AN ARACHNOPHILIAC'S GUIDE TO WORKING IN MIRKWOOD AND THE FORBIDDEN FOREST

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EWASS 2015

WITH


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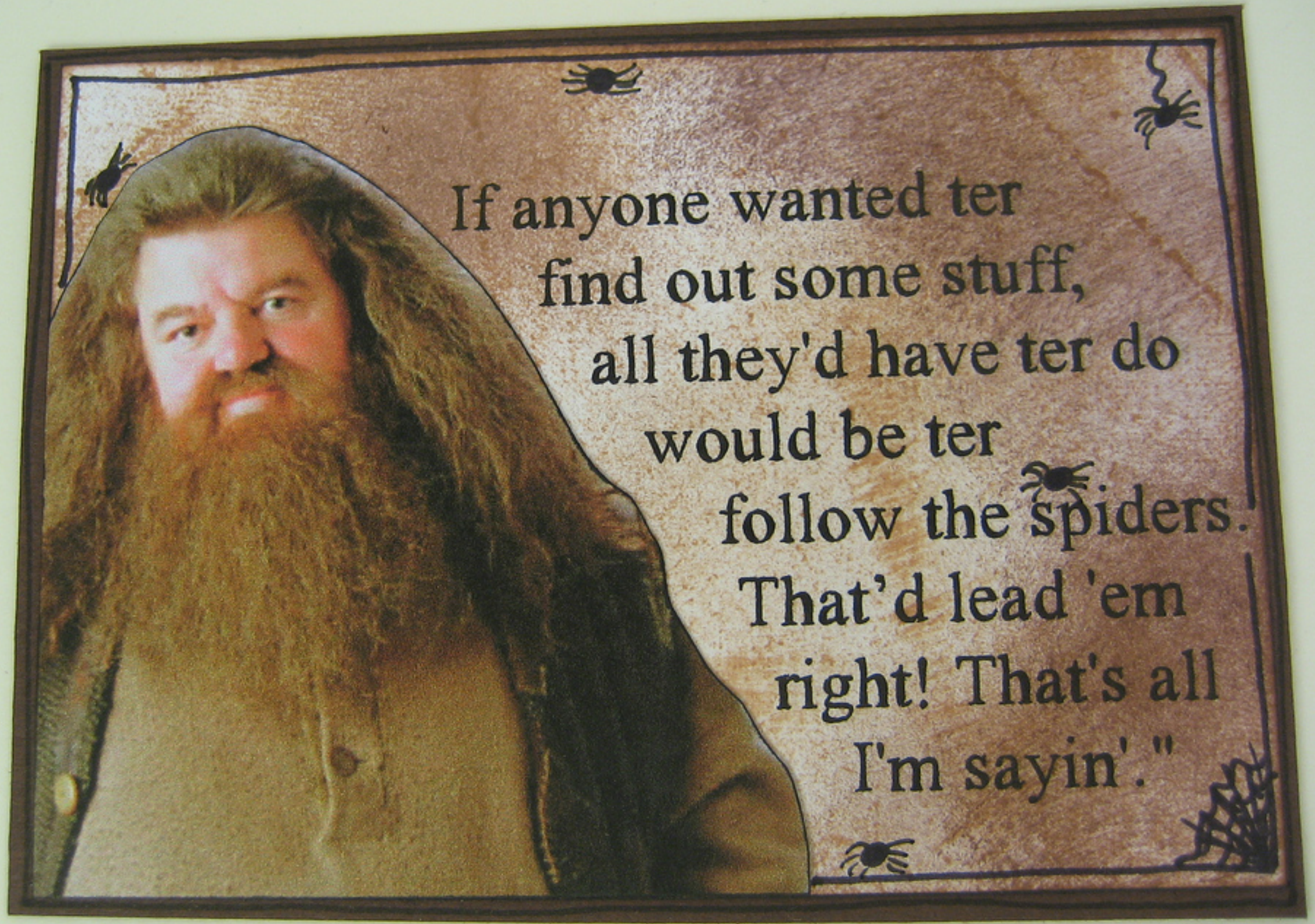
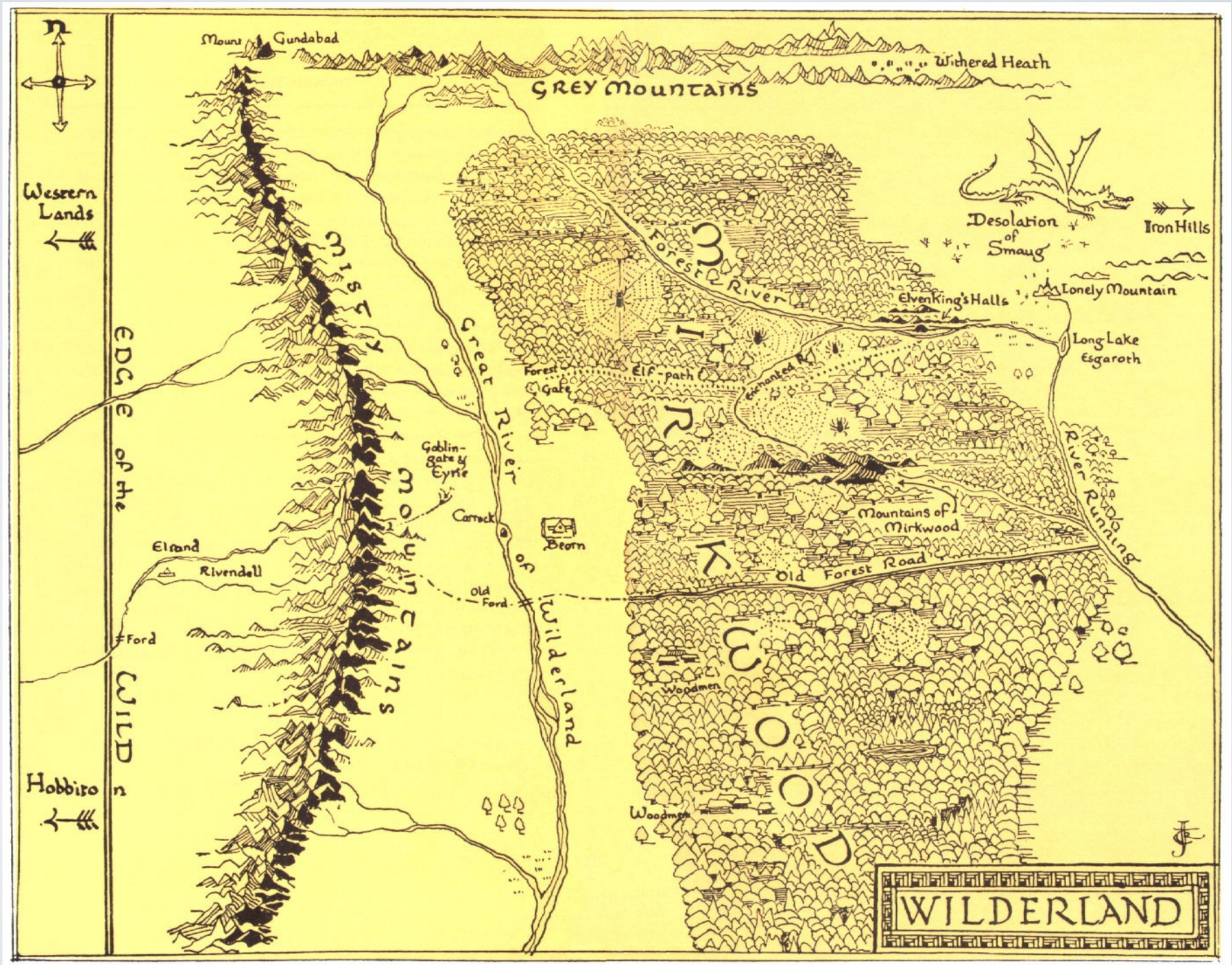
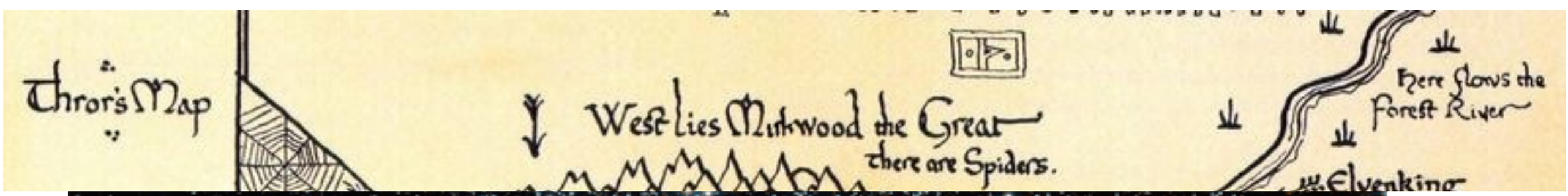
ARE YOU CURIOUS ABOUT…

- **Pulsar Winds?**
- **Accretion?**
- **Neutron star equation of state?**
- **Binary evolution?**
- **Relativistic shocks?**
- **Sources of gamma-rays/anti-matter/ cosmic rays?**
- **Supernovae in binaries?**

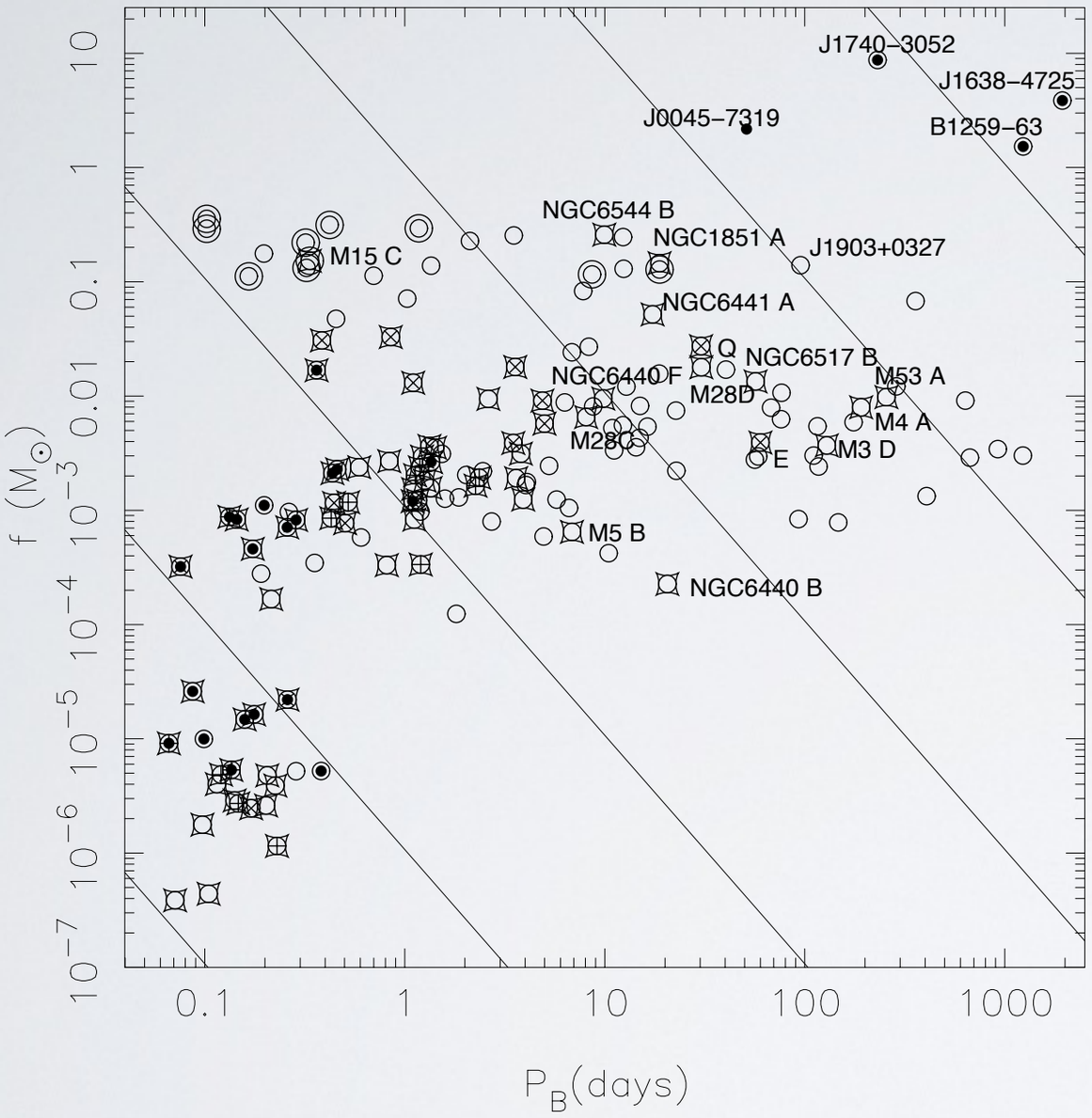

If anyone wanted ter
find out some stuff,
all they'd have ter do
would be ter
follow the spiders.
That'd lead 'em
right! That's all
I'm sayin'."

Do we go far over the Misty Mountains cold?




Thror's Map
West lies Mirkwood the Great
there are Spiders.
Here flows the
Forest River
Elvenking

Spiders in the Mirky Woods of Globular Clusters



Globular Cluster MSPs (from Paulo Freire's webpage)

http://www.naic.edu/~pfreire/GCpsr.html

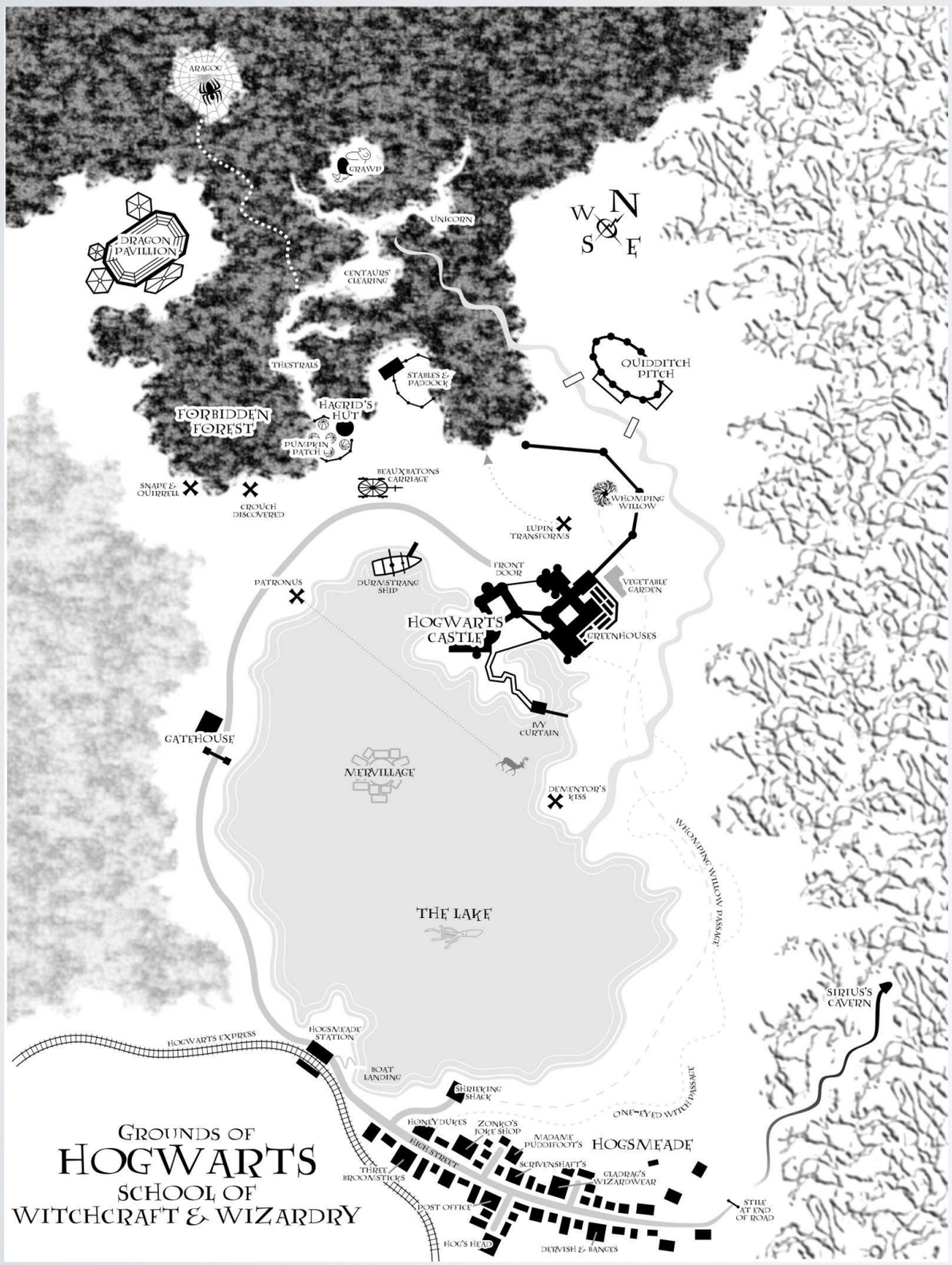
Lots of interesting Spiders in one place which have been regularly monitored for decades

Terzan 5 has 2 BW + 3 RB (out of 34 MSPs) 5.5 kpc away
47 Tuc has 5 BW + 1 RB (out of 22 MSPs) 4kpc away

Rich, extensive radio archive for eclipse studies and orbital variations!

BUT hard to determine intrinsic spin down, crowded optical fields, too distant for gamma-ray studies, etc.

