WHAT ARE GALACTIC FIELD BLACK WIDOWS AND REDBACKS GOOD FOR?

(EVERYTHING BUT GRAVITY WAVES)

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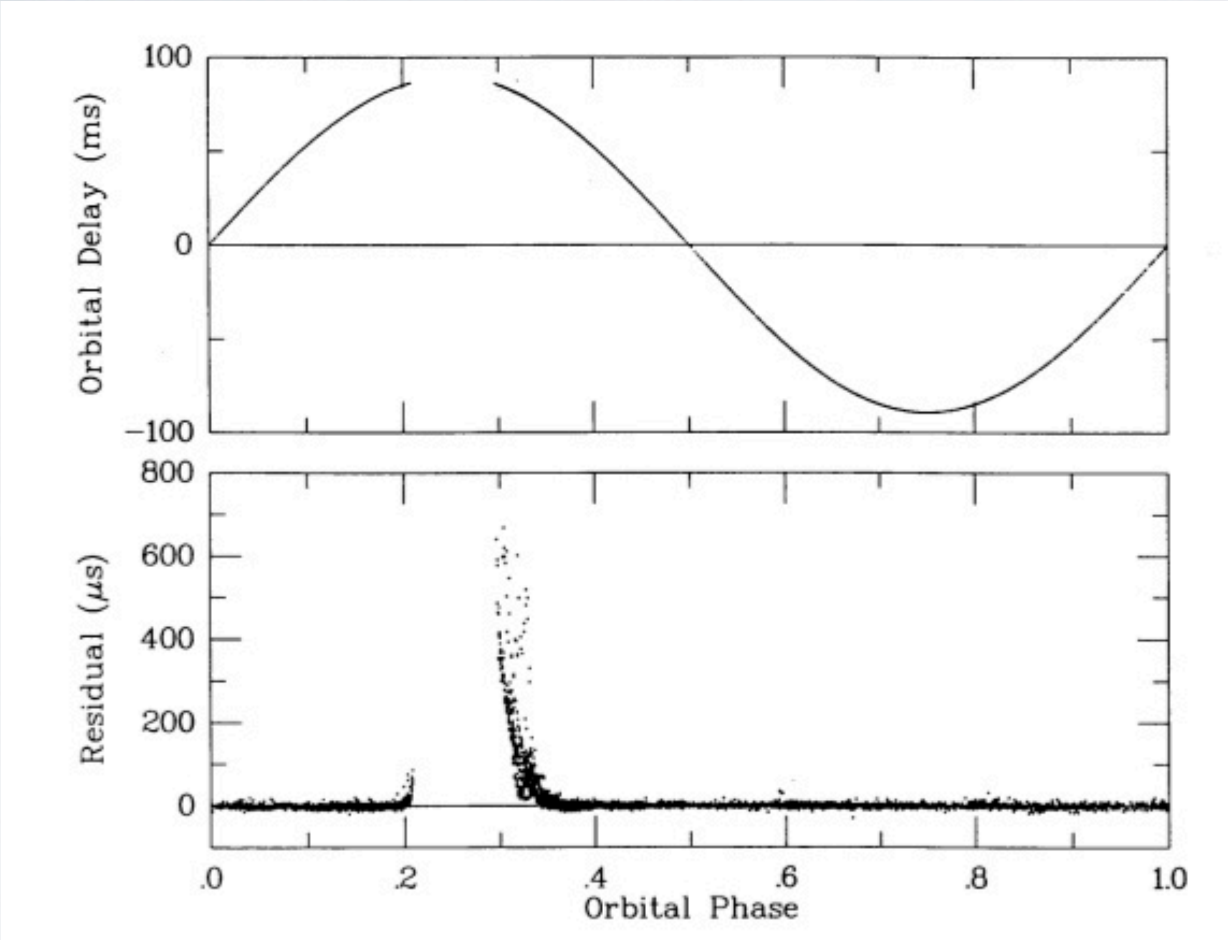
Eureka Scientific
Jan. 22, 2013
Aspen, CO

THE Black Widow PSR B1957+20

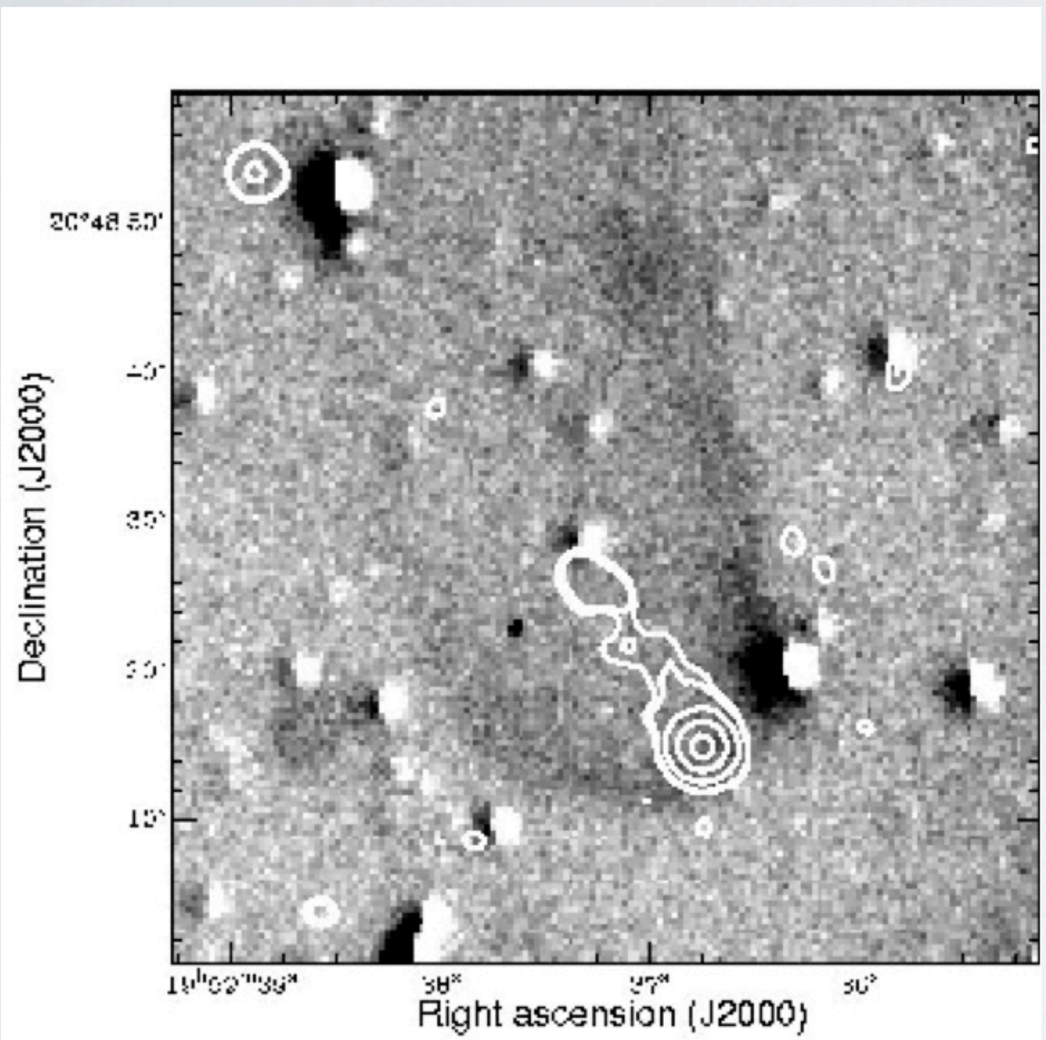


Fruchter et al. 1990

- 1.6 ms pulsar discovered by Fruchter et al. (1988) at Arecibo
- 9.2 hour orbit around very low mass (~0.02 solar) companion
- shows regular radio eclipses which is evidence of intrabinary material
- optical shows large orbital variation with peak magnitude ~20.3 -- evidence of illumination by pulsar (Fruchter et al 1988)

THE Black Widow PSR B1957+20

- Hα nebula direct evidence of pulsar wind (Kulkarni et al. 1988) Possible "standard" TeV PWN?

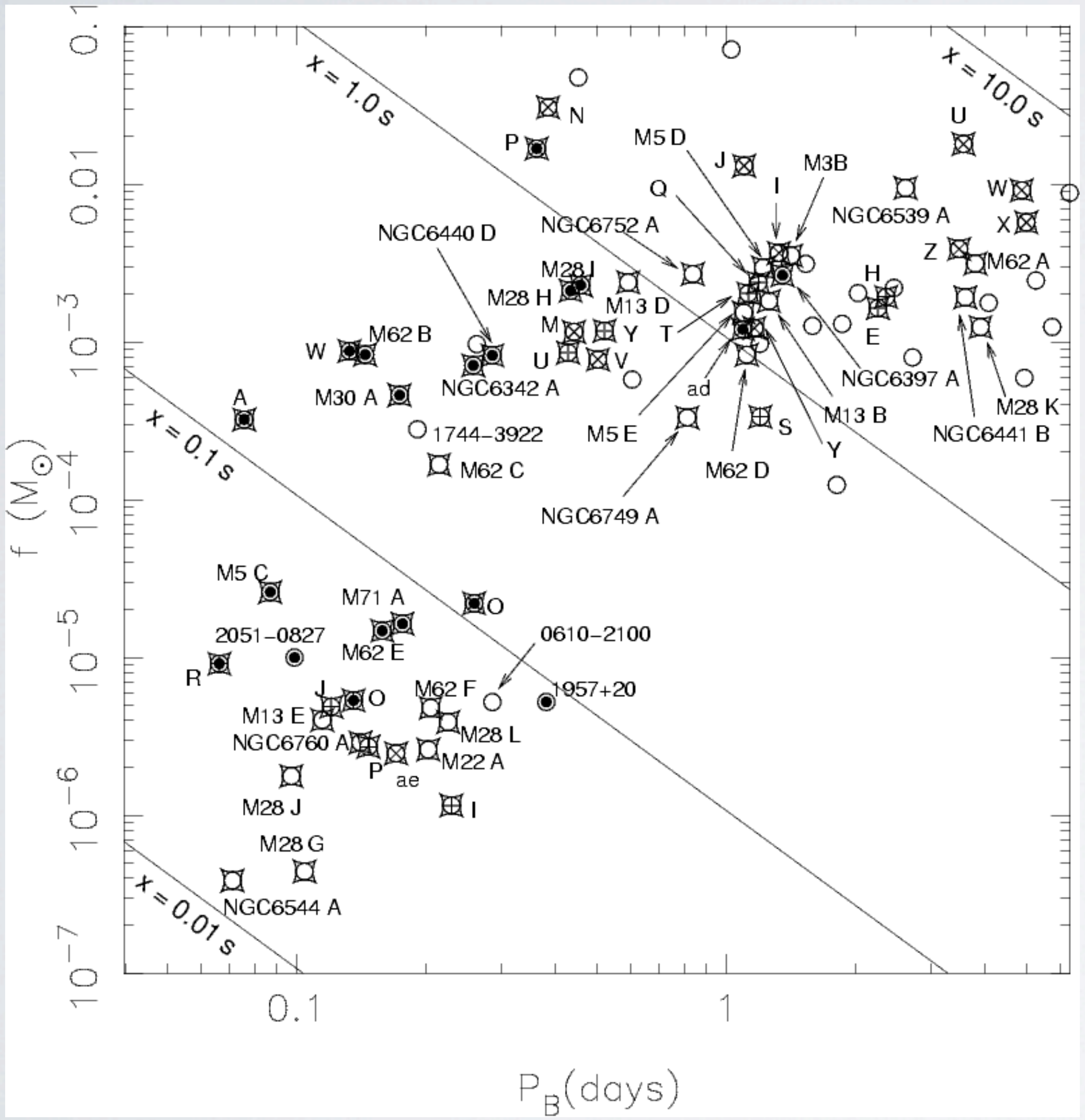


Stappers et al. 2003

- X-rays from point source and nebular tail (Stappers et al. 2003)
- X-rays of point source show evidence for orbital modulation, power-law spectrum (eg. Huang and Becker 2007)
- Interpretation is pulsar ablating companion, perhaps eventually completely evaporating it
- Pulsar wind interacts with ablated material causing an intrabinary shock

“Black Widows” as a Class

Low mass pulsar binaries, early 2009
P. Freire



See Paulo Freire’s web page of MSPs in GCs for complete list of GC BWs and RBs
http://www.naic.edu/~pfreire/GCpsr.html

Many MSPs, including black widows, are found in globular clusters, but cluster potential makes intrinsic spin-down difficult to determine

Black widows are a distinct population with very low mass companions.

In addition, there is a related population of eclipsing MSPs with low mass companions (Redbacks), at least some of which seem to be ordinary stars rather than white dwarfs

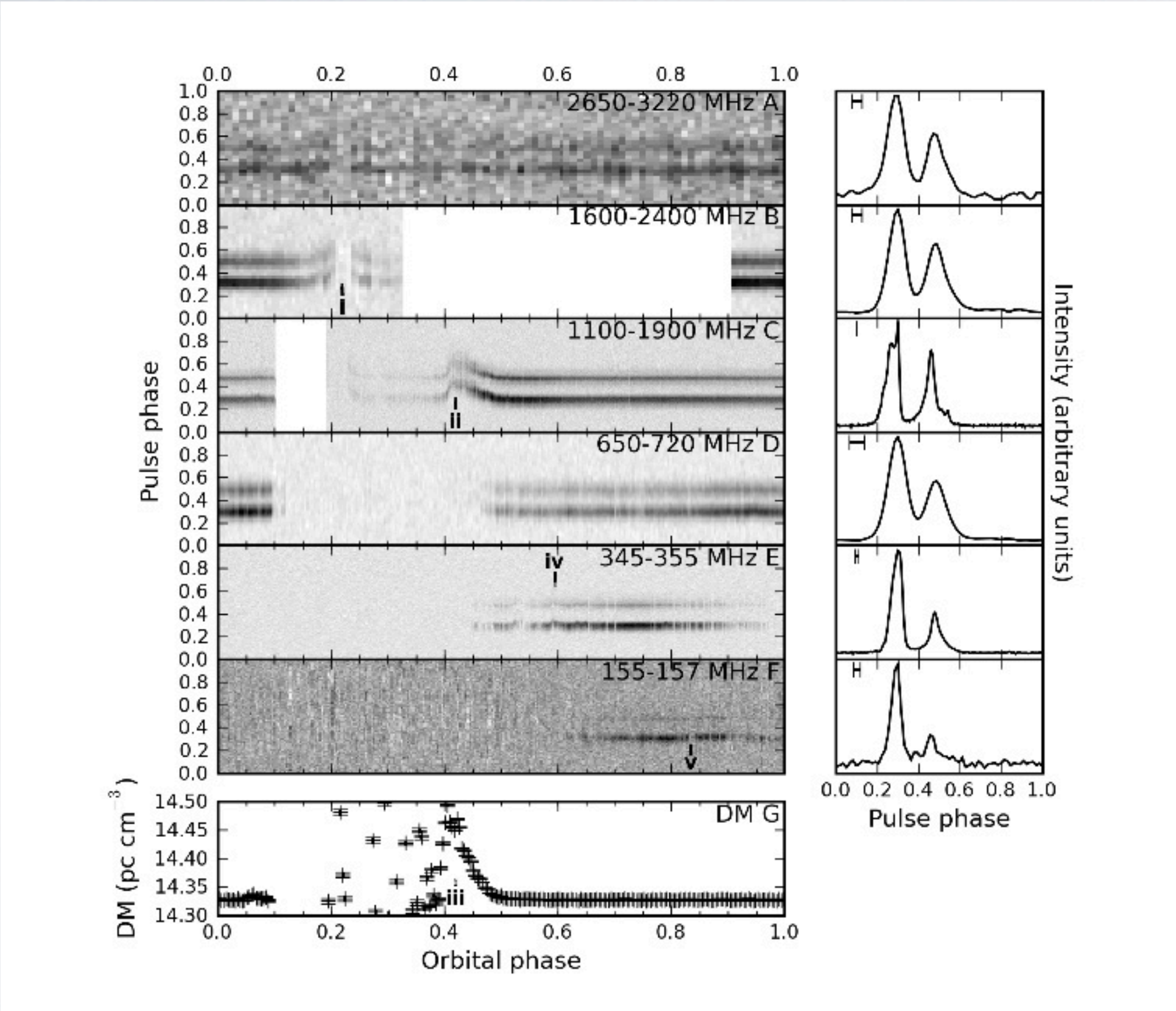
Total of 18 BWs and 12 RBs in GCs

LOTS OF DISTANT GLOBULAR CLUSTER BWS AND RBS

• Terzan 5	2 BWs + 3RB	5.5 kpc	
• 47 Tuc	5 BWs + 2RB	4 kpc	HESS < 7×10^{-13} Aharonian et al. 2009
• M13	1 BW	7 kpc	MAGIC <5×10^{-12} Anderhub et al. 2009
• All GCs	18 BW + 12RB		

See Paulo Freire's web page (AND TALK!) of MSPs in GCs for complete list
http://www.naic.edu/~pfreire/GCpsr.html

PSR J1023+0038:
A Redback Caught in the Act!

