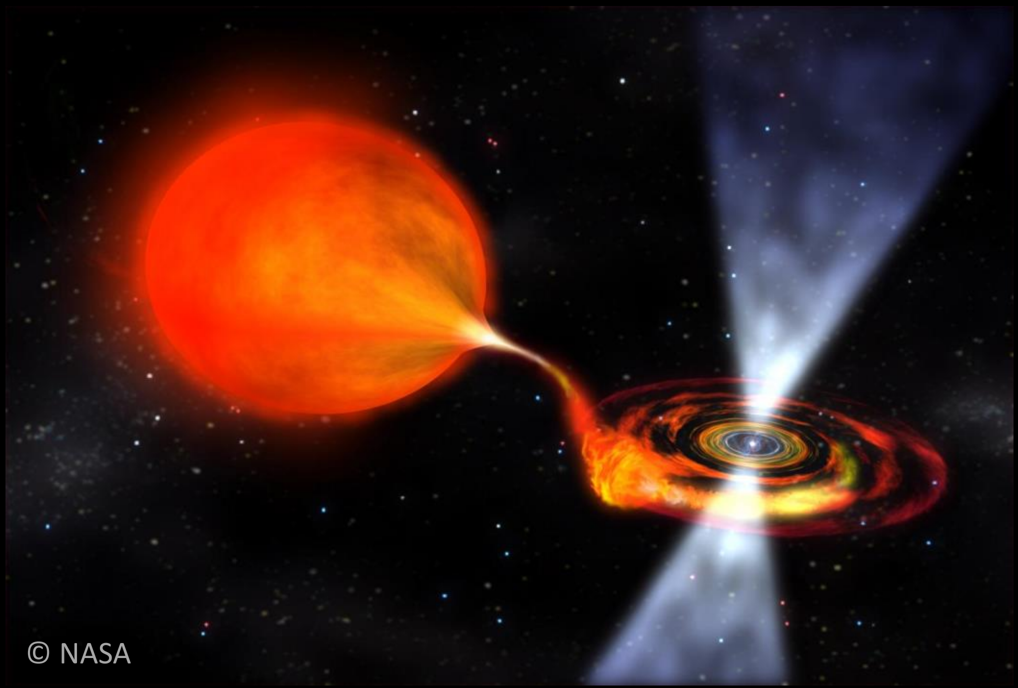
Tracking the Spin Period Evolution of Accretion-Powered Pulsars



family given
Hu Chin-Ping (胡 欽評, フー チンピン)
京都大学 理学研究科 宇宙物理学教室
JSPS International Research Fellow

Accretion Power

- Energy source of an accreting compact object: gravitational energy of accreting matter.
  - For a mass accretion rate $\dot{m}$, the available power is

$$P = \eta \dot{m} c^2$$

  - Accretion efficiency $\eta \sim 0.1$ for an NS and $\eta \sim 0.05 - 0.5$ for a BH.
    - Thin disk
  - Much higher than nuclear fusion $\eta \sim 10^{-4}$
  - Emit strong X-rays

Accreting Neutron Stars

Low-Mass X-ray Binaries
$M_c \lesssim 1 M_\odot$

Roche-Lobe Overflow
- Main Sequence
- White Dwarf
- X-ray bursters
- Accreting Pulsars
- Millisecond pulsars

Wind Fed
- Red Giant
- Slow rotators

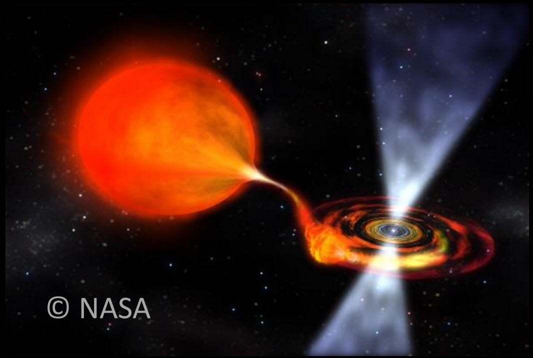
High-Mass X-ray Binaries
$M_c \gtrsim 10 M_\odot$

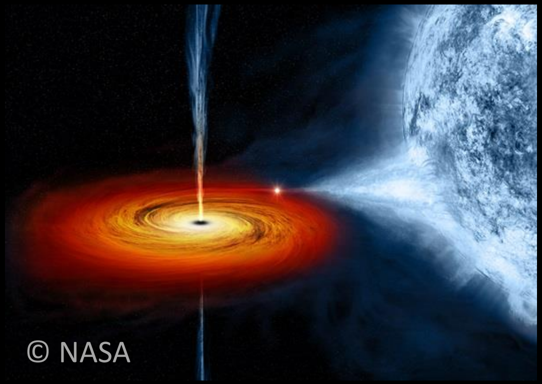
Roche-Lobe Overflow
- Supergiant
- $P \lesssim 10s$
- Bright

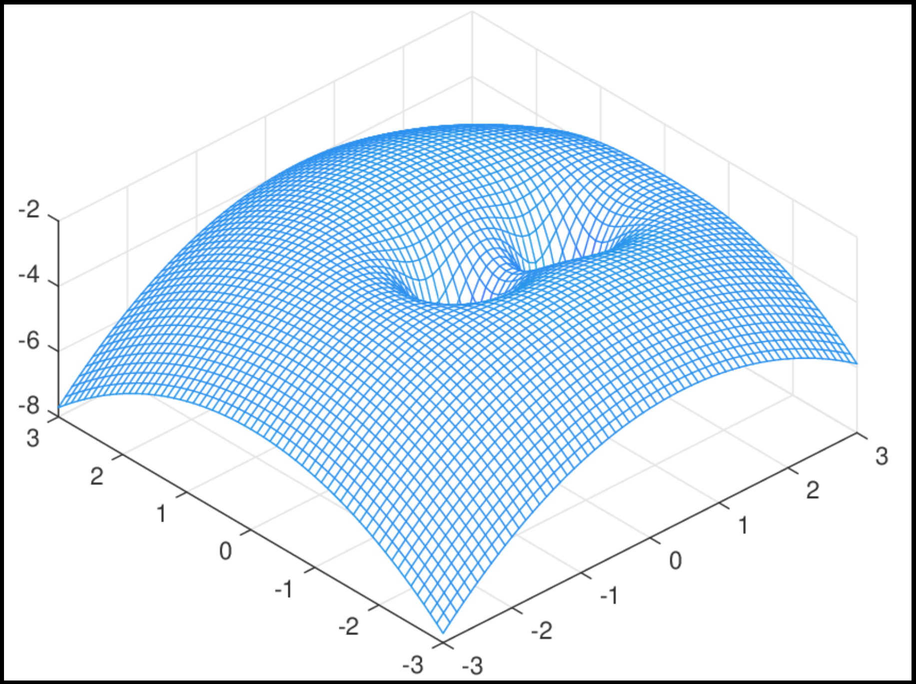
Wind Fed
- Supergiant
- Slow rotators
- Faint
- Direct-wind vs disk-wind

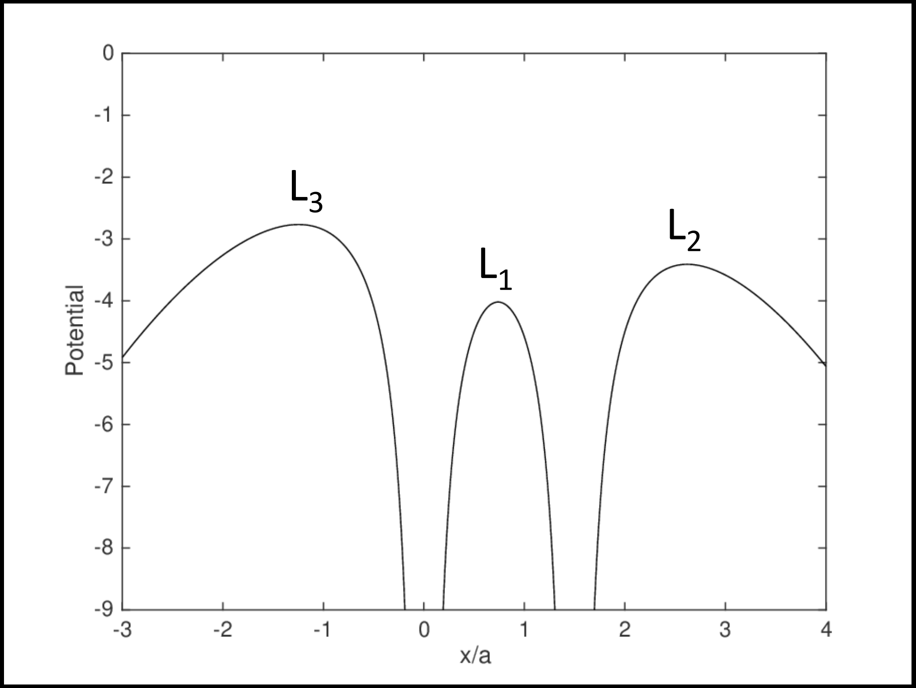
Be X-ray Binaries
- Be stars
- Equatorial mass outflow
- Regular outbursts

Roche-Lobe Overflow

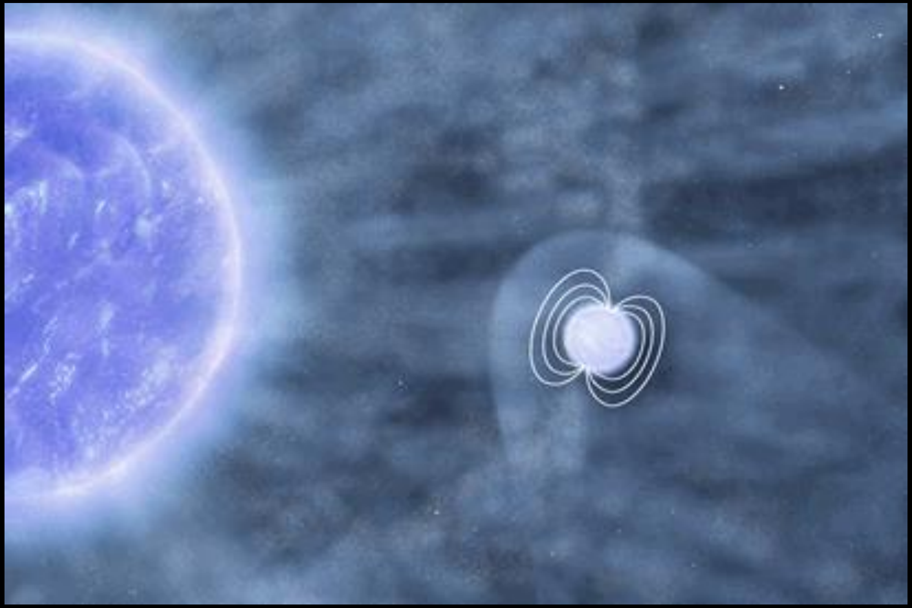








Wind Accretion



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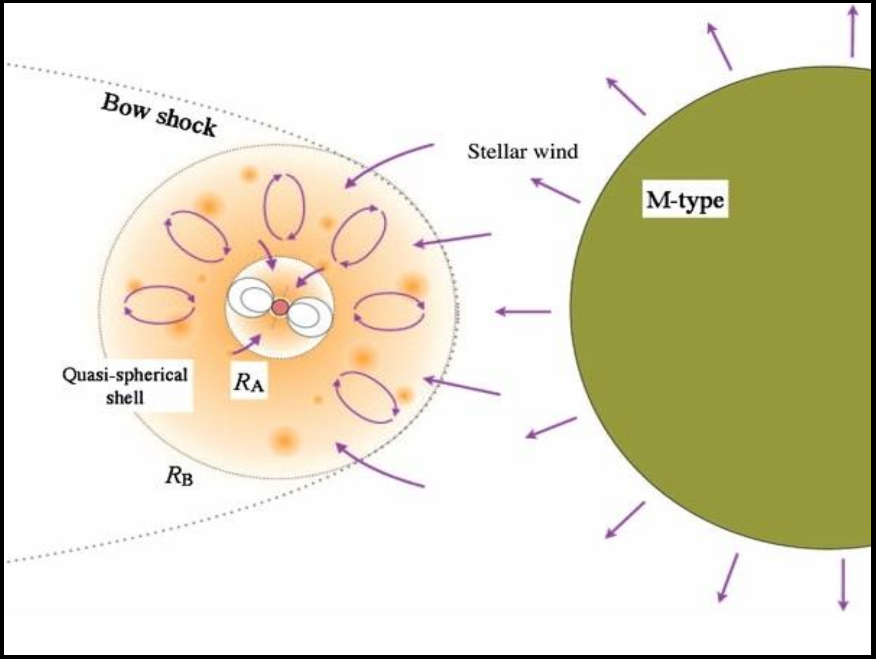
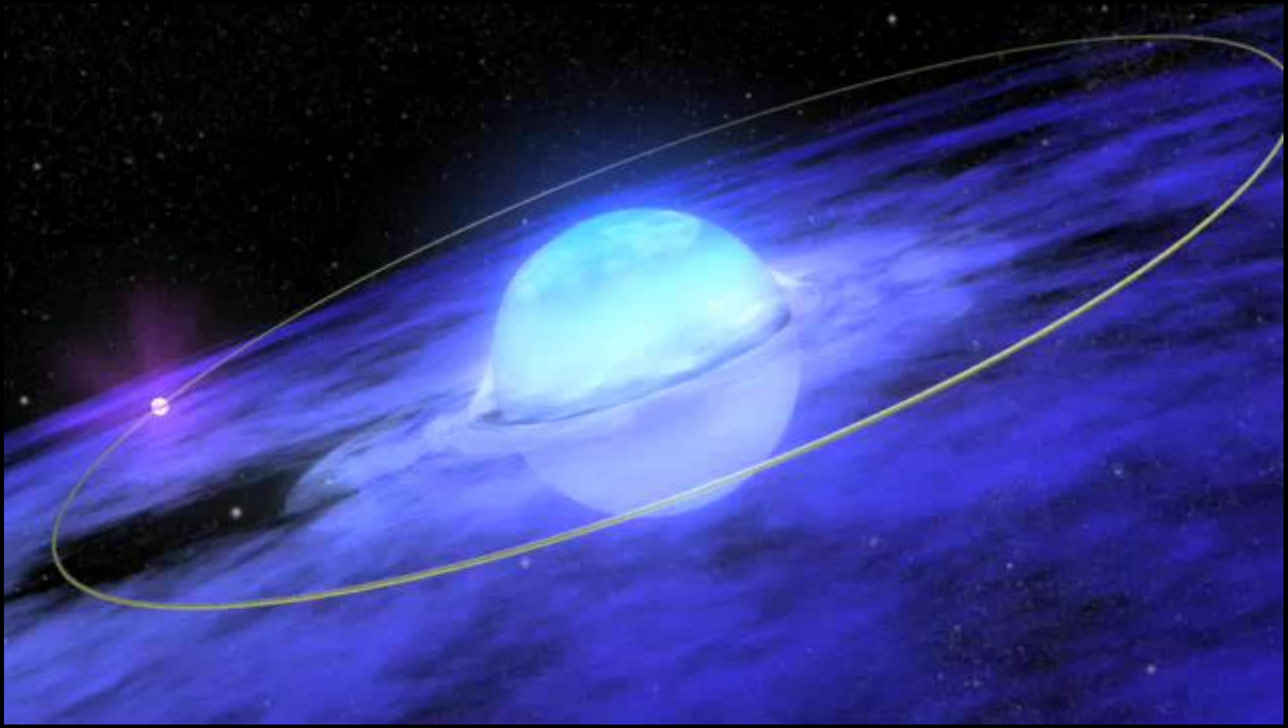
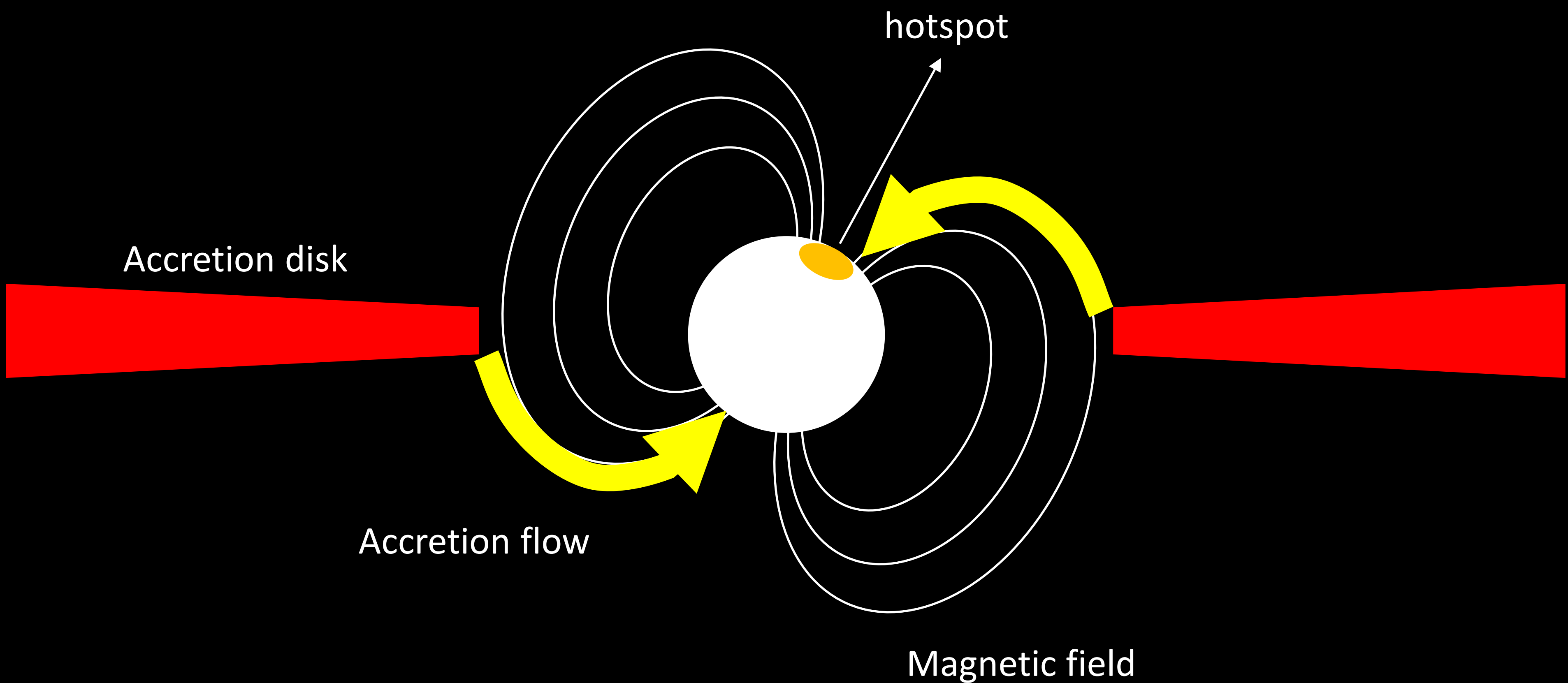


