Measurements of Gravitational Waves and other Relativistic Parameters in the First Binary Pulsar PSR B1913+16

Joel M. Weisberg

Carleton College, Northfield, MN, USA

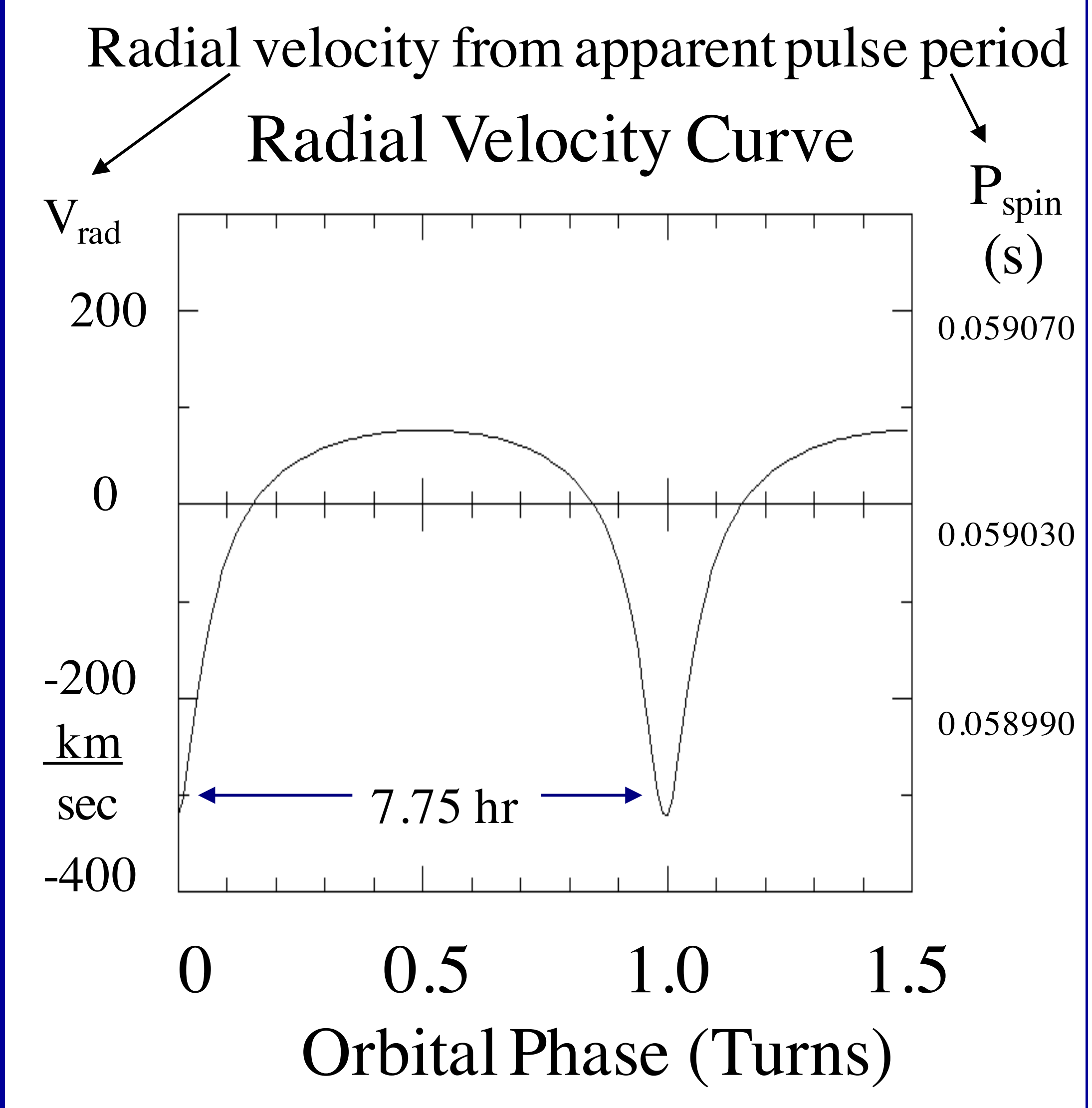
With thanks to Joseph Taylor, David Nice, and Yuping Huang

305-m dish at Arecibo, PR (modern view)

PSR B1913+16: *Not* a vanilla pulsar! First binary pulsar, discovered by Hulse & Taylor at Arecibo in 1974.

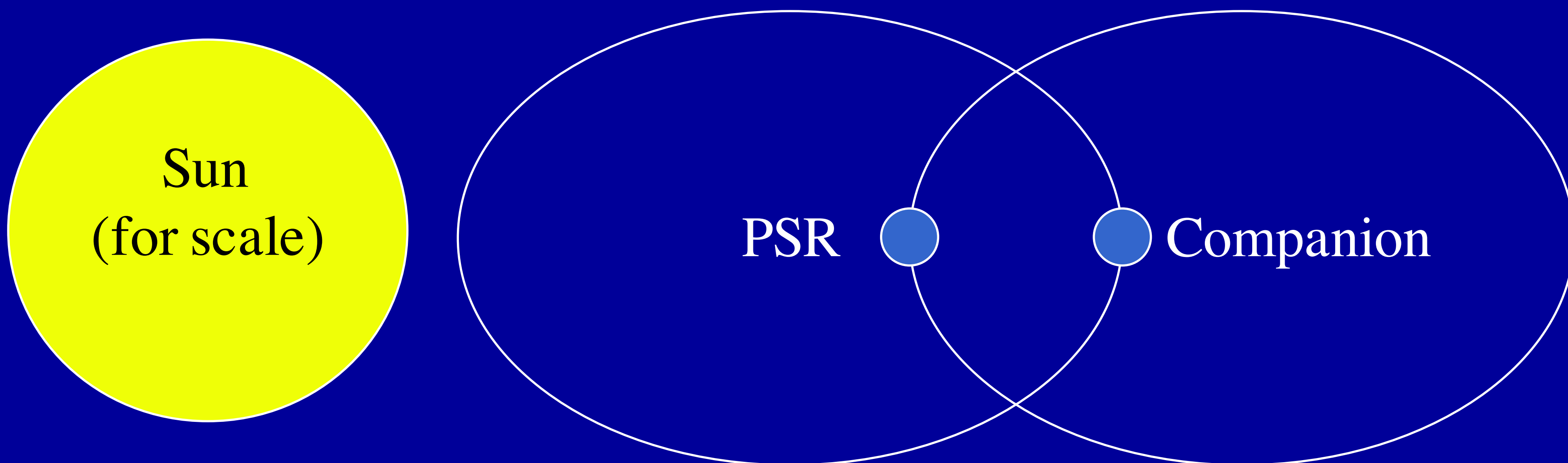
Classical Doppler equation (for *any* clock):

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu} = \frac{\Delta P_{spin}}{P_{spin}} = \frac{v_{radial}}{c}$$



PSR B1913+16: An ideal relativistic laboratory

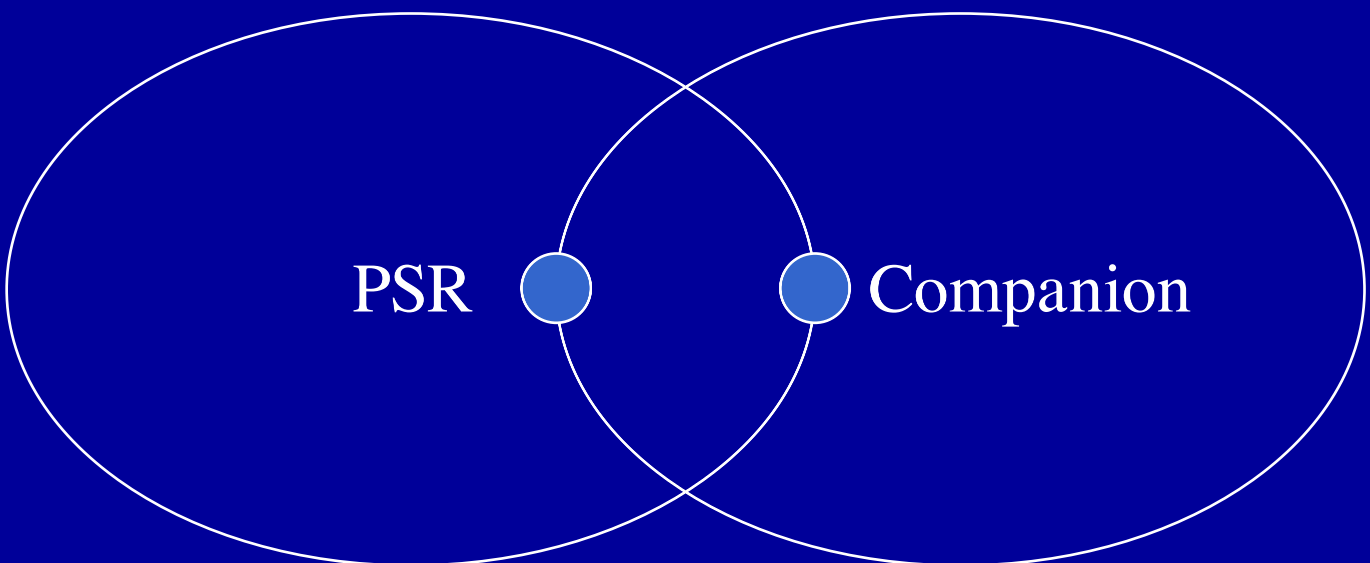
- Orbital speed at periastron: $v \sim 400$ km/s
- Component separation at periastron: $r \sim 1\ R_{sun}$
- Double neutron star system (one visible pulsar)
- Neutron star relativistic parameter: $G\ M\ /\ c^2\ R_{surf} \sim 0.2$
- Time of arrival (TOA) uncertainty: ~12 μs in 5 minutes (today)



To *use* PSR B1913+16 as a relativistic laboratory, determine *all* physical parameters of the system.

- Masses of the two stars: m_{psr} and $m_{companion}$
- Orbital period P_b, eccentricity e, semimajor axes a_{psr} and $a_{companion}$
- Longitude and epoch of periatron ω_o and T_o

Seven are needed to completely specify the system



Relativistic Gravitational Laboratory *Characterization*

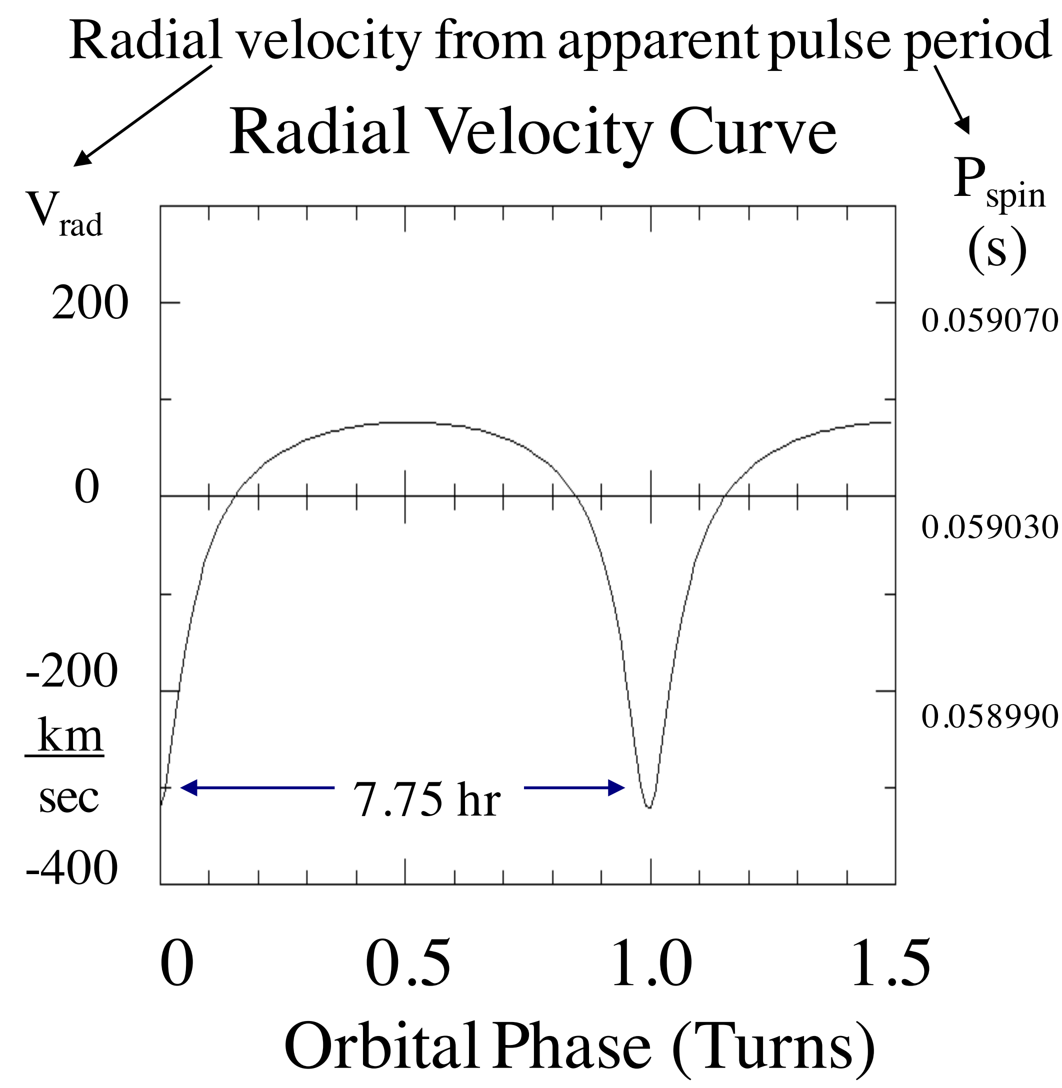
Radial velocity curve determines 5 of the 7 quantities that are required to specify the orbiting system completely:

$P_b = 7.75$ hr

$a_{psr} \sin(i) = 2.34$ lt-sec

$e = 0.617$

$T_o; \omega_o$



Relativistic Gravitational Laboratory *Characterization*

Radial velocity curve determines 5 of the 7 quantities that are required to specify the orbiting system completely:

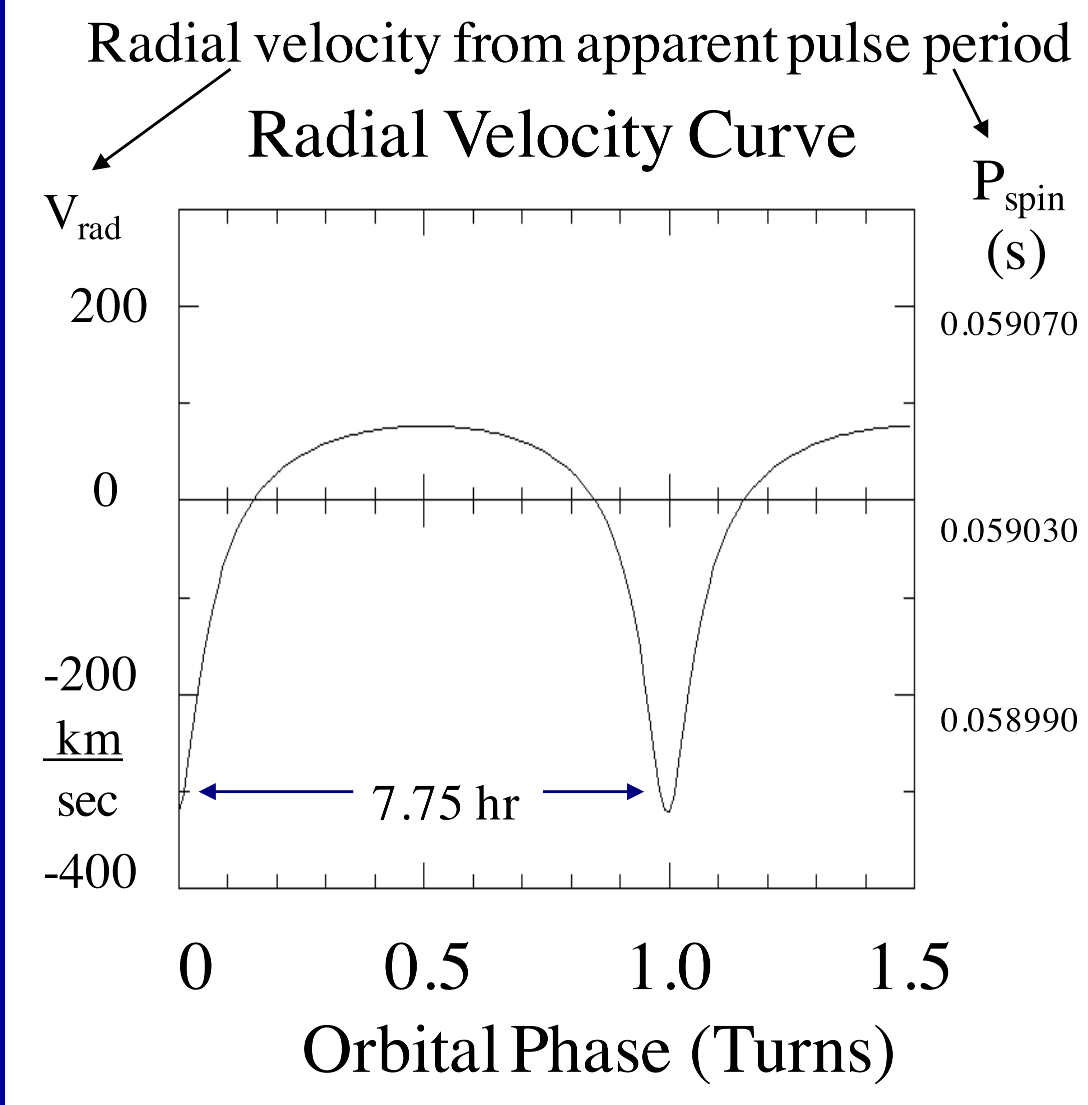
$P_b = 7.75$ hr

$a_{psr} \sin(i) = 2.34$ lt-sec

$e = 0.617$

$T_o; \omega_o$

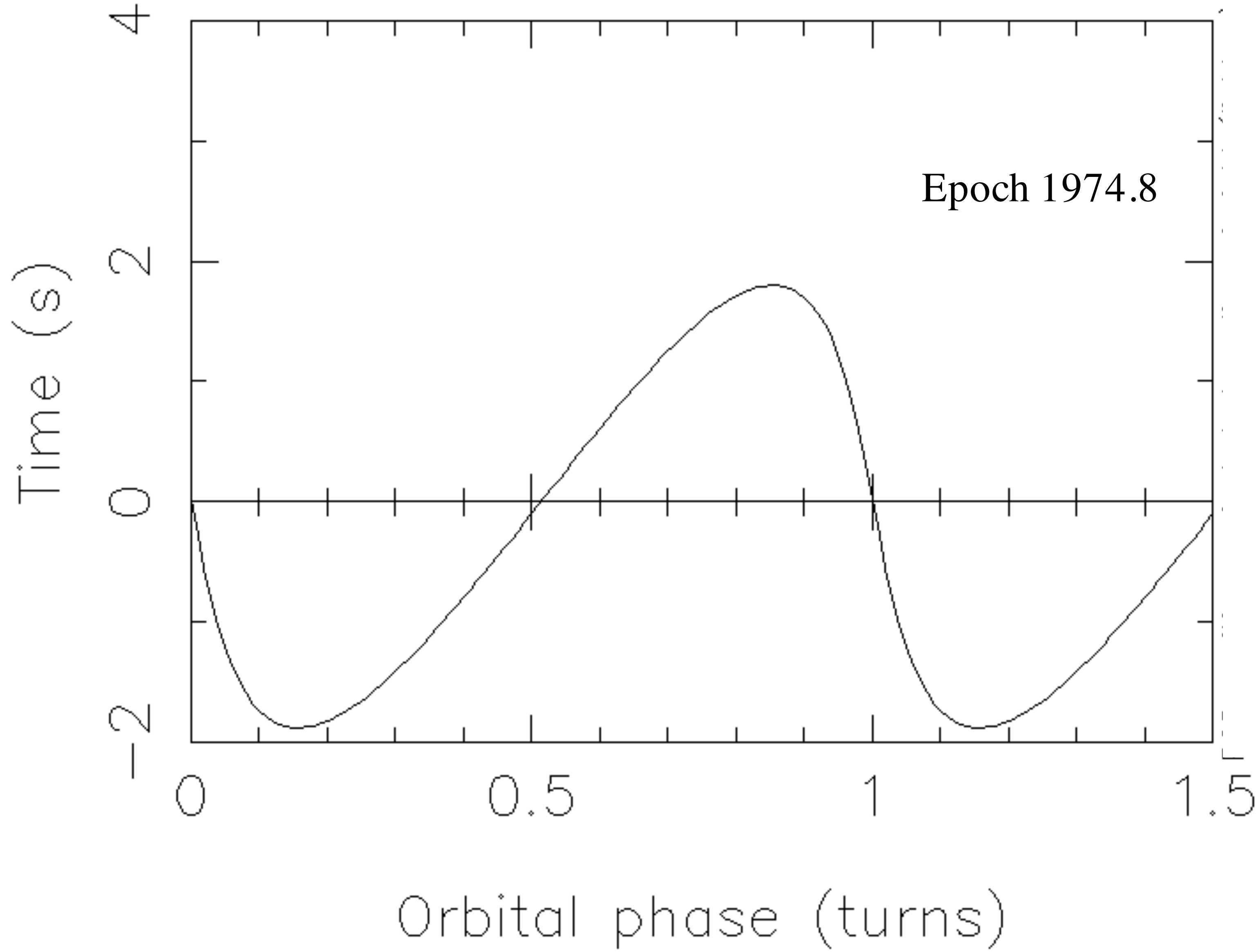
Two more measurables are needed!



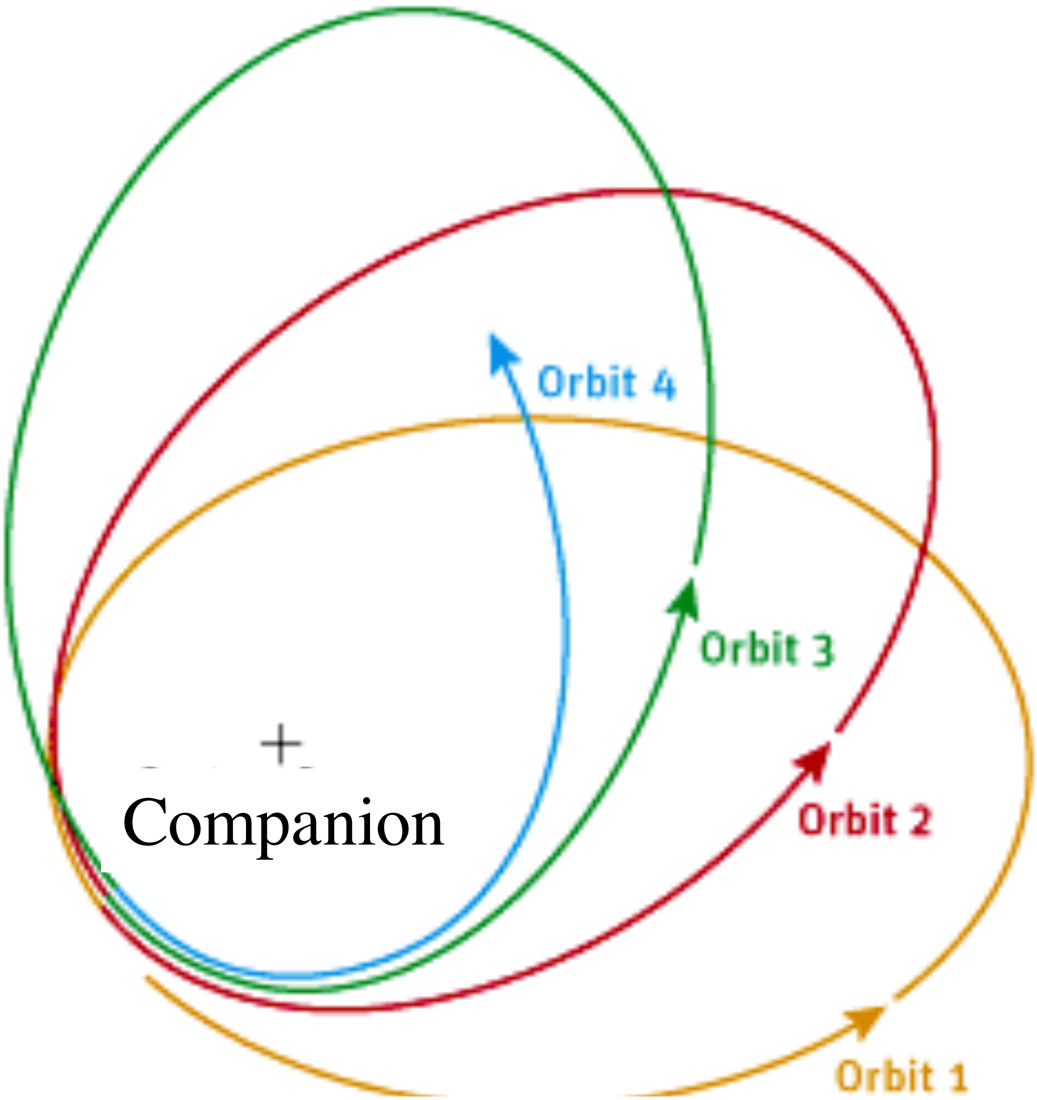
Joel ↑ and Joe Taylor ↑ with our "Mark I" Observing System, Arecibo Observatory control room, ~1980