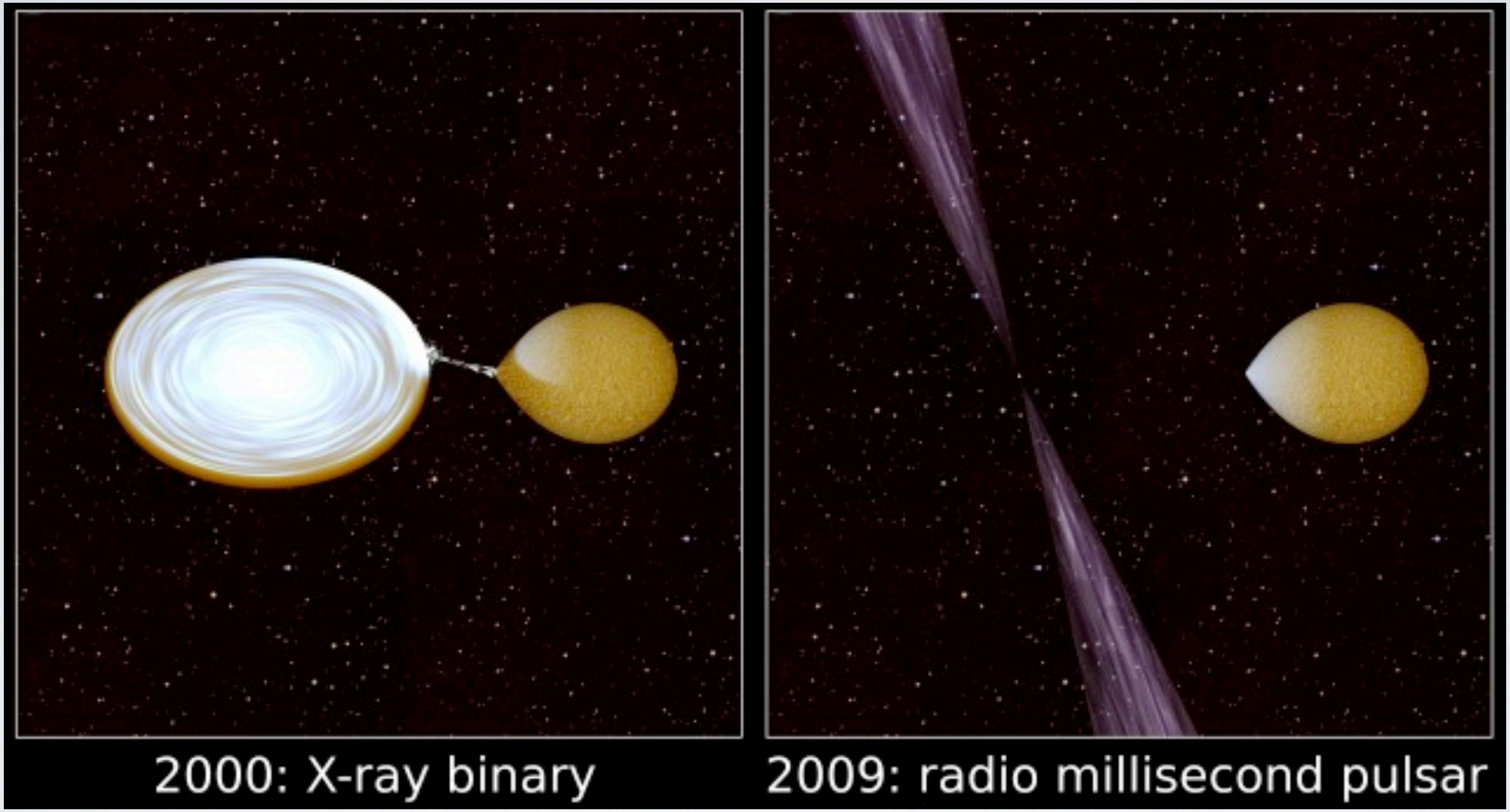


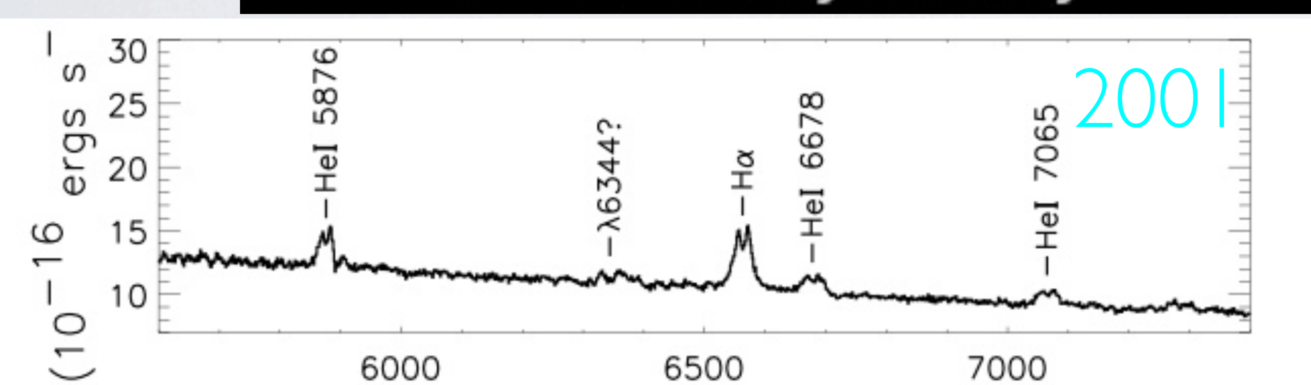
Archibald et al. 2009

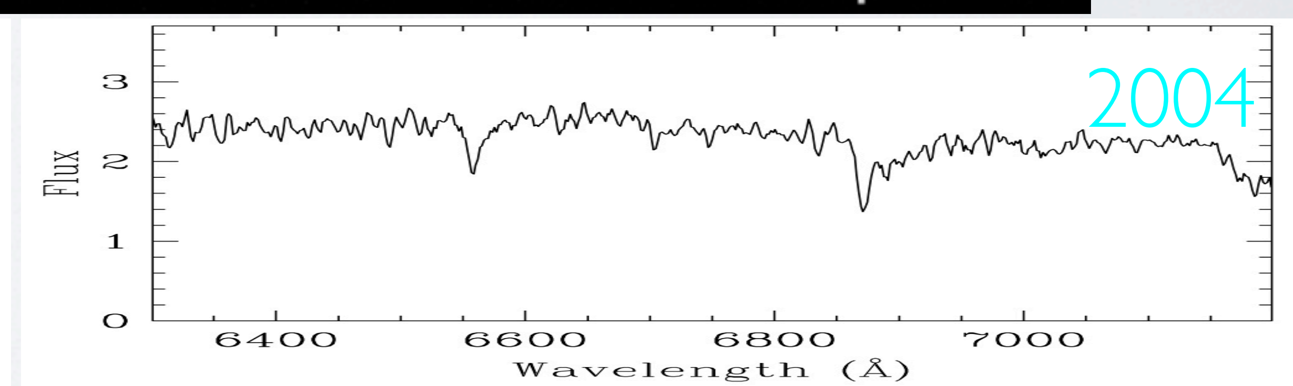
- 1.69 ms pulsar in 4.8hr orbit discovered in GBT 350MHz Drift Scan Survey (Archibald et al. 2009)
- 0.2 solar mass non-degenerate companion, luminosity a few tenths solar
- eclipses and orbitally modulated X-ray emission suggest intrabinary shock
- photon density near shock similar to PSR B1259-63
- Parallax measures d ~1.3 kpc compared to DM estimate of ~0.6 kpc (Deller et al. 2012).

"The Redback spider is one of only two animals to date where the male has been found to actively assist the female in sexual cannibalism. In the process of mating, the much smaller male somersaults to place his abdomen over the female's mouthparts. In about 2 out of 3 cases, the female consumes the male while mating continues. Males who are not eaten die soon after mating."
-- Wikipedia

Caught in the Act of Recycling?





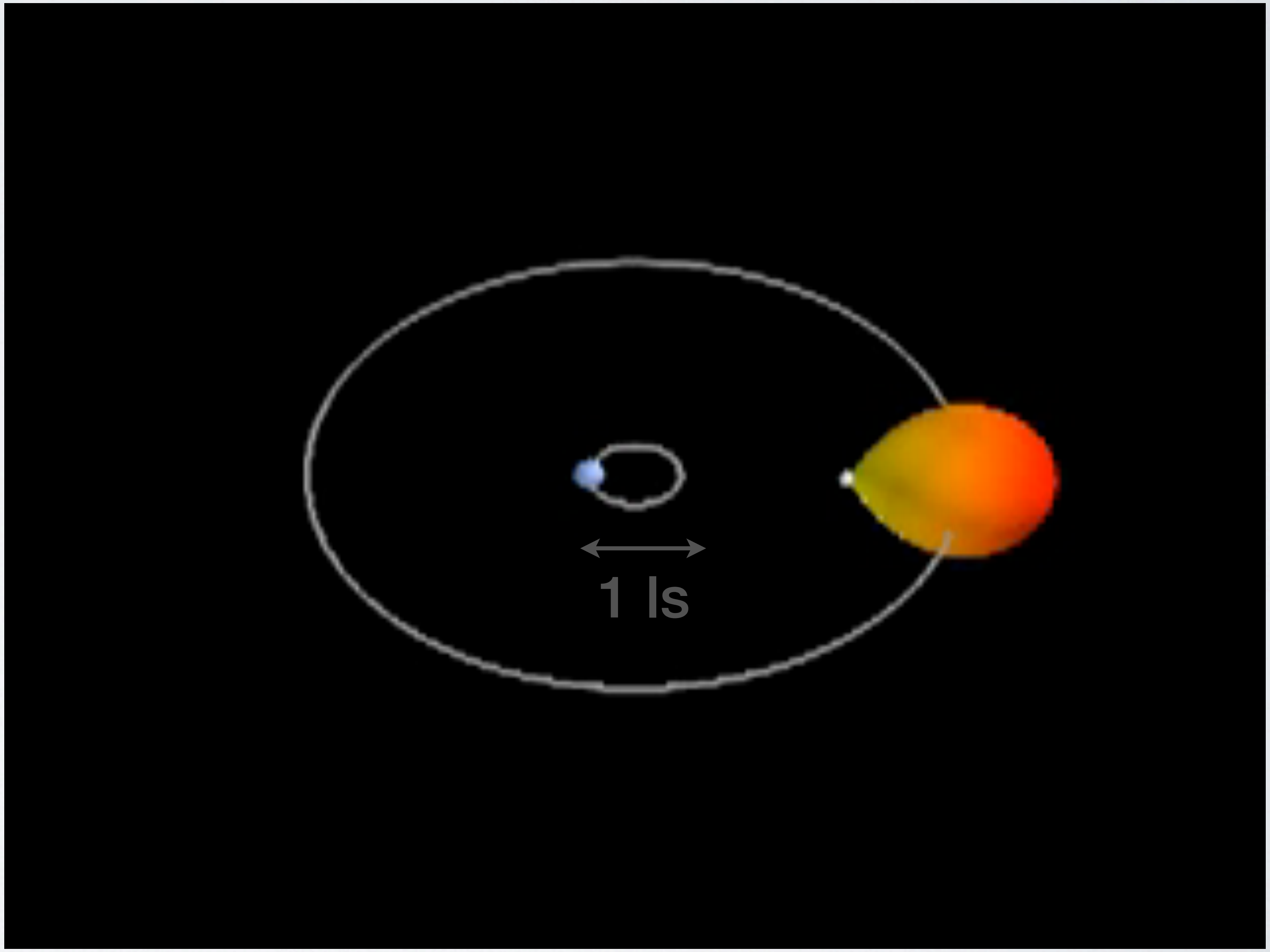


Wang et al. 2009

Homer et al. 2006

PSR J1023+0038: A Very Compact System

- Binary system few lightsec across, ~10^4 light cylinder radii (compared to ~$4X10^8$ for the Crab)
- Weak Fermi source, pulsations not yet detected
- ~20 Hr observation with VERITAS yields upper limit (> 280 GeV) ~ 1% Crab



