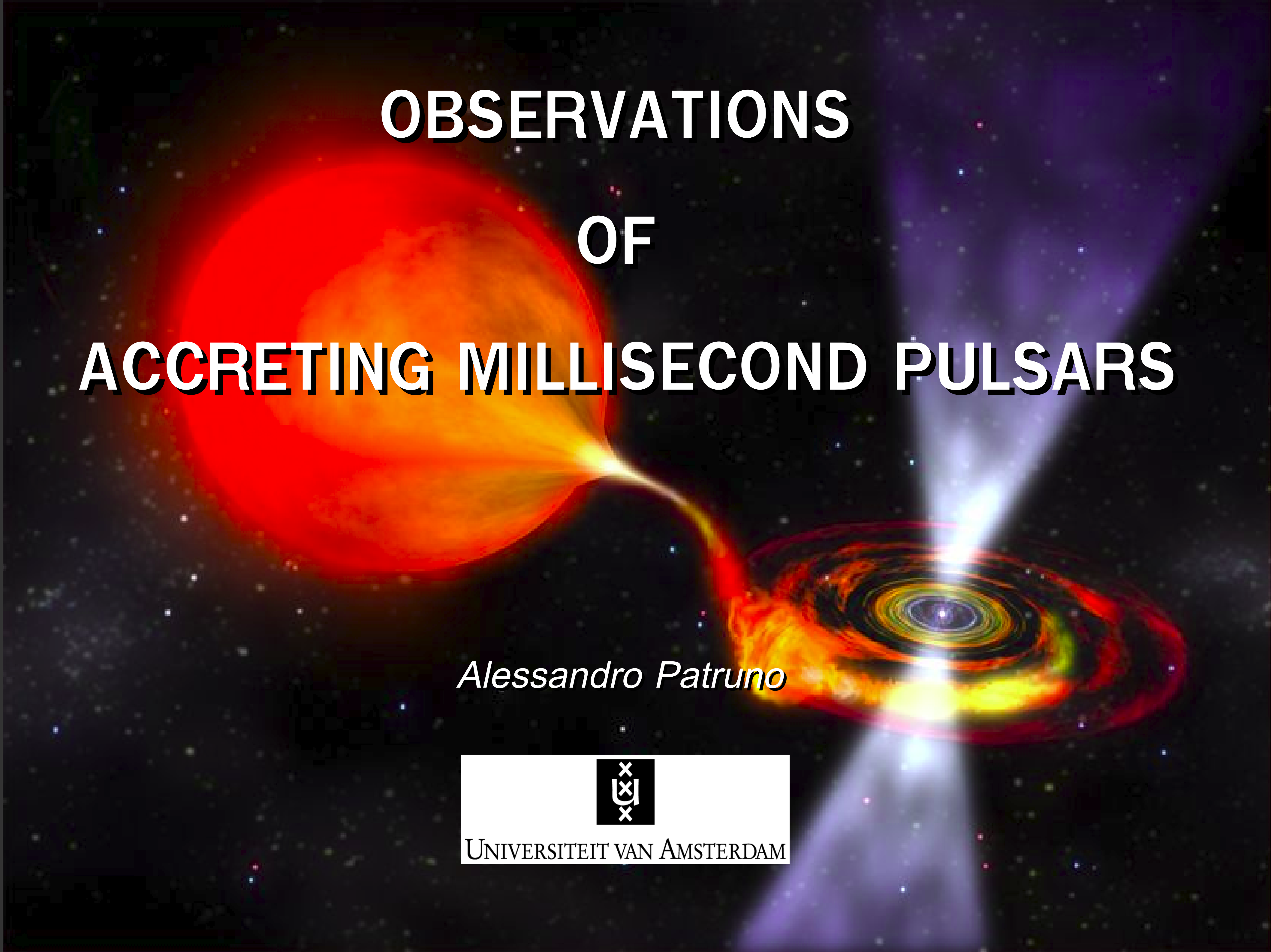
OBSERVATIONS

OF

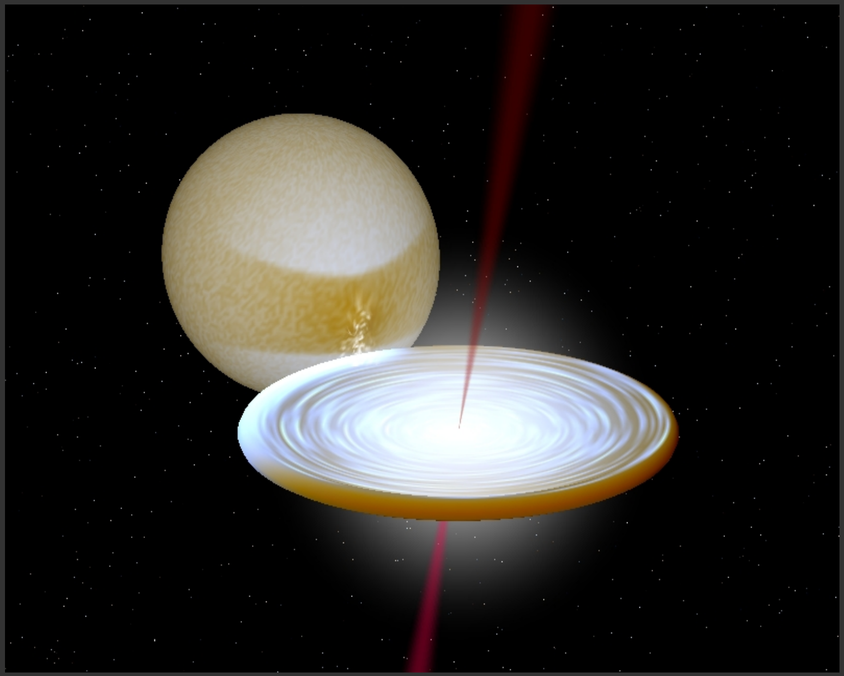
ACCRETING MILLISECOND PULSARS

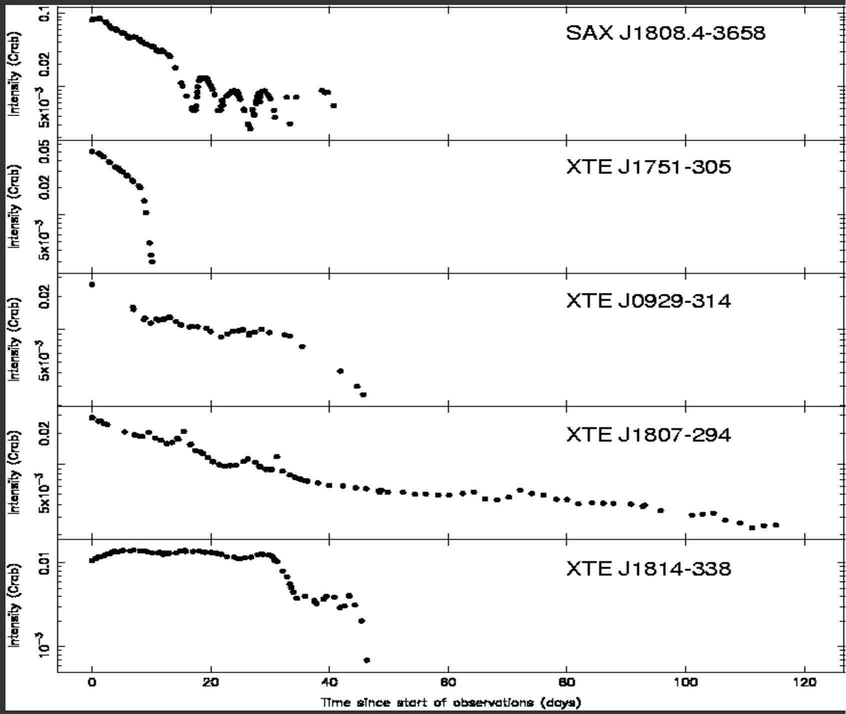


Alessandro Patruno

UNIVERSITEIT VAN AMSTERDAM

Accreting Millisecond Pulsars



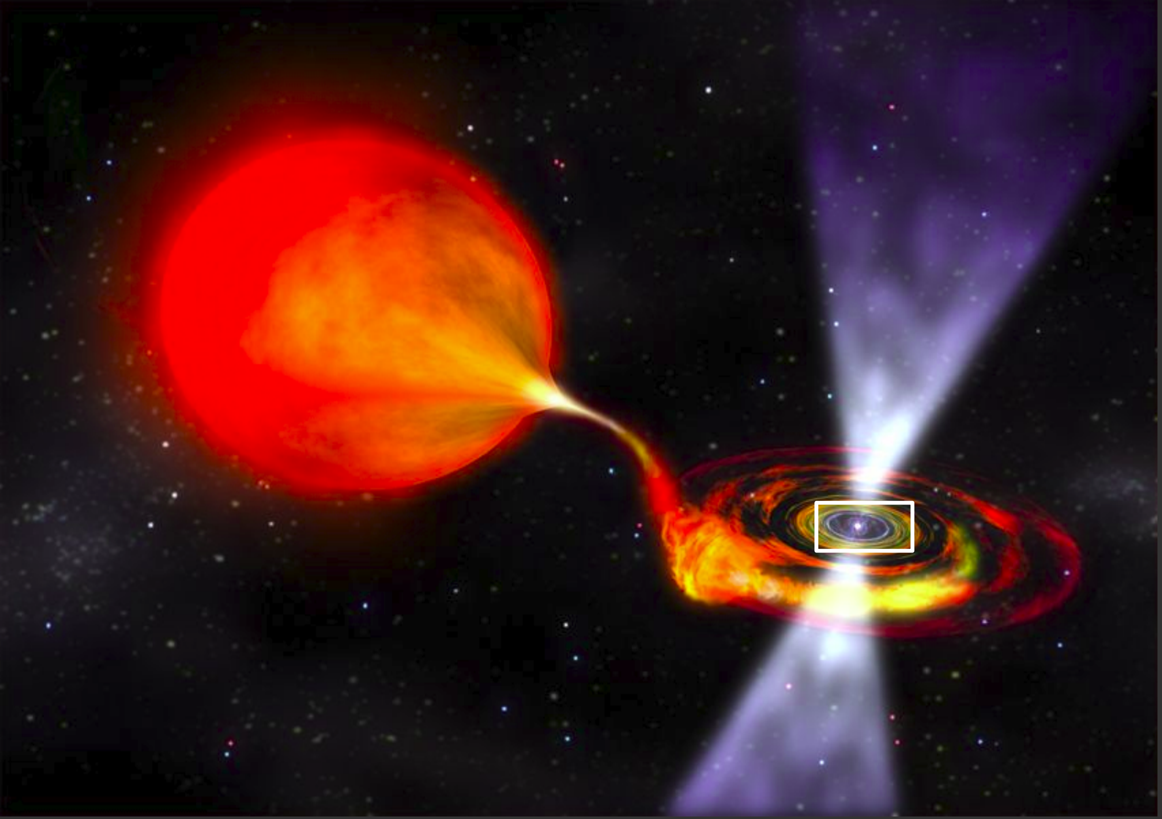


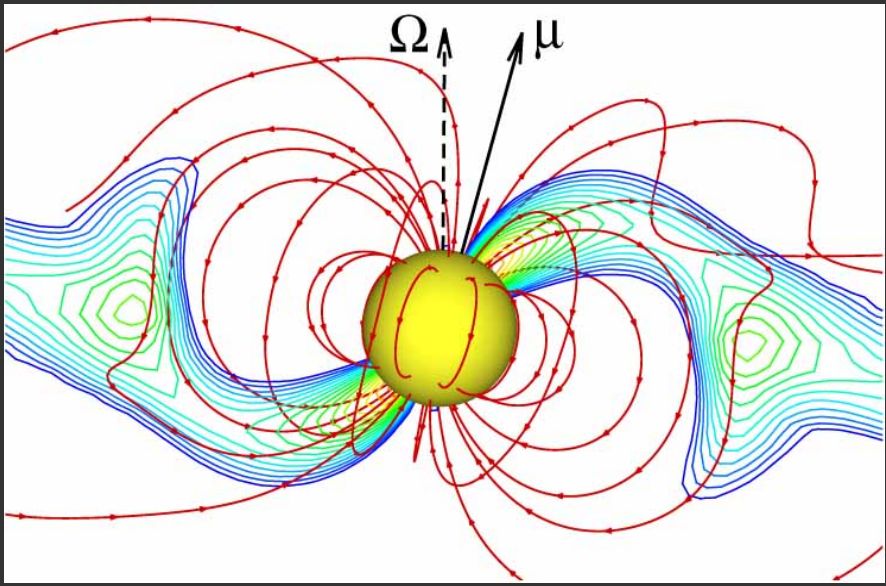
Wijnands 2005

Outburst: period of high level activity with large accretion on the neutron star

Quiescence: period of low level activity with almost no accretion on the neutron star

WHICH PHYSICS ?



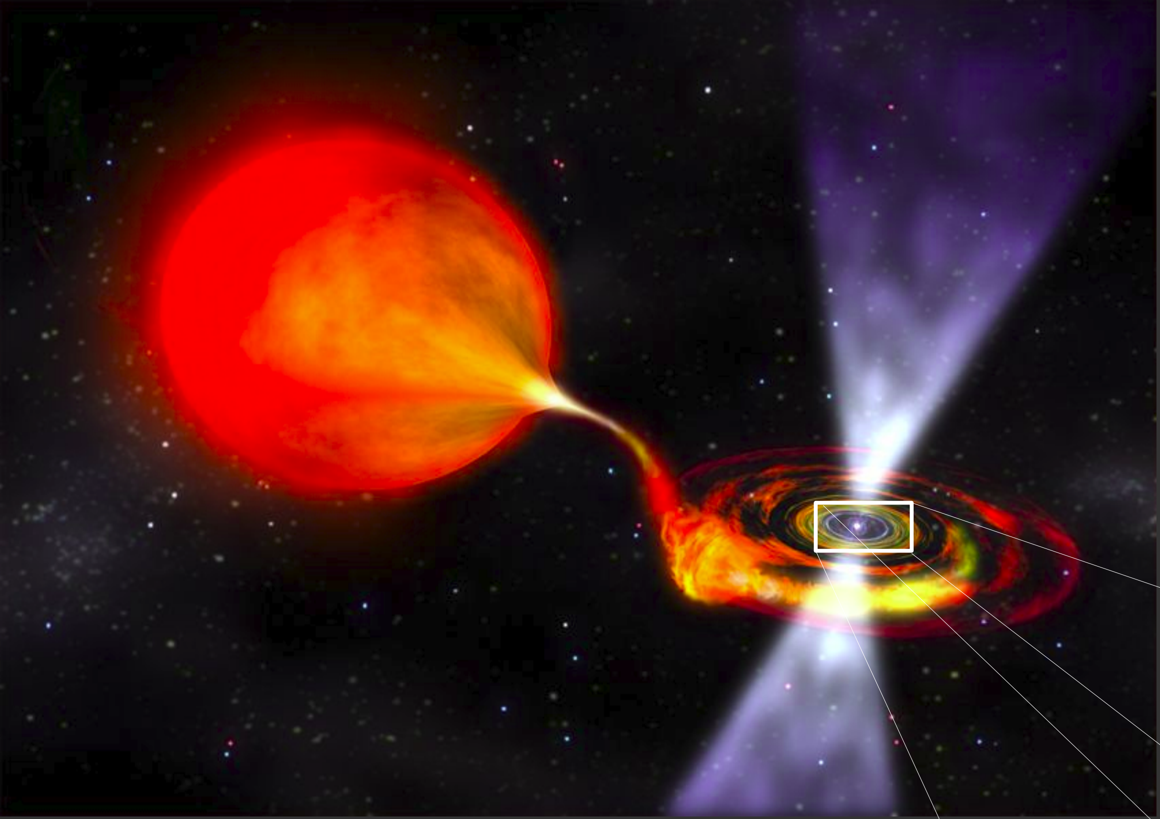


Accretion Torques --> Gravitational Waves

