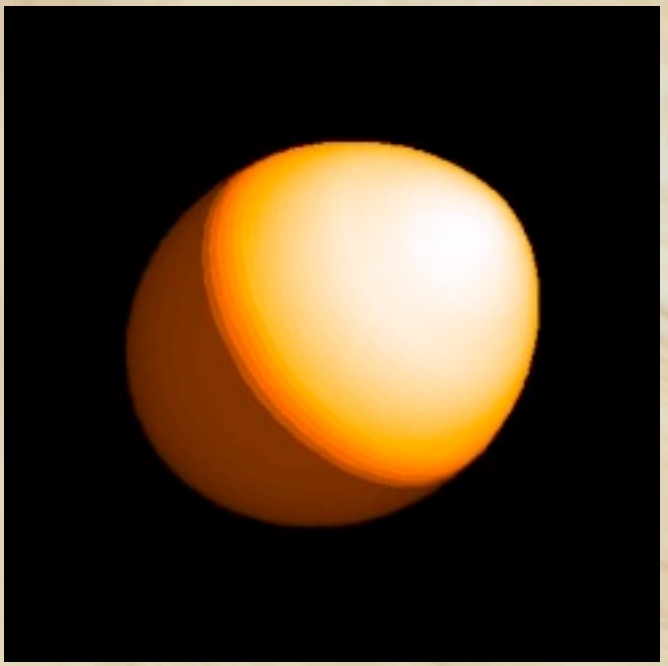
Lessons from Irradiated Pulsar Binaries



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University of Southampton

High Time Resolution Optical Astrophysics
Royal Astronomical Society, London
12 April 2013

Pulsars as (Neutron Star) Radio Lighthouses

Radio timing:

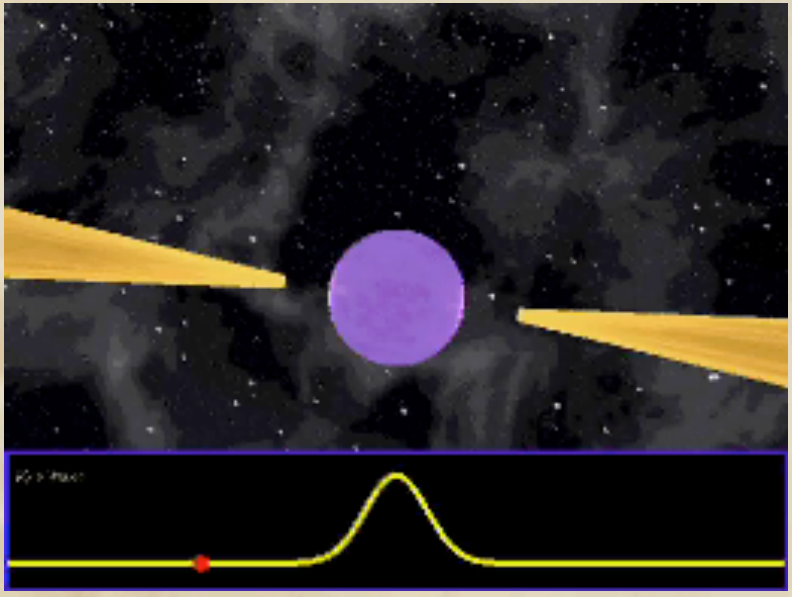
- Very accurate orbital parameters

Radio emission is rotation-powered:

- Most energy carried away by relativistic wind

$L_{radio} \sim 10^{-[10,4]} L_{spin\text{-}down}$

$L_{gamma\text{-}ray} \sim 10^{-[3\text{-}1]} L_{spin\text{-}down}$



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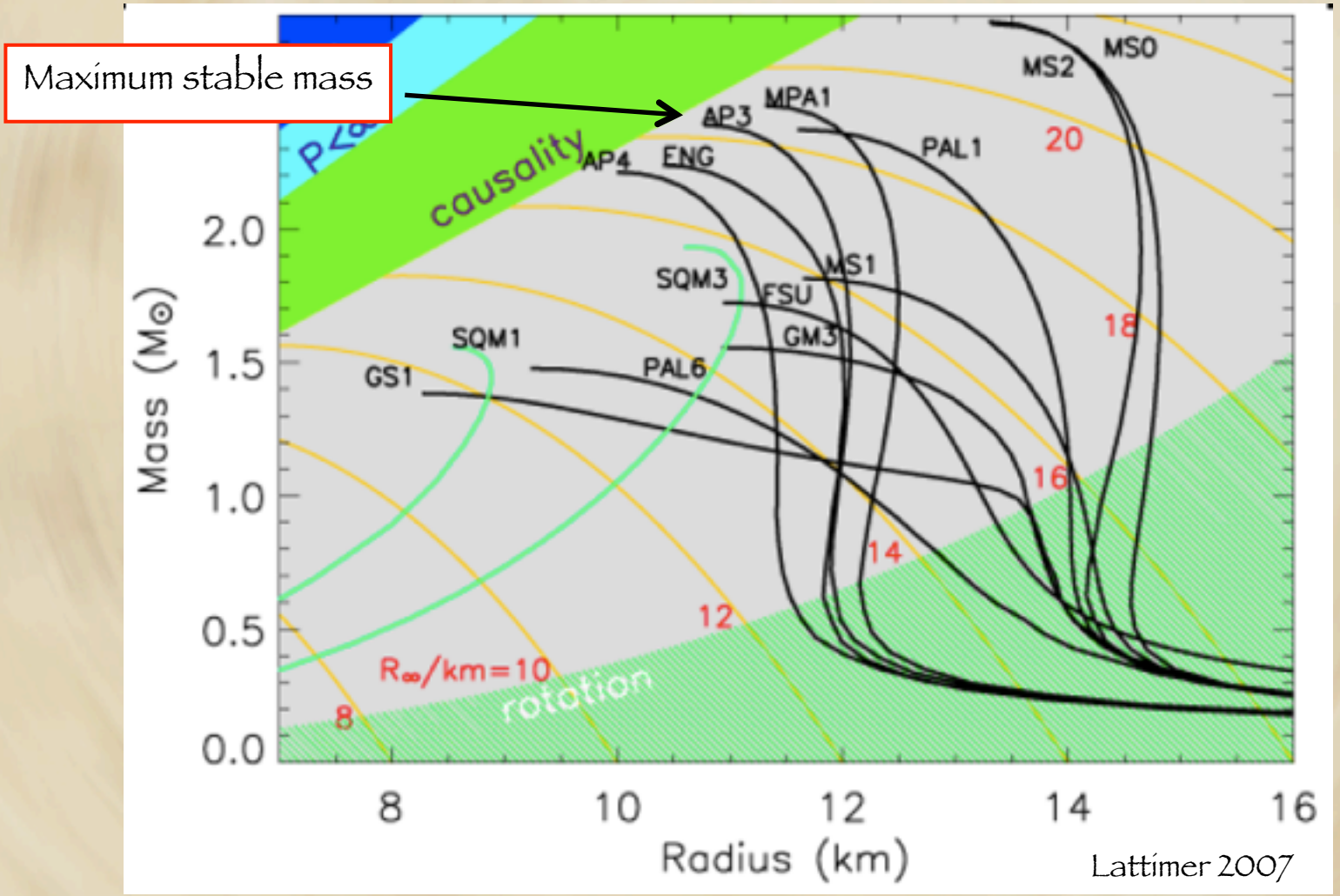
Optical work in this talk:

- High-time resolution... as orbital phase-resolved
- Multi-colour imaging (e.g. ULTRACAM)

