The strong equivalence principle with the pulsar PSR J0337+1715

Based on: **G.Voisin**[1], I. Cognard, P. C. C. Freire, N. Wex, L. Guillemot, G. Desvignes, M. Kramer, and G. Theureau, A&A 638, A24 (2020) (hal-04113116, arxiv:2306.01336)
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Abstract: The strong equivalence principle (SEP), or universality of free fall, is one of the funding postulates of the theory of general relativity (GR). PSR J0337+1715 is the only known pulsar orbiting with two white dwarfs (WD) and exhibits good timing properties. These particularities have enabled SEP tests with a neutron star (NS) three orders of magnitude than previously possible. We expose here such results based on pulsar timing data from the Nançay radio telescope.

Introduction 1: Free-fall of a strongly self-gravitation body

SEP generalises the weak equivalence principle (WEP) to self-gravitating bodies [1]. It is a fundamental postulate of GR. While WEP can be tested by experiments such as MICROSCOPE [2], SEP requires astronomical bodies.

In the Solar system, SEP can be tested in the weak-field regime quantified by compacities $\varepsilon \ll 1$ with $\varepsilon = GM/Rc^2$ (G : gravitational constant; M: mass; R : radius; c: speed of light). For example, Lunar Laser Ranging (LLR) allows for exquisite SEP tests in the Earth-Moon-Sun system [3] with compacities $\varepsilon_{Moon} \sim 10^{-11}$, $\varepsilon_{Earth} \sim 10^{-10}$ and $\varepsilon_{Sun} \sim 10^{-6}$.

However, some theories predict departure from SEP mostly in the strong-field regime (e.g. [4]) requiring a compact object to be tested. Pulsars are both very compact with $\varepsilon_{NS} \sim 0.15$ (0.5 for Schwartzschild's black holes) and relatively easy to observe.

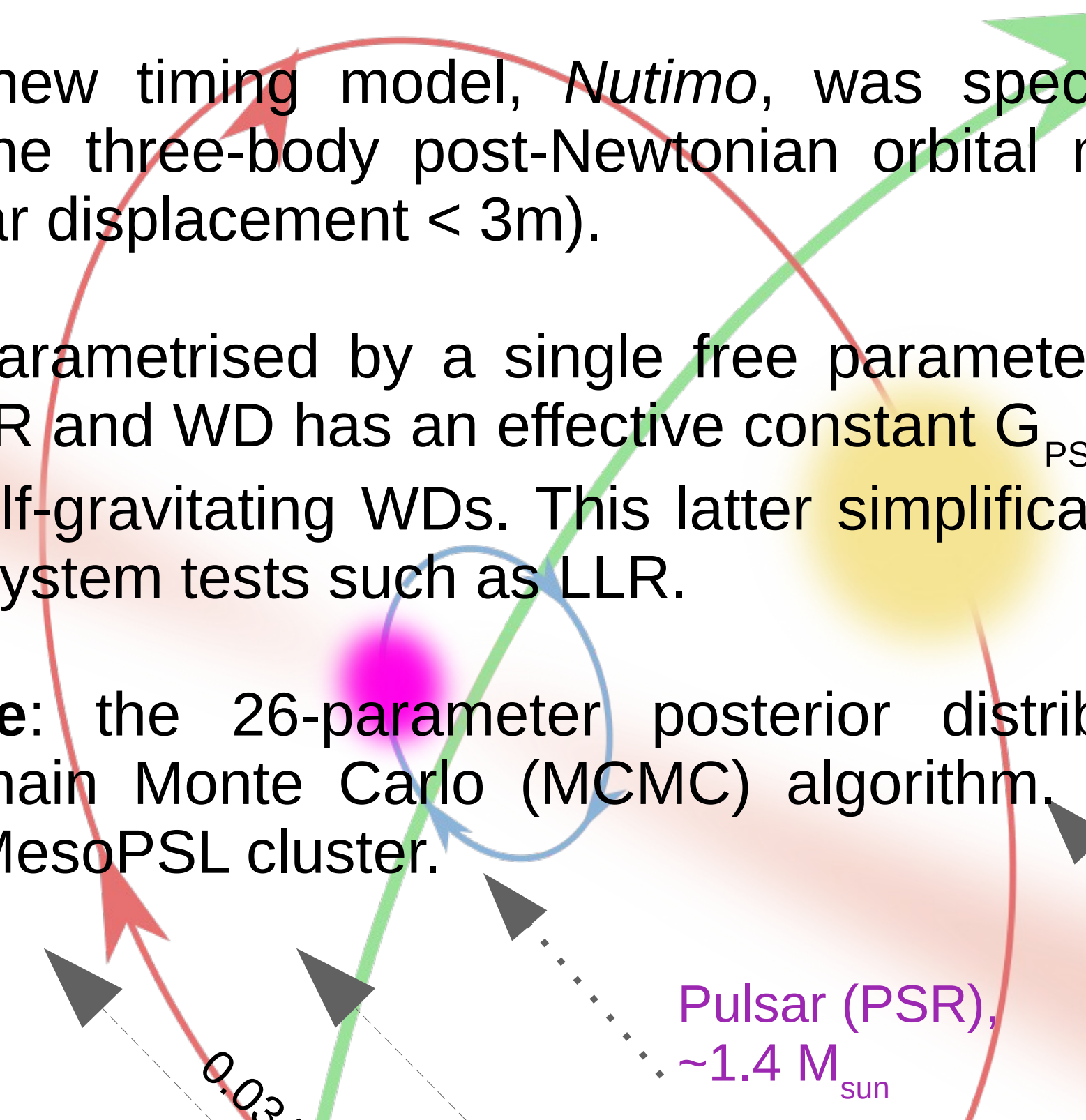
Methods:

Observations: The Nançay Radio Telescope (Observatoire de Paris) produced 9303 times of arrival in four 128MHz frequency bands between July 2013 and October 2019. Average uncertainty is ~2µs.

Timing model: A new timing model, *Nutimo*, was specifically developed in order to numerically compute the three-body post-Newtonian orbital motion and timing delays with accuracy < 10 ns (pulsar displacement < 3m).

SEP test: SEP is parametrised by a single free parameter Δ such that the gravitational interaction between PSR and WD has an effective constant $G_{PSR\text{-}WD} = (1+\Delta)G$, where G is used between the weakly self-gravitating WDs. This latter simplification is possible thanks to prior knowledge from Solar system tests such as LLR.

Bayesian inference: the 26-parameter posterior distribution was inferred using a parallelised Markov Chain Monte Carlo (MCMC) algorithm. Computation required approx. 200,000 CPUh on the MesoPSL cluster.



Introduction 2: Testing gravity with pulsar timing

Pulsars emit a narrow beam of radio waves rotating with the star producing extremely stable pulse which arrival times can be tracked at microsecond level.

In presence of a companion arrival times are shifted due to delays which are geometric (displacement of the pulsar) or relativistic (Shapiro, time dilation…). Orbital parameters and masses can be extracted from this signal with exquisite accuracy. Thanks to this, binary systems already provide excellent tests of GR at post-newtonian order (see Fig. 4 and [5]), but only triple systems can be sensitive to SEP violation at leading order.

PSR J0337+1715 is the only pulsar in a triple system with two WDs [6]. Its configuration is ideal for testing SEP [7].

Results 1: Pulsar timing and system characterisation

Post-fit timing residuals are shown in Fig. 1, showing excellent agreement with the model. Pulsar mass is 1.44(1) M_{sun}, 0.198(2) M_{sun} for the inner WD and 0.411(4) M_{sun} for the outer WD. Inner and outer orbital periods are 1.62940(3) days and 327.255(5) days resp. The whole corner plot is shown in Fig. 2.