Fast Pulsars & Pulse Profile Modeling --> EoS of Ultra Dense Matter

Magnetic Field Evolution -->Crust structure/Superfl.-Supercond.

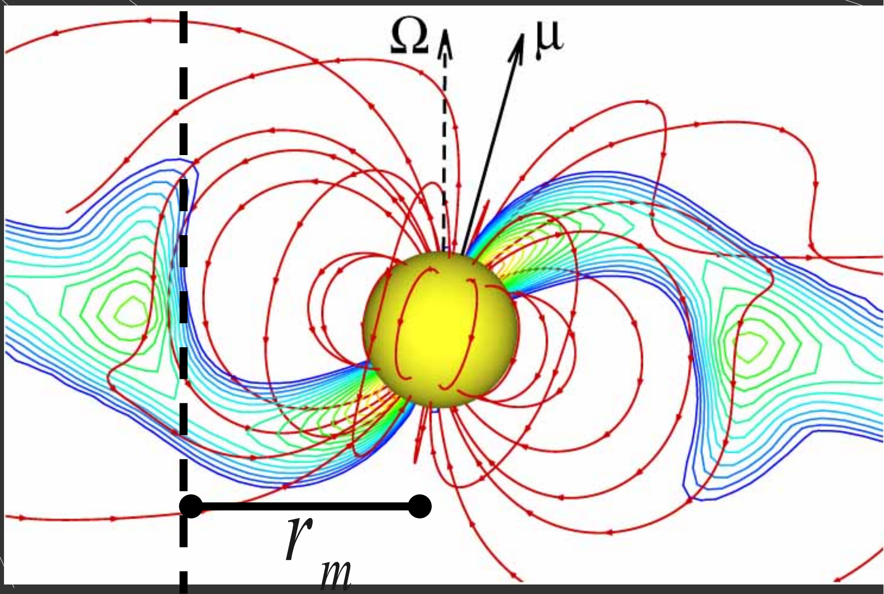
ACCRETION TORQUES



ACCRETION TORQUES

$$P_{mag} = \frac{B^2}{8\pi} >> (P_{gas}, P_{ram})$$

$$r_m \propto \left(\frac{2\mu^2 G^2 M_{NS}^2}{\dot{M}} \right) \propto M_{NS}^{1/7} R^{-2/7} \dot{M}^{-2/7} \mu^{4/7}$$



<u>Length scales</u>:

r_m = magnetospheric radius, where $\frac{B^2(r_m)}{8\pi} \sim \rho\, v^2(r_m)$

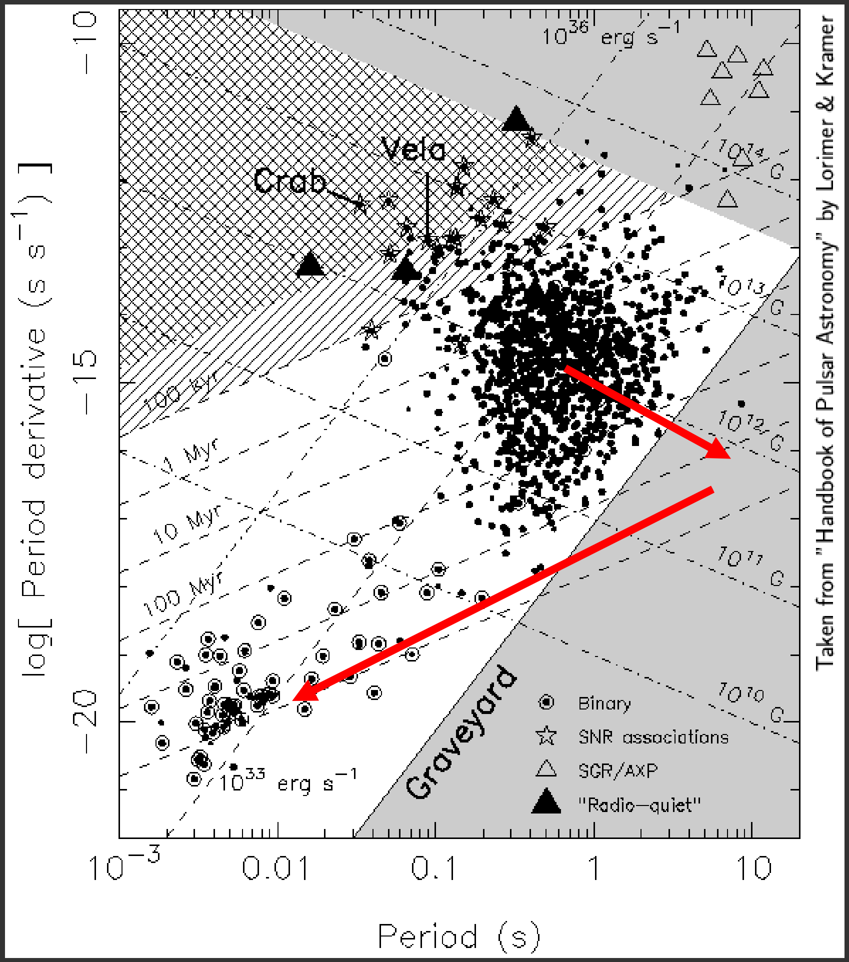
r_{ϖ} = corotation radius, where $\Omega_{kep}(r_{co}) = \Omega_{rot}$

