

Unveiling the Graviton Mass Bounds through Analysis of 2023 Pulsar Timing Array Datasets

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Abstract

Strong evidence for the Helling-Downs correlations have been reported by several pulsar timing array collaborations in middle 2023. In this work, we study the state-of-the-art graviton mass bounds by analyzing the observational data of overlap reduction functions from NANOGrav 15-year data release and CPTA first data release. The data analysis places upper limits on the graviton mass at 95% confidence level, namely, $m_g \lesssim 0.43 \times 10^{-23} \text{eV}$ for NANOGrav and $m_g \lesssim 0.57 \times 10^{-23} \text{eV}$ for CPTA. In addition, we discuss implications of these results for scenarios of ultralight tensor dark matter.

Full Text

Preamble

Unveiling Graviton Mass Bounds through Analysis of 2023 Pulsar Timing Array Datasets

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Strong evidence for Hellings-Downs correlations has been reported by several pulsar timing array collaborations in mid-2023. In this work, we study state-of-the-art graviton mass bounds by analyzing observational data of overlap reduction functions from the NANOGrav 15-year data release and the CPTA first data release. Our data analysis places upper limits on the graviton mass at 95% confidence level, namely $m_g \lesssim 0.43 \times 10^{-23} \text{eV}$ for NANOGrav and

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Introduction

Based on Einstein's theory of general relativity, Hellings-Downs (HD) correlation curves have been proposed to characterize a stochastic gravitational-wave background (SGWB) in the pulsar timing array (PTA) band [?]. Recently, strong evidence for a stochastic signal spatially correlated among multiple pulsars was reported by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) [?] and the Chinese PTA (CPTA) Collaborations [?], respectively. In particular, the HD correlations were claimed to achieve statistical significance of $\sim 3\sigma - 4\sigma$ by NANOGrav and 4.6σ by CPTA. The European PTA (EPTA) [?] and Parkes PTA (PPTA) [?] Collaborations also reported that their datasets are compatible with HD correlations.

However, the overlap reduction functions (ORFs) for a theory of massive gravity could differ from the HD correlations. They depend on the graviton speed and thus on the graviton mass, but recover the HD correlations in the massless limit [?, ?]. Massive gravity was first proposed by Fierz and Pauli in 1939 [?]. It has been extensively studied over the subsequent more than eighty years, and the graviton mass has been constrained by numerous laboratory and astronomical observations (e.g., see reviews in Ref. [?] and references therein).

For a typical frequency band, the lower limit on the graviton speed can be recast into an upper bound on the graviton mass. Throughout this work, we define the speed of light as unity.

For an SGWB, the arrival times of radio pulses from two pulsars would be spatially correlated, with the angular correlation defined as

$$\gamma_{ab}(v_g) = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_{\ell} P_{\ell}(\cos \zeta_{ab}),$$

where the subscript ab denotes the cross-correlation of two pulsars a and b with angular separation ζ_{ab} , and the angular power spectrum C_{ℓ} is defined as

$$C_{\ell} = \frac{\pi}{2} J_{\ell}(v_g, fD_a) J_{\ell}^*(v_g, fD_b),$$

where $f = \omega/(2\pi)$ is the frequency of gravitational waves and D_c denotes the distance to the c -th pulsar. To simplify this definition, we introduce a function of the form

$$J_{\ell}(v_g, y) = \sqrt{\frac{(\ell + 2)!}{(\ell - 2)!}} \int_0^{2\pi y v_g} e^{ix/v_g} \frac{j_{\ell}(x)}{x^2} dx,$$

where $j_{\ell}(x)$ denotes the spherical Bessel function for the ℓ -th multipole. Following Refs. [?, ?], we recast the angular correlation $\gamma_{ab}(v_g)$ into ORFs $\Gamma_{ab}(v_g)$

by normalizing the former such that $\Gamma_{aa}(v_g = 1) = 0.5$, where the subscript aa denotes the auto-correlation of the a -th pulsar.

Note that the HD correlation curves are recovered by these correlations in the massless limit.