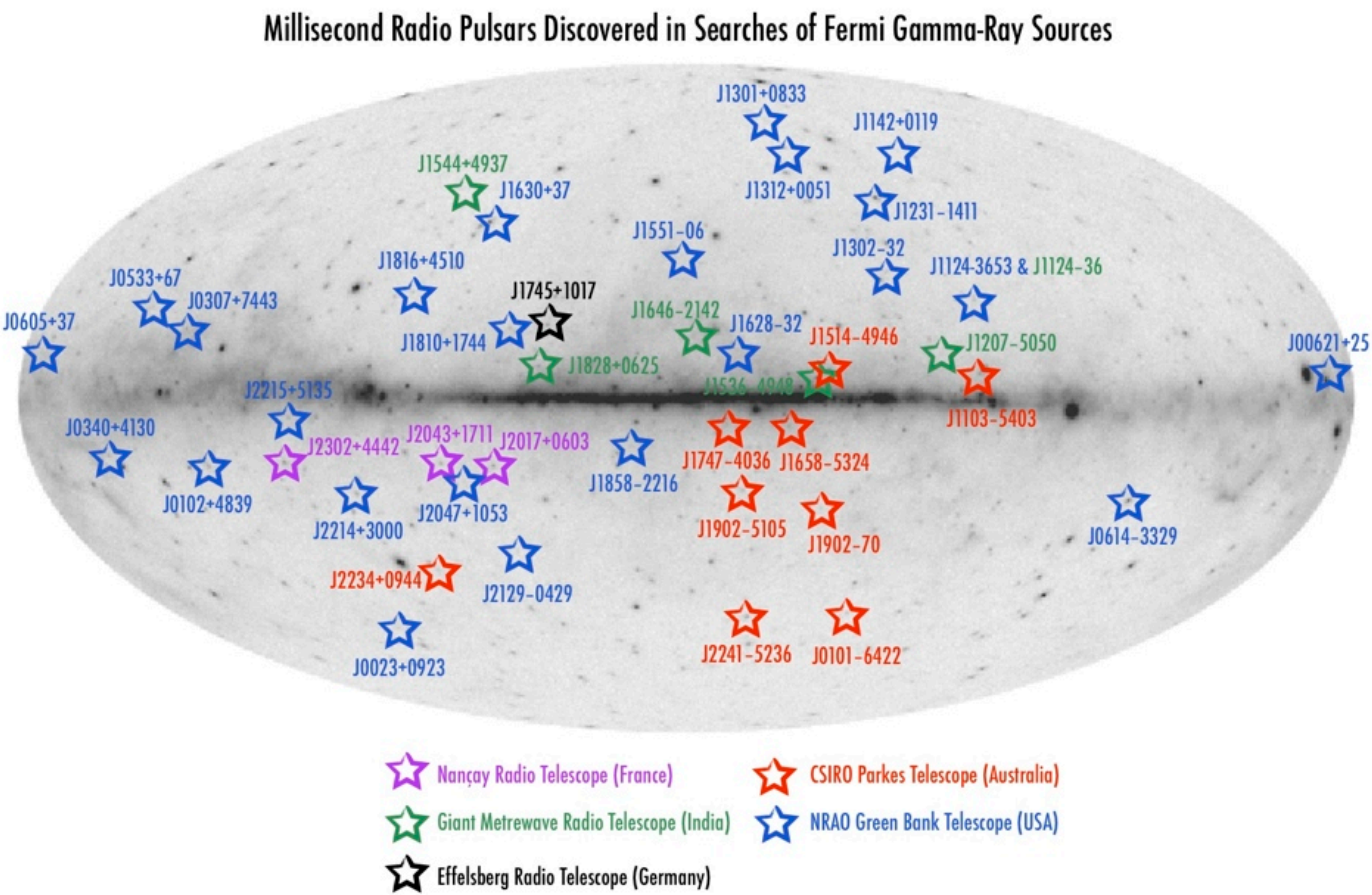


Figure Courtesy Paul Ray and Fermi PSC

MSPs From Surveys of Fermi Sources,

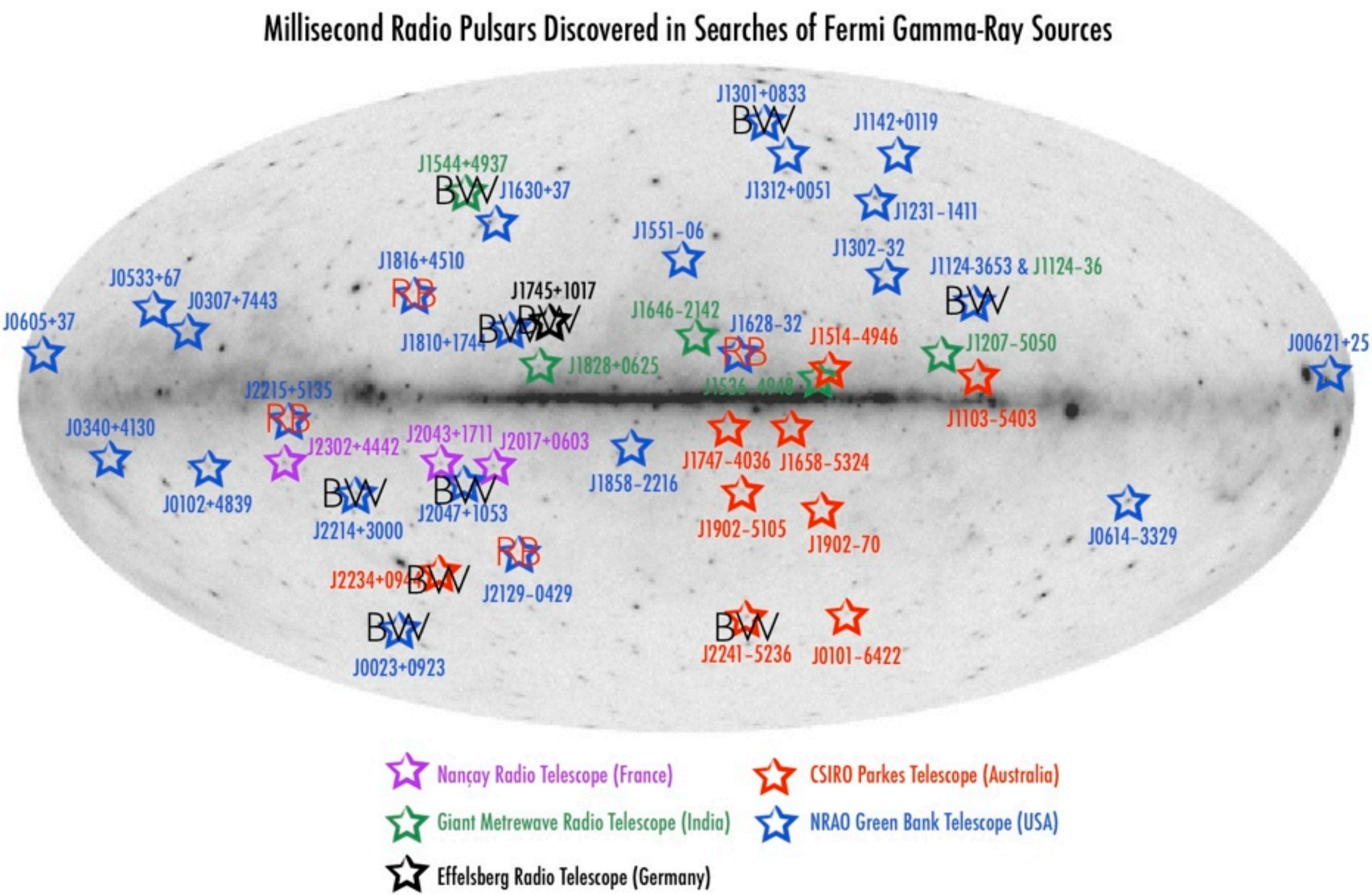
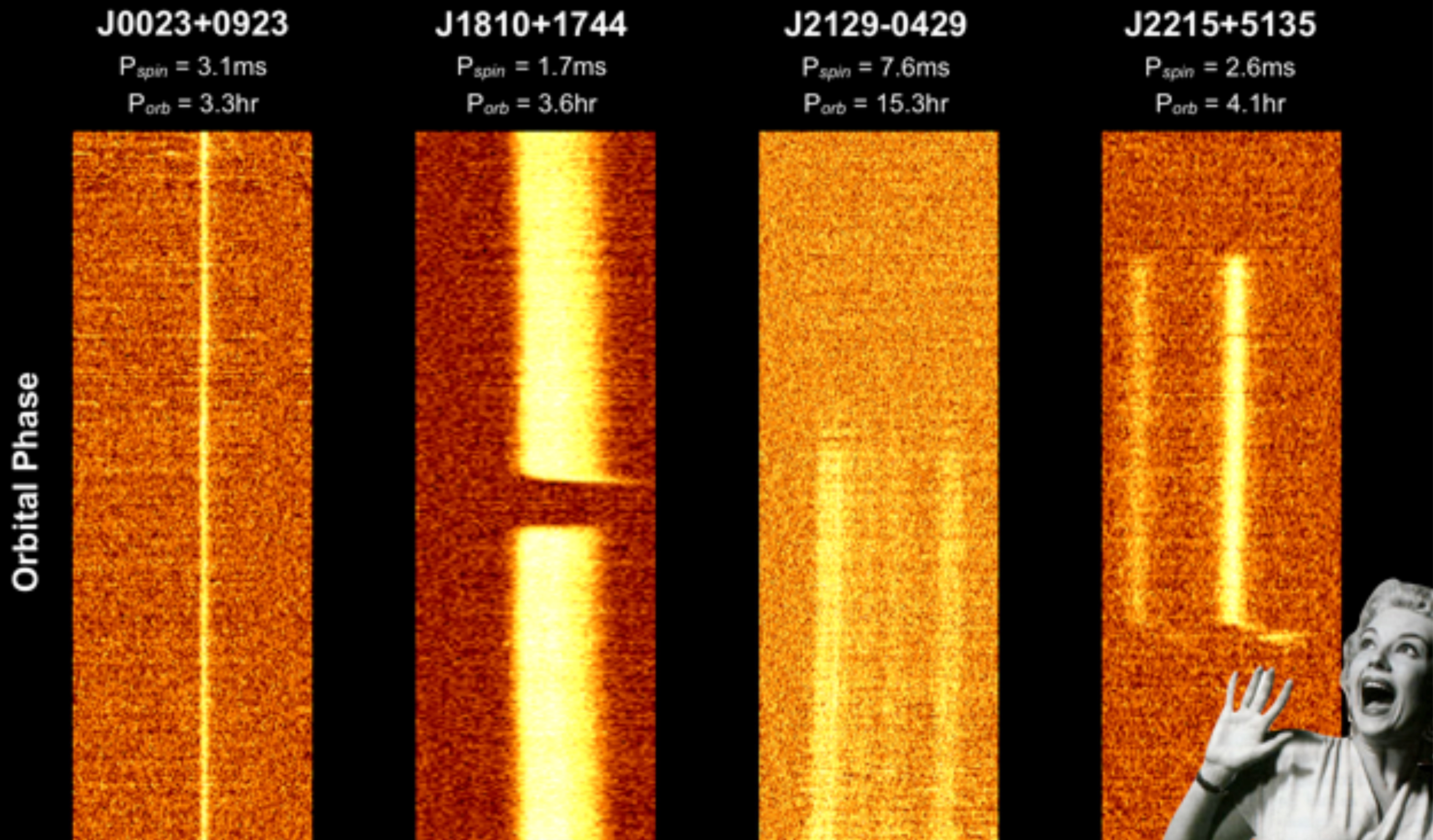


Figure Courtesy Paul Ray and Fermi PSC

Attack of the Gamma-Ray Spiders from Space

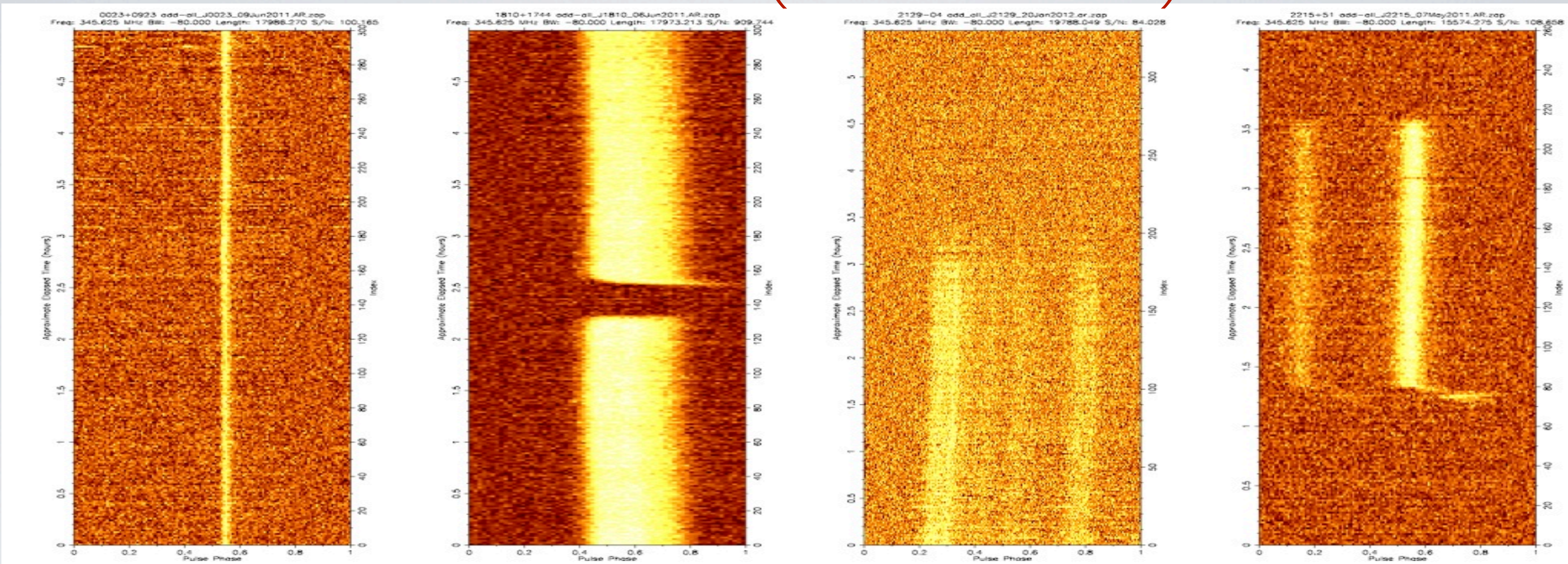
starring...

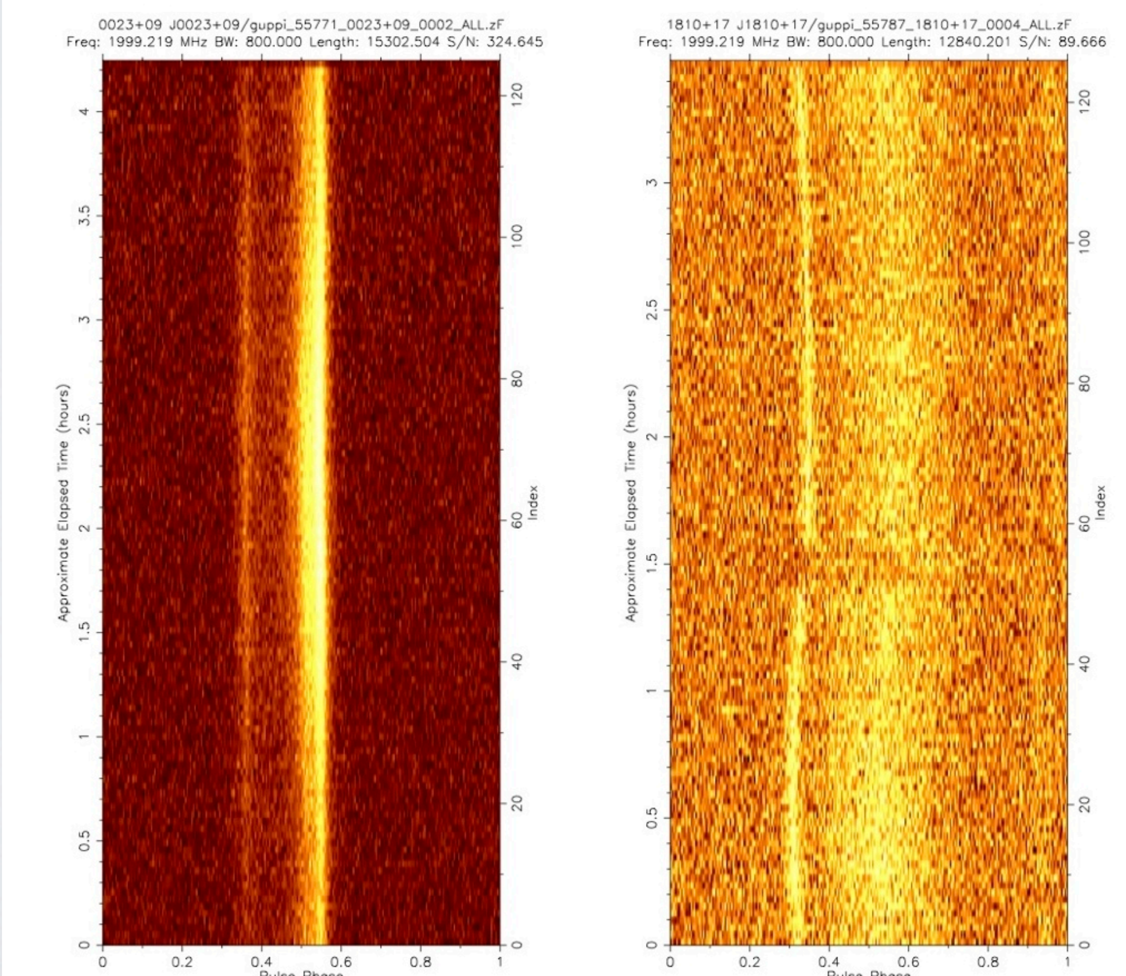


Black Widows **Redbacks**

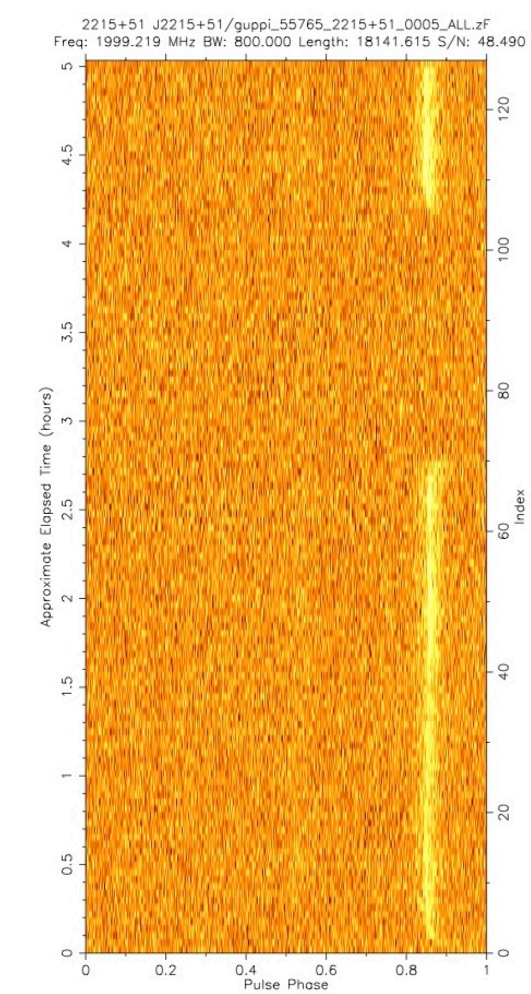
Figure Courtesy Jason Hessels

350MHz (Westerbork)





