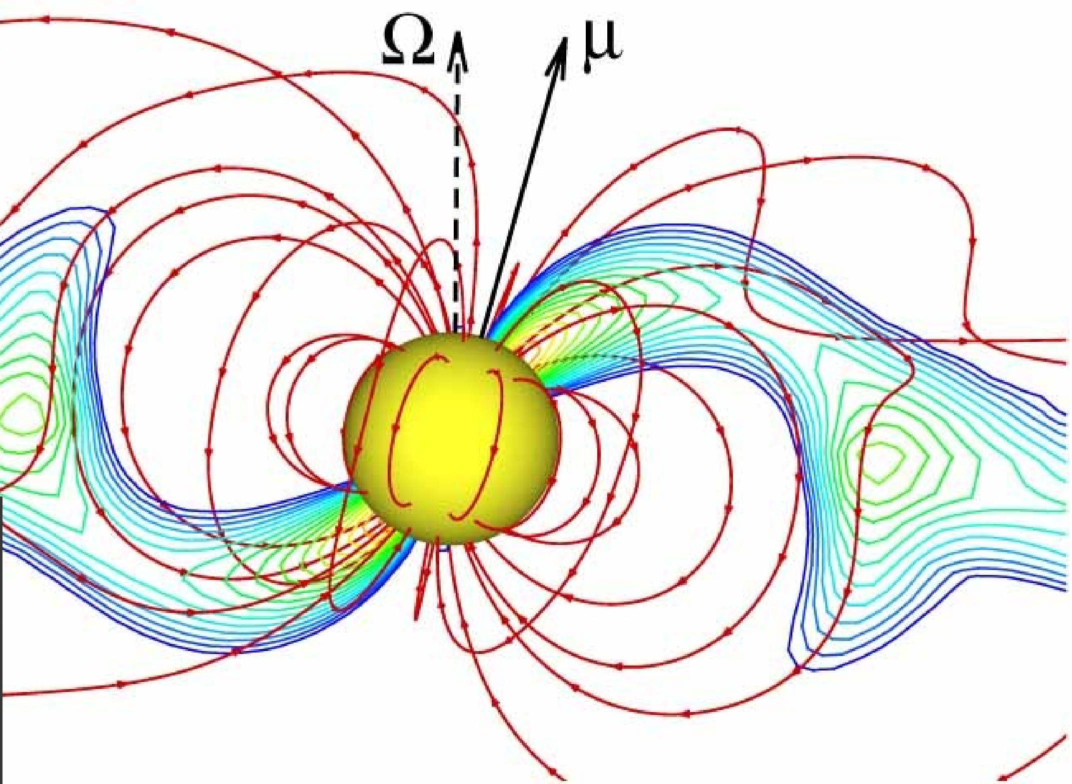
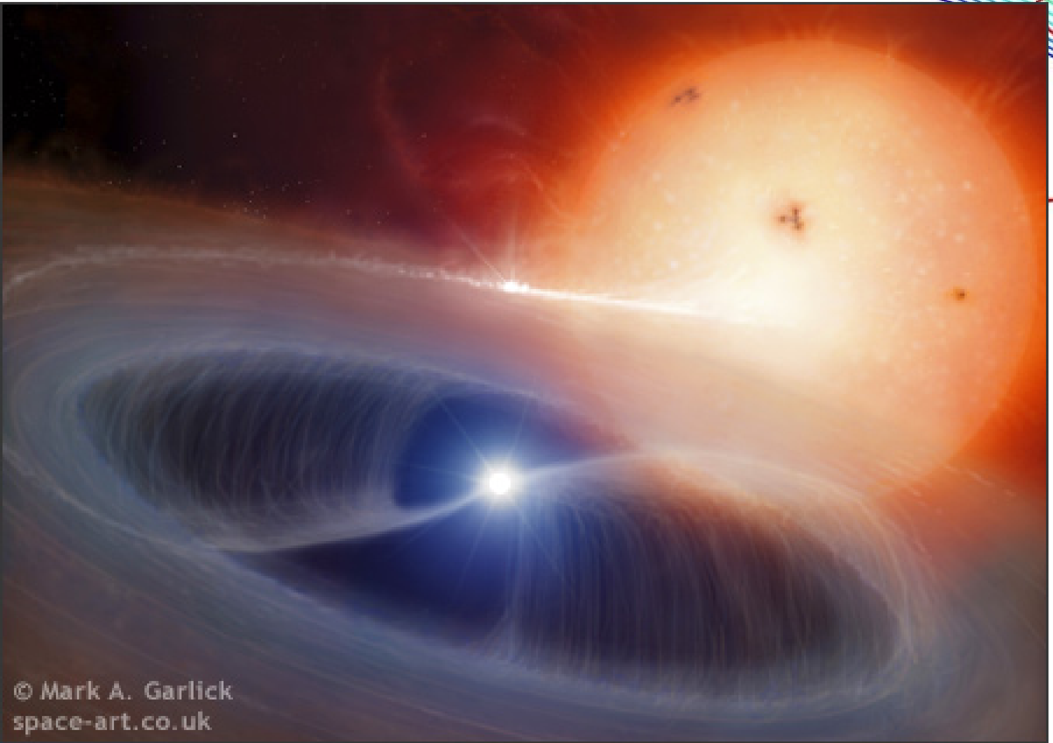
Low-level accretion onto highly magnetized neutron stars





Sergey Tsygankov
Tuorla Observatory, Finland

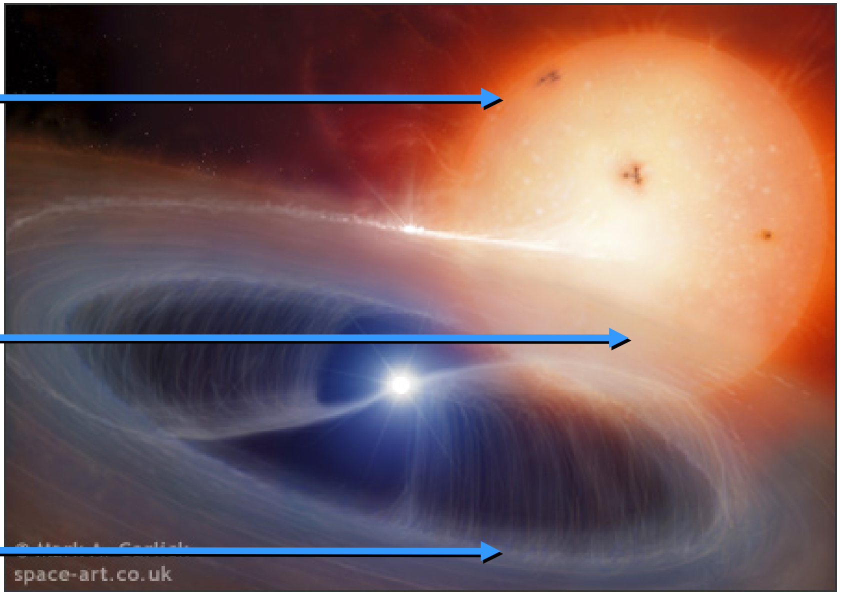
X-ray pulsar

Rotating Neutron Star in binary systems

High mass companions

Mass capture from wind/disk

High B-fields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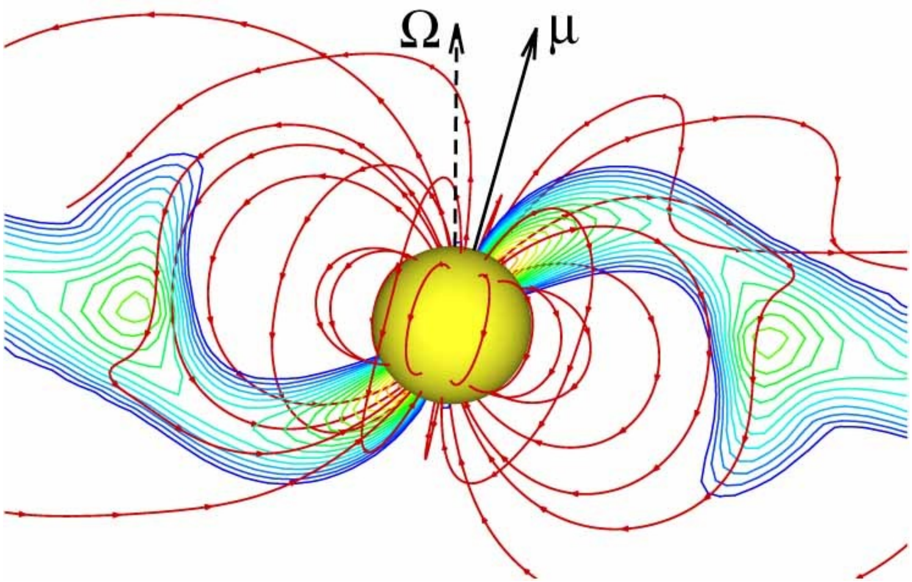
Disruption of disk by B-field

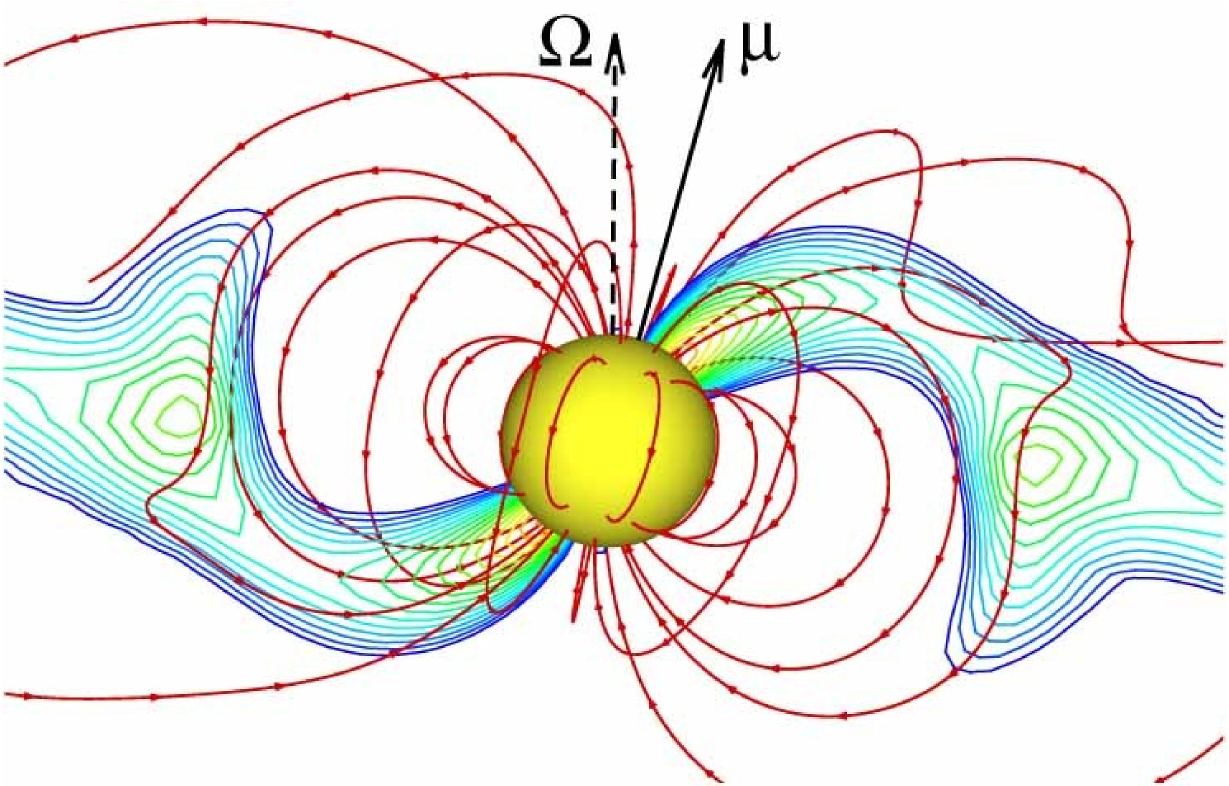
Matter channeled onto star



Neutron star parameters:

$M_{NS} \sim 1.5\text{-}2\ M_{sun}$
$R_{NS} \sim 10\text{-}15$ km (10^6 sm)
$P_{spin} \sim 1 - 10^3$ s
$\mathbf{B_{NS} \sim 10^{12}\ G}$

X-ray pulsar



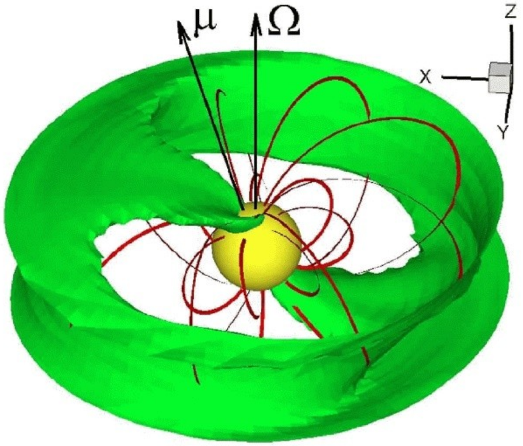
$$r_{\rm co} = \left(\frac{GM}{\Omega^2}\right)^{1/3}$$

Keplerian and stellar-rotation frequencies are equal

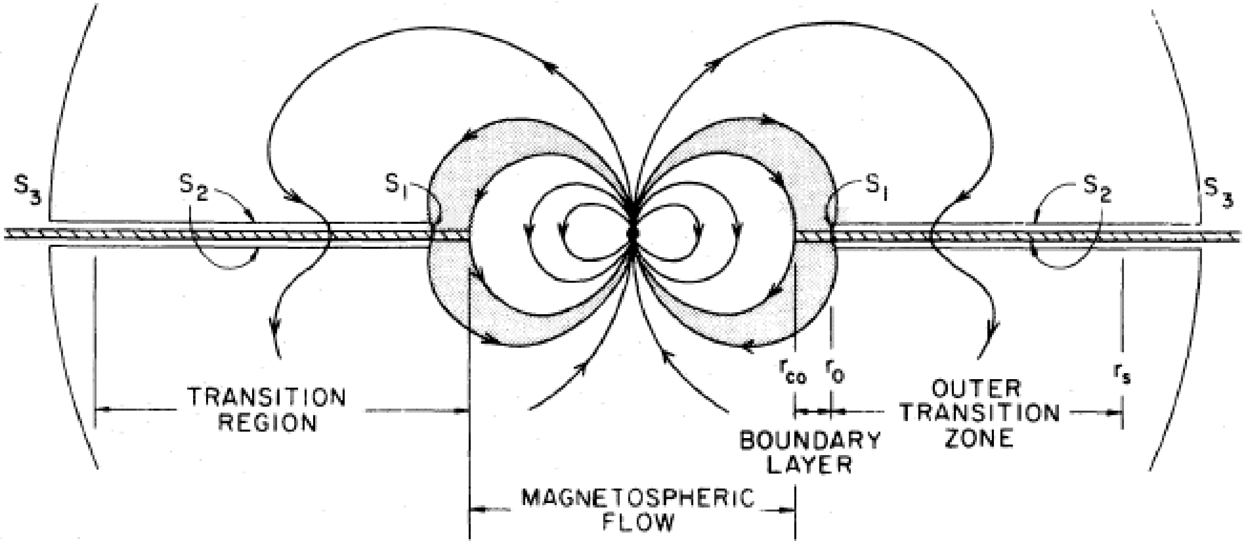
$$r_{\rm A} = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$$

Alfven radius: magnetic pressure equals to the ram pressure of gas in spherical free-fall from infinity

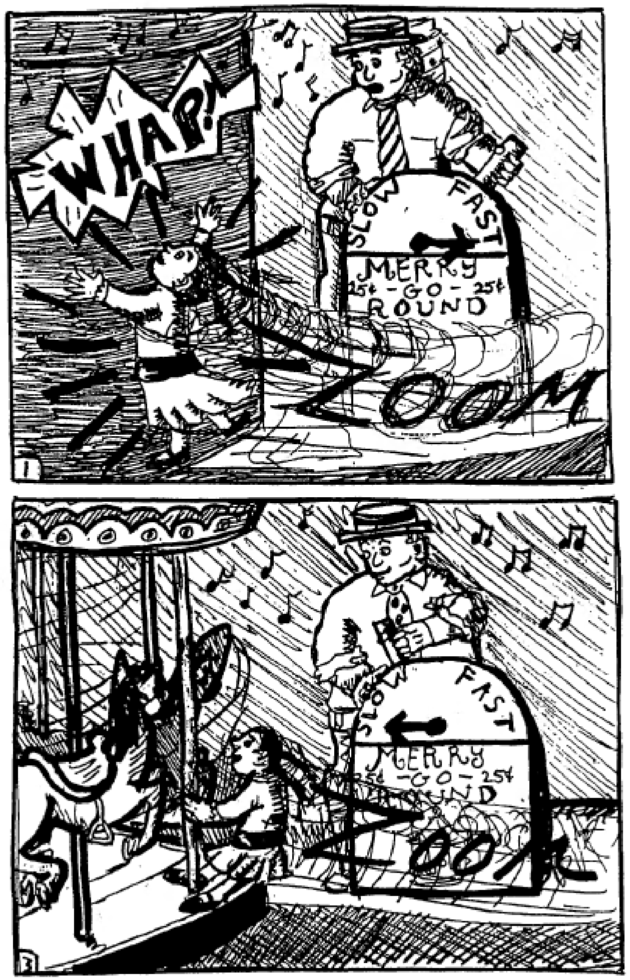
$$r_{\rm m} = \xi r_{\rm A}$$



Romanova et al. 2009



Propeller effect



Patterson, 1994

$R_m < R_c$ - accretion is possible

$R_m > R_c$ - accretion is prohibited due to centrifugal barrier

$$r_{\rm co} = \left(\frac{GM}{\Omega^2}\right)^{1/3}$$

Keplerian and stellar-rotation frequencies are equal

$$r_{\rm A} = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$$

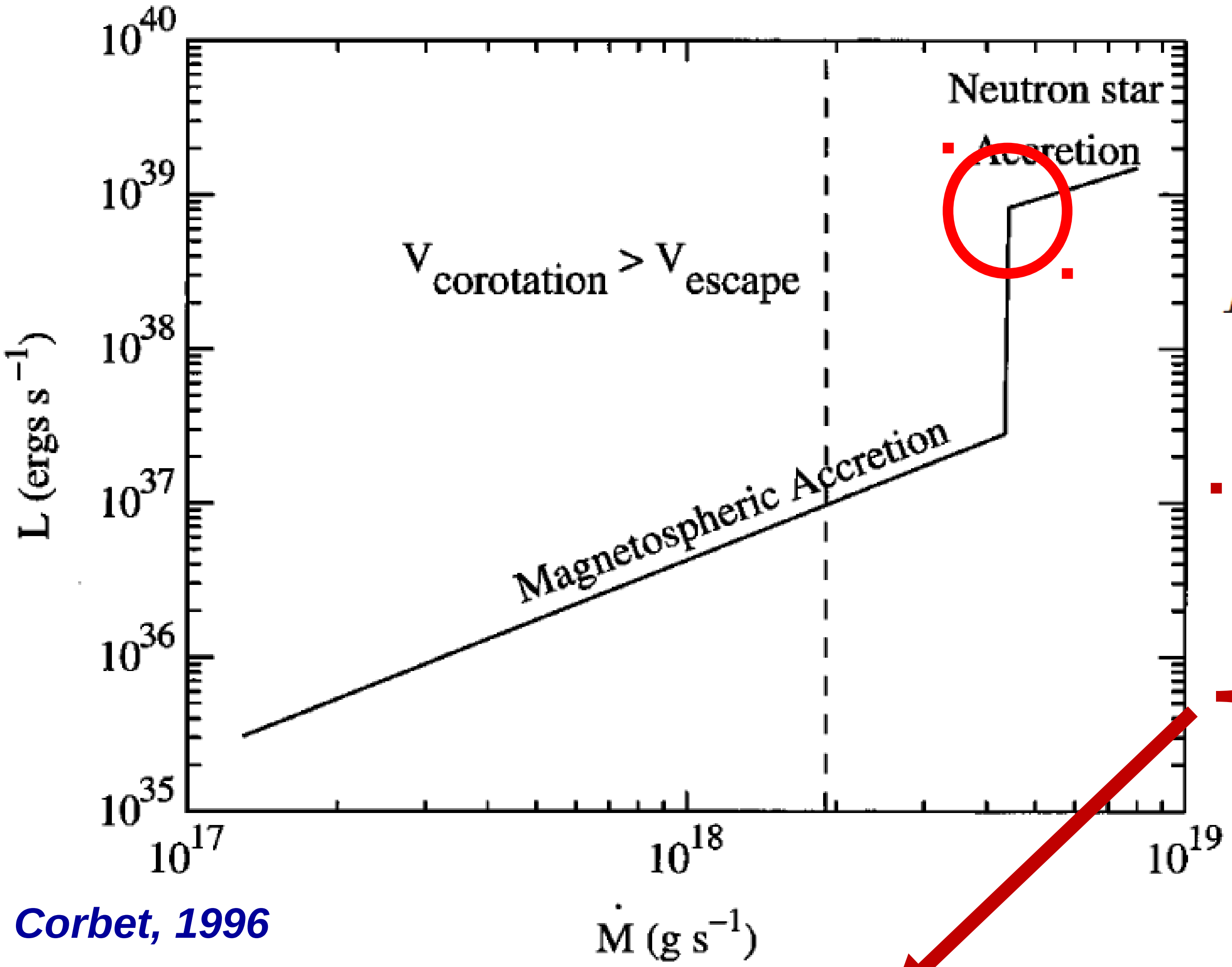
Alfven radius: magnetic pressure equals to the ram pressure of gas in spherical free-fall from infinity

$$r_{\rm m} = \xi r_{\rm A}$$

“Propeller effect”