Spiders on the School Grounds!



We thought nearby systems were rare… we were very wrong!

In the early 90s, low frequency surveys with Parkes and Arecibo began finding lots of field MSPs, but hardly any with P < 1day

But once acceleration searches became standard, nearby, compact systems started showing up in surveys (although sometimes publication was slow…)

And then we were given a Marauder's Map for MSPs (AKA Fermi)

One Fermi Directed Survey (GBT 350Mz)

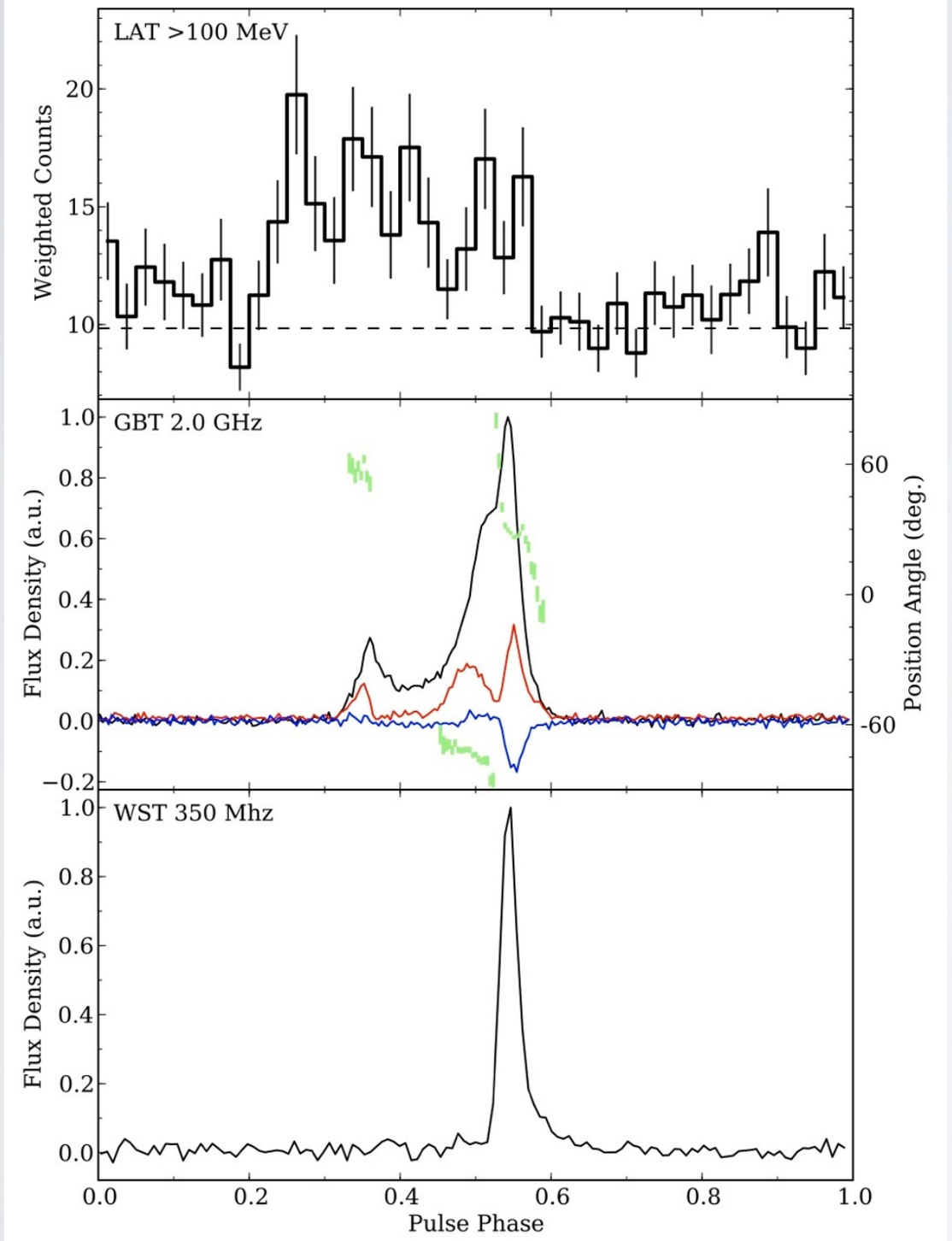
Bangale et al. to be published RSN (really!)

- 49 UNIDed Fermi sources in 1st Fermi Catalog, 35 minute pointings (Only ~30 hours of telescope time!)

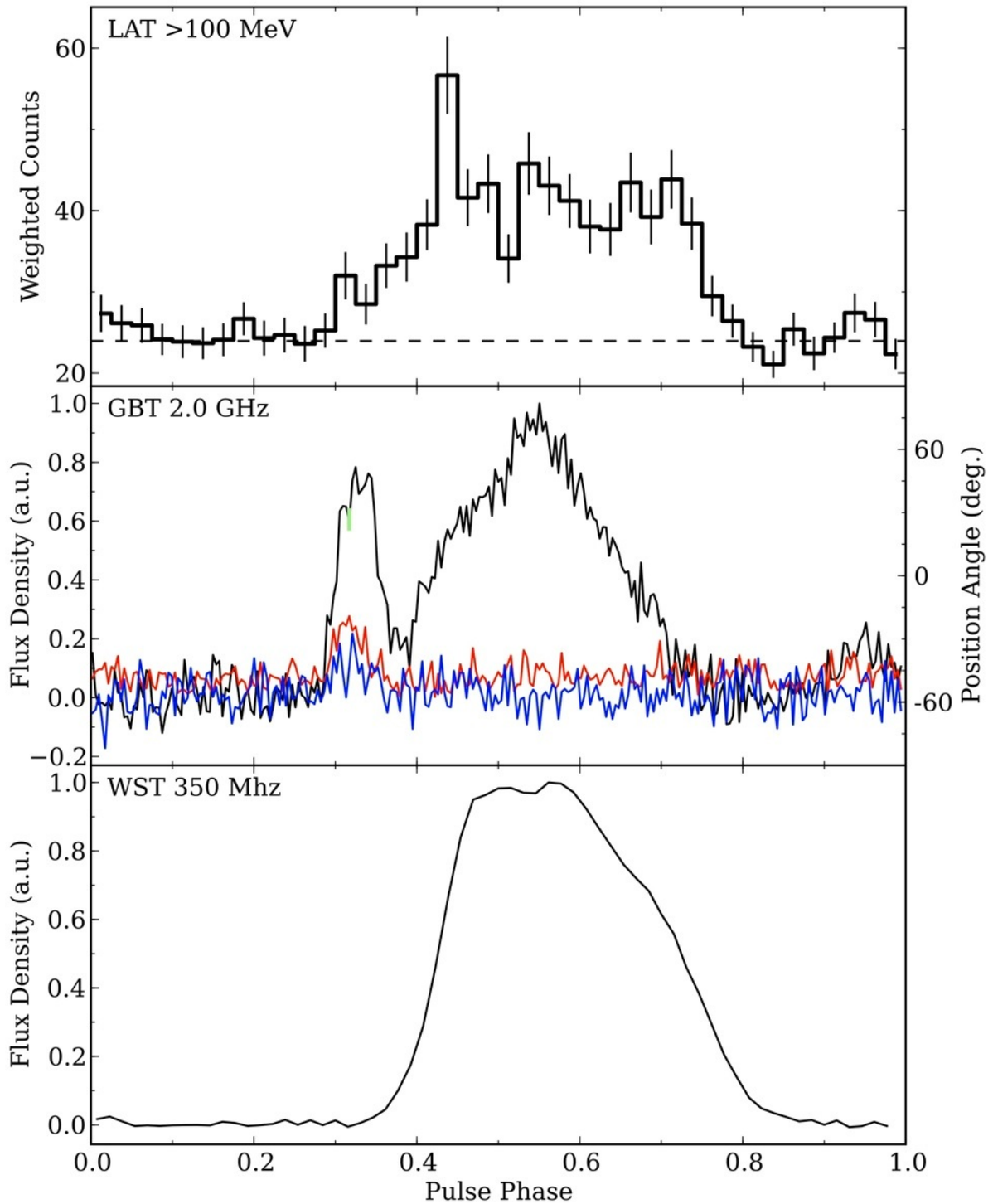
- **10** New MSPs (including **3 black widows**, **2 redbacks** and one **almost a redback**)

- 8 other MSPs detected but first discovered in other surveys (including 2 black widows)

Radio and Gamma-Ray Pulse Profiles

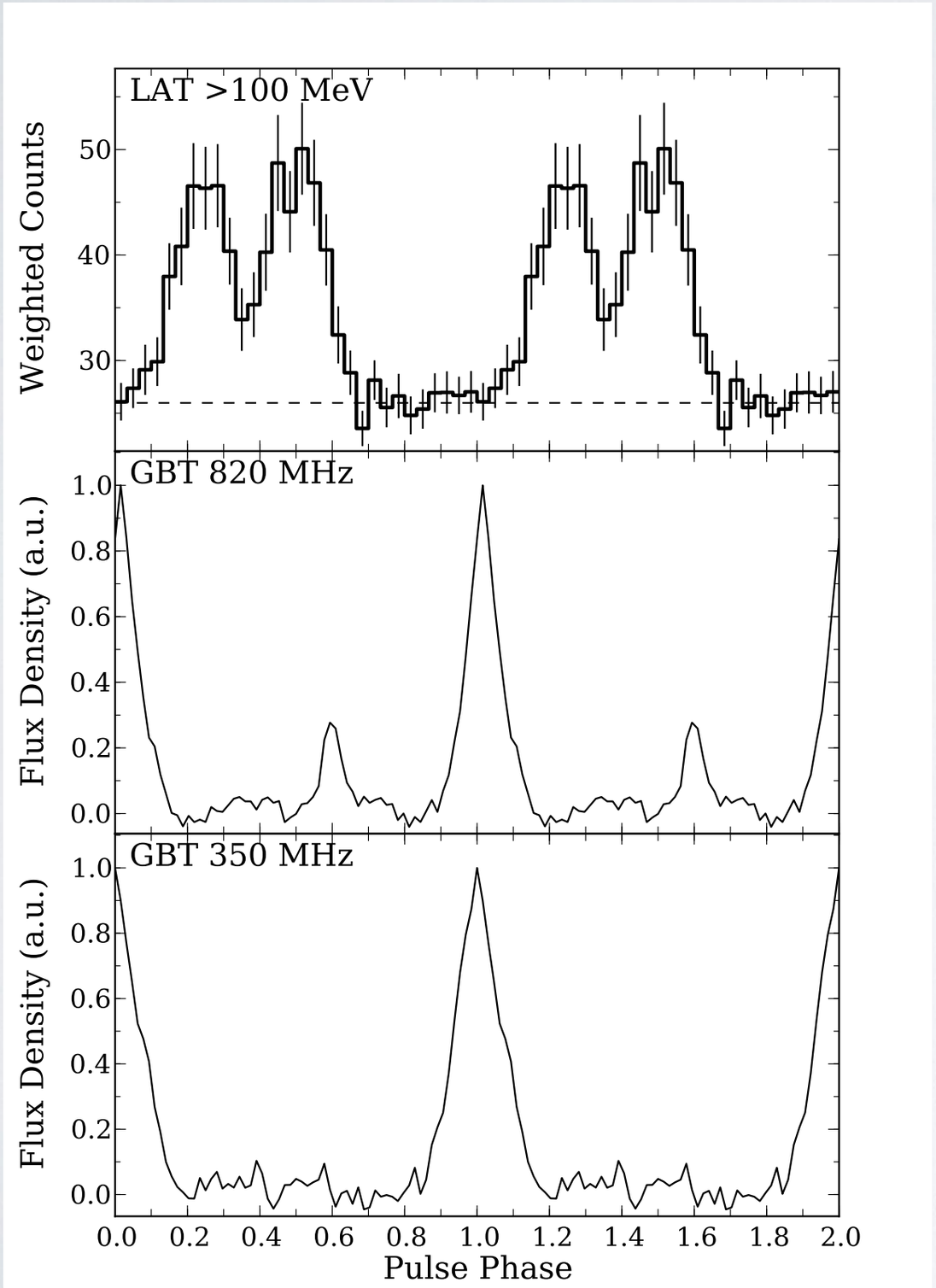


PSR J0023+0923



PSR J1810+1744

PSR J1302-3258
Almost a redback?



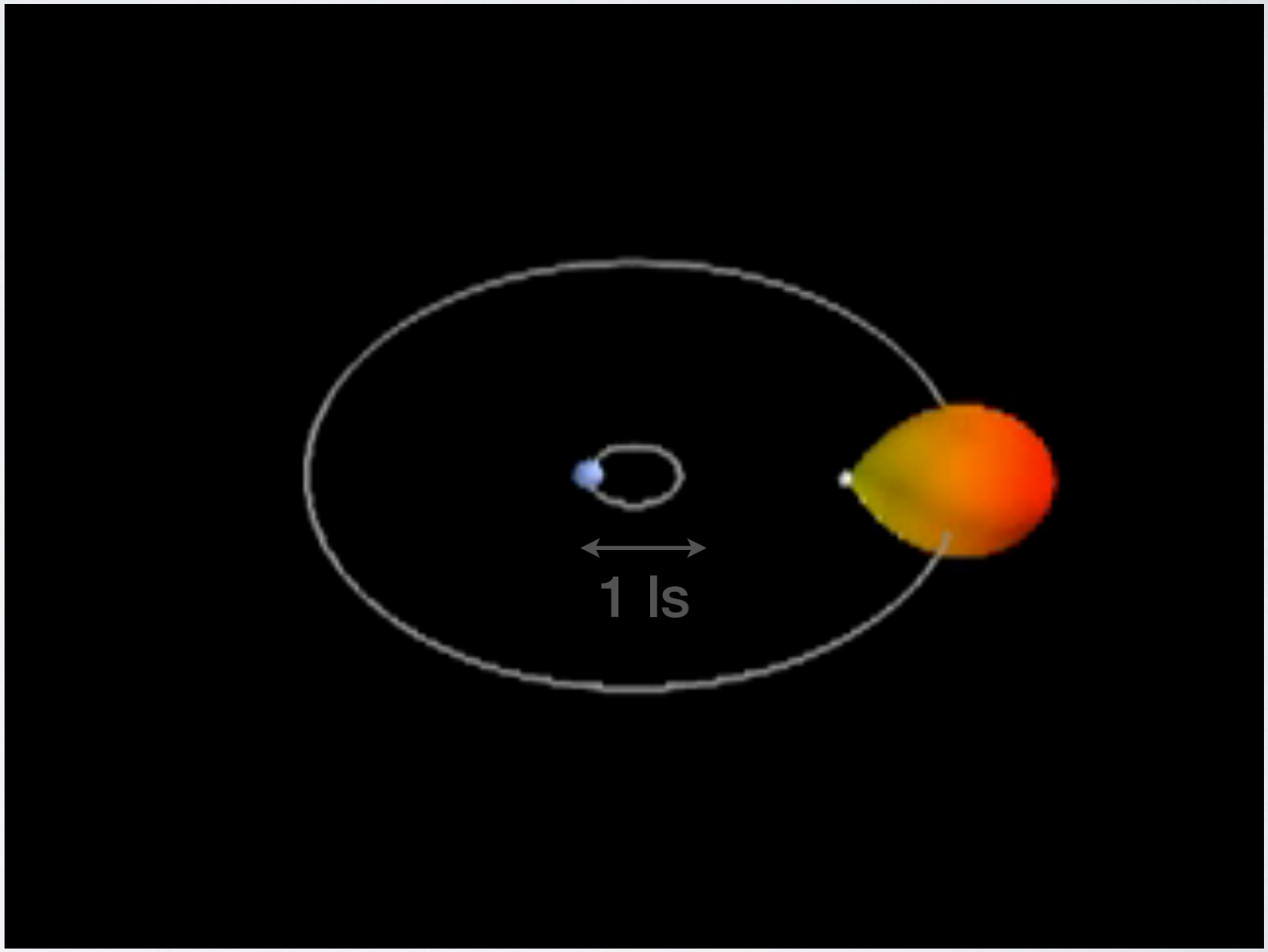
- 3.77ms pulsar in a 15.4 hour orbit around > 0.15 solar mass companion,
- $\dot{E} \sim 5 \times 10^{33}$ erg/s
- DM distance of 0.9kpc
- Hints of brief or partial eclipses
- However, companion very faint in optical and 10ks Chandra observation detected only 16 photons, none above 2 keV

