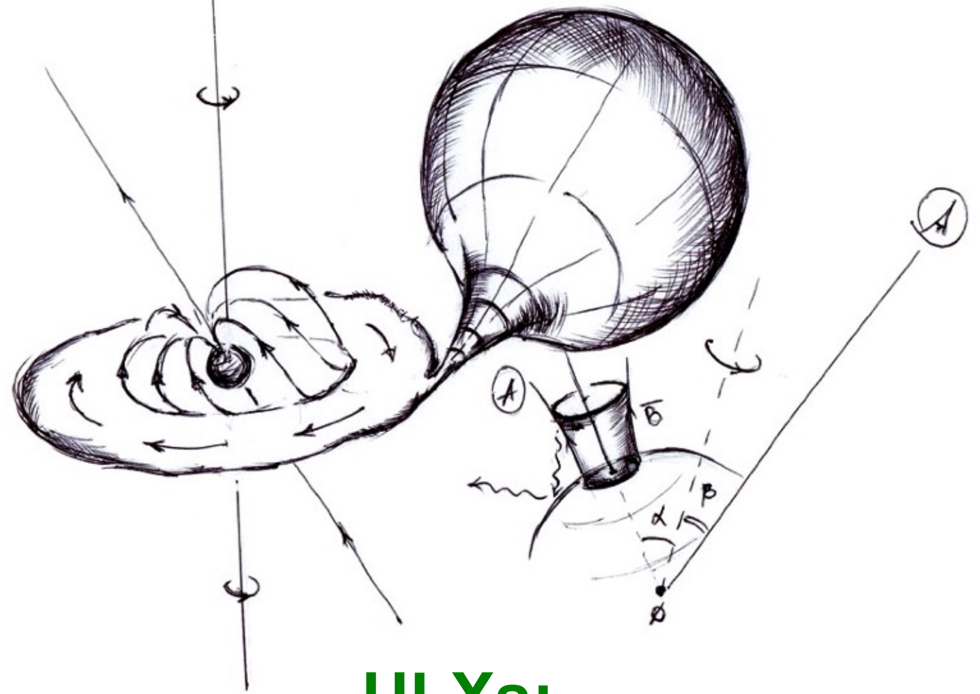


ULXs: The Strongest and the Brightest Magnets in the Universe

Alexander Mushtukov
V.F. Suleimanov, S.S. Tsygankov, V. Doroshenko, J. Poutanen,
P. Verhagen, A. Ingram, M. van der Klis

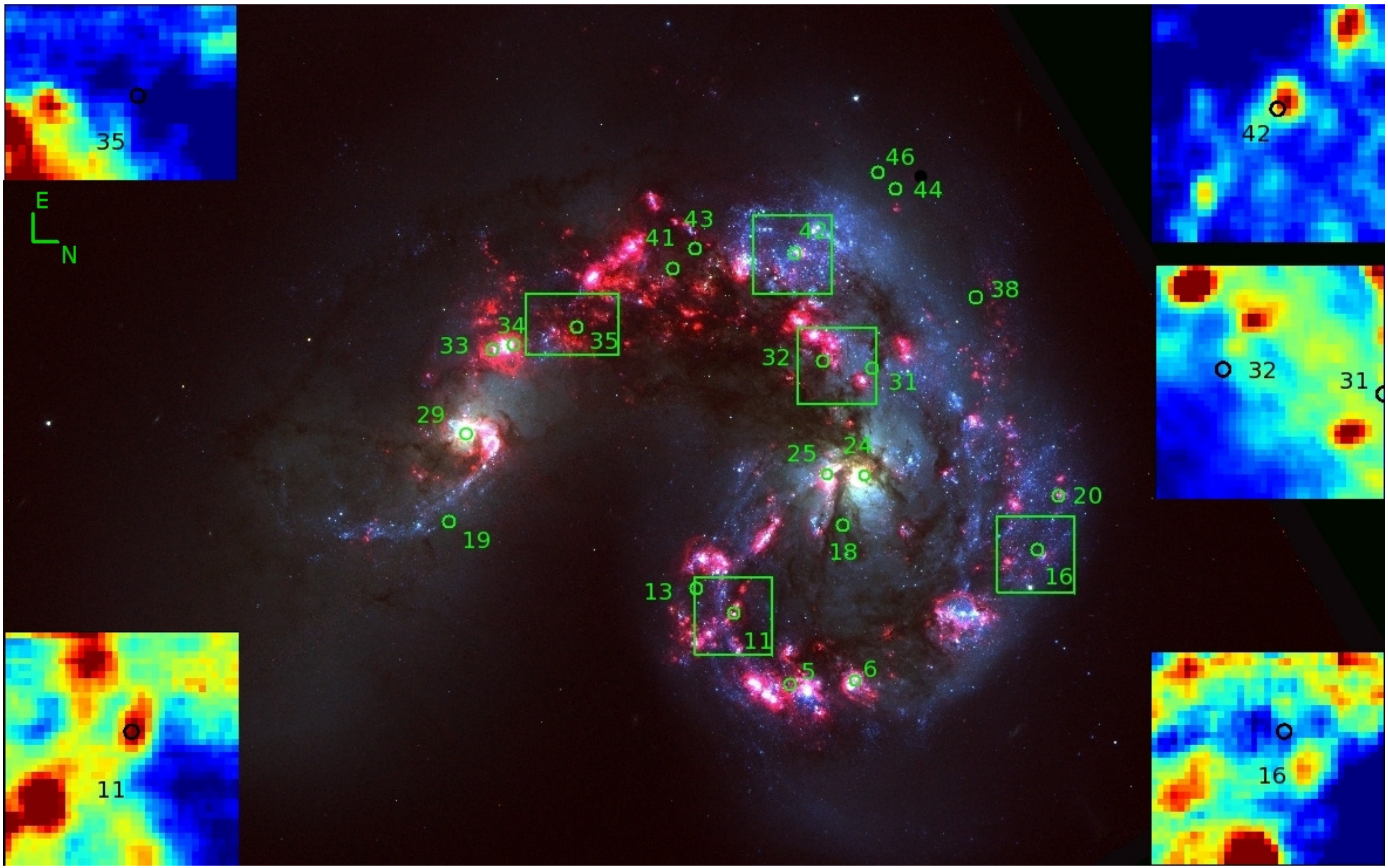
17 June 2019
Tübingen

NWO

Universiteit Leiden

Ultraluminous X-ray Sources (ULXs)

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



Poutanen+, 2013, MNRAS, 432

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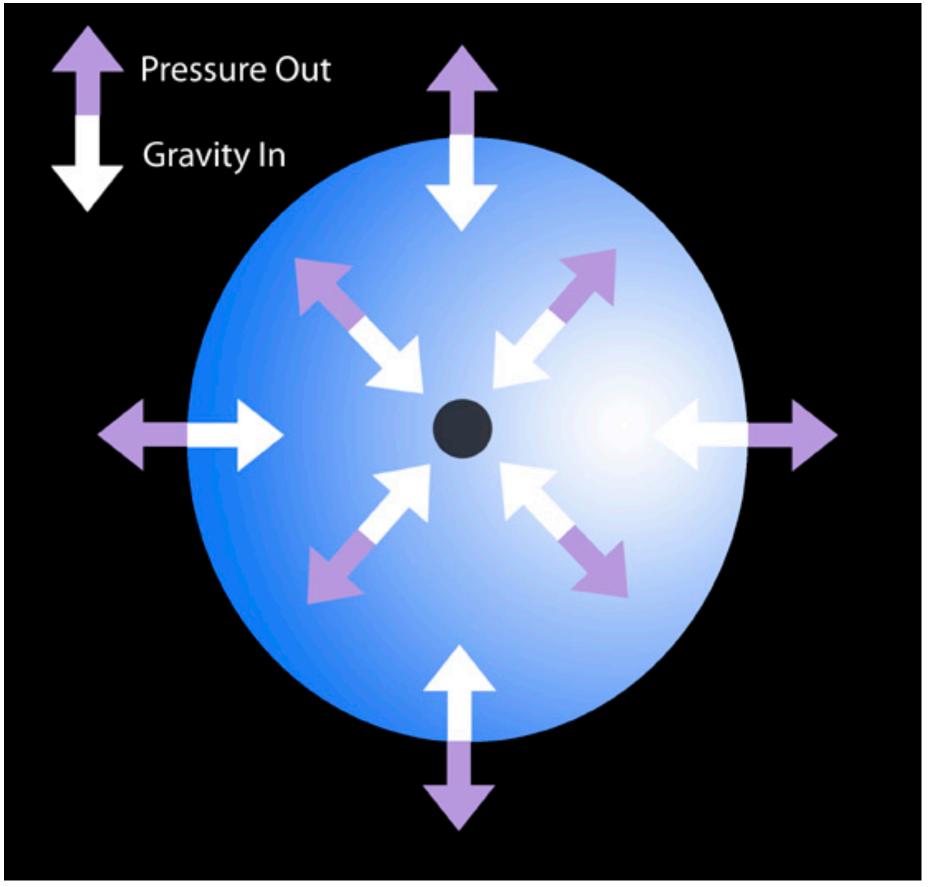
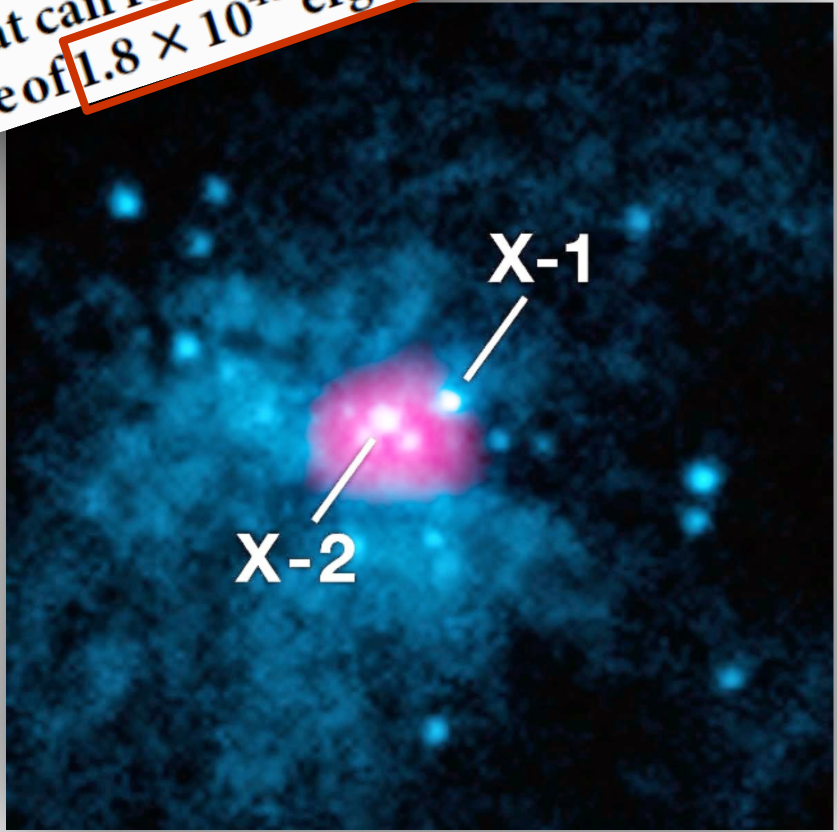


$$L_{\rm Edd} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}} \approx 1.3 \times 10^{38} \frac{M}{M_\odot} \ \text{erg s}^{-1}$$

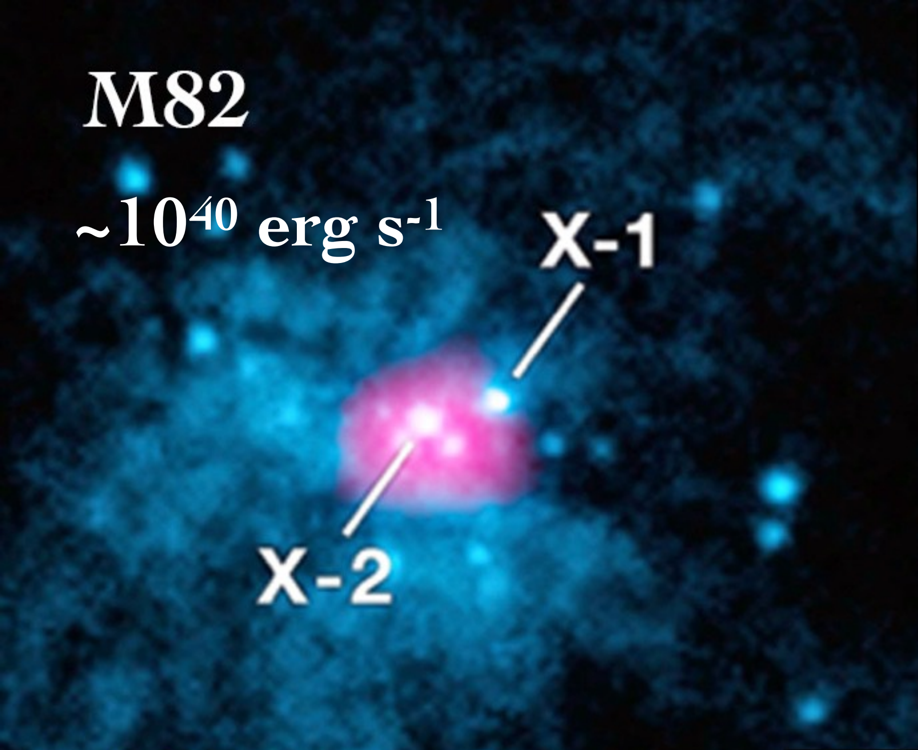
Pulsations from ULX in M82

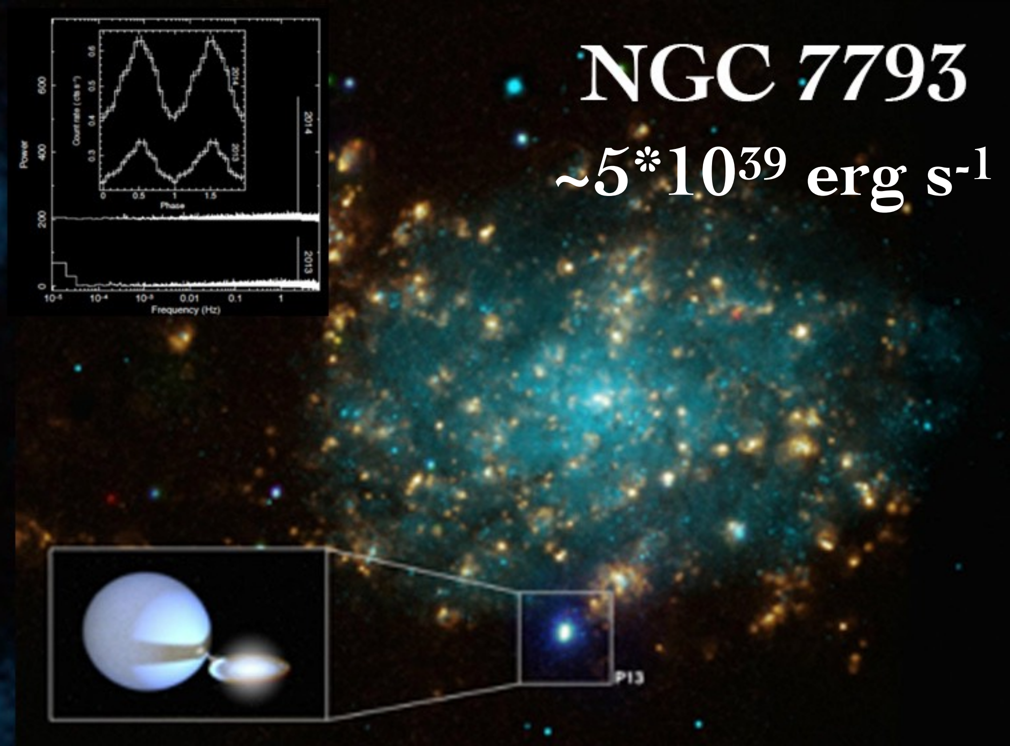
and the modulation arises from its binary orbit. The pulsed flux alone corresponds to an X-ray luminosity in the 3–30 kiloelectronvolt range of 4.9×10^{39} ergs per second. The pulsating source is spatially coincident with a variable source[4] that can reach an X-ray luminosity in the 0.3–10 kiloelectronvolt range of **1.8×10^{40} ergs per second[1]**. This

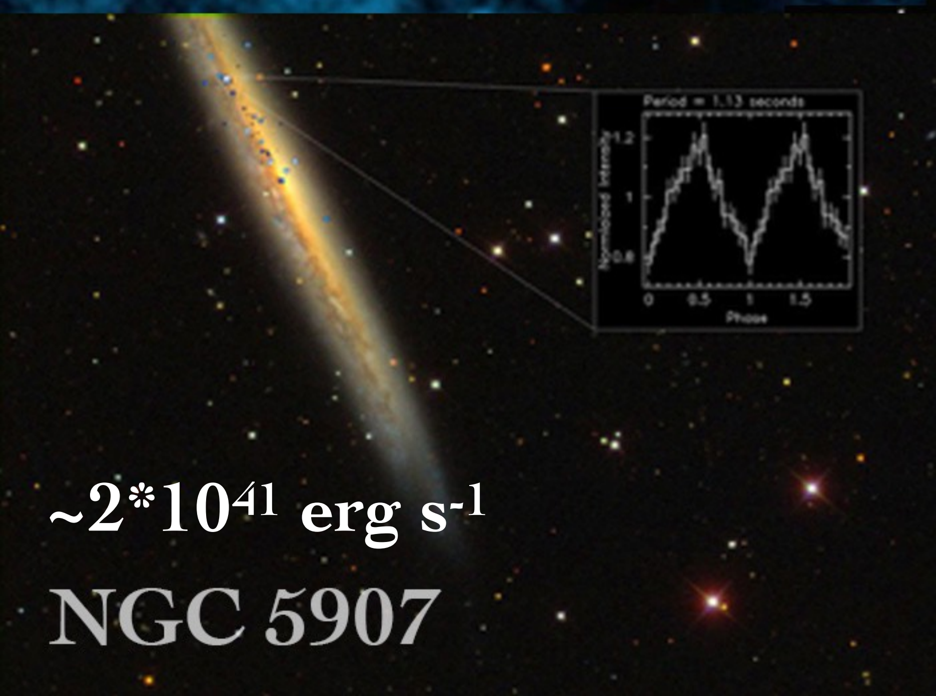
Pulse period ~1.37 sec

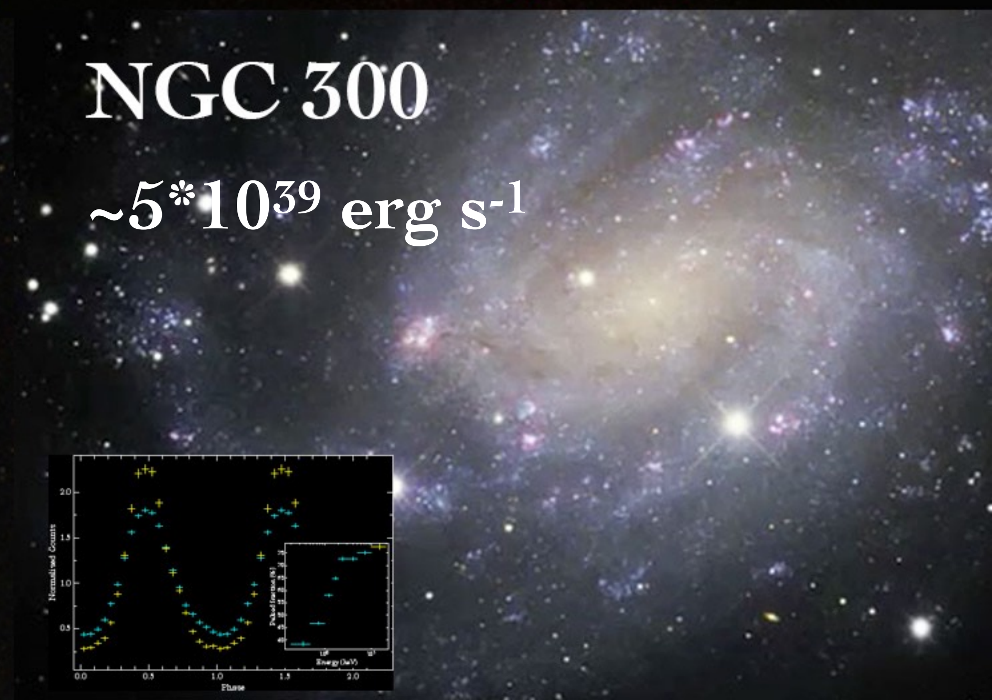


Bachetti+ 2014, Nature


M82
~10^{40} erg s^{-1}
X-1
X-2


NGC 7793
~$5*10^{39}$ erg s^{-1}
Frequency (Hz)
Phase
P13


Period = 1.13 seconds
Normalized Intensity
Phase
~$2*10^{41}$ erg s^{-1}
NGC 5907


NGC 300
~$5*10^{39}$ erg s^{-1}
Normalized Counts
Phase

Neutron Stars

Product of supernova explosions

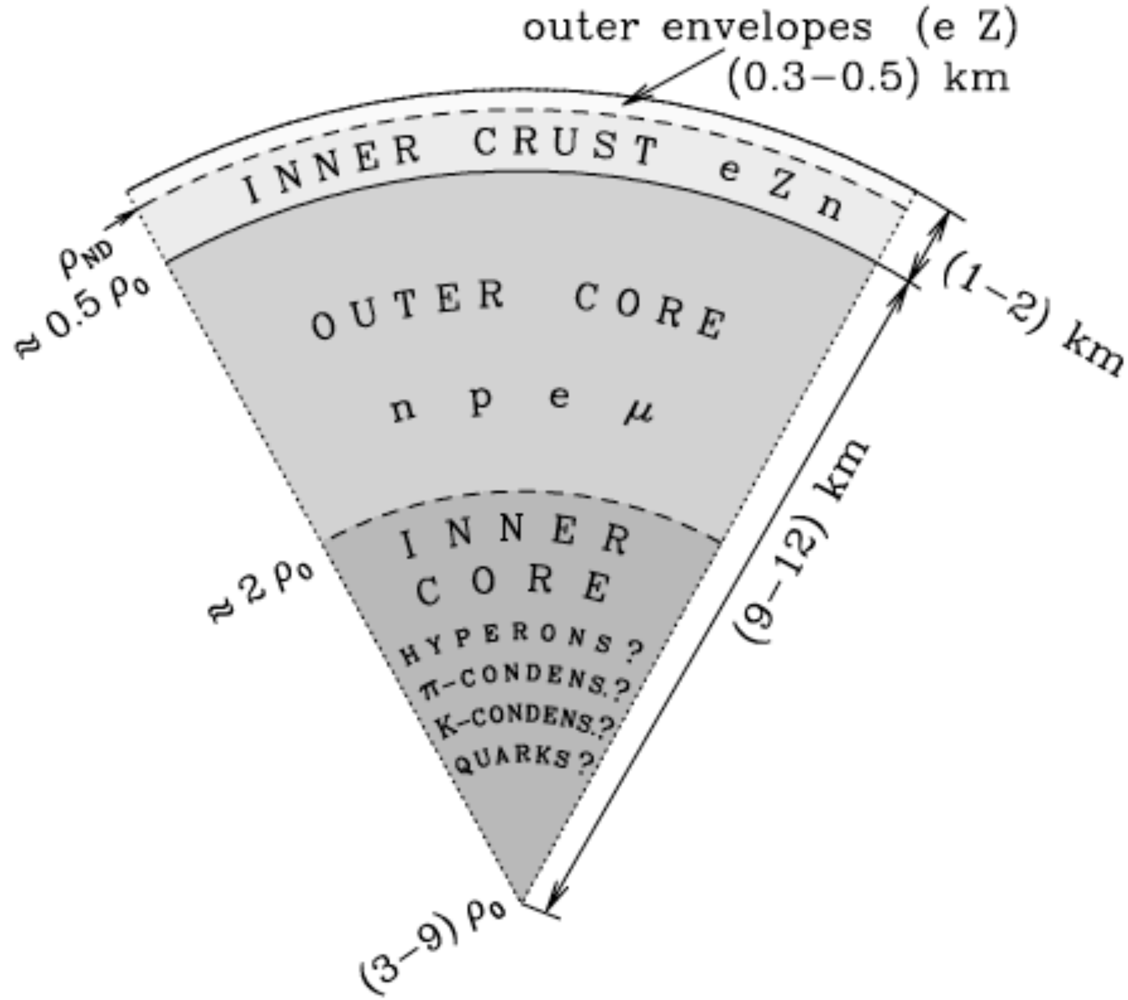
Mass: 1.5 M_{sun}
Radius: 10 km

Mass density

$>10^{14}$ g cm^{-3}

The Highest Density in the Universe

Neutron Stars



Typical mass and radius:

$$M \sim 1.4\,M_\odot$$

$$R \sim 10\ \text{km}$$

The fundamental problem of the EOS of superdense matter constitutes the main mystery of neutron stars.