TOAs around the orbit

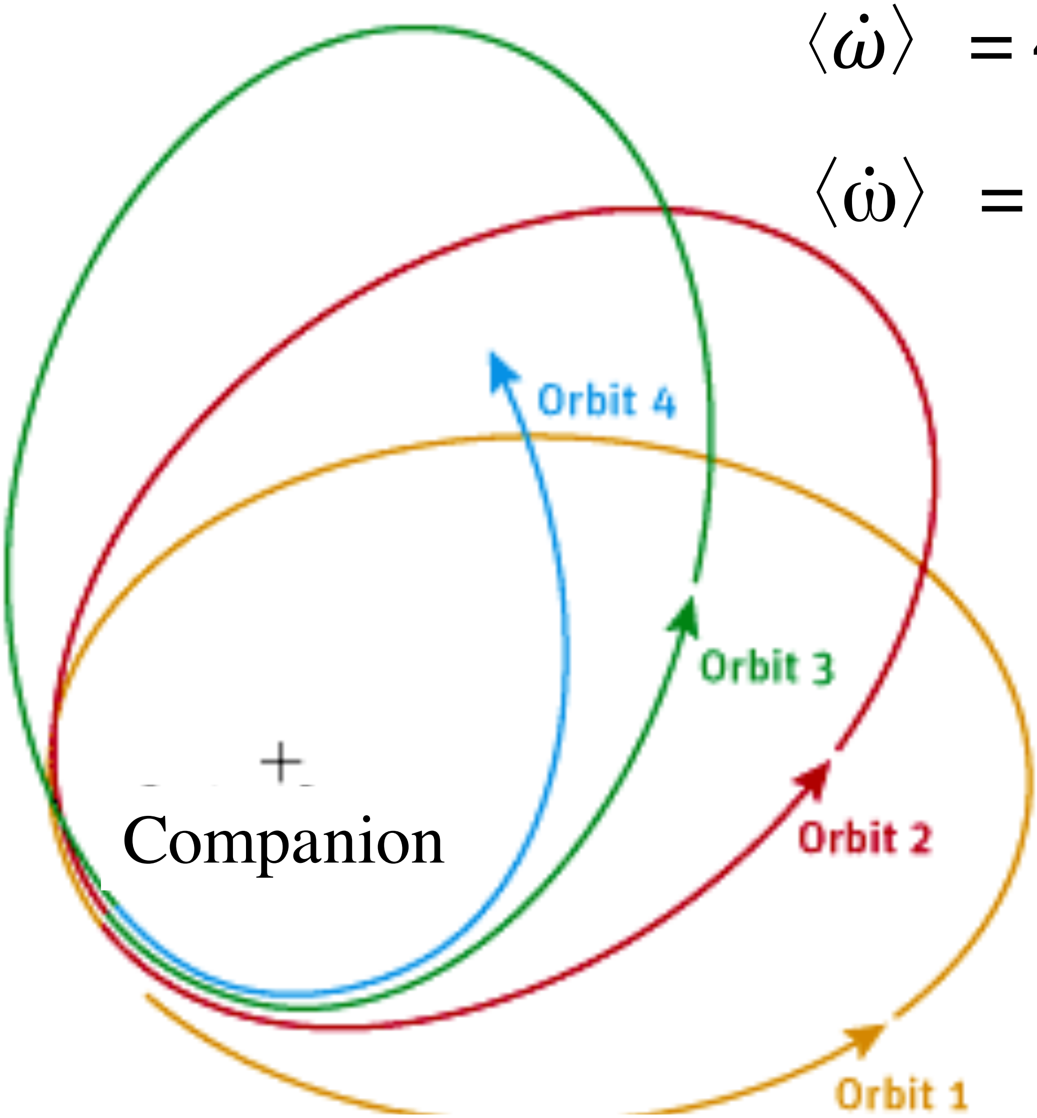
Current precision: ~12 μs with Δt=5 min and Δf=100 MHz



Advance of Periastron $\langle\dot{\omega}\rangle$.
The Sixth Measurable (of seven).



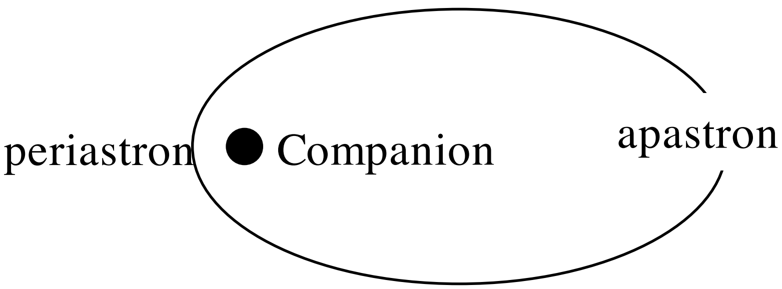
Advance of Periastron $\langle\dot{\omega}\rangle$.
The Sixth Measurable (of seven).



$\langle\dot{\omega}\rangle$ = 4.23 deg / yr.

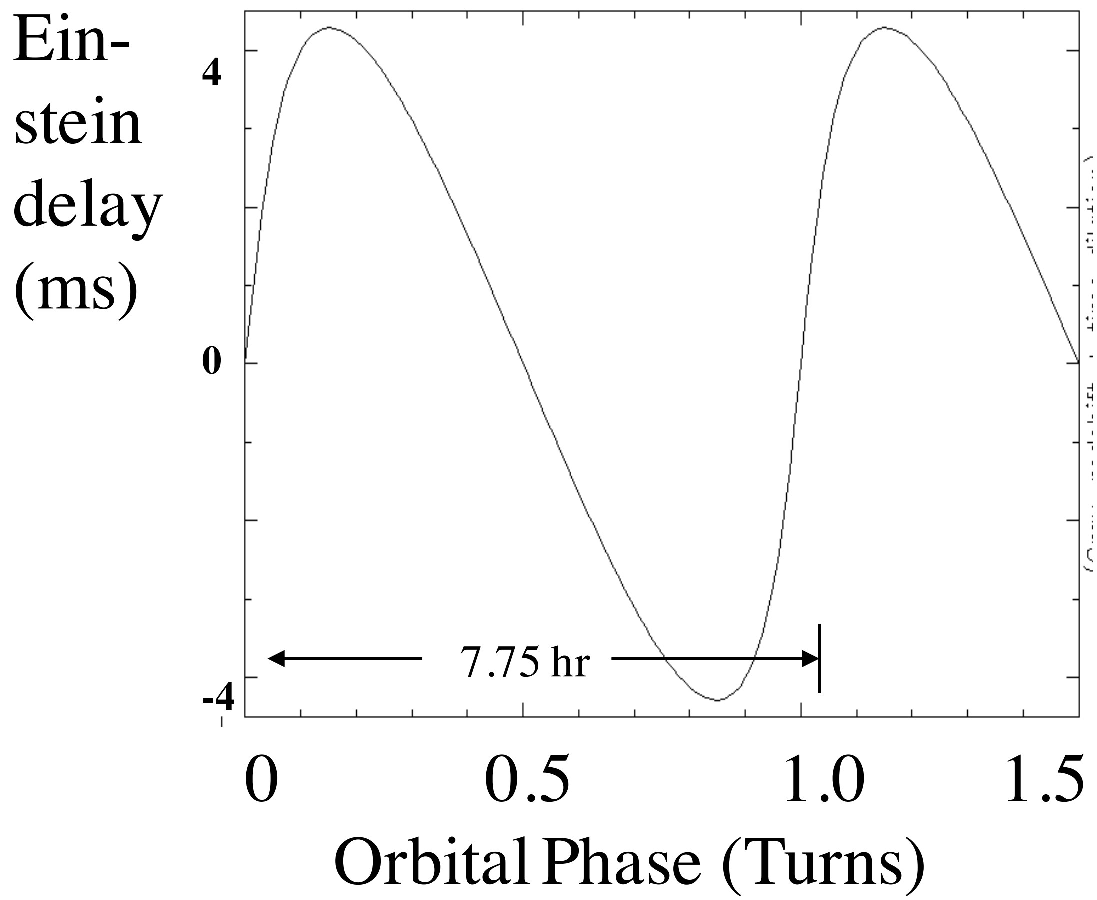
$\langle\dot{\omega}\rangle = 3\,(P_b/2\pi)^{-5/3}\,(m_p+m_c)^{2/3}/(1-e^2)$

Grav. Redshift-Time Dilation "Einstein" Term γ: The Seventh Measurable (of seven)

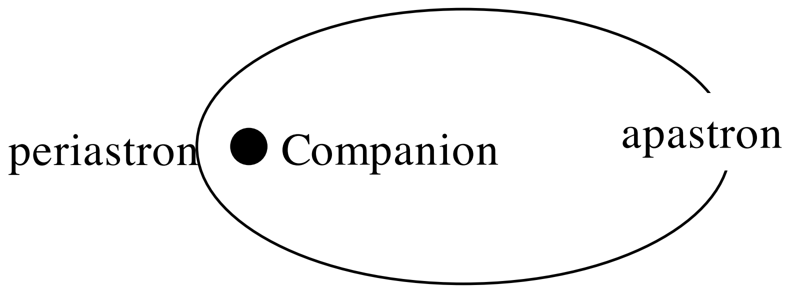


γ is composed of:

- **Gravitational redshift variations around the elliptical orbit**
- **Time dilation variations around the elliptical orbit**



Grav. Redshift-Time Dilation "Einstein" Term γ: The Seventh Measurable (of seven)

