Upgrading the Gamma-ray Pulsar Timing Array: Data Release 2

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The merger of supermassive black hole binaries across cosmological time is expected to fill the universe with a low-frequency (nHz) gravitational wave background (GWB), which can be detected with pulsar timing arrays (PTAs), ensembles of precisely monitored millisecond pulsars (MSPs). Recently, PTAs that use large radio telescopes have published evidence consistent with such a background, with a dimensionless amplitude of $A_{\mathrm{gwb}} \sim 2.5 \times 10^{-15}$. In previous work we have developed and presented a Gamma-ray Pulsar Timing Array (GPTA), a complementary approach that uses the *Fermi* Large Area Telescope (LAT) to monitor MSPs. The smaller collecting area of the LAT is balanced by much simpler noise models, reduced systematic uncertainties, and access to different MSPs than are used in radio PTAs. Here, we present preliminary results from the second data release, DR2, of the GPTA. We have increased the set of monitored MSPs from 35 to 57 and the data span from ~12.5 yr to 14.5 yr, and we have implemented improved models of the γ-ray pulse profiles. With the preliminary DR2, we find a 95% confidence upper limit on the GWB amplitude that has decreased from the DR1 result $A_{\mathrm{gwb}} < 10 \times 10^{-15}$ to about $A_{\mathrm{gwb}} < 6.7 \times 10^{-15}$.

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1. Introduction

Pulsars [1] are spinning, highly-magnetized neutron stars capable of accelerating of particles to ultrarelativistic energies. Beams of broadband radiation from these particles extend from radio to $>10\,\mathrm{GeV}$ γ rays and cause the eponymous pulsing phenomenon as stellar rotation sweeps them repeatedly over the Earth. Energy loss slows the rotation, but in some binaries that survive the initial supernova, subsequent evolution of and mass transfer from the companion can spin the neutron star up, "recycling" [e.g. 2] it into a millisecond pulsar (MSP). MSPs spin at hundreds of Hz and pulse with extreme regularity, and a technique known as pulsar timing enables their use as precise cosmic clocks. One of the most well-known results is the measurement of the decrease in orbital period of the double neutron star system hosting PSR B1913+16 [3]. This 59-ms pulsar is only mildly recycled, the process having terminated with the supernova explosion that produced the second neutron star. Since this first (indirect) discovery of gravitational waves, the timing of other MSPs has enabled many other stringent tests of General Relativity [4].

A related application of MSP timing is the search for much lower-frequency ($f \sim 10^{-9}\,\mathrm{Hz}$) gravitational waves (GW), which subtly shift the observed spin frequencies of pulsars [5]. For a monochromatic GW source, such shifts would exhibit perfect quadrupole correlations that depend on the source position and polarization. If instead a random superposition of GWs forms a stochastic background, then a reduced set of correlations, which depend only on the angular separation of pulsars, results: the "Helllings-Downs" relation [6]. Detecting such correlations clearly requires monitoring an ensemble of MSPs, and the resulting experiments are known as pulsar timing arrays (PTAs).

Such a stochastic GW background (GWB) is expected from the decaying orbits of supermassive black hole (SMBH) binaries at the center of post-merger galaxies [7]. The superposition of monochromatic waves from many such SMBH binaries over cosmic time yields, assuming circular orbits and other simplifications, a power law [8] spectrum of GW with characteristic strain

$$h(f) = A_{\mathrm{gwb}} \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{\alpha} . \tag{1}$$

The spectral index α is $-2/3$ for GW-driven binary inspirals, while the dimensionless strain amplitude A_{gwb} reflects the typical masses of the merging black holes. (See [9] for a review of the physics of SMBH mergers and the range of expected signals.) The Doppler shifts in pulsar spin frequencies from this GW spectrum induce random variations in pulse times of arrival that have a power spectral density

$$P(f)\,[\mathrm{yr}^3] = \frac{A_{\mathrm{gwb}}^2}{12\pi^2} \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-\Gamma} , \tag{2}$$

with $\Gamma = 3 - 2\alpha = 13/3$ for circular SMBHs. This is a "red" spectrum with relatively much more power at lower frequencies.

