Pulsing ULXs as highly magnetized neutron stars

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Outlook

Introduction. Pulsing ULXs.

Accretion columns. Basic ideas.

Maximum possible luminosities.

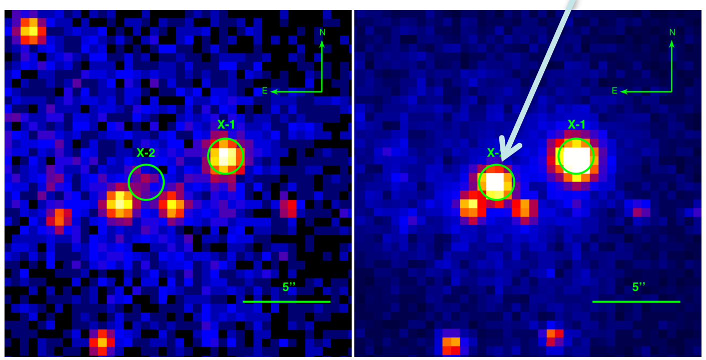
Magnetic opacities importance.

Geometry of accretion flow importance.

Conclusions.

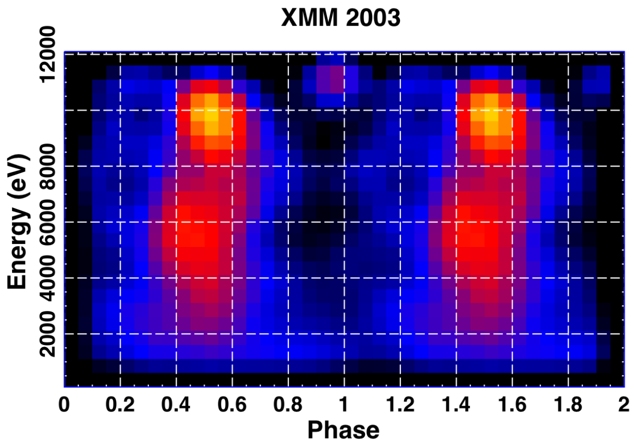
Pulsing ULXs

X-2



Pulsing ULX M82 X-2
(Bachetti et al., Nature, 2014)

L ≈10^{40} erg s^{-1} ,   P ≈1.37 s

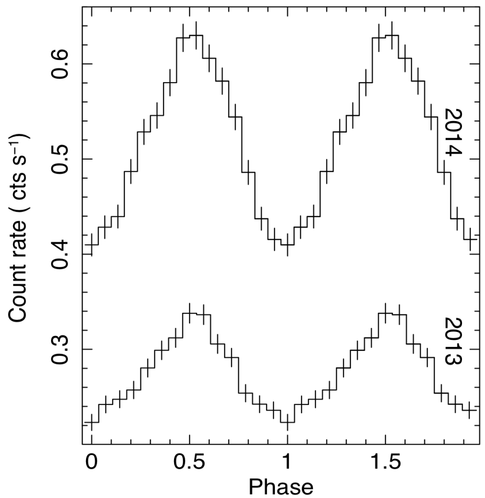


Pulsing ULX in NGC 5907
(Israel et al., Science 2017)

L >10^{41} erg s^{-1} ,   P ≈1.43-1.13 s

Pulsing ULX in NGC 7793 P13
(Israel et al., MNRAS 2017)

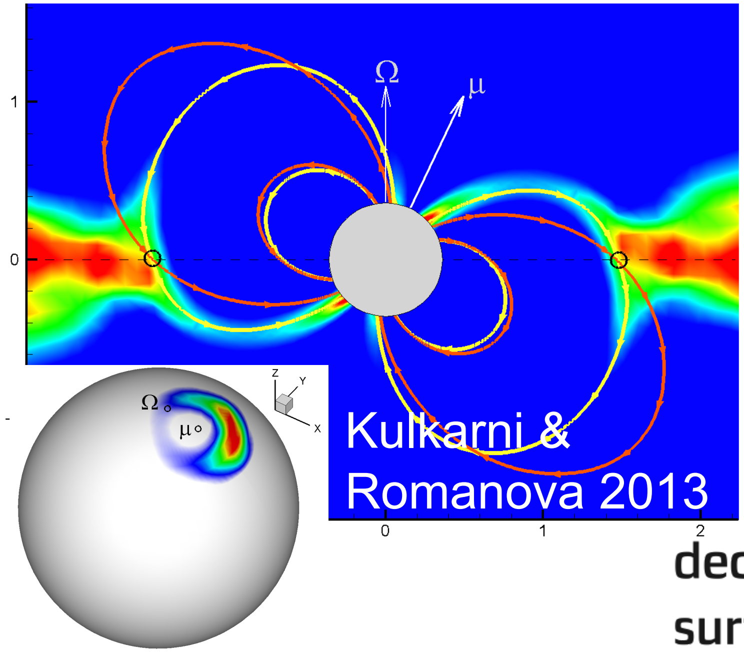
L > 2 10^{39} erg s^{-1} ,   P ≈ 0.42 s



Many transient X-ray pulsars have higher luminosities
during giant (type II) outbursts

Super-Eddington fluxes.

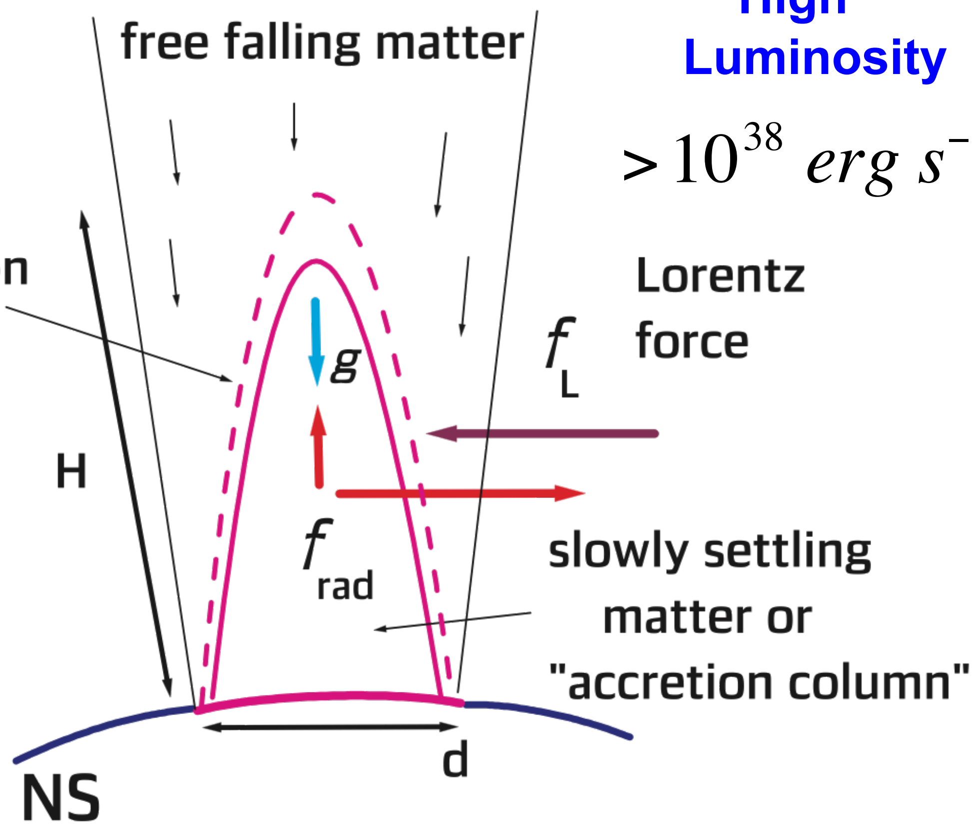
Magnetic field importance.



