PEKING UNIVERSITY 北京大学

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Stringent Tests of Gravity with **Highly Relativistic** Binary Pulsars in the Era of **LISA and SKA**

Xueli Miao(缪雪丽)

Cooperators: Heng Xu, Lijing Shao, Chang Liu, Boqiang Ma.

X. Miao, et al. submit to ApJ

Gravity tests with binary pulsars

- Varying-G theory, PSRs J1713+0747, J1738+0333 and J0437−4715. (W. Zhu et al. 2019)

$$\dot{G}/G = (-0.1 \pm 0.9) \times 10^{-12}\,\mathrm{yr}^{-1}$$

- Massive graviton theories:
  - Fierz–Pauli-like massive gravity, 9 binary pulsar systems (X. Miao et al. 2019)

$$m_g < 5.2 \times 10^{-21}\,\mathrm{eV}/c^2$$

  - Cubic Galileon massive gravity, 14 binary pulsar systems (L. Shao et al. 2020)

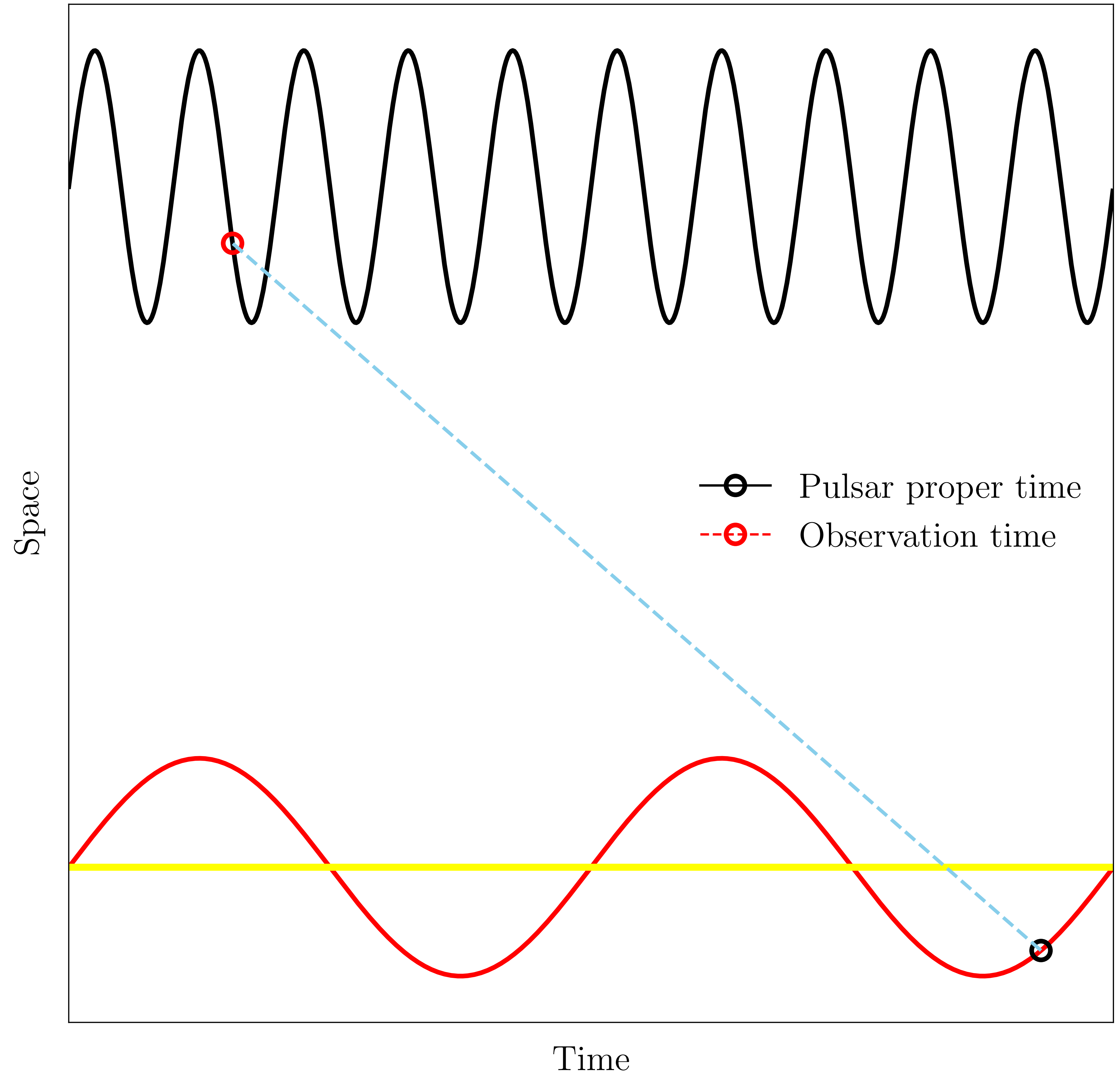
$$m_g < 2 \times 10^{-28}\,\mathrm{eV}/c^2$$

