DETECTION OF GRAVITATIONAL WAVES USING PULSAR TIMING

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Pulsars are very stable clocks in space which have many applications to problems in physics and astrophysics. Observations of double-neutron-star binary systems have given the first observational evidence for the existence of gravitational waves (GWs) and shown that Einstein’s general theory of relativity is an accurate description of gravitational interactions in the regime of strong gravity. Observations of a large sample of pulsars spread across the celestial sphere forming a “Pulsar Timing Array” (PTA), can in principle enable a positive detection of the GW background in the Galaxy. The Parkes Pulsar Timing Array (PPTA) is making precise timing measurements of 20 millisecond pulsars at three radio frequencies and is approaching the level of timing precision and data spans which are needed for GW detection. These observations will also allow us to establish a “Pulsar Timescale” and to detect or limit errors in the Solar System ephemerides used in pulsar timing analyses. Combination of PPTA data with that of other groups to form an International Pulsar Timing Array (IPTA) will enhance the sensitivity to GWs and facilitate reaching other PTA goals. The principal source of GWs at the nanoHertz frequencies to which PTAs are sensitive is believed to be super-massive binary black holes in the cores of distant galaxies. Current results do not significantly limit models for formation of such black-hole binary systems, but in a few years we expect that PTAs will either detect GWs or seriously constrain current ideas about black-hole formation and galaxy mergers. Future instruments such as the Square Kilometre Array (SKA) should not only detect GWs from astrophysical sources but also enable detailed studies of the sources and the gravitational theories used to account for the GW emission.

Keywords: pulsars: general — gravitational waves

1. Introduction

A pulsar is a rapidly rotating neutron star with very strong magnetic fields both inside and outside the star, most likely formed in a supernova explosion at the end of the life of a massive star. The combination of strong magnetic field and rapid rotation generates enormous electric fields which accelerate charged particles in the surrounding magnetosphere to ultra-relativistic energies. These particles radiate beams of emission which sweep across the sky as the star rotates. If one or more of these beams cross the Earth each rotation we can detect the neutron star as a pulsar. The interval between pulses, known as the pulse period, is equal to the
rotation period of the star. There are currently more than 1800 pulsars known. Almost all of these lie within our Galaxy, typically at distances of a few kiloparsec.

There are two main classes of pulsar: “normal” pulsars and “millisecond” pulsars (MSPs). Most normal pulsars have periods of between 0.1 and 5 seconds, whereas MSPs have much shorter periods, generally between 2 and 50 ms, hence the name. Most MSPs are binary, that is, in orbit with another star. Orbital periods are typically days or months, but can be as short as a few hours. Only a small proportion of normal pulsars, just over 1%, are binary. This gives a pointer to the mechanism by which MSPs get their very short period – it is believed that they were old, slow and probably dead pulsars which were spun up by accretion of mass and angular momentum from an evolving binary companion star (see, e.g., Ref. 2). As well as increasing the spin frequency, the accretion evidently reduces the effective magnetic field by several orders of magnitude. Despite this, the increased spin rate is generally sufficient to reactivate the emission beams – hence the resulting short-period pulsars are often known as “recycled” pulsars. Most of these are MSPs.

In general, pulsars are most easily detected at radio wavelengths and hence most pulsar surveys are carried out in the radio band (see, e.g., Ref. 3). However, with the recent launch of the Fermi Gamma-ray Space Telescope, an increasing number of pulsars, mostly young but also including many MSPs, have been found or detected at gamma-ray wavelengths. At the time of writing, the number of reported gamma-ray detected pulsars is 46.