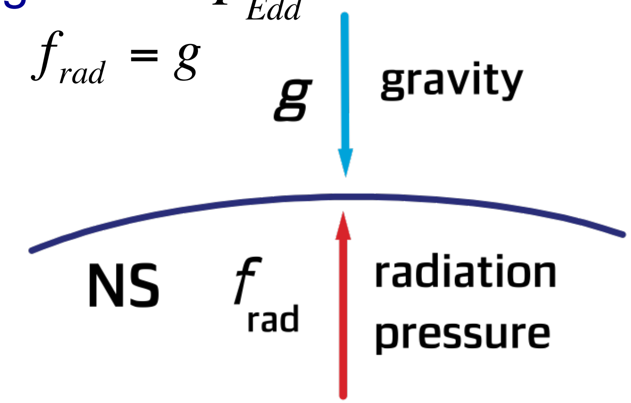
$$f_L >> g \quad \rightarrow \quad F >> F_{Edd}$$

High Luminosity

$$> 10^{38} \; erg \; s^{-1}$$



Eddington flux F_{Edd} from $f_{rad} = g$



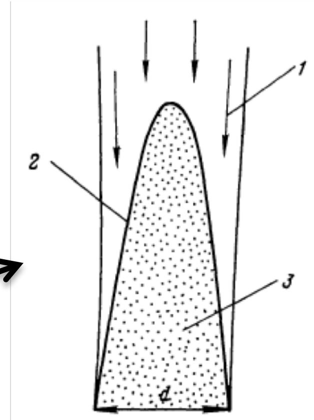
Eddington luminosity $L_{Edd} = \dfrac{4\pi GMc}{0.2(1+X)} \approx 1.4 \cdot 10^{38} \dfrac{M}{M_\odot}$ erg s^{-1}

Models: Some previous works

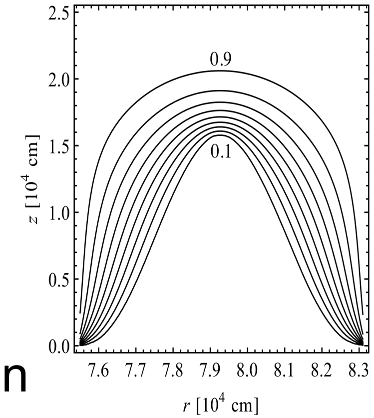
Basko & Sunyaev 1976 — Basic ideas, first numerical models

Wang & Frank 1981 — First 2D simulations

Lyubarskij & Sunyaev 1988 — Physics of accretion column structure

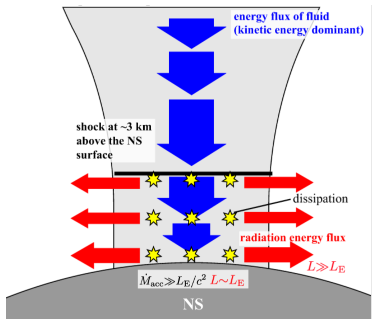


Becker & Wolff 2007 + — Spectra



Postnov et al. 2015 — 2D models, diffusion approximation for radiation transfer

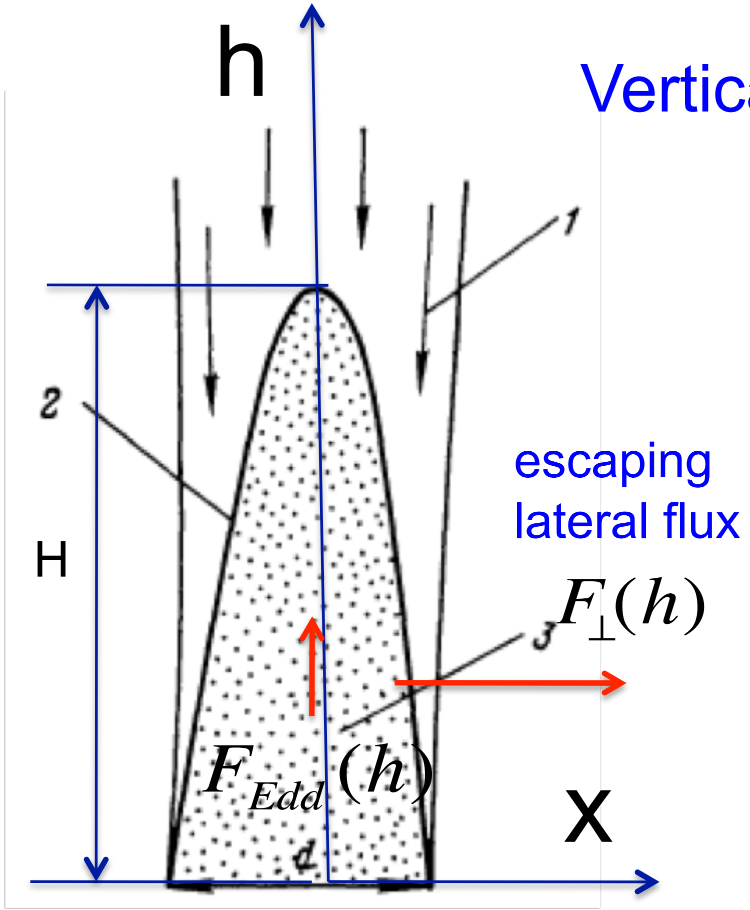
Kawashima et al 2016 — 2D radiation-hydrodynamic simulations



Radiation supported accretion column

Main assumptions

on the base of Lubarsky & Sunyaev 1988 and Basko & Sunyaev 1976



optically thick structure

Vertical direction

Hydrostatic equilibrium

$$F_{II}(h) = F_{Edd}(h), \quad P_{tot} \approx P_{rad} \approx \frac{\varepsilon_{rad}}{3} = \frac{aT^4}{3}$$

$$\frac{dP_{rad}(h)}{dh} = -\rho \frac{\kappa_{II} F_{Edd}(h)}{c}$$

magnetic opacities

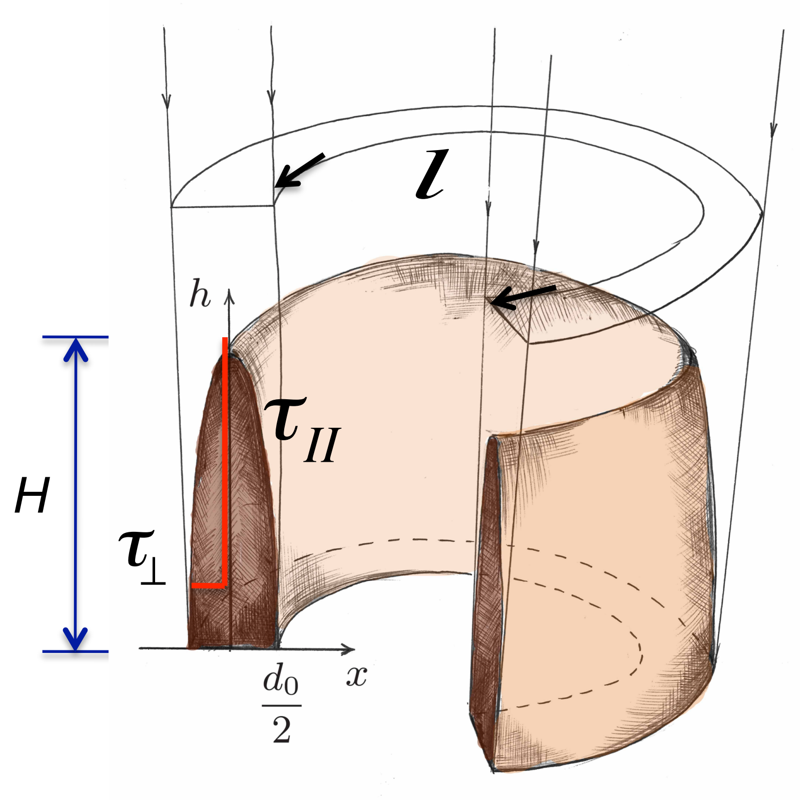
Horizontal direction

Radiation transfer

$$\frac{d\varepsilon_{rad}(x,h)}{dx} = -3\rho \frac{\kappa_\perp F_\perp(h)}{c} \frac{2x}{d}$$

Radiation supported accretion column

Toy model: Constant density.