There are thus two key signatures of a stochastic GWB in PTA data: (1) a steep spectrum noise process that is common to all monitored pulsars; (2) partial correlation of the noise between pulsars, with a strength that depends on pulsar angular separation according to [6]. Because the Hellings-Downs correlations are relatively weak, the first mechanism provides the higher signal-to-noise ratio. However, as we detail further below, other processes can mimic this channel, so the second path is considered the gold standard of evidence for detection of a GWB.
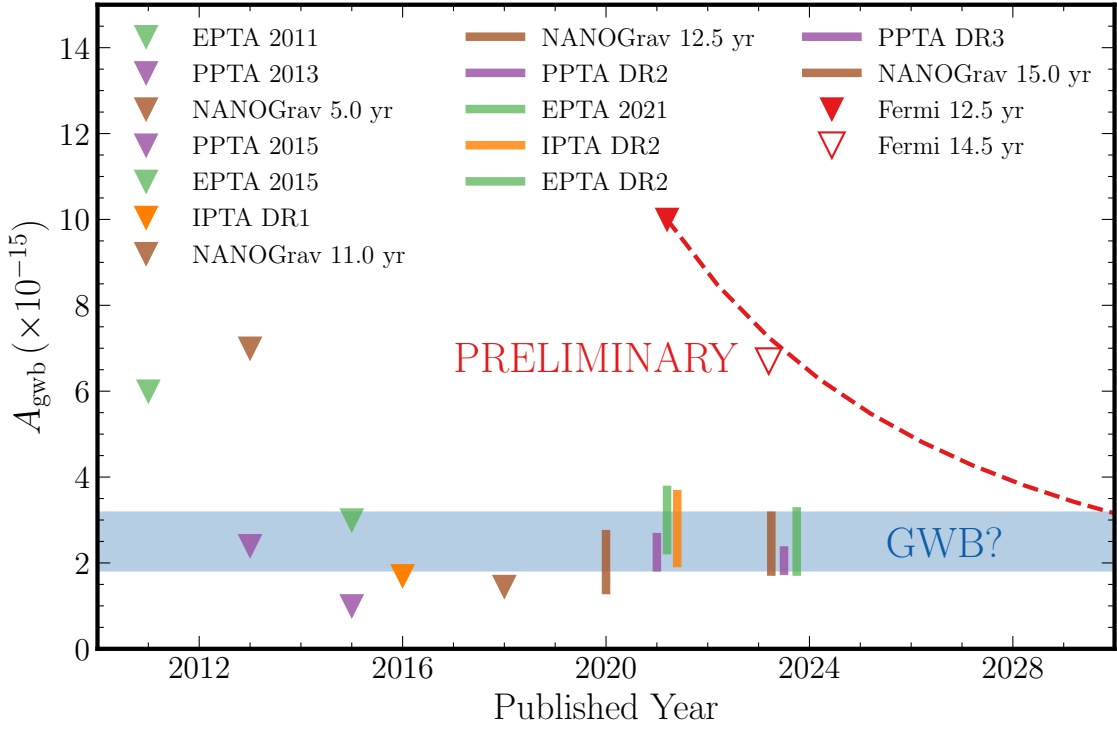
Figure 1: Upper limits (downward triangles) on, and candidate signal ranges (bars) of, the amplitude A_{gwb} of a stochastic gravitational wave background with spectrum given by Equation 1 with $\alpha = -2/3$. The shaded blue bar, for illustration, indicates the common credible range for the candidate GWB amplitude. The red dashed line indicates the expected $\propto T_{obs}^{-13/6}$ scaling expected in the weak-signal regime [10]. The preliminary GPTA DR2 limit lies below this scaling due to analysis improvements.

PTA experiments using radio telescopes have been searching for this background for nearly two decades, producing increasingly deep limits (Figure 1). In 2021, three PTAs published detections of a common noise process consistent with predictions for a GWB from SMBH binaries, and in 2023, PTAs published [11, 12] evidence for Hellings-Downs correlations associated with the common noise, the first candidate detection of a stochastic GWB.

The impressive detection of this candidate GWB requires the mitigation of many strong foreground noise sources, most importantly MSP "spin noise"—intrinsic to the pulsar—and effects from the propagation of radio waves through the ionized interstellar medium, e.g. [13]. γ rays are immune to such effects. Furthermore, the best-timed γ-ray MSPs are generally different to the best-timed radio MSPs, offering unique baselines. Consequently, a Gamma-ray Pulsar Timing Array (GPTA) offers an important complementary capability in detecting and characterizing the GWB.

