Einstein's gravity as seen by a cosmic lighthouse keeper

Michael Kramer

Abstract The last years have seen continuing activities in the exploration of our understanding of gravity, motivated by results from precision cosmology and new precision astrophysical experiments. At the centre of attention lies the question as to whether general relativity is the correct theory of gravity. In answering this question, we work not only towards correctly interpreting the phenomenon of "dark energy" but also towards the goal of achieving a quantum theory of gravity. In these efforts, the observations of pulsars, especially those in binary systems, play an important role. Pulsars do not only provide the only evidence for the existence of gravitational waves so far, but they also provide precision tests of general relativity and alternative theories of gravity. This talk summarizes the current state-of-art in these experiments and looks into the future.

1 Introduction

This conference celebrated Einstein's time in Prague 100 years ago. As detailed during the conference and in these proceedings, important groundwork for the later theory of general relativity (GR) was achieved by Einstein during this time. Now, at the time of writing, we are less than three years away from celebrating the centenary of Einstein's greatest achievement. And yet, we have also seen a lot of presentations at this conference that addressed the properties and experimental consequences of alternative theories of gravity. As a matter of fact, nearly a hundred years later, efforts in testing GR and its concepts are still being made by many colleagues around the world, using many different approaches. To date GR has passed all these experimental and observational tests with flying colours, but in light of recent progress

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Michael Kramer
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany; Jodrell Bank Centre for Astrophysics, University of Manchester, Oxford Road, Manchester M13 9PL, UK e-mail: mkramer@mpifr.de

in observational cosmology in particular, the question of as to whether alternative theories of gravity need to be considered is as topical as ever.

Many experiments are designed to achieve ever more stringent tests by either increasing the precision of the tests or by testing different, new aspects. Some of the most stringent tests are obtained by satellite experiments in the solar system, providing exciting limits on the validity of GR and alternative theories of gravity. However, solar-system experiments are made in the gravitational weak-field regime, while deviations from GR may appear only near the Planck scale or in strong gravitational fields.

We are all very much looking forward to the first direct detection of gravitational waves with ground-based (and hopefully, eventually, space-based) detectors, which will not only open a completely new window to the Universe but which will also provide superb tests of GR under strong-field conditions. Meanwhile, it happens that nature provides us with an almost perfect laboratory to test the strong-field regime - in the form of binary radio pulsars.

1.1 Pulsars

Pulsars are rotating neutron stars that emit a radio beam that is eventually powered by the pulsars' rotational energy and that is centred on the magnetic axis of the neutron star. As the magnetic axis and the hence the beam are inclined to the rotation axis, the pulsar acts as a cosmic lighthouse, and a pulsar appears as a pulsating radio source. The moment of inertia and the stored rotational energy of pulsars are large, so that in particular the fast rotating millisecond pulsars deliver a radio "tick" per rotation with a precision that rivals the best atomic clocks on Earth. Corresponding pulse (or spin) periods range from 1.4 ms to 8.5 s. As they concentrate an average of 1.4 solar masses on a diameter of only about 20 km, pulsars are exceedingly dense and compact, representing the densest matter in the observable universe. The resulting gravitational field near the surface is large, enabling strong-field tests of gravity.

For these tests, it is irrelevant how this emission is created, as long the lighthouse effects sends us a regular beacon. That is useful, because after more than 40 years of pulsar research, the details of the actual emission process still elude us. However, we have a basic understanding that is sufficient to perform the experiments described later. In our straw-man model, the high magnetic field of the rotating neutron star ($B_{\rm surf} \sim 10^8 - 10^{14}$ Gauss) induces a huge electric quadrupole field and an electromagnetic force that exceeds gravity by ten to twelve orders of magnitudes. Charges are pulled out easily from the surface, and the result is a dense, magnetized plasma that surrounds the pulsar. The strong magnetic field forces the plasma to co-rotate with the pulsar like a rigid body. This co-rotating *magnetosphere* can only extend up to a distance where the co-rotation velocity reaches the speed of light[1]. This dis-

[1] Strictly speaking, the Alfvén velocity will determine the co-rotational properties of the magnetosphere.

tance defines the so-called light cylinder which separates the magnetic field lines into two distinct groups, i.e. *open and closed field lines*. Closed field lines are those which close within the light cylinder, while open field lines would close outside. The plasma on the closed field lines is trapped and will co-rotate with the pulsar forever. In contrast, plasma on the open field lines can reach highly relativistic velocities and can leave the magnetosphere, creating the observed well-confined radio beam at a distance of a few tens to hundreds of km above the pulsar surface. It is this beam which creates the pulsating signals once per rotation when it points towards Earth.

1.2 Pulsars and their companions

The idea behind the usage of pulsars for testing GR and alternative theories of gravity is straightforward: if the pulsar is in orbit with a binary companion, we use the measured variation in the arrival times of the received signal to determine and trace the orbit of the pulsar about the common centre of mass as it moves in the curved space-time of the companion.

This "pulsar timing" experiment is simultaneously clean, conceptually simple and very precise. The latter is true since when measuring the exact arrival time of pulses at our telescope on Earth, we do a ranging experiment that is vastly superior in precision than a simple measurement of Doppler-shifts in the pulse period. This is possible, since the pulsed nature of our signal links tightly and directly to the rotation of the neutron star, allowing us to count every single rotation of a neutron star. Furthermore, in this experiment we can consider the pulsar as a test mass that has a precision clock attached to it.

