Super-Eddington accretion luminosity of highly magnetized neutron stars

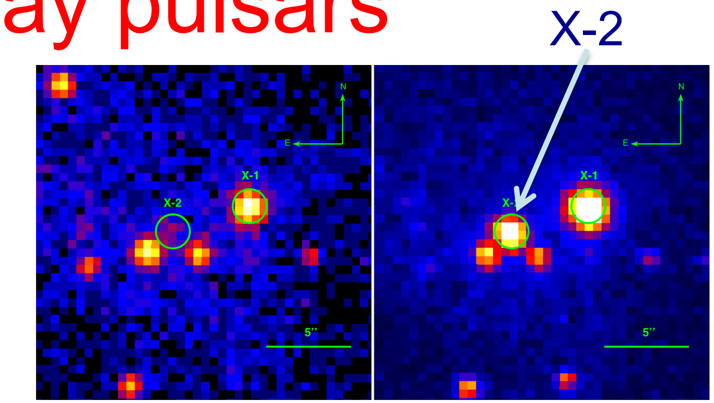
Alex Mushtukov, Valery Suleimanov
Sergey Tsygankov, Juri Poutanen

Breaking The Limits

Super-Eddington accretion
on compact objects.
September 22, 2016, Arbatax (OG), Italy

Super-Eddington X-ray pulsars

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



$L \approx 10^{40}$ erg s^{-1} , $P \approx 1.37$ s

Other pulsing ULX ! See Israel's talk

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

$0.2(1+X) = \kappa_T$ - electron scattering opacity, $X \approx 0.74$ – hydrogen mass fraction

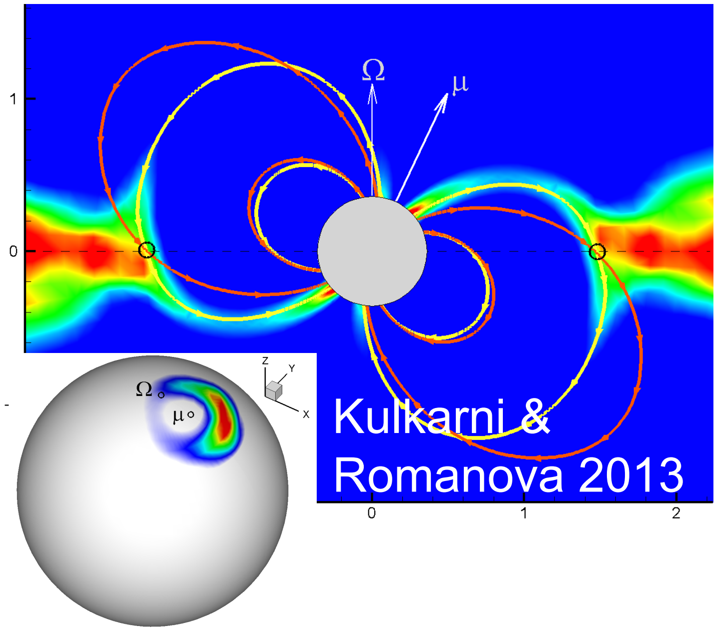
Many transient X-ray pulsars have higher luminosities
during giant (type II) outbursts

LMC X-4 - up to $2 \cdot 10^{39}$ erg s^{-1} in flares (Moon et al. 2003);
SMC X-1 $\approx 7 \cdot 10^{38}$ erg s^{-1} (Naik & Paul 2004);
A0538-66 up to $8 \cdot 10^{38}$ erg s^{-1} (Maraschi et al. 1983);
GRO J1744-28; V0332+53 etc.

(Tsygankov et al. 2016)

Super-Eddington fluxes.

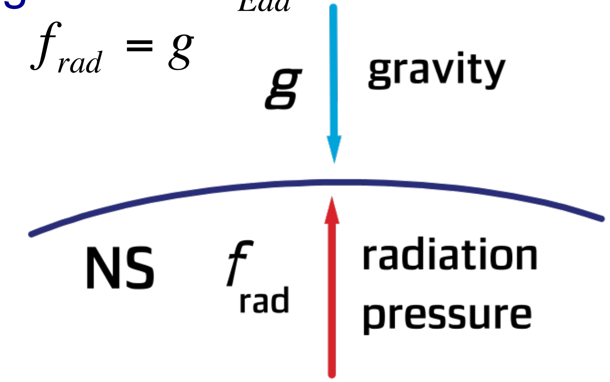
Magnetic field importance.



Kulkarni & Romanova 2013

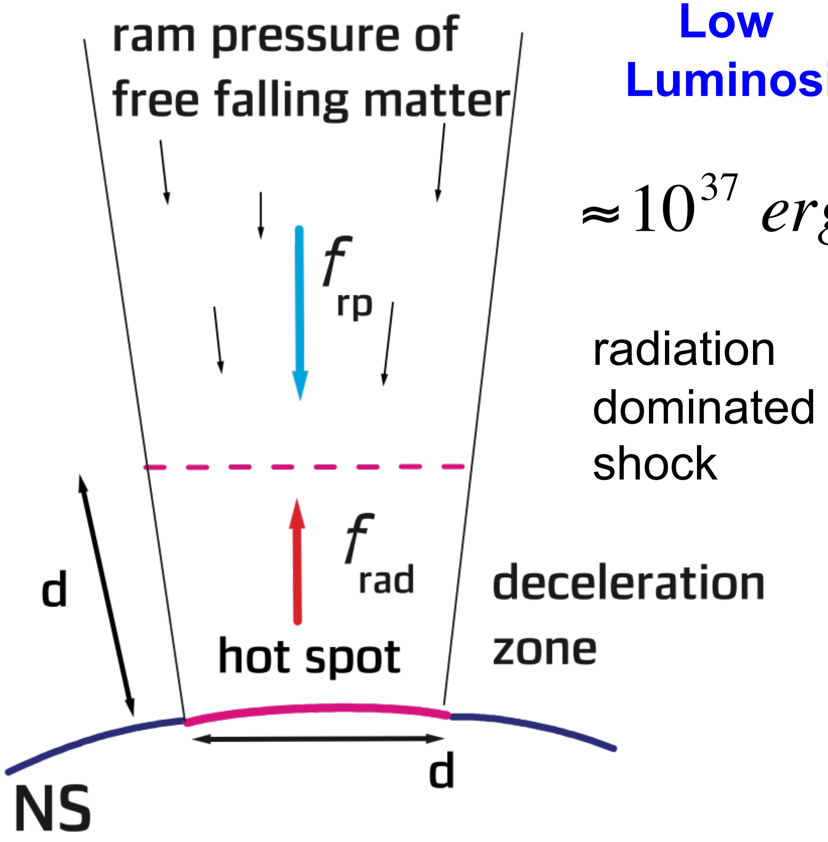
$$f_{rp} = V_{ff}^{2}/d > g \quad \rightarrow \quad F > F_{Edd}$$

