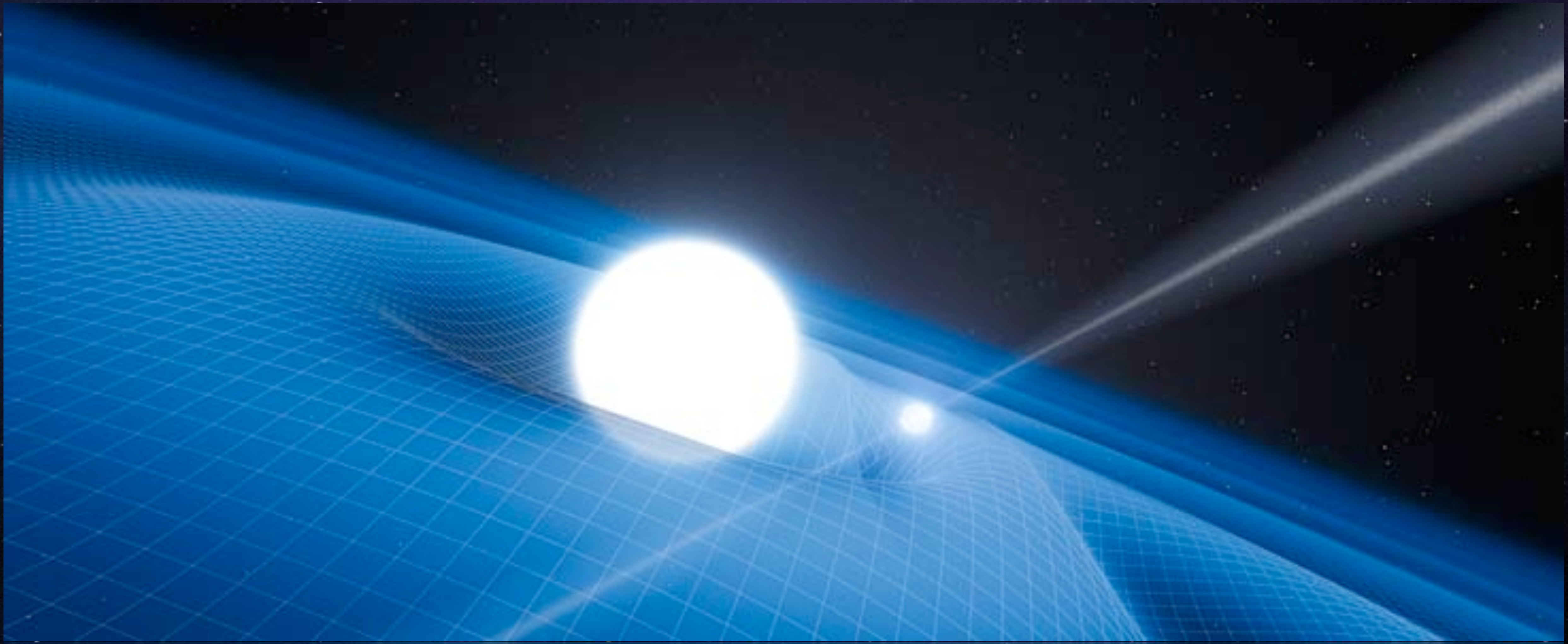
Neutron Stars as probes of relativistic gravity



Marta Burgay

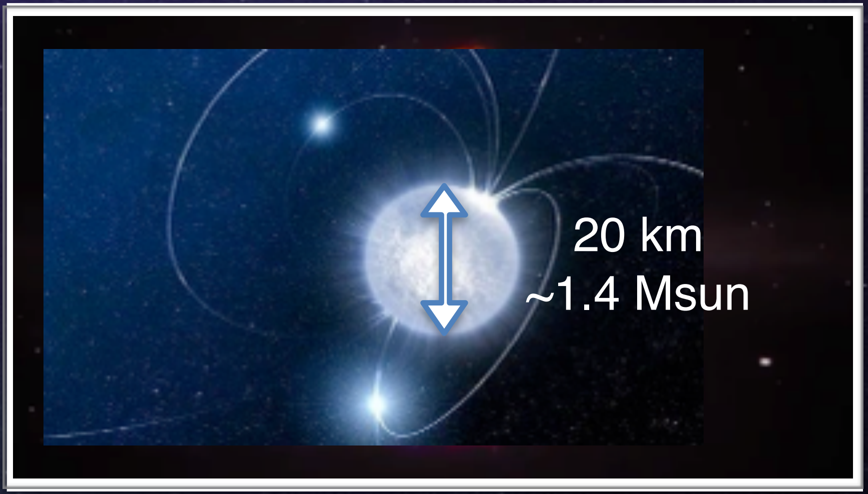
INAF – Osservatorio Astronomico di Cagliari

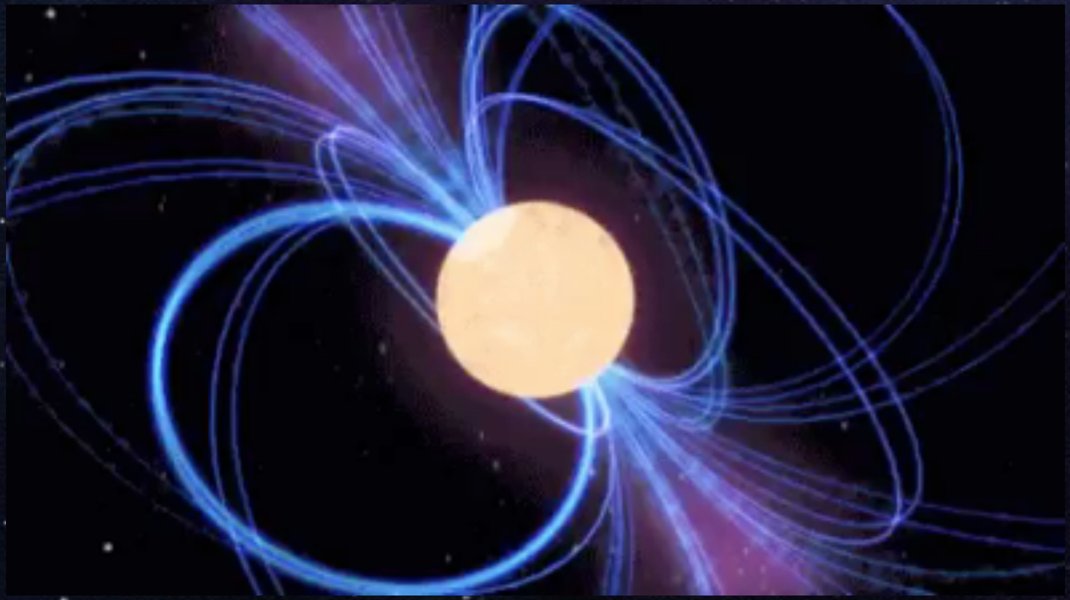
Outline

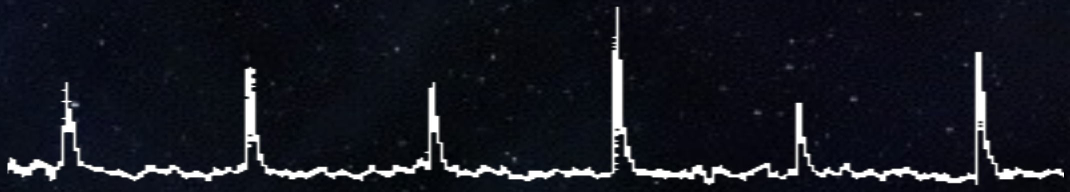
- Neutron stars and pulsars
- The neutron star zoo
- Timing: using pulsars as precision clocks
- Pulsars and GR: relativistic binaries
- Pulsars and GR: timing arrays for GW

Neutron Stars

- Born in core-collapse SN
- Predicted by Baade & Zwiky in 1933
- Discovered by Bell & Hewish (Nobel 1973) in 1967 through the detection of regular radio pulses



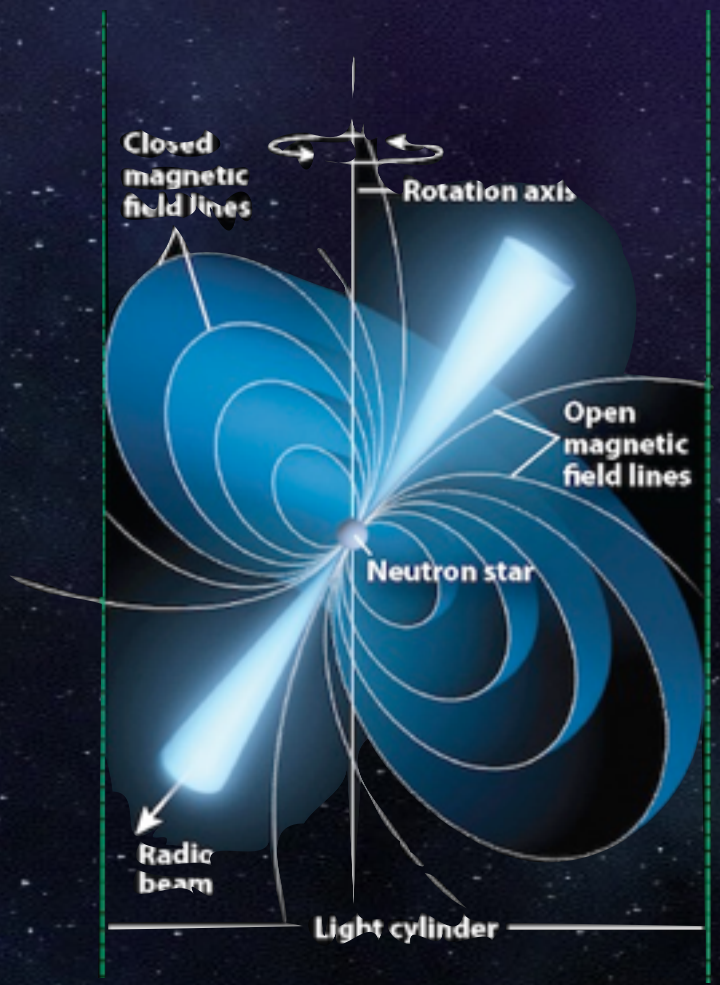




- Rapidly rotating, highly magnetised NSs
- Emitting beams of Radio waves at the expenses of rotational energy

PULSARS ENERGETICS

ROTATION OF THE NS MAGNETIC DIPOLE POWERS THE EMISSION (PACINI 1967, GOLD 1968



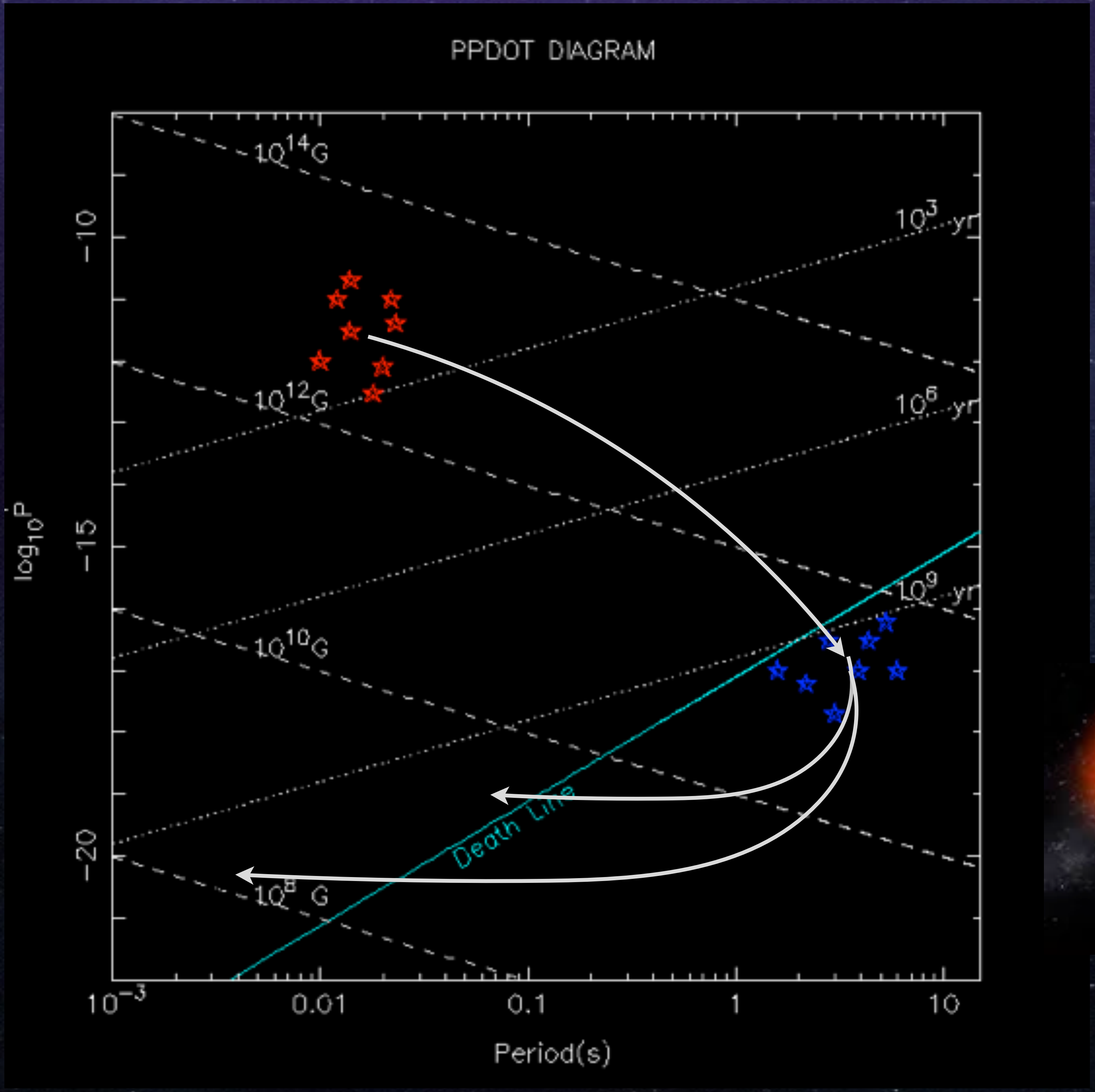
$$\frac{dE_{EM}}{dt} = -\frac{2}{3c^3}\left(B_s R_{NS}^3 \sin(\alpha)\right)^2 \left(\frac{2\pi}{P_s}\right)^4$$

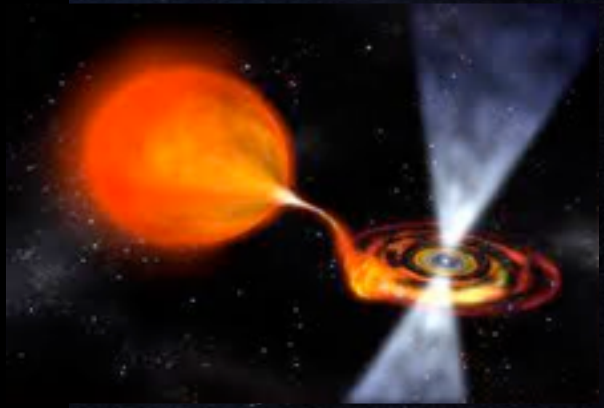
$$\frac{dE_{EM}}{dt} = \frac{dE_{kin}}{dt} = I_{ns}\Omega_s\dot{\Omega}_s = -\frac{4\pi^2 I_{ns}\dot{P}_s}{P_s^3}$$

$$B_s = 3.2 \, x \, 10^{19}\left(P_s(s)\dot{P}_s\right)^{1/2} G$$

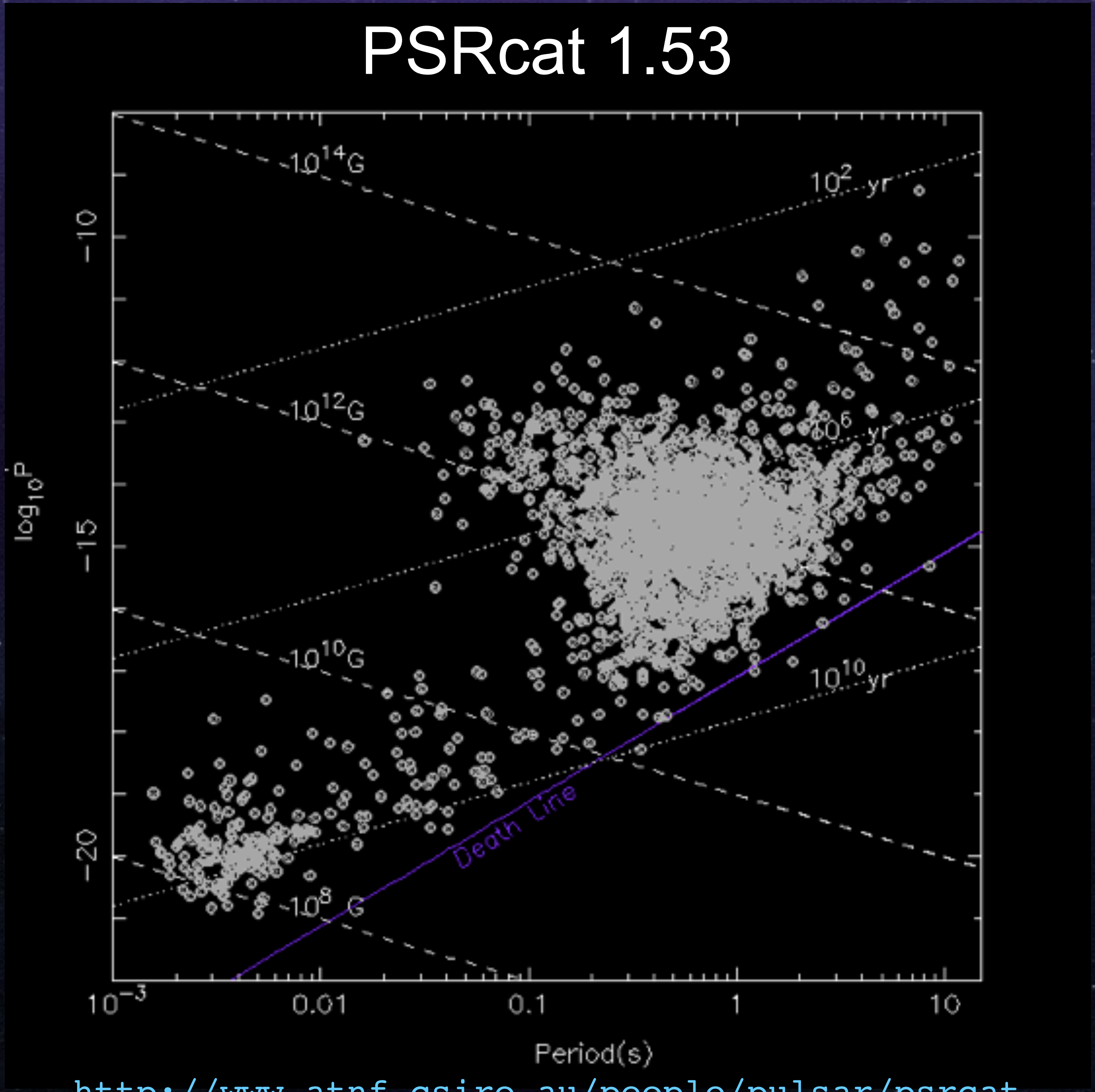
$$\tau_{sd} = \frac{P_s}{2\dot{P}_s}$$

Radio Pulsars



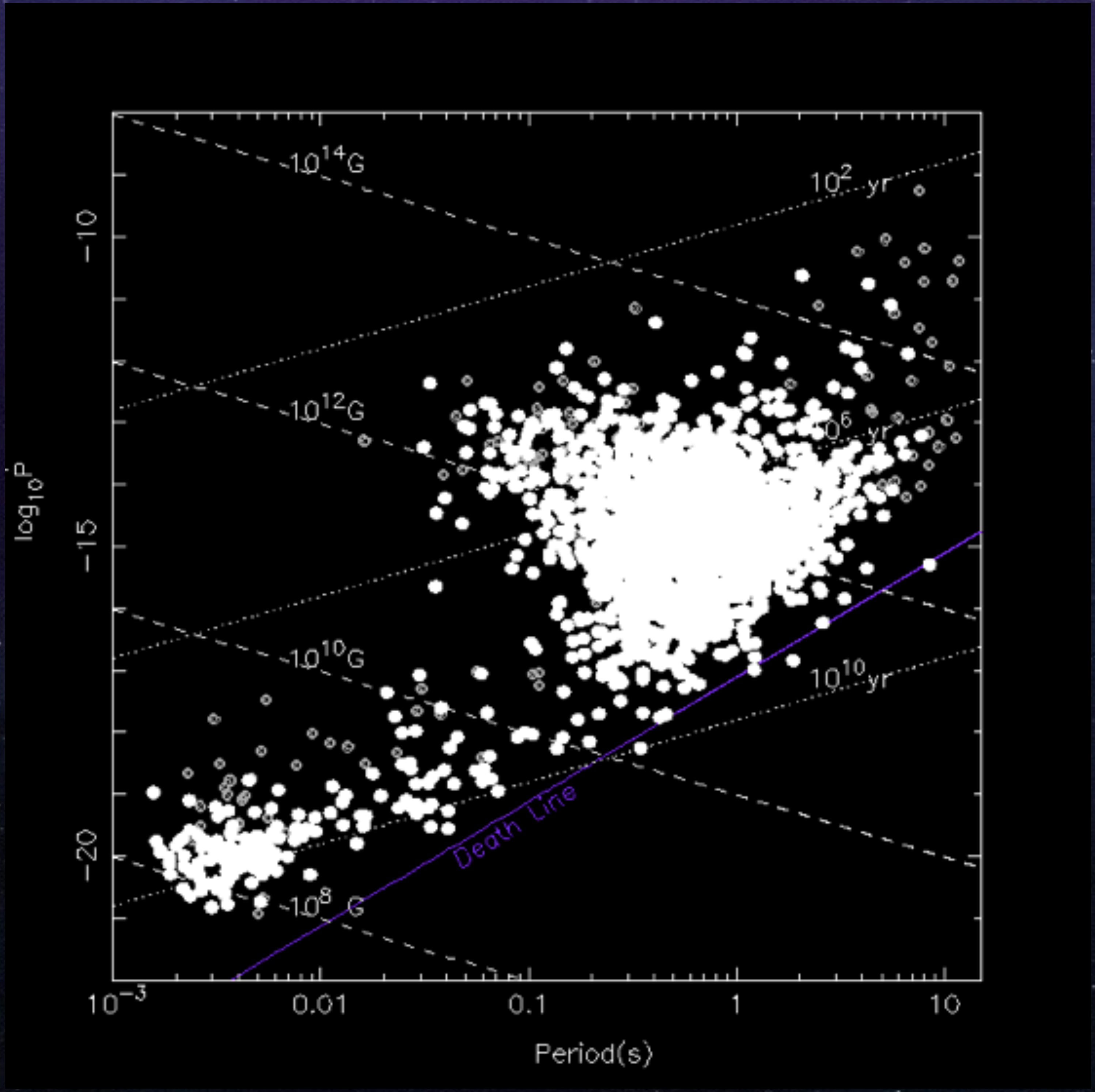


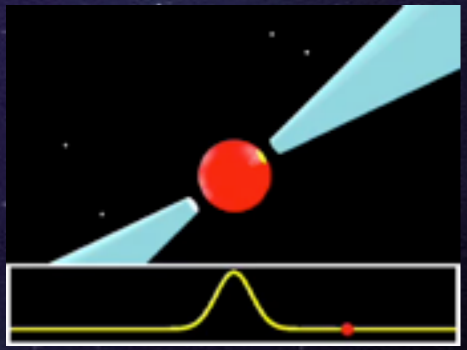
The neutron star Zoo



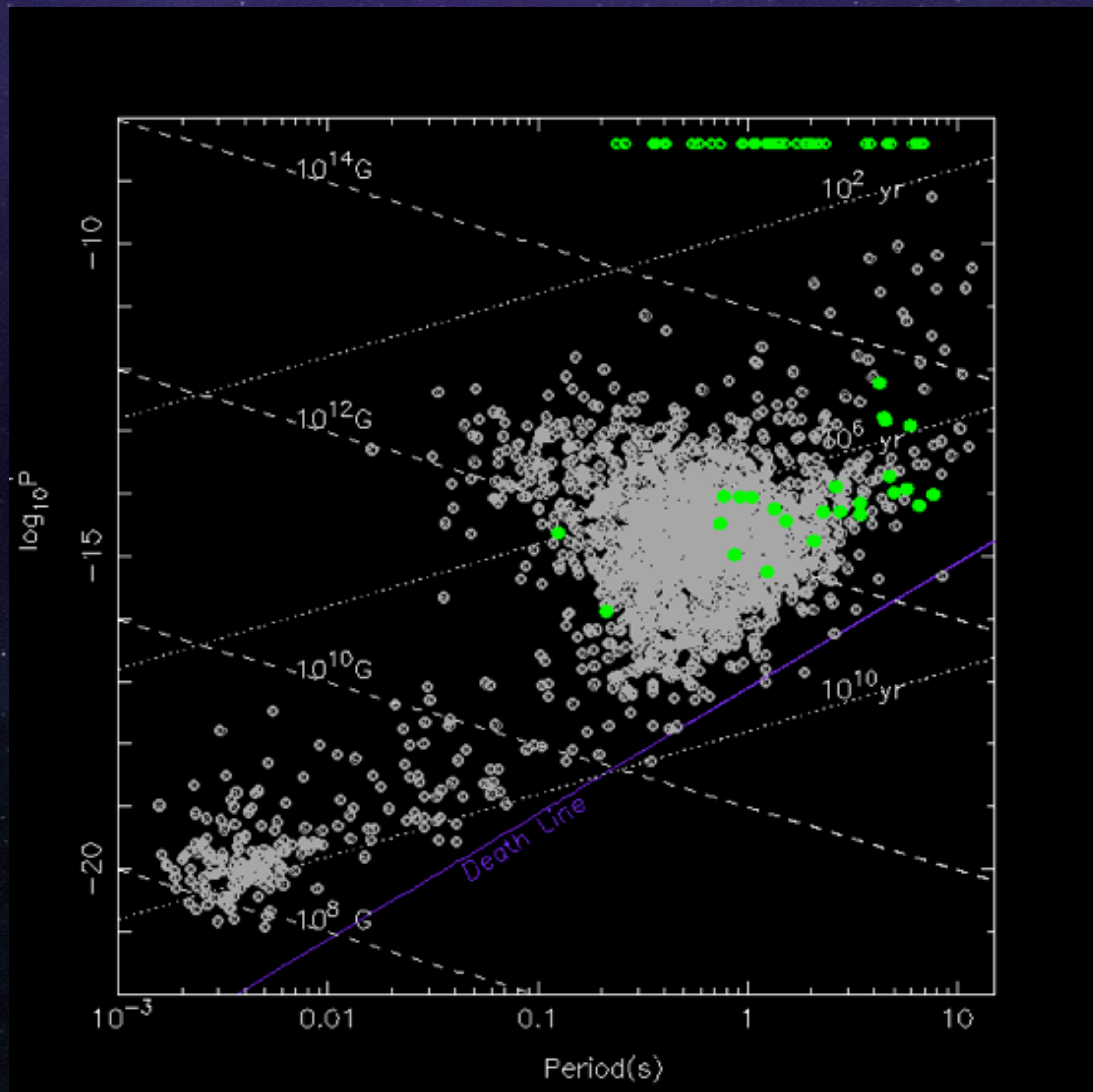
http://www.atnf.csiro.au/people/pulsar/psrcat