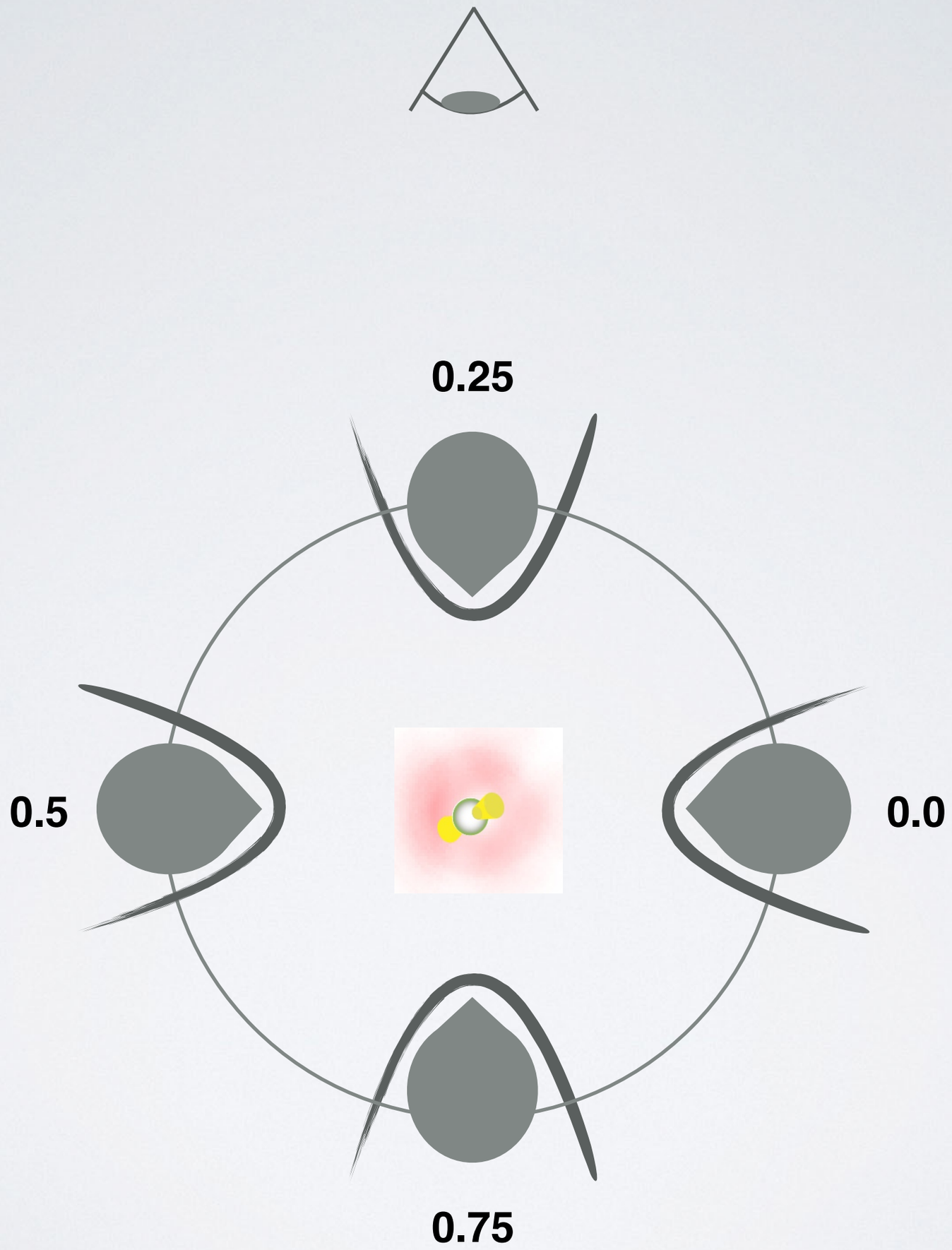
Redbacks: Very Compact Systems with non-degenerate companions

- Binary systems a few lightsec across

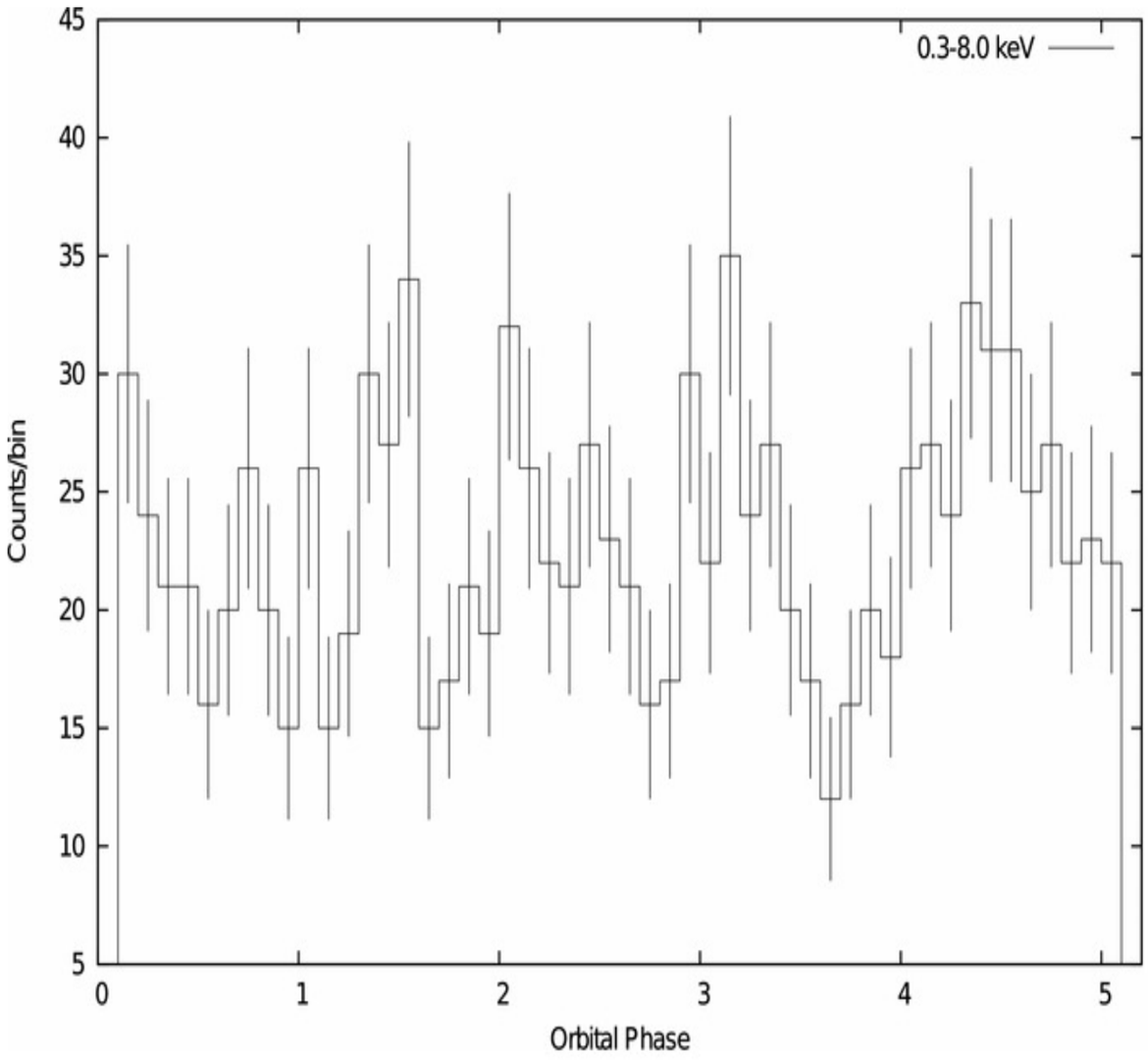
- Shock forced at companion ~10^4 light cylinder radii away (compared to ~$4X10^8$ for the Crab's inner torus)

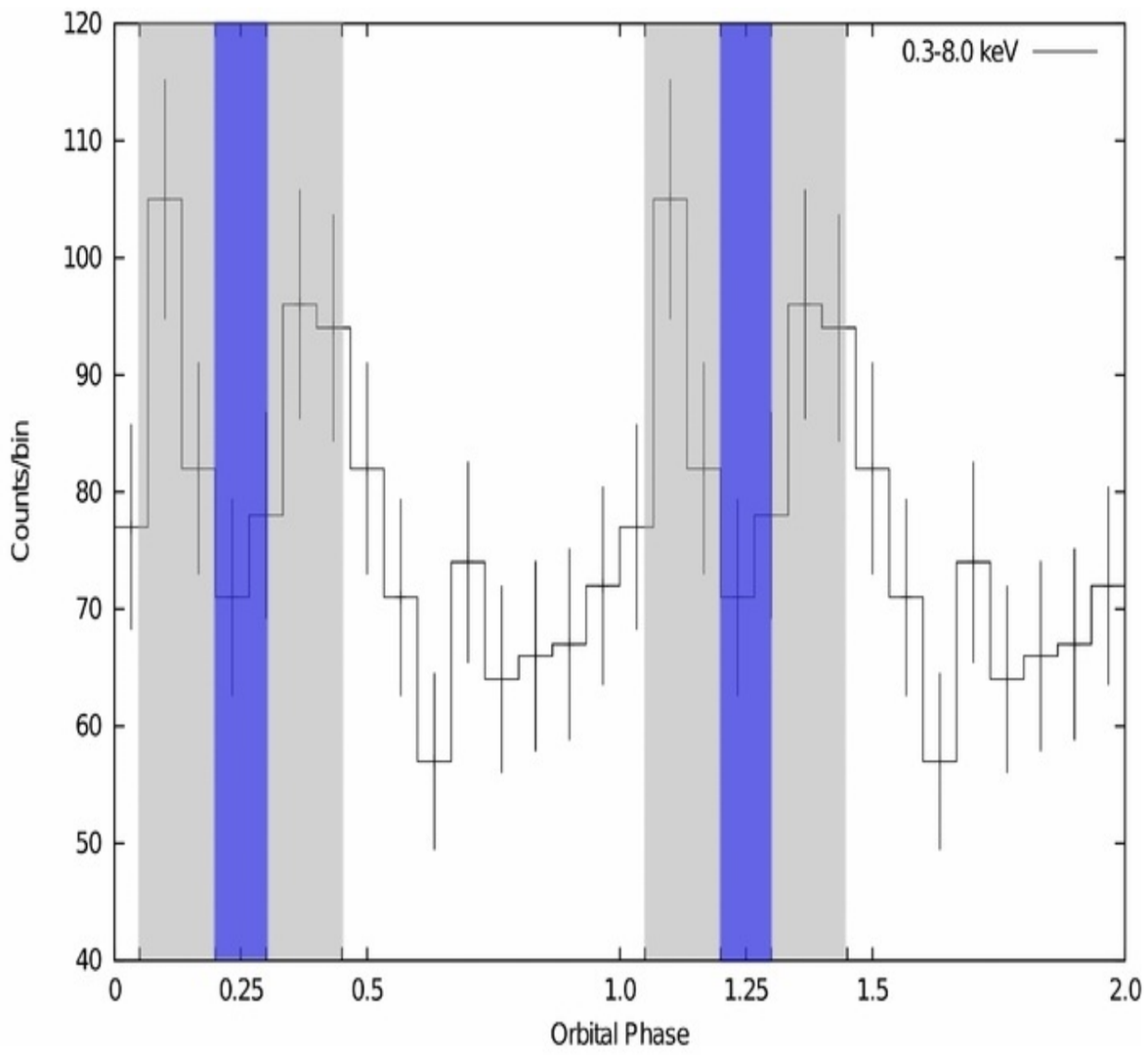
- Binary separation ~4-5 times the radius of the companion




0.25
0.5
0.0
0.75

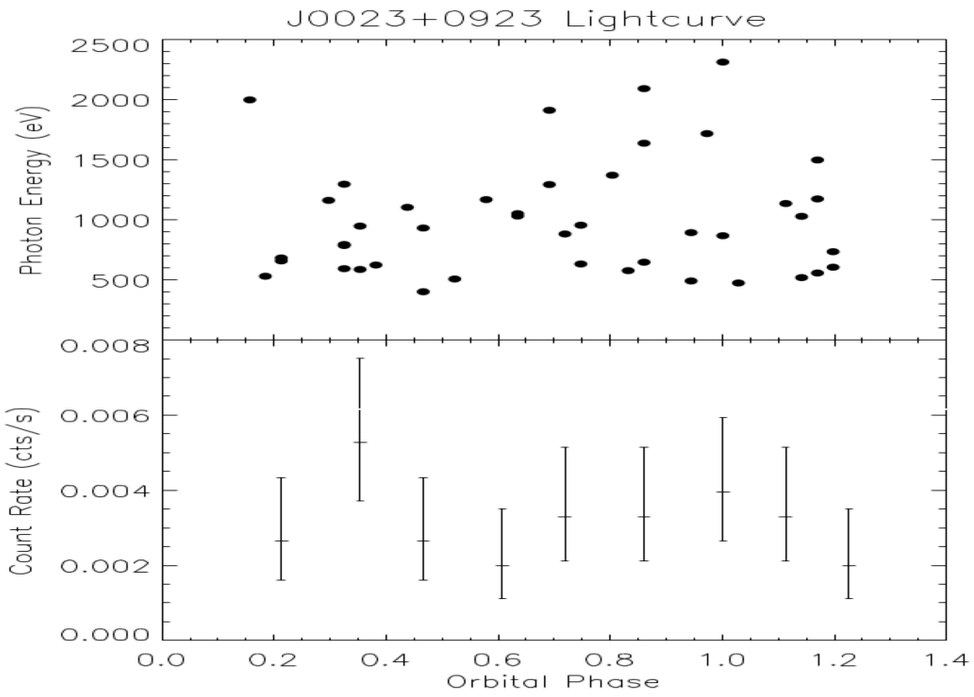
THE Black Widow PSR B1957+20
Orbital Modulation of X-Rays