- Bound Post-Newtonian (PN) parameters to test gravity theories

Parameter	**Limit (95% C.L.)**	**Pulsar Experiment**	
$\hat{\xi}$	$<3.9 \times 10^{-9}$	PSRs B1937+21 and J1744−1134	(L. Shao et al. 2013)
$\hat{\alpha}_1$	$-0.4^{+3.7}_{-3.1} \times 10^{-5}$	PSR J1738+0333	(L. Shao et al. 2012)
$\hat{\alpha}_2$	$<1.6 \times 10^{-9}$	PSRs B1937+21 and J1744−1134	(L. Shao et al. 2013)
$\hat{\alpha}_3$	$<4 \times 10^{-20}$	PSR J1713+0747	(W. Zhu et al. 2013)
$\hat{\zeta}_2$	$<1.3 \times 10^{-5}$	Combination of several pulsars	(X. Miao & J. Zhao et al. 2020)

Pulsar Timing

- Measure the **times of arrival (TOAs)**
- Use an appropriate **timing model**
- Fit to get **a phase-connected solution**



Timing model

$$
\begin{aligned}
t_{\rm SSB} = t_{\rm topo} + t_{\rm corr} - \Delta D/f^2 \\
+ \Delta_{\rm R\odot} + \Delta_{\rm S\odot} + \Delta_{\rm E\odot} \\
+ \Delta_{\rm RB} + \Delta_{\rm SB} + \Delta_{\rm EB} + \Delta_{\rm AB}
\end{aligned}
$$

Damour-Deruelle (DD) timing model

- Römer delay $\Delta_{\rm RB} = x \sin\omega \left[\cos u - e\left(1+\delta_r\right)\right] + x\left[1 - e^2\left(1+\delta_\theta\right)^2\right]^{1/2} \cos\omega \sin u$
- Shapiro delay $\Delta_{\rm SB} = -2r \ln\left\{1 - e\cos u - s\left[\sin\omega(\cos u - e) + \left(1-e^2\right)^{1/2}\cos\omega\sin u\right]\right\}$
- Einstein delay $\Delta_{\rm EB} = \gamma \sin u$

T. Damour & J. H. Taylor, 1992

Post-Keplerian (PK) parameters

$$t_{\rm SSB} - t_0 = F\left[T; \{p^{\rm K}\}; \{p^{\rm PK}\}; \{q^{\rm PK}\}\right]$$

$$\{p^{\rm K}\} = \{P_b, \omega_0, T_0, e_0, x_0\}$$

$$\{p^{\rm PK}\} = \{\dot{\omega}, \gamma, \dot{P}_b, r, s, \delta_\theta, \dot{e}, \dot{x}\}$$

