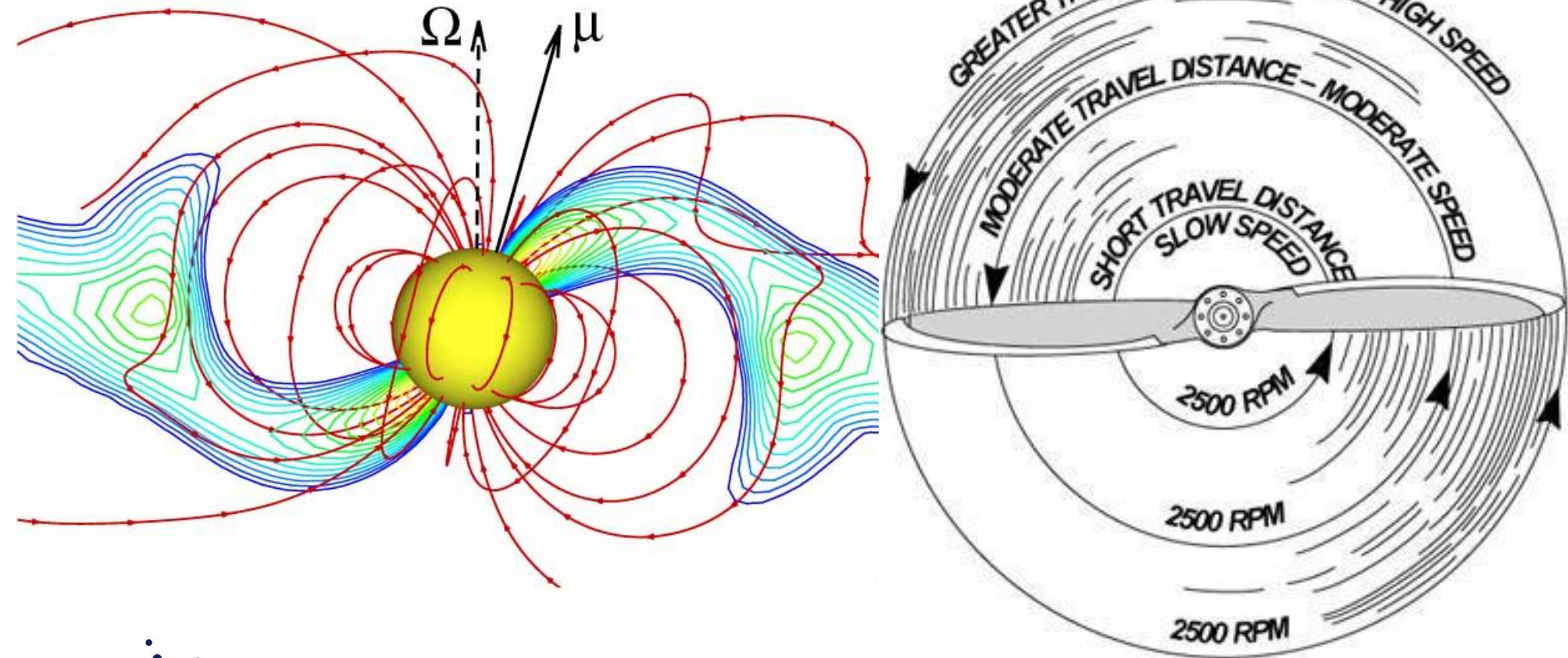
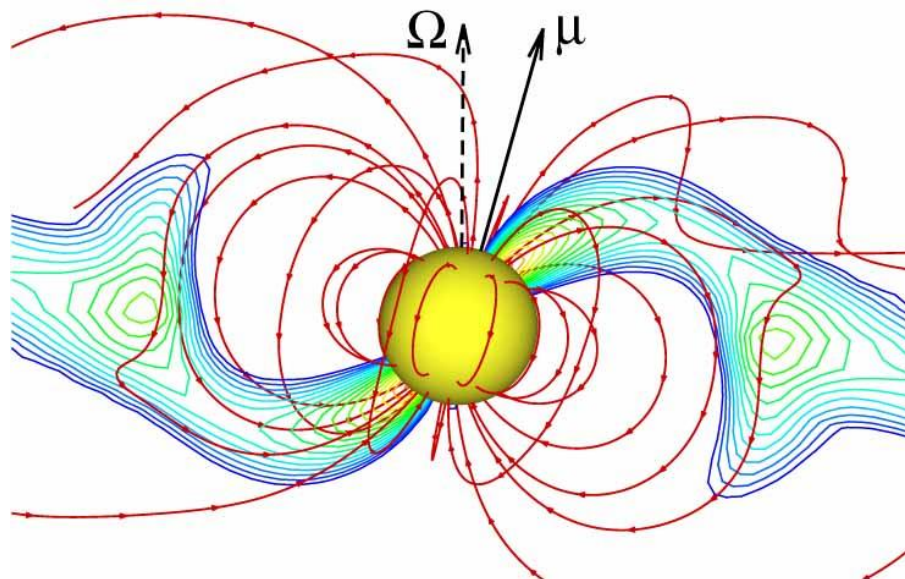
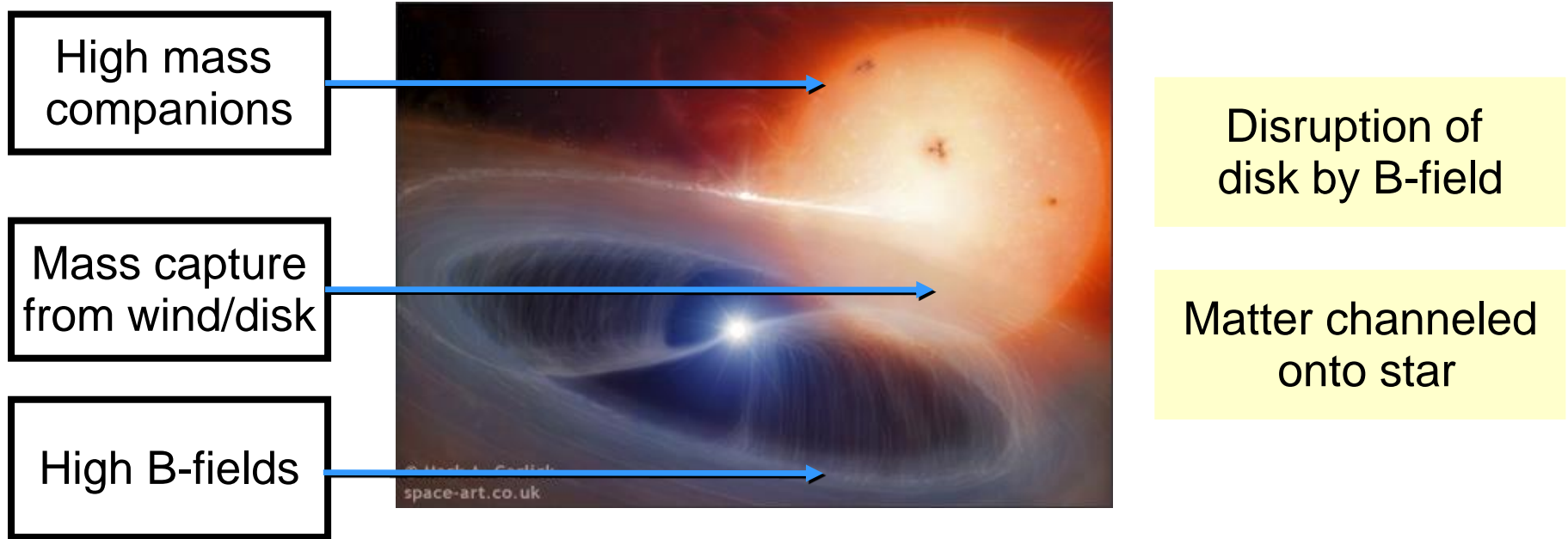


# Propeller effect in X-ray pulsars



# X-ray pulsar

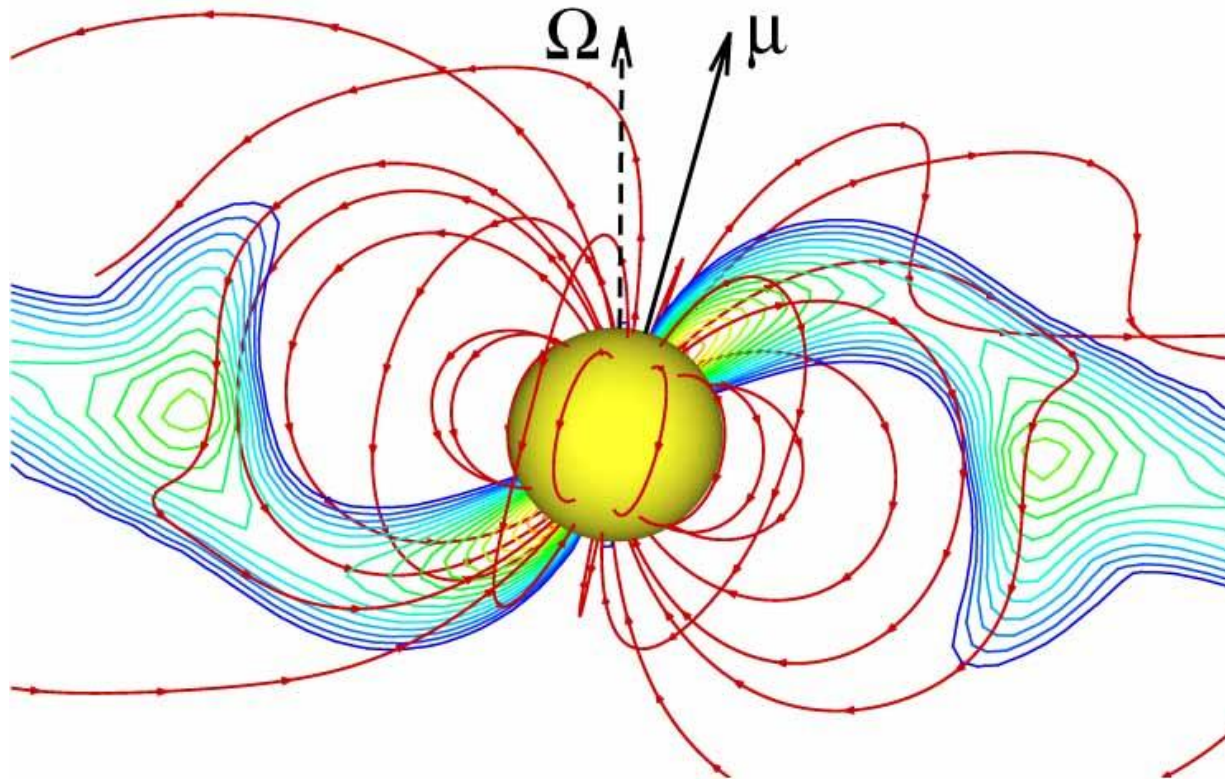
Rotating Neutron Star in binary systems



## Neutron star parameters:

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

# X-ray pulsar



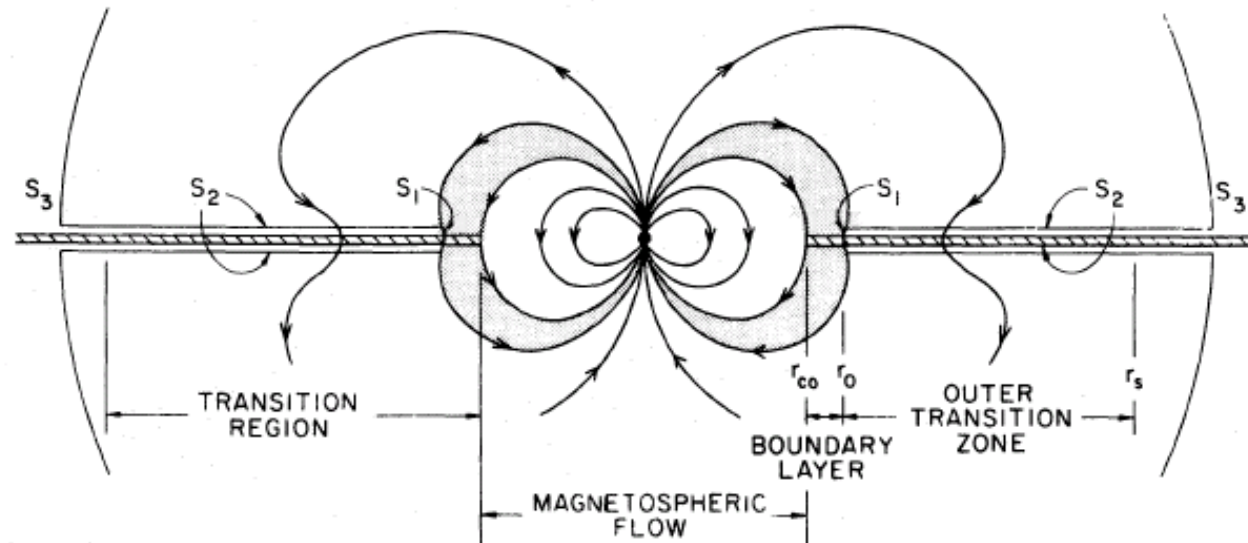
$$r_{\text{co}} = \left( \frac{GM}{\Omega^2} \right)^{1/3}$$