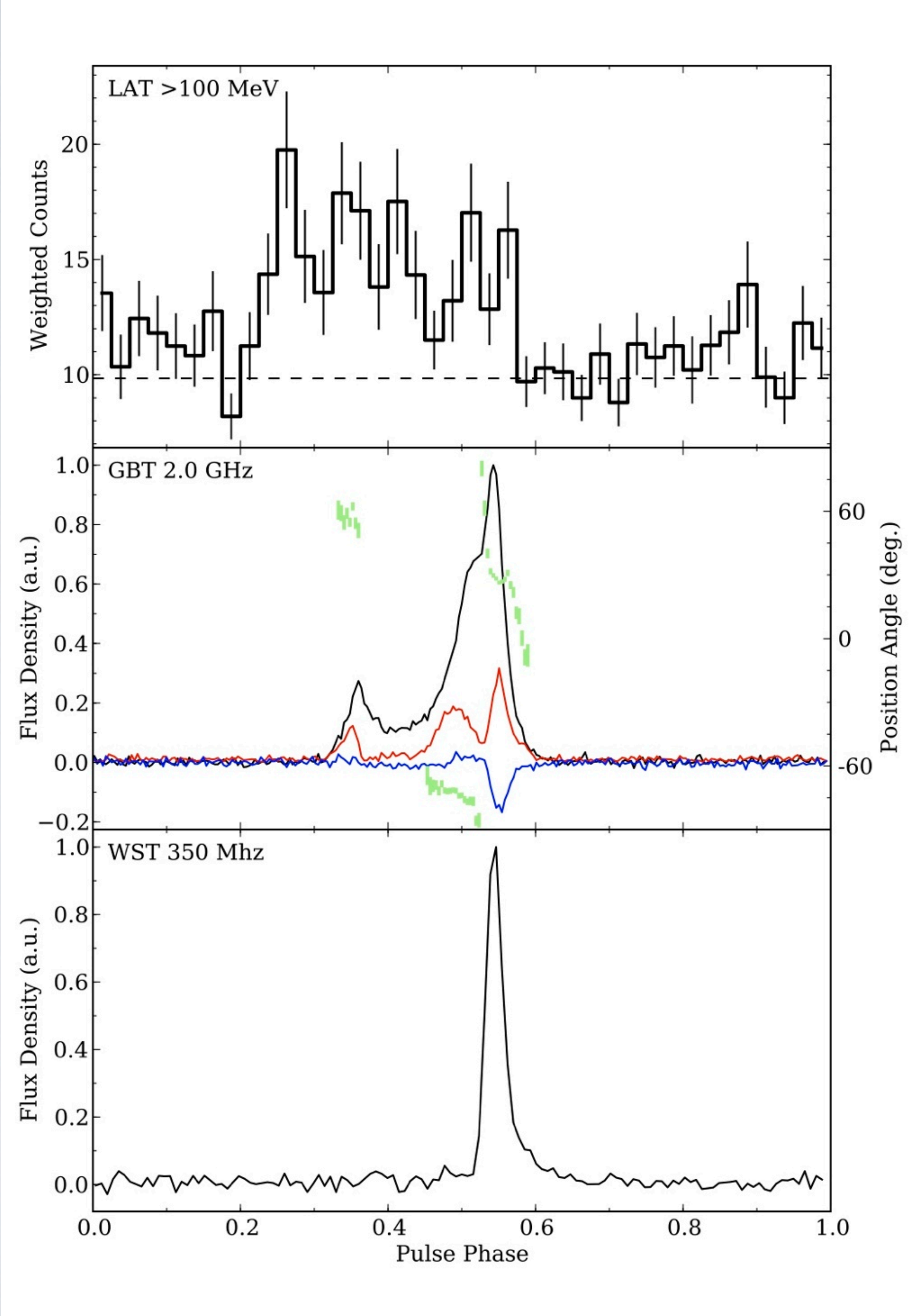
Large changes in eclipse fraction and pulse profile with frequency



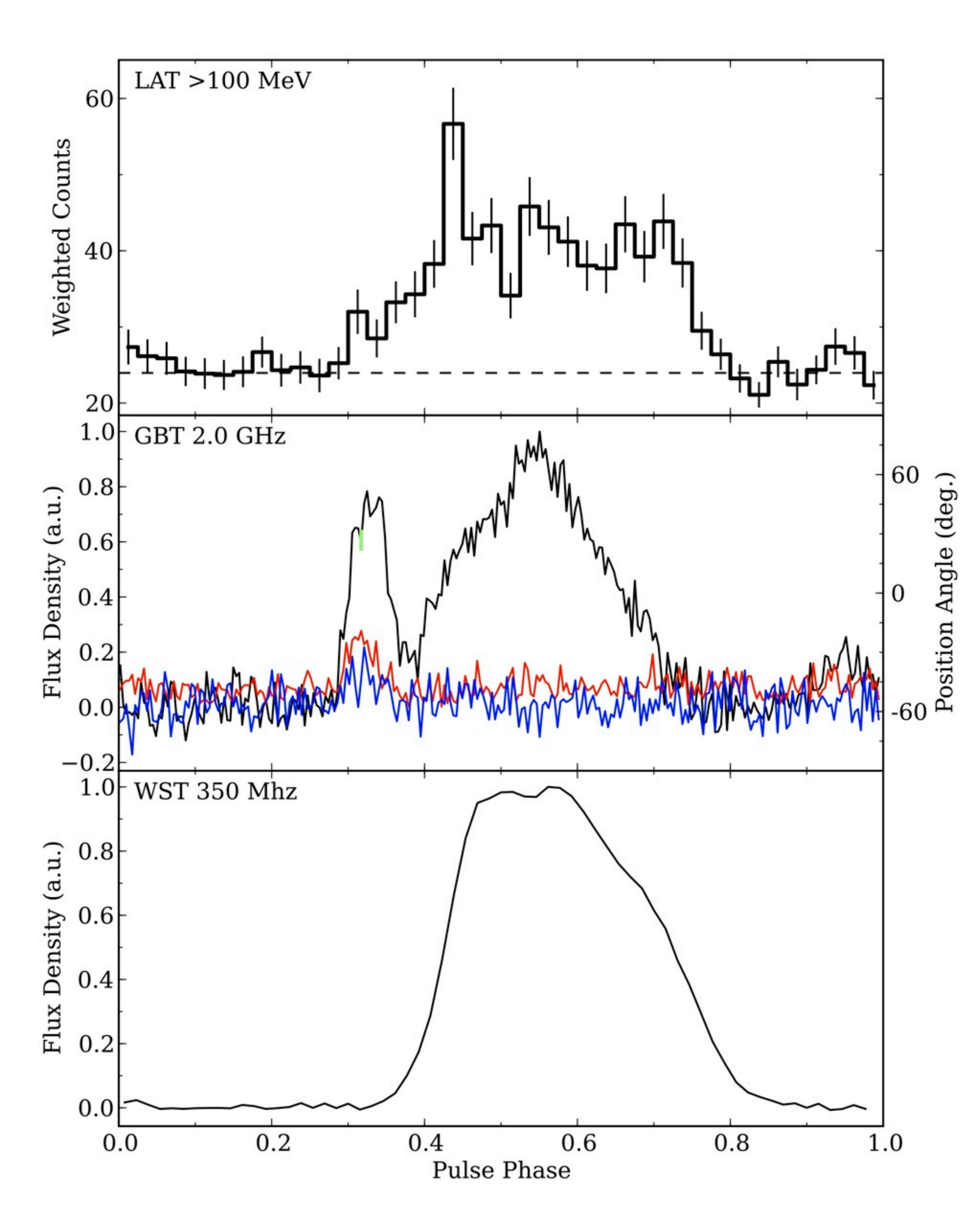
Hessels et al. (in prep)

2 GHz (GBT)

Radio and Gamma-Ray Pulse Profiles



PSR J0023+0923



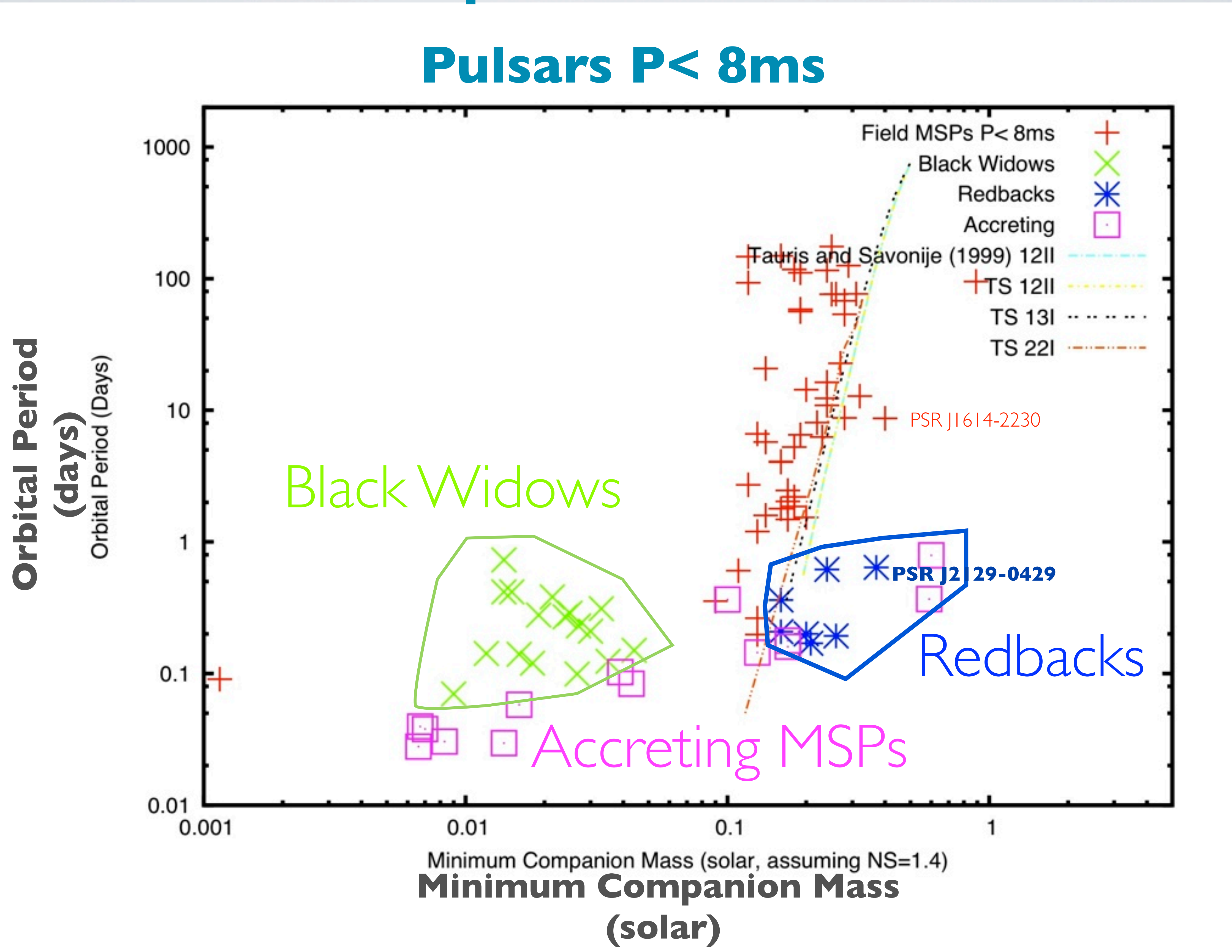
PSR J1810+1744

Black Widows and Redbacks in Galactic Field

	Pulsar	P_s (ms)	$\dot{E}/10^{34}$ (erg/s)	d_{NE2001} (kpc)	P_B (hrs)	M_C (min. solar)
Old BWs	B1957+20 F	1.61	11	2.5	9.2	0.021
	J0610-2100 F	3.86	0.23	3.5	6.9	0.025
	J2051-0827	4.51	0.53	1.0	2.4	0.027
New BWs	J1311-3430[O] F	2.56	4.9	1.4	1.56	0.008
	J2241-5236[P] F	2.19	2.5	0.5	3.4	0.012
	J2214+3000[G8] F	3.12	1.9	3.6	10.0	0.014
	J1745+1017[N] F	2.65	1.3	1.3	17.5	0.014
	J2234+0944[P] F	3.63	1.6	1.0	10	0.015
	J0023+0923[G3] F	3.05	1.6	0.7	3.3	0.016
	J1544+4937[M] F	2.16	1.2	1.2	2.8	0.018
	J1446-4701[1] F	2.19	3.8	1.5	6.7	0.0019
	J1301+08[G8] F	1.84	6.7	0.7	6.5	0.024
	J1124-3653[G3] F	2.41	1.6	1.7	5.4	0.027
	J2256-1024[3] F	2.29	5.2	0.6	5.1	0.034
	J2047+1053[G8] F	4.29	1.0	2.0	3.0	0.035
	J1731-1847[1]	2.34	7.6	2.5	7.5	0.04
	J1810+1744[G3] F	1.66	3.9	2.0	3.6	0.044
New RBs	J1628-3205[G8] F	3.21	1.35	1.2	5.0	0.16
	J1816+4510[4] F	3.19	5.2	2.4	8.7	0.16
	J1023+0038[3] F	1.69	~5	0.6 (1.3)	4.8	0.2
	J2215+5135[G3] F	2.61	6.2	3.0	4.2	0.22
	J1723-28[2]	1.86	4.6	0.75	14.8	0.24
	J2339-0533[O] F	2.88	2.3	0.4	4.6	0.26
	J2129-0429[G3] F	7.61	3.9	0.9	15.2	0.37

F=Fermi detected; 1. HTRUPS Keith et al. 2010 2. PMB pulsar, Crawford et al. 2010 3. GBT Drift Scan 4. GBNCC
Fermi targeted discoveries: G8=GBT 820 MHz, G3=GBT 350 MHz, N=Nancay, P=Parkes, M=GMRT, O=optical

Black Widows and Redbacks
Minimum Companion Mass vs. Orbital Period



Binary Evolution of Spiders?