While, strictly speaking, binary pulsars move in the weak gravitational field of a companion, they do provide precision tests of the strong-field regime. This becomes clear when considering that the majority of alternative theories predicts strong self-field effects which would clearly affect the pulsars' orbital motion. Hence, tracing their fall in a gravitational potential, we can search for tiny deviations from GR, providing us with unique precision strong-field tests of gravity.

As a result, a wide range of relativistic effects can be observed, identified and studied. These include so far:

- Precession of periastron
- Gravitational redshift
- Shapiro delay due to curved space-time
- Gravitational wave emission
- Geodetic precession, relativistic spin-orbit coupling
- Speed of gravity

But we can also convert our observations in tests of concepts and principles deeply embedded in theoretical frameworks, such as

- Strong Equivalence Principle (grav. Stark effect),
- Lorentz invariance of gravitational interaction,

- Non-existence of preferred frames,
- Conservation of total momentum,
- Non-variation of gravitational constant,

which also leads to stringent limits on alternatives theories of gravity, e.g. tensor–scalar theories, Tensor-Vector-Scalar (TeVeS) theories.

1.3 Nature is kind...

The various effects or concepts to be tested require sometimes a rather different type of laboratory. For instance, to test the violation of the Strong-Equivalence-Principle, one would like to use a binary system that consists of different types of masses (i.e. with different gravitational self-energy), rather than a system made of very similar bodies. Fortunately, nature has been kind.

At the moment, we know about 2000 pulsars, with about 10% of these in binary systems. The shortest orbital period is about 90 min while the longest period is 5.3 yr (e.g. [1]). We find different types of components, i.e. main-sequence stars, white dwarfs (WD), neutron stars (NS) and even planets. Unfortunately, despite past and on-going efforts, we have not yet found a pulsar about a stellar black hole companion or about the supermassive black hole in the centre of our Galaxy [2]. Double neutron star systems are rare but usually produce the largest observable relativistic effects in their orbital motion and, as we will see, produce the best tests of general relativity for strongly self-gravitating bodies. In comparison, pulsar - white dwarf systems are much more common. Indeed, most pulsar companions are white dwarfs, with a wide range of orbital periods, ranging from hours to days, weeks and months. Still, many of them can be used for tests of gravitational theories where we utilize the fact that white dwarfs and neutron stars differ very significantly in their structure and, consequently, self-energies.

1.4 Precision experiments

Using pulsar timing techniques, we make extremely precise measurements that allow us to probe gravitation with exquisite accuracy. Table 1 gives an idea about the precision that we already achieve today. As discussed later in this contribution, with future telescopes like the “Square Kilometre Array”, the precision will even be enhanced by at least two orders of magnitudes and should, for instance, allow us to find a pular orbiting SGR A*, which would provide the mass of the central black hole to a precision of an amazing $1M_\odot$! It would also allow us to measure the spin of the black hole with a precision of 10^{-4} to 10^{-3} (enabling tests of the “cosmic censorship conjecture”) and the quadrupole moment with a precision to 10^{-4} to 10^{-3} (thus enabling tests of the “no-hair theorem”). See later and [2] for more details.

Table 1 Examples of precision measurements using pulsar timing as a variation demonstration what is possible today. The digit in bracket indicates the uncertainty in the last digit of each value. References are cited.

Masses:		
Masses of neutron stars:	$m_1 = 1.4398(2)\,M_\odot$	[3]
	$m_2 = 1.3886(2)\,M_\odot$	[3]
Mass of WD companion:	$0.207(2)\,M_\odot$	[4]
Mass of millisecond pulsar:	$1.67(2)\,M_\odot$	[5]
Main sequence star companion:	$1.029(8)\,M_\odot$	[5]
Mass of Jupiter and moons:	$9.547921(2) \times 10^{-4}\,M_\odot$	[6]
Spin parameters:		
Period:	5.757451924362137(2) ms	[7]
Orbital parameters:		
Period:	0.102251562479(8) day	[8]
Eccentricity:	$3.5(1.1) \times 10^{-7}$	[9]
Astrometry:		
Distance:	157(1) pc	[7]
Proper motion:	140.915(1) mas yr^{-1}	[7]
Tests of general relativity:		
Periastron advance:	4.226598(5) deg yr^{-1}	[3]
Shrinkage due to GW emission:	7.152(8) mm/day	[8]
GR validity (obs/exp):	1.0000(5)	[8]
Constancy of grav. Constant, $\dot{G}/G$:	$-0.6(1.6) \times 10^{-12}$ yr^{-1}	[9]

2 The Hulse-Taylor pulsar: gravitational wave damping

The first binary pulsar to ever be discovered happend to be a rare double neutron star system. It was discovered by Russel Hulse and Joe Taylor in 1974 [10]. The pulsar, B1913+16, has a period of 59 ms and is in eccentric ($e = 0.61$) orbit around a unseen companion with an orbital period of less than 8 hours. It became soon clear that the pulsar does not follow the movement expected from a simple Keplerian description of the binary orbit, but that it shows the impact of relativistic effects. In order to describe the relativistic effects in a theory-independent fashion, one introduces so-called "Post-Keplerian" (PK) parameters that are included in a timing model to accurately describe the measured pulse times-of-arrival (see e.g. [1] for more details).