Keplerian and stellar-rotation frequencies are equal

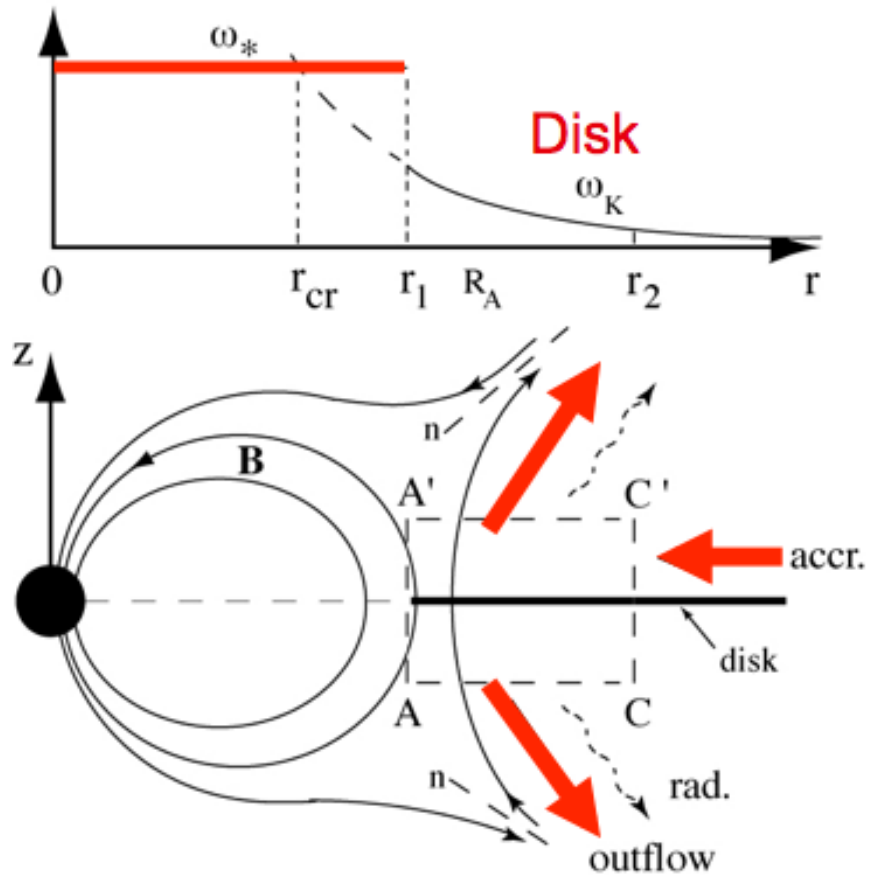
$$r_A = \left( \frac{\mu^4}{2GM\dot{M}^2} \right)^{1/7}$$

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

$$r_m = \xi r_A$$



# Propeller!



$R_m < R_c$  - accretion is possible

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

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

Keplerian and stellar-rotation frequencies are equal

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

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

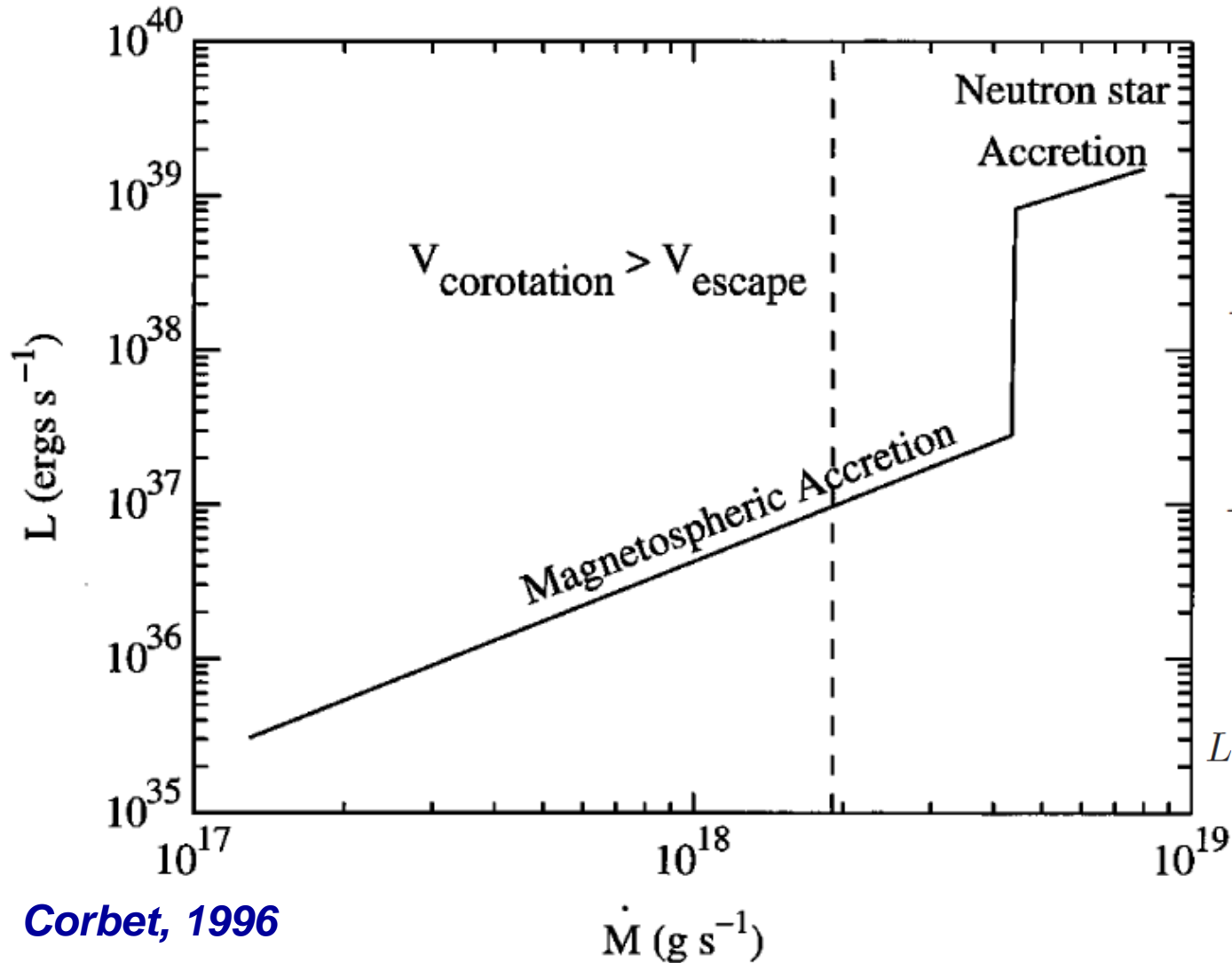
*Romanova et al.*

“Propeller effect”

*Illarionov & Sunyaev, 1975*

$$r_m = \xi r_A$$

# Magnetospheric accretion



**Corbet, 1996**

FIG. 1.—Luminosity as a function of mass accretion rate for A0538–66 ( $P_{\text{spin}} = 0.069$  s). The discontinuity occurs at the transition from magnetospheric to neutron star accretion. The neutron star is assumed to have a mass of  $1.4 M_{\odot}$ , a radius of 10 km, and  $\mu = 10^{29} \text{ G cm}^3$ . For mass accretion rates less than that indicated by the dashed line, material forced to corotate with the neutron star will acquire a velocity greater than the escape velocity from the neutron star.

$$R_c = R_m$$

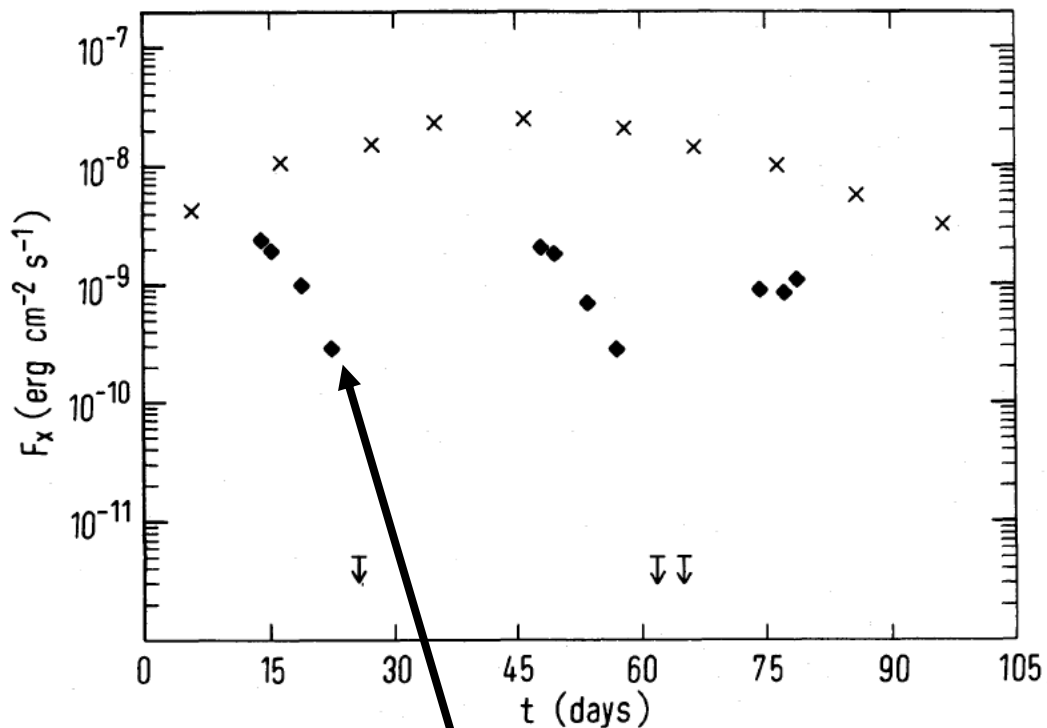
$$L_{\text{lim}}(R) \simeq \frac{GM\dot{M}_{\text{lim}}}{R}$$

$$L_{\text{lim}}(R_c) = \frac{GM\dot{M}_{\text{lim}}}{R_c}$$

$$L_{\text{lim}}(R_c) = \frac{GM\dot{M}_{\text{lim}}}{R_c} = L_{\text{lim}}(R) \frac{R}{R_c}$$

