Gamma-ray Observations of Millisecond Pulsars Constrain the Low-frequency Gravitational Wave Background

The *Fermi* Large Area Telescope Collaboration

Summary: A new, direct method uses high-energy data to probe low-frequency gravitational waves from supermassive black holes.

Binary supermassive black holes in the hearts of merged galaxies fill the Universe with a low-frequency gravitational wave background (GWB). Long-term monitoring of millisecond pulsars (MSPs) with radio telescopes has recently revealed a signal which could originate from a nHz GWB with a strain amplitude $A_{\rm gwb} \sim 2 - 3 \times 10^{-15}$, but which could have other astrophysical or measurement-related origins. The *Fermi* Large Area Telescope has enabled γ-ray observations of MSPs, and using 35 bright MSPs and 12.5 yr of data, we have searched for a GWB and placed a 95% confidence upper limit on $A_{\rm gwb} < 1.0 \times 10^{-14}$. This new, independent constraint is also the most direct, because it relies on simple models and γ-ray data which are free from many of the confounding effects present in radio observations. The sensitivity is expected to improve to $A_{\rm gwb} = 2 \times 10^{-15}$ with ten years of additional data, which will rule out or strengthen the case for a GWB origin of the signal. This result, not envisioned before the launch of *Fermi*, represents a powerful new capability in gravitational wave science.

Main Text

Pulsars (*1*) are spinning neutron stars whose beams of broadband radiation extend from radio to γ rays and appear to pulse as they sweep repeatedly over the Earth. Millisecond pulsars spin at hundreds of Hz and pulse with extreme regularity, functioning as celestial clocks distributed across the sky and throughout the Galaxy. The timing of individual MSPs with radio telescopes has already enabled stringent tests of General Relativity (*2*), and now long-term monitoring campaigns of ensembles of MSPs are poised to detect low-frequency gravitational waves. Such waves are expected from the decaying orbits of supermassive black hole (SMBH) binaries which have sunk into the centers of merged galaxies (*3*). At separations of $\sim$0.01 pc (2000 a.u.), the energy loss is entirely due to gravitational waves (GW), and General Relativity yields a simple relationship between the orbital period and the GW frequency (f) and amplitude. The superposition of GWs from many such binaries throughout the Universe generates a background signal (GWB) which, in its simplest form, is the power law (*4*)

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

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. If black holes cannot reach the centers of merged galaxies efficiently, there will be relatively fewer wide binaries, depleting the GW power at low frequencies and leading to a spectral turnover. Thus, the precise features of the measured GWB carry a wealth of information about the distribution of black hole masses and the dynamical evolution of SMBH binary systems (*5*).

This GWB can be detected with ensembles of MSPs—known as pulsar timing arrays (PTAs) (*6, 7*)—by monitoring the times of arrival (TOAs) of the steady pulses from each pulsar, which arrive earlier or later than expected due to the spacetime perturbations. Because the GWB is the sum of many individual sources, the induced TOA variations are random and differ for each pulsar, but their power spectral densities have a common spectrum,

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

with $\Gamma = 3-2\alpha = 13/3$ for SMBHs. This is a "red" spectrum with relatively much more power at lower frequencies. Although the GWB varies throughout the Galaxy, all the pulsar observations are made at approximately the same place—the Earth—causing a hallmark quadrupolar correlation in the TOA variations between each pulsar. This "Hellings and Downs" correlation is the unique signature of a true GWB (*8*).

Since the typical correlation coefficient is only ∼0.1, the GWB will first manifest as a set of independent signals from each pulsar whose power spectra are all consistent with Equation 2. Recently, radio PTAs have detected (*9–11*) a signal of modest significance which could be interpreted as such a "common mode" compatible with $\alpha = -2/3$ and $A_{\mathrm{gwb}} \sim 2-3\times 10^{-15}$; see Figure 1. These signal characteristics are in good agreement with some predictions for the GWB (*5*), but because no spatial correlations have been detected, it could have other origins.

One strong possibility is "spin noise" (*12*), approximately power-law red noise intrinsic to each pulsar with observed values of the spectral index (Γ) of 2–7 for MSPs (*13, 14*). Possible origins of spin noise include superfluid turbulence in the neutron star (*15*) and switching between equilibrium states of the pulsar magnetosphere (*16*). Pulsars with spin noise spectra that have similar shapes but different amplitudes—thus inconsistent with a GWB—can nonetheless be well characterized by a common mode signal (*10*).

