Testing the Theories of Gravitation with Pulsars

— Progress of the FAST project

Speaker: Xueli Miao (缪雪丽)

Collaborators: Weiwei Zhu, Michael Kramer, Paulo Freire, Lijing Shao, Lingqi Meng, Yuan Mao, Norbert Wex, Jumei Yao, Chenchen Miao, Huangchen Hu, Yanjun Guo, Emannual Fonseca, David Champion, Chengming Zhang

FAST/Future Pulsar Symposium 12

Nanyang Henan, 2023.07.05

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

Introduction

Pulsar, stably spinning neutron stars (NSs), **high magnetic field** (10^8 G – 10^{15} G), **high matter density** (~ 10^{15} g/cm^3), **high pressure** (~ 10^{36} erg/cm^3)

* In 1967, the first pulsar PSR B1919+21 was discovered (Hewish, et al., 1968)

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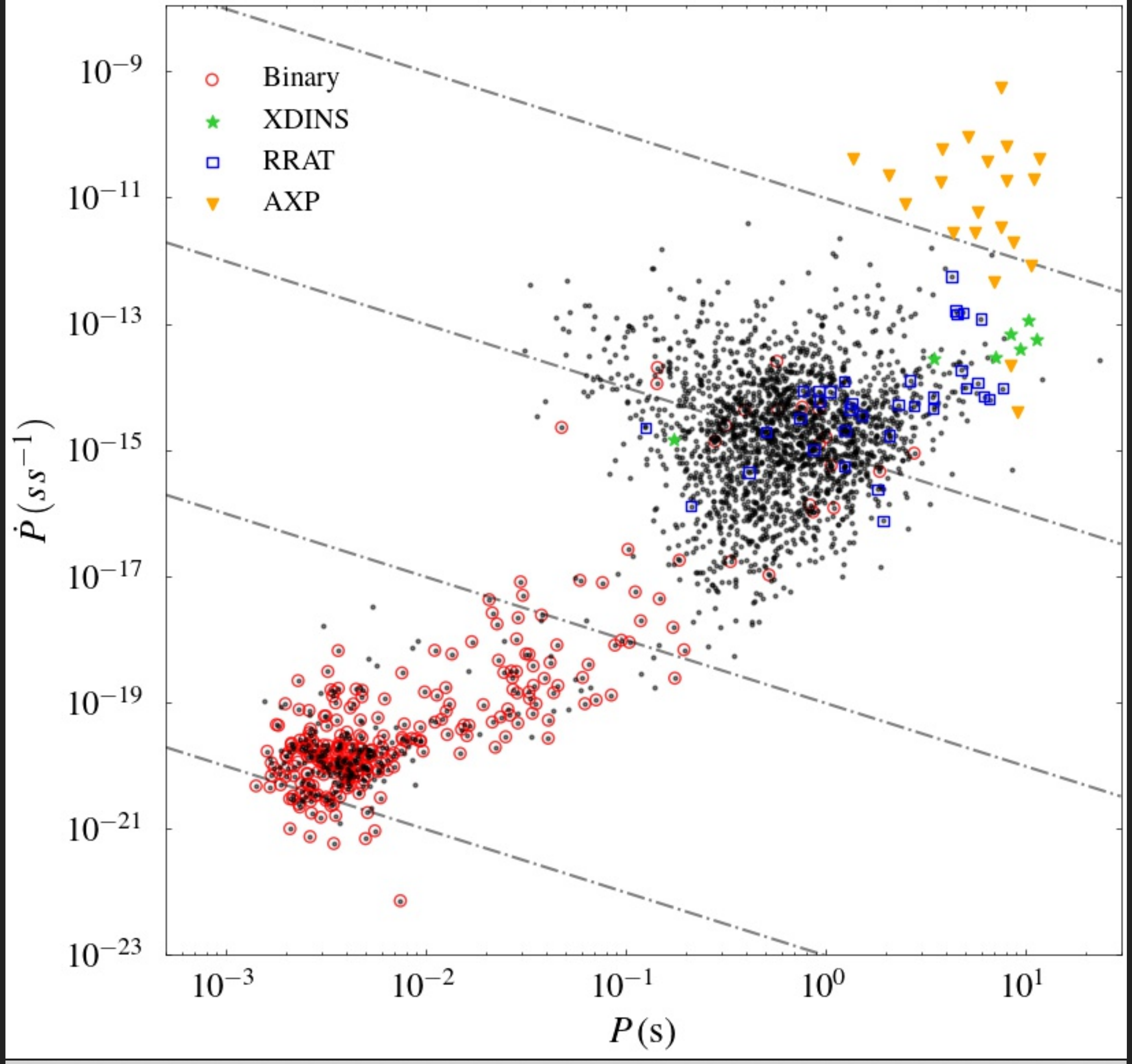

D. R. Lorimer & M. Kramer. 2005

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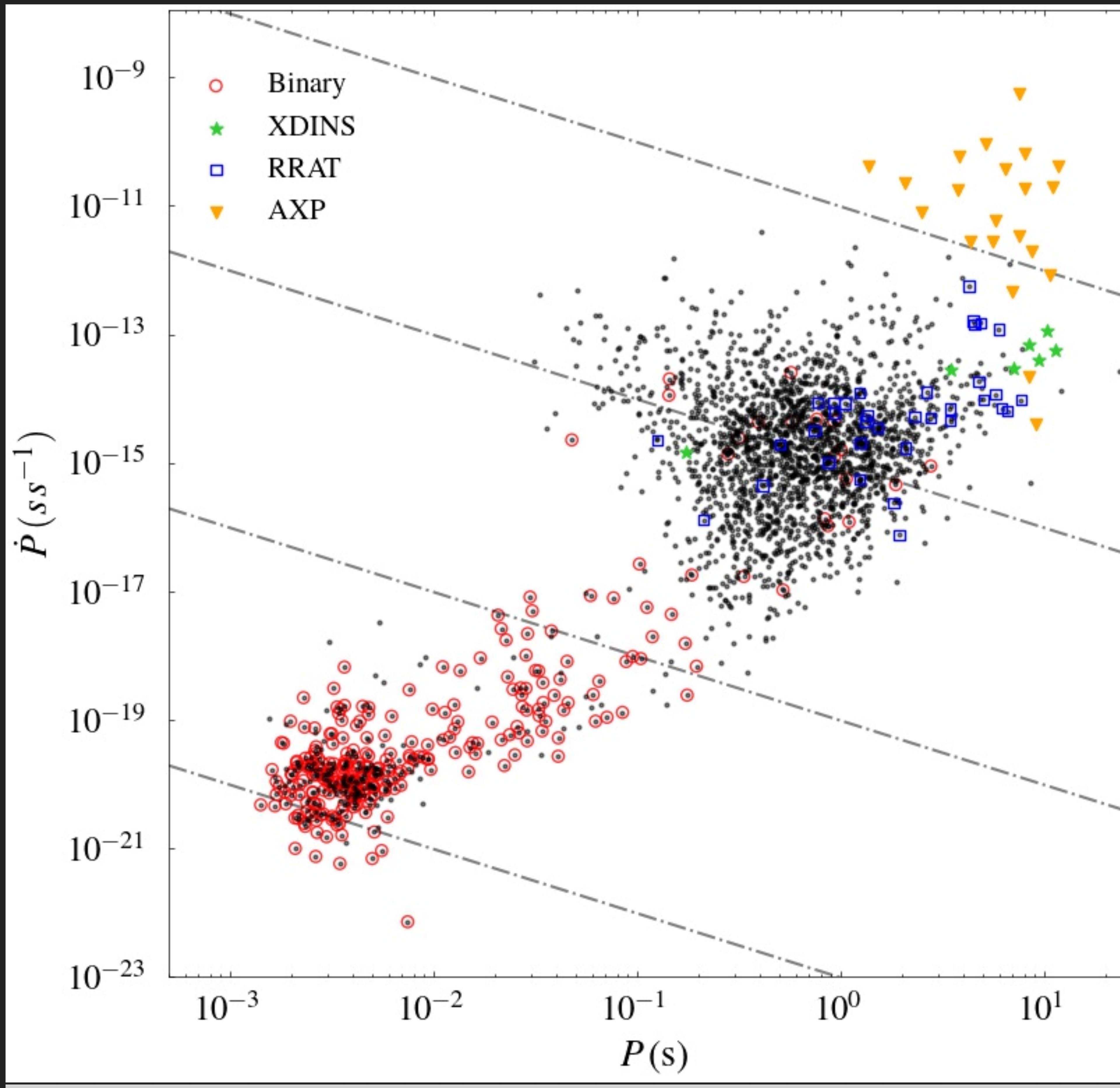

More than 3000 pulsars have been detected, where **10% are binary pulsar system**

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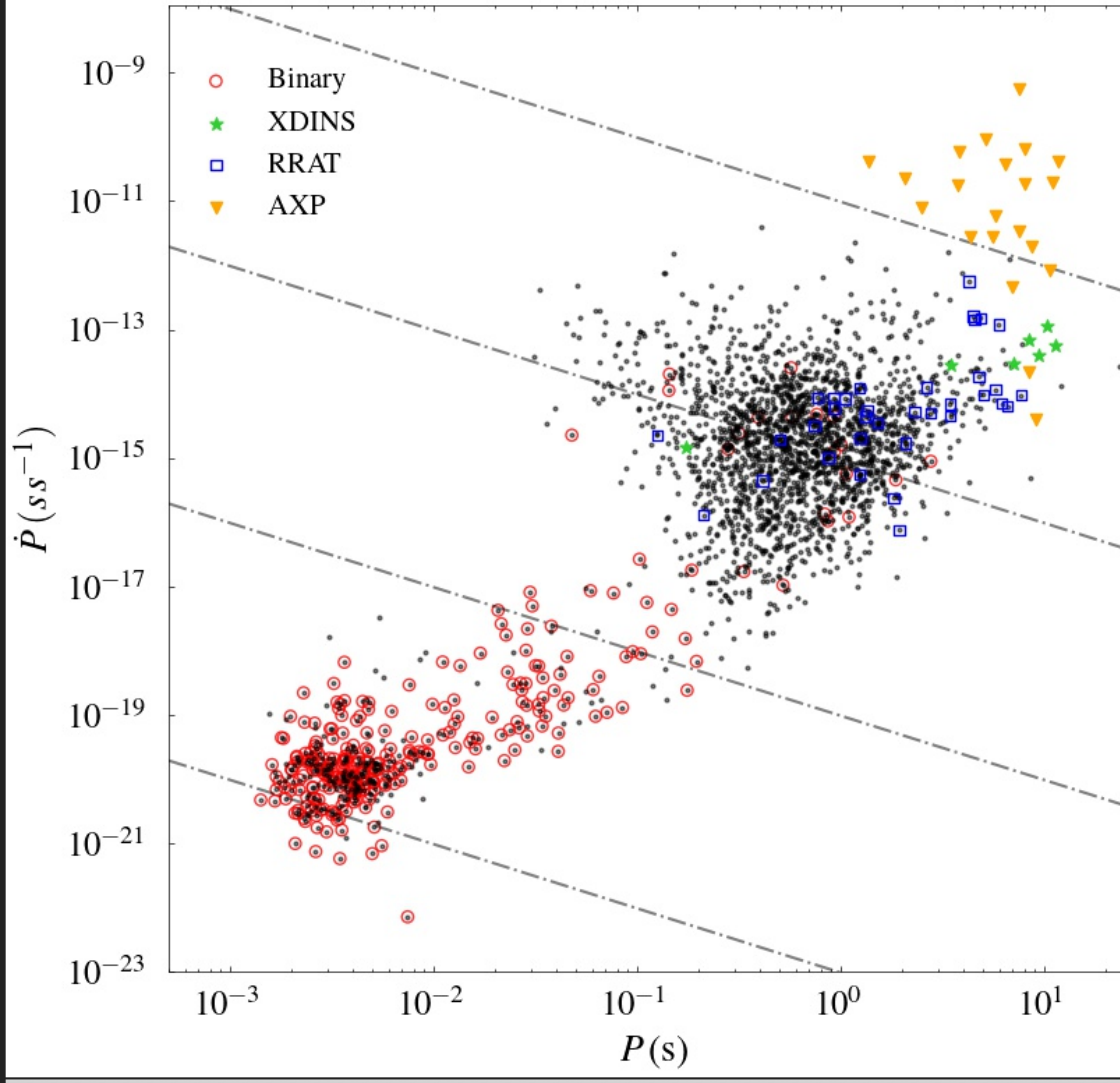

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✓ The equations of state of NSs
✓ Gravity tests
✓ Interstellar medium study
✓ Gravitational wave detection
✓ Planet physics

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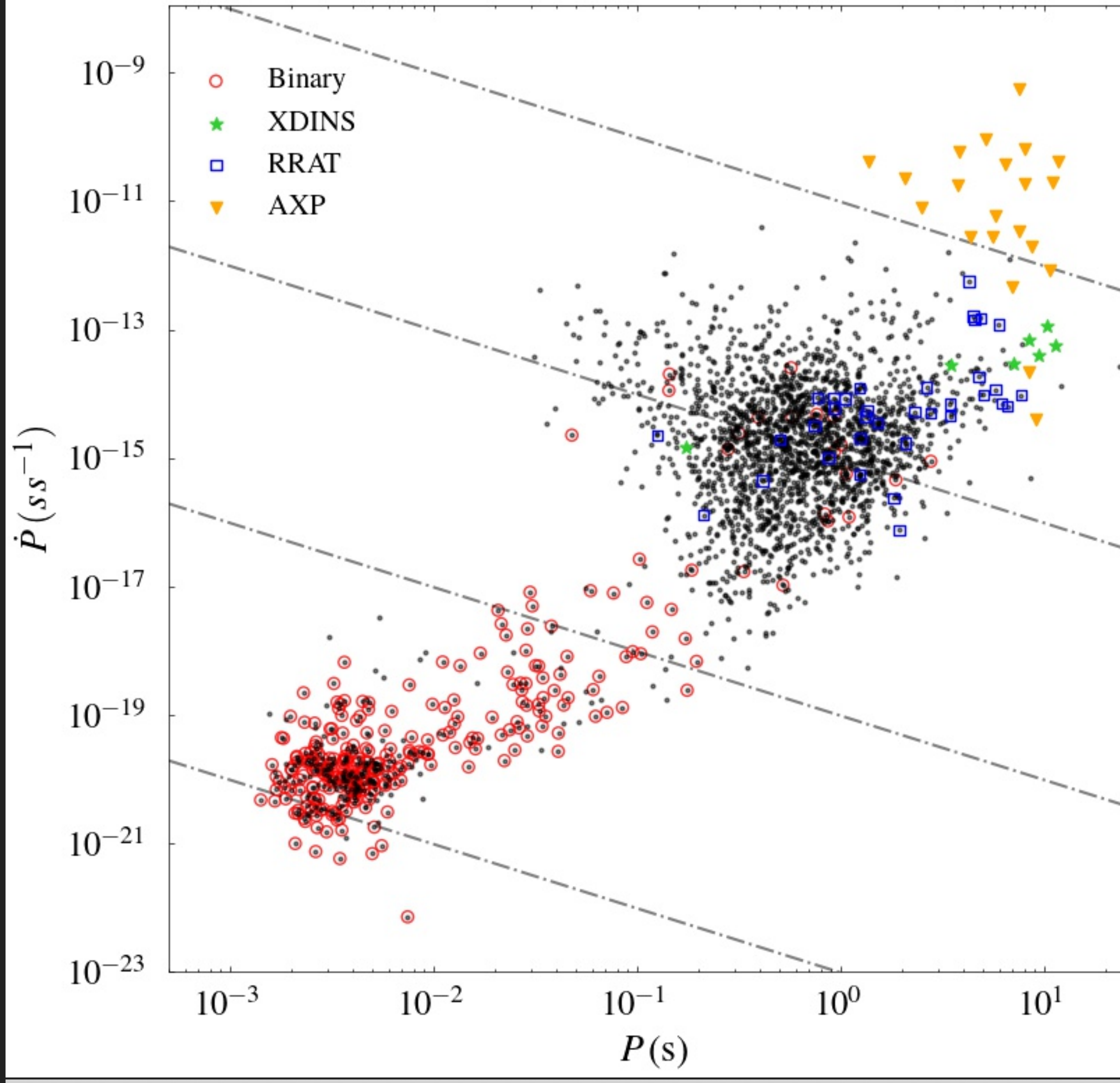

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Gravity tests

N. Wex. 2014
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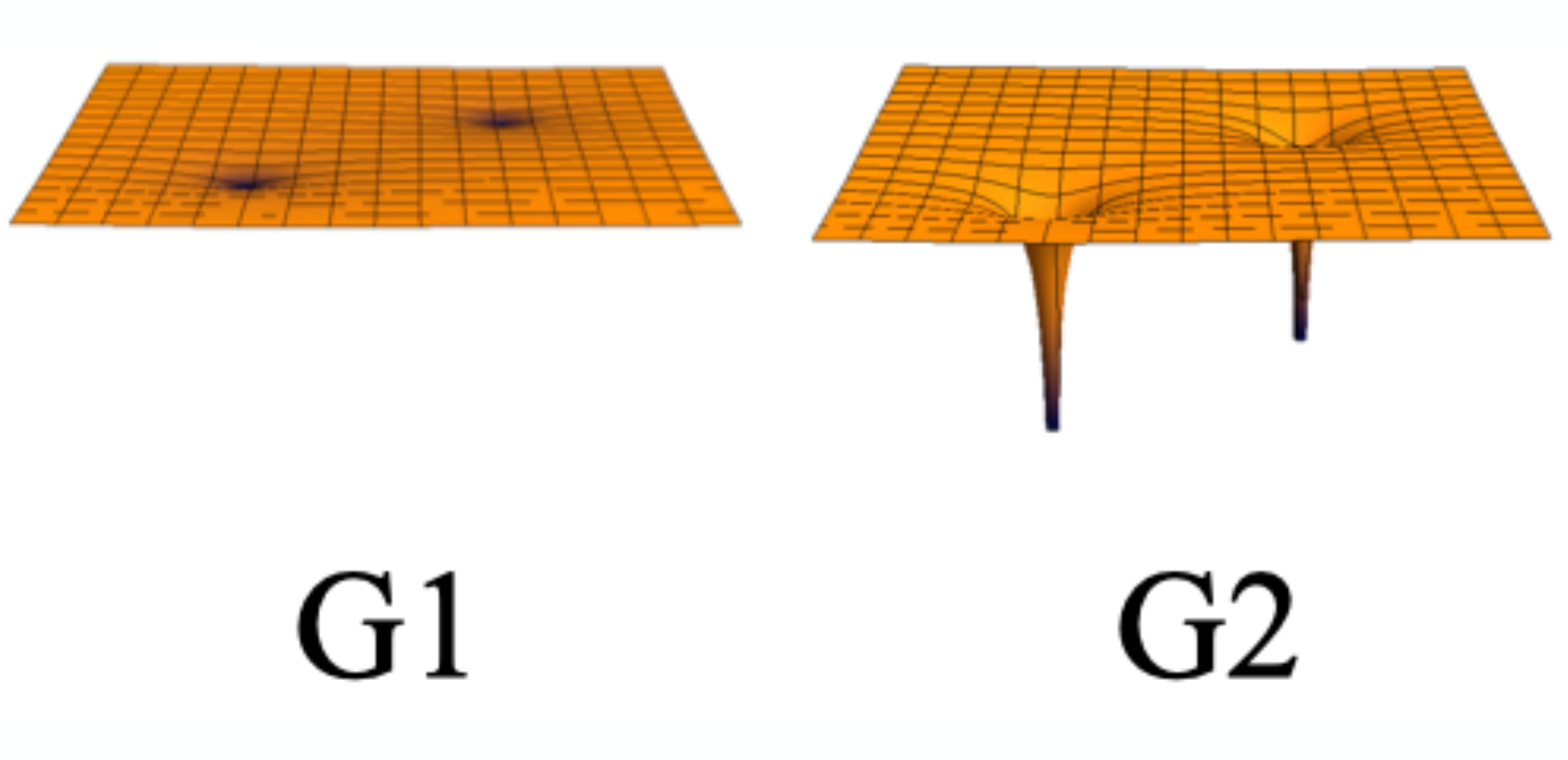
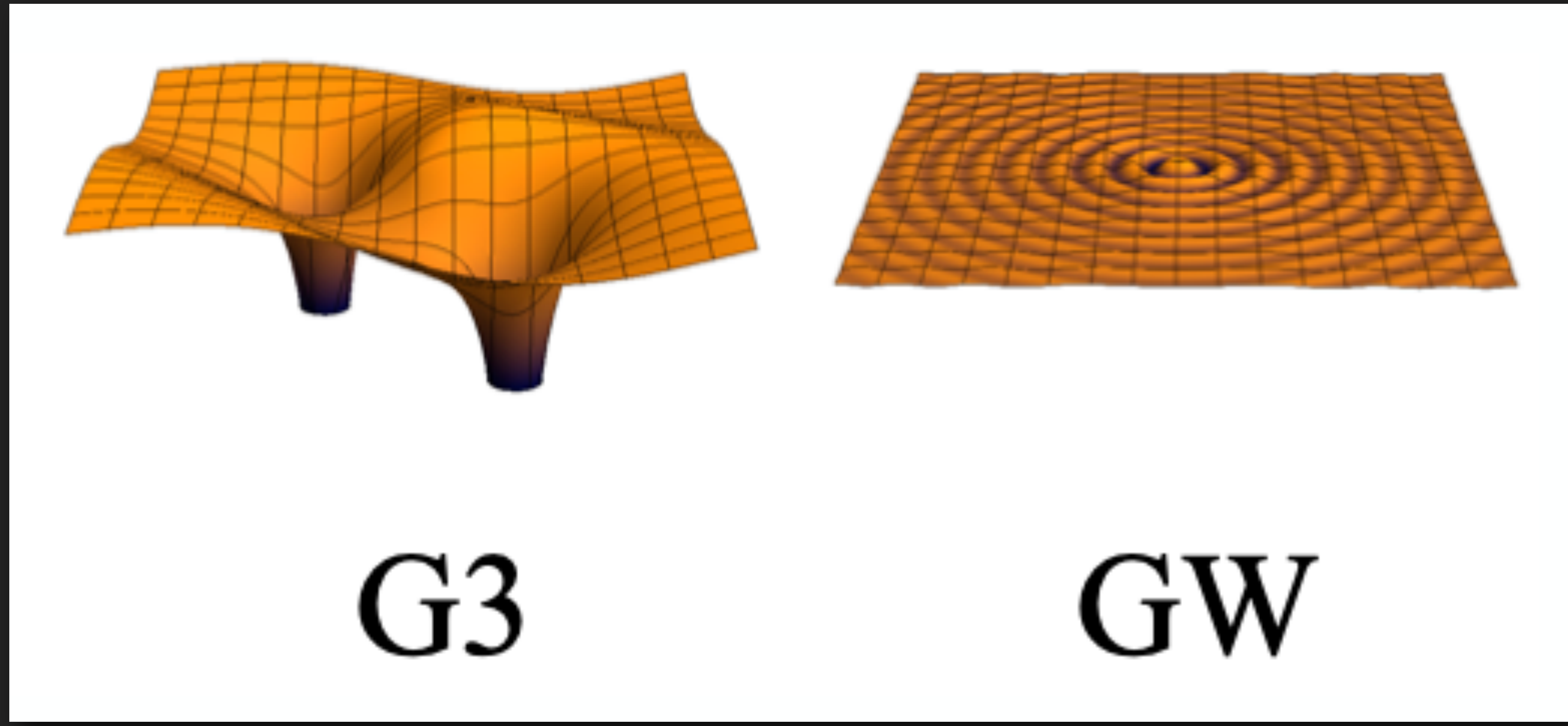


