Accreted highly magnetized neutron stars: recent progress

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Current observational situation

Observatories and instruments in orbit: Chandra, XMM-Newton, Swift, INTEGRAL, Fermi/GBM, NuSTAR, NICER, MAXI

Timing capabilities: from ~10^{-5} to 10^{8} sec

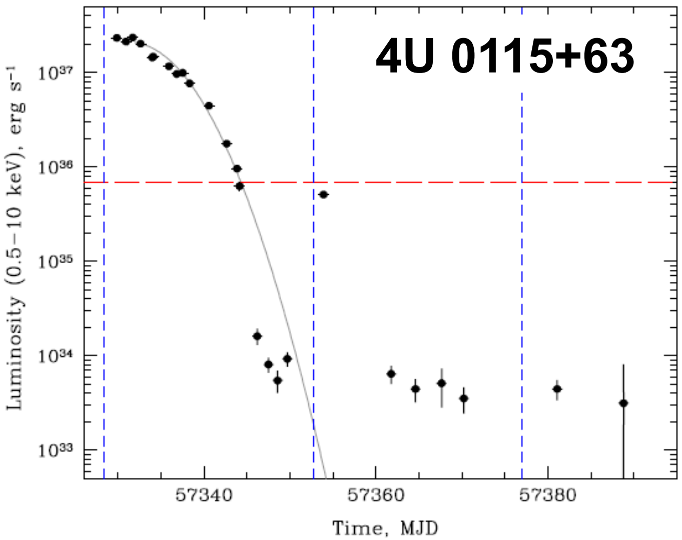
Spectral ranges: ~0.5 – 200 keV

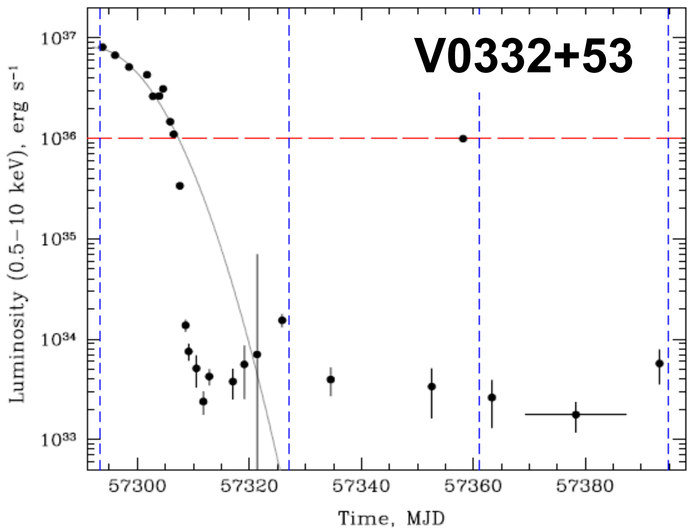
Luminosities: from 10^{32} to 10^{40} erg/s

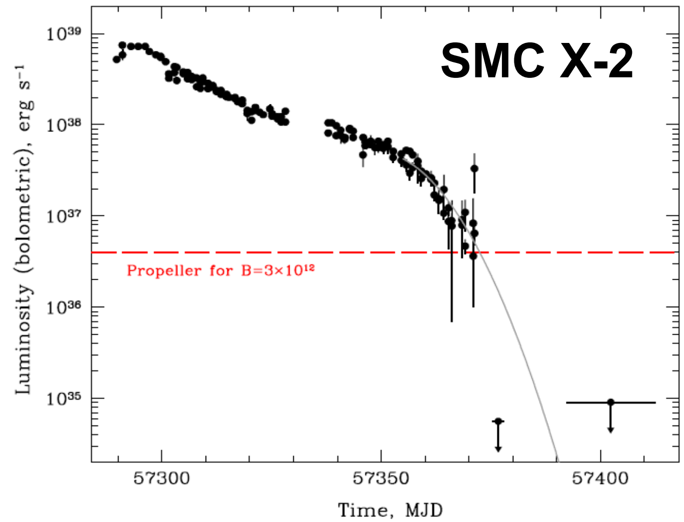
High sensitity and flexibility (regular, TOO, monitoring)

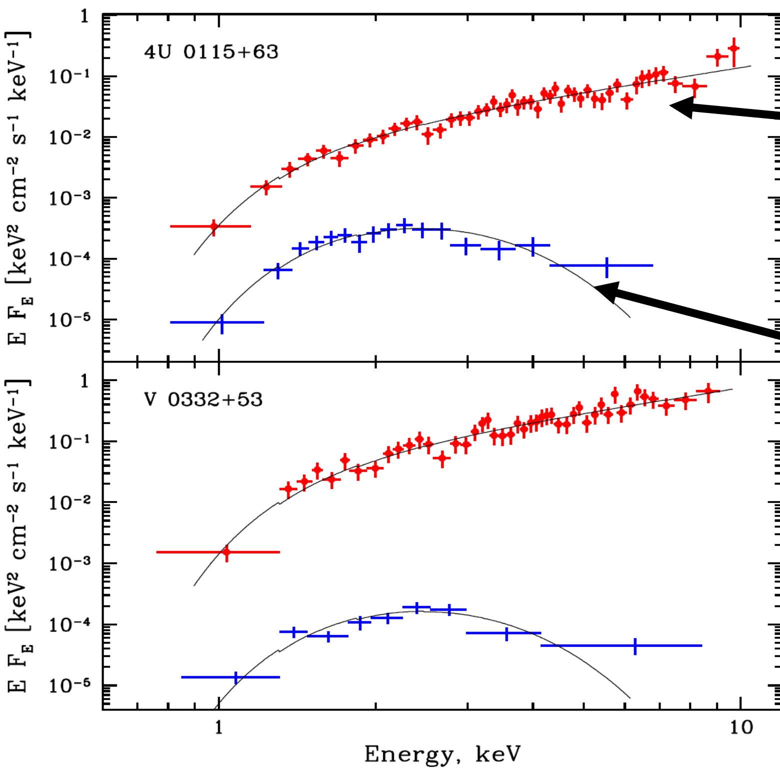
Swift/XRT monitoring campaign: more than dozen sources, total exposure > 1 Msec, hundreds observations

