Ultraluminous X-ray pulsars

Juri Poutanen

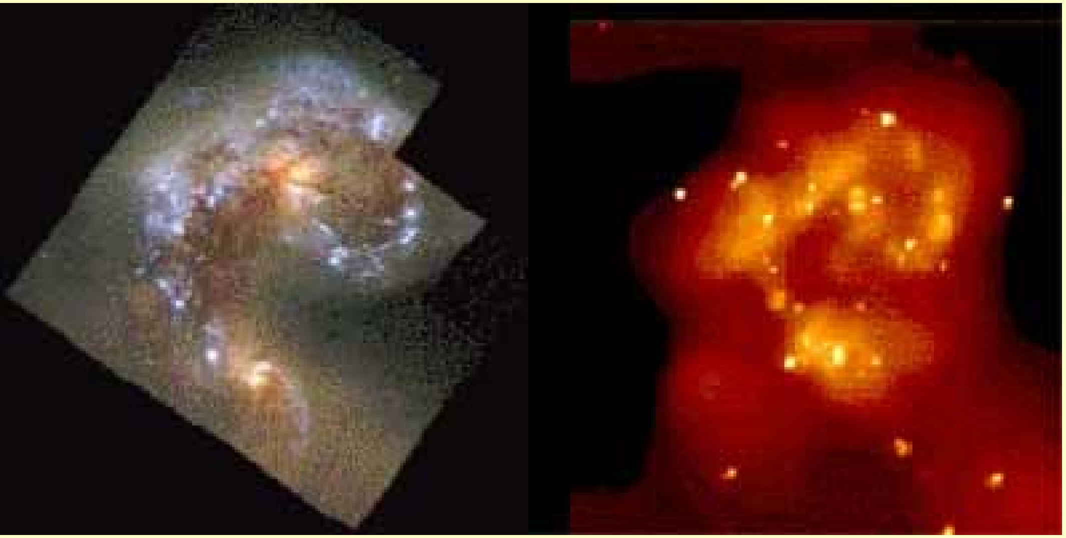
(University of Turku, Finland)

Sergey Tsygankov, Alexander Mushtukov, Valery Suleimanov, Alexander Lutovinov, Anna Chashkina, Pavel Abolmasov

Plan:

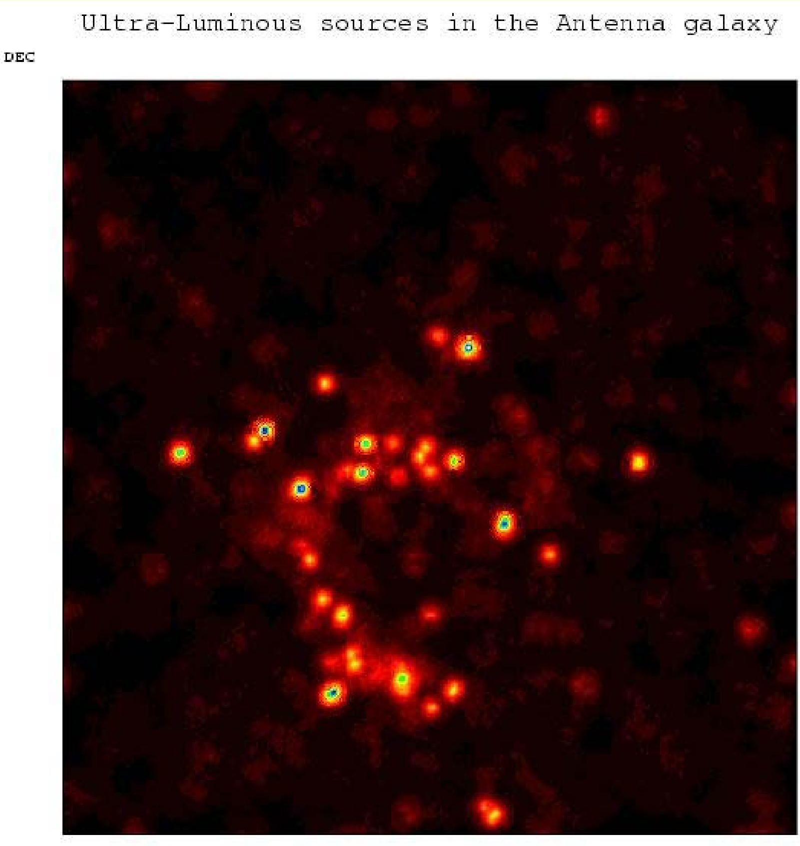
- ULX - general properties (before 2014)
- Models (before 2014)
- ULX pulsars: P, Pdot, B?
- In spin equilibrium or not? Beamed or not? Winds or not?

Ultra- Luminous X-ray Sources



ULX are discovered with Einstein observatory in the 80s.

- Bolometric luminosity > Eddington limit for a $20\ M_\odot$ black hole ($3\text{x}10^{39}$ erg/s) - $M_{BH} < 20\ M_\odot$ from “normal” stellar evolution
- Not at galaxy nucleus (not AGN)
- Unresolved (< 0.6” with *Chandra*)



HST and Chandra images of the star-forming galaxy NGC4038- the “Antennae”

Models for ULX (before 2014)

- Super-Eddington accretion onto a stellar-mass black hole (e.g. King 2001, Begelman et al. 2006, Poutanen et al. 2007)
- Sub-Eddington accretion onto intermediate mass black holes (Colbert & Mushotzky 2001)
- Young rotation-powered pulsar (Medvedev & Poutanen 2013)
- Accreting X-ray pulsars (discussed by us already in 2010).

Super-Eddington accretion

- Slim disk models Accretion rate is large, but most of the released energy is advected towards the BH.

$$\dot{M}(r) = \dot{M}_0$$

- Super-disks with winds

Accretion rate is large, but most of the mass is blown away by radiation. Only the Eddington rate goes to the BH.

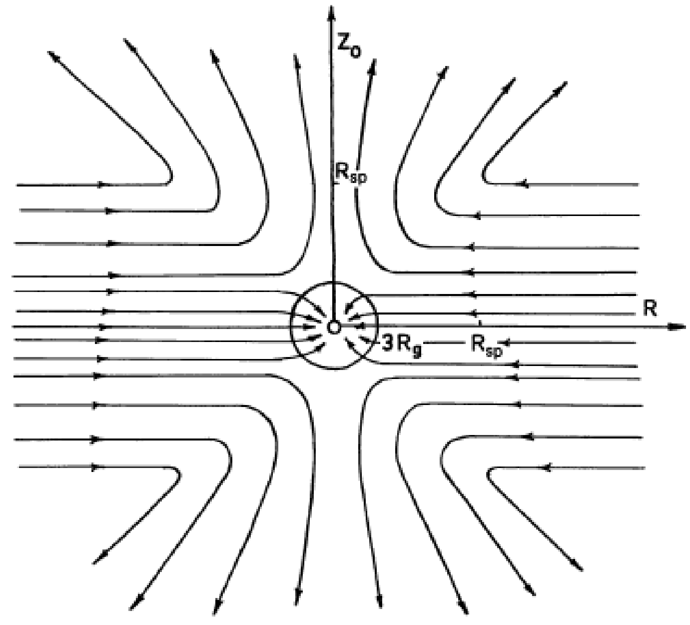


Fig. 8. Lines of matter flow at supercritical accretion (the disk section along the Z-coordinate). When $R < R_{sp}$ spherization of accretion takes place and the outflow of matter from the collapsar begins

$$\dot{M}(r) = \dot{M}_0 \frac{r}{R_{sph}}$$

$$\dot{M}(r_{in}) = \dot{M}_{Edd}$$

$$R_{sph} \approx R_{\mathrm{in}} \frac{\dot{M}_0}{\dot{M}_{Edd}}$$ - spherization radius

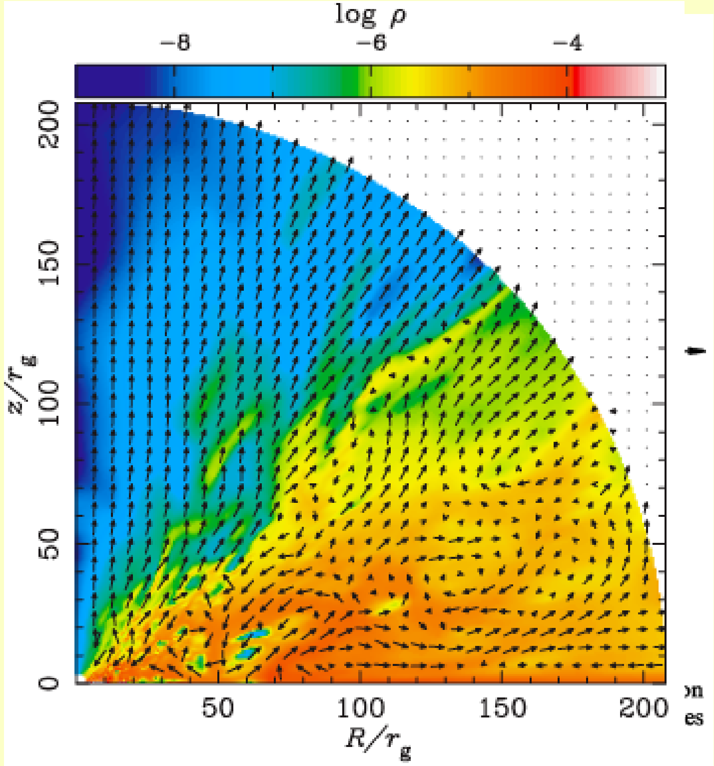
Shakura & Sunyaev 1973

Super-Eddington accretion

- Slim disk models Accretion rate is large, but most of the released energy is advected towards the BH. $\dot{M}(r) = \dot{M}_0$

- Super-disks with winds

  Accretion rate is large, but most of the mass is blown away by radiation. Only the Eddington rate goes to the BH.



$$\dot{M}(r) = \dot{M}_0 \frac{r}{R_{sph}}$$

$$\dot{M}(r_{in}) = \dot{M}_{Edd}$$

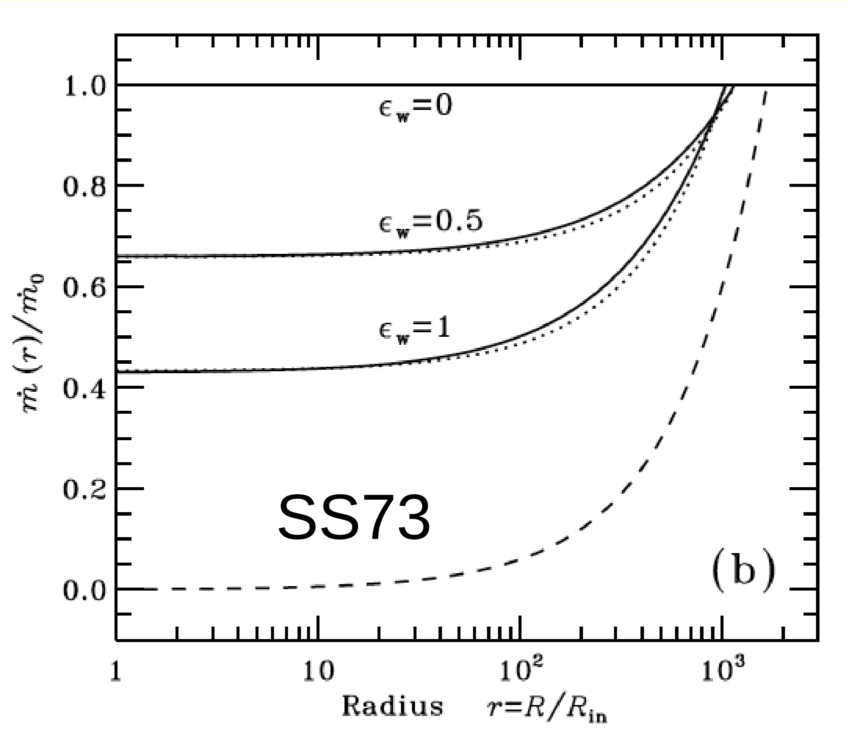
$$R_{sph} \approx R_S \frac{\dot{M}_0}{\dot{M}_{Edd}}$$ -spherization radius

