



Testing Gravity with Binary Pulsars in the SKA Era

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Binary (and trinary) radio pulsars are natural laboratories in space for understanding gravity in the strong field regime, with many unique and precise tests carried out so far, including the most precise tests of the strong equivalence principle and of the radiative properties of gravity. The Square Kilometre Array (SKA) telescope, with its high sensitivity in the Southern Hemisphere, will vastly improve the timing precision of recycled pulsars, allowing for a deeper search of potential deviations from general relativity (GR) in currently known systems. A Galactic census of pulsars will, in addition, will yield the discovery of dozens of relativistic pulsar systems, including potentially pulsar – black hole binaries, which can be used to test the cosmic censorship hypothesis and the “no-hair” theorem. Aspects of gravitation to be explored include tests of strong equivalence principles, gravitational dipole radiation, extra field components of gravitation, gravitomagnetism, and spacetime symmetries. In this chapter, we describe the kinds of gravity tests possible with binary pulsar and outline the features and abilities that SKA must possess to best contribute to this science.

1 Introduction

Even in this era of routine gravitational wave (GW) detections from merging neutron stars (NSs) and black holes (BHs), pulsars have a unique and complementary role to play in the understanding of neutron star interiors and gravity. Pulsars stand a class apart in being the only strong-field gravity experiment that provides tests of gravity theories with precisions that are orders of magnitude better than their counterparts in many observables. The Square Kilometre Array (SKA) telescope will open up the next frontier for these tests by providing improved timing of known pulsars, and more excitingly, by finding more relativistic binaries that will improve the precision, nature and extent of these tests.

In November 1915, Albert Einstein published the final paper that completed his theory of gravity and spacetime (Einstein, 1915), now known as general relativity (GR), fundamentally changing our view of gravity and spacetime. During its first fifty years, GR was considered a theoretical tour-de-force but one with little observational evidence. Only in the 1960s did technology usher in the remarkable field of experimental gravity (cf. reviews in Misner et al. (1973); Will (2018)). Over the subsequent sixty years, GR has passed all experimental tests in laboratories, in the Solar System and in various stellar systems (Berti et al., 2015; Will, 2018), particularly with state-of-the-art radio observations near black holes (Event Horizon Telescope Collaboration, 2019, 2022) and high precision observations of radio pulsars (Lorimer, 2005; Freire & Wex, 2024) – the topic of this work.

The surprising 1967 discovery of radio pulsars, and the subsequent demonstration that they were neutron stars, was an extraordinary breakthrough, for several reasons. First, it demonstrated the existence of neutron stars. Although their structure had been calculated in detail in the late 1930s (Tolman, 1939; Oppenheimer & Volkoff, 1939), it had not been fully established until then. Second, the association of fast-spinning pulsars with the Crab and Vela supernova remnants demonstrated that neutron stars (and pulsars) are the end stages of the lives of at least some very massive stars; indeed suggesting that the instantaneous loss of the enormous binding energy of the newly formed neutron star is the power source of supernovae, as had been hypothesized by Baade & Zwicky (1934). Third, their radio beams, which, akin to the sweeping signals of a rotating lighthouse creates apparent pulses, allow for the extremely precise monitoring of the spin of the star, and for the measurement of its precise position and proper motion. Critically for tests of gravity, the observed radio pulsations from NS in binaries also lead to precise measurements of the orbital motion.

The years 2024 and 2025 mark the 50th anniversary of the discovery of the first binary pulsar (a double neutron star system known as PSR B1913+16) and its publication (Hulse & Taylor, 1975). In the following years, precise radio timing of this system provided the first tests of GR for strongly self-gravitating objects, in this case neutron stars (NSs), and provided experimental confirmation of the existence of gravitational waves (Taylor et al., 1979; Taylor & Weisberg, 1982). By the end of the 1980s, this experiment had confirmed that the system was losing orbital energy due to gravitational wave emission within 1% of the rate predicted by GR (Taylor & Weisberg, 1989).

The Hulse-Taylor system opened a new window on the Universe: not only did it confirm the existence of GWs and verify that they conform (within measurement accuracy) to the predictions of

GR, but also the inevitable mergers among systems like PSR B1913+16¹ in the Universe provided guaranteed a source population for ground-based GW detectors, facilitating the construction of the Laser Interferometer Gravitational Wave Observatory (LIGO), Virgo, and KAGRA. This year, 2025, marks the 10th anniversary of the first direct GW detection, GW150914 (Abbott et al., 2016) from two merging BHs. In the mean time, there is also a confirmed detection of GWs from two NS-NS mergers (Abbott et al., 2017; Savchenko et al., 2017; Abbott et al., 2020).

Following the discovery of the first pulsar binary, discovery and tests of gravity theories from such systems have also advanced significantly. In particular, the timing of the double pulsar Burgay et al. (2003); Lyne et al. (2004) has resulted in a leap in precision of the measured orbital decay of a binary pulsar Kramer et al. (2021). The discovery of a millisecond pulsar in a triple star system has provided an improvement of the test of the universality of free fall for strongly self-gravitating objects (Archibald et al., 2018; Voisin et al., 2020), which is three orders of magnitude more precise than any such previous tests. A set of pulsar - white dwarf systems has significantly constrained the possibility of dipolar gravitational wave emission; these fundamental tests of the nature of gravitational waves have introduced tight constraints on alternative theories of gravity and have largely ruled out the phenomenon of matter induced spontaneous scalarisation (Zhao et al., 2022). Further details on this can be found in section 3. The high sensitivity of SKA will allow the more precise timing of known pulsars and will discover dozens of rare relativistic binary systems that will facilitate new and novel tests of gravity. The science case presented here builds upon the previous descriptions of SKA Key Science presented by Cordes et al. (2004); Kramer et al. (2004) and Shao et al. (2015).

While we limit ourselves to Galactic field stellar mass binaries in this chapter, complementary tests of gravity can be performed with a pulsar orbiting the supermassive black hole at the centre of our Galaxy (See Abbate et al. 2026) and exotic gravitational laboratories can be unearthed through targeted searches of globular clusters (See Bagchi et al. 2026). Many techniques used here can also be used to obtain a measurement of the Moment of Inertia of neutron stars (See Basu et al. 2026).

2 General Relativity and its extensions

2.1 Effects predicted by general relativity

Although General Relativity (GR) is in a sense the most simple and consistent theory of gravity, it predicts a wealth of effects that can be confronted with experiments, and in particular with pulsar observations (Will, 2018). As binary pulsars generate strong gravitational fields, such tests are complementary to weak field tests conducted in say, the Solar System. This circumstance is true for both the common (neutron star–white dwarf or double neutron star) systems and, even more so, for pulsar–black hole (PSRBH) binaries. In the latter case, the SKA will provide constraints on GR that are better than such as gravitational wave observations, Solar System experiments, stellar orbits around Sgr A*, or imaging with the Event Horizon Telescope (see also Figure 2).

GR effects in binary systems can be generally divided into the following categories: effects on the orbits of the two component masses, effects due to the non-negligible spin of the component stars,

¹Because of the energy loss from GW emission, the two neutron stars are now 180 m closer to each other than at the time of discovery in 1974; in 300 million years they will inevitably collide.

gravitational radiation, and effects on the signal propagation. For the particular case of PSRBH binaries, predictions on the nature of black holes, such as the cosmic censorship conjecture can also be tested (Liu et al., 2014). We next explain these effects briefly.

2.1.1 Effects on the orbits of the two component stars

While in Newtonian gravity, binaries move on ellipses in a single orbital plane, this is no longer true in GR. The most prominent effect is the advance of the argument of periastron ω , causing a relativistic precession of the ellipse along its orbital plane. For example, in the double neutron star system PSR J1946+2052, $\dot{\omega}$ amounts to about 25.6 degree per year (Stovall et al., 2018; Meng et al., 2025), illustrating the enormous impact of relativistic effects in compact, eccentric binaries.²

2.1.2 Effects due to non-negligible spin of the component stars

At higher orders, the spin of the component stars also has a gravitational influence on the orbit. First derived by Lense & Thirring (1918), it causes an additional periastron advance as well as a precession of the orbital plane around the total angular momentum of the system; this results in a change of the orbital inclination i and on the longitude of the ascending node Ω . In the double pulsar system, the Lense-Thirring contribution to the advance of periastron is of the same order of magnitude as the second order post-Newtonian correction to $\dot{\omega}$, but they have not yet been measured independently (Kramer et al., 2021). Presently, the only binary pulsar system where evidence for the Lense-Thirring frame-dragging has been found is the system containing PSR J1141–6545 and a massive WD (Venkatraman Krishnan et al., 2020). Due to its unusual binary evolution, the WD was spun up to spin periods of only a few hundred seconds, which contributed to a precession of the orbit that is detectable via the variation of i and its effect on the projected semi-major axis of the pulsar orbit, $x \equiv a_p \sin i/c$ where a_p is the semi-major axis of the pulsar orbit (Venkatraman Krishnan et al., 2020). The Lense-Thirring precession of a binary system consisting of a pulsar and a stellar-mass black hole was investigated in Wex & Kopeikin (1999). Given some favourable configurations, the precession can be measured and used to derive the spin and even the quadrupole moment of the black hole (Liu et al., 2014). The spin might be measurable in the near future if the high-mass companion to PSR J0514–4002E (Barr et al., 2024) turns out to be a fast-spinning black hole, *but only with the sensitivity of the SKA*.

Another relativistic effect due to the spin of the pulsar is the de-Sitter effect, also called geodetic precession. It originates from parallel transport of the spin vector of the pulsar along its orbit, which causes a precession if the spin is misaligned from the orbital angular momentum. In the double pulsar system this effect was responsible for pulsar B’s radio emission beam to precess out of our line of sight in 2008. Although tests of geodetic precession are currently not competitive with the Gravity Probe B result of 0.28% (Everitt et al., 2011), pulsar experiments provide a complementary test involving strongly self-gravitating objects (Breton et al., 2008; Fonseca et al., 2014; Desvignes et al., 2019; Lower et al., 2024). In addition to the geodetic precession, the spin-spin coupling, also called the Schiff effect (Schiff, 1960), will introduce another precession in a generally different direction; this effect, which is about two orders of magnitude smaller than the de-Sitter effect. This effect

²For comparison, Mercury’s relativistic precession is about 43 arcseconds per century, at least four orders of magnitude lower than that has been observed with DNS systems!

however, is very unlikely to be measured with pulsars. Geodetic precession also provides the possibility of providing a 2D view of the pulsar’s emission geometry which is helpful in understanding pulsar emission and the magnetosphere. This prospect is discussed in (Oswald et al., 2025).

2.1.3 Gravitational radiation

The first ever (indirect) detection of GW emission in the Hulse-Taylor system was a major breakthrough in astrophysics and a triumph for GR (Taylor et al., 1979; Taylor & Weisberg, 1982, 1989). After decades of observations, the orbital decay due to GW emission in this system has validated GR at the 0.16% level (Weisberg & Huang, 2016). Meanwhile, this effect has been seen in a number of other systems, but few have achieved a better precision, like PSR J1946+2052, where GR is validated at the 0.09% limit (Meng et al., 2025), the best current results have been obtained from the timing of the double pulsar (see Section 3 for details, and Freire & Wex (2024) for a review).

2.1.4 Effects on signal propagation

The gravitational field of the two-body system also affects the signal propagation. Special relativistic effects include the Doppler shift and aberration (Stairs et al., 2004). In GR, in addition, the gravitational redshift as seen by a distant observer has to be considered, which is (together with the second-order Doppler effect) encoded in the Einstein delay γ (Damour & Deruelle, 1986; Damour & Taylor, 1992). A prominent GR effect on the signal is the Shapiro delay, which accounts for the extra path length of the trajectory near a massive object. In the pulsar timing model, the Shapiro delay is usually split into a range and a shape parameter, which are measured separately, if the timing precision, companion mass and inclination angle are favourable. The Shapiro delay is largest during superior conjunction, when both masses are approximately on our line of sight. For example, in the double pulsar system, which is seen almost edge-on from the Earth, the Shapiro delay amounts to $130 \mu\text{s}$ (Kramer et al., 2021). For such edge-on systems, the deflection of light due to the companion’s gravitational field can also become relevant (Schneider, 1990; Lai & Rafikov, 2005), as well as the retardation effect due to the motion of the companion during the propagation of the signal (Kopeikin & Schäfer, 1999; Rafikov & Lai, 2006a). The deflection of light also adds corrections to the above mentioned aberration (Doroshenko & Kopeikin, 1995; Rafikov & Lai, 2006b; Hu et al., 2022). Delays on the signal propagation in PSRBH systems, due to the spin of the black hole, have been investigated for stellar masses (Wex & Kopeikin, 1999) and in extreme mass ratio systems (Ben-Salem & Hackmann, 2022), but are challenging to disentangle from the bending delay.

