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Gravitational Wave Detection with Pulsar Timing

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Abstract. With pulsar timing experiments gravitational waves can be detected in much the same way as with laser interferometers. Primary source candidates include a postulated stochastic background of gravitational waves by merging supermassive black hole systems in the cores of galaxies, and individual such systems. We provide upper limits from current pulsar timing array experiments, and highlight the technicalities involved in making an actual detection. As an overview, we describe the pulsar timing data, the data analysis techniques currently in use to search for these gravitational waves, and we discuss the potential detectable sources of future pulsar timing array experiments.

1. Introduction

In the past several decades, the pulsar timing technique (e.g. Lorimer & Kramer 2004, for an overview) has been successfully used to obtain some of the most exciting results in astrophysics. For instance, the first confirmation of gravitational waves was provided by observing the binary system B1913+16 (Taylor & Weisberg 1982), the first extra-Solar planets were discovered orbiting the pulsar B1257+12 (Wolszczan & Frail 1992), and the most accurate tests to date of general relativity have been obtained by studying the double pulsar (Kramer et al. 2006). More recently, Champion et al. (2010) have shown how to measure the solar system planet masses with pulsar timing, and Hobbs et al. (2012) have developed a pulsar-based timescale independent of terrestrial time standards.

Even though the system B1913+16 has provided the first evidence of the existence of gravitational waves, this result is generally considered as an indirect detection: the presence of the gravitational waves is demonstrated at the point of emission of the gravitational waves. A direct detection would consist of a demonstration of the presence of gravitational waves at some location different from the point of emission.

Sazhin (1978) and Detweiler (1979) showed that low-frequency gravitational waves induce detectable timing residuals in high-precision pulse arrival times observations. However, it is difficult to definitively distinguish between the effects of gravitational waves and possible other effects such as the irregularities in the pulsar spin frequency, inaccuracies in the solar system planetary ephemeris, and interstellar medium propagation effects. By looking for correlated behaviour in the timing residuals of many pulsars, which has a unique signature for gravitational waves, the presence of gravitational waves can be uniquely demonstrated (Hellings & Downs 1983). When a collection of pulsars is used to search for such gravitational wave induced correlated signals, this is referred to as a *pulsar timing array* (PTA).

The first attempt to create such a PTA in which enough pulsars are observed with sufficient timing accuracy to search for correlated signals was the effort of Foster & Backer (1990). Nowadays, three dedicated projects exist that observe an array of pulsars with the primary purpose of gravitational wave detection:

- the Australian-based programme PPTA, the Parkes Pulsar Timing Array, which uses data from the Parkes telescope (Hobbs et al. 2009; Verbiest et al. 2010). To date the PPTA is the only PTA project in the Souther Hemisphere. Every two-three weeks, each of the 20 in the PPTA included pulsars is observed.

- the North American based programme NANOGRav, North American Nanohertz Observatory for Gravitational Waves, which uses both the Greenbank Telescope (GBT), and the Arecibo radio telescope. These telescopes are currently obtaining approximately monthly observations on 24 pulsars (Jenet et al. 2009; Demorest et al. 2012).

- the European programme EPTA, European Pulsar Timing Array, which uses five different 100-m class radio telescopes: the Lovell telescope near Manchester, United Kingdom, the Westerbork Synthesis Radio Telescope (WSRT) in the north of the Netherlands, the Effelsberg Telescope (EFF) near Bonn in Germany, the Nancay Radio Telescope (NRT) near Nancay in France, and the Sardinia Radio Telescope (SRT) in Sardinia, Italy, which is expected to become operational in 2012 (Tofani et al. 2008). As well as using each of these telescopes as individual instruments, the Large European Array for Pulsars (LEAP) project will allow these telescopes to act as a phased array giving the equivalent sensitivity of a 200 m telescope (Ferdman et al. 2010).

Although these three projects independently strive to detect gravitational waves, it is likely that a first detection of gravitational waves by a PTA will occur as a result of a joint effort of all three PTA projects: the International Pulsar Timing Array (IPTA) (Hobbs et al. 2010). Currently the three project are preparing for such a first combined analysis.

