Neutron Star Masses

David Nice, Lafayette College

IAU XXVIII General Assembly, Beijing, August 2012

This set of slides differs slightly from the set presented in the conference.
Some redundant figures have been deleted.

Outline

(a) Introduction
(b) The most massive neutron stars
(c) Masses of neutron star sub-populations
(d) Conclusion

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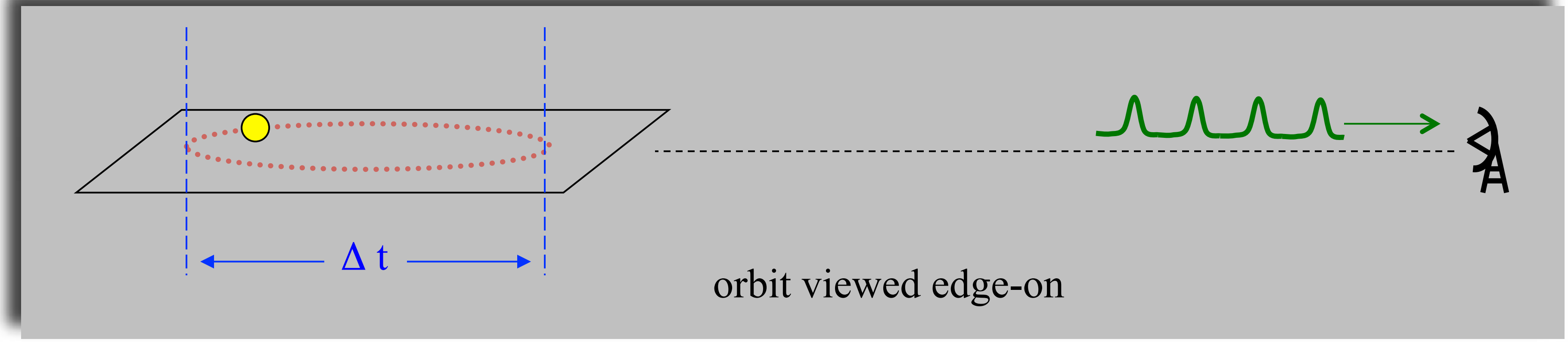
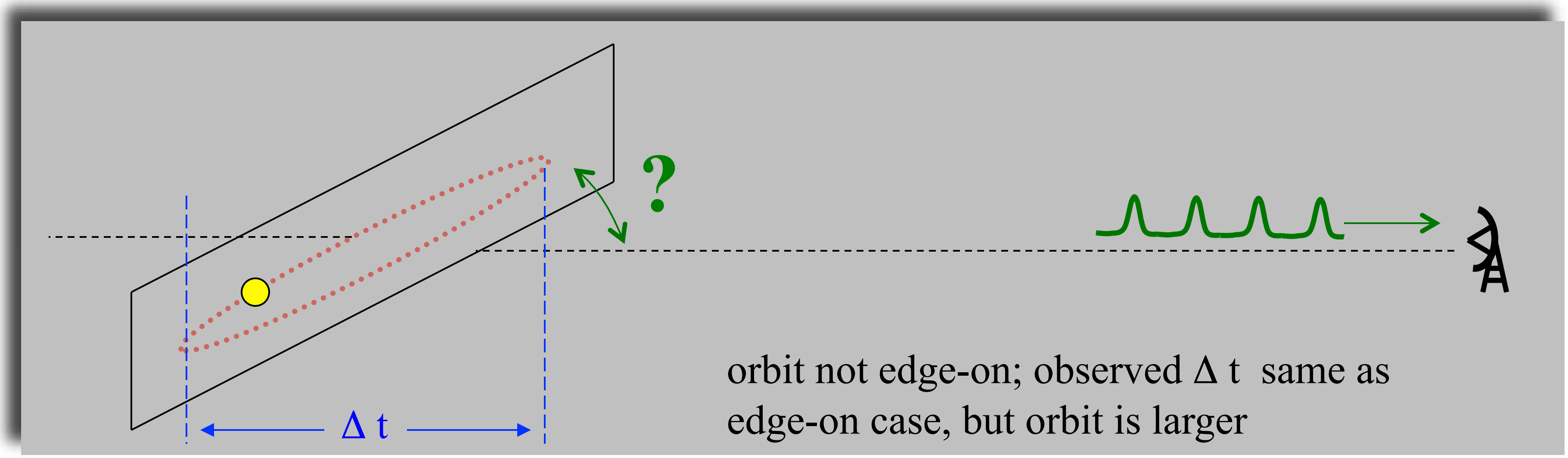
Pulsar in Keplerian orbit observed via pulsar timing

Parameterized by: orbital period, projected semi-major axis, eccentricity, angle of periastron, time of periastron passage

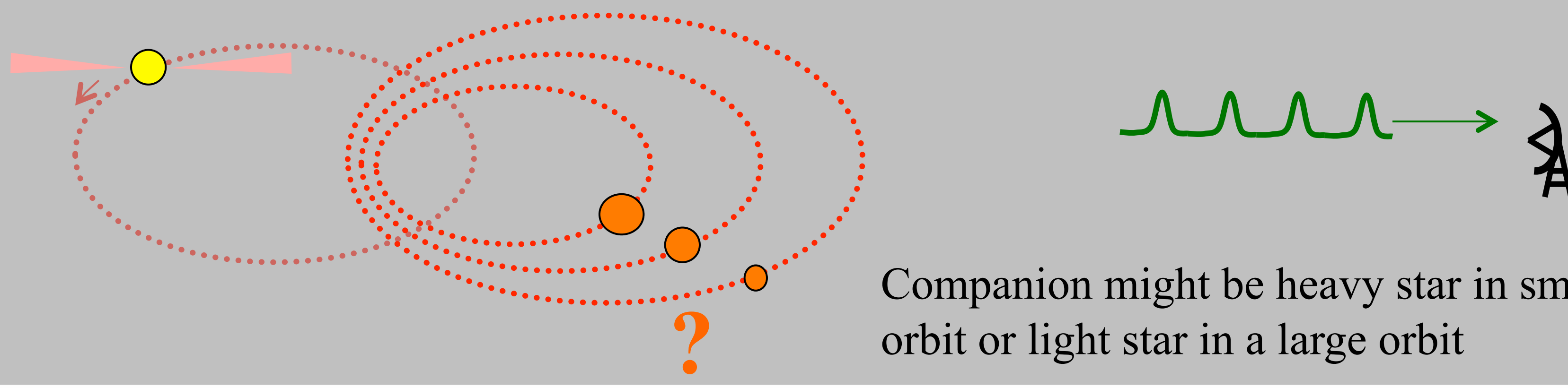


Ambiguity 1: orbit inclination is unknown.



Pulsar in Keplerian orbit observed via pulsar timing
Parameterized by: orbital period, projected semi-major axis, eccentricity, angle of periastron, time of periastron passage

Ambiguity 2: Companion mass and orbit size are unknown.

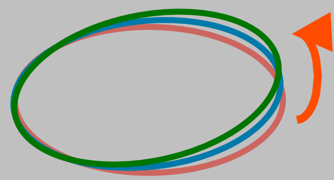


Companion might be heavy star in small orbit or light star in a large orbit

Because of these ambiguities, pulsar timing observations of a Keplerian 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.

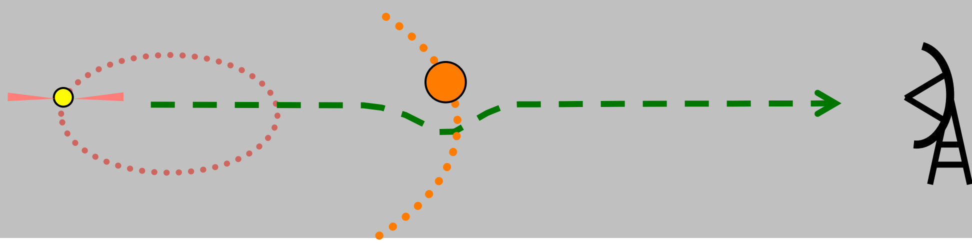
We need <u>two</u> additional measurements.

