Testing Gravity Theories with Double Neutron Stars — PSRs J1913+1102 & J1946+2052

General Relativity Tests Project with FAST

Speaker: Xueli Miao

Collaborator: L. Meng, W. Zhu, P. C. C. Freire, N. Wex, M. Kramer, et al.

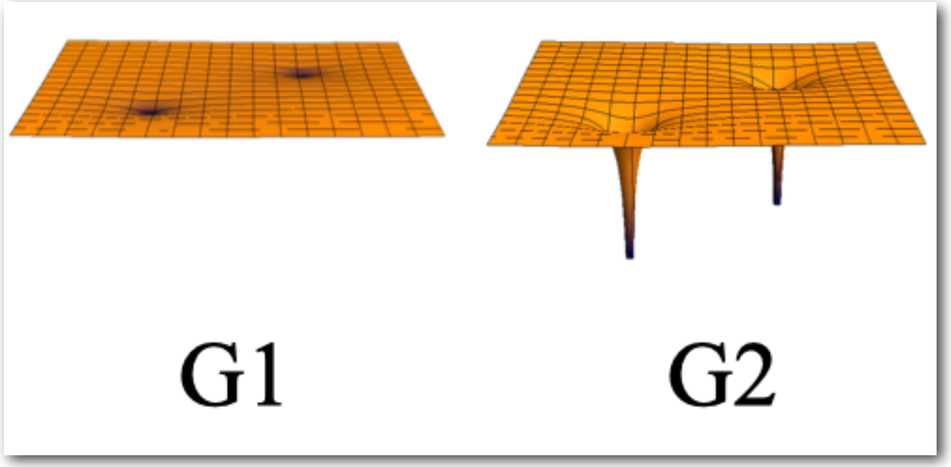
FAST/Future Pulsar Symposium 14

Qingdao Shandong, 2025.07.04

NAOC 中国科学院国家天文台 NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

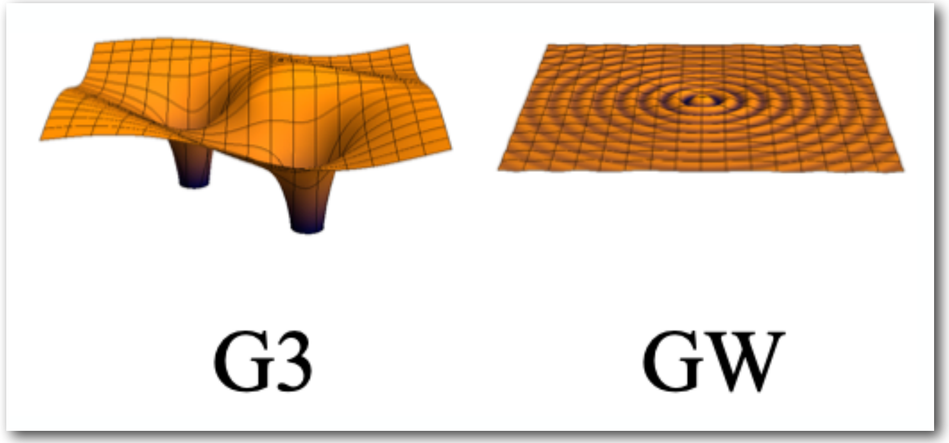
MAX PLANCK INSTITUTE FOR RADIO ASTRONOMY