Vertical direction

Hydrostatic equilibrium

$$\varepsilon_{rad}(0,h) \approx 3\frac{\tau_{II}}{c} F_{Edd}(h)$$

Horizontal direction

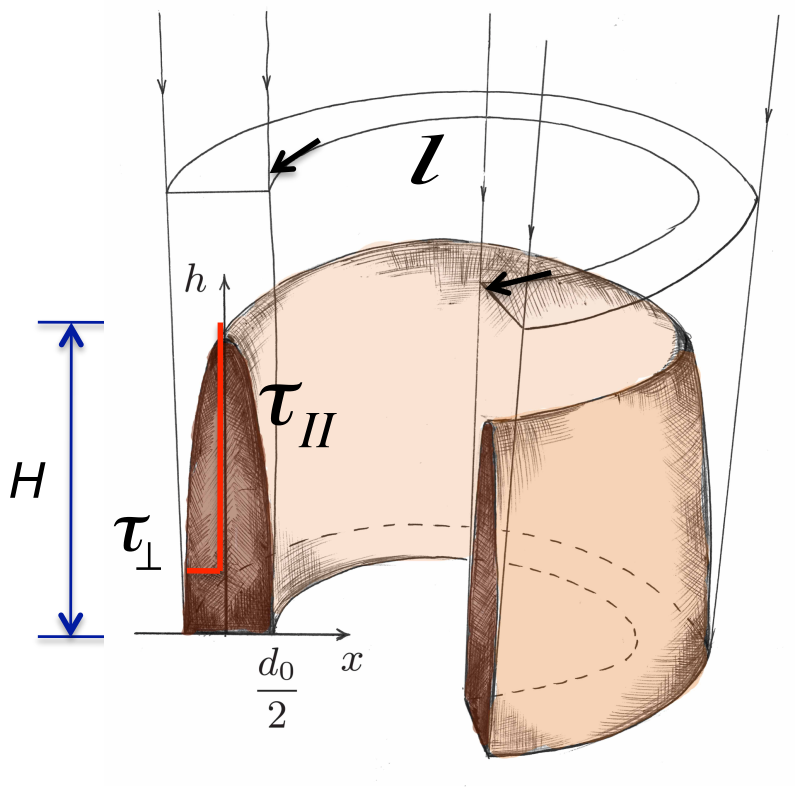
Radiation transfer

enhancement factor

$$F_{\perp}(h) \approx \frac{2c\,\varepsilon_{rad}(0,h)}{3\,\tau_{\perp}} \approx 2\frac{\tau_{II}}{\tau_{\perp}} F_{Edd}(h)$$

Radiation supported accretion column

Toy model: Constant density.



$$F_\perp(h) \approx 2\frac{\tau_{II}}{\tau_\perp} F_{Edd}(h)$$

Integration over the surface

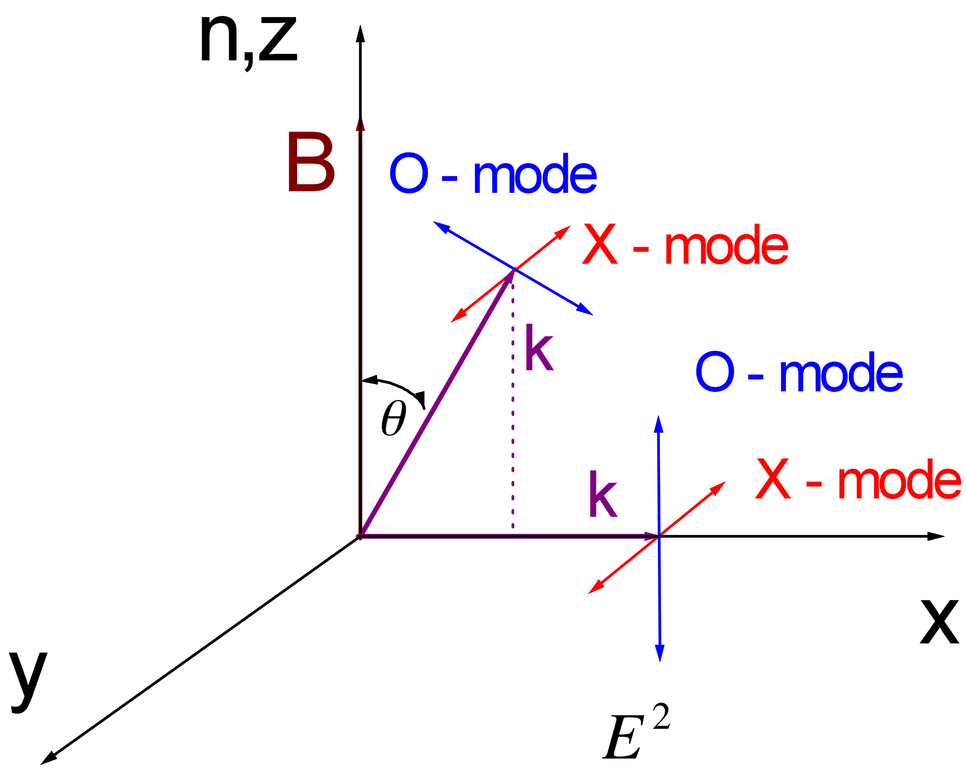
$$L \approx 40\left(\frac{l/d}{50}\right)\left(\frac{\kappa_T}{\kappa_\perp}\right) f(H/R)\, L_{Edd}$$

$$L^{**}(H=R) \approx 2\times 10^{39}\left(\frac{l/d}{50}\right)\left(\frac{\kappa_T}{\kappa_\perp}\right) \quad \text{erg s}^{-1}$$

$$H(x) \approx H\left(1-4\frac{x^2}{d^2}\right)$$ approximate parabolic shape

Magnetic opacities

Description of the radiation transfer using two normal modes



$$\kappa_X \propto \kappa_T \frac{E^2}{(E - E_C)^2}, \quad \kappa_O \propto \kappa_T$$

Photon energy

$$E = h\nu$$

Cyclotron energy

$$E_C = 11.5\,(B/10^{12}\ G)\ \text{keV}$$

Magnetic opacities

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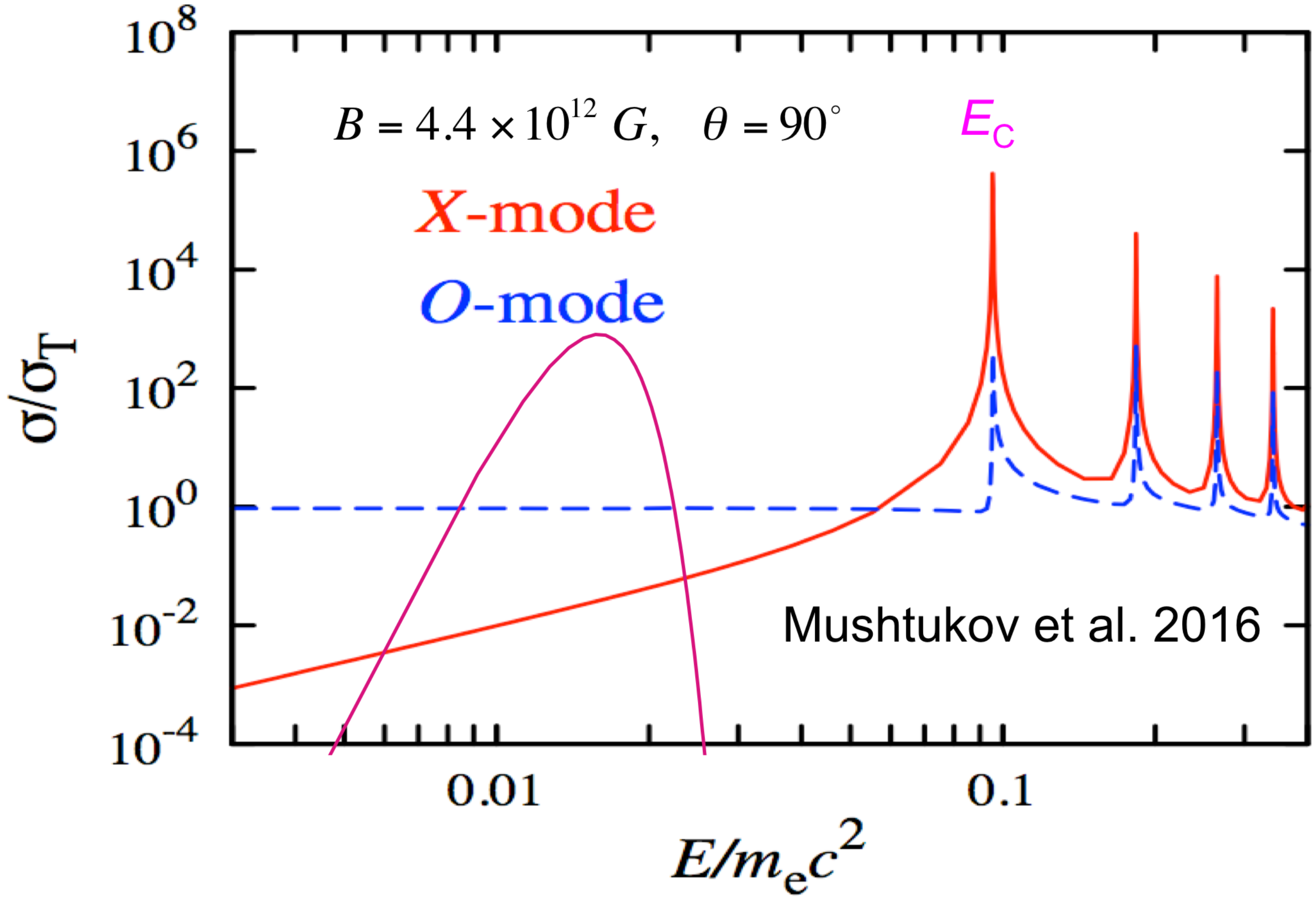
$$\kappa_O \propto \kappa_T$$