A second possible origin and a major complication for radio pulsar timing are the frequency-dependent effects of propagation through the solar wind and the ionized interstellar medium (IISM). Pulsed radio emission at frequency ν suffers a delay $\tau = 4.15\,\mathrm{ms}\times\mathrm{DM}\,[\mathrm{pc\,cm^{-3}}]\times\nu\,[\mathrm{GHz}]^{-2}$, with the dispersion measure (DM) being the electron column density. The DM to a pulsar varies with time due to relative motion of the Earth and pulsar, and must be repeatedly

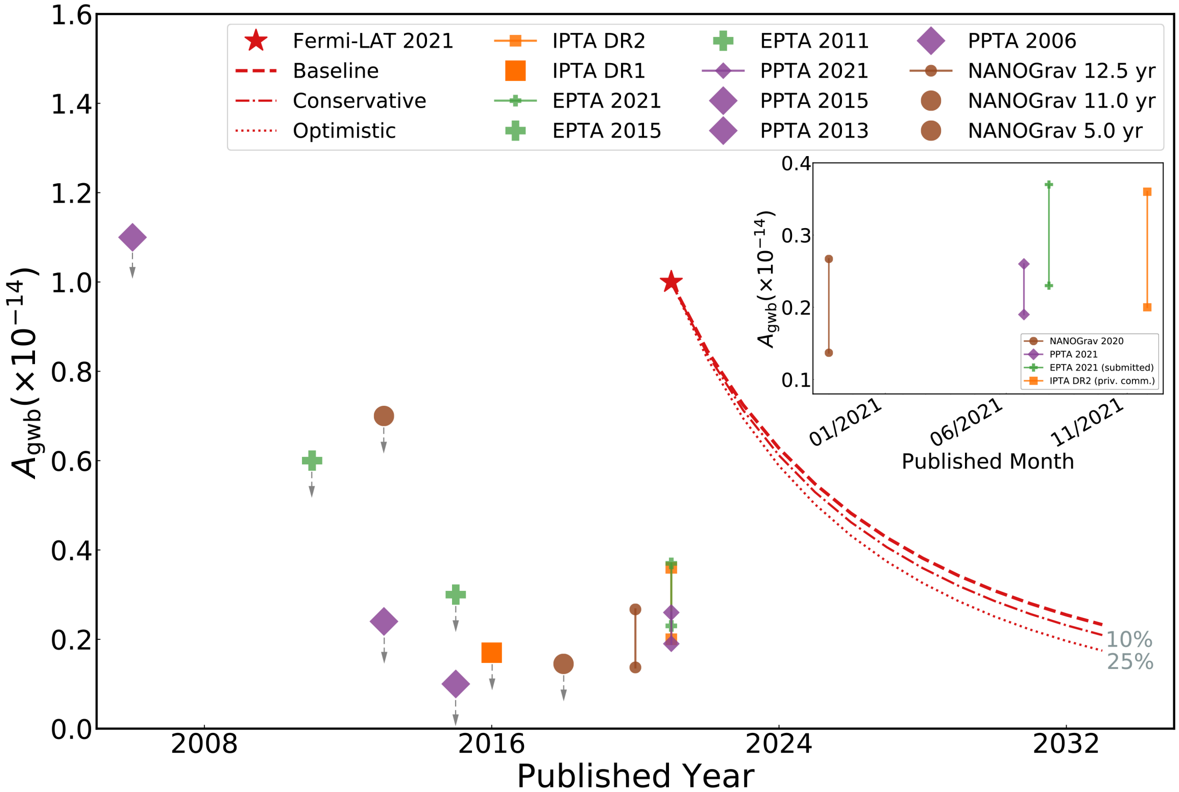

Figure 1: Inferred values of the amplitude A_{gwb} assuming $\alpha = -2/3$, expected from the superposition of gravitational waves from merging black holes, from this work and from the literature (references in supplementary text). Each PTA is represented by a unique marker. Upper limits are shown with arrows while the recent detections of potentially GWB-like signals are indicated with boundaries of amplitude ranges. These results are depicted more clearly in the inset panel. The *Fermi*-LAT 95% upper limit, 1.0×10^{-14}, is shown as a star. The projected baseline sensitivity from accumulating more data is shown along with conservative (10%) and optimistic (25%) improvements on this baseline from analysis enhancements.

measured using multi-frequency observations, introducing potentially hundreds of additional degrees of freedom to timing models. Since the propagation paths of radio waves through the IISM depend on ν, the DM itself is frequency-dependent (*17, 18*), so some of this delay is unmeasurable. Other effects, such as scatter broadening, can only be corrected for bright pulsars, with some components still remaining unmeasurable (*19, 20*). Because the IISM itself is turbulent, these uncorrected delays introduce additional red noise to radio pulsar timing data, with amplitudes comparable to potential GWB signals (*20*). As with spin noise, IISM-induced noise with similar spectra could mimic a GWB signal. The variable solar wind contributes similar dispersive delays which are only partially captured by current models (*21*), and due to its large angular extent, uncorrected delays are correlated amongst pulsars.