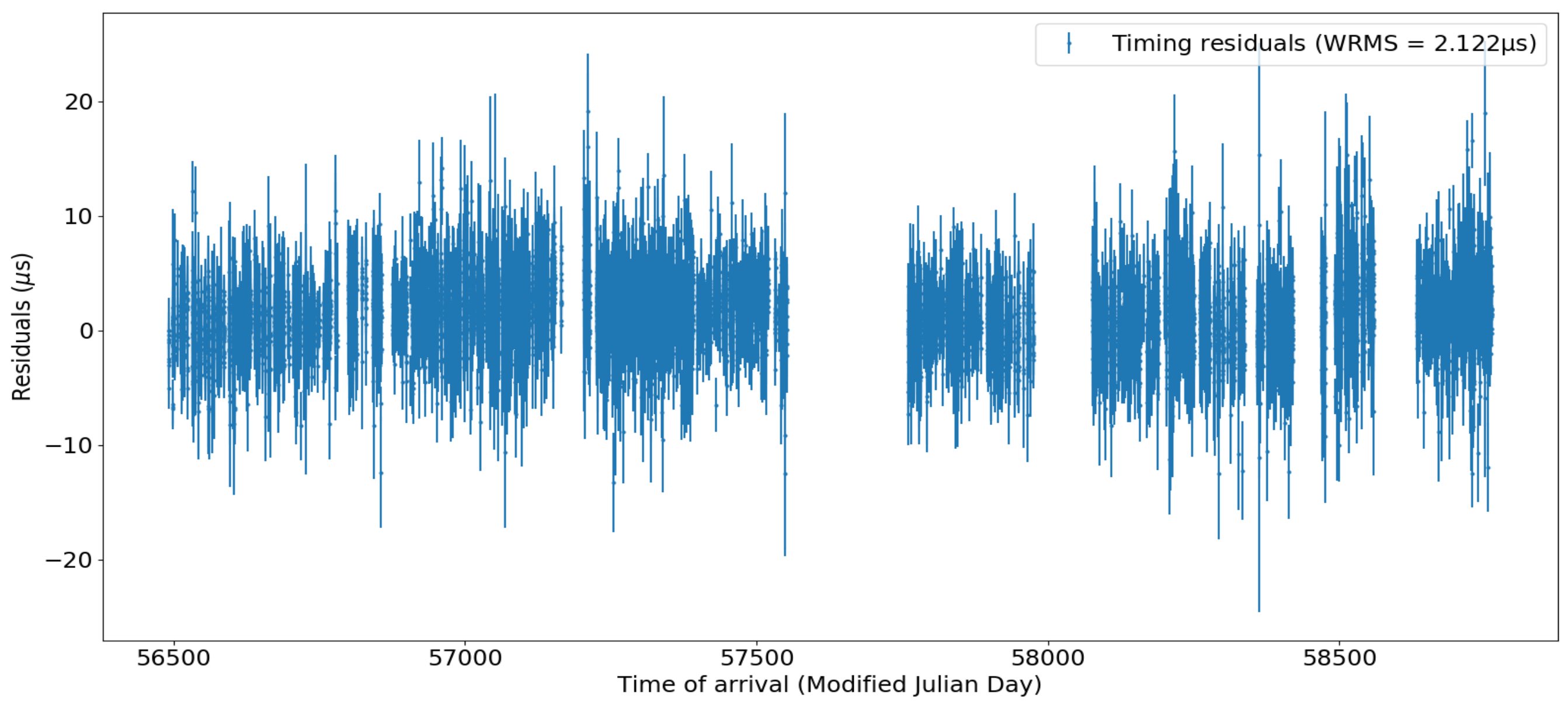


Fig. 1 : Post-fit timing residuals of PSR J0337+1715.

Results 2: Strong Equivalence Principle constrained

We obtain $|\Delta| < 2\times10^{-6}$ at 95% confidence level, Fig. 2. This is confirming the 2.6×10^{-6} independently obtained by [8].

