

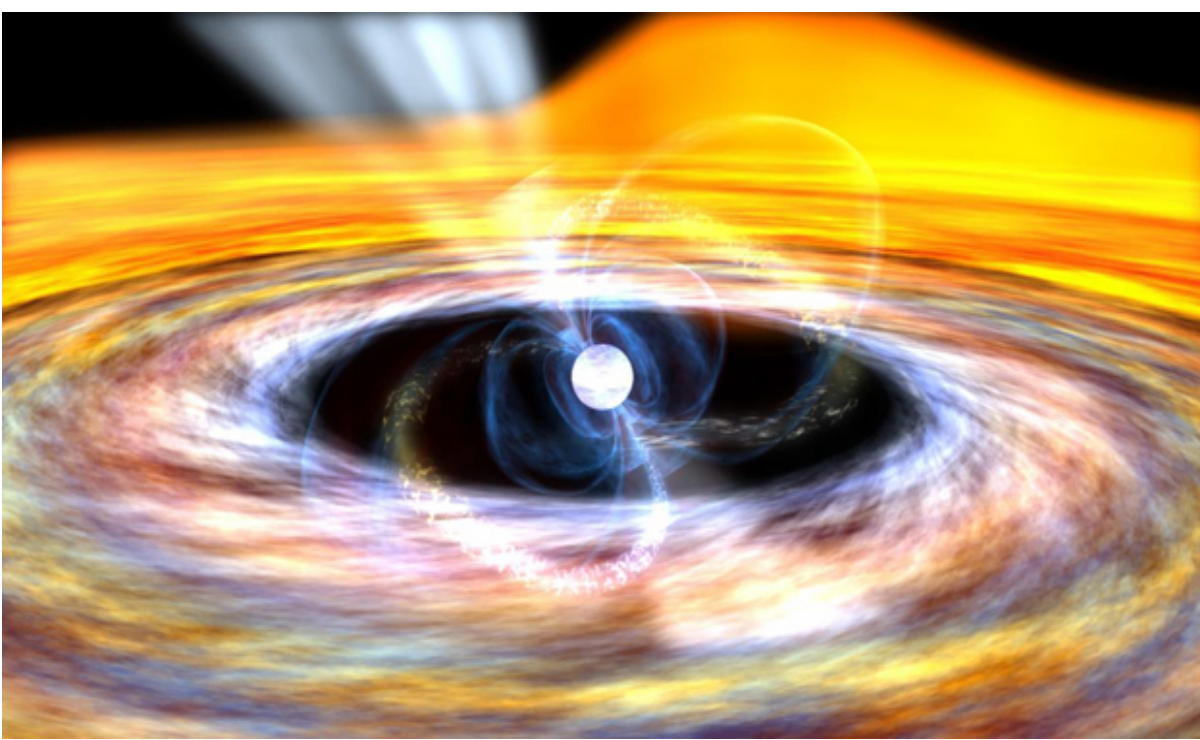
On the maximum accretion luminosity of magnetized neutron stars: connecting XRP's and ULXs

Alexander Mushtukov

*Istanbul
26 April 2016*



Accreting magnetized neutron stars: X-ray pulsars



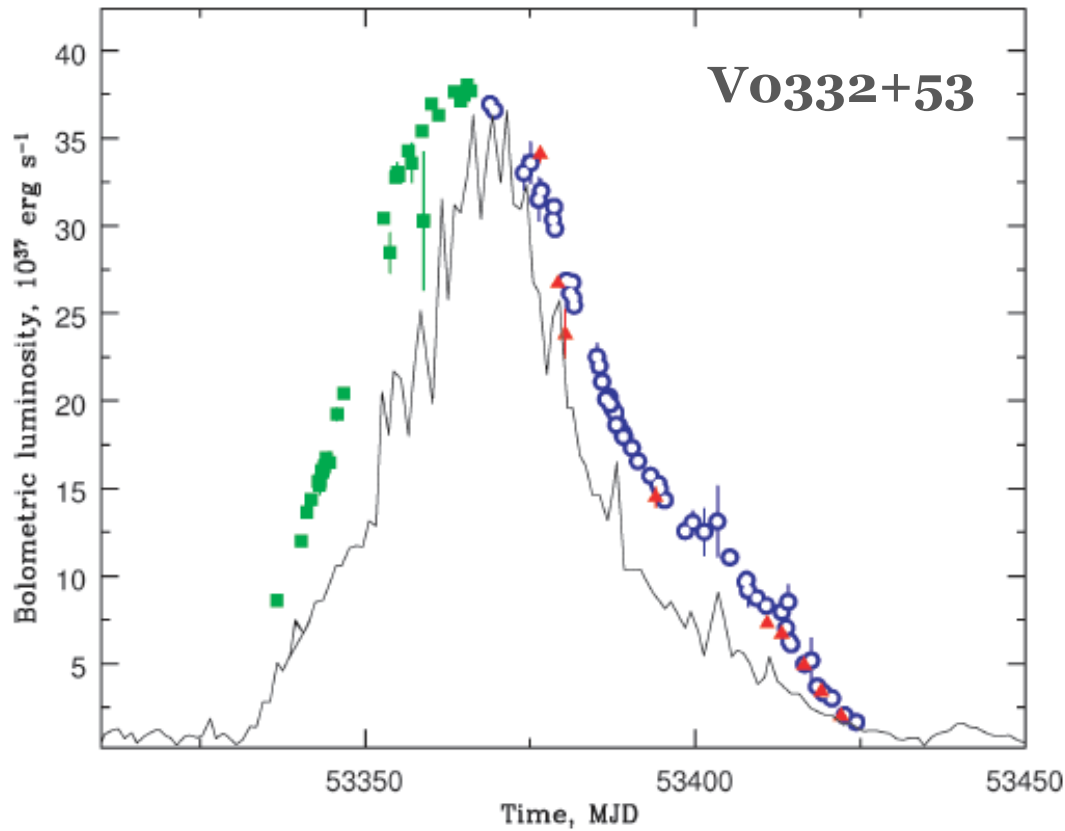
$$B \gtrsim 10^{12} \text{ G}$$

$$L_X \approx \frac{GM\dot{M}}{R}$$
$$\approx 1.5 \times 10^{20} \dot{M} \text{ erg s}^{-1}$$

Eddington luminosity:

$$L_{\text{Edd}} = \frac{4\pi GMm_p c}{\sigma_T} \approx 1.3 \times 10^{38} \frac{M}{M_\odot} \text{ erg s}^{-1}$$

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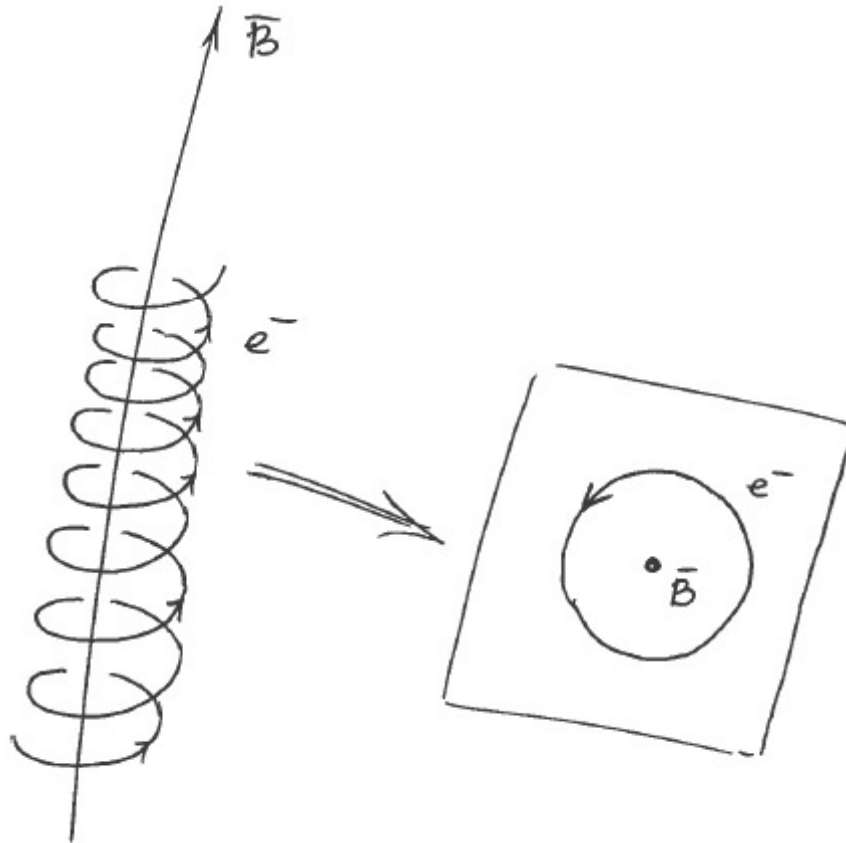
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Strong magnetic fields

$$B_{\text{cr}} = m_e^2 c^3 / e \hbar = 4.412 \times 10^{13} \text{ G}$$

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Strong magnetic fields

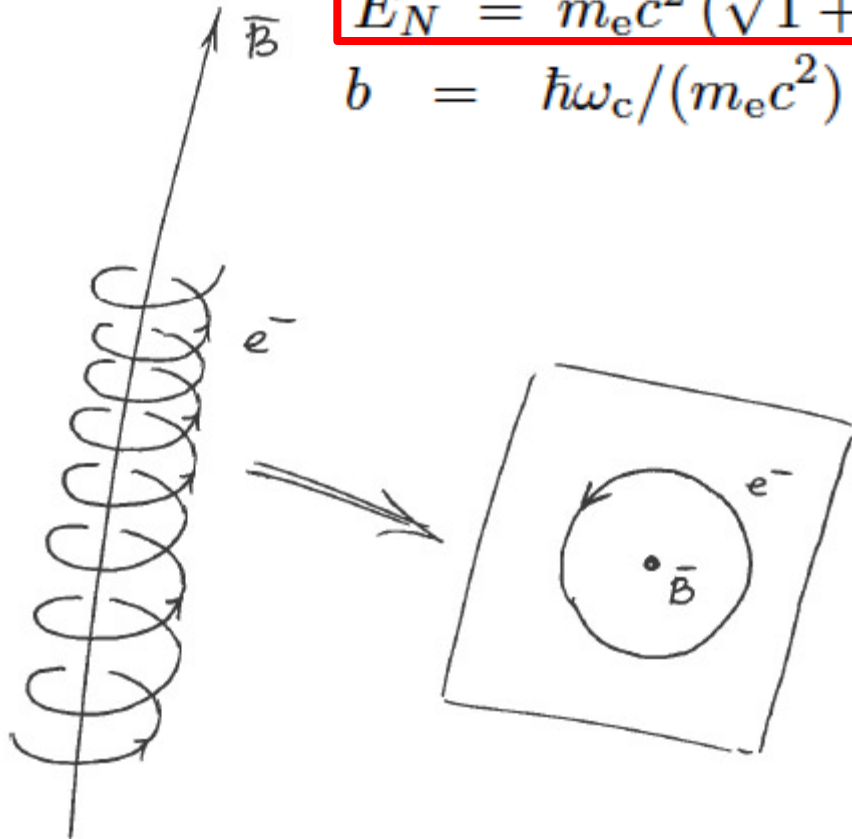
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Elementary processes can have another behavior in comparison with a case when B-field is weak or absent. Even particles should be described in the another way:

•Electrons occupy Landau levels:

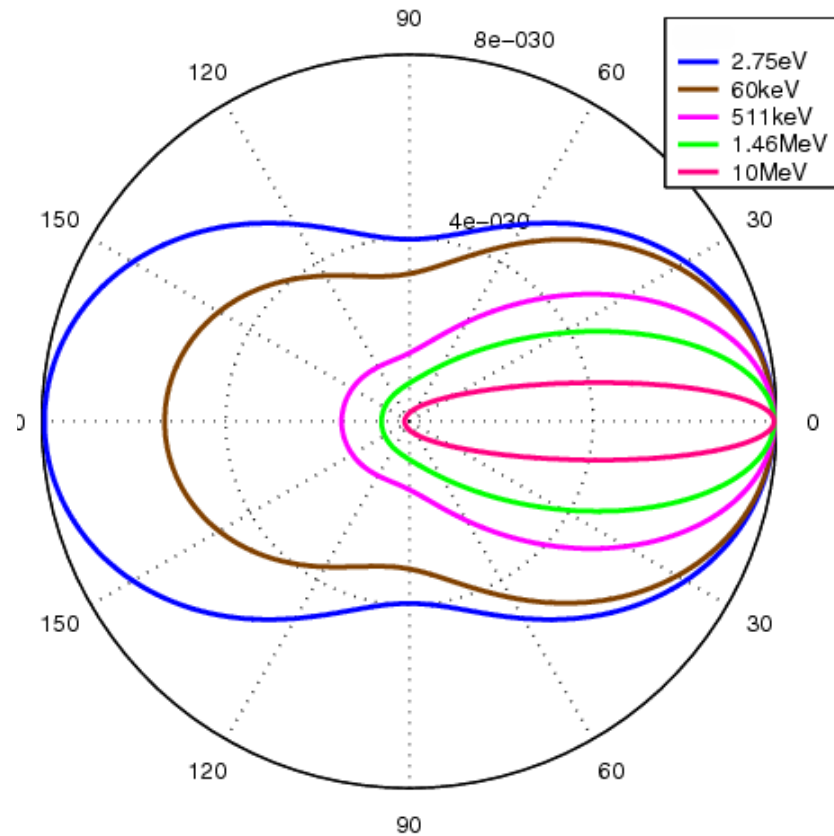
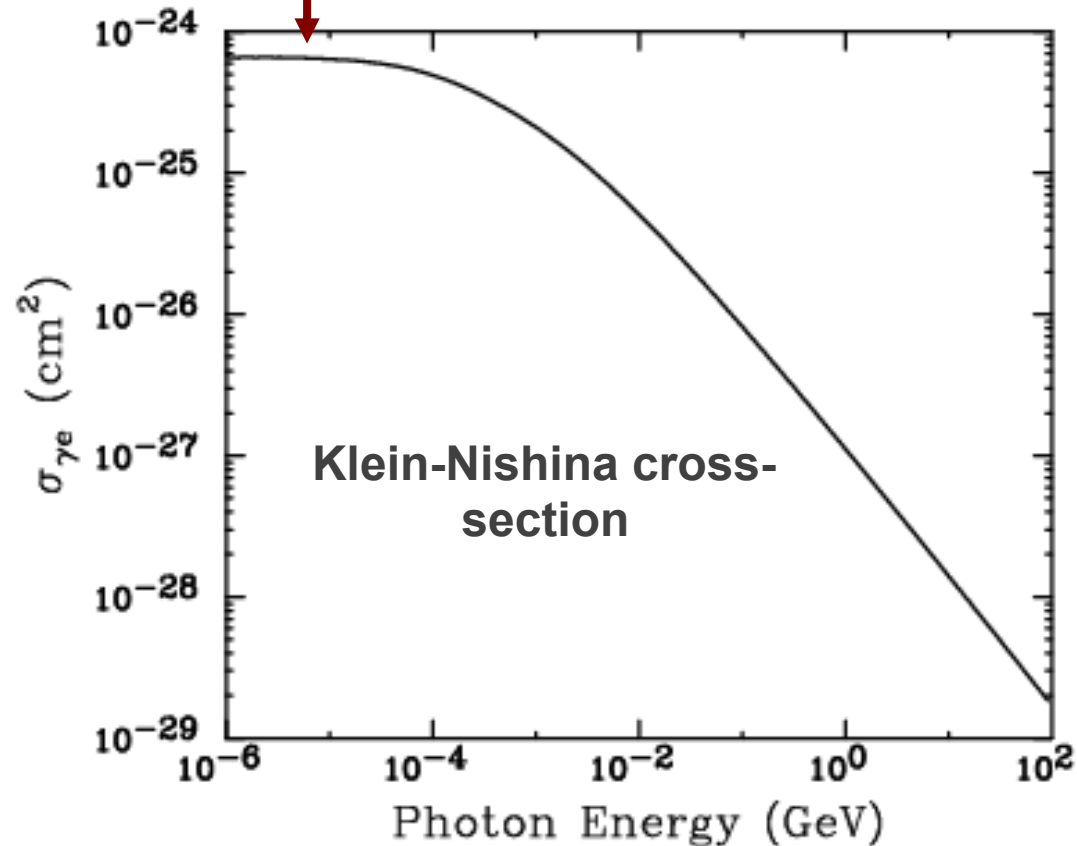
$$E_N = m_e c^2 (\sqrt{1 + 2bN} - 1) \quad (N = 0, 1, 2, \dots)$$

$$b = \hbar \omega_c / (m_e c^2) = B / B_{\text{QED}} = B_{12} / 44,14$$

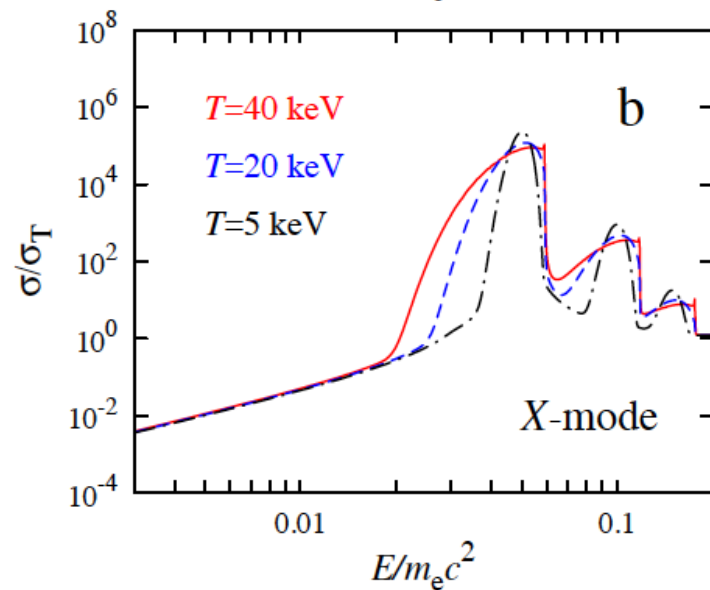
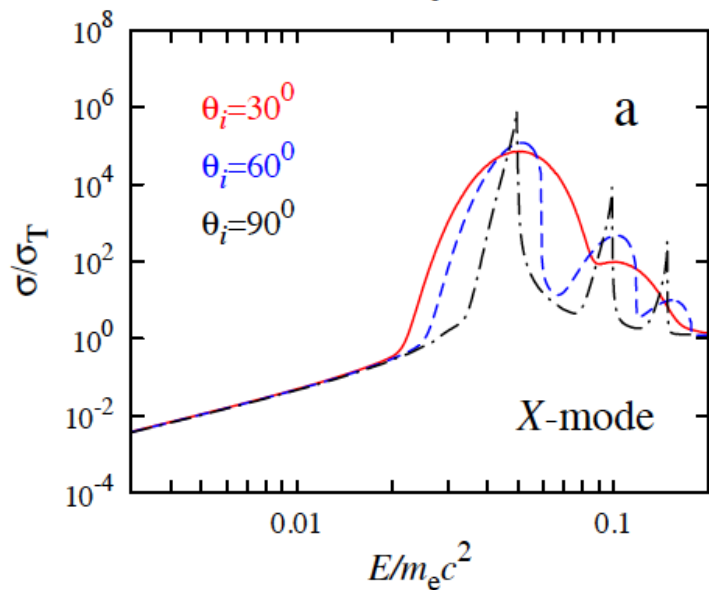
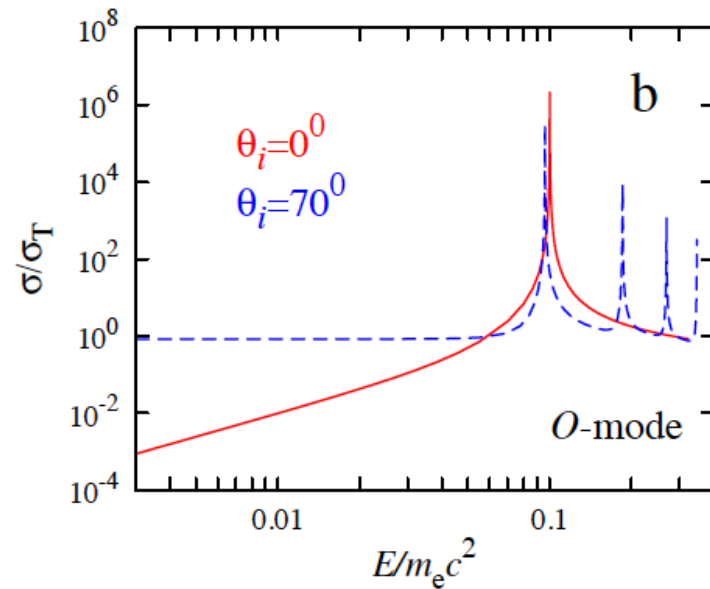
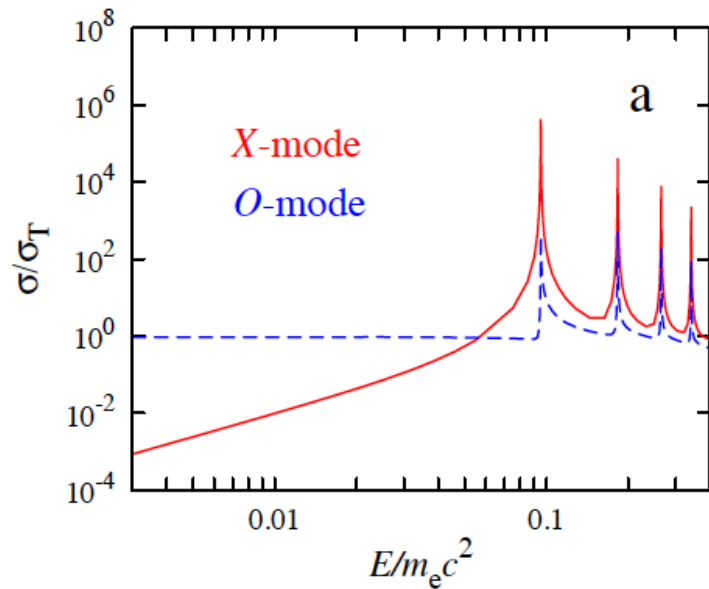