2.2 Testing GR and alternative gravity theories using pulsar timing

In order to test for effects beyond GR, a set of theory-independent “post-Keplerian” (PK) parameters are introduced (Damour & Deruelle, 1986; Damour & Taylor, 1992) (see Table 1 for a collection of the most important PK parameters relevant for this work). These are phenomenologically added to the pulsar timing model, and hence have the advantage of being theory agnostic. Hence, PK parameters that are used to specify relativistic effects are at times also contaminated by other astrophysical and astrometric effects. For example, the observed orbital decay parameter, \dot{P}_b , has “kinematic” contributions, which result from the proper motion of the system and the difference of Galactic accelerations between that system and the Solar System Barycentre (Damour & Taylor

(1991). Here, unless otherwise stated, we assume that non-gravitational contributions to the PK parameters are adequately corrected for or demonstrably negligible in effect.

If so, in the case of two well-separated masses with negligible spin contributions, the PK parameters are functions of the well-measured Keplerian parameters, the component masses, the equation of state (EOS) of stellar matter, and the parameters describing the gravitational theory (Damour & Taylor, 1992).

Measuring two PK parameters, we can use a specific theory of gravity to determine the component masses of the system, which are important to study stellar evolution theories and, in some cases, to constrain the NS EOS (Watts et al., 2015). If more PK parameters are measured, then the theory can be tested by a self-consistency argument — using the masses derived in the first stage one should be able to predict the subsequent PK measurements. Another way of viewing this is the so-called “mass-mass diagram” (see Figure 1 for an example of such a test with the Hulse-Taylor pulsar, Weisberg & Huang 2016). For a gravitational theory to pass the test(s), all curves in the diagram should intersect in some region, *i.e.*, the theory must be able to describe the component masses in a self-consistent way (Taylor & Weisberg, 1982).

Of all double neutron star (DNS) systems, the most relevant for tests of gravity theories is the double pulsar. This system has a unique combination of characteristics that make it, in many respects, the best pulsar laboratory for gravity. At the time of discovery, it was by far the most compact double neutron star (DNS) system known in our Galaxy (Burgay et al., 2003)³. Additionally, the detection of radio pulsations from its NS companion (Lyne et al., 2004) made it the first (and thus far the only) double pulsar known. Furthermore, it is also the most edge-on system known Kramer et al. (2006), providing the most precise measurement of Shapiro delay (Shapiro, 1964) as predicted by GR. This alignment also makes the pulses from the ‘A’ pulsar to be eclipsed by the magnetosphere of the ‘B’ pulsar, thereby modulating the intensity of pulses from A with the spin frequency of B Breton et al. (2008); Lower et al. (2024) While the current results from its timing analysis are discussed in detail in the next section, we also refer to Kramer & Wex (2009) who used the double pulsar to demonstrate the use of a Lagrangian

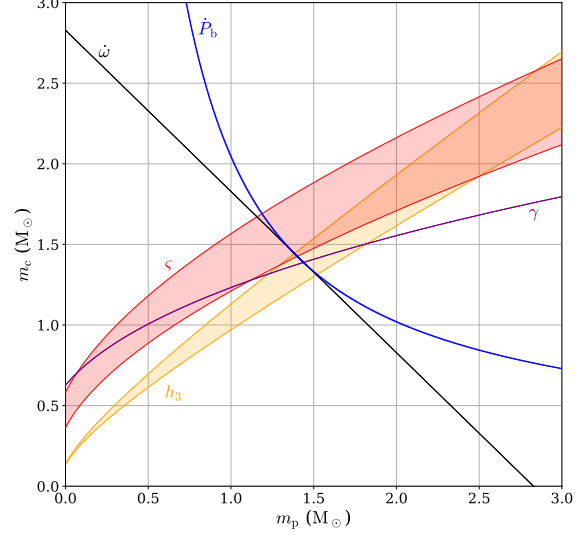


Figure 1: The mass-mass diagram of the Hulse-Taylor pulsar, PSR B1913+16 based on the PK parameters measured by Weisberg & Huang (2016). In the figure the underlying gravitational theory is assumed to be GR. Under this theory, we can calculate bands denoting the $1 - \sigma$ uncertainties in the component masses inferred from various relativistic effects. The fact that all bands meet at the same region in the diagram implies that GR passes these tests and provides a self-consistent description of the masses. Figure from Freire & Wex (2024), reused without changes under a Creative Commons Attribution 4.0 International License.

³This is no longer true since the discovery of PSR J1946+2052 (Stovall et al., 2018).

Table 1: The most important PK parameters that could be used in pulsar timing of binaries (Blandford & Teukolsky, 1976; Damour & Deruelle, 1986; Damour & Taylor, 1992; Wex & Kopeikin, 1999; Lorimer & Kramer, 2004; Edwards et al., 2006). In practice, for a specific binary pulsar, only some PK parameters are measured, depending on the characteristics of the pulsar timing experiment.

Parameter	
$\dot{\omega}$	time derivative of the longitude of periastron ω
γ	amplitude of the Einstein delay
\dot{P}_b	time derivative of the orbital period P_b
r	range of the Shapiro delay
s	shape of the Shapiro delay
Ω_{SO}	precession rate of the pulsar spin
δ_θ	mismatch in eccentricities (see text)
\dot{e}	time derivative of the orbital eccentricity e
\dot{x}	time derivative of the projected semimajor axis of the pulsar orbit x
$\ddot{\omega}$	second time derivative of the longitude of periastron
\ddot{x}	second time derivative of the projected semimajor axis of the pulsar orbit

that generalizes the Lagrangian of the post-Newtonian orbital dynamics to the strong-field regime to test fully conservative theories of gravity with a modified Einstein–Infeld–Hoffmann formalism.

2.3 Scalar-Tensor theories of gravity

Scalar-tensor theories of gravity can be considered as the simplest extensions to GR. Many of them, including the Jordan–Fierz–Brans–Dicke (JFBD) theory and Damour–Esposito-Farèse (DEF) theory, are metric theories that satisfy the Einstein Equivalence Principle (EEP). However, the additional scalar fields break the Strong Equivalence Principle (SEP), which is a general feature of such alternative gravity theories; GR is perhaps the only theory that fully embodies the SEP.

Breaking the SEP leads to some observable effects. Two discussed in detail here are the emission of dipolar radiation and the violation of the universality of free fall (UFF) for self-gravitating bodies. Asymmetric systems like pulsar-WD (PSRWD) binaries are particularly suitable for constraining these theories as these effects generally depend on the difference of the sensitivity of each body, which is a quantity that is related to the self-gravity or compactness of the object, and hence can be very different for NSs and WDs (Will, 2018).

The emission of dipolar GWs was first predicted to occur for the JFBD theory by Eardley (1975); but it is a general feature of alternative theories of gravity. Limits on their detection, especially by pulsar - white dwarf binaries, are especially powerful probes of DEF gravity. As discussed more in the next section, dipolar GWs have never been detected, and this has introduced very stringent constraints on SEP violation, and on many alternative theories of gravity.

Regarding tests of the UFF, a way of detecting it is via the Nordtvedt effect (Nordtvedt, 1968). This is similar to the Stark effect, where a neutral atom is polarised by a strong external electrical field. In its gravitational equivalent, a binary system consisting of two objects that fall in an external

gravitational field with slightly differing accelerations will see their orbit "polarised", i.e., acquire a secularly evolving eccentricity. UFF test was one of the motivations for the lunar Laser Ranging (LLR) experiments (Hofmann & Müller, 2018).

In the experiments discussed here, instead of the Earth and Moon falling in the field of the Sun, we have a pulsar and its binary companion (preferably a WD) falling in the field of the Milky Way Galaxy (Damour & Schäfer, 1991), the latter's gravitational acceleration provides the external "polarising" force. The best way of detecting this effect currently is via a detection of the variation of the orbital eccentricity (Freire et al., 2012a). This method resulted in the limit from PSR J1713+0747 (Zhu et al., 2019), which has been used to constrain a possible long-range fifth force (additional force to the 4 fundamental forces of nature) induced by dark matter (Shao et al., 2018). Compared to the lunar laser ranging test, pulsar experiments have the advantage of the much stronger binding energy of NSs but also the disadvantage of the much weaker gravitational acceleration caused by the Galaxy. As discussed by Freire et al. (2012a), the ideal system would be a millisecond pulsar (MSP) in a hierarchical triple star system, where the distant member of the system would cause a much stronger gravitational acceleration of an "inner" binary containing the MSP. Such a system containing the pulsar J0337+1715 and two white dwarfs was soon discovered soon after (Ransom et al., 2014), with the results confirming the expectation of Freire et al. (2012a). As we will see in the next section, no violation of the UFF has been detected, providing especially stringent limits on many alternative theories of gravity.

2.4 Quadratic gravity theories

Theories like the DEF theory predict an interesting phenomenon called *matter induced spontaneous scalarization* (Damour & Esposito-Farese, 1993). Such theories can show large deviations from GR in the non-perturbative regime of a pulsar binary while still satisfying all constraints from weak-field experiments. Hence this effect cannot be tested in the Solar System. Currently, based on the constraints of the dipolar GW emission of 7 binary pulsar systems, the neutron star's effective scalar coupling α_A has been limited to a level of $|\alpha_A| \lesssim 6 \times 10^{-3}$, which excludes the possibility of matter induced spontaneous scalarization of NSs in the original DEF theory (Shao et al., 2017; Zhao et al., 2022). Nevertheless, other varieties of DEF-like theories still remain unconstrained if the scalar field has a mass which suppresses the dipolar radiation at infinity. In this case, depending on the wavelength of the scalar field, the theory may leave detectable imprints in the pulsar orbital dynamics or the properties of the pulsar such as its mass-radius relationship and moment of inertia (Doneva & Yazadjiev, 2016; Altaha Motahar et al., 2017; Xu et al., 2020). These effects can be important targets for future timing observations given that the current timing of the double pulsar system already shows the potential of measuring some of them (Hu et al., 2020).

Quadratic gravity theories are well-motivated from an effective field theory point of view with Einstein-scalar-Gauss-Bonnet (EsGB) theories and Chern-Simons (CS) gravity theories representing well studied classes, that involve scalar fields that are coupled to an invariant.

In EsGB theories the choice of the coupling function is crucial for the resulting pulsar properties. For linear or dilatonic coupling functions the pulsars are always scalarized. However, in the linear (shift-symmetric) case, the pulsars do not carry scalar charge and therefore are not constrained by orbital

decay due to dipole radiation (Yagi et al., 2016). Constraints arise due the observed maximum neutron star mass (Pani et al., 2011; Yordanov et al., 2024). In contrast, a dilatonic coupling function allows for a small scalar charge (Kleihaus et al., 2016). Here the maximum mass and the binary pulsar orbital decay due to dipole radiation both significantly constrain the coupling parameters in different regimes (Yordanov et al., 2024). The present strongest bounds are obtained from the gravitational wave signals during BH-NS and BH-BH inspirals (Corman & East, 2024; Sanger et al., 2024; Julie et al., 2025). On the other hand, when the coupling function allows for curvature induced spontaneous scalarization of neutron stars (analogous to matter induced spontaneous scalarization in DEF), the orbital decay of WD-NS binaries provide the strongest constraints (Especially PSRs J0348+0432, J1012+5307, J2222–0137, J1141–6545 and J1738+0333) (Yordanov et al., 2024).

In CS gravity theories a non-dynamical or dynamical pseudoscalar field is coupled to the parity violating CS term. For a non-dynamical field, the periastron precession of the double pulsar PSR J0737–3039A yields a very strong constraint on the scalar field that is 10^{11} times stronger than solar system constraints (Yunes & Spergel, 2009). Binary pulsar observations in widely separated binaries do not place stringent constraints on dynamical CS gravity, since the scalar field source is too small (Yagi et al., 2013). Here the most stringent current constraint is from NS-NS mergers (Silva et al., 2021).

2.5 Massive gravity

In GR, gravity is mediated by a massless spin-2 graviton. In extensions of GR, some alternative gravity theories propose that the graviton has a nonzero mass, and these theories remain viable as they have not been entirely ruled out. Consequently, various approaches exist to study the mass of the graviton. Binary pulsar systems also play an important role in tests of massive gravity.

Finn & Sutton (2002) introduced a phenomenological term in the Lagrangian for linearized gravity with a mass term of the form $\sim m_g^2 (h_{\mu\nu}^2 - \frac{1}{2}h^2)$. This choice ensures that the theory reduces to GR when $m_g \rightarrow 0$ and yields the wave equation in its standard form. In this formulation, the massive graviton induces additional gravitational wave radiation. The observed \dot{P}_b from binary pulsars can be employed to limit the graviton mass. Finn & Sutton (2002) used PSRs B1913+16 and B1534+12 to first constrain m_g using pulsars. Subsequently, Miao et al. (2019), using 9 well-timed binary pulsars and Bayes' theorem, provided an improved limit of $m_g < 5.2 \times 10^{-21}$ eV/ c^2 at the 90% confidence level.