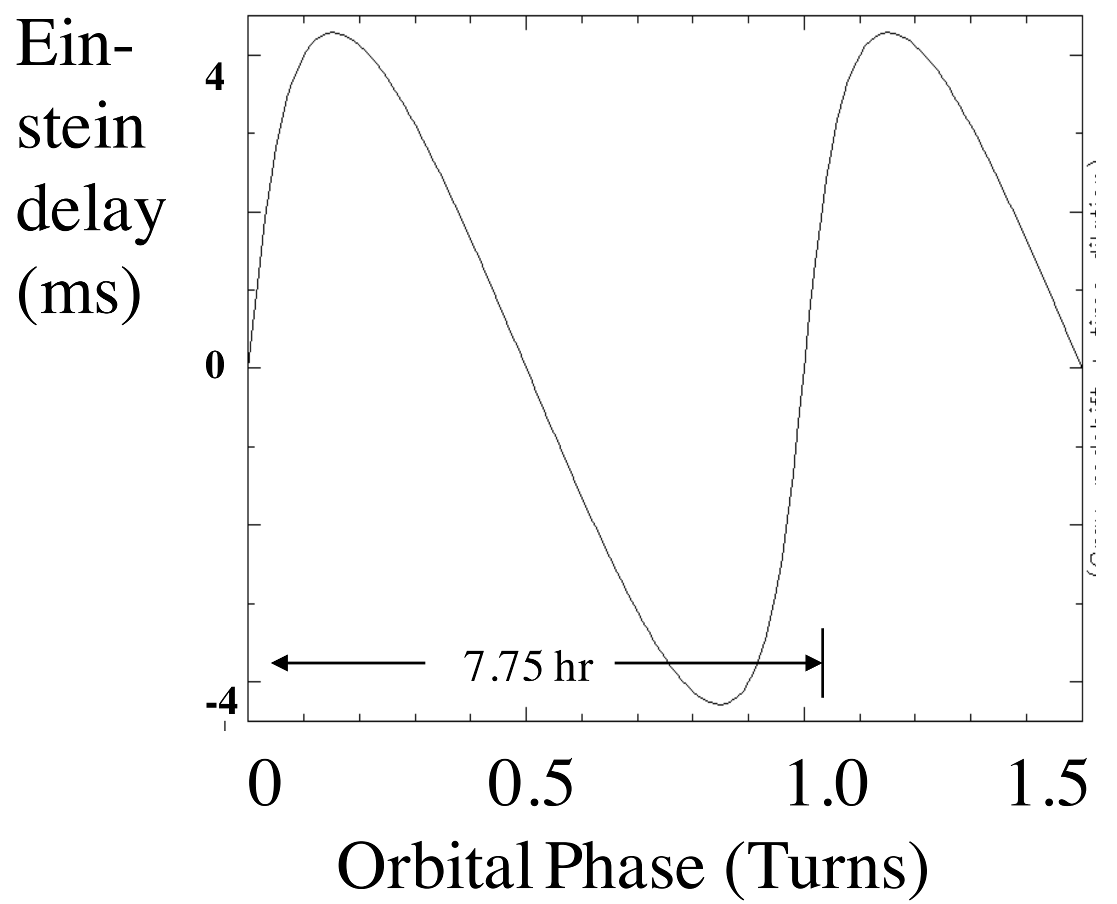


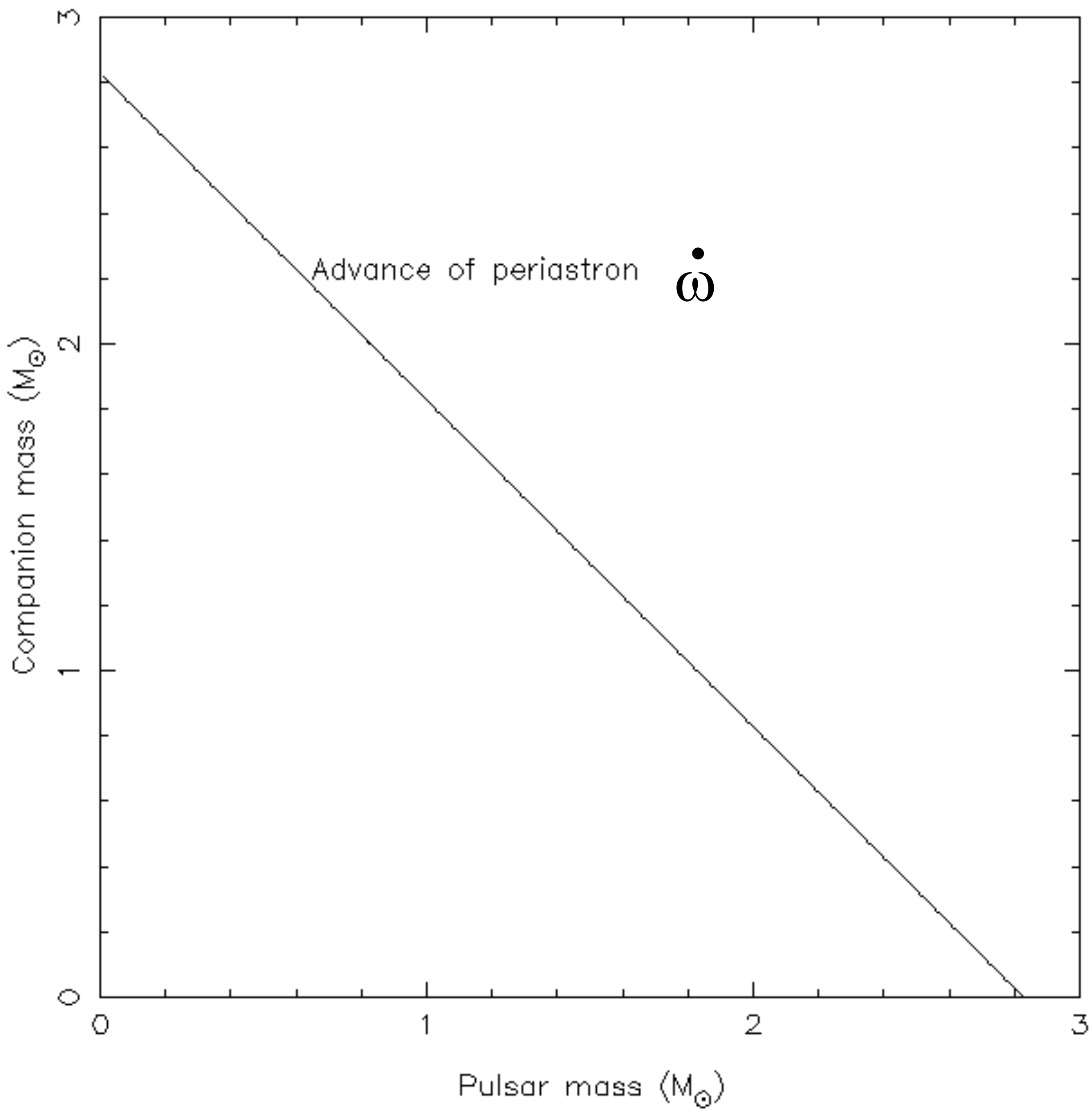
γ is composed of:

- **Gravitational redshift variations around the elliptical orbit**
- **Time dilation variations around the elliptical orbit**

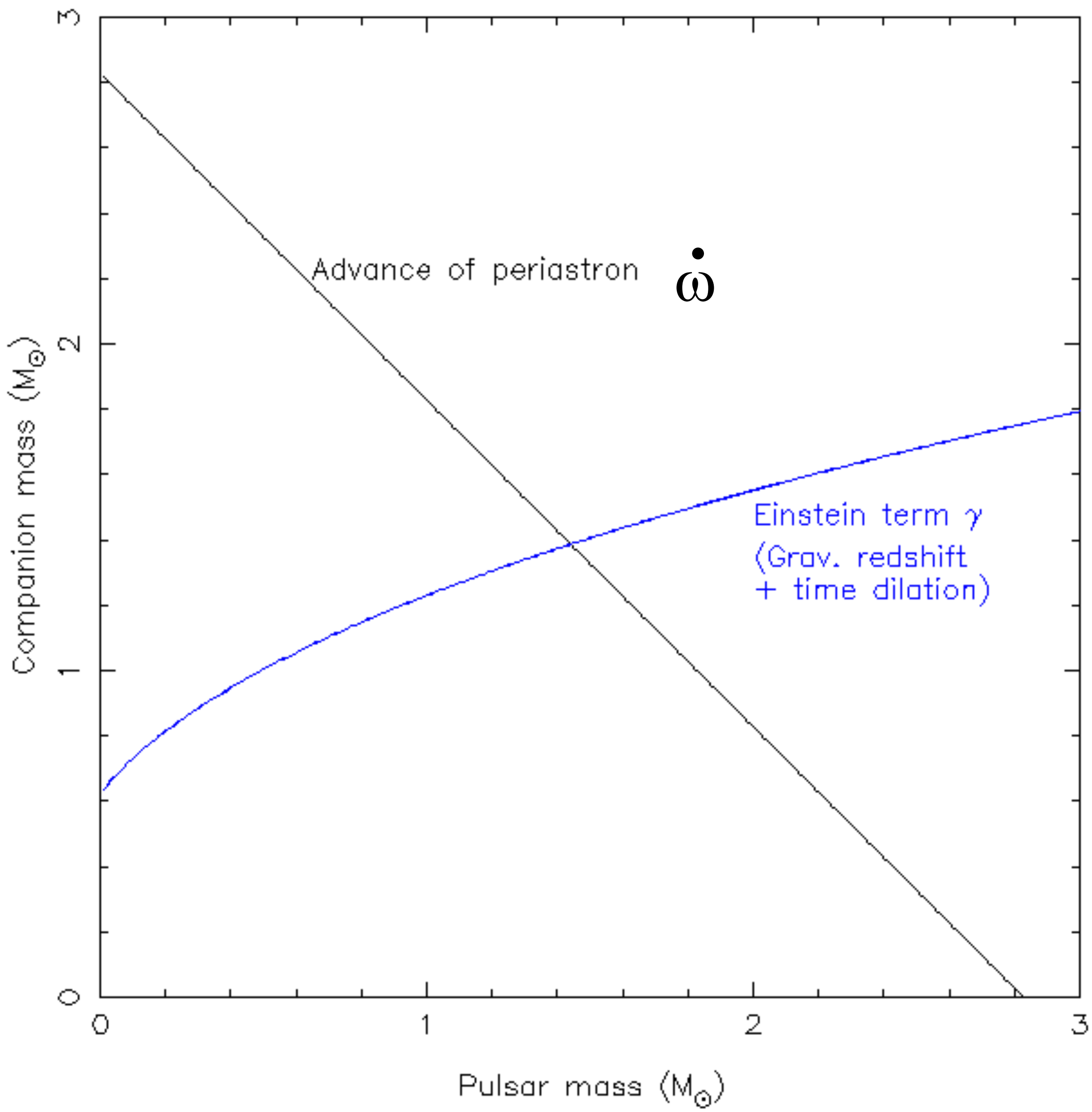
$\gamma = 0.0043$ s.

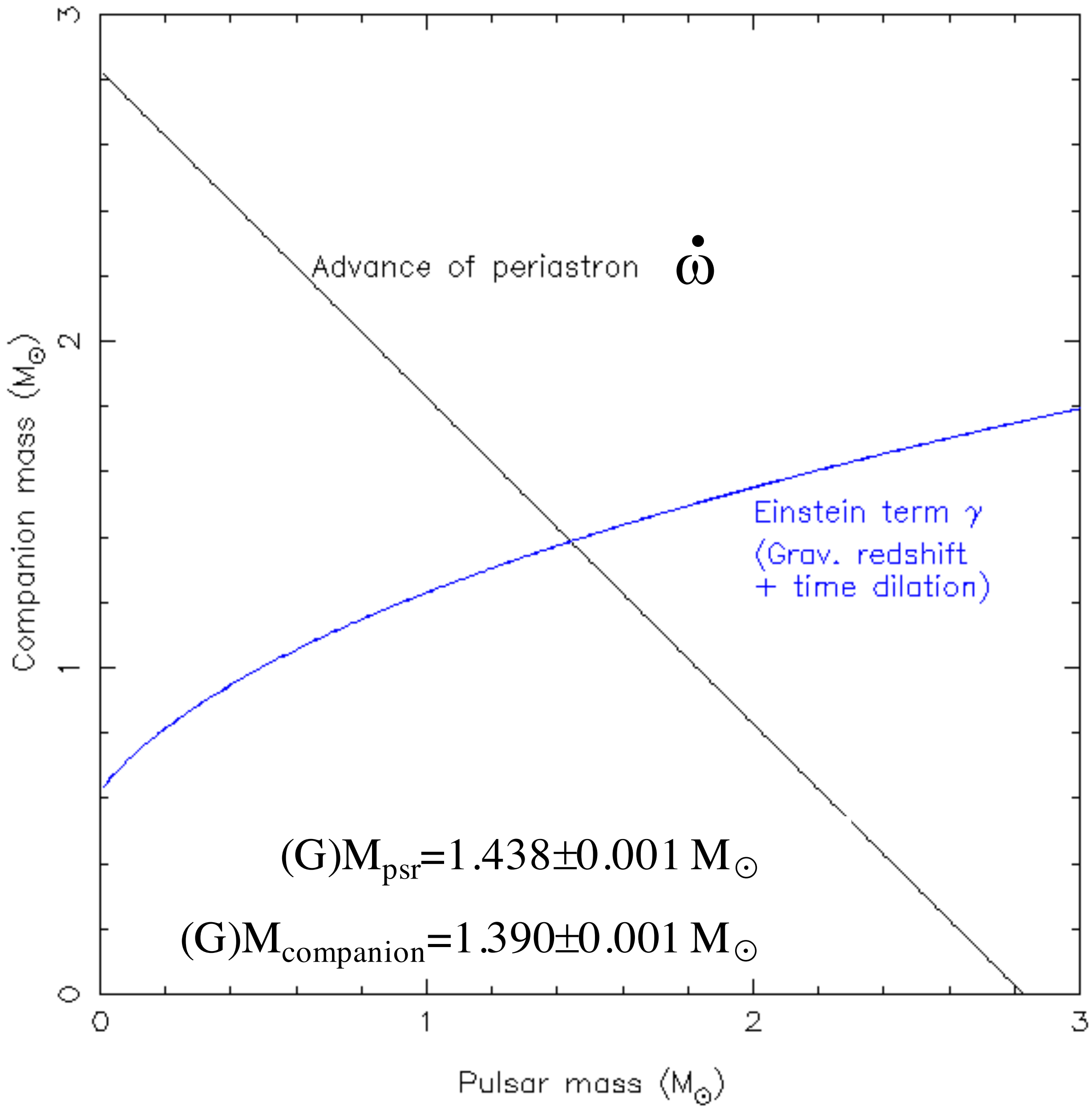
$$\gamma = e\,(P_b/2\pi)^{1/3}\, m_c\,(m_p+2m_c)\,/\,(m_p+m_c)^{4/3}$$