The Recycling Scenario

Angular momentum is transferred from the accreting gas to the neutron star: the neutron star spins up

$$N \approx \dot{M}\sqrt{G M_{NS} r_m}$$

$$\dot{\nu} = \frac{N}{2\pi I} \propto \dot{M}^{6/7}$$

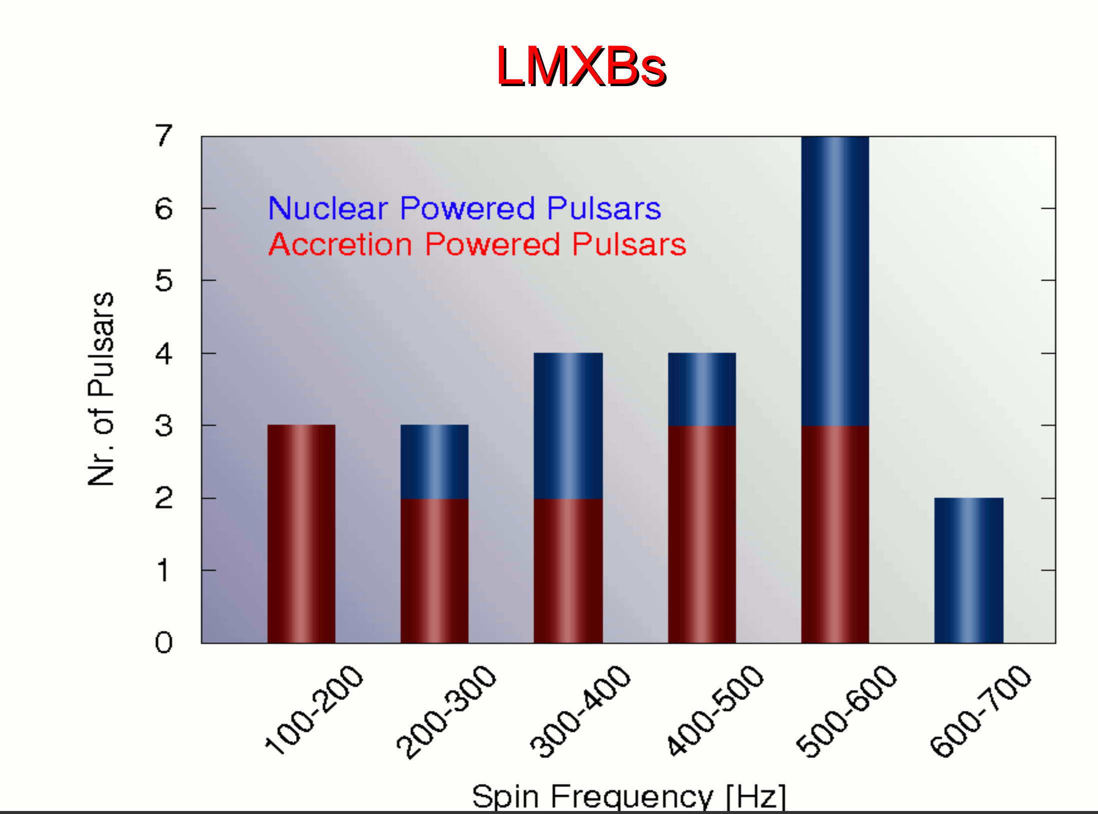


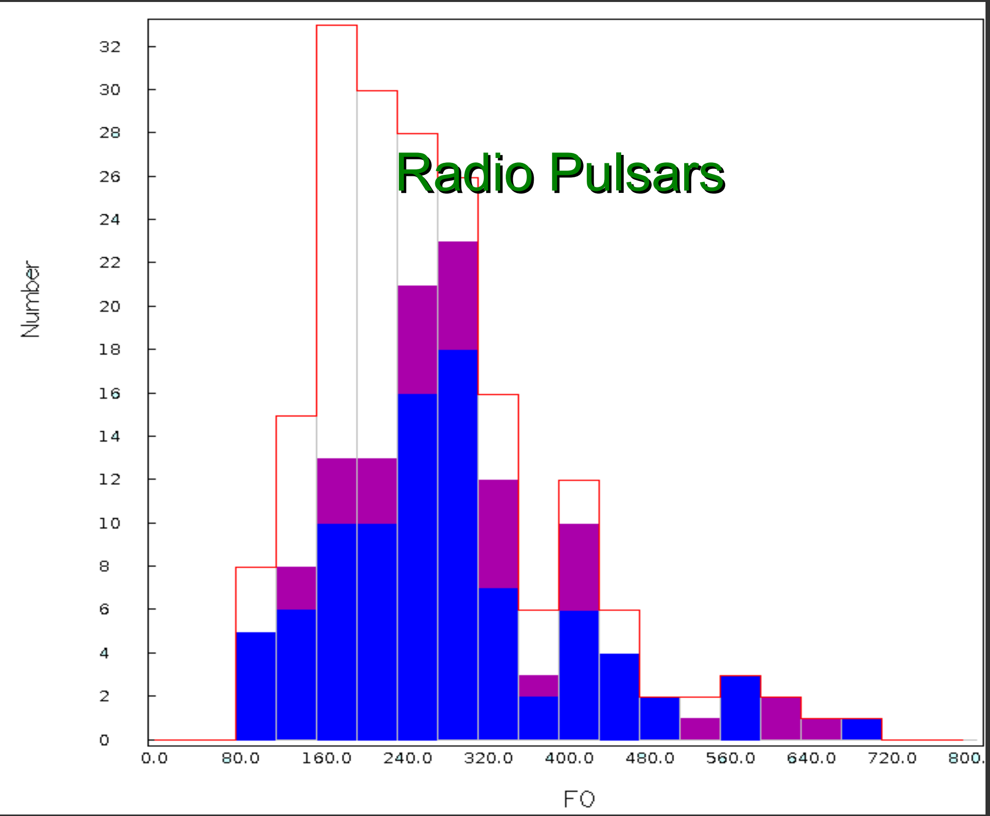
If the neutron star has a dynamically important magnetic field, then it is might become an accreting pulsar

13 AMXPs known

Source	ν_s (Hz)	P_{orb} (min)	f_x ($M_\odot$)	$M_{c,min}$ ($M_\odot$)	Type I Bursts	B-O
SAX J1808.4–3658 .	401	121	3.8×10^{-5}	0.043	Yes	Yes
XTE J1751–305	435	42.4	1.3×10^{-6}	0.014	No	No
XTE J0929–314	185	43.6	2.9×10^{-7}	0.0083	No	No
XTE J807–294	190	40.1	1.5×10^{-7}	0.0066	No	No
XTE J1814–338	314	257	2.0×10^{-3}	0.17	Yes	Yes
IGR J00291+5934 . .	599	147	2.8×10^{-5}	0.039	No	No
HETE J1900.1–2455	377	83.3	2.0×10^{-6}	0.016	Yes	Yes
Swift J1756.9–2508	182	54.7	1.6×10^{-7}	0.007	No	No
Aql X–1	550	1194	N/A	N/A	Yes	Yes
SAX J1748.9–2021 .	442	522	4.8×10^{-4}	0.1	Yes	No
NGC6440 X-2	206	57	1.6×10^{-7}	0.0067	No	No
IGR J17511-3057 . .	245	208	1.1×10^{-3}	0.13	Yes	Yes
Swift J1749.4-2807 .	518	529	5.5×10^{-2}	0.59	No	No

Spin Frequency Distribution





Chakrabarty et al. 2003, Patruno 2010

Measured Effect of Accretion Torques

Source Name	Spin Freq. Derivative (Expected)	Spin Freq. Derivative (Measured)
SAX J1808.4-3658	9e-14 Hz/s	< 2.5e-14 Hz/s
XTE J1807-294	1e-13 Hz/s	< 4e-14 Hz/s
XTE J1814-338	4e-14	<1.5e-14 Hz/s
SWIFT J1756.9	2e-13 Hz/s	<3e-13 Hz/s
IGR J00291+5934	1e-12 Hz/s	5e-13 Hz/s

