Measurements of Neutron Star Masses

with a strong emphasis on millisecond binary radio pulsar timing

David Nice, Lafayette College

Physics of Neutron Stars 2014, Saint Petersburg

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1. Motivation
2. How to measure neutron star masses by timing binary millisecond pulsars
3. Interesting recent measurements of neutron star masses.
4. Why there will be more and better measurements in the future.

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Motivation 1. Nuclear equation of state.

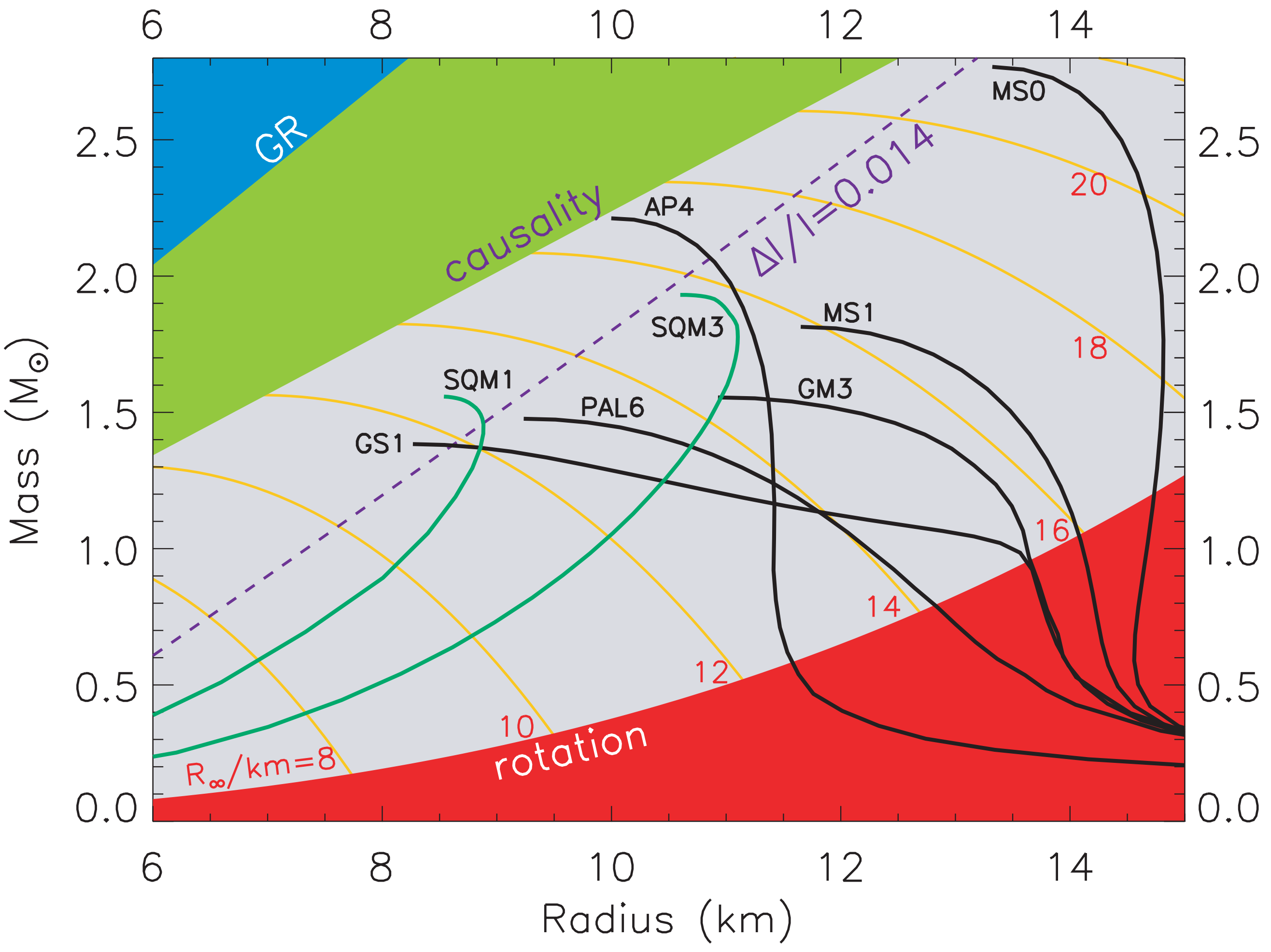


Figure: Lattimer & Prakash 2004 (Science 304: 536)

Motivation 2. Pulsar Binary Evolution

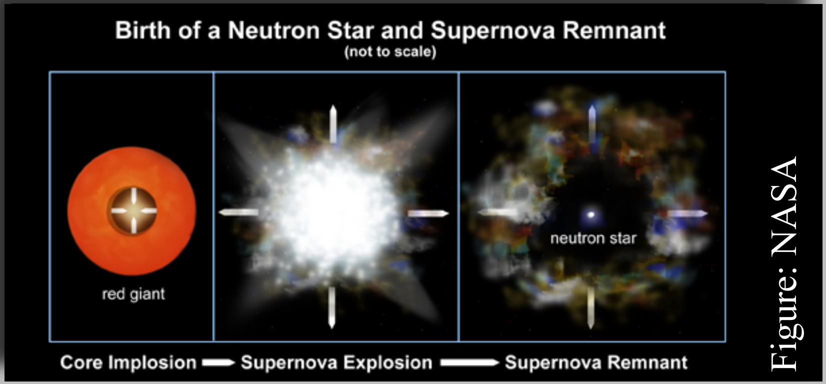


Figure: NASA

Birth Mass

+

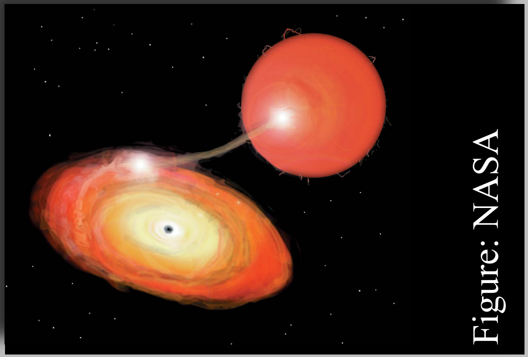
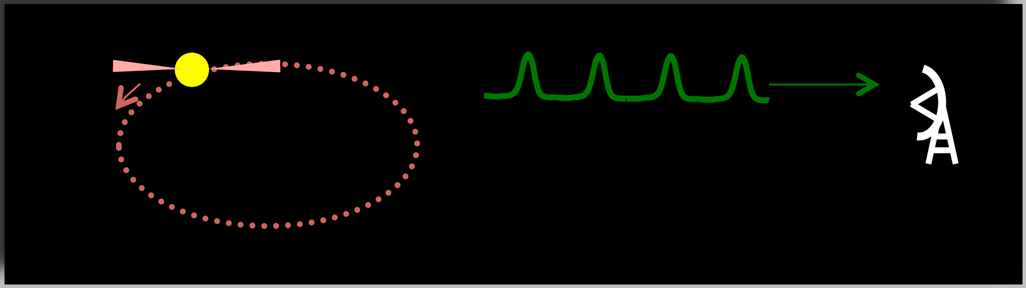


Figure: NASA

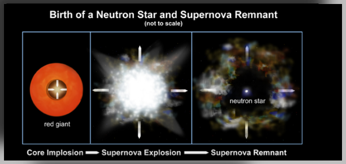
Accreted Mass
(for recycled pulsars)

=



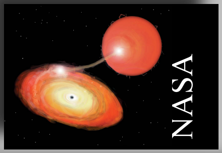
Observed Mass

Motivation 2. Pulsar Binary Evolution



Birth Mass

+



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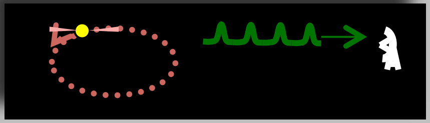
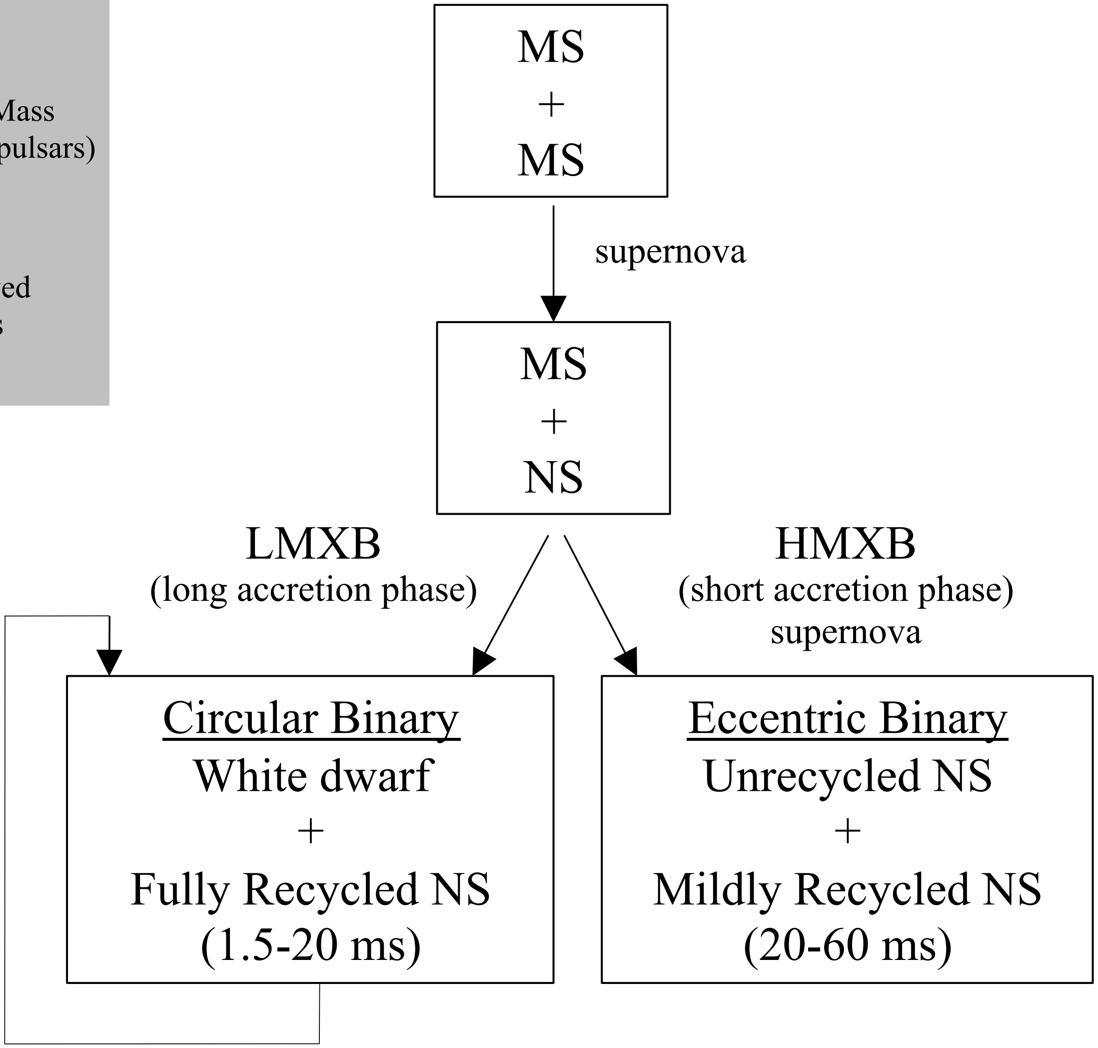


Observed
Mass



MS
+
MS

supernova

MS
+
NS

LMXB
(long accretion phase)

HMXB
(short accretion phase)
supernova

<u>Circular Binary</u>
White dwarf
+
Fully Recycled NS
(1.5-20 ms)

<u>Eccentric Binary</u>
Unrecycled NS
+
Mildly Recycled NS
(20-60 ms)

Ablation of companion
Additional accretion
(black widow & redback systems)