$$\{q^{\rm PK}\} = \{\delta_r, A, B, D\}$$

$$\dot{\omega} = 3T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\left(m_p+m_c\right)^{2/3}$$

$$\gamma = T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3} e\frac{m_c\left(m_p+2m_c\right)}{\left(m_p+m_c\right)^{4/3}}$$

$$r = T_\odot m_c$$

$$s = \sin i = T_\odot^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3} x\frac{\left(m_p+m_c\right)^{2/3}}{m_c}$$

$$\dot{P}_b = -\frac{192\pi}{5}T_\odot^{5/3}\left(\frac{P_b}{2\pi}\right)^{-5/3} f(e)\frac{m_p m_c}{\left(m_p+m_c\right)^{1/3}}$$

$\dot{\omega}$	γ	r	s	$\dot{P}_b$
$T_{\rm obs}^{-3/2}$	$T_{\rm obs}^{-3/2}$	$T_{\rm obs}^{-1/2}$	$T_{\rm obs}^{-1/2}$	$T_{\rm obs}^{-5/2}$
P_b^1	$P_b^{4/3}$	P_b^0	P_b^0	P_b^3

T. Damour & J. H. Taylor, PRD, 1992

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P_b^1	$P_b^{4/3}$	P_b^0	P_b^0	P_b^3

T. Damour & J. H. Taylor, PRD, 1992

A multimessenger strategy: LIAS & SKA

Koutarou Kyutoku et al. 2018

- Radio detection, the shortest orbital period double neutron star (DNS) system is PSR J1946+2052, $P_b = 0.078$ day

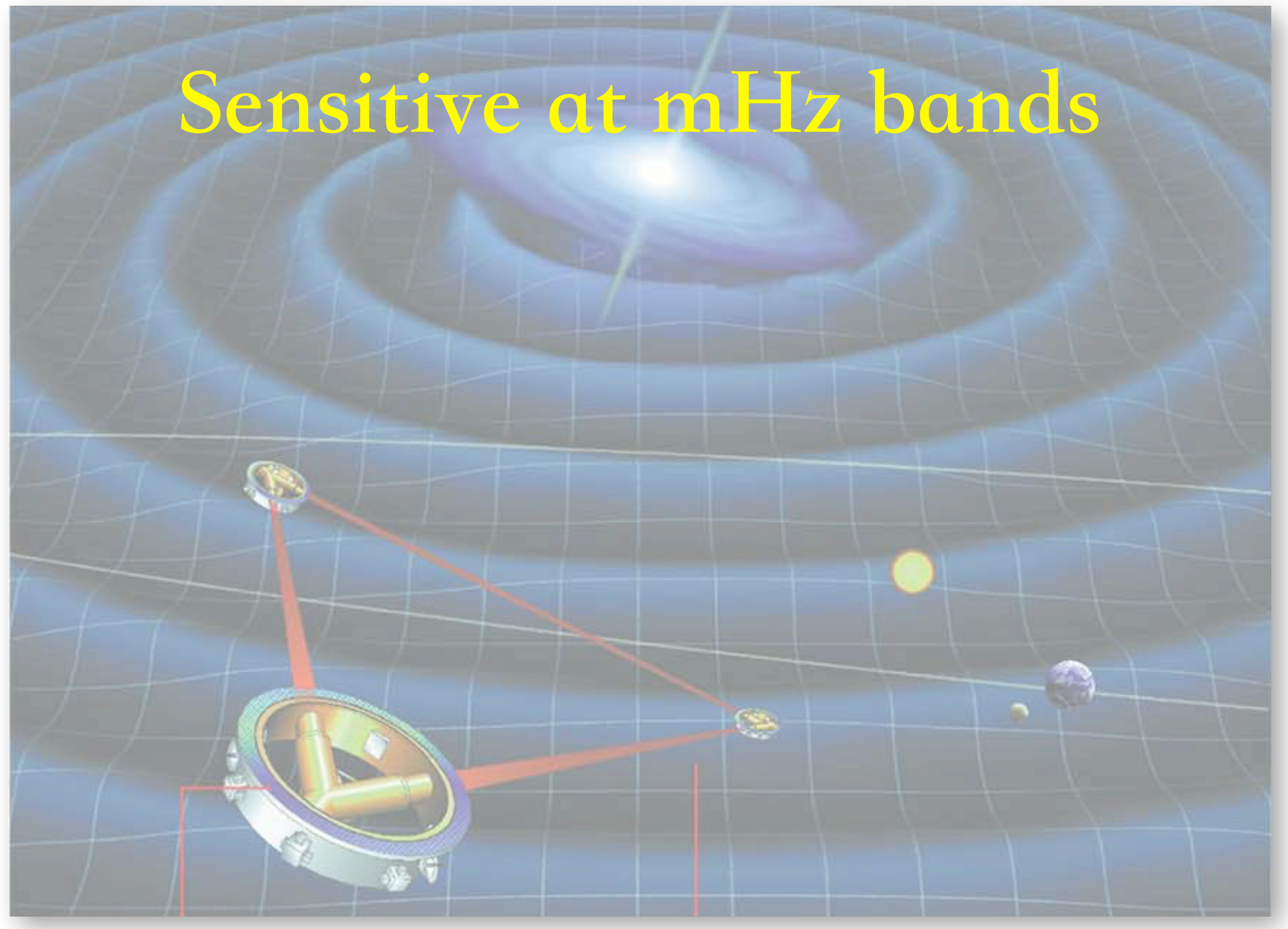
- Gravitational wave detection, 2 DNSs system near the phase of merger, GW170817 & GW190425