Neutron Star's Terra Incognita

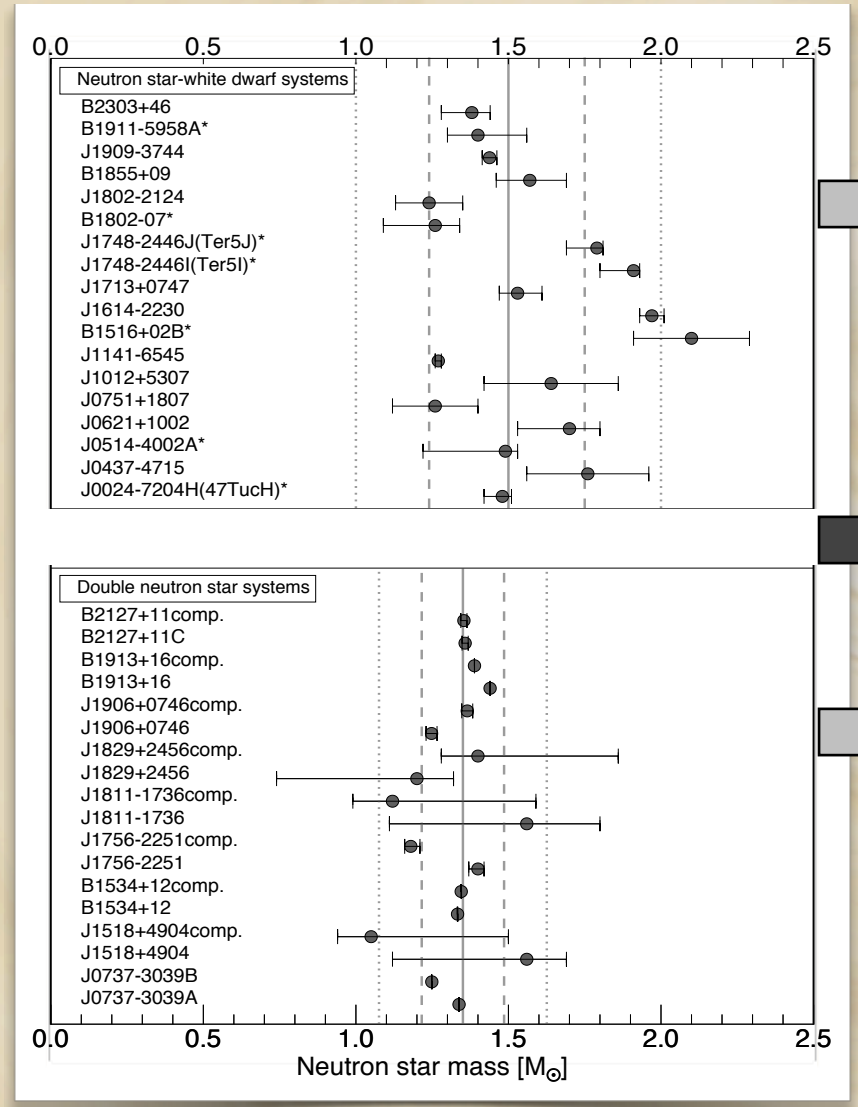
"Most" outstanding neutron star question: Equation of State

Predicts mass-radius relationship, determines internal structure.



Lattimer 2007

Measuring Neutron Star Masses



Via white dwarfs

(atmosphere modelling and radial velocity)

Via irradiated systems

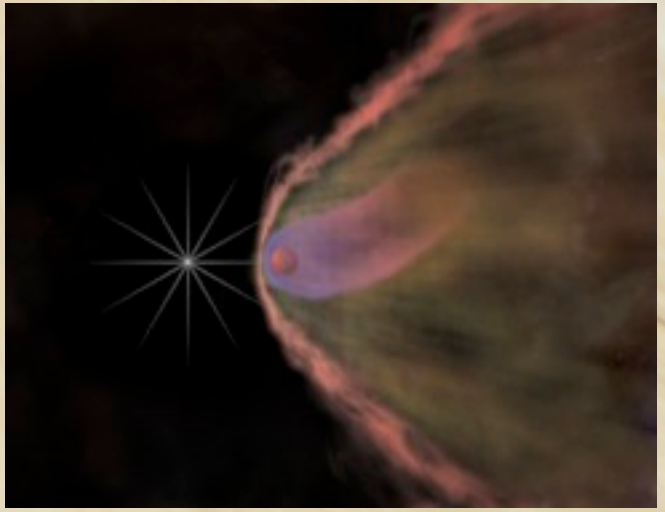
Via pulsar timing

(post-Keplerian orbital parameters)

Needs to be relativistic

Irradiated Pulsar Binaries

- Energetic (E ~ 10^{35} erg/s) rapidly rotating pulsars (P ~ few ms)
- Compact orbits (few hours)
- Two classes:
  - "Black widows": very low-mass companions (~0.03 $M_\odot$)
  - "Redbacks": low-mass companions (~0.2 $M_\odot$)



Evidence of ablation of the companion:

- Radio eclipses

Paradigm:

May harbour heavy pulsars because of long mass transfer episode.

Meet the Family

1988-2009: 3 known systems

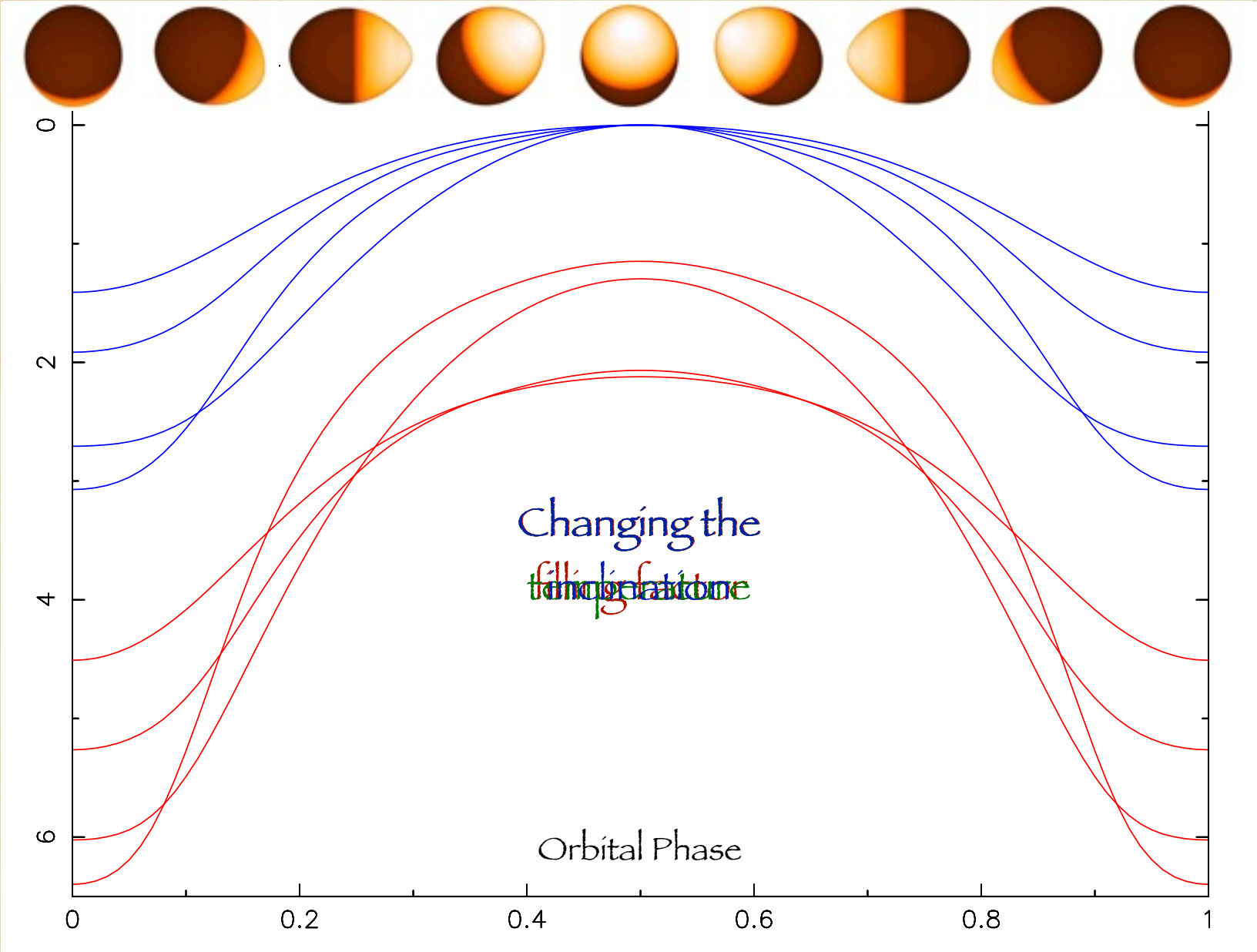
2009-today: > 20 known systems

Irradiated systems found in targeted radio follow-ups of Fermi point sources.