# **Observational manifestation**

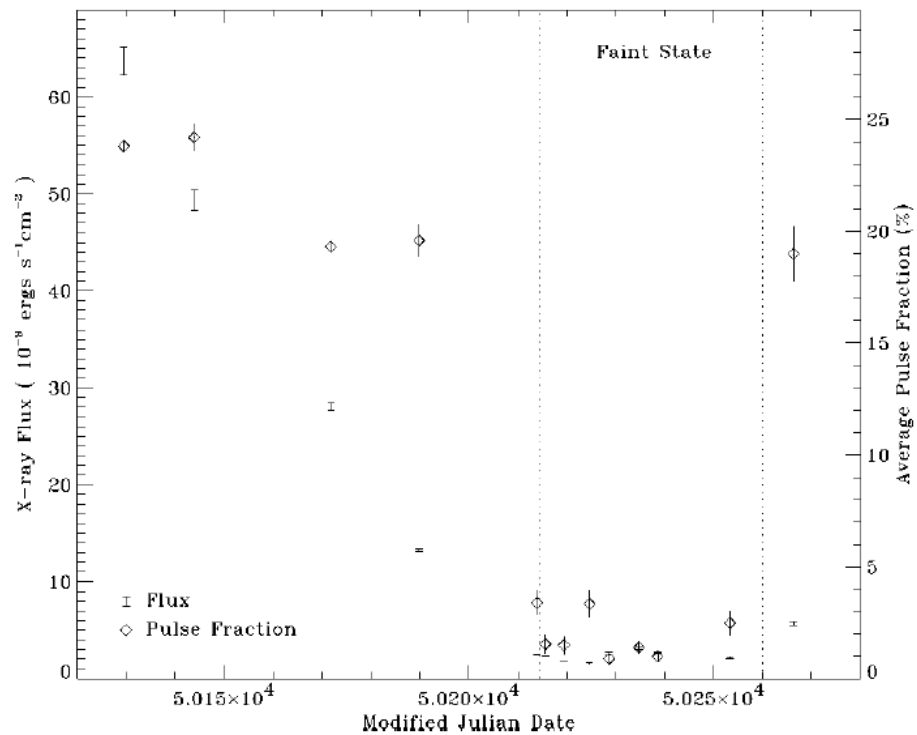
# V 0332+53



$$L_{\text{lim}} = 2.6 \times 10^{36} \text{ erg/s}$$

*Stella et al., 1986*

# GRO J1744-28

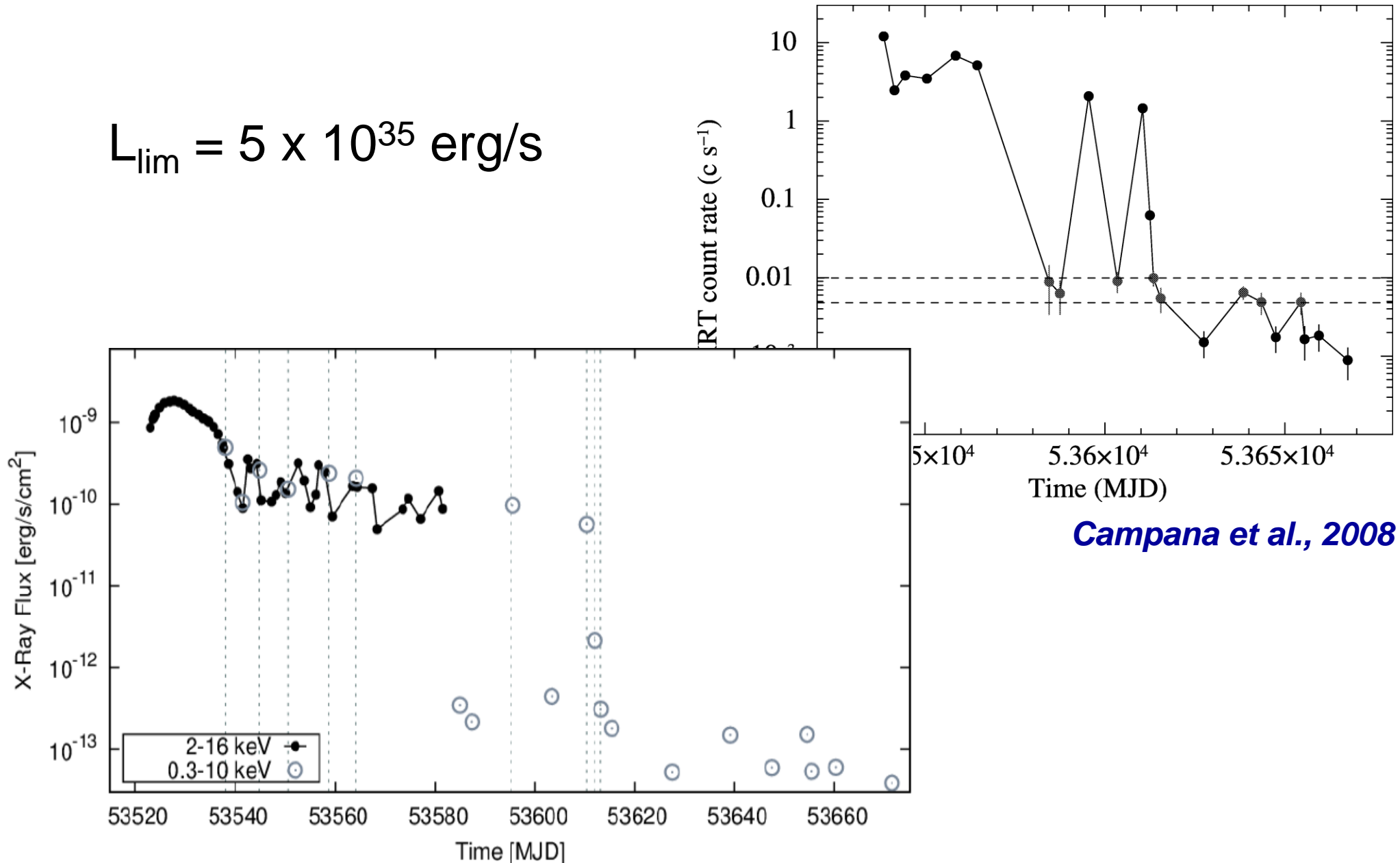


$$L_{\text{lim}} = 3 \times 10^{37} \text{ erg/s}$$

*Cui, 1997*

# SAX J1808.4-3658

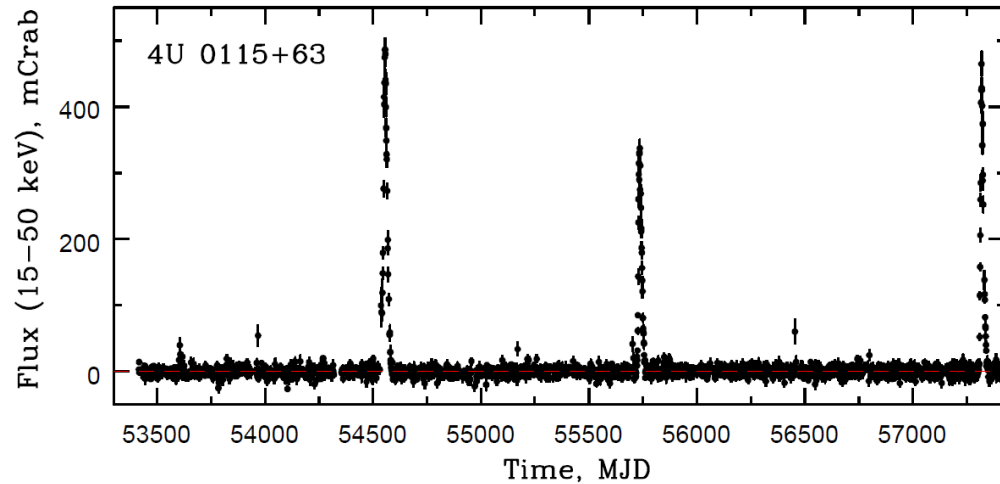
$$L_{\text{lim}} = 5 \times 10^{35} \text{ erg/s}$$