Because neutron stars are tiny, with a radius of about 15 km, but massive, typically about 1.4 M☉, their rotation period is extremely stable – they are very difficult to slow down or spin up! It is this property which makes pulsars extraordinarily useful as probes. This is especially true for MSPs as they have narrow pulses (in time units) and hence measurements of pulse delays and periodicities have higher precision compared to normal pulsars. Having an array of precise clocks spread through the Galaxy enables many different investigations, for example, studies of the interstellar medium, pulsar astrometric measurements, including proper motions and even annual parallaxes in some cases, and potentially the direct detection of gravitational waves (GWs). The fact that most of the MSPs are in orbit with another star is a bonus as it allows many additional properties relating to binary motion to be investigated.

For double-neutron-star binary systems measurement of relativistic perturbations to the orbital parameters is generally possible, thereby allowing precise determinations of neutron star masses and making possible stringent tests of general relativity (GR) and other gravitational theories in the strong-field regime. The famous Hulse-Taylor binary pulsar, PSR B1913+16, was the first binary pulsar to be discovered. Precise timing measurements over 30 years have given significant measurements of three relativistic or “Post-Keplerian” parameters, leading to accurate mass determinations for the two stars which confirm that it is a double-neutron-star...

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*See the ATNF Pulsar Catalogue at www.atnf.csiro.au/research/pulsar/psrcat.*
system. They have also shown that the observed orbit decay is consistent with the predictions of GR for energy loss from the system in GWs, thereby providing the first observational evidence for the existence of these waves. The Double Pulsar, PSR J0737-3039A/B, discovered at Parkes in 2003/4, is an even more relativistic binary system than the Hulse-Taylor binary. Relativistic precession of the longitude of periastron is an amazing $17^\circ \text{yr}^{-1}$ and was detected in just a few days of observation. In less than three years of observation five Post-Keplerian parameters have been observed, which together with the mass ratio of the two stars (measurable since both stars are detected as pulsars), has shown that GR accurately predicts the motions of the two stars at a level of precision exceeding 0.05%, the most precise test so far in this strong-field regime.

The main topic of this presentation is the current effort to make a direct detection of GWs using pulsar timing. The concept of a “Pulsar Timing Array” (PTA) is described in Section 2 and Section 3 describes the Parkes Pulsar Timing Array (PPTA) in some detail. Section 4 discusses some of the implications of current results and prospects for the future. Finally, the main points are summarised in Section 5.

2. Pulsar Timing Arrays and Detection of Gravitational Waves

The existence of GWs, fluctuations in spacetime which propagate at the speed of light, is a prediction of Einstein’s general theory of relativity and other subsequent theories of relativistic gravitation. GWs are generated by acceleration of massive objects. Sources of primary interest in the astrophysical context are fluctuations in density and hence spacetime from the inflationary era of cosmological expansion, oscillations of cosmic strings in the early Universe, formation of massive black holes, binary super-massive black holes in the cores of galaxies, coalescing double-neutron-star binary systems and compact X-ray binaries in our Galaxy. Each of these sources emits a characteristic spectrum of GWs and in principle they can be identified by this spectrum and the time-dependence of the GW signal. Most of the sources consist of a random accumulation of signals from thousands or millions of individual sources and hence form a stochastic background of GWs which we can observe.

Huge efforts have gone into making a direct detection of GWs over the past few decades. Recently these efforts have been dominated by the development of laser-interferometer systems such as LIGO and VIRGO. These systems have two perpendicular interferometer arms, typically of length 3 or 4 km, and are sensitive to GWs in the frequency range 100 – 500 Hz. Their primary source of interest is coalescence of double-neutron-star binary systems. They have been operating in their “initial” configuration for several years with significant upper limits on several types of source (e.g., Ref. [13][14]). Efforts are currently under way to develop “advanced” configurations which will have improved sensitivity. For example, full operation of Advanced LIGO is expected in 2014. Another significant project, still in the planning stage, is LISA, a system with three spacecraft in a triangular array.
trailing the Earth in its orbit about the Sun. The interferometric arm length for LISA is about 5 million km, giving it sensitivity to GWs in the 0.1 – 100 mHz band. Prime targets for LISA will be the final stages of coalescence of super-massive black-hole binary systems in galaxy cores and Galactic X-ray binary systems. Its planned launch date is 2020.

