1 from Ref. [1] (also see Fig. 1 of this work). The expectation ($\mu$) refers to (i) the stacked MSP spectrum, or (ii) the stacked MSP + DM spectrum for a 34 GeV particle annihilating into $b\bar{b}$. We sum over all bins with the exception of those containing an upper-limit, i.e. $N = 11$. Models are compared by computing $\Delta T S$. Applying this analysis to the actual data from 47 Tuc instead of simulated data, yields $\Delta T S = 36$. We thus agree with Ref. [1] that there appears to be a significant discrepancy when the stacked MSP spectrum is used to fit the emission from 47 Tuc (see Fig. 1).

We note that $\Delta T S = 36$ obtained in this work is slightly smaller than that obtained by Ref. [1] ($\Delta T S = 40$). Most likely this is due to a number of differences in the analyses. Ref. [1] uses 10 logarithmic bins per decade, instead of the 5 logarithmic bins per decade used in this work. Moreover, Ref. [1] fit the MSP and MSP + DM spectra to 47 Tuc using the Fermi Science Tools [14], whereas we perform a Gaussian likelihood analysis using the (simulated) spectrum of 47 Tuc directly. However, since the difference in $\Delta T S$ obtained for the spectrum of 47 Tuc between our work and that of Ref. [1] is small, we do not expect any qualitative effect on the conclusion of this work due to differences in the analyses.

### III. RESULTS

On average our realizations of 47 Tuc contain $\mathcal{O}(50)$ MSPs, but this can differ by a factor $\sim 2$ for individual realizations. These numbers are compatible with the observed number of MSPs in 47 Tuc [15]. Half of the flux is typically contributed by the 5 brightest sources. In Fig. 1 we show the spectrum of 47 Tuc as derived by Ref. [1] (black errorbars) and the MSP spectra derived in our simulations (green). The dark green line is the median, with the dark (light) green band representing the 68% (95%) containment interval. Within errors, the simulated MSP spectra agrees with the observed spectrum in 47 Tuc. For reference we also show the best-fit stacked MSP spectrum (solid red). The black solid line shows the best-fit stacked MSP (dashed red) + DM spectrum (dashed blue) spectrum.

Figure 2 shows the p-value for a particular $\Delta T S$ improvement in the fit to the mock spectra of 47 Tuc when a dark matter component, characterized by $M_{DM} = 34$ GeV and annihilation into $b\bar{b}$, is included on top of the stacked MSP spectrum from Ref. [7]. The results can be interpreted in a frequentist fashion. Let the null hypothesis ($H_0$) be MSPs only. The alternative hypothesis ($H_1$) represents a need for dark matter with fixed mass. We choose between the two models by fitting a stacked MSP spectrum and the same spectrum plus a DM signal to the data. Ref. [1] reports $\Delta T S = 40$ for the data from 47 Tuc. From Fig. 2 we find that this corresponds to a p-value of $p = 0.09$ (solid green line), or 1.3σ [16]. In other words, there is no significant evidence for an additional, DM-like, component.

We repeated the above exercise only sampling spectra from the 16 brightest sources, which have a flux $F \geq 2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ above 100 MeV. For the brightest sources we expect the most accurate determination of the
FIG. 2. p-value for a particular $\Delta TS$ when a DM signal, corresponding to a 34 GeV particle annihilating to $b\bar{b}$, is included on top of the stacked MSP spectrum of Ref. [7]. The green line is for our benchmark simulation in which we sample luminosities from a log-normal luminosity function [10] and spectra are drawn from the 39 sources in the 2PC [7]. The dotted-blue line is derived only sampling spectra from the brightest sources. Then dotted-magenta line corresponds to a scenario in which no single MSP contributes more than 10% to the total flux of 47 Tuc. Finally, the black-dashed horizontal lines correspond to 1, 2, 3.$\sigma$.

Our analysis shows that a stacked MSP spectrum, as applied by Ref. [1], is insufficient to account for the variation in spectra that can come from different MSP populations. We have shown that in case of the data of 47 Tuc an additional DM component is not required. Finally, we note that we fixed the dark matter mass to 34 GeV. Letting the mass float can only shift the lines in Fig. 2 further to the right and thus would imply even larger p-values for $\Delta TS$, strengthening our conclusions.

IV. CONCLUSION

We simulated mock data for a population of MSPs, with characteristics similar those in the Milky-Way disk, representative of that in 47 Tuc. It was shown that if the spectra of these populations are fit with the stacked MSP spectrum from Ref. [7] an additional DM spectrum corresponding to $M_{DM} = 34$ GeV and annihilation into $b\bar{b}$ typically improves the fit, because the stacked MSP spectrum does not capture the variation in the spectra of different MSP populations. Using our simulations we were able to assign a p-value to findings of Ref. [1], who found $\Delta TS = 40$ improvement when including DM, instead of a stacked MSP spectrum only, in a fit to the actual spectrum of 47 Tuc. We find that under all circumstances $\Delta TS = 40$ has a high-probability of occurring and does not imply potential evidence for an additional spectral component ($\lesssim 2\sigma$). Rather, the discrepancy claimed by Ref. [1] arises because they represent the MSP-induced $\gamma$-rays in 47 Tuc by a stacked spectrum of MSPs. Stacked spectra are constructed to provide a proper fit to all MSP spectra simultaneously [7], but do not necessarily reflect accurately the total emission from a population of MSPs, which can show large variations even when coming from a few dozen of sources. We conclude that there is no evidence for dark matter from the globular cluster 47 Tuc.

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