Pulsar Timing Array Experiments

J. P. W. Verbiest\textsuperscript{*}, S. Osłowski and S. Burke-Spolaor

Abstract Pulsar timing is a technique that uses the highly stable spin periods of neutron stars to investigate a wide range of topics in physics and astrophysics. Pulsar timing arrays (PTAs) use sets of extremely well-timed pulsars as a Galaxy-scale detector with arms extending between Earth and each pulsar in the array. These challenging experiments look for correlated deviations in the pulsars’ timing that are caused by low-frequency gravitational waves (GWs) traversing our Galaxy. PTAs are particularly sensitive to GWs at nanohertz frequencies, which makes them complementary to other space- and ground-based detectors. In this chapter, we will describe the methodology behind pulsar timing; provide an overview of the potential uses of PTAs; and summarise where current PTA-based detection efforts stand. Most predictions expect PTAs to successfully detect a cosmological background of GWs emitted by supermassive black-hole binaries and also potentially detect continuous-wave emission from binary supermassive black holes, within the next several years.

\textsuperscript{*} corresponding author
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Introduction

Neutron stars are the collapsed cores of massive stars that have undergone a supernova explosion after the end of nuclear burning and are supported from further collapse by neutron degeneracy pressure [12, 52, 114]. Since neutron stars are far more compact than their progenitor stars, they tend to exhibit very short rotational periods and extremely strong magnetic fields, as shown in Figure 1. Generally the magnetic axis is not aligned with the spin axis, so magnetic dipole radiation that is created in the neutron star’s atmosphere is swept around in space, somewhat like the beam of a lighthouse (this is the so-called “lighthouse model”). Depending on the orientation of the beam and its width, Earth may fall within that radiation beam once per rotation – which then causes the neutron star to be detected as a source of pulsed radiation, otherwise referred to as a “pulsar”.

Radio Emission from Pulsars

Following the lighthouse model described above, it is natural to expect that pulsars appear to the observer as so-called “pulse trains”: pulses of emission separated by a fixed period that equals the spin. These appear with a shape defined by the plasma properties in the pulsar’s magnetosphere, which can differ greatly from one pulsar to the next (see Figure 2). The emission mechanism of pulsars is understood in broad terms [see e.g., 109]. A few intriguing observational facts have been identified over the half century since the first pulsars were discovered. Most importantly, it has been shown that for most pulsars, the exact shape of individual pulses changes randomly from one period to the next. In contrast, however, the average shape of the pulsed emission is typically stable on timescales from minutes up to decades [56]. This implies that for any given pulsar, the pulsed emission can be averaged after accounting for the pulsar’s rotational period. The average pulse shape that can be obtained in this way is unique for the pulsar and can be thought of as a fingerprint. At radio wavelengths this average and reproducible pulse shape is typically called the pulse profile of the pulsar, whereas the term light curve is more common at higher frequencies (gamma and X-rays). The shape of the profile is defined by the emitting geometry in the pulsar magnetosphere. Since it is expected that the emission height is different for photons with different frequencies [36], it stands to reason that the shape of the pulse profile also typically differs with observing frequency (again, see Figure 2).
Not all pulsars have a stable pulse profile and not all pulsars emit radiation all the time. Indeed, a veritable zoo of pulsar emission phenomena has been discovered, studied and described throughout the years. There are so-called “nulling” pulsars [15], which often turn off, only to reappear at some point after. Some pulsars null for minutes on end, others for hours – some even turn off for months or years (at which point they are also called “intermittent” pulsars), suggesting an almost continuous distribution all the way up to so-called “RRATs” (Rotating Radio Transients), which only sporadically emit one or several pulses of radiation [108, 29]. Another category of pulsar emission is displayed by the “moding” pulsars [14]. These do not have one characteristic fingerprint, but two or three – and they arbitrarily change between them: while one day their pulse profile may look one way, the next day it may look different, only to go back to its original state on day three. Moding can also have a wide range of possible time scales, from single pulses all the way up to months or years between mode changes. Finally, there are drifting pulsars [46]. These “drifters” also have a well-defined pulse period that is readily and repetitively measurable on timescales of minutes to hours, but on timescales of seconds that pulse period seems to be overestimated, as the pulse appears to come a bit too late.
Fig. 2 Pulse profile shapes vary across pulsars and observing frequencies. Shown are pulse profiles for two traditional PTA pulsars: PSR J0437–4715 (left column), and PSR J1022+1001 (right column); and for each pulsar this profile is shown at three different observing frequencies: at \( \sim 726 \text{ MHz} \) (top row), \( \sim 1369 \text{ MHz} \) (middle row) and \( \sim 3100 \text{ MHz} \) (bottom row). Total intensity profiles are shown in full black lines, linear polarisation in dashed red lines and circular polarisation in blue dotted lines. The tendency of getting sharper profile shapes at higher frequencies causes the timing precision to increase at those frequencies, although generally the noise level also increases due to the steep spectrum of pulsars [20, 65]. Consequently, most pulsar timing to date has been carried out at intermediate frequencies around 1.4 GHz. Finally, while this figure only shows profiles for MSPs, the evolution with frequency has been shown to be far more extreme in the case of slow pulsars [79]. (These plots were made based on the public data published by Dai et al. [39] and contain hundreds of hours of observing time at the higher frequencies, causing the radiometer noise to be barely visible.)
after each rotation, only to “reset” after a few dozen rotations, leading to the more stable long-term periodicity.

Luckily for pulsar astronomers, the nulling, moding and drifting pulsars have turned out to be the exception rather than the rule and the majority of pulsars manifest themselves as predictably repetitive pulses of emission that have arbitrary pulse shapes on timescales of seconds, but stable and well-defined pulse shapes on timescales from minutes upwards.

**Pulsar Lifecycle and Spin Properties**

Whereas the first few pulsars that were discovered appeared to be a fairly homogeneous group of objects, extensive surveys have continuously expanded the parameter space in which pulsars have been discovered; and consequently a wide variety of pulsar types is now known.

After the formative supernova explosion, pulsars start their new life as so-called “young” pulsars with spin periods of a few tens of milliseconds and a magnetic field strength of order $10^{12}$ G at their surface [132, 24]. The emission of magnetic dipole radiation does make them lose angular momentum and consequently their rotation slows down gradually, typically by about $10^{-13}$ seconds per second. The youngest and most well-known example of this class of pulsars is the Crab pulsar which was formed in a supernova explosion in 1054 CE [97, 136], which has been recorded by several civilisations across the world.

After the first few thousand years, the spin period of young pulsars has slowed down sufficiently to have an appreciable impact on the spindown itself, which slows down their evolution. At this point they turn into the first discovered type of pulsar: the so-called “slow” pulsars or “canonical” pulsars. These are pulsars with rotation periods between about a tenth of a second and roughly ten seconds. Their magnetic fields are thought to have strengths of roughly $10^{10}$ G to $10^{13}$ G and they are expected to have formed thousands to hundreds of millions of years ago (see Figure 1). Their spin period gets longer by about $10^{-14}$ s every second, as they lose angular momentum slowly but steadily. This loss in angular momentum causes them to eventually rotate too slowly to produce detectable amounts of radio waves and so after about a billion years they “turn off” and become undetectable [125].

Most of the slow pulsars are solitary objects that were either born as solitary stars, or broke free from their companion stars during their supernova explosion. A small sub-set, however, do have companion stars that are almost without exception main-sequence stars. When these main-sequence stars evolve and turn into red giants, it is not uncommon that their outer atmospheric layers stray into the gravitational well of the pulsar and cause it to accrete matter; and along with the matter, angular momentum. These pulsars are then spun-up while their magnetic field decays. The result is a “millisecond” pulsar (MSP), with spin periods between 1 ms and about 30 ms. Due to the accretion process, MSPs have relatively weak magnetic fields ($10^9$ G or less) and consequently their spin-down rates are also far lower than for slow pulsars (typ-
ically of the order of $10^{-20}$ s/s). As a result the rotational and emission properties of MSPs are not thought to appreciably evolve over their lifetimes. For an overview of formation and evolution of MSPs see [3, 22].