Gravitational waves in our Galaxy modulate the apparent period of pulsars observed on Earth. The modulation is actually the difference between the varying gravitational potential at the pulsar and that at the Earth. For a stochastic background of GWs, these two modulations are uncorrelated. With observations of just one (or a few) pulsars, a limit can be placed on the amplitude of the GW background in the Galaxy since any modulation due to GWs in the Galaxy cannot be much greater than the smallest observed rms timing residual. The expected GW spectrum from the ensemble of binary super-massive black holes in galaxies is very “red”, that is, stronger at low frequencies (e.g., Ref. 16). Also, the sensitivity of pulsar timing experiments depends on the accumulated pulse phase offset due to the GW signal, that is, on the integral of the pulse frequency modulation. For both of these reasons, pulsar timing experiments are most sensitive to long-period GW signals, with maximum sensitivity at periods comparable to the data span, typically several years, corresponding to GW frequencies of about 10 nHz.

Analysis of an 8-year span of Arecibo observations of PSR B1855+09 by Kaspi, Taylor & Ryba placed a limit on the energy density of the GW background relative to the closure density of the Universe, $\Omega_{gw}$, of about $10^{-7}$ at a frequency of approximately $1/(8 \text{ yr})$ or 4 nHz. More recently Jenet et al. have combined the Kaspi et al. Arecibo data set with Parkes observations of seven pulsars made as part of the PPTA project to place the best limit so far: $\Omega_{gw} \sim 2 \times 10^{-8}$ at $\nu_{gw} \sim 1/(8 \text{ yr})$. The implications of this limit will be discussed in Section 4.

Setting a limit on the strength of the GW background is of interest, but not as interesting as making an actual detection of GWs! With observations of many pulsars spread across the celestial sphere and long data spans, we can in principle achieve this more ambitious goal. Such an observational system is known as a “Pulsar Timing Array” (PTA). Making an actual detection of GWs relies on the fact that a GW passing over the Earth produces a correlated signal in the residuals of different pulsars. For a stochastic GW background signal in GR, the correlation between the residuals for pairs of pulsars is dependent only on the angular separation of the pulsar pair. The expected correlation as a function of angular separation is shown in Fig. 1. For pulsars which are close together on the sky the correlation coefficient is 0.5, not 1.0 because the modulations by GWs passing over the pulsars are uncorrelated. This uncorrelated signal also results in the scatter in correlation for the simulated points at similar angular separation. For pulsars which are separated by about 90° on the sky, the expected correlation is negative because of the quadrupolar nature of GWs and it goes positive again for pulsars which are more-or-less in opposite directions.

GWs are not the only thing that can produce a correlated signal in the timing
residuals. All pulsar timing data are referenced to an established timescale, for example, TT(TAI) or TT(BIPM09). These timescales are based on weighted averages of data from atomic frequency standards at laboratories around the world. These frequency standards are not perfect and hence the international timescales are subject to various instabilities. In principle, these instabilities are detectable using pulsar timing observations, since the pulsar periods are not subject to terrestrial influences to any significant extent. For example, if during PTA observations all pulsars are observed to be running slower than average, then this probably means that the reference timescale is running fast. This signal has no spatial signature and so can be thought of as a monopole as compared to the quadrupolar signal from a GW. We can therefore use the pulsar data to establish a “Pulsar Timescale” which, over long intervals, may be more precise than the best timescales based on terrestrial atomic clocks. It is important to note that, because of the intrinsically unknown pulsar spin frequency and slow-down rate, pulsar timing analyses must solve for these terms thereby removing any sensitivity to linear or quadratic terms in the GW signal and Pulsar Timescale.