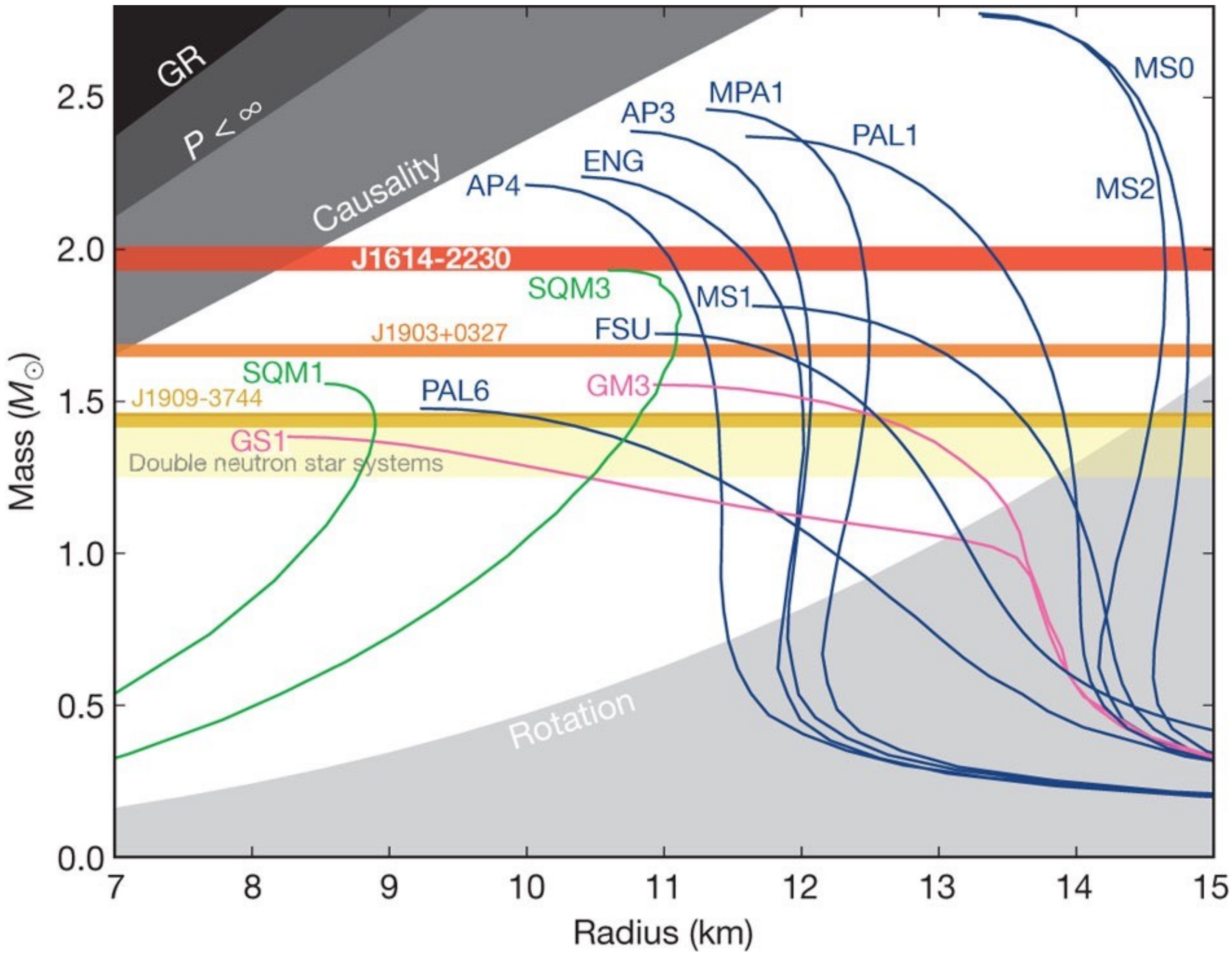
Mean mass density:

$$\bar{\rho} \simeq 3M/(4\pi R^3) \simeq 7 \times 10^{14}\ \text{g cm}^{-3} \sim (2-3)\,\rho_0$$

Normal nuclear density:

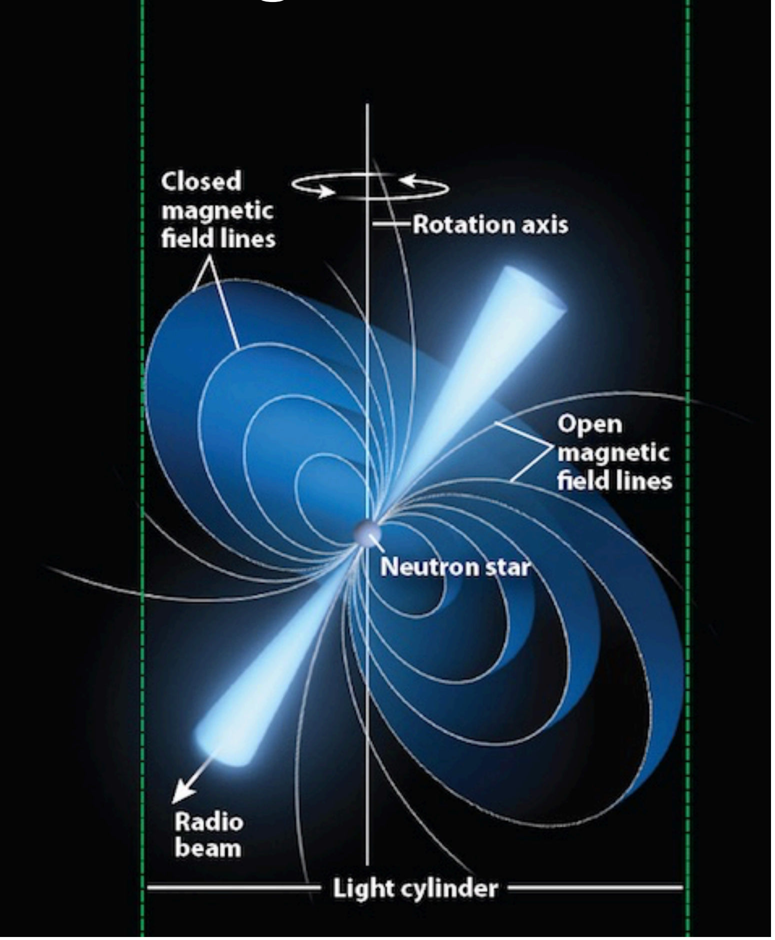
$$\rho_0 = 2.8 \times 10^{14}\ \text{g cm}^{-3}$$

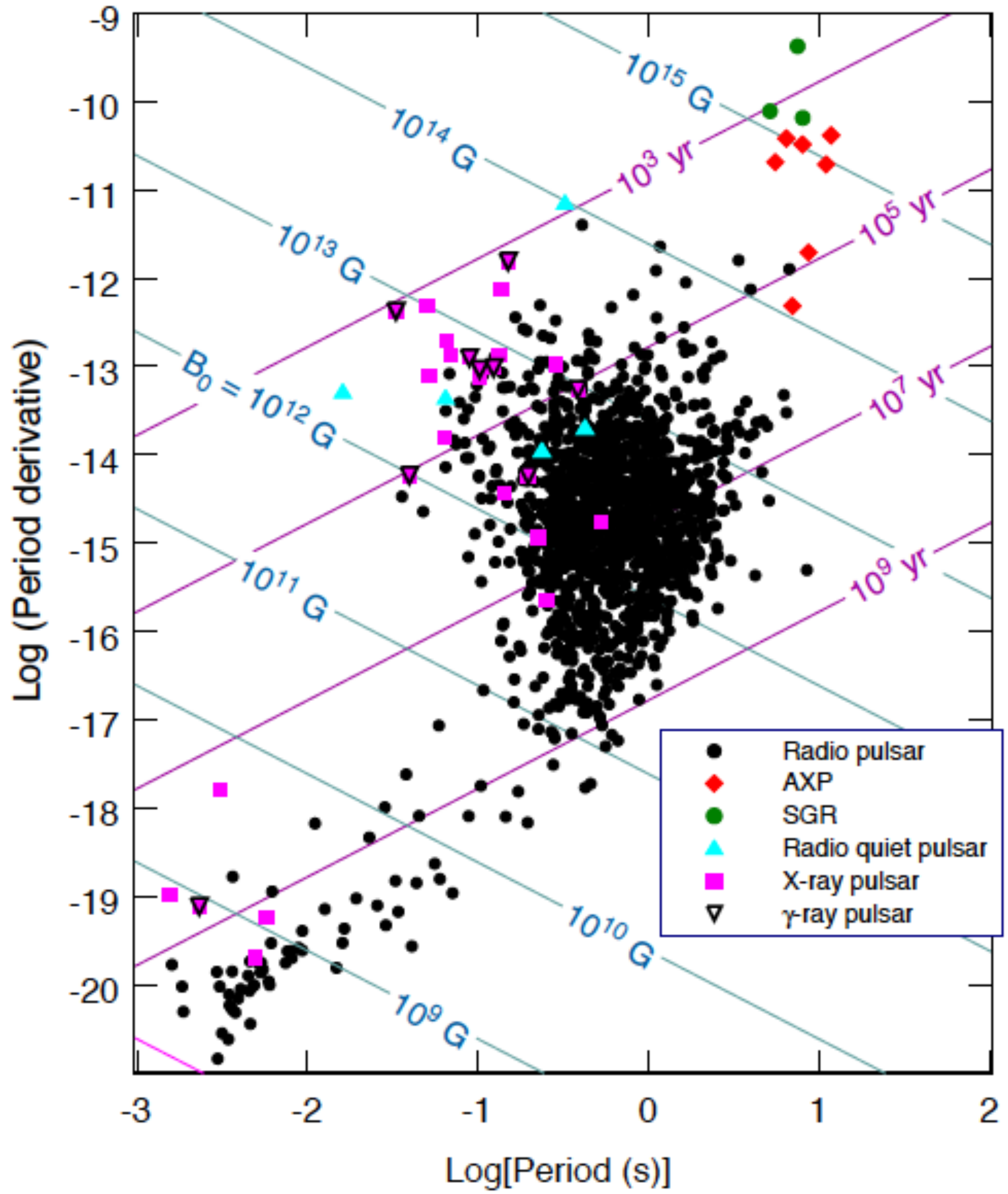
Mass-Radius relation for neutron stars



Demorest et al. (2010)

Magnetic fields

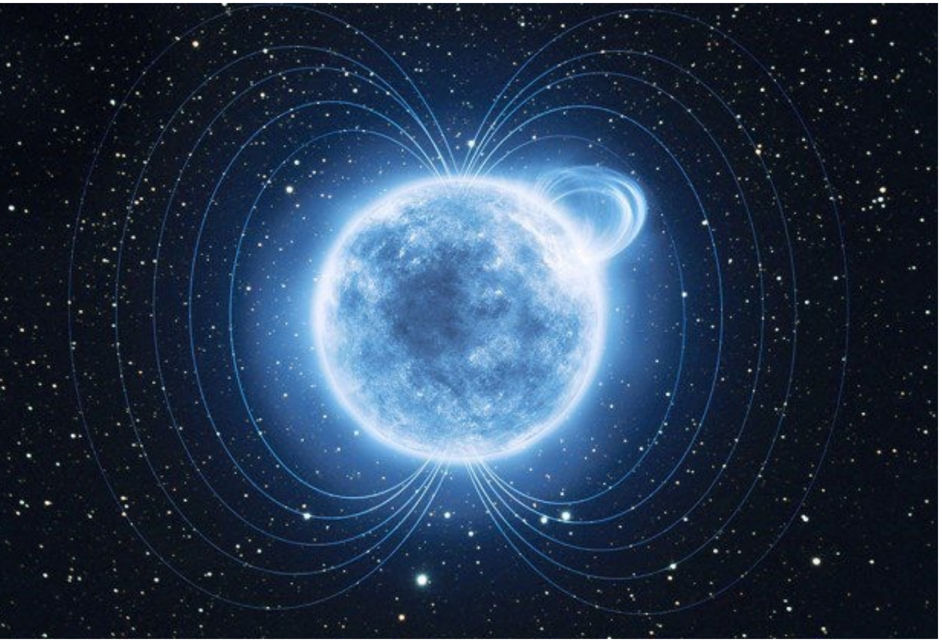




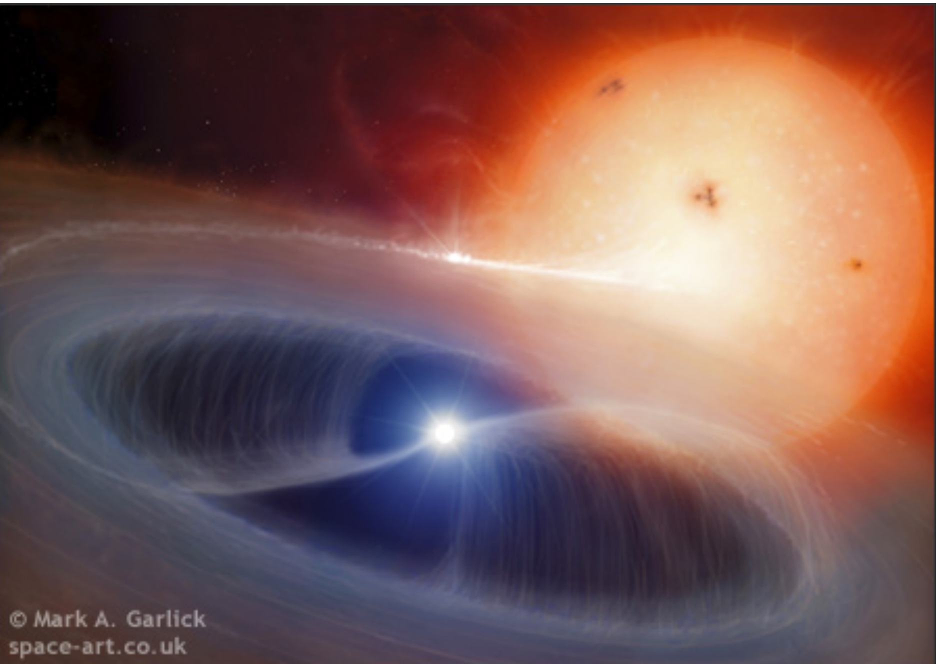
$$\dot{P}_{15} \equiv \dot{P}/(10^{-15}\,\mathrm{s\,s^{-1}})$$

$$B_s = \left(\frac{3Ic^3P\dot{P}}{2\pi^2R^6}\right)^{1/2} \simeq 2\times10^{12}\mathrm{G}\,(P\dot{P}_{15})^{1/2}$$

What if neutron star has a companion?



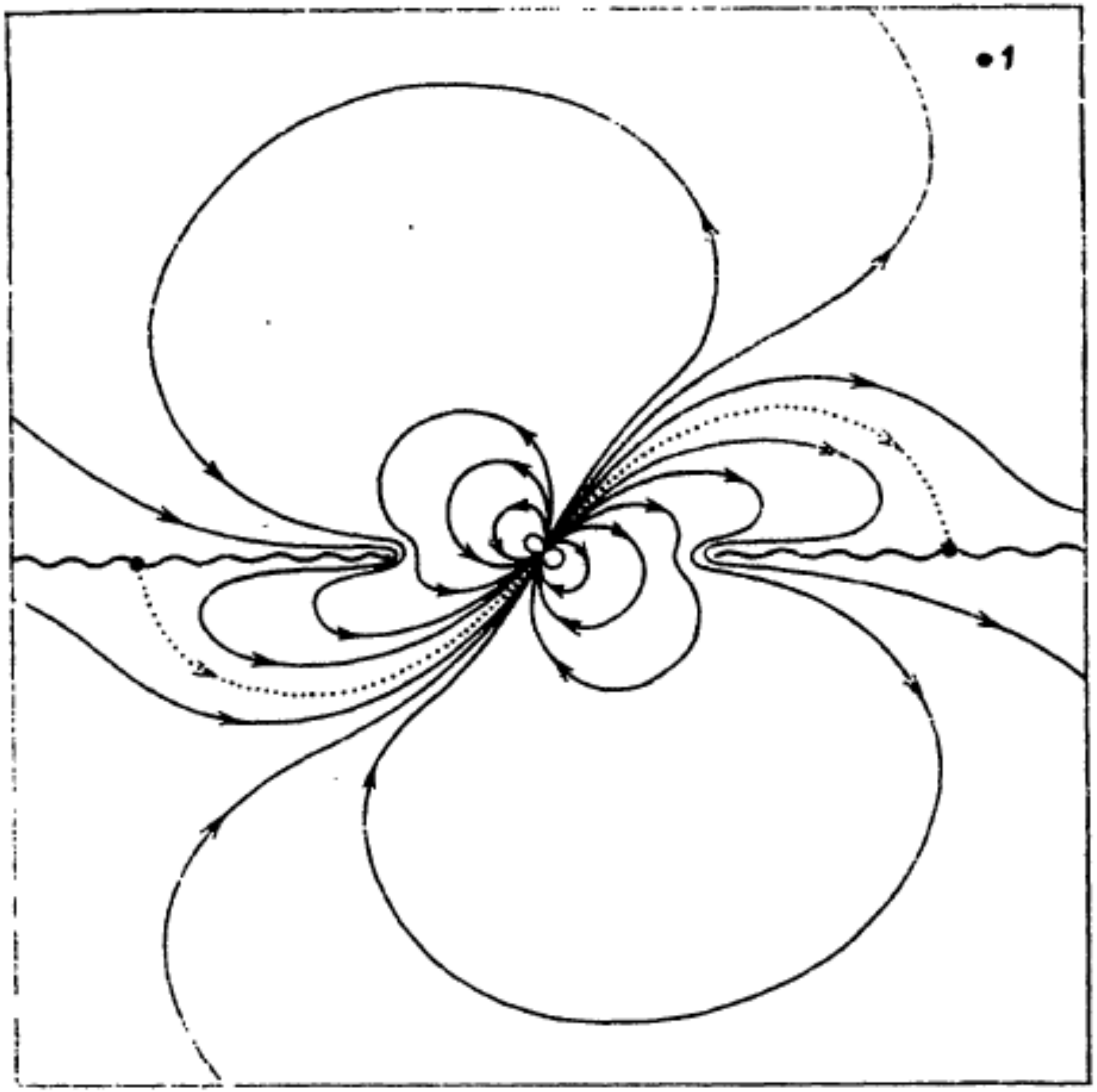
Some neutron stars are isolated and dim



If neutron star has a close companion,
it absorbs material
and
can be extremely bright.