Averaging over thermal spectrum is important

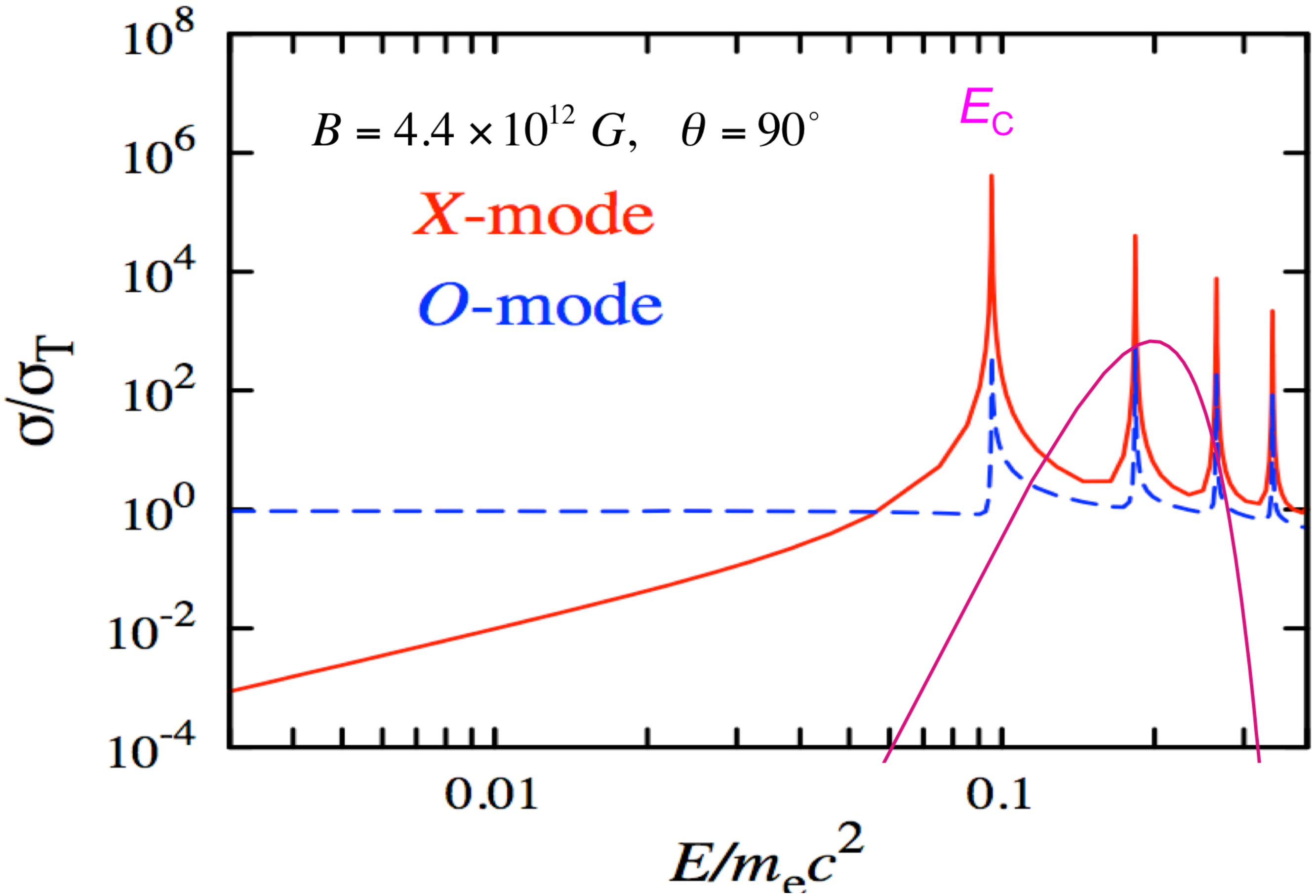
$$kT << E_C \quad \rightarrow \quad \kappa_\perp << \kappa_T$$



Magnetic opacities

Averaging over thermal spectrum is important

$$kT \geq E_C \quad \longrightarrow \quad \kappa_\perp \approx \kappa_T$$



Mushtukov et al. 2016

Accretion geometry importance

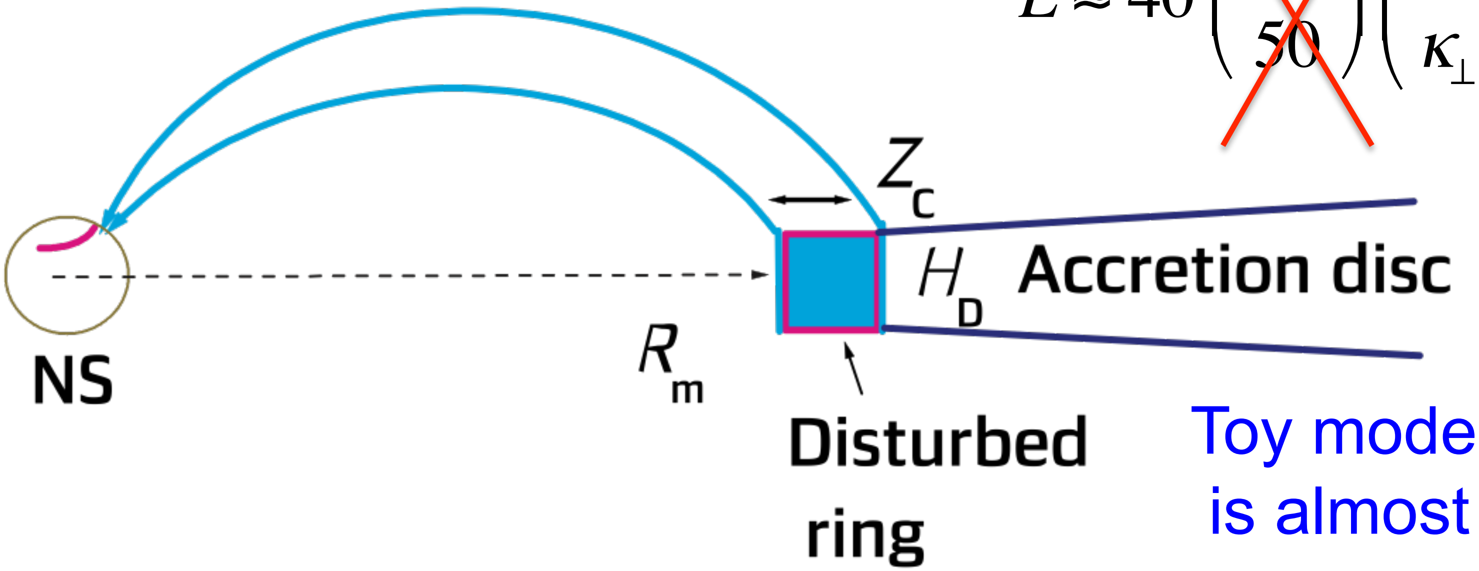
Low luminosity. Gas pressure dominated disc.

Assumption: accretion curtain thickness equals accretion disc thickness

$$Z_C = H_D$$

$$H_D \propto L^{3/20} \quad \rightarrow \quad l/d \propto L^{-4/35}$$

$$L^{1.1} \approx 40 \cancel{\left(\frac{l/d}{50}\right)} \left(\frac{\kappa_T}{\kappa_\perp}\right) f\,(H/R)\; L_{Edd}$$