Enoto et al. (2014)

Be X-ray Binary

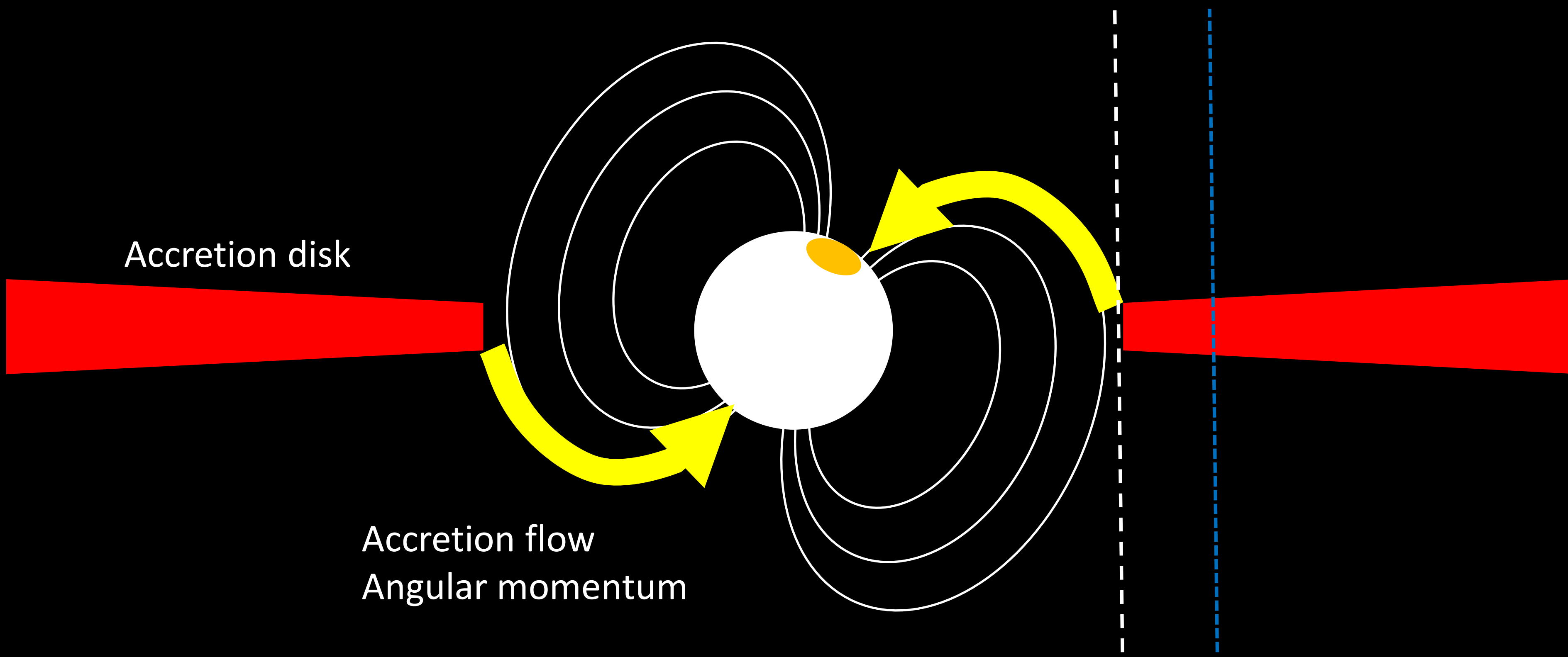


Accretion-Powered Pulsar



Spin-up the NS

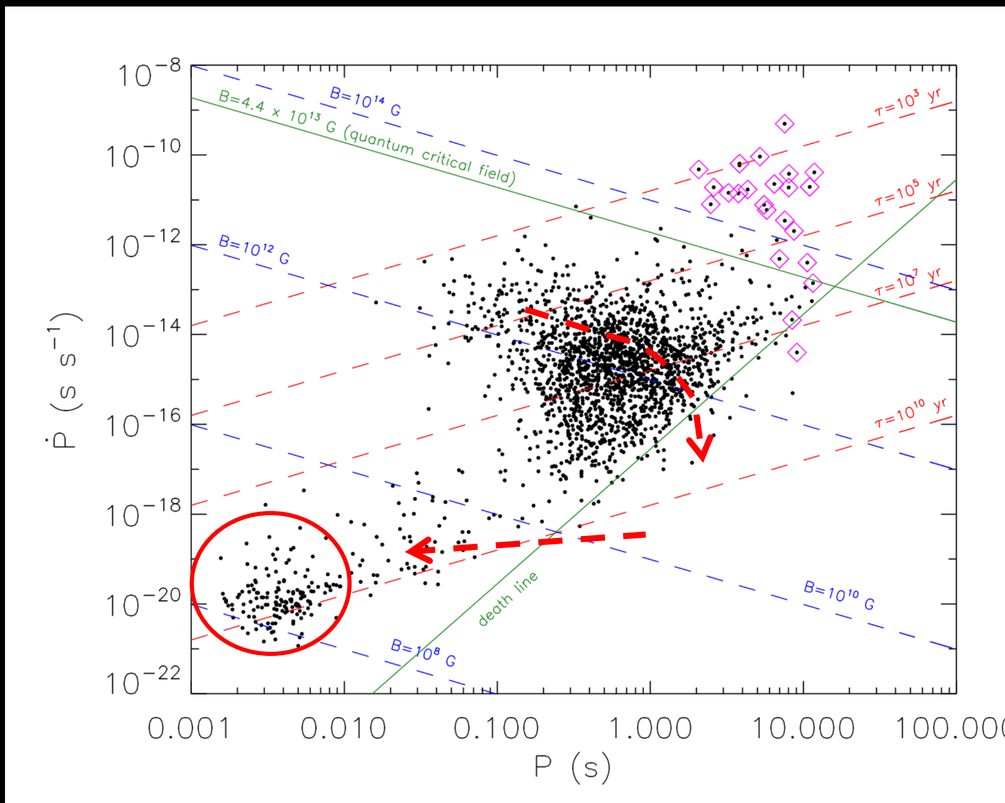
$$r_m = \xi r_A = \xi \left(\frac{\mu^4}{2GM\dot{M}^2} \right)^{1/7}$$



Accretion Torque $N_0 = \dot{M}\sqrt{GMr_{in}}$

$$r_{co} = \left(\frac{GMP_{spin}^2}{4\pi^2} \right)^{1/3}$$

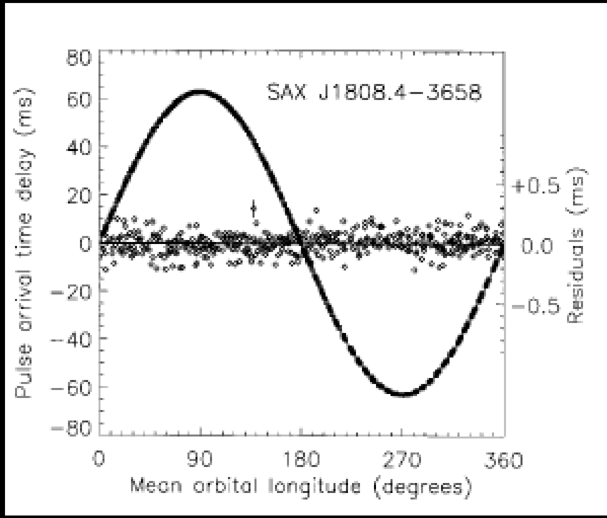
Millisecond Pulsar

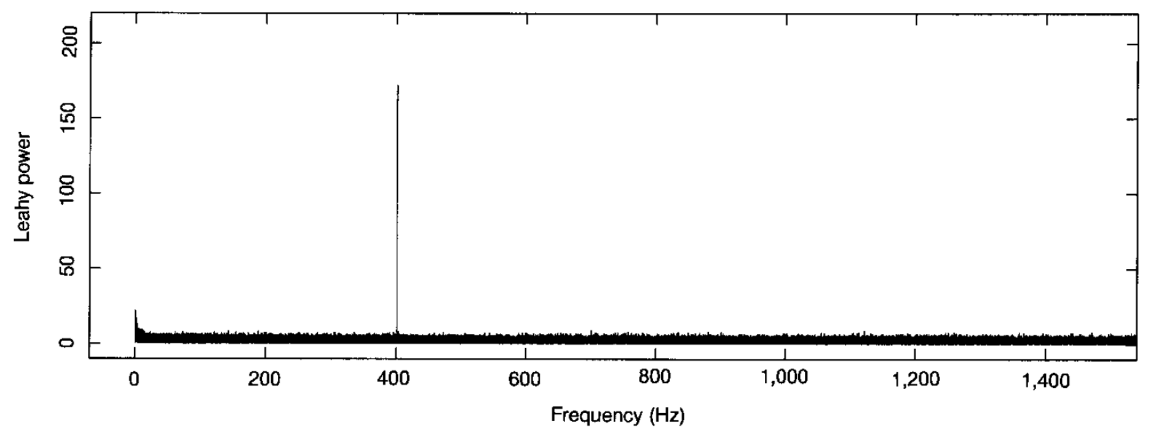


Recycled Pulsar

First MSP in LMXB

- Transient Source
- Discovered in 1996
- Pulsation discovered in 1998
- Spin = 2.5 ms
- Orbital period = 2hr





Wijnands & van der Klis (1998)

Transformers

- PSR J1023+0038
- IGR J18245-2452/PSR J1824–2452I
- XSS J12270-4859

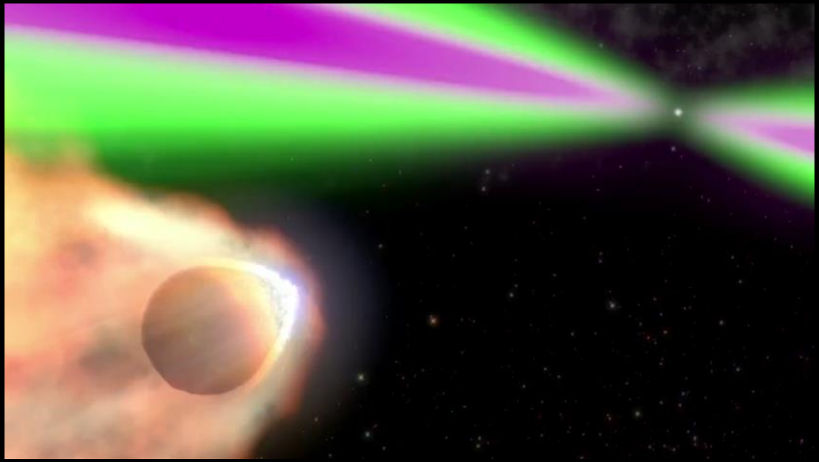
Table 1 | Spin and orbital parameters of IGR J18245–2452 and PSR J1824–2452I

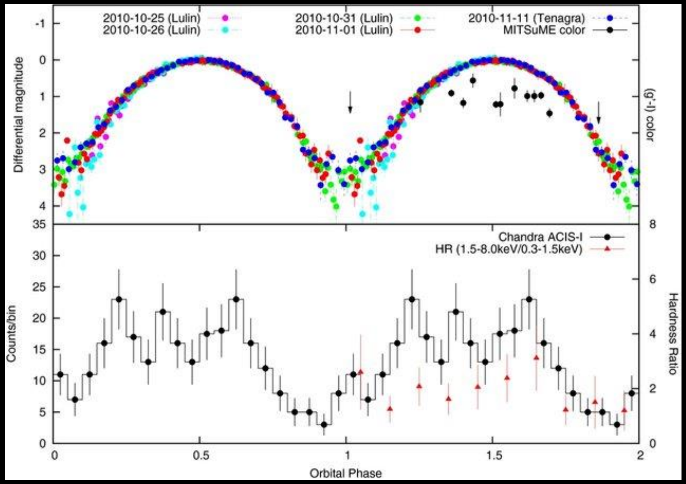
Parameter	IGR J18245–2452	PSR J1824–2452I
Right ascension (J2000)	18 h 24 min 32.53(4) s	
Declination (J2000)	–24° 52′ 08.6(6)″	
Reference epoch (MJD)	56386.0	
Spin period (ms)	3.931852642(2)	3.93185(1)
Spin period derivative	$<1.3 \times 10^{-17}$	
Root mean square of pulse time delays (ms)	0.1	
Orbital period (h)	11.025781(2)	11.0258(2)
Projected semimajor axis (light-seconds)	0.76591(1)	0.7658(1)
Epoch of zero mean anomaly (modified Julian date)	56395.216893(1)	
Eccentricity	$\leq 10^{-4}$	
Pulsar mass function ($M_{\odot}$)	$2.2831(1) \times 10^{-3}$	$2.282(1) \times 10^{-3}$
Minimum companion mass ($M_{\odot}$)	0.174(3)	0.17(1)
Median companion mass ($M_{\odot}$)	0.204(3)	0.20(1)

Papitto et al. (2013)

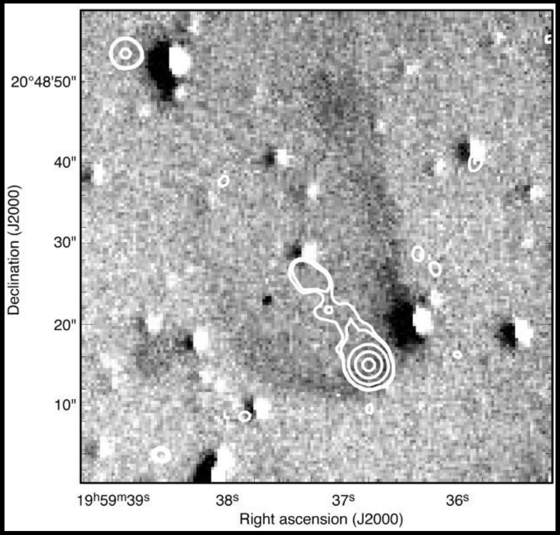
Black Widows & Redbacks

- Black Widows: $\mathrm{M_c} < 0.1\, M_{\odot}$
- Redbacks: $M_c \sim 0.2 - 0.4 M_{\odot}$
- Intra-binary shock
- Heating/evaporation





Kong et al. (2012)



Stappers et al. (2003)

Search for Gamma-ray MSPs

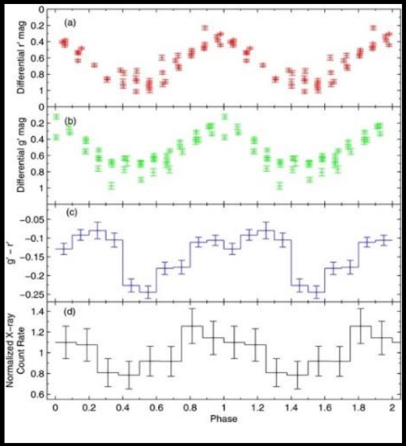
Fermi Gamma-ray source catalog

Spectral Curvature, Variability, …

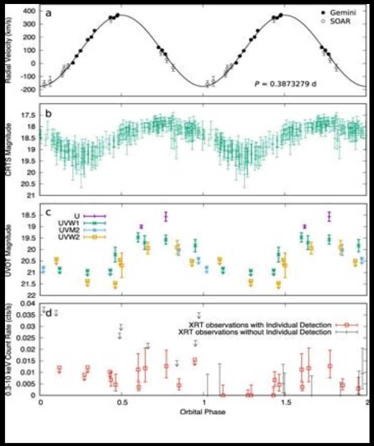
Millisecond Pulsar Candidates

Optical & X-ray orbital variability?