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



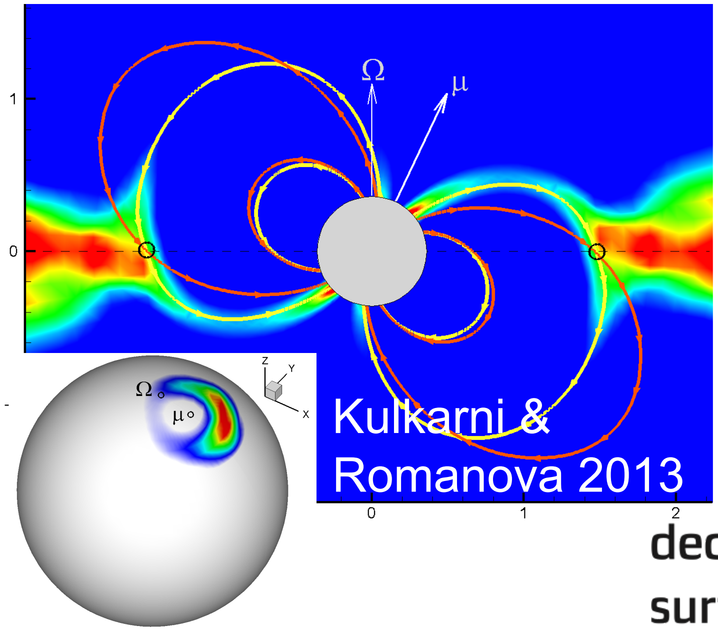
Low Luminosity

$\approx 10^{37}\ erg\ s^{-1}$



Super-Eddington fluxes.

Magnetic field importance.



Kulkarni & Romanova 2013

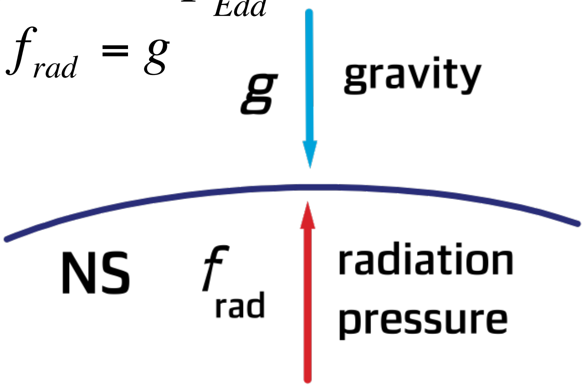
$$f_L >> g \quad \rightarrow \quad F >> F_{Edd}$$

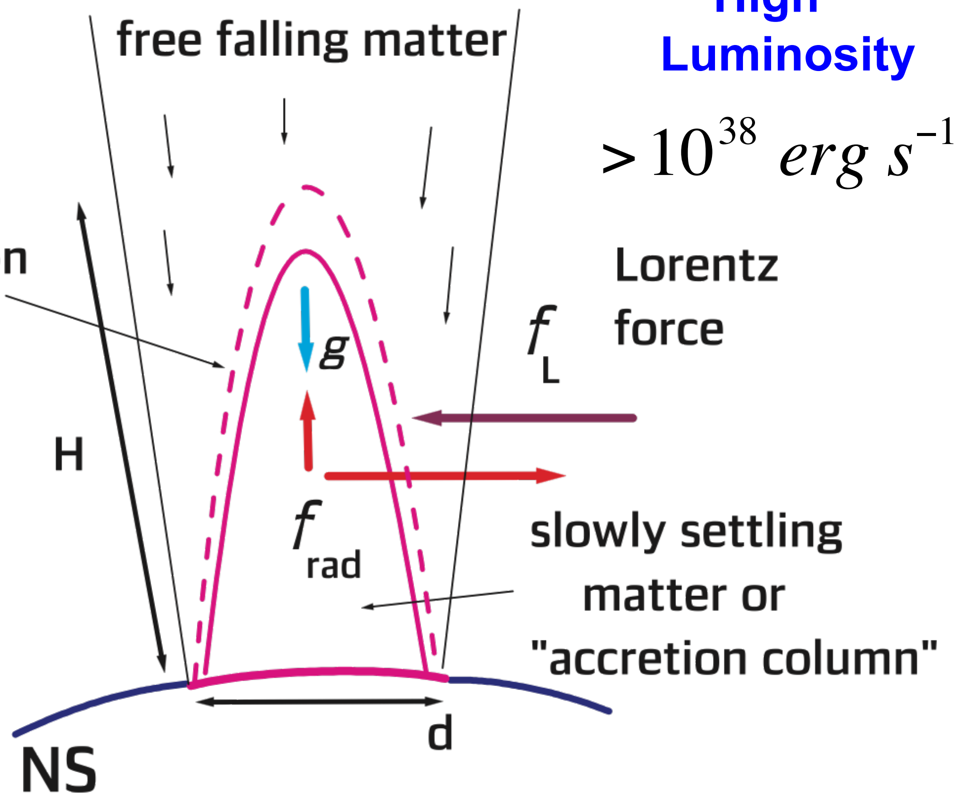
High Luminosity

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

Eddington flux F_{Edd}

from $f_{rad} = g$





Models: Some previous works

Basko & Sunyaev 1976 — Basic ideas, first numerical models

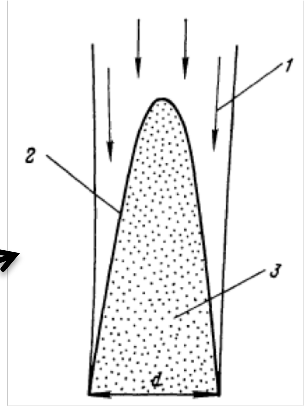
Wang & Frank 1981 — First 2D simulations

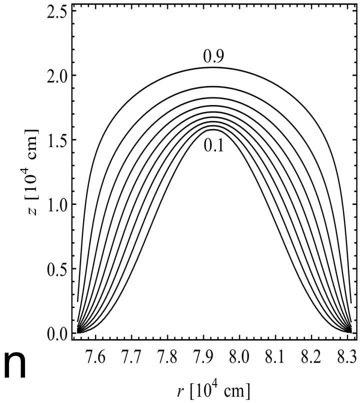
Lyubarskij & Sunyaev 1988 — Physics of accretion column structure