Propeller effect







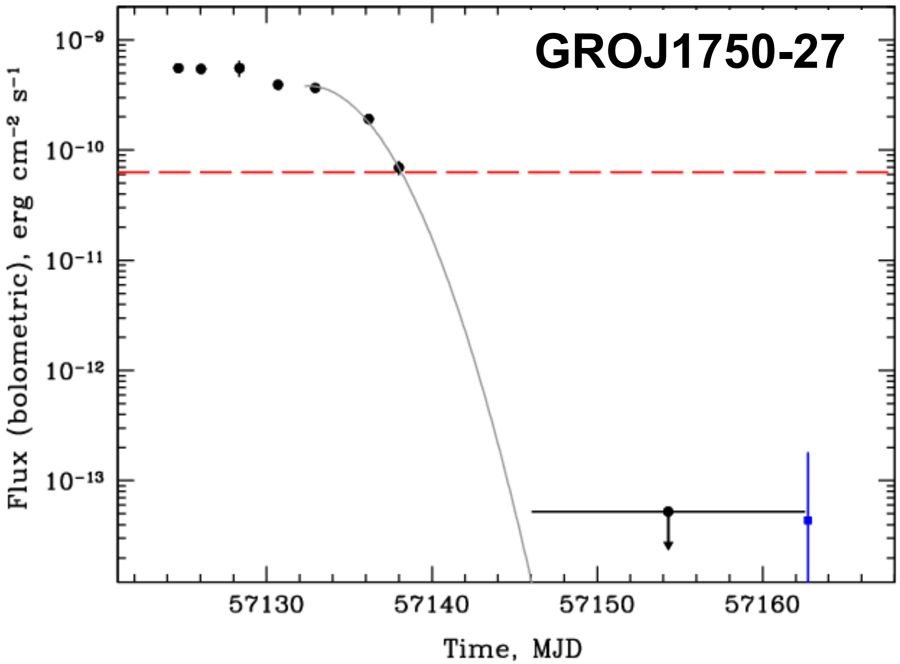


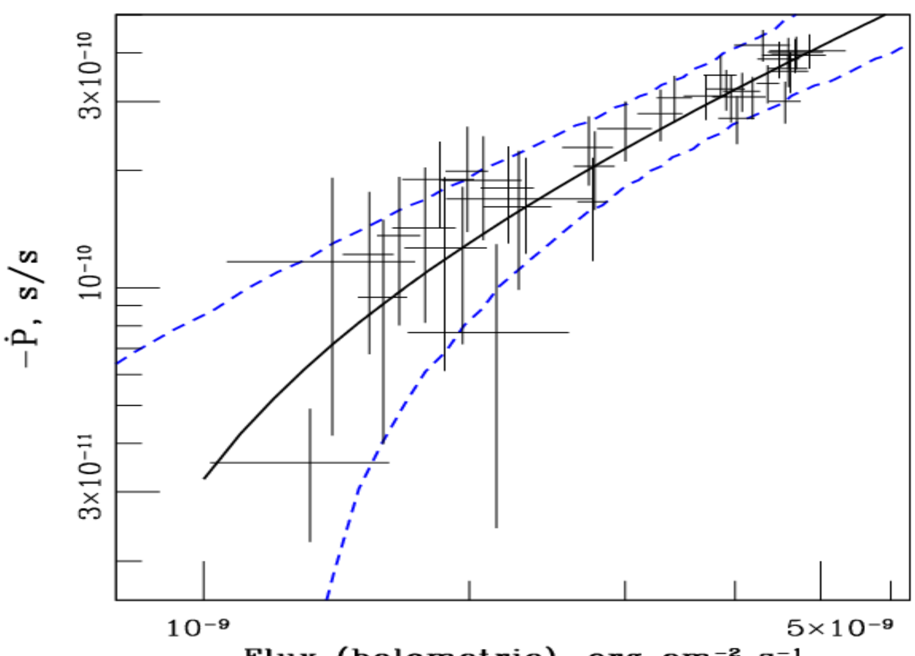
Absorbed power-law
Gamma = 0.4 – 0.7

Black body with
kT = 0.5 keV

Tsygankov et al., 2016
Lutovinov et al., 2017

Propeller effect



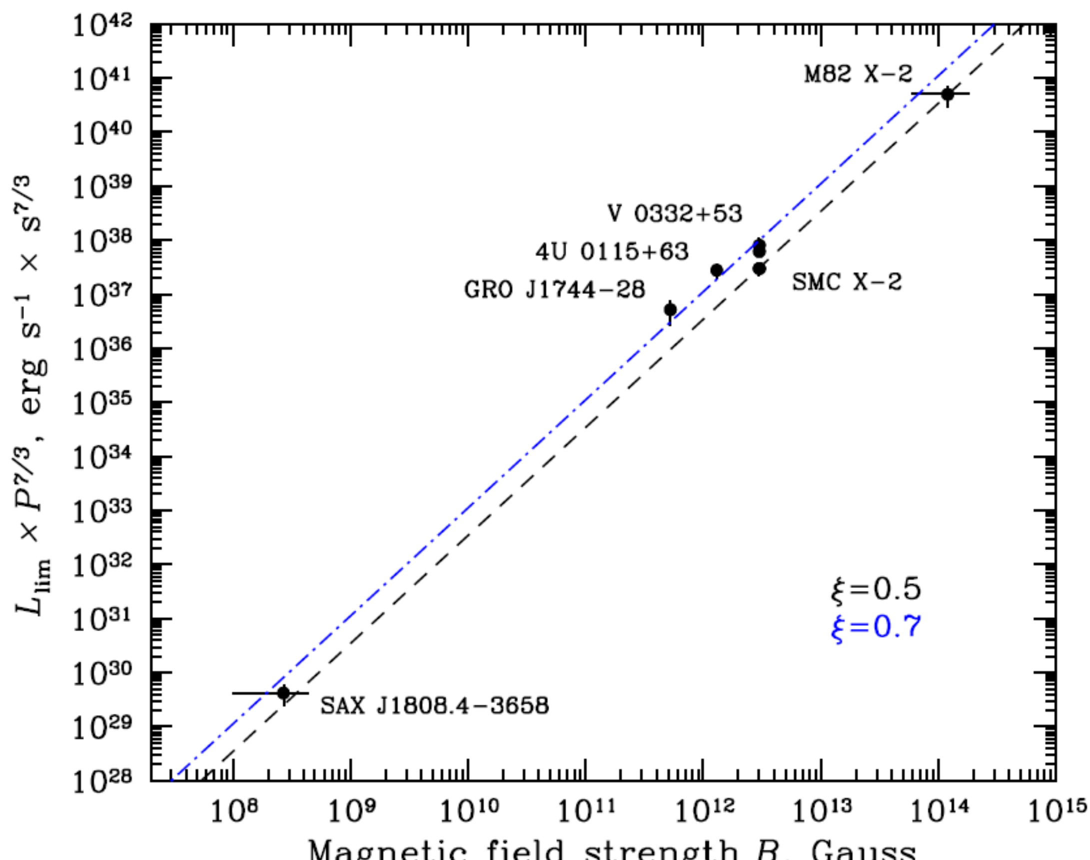


B ≃ (3.5 – 4.5) x10^{12} G

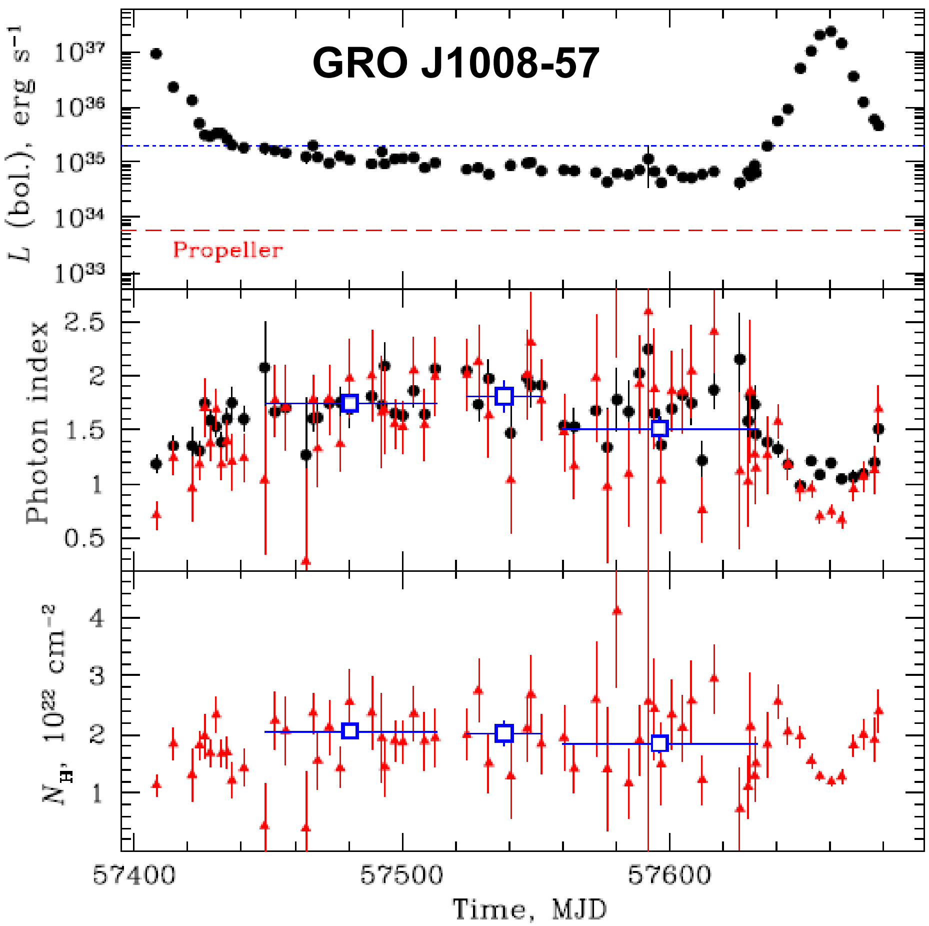
D ~ 18 kpc

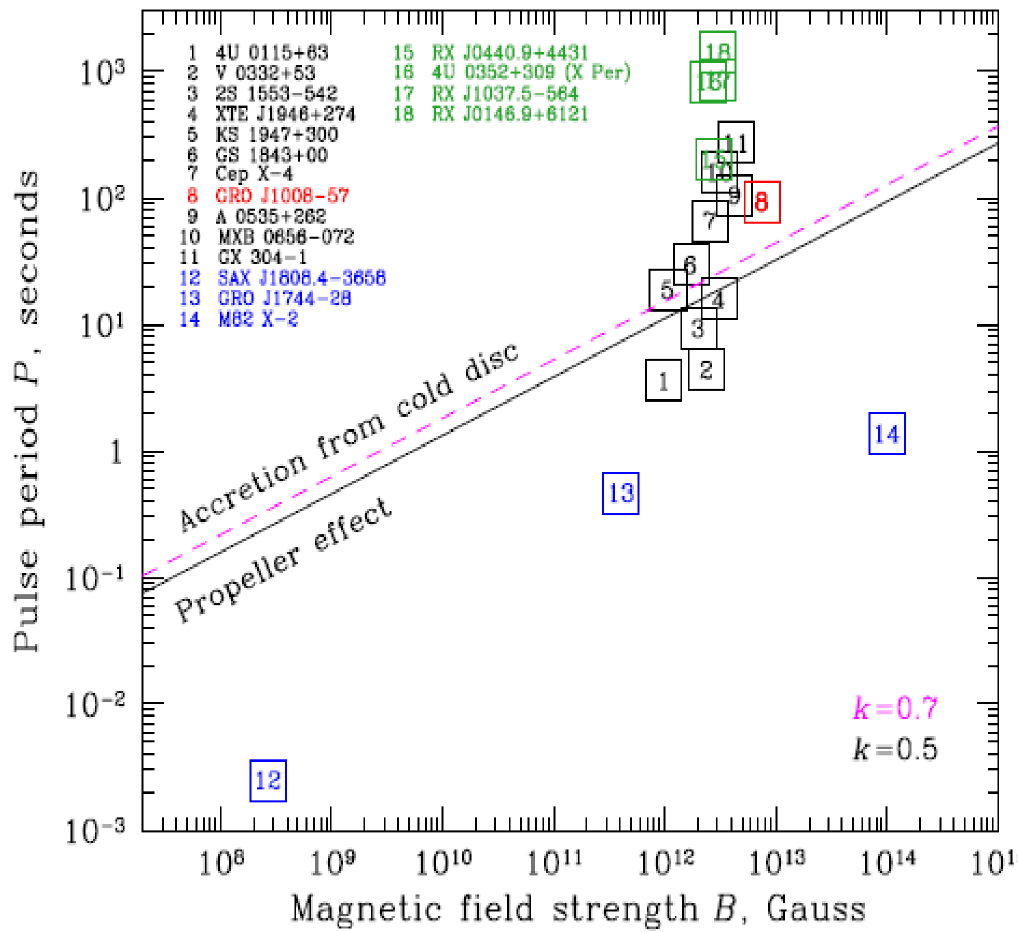