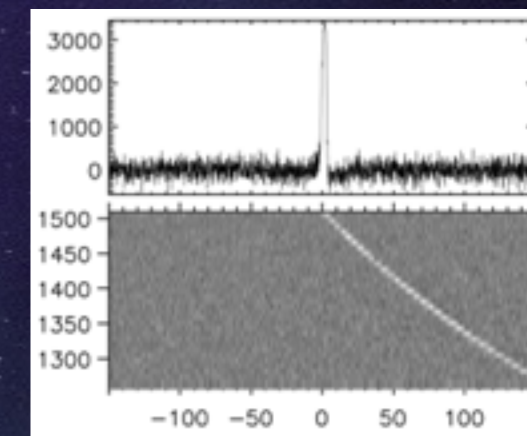
The neutron star Zoo

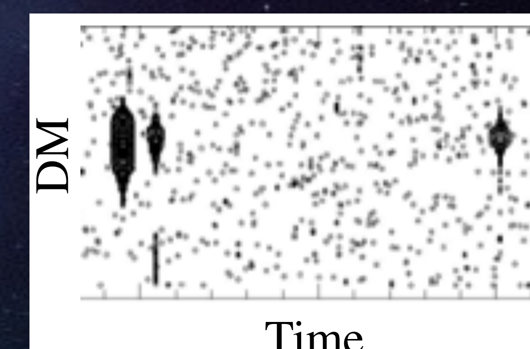




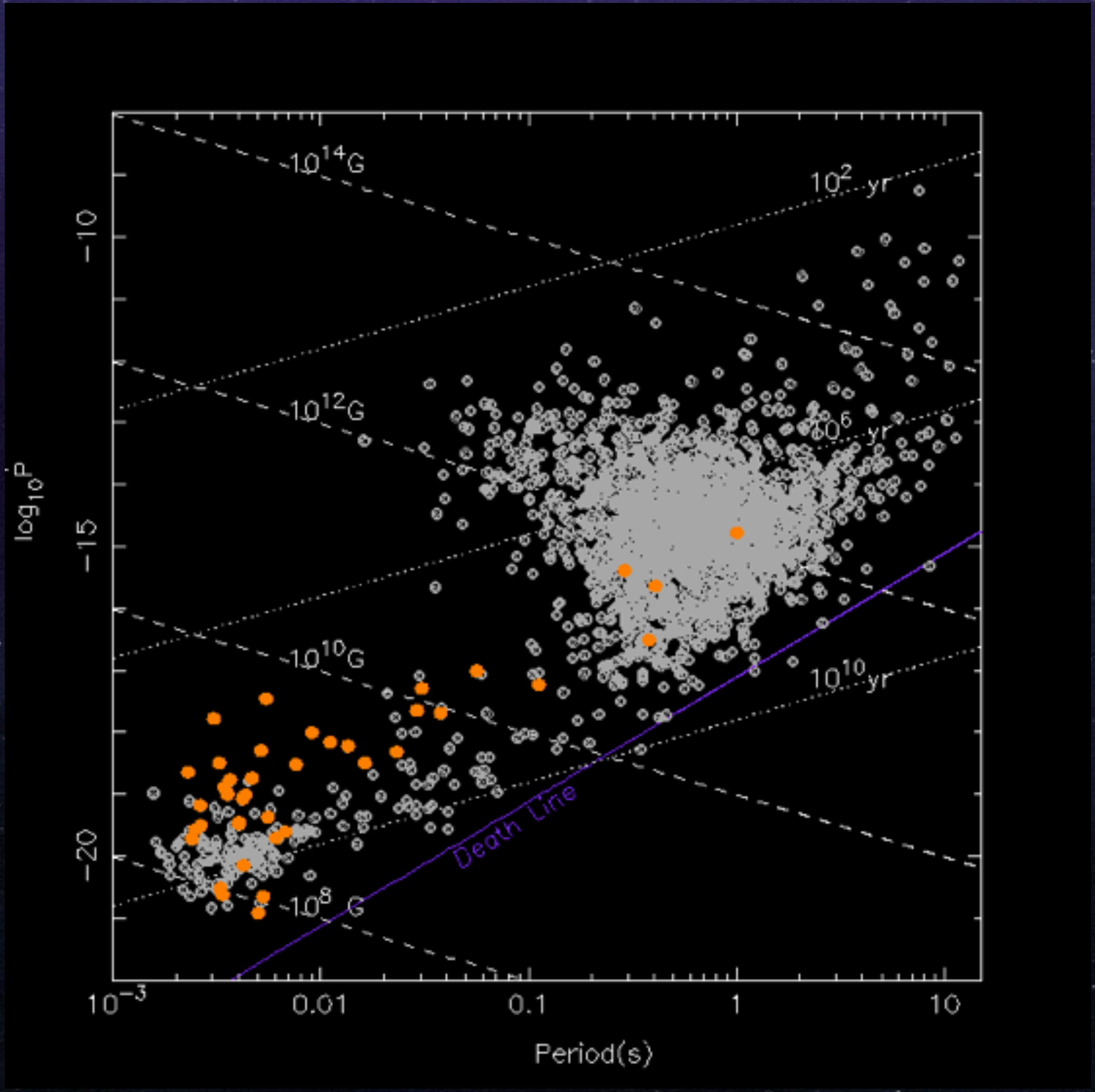
The neutron star Zoo

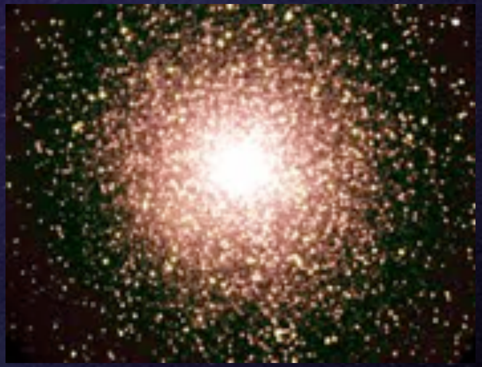




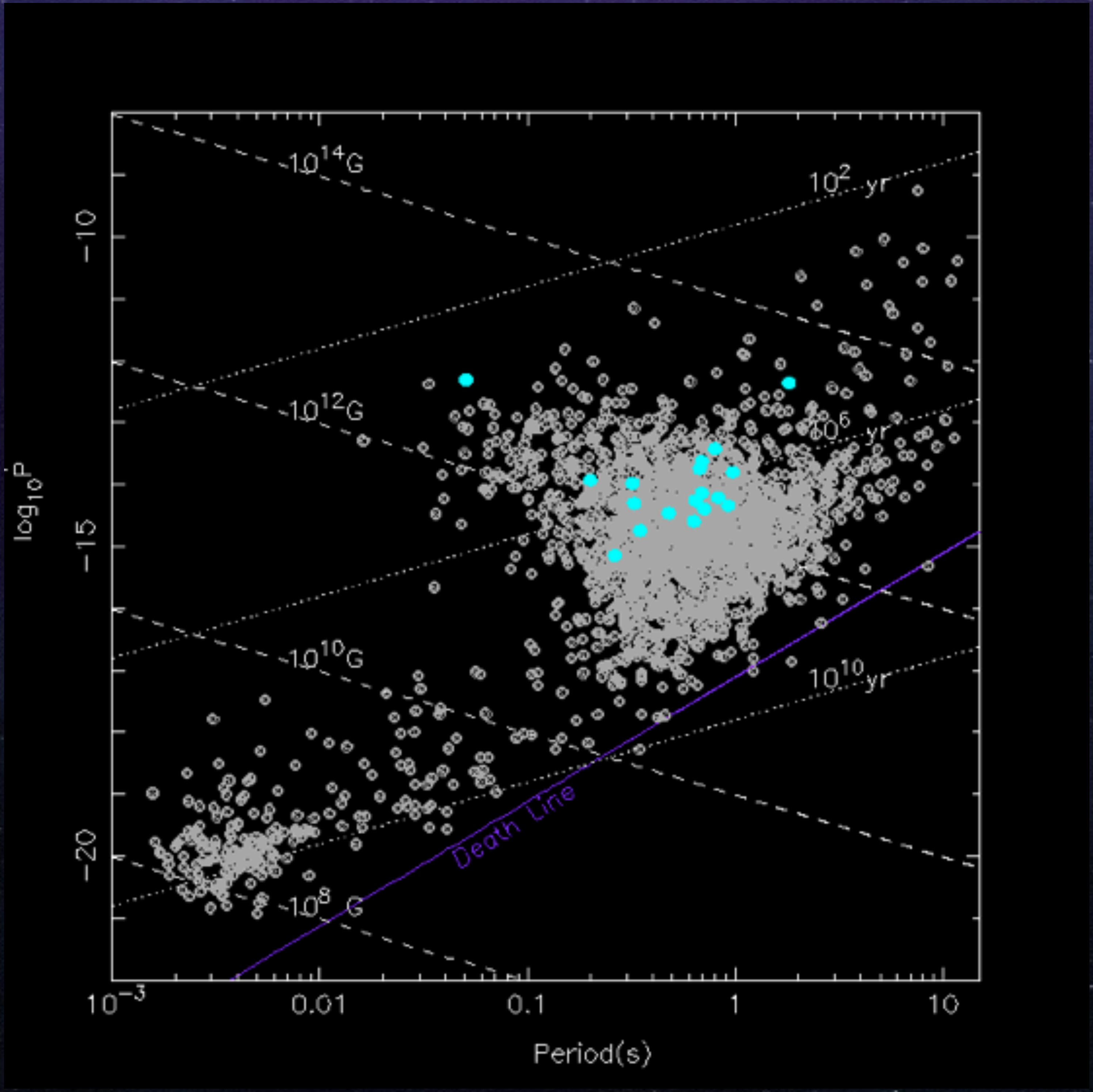


The neutron star Zoo

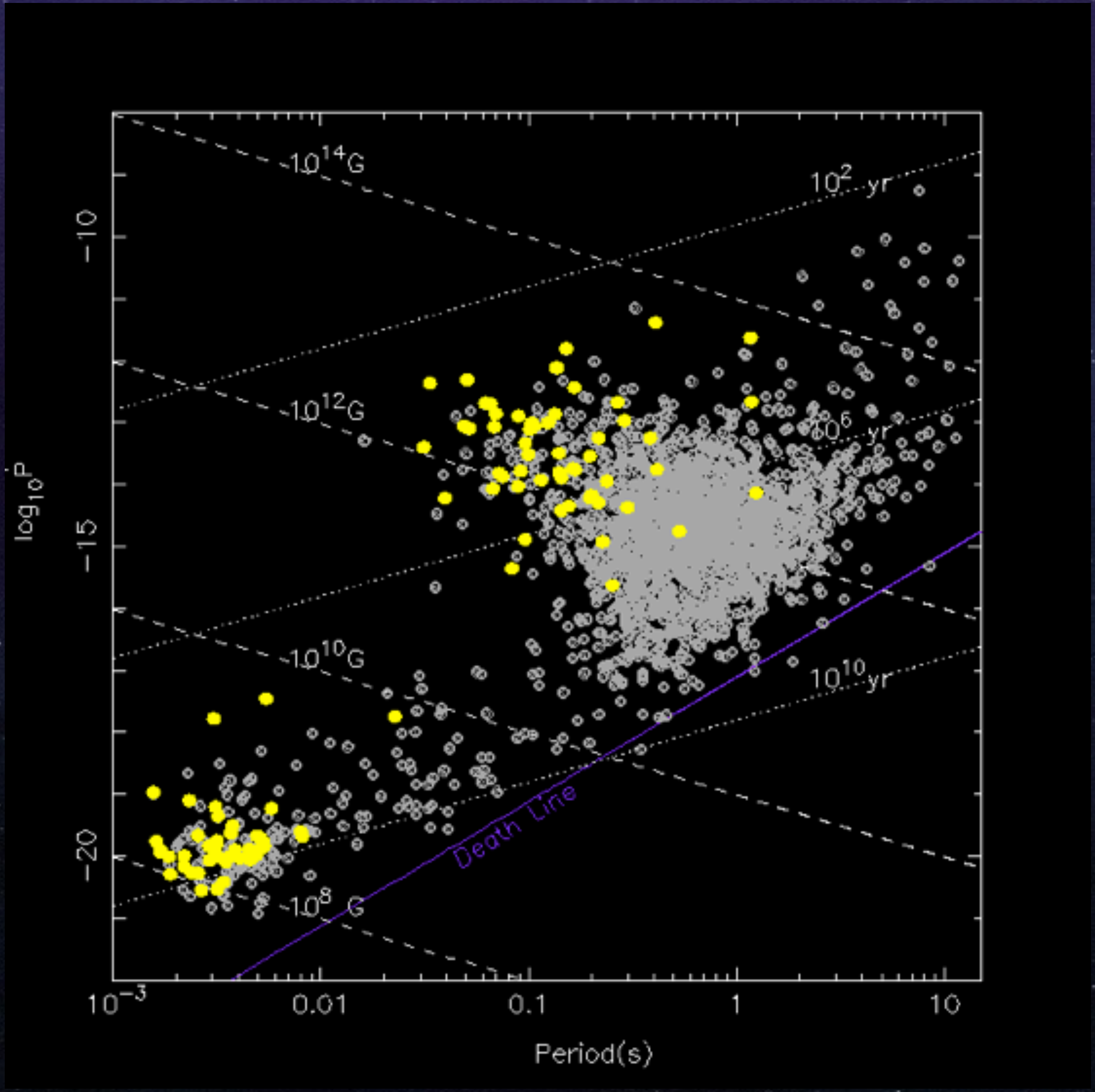


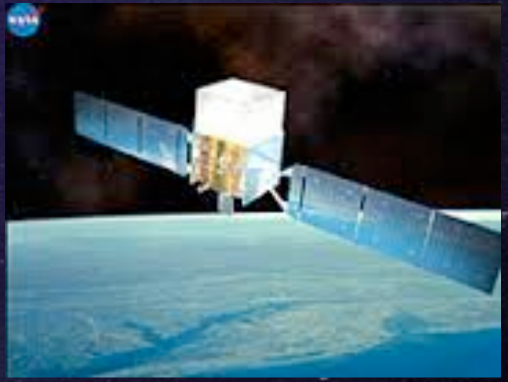


The neutron star Zoo

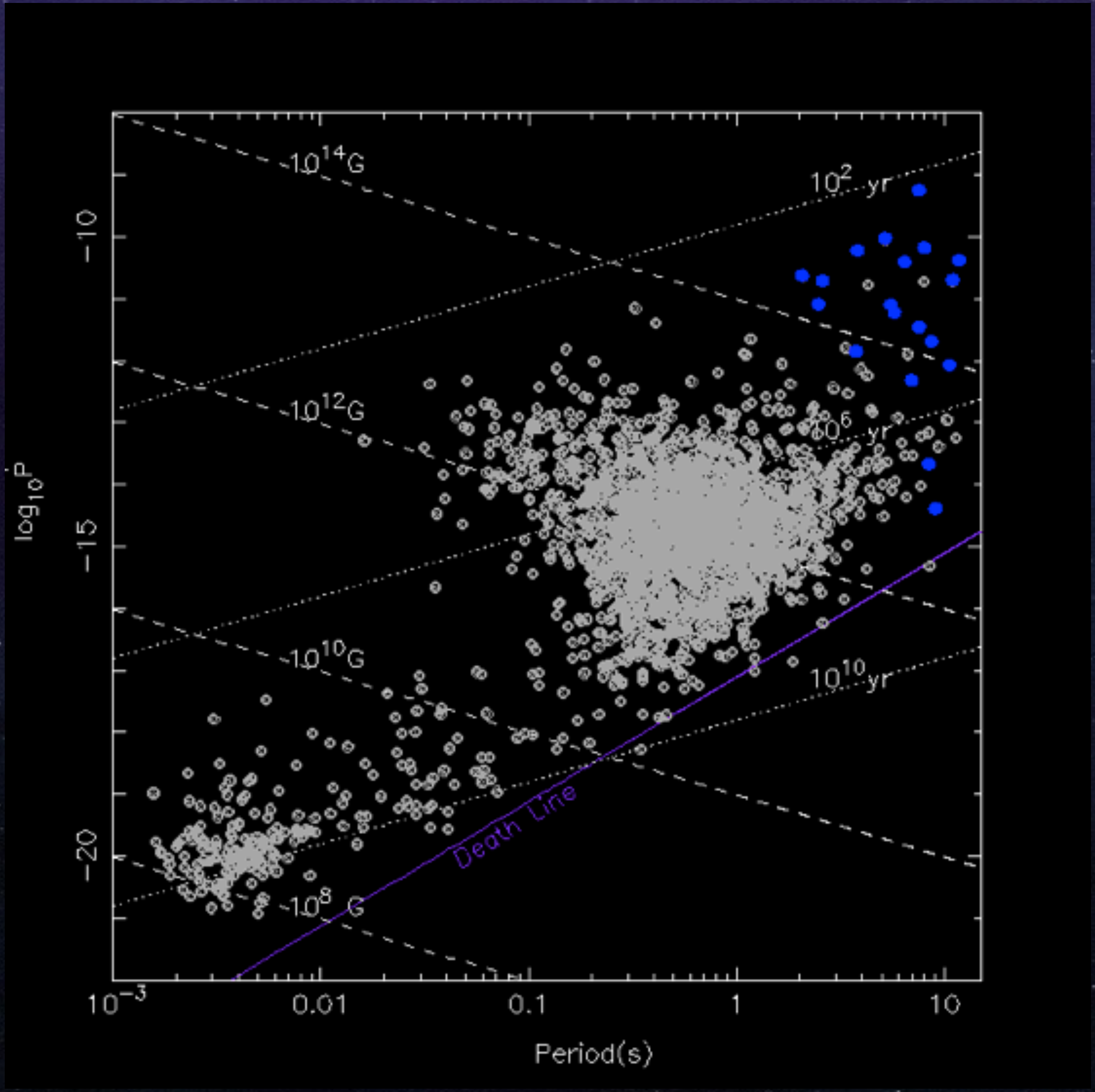


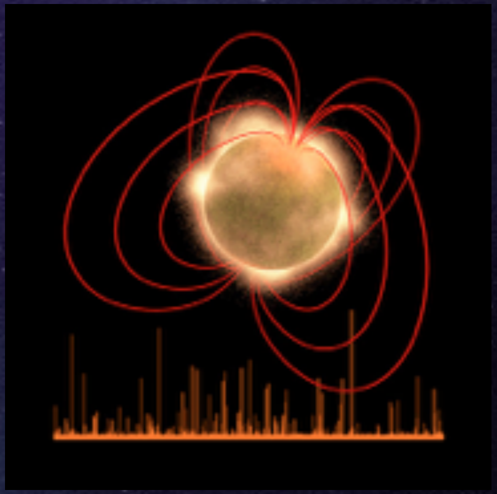
The neutron star Zoo



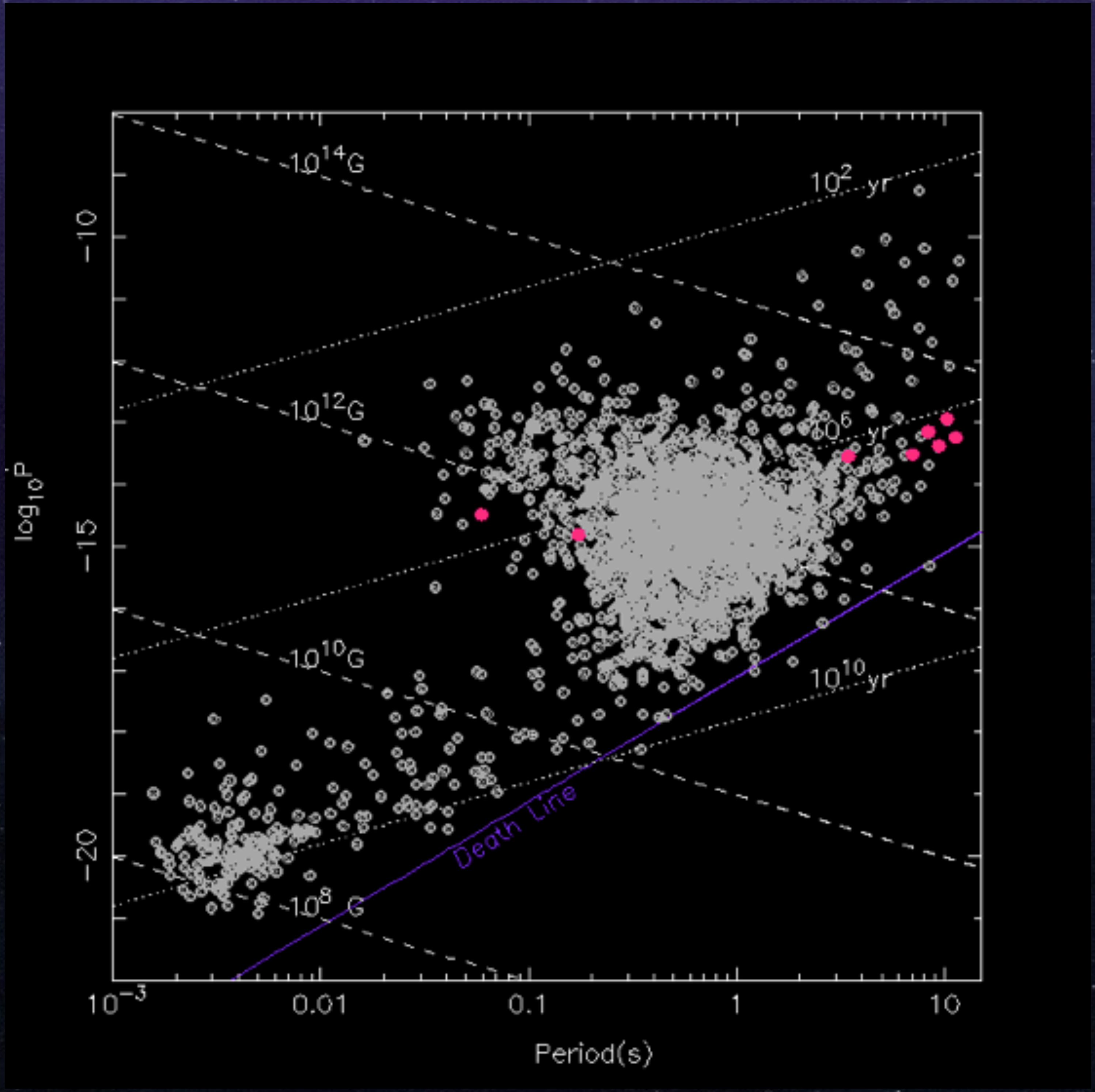


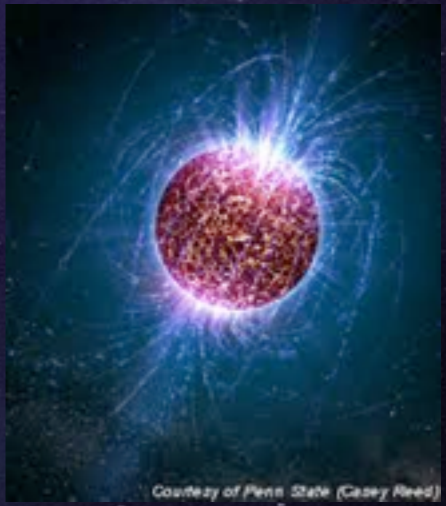
The neutron star Zoo



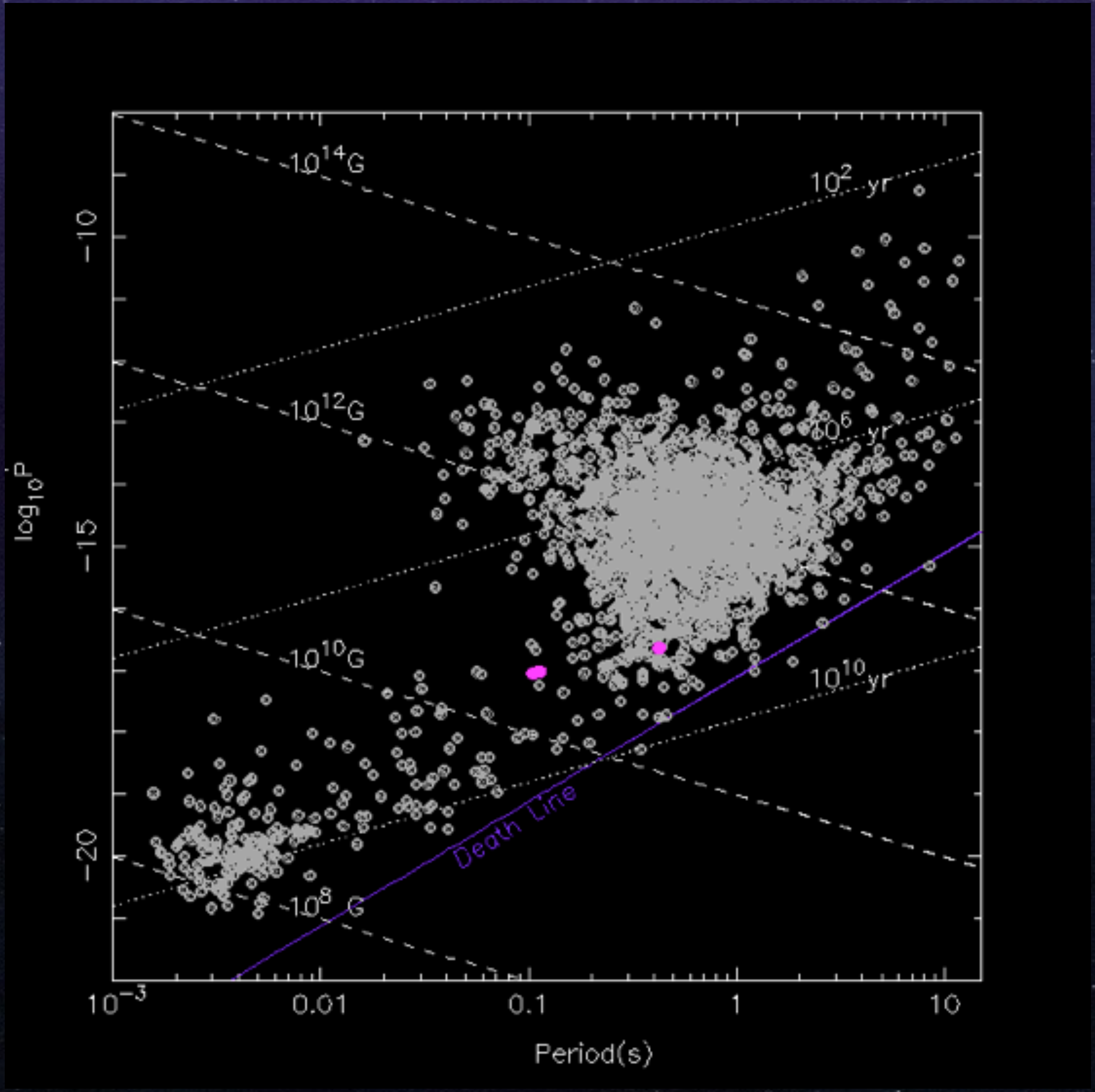


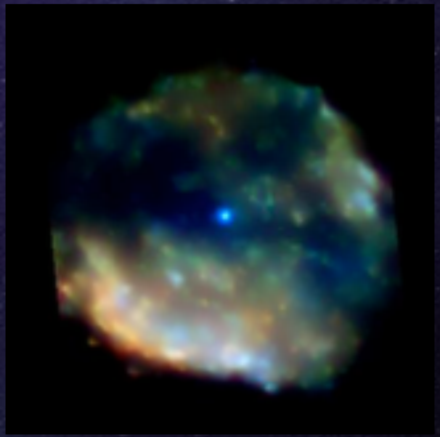
The neutron star Zoo



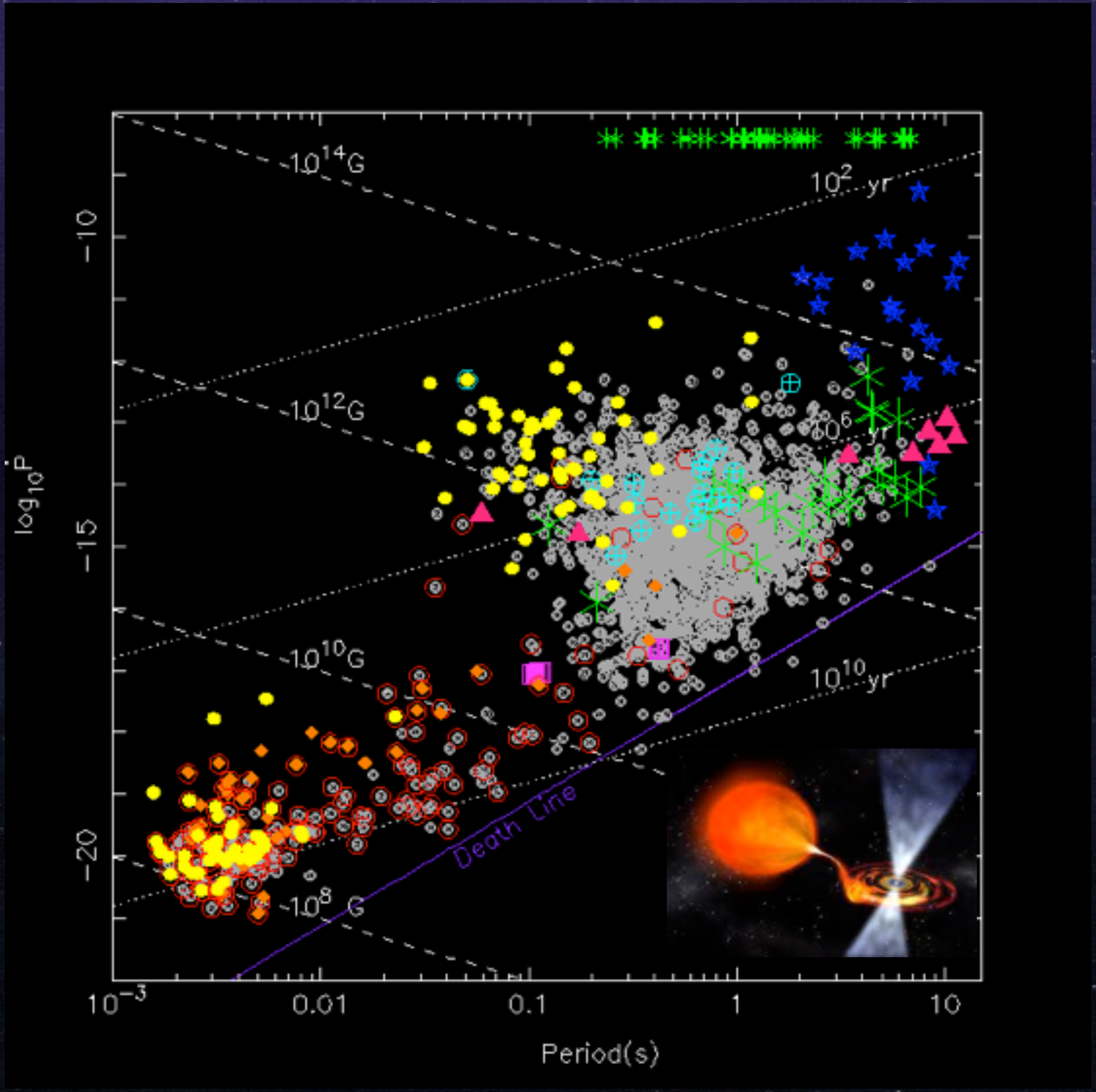


The neutron star Zoo

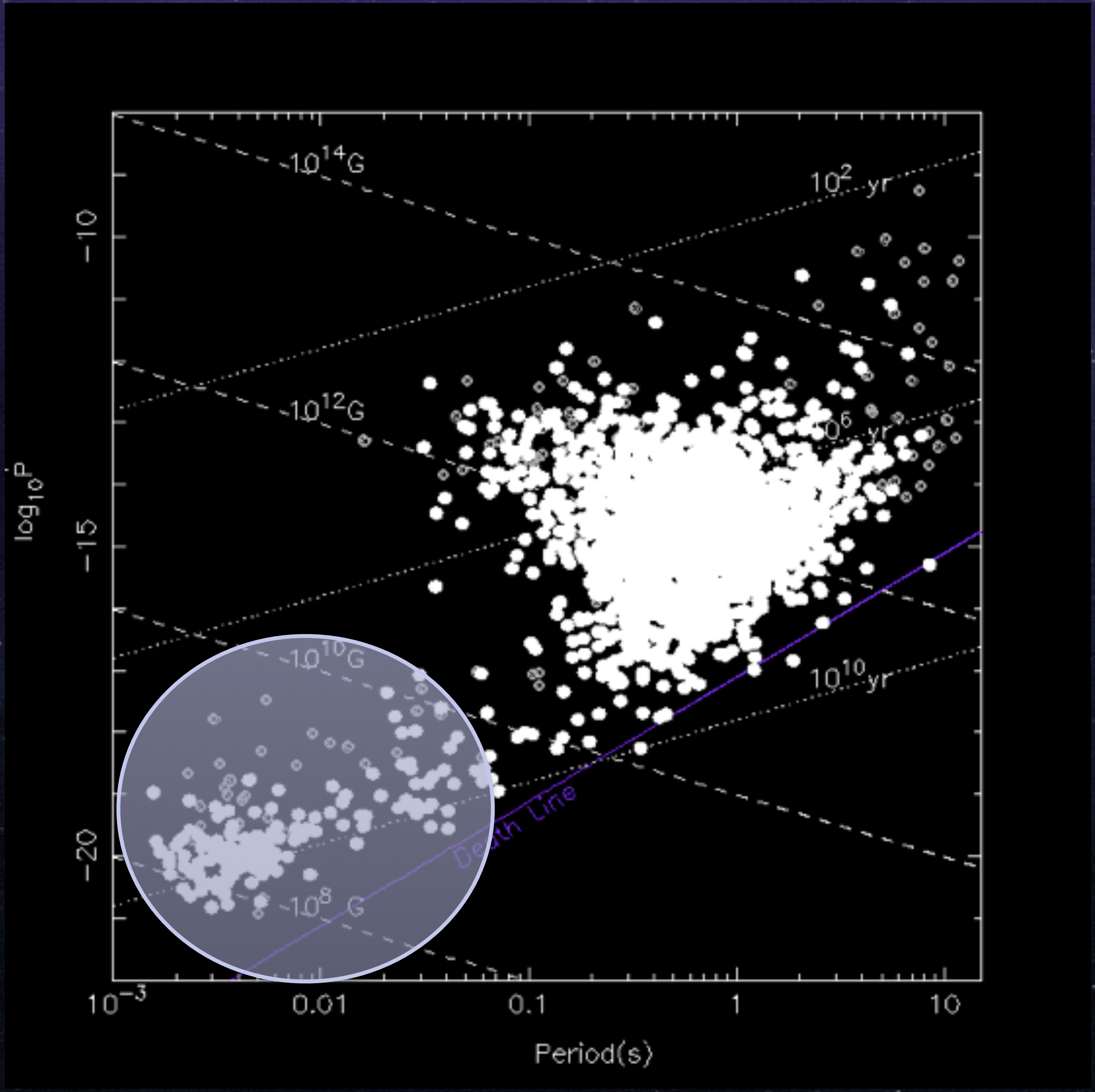


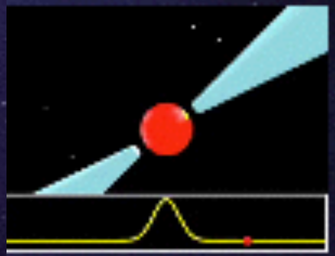


The neutron star Zoo

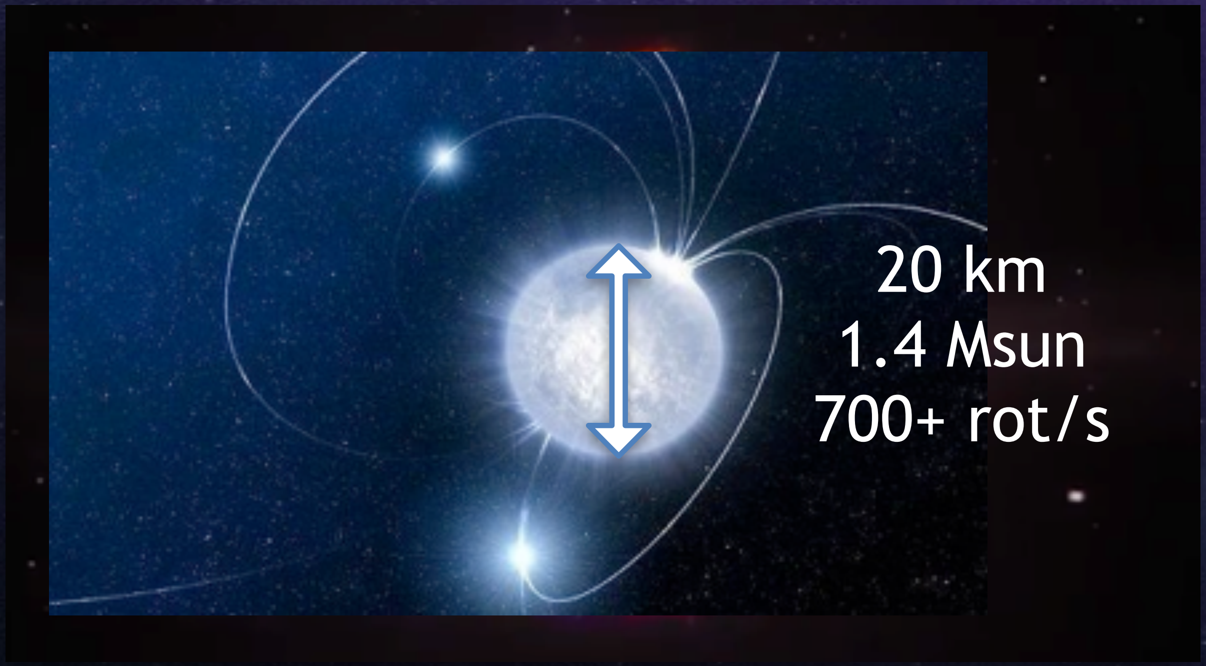


Radio Pulsars





Pulsars as Clocks



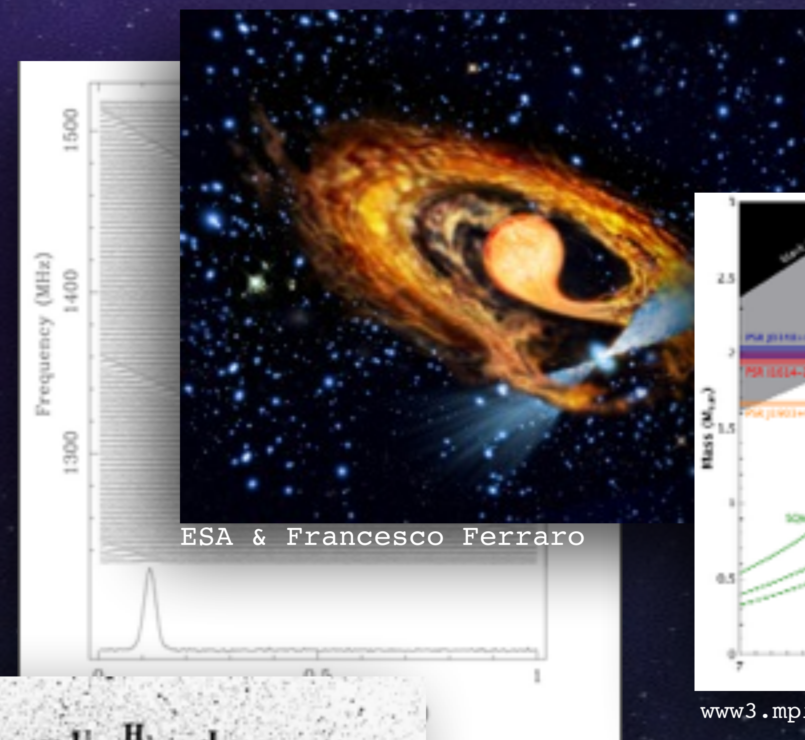