Given the extremely small spin periods, stable pulse profiles for MSPs can already be obtained in a matter of minutes or even seconds. Furthermore, to date, only very few MSPs [101] have been demonstrated to show any of the anomalous emission properties (nulling, moding, drifting) mentioned in the previous section that some of the slow pulsars display. Finally, due to the much larger angular momentum, MSPs have turned out to be far more stable clocks than slow pulsars. These are the reasons why MSPs have become known as “nature’s gift to physics”: the perfect Einstein clock that can be used to test a wide range of relativistic predictions.

Pulsar Timing and Pulsar Timing Arrays

Pulsar timing is a method that exploits the highly regular spin period of pulsars and their predictable pulse shapes, to study a wide range of questions in physics and astrophysics. In essence, when doing pulsar timing, one monitors the times at which subsequent pulses from a pulsar arrive at an observatory. These observed pulse-arrival times or ToAs are then compared to a mathematical model that attempts to quantify all the factors that impact the travel time of the electromagnetic waves on their way from the pulsar to the Earth. In practice, a number of complications need to be dealt with, as outlined below. A more advanced approach is to use multiple pulsars – an “array” of pulsars – to look for signals that correlate between different pulsar pairs. Such experiments are called “pulsar timing arrays” (PTAs).

Template Profiles

In its simplest form, pulsar timing could be based on the times when the peaks in a train of pulses are detected. In order to increase the measurement precision, one could also take the intensity-weighted average arrival time of any given pulse. A far more powerful method, however, is to use the information encoded in the shape of the pulse, to measure the arrival time relative to a standardised pulse shape. This can be thought of as the ultimate, noise-free pulse profile. Obtaining such a standardised pulse shape or “template profile” is necessarily an iterative process. Fundamentally, as many pulses should be averaged together as possible. However, in order to align said pulses, an accurate pulsar timing model should be used to predict the phase of subsequent pulses to a precision far better than the time-resolution afforded by a typical observation. To give an example, we aim to predict arrival times to a precision of nanoseconds while typical observations have phase resolution on the order of microseconds. The use of all of the information contained in a complex pulse
profile, through the use of a template profile, allows one to achieve this necessary magnitude of improvement.

Since the creation of the template profile itself is the very start of the path towards a functional pulsar timing model, typically the entire process gets iterated so that the template profile and the timing model can both improve until their solutions converge.

A danger in the creation of template profiles is so-called “self-standarding”. This is a phenomenon that occurs when the data that are being used in the timing, are also used to construct the template profile. Specifically, if the number of observations that are combined to construct the template profile is too low (a typical rule of thumb is that “too low” is less than a few thousand), then the noise within the observation can be “recognised” in the template profile, leading to inaccurate offset measurements [as illustrated clearly in Appendix A1 of 64]. Consequently, many timing experiments make use of analytic models to describe the template profile. These may not always be able to perfectly model all the pulse-shape features, but they avoid timing corruptions caused by self-standarding. Alternatively, a smoothing filter may be applied to the template, in order to reduce the correlating noise [41].

It was mentioned earlier that pulse profile shapes typically change with the observing frequency. This should ideally be taken into account when constructing the template profile, i.e. the template profile should effectively have a dependence on observing frequency, too. In most published works this has not been the case because the bandwidth of pulsar observations used to be sufficiently narrow that frequency evolution of the pulse profiles was effectively undetectable, but over the last decade (fractional) bandwidths of observing systems have increased so significantly that so-called “frequency-resolved” template profiles are rapidly becoming the norm rather than the exception. Also in this case, one can either create an analytic description of the profile in two dimensions [115, 95] or use a template purely based on accumulated data [45].

**Template Matching**

Once a template profile has been created, it can be used to calculate the ToAs of the various observed pulse trains. Since most pulsars are so faint that individual pulses cannot be detected and because single pulses are usually not all alike, standard pulsar-timing experiments do not time individual pulses, but average subsequent pulses modulo the pulse period\(^1\). This averaging procedure is commonly referred to as **folding** – it reduces the time resolution of the observations while **phase** resolution is maintained. Typical values for the time resolution of pulsar-timing data after folding, are anywhere from minutes to one hour, depending on the brightness of the pulsar and the goal of the experiment. Phase resolution is defined by the number of

\(^1\) At this point the question of which pulse is being timed exactly, is in principle an arbitrary choice, but the most commonly used pulsar-timing software uses a pulse in the centre of the observation.
bins across the profile, with typical values ranging from 128 to 2048, depending on
the sensitivity of the telescope and the bluntness or sharpness of the pulse profile.

The folded pulse profiles could be cross-correlated with the template profile in
order to achieve the phase of the observation—which can then be added to the ob-
servation’s time stamp in order to achieve a ToA. In practice this measurement is
commonly undertaken in the Fourier domain, as explained in detail in the appendix
of Taylor [143]. Since an offset in the cross-correlation is equivalent to a phase gra-
dient in the cross-power spectrum, typically ToAs are determined by least-squares
fitting the phase gradient in the cross-power spectrum of the template profile and
the folded observation. The phase offset resulting from this is then added to the
observation’s time stamp.

The measurement uncertainty of these phase offsets—and hence of the ToAs—is
an important value as well, since many pulsars appear to have highly variable flux
densities (a process caused by the interstellar medium, called scintillation), which
means that not every ToA carries as much information and hence should not be
weighted equally. Specifically, the pulse profile that is to be timed will contain a
certain amount of white noise called radiometer noise, which depends on the obser-
vational properties of the pulsar and the observing system as follows [96]:

$$\sigma_{\text{ToA}} \propto \frac{S}{N} = \beta \sqrt{n_p l_{\text{int}} \Delta f} \frac{T_{\text{peak}}}{T_{\text{sys}}} \sqrt{W (P - W)} \frac{P}{P},$$

(1)

where $\sigma_{\text{ToA}}$ is the ToA uncertainty, $S/N$ is the signal-to-noise ratio of the observa-
tion, $\beta$ is a factor which describes instrumental losses, e.g. due to digitisation, $n_p$,
$l_{\text{int}}$ and $\Delta f$ are respectively the number of polarisations combined, the integration
time and the bandwidth of the observation, $T_{\text{peak}}$ is the brightness temperature of
the pulsar at the peak of its profile and $T_{\text{sys}}$ is the brightness temperature (i.e. noise)
of the observing system, which typically includes corrections for cable losses, instru-
mmental gain, spill-over and sky noise, amongst other things. $W$ is the equivalent
width of the pulse profile, defined as the integrated pulse intensity divided by the
peak intensity and $P$ is the pulse period.