Lutovinov et al., 2019

will appear 15/01 in astro-ph



Accretion from the cold disk





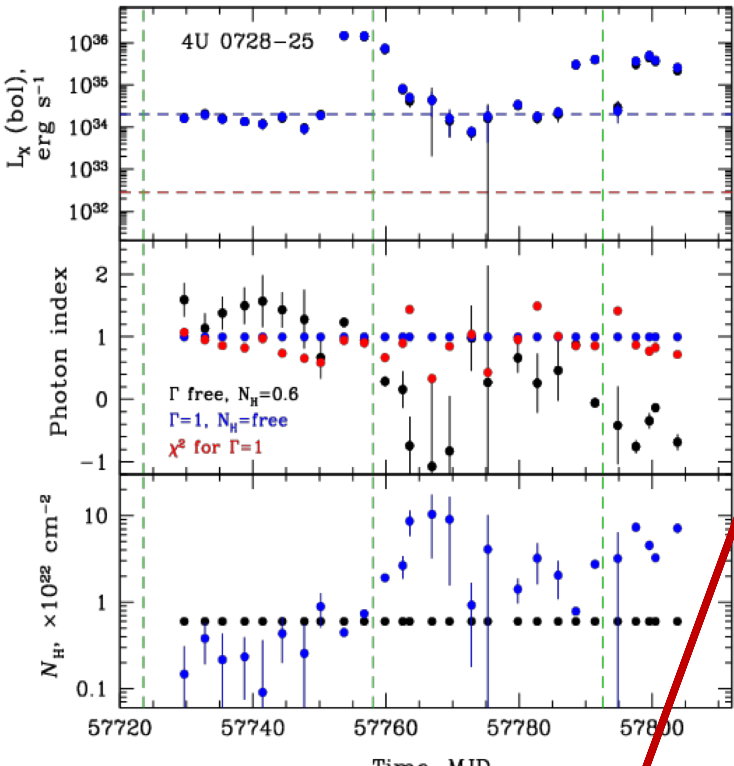
$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times10^{37}\xi^{7/2}B_{12}^{2}P^{-7/3}M_{1.4}^{-2/3}R_6^5\,{\rm erg\ s^{-1}}$$

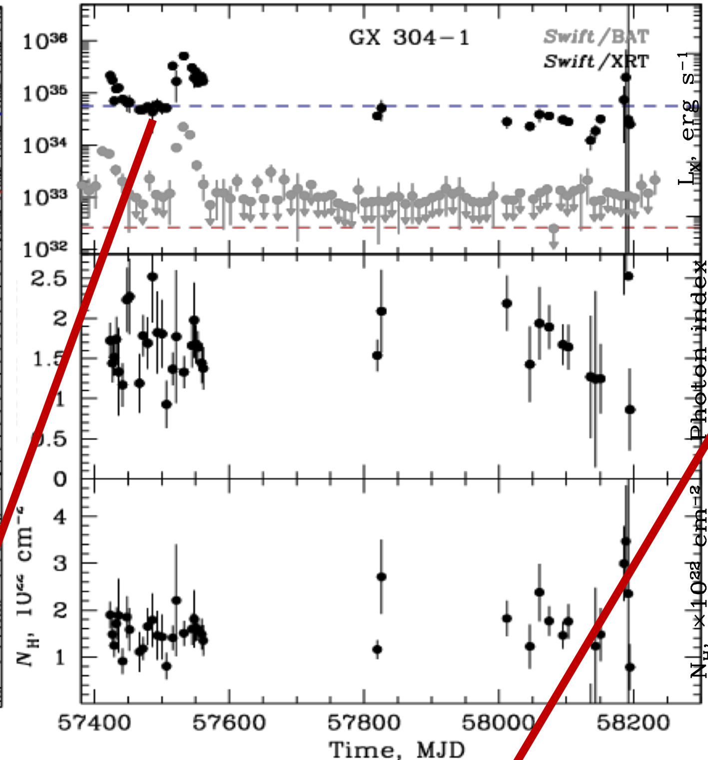
$$L_{\rm cold} = 9\times10^{33}\,k^{1.5}\,M_{1.4}^{0.28}\,R_6^{1.57}\,B_{12}^{0.86}\quad{\rm erg\,s^{-1}}$$