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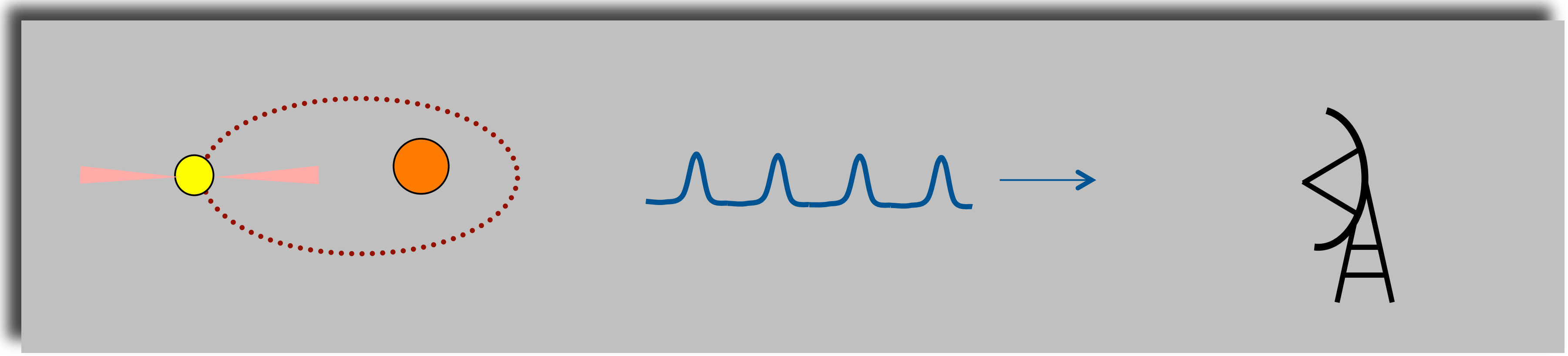
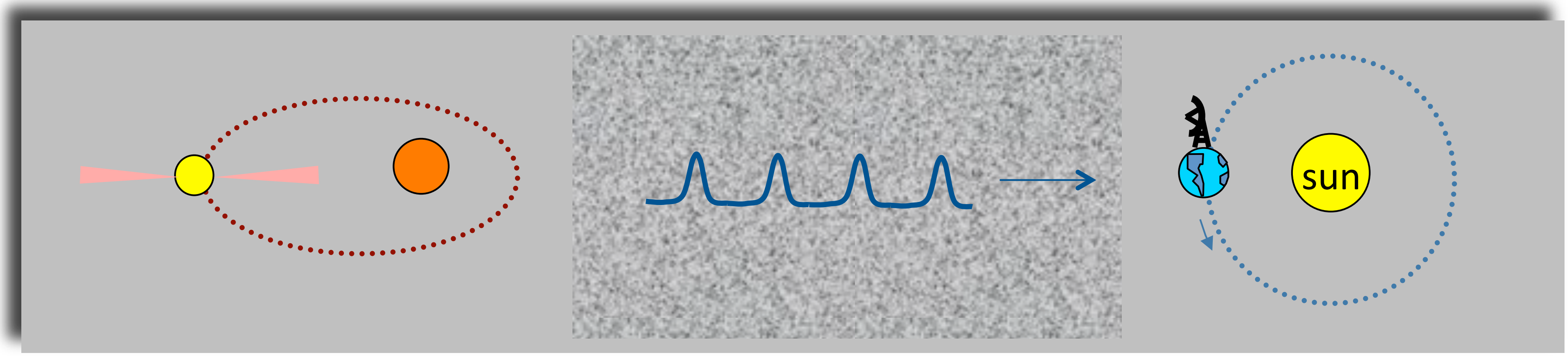
Timing the pulses.
Mapping out an orbit.



Timing the pulses.
Mapping out an orbit.
Actually, it is a little more complicated….



rotation period
rotation period derivative
timing noise

Keplerian orbital elements
relativistic orbital elements

kinematic perturbations of orbital elements (secular and annual phenomena)

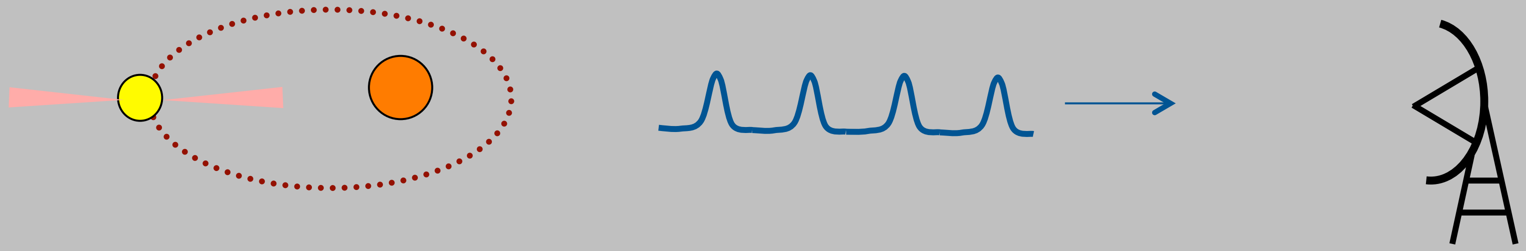
dispersion measure
dispersion meas. variations

nanohertz gravitational waves

position
proper motion
parallax

solar wind dispersion

Timing the pulses.
Mapping out an orbit.



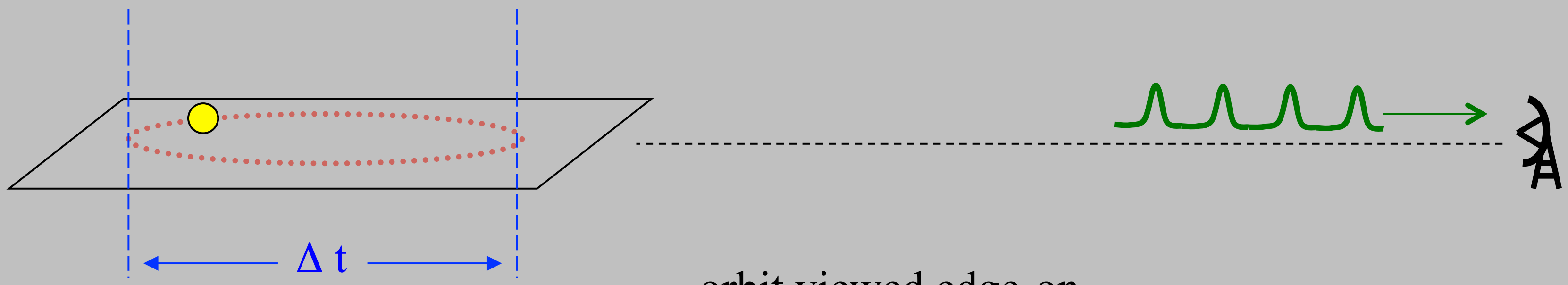
In classical physics physics (non-relativistic), the orbit is characterized by:

- orbital period
- semi-major axis projected along the line-of-sight
- eccentricity
- angle of periastron
- time of periastron passage

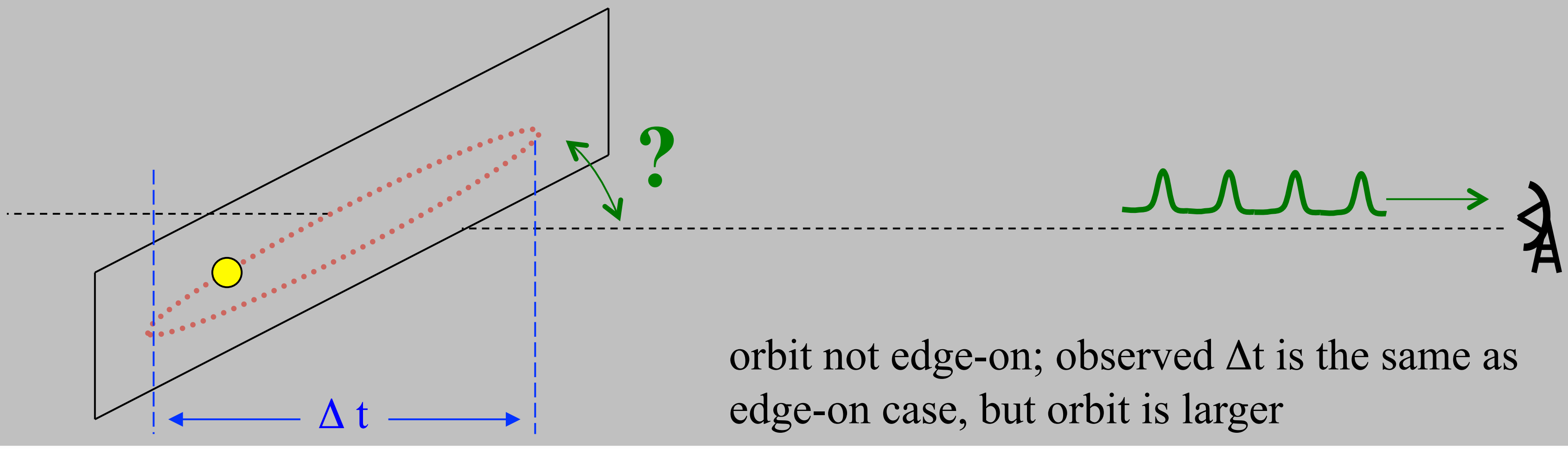
The motion of the pulsar is determined by the gravitational interaction between the pulsar and companion stars, which depends on the pulsar mass, m_1, and the companion mass, m_2.
However, the masses cannot be directly inferred from the parameters listed above.
Why not?→ see next two slides

Ambiguities in observations of a classical radio pulsar orbit

1. Orbit inclination is unknown.



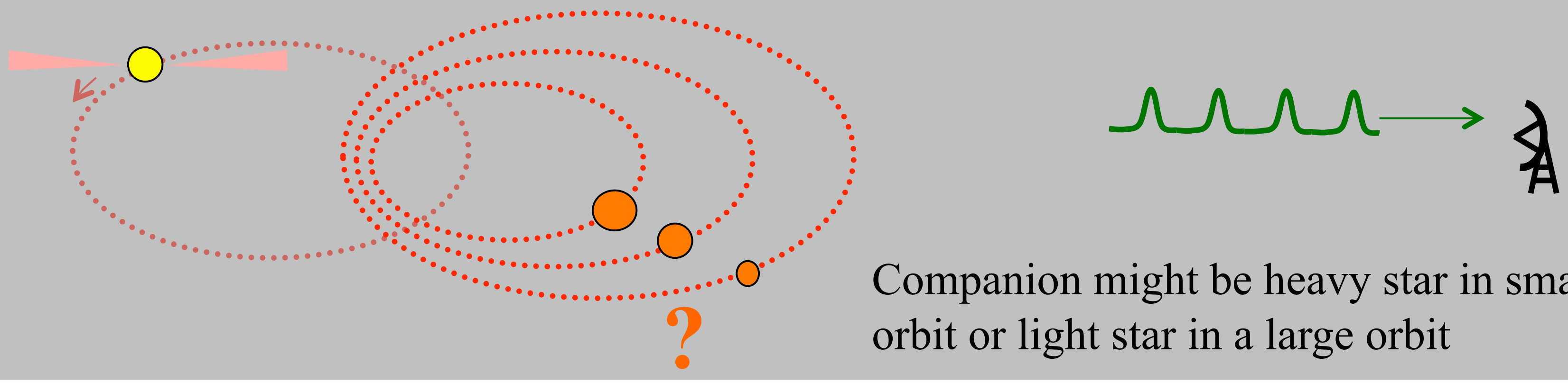
orbit viewed edge-on



orbit not edge-on; observed Δt is the same as edge-on case, but orbit is larger

Ambiguities in observations of a classical radio pulsar orbit

2. Characteristics of the companion star and its orbit are unknown.



Companion might be heavy star in small orbit or light star in a large orbit

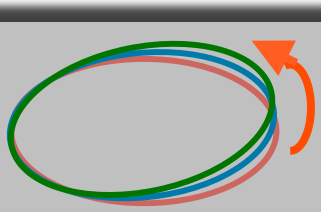
Because of these ambiguities, pulsar timing observations of a classical orbit does not tell us everything we want to know about the orbital system. In particular, we cannot infer either the pulsar mass, m_1, or the companion mass, m_2.

