Closing a spontaneous-scalarization window with binary pulsars

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Abstract
Benefitting from the unequaled precision of the pulsar timing technique, binary pulsars are important testbeds of gravity theories, providing some of the tightest bounds on alternative theories of gravity. One class of well-motivated alternative gravity theories, the scalar–tensor gravity, predict large deviations from general relativity for neutron stars through a nonperturbative phenomenon known as spontaneous scalarization. This effect, which cannot be tested in the Solar System, can now be tightly constrained using the latest results from the timing of a set of seven binary pulsars (PSRs J0348+0432, J1012+5307, J1738+0333, J1909–3744, J2222–0137, J0737–3039A, and J1913+1102), especially with the updated parameters of PSRs J2222–0137, J0737–3039A and J1913+1102. Using new timing results, we constrain the neutron star’s effective scalar coupling, which describes how strongly neutron stars couple to the scalar field, to a level of $|\alpha_A| \lesssim 6 \times 10^{-3}$ in a Bayesian analysis. Our analysis is thorough, in the sense that our results apply to all neutron star masses and all reasonable equations of state of dense matters, in the full relevant parameter space. It excludes the possibility of spontaneous scalarization of neutron stars, at least within a class of scalar–tensor gravity theories.

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

1. Introduction

In Einstein’s theory of general relativity (GR) [1], gravitational waves (GWs) have a quadrupole structure and, to the leading order, binary systems lose their orbital energy and angular momentum via GWs according to the quadrupole formula [2, 3]. This has been verified experimentally since the detection of orbital decay caused by the emission of GWs in the radio pulsar-neutron star (PSR-NS) system PSR B1913+16, the famous Hulse–Taylor binary discovered in 1974 [4, 5]. Indeed, the observed orbital decay matches the GR expectation for the emission of quadrupolar waves within experimental precision [6]; for a review, see reference [7].

However, discoveries like cosmological inflation, dark energy, and dark matter have greatly motivated the development of many alternative theories of gravity [8]. Among the best studied—and among the few that can make testable predictions for binary pulsars—are the $T_1(\alpha_0, \beta_0)$ family of mono-scalar–tensor theories of gravity, proposed by Damour and Esposito-Farèse [9] (hereafter, the DEF gravity). These include the Jordan–Fierz–Brans–Dicke gravity [10–13] as the special sub-class with $\beta_0 = 0$. These and other scalar–tensor gravity (STG) theories predict that, in addition to the quadrupolar GWs predicted by GR, there are additional monopolar and dipolar components to GW emission arising from scalar fields. Consequently, binary star systems consisting of scalarized bodies evolve faster in their orbital decay. Here the dipolar GW emission is of particular importance since it enters the equations of motion of a two-body system already at the 1.5 post-Newtonian (PN) level [14]. In contrast, the contribution of quadrupolar radiation corresponds to 2.5 PN at the lowest order.

In the presence of a scalar field, the amount of dipolar GW emission depends strongly on the difference between the effective scalar couplings, denoted as $\alpha_A$ for body ‘A’, of the binary components. The quantity $\alpha_A$ measures the effective coupling strength between the scalar field and the scalarized star. Depending on the parameters of the specific STG theory, $\alpha_A$ can be of order unity for scalarized NSs even if its weak-field limit, $\alpha_0$, is very close to zero [15]. This nonperturbative effect is known as ‘spontaneous scalarization’ [9]. Because $\alpha_0$ is small, such a possibility in the strong-field regime cannot be tested with Solar System experiments. Recently, references [16–18] have investigated the constraints on dipolar GW emission using GW observations from the coalescences of compact objects [19–21].

The close agreement between the measured orbital decay of the Hulse–Taylor pulsar and the GR prediction for quadrupolar GW emission had already introduced, in the mid-1990s, important constraints on DEF gravity [22]. However, given the vastly different gravitational binding energies of NSs and white dwarfs (WDs), it was already clear that in general they have very different couplings to the scalar field of the theory. This difference results in a potentially observable contribution to the orbital period change of PSR-WD systems arising from the emission of dipolar GWs, or in its absence, very tight constraints on STG theories [22–24].