*Campana et al., 2008*

*Patruno et al., 2016*

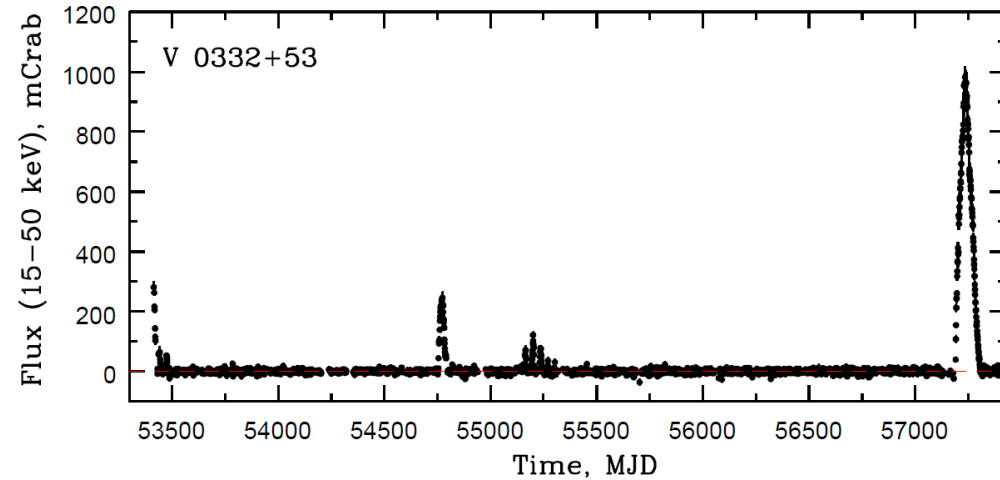
# 4U 0115+63 and V 0332+53 in 2015



$$P_{\text{spin}} = 3.6 \text{ s}$$

$$E_{\text{cyc}} \sim 12 \text{ keV}$$

$$d = 7 \text{ kpc}$$

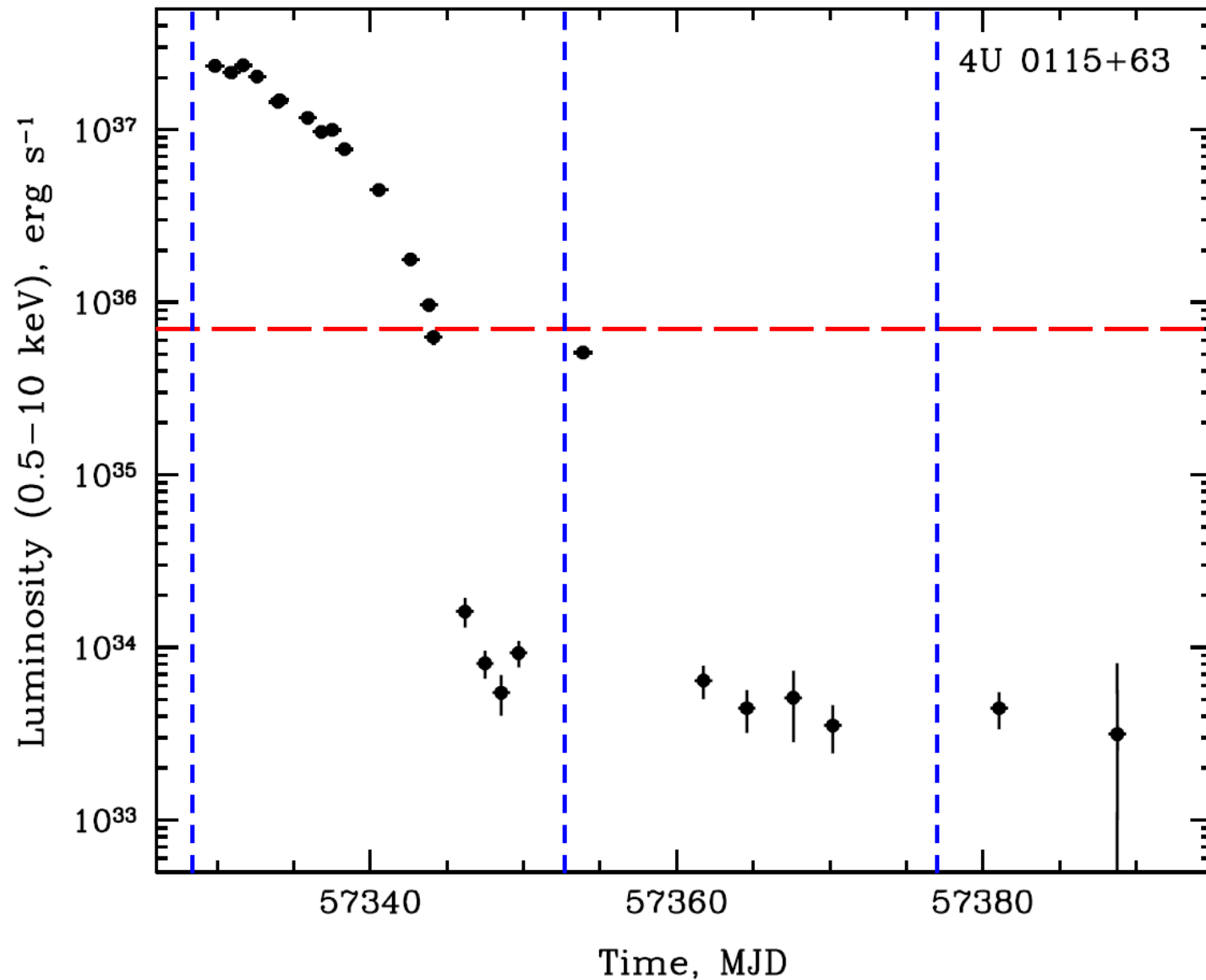


$$P_{\text{spin}} = 4.3 \text{ s}$$

$$E_{\text{cyc}} \sim 30 \text{ keV}$$

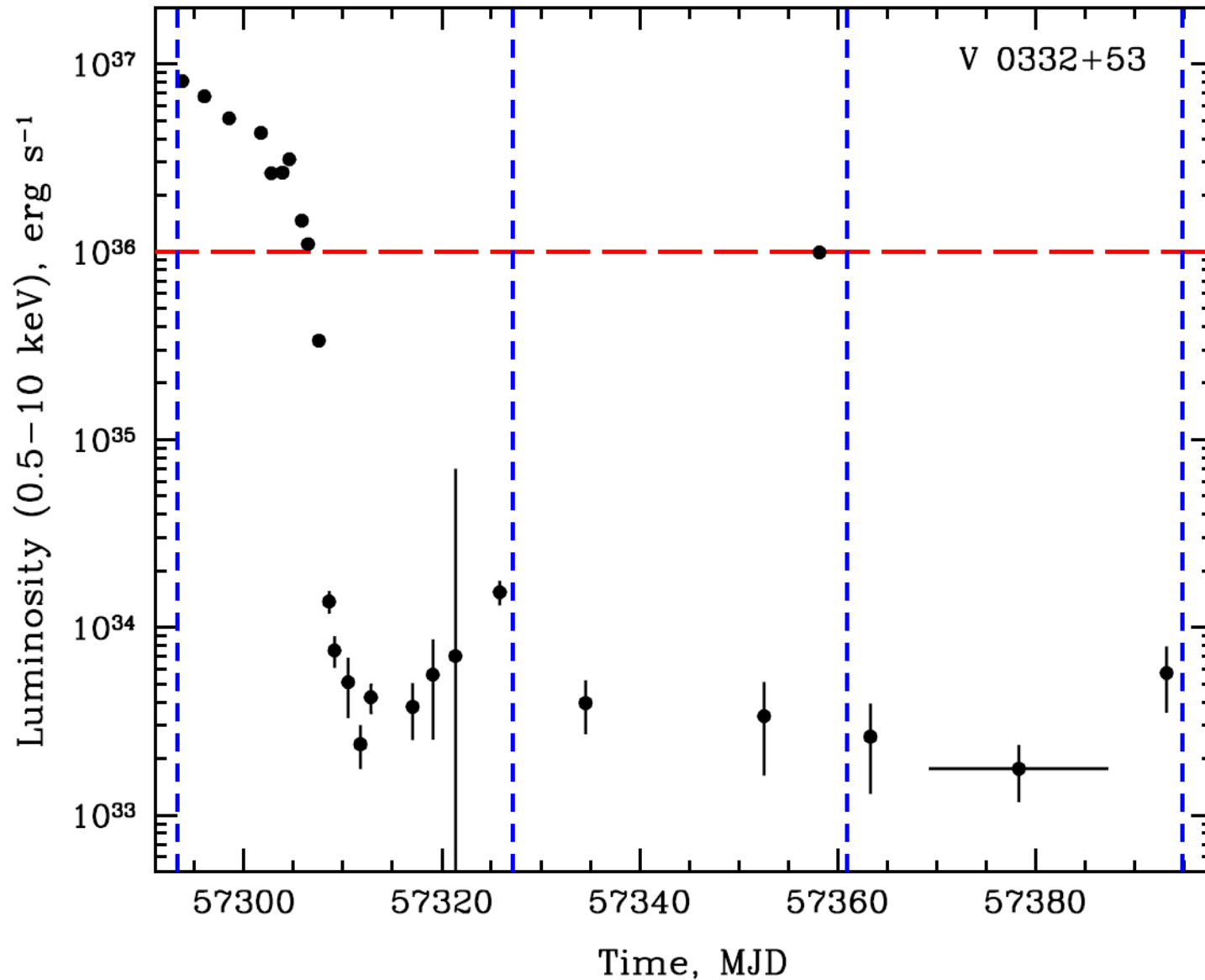
$$d = 7 \text{ kpc}$$

# 4U 0115+63 and V 0332+53 in 2015



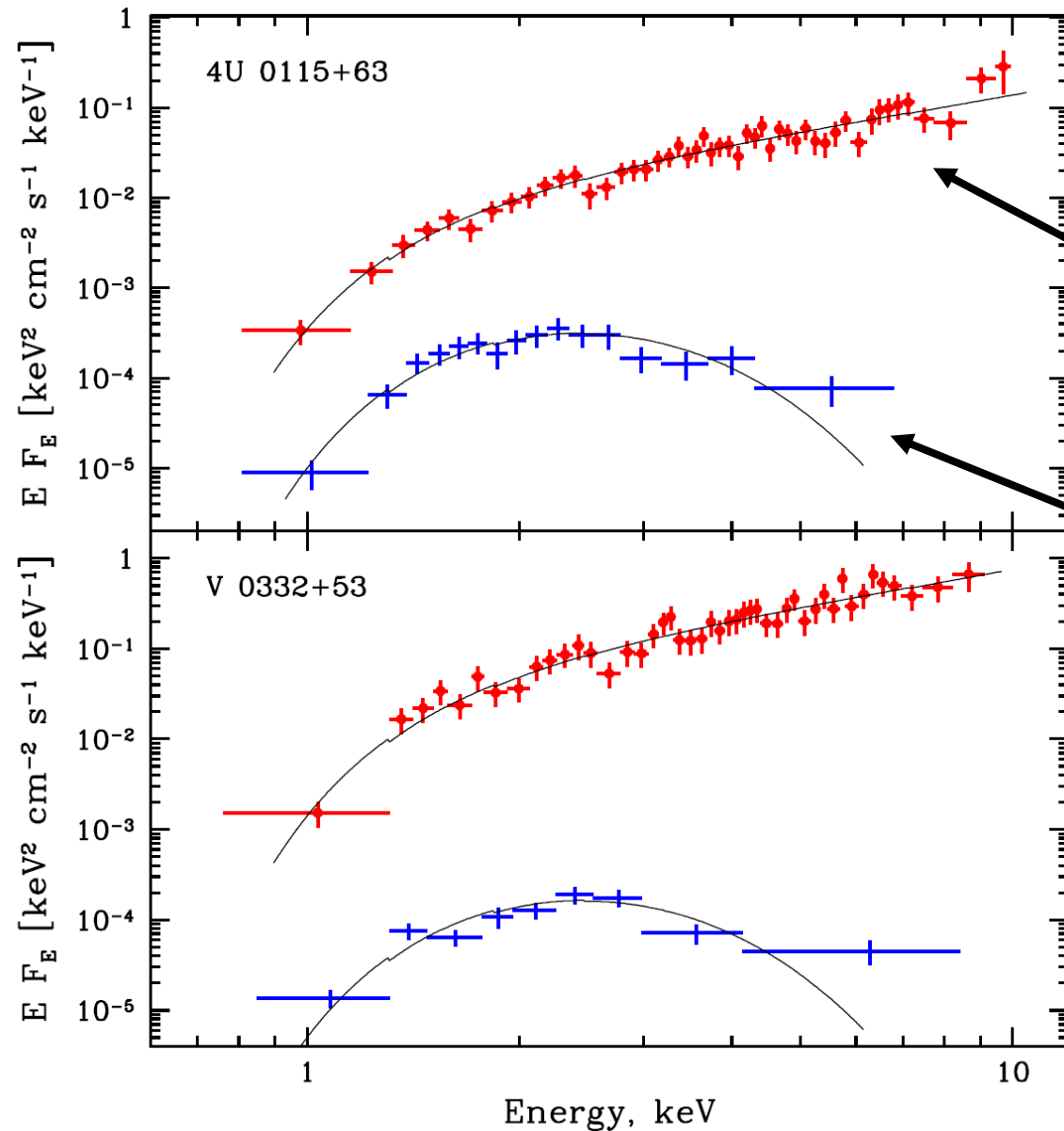
$$L_{\text{lim}} = 7 \times 10^{35} \text{ erg/s}$$

# 4U 0115+63 and V 0332+53 in 2015



$$L_{\text{lim}} = 1 \times 10^{36} \text{ erg/s}$$

# 4U 0115+63 and V 0332+53 in 2015



Absorbed power-law  
 $\Gamma = 0.4 - 0.7$

Black body with  
 $kT = 0.5 \text{ keV}$

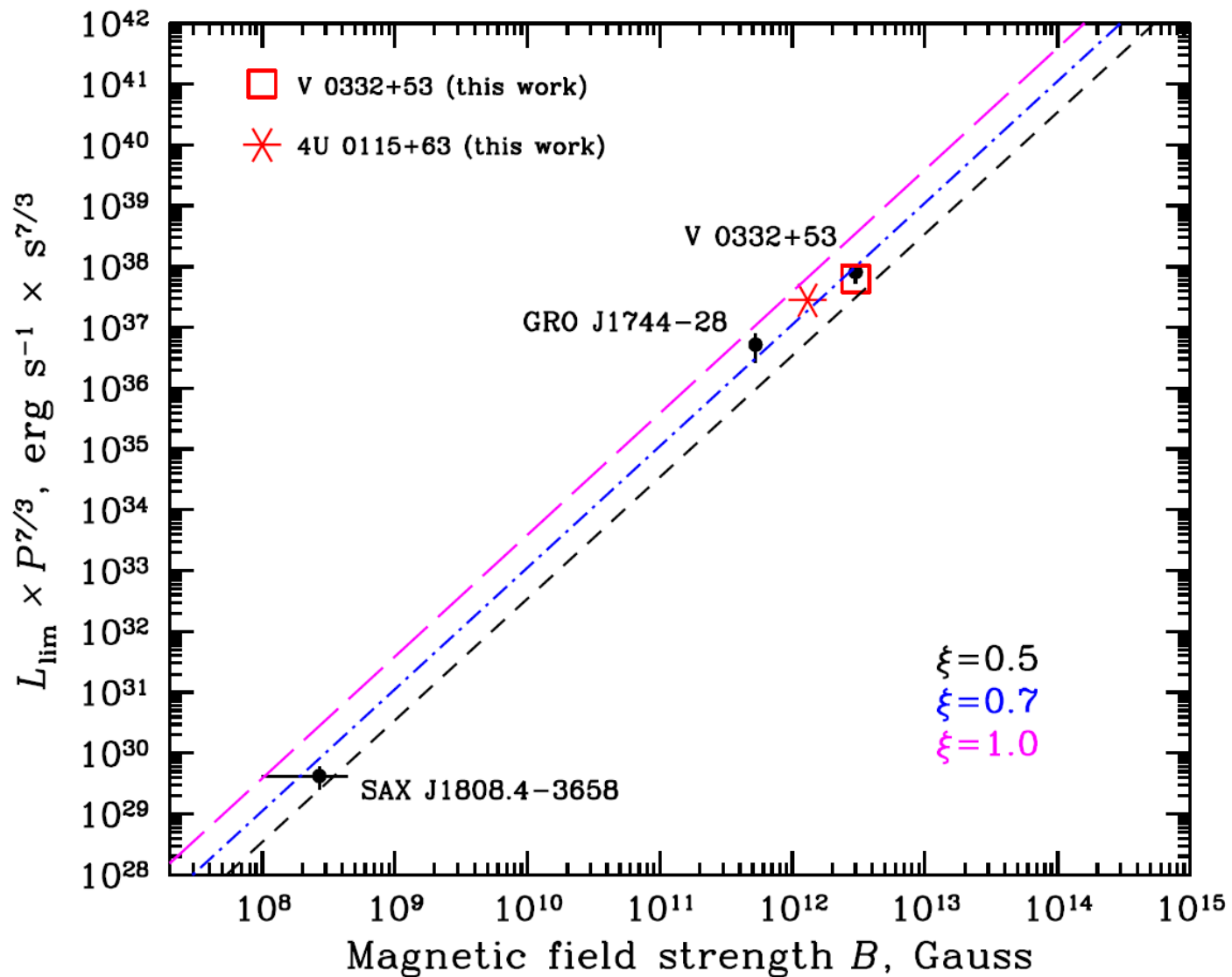
# Propeller in action

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

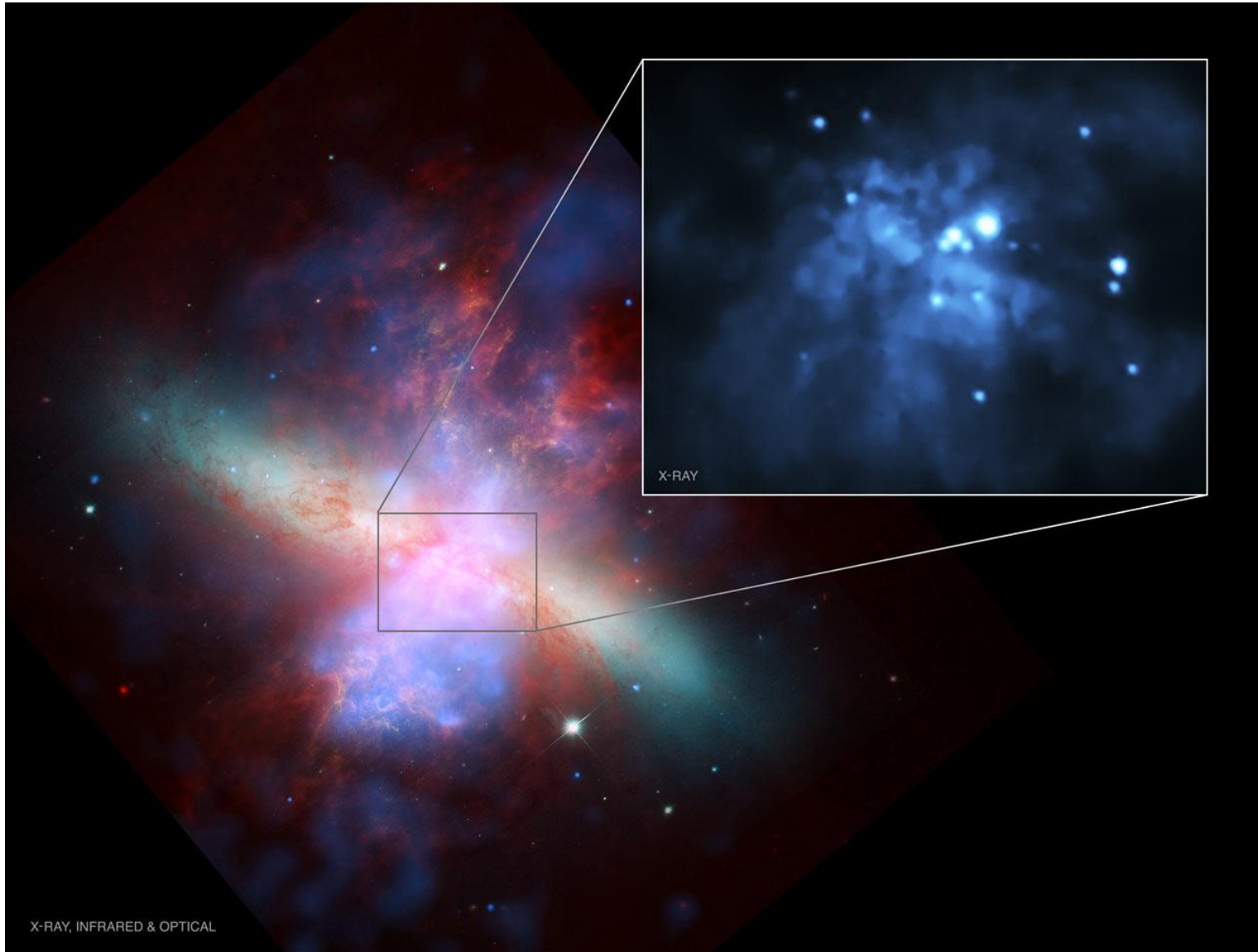
$$r_{\text{co}} = \left( \frac{GM}{\Omega^2} \right)^{1/3}$$