P = 0.00155780652149318686248 ± 0.00000000000000000000003 sec

WE CAN PREDICT THE TIME OF ARRIVAL OF PULSES WITHIN

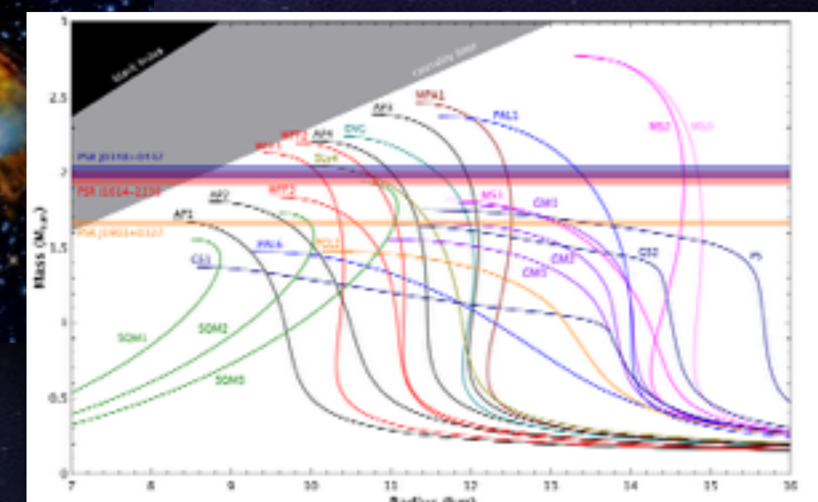
FEW ns OVER 1 YEAR !

PULSARS AS LABORATORIES

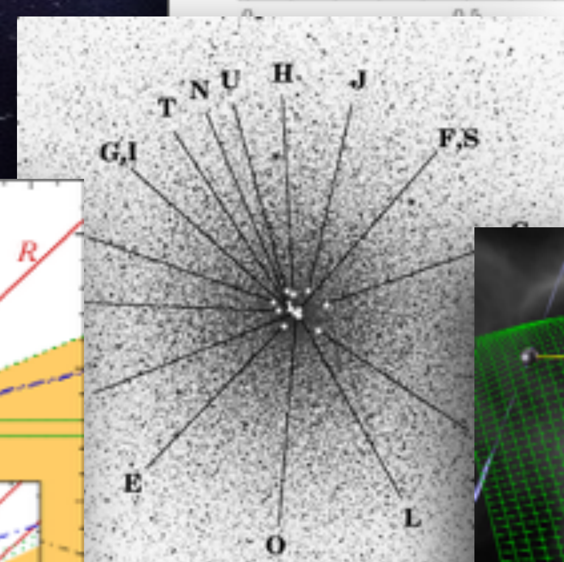
- ISM & GALACTIC B FIELD
- BINARY EVOLUTION
- EOS OF NUCLEAR MATTER
- GLOBULAR CLUSTER STUDIES
- GW DETECTION IN PTAS
- TESTS OF RELATIVISTIC GRAVITY
- …



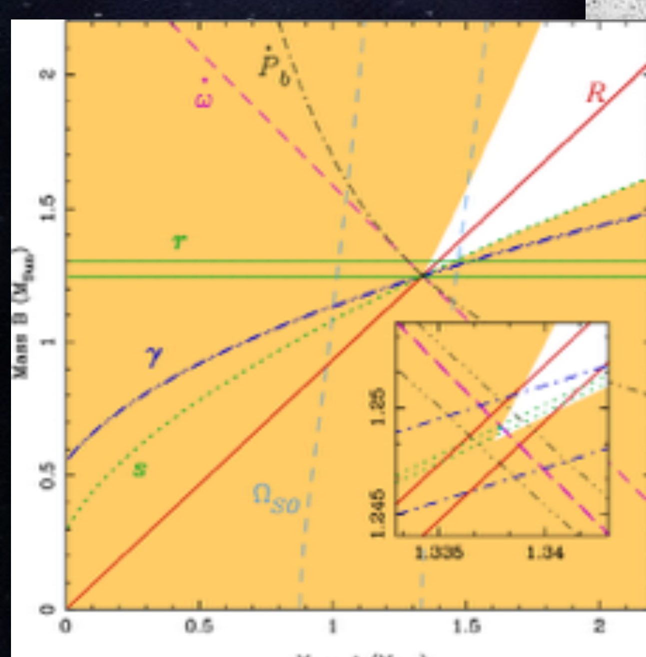
ESA & Francesco Ferraro



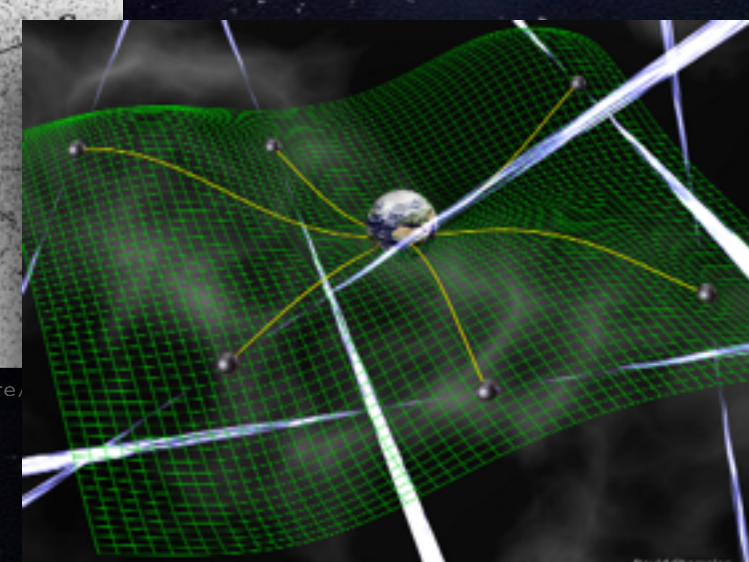
www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html



pifr-bonn.mpg.de/staff/pfreire/



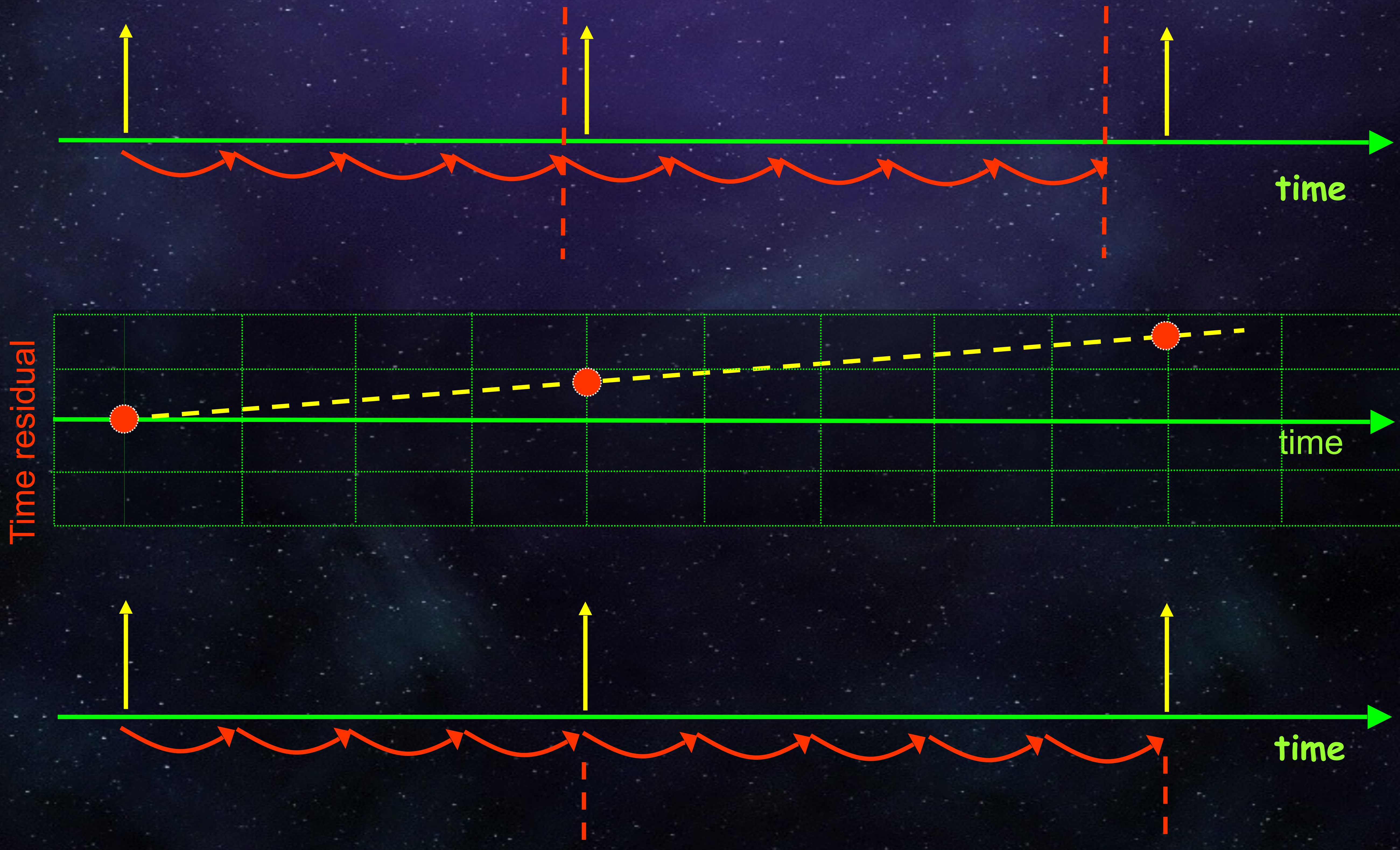
Kramer et al. in prep.


David Champion

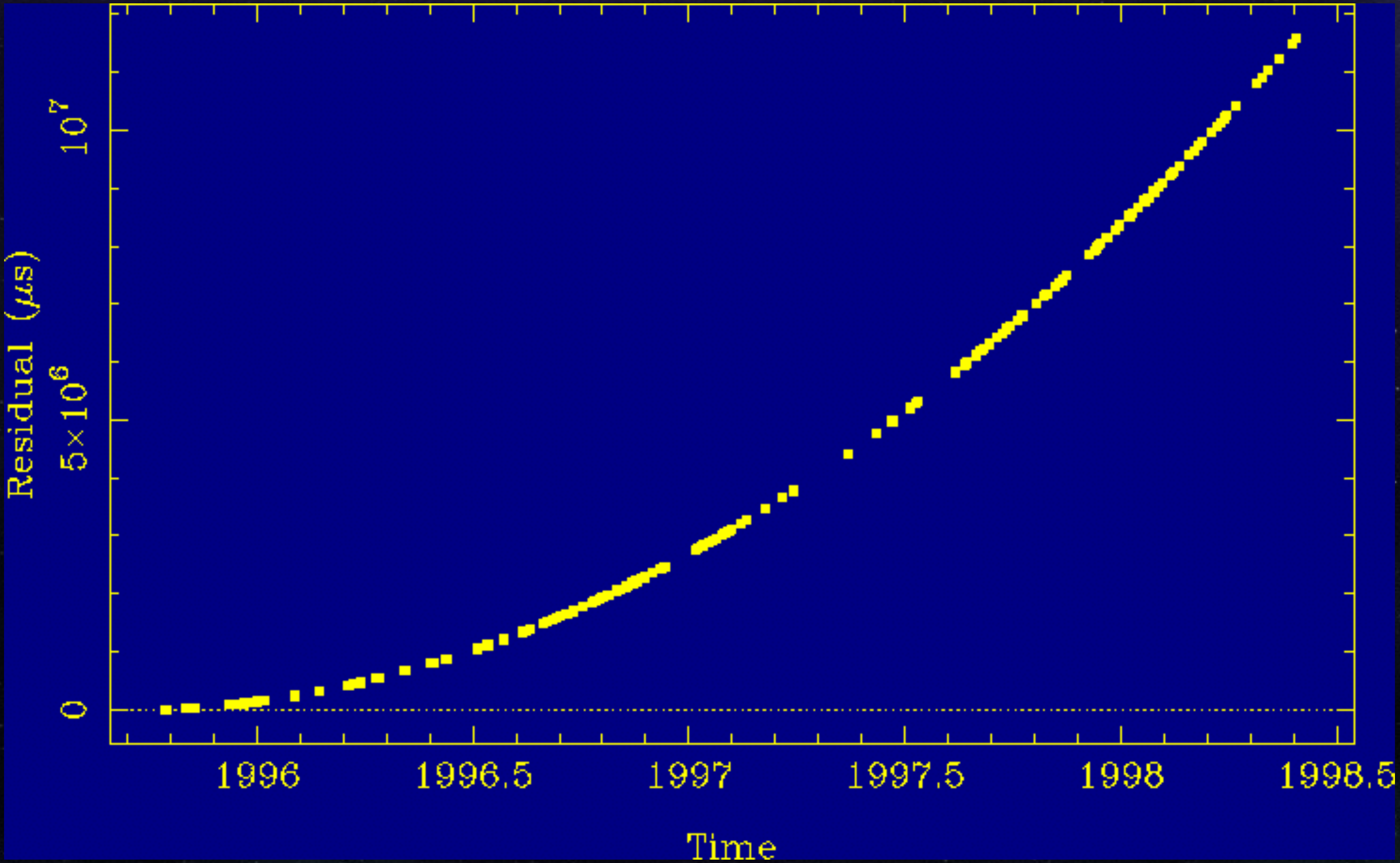
Pulsar Timing

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

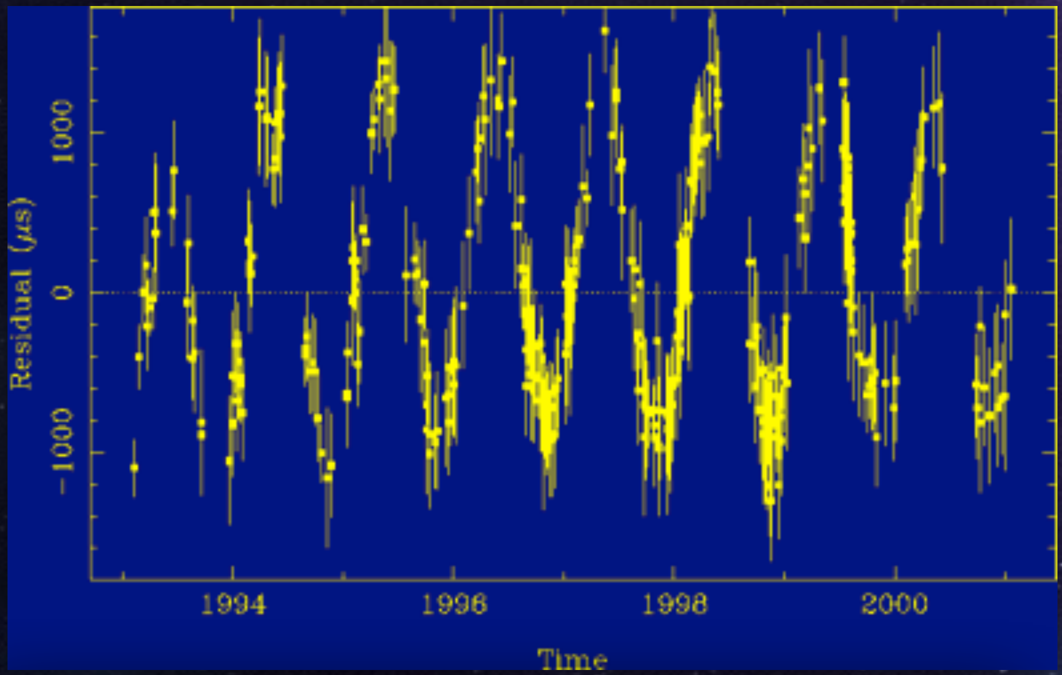
Pulsar Timing

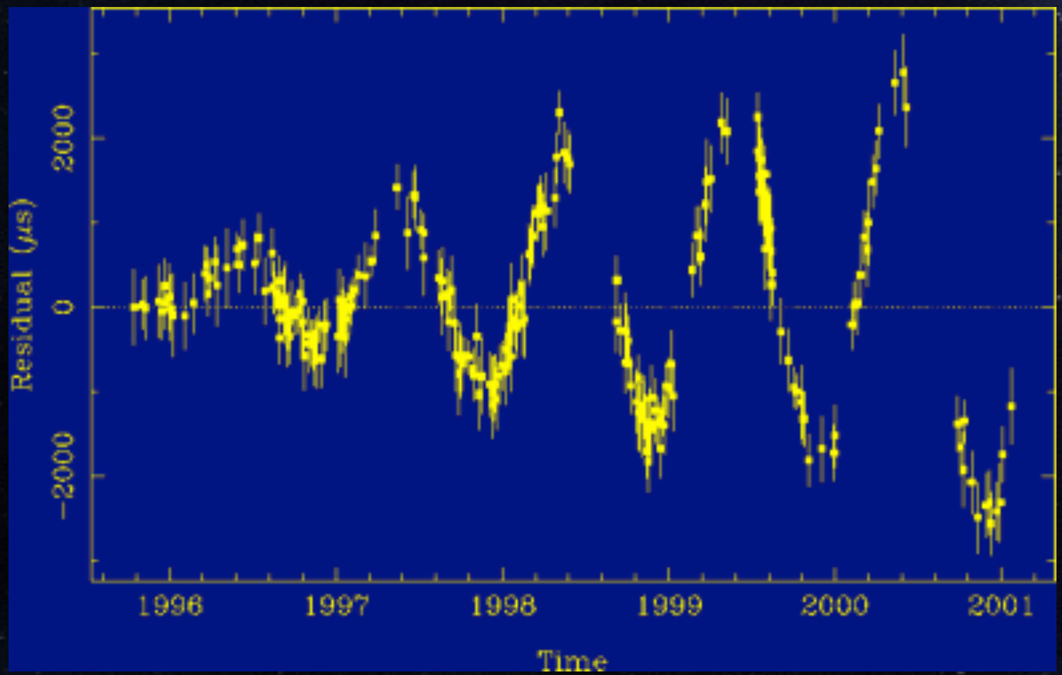


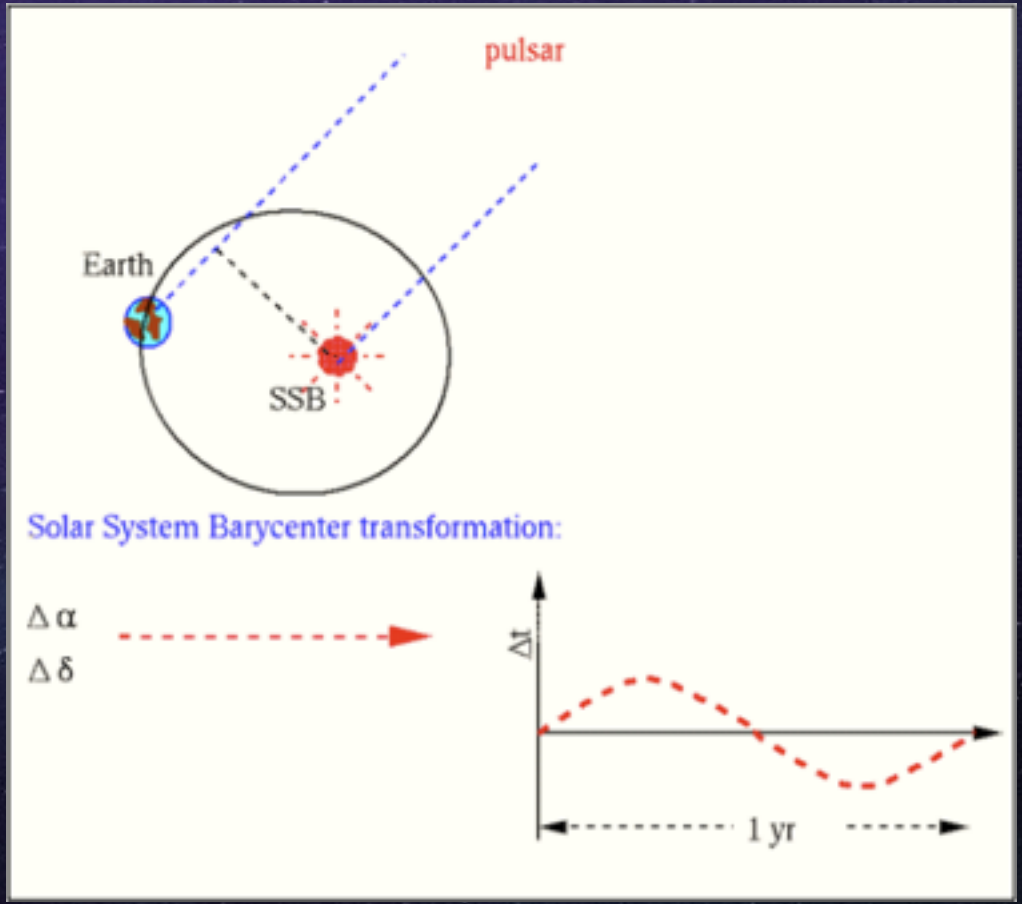
PULSAR TIMING



PULSAR TIMING







$$t_{\rm SSB} = t_{\rm obs} + t_{\rm clk} - D/f^2 + \Delta_R + \Delta_S + \Delta_E$$