Indeed, some of the most stringent limits on dipolar GW emission and DEF gravity obtained since then have been derived from the measurements of orbital decay of PSR-WD systems. Two prime examples are PSRs J1738+0333 [25, 26] and J0348+0432 [27]: their observed orbital decays conform to the GR expectation within experimental precision and no dipolar
GW emission is detected [28, 29]. This also has considerably tightened the constraints on the existence of spontaneous scalarization.

Given the comparably large difference in NS masses between PSRs J1738+0333 and J0348+0432 (1.47±0.07 M⊙ [25] and 2.01 ± 0.04 M⊙ [27] respectively), their limits on dipolar GW emission do not exclude spontaneous scalarization entirely: as first pointed out by Shibata et al [30], for certain equations of state (EOS) for matter at densities above that of the atomic nucleus, particularly those that predict a maximum NS mass near 2 M⊙, spontaneous scalarization can still occur for NS masses in between those of PSRs J1738+0333 and J0348+0432. This is the ‘mass gap of spontaneous scalarization’, which approximately extends in the NS mass interval [1.60 M⊙, 1.95 M⊙], as suggested by Shao et al [23] in 2017.

To fill this gap, similar radiative tests [17, 23] have been conducted for NSs with masses within this mass gap, like the PSR-WD systems, PSRs J1012+5307 [32–34], J1909−3744 [34–36], and J2222−0137 [37]. Although by 2017 such systems were already useful, they were not yet as constraining as the tests for PSRs J1738+0333 and J0348+0432 [17, 23], and for that reason the mass gap of spontaneous scalarization remained open.

As we show in this paper, the situation has now changed because of a set of new experimental results which we list in section 2. In a Bayesian analysis of these results in section 3, we find an upper limit in section 4 on the scalar coupling to any NSs of |αA| ≲ 6 × 10^{-3}. This means that spontaneous scalarization—the prominent non-perturbative deviation from GR predicted by STG theories—is now ruled out for all NS masses of all existing EOSs at such a level, at least within a class of massless STG theories that we consider.

2. New experimental results

We now list the recent experimental results of interest to our investigation. One of the novelties is that two special PSR-NS systems have become useful for our tests, which were previously dominated by PSR-WD systems.

First, the previous measurement of the orbital decay of PSR J1012+5307 is now complemented by improved spectroscopic mass measurements [38] and a new, more precise distance measurement [39]. These allow the determination of more precise limits on the dipolar GW emission in this system.

Second, the parameters for PSR J1909−3744 have also been updated [40].

Third, and more importantly, the masses and the variation of the orbital period of PSR J2222−0137 are now measured, respectively, 6 and 12 times more precisely than in the previous study of this system [41].

Fourth, measurements of the component masses and the rate of orbital decay for PSR J1913+1102, a recently discovered PSR-NS system [42], are now available [43]. This system is important because the pulsar’s mass (1.62 ± 0.03 M⊙) is within the mass gap. Furthermore, the NS companion is much lighter, 1.27 ± 0.03 M⊙, than the visible pulsar. This mass asymmetry results in a comparably large asymmetry in the compactness \( C_A \equiv GM_A/c^2R_A \) of the two components (\( C_c \approx 0.75C_p \)), where \( R_A \) denotes the radius of body A, and subscripts ‘p’ and ‘c’ refer to the pulsar and its companion respectively. In the strong gravitational fields of a NS, \( \alpha_A \) depends in a strongly non-linear way on \( C_A \), which can lead to an order-one asymmetry in the \( \alpha_A \) of the components of this binary and therefore significant dipolar GW emission.

\( \text{\footnotesize{7}} \) For extremely stiff EOSs spontaneous scalarization could in principle occur in NS masses above 2 M⊙. Such EOSs, however, have been excluded in the meantime by the binary NS merger event GW170817 [31].
Table 1. Relevant binary parameters of the three PSR-WD systems: PSR J0348+0432 [27], J1012+5307 [34, 38, 39], and J1738+0333 [25, 26]. The italic parameters \( m_{\text{obs}}^p \) are derived from the observed mass ratio \( q \) and \( m_{\text{obs}}^c \), obtained from high-resolution spectroscopy observations of the WDs in combination with WD models. The standard 1 – \( \sigma \) uncertainties are given in the units of the least significant digits in parentheses.