Search for pulsations



Kong et al. (2013)



Li et al. (2018)

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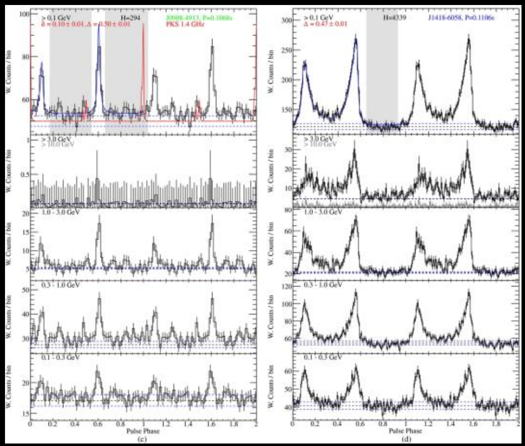
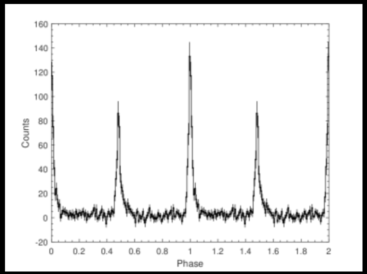
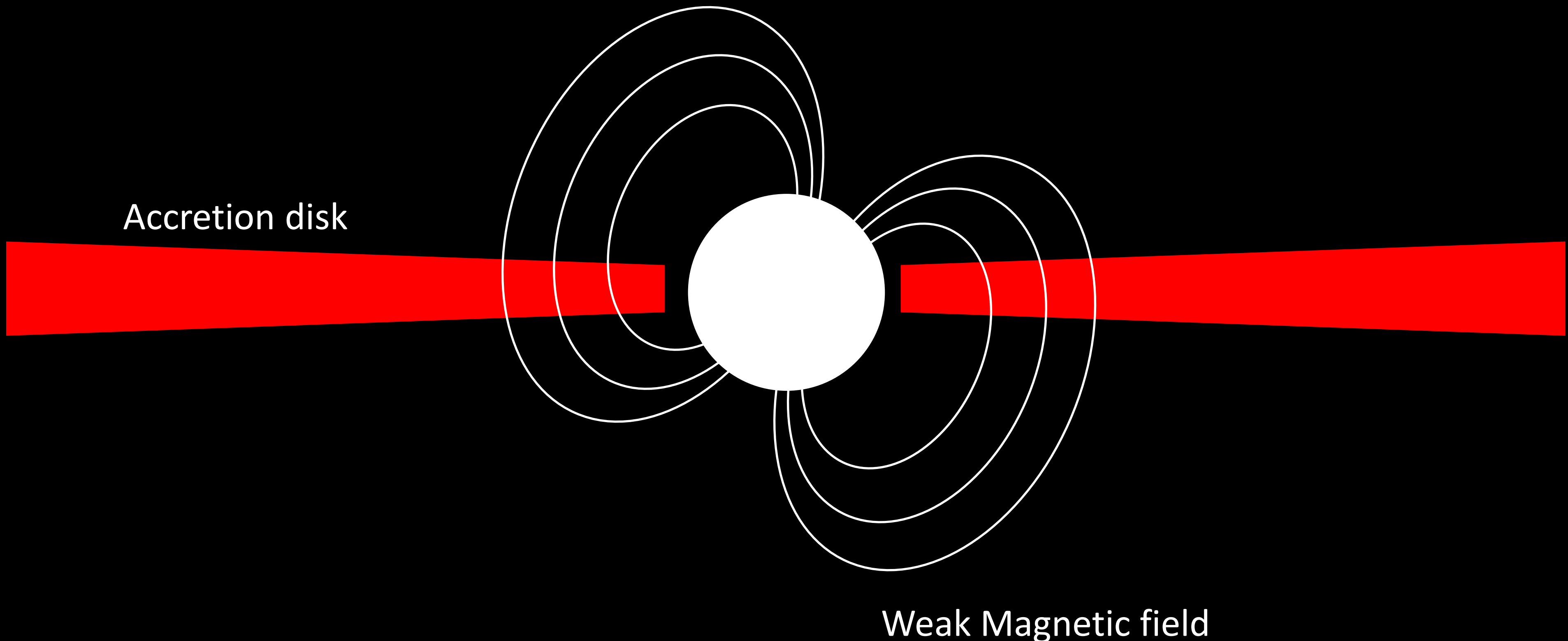


Abdo et al. (2013)

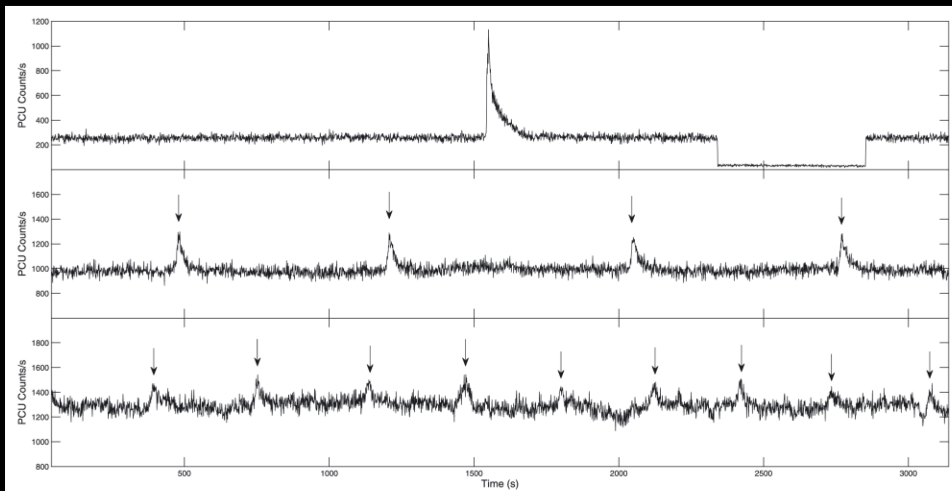


Limyansky et al. in prep

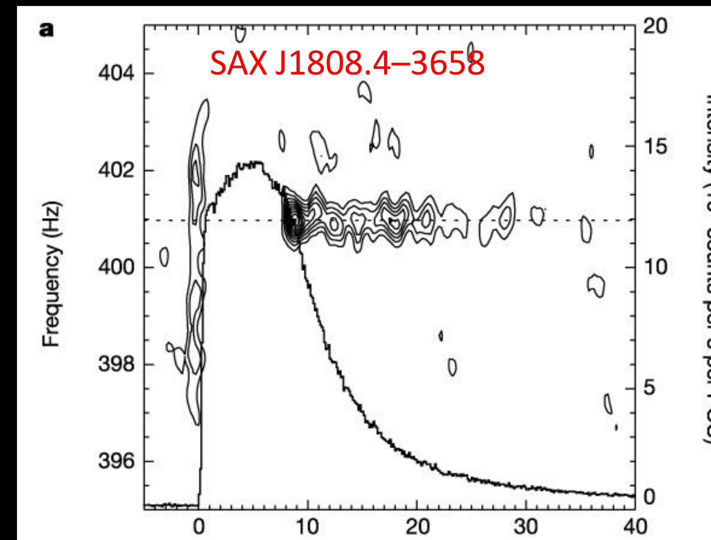
Extremely Weak Field



X-ray Burst & Burst QPO

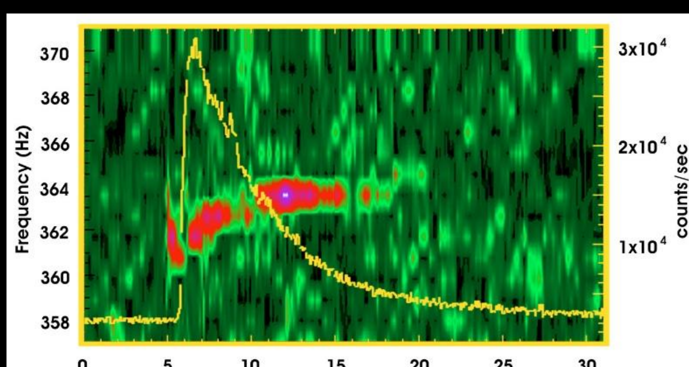


Motta et al. (2011)



Chakrabarty et al. (2003)

Nuclear Powered Pulsar



Strohmayer & Markwardt (1999)

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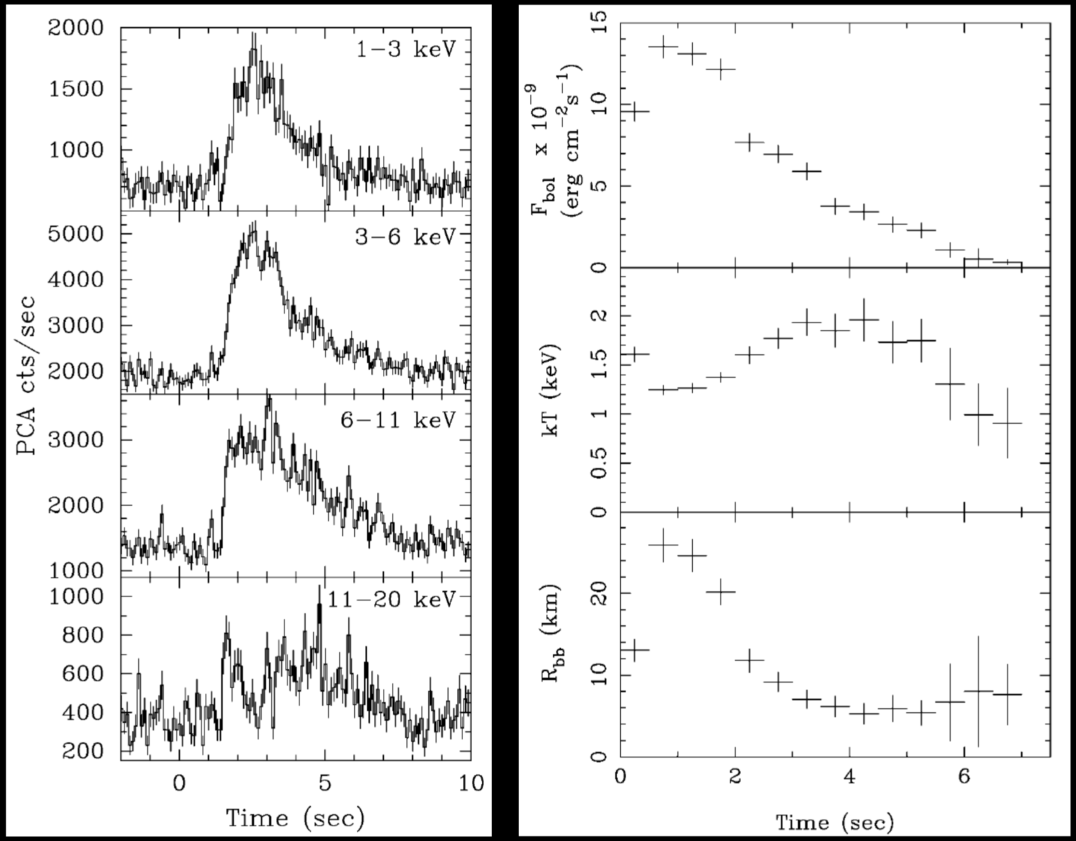
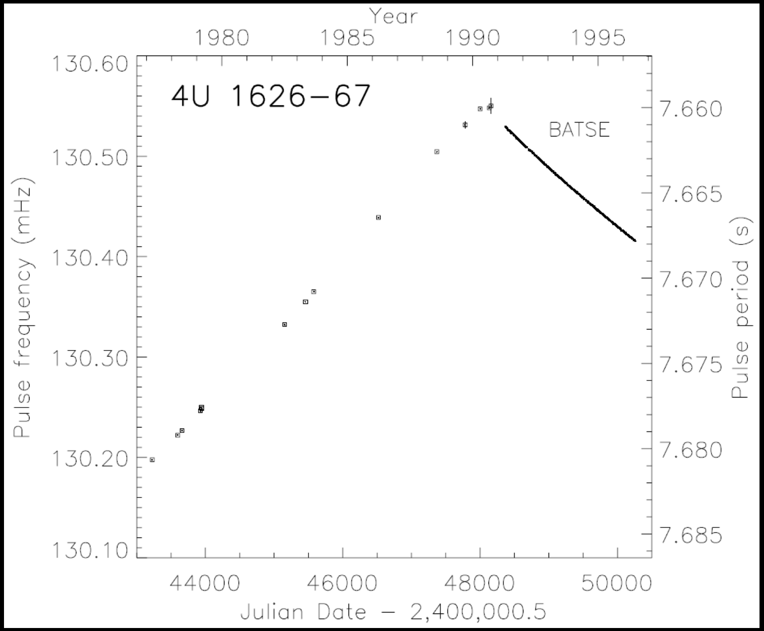
Photospheric Radius Expansion

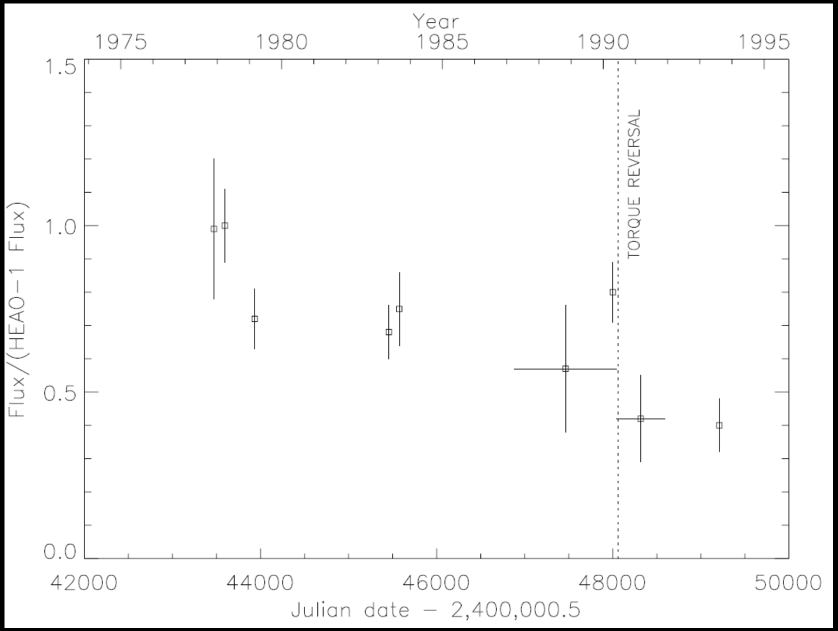


Smale (1998)

- Mass-Radius relation
- Standard candle for distant measurement

Torque Reversal – 4U 1626-67

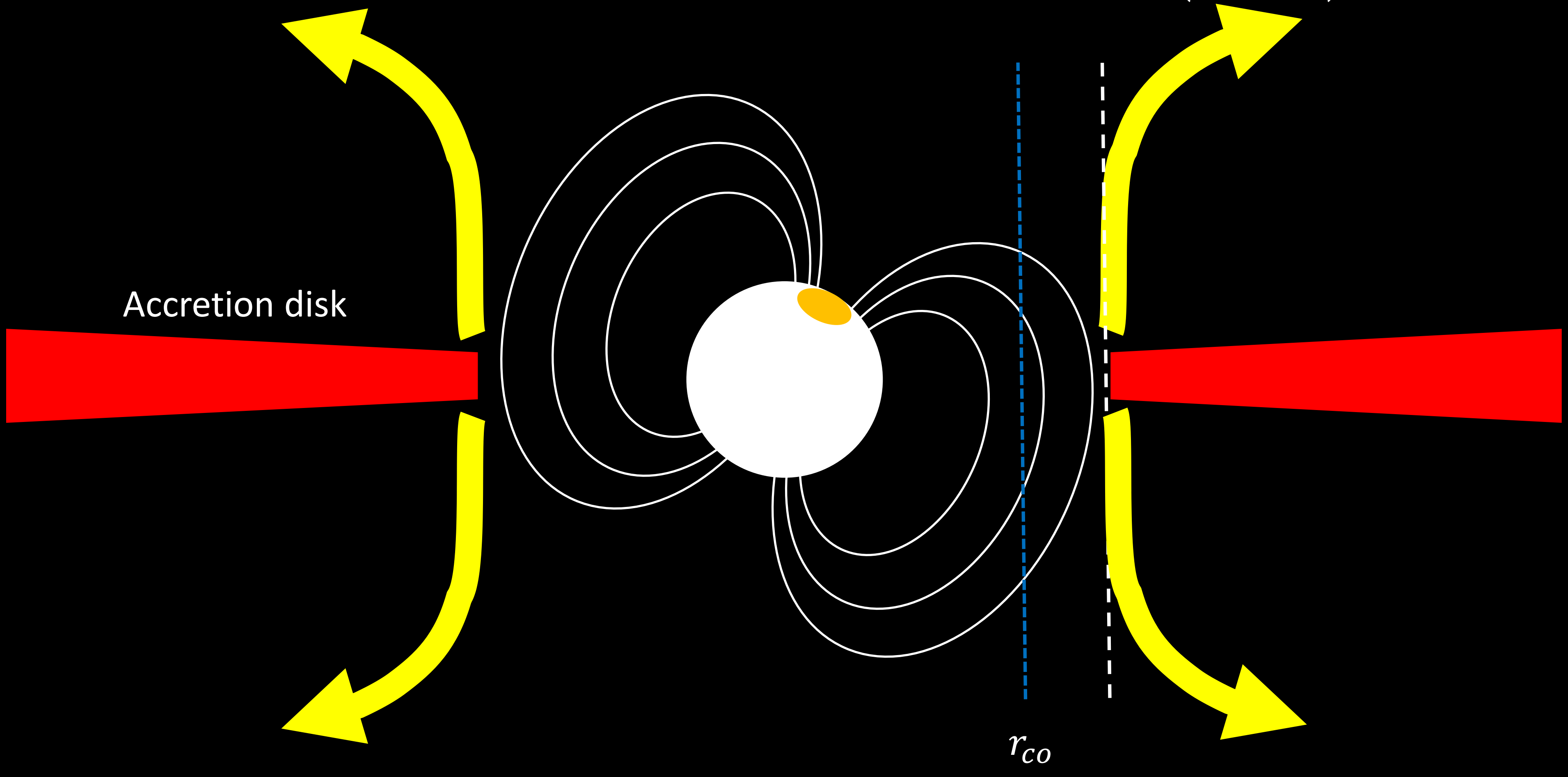




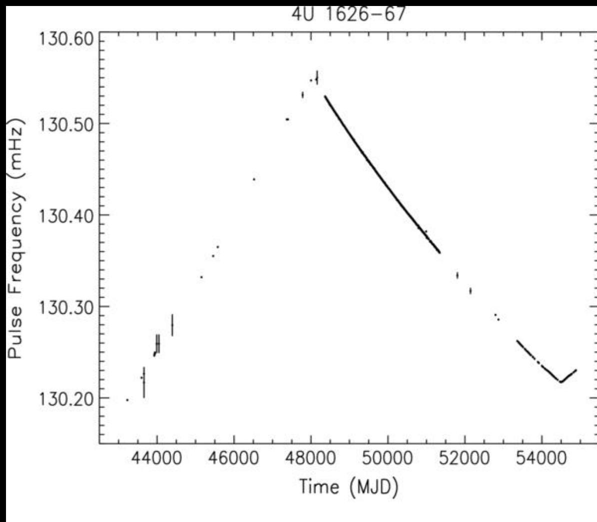
Chakrabarty et al. (1977)