Ohsuga et al. 2005;

Super-Eddington accretion

Super-disks with winds and advection

Accretion rate is large, a lot of mass is blown away by radiation (using fraction ε_W of available radiative flux), but still a significant fraction goes to the BH.



$$\dot{M}(r) = \dot{M}_0 + \left(\dot{M}_0 - \dot{M}_{in}\right)\frac{r}{R_{sph}}$$

$$\frac{\dot{M}_{in}}{\dot{M}_0} = \frac{1-a}{1-a(0.4\dot{m}_0)^{-1/2}}$$

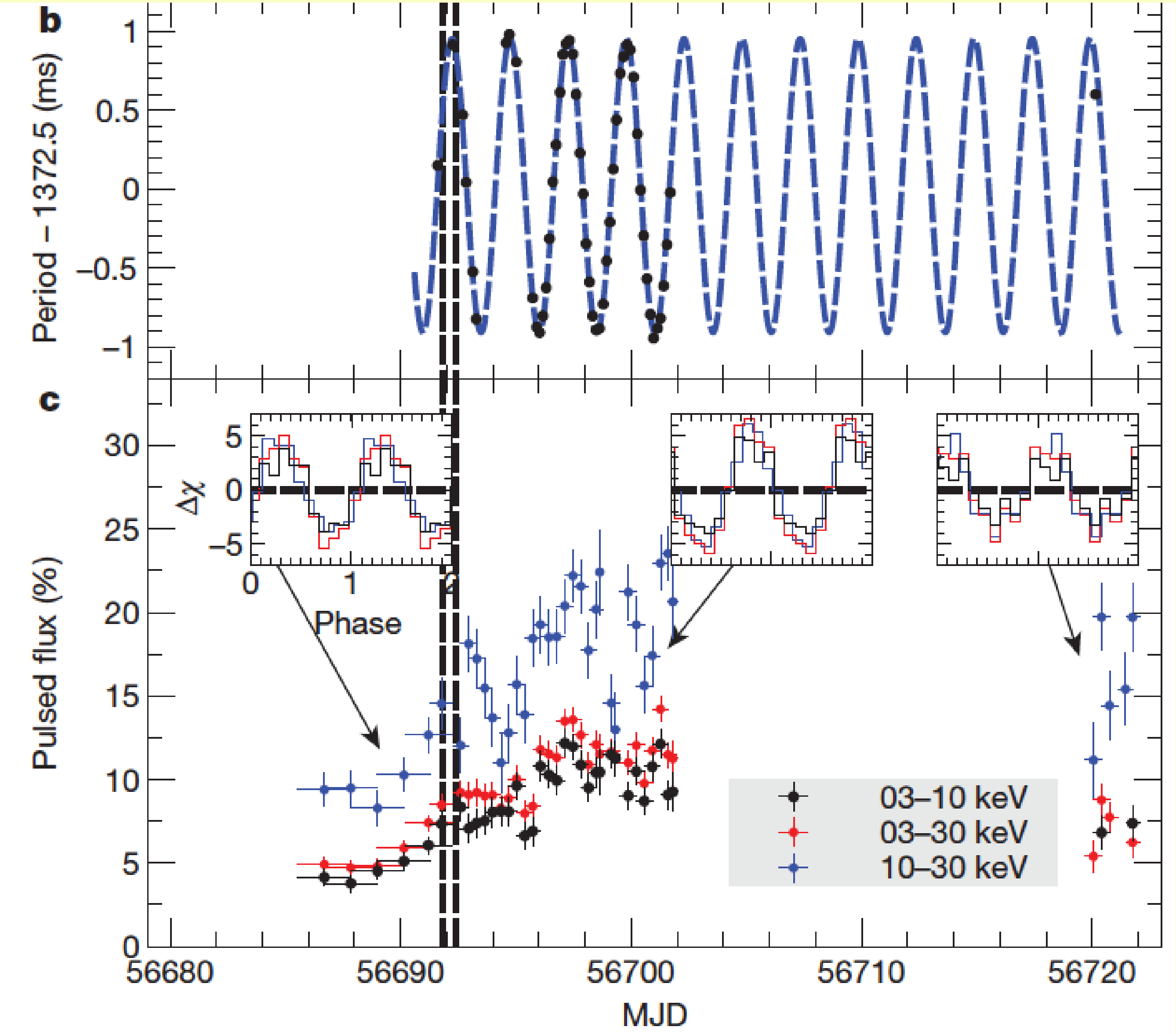
$$a = \varepsilon_W(0.83 - 0.25\varepsilon_W)$$

Poutanen et al. (2007)

ULX pulsars

- M82 X-2 pulsar was discovered by Nustar (Bachetti et al. 2014)
- Pulsations were searched for before with XMM-Newton without much success.
- Two more sources were found later in XMM-Newton and Nustar data (Israel et al. 2017a,b; Fürst et al. 2017).

M82 X-2

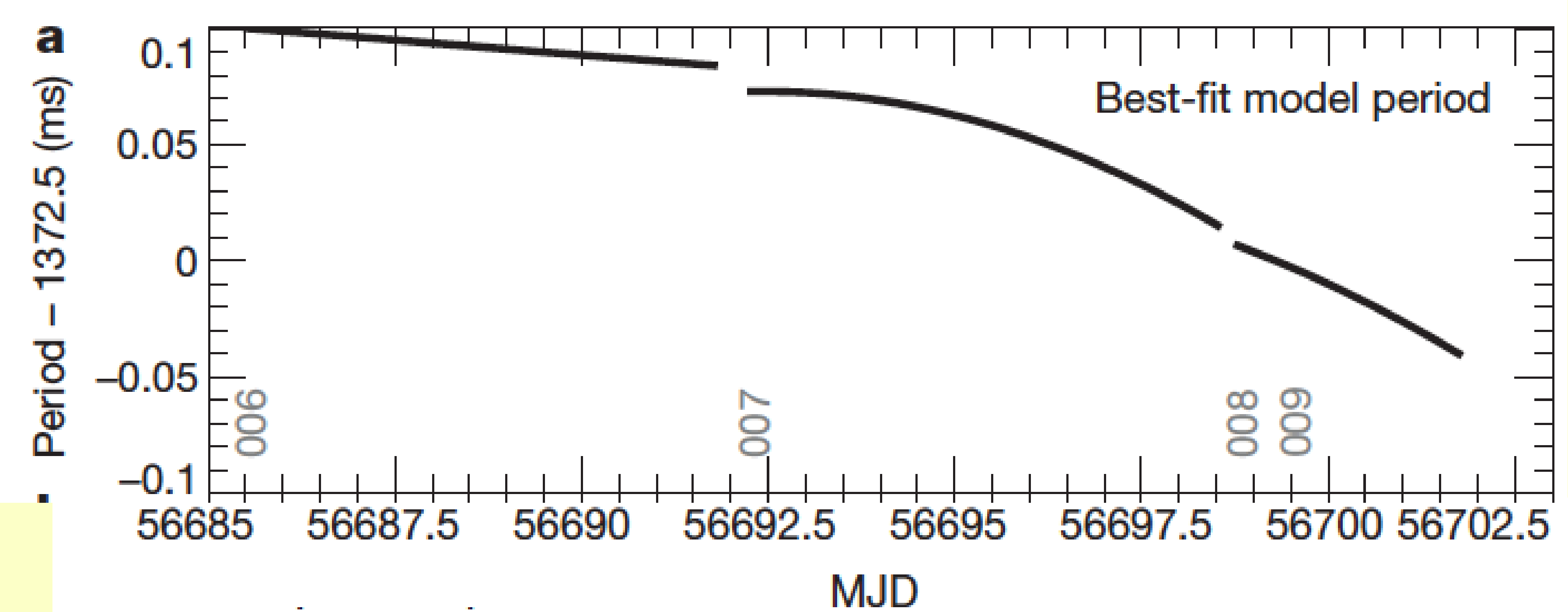


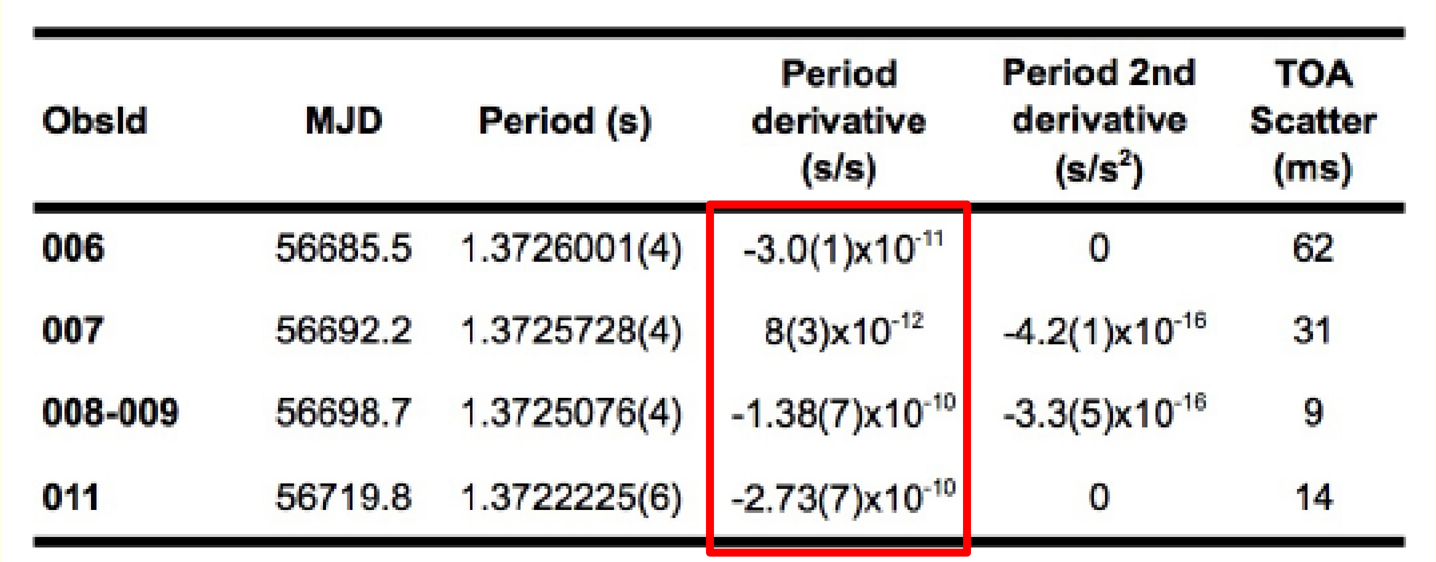
Bachetti et al. 2014

M82 X-2

- Orbital period 2.518 days
- Mass function 2.1 solar mass =>
- For 1.4 solar mass neutron star, companion has M_c>5.2 solar mass for i<60 deg.
- Unstable accretion from a more massive companion on thermal timescale => huge Mdot (like SS433).