| Pulsar     | \( \text{J0348+0432} \) | \( \text{J1012+5307} \) | \( \text{J1738+0333} \) |
|------------|-------------------------|------------------------|---------------------|
| Orbital period, \( P_b \) (d) | 0.102424062722(7) | 0.604672722901(13) | 0.3547907398724(13) |
| Eccentricity, \( e \) | 2.4(10) \( \times 10^{-6} \) | 1.30(16) \( \times 10^{-6} \) | 3.4(11) \( \times 10^{-7} \) |
| Observed \( P_b \), \( P_b^{\text{obs}} \) (fs s\(^{-1} \)) | \(-273(45)\) | \(61(4)\) | \(-17.0(31)\) |
| Excess \( P_b \), \( P_b^{\text{ex}} \) (fs s\(^{-1} \)) | \(-15(46)\) | \(4.8(51)\) | \(3.15(369)\) |
| Mass ratio, \( q \equiv m_{\text{obs}}^p / m_{\text{obs}}^c \) | 11.70(13) | 10.44(11) | 8.1(2) |
| Pulsar mass, \( m_{\text{obs}}^p \) (M\(_{\odot}\)) | 2.01(4) | 1.72(16) | 1.47(7) |
| Companion mass, \( m_{\text{obs}}^c \) (M\(_{\odot}\)) | 0.172(3) | 0.165(15) | 0.181(8) |

Table 2. Same as table 1, but for two PSR-WD systems where the `observed` masses have been obtained from the observed Shapiro delay assuming GR: PSRs J1909−3744 [40] and J2222−0137 [41].

| Pulsar     | \( \text{J1909−3744} \) | \( \text{J2222−0137} \) |
|------------|-------------------------|------------------------|
| Orbital period, \( P_b \) (d) | 1.533449474305(5) | 2.44576437(2) |
| Eccentricity, \( e \) | 1.15(7) \( \times 10^{-7} \) | 0.00038092(1) |
| Observed \( P_b \), \( P_b^{\text{obs}} \) (fs s\(^{-1} \)) | \(-510.87(13)\) | \(250.9(76)\) |
| Excess \( P_b \), \( P_b^{\text{ex}} \) (fs s\(^{-1} \)) | \(-1.7(78)\) | \(-0.3(76)\) |
| Pulsar mass, \( m_{\text{obs}}^p \) (M\(_{\odot}\)) | 1.492(14) | 1.831(10) |
| Companion mass, \( m_{\text{obs}}^c \) (M\(_{\odot}\)) | 0.209(1) | 1.319(40) |

Fifth, new measurements have become available from the timing of PSR J0737−3039A [44]. This system is important because the new measurement of its orbital decay is 250 times more precise than the previously published value [45], and about 25 times more precise than the latest limit on the Hulse–Taylor binary [6]. This extreme precision more than compensates for the relatively small mass difference between the two NSs in the system and the fact that none of them is in the mass range where spontaneous scalarization can still occur, which starts at 1.6 M\(_{\odot}\) for most EOSs.

Overall, we collect the relevant updated parameters from these pulsars in three tables: the relevant parameters for the five asymmetric PSR-WD binaries are shown in tables 1 and 2, and the relevant parameters from the two PSR-NS systems are listed in table 3. The seven binary pulsar systems collected in these three tables densely cover a wide NS-mass range, from 1.25 M\(_{\odot}\) to about 2.0 M\(_{\odot}\).\(^8\) Quite generally, given the rather large uncertainty in our knowledge of the EOS of NS matter, such a dense coverage is key for constraining certain highly non-linear strong-field deviations from GR, like spontaneous scalarization in DEF gravity.

3. The Bayesian inference framework

Here, we investigate the spontaneous scalarization in the DEF theory and obtain the bounds on scalar couplings \( \alpha_A \) from the observed binary pulsar parameters with the help of Bayesian

\(^8\) It is quite likely that 2 M\(_{\odot}\) might be the upper end of the so far measured NS masses. There are arguments that the mass of the current record holder PSR J0740+6620 [46] does not (significantly) exceed 2 M\(_{\odot}\). [47].
Table 3. Same as table 1, but for two PSR-NS systems: PSRs J1913+1102 [43] and J0737–3039A [44]. The given ‘observed’ masses are taken from references [43, 44] respectively, where they have been determined from the two most constraining observed post-Keplerian parameters assuming GR.

