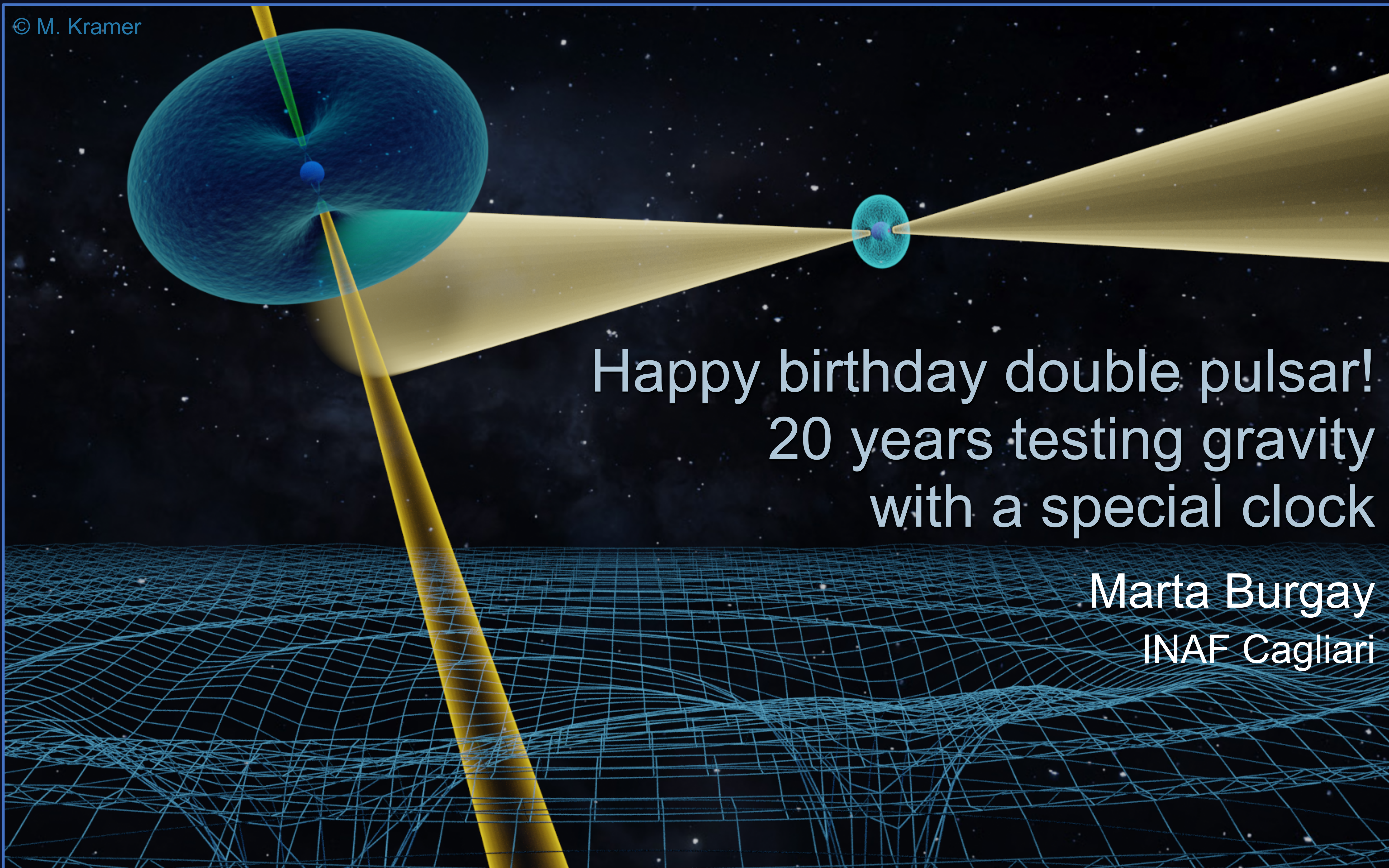
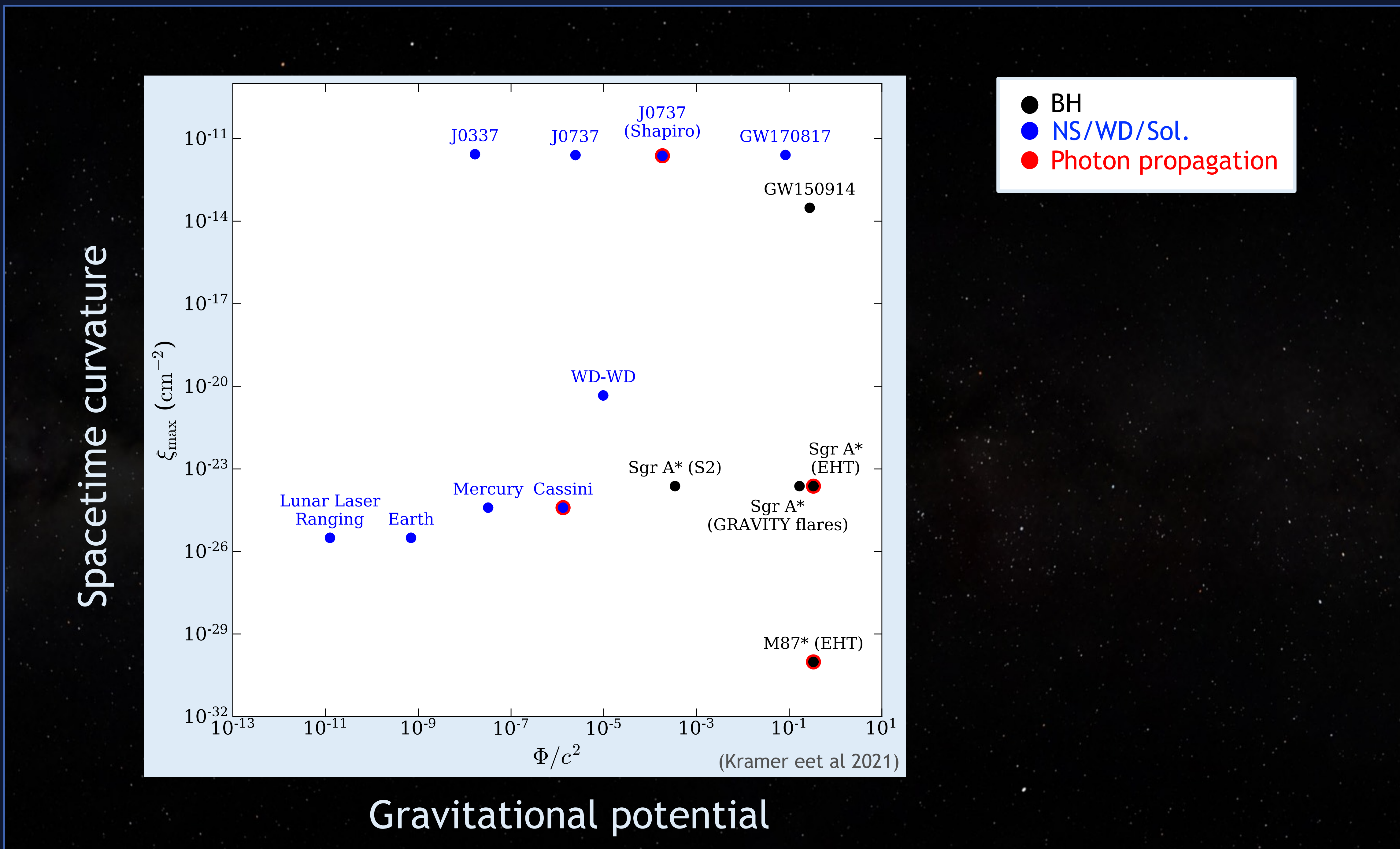


Happy birthday double pulsar!
20 years testing gravity
with a special clock

Marta Burgay
INAF Cagliari

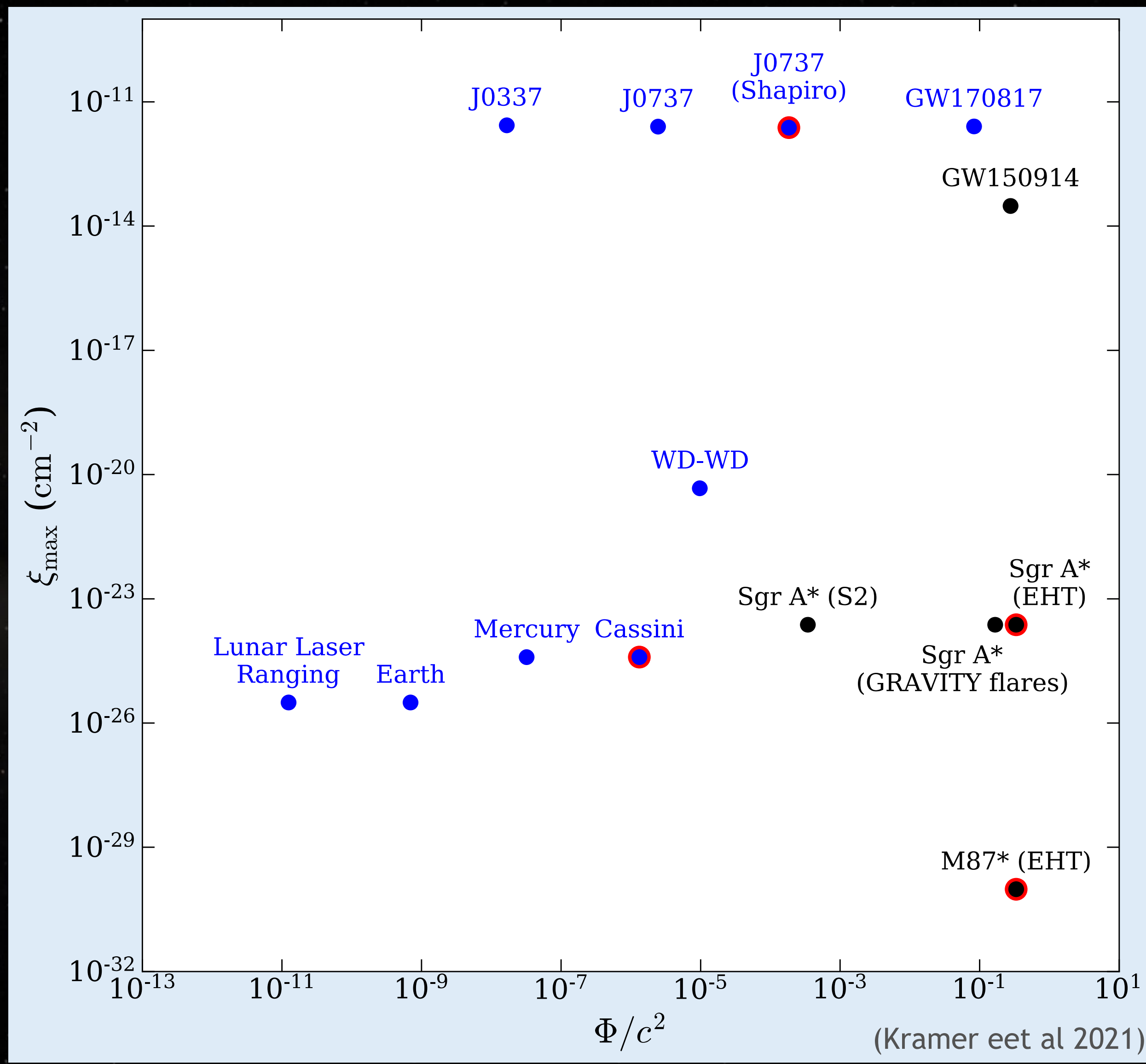
Testing GR



Spacetime curvature
$\xi_{\rm max}$ (cm^{-2})
10^{-11}
10^{-14}
10^{-17}
10^{-20}
10^{-23}
10^{-26}
10^{-29}
10^{-32}
J0337
J0737
J0737 (Shapiro)
GW170817
GW150914
WD-WD
Sgr A* (S2)
Sgr A* (EHT)
Sgr A* (GRAVITY flares)
Lunar Laser Ranging
Earth
Mercury
Cassini
M87* (EHT)
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
Φ/c^2
(Kramer eet al 2021)
BH
NS/WD/Sol.
Photon propagation
Gravitational potential

Testing GR

Spacetime curvature



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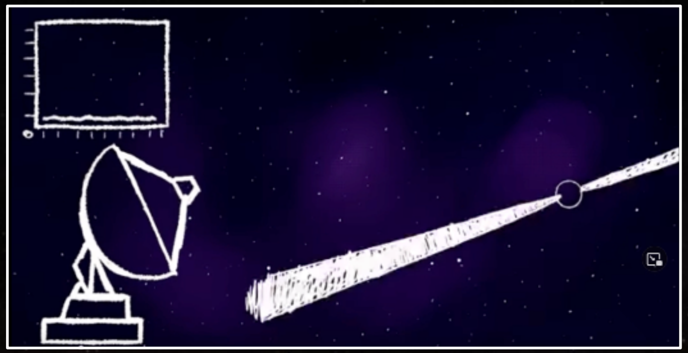

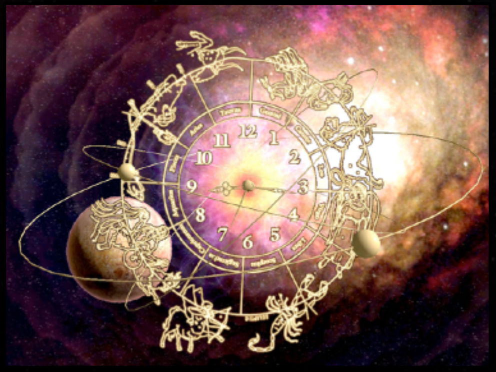

Pulsar Timing

See how the clock falls into curved spacetime

- Predicting ToAs on the basis of a model
- Measuring Times of Arrival (ToAs) from repeated obs
- Creating timing residuals
- Fitting for model parameters to remove trends

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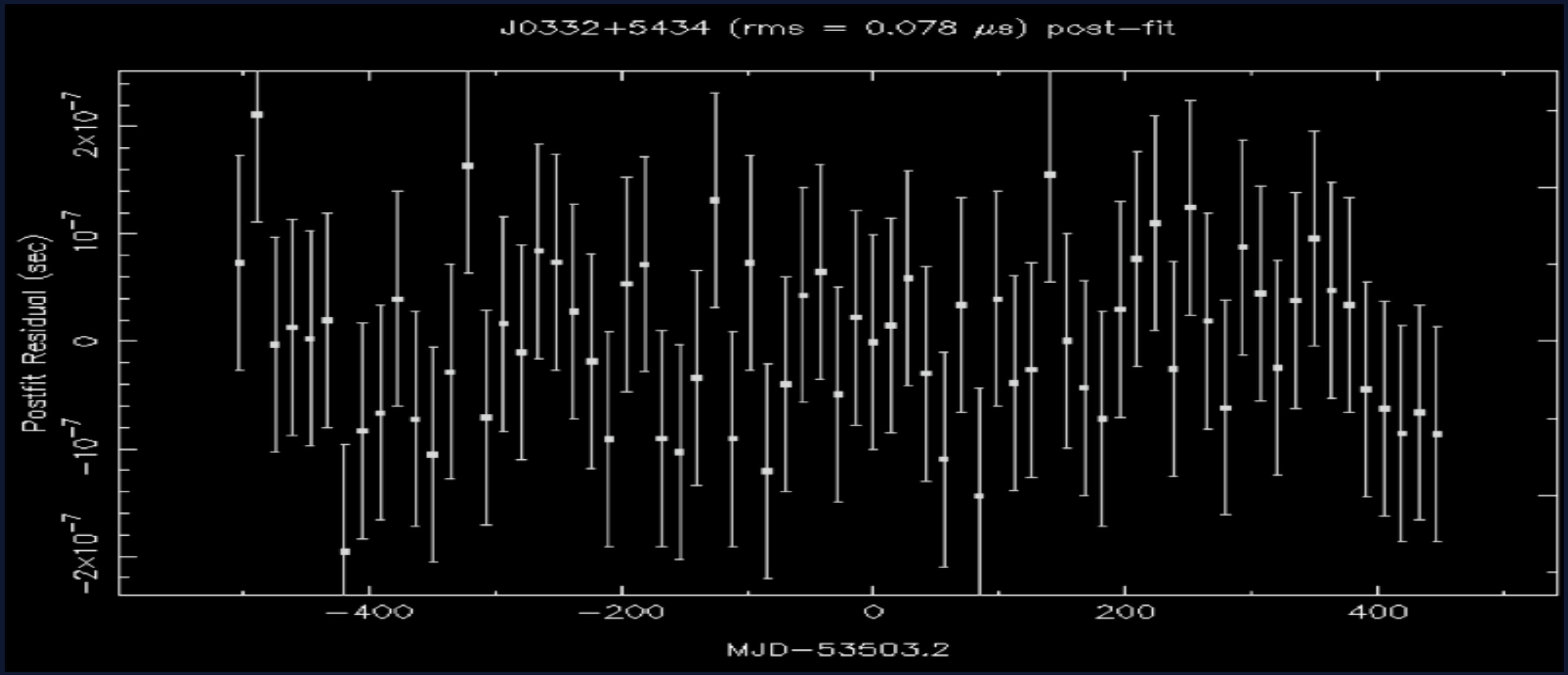

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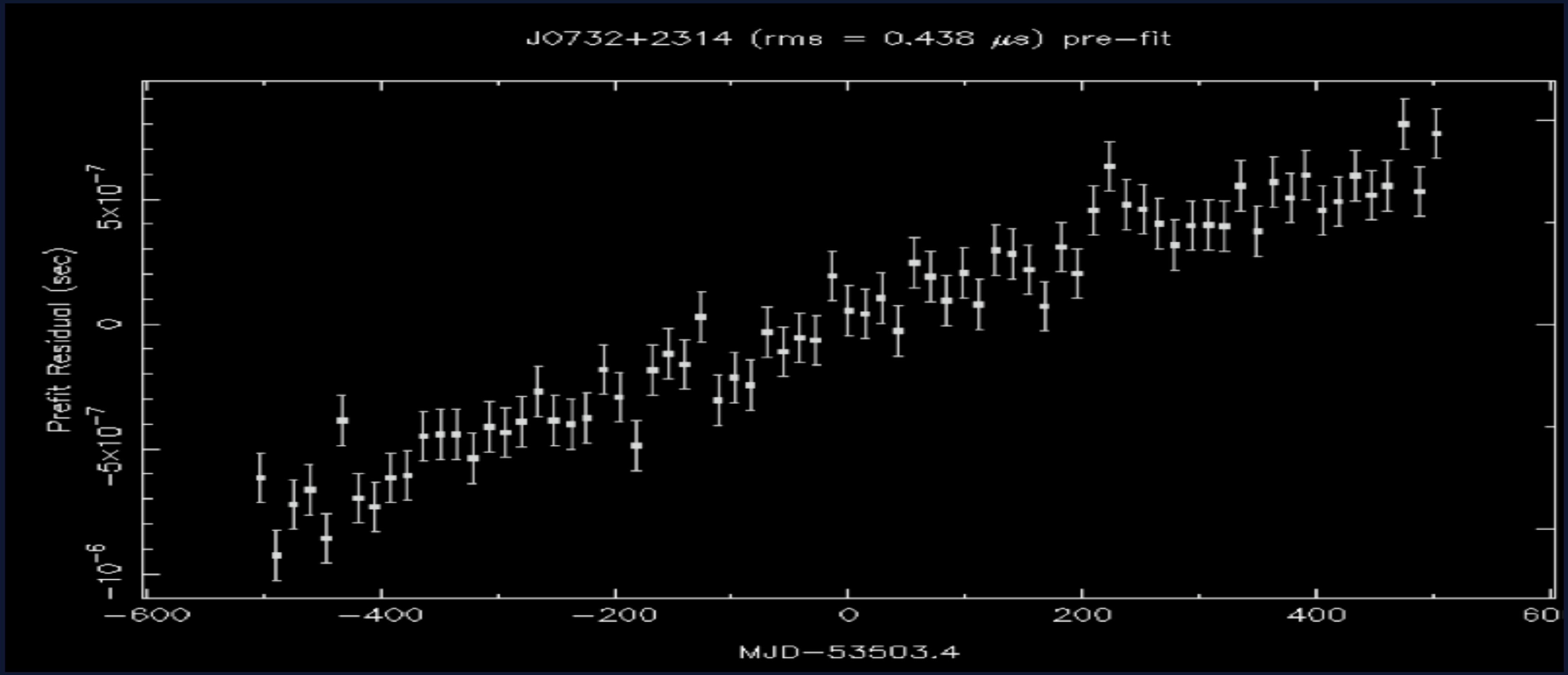

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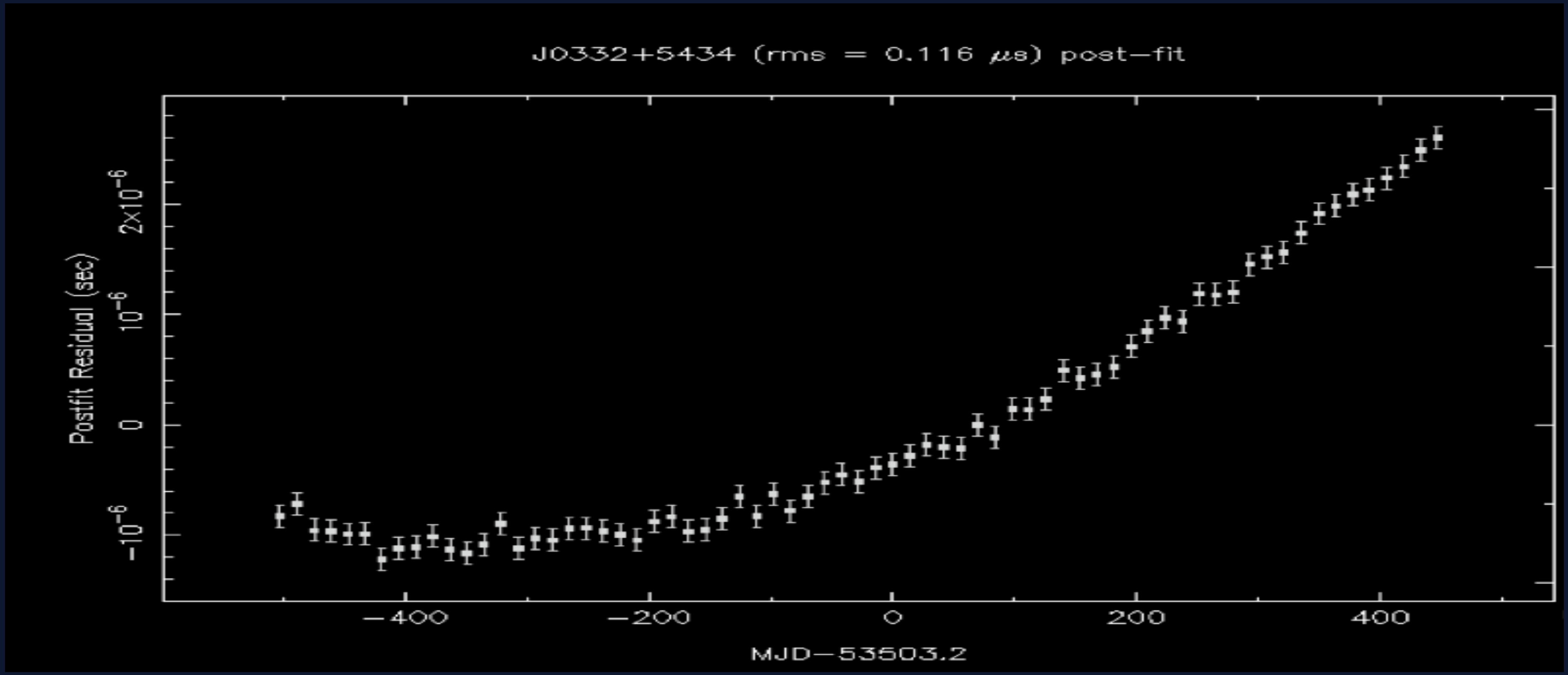

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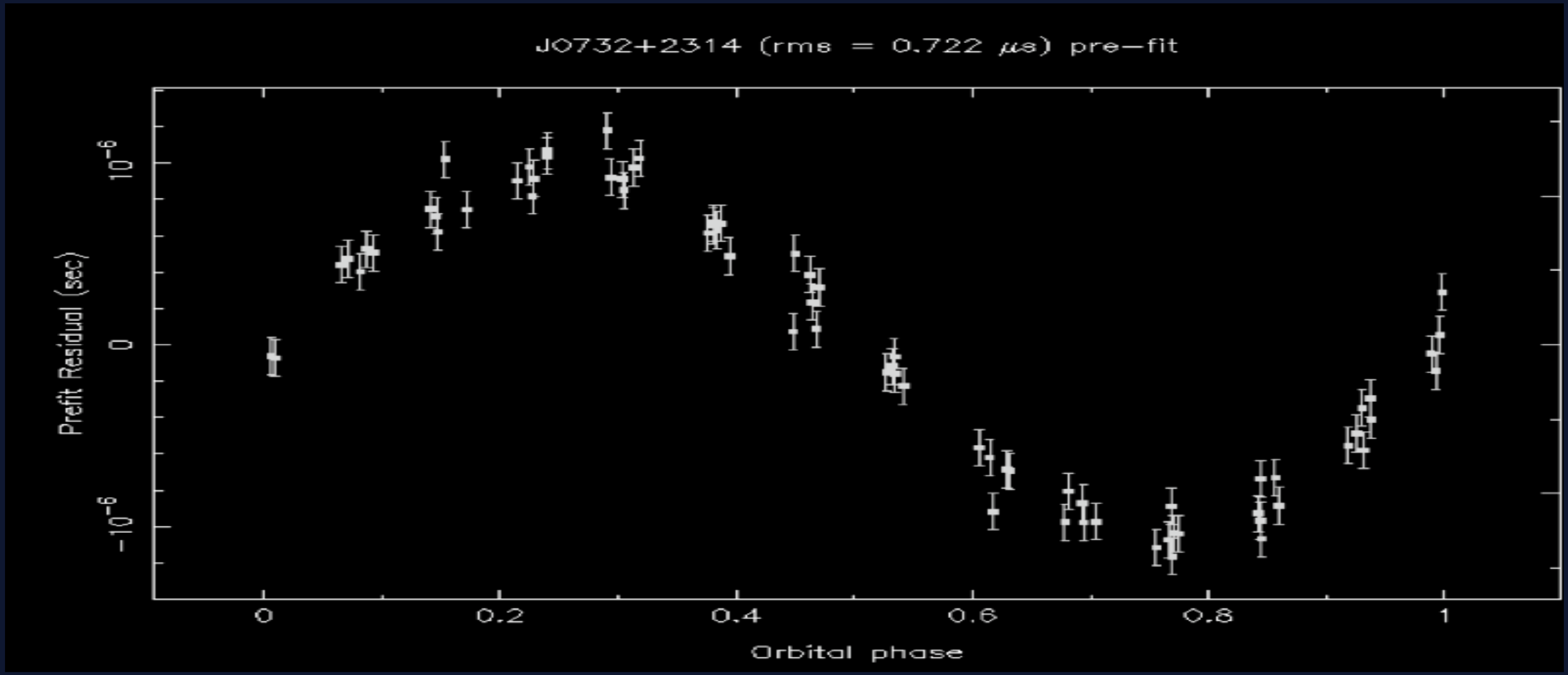

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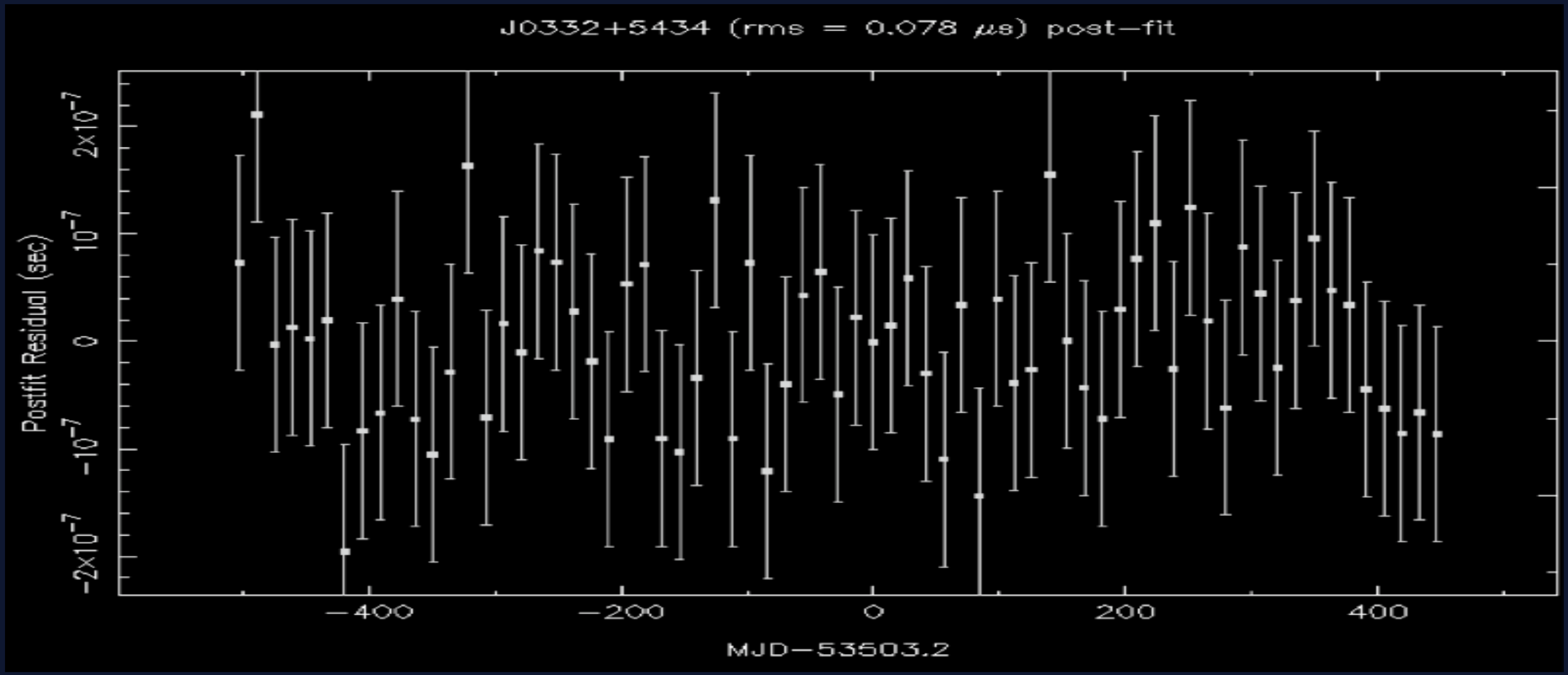


Pulsar Timing

For some binary pulsars, the accuracy of the ToA data is so high that - by using only the keplerian description - one cannot obtain an acceptable timing solution.