We also depend on Solar System ephemerides to give the position of the Earth relative to the Solar System barycentre at any given time. Most pulsar analyses use ephemerides produced by NASA’s Jet Propulsion Laboratory, for example DE405.

\[\text{See also } \text{www.bipm.org/en/scientific/ta}i/\]
to derive the barycentric corrections. These ephemerides are also not perfect and hence the correction can be in error. In the pulsar timing analysis this is equivalent to an error in the Earth’s velocity with respect to an inertial frame and hence shows up as a spatial dipole signature in the timing residuals.

Therefore in principle we can separate these three global timing signatures by their dependence on the position of the pulsars on the sky. In fact, both the reference timescales and the Solar System ephemerides are both very precise and these signatures have not yet been detected in PTA data. However, differences between successive realisations of the timescales and the ephemerides suggest that pulsar timing is capable of detecting errors in current versions. Similarly, we have not yet detected GWs, but estimates of the expected GW background amplitude and of the effect of this background on pulsar timing data suggest that with current technology, GW signals should be detectable with 5 – 10 years of high-quality timing data for at least 20 MSPs. Frequent observations, typically every 2 – 3 weeks, are required to adequately sample the expected signals and to improve sensitivity. Observations at two or more radio frequencies are required to remove variable interstellar dispersion delays.

Fig. 2 shows that there are about 30 MSPs known which are strong enough and have sufficiently short periods to be suitable for PTA projects, i.e. to give rms timing residuals of less than about 1 $\mu$s with observation times of an hour or so with existing observing systems. Most of these are south of the celestial equator, although hopefully on-going searches will uncover more suitable pulsars with a wider distribution on the sky. Currently there are three major PTA projects gathering high-quality timing data:

- The European Pulsar Timing Array (EPTA)
- The North American pulsar timing array (NANOGrav)
- The Parkes Pulsar Timing Array (PPTA)

The EPTA uses radio telescopes at Effelsberg, Jodrell Bank, Nançay and Westerbork to obtain data. Normally observations are made separately at the different telescopes, but there is a plan to combine signals in real time to improve the sensitivity. Currently the EPTA is obtaining good quality data for about nine pulsars. NANOGrav uses the Arecibo and Green Bank Telescopes and currently has good quality data for about 17 MSPs. The PPTA uses the Parkes radio telescope and currently has good quality data for 20 MSPs.

These three groups are collaborating to form the International Pulsar Timing Array (IPTA). In the future we can expect other PTAs to join this effort; for example, groups at the FAST and other radio telescopes in China plan to undertake a PTA project. Combining data sets gives better sampling of pulsars common to two or more PTAs and also increases the total number of pulsars observed, giving better coverage of the celestial sphere. Both of these things help improve our sensitivity to GWs.
Fig. 2. The celestial distribution of pulsars suitable for PTA observations. The diameter of the circle is inversely related to the pulsar period and the circle is filled if the mean 1400 MHz flux density is more than 2 mJy. The dashed line is the northern declination limit of the Parkes radio telescope. PPTA pulsars are marked by a star.

3. The Parkes Pulsar Timing Array

The PPTA project uses the Parkes 64-m radio telescope of the Australia Telescope National Facility (ATNF) to observe 20 MSPs at 2 – 3 week intervals. The project is based at the ATNF and has about 25 team members, including five students, with principal collaborating groups at the Swinburne University of Technology (led by Matthew Bailes), the University of Texas at Brownsville (led by Rick Jenet) and the University of California, San Diego (led by Bill Coles). The 20 MSPs observed by the PPTA are indicated in Fig. 2. Observations are made at three frequencies, around 700 MHz, 1400 MHz and 3100 MHz.

Observations at 1400 MHz use the centre beam of the 20cm Multibeam receiver which has a bandwidth of 256 MHz and a system equivalent flux density of about 30 Jy. Observations at the other two bands are made simultaneously using the 10cm/50cm dual-band receiver which has bandwidths of 64 MHz and 1024 MHz at 50cm and 10cm respectively. System equivalent flux densities are about 64 Jy and 48 Jy, respectively, in the two bands. Data are recorded using two different systems, polyphase digital filterbanks, which have bandwidths up to 1024 MHz, and a baseband recording system, CPSR2, which records two 64-MHz bands. Data are processed using the PSRCHIVE programs and the TEMPO2 timing analysis program. The PPTA observing system is described in more detail by Manchester et al. (Ref. 33).