Finn & Sutton (2002) focuses solely on the two tensor modes. However, for the spin-2 massive graviton, there could be five degrees of freedom in the propagation, including two additional vector modes and one scalar mode. The vector modes can be ignored, because they usually do not couple to matter in the decoupling limit (de Rham et al., 2017). The extra scalar mode can couple to matter and induce a fifth force. By introducing the Vainshtein mechanism (Babichev & Deffayet, 2013), the scalar mode can be decoupled, suppressing the fifth force, allowing massive gravity theories to recover GR when $m_g \rightarrow 0$. The simplest model describing this is called the cubic Galileon (Nicolis et al., 2009), a Lorentz-invariant massive gravity model. The extra scalar mode can lead to extra GW radiation, which includes not only quadrupole radiation but also monopole and dipole radiation. However, in the vast majority of cases, the quadrupole radiation dominates (de Rham et al.,

Table 2: List of generic parameters subject to gravity tests (including the ten PPN parameters; first group); their physical meaning and predictions for them in GR and fully conservative and semi-conservative gravity theories (under “c/sc”; the parameters α_1 and α_2 are 0 in fully conservative theories). Reused without changes under a [Creative Commons Attribution 4.0 International License](#) from the review by [Freire & Wex \(2024\)](#).

Parameter	GR	c/sc	Physical meaning
γ_{PPN}	1	γ	Space curvature produced by unit rest mass
β_{PPN}	1	β	Non-linearity in superposition law for gravity
ξ	0	ξ	Preferred-location effects
α_1	0	α_1	Preferred-frame effects
α_2	0	α_2	Preferred-frame effects
α_3	0	0	Preferred-frame effects and non-conservation of momentum
ζ_1	0	0	Non-conservation of momentum
ζ_2	0	0	Non-conservation of momentum
ζ_3	0	0	Non-conservation of momentum
ζ_4	0	0	Non-conservation of momentum
η	0	η	Nordtvedt effect; combination of seven PPN parameters (Will, 1993)
κ_{D}	0	κ_{D}	Dipolar radiation coupling
\dot{G}/G [yr^{-1}]	0	\dot{G}/G	Variation of Newton’s gravitational constant

2013; [Shao et al., 2020](#)), and only when $e \geq 0.9$ does monopole radiation become dominant and dipole radiation becomes visible. Thus, in general, we only need to consider quadrupole radiation. Following this, [Shao et al. \(2020\)](#) chose 14 well-timed binary pulsars and placed a bound on the graviton mass, $m_g \leq 2 \times 10^{-28} \text{ eV}/c^2$ at the 95% confidence level. This is four to five orders of magnitude more stringent than limits derived from PTAs ([Wang & Zhao, 2024](#)), but not as stringent as limits given by cosmological observations and their comparison with simulations, which can result on upper limits of $m_g \sim 1 \times 10^{-33} \text{ eV}/c^2$ ([de Rham et al., 2013](#)) but are, however, more model dependent.

2.6 Preferred-frame effects (PFEs)

Apart from these theory-specific discussions, we can probe the symmetries of the gravitational interaction in a more theory-independent way.

In certain alternative gravity theories, the gravitational interaction may violate the local Lorentz invariance (LLI) in the gravitational interaction, implying the existence of a preferred reference frame. Apart from the PK parameters, ([Will & Nordtvedt, 1972](#)) proposed the parametrized post-Newtonian (PPN) framework through a post-Newtonian expansion, assuming weak-field and slow-motion conditions. Within the PPN parametrization, LLI violation is characterized by the parameters $\hat{\alpha}_1$, $\hat{\alpha}_2$ and $\hat{\alpha}_3$, which are listed in Table 2. The parameter $\hat{\alpha}_3$ has been tightly constrained to very high precision and is associated with the energy-momentum conservation violation, see Table 2. Consequently, studies of LLI typically focus on $\hat{\alpha}_1$ and $\hat{\alpha}_2$, as their values might be non-zero in conservative or semi-conservative gravity theories ([Will, 1993](#)). A nonzero $\hat{\alpha}_1$ can cause the additional motion of a binary pulsar system relative to a preferred reference frame, typically chosen as the Cosmic Microwave Background ([Damour & Esposito-Farese, 1992](#)). A nonzero $\hat{\alpha}_2$ induces spin precession in a pulsar around its direction of motion relative to the preferred frame ([Shao et al., 2013](#)). In a binary pulsar system, a nonzero $\hat{\alpha}_2$ causes the orbital angular momentum of a binary pulsar to precess around the direction of the velocity of the binary system with respect to the preferred frame ([Shao](#)

et al., 2015). For binary systems with low eccentricities, the effects induced by $\hat{\alpha}_1$ and $\hat{\alpha}_2$ decouple such that they can be tested independently (Shao & Wex, 2012).

Damour & Esposito-Farèse (1992) provided a geometrical way to constrain $\hat{\alpha}_1$ with eccentricity binary pulsars. The eccentricity vector $\mathbf{e}(t)$ can be expressed as a vectorial superposition of a ‘rotating eccentricity’ $\mathbf{e}_R(t)$ and a fixed ‘forced eccentricity’ \mathbf{e}_F . The component $\mathbf{e}_R(t)$ has a constant magnitude and rotates in the orbital plane with the relativistic periastron advance.

The component \mathbf{e}_F is parallel to the binary orbital plane and perpendicular to the velocity of the binary system with respect to the preferred frame, \mathbf{w} . Because $\mathbf{e}(t)$ is a sum of $\mathbf{e}_R(t)$ and \mathbf{e}_F , and the orientation of $\mathbf{e}_R(t)$ is unknown, we cannot directly constrain $\hat{\alpha}_1$ using the observed value of e . However, as $\mathbf{e}_R(t)$ rotates with a rate of the relativistic precession of periastron, the orientation of $\mathbf{e}_R(t)$ changes with time. When the timing observation span is long enough to accumulate a significant angle $\Delta\theta$ and break the possible cancellation of $\mathbf{e}_R(t)$ and \mathbf{e}_F , we can then constrain $\hat{\alpha}_1$ with binary pulsars, as discussed in Table 3.

If $\hat{\alpha}_2$ is non-zero, a solitary pulsar undergoes precession around its velocity \mathbf{w} relative to the preferred frame, and the precession rate is given by Nordtvedt (1987),

$$\Omega_{\hat{\alpha}_2}^{\text{prec}} = -\hat{\alpha}_2 \frac{\pi}{P} \left(\frac{w}{c} \right)^2 \cos \psi, \quad (1)$$

where ψ is the angle between the spin direction and \mathbf{w} .

In binary pulsar systems, a nonzero $\hat{\alpha}_2$ induces the orbital angular momentum to precess around the direction of \mathbf{w} . In Eq. (1), the spin period P is changed to the orbital period P_b . Shao & Wex (2012) have used binary pulsar systems J1012+5307 and J1738+0333 to derive the limit, $|\hat{\alpha}_2| < 1.8 \times 10^{-4}$ at 95% confidence. However, this constraint from binary pulsar systems is five orders of magnitude weaker than the current limit from solitary pulsars discussed in the next section.

As an example of Lorentz-violating gravity theories let us now briefly address Einstein-Æther gravity, where the preferred frame is modelled through a timelike unit vector, the æther field. Here the strong constraints on $\hat{\alpha}_1$ and $\hat{\alpha}_2$ can be exploited to reduce the four coupling constants of the theory to just two independent coupling constants (Yagi et al., 2014b,a). Since Einstein-Æther gravity also

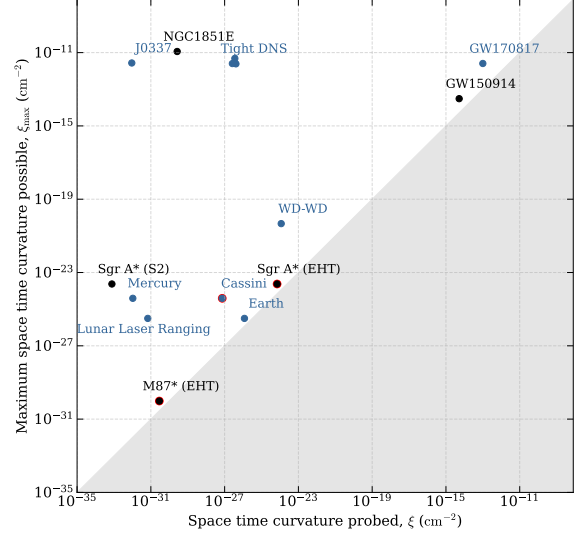


Figure 2: Comparison of different gravity experiments in terms of spacetime curvature probed and maximum spacetime curvature possible. The y-axis gives the maximum spacetime curvature in the system. Since the Y axis is the maximum value of the X axis, the lower diagonal is greyed out as impossible. The curvature is calculated as the square-root of the Kretschmann scalar $R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}$ (full contraction of the Riemann tensor). ‘Earth’ stands for near-Earth orbit experiments, like Gravity Probe B. Figure adapted from Wex & Kramer (2020).

allows for dipole radiation, these two coupling constants have been strongly constrained by the observed orbital decay of binary pulsars (PSR J1141–6545, PSR J0348+0432, and PSR J0737–3039) (Yagi et al., 2014b,a), as well as pulsars (PSR J1738+0333, PSR J0348+0432, PSR J1012+5307, PSR J0737–3039) and the triple system PSR J0337+1715 (Gupta et al., 2021).

For binary pulsars that exhibit a high rate of periastron advance, [Wex & Kramer \(2007\)](#) presented an alternative phenomenological methodology for measuring PFEs. They showed that, in such systems, the existence of a preferred frame for gravity leads to an observable signature in the timing data. In the presence of PFEs, one can expect a set of new timing parameters describing these signatures to exhibit a unique relationship that can be incontrovertibly measured and tested, like for instance, the measurement of a vector measuring an external polarisation of the orbit \mathbf{e}_F (for a summary of the existing literature, see section 5.1 of [Freire & Wex, 2024](#))⁴. While the Double Pulsar was the only system available for such an experiment at the time, it was later found that the combination of several suitable systems can result in a “PFE antenna array”, as demonstrated from the timing of two binary pulsars by (see e.g., section 5 of [Shao & Wex, 2012](#)). This, along with improved timing of those pulsars and new sources to be discovered by the SKA will provide a much deeper sensitivity to possible violations of local Lorentz invariance in strong gravitational fields in all directions of the sky.

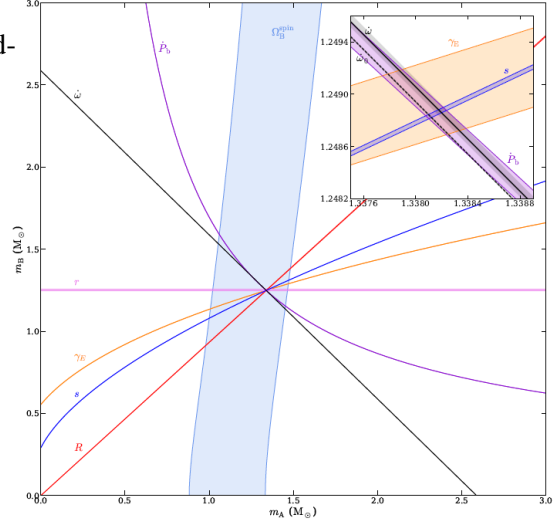


Figure 3: The mass-mass diagram of PSR J0737–3039A/B, also known as the double pulsar ([Kramer et al., 2021](#)). In the figure the underlying gravitational theory is assumed to be GR. The inset is an expanded view of the region of principal interest, where the intersection of all curves within a small region within measurement uncertainties means that GR has passed all these tests. For more details, see [Kramer et al. \(2021\)](#), figure from [Freire & Wex \(2024\)](#), reused without changes under a [Creative Commons Attribution 4.0 International License](#).

3 Current observational constraints

In the 50 years since the discovery of the Hulse-Taylor pulsar (PSR B1913+16), hundreds of new binary pulsars have been discovered. The last decade - corresponding to the time since the previous version of this chapter ([Shao et al., 2015](#)) - has seen major progress in tests of gravity theories with these systems (for a detailed review, see [Freire & Wex, 2024](#)). Some highlights include:

First, the timing update on PSR B1913+16 has confirmed that the orbital decay agrees well with the GR prediction with a relative precision of 0.16% ([Weisberg & Huang, 2016](#)).

⁴No adequate implementation of the measurement of \mathbf{e}_F exists yet because there has yet been no need to do so. A partial solution of this problem has been the measurement of the variation of the orbital eccentricity of binary pulsars, from which stringent limits can already be derived. See e.g. ([Shao & Wex, 2012](#)).