X-ray pulsar

Accretion Disc and its Interaction with B-field



The inner disc radius:

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

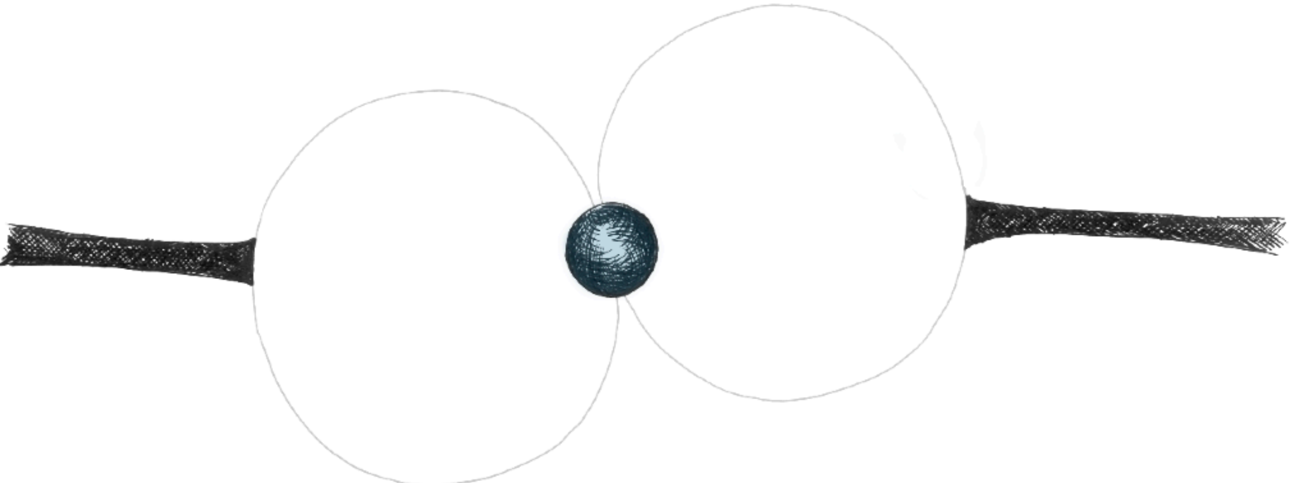
$$r_{\mathrm{m}} = \xi r_{\mathrm{A}}$$

Co-rotational radius:

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

Keplerian and stellar-rotation frequencies are equal

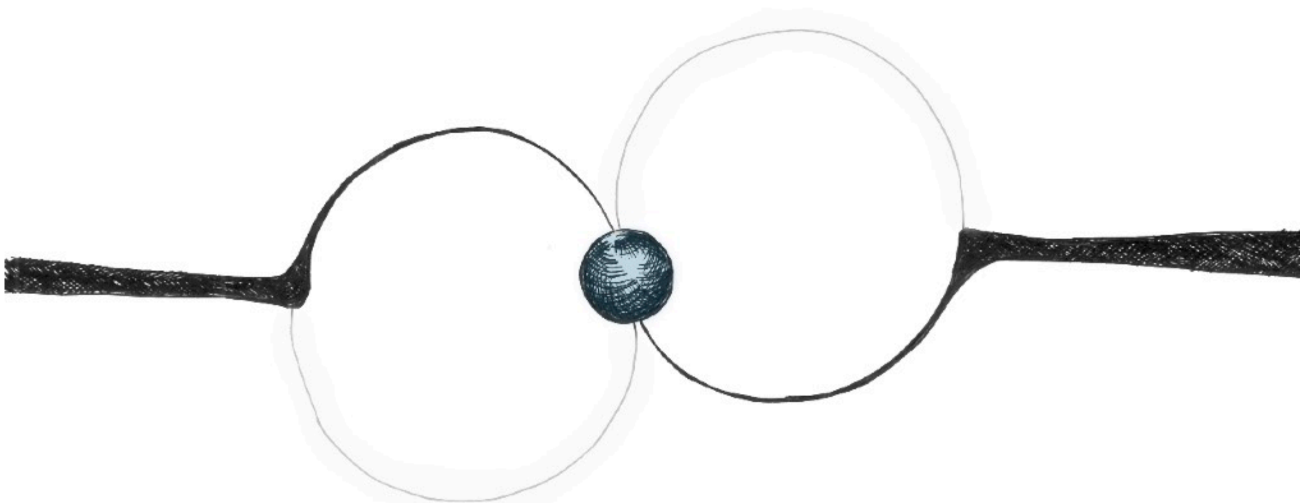
"Propeller" state



$r_m > r_{co}$

accretion is prohibited due to centrifugal barrier

Accretion state

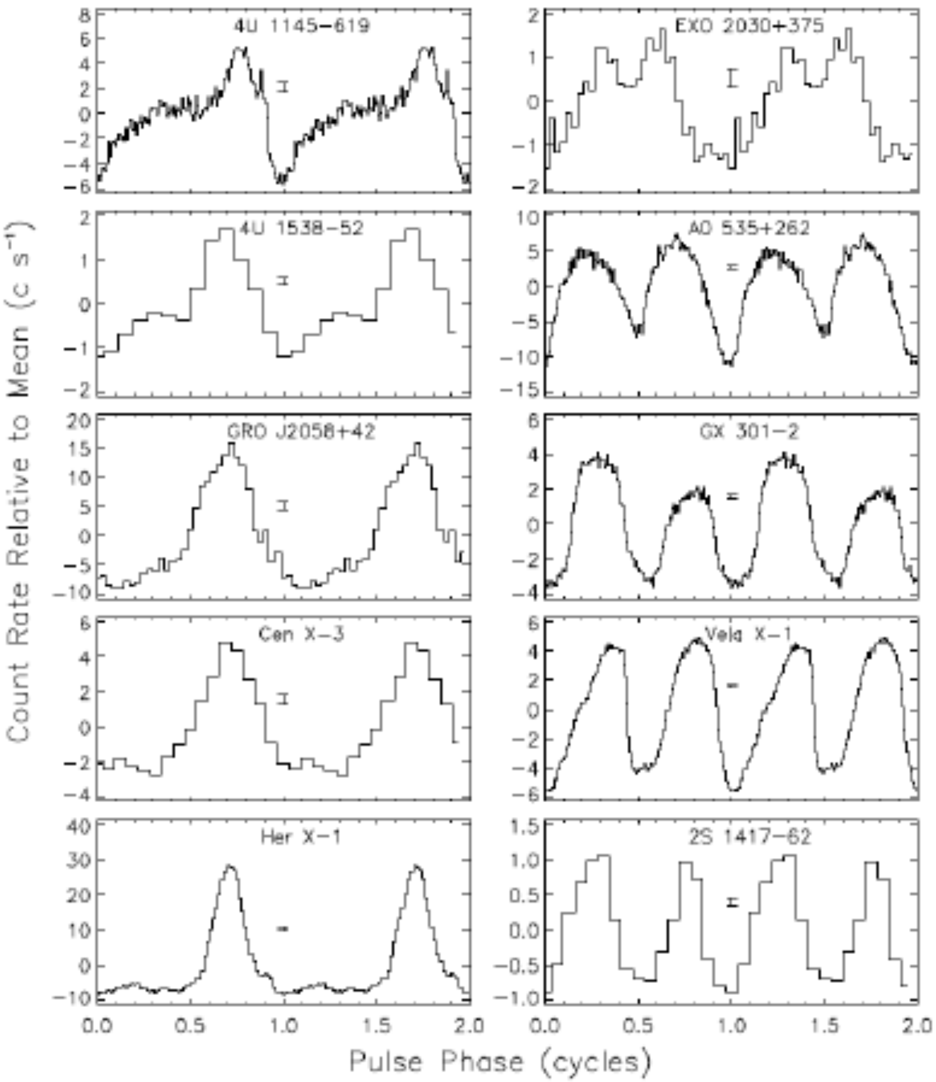


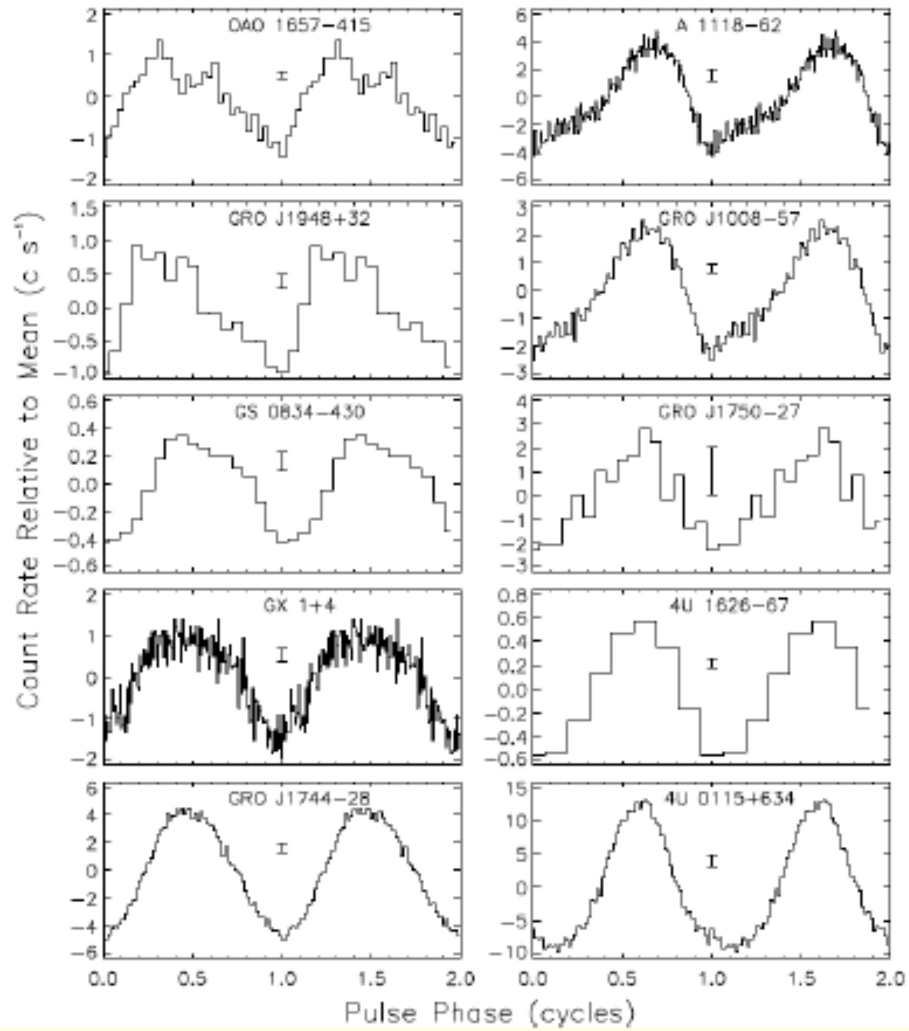
$r_m < r_{co}$

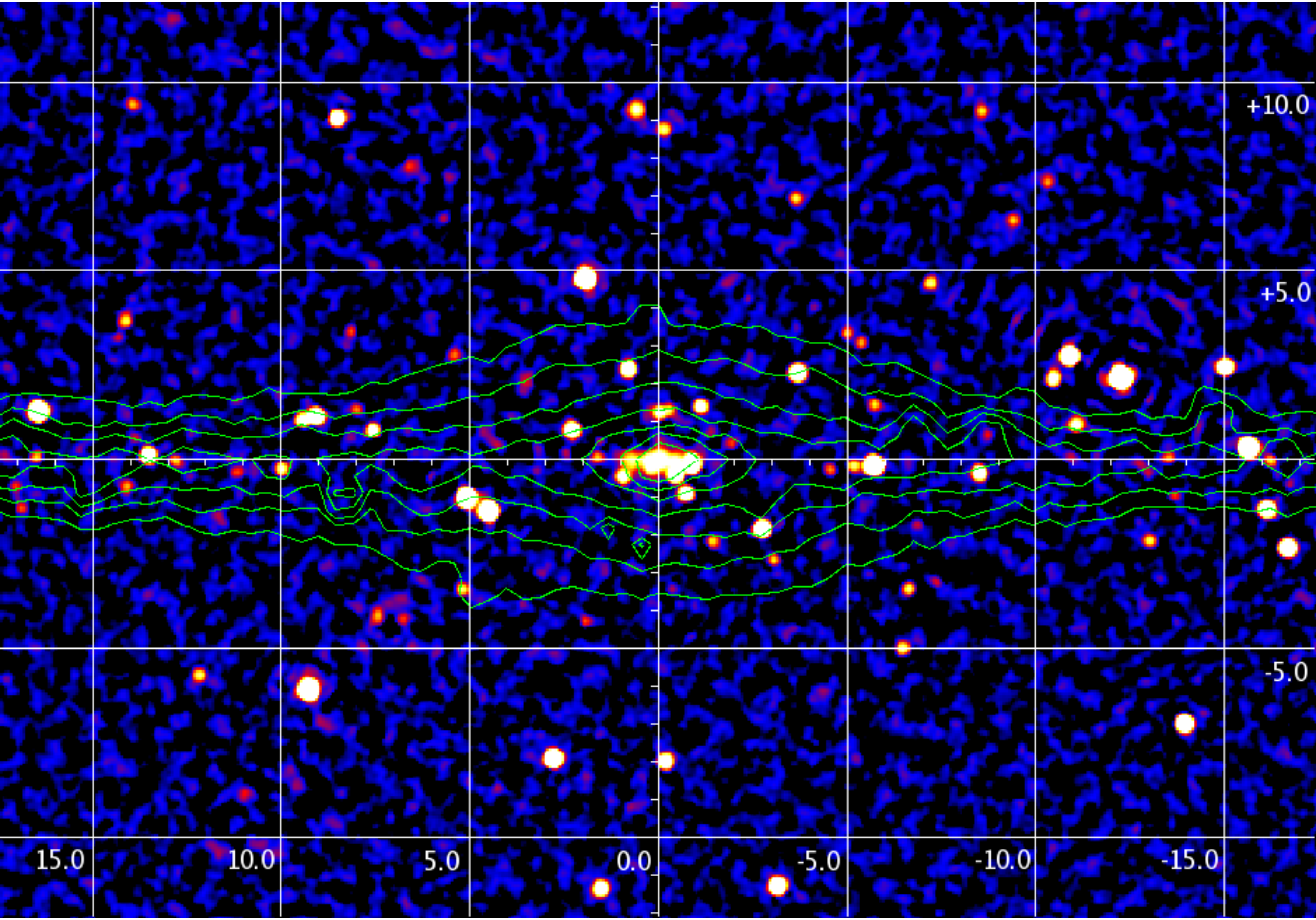
accretion is possible

Illarionov & Sunyaev, 1975

X-ray pulsars: pulse profiles

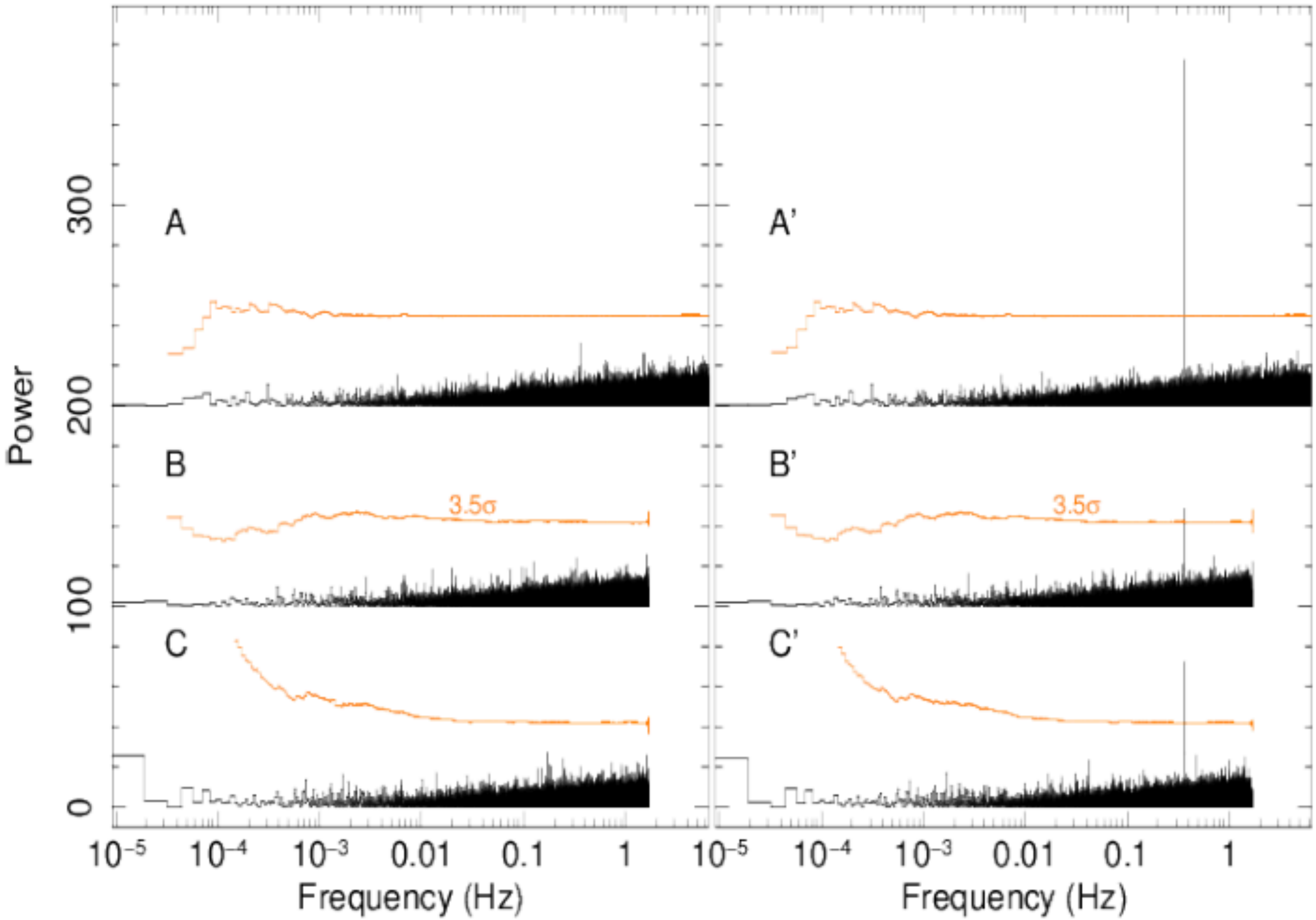






+10.0
+5.0
-5.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0

On the detection of pulsations in ULXs



Rodríguez Castillo+, 2019, arXiv:1906.04791

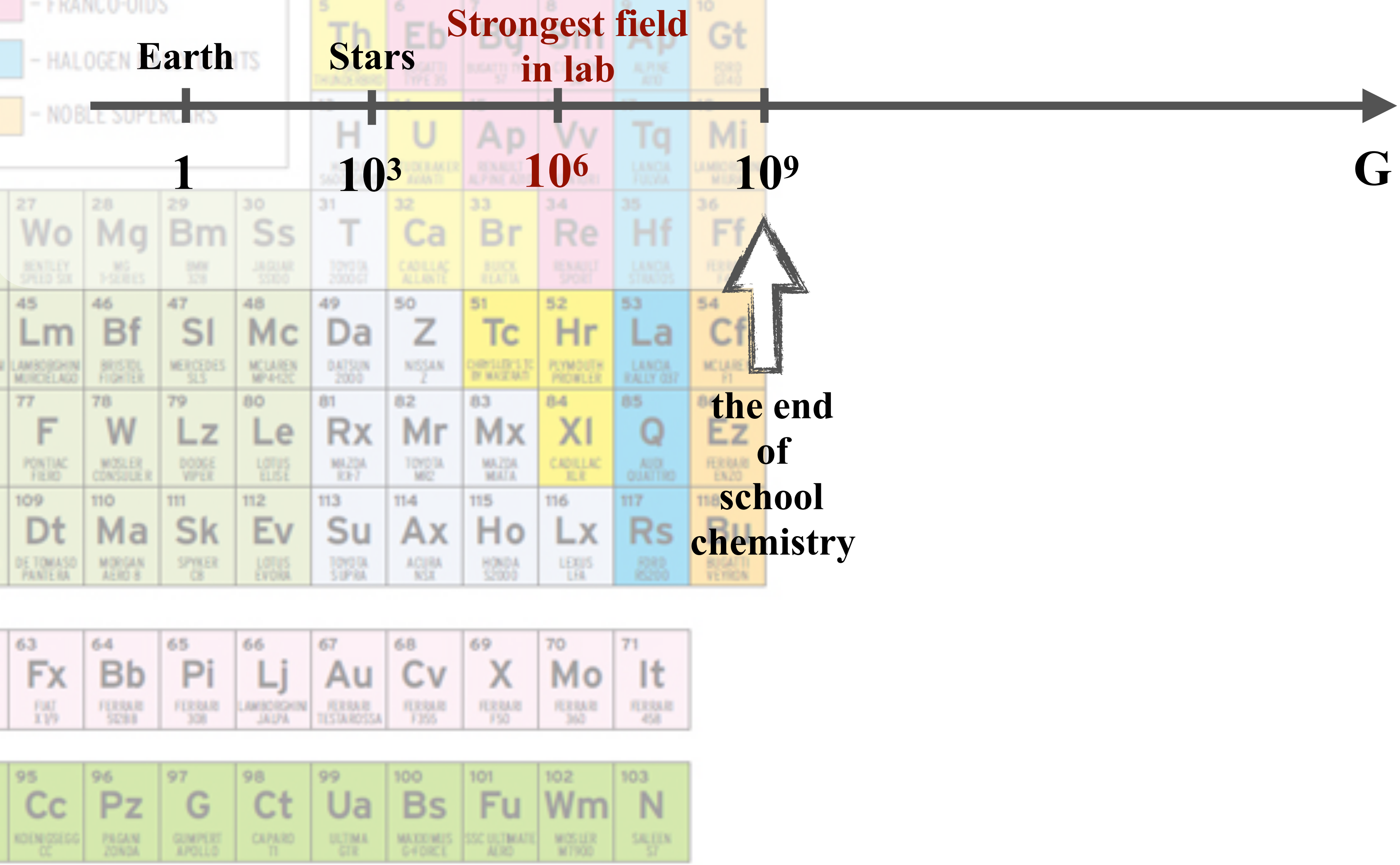
Magnetic field strengths

Magnetic field strengths

Magnetic field strengths

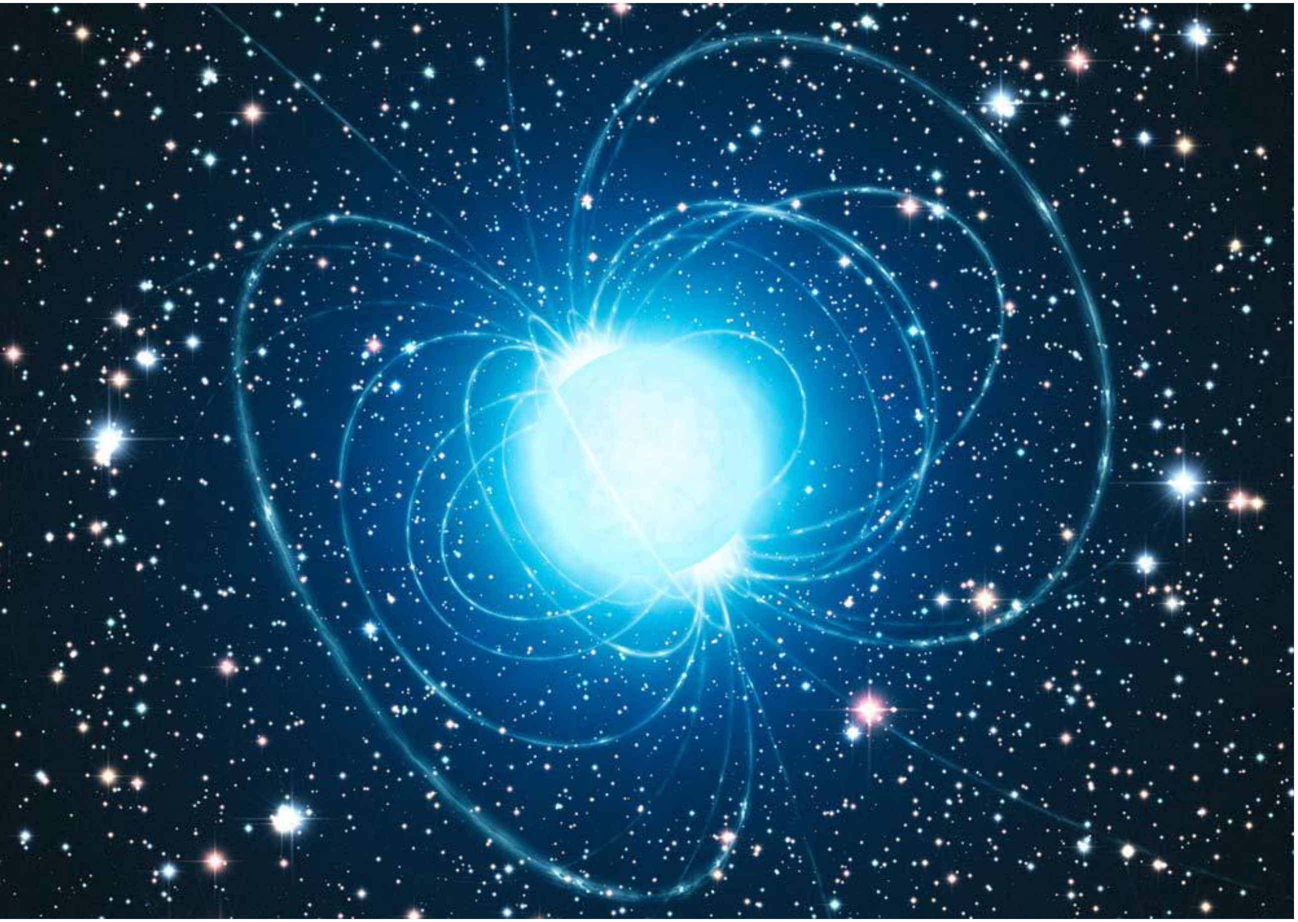
Earth	Stars	Strongest field in lab	
1	10^3	10^6	G

Magnetic field strengths



Magnetic field strengths

Earth	Stars	Strongest field in lab		Young neutron stars	
1	10^3	10^6	10^9	10^{12-15}	G

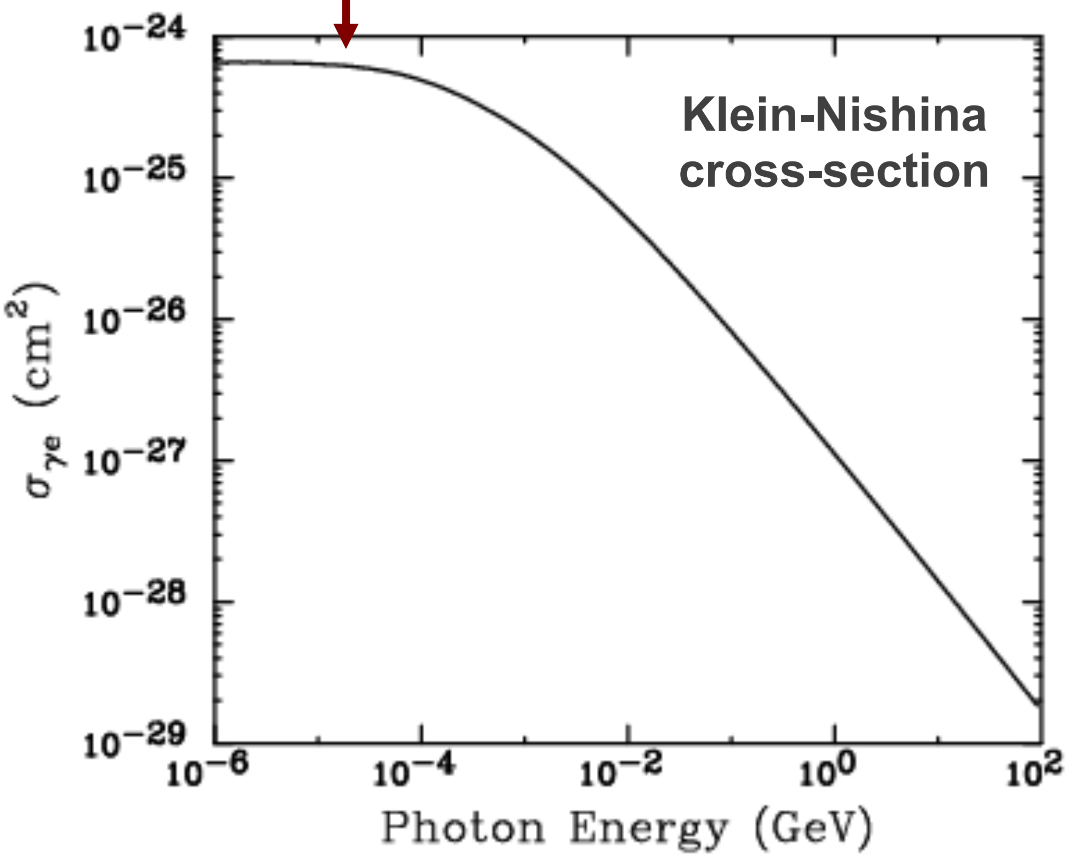


Extreme physics

Deviations from Quantum Electrodynamics?

Compton scattering: non-magnetic case

$$\sigma_{\mathrm{T}} = \frac{8\pi}{3}\left(\frac{e^2}{m_{\mathrm{e}}c^2}\right)^2 \approx 6.65 \times 10^{-25}\,\mathrm{cm}^2$$



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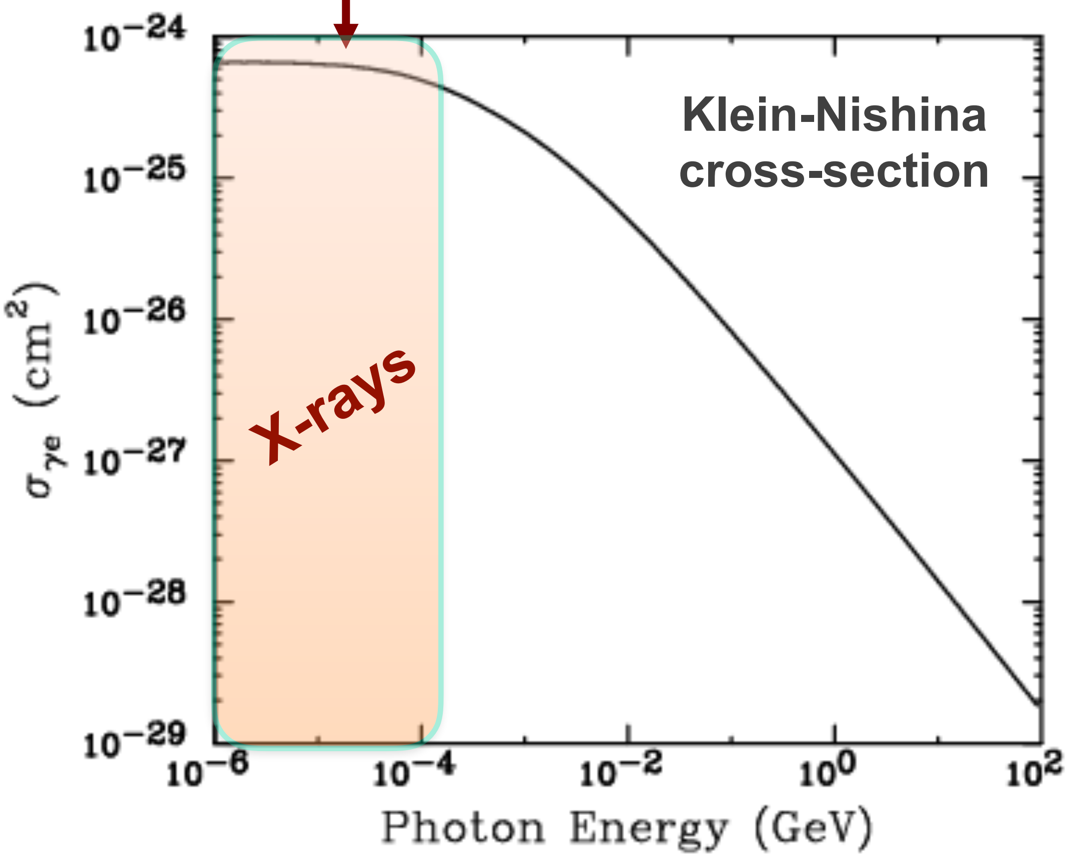


Strong magnetic fields

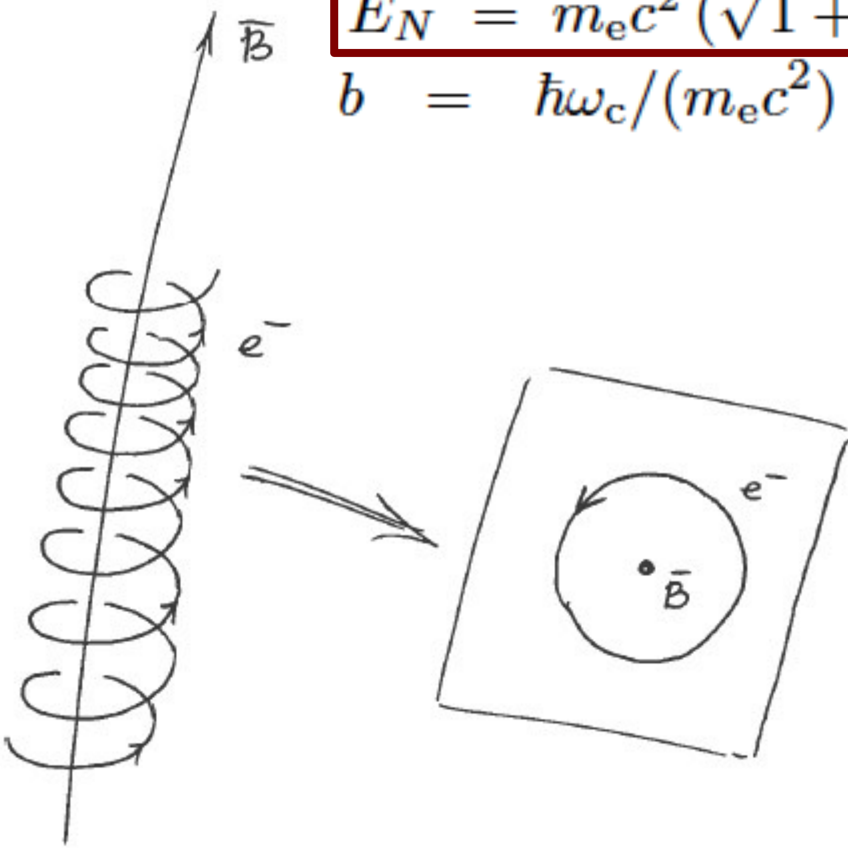
$$B_{\rm cr} = m_{\rm e}^2 c^3 / e\hbar = 4.412 \times 10^{13}\ {\rm G}$$

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:

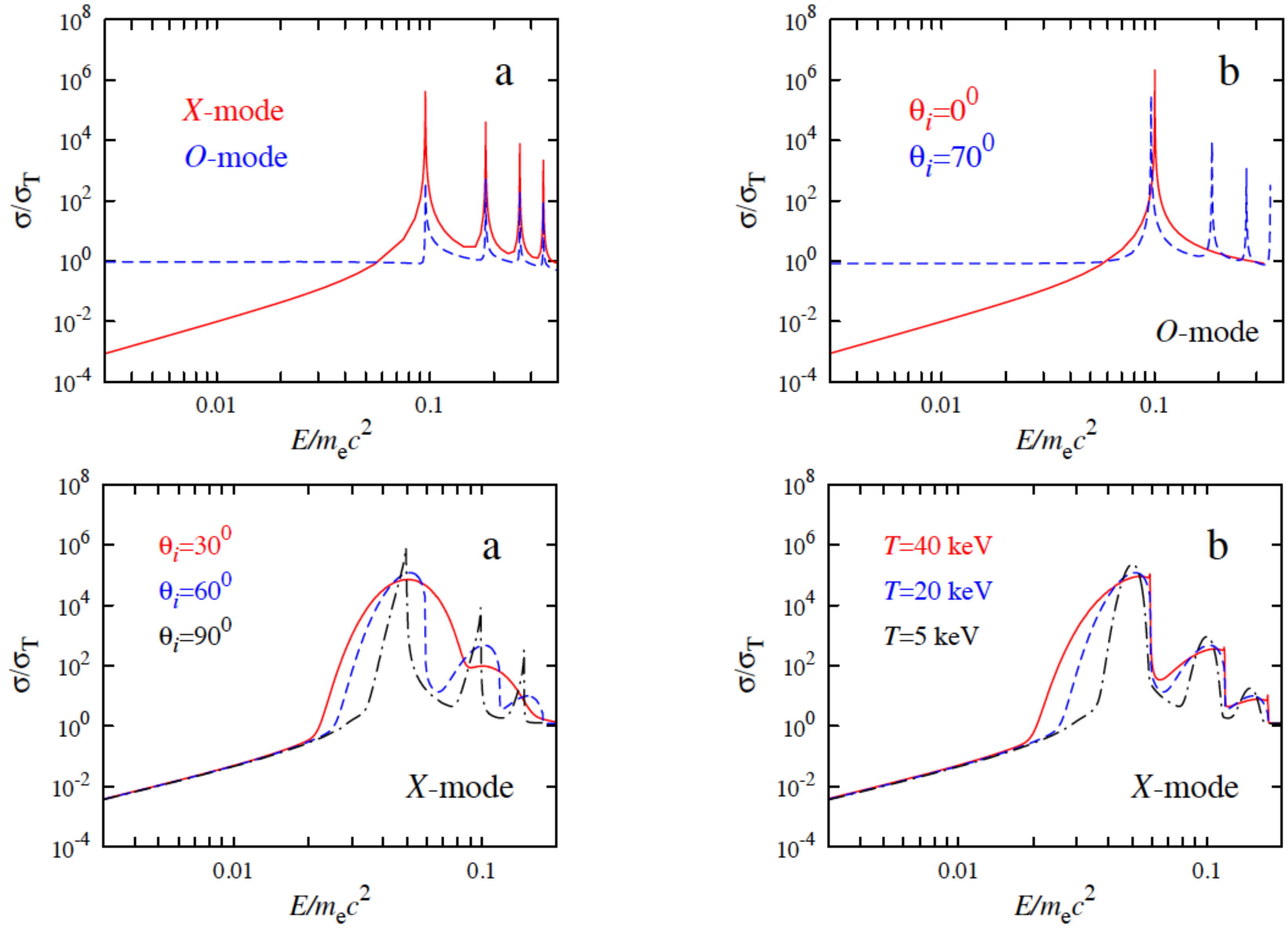
•Electrons occupy Landau levels:

$$E_N = m_{\rm e}c^2\left(\sqrt{1+2bN} - 1\right) \quad (N = 0, 1, 2, \ldots)$$

$$b = \hbar\omega_{\rm c}/(m_{\rm e}c^2) = B/B_{\rm QED} = B_{12}/44{,}14$$

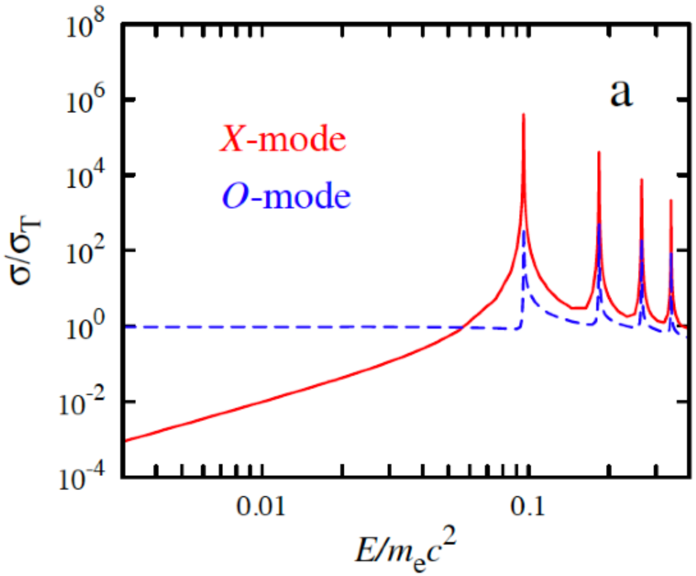


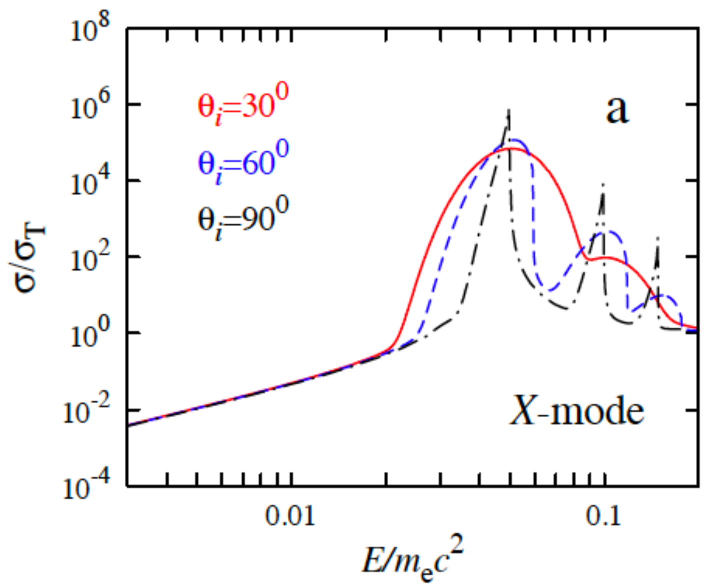
Compton scattering in a strong magnetic field



