EPJ Web of Conferences **319**, 09004 (2025) https://doi.org/10.1051/epjconf/202531909004
RICAP-24

Probing the Universe using Pulsar Timing Arrays

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Abstract. Supermassive black holes (SMBH), found at the centers of galaxies, have been observed in the early Universe, yet their rapid growth remains an open question. When SMBHs form binary systems during galaxy mergers, they are expected to emit strong gravitational waves (GW). A large population of such binaries would produce a stochastic gravitational wave background (GWB), detectable through perturbations in the timing of millisecond pulsars. In 2023, Pulsar Timing Array (PTA) collaborations reported evidence for a GW signal in their datasets, with the most plausible explanation being a population of SMBH binaries, although other cosmological sources cannot be ruled out. This paper reviews the current understanding of SMBH formation and growth, introduces the PTA method for detecting GWs, and discusses the interpretations of the 2023 results. The results provide promising evidence for the presence of a GWB, offering new insights into SMBH binaries and opening avenues for further exploration of the early universe.

1 Introduction

Supermassive black holes (SMBH), which reside at the centers of galaxies, are among the most massive objects in the universe. Observations have confirmed the existence of these black holes in the early universe, even at redshifts $z \sim 6$, less than a billion years after the Big Bang. Despite their prevalence, the mechanisms that drive their rapid growth during this early cosmic period remain poorly understood. Various theoretical models have been proposed to explain the formation and evolution of SMBHs, yet none can fully account for the observed population.

When galaxies merge, the SMBHs at their centers are expected to form binary systems. These systems, in turn, should emit strong gravitational waves (GW), ripples in spacetime predicted by general relativity. A large population of SMBH binaries would produce a stochastic gravitational wave background (GWB), a random, stationary signal that can be detected across the universe. Pulsar Timing Array (PTA) collaborations, which use precise timing measurements of millisecond pulsars, aim to detect GWs through the subtle perturbations they induce in pulsar timing data [1]. In 2023, several PTA collaborations reported strong evidence for the presence of a GW signal in their datasets [2–5]. While the most plausible explanation for this signal is the presence of a population of SMBH binaries, alternative cosmological sources may also contribute. The interpretation of these findings remains ongoing, with significant work needed to fully understand the origin and implications of the observed signals.

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In this paper, we introduce the PTA methodology and its role in GW detection. Finally, we discuss the 2023 results and explore their potential interpretations.

2 PTA : Pulsar timing array

Pulsar timing array (PTA) collaborations aim to detect GW signals in the nanohertz frequency band using high precision timing measurements of millisecond pulsars. The main target of PTAs is the GWB that is generated by a population of supermassive balck hole binaries (SMBHBs) in the Universe. SMBHBs are formed through galaxy merger. When galaxies merge, the SMBHs at their center start to orbit one another to form a binary system. This binary system shrinks significantly through environmental effects. We identify 3 main stages : (i) at kpc separation, the central SMBHs experience dynamical friction through gravitational interaction with smaller bodies of the merged galaxies' environment, (ii) at pc separation, the last remaining stars between the SMBHs get ejected by slingshot effect, this is the stellar hardening phase, (iii) at mpc separation, the SMBHB enters the GW emission phase where it looses energy only through GW radiation. For a large population of SMBHs in the Universe, the sum of all their GW emissions would produce a stochastic GW noise known as gravitational wave background (GWB).

2.1 Millisecond pulsars

Millisecond pulsars are very old pulsars, observed in the radio frequency-band, that got reaccelerated (recycled) through accretion by stealing angular momentum to a binary companion star. They are very stable in their rotation and allow extremely precise astrophysical timing measurement (with a precision up to the nanosecond). The passage of a GW would modulate the measured time of arrival (TOA) of the pulses at the radio-telescope. In theory, the high timing precision of pulsars is sufficient to see the effect of a GW [1].

2.2 Timing residuals

Pulsar timing requires to predict the TOAs of pulses with high precision. We construct a timing model that accounts for all physical processes that occur between emission and reception of the pulse (pulsar spin rate, pulsar spin-down, Einstein delay, Shapiro delay, ...). We define the timing residuals δt as the difference between the predicted TOAs and the actually observed TOAs. If no GW signal is present, the δt should be centered on zero. If there is a GW signal, the δt will contain all the information about that GW signal. The data analysis pipelines of PTA collaborations search for specific GW signatures in the timing residuals of the monitored pulsars.