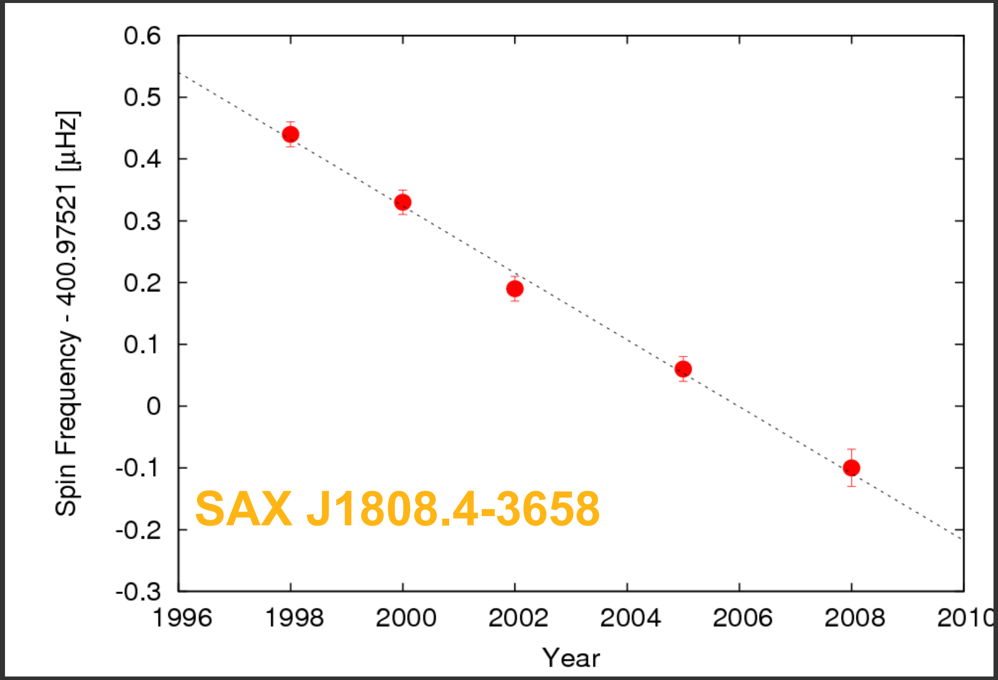
Why the spin up (if any) is much smaller than expected ?

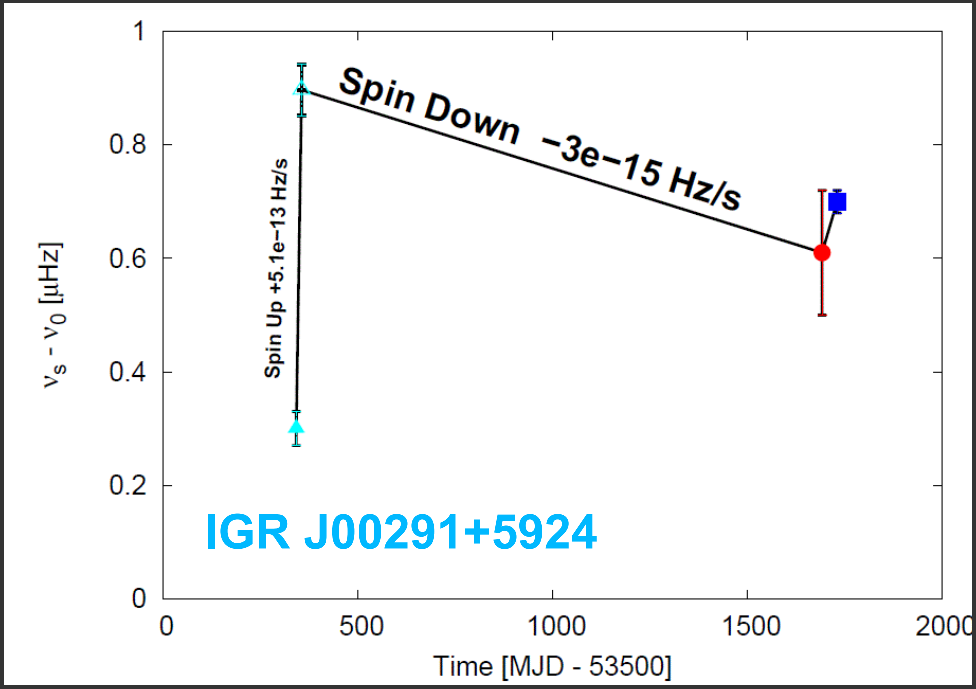
Gravitational Waves ?

(Bildsten 1998)

RECYCLING SCENARIO

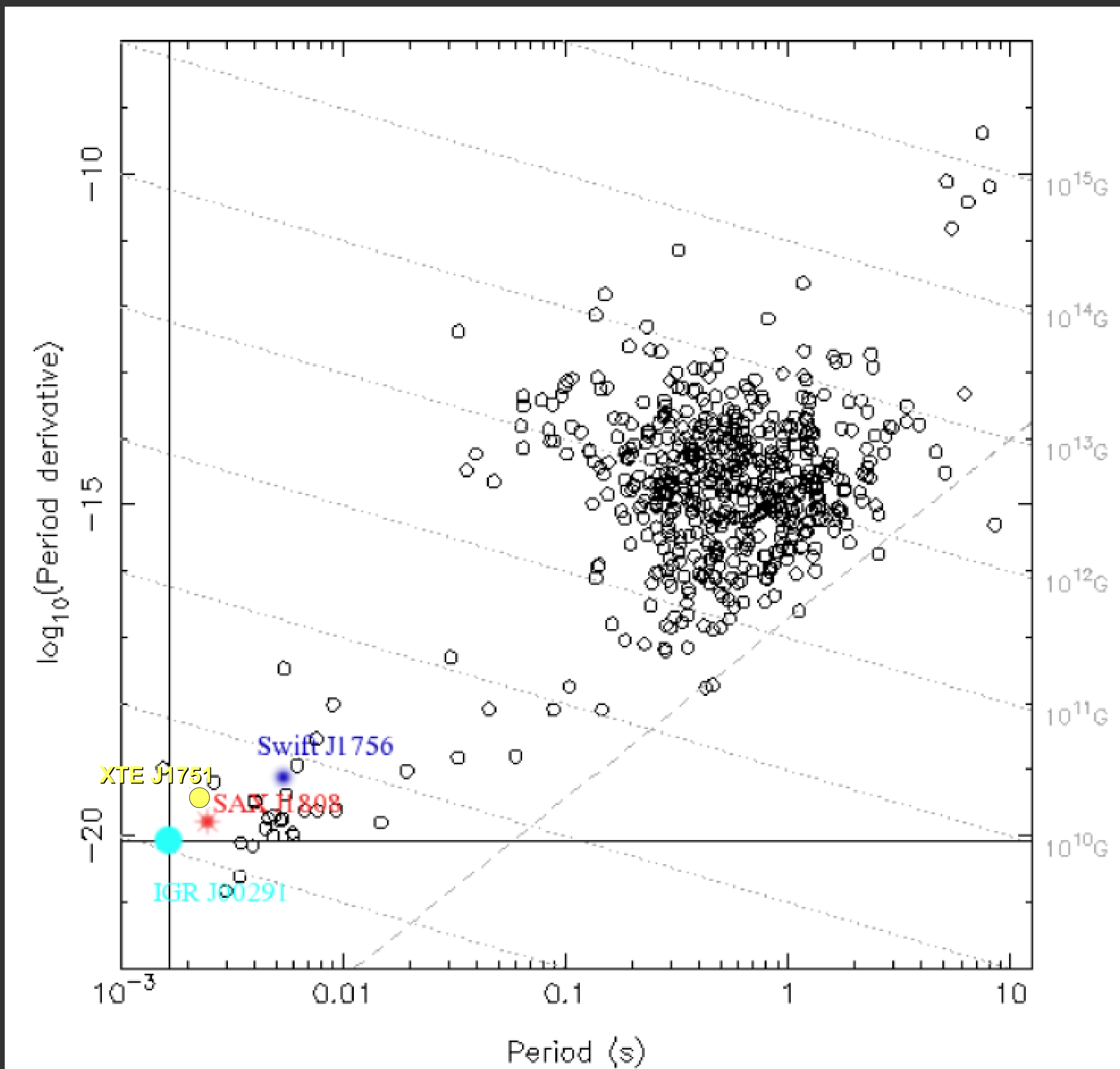
Long Term Spin Evolution





Hartman et al. 2008, 2009, 2011, Patruno 2010, Papitto et al. 2011

The Recycling Scenario for AMXPs



Hypotheses:

1. B field is purely dipolar

2. Spin down in quiescence is dominated by magneto dipole radiation

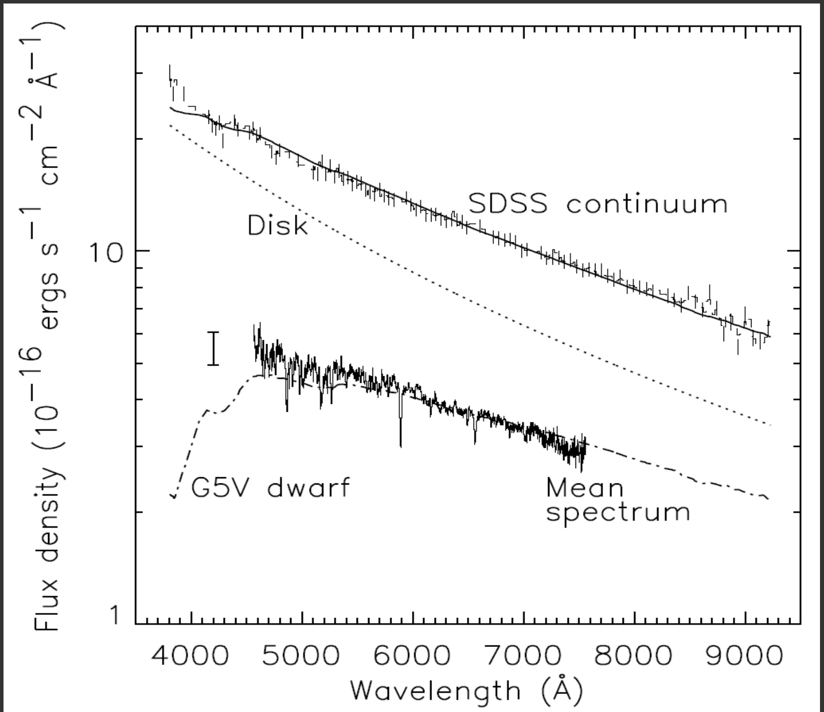
IGR J00291+5934	1.5 - 2.0 x 10^8 G
SAX J1808.4-3658	2.0 - 2.8 x 10^8 G
Swift J1756.9-2508	0.4 - 9 x 10^8 G
XTE J1751-245	3.6-4.4 x 10^8 G