Toy model dependence is almost unchanged

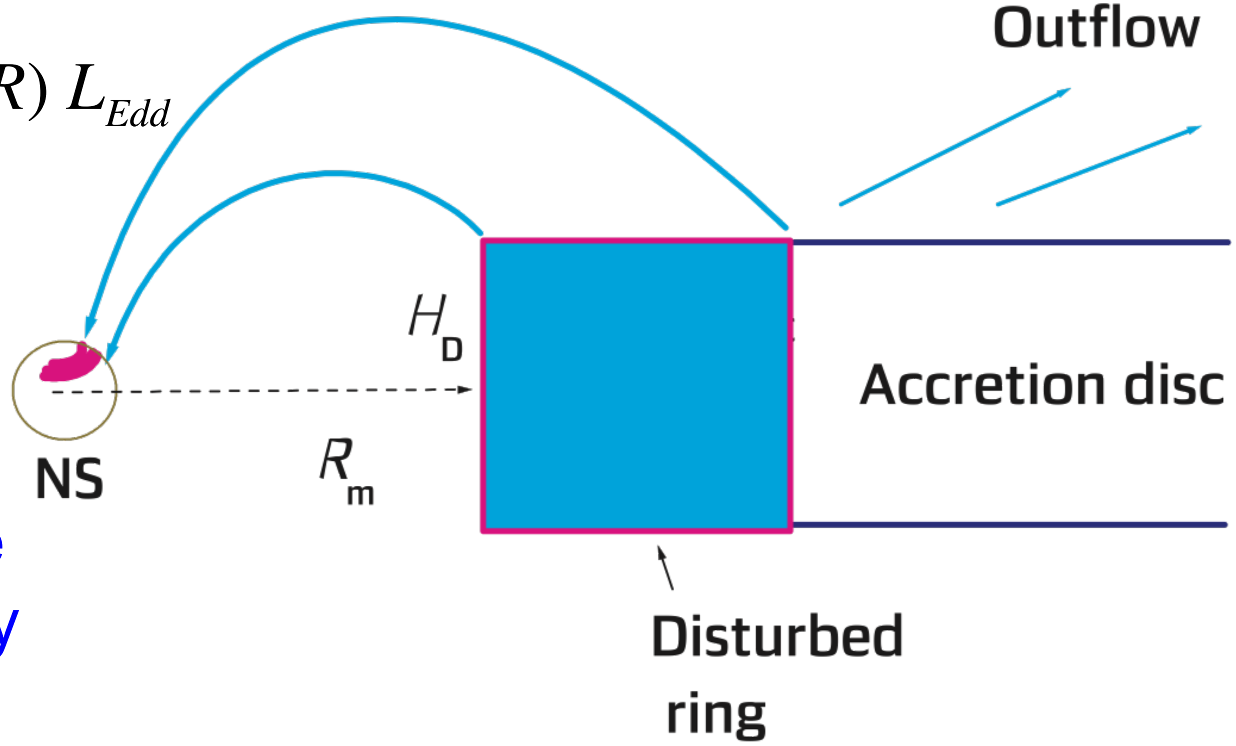
Accretion geometry importance

High luminosity. Radiation pressure dominated disc.

Assumption: the same $Z_C = H_D$. BUT $H_D \approx R_m$ **?**

$$H_D \propto L \rightarrow l/d \propto L^{-9/7}$$

$$L^{2.3} \approx 40 \cancel{\left(\frac{l/d}{50}\right)} \left(\frac{\kappa_T}{\kappa_\perp}\right) f(H/R)\, L_{Edd}$$



Toy model dependence is changed significantly

Numerical (pseudo) one-dimensional model. Final assumptions.

Aim is to find the column height H which corresponds to given L

Quasi-dipole geometry $$B(h) = B\left(\frac{R+h}{R}\right)^{-3}$$

Mass conservation low $$\frac{\dot{M}}{2S_D} = \rho V$$

channel cross-section

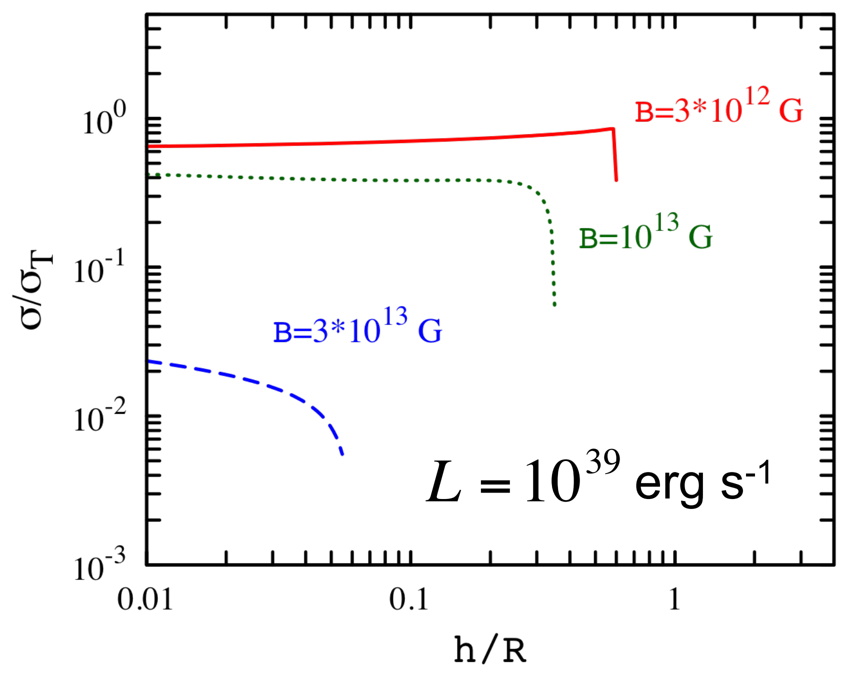
Velocity profile (by hand, weak point) $V \propto h^{\xi}, \quad V(H) = V_{ff}(H)/7$

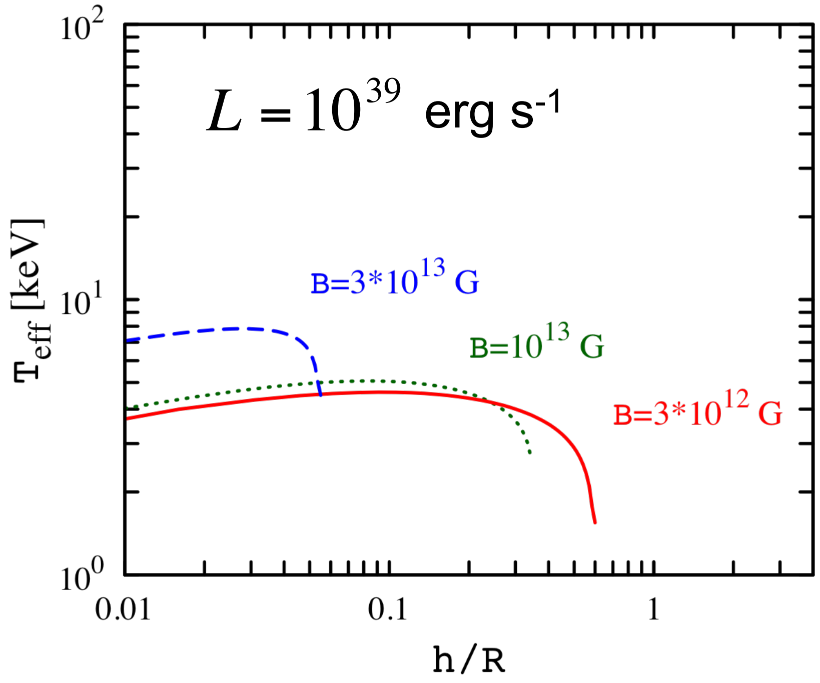
$\xi = [1 \div 5]$ Wang & Frank 1981 $\xi = 5$ Basko & Sunyaev 1976

results coincides inside factor of two

Iteration scheme, because $\kappa_{\perp}$ depends on temperature T

Numerical (pseudo) one-dimensional model. Some results.