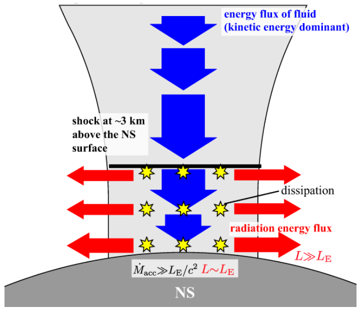
Becker & Wolff 2007 + — Spectra

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

Kawashima et al 2016 — 2D radiation-hydrodynamic simulations



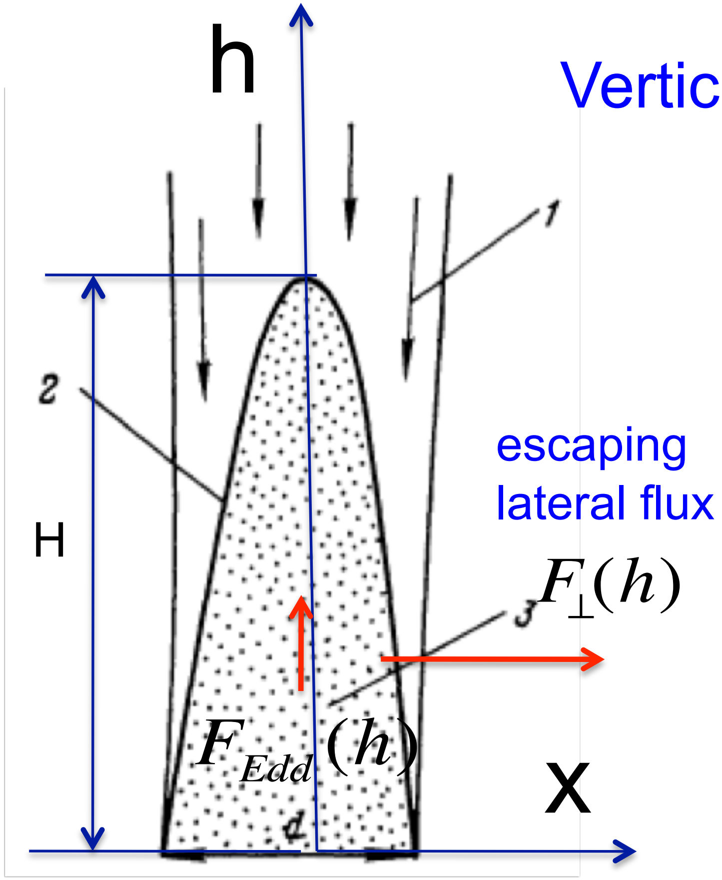




Radiation supported accretion column

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

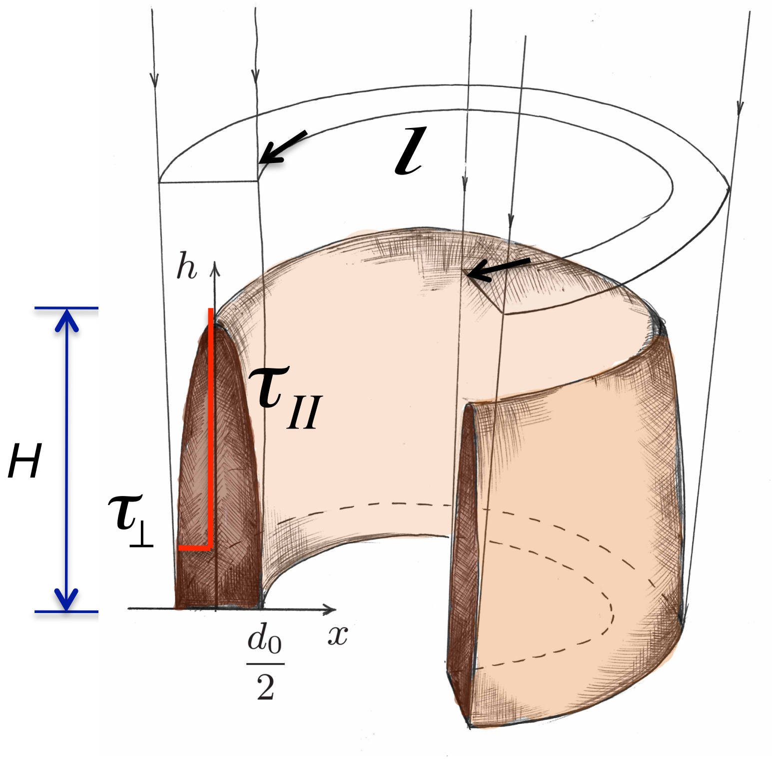
Horizontal direction

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

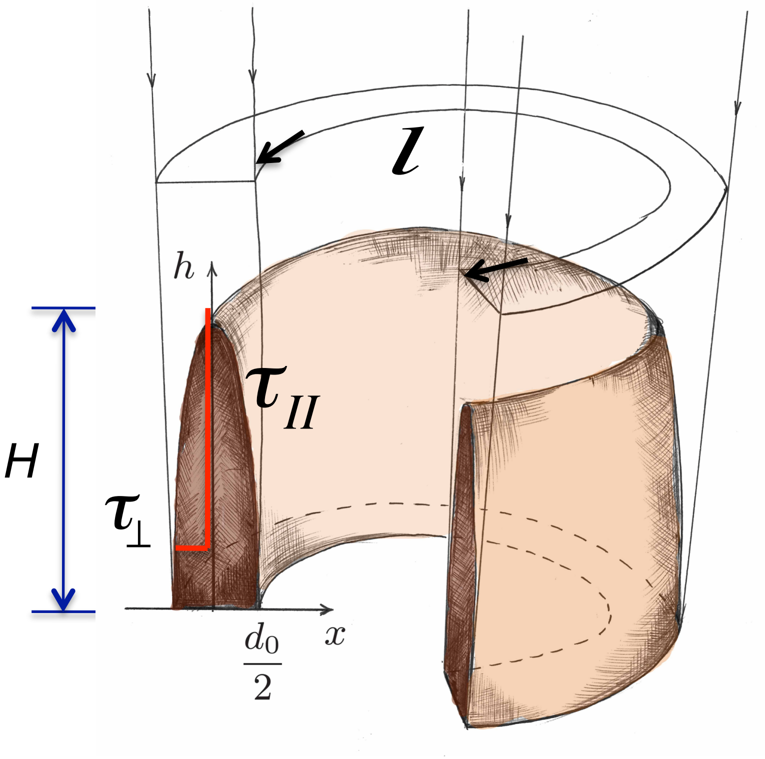
Radiation transfer

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