| Pulsar          | J1913+1102 | J0737–3039A |
|-----------------|------------|-------------|
| Orbital period, $P_b$ (d) | 0.206 252 3345(2) | 0.102 251 559 2973(10) |
| Eccentricity, $e$ | 0.089 531(2) | 0.0877 770 23(61) |
| Observed $\dot{P}_b$, $\dot{P}_{obs}^b$ (fs s$^{-1}$) | -480(30) | -1247.920(78) |
| Excess $\dot{P}_b$, $\dot{P}_{xs}^b$ (fs s$^{-1}$) | -34.0(285) | 0.05(8) |
| Einstein delay parameter, $\gamma_E^{obs}$ (ms) | — | 0.384 045(94) |
| Pulsar mass, $m_p^{obs}$ (M$_\odot$) | 1.62(3) | 1.33818(1) |
| Companion mass, $m_c^{obs}$ (M$_\odot$) | 1.27(3) | 1.24887(1) |

We collect the latest observations of seven binary pulsars and perform the Markov-chain Monte Carlo (MCMC) technique with EOSs to update the posterior distributions of the relevant parameters. As the likelihood function is evaluated over and over, these distributions will converge to the proper and stable results, which are consistent with astrophysical observations.

To derive the constraints on the DEF theory, we need to solve the structure of NSs, which depend on the EOSs. References [27, 46] indicate that the maximum mass of a NS should be somehow greater than 2.0 $M_\odot$. Therefore, we select 13 EOSs that are consistent with this condition in our work. In addition, recently, Dietrich et al [48] combined the multi-messenger observations of GW170817, the x-ray and radio measurements of pulsars, and nuclear-theory computations to constrain the NS’s properties. As a result, they showed the radius of a 1.4 M$_\odot$ NS is $R = 11.75^{+0.86}_{-0.81}$ km at the 90% confidence level (CL); for other constraints, see reference [49] and references therein. The EOSs we use, except for WFF1 and BSk22, are all supported by the results from reference [48]. The mass-radius relations are shown in figure 1 (see reference [50] for a review).

Here, following the method in references [17, 23, 51], we apply MCMC techniques to obtain bounds on the spontaneous scalarization. Given the priors, MCMC simulations evaluate the likelihood functions $\sim 10^5–10^6$ times, and then derive the posteriors that are consistent with observations. We use the following logarithmic likelihood function,

$$\ln L_{PSR} = -\frac{N_{PSR}}{2} \sum_{i=1}^{N_{PSR}} \left[ \frac{(m_p - m_{p}^{obs})^2}{\sigma_{m_p^{obs}}} + \frac{(m_c - m_{c}^{obs})^2}{\sigma_{m_c^{obs}}} + \frac{(\dot{P}_{b}^{dipole} - \dot{P}_{b}^{obs})^2}{\sigma_{\dot{P}_b^{obs}}} + \frac{(\gamma_E - \gamma_E^{obs})^2}{\sigma_{\gamma_E^{obs}}} \right]_i.$$

(1)

Here, we use $N_{PSR}$ binary pulsars, including their excess orbital decay $\dot{P}_{b}^{obs}$, Einstein delay $\gamma_E^{obs}$, as well as binary masses $m_{p}^{obs}$ and $m_{c}^{obs}$ ($P_{b}^{obs}$ is the observed orbital decay for each system $P_{b}^{obs}$ minus the sum of the kinematic effects caused by the Galactic acceleration and the proper motion of the system and the prediction of GR for its orbital decay [52, 53]). Note that the $\gamma_E$ term is only included for PSR J0737–3039A [44]. $\dot{P}_{b}^{dipole}$ is the dipolar contribution to the orbital decay from the scalar field. We use the DEF theory as an example. The prior distribution for the theory parameter $\log_{10} |\alpha_0|$ is chosen to be flat in the range $[-5.3, -2.5]$. We choose
the uniform prior on the other theory parameter $-\beta_0$ in the range $[4.0, 4.8]$. The choice is the same as reference [17].

The usage of the ‘observed’ masses from tables 1–3 in the combined test, i.e. equation (1), requires some justification, since they were derived on the basis of GR (or simply Newtonian gravity in case of the WD models).