Gravity tests in different regimes



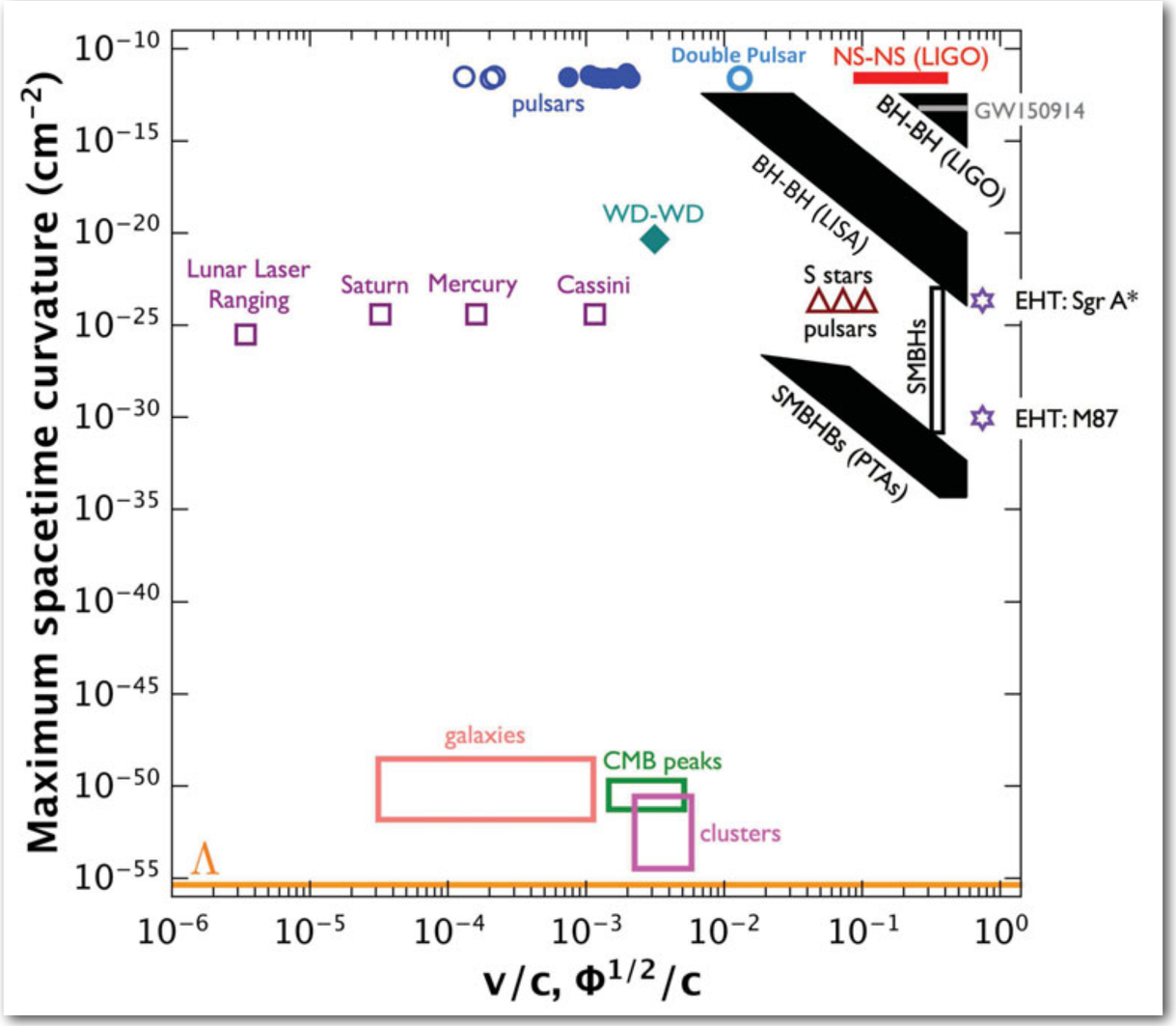
Quasi-stationary weak-field regime

Quasi-stationary strong-field regime



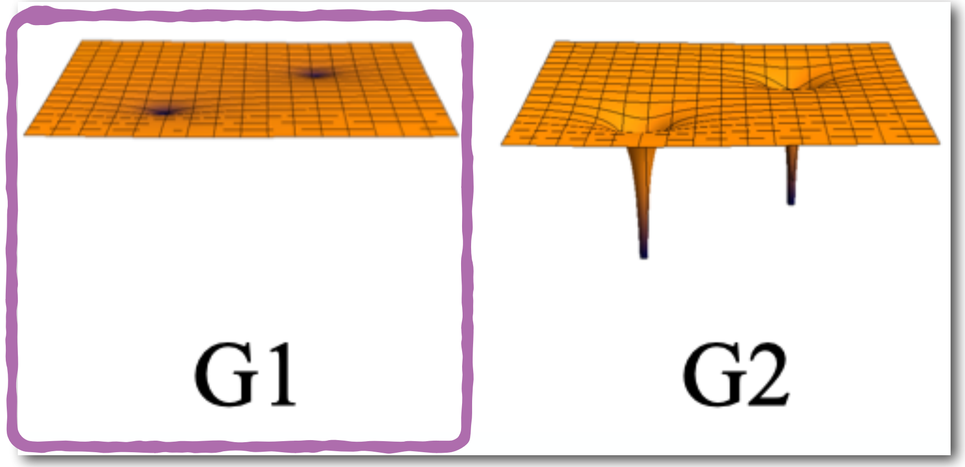
Highly-dynamical strong-field regime

Radiation regime



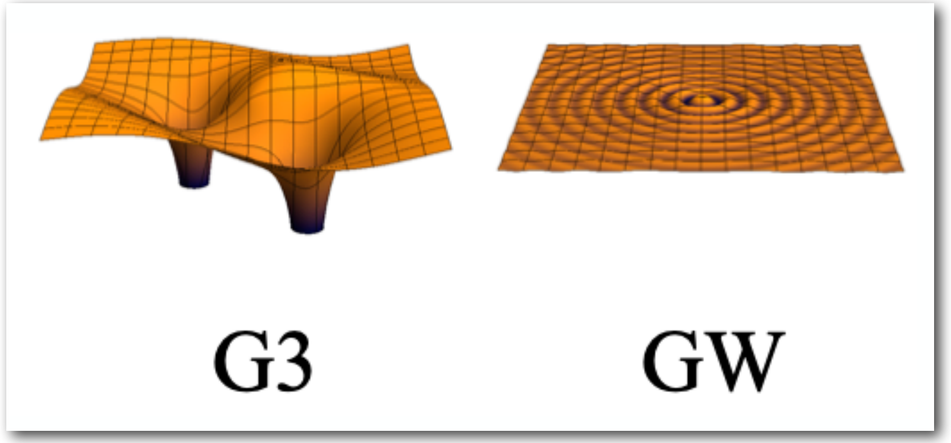
N. Wex. 2014 M. Kramer. 2017

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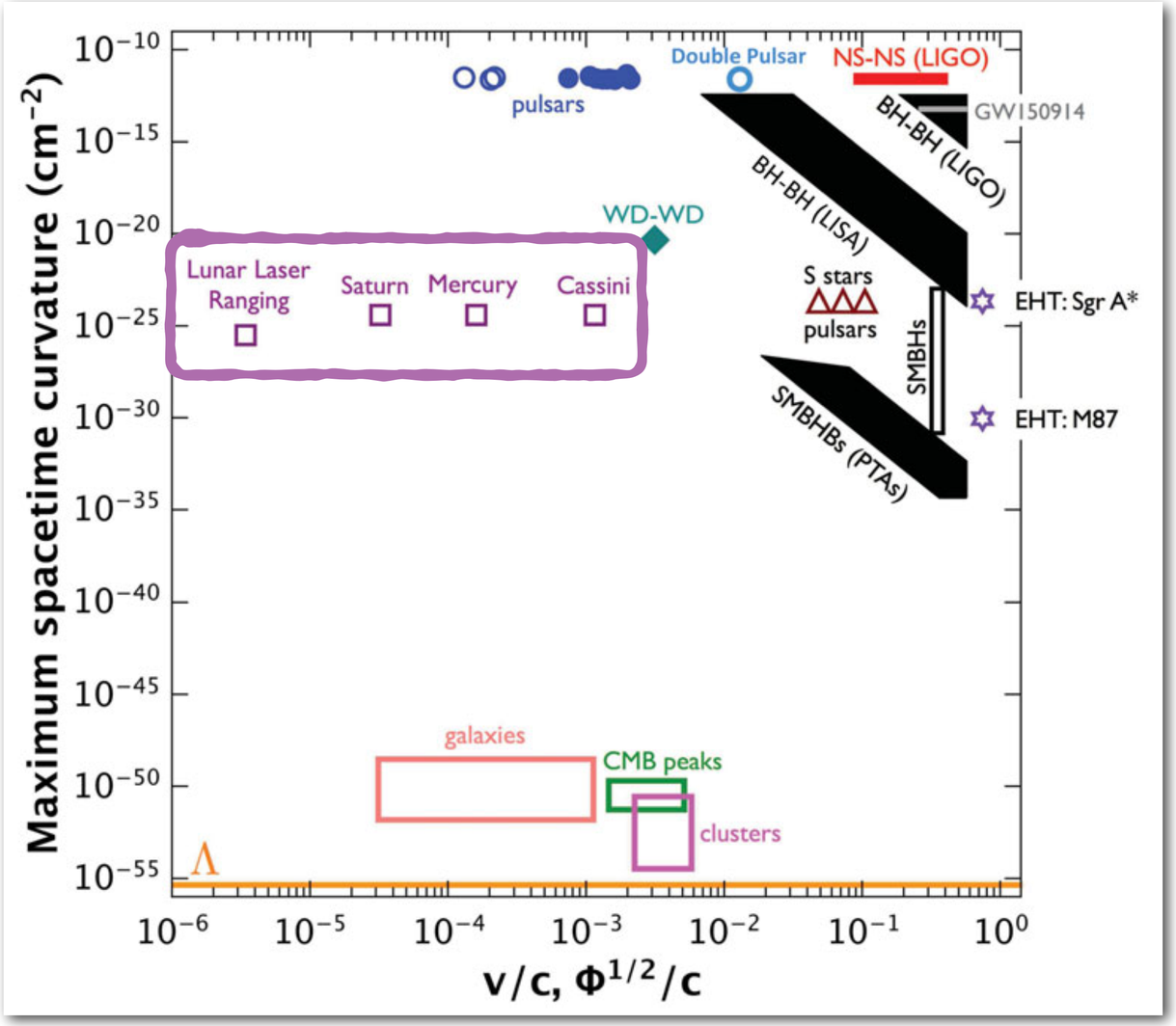
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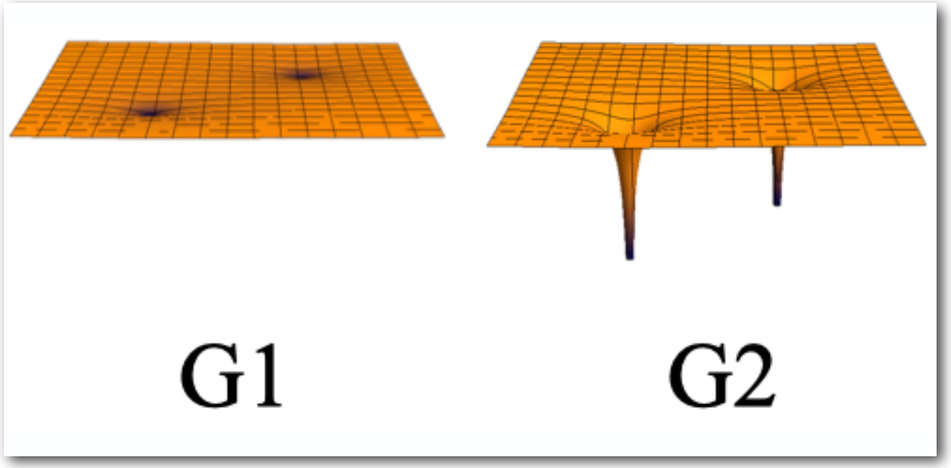
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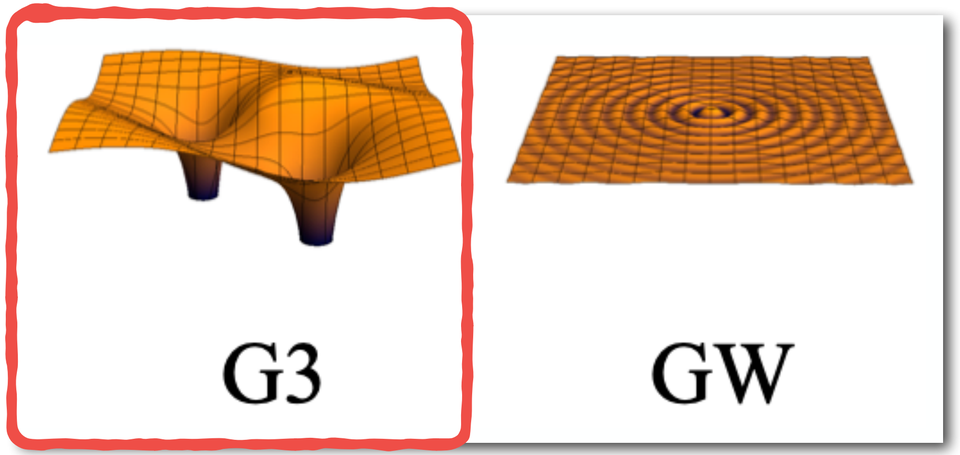
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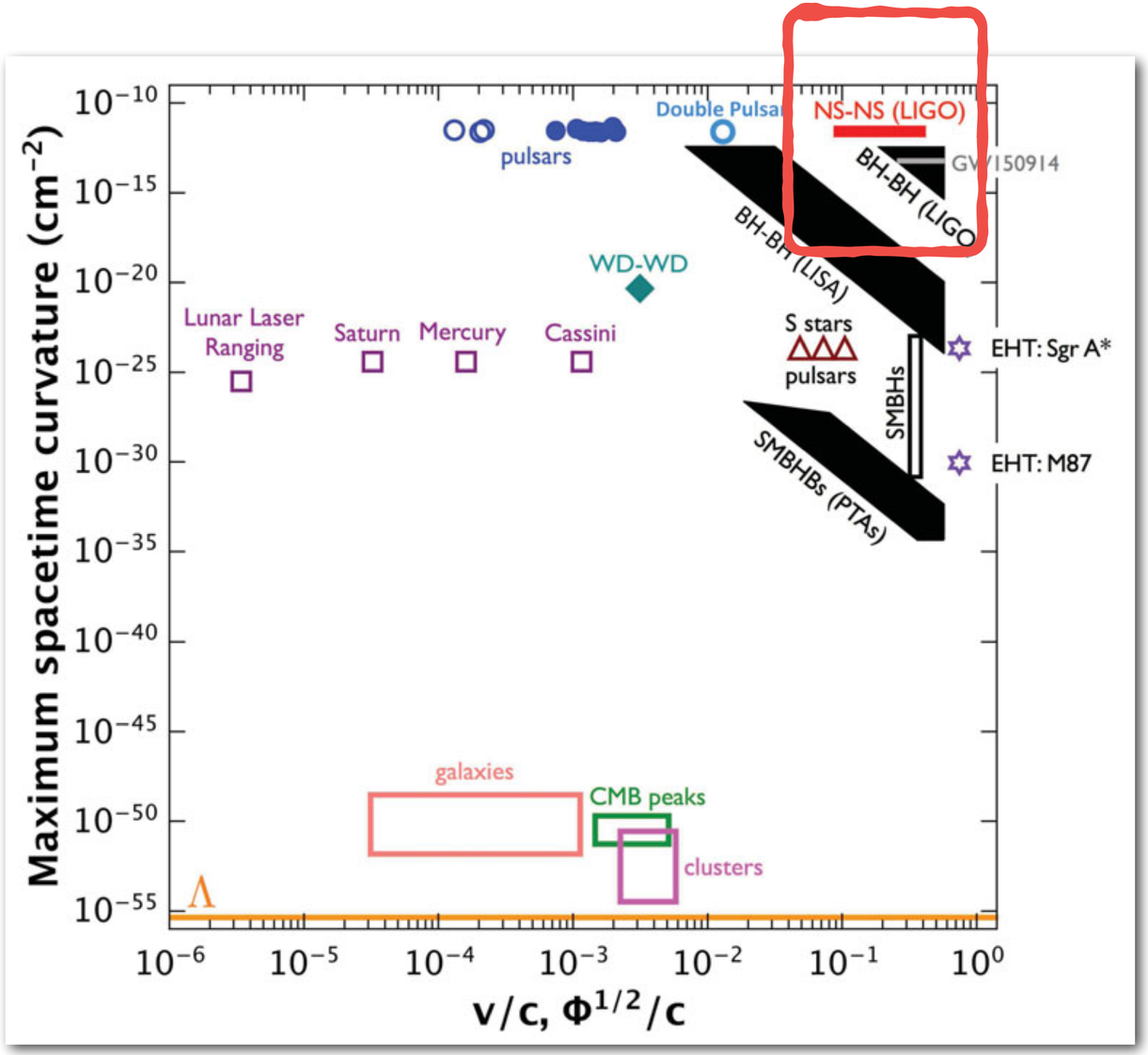