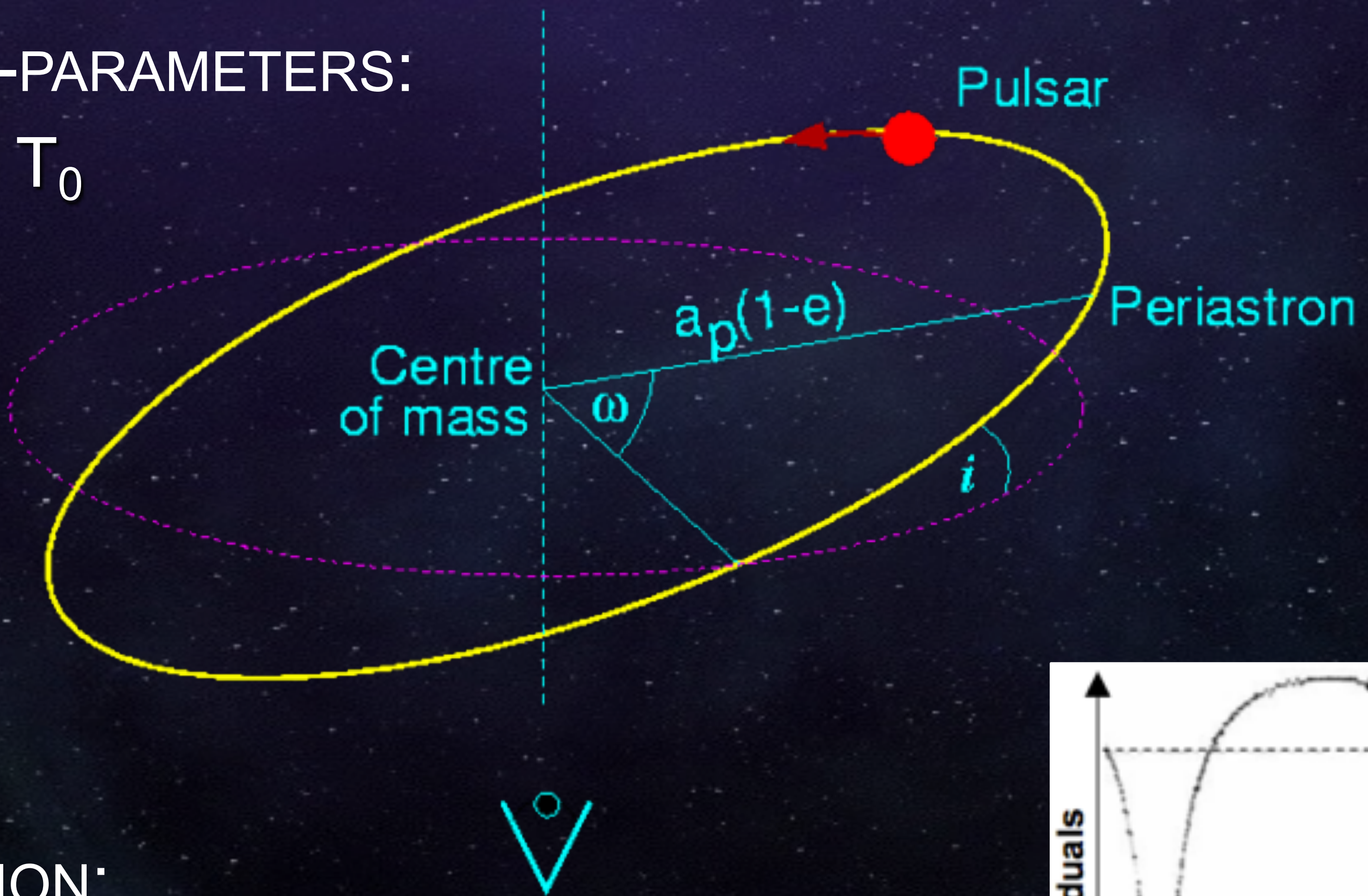
Pulsar Timing

The *pulsarcentric* ToAs (i.e. ToAs expressed in pulsar proper time) must be transformed to the Pulsar System Barycenter (PSB)

$$\boldsymbol{t_{PSR\text{-}BARY}} = \boldsymbol{T_{psr}} + \Delta_{\mathrm{R,b}} + \Delta_{\mathrm{E,b}} + \Delta_{\mathrm{S,b}} + \Delta_{\mathrm{A}}$$

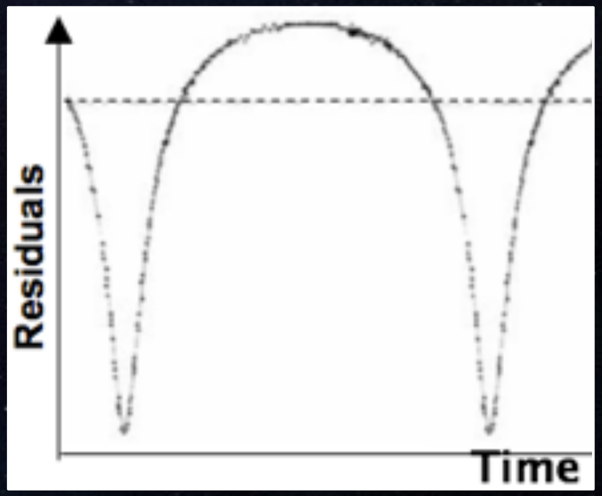
Pulsar Timing

- 5 Keplerian-parameters:
  P_{orb} a_p, e, ω, T_0

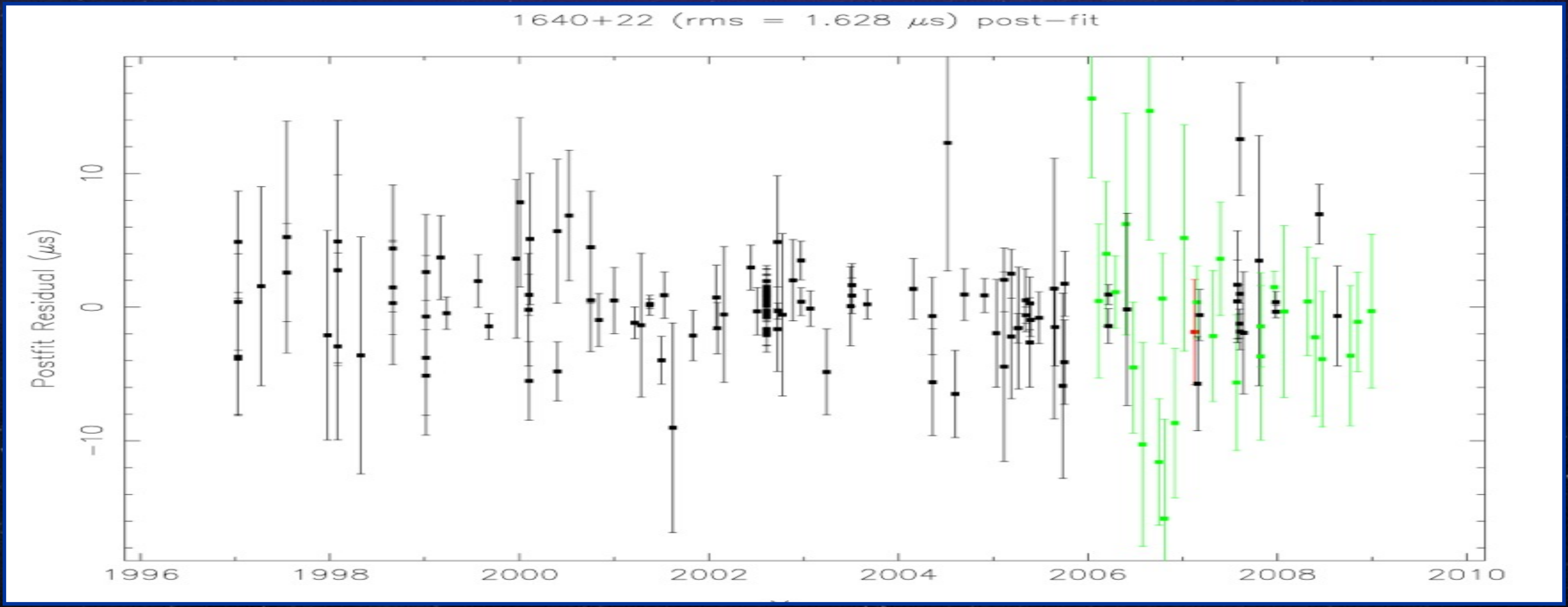


- Mass function:

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



Pulsar Timing



A good timing model gives randomly distributed timing residuals with a small rms

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.

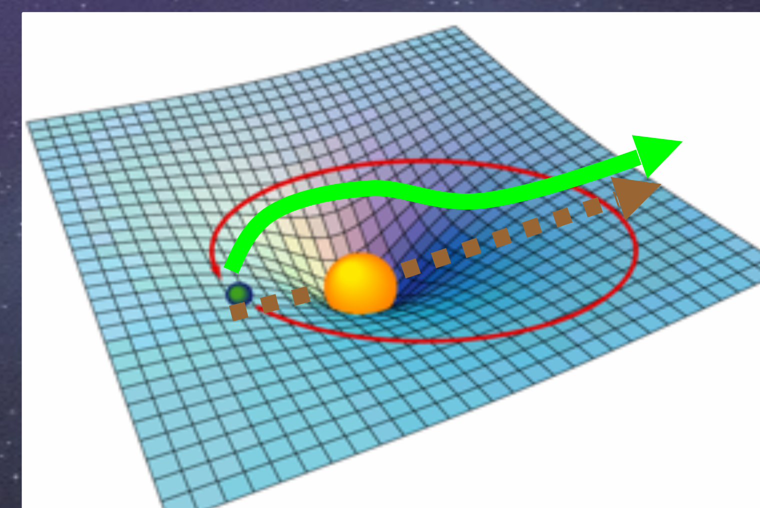
Additional physics is needed!

GOING BEYOND KEPLER...

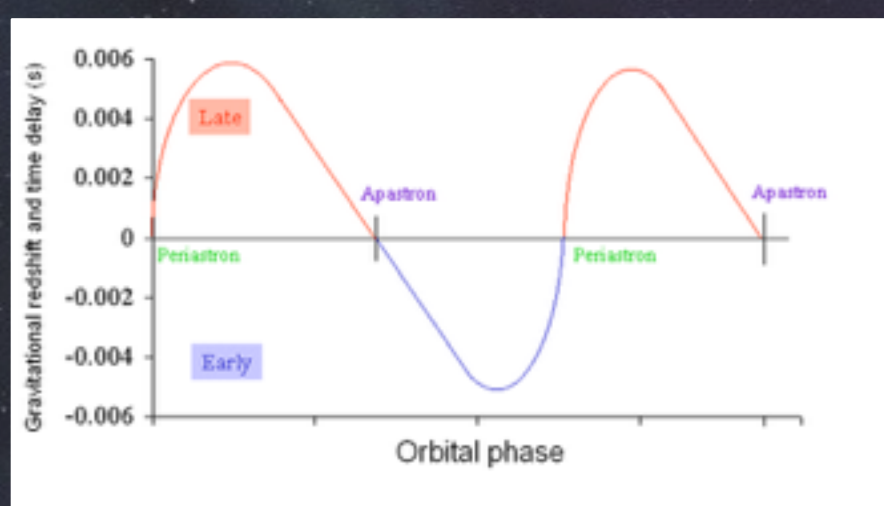
POST-KEPLERIAN (PK) FORMALISM [DAMOUR & DERUELLE 1986]

Periastron Precession - $\dot{\omega}$

Shapiro Delay r & s



Gr. redshift & time dilation - γ



Orbital decay $\dot{P}_b$

Testing Relativistic Gravity

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

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

$$r = T_\odot m_c,$$

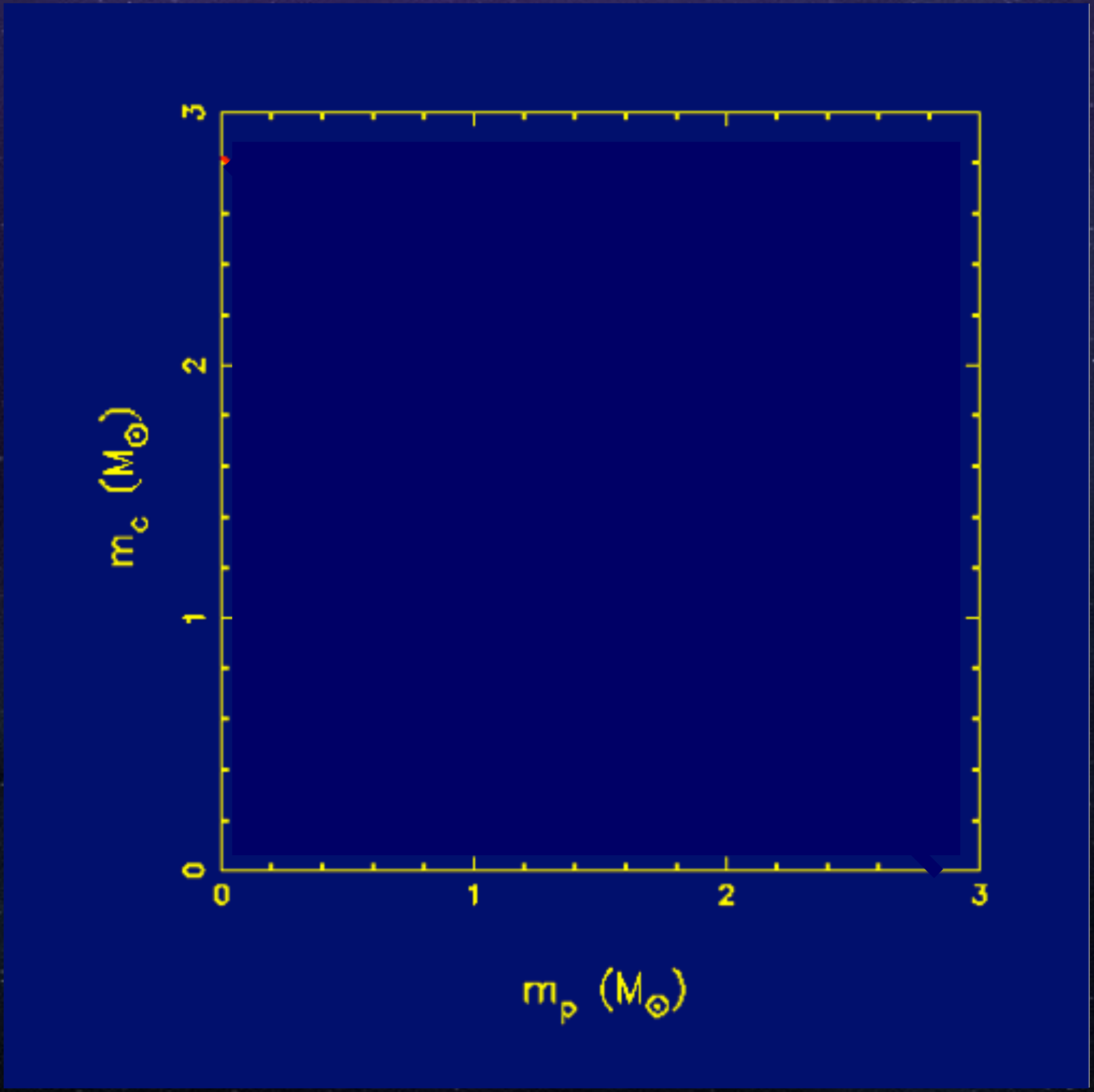
Shapiro delay (amplitude)

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

Shapiro delay (shape)

GR tests!

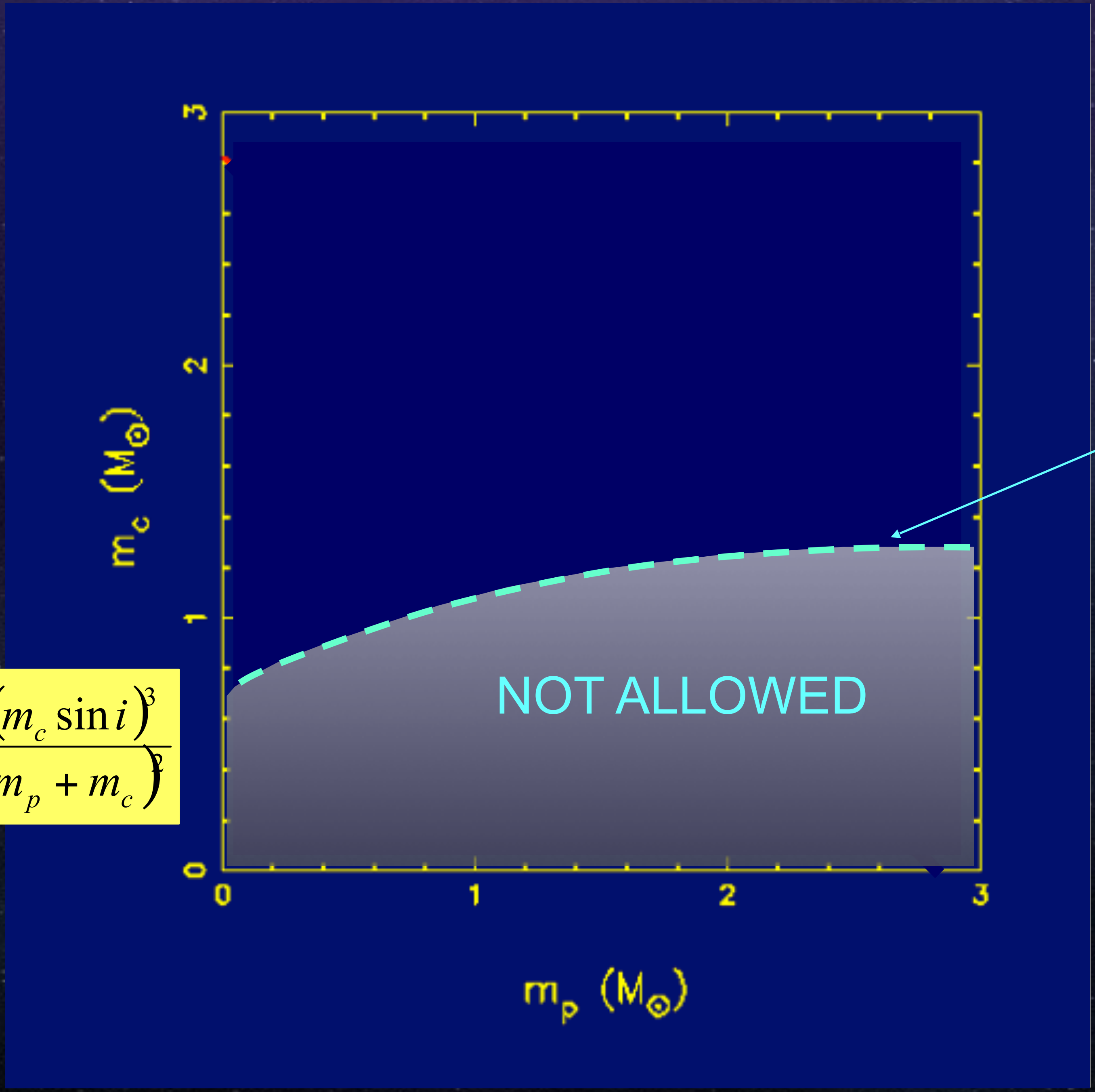
Testing Relativistic Gravity



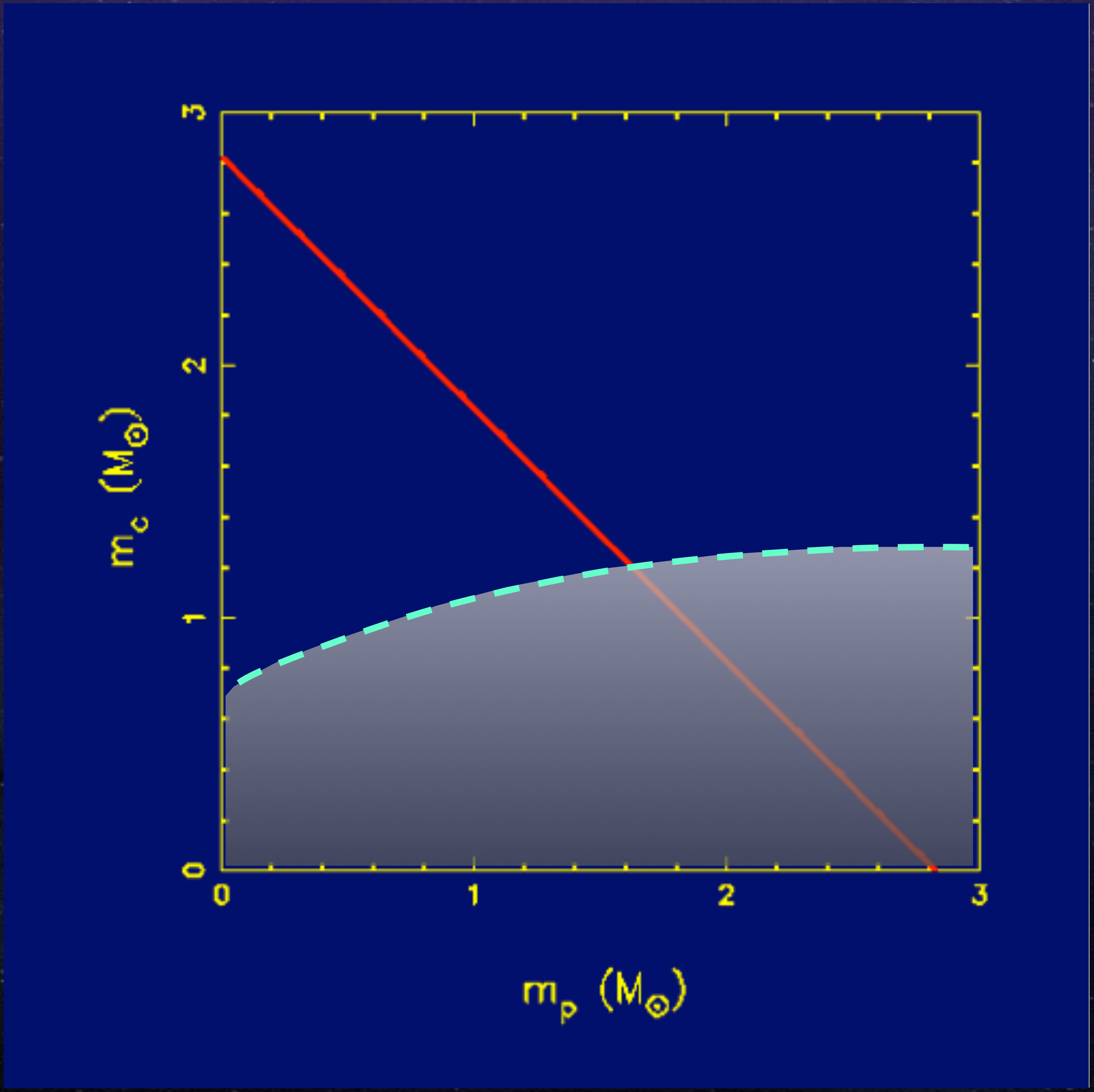
Testing Relativistic Gravity

Mass Function constraints

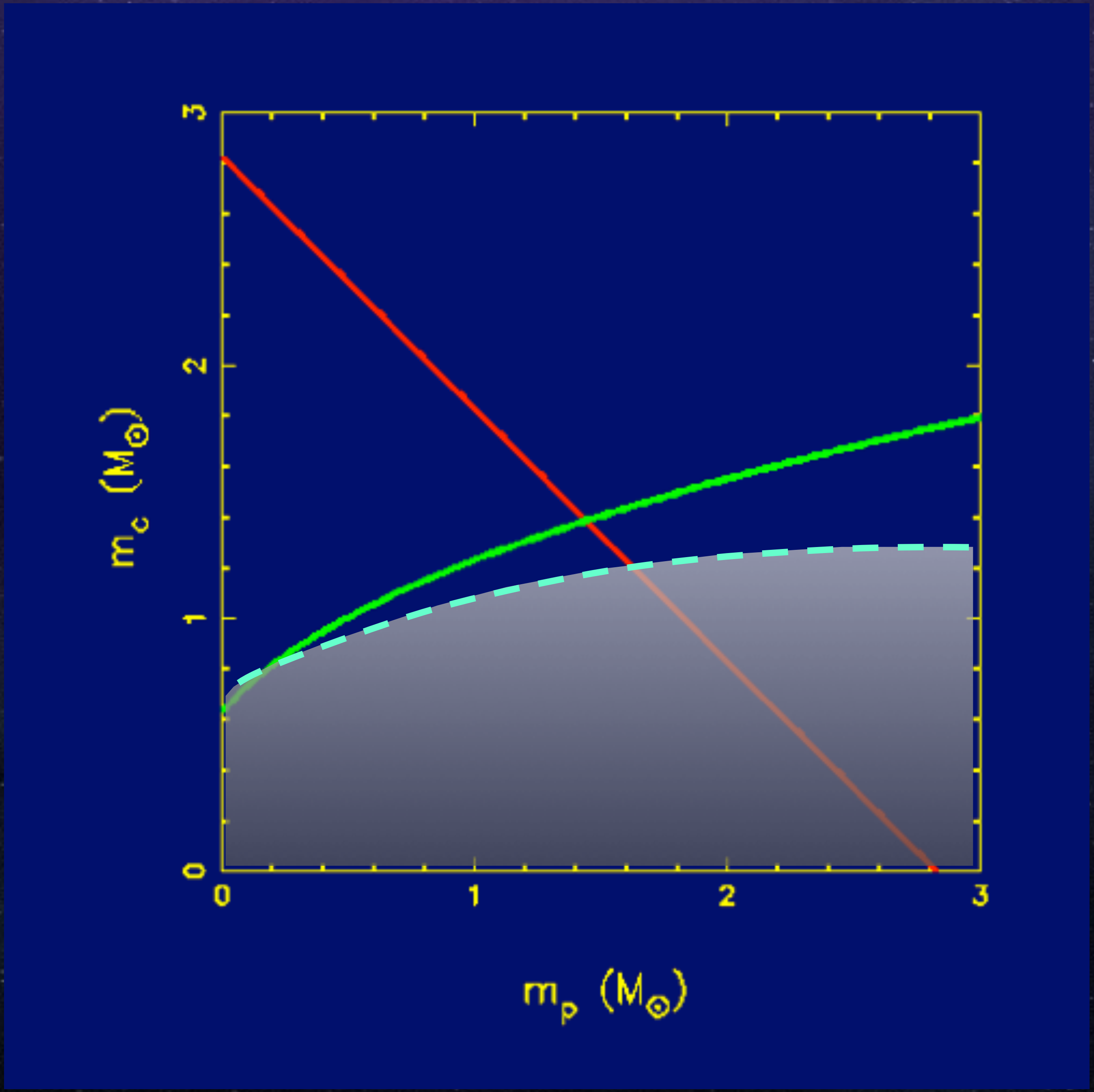
$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{(a_p \sin i)^3}{P_{orb}^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$