We need <u>two</u> additional measurements.

$$\left(\frac{2\pi}{P_b}\right)^2 \frac{(a_1 \sin i)^3}{G} = f_1 = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$

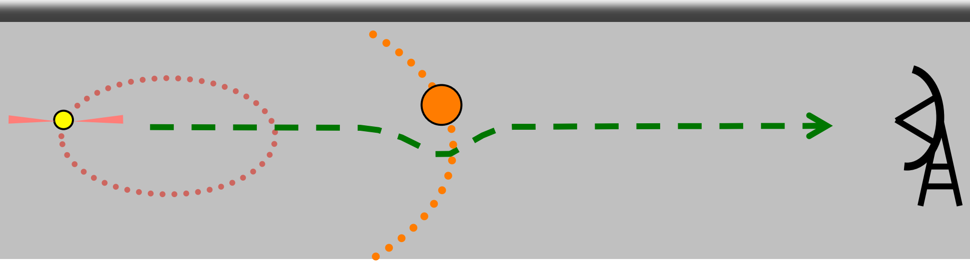
Obtaining additional orbital measurements:
1. Relativistic orbital phenomena

Precession



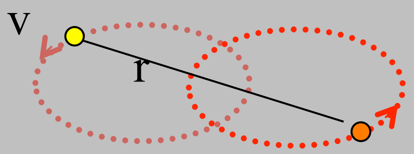
$$\dot{\omega} = 3\,\frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\left[(m_1+m_2)\right]^{2/3}$$

Shapiro Delay



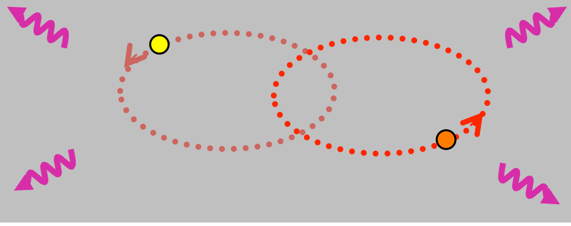
$$\Delta t = 2\frac{G}{c^3}m_2\,\ln\left[\,1-\sin i\,\sin(\varphi-\varphi_0)\,\right]$$

Grav Redshift/Time Dilation



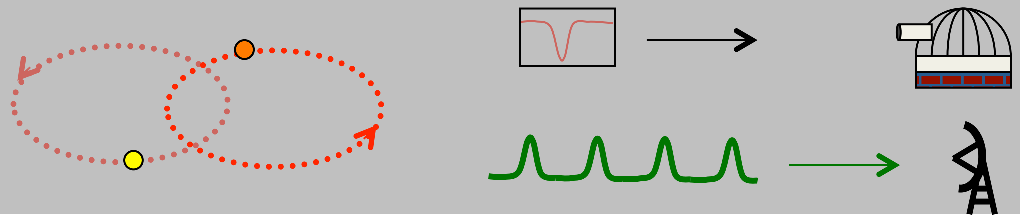
$$\gamma = \frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{1/3} e\,\frac{m_2(m_1+2m_2)}{(m_1+m_2)^{4/3}}$$

Gravitational Radiation



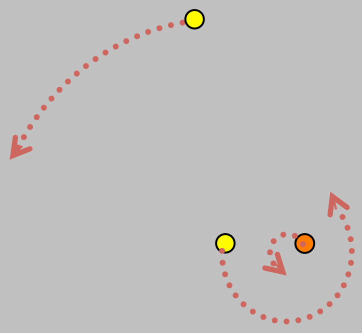
$$\dot{P}_b = -\left(\frac{192\pi}{5}\right)\frac{G^{5/3}}{c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{1}{(1-e^2)^{7/2}}\,\frac{m_1 m_2}{(m_1+m_2)^{1/3}}$$

Obtaining additional orbital measurements:
2. Classical observations beyond the pulsar binary motion



Observation of companion star orbit

$$\frac{m_1}{m_2} = \frac{a_1 \sin i}{a_2 \sin i}$$



Triple system:
pulsar with two companion stars

Three-body system cannot be solved analytically. Numerical integration yields mass and inclination values for all three bodies.

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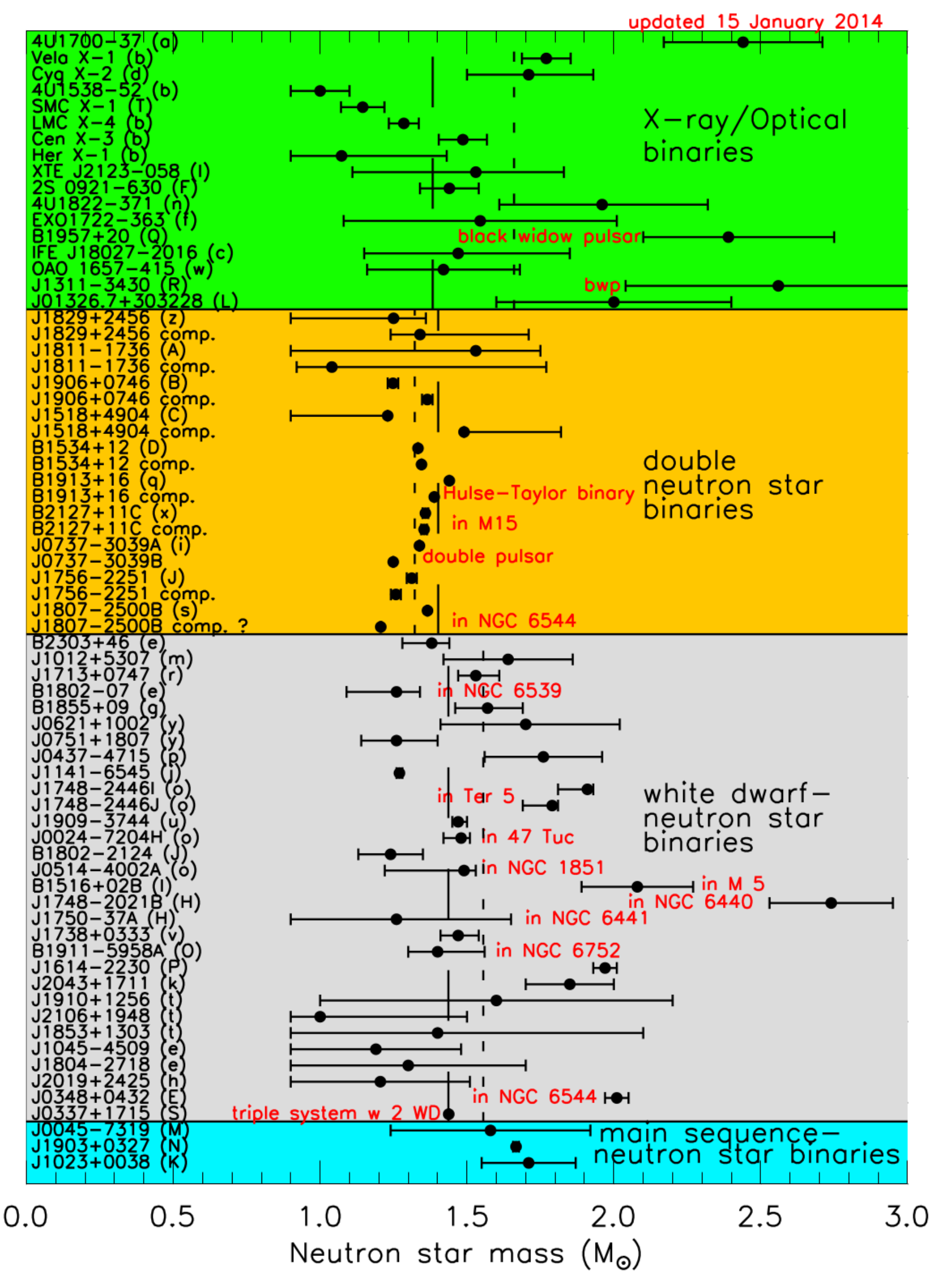
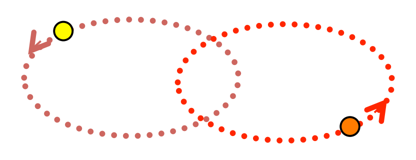
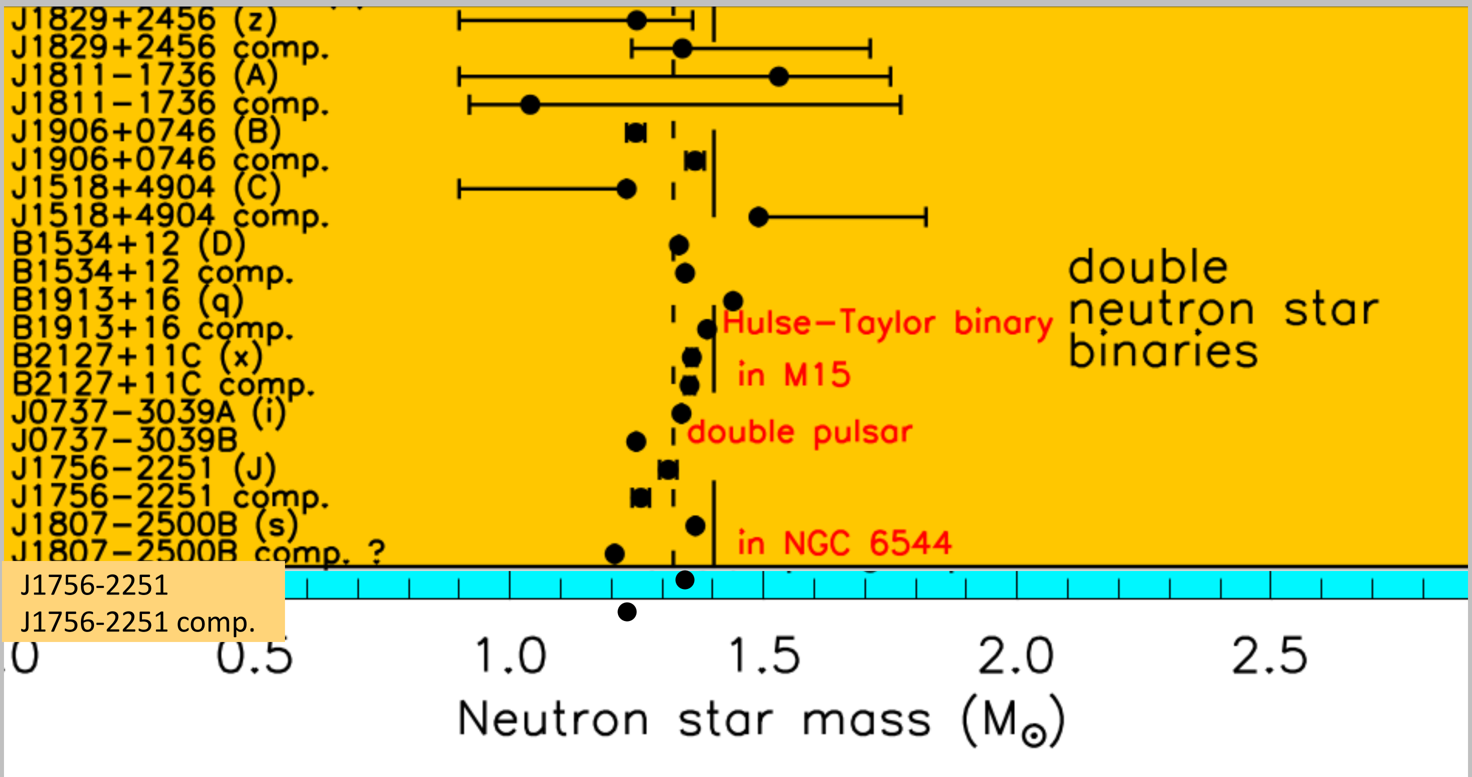


Figure: Jim Lattimer
stellarcollapse.org/nsmasses

Neutron Star-Neutron Star binaries

- Mildly recycled pulsars (P~20 to 60 ms)
- Highly eccentric orbits
- Short orbital periods (usually)





Notes:

PSR J1756-2251. Ferdman et al 2014 (MNRAS in press) m_1=1.230(7) m_2=1.341(7).

PSRJ1906+0746. van Leeuwen et al 2014 (in prep). Young pulsar. m_1=1.323(11), m_2=1.290(11). Nature of companion unclear.

PSRJ1807-2500B=NGC6544B. Lynch et al 2012 (ApJ 745:109). P=4.8 ms, fully recycled. Nature of companion unclear. Likely that present system formed in exchange interaction.