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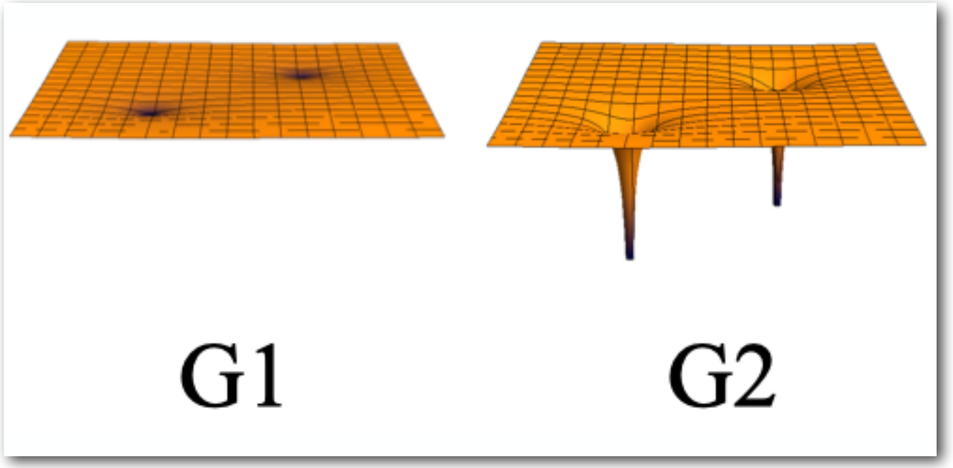
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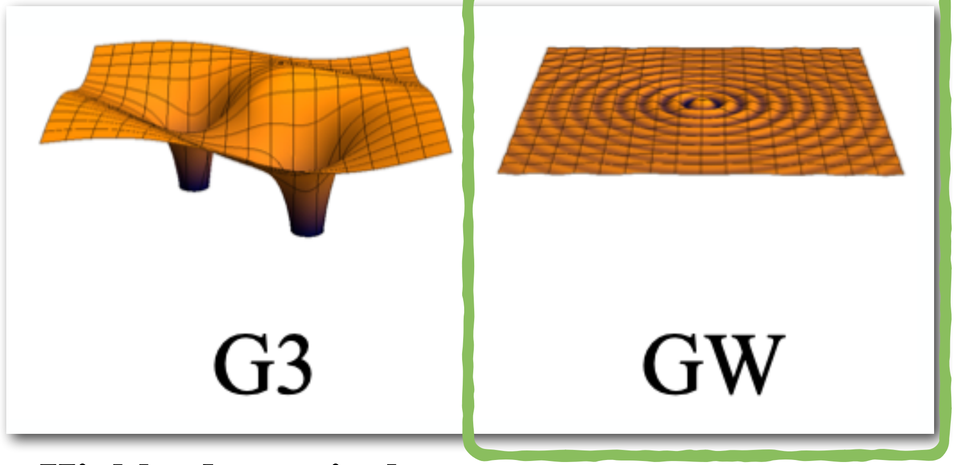
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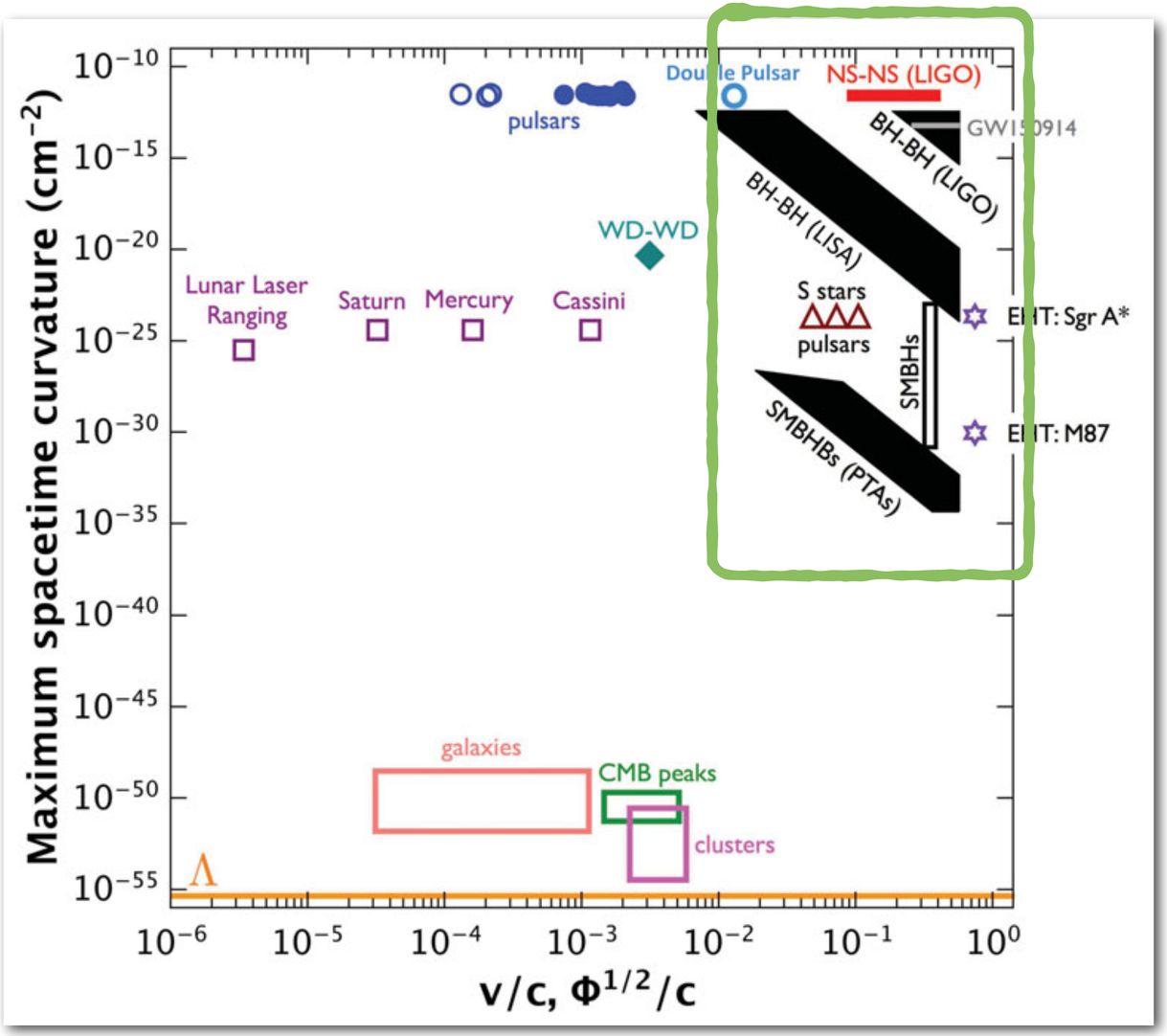
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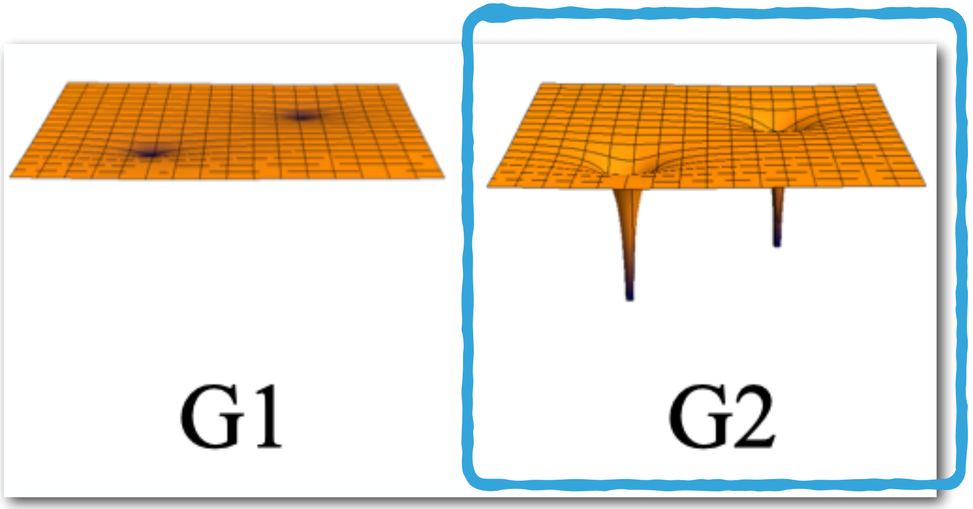
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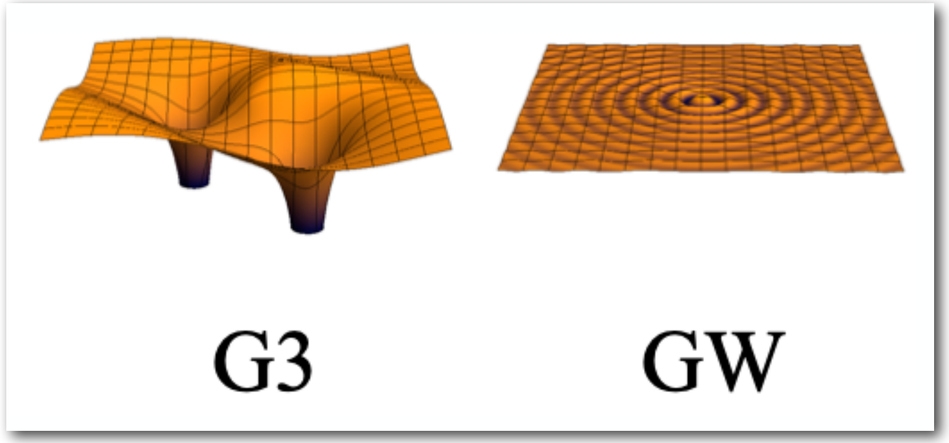
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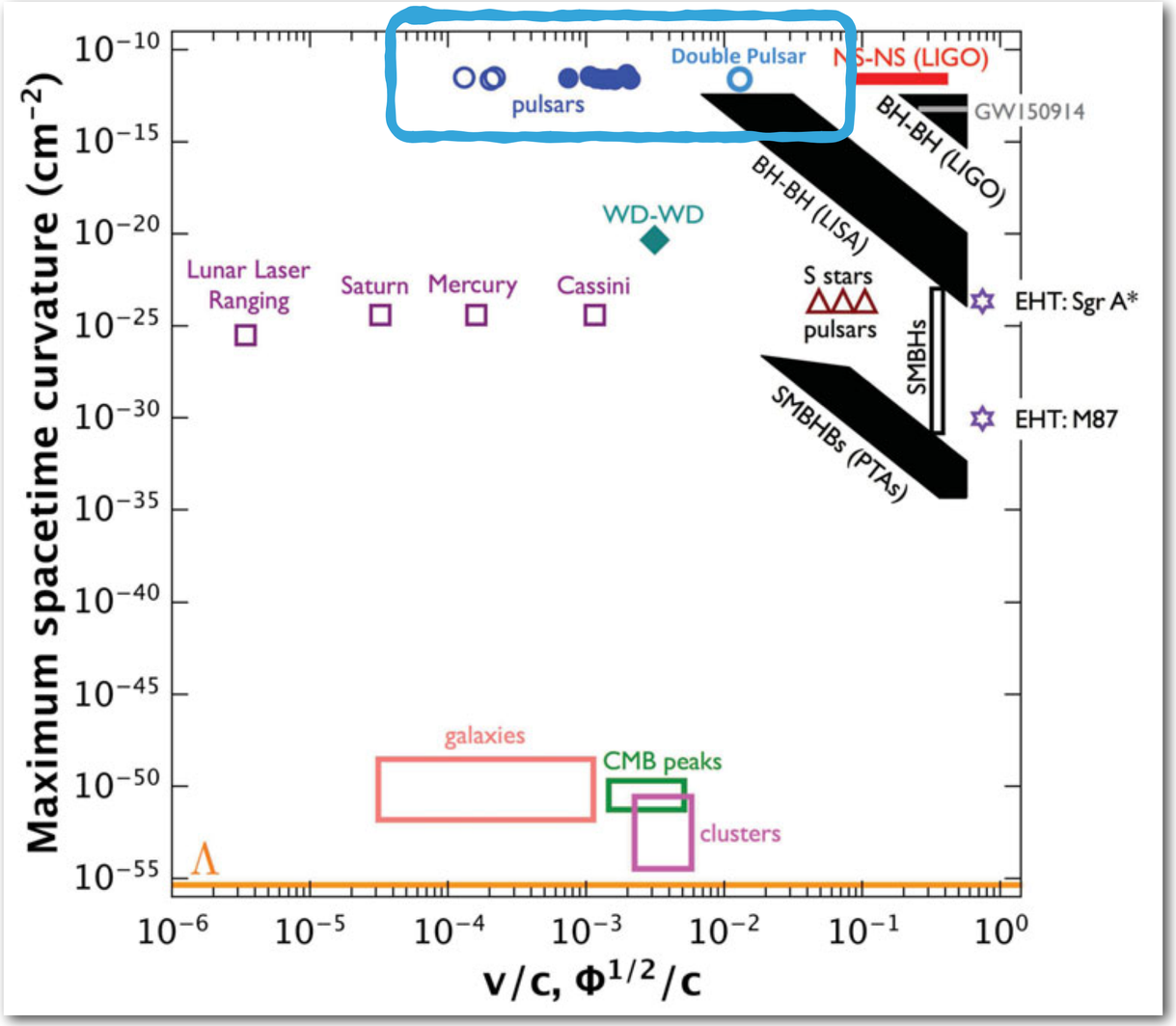
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Highly-dynamical strong-field regime