Advance of periastron $\dot{\omega}$
Companion mass ($M_\odot$)
Pulsar mass ($M_\odot$)
0
1
2
3
0
1
2
3

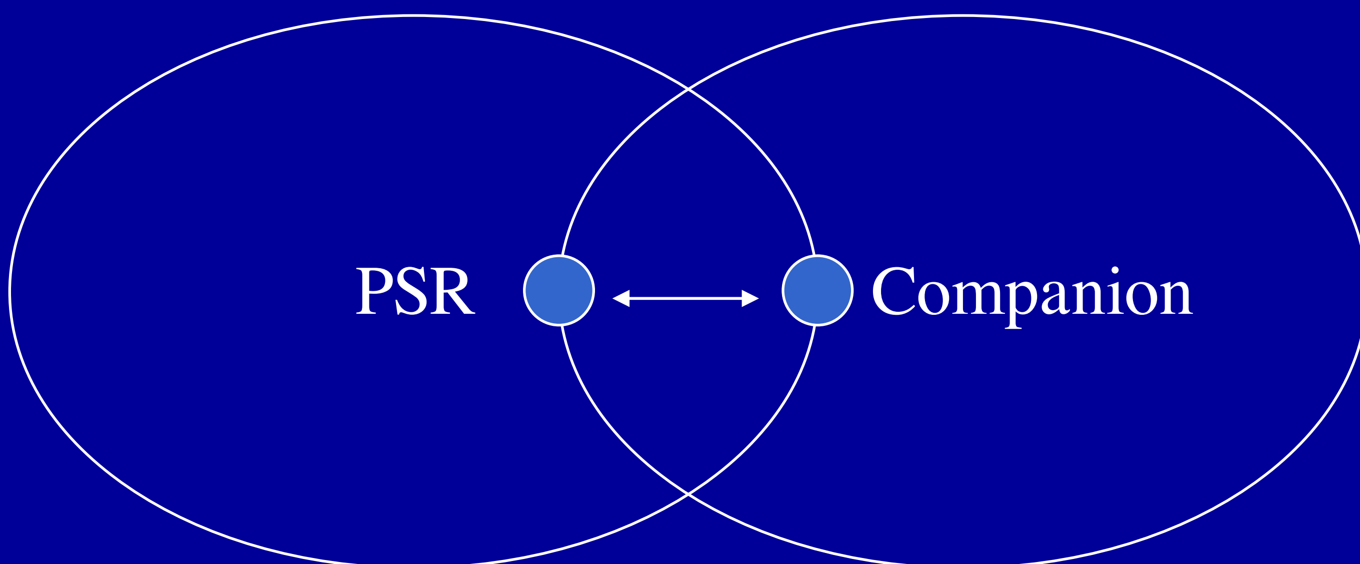

Advance of periastron $\dot{\omega}$
Einstein term γ
(Grav. redshift
+ time dilation)
Companion mass ($M_\odot$)
Pulsar mass ($M_\odot$)
0
1
2
3
0
1
2
3



Advance of periastron $\dot{\omega}$
Einstein term γ
(Grav. redshift
+ time dilation)
(G)M_{psr}=1.438±0.001 $M_\odot$
(G)$M_{companion}$=1.390±0.001 $M_\odot$
Companion mass ($M_\odot$)
Pulsar mass ($M_\odot$)
0
1
2
3
0
1
2
3

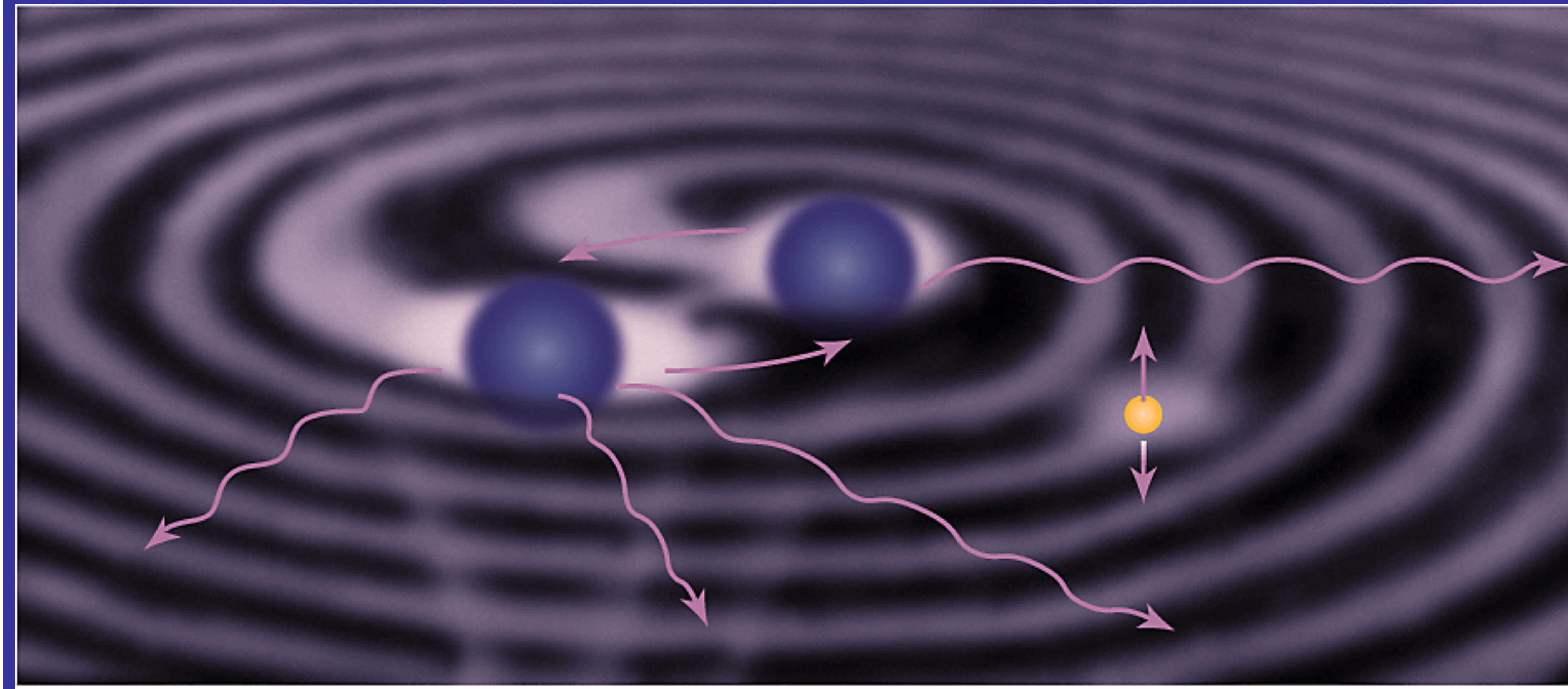
To use PSR B1913+16 as a relativistic laboratory, we measured seven independent quantities, from which *all* physical parameters of the system can be determined.

- Component masses
- Orbital inclination $i = 47.2$ deg
- *Absolute* separations (e.g. periastron separation is 1.1 R_{sun}).



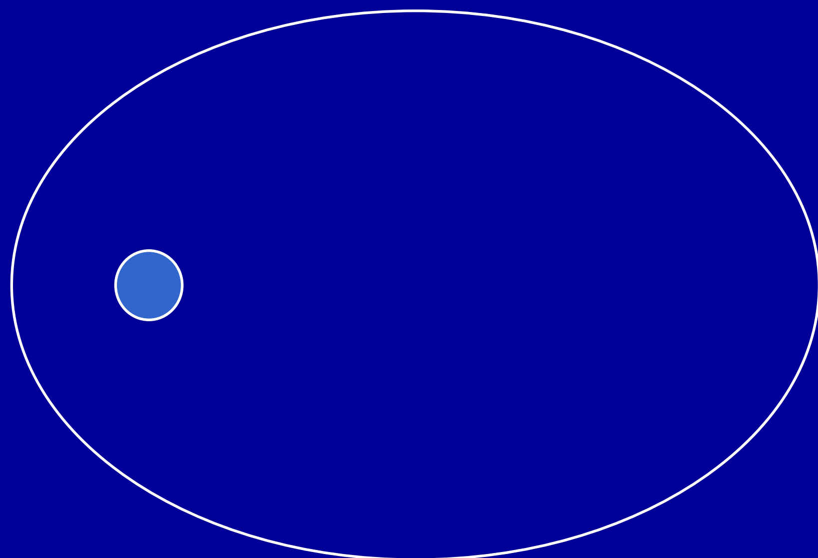
[redacted]

Gravitational waves from the binary system



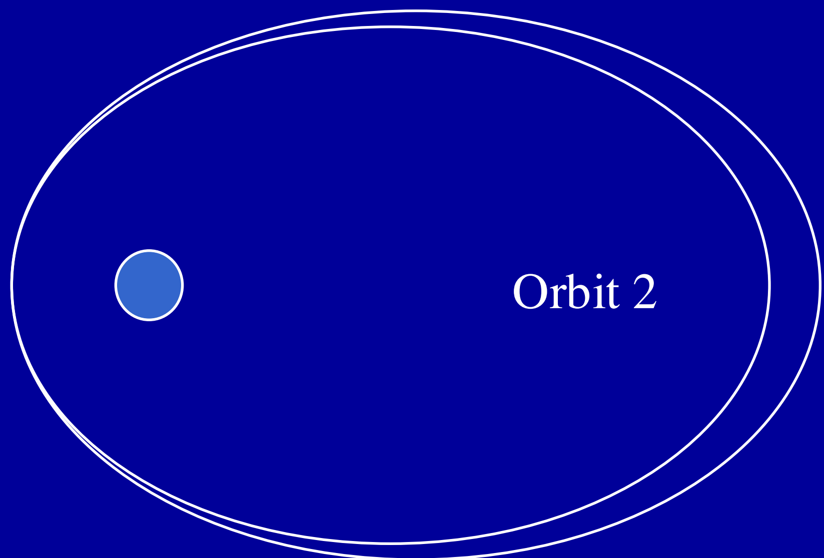
(ref: Arny)

Gravitational wave emission will lead to orbital decay as energy is radiated away

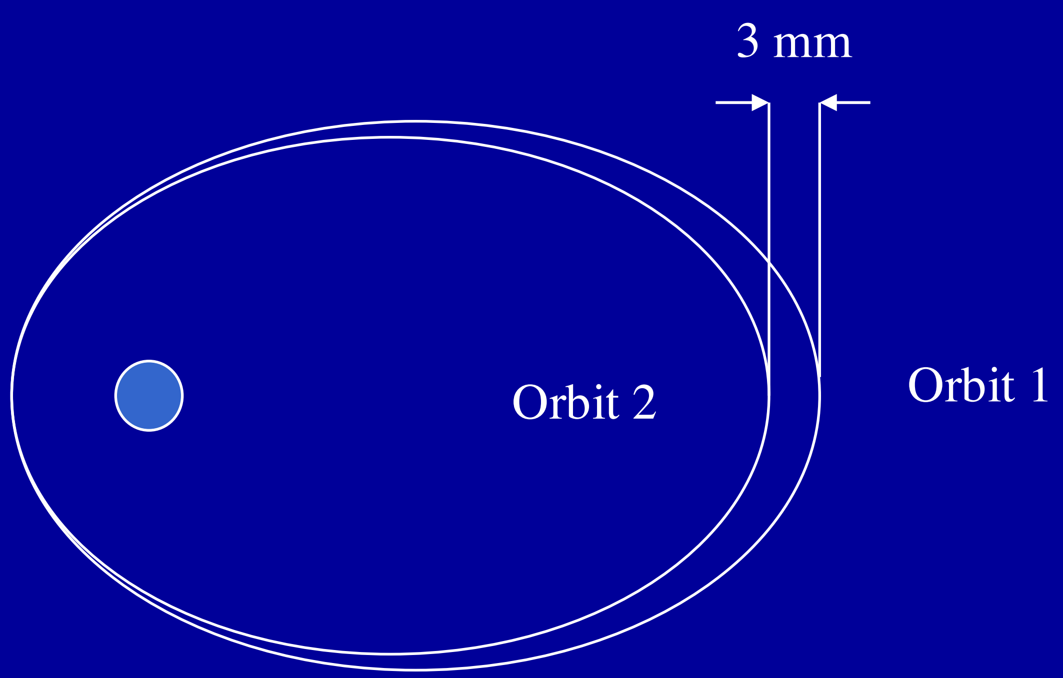


Orbit 1

Gravitational wave emission will lead to orbital decay as energy is radiated away