Compton scattering: non-magnetic case

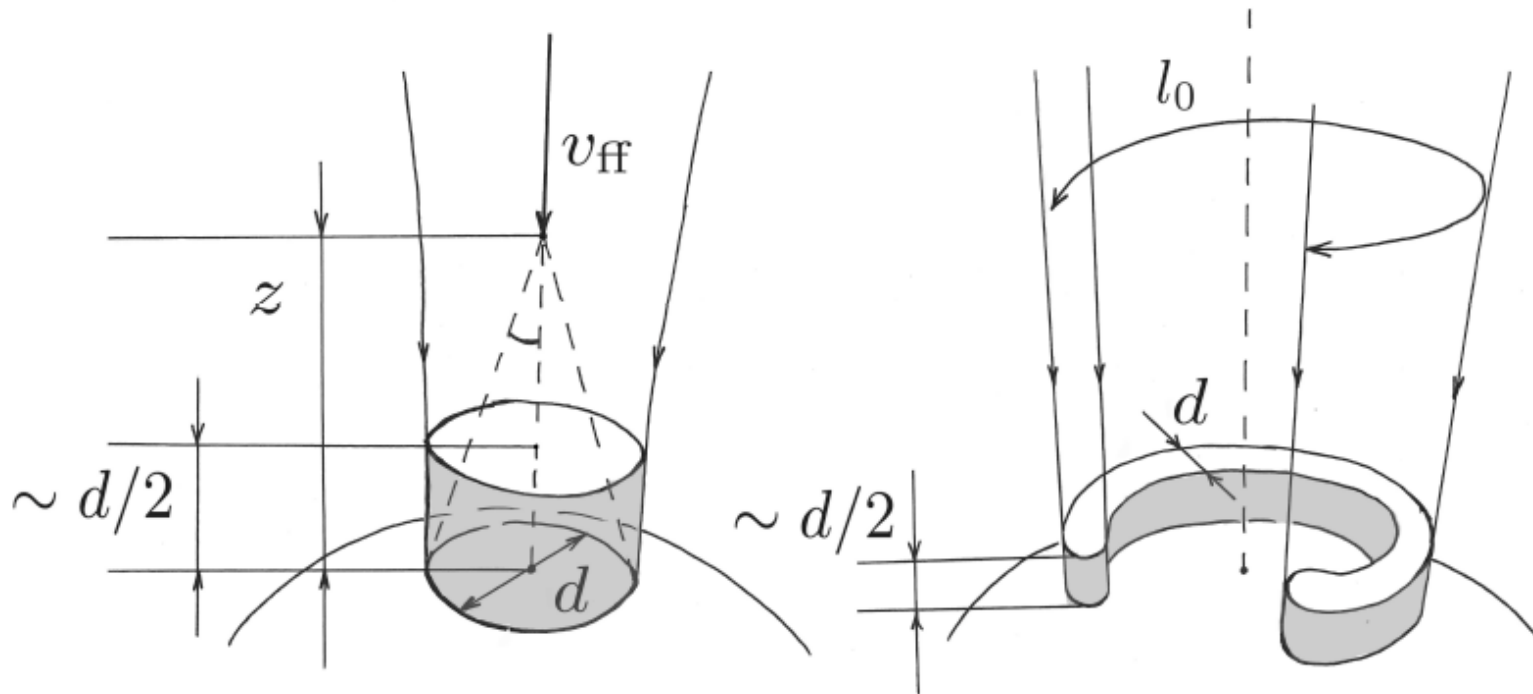
$$\sigma_T = \frac{8\pi}{3} \left(\frac{e^2}{m_e c^2} \right)^2 \approx 6.65 \times 10^{-25} \text{ cm}^2$$



Compton scattering in a strong magnetic field



Critical luminosity

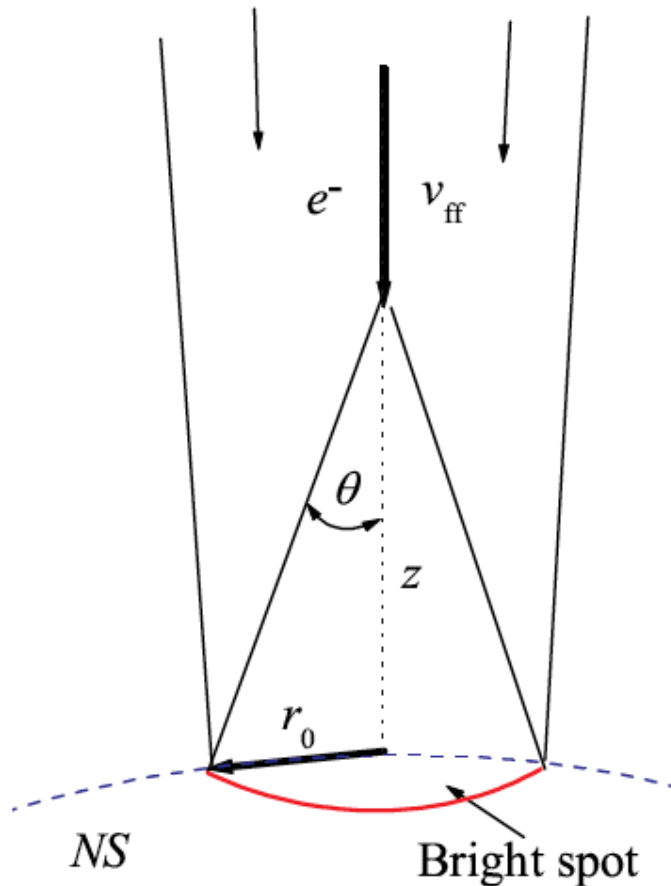


$$L^* = 4 \times 10^{36} \left(\frac{\sigma_T}{\sigma_{eff}} \right) \left(\frac{l_0}{2 \times 10^5 [cm]} \right) \frac{1}{R_6} \frac{M}{M_\odot} \quad [\text{erg s}^{-1}]$$

$$L_{\text{Edd}} = \frac{4\pi GMm_p c}{\sigma_T} \approx 1.3 \times 10^{38} \frac{M}{M_\odot} \text{ erg s}^{-1}$$

Critical luminosity: radiation pressure

$$F_R = \frac{1}{c} \sum_{j=1}^2 \int_0^{\infty} dE \int_{(4\pi)} d\Omega \cdot \mu \sigma_j(E, \mu | T_e) I_j(E, \mu) = \frac{2\pi}{c} \sigma_{eff} H$$

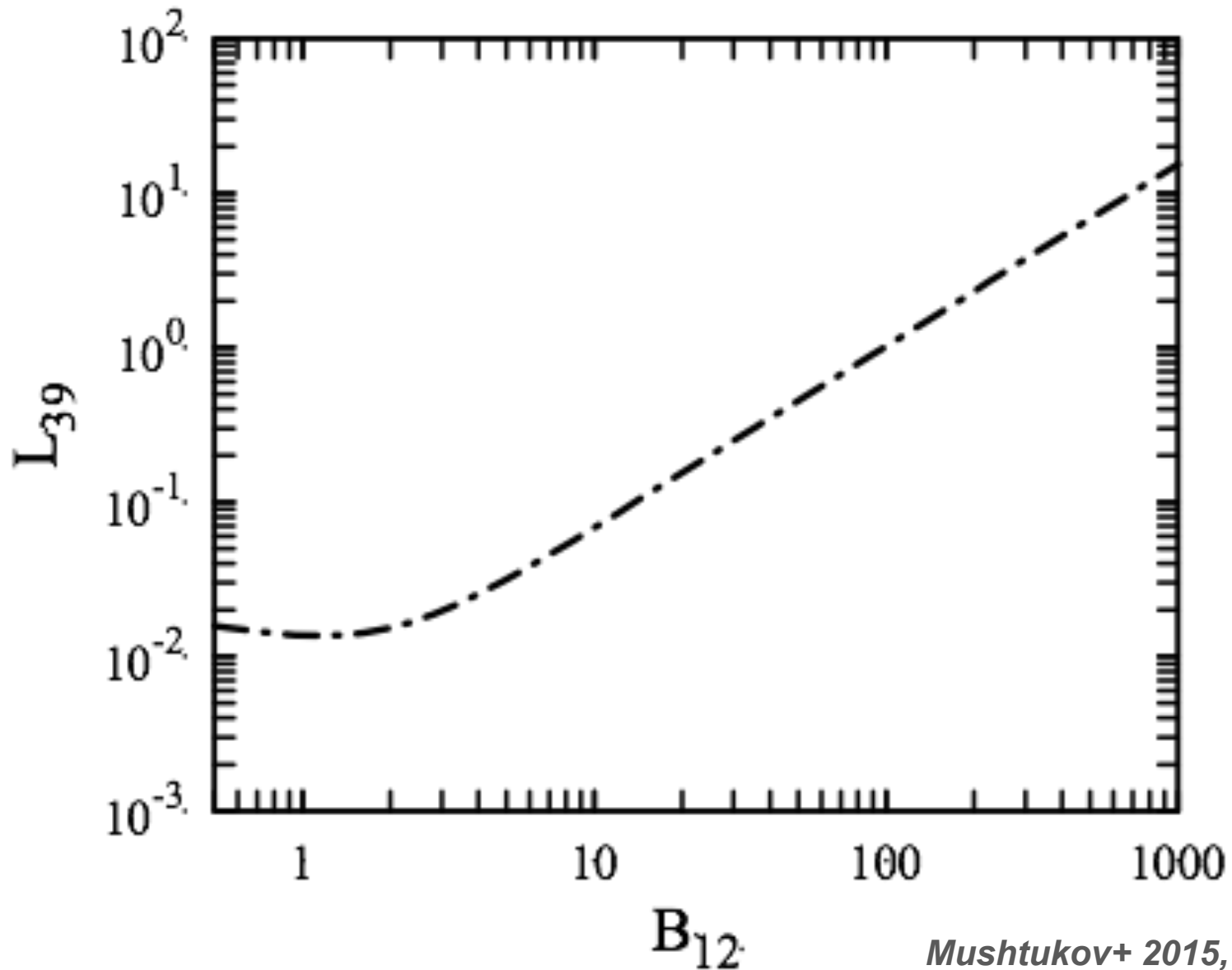


Optically thick case:

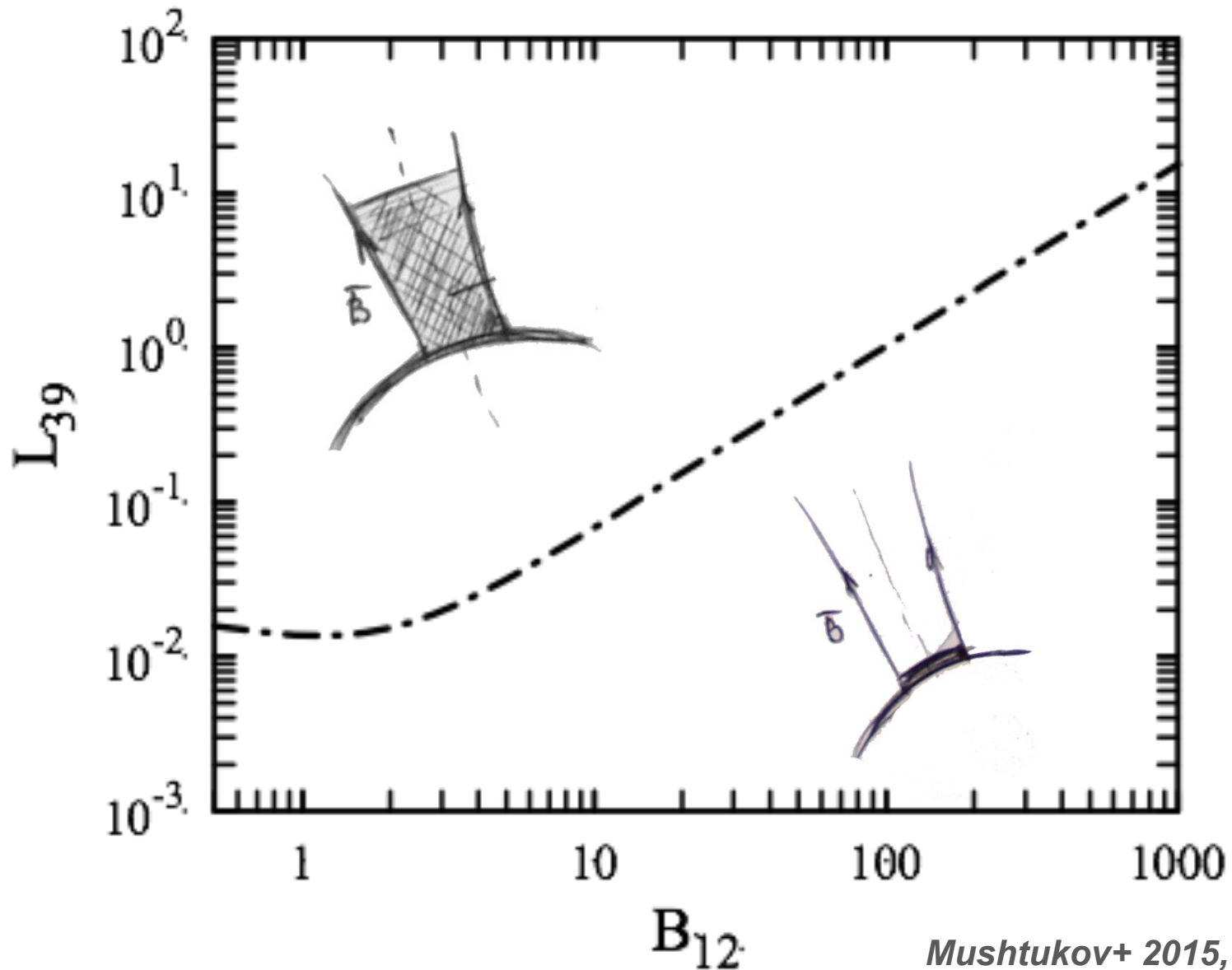
$$\frac{1}{\bar{\sigma}_j} = \frac{3 \int_0^{\infty} dE \int_0^1 d\mu \cdot \mu^2 \frac{dB_E(T)/dT}{\sigma_j(E, \mu, T_e)}}{\int_0^{\infty} dE \cdot dB_E(T)/dT}$$

$$\tau_T \gtrsim 3 \Lambda^{1/2} L_{37}^{6/7} B_{12}^{2/7}$$

Critical luminosity



Critical luminosity



Accretion column model

Dipole magnetic field.