In this work, we give an overview of ongoing PTA projects, with an emphasis on the data analysis to give a perspective for the laser interferometry community. In Section 2 we describe pulsar timing observations, and the technical details required to do gravitational wave data analysis. We describe the potential sources of gravitational wave for PTAs in Section 3, with the data analysis methods to detect these sources described in Section 4. Finally, we provide a short outlook in Section 5, and conclusions in Section 3.

2. Pulsar timing observations

In this section we present a brief overview of the typical data reduction pipeline for pulsar timing, with an emphasis of the end-product: the pulse times of arrival (TOAs), and the timing residuals. These details of pulsar timing observations provide some perspective for readers with a background in laser interferometry gravitational wave detectors.

2.1. Obtaining a solution to the timing-model

The goal of pulsar timing is to produce a highly accurate description of the arrival times of the pulses. This comprises of building a physical model of the pulsar trajectory, the pulse propagation, and the pulsar spin evolution in relativistic binary. Such a model is referred to as the *timing-model*. Construction of and finding a solution to the timing-model is the main purpose of standard pulsar timing software packages (e.g. Tempo2 Hobbs et al. 2006).

Not all components of the relative motion of the earth with respect to the pulsar have to be determined through pulsar timing observations. For instance, one standard practice performed in some timing packages is to calculate the TOAs as if they are observed at the solar system barycentre, thereby completely accounting for the relative movement of the Earth with respect to that barycentre. This requires a very accurate description of the solar system ephemeris, obtainable from standard sources like the Jet Propulsion Lab (JPL) ephemeris, developed for space missions.

A full description of some other components responsible for delays of the pulses travelling towards the earth are not obtainable through other means than pulsar timing. Examples include the pulsar spin evolution and the pulsar ephemeris. The parameters describing these components of the timing-model are referred to as timing-model parameters. Estimates of these timing-model parameters are usually found through quantities called timing *timing residuals*. Timing residuals are the deviations of the observed TOAs from the TOAs as predicted by the timing-model. Typically, the timing-model parameters are determined by minimising the timing residuals in a linear least-squares fit (Hobbs et al. 2006; Edwards et al. 2006, see also Section 2.2 of this work). Constructed this way, the timing residuals and the best-fit timing-model form a consistent whole; the timing residuals are formed using the best-fit timing-model, and the timing-model is obtained by a minimisation of the timing residuals.

Because of the circular dependence of the timing residuals and the timing-model parameters, one must always take into account the fact that certain parameters have been fit for when analysing timing residuals for the presence of other signals, like gravitational waves. Mathematically, a linear time-varying filter is always applied to signals in the timing-residuals, thereby modifying the signature of any gravitational wave signal in the data. Especially in the case of stochastic sources like the background of gravitational waves, as we discuss in Section 4.1, a lot of the low-frequency power is absorbed by the fitting process.

2.2. Least-squares fitting

In this section we briefly describe the TOAs, and the likelihood function of the timing residuals. This likelihood forms the basis of the least-squares fitting routines as they are routinely used in pulsar timing, and outlines some details of the differences with respect to laser interferometry gravitational wave detectors.

The observed TOAs contain contributions from both deterministic and stochastic processes. We describe the n TOAs of a single pulsar as:

$$\vec{t}^{\mathrm{arr}} = \vec{t}^{\mathrm{det}} + \vec{\delta t}^{\mathrm{rgp}}, \tag{1}$$

where the n elements of $\vec{t}$ are the observed TOAs, $\vec{t}^{\mathrm{det}}$ are the deterministic contributions to the TOAs, and $\vec{\delta t}^{\mathrm{rgp}}$ are the stochastic contributions to the TOAs, which we assume to be well-modelled by a random Gaussian process with some power spectral density.

For a random Gaussian process, the behaviour of $\vec{\delta t}^{\rm rgp}$ is completely described by the covariance matrix $C_{ij} = \langle \delta t_i^{\rm rgp} \delta t_j^{\rm rgp} \rangle$, where the $\langle \ldots \rangle$ denotes the ensemble average. Theoretically, C can be calculated from the power spectral density through the Wiener-Khinchin theorem.