2. The Gamma-ray PTA

The Large Area Telescope (LAT) [14] on the *Fermi* Gamma-ray Space Telescope has been performing a survey of the sky between 30 MeV and 1 TeV since August, 2008. One of its early successes was the detection of γ-ray pulsations from a population of known MSPs [15]. Since then,

radio searches for pulsations in unassociated LAT sources [16] have been particularly efficient in discovering new MSPs, and the population of γ-ray MSPs has grown to >100.

Because Fermi monitors all of these pulsars continually, its data set is effectively a PTA. [17] selected 35 of the γ-brightest MSPs and analyzed about 12.5 yr of LAT data, placing a surprisingly deep[1] limit on the GWB amplitude $A_{\mathrm{gwb}} < 10^{-14}$. Due to the steep spectrum of the GWB signature, **in the weak-signal regime**, the sensitivity of PTAs scales quickly with the length of the data span, $\propto T_{\mathrm{obs}}^{-13/6}$ [10]. This motivates an update of the data set to the nearly 15 yr that have elapsed since launch, and a new analysis.

3. GPTA Data Release 2

We prepare the data following the same method as [17], but increase the span through approximately March of 2023.[2] This preliminary version of DR2 uses only about 14.5 yr of data; the final release will occur after 15 yr of data are available, in early Aug 2023. We do not expect any substantial changes from this pending update. Besides the increase in data span, there are two major improvements in DR2: more pulsars, and the adoption of energy-dependent pulse profiles.

Figure 2 shows the LAT MSP sample as a function of two quantities. $\delta \log \mathcal{L}$ is the difference in log likelihood relative to a null hypothesis with no pulsations, and proxies the overall significance. A sufficiently large value mitigates cases where timing model parameters are not well constrained (overfitting). On the y-axis is the characteristic noise in the power spectral density; this latter quantity is correlated with $\delta \log \mathcal{L}$ but also accounts for the "clock quality" of an MSP, namely its spin frequency and pulse width. Lower white noise provides better constraints on the GWB. The 35 MSPs in DR1 were selected by requiring $\delta \log \mathcal{L} > 200$ and the white noise level $< 5 \times 10^{-10}\, \mathrm{s}^2$ yr. For DR2, we have loosened these constraints to $\delta \log \mathcal{L} > 150$ and a white noise level $< 2 \times 10^{-9}\, \mathrm{s}^2$ yr, yielding an additional 22 MSPs. Although these MSPs are of poorer quality, including them is of interest for GWB detection because, in the strong signal regime, the GWB S/N ratio scales more favorably with the number of monitored pulsars [10]. Five MSPs, which otherwise satisfy the cuts, are excluded from both releases due to excessive timing noise or strong, random variations in orbital period.

The pulse profiles in DR1 were modeled as wrapped gaussians. γ-ray pulse profiles evolve as a function of energy (see e.g. the third *Fermi* LAT pulsar catalog [18]), and we implemented new pulse profile models with parameters that are not fixed but depend linearly on logarithmic energy, capturing the vast majority of observed variation. Figure 3 illustrates the pulse profile evolution for PSR J0614−3329 and compares the old and new models. At low energies, the peaks have comparable amplitude, while at higher energies, the leading peak becomes dominant. Both peaks become narrower. Although the previous model, taking the average of this trend, is not biased, it loses information that can better constrain signals. Thus, the new models increase sensitivity to the GWB.

These new models also reduce systematic uncertainty, because the previous models are only unbiased **if the distribution of photons in energy is static**. Changes in the photon energy

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[1]The collecting area of the LAT is less than $1/10,000th$ of the typical radio telescope used for PTA work.