WDs are weakly self-gravitating bodies ($\alpha_A \approx \alpha_0$), and therefore masses obtained from spectroscopy or Shapiro delay are practically identical to the GR masses. Differences are of the order $\alpha_0^2$, which is globally constrained to $\lesssim 10^{-5}$ by the Cassini experiment [54, 55], and to $\lesssim 10^{-7}$ by pulsars in the $\beta_0$ range of interest here (see e.g. reference [44]). Given that the mass ratio $q$ in table 1 is the same in GR and STG (see e.g. reference [54]) and that the mass function (used to derive the pulsar mass from the observed Shapiro shape parameter in table 2) is very close to GR due to the small $\alpha_0$, we can safely use the GR pulsar masses for all PSR-WD systems.

For the two PSR-NS systems in table 3, the argument is less obvious. In a single system test, we have explored the $\alpha_0 - \beta_0$ space allowed by the observed post-Keplerian parameters published in references [43, 44] (cf references [22, 56] for the details of the method). For all EOSs used here, we find that for $\beta_0 \leq -4$ the masses determined by DEF gravity deviate $\lesssim 2 \times 10^{-3}$ $M_\odot$ for PSR J1913+1102 and $\lesssim 10^{-6}$ $M_\odot$ for PSR J0737−3039 from those calculated with GR. In both cases this is an order of magnitude smaller than the corresponding (measurement) uncertainties.

To summarize, for the parameter space of interest in this paper, for all seven systems the deviations from the GR masses are everywhere considerably smaller than the corresponding

\begin{figure}
\centering
\includegraphics[width=\textwidth]{mass_radius_relation.png}
\caption{The mass-radius relations of NSs in the theory of GR for different EOSs we adopt. The solid lines represent EOSs that are consistent with the result from reference [48], and the EOSs that deviate are marked as dashed lines. The green and red regions depict the mass constraints with 1-$\sigma$ uncertainty from PSRs J0348+0432 [27] and J0740+6620 [46], respectively.}
\end{figure}
Figure 2. The 90% CL upper limits on the effective scalar coupling $\alpha_A$. On the left, we plot the limits obtained with the current experimental results for the pulsars considered by reference [23]. On the right, we see the limits obtained with all seven pulsars in our sample.

mass uncertainties. Hence, the GR masses in tables 1–3 can be used directly in the combined analysis.

4. Limits on scalar–tensor gravity

In many cases, STG theories predict for the systems listed above a significant scalar dipole and consequently a considerable loss of orbital energy via dipolar GWs [55]. For that reason, the close agreement of the intrinsic $\dot{P}_b$ with GR can be used to constrain these theories [28]. We focus on the DEF gravity as an example. In these theories, the contribution of dipolar radiation to $\dot{P}_{xs}^b$ is, to leading order, given by

$$\dot{P}_{dipole}^b = \frac{4\pi^2 G_s}{c^3 P_b} \frac{m_p m_c}{m_p + m_c} \frac{1 + e^2/2}{(1 - e^2)^{5/2}} \left(\alpha_p - \alpha_c\right)^2,$$

where $G_s = G_N/(1 + \alpha_0^2)$ denotes the bare gravitational constant [57], $\alpha_p$ and $\alpha_c$ are the effective scalar couplings of the pulsar and the companion, and all other relevant quantities can be found in tables 1–3.

The limits on $T_1(\alpha_0, \beta_0)$ determined using the above seven binary pulsars in a combined, multi-EOS, multi-pulsar analysis are shown in figure 2. These cover the whole parameter space where spontaneous scalarization can occur, and the full range of observed NS masses. For a comparison, we repeat the same exercise without the recent results on the intermediate-mass pulsars.

In this and the following figures, the black/red/blue triangles are the upper limits at 90% CL from individual pulsars. For parameters other than $\dot{P}_{xs}^b$, we use their central values listed in tables 1–3. For $\dot{P}_{xs}^b$, we conservatively use a Gaussian function as its probability density function (PDF),

$$\text{PDF of } \dot{P}_{xs}^b = \begin{cases} N \left(0, (\dot{P}_{xs}^b)^2 + (\sigma_{\dot{P}_{xs}^b})^2\right), & \dot{P}_{xs}^b > 0, \\ N \left(\dot{P}_{xs}^b, (\sigma_{\dot{P}_{xs}^b})^2\right), & \dot{P}_{xs}^b \leq 0. \end{cases}\quad (3)$$
Table 4. Different scenarios for investigating the upper limits on $\alpha_A$.