Additional physics is needed and can be tested

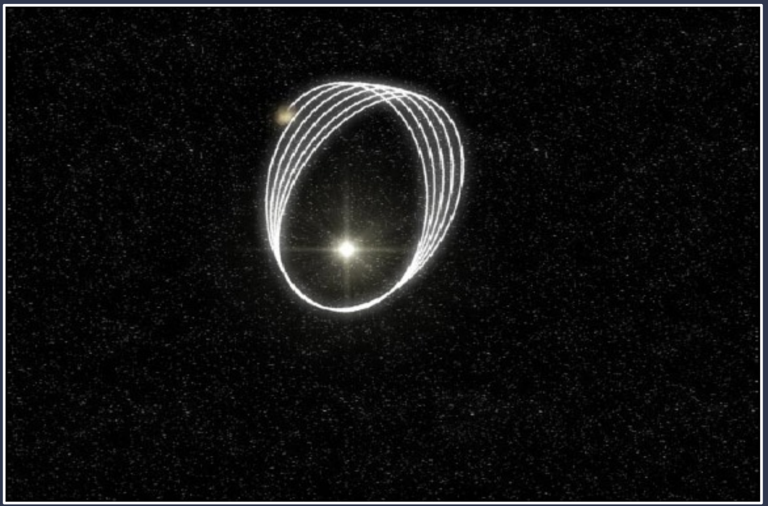
Pulsar Timing

Post-Keplerian (PK) formalism [Damour & Deruelle 1986]

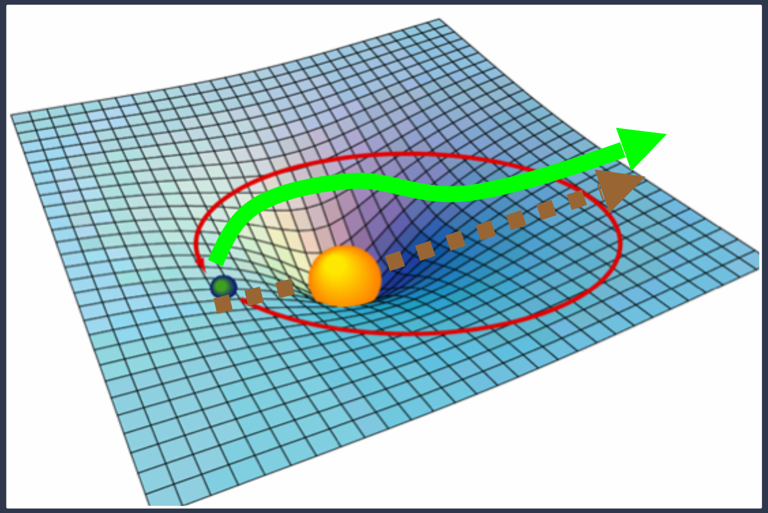
Pulsar Timing

Post-Keplerian (PK) formalism [Damour & Deruelle 1986]

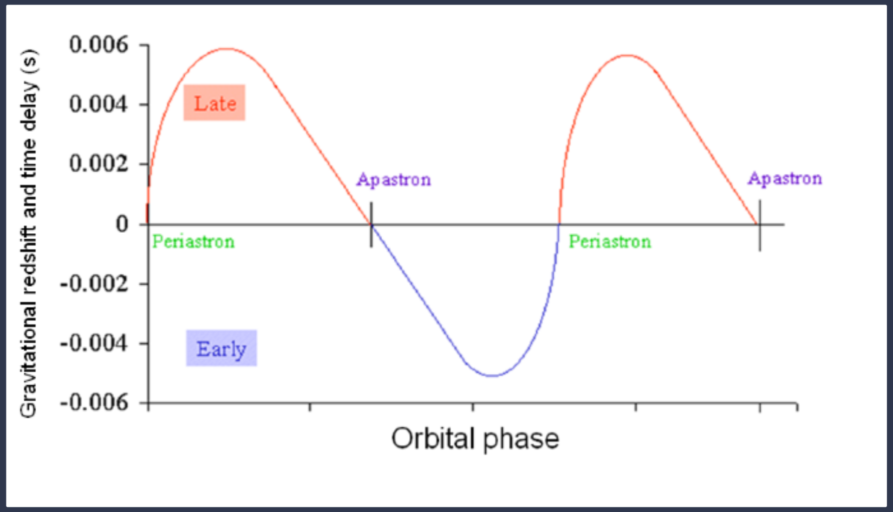
Periastron Precession - $\dot{\omega}$



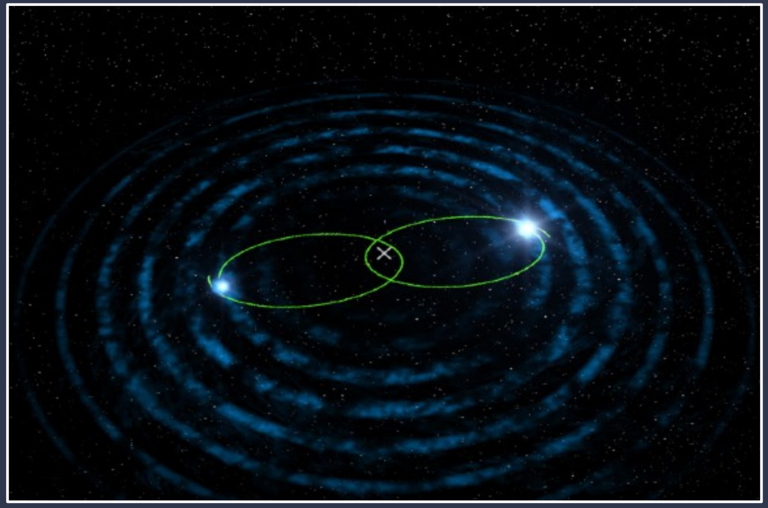
Shapiro Delay r & s



Gr. redshift & time dilation - γ



Orbital decay $\dot{P}_b$



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

Periastron precession

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

Time dilation & gravitational redshift

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) (1 - e^2)^{-7/2} T_\odot^{5/3} m_p m_c M^{-1/3} ,$$

Orbital period decay

$$r = T_\odot m_c ,$$

Shapiro delay (range)

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_c^{-1} .$$

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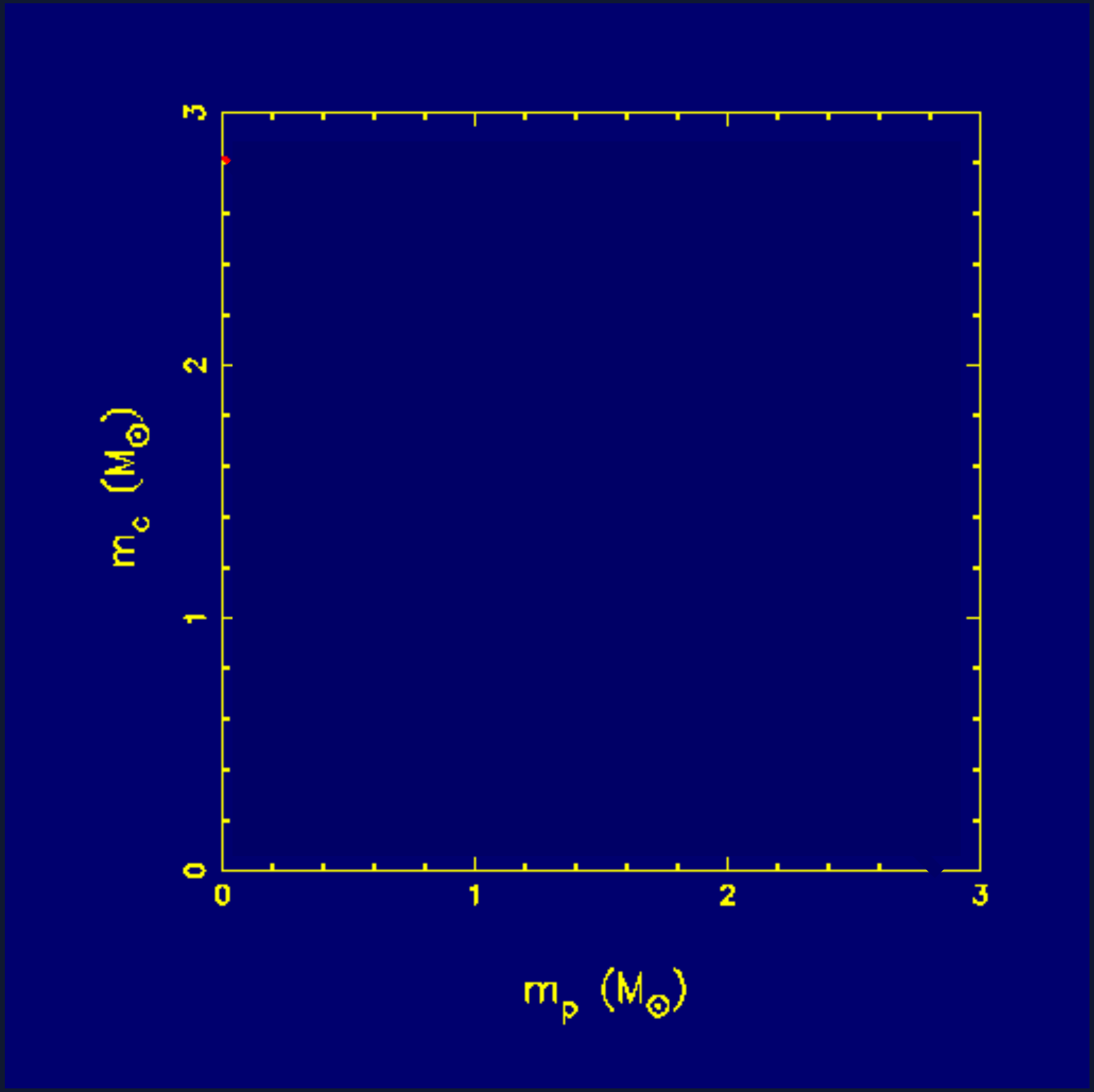
Shapiro delay (shape)

↓

n - 2 GR tests!

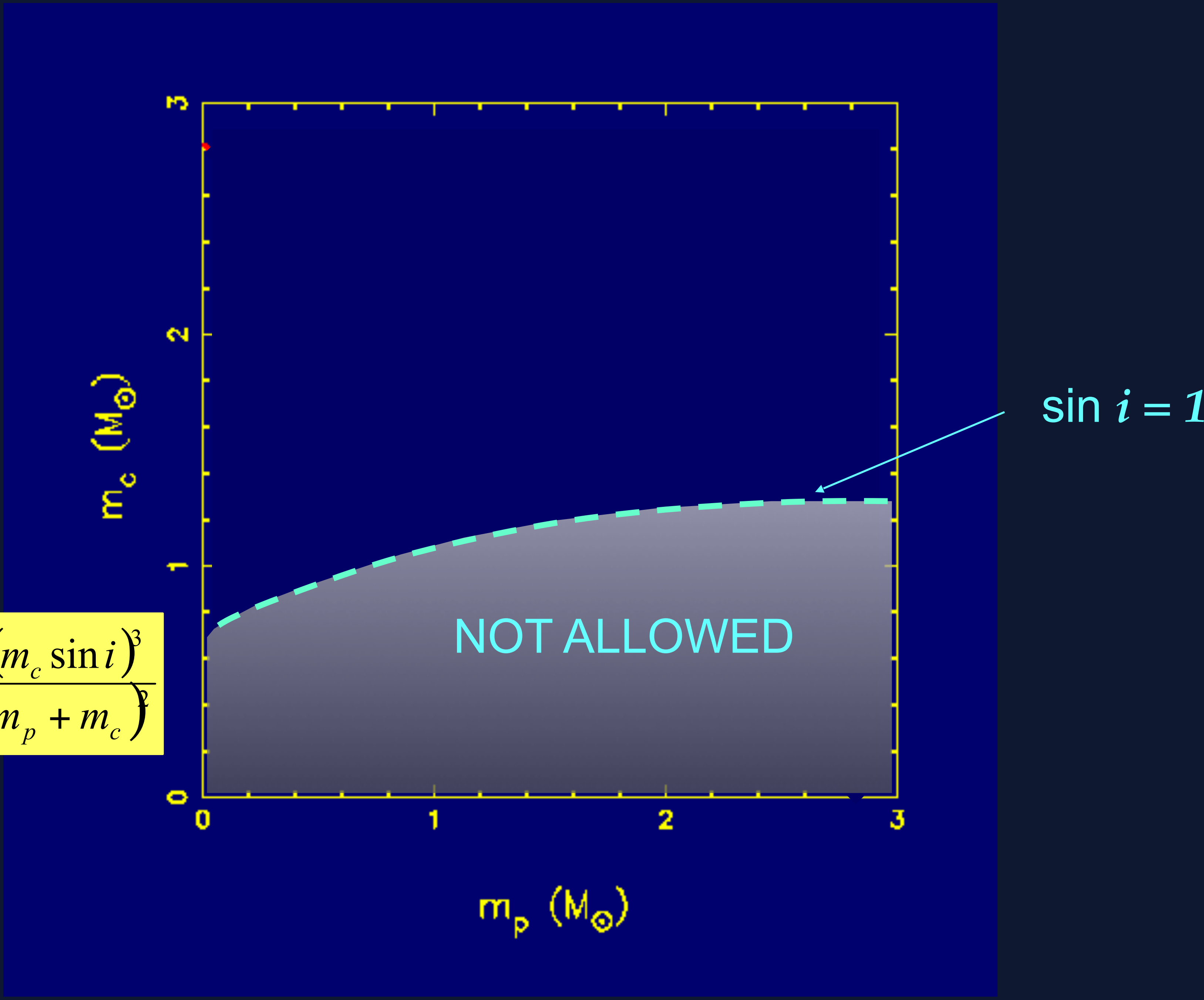
Testing Relativistic Gravity



Testing Relativistic Gravity

Mass Function constraints

$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{(a_p \sin i)^3}{P_{orb}^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$



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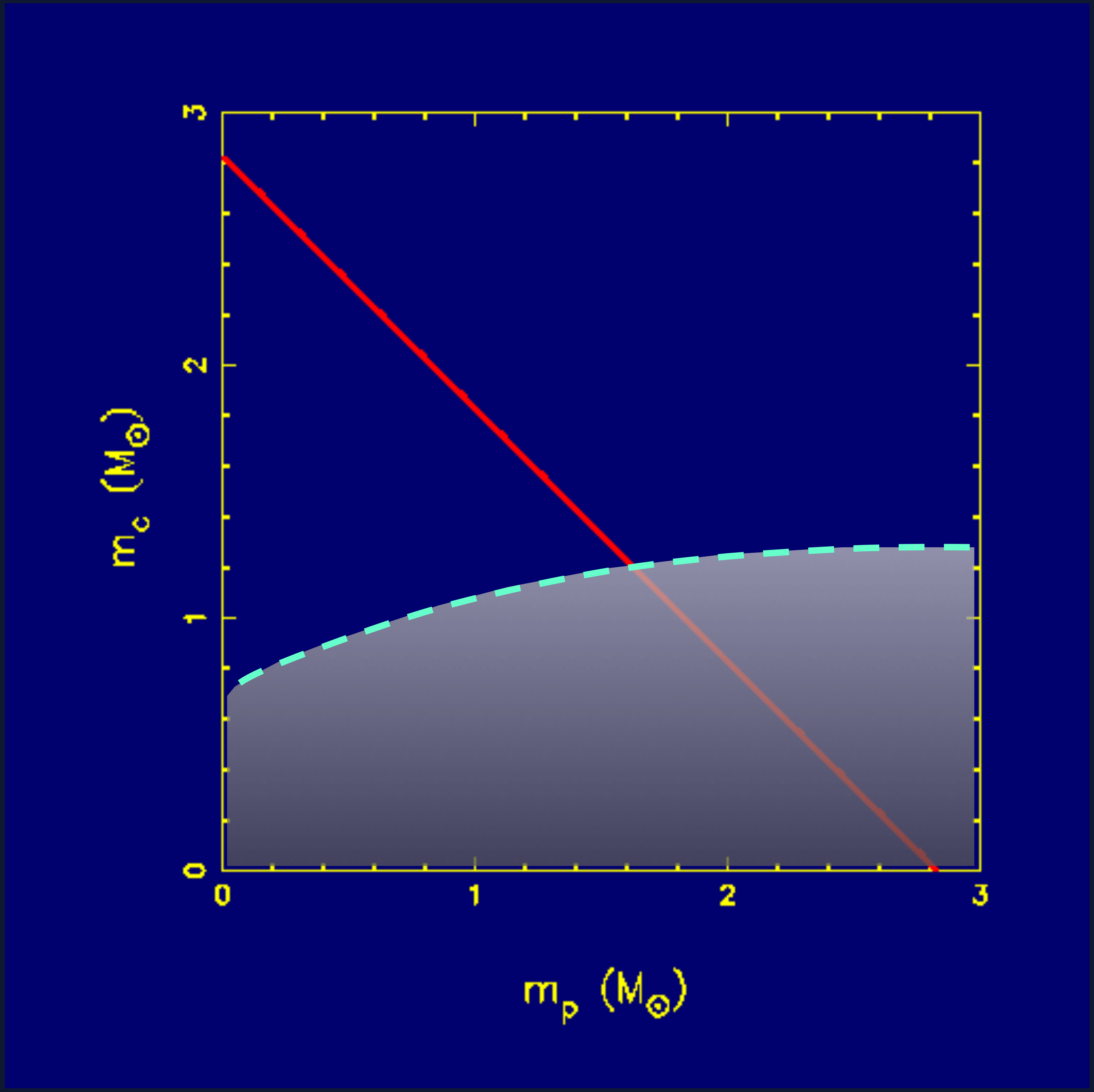

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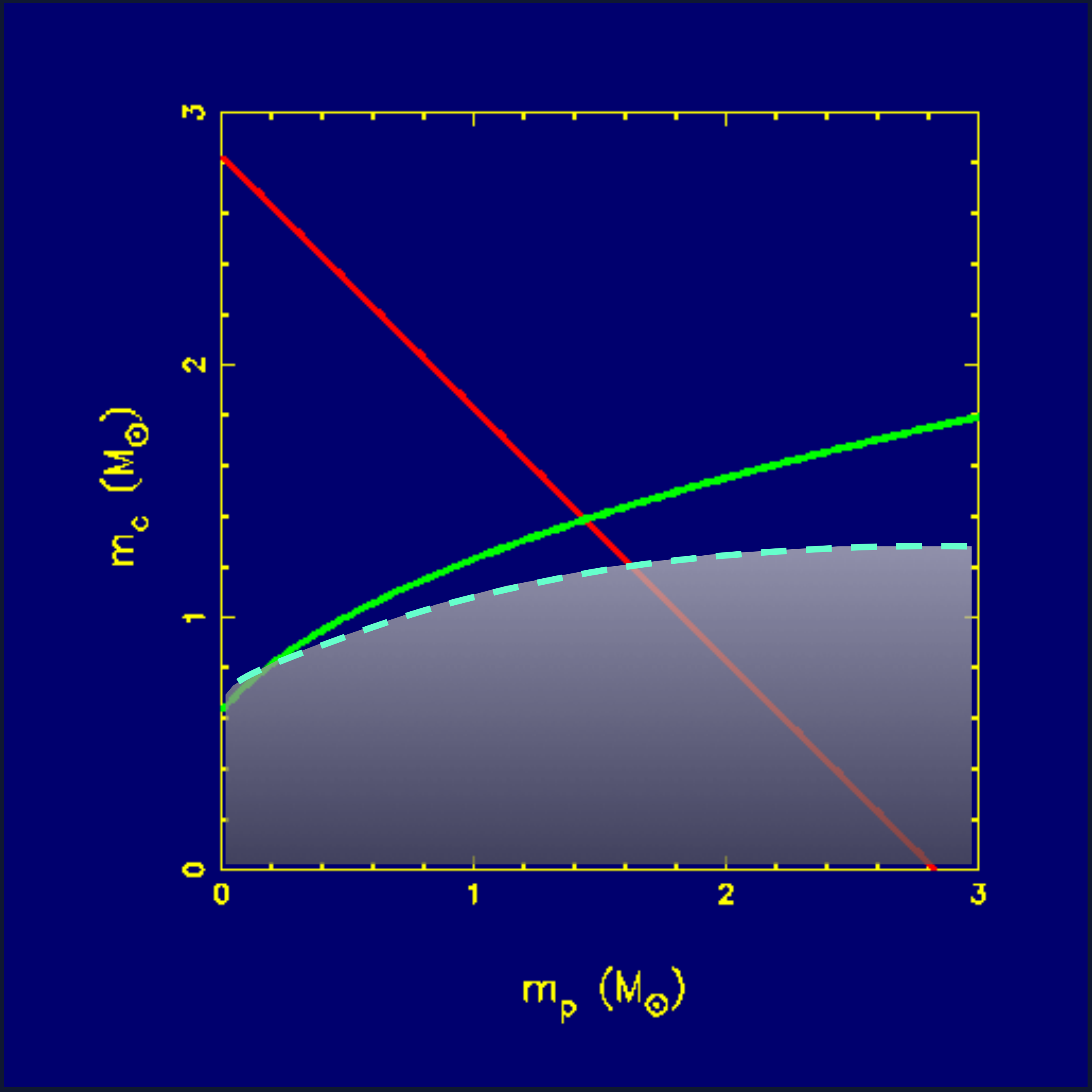

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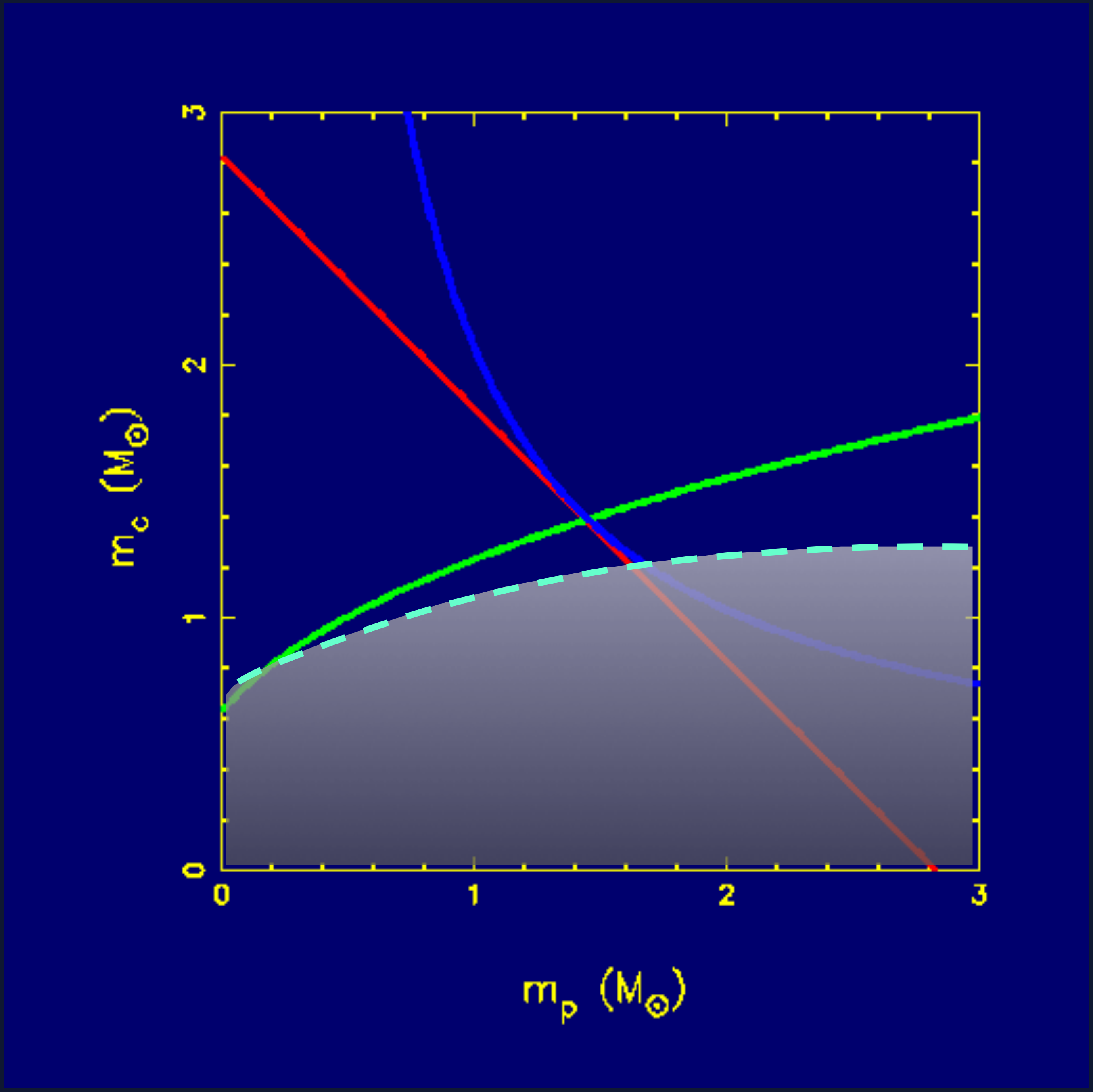

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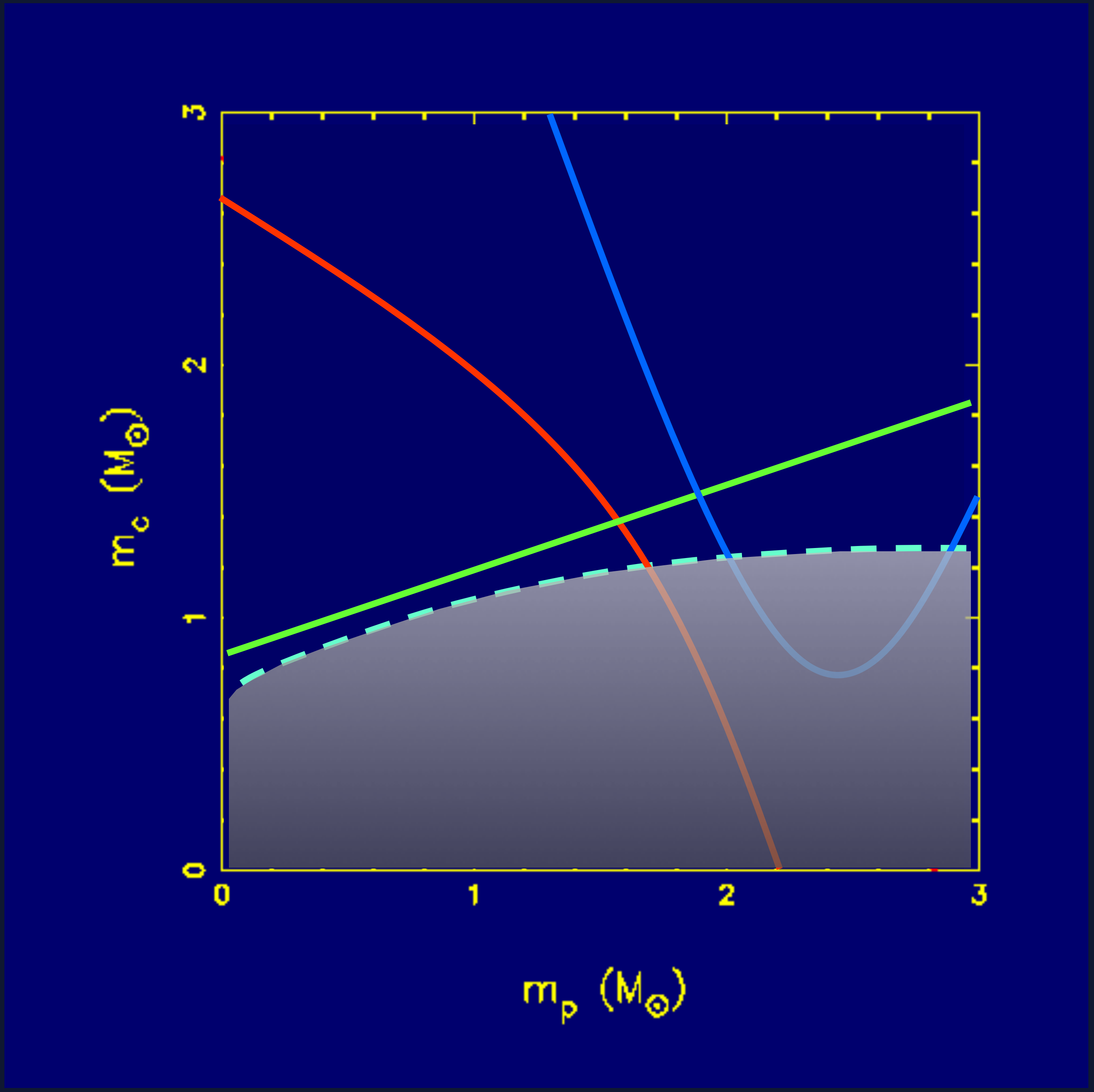

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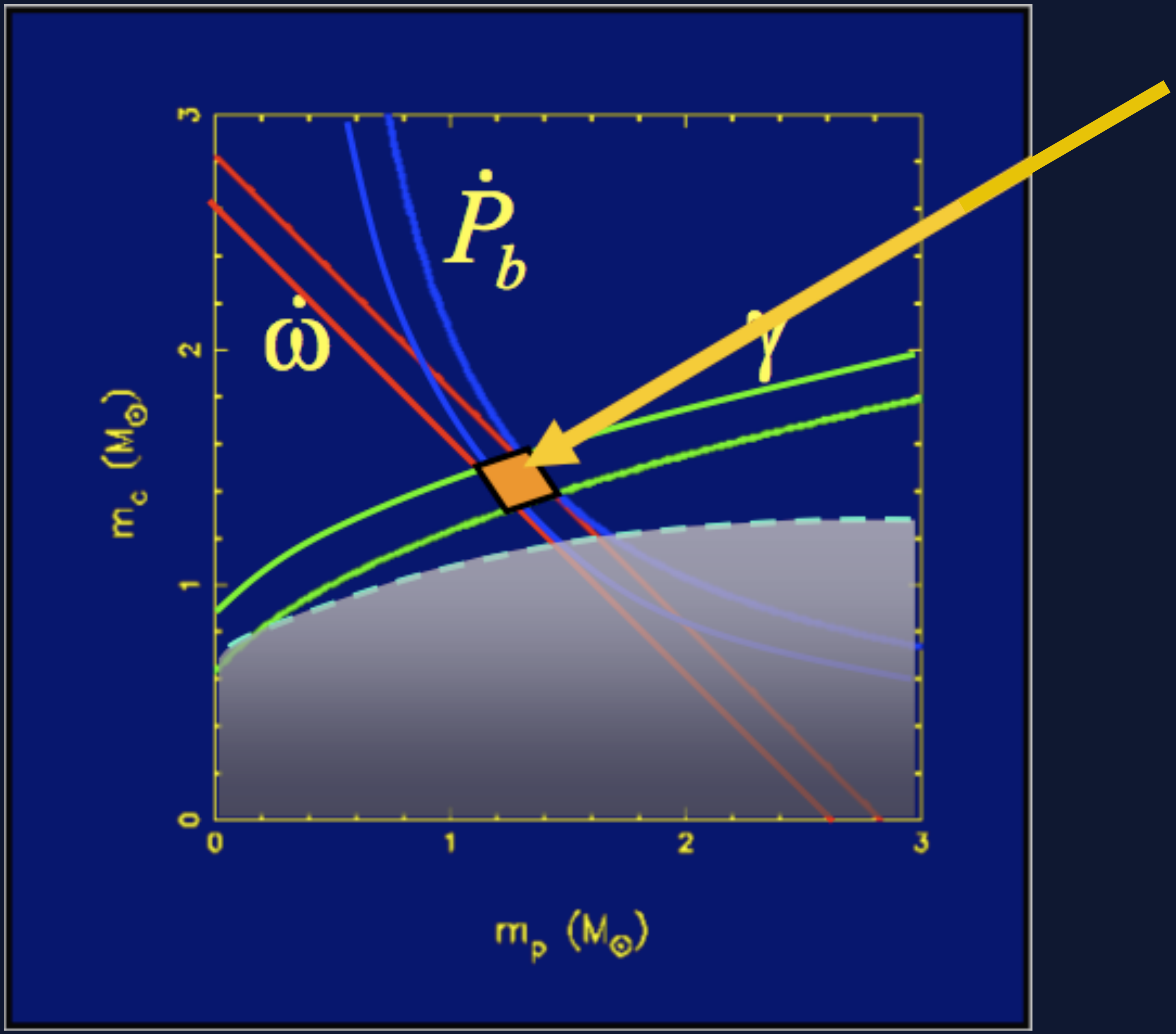


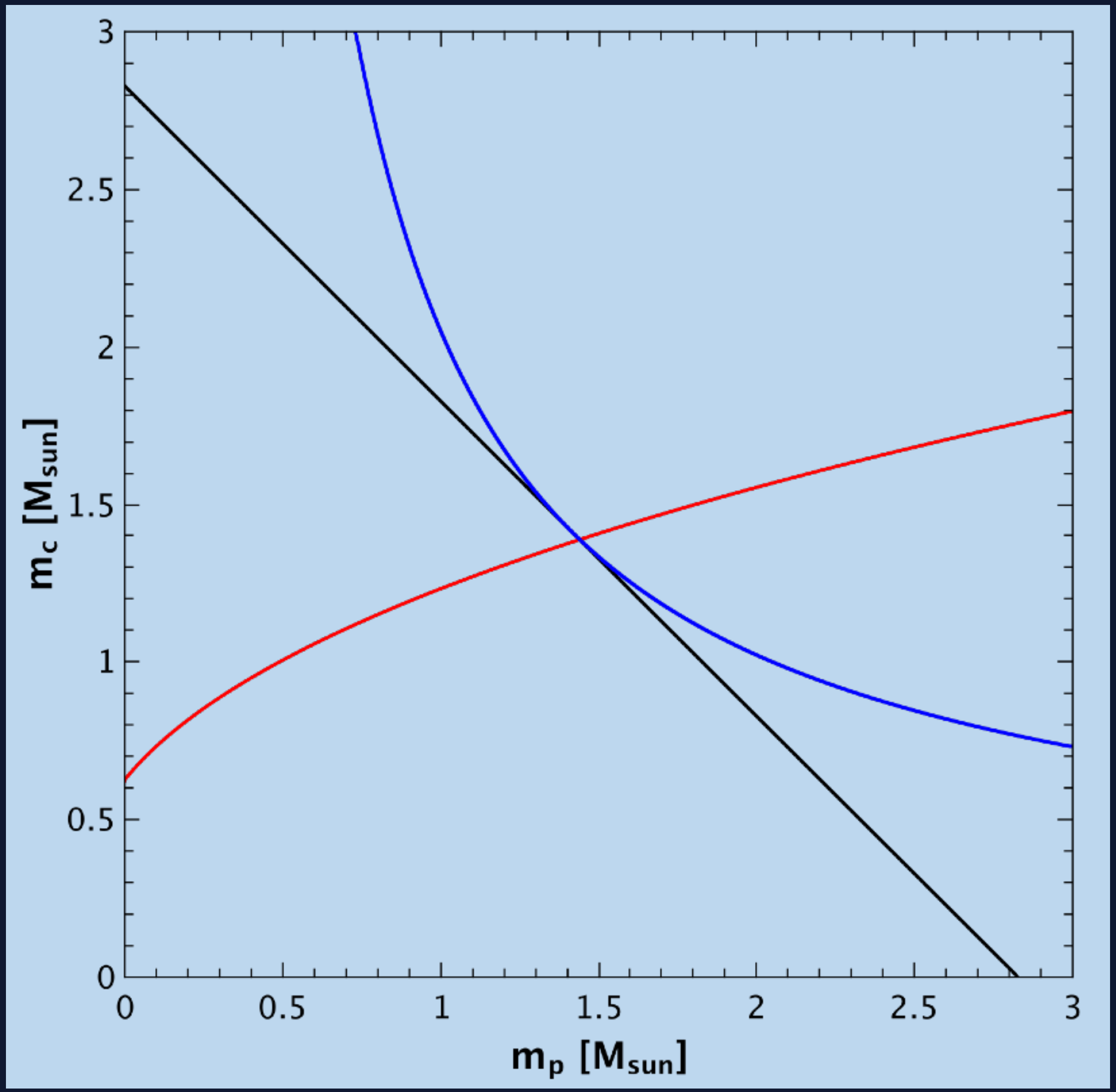
Testing Relativistic Gravity

PSR B1913+16

Discovered in 1974 [Hulse & Taylor '75]