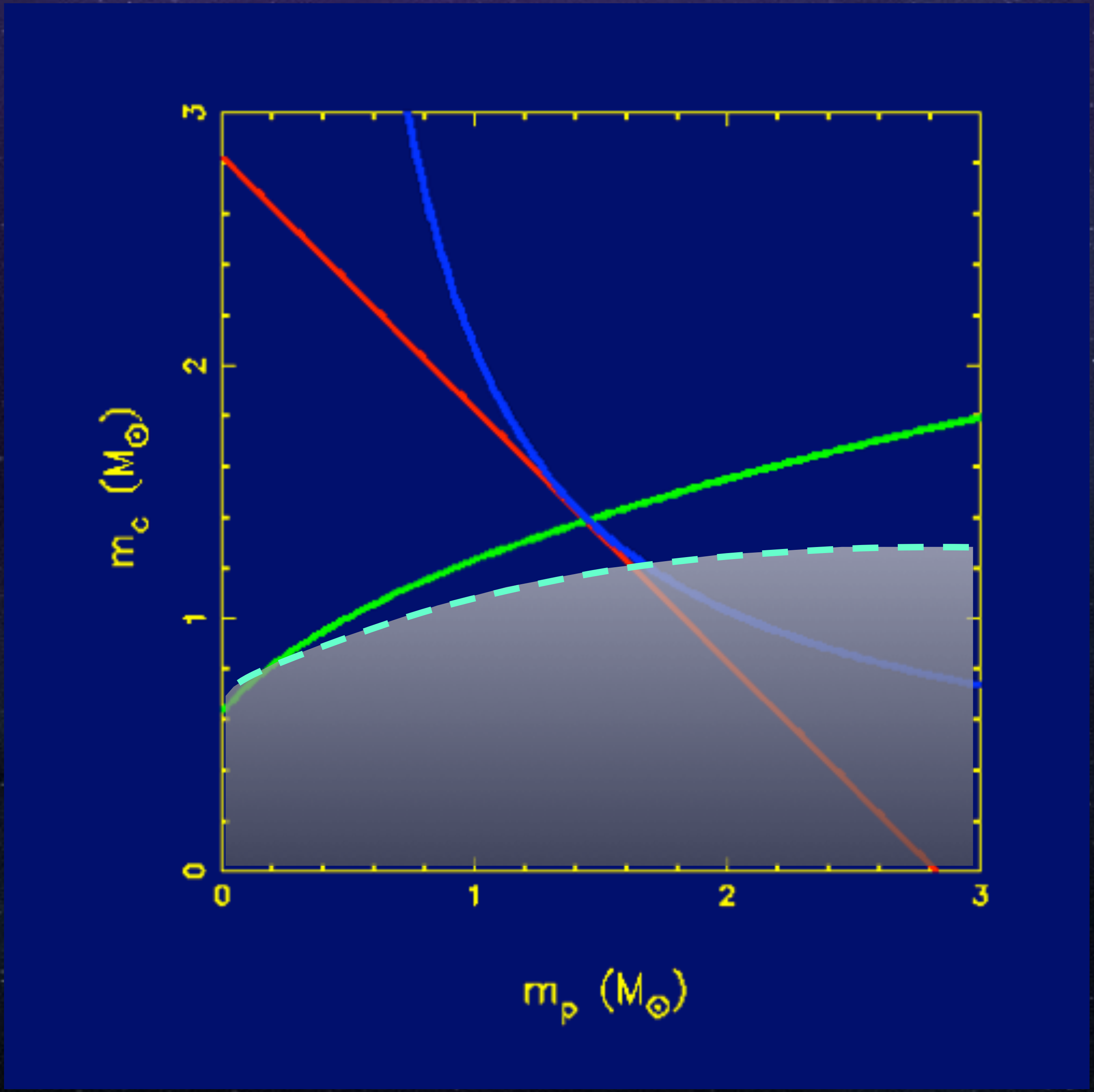
Testing Relativistic Gravity



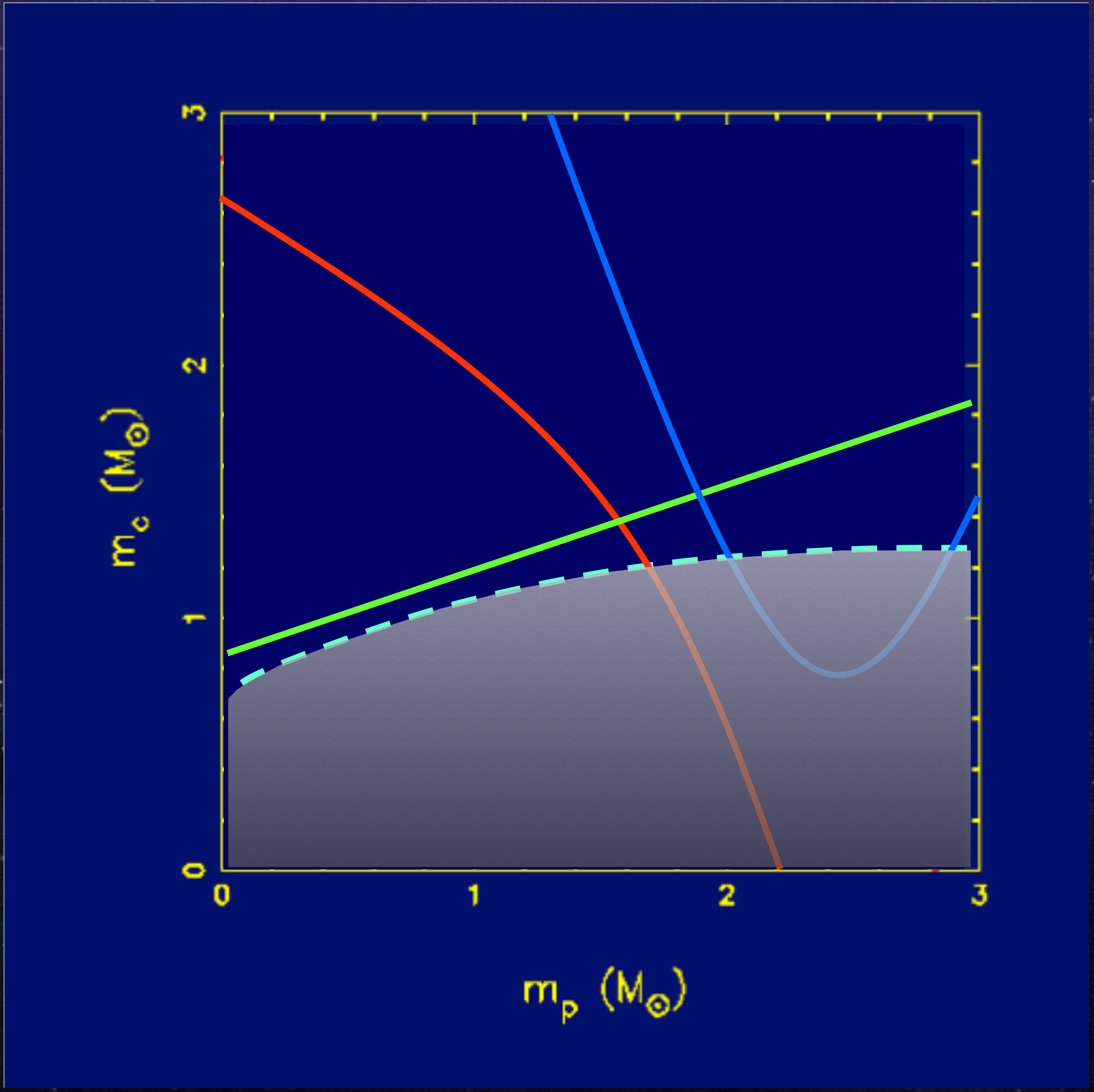
Testing Relativistic Gravity



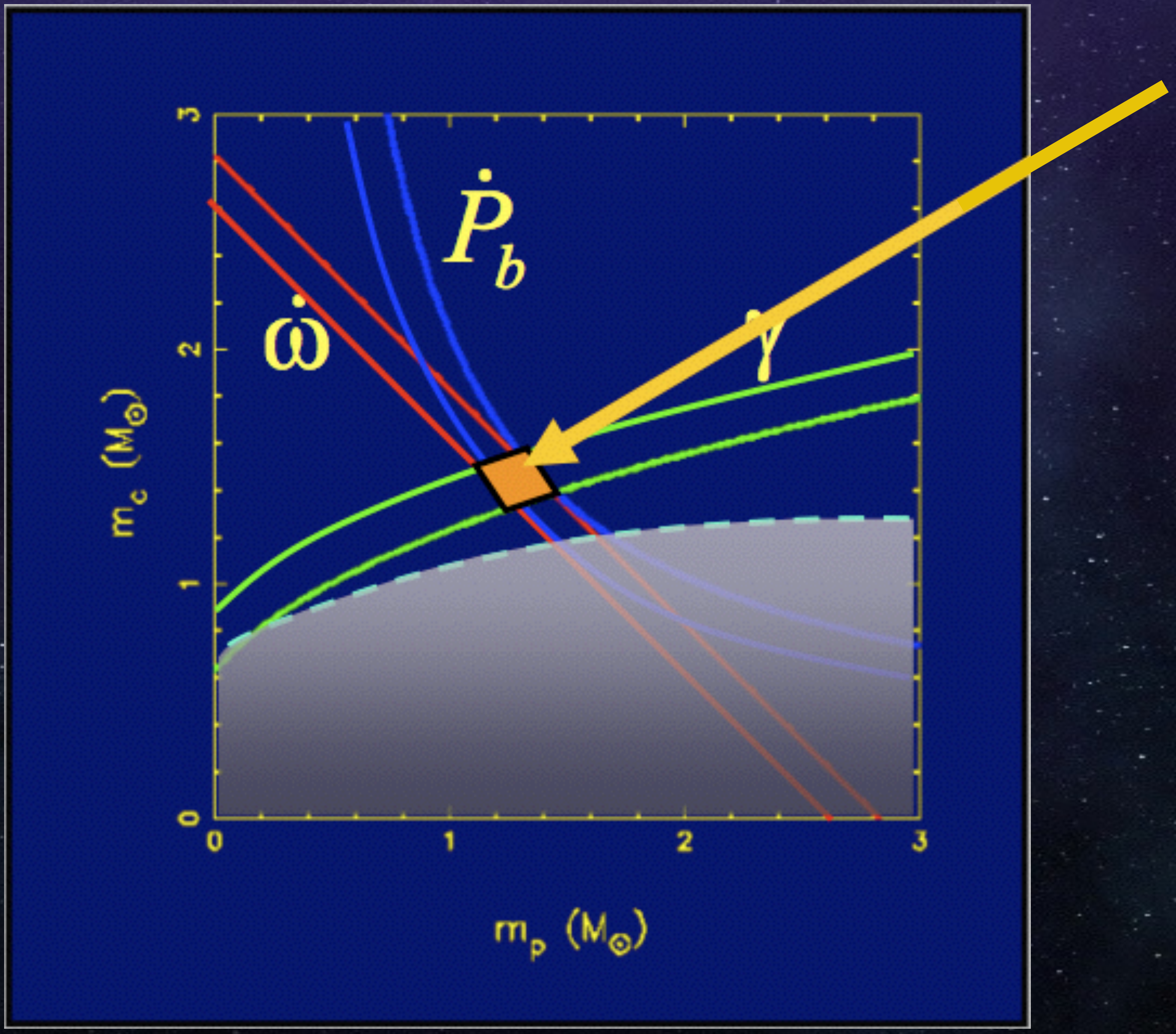
Testing Relativistic Gravity



Testing Relativistic Gravity



Testing Relativistic Gravity



Testing Relativistic Gravity

DNSs best test beds: 16+ in catalogue

PULSAR	Pspin [ms]	DM [pc/cm^3]	Porb [day]	ap sin(i) [lt-s]	Mc+Mp [Msun]	ecc	Age [10^8 yr]	TimeMerg [10^8 yr]
J0737-3039	22.70	48.91	0.10	1.42	1.34+1.25	0.09	2.1	0.85
J1518+4904	40.93	11.61	8.63	20.04	2.72	0.25	200	>Hubble
B1534+12	37.90	11.62	0.42	3.72	1.33+1.33	0.27	2.5	27.0
J1756-2251	28.45	121.60	0.32	2.75	2.57	0.18	tbd	11.0
J1811-1736	104.18	477.00	18.78	34.78	2.57	0.82	970	>Hubble
J1829+2456	41.00	13.90	1.18	7.24	>1.22 <1.38	0.14	tbd	>Hubble
B1913+16	59.03	168.77	0.32	2.34	1.387+1.441	0.62	1.1	3.0
J1906+0746	144.10	217.78	0.17	1.42	1.25+1.37	0.08	0.001	3.0
B2127+11C	30.53	67.13	0.34	2.52	1.36+1.34	0.68	1.0	2.2

Testing Relativistic Gravity

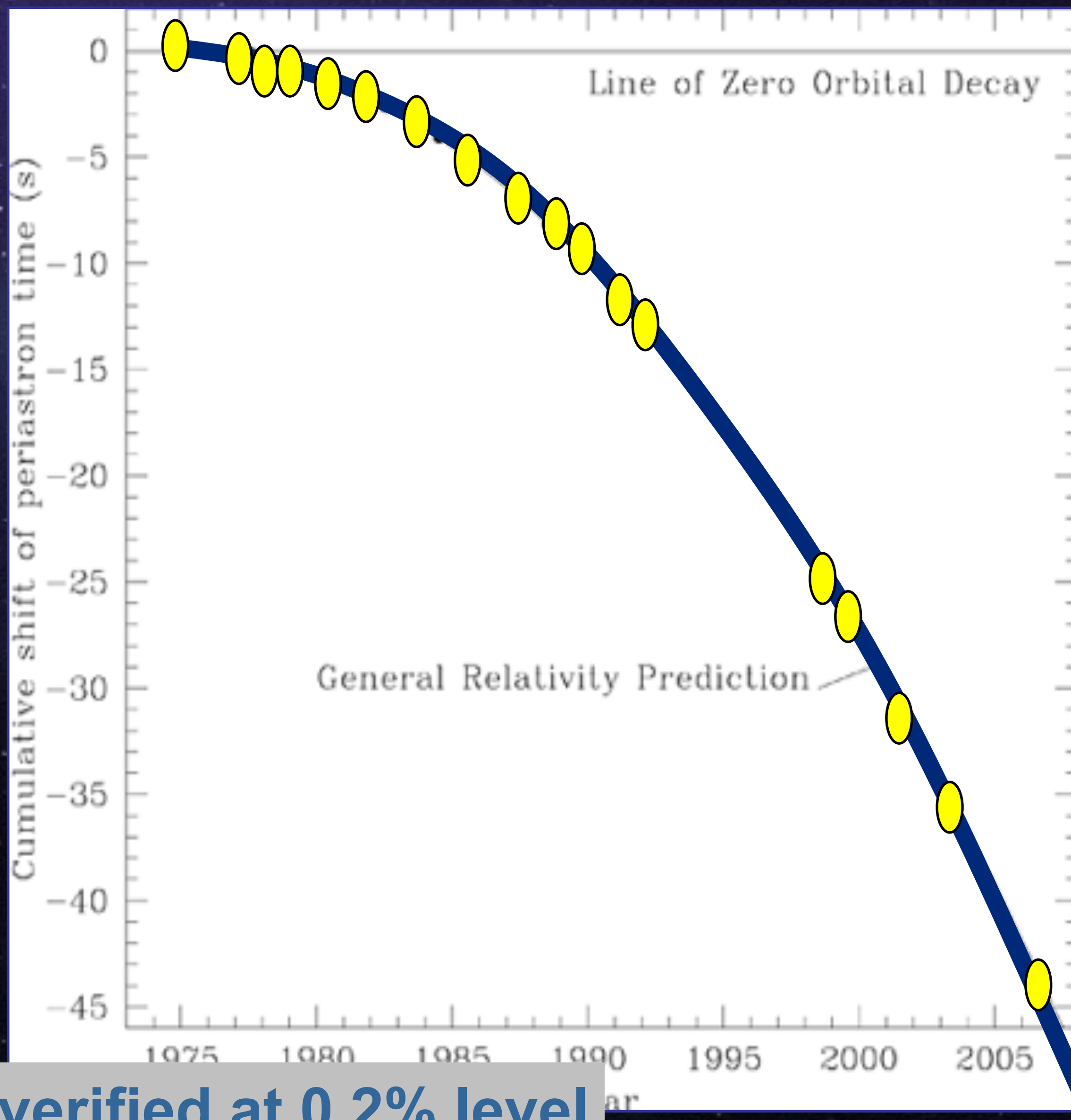
PSR B1913+16

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, $\dot{P}_B$

NOBEL PRIZE 1993 Taylor & Hulse



GR verified at 0.2% level

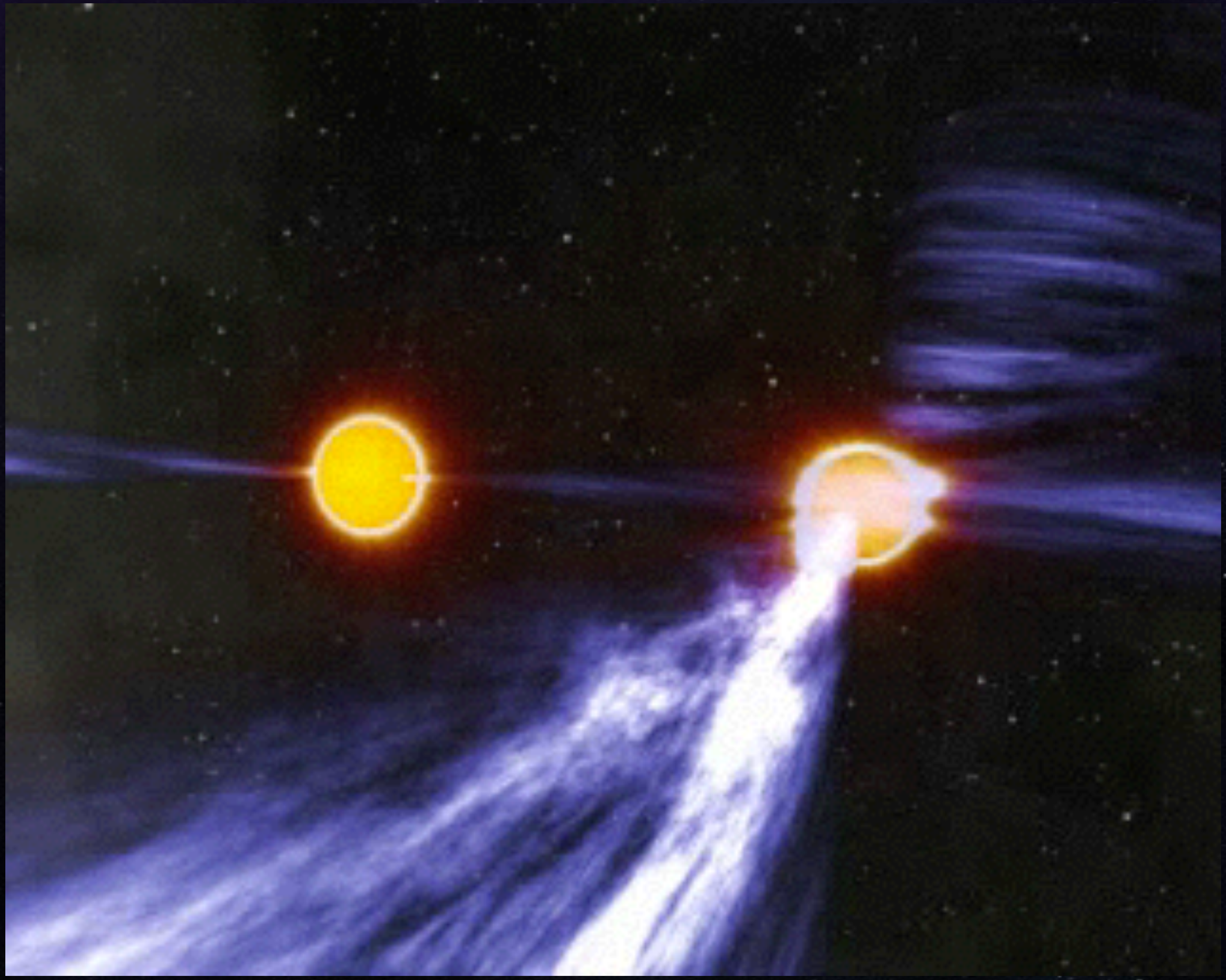
[Weisberg et al. 2010]

Testing Relativistic Gravity

PSR J0737-3039A/B

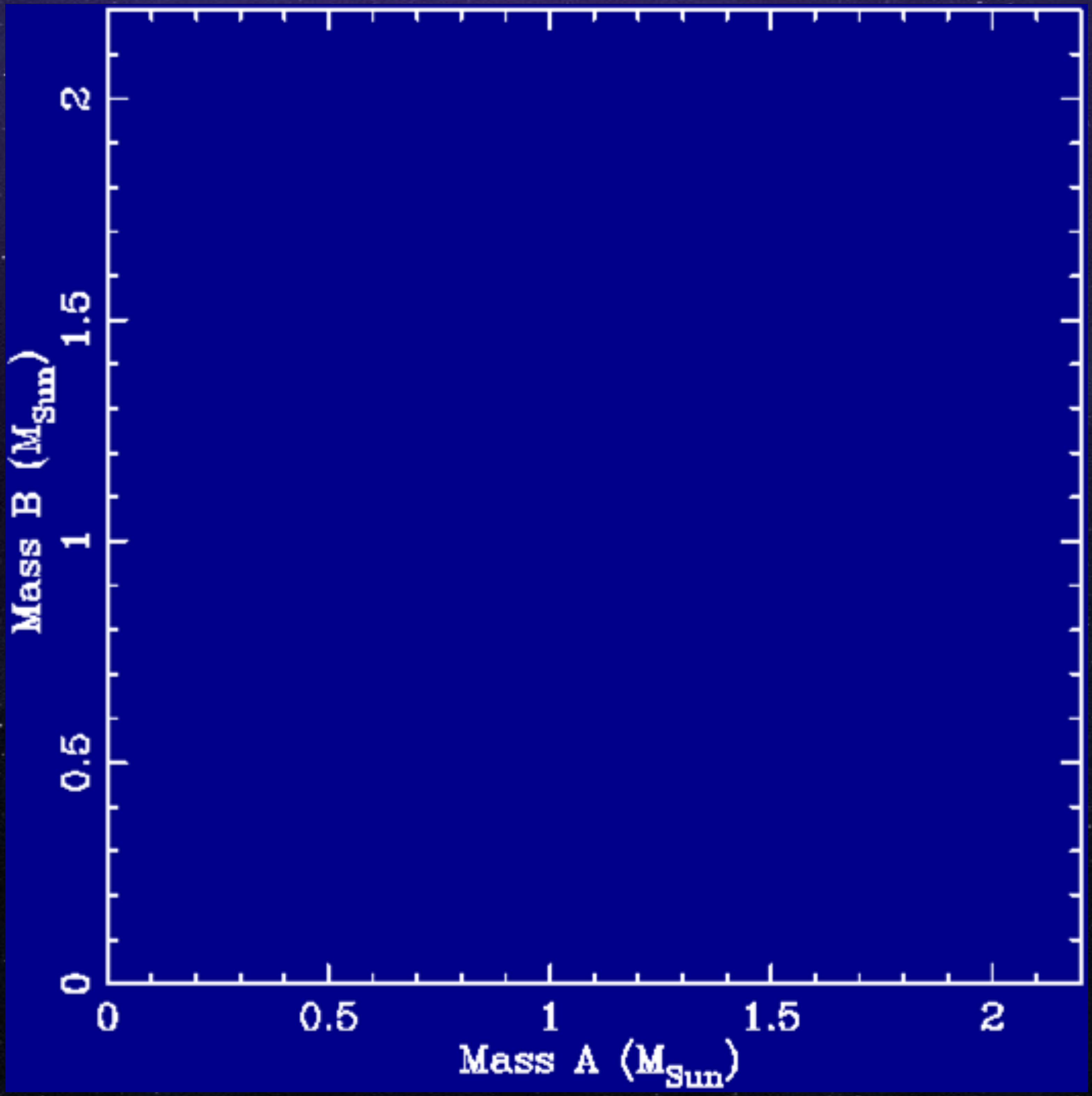
Discovered in 2003-2004 [Burgay et al '03; Lyne et al. '04]

- PSR+PSR!
- P_{SPIN} = 23 ms + 2.7 s
- P_{ORB} = 2.4 hr
- Ecc = 0.09
- i = 89.29º
- Orb vel = 0.02 c !!!