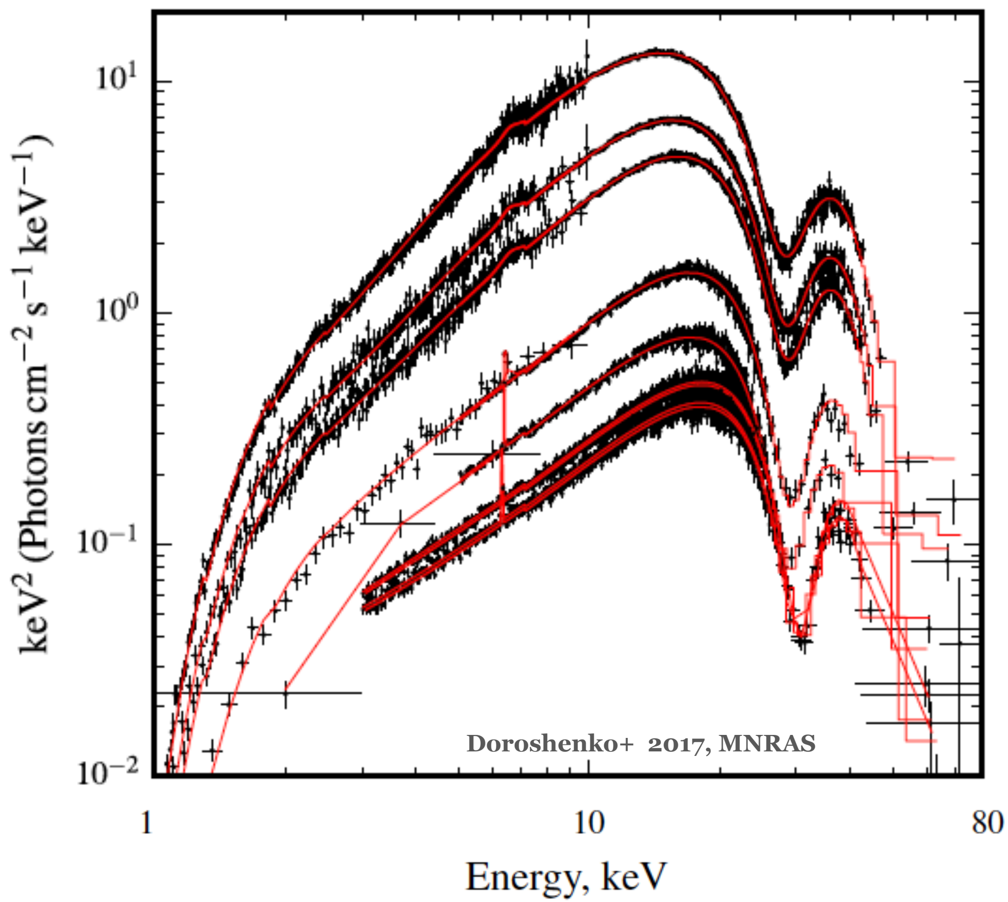
X-ray pulsar

Typical spectra





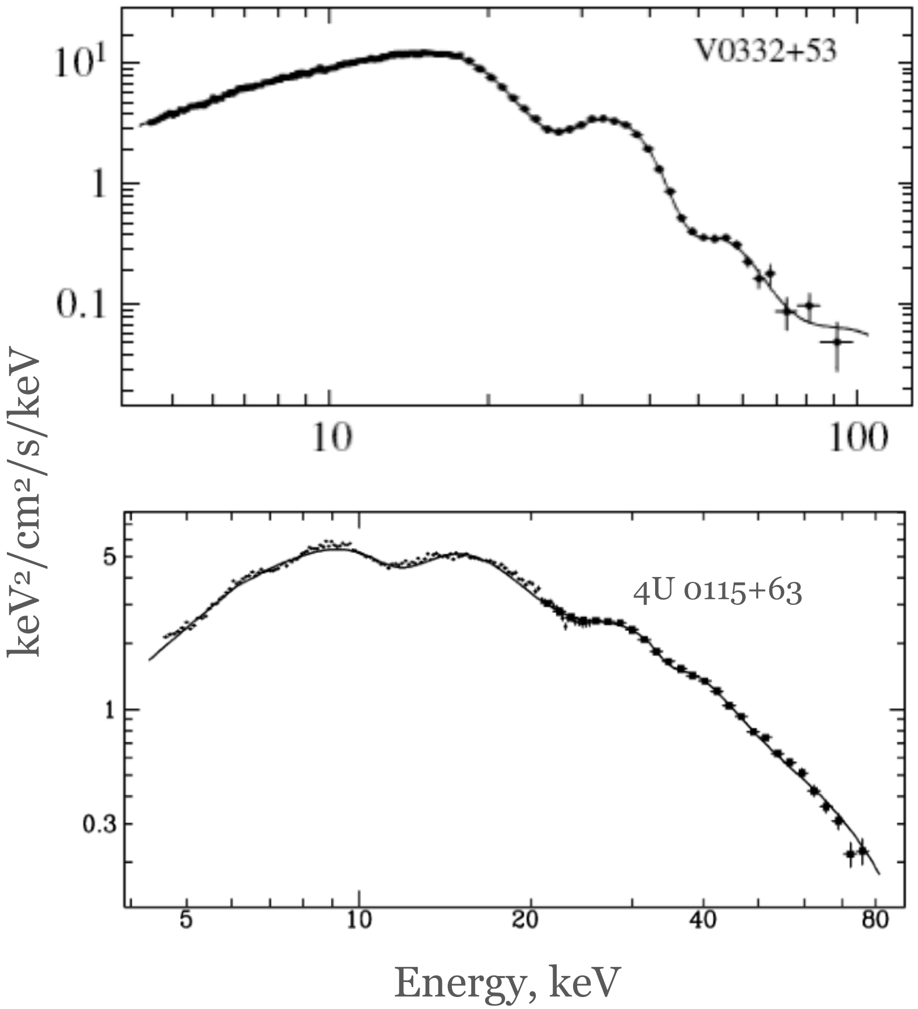
Spectra of V 0332+53 at different luminosity states



$$E_{\rm cyc} = 11.6\, B_{12}\, {\rm keV}$$

X-ray pulsar

Typical spectra

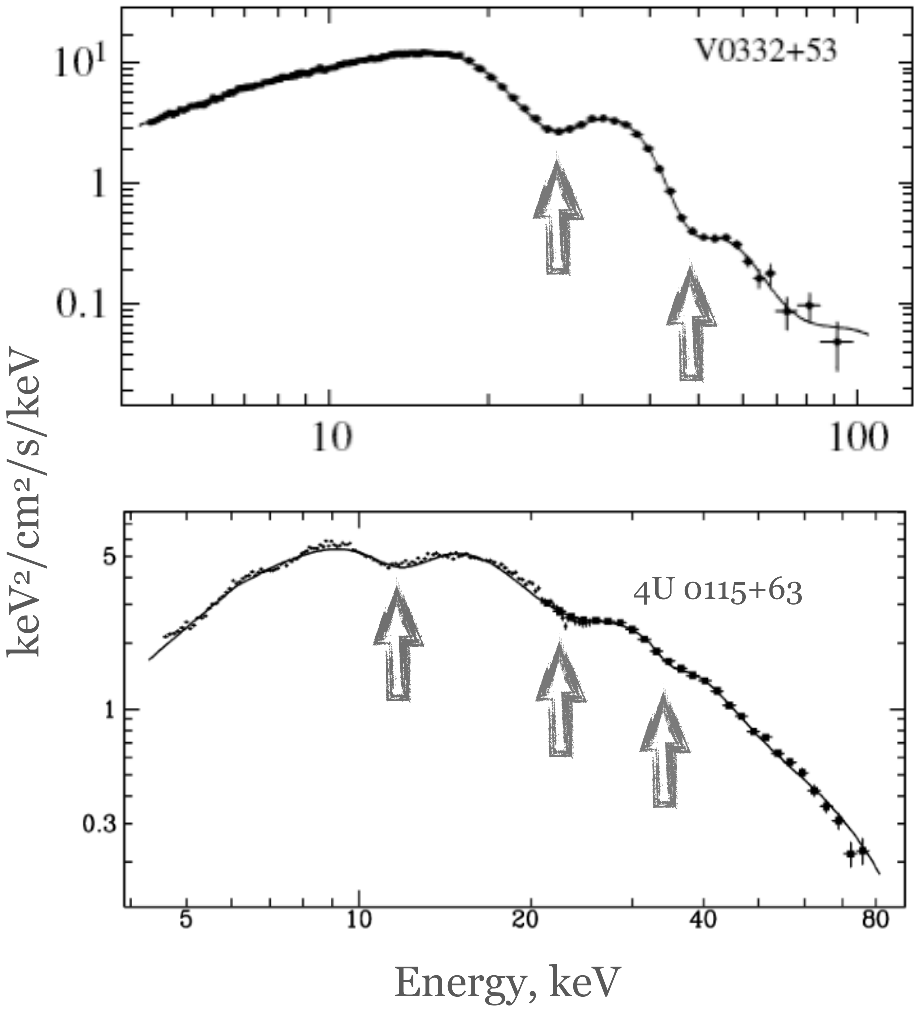


$$E_{\rm cyc} = 11.6\, B_{12}\,\rm keV$$

Source name	Cyclotron energy, keV
4U 0115+63 (−)	11.5, 20.1, 33.6, 49.5, 53
V 0332+53 (−)	28, 53, 74
4U 0352+309 (X Per)	29
RX J0440.9+4431	32
RX J0520.5-6932	31.5
A 0535+262	50, 110
MXB 0656–072	36
Vela X-1 (+)	27,54
GRO J1008-57	$88^?$, 75.5
1A 1118–61	55
Cen X-3	28
GX 301–2	37, 48
GX 304–1 (+)	50.8
4U 1538–52	20, 47
Swift J1626.6–5156	10
4U 1626–67	37
Her X-1 (+)	42
OAO 1657–415	36
GRO J1744–28	4.7
IGR J18179–1621	21
GS 1843+00	20
4U 1907+09	19, 40
4U 1909+07	$44^?$
XTE J1946+274	36
KS 1947+300	12.5
EXO 2030+375	$11^?$, $36^?$, $63^?$
Cep X-4	30

X-ray pulsar

Typical spectra



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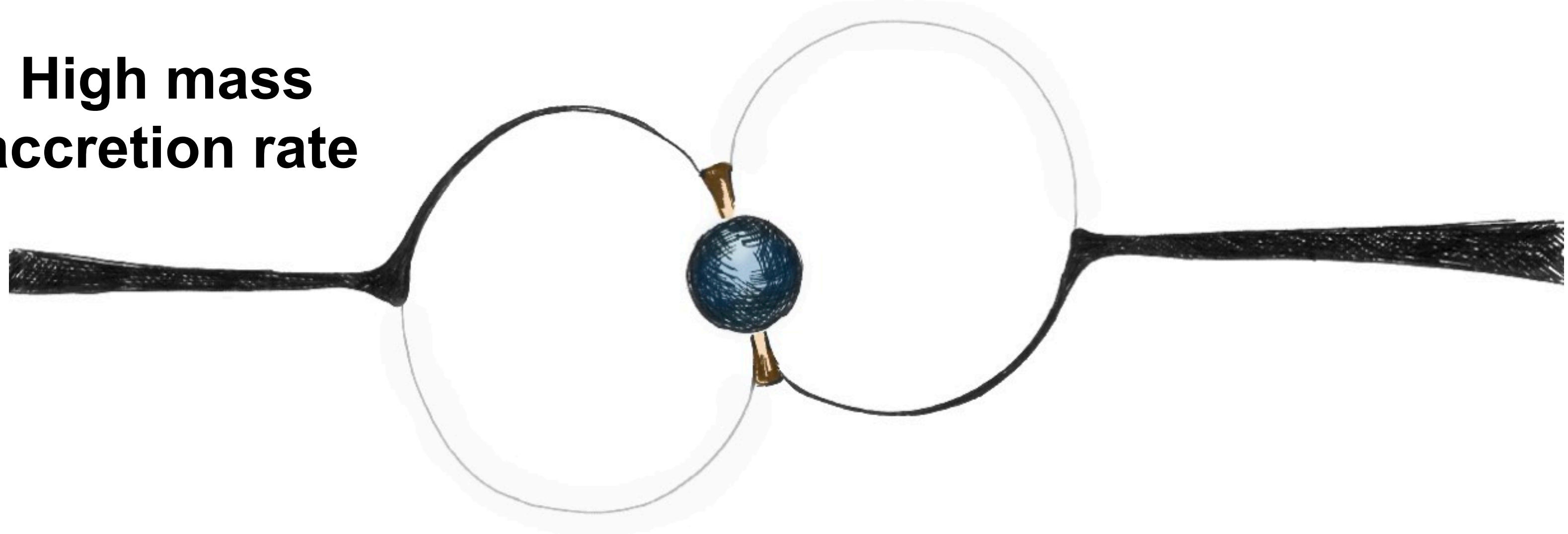
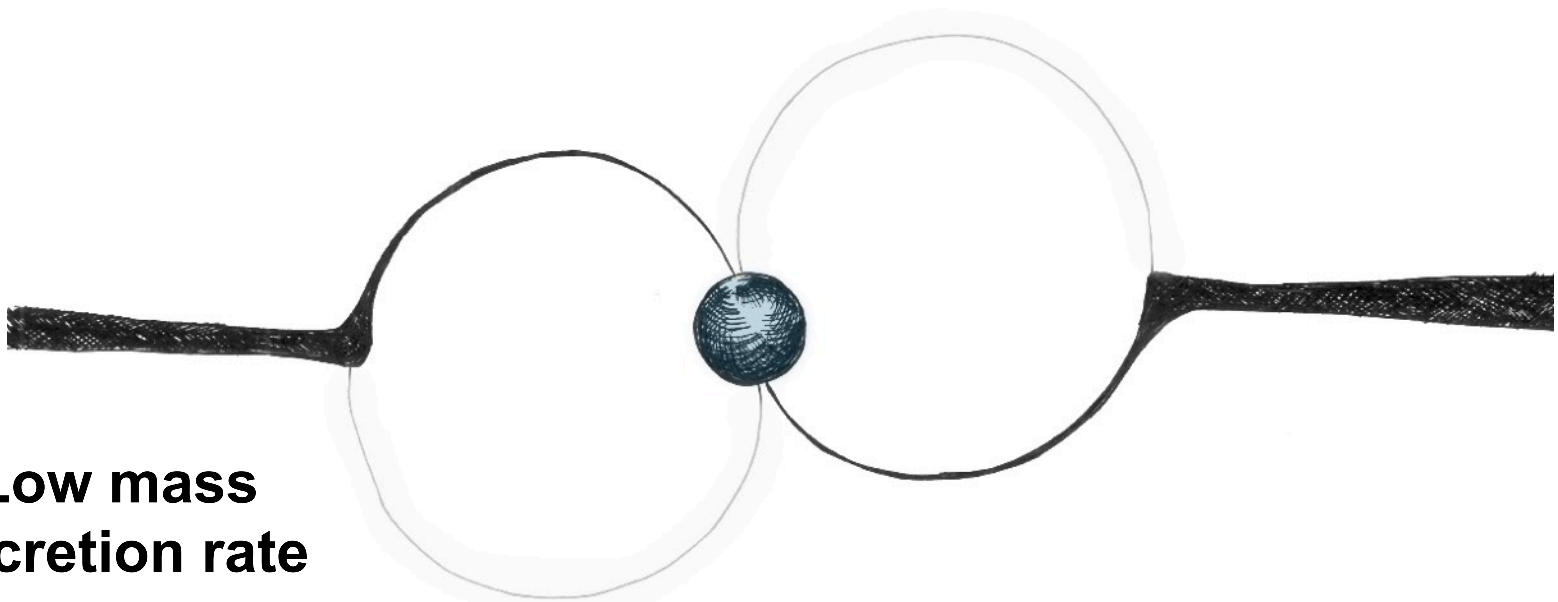
High mass accretion rate

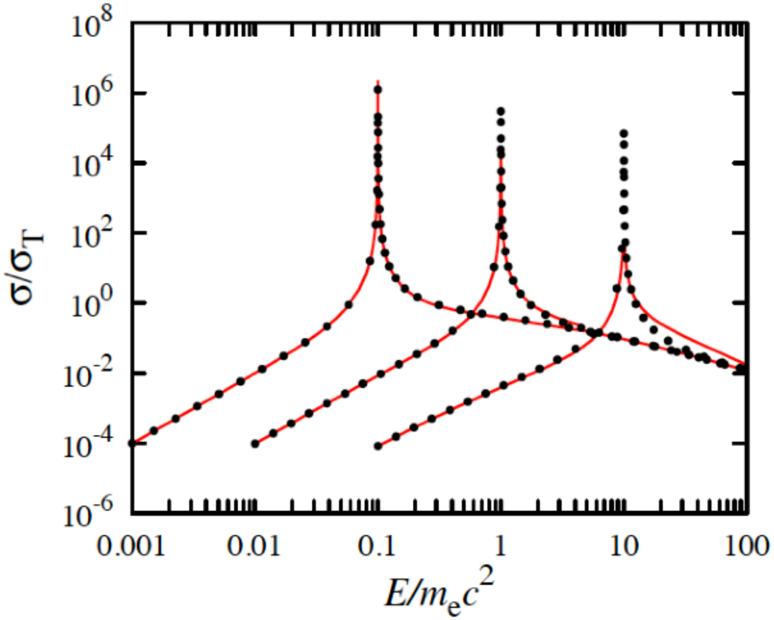


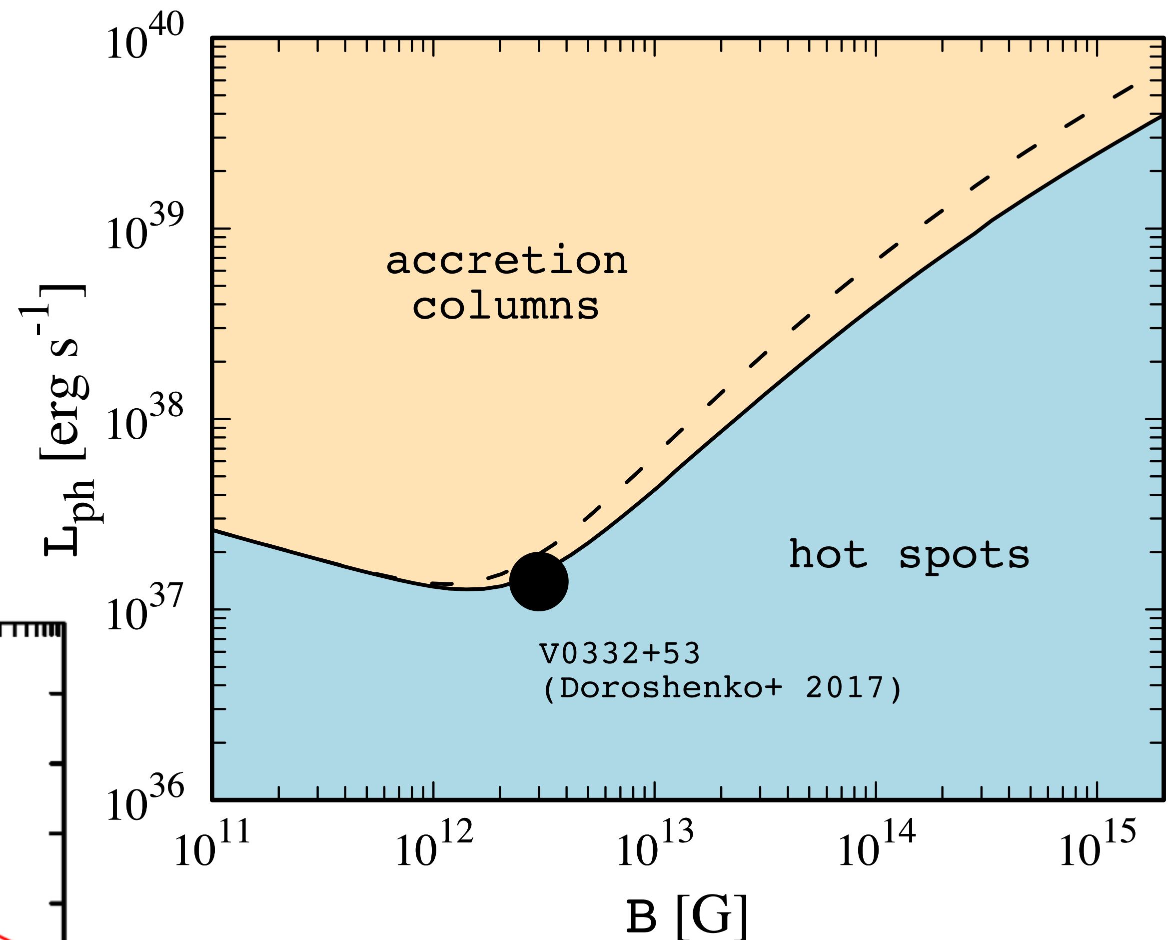
Critical luminosity



Low mass accretion rate

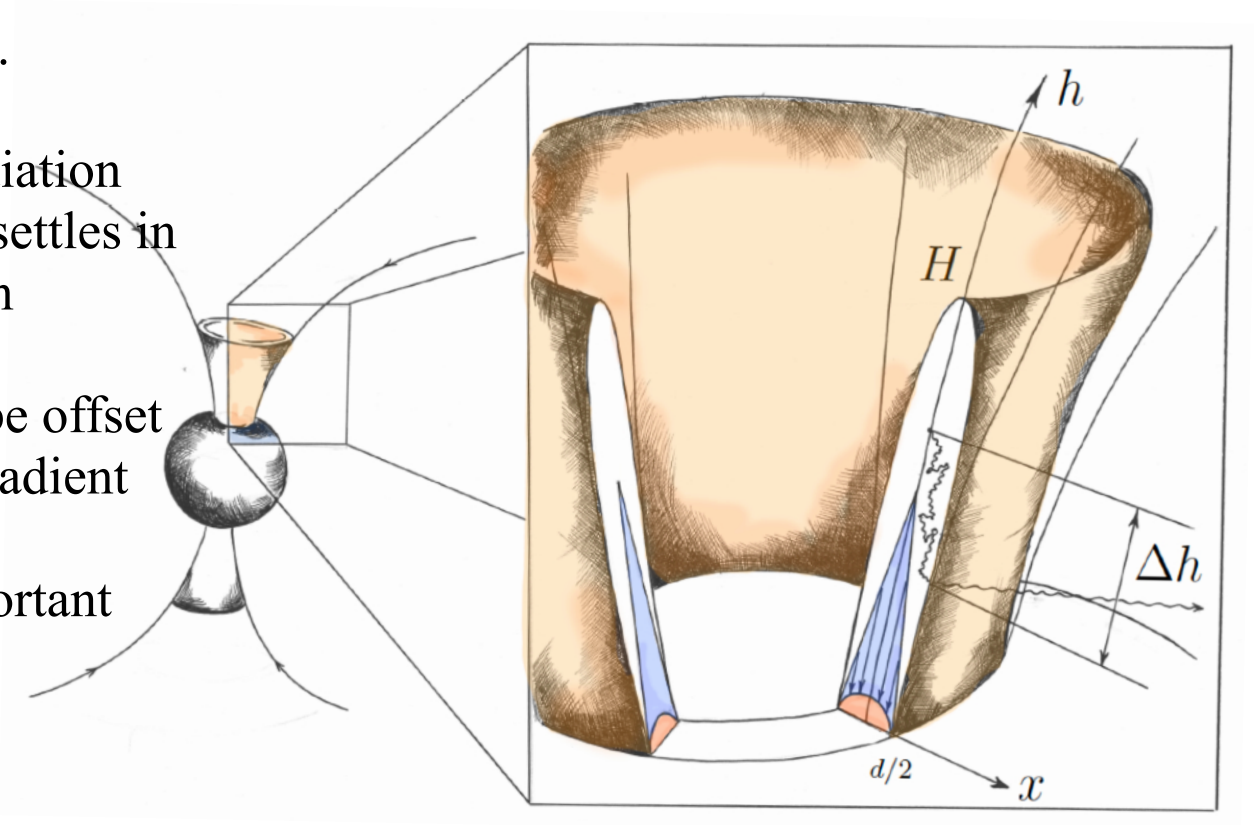
Critical luminosity





Above the critical luminosity: accretion column

Dipole magnetic field.
*
Accretion flow stops at radiation dominated shock and slowly settles in inside a sinking region
*
The gravitational force will be offset by the radiation pressure gradient
*
The gas pressure is unimportant