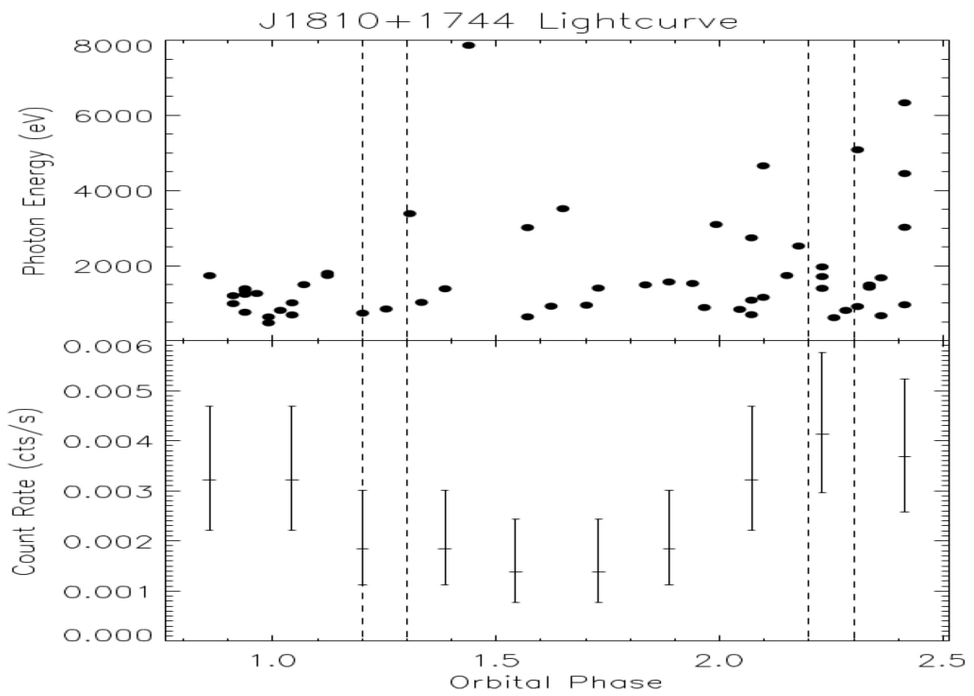


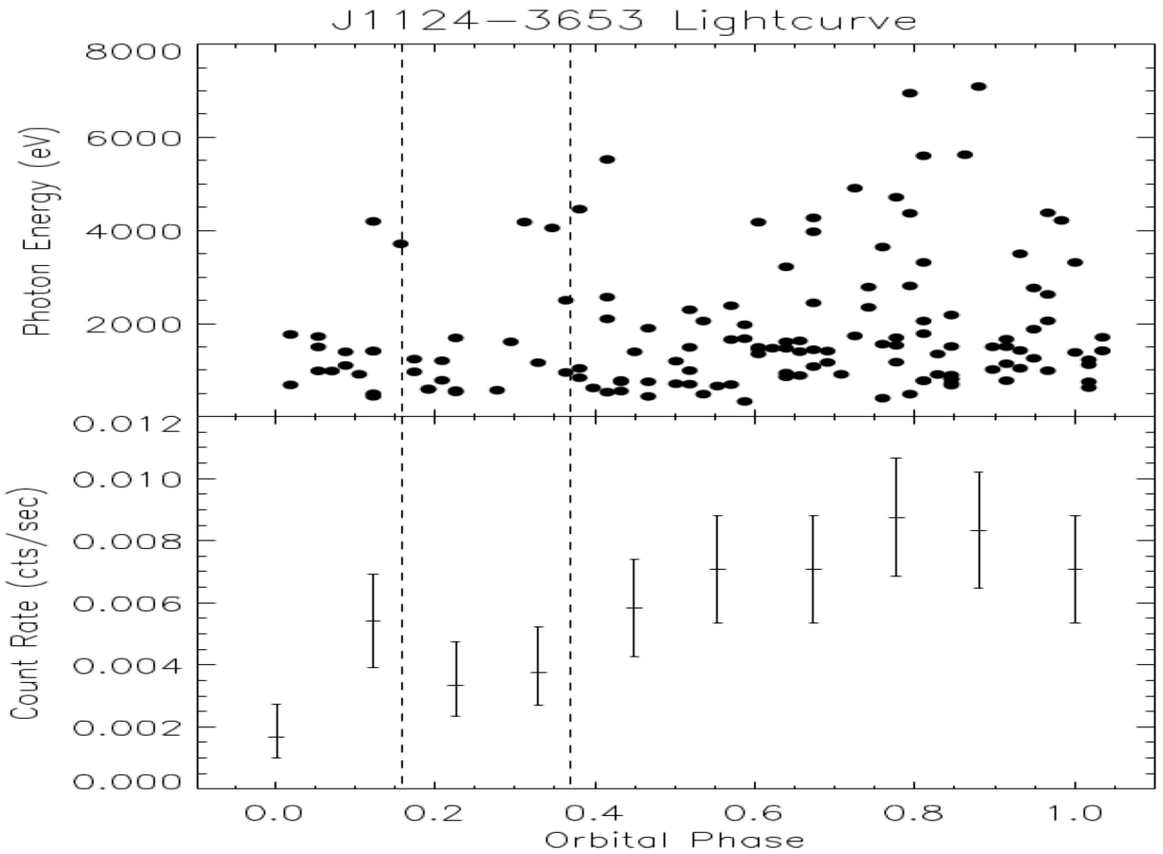


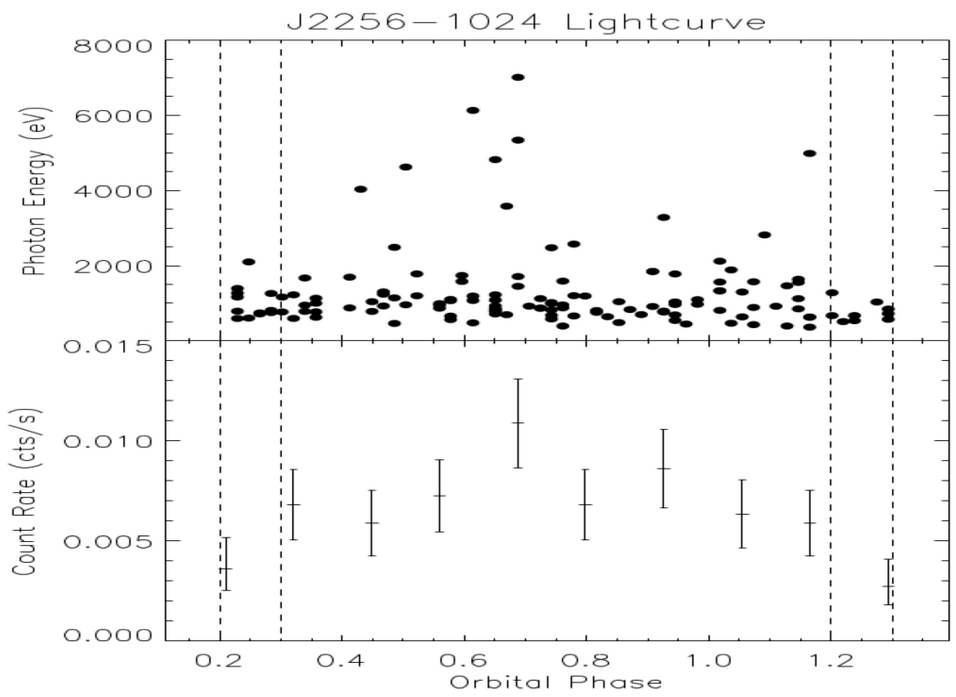
Huang et al. 2012

Some Other Black Widows



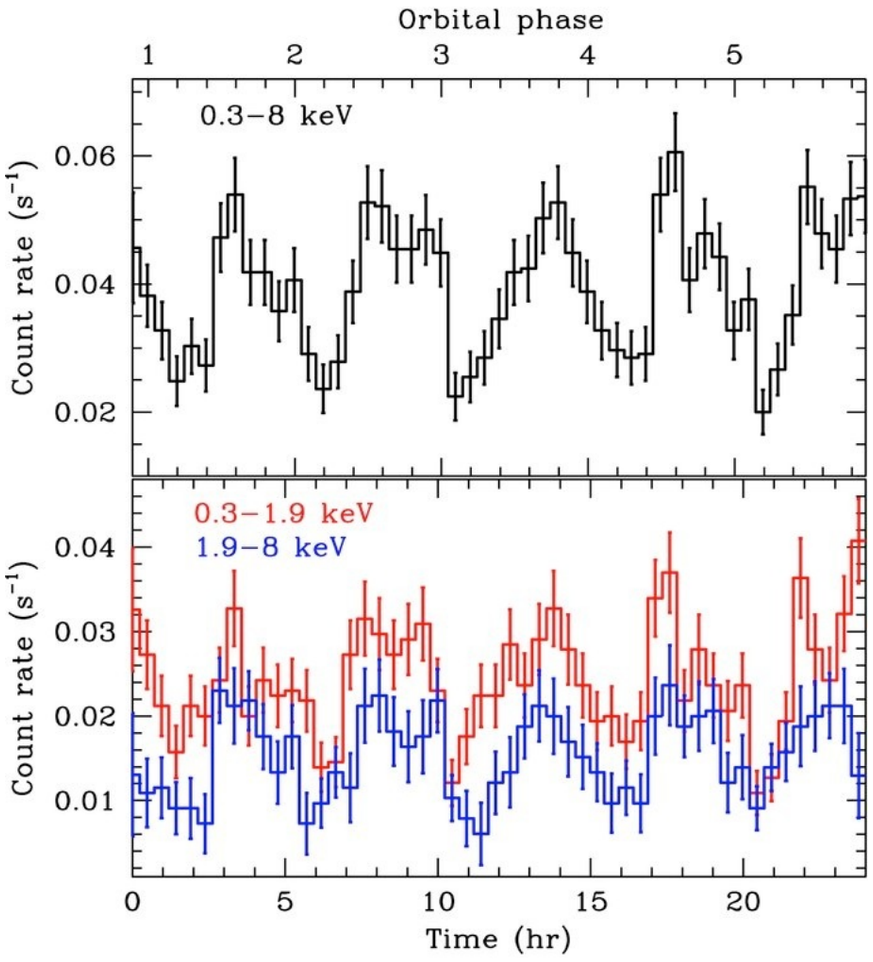




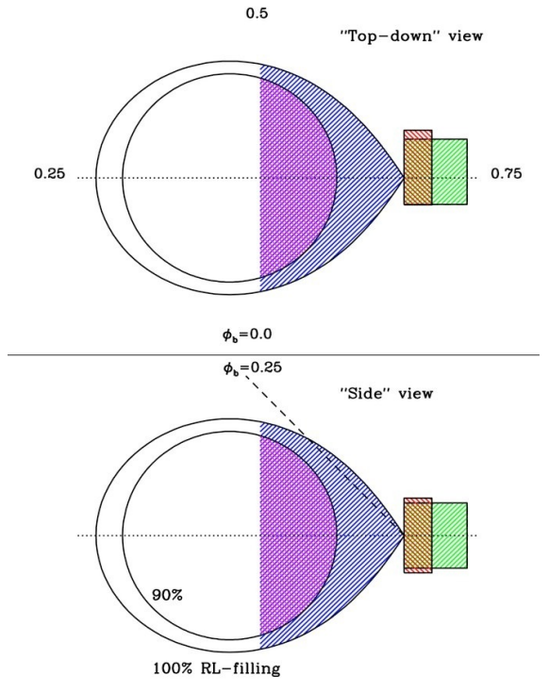


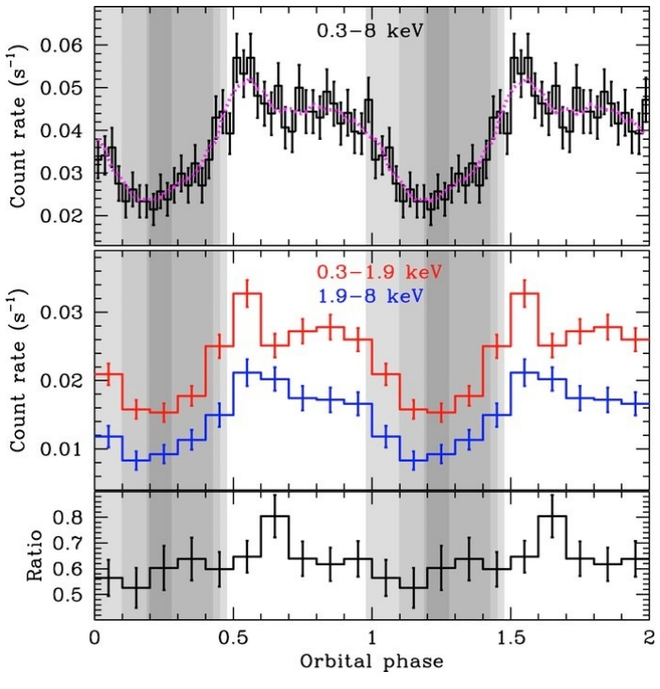
Gentile et al. 2014

PSR J1023+0038 in X-Rays

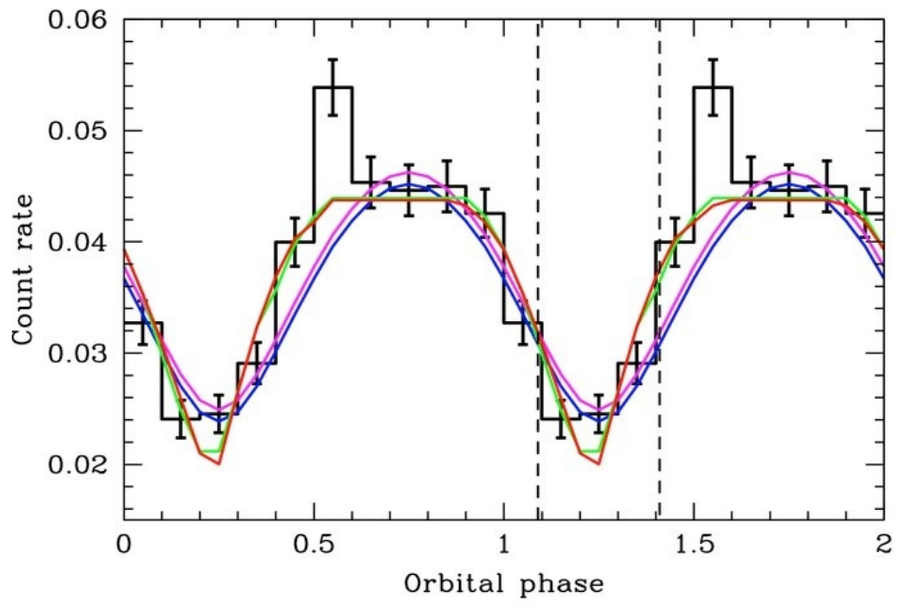


- Light Curve suggests emission site small — no larger than companion
- Luminosity suggests high magnetic field at shock (possibly high σ)?
  - If wind equatorially enhanced, required efficiency is less



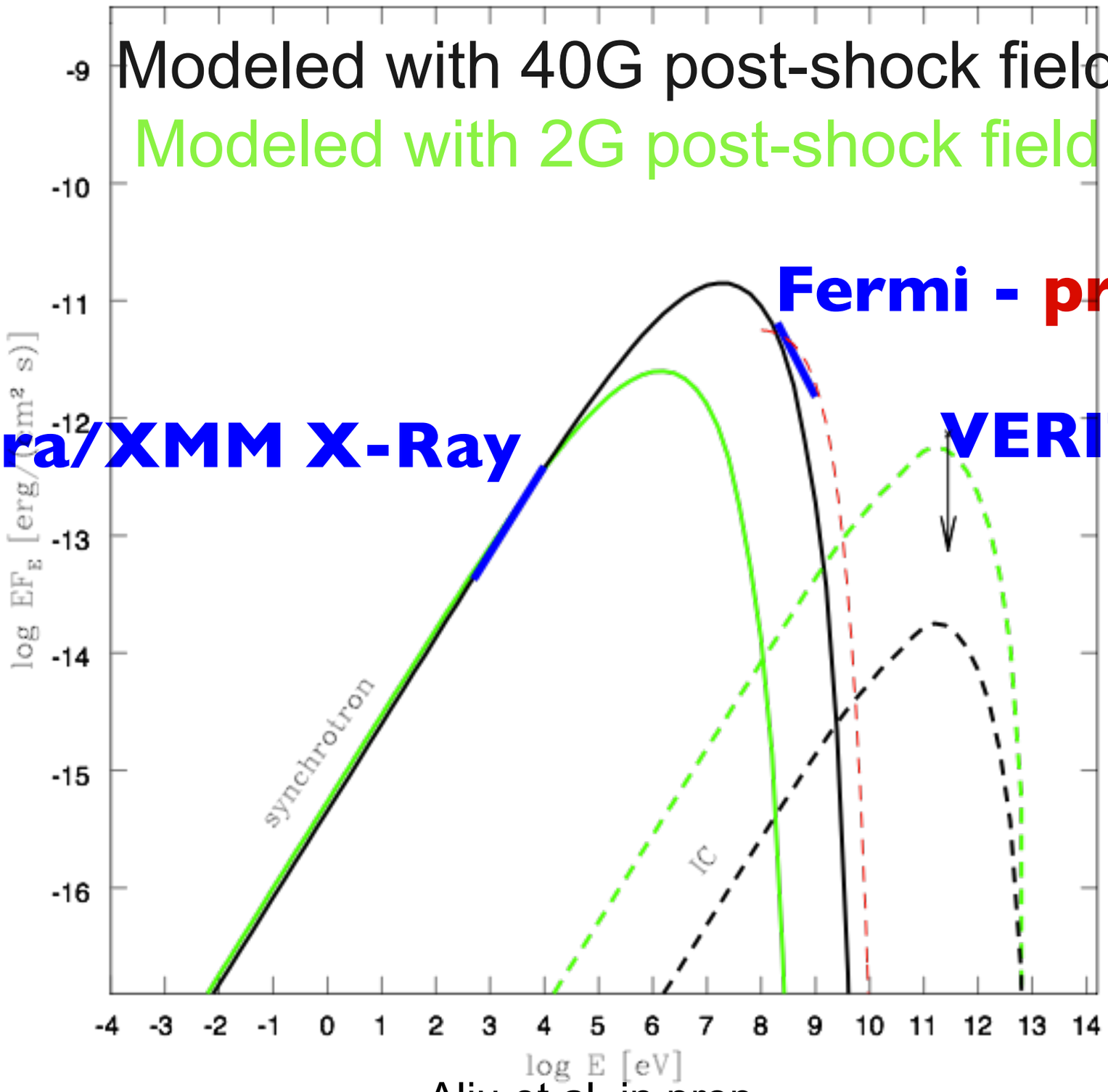


Bogdanov et al. 2011



PSR J1023+0038
Shock Spectrum => σ>>1??

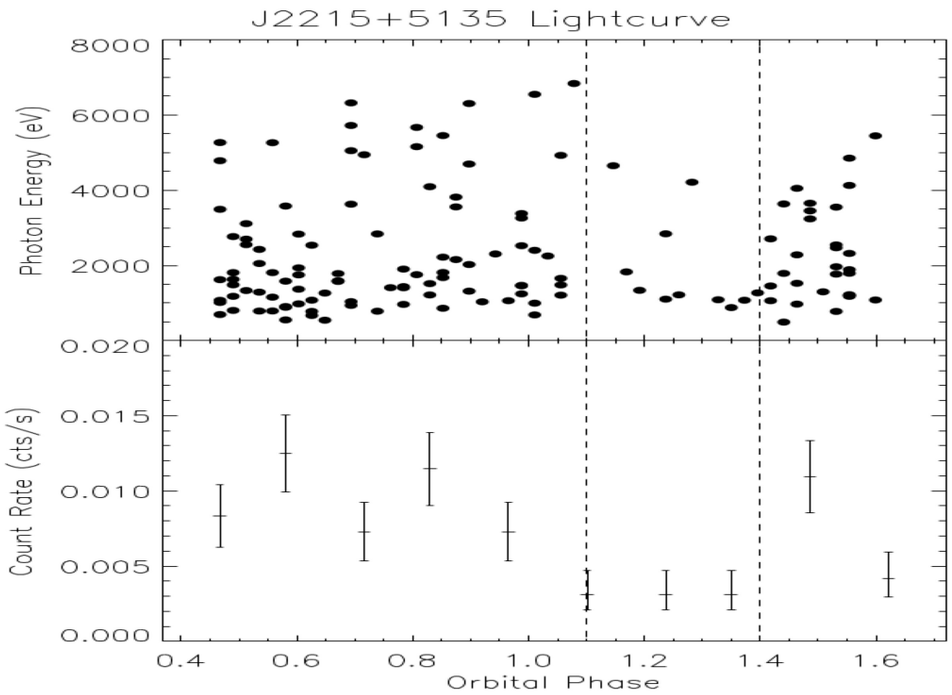
(Or could the companion's magnetic field be important??)