The timing-model we discussed in Section 2.1 is completely contained within $\vec{t}^{\rm det}$. In practice, so-called pre-fit timing residuals are produced with first estimates β_{0i} of the m timing-model parameters β_i; this initial guess is usually precise enough so that a linear approximation of the timing-model can be used to obtain a better fit to the timing-model. In this linear approximation, the timing-residuals depend linearly on $\xi_a = \beta_a - \beta_{0a}$:

$$\vec{\delta t} = \vec{\delta t}^{\rm prf} + M\vec{\xi}, \tag{2}$$

where $\vec{\delta t}$ are the timing-residuals in the linear approximation to the timing-model, $\vec{\delta t}^{\rm prf}$ is the vector of pre-fit timing-residuals, $\vec{\xi}$ is the vector with timing-model parameters, and the $(n \times m)$ matrix M is the so-called design matrix (van Haasteren et al. 2009), which describes how the timing-residuals depend on the timing model parameters.

The likelihood of the timing-residuals is given by (van Haasteren et al. 2009):

$$P(\vec{\delta t}|\vec{\xi}, \vec{\phi}) = \frac{\exp\left(\frac{-1}{2}\left(\vec{\delta t} - M\vec{\xi}\right)^T C^{-1}\left(\vec{\delta t} - M\vec{\xi}\right)\right)}{\sqrt{(2\pi)^n \det C}}, \tag{3}$$

where $\vec{\phi}$ are the parameters fully describing the covariance matrix $C = C(\vec{\phi})$. This likelihood is the basis for several current methods designed to analyse stochastic signals in pulsar timing data.

The traditional method of analysing pulsar timing data consists of only including the TOA uncertainties in the construction of the covariance matrix C. These uncertainties then populate the diagonal elements $C_{ij} = \delta_{ij}\sigma_i^2$, with δ_{ij} the Kronecker δ. In that case, the maximum likelihood (ML) of Equation (3) becomes the weighted least-squares (WLS) solution. This WLS is one of the standard solutions of for instance Tempo2 (Hobbs et al. 2006; Edwards et al. 2006).

3. Potential sources of PTA-observable GWs

Due to the observation cadence of the pulsars, and the size of the detector (the earth-pulsars system), the PTAs are sensitive to very low-frequency gravitational waves (10^{-9}—10^{-8}Hz). In this section we briefly review the theoretically predicted source candidates.

3.1. Deterministic sources: continuous waves and bursts

Almost 10 years ago, Sudou et al. (2003) reported a possible supermassive black hole binary system in the radio galaxy 3C66B. Such a system would be observable in the PTA frequency band, and subsequent work by Jenet et al. (2004) showed that the gravitational waves coming from this system would have produced a clearly detectable signal in the TOAs of existing datasets. The non-detection of the expected gravitational wave signal convincingly ruled out the postulated supermassive black hole binary; a good demonstration of the potential resolvability of continuous gravitational waves of PTAs.