| Scenarios       | J0348 | J1738 | J1909 | J1012 | J2222 | J1913 | J0737 |
|-----------------|-------|-------|-------|-------|-------|-------|-------|
| NSWWD3s         | ✓     | ✓     | ✓     | —     | —     | —     | —     |
| NSWWD4s         | ✓     | ✓     | ✓     | ✓     | —     | —     | —     |
| NSWWD5s         | ✓     | ✓     | ✓     | ✓     | ✓     | —     | —     |
| NSWWD5s+J1913   | ✓     | ✓     | ✓     | ✓     | ✓     | ✓     | —     |
| J0737           | —     | —     | —     | —     | —     | ✓     | —     |
| NSWWD5s+J1913+J0737 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

In addition, for five PSR-WD binaries, the triangles are the values $(\alpha_p - \alpha_c) = \alpha_p$. The limits on $\alpha_A$ from our combined analysis of binary pulsars in Bayesian framework for different EOSs are shown as solid/dotted lines.

For comparison, we also show the result of the difference in effective scalar coupling $\Delta \alpha$ from GW170817 [58]. In addition, for future GW observatories, advanced LIGO (aLIGO) at its design sensitivity, Cosmic Explorer (CE), and Einstein Telescope (ET), the expected limits on the $\Delta \alpha$, i.e. the most optimistic limits on $\alpha_A$, are given via the method of Fisher information matrix. For them, a binary NS merger with a 1.25 M$_\odot$ companion at a luminosity distance of 200 Mpc was assumed (see e.g. references [23, 59]). Note that all upper limits on the effective scalar couplings $\alpha_A$, as well as uncertainties in the NS masses are plotted at 90% CL. The figure has two panels for easy comparison of different pulsar sets.

Our main result comes out very clearly in figure 2: the inclusion of the new systems with intermediate NS masses (PSRs J1913+1102, J1012+5307 and J2222–0137), plus the precise results for PSR J0737–3039A, have greatly constrained spontaneous scalarization for the NS mass range where it was still previously allowed, say in the range of [1.50 M$_\odot$, 2.0 M$_\odot$]. Within this mass range, we find that $|\alpha_A| \gtrsim 0.006$ is excluded with significance larger than 90%. Furthermore, our analysis shows that although our limits on $\alpha_A$ cannot be improved by the future advanced LIGO, even smaller deviations will be detectable by the next generation of ground-based GW detectors (i.e. ET and CE), which therefore have the potential to significantly improve on these new limits from binary pulsars.

In order to understand the ability to constrain the parameter space from different pulsars, we now investigate limits on $\alpha_A$ using different sets, listed in table 4.

For each of those sets, we performed the MCMC technique for all the EOSs we adopted, as described above. The results are shown in figures 3–5.

In figure 3, the left panel shows the constraints at 90% CL with only PSRs J1738+0333, J1909–3744 and J0348+0432 (same as the left panel in figure 2), the right panel shows the effect of introducing PSR J1012+5307. As we can see, for all the 13 EOSs we consider [60], the inclusion of PSR J1012+5307 narrows down the mass range of spontaneous scalarization and improves the upper limits on $\alpha_A$ to $|\alpha_A| \lesssim 0.1$. The individual bound from PSR J1012+5307 is competitive, but due to the large uncertainty of its mass, it introduces only weak constraints to the global upper limits on $\alpha_A$. Therefore, a wide $m_A \in [1.60 M_\odot, 1.95 M_\odot]$ scalarization window remains open.

Figure 4 further introduces two binaries, PSRs J2222–0137 and J1913+1102, which are shown in the left and right panels, respectively. With the help of these binaries, on the whole mass range, $|\alpha_A|$ has been constrained to be $\lesssim 10^{-2}$ with 90% confidence, which roughly equals to the (optimistic) limit expected from future aLIGO for a binary NS merger at a luminosity distance of 200 Mpc [61]. The significantly improved constraints result directly from these two pulsars having well determined masses that are well within the mass gap.
identified in figure 3. These two pulsars contribute fundamentally to the closure of the gap of mass scalarization.