The radiometer noise is the most fundamental factor limiting pulsar-timing pre-
cision, in the sense that it is present in all observations and is determined to a large
degree by the fixed properties of the pulsar and the technical capabilities of the tele-
scope. Traditionally it was quantified as the formal uncertainty of the phase-gradient
fit described above, although it has been shown that in the low-$S/N$ regime this can
cause irregularities [see 7, App. B], leading people to either remove ToAs below a
certain $S/N$ level (e.g. requiring $S/N > 8$) or to apply more advanced, Monte-Carlo-
based uncertainty estimations, as was proposed as “good pulsar timing practice” by
Verbiest et al. [153].
Timing Model Determination

Once the ToAs have been measured, they need to be compared to predicted arrival times provided by a pulsar timing model. A timing model is a mathematical formula that predicts the arrival time of a pulse based on a set of timing-model parameters. Generally, the timing model is defined in two steps [see also 143, 47]. In the first step, the measured pulse arrival time $t_{\text{obs}}$ is referred to a time of emission at the pulsar $t_{\text{PSR}}$. This is achieved by accounting for all known propagation and geometric delays:

$$t_{\text{PSR}} = t_{\text{obs}} - \Delta_{\odot} - \Delta_{\text{IISM}} - \Delta_{\text{Bin}}.$$  

Specifically, first the pulse ToA is transferred to the Solar System barycentre (i.e., corrected by a delay $\Delta_{\odot}$), which is the inertial reference frame most commonly used in pulsar timing. This transformation includes correction factors for relativistic effects caused by the mass distribution in the Solar system and the Earth’s orbital and rotational velocity, for atmospheric propagation delays (note these have mostly been neglected to date but will become important with the next generation of radio telescopes), for light-propagation times (the so-called Roemer delay), parallax effects, frequency-dependent propagation delays induced by the Solar Wind and corrections for the observatory clock.

After the ToAs have been transferred to the Solar System barycentre, interstellar propagation delays ($\Delta_{\text{IISM}}$) are corrected for. As described in more detail in the next section, these delays have long been treated as dependent on the observing frequency, but constant in time. With increased measurement precision provided by wider bandwidths and lower observing frequencies, time-variable models of interstellar dispersive delays are now becoming more common.

For pulsars that inhabit binary systems, there is one further transformation, namely from the barycentre of the binary system to the pulsar (delay $\Delta_{\text{Bin}}$). This includes the Roemer delay based on a Keplerian description of the binary orbit, but can also contain relativistic effects such as the Shapiro Delay (time dilation caused by the companion star’s gravitational field), the Einstein delay (time dilation caused by the pulsar’s gravitational field and gravitational redshift) or a host of other more complex effects, dependent on the binary’s properties. [See 47, for a complete listing.]

Once the time of emission $t_{\text{PSR}}$ is determined, it can be converted to a rotational phase based on a spin-down model that is usually simply described as a Taylor expansion:

$$\phi (t_{\text{PSR}}) = \nu (t_{\text{PSR}} - t_0) + \frac{1}{2} \dot{\nu} (t_{\text{PSR}} - t_0)^2 + \ldots,$$

(2)

where $\nu$ is the spin frequency of the pulsar, $\dot{\nu}$ its first derivative and $t_0$ an arbitrary reference epoch. Standard electromagnetic theory predicts a second frequency derivative $\ddot{\nu} = \frac{3}{2} \nu \dot{\nu}$, but in practice this is immeasurably small in the case of MSPs and is typically obscured by other effects (so-called timing noise, see further) in most slow pulsars. Consequently, by default pulsar timing models contain a spin
frequency and frequency derivative but not usually any higher-order spin frequency derivatives.

Initial timing models are derived from pulsar-search observations. These are raw time series that are not folded, but instead are Fourier transformed in order to obtain an instantaneous pulse period. By monitoring the pulse frequency evolve over several such observations, an initial estimate of the spindown and of the binary orbit can be determined. This then constitutes an initial timing model that can be used to predict the pulse frequency for future observations, allowing the data to be folded in real-time, which makes observations much less demanding in terms of data-storage and processing power requirements.

When a basic timing model has been constructed that is able to predict the arrival time of future observed pulses to well within a pulse period, it is said that “phase connection” has been achieved. From this point forward, the phases calculated in Equation 2 can be used to improve the timing model. Effectively, these phases should all be zero if the timing model was perfect and no corrupting noise sources were present. Consequently, any deviation from zero highlights effects which do affect the observations, but are not taken into account (correctly) by the timing model. These differences between the observation and the model are called the timing residuals and they lie at the core of pulsar-timing analyses. Indeed, the art of pulsar timing is to optimise and extend the timing model to decrease these timing residuals. In the optimal case, the timing residuals will only consist of white noise which is accurately quantified by the uncertainties of the ToAs. In this case the timing is fully dominated by the radiometer noise described earlier.

Each parameter that is contained in the timing model affects the timing residuals in a well-defined way, which is called the timing signature of this parameter. Consequently, simply by visual inspection of the timing residuals, particular errors can sometimes easily be picked out, as shown in Figure 3. In most practical cases the uneven spacing between observations, the variability in the ToA uncertainty and the combination of multiple timing signatures in incomplete or outdated timing models make the analysis of timing residuals rather more complex than these simplified examples suggest.

**Interstellar Propagation Delays**

A particular source of difficulty when analysing pulsar-timing data, is the impact of the ionised part of the interstellar medium (also referred to as the IISM). The refractive index of the interstellar medium is determined by the plasma frequency, which is dependent on the local electron density [96]:

$$f_p = \sqrt{\frac{e^2 n_e}{\pi m_e}} \approx 8.5 \text{kHz} \sqrt{n_e},$$
Fig. 3 Examples of pulsar timing residuals. The top-left figure shows a typical PTA data set taken from [106]. The residuals are not purely white in this case, most likely due to a combination of uncorrected variations in interstellar propagation delays and interstellar dispersion. In the top-right figure the impact of a 1% change in the spindown is demonstrated, leading to a clear quadratic trend in the residuals as the spin period gets increasingly incorrect as time progresses. The bottom-left figure shows a positional offset of 0.1 arcsec in both right ascension and declination, leading to an annual sine wave with constant amplitude. The bottom-right plot shows what happens in contrast if the position is correct (at the reference epoch near the start of this data set) but the proper motion is 10% incorrect. This causes a linear increase in positional error and hence induces an annual sine wave with linearly growing amplitude.

where $e$ is the electron charge, $n_e$ is the electron density in units of cm$^{-3}$ and $m_e$ is the electron mass. Given that plasma frequency, the refractive index for a photon with frequency $f$ can be determined as: $\mu = \sqrt{1 - \left(\frac{f_p}{f}\right)^2}$. Since the group velocity of electromagnetic waves is dependent on the refractive index ($v_g = \mu c_0$), this leads to a frequency-dependent group velocity which is observable as a frequency-dependent propagation delay:

$$\Delta t = \frac{f_p^2 - f^2}{K} \text{DM},$$
where $\text{DM}$ is the “dispersion measure” defined below and the constant $K = \frac{1}{\mathcal{D}} = 2.41 \times 10^{-4} \text{MHz}^{-2} \text{pc/cm}^{-3}\text{s}$ is the inverse of the “dispersion constant”. Theoretically, the dispersion constant could be determined to higher precision (specifically, $\mathcal{D} \equiv \frac{c^2}{8\pi mc}$), but in pulsar timing it has traditionally been fixed as given above [80].

The dispersion measure is straightforwardly defined as the integrated electron content along the line of sight between the telescope and the pulsar:

$$\text{DM} = \int_0^D n_e \text{d}l,$$

where $n_e$ is the electron density in cm$^{-3}$, $D$ is the pulsar distance in pc and DM is typically expressed in units of pc/cm$^{-3}$. However, given that in most pulsar-timing software $\mathcal{D}$ has been defined fixed at the above-mentioned value and since the actual observable is $\mathcal{D} \times \text{DM}$, in practice most DM measurements would require a slight correction before being interpreted as physical electron density measures, as described by Kulkarni [80].

Due to the typically high spatial velocities of radio pulsars [up to 1000 km/s and beyond 33], the line of sight along which the pulses travel to Earth sweeps through interstellar space; and due to the numerous turbulent structures that are present throughout that space [5], this motion causes the DM to change as a function of time. While such variability has long been known to exist, it was mostly detectable as a slowly-varying, red-noise process. Since the turn of the century, however, with improved instrumental sensitivity, ever more precise measurements of DM variations in time have been detected and accurate modelling of DM($t$) is becoming a complex and essential part of pulsar timing experiments [70, 74].