Cyclotron energy

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

Photon energy

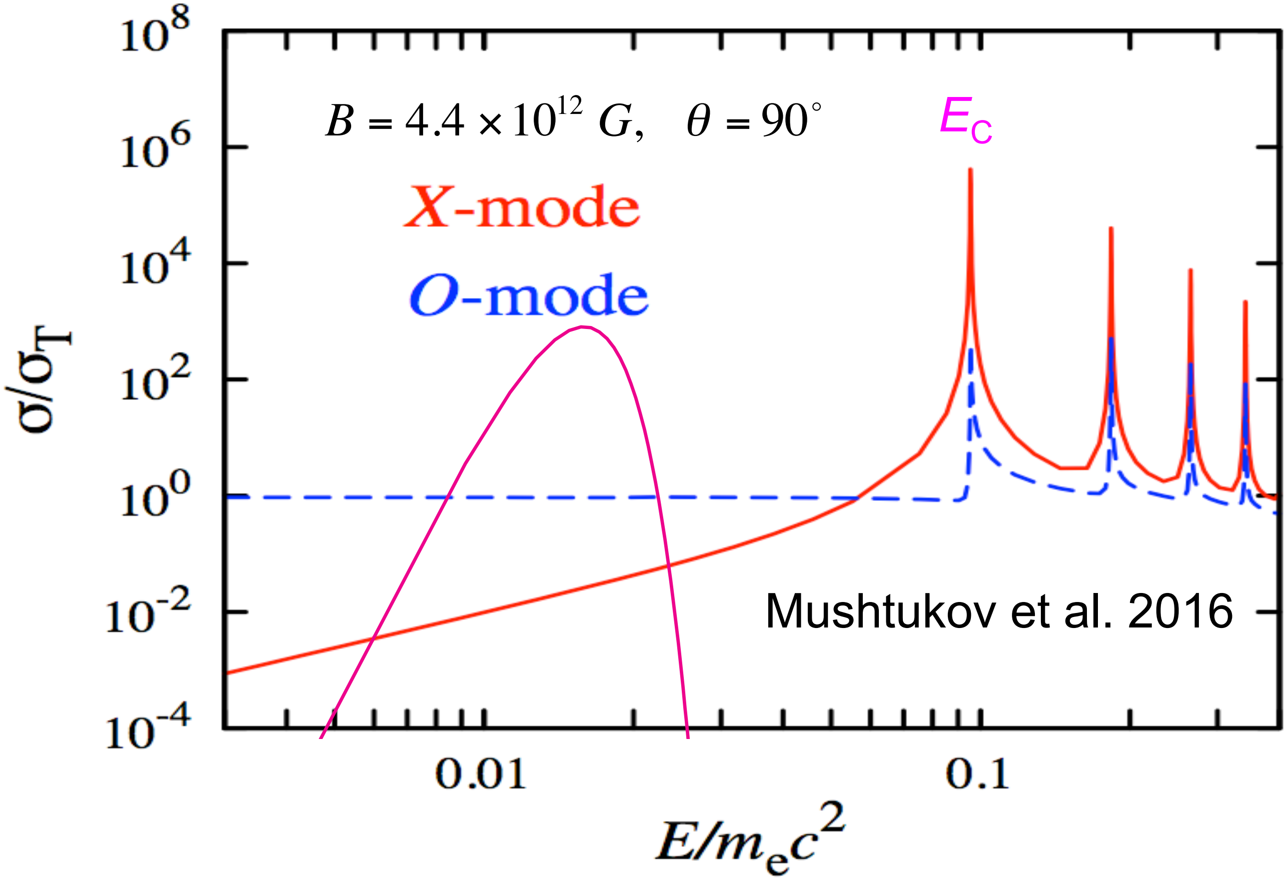
$$E = h\nu$$

$$\kappa_X \propto \kappa_T \frac{E^2}{\left(E - E_C\right)^2}$$

$$\kappa_O \propto \kappa_T$$

Averaging over thermal spectrum is important

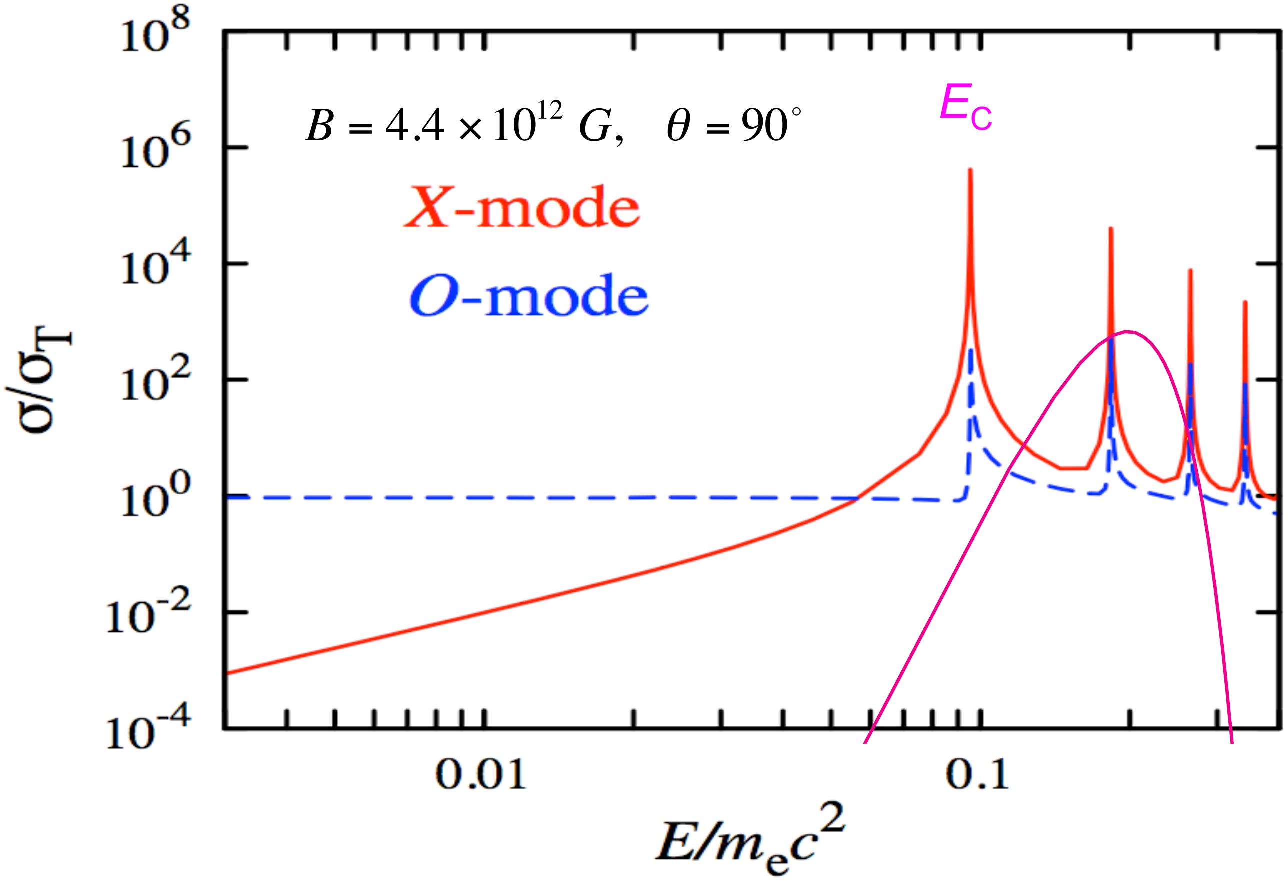
$$kT << E_C \quad \rightarrow \quad \kappa_\perp << \kappa_T$$



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

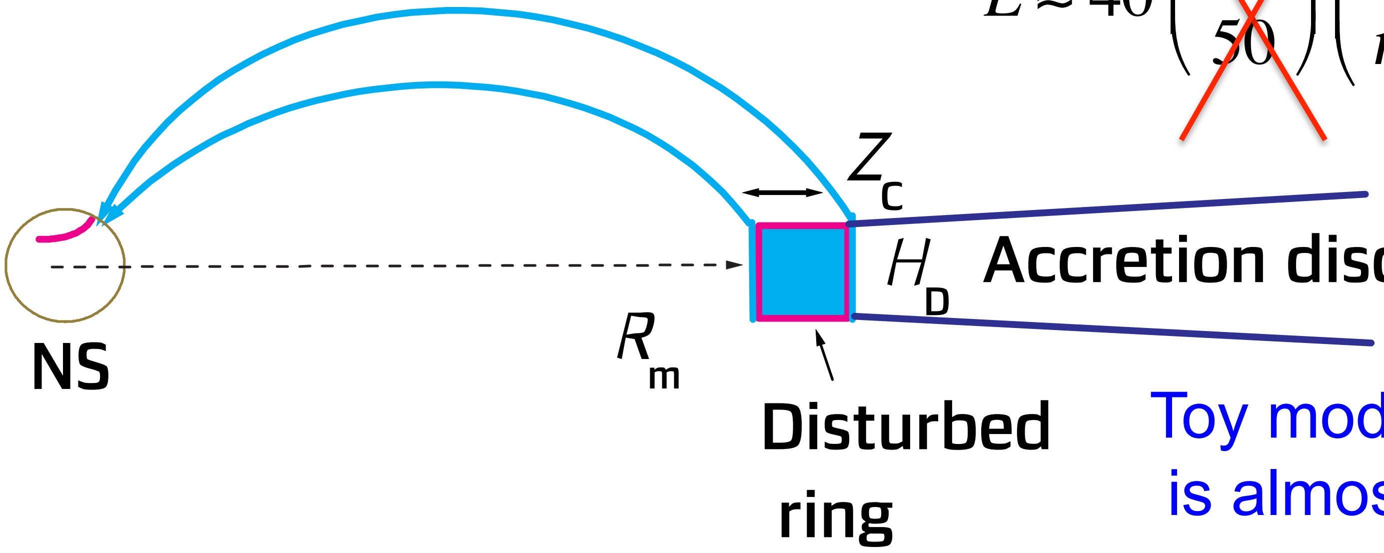
Low luminosity. Gas pressure dominated disc.