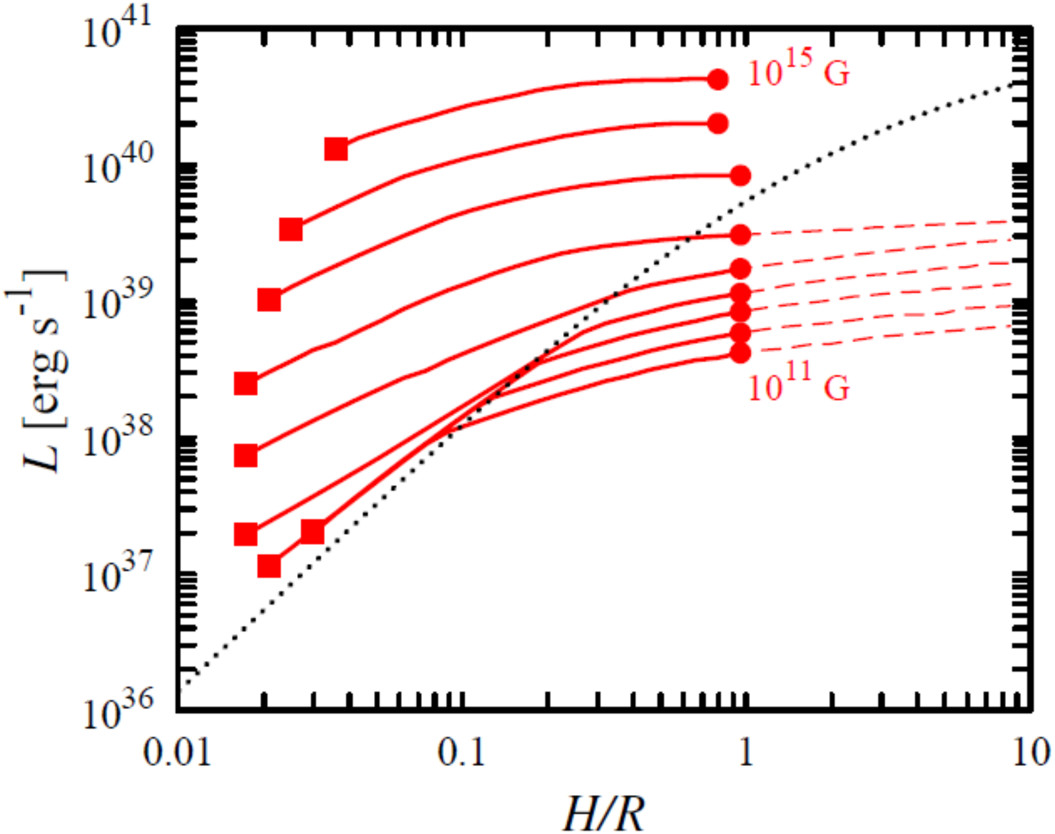


Crude analytical estimation:

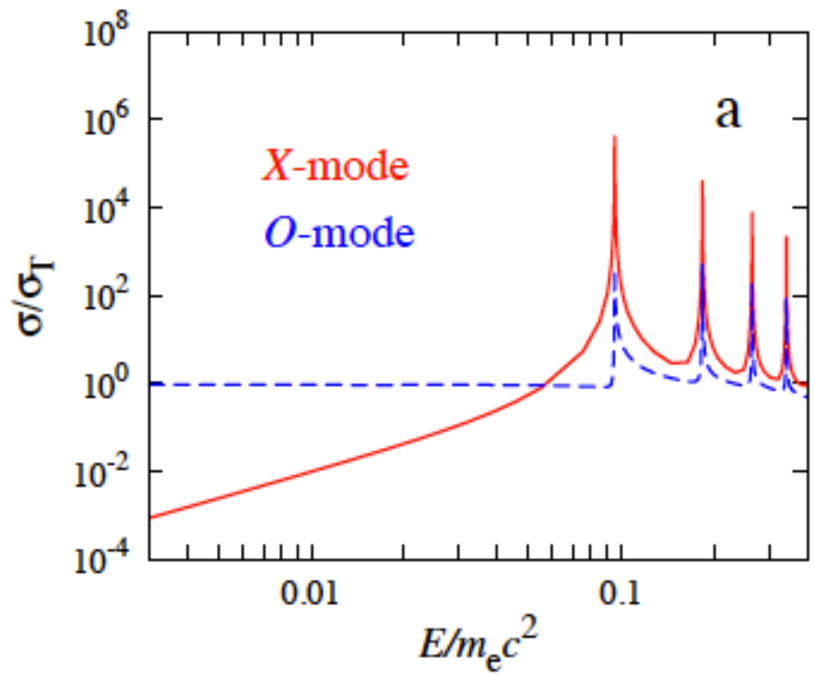
$$L(H=R) \approx 1.8\times 10^{39}\left(\frac{l_0/d_0}{50}\right)\left(\frac{\kappa_\mathrm{T}}{\kappa_\perp}\right)\frac{M}{\mathrm{M}_\odot}\mathrm{erg\,s}^{-1}$$

Stable accretion columns cannot be infinitely bright

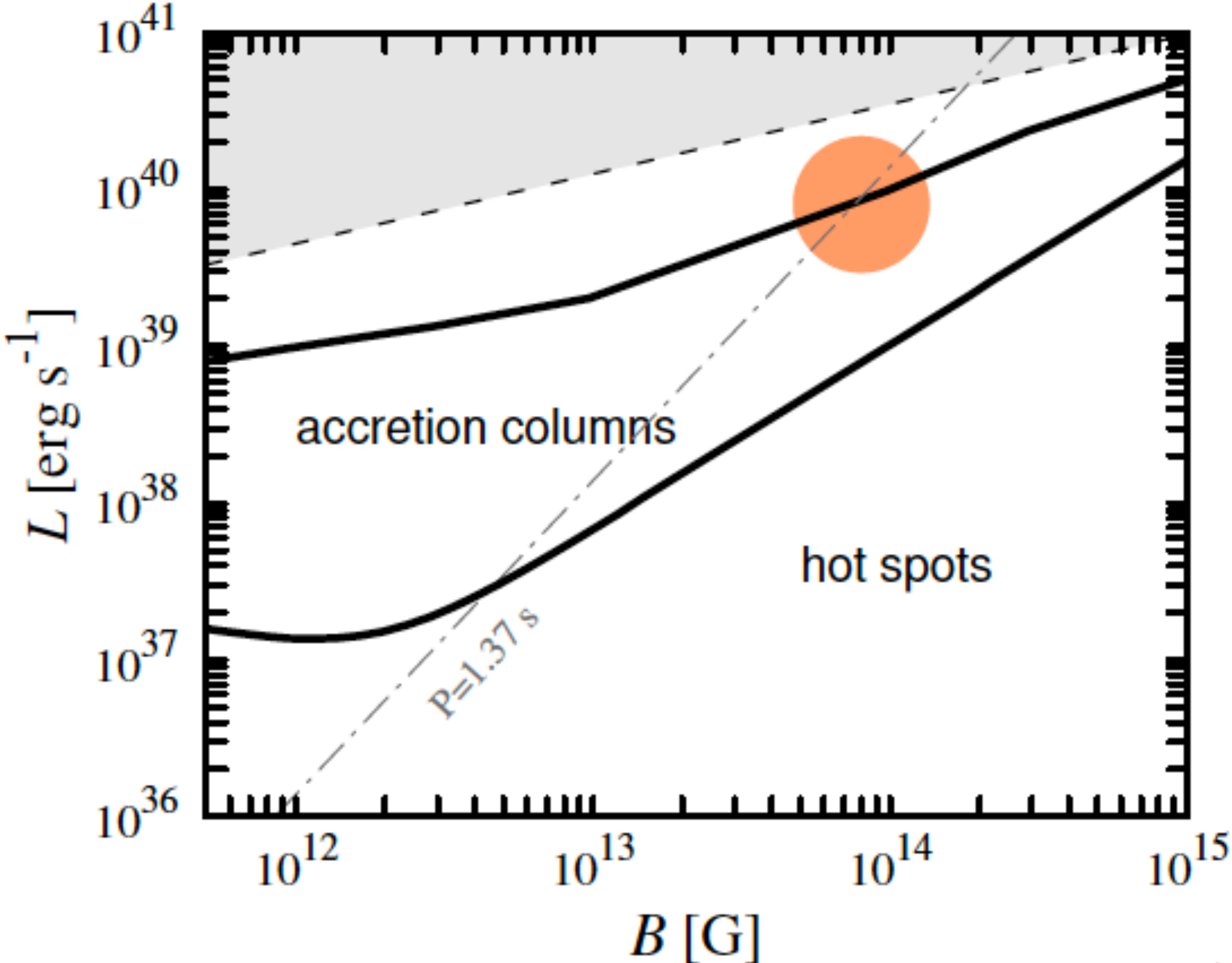
Luminosity of accretion column as a function of column height



Scattering cross-section:
The higher the mass accretion rate
=> the higher the temperature
=> the higher photon energy
=> the higher the cross-sections

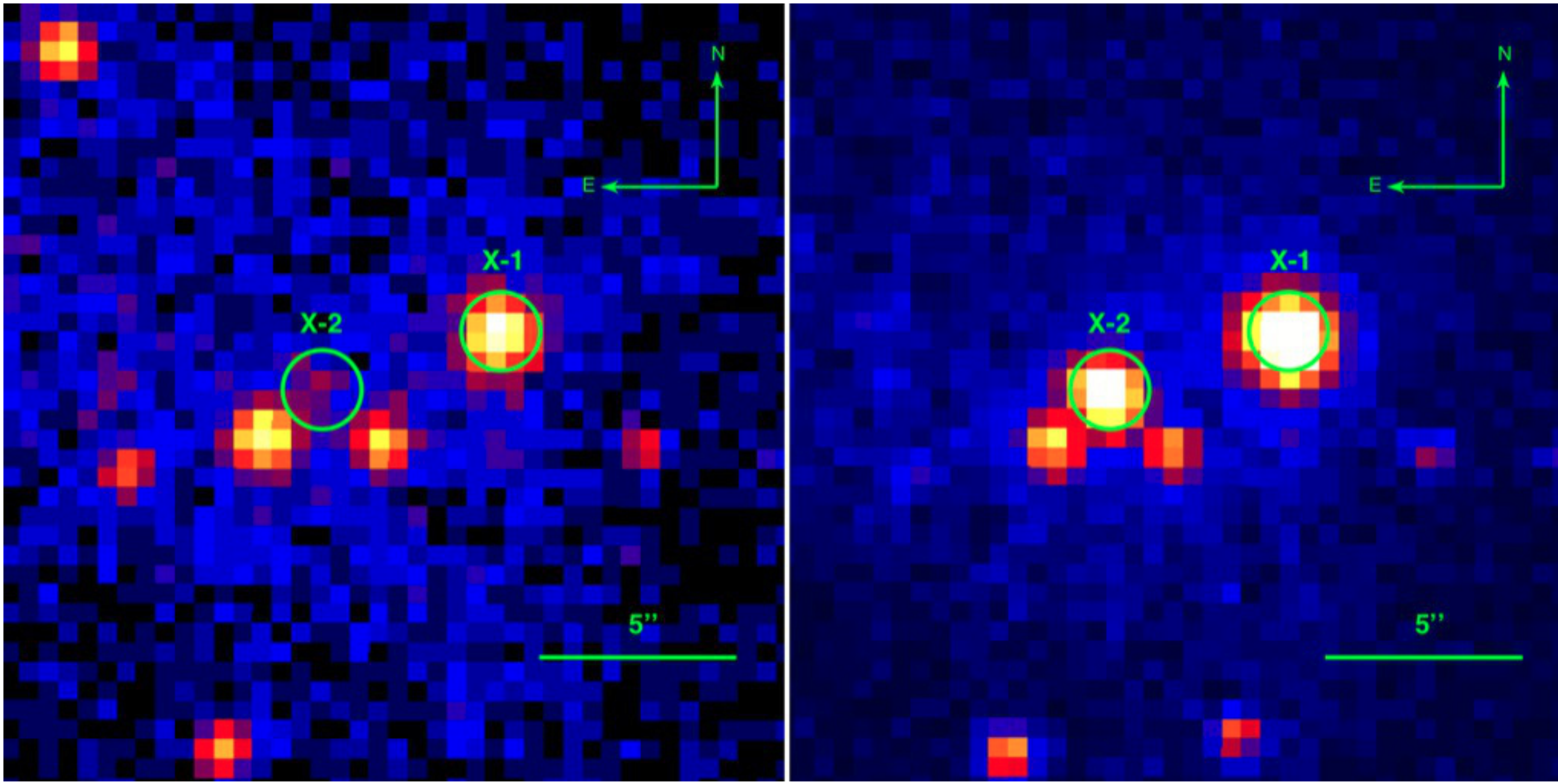


Pulsations from ULX in M82: explanation

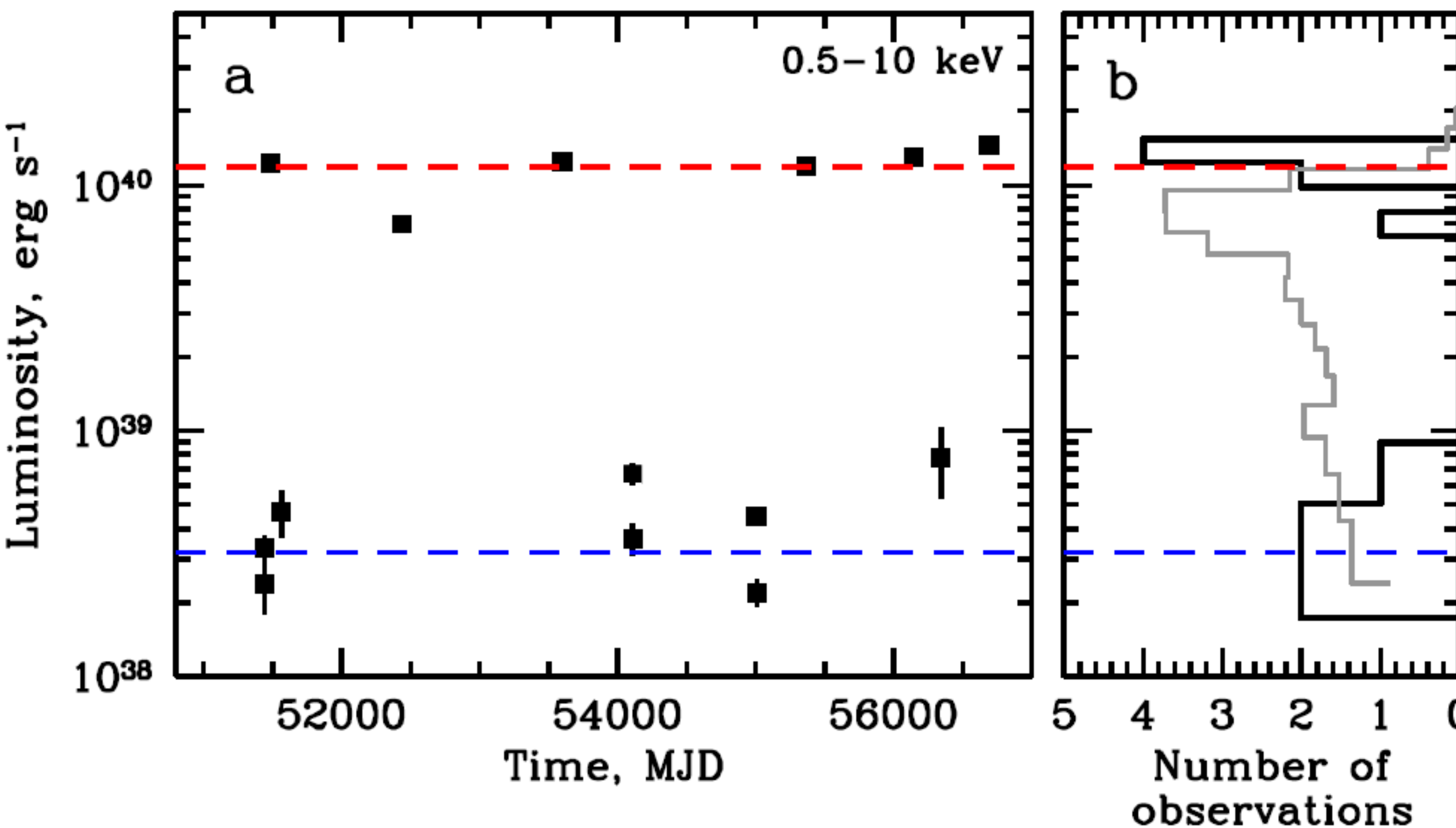


$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times10^{37}k^{7/2}B_{12}^{2}P^{-7/3}M_{1.4}^{-2/3}R_6^5\ {\rm erg\ s^{-1}}$$

