A new limit on local Lorentz invariance violation of gravity from solitary pulsars

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Abstract
Gravitational preferred frame effects are generally predicted by alternative theories that exhibit an isotropic violation of local Lorentz invariance of gravity. They are described by three parameters in the parametrized post-Newtonian formalism. One of their strong-field generalizations, $\hat{\alpha}_2$, induces a precession of a pulsar’s spin around its movement direction with respect to the preferred frame. We constrain $\hat{\alpha}_2$ by using the non-detection of such a precession using the characteristics of the pulse profile. In our analysis we use a large number of observations from the 100 m Effelsberg radio telescope, which cover a time span of approximately 15 years. By combining data from two solitary millisecond pulsars, PSRs B1937+21 and J1744−1134, we get a limit of $|\hat{\alpha}_2| < 1.6 \times 10^{-9}$ at 95\% confidence level, which is more than two orders of magnitude better than its best weak-field counterpart from the Solar system.

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(Some figures may appear in colour only in the online journal)

1. Introduction

There are many models and test frameworks involving Lorentz violation in the gravitational sector, such as the vector–tensor theory in [68], TeVeS gravity [7, 52], Einstein–Æther theory [32], Hořava–Lifshitz gravity [9, 30], and the standard model extension of gravity [6, 36]. A preferred frame, possibly associated with the distribution of matter in the Universe, may result, if the Lorentz violation is isotropic in a specific frame.
The existence of a preferred frame would induce various preferred frame effects (PFEs) that can be probed through different physical observables. In the parametrized post-Newtonian (PPN) formalism \[66, 68\], PFEs are characterized by three parameters, \(\alpha_1, \alpha_2\) and \(\alpha_3\). In Einstein’s general relativity (GR), \(\alpha_1 = \alpha_2 = \alpha_3 = 0\). Their strong-field generalizations are denoted as \(\hat{\alpha}_1, \hat{\alpha}_2,\) and \(\hat{\alpha}_3\), and again in GR, \(\hat{\alpha}_1 = \hat{\alpha}_2 = \hat{\alpha}_3 = 0\). Nevertheless, one can have non-zero values of these parameters in alternative gravity theories \[66, 67\].

Observational implications of PFEs have been studied by several authors using different methods, \(\alpha_i\) (as well as \(\hat{\alpha}_i\); \(i = 1, 2, 3\)) are constrained to high precision from geophysics, Solar system, and pulsar timing experiments \[12, 48, 54, 58, 65\]. We briefly present the best limits of \(\alpha_i\) (or \(\hat{\alpha}_i\)) below.

- Currently, the best limit on \(\hat{\alpha}_1\) comes from the orbital dynamics of the binary pulsar PSR J1738 + 0333 \[22\], which gives a robust limit \[54\],
  \[
  \hat{\alpha}_1 = -0.4^{+3.7}_{-3.1} \times 10^{-5}, \quad (95\% \text{ CL}).
  \] (1)

- The best limit on \(\alpha_2\) comes from the alignment of the Sun’s spin with the orbital angular momentum of the Solar system \[47\] (note, \(\alpha_{2}^{\text{Nordtvedt}} = \frac{1}{2}\alpha_2\)), which gives
  \[
  |\alpha_2| < 2.4 \times 10^{-7}.
  \] (2)

- The best limit on \(\hat{\alpha}_3\) comes from the orbital dynamics of the statistical combination of a set of binary pulsars \[58\], which gives a probabilistic limit,
  \[
  |\hat{\alpha}_3| < 4.0 \times 10^{-20}, \quad (95\% \text{ CL}).
  \] (3)

As shown above, except for \(\alpha_2\), pulsar timing observations have provided better limits than those from Solar system experiments. Here, however, one has to keep in mind, that pulsars are also sensitive to strong-field deviations, which do not occur in the weak-field regime of the Solar system. We note that, in general the preferred frame is not specified. The most natural option from a cosmological perspective is the frame where the cosmic microwave background (CMB) radiation is isotropic. The results discussed in this paper correspond to such a frame, however, see e.g. \[54, 56, 65\] for other preferred frames.

Since the first pulsar discovery in 1967 \[26\] more than 2000 pulsars have been discovered and studied with radio, x-ray and \(\gamma\)-ray observations \[42\]. These celestial objects are intriguing in multiple aspects, e.g., some of them show a long-term rotational stability similar to the stability of atomic clocks \[29\], their high interior density exceeds that of nuclear matter, and their high magnetic field is comparable to or even exceeds the quantum critical value (see references in \[40\]). In particular, one of the most important contributions of pulsars is their unique rôle in tests of gravity theories, especially in the investigation of strong-field deviations from GR. To highlight some great achievements: (i) the Hulse–Taylor pulsar provided the first evidence for the existence of gravitational waves \[60, 61\]; (ii) the double pulsar provided the most accurate tests of GR in the strong-field regime, up to a precision of 0.05\% \[39\]; (iii) pulsar white dwarf systems provided the most stringent tests on the scalar–tensor theories \[1, 22\]. In this paper, we report a new limit on the (strong-field) PPN parameter \(\hat{\alpha}_2\) from solitary millisecond pulsars (MSPs), which surpasses its current best weak-field counterpart from the Solar system \[47\] by more than two orders of magnitude.

The paper is organized as follows. In the next section, we introduce the \(\alpha_2\) (and \(\hat{\alpha}_2\)) parameter and its effect on the spin vector of solitary pulsars, which lays the principle of the test. In section 3, we present our two solitary pulsars, PSRs B1937 + 21 and J1744 – 1134, and the analysis of a large number of observations spanning about 15 years that were obtained from the 100 m Effelsberg radio telescope. Then in section 4, by using the non-detection of profile variation, we set a greatly improved constraint of \(|\hat{\alpha}_2| < 1.6 \times 10^{-9}\) at 95\% confidence.
Figure 1. Angle notations and the $\hat{\alpha}_2$-induced precession of the pulsar spin axis $\hat{s}$ around $\hat{w}$, the movement direction of pulsar with respect to the preferred frame (see text). The coordinate system $(\hat{I}, \hat{J}, \hat{K})$ is defined with $\hat{I}$ pointing to east, $\hat{J}$ pointing to the north celestial pole, and $\hat{K}$ pointing along the line of sight. The unit vector $\hat{e} = \hat{K} \times \hat{s} / |\hat{K} \times \hat{s}|$ is in the sky plane.

level (CL). Section 5 discusses the relevance of our new limit, and briefly summarizes the paper. Throughout the paper, we use boldface letters to represent vectors, and put ‘hat’ onto them to indicate their corresponding unit vectors. Strong-field generalizations of PPN parameters are distinguished explicitly by adding a ‘hat’ onto their corresponding weak-field counterparts.