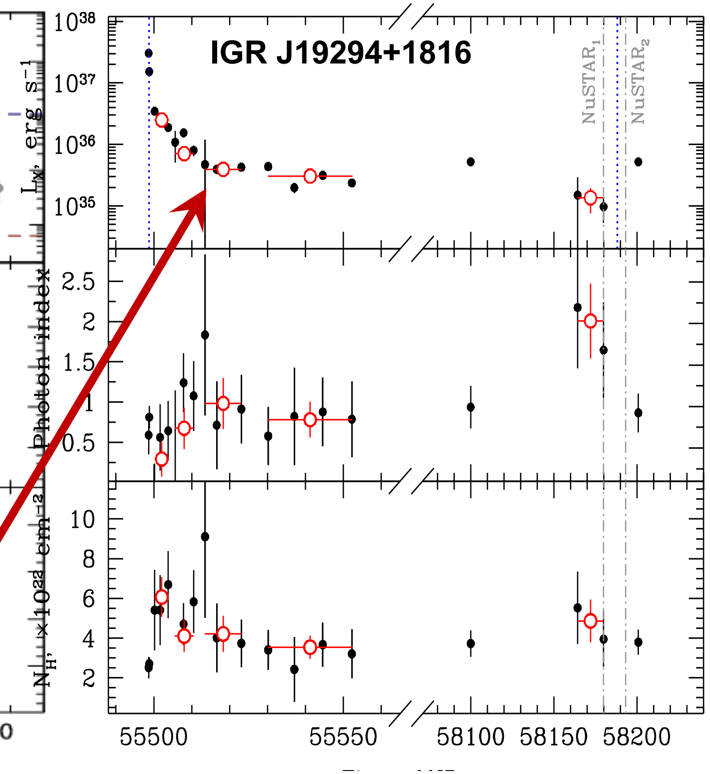
$$P^{*} = 36.6\,k^{6/7}\,B_{12}^{0.49}\,M_{1.4}^{-0.17}\,R_6^{1.22}\quad{\rm s}$$

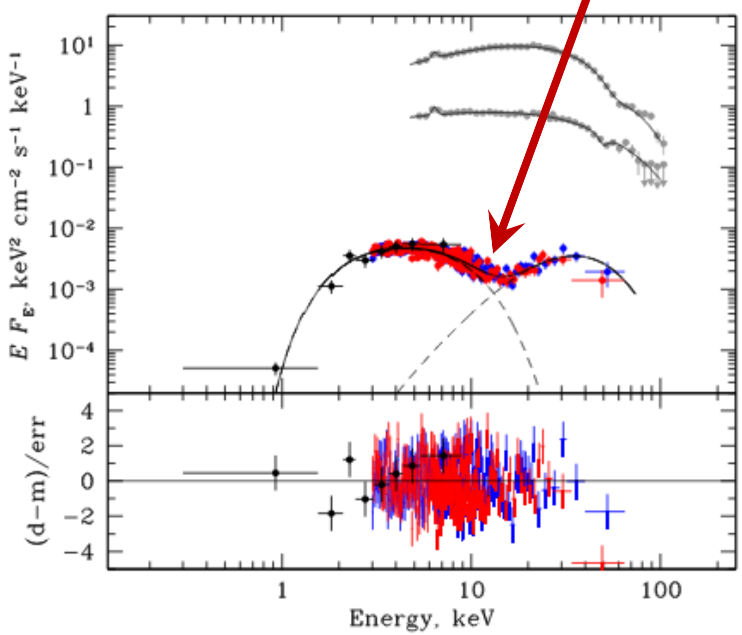
Tsygankov et al., 2017a

Long period pulsars





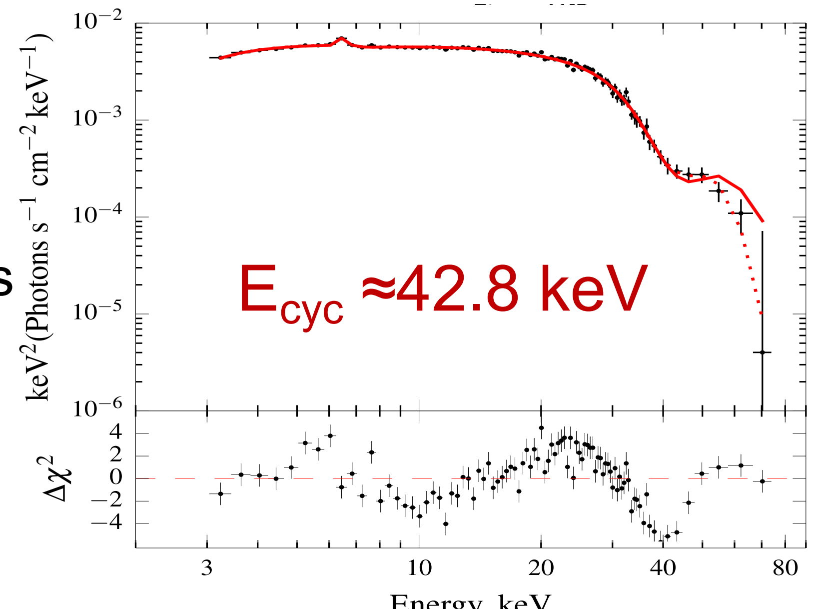




transition to the cold disk at the luminosity around 10^{35} erg/s

Similar to **XPer**

Di Salvo et a. 1998



Tsygankov et al., 2018b

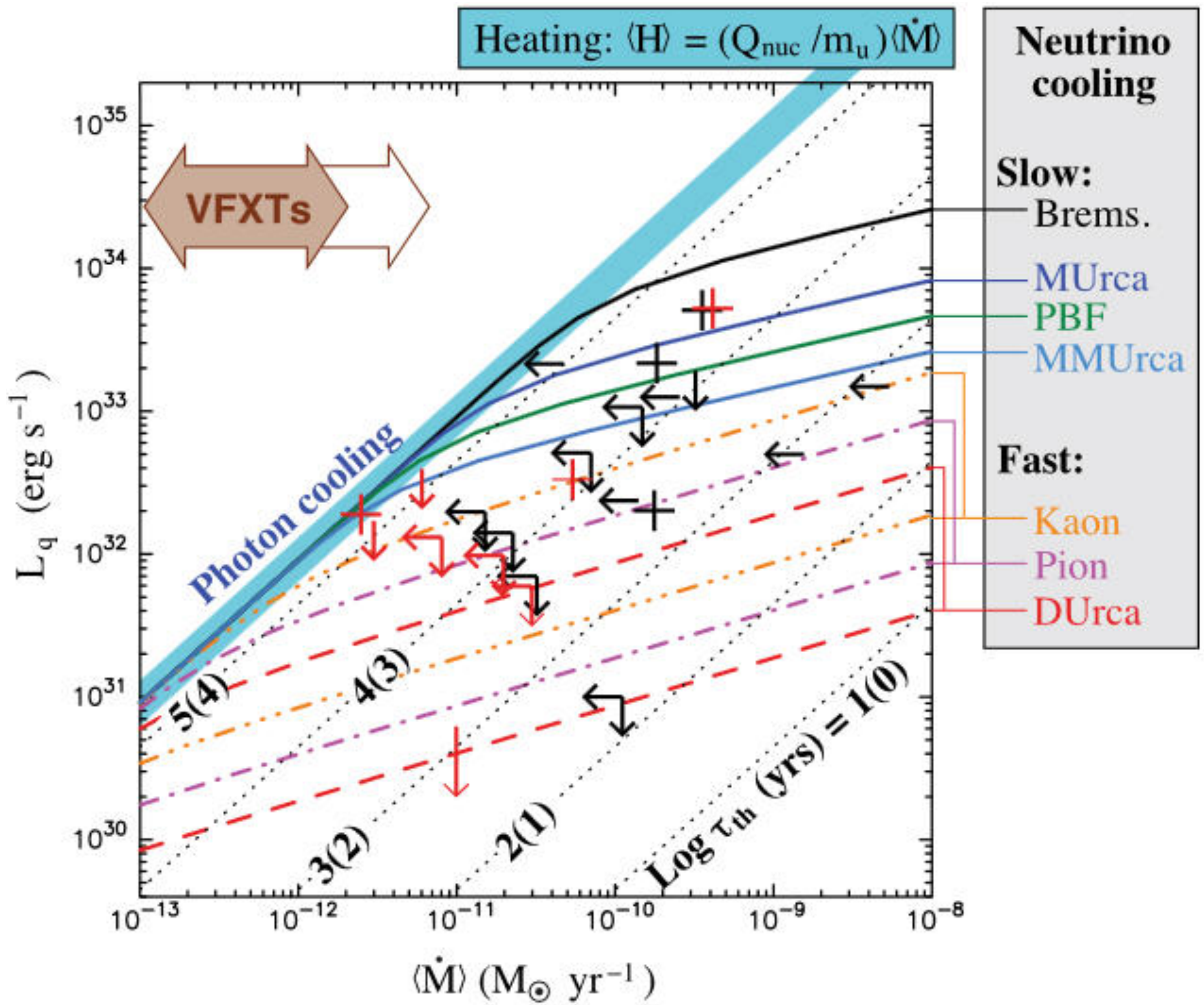
Highly magnetized neutron star in very low states