2.3 Hellings-Downs correlation

Consider the timing residuals for two pulsar a and b, respectively δt_a and δt_b. In the presence of a GW signal, the timing residuals will exhibit a specific quadrupolar correlation pattern known as the Hellings-Downs (HD) correlation [6]. We have

$$\langle \delta t_a \delta t_b \rangle \propto \Gamma(\zeta_{ab}) \tag{1}$$

where ζ_{ab} in the angular separation between pulsar a and b, Γ is the HD correlation.

In the long detector arm limit, this correlation pattern is independent of the Fourier spectrum and frequency of the signal. This is the main target of PTA collaborations since it is the signature of a GW signal. In 2023, they all reported evidence for HD correlations in their datasets.

3 PTA results of 2023

3.1 Evidence for a stochastic GWB

The PTA collaborations reported evidence for the presence of a signal exhibiting HD correlations in their dataset [2–5]. The main candidate for this signal is a large population of SMBHBs in circular orbit emitting GWs and producing a stochastic GWB. The power spectral density (PSD) of this GWB $S_{HD}(f)$ should follow a powerlaw spectrum with amplitude A_{GWB} and spectral index γ_{HD} as $S_{HD}(f) \propto A_{HD} f^{-\gamma_{HD}}$. For a SMBHBs in circular orbit, we expect $\gamma_{HD} = 13/3$. However, the recovered values are different from the predictions. This could be due to an incomplete characterisation of individual pulsar noise, a specific realisation of the SMBHB distribution producing a different spectrum or even other physical processes. In fact, the probabilistic PSD estimate of the observed signal shows that a simple powerlaw is not necessarily the most suitable model. Other sources of GWs may produce similar signals [7, 8].

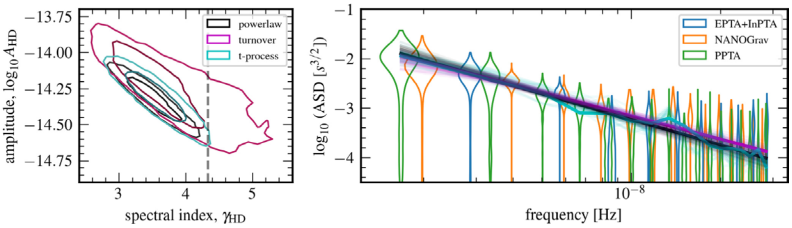

Figure 1. Figure taken from [7] combined results from the EPTA, PPTA and NanoGrav collaborations (left) Posterior probability distributions for A_{HD} and γ_{HD} (right) Probabilistic estimate of the PSD for the HD signal recovered.

3.2 Other sources ?

A GWB can be produced by astrophysical sources or cosmological sources [8]. Among the cosmological processes, we can name (i) a network of cosmic string loops producing GW bursts (ii) an inflationary GWB from the amplification of quantum fluctuations of the gravitational field (iii) a GWB from vortical MHD turbulence at the QCD energy scale (iv) a scalar-induced GWB arising from inflationary scalar perturbations at the 2nd order in perturbation theory.

It was also pointed out in some studies that a single SMBHB emitting a monochromatic GW at $5nHz$ could explain the signal that is observed [9]. With current datasets and data analysis techniques, it is difficult to clearly distinguish a single source from a GWB. This issue will hopefully be addressed in the near future when the combination of worldwide PTA datasets will be finalised, helping to shed new light on the origin of the observed signal.

4 Conclusions

The detection of a GW signal by Pulsar Timing Array (PTA) collaborations in 2023 marks a significant milestone in astrophysics, offering new insights into the population of SMBHBs and the broader universe. While the most likely source of the signal is a stochastic GWB produced by these massive binary systems, alternative explanations, including those of cosmological origin, cannot be ruled out at this stage.

As more data are collected and analyzed, it is anticipated that PTAs will provide an even clearer picture of the GW universe. The combination of PTA datasets in the context of the International PTA collaboration [7], together with the next generation of radio-telescopes [10], will open a new era of astrophysical research. Future detections may help disentangle the various contributions to the stochastic GWB and deepen our understanding of SMBH binary populations, their formation history, and their role in galaxy evolution. Additionally, potential discoveries of other sources, such as exotic cosmological phenomena, could revolutionise our understanding of the early Universe.

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