2. Preferred frame effects and $\hat{\alpha}_2$-induced spin precession

Let us first summarize some key theoretical ingredients for the $\alpha_2$ test. The $\alpha_2$-related many-body post-Newtonian Lagrangian term reads [12, 47],

$$L_{\alpha_2} = \frac{\alpha_2}{4} \sum_{i \neq j} \frac{G m_i m_j}{c^2 r_{ij}} \left[ (\mathbf{v}_i^0 \cdot \mathbf{v}_j^0) - (\hat{n}_{ij} \cdot \mathbf{v}_i^0) (\hat{n}_{ij} \cdot \mathbf{v}_j^0) \right],$$

where $\mathbf{v}_i^0$ is the velocity of body $i$ with respect to the preferred frame, $r_{ij}$ is the coordinate separation of objects $i$ and $j$, and $\hat{n}_{ij} \equiv (\mathbf{r}_i - \mathbf{r}_j) / r_{ij}$. The velocity of the center-of-mass of the many-body system with respect to the preferred frame we denote by $\mathbf{w}$. Nordtvedt showed that, as a result of (4), the spin axis of a massive body precesses around $\hat{w}$. The precession has an angular velocity [47],

$$\Omega_\text{prece} = -\frac{\alpha_2}{2} \left( \frac{2\pi}{P} \right) \left( \frac{u}{c} \right)^2 \cos \psi,$$

where $P$ is the spin period of the body’s rotation, $\psi$ is the angle between $\mathbf{w}$ and the spin direction $\hat{s}$ (see figure 1 for angles and an illustration of the precession), and $u \equiv |\mathbf{w}|$. A similar consequence was also found in the orbital dynamics of a binary system (see (24) in [54]), where a (strong-field) $\hat{\alpha}_2$ induces a precession of the orbital angular momentum around $\mathbf{w}$ for a small-eccentricity binary.

As mentioned before, Nordtvedt [47] used the current alignment of the Sun’s spin with the orbital angular momentum of the Solar system, to limit such a precession. His limit (2)
has remained the best limit of $\alpha_2$ for more than a quarter of a century. The crucial assumption inherent is that the Sun’s spin was aligned with the Solar system angular momentum five billion years ago when the Sun was born. A weaker but more robust limit on $\alpha_2$ comes from a long-term project called lunar laser ranging (LLR), which gives [45]

$$\alpha_2 = (1.8 \pm 5.0) \times 10^{-5}, \quad (95\% \text{ CL}),$$

from an analysis of 35 years of data. It is two orders of magnitude weaker than that of (2). The best limit in the strong field is from pulsar timing experiments on pulsar binaries PSRs J1012 + 5307 and J1738 + 0333 [54],

$$|\dot{\alpha}_2| < 1.8 \times 10^{-4}, \quad (95\% \text{ CL}).$$

The remarkable limit (2) obtained by Nordtvedt [47] benefited enormously from a long baseline of time of approximately five billion years. However, as we can see from (5), one can also take advantage of the short spin period of MSPs to achieve a tight constraint. This method was originally suggested in [47] shortly after the discovery of the first MSP. We present the first detailed analysis in this direction.

With a non-vanishing $\dot{\alpha}_2$, a spinning pulsar would precess around its ‘absolute’ velocity, $\hat{w}$, with an angular velocity (5). As a result of the precession, the angle, $\lambda$, between the pulsar spin axis and our line of sight changes with time (see figure 1), so that different portions of the pulsar emission beam are observed at different epochs. Consequently, one expects to detect characteristic changes in the measured pulse profile as a function of time. For solitary pulsars, from pure geometrical consideration we have (see also (2) in [4]),

$$\frac{d\lambda}{dt} = \Omega_{\text{pre}} \hat{w} \cdot \left( \frac{\hat{K} \times \hat{s}}{|\hat{K} \times \hat{s}|} \right) \equiv \Omega_{\text{pre}} \cos \theta,$$

where $\theta$ is the angle between $\hat{w} = w/w$ and $\hat{e} = \hat{K} \times \hat{s}/|\hat{K} \times \hat{s}|$. The unit vector, $\hat{e}$, gives the line of nodes associated with the intersection of the sky plane and the equatorial plane of the pulsar (see figure 1).

Current observational technologies are already sensitive enough to detect such a change, if it exists. Indeed, similar changes in pulsar profiles have been observed before, albeit under the influence of geodetic precession, e.g. for, PSR B1913 + 16, PSR B1534 + 21, PSR J1141 – 6545, and PSR J0737 – 3039B [37, 44, 49, 57, 64]. Geodetic precession occurs in binary pulsars due to the curvature of spacetime near gravitating bodies, where the proper reference frame of a freely falling object suffers a precession with respect to a distant observer. The caused pulse profile changes manifested themselves in various forms [18], such as changes in the amplitude ratio or separation of two pulse components [37, 64], the shape of the characteristic swing of the linear polarization [57], or the absolute value of the position angle [44].

For our purpose, to avoid complications due to spin–orbit coupling, we choose solitary pulsars to limit $\dot{\alpha}_2$. In our solitary pulsars below, if there exists an $\dot{\alpha}_2$-induced precession, we are also expected to observe one or several of the above mentioned changes in the pulse profile. On the other hand, if we do not see any changes in the observations, we can constrain $\dot{\alpha}_2$. As an example of such a non-detection, in figure 2 we plot two pulse profiles of PSR B1937 + 21 obtained at different epochs. One was obtained on 2 September 1997, while the other was obtained on 6 June 2009. Details of the used observing system will be given in section 3. Instrumental effects are responsible for the ‘dips’ around the pulse. We have not removed these effects since we only use data from one backend and the dips remain unchanged in time and do not introduce any temporal variation in the profiles. We can immediately see from figure 2 that within noise, there is no visible change in the pulse profile for this pulsar.
Figure 2. Comparison of two pulse profiles of PSR B1937 + 21 obtained at two different epochs—the black one was obtained on 2 September 1997, while the red one was obtained on 6 June 2009. The main peak is aligned and scaled to have the same intensity. Uncertainties in pulse profiles are illustrated at the right bottom corner. Notations used in figure 4 include: the first component of the main-pulse (MP1), the second component of the main-pulse (MP2), the interpulse (IP), the separation between MP1 and IP (SEP0), the separation between leading MP1 and trailing IP (SEP1), and the separation between trailing MP2 and leading IP (SEP2).