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N. Wex. 2014 M. Kramer. 2017

Test GR with binary pulsars

Post-Keplerian (PK) parameters in GR

$$\dot{\omega} = 3T_{\odot}^{2/3}\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\left(m_{\rm p}+m_{\rm c}\right)^{2/3}$$

$$\gamma = T_{\odot}^{2/3}\left(\frac{P_{\rm b}}{2\pi}\right)^{1/3} e\frac{m_{\rm c}\left(m_{\rm p}+2m_{\rm c}\right)}{\left(m_{\rm p}+m_{\rm c}\right)^{4/3}}$$

$$r = T_{\odot}m_{\rm c}$$

$$s = \sin i = T_{\odot}^{-1/3}\left(\frac{P_{\rm b}}{2\pi}\right)^{-2/3} x\frac{\left(m_{\rm p}+m_{\rm c}\right)^{2/3}}{m_{\rm c}}$$

$$\dot{P}_{\rm b} = -\frac{192\pi}{5}T_{\odot}^{5/3}\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3} f(e)\frac{m_{\rm p}m_{\rm c}}{\left(m_{\rm p}+m_{\rm c}\right)^{1/3}}$$

D. R. Lorimer & M. Kramer. 2005

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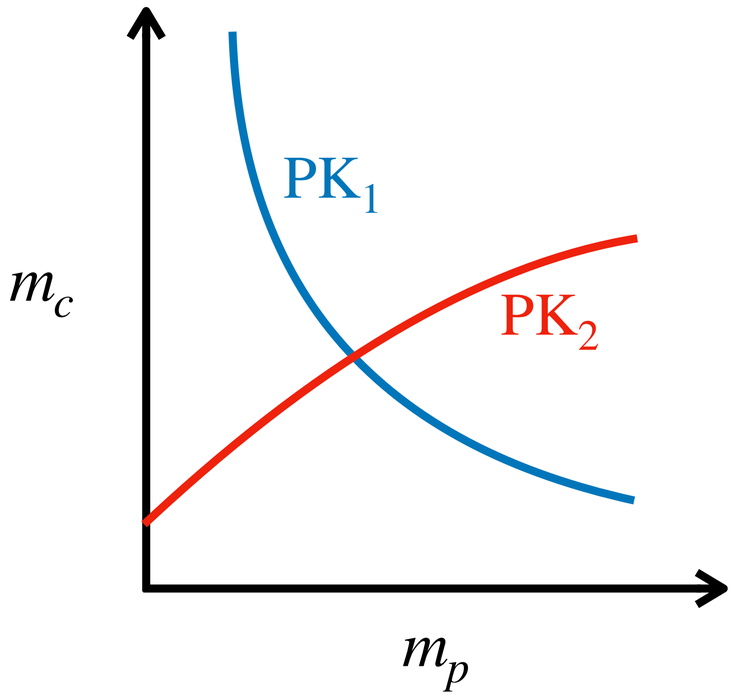
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If 2 PK parameters are detected, we can measure the masses of the pulsar and the companion



D. R. Lorimer & M. Kramer. 2005

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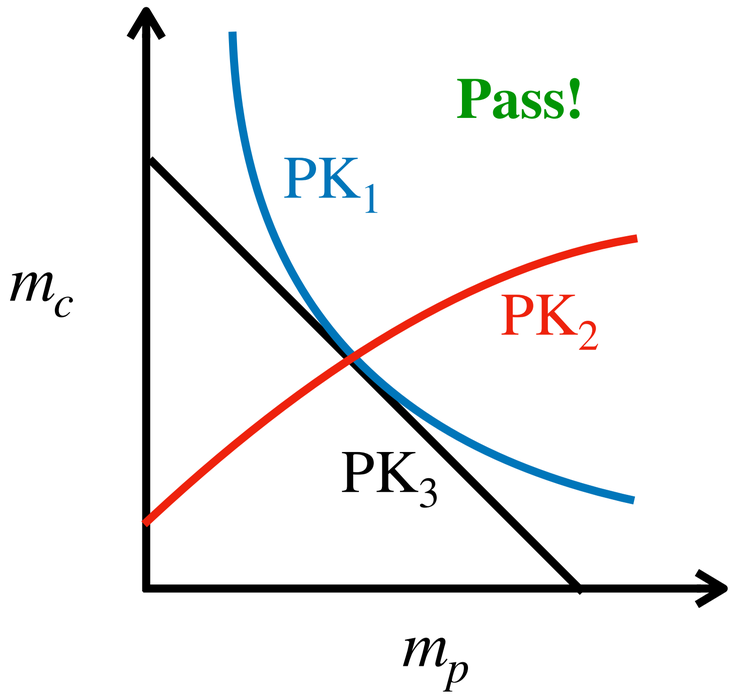
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Test GR with binary pulsars

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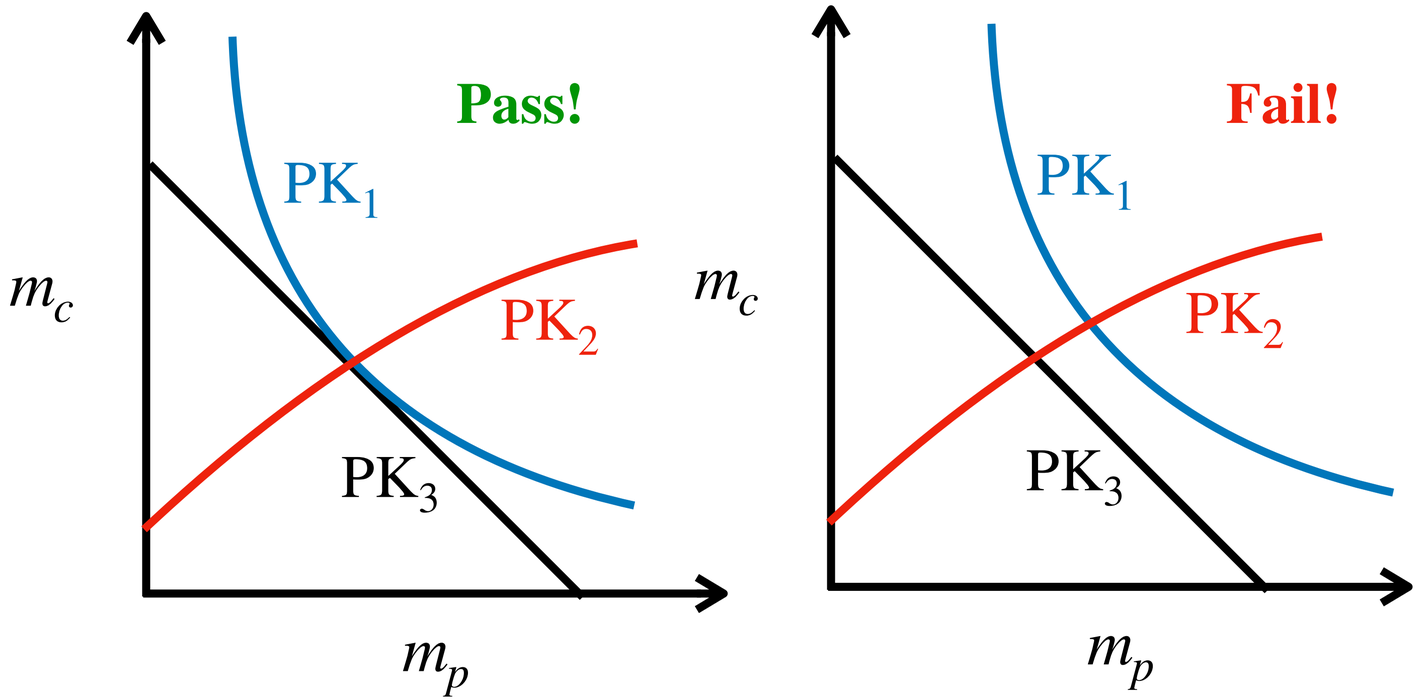
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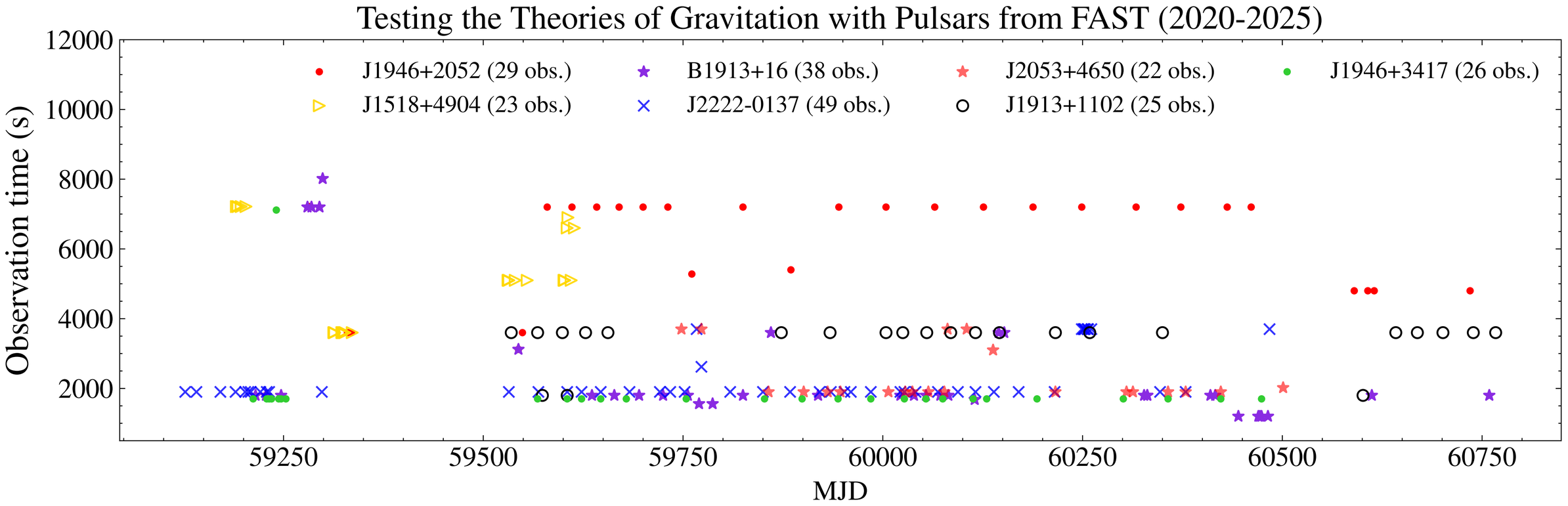
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“Testing the Theories of Gravitation with Pulsars”