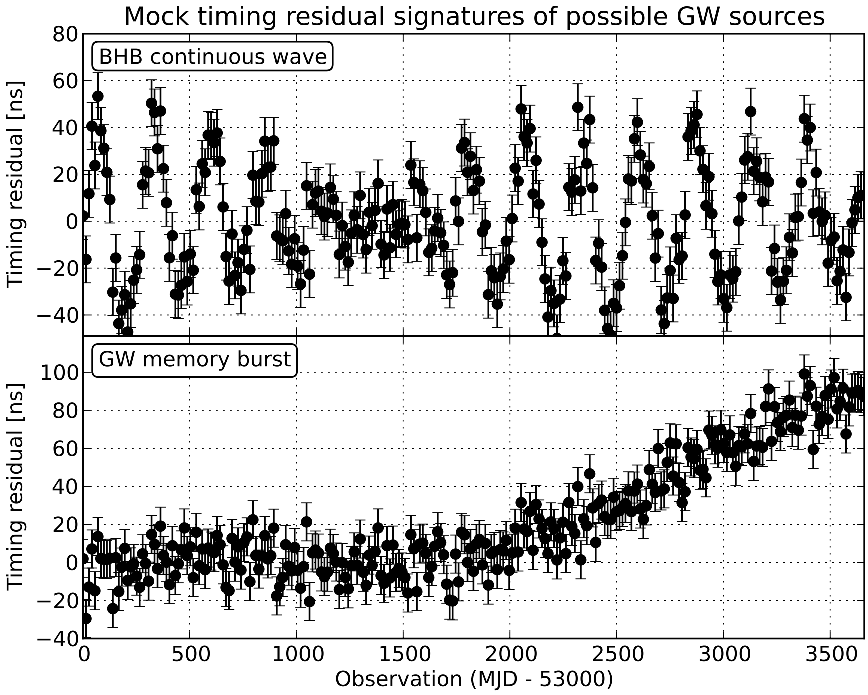

Figure 1. Injected continuous gravitational waves in mock timing-residuals with an rms of 10ns. Currently no PTA is capable of reaching this kind of sensitivity, but the Square Kilometre Array (Dewdney et al. 2009) may be able to time pulsars to this precision. In the upper panel we show the signal as it would be generated by a massive black-hole binary with a chirp mass of $\mathcal{M} = 2 \times 10^8 M_\odot$ at a frequency of $f = 5\times10^{-8}$ Hz. In the bottom panel we show the gravitational wave memory signal, uncorrected for the timing-model, where the burst hit the earth at MJD 54700.

Nowadays there is wide interest in the detection problem of continuous gravitational-wave sources in pulsar timing data. Though any object with a changing mass quadrupole moment emits gravitational waves, roughly two plausible sources of continuous gravitational waves are currently being explored in the literature: continuous waves from inspiring binary stars, like supermassive black-hole binaries, and continuous waves originating from bursts of gravitational wave memory (Seto 2009; van Haasteren & Levin 2010; Pshirkov et al. 2010; Cordes & Jenet 2012). In Figure 1 we present examples of these two types of continuous gravitational waves.

Some sources of burst gravitational wave emission may be detectable with pulsar timing experiments, including the formation of supermassive black holes (Thorne & Braginskii 1976), highly eccentric supermassive black hole binaries (Enoki & Nagashima 2007), close encounters of massive objects (Kocsis et al. 2006), and cosmic string cusps (Damour & Vilenkin 2005).

3.2. Stochastic backgrounds

A stochastic background of gravitational waves could theoretically be generated by several different mechanisms, including: large number of black-hole binaries located at the centres of galaxies (Begelman et al. 1980; Phinney 2001; Jaffe & Backer 2003; Wyithe & Loeb 2003; Sesana et al. 2008), by relic gravitational waves (Maggiore 2000; Grishchuk 2005), which are faint remnant radiation left over from the big bang analogous to the cosmic microwave background, and by oscillating cosmic-string loops (Damour & Vilenkin 2005; Ölmez et al. 2010; Sanidas et al. 2012). Usually, these backgrounds are assumed to be isotropic due to their composition of many individually unresolvable single sources, though that assumption may not be valid at all frequencies (e.g. Sesana et al. 2008). Anisotropy of a potential stochastic background of gravitational waves is an area of active research; here we will ignore this aspect, and focus only on isotropic backgrounds.

Compared to deterministic gravitational wave signals, stochastic gravitational wave signals are challenging to disentangle from non-gravitational wave signals, because there are no specific waveforms that can be matched with them. The characteristic feature of a stochastic gravitational wave background in the observations of a single pulsar is its power spectral density in the timing residuals, which unfortunately can be similar to the signature of timing noise ("red spin noise" Cordes & Shannon 2010; Shannon & Cordes 2010) in millisecond pulsars. Therefore, the uniqueness of a stochastic gravitational wave background signal resides in the correlations such a signal induces between the timing residuals of different pulsars (Hellings & Downs 1983). These correlations are shown in Figure 2. A detection of a stochastic gravitational wave background should consist of an unambiguous demonstration of the presence of the correlations of Figure 2 in the observations. Recently, Lee et al. (2012) provided a framework to calculate how to optimise the observing schedule of PTAs to be optimally sensitive to the correlations of a stochastic background.