Gravitational wave emission will lead to orbital decay as energy is radiated away



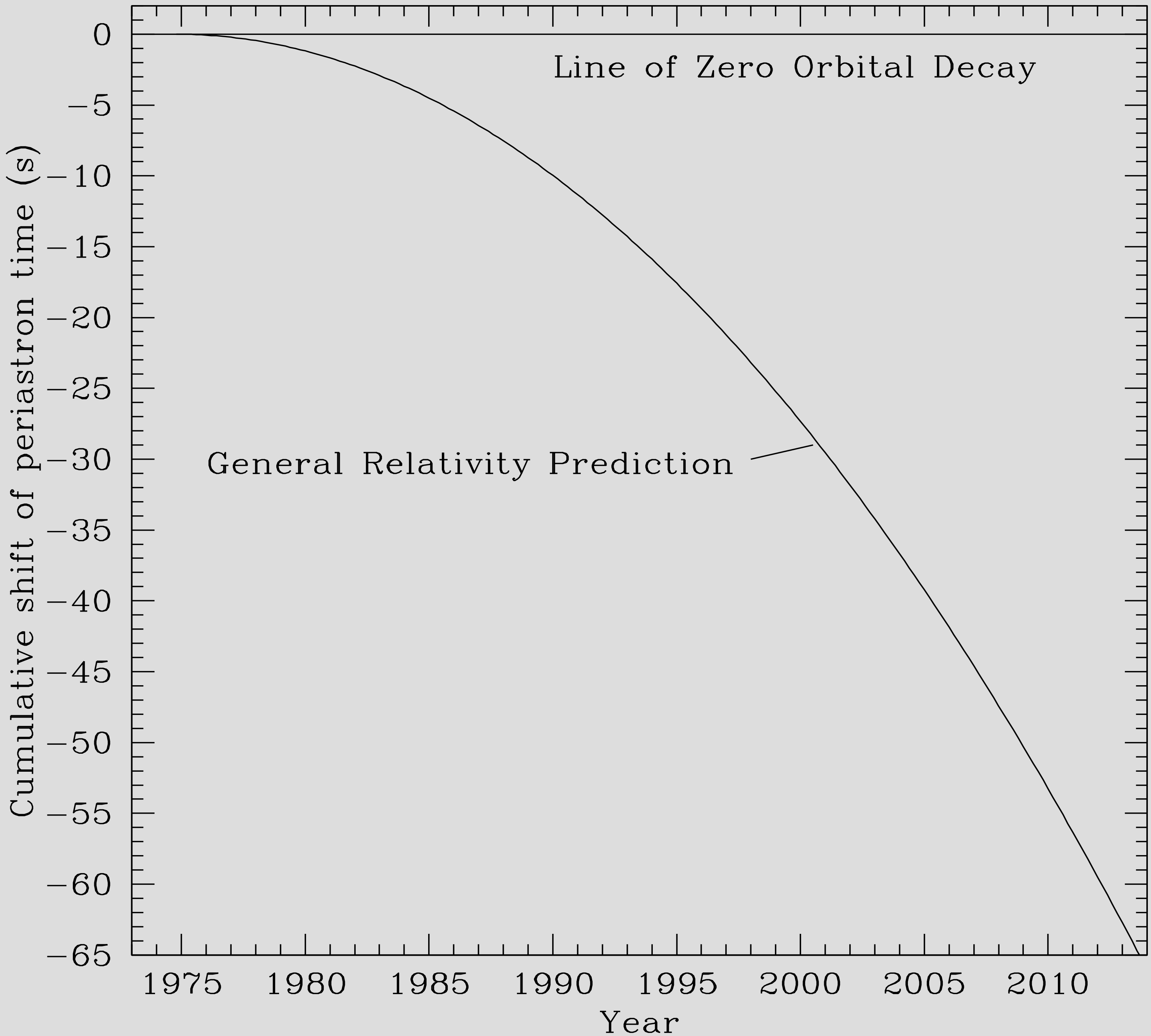
Predicted GR orbital decay rate, expressed as orbital period change, $\dot{P}_b$:

$$\dot{P}_b = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)^{-7/2}\times$$

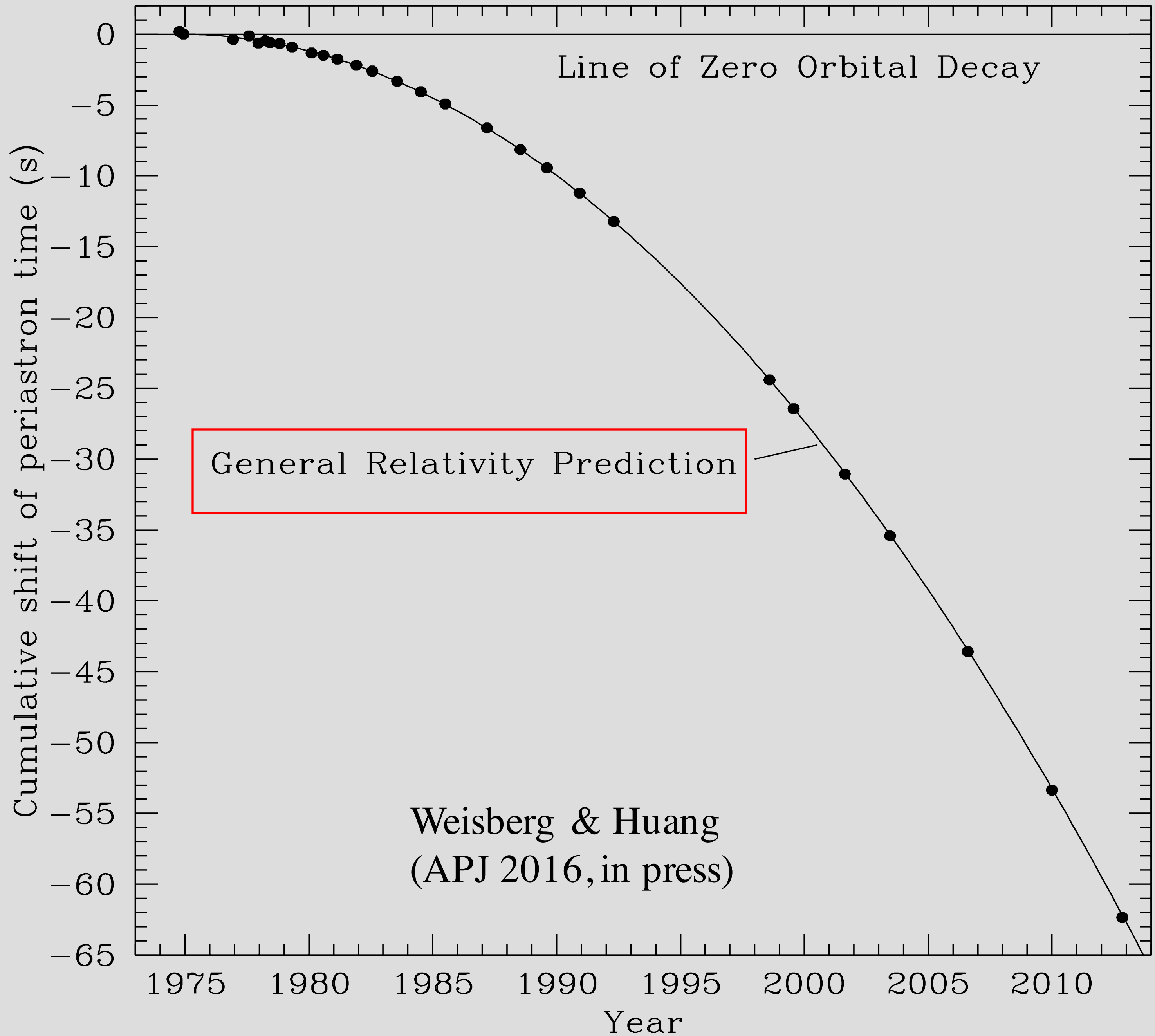
$$\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)m_p m_c(m_p+m_c)^{-1/3}.$$

$= (-2.40263 \pm 0.00005)\text{x}10^{-12}$ s / s)

Orbital decay of B1913+16



Orbital decay of B1913+16



However, the observed orbital period change $\dot{P}_b$, may have other causes besides gravitational radiation emission . . .

E.g., galactic *acceleration* of binary system w.r.t. solar system.

Classical Doppler equation (for *any* clock; e.g. the orbital period P_b):

$$v_{radial} = c\frac{\Delta P_b}{P_{bo}} = c\frac{P_b - P_{bo}}{P_{bo}}$$

$$a_{radial} \equiv \frac{d}{dt}(v_{radial}) = \frac{d}{dt}\left(c\frac{P_b - P_{bo}}{P_{bo}}\right) = \frac{c}{P_{bo}}\left(\frac{dP_b}{dt}\right)_{kinematic}$$

$$a_{radial} \rightarrow \left(\frac{dP_b}{dt}\right)_{kinematic}$$

Orbital decay rate of PSR B1913+16 (corrected for kinematic effect), compared to GR

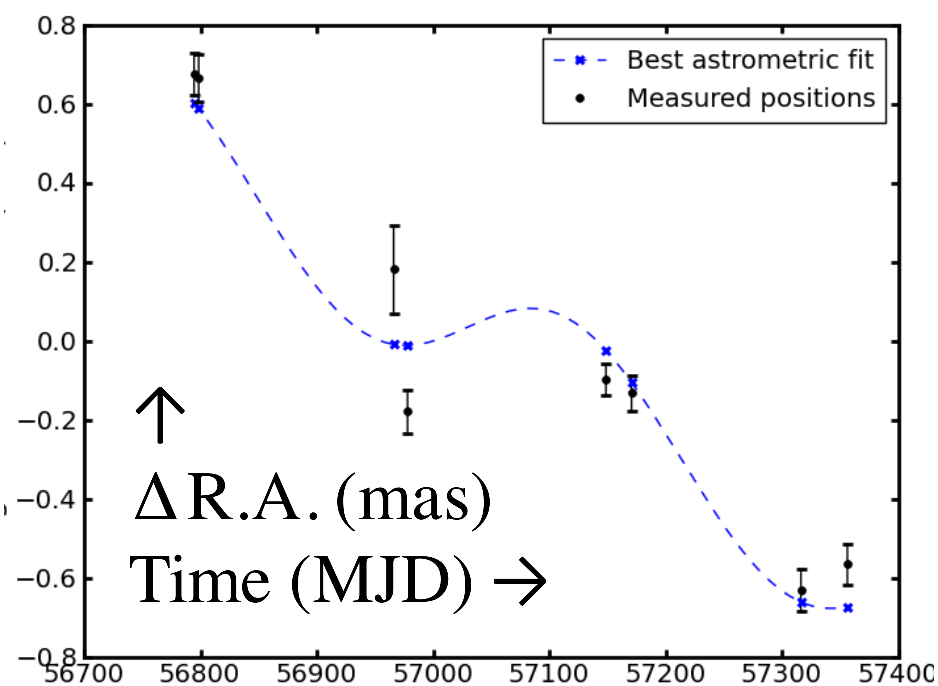
$$\frac{\dot{P}_{\mathrm{b,obs,corrected}}}{\dot{P}_{\mathrm{b,GR}}} = 0.9983 \pm 0.0016 \quad \text{[Weisberg \& Huang (2016)]}$$

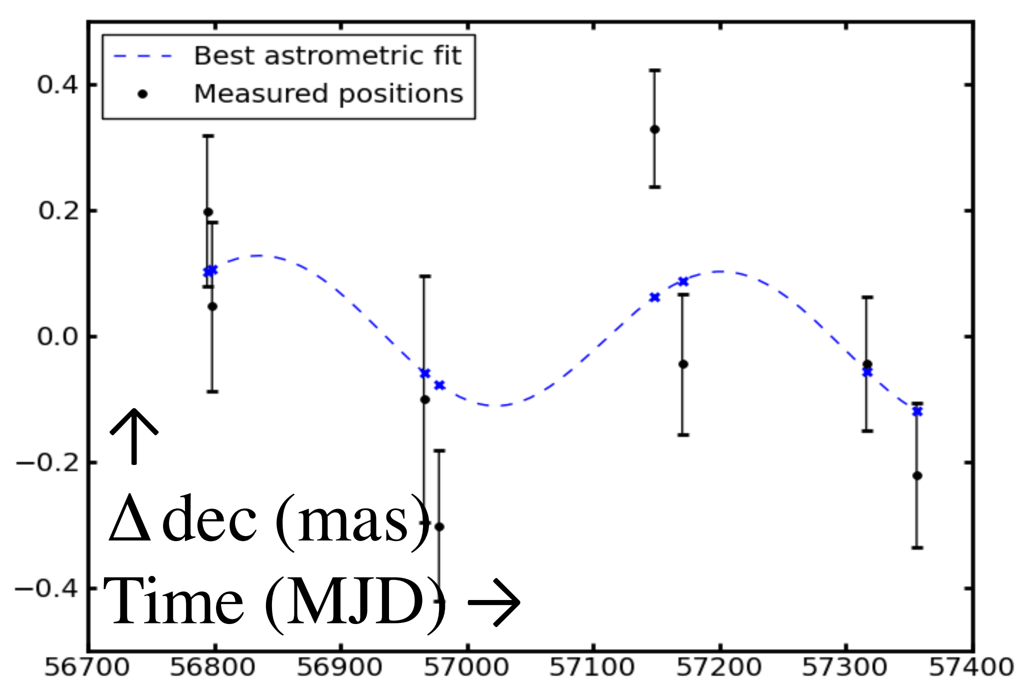
The uncertainty is dominated by uncertainty in kinematic effect, which is dominated by pulsar distance uncertainty (Weisberg et al 2008).