1.88 hr

- Signal suffer a severe Doppler smearing which is due to orbital motion

No $P_b \sim 10$ min

- Instrument only sensitive to the merger phase of DNS



Laser Interferometer Space Antenna (LISA)

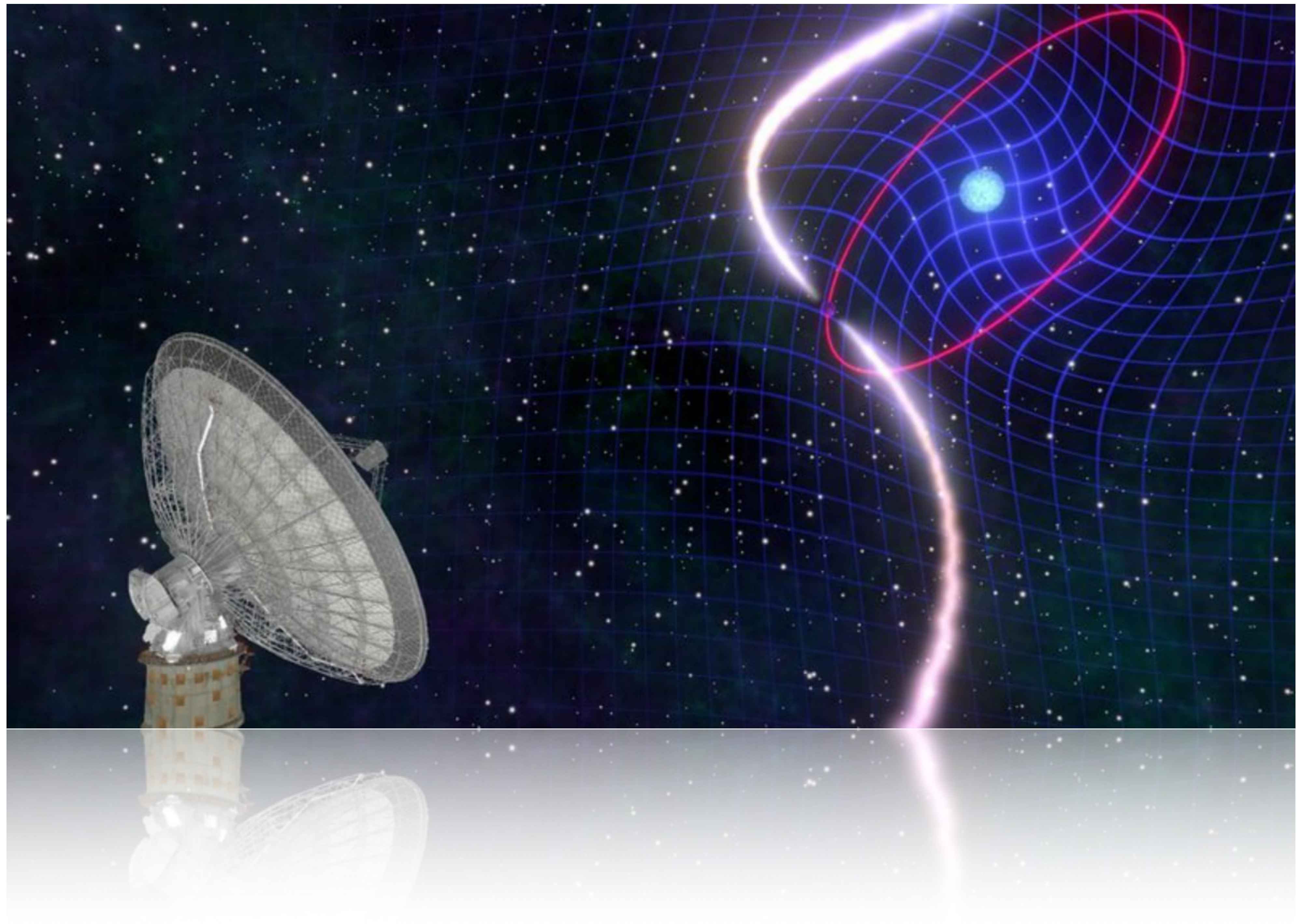
Provide the information of on the location and orbital parameters of DNSs

Discover $P_b \sim 10$ min

Provide the high precision of TOAs

Square Kilometre Array (SKA)

Simulation parameters



	PSR-NS I	PSR-NS II
m_p	1.3	1.35
m_c	1.7	1.44
Eccentricity, e	0.1	0.1
Orbital inclination, i	60°	60°
$\sigma_{\rm TOA}$	100 ns & 1 μs	100 ns & 1 μs

$$\dot{\omega} = 3T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}(m_p+m_c)^{2/3},$$

$$\gamma = T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3} e\frac{m_c(m_p+2m_c)}{(m_p+m_c)^{4/3}},$$