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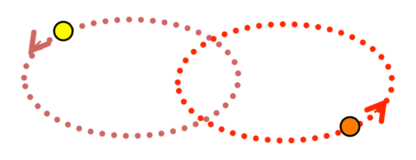

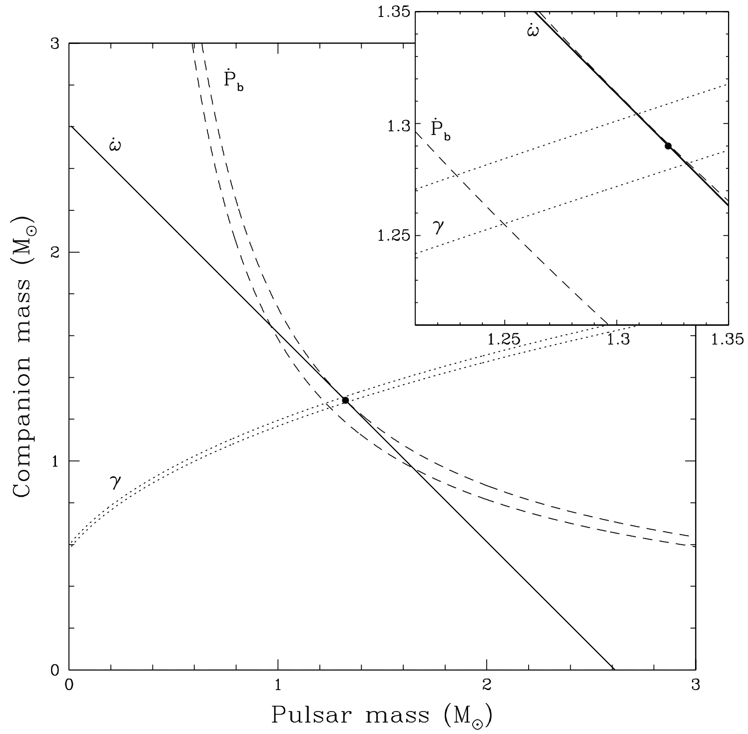

Figure 8. Mass-mass diagram for the ephemeris presented in Table 3. The lines represent the values of m_1 and m_2 allowed by the three measured post-Keplerian parameters: $\dot{\omega}$ (the solid line), γ (the dotted lines) and $\dot{P}_b$ (the dashed lines). The dot indicates the best-fit value for m_1 and m_2.

$$\dot{\omega} = 3\,\frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\left[(m_1+m_2)\right]^{2/3}$$

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Example of measuring m1, m2
PSR J1906+0746, 4 hr orbit, e=0.085
Leeuwen et al 2014, ApJ, submitted

Precession rate:

7.5841±0.0005 deg/yr

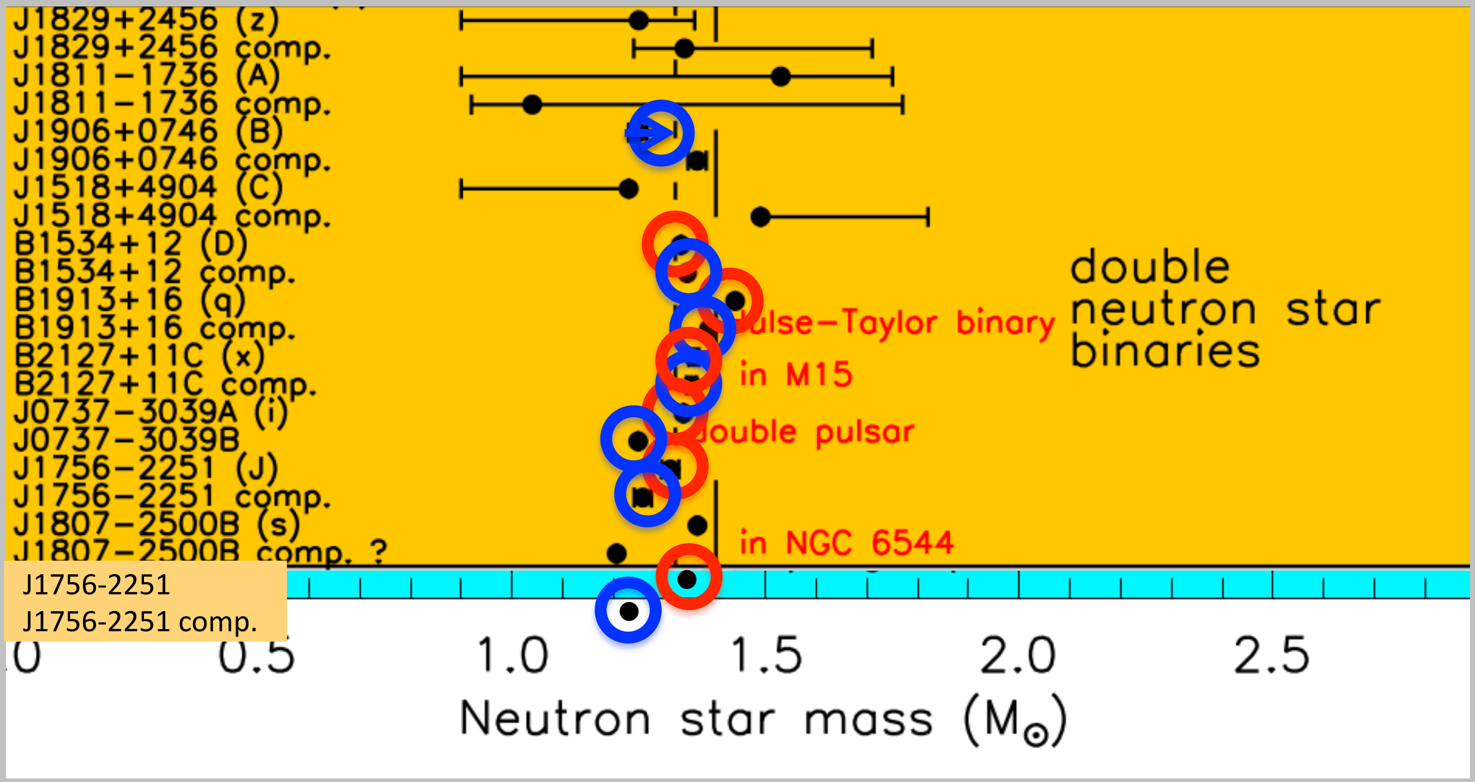
➔ $m_1+m_2=2.6133\pm0.0002M_\odot$

Precession and γ:

$m_1=1.323\pm0.011M_\odot$
$m_2=1.290\pm0.011M_\odot$

○ Mildly recycled (spun-up pulsar)

○ Not recycled



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Summary

- *Unrecycled* neutron stars: $1.23 M_\odot$ to $1.38 M_\odot$.

  Caveat: almost all measured in the same type of system, NS-NS binaries

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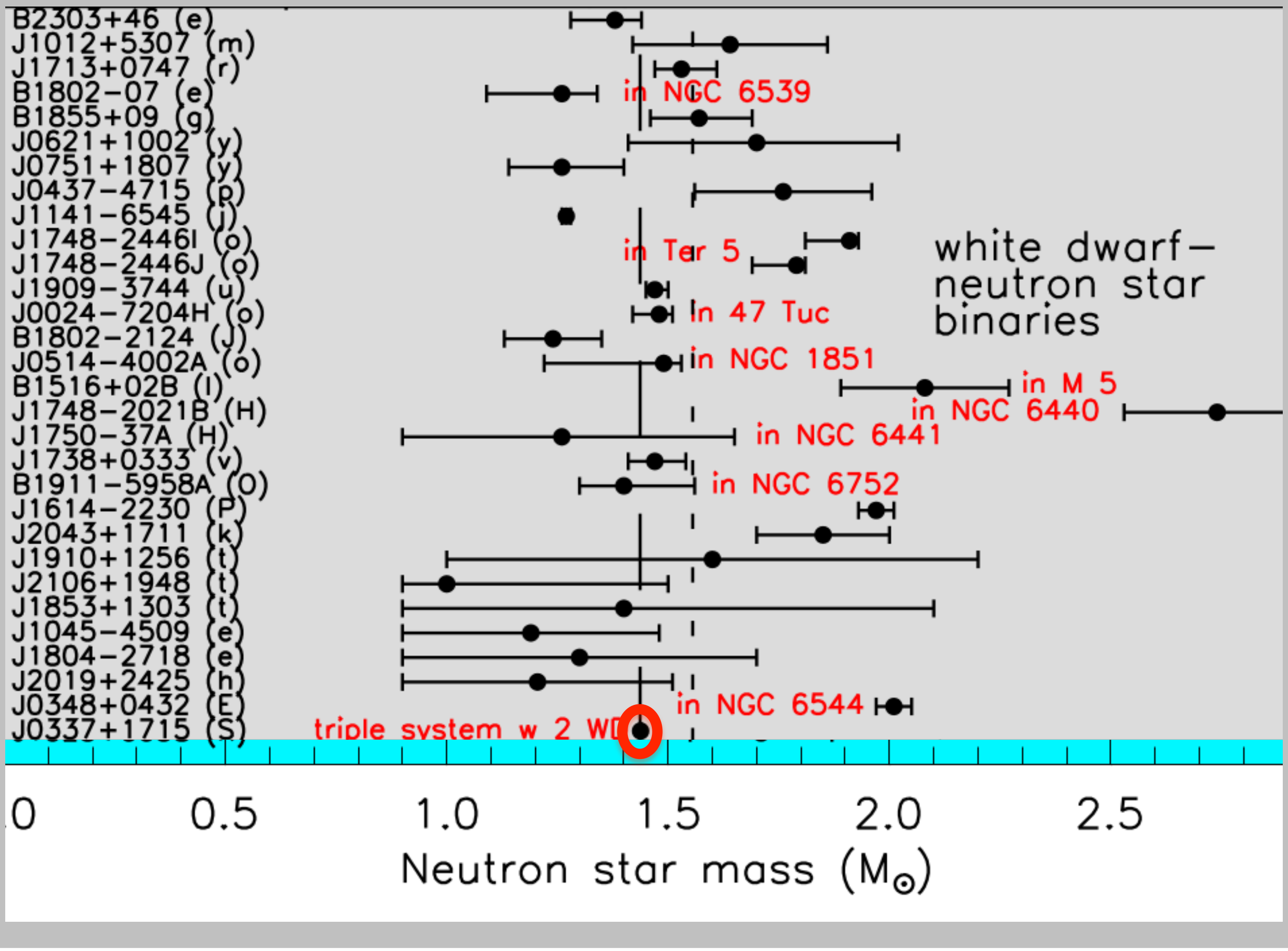
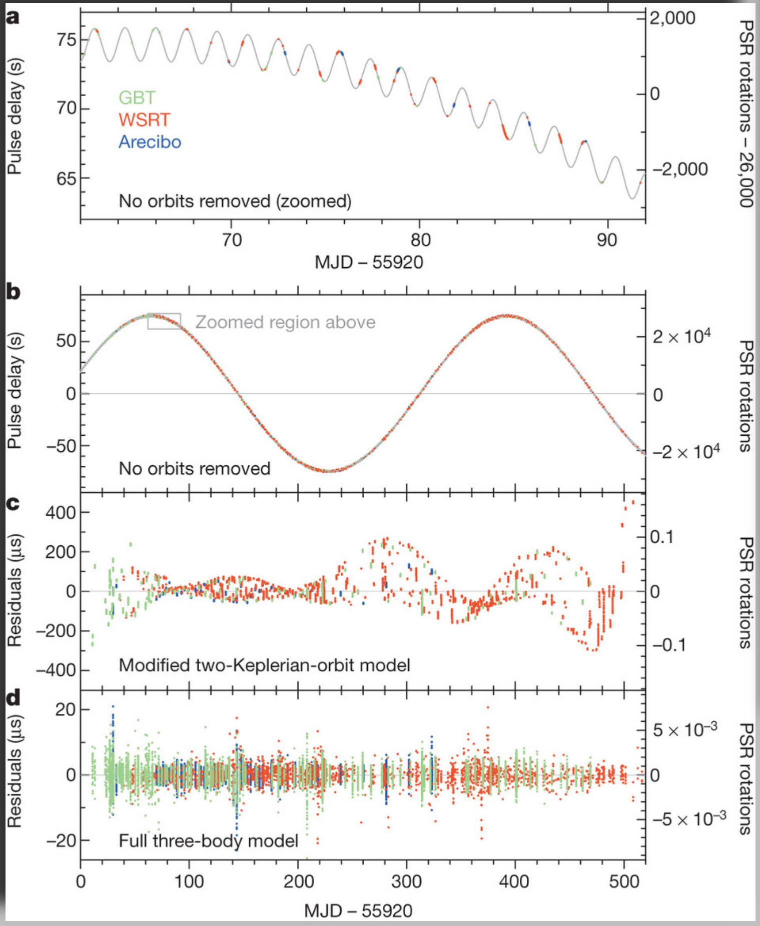
Neutron Star-White Dwarf Binaries

- Circular orbits; pulsar periods 1.5 to 20 ms
- Light white dwarf companions (typically)



Millisecond Pulsar Triple System
PSR J0337+1715

Ransom *et al.* 2014 (Nature 505: 521)



Triple system:

- Pulsar, 2.7 ms (fully recycled)
- White dwarf, $0.2M_\odot$, 1.6 day orbit
- White dwarf, $0.4M_\odot$, 327 day orbit

Numerically integrate 3-body gravitational interaction to find best model for the system. This determines masses and inclinations.

$$m_1=1.4378\pm0.0013M_\odot$$

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- *Fully recycled* neutron stars: need not be heavier than mildly recycled NS.

  Triple pulsar J0337+1715 is fully recycled but only $1.44M_{\odot}$.

