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PROBING THE UNIVERSE WITH LOW FREQUENCY GRAVITATIONAL WAVES

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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.

Keywords: Supermassive black holes, pulsar, gravitational waves

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 (Detweiler 1979). In 2023, several PTA collaborations reported strong evidence for the presence of a GW signal in their datasets (Antoniadis et al. 2023; Agazie et al. 2023; Reardon et al. 2023; Xu et al. 2023). 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.

In this paper, we first review the formation and growth mechanisms of SMBHs. We then introduce the PTA methodology and its role in GW detection. Finally, we discuss the 2023 results and explore their potential interpretations.

2 The growth of supermassive black holes

2.1 Accretion

Supermassive black holes (SMBH) are extremely massive black holes (with a mass greater than $10^6 M_\odot$) that are located at the center of galaxies. These objects are already observed in the early Universe, at $z \sim 6$, and explaining their rapid growth is still an active area of research (Volonteri 2010). The main process through

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which SMBH are expected to grow is accretion : when the SMBH swallows the surrounding matter. The mass of the SMBH M_{BH} grows exponentially as

$$M_{BH}(t) = M_{BH,0} \times \exp\left[\frac{\epsilon}{t_{Edd}}(t - t_0)\right] \tag{2.1}$$

with $t_{Edd} \sim 0.45$ Gyr, the characteristic accretion time (Eddington time), ϵ an efficiency coefficient and $M_{BH,0}$ the mass of the SMBH at time t_0.

Equation 2.1 tells us that the exponential growth will strongly depend on the initial mass of the growing black hole $M_{BH,0}$. To form SMBHs, the accretion has to start from black hole "seeds" of mass $M_{BH,0}$ (Volonteri 2010; Izquierdo-Villalba et al. 2024). We divide those seeds into two categories : the light seeds and the heavy seeds.

2.1.1 Light seeds

In the early Universe, the dark matter clumped to form overdense regions called mini-halos of $\sim 10^6 M_\odot$ where the baryonic matter collapsed to eventually ignite the first generation of stars : Population III stars. Light seeds would be the result of Population III stars going supernova, leaving behind black holes with masses of about $10 - 100 M_\odot$ at $z \sim 20 - 32$. The seeds could grow through accretion of the surrounding matter and result in SMBH at $z \sim 6$.

2.1.2 Heavy seeds

There are multiple channels to form heavy seeds with a mass of $\sim 10^5 M_\odot$. In general, they form in more massive halos ($\sim 10^8 M_\odot$) at higher redshift ($z \sim 5 - 12$), but since they are more massive, it takes less time for them to grow and become a SMBH. Among the various formation channels, we can name :

- **Runaway stellar merger :** where the collision of stars in nuclear clusters at the center of proto-galaxies produce heavy black holes.
- **Direct collapse :** where a heavy seed grows through the direct collapse of baryonic matter. This regime can be achieved only if star formation is suppressed in the halo. When UV radiations from neighbouring halos split molecular hydrogen, there is no efficient cooling mechanism that allows baryonic matter to clump and form stars.
- **Merger induced :** when proto-galaxies collide, the collision can form heavy seeds.

2.2 Supermassive black hole binaries

Supermassive black hole binaries (SMBHB) 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).

3 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 SMBHBs in the Universe.

3.1 Millisecond pulsars

Millisecond pulsars are very old pulsars, observed in the radio frequency-band, that got re-accelerated (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 (Detweiler 1979).

3.2 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.

3.3 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 (Hellings & Downs 1983). We have

$$\langle \delta t_a \delta t_b \rangle \propto \Gamma(\zeta_{ab}) \tag{3.1}$$

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.

4 PTA results of 2023

4.1 Evidence for a stochastic GWB

The PTA collaborations reported evidence for the presence of a signal exhibiting HD correlations in their dataset (Antoniadis et al. 2023; Agazie et al. 2023; Reardon et al. 2023; Xu et al. 2023). 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 (Agazie et al. 2024; Antoniadis, J. et al. 2024a).

4.2 Other sources ?

A GWB can be produced by astrophysical sources or cosmological sources (Antoniadis, J. et al. 2024a). 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 (Antoniadis, J. et al. 2024b). 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.

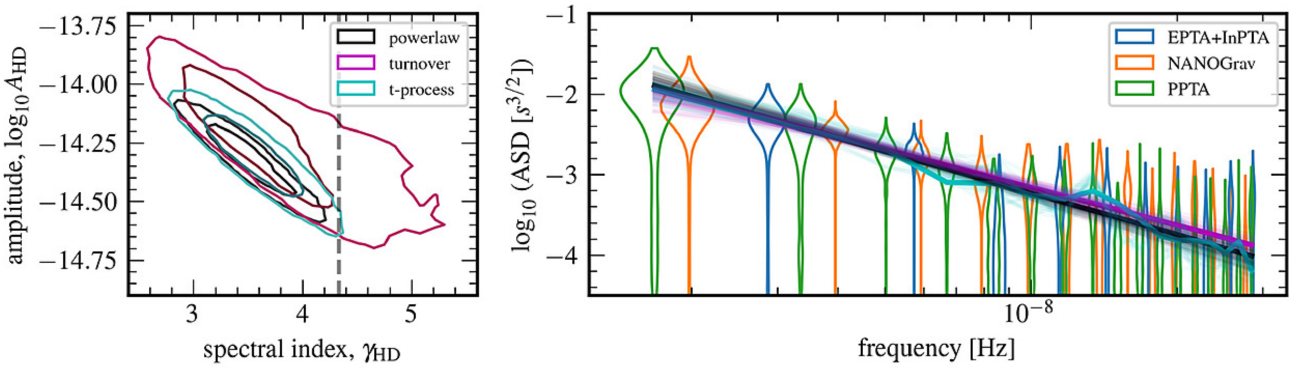

Fig. 1. Figure taken from Agazie et al. (2024) combined results from the EPTA, PPTA and NanoGrav collaborations (left) Posterior probability distributions for A_{HD} and γ_{HD} (right) Probabilistic estimate of the PSD for the HD signal recovered.

5 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. Understanding the rapid formation and growth of SMBHs, especially in the early universe, remains one of the major challenges in astrophysics. The PTA results add a valuable observational constraint to the theoretical models, suggesting that SMBH mergers are not only frequent but may contribute significantly to the GW background. However, the full interpretation of the signal requires further study, including more precise modeling of potential sources and their contribution to the observed data.

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 (Agazie et al. 2024), together with the next generation of radio-telescopes (Bhat et al. 2018), 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.

Thank you!

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