Figure 3. A comparison of two pulse profiles of PSR J1744 − 1134 obtained during two different epochs—the black one was obtained on 29 April 1998, while the red one was obtained on 8 September 2008. The peak is aligned and scaled to have the same intensity. Uncertainties in pulse profiles are illustrated at the left bottom corner. Inset shows the zoom-in of the main-pulse (corresponding to the black profile in the main figure), and it also shows our analytical fitting to the pulse and the corresponding three components (see text).

over more than ten years. The two profiles are chosen solely based on a large time separation and a low level of noise, so that no bias is introduced. A similar overlap of two pulse profiles for the other pulsar in our test, PSR J1744 − 1134, is shown in figure 3. The profiles were obtained on 29 April 1998 and 8 September 2008. There exists no visible difference within
noise level. These two solitary pulsars are selected from the known population of MSPs, based on their figure of merit for the $\hat{\alpha}_2$ test. The figure of merit is roughly $P^{-1}T_{\text{obs}}^{3/2}$ where $T_{\text{obs}}$ is the observational time span. We also require the pulsars to have proper motion measurements from pulsar timing and geometry information from the combination of radio and $\gamma$-ray observations. The reason for the figure of merit and these requirements will become clear later.

To achieve a quantitative constraint, we need to relate the change in $\lambda$ with that of a profile. One can confidently consider the pulse profile as a cross-sectional cut through the pulsar’s emission beam [40]. To quantify the (non-)change of pulsar geometry from a pulse profile, we should introduce a basic emission model. We use the simplest geometrical cone model [23], which only assumes that radio beam is centered on the magnetic axis, causing the ‘lighthouse’ effect of a pulsar as it rotates around the spin axis. This approximation avoids most of the model dependent aspects of pulsar emission, and sufficiently reproduces the basic features of the two solitary pulsars we are using here. We note in passing that the limit on the pulsar spin precession does not depend on this assumption significantly, as shown in the geodetic precession analysis for PSR J0737−3039A [43]. The latter is also a non-detection case, where authors showed that a non-zero ellipticity for the radiation beam gives no significantly improved fits to the data, and a circular beam describes the data equally [43].

From the cone model, it was shown from geometry [23, 40],

$$\sin^2 \left( \frac{W}{4} \right) = \frac{\sin^2 (\rho/2) - \sin^2 (\beta/2)}{\sin (\alpha + \beta) \sin \alpha},$$

(9)

where $W$ is the width of the pulse, $\alpha$ is the angle between $\hat{s}$ and the magnetic axis, $\beta \equiv 180^\circ - \lambda - \alpha$ is the impact angle, and $\rho$ is the semi-angle of the opening radiating region (for details, see [40] and references therein).

Adopting a plausible assumption that the radiation property ($\alpha$ and $\rho$) has no change during the observational span $\sim$15 years [40], i.e. $d\alpha/dt = d\rho/dt = 0$, we can relate the change in $\lambda$ with the change in the pulse width (see also (4) in [11]),

$$\frac{d\lambda}{dt} = \frac{1}{2} \frac{\sin(W/2)}{\cot \lambda \cos(W/2) + \cot \alpha} \frac{dW}{dt} \equiv A \frac{dW}{dt},$$

(10)

where $A \equiv \sin(W/2)/(2 \cot \lambda \cos(W/2) + 2 \cot \alpha)$. Hereafter we use the width at 50% intensity level, $W_{50}$, as a proxy of $W$. Now we can quantify the (non-)change of the pulsar orientation with respect to the Earth through the (non-)change in the pulse width. In the next section, detailed constraints on the (non-)change of pulse width are derived, which are used to put a limit on $\hat{\alpha}_2$ in section 4.

3. Observations and pulse profile analysis

In this section, we present our observations of two solitary pulsars with the 100 m Effelsberg telescope and our detailed analysis of pulse profiles.

All data were obtained with the 100 m Effelsberg radio telescope, operated by the Max-Planck-Institut für Radioastronomie, Bonn, Germany. The observations are part of the pulsar timing program (see e.g. [20, 25]). In order to examine the profile stability over time, it is important to use data obtained with as few changes in the observing system as possible. The major components of the system are the telescope, the receiver (frontend) and the data processor (backend).

The observations span from September 1997 for PSR B1937 + 21 and January 1997 for PSR J1744 − 1134, to the present. Receiver systems operating at a frequency around 1400 MHz

4 Other choices, like the width at a 10%-level do not change the result in the following significantly.
were used, being sensitive to two orthogonally left-hand and right-hand circularly polarized signals. The frequency of the signals was mixed to baseband and fed into a data acquisition system known as the Effelsberg-Berkeley Pulsar Processor (EBPP) [2]. The EBPP is a coherent dedispersion backend which means that it completely removes the signal dispersion effect of the interstellar medium (ISM) caused by free electrons along the line of sight. If left uncorrected this causes an apparent broadening of the pulse. The time resolution of our equipment was 1.4 \( \mu s \) for PSR B1937 + 21 and 0.6 \( \mu s \) for PSR J1744 – 1134. In the backend the signal from the channels is directed to the dedisperser boards where online coherent dedispersion takes place according to the recorded dispersion measure (DM)\(^5\). The output signals are folded using the topocentric pulse period (i.e. individual pulses are phase-aligned and added), and are later integrated in phase. The EBPP is the longest-running coherent dedispersion backend dedicated to high precision pulsar timing, making its database uniquely suited this work. The total bandwidth of the EBPP is dependent on the source’s dispersion smearing at the observing frequency and has a maximum value of 112 MHz. The observational bandwidth for PSR B1937 + 21 is 44 MHz, while for PSR J1744 – 1134, all data have 112 MHz of bandwidth apart from the first two observations in January 1997 which have 56 MHz of bandwidth. The frontend of the telescope changed once in July 2009, resulting in a change of the central frequency from 1410 to 1360 MHz. Frequency evolution of the profile is very small for MSPs but we quantified the change in profiles in section 3.1.