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



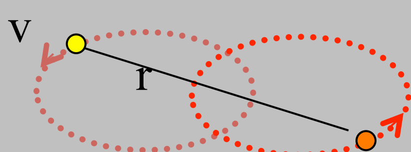
Precession

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



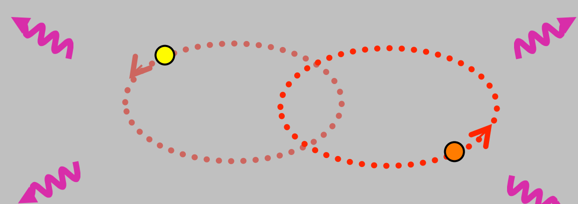
Shapiro Delay

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



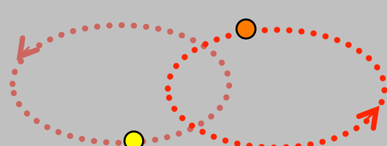
Grav Redshift/Time Dilation

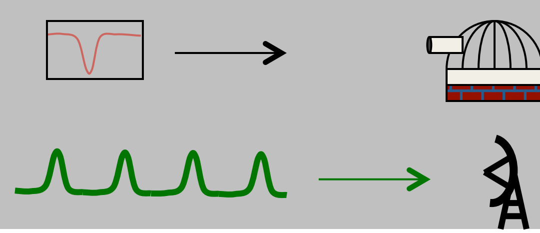
$$\gamma = \frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{1/3} e\,\frac{m_2(m_1+2m_2)}{(m_1+m_2)^{4/3}}$$



Gravitational Radiation

$$\dot{P}_b = -\left(\frac{192\pi}{5}\right)\frac{G^{5/3}}{c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{1}{(1-e^2)^{7/2}}\frac{m_1m_2}{(m_1+m_2)^{1/3}}$$





Second Orbit

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

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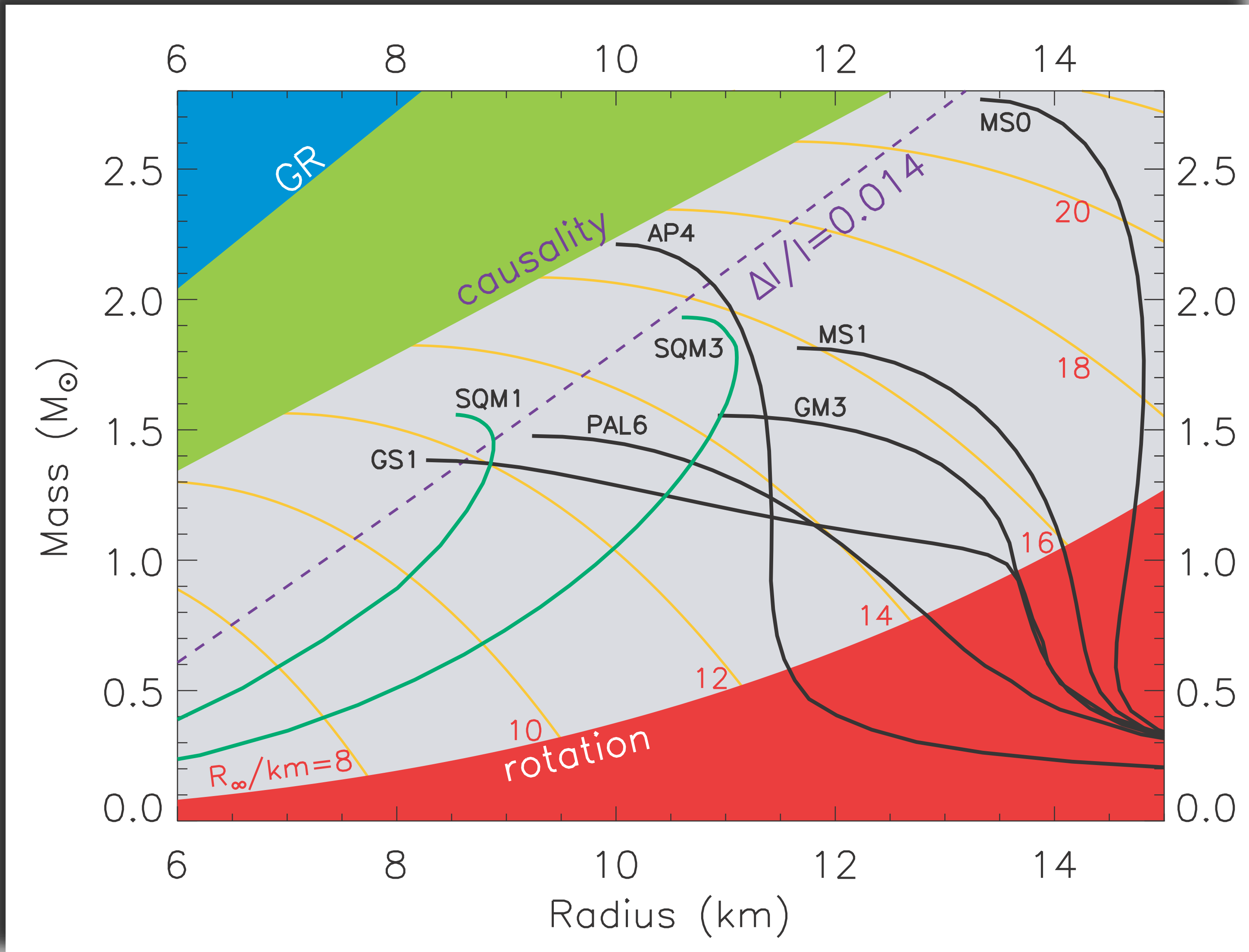


Figure: Lattimer & Prakash 2004 (Science 304: 536)