Regular PPTA observations commenced in mid-2004. Since then, data recording and analysis systems have been steadily improved. Table I lists the 20 pulsars being observed and the current timing performance. The pulsar period and dispersion measure (DM) are given, along with the orbital period if the pulsar is a member of a binary system. The final column gives the rms timing residual from a fit to approximately 1.5 years of data with one of the more recent digital filterbank sys-
Table 1. PPTA pulsars and PDFB2 timing results

| PSR     | Period (ms) | DM (cm\(^{-3}\) pc) | Orbital Period (d) | Band  | Rms Residual (\(\mu s\)) |
|---------|-------------|----------------------|--------------------|-------|-------------------------|
| J0437−4715 | 5.757       | 2.65                 | 5.74               | 10cm  | 0.06                    |
| J0613−0200 | 3.062       | 38.78                | 1.20               | 20cm  | 0.54                    |
| J0711−6830 | 5.491       | 18.41                | –                  | 20cm  | 1.27                    |
| J1022+1001 | 16.453      | 10.25                | 7.81               | 10cm  | 1.80                    |
| J1024+0719 | 5.162       | 6.49                 | –                  | 20cm  | 1.06                    |
| J1045−4509 | 7.474       | 58.15                | 4.08               | 20cm  | 1.59                    |
| J1600−3053 | 3.598       | 52.19                | 14.34              | 20cm  | 0.28                    |
| J1603−7202 | 14.842      | 38.05                | 6.31               | 20cm  | 0.96                    |
| J1643−1224 | 4.622       | 62.41                | 147.02             | 20cm  | 0.94                    |
| J1713+0747 | 4.570       | 15.99                | 67.83              | 10cm  | 0.20                    |
| J1730−2304 | 8.123       | 9.61                 | –                  | 20cm  | 1.62                    |
| J1732−5049 | 5.313       | 56.84                | 5.26               | 20cm  | 2.89                    |
| J1744−1134 | 4.075       | 3.14                 | –                  | 10cm  | 0.41                    |
| J1824−2452 | 3.054       | 119.86               | –                  | 20cm  | 1.95                    |
| J1857+0943 | 5.362       | 13.31                | 12.33              | 20cm  | 0.45                    |
| J1909−3744 | 2.947       | 10.39                | 1.53               | 10cm  | 0.11                    |
| J1939+2134 | 1.558       | 71.04                | –                  | 10cm  | 0.17                    |
| J2124−3358 | 4.931       | 4.62                 | –                  | 20cm  | 2.86                    |
| J2129−5721 | 3.726       | 31.85                | 6.63               | 20cm  | 1.49                    |
| J2145−0750 | 16.052      | 9.00                 | 6.84               | 20cm  | 0.36                    |

tems, PDFB2. The rms residuals refer to summed data from a single observation, typically one hour in duration. These results show that we are close to achieving the timing precision that is required for a positive detection of GWs, assuming that the predictions of the amplitude of the GW stochastic background signal in the Galaxy are correct.

Further improvement in the precision of these arrival times can be expected with improved signal processing and the spans of good quality data are increasing. Analysis of 10-year spans of archival Parkes data combined with CPSR2 data up to 2008 for the PPTA pulsars by Verbiest et al. (Ref. [34]) has shown that, for most of the PPTA pulsars, there is no evidence for intrinsic period fluctuations above the instrumental noise level over these long data spans. Although this study needs to be extended with higher quality data over similarly long data spans, the result is very encouraging for PTA detection of GWs as it indicates that these efforts will not be significantly limited by intrinsic pulsar period irregularities. Also, as mentioned above, combining PPTA data with data from other PTAs will also improve GW detection sensitivity. The prospects for GW detection using pulsar timing in the next few years are good!