One particular component that contributes to temporal variations in DM, is the Solar Wind. Due to the annual motion of lines of sight – particularly for pulsars near the ecliptic plane – the additional dispersion caused by the Solar Wind has a clear annual signature, which is typically modelled straightforwardly by assuming the Solar Wind to be homogeneous and spherically symmetric [47]. Generally, it is assumed that such a straightforward model would suffice for the purposes of high-precision pulsar timing, except perhaps closest to the Sun, so in addition to the spherical models, PTAs have tended to remove ToAs for observations that took place within 5-10 degrees of the Sun [153]. It has been attempted to extrapolate optical observations of the Sun to derive a more detailed, inhomogeneous model of the Solar Wind for pulsar-timing purposes [157], but while this model was shown to provide an accurate spectrum of inhomogeneities, it does not provide accurate corrections for pulsar-timing experiments [146].

In addition to dispersion, the IISM introduces a host of other propagation effects, as recently reviewed by Stinebring [138]. In most cases these effects are not limiting timing precision yet, although time-variable scattering (also referred to as multi-path propagation – a phenomenon that widens the pulse shape through increased travel path lengths) has been shown to be relevant in the timing of at least one MSP [92].
Timing Noise

Probably the hardest effect to mitigate in pulsar timing is the so-called “timing noise”. This term is generically applied to any timing residuals that are not white noise and cannot be corrected for by any of the deterministic timing-model parameters or by frequency-dependent DM models. Presumably this typically long-term noise is caused by inherent rotational instabilities in the neutron star itself [78], although the physical mechanism is as yet not known.

Timing noise has been studied extensively in slow pulsars [99, 59], where it is highly common. In MSPs, timing noise has been shown to be far less common, or to exist only at much lower levels [152, 91]. Nevertheless, as the length of pulsar-timing data sets grows and the timing precision increases, the prevalence of timing noise – and the importance of mitigation techniques – continues to increase even in MSP timing projects [10].

Other Noise Sources

After the timing model is optimised and the IISM variations are modelled and corrected for, ideally the timing residuals should be spectrally white and normally distributed. In practice a wide range of effects can negatively affect the timing, as recently reviewed by Verbiest and Shaifullah [151], although in practice the primary impact aside from the IISM and timing noise, is pulse phase jitter, also known as SWIMS. The work by Lam et al. [81] on 37 MSPs, shows that jitter is relevant primarily at low frequencies (particularly at observing frequencies below 1 GHz) but less so at higher frequencies, where high-precision pulsar timing is most commonly done. Since the importance of pulse jitter is strongly dependent on the sensitivity of the telescope (and on the available bandwidth), jitter will become an even more important source of noise in the next generation of radio telescopes [94]. One approach to avoid jitter-dominated timing, would be to divide up large interferometric telescopes into less-sensitive sub-arrays which allows more effective scheduling with lower jitter noise [135]. Another approach is to mitigate jitter noise in post processing as demonstrated in Osłowski et al. [112, 113].

Pulsar Timing Software

All of the analysis described above tends to be carried out with two separate types of data-analysis tools. Firstly one needs software that can process the raw observation files: the so-called archives that store radio-wave intensity as a function of polarisation, pulse phase, frequency and time. Secondly one needs model-fitting software that analyses the ToAs and the related timing models.
The primary software package that is used globally to analyse pulsar archives in the context of pulsar timing, is PSRCHIVE \cite{63, 150}. The only exception to the use of PSRCHIVE for the analysis of pulsar archives and the creation of ToAs is the possible creation of broadband ToAs with analytic, frequency-dependent templates. For this purpose, the purpose-built PulsePortraiture software \cite{115} is used increasingly commonly. For the analysis of ToAs and timing models, however, a larger variety of software packages has been developed. The most common ToA-analysis package is TEMPO2 \cite{62}, which is fundamentally a C/C++ translation of the much older, Fortran 77-based TEMPO package \cite{111}, which is still being used, often in parallel with TEMPO2. More recently, the PINT package was developed \cite{98}, which is an independent timing package written in Python and which is primarily used in North America.

Extending pulsar-timing software to constrain or detect correlated signals, such as those from GWs, is a non-trivial effort. Whereas frequentist methods have occasionally been implemented as part of packages like TEMPO2, it has become far more common to build independent software packages that are specifically aimed at Bayesian analyses of the timing model—including correlated signals. These packages tend to be written in Python and use Python wrappers around the source code of the standard pulsar-timing packages mentioned above—most commonly TEMPO2. The most recently used package for such advanced ToA analysis (including GW analyses) is ENTERPRISE \cite{48}; two commonly used earlier packages are TEMPO-NEST \cite{89} and PICCARD \cite{149}.

**Gravitational Waves and Other Correlated Signals**

In the previous sections we focussed on pulsar-timing effects and phenomena that affect each pulsar independently in fully unrelated ways. This is typical of the traditional single-pulsar timing experiments that have been the mainstream of pulsar-timing research ever since the first pulsar discovery. However, thoughout the 1980s the realisation developed that some signals might have timing signatures that correlate between pairs of pulsars \cite{57, 123, 50}. These signals would require a new, more complex analysis as they require a joint analysis of a larger number, say an array, of pulsars. The concept of the PTA was born, but would not come to full fruition until the start of the new millennium, after the number of known pulsars (and the num-

\footnotesize

\begin{itemize}
  \item \textsuperscript{2} \url{http://psrchive.sourceforge.net}
  \item \textsuperscript{3} \url{https://github.com/pennucci/PulsePortraiture}
  \item \textsuperscript{4} \url{https://bitbucket.org/psrsoft/tempo2/}
  \item \textsuperscript{5} \url{https://github.com/nanograv/tempo}
  \item \textsuperscript{6} \url{https://github.com/nanograv/PINT}
  \item \textsuperscript{7} \url{https://github.com/nanograv/enterprise}
  \item \textsuperscript{8} \url{https://github.com/LindleyLentati/TempoNest}
  \item \textsuperscript{9} \url{https://github.com/vhaasteren/piccard}
\end{itemize}
ber of PTA-worthy pulsars) had dramatically increased following a couple of highly successful surveys, primarily in the inner Galaxy $[103, 104]$. In the following paragraphs, an overview will be given of typical correlated signals in pulsar-timing data, with particular focus on the signature of gravitational waves.

**Correlated Signals in Pulsar Timing Data**

As described above, pulsar timing is effectively a model-fitting exercise where deterministic parameters get optimised as increasing amounts of data constrain the timing model. In addition to the deterministic components of the timing model, there are non-deterministic effects like DM variations or jitter noise that affect the timing differently for each pulsar. Finally, there are signals – both deterministic and non-deterministic – that affect all pulsars in similar ways. Three types of such correlated signals have been described to date $[123, 50]$:

- a monopolar signal that would most likely arise from imperfections in the reference clock $[60, \text{e.g.}]$,
- a dipolar signal that is most likely related to the Solar-System ephemerides $[53, \text{e.g.}]$ and
- a quadrupolar signal that is predicted to arise from gravitational waves $[57]$.

These correlated signals require more complex approaches: Solar-System ephemeris models could be updated with the pulsar-timing data $[32, 53, 147]$, but clock signals and gravitational-wave signatures are in essence random and hence the actual correlations between timing of different pulsars need to be used in order to determine those. For monopolar (or clock) signals, this has been successfully achieved a number of times $[122, 60]$, but quadrupolar (or gravitational wave) signal have so far not been unambiguously detected, partly also because all these signals interact, making a clear detection of the highest-order correlated signal (i.e. the gravitational waves) dependent on accurate determination of all other correlated signals $[145]$.