For the Hulse-Taylor pulsar, it was soon measured that the system showed a relativistic advance of its periastron, comparable to what is seen in the solar system for Mercury, albeit with a much larger amplitude of $\dot{\omega} = 4.226598 \pm 0.000005$ deg/yr [3]. GR predicts a value for the periastron advance that depends on the Keplerian parameters and the masses of the pulsar and its companion:

$$\dot{\omega} = 3T_\odot^{2/3} \left(\frac{P_\mathrm{b}}{2\pi}\right)^{-5/3} \frac{1}{1-e^2} (m_\mathrm{p}+m_\mathrm{c})^{2/3}. \quad (1)$$

Here, $T_\odot$ is a constant, P_b the orbital period, e the eccentricity, and m_p and m_c the masses of the pulsar and its companion. See [1] for further details.

The Hulse-Taylor pulsars also shows the effects of gravitational redshift (including a contribution from a second-order Doppler effect) as the pulsar moves in its elliptical orbit at varying distances from the companion and with varying speeds. The result is a variation in the clock rate of with an amplitude of $\gamma = 4.2992 \pm 0.0008$ ms [3]. In GR, the observed value is related to the Keplerian parameters and the masses as

$$\gamma = T_\odot^{2/3} \left(\frac{P_\mathrm{b}}{2\pi}\right)^{1/3} e\frac{m_\mathrm{c}(m_\mathrm{p}+2m_\mathrm{c})}{(m_\mathrm{p}+m_\mathrm{c})^{4/3}}. \quad (2)$$

We can now combine these measurements. We have two equations with a measured left-hand side. On the right-hand side, we measured everything apart from two unknown masses. We solve for those and obtain, $m_\mathrm{p} = 1.4398 \pm 0.0002 M_\odot$ and $m_\mathrm{c} = 1.3886 \pm 0.0002 M_\odot$ [3]. These masses are correct if GR is the right theory of gravity. If that is indeed the case, we can make use of the fact that (for point masses with negligible spin contributions), the PK parameters in each theory should only be functions of the a priori unknown masses of pulsar and companion, m_p and m_c, and the easily measurable Keplerian parameters [11][2]. With the two masses now being determined using GR, we can compare any observed value of a third PK parameter with the predicted value. A third such parameter is the observed decay of the orbit which can be explained fully by the emission of gravitational waves. And indeed, using the derived masses, and the prediction of general relativity, i.e.

$$\dot{P}_\mathrm{b} = -\frac{192\pi}{5} T_\odot^{5/3} \left(\frac{P_\mathrm{b}}{2\pi}\right)^{-5/3} \frac{\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)}{(1-e^2)^{7/2}} \frac{m_\mathrm{p}m_\mathrm{c}}{(m_\mathrm{p}+m_\mathrm{c})^{1/3}}, \quad (3)$$

one finds an agreement with the observed value of $\dot{P}_\mathrm{b}^\mathrm{obs} = (-2.423 \pm 0.001) \times 10^{-12}$ [3] – however, only if a correction for a relative acceleration between the pulsar and the solar system barycentre is taken into account. As the pulsar is located about 7 kpc away from Earth, it experiences a different acceleration in the Galactic gravitational potential than the solar system (see e.g. [1]). The precision of our knowledge to correct for this effect eventually limits our ability to compare the GR prediction to the observed value. Nevertheless, the agreement of observations and prediction, today within a 0.2% (systematic) uncertainty [3], represented the first evidence for the existence of gravitational waves. Today we know many more binary pulsars where we can detect gravitational wave emission. In one particular case, the measurement uncertainties are not only more precise, but also the systematic uncertainties are much smaller, as the system is much more nearby. This system is the Double Pulsar.

[2] For alternative theories of gravity this statement may only be true for a given equation-of- state.

3 The Double Pulsar

The Double Pulsar was discovered in 2003 [12, 13]. It does not only show larger relativistic effects and is much closer to Earth (about 1 kpc) than the Hulse-Taylor pulsar, allowing us to largely neglect the relative acceleration effects, but the defining unique property of the system is that it does not consist of one active pulsar and its *unseen* companion, but that it harbours two *active* radio pulsars.

One pulsar is mildly recycled with a period of 22 ms (named "A"), while the other pulsar is young with a period of 2.8 s (named "B"). Both orbit the common centre of mass in only 147-min with orbital velocities of 1 Million km per hour. Being also mildly eccentric ($e = 0.09$), the system is an ideal laboratory to study gravitational physics and fundamental physics in general. A detailed account of the exploitation for gravitational physics has been given, for instance, by [14, 15, 16]. An update on those results is in preparation [8], with the largest improvement undoubtedly given by a large increase in precision when measuring the orbital decay. Not even ten years after the discovery of the system, the Double Pulsar provides the best test for the accuracy of the gravitational quadrupole emission prediction by GR far below the 0.1% level.