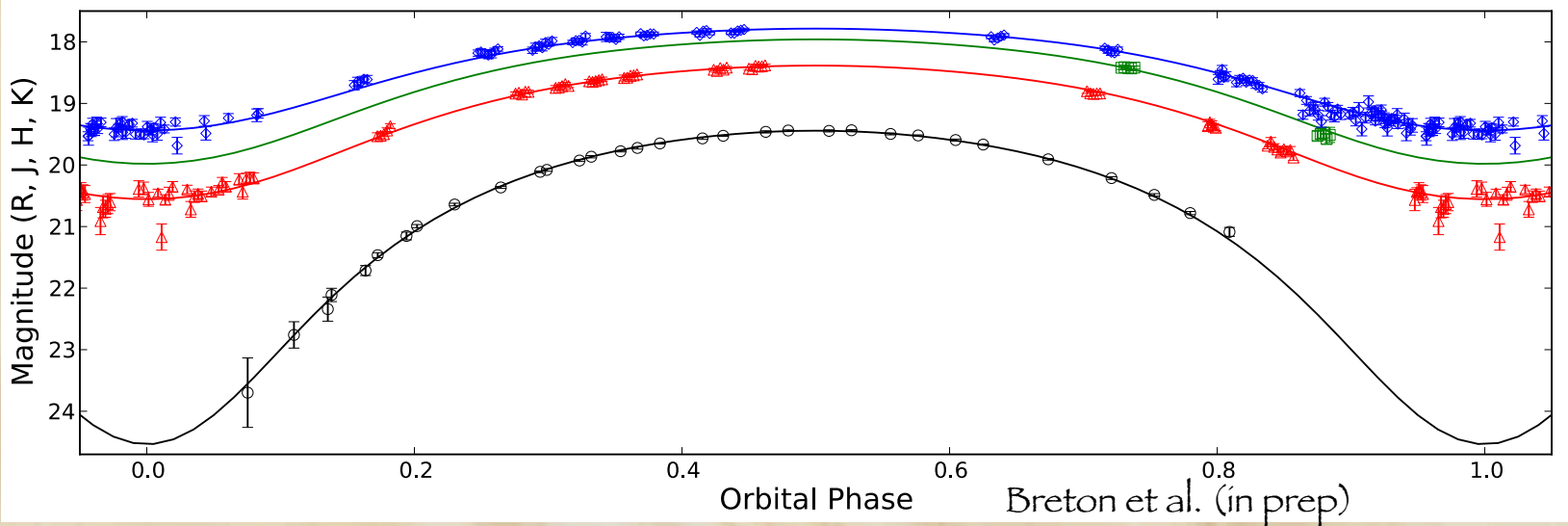
Pulsar[1]	P_s (ms)	$\dot{E}/10^{34}$ [2] (erg/s)	d_{NE2001} (kpc)	P_B (hr)	M_c [3] (solar)	ref.
Old Black Widows						
B1957+20 F	1.61	11	2.5	9.2	0.021	Fruchter *et al.* (1990)
J0610−2100	3.86	0.23	3.5	6.9	0.025	Burgay *et al.* (2006)
J2051−0827	4.51	0.53	1.0	2.4	0.027	Stappers *et al.* (1996)
New Black Widows						
J2241−5236 F	2.19	2.5	0.5	3.4	0.012	Keith *et al.* (2011)
J2214+3000 F	3.12	1.9	3.6	10.0	0.014	Ransom *et al.* (2011)
J1745+1017 F	2.65	1.3	1.3	17.5	0.014	Barr *et al.* (2012)
J2234+0944 F	3.63	1.6	1.0	10	0.015	Keith *et al.* (2012a)
J0023+0923 F	3.05	1.6	0.7	3.3	0.016	Hessels *et al.* (2011)
J1544+4937 F	2.16	1.2	1.2	2.8	0.018	Bhattacharyya *et al.* (2012)
J1446−4701 F	2.19	3.8	1.5	6.7	0.019	Keith *et al.* (2012)
J1301+0833 F	1.84	6.8	0.7	6.5	0.024	Ray *et al.* (2012)
J1124−3653 F	2.41	1.6	1.7	5.4	0.027	Hessels *et al.* (2011)
J2256−1024 F	2.29	5.2	0.6	5.1	0.034	Boyles et al.(2011)
J2047+10 F	4.29	1.0	2.0	3.0	0.035	Ray *et al.* (2012)
J1731−1847	2.3	??	2.5	7.5	0.04	Bates et al.(2011)
J1810+1744 F	1.66	3.9	2.0	3.6	0.044	Hessels *et al.* (2011)
New Redbacks						
J1628−32 F	3.21	1.8	1.2	5.0	0.16	Ray *et al.* (2012)
J1816+4510 F	3.19	5.2	2.4	8.7	0.16	Kaplan *et al.* (2012)
J1023+0038 F	1.69	$\sim 5-10$	0.6	4.8	0.2	Archibald *et al.* (2009)
J2215+5135 F	2.61	6.2	3.0	4.2	0.22	Hessels *et al.* (2011)
J1723−28	1.86	??	0.75	14.8	0.24	Crawford *et al.* (2010)
J2129−0429 F	7.61	3.9	0.9	15.2	0.37	Hessels *et al.* (2011)

Roberts (2012)