The 2021 update on the timing of the double pulsar system by [Kramer et al. \(2021\)](#) and modelling of its unique eclipse phenomenon by [Lower et al. \(2024\)](#) has provided a record of 11 independent tests of GR in this system. Some of these can be visualised in its mass-mass diagram (Figure 3). These tests include:

- The most precise test ever of the radiative properties of gravity: the orbital decay matches the GR prediction within a $1-\sigma$ uncertainty of 0.0063%, which is 25 times more precise than the test by [Weisberg & Huang \(2016\)](#).
- Four of the tests are of next-to-leading order relativistic effects detected in this system, representing a first in pulsar timing. One example of this is the Shapiro delay in this system, which probes spacetimes with curvatures that are 10^9 and 10^3 times larger than those probed by black hole imaging around M87 ([Event Horizon Telescope Collaboration, 2019](#)) and Sagittarius A* ([Event Horizon Telescope Collaboration, 2022](#)), and about 10^6 times larger than in similar experiments in the Solar System ([Bertotti et al., 2003](#)). A comparison with various pulsar systems and other gravity experiments is shown in Figure 2. While Shapiro delay has in general been seen in other binaries before, this system required the accounting of post-Newtonian corrections at the 1.5PN level caused by the moving companion and aberration effects due to light bending had to be taken into account for the first time. These next-to-leading-order (NLO) signal propagation effects have been independently tested and further improved with MeerKAT observations ([Hu et al., 2022](#)), which *clearly show the potential for improvements provided by the SKA*.
- Another example is the advance of periastron, where second-order effects including the Lense-Thirring effect, had to be taken into account to calculate the masses correctly. With continued timing provided by MeerKAT and the SKA, these observations have a clear potential for measuring the moment of inertia of PSR J0737–3039A ([Hu et al., 2020](#)).
- Finally, independent timing of both pulsars combined with tracking of secular changes in the radio eclipses of PSR J0737–3039A by the plasma-filled magnetosphere of PSR J0737–3039B offers a novel means of testing spin-orbit coupling in strong-field gravity ([Breton et al., 2008](#)). Current constraints from modelling the eclipses detected over a 3 yr period by MeerKAT match the prediction from GR at the 6.1% level ([Lower et al., 2024](#)).

These impressive tests have been complemented with a host of experiments on other systems that have probed — and in one case will probe — additional aspects of gravity theories, in particular the aforementioned effects from the violation of the SEP, dipolar GW emission in the orbital decay of binary pulsars or UFF violation via the detection of Nordtvedt effect. As discussed above, these effects are expected to be especially strong in asymmetric systems, like PSRWD systems. Searching for them is especially important for two reasons: 1) They are generally predicted by alternative theories of gravity, and 2) Detecting them would falsify GR. The first reason implies that a non-detection constrains alternative theories of gravity that predict that effect.

- A set of radiative tests with pulsar - WD systems, like PSR J1738+0333 and PSR J2222–0137 ([Freire et al., 2012b](#); [Guo et al., 2021](#)) and the asymmetric DNS J1913+1102 ([Ferdman et al., 2020](#)) have introduced stringent limits on DGW emission. This represents one of the most

fundamental tests of the nature of gravitational waves; the results show that they are, within the measurement precision, purely quadrupolar as predicted by GR.

- Because of the high masses of PSR J2222–0137 and J1913+1102, these tests have also largely ruled out the phenomenon of matter induced spontaneous scalarization (Zhao et al., 2022), a highly non-linear, non-perturbative enhancement of the scalar charge of NS that is generally predicted for some NS masses by scalar-tensor theories of gravity (Damour & Esposito-Farese, 1993).
- The discovery of PSR J0337+1715, the first millisecond pulsar in a triple stellar system, where the other two components are WDs (Ransom et al., 2014) has allowed a limit on the UFF violation parameter for neutron stars from the lack of detection of the Nordtvedt effect (Δ) of $\Delta < 2.0 \times 10^{-6}$ (Archibald et al., 2018; Voisin et al., 2020, 2024), which is 3 orders of magnitude better than any previous limits on the UFF of neutron stars. In particular, this results in the most restrictive limit on the ω parameter of the JFBD theory of gravity, $\omega_{BD} > 150,000$ (Voisin et al., 2020; Freire & Wex, 2024), which is stronger than the Solar System limit from Cassini (Voisin et al., 2020; Bertotti et al., 2003).
- In 2022, Ridolfi et al. (2022) used MeerKAT to discover 13 new pulsars in the globular cluster NGC 1851. One of these, PSR J0514–4002E, is in a binary system with a total mass of $3.887 \pm 0.004 M_{\odot}$ (Barr et al., 2024), which is significantly larger than for any other DNS systems known in the Galaxy. The companion mass is somewhere between 2.1 and 2.7 M_{\odot} ; this means it is in the mass gap between the most high-mass NSs and least massive BHs and it could be either. If the companion is a BH, it will likely be spinning fast (Barr et al., 2024), opening the prospect for the detection of the Lense-Thirring effect in this system and a test of the cosmic censorship hypothesis. *The latter might only be achievable with the precise timing to be provided by the SKA.*

The experimental limits on the PPN parameters listed in Table 2 (and their effective strong-field counterparts) are summarised in Table 3. As we can see, there is a strong complementarity between pulsar and Solar System tests, but in several cases the best (and in two cases, the only) constraints come from pulsar experiments.

As discussed in Section 2, some of these parameters deserve a more detailed mention:

- Shao & Wex (2012) have used 10 years of timing results of PSR J1738+0333 and derived the constraint, $\hat{\alpha}_1 = -0.4^{+3.7}_{-3.1} \times 10^{-5}$ at 95% confidence. In 2020, Liu et al. (2020) have used 15-yr timing of PSR J1909–3744 and improve the limit to, $|\hat{\alpha}_1| < 2.0 \times 10^{-5}$ at 95% confidence.
- Shao et al. (2013) have used millisecond pulsars B1937+21 and J1744–1134 with 15 years of timing data and placed a constraint, $|\hat{\alpha}_2| < 1.6 \times 10^{-9}$ at 95% confidence.
- The limits on k_D and the Nordtvedt parameter η are derived from the aforementioned limits on dipolar GW emission and the violation of the UFF.

Parameter	Solar-system test	Limit	Pulsar test (eff. PPN)	Limit
γ_{PPN}	Cassini, Shapiro delay	$2 \times 10^{-5} \dagger$	double pulsar, Shapiro delay (Hu et al., 2022)	$7 \times 10^{-3} \dagger$
β_{PPN}	Perih. shift of Mercury; MESSENGER	$2 \times 10^{-5} \dagger$	—	—
ξ	Solar alignment with ecliptic	4×10^{-7}	Two solitary pulsars (Shao & Wex, 2013)	4×10^{-9}
α_1	LLR	2×10^{-4}	J1909–3744 (Liu et al., 2020)	2×10^{-5}
α_2	Solar alignment with ecliptic	4×10^{-7}	Two solitary pulsars (Shao et al., 2013)	2×10^{-9}
α_3	Perihelion shift of Earth and Mercury	2×10^{-7}	J1713+0747 (Zhu et al., 2019)	4×10^{-20}
ζ_1	Combined PPN limits	2×10^{-2}	—	—
ζ_2	—	—	Multiple binary pulsars (Miao et al., 2020)	10^{-5}
ζ_3	Lunar acceleration	10^{-8}	—	—
ζ_4	Not independent	—	—	—
η	LLR	7×10^{-5}	J0337+1715 (Voisin et al., 2020, 2024)	2×10^{-5}
κ_{D}	—	—	J1738+0333 (Freire et al., 2012b)	2×10^{-4}
\dot{G}/G [yr ⁻¹]	LLR	10^{-14}	J1713+0747 (Zhu et al., 2019)	5×10^{-13}

Table 3: Comparison of Solar System and binary pulsar tests for the parameters listed in Table 2. Binary pulsars test strong-field “effective” PPN parameters. For the sake of simplicity, we only give leading order values for all limits in this table. Table adapted from review by Freire & Wex (2024).

\dagger Limit on deviation from 1.

4 The Role of the SKA

The SKA Phase 1 efforts at low and mid frequencies are of extreme importance to testing gravity, not only in improving tests of gravity with presently timed systems, but also in discovering new binaries that are in tighter, more relativistic orbits. In this section, we outline the most important features and characteristics needed for the SKA that will be crucial for this science.

4.1 Instantaneous sensitivity

Contrary to often popular consensus about astronomical observations, one cannot just “integrate longer” to achieve the desired sensitivity in a binary pulsar experiment. This is because each radio frequency resolved time of arrival estimate (ToA) requires enough frequency and orbital resolution, while also having enough timing precision to unambiguously detect relativistic effects and to

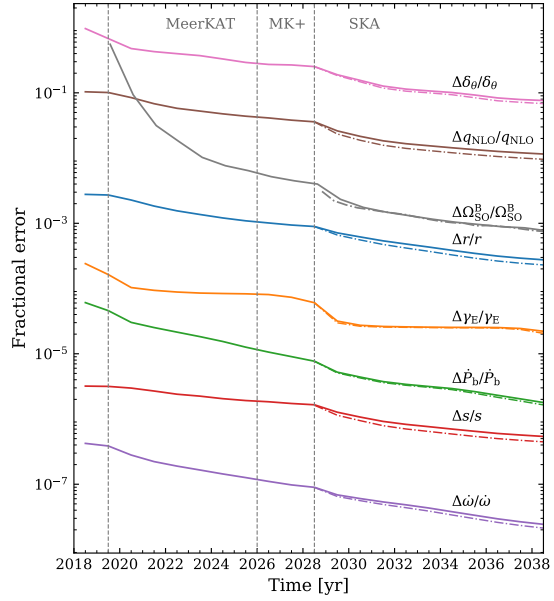
Table 4: Summary of observing cadence T_{cad} , length of each observation T_{obs} , and sub-integration time T_{sub} assumed for the simulation. For PSR J0514–4002E, an additional 20-hr campaign every year is assumed.

Pulsar name	T_{cad} [days]	T_{obs} [min]	T_{sub} [s]
PSR J0737–3039A	30	180	30
PSR J1946+2052	60	120	30
PSR J1913+1102	30	60	240
PSR J1036–8317	90	480	300
PSR J0514–4002E	30	120	1800

disentangle interstellar medium effects with the pulsar’s orbital dynamics. A rule of thumb is to obtain at least an orbital resolution of $< 10^{-2}$ in orbital phase for a clear, unambiguous measurement of orbital/relativistic parameters. Even for a pulsar with a relatively long orbit of about 5 days, the ideal maximum integration time per ToA is only about 7 minutes. For a pulsar like the double pulsar, this is roughly 30 seconds. These small integration times place enormous importance on the instantaneous sensitivity of the telescope. The difference between the two configurations of the SKA-mid currently considered (AA* and AA4; Sridhar 2023), could make or break the detection of orbital effects such as Shapiro delay for some systems.

This is perhaps best seen in the double pulsar, where adding just 5-years of MeerKAT data to a 16-year historic dataset, we can already measure the Shapiro delay with $3\times$ the significance, including higher order contributions to the effect such as gravitational retardation and light bending, as described in the previous section (Hu et al., 2022).

In order to further emphasize the improvements in the double pulsar as our current flagship pulsar for this science, we perform simulations of ToAs observed with the SKA for a 10-year experiment from 2028 with both AA* and AA4 configurations. Here, and in all other simulations presented in this chapter, unless explicitly stated otherwise, we use historic observations of the source to determine the desired cadence/orbital campaign and full-orbit observations and we determine the expected ToA precision from observations using MeerKAT and/or FAST telescopes. The details of telescope parameters and expected timing precision are summarised in Table 5. Table 4 lists the observation details considered for these pulsars for the simulations.

**Figure 4:** Fractional error of PK parameters for J0737–3039A with simulated future data. The solid lines represent results using AA* and the dash-dotted lines represent results using AA4.

The expected improvements in the precision of the PK parameters of the double pulsar, based on nominal simulations that span up to 2038 in the future, and combines the 16-year (Kramer et al., 2021) and 21-year dataset (including MeerKAT; Hu et al., in prep.) for the Double Pulsar, is reported in Table 6. The fractional improvements are also shown in Figure 4: We obtain improvements of a factor of 12–38 and 5–13 for the various PK parameters with respect to these two datasets.

Additionally, there will also be improvements to the timing parallax and proper motion of 9–100 times the present measurements from a combination of Very Long Baseline Interferometry (VLBI) and timing (Kramer et al., 2021), assuming that DM variations can be adequately modelled. A complementary result that can be obtained from the same observations is the measurement of the moment of inertia of pulsar A which provides constraints on the neutron star EOS (Hu et al. 2020; Kramer et al. 2021, Hu et al. in prep.).

We also simulated the anticipated improvement in geodetic precession rate of pulsar B in the double pulsar through joint MeerKAT+SKA observations. Off-eclipse ‘noise’ from intrinsic flux density fluctuations in pulsar A were sampled from existing MeerKAT-UHF light curves, while the radiometer noise in the eclipse troughs were scaled by a factor of 1/3 for SKA-Mid AA* and 1/4 for AA4. Using an assumed monthly observing cadence, we then fit the resulting eclipse light curves using the hierarchical inference approach in Lower et al. (2024). The resulting evolution in $\Omega_{\text{SO}}^{\text{B}}$ is shown by the grey trace in Figure 4. Note, the simulation assumes that systematic differences between observed and simulated eclipse light curves will have been overcome. This is currently the dominant source of systematic uncertainty in the eclipse-derived precession rate (Breton et al., 2008; Lower et al., 2024).