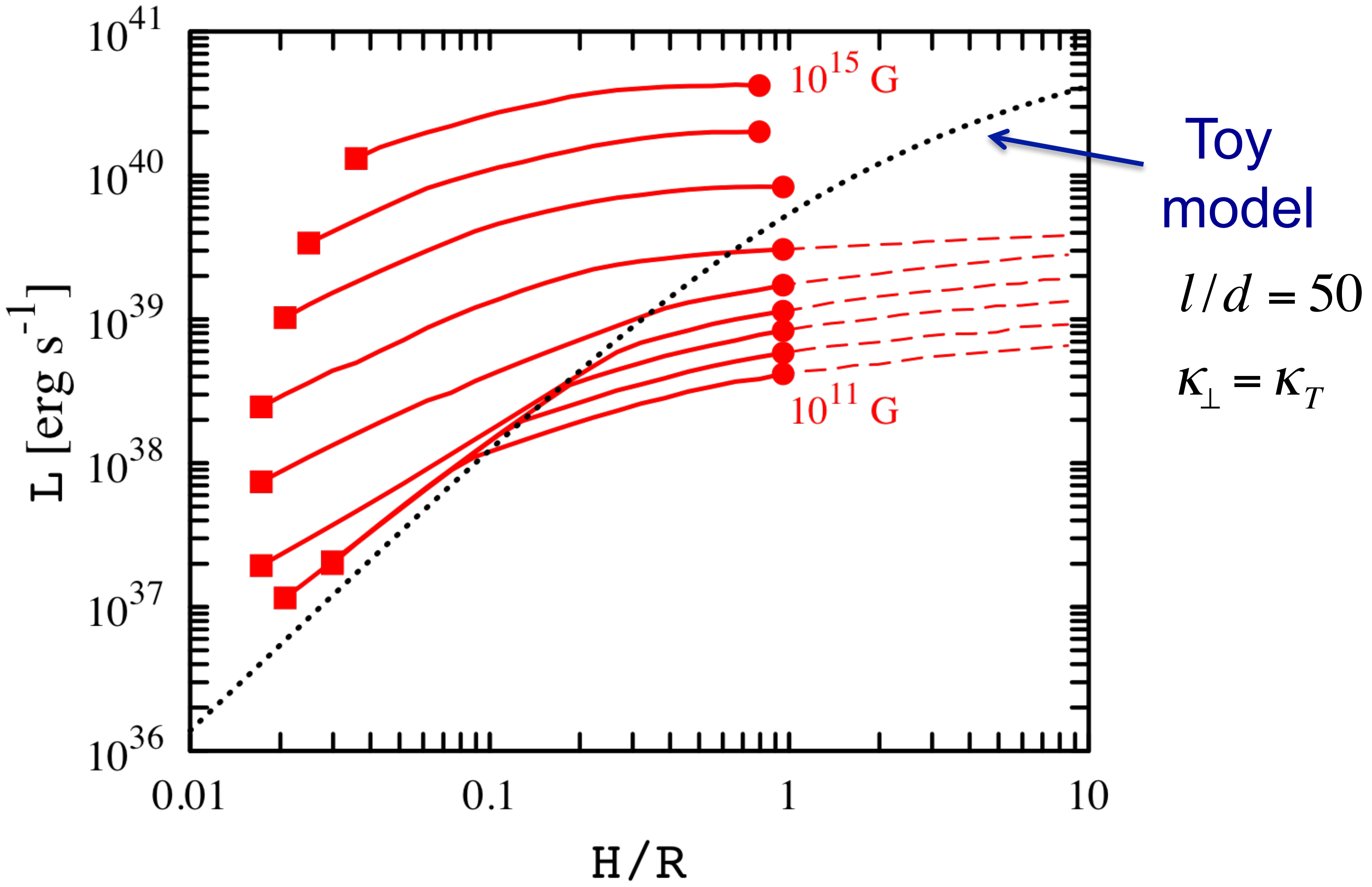




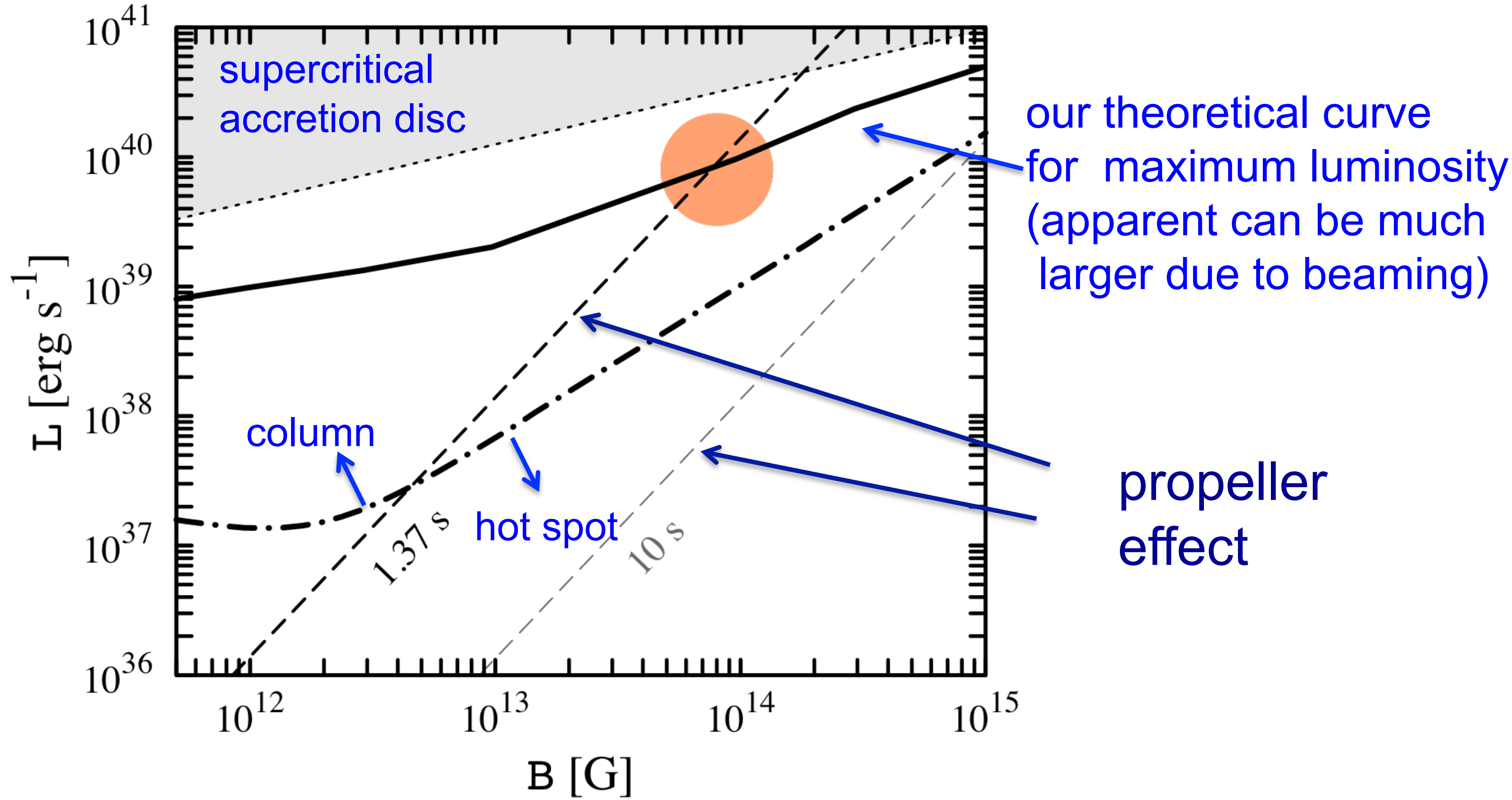
Higher NS magnetic field strength B $\rightarrow$ less opacity $\kappa_\perp$ and optical thickness $\tau_\perp$ $\rightarrow$ higher effective temperature T_{eff}

$\rightarrow$ less column height at the same luminosity or higher luminosity at the same column height