4. Discussion

Current PTAs are most sensitive to GWs in the frequency range 3 – 10 nHz. The astrophysical GW signal in this frequency range most likely to be detected is a stochastic background from super-massive black-hole binary systems in the cores
Simulations of the expected GW signal by Sesana, Vecchio & Colacino (Ref. 25) show that it is dominated by radiation from galaxies with intermediate redshifts $z \sim 1$ (Fig. 3) and that the strongest signals come from systems with black-hole masses of $10^9 - 10^{10} \, M_\odot$.

![Figure 3](image)

**Fig. 3.** Contribution of different redshift intervals to the stochastic GW background for two GW frequencies, $8 \times 10^{-9} \, \text{Hz}$ (upper curve in each subplot) and $10^{-7} \, \text{Hz}$ (lower curve in each subplot). The upper panel shows the signal amplitude and the lower panel shows the number of galaxies contributing. The solid lines are from a Monte Carlo method and the dashed lines are from a semi-analytic approach. (From Ref. 25)

**Fig. 4** shows the range of model predictions for the strain amplitude as a function of GW frequency. Current published limits (e.g., Ref. 18) do not constrain the model, but the “ideal” PPTA or, more realistically, longer data spans with current instrumentation and combined IPTA data sets will either detect the stochastic GW background or significantly modify our current understanding of black-hole formation in galaxy cores and/or galaxy merger processes. Future instruments such as the Square Kilometre Array (SKA) will have enormously improved sensitivity and are expected to obtain high-precision TOAs for hundreds of MSPs. With a data span of five years or more, this will certainly give a significant detection of GWs unless the current predictions are totally wrong. It will enable not just a detection of GWs, but also detailed study of the signal. For example, if one of several non-Einsteinian theories of gravitation is correct, then GWs will have
polarization properties which differ from those predicted by GR and this will have an effect on the observed correlations. Even current results are constraining some proposed sources of the GW background. For example, the results presented by Jenet et al. (Ref. 18) limit the equation of state of matter at the epoch of inflation, \( w = P/\epsilon > -1.3 \) (cf. Ref. 38) and the tension in cosmic strings (cf. Ref. 39).

Fig. 4. The range of predictions of the strain amplitude as a function of GW frequency from different models is represented by the hashed area. The lines within this region are predictions from particular models. The long-dashed lines are the approximate sensitivity limits for PTAs, with the upper one being the current best published limit, the middle one being an “ideal” PPTA with 20 pulsars, 100 ns rms timing residuals and a 5-year data span, and the lower one is a prediction of the limit obtainable with the proposed Square Kilometer Array radio telescope after 10 years. (From Ref. 25.)

Intermediate-mass black holes (IMBHs), with masses in the range of a few 100 to a few 1000 M\(_{\odot}\), have been invoked as the basis of the so-called ultra-luminous X-ray sources (see Ref. 40 for a review). IMBHs are difficult to form by aggregation of stellar-mass objects. It has been suggested by Saito & Yokoyama (Ref. 41) that the most likely formation path is by collapse of overdense regions at the end of the inflation era. Saito & Yokoyama show that formation of such IMBHs at this time will lead to a potentially detectable background of GWs. Fig. 5 shows the spectrum of the emitted GWs. The GW frequency is dependent on the mass of the formed black hole and is in the PTA range for IMBHs. In fact, the predicted amplitude of the GW background from IMBH collapse is greater than the limits already placed by pulsar timing, making primordial formation of IMBHs unlikely. This raises the
issues of whether or not such IMBHs exist, what the energy source of ultra-luminous X-ray sources is and maybe even whether or not these X-ray sources are actually ultra-luminous.