[2]The update and expansion of the pulsar sample was carried out over several months, giving a "ragged edge" to the data span. The final data set will be uniformly 15 yr in length.
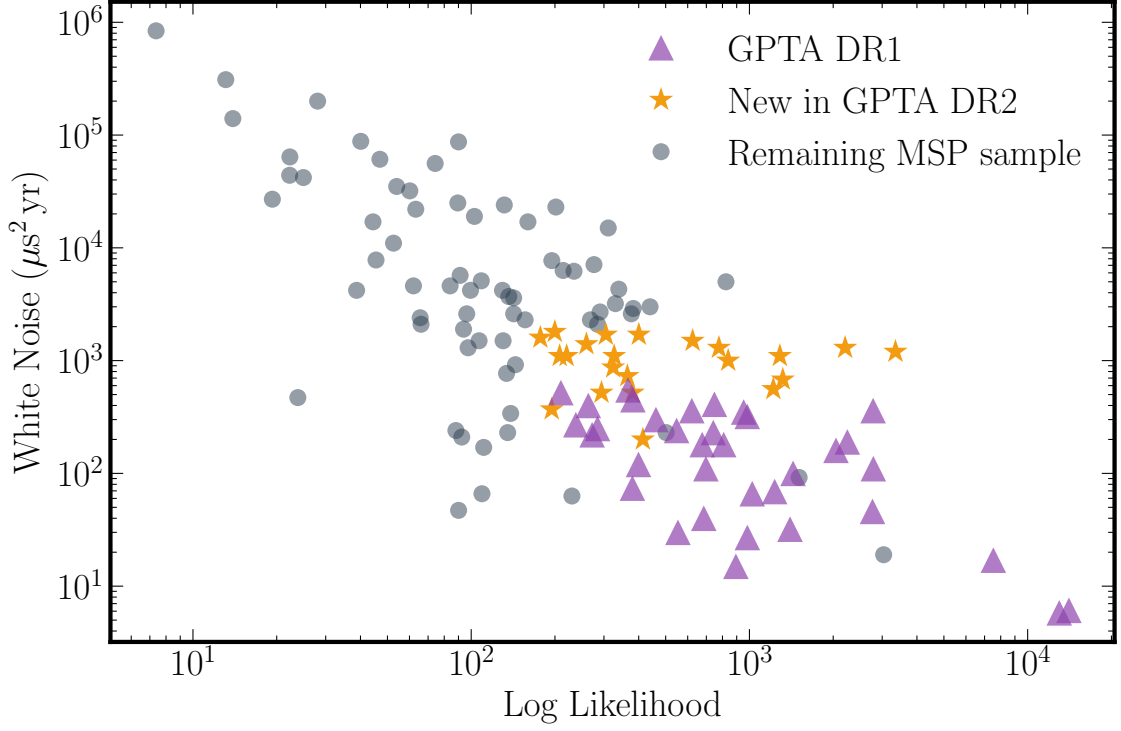
Figure 2: The detected γ-ray pulsar population as a function of the log likelihood difference (see text) and an estimated level of the white noise in the power spectral density. The former is an estimate of the overall significance of the source, while the latter is a better metric for sensitivity to GW. The 35 MSPs considered by [17] are indicated as GPTA DR1; an additional 22 MSPs are targeted for release in DR2.

distribution coupled with energy evolution would change the effective pulse shape and appear as a timing signal. Averaged over a spacecraft precessional period, the exposure to a given source—and thus the energy distribution—is generally stable. However, changes to the survey strategy, particularly the change in rocking angle in 2009 and the modified survey following the 2018 Solar Array Drive Assembly anomaly, produce small variations in both total exposure and in the relative exposure over the LAT energy range. Because the new models accurately describe the pulse shape at all energies, they mitigate such variations.

Using the new dataset and both the old (energy-independent) and new (energy-dependent) pulse profile models, we repeated the "unbinned" analysis of [17] to estimate a 95% confidence limit on the GWB amplitude, A_{gwb}. Depending on the precise details of the noise modeling, we obtain a range of upper limits. With the old models, we find $A_{\mathrm{gwb}} < 6.9 - 7.5 \times 10^{-15}$, while with the new energy-dependent models, $A_{\mathrm{gwb}} < 6.4 - 7.0 \times 10^{-15}$. We report the mid-range value, $A_{\mathrm{gwb}} < 6.7 \times 10^{-15}$, as a characteristic limit. We also note that this approach only constrains common noise processes and does not make use of correlation information.