In order to perform this test, we first determine the mass ratio of pulsar A and B from their relative sizes of the orbit, i.e. $R = x_B/x_A = m_A/m_B = 1.0714 \pm 0.0011$ [14]. Note that this value is theory-independent to the 1PN level [17]. The most precise PK parameter that can be measured is a large orbital precession, i.e. $\dot{\omega} = 16.8991 \pm 0.0001$ deg/yr. Using Eq. (1), this measured value and the mass ratio, we can determine the masses of the pulsars, assuming GR is correct, to be $m_A = (1.3381 \pm 0.0007) M_\odot$ and $m_B = (1.2489 \pm 0.0007) M_\odot$.

We can use these masses to compute the expected amplitude for the gravitational redshift, γ, if GR is correct. Comparing the result with the observed value of $\gamma = 383.9 \pm 0.6 \mu$s, we find that theory (GR) agrees with the observed value to a ratio of 1.000 ± 0.002, as a first of five tests of GR in the Double Pulsar.

The Double Pulsar also has the interesting feature that the orbit is seen nearly exactly edge-on. This leads to a 30-s long eclipse of pulsar A due to the blocking magnetosphere of B that we discuss further below, but it also leads to a "Shapiro delay": whenever the pulse needs to propagate through curved space-time, it takes a little longer than travelling through flat space-time. At superior conjunction, when the signal of pulsar A passes the surface of B in only 20,000km distance, the extra path length due to the curvature of space-time around B leads to an extra time delay of about 100μs. The shape and amplitude of the corresponding Shapiro delay curve yield two PK parameters, s and r, known as *shape* and *range*, allowing two further tests of GR. s is measured to $s = \sin(i) = 0.99975 \pm 0.00009$ and is in agreement with the GR prediction of

$$s = T_\odot^{-1/3} \left(\frac{P_b}{2\pi} \right)^{-2/3} x \, \frac{(m_A + m_B)^{2/3}}{m_B}, \tag{4}$$

(where x is the projected size of the semi-major axis measured in lt-s) within a ratio of 1.0000 ± 0.0005. It corresponds to an orbital inclination angle of 88.7 ± 0.2 deg, which is indeed very close to 90 deg as suggested by the eclipses. r can be measured with much less precision and yields an agreement with GR's value given by

$$r = T_{\odot} m_B, \tag{5}$$

to within a factor of 0.98 ± 0.02.

A fourth test is given by comparing an observed orbital decay of 107.79 ± 0.11 ns/day to the GR prediction. Unlike the Hulse-Taylor pulsar, extrinsic effects are negligible and the values agree with each other without correction to within a ratio of 1.000 ± 0.001. This is already a better test for the existence of GW than possible with the Hulse-Taylor pulsar and will continue to improve with time. Indeed, at the time of writing the agreement has already surpassed the 0.1% level significantly [8].

4 Relativistic spin-orbit coupling

Apart from the Shapiro-delay, the impact of curved space-time is also immediately measurable by its effect on the orientation of the pulsar spin in a gyroscope experiment. This effect, known as geodetic precession or de Sitter precession represents the effect on a vector carried along with an orbiting body such that the vector points in a different direction from its starting point (relative to a distant observer) after a full orbit around the central object. Experimental verification has been achieved by precision tests in the solar system, e.g. by Lunar Laser Ranging (LLR) measurements, or recently by measurements with the Gravity Probe-B satellite mission (see [18] for a review of experimental tests). However, these tests are done in the weak field conditions of the solar system, so that pulsars provide the only access to the strong-field regime.

In binary systems one can interpret the observations, depending on the reference frame, as a mixture of different contributions to relativistic spin-orbit interaction. One contribution comes from the motion of the first body around the centre of mass of the system (deSitter-Fokker precession), while the other comes from the dragging of the internal frame at the first body due to the translational motion of the companion [19]. Hence, even though we loosely talk about geodetic precession, the result of the spin-orbit coupling for binary pulsar is more general, and hence we will call it *relativistic spin-precession*. The consequence of relativistic spin-precession is a precession of the pulsar spin about the total angular moment vector, changing the orientation of the pulsar relative to Earth.

Since the orbital angular momentum is much larger than the angular momentum of the pulsar, the orbital spin practically represents a fixed direction in space, defined by the orbital plane of the binary system. Therefore, if the spin vector of the pulsar is misaligned with the orbital spin, relativistic spin-precession leads to a change in viewing geometry, as the pulsar spin precesses about the total angular momentum vector. Consequently, as many of the observed pulsar properties are determined by the relative orientation of the pulsar axes towards the distant observer on Earth, we should expect a modulation in the measured pulse profile properties, namely its shape and polarisation characteristics [20]. The precession rate is another PK parameter and given in GR by (e.g. [1])

$$\Omega_{\rm p} = T_{\odot}^{2/3} \times \left(\frac{2\pi}{P_{\rm b}}\right)^{5/3} \times \frac{m_{\rm c}(4m_{\rm p}+3m_{\rm c})}{2(m_{\rm p}+m_{\rm c})^{4/3}} \times \frac{1}{1-e^2} \tag{6}$$

In order to see a measurable effect in any binary pulsar, *a)* the spin axis of the pulsar needs to be misaligned with the total angular momentum vector and *b)* the precession rate must be sufficiently large compared to the available observing time to detect a change in the emission properties. Table 2 lists the known Double Neutron Star Systems which typically show the largest degree of relativistic effects due to the often short eccentric binary orbits. However, the last entry in the table is PSR J1141−6545 which is a relativistic system with a white dwarf companion. Those pulsars that are marked with an asterisk have been identified as pulsars showing relativistic spin precession. Note that the top 5 out of 8 sources (with a known expected precession rate) indeed show the effect.