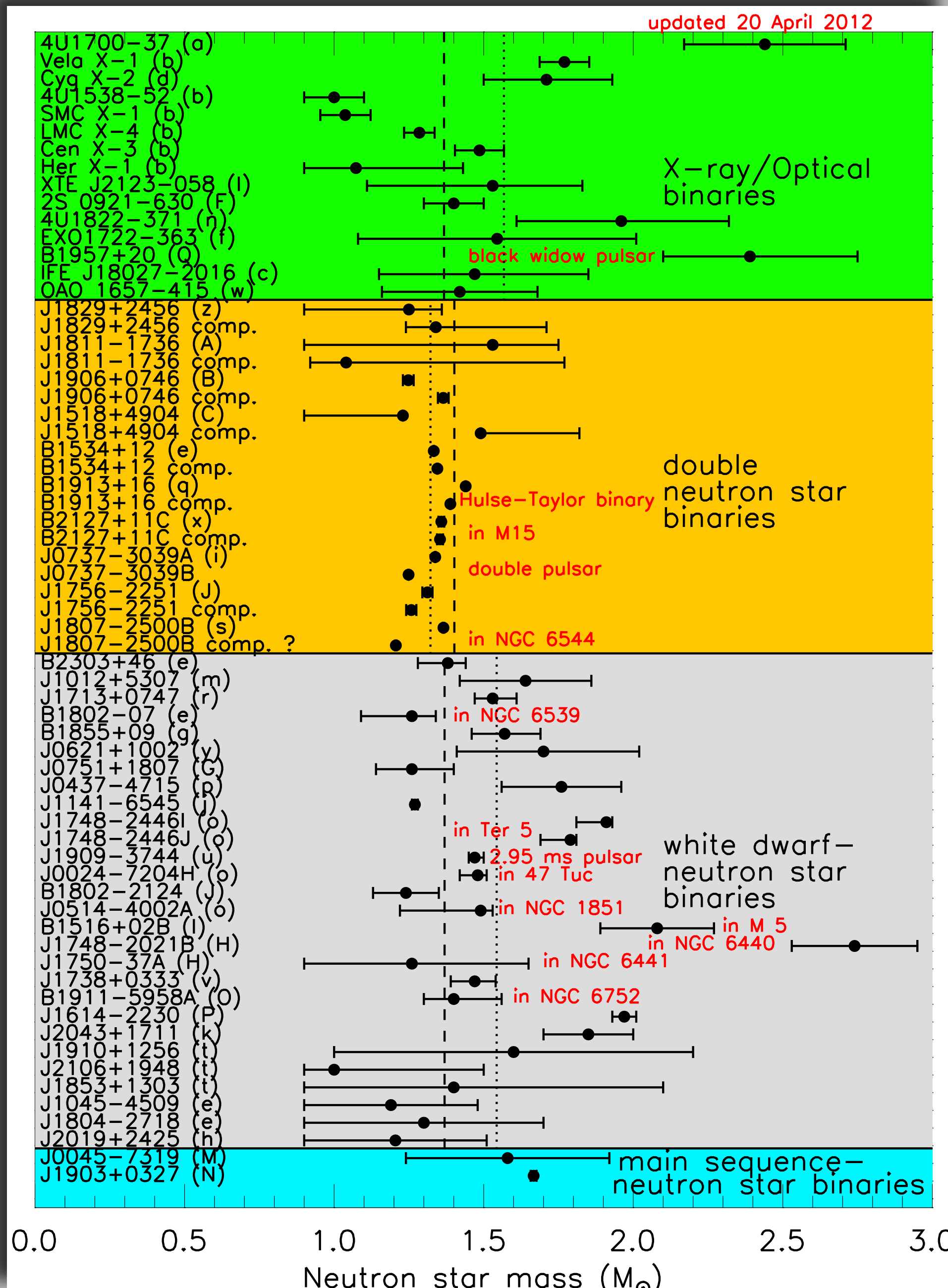


Figure: Jim Lattimer
stellarcollapse.org/nsmasses

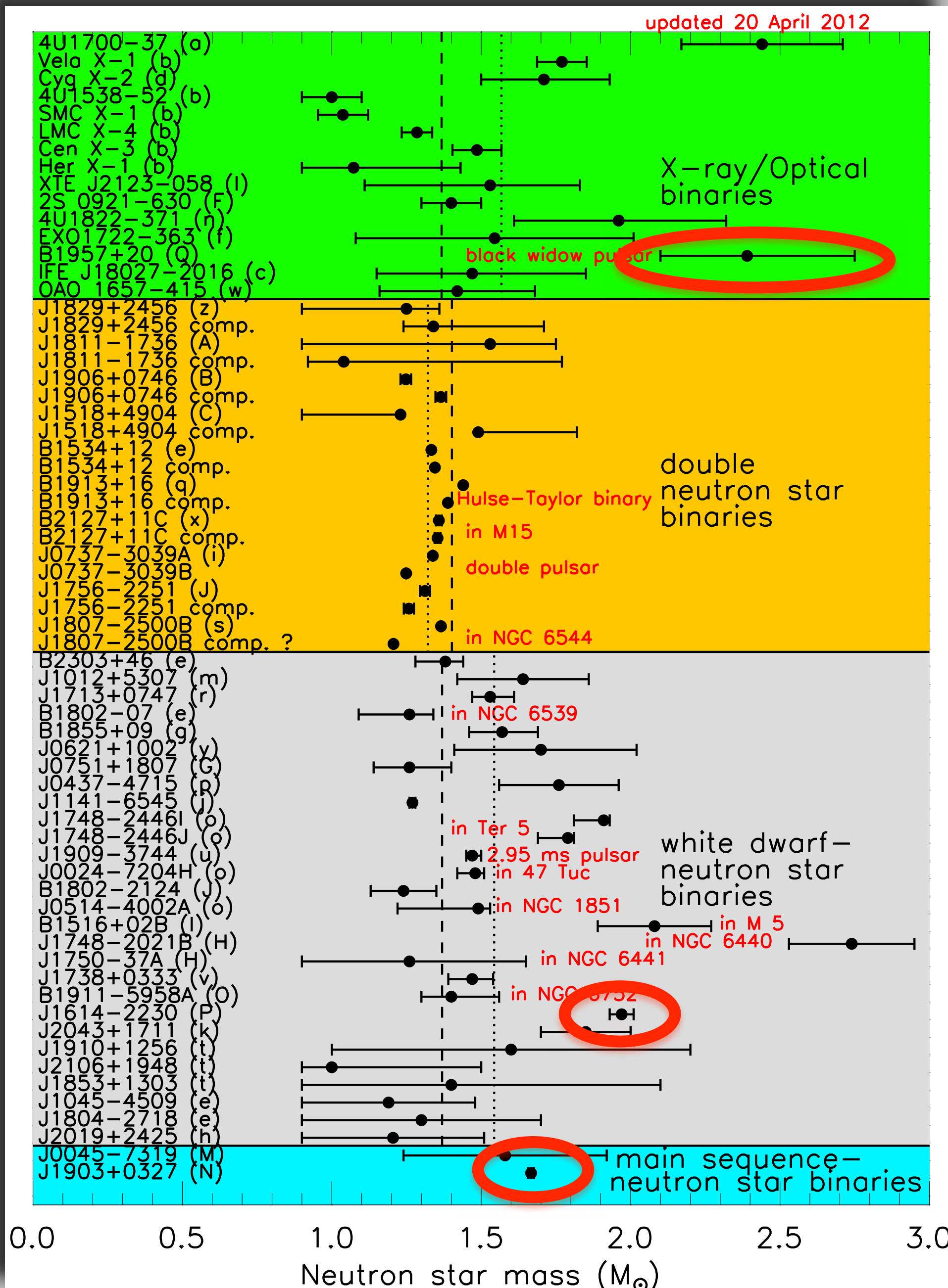
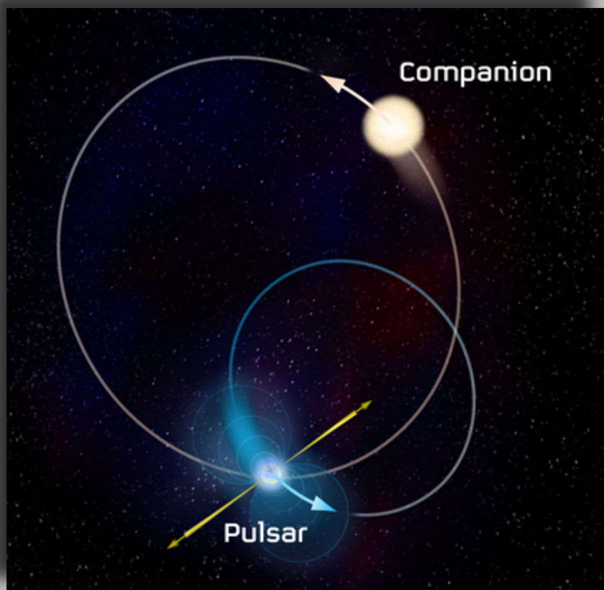


Figure: Jim Lattimer
stellarcollapse.org/nsmasses

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
Main sequence companion
⇒ unique evolution

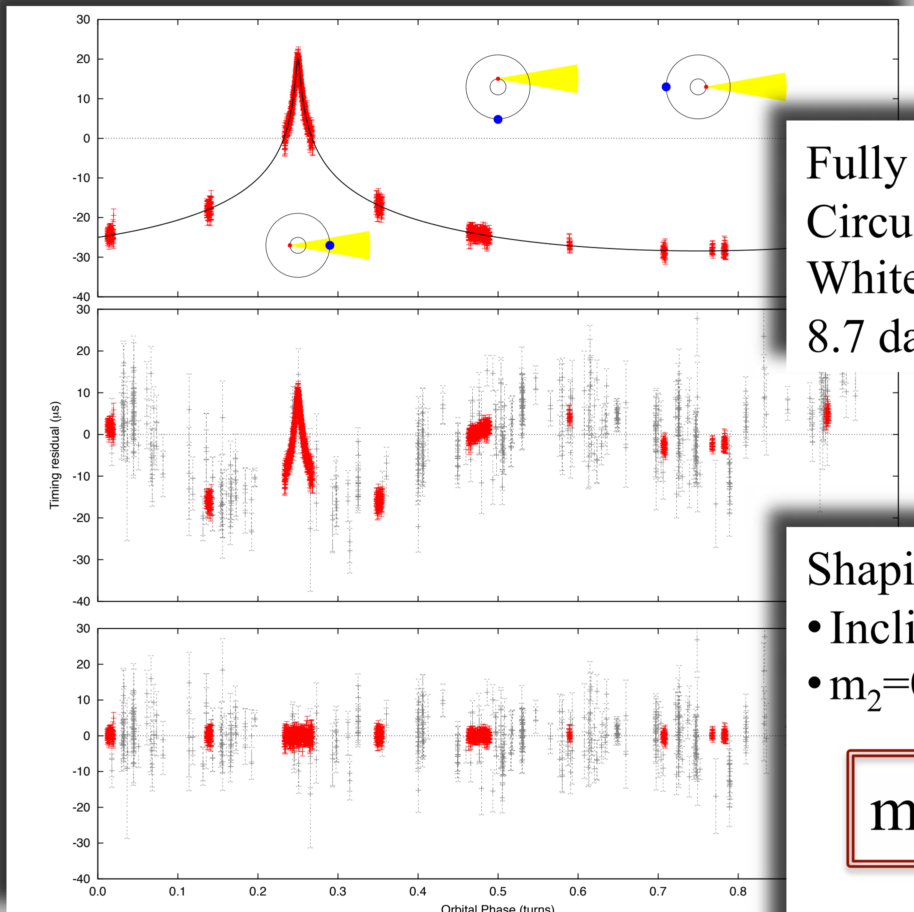
Precession
- 0.0002400(2)°/yr
  $\Rightarrow m_1+m_2=2.70\pm0.03M_\odot$