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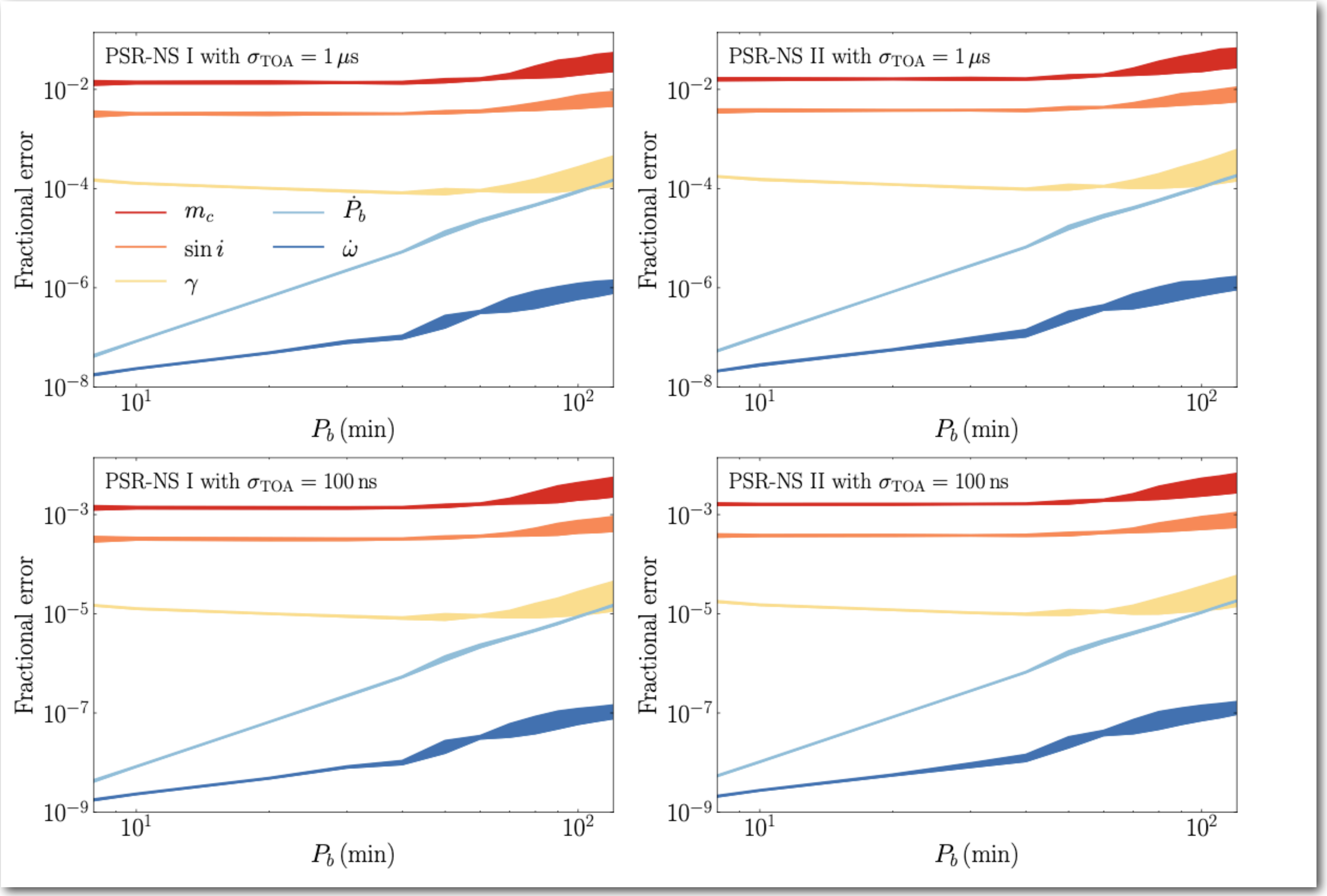