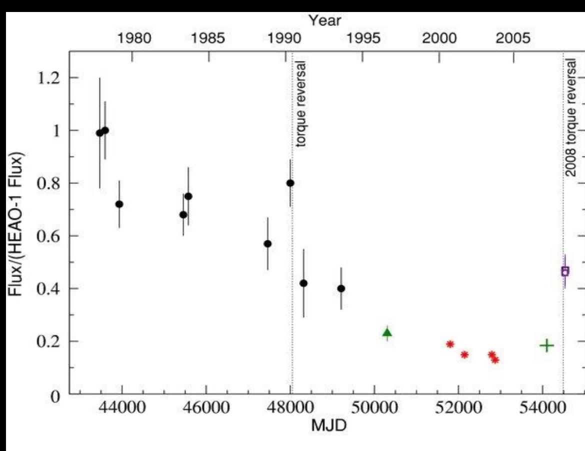
Spin Period Evolution

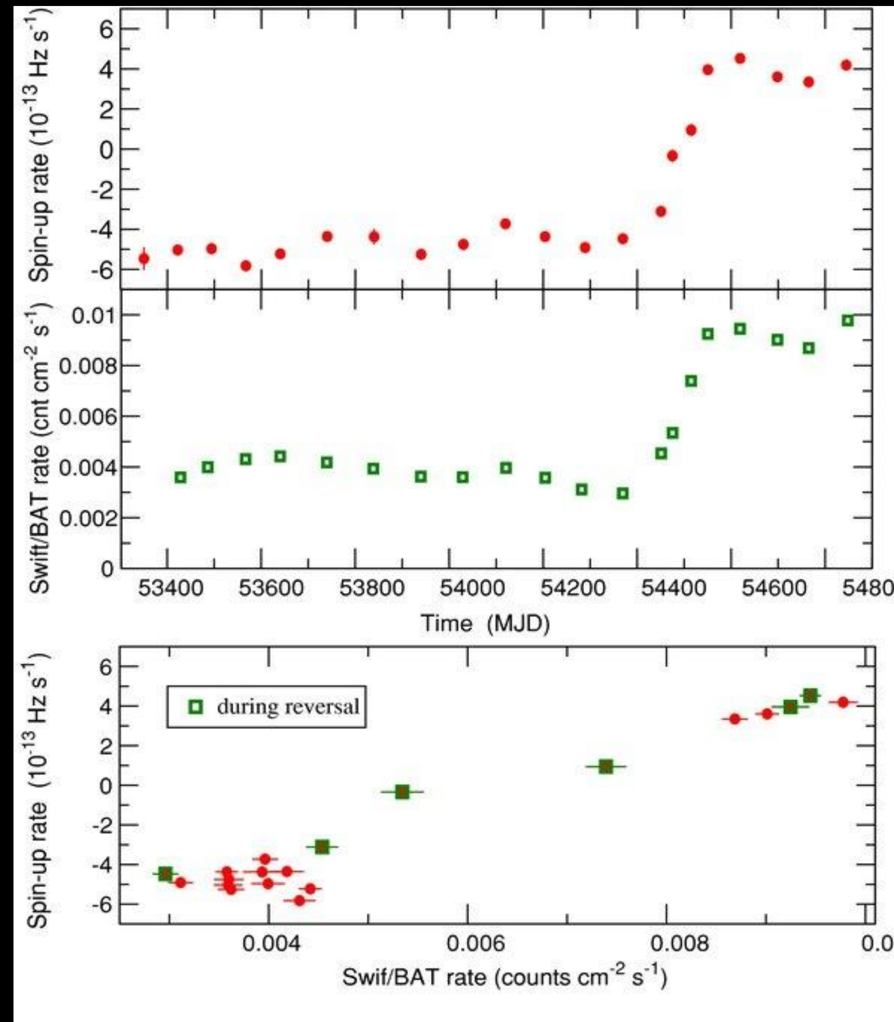
$$r_m = \xi r_A = \xi \left(\frac{\mu^4}{2GM\dot{M}^2} \right)^{1/7}$$



Torque Reversal





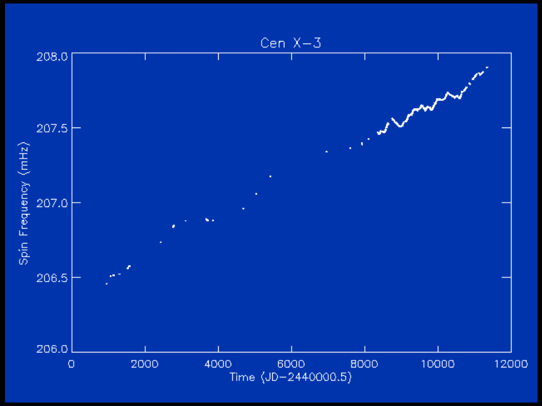


Disk-magnetosphere coupling

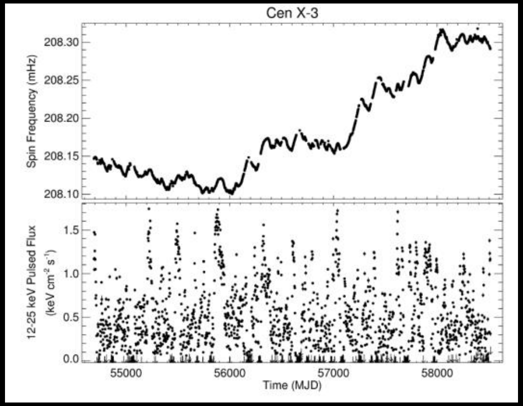
Camero-Arranz et al. (2010)

Cen X-3

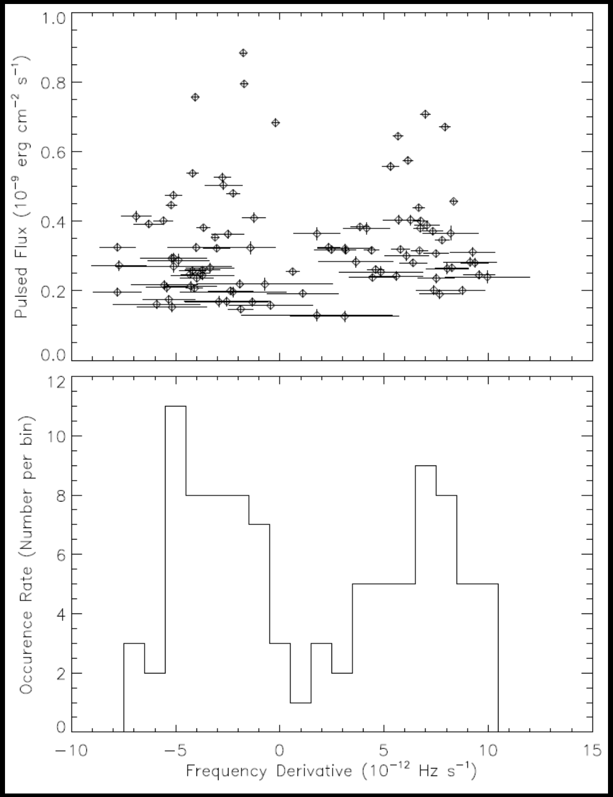
- Before BATSE: $\dot{\nu} = 8 \times 10^{-13}$ Hz s^{-1}, 5 times smaller than the theoretical prediction.
- After BATSE: steady spin-up and spin-down with a much larger rate and 10-100 day timescale.
- Not well understood (equilibrium? warp disk? disk-magnetosphere coupling? change of disk state?)



BATSE Monitoring

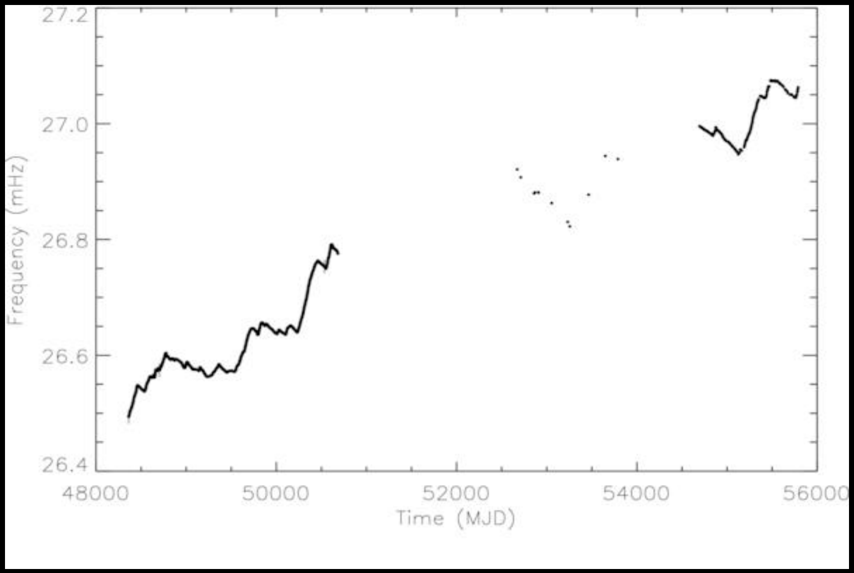


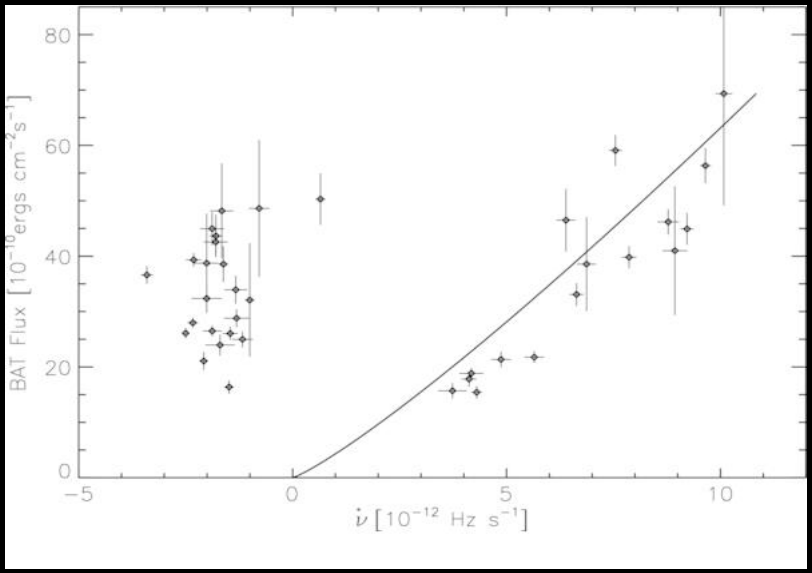
Fermi GBM Monitoring



Bildsten et al. (1997)

Wind Fed Systems

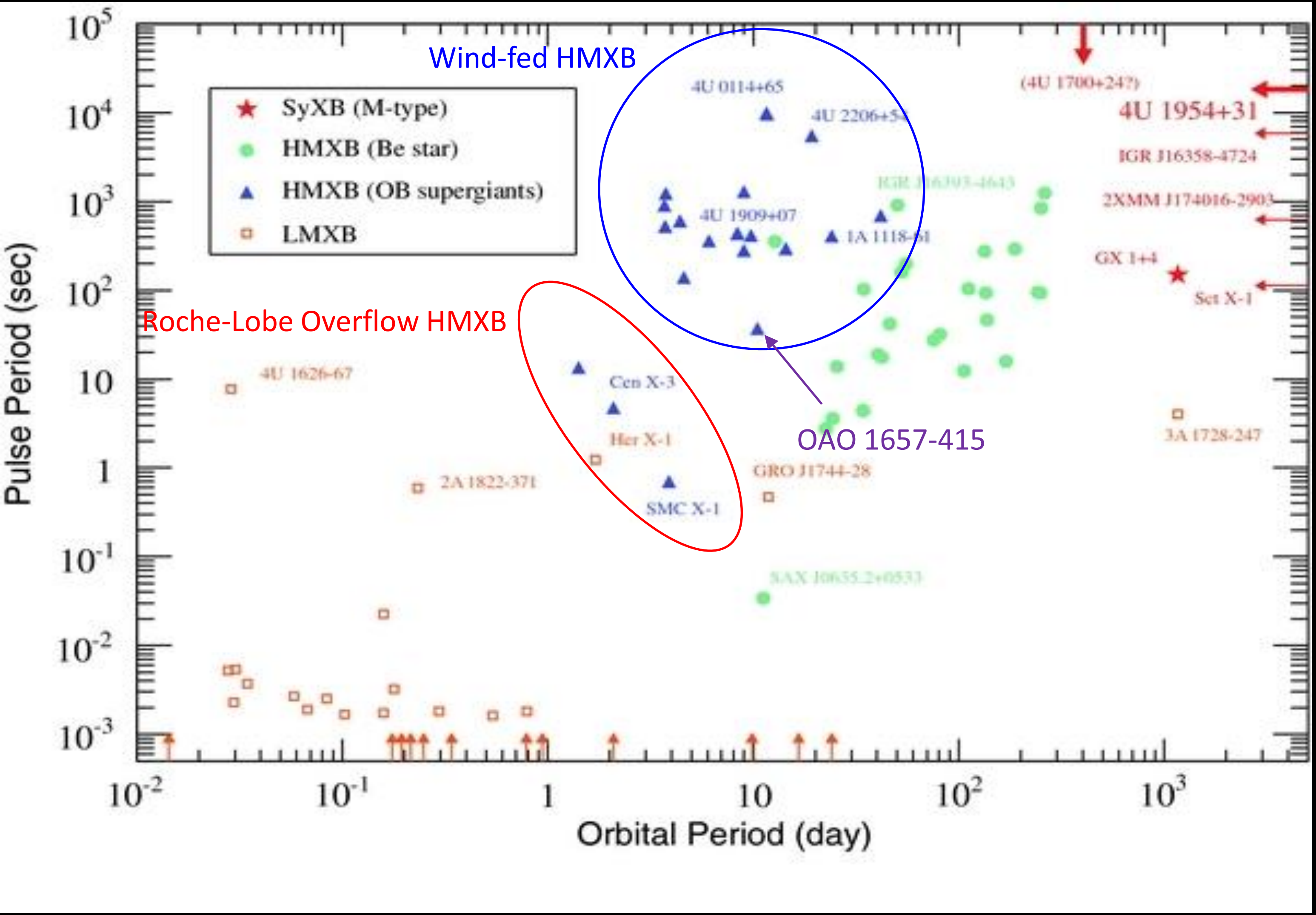




- OAO 1657-415
- Transition between disk-wind and direct-wind accretion?