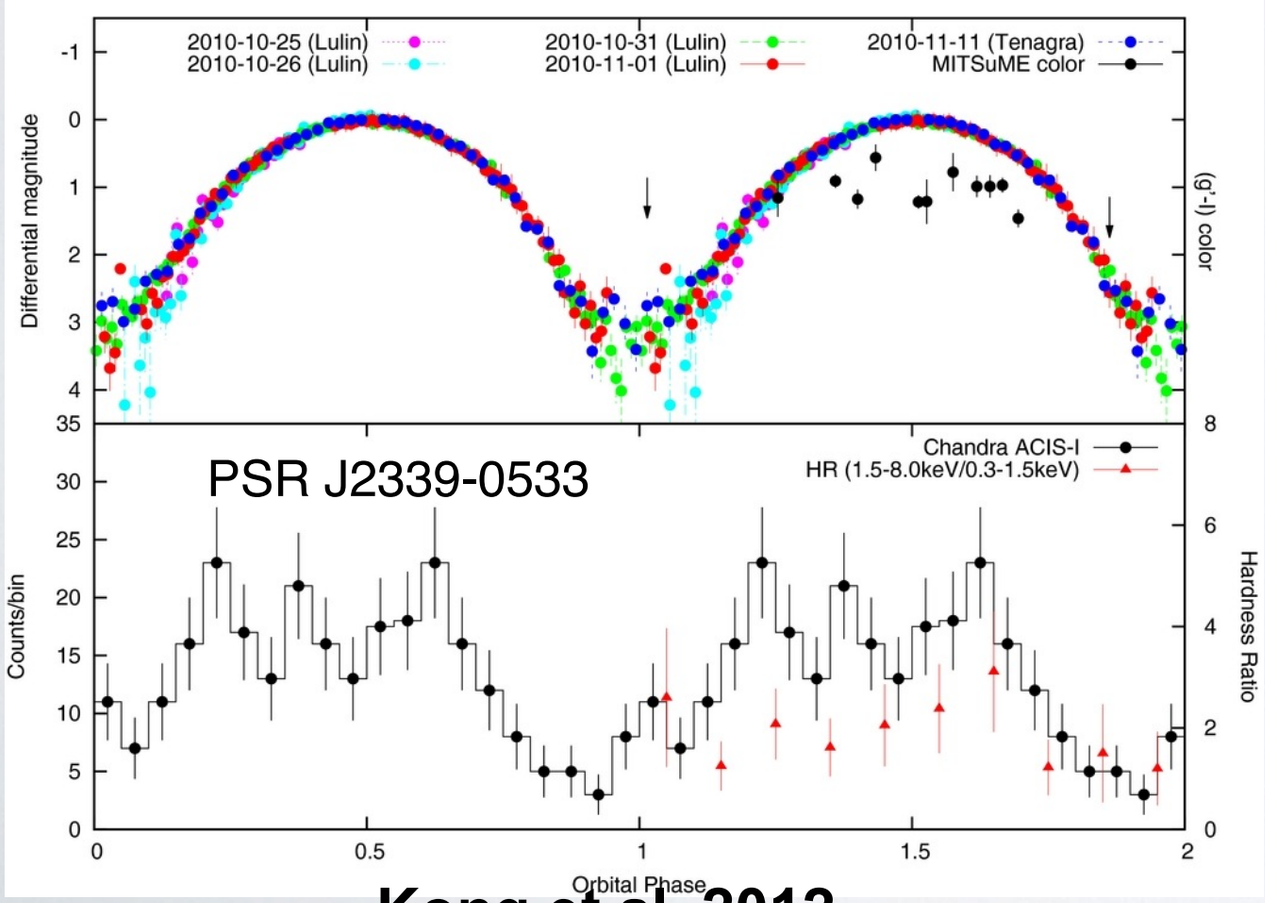


Aliu et al. in prep

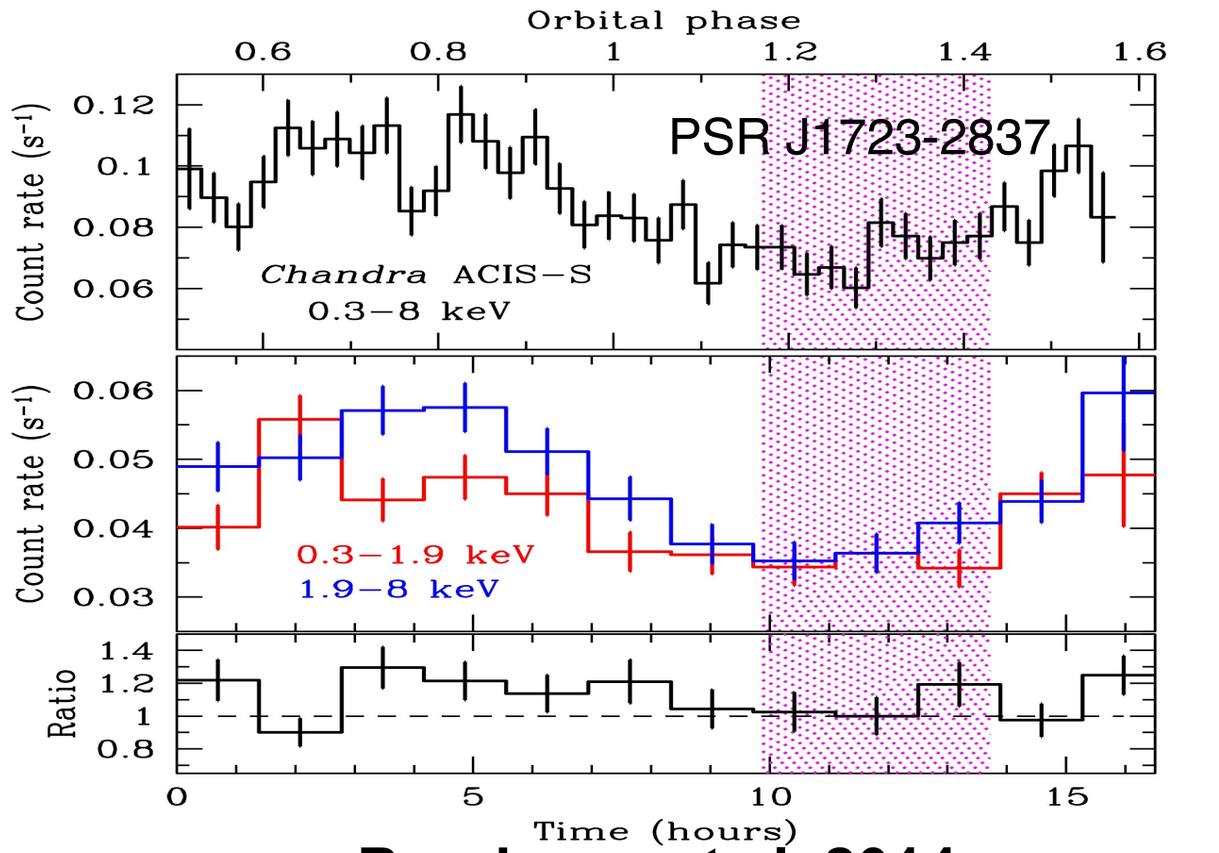
Some Other Redbacks

Gentile et al. 2014

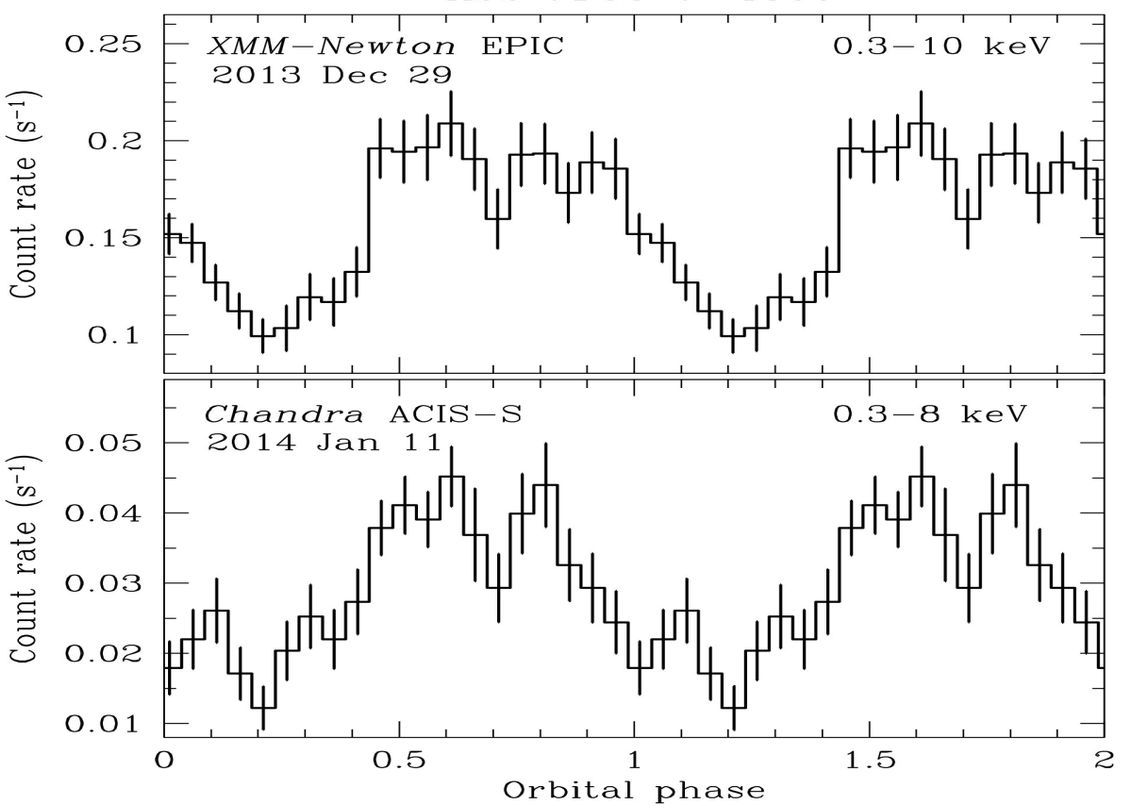




Kong et al. 2012

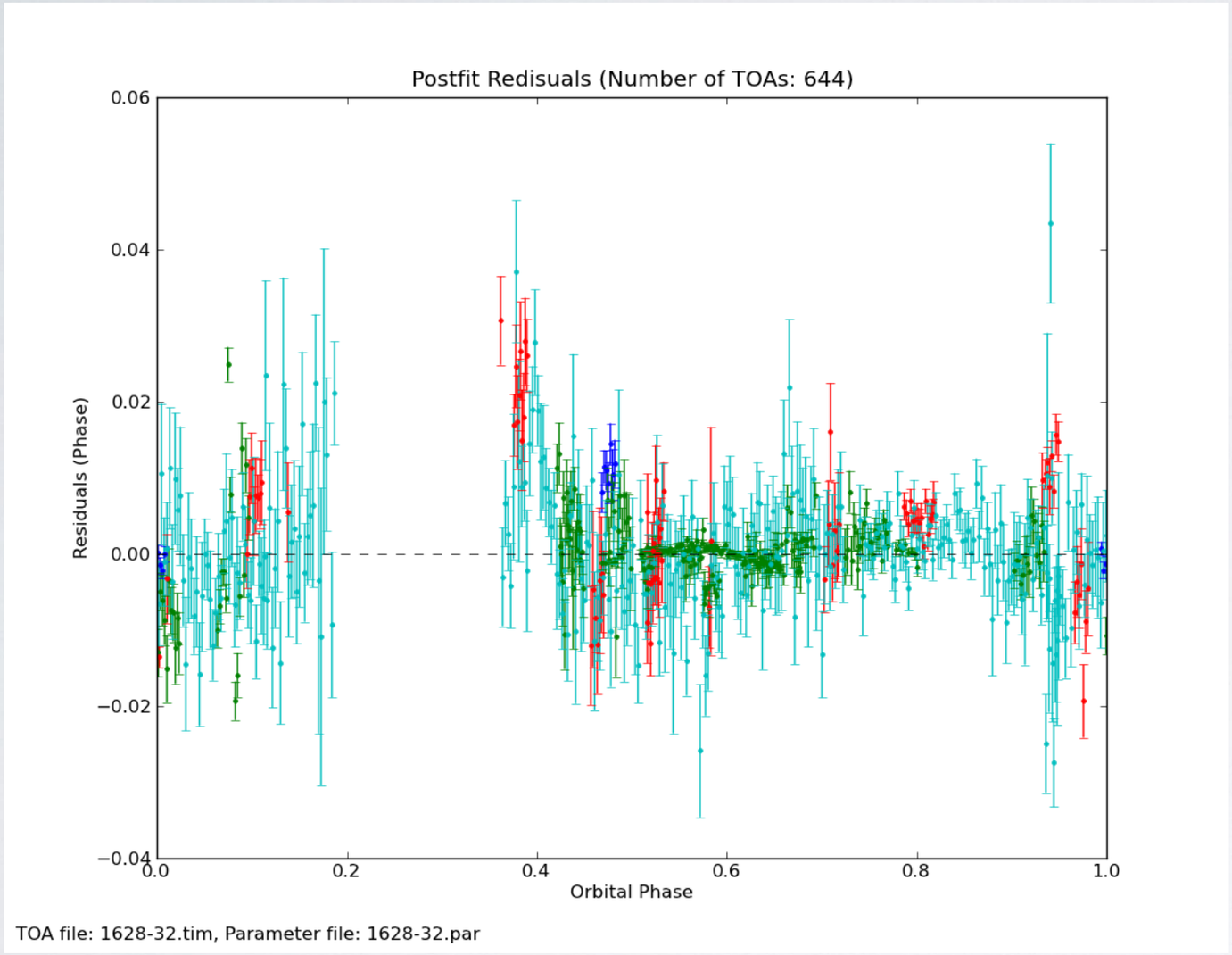


Bogdanov et al. 2014

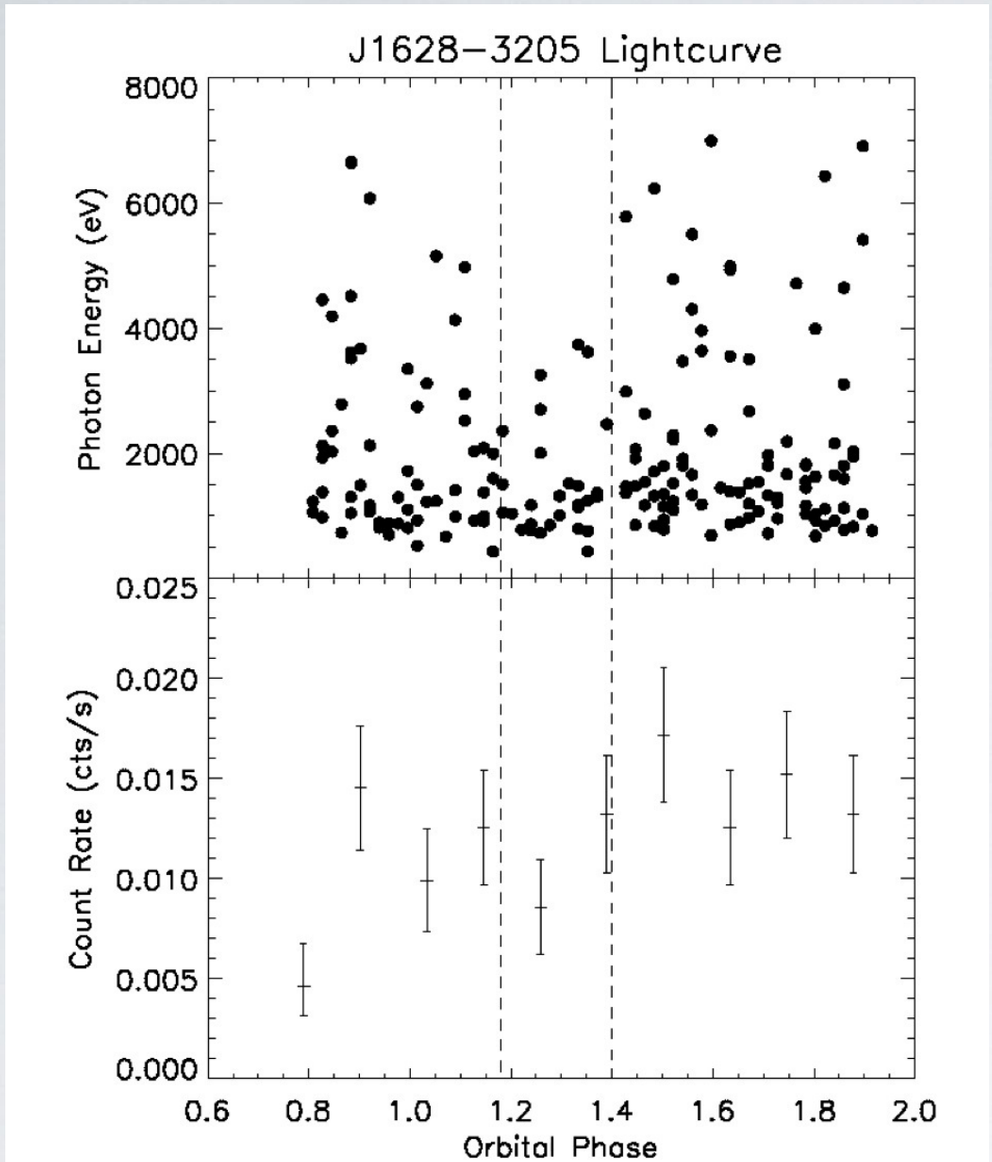


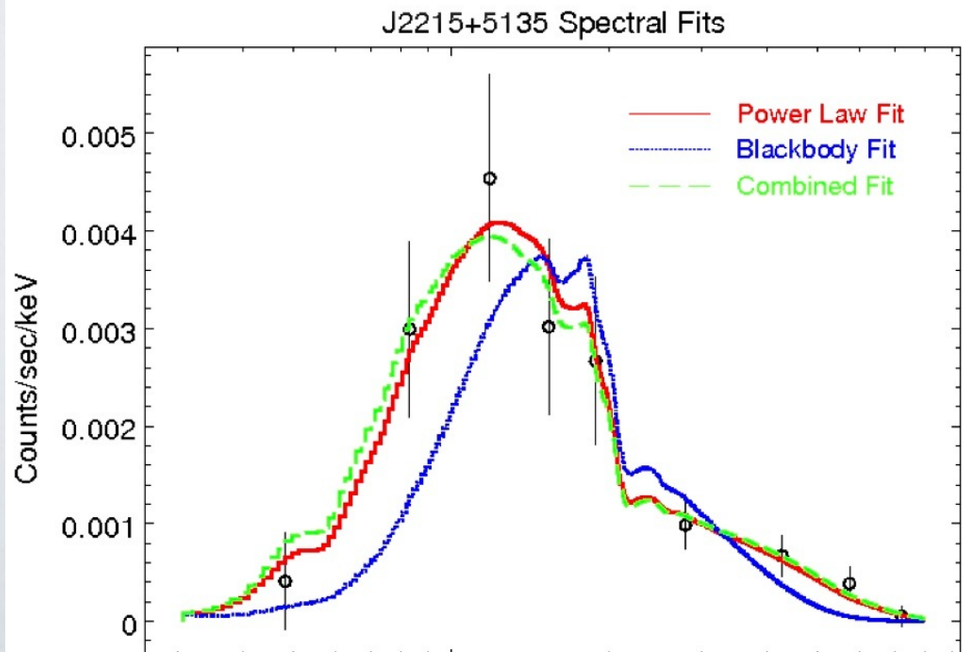
THE REDBACK PSR J1628-3205

(Found in 820MHz survey of Fermi sources, PI Ransom)