**Effect of Gravitational Waves**

The effect of GWs on pulsar timing was first described by Detweiler $[44]$ and more recently clearly summarised by Sesana and Vecchio $[130]$. Fundamentally, a GW passing over the Earth-pulsar system will introduce a time-variable redshift into the pulsed signal:

$$z(t, \hat{\Omega}) \equiv \left( \nu(t, \hat{\Omega}) - \nu_0 \right) / \nu_0,$$

where $\hat{\Omega}$ is the direction of propagation of the GW, $\nu_0$ is a reference frequency and $\nu(t, \hat{\Omega})$ is the observed pulse frequency which is defined by the geometry of the system (pulsar and GW position with respect to the observer) and the GW properties (polarisation and amplitude). The integral of these redshifts quantifies the impact on the timing residual:
\[ r(t) = \int_0^t z(t', \dot{\Omega}) dt' \]

for an observation taken a time \( t \) after the first observation in our data set. Furthermore, the observed redshift is only dependent on the perturbation of the space-time metric at the position of the pulsar at the time when the pulse was emitted; and the space-time perturbation at the location of Earth when the pulse was received.

A more straightforward way of putting this is that the GW impact on the pulsar timing residuals has two equally large components: a so-called \textit{"pulsar term"} that quantifies the impact of the GW on the emission of the pulse; and an \textit{"Earth term"} which quantifies the impact of the GW on the detection of the pulse on Earth. For non-evolving, sinusoidal GWs, the Earth and pulsar terms will be identical except for a phase offset between the two. Furthermore, the Earth term will affect all pulsars equally (albeit modulated in a quadrupolar way, as described by the so-called Hellings-and-Downs curve \cite{57}, see Figure 4) whereas the pulsar term will have a different phase offset for each pulsar, since the phase of the pulsar term depends on the distance to the pulsar.

For such mono-chromatic signals, this phase offset could in principle be measured along with the pulsar distance, allowing extremely precise localisation of both the GW source and the pulsars in the array \cite{87}. Such an experiment would, however, require a level of timing precision that is not realistically achievable with present-day telescopes (but may be achievable with the next generation Square Kilometre Array or SKA). At present, therefore, the pulsar term is typically considered a noise term, while the Earth term is the actual quadrupolar signal we hope to detect. The amplitude of the correlated signal will give insights into the GW’s origins (see the next Section), whereas the shape of the correlation curve could constrain fundamental physics of gravitational waves, like their polarisation properties \cite{86} and propagation speed \cite{84}. Furthermore, deviations from the theoretically expected Hellings-and-Downs curve can be expected for anisotropic backgrounds of GWs, where a few bright sources stand out above the background and cause a correlation function that is not only dependent on the angle between pulsars, but also on their location on the sky \cite{144}.

**GW Sources in the PTA Band**

The sensitivity of PTAs to GWs is limited in terms of the GW frequency by the length of the observing time span and the cadence of the observations. Specifically, PTAs are most sensitive near a frequency of \( 1/T \) where \( T \) is the length of the data set, i.e. on the order of a decade or more, which corresponds to a frequency on the order of nanohertz. Since the GW impact is a change in the pulse frequency \cite{44}, but the timing residuals are phases, i.e. effectively integrals over pulse frequency, the sensitivity of PTAs decreases with increasing frequency down to the Nyquist frequency \( 2/C \) where \( C \) is the cadence of the observations, typically of the order of
weeks or a month, which corresponds to a frequency cut-off of the order of micro-hertz.

This frequency range makes PTAs particularly complementary with other GW detectors like LIGO [10 Hz–10 kHz, 107] and LISA [0.1 mHz–1 Hz, 4]; and competitive with proposed GW detection methods based on space-based VLBI [28, 26]. The difference in GW frequencies furthermore implies that different sources of GWs can be expected to be detectable with PTAs. Specifically, four types of sources are anticipated, as described below. Example timing residuals induced by these four types of GW are shown in Figure 5.

Gravitational wave background (GWB): A GWB is a superposition of GWs from a large number of GW sources that add incoherently. The most likely GWB in the PTA frequency range is widely expected to arise from supermassive black hole binaries and predictions for its spectrum and amplitude are based on simulations such as the Millennium Run [129] or the Illustris simulation [75]. Specifically, the power spectrum of this GWB is expected to have a power-law shape with slope $-2/3$ and is likely to flatten or even tip over at GW frequencies lower than $\sim 0.1 \text{ yr}^{-1}$ [34]. Alternative backgrounds have been proposed [see, e.g. 27,
Fig. 5 Example timing residuals for four GW types on three different pulsars. These four panels show what the timing residuals that are caused by GWs could look like. The top-left panel shows the influence of a GWB (with characteristic strain amplitude $10^{-15}$ and spectral index $-2/3$), the top-right panel that of a CW (from a $10^9 M_\odot$ equal-mass binary supermassive-black hole at redshift $z = 0.01$), the bottom-left panel shows a BWM (with strain amplitude $5 \times 10^{-15}$) and the bottom-right panel shows a GW burst (without memory and with arbitrary waveform). The three different colors show the impact on different pulsars (i.e. different sky locations), with red showing the timing residuals of PSR J0437–4715, blue those of PSR J1012+5307 and black those of PSR J1713+0747. The simulated measurement uncertainty is 1 ns and no intrinsic spin noise or DM variations were included in the simulations. The top figure in each panel shows the pre-fit residuals (i.e. the raw GW signature), whereas the bottom plot shows the post-fit residuals. The difference between these is caused by fitting of the standard timing-model parameters. As can be seen, most of the power of the GWB is absorbed in the timing-model fit, since its long-term signature resembles the timing signatures of the pulse period and spindown, which absorb most of the signal. Such absorption of GW residuals in common timing-model parameters is less likely to happen for CWs or bursts, unless they happen to have a periodicity that is close to a year (or an integer fraction or multiple thereof) or to the orbital period of the pulsar being timed.
with differences in both spectral shapes and amplitudes, implying that an eventual detection would be able to differentiate between the origins of the GWB, or would be able to place constraints on the galaxy-merger history of the Universe.

Continuous waves (CWs): Continuous GWs in the PTA band are expected from single supermassive black-hole binaries that are close enough to Earth to stand out beyond the GWB. With improved sensitivity, a detection of CWs is generally expected to follow within a few years from a GWB detection [124, 110].

GW bursts: Single GW events like close encounters between supermassive black holes or some cosmic string interactions [40], could result in a single burst of GWs, which might be detectable provided the burst itself lasts sufficiently long for it to affect multiple subsequent pulsar observations (i.e. at the very least days long); and provided the burst is sufficiently bright to stand out of the noise.

Bursts with memory (BWMs): Bursts that are too faint to be detected directly, could still be detected as a “memory event” or a BWM. In this case it is the permanent deformation of the space-time metric [49] that has a lasting impact on the pulse frequency, causing the impact on the timing to accumulate over time.

Present PTA Constraints

Around the world, collaborations have emerged to carry out the large-scale observational campaigns required for GW detection with PTAs. The Australian Parkes PTA [PPTA, see 106] was the first one, commencing observations in 2005 and revising some of the original theoretical work [67, 68]. Centred around the 64-m Parkes radio telescope, they have been monitoring between 20 and 30 pulsars using both dedicated observations [76] and archival data [152]. The PPTA last placed a limit on the GWB in 2015 [131], finding that the normalised amplitude at a frequency of 1 yr$^{-1}$ must be lower than $10^{-15}$ with 95% confidence – which started to get into the area of theoretically predicted amplitudes at the time; this limit is still the most constraining bound on a GWB in the PTA band to date. Most recently, the PPTA has focussed its efforts on alternative sources of GWs, such as ultra-light scalar-field dark matter [118] as well as CWs and BWMs [100]; alongside a more intensive commitment to the global International PTA (see below) and instrumental development [61].