M82 as seen by Chandra

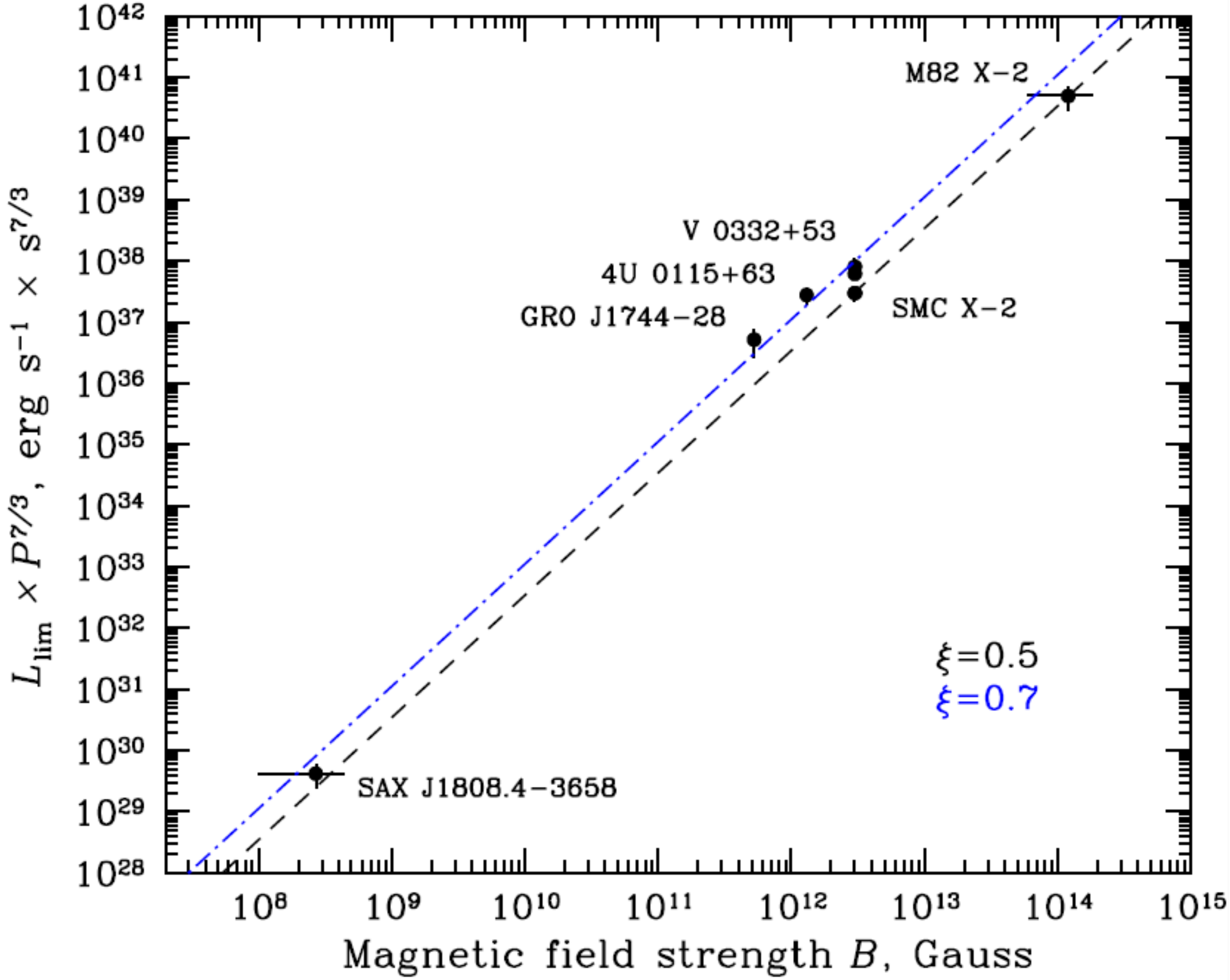


M82 X-2 intensity distribution

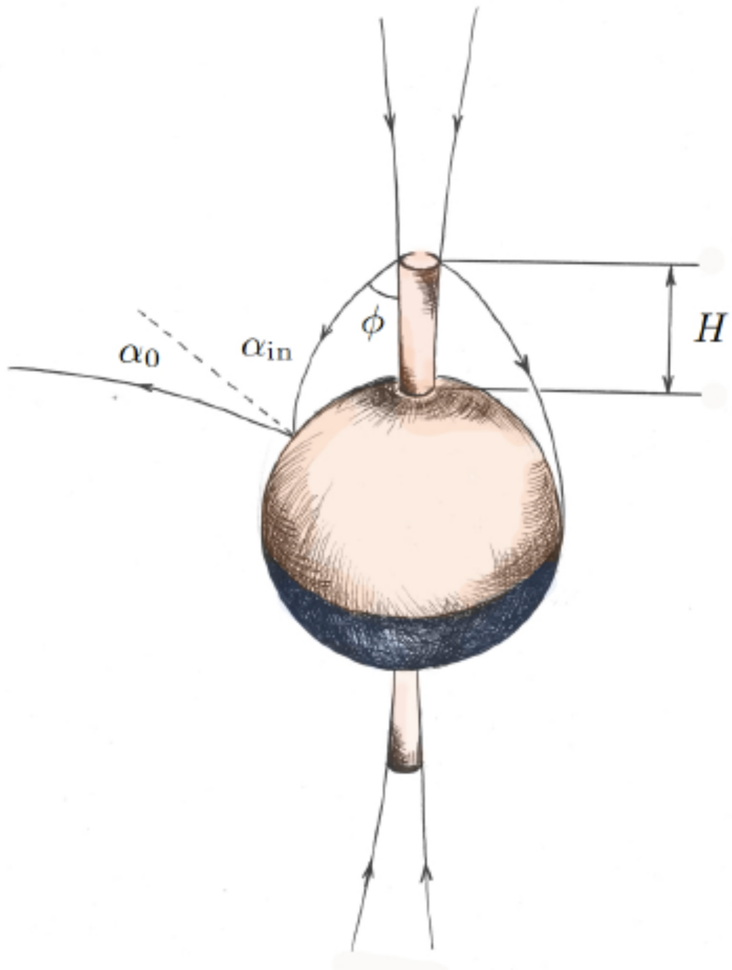


Propeller in action

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



Accretion column: radiation beaming



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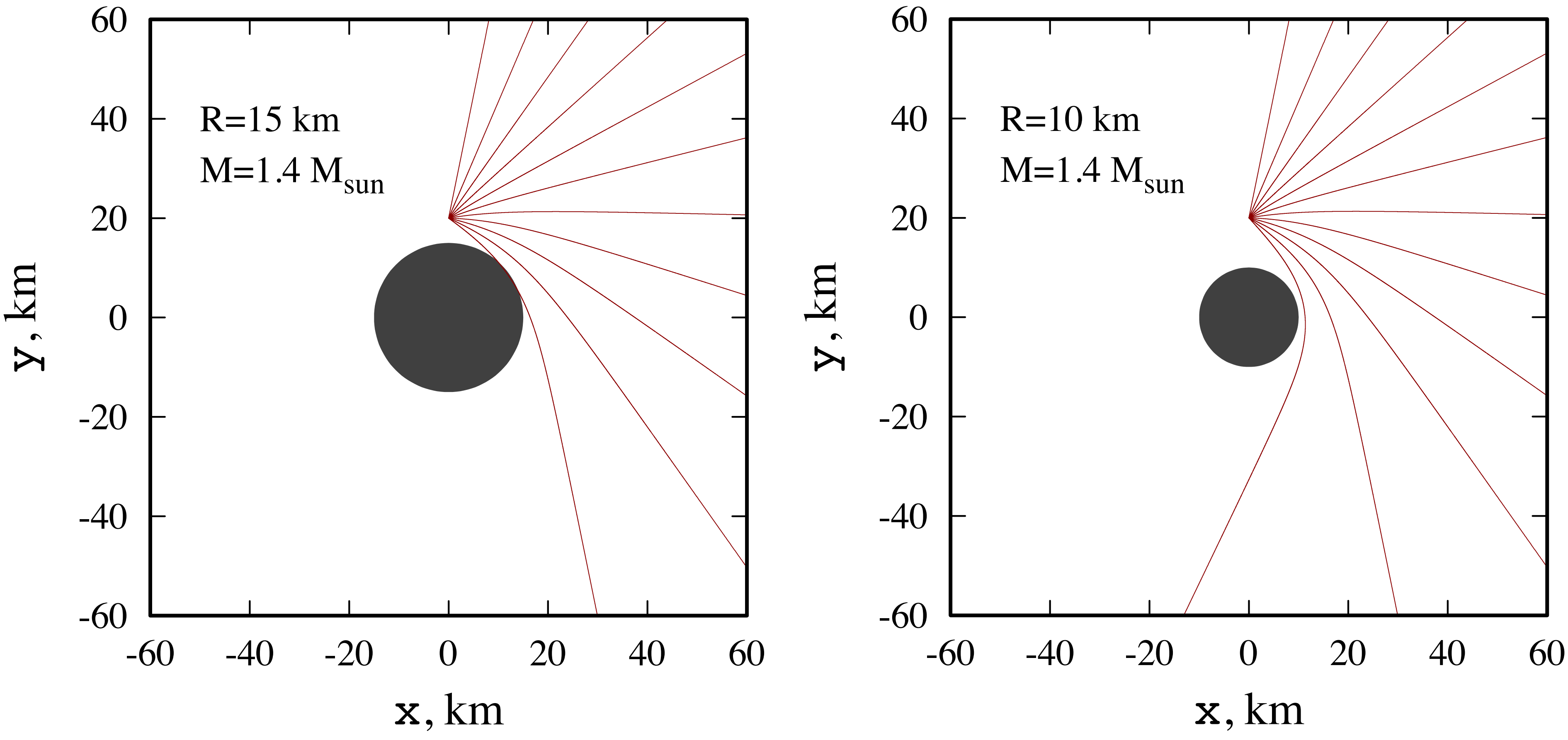

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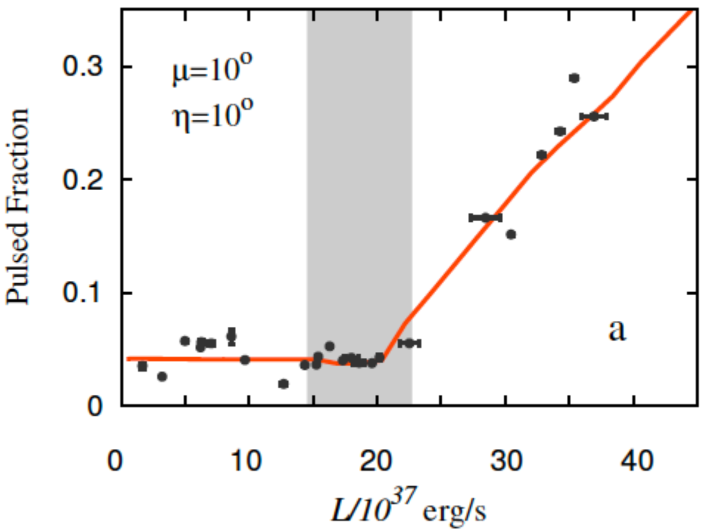
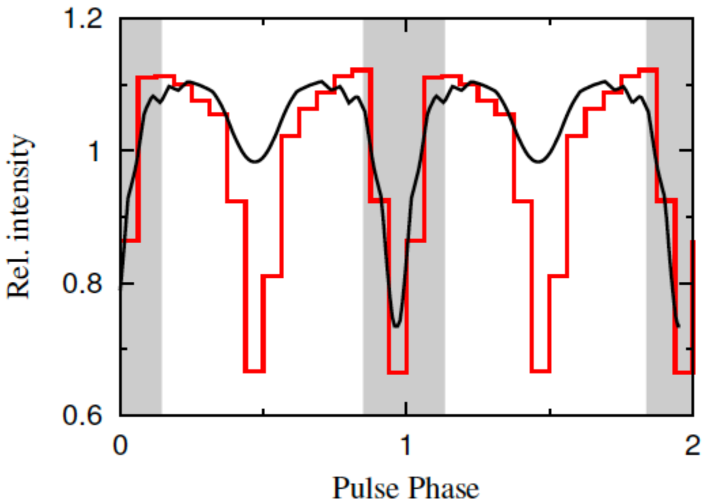
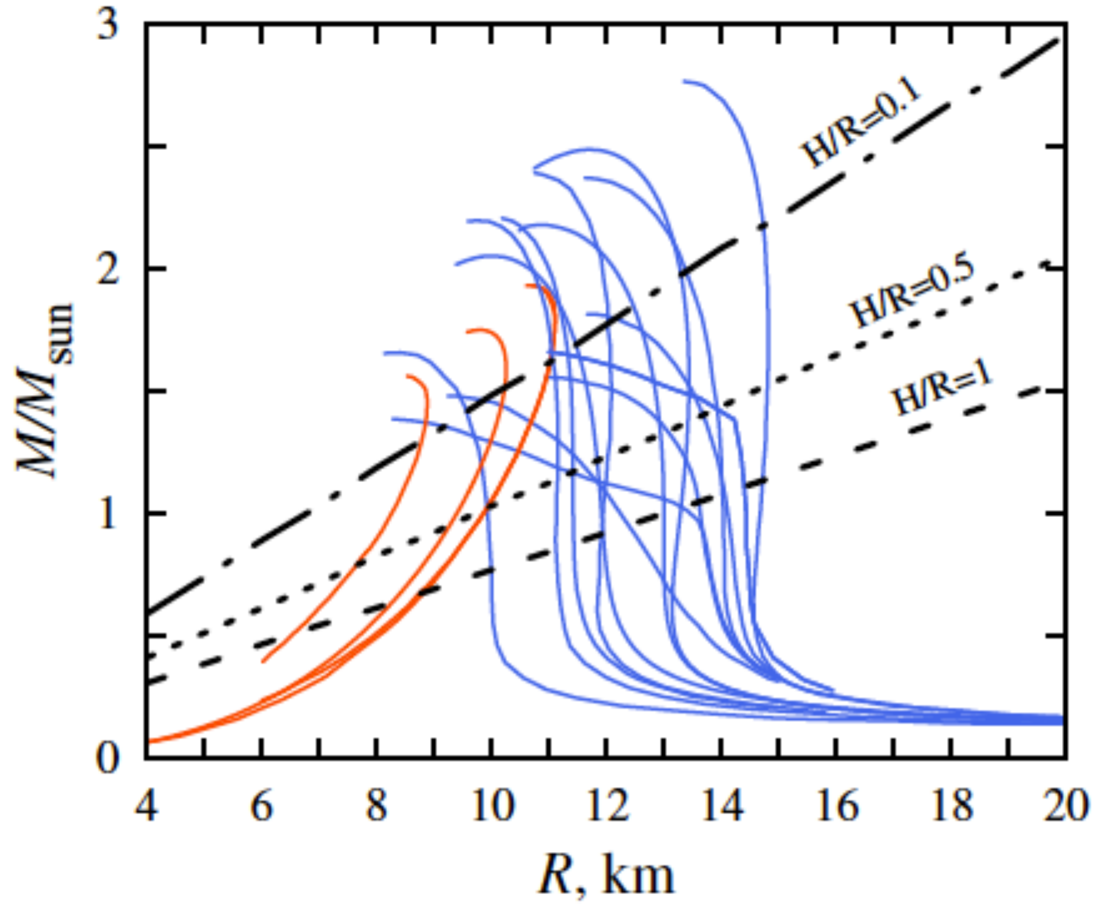




Accretion column eclipses
and
neutron star mass-radius relation

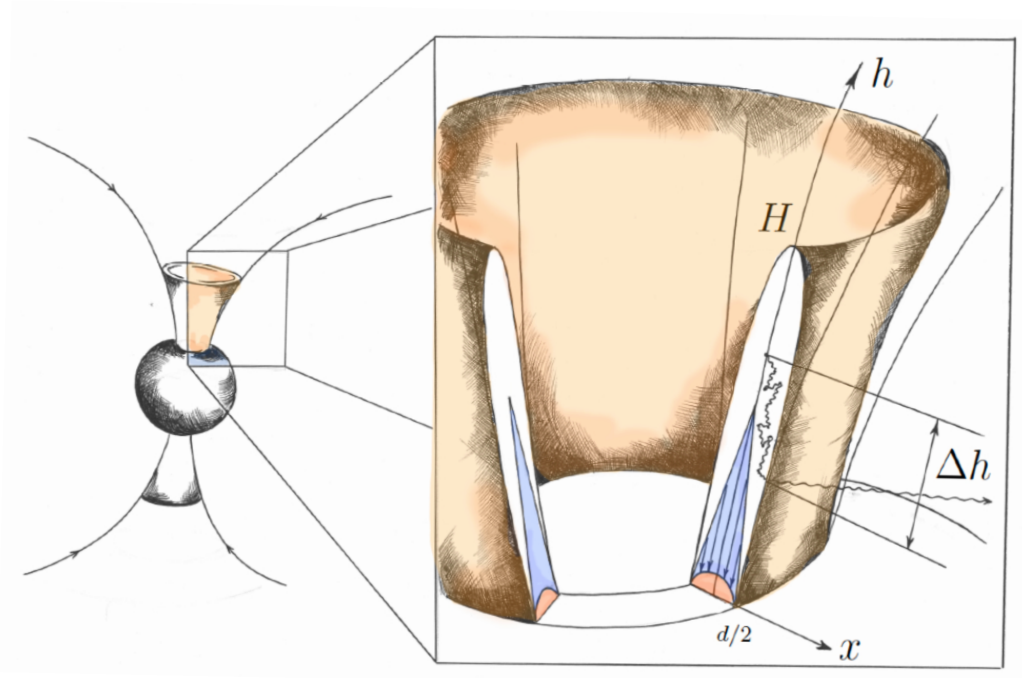


Accretion column:
Advection and Neutrino pulsars

Typical time of photon escape:

$$t_{\rm diff} = \frac{\tau d}{2c} \approx 5\times 10^{-4}\,\frac{\dot{m}_{10} d_4^2 \kappa_{\rm e}}{\beta}\ \ {\rm s}$$

$$\frac{\partial}{\partial h}\left[\left(-\frac{\rho G M}{R+h} + \frac{\rho v^2}{2} + \varepsilon_{\rm tot} + P_{\rm tot} + 2n_+ m_{\rm e} c^2\right) v\right] = Q^-$$

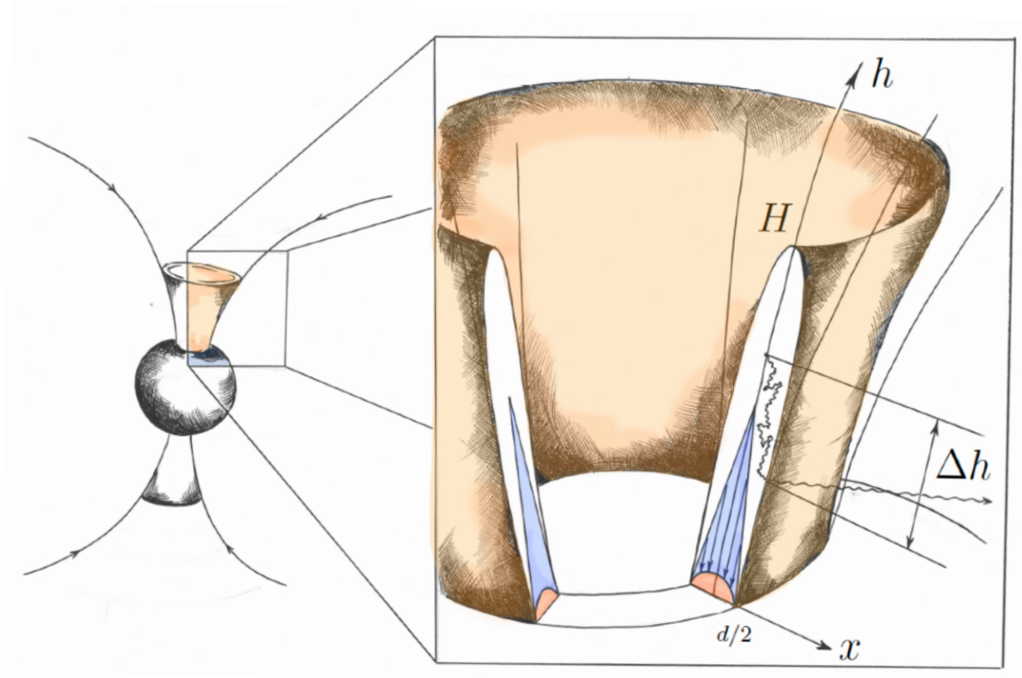


Accretion column: Advection and Neutrino pulsars

Typical time of photon escape:

$$t_{\rm diff} = \frac{\tau d}{2c} \approx 5\times 10^{-4}\,\frac{\dot{m}_{10} d_4^2 \kappa_{\rm e}}{\beta}\ \ {\rm s}$$

$$\frac{\partial}{\partial h}\left[\left(-\frac{\rho GM}{R+h}+\frac{\rho v^2}{2}+\varepsilon_{\rm tot}+P_{\rm tot}+2n_+ m_{\rm e} c^2\right)v\right] = Q^-$$



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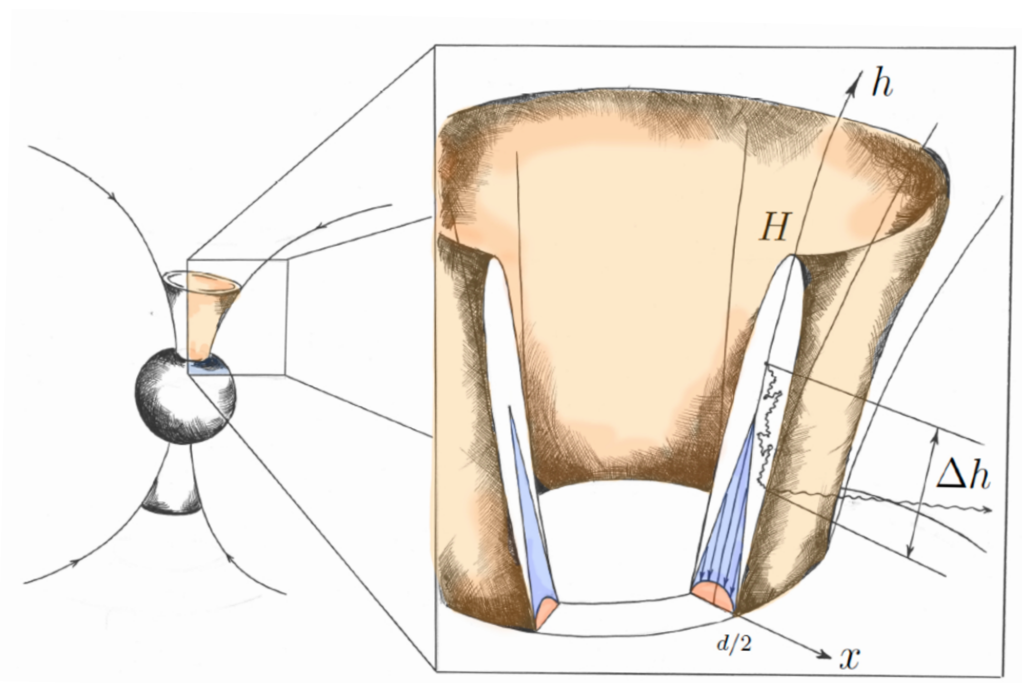

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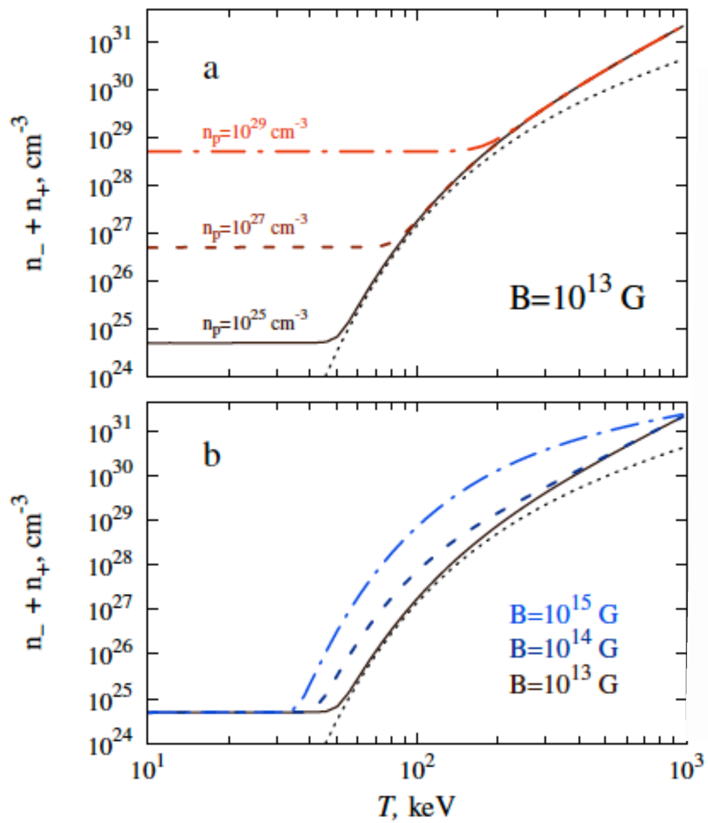