The data were reduced using the PSRCHIVE package [31]. Each profile we use is a \( \sim \) 30 min integration. This is achieved by adding shorter integrations made with no more than 1 h separation. Throughout the pulse profile fitting analysis discussed in the following, we use the off-pulse root-mean-square as the profile’s flux uncertainty.

3.1. PSR B1937 + 21

PSR B1937 + 21 (a.k.a PSR J1939 + 2134) was the first MSP discovered, with a spin period of 1.56 ms [3]. Because of its brightness and later as a target of pulsar timing array (PTA) projects [20, 25, 28], it has been observed frequently since its discovery. PSR B1937 + 21 shows a strong main-pulse (MP1) with a second weaker component (MP2) and a strong interpulse (IP), see figure 2 for illustrations. The main-pulse and interpulse are separated by \( \sim 188^\circ \), hence they may be produced by two opposite magnetic poles sweeping over the Earth. Another possibility is that they are produced by a single magnetic pole with a wide opening angle and a hollow cone emission pattern.

In order to examine the profiles, we performed least-square fitting of parabolas to the peaks of the three components. The simplicity of the components’ shapes allows good fits with a simple and symmetric function, preserving linearity of the fitting procedure. For each component we obtained the peak intensity and its corresponding longitude value as well as its \( W_{50} \). We investigated the time stability of the pulse profile using five different measurements of widths and component separations (see figure 2 for definitions) and also two measurements of amplitude ratios of different components. The results from fitting are plotted in figure 4 as a function of time.

One can see that the seven quantities characterizing the pulse profile are very stable over the 15 years of observation. We also plotted twelve high signal to noise ratio (S/N) profiles in the left panel of figure 5. These profiles span almost uniformly the whole observing period from 1997 to 2011. In the right panel of figure 5, the difference between profiles is present after subtracting a reference profile. The highest S/N reference profiles are chosen for each

\[ DM = \int n_e \, dl \] \(^40\).
frequency—one obtained on 4 January 1999 for 1410 MHz and one obtained on 26 August 2010 for 1360 MHz. We can see from the residuals that no evolution over time in the profile is visible.

Concerning the frequency dependence of $W_{50}$, in general normal pulsars$^6$ show a systematic increase in pulse width when observed at lower frequencies [40], while MSPs $^6$

Normal pulsar usually means a non-recycled pulsar with a spin period $P$ larger than 30 ms, and a spindown rate $\dot{P} \sim 10^{-18}$ to $10^{-15}$ s$^{-1}$; see references in [40] for details.

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Figure 4. Pulse profile characteristics of PSR B1937 + 21, as a function of modified Julian date (MJD); see figure 2 for notations. The amplitude ratios in (f)–(g) are measured from peak to peak. Black circles are observations made at 1410 MHz, while blue squares are observations made at 1360 MHz. Years of observations are indicated at the top of the figure.
in general show very little evolution of pulse width with frequency [38]. Nevertheless, for both normal pulsars and MSPs, profile evolution, in terms of peak intensities, width and phase, was observed. In figure 4, one can see that there is no large difference between two frequencies. However, in our accurate data, we found that a subtle change between two frequencies is needed. Therefore we fitted $W_{50}$’s of the main-pulse and the interpulse with the following formula,

$$W_{50}(t) = W_{50} + \frac{dW_{50}}{dt} t + \Delta W_{50} \Theta(t - t_0),$$

(11)

where $\Delta W_{50}$ is the ‘jump’ of width between measurements made at 1360 and 1410 MHz, $\Theta(t)$ is the Heaviside step function, and $t_0$ is the time when observations were shifted from 1410 to 1360 MHz.

We simulated $10^6$ sets of profile widths against time according to the measurements and uncertainties in figure 4(a), and then fitted simultaneously for three parameters in (11) for each set of profile widths. The fitted parameters were accumulated as histograms with $10^6$ entries. We read out the fitting results and their uncertainties from the central values and the widths of these histograms respectively. They are tabulated in the last three rows in table 1.
where uncertainties are rescaled by the square root of the reduced fitting $\chi^2_{\text{red}}$. The results show the need of a tiny jump $\Delta W_{50} \simeq 0.1\,$s (about one third of a bin in the EBPP profile data).

We investigated the possible origin of the jump by effects associated with ISM. For pulsars such as PSR B1937 + 21 with high DM, $\Delta W_{50}$ may reflect the scattering effects from the irregularities in the ISM, which usually produce a one-sided exponential tail for pulsar profiles [40]. The scattering timescales for the two frequencies are listed in table 1, and are based on an empirical dependence on DM and frequency [8]. The broadening in the pulse width from the scattering is negligible. The empirical relation in [8] is poorly constrained and may introduce overestimation or underestimation to an amount of several times, however, after taking the uncertainties into account, the effects from scattering are still too small to account for the $\Delta W_{50}$ we obtained from fitting. Another factor to consider is temporal DM variation. It is well known that the DM varies with time and various efforts were made to measure these variations systematically, see e.g. [69]. If the DM at the observatory is not properly updated, then the dedispersion would be imperfect, leading to a broader pulse. We have calculated the width difference between the two frequency bands for a DM value that deviates as much as 0.05 cm$^{-3}$ pc from the correct value (it would take decades without updating the DM value to get such a large deviation for PSR B1937 + 21 [51, 69]), and we found that the $\Delta W_{50}$ between the 1410 and 1360 MHz bands are below a few times 0.001s. Therefore, the effects from DM variation are also negligible. In order to test for the possibility that $\Delta W_{50}$ is caused by profile evolution we made use of data taken at Effelsberg with Asterix, a new backend that has run in parallel with the EBPP from 2011. Asterix has a broader bandwidth of 200 MHz. The frequency range covers both frequency bands of the EBPP backend. We selected the Asterix frequency range accordingly.