- 3.21 ms spin period
- 5.0 hr orbital period
- Minimum $M_C \sim 0.16\ M_{sol}$
- Shows radio eclipses
- $D_{ne2001} \sim 1.2$ kpc
- $B \sim 2.2 \times 10^8$ G
- $\dot{E} \sim 1.8 \times 10^{34}$ erg/s
- Companion Roche Lobe filling, minimally heated (Li et al. 2014)

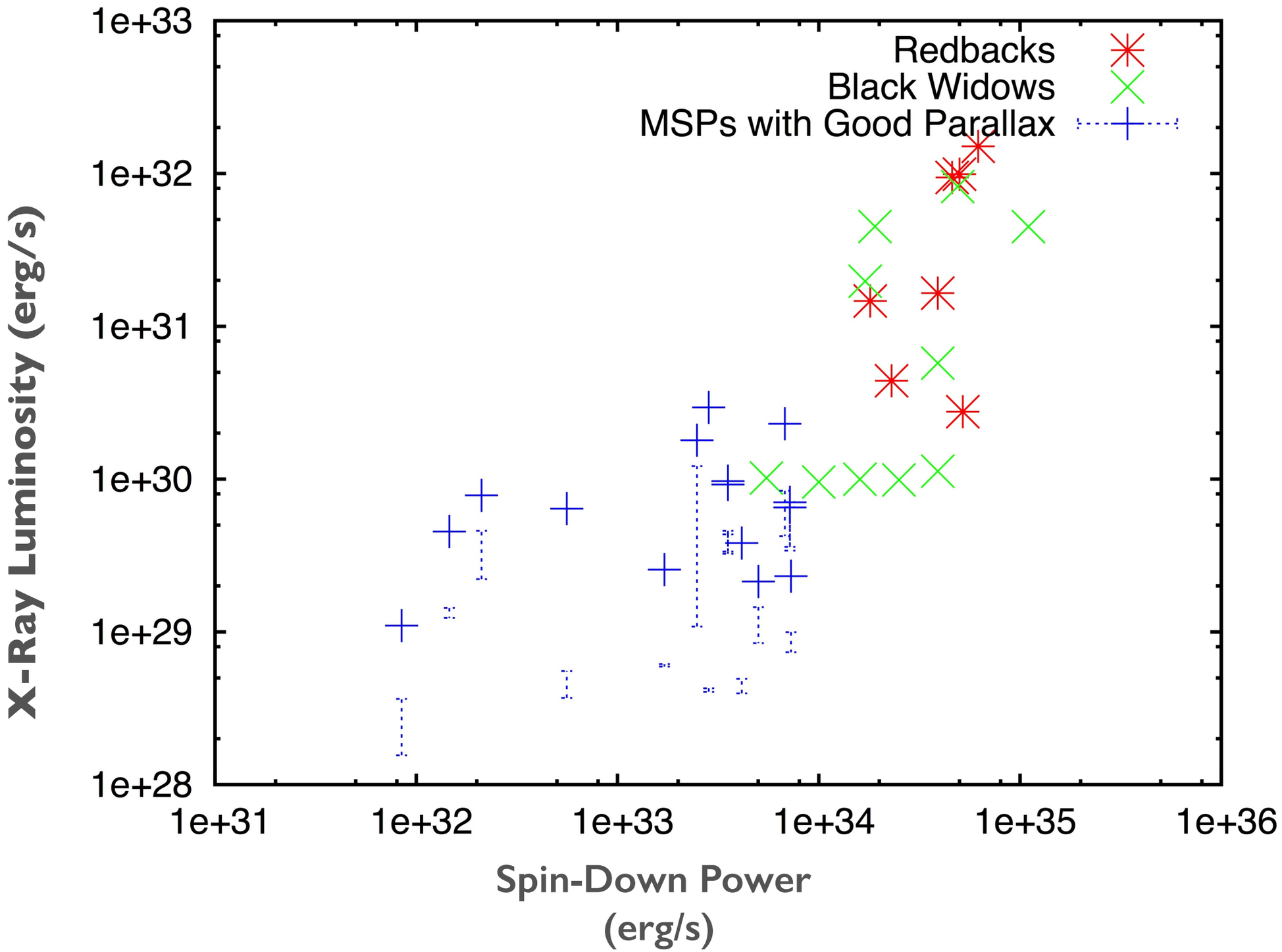




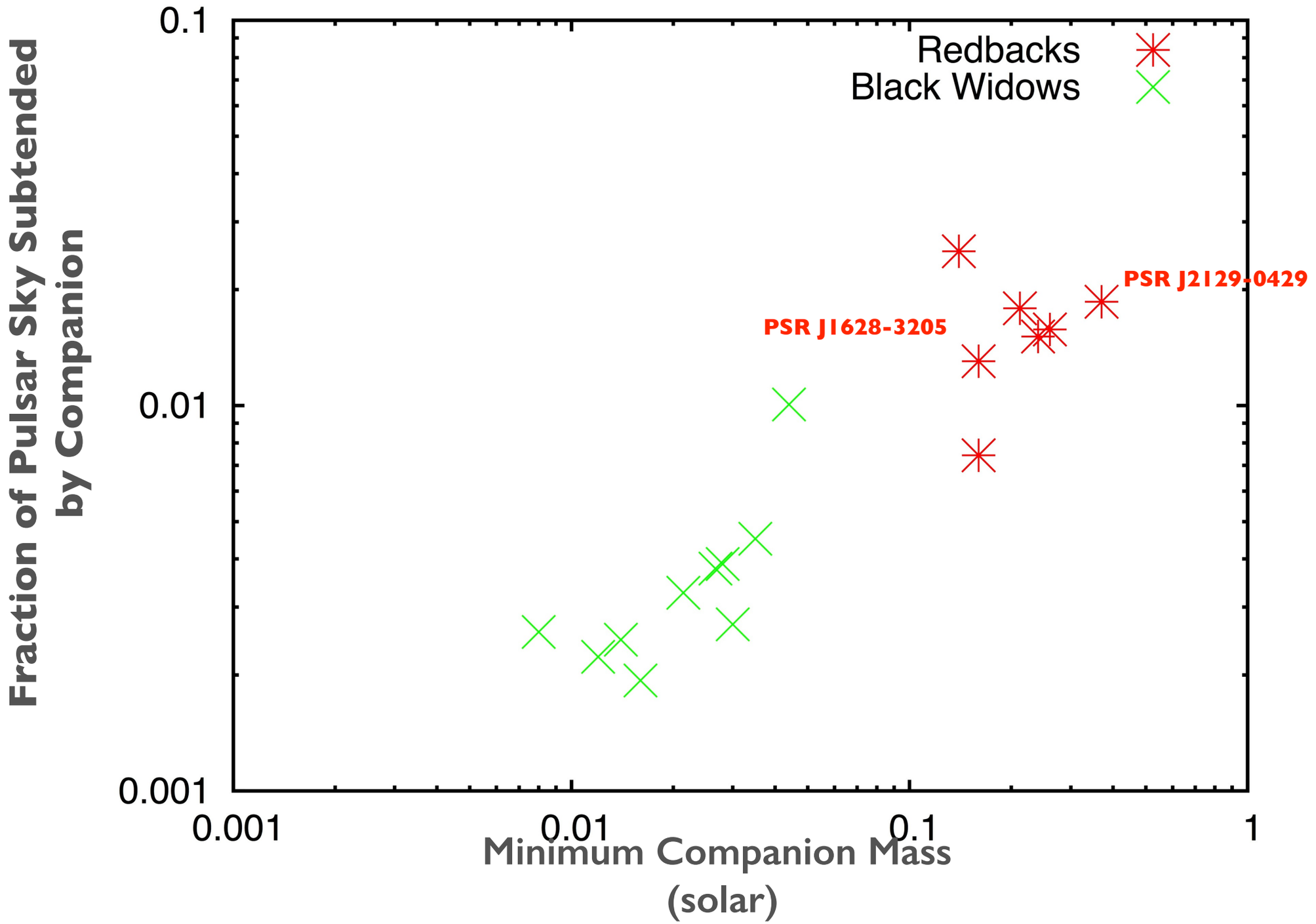
- 20 ks Chandra obs
- ~180 counts
- Power law component, probably blackbody as well
- $L_x \sim 2 \times 10^{31}$ erg
- Probably variable, need better statistics

Roberts et al. 2015

Black Widows and Redbacks
X-Ray Luminosity vs. Spin-Down Power

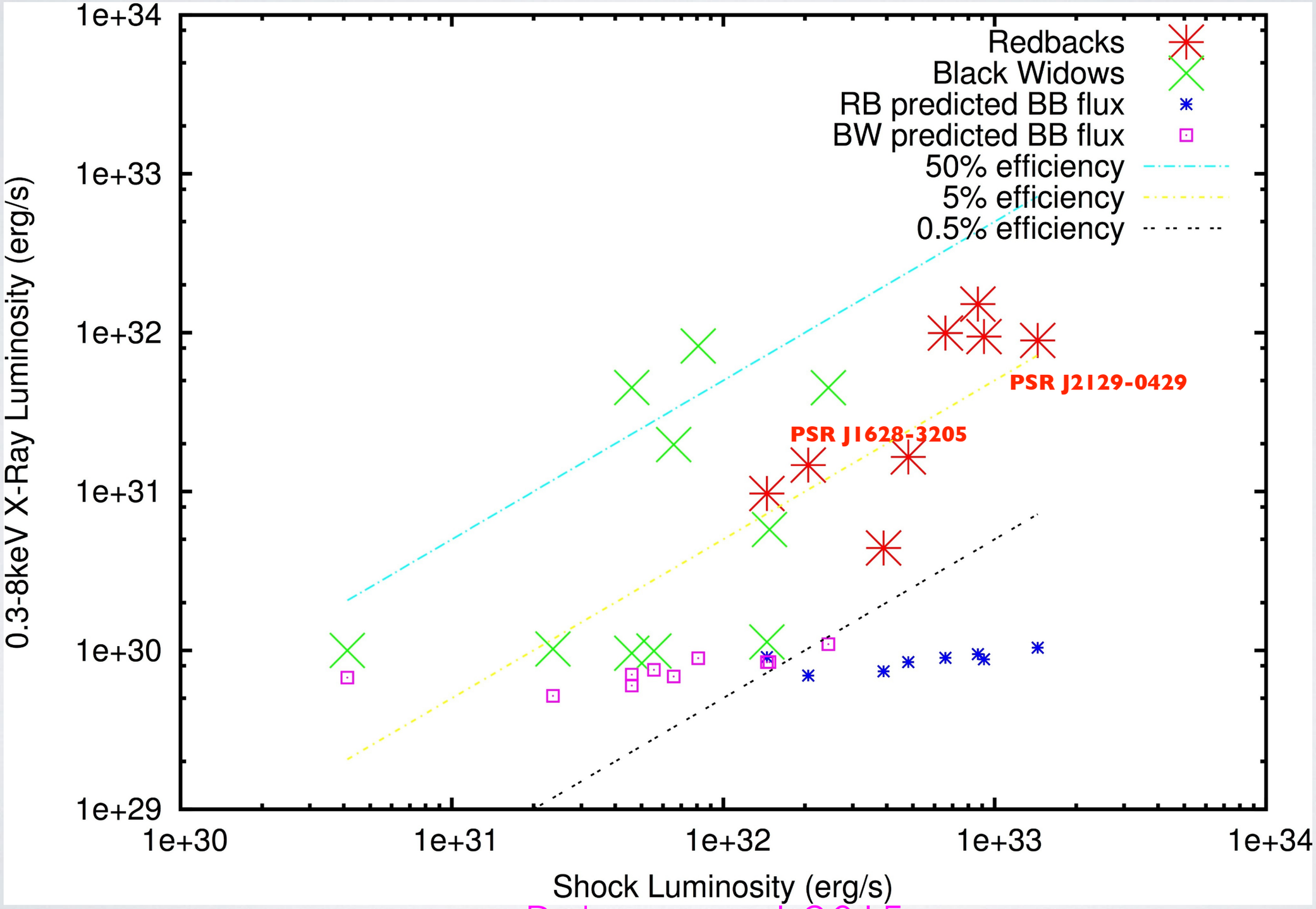


Black Widows and Redbacks
Minimum Companion Mass vs. Fraction of Sky



Black Widows and Redbacks
X-Ray Flux vs. Shock Flux (Assuming shock size ~ companion size)

If pulsar wind isotropic, conversion of wind energy into soft X-rays ~1-50%



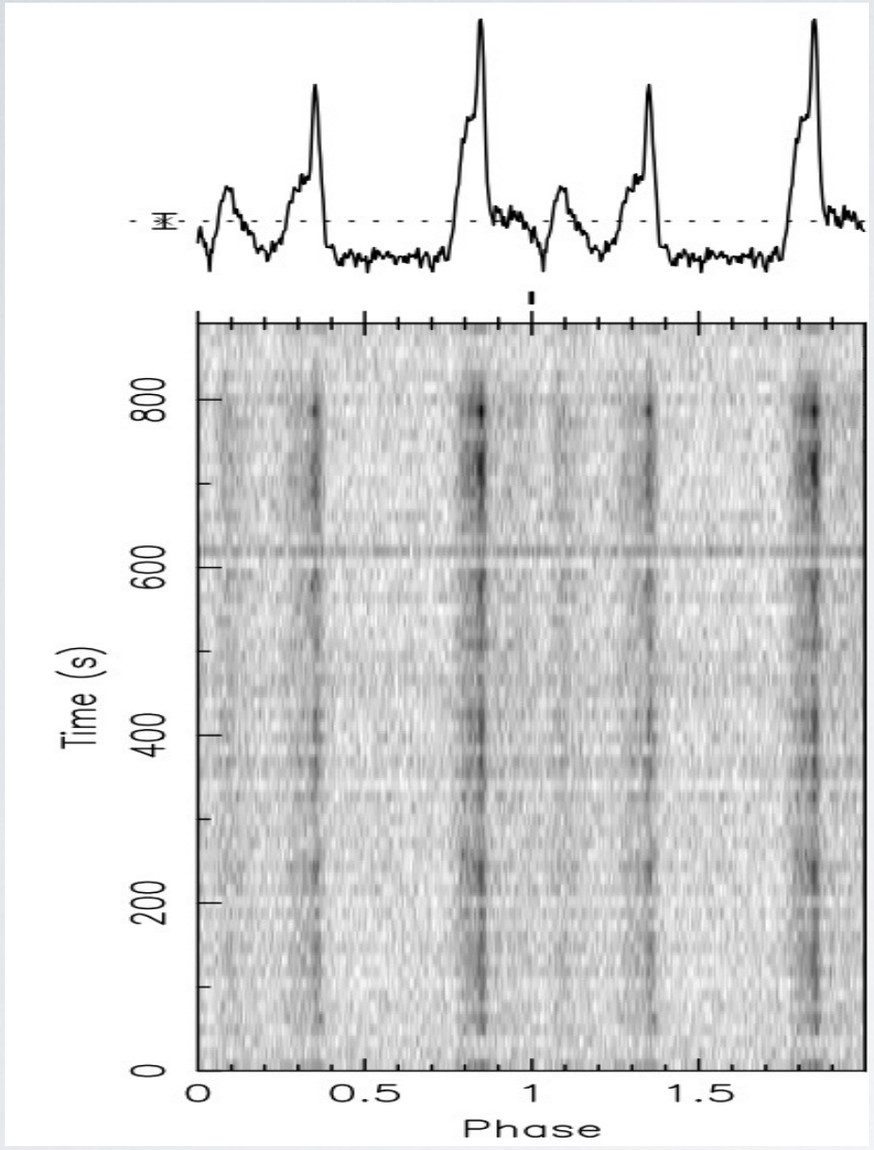
Roberts et al. 2015

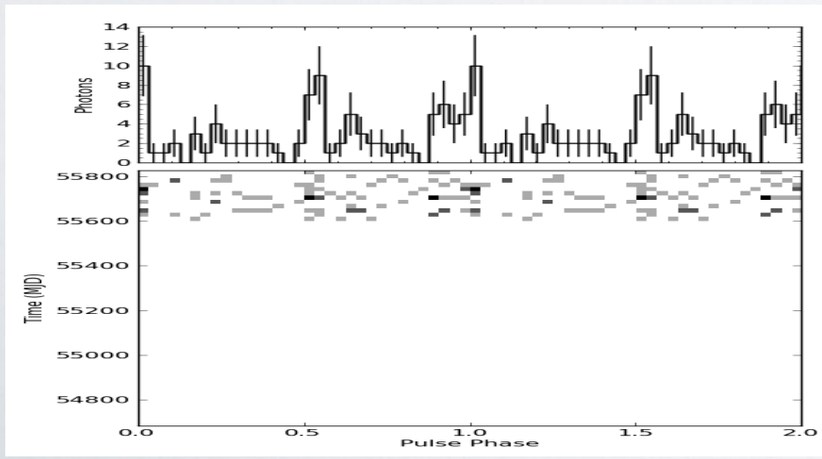
A Few Caveats

- MSP masses likely significantly greater than 1.4 solar, affecting Roche-lobe estimate of companion
- MSP radii possibly >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, most are not corrected, ***Need more timing and/or VLBI!***
- Some have inclination estimates from optical lightcurves, some don't. ***Need more optical fits!***
- DM distances very rough. ***Need more parallaxes!***