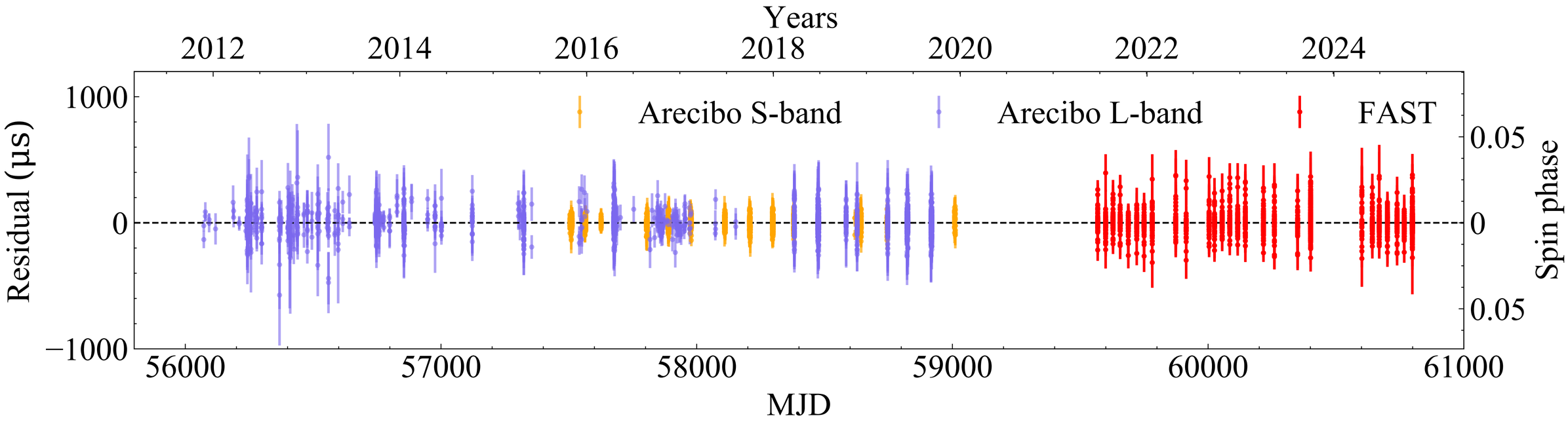


National Astronomical Observatories of the Chinese Academy of Sciences (NAOC) and Max Planck Institute for Radio Astronomy (MPIfR) have established close collaborations in radio astronomy. One prominent joint effort focuses on high-precision timing of relativistic pulsar binary systems using the Five-hundred-meter Aperture Spherical radio Telescope (FAST) to carry out stringent tests of gravitational theories. Between 2020 and 2025, under the collaborative project *“**Testing the Theories of Gravitation with Pulsars**”*, we have been granted **182 hours** of observing time on FAST.

PSR J1913+1102, the asymmetric DNS system

PSR J1913+1102, a PSR-NS system discovered by the Arecibo PALFA pulsar survey in 2012, has a spin period of 27.2 ms in a mildly eccentric orbit with an orbital period of 4.95 hours.

Ferdman et al. (2020) measured three PK parameters $\dot{\omega}$, γ and $\dot{P}_{\rm b}$, and assuming GR, derived the mass ratio $q = m_c/m_p = 0.78 \pm 0.03$, identifying it as the most asymmetric DNS that will merge in the Hubble time.



The residual times of arrival (ToAs), which are from 2012 to 2025

X. Miao. et al. in preparation

PSR J1913+1102, the asymmetric DNS system

Here, we present updated timing results for PSR J1913+1102 based on combined data from the FAST and Arecibo telescopes (from 2012 to 2025). There are the timing results of four PK parameters with DDFWHE binary model

$\dot{\omega}$ (deg yr^{-1})	γ (ms)	$\dot{P}_{\rm b}$	$h_3(\mu{\rm s})$
5.6511(3)	0.478(4)	$-0.451(6) \times 10^{-12}$	1.7(6)

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In GR

$$\dot{\omega} = 3T_{\odot}^{2/3}\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\left(m_{\rm p}+m_{\rm c}\right)^{2/3} \qquad \gamma = T_{\odot}^{2/3}\left(\frac{P_{\rm b}}{2\pi}\right)^{1/3} e\frac{m_{\rm c}\left(m_{\rm p}+2m_{\rm c}\right)}{\left(m_{\rm p}+m_{\rm c}\right)^{4/3}}$$

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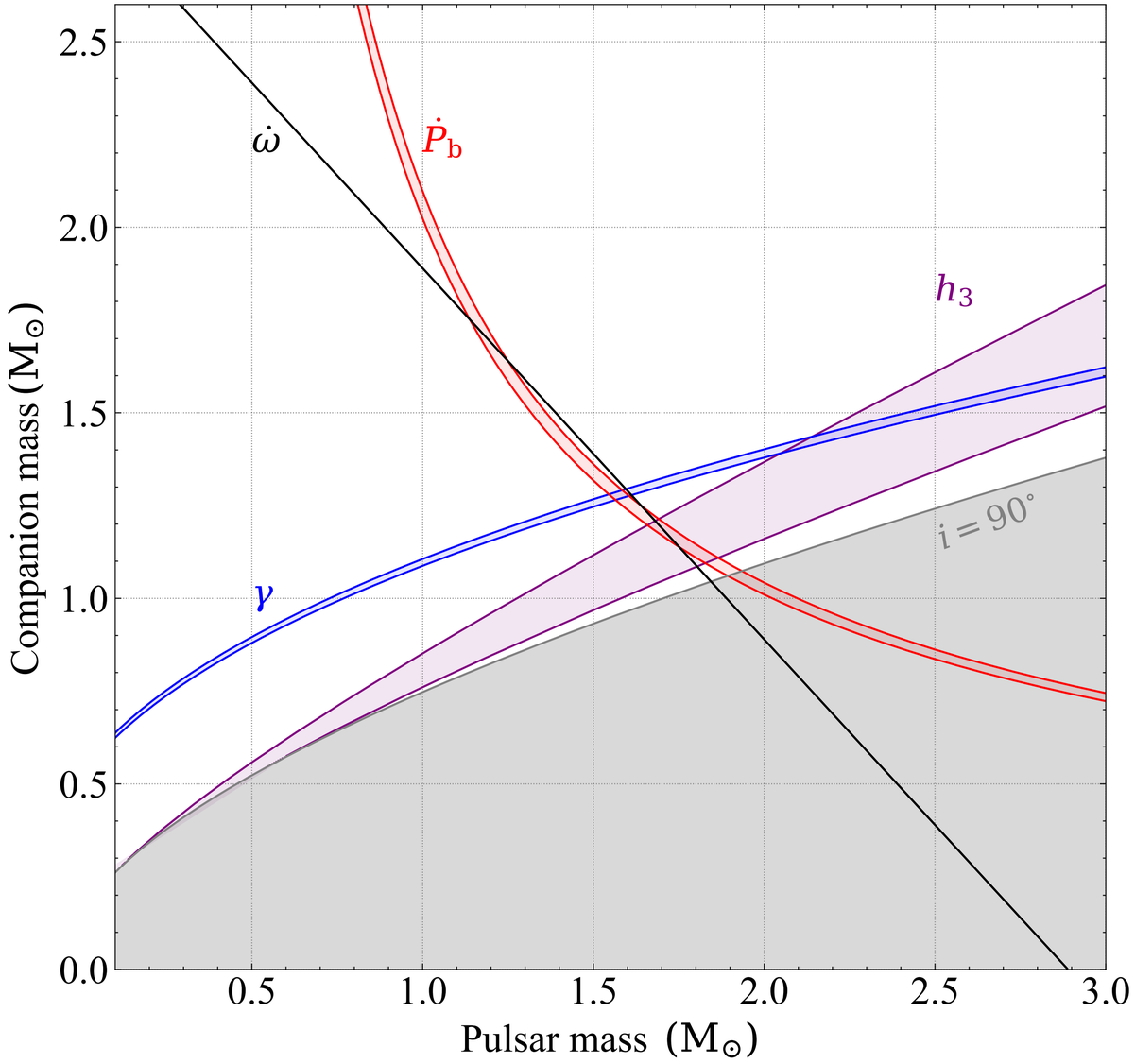
In GR

$$m_{\rm c} = 1.287(8)\,{\rm M}_\odot, m_{\rm p} = 1.605(8)\,{\rm M}_\odot, q = 0.801 \pm 0.009$$

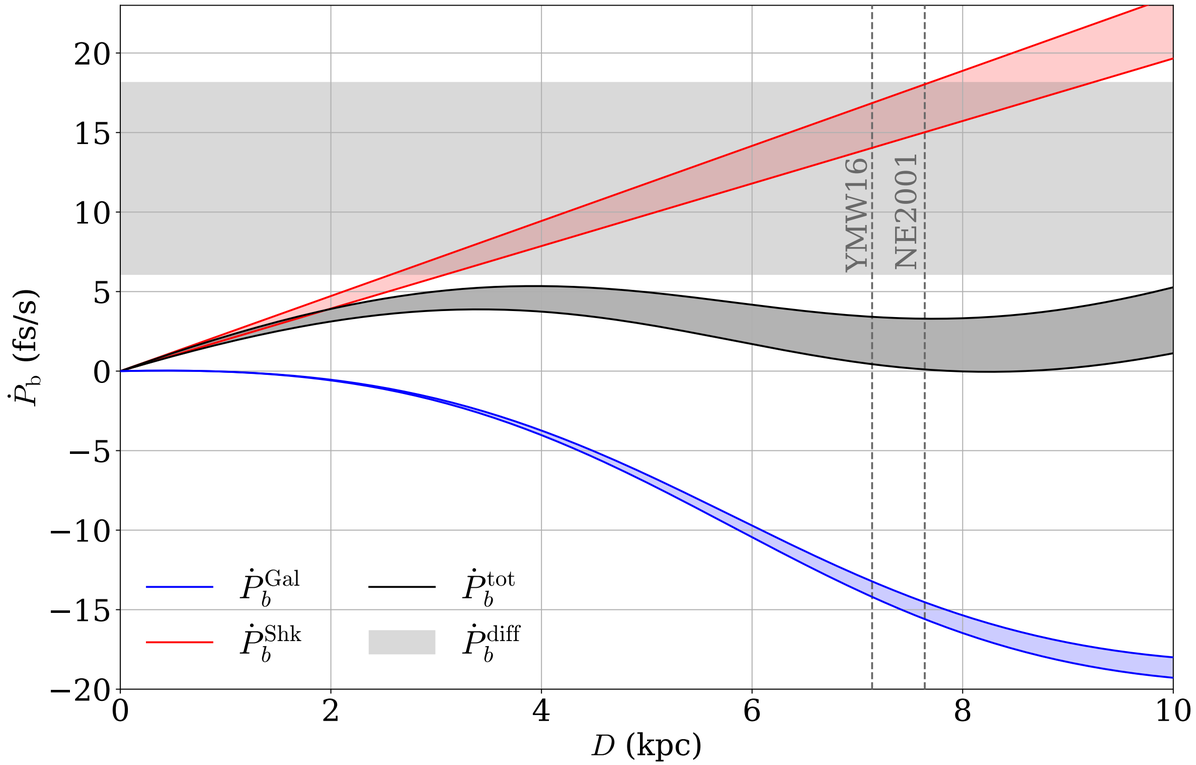
Relative to Ferdman et al. (2020), we have already improved the precision of PK parameters and the masses by a factor of 3.