Illarionov & Sunyaev, 1975

Propeller effect



Corbet, 1996

$$R_{\rm c} = R_{\rm m}$$

$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R}$$

$$r_{\rm co} = \left(\frac{GM}{\Omega^2}\right)^{1/3}$$

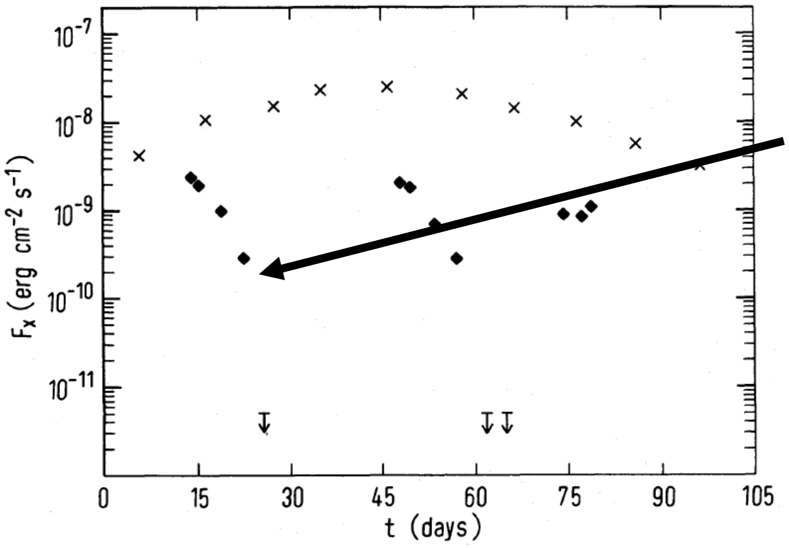
$$r_{\rm A} = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$$

$$r_{\rm m} = \xi r_{\rm A}$$

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

Observational manifestation

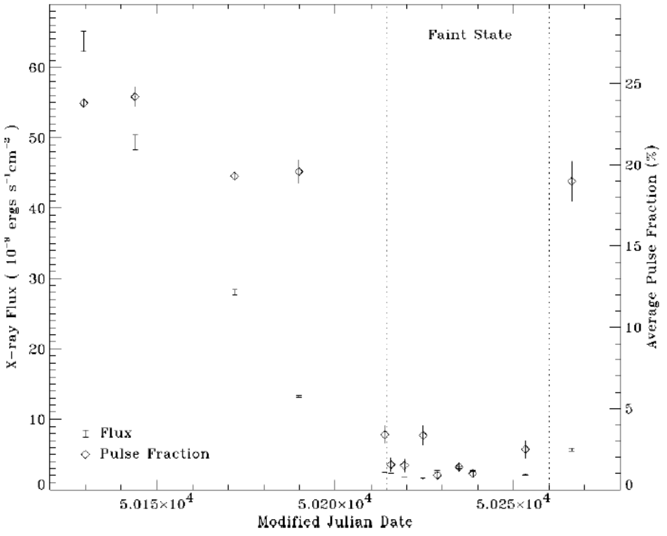
V 0332+53



L_{lim} = 2.6 x 10^{36} erg/s

Stella et al., 1986

GRO J1744-28

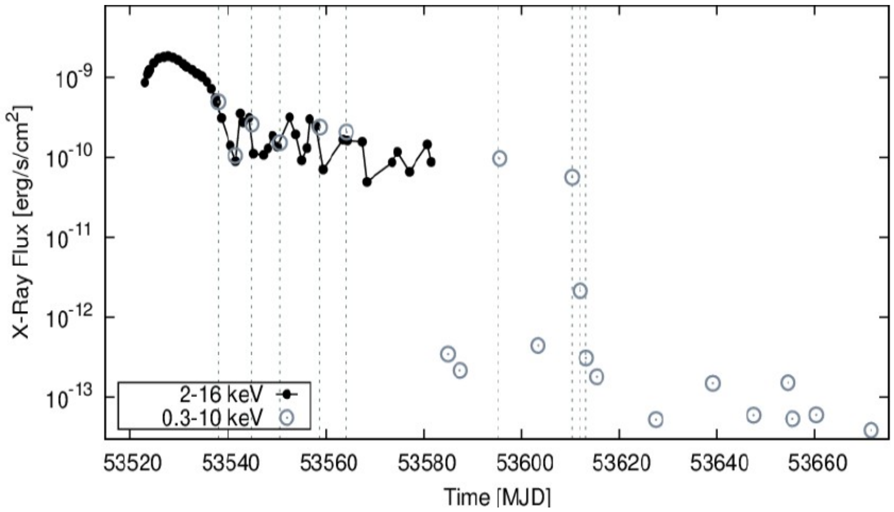


L_{lim} = 3 x 10^{37} erg/s

Cui, 1997

SAX J1808.4-3658

L_{lim} = 5 x 10^{35} erg/s



Patruno et al., 2016

Campana et al., 2008

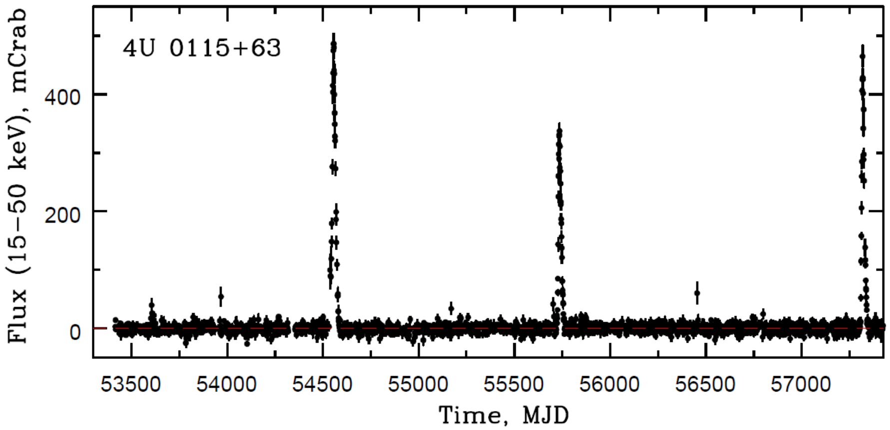
Observations of the propeller effect

What is needed:

- wide range of the mass accretion rate;
- independently measured magnetic field (desired);
- sensitive and flexible X-ray telescope.