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Accretion flow stops at radiation dominated shock and slowly settles in inside a sinking region

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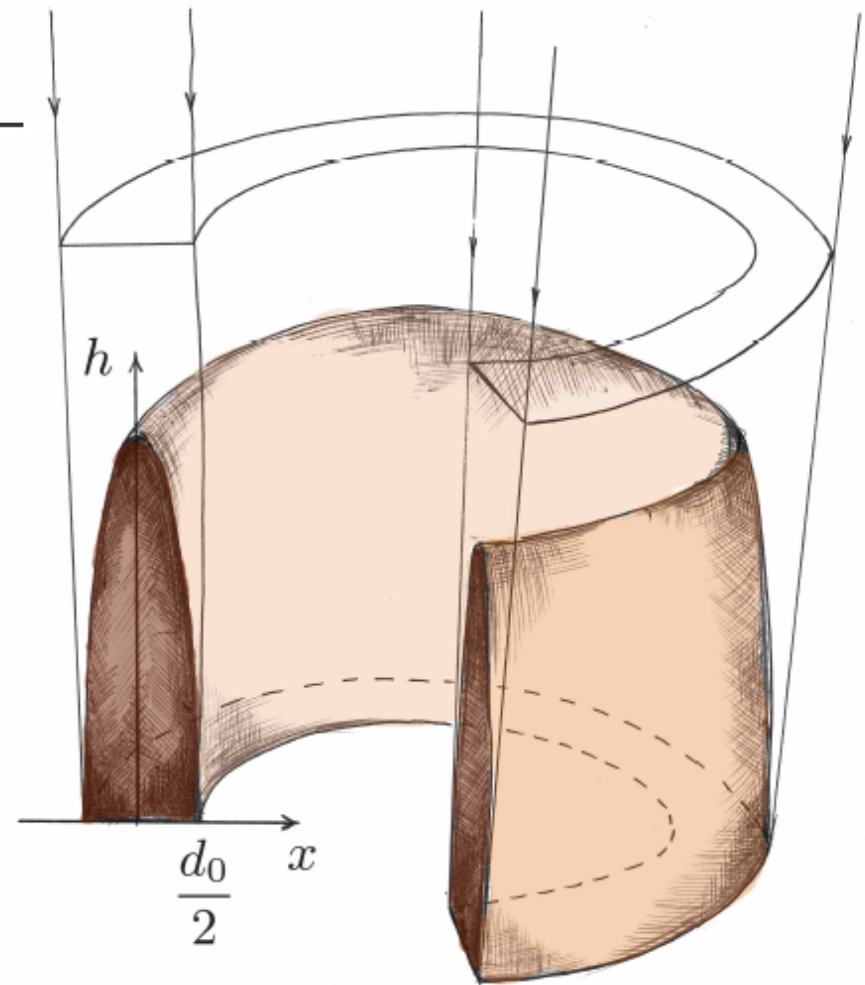
The gravitational force will be offset by the radiation pressure gradient only

*

The gas pressure is unimportant

*

Neutrino emission is negligible



Accretion column model

$$\frac{dP_{\text{rad}}(x=0, h)}{dh} = -\rho \frac{GM}{(R+h)^2}$$

Along the accretion channel:

$$P_{\text{rad}}(x, h) \approx \int_h^{H_x} \rho \frac{GM}{(R+y)^2} dy + \frac{2}{3} \frac{F_{\text{Edd}}(H_x)}{c}$$

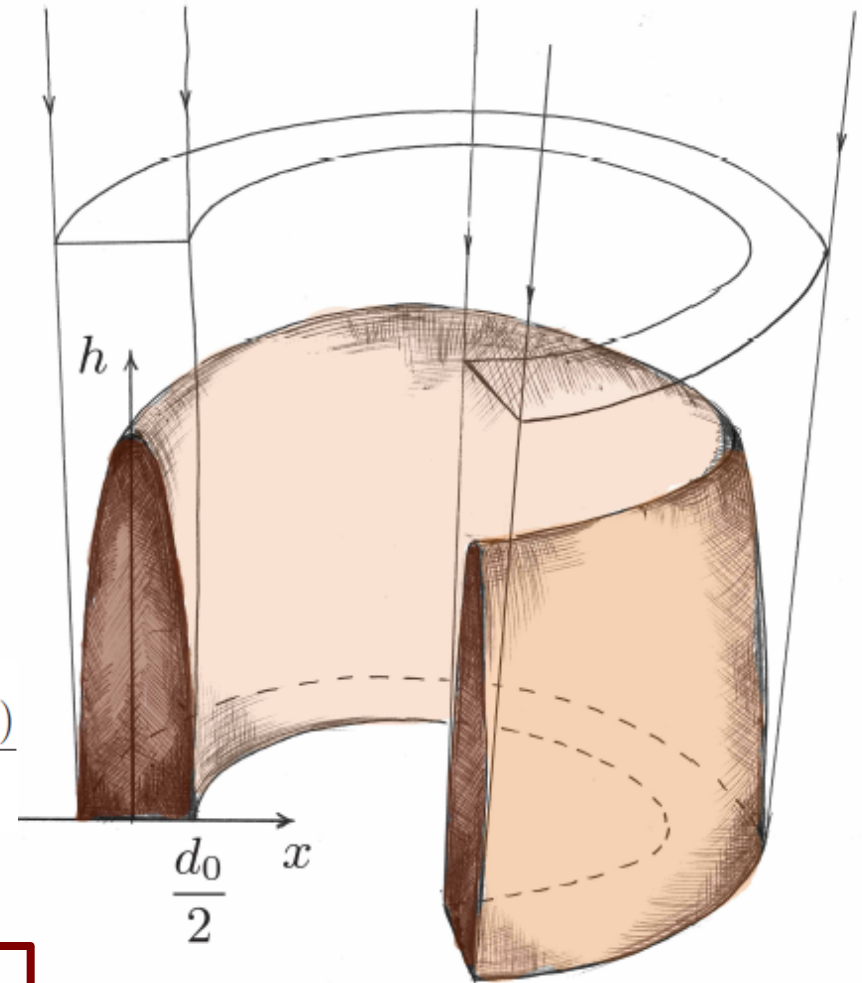
Across the accretion channel:

$$P_{\text{rad}}(x, h) \approx \frac{2\rho}{dh} \frac{F_{\perp, \text{esc}}(h)}{c} \int_x^{d_h/2} \kappa_{\perp} z dz + \frac{2}{3} \frac{F_{\perp, \text{esc}}(h)}{c}$$

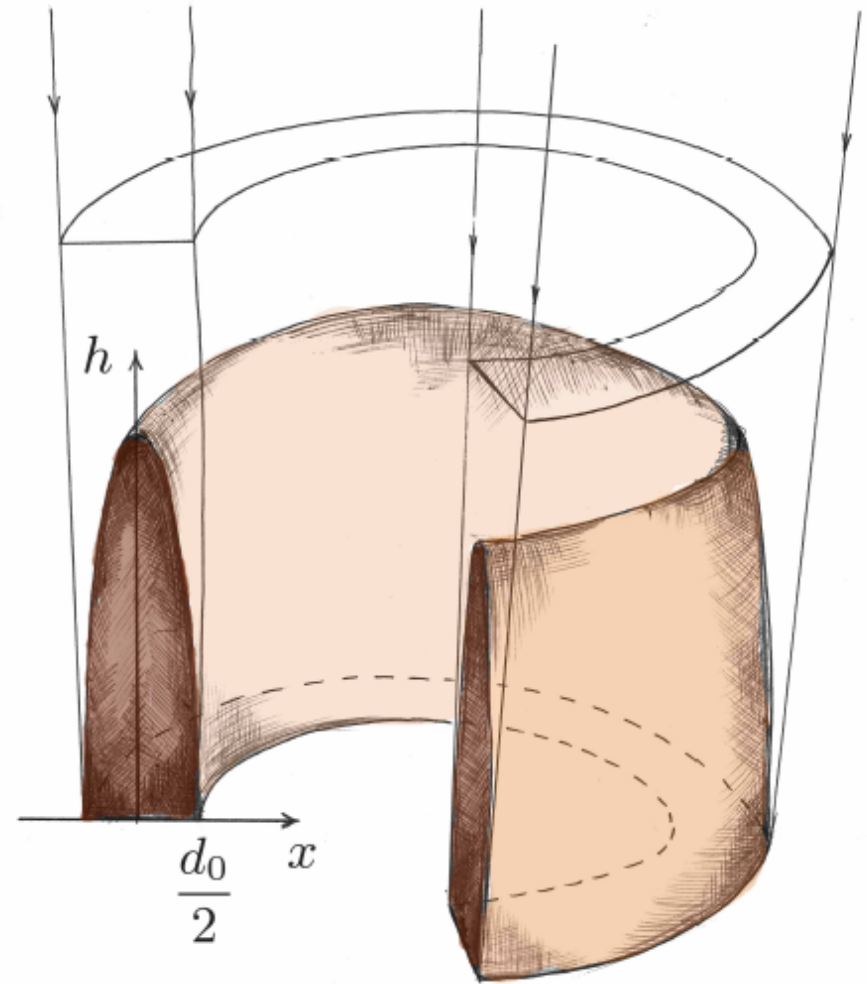
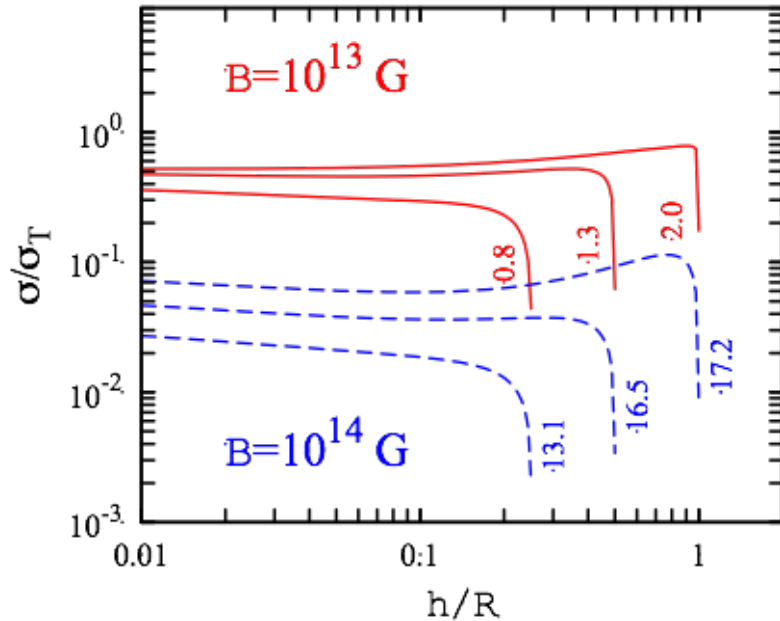
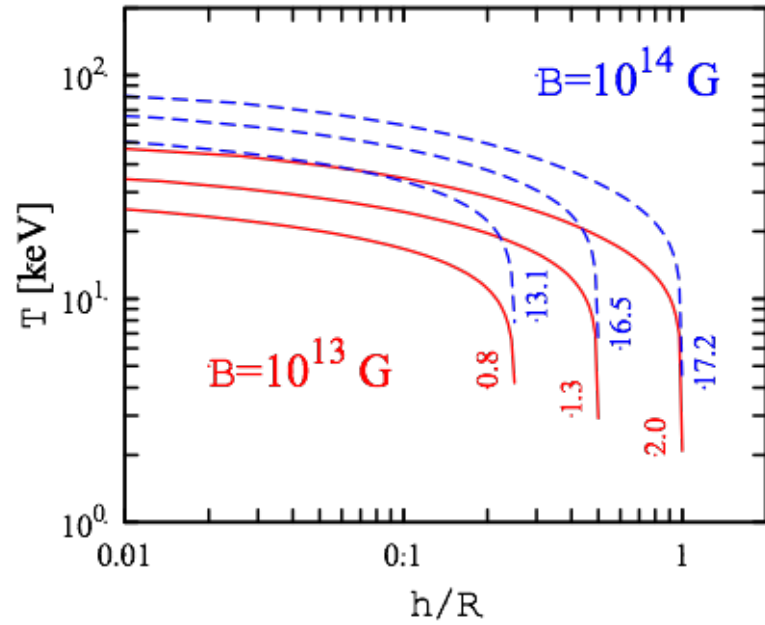
Across the accretion channel:

$$L \approx 38 \left(\frac{l_0/d_0}{50} \right) \left(\frac{\kappa_{\text{T}}}{\kappa_{\perp}} \right) f \left(\frac{H}{R} \right) L_{\text{Edd}}$$

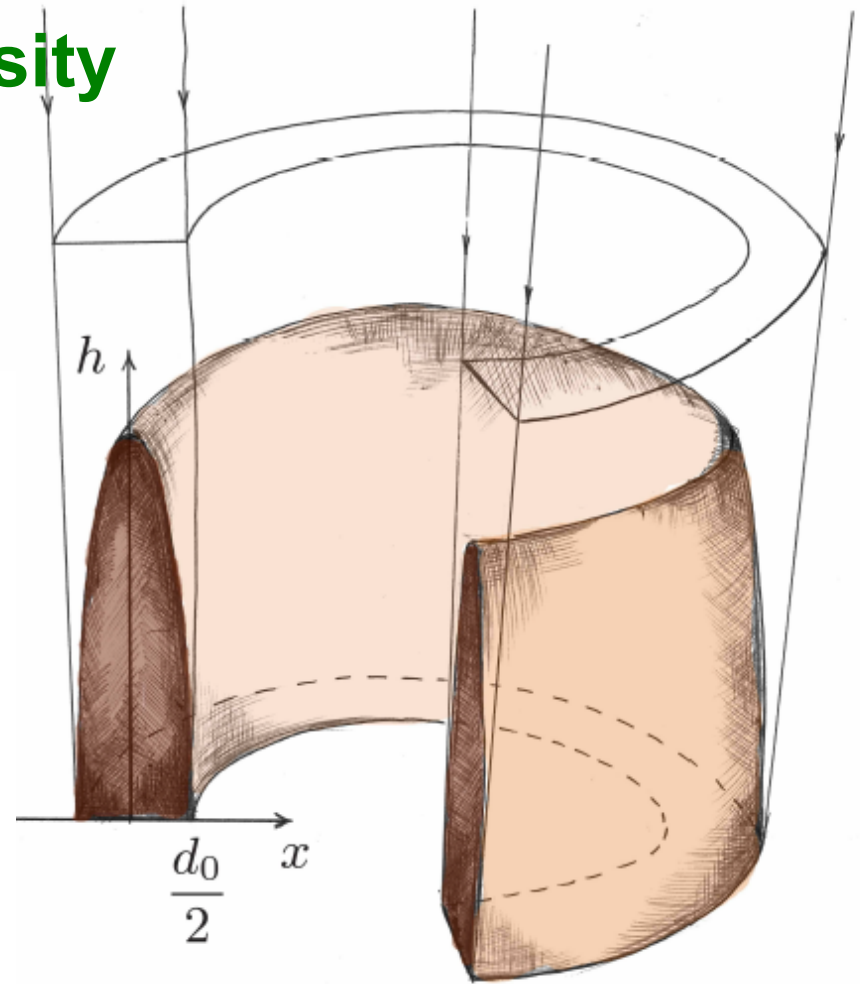
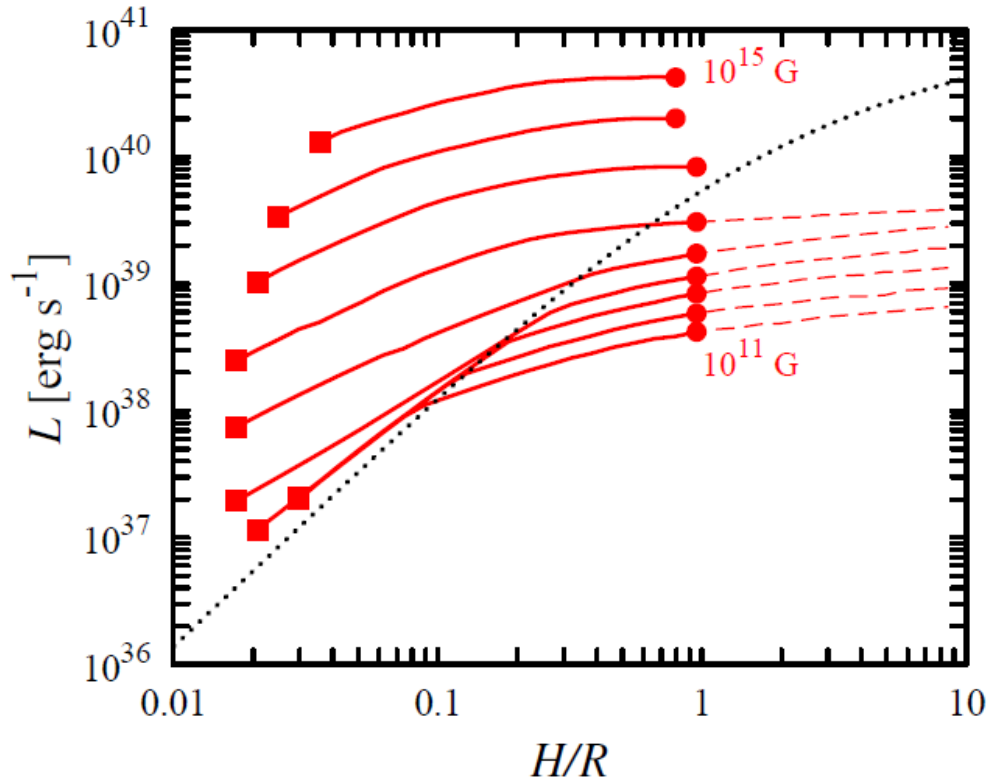
where $f \left(\frac{H}{R} \right) = \log \left(1 + \frac{H}{R} \right) - \frac{H}{R+H}$