### Table 1. Relevant quantities of PSRs B1937 + 21 and J1744 – 1134 for the $\hat{a}_2$ test. Most quantities are from pulsar timing [62], while the orientation and radiation quantities ($\alpha$ and $\zeta$) were obtained from model fitting to radio and $\gamma$-ray lightcurves (PSR B1937 + 21 [24] and PSR J1744 – 1134 [34]). The Lutz–Kelker bias in the timing parallax was corrected [63]. The scattering timescales were calculated according to an empirical relationship in [8], and listed for 1410 MHz/1360 MHz. The pulse width and its time derivative are from this work. For PSR B1937 + 21, quantities for $\hat{\Omega}$ (left) and $\hat{I}$ (right) are both tabulated. Parenthesized numbers represent the 1-$\sigma$ uncertainty in the last digits quoted.

| Pulsar       | B1937 + 21          | J1744 – 1134         |
|--------------|---------------------|----------------------|
| Discovery (year) | 1982 [3]           | 1997 [5]             |
| Right Ascension, $\alpha$ (J2000) | $19^h39^m38.561^s297.2^d$ | $17^h44^m29.403^s209.4^d$ |
| Declination, $\delta$ (J2000) | $+21^\circ34^\prime59.12950^\prime(4)$ | $-11^\circ34^\prime54.6600^\prime(2)$ |
| Spin period, $P$ (ms) | 1.557 806 53910(3) | 4.074 545 940 854 022(8) |
| Reference epoch for $\alpha$, $\delta$ and $P$ (MJD) | 54219 (right) | 53742 (left) |
| Proper motion in $\alpha$, $\mu_\alpha$ (mas yr$^{-1}$) | 0.072(1) | 18.804(8) |
| Proper motion in $\delta$, $\mu_\delta$ (mas yr$^{-1}$) | -0.415(2) | -9.4(3) |
| Parallax, $\pi$ (mas) | 0.14$^{+0.05}_{-0.03}$ | 2.4(1) |
| Dispersion measure, DM (cm$^{-3}$ pc) | 71.0227(5) | 3.1380(3) |
| Magnetic inclination, $\alpha$ ($^\circ$) | $75^{+8}_{-6}$ | $105^{+5}_{-8}$ |
| Observer angle, $\zeta$ ($^\circ$) | 80(3) | 85(3) |
| Scattering timescale, $\tau_s$ (ns) | 826/949 | 0.20/0.23 |
| Time span of data used in this work (MJD) | 506 93–557 25 | 504 60–559 62 |
| Pulse width at 50% intensity, $W_{50}$ ($^\circ$) | 8.281(9) | 10.245(17) |
| Time derivative of $W_{50}$, $dW_{50}/dt$ (10$^{-3}$ deg yr$^{-1}$) | -3.2(34) | 3.5(66) |
| Jump between two frequencies, $\Delta W_{50}$ ($^\circ$) | 0.12(3) | 0.04(6) |
to emulate the EBPP characteristics and found a jump $\Delta W_{50} \simeq 0.07^\circ \pm 0.03^\circ$ between two frequencies, which is consistent with the jump from the EBPP backend. Consequently, we conclude that $\Delta W_{50}$ reflects an evolution of the pulsar profile width with frequency\footnote{See also figure 13 in [38] for the evolution of pulse profile of PSR B1937 + 21 with frequency. Note that in the relevant frequency bands, the dip between MP1 and MP2 gets deeper when frequency increases, consequently the width of MP1 gets narrower. This is also consistent with the $\Delta W_{50}$ measurement here.}

The same Monte Carlo fitting analysis was also applied to the interpulse (figure 4(b)); see table 1 for the fitted results. We detected no changes in the pulse width against time for the interpulse as well.

For both the main-pulse and the interpulse, we find no evidence of changes in the pulse width over time. We also performed hypothesis test to test the necessity of a non-zero $(dW_{50}/dt)$ for main-pulse and interpulse. Our null hypothesis is that, the inclusion of $(dW_{50}/dt)$ does not provide a significantly better fit. $F$-tests give $p$-values of 0.22 and 0.31 for the null hypothesis of the main-pulse and interpulse respectively, which clearly show that the inclusion of a non-zero $(dW_{50}/dt)$ does not provide a significantly better fit to the data\footnote{The $p$-value from the test is the probability of obtaining a test statistic at least as extreme as the one that is actually observed, assuming that the null hypothesis is true [50]. In our cases, the test statistic is $F$ statistic which follows an $F$ distribution.}

\subsection{PSR J1744 − 1134}

PSR J1744 − 1134 was discovered in 1997 through the Parkes 436 MHz survey of the southern sky [5]. It has a spin period of 4.07 ms, and later as a target in the PTA projects [28], it is being observed frequently. PSR J1744 − 1134 has a sharp pulse with a $W_{50} \sim 12.5^\circ$ at 1410 MHz, see figure 3. Because of a long observational span in time and continuous observations since its discovery, it is also a good laboratory to test the local Lorentz invariance of gravity.

We used 65 observations spanning about 15 years obtained with the 100 m Effelsberg radio telescope. In order to measure the pulse width accurately, we again try to describe the profile by an analytic function. The pulse profile of PSR J1744 − 1134 is different from that of PSR B1937 + 21, where we used fits of parabolas to parts of the pulse to determine the width. The same method cannot be applied here, and different functions need to be used. Despite the apparent simplicity of the pulse, a good fit to a high S/N pulse profile is not trivial, see e.g. figure 4 in [41] where seven Gaussian components were used for the whole profile at 1400 MHz observational frequency (five Gaussian components for the main-pulse). In this work we used three components to fit the main-pulse of PSR J1744 − 1134. These components have close center values, so using three Gauss functions would often not give a stable fitting result, unless we a priori fix the means of them. Therefore we used three components with different shapes (one Gauss function and two Landau functions with opposite orientations) to break the degeneracy and achieve a stable fitting. A typical fitting is shown in the inset of figure 3. For each observation, we generated $10^4$ realizations of the profile according to measurement and measurement uncertainty. Then for each profile, we fitted the three components analytically. $W_{50}$ is obtained from the analytical sum of these components. Hence for one observation, we have a distribution of pulse width with 10 000 entries. A width with an uncertainty is drawn from this distribution. Finally the uncertainty is rescaled by the square root of the fitting $\chi^2_{red}$. The result is plotted in figure 6 as a function of time. No clear evolution over time is seen from the pulse width. Because of fewer observations and lower S/N of the profile data on average of PSR J1744 − 1134, the uncertainties in $W_{50}$ are in general larger than that of PSR B1937 + 21.

Twelve high S/N profiles of PSR J1744 − 1134 are present in figure 7 in a similar way as PSR B1937 + 21 in figure 5. For this pulsar, we see no evolution between two frequencies. We
Figure 6. Pulse width at 50% intensity level of PSR J1744 $-$ 1134, as a function of time. Black circles are observations made at 1410 MHz, while blue squares are observations made at 1360 MHz. Errors are rescaled by the square root of the fitting $\chi^2_{\text{red}}$. The gray region shows the 3-$\sigma$ band of our linear fitting. The years of observations are indicated at the top of the figure.