The European PTA [EPTA, see 43] also commenced in 2005, soon after the PPTA and also relies on a combination of specific PTA data and archival monitoring data, adding up to a total of 42 MSPs [43]. To date, the EPTA has primarily used data from the Jodrell Bank 76.2-m Lovell telescope, the 100-m Effelsberg Radio Telescope, the 300-by-35-m decimetric radio telescope at Nançay observatory and the Westerbork Synthesis Radio Telescope which is an interferometric array consisting of 14 antennae of 25-m diameter. Their most recent limit also dates back to 2015 [90], but is slightly less constraining, at $A_{1/\text{yr}} < 3.0 \times 10^{-15}$. The same data set has been used to place constraints on CWs [13] and possible anisotropies in the GWB [144]. Finally, dedicated, high-cadence, data were used to place constraints in the microhertz
regime [116]. In recent years, the EPTA has primarily focussed on instrumental development with new data-recording systems [83, e.g.], the commissioning of a new 64-m radio telescope in Italy [SRT, see 119] and the interferometric combination of all mayor EPTA telescopes in the “Large European Array for Pulsars” (LEAP) project [19]. The EPTA has also had a strong involvement in the commissioning of the LOw-Frequency ARray [LOFAR, see 148], which has shown to be a useful telescope for monitoring not only MSPs [77] but particularly DMs [45, e.g.].

The third major PTA is the North-American Nanohertz Observatory for Gravitational waves [NANOGrav 41]. NANOGrav has been particularly involved in pulsar searches and as such their source list has been continuously expanding, counting 48 MSPs at their current data release [https://data.nanograv.org and 82]. The latest and most constraining limit on the amplitude of the GWB, is $A_{1/yr} < 1.45 \times 10^{-15}$ [9], slightly above the PPTA limit. Within the last few years, NANOGrav has also placed significant bounds on BWMs [2] and on CWs [1]; and placed a specific limit on the proposed binary black-hole system in the radio galaxy 3C66B [142, 11].

The three original PTAs mentioned above joined forces to further increase sensitivity and in an attempt to decrease the time to the first GW detection in the nHz regime. As described by Manchester and IPTA [102], the first joint PTA meeting took place in 2008, but the formal establishment of the International PTA (IPTA) did not happen until 2011. Since then, the IPTA has released two combined data sets [153, 117] and has indicated that an improvement in GWB sensitivity by a factor of about two should be expected, but no full GW analysis has been carried out on IPTA data so far, given the complexities involved with the highly inhomogeneous nature of the data set. These inhomogeneities and complexities [discussed and listed in 153] are a specific challenge for any combined PTA experiment and often requires additional research regarding detailed aspects of the analysis, or development of new methods that are able to deal with such inhomogeneous data. A lot of progress has been made in recent years in this regard, particularly with the advent of Bayesian analysis software packages like TEMPONEST [89, 91] and ENTERPRISE [48], amongst others. So far, the first IPTA data combination has been used by Hobbs et al. [60] to construct a pulsar-based time standard (thereby solving for any monopolar correlations in the data), while Caballero et al. [31] used it to constrain errors in the Solar-System ephemeris models used. A comprehensive GW analysis is planned for the second data release. Meanwhile, analysis tools are being tested on mock data challenges [54, 151, 17].

As a new generation of telescopes is being constructed on the pathway to the SKA, a number of new PTAs have recently emerged. Specifically, the Indian PTA [InPTA, 71] has been formed in 2018 and uses high-precision timing data from the upgraded Giant Metre-wave Radio Telescope (uGMRT) and low-frequency data from the Ooty Radio Telescope (ORT). The Chinese PTA [CPTA 85] uses the Five-hundred meter Aperture Spherical Telescope (FAST), the Xingjiang Qitai 110-m Radio Telescope (QTT) and a network of 100-m-class radio telescopes across China and predict to go well below current sensitivity limits after even a few years of observing. Finally, the South-African MeerKAT telescope [69] is being used by
the international MeerTIME consortium [16] to produce (amongst other things) a highly sensitive PTA data set, part of which will be taken at relatively high radio frequencies, between 1.7 and 3.5 GHz, thereby limiting the impact of interstellar effects.

### Table 1 Summary of present limits on GWs from PTA data.

| GW Type | EPTA | NANOGrav | PPTA | IPTA |
|---------|------|----------|------|------|
| GWB$^a$ | $3.0 \times 10^{-15}$ | $1.45 \times 10^{-15}$ | $1.0 \times 10^{-15}$ | $1.7 \times 10^{-15}$ |
|         | Lentati et al. [90] | Arzoumanian et al. [9] | Shannon et al. [131] | Verbiest et al. [153]$^b$ |
| BWM$^c$ | – | $1.5/\text{yr}$ | $0.75/\text{yr}$ | – |
|         | – | Arzoumanian et al. [8] | Wang et al. [154] | – |
| CW$^d$  | $1.5 \times 10^{-14}$ | $3.0 \times 10^{-14}$ | $1.7 \times 10^{-14}$ | – |
|         | Babak et al. [13]$^e$ | Arzoumanian et al. [6] | Zhu et al. [159] | – |

$^a$ Limits on the GWB are typically given as upper limits on the dimensionless strain amplitude at a frequency of 1/yr.

$^b$ Verbiest et al. [153] note that the limit derived from the IPTA data set was only indicative and not rigorous as a full analysis was deferred to a future paper.

$^c$ BWMs can be quantified in many ways. In order to provide some comparative measure, this table presents the upper limit on the burst rate for bursts with normalised characteristic strain amplitude $10^{-13}$.

$^d$ Limits for CWs are given as upper bounds on $h_0$, at a GW frequency of 10 nHz.

$^e$ Babak et al. [13] don’t give a specific value; the number given is based on their Figure 3.

### Recent and Ongoing Improvements in PTA Sensitivity

Much of the present interest in PTA experiments derives from the work by Jenet et al. [67] who predicted that a GWB should be detectable after a mere 5 years of timing on 20 pulsars, with a timing residual RMS of 100 ns – a level of precision that had only recently been demonstrated to be achievable in practice [141]. Subsequently, it became clear that the ideal PTA (20 pulsars, 5 years and 100 ns RMS) was unlikely to ever become a reality since the pulsar population is by nature highly inhomogeneous, implying a few pulsars would be likely to be timed at better precision than 100 ns, but most probably would not. Consequently, scaling relations were derived, first by Jenet et al. [68] and later by Siemens et al. [133], to allow fine-tuning of PTA experiments with a view to optimising sensitivity and shortening detection time scales.

Siemens et al. [133] showed that the S/N of a GWB in a PTA data set scales with typical properties of the data set as follows:

$$S/N \propto \mathcal{N} c^{3/26} \mathcal{A}^{3/13} \mathcal{T}^{-1/2} \sigma^{-3/13},$$  

(3)
where $N$ is the number of pulsars, $C$ is the cadence of the observations, $A$ is the amplitude of the GWB, $T$ is the length of the timing data set and $\sigma$ is the RMS of the timing residuals. While this analysis makes some basic simplifications in terms of data homogeneity, it does show clearly the very strong dependence of PTA sensitivity on the number of pulsars in the array. Consequently, a large number of pulsar surveys have been undertaken in recent years to increase the number of PTA-useable MSPs, as described below. The dependence on all other parameters is far less significant, except for the data length, which still adds considerably. In the low-S/N regime, Siemens et al. [133] show that a PTA’s sensitivity scales most strongly with the data length: $S/N \propto T^{13/3}$, in close agreement with the earlier findings of Jenet et al. [67]. For long data sets the sensitivity is however affected by the level at which other long-period signals can be mitigated. Most significantly this refers to DM variations which can be mitigated provided the observing set-up has been well chosen. Pulsar timing noise is equally important, but in the absence of predictive models or independent estimates of this noise source, the only possible approach is to limit its impact by post-facto modelling and subtraction. Finally, in the intermediate S/N regime (i.e. as we get closer to detections rather than mere limits), the sensitivity to a GWB is only weakly related to the timing precision of the MSPs, but for single sources of GWs the timing precision is still the dominant factor, consequently some efforts are being made to further improve the timing precision of MSPs by instrumental improvements and building of new telescopes. At the end of this section, a brief overview is given about various studies that quantify how all of these improvements are likely to affect the time to the first GW detection with PTAs – which mostly agree a detection within years to at most a decade is highly likely.