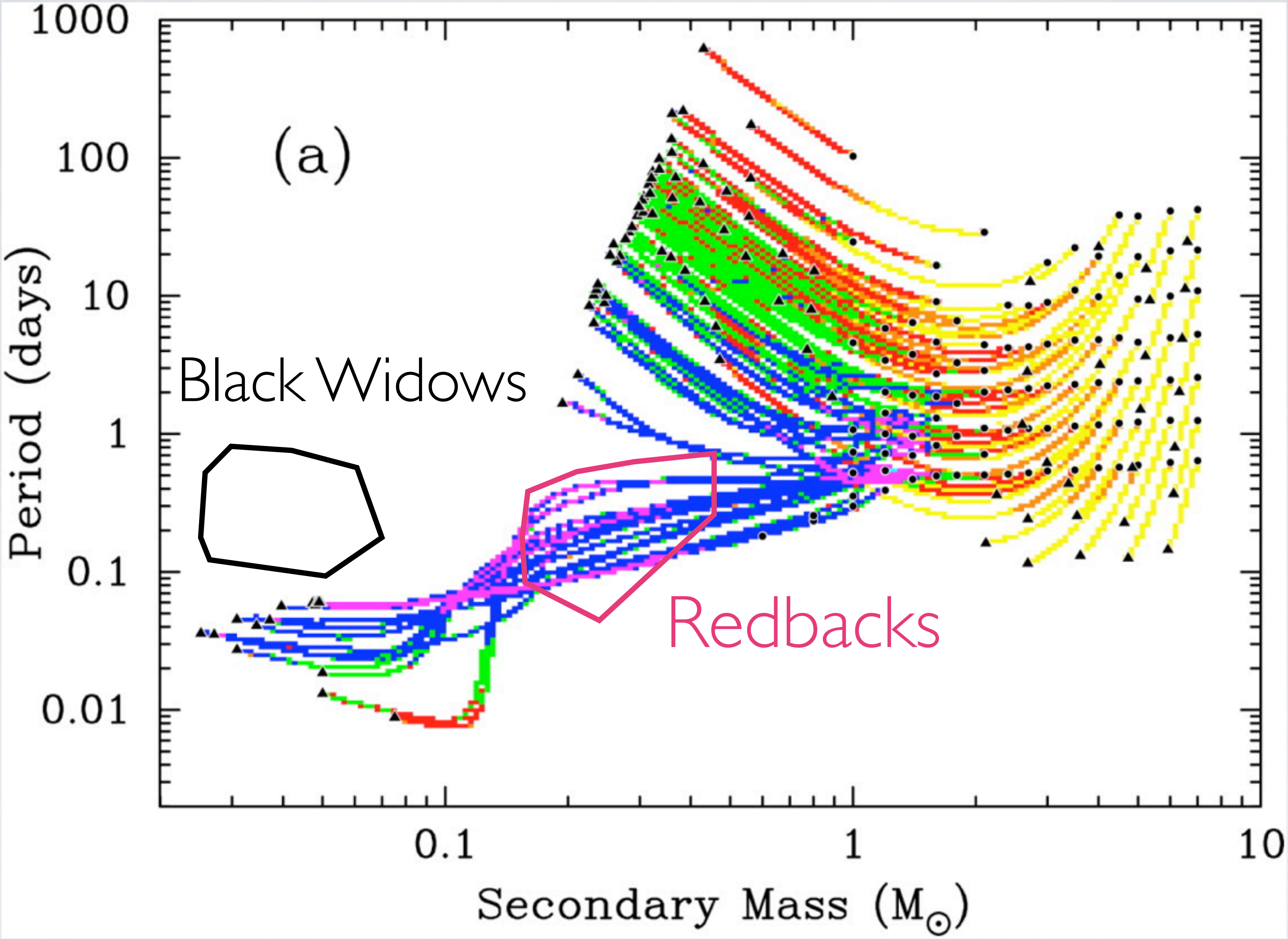
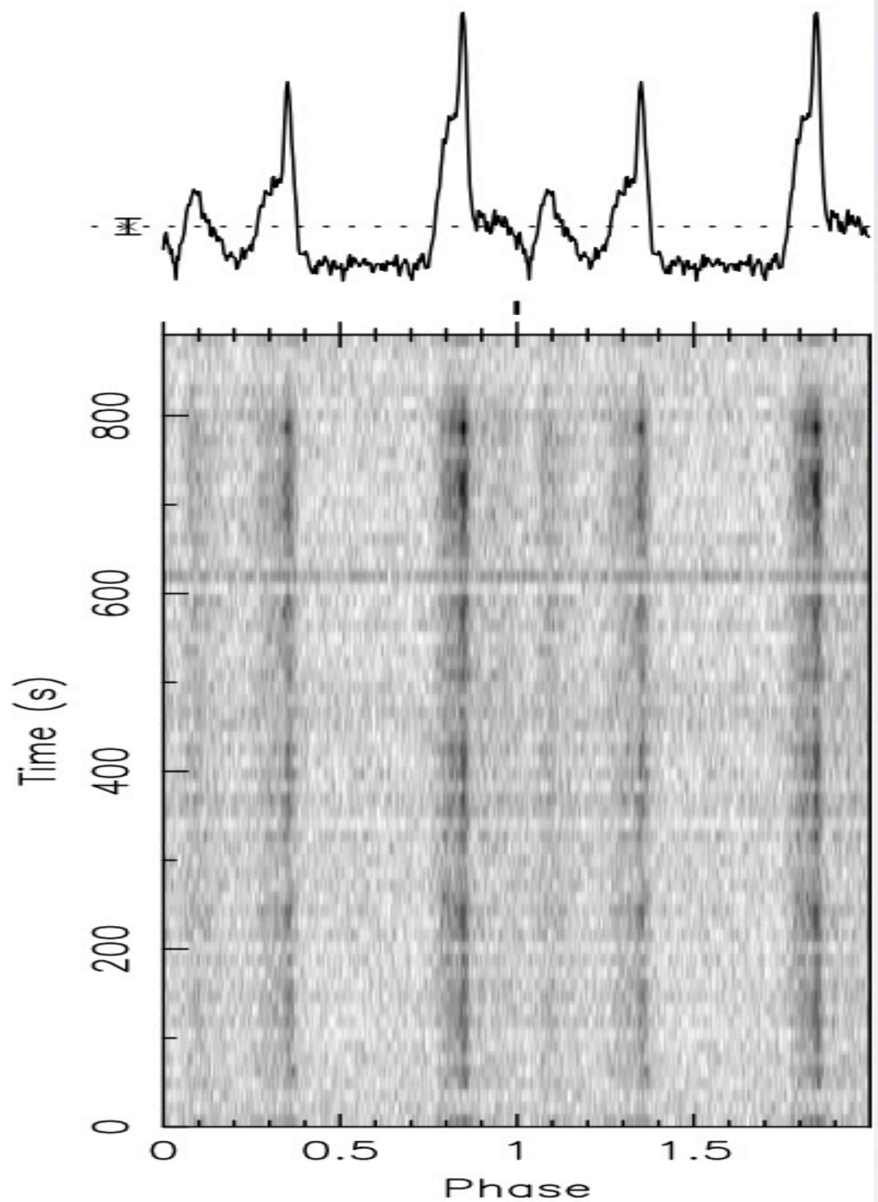
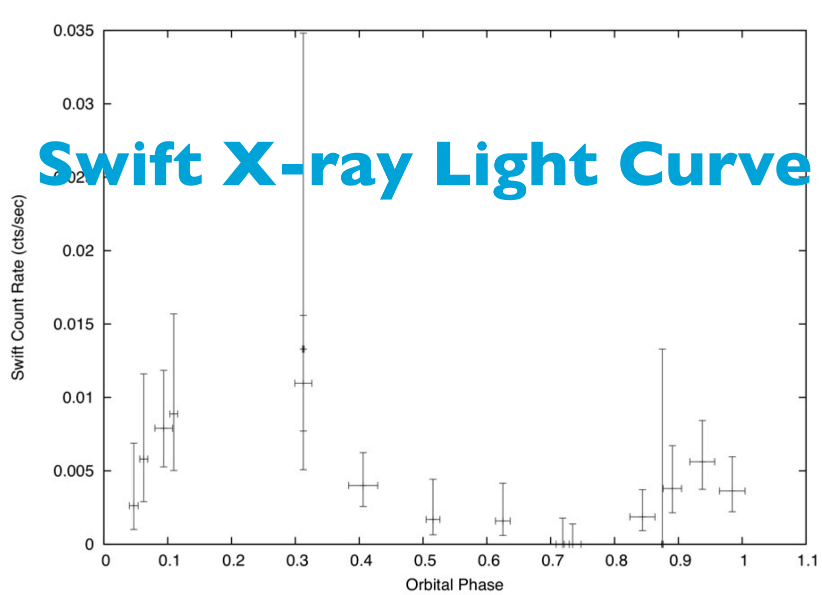


figure adapted from Podsiadlowski et al. 2001

PSR J2129-0429: A HIGH MAGNETIC FIELD REDBACK





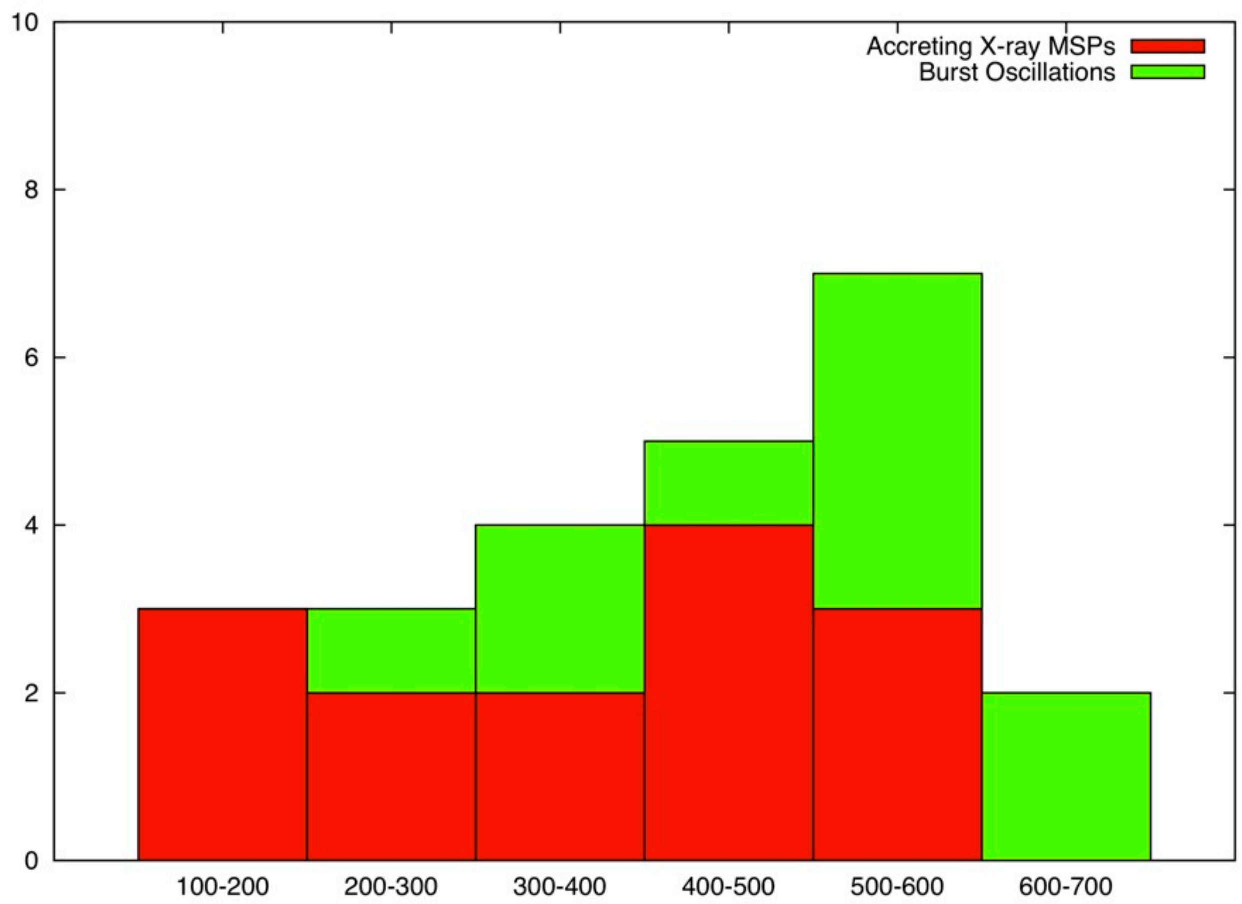
Swift X-ray Light Curve

- **7.61 ms period**
- 15.2 hr orbit
- Orbital separation ~ 8000 light cylinder radii
- **Minimum M_C ~ 0.37 M_{sol}**
- Shows extensive radio eclipses
- Strong X-ray orbital modulation
- **D_{NE2001} ~ 0.9 kpc**
- Bright UV Counterpart
- Filling Fraction ~95%, pulsar mass > 1.7 solar (Bellm et al. 2013)
- **B ~ 1.6 X 10^9 G**
- Large Orbital Period Changes

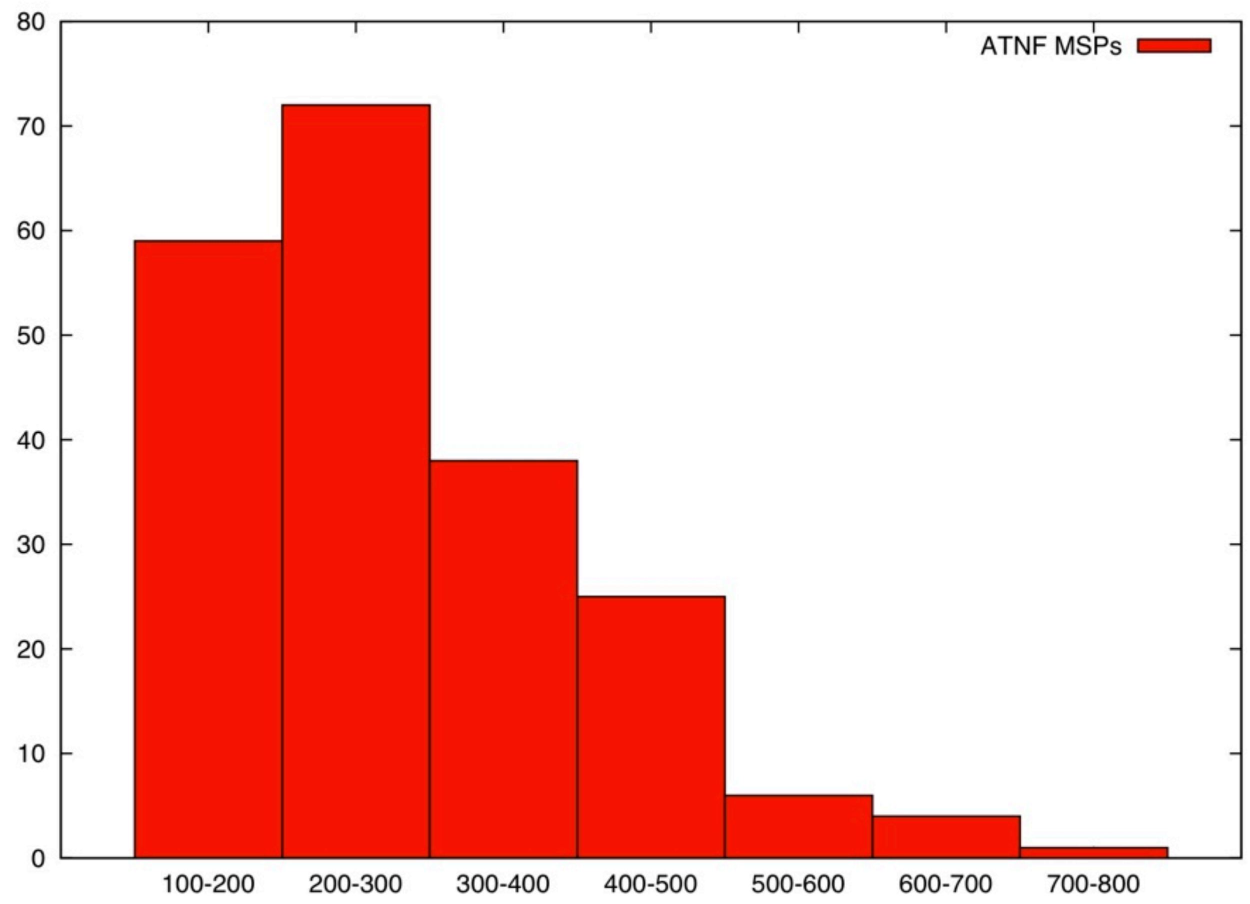
Hessels et al. (in prep)