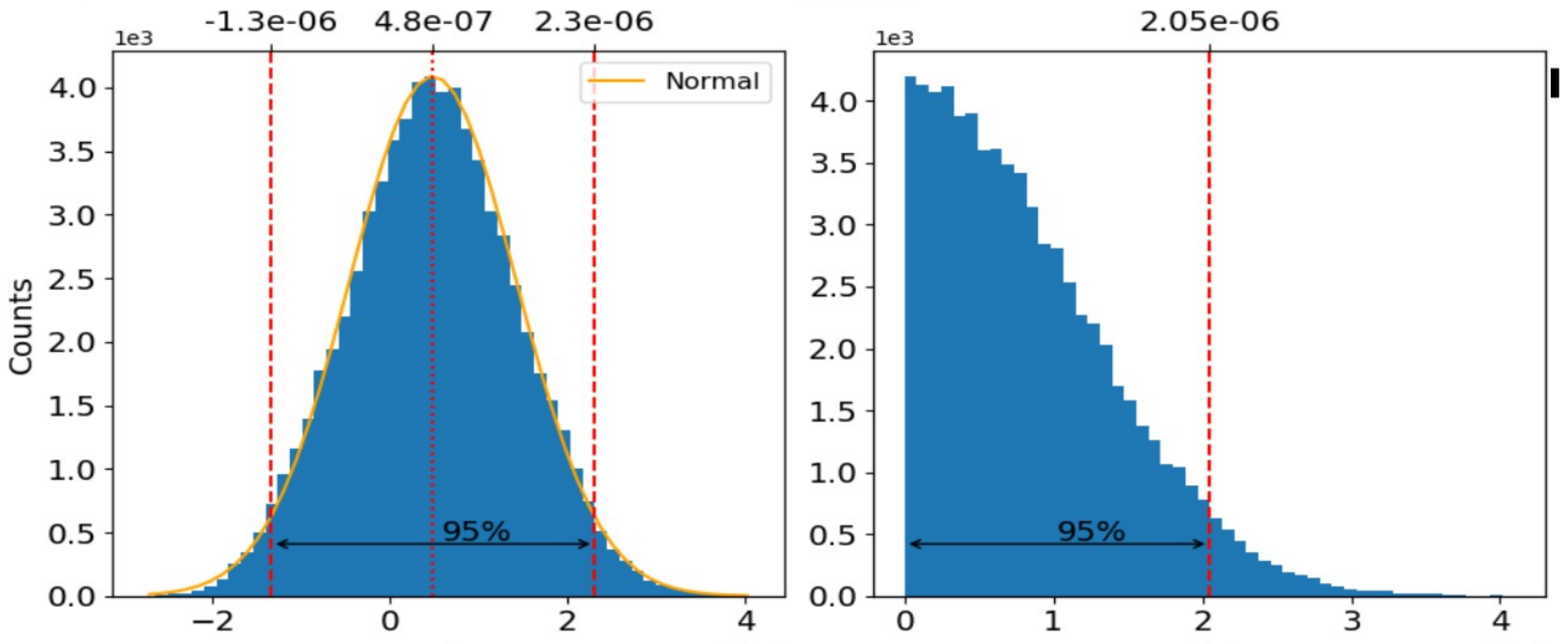


Fig 3 : Marginalised posterior distribution function of Δ sampled by MCMC (see Methods).