M82 X-2 spin up





ObsId	MJD	Period (s)	Period derivative (s/s)	Period 2nd derivative (s/s^2)	TOA Scatter (ms)
006	56685.5	1.3726001(4)	$-3.0(1)\times10^{-11}$	0	62
007	56692.2	1.3725728(4)	$8(3)\times10^{-12}$	$-4.2(1)\times10^{-16}$	31
008-009	56698.7	1.3725076(4)	$-1.38(7)\times10^{-10}$	$-3.3(5)\times10^{-16}$	9
011	56719.8	1.3722225(6)	$-2.73(7)\times10^{-10}$	0	14

Spin equilibrium in M82 X-2

- P/Pdot=300 yr
- Object has to be close to spin equilibrium.
- Pdot (which even changes the sign) does not really tell anything about Mdot or B-field, because the accretion and magnetic torques are in balance.
- Maximum Pdot gives a lower limit on the accretion rate.

Minimum Mdot

- Maximum spin up torque is $\dot{M}(GMr_{\rm c})^{1/2}$

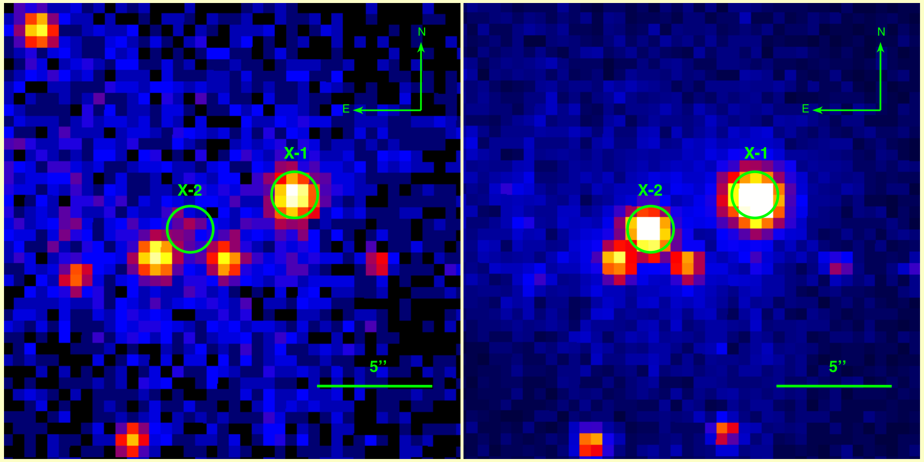
$$-2\pi I\dot{P}/P^2 \leq \dot{M}(GMr_{\rm c})^{1/2}$$

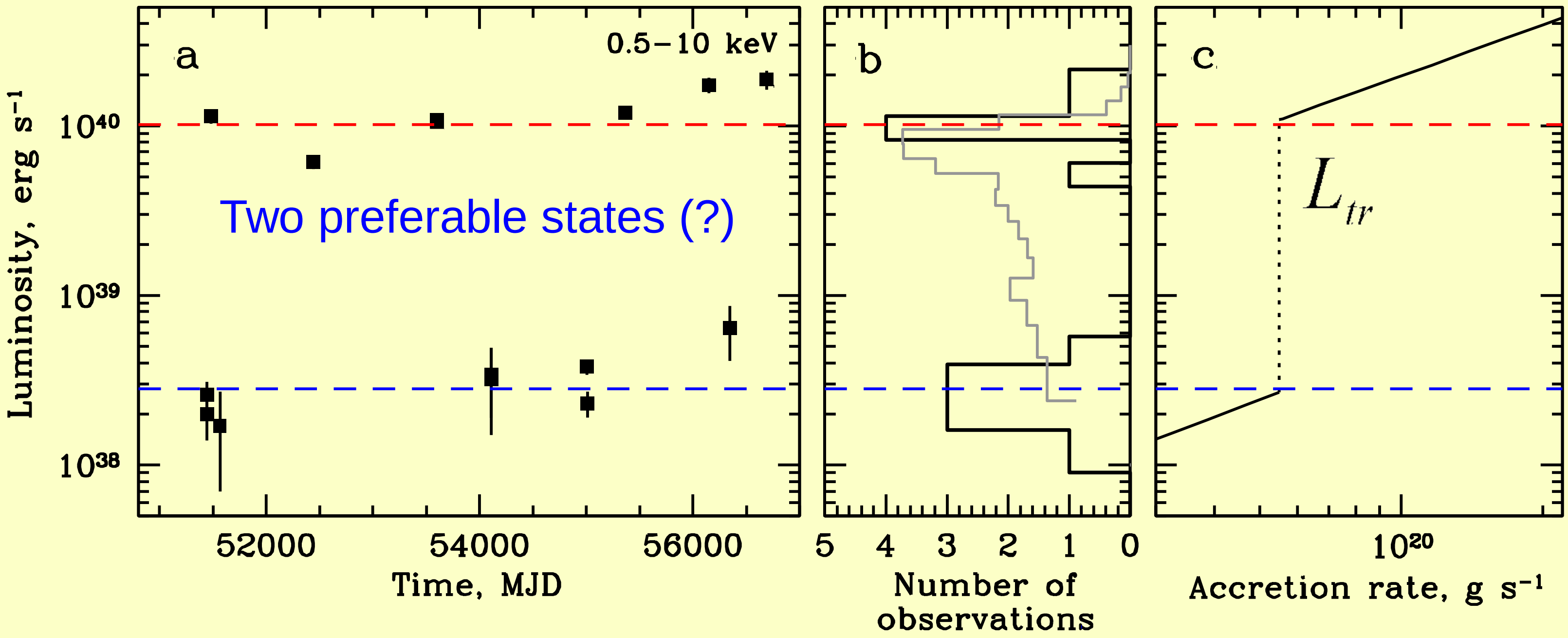
$$\dot{M} \geq 3.55\times 10^{18}\,\dot{P}_{-10}P^{-7/3}\,{\rm g s^{-1}}$$

- M82 X-2 $\dot{P} \simeq -2.7\times 10^{-10}\ {\rm s s^{-1}}$ $\dot{M} \geq 4.6\times\ 10^{18}\,{\rm g s^{-1}}$

Possible propeller effect in M 82 X-2

Tsygankov et al. 2016

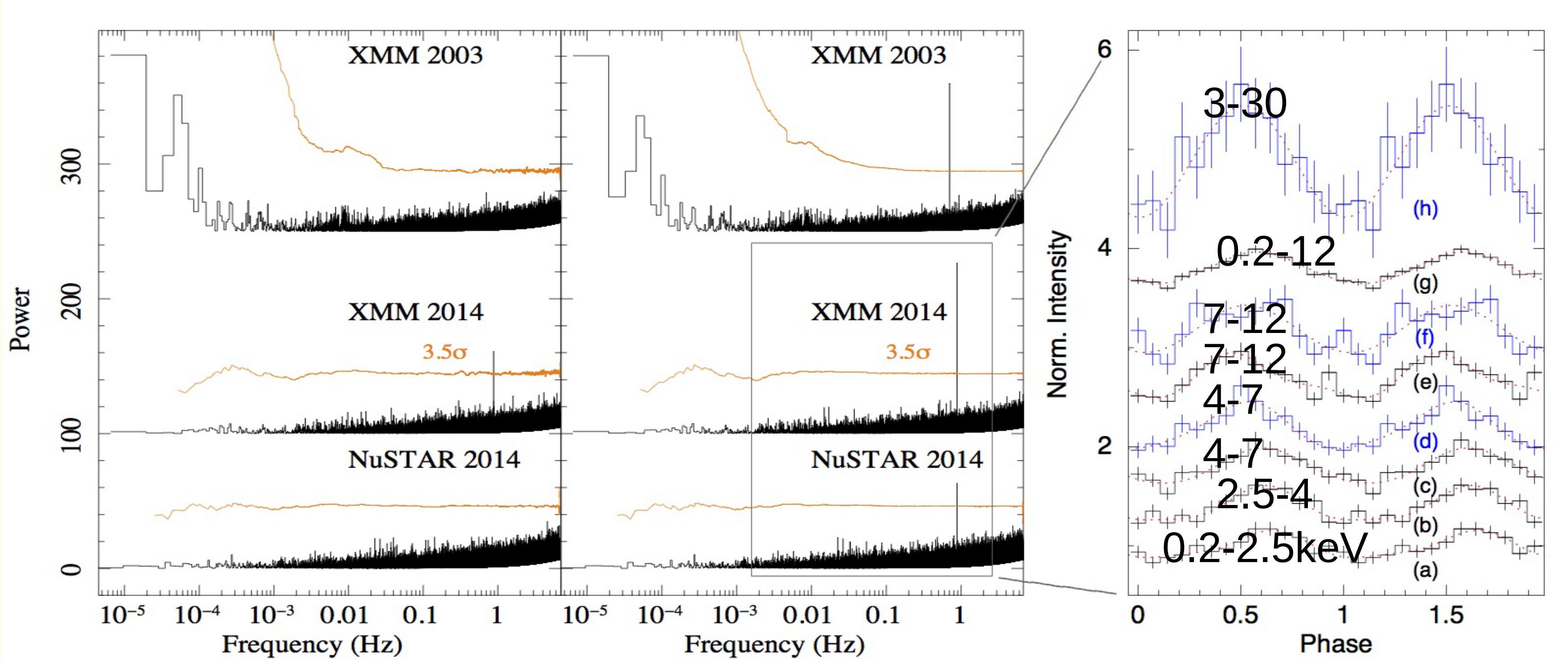


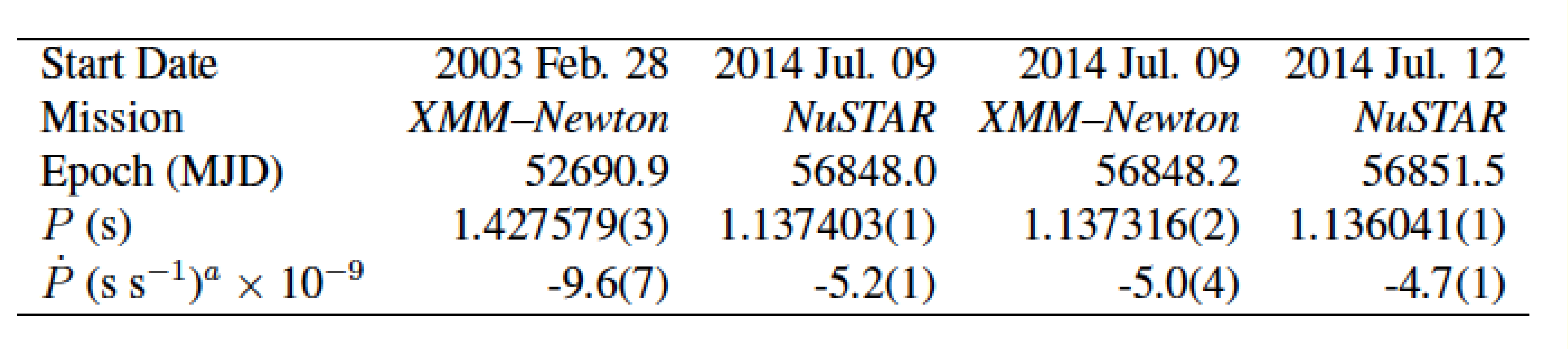


Two preferable states (?)

Transitions due to propeller effect at $R_m = R_{CO}$?