As a final point, we note that it is important to obtain a good, localised sampling of the orbit at every observing session of a binary pulsar – hence the observing time per session is not solely a function of flux density, and even bright pulsars need to be observed for a sufficiently long time per session.

4.2 Observing strategy and duration

While all pulsar experiments need regular observations (henceforth “cadence observations”) to maintain their timing baseline, it is vital for binary pulsar timing observations to also regularly sample the entire orbit. To simplify scheduling constraints, this is periodically done (every few months) either via “full-orbit observations” if the orbital period is sufficiently short, or via so-called orbital campaigns wherein we perform long observations covering specific orbital phases such as superior conjunction and periastron passage along with daily observations covering the rest of the orbit. Incomplete sampling of the orbit (especially for highly eccentric systems where random observing slots are more likely to end up on just one side of the orbit) has been seen to significantly bias the estimates of some relativistic parameters (Kramer et al., 2021). Hence, the SKA needs to have a flexible scheduler that is capable of conducting these observations at the required times.

4.3 Targeted pulsar searches for short period binaries with compact companions

Although the SKA will deliver prompt refinements to the timing of known relativistic binaries, transformative advances will surely come from new discoveries either through ongoing surveys with existing facilities or through the SKA itself. To understand this better, let’s revisit Figure 2

Table 5: Summary of simulation setup for different observing phases and ToA uncertainty σ_{ToA} assumed in the simulation of five pulsars (for the sub-integration time given in Table 4 over the full bandwidth). For PSR J0737–3039A, the ToA uncertainties for both UHF and L band are listed, whereas for other pulsars only L band is shown. For MeerKAT+, 20 SKA antennas are added to 64 MeerKAT antennas, however a maximum of 64 antennas can be used for observations.

Telescope	MeerKAT	FAST	MeerKAT+	SKA AA*	SKA AA4
Number of antennas	64	1	64 of 84	144	197
Effective diameter [m]	108	300	111	172	204
Observing period [yr]	2019-2025	2025-2028	2026-2028	2028-2038	2028-2038
Observing band	UHF/L	L	UHF/L	1/2	1/2
Pulsar name	$\sigma_{\text{ToA}} [\mu\text{s}]$				
PSR J0737–3039A	1.6/2.8	-	1.5/2.7	0.6/1.1	0.5/0.8
PSR J1946+2052	-	8.0	-	19.1	13.6
PSR J1913+1102	-	26.0	-	62.1	44.2
PSR J1036–8317	0.60	-	0.57	0.24	0.17
PSR J0514–4002E	16.0	-	15.1	6.3	4.8

Table 6: Predictions of improvements in the precision of PK parameters for PSR J0737–3039A using simulated SKA data. We use the 16yr data from Kramer et al. (2021) and 5 years of MeerKAT data to obtain a 21-year initial dataset (Hu et al. in prep.). To this, we add 10-years of SKA AA4 data to obtain the “Comb AA4” dataset with TOAs from 2003-2038. The second and third columns show, the improvement in the precision of PK parameters in comparison to the 16- and 21-yr datasets as a ratio of their detection significances. The last column shows the absolute fractional uncertainties (i.e. uncertainty/mean value) for these parameters in Comb AA4. The parameter q_{NLO} is the scaling factor of NLO signal propagation effects.

	Comb AA4 / 16yr	Comb AA4 / 21yr	Fractional uncertainties for Comb AA4
$\dot{\omega}$	36.2	12.6	2.1×10^{-8}
γ_{E}	11.8	4.5	2.1×10^{-5}
\dot{P}_{b}	38.0	10.9	1.6×10^{-6}
s	21.5	6.9	7.2×10^{-4}
q_{NLO}	13.5	4.8	1.0×10^{-2}
m_{c}	14.8	5.9	2.3×10^{-4}
δ_{θ}	15.1	5.5	6.9×10^{-2}

that contrasts the space-time curvature currently sampled by each experiment with the theoretical maximum reachable for the same class of sources. From this, we can infer (i) binary-pulsar timing and gravitational-wave detections of compact mergers have the best potential to probe the deepest space-time curvatures, and (ii) binary pulsars retain by far the greatest headroom, with existing systems still ~ 15 orders of magnitude shy of their ultimate potential. Because pulsars permit tracking of relativistic effects at precisions unmatched by any other strong-field probe, pushing them toward higher curvature remains essential—even if ground-based interferometers have otherwise already sampled more extreme gravitational potentials. Moreover, the statistical power of gravity tests in pulsar binaries scales steeply with orbital period, viz $P_{\text{b}}^{-\frac{8}{3}}$ (Batra et al., 2024); thus,

every newly discovered short-period system not only probes deeper curvature but also will overtake the constraints set by all currently timed binaries at an accelerated pace. Although the presently known binaries have wildly different orbital parameters, this general trend can be observed: PSR J0737–3039A with $P_b \simeq 2.5$ h and a 16-yr timing baseline, now can test GR 25 \times better than the original binary binary PSR B1913+16 ($P_b \simeq 8$ h), while the even more compact PSR J1946+2052 ($P_b \simeq 1.8$ h) achieves a factor of 2 \times improvement with only 7 years of observations. Based on these discussions, it is evident that the next frontier of binary pulsar tests must be to find binaries with shorter orbital periods and/or with heavier compact companions such as high mass NSs or black holes.

The presently envisioned pulsar search pipeline for the SKA’s Galactic plane surveys (assuming the envisioned 10-minute observing times) is unfortunately largely insensitive to binaries in this regime. The main reason for this is that the orbital corrections for SKA pulsar searches assume that within an observation the change in the apparent pulse period can be adequately modelled by a constant “acceleration”. While this assumption has been used in most of the historic surveys so far and have obtained a plethora of binaries including the double pulsar, short orbit binaries found via this method can be attributed to either the pulsar being bright enough to be detected even with residual orbital smear or be in highly eccentric orbits that facilitated catching them at an orbital phase when the acceleration approximation is still valid. With 10 minute observing times, acceleration searches are nominally sensitive to > 100 minute orbits. In the mean time, PSR J1946+2052 which has an orbit of ca. 100 minutes will have accumulated ~ 15 yr of timing baseline and hence would have already provided competitive strong-field tests at the very curvature scale that the standard SKA acceleration search is poised to be sensitive to. The best way for SKA to remain competitive in this space is to change the search methodology to be sensitive to orbits shorter than 100 minutes, where discoveries can test gravity at steeper curvatures and reach better precisions than PSR J1946+2052 at an accelerated space.

Searches with SKA-low benefit from the fact that the large field of view facilitates multiple surveys of the sky that somewhat mitigates this issue. However, searches at these frequencies are will be limited by interstellar dispersion and scattering for mildly recycled pulsars except for the top part of the band, which is unfortunately contaminated with higher radio frequency interference. SKA-mid in this case offers the best chance at detection. However, it is reasonable to expect that a full survey of the Galactic plane will only happen once. To maximise our sensitivity to short orbit binaries, it is imperative to perform additional targeted searches that retain sensitivity to short orbits. This can be achieved via template bank searches, where we model the orbital motion with a full Keplerian

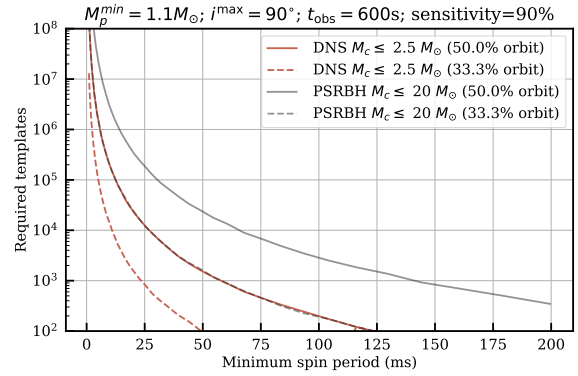


Figure 5: Required number of circular orbit templates as a function of minimum spin period of the pulsar for a SKA-mid survey for DNS and PSRBH systems denoted as red and gray lines respectively. The dotted and solid lines assume that there is 33.3% and 50% of the orbit within the observation respectively.

circular or elliptical orbit (c.f. Balakrishnan et al. (2022)).

Keplerian bank searches generally take orders of magnitude longer compared to traditional searches, which is partly why they were never widely adopted in historic surveys. However, the rapid growth in computing, especially using graphics processing units, have already made this a possibility for targeted searches of locations such as Globular clusters and the Galactic Centre. In order to understand the computation need required to carry out a circular orbit search with SKA-mid, we consider a scenario where we have 10-minute observing times, and we limit ourselves to finding 0.5-2 hour orbits.

We restrict the minimum pulsar mass to be $1.17M_{\odot}$, a maximum inclination of 90 degrees and a search sensitivity (equivalent to the “tolerance” in acceleration searches) of 90%. Figure 5 shows the total number of templates needed for this search as a function of the fastest spin period $P_{\text{spin}}^{\text{min}}$ to be sensitive to, assuming the maximum companion mass to be $2.5M_{\odot}$ and $20M_{\odot}$ for DNS and PSRBH searches respectively. As it can be seen from the figure, the number of templates are a steep function of the minimum spin period that we choose to be sensitive to. In case of dynamic locations such as globular Clusters, we do not possess any prior information of the distribution of pulsar spin periods in DNS and PSRBH binaries. However, for the Galactic plane, one can use the wisdom from binary evolution: We expect DNS systems to have mildly recycled pulsars of periods $P_{\text{spin}}^{\text{min}} \simeq 20$ ms. We also expect pulsars in Galactic PSRBH systems are likely not recycled at all; their spin periods, at our target orbital periods are expected to be well beyond $P_{\text{spin}}^{\text{min}} > 100$ ms. Assuming a conservative $P_{\text{spin}}^{\text{min}} = 15$ ms for DNS and $P_{\text{spin}}^{\text{min}} = 85$ ms for DNS and PSRBH searches respectively, we benchmark how long would take in a computing cluster with Nvidia A100 GPUs. This is represented in Figure 6. This search is already feasible with a relatively miniscule additional investment to the pulsar search subsystem. We note that the caveat to the non-recycled PSRBH searches that a significant fraction of those pulsars might have their radio emission switched off at this point of their isolated binary evolution. However, as it can be seen Figure 6, the PSRBH searches are cheaper than the DNS searches.

We also note that targeted searches of such binaries in high probability regions for finding such binaries, viz globular clusters and the Galactic centre need to be highly prioritised. These locations are small enough to use the 16 available pulsar timing beams to record coherently dedispersed filterbank data, that can be saved to disk and sent to regional centres for post processing.

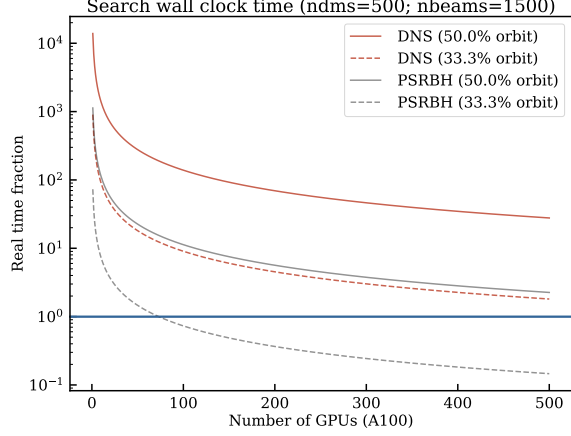


Figure 6: Wall clock pulsar search run time as a function of number of A100 GPUs for circular orbit searches for DNS and PSRBH binaries. The colors and line styles are same as 5.

Table 7: Propagated Keplerian and PK parameters of PSR J0737–3039A and PSR J0514–4002E after their respective time of evolution. The Shapiro delay parameters of PSR J0737–3039A remain unchanged, while inclination angle of J0514–4002E is too low to detect any Shapiro delay. The quoted values of \dot{P}_b are the theoretical predictions according to general relativity theory.

Evolved form of PSR	Time Gyr	P_b hours	e	x ls	$\dot{\omega}$ deg yr ⁻¹	γ_E ms	\dot{P}_b s s ⁻¹
J0737–3039A	0.072	1.08	0.017	0.600	65.950	0.124	-1.908×10^{-12}
J0514–4002E	380	7.29	0.08	3.2955	3.603	0.0009	-3.7782×10^{-13}

Table 8: ToA measurement scheme and ToA uncertainty used in the simulation of the evolved versions of J0737–3039A and J0514–4002E shown in Table 7. All observations are assumed to be at L-band, with a central frequency of 1.3GHz and a bandwidth of 0.8 GHz. The ToA integration times, sub-bands, and observing strategy are kept as close as possible to the most recent MeerKAT studies of J0737–3039A and J0514–4002E (Hu et al., 2022; Barr et al., 2024).