Besides a stochastic background induced by gravitational waves, other mechanisms may produce a stochastic background signal in the timing residuals. For instance, inaccuracies in terrestrial time standards may also produce a stochastic background signal in the timing residuals. The TOAs produced at the end of the data reduction pipeline are all relative to an atomic timescale, computed by the Bureau International des Poids et Mesures (BIPM) with respect to local atomic clocks distributed around the globe. This terrestrial time standard, referred to as International Atomic Time (or Temps Atomique International, TAI), is accurate enough for most applications in science. However, pulsars are such accurate instruments that inaccuracies in TAI are in principle detectable in observations. Recently, Hobbs et al. (2012) have shown that a new time standard independent from any existing terrestrial clocks can be constructed using an ensemble of pulsars. This ensemble pulsar time standard allows for a completely independent check of TAI. If there are indeed inaccuracies in TAI, this signal would show up as a stochastic background signal in the timing residuals not unlike a stochastic background of gravitational waves. However, the correlations are uniform between all pulsars, which makes this signal clearly distinguishable from the correlated signal shown in Figure 2.

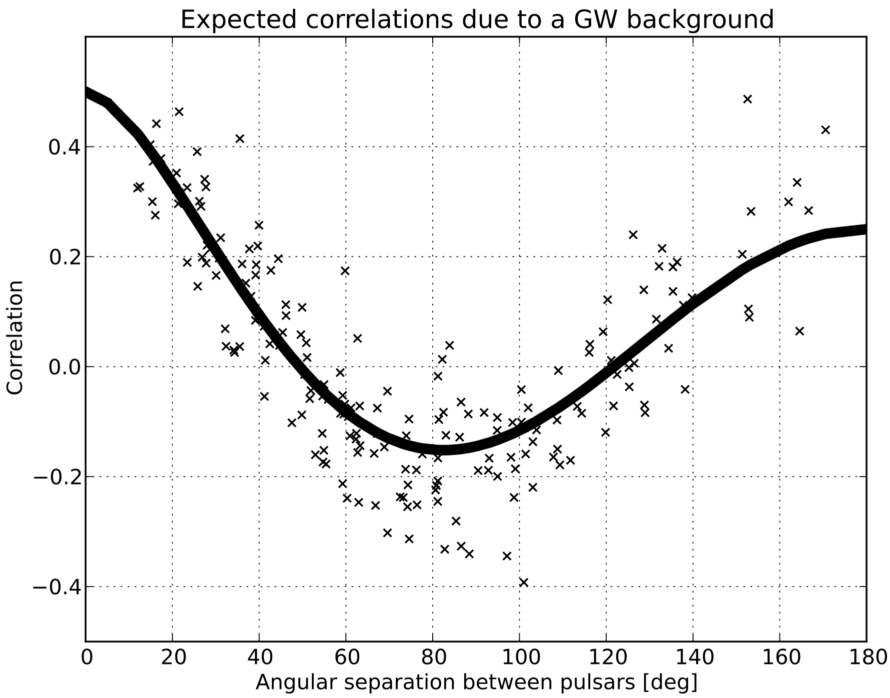

Figure 2. The expected correlation in the timing residuals of pairs of pulsars as a function of angular separation for an isotropic gravitational wave background (Hellings & Downs 1983). The estimated correlations marked with 'x' are for pulsar pairs of a simulated PTA, obtained from an idealised noiseless mock dataset, with a gravitational wave background signal with spectral index $\alpha = -2/3$ (Jenet et al. 2005). The scatter is due to the self-noise in the background.

4. Data analysis

As discussed in Section 2.2, the likelihood of Equation (3) forms the basis of several current methods of pulsar timing array data analysis. In this section we discuss some of the currently developed methods to search for gravitational wave signals in pulsar timing data.

4.1. Analysis of timing noise

However stable timekeepers millisecond pulsars may be, they are still subject to stochastic changes in the rotational rate, thought to be due to the random angular-momentum exchange between the normal and superfluid components of the pulsar. The generic term for this kind of noise is pulsar timing noise, or "red spin noise" (Cordes & Shannon 2010; Shannon & Cordes 2010). Other sources of noise that limit the pulsar's applicability as an Einstein-clock include the time-dependent influence of the interstellar medium on the optical path length between the pulsar and the Earth (dispersion measure variations), and the variations in the terrestrial time standards used to generate the TOAs from the raw baseband data. Various sources of noise can be mitigated to some extend (e.g. dispersion measure variations), whereas other sources of noise we must accept as being part of our datasets (e.g. red spin noise). In this section we discuss some methods proposed in the literature that try to incorporate this aspect of the observations in the estimation process of the timing model parameters.