NGC5907 ULX1





Start Date	2003 Feb. 28	2014 Jul. 09	2014 Jul. 09	2014 Jul. 12
Mission	*XMM–Newton*	*NuSTAR*	*XMM–Newton*	*NuSTAR*
Epoch (MJD)	52690.9	56848.0	56848.2	56851.5
P (s)	1.427579(3)	1.137403(1)	1.137316(2)	1.136041(1)
$\dot{P}$ (s s^{-1})^{a} × 10^{-9}	-9.6(7)	-5.2(1)	-5.0(4)	-4.7(1)

Secular $\dot{P} = -8.1 \times 10^{-10}\,\mathrm{s\ s}^{-1}$

Israel et al. (2017)

Minimum Mdot

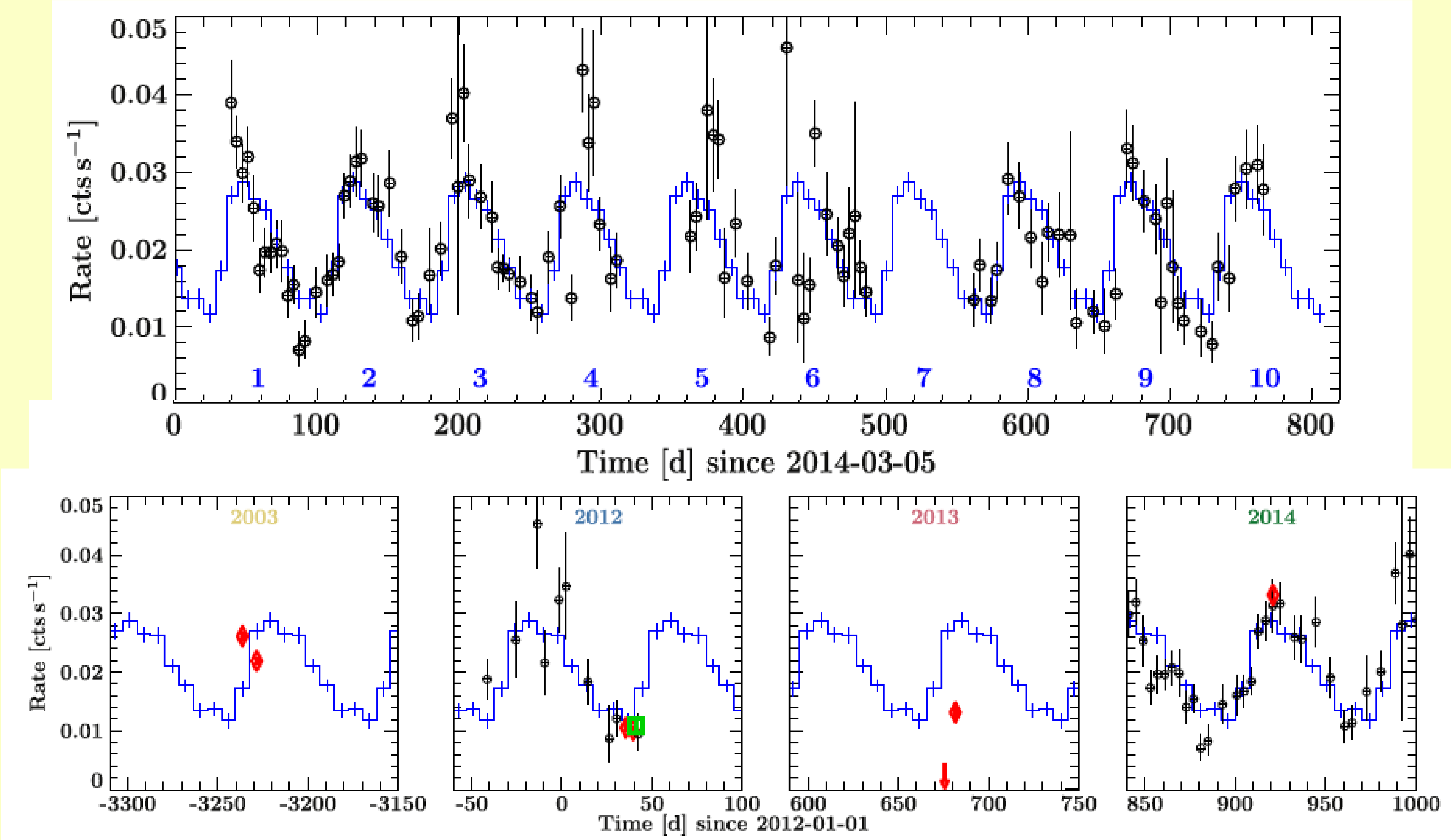
- Maximum spin up torque is $\dot{M}(GMr_{\rm c})^{1/2}$

$$-2\pi I\dot{P}/P^2 \leq \dot{M}(GMr_{\rm c})^{1/2}$$

$$\dot{M} \geq 3.55 \times 10^{18}\,\dot{P}_{-10}P^{-7/3}\,{\rm g s^{-1}}$$

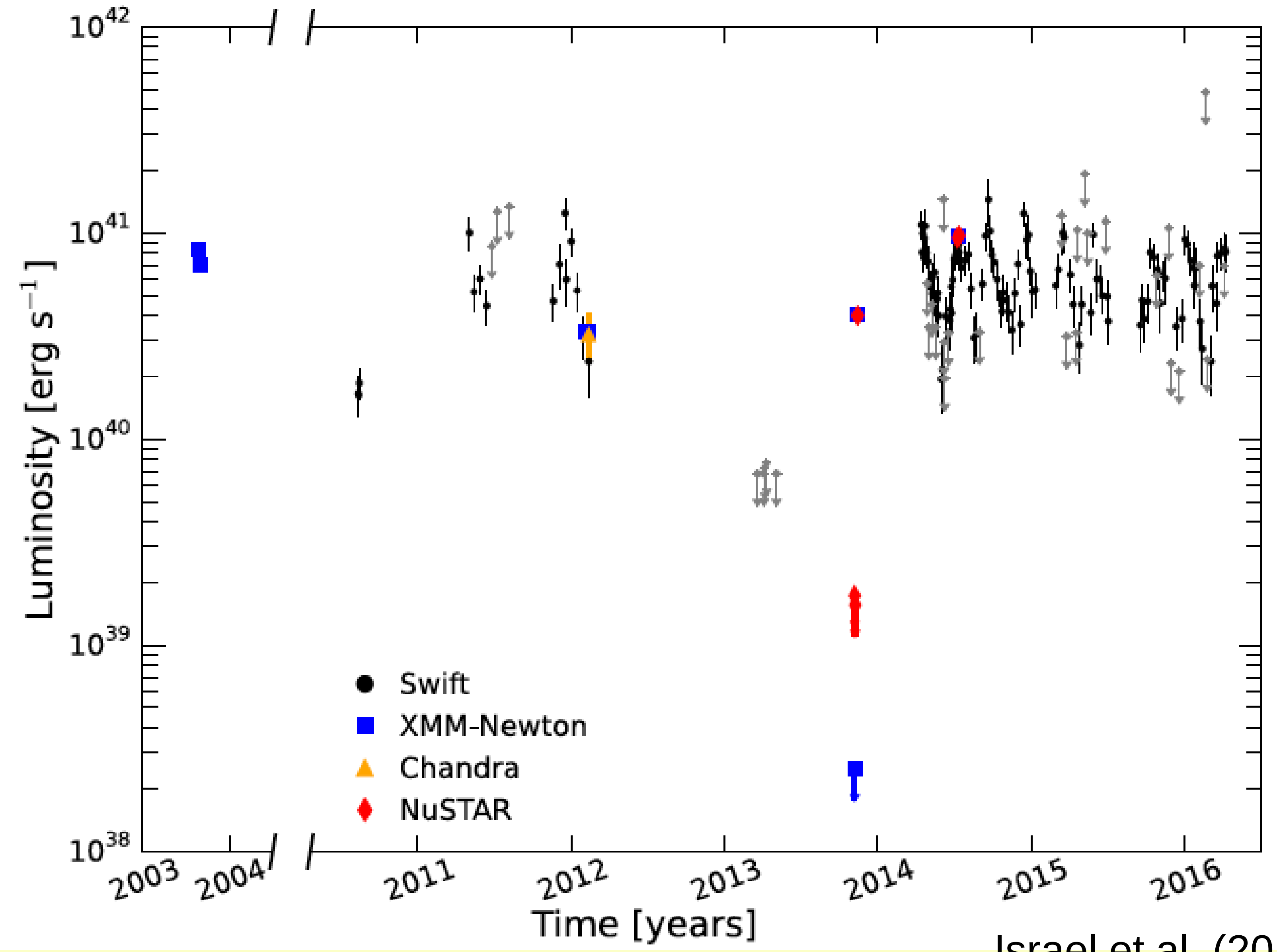
- M82 X-2 $\dot{P} \simeq -2.7\times 10^{-10}\ {\rm s s^{-1}}$ $\dot{M} \geq 4.6\times\ 10^{18}\ {\rm g s^{-1}}$
- NGC 5907 $-9.6\times 10^{-9}\ {\rm s s^{-1}}$ $\dot{M} \geq 1.5\ \times\ 10^{20}\ {\rm g s^{-1}}$

NGC5907 ULX1



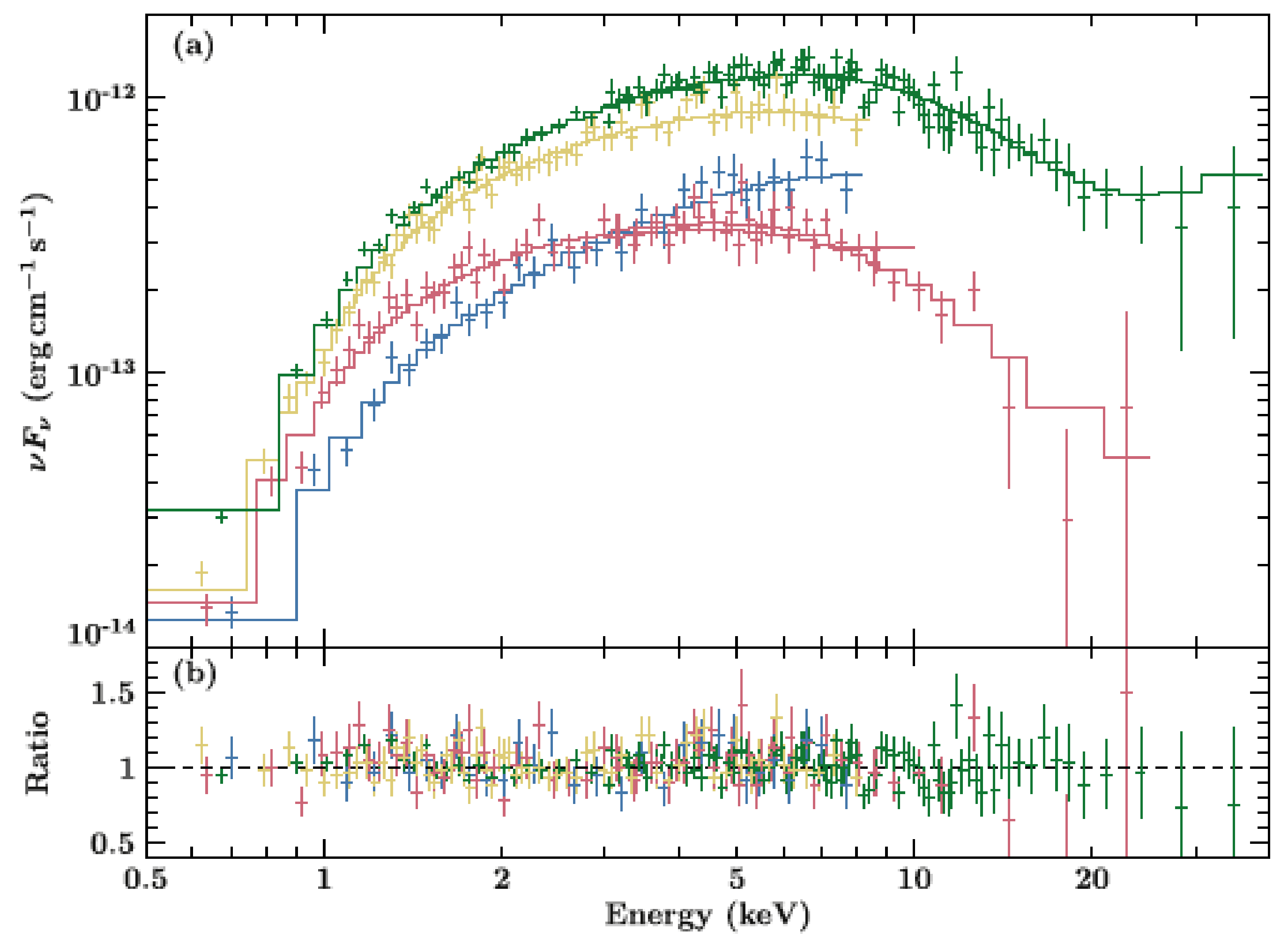
(superorbital?) period 78 days (Walton et al. 2016)