As the most relativistic binary system known to date, we expect a large amount of spin precession in the Double Pulsar system. Despite careful studies, profile changes for A have not been detected, suggesting that A's misalignment angle is rather small (e.g. Ferdman et al. in prep.). In contrast, changes in the light curve and pulse shape on secular timescales [21] reveal that this is not the case for B. In fact, B had been becoming progressively weaker and disappeared from our view in 2009 [22]. Making the valid assumption that this disappearance is solely caused by relativistic spin precession, it will only be out of sight temporarily until it reappears later. Modelling suggests that, depending on the beam shape, this will occur in about 2035 but an earlier time cannot be excluded. The geometry that is derived from this modelling is consistent with the results from complementary observations of spin precession, visible via a rather unexpected effect described in the following.

The change on the orientation of B also changes the observed eclipse pattern in the Double Pulsar, where we can see periodic bursts of emission of A during the dark eclipse phases, with the period being the full- or half-period of B. As this pattern is caused by the rotation of B's blocking magnetospheric torus that allows light to pass B when the torus rotates to be seen from the side, the resulting pattern is determined by the three-dimensional orientation of the torus, which is centred on the precessing pulsar spin. Eclipse monitoring over the course of several years shows exactly the expected changes, allowing to determine the precession rate to $\Omega_{\rm p,B} = 4.77^{+0.66}_{-0.65}$ deg/yr. This value is fully consistent with the value expected GR, providing a fifth test [23]. This measurement also allows to test alternative theories of gravity and their prediction for relativistic spin-precession in strongly self-gravitating bodies for the first time (see [16] for details).

Table 2 DNSs sorted according to the expected relativistic spin precession rate. Also included is PSR J1141−6545 which is in a relativistic orbit about a white dwarf companion. Pulsars marked with an asterisk have been identified of showing spin precession. For sources where no precession rate is listed, the companion mass could not be accurately measured yet, indicating however, that the precession rate is low.

PSR	P(ms)	P_b (d)	x(lt-s)	e	Ω_p (deg yr^{-1})
J0737−3039A/B*	22.7/2770	0.10	1.42/1.51	0.09	4.8/5.1
J1906+0746*	144.1	0.17	1.42	0.09	2.2
B2127+11C*	30.5	0.34	2.52	0.68	1.9
B1913+16*	59.0	0.33	2.34	0.62	1.2
J1756−2251	28.5	0.32	2.76	0.18	0.8
B1534+12*	37.9	0.42	3.73	0.27	0.5
J1829+2456	41.0	1.18	7.24	0.14	0.08
J1518+4904	40.9	8.64	20.0	0.25	–
J1753−2240	95.1	13.63	18.1	0.30	–
J1811−1736	104.2	18.8	34.8	0.83	–
J1141−6545*	394.0	0.20	1.89	0.17	1.4

5 Alternative theories

Despite the successes of GR, a range of observational data have fuelled the continuous development of alternative theories of gravity. Such data include the apparent observation of "dark matter" or the cosmological results interpreted in the form of "inflation" and "dark energy". Confronting alternative theories with data also in other areas of the parameter space (away from the CMB or Galactic scales), requires that these theories are developed sufficiently in order to make predictions. A particular sensitive criterion is if the theory is able to make a statement about the existence and type of gravitational waves. Most theories cannot do this (yet), but a class of theories where this has been achieved is the class of tensor-scalar theories as discussed and demonstrated by Damour and Esposito-Farèse in a series of works (e.g. [24]). For corresponding tests, the choice of a double neutron star system is not ideal, as the difference in scalar change, (that would be relevant, for instance, for the emission of gravitational *dipole* radiation) is small. The ideal laboratory would be a pulsar orbiting a black hole, as the black hole would have zero scalar charge and the difference would be maximised. The next best laboratory is a pulsar-white dwarf system. Indeed, such binary systems are able to provide constraints for alternative theories of gravity that are equally good or even better than solar system limits [9].

A recently studied pulsar-white dwarf system turns out to be very exciting: PSR J0348+0432 harbours a white dwarf whose composition and orbital motion can be precisely derived from optical observations. The results allow us to measure the mass of the neutron star, showing that it has a record-braking value of $2.01\pm0.04M_{\odot}$! This is not only the most massive neutron star known (at least with reliable precision), but the 39-ms pulsar and the white dwarf orbit each other in only 2.46 hours, i.e. the orbit is only tens of seconds longer than that of the Double Pulsar. Even though the orbital motion is nearly circular, the effect of gravitational wave damping is clearly measured. Thereby, the high pulsar mass and the compact orbit make this system a sensitive laboratory of a previously untested strong-field gravity regime. Thus far, the observed orbital decay agrees with GR, supporting its validity even for the extreme conditions present in the system (Antoniadis et al., submitted).