4U 0115+63, V 0332+53 and SMC X-2 in 2015

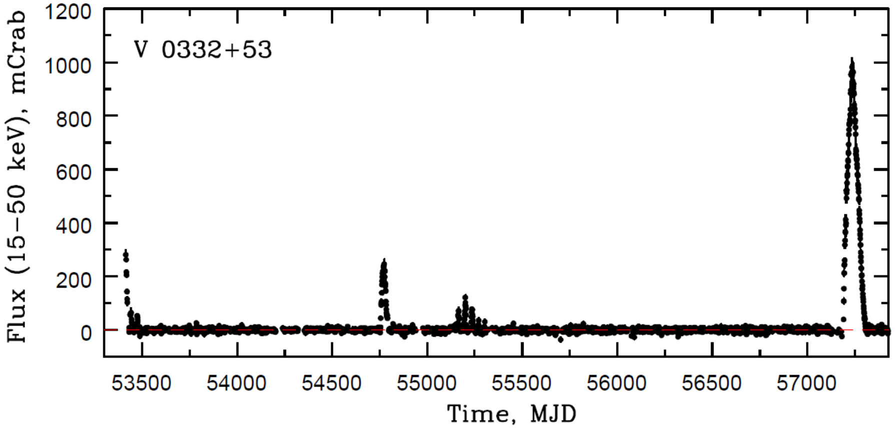
Swift/BAT + XRT monitoring



P_{spin} = 3.6 s

E_{cyc} ~ 12 keV

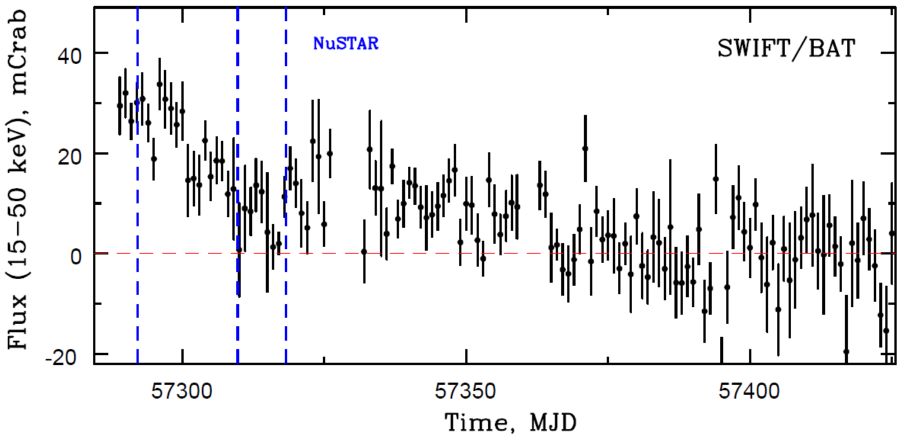
d = 7 kpc



P_{spin} = 4.3 s

E_{cyc} ~ 30 keV

d = 7 kpc

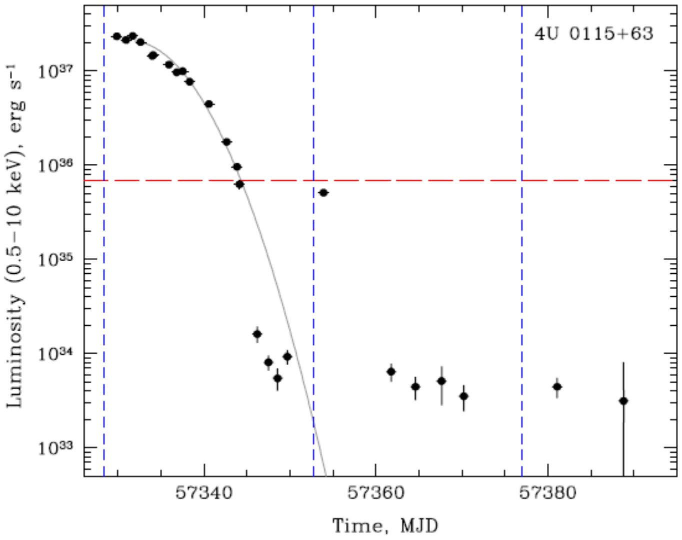


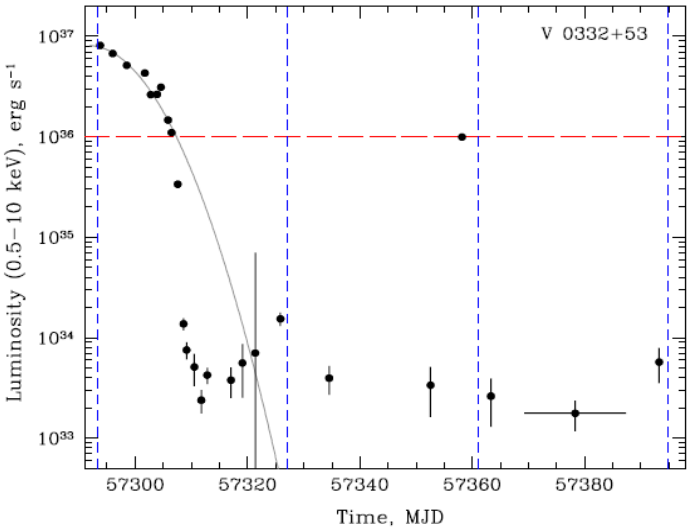
P_{spin} = 2.37 s

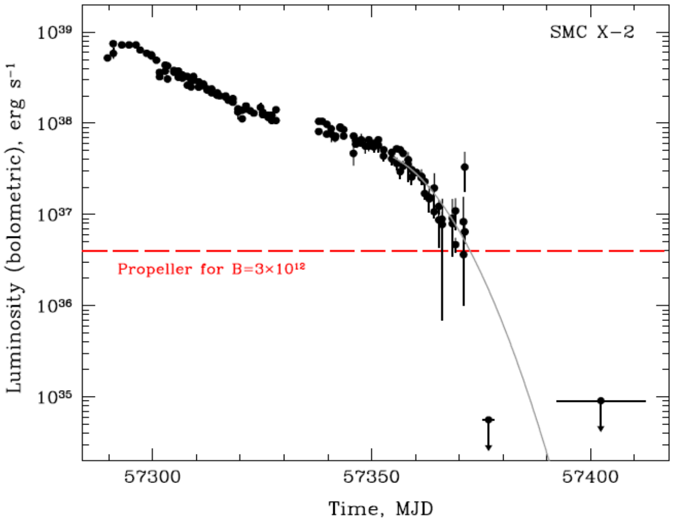
E_{cyc} ~ 27 keV

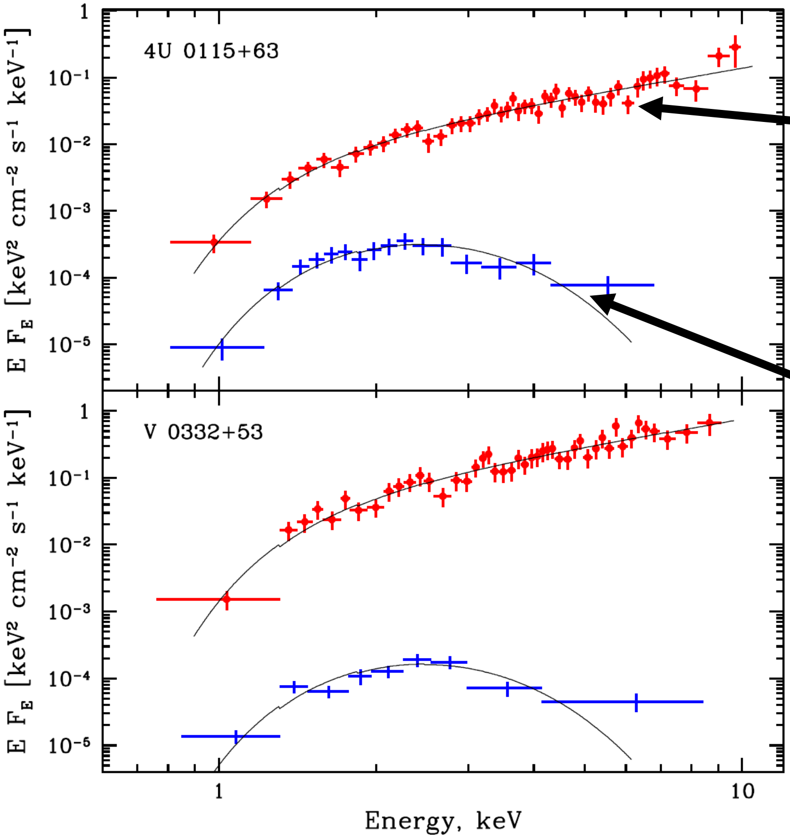
d = 63 kpc

4U 0115+63, V 0332+53 and SMC X-2 in 2015









Absorbed power-law
Gamma = 0.4 – 0.7

Black body with
kT = 0.5 keV

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

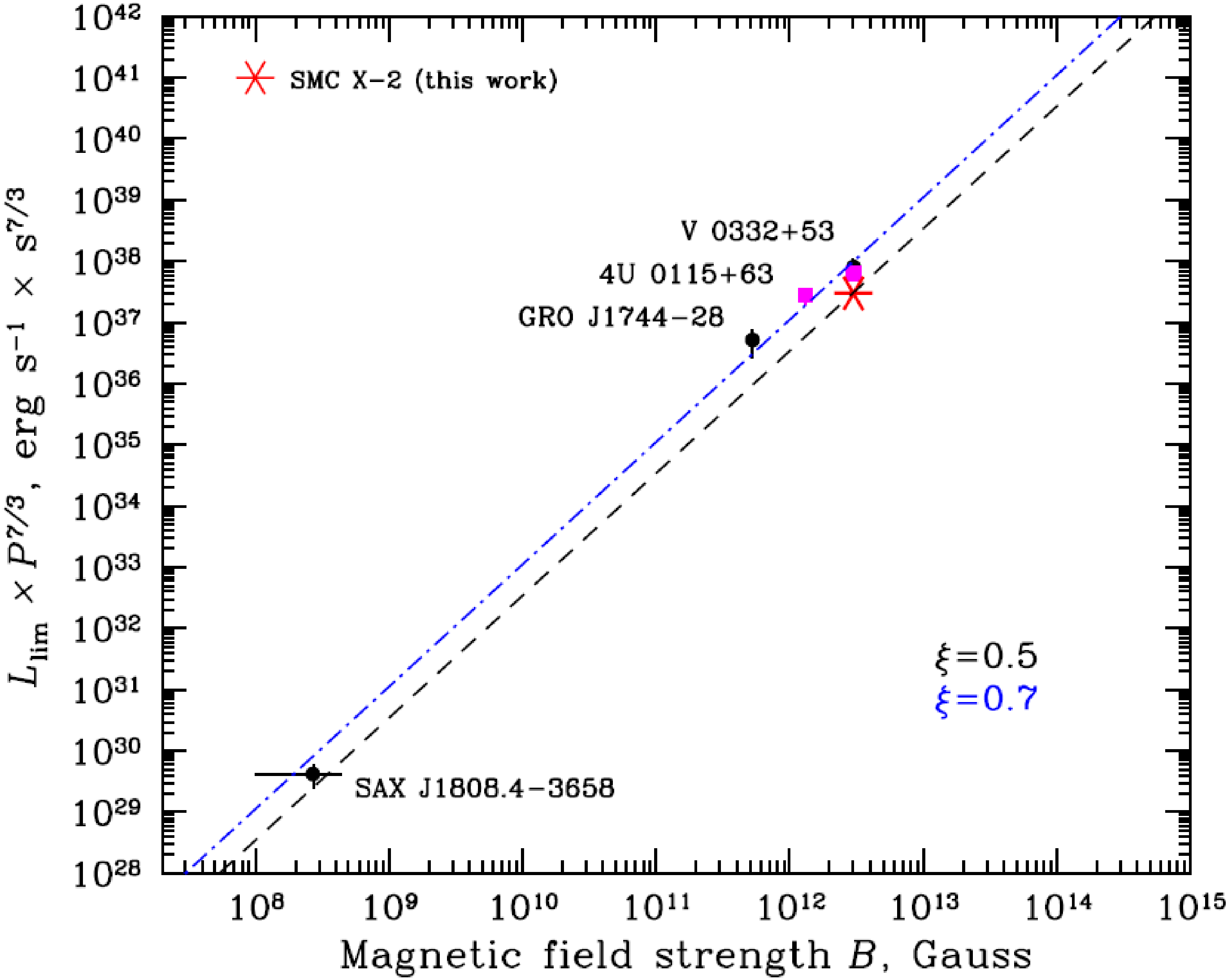
Propeller in action

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

$$r_{\rm co} = \left(\frac{GM}{\Omega^2}\right)^{1/3}$$

$$r_{\rm A} = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$$

$$r_{\rm m} = \xi r_{\rm A}$$



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

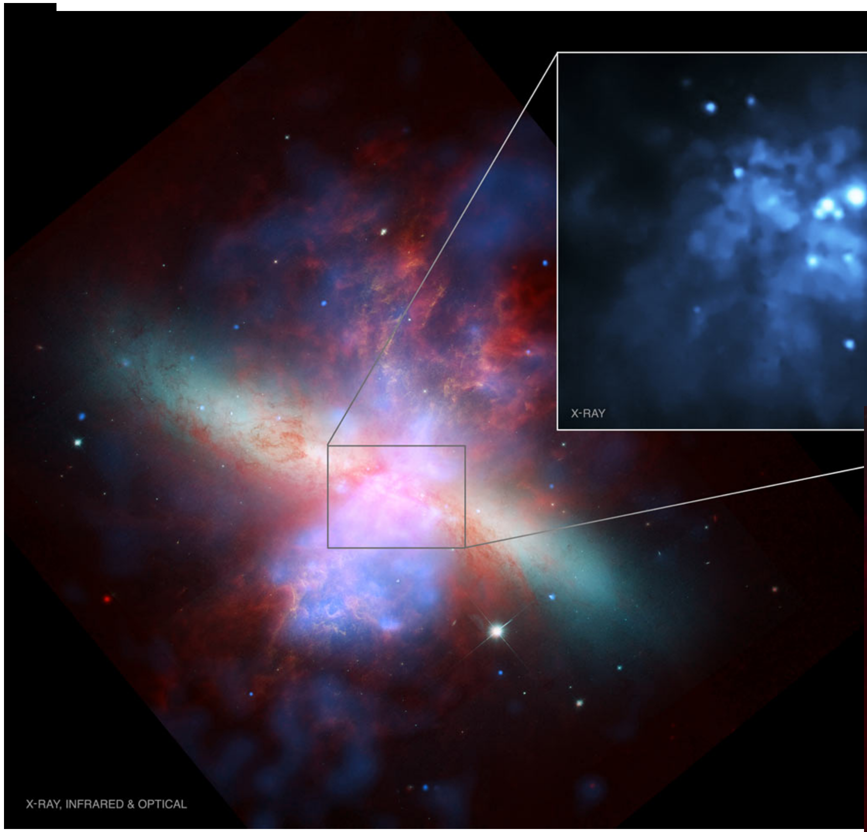
LETTER

$L \sim 100\ L_{Edd}$ for $1.4\ M_{sun}$ mass object!

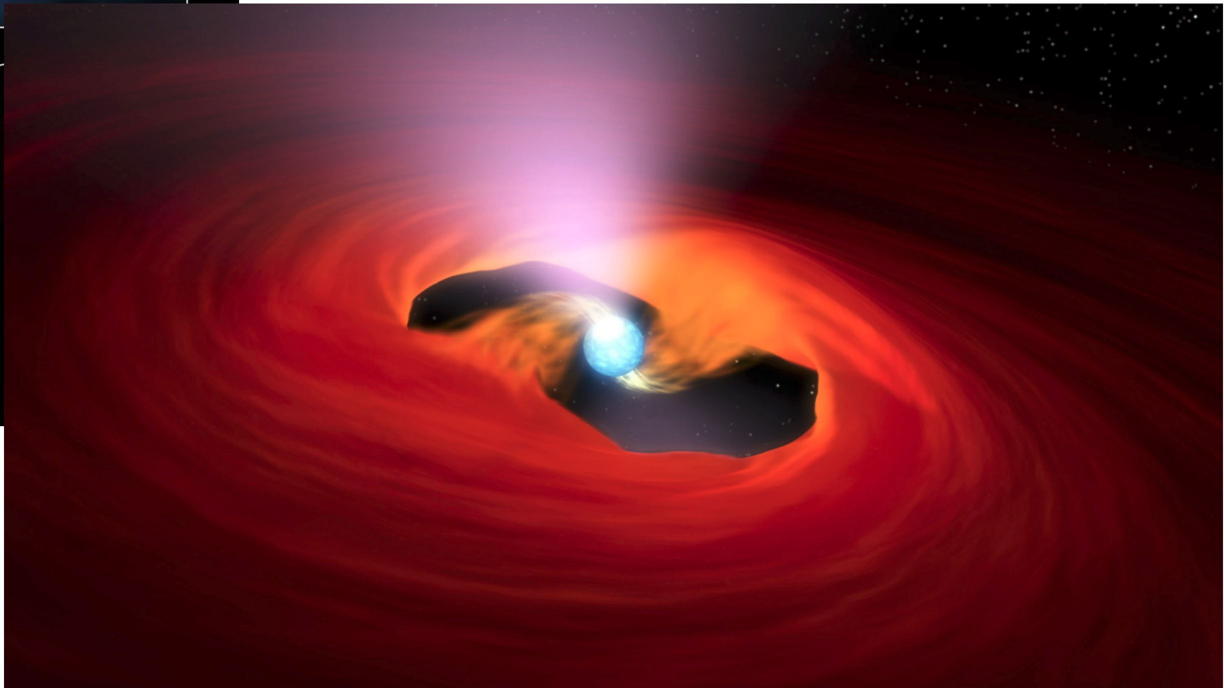
doi:10.1038/nature13791

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]