X. Miao. et al. in preparation

PSR J1913+1102, the asymmetric DNS system



$$\dot{P}_{\rm b,obs} = \dot{P}_{\rm b,int} + \dot{P}_{\rm b,ext} = \dot{P}_{\rm b,int} + \dot{P}_{\rm b,gal} + \dot{P}_{\rm b,shk}$$

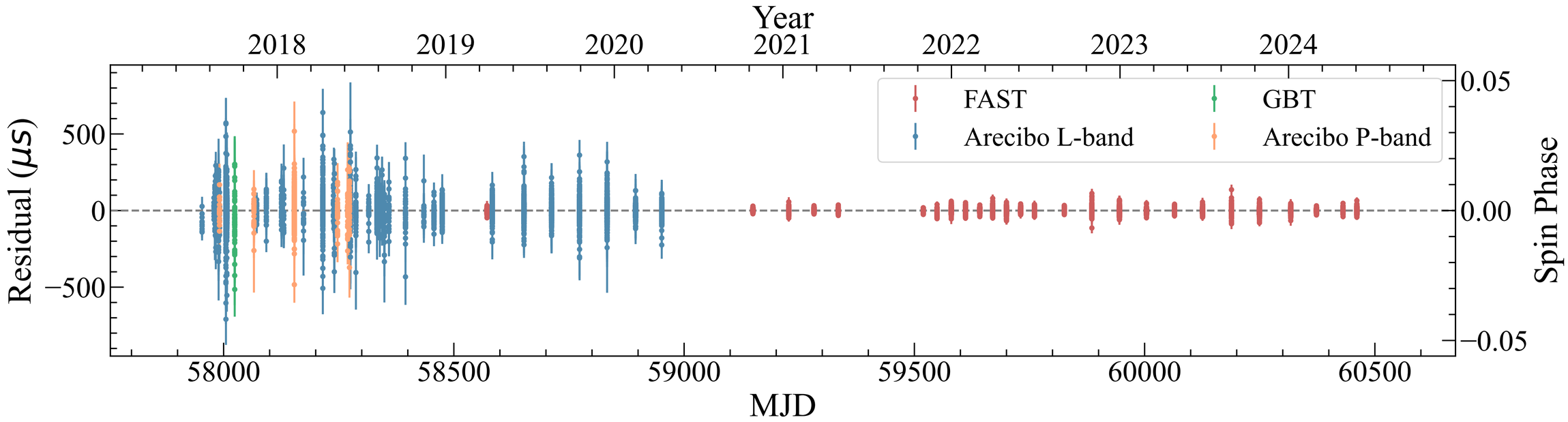


The mass-mass diagram of PSR J1913+1102 (in GR)

X. Miao. et al. in preparation

PSR J1946+2052, the most compact DNS system in the Galaxy

PSR J1946+2052 is a pulsar in a DNS system with the **shortest orbital period (1.88h)** among all known DNS systems in the Galaxy, discovered by Arecibo PALFA pulsar survey (Stovall, et al., 2018, APJL). In this work, we combine 7-year observations from Arecibo, Green Bank Telescope, and FAST to proceed with high-precision timing.



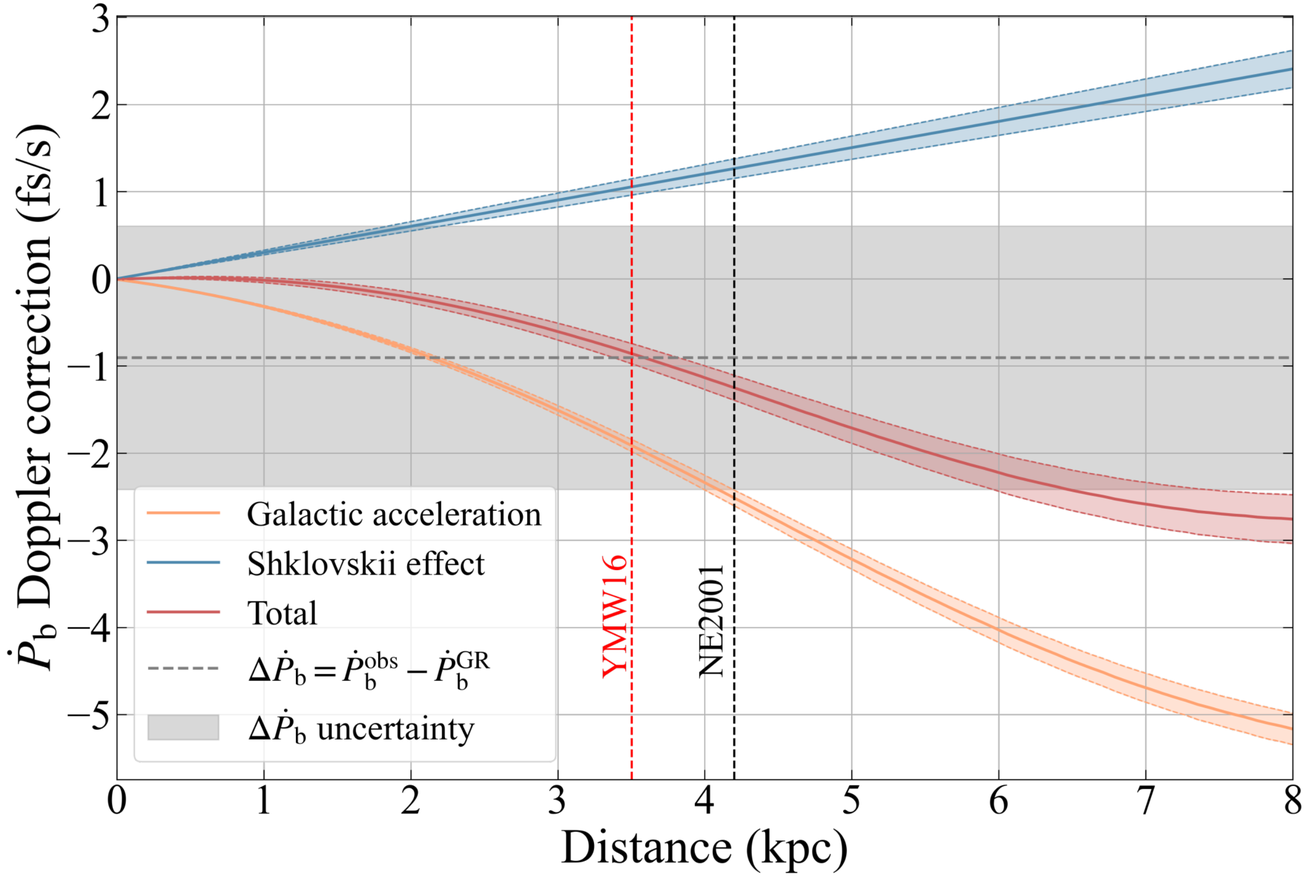
The residual times of arrival (ToAs), which are from 2017 to 2024

L. Meng. et al. submitted

PSR J1946+2052, the most compact DNS system in the Galaxy

$\dot{\omega}$ (deg yr^{-1})	γ (ms)	$\dot{P}_{\rm b}$	$h_3(\mu{\rm s})$	ζ
25.79205(40)	0.2591(6)	$-1.8296(15)\times10^{-12}$	2.58(14)	0.760(36)

The timing results provide precise measurements for five PK parameters



$$\dot{P}_{\rm b,obs}=\dot{P}_{\rm b,int}+\dot{P}_{\rm b,ext}=\dot{P}_{\rm b,int}+\dot{P}_{\rm b,gal}+\dot{P}_{\rm b,shk}$$