6 Detecting gravitational waves with pulsars

The observed orbital decay in binary pulsars detected via precision timing experiments so far offers the only evidence for the existence of gravitational wave (GW) emission. Intensive efforts are therefore on-going world-wide to make a direct detection of gravitational waves that pass over the Earth. Ground-based detectors like GEO600, VIRGO or LIGO use massive mirrors, the relative distance of which are measured by a laser interferometer set-up, while the future space-based LISA detector uses formation flying of three test-masses that are housed in satellites. The change of the space-time metric around the Earth also influences the arrival times of pulsar signals measured at the telescope, so that high-precision MSP timing can also potentially directly detect GWs. Because pulsar timing requires the observations of a pulsar for a full Earth orbit before the relative position between pulsar, Solar System Barycentre and Earth can be precisely determined, only GWs with periods of more than a year can usually be detected. In order to determine possible uncertainties in the used atomic clocks, planetary ephemerides used, and also since GWs are expected to produce a characteristic quadrupole signature on the sky, several pulsars are needed to make a detection. The sensitivity of such a "Pulsar Timing Array" (PTA) increases with the number of pulsars and should be able to detect pulsars in the nHz regime, hence below the frequencies of LIGO ($\sim$kHz and higher) and LISA ($\sim \mu$Hz) (see Fig. 1).

A number of PTA experiments are ongoing, namely in Australia, Europe and North America (see [25] for a summary). The currently derived upper limits on a stochastic GW background (e.g. [26, 27]) are very close to the theoretical expectation for a signal that originates from binary super-massive black holes expected from the hierarchical galaxy evolution model [28, 29]. The best limit has recently been published by the European Pulsar Timing Array (EPTA) that uses the telescopes at Effelsberg, Jodrell Bank, Nancay and Westerbork [30]. Soon the Sardinia Radio Telescope will be added to the EPTA once it is completed.

While the limits are close, it seems that "simply a bit of extra sensitivity is needed" to make a first detection. This is the motivation for the Large European Array for Pulsars (LEAP) project in Europe. It aims to phase-coherently connect Europe's largest radio telescopes to form an Arecibo-sized dish that can observe a large number of millisecond pulsars with high sensitivity enabling high precision pulsar timing. LEAP is part of the EPTA and also acts as a test-bed for technology development for the SKA [27].

Demonstrating the power of PTA experiments, Champion et al. [6] recently used data of PTA observations to determine the mass of the Jovian system independently of the space-craft data obtained by fly-bys. Here, the idea is that an incorrectly known planet mass will result in an incorrect model of the location of the Solar System Barycentre relative to the Earth. However, as discussed the SSB is the reference point for pulsar arrival time measurements, so that a mismatch between assumed and actual position would lead to a periodic signal in the pulsar data with the period being that of the planet with the ill-measured mass. This measurement technique is sensitive to a mass difference of only 0.003% of the mass of the Earth, and 10^{-7}-th of Jupiter's mass.

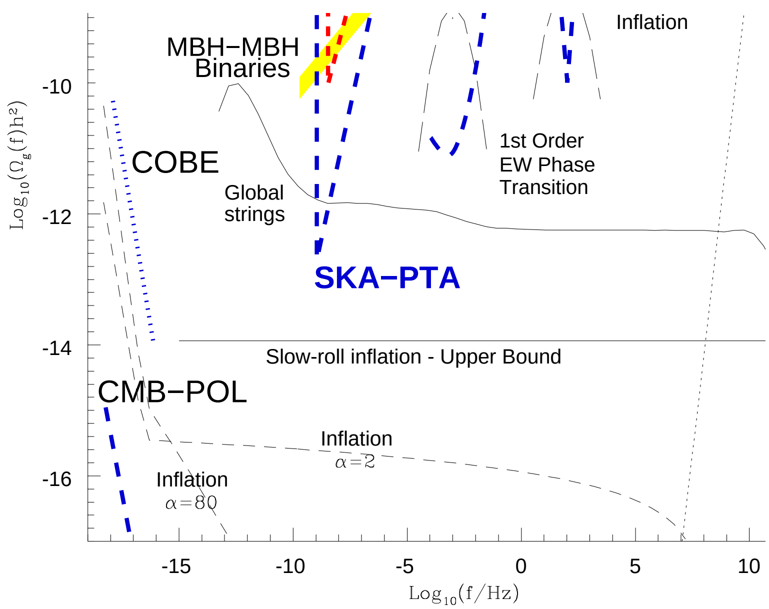

Fig. 1 Summary of the potential cosmological sources of a stochastic gravitational wave (GW) background overlaid with bounds from COBE, current Pulsar Timing Array (PTA) experiments and the goals of CMB polarization experiments, LISA and Advanced LIGO. LEAP will improve on the current best PTA limits by more than two orders of magnitude, enabling the detection of a GW background caused by the merger of massive black holes (MBHs) in early galaxy formation. The amplitude depends on the MBH mass function and merger rate, so that uncertainty is indicated by the size of the shaded area. LEAP is the next logical step towards a PTA realized with the SKA which will improve on the current sensitivity by about four orders of magnitude.