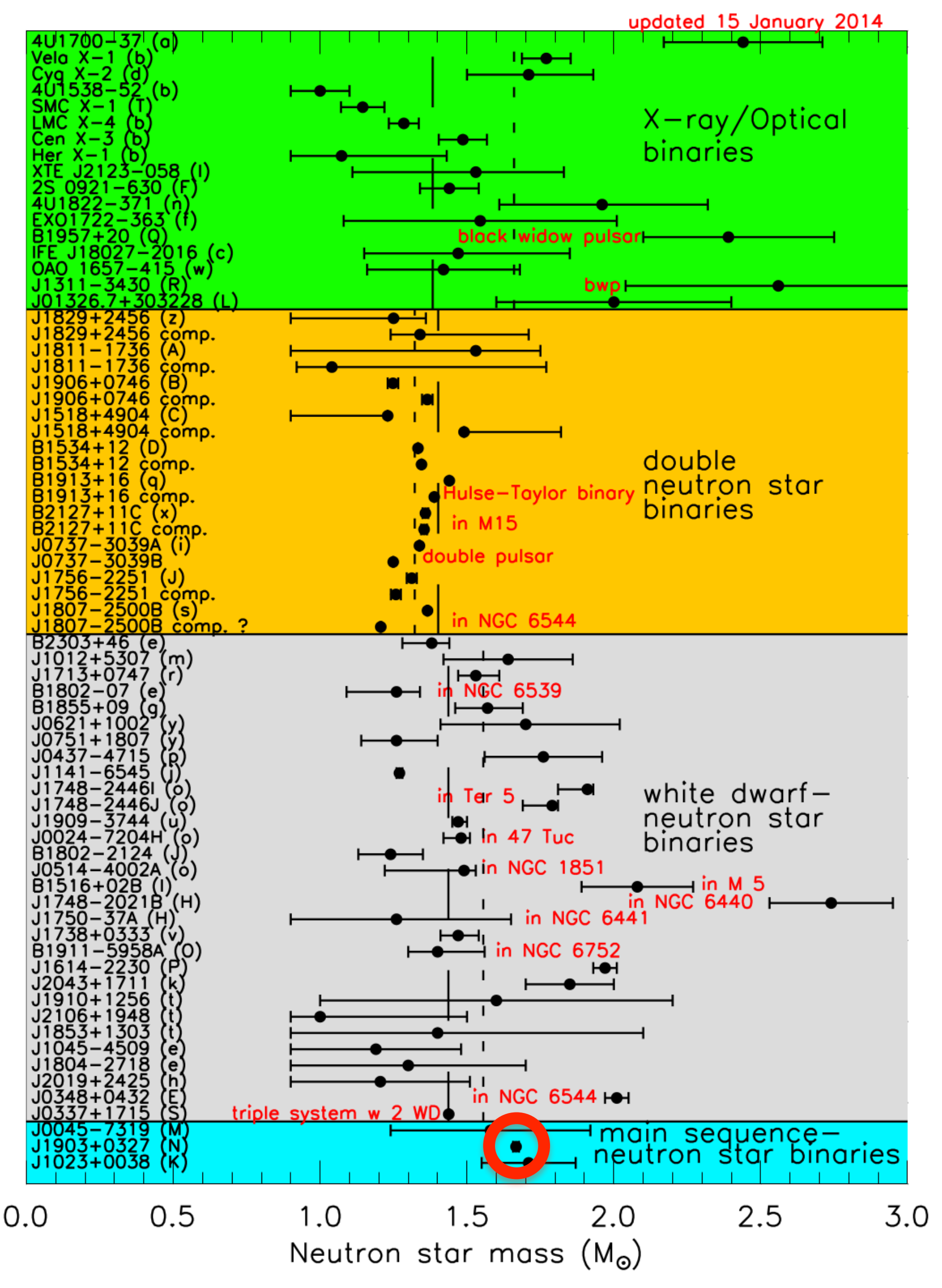
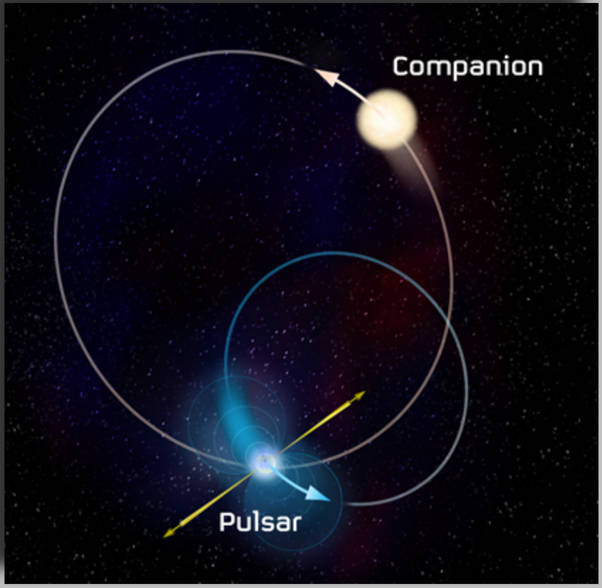


Figure: Jim Lattimer
stellarcollapse.org/nsmasses

Eccentric MSP binary PSR J1903+0327

Champion *et al.* 2008 (Science 320: 1309)

Freire *et al.* 2011 (MNRAS 412: 2763)



Fully recycled P=2.15 ms
Eccentric e=0.44, 95-day orbit
Main sequence companion
⇒ unique evolution

Precession

- 0.0002400(2)°/yr
  $\Rightarrow m_1+m_2=2.70\pm0.03M_\odot$

Shapiro Delay

- Inclination 77.47±0.15°
- $m_2=1.029\pm0.008M_\odot$

$$\boxed{m_1=1.667\pm0.021M_\odot}$$

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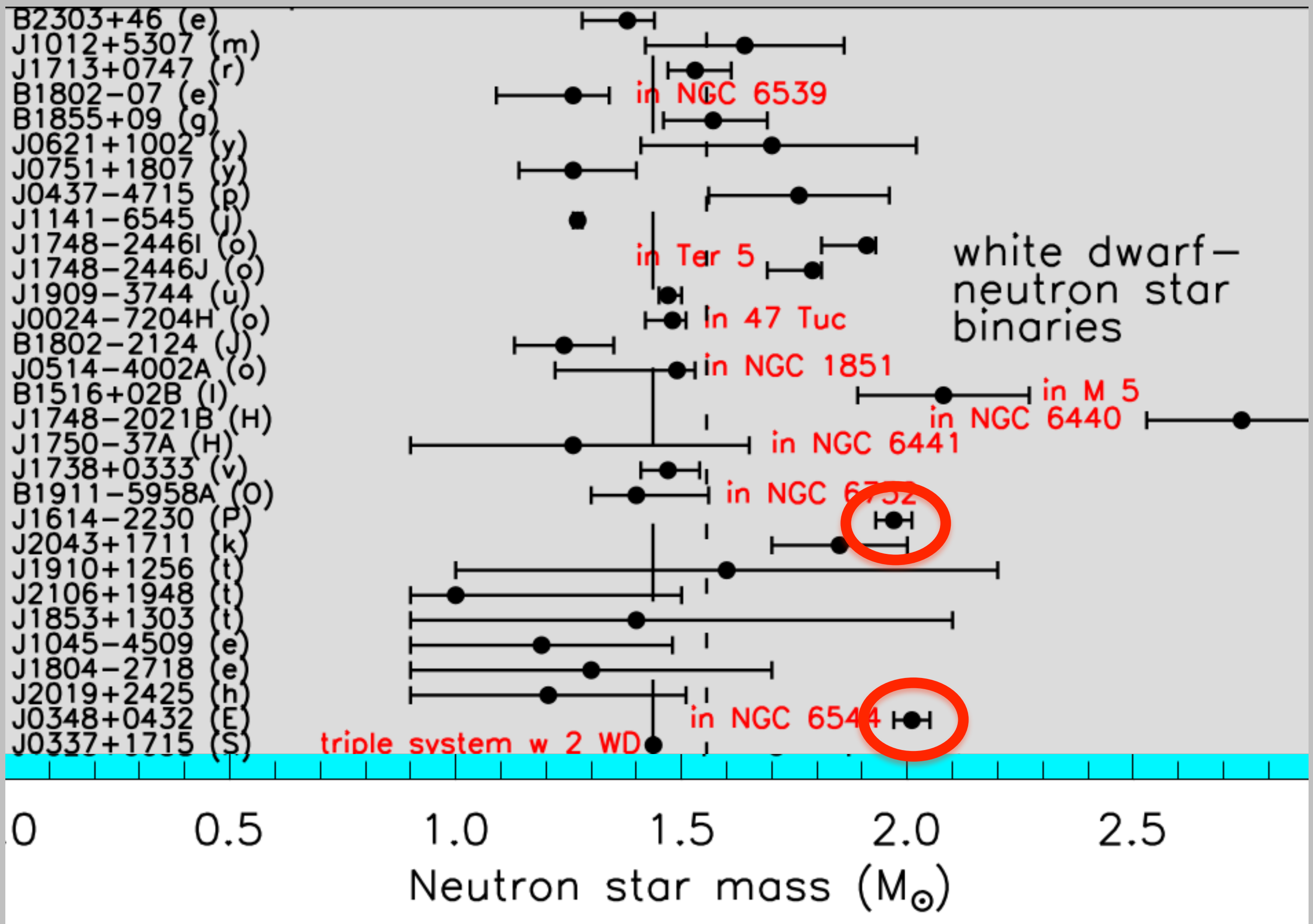
- *Neutron stars can have masses up to at least ~$1.67M_\odot$.*

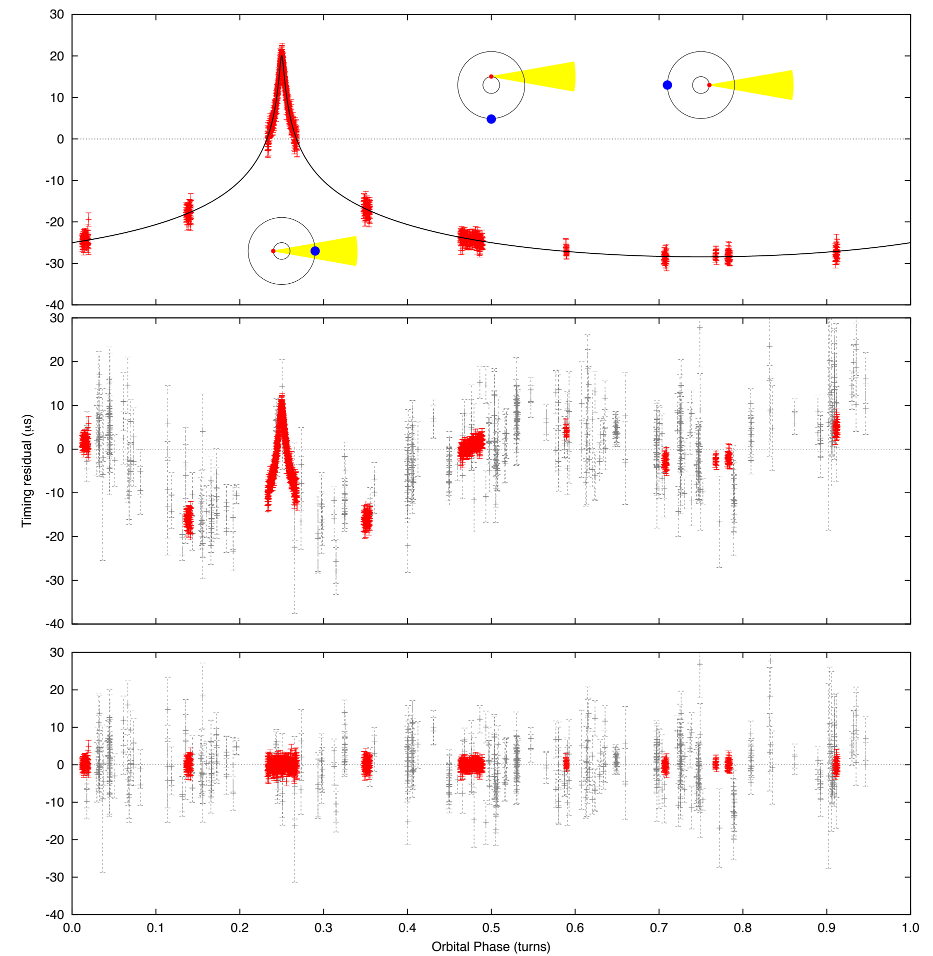
Neutron Star-White Dwarf Binaries

- Circular orbits; pulsar periods 1.5 to 20 ms
- Light white dwarf companions (typically)



PSR J1614-2230
Pulsar-White Dwarf binary

Demorest *et al.* 2010
(Nature 467: 1081)

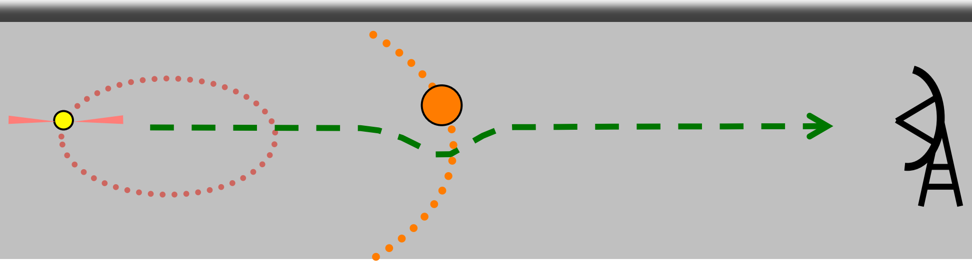


Fully recycled P=3.15 ms
Circular e~10^{-6}
White dwarf companion
8.7 day orbit

Shapiro delay

- Inclination 89.17±0.02°
- $m_2=0.500\pm0.006M_\odot$

$$\boxed{m_1=1.97\pm0.04M_\odot}$$



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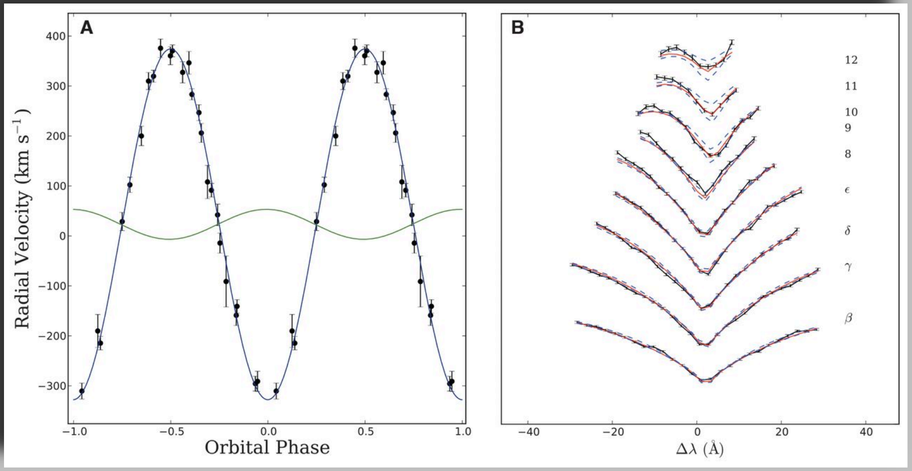
- *Neutron stars can have masses up to at least* ~~*~1.67*$M_\odot$~~ *~2.0*$M_\odot$.