$$\dot{P}_{\rm b}^{\rm int}=-1.8288\times10^{-12}$$

Three tests of GR,

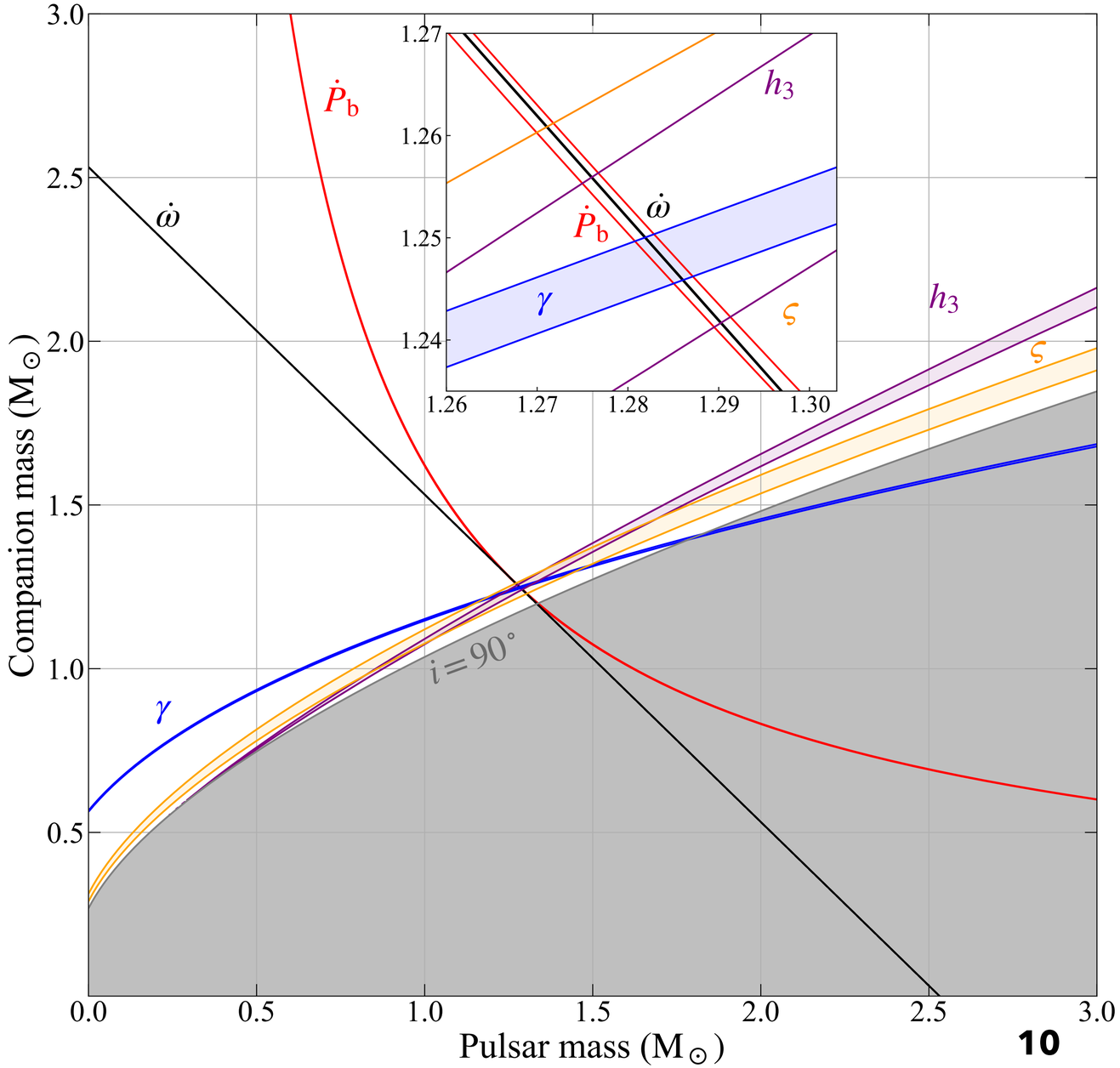
1.The second most precise test of the GR quadrupole formula for the orbital decay:

$$\frac{\dot{P}_{\rm b,int}}{\dot{P}_{\rm b,GR}}=1.00005(91);$$

2. Two tests with the Shapiro delay:

$$\frac{h_3}{h_{3,\rm GR}}=0.997(56),\quad \frac{\varsigma}{\varsigma_{\rm GR}}=1.01(5)$$

PSR J1946+2052, the most compact DNS system in the Galaxy



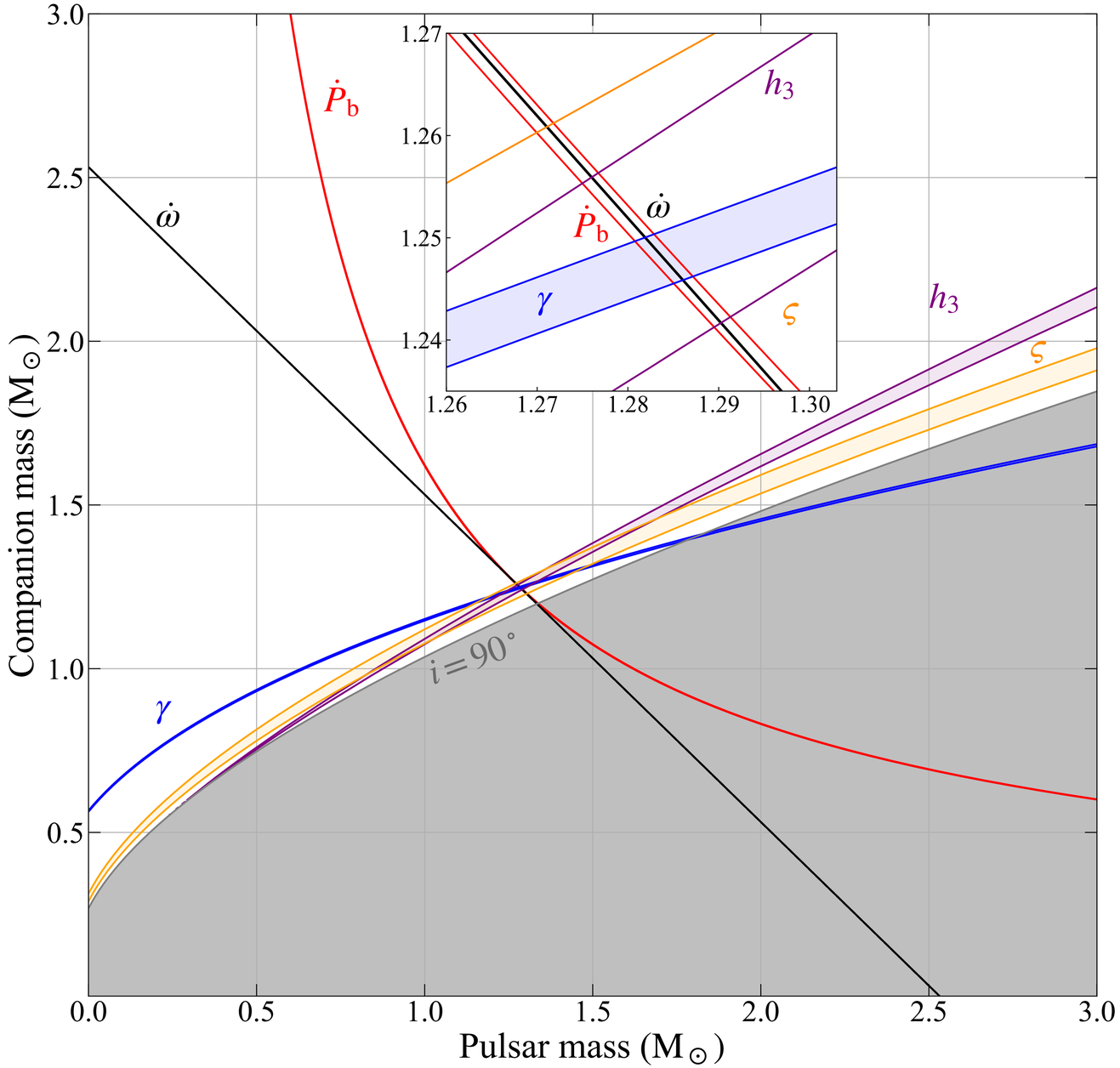
$\dot{\omega}$ (deg yr^{-1})	γ (ms)
25.79205(40)	0.2591(6)

$$M_{\rm tot} = 2.531858(60)\,{\rm M}_\odot$$

$$m_{\rm p} = 1.2838(21)\,{\rm M}_\odot$$

$$m_{\rm c} = 1.2480(21)\,{\rm M}_\odot$$

PSR J1946+2052, the most compact DNS system in the Galaxy



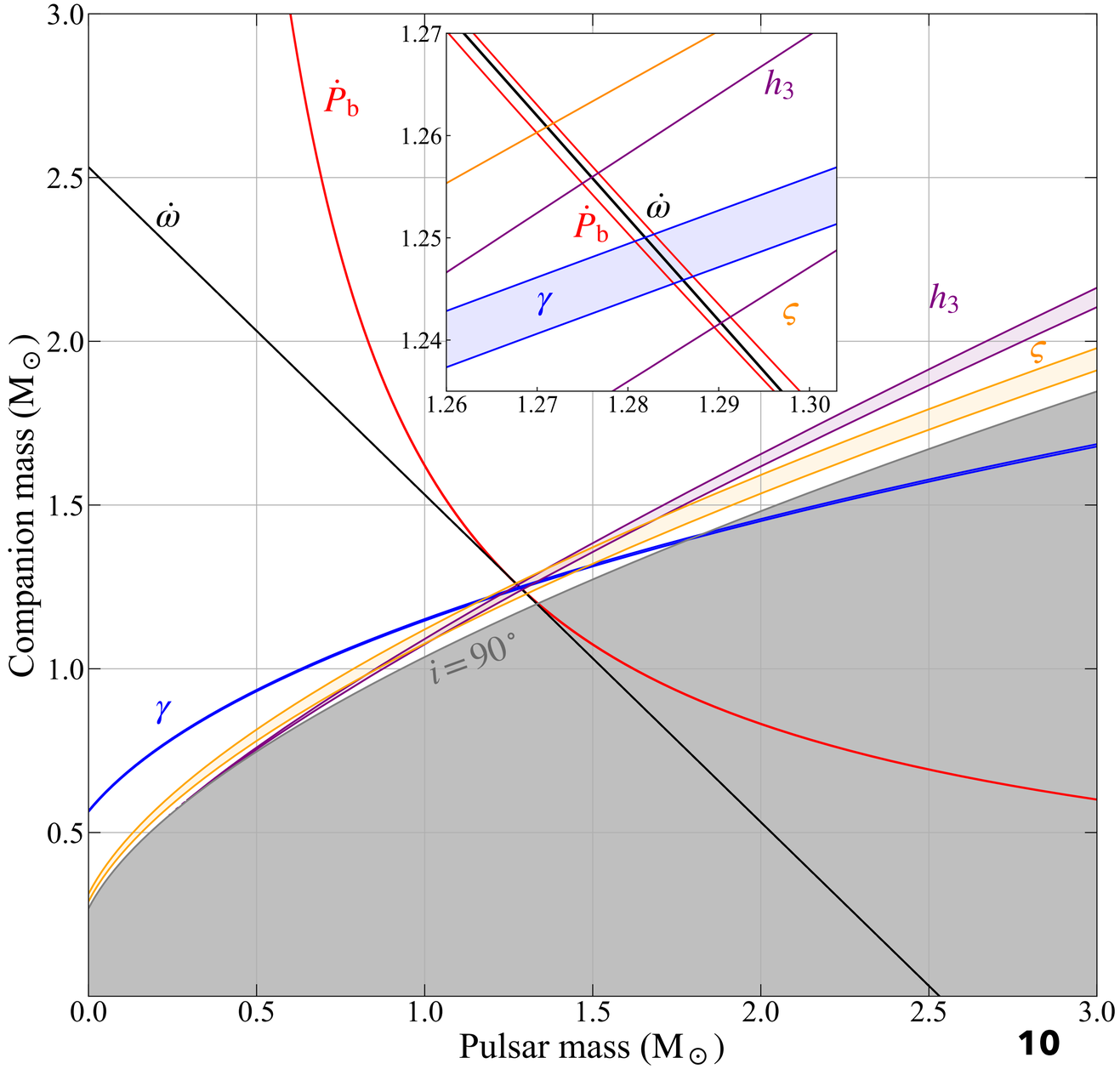
$\dot{\omega}$ (deg yr^{-1})	γ (ms)
25.79205(40)	0.2591(6)