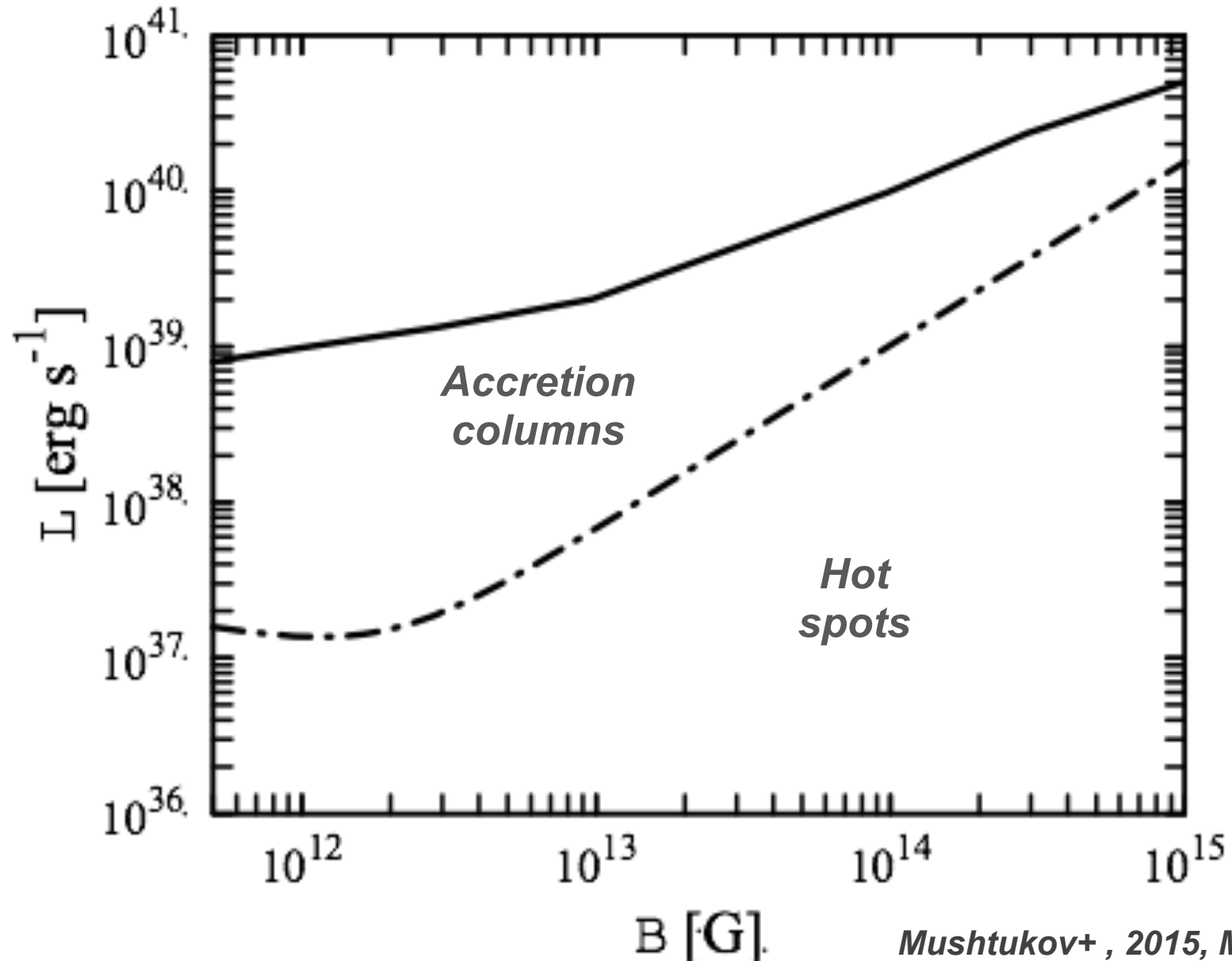
Accretion column model



Maximum accretion luminosity

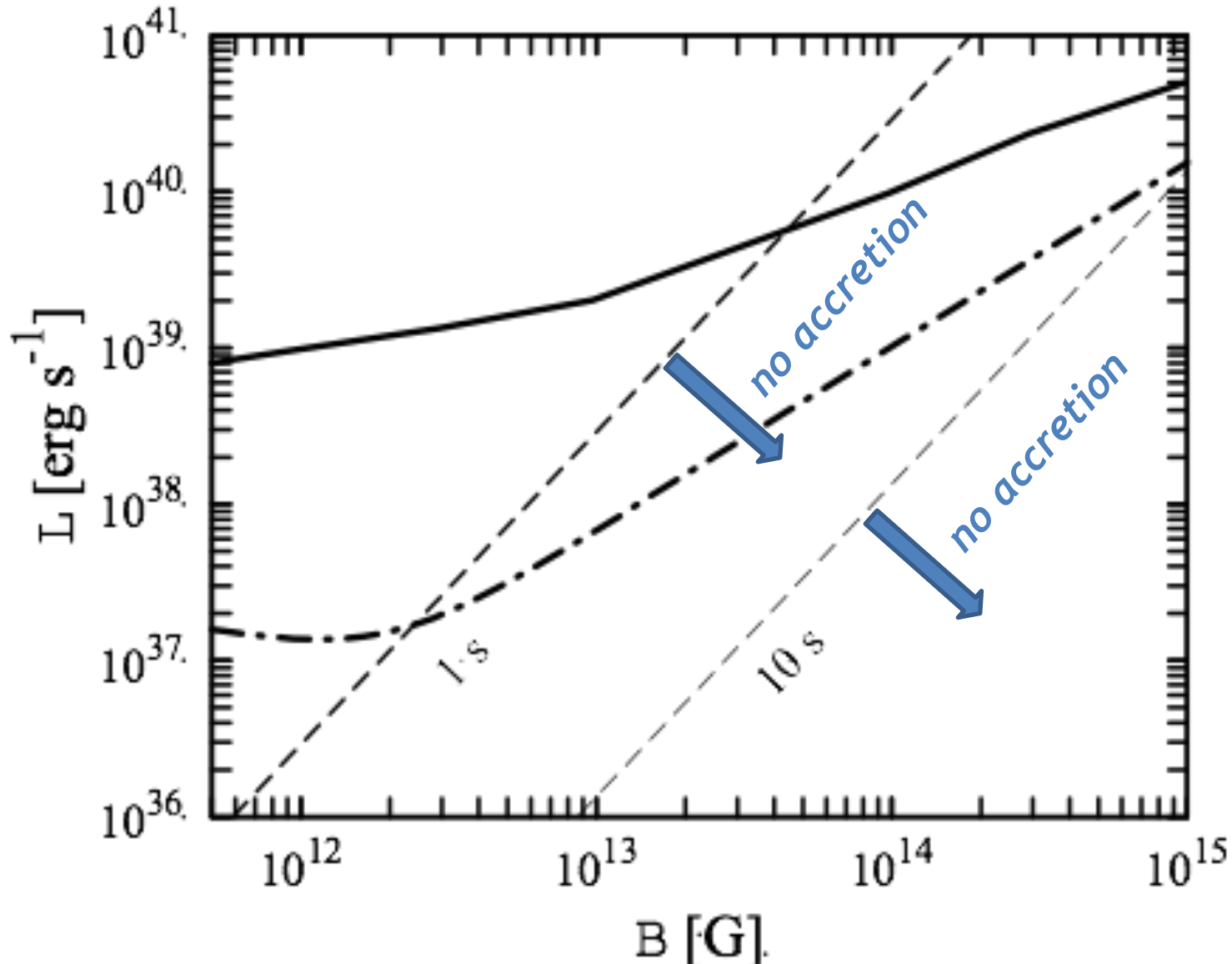


Maximum accretion luminosity



”Propeller effect”: limitation from below

$$L_{39}^{\min} \simeq 7 \times 10^{-2} \Lambda^{7/2} m^{-2/3} R_6^5 B_{12}^2 P^{-7/3}$$



"Propeller effect" and super-critical accretion

Propeller-effect:

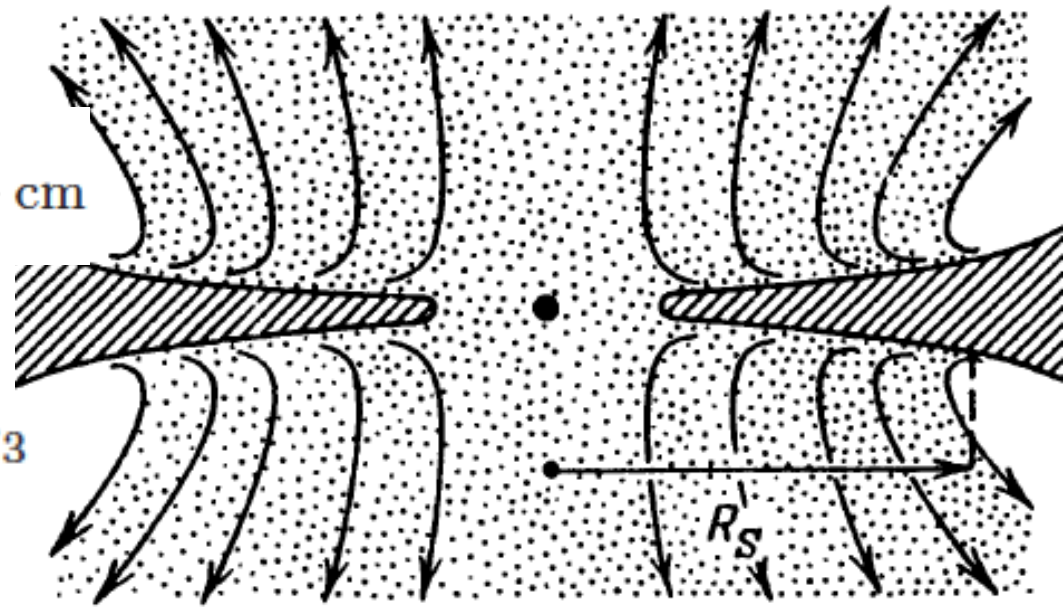
$$L_{39}^{\min} \simeq 7 \times 10^{-2} \Lambda^{7/2} m^{-2/3} R_6^5 B_{12}^2 P^{-7/3}$$

Supercritical accretion:

$$R_{\text{sp}} = \frac{3}{8\pi} \frac{\kappa_{\text{T}}}{c} \dot{M} = 7.5 \times 10^6 \frac{L_{39} R_6}{m} \text{ cm}$$

$$R_{\text{sp}} < R_{\text{m}}$$

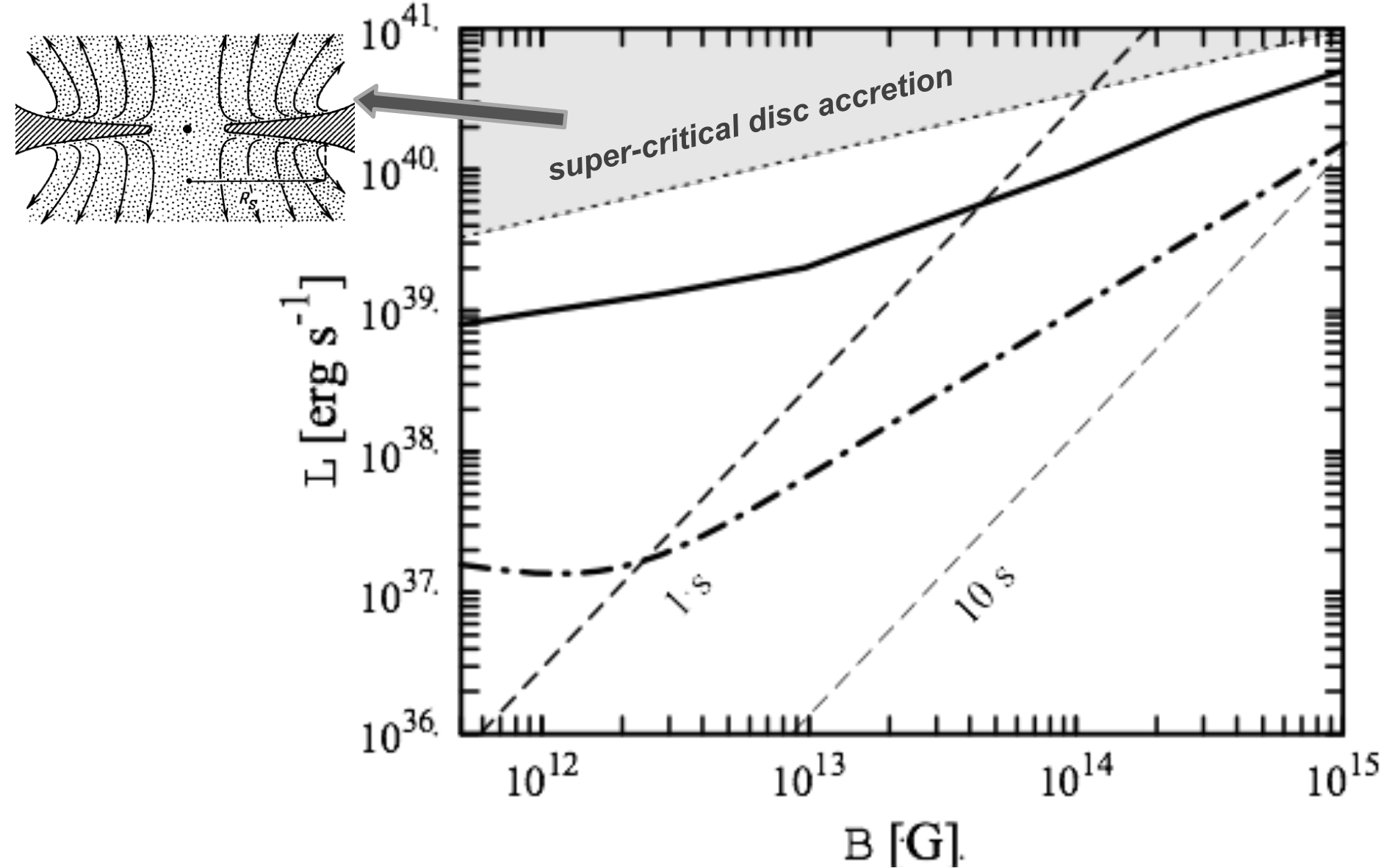
$$L_{39}^{\max} \simeq 5.7 \Lambda^{7/9} B_{12}^{4/9} m^{8/9} R_6^{1/3}$$



$$L^{\min} \propto B^2$$

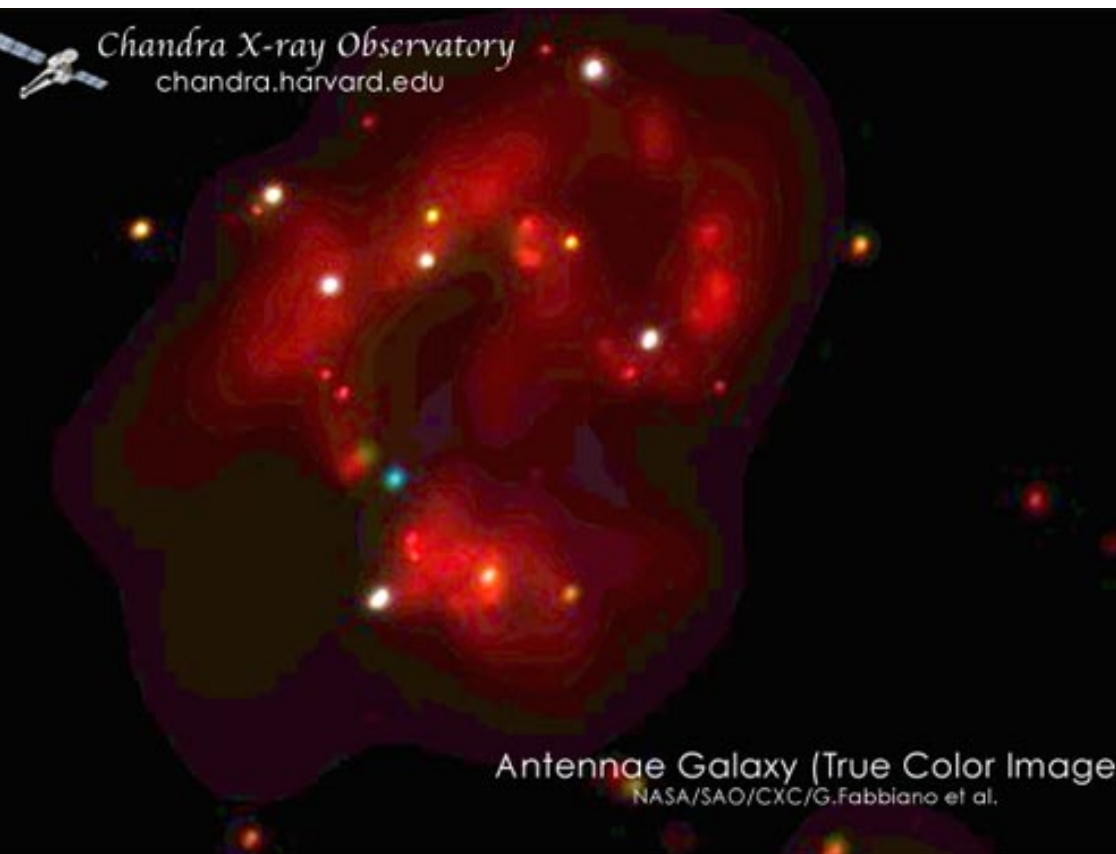
$$L^{\max} \propto B^{4/9}$$

"Propeller effect" and super-critical accretion



ULXs in general

- Off-center bright X-ray sources in nearby galaxies
- Discovered with Einstein X-ray observatory 30 years ago
- X-ray luminosity: $L_x = 10^{39} - 10^{41} \text{ erg s}^{-1}$



$$L_{\text{Edd}} = \frac{4\pi GMm_p c}{\sigma_T}$$
$$\approx 1.3 \times 10^{38} \frac{M}{M_{\odot}} \text{ erg s}^{-1}$$

The theoretical models focused on black holes.