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

$m_1=1.667\pm0.021M_\odot$

Pulsar-White Dwarf binary PSR J1614-2230

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



Fully recycled P=3.15 ms

Circular $e \sim 10^{-6}$

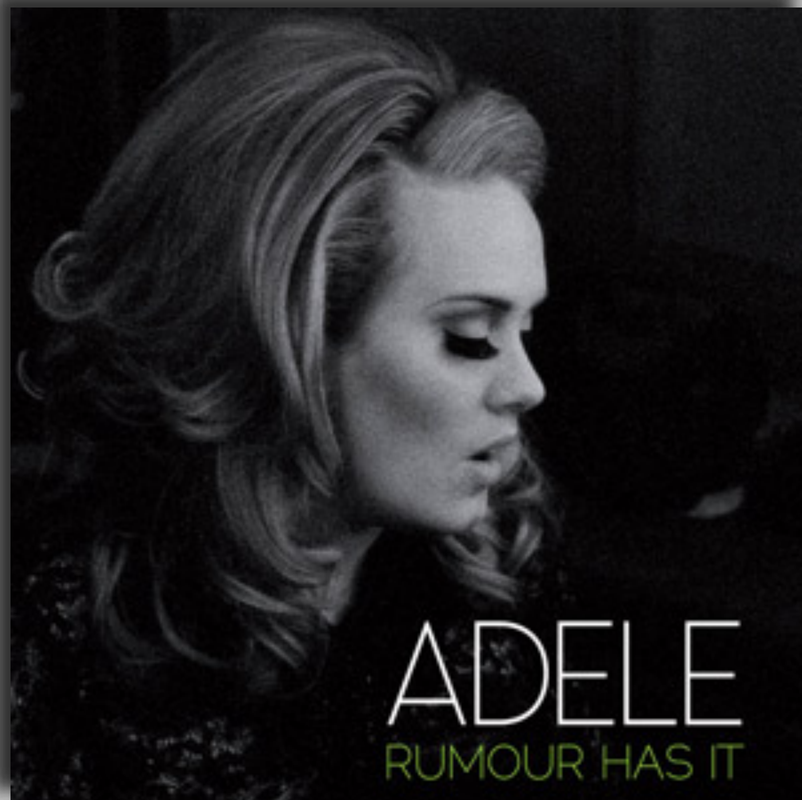
White dwarf companion

8.7 day orbit

Shapiro delay

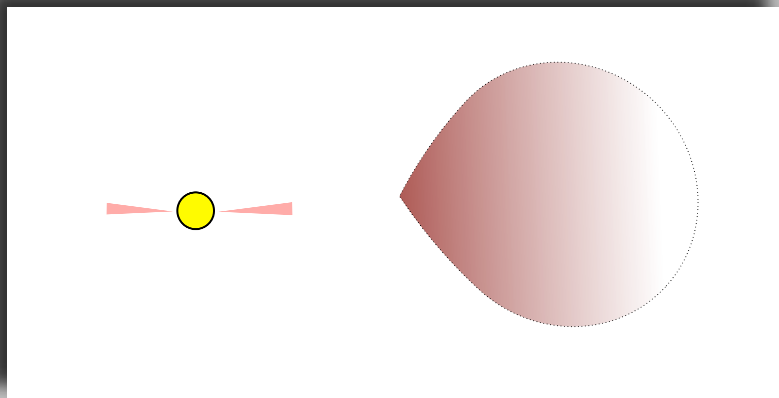
- Inclination 89.17±0.02°
- $m_2 = 0.500 \pm 0.006 M_\odot$

$$m_1 = 1.97 \pm 0.04 M_\odot$$


ADELE
RUMOUR HAS IT

Eclipsing binary PSR B1957+20

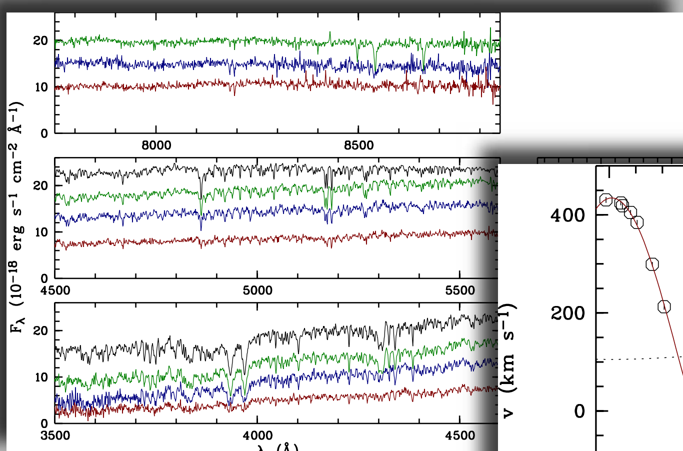
van Kerkwijk, Breton, & Kulkarni 2011 (ApJ 728: 95)