γ-ray observations are immune to IISM and solar wind noise, offering the opportunity to directly measure spin noise and the GWB signal. The Large Area Telescope (LAT) (*22*), launched on NASA's *Fermi* Gamma-ray Space Telescope in 2008, is sensitive to the copious GeV γ-ray power emitted by MSPs. Its 2.4 sr wide field-of-view enables an ongoing survey covering the full sky every 2 orbits ($\sim$3 hr), and the LAT thus constantly records data from all MSPs, currently known or yet to be discovered. Its precise GPS clock records photon arrival times with $<$300 ns precision (*23*), enabling precision pulsar timing. The LAT clearly detects nearly 130[1] (*24*) of the over 400 MSPs currently known in the Milky Way[2].

The large MSP sample, long observing span, remarkable instrument stability (*23*), and absence of IISM uncertainty motivate the creation of the first γ-ray pulsar timing array. Using a sample of the 35 brightest and most stable γ-ray MSPs and 12.5 yr of *Fermi*-LAT data, we searched for the GWB using two different techniques (see supplementary text for a detailed description of MSP selection, data preparation and noise modeling techniques). First, to enable

[1] https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

[2] http://astro.phys.wvu.edu/GalacticMSPs

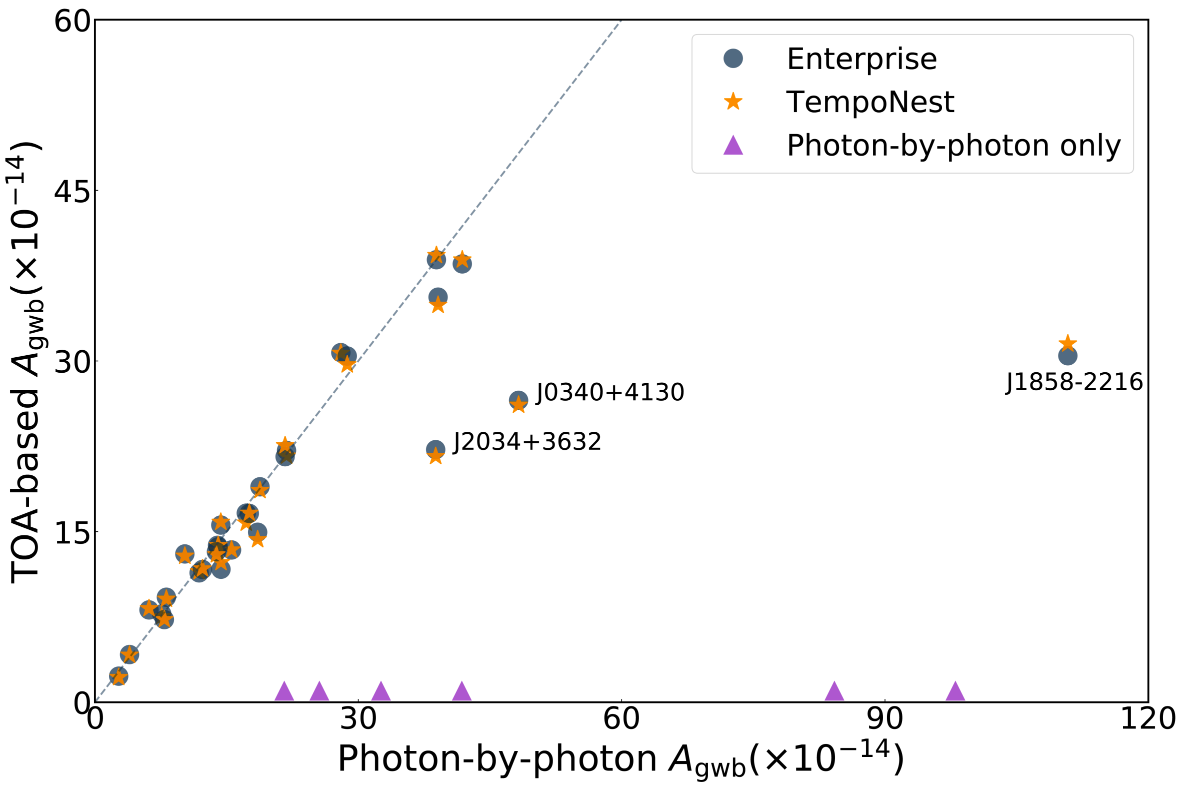

Figure 2: The limits on an $\alpha = -2/3$ GWB for 35 MSPs computed with three methods: two TOA-based codes TEMPONEST and ENTERPRISE are depicted as a function of the limit from a photon-by-photon analysis. Six pulsars, plotted along the x-axis, can only be processed using the photon-based analysis. Generally, mutual agreement is excellent. The exceptions, including the three labeled pulsars, are well understood and are discussed in the supplementary text.