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

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



# Even brighter



## M82 galaxy

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

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

The majority of ultraluminous X-ray sources are point sources that are spatially offset from the nuclei of nearby galaxies and whose X-ray luminosities exceed the theoretical maximum for spherical infall (the Eddington limit) onto stellar-mass black holes<sup>1,2</sup>. Their X-ray luminosities in the 0.5–10 kiloelectronvolt energy band range from  $10^{39}$  to  $10^{41}$  ergs per second<sup>3</sup>. Because higher masses imply less extreme ratios of the luminosity to the isotropic Eddington limit, theoretical models have focused on black hole rather than neutron star systems<sup>1,2</sup>. The most challenging sources to explain are those at the luminous end of the range (more than  $10^{40}$  ergs per second), which require black hole masses of 50–100 times the solar value or significant departures from the standard thin disk accretion that powers bright Galactic X-ray binaries, or both. Here we report broadband X-ray observations of the nuclear region of the galaxy M82 that reveal pulsations with an average period of 1.37 seconds and a 2.5-day sinusoidal modulation. The pulsations result from the rotation of a magnetized neutron star, and the modulation arises from its binary orbit. The pulsed flux alone corresponds to an X-ray luminosity in the 3–30 kiloelectronvolt range of  $4.9 \times 10^{39}$  ergs per second. The pulsating source is spatially coincident with a variable source<sup>4</sup> that can reach an X-ray luminosity in the 0.3–10 kiloelectronvolt range of  $1.8 \times 10^{40}$  ergs per second<sup>4</sup>. This association implies a luminosity of about 100 times the Eddington limit for a 1.4-solar-mass object, or more than ten times brighter than any known accreting pulsar. This implies that neutron stars

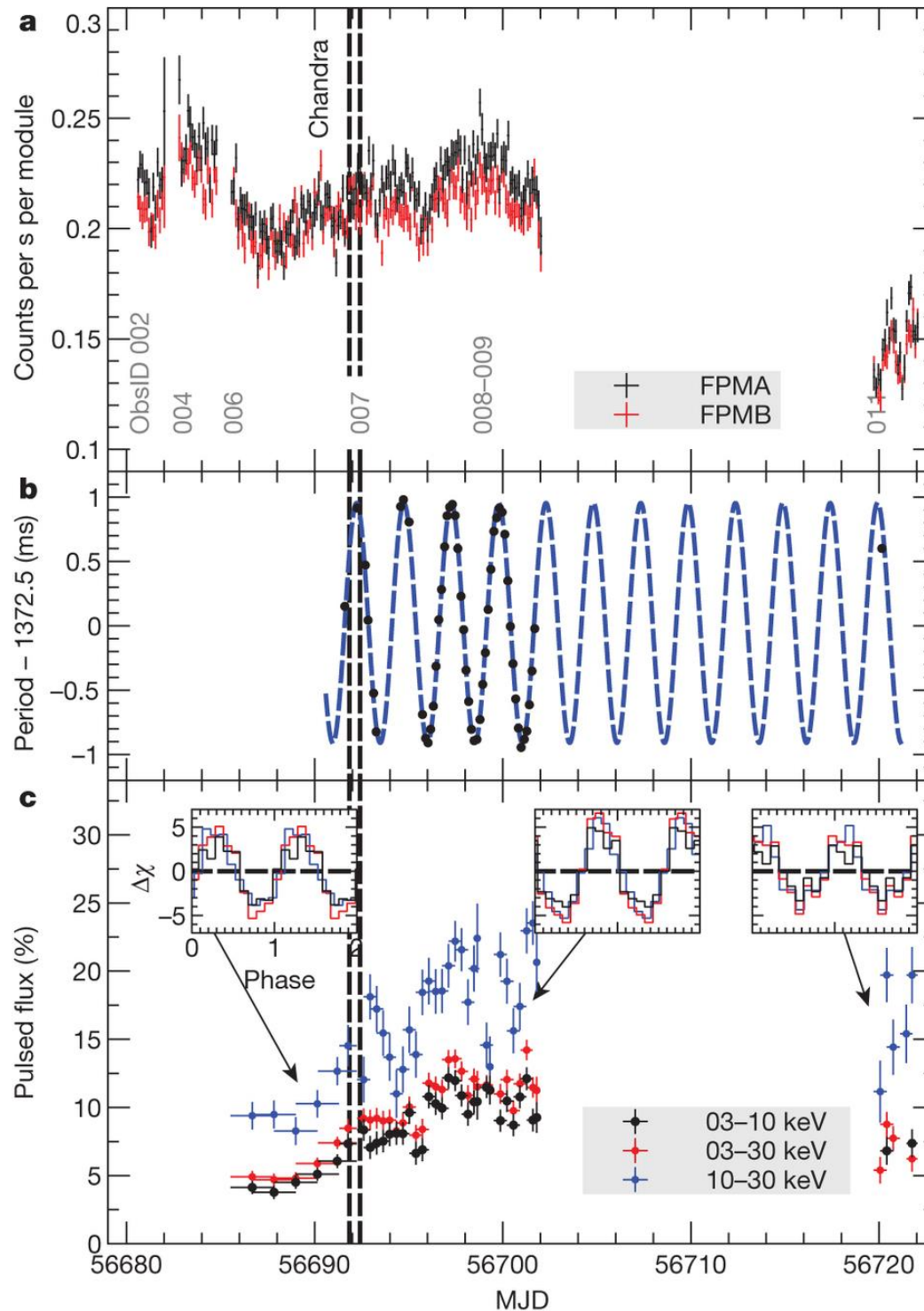
ULXs, the most luminous being M82 X-1<sup>12</sup>, which can reach  $L_X(0.3\text{--}10\text{ keV}) \approx 10^{41}$  erg s<sup>-1</sup>, and the second brightest being a transient, M82 X-2 (also referred to as X42.3+59<sup>13</sup>), which has been observed to reach<sup>4,14</sup>  $L_X(0.3\text{--}10\text{ keV}) \approx 1.8 \times 10^{40}$  erg s<sup>-1</sup>. The two sources are separated by 5", and so can only be clearly resolved by the Chandra X-ray telescope. During the M82 monitoring campaign, NuSTAR observed bright emission from the nuclear region containing the two ULXs. The region shows moderate flux variability at the 20% level during the first 22 days of observation. The flux was then found to have decreased by 60% by the time of the final observation ~20 days later. The peak X-ray flux,  $F_X(3\text{--}30\text{ keV}) = (2.33 \pm 0.01) \times 10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup> (90% confidence; Fig. 1) corresponds to a total 3–30 keV luminosity assuming isotropic emission of  $3.7_{-0.02}^{+0.01} \times 10^{40}$  erg s<sup>-1</sup>.

A timing analysis revealed a narrow peak just above the noise at a frequency of ~0.7 Hz in the power density spectrum. An accelerated epoch folding search<sup>15</sup> on overlapping 30-ks intervals of data found coherent pulsations with a mean period  $P$  of 1.37 s modulated with a sinusoidal period of 2.53 days throughout the 10-day interval starting at modified Julian day (MJD) 56691 (2014 February 03), and also in the last observation at MJD 56720 (Fig. 1). The statistical significance of the pulsations is ~13 $\sigma$  during the most significant 30-ks segments, and >30 $\sigma$  for the entire observation. A refined analysis (see Methods) subsequently enabled the detection of pulsations over a longer interval beginning on MJD 56686. The pulsed flux is variable, ranging from 5% to 13% in the

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

**Bachetti et al., 2014**

# The NuSTAR data



$$P_{\text{spin}} = 1.37 \text{ s}$$

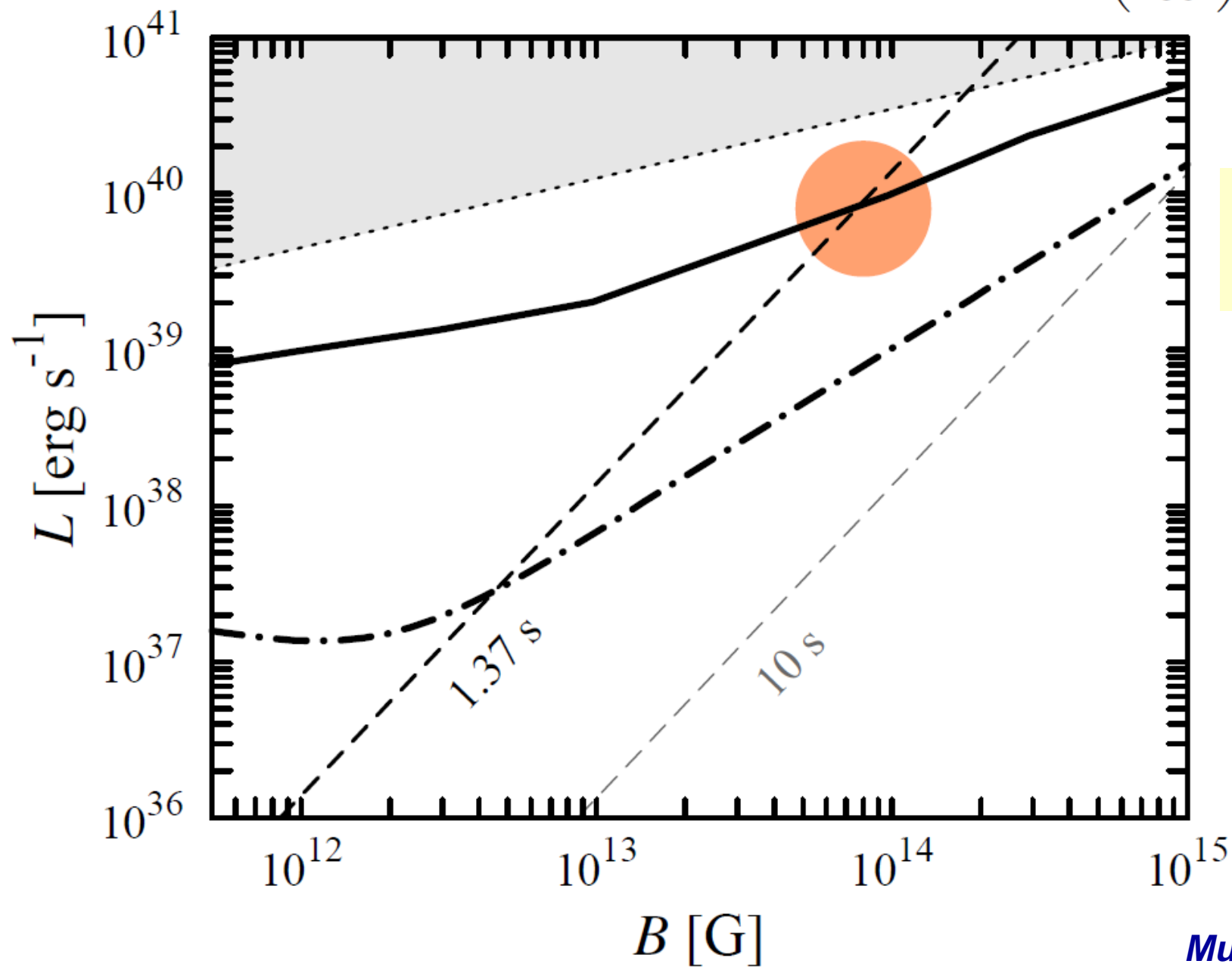
$$P_{\text{orb}} = 2.5 \text{ d}$$

$$M_c > 5.2 M_{\text{sun}}$$

$$a \sin i = 23 \text{ light seconds}$$

# Magnetic field estimations

$$L^{**} = 1.8 \times 10^{39} \left( \frac{l_0/d_0}{50} \right) \left( \frac{\kappa_T}{\kappa_{\perp}} \right) \frac{M}{M_{\odot}} \text{erg s}^{-1}$$



$$\frac{\sigma_{\perp}}{\sigma_T} \approx \left( \frac{E_{\gamma}}{E_{\text{cyc}}} \right)^2$$

$$B_{12} \gtrsim 4 L_{39}^{4/3}$$

# Magnetic field estimations: wide range of possible values

Equilibrium spin period  
and Eddington acc. rate:  
 **$B \sim 10^{12}$  G**

*Bachetti et al., 2014*

Standard accretion  
torque equation:  
 **$B \sim 10^{12}$  G (dipole)**  
 **$B \sim 10^{14}$  G (multipole)**  
Beaming  $\sim 0.2$   
 $M_{\text{NS}} = 2 M_{\text{sun}}$