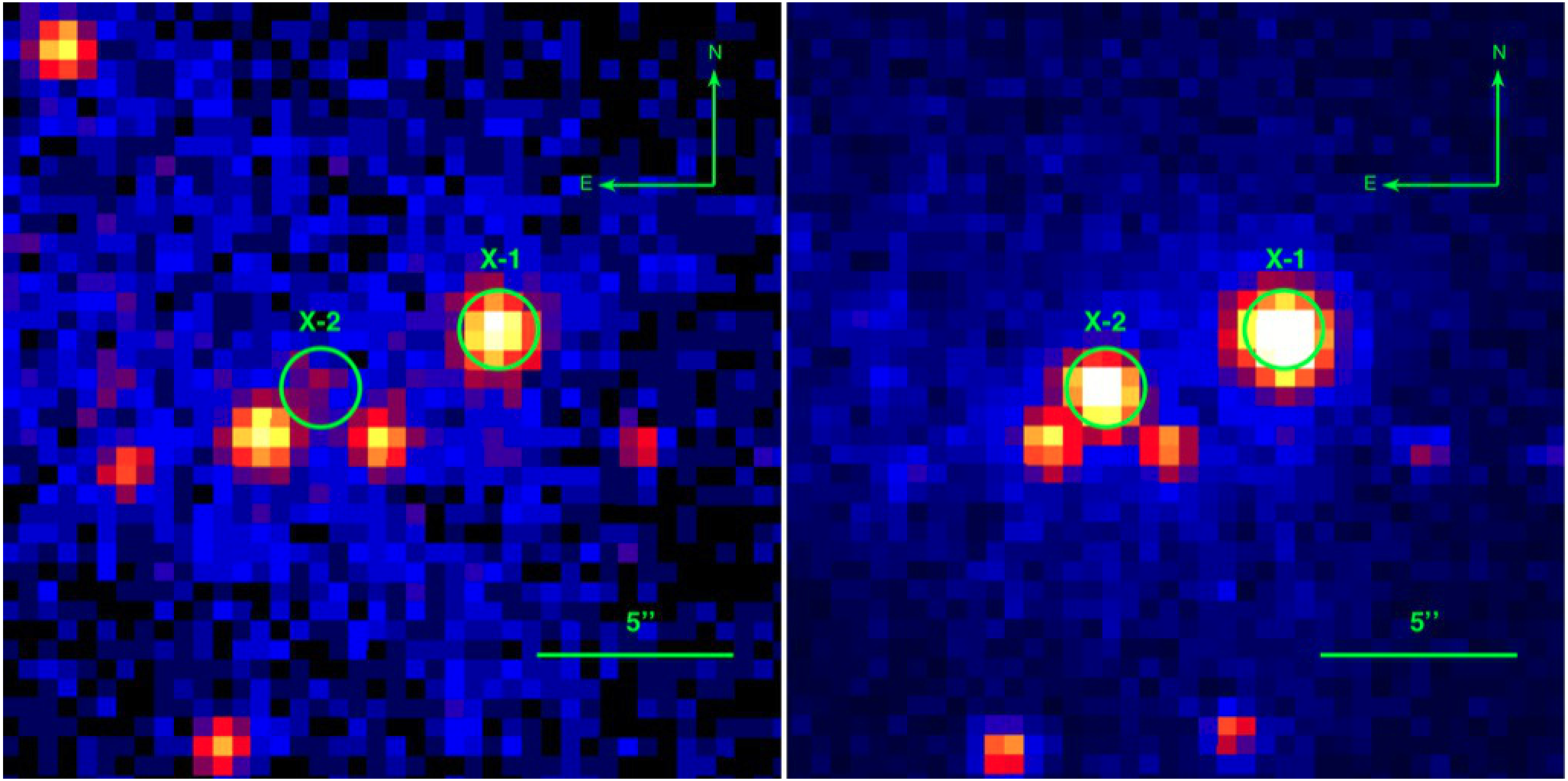


P_{spin}=1.37 s



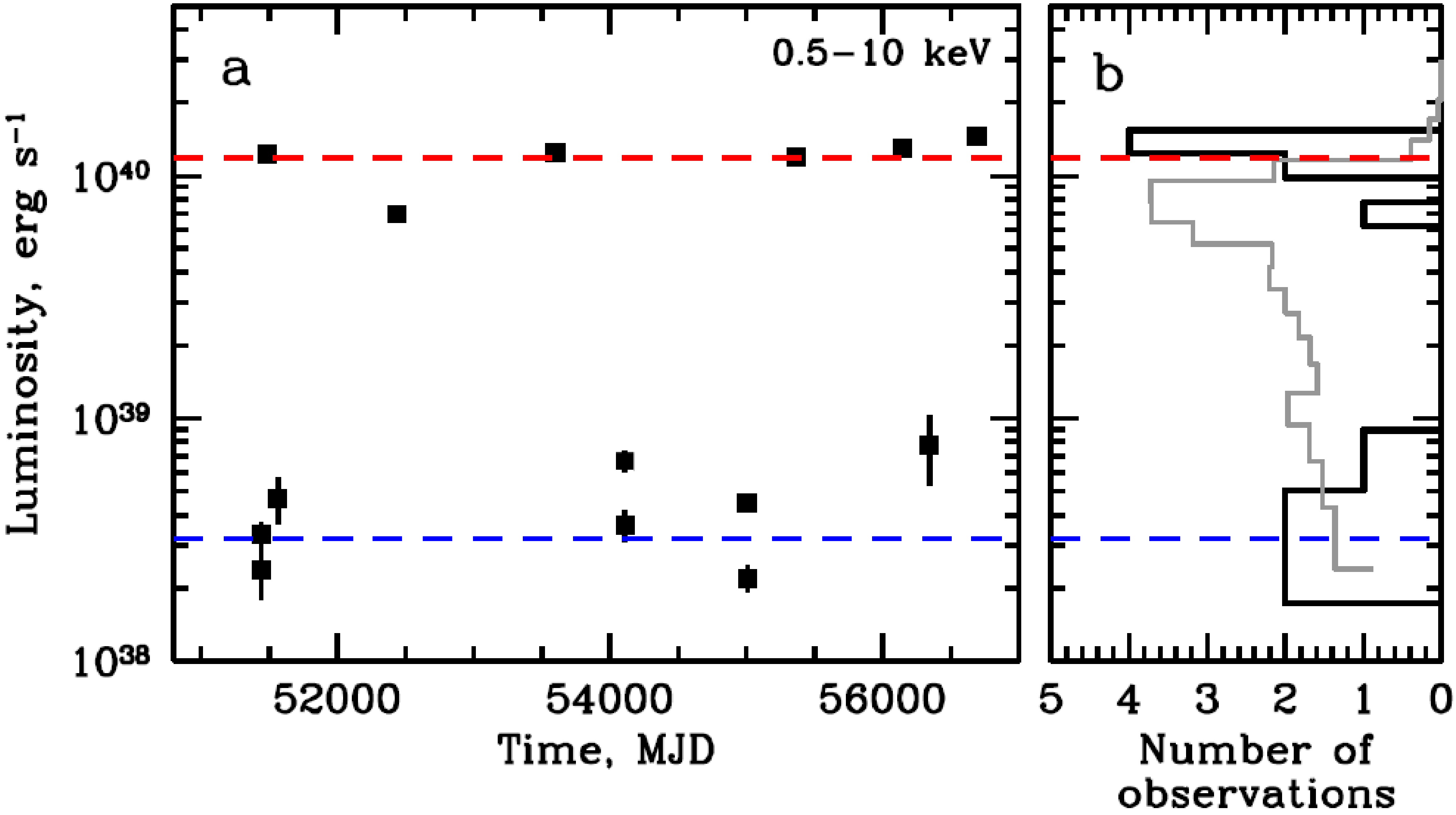
In M82 Galaxy

M82 as seen by Chandra



Tsygankov et al., 2016b

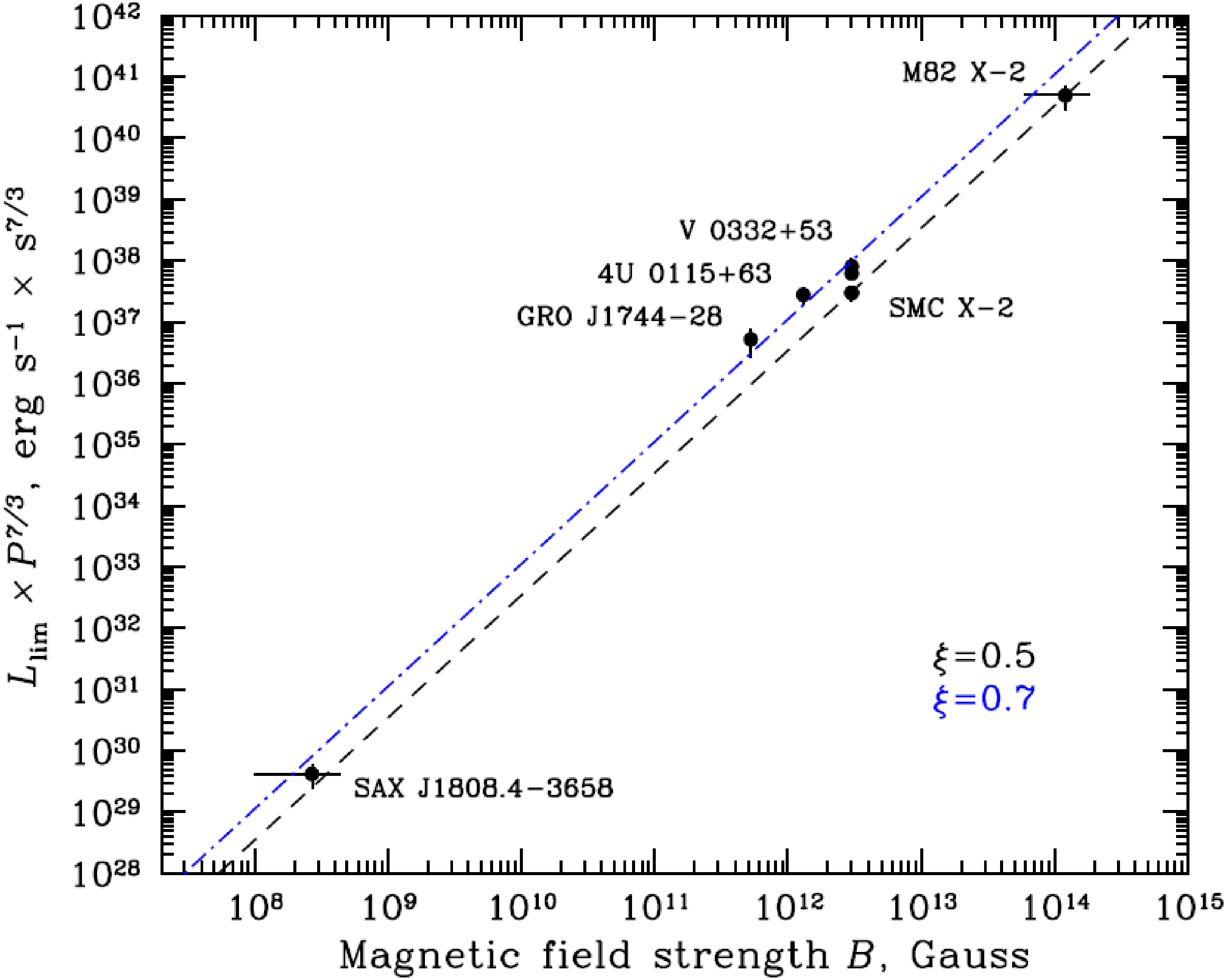
M82 X-2 intensity distribution



Distribution is bimodal

Tsygankov et al., 2016b

Propeller in action



P=1.37 s

ξ = 0.5

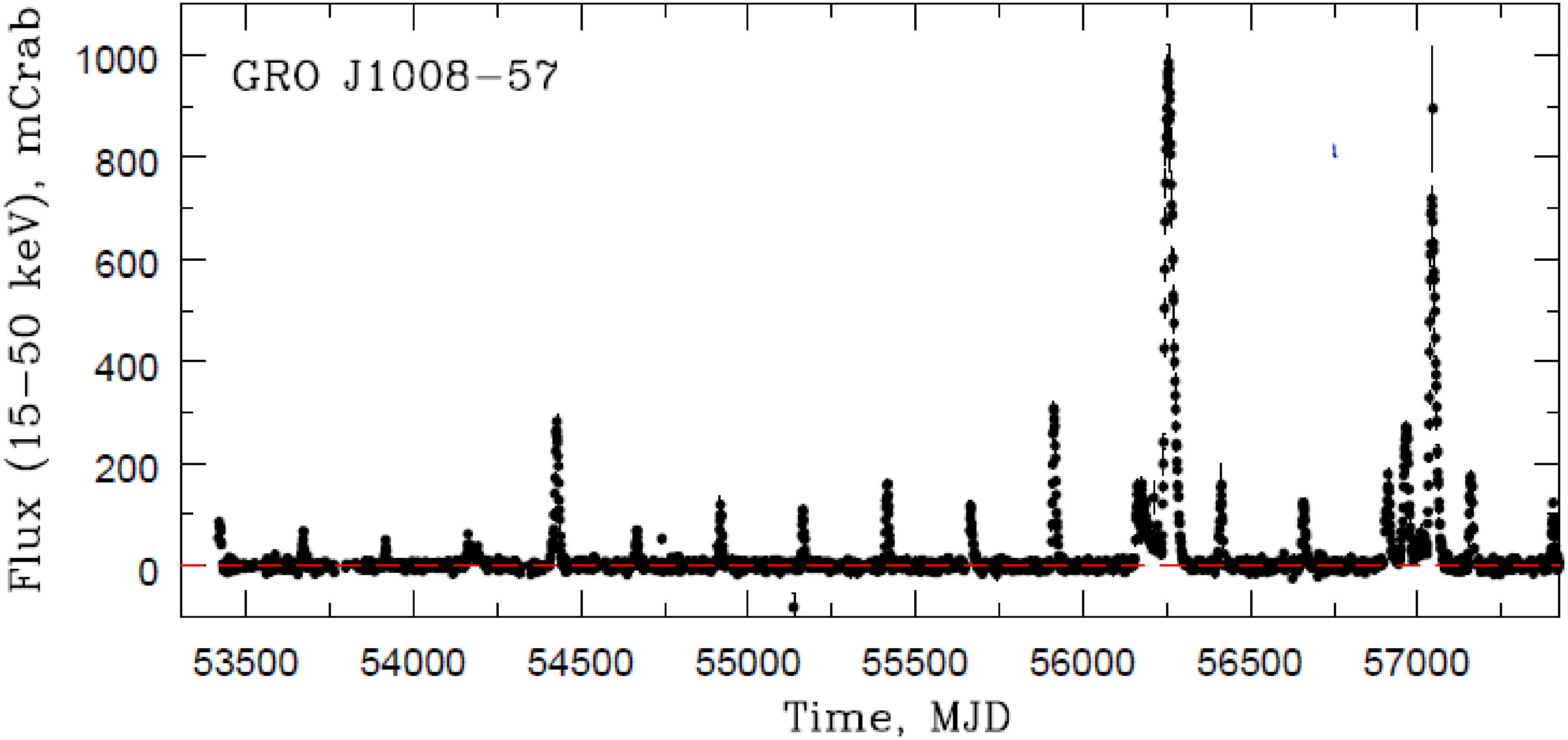
$L_{\rm lim}$=2.0 x 10^{40} erg s^{-1}

B~1.1 x 10^{14} G

Tsygankov et al., 2016b

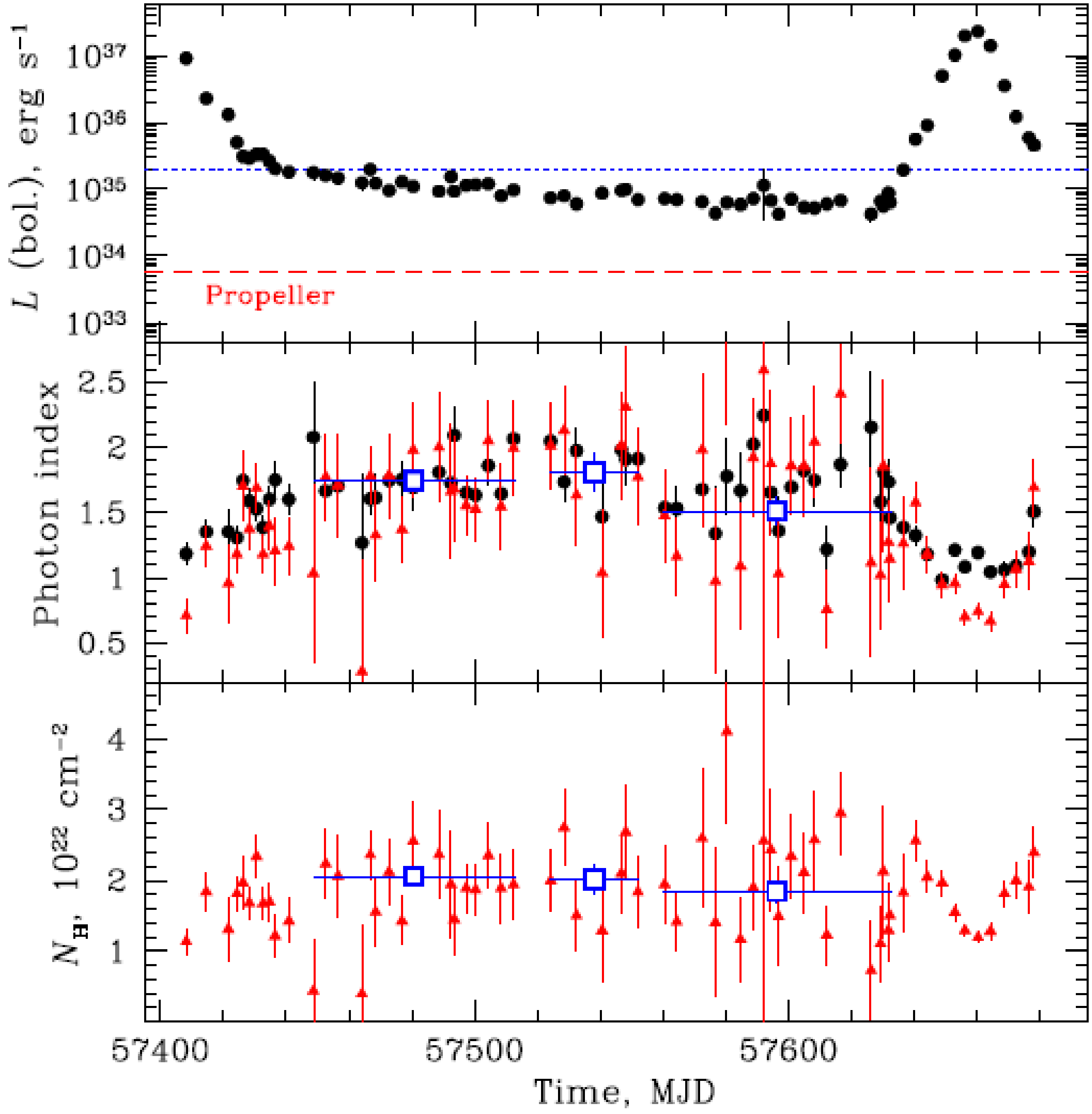
$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times10^{37}\xi^{7/2}B_{12}^{2}P^{-7/3}M_{1.4}^{-2/3}R_{6}^{5}\,{\rm erg\ s^{-1}}$$