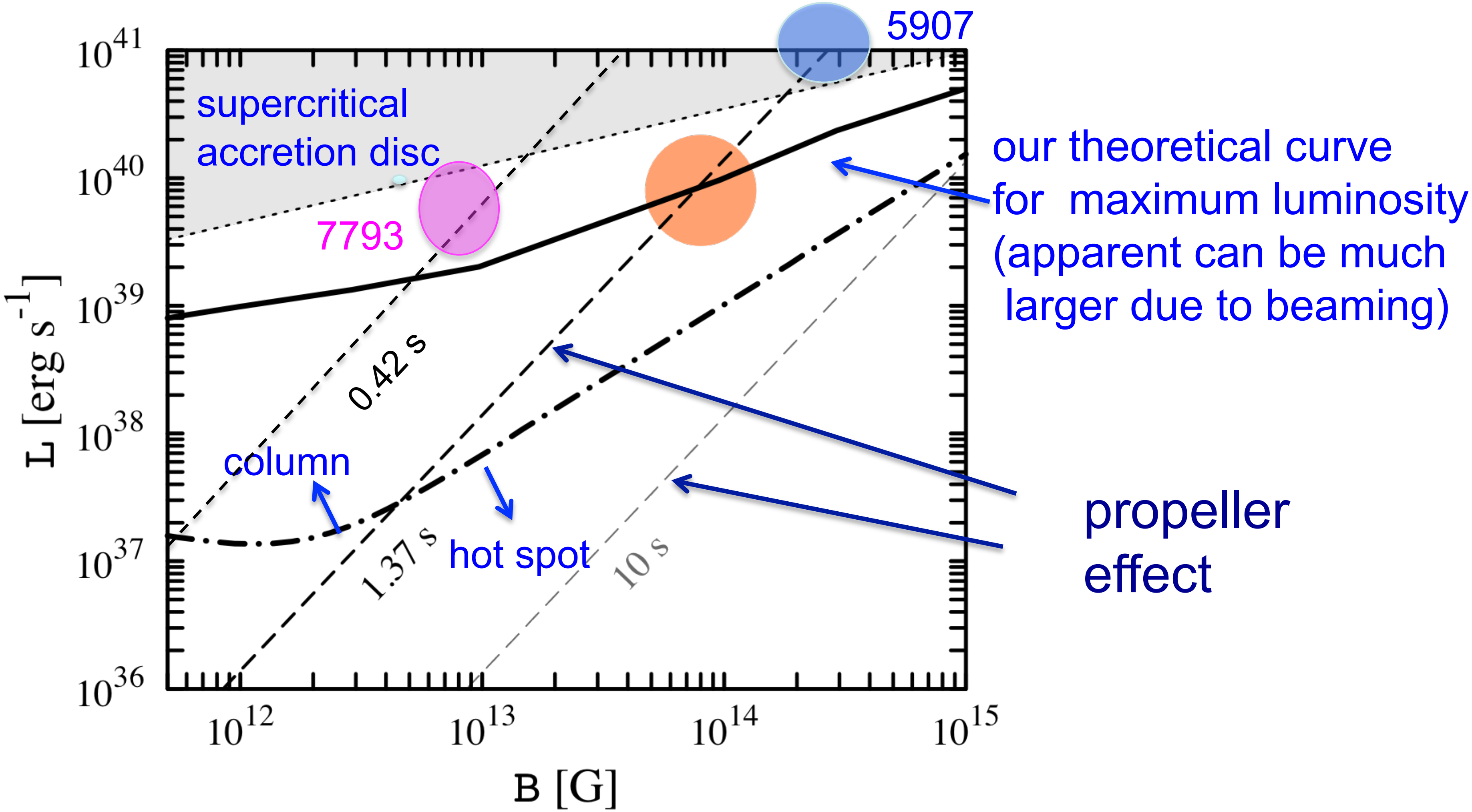
Maximum possible luminosities vs. *B*



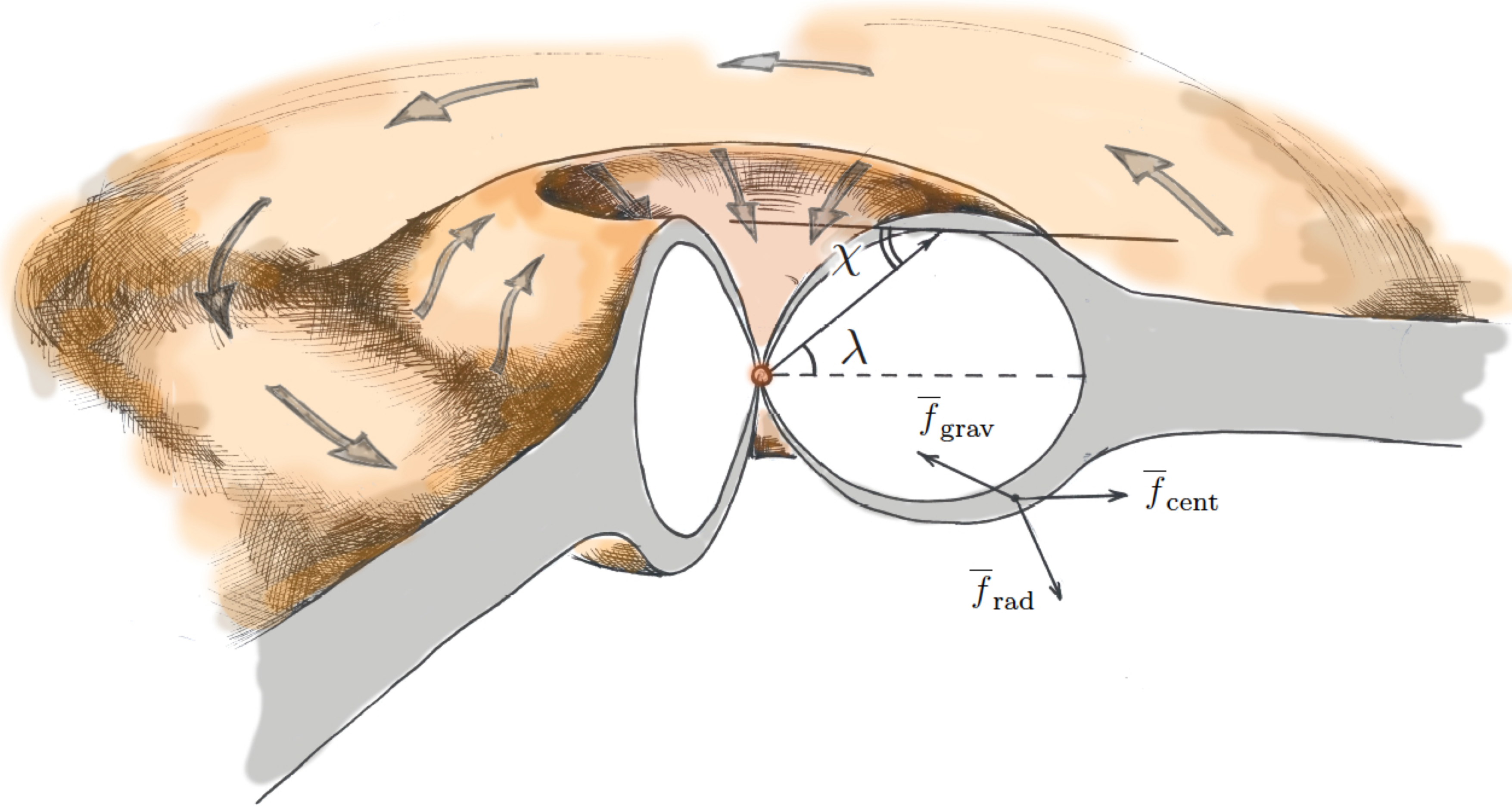
Application to M 82 X-2



Application to other pulsing ULXs



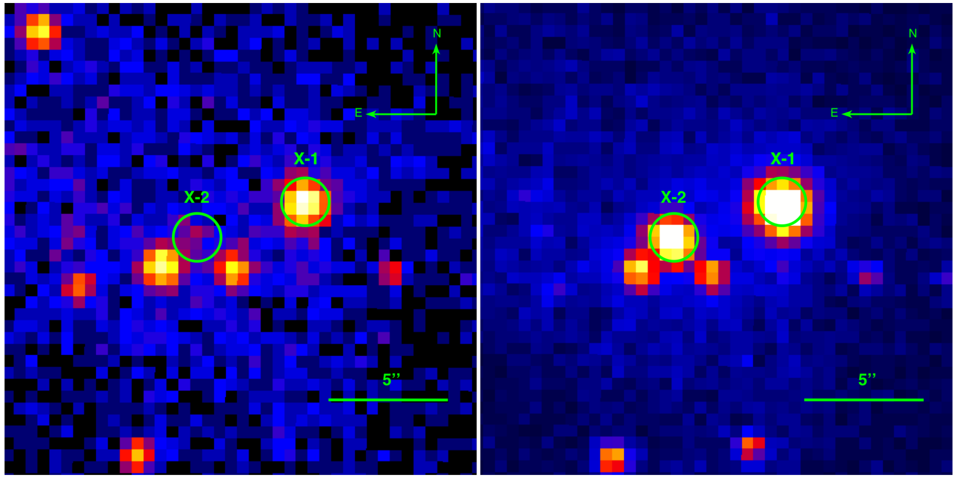
Optically thick envelopes around pulsing ULXs