Pulsations from ULX in M82



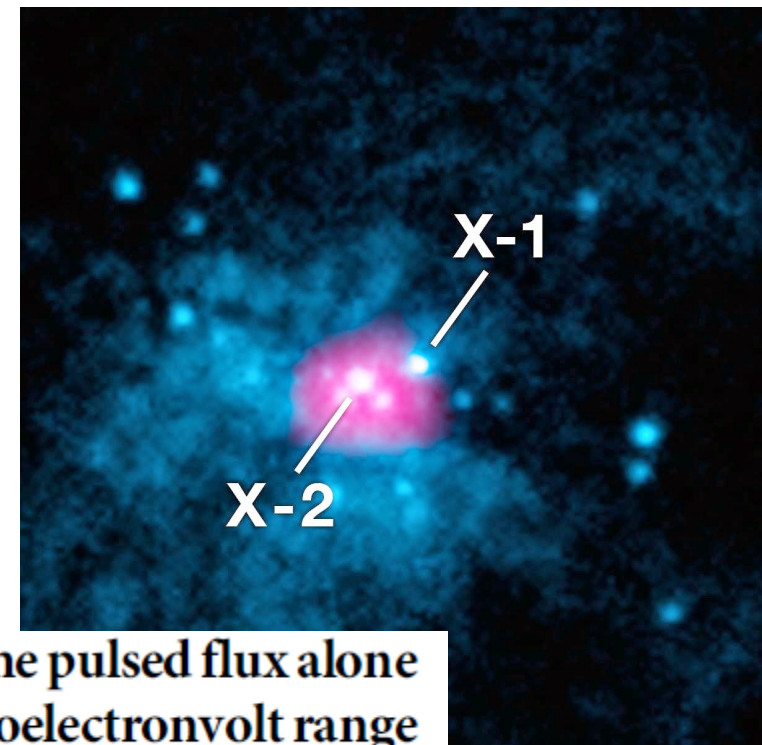
LETTER

doi:10.1038/nature13791

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

M. Bachetti^{1,2}, F. A. Harrison³, D. J. Walton³, B. W. Grefenstette³, D. Chakrabarty⁴, F. Fürst³, D. Barret^{1,2}, A. Beloborodov⁵, S. E. Boggs⁶, F. E. Christensen⁷, W. W. Craig⁸, A. C. Fabian⁹, C. J. Hailey¹⁰, A. Hornschemeier¹¹, V. Kaspi¹², S. R. Kulkarni³, T. Maccarone¹³, J. M. Miller¹⁴, V. Rana³, D. Stern¹⁵, S. P. Tendulkar³, J. Tomsick⁶, N. A. Webb^{1,2} & W. W. Zhang¹¹

$P \sim 1.37$ sec



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 4.9×10^{39} ergs per second. The pulsating source is spatially coincident with a variable source⁴ that can reach an X-ray luminosity in the 0.3–10 kiloelectronvolt range of 1.8×10^{40} ergs per second¹. This

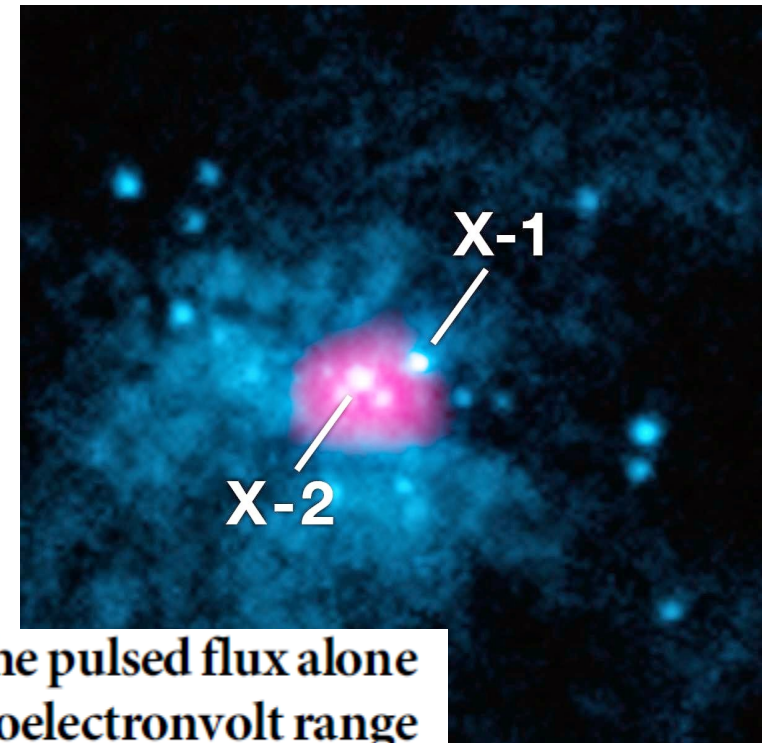
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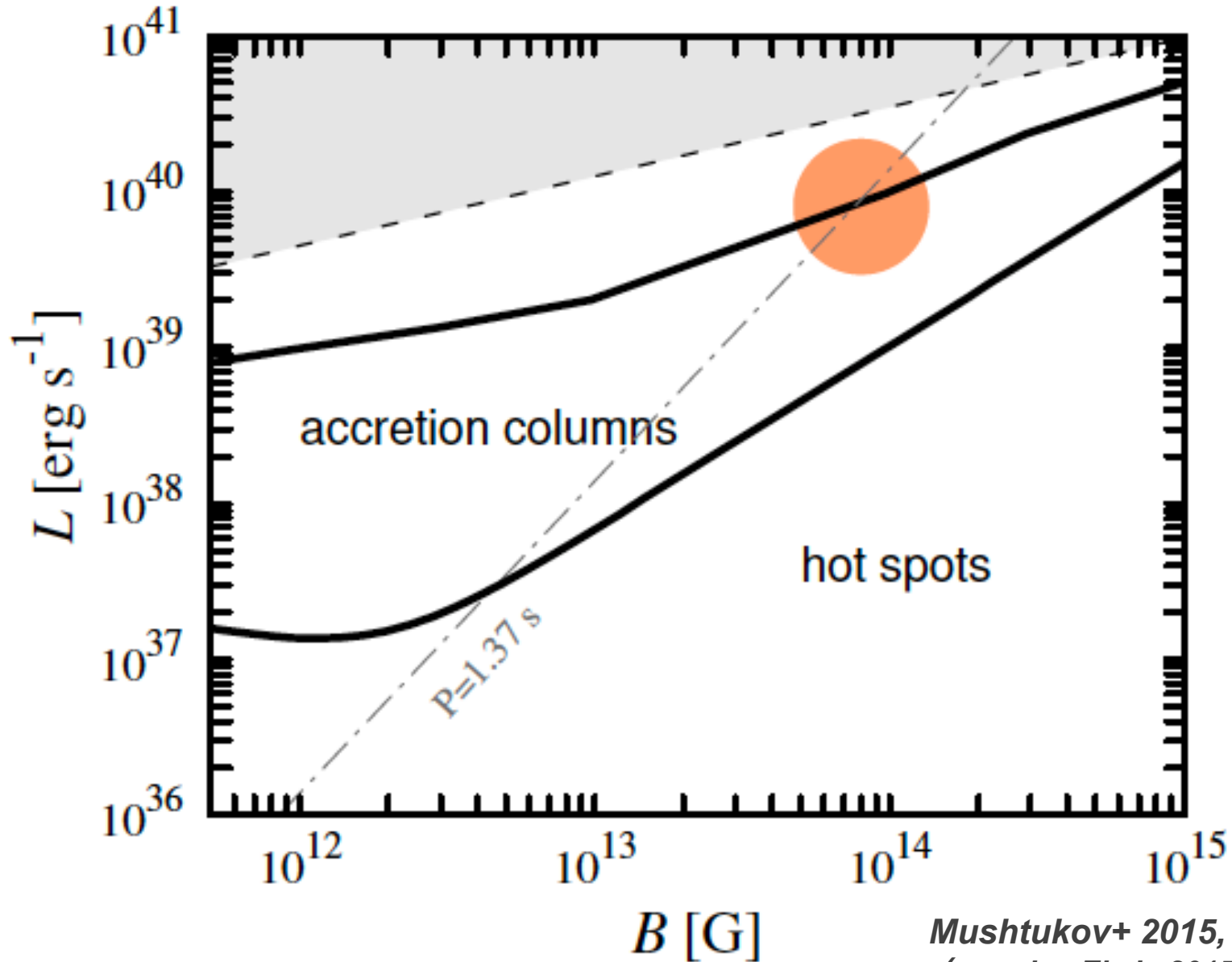
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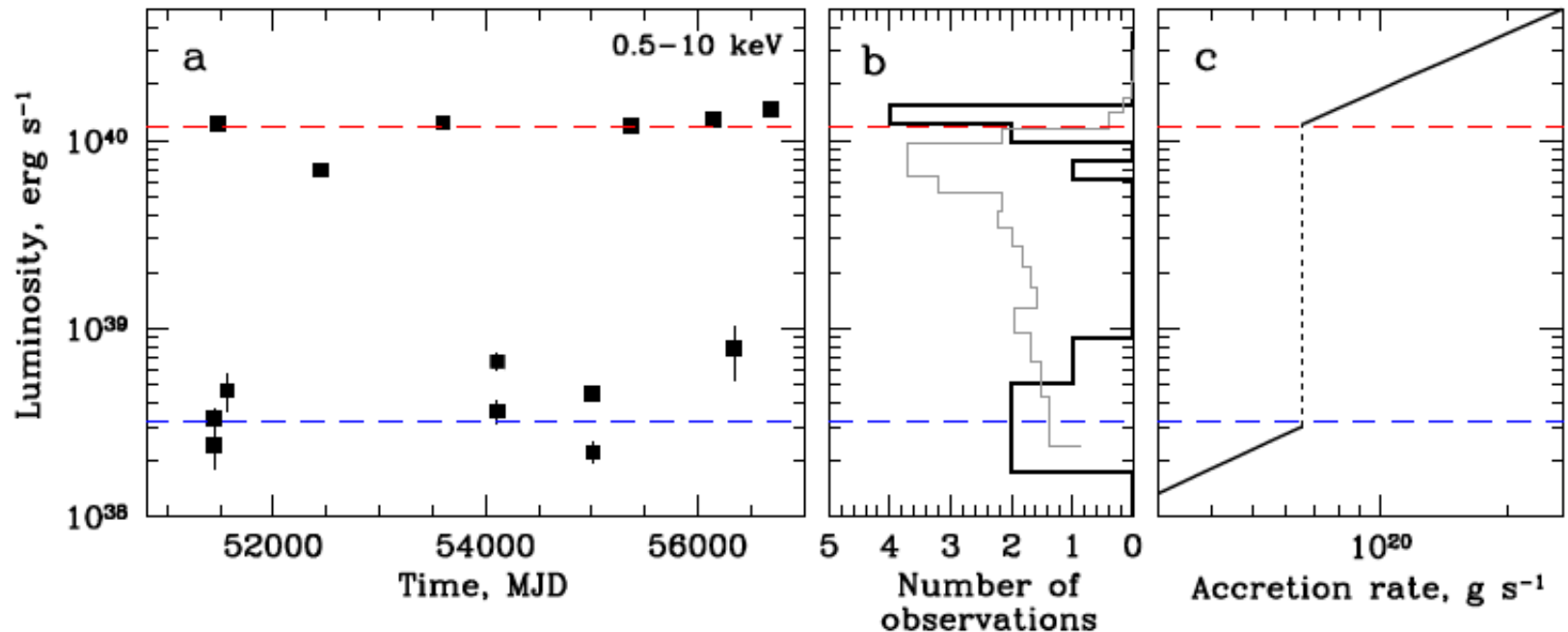
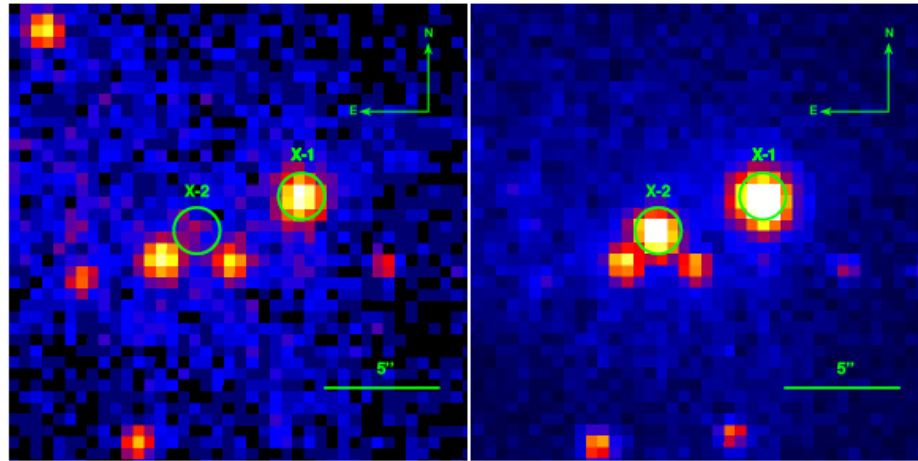