NGC5907 ULX1



Israel et al. (2017)

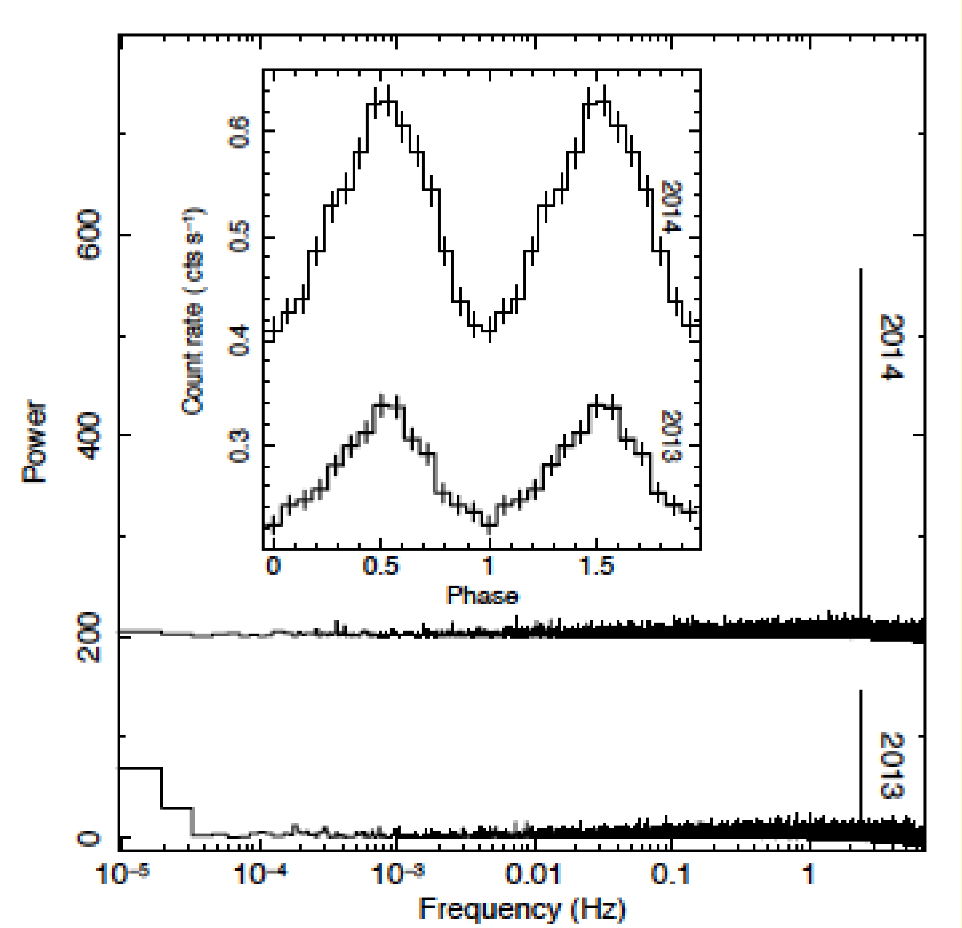
NGC5907 ULX1



Spectra cutoff at 10 keV

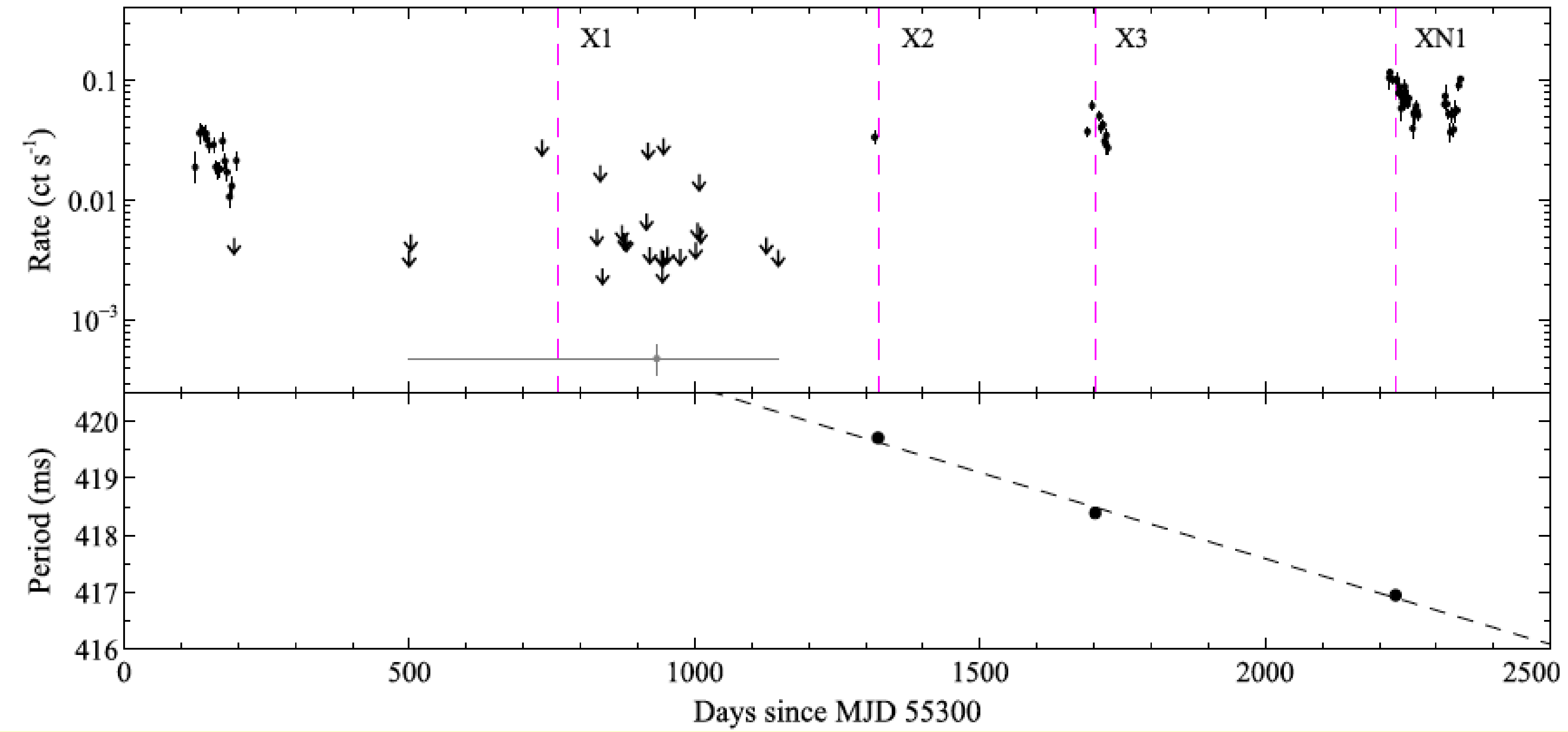
Fürst et al. (2017)

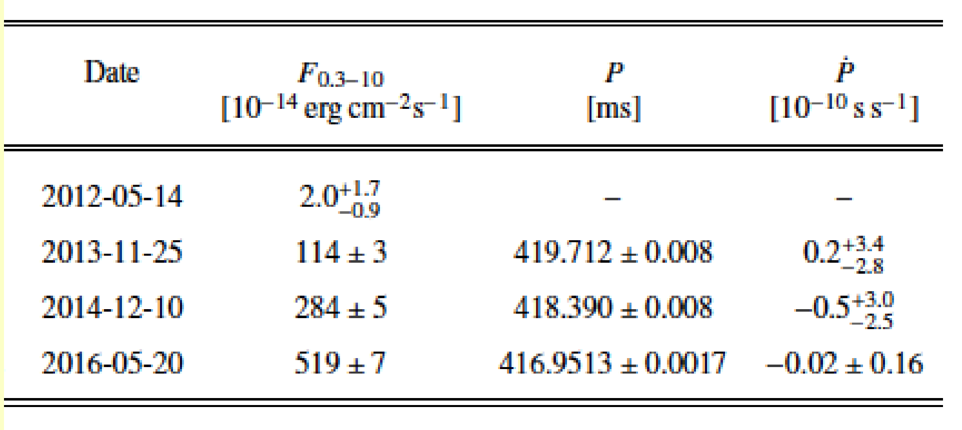
NGC7793 P13



Israel et al. (2017)