In Fig. 1 [Figure 1: see original paper] and Fig. 2 [Figure 2: see original paper], we show the difference between ORFs for massive gravitons and massless gravitons. For comparison, we also reproduce the observed ORFs from NANOGrav [?] (see Fig. 1) and CPTA [?] (see Fig. 2). Roughly, it appears that the observed ORFs fit massive gravitons better than massless gravitons. The data analysis in the following section will confirm these suspicions.

III. Data Analysis and Results

For the NANOGrav 15-year data release, 67 pulsars were monitored with timing baselines longer than 3 years, yielding 2,211 distinct pairs in total. Each pair has a deterministic angular separation. Based on these datasets, the authors of Ref. [?] constructed a minimally modeled Bayesian reconstruction of the inter-pulsar correlation pattern using spline interpolation over seven spline-knot positions (i.e., Fig. 1(d) of their paper). For the CPTA first data release [?], 57 millisecond pulsars were monitored. A 4.6σ statistical significance for the HD correlation between these pulsars was found around 14 nHz (see Fig. 4 [Figure 4: see original paper] of the data release paper).

Analyzing the NANOGrav and CPTA datasets of spatial correlations, we infer the graviton speed, or equivalently the graviton mass, using the log-likelihood

$$-2 \ln \mathcal{L}(v_g|D) = \sum \frac{[\Gamma_{ab}(v_g) - \Gamma_{ab}^D]^2}{(\sigma_{ab}^D)^2},$$

where Γ_{ab}^D denotes the observed ORFs for binned angular separation ζ_{ab} , σ_{ab}^D denotes the corresponding 1σ uncertainty, D represents either the NANOGrav or CPTA datasets, and the summation runs over all binned angular separations. Note that these uncertainties also contain cosmic variance [?, ?, ?].

For our data analysis, the parameter to be inferred is the graviton speed v_g . We adopt uniform priors, i.e., $v_g \in [10^{-2}, 1]$, and conduct Markov-Chain Monte Carlo sampling using the public code `cobaya` [?]. We also use the public `PTAfast` package [?] to compute ORFs. The resulting posteriors of v_g are recast into posteriors of m_g following the relation in Eq. (1), thereby obtaining the upper limit on m_g at 95% confidence level.

Our results are as follows. The posteriors of v_g are depicted in Fig. 3 [Figure 3: see original paper]. We mark the 95% confidence lower limits on v_g with vertical dashed lines, which are $v_g \gtrsim 0.13$ for NANOGrav and $v_g \gtrsim 0.14$ for CPTA. Compared with NANOGrav, CPTA favors a relatively smaller graviton speed. We further display the posteriors of m_g in Fig. 4 [Figure 4: see original paper].

The shaded regions represent the allowed parameter space at 95% confidence level. Consequently, we find upper limits on m_g at 95% confidence level: $m_g \lesssim 4.3 \times 10^{-23}$ eV for NANOGrav and $m_g \lesssim 5.7 \times 10^{-23}$ eV for CPTA. These two bounds are consistent with each other and represent state-of-the-art upper limits on the graviton mass.

IV. Conclusion

In this work, we investigated graviton mass bounds through analysis of the NANOGrav 15-year dataset and the CPTA first data release. By analyzing the ORF data points observed by these two observatories, we inferred the allowed parameter interval for the graviton speed, particularly the posteriors. Recasting the posteriors of graviton speed into posteriors of graviton mass, we obtained state-of-the-art upper limits on the graviton mass: $m_g \lesssim \text{few} \times 10^{-23}$ eV at 95% confidence level.

Our results may have implications for ultralight tensor dark matter [?, ?], which could account for the mystery of dark matter in the universe. In particular, ultralight dark matter in the mass range $m_{\text{uldm}} \sim 10^{-22}$ eV has been used to address several shortcomings of traditional cold dark matter [?, ?]. Ultralight tensor dark matter behaves like massive gravitons, suggesting possible imprints on PTAs. Since our results were obtained through analysis of recent PTA datasets, we find that the preferred mass range for ultralight tensor dark matter is compatible with the upper bounds on graviton mass from this work. A similar study analyzing the NANOGrav 12.5-year dataset can be found in Ref. [?].

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