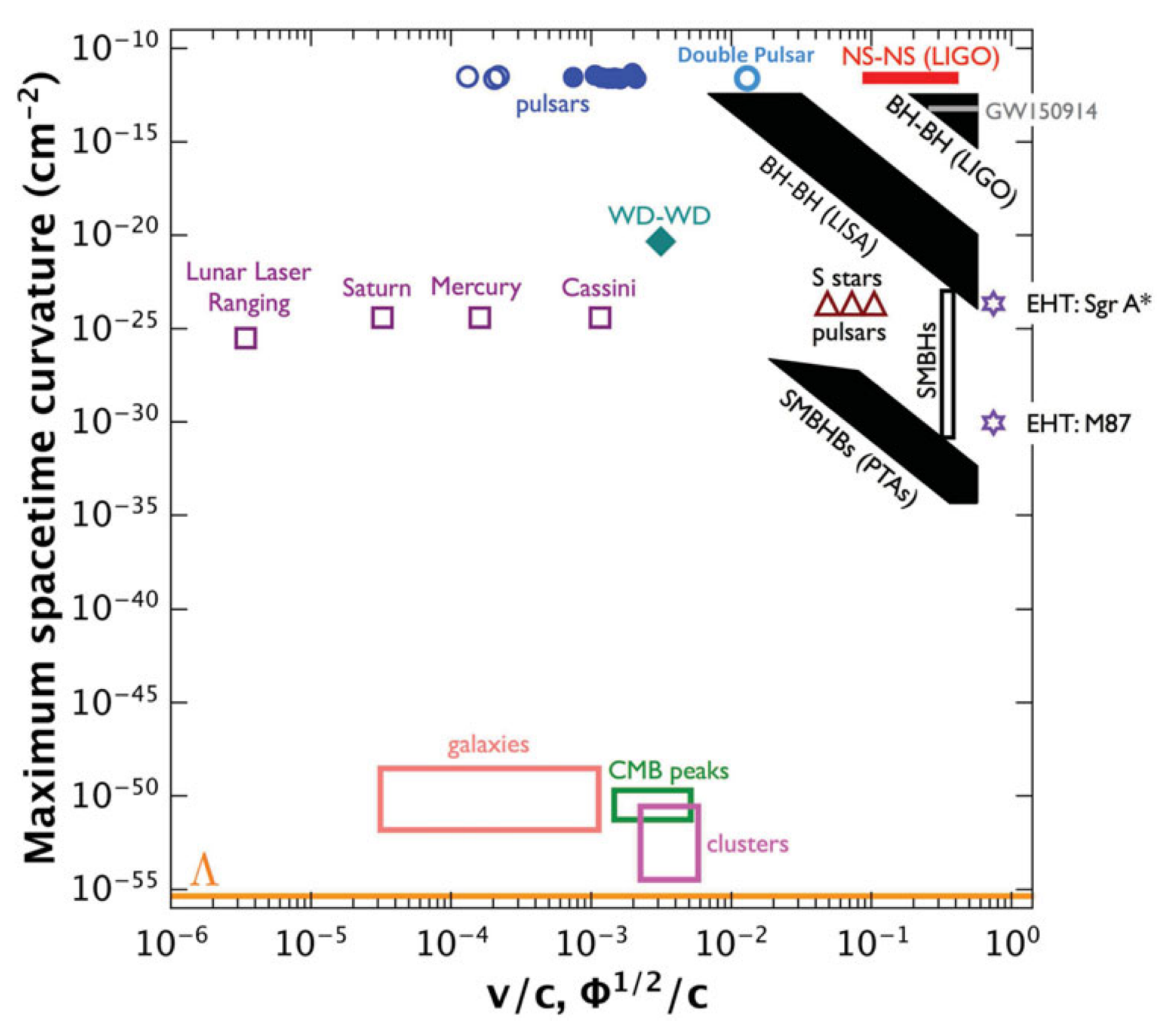
Quasi-stationary weak-field regime

Quasi-stationary strong-field regime



Highly-dynamical strong-field regime

Radiation regime



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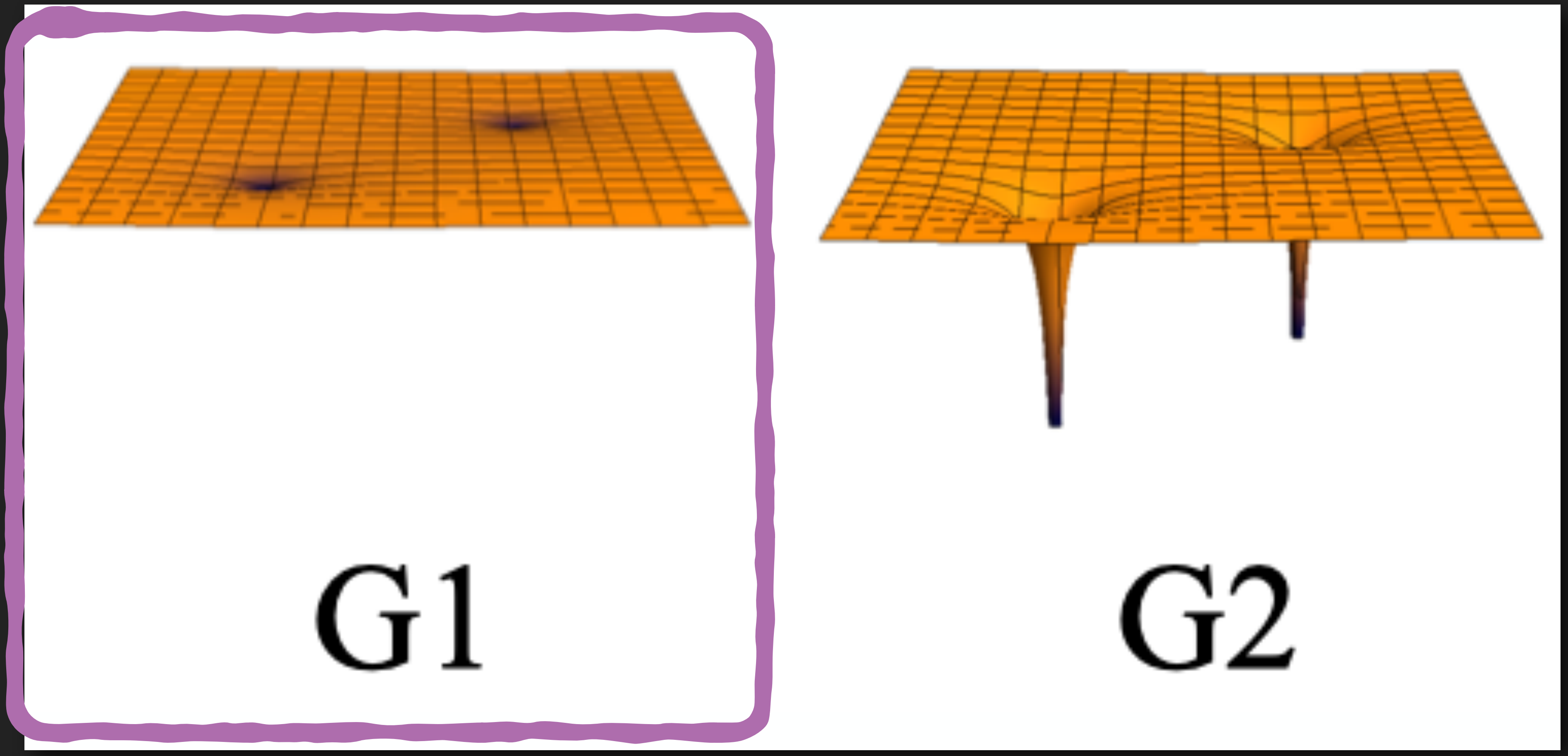

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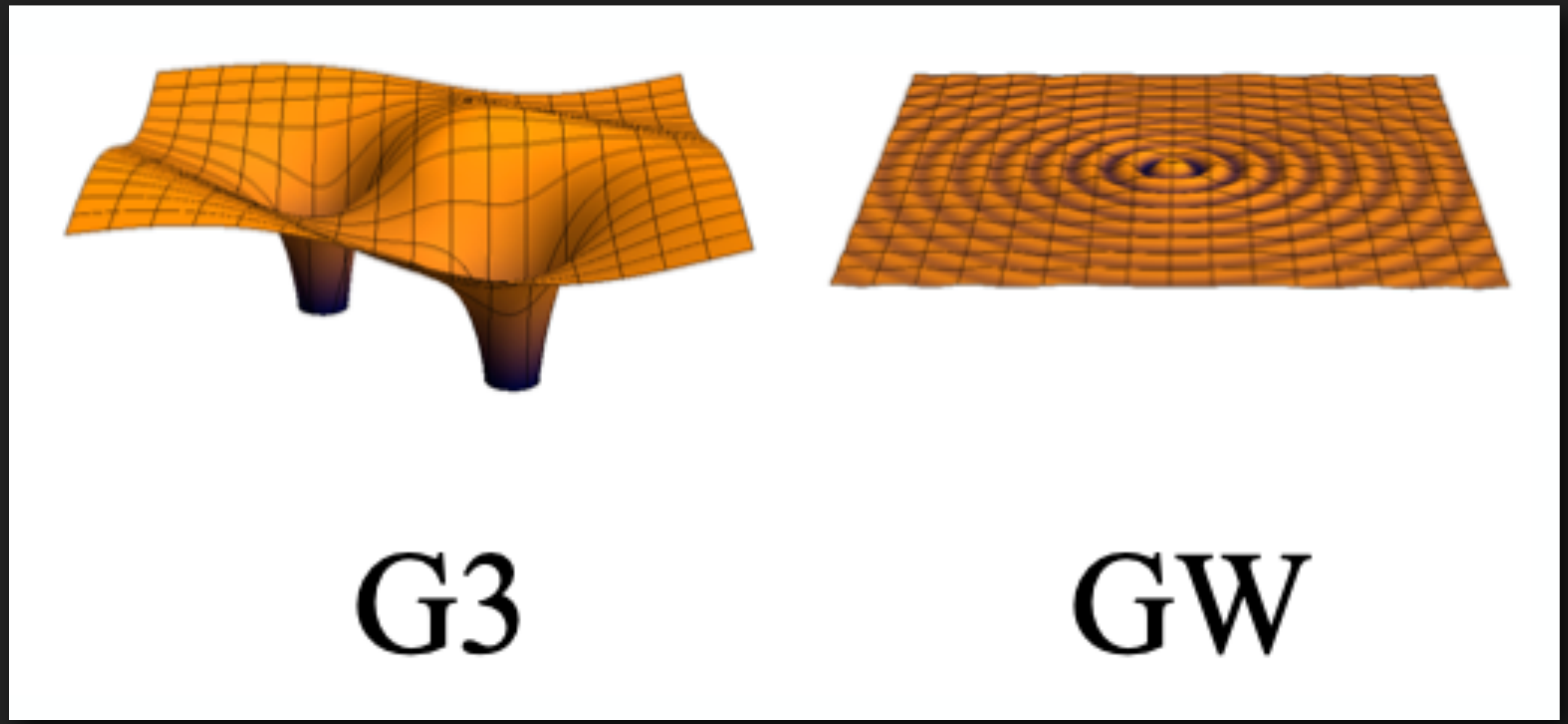

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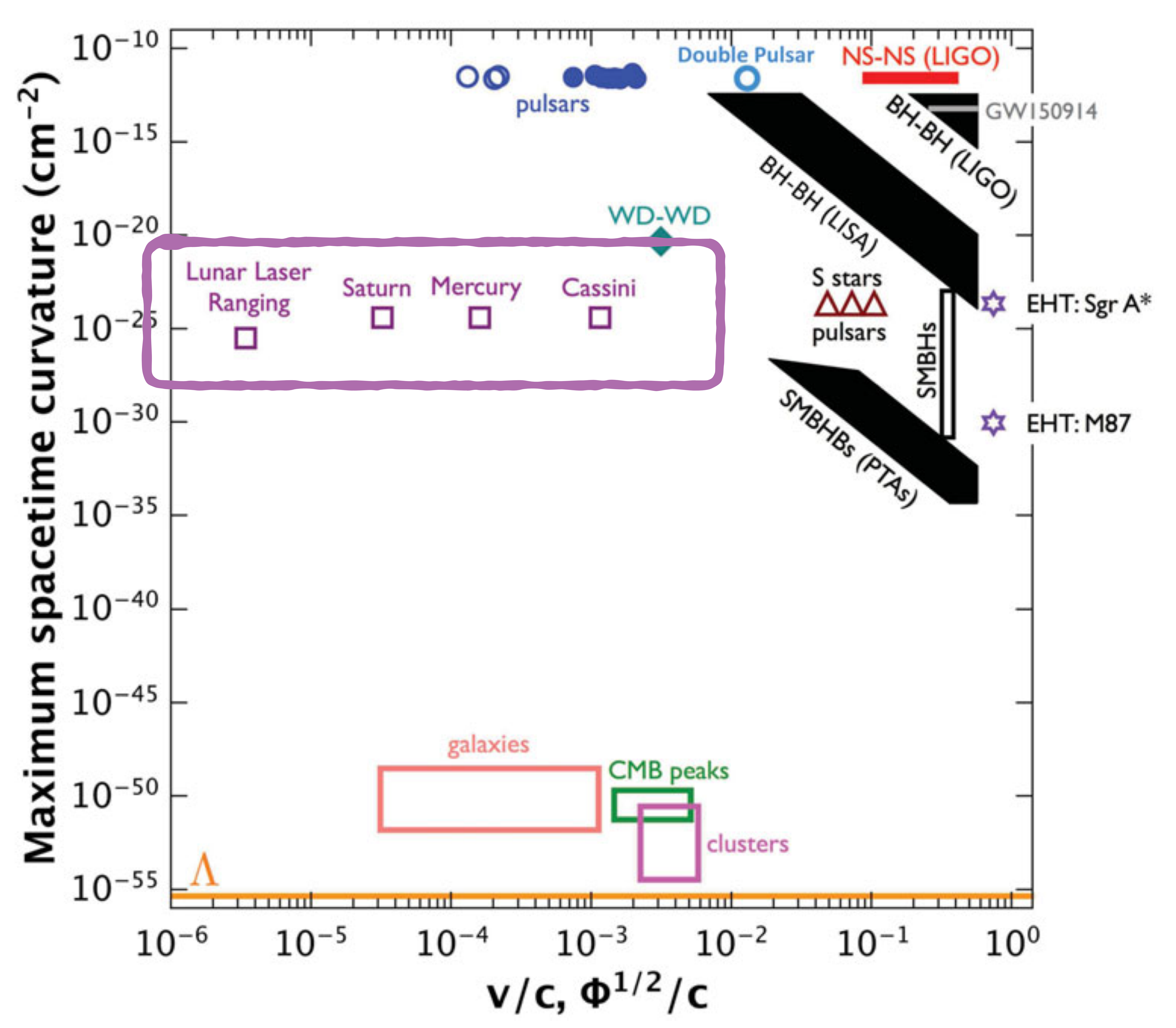

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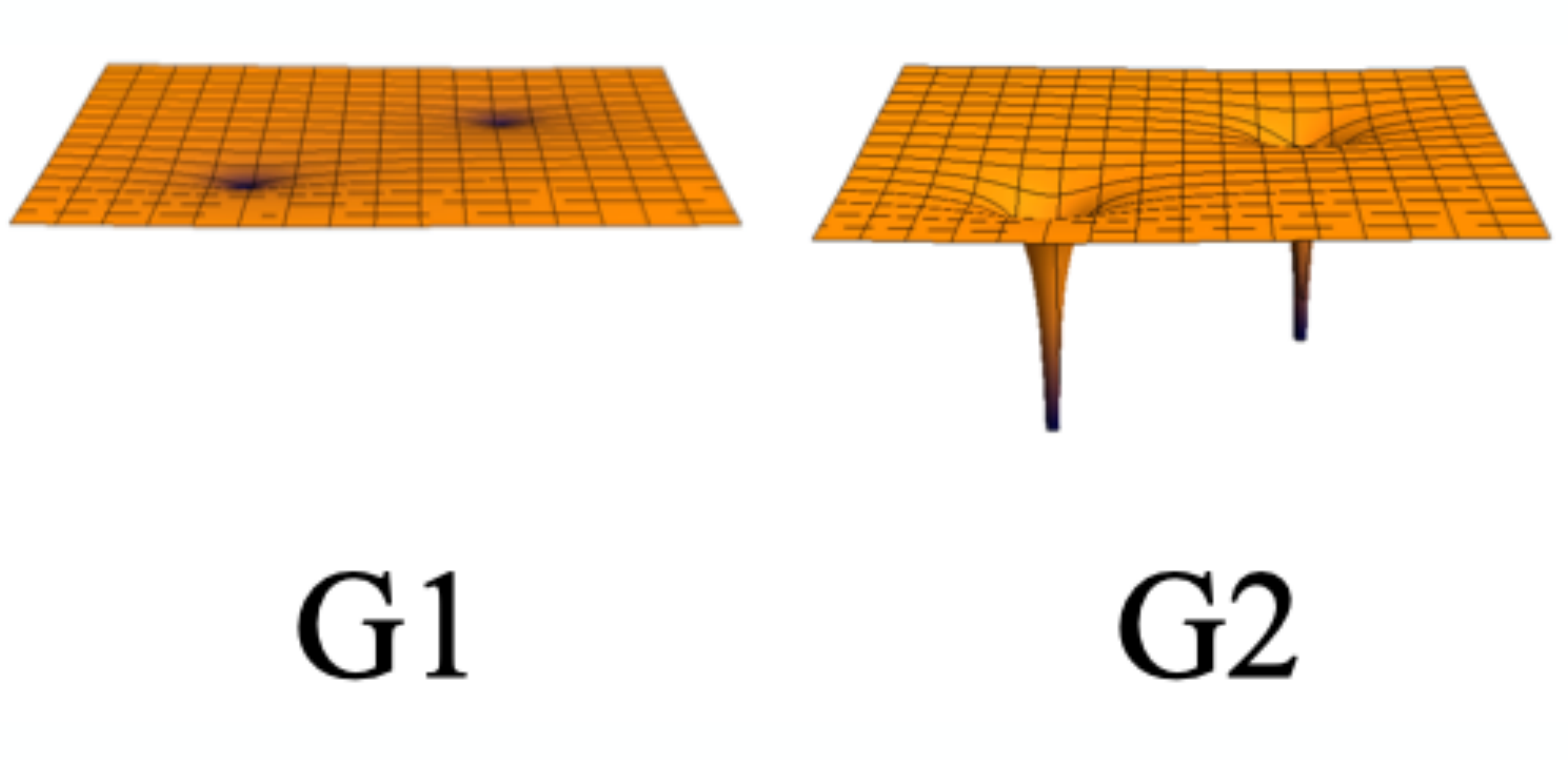