Spin Frequencies: Accreting X-Ray MSPs vs. ATNF Catalog Radio MSPs

AXMSPs & BOs



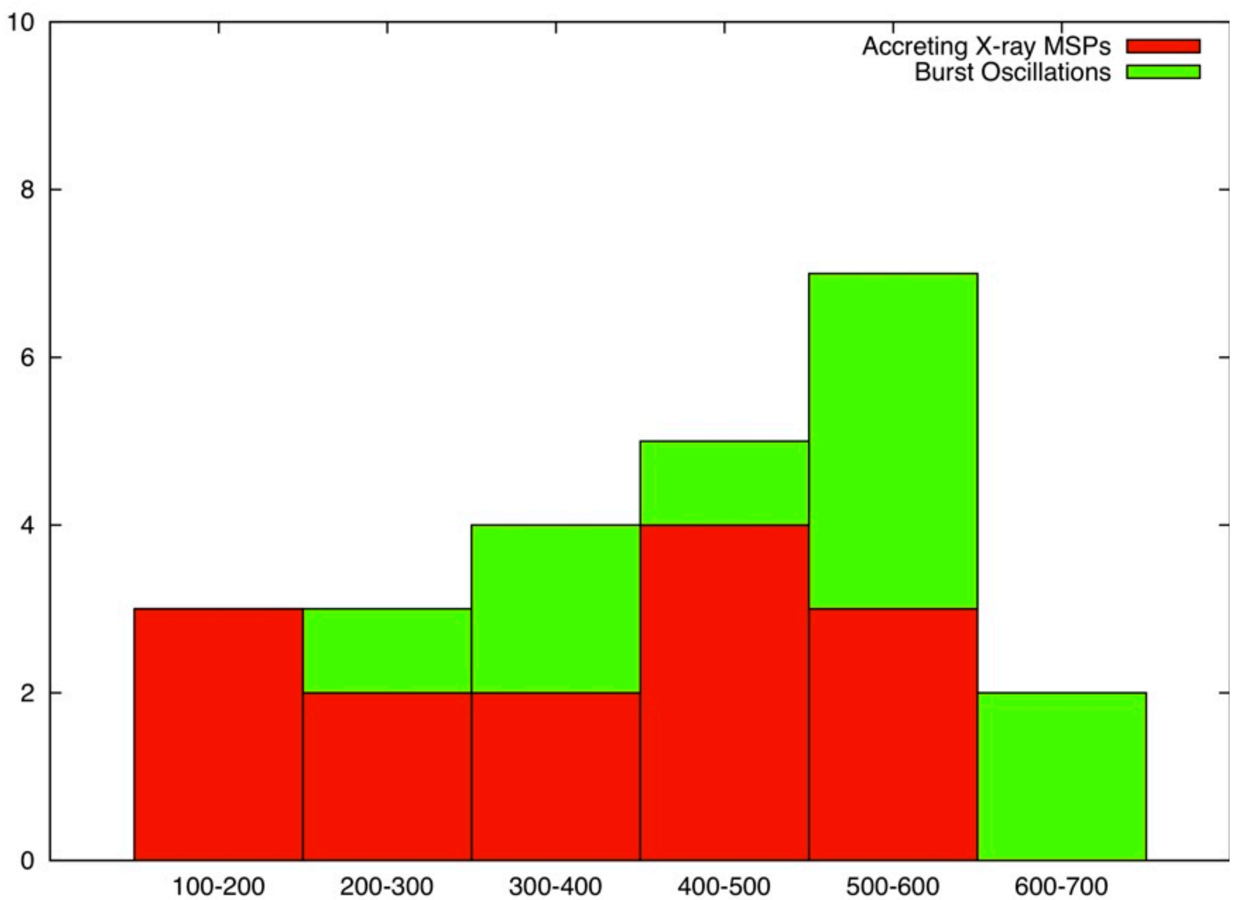
Radio MSPs



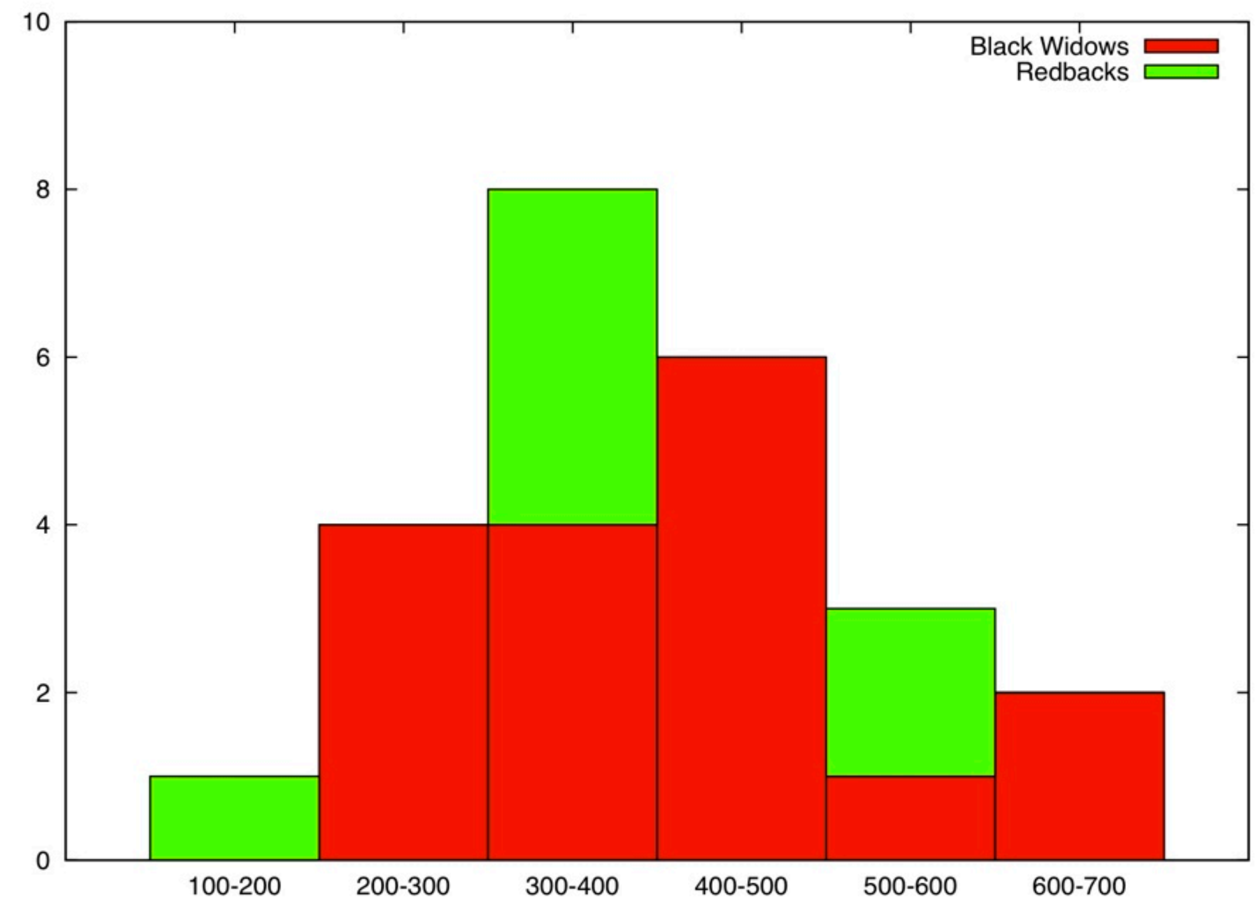
AXMSP Data from Patruno & Watts 2012

Spin Frequencies: Accreting X-Ray MSPs vs. Galactic Field Black Widows and Redbacks

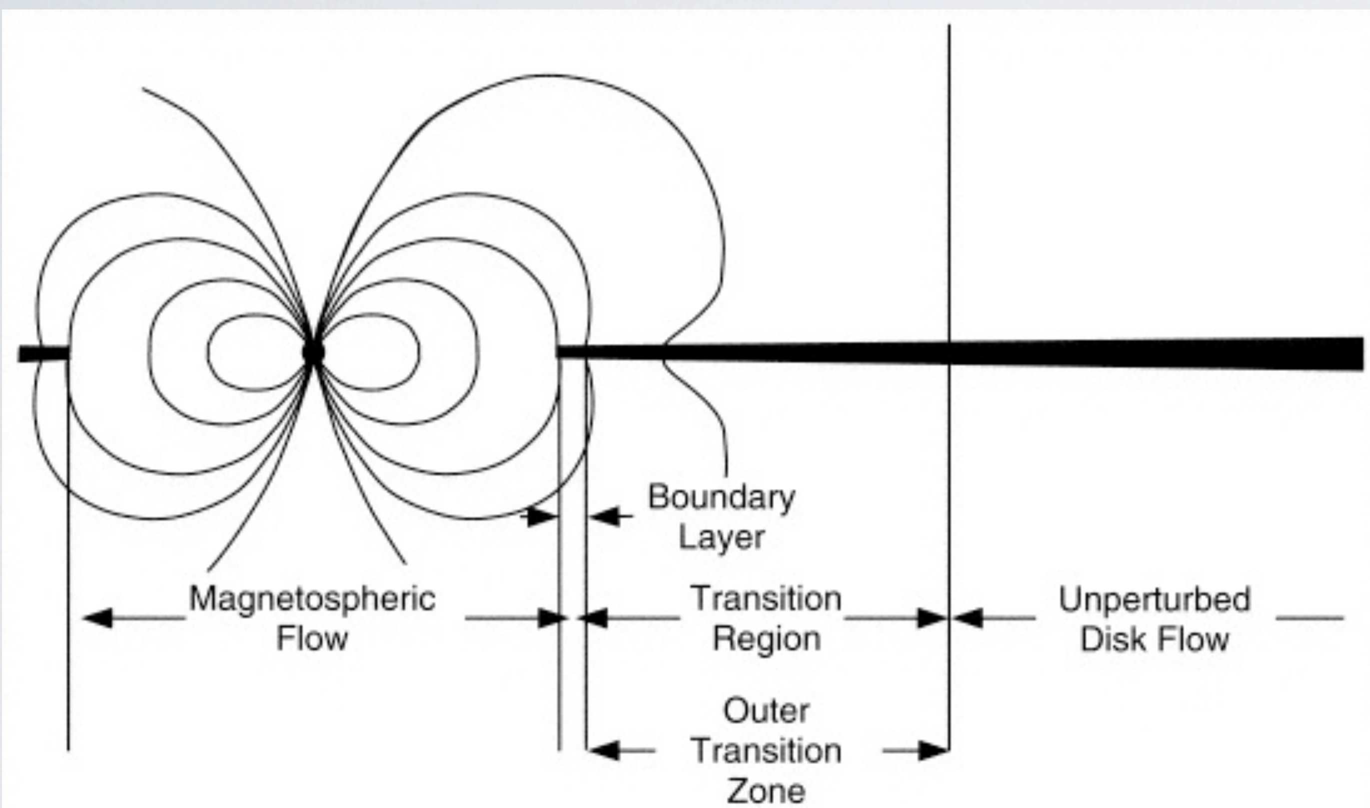
AXMSPs & BOs

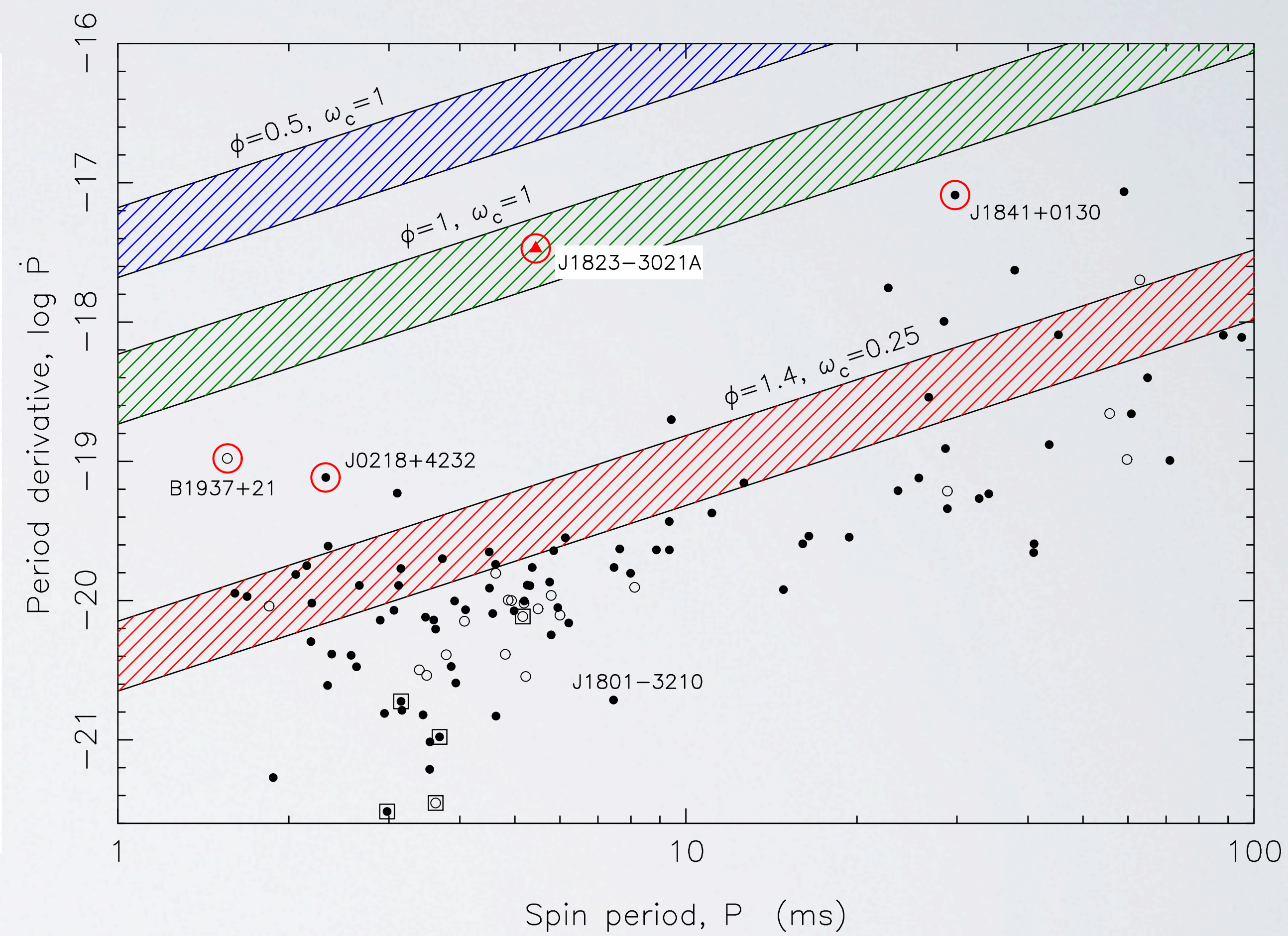


BWs & RBs



Investigating Neutron Star Spin-up



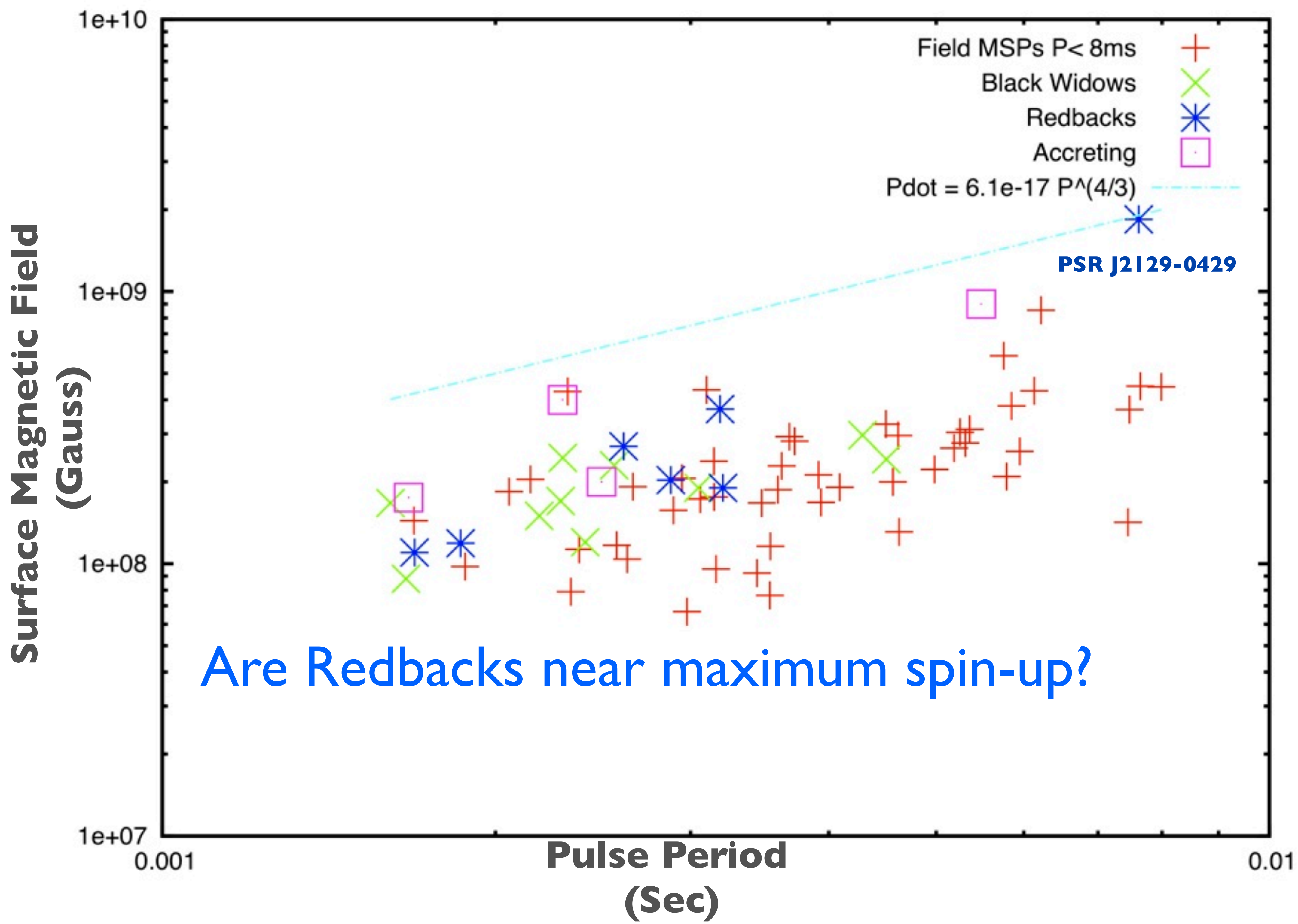


From Tauris et al. 2012

$$\phi \equiv r_{\rm mag}/r_{\rm Alfven}$$

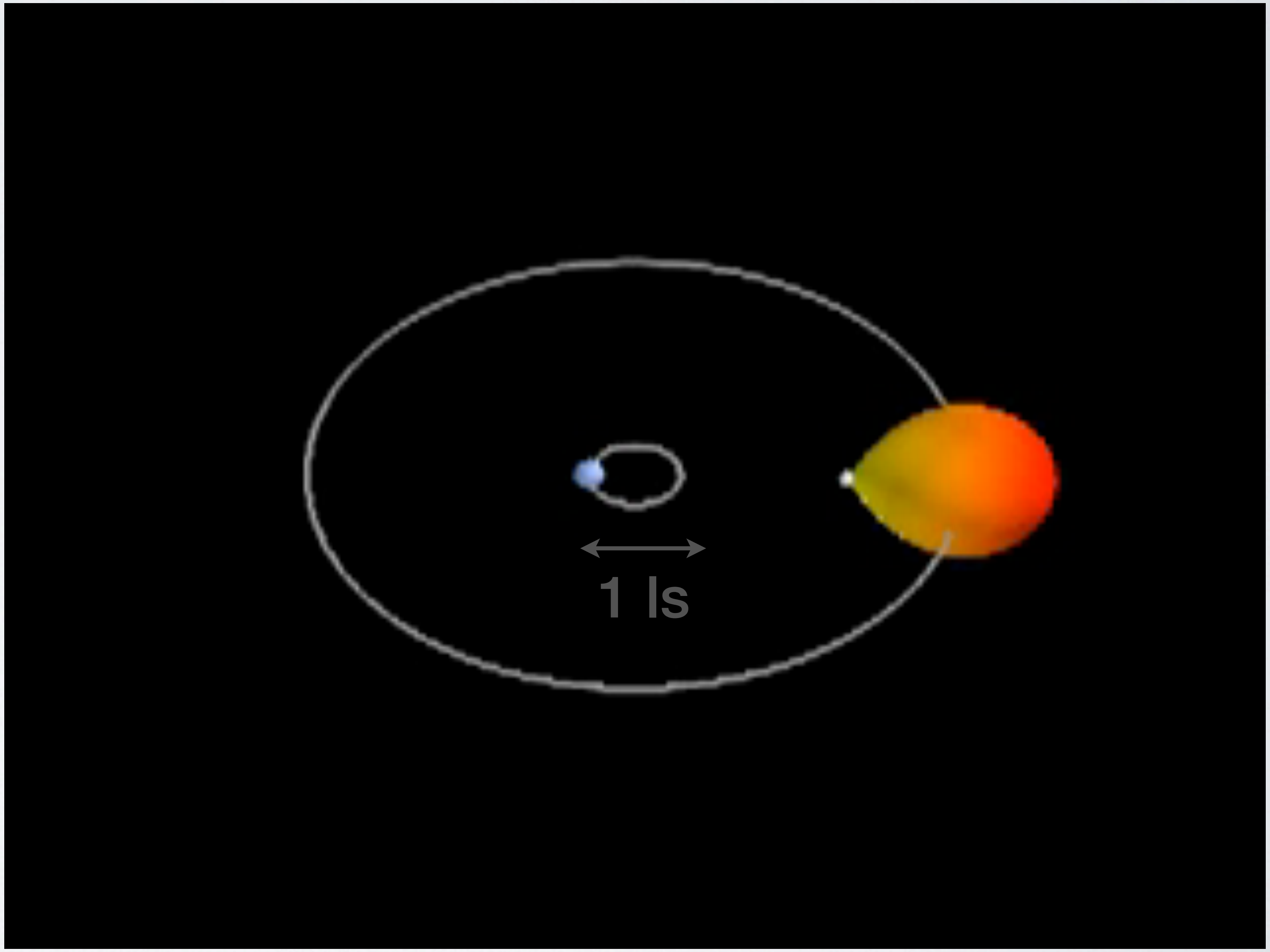
$$\dot{P} = \frac{2^{1/6} G^{5/3}}{\pi^{1/3} c^3} \frac{\dot{M} M^{5/3} P_{\rm eq}^{4/3}}{I} \left(1 + \sin^2 \alpha\right) \phi^{-7/2} \omega_c^{7/3}$$