Assumption: accretion curtain thickness equals accretion disc thickness

$$\boxed{Z_C = H_D}$$

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

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



Toy model dependence is almost unchanged

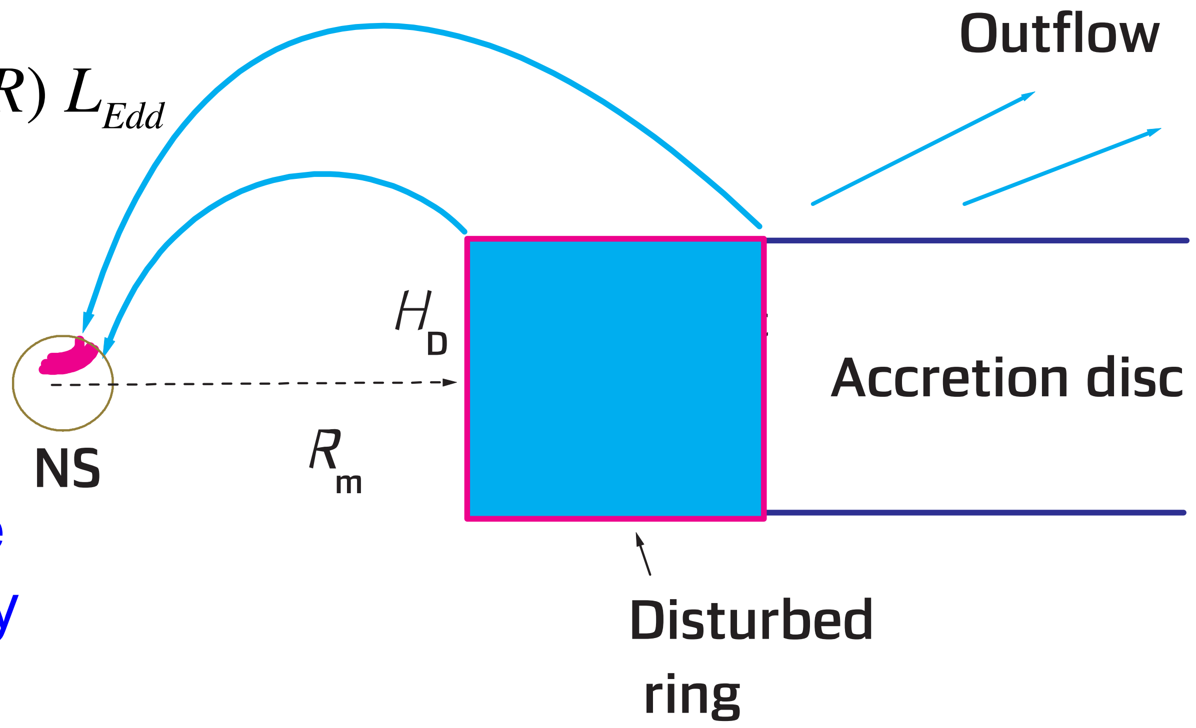
Accretion geometry importance

High luminosity. Radiation pressure dominated disc.

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

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

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



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

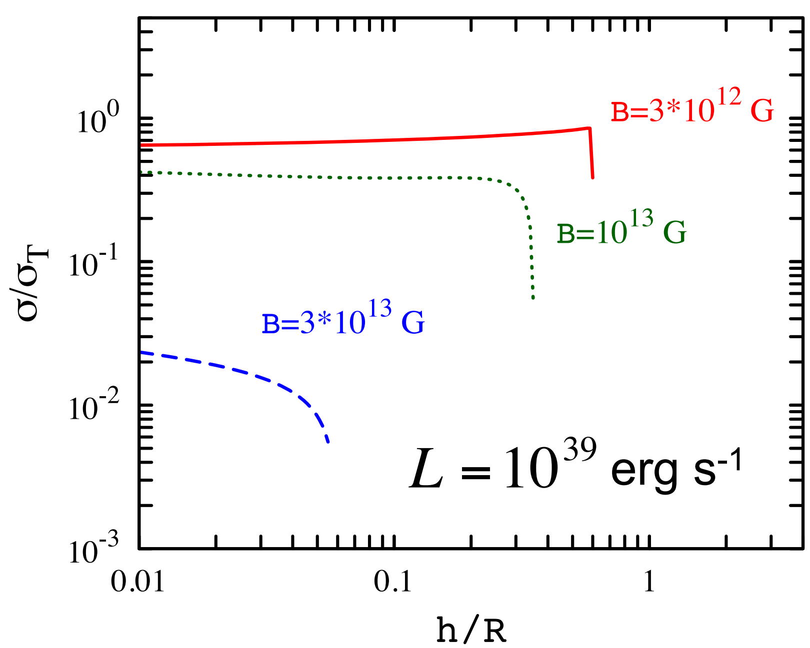
Velocity profile (by hand, weak point) $V \propto h^{\xi}, \quad V(H) = V_{ff}(H)/7$

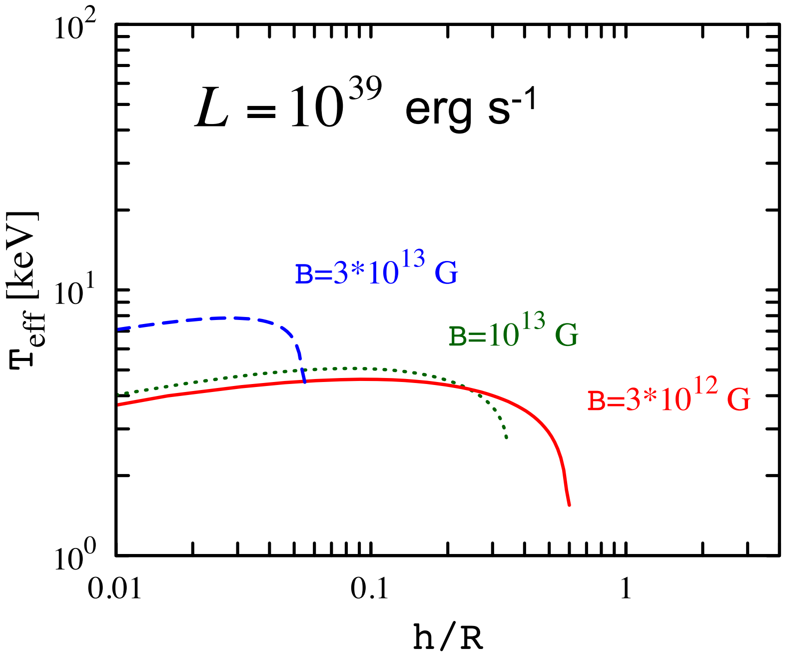
$\xi = [1 \div 5]$ Wang & Frank 1981 $\xi = 5$ Basko & Sunyaev 1976