- PSR+NS
- P_{spin} = 59 ms
- P_{orb} = 7.8 hr
- Ecc = 0.61

- 3 PK parameters: $\dot{\omega}$, γ, $\dot{P}_b$



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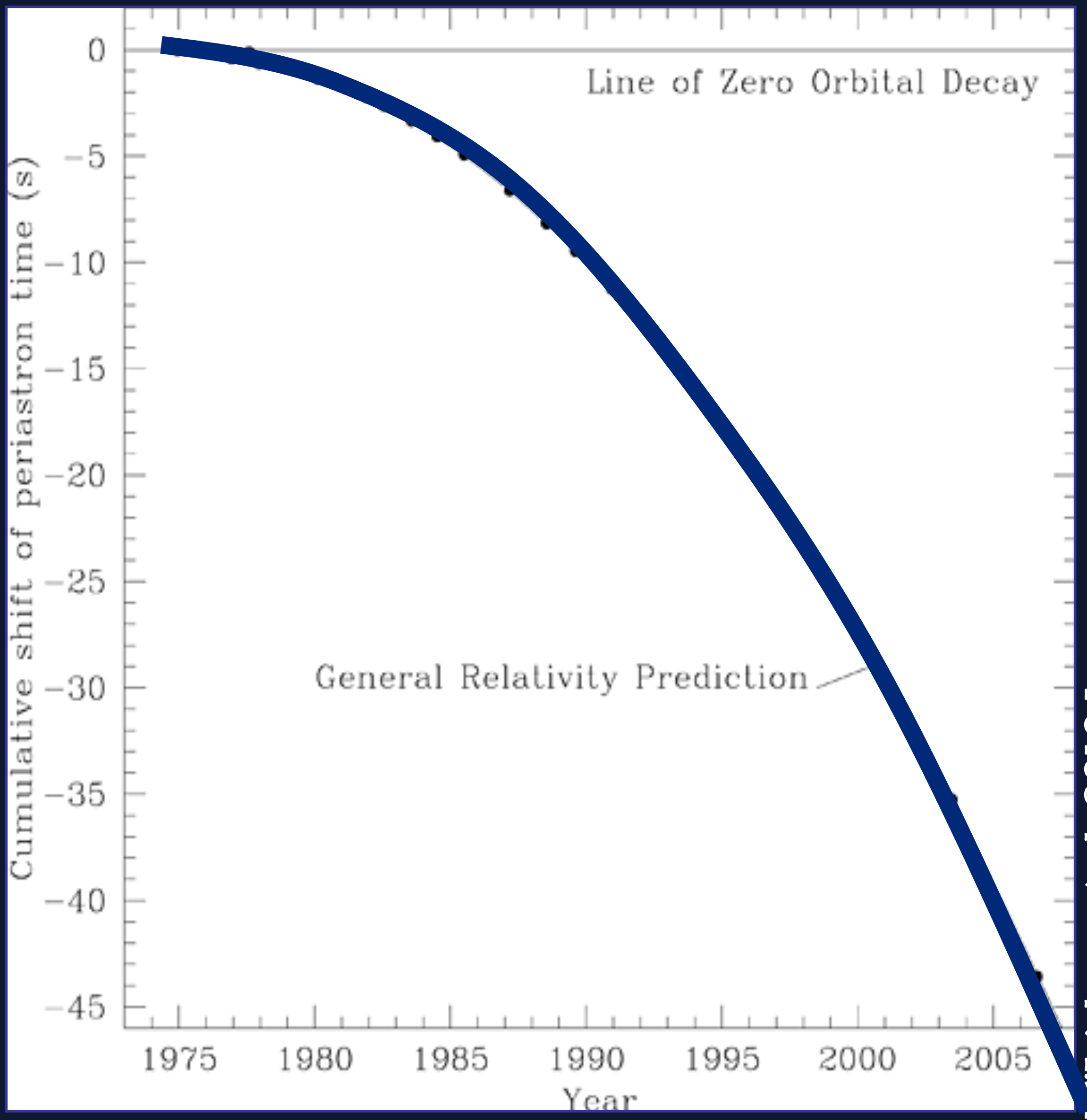

[Weisberg et al. 2010]

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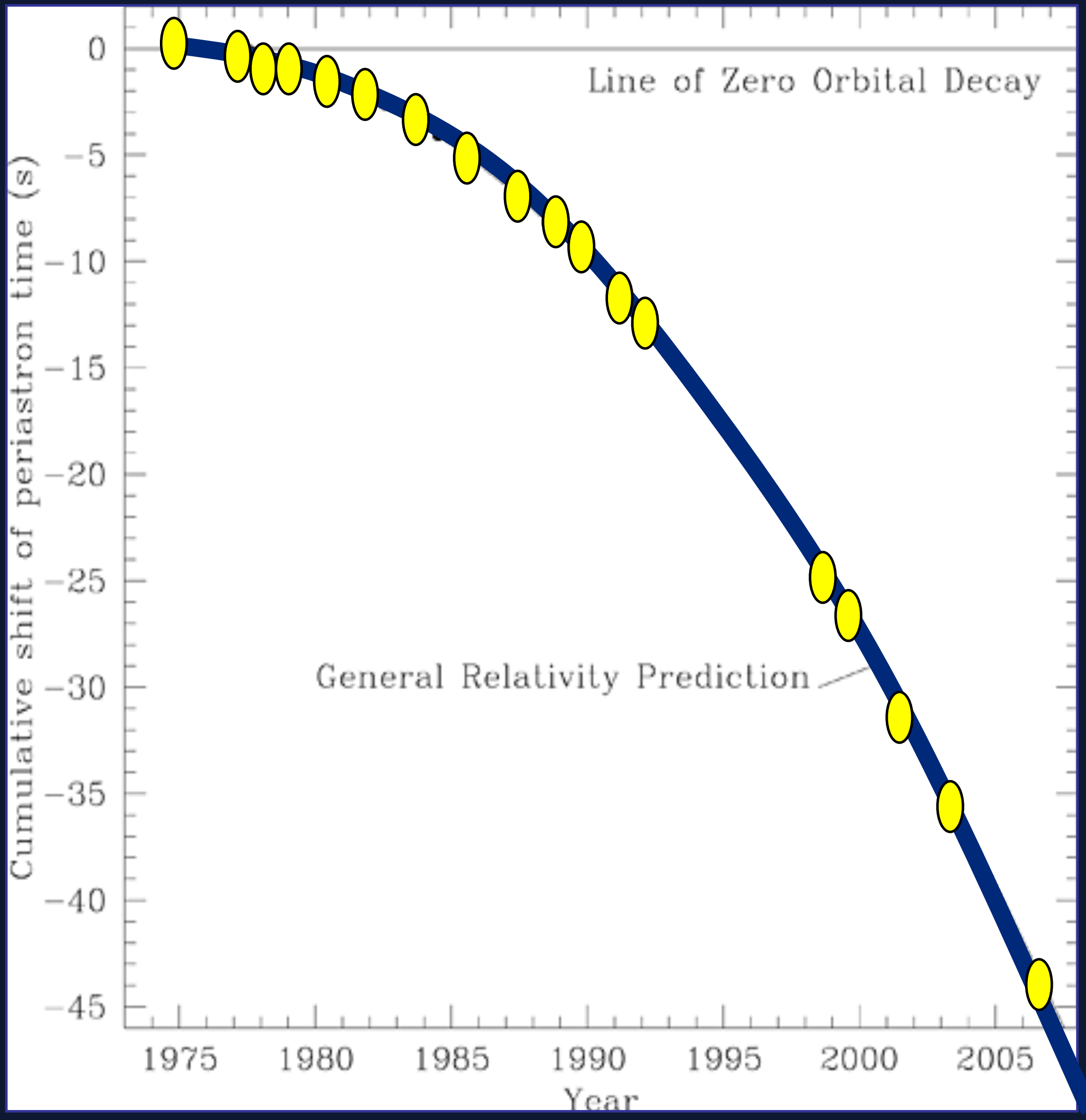

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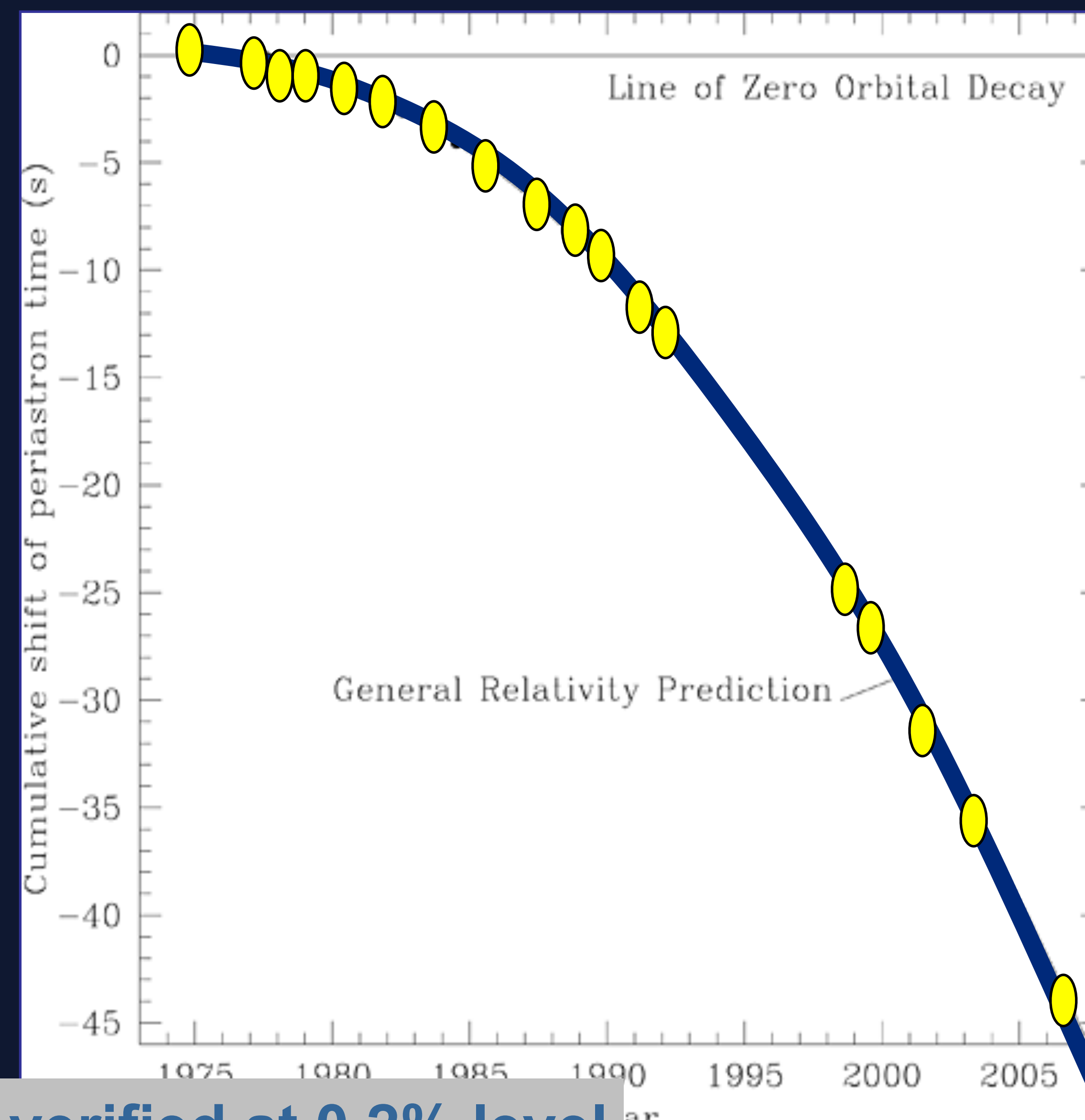
NOBEL PRIZE
1993
Taylor & Hulse



GR verified at 0.2% level

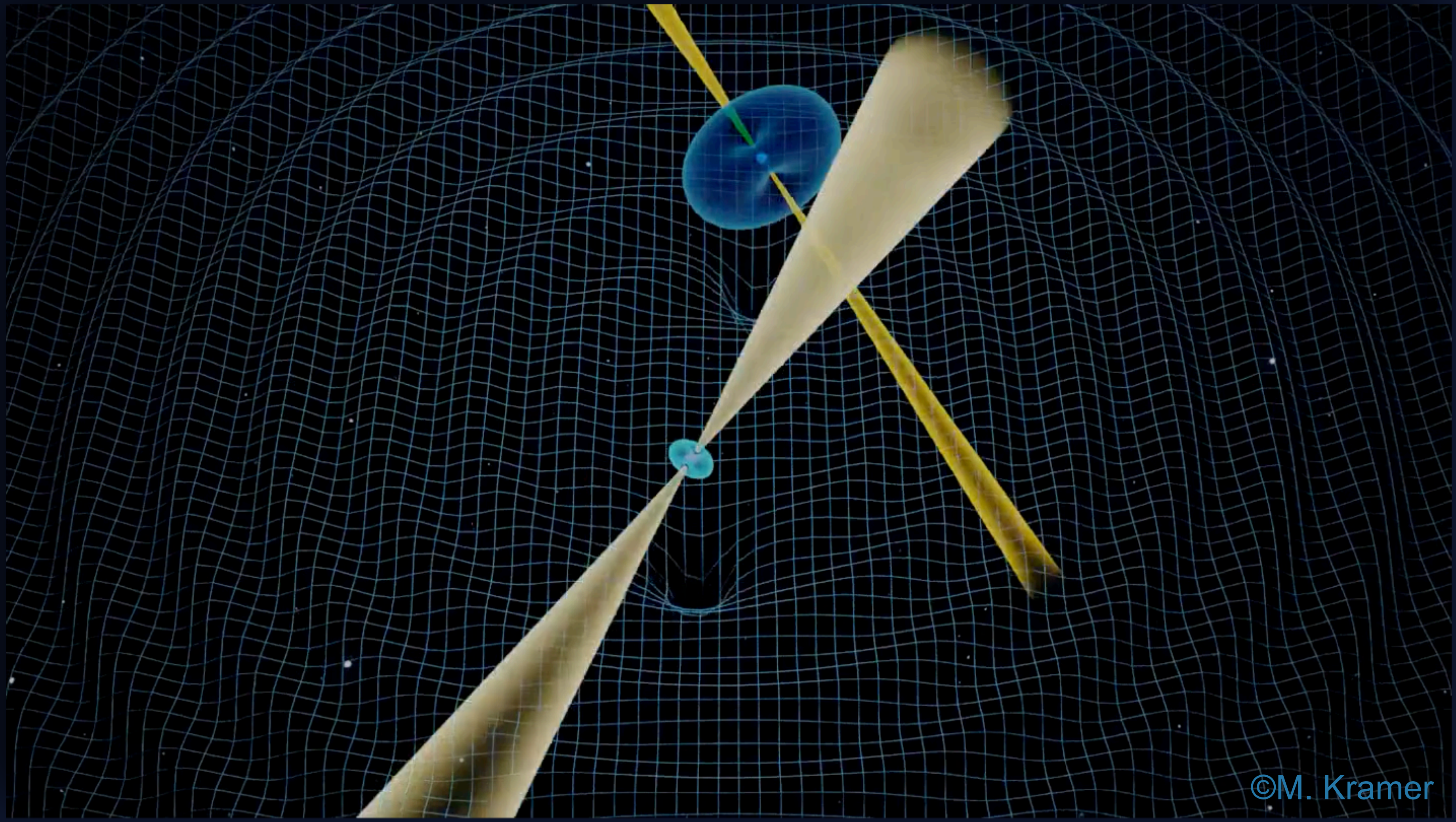
[Weisberg et al. 2010]

Testing Relativistic Gravity

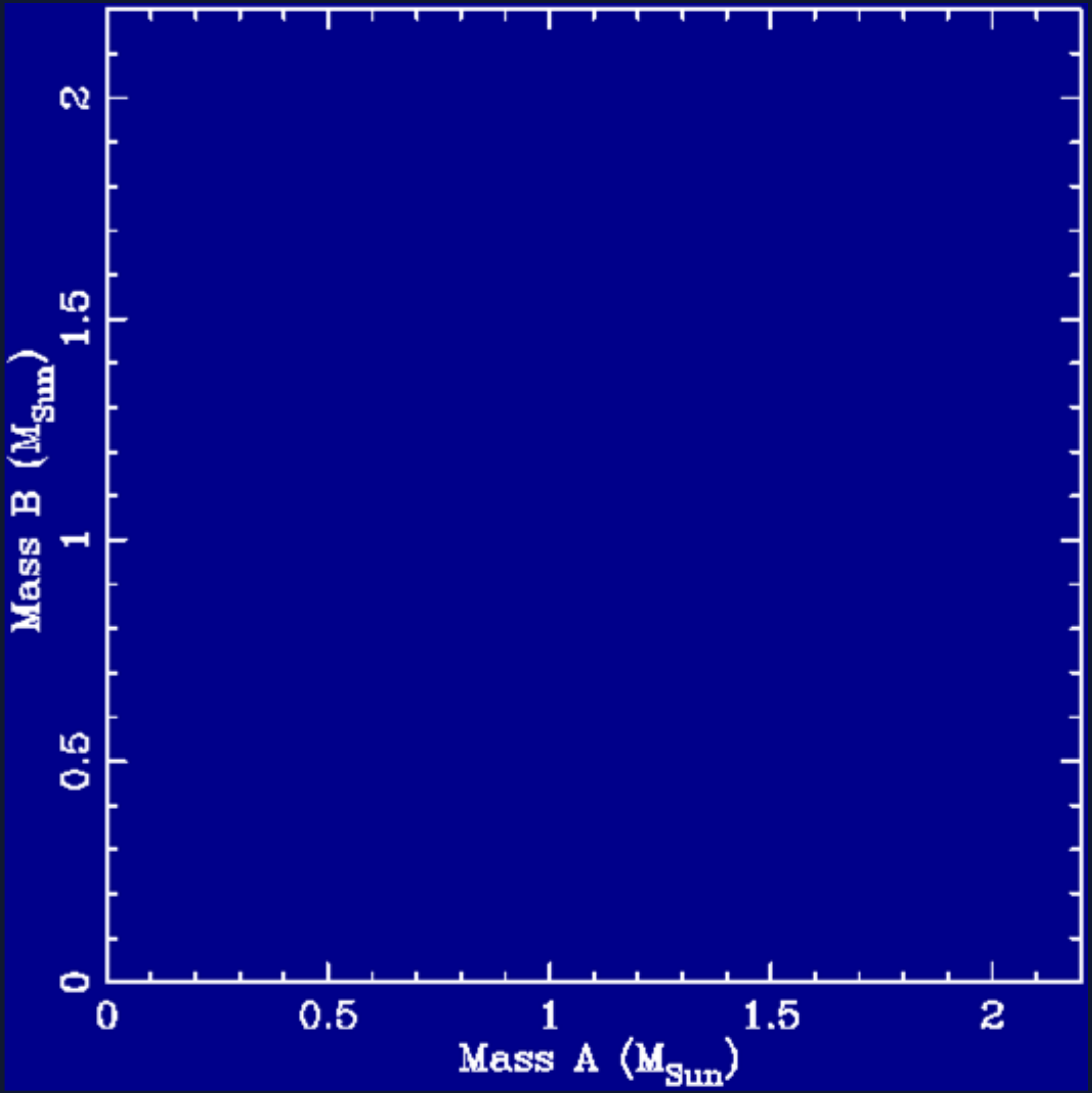
PSR J0737-3039A/B

Discovered in 2003 [Burgay et al '03; Lyne et al. '04]

- PSR+PSR!
- $P_{spin}A$ = 23 ms
- $P_{spin}B$ = 2.7 s
- P_{orb} = 2.4 hr
- Ecc = 0.09
- Orb v = 0.001 c
- i = 89.35°



Testing GR with the Double Pulsar



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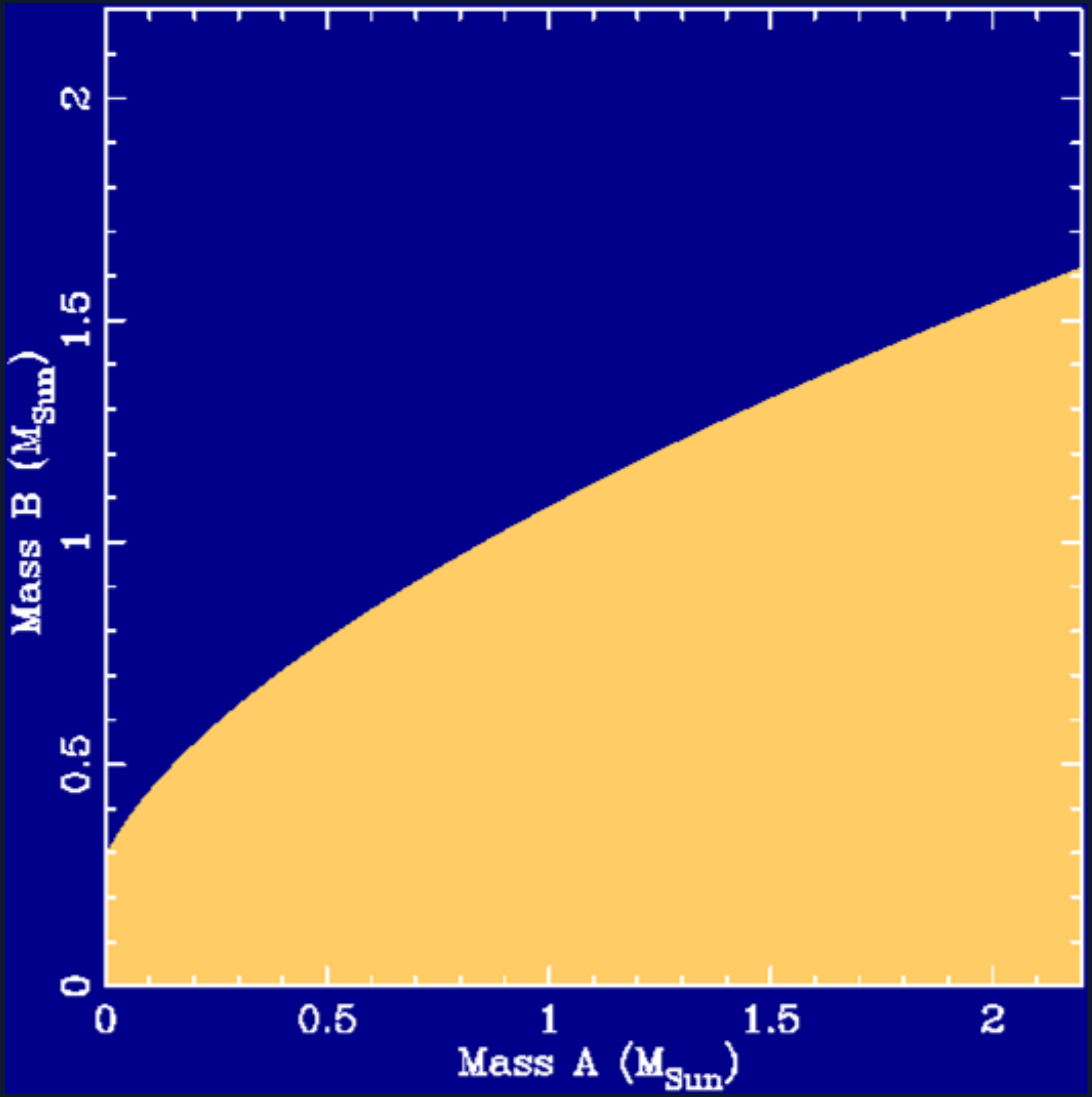

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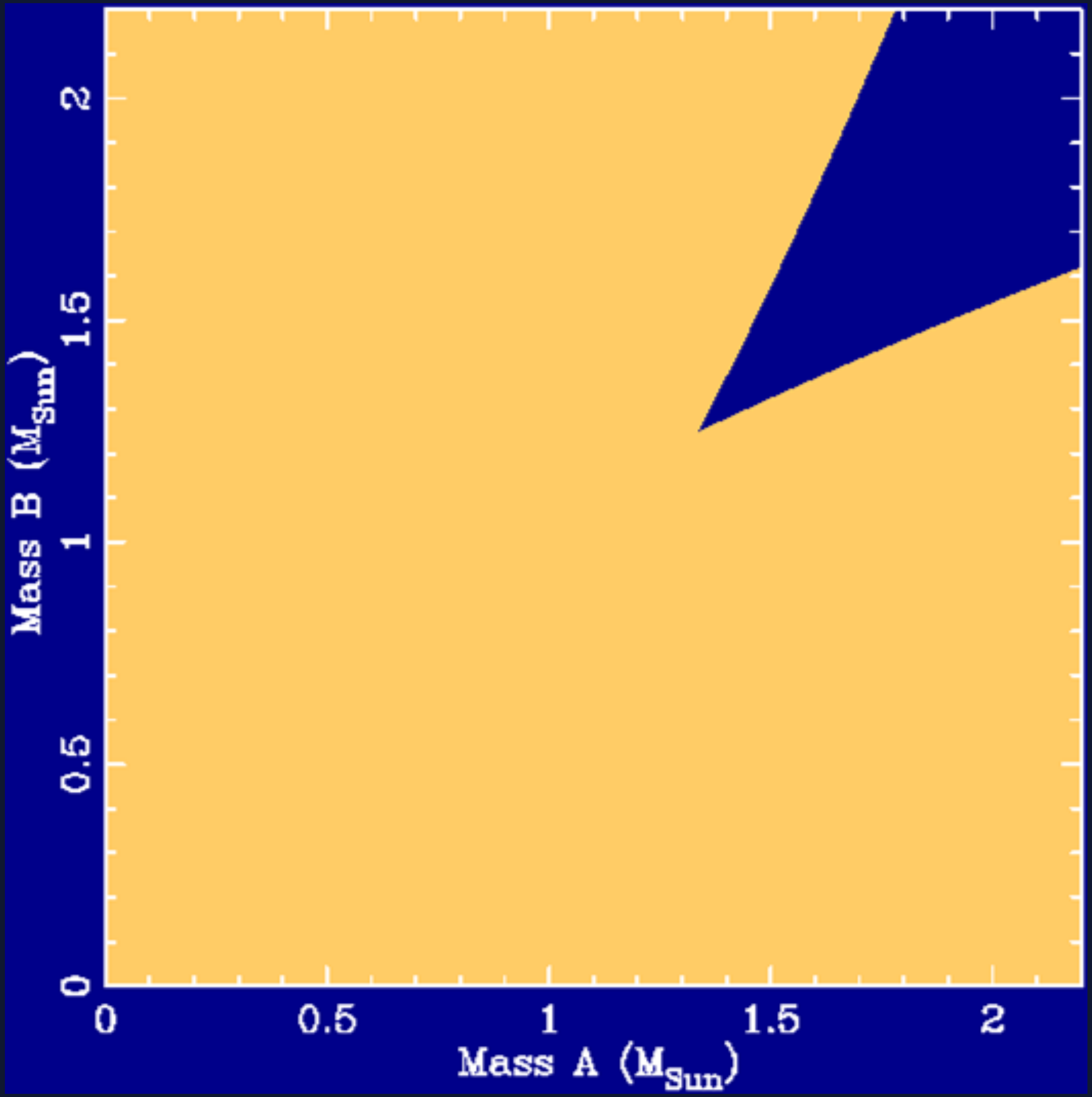

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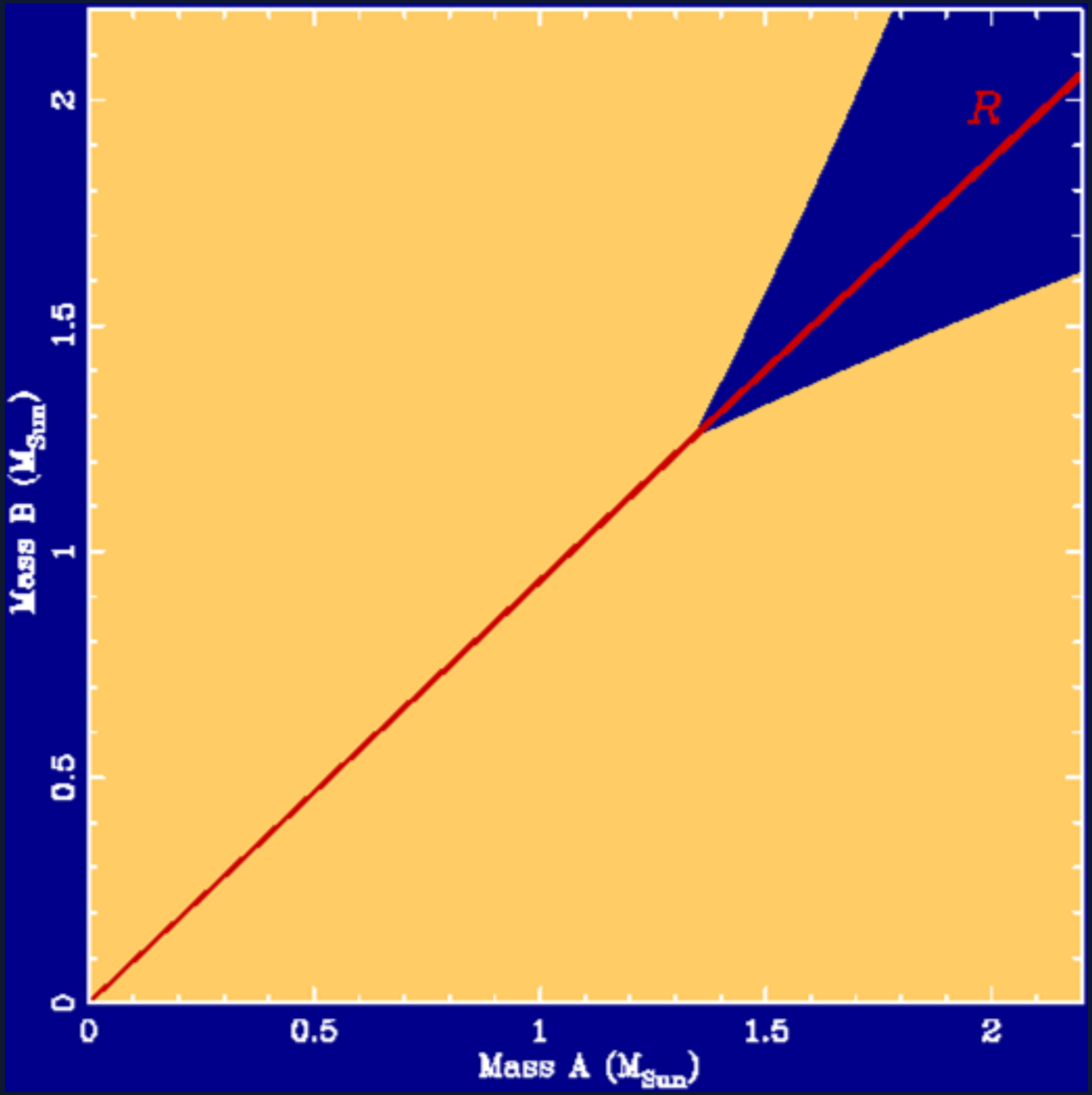

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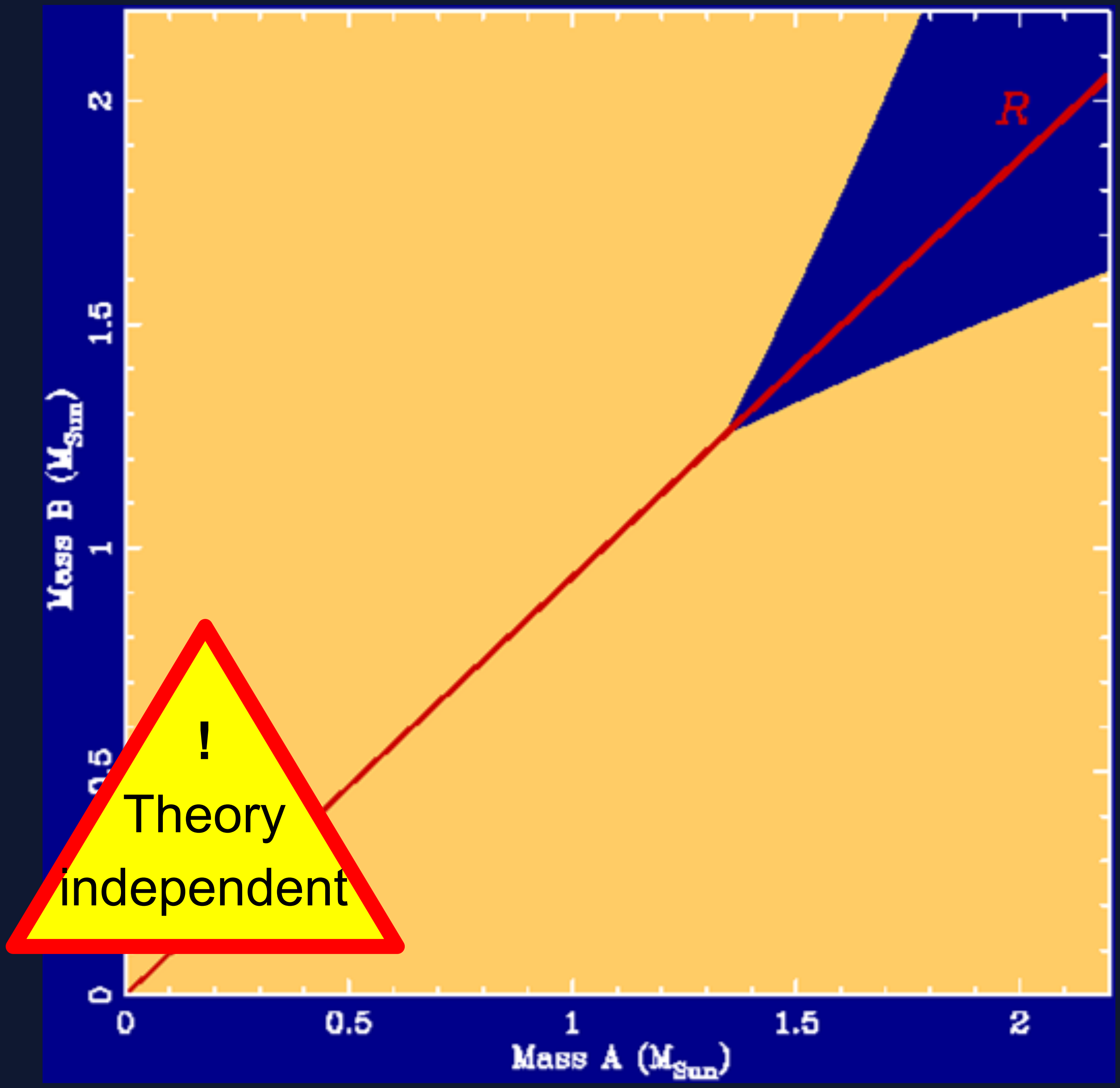