Fig. 5. Spectrum of GWs emitted by formation of black holes at the end of the inflation era (Ref. 41). For a given formation event, the emitted spectrum is concentrated at a GW frequency which is inversely related to the collapsing mass as indicated on the upper x-scale. Spectra are shown for two specific black-hole masses: 600 $M_\odot$ (IMBH, peak around $10^{-8}$ Hz in the PTA frequency range) and $1.5 \times 10^{-11} M_\odot$ (Dark Matter, peak around 0.1 Hz in the LISA frequency range). These spectra peak near the dotted and dashed lines which are envelopes for the GW emission from this mechanism with two different sets of assumptions. Sensitivity limits for other proposed or existing instruments are also shown. Current pulsar limits, indicated by the thick black line, already severely limit IMBH formation by this process. (See Ref. 41 for more details.)

It is possible that future PTAs will have sufficient sensitivity to detect individual sources of GWs. Sesana, Vecchio & Volonteri (Ref. 42) show that current models for the evolution of super-massive binary black holes in galaxies predict that at least one such system will produce a sinusoidal signal of period comparable to the data span with an amplitude of between 5 and 50 ns in timing residuals. A signal of this size is potentially detectable with the IPTA and certainly should be detectable by the SKA. Such a detection would open up the field of GW astronomy, allowing investigation of the source characteristics and the properties of the GW emission itself. For example, it will be possible to localise the source on the sky. Fig. 6 shows a simulation of the ability of the PPTA to determine source positions. Since the PPTA pulsars are predominantly in the southern hemisphere, source positions are better determined in the south with a point-spread function of half-power width...
about 15° or 20°. An improved sky distribution of pulsars and higher sensitivity from the IPTA or SKA will improve the accuracy to which a source can be localised on the sky.

Fig. 6. Localisation of a source of GWs in the northern sky (upper) and in the southern sky (lower) using simulated data for the pulsars observed by the PPTA. The actual assumed source positions are 06h, 45° and 18h, −45°. (Ref. [33])

5. Summary

Pulsars are extremely stable clocks distributed throughout our Galaxy. The high precision to which it is possible to measure pulse arrival times at the Earth and the long data spans now available leads to many interesting applications. For example, pulsar timing has given the first observational evidence for the existence of gravitational waves and shown that Einstein’s general theory of relativity is accurate in the regime of strong gravitational fields. With observations of many pulsars distributed across the celestial sphere – a “Pulsar Timing Array” – we can in principle make a positive detection of gravitational waves from astrophysical sources. Such an array
can also be used to establish a pulsar-based timescale and to identify (or limit) errors in Solar-system ephemerides.

We are now approaching the level of timing precision and data spans which are needed to achieve the main goals of PTA projects. Specifically, if current predictions of the strength of the stochastic GW background in the Galaxy from binary supermassive black holes in the cores of distant galaxies are realistic, within a few years we should be able to make a significant detection of this signal. Other possible sources of a stochastic GW background include fluctuations in the inflation era and oscillations of cosmic strings in the early Universe. Fig. 7 summarises the signals expected from different astrophysical sources and places the PTA in the context of ground- and space-based laser interferometer systems, specifically LIGO and LISA.

![Fig. 7. Spectrum of potentially detectable GW sources and sensitivity curves for PTA systems, the space-based laser interferometer LISA and the ground-based laser interferometer LIGO.](image)

Current efforts are concentrating on eliminating systematic errors from the timing data and improving signal-processing and GW-detection algorithms. While intrinsic period irregularities are significant in a few PTA pulsars, so far they are not a limiting factor for GW detection. Several groups around the world are collaborating to combine data sets to form an International Pulsar Timing Array, which will improve our sensitivity to GWs and help us to reach the other PTA goals. Future
instruments such as the Square Kilometre Array will greatly enhance the sensitivity of these efforts and will surely allow the detection and detailed study of GWs and their sources, both stochastic and individual. These studies have the potential to give new information on the properties of gravitational waves and gravitational interactions in the near and distant Universe.

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