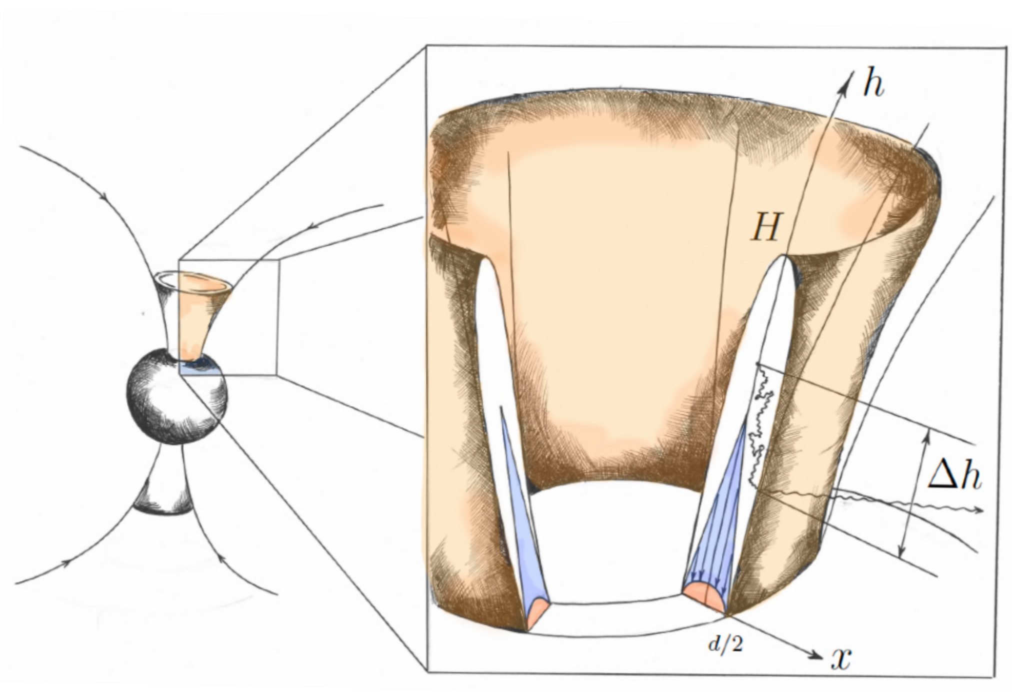

Accretion column: Advection and Neutrino pulsars

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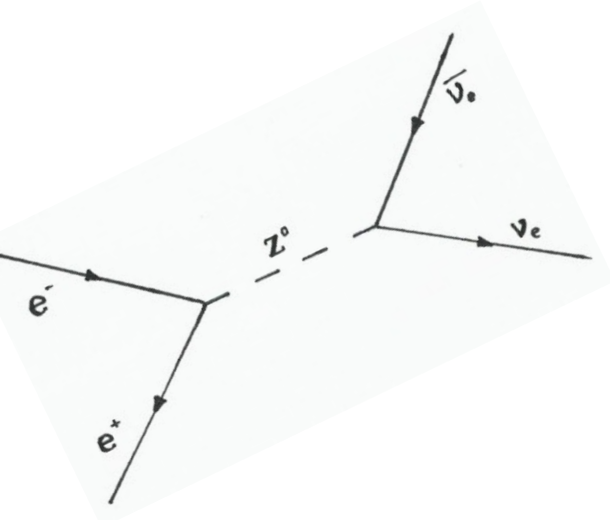

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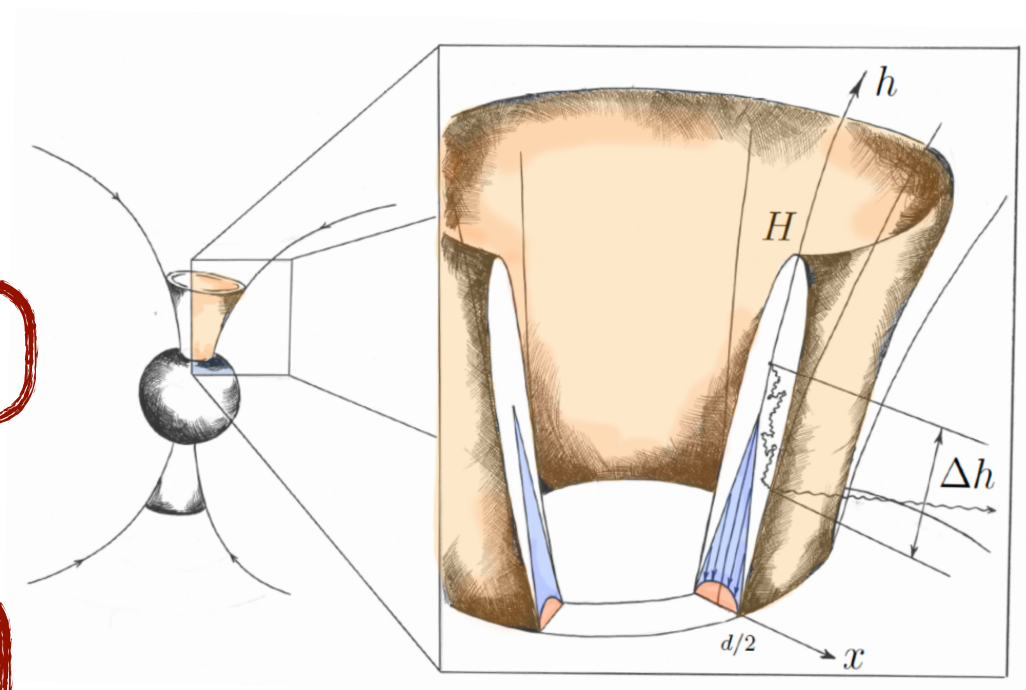
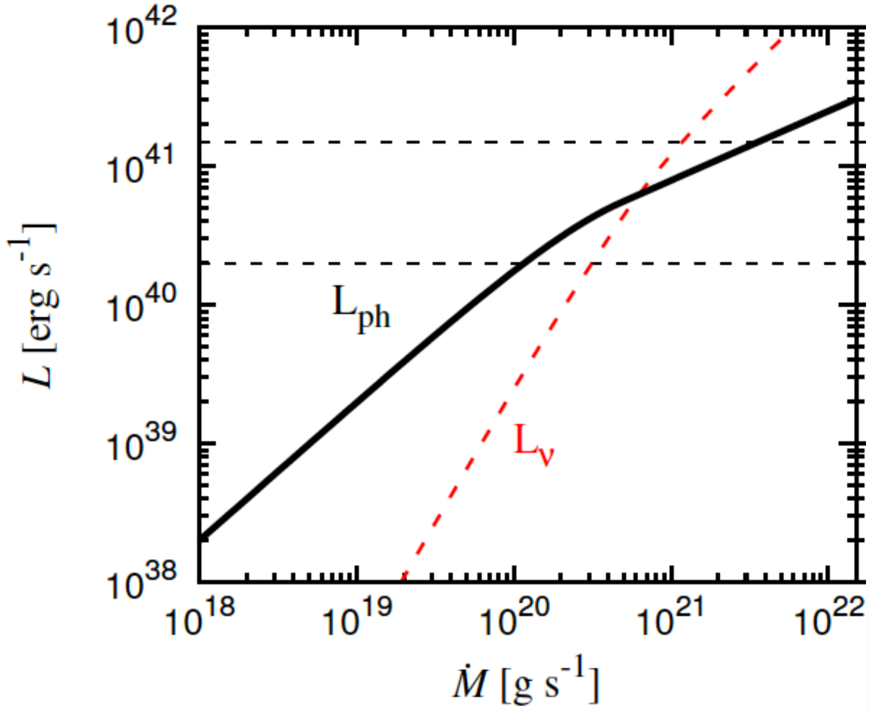
$$e^- + e^+ \longrightarrow \nu + \overline{\nu}$$

The total accretion luminosity:

$$L_{\rm tot} = \frac{G M \dot{M}}{R} = L_{\rm ph} + L_\nu$$



Accretion column: Advection and Neutrino pulsars



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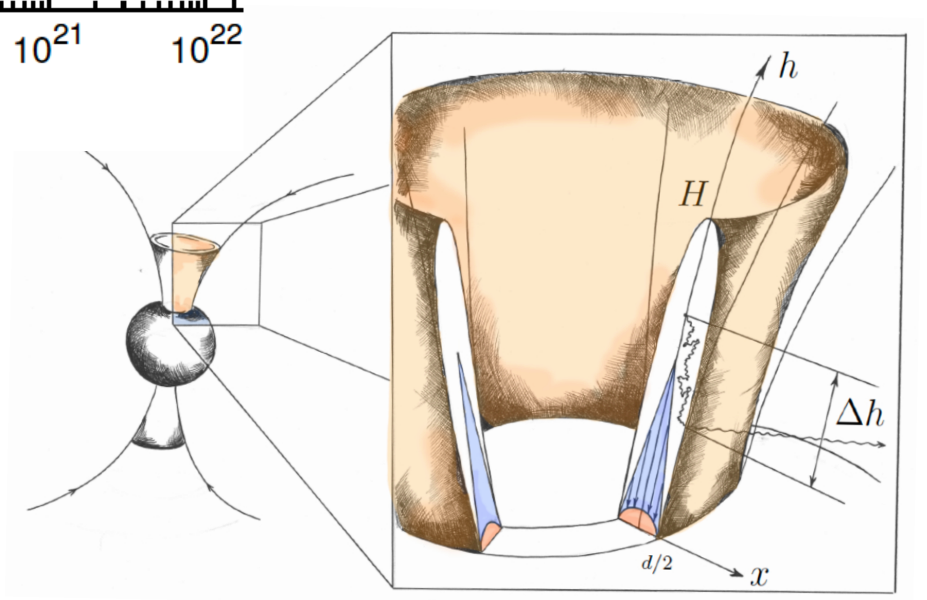
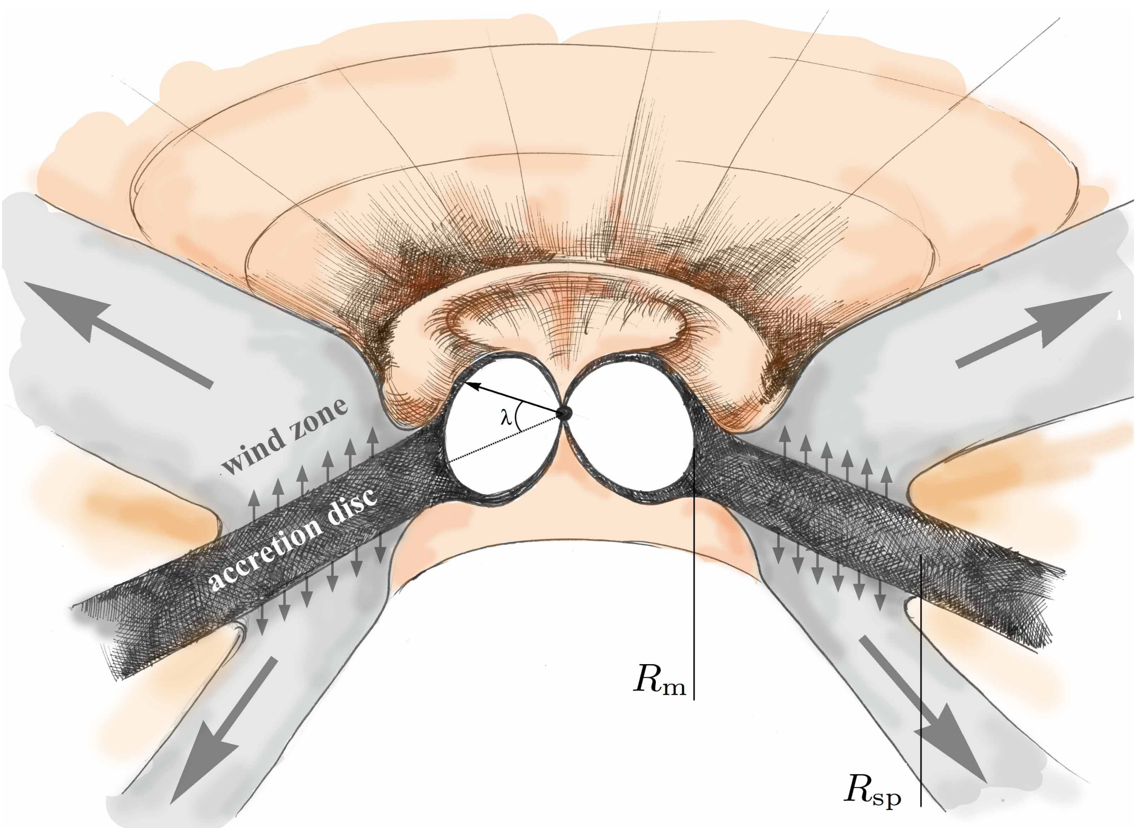
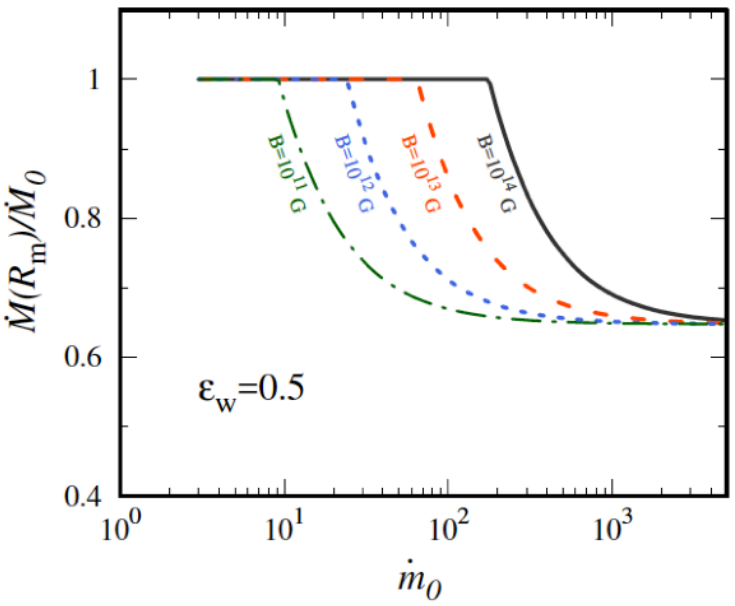
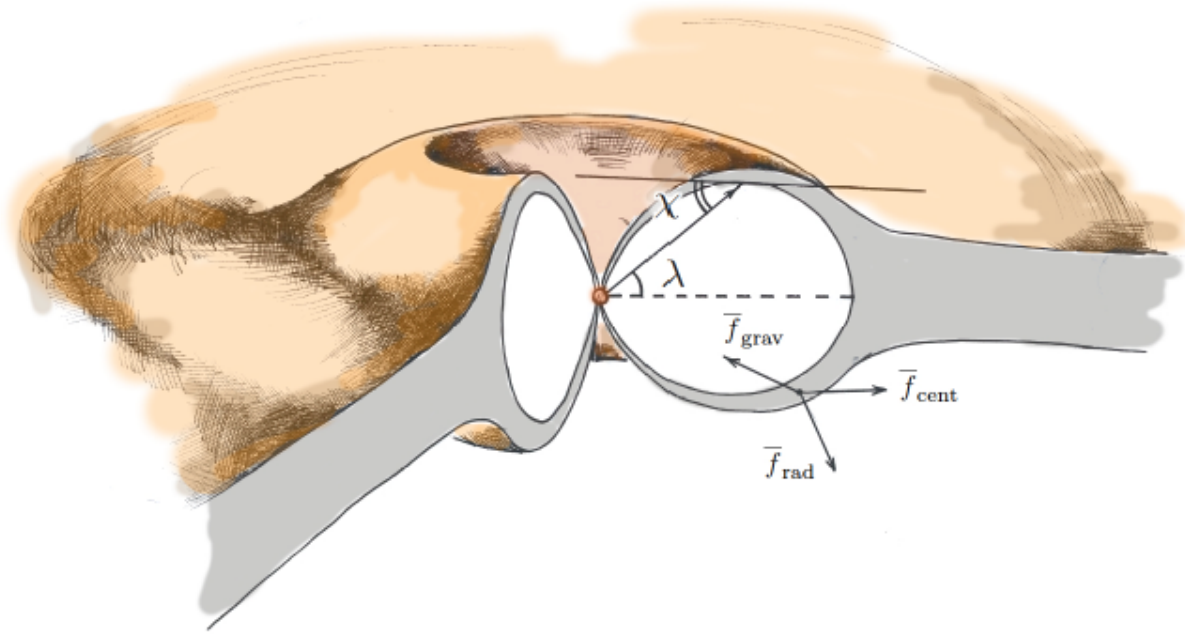


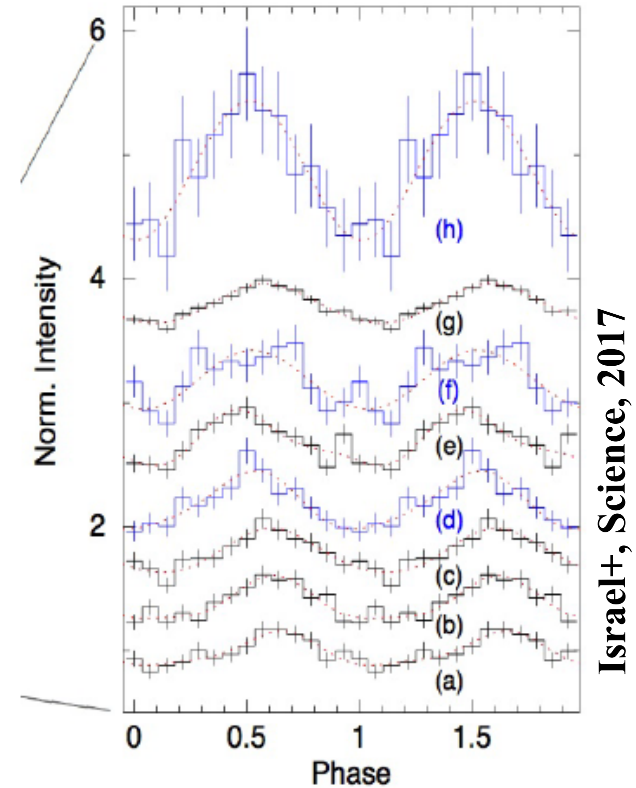
Outflows from accretion discs in ULX pulsars





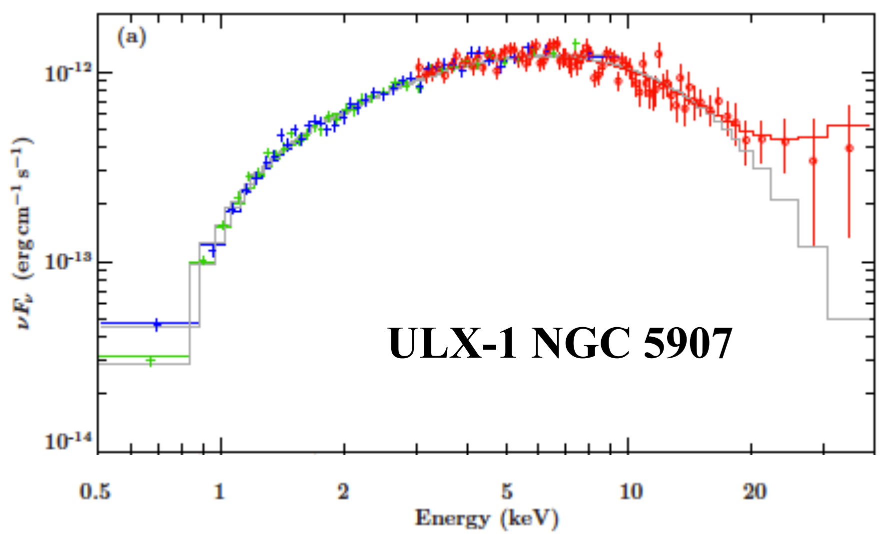
Accretion envelope



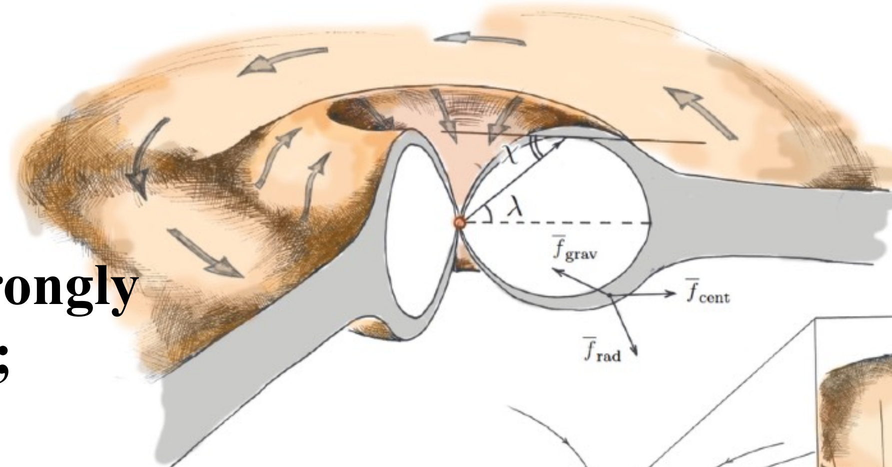


Some consequences:

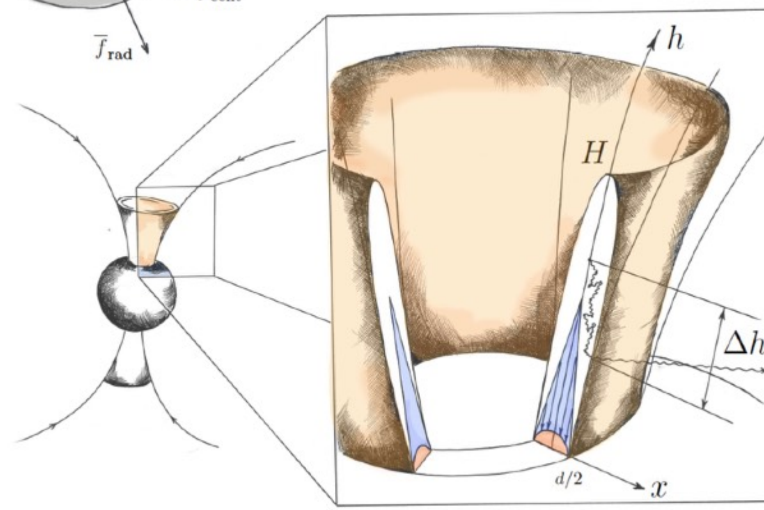
- we hardly see the central NS directly
- spectrum affected by Comptonization by the envelope
- smooth pulse profiles
- suppressed aperiodic variability at high Fourier frequencies
- super-orbital variability because of precession of magnetic dipole



Short Summary



(1) Accretion columns are the central engines in ULXs; their luminosity is strongly affected by geometry;



(2) The column becomes advective at extreme mass accretion rates; advective columns can produce strong neutrino emission;

(3) Bright ULXPs are surrounded by optically thick envelopes. The envelopes determine the observational manifestation of ULX pulsars;

(4) Strong outflow from the accretion disc in ULX pulsars is possible in the case of relatively weak dipole component of magnetic field

But

many and many details remain unclear and/or debated.

(1) magnetic field strength

(2) evolutionary status of ULX pulsars

(3) fraction of NS among ULXs

(4) fate of a companion star

(5) …