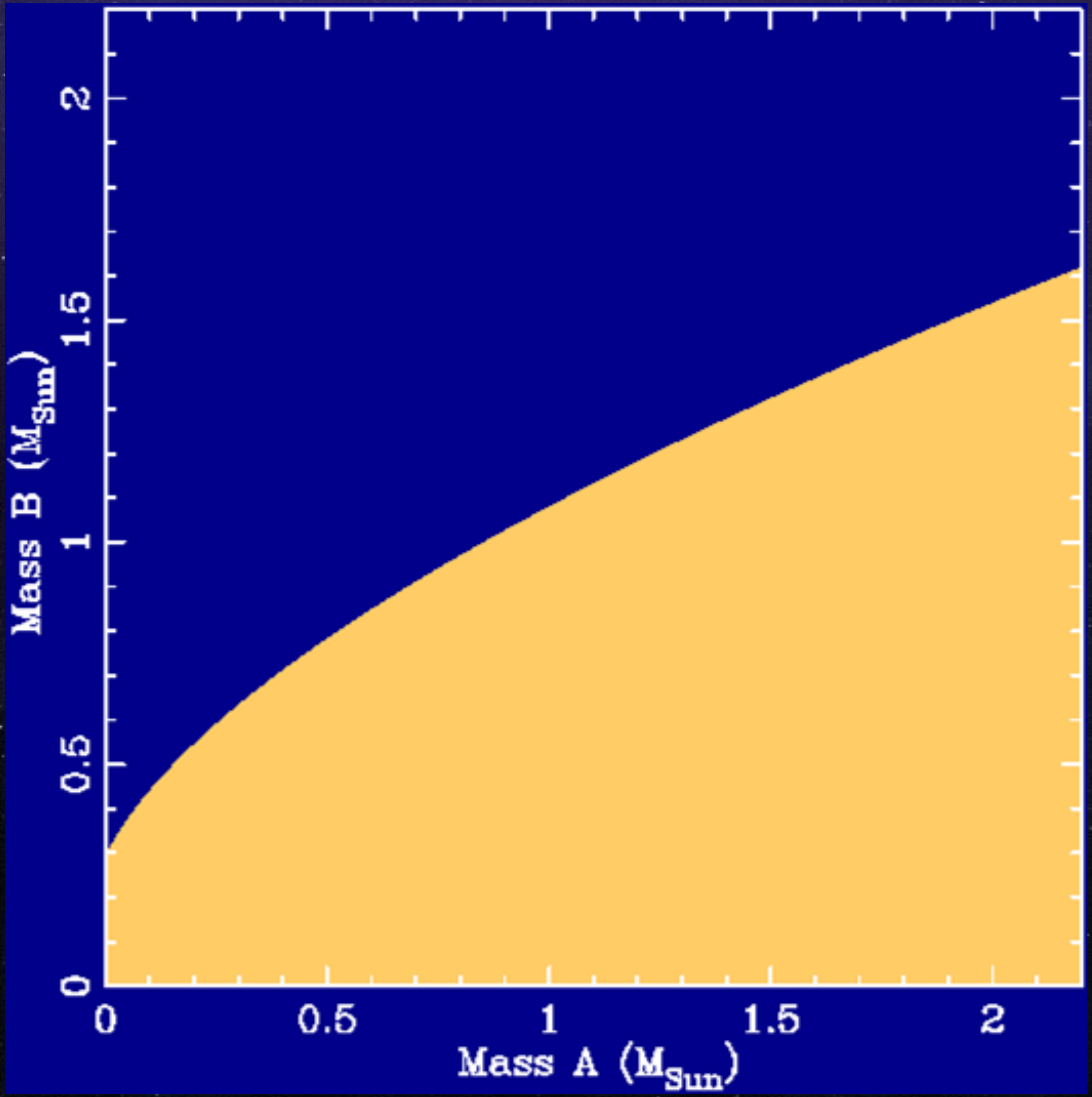


@ John Rowe Animation

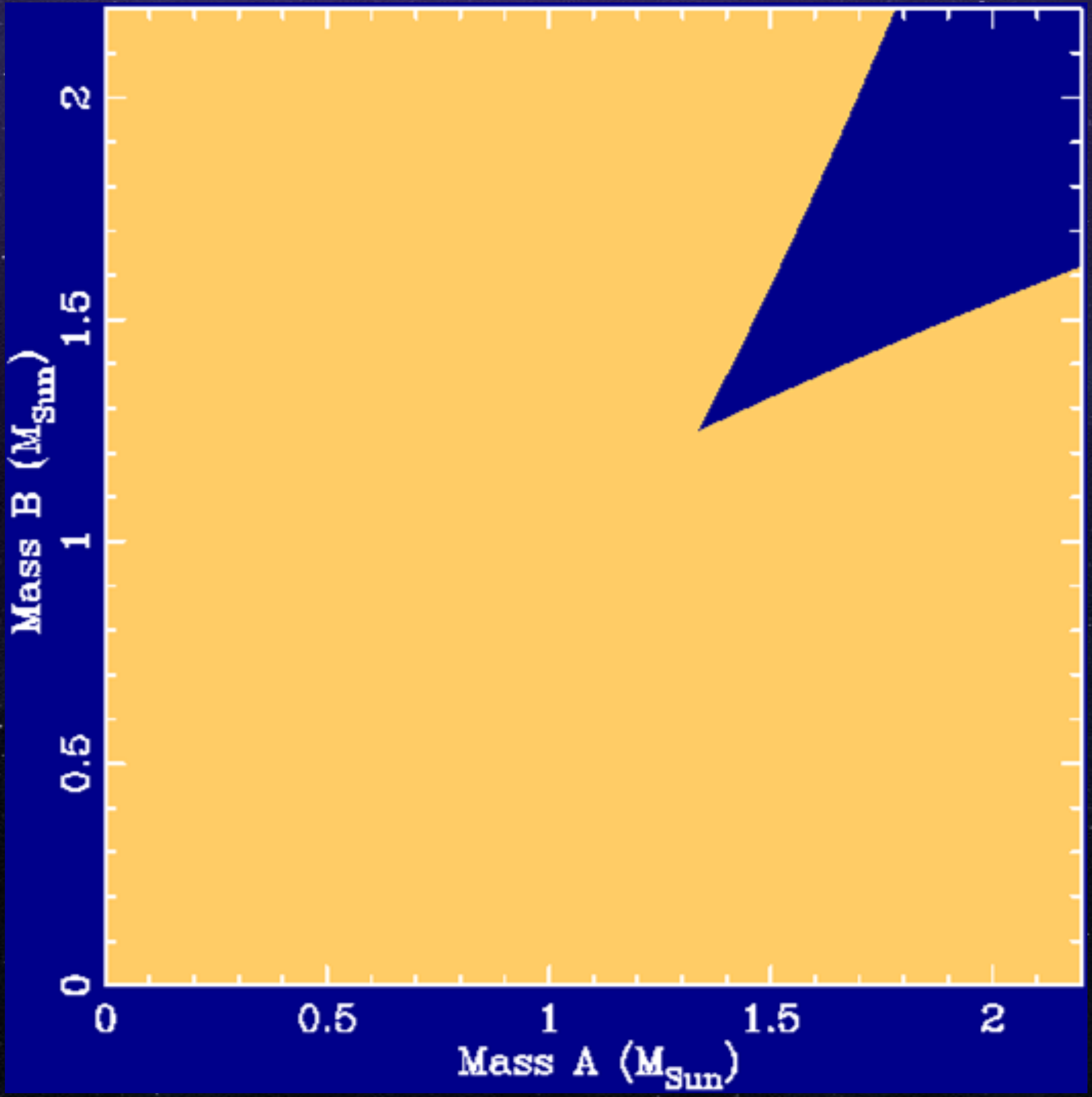
GR WITH THE DOUBLE PULSAR



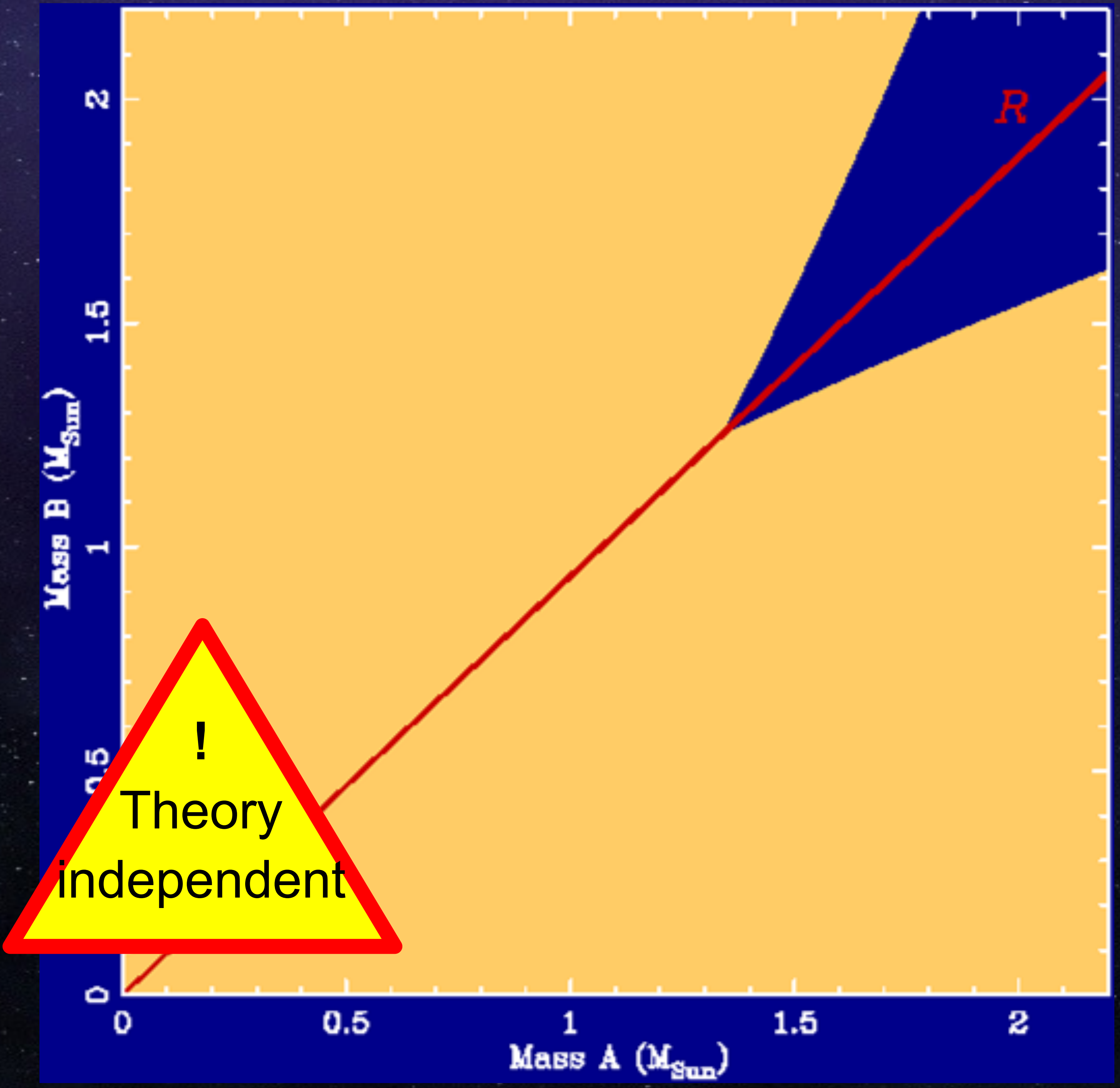
GR WITH THE DOUBLE PULSAR



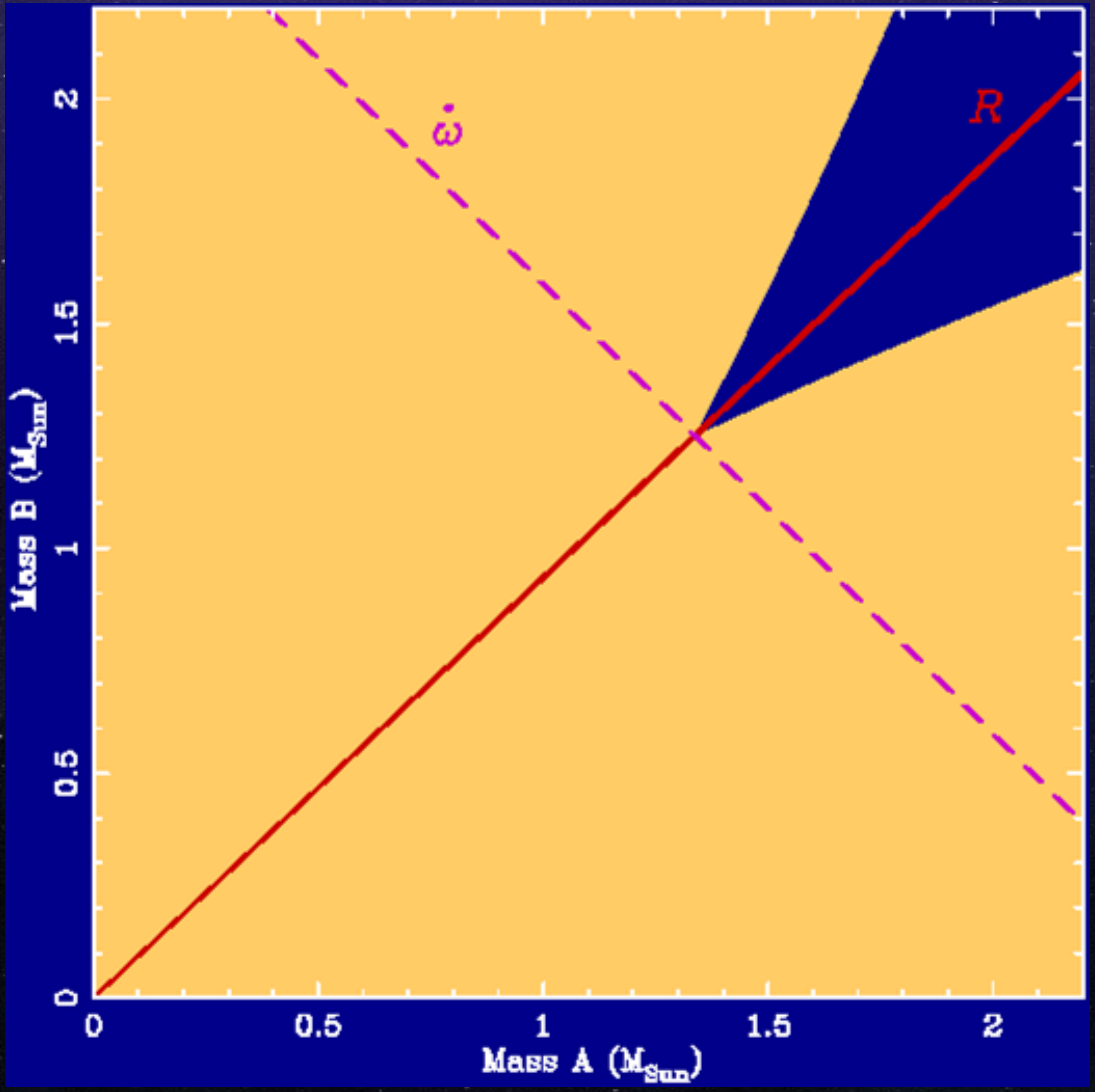
GR WITH THE DOUBLE PULSAR



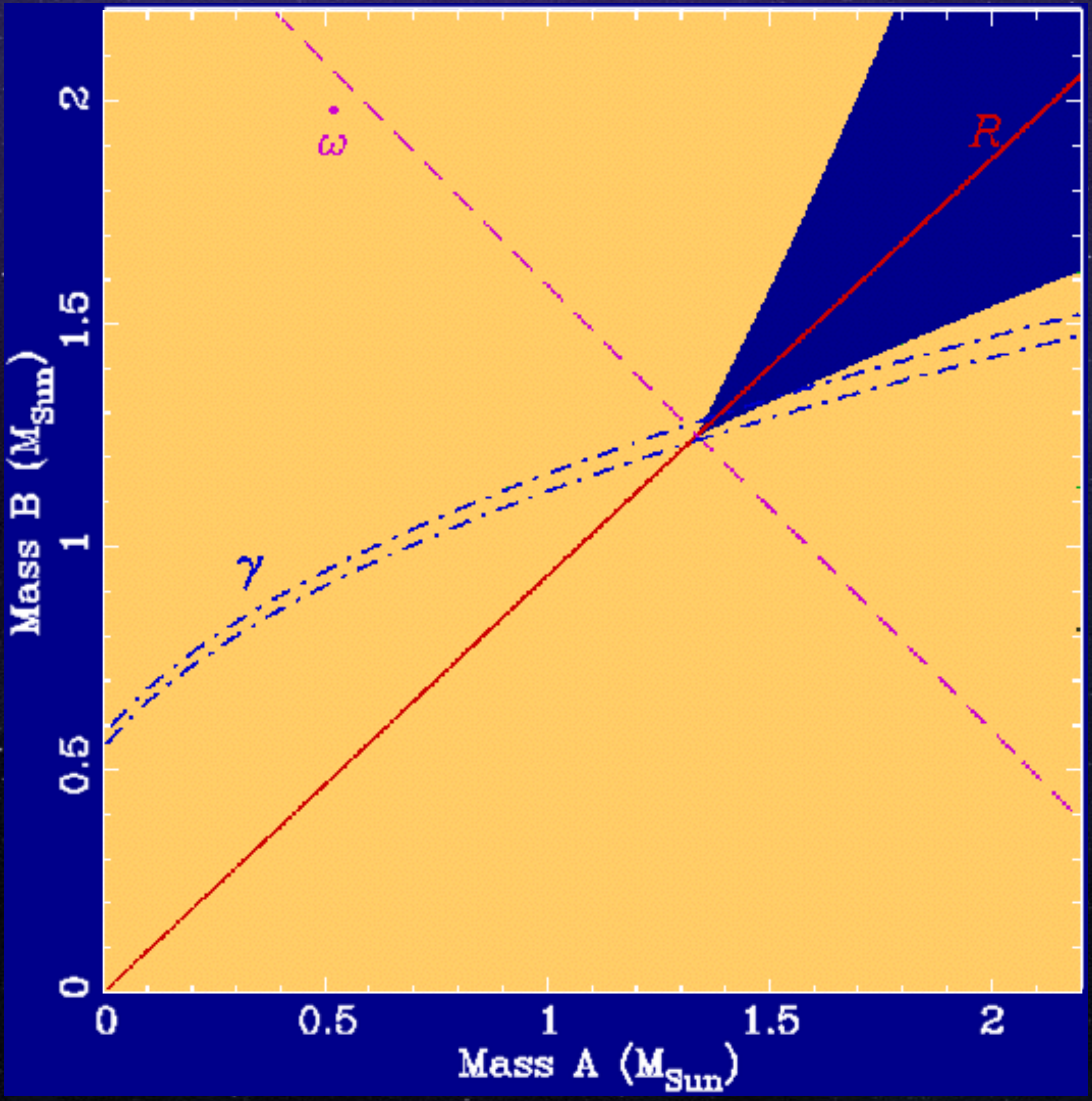
GR WITH THE DOUBLE PULSAR



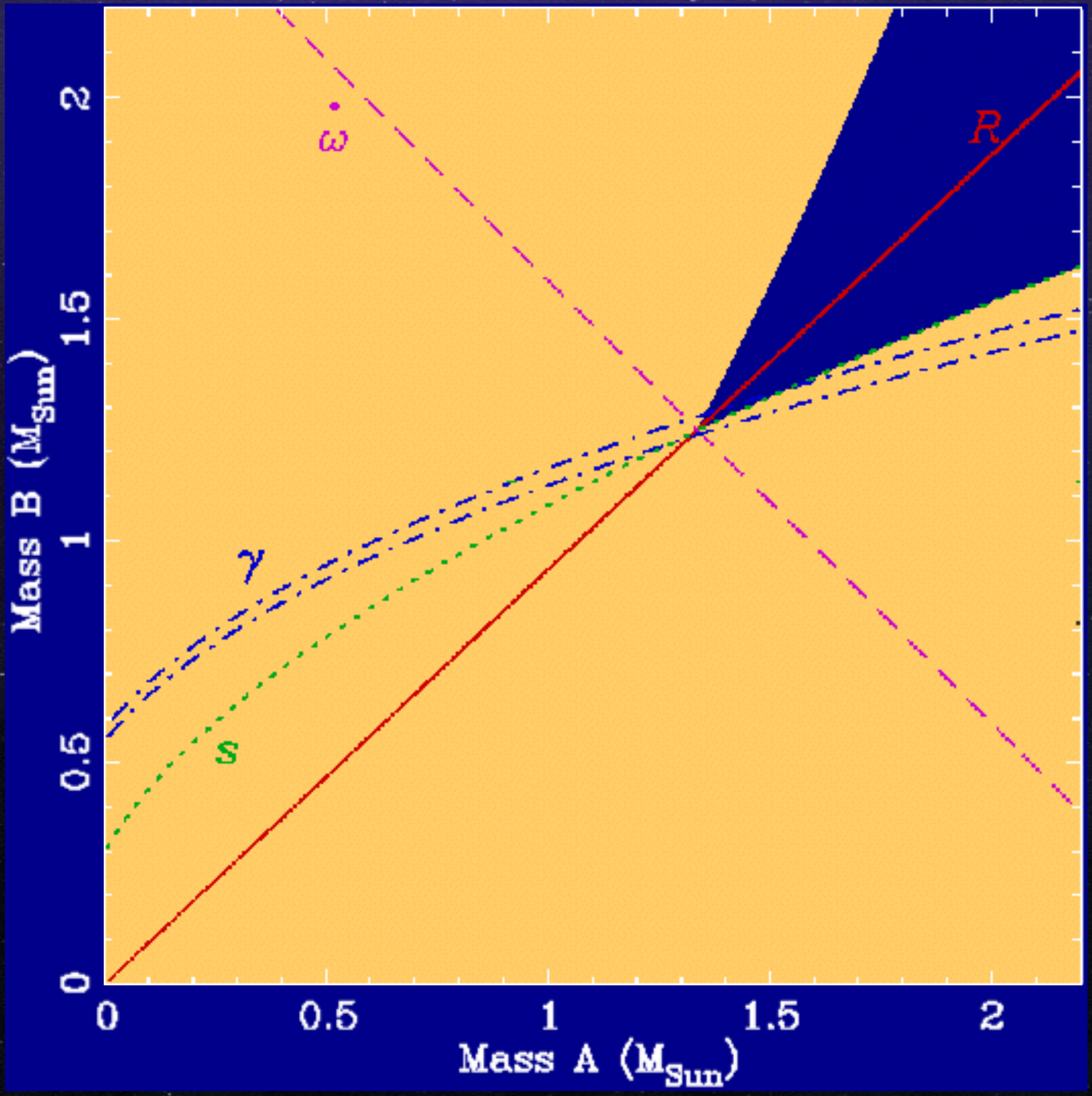
GR with the Double Pulsar



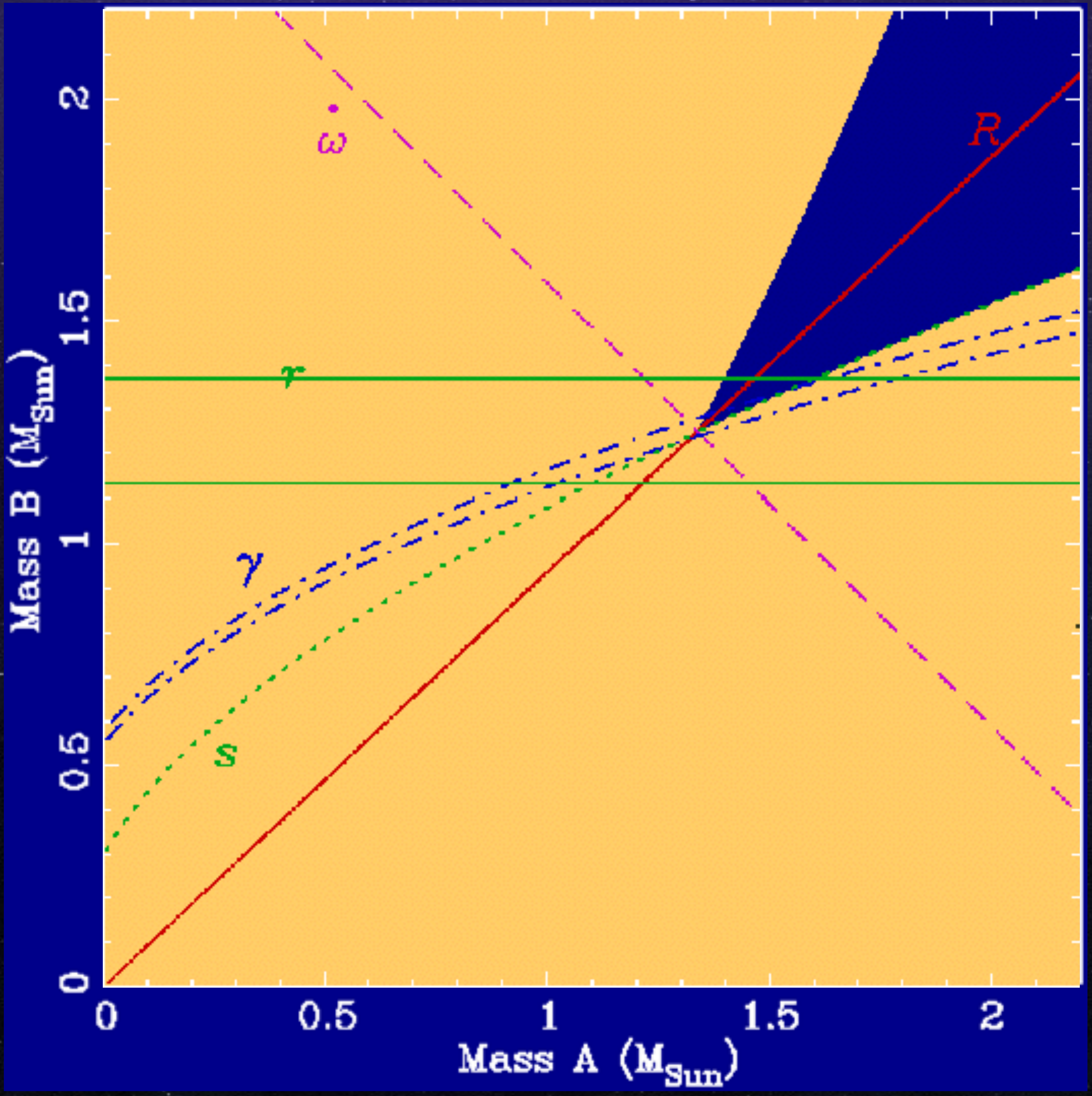
GR with the Double Pulsar



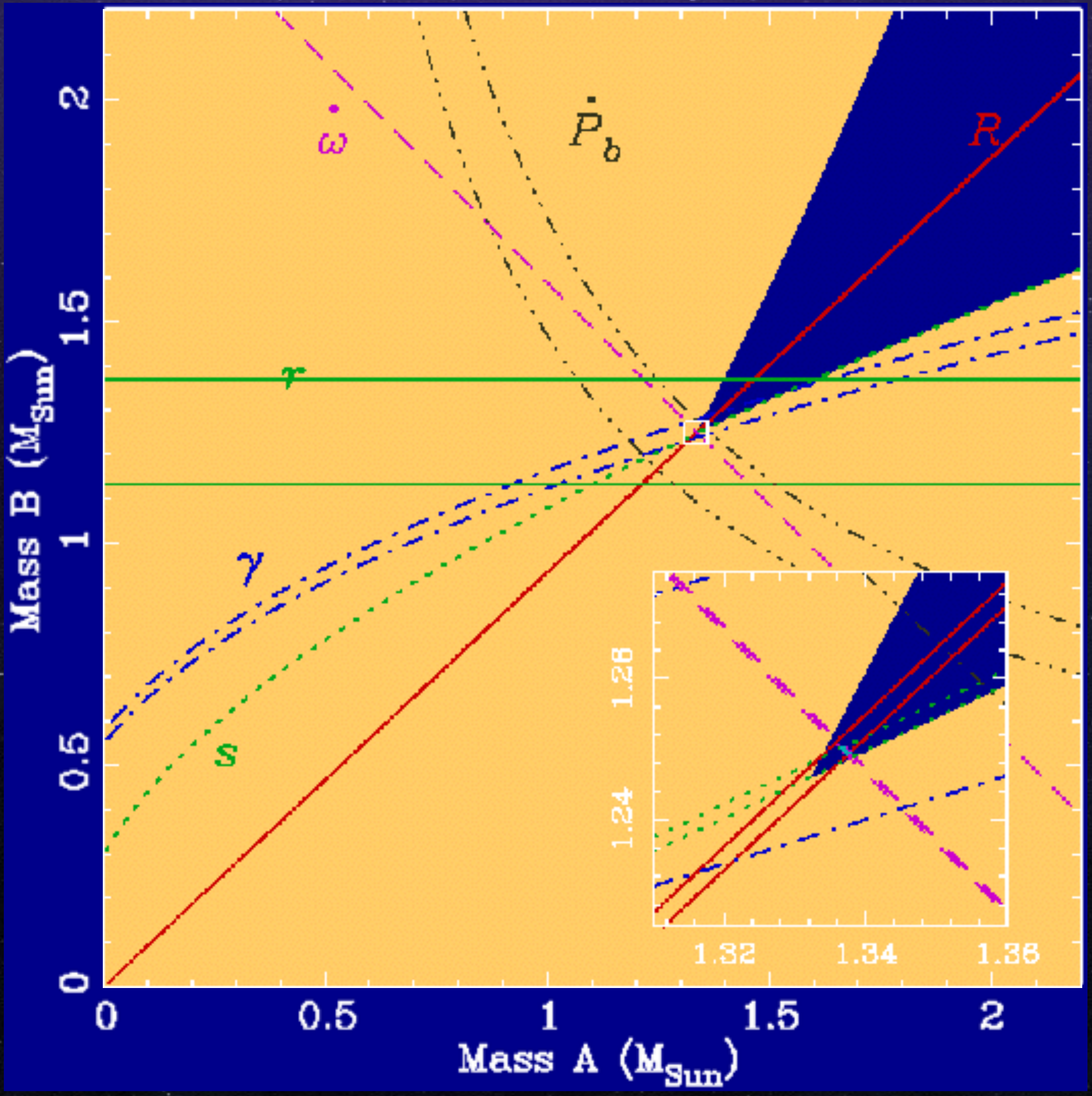
GR with the Double Pulsar



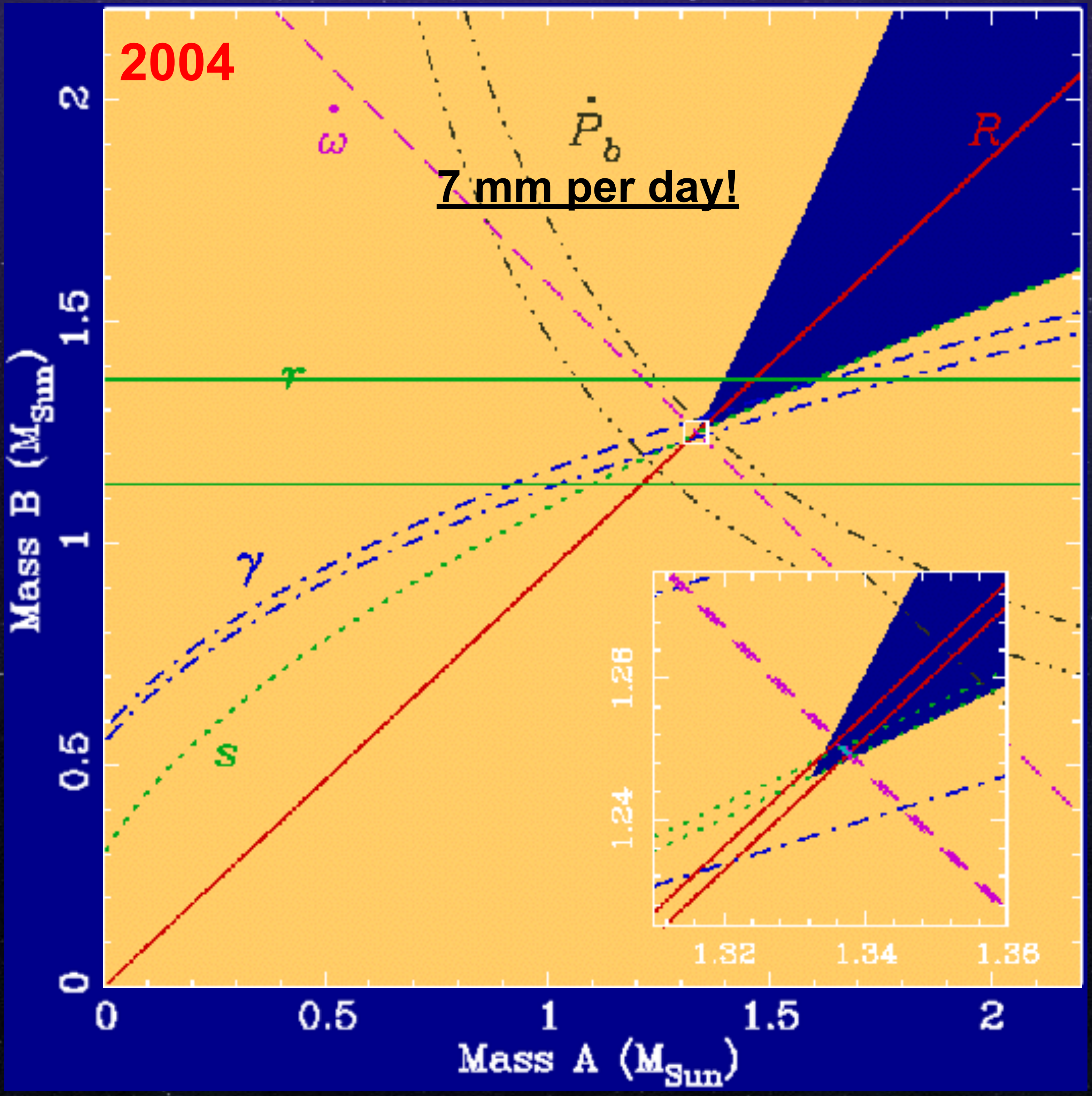
GR with the Double Pulsar



GR WITH THE DOUBLE PULSAR



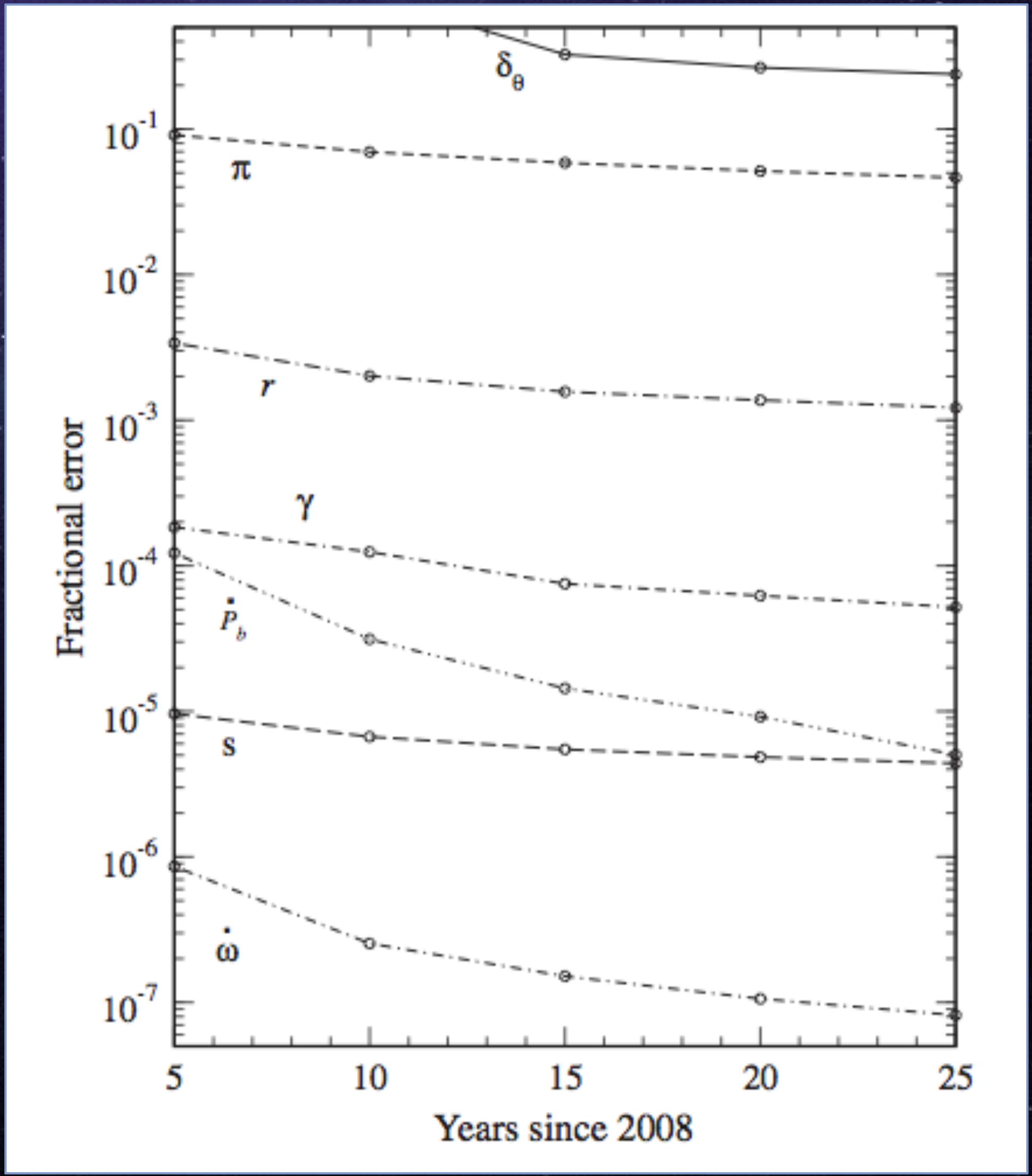
GR with the Double Pulsar



GR WITH THE DOUBLE PULSAR