*Tong, 2015*

Standard accretion  
torque equation:  
 **$B \sim 10^{12} - 10^{13}$  G**  
Beaming, Eddington  
accretion rate

*Christodoulou et al., 2014*

Numerically solving the torque  
equation within the framework  
of the magnetically threaded-  
disc scenario:

**$B \sim 10^{13}$  G**

Beaming  $0.5 < b < 1.0$

*Dall'Osso et al., 2015*

Neutron star is nearly  
an orthogonal rotator

**$B \sim 1.4 \times 10^{13}$  G**

*Lyutikov, 2014*

The torque equilibrium  
condition for the pulsar  
indicates that the dipole  
magnetic field of NS is  
 **$B \sim (2-6) \times 10^{13}$  G**

*Eksi et al., 2014*

Spin-up value implies  
torques consistent with  
the accretion disc  
extending down to the  
vicinity of the stellar  
surface:  **$B \sim 10^9$  G**

*Kluźniak & Lasota, 2015*



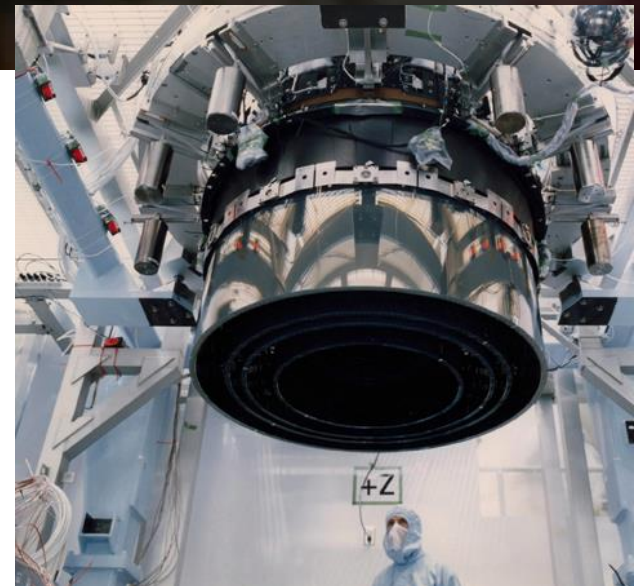
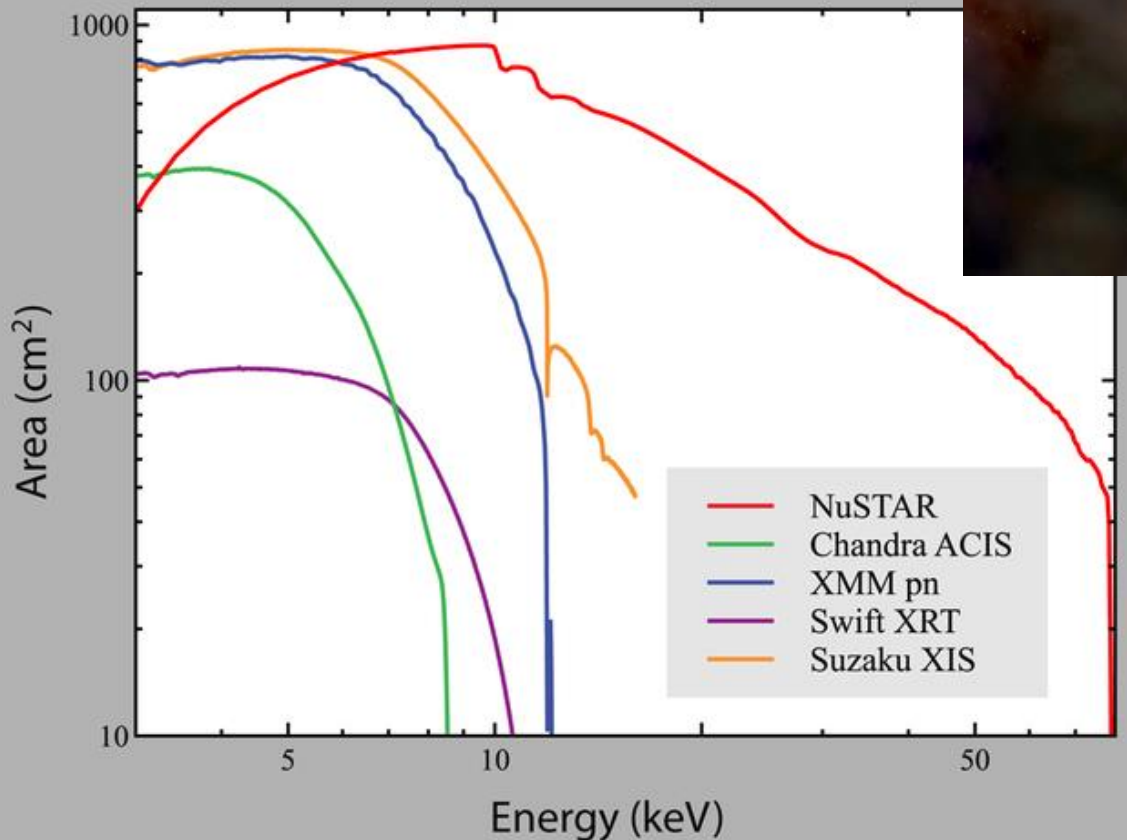
# The Chandra observatory