Figure 7. Same as figure 5, for PSR J1744 $-$ 1134. For the right panel, the pulse profile taken on 27 April 2005 is used as the reference profile for subtraction.

performed the same check as with PSR B1937 + 21 using A r t e r i x data of PSR J1744 $-$ 1134, and no evolution of the profile width between two frequencies is found. Hence, we only used one reference profile for subtraction. From the residuals in the right panel, one finds no change in pulse profile over $\sim$15 years.

The same Monte Carlo and fitting analysis applied to PSR B1937 + 21 (see section 3.1) was implemented for PSR J1744 $-$ 1134. For this pulsar, we used the linear function (11)
without the need of a jump in pulse width. The fitting results from $10^6$ simulations are tabulated in table 1. As was the case for PSR B1937 +21, the measurement of $(dW_{50}/dt)$ shows no significant change in $W_{50}$ over time for PSR J1744 −1134. $F$-test [50] gives a $p$-value of 0.44 for the necessity of a non-zero $(dW_{50}/dt)$.

4. A new $\hat{\alpha}_2$ limit from solitary pulsars

From the pulse-profile analysis of PSRs B1937 +21 and J1744 −1134, tight limits on the change of pulse width have been set (see table 1). We have also examined the profiles of PSRs B1937 +21 and J1744 −1134 from early literature and no change was found. Because of low quality of early data and the use of different backends, they have not been included in the calculations.

By combining (5), (8) and (10), we have

$$\hat{\alpha}_2 = -2A \left[ \frac{2\pi}{P} \left( \frac{w}{c} \right)^2 \cos \psi \cos \vartheta \right]^{-1} \frac{dW}{dt}. \quad (12)$$

The limits on width changes for PSRs B1937 +21 and J1744 −1134 were given in section 3. The others will be discussed in the following.

$A$ is defined in (10) and includes information of the pulse profile, the spin orientation and the emission property. Pulse width is obtained from profile analysis, while $\lambda$ (or equivalently the observer angle $\xi = 180^\circ - \lambda$) and $\alpha$ can be obtained from lightcurve analysis by combining radio and $\gamma$-ray observations. For both PSRs B1937 +21 and J1744 −1134, $\gamma$-ray observations from Fermi Large Area Telescope (LAT) are available [24, 34]. The results from modeling of the radio and $\gamma$-ray emission profiles are quoted in table 1 for PSR B1937 +21 [24] and PSR J1744 −1134 [34].

To obtain the quantities inside the square brackets of (12), besides the well measured spin period (see table 1), we need to know the pulsar’s velocity with respect to the preferred frame, and the pulsar’s spin orientation with respect to it.

First, a preferred frame must be specified. The most natural frame is the one where the CMB radiation is isotropic. The CMB frame is used as the preferred frame in most literature (see however [54, 56, 65] for other local frames), and the constraints of $\alpha_i$ (and $\hat{\alpha}_i$) quoted in section 2 all refer to this frame. We will also use the CMB frame as the preferred frame in the following calculations. This choice basically assumes that the preferred frame is determined by the global distribution of matter in the Universe, and that the fields of the gravitational interaction, which cause the PFEs, are long range, at least comparable to the Hubble radius. The generalization to other frames is straightforward.

From Wilkinson Microwave Anisotropy Probe observations, our Solar system barycenter (SSB) has a peculiar velocity with respect to the CMB frame, $|w_{SSB}| = 369.0 \pm 0.9$ km s$^{-1}$, in the direction of galactic longitude and latitude $(l, b) = (263.99^\circ \pm 0.14^\circ, 48.26^\circ \pm 0.03^\circ)$ [27, 33]. The pulsar velocity with respect to the CMB frame is simply $\vec{w} = \vec{v}_{PSR-SSB} + \vec{w}_{SSB}$, where $\vec{v}_{PSR-SSB}$ is the 3D motion of the pulsar with respect to SSB. The 2D projected movement on the sky plane can be obtained from proper motion and parallax measurements from timing experiments [62] (see table 1). The parallax of PSR B1937 +21 is not well measured, so the distance estimated from it is not accurate. Different Galactic electron density models [10, 53, 59] infer a distance in the range of 3.6–4.8 kpc [70], coarsely consistent with the distance derived from the parallax. Fortunately, because of the small angular proper motion of PSR B1937 +21 ($\mu_T \equiv \sqrt{\mu_{\alpha}^2 + \mu_{\delta}^2} \simeq 0.42$ mas yr$^{-1}$; see table 1), the error of the 2D velocity is less than 10 km s$^{-1}$ even if we underestimate or overestimate the distance by a few kpc. The radial velocity $v_r \equiv \hat{\mathbf{K}} \cdot \vec{v}_{PSR-SSB}$ of solitary pulsars in general is not measurable from pulsar
timing experiments. However, we can see in the following that it only has slight effects on the test. The radial velocity enters in (12) through $w$, in the form of $(w \cdot \hat{s})^9$. From Fermi LAT $\gamma$-ray observations, we can see that the spins of PSRs B1937 + 21 and J1744 − 1134 both lie close to the sky plane ($\zeta \sim 80^\circ$; see table 1), so the unknown radial velocity only has a marginal effect in $(w \cdot \hat{s})$. By assuming that the solitary pulsars are gravitationally bound in the galaxy [35], we find that the reasonable ranges of the radial velocities are $−600 \text{ km s}^{-1} \lesssim v_r \lesssim 200 \text{ km s}^{-1}$ for PSR B1937 + 21 and $−400 \text{ km s}^{-1} \lesssim v_r \lesssim 250 \text{ km s}^{-1}$ for PSR J1744 − 1134, respectively. We use these ranges to test the dependence of our $\hat{a}_2$ limits on the radial velocity later on, and the results only show a weak dependence that alters the limits by $\sim 15\%$ at most. Even if we assume some unphysical radial velocity $|v_r| \gtrsim 1000 \text{ km s}^{-1}$, the limits are altered by $\sim 40\%$ at most. In the case of extremely large radial velocities $|v_r| \gtrsim 1500 \text{ km s}^{-1}$, the $\hat{a}_2$ limits get better with increasing $|v_r|$.