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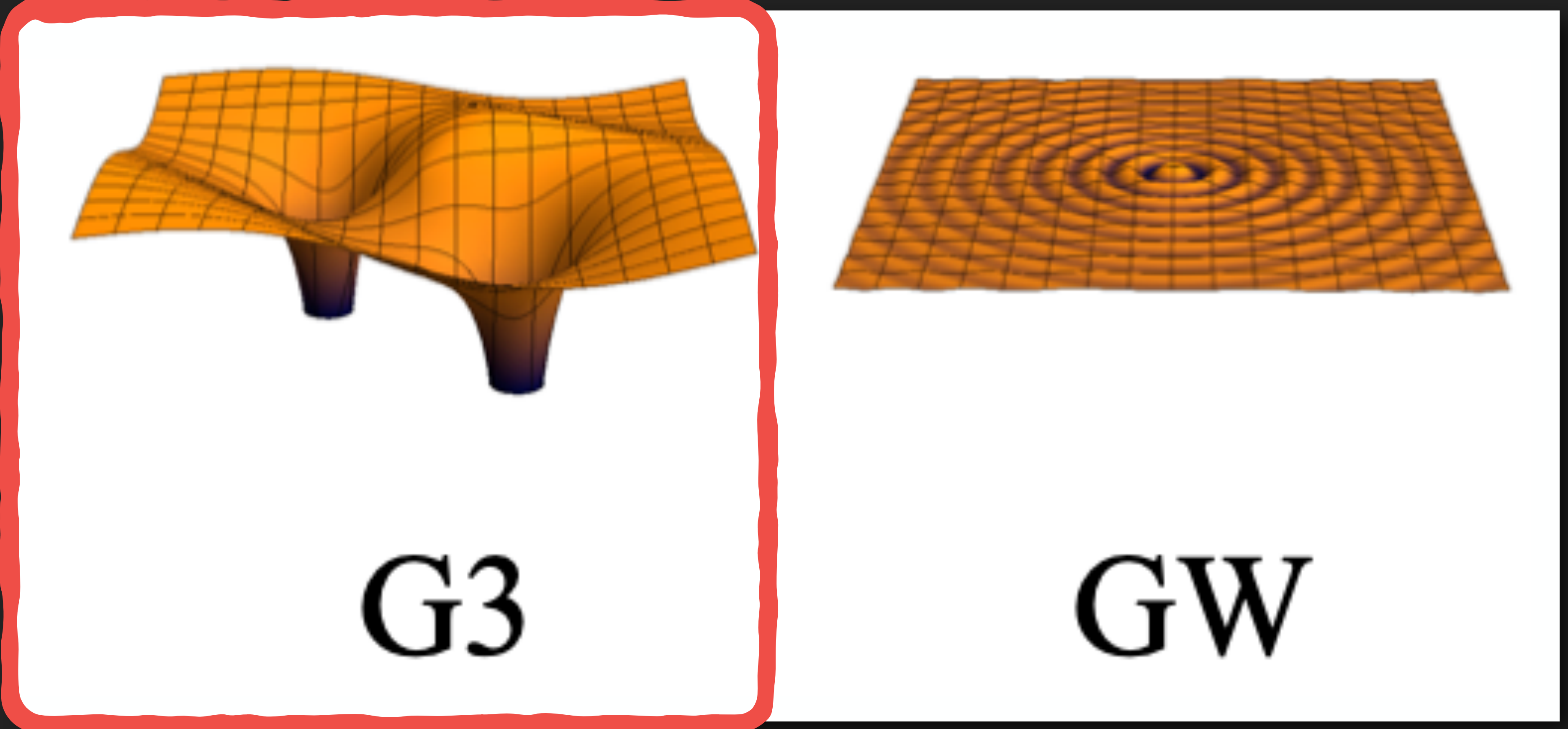

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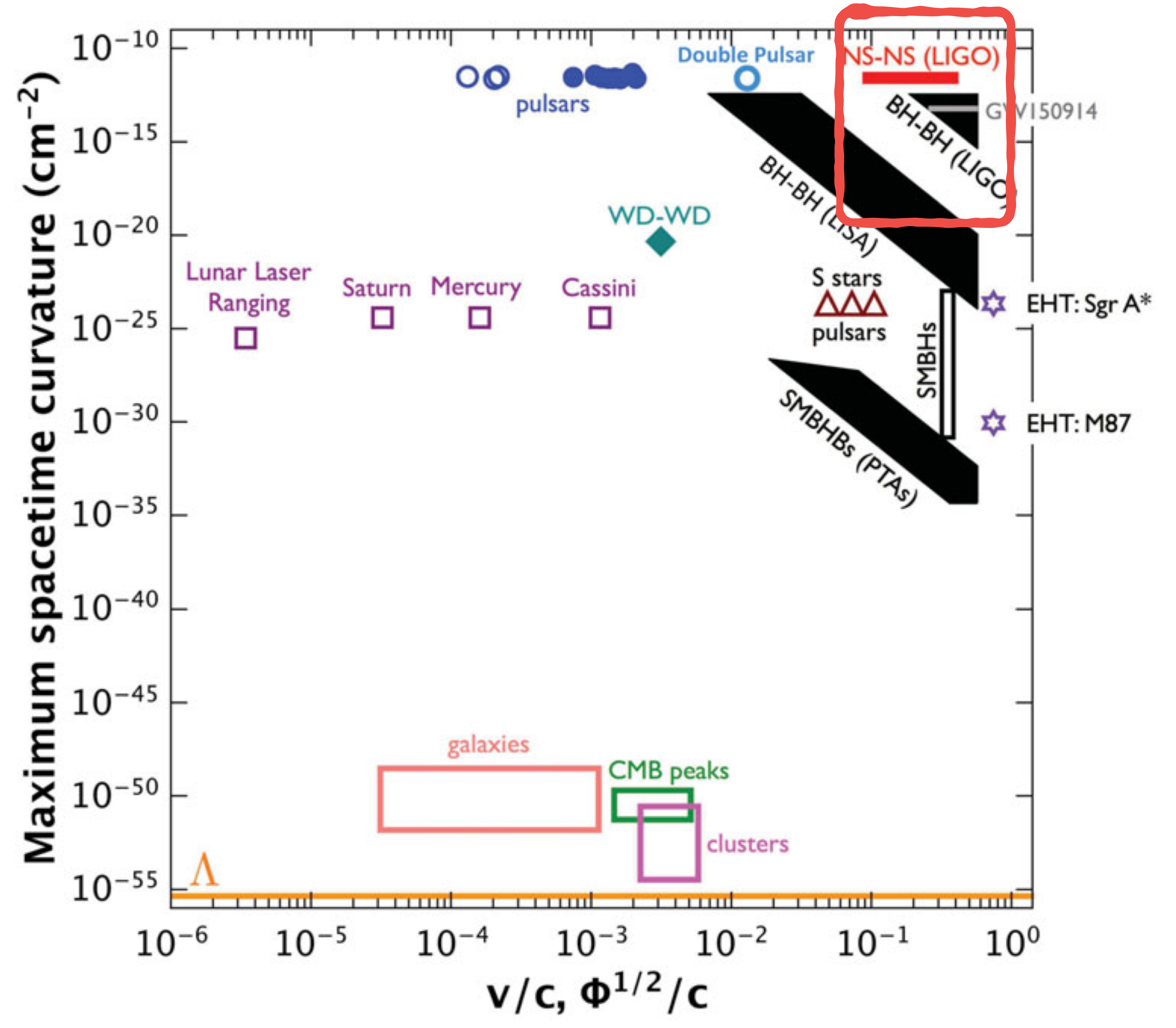

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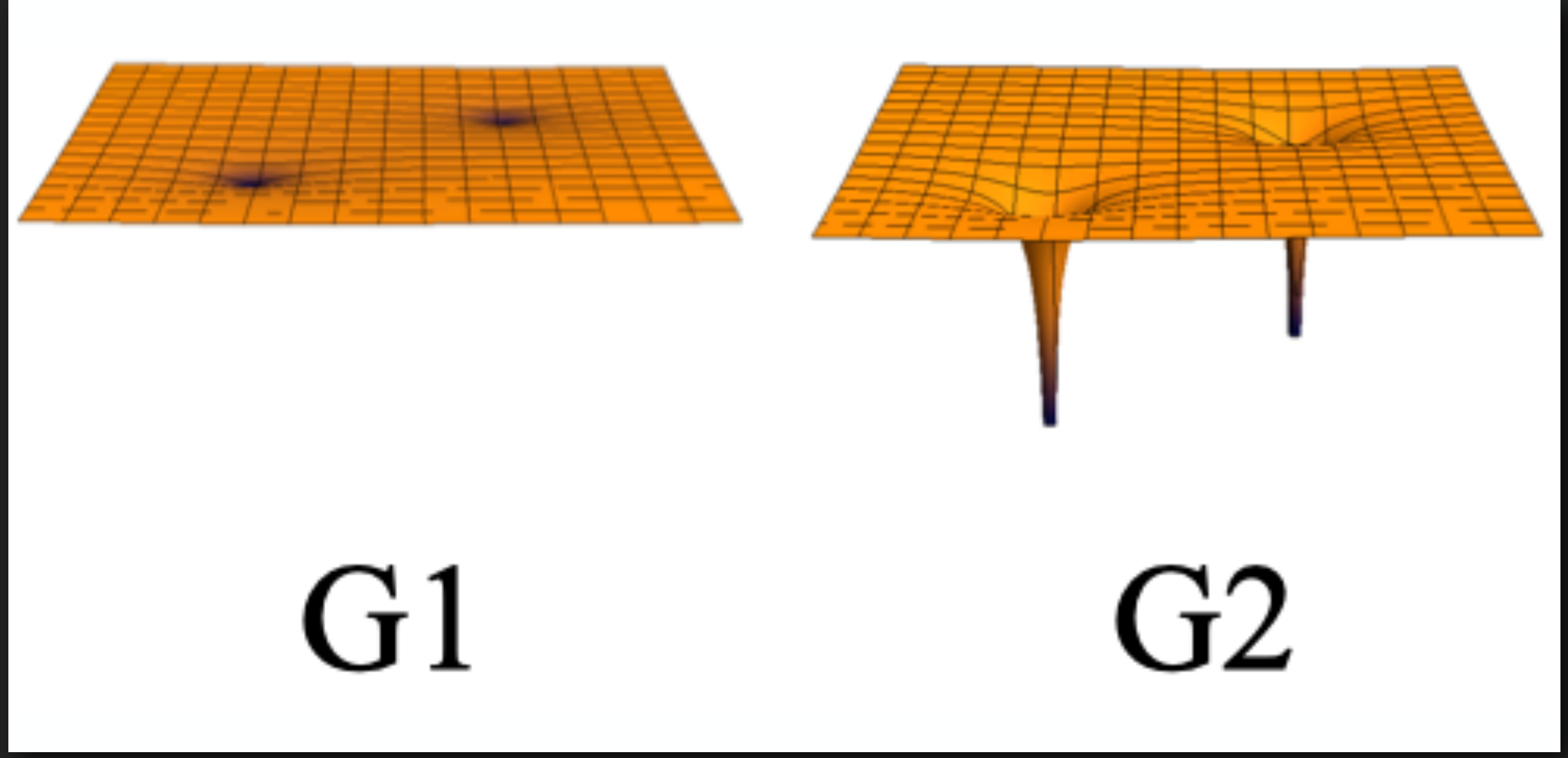

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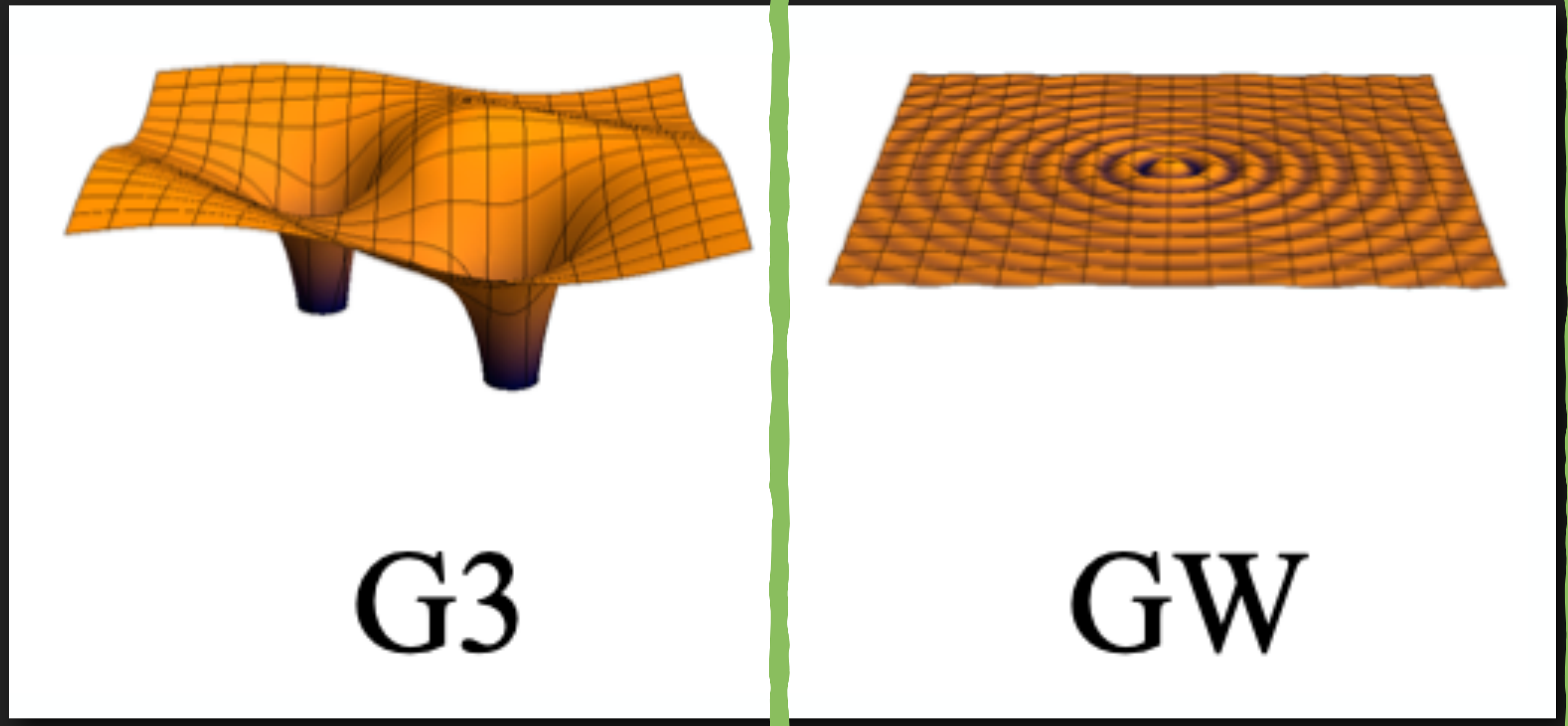

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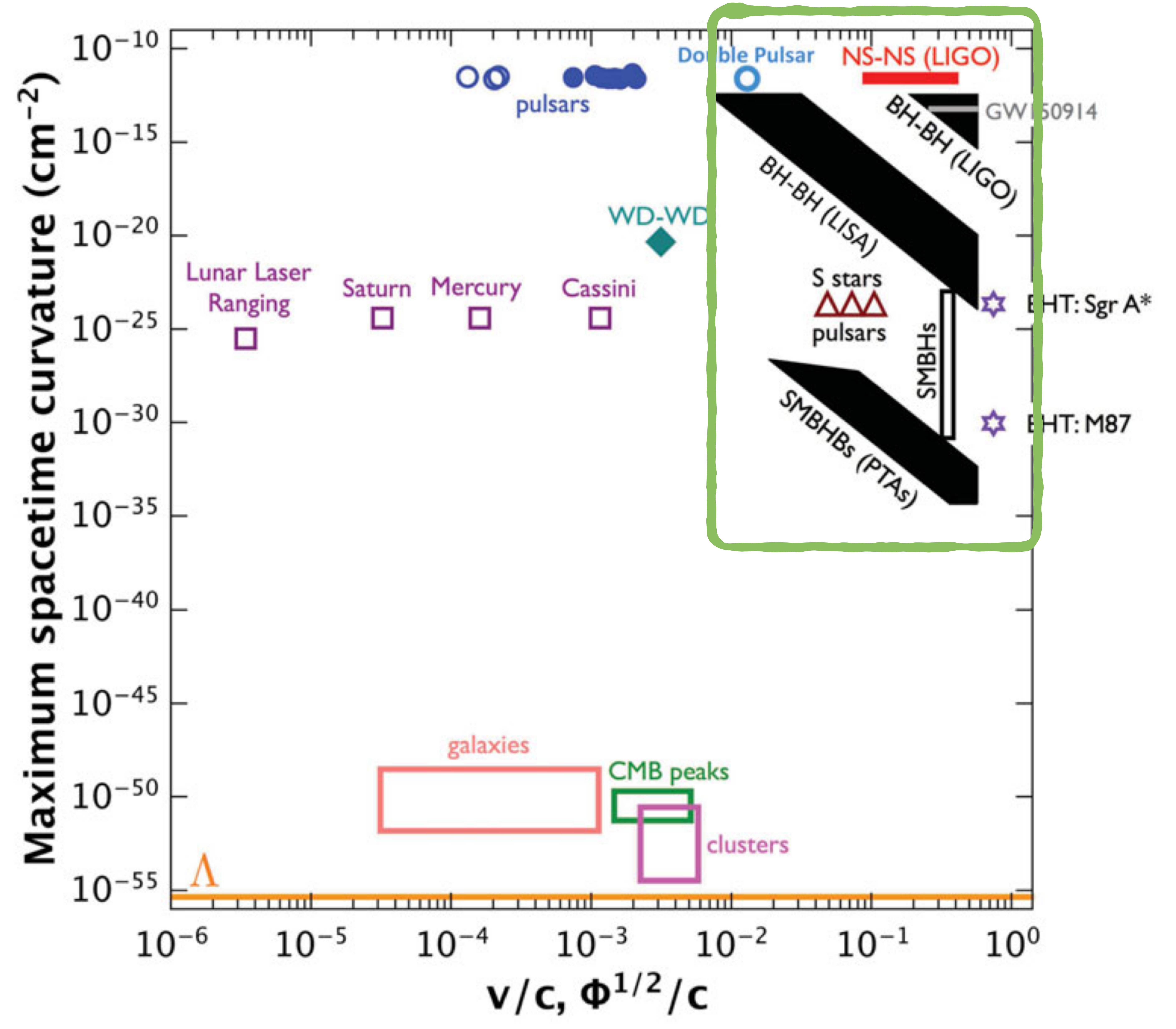