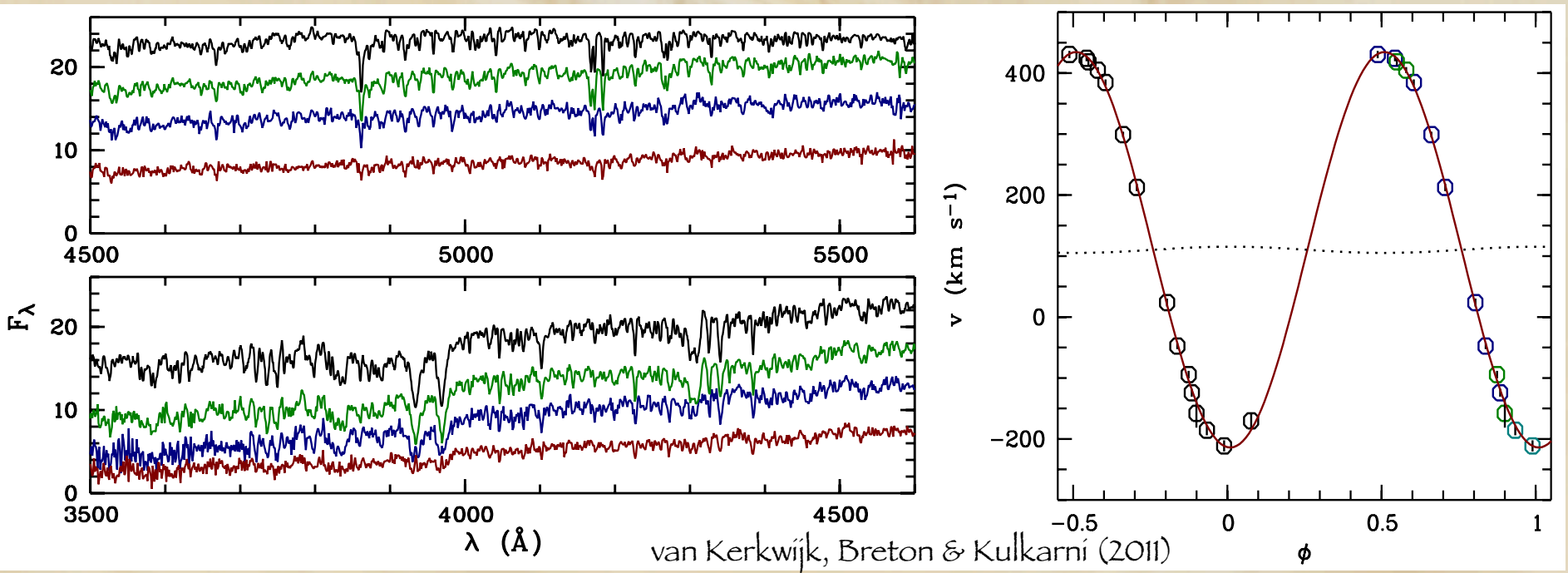
Determining the System Geometry



The Case of the 'Original' Black Widow B1957+20

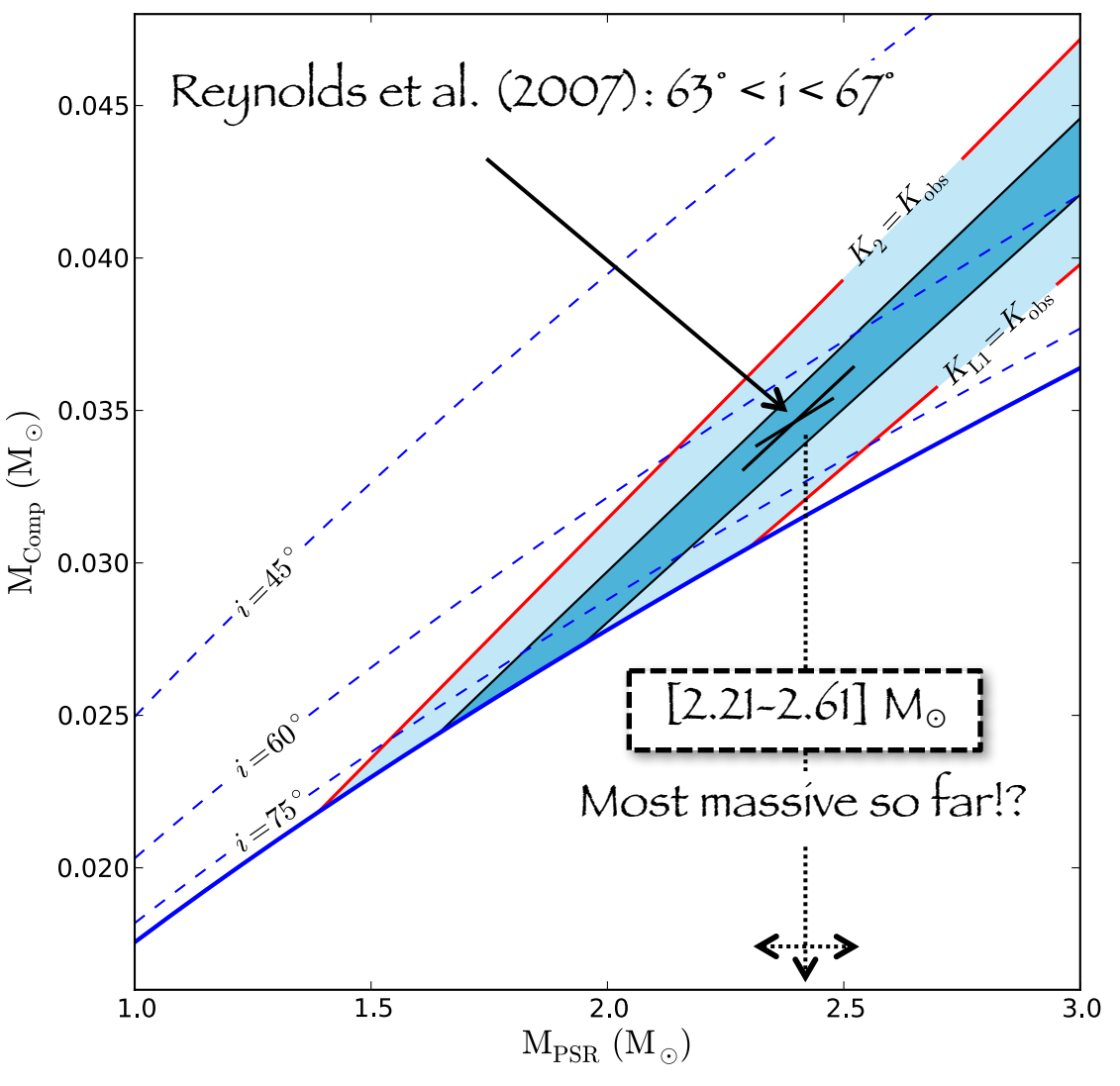


Breton et al. (in prep)

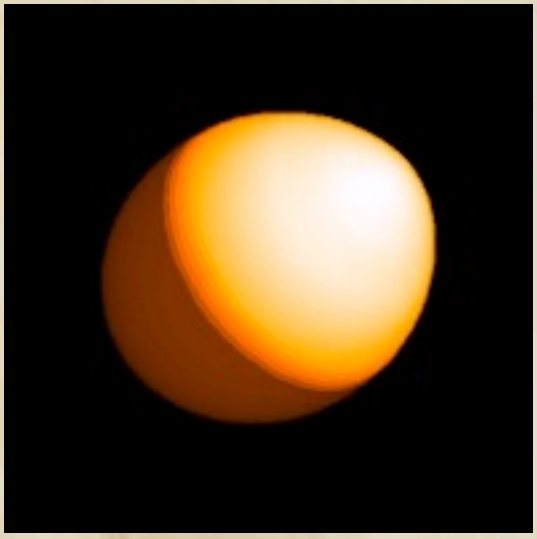


van Kerkwijk, Breton & Kulkarni (2011)

Constraining the Pulsar Mass



van Kerkwijk, Breton & Kulkarni (2011)



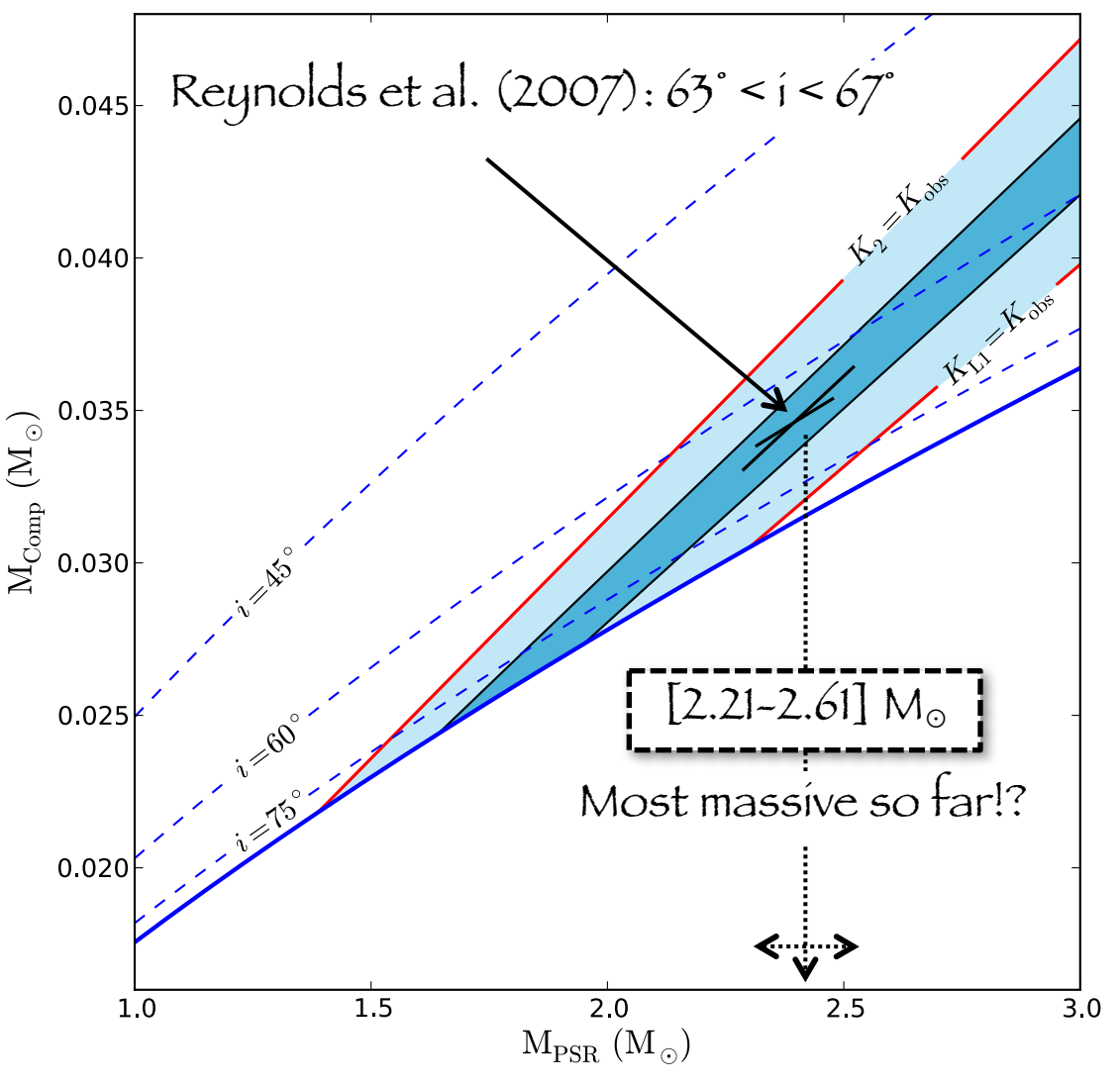
Mass ratio determination is non-trivial:

- Centre-of-light displaced away from centre-of-mass

Solution:

- Modelling time-resolved spectral lightcurves

Constraining the Pulsar Mass



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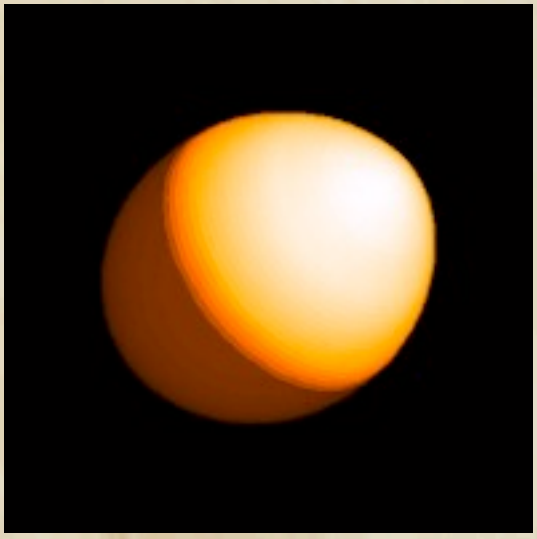


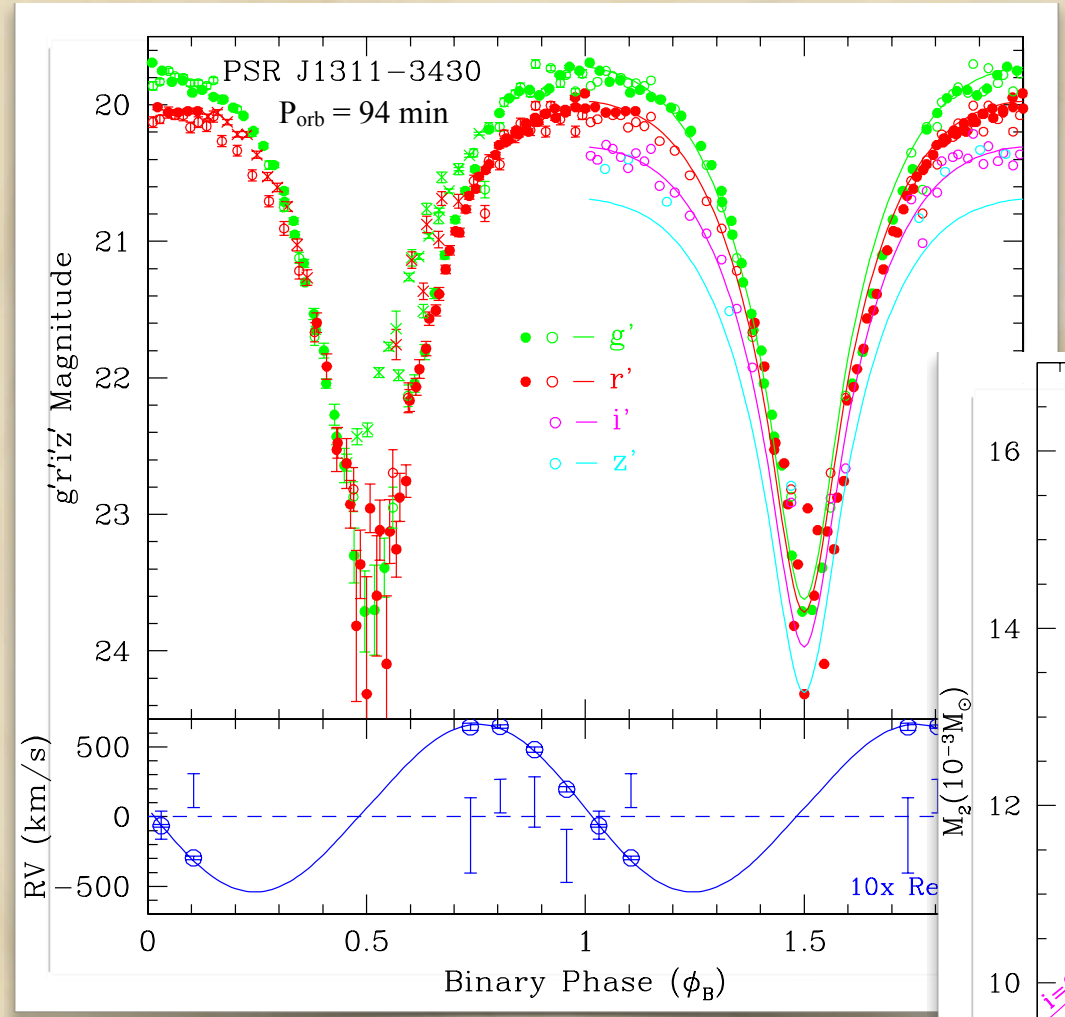
Mass is highly sensitive to orbital inclination:

Error propagates as $\sin^3(i)$

Solution:

High-time resolution, multi-colour images

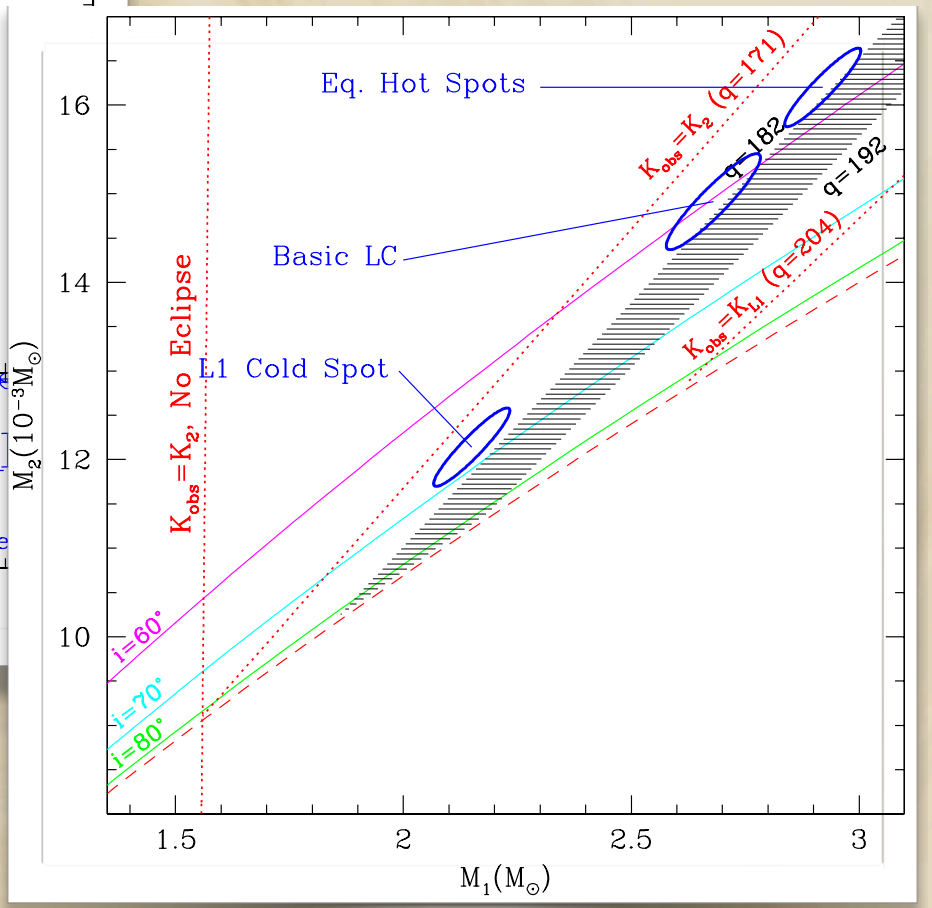
PSR J1311-3430: First γ-Ray Detected MSP



Massive neutron star, but how much?

Flares are seen.

Lightcurve may depart from simple irradiated model.