Pulsar-White Dwarf binary PSR J0348+0432

Antoniadis *et al.* 2013 (Science 340: 1233232)

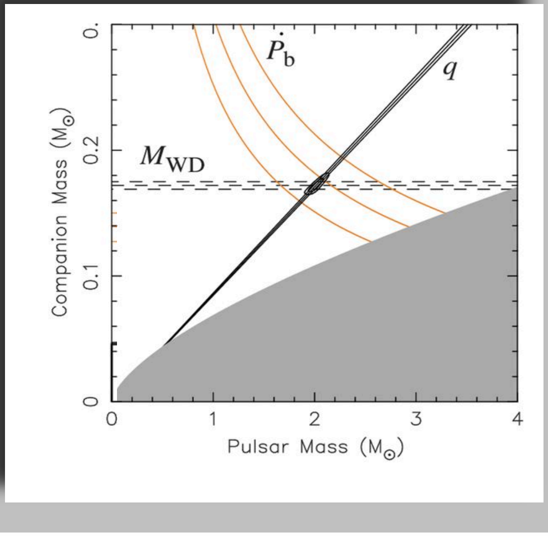


Mildly recycled P=39.12 ms

Circular e~2x10^{-6}

White dwarf companion

2.5 hour orbit



Companion spectroscopy

- T=10120±47±90 K
- log g(cm/s^2)=6.035±0.032±0.060
- $m_2=0.172\pm0.003M_\odot$
- $q=m_1/m_2=11.70\pm0.13$

$$\boxed{m_1=2.01\pm0.04M_\odot}$$

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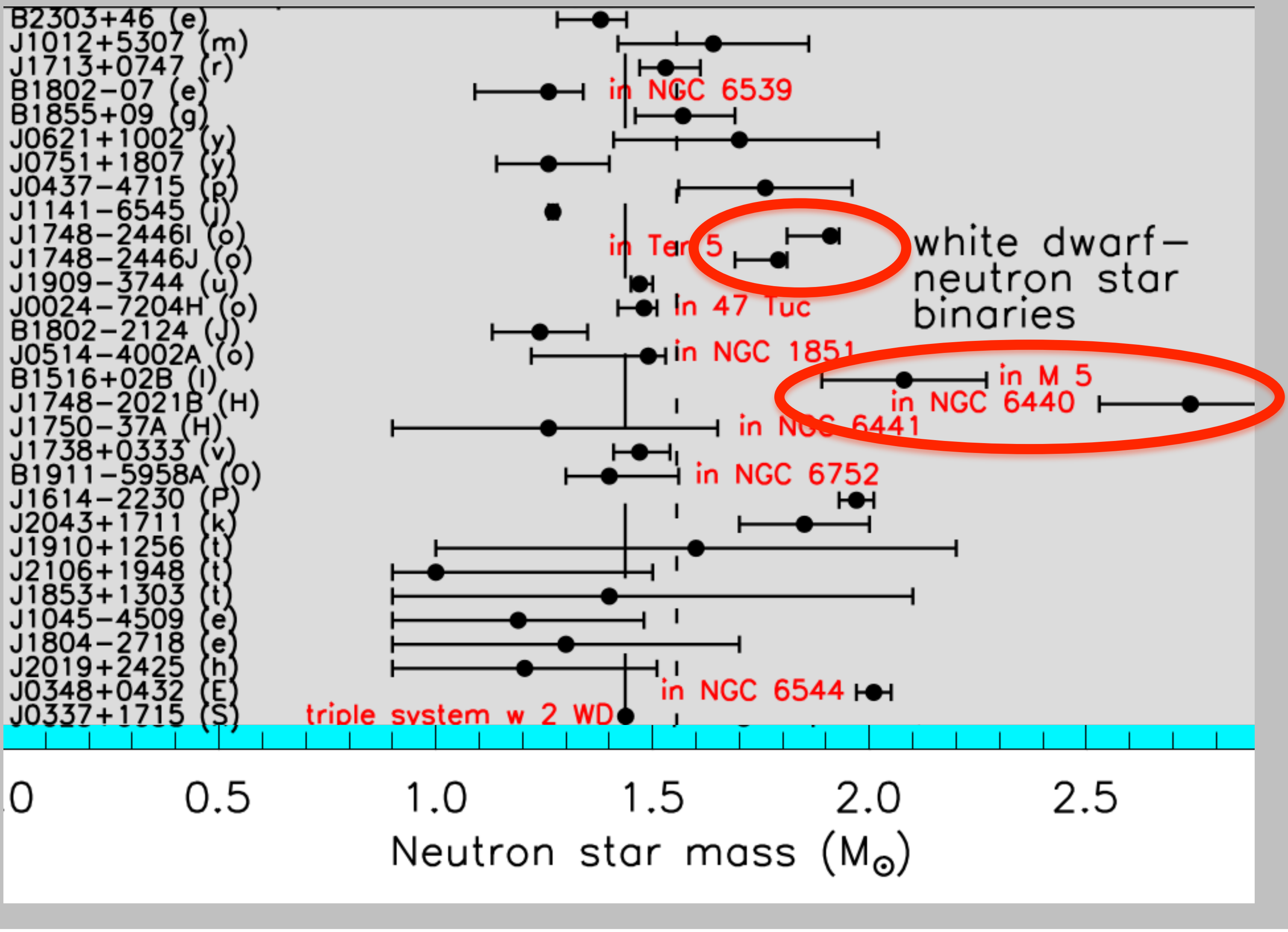
- *Neutron stars can have masses up to at least ~2.0*$M_\odot$.

  Heavy neutron stars have periods similar to both mildly recycled and fully recycled pulsars.

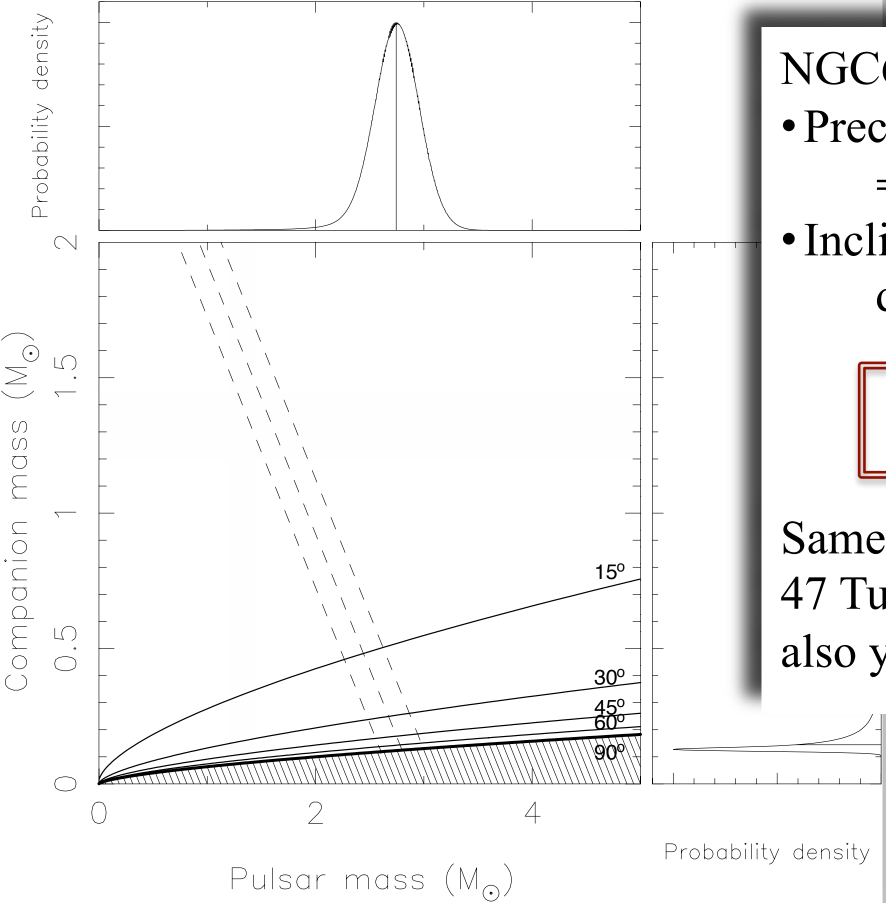
Neutron Star-White Dwarf Binaries

- Circular orbits; pulsar periods 1.5 to 20 ms
- Light white dwarf companions (typically)



Eccentric globular cluster pulsars
47 Tuc I, 47 Tuc J, M5B, NGC6440B

Freire *et al*. 2008 (ApJ 675: 670)
Freire *et al*. 2008 (ApJ 697: 1433)



NGC6440B

- Precession: 0.00391±0.00018°/yr
  $\Rightarrow m_1 = 2.92 \pm 0.20 M_\odot$
- Inclination: Uniform a priori
  distribution of cos i

$$\boxed{m_1 = 2.74 \pm 0.21 M_\odot}$$

Same reasoning for
47 Tuc I, 47 Tuc J, and M5B
also yields relatively large m_1.

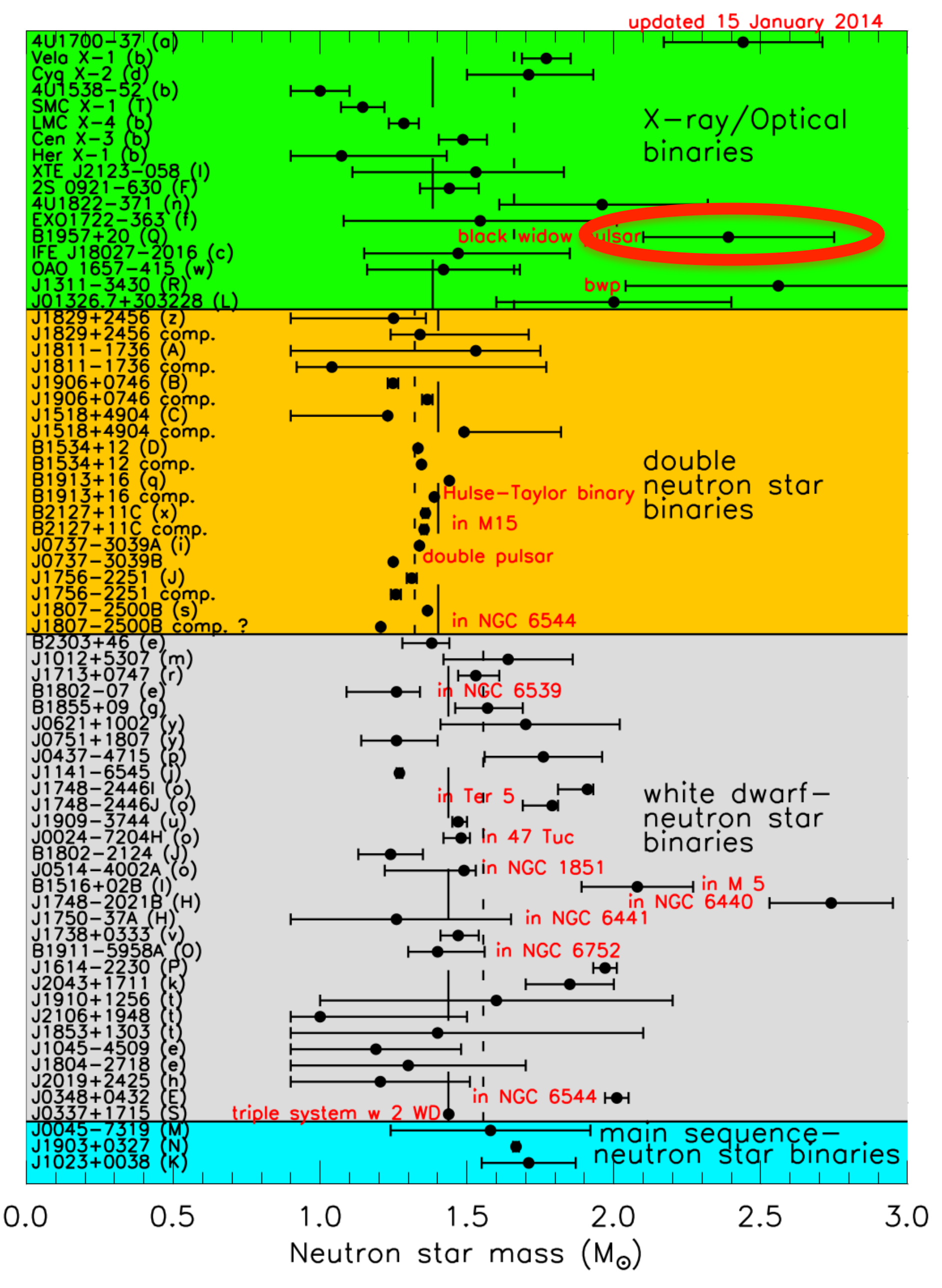
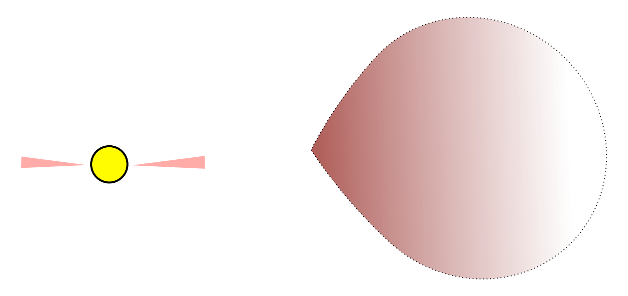