results coincides inside factor of two

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

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

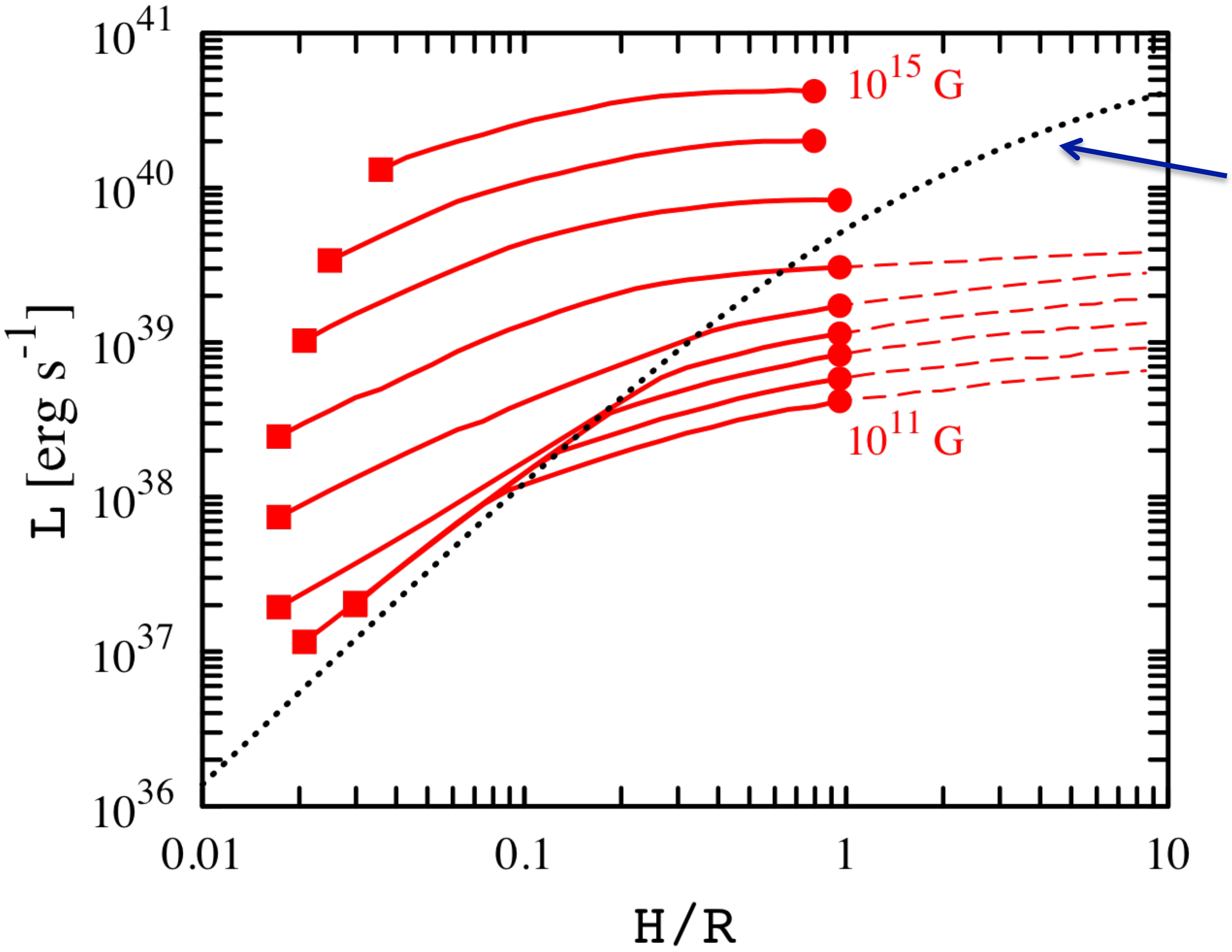




Higher NS magnetic field strength B → less opacity $\kappa_\perp$ and optical thickness $\tau_\perp$ → higher effective temperature T_{eff}

→ less column height at the same luminosity or higher luminosity at the same column height