GRO J1008-57 in 2016



P_{spin} = 94 s, E_{cyc} ~ 80 keV, d = 5.8 kpc

GRO J1008-57 in 2016



P_{spin} = 94 s

E_{cyc} ~ 80 keV

d = 5.8 kpc

Tsygankov et al., 2017

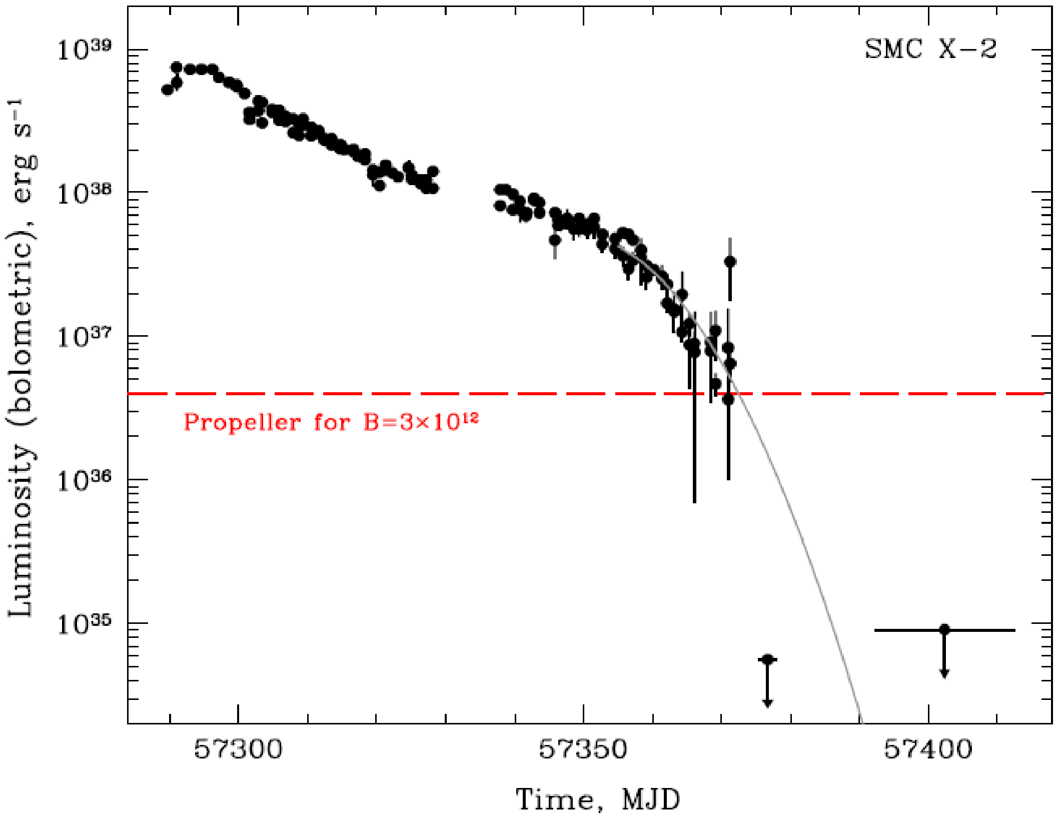
Thermal-viscous instability

Partial ionization of hydrogen at ~6500 K cause an abrupt change in opacity and viscosity making the disc locally unstable.
Critical accretion rate, above which the disc is stable:

$$\dot{M} > \dot{M}_{\rm hot} \approx 6 \times 10^{16} r^{3}_{\rm out,10}\ {\rm g\,s}^{-1}$$