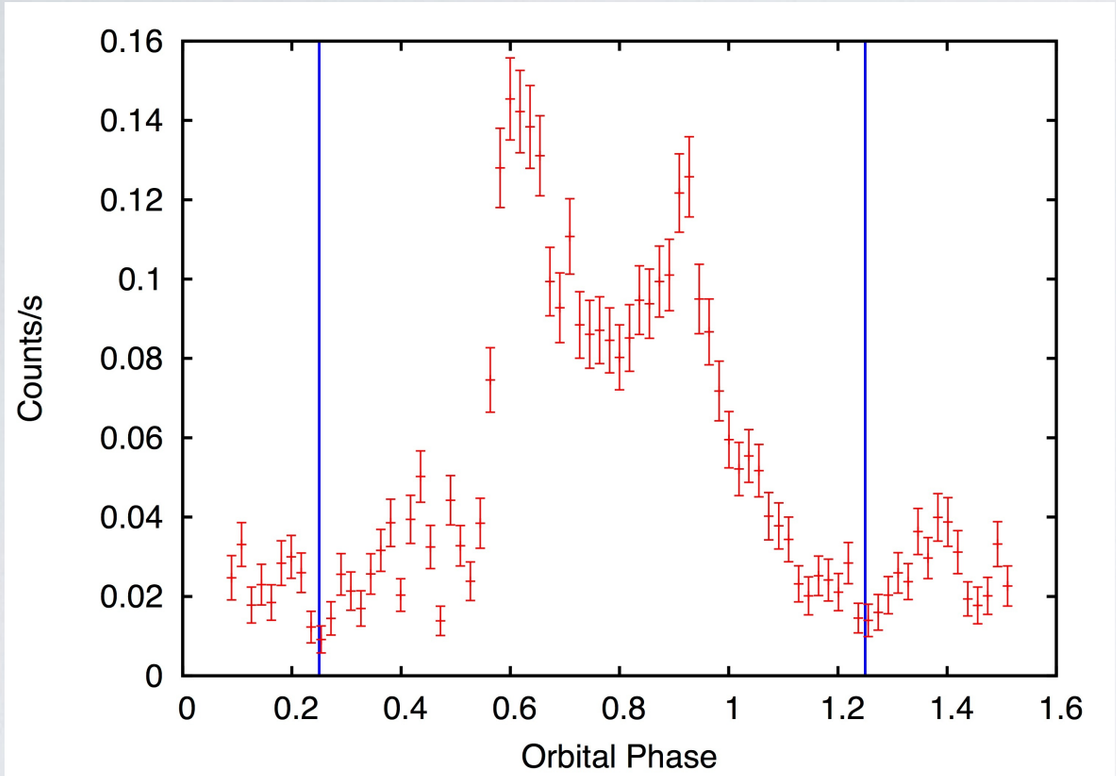
PSR J2129-0429: A YOUNG REDBACK

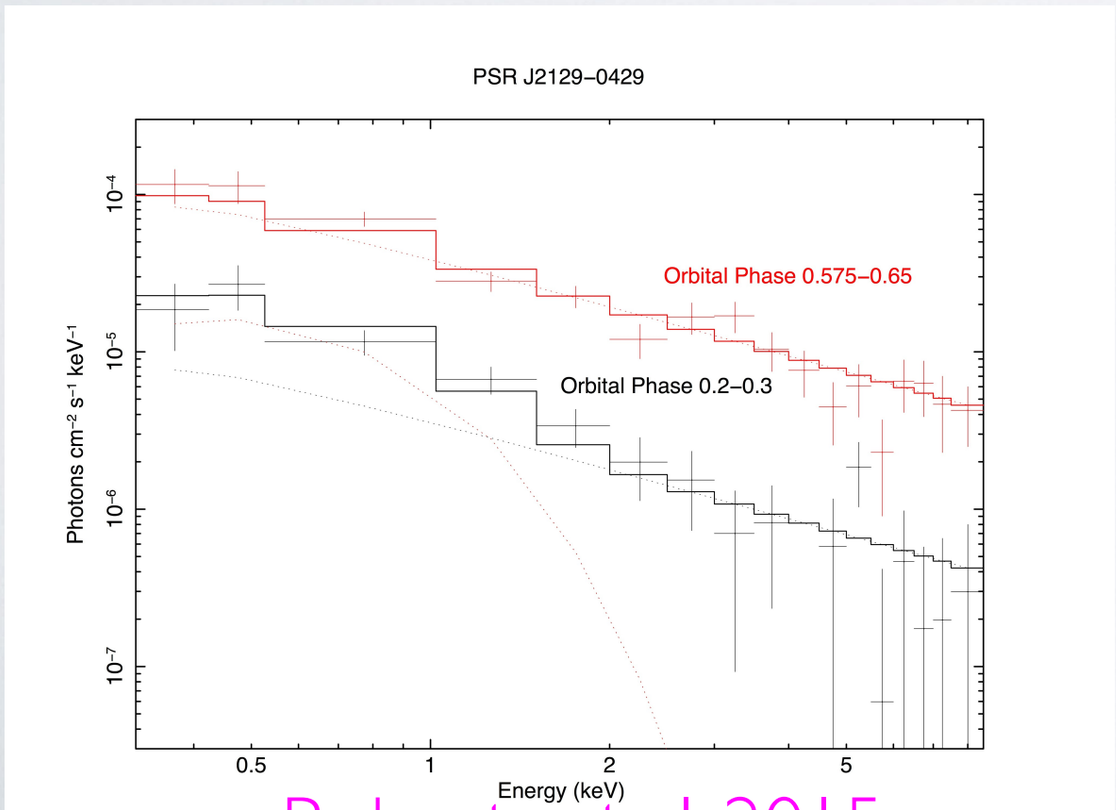




- **7.61 ms period**
- **15.2 hr orbit**
- Orbital separation ~ 8000 light cylinder radii
- **Minimum M_C ~ 0.37 M_{sol}**
- Shows extensive radio eclipses
- E ~ 3.9 x 10^{34} erg
- **D_{NE2001} ~ 0.9 kpc**
- Bright UV Counterpart
- Filling Fraction ~95%, pulsar mass > 1.7 solar, **Highly Inclined**(Bellm et al. 2013)
- **B ~ 1.6 X 10^9 G**
- **LARGE Orbital Period Changes (Orbital energy ~ 10**
- **Pulsations dominate γ-ray**

PSR J2129-0429: A HIGH MAGNETIC FIELD REDBACK

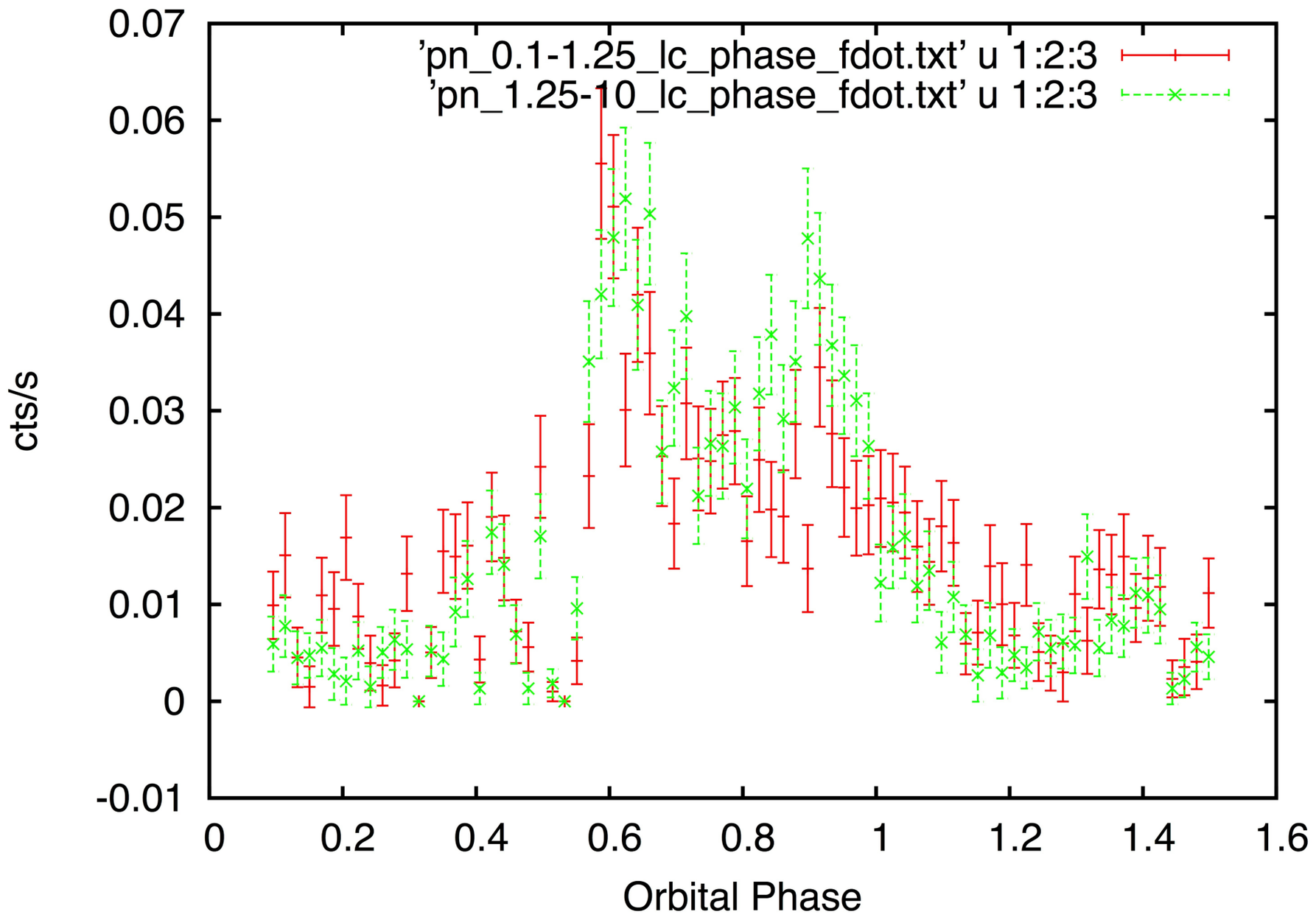




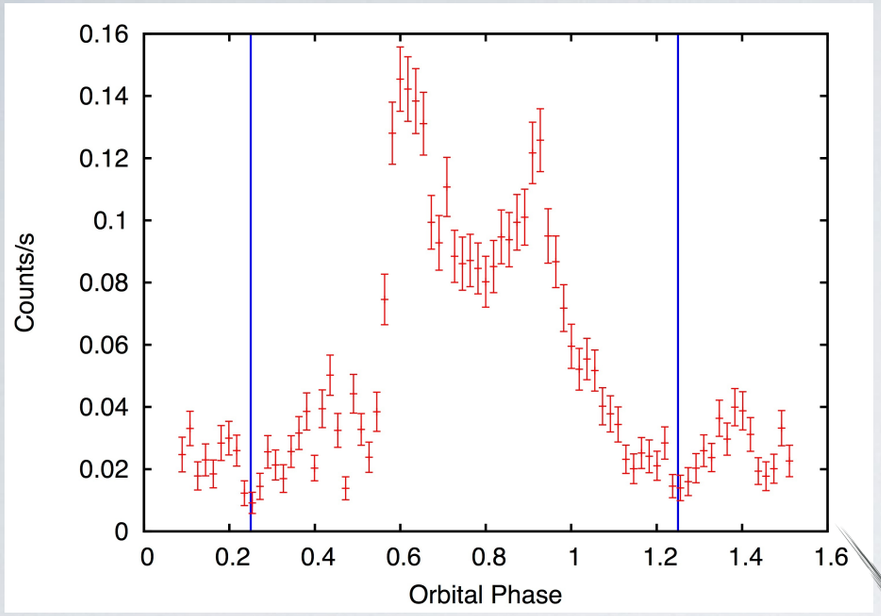
Roberts et al. 2015

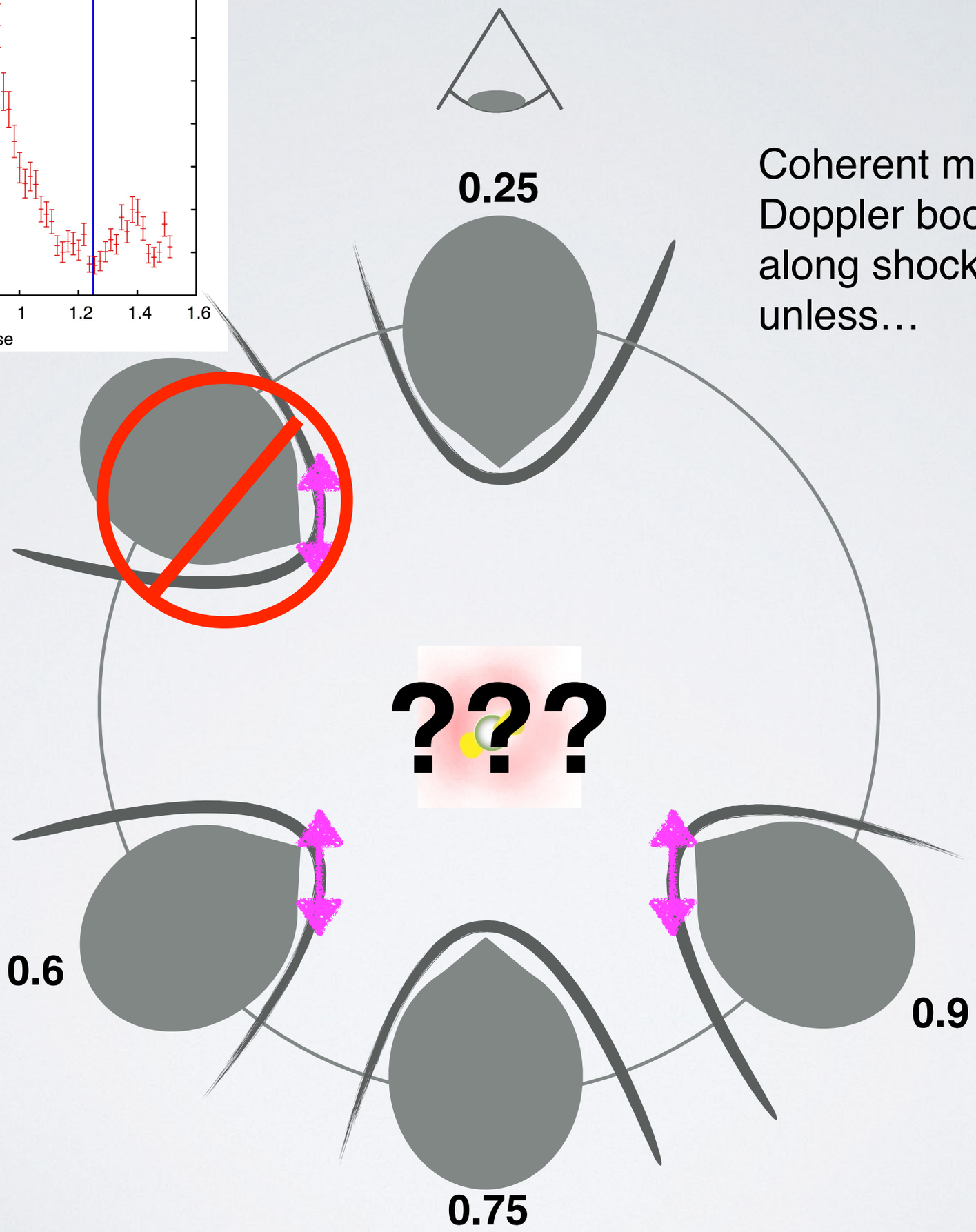
- 70 ks XMM-Newton observation (with no background flares!!!)
- Roughly constant blackbody component, typical of MSP surface emission ($L_{bb} \sim 10^{30}$ erg/s)
- Very hard ($\Gamma \sim 1.0$) power-law component varies by factor of 11
- Spectral index may change with orbital phase