Motivations and aims

Insights into the problem of the accretion on to **magnetized** neutron star at very low mass accretion rates

Study cooling of NSs

VFXTs
LMXBs
Very weak MF

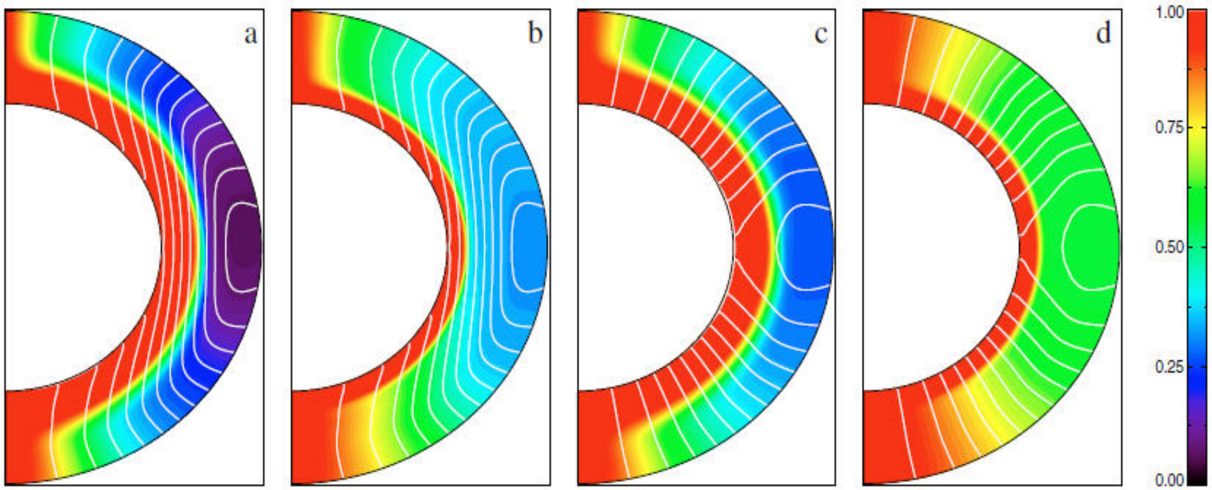


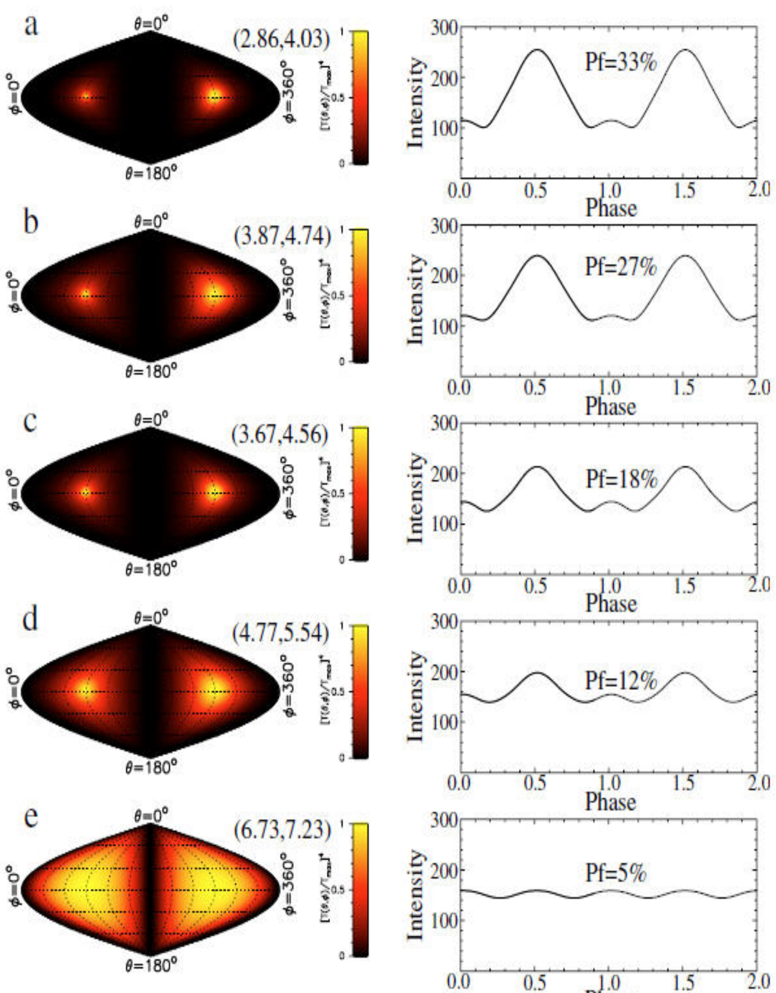
Wijnands et al. 2013

Motivations and aims

Insights into the problem of the accretion on to **magnetized** neutron star at very low mass accretion rates

Cooling of the NSs with magnetic field





Geppert et al. 2006

BeXRB systems (snapshot obs)

Source name	Pulse period (s)	Orbital period (d)	Distance (kpc)	Cyclotron line (keV)	Optical companion
4U 0115+63	3.6	24.3[1]	7.0[2]	11.5[3]	B0.2Ve[2]
V 0332+53	4.375	34.25[4]	7.0[5]	28[6]	O8–9Ve[5]
MXB 0656−072	160.4	101.2[7]	3.9[8]	36[9]	O9.7Ve[10]
4U 0728−25	103	34.5[11]	6.1[12]	–	O8–9Ve[12]
RX J0812.4−3114	31.9	81.3[13]	9.2[14]	–	B0.5V-IIIe[14]
GS 0834−430	12.3	105.8[15]	5.0[16]	–	B0–2 V–IIIe[16]
GRO J1008−57	93.8	249.5[17]	5.8[18]	88[19], 75.5[20]	B0e[21]
2S 1417−624	17.6	42.1[22]	(1.4–11.1)[23]	–	B1 Ve[23]
2S 1553−542	9.3	30.6[24]	20[25,26]	23.5[25]	–
Swift J1626.6−5156	15.377	132.9[27]	10[28]	10[29]	B0Ve[28]
GS 1843+00	29.5	–	(10–15)[30]	20[31]	B0–B2IV–Ve[30]
XTE J1946+274	15.8	169.2[32]	(8–10)[33]	36[34]	B0–B1 IV–Ve[33]
KS 1947+300	18.8	40.4[35]	10[36,37]	12.5[38]	B0Ve[36]
SAX J2103.5+4545	351	12.7[39]	6.5[40]	–	B0Ve[40]
Cep X-4	66.3	21[41]	3.8[42]	30[43]	B1V–B2Ve[42]
SAX J2239.3+6116	1247	262[44]	4.4[44]	–	(B0–2 V–IIIe)[44]

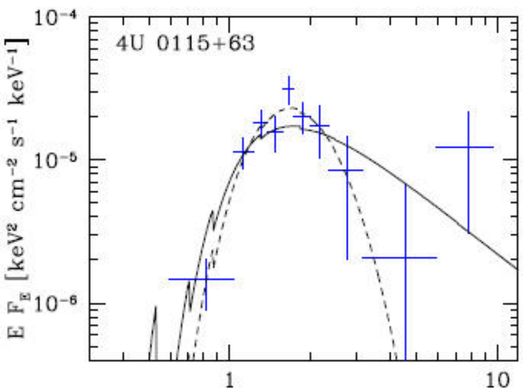
Special program of observations with Chandra

Also: using available XMM and XRT data

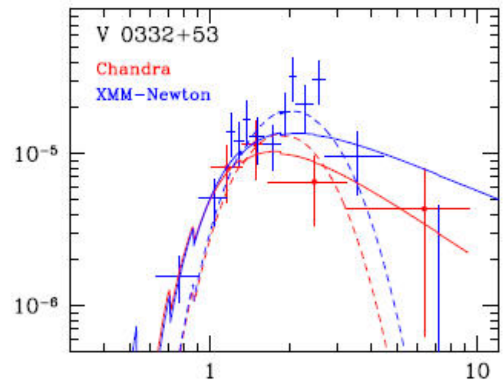
Long term history based on Swift/BAT and ASM/RXTE data