Lasota, 1997

E.g.:



Thermal-viscous instability

Partial ionization of hydrogen at ~6500 K cause an abrupt change in opacity and viscosity making the disc locally unstable.
Critical accretion rate, above which the disc is stable:

$$\dot{M} > \dot{M}_{\rm hot} \approx 6 \times 10^{16} r_{\rm out,10}^{3} \ {\rm g\,s^{-1}}$$

Or below:

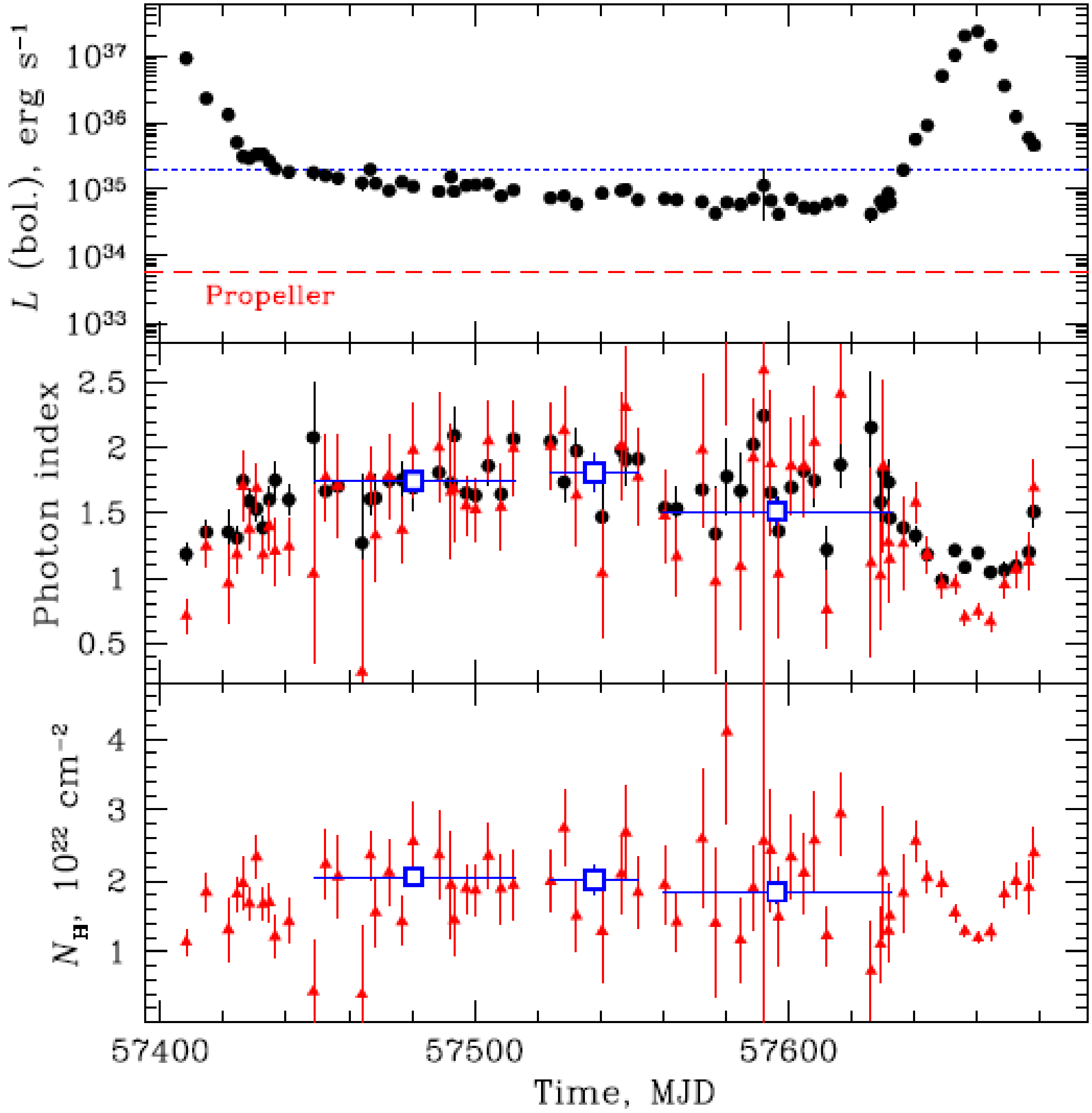
$$\dot{M} < \dot{M}_{\rm cold} \simeq 3.5 \times 10^{15}\, r_{10}^{2.65}\, M_{1.4}^{-0.88} \quad {\rm g\,s^{-1}}$$

Lasota, 1997

Substituting the magnetospheric radius instead of *r*:

$$L < L_{\rm cold} = 9 \times 10^{33}\, k^{1.5}\, M_{1.4}^{0.28}\, R_{6}^{1.57}\, B_{12}^{0.86} \quad {\rm erg\,s^{-1}}$$

GRO J1008-57 in 2016



P_{spin} = 94 s

E_{cyc} ~ 80 keV

d = 5.8 kpc

Tsygankov et al., 2017

Propeller effect vs cold disc

The final state of the source after an outburst is determined by two fundamental parameters of the neutron star: magnetic field and spin period. Equating the expressions for luminosities $L_{\rm cold}$ and $L_{\rm prop}$ one can derive the critical value of the spin period as a function of the neutron star magnetic field:

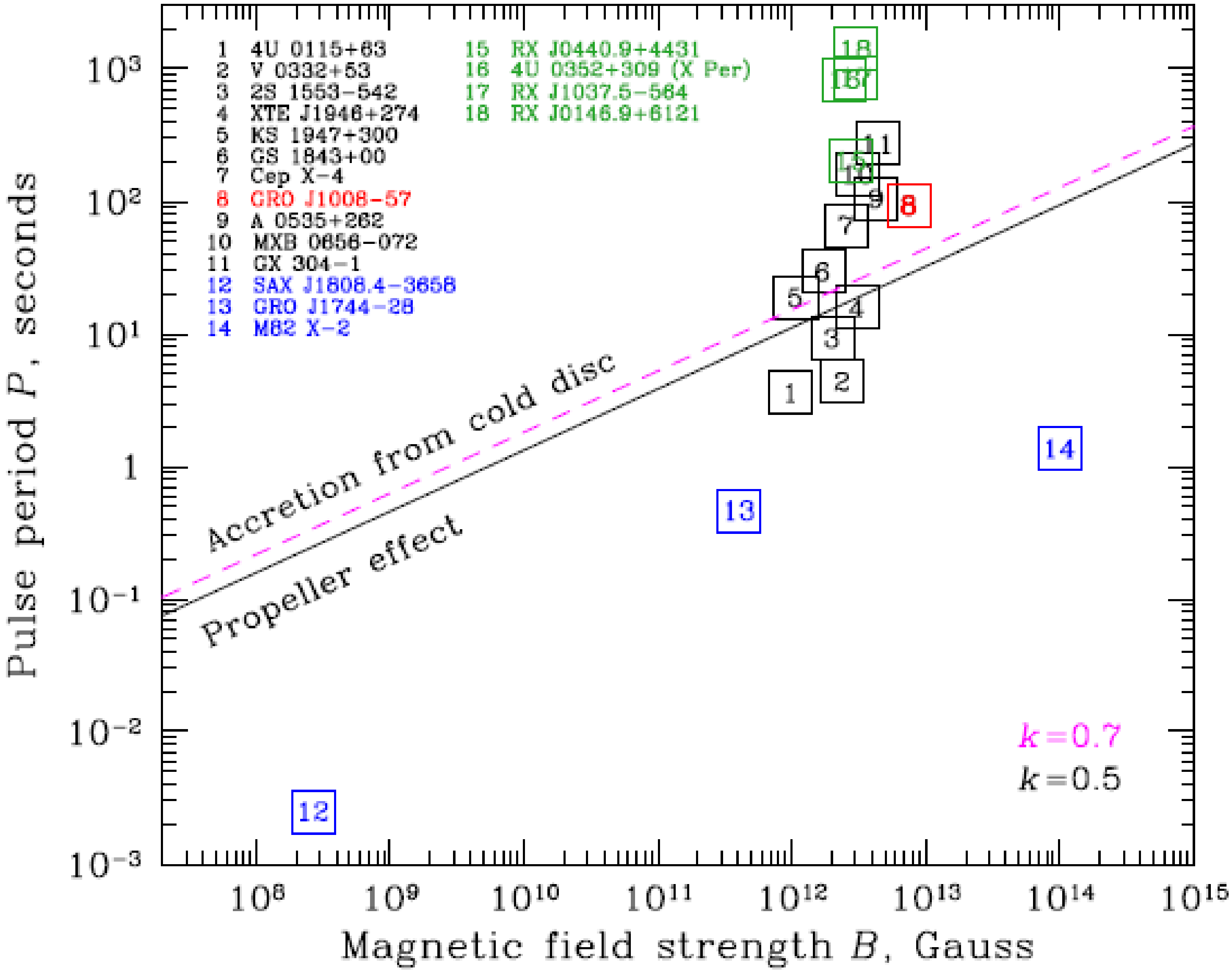
$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times 10^{37}\xi^{7/2}B_{12}^{2}P^{-7/3}M_{1.4}^{-2/3}R_{6}^{5}\,{\rm erg\ s}^{-1}$$

$$L_{\rm cold} = 9\times 10^{33}\,k^{1.5}\,M_{1.4}^{0.28}\,R_{6}^{1.57}\,B_{12}^{0.86}\quad {\rm erg\,s}^{-1}$$