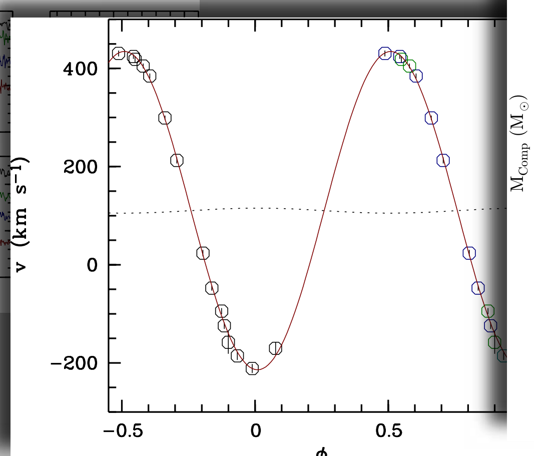


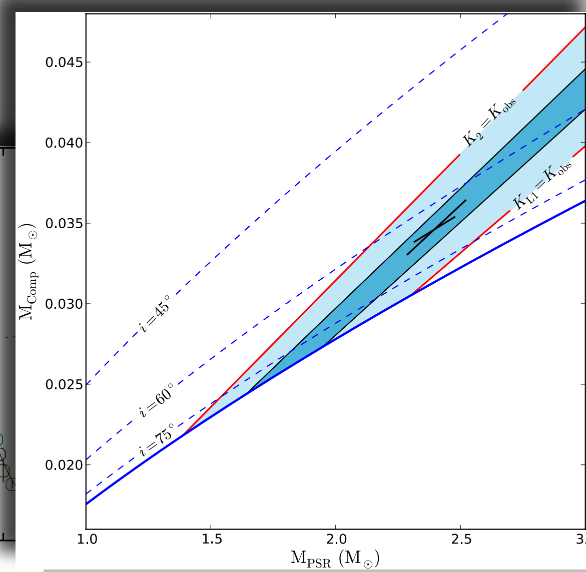
Optical observations

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

$$m_1 = 2.40 \pm 0.12 M_\odot$$







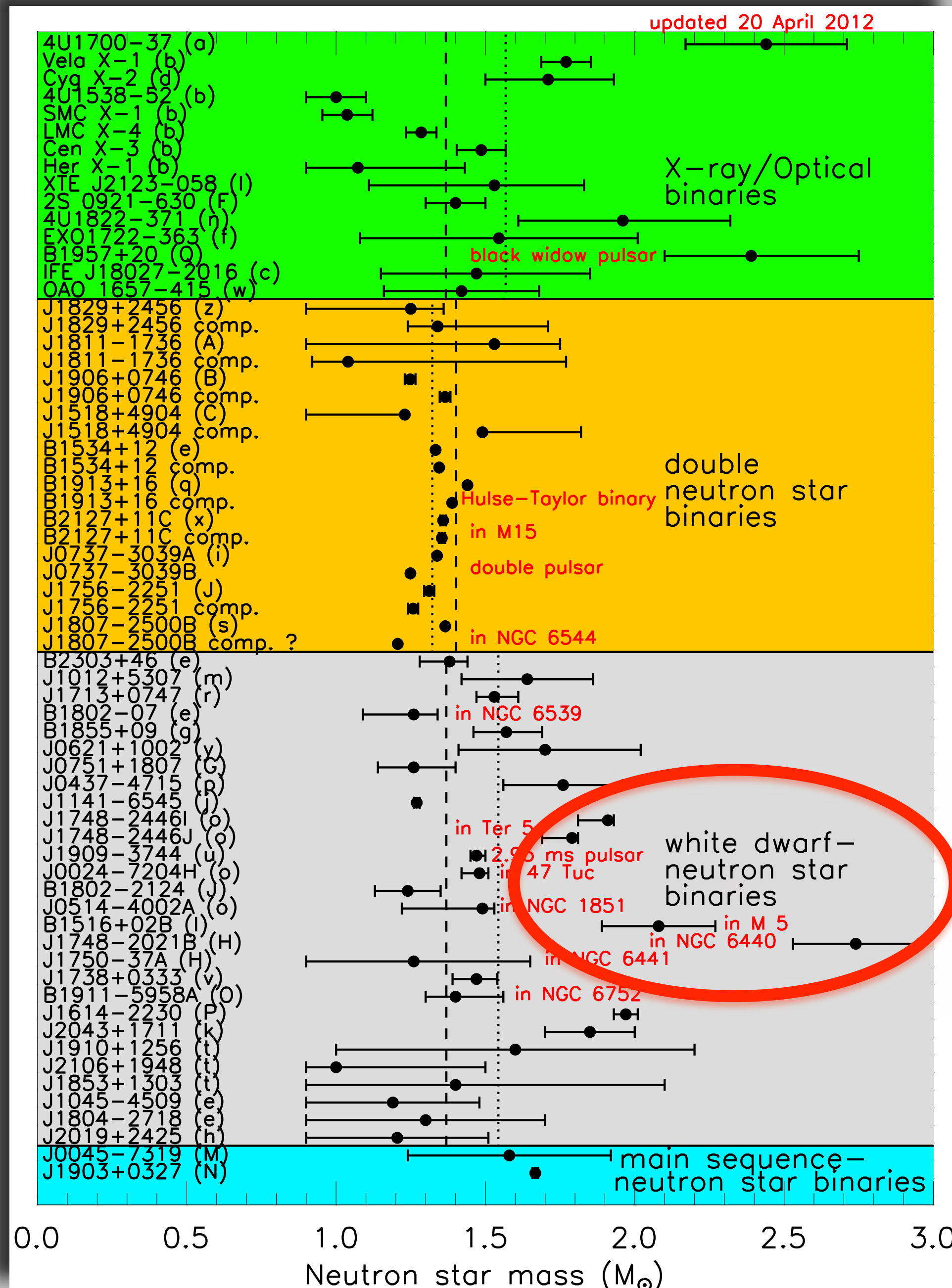
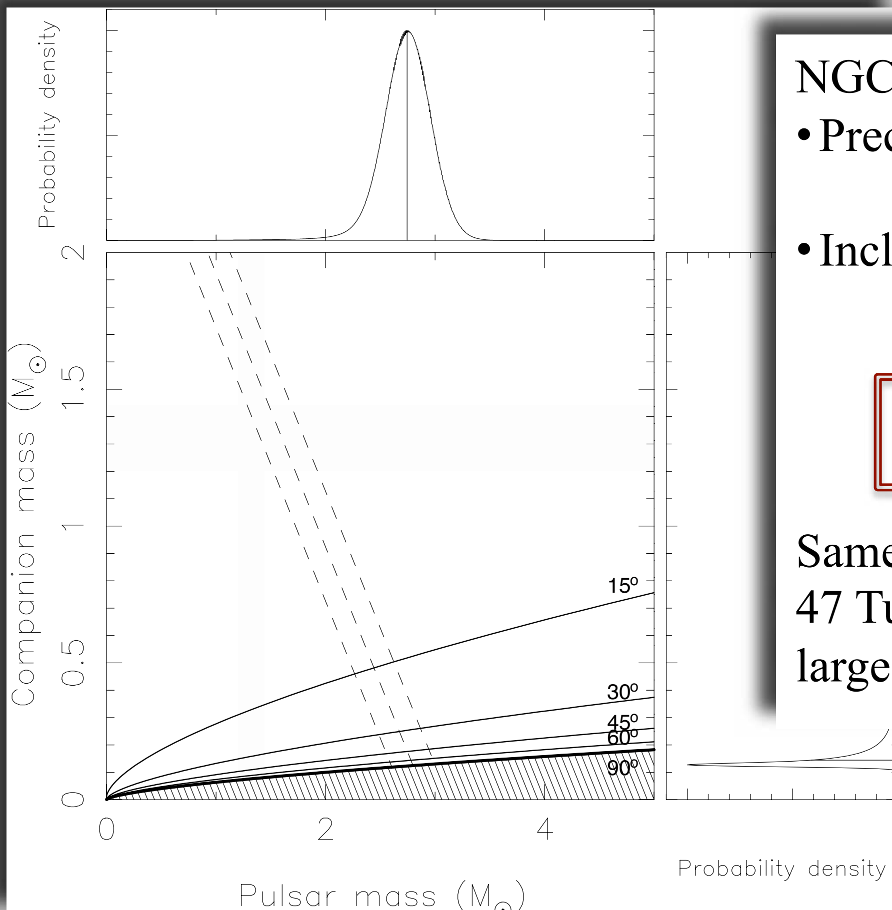


Figure: Jim Lattimer
stellarcollapse.org/nsmasses

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
  $\Rightarrow m_1=2.92\pm0.20M_\odot$
- Inclination: Uniform a priori distribution of cos i

$$m_1=2.74\pm0.21M_\odot$$

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

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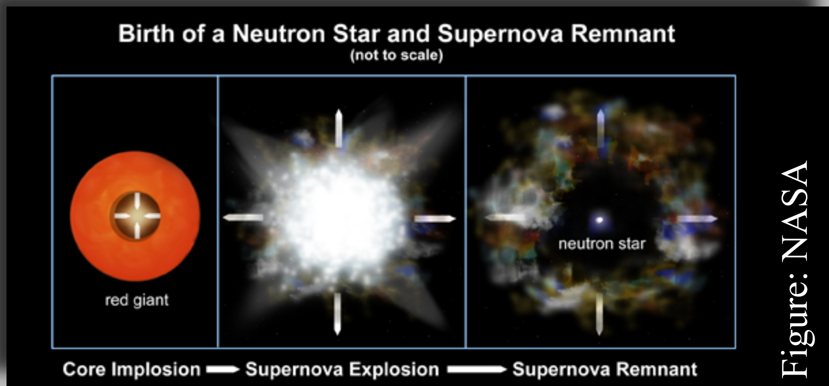
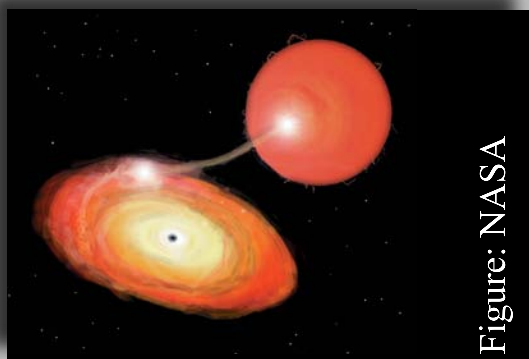