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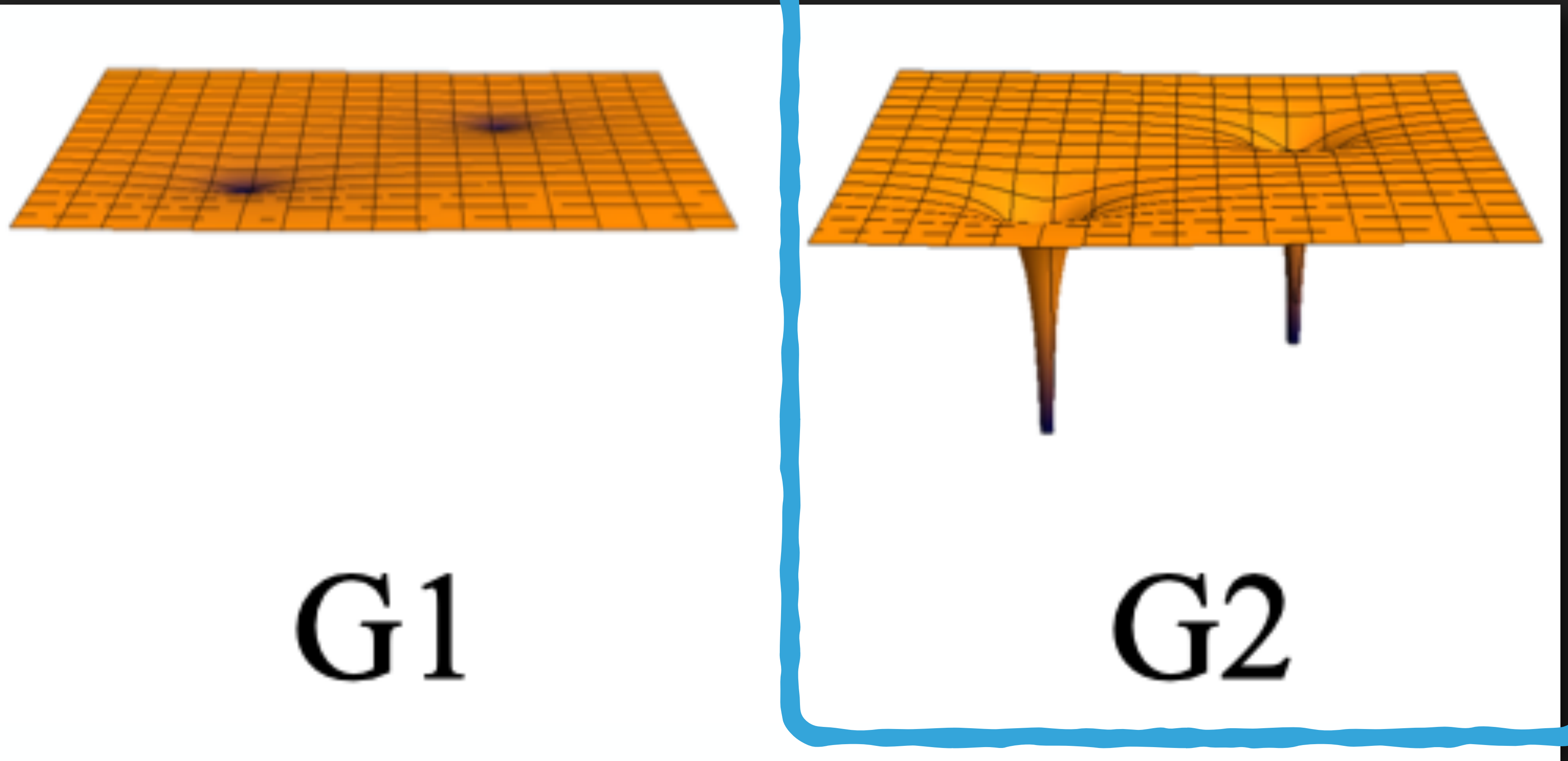

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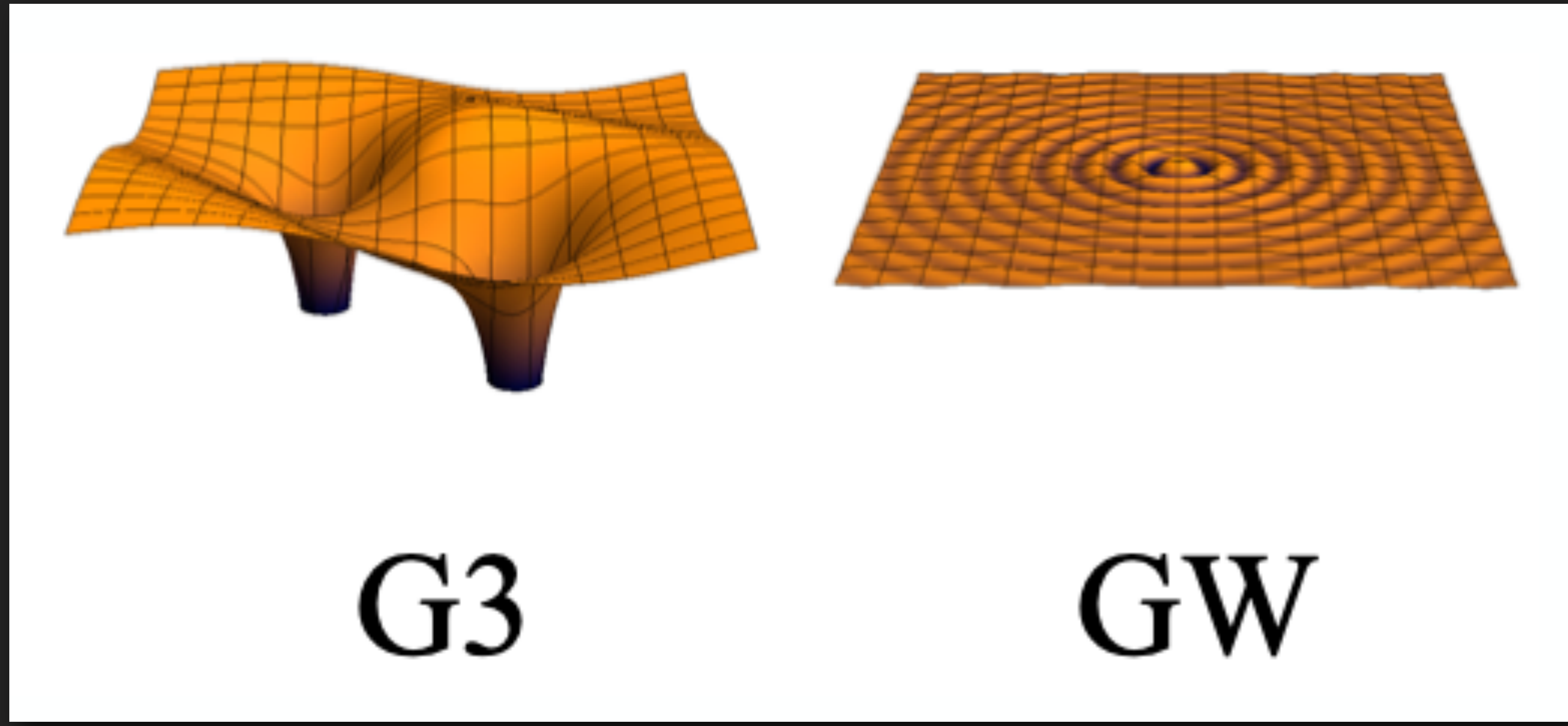

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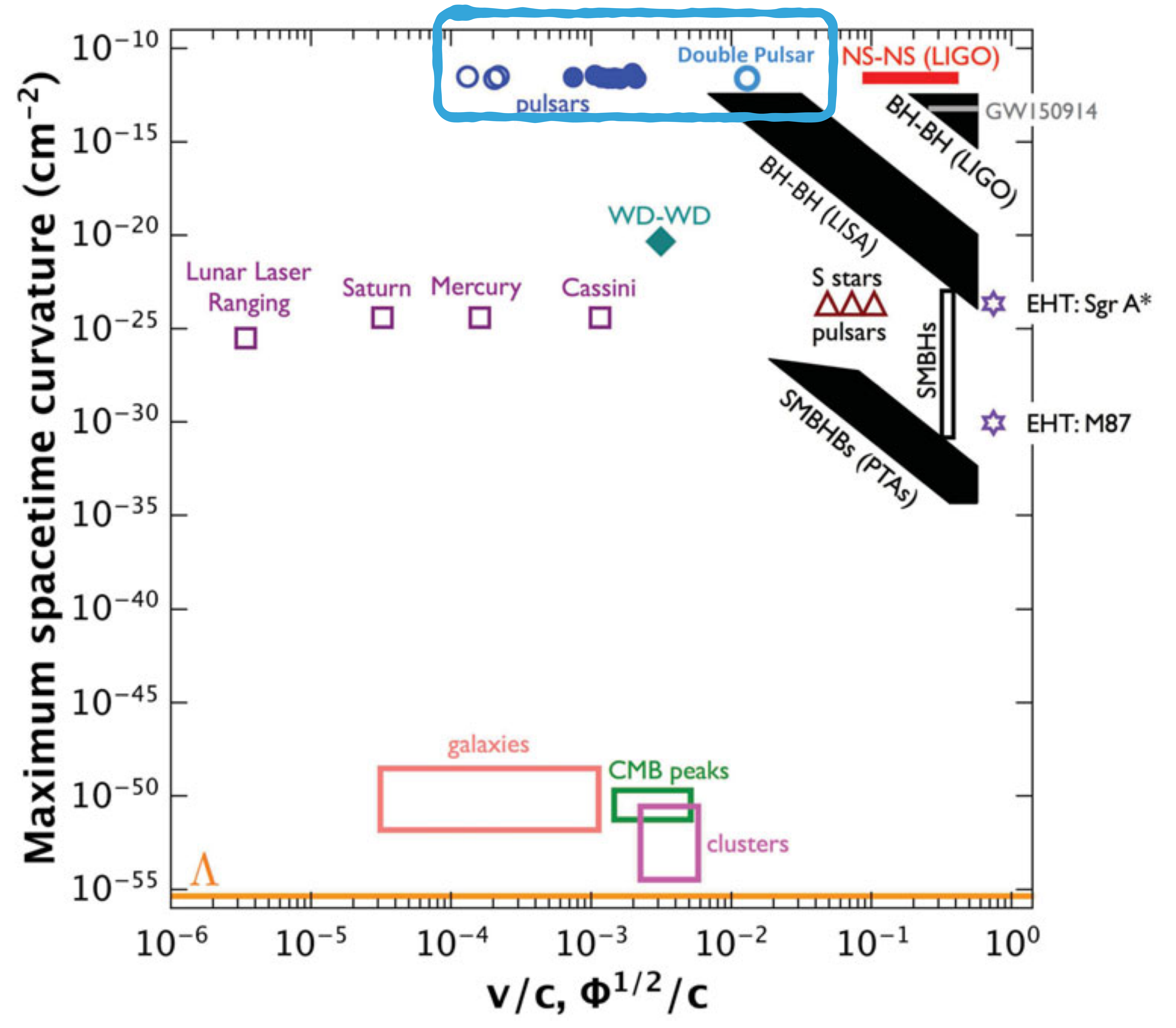

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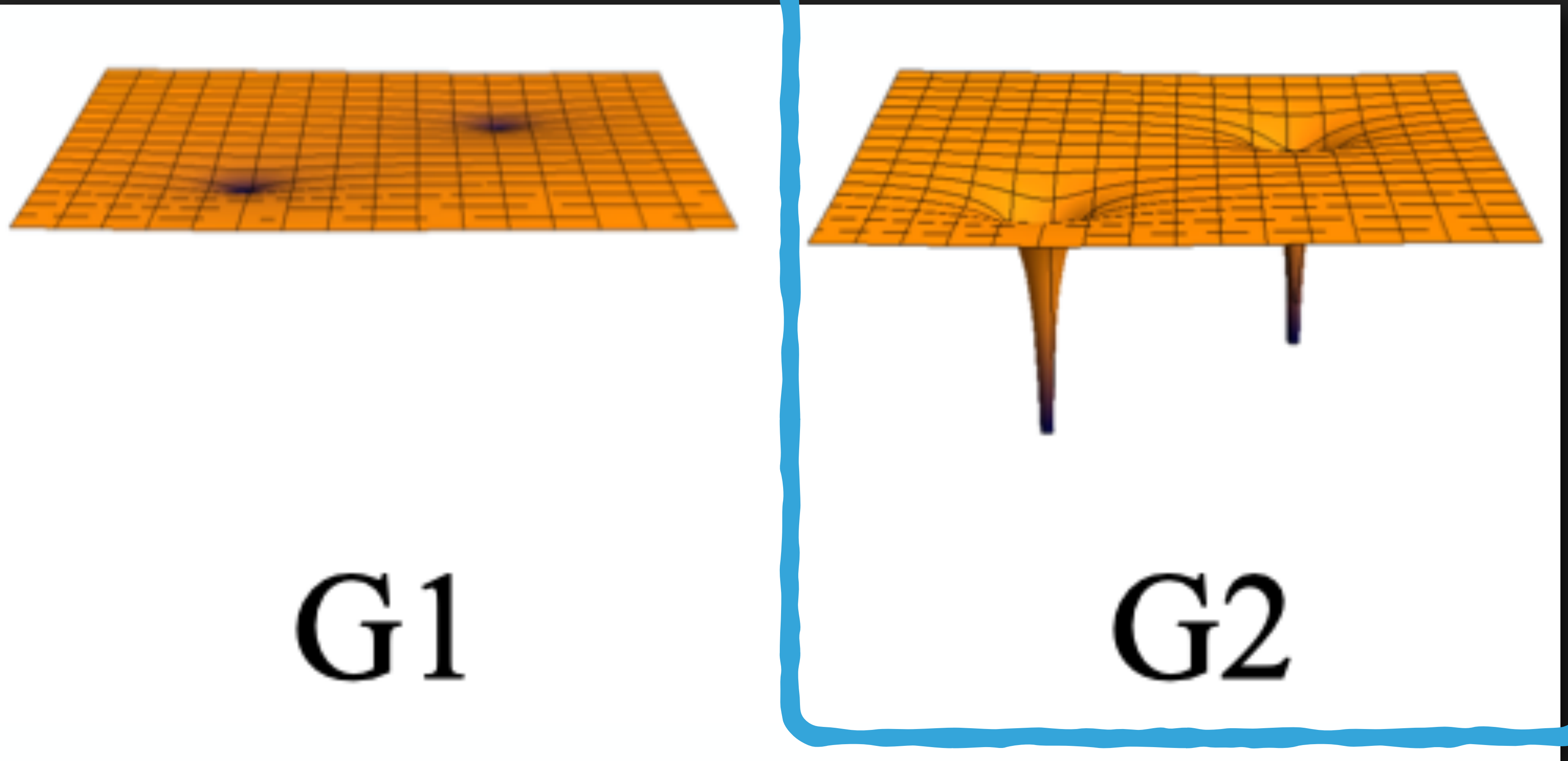

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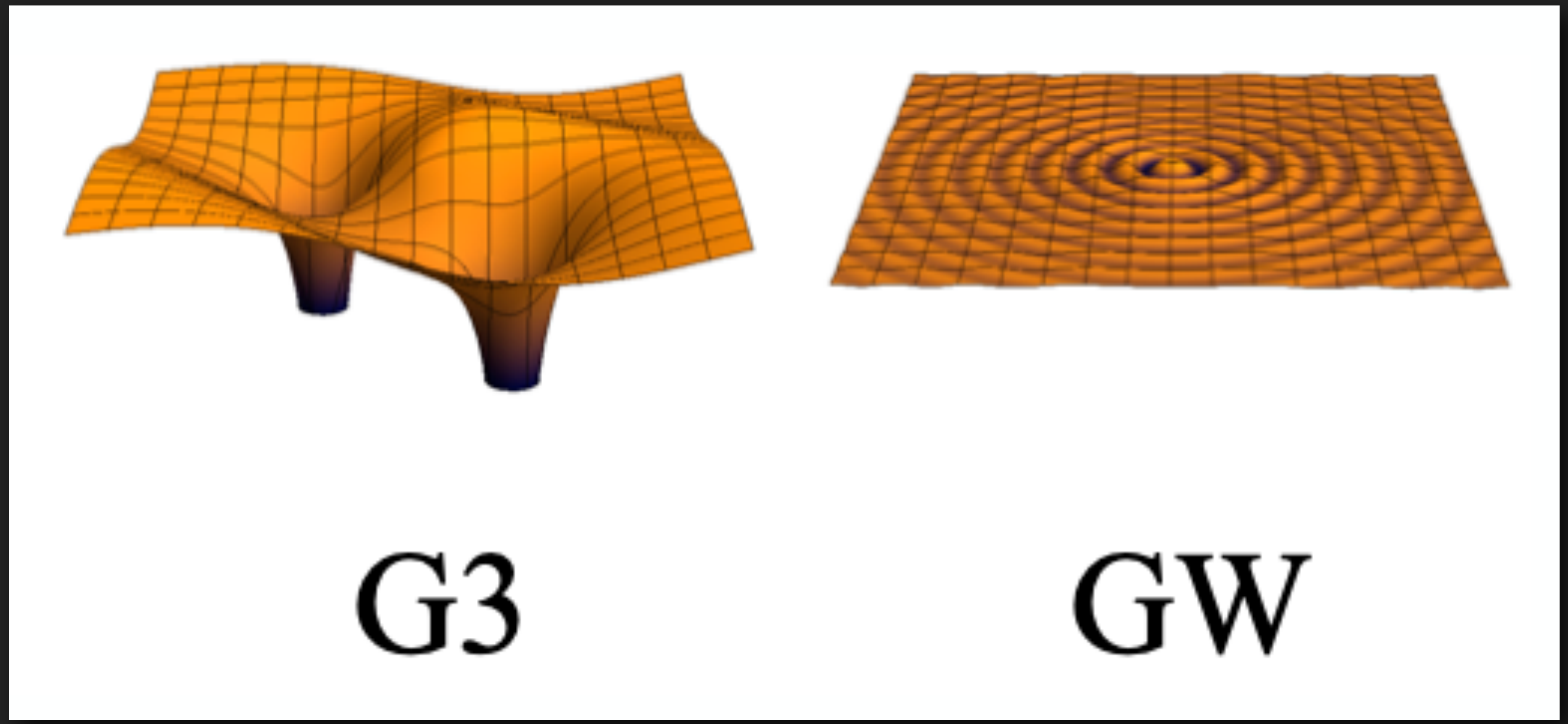