Evolved form of PSR	Integration time (s)	Sub-bands	MeerKAT uncertainty (μ s)	SKA AA* uncertainty (μ s)	SKA AA4 uncertainty (μ s)	Observation length (hours)	Observing cadence (days)
J0737–3039A	32	16	10	4	3	3	30
J0514–4002E	1,200	4	10	4	3	3	30

4.3.1 Potential impact of short period binary discoveries

In this section, we explore the potential benefits of finding binaries with short orbital periods than those presently known, whose discovery will accelerate our ability to test gravity with better precision. To this effect, we compare the expected performance of the SKA AA* and the SKA AA4 configurations by simulating ToAs from potential new discoveries and evaluating the evolution of timing measurements in both scenarios. As specific examples, we choose to simulate time-evolved versions of PSR J0737–3039A and PSR J0514–4002E, which are likely to be part of the population of the Galactic field and globular clusters respectively. The simulated orbital parameters were derived by propagating from the current-day orbital parameters and masses presented in Hu et al. (2022) and Barr et al. (2024) via the orbital decay from gravitational-wave emission (Peters, 1964). For PSR J0737–3039A, we simulate its expected orbital configuration in 72 Myr from now, while for PSR J0514–4002E, we simulate its expected orbital configuration in 380 Gyr from now. While the latter is unrealistic, this exercise purely serves to provide a starting point for our simulations. After obtaining the updated orbital parameters, we also update the newly expected PK parameters. The resulting Keplerian and PK parameters (Orbital period P_b , eccentricity e , projected semi-major axis x , range of Shapiro delay r , shape of Shapiro delay s , rate of periastron advance $\dot{\omega}$, amplitude of the Einstein delay γ_E , and the orbital period derivative \dot{P}_b) are presented in Table 7. Given the strong influence of the globular cluster on PSR J0514–4002E, we assumed for this system $\dot{P}_b = 1.79 \times 10^{-11} \text{ s s}^{-1}$, i.e. the current observed value (Barr et al., 2024), and not the predicted general relativity value, as kinematics effects are dominant.

We simulate ToAs based on previous MeerKAT campaigns and estimating the SKA timing precision. We estimate the sensitivity of the SKA configurations for each of these two systems assuming

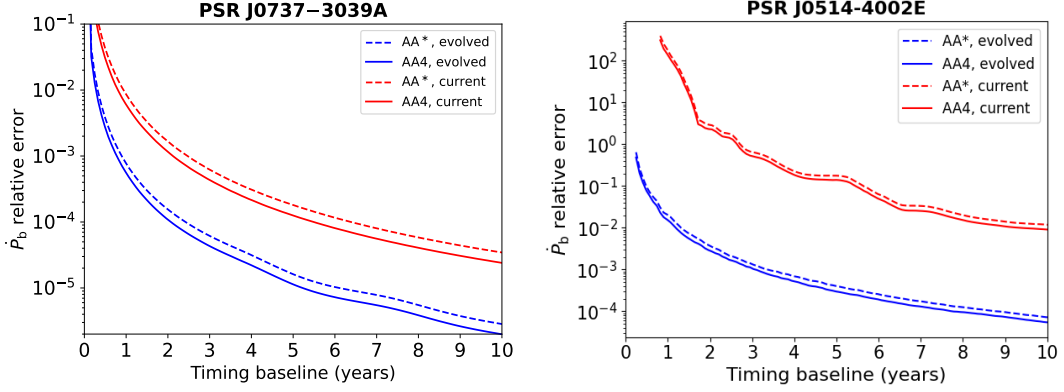


Figure 7: Evolution of the relative error for the derivative of the orbital period as obtained by simulations over ten years of evolved versions of PSR J0737–3039A (with $P_b \simeq 1$ hour) and PSR J0514–4002E (with $P_b \simeq 7$ hours), assuming the SKA AA* and SKA AA4 configurations. We also plot the evolution of the \dot{P}_b measurement assuming the current orbital configurations for comparison. The observing cadence emulates that of the latest published timing experiments on those systems (Hu et al., 2022; Barr et al., 2024). The expected sensitivity of the SKA AA4 consistently reduces the PK measurement uncertainty to 60% of the one derived with the SKA AA* sensitivity.

the same received flux as in the real counterparts of PSR J0737–3039A and PSR J0514–4002E. Both of these systems have had timing experiments with MeerKAT (Hu et al., 2022; Barr et al., 2024), the SKA precursor, constituting a very good basis for scaling the ToA precision from one facility to the other. Based on the increase of surface area from MeerKAT to SKA AA* and SKA AA4, and assuming the same integration time and bandwidth as in the MeerKAT timing experiments, the ToA uncertainty is reduced to 39% in the SKA AA* and to 28% in the SKA AA4. In Table 8, the used ToA uncertainties and observing strategies used for the SKA AA* and SKA AA4 configurations are shown.

We use the configurations stated above to compare the precision of PK measurements in the SKA AA* and the SKA AA4. Assuming discovery in any of these stages of the SKA, the observing schemes are simulated for 10 years for SKA AA* and SKA AA4, and the ToAs are fit with baselines increasing from 0 to 10 years. The results are shown in Figure 7, where the relative uncertainty of the \dot{P}_b measurements are drawn over the increasing timing baseline, for both the evolved versions of PSR J0737–3039A and PSR J0514–4002E in the SKA AA* and SKA AA4 configurations, and with their current orbital configurations as well.

The SKA AA4 configuration has significant advantage over the SKA AA* configuration. Both the the SKA AA* and SKA AA4 configurations achieve very significant results early on, with the SKA AA4 configuration halving uncertainties with respect to the SKA AA* configuration. In long-term timing, when the reduction of \dot{P}_b measurement uncertainty slows down over increasing timing baseline, but it still takes 1-2 years longer for SKA AA* to achieve the same sensitivity as SKA AA4. This demonstrates that the need for SKA AA4 especially for binary pulsar experiments. It is also worth noting that the evolved versions of these two systems yield \dot{P}_b measurements of the same significance as their current versions approximately five years prior. Given the capacity of

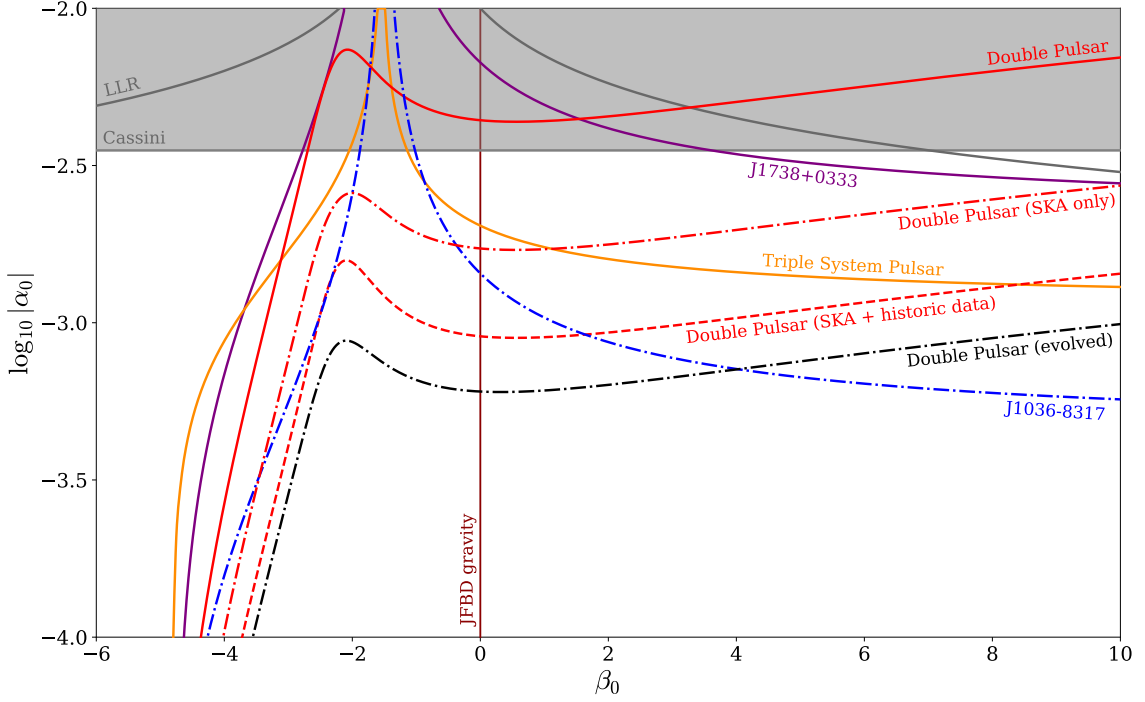


Figure 8: Present and potential future constraints on Damour-Esposito Farésé (DEF) gravity from binary pulsars for the theory’s linear (α_0) and quadratic (β_0) coupling coefficients of the scalar field. When $\alpha_0 = \beta_0 = 0$, then the theory reduces to General Relativity. The solid red line is the constraints from the 16-year dataset of Kramer et al. (2021). The dash-dotted red line is the double pulsar, if it were discovered and timed solely by the SKA-mid AA4. The dashed red line is the improvement when adding 10-years of SKA-mid AA4 data to the 16-year historic dataset. The black dash-dotted line is a putative evolved form of the double pulsar of orbital period ≈ 1 hour, that is discovered and and timed by SKA-mid AA4. Potential constraints from J1036–8317 is given in blue, assuming 10-years of timing with SKA-mid AA4 and constraints on the mass ratio from optical observations of its companion. The present best constraints from J1738+0333 and the triple system are given in purple and orange for reference. Figure produced by Norbert Wex.

the SKA to discover more compact systems akin to the evolved version of PSR J0737–3039A and PSR J0514–4002E, this implies an increased capacity for faster tests of gravity. As an example, we show how the present and evolved form of PSR J0737–3039A improve constraints on scalar tensor gravity in Figure 8.

4.3.2 BH spin measurement from a pulsar—stellar-mass black hole system

A PSRBH system is considered as the holy grail of gravity tests, providing unprecedented opportunity to allow for precision tests of BH physics. If the black hole rotates significantly, by modelling the Lense-Thirring precession of the orbit, both the amplitude and the orientation of the BH spin can be determined (e.g. Wex & Kopeikin 1999; Liu et al. 2014). This, in combination with the BH mass obtained from other PK parameters, will deliver a direct examination of the Cosmic Censorship Conjecture. In GR, this hypothesis requires the spacetime singularity to be hidden within the

event horizon (Penrose, 1979). For a Kerr BH, means

$$\chi \equiv \frac{c}{G} \frac{S}{m_{\text{BH}}^2} \leq 1, \quad (2)$$

where c is the speed of light, G the gravitational constant, S the angular momentum and m_{BH} the BH mass and χ is a dimensionless spin constant. Therefore, a measurement of the mass and the spin of a black hole can be used to test this inequality.

One of the main aims for SKA pulsar surveys is to discover a PSRBH system. In the Galactic plane, a PSRBH system can form by following the standard binary evolution procedures. Here, the pulsar is formed from the supernova explosion of the secondary star, and would be a normal pulsar (NP) without experiencing any recycling. The orbit is expected to be eccentric caused by the kick of the supernova explosion (Yungelson & Portegies Zwart, 1998; Voss & Tauris, 2003). The canonical binary evolution does not produce a PSRBH system where the pulsar is recycled, though exotic mechanisms exist (e.g., Sipior et al., 2004; Pfahl et al., 2005). In contrast, in regions of high stellar density, such as globular clusters and the Galactic Centre, a PSRBH system can be formed through stellar capture during a multiple body encounter (Kulkarni et al., 1993; Faucher-Giguère & Loeb, 2011). Figure 9 shows the anticipated measurement precision of BH spin in both types of systems. For the case of a NP, the BH spin can be measured for compact orbits and fast spinning black holes. In contrast, if the pulsar is an MSP, the anticipated higher timing precision would allow BH spin to be measured for wider orbits or black holes with a low spin.

4.4 Importance of observing bands

Apart from instantaneous sensitivity, it is also imperative to choose the right observing band to maximise the scientific outcome from SKA observations. Although it is generally true that pulsars have higher flux at lower frequencies covered by the UHF and L-band receivers of SKA, the flux of a pulsar is not the only determinant of timing precision. The width of the pulse and presence of high frequency structures in the pulse profile also play an important role, as they directly affect the precision of the template matching technique used to extract ToAs. Pulsars generally tend to narrower pulse profiles and multiple components at higher frequencies partly owing to the radius-to-frequency mapping of pulsar emission, but also to the much mitigated effects of interstellar medium such as pulse scattering. For many relativistic binaries, S-band is more suited as a trade-off between spectral index and profile shape to obtain the best possible ToA precision. A classic example is the pulsar PSR J1913+1102, a ~ 5 hour double neutron star system (Lazarus et al.,

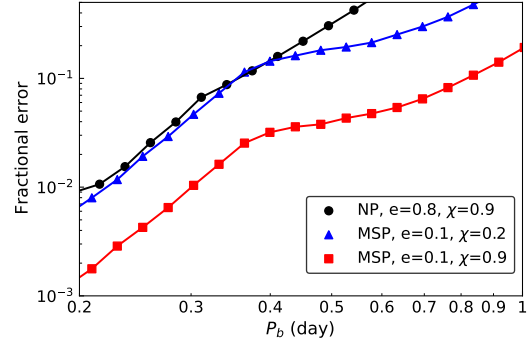


Figure 9: Fractional error of the BH spin measurement as a function of orbital period of a PSR-SBH system. Here we assumed timing observations with weekly cadence and 10-yr time span. For NP, we used $100 \mu\text{s}$ timing precision from each observation. For MSP, we assumed AA4 sensitivity, and 1-hr observations per epoch.