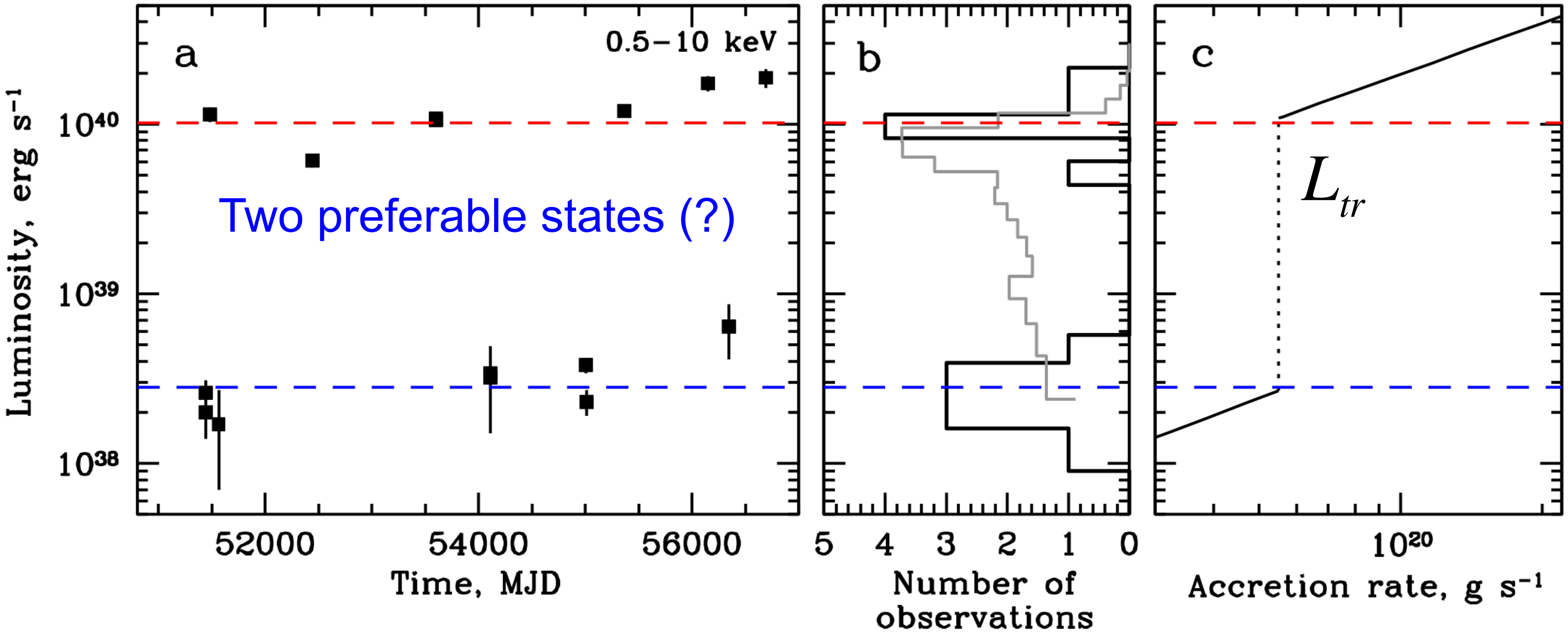


Mushtukov et al. 2017

Possible propeller effect in M 82 X-2

Tsygankov et al. 2016

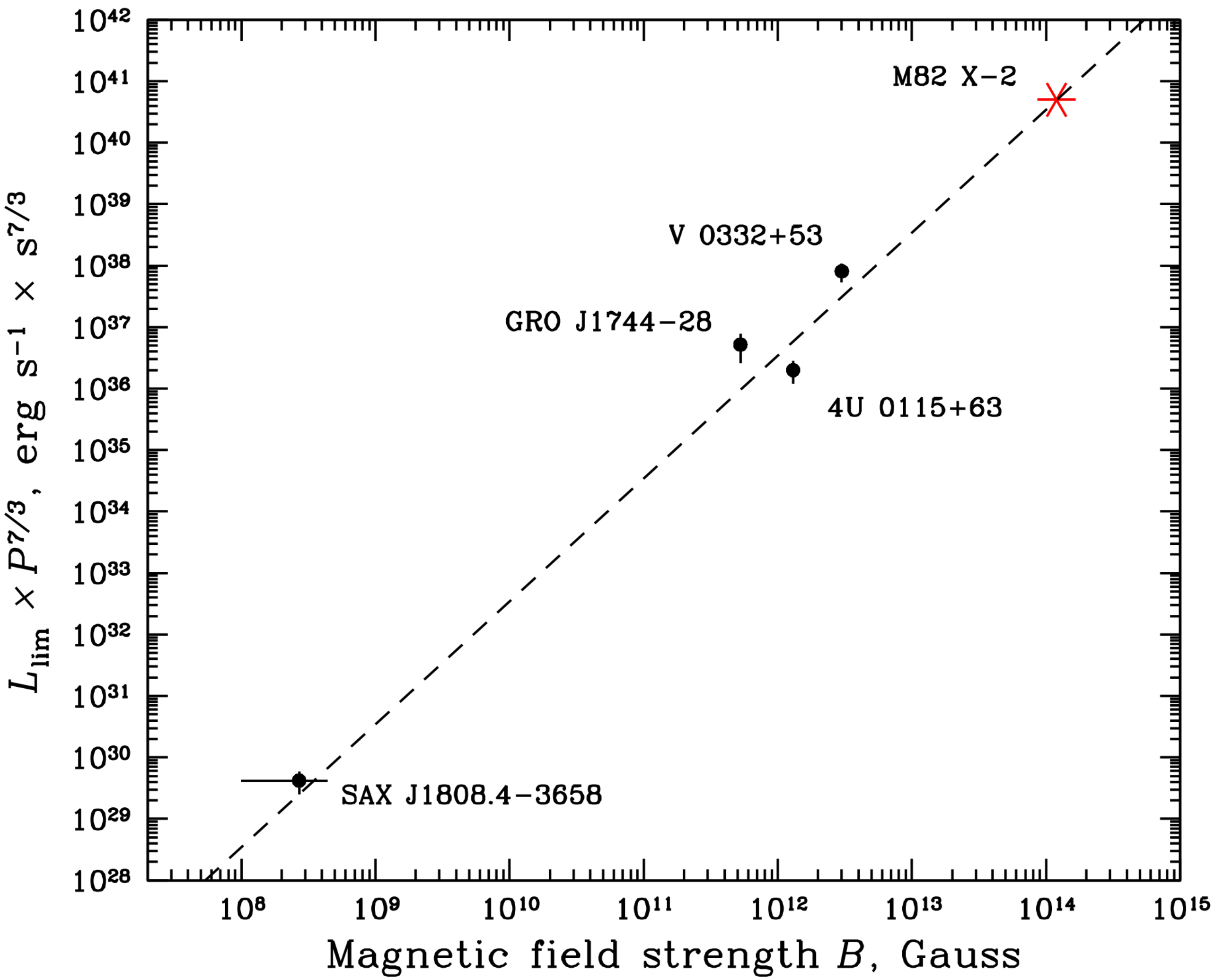




Transitions due to propeller effect at $R_m = R_{CO}$?

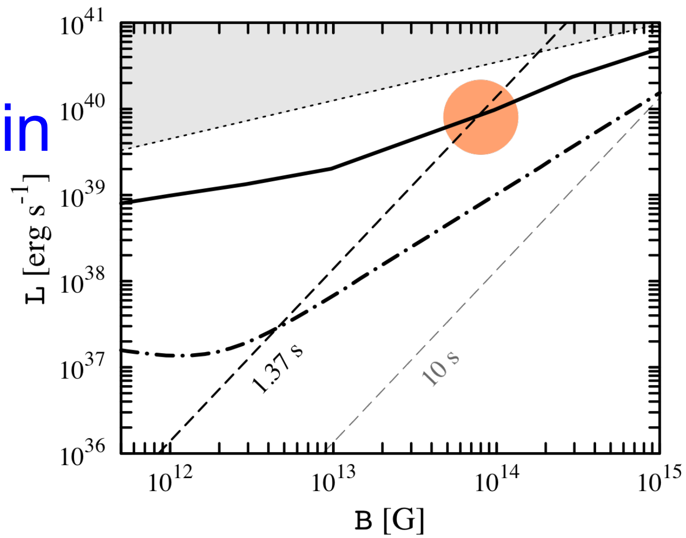
Possible propeller effect in M 82 X-2

$$R_m = R_{CO} \quad \rightarrow \quad B \propto L_{tr}\, P_{sp}^{7/3}$$

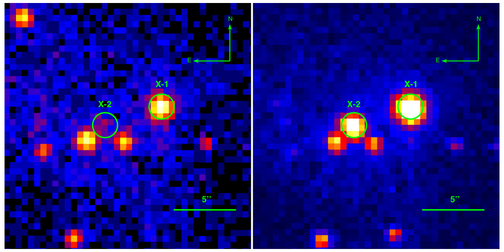


Conclusions

Our simplified model can qualitatively explain high luminous X-ray pulsars existence with luminosities up to 10^{40} erg s^{-1} typical for M82 X-2 assuming high magnetic field strength (10^{14} -10^{15} G).



Possible luminosity transitions in M82 X-2 due to propeller effect confirm B ~10^{14} G (Tsygankov et al. 2016).



Accretion geometry is very important and cannot be correctly included at the moment. There is potential possibility for maximum luminosities increasing due to geometry effects.