After performing Bayesian analysis for J0737 (see the left panel in figure 5), we find that, for the soft EOS WFF1, PSR J0737−3039A puts the tightest bound on $\alpha_A$. The reason is that NS masses of PSR J0737−3039 are close to the scalarization window of WFF1. However, for EOSs with higher scalarization masses, PSR J0737−3039A provides by itself no significant constraints, owing to the low masses of the two NSs in that system. Despite that, even for those EOSs, the inclusion of PSR J0737−3039A in the joint analysis with all other systems is still useful, with lower limits on $\alpha_A$ for the whole NS mass interval, as we can see from a comparison of the right panel (the same as in figure 2) with the right panel of figure 4. This improvement results from a tighter limit on $\dot{P}_b$ of PSR J0737−3039A.
5. Conclusions

In this paper we have used seven binary pulsars in total to further constrain the NSs’ effective scalar coupling ($\alpha_A$) possible within the DEF gravity, in particular for values of $\beta_0$ between $-4.8$ and $-4.0$ where such theories predict strong-field spontaneous scalarization, leading to large scalar charges. In this region, and by extension in the whole parameter space of DEF gravity, we find $|\alpha_A| \lesssim 0.006$. This excludes spontaneous scalarization for the observed range of NS masses, and applies to the full range (from soft to stiff) of allowed EOSs.

These conclusions confirm, in their broad lines, a recent analysis [63], but do so much more thoroughly. That work reaches the conclusion that the scalarization gap is closed based solely on the new experimental results of PSR J1012 + 5307 and especially PSR J2222 − 0137, and by analyzing a limited set of EOSs. Furthermore, in that study the effective scalar couplings are obtained without considering the uncertainties on the masses of the components of these binaries. If we take these uncertainties into account, within a wider set of EOSs, we can see (in the left panel of figure 4) that, for some EOSs, a limited amount of spontaneous scalarization is still possible for NS masses around $1.7 M_\odot$. It is only by including the recent results on two PSR-NS systems (PSRs J0737 − 3039A and J1913 + 1102) that we can close this gap for all NS masses and EOSs considered in this work. Nevertheless, the analysis of reference [63] is in its general aspects significant, particularly in the clear identification of the importance of the new experimental results of PSR J2222 − 0137 [41].

More generally, the analysis presented here demonstrates the absence of (significant) dipolar radiation in binary pulsars for NS masses up to $\sim 2 M_\odot$. This should be of relevance for other gravity theories as well, in particular for theories that predict a similar mass-dependent dynamics for binary pulsars. To give an example, for sufficiently negative $\beta_0$, the Mendes–Ortiz gravity [64] also shows a strongly non-linear behavior (accompanied with very large scalar charges) in the mass range investigated here [65].

We do not want to leave it unmentioned that there are various ways to modify GR such that one can have strongly scalarized NSs ($\alpha_A \sim 1$) and, at the same time, avoid the limits

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9 We have ignored more exotic possibilities, like phase transitions (see e.g. reference [62]). Anyway, excluding certain fine-tuned scenarios, we do not expect a significant change to the constraints of DEF gravity presented here, given the dense coverage on NS masses used in our combined test.
obtained here. For instance, as already emphasized by Antoniadis et al [27], binary pulsar experiments are naturally insensitive to sufficiently short-range/massive fields. They can therefore not exclude spontaneous-scalarization scenarios like in massive DEF gravity [66–68], just to give an example. While the limits presented in figure 2 are already below what is expected for aLIGO, for short-range gravity phenomena related to NSs there is certainly a valuable complementarity between pulsar observations and GW astronomy (see also the discussions on dynamical scalarization in reference [23] and on finite-range scalar forces in reference [71]). Seen in a broader context, our best knowledge of gravity requires the combination of all possible experiments, and pulsar tests that cover such a wide range of NS masses certainly play an important role in this.

Finally, looking into the future, there are good prospects for a relatively fast improvement in the precision of the radiative tests with these binary pulsars, not only from the increase in their timing baselines, but also from the inclusion of new telescopes, like the FAST telescope [72–74] and MeerKAT array [75, 76], which are already taking data of much higher quality than was possible until now. These will further improve with the Square Kilometre Array [77, 78]. These improved limits will either tighten further the limits on dipolar GW emission, or lead to their detection and the falsification of GR.

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Data availability statement
The data that support the findings of this study are available upon reasonable request from the authors.

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10 See, however, the discussion in references [69, 70] on potential future pulsar tests to constrain certain short-range modifications of GR that evade current pulsar experiments.
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