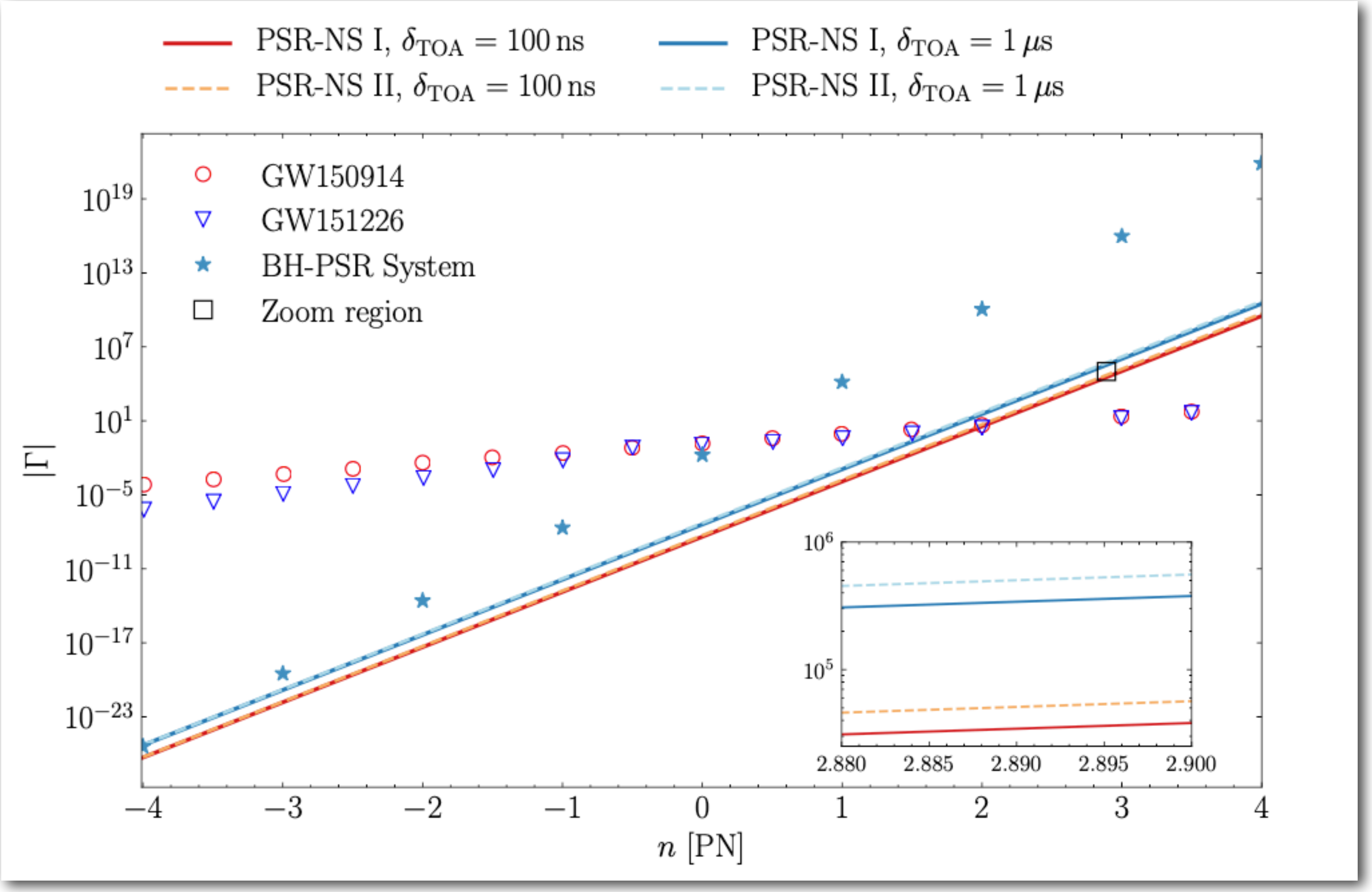
X. Miao, et al. in submitted