NGC7793 P13





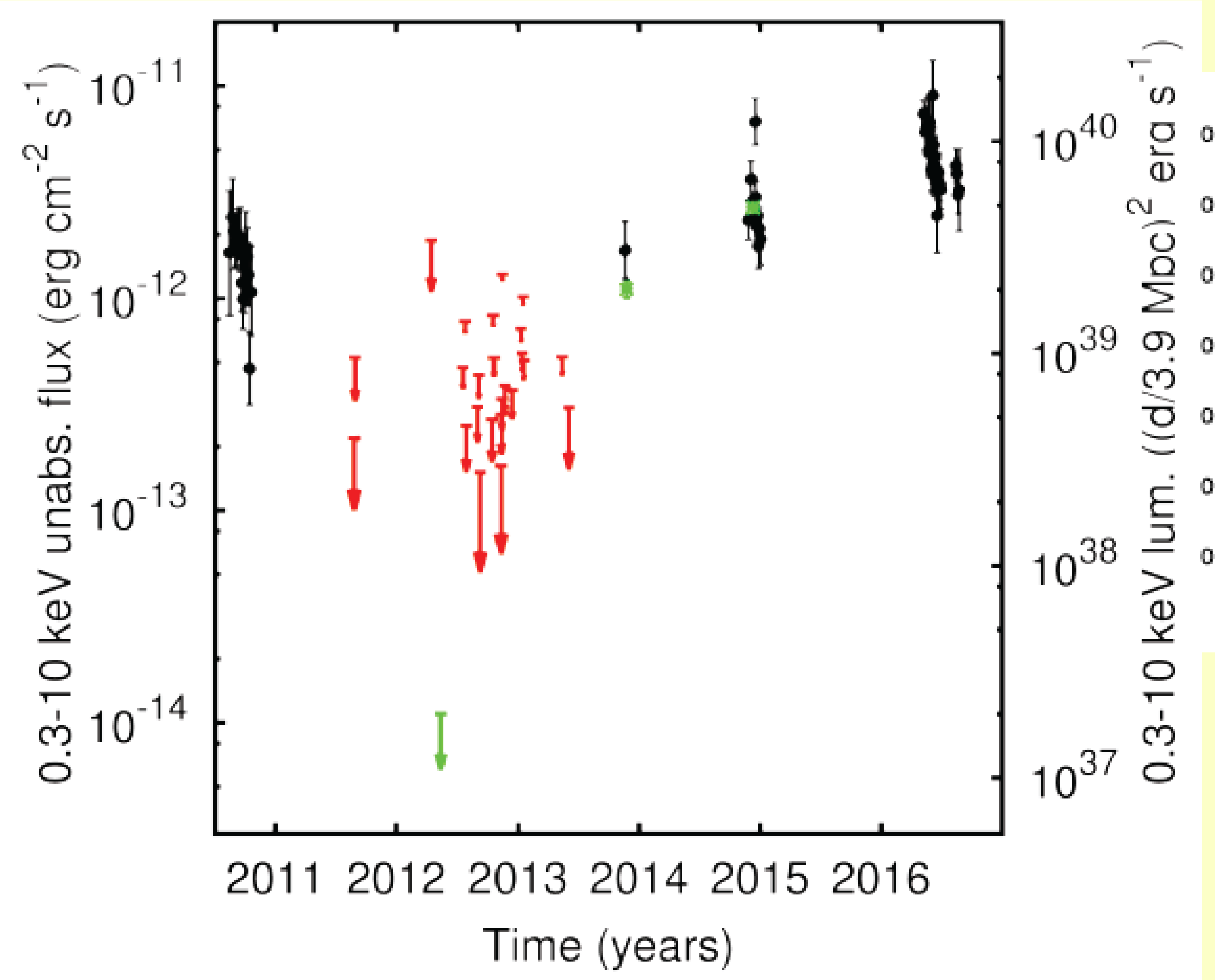
Date	$F_{0.3-10}$ [10^{-14} erg cm^{-2}s^{-1}]	P [ms]	$\dot{P}$ [10^{-10} s s^{-1}]
2012-05-14	$2.0^{+1.7}_{-0.9}$	–	–
2013-11-25	114 ± 3	419.712 ± 0.008	$0.2^{+3.4}_{-2.8}$
2014-12-10	284 ± 5	418.390 ± 0.008	$-0.5^{+3.0}_{-2.5}$
2016-05-20	519 ± 7	416.9513 ± 0.0017	−0.02 ± 0.16

Secular

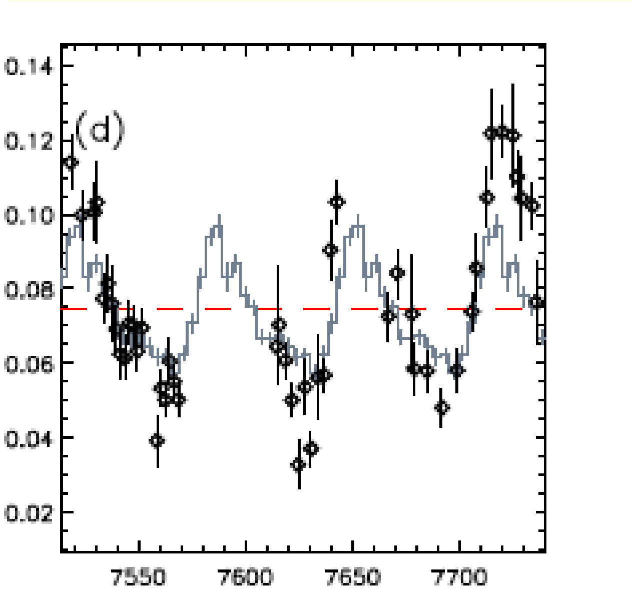
$$\dot{P} = -3 \times 10^{-11} \mathrm{s\ s}^{-1}$$

Fürst et al. (2017); Israel et al. (2017)

NGC7793 P13



Israel et al. (2017)



Hu et al. (2017)

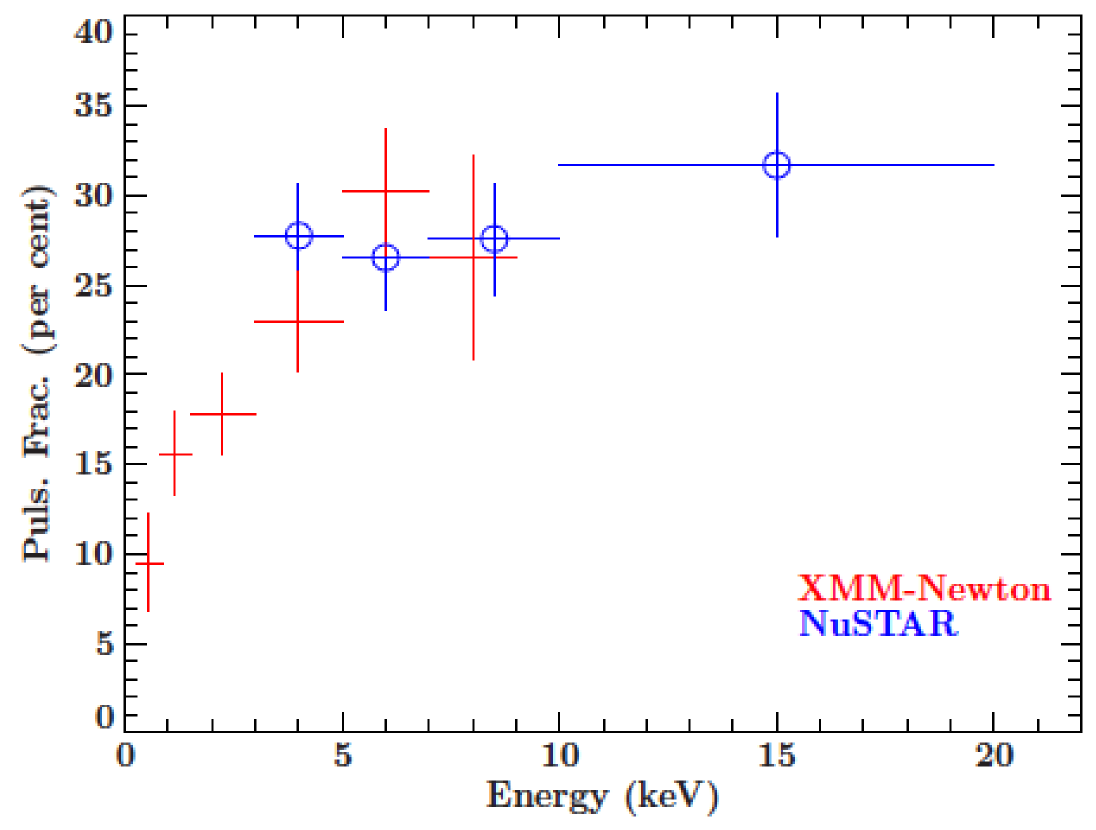
$$P = 65 \text{ d}$$

Superorbital?

$$P_{orb} = 3 - 7 \text{ d?}$$

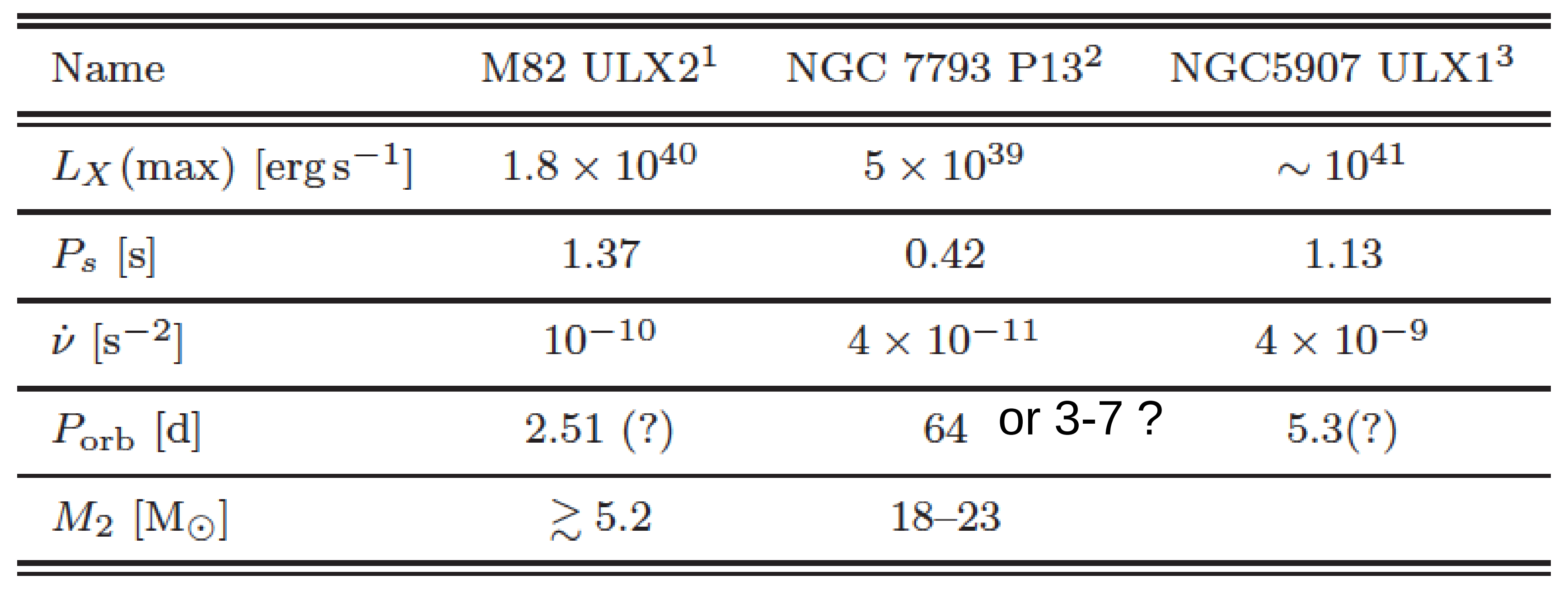
NGC7793 P13

Large pulsed fraction



Fürst et al. (2017)

ULX-pulsars in a nutshell



Name	M82 ULX2[1]	NGC 7793 P13[2]	NGC5907 ULX1[3]
L_X (max) $[\mathrm{erg\,s^{-1}}]$	1.8×10^{40}	5×10^{39}	$\sim 10^{41}$
P_s [s]	1.37	0.42	1.13
$\dot{\nu}$ $[\mathrm{s^{-2}}]$	10^{-10}	4×10^{-11}	4×10^{-9}
P_{orb} [d]	2.51 (?)	64 or 3-7 ?	5.3(?)
M_2 $[\mathrm{M_\odot}]$	$\gtrsim 5.2$	18–23	

- Large pulsed fraction, 20-30%, in all objects
- Huge variations in luminosity

Characteristic radii

$$R_{\mathrm{c}} = \left(\frac{GMP^2}{4\pi^2}\right)^{1/3}$$ $=10^8$ cm Corotation radius