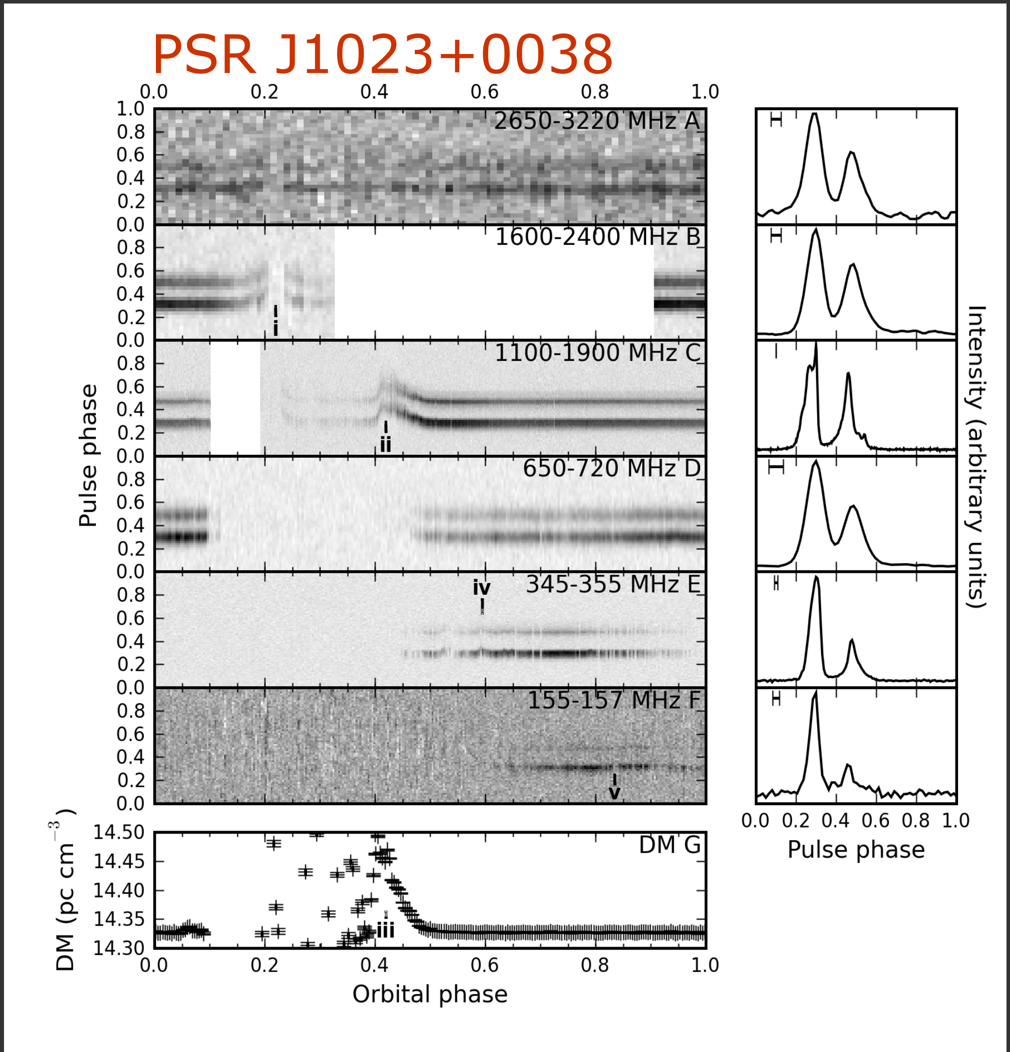
Falanga et al. 2005, Hartman et al. 2009, 2010, Patruno 2010, Ibragimov et al. 2009, Riggio et al. 2011, Patruno et al. 2009

RADIO/ACCRETING PULSAR ?

1.69 ms spin period

4.8 hr orbital period





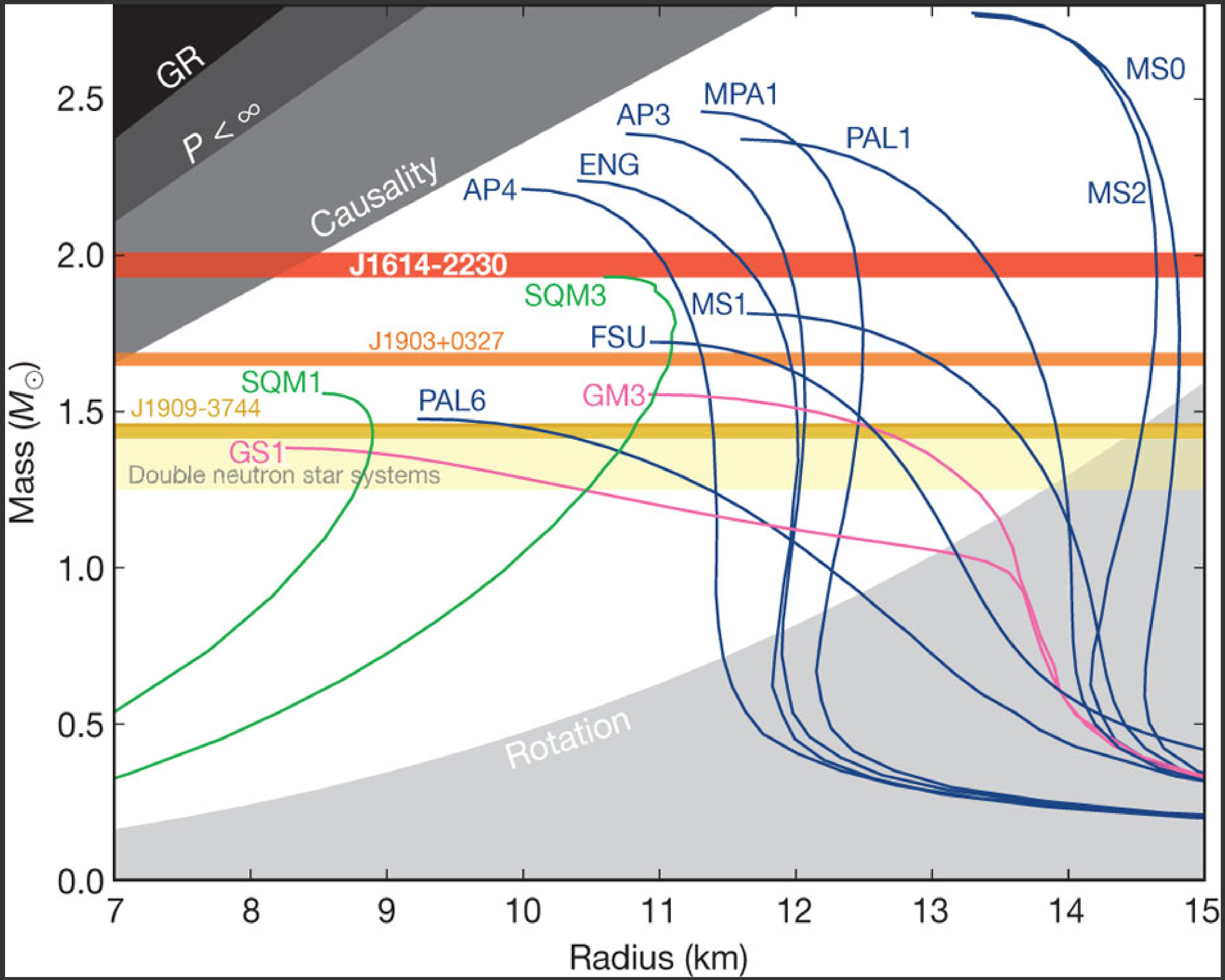
Accretion disk in 2001

Pulses in X-ray with XMM-Newton in 2009 ?

Archibald et al. (2009, 2010), Wang et al. (2010)