4-yr simulation results

X. Miao, et al. in submitted



Theoretical framework



- A generic formalism which provides a mapping between generic non-GR parameters in the orbital decay rate

$$\frac{\dot{P}_b}{P_b} = \frac{\dot{P}_b}{P_b}\bigg|_{\rm GR}\left(1+\Gamma v^{2n}\right)$$

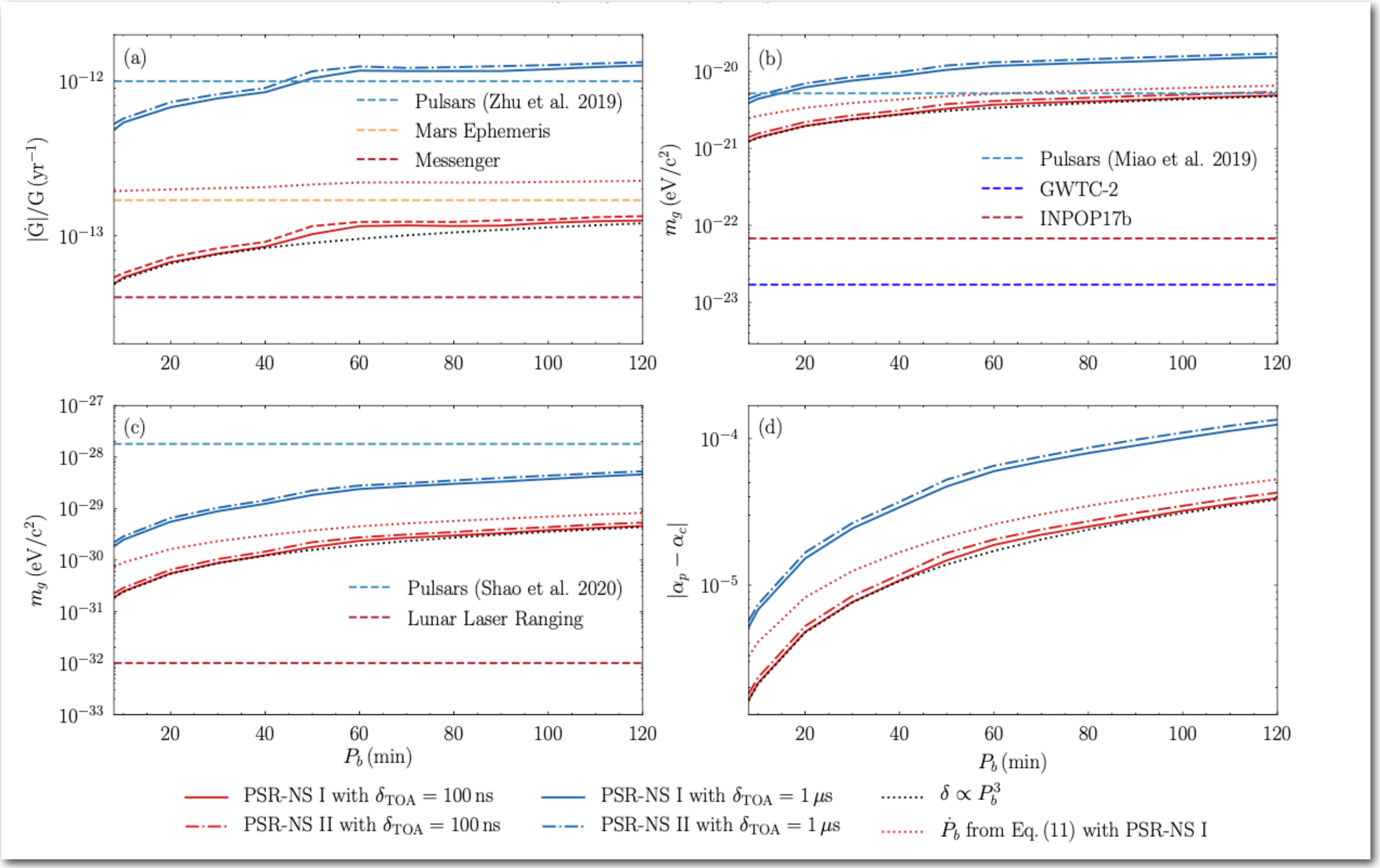
$$\left|\frac{\frac{\dot{P}_b}{P_b} - \frac{\dot{P}_b}{P_b}\Big|_{\rm GR}}{\frac{\dot{P}_b}{P_b}\Big|_{\rm GR}}\right| < \delta$$

$$|\Gamma| < \frac{\delta}{v^{2n}}$$

X. Miao, et al. in submitted

Projected constraints of gravity theories

X. Miao, et al. in submitted



Summary

- Ultra-relativistic PSR-NS systems give constraints from a **strong field** which are complementary gravity tests for the bounds from the Solar System.

- Compared with the previous bounds from binary pulsar systems, the short-orbital-period systems can **significantly improve the constraints** on parameters of some specific gravity theories.

Thank you !!!