Higher order contribution

The second Post-Newtonian and the **Lense-Thirring effect**

$$\dot{\omega} = \dot{\omega}^{1\mathrm{PN}} + \dot{\omega}^{2\mathrm{PN}} + \dot{\omega}^{\mathrm{LT}}$$

PSR J1946+2052, the most compact DNS system in the Galaxy



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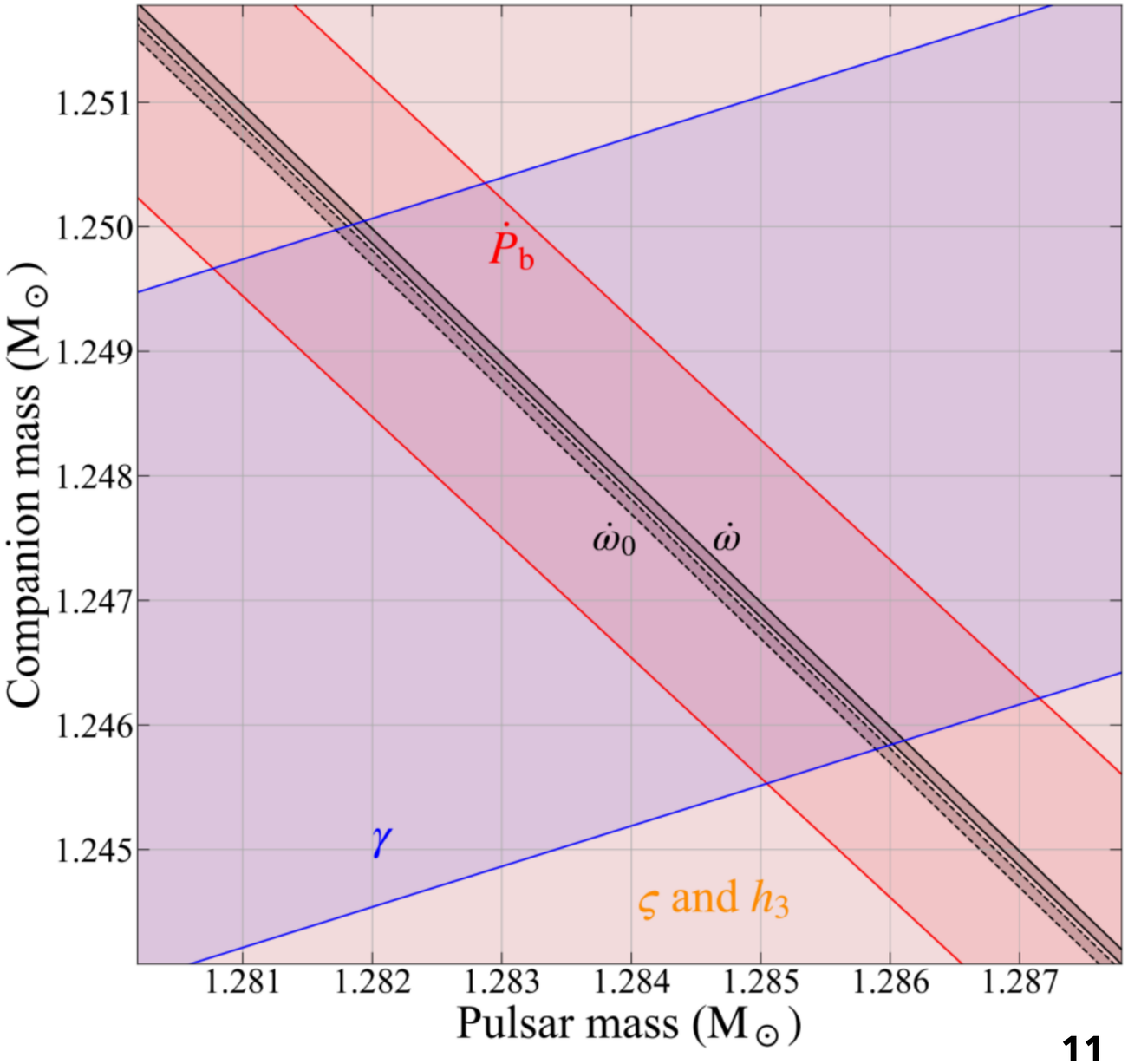
$$\dot{\omega} = \dot{\omega}^{\rm 1PN} + \dot{\omega}^{\rm 2PN} + \dot{\omega}^{\rm LT}$$

$$\dot{\omega}^{\rm 2PN} = 0.00078422(2)\ {\rm deg\ yr^{-1}}$$

$$\dot{\omega}^{\rm LT} = -\,0.000884(1) \times I_{\rm A}^{(45)}\ {\rm deg\ yr^{-1}}$$

For PSR J1946+2052, the 2PN and LT terms are 2 times larger than those in the Double Pulsar.

PSR J1946+2052, the most compact DNS system in the Galaxy



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25.79205(40)	0.2591(6)

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$$\dot{\omega} = \dot{\omega}^{1PN} + \dot{\omega}^{2PN} + \dot{\omega}^{LT}$$

	M	m_c ($M_\odot$)	m_p
$\dot{\omega}^{1PN}$	2.531858(60)	1.2480(21)	1.2838(21)
$\dot{\omega}^{1PN} + \dot{\omega}^{2PN}$	2.531754(60)	1.2478(20)	1.2839(20)
$\dot{\omega}^{1PN} + \dot{\omega}^{2PN} + \dot{\omega}^{LT}$	2.531922(57)	1.2477(21)	1.2842(21)

The role of SKA on PSRs J1913+1102 and J1946+2052

The summary of the simulation setup for observing periods and ToA uncertainty. For SKA AA*/AA4, band 1 is 350-1050 MHz, and band 2 is 950-1760 MHz

Telescope	FAST	SKA AA*	SKA AA4
Number of antennas	1	144	197
Effective diameter (m)	300	172	204
Observing period (yr)	2025-2028	2028-2038	2028-2038
Observing band	L	1/2	1/2
Pulsar name	$\sigma_{\rm TOA}$ (μs)		
PSR J1913+1102	26.0	62.1	44.2
PSR J1946+2052	8.0	19.1	13.6

For PSR J946+2052, we simulated 10 years of SKA AA*/AA4 ToAs (07/2028–07/2038) at L-band and 3 years of FAST ToAs (01/2025–07/2028), combined with previous data (using simulated data), compared to results using 7-year data (Meng et al. in prep.).

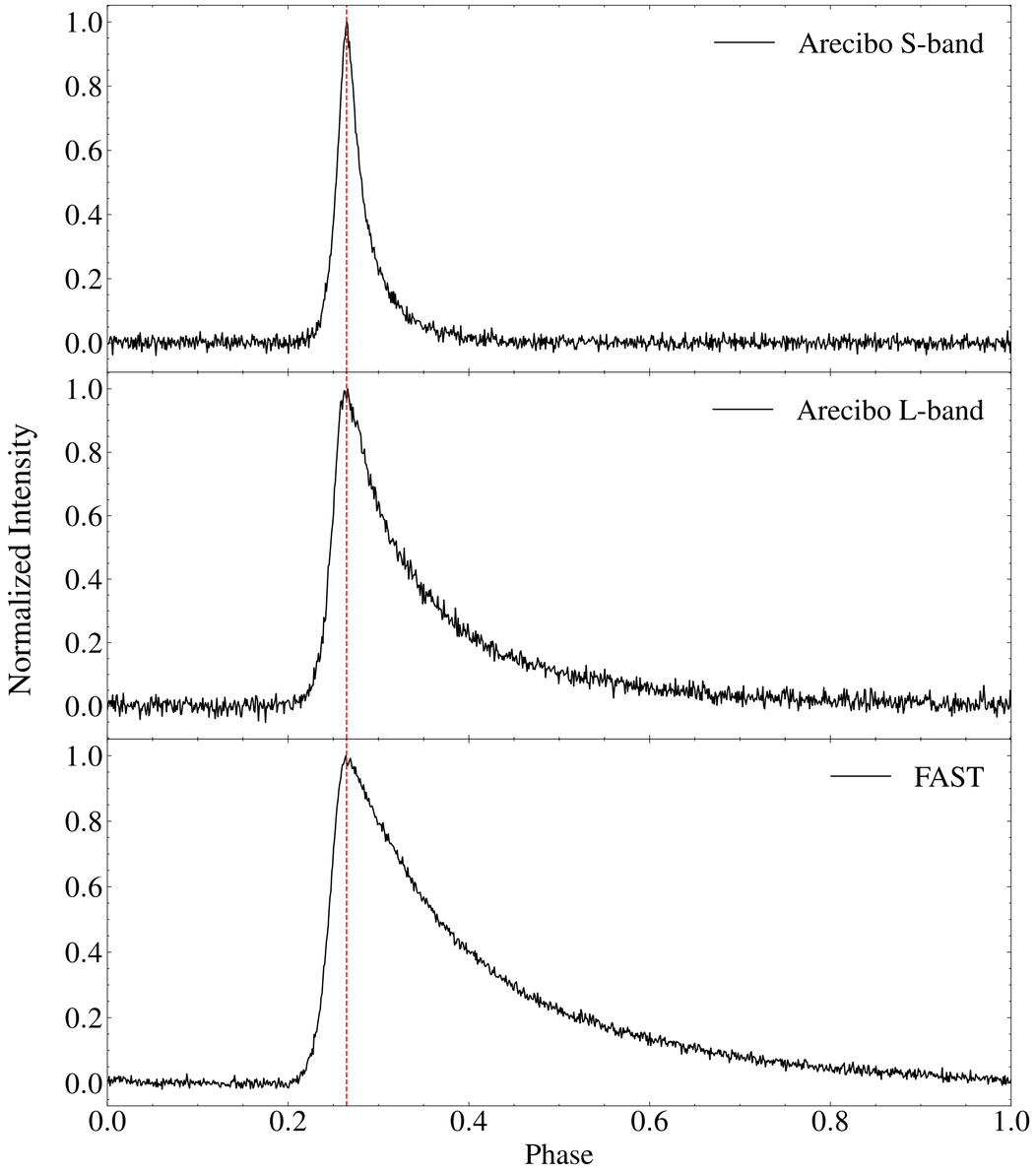
	Comb AA* / 7yr	Comb AA4 / 7yr
$\dot{\omega}$	7.6	8.6
$\gamma_{\rm E}$	2.7	3
$\dot{P}_{\rm b}$	15.5	17.2
h_3	2.0	2.2
ς	1.8	2.0

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

For PSR J1913+1102, given the scattering at L-band, we also simulated parameter precision assuming SKA AA4 can observe at 1650–3050 MHz with 8.5 μs timing errors. **As shown in the last column of the table, S-band observations from SKA would greatly enhance the precision of PK parameter measurements.** So if the SKA can provide observations in the S-band, it would significantly improve the measurement precision of the PK parameters for this system.

Thank you !!!

PSR J1913+1102, the asymmetric DNS system



The profile of this source is badly affected by scattering, and as a result, FAST observations in the L band do not significantly improve the precision of the TOAs.

X. Miao. et al. in preparation