Jenke et al. (2012)

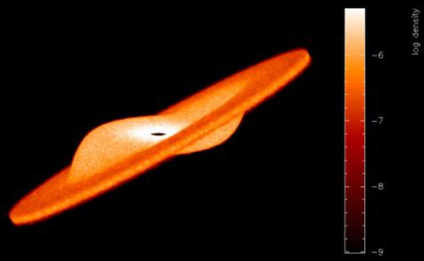
Corbet Diagram



Enoto et al. (2014)

Spin-Superorbital Connection

- Her X-1
  - $P_{spin} = 1.24$ s
  - $P_{orb} = 1.7$ days
  - $P_{sup} = 35$ days
  - $M_c = 2M_{\odot}$



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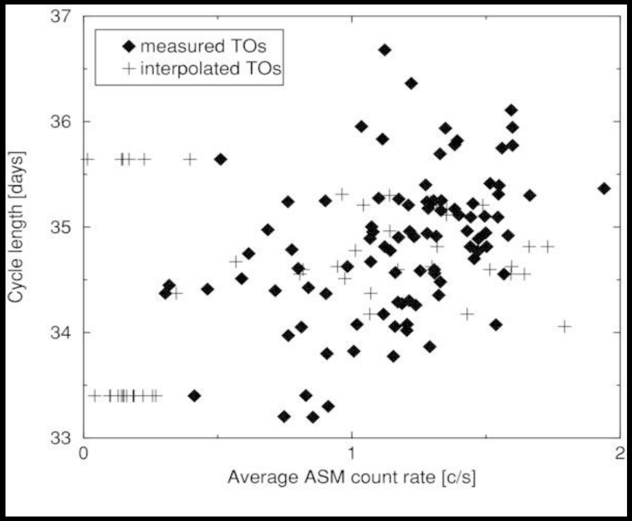
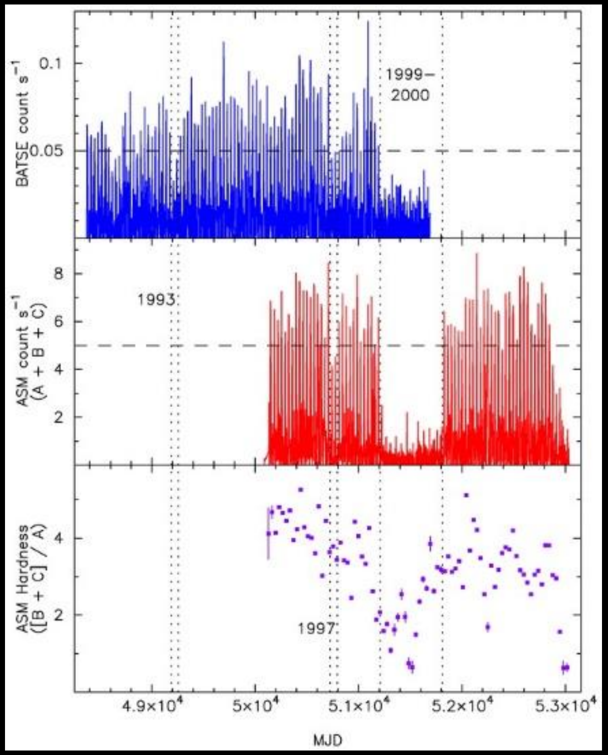
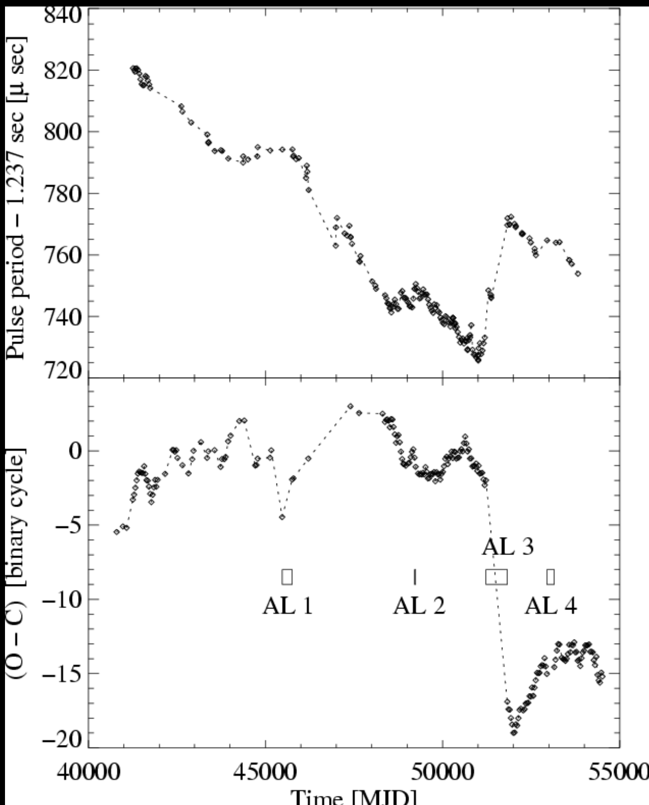


Leahy & Igna (2010)

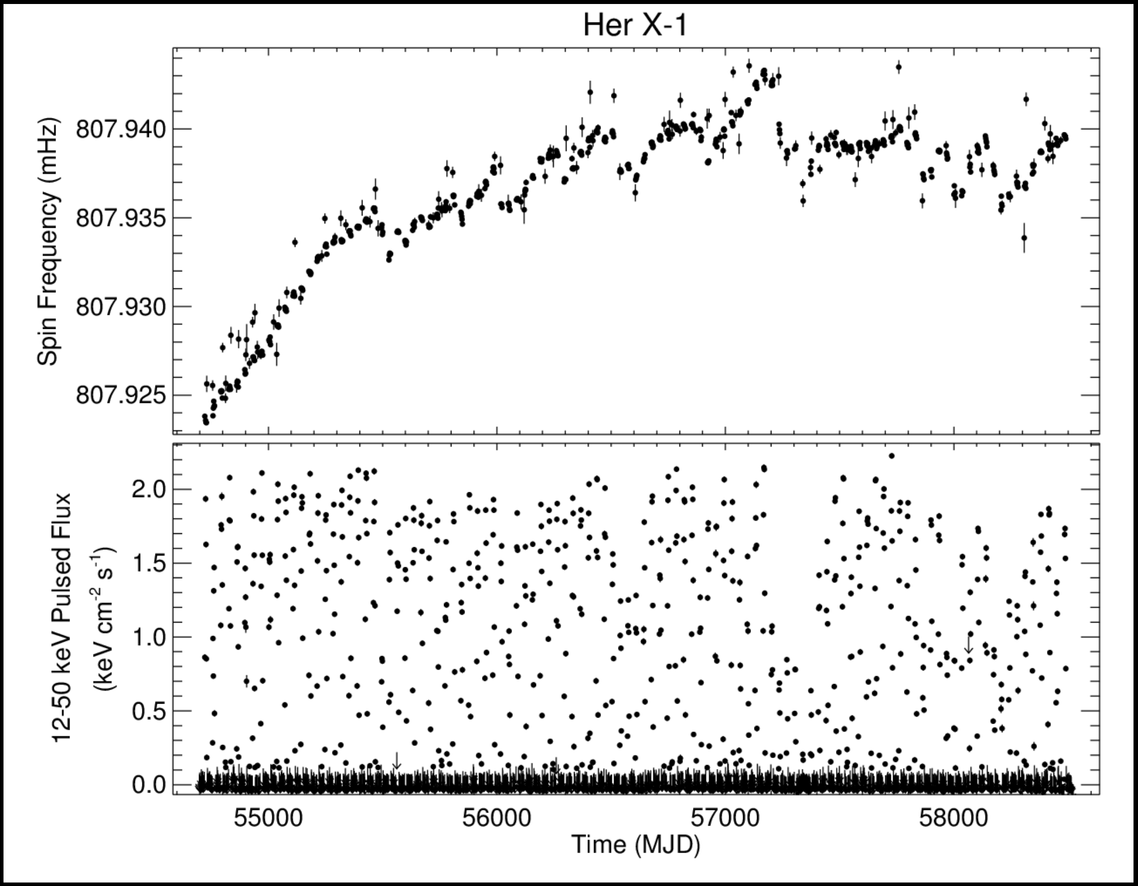


Still & Boyd (2004)

Her X-1



Staubert et al. (2009)



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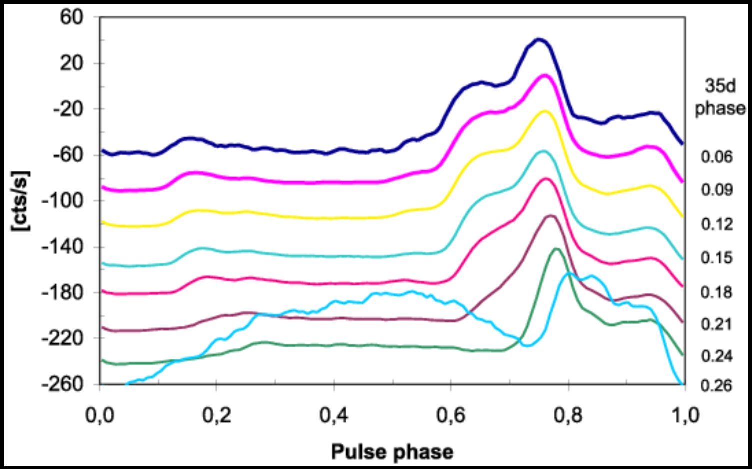
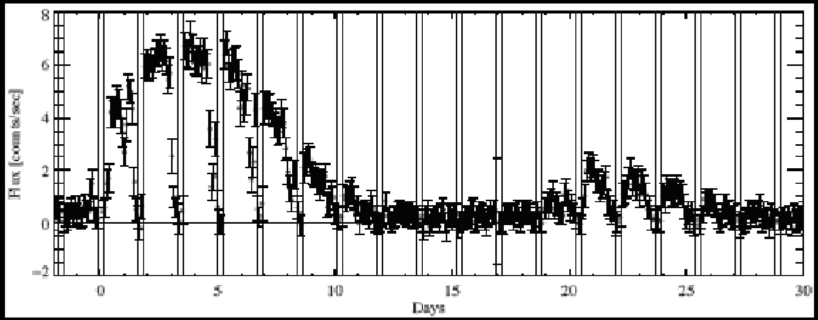
Her X-1

- Two synchronized "Clocks"
  - NS free precession – more stable "pulse profile clock"
  - Disk Precession – less stable "superorbital turn-on clock"
- This synchronization break down during AL3.
  - AL – extremely warp ($> 90°$)?
  - Spin-superorbital connection – feedback between disk precession and NS free precession?



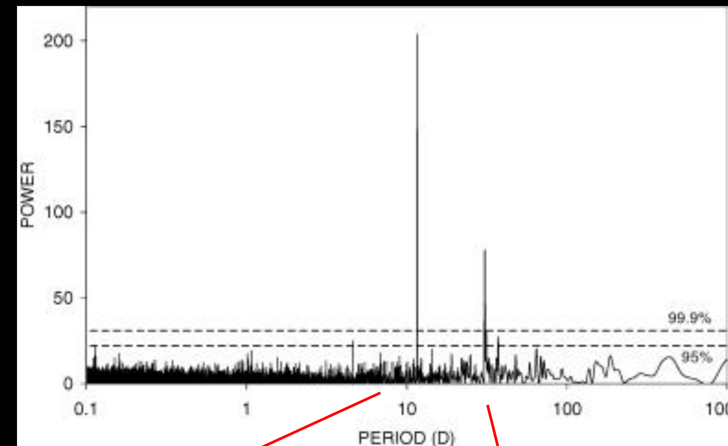
Staubert et al. (2013)



Staubert et al. (2013)

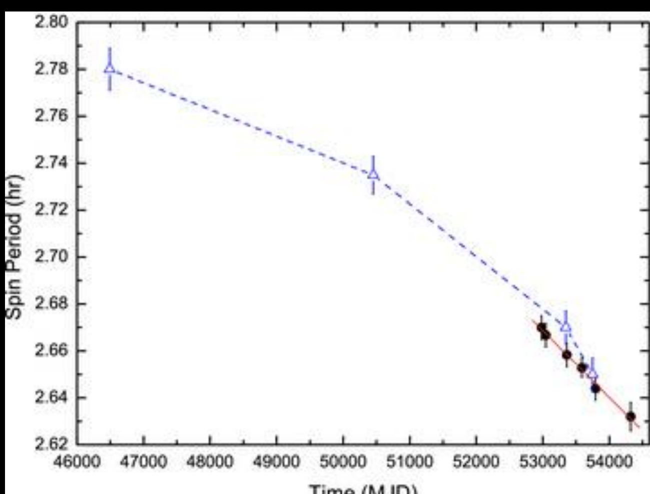
4U 0114+650

- High-Mass X-ray Binary
- Pulse Period ~ 9700s
- Orbital Period ~ 11.6 days (eclipse?)
- Superorbital Period 30.7 days

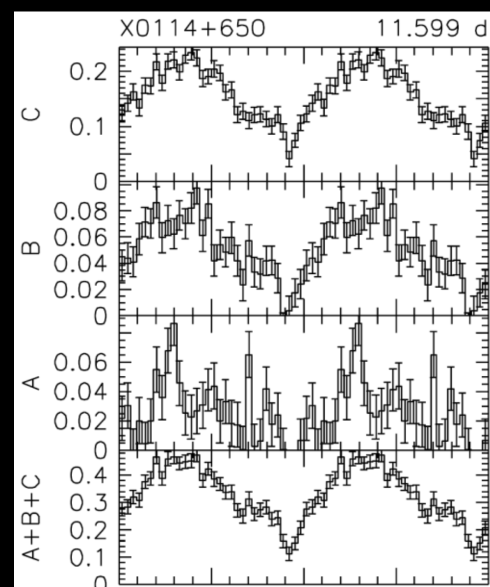


orbital

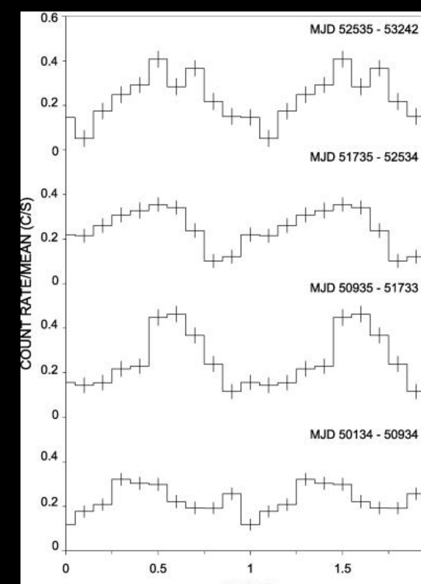
superorbital



Wang (2012)

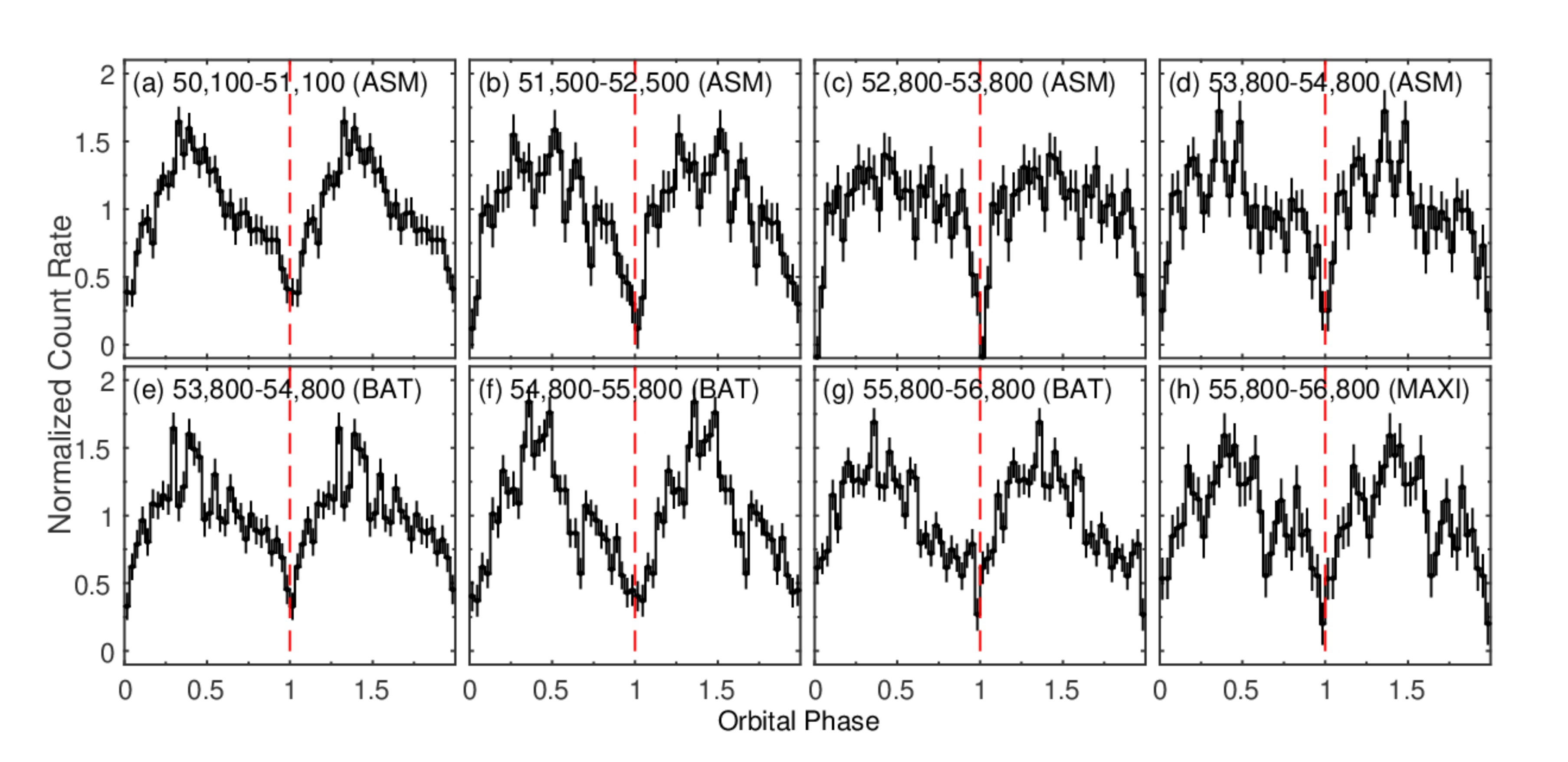


Wen et al. (2006)