In brief, two main approaches exist to the analysis of pulsar timing data in the presence of time-correlated stochastic noise:

- The Cholesky method of Coles et al. (2011), implemented in the Tempo2 plugin spectralModel, is based on a whitening transformation of the timing residuals. The whitening transformation is obtained from an accurate determination of the power spectrum of the timing residuals, robustly taking into account the timing-model fits, red timing noise, and irregular sampling. Mathematically, the timing-model fit based on a whitening transformation is equivalent to the maximum of the likelihood of Equation (3).

- The Bayesian method of van Haasteren et al. (2009); van Haasteren & Levin (2012) is based on marginalisation of Equation (3), where the stochastic model parameters $\vec{\phi}$ are determined from the likelihood simultaneously with the timing-model parameters.

For gravitational wave signal analysis, the most important component of the timing-model is the pulsar spin evolution. Due to the emission of electromagnetic radiation, rotational energy of the pulsar is lost over time, causing the pulsar spin frequency to gradually decrease. This process is referred to as quadratic spindown, because of the quadratic signal this process causes in the timing residuals. Therefore, a quadratic shape is always removed from the timing residuals, which causes a lot of absorption of low-frequency power in any signal in the pulsar timing observations. Since most of the potential gravitational wave signals discussed in Section 3 are or can be low-frequency, the quadratic spindown parameters are very important to be determined correctly when searching for gravitational wave searches in pulsar timing data.

4.2. Stochastic background analysis

Jenet et al. (2005, hereafter J05,) developed a detection statistic that is sensitive to the correlations induced by an isotropic stochastic background of gravitational waves, shown in Figure 2. For each pair of pulsars, the zero-lag correlation between the respective timing residuals can be calculated (shown as the 'x' markers in Figure 2). J05 showed, for expected amplitudes of a gravitational wave background, that this signal could be unambiguously detected if 20 or more pulsars were observed over a period of 5 years, each with an rms timing residual of 100-500 ns.

The work by J05 initiated wider interest in the detection problem of isotropic stochastic gravitational wave backgrounds, resulting in various techniques to measure or constrain such backgrounds of gravitational waves. Currently, the different methods can be roughly divided in two main approaches:

- Detection methods based on the correlation statistic of J05 (e.g. Yardley et al. 2011; Demorest et al. 2012). These methods use an adjusted formulation of the J05 statistic to more optimally incorporate features of real observations, like irregular sampling, and the presence of time-correlated noise discussed in Section 4.1.

- Detection methods based on some formulation of the likelihood of Equation (3) (e.g. van Haasteren et al. 2009; Anholm et al. 2009). These methods use the likelihood as a function of the amplitude (and sometimes other parameters) of the stochastic gravitational wave background to obtain a detection statistic.

Although much work has currently gone into the development of the different analysis methods, there is no consensus yet on what exactly the advantages and disadvantages are of the different methods. To date, no formal comparison has been made between all different data analysis methods. The IPTA has therefore recently decided to periodically release public mock datasets, containing injected gravitational wave signals: the IPTA mock data challenge (Jenet et al. 2012). The first challenge is relatively simple, but subsequent releases are supposed to become increasingly difficult. These mock data challenges should provide a good comparison between the different detection methods.

4.3. Continuous waves and burst analysis

Studies of sensitivity of pulsar timing experiments to single inspiraling binaries have been carried out for decades (Wahlquist 1987; Lommen & Backer 2001; Jenet et al. 2004), but only recently has this subject gained much wider interest due to the ever increasing sensitivity of PTA projects. Recently, van Haasteren & Levin (2010) describe the gravitational wave memory effect, and describe a Bayesian method to detect such a signal. Their method is in effect directly applicable to any deterministic waveform, and explicitly takes into account the complete timing-model fit, unevenly sampled data, and possible red timing noise.

More recently there has been much wider interest in single source detection methods, focusing on producing prospects on parameter estimates (Boyle & Pen 2010; Corbin & Cornish 2010; Lee et al. 2011), burst detection (Finn & Lommen 2010; Pitkin 2012), computational issues (Ellis et al. 2012a,b), optimising sensitivity to single source (Burt et al. 2011), and multiple sources (Babak & Sesana 2012). The only study that has applied their single source detection pipeline on real PTA data has been Yardley et al. (2010), using data of the PPTA.