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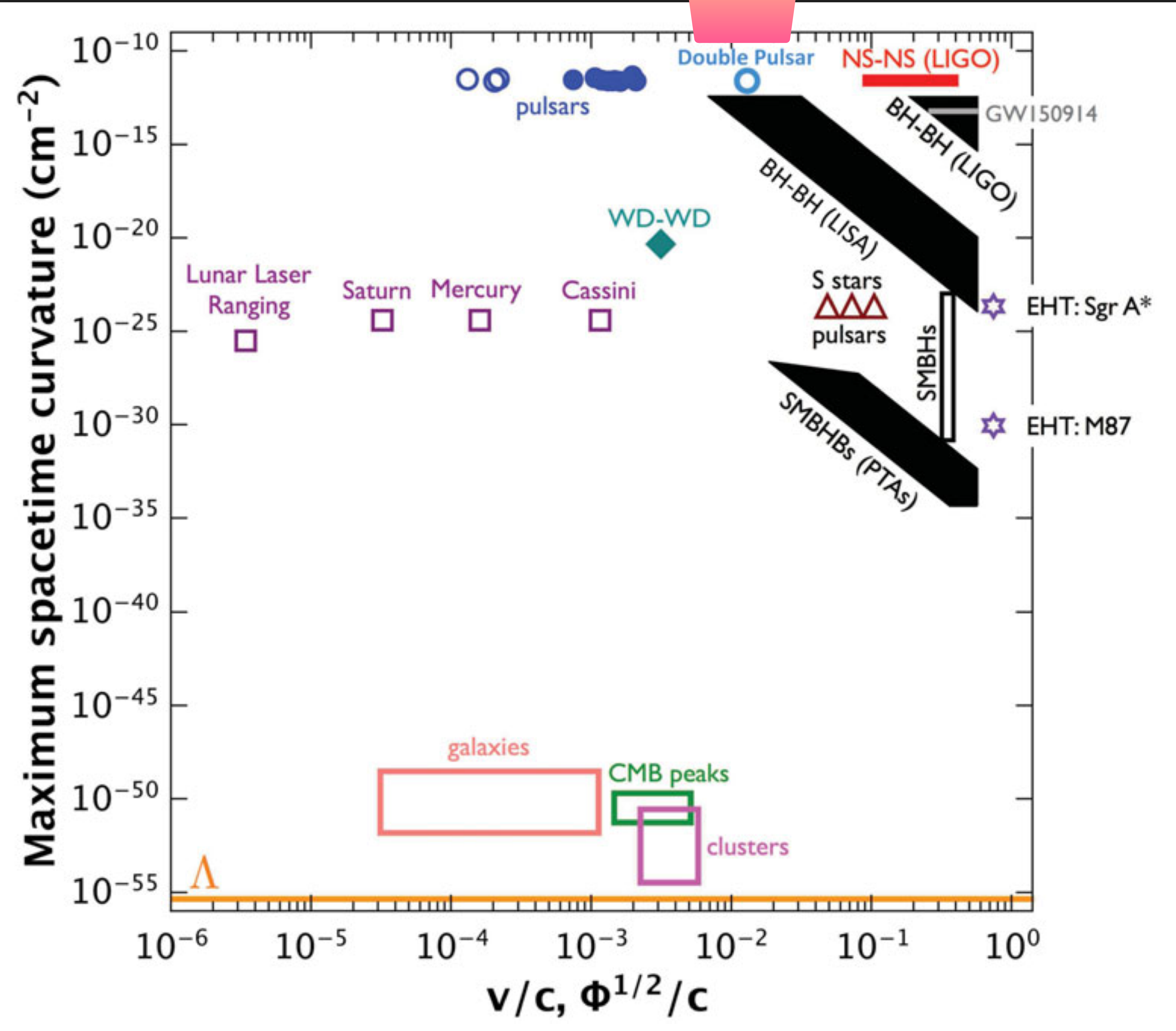

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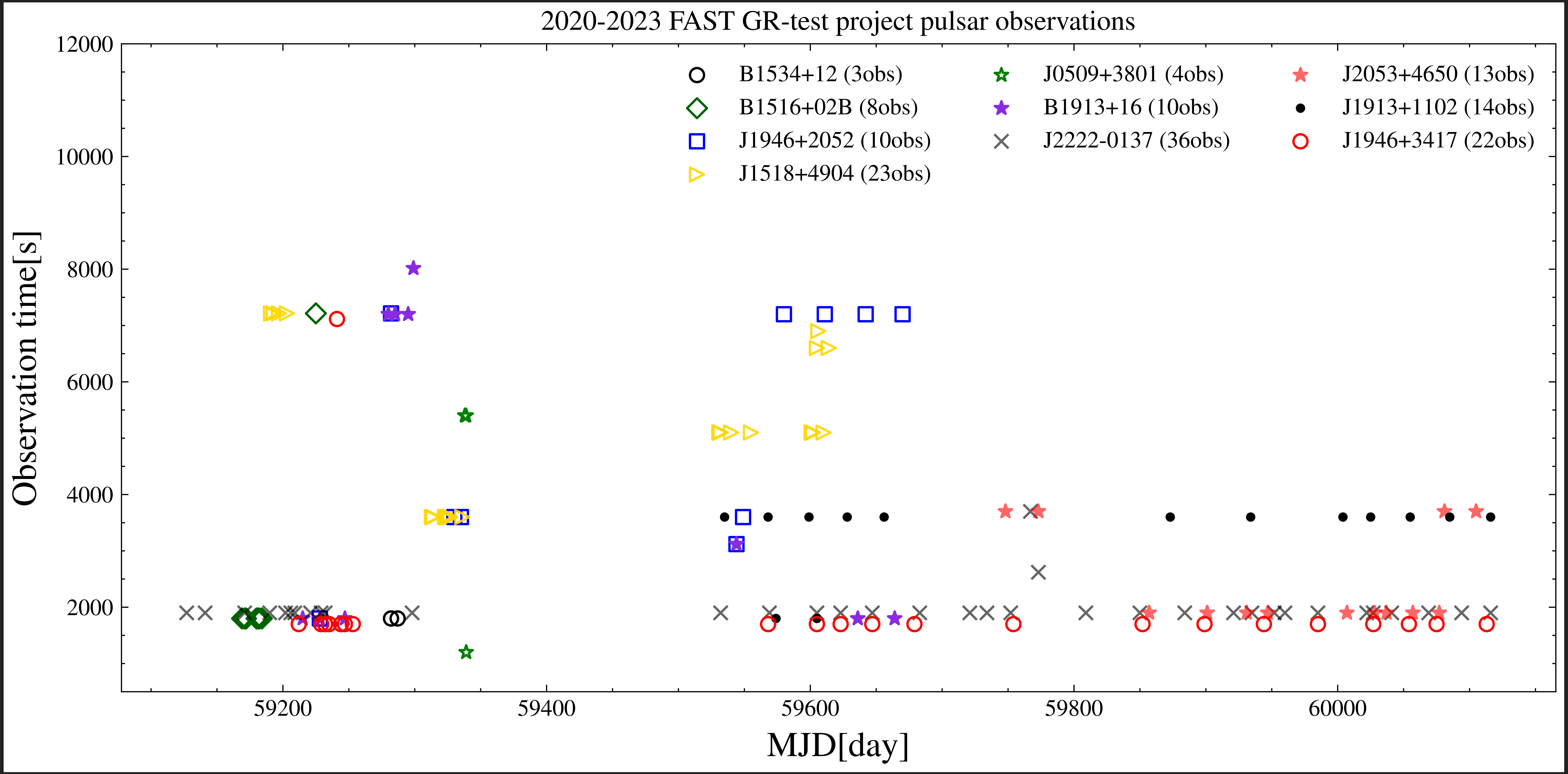

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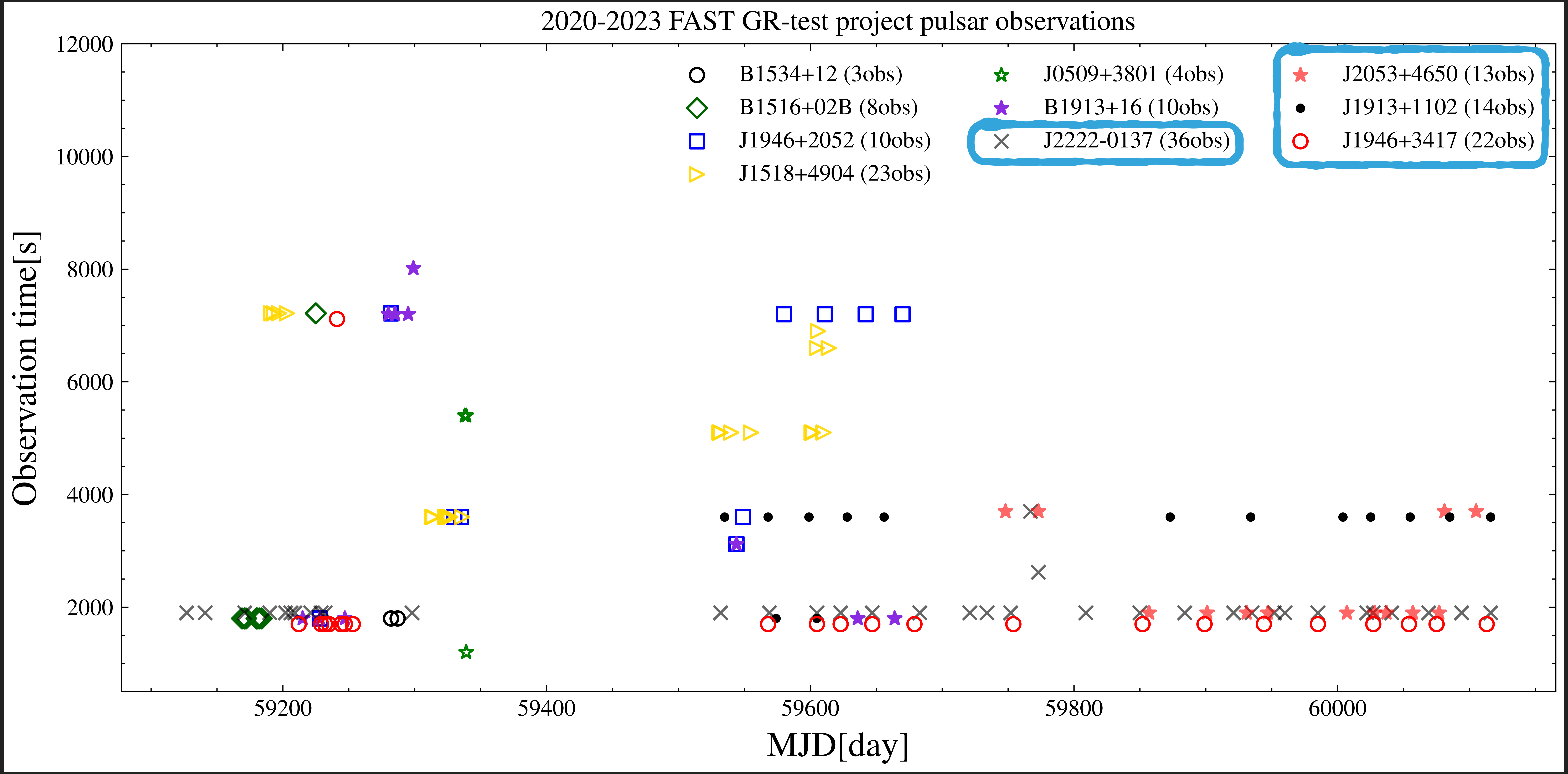
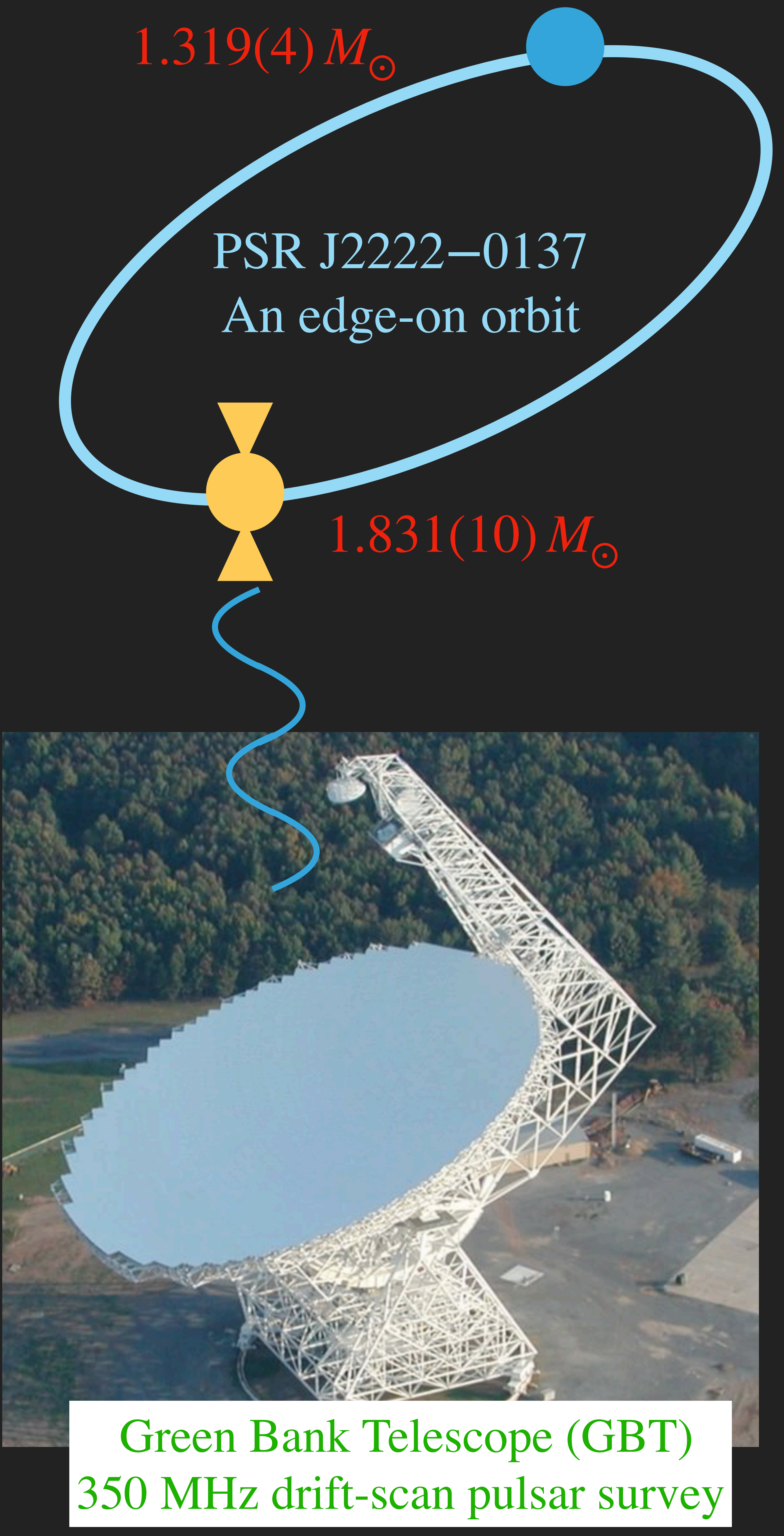


PSR J2222−0137, spin period is 32.8 ms

A recycled pulsar with a massive white dwarf (WD) companion in a 2.44-day orbit

An edge-on orbit allows a highly precise measurement of the Shapiro delay

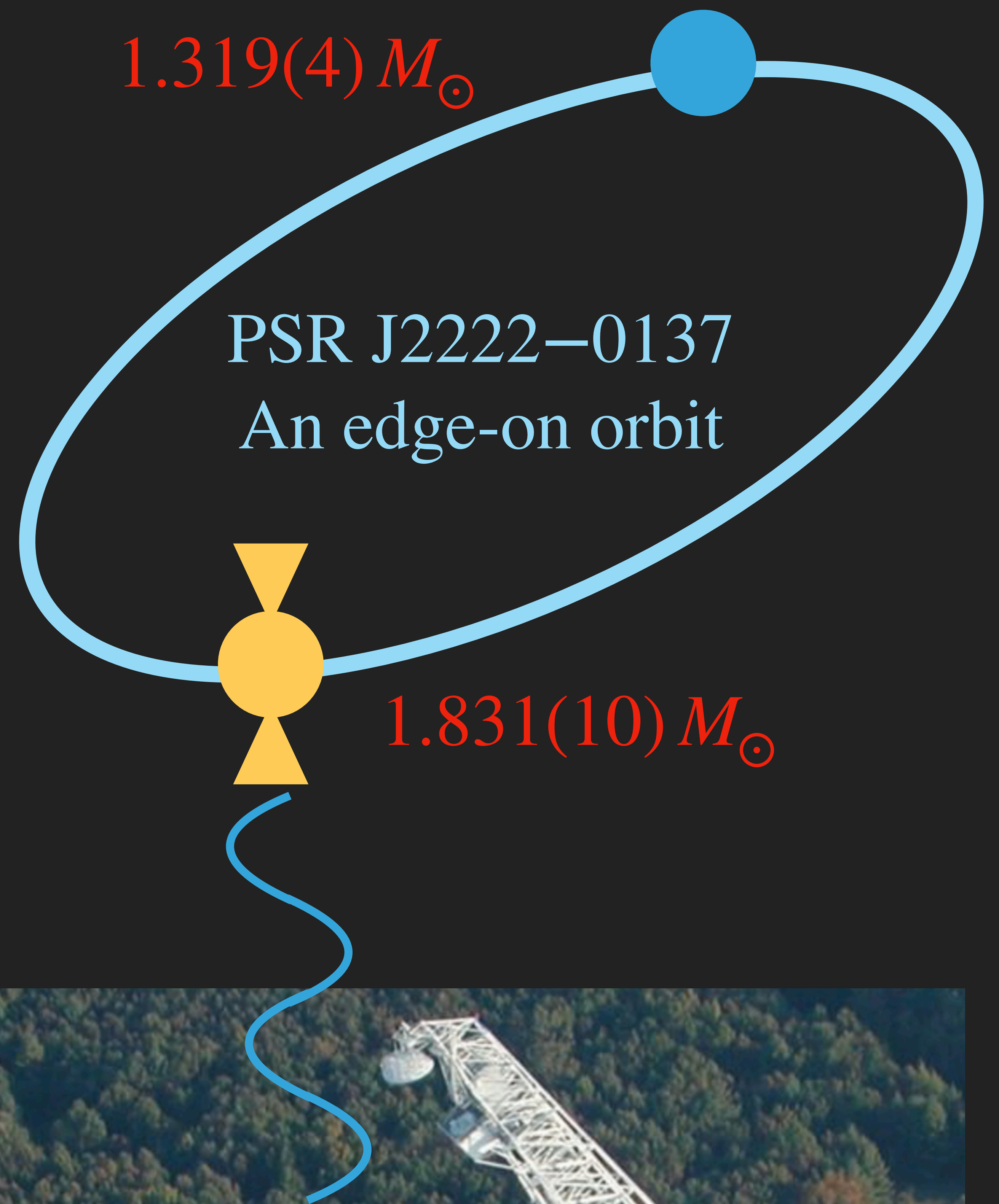


PSR J2222−0137

The most massive double degenerate binary pulsar is known in our Galaxy

Guo et al. 2021

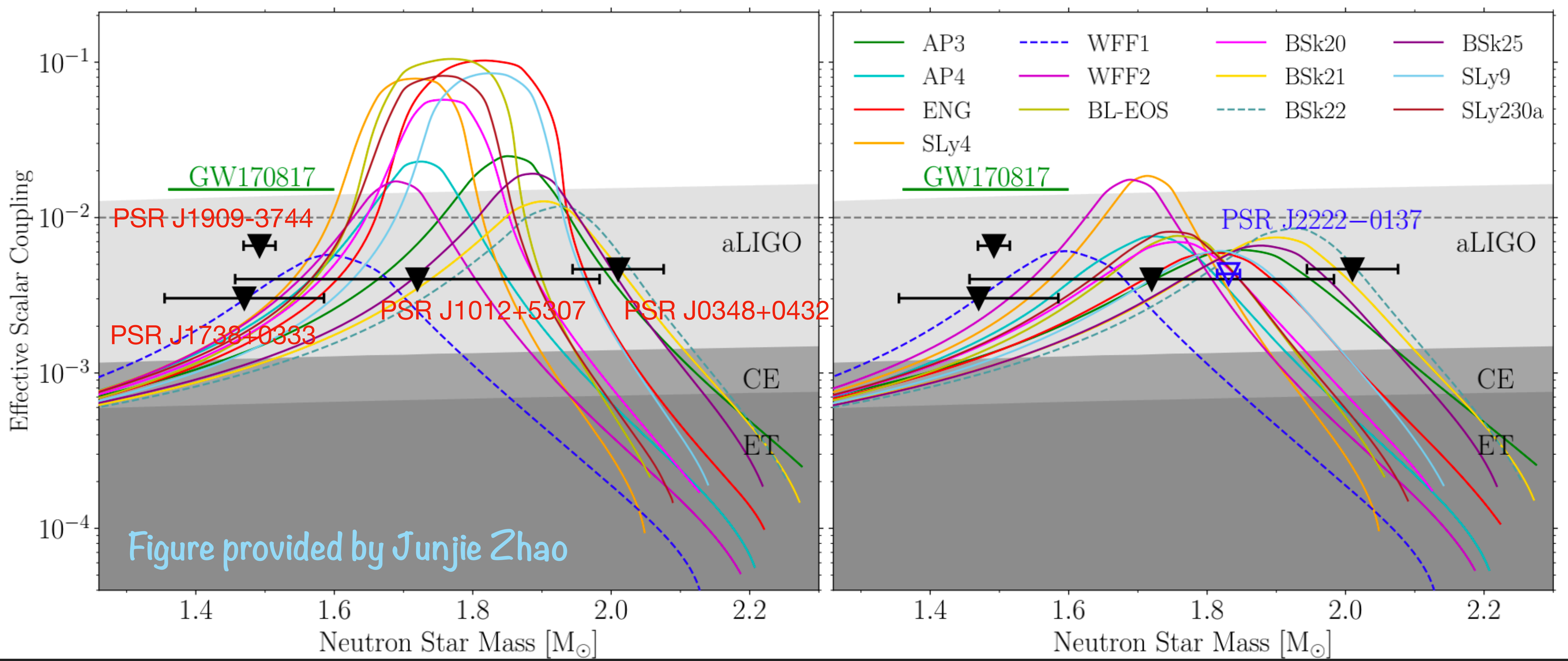
Orbital model	DDGR	DDK	DDK Bayesian grid
Weighted residual rms (μs)	2.759	2.772	-
χ^2	10629.32	10627.89	-
Reduced χ^2	0.9934	0.9934	-
Orbital period, P_b (days)	2.44576436(2)	2.44576437(2)	-
Projected semi-major axis, x (lt-s)	10.84802354(10)	10.8480235(2)	-
Epoch of periastron, T_0 (MJD)	58002.019280(10)	58002.01928(1)	-
Orbital eccentricity, e	0.00038092(1)	0.00038092(1)	-
Longitude of periastron, ω (deg)	120.458(1)	120.458(2)	-
Total mass, M_{tot} ($M_\odot$)	3.135(19)	-	3.150(14)
Companion mass, M_c ($M_\odot$)	1.3153(56)	1.315(12)	1.3194(40)
Rate of advance of periastron, $\dot{\omega}$ (deg yr^{-1})	-	0.09605(48)	-
Derivative of P_b, $\dot{P}_b$ (10^{-12} s s^{-1})	0.2634(74)[a]	0.2509(76)	-
Derivative of x, $\dot{x}$ (10^{-15} lt-s s^{-1})	−7.76(48)	-	-
Orbital inclination (deg)	-	85.284(87)	85.269(41)
Position angle of line of nodes, Ω (deg)	-	191.3(7.0)	187.7(5.7)
Derived parameters			
Mass function, f ($M_\odot$)	0.229142359(10)	0.229142358(12)	-
Pulsar mass, M_p ($M_\odot$)	1.820(14)	-	1.831(10)