application of the well-tested software used for radio data analysis, we directly measured TOAs from the LAT data (*25*). 29 of the 35 pulsars are suitable for this method. However, the TOA estimation procedure requires accumulating data for up to one year, eliminating sensitivity to shorter-timescale signals. To address this shortcoming, we have also implemented a coherent photon-by-photon analysis which retains full sensitivity to signals on all timescales.

For each pulsar, we have both searched for spin noise and derived an upper limit on $A_{\rm gwb}$ using the two codes, TEMPONEST (*26*) and ENTERPRISE (*27*), and with our new method. None of the pulsars show strong evidence for spin noise (supplementary text). A comparison of the single-pulsar $A_{\rm gwb}$ limits for the 29 pulsars common to all three methods (Figure 2) indicates excellent agreement amongst them, aside from a few well-understood exceptions. We have grouped the single pulsars into larger arrays and estimated $A_{\rm gwb}$ limits under a variety of scenarios, including marginalization over possible spin noise and uncertainties in the relative position of Earth, and both excluding and including the quadrupolar spatial correlations expected under General Relativity (see supplementary text). The resulting representative 95% confidence limit is $A_{\rm gwb} < 1.0 \times 10^{-14}$.

This is the most direct—thus potentially the most reliable—constraint on the GWB. It is already within a factor of 3–5 of the level detected by radio PTAs, and it will improve rapidly with additional data, as shown in Figure 1. In the weak signal regime, an ideal PTA becomes more sensitive to $A_{\rm gwb}$ with observing time $t_{\rm obs}$ as $A_{\rm gwb} \propto t_{\rm obs}^{-13/6}$ (*28*). This limit uses 12.5 yr of data, and with an additional 10 years of data it will reach 2.7×10^{-15}. As we detail in the supplementary text, other improvements will lower this to $2.1 - 2.5 \times 10^{-15}$. Because *Fermi* has no consumables onboard, is operating reliably, and its orbit is stable for decades, these are realistic scenarios.

This time frame fits in well with the overall program of detecting and characterizing the GWB: if the signal terrestial PTAs are currently detecting does arise from the GWB, then these

PTAs are now in the strong signal regime and their sensitivity will improve slowly (*28*), requiring up to five more years to detect the hallmark spatial correlations and eight to characterize the spectral shape (*29*). The *Fermi* PTA would detect the same signal with the same amplitude during those years, and provide a clean and independent measurement. If the signal has a non-GWB origin, e.g. from residual IISM variations in radio data, then the *Fermi* limit will continue to decrease. Indeed, there is already some evidence for such IISM effects. Three of the pulsars in our sample have spin noise measurements from radio PTAs. Using the power spectral indices Γ measured from the radio timing data, we have calculated 95% upper limits on spin noise amplitudes from the γ-ray data. Our limits are below the measured values for PSRs J0030+0451 (10% of the measured value) and J1939+2134 (60–70%) but are unconstraining for PSR J0613−0200. This discrepancy implies possible contamination by residual IISM effects of the radio-based spin noise and GWB signal measurements. The γ-ray sensitivity to these spin noise processes will also improve rapidly with time, yielding a detailed understanding of the effects of the IISM on MSP pulsar timing and providing a powerful new way to study the GWB.

Aside from immunity to IISM contamination, *Fermi* PTA data have other key advantages (supplementary text). Perhaps the most important is its little-changed experimental setup: the data are essentially uninterrupted, free from calibration issues and (radio-frequency) interference, and potentially less subject to astrophysical effects such as changes in the radio pulse shape (*30*). This stability makes it particularly well suited to probing GWs with frequencies below $0.1\,\mathrm{yr}^{-1}$. Such low frequencies provide a strong constraint on the spectral shape of the GWB, information about the environments of binary black holes, their distribution of binary eccentricities, and other key features governing the interplay between SMBHs and galaxy growth (*5*).