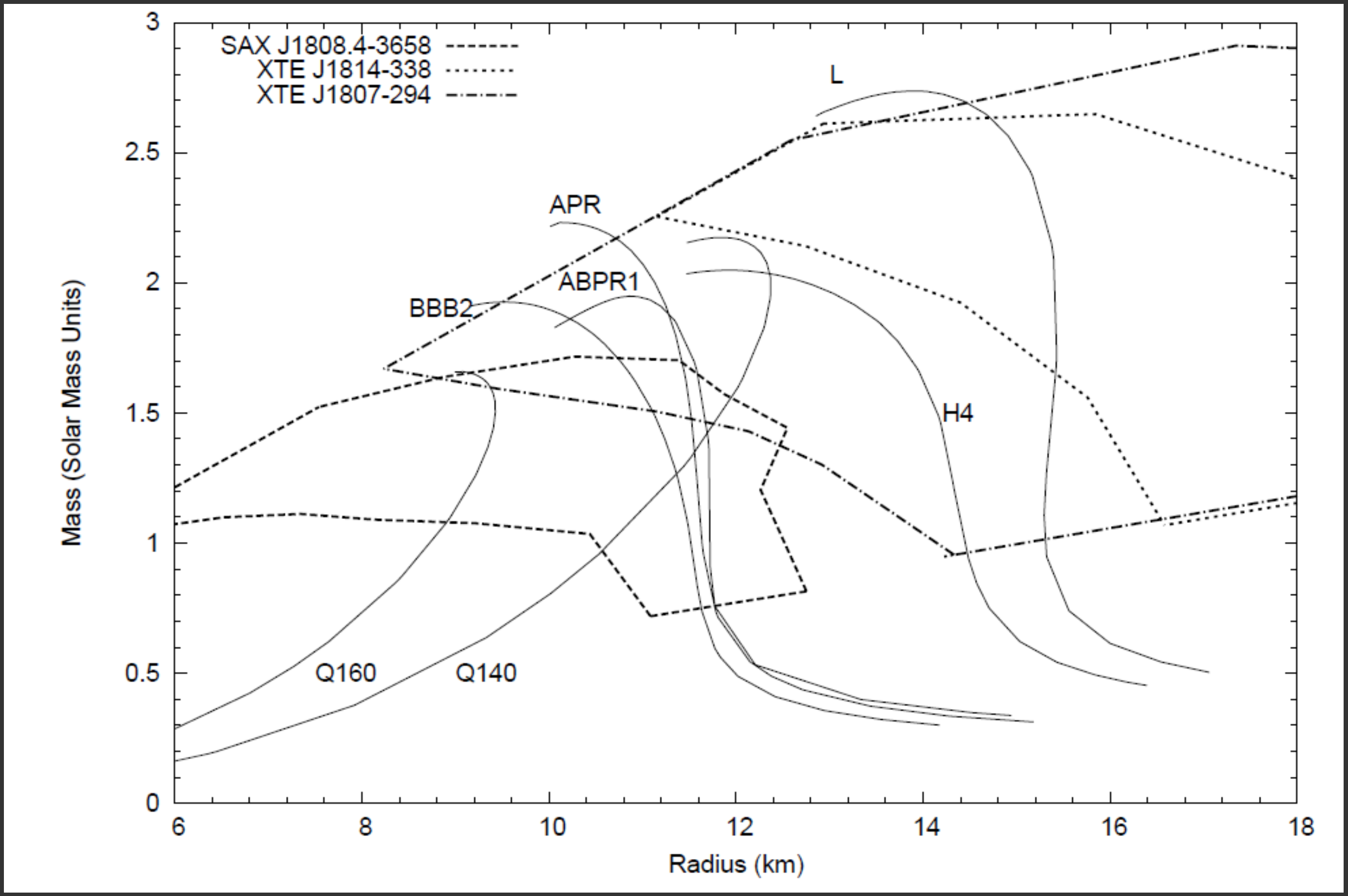
ULTRA DENSE MATTER

Do Sub-ms Pulsars exist ?



Demorest et al. 2010
Hessels et al. 2006

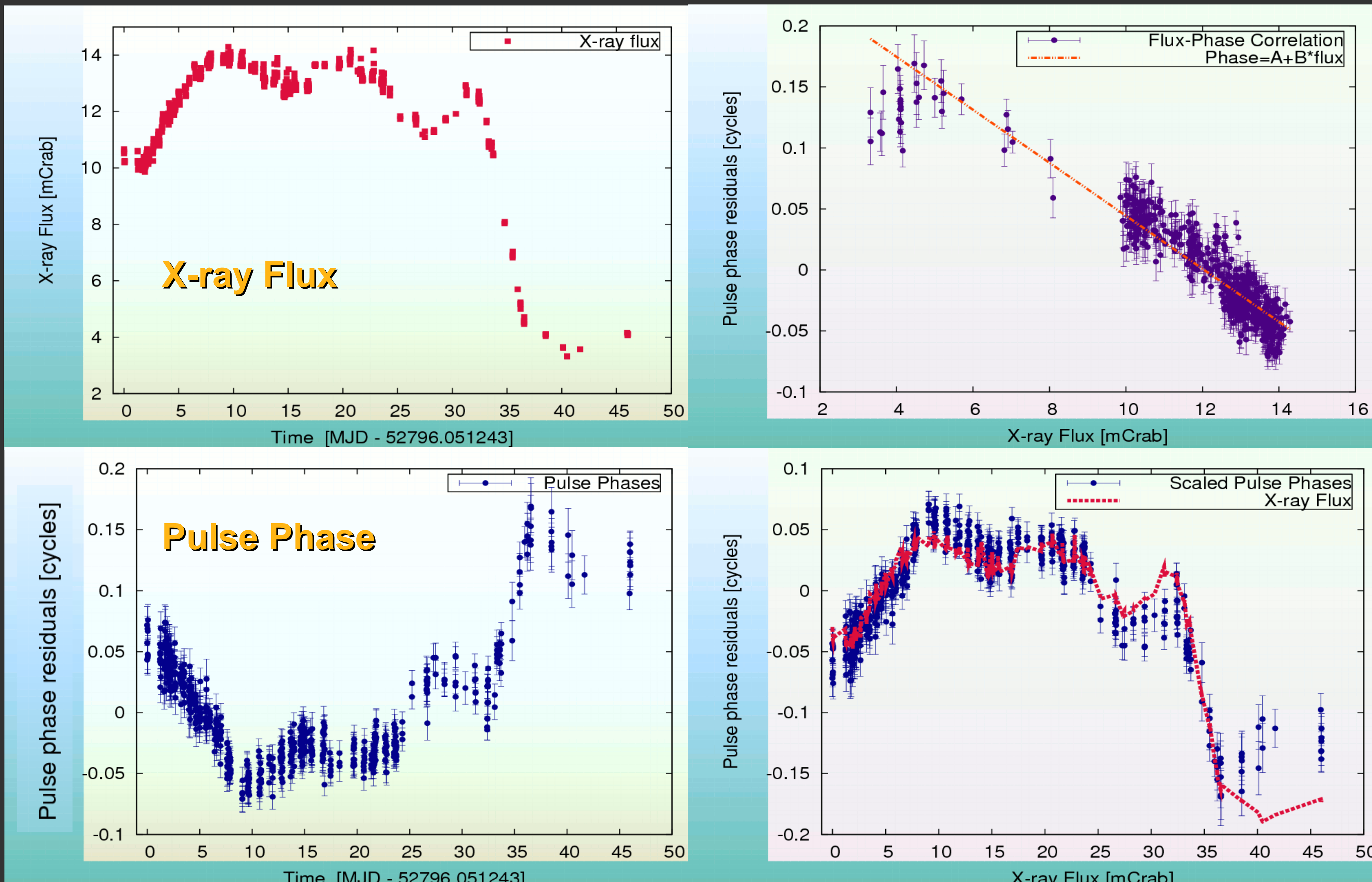
Pulse Profile Modeling



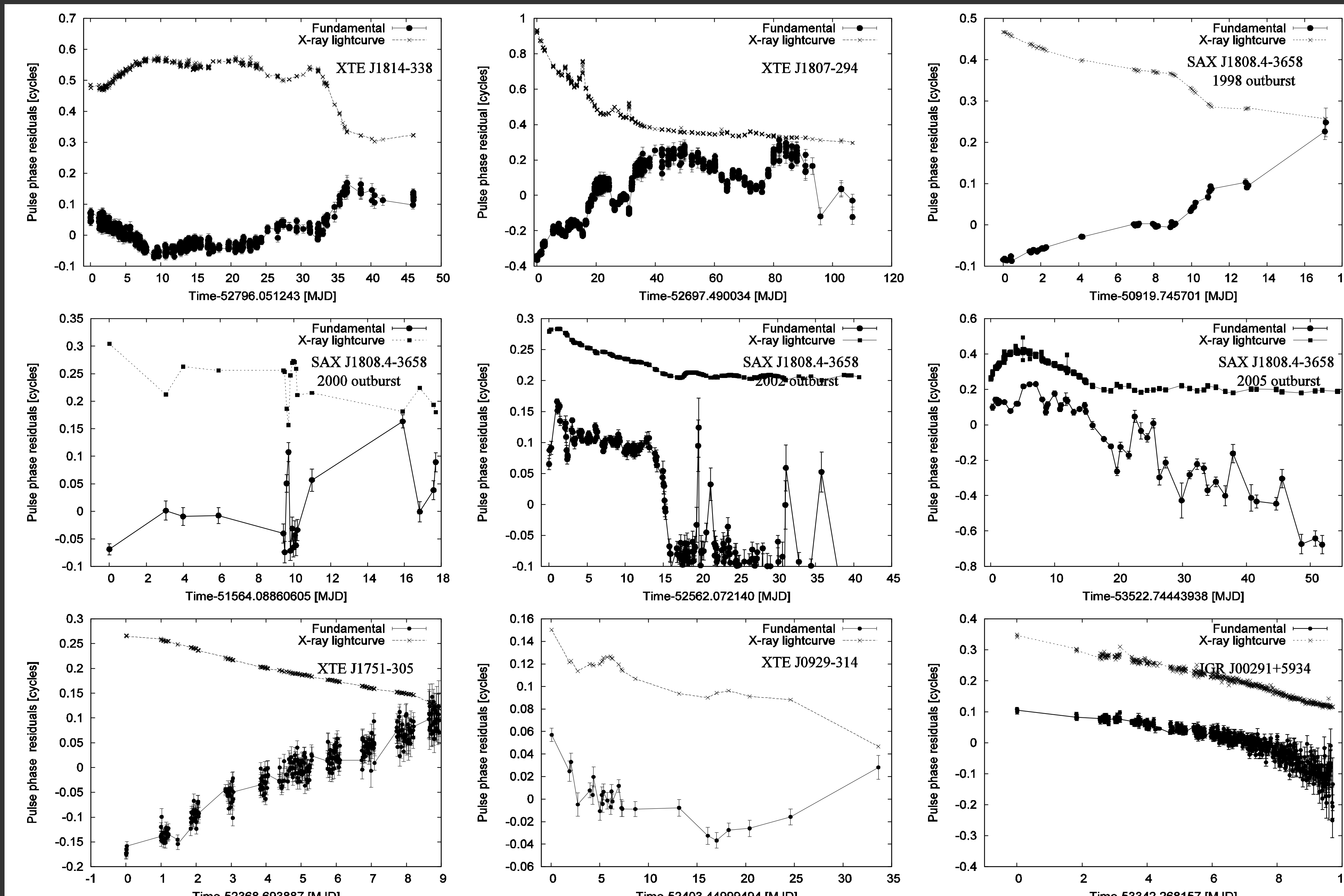
Leahy, Morsink & Chou 2011
See also Poutanen & Gierlinski 2003, Poutanen & Beloborodov 2006, Cadeau et al. 2005, 2007

HOT SPOT MOTION ?