Launched: July 23, 1999

Energy band: 0.2-10 keV

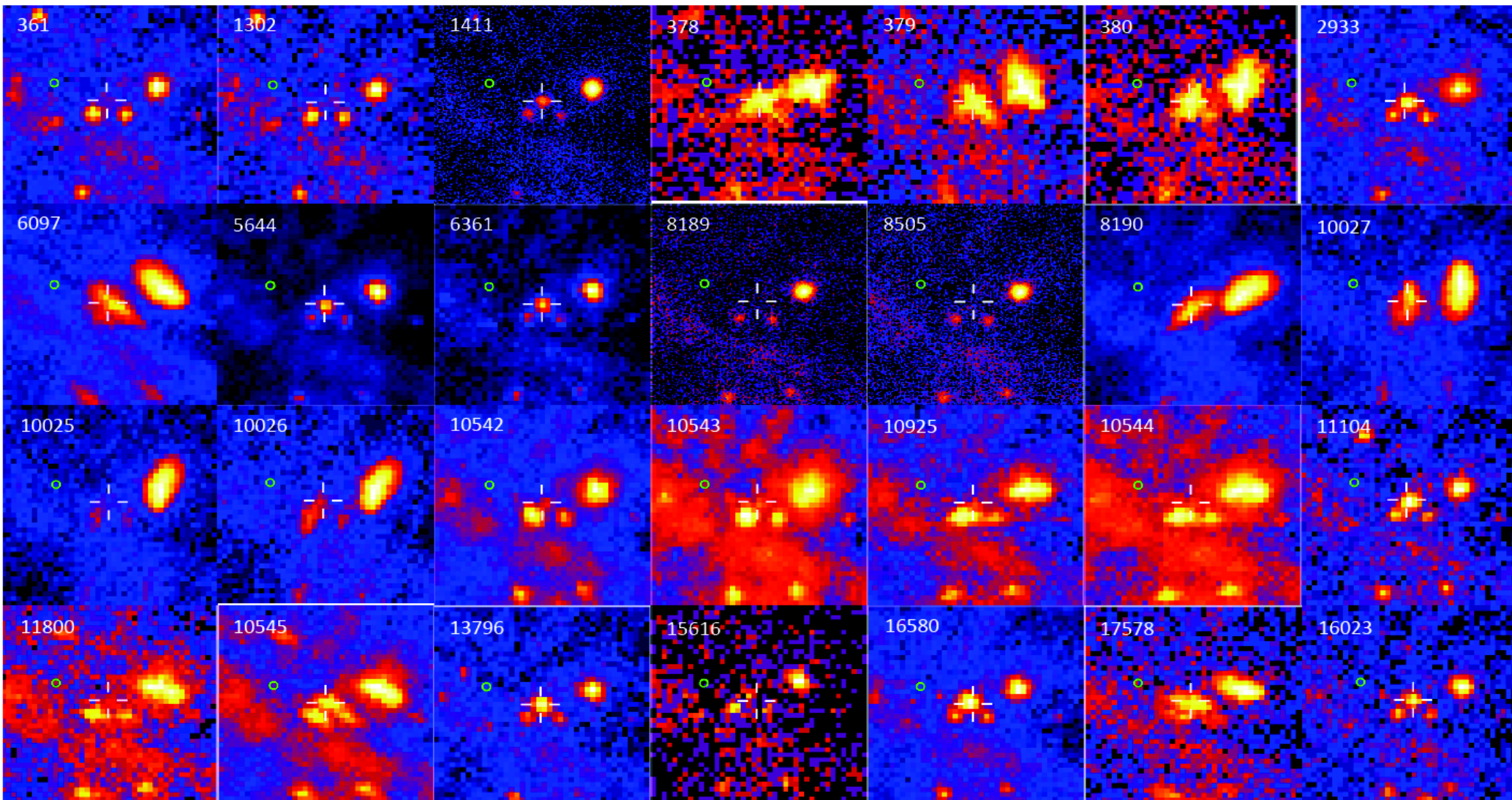
Angular resolution:  $<1''$

Temporal resolution: 3.2 s



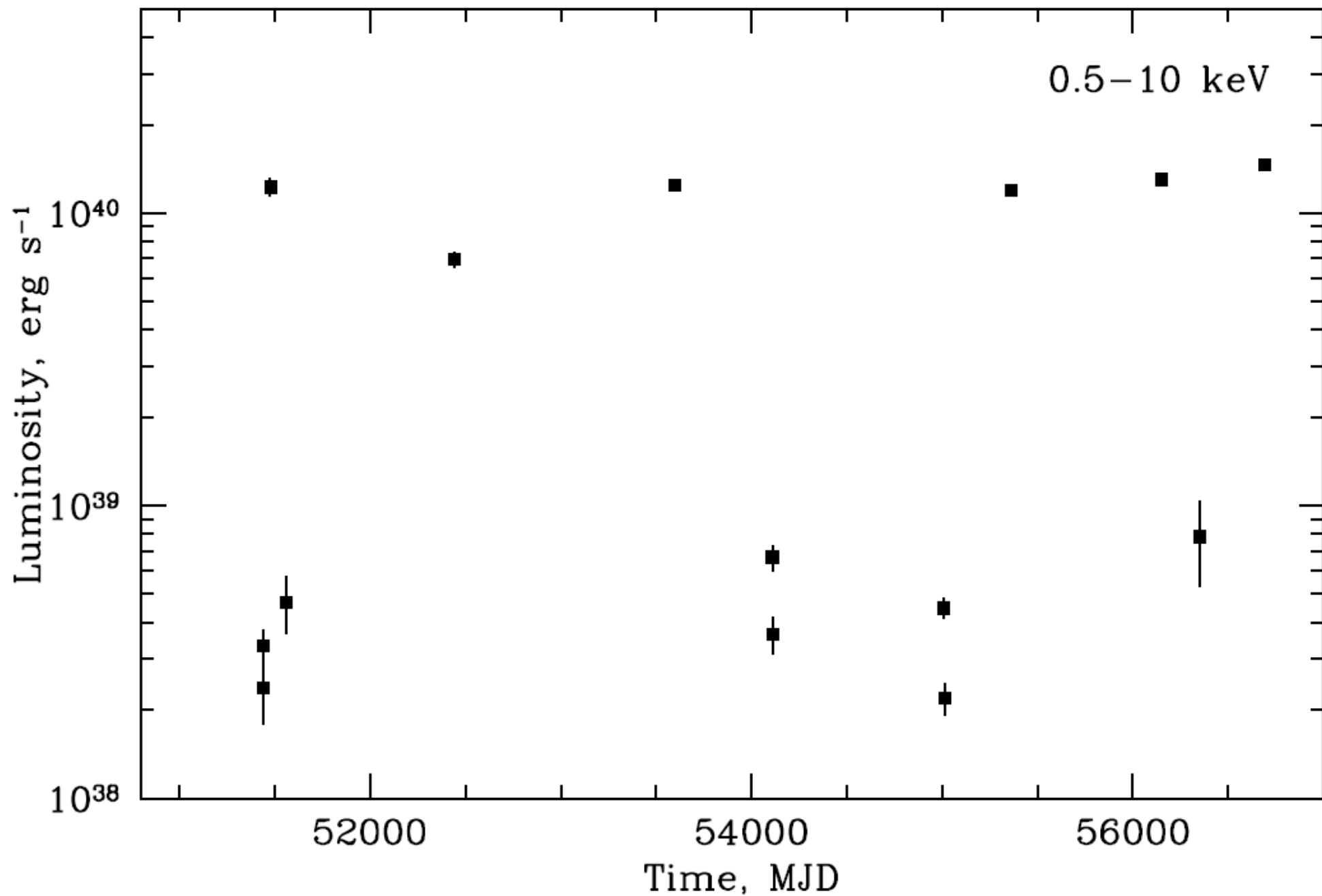
4 mirror pairs

# Chandra observations of M82

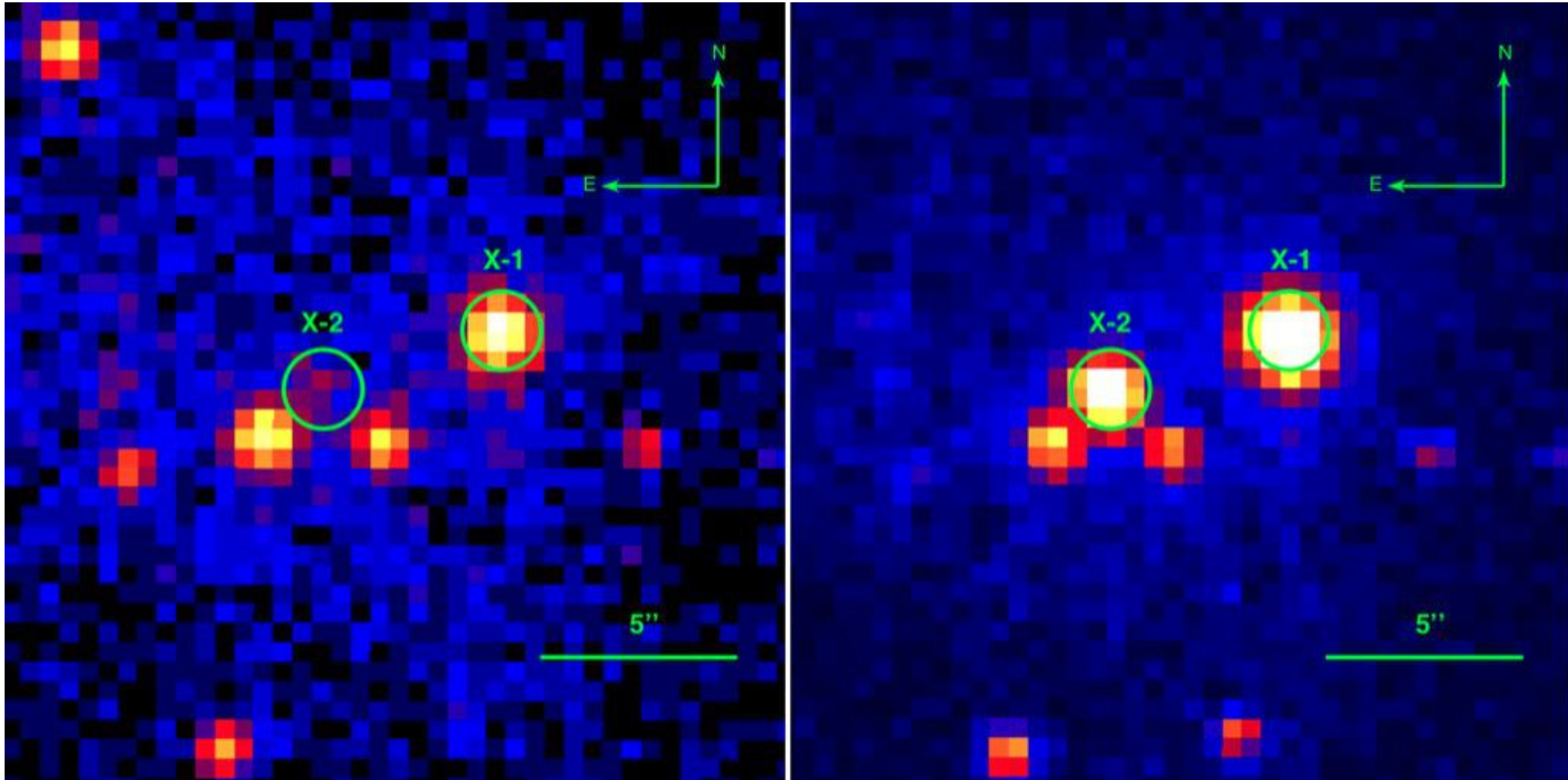


M82 observed by the Chandra observatory during ~15 years more or less evenly resulting in 29 publicly available observations (15 are on-axis)