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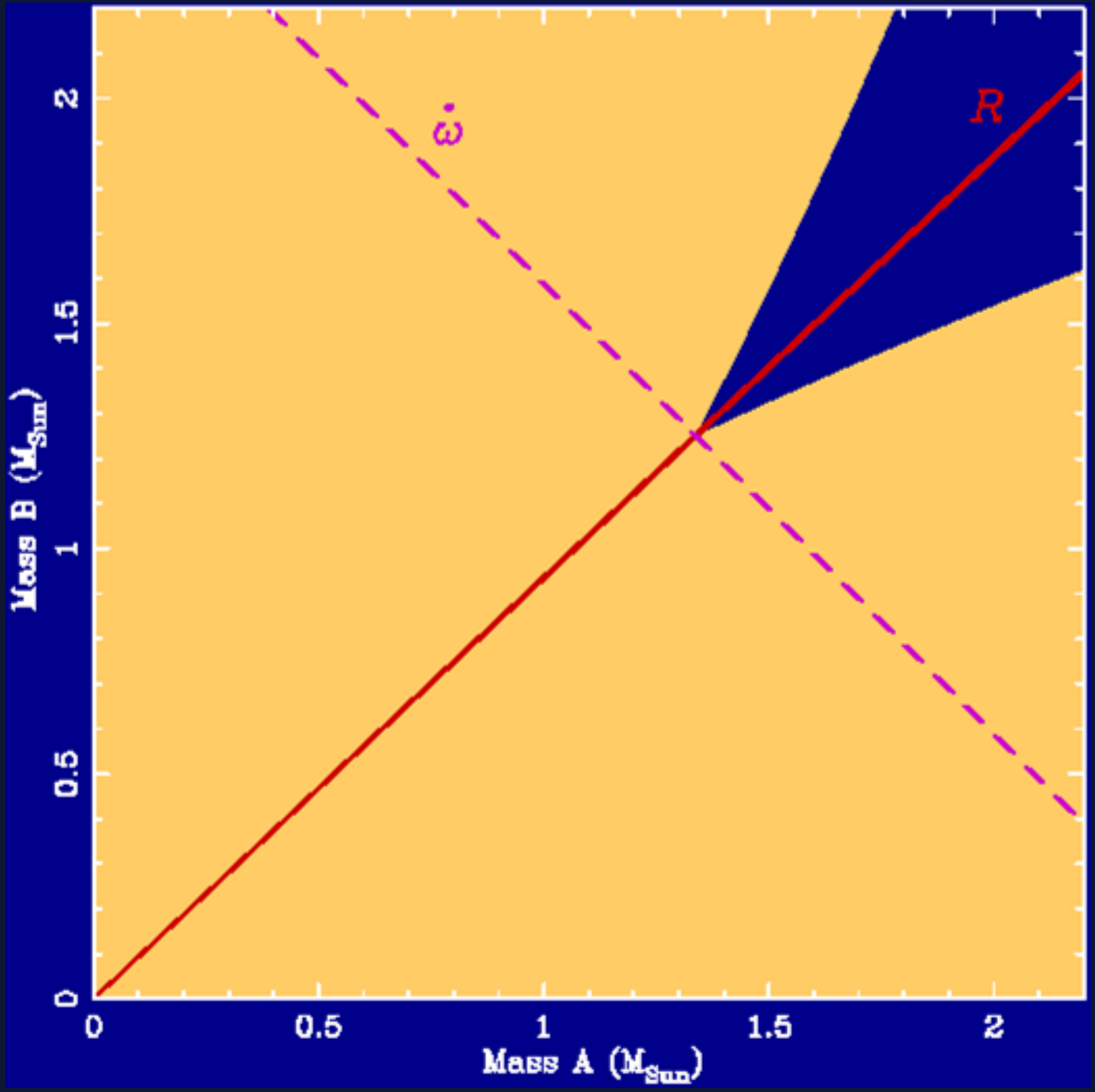

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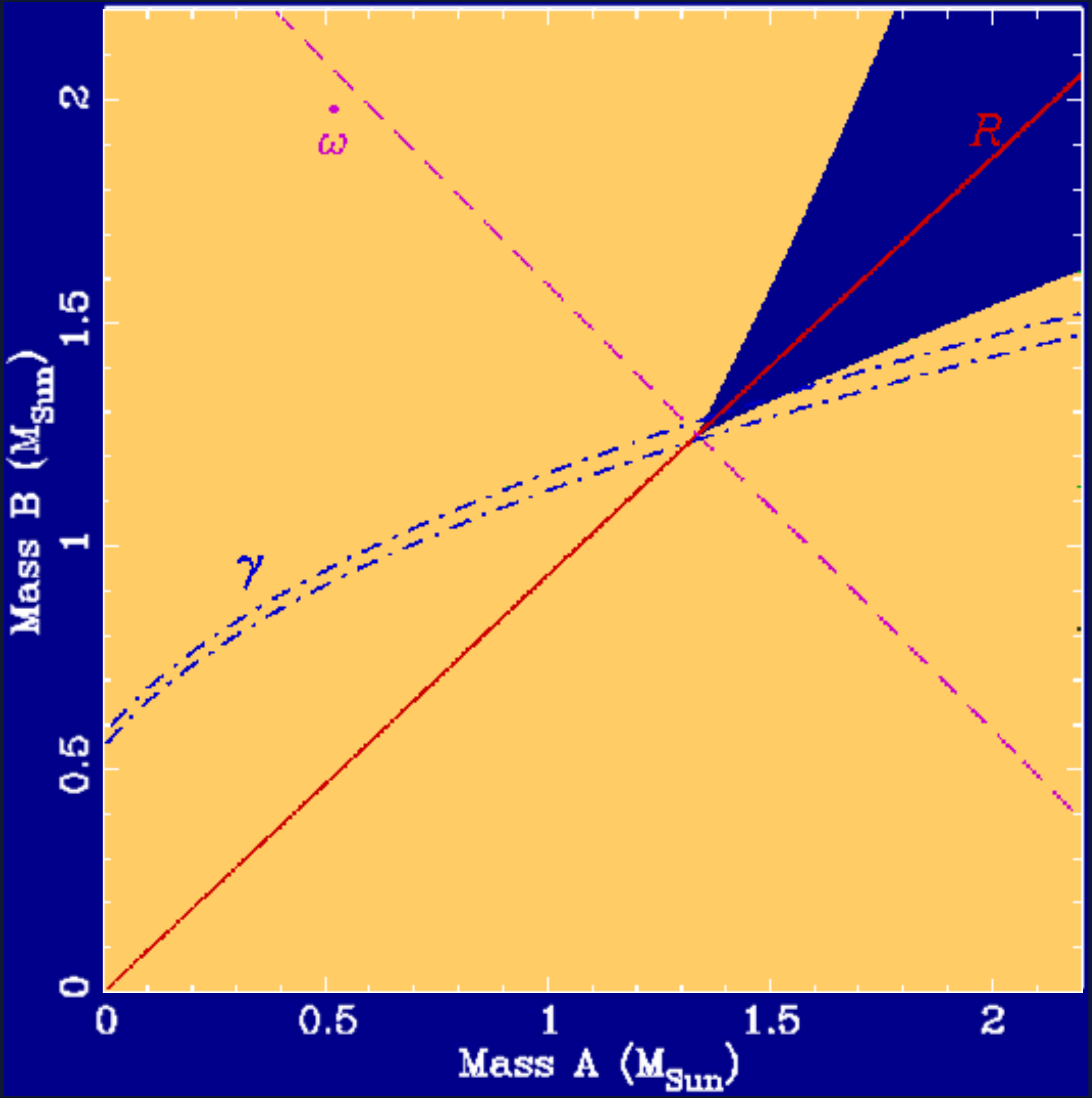

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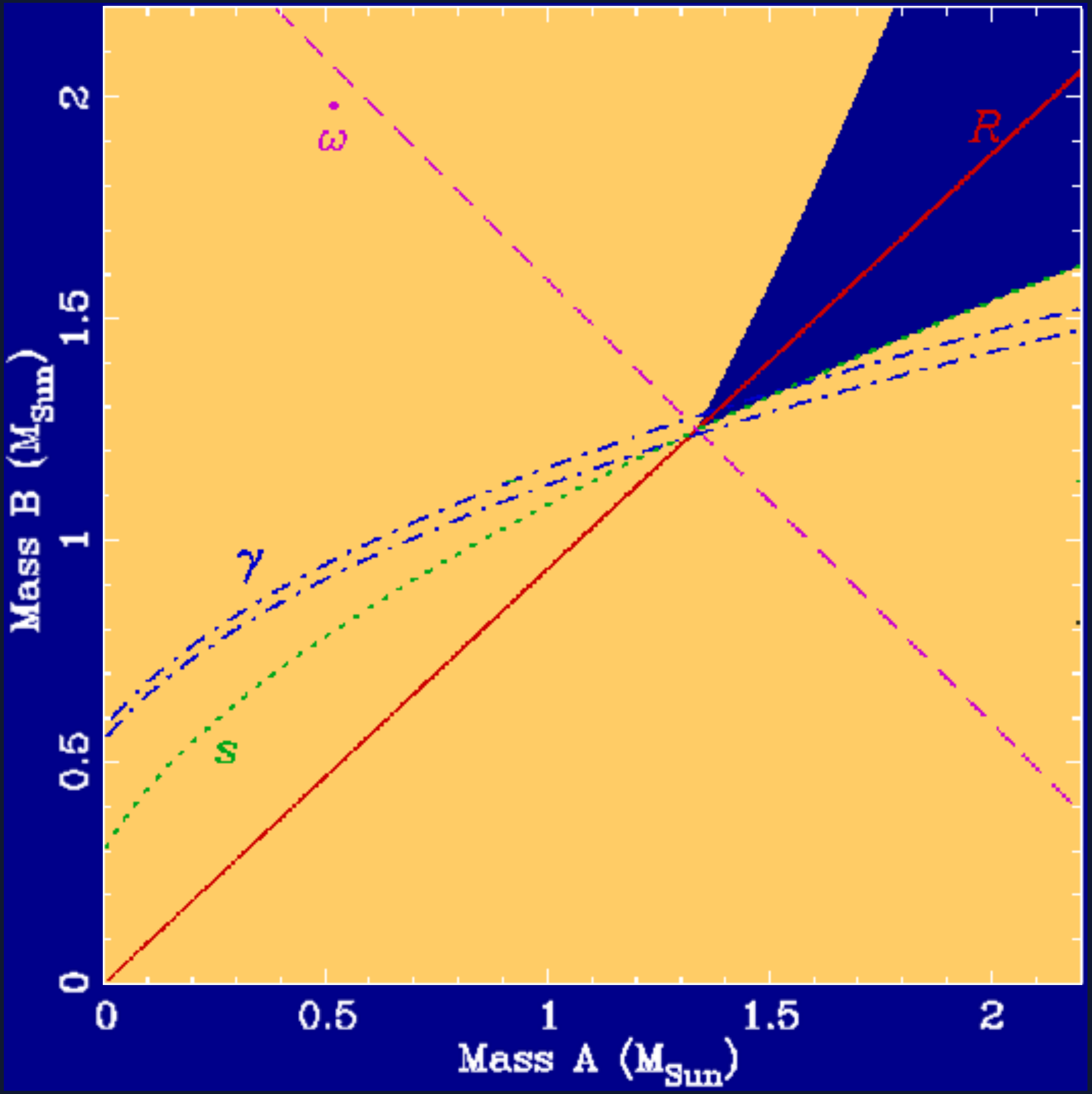

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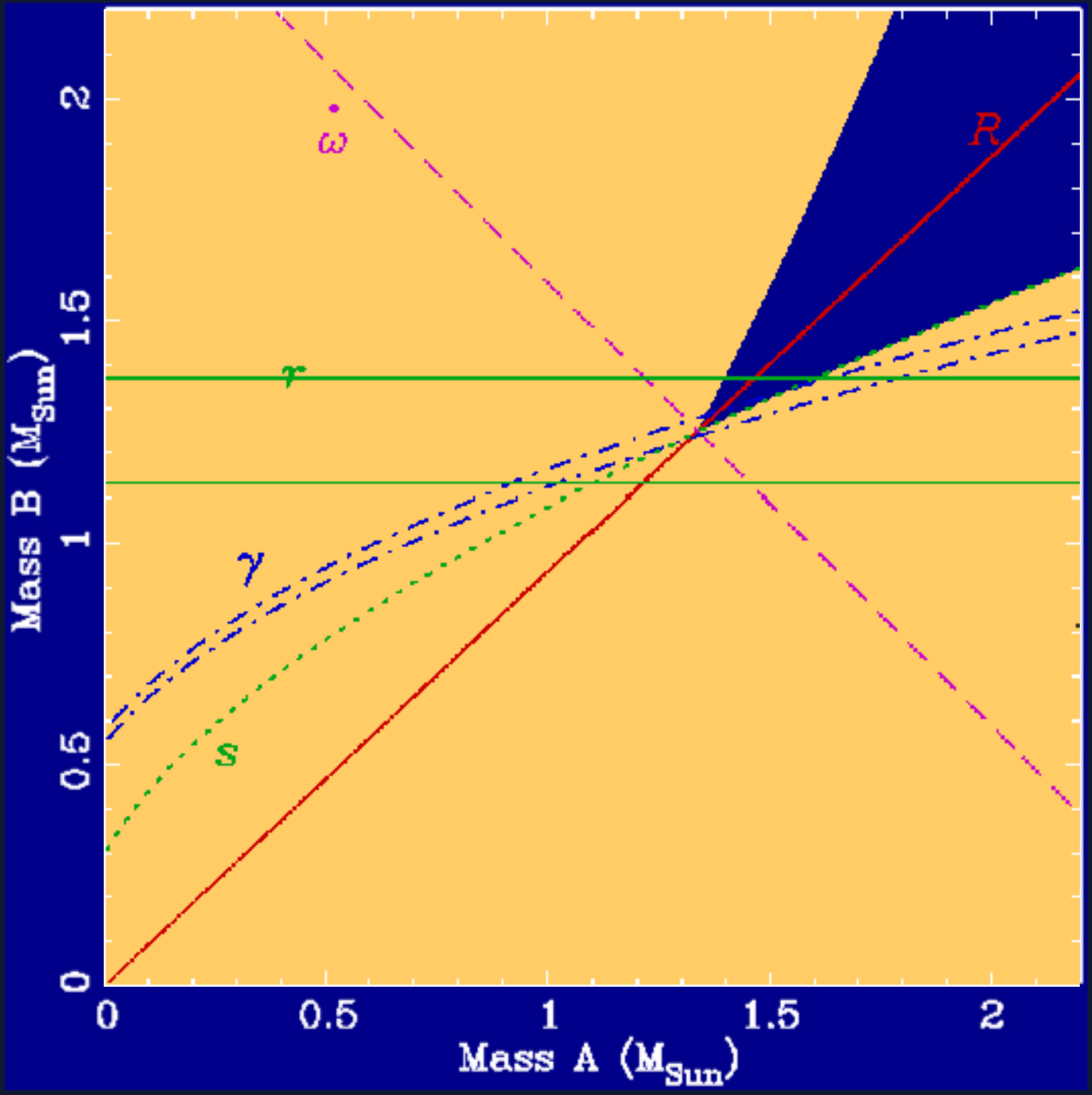

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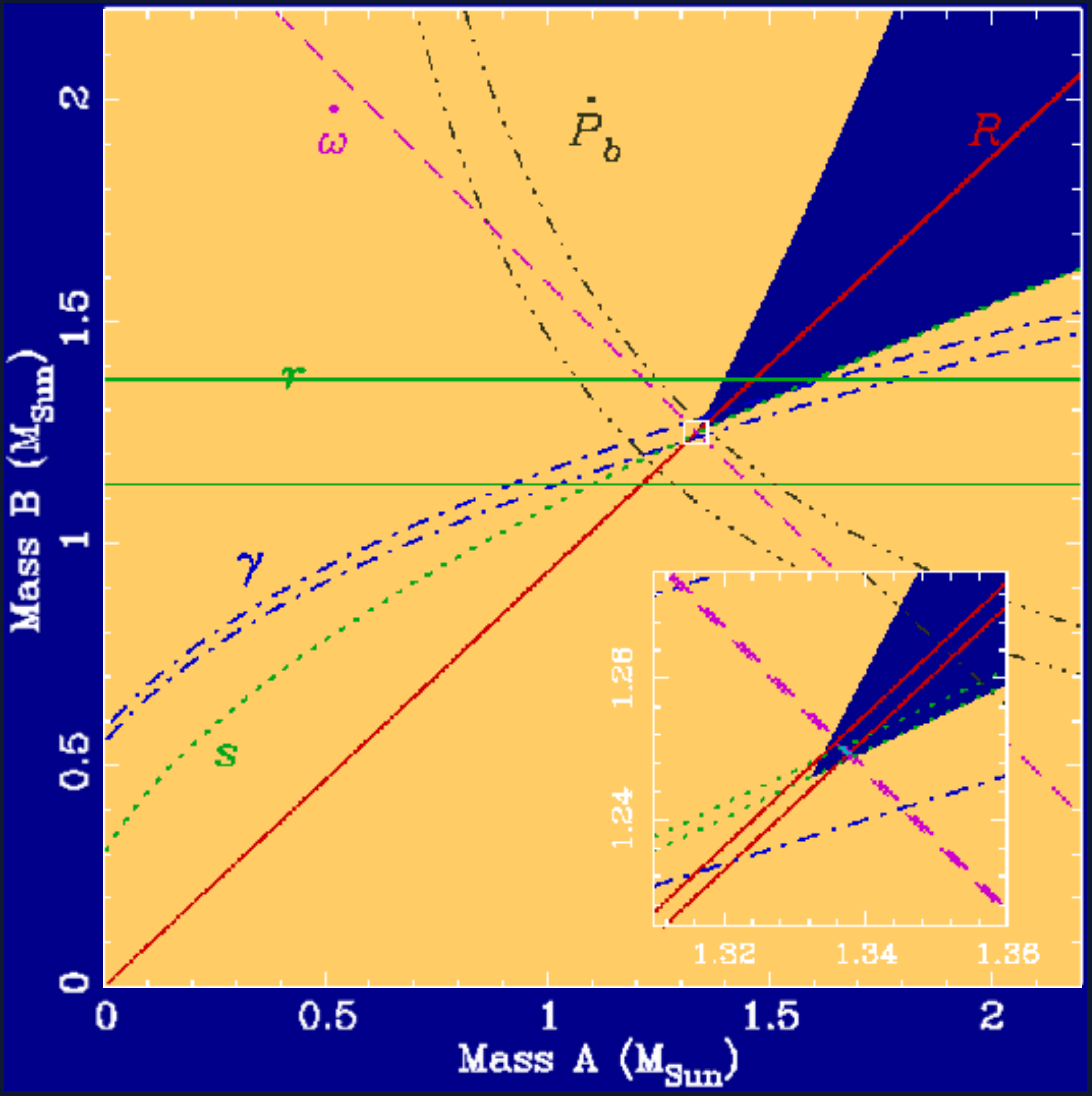

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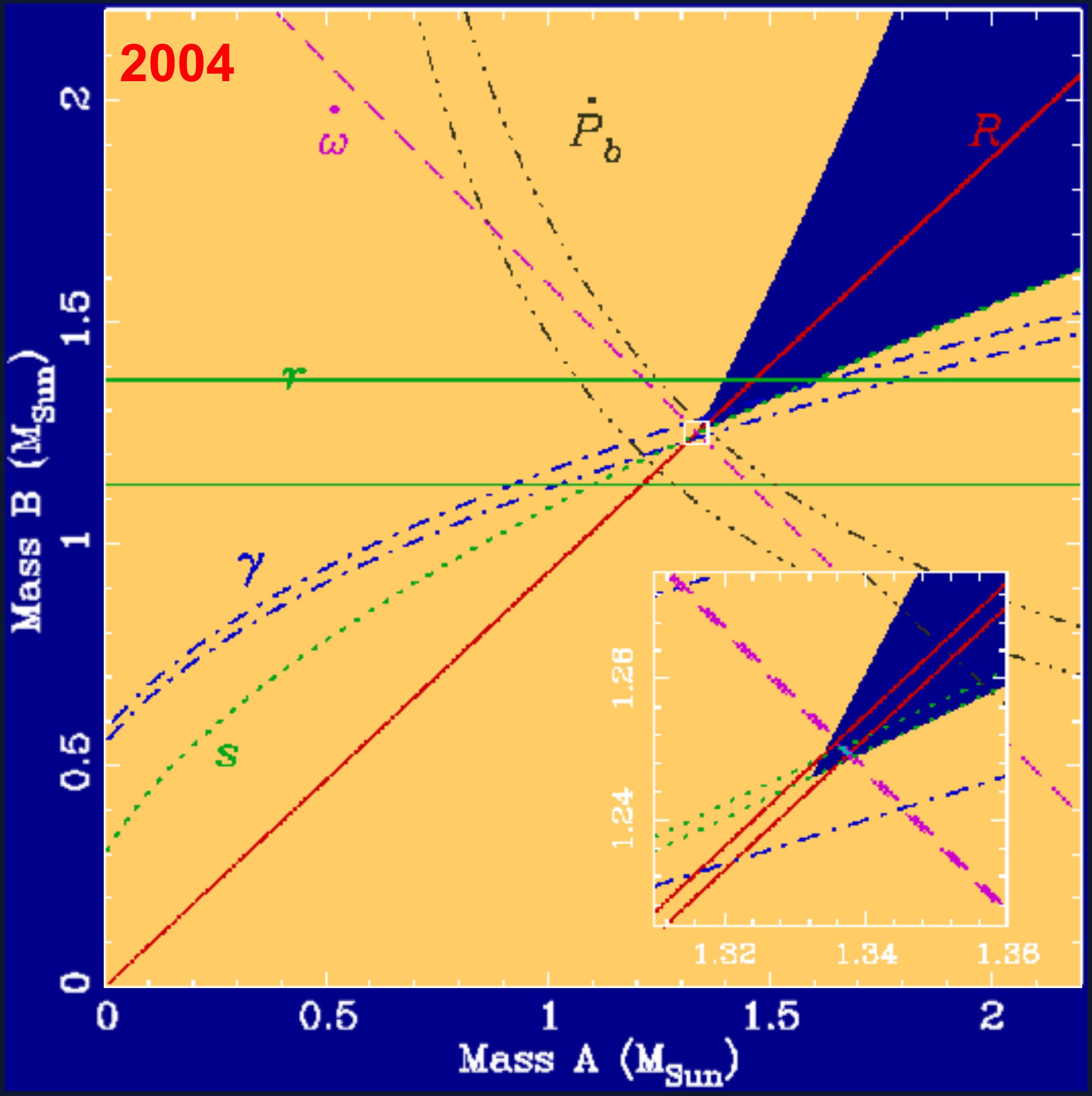
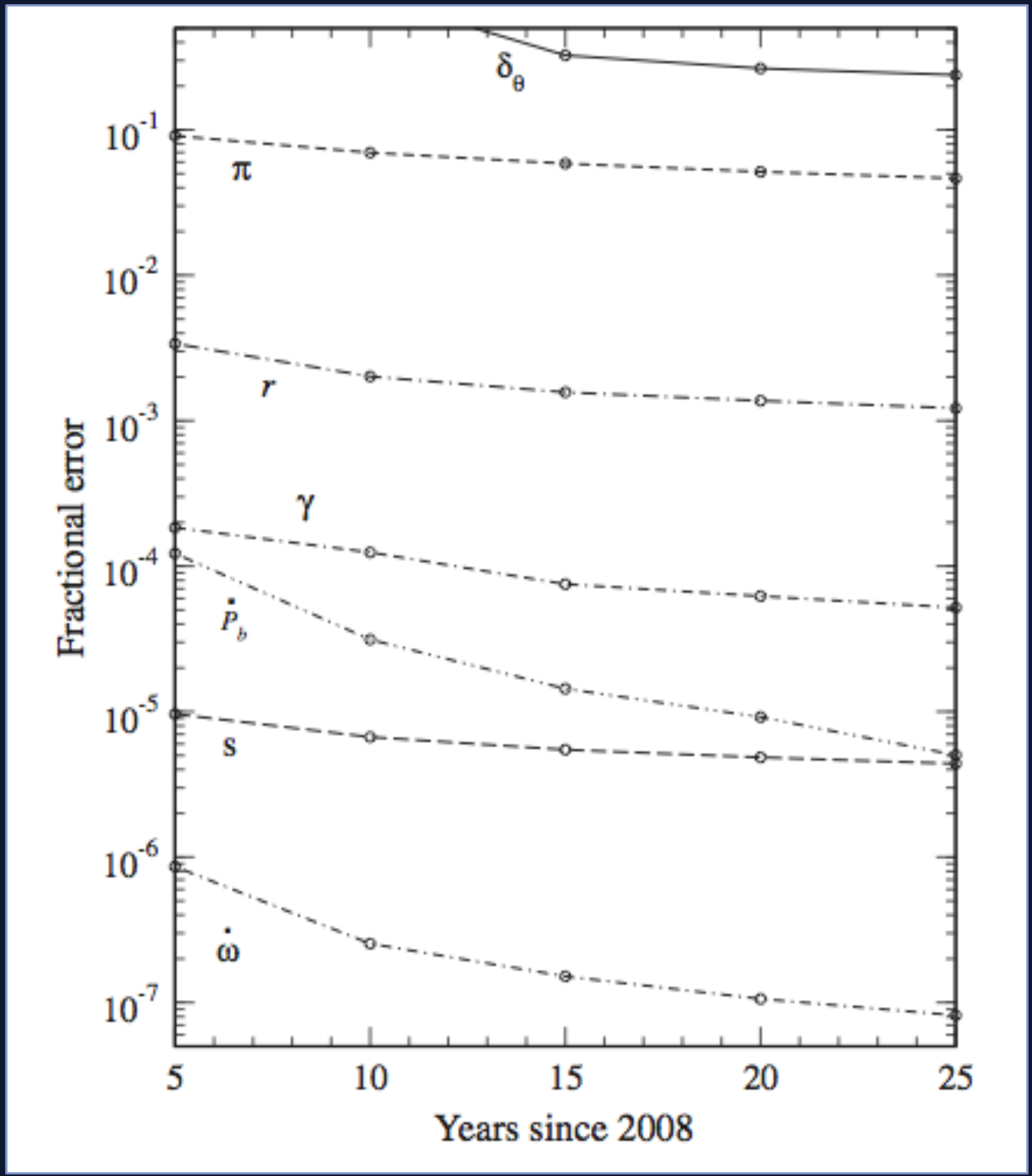


Testing GR with the Double Pulsar

Testing GR with the Double Pulsar

Prospects for timing are excellent:

- precision $\dot{\omega}$ ≈ time$^{1.5}$ P_b
- precision γ ≈ time$^{1.5}$ $P_b^{1.3}$
- precision $\dot{P}_b$ ≈ time$^{2.5}$ P_b^{3}
- precision r, s ≈ time$^{0.5}$



[Kramer & Wex 2009]

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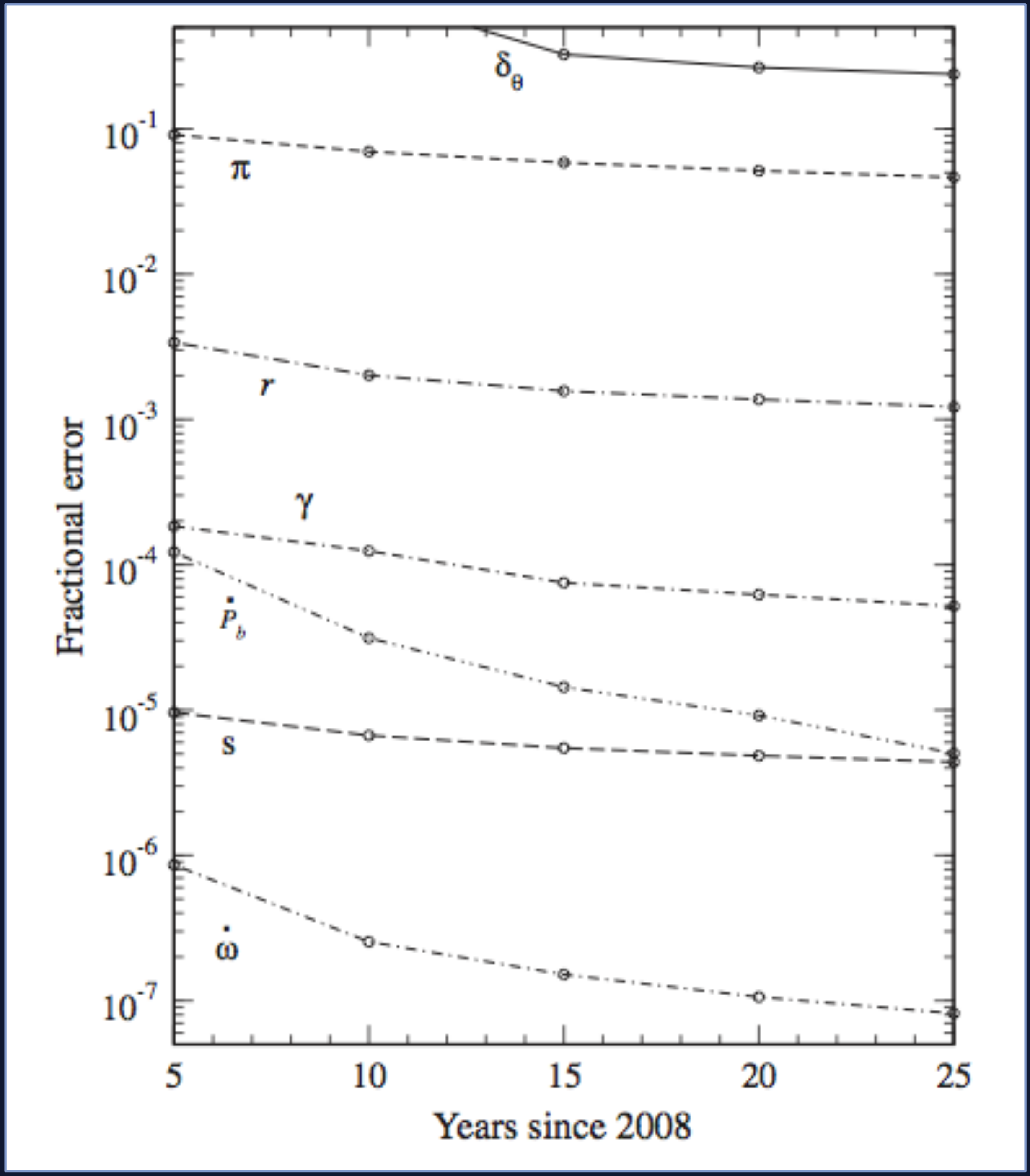
Time = 20 years!