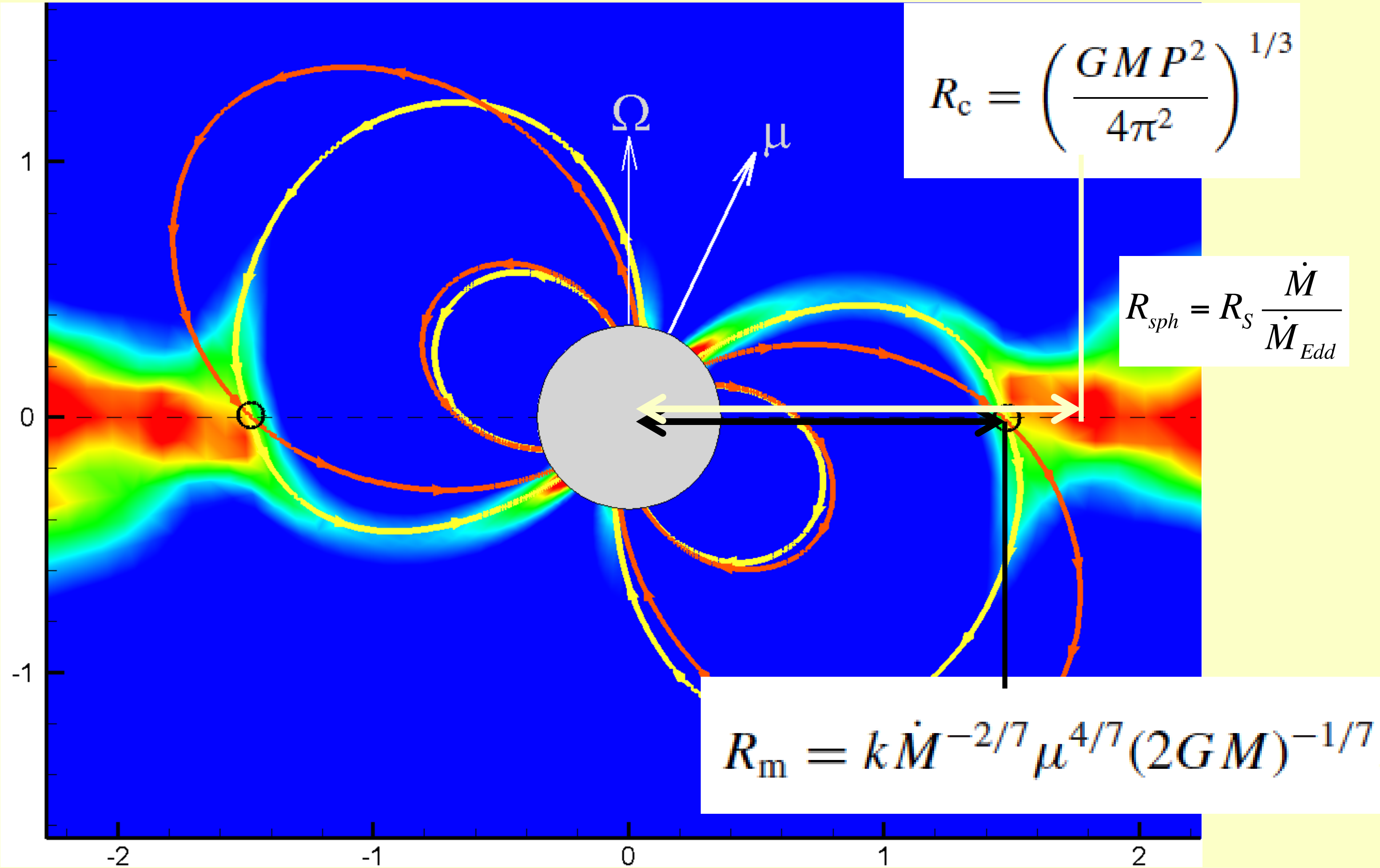
$$R_{\mathrm{sph}} = R_* \frac{\dot{M}}{\dot{M}_{Edd}}$$ Spherization (wind) radius

$$R_{\mathrm{m}} = k\dot{M}^{-2/7}\mu^{4/7}(2GM)^{-1/7}$$ Magnetospheric radius

k - depends on the disc structure
(e.g. Chashkina, Abolmasov, JP 2017)

For M82 X-2 all radii are close to each other
(if no beaming is involved)

Accretion in ULX-pulsars



$$R_c = \left(\frac{GMP^2}{4\pi^2}\right)^{1/3}$$

$$R_{sph} = R_S \frac{\dot{M}}{\dot{M}_{Edd}}$$

$$R_m = k\dot{M}^{-2/7}\mu^{4/7}(2GM)^{-1/7}$$

Kulkarni &
Romanova 2013

Beaming?

- For example, King & Lasota (2016); King, Lasota, Kluzniak (2017) assume strong beaming (by accretion disc wind), by a factor 10-20.
- This also means that the orbital inclination has to be very small.
- The accretion rate is 40 Eddington ones and wind removes 90% of Mdot
- $B=10^{11}$ G, $R_m=20\ R_*$, Mdot to the star = 3 Mdot_Edd.

- How to explain huge variations in the luminosity?
- How to explain >30% pulsed fraction?

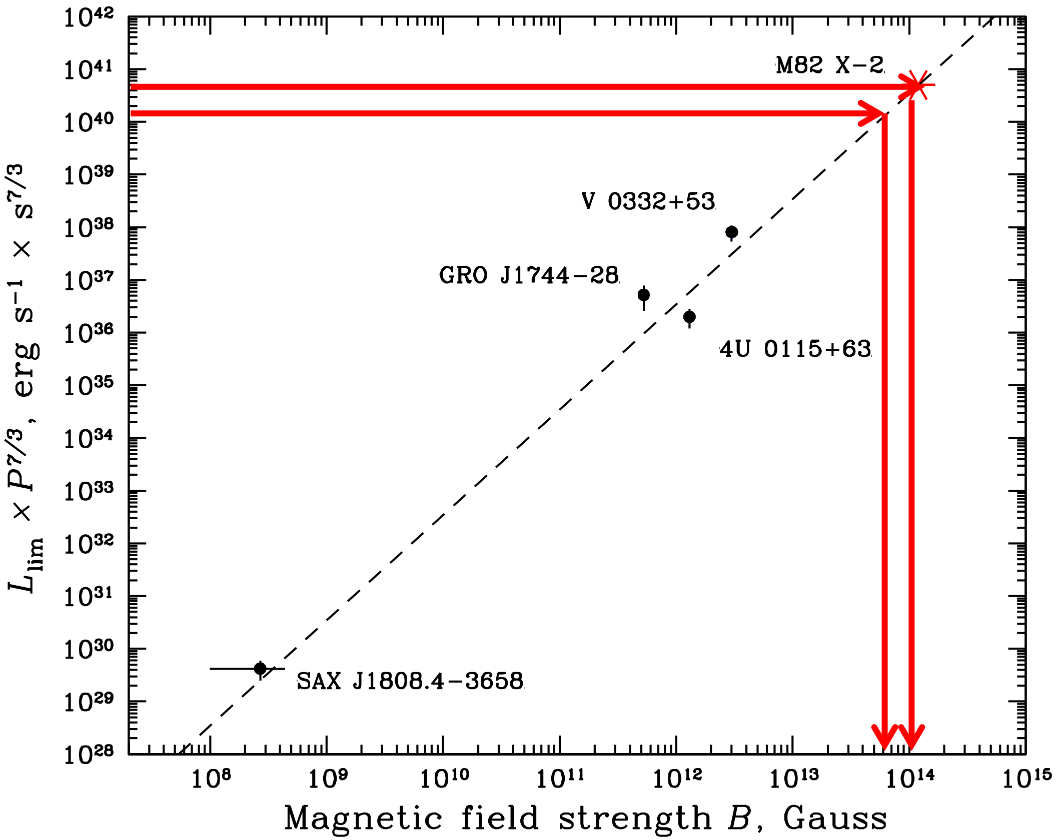
- No strong beaming => large Mdot and large B.

Possible propeller effect in M 82 X-2

$$R_{\mathrm{m}} = R_{\mathrm{c}} \quad \rightarrow \quad B \propto L_{tr} \, P_{sp}^{7/3}$$

$$R_{\mathrm{c}} = \left(\frac{GMP^2}{4\pi^2} \right)^{1/3}$$

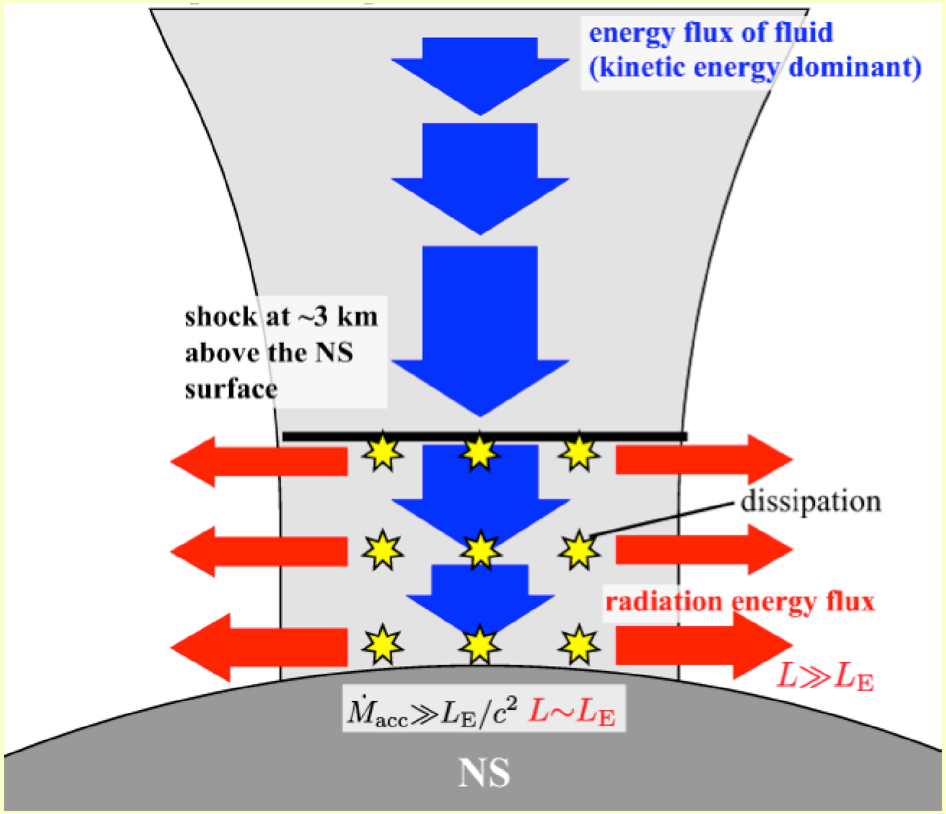
$$R_{\mathrm{m}} = k \dot{M}^{-2/7} \mu^{4/7} (2GM)^{-1/7}$$



How to exceed the Eddington limit?