Tsygankov et al., 2017c

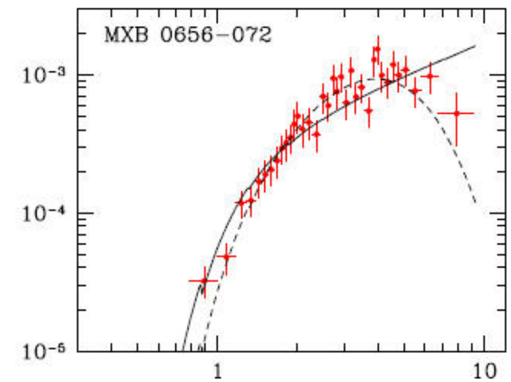
Spectra (I)



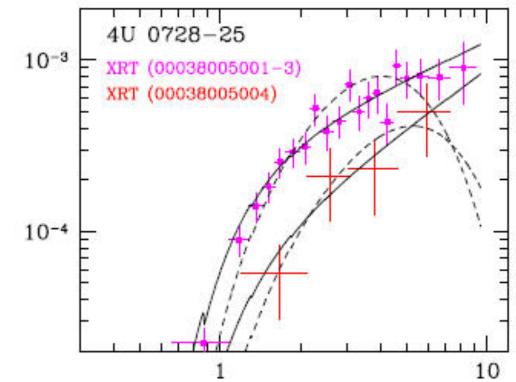
3 yr, 0.3 keV
$6x10^{32}$ erg/s



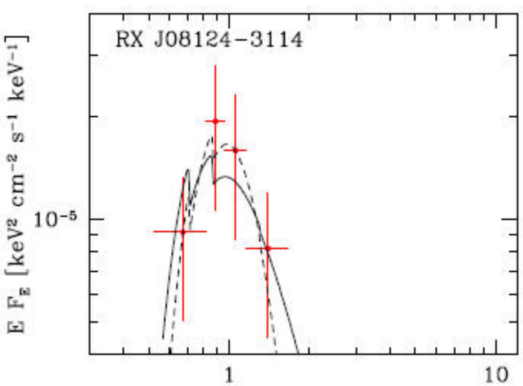
>5 yr, 0.4 keV
$3x10^{32}$ erg/s



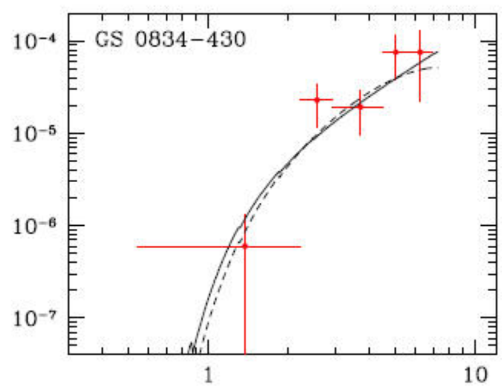
4 yr, 1 keV
$4x10^{33}$ erg/s



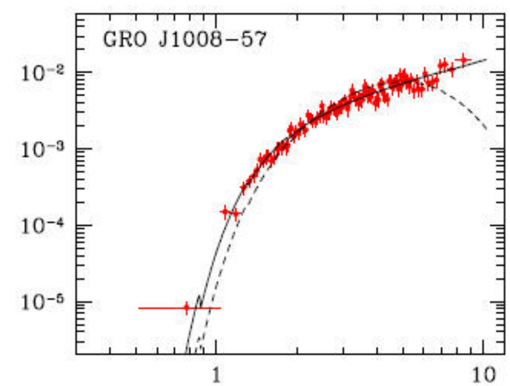
No OB, PL
$1.2x10^{34}$ erg/s



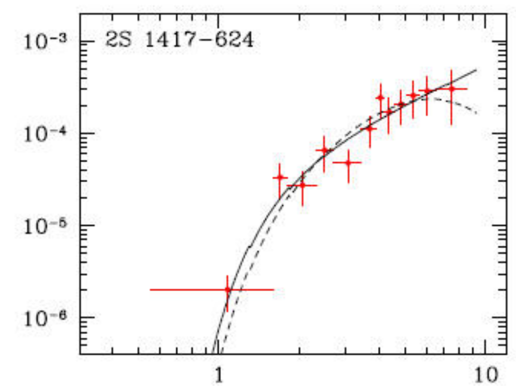
No OB, 0.1 keV
$1.6x10^{33}$ erg/s



<1 yr, ~2 keV
$3x10^{32}$ erg/s
non-thermal

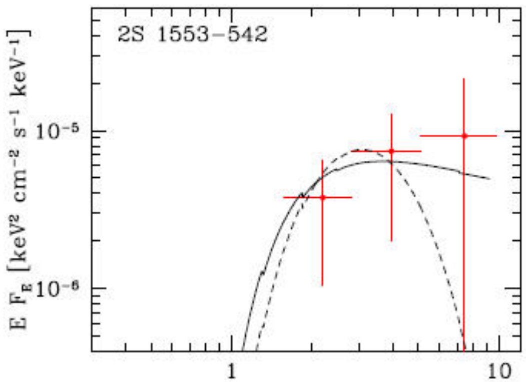


4 m after type II
2 w after type I
PL,$9x10^{34}$ erg/s

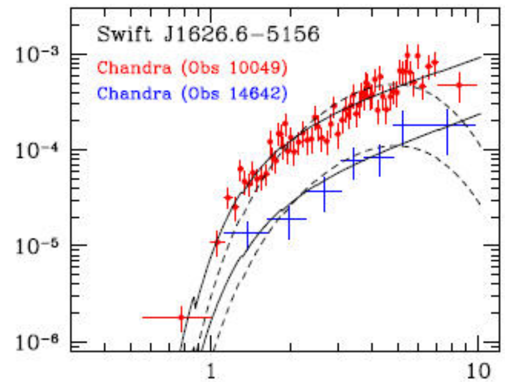


3.3 yr, PL
$3x10^{33}$ erg/s

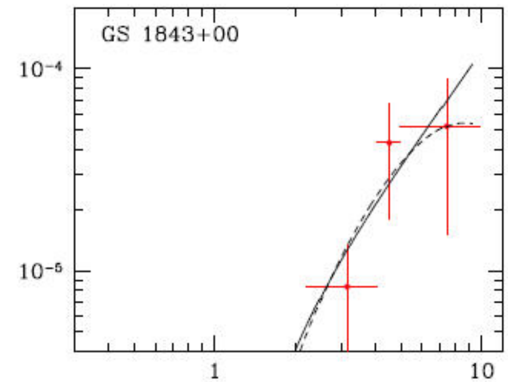
Spectra (II)



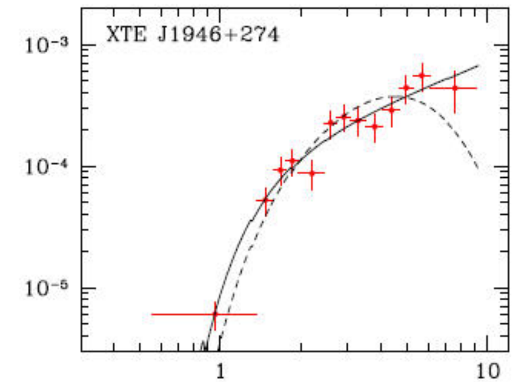
5yr, 0.7 keV
1×10^{33} erg/s



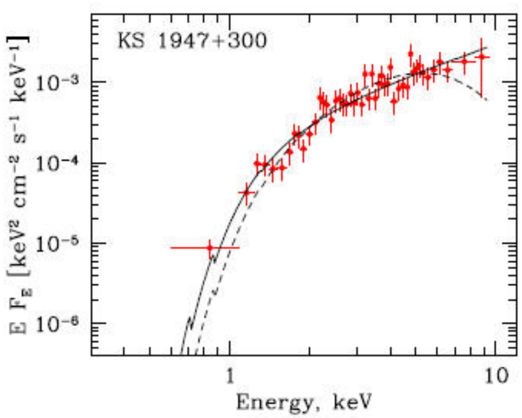
3 and 7yr, PL
$0.4\text{-}1.7\times10^{34}$ erg/s