Black Widows and Redbacks
Pulse Period vs. Magnetic Field



Optical lightcurve constrains system

- Side facing pulsar strongly irradiated
- Orbitally dependent optical flux and temperature
- Light curve depends on high and low T and exact heating profile, inclination, and amount of distortion (fraction of Roche lobe filled)

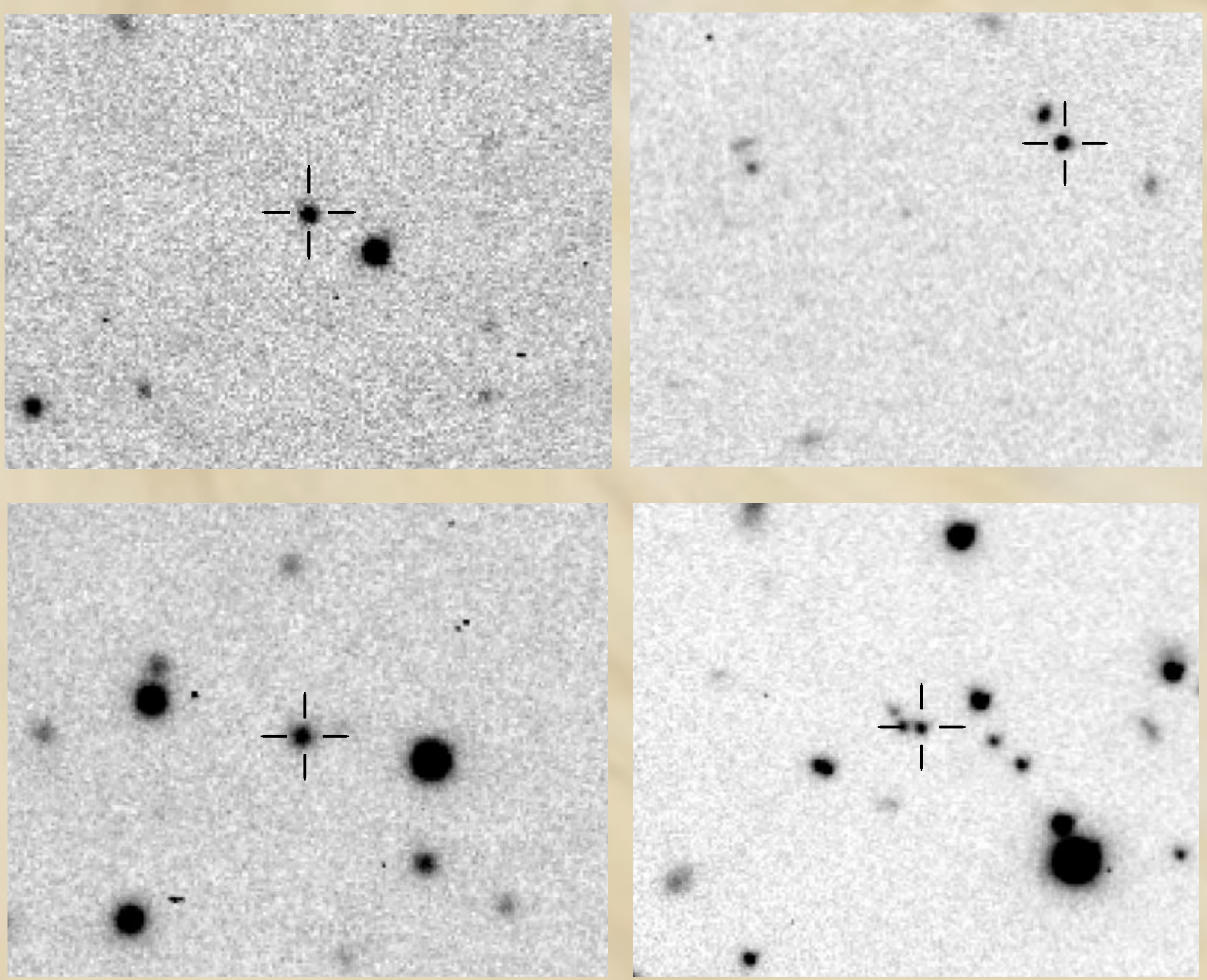


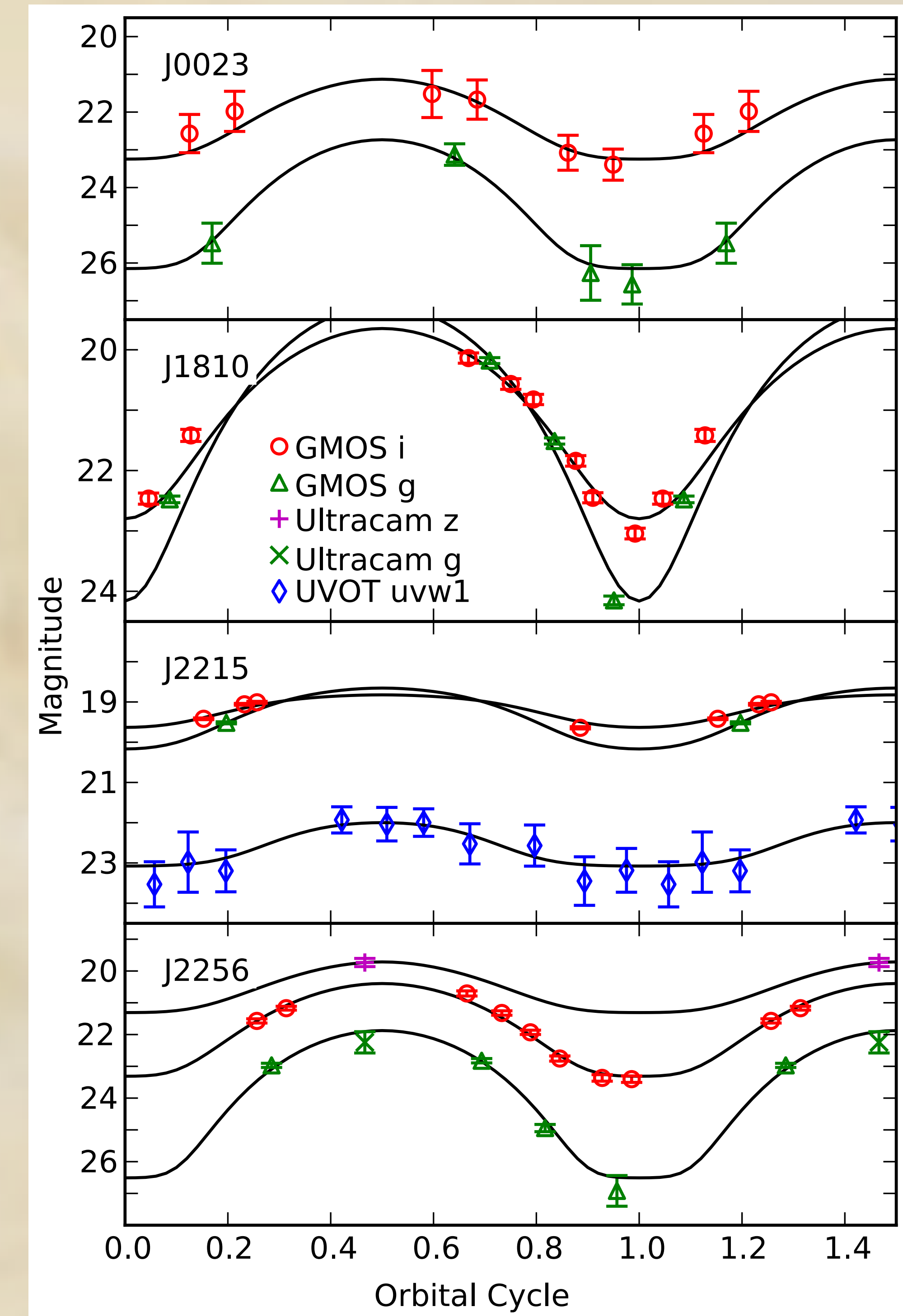
New Black Widows

Four new optical counterparts detected with Gemini

Day/back side temperatures ⇒ irradiation

efficiency ~15% of the spin-down luminosity





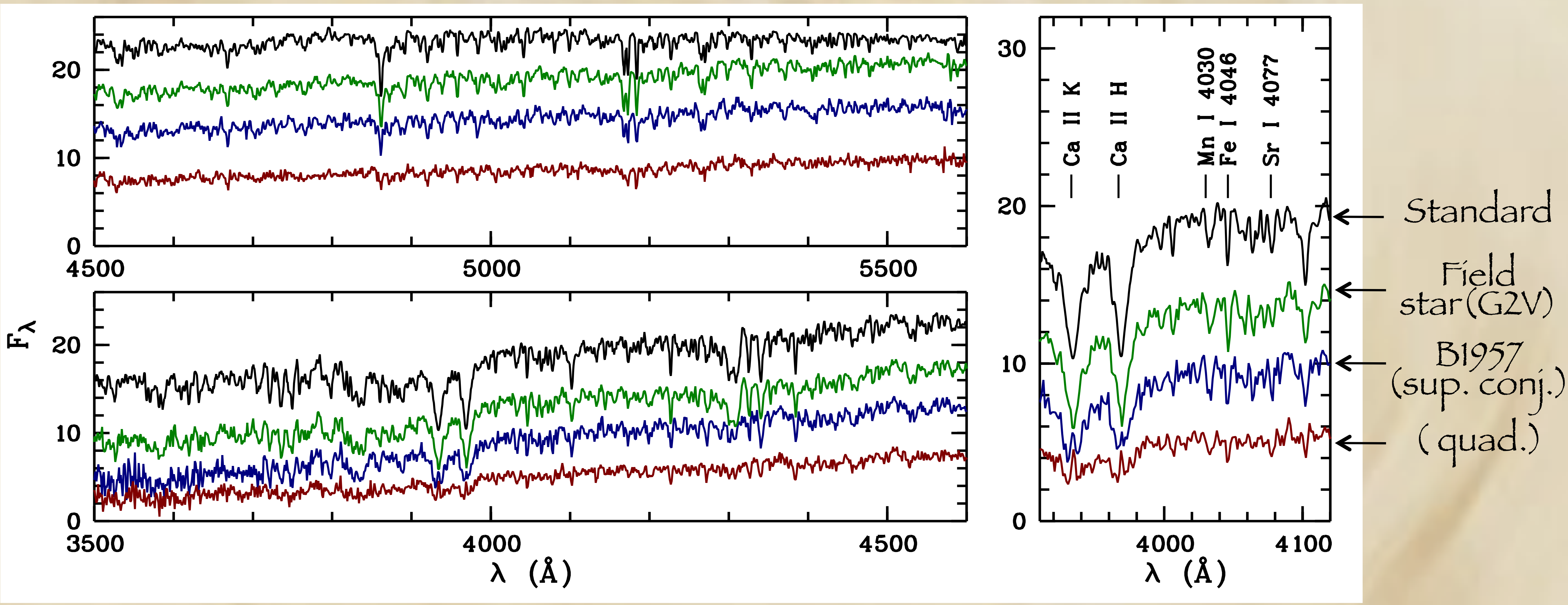
Breton et al. (in prep)

Measuring the Mass of PSR B1957+20

PSR B1957+20 is the black widow archetype (Fruchter 1988).

Phase-resolved spectroscopic observations with LRIS on Keck (van Kerkwijk, Breton & Kulkarni 2011)

Neutron Star Mass ~2.4 Solar?!



van Kerkwijk et al. (2011)

Some Optical Results of Field BWs and RBs

	Pulsar	P_s (ms)	T K	Filling Factor (kpc)	P_B (hrs)	M_{ns} (solar)
Old BWs	B1957+20[1] F	1.61	2500-5800	0.95	9.2	2.4
	J0610-2100[2] F	3.86	3500	High?	6.9	-
	J2051-0827[8]	4.51	2500-2800	0.43/0.95	2.4	
New BWs	J1311-3430[3] F	2.56	3440-12000	0.99	1.56	2.7
	J2241-5236 F	2.19			3.4	
	J2214+3000 F	3.12			10.0	
	J1745+1017 F	2.65			17.5	
	J2234+0944 F	3.63			10	
	J0023+0923[4] F	3.05	2900-4800	0.3	3.3	
	J1544+4937 F	2.16			2.8	
	J1446-4701 F	2.19			6.7	
	J1301+08 F	1.84			6.5	
	J1124-3653 F	2.41			5.4	
	J2256-1024[4] F	2.29	2450-4200	0.4	5.1	
	J2047+10 F	4.29			3.0	
	J1731-1847	2.34			7.5	
	J1810+1744[4] F	1.66	4600-8000	0.8	3.6	
New RBs	J1628-32 F	3.21			5.0	
	J1816+4510[5] F	3.19	15000	0.5	8.7	> 1.8
	J1023+0038[6] F	1.69	5600-6650	0.95	4.8	2.1
	J2215+5135[4] F	2.61	4800-6200	0.99	4.2	
	J1723-28	1.86			14.8	
	J2339-0533	2.88		high?	4.6	
	J2129-0429[7] F	7.61	5750	0.95	15.2	> 1.7

1. van Kerkwijk et al. 2011 2. Pallanca et al. 2012 3. Romani et al. 2012 4. Breton et al. 2013 5. Kaplan et al. 2013 6. McConnell et al. 2012 7. Bellm et al. 2013 8. Stappers et al. 2001

What We Are Learning From Optical Studies about Spiders?

- Multi-color light curve modeling of orbital modulation often suggest Roche lobe filling factors of ~1.0 for BOTH Black Widows and Redbacks → BLOATED COMPANIONS
- Optical spectra have photospheric lines that can be used for radial velocity measurements. Combined with photometric light curve models, strong mass constraints can be obtained.
- Geometry of system obtained, combined with radio polarization and assumption of spin-orbit alignment, constrain MSP geometry.
- Distinctive light curves can be used to identify "hidden" Spiders

ACCURATE DISTANCES ARE NEEDED!