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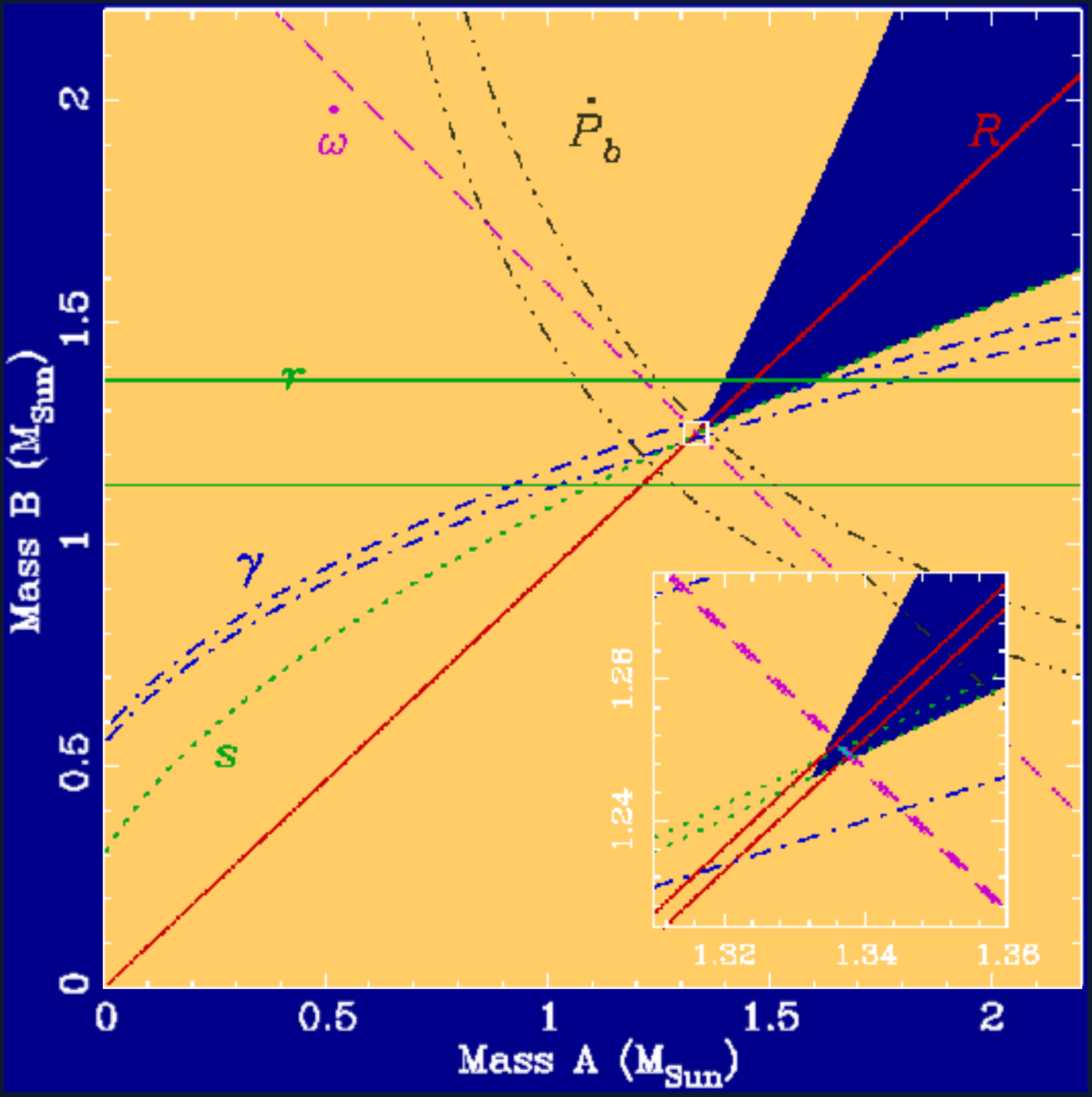

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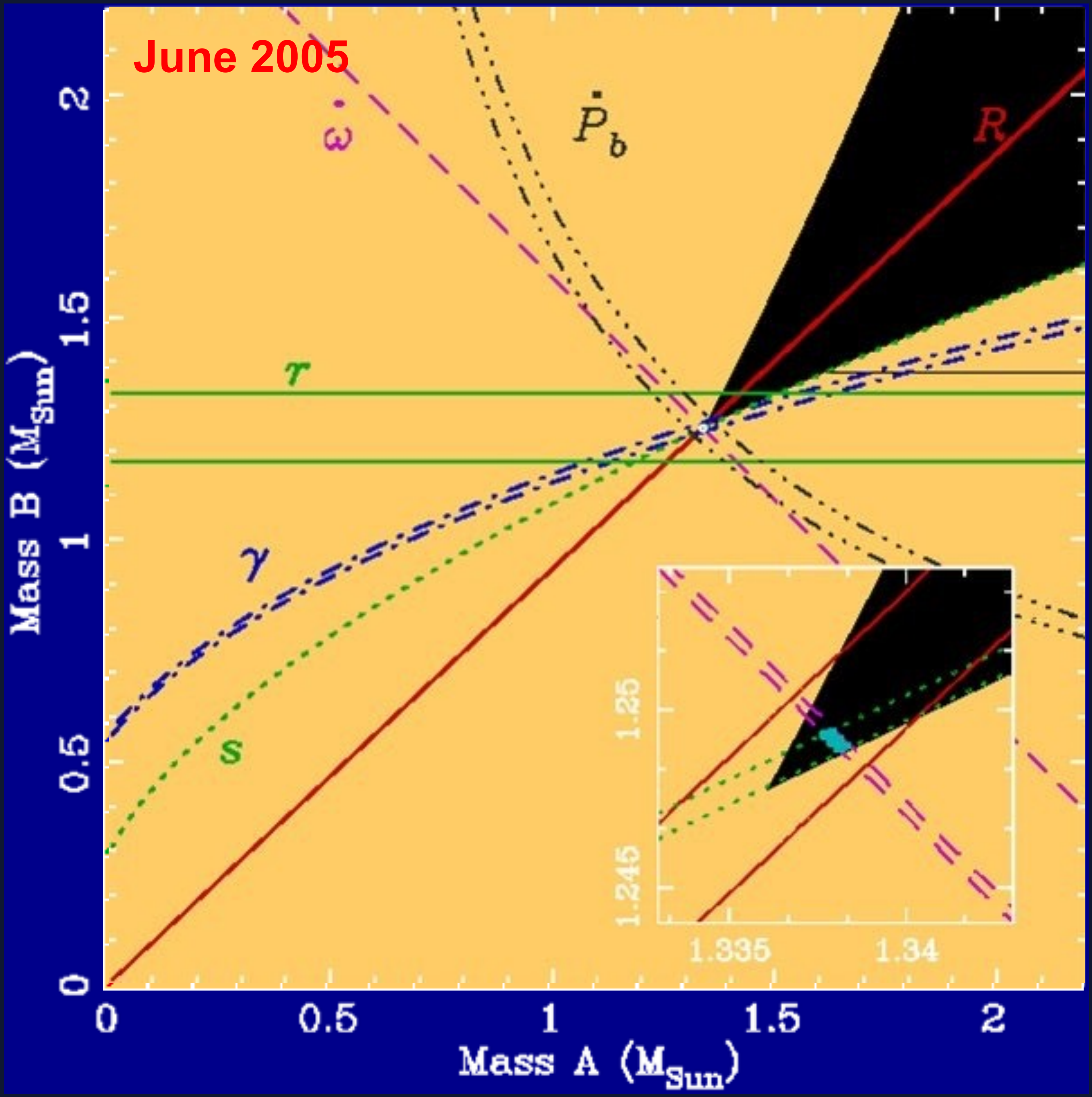

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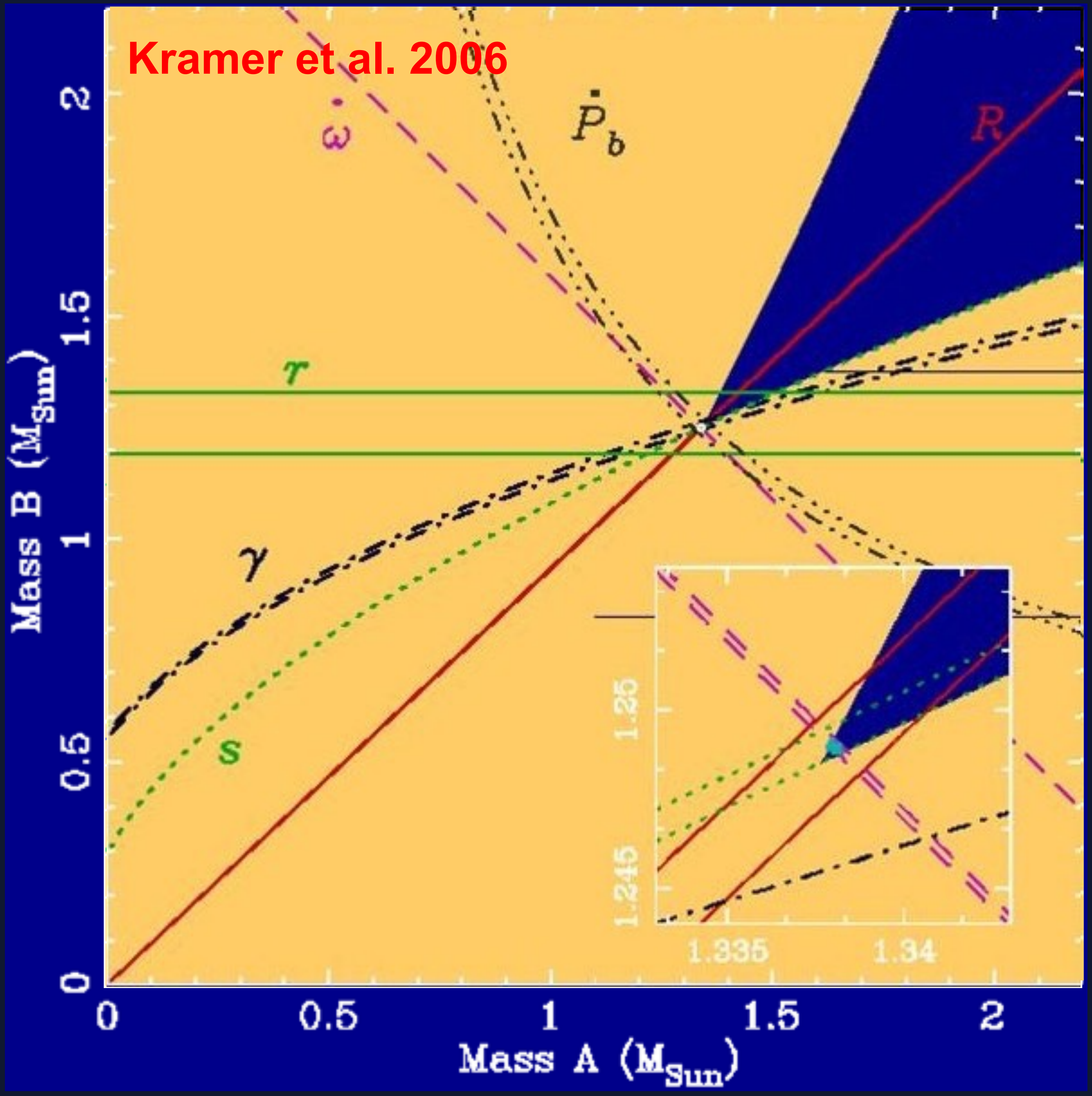

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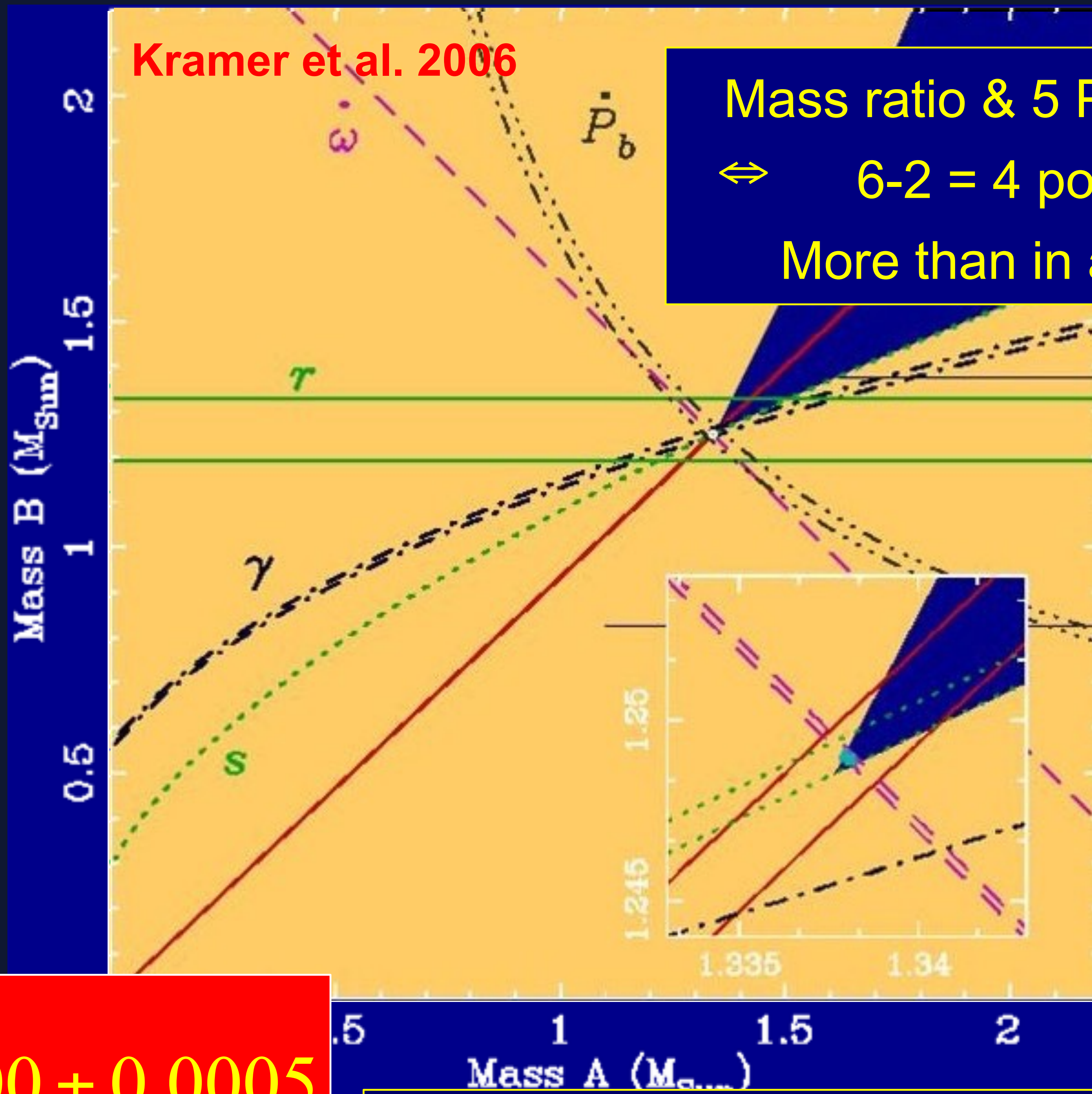

Mass ratio & 5 PK parameters

⇔ 6-2 = 4 potential tests!

More than in any system!

$$\frac{s^{\exp}}{s^{\mathrm{obs}}} = 1.0000 \pm 0.0005$$

GR verified with 0.05% precision!

Testing GR with the Double Pulsar

- Kramer et al 2021: 1 million ToAs!

PHYSICAL REVIEW X **11,** 041050 (2021)

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Strong-Field Gravity Tests with the Double Pulsar

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Testing GR with the Double Pulsar

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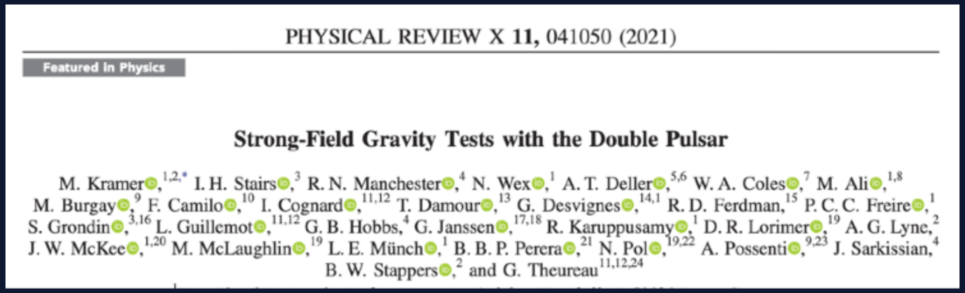
- Precision higher than ever!



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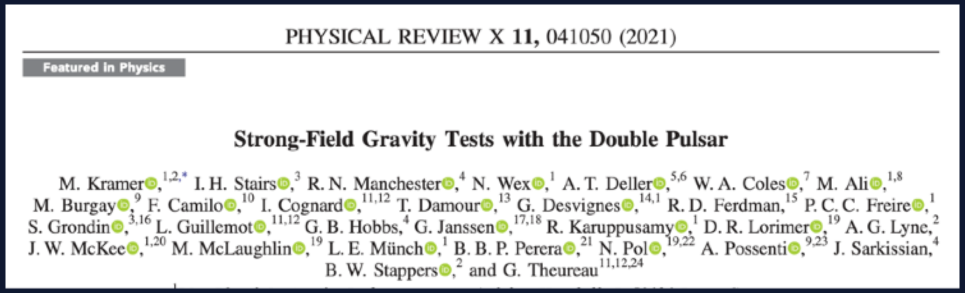

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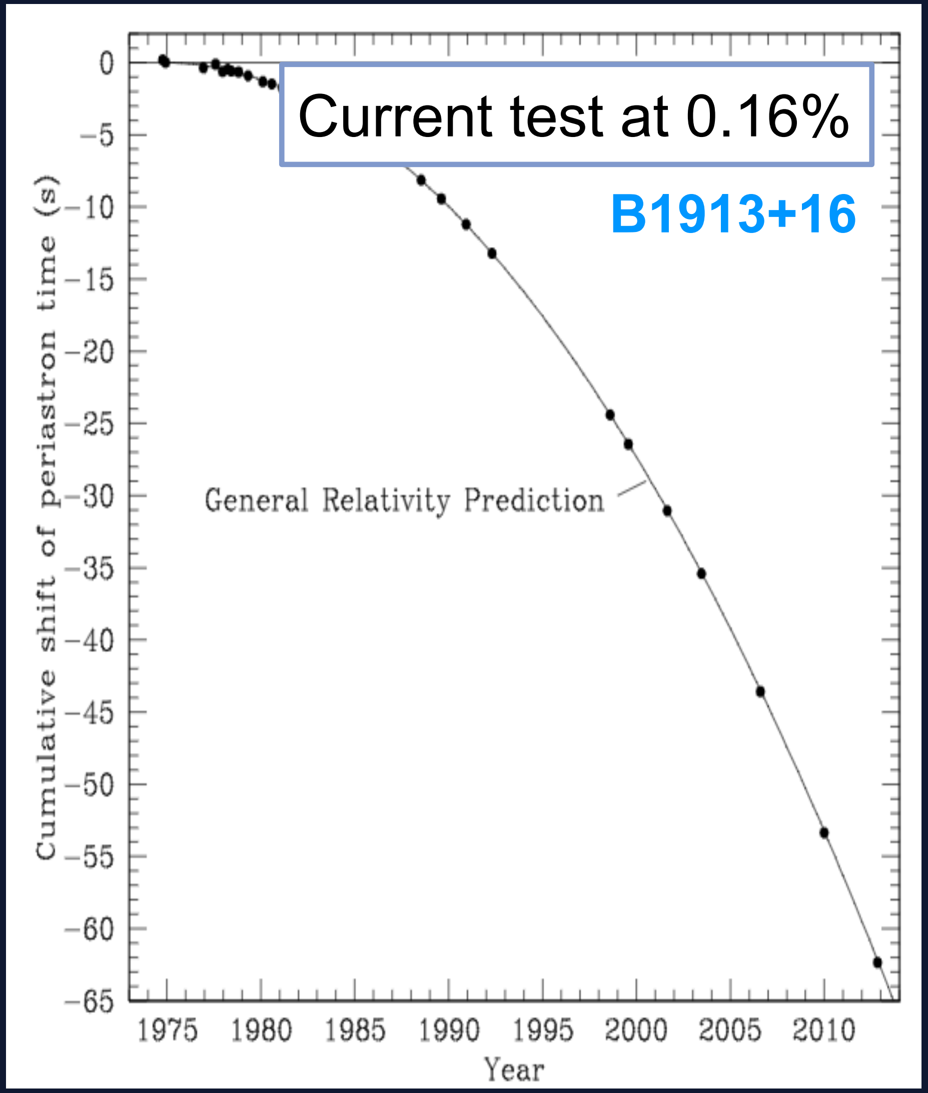

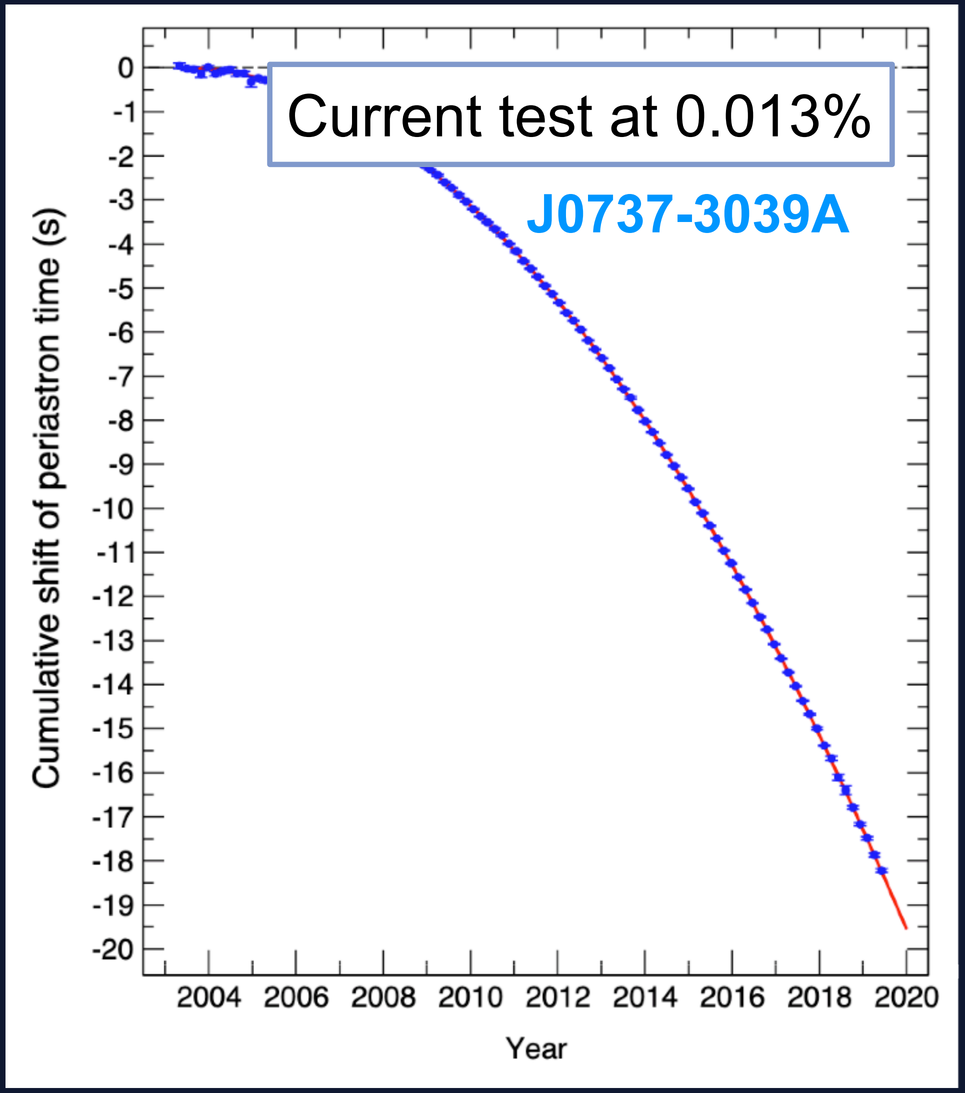

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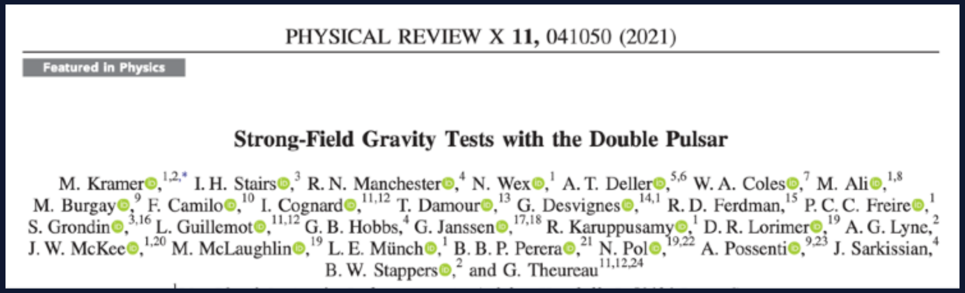
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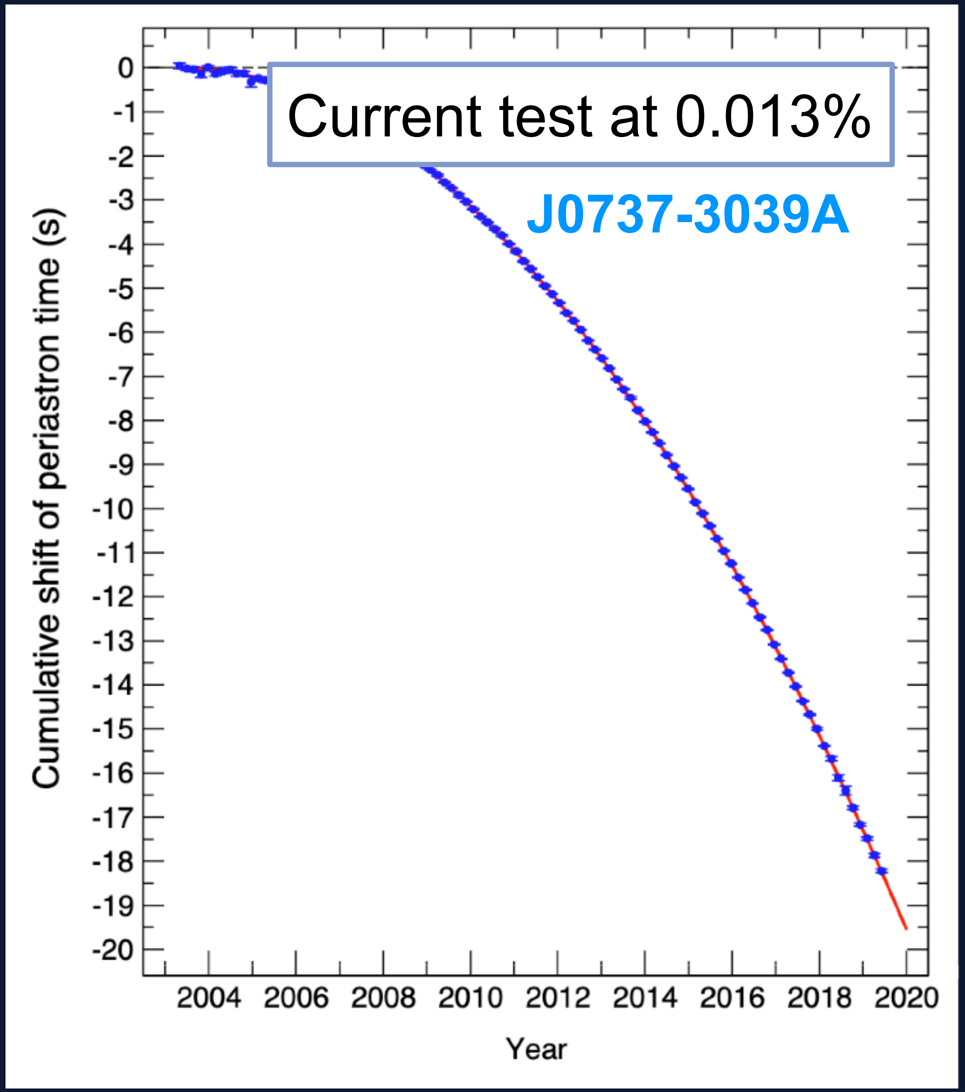

Orbit shrinks by 7 mm/day

Precision so high that we need to take into account relativistic mass loss

8.4 Million tons/s — 3.2 x 10^{-21} M_A/s

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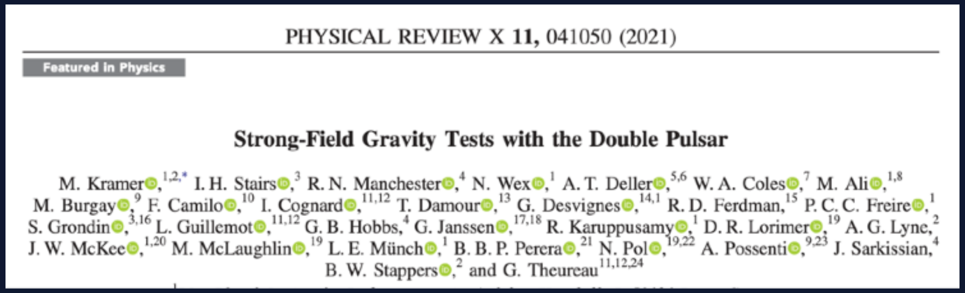
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Orbital period, P_b (day)	0.1022515592973(10)
Projected semimajor axis, x (s)	1.415028603(92)
Eccentricity (Kepler equation), e_T	0.087777023(61)
Epoch of periastron, T_0 (MJD)	55700.233017540(13)
Longitude of periastron, ω_0 (deg)	204.753686(47)
Periastron advance, $\dot{\omega}$ (deg yr^{-1})	16.899323(13)
Change of orbital period, $\dot{P}_b$	$-1.247920(78)\times 10^{-12}$
Einstein delay amplitude, γ_E (ms)	0.384045(94)
Logarithmic Shapiro shape , z_s	9.65(15)
Range of Shapiro delay, r ($T_\odot$)*	1.2510(43)
NLO factor for signal prop., q_{NLO}	1.15(13)
Relativistic deformation of orbit, δ_θ	$13(13)\times 10^{-6}$

Orbit has precessed by >300 deg
2PN contribution at 35σ

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Has consequences on the measurement of the Moment of inertia

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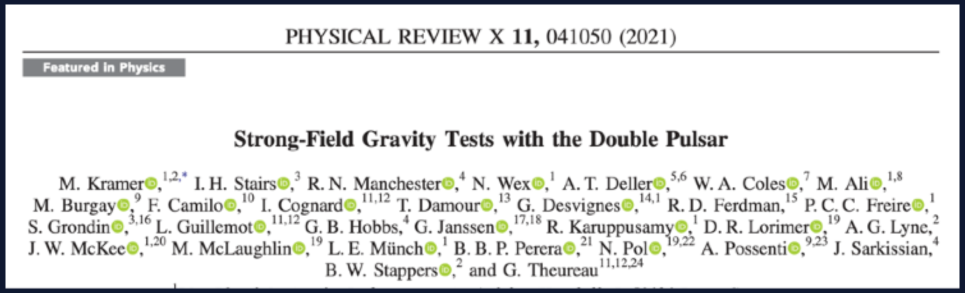
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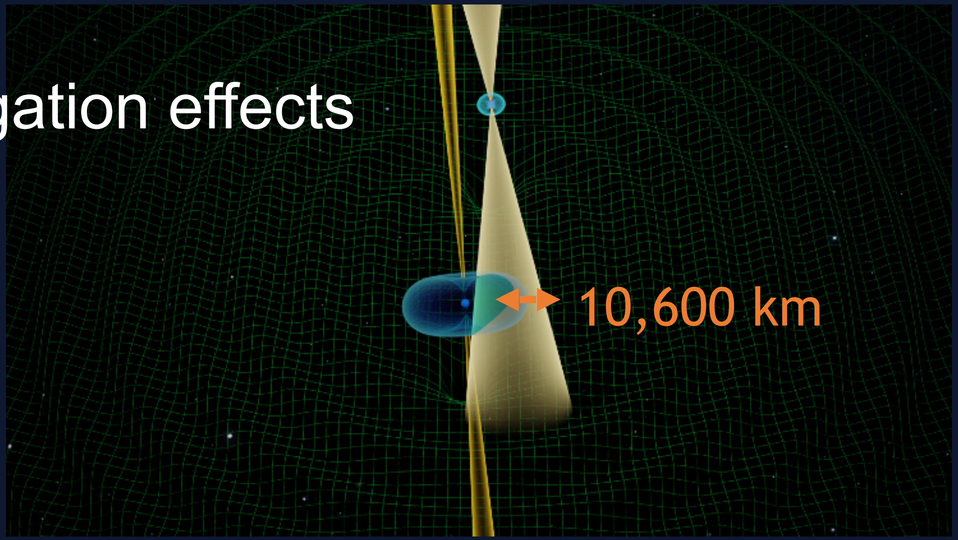

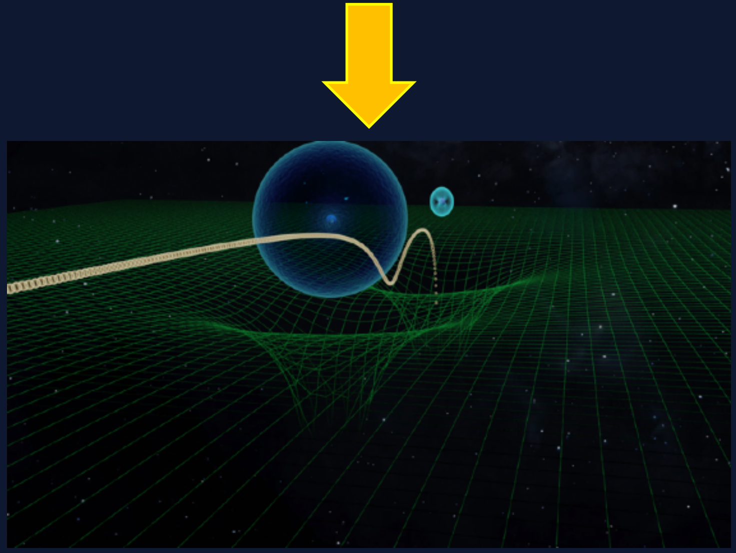

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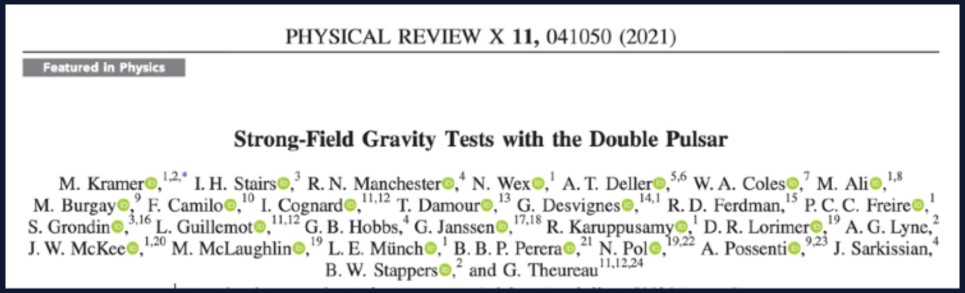
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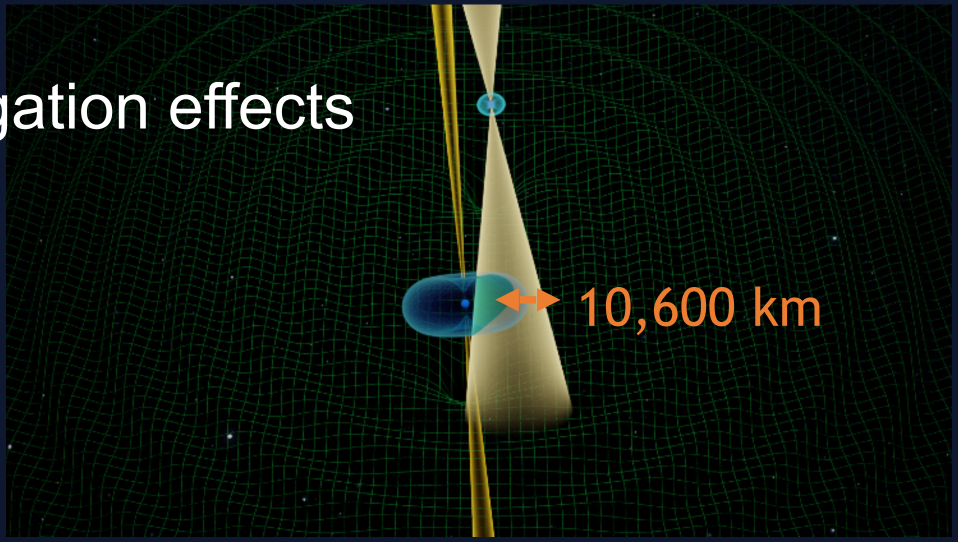

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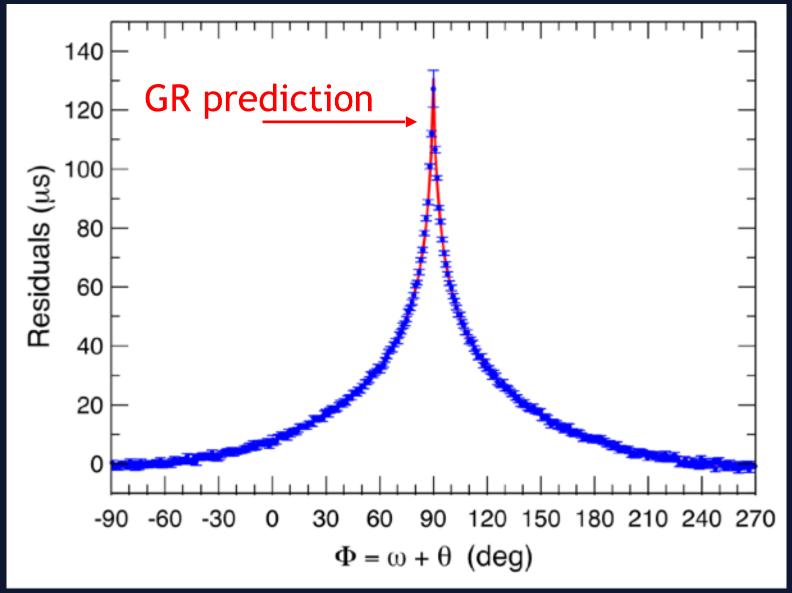