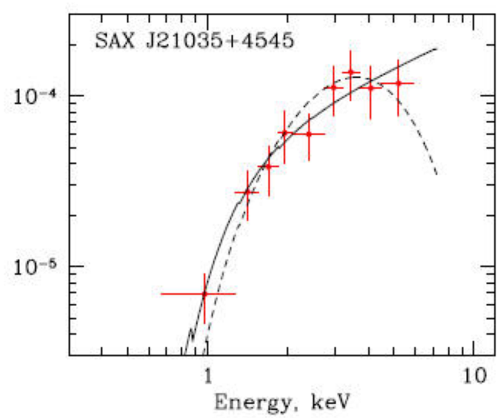
3yr, few phs
2×10^{33} erg/s



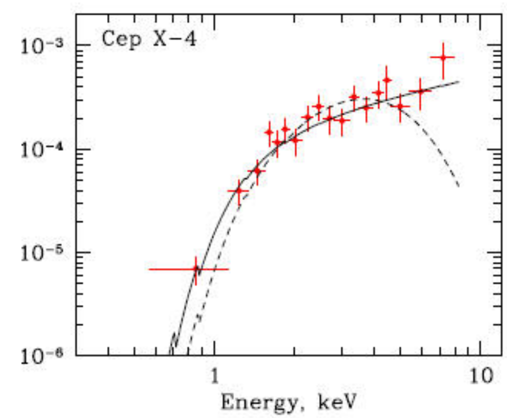
2yr, PL
10^{34} erg/s



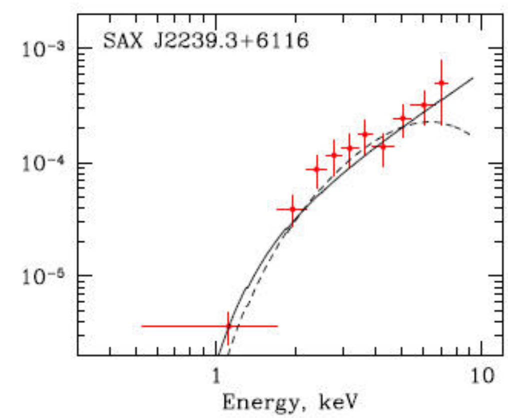
9 m, PL
4.5×10^{34} erg/s



<1 yr, ~1 keV or
PL 1.2
2×10^{33} erg/s



4 yr, PL
2×10^{33} erg/s



No OB,
PL or BB???
1.1×10^{33} erg/s

Observational conclusions

The whole sample of sources can be roughly divided into two distinct groups:

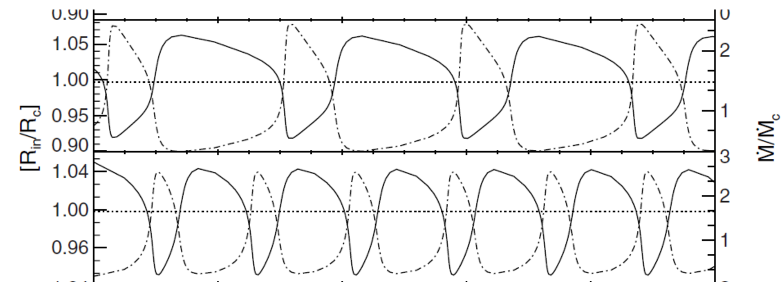
(i) relatively bright objects with a luminosity around 10^{34} erg s^{-1} and (hard) power-law spectra
(4U0728-25, GROJ1008-57, SwiftJ1626.6-5156, XTEJ1946+274, KS1947+300, several possible candidates)
X-ray pulsations were detected from five objects in group (i) with quite a large pulse fraction of 50–70 per cent.

(ii) fainter ones showing thermal spectra (4U0115+63, V0332+53, MXB0656-072, RXJ0812.4-3114)

BUT! There is no correlation between the emission temperature and time after the last outburst, i.e. we don’t’ see cooling directly.
WHY?

Emission in the very low state can be originated and contaminated by different factors

- Leakage of matter through the centrifugal barrier



- Magnetospheric accretion $$T_{\rm keV}(r = R_{\rm m}) \simeq 0.03\, B_{12}^{-3/7} L_{37}^{13/28}.$$

- Thermal emission from the cooling NS

- *Coronal activity of the companion star*

Origin of the very low emission of NSs

- Thermal emission from the cooling NS:

The matter accumulated during outbursts compresses the original NS crust and enriches it with low-Z elements.

It leads to non-equilibrium reactions (electron captures, neutron emissions, pycnonuclear reactions).

Most of this heat is conducted inwards to the core, but a small part is radiated from the NS surface as thermal photons

"Deep crustal heating" model *Brown et al., 1998*

$$L_q \approx 6 \times 10^{32} \text{ ergs s}^{-1} (\langle \dot{M} \rangle / 10^{-11} \ M_\odot \text{ yr}^{-1}), \qquad (5)$$