There are other potential sources of power-law GWBs with various spectral indices, α,

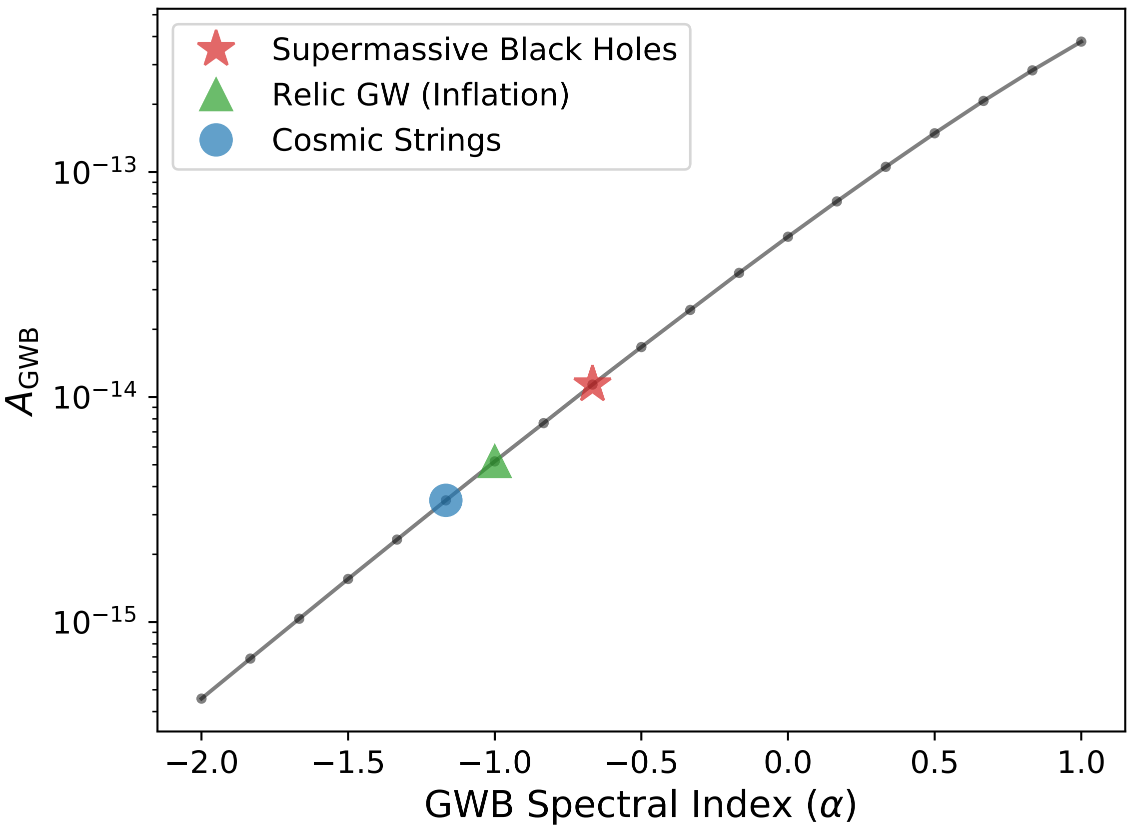

Figure 3: The 95% limiting value on A_{gwb} from *Fermi*-LAT data for a range of assumed spectral indices, α. Possible sources producing power laws are indicated (see text).

such as $\alpha = -1$ for relic GWs originating in scale-invariant inflation in the early Universe (*31*). Decaying cosmic strings can produce power-law spectra under a variety of scenarios, e.g. (*32*). To constrain such sources, we have computed corresponding 95% upper limits on $A_{\rm gwb}$, as shown in Figure 3. Yet other models are not well described by power laws, but predict the strongest emission in or near the PTA band. Early-universe phase transitions can produce GW emission peaking around 0.03 yr^{-1} (*33*), while some dark photon models (*34*) predict an oscillating gravitational potential whose frequency depends directly on the dark matter particle mass. Such scenarios again highlight the value of the low frequencies probed by the long, uninterrupted *Fermi* data set.

This *Fermi* PTA is a powerful new capability in γ-ray astrophysics. It can independently test GWB-like signals detected by radio PTAs, and it can improve our understanding of radio data by providing measurements free from the effects of the IISM. Most of the constraining power of the γ-ray data comes from the brightest pulsars, which are amenable to the TOA-based approach. These data are compact and the noise models are simple, so they can be included alongside radio PTA data with little computational burden. Thus, although the *Fermi* PTA will become more sensitive in the future, analyses which combine the strengths of the γ-ray and radio bands can begin now.

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Supplementary materials

Materials and Methods

Figs. S1 to S4

Tables S1 to S8

References *(35-89)*