Maximum possible luminosities vs. *B*

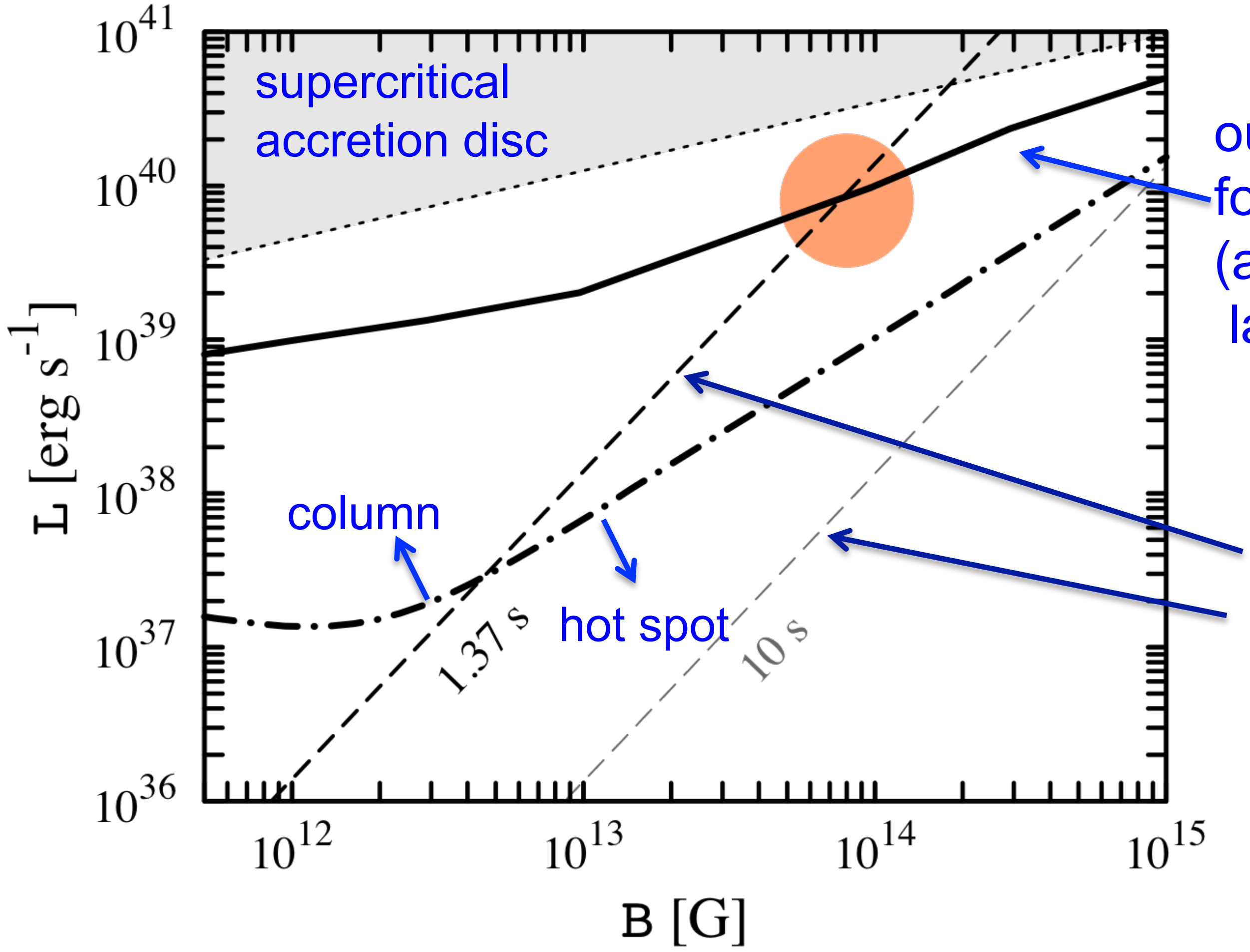


Toy model

$l/d = 50$

$\kappa_{\perp} = \kappa_T$

Application to M 82 X-2



supercritical
accretion disc

column

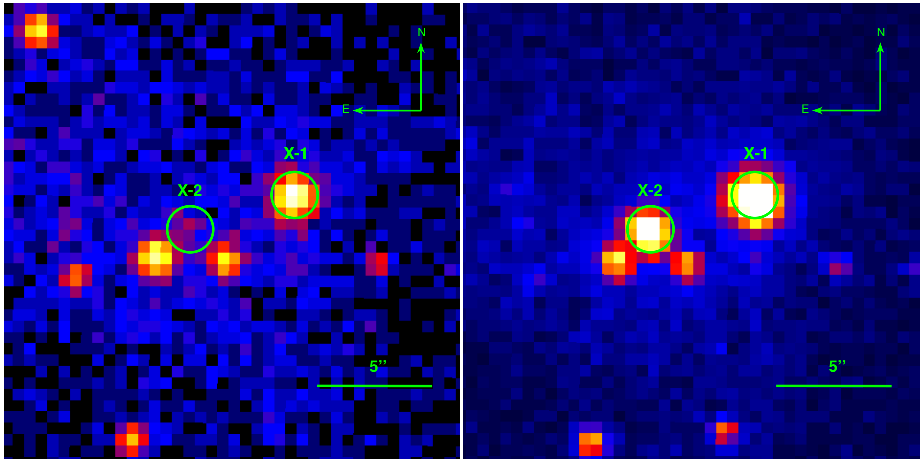
hot spot

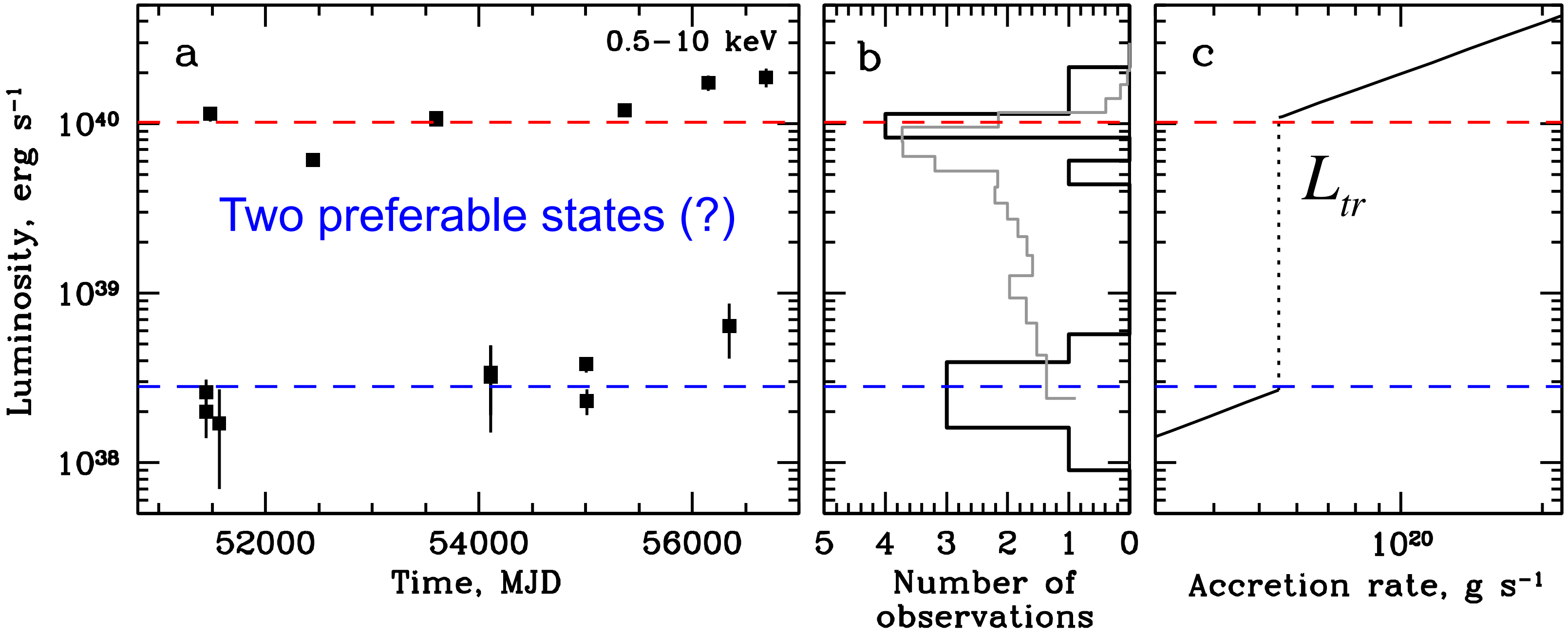
our theoretical curve
for maximum luminosity
(apparent can be much
larger due to beaming)