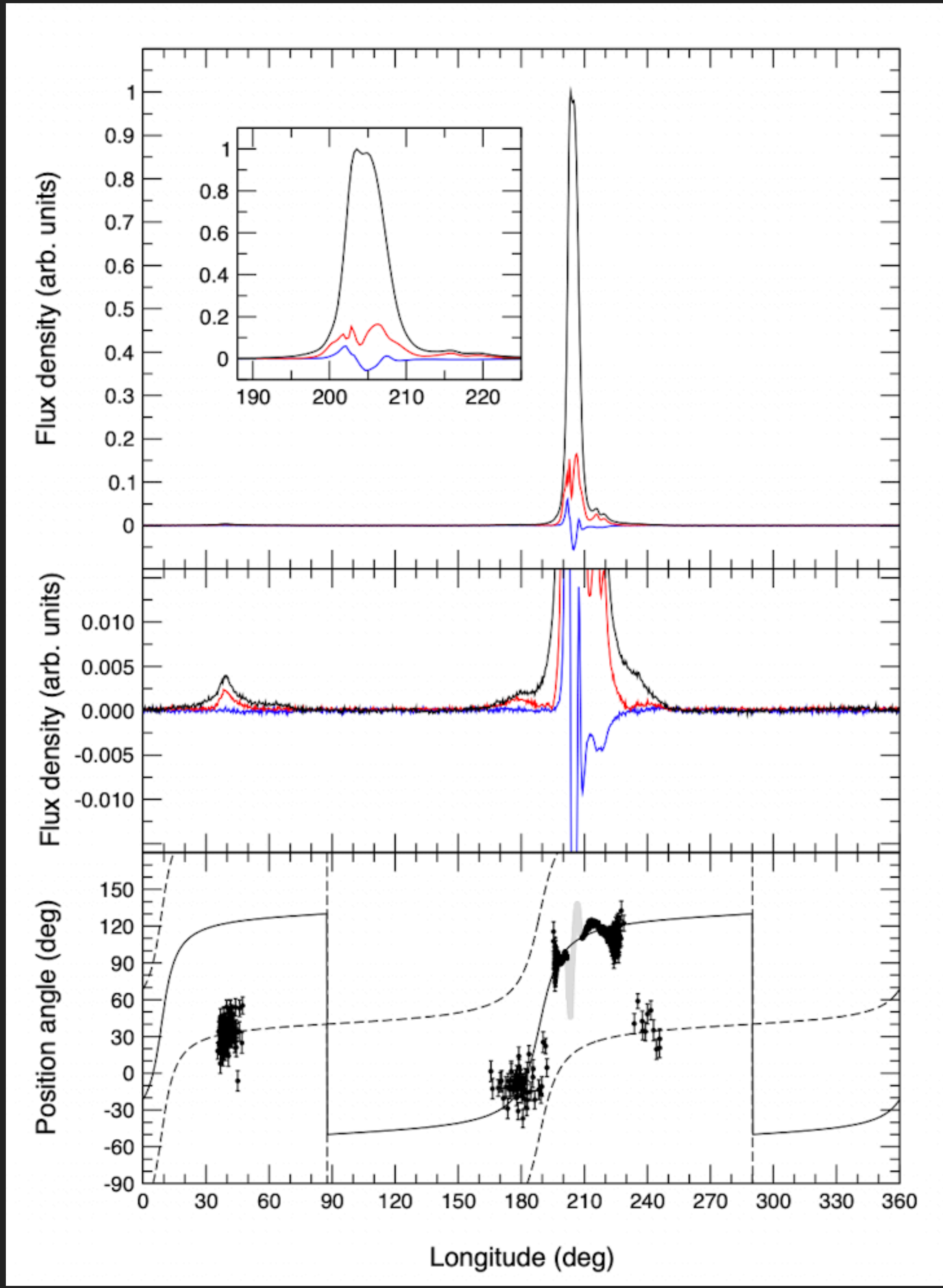
Green Bank Telescope (GBT)
350 MHz drift-scan pulsar survey

PSR J2222−0137: the ideal laboratory of scalar-tensor theories

- The largely different gravitational binding energies of the PSR-WD can provide a tighter constraint on the coupling parameter of the scalar field
- The pulsar mass [1.831(10) $M_\odot$] places it in a NS mass range that had previously not been probed by precise tests of scalar-tensor theories, and it can play an important role to constrain the coupling parameter of Damour-Esposito-Farèse (DEF) gravity



PSR J2222−0137's observations by FAST

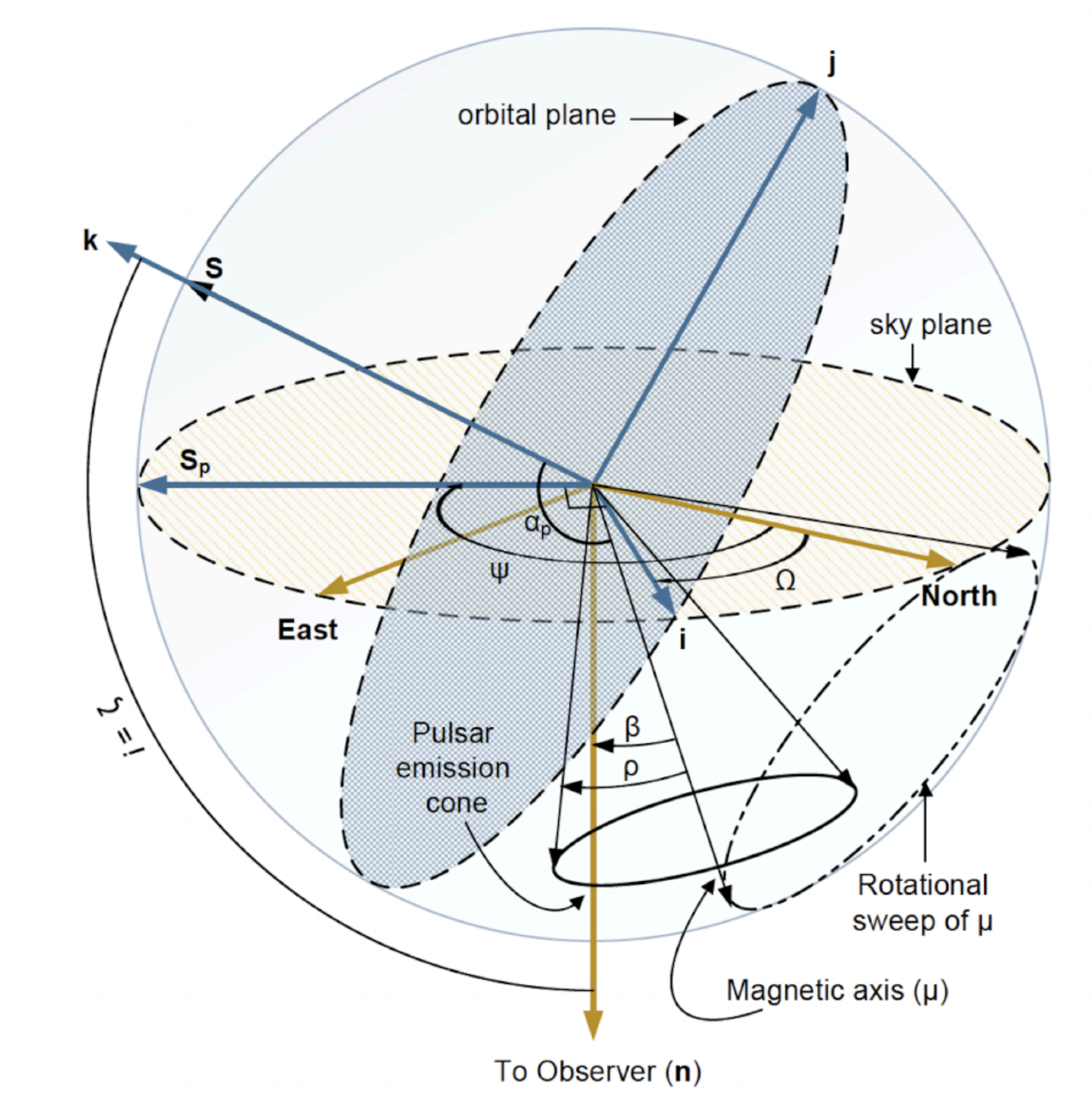


Orbital geometry $i = 85.27(4)$ deg
$\Omega = 189^{+19}_{-18}$ deg

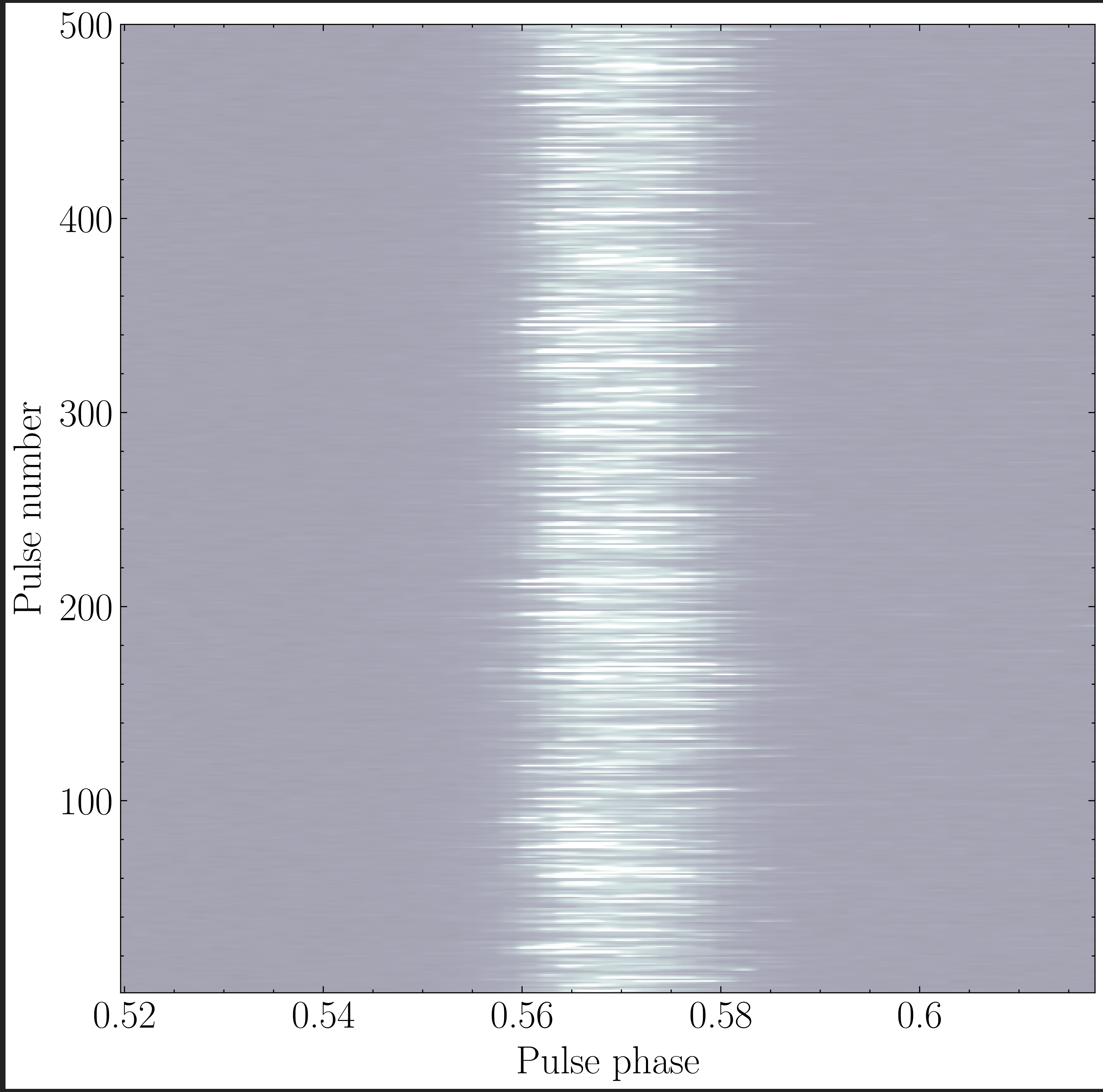
Spin geometry $\alpha = 91(1)$ deg
$\beta = -7.2(6)$ deg

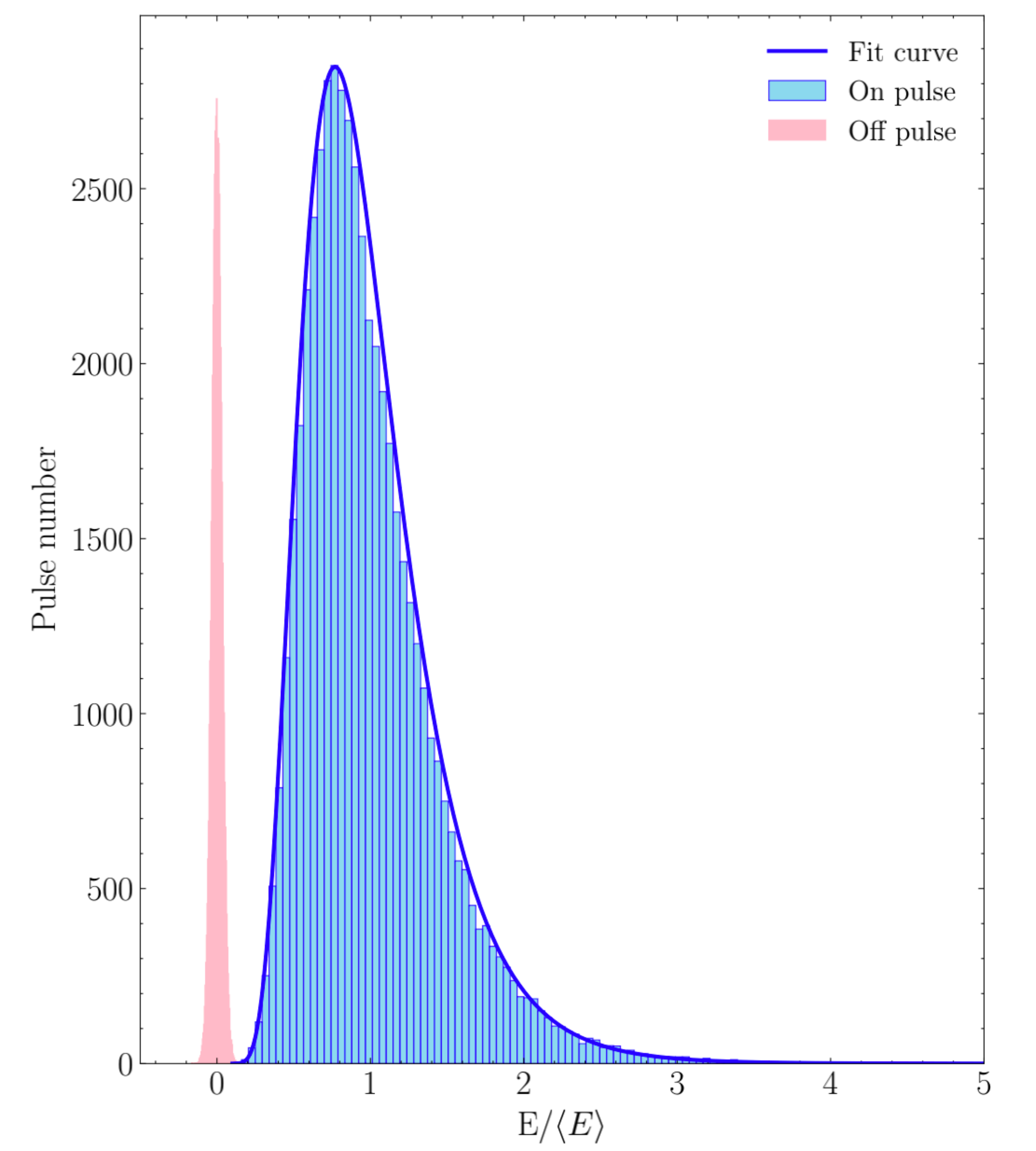
High signal-to-noise ratio observation provides an improved polarization study and reveals the existence of an **inter-pulse** first time