**Pulsar Surveys**

In order to increase the sample of MSPs that can be used in PTA experiments, a number of pulsar surveys have been undertaken in recent years and are being planned for the near future. Specifically, two long-lasting surveys have been running on the Arecibo radio telescope for most of the past decade: the P-Alfa survey [37] and the Arecibo drift-scan survey [42]. In addition, the Effelsberg and Parkes radio telescopes (in Germany and Australia respectively) are continuing their all-sky partner surveys HTRU North and South [18, 73]. Parkes has simultaneously been equipped with cutting-edge processing technology as part of the SUPERB [72] survey, which aims to do real-time searches for pulsars and fast radio bursts. Data from the Green Bank Telescope (GBT) continues to be analysed in the Green Bank Northern Celestial Cap (GBNCC) survey [140]. At low frequencies, the LOFAR telescope [148] is finishing processing of the LOFAR Tied-Array All-Sky Survey [LOTAAS, 126] and at the GMRT the GMRT High-Resolution Southern Sky survey (GHRSS) is ongoing [23]. New telescopes are also getting up to speed on pulsar surveys, with the first successful discoveries published by the FAST telescope [158, 120], as part of the
Commensal Radio Astronomy FAST Survey (CRAFTS) and survey observations recently commenced for the MeerKAT “TRAPUM” survey [137].

**IISM Studies**

In order to increase sensitivity of pulsar-timing data sets to long-term signals like those expected from a GWB, it is of utmost importance to understand, mitigate and model any long-term signals that may be affecting the timing. Most such effects are deterministic effects contained in the timing model, but two more complex sources of red noise exist: timing noise and IISM noise. As discussed earlier, the origin of timing noise has not been unequivocally determined and consequently most models are rather ad-hoc power-law descriptions of uncorrelated timing signatures. IISM noise (or DM variations) is different, since it is the only known effect that causes a frequency dependence in timing residuals.

The frequency dependence of IISM noise implies that in principle it can be measured and modelled independently from all the other timing-model parameters and correlated signals, because it can fully rely on the frequency resolution of the data. Specifically, three scenarios could be envisaged for measuring and correcting DM variations in pulsar-timing data [66]:

- **Multiple different observing bands**: When more than one observing band is used, the frequency difference between the bands can be used as a lever arm that enables high-precision DM estimates. This idea has been implemented both with co-axial receivers and, more recently, with ultra-broadband receivers such as the UWL in Parkes [61] and similar observing systems at the Effelsberg and Green Bank radio telescopes, often not using actual instantaneous observations, but by determining an average DM over a range of dates [74]. In this scenario, care must be taken in the allocation of the observing time, since the DM sensitivity of the data will scale with the square of the observing wavelength, but the timing precision may not, depending on the spectral index of the pulsar. Specifically, since on average pulsars have a spectrum that is flatter than $\nu^{-2}$ [65] and since the sky background noise is steeper than typical pulsar spectra [155], it is likely that the low-frequency band will still have superior sensitivity to DM, but have worse timing precision overall. For observations beyond 1.4 GHz, however, the situation often reverses, in that higher-frequency bands may have both less sensitivity to dispersion and lower timing precision [see, e.g. 83]. This implies a change in integration time depending on the observing frequency, may be in order. A more extensive analysis of post-correction ToA precision in this scenario, is given by Lee et al. [88].

- **Low-frequency monitoring**: As a possible way to mitigate the complexities of balancing DM and timing precision, one could attempt to monitor pulsars at low frequencies (generally at or below 400 MHz) and derive independent DM time series from those low-frequency data, to correct the higher-frequency data. This has the additional advantages that the DM modelling is now fully independent
from the higher-frequency timing; and at low frequencies DM corrections could often be measured within a single observation, which avoids correlations with effects like timing noise or other timing-model parameters. This approach has its own drawbacks because other IISM effects like scattering also become more pronounced at low frequencies and so the DM measurements may be biased or corrupted. Finally, in some cases the differences in Fresnel scale\(^{10}\) at the top and bottom of the observing band make it possible that the actual space probed by electrons at different frequencies is slightly different – and hence the DM as well. This results in a frequency-dependent DM, which has been theoretically predicted\(^{38}\) and observed\(^{45}\), but the overall impact of this phenomenon on PTA sensitivity has so far not been accurately quantified.

- **High-frequency timing:** Finally, with sufficiently sensitive telescopes, the main observing frequency could be moved to higher frequencies, where the IISM effects are weaker. Pulsars also tend to be fainter at those frequencies, but in the case of highly sensitive telescopes, this may be a blessing since it implies jitter noise will be less significant, as more pulses will need to be averaged per observation. However, with present telescopes, this approach may require too much observing time\(^{83}\) – with more sensitive, future, telescopes it may become a realistic option.

When it comes to effects of the IISM, dispersion is only the peak of the iceberg. Things get a lot more complex when we consider multi-path propagation or scattering. This phenomenon arises when some of the photons get deviated from the straight line between the pulsar and Earth due to refraction; and later get refracted back into the line of sight. In its simplest form, for a thin scattering screen with density inhomogeneities that follow a Kolmogorov spectrum, this should cause a delay in photon arrival time which scales with the observing frequency to the fourth power:

\[ \tau_{\text{scat}} \propto \nu^{-\alpha}, \]

where the scattering index \(\alpha\) is theoretically expected to be 4.4. In practice, Bhat et al.\(^{21}\) have measured an average spectral index of the scattering strength of \(\alpha = 3.9 \pm 0.2\), slightly inconsistent with theory. More detailed studies at lower frequencies\(^{51}\) have shown that in many cases the frequency scaling of the scattering was more consistent with a highly anisotropic scattering screen than with the typical Kolmogorov screen.

Regardless of the frequency scaling, the primary observable effect of scattering in pulsar timing is that the pulse profile gets smeared out and gets a characteristic exponential tail. This worsens timing precision since it can wash out features and it may corrupt the DM measurement (although absolute DM measurements may not be necessary for pulsar-timing experiments anyway), but in principle this would not affect GW sensitivity as long as the effect is constant in time.

The strength of scattering does change in time, though, as can most readily be seen by inspecting a “dynamic spectrum”: a plot of pulsed intensity as a function

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\(^{10}\) The Fresnel scale is a basic measure for the size of the Fresnel zone, which in turn is the region of space a signal can travel through between emitter and receiver.
of frequency and time. Such time-variable spectra often show changes in pulse intensity – a phenomenon known as **scintillation**. Diffractive scintillation (as shown in Figure 6) occurs when photons travelling from the pulsar to Earth meet refractive structures and get slight phase shifts due to location-dependent refractive indices. These phase-shifts cause constructive and destructive interference which are seen as bright and dark paths in the dynamic spectrum. Since scattering and diffractive scintillation are effectively two different observables caused by the same turbulent and diffractive structure, it should not come as a surprise that they are related – in fact, they are inversely proportional [93]. An extensive analysis of PTA data carried out by Levin et al. [93] quantified the variations in diffractive scintillation and consequently estimated how variable scattering is in typical PTA observations. This analysis showed that at present levels of sensitivity, scattering variations are only rarely a real concern [with one exception studied in detail by 92], but in the next era of highly sensitive telescopes (notably MeerKAT, FAST and SKA), this will probably change.