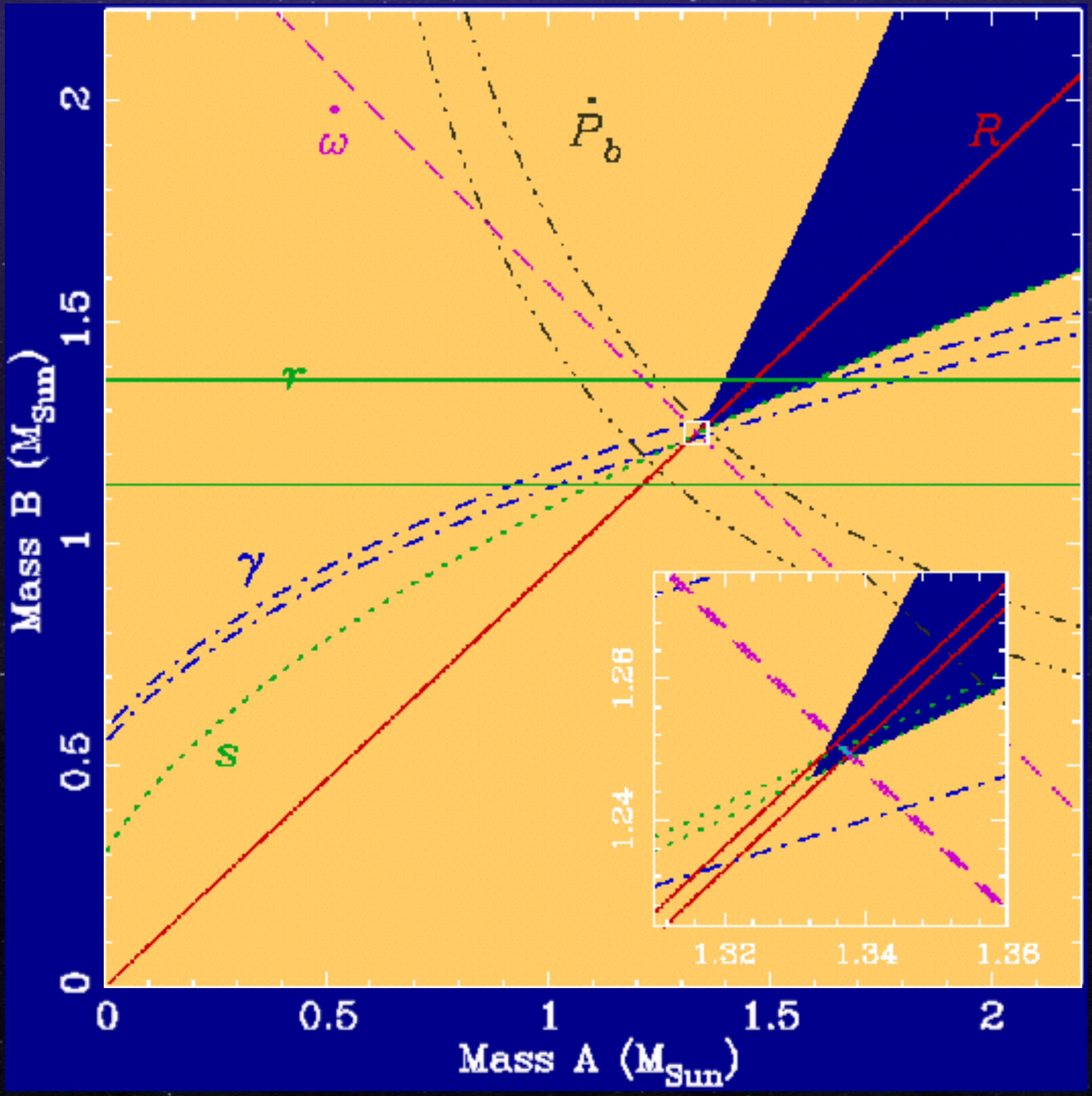
PROSPECTS FOR TIMING ARE EXCELLENT:

- PRECISION ω ≈ TIME$^{1.5}$ P_B
- PRECISION γ ≈ TIME$^{1.5}$ $P_B^{1.3}$
- PRECISION P_B ≈ TIME$^{2.5}$ P_B^{3}
- PRECISION r, s ≈ TIME$^{0.5}$

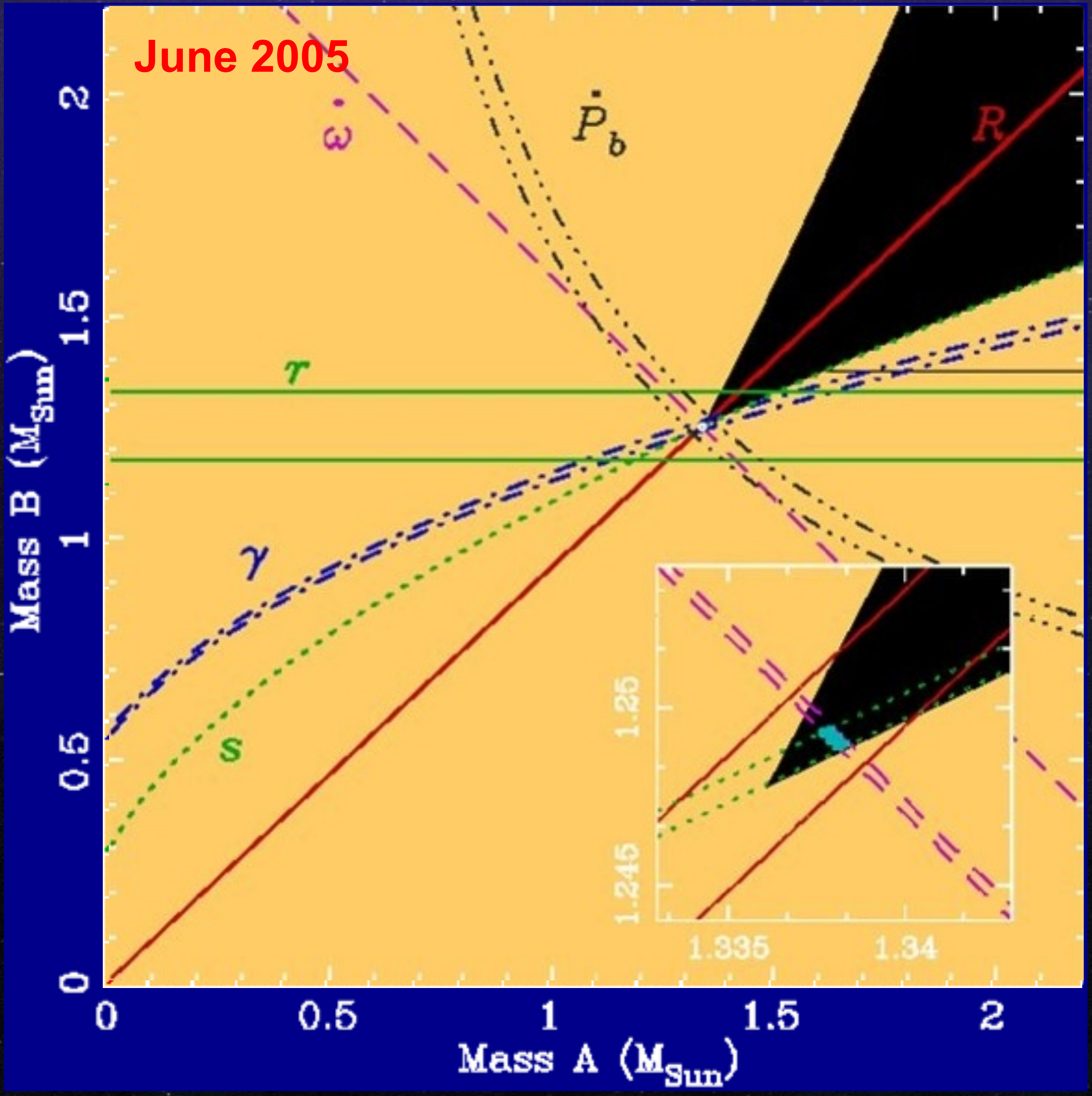


[Kramer & Wex 2009]

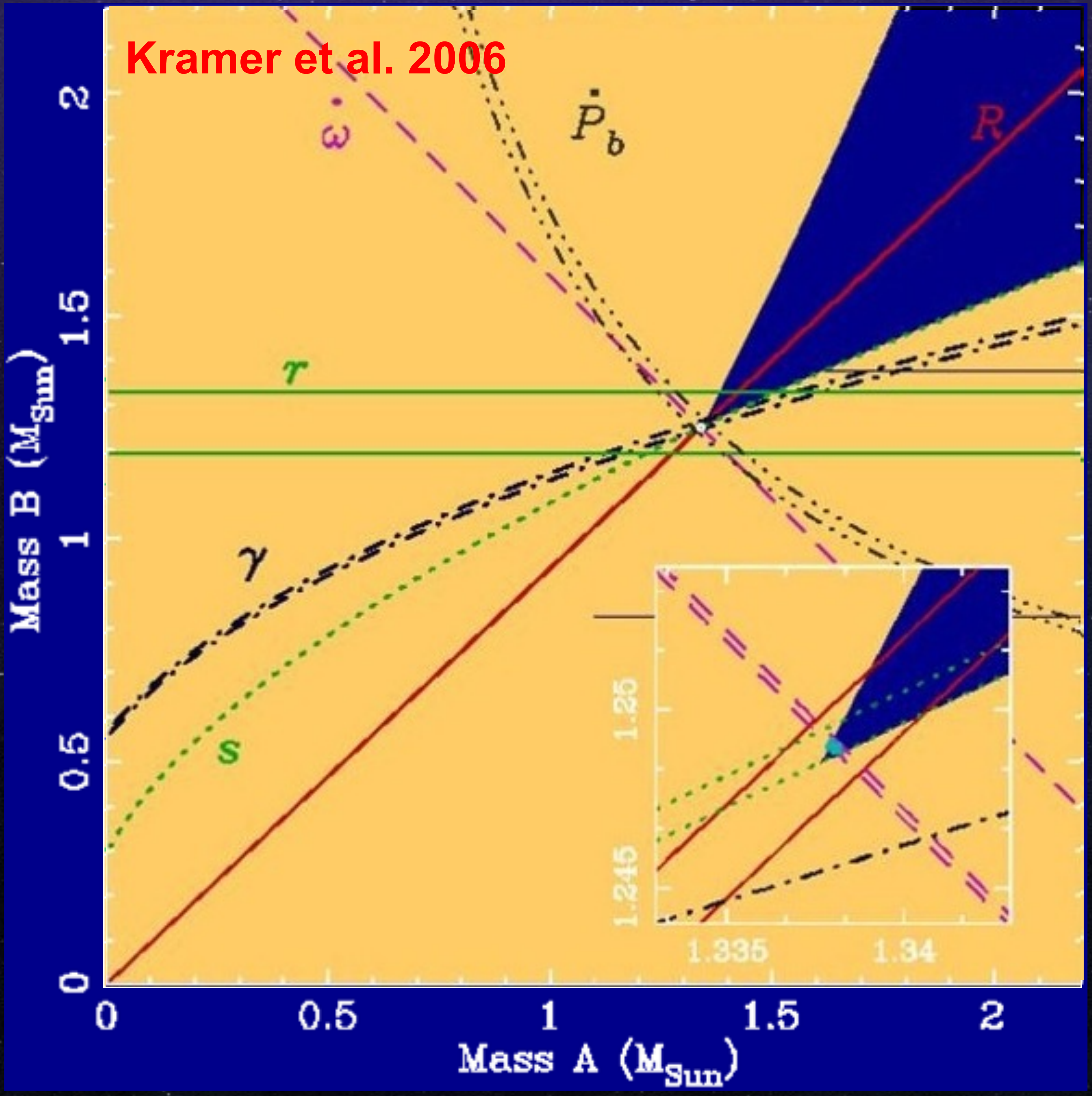
GR WITH THE DOUBLE PULSAR



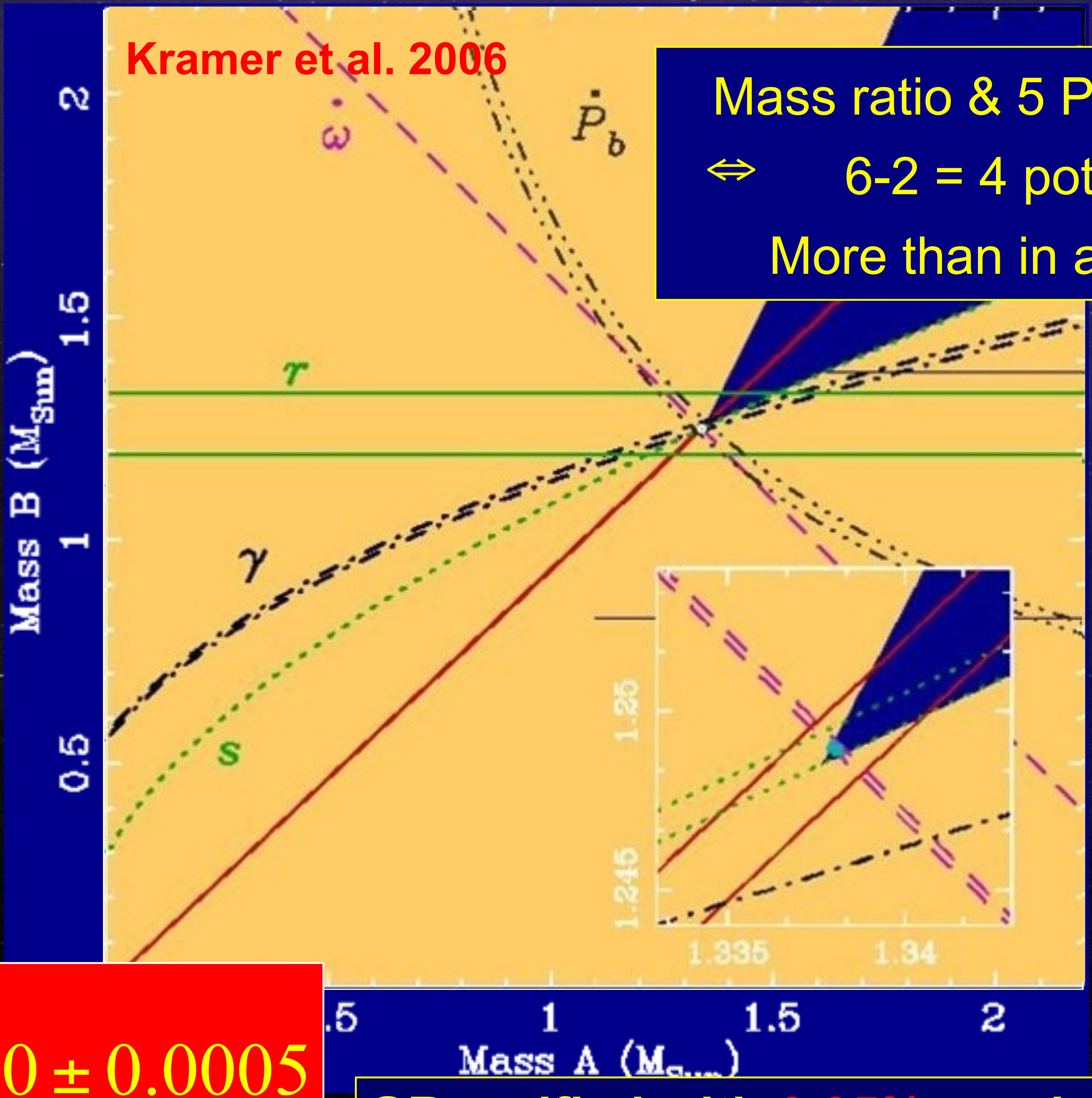
GR WITH THE DOUBLE PULSAR



GR with the Double Pulsar



GR WITH THE DOUBLE PULSAR



Mass ratio & 5 PK parameters

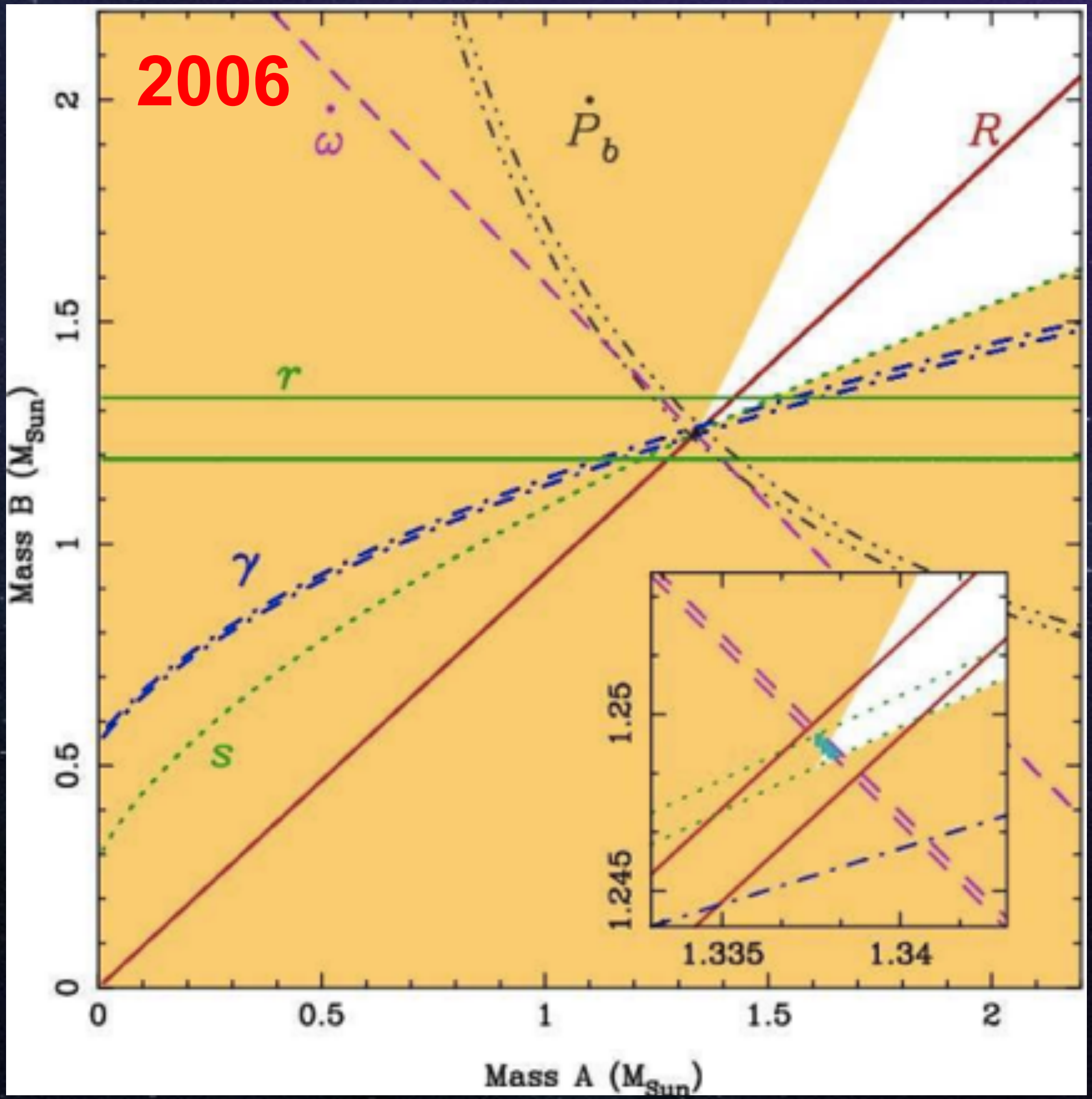
⇔ 6-2 = 4 potential tests!

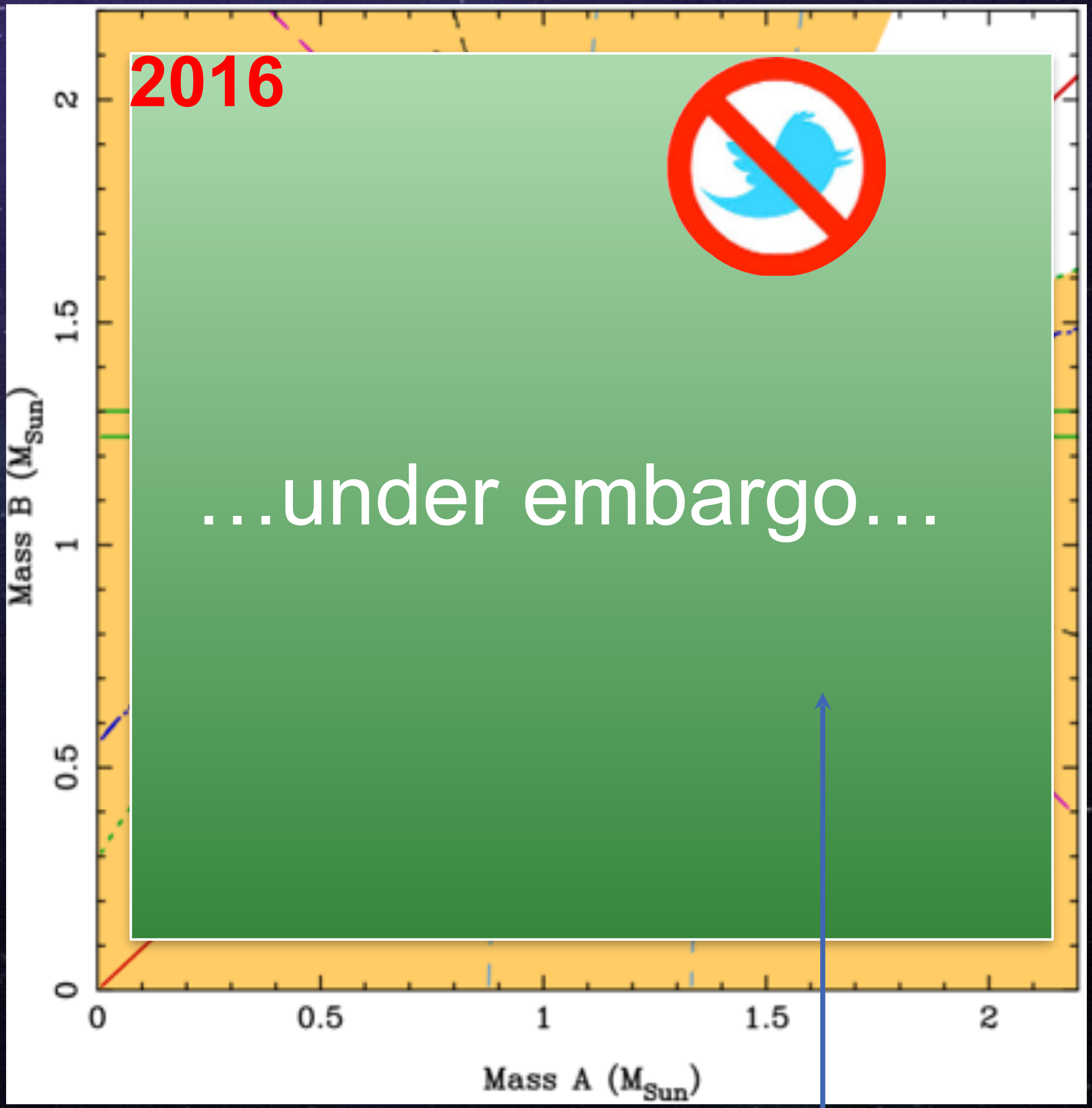
More than in any system!

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

GR verified with 0.05% precision!