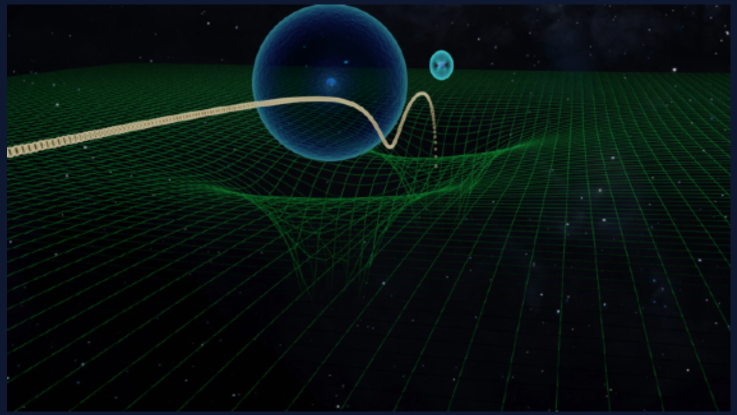

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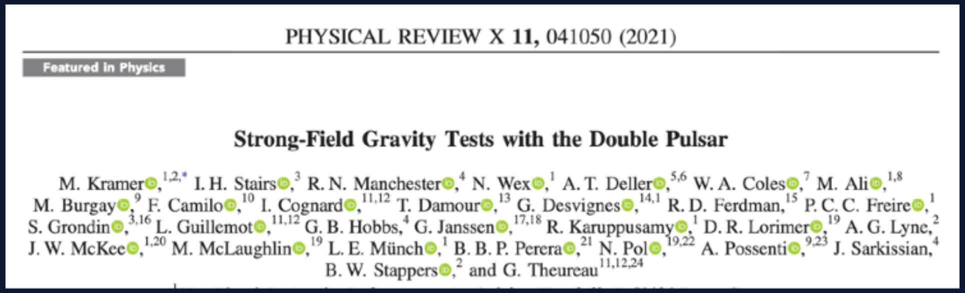
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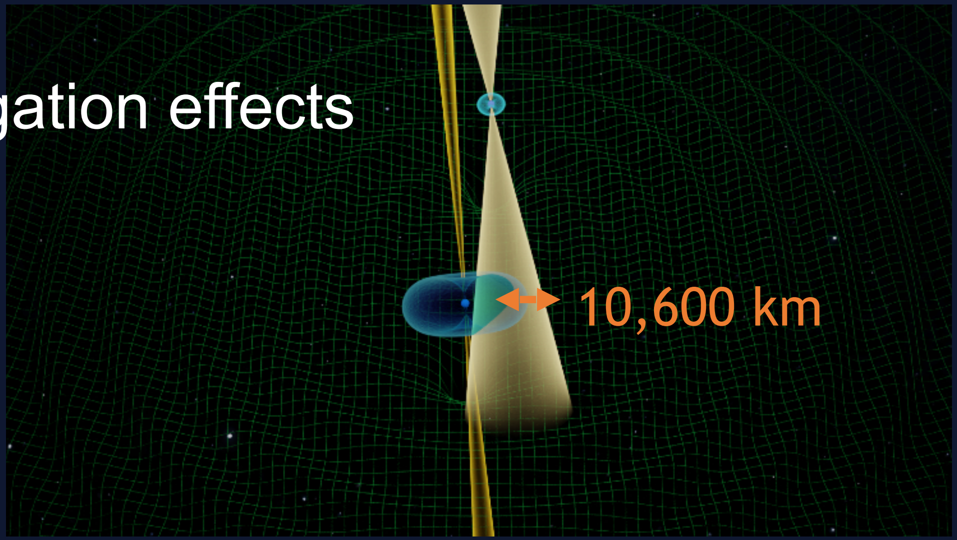

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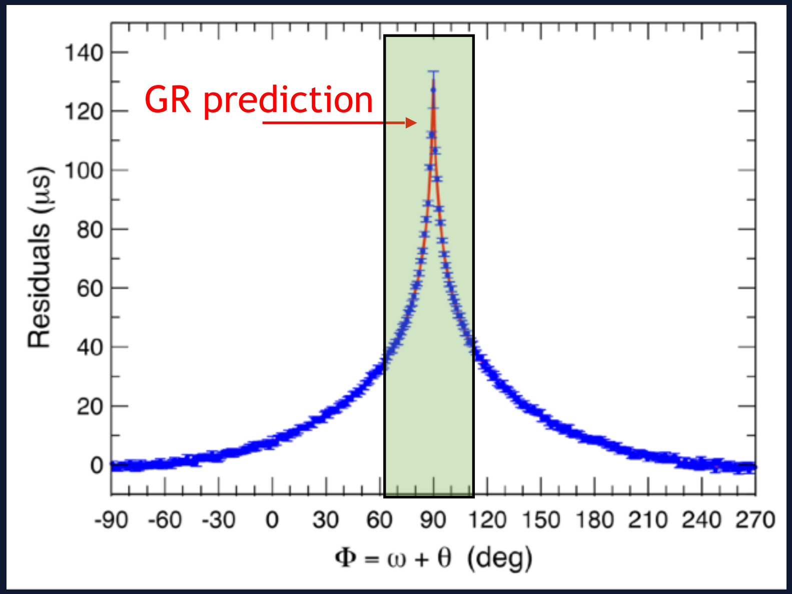

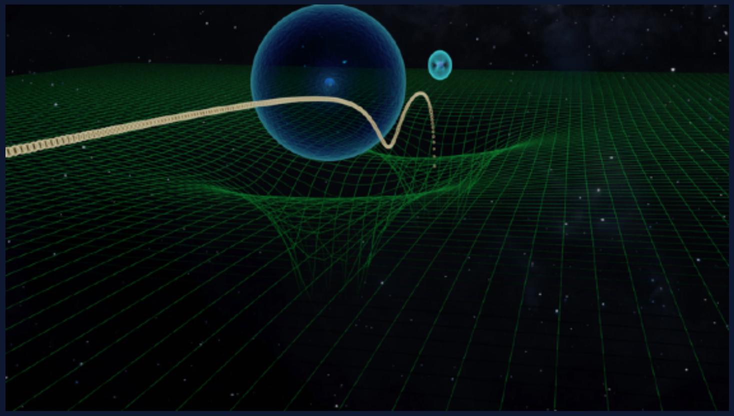

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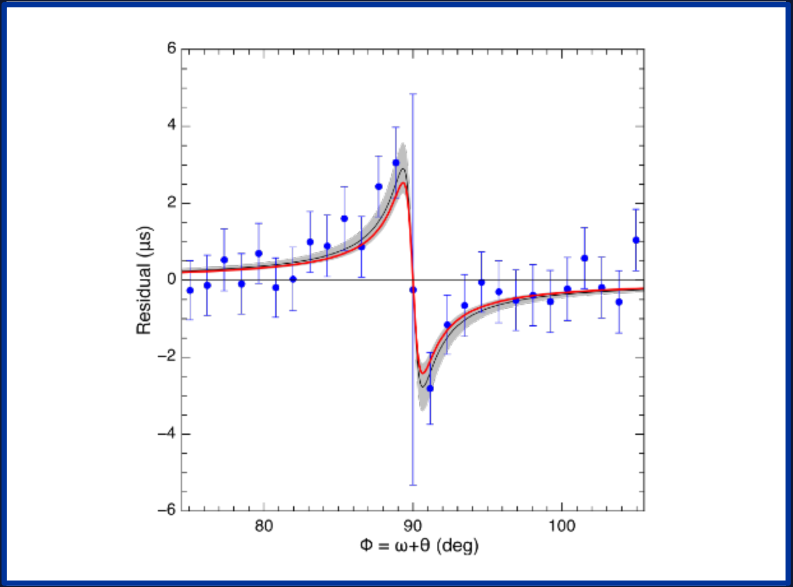

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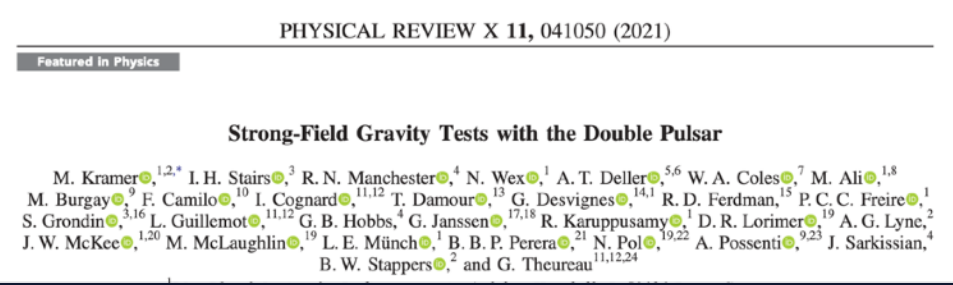
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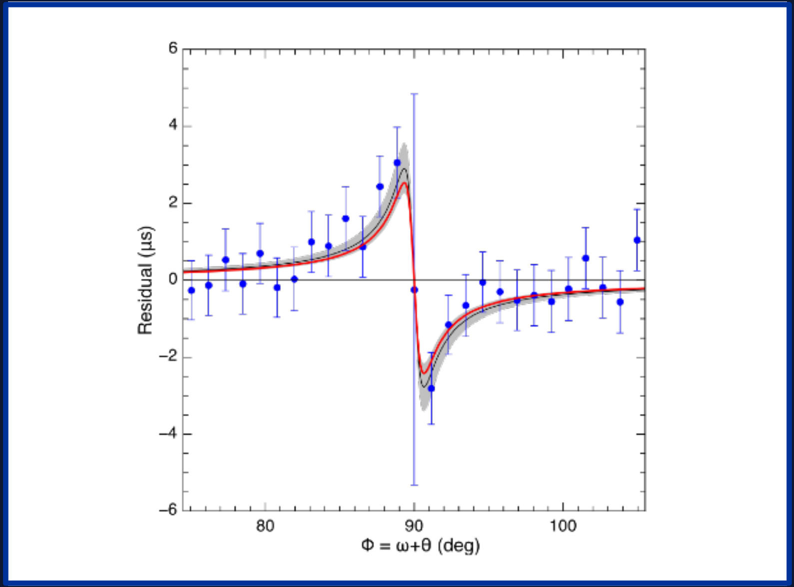
Two additional effects:



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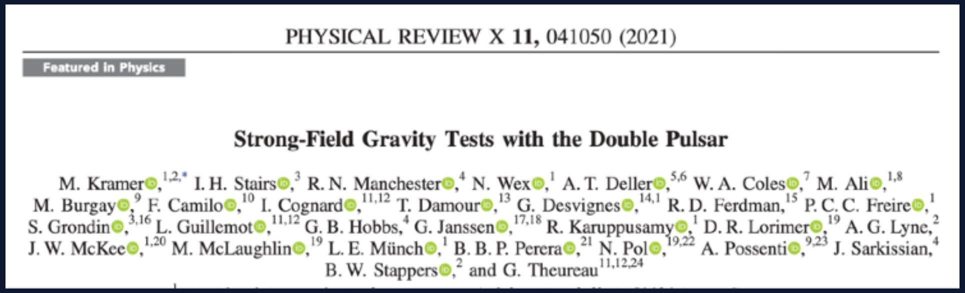
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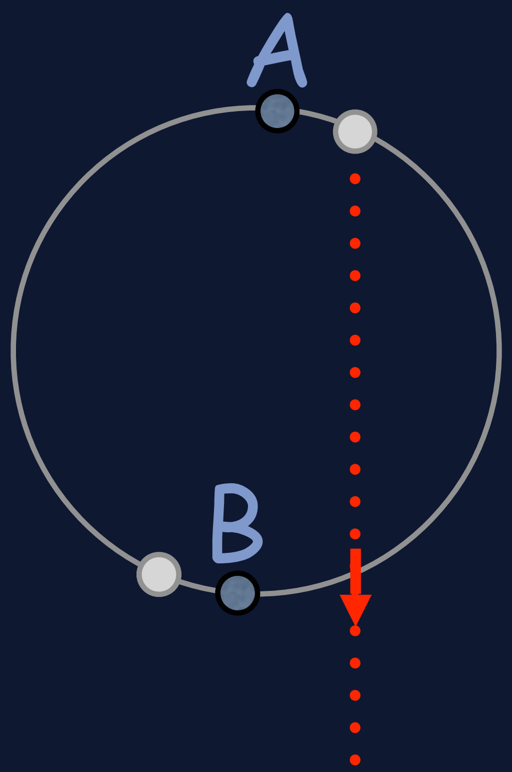
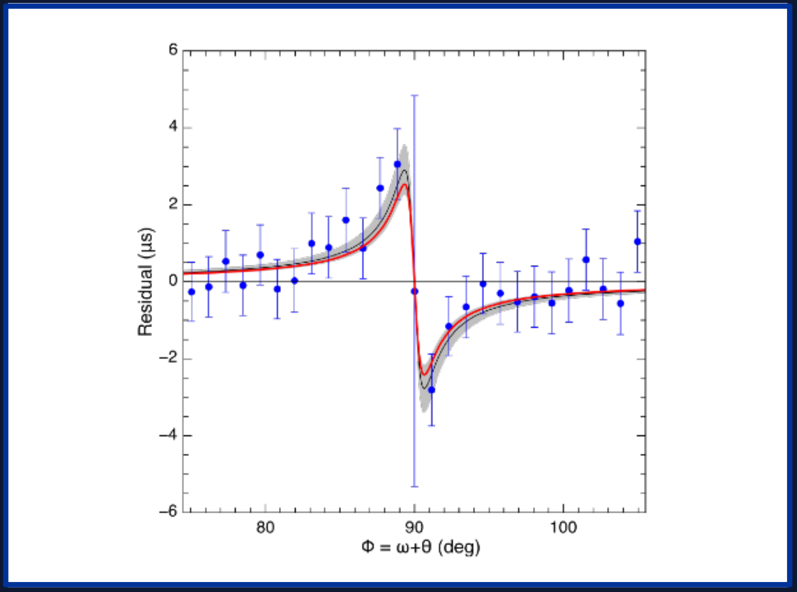


Two additional effects:

Retardation



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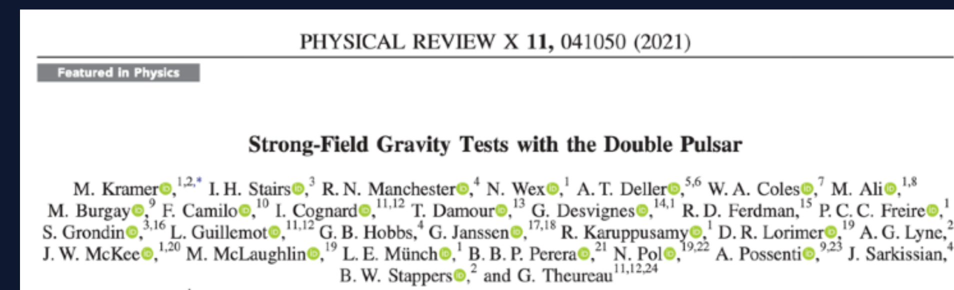

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Strong-Field Gravity Tests with the Double Pulsar

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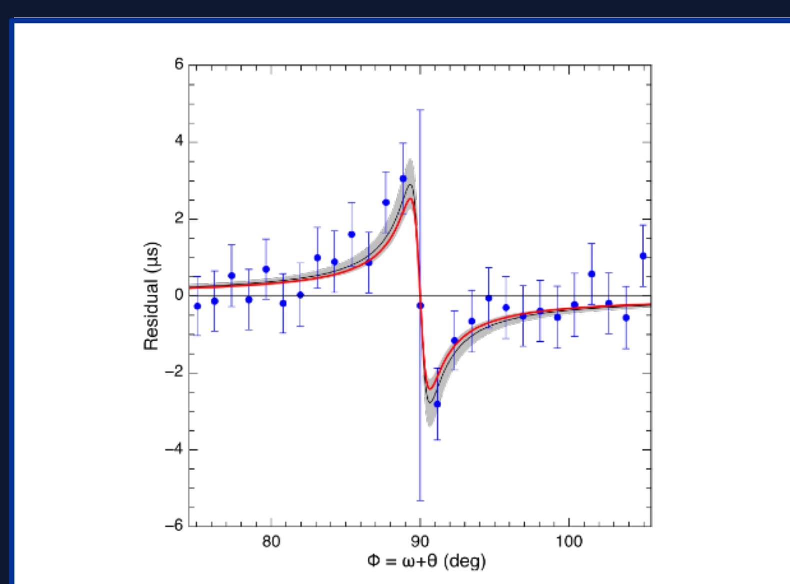

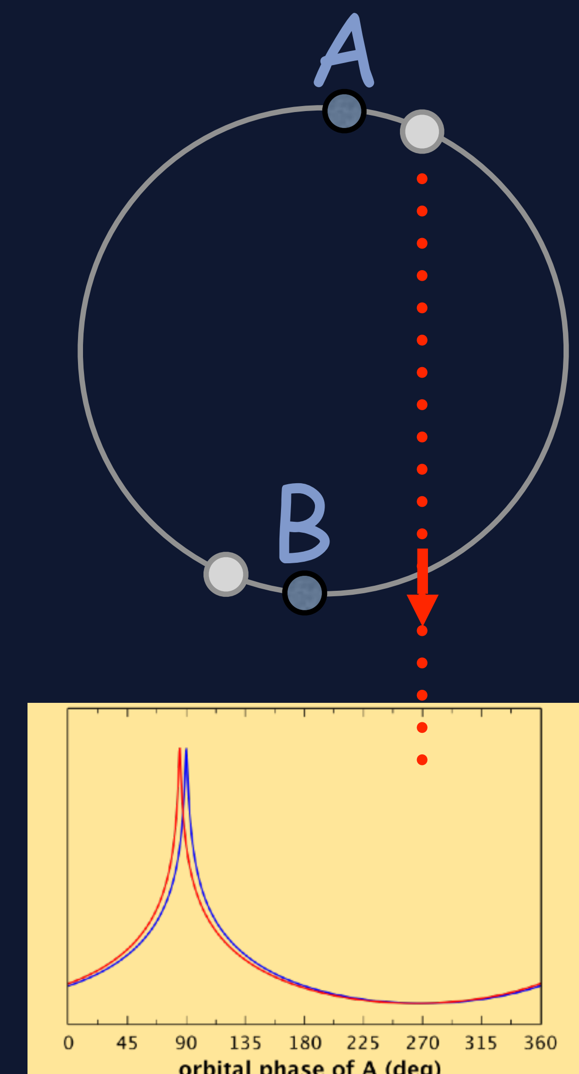

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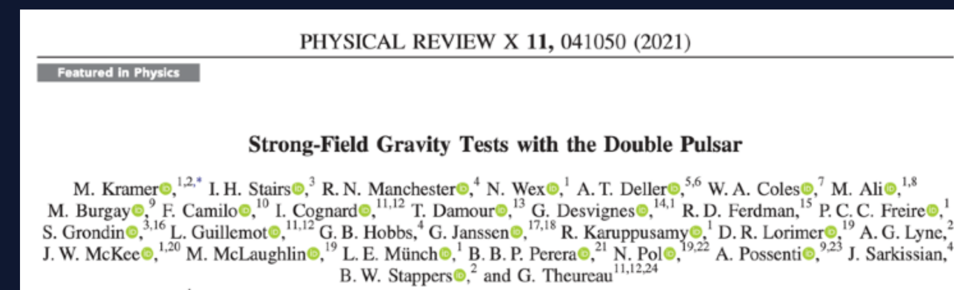
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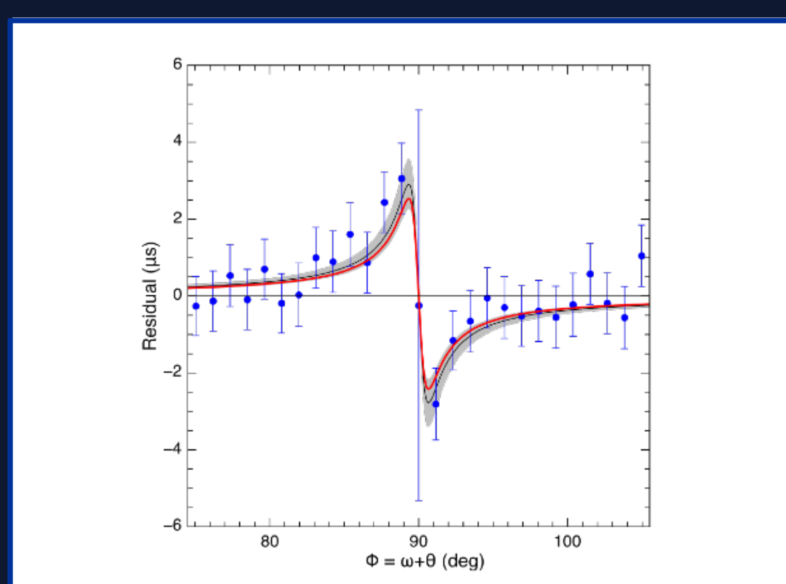

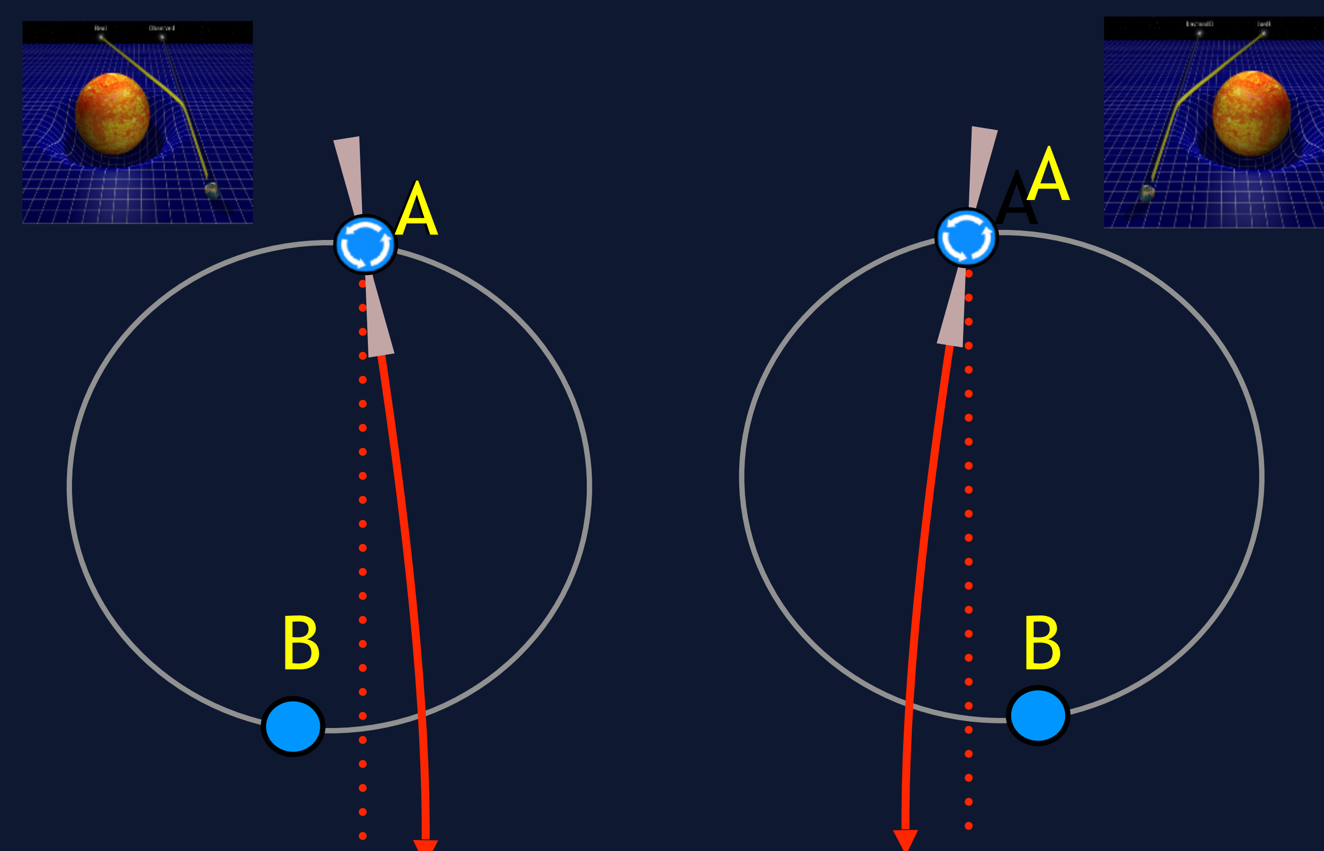

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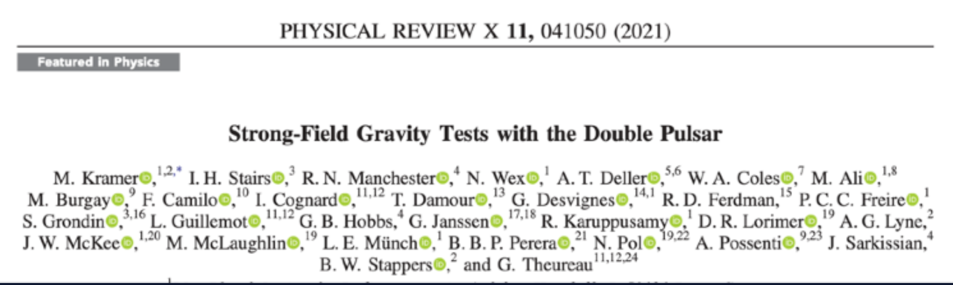
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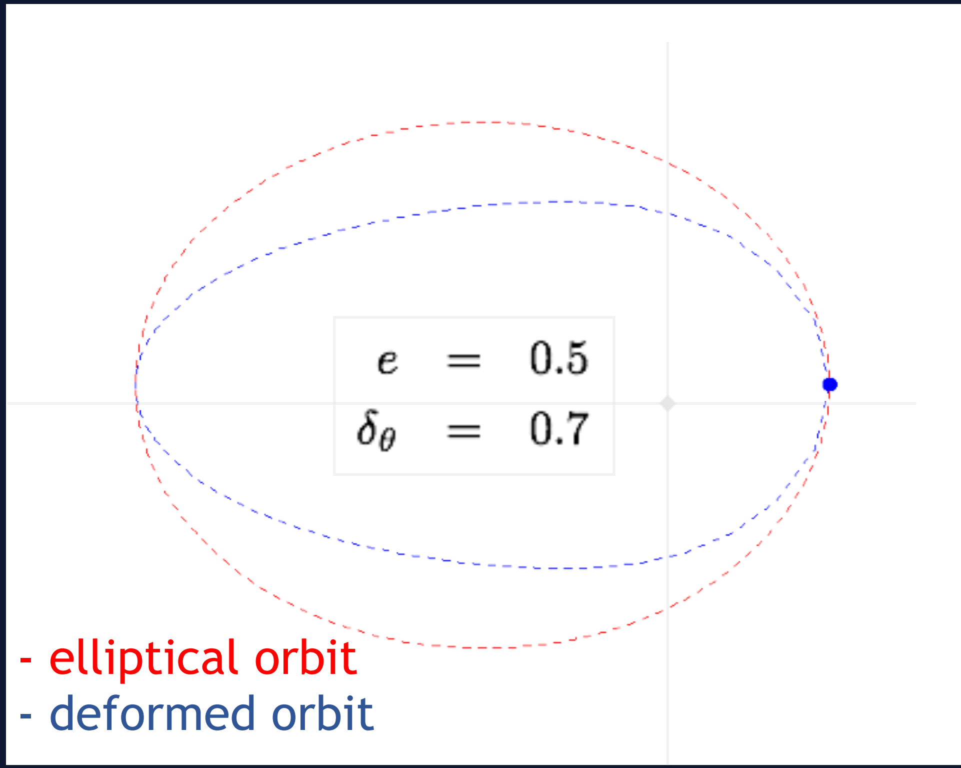

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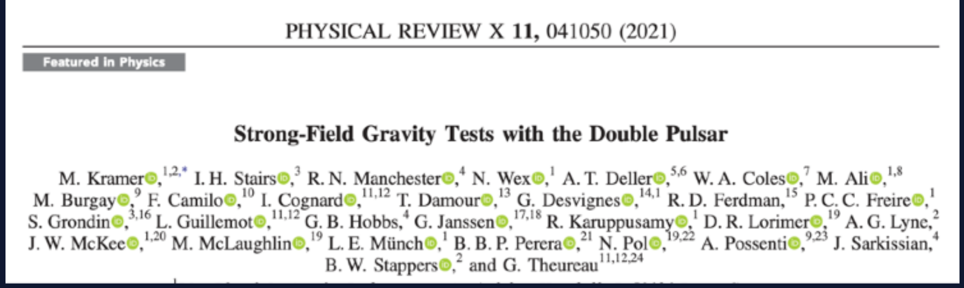
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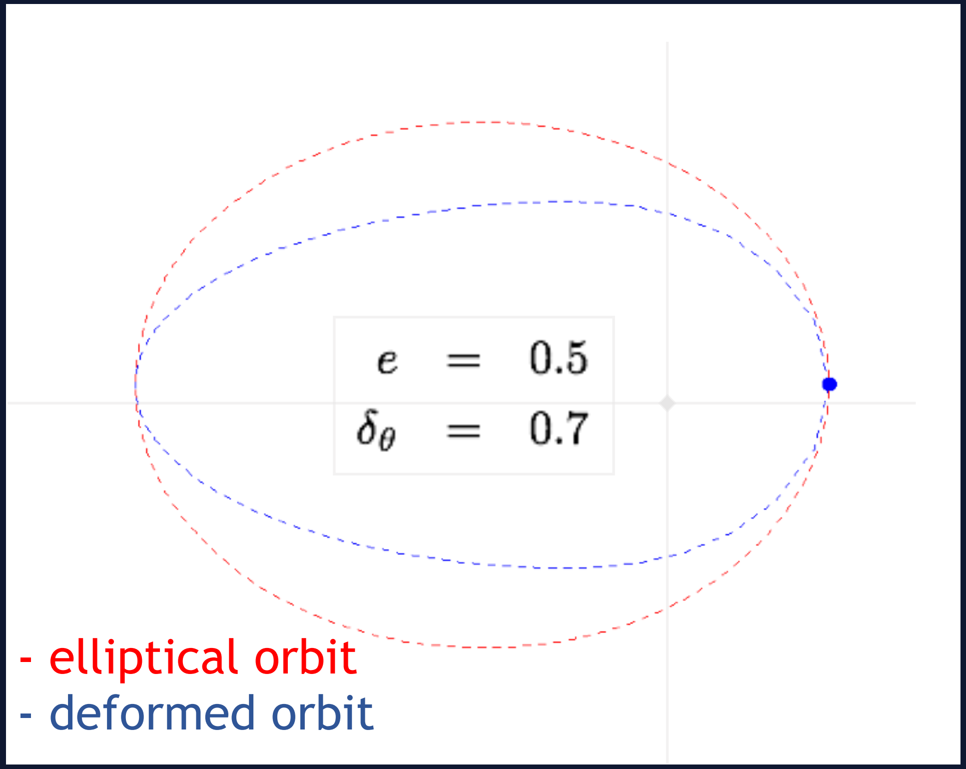
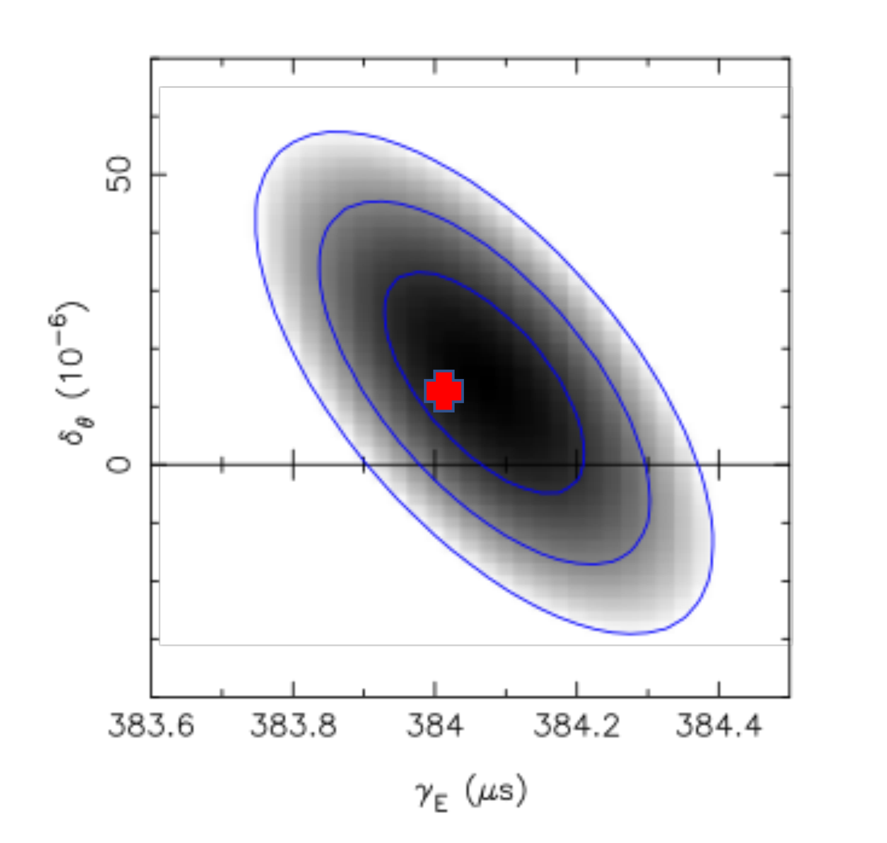
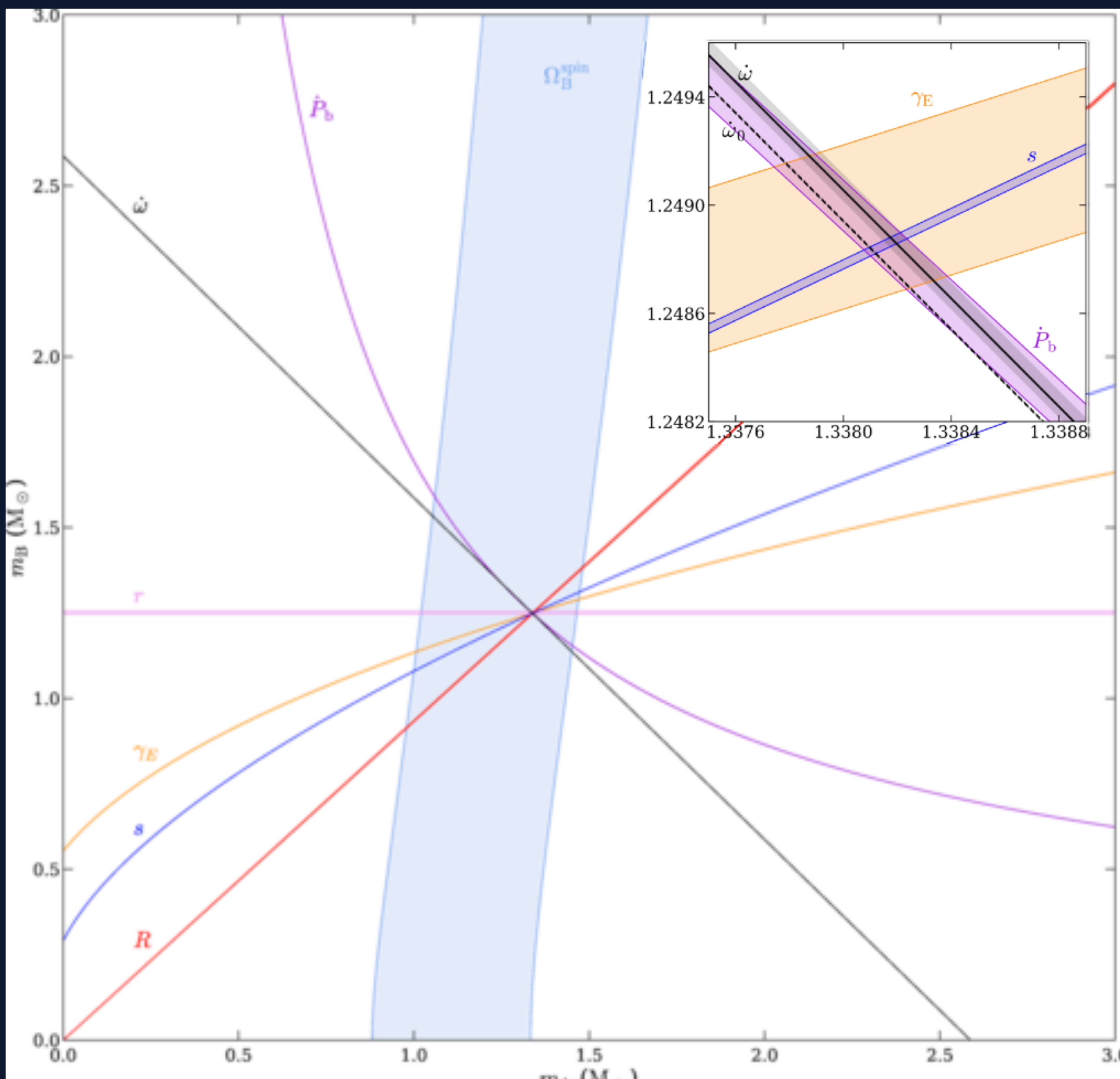