Table 9: Improvements in the precision of PK parameters for PSR J1913+1102 with SKA. We produce two simulated datasets between 2028-2038, using SKA AA* and SKA AA4 configurations at L-band, combined with existing 12-year dataset (Miao et al. submitted) to form Comb AA* and Comb AA4 datasets respectively. The second and third columns show the improvements in measurement precision when using Comb AA* and Comb AA4 compared to the current 12-yr data as the ratio of their detection significances. The final column shows the improvements obtained when timed using a hypothetical S-band receiver with the SKA instead (1650 to 3050 MHz).

	Comb AA* / 12yr	Comb AA4 / 12yr	Comb AA4 (S Band)/12yr
$\dot{\omega}$	3.8	4.5	9.1
γ_E	1.8	1.9	2.9
\dot{P}_b	5.9	6.7	16.2
h_3	2.0	2.3	5.4

2016; Ferdman et al., 2020). Its pronounced mass asymmetry makes it a prime target for testing dipolar gravitational-wave emission in scalar–tensor gravity. Following Arecibo’s closure, FAST has provided continued timing of this source since November 2021. We simulated 10 yr of SKA AA*/AA4 ToAs (2028–2038) taken at L-band and combined them with Arecibo + FAST data; The resultant parameters (Table 9) show no significant improvement, reflecting FAST’s $\sim 5\times$ higher antenna gain relative to SKA-mid even at its AA4 configuration. However, keeping everything else fixed and just changing the observations to be at S-band instead, we obtain an improvement of $> 2\times$ for most of the parameters, as seen in Table 9. The above serves as a poster child for why the inclusion of an S-band receiver to SKA Phase 1 will provide the best returns for the time invested on some observed pulsars. S-band also serves as a good trade off for pulsar flux and interferometric precision for VLBI experiments as described in detail later.

4.5 Multiwavelength contributions to gravity tests

While for most pulsars, measuring relativistic effects and testing gravity involve decades of radio observations, the presence of optically bright WD companions has allowed the determination of additional mass constraints for these rare systems via the combination of radio and optical data. The optical spectroscopy adds an independent WD mass estimate from measurements of the width of the Balmer lines Antoniadis et al. (2013), although there can be systematic uncertainties that need to be carefully accounted for (c.f. Saffer et al. (2025)). By combining the radial velocity measurements of the WD and pulsar, a precise mass ratio can also be obtained; combining all of these, the component masses of the system can be precisely estimated. If the system has a short enough orbital period, it exhibits relativistic effects that can be measured in a theory-independent way from pulsar timing. These effects are then compared with predictions of theories of gravity, computed using the optical mass measurements, thereby performing a test of those theories.

A prime example of this technique is PSR J1738+0333 which has a $V = 21.7$ WD companion (Freire et al., 2012b). Optical spectroscopy of this companion allowed precise mass measurements: the companion mass is $0.181^{+0.007}_{-0.005} M_\odot$ and the pulsar mass is $1.47^{+0.07}_{-0.06} M_\odot$. For these masses, GR predicts a decay of the orbital period (\dot{P}_b) due to gravitational wave (GW) emission of $-27.7^{1.5}_{-1.9} \times 10^{-15} s s^{-1}$. The actual measurements from pulsar timing of $-25.9 \pm 3.2 \times 10^{-15} s s^{-1}$

are consistent with GR's prediction, and hence GR passes this test. However, this is not the case for many alternative gravity theories. For instance, a significant part of the parameter space of Damour-Esposito-Farèse (DEF) gravity (Damour & Esposito-Farèse, 1992; Freire et al., 2012b) was ruled out by this experiment. This system continues to be the best test for some parts of the parameter space of DEF gravity to date. This is possible because the PSR J1738+0333 system is gravitationally asymmetric: it has a strongly gravitating NS with a weakly gravitating WD companion. Such an arrangement enhances the amplitude of DGW emission predicted by a number of alternative theories of gravity (such as DEF gravity). This additional DGW emission was not observed in the orbital decay of PSR J1738+0333, thus ruling out such theories.

A similar pulsar where SKA could potentially play a significant role is PSR J1036–8317, a 3.4 ms pulsar in an 8 hr circular orbit around an optically bright HeWD. Observations with the MeerKAT telescope showed a 10× increase in precision compared to earlier Parkes observations, and have already hinted at a 2-3 σ measurement of the orbital period decay. The position of this pulsar is coincident with a *Gaia* source, inferred to be a WD based on its magnitude and color. Optical observations of this with the NTT telescope have already been done; we expect a measurement of its radial velocity and surface gravity, from which we can infer the binary mass ratio and the mass of the WD to a precision that is twice that of PSR J1738+0333. SKA observations of this system would soon solidify the measurement of \dot{P}_b and also produce independent mass measurement via the Shapiro delay. Our nominal simulations show a 100× improvement in \dot{P}_b and an independent 14 σ measurement of the masses. All these measurements together have the potential to surpass PSR J1738+0333's records and provide the most stringent, radiative test of scalar tensor gravity. Assuming nominal values for the pulsar and companion masses of the PSR J1036–8317 system, potential constraints from SKA timing are plotted in Fig 8. It can be seen that the pulsar has the potential to become the most constraining system for positive β_0 values.

4.6 The importance of SKA VLBI

VLBI observations of pulsars contribute to gravitational tests primarily by measuring the parallax and/or proper motion more precisely than can be achieved using pulsar timing, reducing the uncertainty in timing parameters that depend on these quantities. High precision VLBI astrometry to facilitate these goals requires a combination of high sensitivity (to minimise statistical uncertainty on the position measurement, especially for faint pulsars) and excellent calibration (to minimise systematic position shifts caused by unmodelled propagation delays). The latter requirement is best fulfilled by observing calibrator sources that are closer to the target pulsar (to minimise spatial extrapolation errors) and/or to observe multiple calibrator sources, enabling calibration solutions to be interpolated to the target pulsar position (c.f. Chatterjee et al. 2009).

To date, the second requirement (nearby calibrator sources) has meant that the largest and most precise VLBI astrometry campaigns on pulsars have been performed using the Very Long Baseline Array, as its relatively large field of view means that nearby calibration sources can generally be observed contemporaneously at L-band frequencies (e.g. Deller et al., 2019; Ding et al., 2023). Pulsars that are not visible from the northern hemisphere have been much more challenging to enact VLBI, as the large dishes and phased arrays used in the Southern Long Baseline Array have precluded the use of in-beam calibration and hence highly precise astrometry for pulsars further

South.

The inclusion of SKA-VLBI as an element of southern VLBI arrays will facilitate a substantial improvement for these southern pulsars, since the SKA will provide multiple tied beams enabling contemporaneous calibration to be derived for multiple sources within ~ 30 arcminutes of the target pulsar. For pulsars south of a declination of ~ -25 degrees, the theoretical astrometric precision achievable with VLBI will jump from well below that achievable in the North currently, to better than the current state of the art. The point source sensitivity of a VLBI array containing SKA1-mid (AA4) plus other southern antennas providing at least a 30 arcminute field of view at L band is a factor of four better than the current VLBA, driving an astrometric improvement of the same order and making it possible to make precise parallax measurements for sources up to distances of 10 kpc and even beyond (as current-generation surveys can already provide 10% level parallax accuracy out to 2.5 kpc routinely; Deller et al., 2019). This is a result of the improved sensitivity both directly impacting the target pulsar signal-to-noise (and hence nominal astrometric precision) and the calibration fidelity (enabled by the transition from calibration extrapolation from a single nearby in-beam calibrator, to interpolation between solutions provided by multiple in-beam calibrators, reducing systematic sources of error).

The most significant impact of this capability will be for pulsars in southerly regions inaccessible to northern hemisphere facilities (such as PSR J1141–6545), and the faintest pulsars where point source sensitivity is the limiting factor to astrometric precision. Astrometric precision for SKA-VLBI can also be improved by observing at S band rather than L band, as the impact of ionospheric modelling errors decreases. This is yet another reason to consider the inclusion of S band receivers in SKA-mid Phase 1.

4.7 Impact of multimessenger observations

In the future, with the continued construction of more telescopes and gravitational wave detectors, multimessenger detection will undoubtedly become a cornerstone of astrophysics research. The SKA will play an important role in multimessenger detection of observed relativistic binaries. To date, more than 20 DNS systems have been discovered by radio telescopes. Among these DNS systems, PSR J1946+2052 has the shortest orbital period, namely $P_b = 1.88$ hr. GW observations from LIGO/Virgo have detected two DNS systems that are in the merger phase. Therefore, the orbital period of the discovered DNSs has a gap between ~ 2 hr and ~ 1 ms at the phase of merger. Detecting DNS systems with orbital periods on the order of minutes would provide an even more relativistic laboratory for testing theories of gravity. But we have not yet discovered DNS systems with $P_b \sim \text{min}$ by radio observations yet, because the fast-changing Doppler shift caused by the orbital acceleration of the pulsar smears the pulsar signal in the Fourier domain, and correcting the smearing will be computationally prohibitive. Some techniques such as the sideband search method of PRESTO (Ransom et al., 2003) partly overcomes this problem.

Laser Interferometer Space Antenna (LISA), a future space-based GW detector, which is expected to be operational in the 2030s, is sensitive to mHz bands, making DNS systems with orbital periods of approximately minutes prime candidates for detection. Kyutoku et al. (2019) proposed a multimessenger strategy combining SKA and LISA to search for radio pulsars in orbits with periods

shorter than 10 minutes. LISA achieves precise sky localization, reducing the search area for the SKA to a very small region of a few degrees on the sky. This significantly decreases the number of required pointings and improves the efficiency of SKA observations. Additionally, LISA provides high-precision measurements of orbital frequency and binary parameters, such as chirp mass and inclination angle. These parameters are critical for correcting Doppler smearing in the SKA's radio observations of pulsars in tight binary systems. By combining these capabilities, LISA dramatically enhances the SKA's ability to detect faint radio pulsars in short-period binary systems, especially those with orbital periods shorter than 10 minutes.

5 Summary

As discussed in section 2, GR and its extensions predict a rich array of phenomenology that is observable in the timing of radio pulsars. As discussed in section 3, and more extensively by [Freire & Wex \(2024\)](#), the timing of radio pulsars has provided some of the best tests of gravity theories. These are strong-field effects in the sense that the pulsars themselves have substantial gravitational binding energies. This implies that radio timing makes binary pulsars extremely sensitive to violations of symmetries of the gravitational interaction, like the strong equivalence principle, even if the orbits themselves are not very compact, as in the case of the pulsar in a triple star system. Compact binary pulsars provide the most precise tests known of the quadrupole formula for the orbital decay induced by gravitational wave emission, which are fundamental tests of the radiative properties of gravity.

As discussed in section 4, the prospects for improvements in these precision for the near future are excellent, especially with the sensitivity of the SKA:

- The continuation of some of the timing experiments of known systems with the higher sensitivity of the SKA will greatly improve many of the tests done with these systems. For instance, continued timing of the double pulsar, which assumes the use of the SKA, might constrain the MoI of PSR J0737–3037A to within 10% by 2030 ([Hu et al., 2020](#)), apart from significantly improving the precision in the measurement of the orbital decay and other gravity tests (section 4.1). Although such a determination of the MoI assumes GR to provide the correct description of the needed PK parameters (and will eventually help to constrain the EoS), interpreted as a LT test it still allows to probe for significant short-range deviations from GR that only affect pulsar A locally (see discussion in [Hu et al. 2020](#)). As an example of the impact of sensitivity, just 3 years of MeerKAT data yielded a photon propagation test in the double pulsar ([Hu et al., 2022](#)) that is a factor of two better than the previous one based on 16 years of data from 6 different telescopes ([Kramer et al., 2021](#)).
- The pulsar field in general has been driven, from the start, by the discovery of more relativistic binary systems. The rate of pulsar discoveries has recently increased significantly, with 1000 new pulsars having been found by FAST and MeerKAT already. The rate will increase further with the sensitivity of the SKA. Furthermore, the rate of discovery of recycled pulsars - and especially recycled pulsars in very compact orbits - is increasing even faster, because of the much improved time and spectral resolution of the search data, the much improved computing capabilities and search algorithms.