Guo et al. 2021



PSR J2222-0137 single pulse analysis



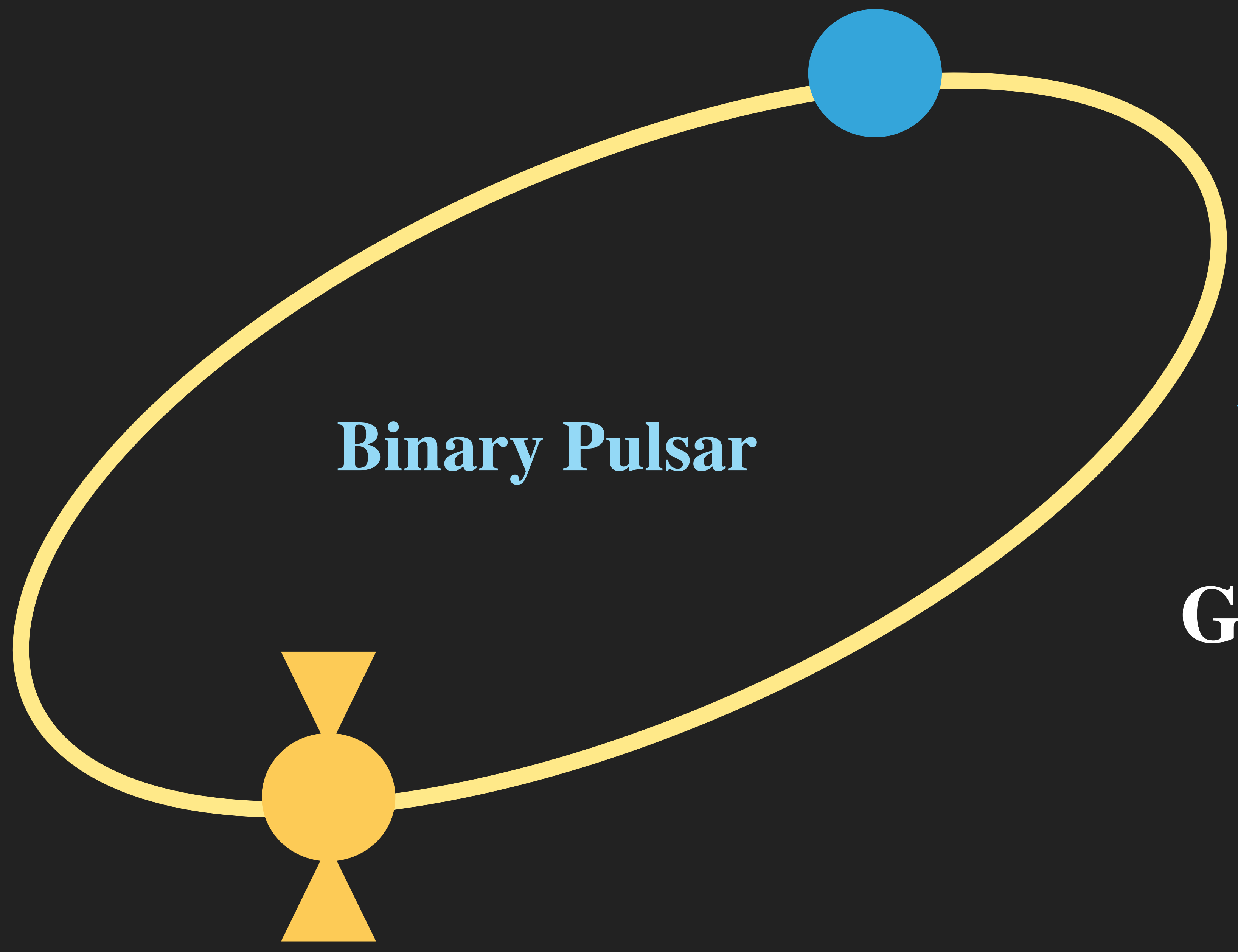


The pulse stack of 500 continuous pulses, and the time resolution is 64.06 μs

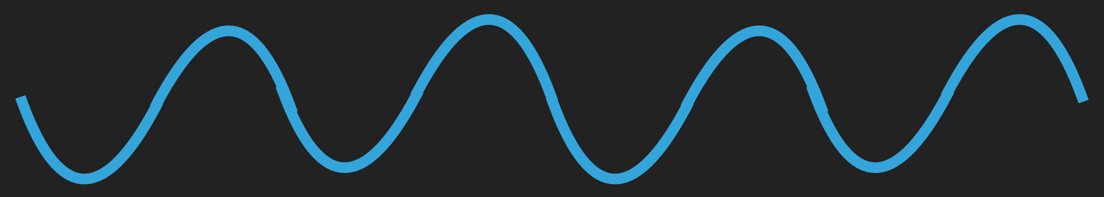
Miao et al. submitted

PSR J1946+3417

A binary pulsar has a massive ($m_p = 1.83\,M_\odot$) millisecond pulsar in an eccentric ($e = 0.13$) 27-day orbit with a white dwarf ($m_c = 0.26\,M_\odot$)



$$\dot{P}_b^{\mathrm{obs}} = \dot{P}_b^{\mathrm{GR}} + \dot{P}_b^{\mathrm{gal}} = -\,16.7 \pm 1.4 \times 10^{-12}\ \mathrm{s\ s^{-1}}$$



Gravitational wave emission

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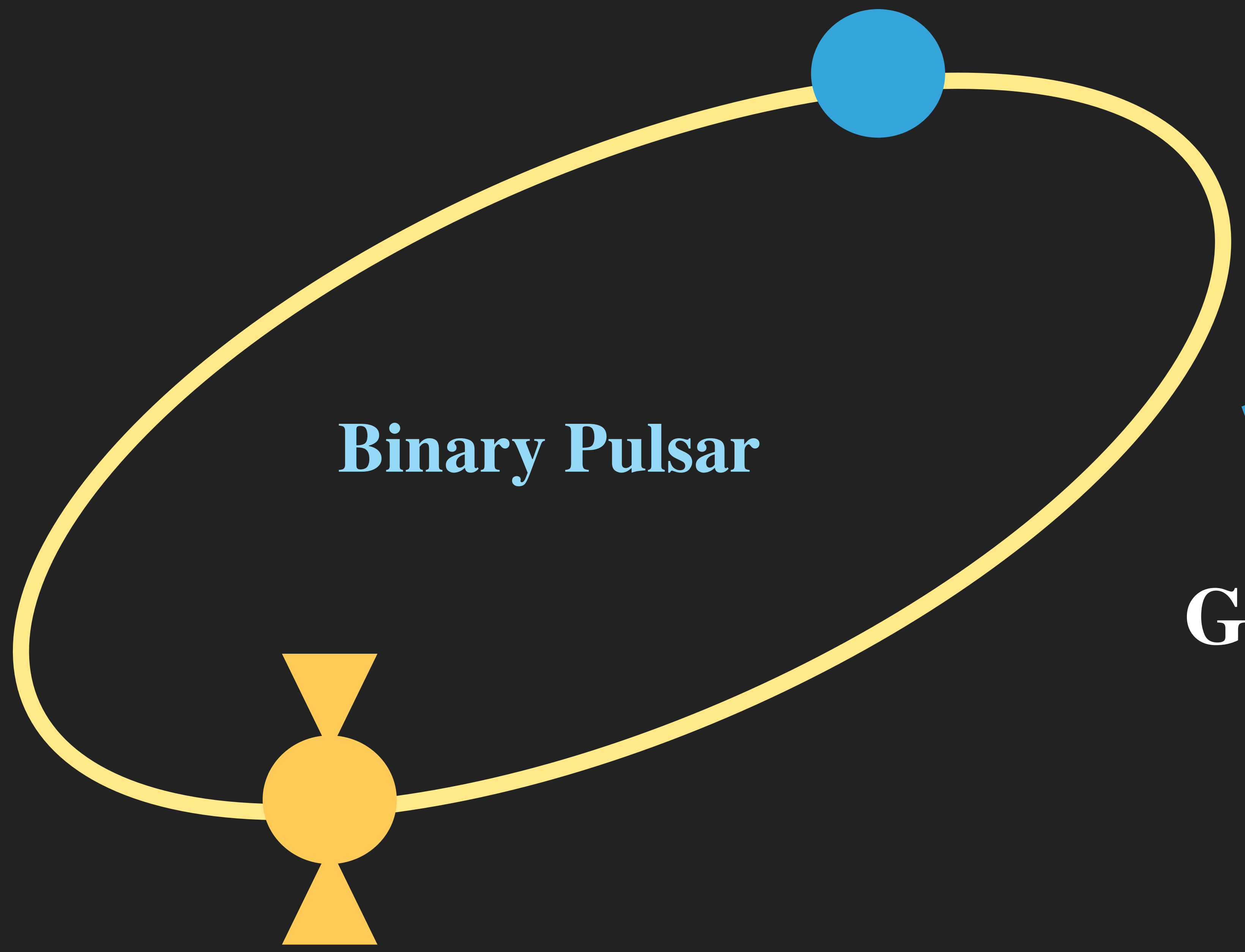

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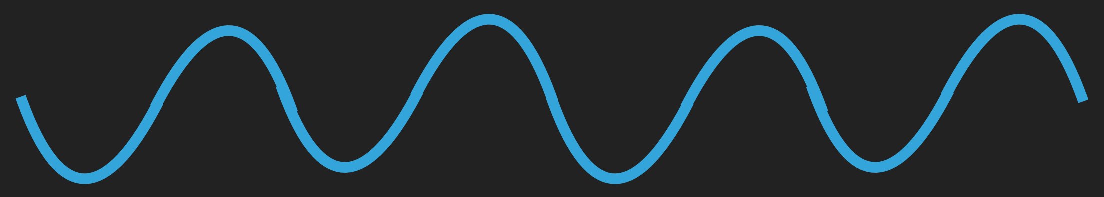

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A significant **non-Galactic** component

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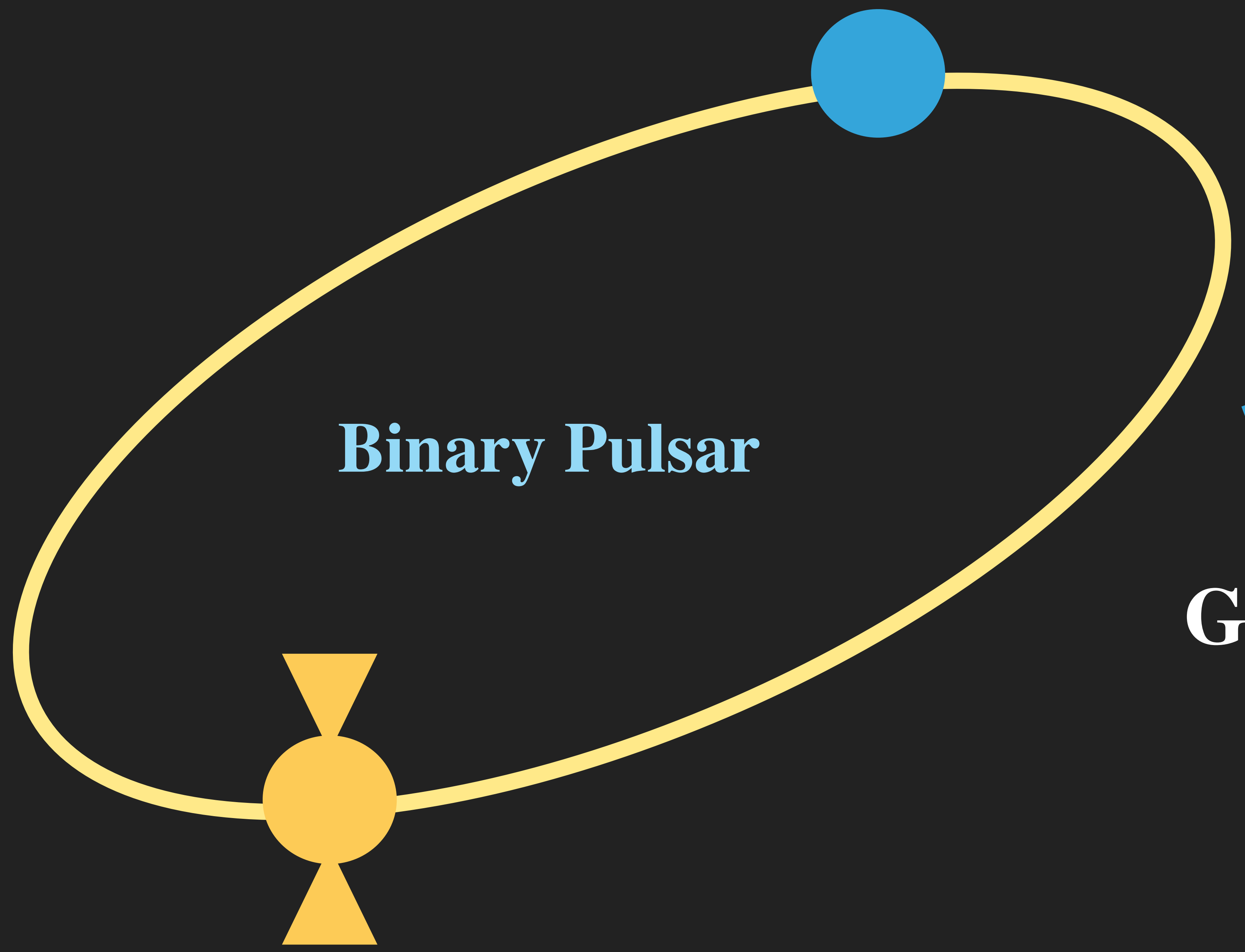

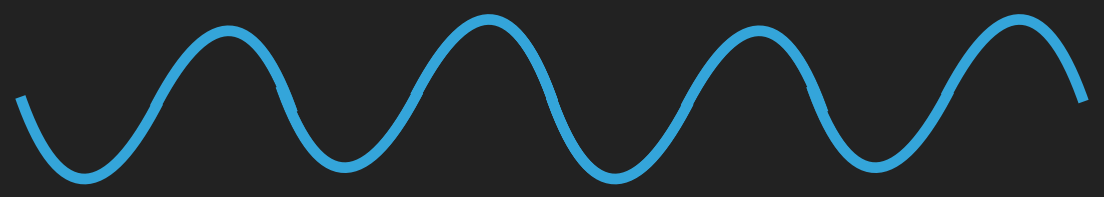

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A suspected **triple system**?

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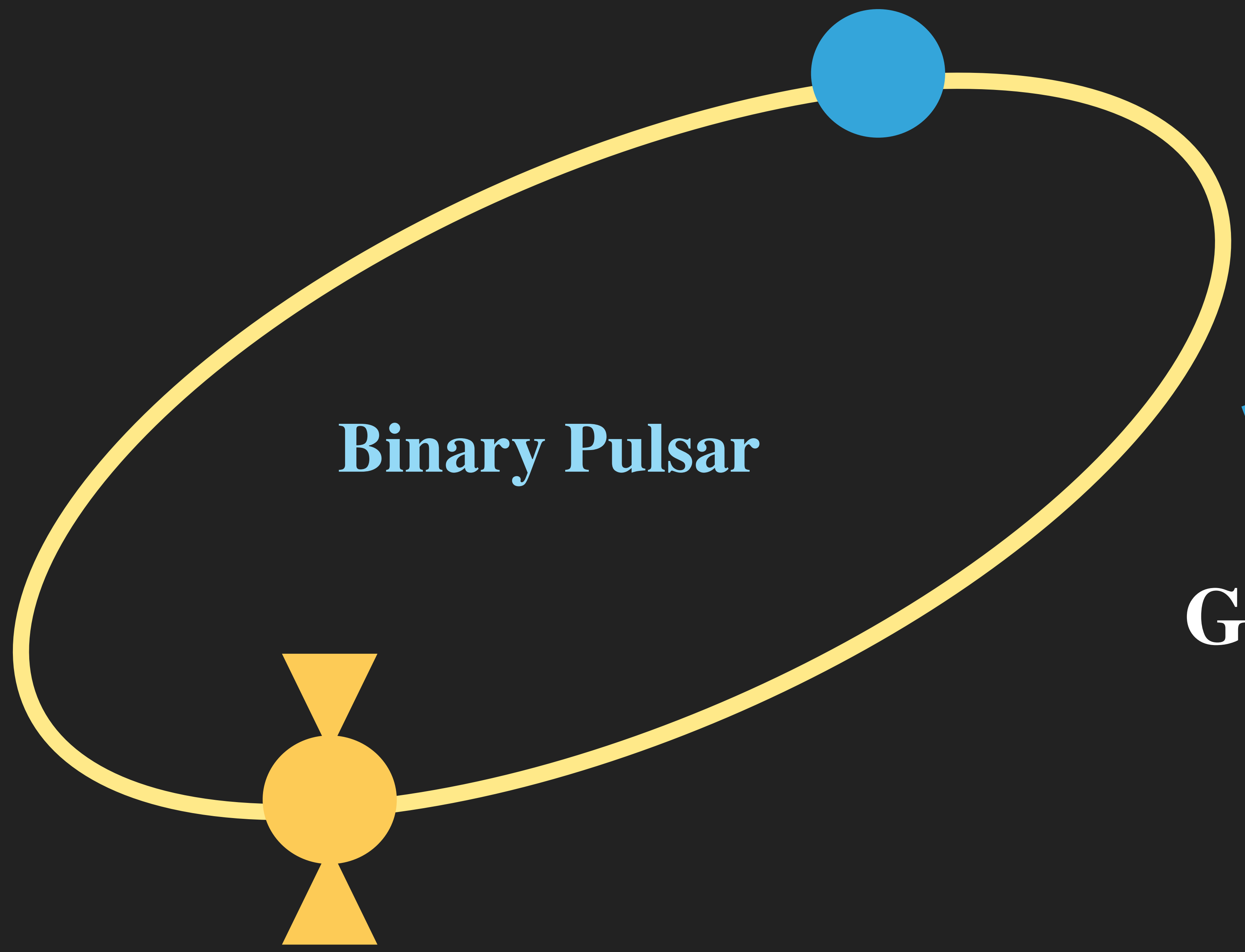
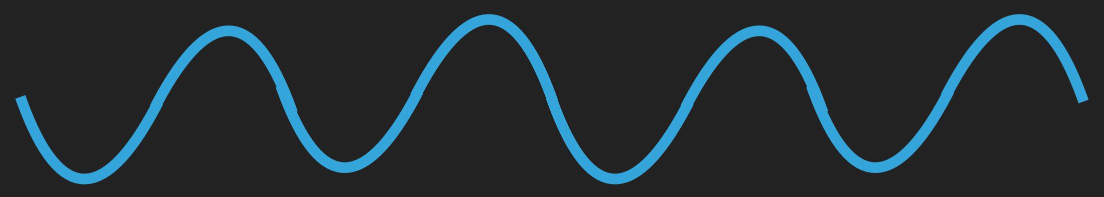
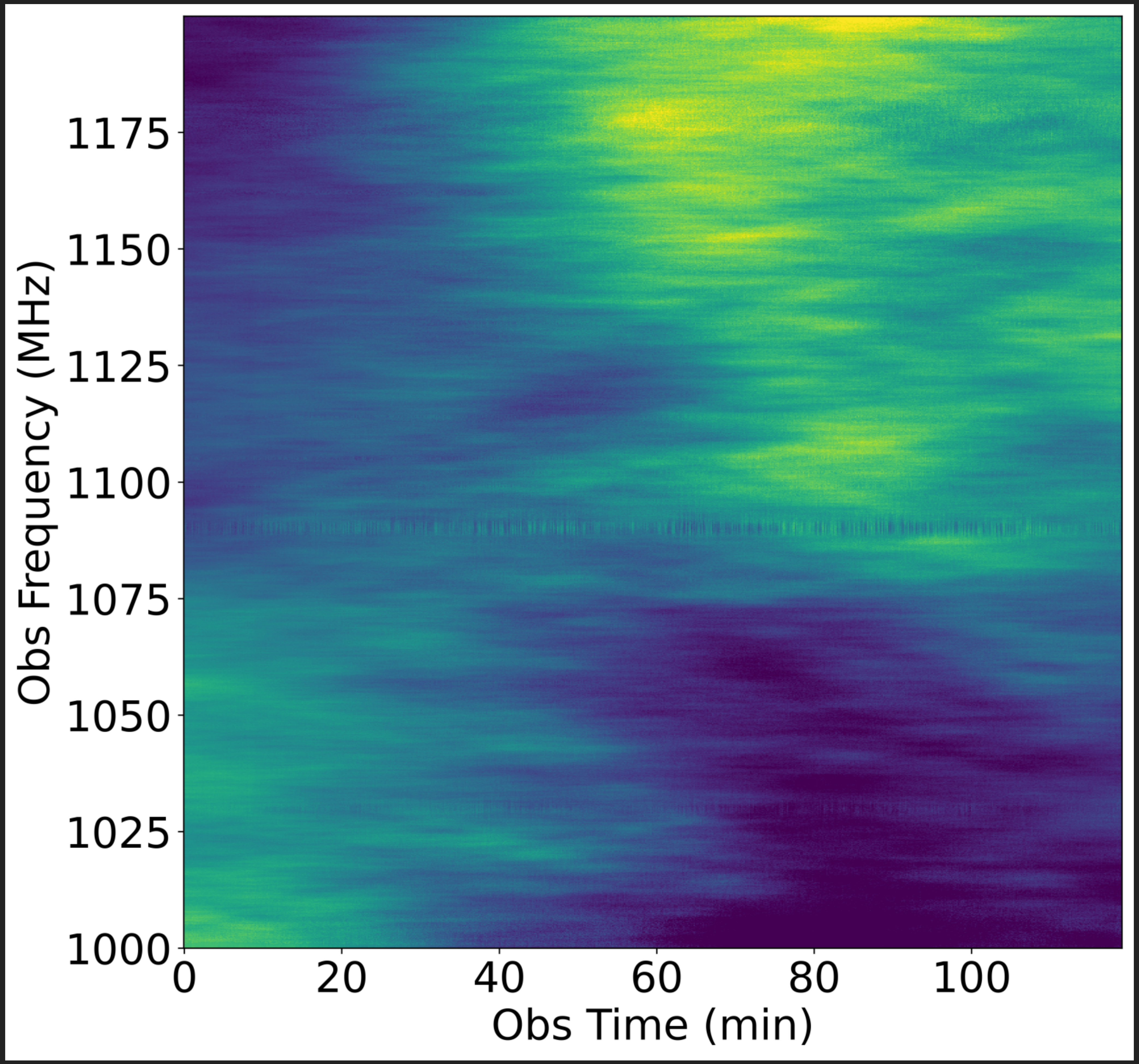