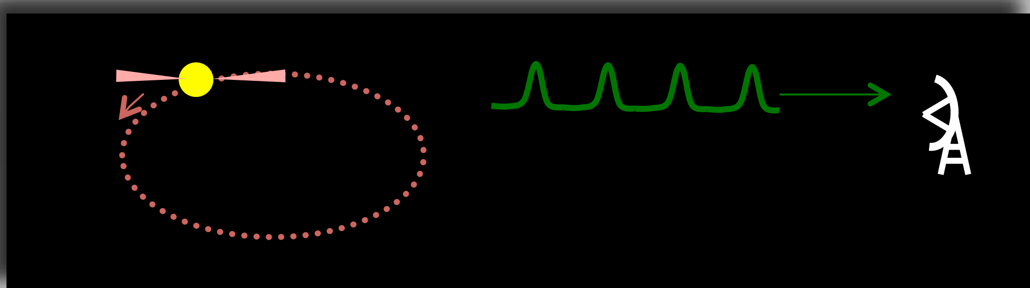
Birth Mass

+

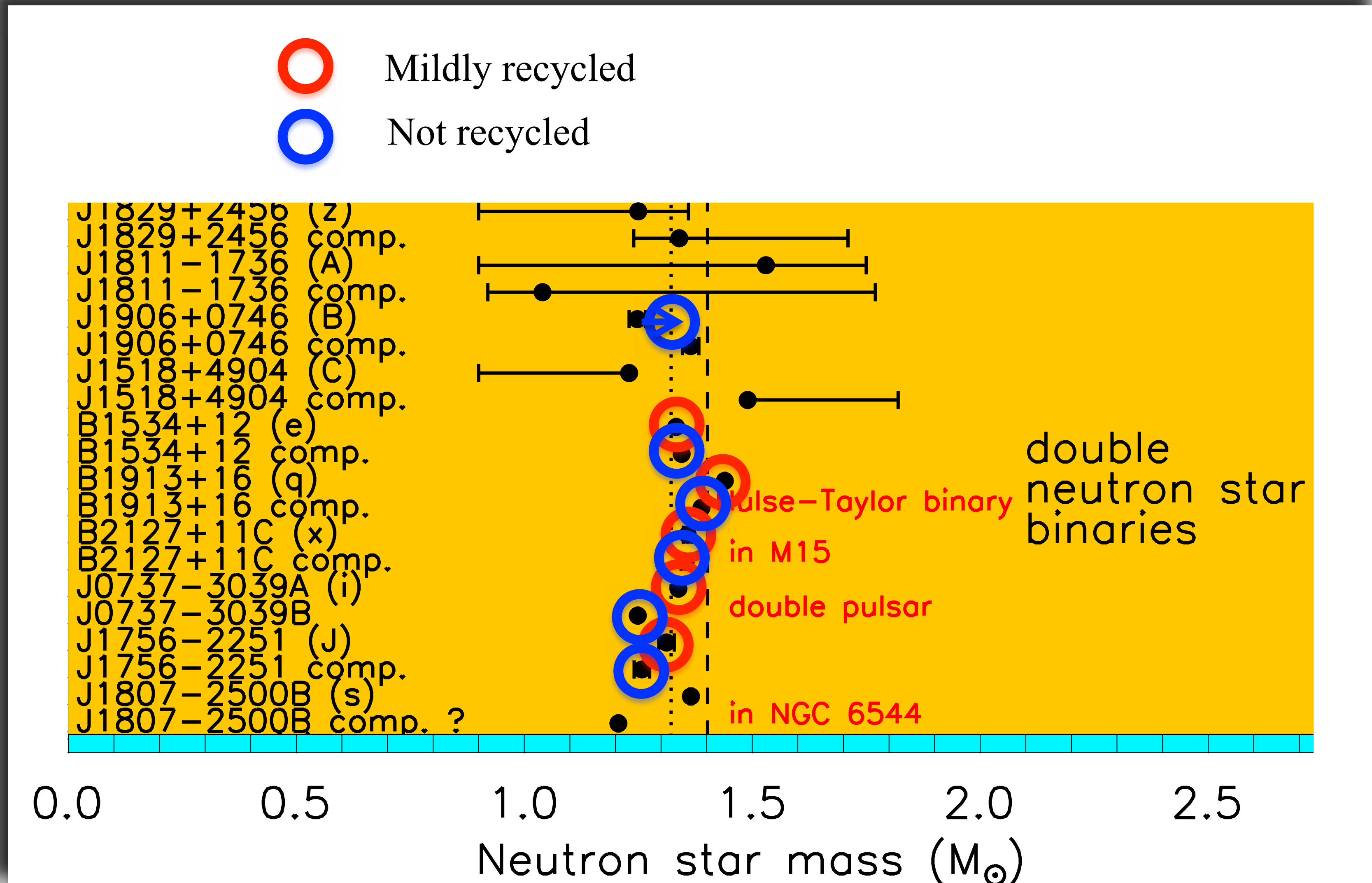


Accreted Mass
(for recycled pulsars)

=



Observed Mass



Notes: PSRJ1906+0746. Kasian 2012 (PhD Thesis). Young pulsar. m1=1.323(11), m2=1.290(11). Nature of companion not clear. PSRJ1807-2500B=NGC6544B. Lynch et al 2012 (ApJ 745:109). P=4.8 ms, fully recycled. Nature of companion not clear. Likely that present system formed in exchange interatction.

Thorsett & Chakrabarty 1999
ApJ 512:288

Bayesian analysis of all pulsar masses.

All pulsars: $1.35 \pm 0.04 M_{\odot}$

Schwab, Podsiadlowski, & Pappaport 2010
ApJ 719:722

Model cumulative distribution of pulsar masses, test with Kolmogorov-Smironv and Anderson-Darling test. Six NS-NS systems and two NS-WD systems.

Two populations:
- $1.246 \pm 0.008 M_{\odot}$ (four pulsars)
- $1.345 \pm 0.025 M_{\odot}$ (ten pulsars)

Argued that the low-mass and high-mass populations are consistent with electron capture supernovae and iron core collapse supernovae, respectively.

Kiziltan, Kottas, & Thorsett 2010
arXiv:1011.4291

Bayesian analysis of NS-NS systems and NS-WD systems.

- NS-NS: $1.35 \pm 0.13 M_{\odot}$
- NS-WD: $1.50 \pm 0.25 M_{\odot}$

Argued that the difference in mass ranges was due to accretion in the formation of the NS-WD systems.

Özel et al. 2012
arXiv:1201.1006

Bayesian analysis segregating categories of NS based on evolution and accretion history.

- All NS-NS: $1.33 \pm 0.06 M_\odot$
- Recycled NS-NS: $1.35 \pm 0.06 M_\odot$
- Non-recycled NS-NS: $1.32 \pm 0.07 M_\odot$

- Fully recycled: $1.48 \pm 0.20 M_\odot$
- Slow or Accreting: $1.28 \pm 0.24 M_\odot$

Conclude that tight mass distribution of NS-NS systems requires relatively rare NS formation channel.

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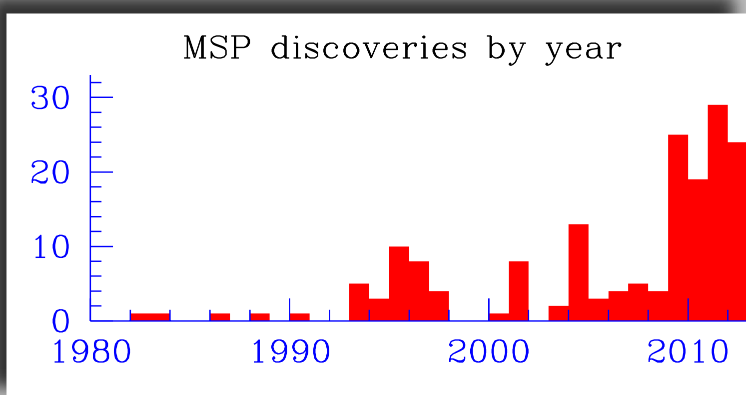
The future I.   New millisecond pulsar discoveries.