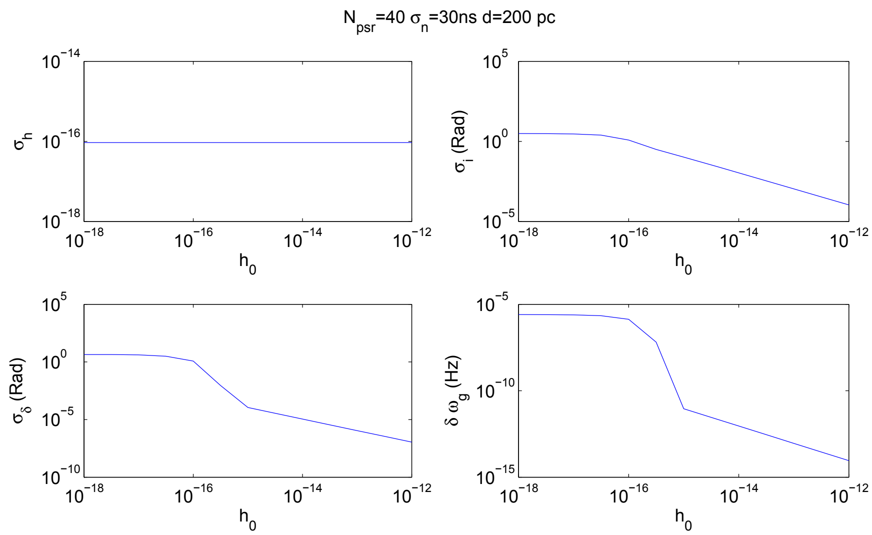

Fig. 2 Results of computations for the detection of a single GW source with the help of a PTA consisting of 40 pulsars with an average timing precision of 300 ns at a typical distance of 200 pc [31]. *top left)* Error in measuring the characteristic strain amplitude of a single GW source for a variety of signal strengths. *top right)* corresponding error in orbital inclination measurement, *bottom left)* positional error on the sky and *bottom right)* error in determining the gravitational wave frequency. See [31] for details.

If LEAP or other experiments do not detect GWs in the next few years, a first detection is virtually guaranteed with the more sensitive Phase I of the SKA. But the science that can eventually be done with the full SKA goes far beyond simple GW detection – a whole realm of astronomy and fundamental physics studies will become possible. For instance, it will be possible to study the properties of gravitational waves, such as their polarisation properties or the mass of the graviton. [32, 33]. This is achieved by measuring the degree of correlation in the arrival time variation of pairs of pulsars separated by a certain angle on the sky. A positive correlation is expected for pulsars in the same direction or 180 deg apart on the sky, while pulsars separated by 90 deg should be anti-correlated. The exact shape of this correlation curve obviously depends on the GW polarisation properties [32] but also on the mass of the graviton [33]. The latter becomes clear when we consider that a non-zero mass leads to a dispersion relation and a cut-off frequency $\omega_{\rm cut} = m_{\rm g}c^2/\hbar$, below which a propagation is not possible anymore, affecting the degree of correlation possible between two pulsars. With a 90% probability, massless gravitons can be distinguished from gravitons heavier than 3×10^{-22} eV (Compton wavelength $\lambda_{\rm g} = 4.1\times10^{12}$ km), if bi-weekly observation of 60 pulsars are performed for 5 years with pulsar RMS timing accuracy of 100 ns. If 60 pulsars are observed for 10 years with the same accuracy, the detectable graviton mass is reduced to 5×10^{-23} eV ($\lambda_{\rm g} = 2.5\times10^{13}$ km) [33].

In addition to detecting a *background* of GW emission, the probability of detecting a *single* GW source increases from a few percent now to well above 95% with the full SKA. We can, for instance, expect to find the signal of a single super-massive black hole binary. Considering the case when the orbit is effectively not evolving over the observing span, we can show that, by using information provided by the "pulsar term" (i.e. the retarded effect of the GW acting on the pulsar's surrounding space time), we can achieve a rather astounding source localization. For a GW with an amplitude exceeding 10^{-16} and PTA observations of 40 pulsars with weekly timing to 30 ns precision, one can measure the GW source position to an accuracy of better than$\sim$ 1 arcmin (Fig. 2, [31]). With such an error circle, an identification of the GW source in the electromagnetic spectrum should be easily feasible. We note that in order to achieve such a result, a precise distance measurement to the pulsars is needed, which in turn can then be improved further during the fitting process that determines the orbital parameters of the GW source. Fortunately, the SKA will be a superb telescope to do astrometry with pulsars [34].

7 The Future and the ultimate laboratory

Essentially all upcoming and future telescopes will contribute in one way or the other to advances in the field of pulsar astrophysics. LOFAR will find a large number of neutron stars that are potential sources for tests of relativity or pulsar timing array experiments that attempt to directly detect gravitational waves [35]. Even though these experiments are performed at high frequencies, LOFAR can find appropriate sources and also monitor the interstellar weather that needs to be corrected for in high precision timing. The Chinese FAST telescope will have a collecting area that will allow us to find and time pulsars that will be significantly better than currently achieved with Arecibo [36]. However, the real big advance for pulsars and their applications will be achieved with the Square Kilometre Array (SKA).