For the pulsar spin orientation, as mentioned before, $\zeta$ can be inferred from the combination of radio and Fermi LAT observations. The remaining unknown is the azimuthal angle $\eta$ of the pulsar spin $\hat{s}$ around the line of sight (see figure 1), which is not an observable from pulsar observations for PSRs B1937 + 21 and J1744 − 1134 and will be treated as a random variable.

We set up Monte Carlo simulations to account for measurement errors and the unknown $\eta$ and the unknown radial velocity. In our simulation, we assume that the radial velocity follows a Gaussian distribution with a zero mean and a 100 km s$^{-1}$ spread, and $\eta$ is treated as a random variable uniformly distributed in (0°, 360°), in the same way as that of [12, 17]. As mentioned before, we also set up various Monte Carlo simulations for different radial velocities, where only a weak dependence on the choice of the radial velocity is found, at most altering our results by $\sim 15\%$ under the assumption that the solitary pulsars are bound in the gravitational potential of the Galaxy. Because of the unknown $\eta$, our final result is a probabilistic constraint, the same as the strong equivalence principle test in [17] and the $\hat{a}_1$ test in [12]. It is the main limitation of these tests (see [54] for a robust $\hat{a}_1$ test where such a probabilistic assumption was overcome). Through 10$^5$ simulations, we got the probability density functions (PDFs) of $\hat{a}_2$ from PSRs B1937 + 21 and J1744 − 1134 according to (12). They are plotted in figure 8 as a blue dashed histogram and a red dotted histogram, respectively. From these PDFs, we obtain

$$\text{PSRB}1937+21: \quad |\hat{a}_2| < 2.5 \times 10^{-8}, \quad (95\% \text{ CL}),$$

$$\text{PSR}J1744−1134: \quad |\hat{a}_2| < 1.5 \times 10^{-8}, \quad (95\% \text{ CL}).$$

They are already much better than the limit (2) from the Solar system. For these limits, PSR B1937 + 21 benefits from a smaller spin period and a tighter constraint on $dW_{\text{sp}}/dt$ (see table 1), however PSR J1744 − 1134 benefits from a more favorable emission geometry (a smaller $A$). In total, PSR J1744 − 1134 gives a slightly better limit than PSR B1937 + 21. The analysis for PSR B1937 + 21 is based on the main-pulse (MP1 in figure 2). Likewise, one could use the interpulse (IP in figure 2) to constrain a precession of PSR B1937 + 21, which leads to a similar, even slightly more constraining limit because of a smaller $A$. We therefore stay with the more conservative value derived from the main-pulse. Similarly, even though the results at $\gamma$-ray frequencies convincingly rule out such an interpretation, one may consider the main- and interpulse as the result of a single very wide cone. In that case, the interpretation of the change in width as described in (10) will need to be recasted in terms of the IP–MP separation (SEP0 in figures 2 and 4). Such an interpretation would give similar limits.

$^9$ It has no contribution to $(w \cdot \hat{e})$ because by definition $\hat{e}$ is in the sky plane.
We can immediately see that the above two numbers are located far outside the $\hat{\alpha}_2$ range plotted in figure 8. This is due to the fact that these PDFs have very long tails (compared with the normal distribution). The reason for the long tail was analyzed explicitly in [54] for a similar $\hat{\alpha}_2$ test from binary dynamics. They are due to unfavorable geometrical configurations where $\cos \psi \simeq 0$ and/or $\cos \vartheta \simeq 0$. From (12), we can see that $\hat{\alpha}_2$ is unconstrained at these configurations. Fortunately, as in [54] one can take advantage of the probabilistic consideration by using more than one system to suppress the long tails. The probability that both pulsars are at their unfavorable orientation is small. For this reason we use more than one solitary pulsar. By assuming that PSRs B1937 + 21 and J1744 − 1134 are independent and that they have approximately the same $\hat{\alpha}_2$ value, we got a combined PDF for $\hat{\alpha}_2$. It is shown in figure 8 as a solid black histogram. The long tail is highly suppressed as one expects. From the combined PDF, we get

$$|\hat{\alpha}_2| < 1.6 \times 10^{-9}, \quad (95\% \text{ CL})$$

which is significantly better than that of (2) from the Solar system [47], and more than four orders of magnitude better than the limit (6) from LLR [45].

To compare our results with the limit (2) graphically, a logarithmic scale is needed. We plot in figure 9 the CLs to exclude a specific $\hat{\alpha}_2$ value versus log $|\hat{\alpha}_2|$, from PSRs B1937 + 21 and J1744 − 1134 and their combination. The limit (2) is plotted as an exclusion region in gray. The improvement of the limit by orders of magnitude is obvious.

5. Discussions

Strictly speaking, the comparison between (2) and (15) is only phenomenological. $\alpha_2$ and $\hat{\alpha}_2$ probe different aspects of the local Lorentz symmetry of gravity, namely weak fields and strong fields. It was explicitly shown that in the strong fields, one can have a different PPN parameter in the scalar–tensor theories through a mechanism called ‘scalarization’ similar
to the well known phenomenon ‘phase transition’ [14]. As an example, in the scalar–tensor gravity the PPN parameter $\gamma$ generalizes to

$$\hat{\gamma} = \gamma_{AB} = 1 - \frac{2\alpha_A\alpha_B}{1 + \alpha_A\alpha_B},$$

(16)

for a binary pulsar system, where $\alpha_A$ and $\alpha_B$ are the effective scalar coupling constants of the pulsar and its companion, respectively [13]. The weak-field PPN parameter $\gamma$ is recovered for $\alpha_A = \alpha_B = \alpha_0$. In GR one has $\hat{\gamma} = \gamma = 1$. Similarly, we may expect that $\hat{\alpha_2}$ deviates from its weak-field PPN correspondent $\alpha_2$ due to strong-field contributions. The strong-field $\hat{\alpha_2}$ in the Einstein-Æther theory can be found in [19]. In the absence of non-perturbative effects, one can expand $\hat{\alpha_2}$ in the compactness $C$ of the body [15]. In our case, we would write an expansion like,

$$\hat{\alpha_2} = \alpha_2 + K_1C + K_2C^2 + \ldots,$$

(17)

where $K_i$ are coefficients characterizing deviations from GR, and $C \simeq GM/Rc^2$ for a body with mass $M$ and radius $R$. The compactnesses for the Earth and the Sun are roughly $C_{\oplus} \sim 10^{-9}$ and $C_{\odot} \sim 10^{-6}$, respectively, which suppress $K_i$-related ($i = 1, 2, \ldots$) physical effects dramatically. In contrast, neutron stars have $C_{NS} \sim 0.2$, which is one of the reasons why pulsars are ideal probes for gravity effects associated with strong gravitational fields. From (17) one can see that, the $\hat{\alpha_2}$ limit from pulsars is $\sim 10^5$ times more sensitive to the $K_1$ parameter and $\sim 10^{10}$ times more sensitive to the $K_2$ parameter than that of the Solar system test (2). It is even more sensitive compared with the constraint (6) from the ranging experiment of the Sun–Earth–Moon dynamics. This supports the importance of the strong-field $\hat{\alpha_2}$ limit (15).