A further complication could arise from a higher-order effect where scattering and diffractive scintillation combine in what are known as “**scintillation arcs**” [139]. This primarily occurs in highly anisotropic media, when the majority of the radiation comes from the pulsar (essentially a point source), but significant amounts of energy come from other, typically straight and narrow, structures on the sky. It causes ripples across the dynamic spectrum, which are more easily noticed in the 2D Fourier transform of the dynamic spectrum – this is also called the “**secondary spectrum**” (see right-hand side of Figure 6). The initial discovery of secondary spectra is still relatively recent and since these tend to be faint features which require high sensitivity and high resolution (i.e. large data rates), their study has only developed slowly. However, early studies by Hemberger and Stinebring [58] already showed how these phenomena can impact timing significantly. Turning this around, Reardon et al. [121] showed how scintillation arcs can actually be useful for timing, as they can provide independent constraints on timing-model parameters. The study of how to use scintillation arcs, or what effects they really do have on PTA experiments, has only just begun, so at present their impact is not fully clear yet.

A final concerning occurrence that the IISM may create, are frequency-dependent DMs (also often – and confusingly – named “chromatic DMs”). The principle behind frequency-dependent DMs is as follows: in wide-band observations, photons with a wide range in wavelengths are observed. These photons did not all travel through the same space – in fact, since the Fresnel scale is frequency-dependent, there is a bias that causes lower-frequency photons to be able to travel through a wider region of space than higher-frequency photons. If the variations in electron density are sufficiently extreme – or if measurement precision is sufficiently high – this would imply that the high-frequency photons may sample a different electron distribution than the low-frequency photons. Consequently, the DMs measured at the top and bottom of the observing bands may be different because they refer to different parts of space.

While the concept of frequency-dependent DMs had been known for much longer, the theoretical description was first laid out by Cordes et al. [38]. Detec-
Fig. 6 Dynamic and secondary spectrum of PSR J0826+2637 (PSR B0823+26). Left: the dynamic spectrum of a half-hour observation on PSR J08216+2637 with the LOFAR core. Shown is the pulsed intensity on an arbitrary colour scale (units are uncalibrated) for a segment of 5-MHz bandwidth, centred on 147.5 MHz. The bright patches are called scintles and are caused by diffractive scintillation. Less clear is the higher-frequency corrugations that run diagonally across this dynamic spectrum and which are caused by a combination of diffractive and refractive scintillation. Right: this figure shows the secondary spectrum of the left-hand plot, i.e. the 2D Fourier transform, whereby the power levels are shown on a logarithmic scale. A highly asymmetric arc is visible, extending out to fractions of a millisecond at negative fringe frequencies (also called “Doppler rates”) but only out to about 0.1 ms at positive fringe frequencies. Figure courtesy of Ziwei Wu.

Sensitivity Predictions

As mentioned earlier, as PTAs edge closer to a GW detection, the number of pulsars in the array is of key importance for the PTA’s sensitivity. Since predicting pulsar discoveries is infamously hard, it is equally hard to make accurate predictions of PTA sensitivity given future pulsar discoveries, yet several papers have demonstrated...
the validity of the adage “More pulsars is more sensitivity”. Most recently, Kelley et al. [75] showed that – assuming ongoing regular discoveries of MSPs that can be timed at high precision – all PTAs could hope to detect GWs within a few years; and all were virtually guaranteed a detection within a decade.

Based on the most up-to-date predictions for a GWB in the PTA band and realistic numbers from existing PTA experiments, Rosado et al. [124] showed that the most likely scenario would be that a GWB would be detected in about one to two decades time. A detection of CWs was also not unrealistic, but would probably take somewhat longer. Rosado et al. [124] did not investigate the impact of increasing the number of MSPs in the array, but did evaluate the impact of more sensitive systems – the SKA in particular and found that with the full SKA, a GWB should be detectable within a few years; and CWs within about a decade.

The idea that a highly sensitive telescope could detect GWs within a few years, even with existing pulsars, was also demonstrated by Lee [85], who drew essentially the same conclusion for the CPTA with its unprecedentedly sensitive set of telescopes. Also Lazarus et al. [83] investigated the impact of improved sensitivity on PTA detection time scales, this time in the context of improved receiver and recording systems. Specifically, they estimated that the new recording system at Effelsberg would improve the telescope’s sensitivity to a GWB by a factor of up to three compared to the status quo, in only four years time. They furthermore continued the work by Lee et al. [88] to demonstrate how wide-band and low-frequency observing systems might aid the detection of GWs by efficiently correcting DM variations and thereby keeping the timing RMS low. Verbiest et al. [153] approached the sensitivity improvements in a very complementary way, showing that global collaboration and sharing of data would lead to approximately a factor of two improvement in GW sensitivity.

It is also possible that the coming years continue to bring non-detections; this could occur if we encounter an unexpected instrumental noise floor, such as intrinsic pulsar noise or a high level of ephemeris uncertainty. However, this scenario is unlikely to be an issue. Pulsar noise can be overcome by targeted noise modelling [as in 55], or by simply adding more pulsars to a PTA, which will beat down noise that is uncorrelated between different pulsars, thus still raising our sensitivity to the correlated GW signals. Regarding uncertainties in the Solar-System ephemerides, as previously noted on page 15, ephemerides uncertainties are correlated. The signal, however, is dipolar thus we can attempt to measure and remove it, even if there is some leakage between dipolar and quadrupolar signals [145]. In addition, it has been demonstrated that PTAs are already breaching the accuracy of published ephemerides, and techniques have been developed to overcome such uncertainties [147].

Regardless, current upper limits on the GWB are already impacting our understanding of the evolution of galaxies and their supermassive black hole residents [131, 134, 9, 34], in addition to placing novel constraints on cosmic strings [9, 156] and exotic forms of dark matter [e.g. 35]. For the interested reader, the wealth of accessible science with GW limits and detections is the subject of another large review [30].
For the purposes of this review, it suffices to say that if our limits continue to improve around an order of magnitude beyond their current point, it would be astrophysically surprising. This is because even the most pessimistic simulations of supermassive binary black hole evolution (where no galaxy merger results directly in a binary supermassive black hole due to inefficient inspirals) still result in signals detectable at the $h_{\nu r} > 10^{-16}$ level \[25\]. See also the “Massive Black Hole Mergers” chapter of this edition by E. Barausse and A. Lapi.

In summary, there are a variety of ways in which PTAs can further gain sensitivity and all of these ways are being explored. Essentially all predictions conclude a detection is likely within the next few years or at most within the next decade – regardless of which particular improvement is being studied. This is not surprising given that our most reliable predictions on the strength of the GWB are right up against our most constraining limit \[131, 9\], which strongly implies a detection is bound to be imminent.

Summary

The extreme properties of the spinning neutron stars called pulsars enable a unique experiment to detect GWs in a spectral range that is highly complementary with other mature GW projects like LIGO and LISA. PTAs are expected to make the first detection of nHz GWs within the next few years and in doing so, will allow new and unprecedented constraints on galaxy formation and evolution scenarios. The way forward is long and hard, however, as data sets are complex and highly heterogeneous and a variety of noise sources need to be dealt with. Instrumental upgrades and extension and improvement of observing schedules and source lists are underway to further enhance sensitivity – a process that will culminate in the ultimate PTA to be ran on the telescope of the future: the SKA. With the added collecting area and the larger number of pulsars that the SKA will be able to time at high precision, GW astronomy in the nHz range can be expected to properly take off.

Cross-References

Barausse & Lapi, “Massive Black Hole Mergers”

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