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

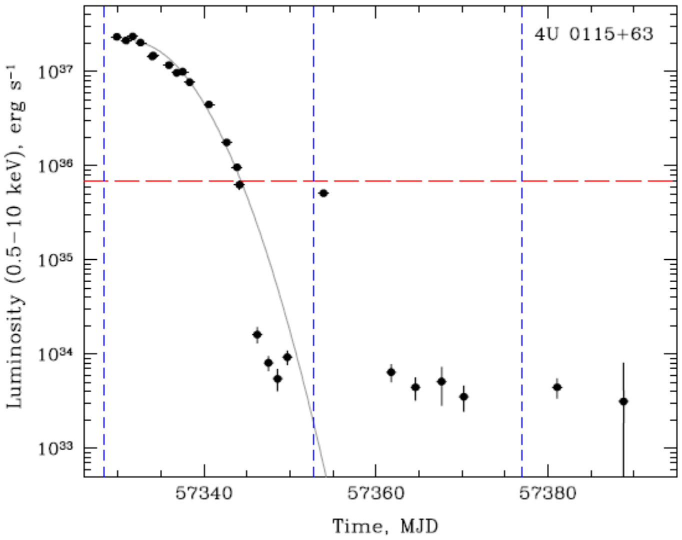
Tsygankov et al., 2017

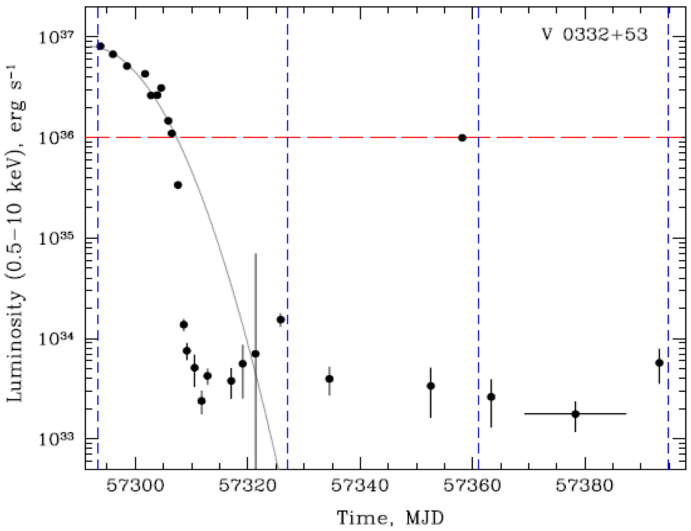
Propeller effect vs cold disc

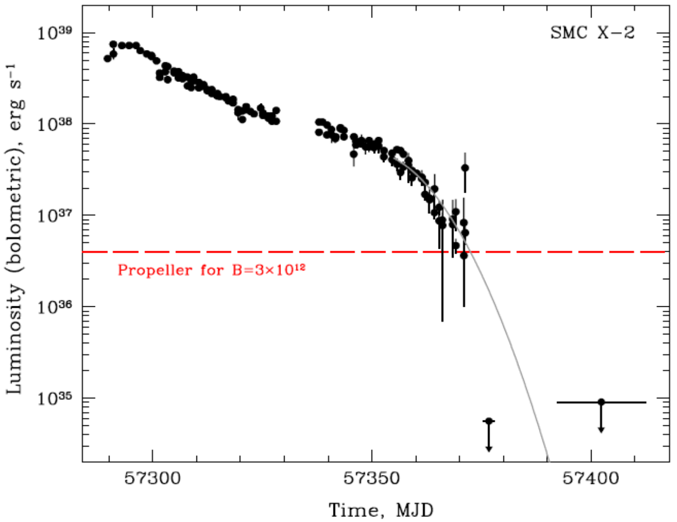


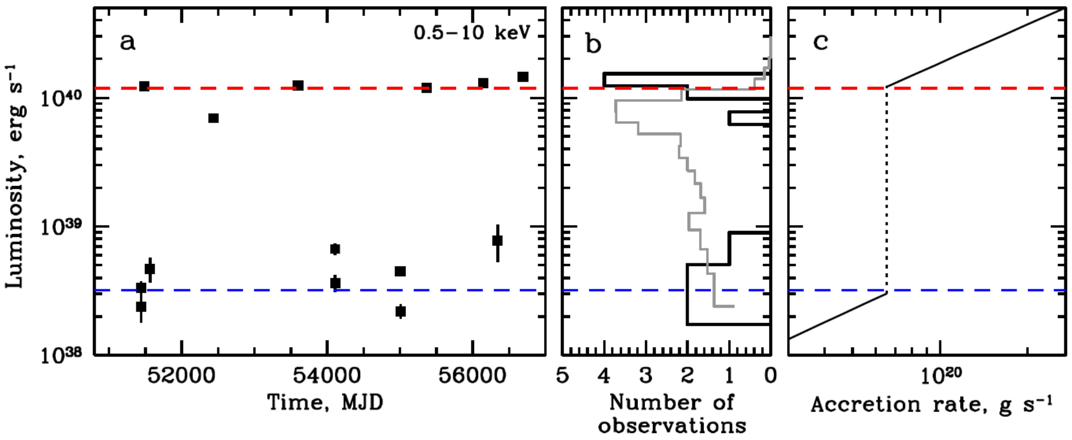
$$P^* = 36.6\,k^{6/7}\,B_{12}^{0.49}\,M_{1.4}^{-0.17}\,R_6^{1.22}\quad \mathrm{s}$$

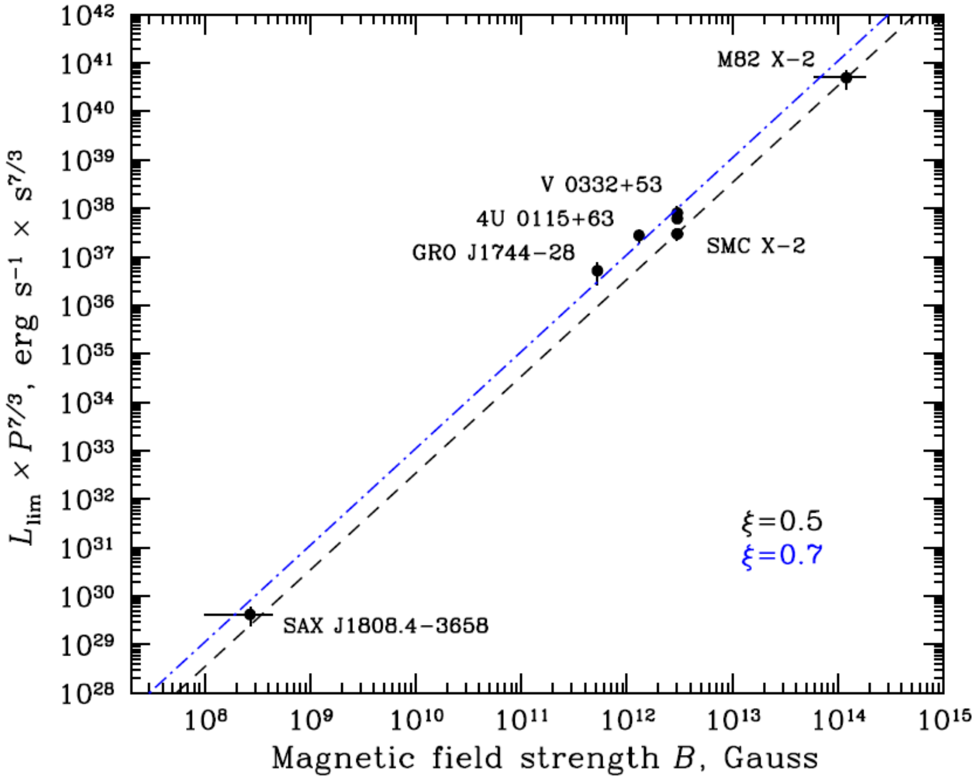
Conclusion (I)

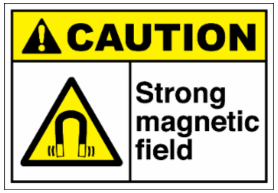








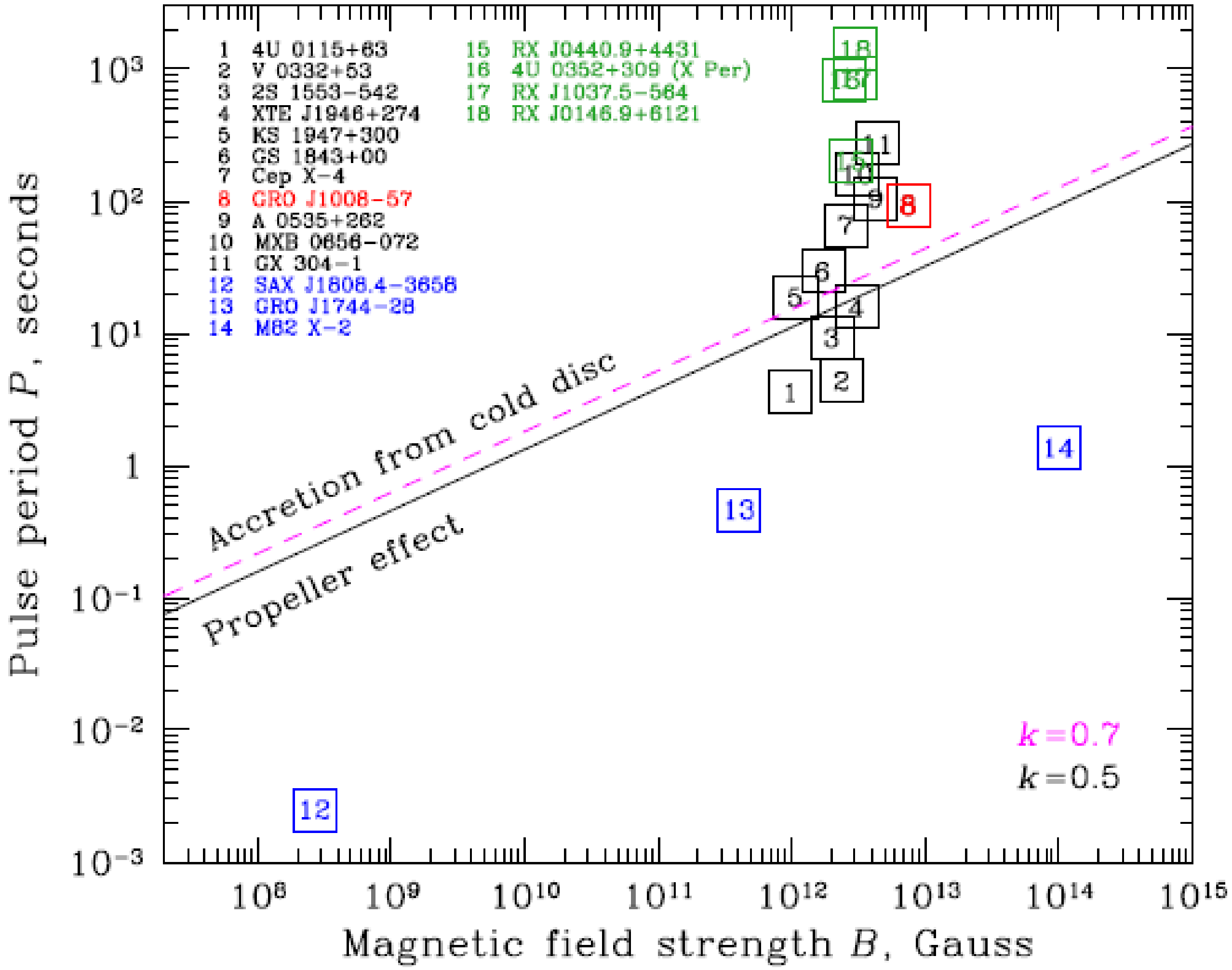




M82 X-2: B ~ 10^{14} G

Conclusion (II)

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



Stable accretion from the cold disc
vs
propeller effect