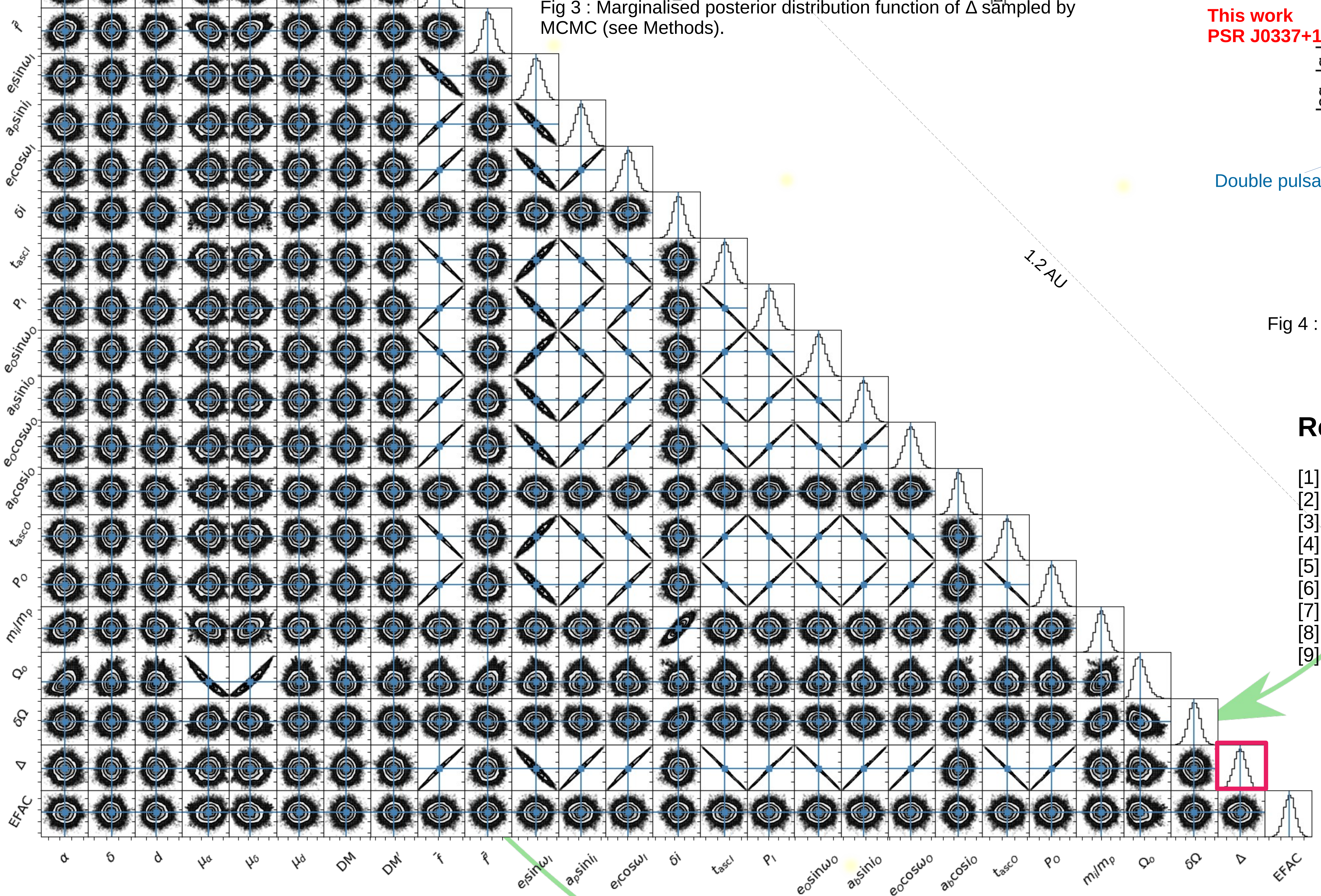


Fig 2 : Corner plot of the posterior distribution function of parameters of the fit. Along the diagonal are marginalised single parameter histograms. The histogram framed in red corresponds to the left panel of Fig. 3. Non-diagonal elements are two-parameter marginalised plots that exhibit correlations.

Results 3: Constraint on Damour-Esposito-Farèse (DEF) scalar-tensor theory [9]

In the strongly self-gravitating regime, generic approaches such as the parametrised post-newtonian frame are not possible and one needs to cast the constraints into a specific theory. The DEF theory depends on 2 parameters forming a plane in Fig. 4 where we see that pulsar tests limit most of the parameter space (keeping in mind they build upon Solar system tests).