PULSE PHASE X-RAY FLUX CORRELATION

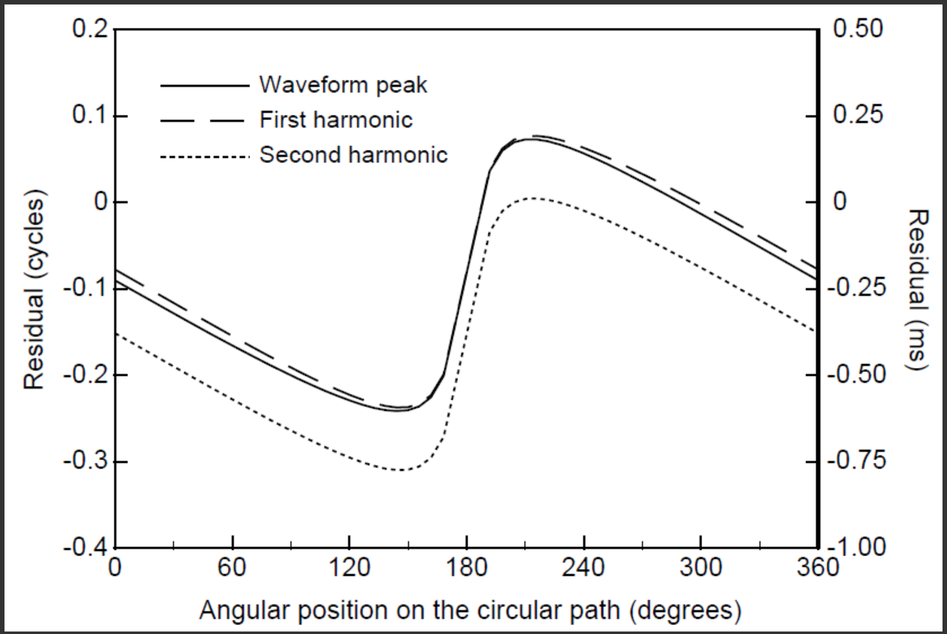


Patruno, Wijnands & van der Klis 2009; Haskell & Patruno 2011

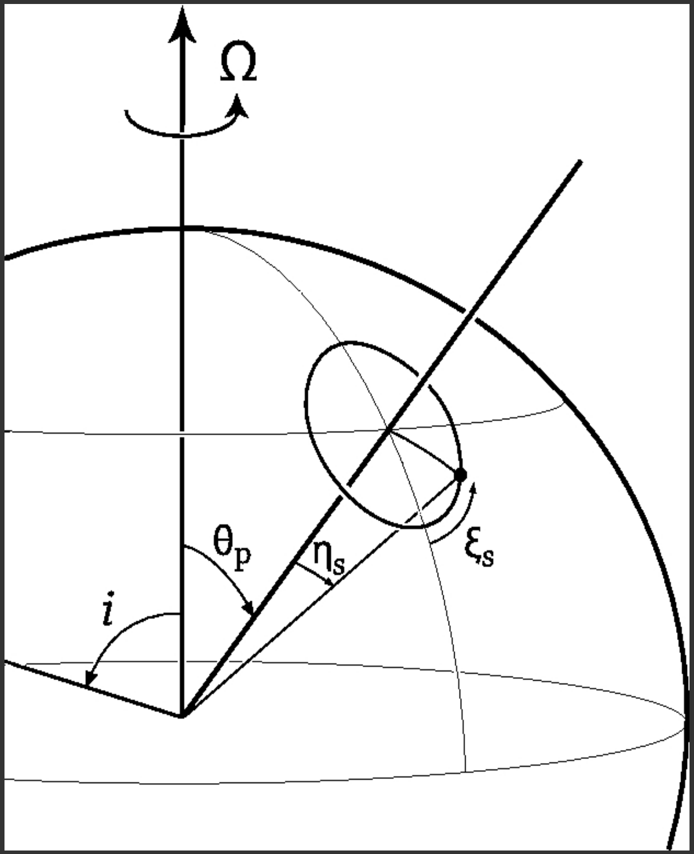


Patruno, Wijnands & van der Klis 2009

HOT SPOT DISPLACEMENTS



Lamb et al. (2009)

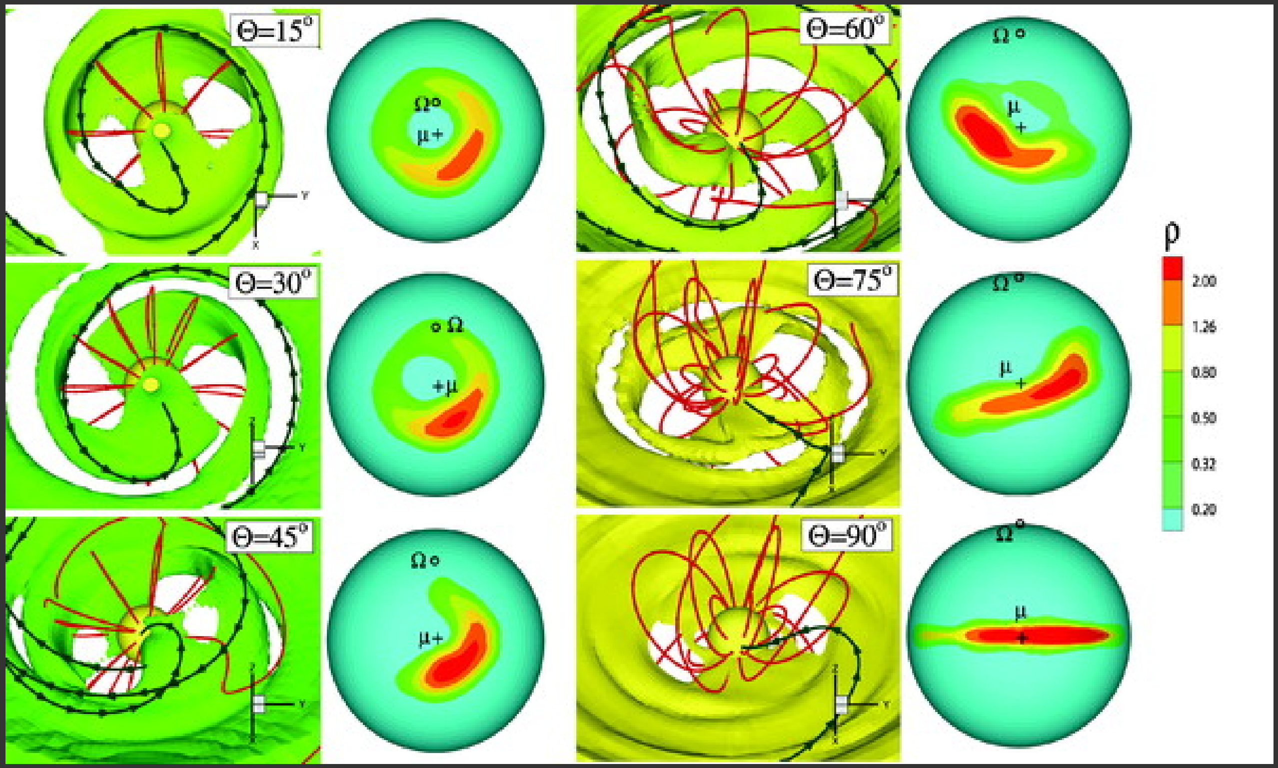


SAX J1808-3658: 0.2 cycles in 2002-2005-2008 outbursts (Burderi et al. 2006, Hartman et al. 2008,2009)

XTE J1807-294: up to 0.6 cycles (Chou et al. 2007, Patruno et al. 2010)

XTE J1814-338: 0.3 cycles (Watts et al. 2008, Haskell & Patruno 2011)

MHD Simulations

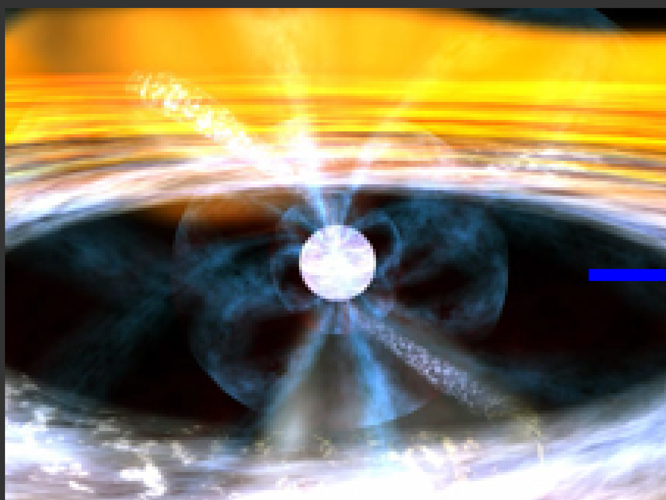


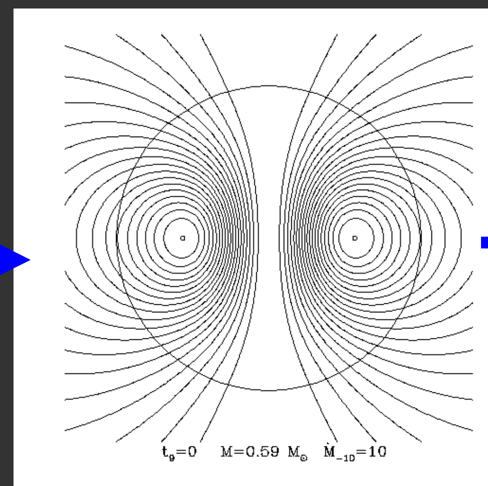
Romanova et al. 2004

CONCLUSIONS

- Strong evidence that AMXPs are indeed the pro-genitors of radio ms-pulsars.
- Some AMXPs show no clear evidence of accretion torques. Presence of GWs ? Some AMXPs are close to spin equilibrium ? No sub-ms pulsars ??
- Understanding of pulse profile formation is improving: promising potential to constrain EoS of ultra-dense matter