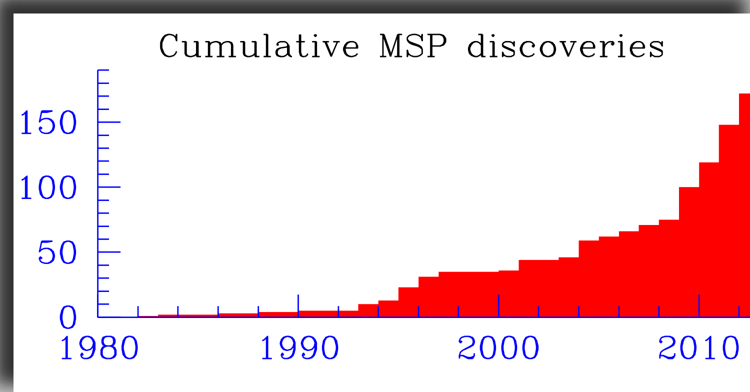
Session 1: Pulsar Discovery I

10.35	The HTRU surveys for pulsars & fast transients	Michael Keith
10:55	The PALFA Survey: Going to great depths to find radio pulsars	Patrick Lazarus
11:15	The hunt for new pulsars with the Green Bank Telescope	Ryan Lynch
11:35	New results from LOFAR	Ben Stappers
11:55	Conducting the deepest all-sky pulsar survey ever:	
	The All-Sky High Time Resolution Universe Legacy Survey	Cherry Ng
12:15-12:30	A search for pulsars in the central parsecs of the Galactic Center	Andrew Siemion

Session 3: Pulsar discovery II and Poster Session

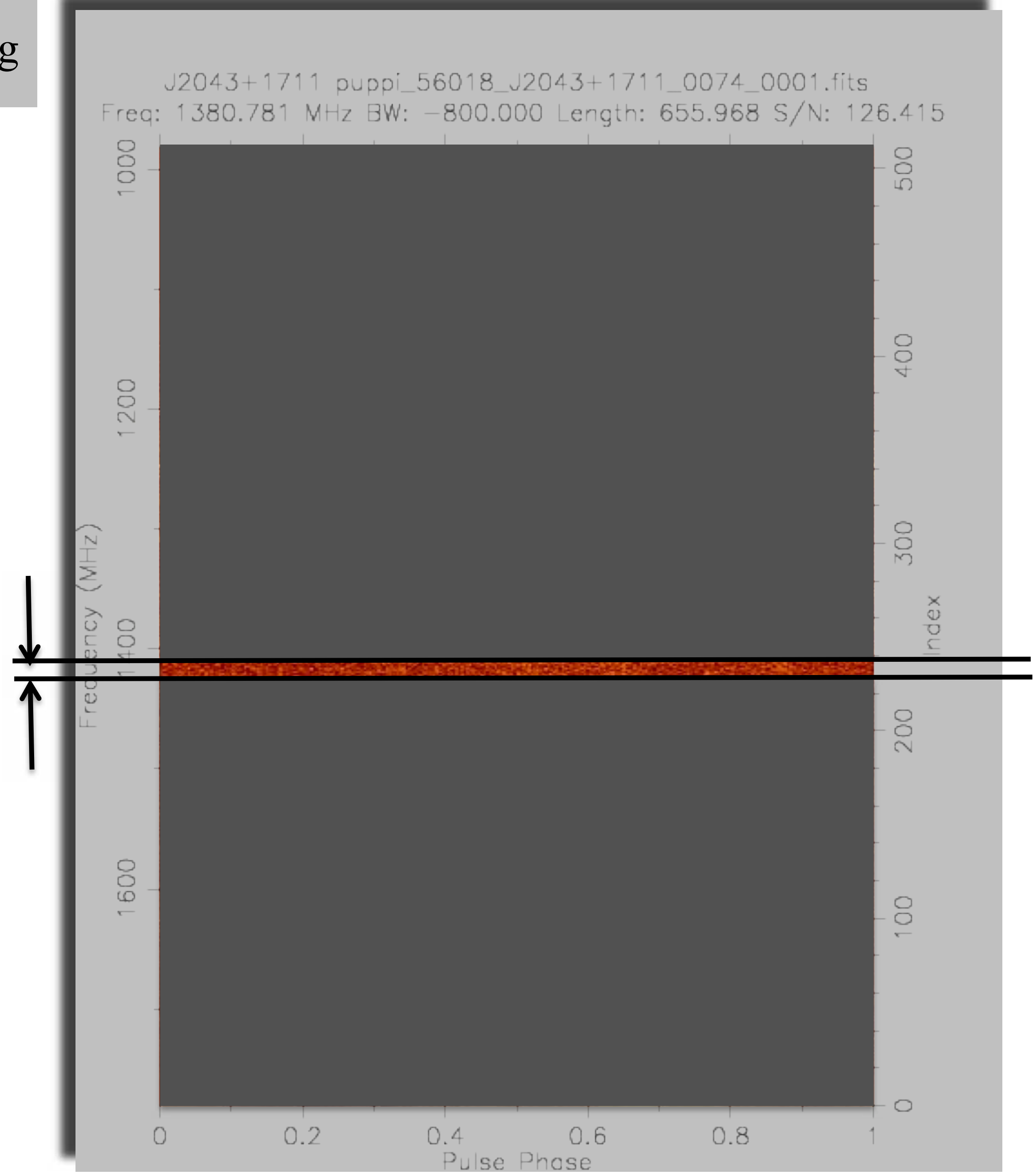
16:00	Fermi LAT Searches for gamma-ray pulsars	Pablo Saz Parkinson
16:20	Radio counterparts of gamma-ray pulsars	Lucas Guillemot





Galactic (non-cluster) MSPs. Data from Dunc Lorimer, astro.phys.wvu.edu/GalatcicMSPs

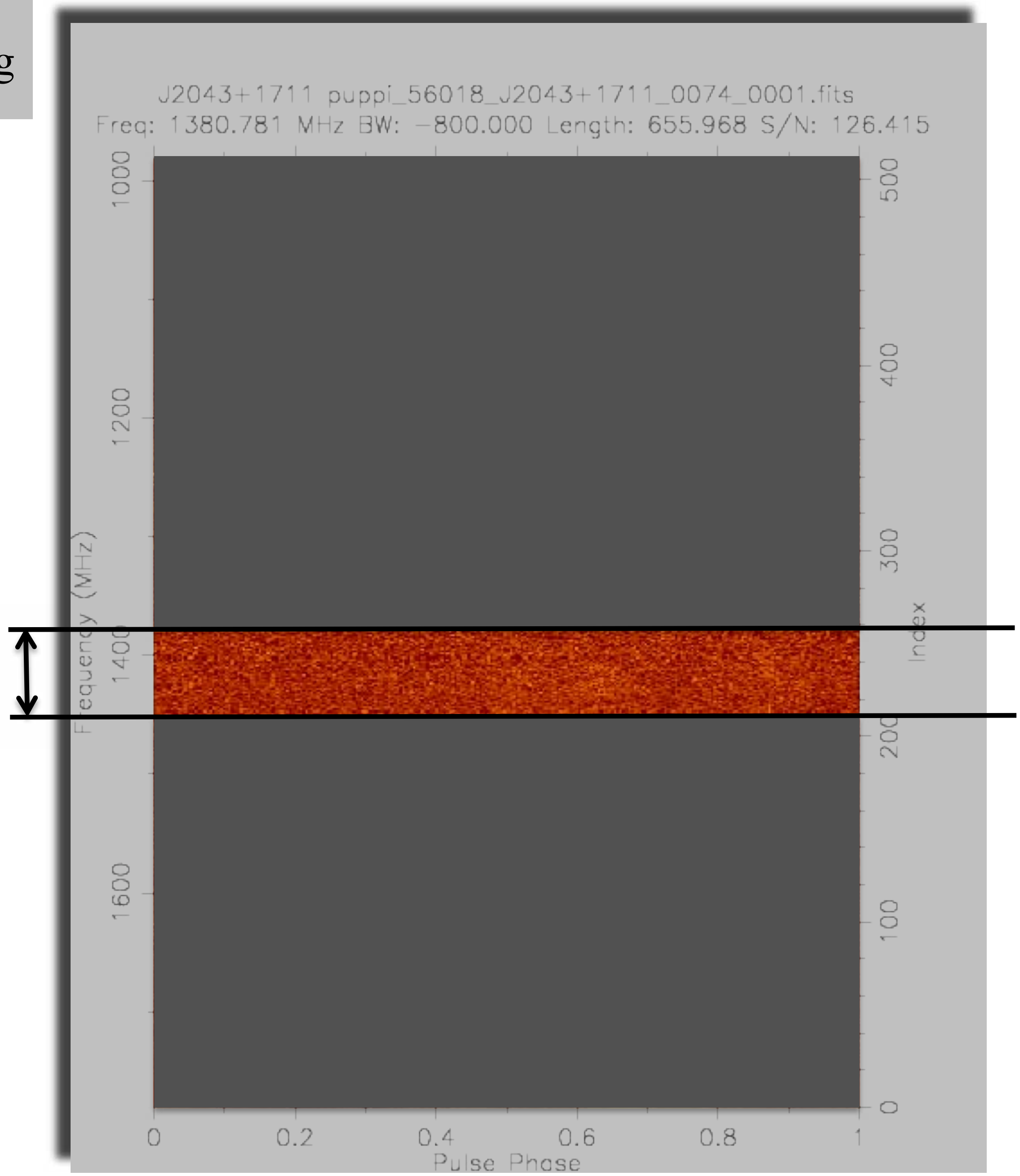
The future II.
Wide bandwidth high precision timing