Farrell et al. (2008)

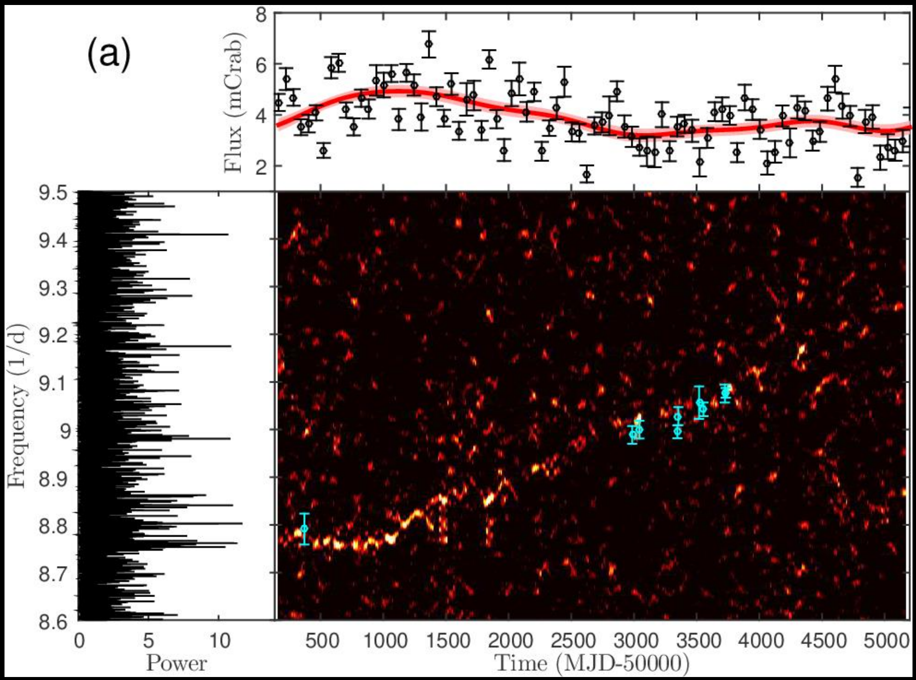
Orbital Profile Variability



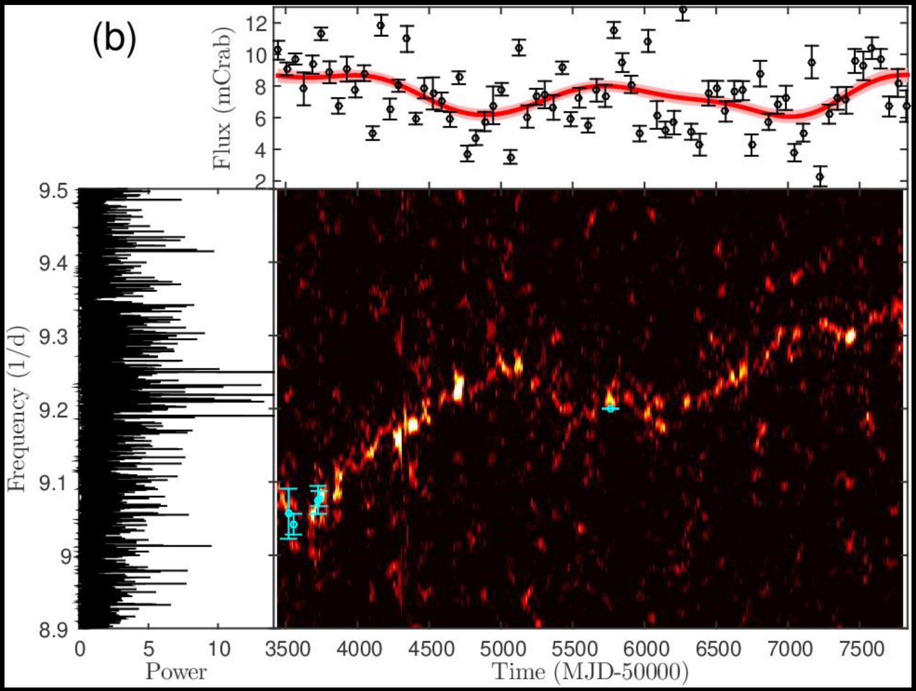
Hu et al. (2017)

Spin Period Evolution

RXTE ASM



Swift BAT

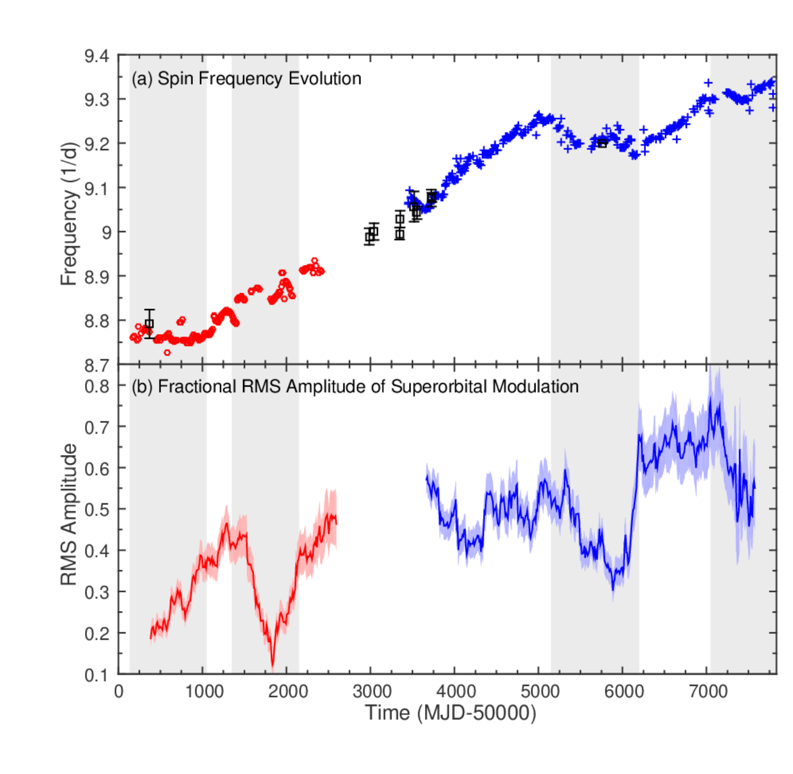


Hu et al. (2017)

Spin-Superorbital Connection

Table 2
Five Spin Evolution Epochs of 4U 0114+650

Time Interval (MJD-50000)	$\dot{P}_{spin}$ (10^{-7} s s^{-1})	Flux Trend
0–1000	4 ± 3	Increase
1000–2500	-15.0 ± 0.7	Decrease
3700–5000	-16.8 ± 0.8	Decrease
5000–6000	6 ± 2	Increase
6000–7000	-17 ± 1	Decrease
3500–7700	-5.6 ± 0.6	…



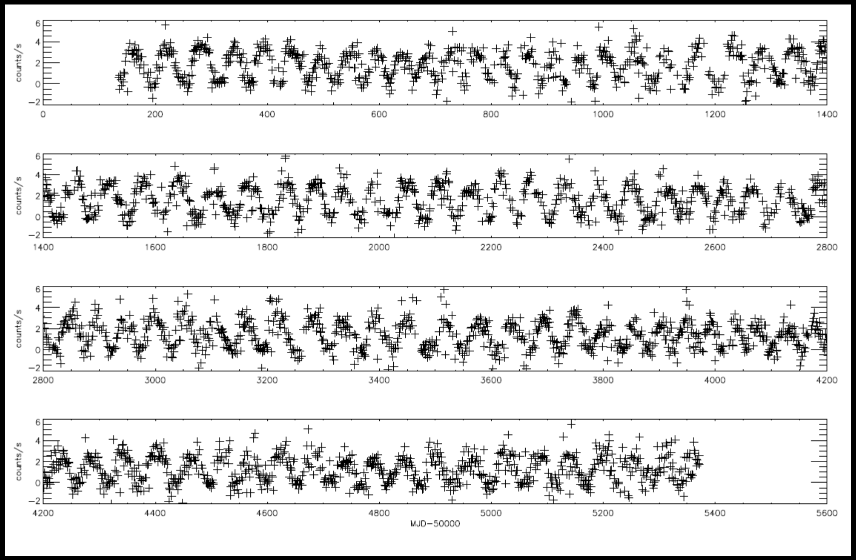
Hu et al. (2017)

Possible Explanation

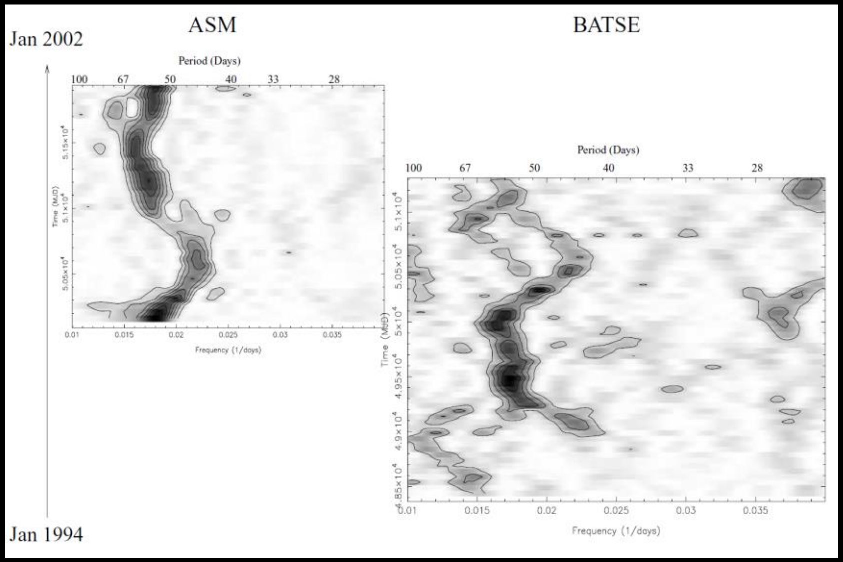
- Fast-wind epoch
  - Strong, fast, anisotropic wind
  - Orbital dependent(?)
  - Dominated by direct-wind accretion
  - Spin-down/random walk
  - Low superorbital amplitude
- Slow-wind epoch
  - Weak wind, luminosity decreases
  - Orbital independent(?)
  - Dominated by disk-wind accretion
  - Secular spin-up
  - High superorbital amplitude

SMC X-1

- High-Mass X-ray Binary
  - Pulse Period ~ 0.7s
  - Orbital Period ~ 3.9 days (eclipse)
  - Superorbital Period 40 – 60 days
- Super-Eddington source.

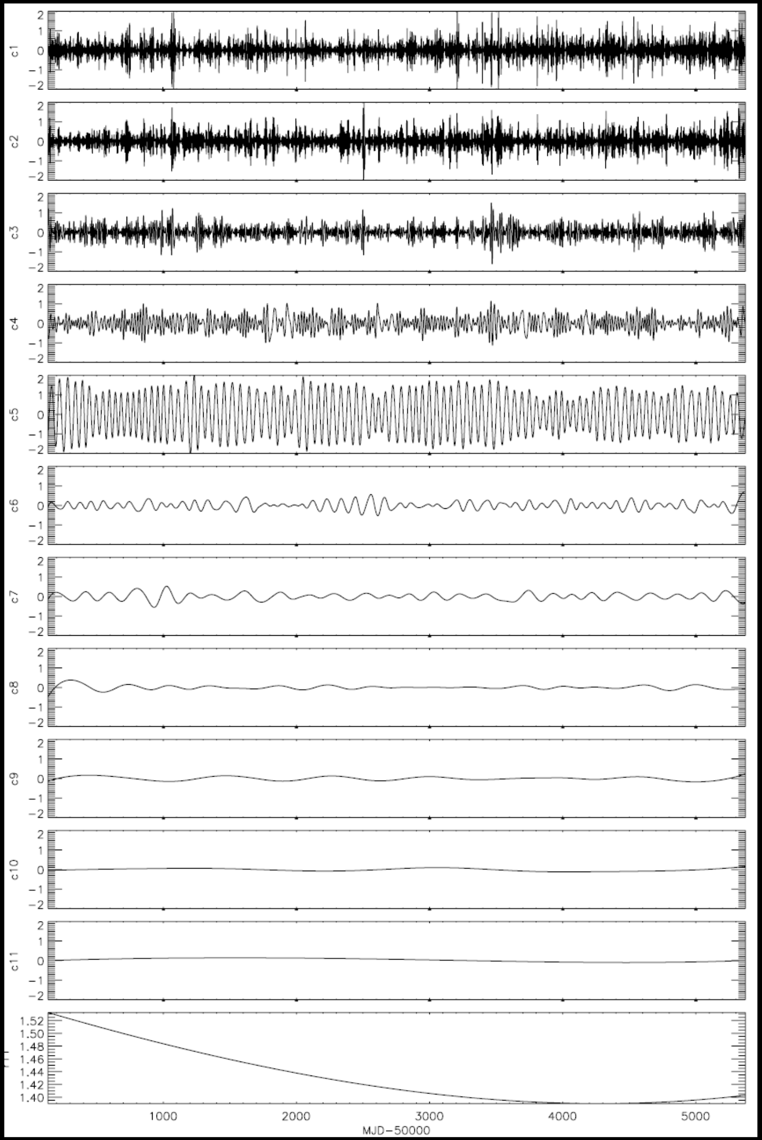


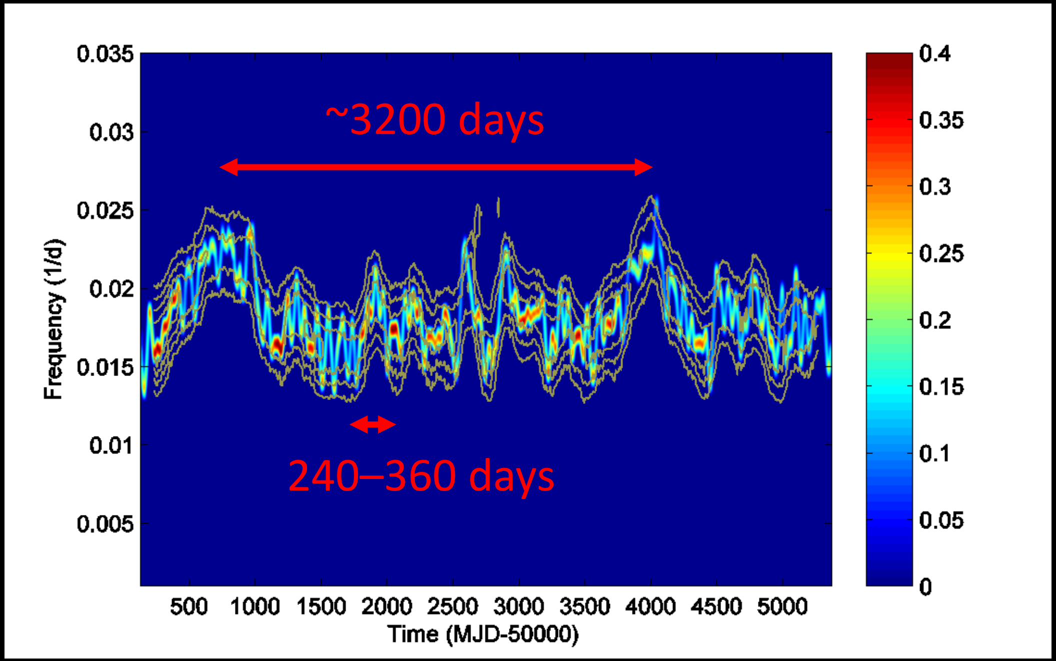
Hu et al. (2011)

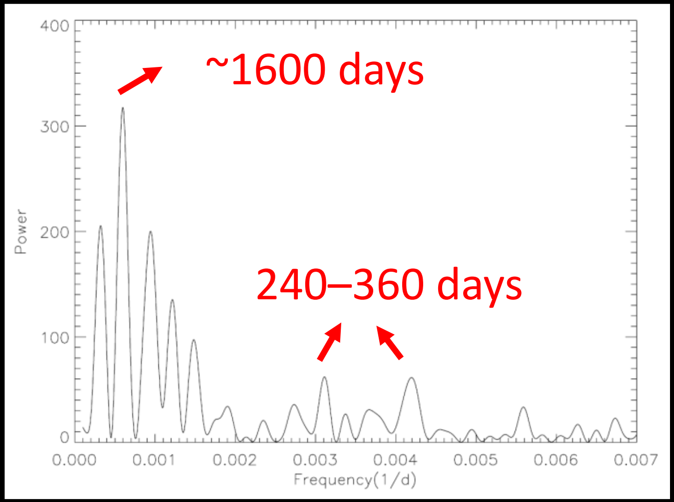


Clarkson et al. (2003)