THE Black Widow PSR B1957+20

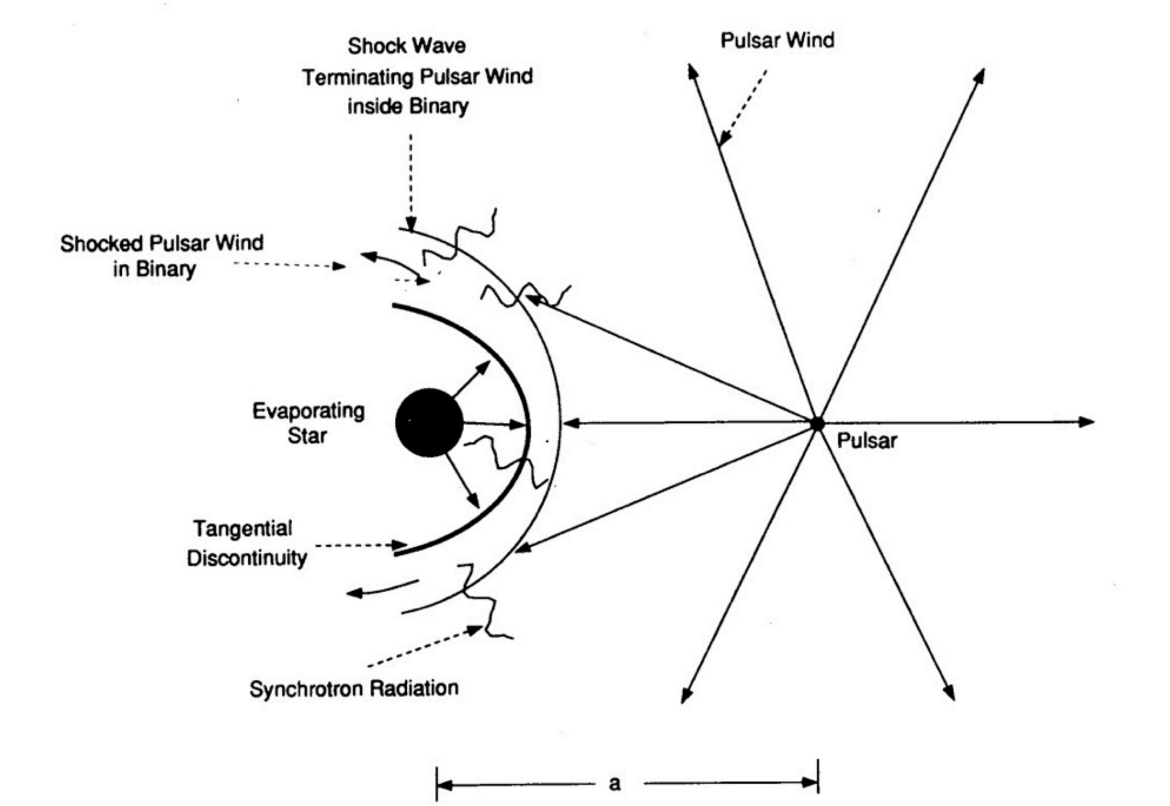


FIG. 2 Schematic representation of the shock geometry near the companion star.

Arons and Tavani 1993

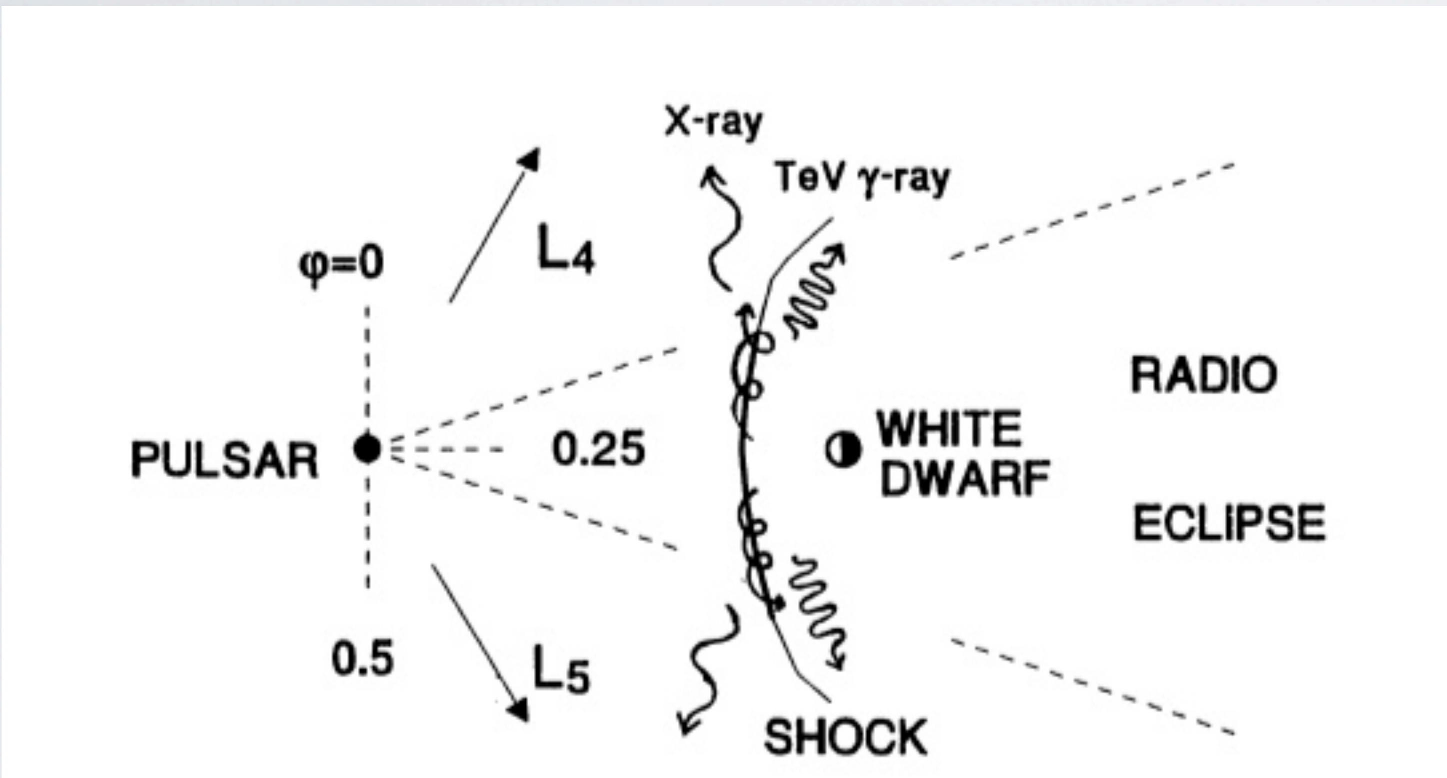
- Arons and Tavani (1993) model developed for high energy emission from Black Widow, predicted electrons accelerated to 3 TeV in intrabinary shock

- $\dot{E} \sim 1 \times 10^{35}$ erg/s

- Although circular, orbital modulation can arise from obscuration by shock, intrinsic emission beaming from magnetic field, and doppler boosting

THE Black Widow PSR B1957+20

Shock distance of lt-secs may imply high B, σ at shock



Raubenheimer et al. 1995

- Possibility of "hidden" γ-ray sources (Tavani 1993). Black Widow proposed source of TeV emission in 1995.
- Estimated luminosity depends on distance to shock, fraction of wind involved, magnetic field of pulsar, optical emission from companion, magnetization of wind, ion fraction BUT primarily, still $\dot{E}/d^2$

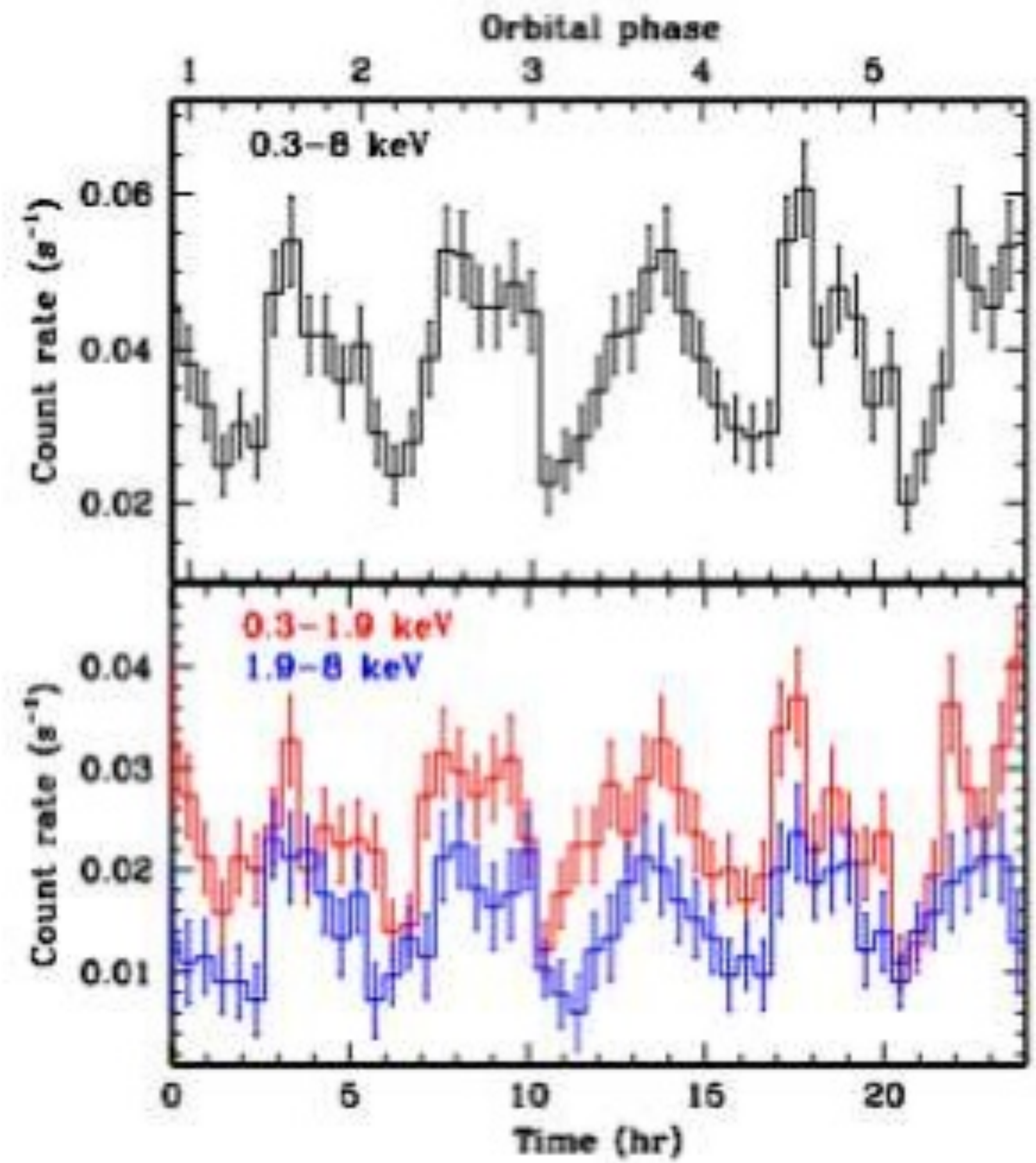
Can We Learn About Pulsar Winds From Spiders?

- A large object is in the path of the ultra-relativistic wind, much closer than eg. the termination shock of the Crab. A natural multi-TeV linear collider!
- We see the shock from different orientations, leading to X-ray modulation.
- System and pulsar geometry can be well determined
- Short orbits allow for many repeated measurements
- Potentially GeV-TeV emission as in PSR B1259-63 (not yet definite, although suggestion of > 3 GeV emission in PSR B1957+20 by Wu et al. 2012).

X-RAY OBSERVATIONS

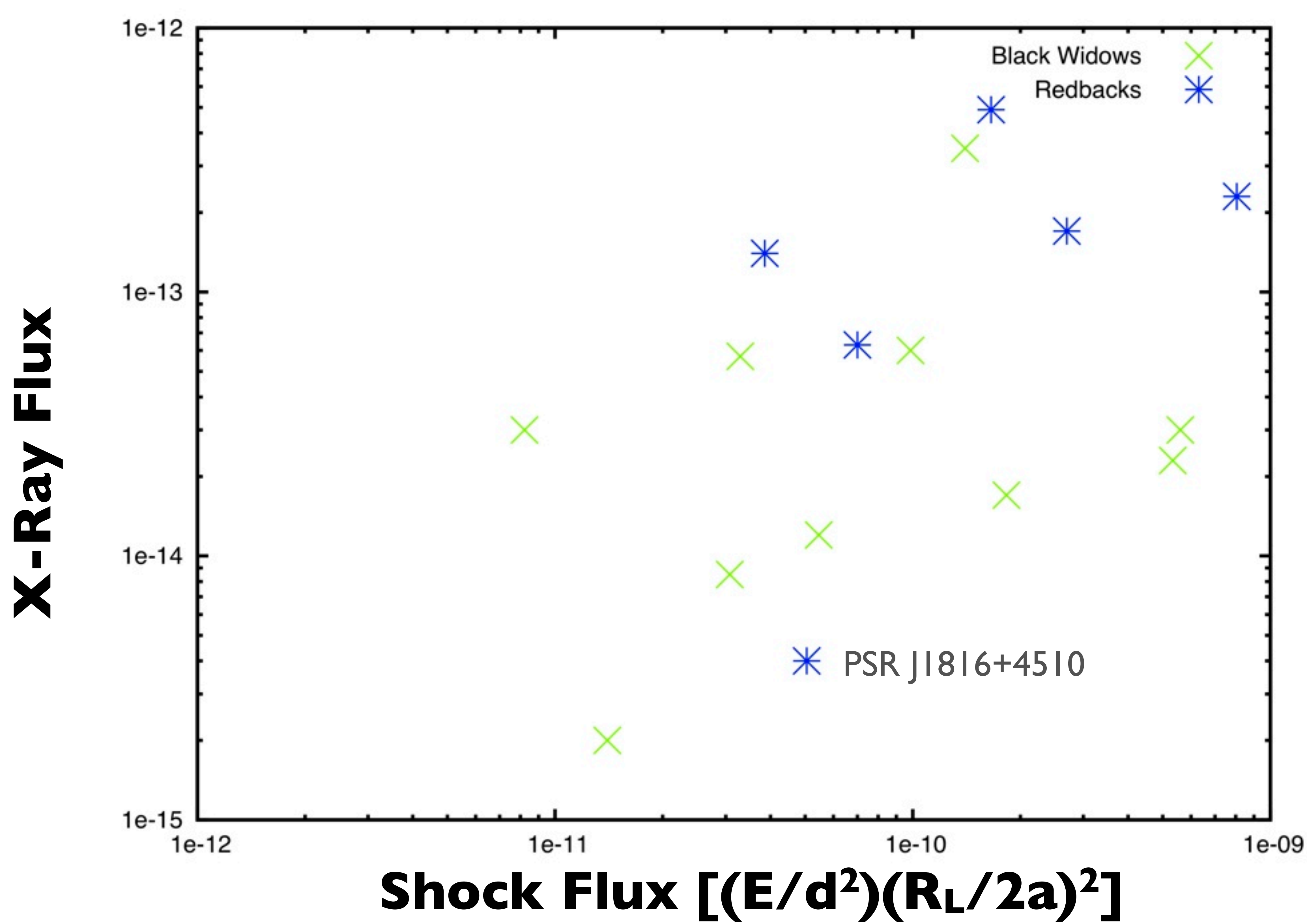
- Most Spiders seem to have X-ray counterparts
- Usually Blackbody + Power Law spectra
- Many exhibit orbital variability in non-thermal X-rays
- Not very bright, good statistics require fairly extensive observations
- So far, only PSR B1957+20 shows clear extended emission

PSR J1023+0038 X-Ray Orbital Light Curve



Bogdanov et al. 2011

X-Ray Emission Enhanced by Shocks



A Few Comments About Energetics

- MSP masses can be significantly greater than 1.4 solar, and radii likely >10km, hence moment of inertia likely 1.5-4 times larger than canonical 10^{45}
- Spin derivatives are affected by Shklovskii effect. Need proper motions
- Orbital plane and spin axis aligned: equatorially enhanced pulsar wind concentrates larger fraction of power into orbital plane
- Fermi pulsed emission from MSPs can be highly efficient, assumption that nearly all spin-down power goes into wind not valid?

So Many Spiders in the Neighborhood!

- Lots of nearby Black Widows and Redbacks in the field
- Most are Fermi sources, emission dominated by pulsations?
- Optically bright, mostly non-degenerate companions filling substantial fraction of Roche lobe
- Masses and orbital geometry can be determined from optical studies of companions
- Redbacks may be ultra-compact X-ray binary progenitors
- May switch back and forth between accreting source and rotation powered source
- May represent maximum spin-up for a given magnetic field.
- Black Widows may be post ultra-compact X-Ray binaries
- Many more wind-wind shocks to study in sources where the parameters can be very precisely determined
- Orbital period changes can (maybe) probe companion's structure
- Radio emission could be completely hidden
- Nature's linear colliders!