All this will very likely lead to the discovery not only of more extreme versions of the currently known systems, which will allow new leaps in the precision for the types of tests described above, but also of completely new types of systems, such as pulsar-BH binaries, perhaps more massive and compact than NGC 1851E (Barr et al., 2024). Such systems will allow gravity tests that were until now beyond the testing power of pulsar timing (Wex & Kopeikin, 1999; Liu et al., 2014; Seymour & Yagi, 2018). The sensitivity of the SKA will be very important for timing these new discoveries, which are likely to be weak (see Sect. 4.3.1).

The prospect of detecting very compact binary pulsars, especially DNSs (or pulsar-BH systems), is of paramount importance for tests of gravity theories. A general reason is the attainable significance of the radiative test in the presence of contaminants, which improves as $P_b^{-8/3}$. Such systems would also allow the measurement of the full precession cycle of relativistic spin-orbit coupling on reasonable timescales: for instance, a DNS with an orbital period of 30 min would have a geodetic precession period of about 5 years, which would then be measured precisely from the repeating changes in the pulse profile of the system. Hence all-sky or Galactic plane searches for these systems must be sensitive to these orbital periods.

- As discussed in section 4.6 tests will be further improved if the SKA has a VLBI capability. For many pulsars - including PSR J0737–3039A - the limiting factor in the precision of gravity tests is the lack of knowledge of the distance to the pulsar (Kramer et al., 2021). The VLBI capability should greatly improve the measurement of pulsar distance
- As discussed in section 4.7, the SKA will have several synergies with other wavelengths and with GW observatories. In particular, *it is extremely important that it operate at the same time as the Laser Interferometry Space Antenna (LISA)*. This opens up a great synergy: Very compact binary pulsars to be found by the SKA will be detectable at good S/N by LISA mission if they are not too distant from Earth (Thrane et al., 2020). This mission will also find, independently, the most compact NS–NS, NS–WD or NS–BH systems of our Galaxy (Lau et al., 2020). Perhaps some of these NSs will be detectable as pulsars in targeted radio surveys. In either case, binary pulsar experiments would become “multi-messenger” experiments, allowing entirely new tests of gravity theories (Thrane et al., 2020; Miao et al., 2021).

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References

- Abbate, F. . 2026, in *Advancing Astrophysics with the SKA – II (AASKAII)*, arXiv search: Report number AASKAII/Abbate01
- Abbott, B. P. . 2016, , 116, 061102
- . 2020, , 892, L3
- . 2017, , 119, 161101
- Altaha Motahar, Z. . 2017, *Phys. Rev. D*, 96, 064046
- Antoniadis, J. . 2013, *Science*, 340, 448
- Archibald, A. M. . 2018, , 559, 73
- Baade, W. & Zwicky, F. 1934, *Proceedings of the National Academy of Science*, 20, 259
- Babichev, E. & Deffayet, C. 2013, *Classical and Quantum Gravity*, 30, 184001
- Bagchi, M. . 2026, in *Advancing Astrophysics with the SKA – II (AASKAII)*, arXiv search: Report number AASKAII/Bagchi01
- Balakrishnan, V. . 2022, , 511, 1265
- Barr, E. D. . 2024, *Science*, 383, 275
- Basu, A. . 2026, in *Advancing Astrophysics with the SKA – II (AASKAII)*, arXiv search: Report number AASKAII/AvishekBasu01
- Batnikov, A. . 2024, , 686, A101
- Ben-Salem, B. & Hackmann, E. 2022, , 516, 1768

- Berti, E. . 2015, *Classical and Quantum Gravity*, 32, 243001
- Bertotti, B. . 2003, , 425, 374
- Blandford, R. & Teukolsky, S. A. 1976, , 205, 580
- Breton, R. P. . 2008, *Science*, 321, 104
- Burgay, M. . 2003, , 426, 531
- Chatterjee, S. . 2009, , 698, 250
- Cordes, J. M. . 2004, , 48, 1413
- Corman, M. & East, W. E. 2024, *Phys. Rev. D*, 110, 084065
- Damour, T. & Deruelle, N. 1986, *Annales de L'Institut Henri Poincare Section (A) Physique Theorique*, 44, 263
- Damour, T. & Esposito-Farese, G. 1992, *Phys. Rev. D*, 46, 4128
- Damour, T. & Esposito-Farèse, G. 1992, , 46, 4128
- Damour, T. & Esposito-Farese, G. 1993, , 70, 2220
- Damour, T. & Schäfer, G. 1991, *Journal of Mathematical Physics*, 32, 127
- Damour, T. & Taylor, J. H. 1991, , 366, 501
- . 1992, , 45, 1840
- de Rham, C. . 2017, *Reviews of Modern Physics*, 89, 025004
- de Rham, C. . 2013, *Physical Review D*, 87, 044025
- de Rham, C. . 2013, , 87, 044025
- Deller, A. T. . 2019, , 875, 100
- Desvignes, G. . 2019, *Science*, 365, 1013
- Ding, H. . 2023, , 519, 4982
- Doneva, D. D. & Yazadjiev, S. S. 2016, *JCAP*, 11, 019
- Doroshenko, O. V. & Kopeikin, S. M. 1995, , 274, 1029
- Eardley, D. M. 1975, , 196, L59
- Edwards, R. T. . 2006, , 372, 1549
- Einstein, A. 1915, *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften*, 844
- Event Horizon Telescope Collaboration. 2019, *The Astrophysical Journal Letters*, 875, L1
- . 2022, *The Astrophysical Journal Letters*, 930, L12

- Everitt, C. W. F. . 2011, *Phys. Rev. Lett.*, 106, 221101
- Faucher-Giguère, C.-A. & Loeb, A. 2011, , 415, 3951
- Ferdman, R. D. . 2020, , 583, 211
- Finn, L. S. & Sutton, P. J. 2002, , 65, 044022
- Fonseca, E. . 2014, , 787, 82
- Freire, P. C. C. . 2012a, *Classical and Quantum Gravity*, 29, 184007
- Freire, P. C. C. & Wex, N. 2024, *Living Reviews in Relativity*, 27, 5
- Freire, P. C. C. . 2012b, , 423, 3328
- Guo, Y. J. . 2021, , 654, A16
- Gupta, T. . 2021, *Class. Quant. Grav.*, 38, 195003
- Hofmann, F. & Müller, J. 2018, *Classical and Quantum Gravity*, 35, 035015
- Hu, H. . 2022, , 667, A149
- Hu, H. . 2020, *Mon. Not. Roy. Astron. Soc.*, 497, 3118
- Hulse, R. A. & Taylor, J. H. 1975, , 195, L51
- Julié, F.-L. . 2025, *Phys. Rev. D*, 111, 024016
- Kleihaus, B. . 2016, *Phys. Rev. D*, 93, 064077
- Kopeikin, S. M. & Schäfer, G. 1999, , 60, 124002
- Kramer, M. . 2004, , 48, 993
- . 2006, *Science*, 314, 97
- . 2021, *Physical Review X*, 11, 041050
- Kramer, M. & Wex, N. 2009, *Classical and Quantum Gravity*, 26, 073001
- Kulkarni, S. R. . 1993, 364, 421
- Kyutoku, K. . 2019, , 483, 2615
- Lai, D. & Rafikov, R. R. 2005, , 621, L41
- Lau, M. Y. M. . 2020, *MNRAS*, 492, 3061
- Lazarus, P. . 2016, , 831, 150
- Lense, J. & Thirring, H. 1918, *Physikalische Zeitschrift*, 19, 156
- Liu, K. . 2014, 445, 3115
- Liu, K. . 2014, *Mon. Not. Roy. Astron. Soc.*, 445, 3115

- Liu, K. . 2020, , 499, 2276
- Lorimer, D. R. 2005, *Living Reviews in Relativity*, 8, 7
- Lorimer, D. R. & Kramer, M. 2004, *Handbook of Pulsar Astronomy*, Vol. 4
- Lower, M. E. . 2024, , 682, A26
- Lyne, A. G. . 2004, *Science*, 303, 1153
- Meng, L. . 2025, , 704, A153
- Miao, X. . 2019, , 99, 123015
- . 2021, , 921, 114
- . 2020, , 898, 69
- Misner, C. W. . 1973, *Gravitation*
- Nicolis, A. . 2009, , 79, 064036
- Nordtvedt, K. 1968, *Physical Review*, 169, 1014
- . 1987, , 320, 871
- Oppenheimer, J. R. & Volkoff, G. M. 1939, *Physical Review*, 55, 374
- Oswald, L. S. . 2025, submitted
- Pani, P. . 2011, *Phys. Rev. D*, 84, 104035
- Penrose, R. 1979, in *General Relativity: An Einstein centenary survey*, ed. S. W. Hawking & W. Israel, Vol. 1 (Cambridge; New York: Cambridge University Press), 581–638
- Peters, P. C. 1964, *Physical Review*, 136, 1224
- Pfahl, E. . 2005, , 628, 343
- Rafikov, R. R. & Lai, D. 2006a, , 73, 063003
- . 2006b, , 641, 438
- Ransom, S. M. . 2003, , 589, 911
- . 2014, , 505, 520
- Ridolfi, A. . 2022, , 664, A27
- Saffer, A. . 2025, , 983, L20
- Sänger, E. M. . 2024
- Savchenko, V. . 2017, , 848, L15
- Schiff, L. I. 1960, *Phys. Rev. Lett.*, 4, 215
- Schneider, J. 1990, , 232, 62

- Seymour, B. & Yagi, K. 2018, , 98, 124007
- Shao, L. . 2013, *Classical and Quantum Gravity*, 30, 165019
- Shao, L. . 2017, *Phys. Rev. X*, 7, 041025
- Shao, L. . 2015, in *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 42
- Shao, L. & Wex, N. 2012, *Class. Quant. Grav.*, 29, 215018
- Shao, L. & Wex, N. 2012, *Classical and Quantum Gravity*, 29, 21.5018
- . 2013, *Classical and Quantum Gravity*, 30, 165020
- Shao, L. . 2015, in *13th Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Astrophysics, and Relativistic Field Theories*, 1704–1706
- Shao, L. . 2018, *Phys. Rev. Lett.*, 120, 241104
- Shao, L. . 2020, , 102, 024069
- Shapiro, I. I. 1964, , 13, 789
- Silva, H. O. . 2021, *Phys. Rev. Lett.*, 126, 181101
- Sipior, M. S. . 2004, , 354, L49
- Sridhar, S. 2023, SKAO staged delivery, array assemblies and layouts, Report SKAO-TEL-0002299, SKA Observatory (SKAO)
- Stairs, I. H. . 2004, *Phys. Rev. Lett.*, 93, 141101
- Stovall, K. . 2018, *ApJL*, 854, L22
- Taylor, J. H. . 1979, , 277, 437
- Taylor, J. H. & Weisberg, J. M. 1982, , 253, 908
- . 1989, , 345, 434
- Thrane, E. . 2020, *MNRAS*, 493, 5408
- Tolman, R. C. 1939, *Physical Review*, 55, 364
- Venkatraman Krishnan, V. . 2020, *Science*, 367, 577
- Voisin, G. . 2020, , 638, A24
- . 2024, arXiv e-prints, arXiv:2411.10066
- Voss, R. & Tauris, T. M. 2003, , 342, 1169
- Wang, S. & Zhao, Z.-C. 2024, , 109, L061502
- Watts, A. . 2015, in *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 43
- Weisberg, J. M. & Huang, Y. 2016, , 829, 55

- Wex, N. & Kopeikin, S. 1999, 513, 388
- Wex, N. & Kopeikin, S. M. 1999, , 514, 388
- Wex, N. & Kramer, M. 2007, , 380, 455
- . 2020, *Universe*, 6, 156
- Will, C. M. 1993, *Theory and Experiment in Gravitational Physics*
- . 2018, *Theory and Experiment in Gravitational Physics*
- Will, C. M. 2018, *Theory and Experiment in Gravitational Physics* (Cambridge University Press)
- Will, C. M. & Nordtvedt, Jr., K. 1972, , 177, 757
- Xu, R. . 2020, *Phys. Rev. D*, 102, 064057
- Yagi, K. . 2014a, *Phys. Rev. D*, 89, 084067, [Erratum: *Phys.Rev.D* 90, 069902 (2014), Erratum: *Phys.Rev.D* 90, 069901 (2014)]
- . 2014b, *Phys. Rev. Lett.*, 112, 161101
- . 2016, *Phys. Rev. D*, 93, 024010
- . 2013, *Phys. Rev. D*, 87, 084058, [Erratum: *Phys.Rev.D* 93, 089909 (2016)]
- Yordanov, P. Y. . 2024, *Astron. Astrophys.*, 687, A17
- Yunes, N. & Spergel, D. N. 2009, *Phys. Rev. D*, 80, 042004
- Yungelson, L. & Portegies Zwart, S. F. 1998, arXiv:astro-ph/9801127
- Zhao, J. . 2022, *Classical and Quantum Gravity*, 39, 11LT01
- Zhu, W. W. . 2019, *Mon. Not. Roy. Astron. Soc.*, 482, 3249