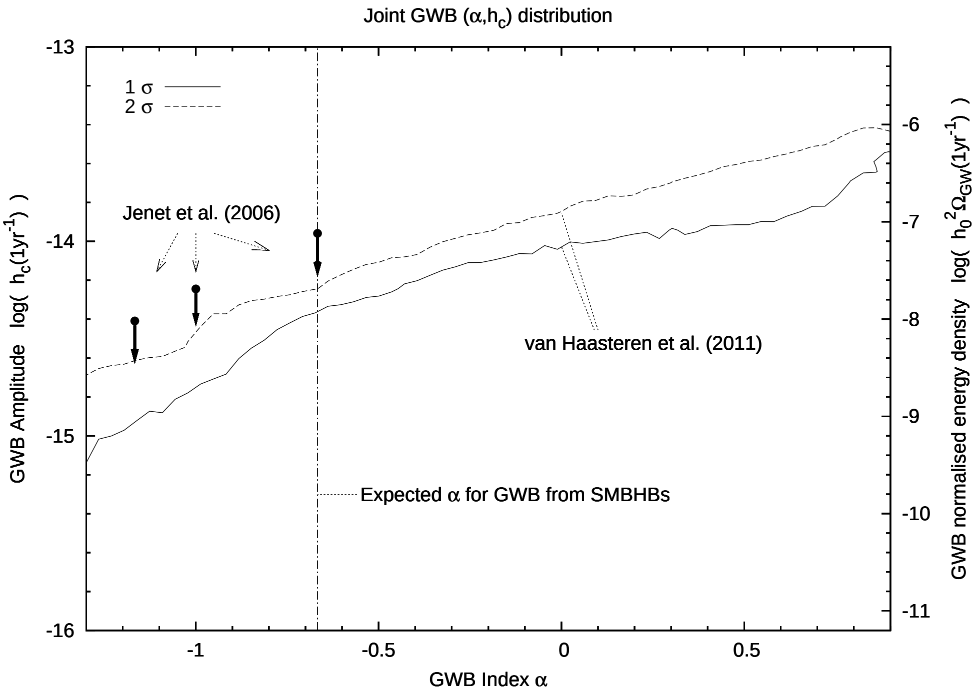

Figure 3. The most-constraining published upper limit on the isotropic stochastic gravitational wave background to date, published in van Haasteren et al. (2011). This was an analysis of data of three telescopes of the EPTA using a Bayesian analysis method. This analysis assumes a power-law power spectral density with spectral index α (x-axis), and characteristic strain amplitude h_c (y-axis) as defined in van Haasteren et al. (2011). The 68% (1σ) and 95% (2σ) credible regions are indicated, with limits of the PPTA of Jenet et al. (2006) shown as the points with arrows. For an ensemble of supermassive black-hole binaries (SMBHBs), the spectral index is expected to be $\alpha = -2/3$ (Phinney 2001).

5. Current limits and future prospects

The first detection of gravitational waves with PTAs is likely to be a detection of a stochastic background of gravitational waves. The currently best published upper limit on such a background is presented in Figure 3 (van Haasteren et al. 2011). However, with the spectral index expected to be $\alpha = -2/3$, the sensitivity of PTAs will grow as $T^{5/3}$, with T the duration of the experiment. Provided that the millisecond pulsars do not display too much red spin noise (Verbiest et al. 2009), the PTAs will become sensitive enough to probe the full range of predicted gravitational wave background levels within the next decade (Sesana et al. 2008).

6. Conclusions

It is possible that gravitational waves will be detected within the next decade by international pulsar timing array projects. Recent significant increases in sensitivity of pulsar timing arrays have resulted in wider theoretical attention. This has resulted in more advanced data analysis methods for sources of continuous gravitational waves, for stochastic backgrounds of gravitational waves, and for gravitational wave bursts. We have discussed the current pulsar timing data analysis techniques, and the potential sources of gravitational waves. Using a pulsar array as a gravitational wave detector is complimentary to other searches that are attempting to detect much higher-frequency gravitational waves.

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