PSR J2129-0429: A HIGH MAGNETIC FIELD REDBACK

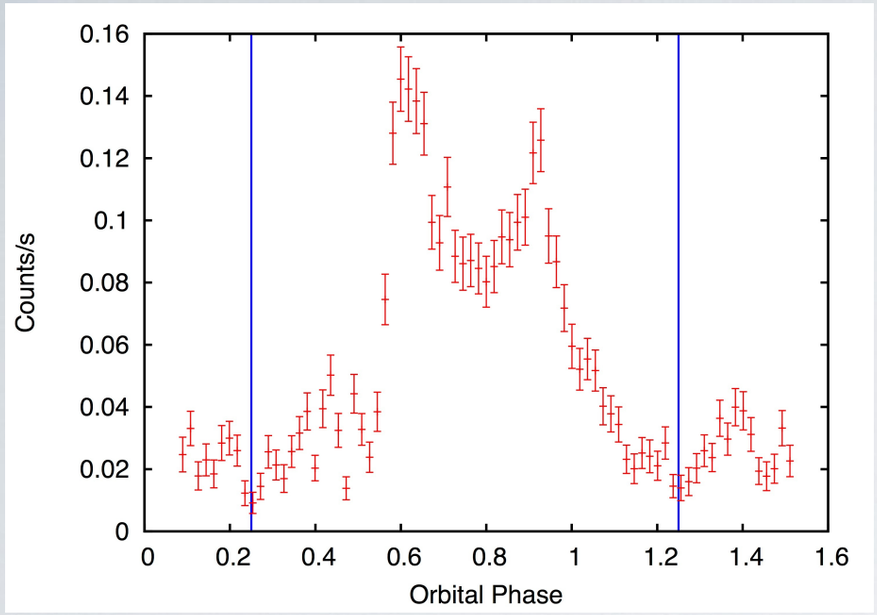


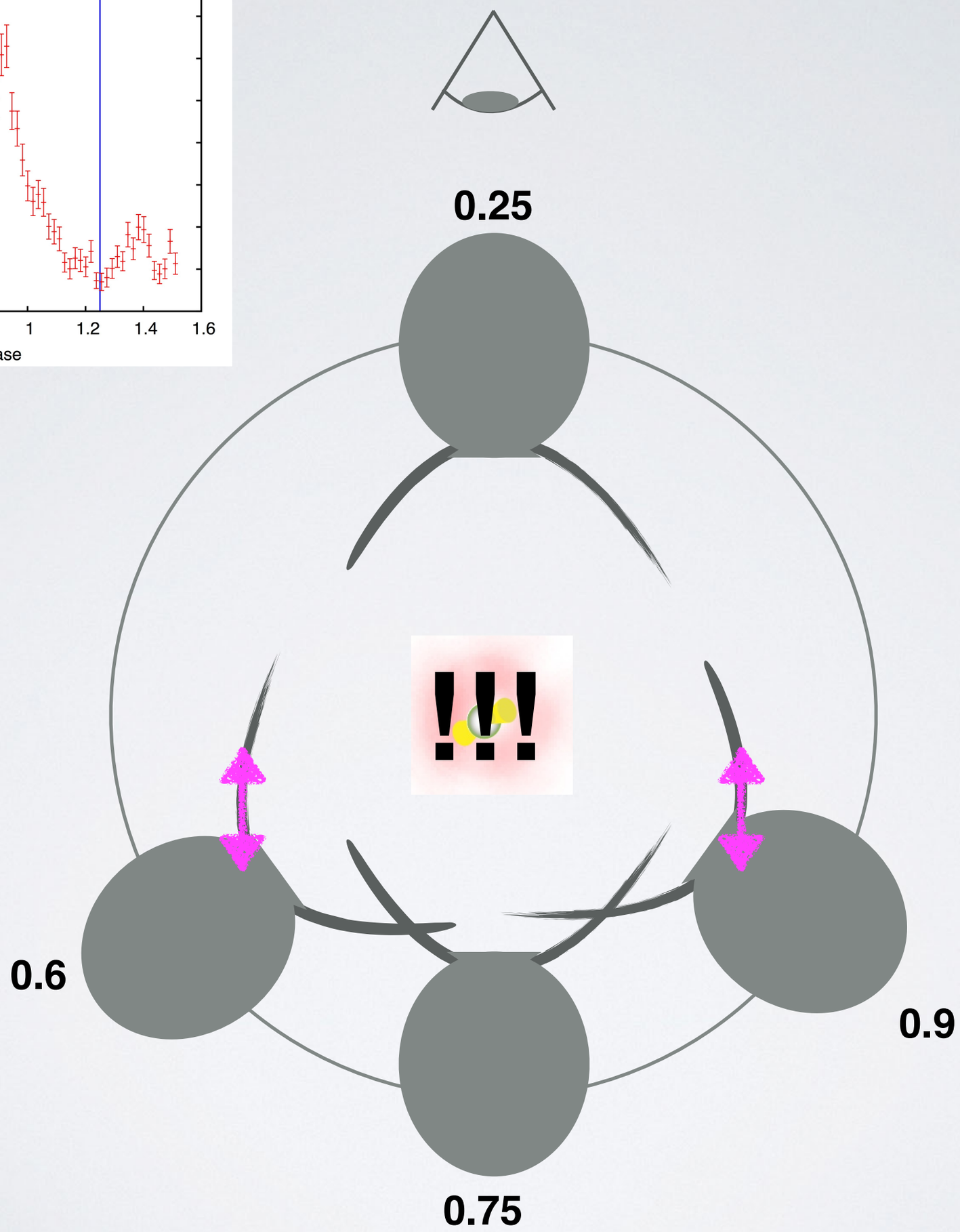
Roberts et al. 2015





Coherent magnetic field and
Doppler boosting
along shock doesn't work
unless…


Counts/s
Orbital Phase
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6


0.25
!!!
0.6
0.9
0.75

CAN WE EXPLAIN THE HIGH X-RAY EFFICIENCIES AND THE DOUBLE PEAKED LIGHT CURVES BY INVOKING THE COMPANION'S MAGNETIC FIELD?

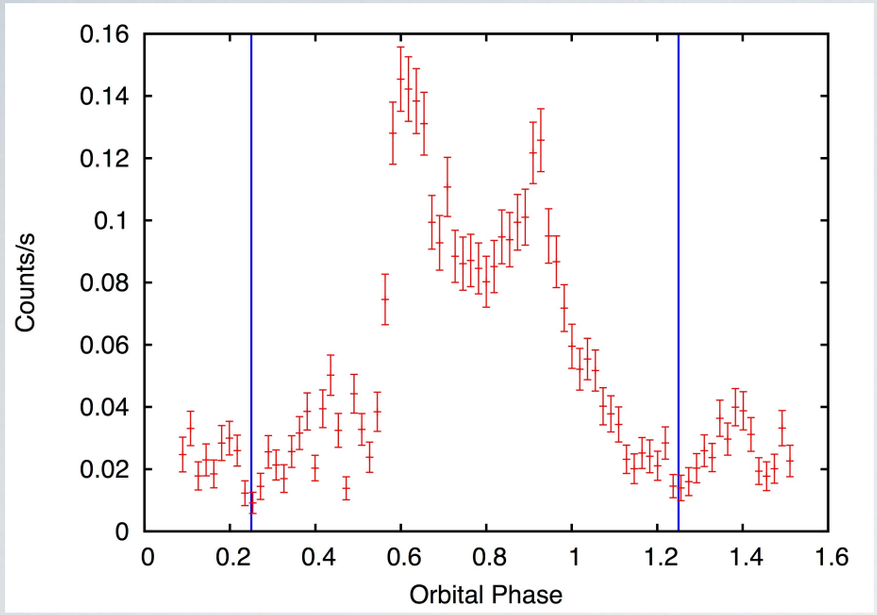
- The magnetic field required for pressure balance of the wind at the stellar surface is ~7G in the PSR J2129-0429 system

- Rapidly rotating (P < 1day) M stars have been observed to have magnetic fields of hundreds or even thousands of Gauss (Morin

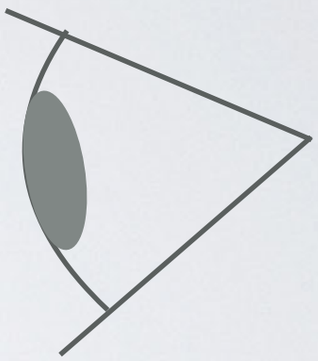
- A hundred Gauss surface dipole field corresponds to 7 G at ~1.5 stellar radii

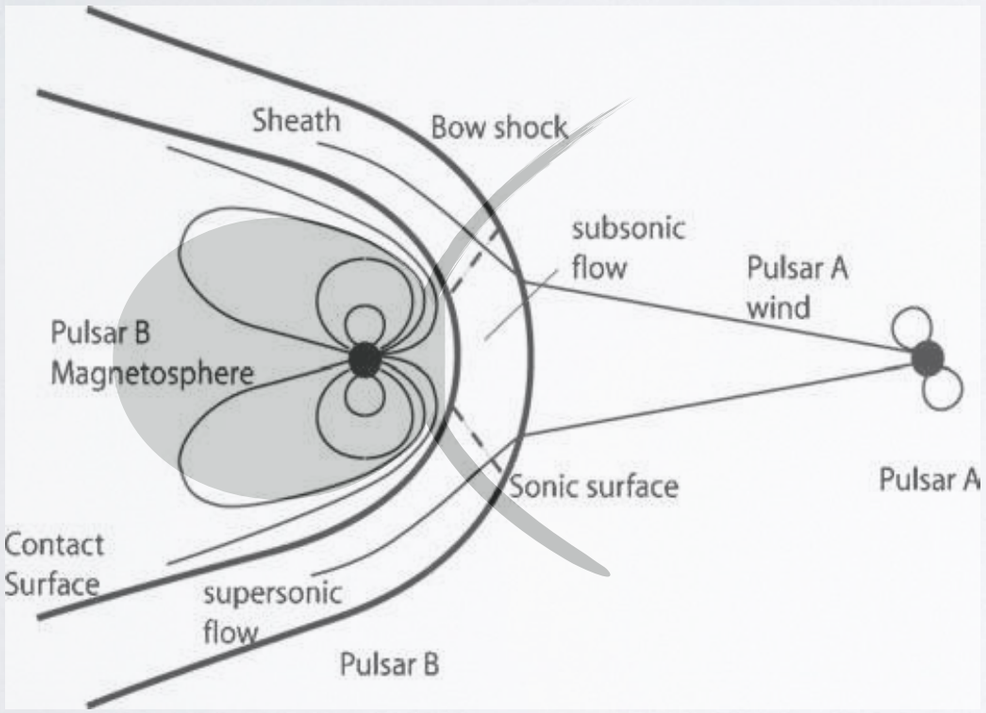
- X-Ray synchrotron luminosity proportional to B^2

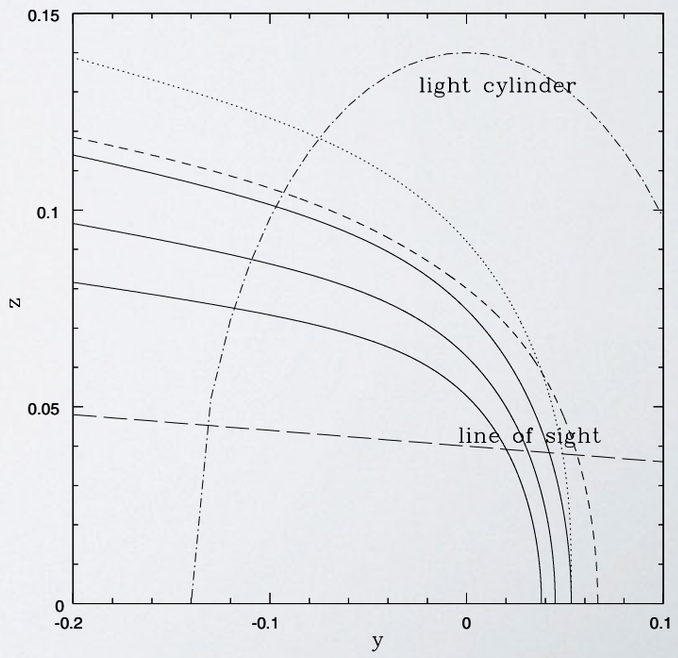
- Pulsar wind may have $\sin^2 \theta$ dependence



CAN WE EXPLAIN THE HIGH X-RAY EFFICIENCIES AND HARD SPECTRUM BY INVOKING A SHOCK AGAINST THE COMPANION'S MAGNETIC FIELD?

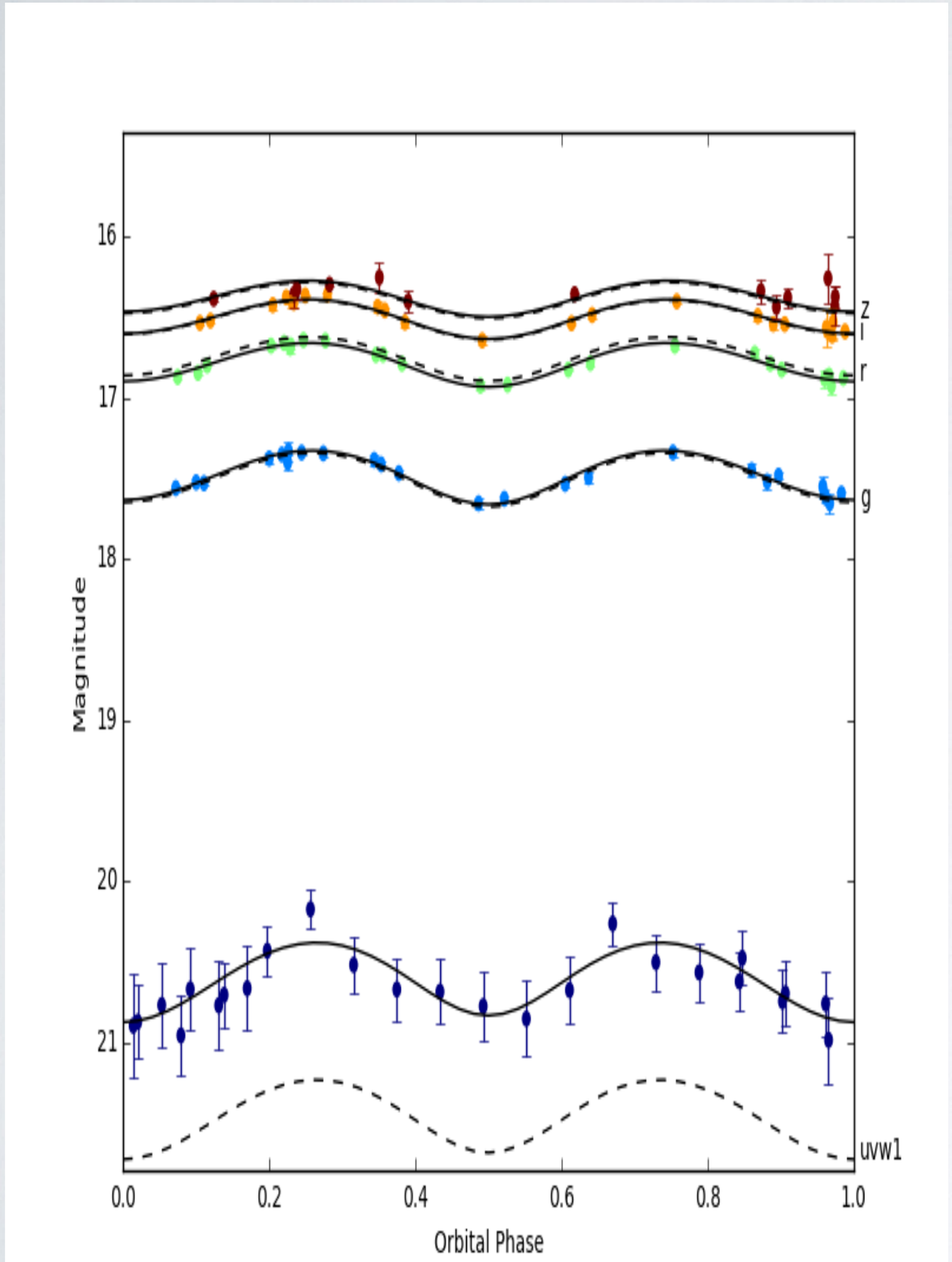






Figures adapted from Lyutikov 2004

OPTICAL PHOTOMETRY OF PSR J2129-0429



Roberts et al. 2015

- 25, 100s observations in g',r',i' and z' taken over a period of 1 month with LCOGT
- uvw1 data from XMM-Newton optical monitor
- Light curve modeled using ICARUS (R. Breton)
- T~5400K , only mild irradiation (1650K)
- excess UV emission of ~1 mag may indicate significant magnetic field activity

Thoughts and wild Speculations about PSR J2129-0429 (and Spiders in general??)

- Shocks likely not bigger than companion, otherwise why such large orbital variation?
- Emission harder than PWN shock emission, and much more efficient
- Is wind concentrated in orbital plane (low magnetic inclination angle)?
- Does magnetic field of companion confine wind?
- Does magnetic field of companion act as a "sail" redirecting wind towards companion to heat hot spots on companion (Eichler 1992)?
- Can Faraday rotation be used to probe companion's magnetic field?
- Do orbital variation result from tidal distortions of companion? Is tidal heating important enough to expand the radius of the companion enough to initiate mass transfer (Applegate and Shaham 1994)?
- Can angular momentum be transferred via the pulsar wind interacting with companion's magnetic field rather than mass loss from the system?
- Is the eclipsing material intrabinary or in magnetotail of companion?
- Can accretion phase pulsations not be accretion powered?
- Can we learn anything interesting from geometric eclipses by companion?

What to do?

- Long term, regular, high precision timing!
- Detailed eclipse studies including Faraday rotation searches
- More studies of unpulsed radio emission?
- More X-ray observations above 10 keV
- LOTS more X-ray data
- Long term monitoring of optical flux/colors
- Shock models which include non-isotropic pulsar winds and companion magnetic fields
- Ditto for accretion mode models— plus consideration of inclined magnetic fields for propellor models and striped winds for wind bubbles only a few light cylinder radii in diameter