Romani et al. (2012)

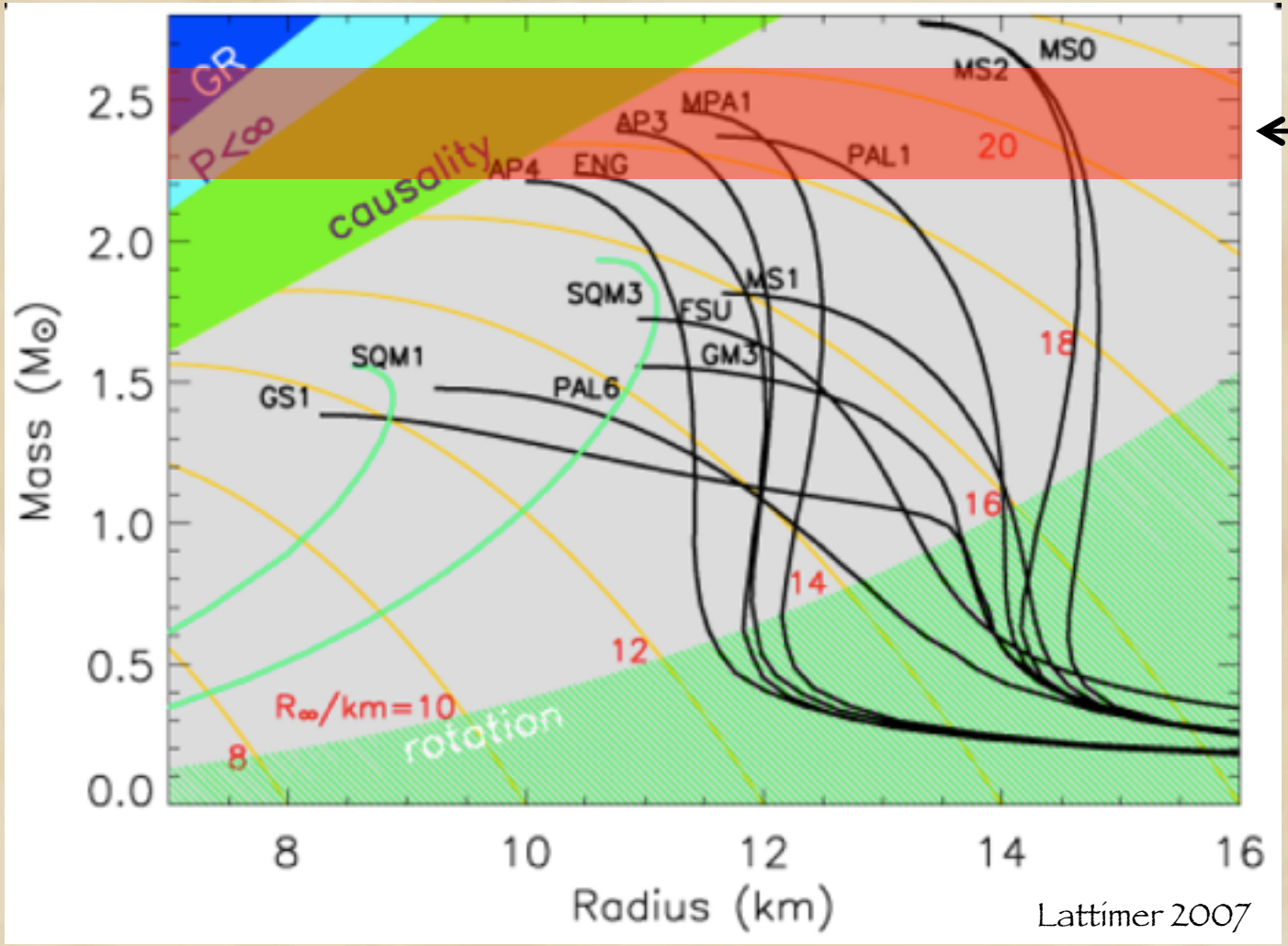
Using GROND: 7-channel, fast imager

The Lessons

Equation of State

Excluding several equations of state…

'Stiff' EoS are preferred



PSR B1957+20

Lattimer 2007

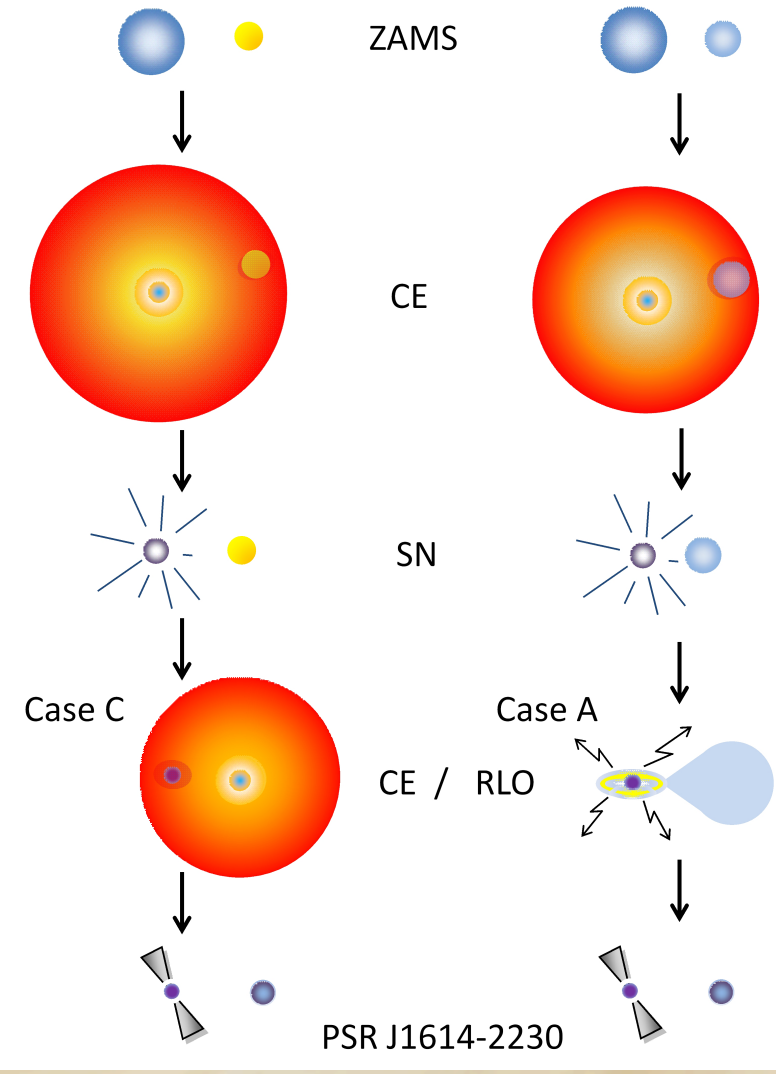
Canonical Neutron Star Mass, Not

Difficult systems to form (e.g. compact orbit):

- Did not accrete much large mass
- Accretion efficiency could be low

From the sample of pulsar masses:

- Probably not all neutron stars born around the same mass

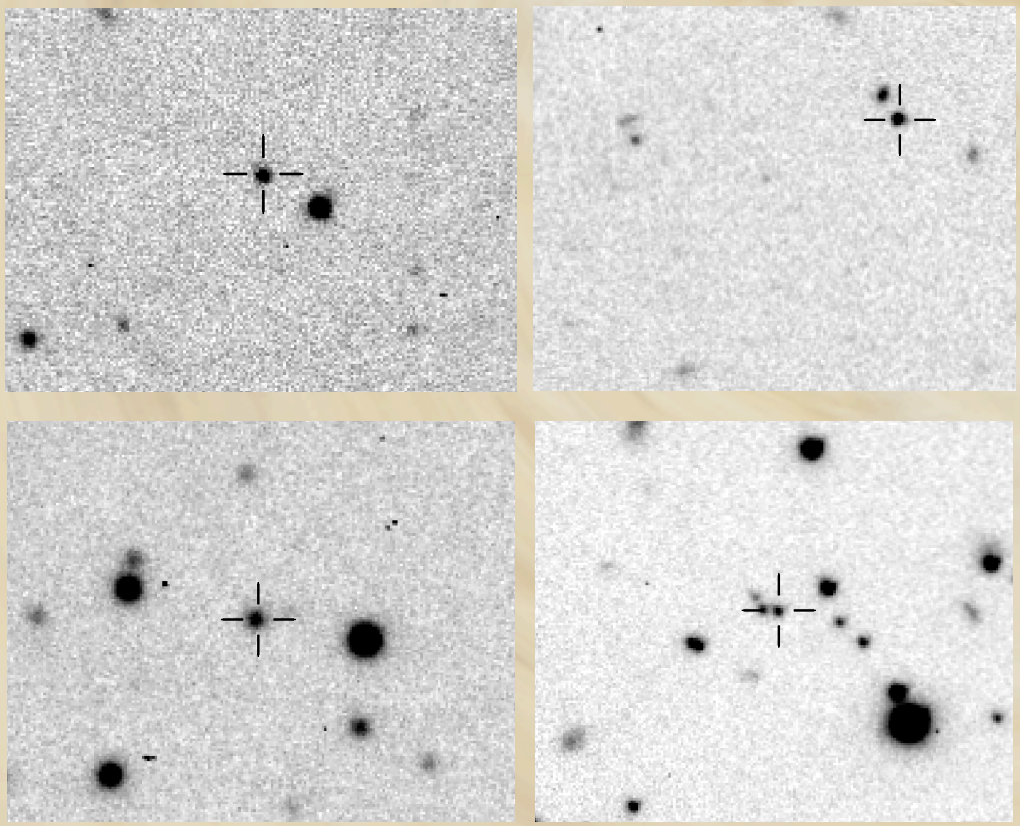


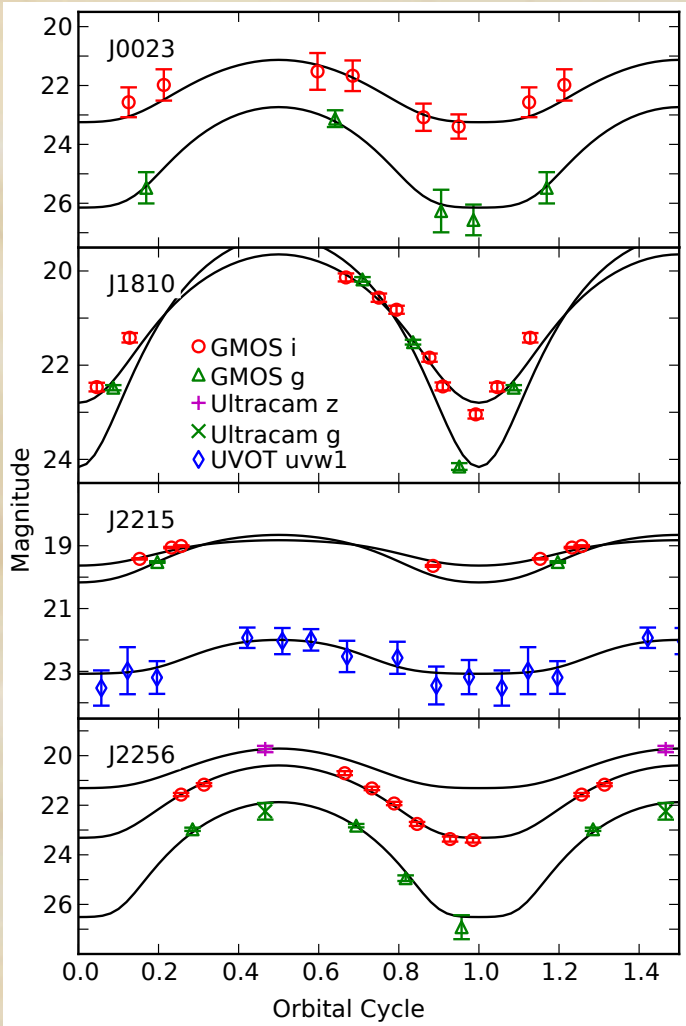
Tauris et al. (2011)

More New Black Widows

Four new optical counterparts detected with Gemini.
ULTRACAM studies are underway.

- Reflection effects amount 10-30% of spin-down luminosity
- Some of them might only partly fill their Roche-lobe

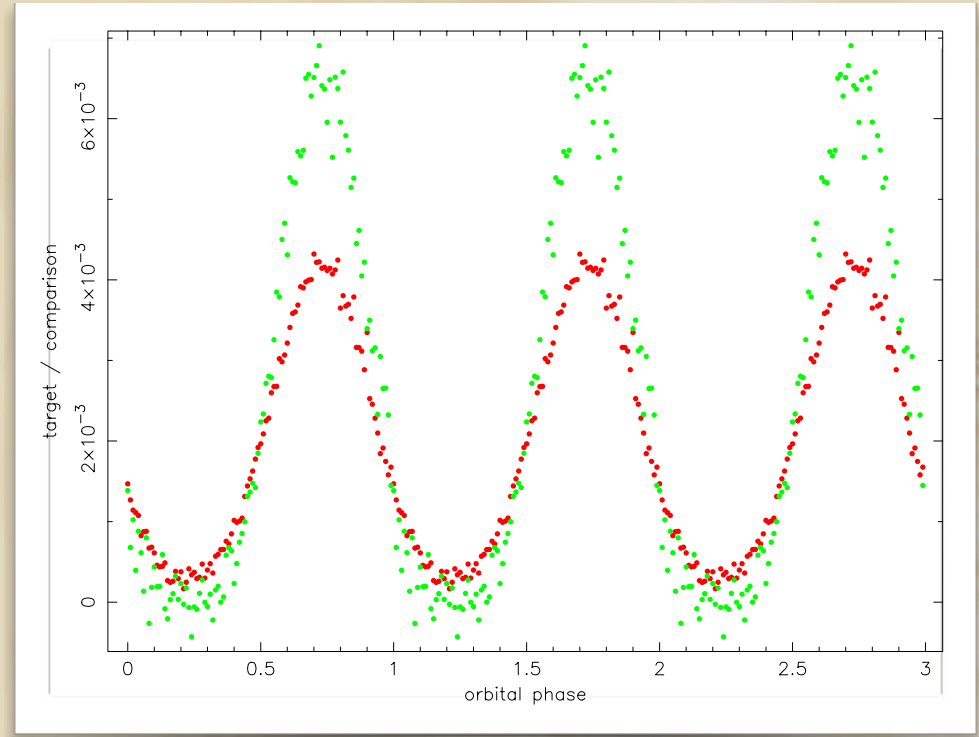




Breton et al. (2013)

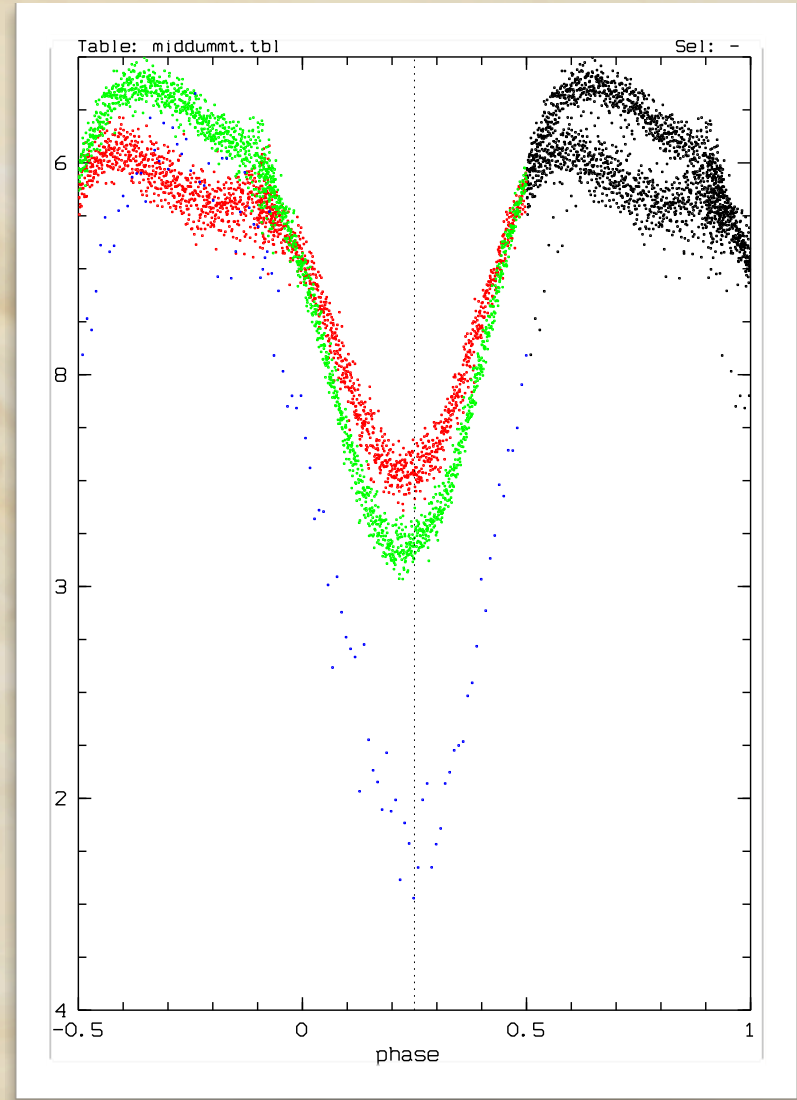
Studying the Behaviour of Spiders

"Normal": PSR J2256-1024



Breton et al. (in prep.)