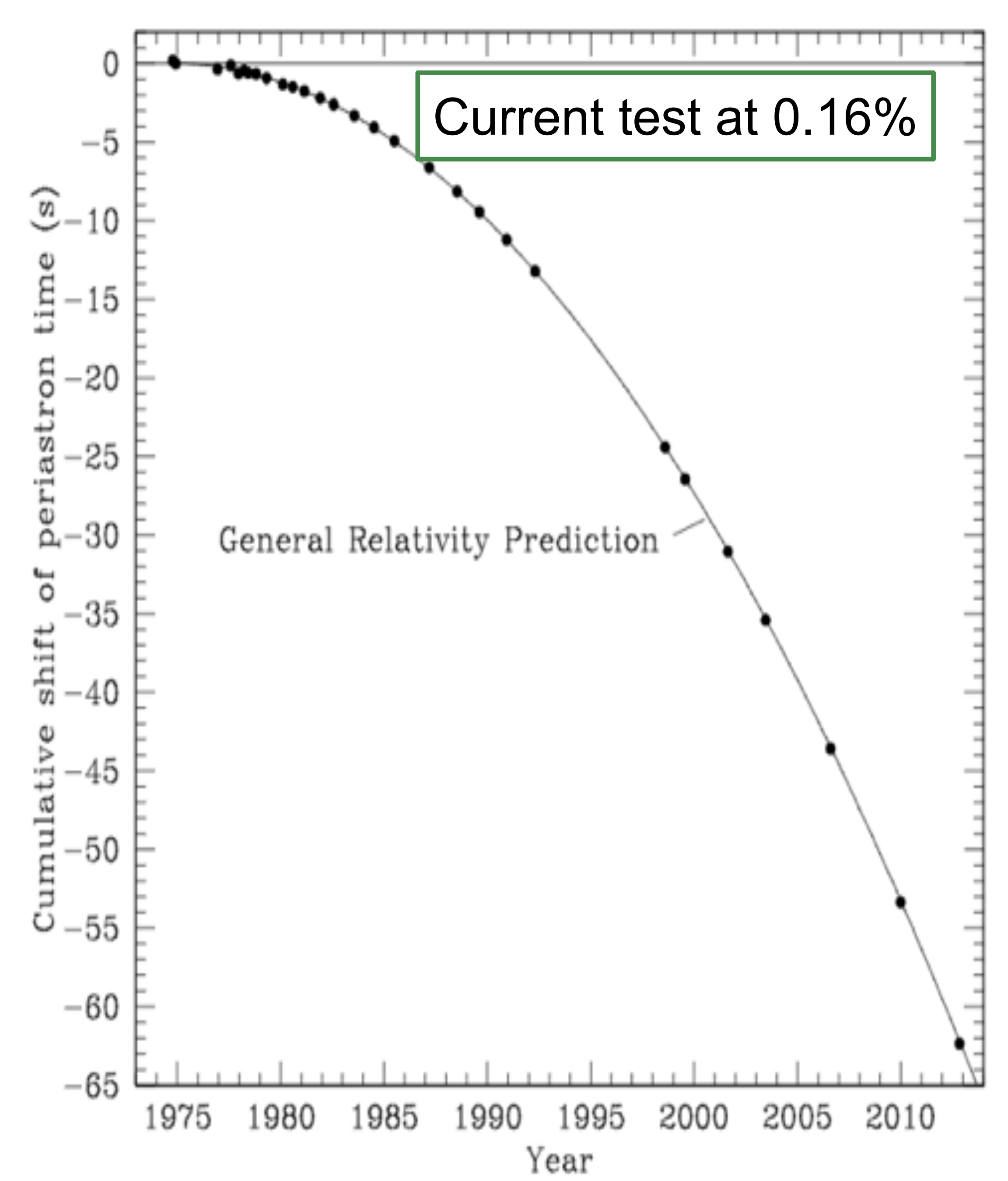
GR with the Double Pulsar

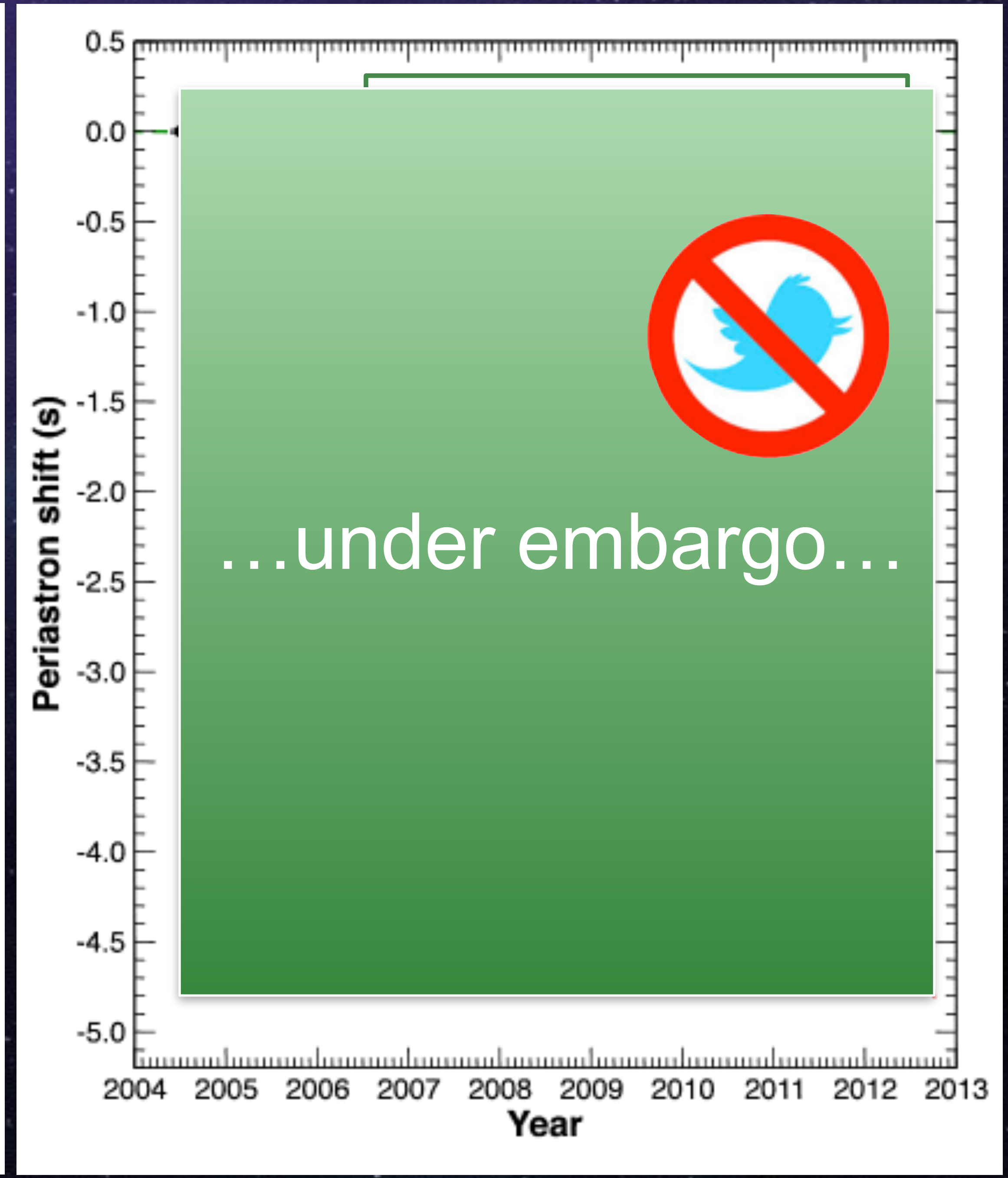




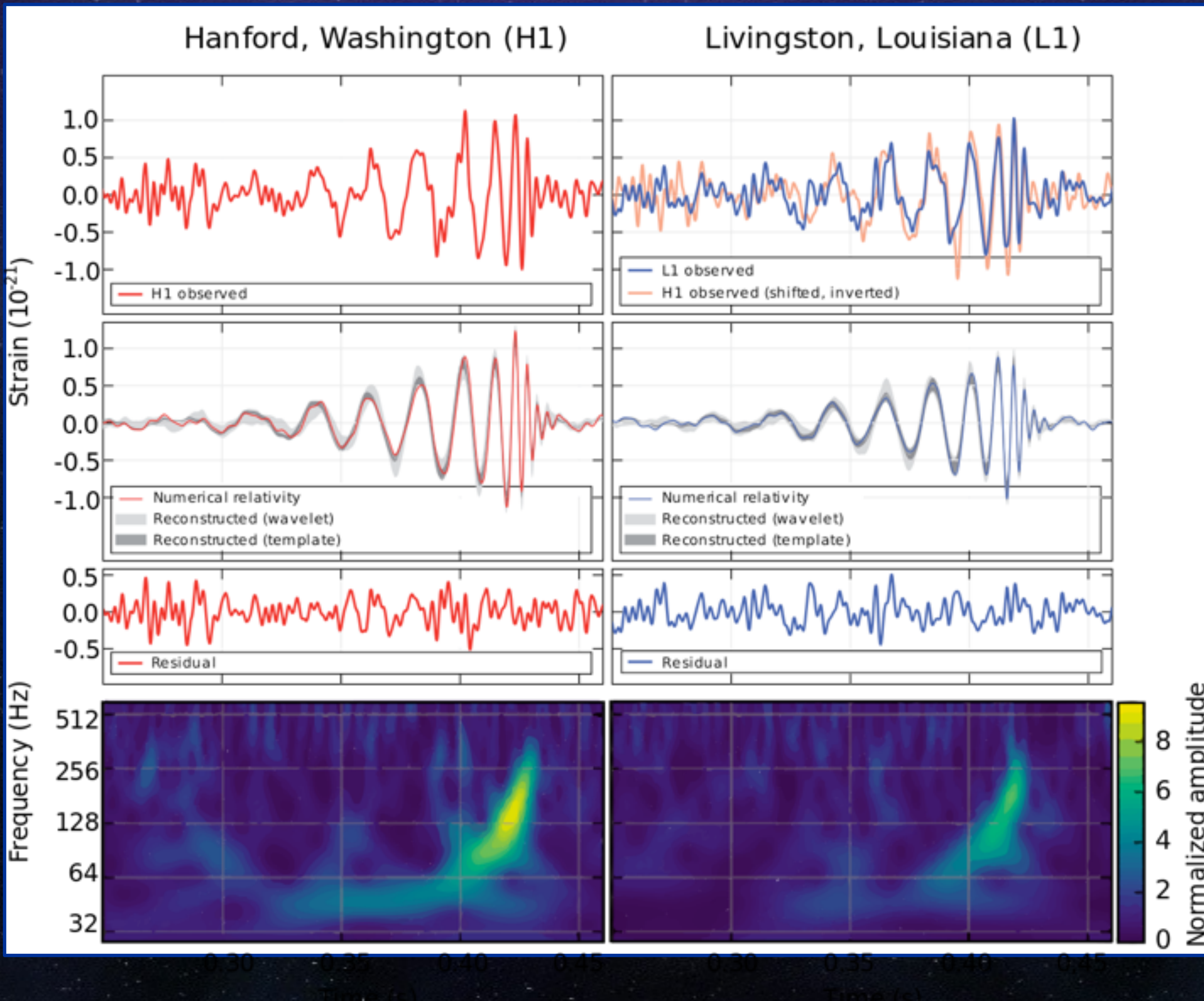
$m_A =$ $M_\odot$
$m_B =$ $M_\odot$

GR with the Double Pulsar

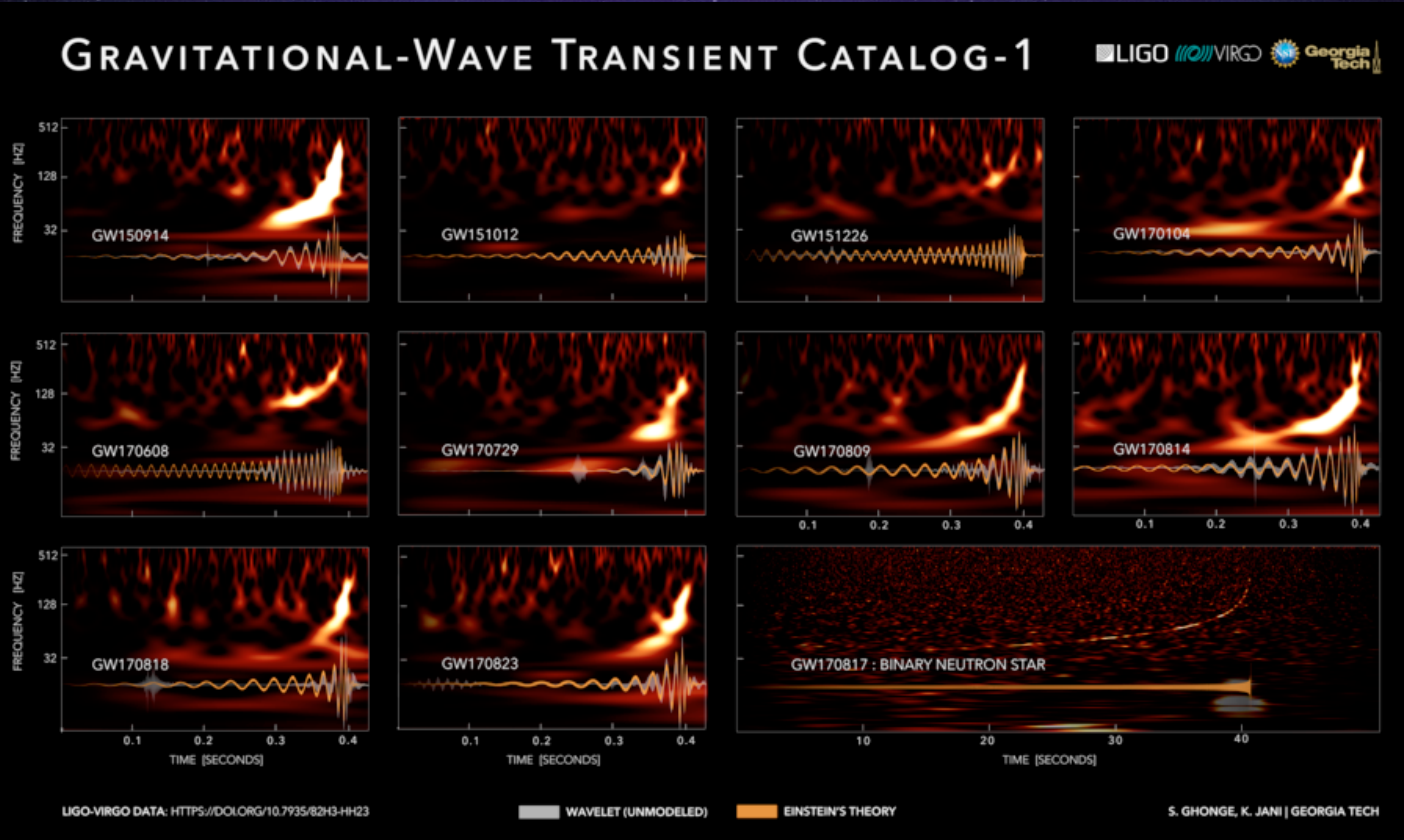




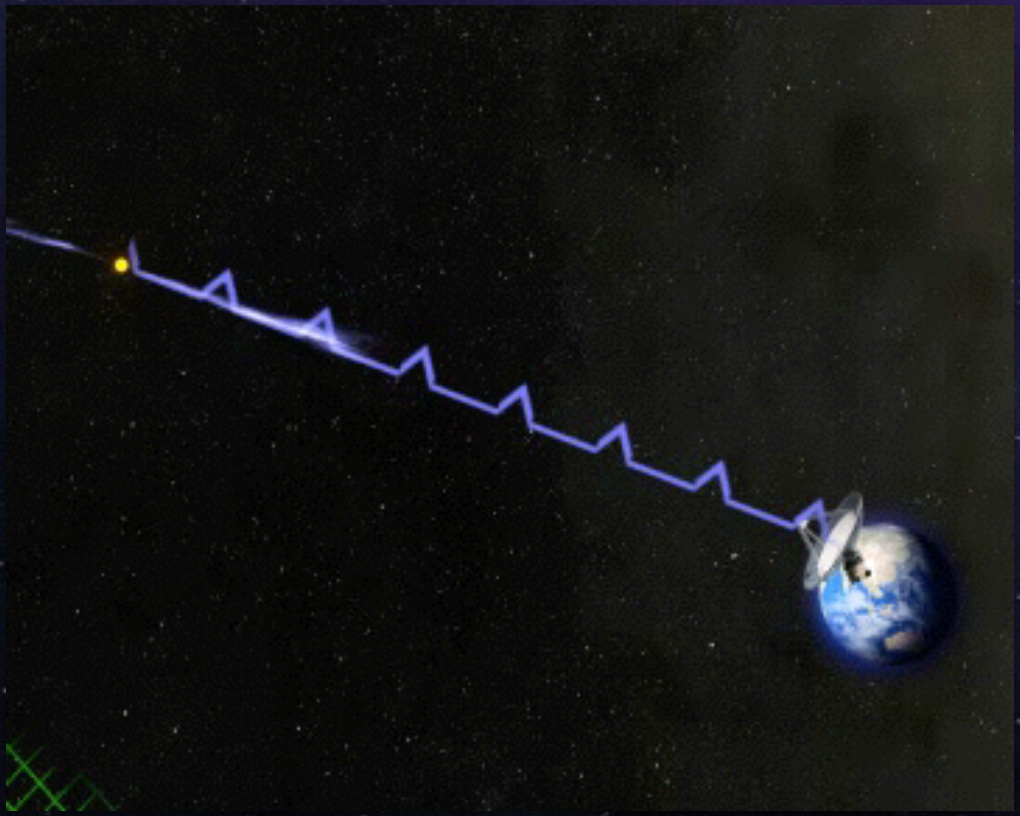
Gravitational Waves

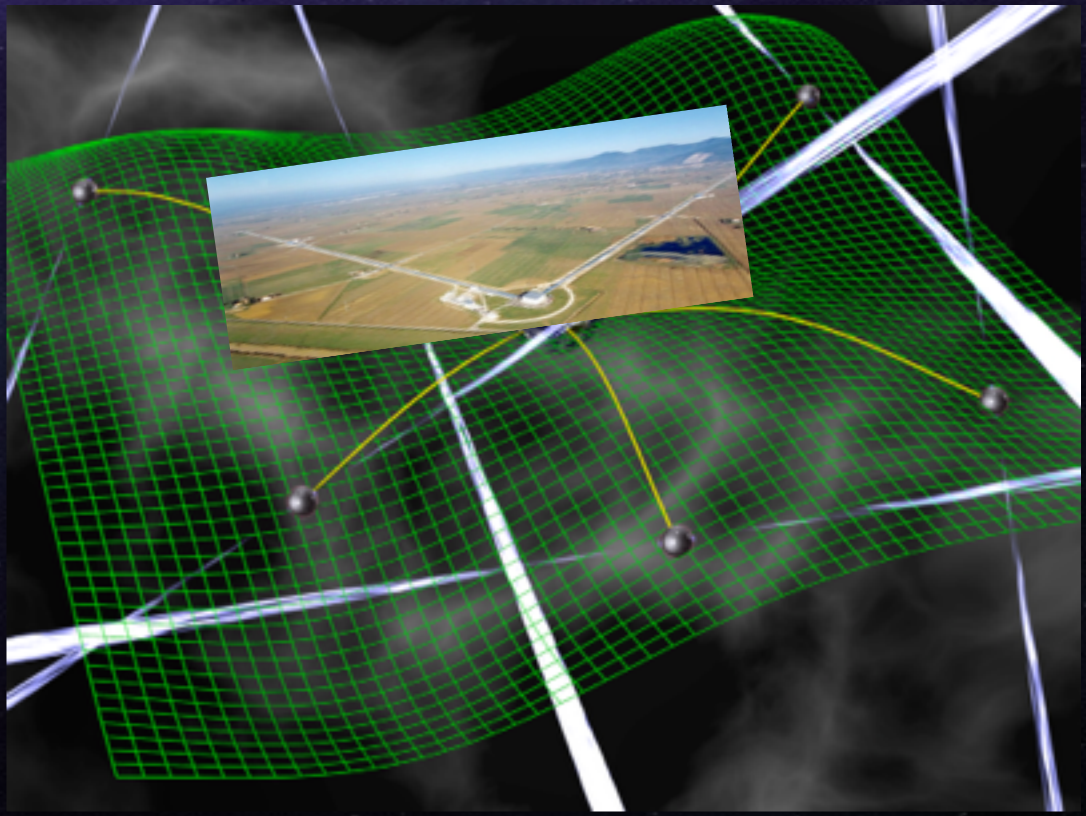


Gravitational Waves

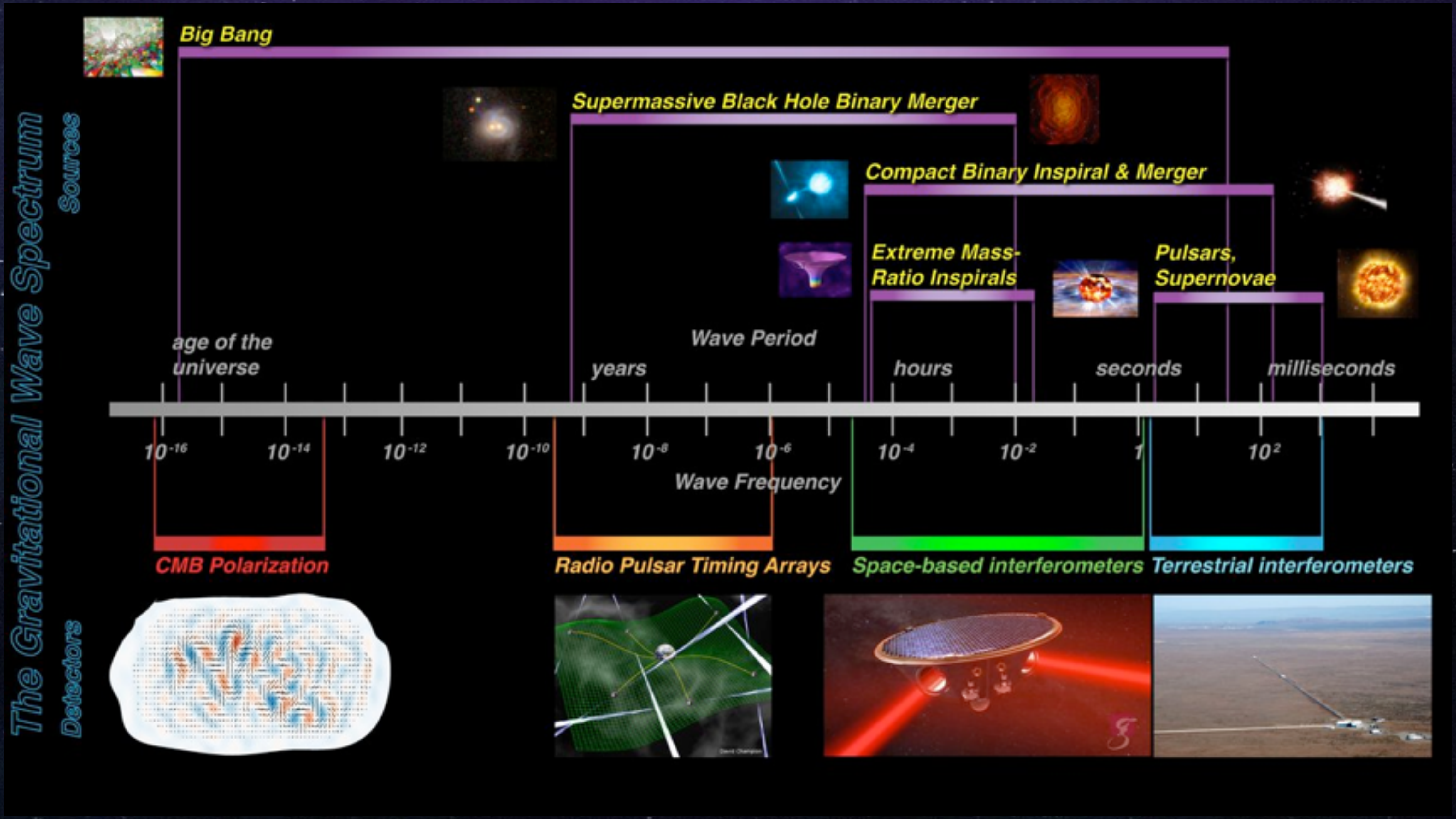


Pulsars and GWs





PULSARS AND GWS



PULSAR TIMING ARRAYS

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

EPTA

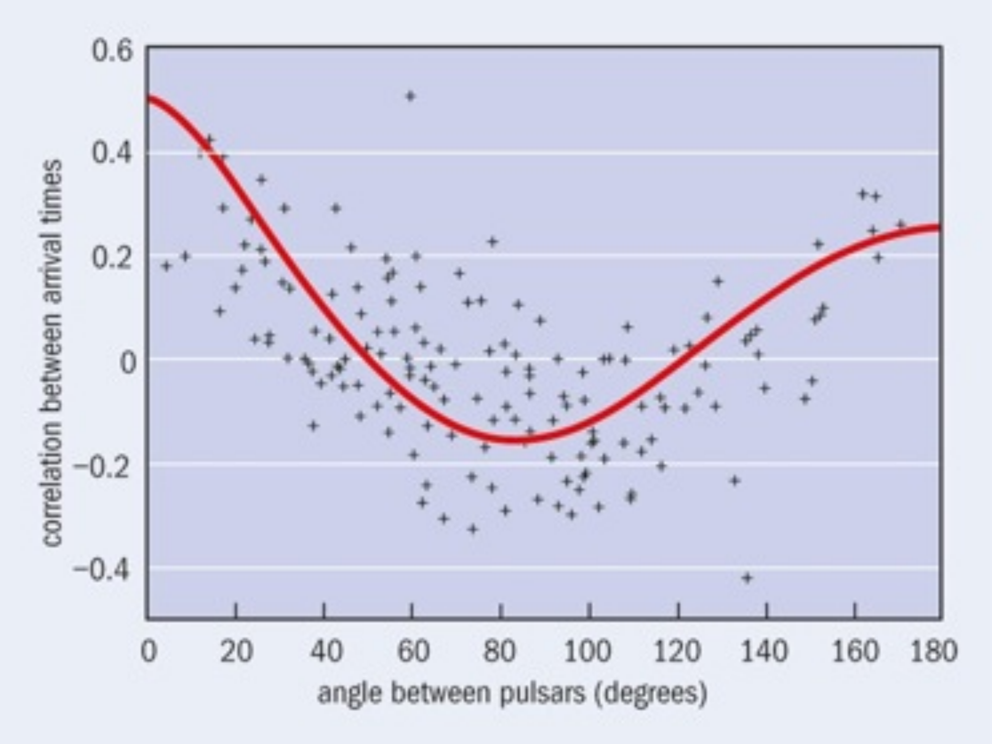
NANOGrav

PPTA

Pulsar Timing Arrays

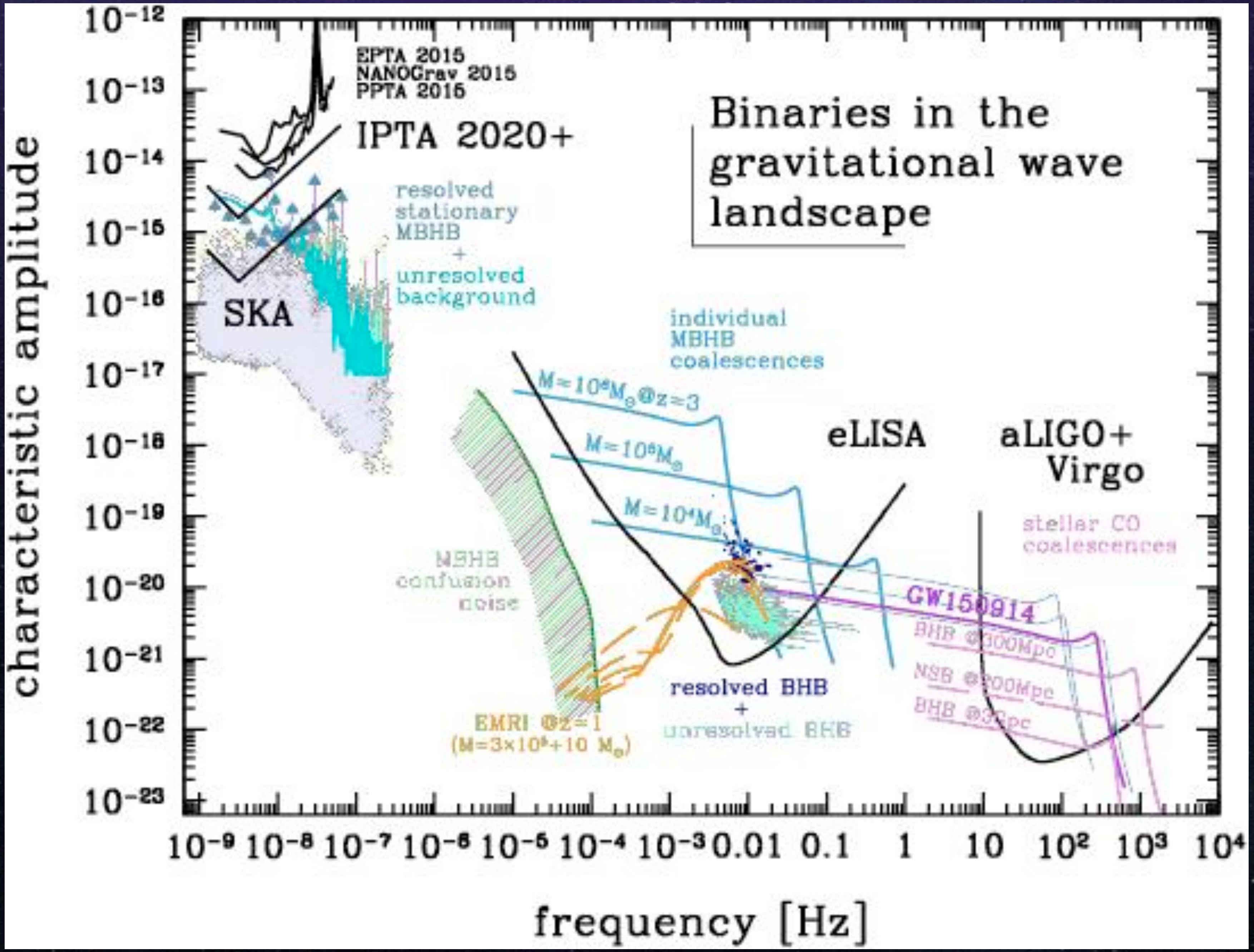
PTAs are arrays of pulsars & arrays of telescopes.

To exclude other sources of ToA variations
- Multiple telescopes
- Multiple pulsars, looking for correlations



No detection so far, but constraining upper limits

Pulsar Timing Arrays

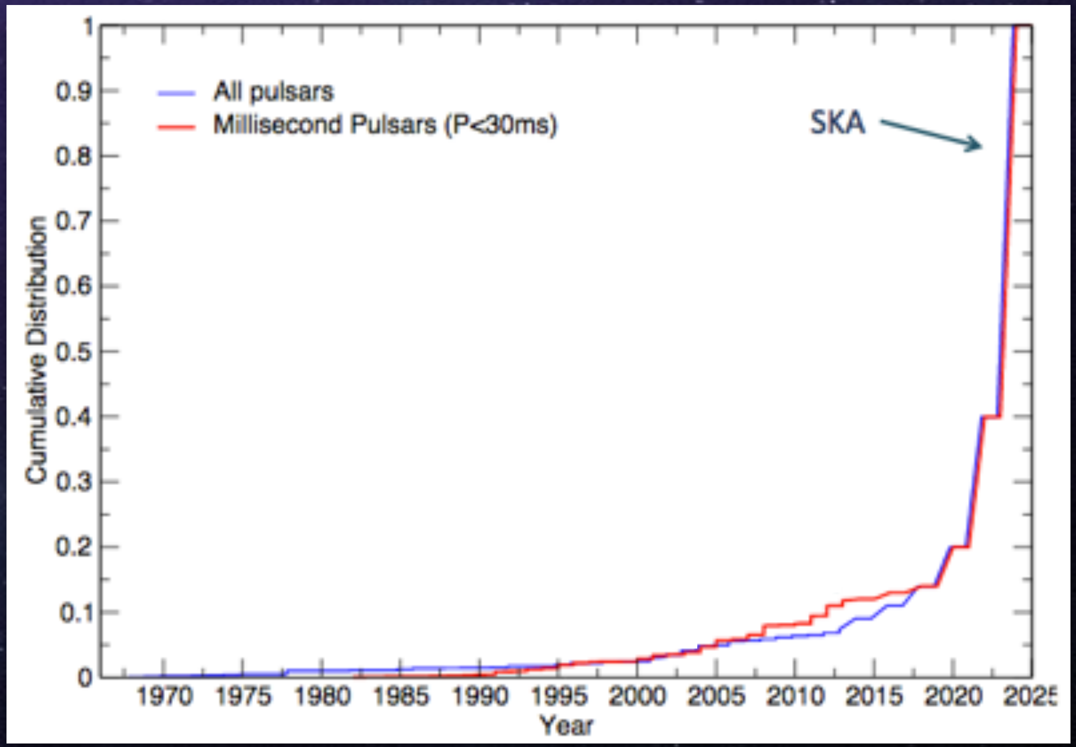


A. Sesana

FUTURE

- With SKA-1
  ~30,000 new pulsars
  ~2000 MSPs
  ~200 relativistic binaries

- Timing precision increased by 5-10



SUMMARY

- BINARY AND MILLISECOND PULSARS ARE FANTASTIC TEST BEDS FOR RELATIVISTIC GRAVITY
- AFTER 15 YEARS (AND 38 METERS TRAVELLED) FROM DISCOVERY, THE DOUBLE PULSAR IS STILL THE GREATEST OF THEM ALL
- PULSARS ARE BOTH EMITTERS AND DETECTORS OF GRAVITATIONAL WAVES
- ON-GOING AND FUTURE EXPERIMENTS ARE DISCOVERING AND WILL DISCOVER MANY MORE SUCH EXTREME LABORATORIES
- SKA WILL ALLOW US TO MAKE BIG STEPS FORWARD:
  - HIGHER SEARCH SPEED: 3-4X (10-12X) MORE PULSARS
  - HIGHER TIMING QUALITY: 5-10X (10-100X) BETTER TOA

THANK YOU FOR YOUR ATTENTION