Pulsar parallax experiment to improve galactic acceleration correction to $\dot{P}_{\mathrm{b}}$ (Deller et al 2016).

$\pi = 0.18 \pm 0.05$ mas

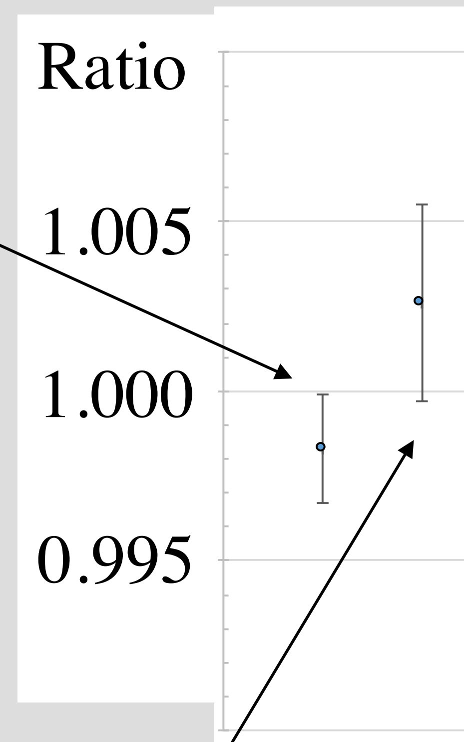
$d = 5.6\ (+2.1, -1.3)$ kpc





Orbital decay rate of PSR B1913+16 (*corrected for kinematic effect*), compared to GR

$$\frac{\dot{P}_{\mathrm{b,obs,corrected}}}{\dot{P}_{\mathrm{b,GR}}} = 0.9983 \pm 0.0016$$ [Weisberg & Huang (2016)]

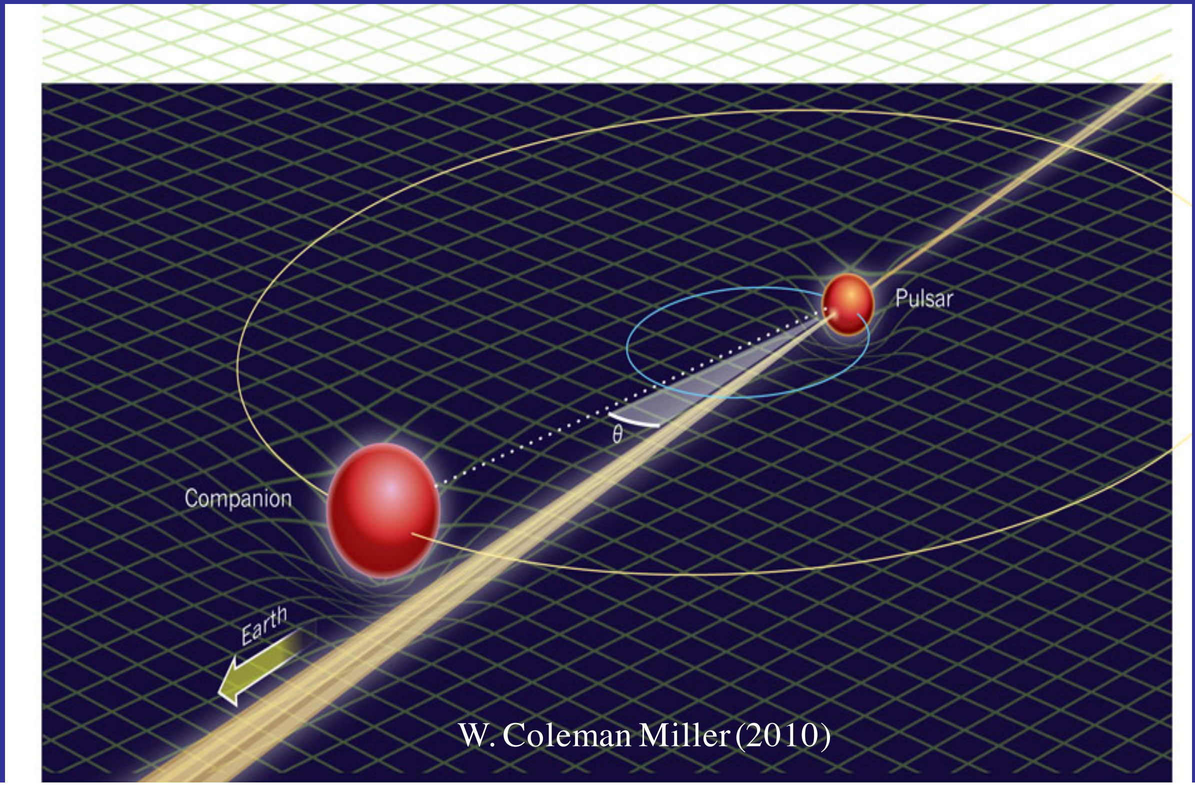


Now, with these new parallax measurements,

$$\frac{\dot{P}_{\mathrm{b,obs,corrected}}}{\dot{P}_{\mathrm{b,GR}}} = 1.0026 \pm 0.0029$$ [Deller et al (2016)]

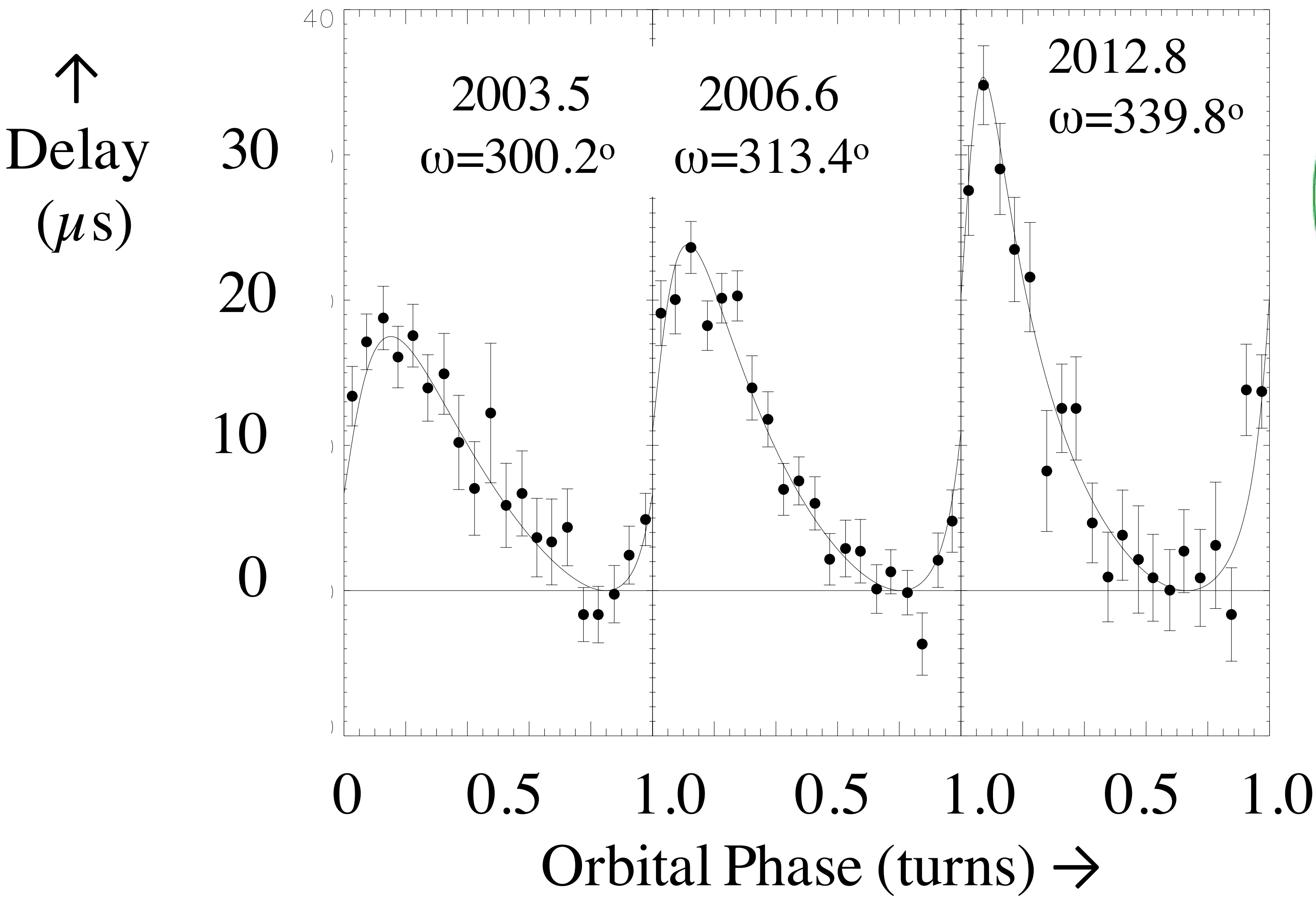
A New Relativistic Test in B1913+16: The "Shapiro" Gravitational Propagation Delay

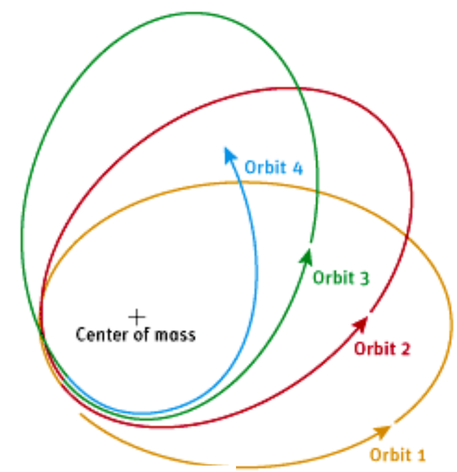
- "Fourth Classical Test of GR" -- I.I. Shapiro (1964)
- Signals are delayed when passing near a massive body, which curves spacetime in its vicinity.