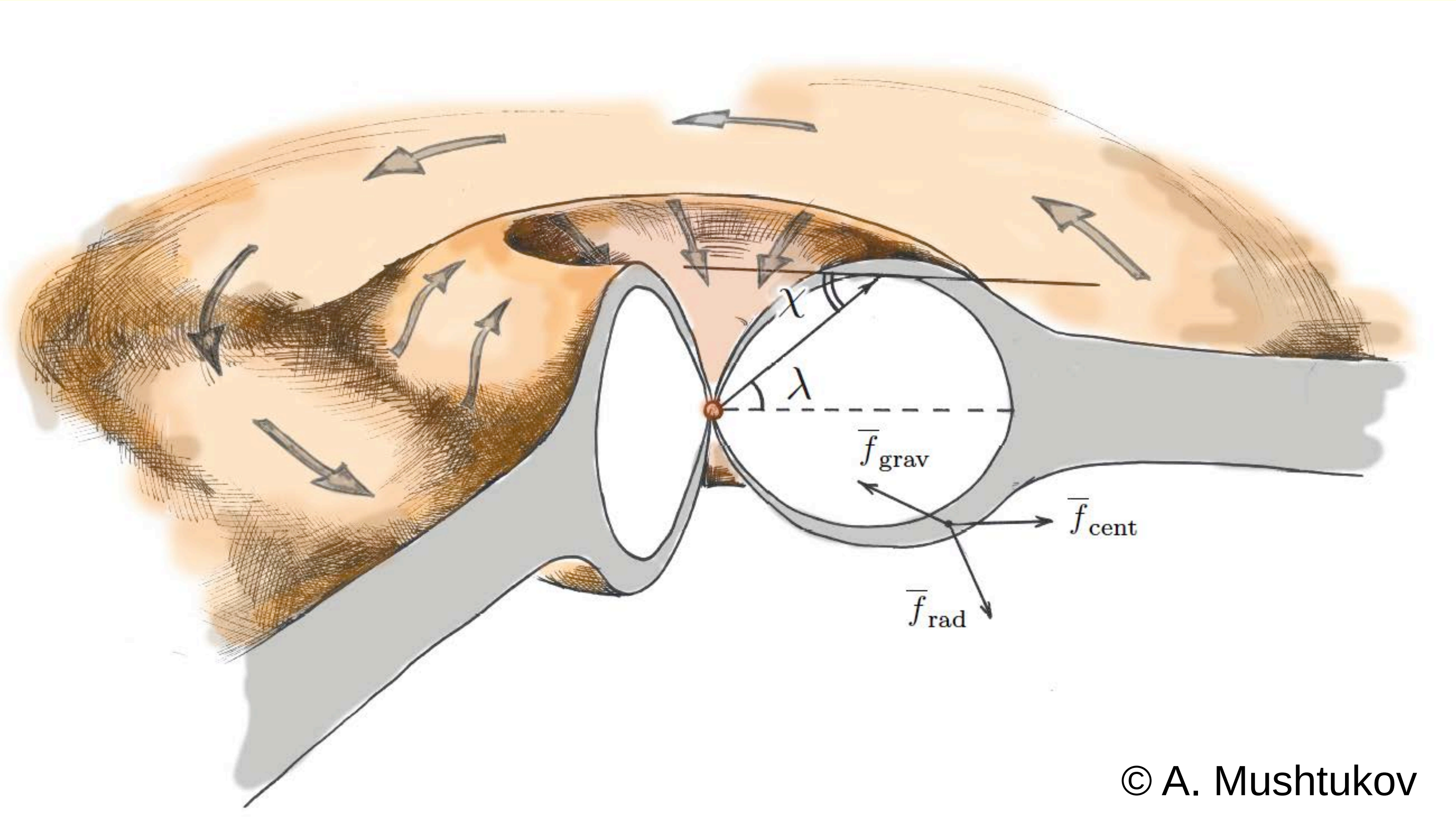
Geometrical effect (accretion disc, accretion column; photons escape sideways)

Basko & Sunyaev 1976
Wang & Frank 1981
Lyubarskij & Sunyaev 1988
Mushtukov et al. 2015
Postnov et al. 2015
Kawashima et al. 2016



- Photon bubbles (Klein+1996; Begelman 2006)
- Strong B-field reduction of the scattering cross-section; for X-mode $\sigma_\perp(E) \simeq \sigma_T (E/E_{cycl})^2$

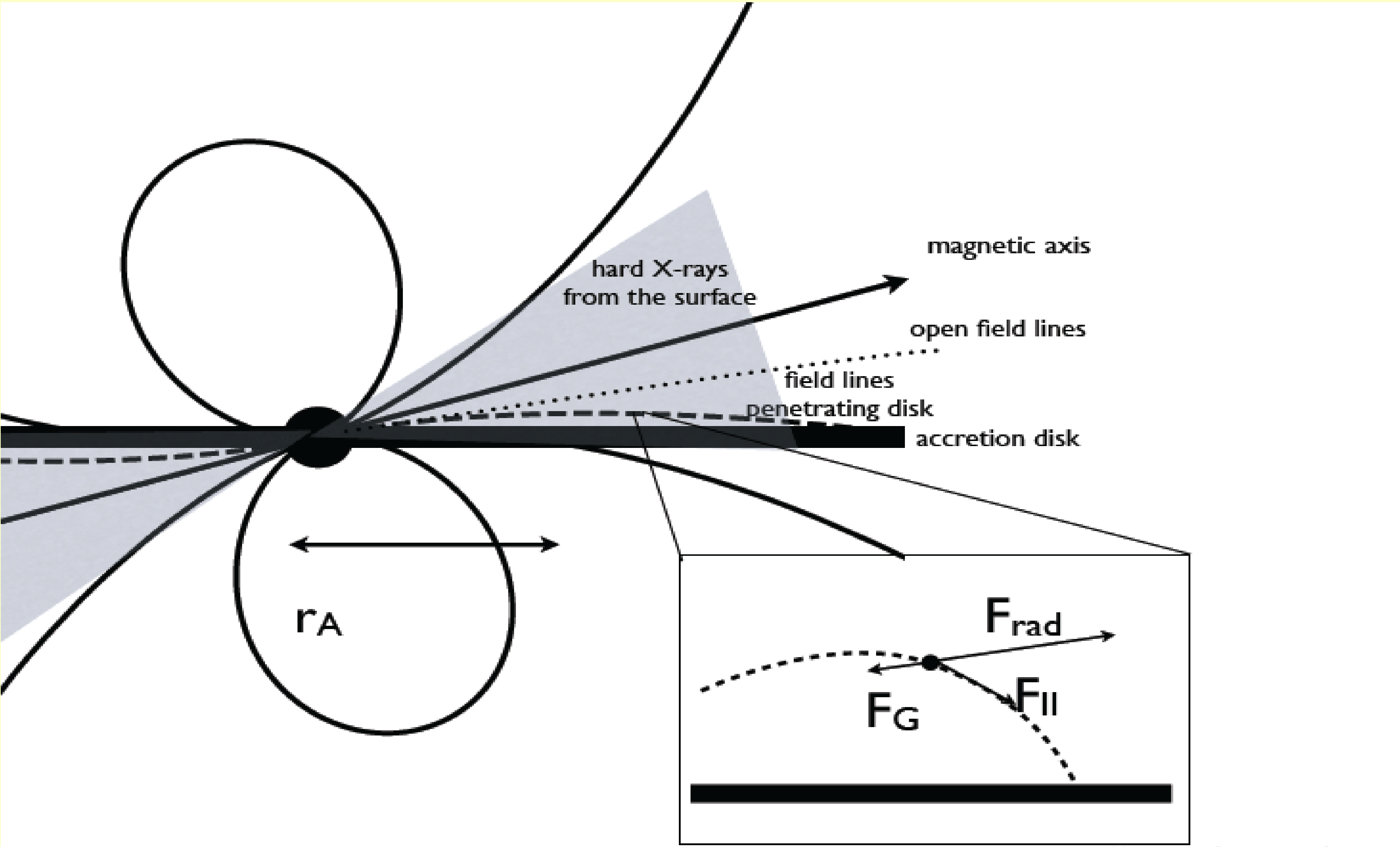
Spectrum formation in ULX-pulsars



© A. Mushtukov

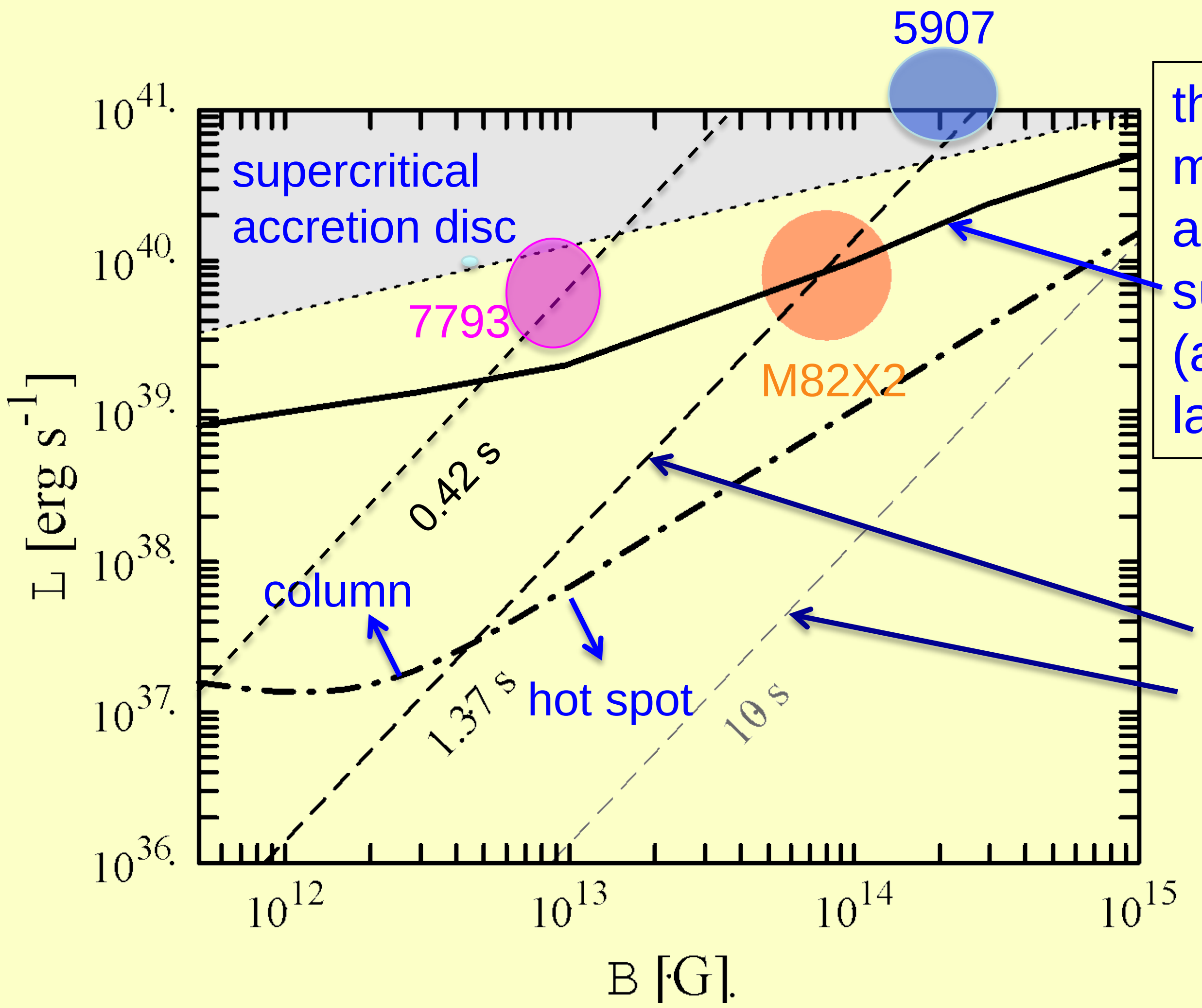
1. Accretion disc – soft
2. Accretion column – hard
3. Optically thick envelope – anything in between

How to force the gas to accrete?



Lyutikov (2014)

ULX-pulsars: luminosity, B-field



theoretical curve for maximum luminosity of an Eddington supported column (apparent can be larger due to beaming)

propeller effect

Conclusions

- ULX-pulsars clearly show that neutron stars can exceed Eddington limit by a factor of >100
- There is probably no strong beaming involved
- If the sources are close to the equilibrium (as supported by huge luminosity variations), the B-field has to be 10^{13}-10^{14} G.
- Highly super-Eddington luminosities can be reached due to geometric effects, reduced opacity and photon bubbles.