SCIENTIFIC SUMMARY

Towards the Detection of the Nanohertz Gravitational-wave background: The analysis of a candidate red signal by European Pulsar Timing Array

What is the European Pulsar Timing Array and why is the signal we have analyzed important?

The European Pulsar Timing Array (EPTA) is a network of European radio observatories and research groups specializing in data analysis and modelling of gravitational waves (GWs) with the main aim of detecting low-frequency GWs. It has recently used a 24-year long data set to examine a common signature in the data of six millisecond pulsars (MSPs), which started appearing in the 18-year long data set, originally examined in 2015. The spectral properties of the signature classify it as a low-frequency signal present in all MSPs (a so called "Common Red Signal", CRS), which is consistent with the theoretical predictions of a stochastic gravitational-wave background (GWB) generated by the cosmic population of supermassive black hole binaries located in the cores of merging galaxies. However, the CRS does not have all the necessary properties measured well enough to confirm it as the sought GW signal. Nonetheless, with increasingly better quality data our measurement of the required CRS properties also improves. The EPTA is extending its dataset to at least 25 MSPs to improve the measurement precision of all common-signal properties, and with the development of protocols for data and analysis validations the detection of the GWB with pulsar timing data is becoming a realistic possibility.

Pulsar Timing Arrays and GW searches

A Pulsar Timing Array (PTA) is a network of pulsars, highly magnetized spinning neutron stars that emit beams of radio radiation. When the beams are not aligned with the rotational axis, during each rotation, if the beams point towards us, we receive a pulse of radio waves, much as we observe a lighthouse from afar. The exceptional density of these compact stars means that the MSPs, in particular, are very stable rotators. The highly predictable times-of-arrival (TOAs) of the pulses are like the ticks of a very precise cosmic clock which allows astronomers to use MSPs to measure even very small variations in the length of the path followed by radio waves traveling between the pulsar and the observer. The propagation of a GW deforms the spacetime and hence causes tiny delays or advancements in the observed TOAs. However, many other effects (unrelated to GWs) can impart variations of that size on the measurements of any given pulsar. Hence, we cannot rely on a single pulsar to safely detect GWs, and need to monitor the variations of the TOAs in an ensemble of pulsars, i.e. in a PTA. In summary, every pulsar in a PTA acts as an arm of a giant Galactic-scale detector that traces the GW in a different direction.

Supermassive black-hole binaries and the stochastic GWB

Ground-based detectors such as LIGO/Virgo/KAGRA observe high frequency (hundreds of Hertz) GWs from short lasting collisions of stellar-mass black holes and neutron stars. PTAs can extend the GW observing window down to very low, nHz (10^{-9} Hz) frequencies, by observing GWs from slowly inspiralling supermassive black-hole binaries (SMBHBs) hosted at the centres of galaxies. Since they are located at cosmological distances, the study of the

SMBHBs can provide unique details for the formation and evolution of the galaxies and the observed large-scale structure of the Universe. Various investigations predict that PTAs may be able to first detect the stochastic GW signal formed by the superposition of the GWs emitted by the cosmic population of SMBHBs. This signal is known as the Gravitational-Wave Background (GWB) and is expected to be louder (i.e. easier to be detected with current experiments) than any single SMBHB signal. The GWB will be seen as an isotropic (uniform power in all directions), red-spectrum (increasing power at lower GW frequencies) signal that will induce TOA variations to all the pulsars in a PTA, with a specific cross-correlation between pulsar pairs, dictated by each pair's angular separation on the sky (i.e. the GWB is characterized by a specific *spatial correlation*). In the context of general relativity the fingerprint of the spatial correlation due to a GWB takes the shape of the so-called *Hellings-Downs* curve.

What does the EPTA observe?

The presence of a GWB manifests as an additional *noise* perturbing the clock-like rhythm of the TOAs collected for any observed MSP. In a very simplistic way, a GWB detection experiment is a search for a noise signal which is common to the TOAs of all the MSPs of a PTA, which cannot be better modelled with other known kinds of noise, and which shows some expected signatures, in terms of spectral properties and spatial correlation among TOAs of MSP pairs. Previous experiments could only place upper limits on the amount of unmodeled noise seen in one or in a small number of pulsars and that directly translated into upper limits to the strength of any underlying GWB (this concept of strength is technically quantified as the so-called *strain amplitude* of the GWB). As the GWB signal is stationary (its statistical properties are unchanged over time), by extending the timespan and improving the precision of a data set, it is expected that these upper limits should progressively lower until either the GWB signal starts to appear stronger than the intrinsic noise levels of our pulsars (which dictate the uncertainty of the TOAs), or we hit a low level systematic noise floor in the data that we are not properly modelling. During the development of our first complete data release in 2015-2016, the EPTA first began noticing a floor on the strength of the assumed GWB, as our strain upper limits could not be improved beyond a point by adding more data. As we did not know the origin of this signal, we used to refer to it as a "common red signal" (CRS). As at first this signal was only marginally above the data noise, the EPTA only placed upper limits on the GWB and continued a campaign to improve the quality of the data, while monitoring if the CRS would become stronger, or disappear, as expected from random statistical fluctuations. With the new, vastly improved second EPTA data release, we now measure the CRS with high statistical significance. Its properties appear consistent with those we measured in 2015, as expected from a stationary signal. It is also important that our partner PTA groups in North America (NANOGrav) and Australia (PPTA) have also seen similar signals in their independent data sets.