4. Discussion

The DR1 limit, $A_{\mathrm{gwb}} < 10 \times 10^{-15}$, was expected to scale to 7.3×10^{-15} simply by growing from 12.5 to 14.5 yr of data, and we see that the DR2 results that used the old pulse profile models agree
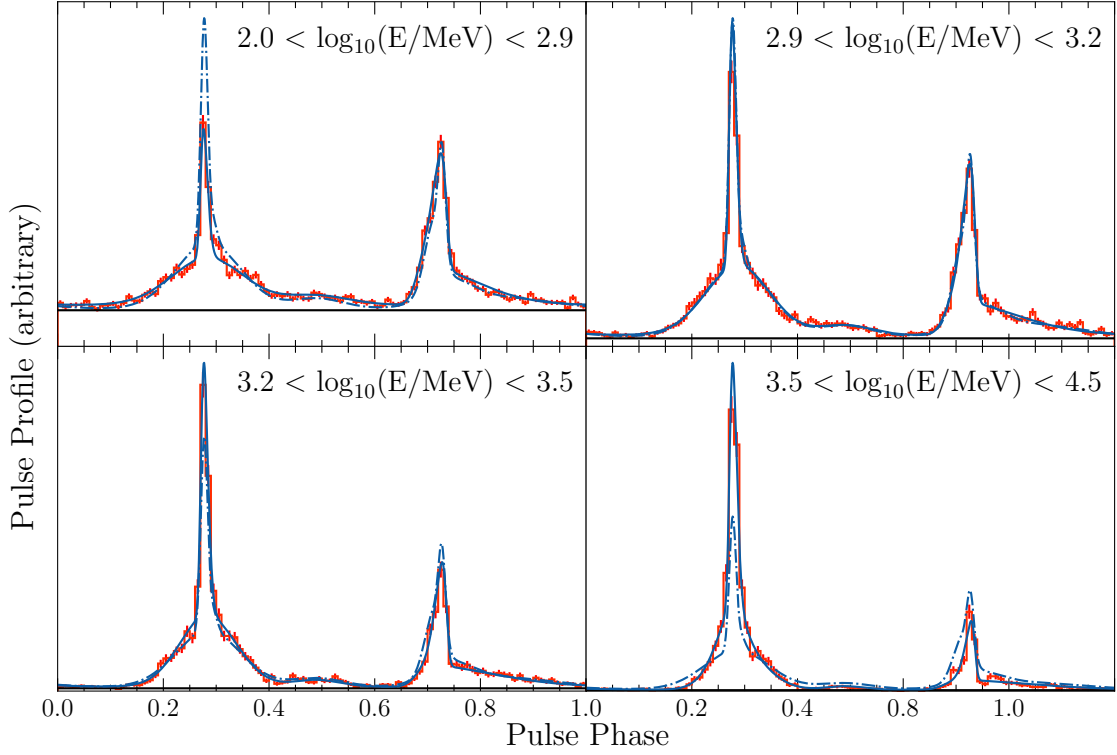
Figure 3: The observed and modeled pulse profiles for PSR J0614−3329, one of the bright γ-ray MSPs, are shown in four energy bands. The dot-dash line indicates the previous pulse models, while the solid lines indicate the new energy-dependent models. The energy ranges are annotated and are nonuniform in order to provide roughly equal statistical weight.

closely with this expectation. Because our preliminary analysis here did not incorporate spatial information (Hellings-Downs relations), the additional pulsars in the sample do not contribute much to the improvement, but will become important as the GPTA sensitivity passes into the strong-signal regime.

With this scaling alone, as Figure 1 indicates, the GPTA sensitivity should reach the level of the GWB candidate signal by 2030. However, including energy-dependence in the pulse profile modeling improves the sensitivity by nearly 10%. A final analysis of the GPTA DR2 data will include spatial correlations, which should include the sensitivity by another 10–15%.

5. Conclusion

The GPTA offers a key, complementary capability to radio PTAs, being able to observe pulsar spin noise and the GWB independently of interstellar medium propagation effects. We have presented a preliminary version of a new data release, DR2, which shows that the sensitivity is growing as expected and that new analysis techniques are effective. Future data releases will include additional analysis improvements. And unlike with radio PTAs, newly discovered MSPs—e.g. from MeerKAT searches [19]—immediately have the full length of LAT data available and provide their

full sensitivity to GWB searches. Thus, we confidently conclude that the GPTA should detect the GWB candidate signal within the next 5 years.

Acknowledgments

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