It is clear that the SKA will have a huge impact on the study of pulsars and their applications, in particular in using them for our understanding gravity. Some of the questions directly addressed with SKA pulsar studies are:

- What is the nature of gravity? Was Einstein right? Is gravity described by a tensor field or are there additional scalar fields, as it is sometimes proposed to explain Dark Energy?
- What are the properties of gravitational waves? Do gravitons have Spin 2? What is the mass of gravitons and hence the propagation speed of gravitational waves?
- What happens in strong gravitational fields, in conditions of extreme curvature and near singularities? What are the properties of Black Holes? Do the no-hair and cosmic censorships theorems hold?

Answering these questions requires a survey for pulsars and the high-precision timing of a selected sample of those. In these searches, we can in particular expect to find the first pulsar-black hole systems.

What makes a binary pulsar with a black-hole companion so interesting is that it has the potential of providing a superb new probe of relativistic gravity. As pointed out by Damour & Esposito-Farese [37], the discriminating power of this probe might supersede all its present and foreseeable competitors. The reason lies in the fact that such a system would be very sensitive to strong gravitational self-field effects, making it for instance an excellent probe for tensor-scalar theories.

But also for testing the black hole properties predicted by GR, a pulsar-BH system will be superb laboratory. Wex & Kopeikin [38] showed that the measurement of classical and relativistic spin-orbit coupling in a pulsar-BH binary, in principle, allows us to determine the spin and the quadrupole moment of the black hole. This would test the "cosmic censorship conjecture" and the "no-hair theorem". While [38] showed that with current telescopes such an experiment would be almost impossible to perform (with the possible exception of pulsars about the Galactic centre black hole), Kramer et al. [39] pointed out that the SKA sensitivity should be sufficient. Indeed, this experiment benefits from the SKA sensitivity in multiple ways. On one hand, it provides the required timing precision but it also allows to perform the Galactic Census which should eventually deliver the sample of pulsars with a BH companion. As shown recently by [2] it should be "fairly easy" to measure the spin of the GC black hole with a precision of $10^{-4} - 10^{-3}$. Even for a pulsar with a timing precision of only 100μs, characteristic periodic residuals would enable tests of the no-hair theorem with with a precision of one percent or better (see Fig. 3)!

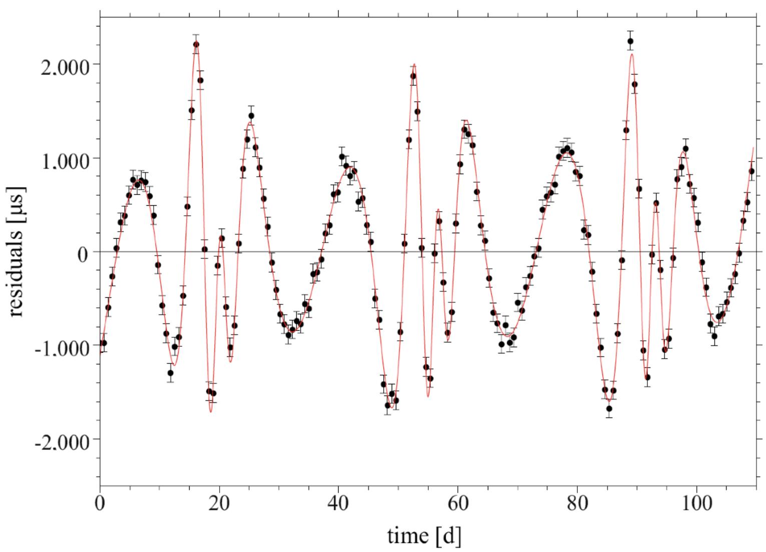

Fig. 3 Timing residuals of a pulsar orbiting the super-massive BH in the Galactic Centre in a 0.1-yr orbit. Shown are 3 orbits with an eccentricity of $e = 0.4$ for an extreme Kerr BH. Even with a timing precision of only 100μs, the characteristic periodic residuals caused by the BH's quadrupole moment are clearly visible [2].

8 Summary & Conclusions

A variety of experiments and observational data exist that allow us to test our understanding of gravity with increased precision. So far, general relativity has passed all tests with flying colours but the apparent existence of "Dark Energy" challenges this simple picture. It is clear that the observations of pulsars will continue to play an important part in testing general relativity and its alternatives. We expect to detect gravitational waves not only indirectly but also directly using pulsar observations, and we have all reasons to believe that future searches will yield pulsars that can probe the space-time around black holes. Combined with the results of other experiments, namely the detection of gravitational waves with ground based detectors, we can expect a bright future for our understanding of gravity.

I want to conclude with a quote from Einstein, which he made in a letter to Arnold Sommerfeld on December 9th, 1915, a few days after he presented his final field equations. Delighted by the fact that his theory could predict correctly the Mercury perihelion advance, he wrote:

"Wie kommt uns da die pedantische Genauigkeit der Astronomie zu Hilfe, über die ich mich im Stillen früher oft lustig machte!"

Unfortunately, Einstein died more than ten years before pulsars were discovered. But he once also said that if he were not a physicist, he would like to be a lighthouse keeper. I dare to think that he would also have liked, perhaps, to be a pulsar astronomer, i.e. a cosmic lighthouse keeper who can enjoy precision astronomy and the science possible it.

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