However, we cannot yet measure the Hellings-Downs curve with statistical significance, prohibiting any claim over the physical origin of the CRS as a GWB. Instead, we focused on a multidirectional approach to verify the presence and spectral properties of the CRS as a template for future efforts for a GWB detection, and studied multiple possibilities for the signal's origin.

How was the CRS studied and what are its properties?

The search for any common signal in PTA data requires that each pulsar is first well understood, with a high-precision *timing model* capable of accurately predicting its rotational and orbital behaviour, and a *noise model* that statistically quantifies the measurement errors and statistical fluctuations in the data. One then combines all that information to search for any additional red signal in the data that is common to all pulsars. If such a CRS is recovered, the cross-correlation coefficient of the TOAs of all pulsar pairs is measured and examined to see whether it fits the Hellings-Down curve or not. In particular, the EPTA made two separate end-to-end analyses of the data by two independent teams, including pulsar noise analysis and CRS searches. Each team employed independently developed analysis software, each using different mathematical and statistical frameworks. The two analyses gave completely consistent results, increasing our trust in the presence of the CRS and its measured properties.

What else can the CRS be?

Multiple signals have been identified for many years in the literature as possible CRS contaminants of PTA data. These include (1) an apparent common signal due to red noise which is similar in all the MSPs of the PTA, but not showing any spatial correlation; we call that a common uncorrelated red noise (CURN). (2) a CRS caused by errors in the time standards used to measure the TOAs. (3) a CRS induced by the occurrence of errors in the planetary parameters which are reported in the Solar-system ephemeris (SSE) and used in the pulsar timing models. All these sources were modelled and a series of tests showed that the CURN and the occurrence of a GWB are the two most likely responsible for the observed CRS, whereas the clock errors are the least likely origin. The effects of possible SSE errors received special attention in PTA work, as they are potentially measurable and are demonstrated to have a significant chance to induce false-positive GWB detections. The EPTA has made a novel analysis, in which three different independently developed models of such errors, based on data from three independent SSEs and with different modelling principles, were used to mitigate the effects of SSE errors. All three approaches provided consistent results indicating that an SSE origin of the signal remains more unlikely than either a GWB or CURN.

Next steps

Despite all the positive results of our work, further studies need to be done. The different analyses demonstrated the soundness and consistency of the analysis codes when used under the same assumptions. We therefore now examine the impact of different approaches in the modelling of pulsar timing and noise, as improper models can bias the recovered spectral properties of the CRS. We are also extending our dataset from six to about 25 pulsars in order to increase the precision of the common-signal spatial correlation curve. We have also initiated a partnership with the Indian Pulsar Timing Array which can provide quality low radio frequency data to further mitigate noise from the interstellar medium and improve the CRS spectral-properties measurements even more. The EPTA is also working in coordination with NANOGrav and the PPTA in the context of the International Pulsar Timing Array (IPTA) consortium to further develop and cross-check data, analysis and validation methods, and examine the outcome from analysis of IPTA data combinations.

FIGURE

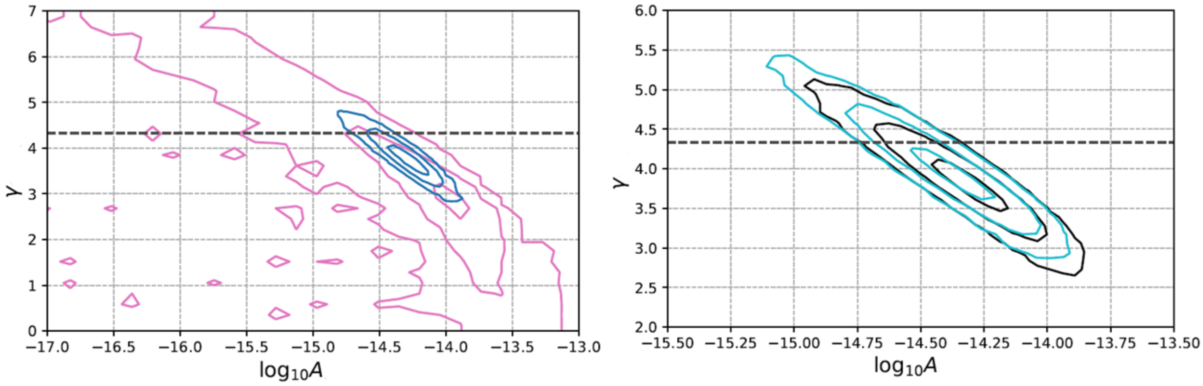

Figure.1: *Right Panel:* Results from the EPTA search for a common red signal (CRS) in the data of six pulsars, using two independent analysis pipelines, noted with different colours. The CRS spectrum here is modelled as the GWB is theoretically predicted, i.e. as a two-parameter, power-law spectrum. The two parameters are the amplitude A and the spectral index γ. The dashed horizontal line denotes the spectral index value theoretically calculated for the case of circular SMBHBs. The calculated probability distribution for the spectral parameters is represented with three levels of confidence (68%, 95%, 99.7%), the highest of which is associated with the outermost lines. The black and the light blue lines are delimiting very similar allowed spaces for the two parameters, indicating that the two independent pipelines produce nicely matching results. *Left Panel:* Comparison of the CRS spectral properties between the current EPTA data set of 2021 (blue) and the previous data set of 2016 (pink). One can see the remarkable improvement in the present measurement of the spectral properties since 2016, when the parameter values were very uncertain beyond the 95% level of confidence.