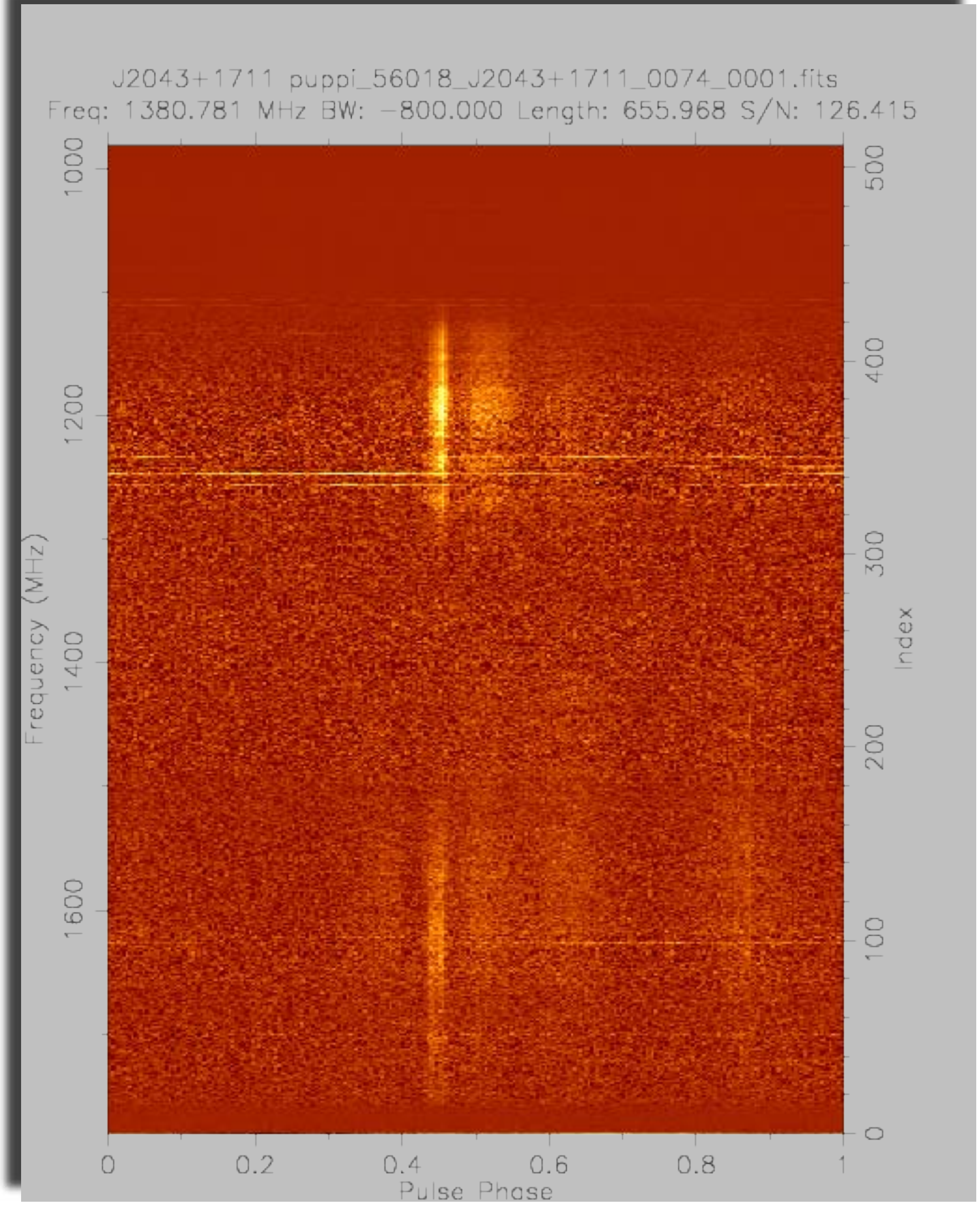
Arecibo Mark4
1998-2006
10 MHz bandwidth

The future II.
Wide bandwidth high precision timing

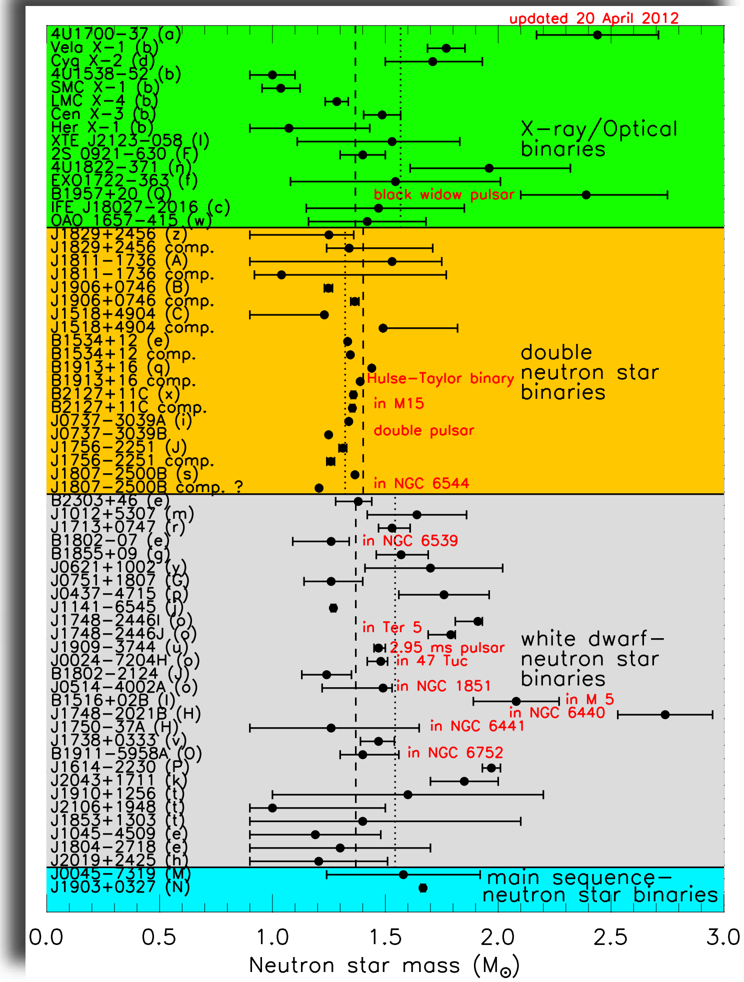
GASP(GBT)/ASP(Arecibo)
2005–2012±
64 MHz bandwidth



The future II.
Wide bandwidth high precision timing



GUPPI (GBT), PUPPI (Arecibo)
2011±–
800 MHz bandwidth



Summary

- Precise NS mass measurements of ~2$M_\odot$ are pushing limits of equation-of-state models

- NS sub-population masses
  - Unrecycled NS in NS-NS binaries: relatively light; narrow distribution
  - Mildly recycled NS in NS-NS binaries: slightly heavier; narrow distribution
  - Fully recycled NS: significantly heavie;, wider distribution
  - Unrecycled NS not in NS-NS binaries: relatively wide disbribution?

- Dozens of new discoveries, coupled to vastly improved instrumentation, promise many more mass measurements in the coming years.