Gravitational wave emission

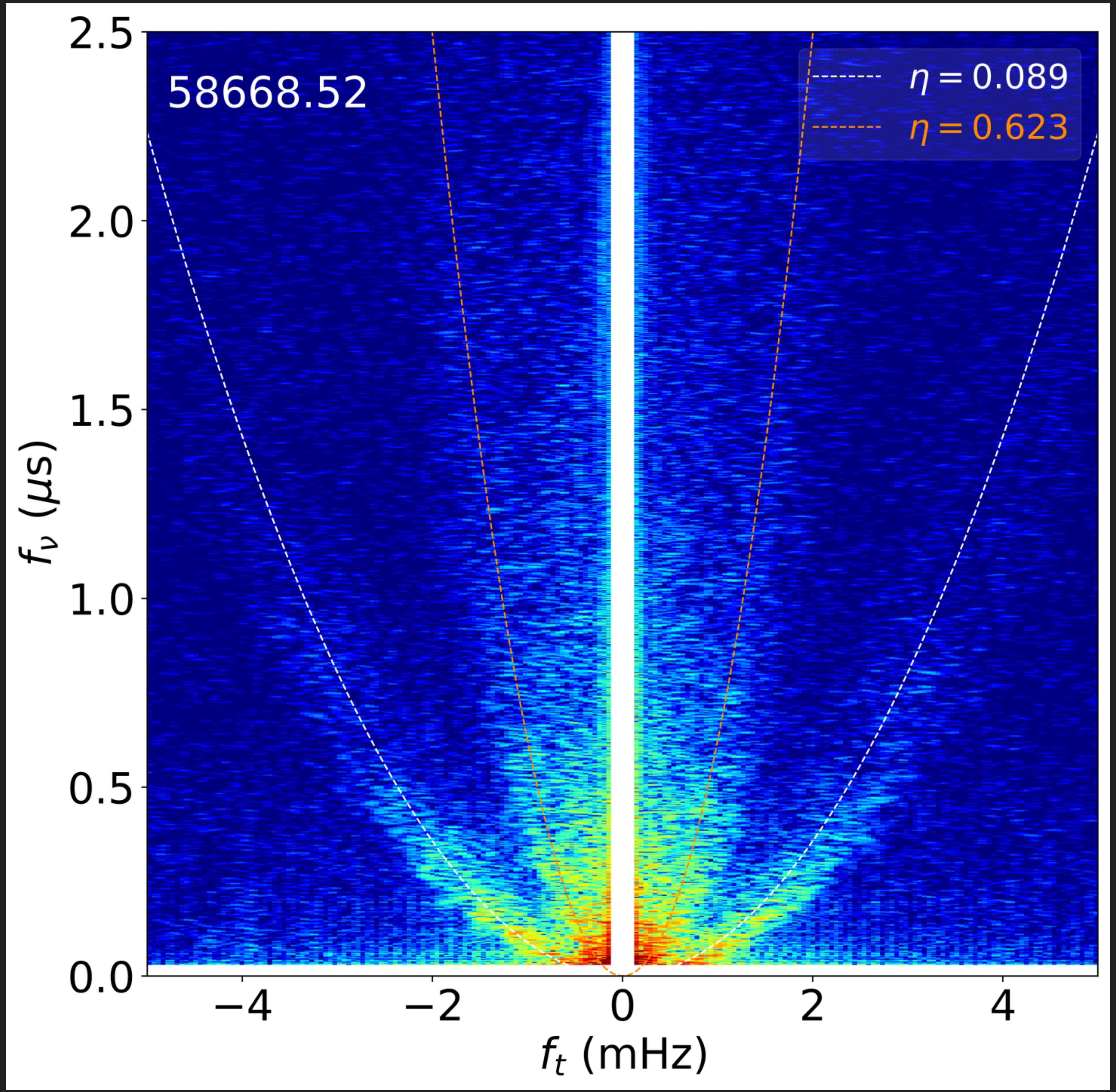
PSR J1518+4904

Yuan et al., in preparation



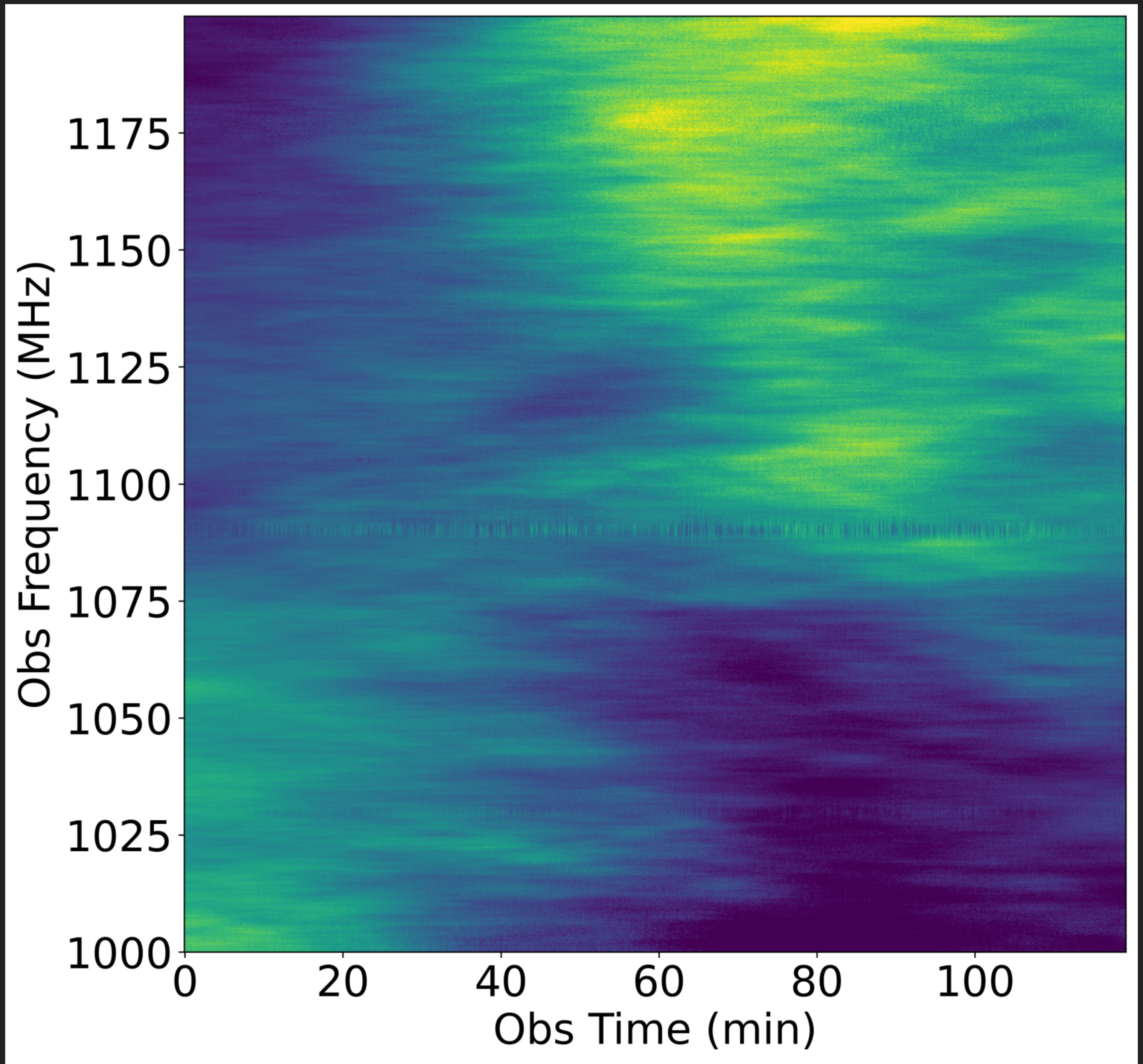
The secondary spectrum

$$\eta = \frac{Ds(1-s)}{2V_{\rm eff}^2 \cos\phi}$$



PSR J1518+4904

Yuan et al., in preparation



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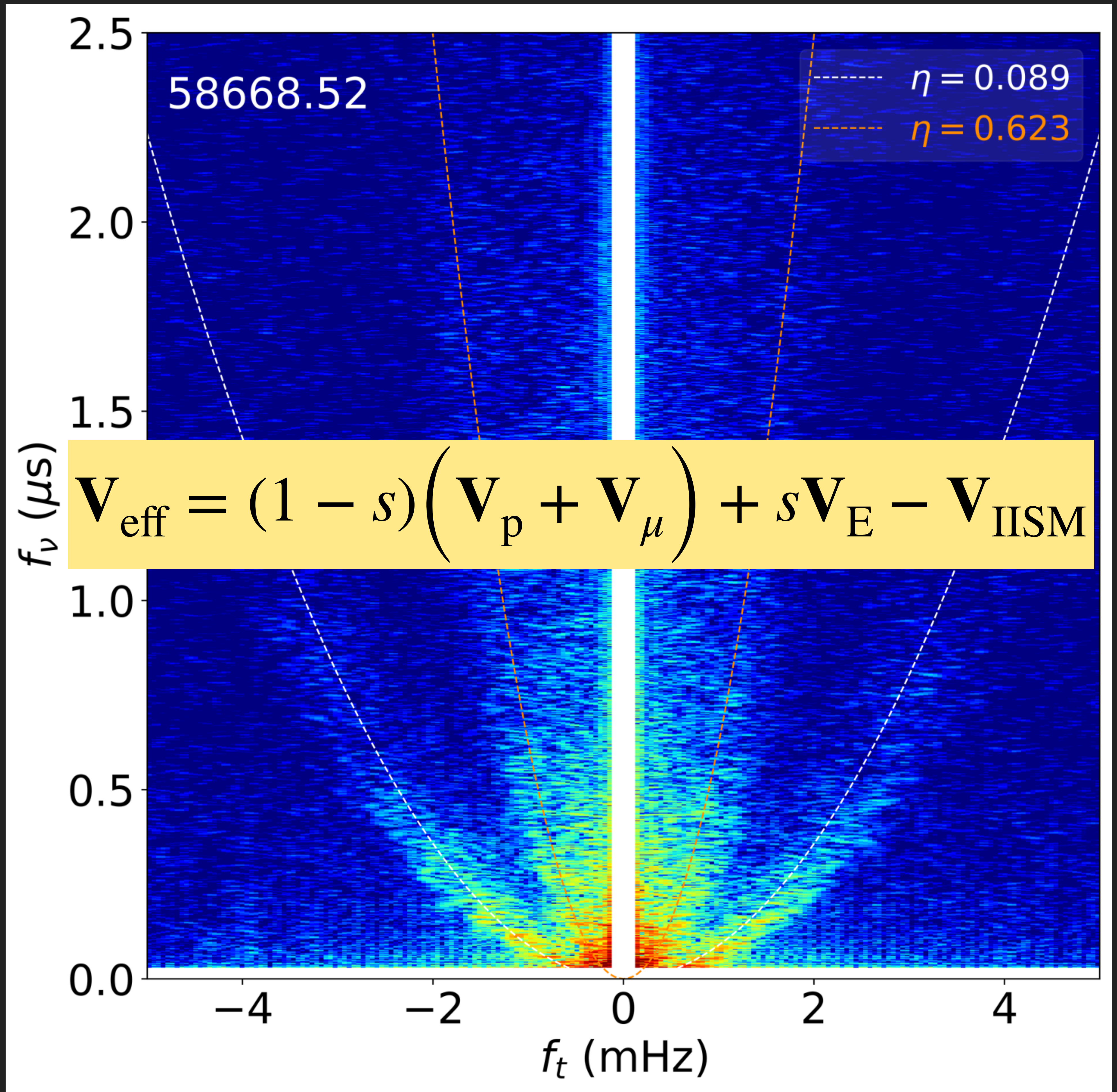


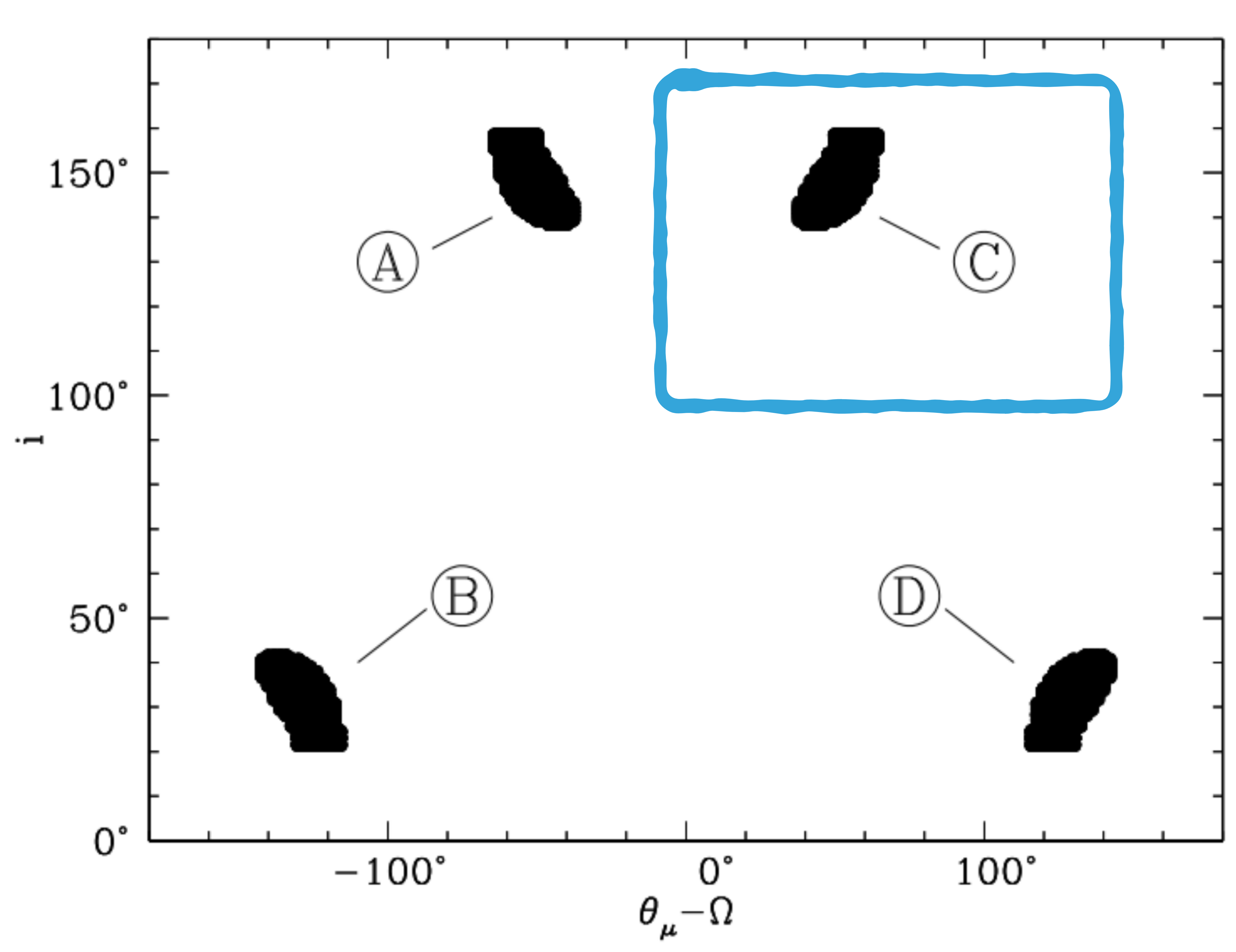
$$\mathbf{V}_{\rm eff} = (1-s)\left(\mathbf{V}_{\rm p} + \mathbf{V}_{\mu}\right) + s\mathbf{V}_{\rm E} - \mathbf{V}_{\rm IISM}$$

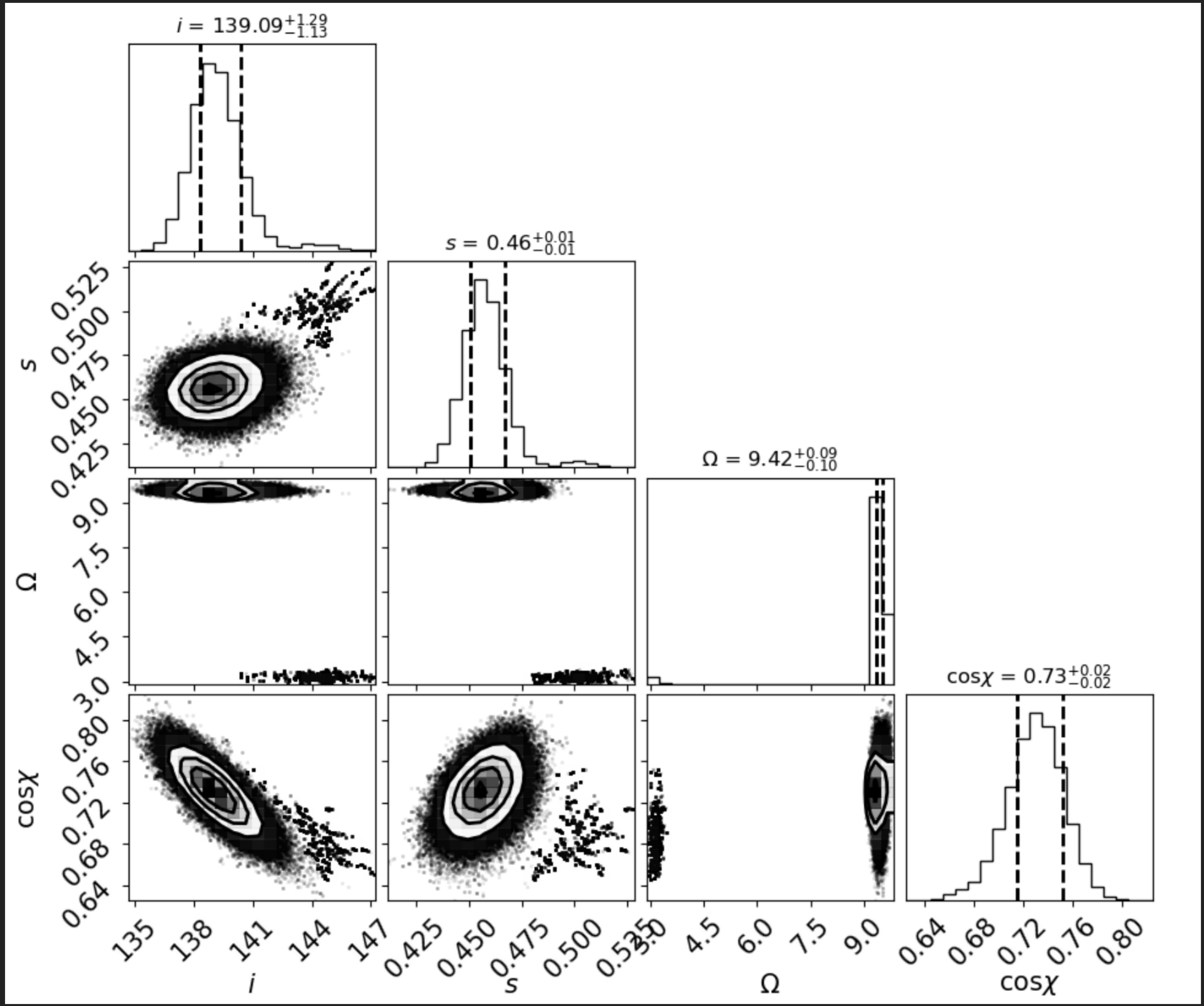
Yuan et al., in preparation

PSR J1518+4904

Yuan et al., in preparation

$$i \sim 139^\circ \pm 1^\circ, \Omega \sim 9^\circ \pm 0.1^\circ$$





Summary

PSR J2222−0137: ***Yanjun Gou et al., A&A, 2021*** **(Timing and GR tests)**
Xueli Miao et al., submitted to MNRAS **(Single pulses analysis)**
PSR J1946+2052: ***Lingqi Meng et al., in preparation*** **(Measure geodetic precession)**
PSR J1518+4904: ***Mao Yuan et al., in preparation*** **(Measure scintillation arc to get the geometry of orbit)**
PSR J1946+3417 prepare to write the paper
Other binary pulsars continue timing

Thank you !!!