Putting it all together



Relativistic effect	Parameter	Obs./GR pred.
Shapiro delay shape	s	1.00009(18)
Shapiro delay range	r	1.0016(34)
Time dilation	γ_E	1.00012(25)
Periastron advance	$\dot{\omega} \equiv n_b k$	1.000015(26)
GW emission	$\dot{P}_b$	0.999963(63)
Orbital deformation	δ_θ	1.3(13)
Spin precession	Ω_B^{spin}	0.94(13)*
Tests of higher order contributions		
Lense-Thirring contrib. to k	λ_{LT}	0.7(9)
NLO signal propagation	q_{NLO}[total]	1.15(13)
...from signal deflection	q_{NLO}[deflect.]	1.26(24)
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- 7 Post-Keplerian parameters (+R)
- Next-to-leading order in signal propagation
- Most precise strong-field test of GR
- Start to probe MoI and Equation-of-State
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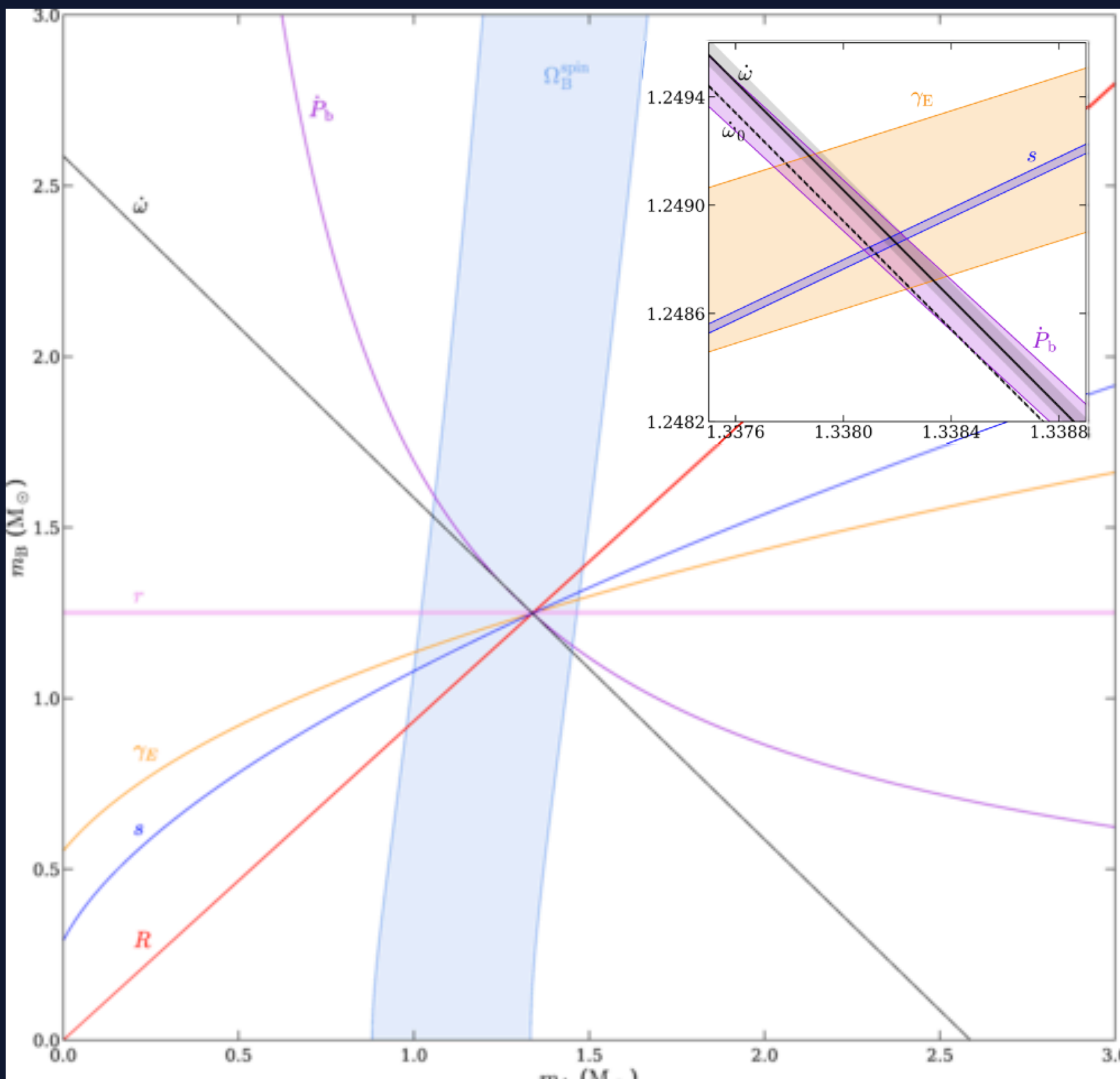
- MeerKAT improves timing by factor 2-3!

Putting it all together



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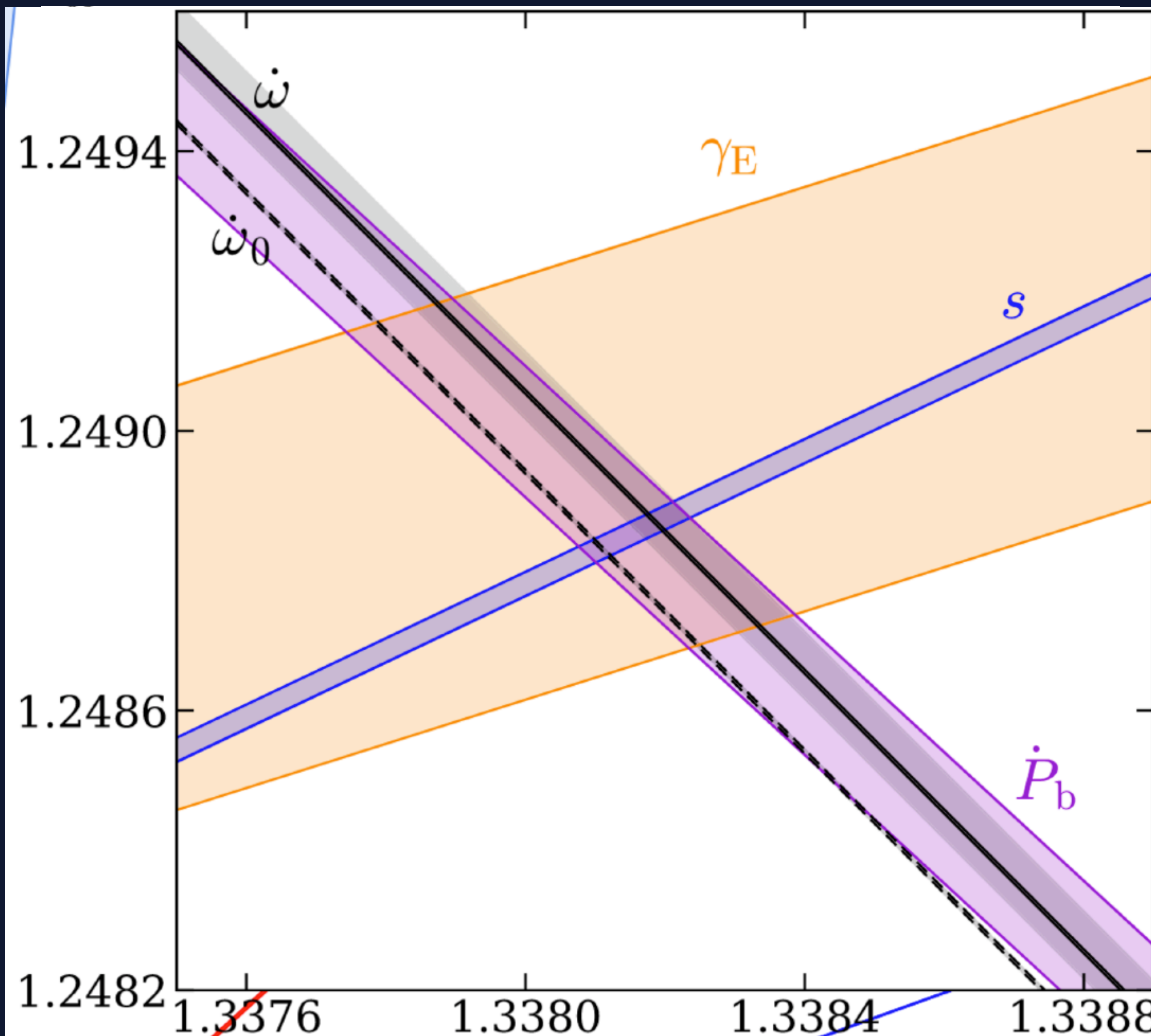
$$\dot{\omega} = \dot{\omega}^{1PN} + \dot{\omega}^{2PN} + \dot{\omega}^{LT,A}$$

$$\dot{\omega}^{LT,A} \simeq -3.77 \times 10^{-4} \times I_A^{(45)} \deg \mathrm{yr}^{-1}$$

Moment of inertia

Putting it all together



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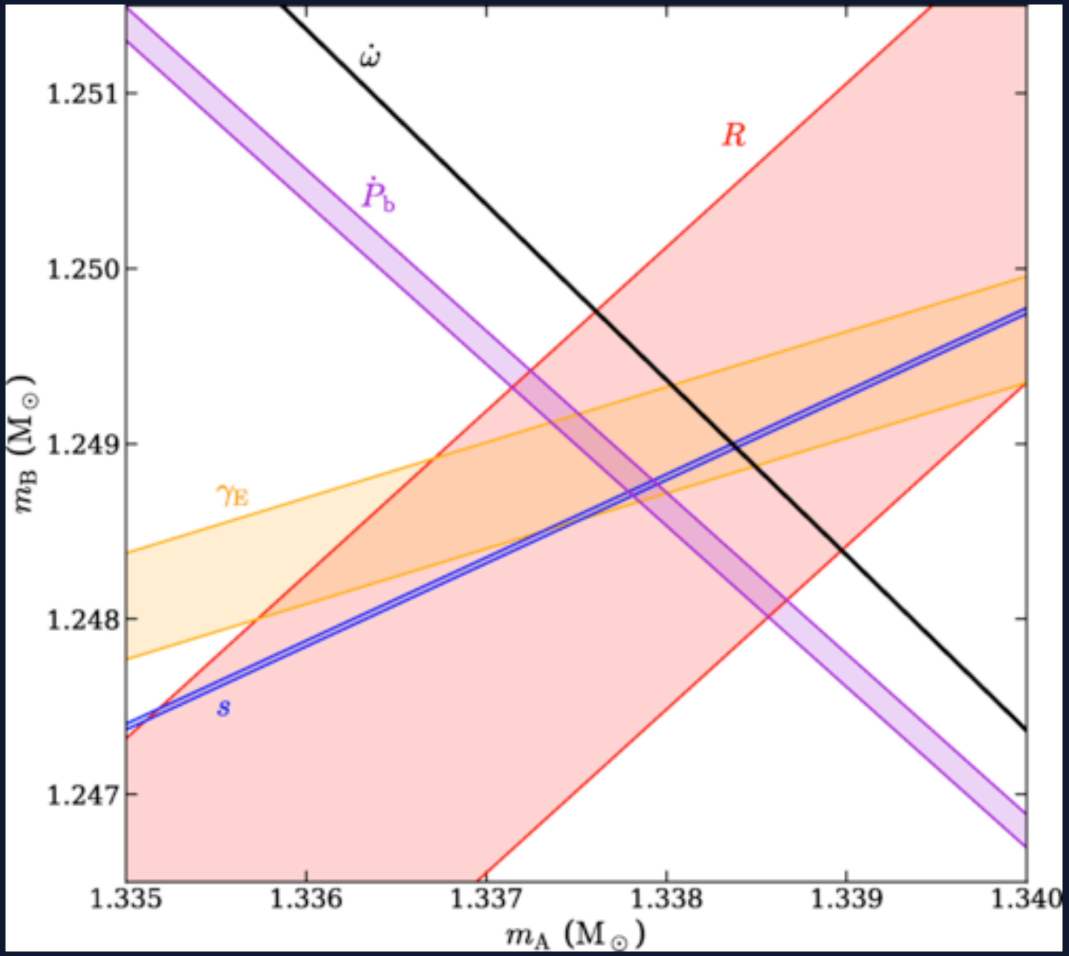
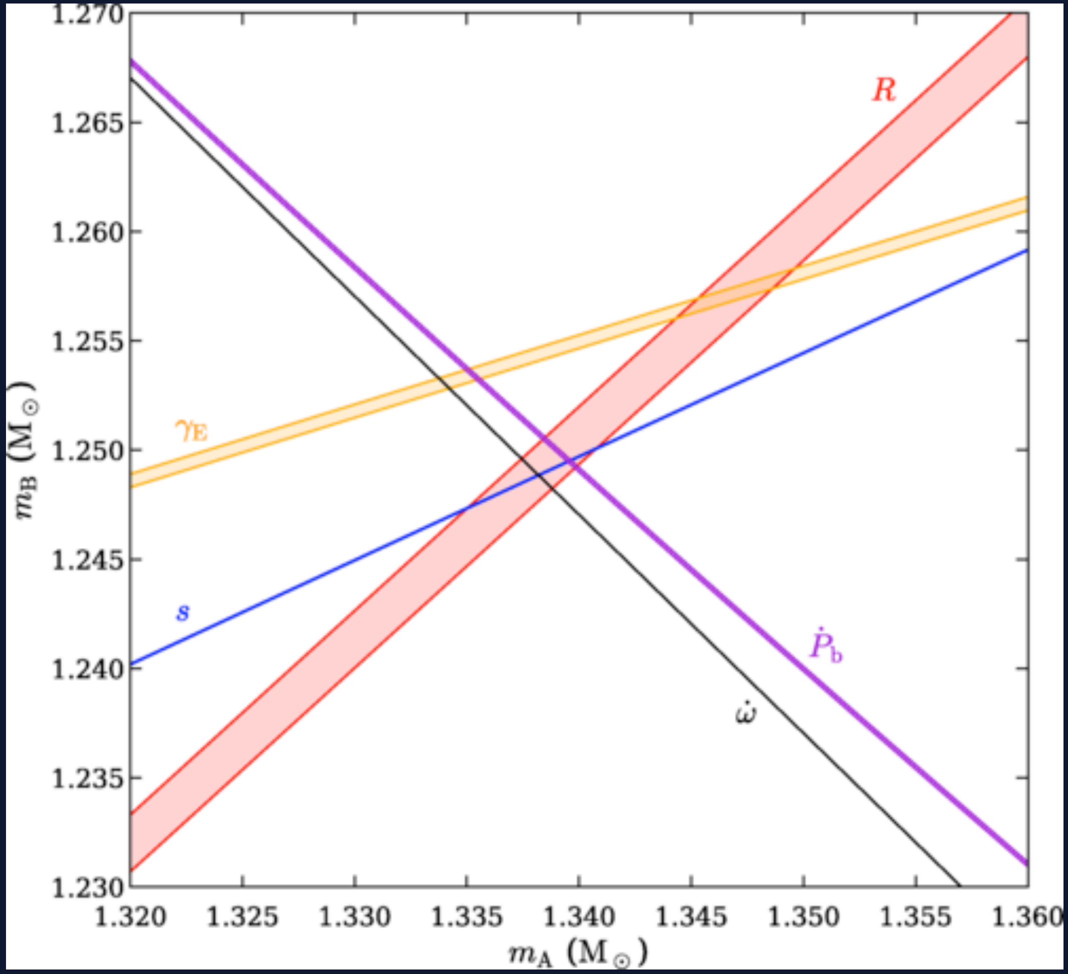
Moment of inertia

Thank you for your attention!

GR works very well, while…

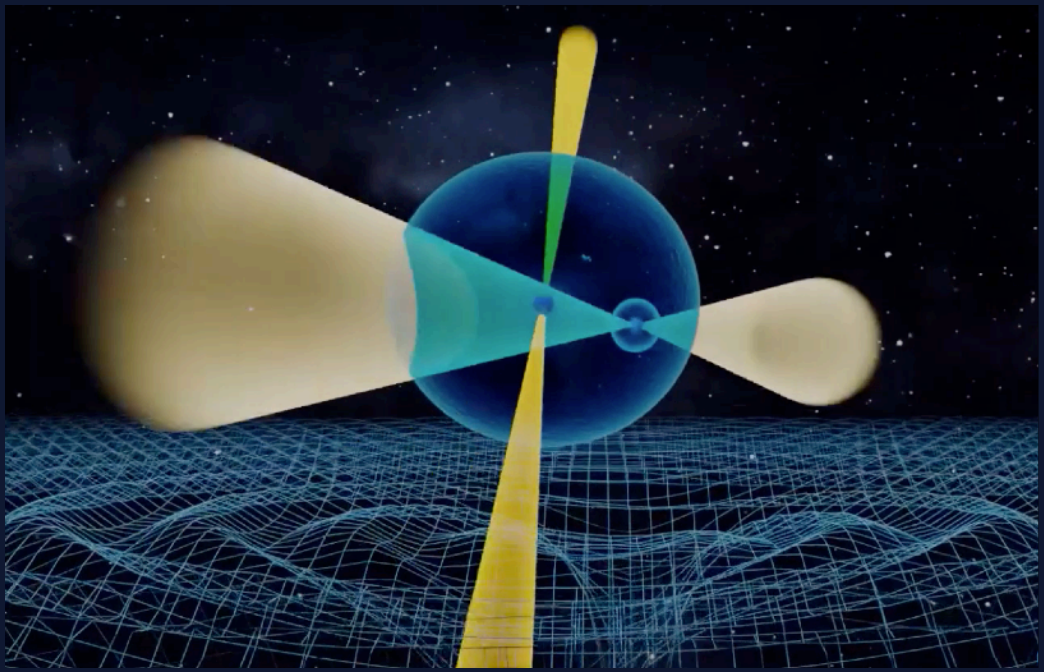


Damour–Esposito-Farèse (DEEF)



Tensor-Vector-Scalar (TeVeS)

Relativistic spin precession



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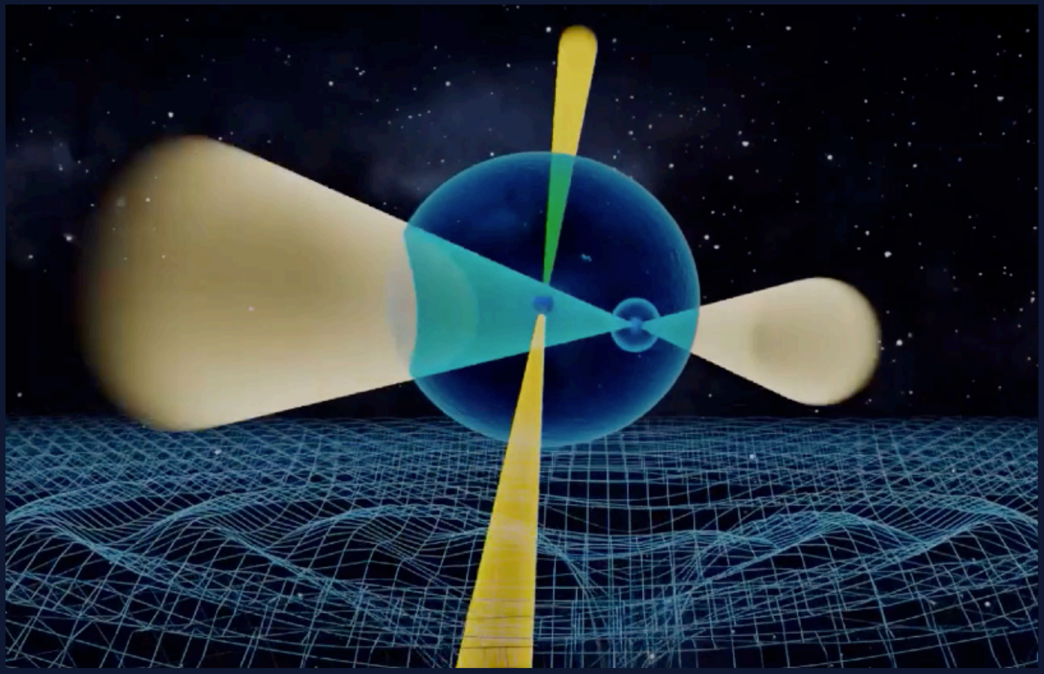

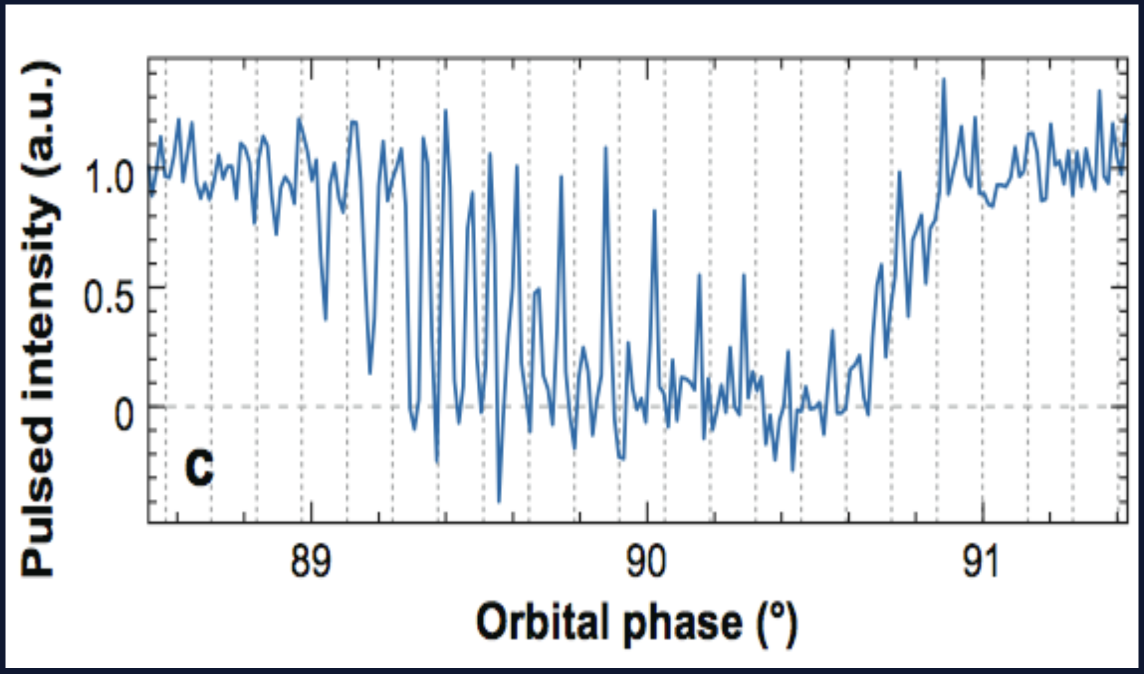

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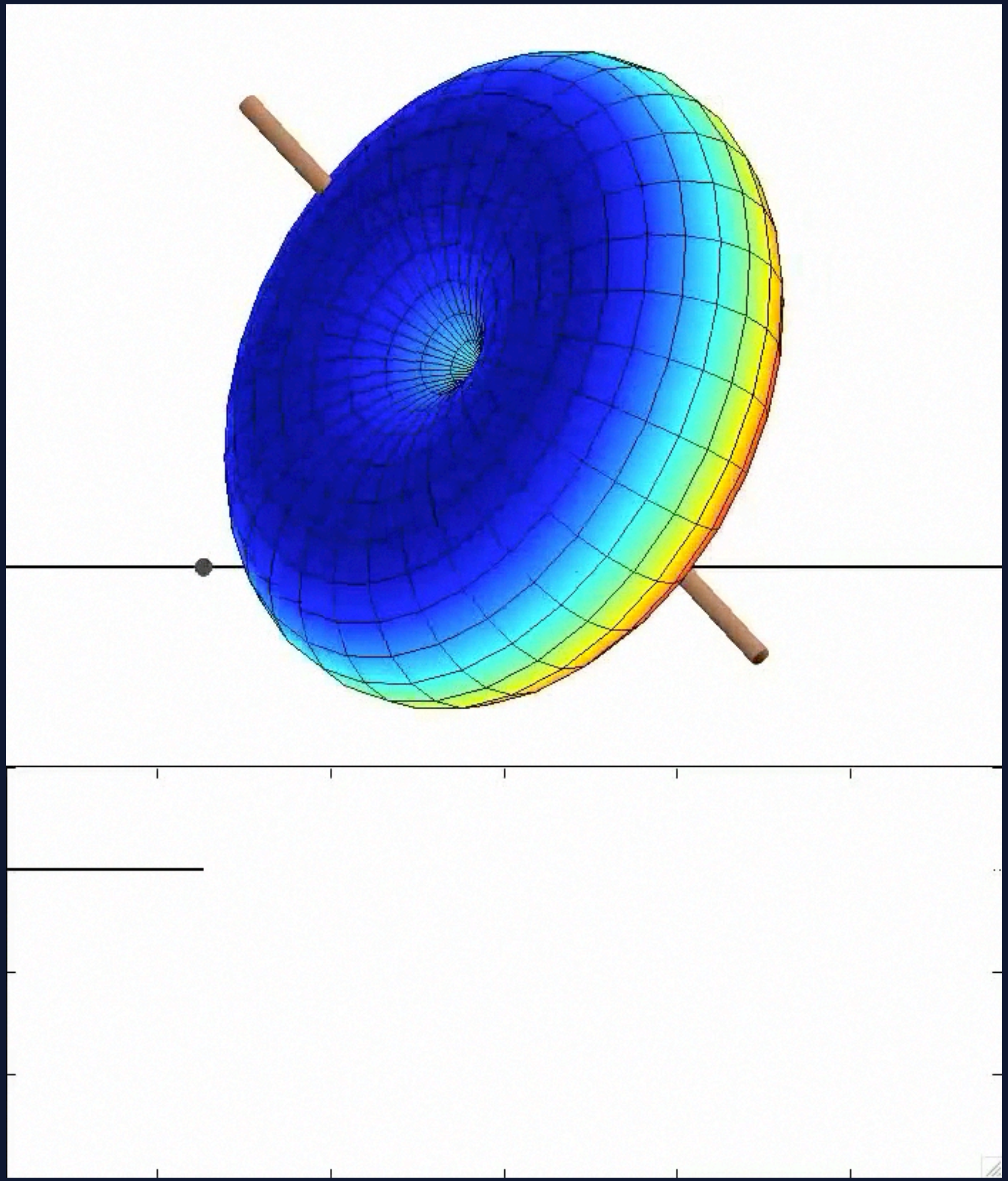

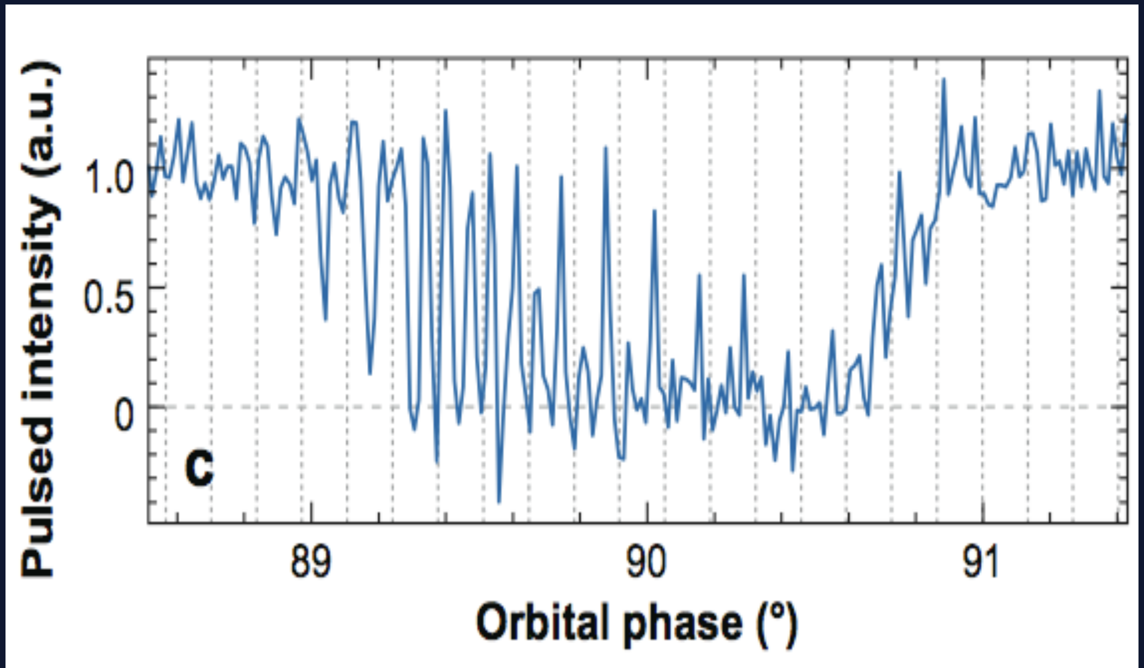

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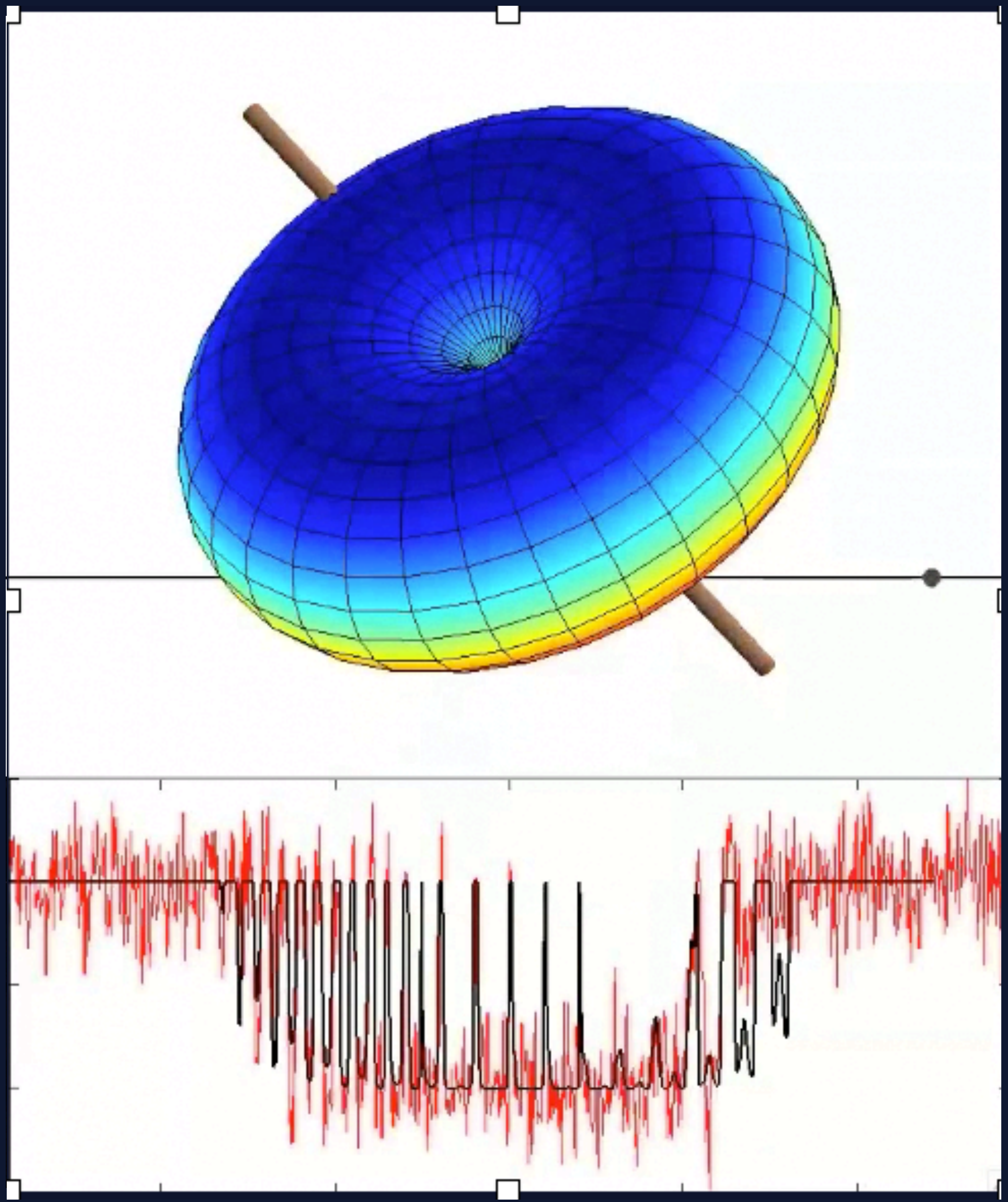