HHT

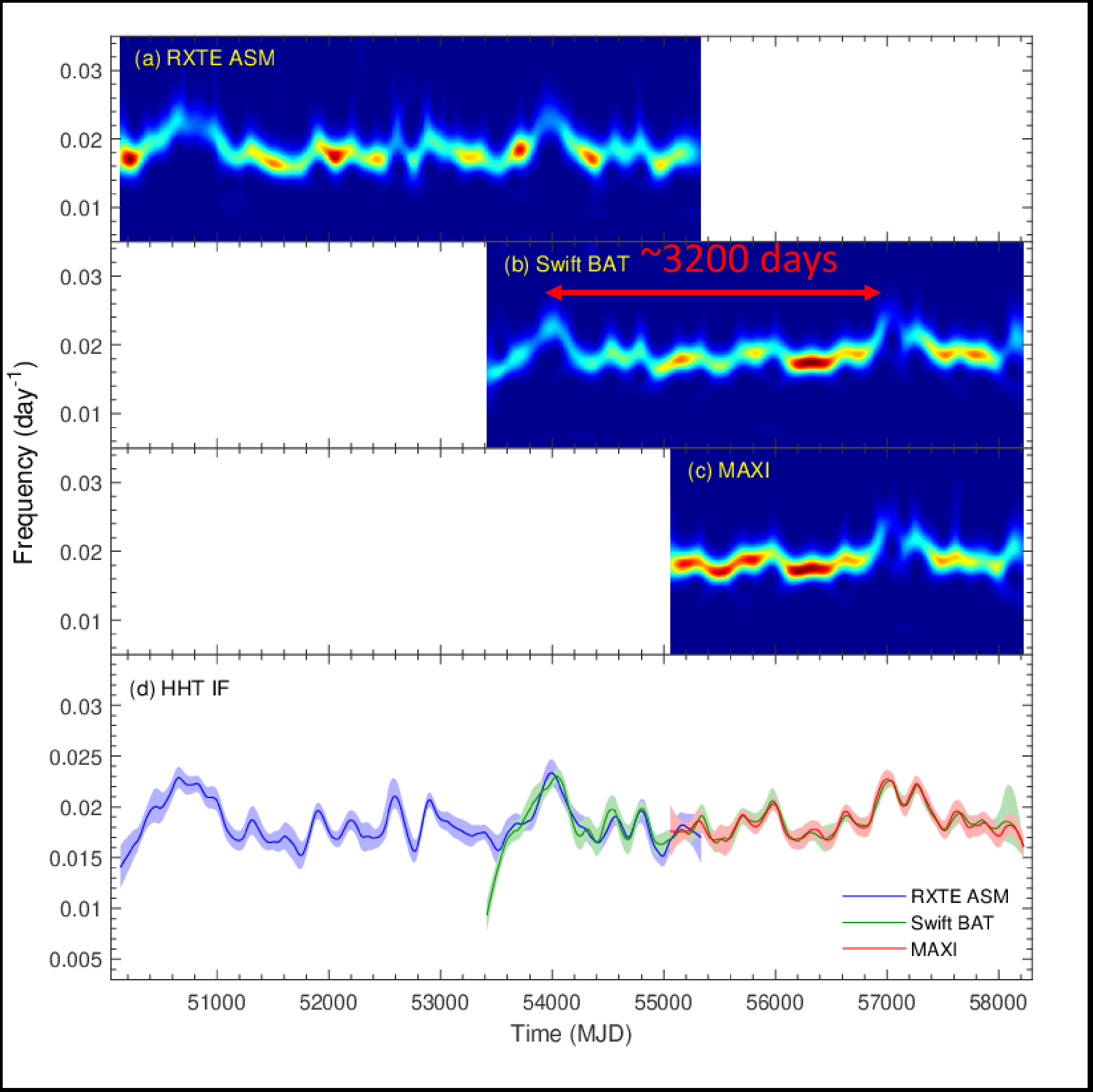




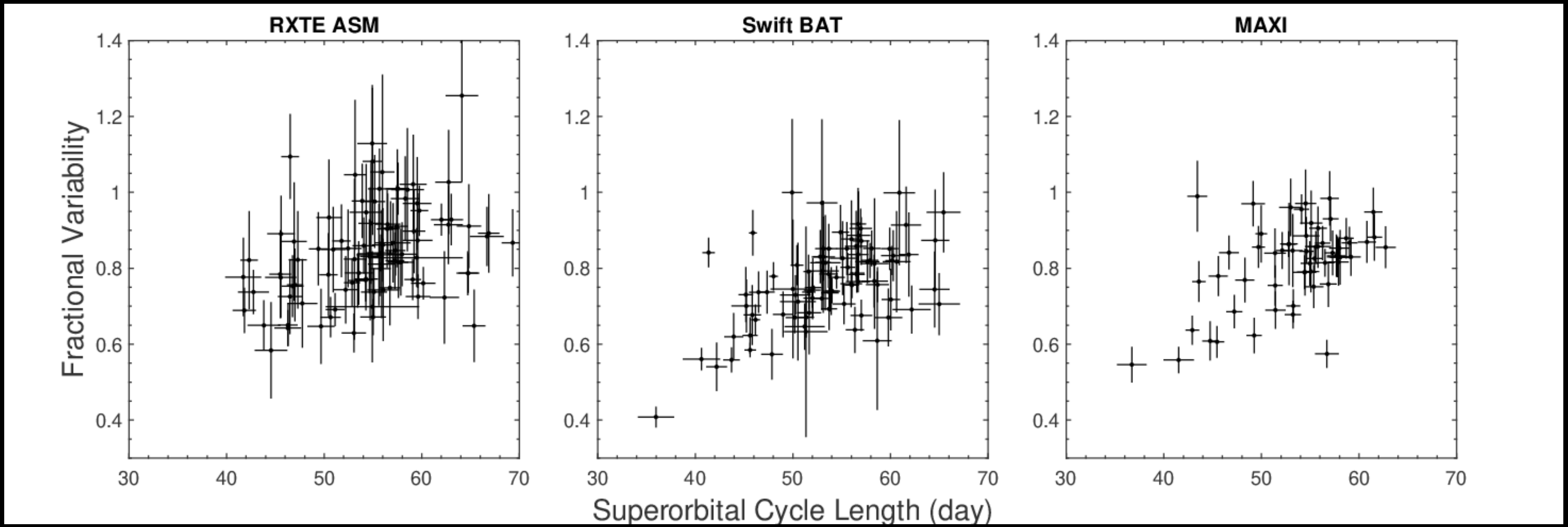


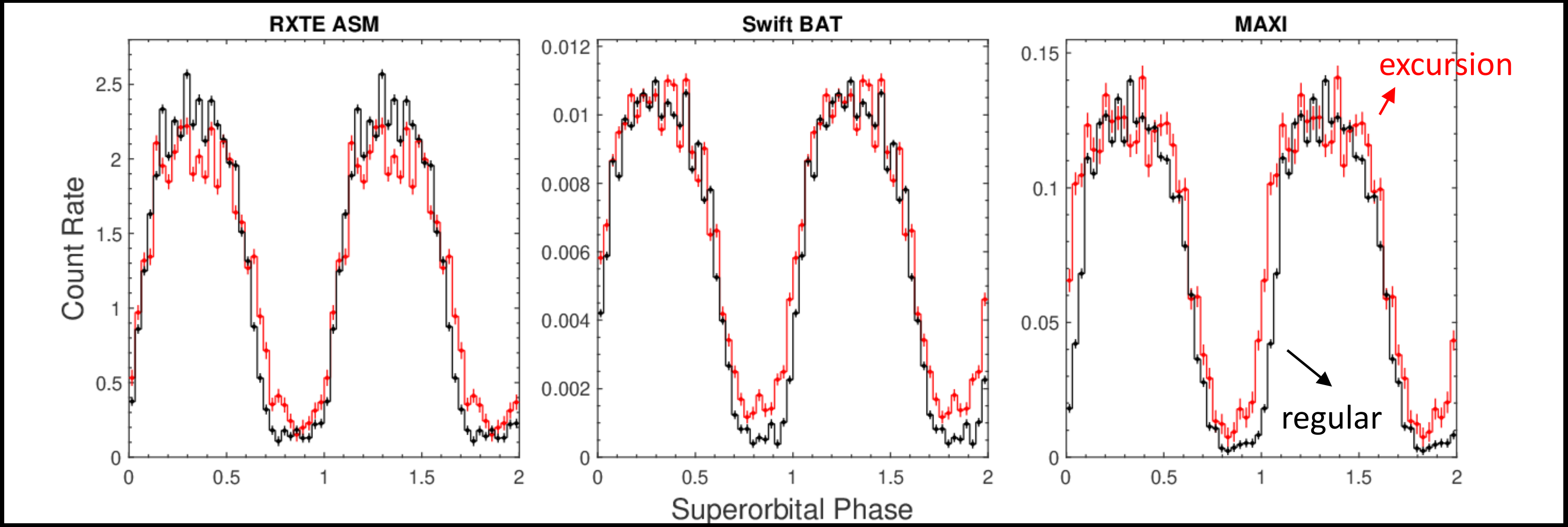
Hu et al. (2011)