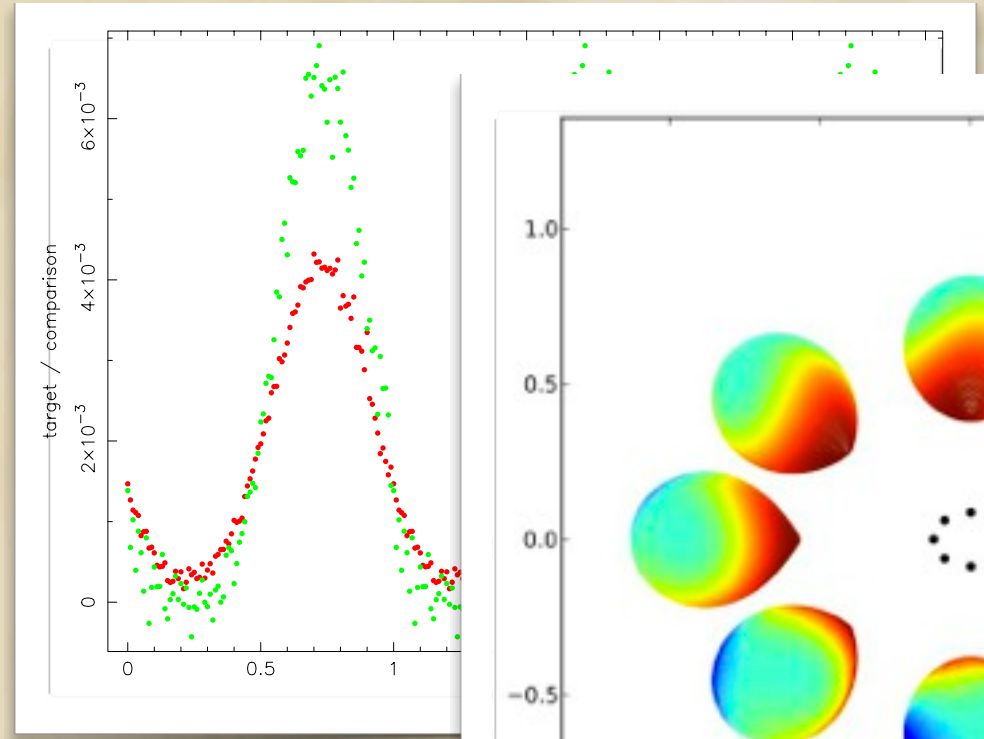
"Peculiar": PSR J1023+0038

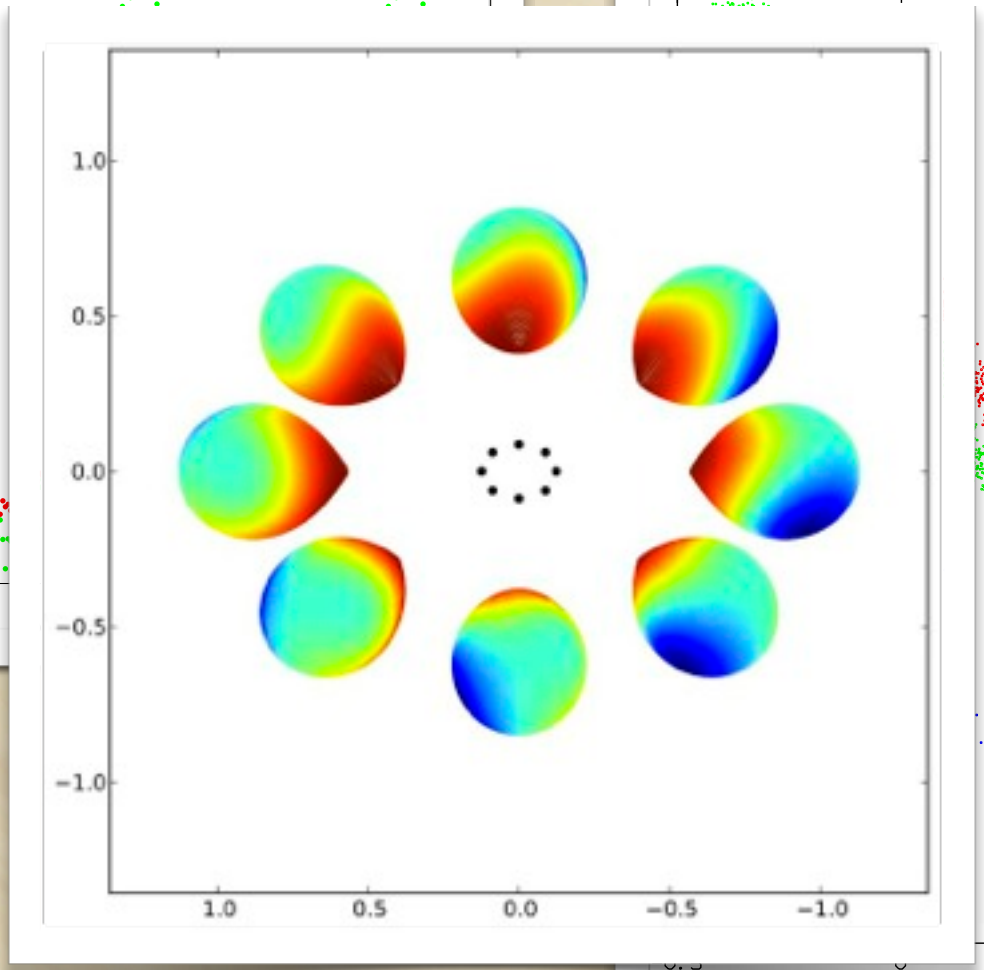


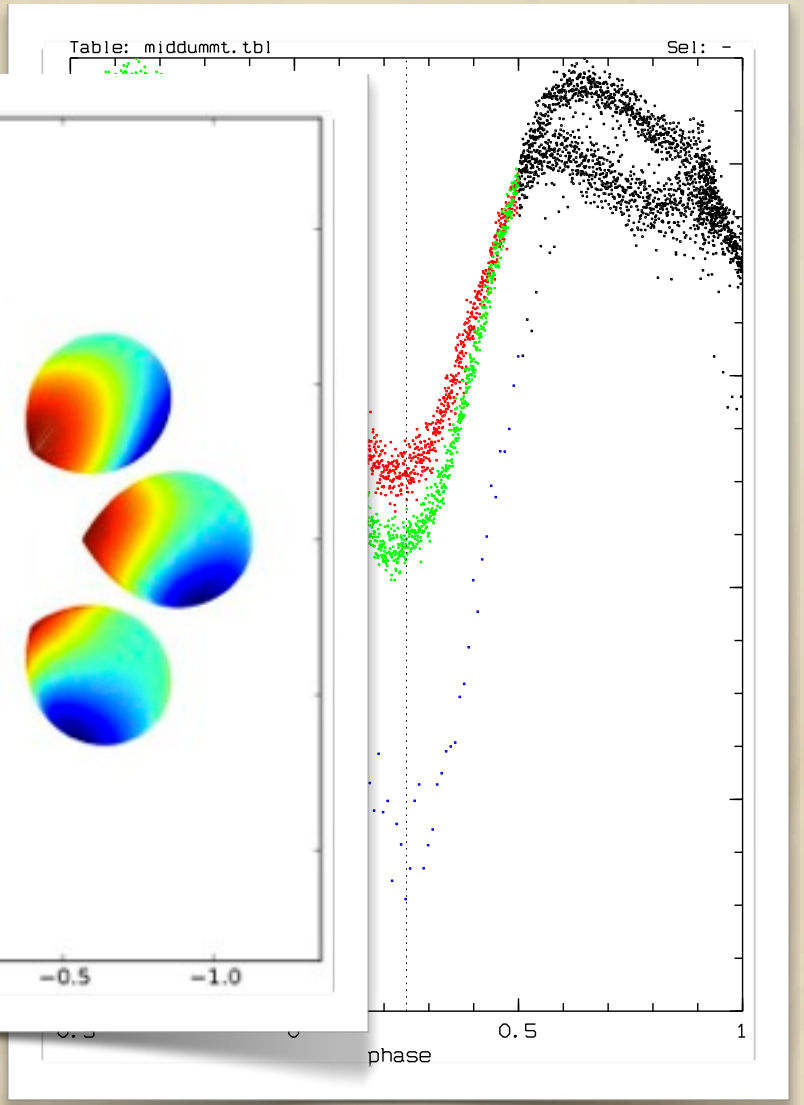
Studying the Behaviour of Spiders

"Normal": PSR J2256-1024

"Peculiar": PSR J1023+0038







Conclusions

Neutron star mass proxy via irradiated systems:

- PSR B1957+20: probable mass [2.21-2.61] $M_\odot$
- PSR J1311-3430: mass > 2 $M_\odot$, up to ~2.7 $M_\odot$

Neutron star masses:

- Equation of state most likely stiff
- Probably not all born at a canonical mass

Binary physics

- Reflection effects ~10-30% of $L_{spin-down}$
- Hints that system may only partly fill their Roche lobe
- 'Strange' lightcurves, why?

All of the above require time resolution and multiple colours + spectroscopy