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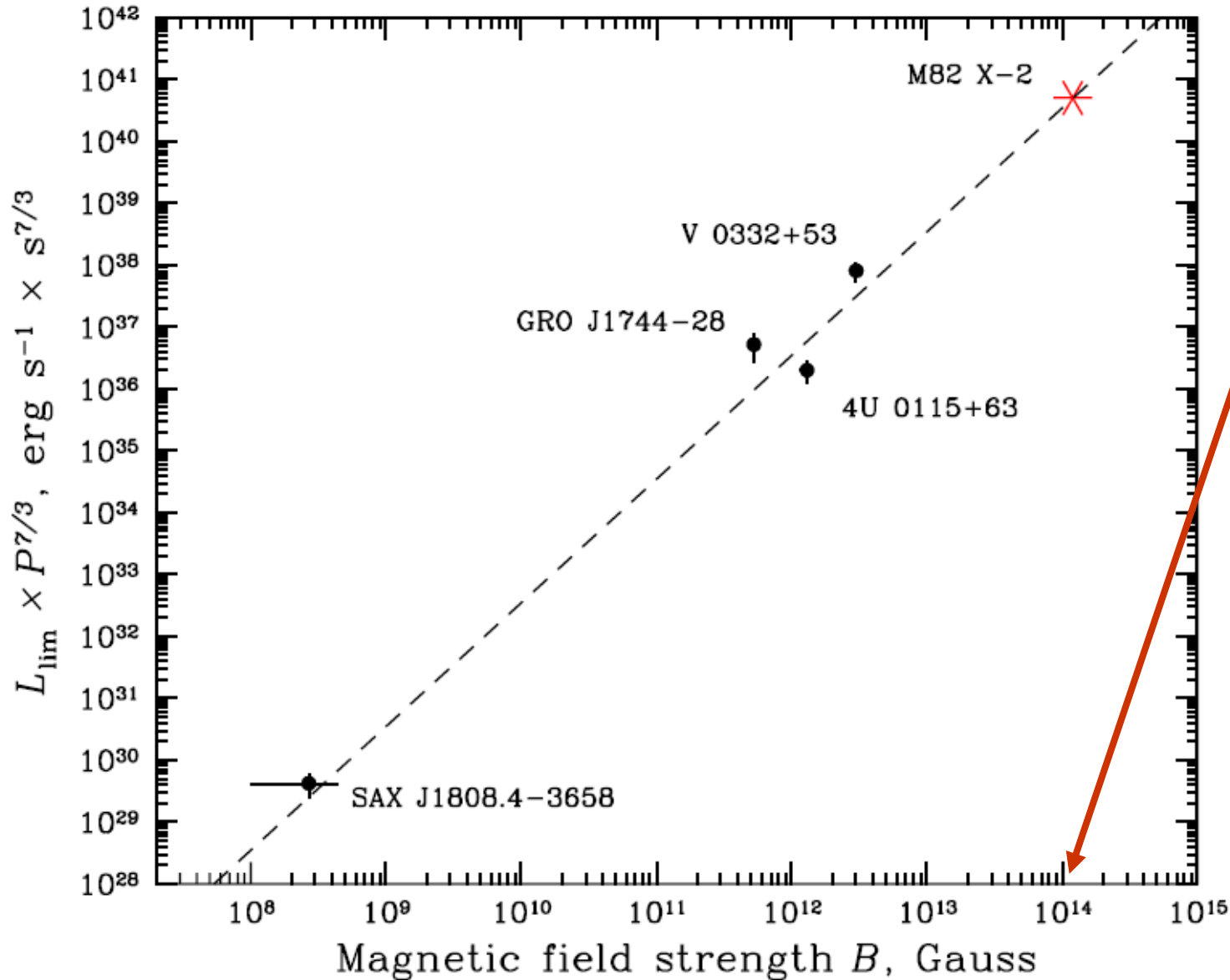
Pulsations from ULX in M82: explanation



Pulsations from ULX in M82: propeller effect

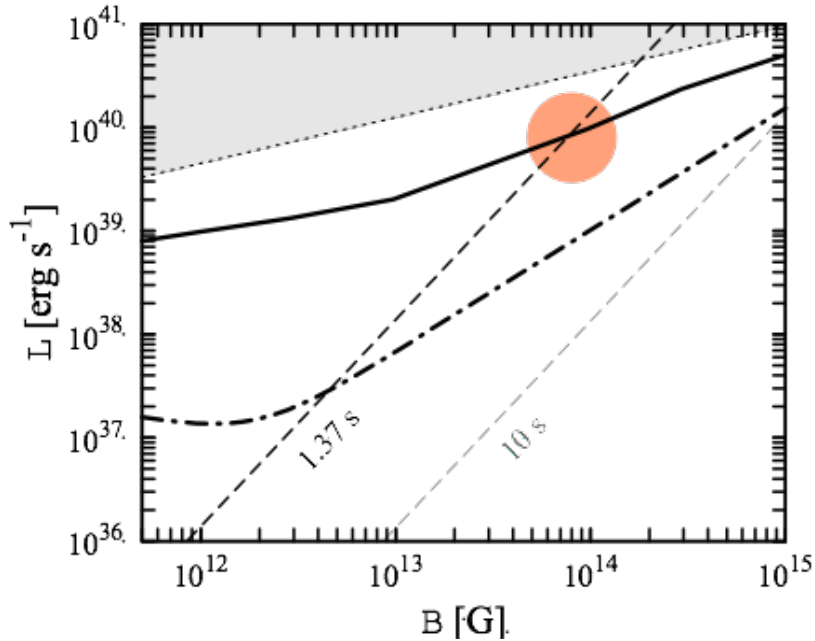


Pulsations from ULX in M82: propeller effect



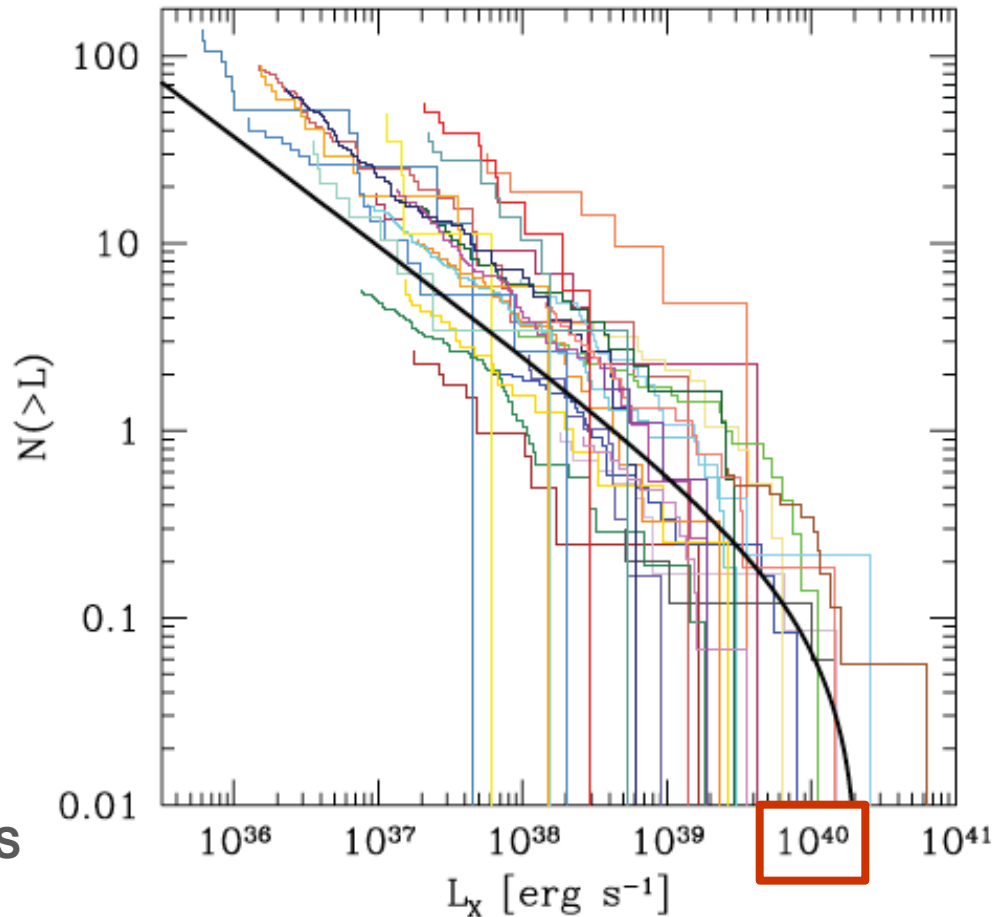
$\sim 10^{14}$ G

Maximum luminosity of NS, ULXs & HMXBs



Because of a set of restrictions it seems that the luminosity $\sim \text{few} \times 10^{40} \text{ erg/s}$ is a good estimation for maximum accretion NS luminosity.

This value coincides with the cut-off value of HMXB X-ray luminosity function.



Mushtukov+ , 2015, MNRAS, 454
Mineo+ 2012, MNRAS, 419