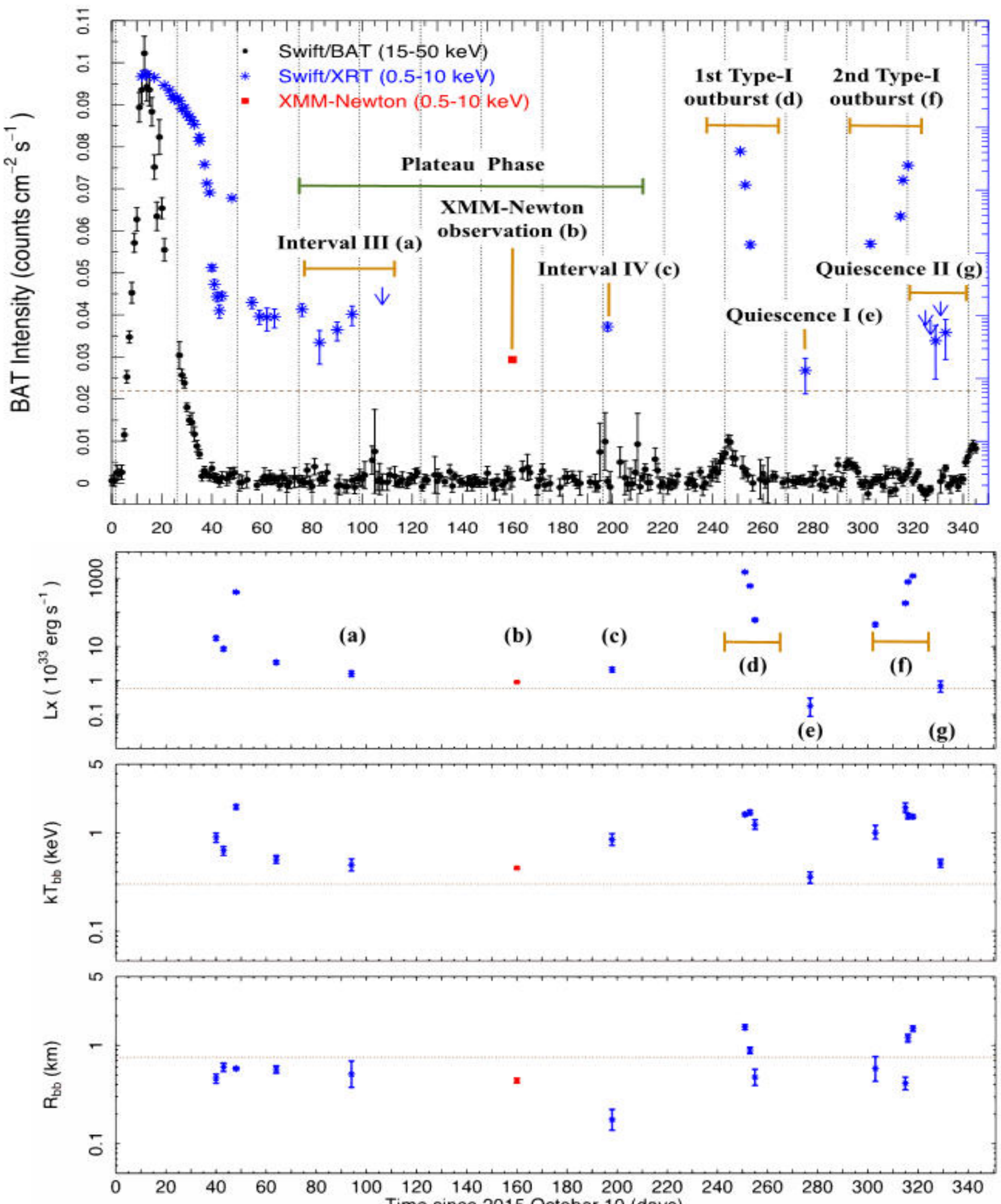
Rutledge et al., 2007

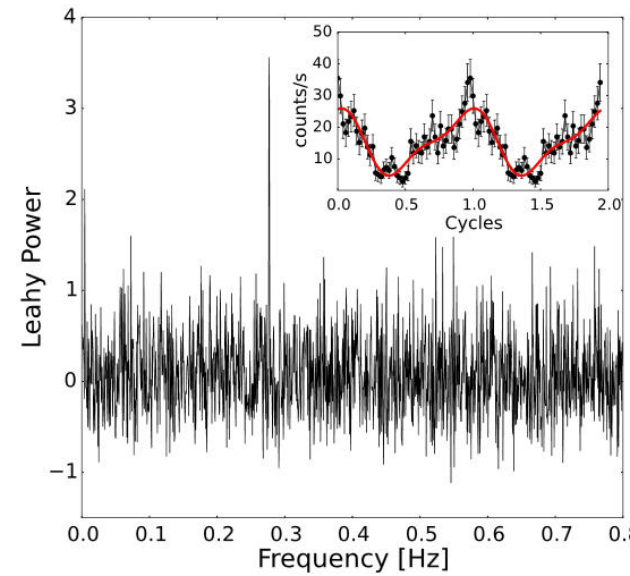
Source	Period[a] (s)	$L_{\rm prop}(R)$[b] (10^{33} erg s^{-1})	$\langle\dot{M}\rangle$[c] (10^{-10} M$_\odot$ yr^{-1})	$L_{\rm q}$[d] (10^{33} erg s^{-1})	$L_{\rm bb}$[e] (10^{33} erg s^{-1})	$L_{\rm pl}$[f] (10^{33} erg s^{-1})
4U 0115+63	–	174	0.7	4.3	$0.59^{+0.07}_{-0.06}$	$1.14^{+0.20}_{-0.15}$
V 0332+53	–	991	1.0	5.5	$0.26^{+0.07}_{-0.06}$	$0.54^{+0.28}_{-0.16}$
V 0332+53 (XMM)	–	991	1.0	5.5	$0.34^{+0.04}_{-0.04}$	$0.59^{+0.09}_{-0.08}$
MXB 0656−072	–	0.3	0.2	1.3	$3.80^{+0.27}_{-0.25}$	$5.62^{+0.40}_{-0.38}$
4U 0728−25 (XRT aver)	–	[g]	0.2	1.3	$7.91^{+0.57}_{-0.36}$	$11.2^{+0.5}_{-0.7}$
RX J0812.4−3114	–	[g]	0.4	2.2	$1.60^{+0.82}_{-0.62}$	$2.54^{+1.58}_{-1.05}$
GS 0834−430	–	[g]	0.3	1.9	$0.27^{+0.29}_{-0.12}$	$0.37^{+0.27}_{-0.16}$
GRO J1008−57	–	5.5	1.0	5.6	$66.8^{+1.6}_{-1.5}$	$94.3^{+2.2}_{-2.1}$
2S 1417−624	–	[g]	0.3	2.1	$2.01^{+0.46}_{-0.38}$	$2.66^{+0.54}_{-0.40}$
2S 1553−542	–	119	1.5	8.8	$1.05^{+0.65}_{-0.44}$	$2.24^{+7.99}_{-1.09}$
Swift J1626.6−5156 (10049)	15.3360(6)	5.9	0.7	4.3	$12.5^{+0.6}_{-0.6}$	$17.3^{+0.8}_{-0.8}$
Swift J1626.6−5156 (14642)	–	5.9	0.7	4.3	$2.87^{+0.66}_{-0.48}$	$4.15^{+0.84}_{-0.70}$
GS 1843+00	–	5.1	1.2	7.3	$1.55^{+1.34}_{-0.66}$	$2.00^{+1.32}_{-0.77}$
XTE J1946+274	15.760(3)	67	0.3	1.9	$8.06^{+0.78}_{-0.71}$	$11.6^{+1.1}_{-1.0}$
KS 1947+300	18.802(3)	3.7	1.8	10.5	$32.9^{+2.4}_{-1.5}$	$46.5^{+3.3}_{-2.1}$
SAX J21035+4545	350.7(1.1)	[g]	0.5	3.2	$1.49^{+0.22}_{-0.16}$	$2.42^{+0.36}_{-0.31}$
Cep X-4	66.38(3)	1.7	0.05	0.3	$1.22^{+0.15}_{-0.11}$	$1.94^{+0.19}_{-0.21}$
SAX J2239.3+6116	–	[g]	0.06	0.4	$1.01^{+0.29}_{-0.23}$	$1.46^{+0.34}_{-0.27}$

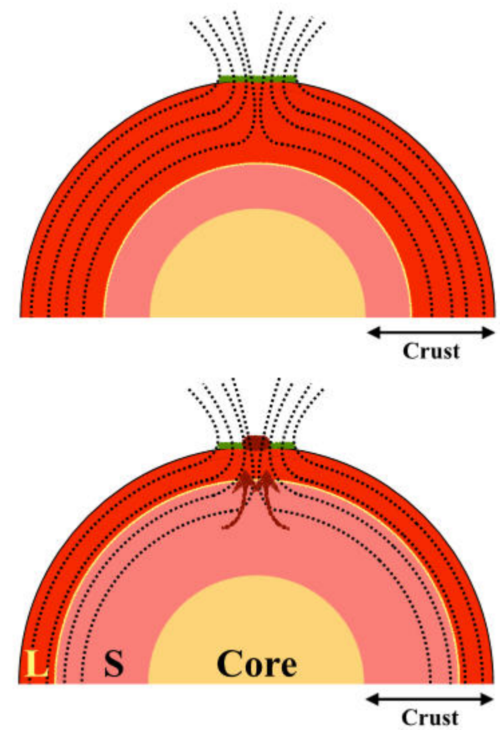
$$L_{\rm prop}(R) = \frac{GM\dot{M}_{\rm prop}}{R}$$
$$\simeq 4 \times 10^{37} k^{7/2} B_{12}^2 P^{-7/3} M_{1.4}^{-2/3} R_6^5 \,{\rm erg\ s^{-1}}$$

$$L_{\rm q} = (\langle\dot{M}\rangle/10^{-11}{\rm M_\odot yr^{-1}}) \times 6 \times 10^{32}\ {\rm erg\ s^{-1}}$$

Cooling in 4U0115+63



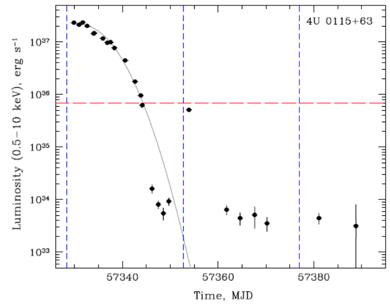




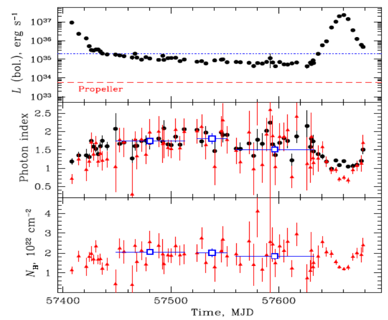
Wijnands, Degenaar 2016, *Ruoco Escorial et al. 2017*

Conclusions

- Strong progress in the study of highly magnetized neutron stars in last years
- Direct detection of the propeller effect



- New paradigm of the cold accretion disk



- First systematic study of Be systems in quiescent state to study cooling of NS with a strong magnetic fields