W. Coleman Miller (2010)

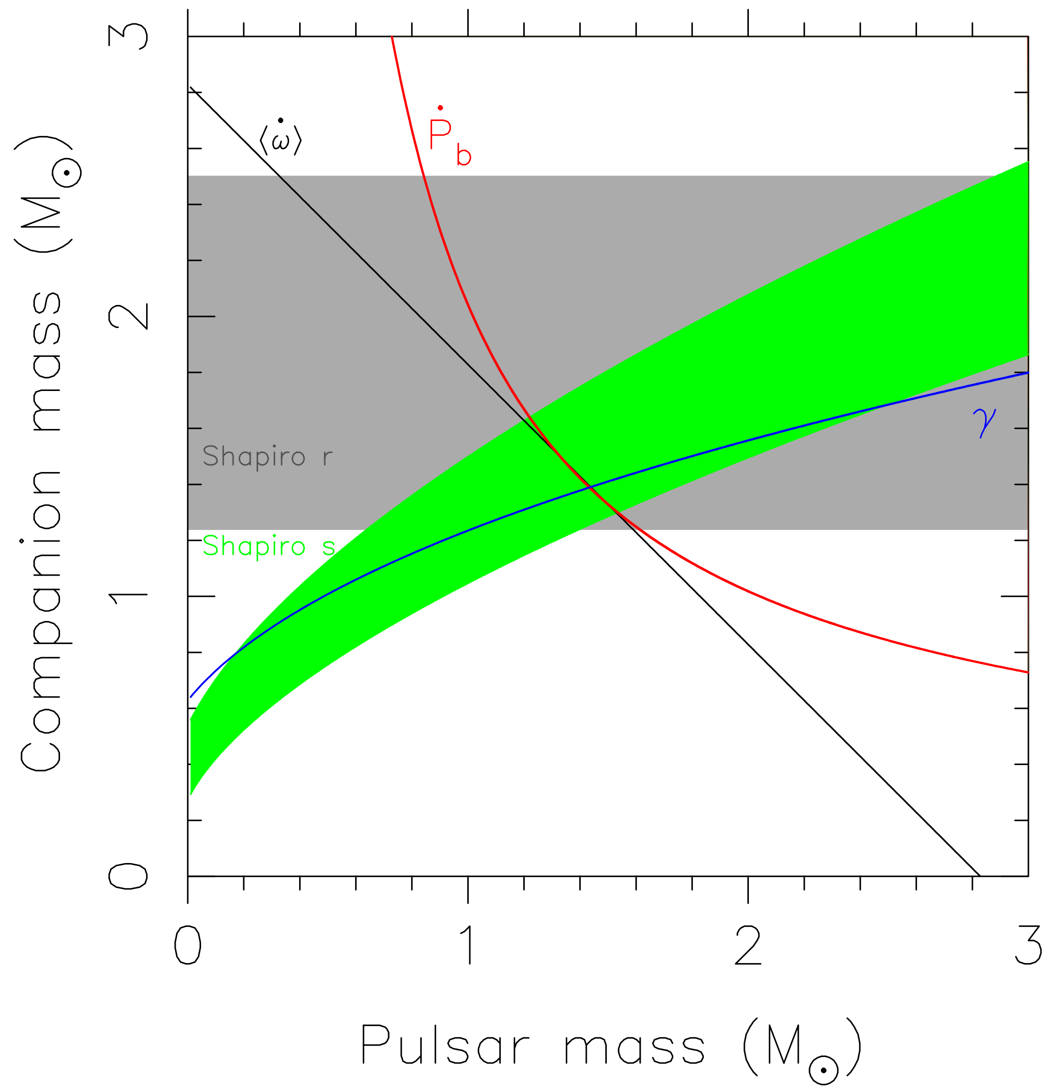
Another Pair of Relativistic Measurables: Shapiro Gravitational Propagation Delay





Weisberg & Huang (2016)

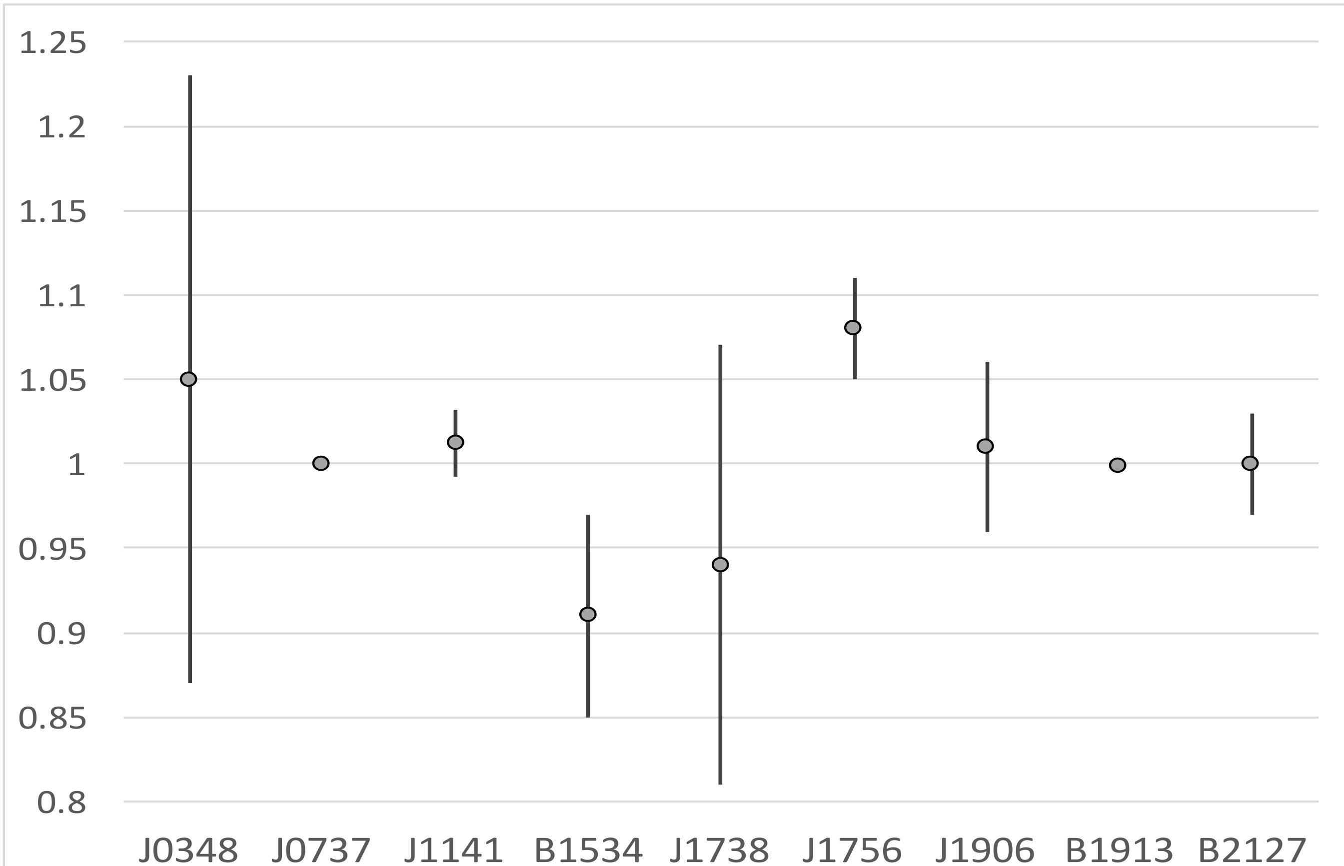
Each orbital measurable beyond the first seven, represents an independent test of relativistic gravitation



Weisberg & Huang (2016)

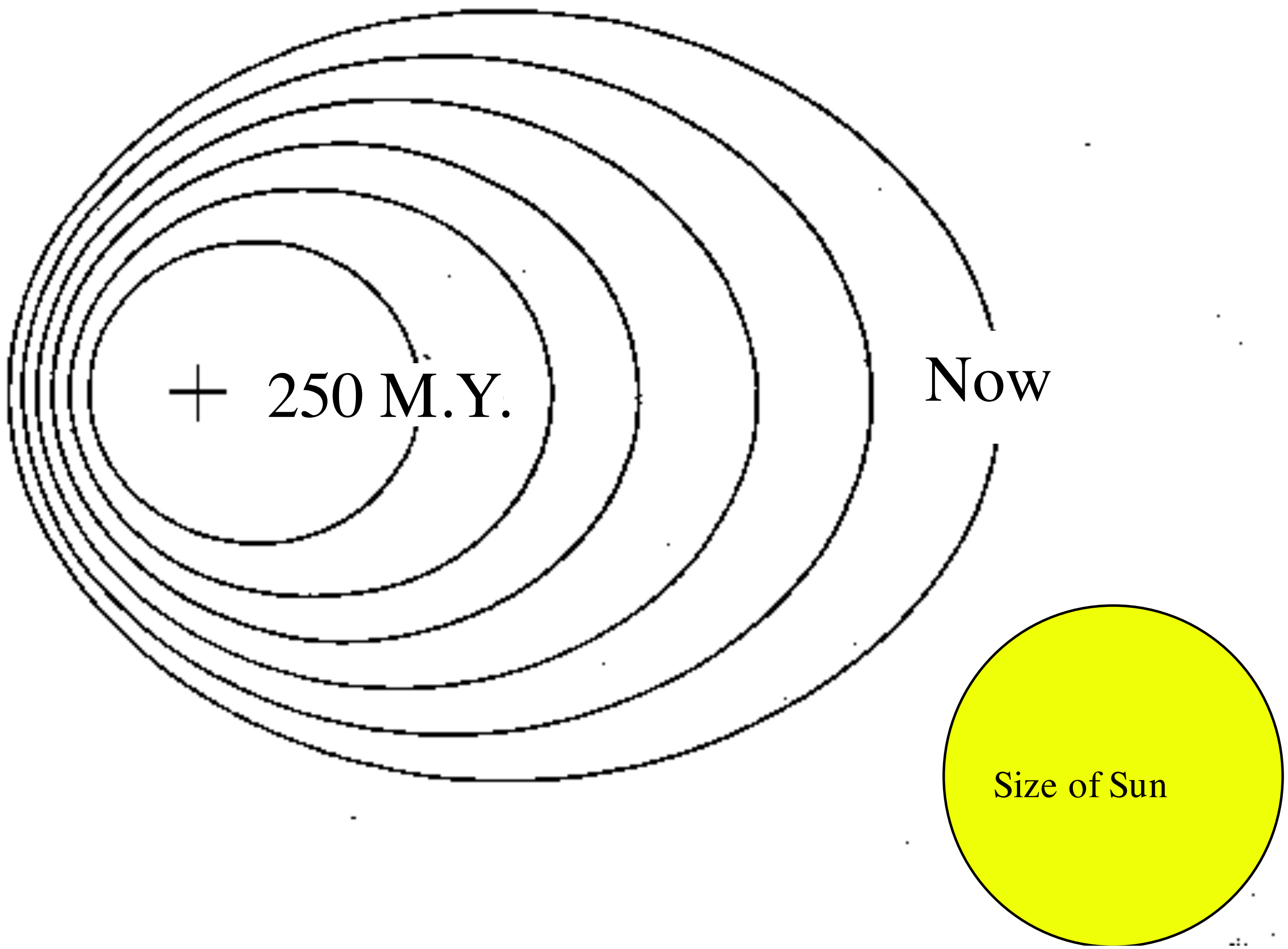
Comparison of Gravitational Radiation-Induced Orbital Decay with GR Prediction in Binary PSR

$$\frac{\dot{P}_{\mathrm{b,\ obs,\ corrected}}}{\dot{P}_{\mathrm{b,\ GR}}}$$



Data from Weisberg & Huang 2016, APJ, in press; plus:
--J0737: Wex, this conference.
--J1141: Vivek Krishnan, this conference.

The future fate of B1913+16 in 50 Million Year Timesteps



The (Experimental) Future for relativistic gravity tests

More terrestrial interferometer results, such as the LIGO dual-black hole merger observations in September, October (?), and December!

Near simultaneous multiwavelength / multimessenger observations

More binary pulsar tests of more relativistic parameters

Pulsar Timing Array measurements

Space interferometers

Thanks!

Comparison of Gravitational Radiation-Induced Orbital Decay with GR Prediction in Binary Pulsars

PSR	$\dot{P}_b^{intr}/\dot{P}_b^{GR}$	Ref.
J0348+0432	1.05 ± 0.18	Antoniadis et al. (2013)
J0737-3039	~~1.003 ± 0.014~~	~~Kramer et al. (2006)~~
J1141-6545	~~1.04 ± 0.06~~	~~Bhat, Bailes, & Verbiest (2008)~~
B1534+12	0.91 ± 0.06	Stairs et al. (2002)
J1738+0333	0.94 ± 0.13	Freire et al. (2012)
J1756-2251	1.08 ± 0.03	Ferdman et al. (2014)
J1906+0746	1.01 ± 0.05[a]	van Leeuwen et al. (2015)
B1913+16	0.9983 ± 0.0016	This work
B2127+11C	1.00 ± 0.03	Jacoby et al. (2006)

[a] Assumes negligible proper motion.

Wex talk, prelim:
0.9999±0.0001

1.012±0.02
(Vivek Krishnan Poster)

(From Weisberg & Huang 2016, APJ, in press)