It is worth mentioning that, when discussing the constraints on strong-field parameters of alternative gravity theories, one should be aware of a potential compactness-dependent nature of these parameters, especially when combining different systems. Our $\hat{\alpha_2}$ test (15) assumes that $\hat{\alpha_2}$ is approximately the same for PSRs B1937 + 21 and J1744 − 1134. However, in the presence of phenomena related to some critical mass, like the spontaneous scalarization

Figure 9. Comparisons of our limits on $|\hat{\alpha_2}|$ with that from the Solar system [47]. The curves show the CLs to statistically reject such an $|\hat{\alpha_2}|$ according to the measurements from PSR B1937 + 21 (blue dashed line), PSR J1744 − 1134 (red dotted line), and their combination (black solid line). The Solar system constraint (2) on the weak-field $\alpha_2$ [47] is illustrated as the gray region, and the combined limit (15) at 95% CL is also indicated.
discovered in the scalar–tensor theory [14], even a small difference in masses does not allow such an assumption (see [1, 16, 22] for constraints on such critical phenomena). Therefore, the comparison between (2), (6), (7) and (15) is only phenomenological. More strictly, they measure different aspects of gravity under different circumstances, such as the gravitational environments of the Sun, the Sun–Earth–Moon orbital dynamics, the pulsar-white dwarf orbital dynamics, and the solitary pulsars.

The main result of the paper (15) is phenomenological in the PPN framework, nevertheless, it is relevant to some alternative gravity theories with local Lorentz invariance violation, like the Hořava–Lifshitz gravity [9, 30], the Einstein-Æther theory [21, 32] and the TeVeS theory [7, 52]. A detailed comparison with these alternative gravity theories has to account for possible strong-field dependences. Such an analysis is beyond the scope of this paper.

As one can see from figures 8 and 9, the improvement of the combined limit over that from a single pulsar is significant. The combined limit (15) is ten times better than the one solely obtained from PSR B1937 + 21 or PSR J1744 − 1134. This reveals the probabilistic consideration inherent as well as the directional dependence of PFEs. When pulsars located differently and moving with different velocities in different directions are used, the constraint on PFEs is much stronger than solely from one object. It is also demonstrated in [65] for binary pulsars under a similar concept, called ‘PFE antenna array’. In the \( \hat{\alpha}_2 \) test, we include two solitary pulsars with highest figure of merit (see below). Through our simulations, we found that by including more pulsars with lower figure of merit, the improvement is not significant. However, two pulsars are the minimum requirement to suppress the long tails discussed earlier.

The figure of merit of the \( \hat{\alpha}_2 \) test proposed here can be extracted from (12). In general, it depends on the upper limit on the change of pulse width, the spin period, the ‘absolute’ velocity \( \mathbf{w} \), the pulsar’s spin orientation with respect to \( \mathbf{w} \) and the line of sight, and also some emission properties encoded in \( \mathcal{A} \). After dropping complicated dependence, one can see that the power of the test is roughly proportional to \( |P(\mathbf{w}/d\mathbf{t})^{\text{upper}}|^{-1} \), where \( (\mathbf{w}/d\mathbf{t})^{\text{upper}} \) is the upper limit of the change in the pulse width and \( P \) is the pulsar spin period. Hence one can see that the solitary pulsars with short spin period and smaller \( (\mathbf{w}/d\mathbf{t})^{\text{upper}} \) are more useful in setting a tight constraint of \( \hat{\alpha}_2 \).\(^{10}\) The quantity \( (\mathbf{w}/d\mathbf{t})^{\text{upper}} \) can depend on different factors, like the luminosity of the emission, and the pulse width. If we conservatively assume no improvement in the observational technologies, it scales roughly as \( T_{\text{obs}}^{-3/2} \), where \( T_{\text{obs}} \) is the observational time span. Hence finding more pulsars with short spin period, and continuous observations on known MSPs both help in improving the \( \hat{\alpha}_2 \) limit. In the era of new telescopes, like the Five-hundred-meter Aperture Spherical Telescope [46] and the Square Kilometre Array [55], with more dedicated technologies, more pulsars are to be found for sure and data with better quality are guaranteed. On the other hand, many stable MSPs are also used in the PTA projects [20, 25, 28] and being observed continuously (like PSRs B1937 + 21 and J1744 − 1134), hence the \( \hat{\alpha}_2 \) test proposed here can be achieved as a byproduct from other science programs, and is expected to improve continuously.

In summary, we proposed to use the non-detection of spin precession of solitary pulsars from pulse profile analysis to constrain the strong-field PPN parameter \( \hat{\alpha}_2 \). Two solitary pulsars, PSRs B1937 + 21 and J1744 − 1134, are used to get a combined limit of \( |\hat{\alpha}_2| < 1.6 \times 10^{-9} \) at 95% CL (see (15)), which is significantly better than the limit (2) obtained from the Solar system [47]. Moreover, the \( \hat{\alpha}_2 \) test with solitary pulsars is based on regular observations over the whole time span, excluding for instance a 360° precession between the starting and the end

\(^{10}\) However, in general, all dependences in (12) contribute; for example, although PSR B1937 + 21 has a higher \( P(\mathbf{w}/d\mathbf{t})^{\text{upper}} \) compared with PSR J1744 − 1134, it gets a slightly worse constraint on \( \hat{\alpha}_2 \) than PSR J1744 − 1134 because of a significantly larger \( \mathcal{A} \).
points. In contrast to the Solar limit, our test will continuously improve the limit from finding new pulsars as well as long-term regular observations on known pulsars.

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