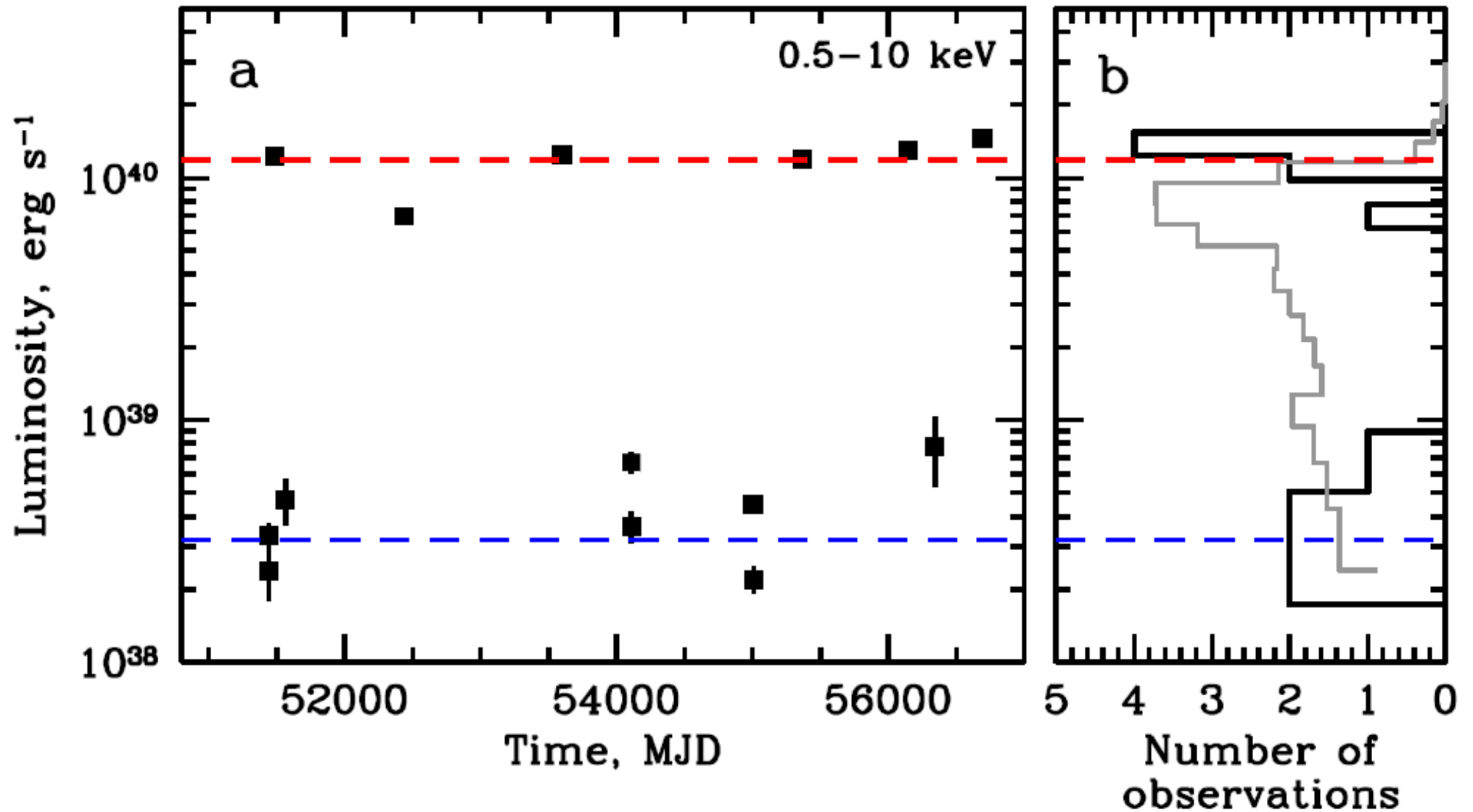
# M82 X-2 light curve



# M82 as seen by Chandra

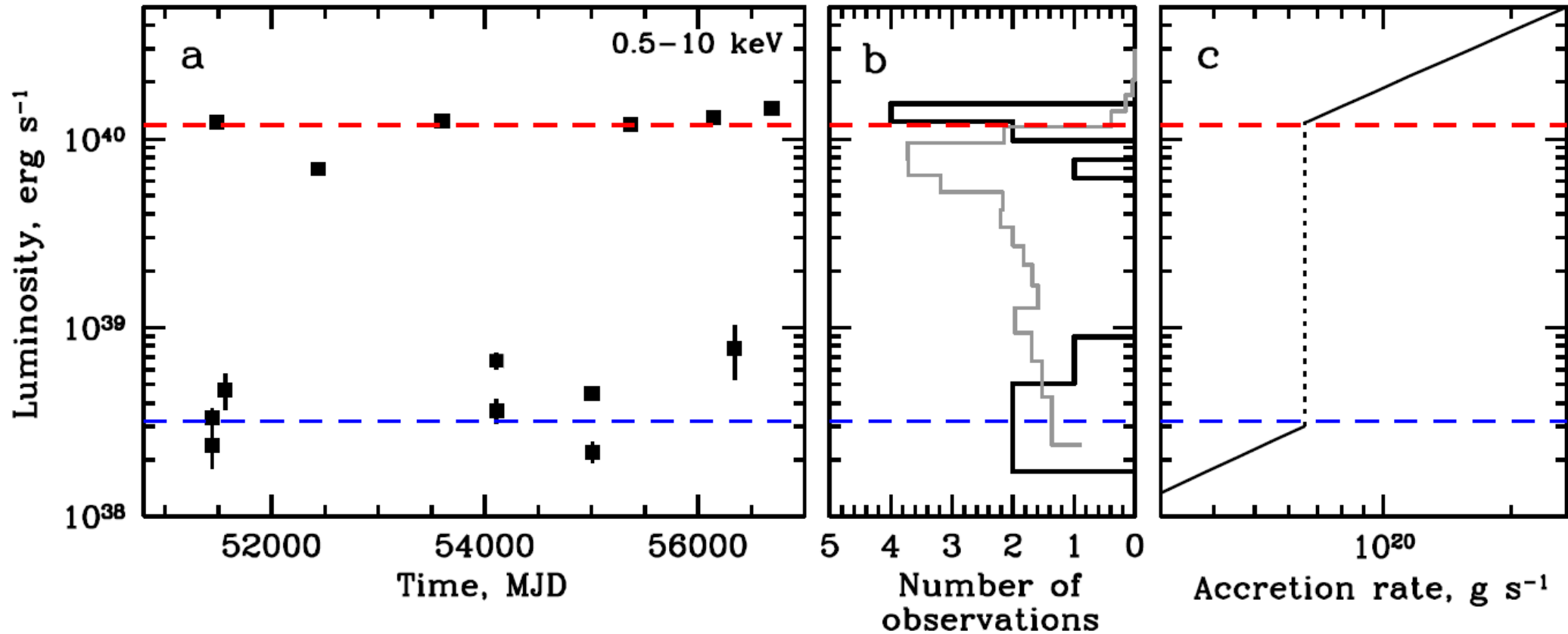


# M82 X-2 intensity distribution



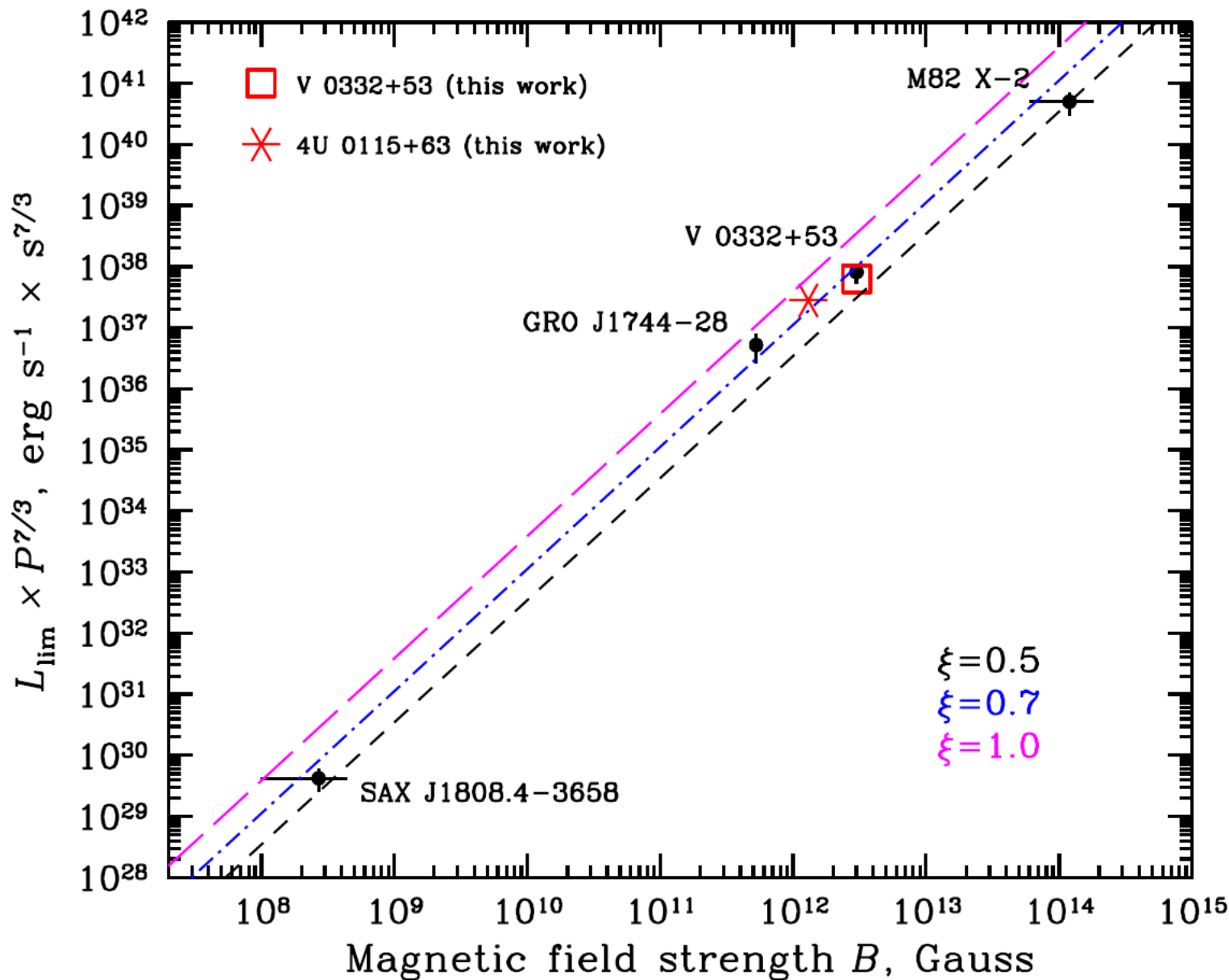
**Distribution is bimodal**

# Propeller in action



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

# Propeller in action



$P = 1.37 \text{ s}$

$\xi = 0.5$

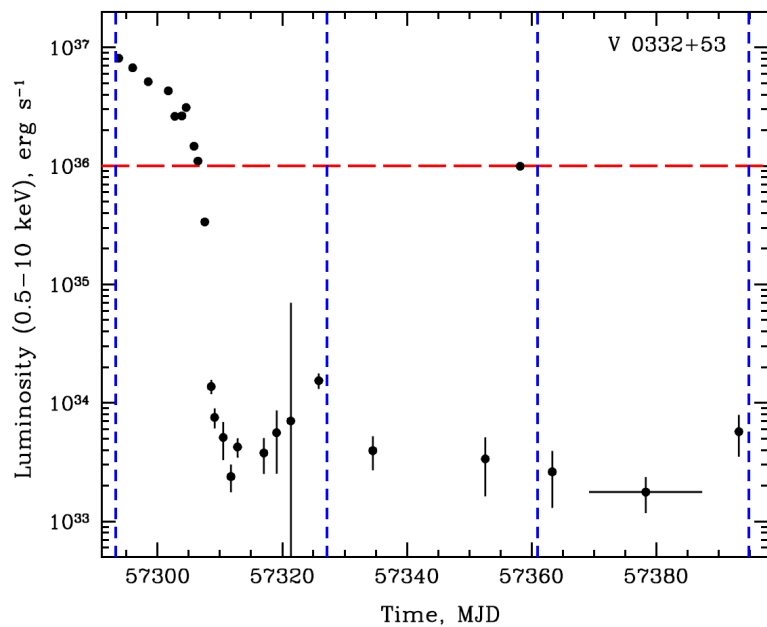
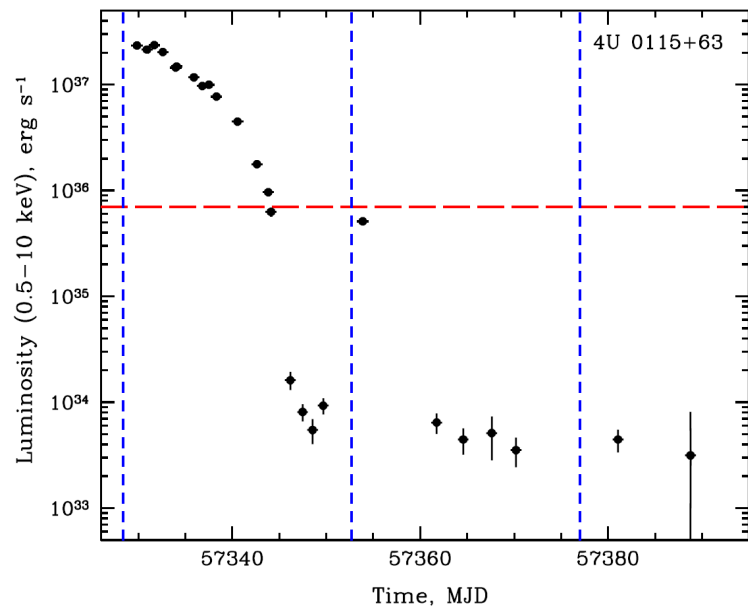
$L_{\text{lim}} = 2.0 \times 10^{40} \text{ erg s}^{-1}$   
 $B \sim 1.1 \times 10^{14} \text{ G}$

$\xi = 0.5$   
 $\xi = 0.7$   
 $\xi = 1.0$

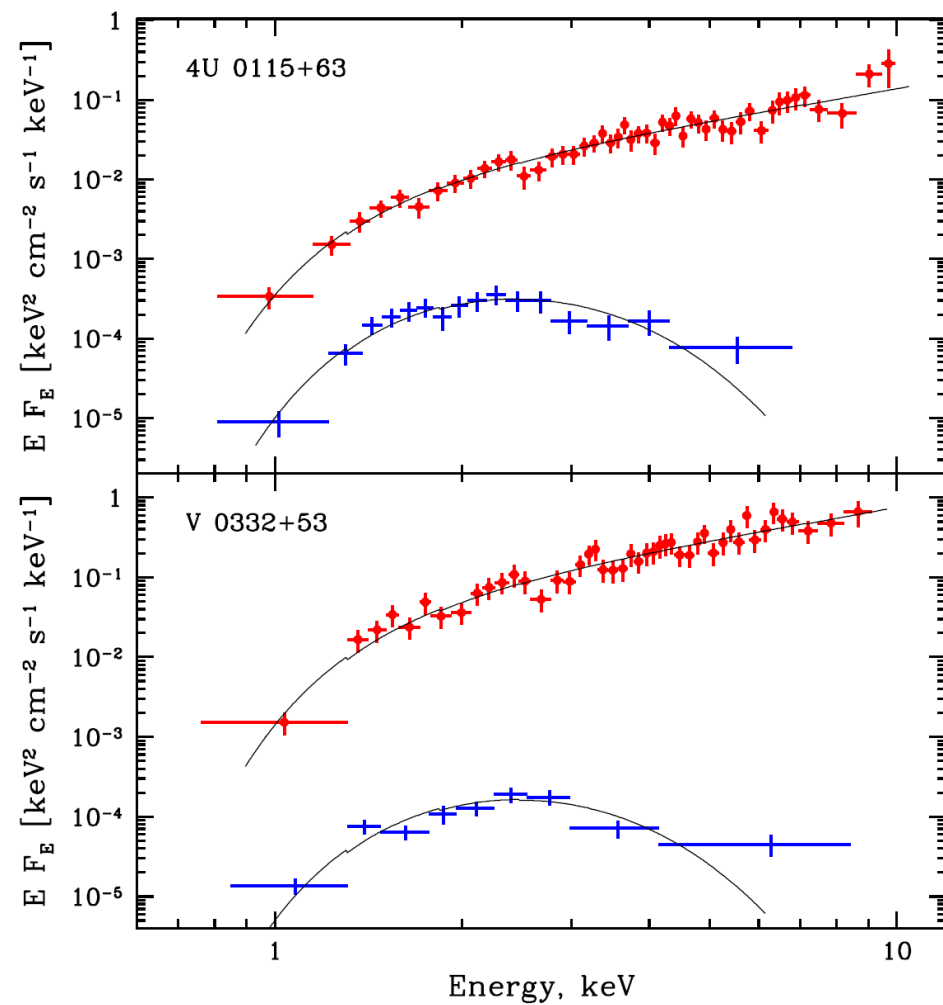
*Tsygankov et al., 2016b*

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

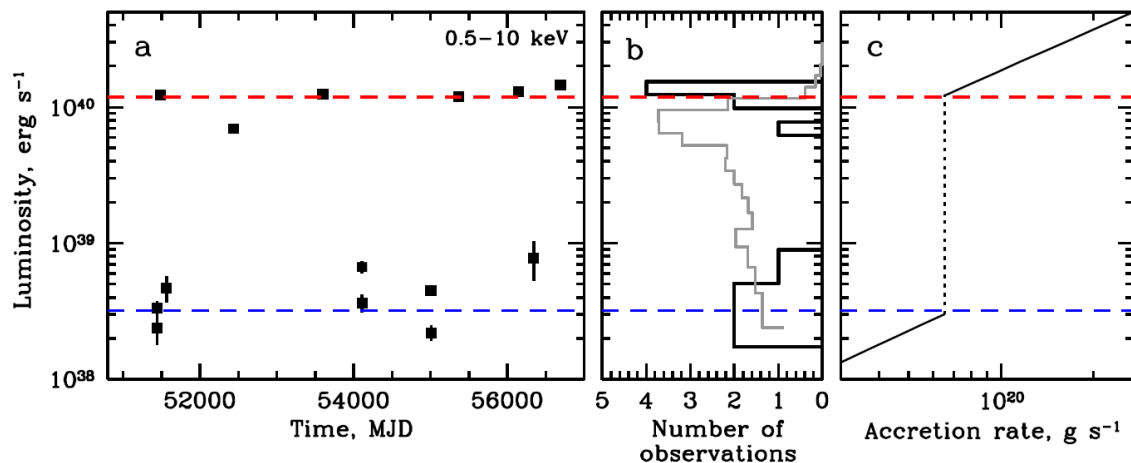
# Conclusion (I)



4U 0115+63 and  
V 0332+53 in 2015



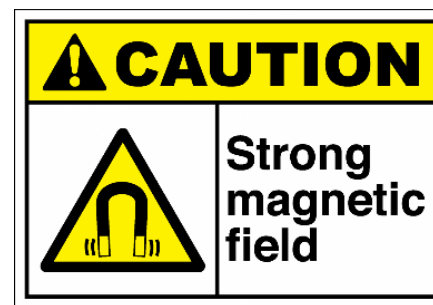
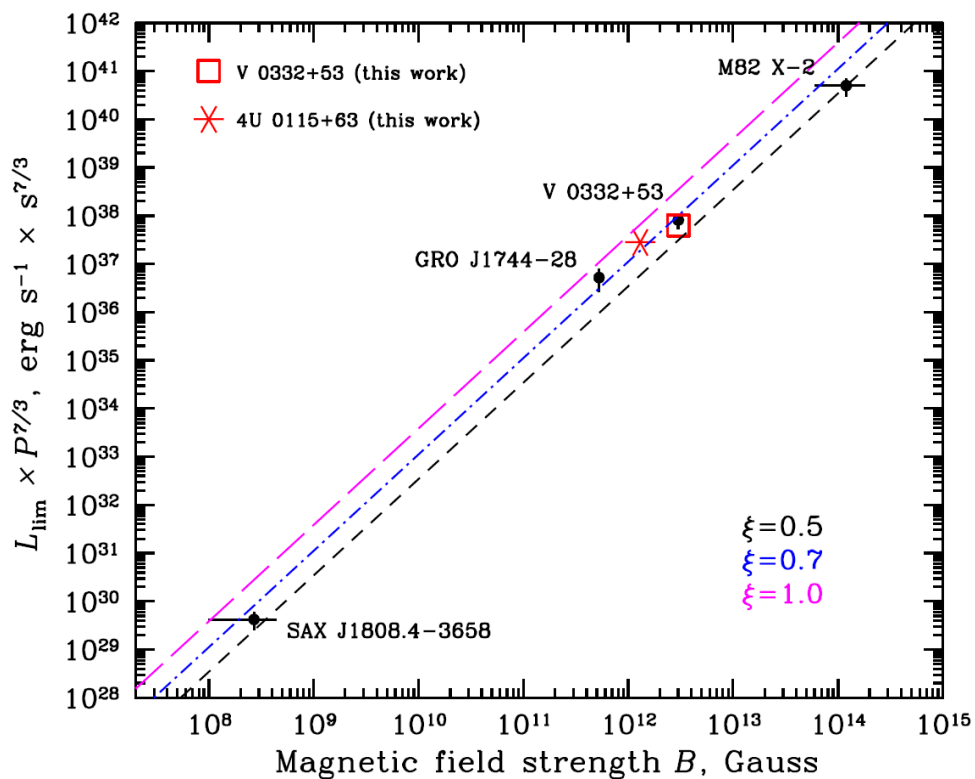
# Conclusion (II)



M82 X-2

Bimodal distribution of flux:  
propeller effect in action

Magnetic field strength  
 $B \sim 10^{14}$  G



# Why is it interesting?

- Confirmation of the whole paradigm of X-ray pulsars
- Determination of the magnetic field strength without measuring the cyclotron line
- Dipole component can be compared to the surface field (from  $E_{\text{cyc}}$ ) => estimation of the multipole components
- Disc-magnetosphere interaction