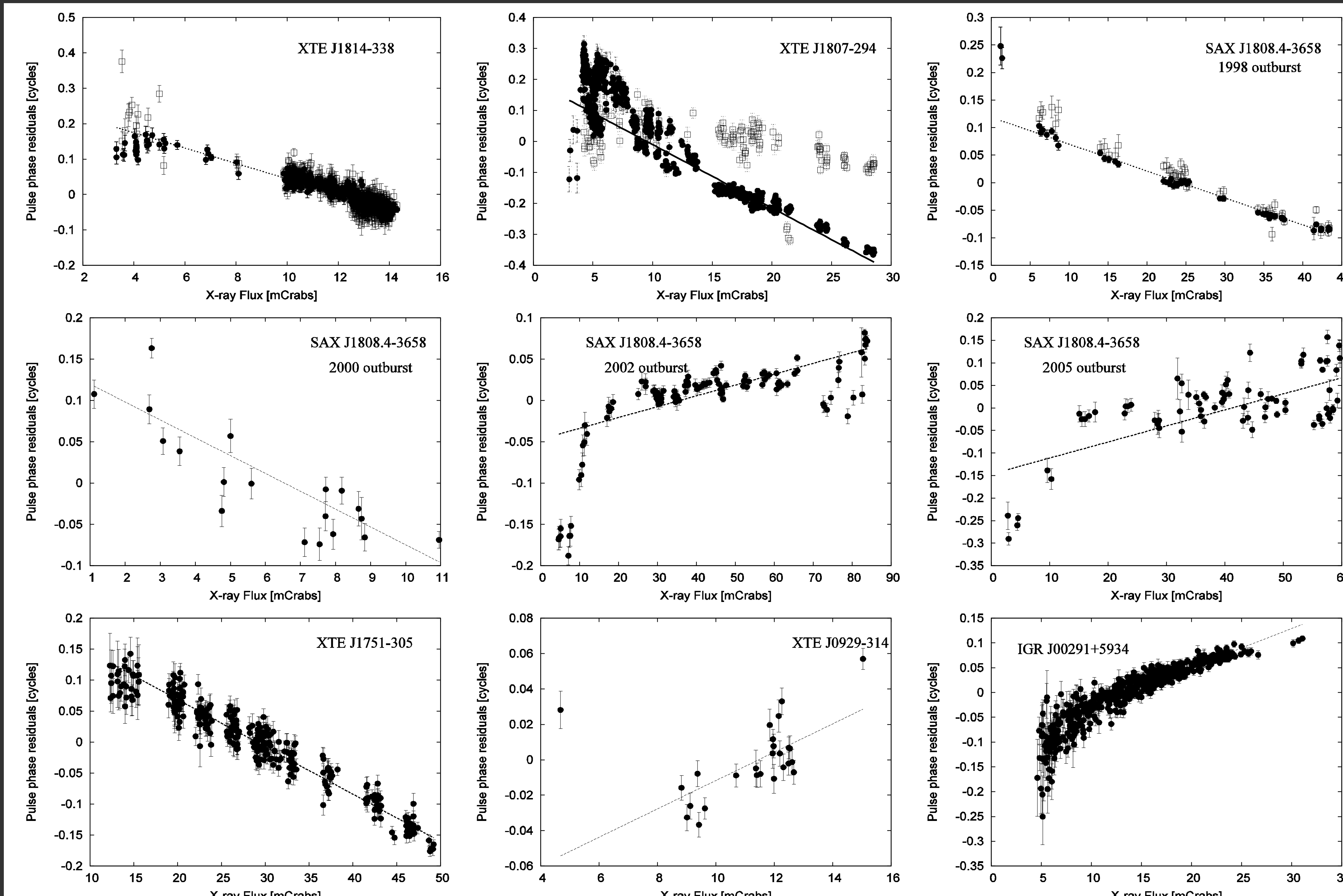
Why only a small number of LMXBs pulsates ?



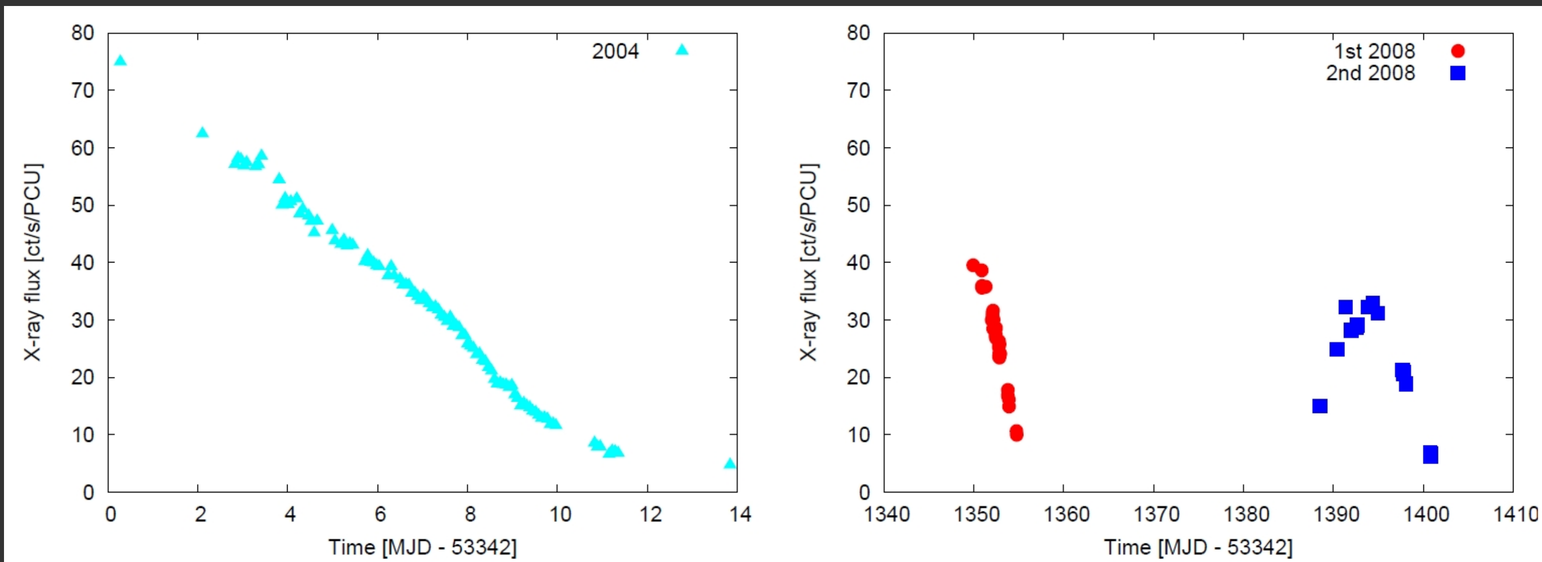


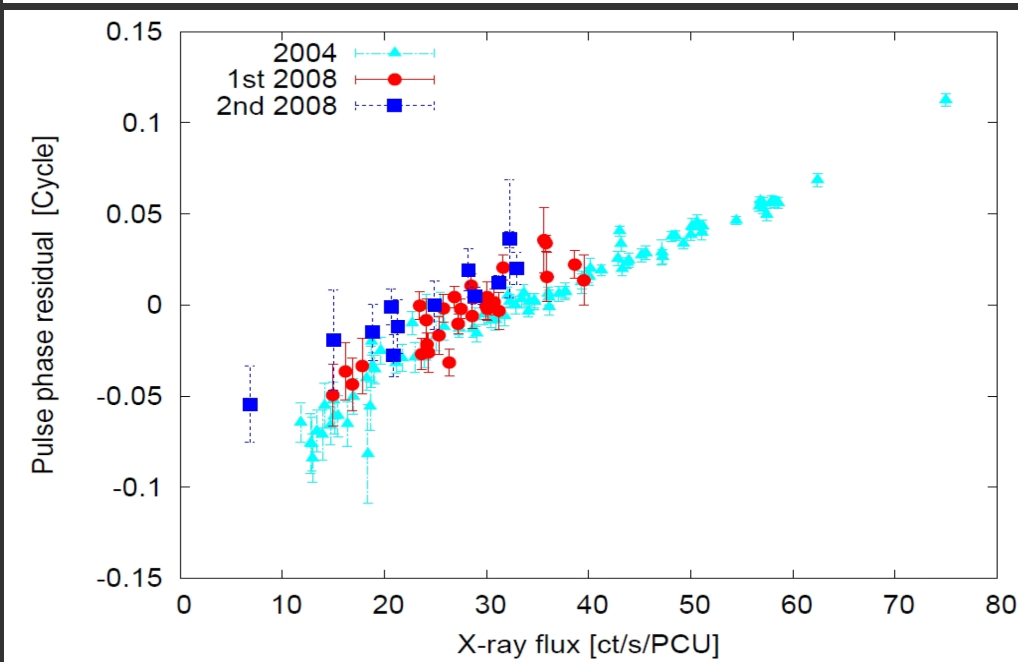
Several mechanism might explain the lack of pulsations in many LMXBs:

1. Magnetic Burial (Cumming et al. 2001)
2. Rotational and Magnetic Poles Alignement (Lamb et al. 2009)
3. Smearing and Scattering of Pulsed Emission (Brainerd & Lamb 1987)
4. Gravitational Lensing (Wood, Ftaclas & Kearney 1988)
5. Interchange Instabilities (Kuulkarni & Romanova 2008)


XTE J1814-338
XTE J1807-294
SAX J1808.4-3658
1998 outburst
SAX J1808.4-3658
2000 outburst
SAX J1808.4-3658
2002 outburst
SAX J1808.4-3658
2005 outburst
XTE J1751-305
XTE J0929-314
IGR J00291+5934
Pulse phase residuals [cycles]
X-ray Flux [mCrabs]

HOT SPOT MOTION ?





Evidence that <u>the same</u>
ordered process
is at work in
<u>different outbursts</u>

Patruno 2010