propeller
effect

Possible propeller effect in M 82 X-2

Tsygankov et al. 2016



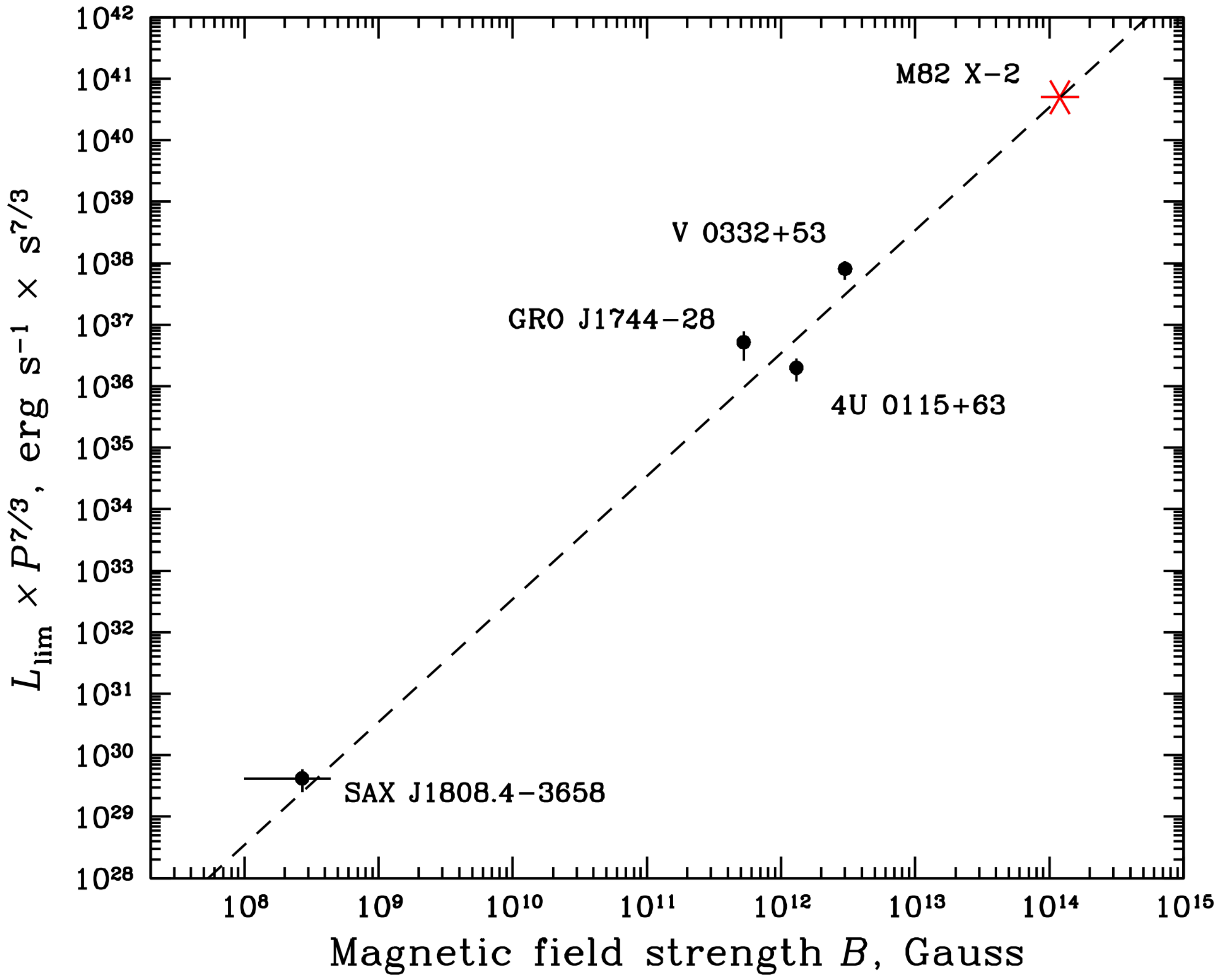


Two preferable states (?)

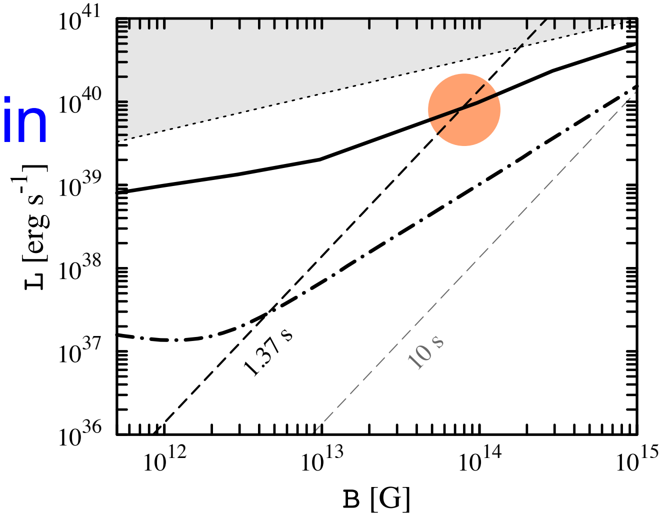
Transitions due to propeller effect at $R_m = R_{CO}$?

Possible propeller effect in M 82 X-2

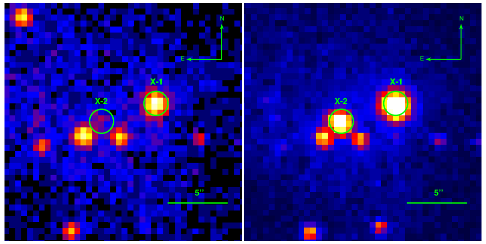
$$R_m = R_{CO} \quad \rightarrow \quad B \propto L_{tr} \, P_{sp}^{7/3}$$



Conclusions

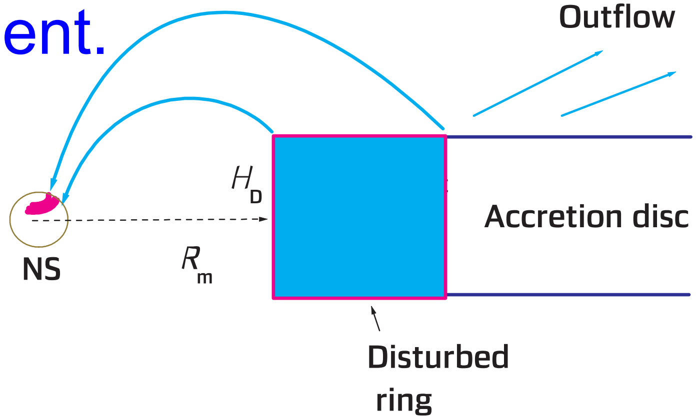


Our simplified model can qualitatively explain high luminous X-ray pulsars existence with luminosities up to 10^{40} erg s^{-1} typical for M82 X-2 assuming high magnetic field strength (10^{14} -10^{15} G).



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.

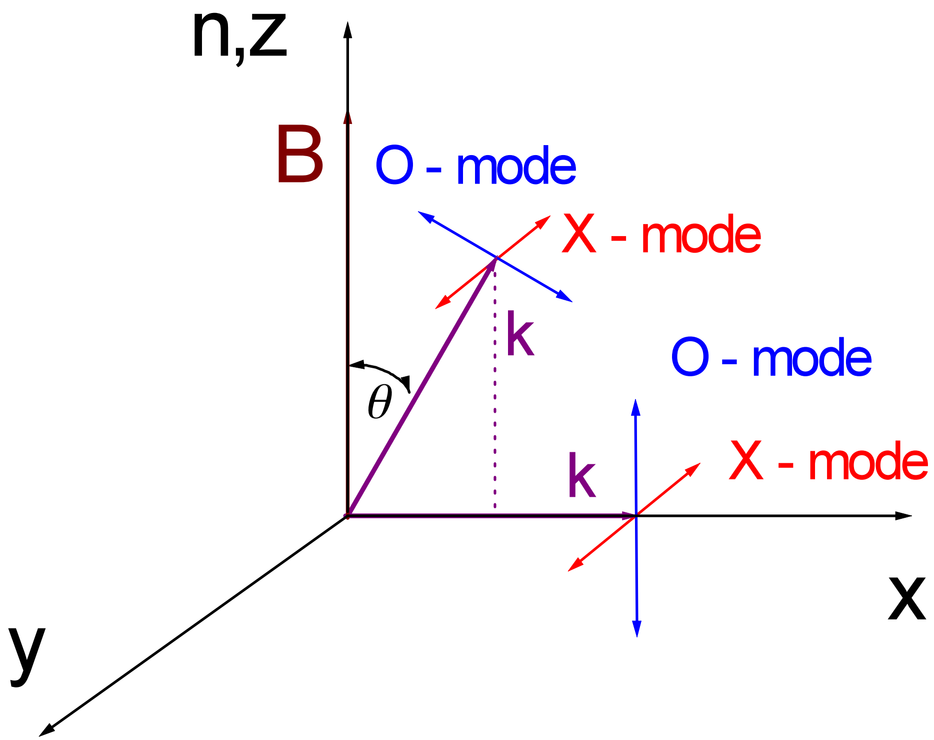


Outlook

Introduction.
    Super-Eddington X-ray pulsars.
Magnetic field importance.
    Super-Eddington fluxes.
Accretion columns. Basic ideas.
Maximum possible luminosities.
Conclusions.

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

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