Figure: Jim Lattimer
stellarcollapse.org/nsmasses

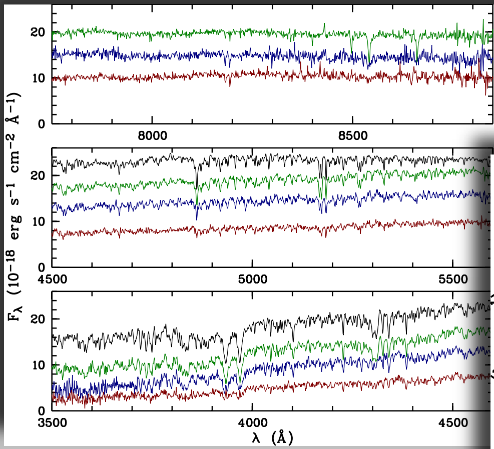
Eclipsing binary PSR B1957+20

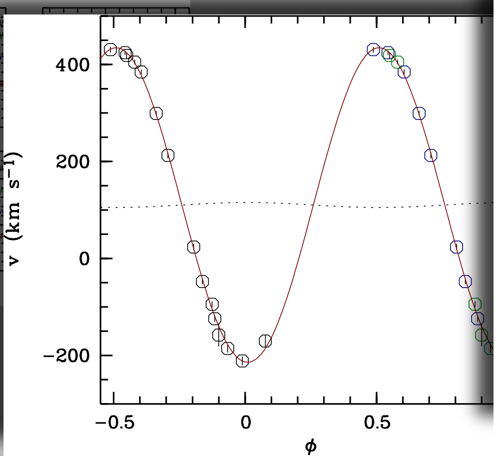
van Kerkwijk, Breton, & Kulkarni 2011 (ApJ 728: 95)

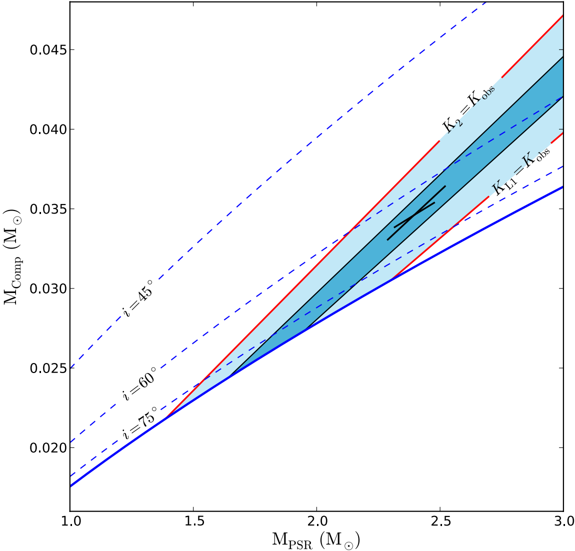


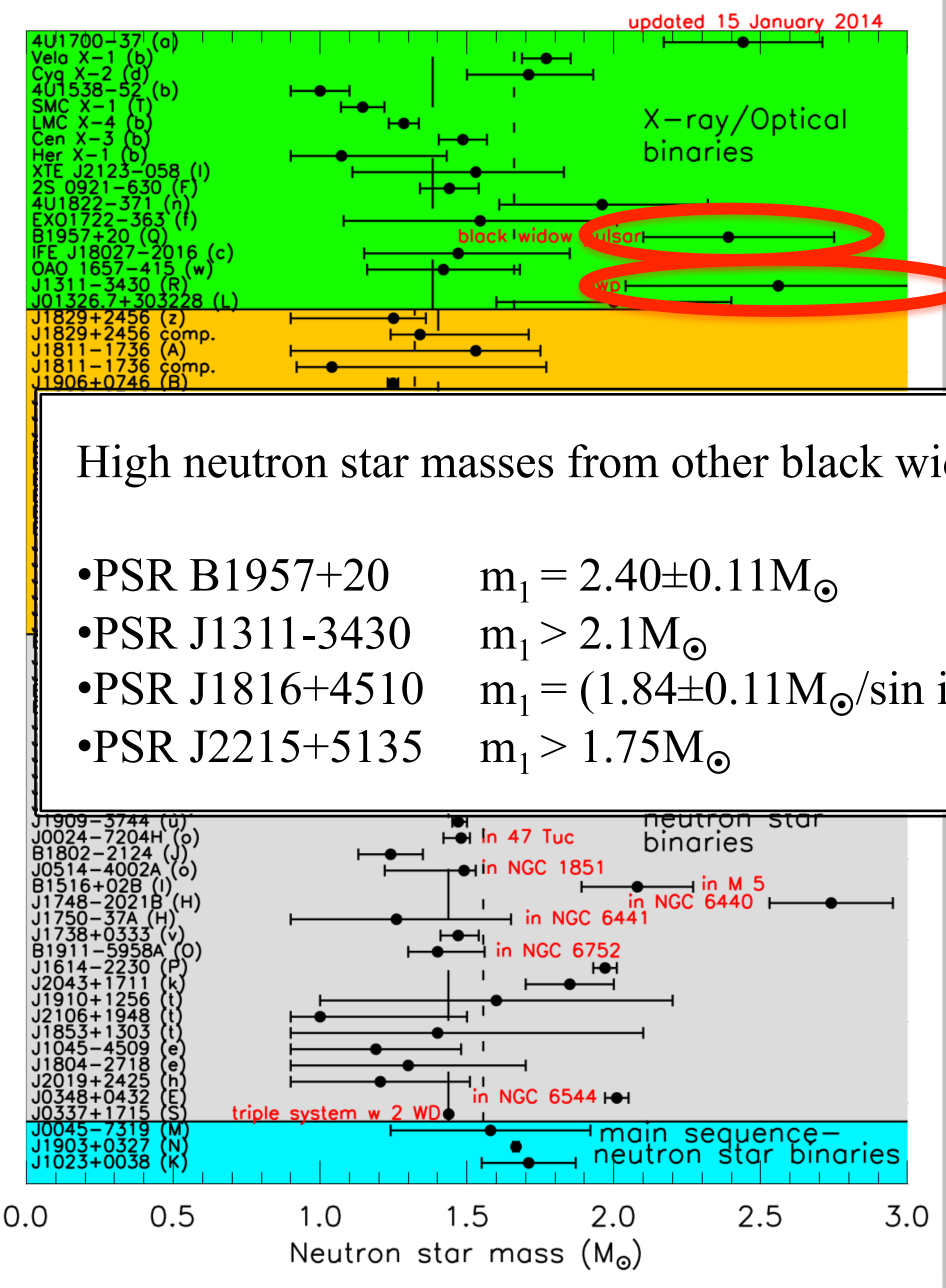
Optical observations
- Light curve ⇒ inclination
- Spectra ⇒ orbit⇒ m_1/m_2

$$\boxed{m_1 = 2.40 \pm 0.12 M_\odot}$$









High neutron star masses from other black widow/redback systems:

- PSR B1957+20 $m_1 = 2.40 \pm 0.11 M_\odot$ (van Kerkwijk et al 2011)
- PSR J1311-3430 $m_1 > 2.1 M_\odot$ (Romani et al 2012)
- PSR J1816+4510 $m_1 = (1.84 \pm 0.11 M_\odot / \sin i)^3$ (Kaplan et al 2013)
- PSR J2215+5135 $m_1 > 1.75 M_\odot$ (Schroeder & Halpern 2014)

Figure: Jim Lattimer
stellarcollapse.org/nsmasses

<u>Summary</u>

- *Unrecycled* neutron stars: $1.23M_\odot$ to $1.38M_\odot$.

  Caveat: almost all measured in the same type of system, NS-NS binaries

- *Mildly recycled* neutron stars: slightly heavier than unrecycled neutron stars

  Caveat: PSR B1534+12 is counterexample, lighter than its unrecycled companion

- *Fully recycled* neutron stars: need not be heavier than mildly recycled NS.

  Triple pulsar J0337+1715 is fully recycled but only $1.44M_\odot$.

- *Neutron stars can have masses up to at least ~$2.0M_\odot$, <u>perhaps even ~$2.4M_\odot$</u>.*

  Heavy neutron stars have periods similar to both mildly recycled and fully recycled pulsars.

  <u>All neutron stars in black widow/redback binaries with measured masses are heavy.</u>

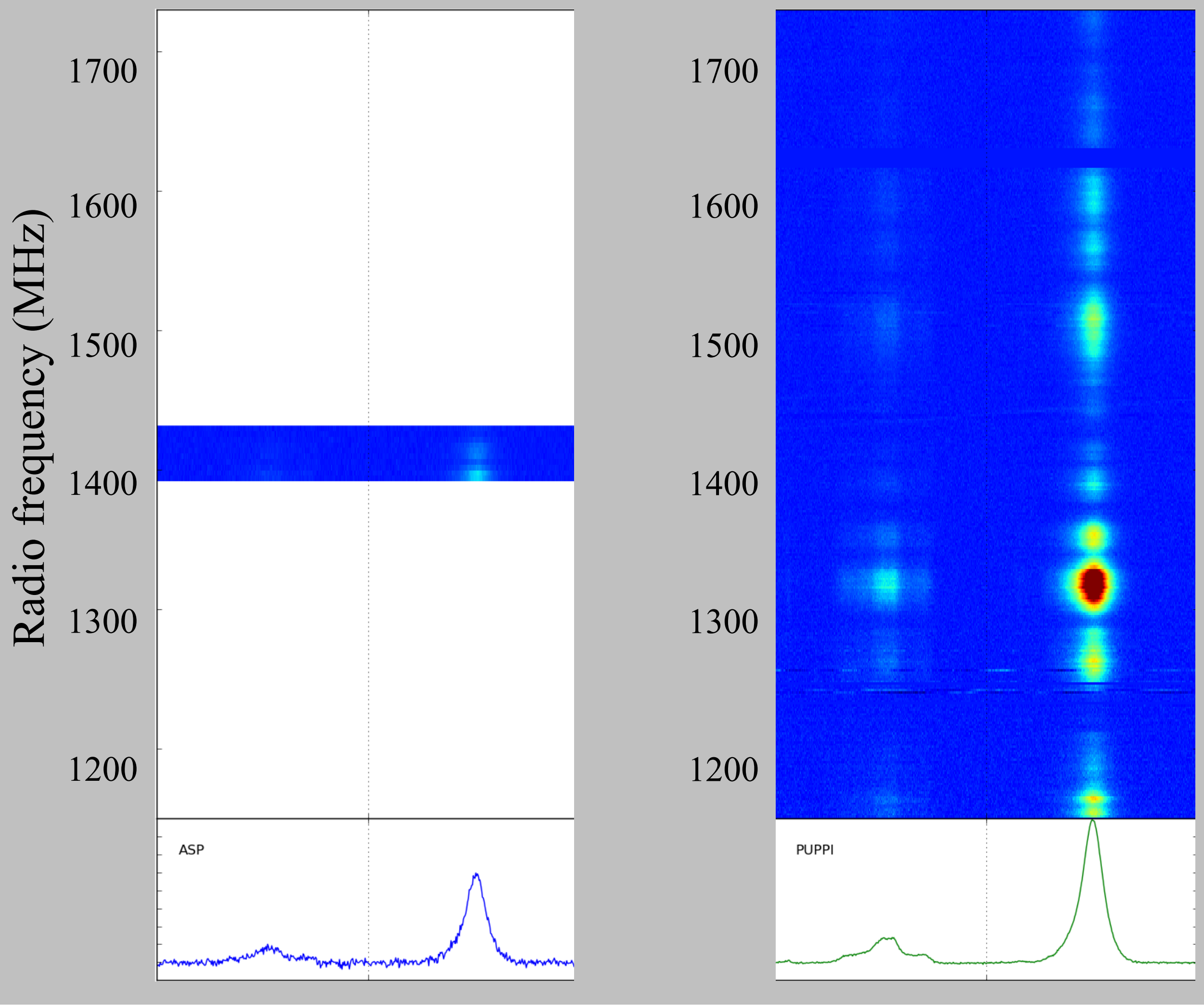
1. Motivation
2. How to measure neutron star masses by timing binary millisecond pulsars
3. Interesting recent measurements of neutron star masses.
4. Why there will be more and better measurements in the future.