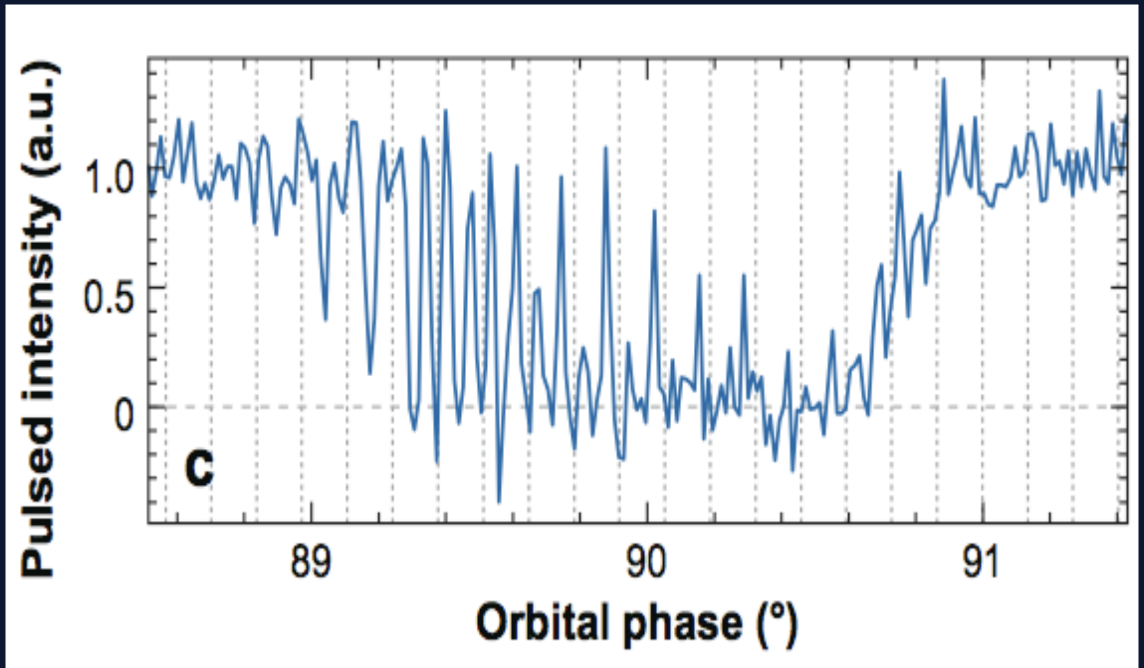

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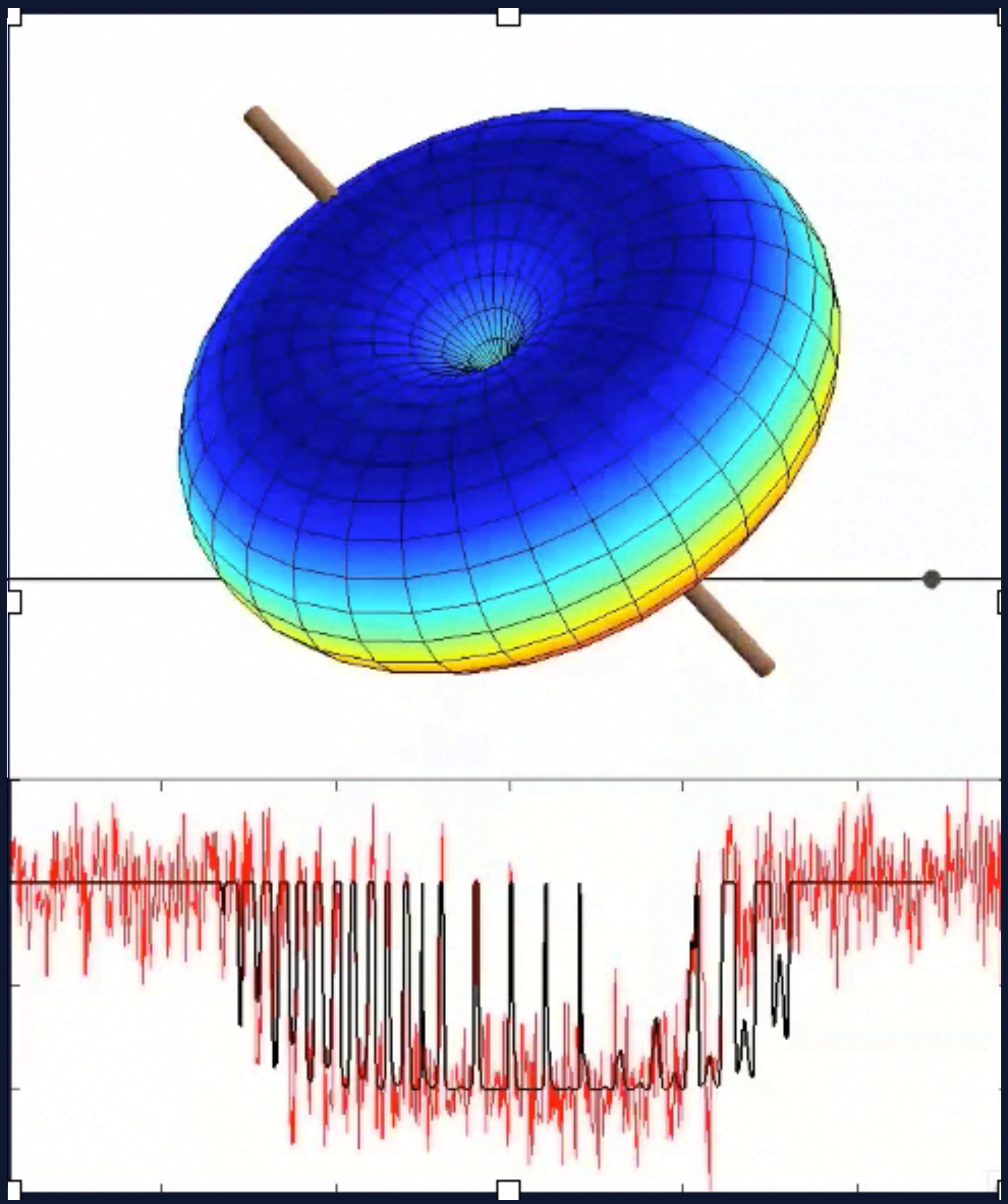

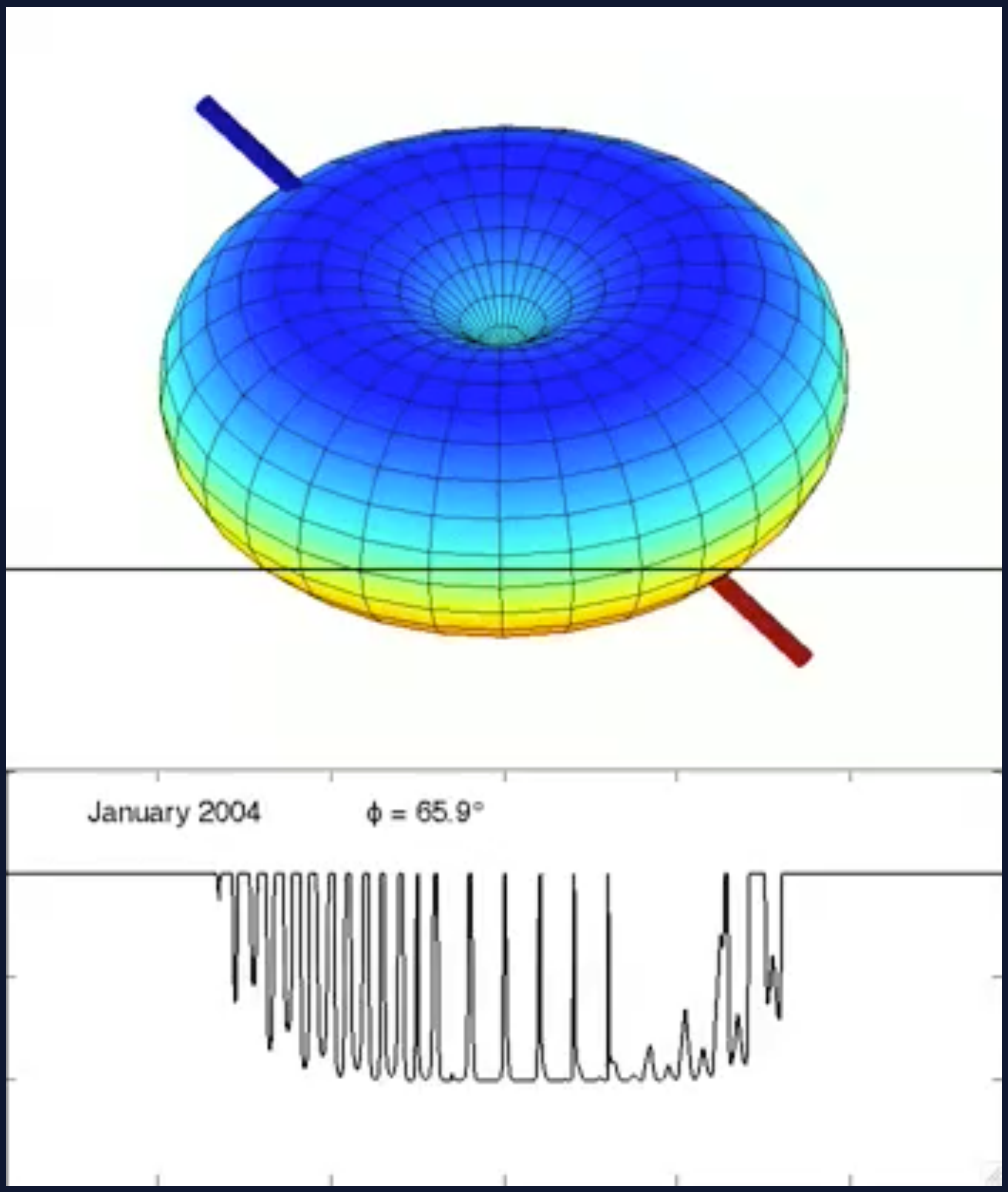

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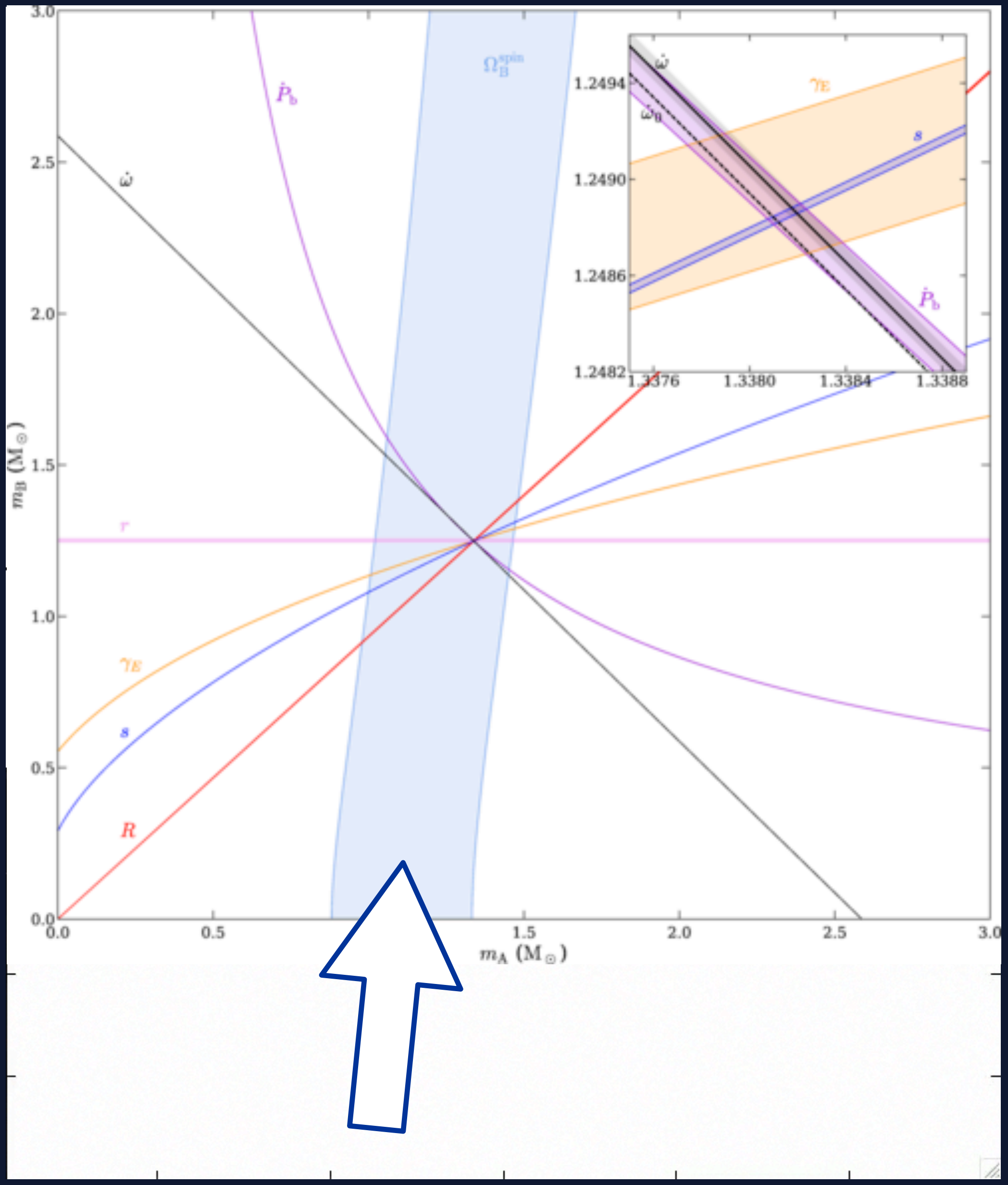

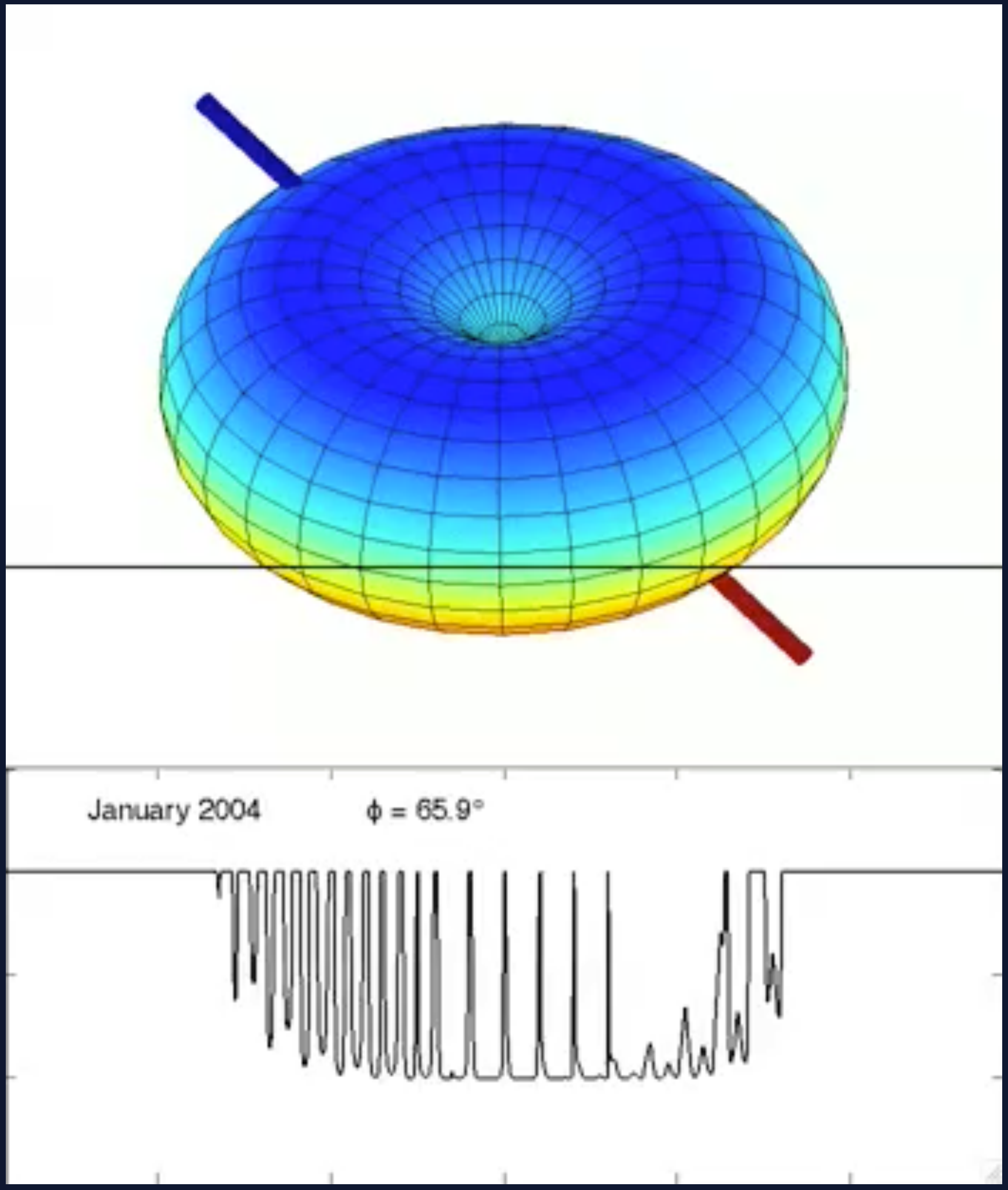

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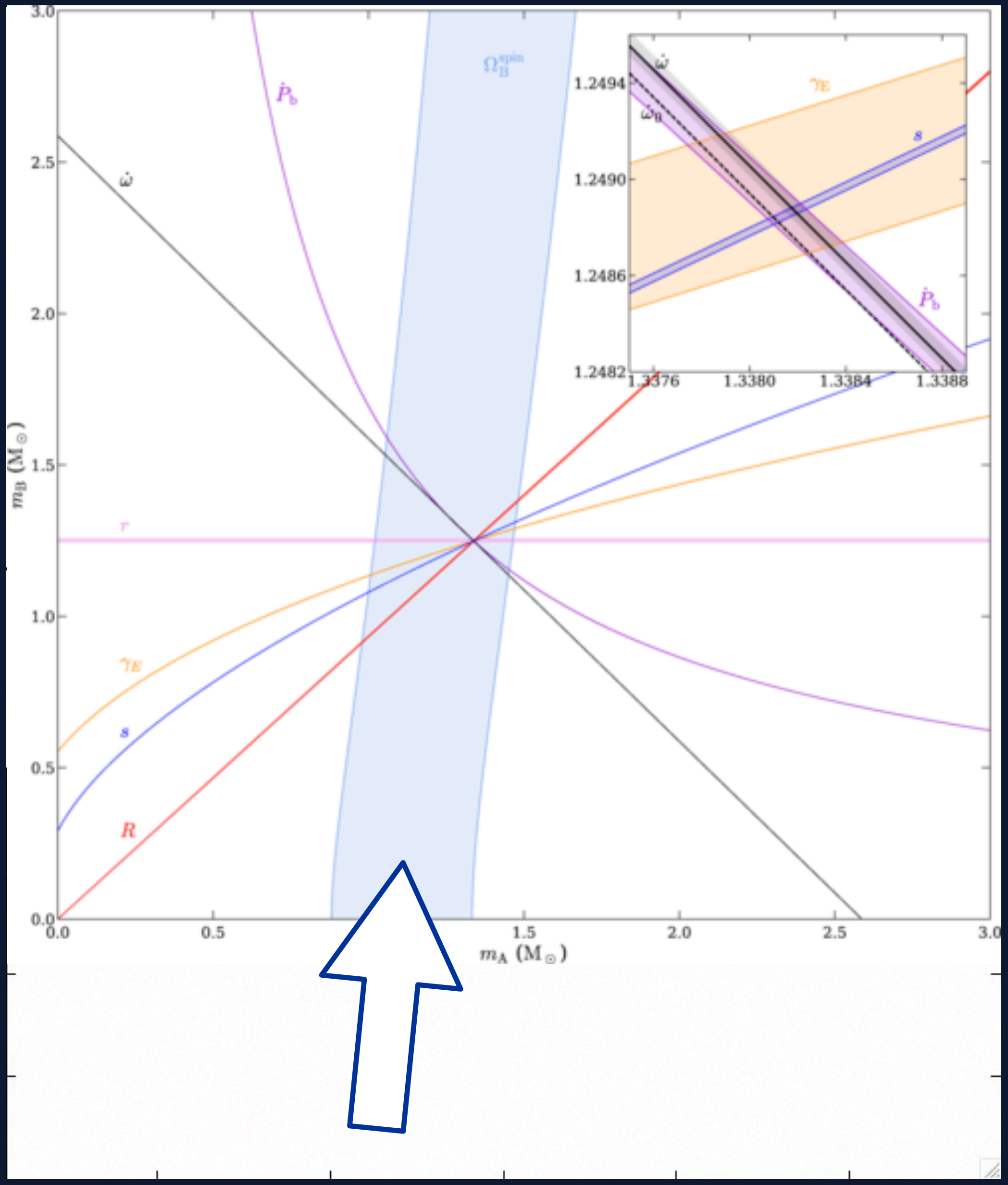

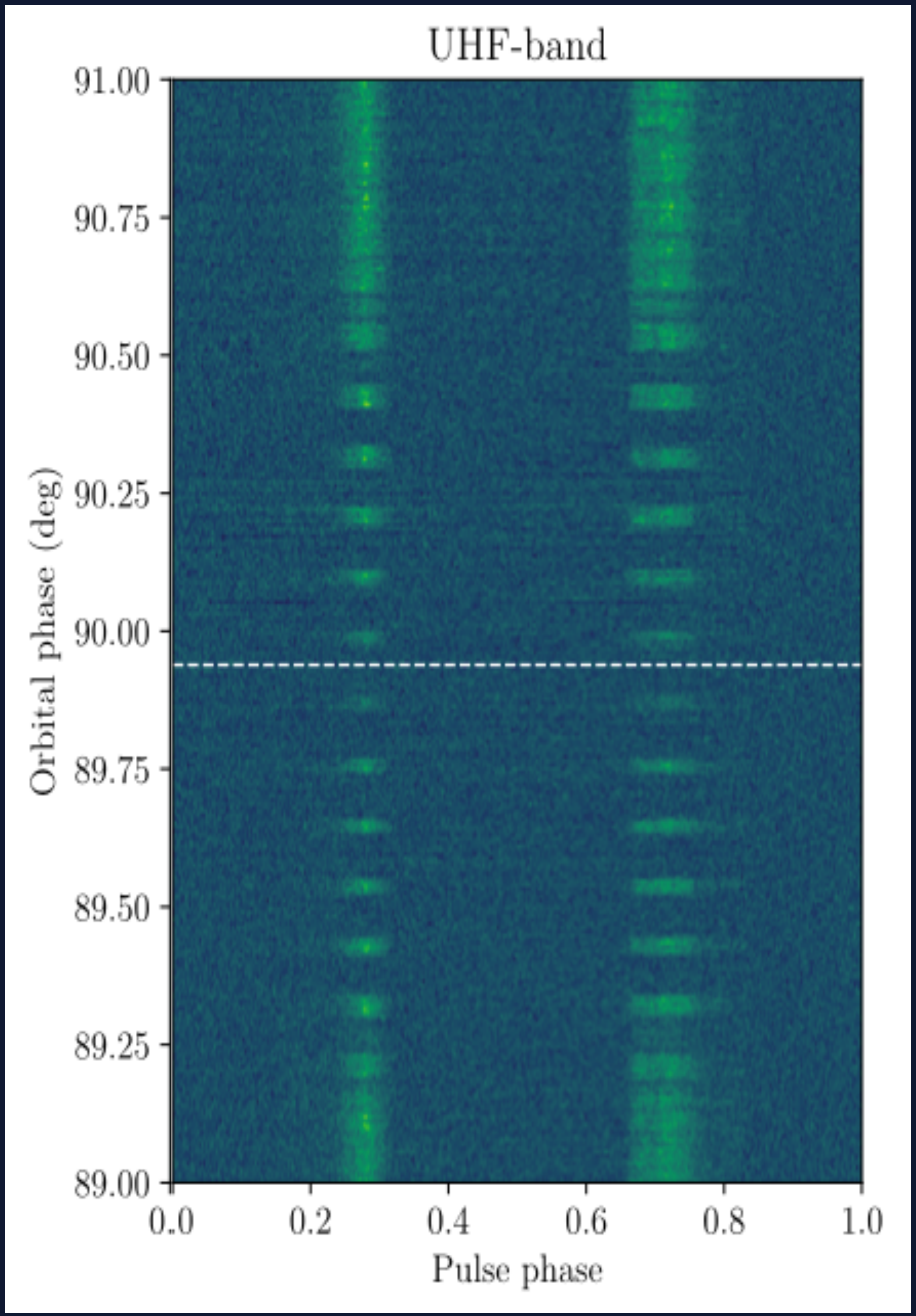

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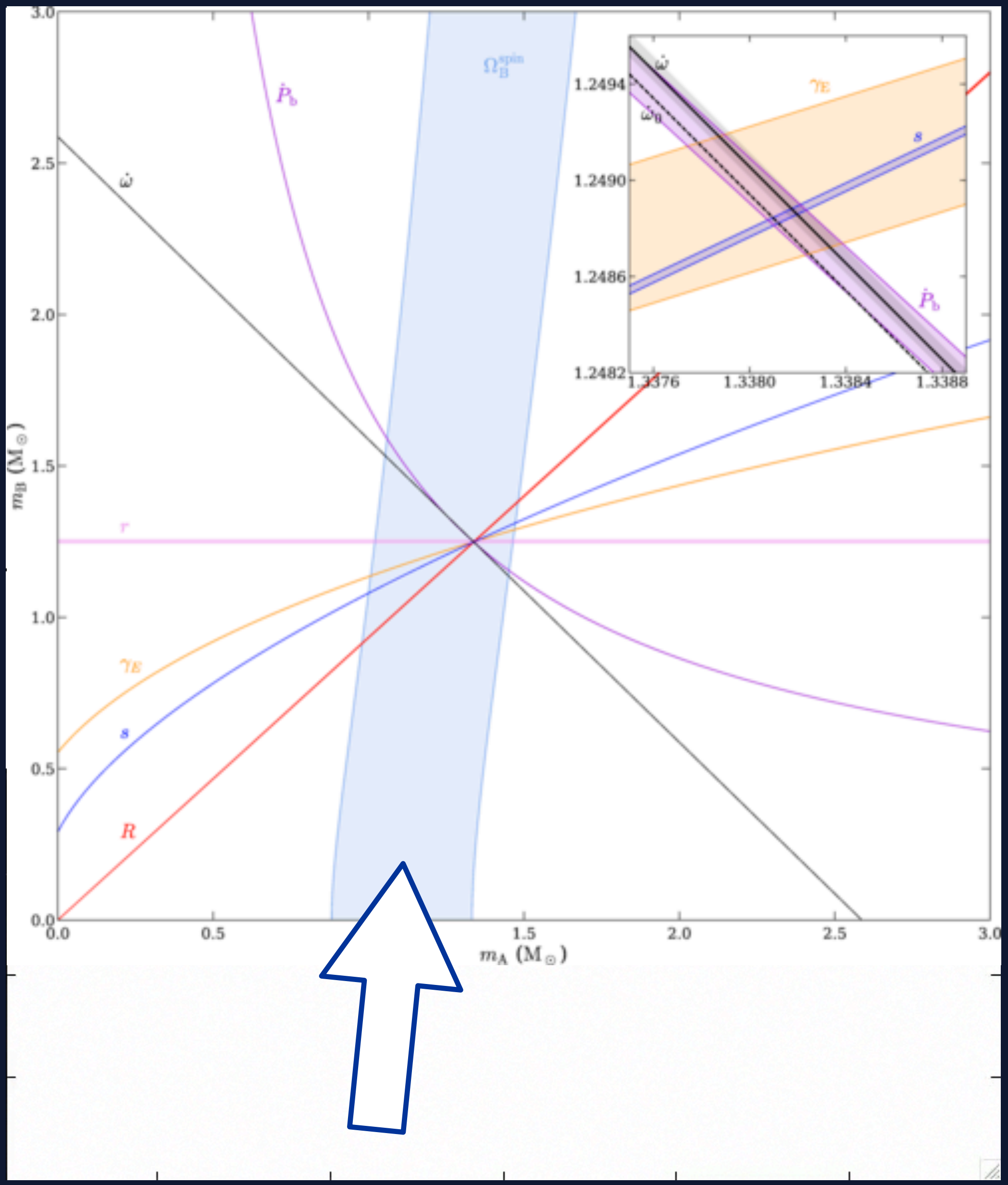

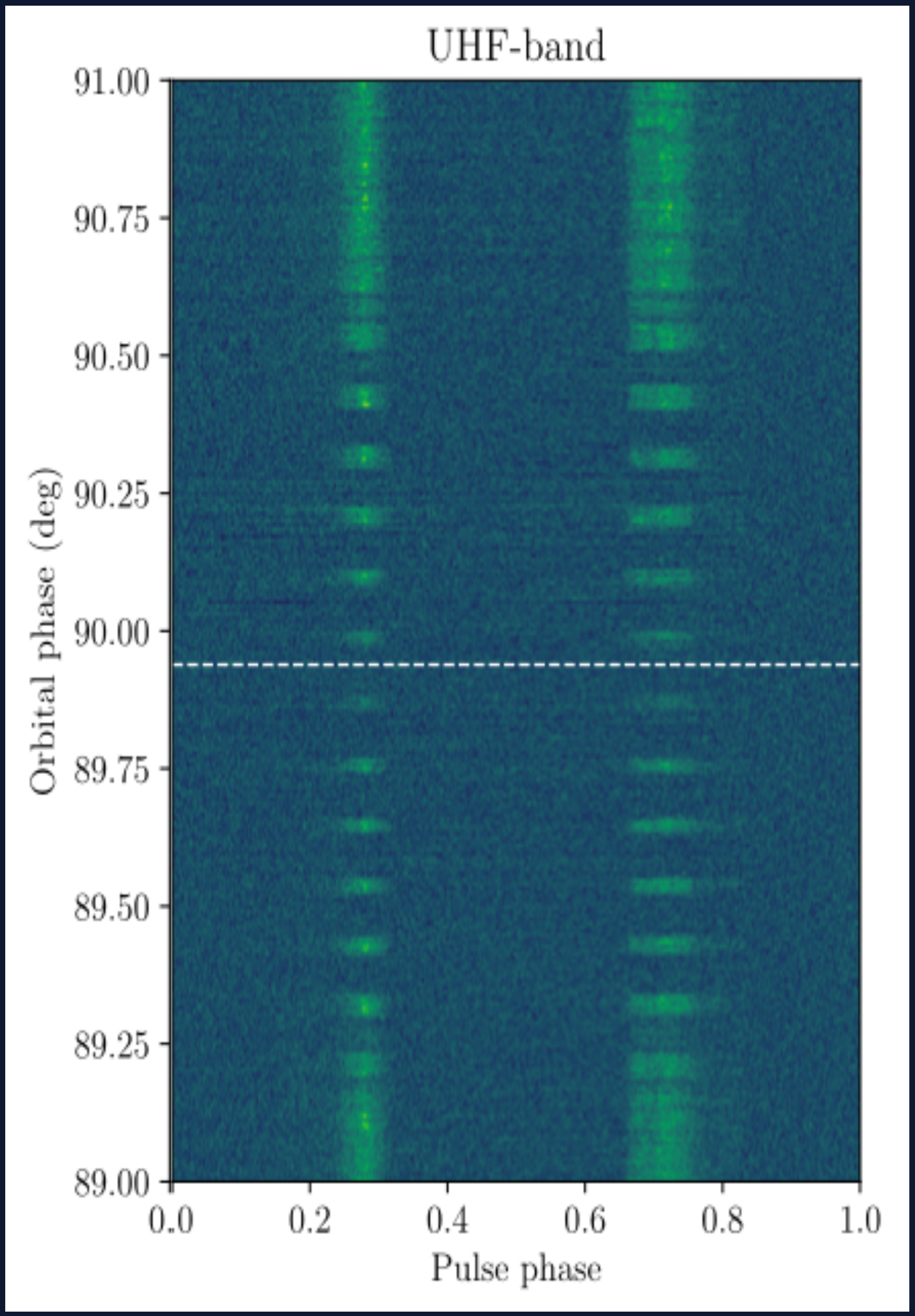

N.b. because of this, B has precessed outside our line of sight.

No longer a Double Pulsar!