ASM vs BAT vs MAXI

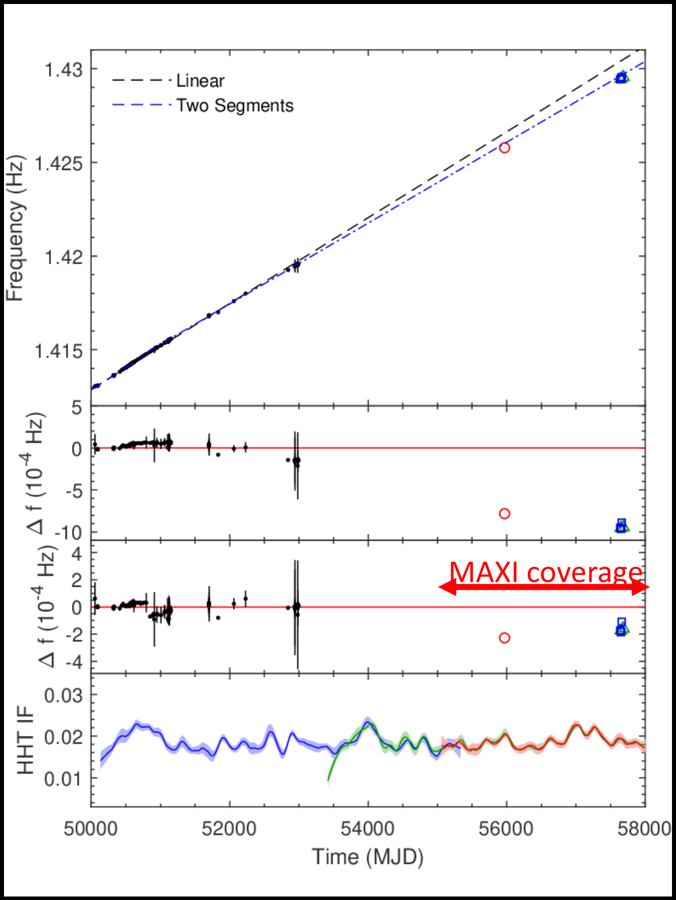


Fractional Variability vs Cycle Length

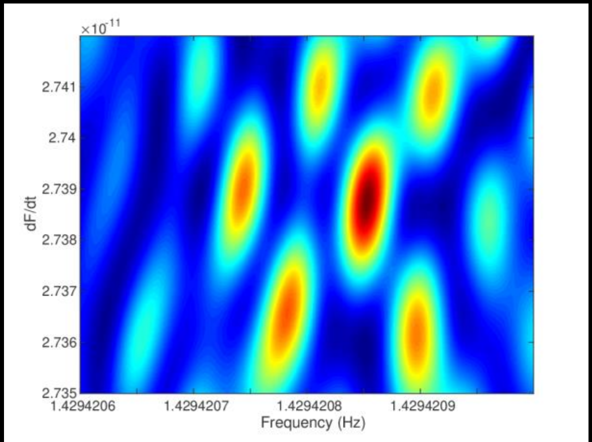




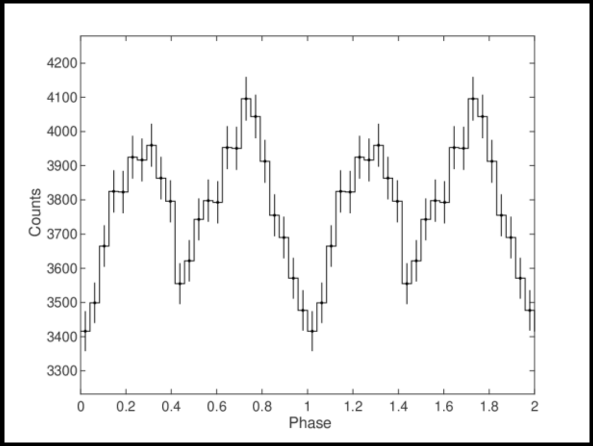
Spin-Superorbital Connection



~20k x 30k pairs of f and $\dot{f}$, 20k events

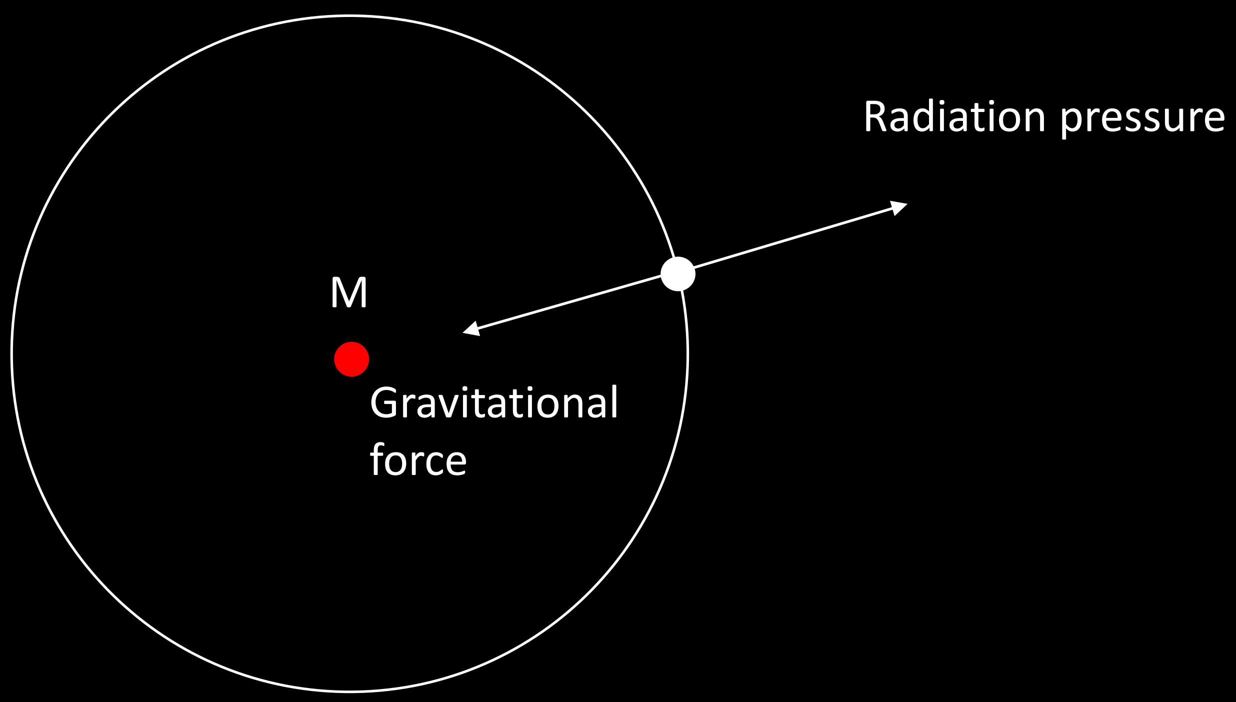


Stacked pulse profile with 750 d MAXI data

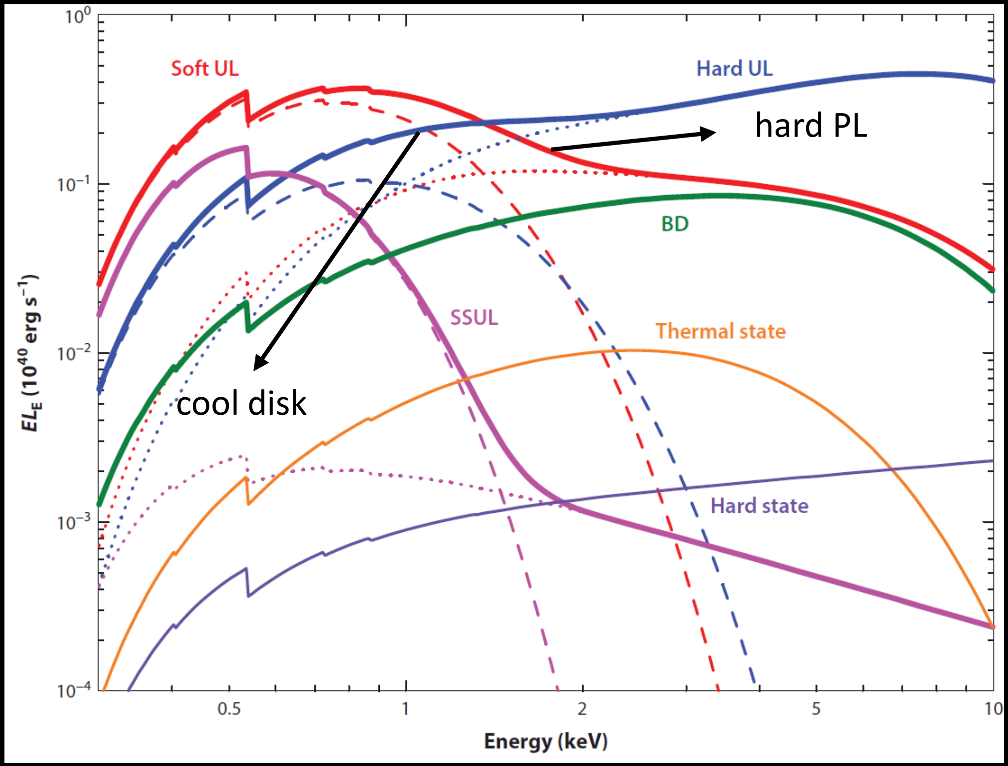


Ultraluminous X-ray Sources

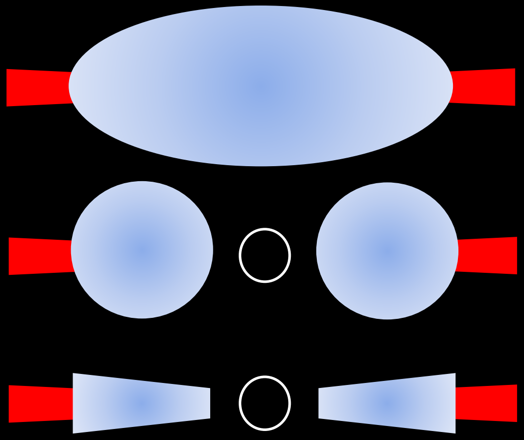
- ULXs: $L > L_{Edd}$ of a 10 $M_\odot$ BH
  - $L_{Edd} = \frac{4\pi c G M m_p}{\sigma_T} \sim 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right)$ erg s^{-1}, where m_p is the proton mass, σ_T is the Thomson cross section, and M is the BH mass.

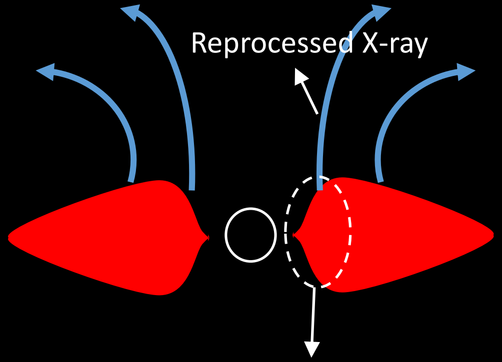


Super-Critical Accretion



Kaaret et al. (2017)





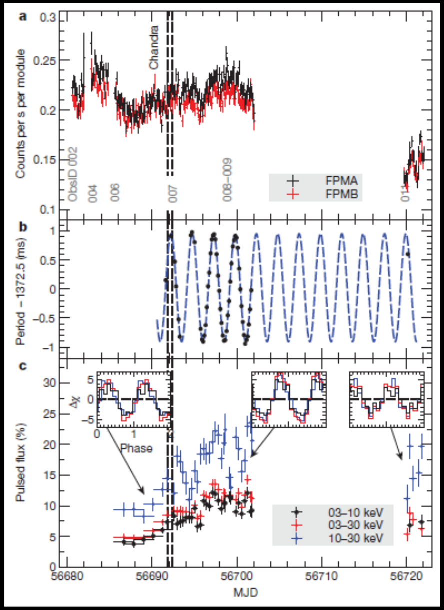
Ultraluminous Pulsars

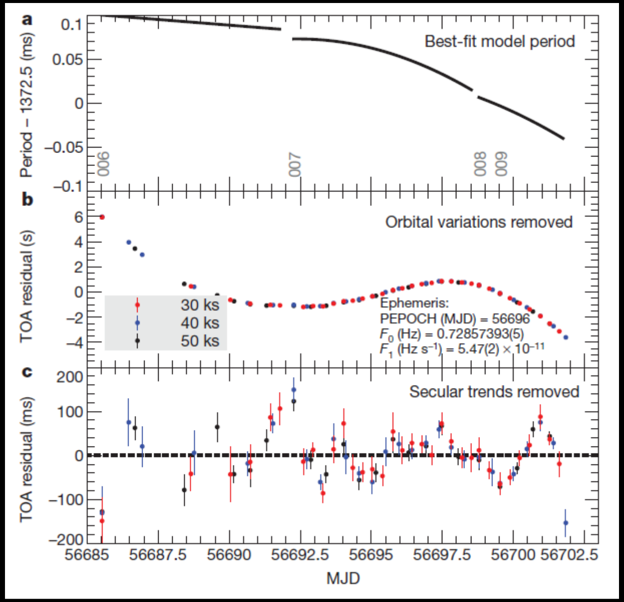
LETTER

doi:10.1038/nature13791

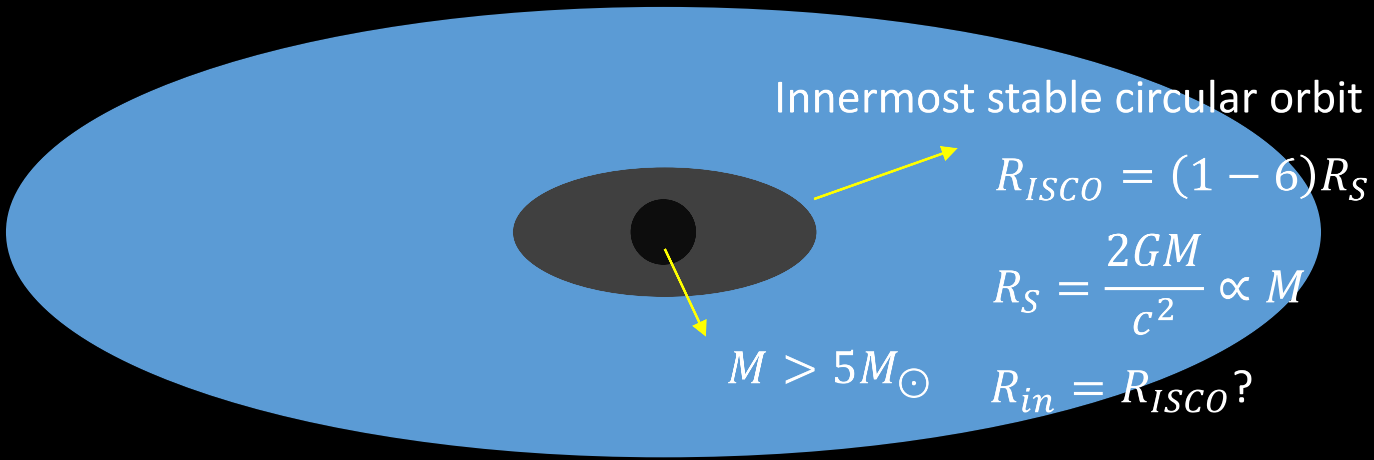
An ultraluminous X-ray source powered by an accreting neutron star

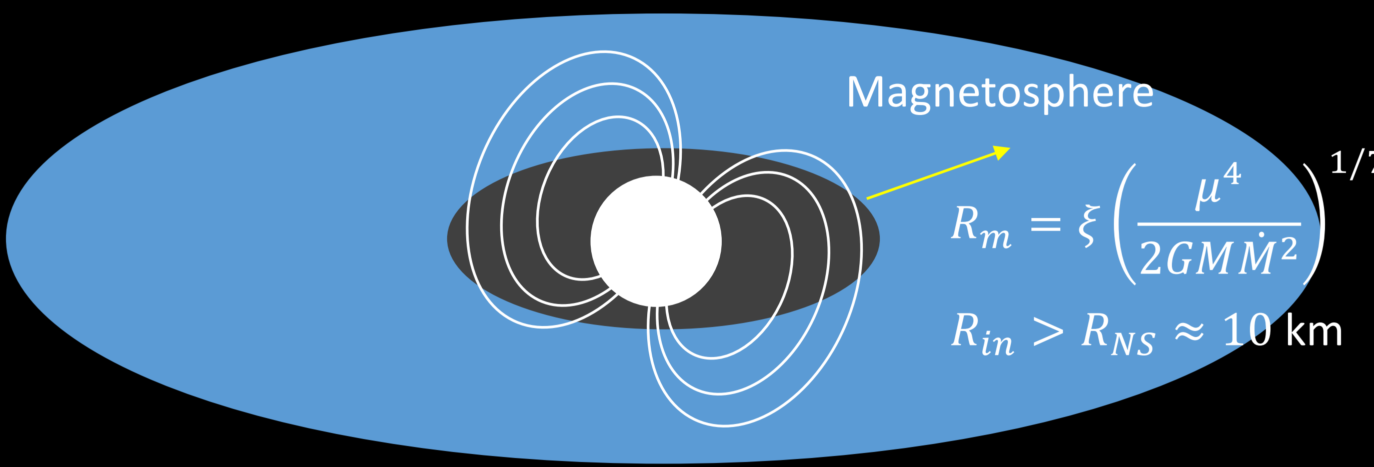
M. Bachetti[1,2], F. A. Harrison[3], D. J. Walton[3], B. W. Grefenstette[3], D. Chakrabarty[4], F. Fürst[3], D. Barret[1,2], A. Beloborodov[5], S. E. Boggs[6], F. E. Christensen[7], W. W. Craig[8], A. C. Fabian[9], C. J. Hailey[10], A. Hornschemeier[11], V. Kaspi[12], S. R. Kulkarni[3], T. Maccarone[13], J. M. Miller[14], V. Rana[3], D. Stern[15], S. P. Tendulkar[3], J. Tomsick[6], N. A. Webb[1,2] & W. W. Zhang[11]





Black Hole vs Neutron Star





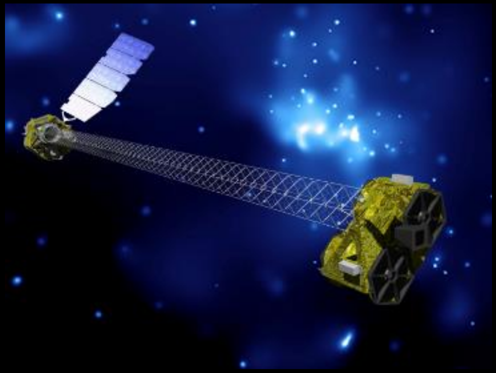
Magnetic Field & Luminosity

- The luminosity of an NS can have $L > L_{Edd}$ if the surface magnetic field is very high
  - The electron scattering cross sections is much lower than the Thomson cross section ($L_{Edd} = \frac{4\pi c G M m_p}{\sigma_T}$).
  - $B \sim 10^{15}$ G can have $L \sim 10^{41}$ erg/s
  - P_{spin} inferred B field is much lower

Name	M82 X-2	NGC 7793 P13	NGC 5907 ULX1	NGC 300 ULX1
Peak L (erg/s)	1.8×10^{40}	5×10^{39}	10^{41}	5×10^{39}
$P_s(s)$	1.37	0.42	1.13	40 – 20
$\dot{\nu}\ (s^{-2})$	10^{-10}	4×10^{-11}	4×10^{-9}	$10^{-9} - 10^{-10}$
$P_{orb}(day)$	2.51	65(?)	~5.3	?
$P_{sup}(day)$	~60	~2700(?)	78	?

Super-Critical Accretion

- Super-critical accretion?
  - Eddington limited accreting NS with magnetar-level B field have $P \gtrsim 0.1$s.
  - Time resolution of XMM-Newton (~0.1s) and Chandra (3s)
  - Low B-field ULPs with super-critical accretion can have much shorter period.
    - NuSTAR, NICER, and future eXTP...



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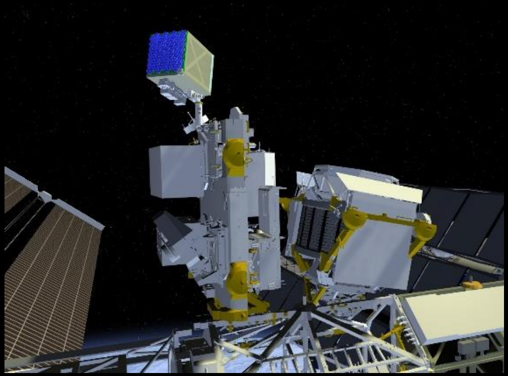

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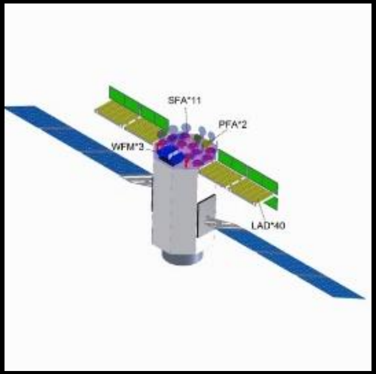

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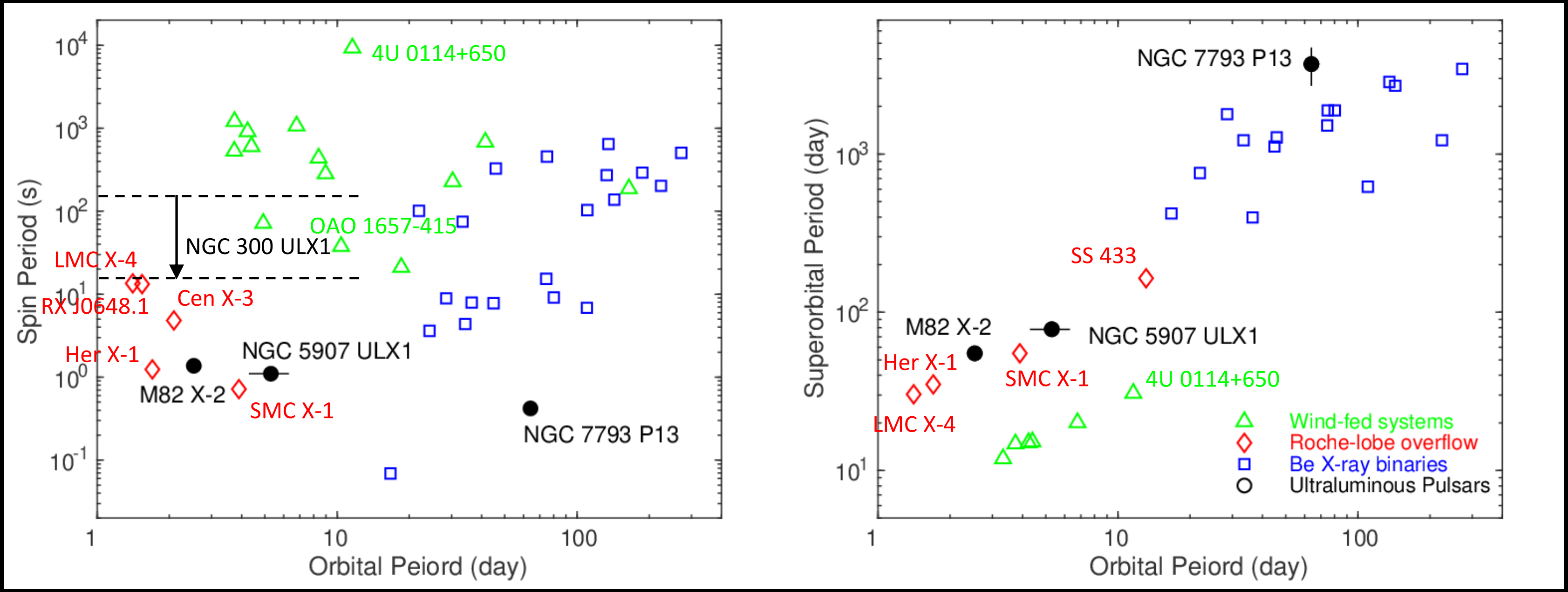
Spin-Orbital-Superorbital Relation

- If the 65-d modulation is orbital and the 3000 d modulation is superorbital, NGC 7793 P13 could be a Be X-ray binary.
  - Roche-lobe size is larger than the Companion star radius
  - Search for the feature of Be star?
  - The magnetar argument may not be valid because the accretion mechanism may not be disk-fed.



Summary

- Neutron stars in binary systems show a variety of timing properties.
  - MSPs, burst QPOs, black widows, red backs reveal the evolution of NS in binary systems.
  - Spin frequency evolution gives hints about accretion mechanisms and the connection between the NS, B-field, and disk.
- Remaining open questions
  - Origin of timing noise in accreting system?
  - Upper limit of NS spin?
  - Equation of state of NSs?
  - Torque reversal?
  - Free precession vs disk warp?
  - …..

Thank You