The future I.

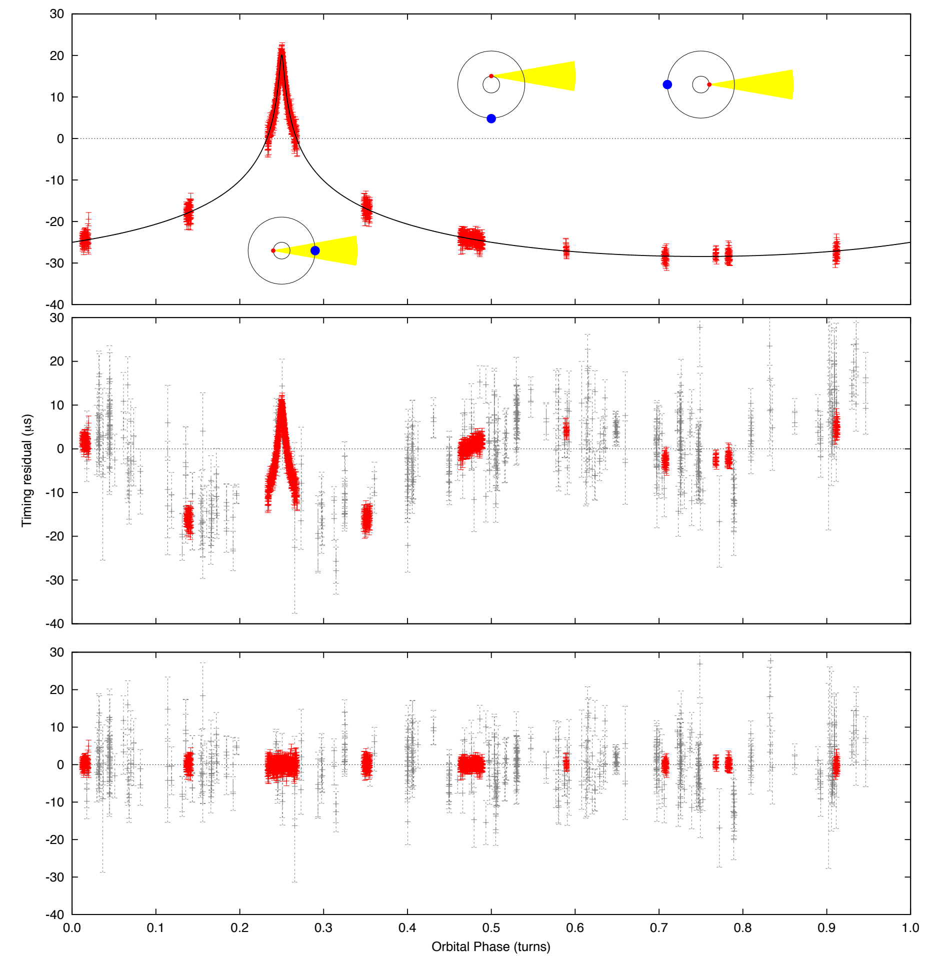
Wide bandwidth high precision timing

64 MHz bandwidth
GASP (GBT) 2005-2011
ASP (Arecibo) 2005-2012

800 MHz bandwidth
GUPPI (GBT) 2011-
PUPPI (Arecibo) 2012-



PSR J2214+3000 at Arecibo.
Adapted from figure by Paul Demorest.



PSR J1614-2230
Pulsar-White Dwarf binary

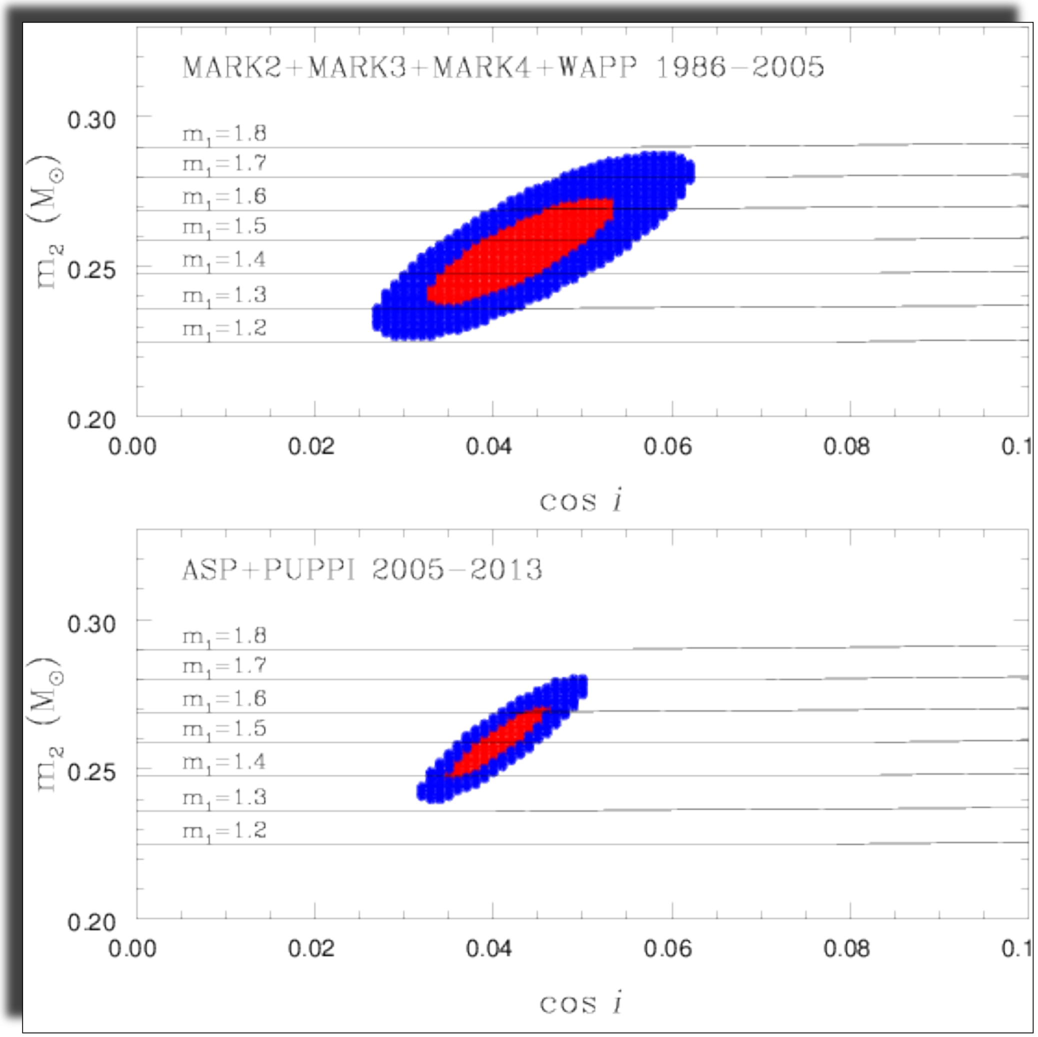
Demorest *et al.* 2010
(Nature 467: 1081)

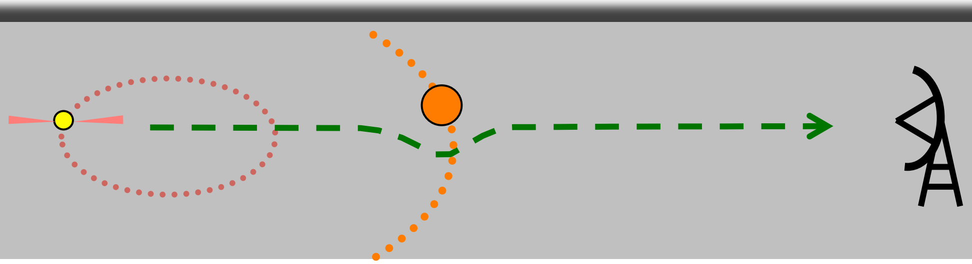
Red points:
GUPPI (wideband)

Gray points:
previous-generation instruments

PSR B1855+09 Shapiro Delay

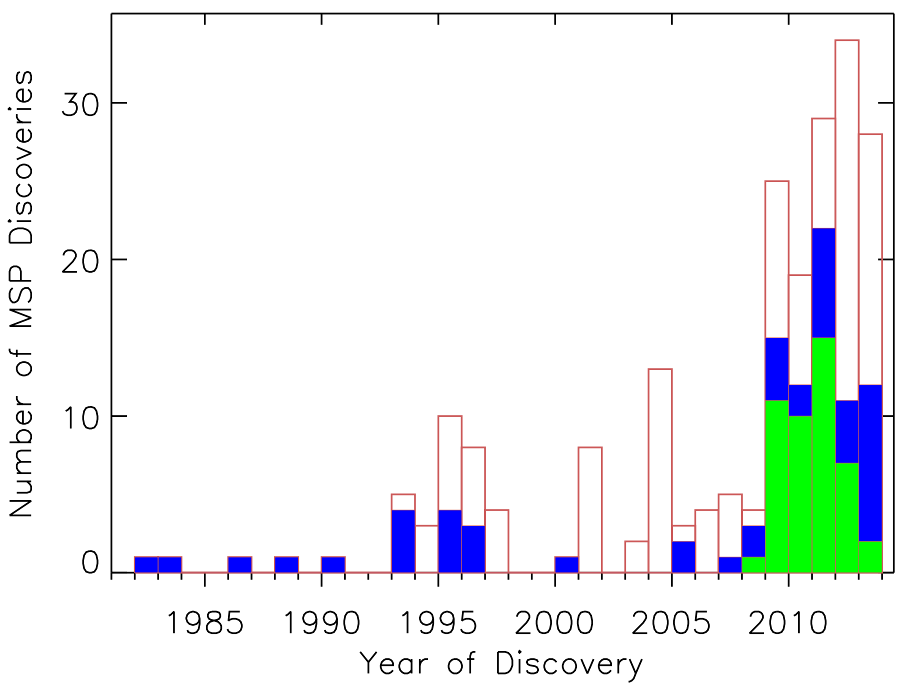
Preliminary unpublished
NANOGrav data





$$\Delta t = 2\frac{G}{c^3} m_2 \ln\left[\, 1 - \sin i \, \sin(\varphi - \varphi_0) \,\right]$$

The future II. New millisecond pulsar discoveries.



Galactic (non-globular-cluster) millisecond pulsars by year of discovery (based on discovery publication date), at Arecibo, Green Bank, and other telescopes.

For an up-to-date list: http://astro.phys.wvu.edu/GalacticMSPs/GalacticMSPs.txt
Figure: Maura McLaughlin

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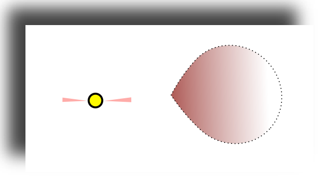

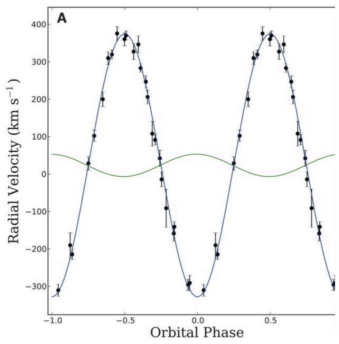

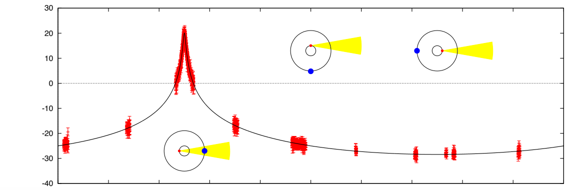

stellarcollapse.org/nsmasses