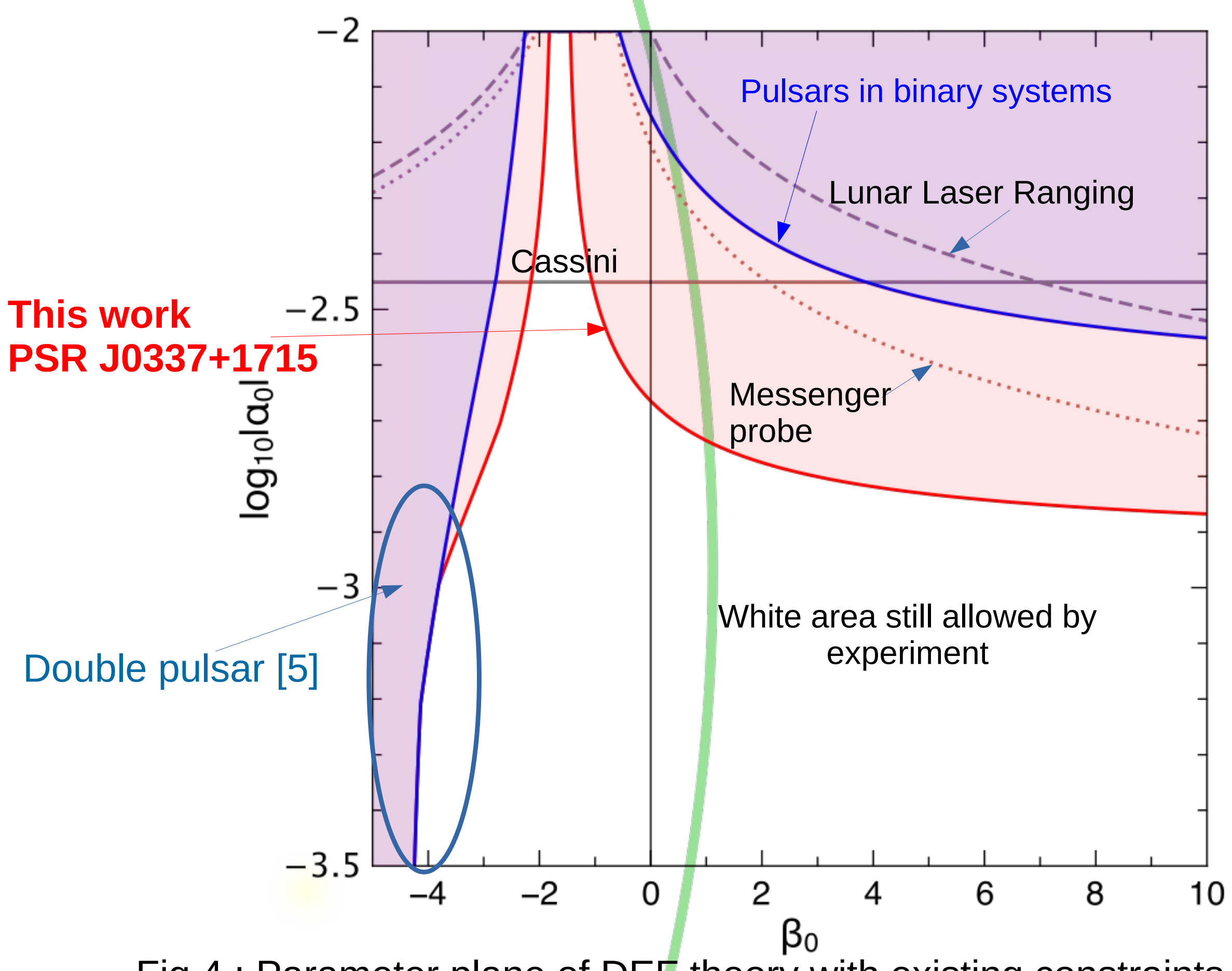


Fig 4 : Parameter plane of DEF theory with existing constraints. GR is $\alpha_0=\beta_0=0$. White area is yet unconstrained.

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