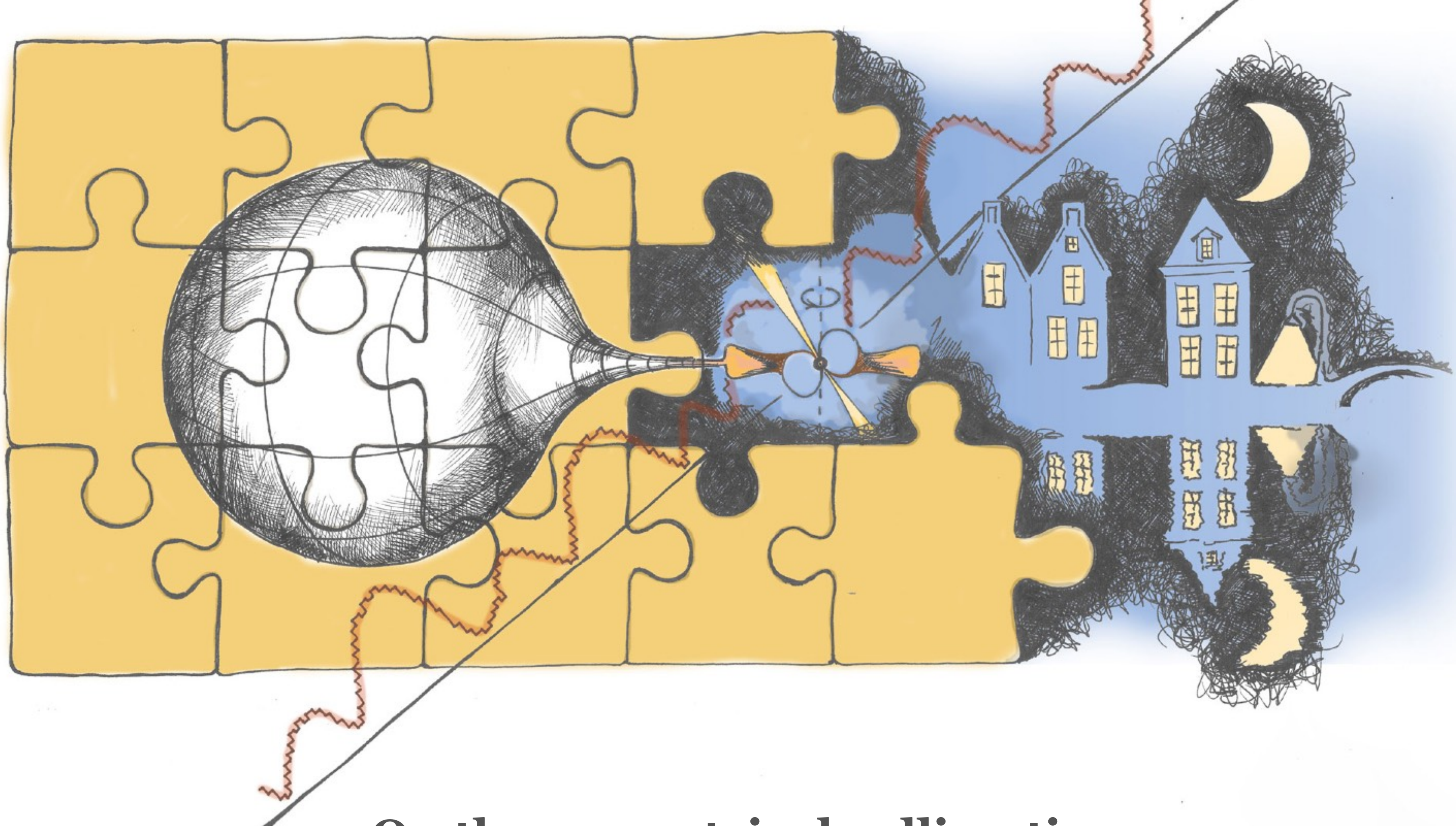
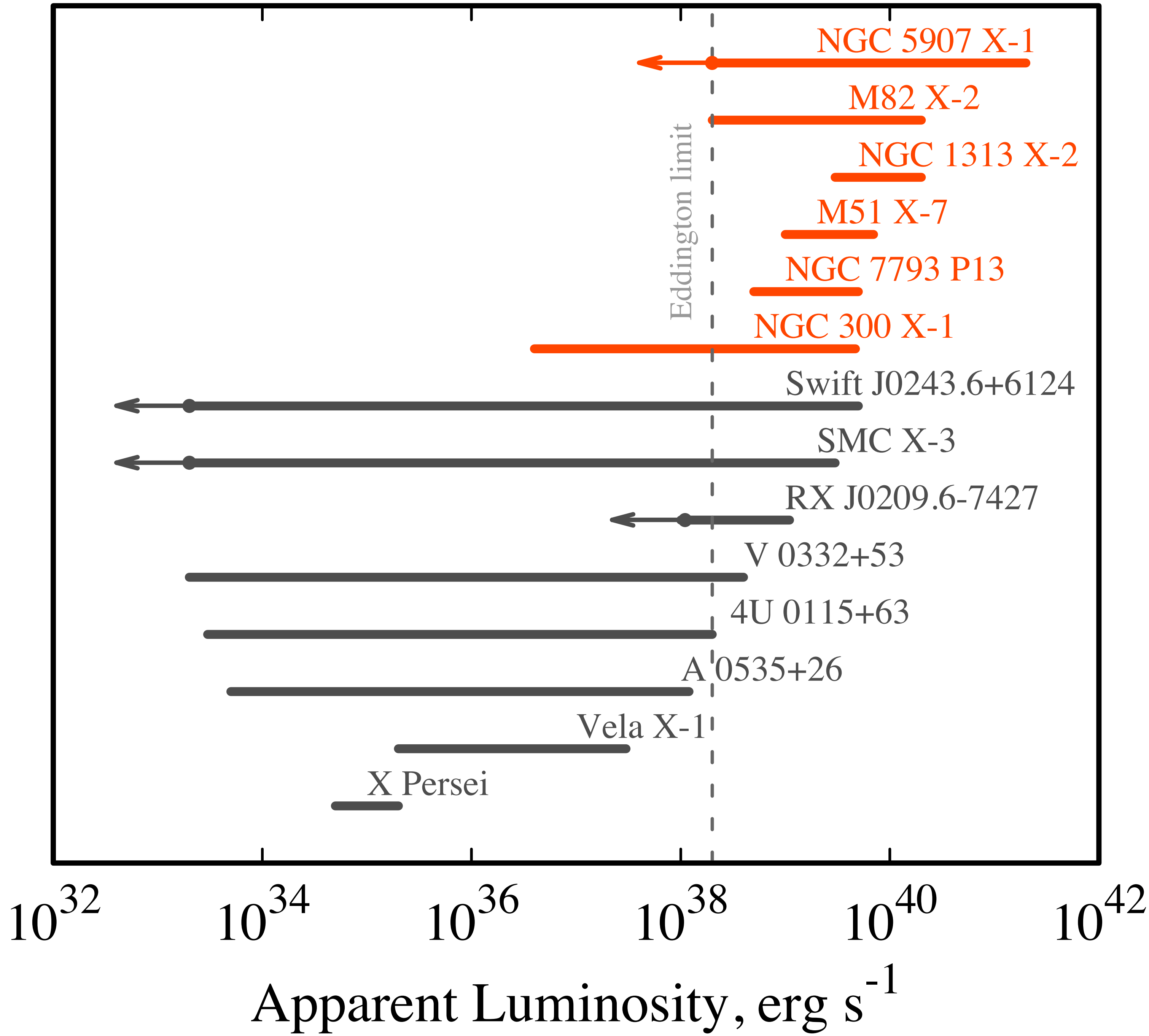


On the geometrical collimation in X-ray pulsars

(arXiv:2011.09710 & arXiv:2211.08952)

Alexander Mushtukov

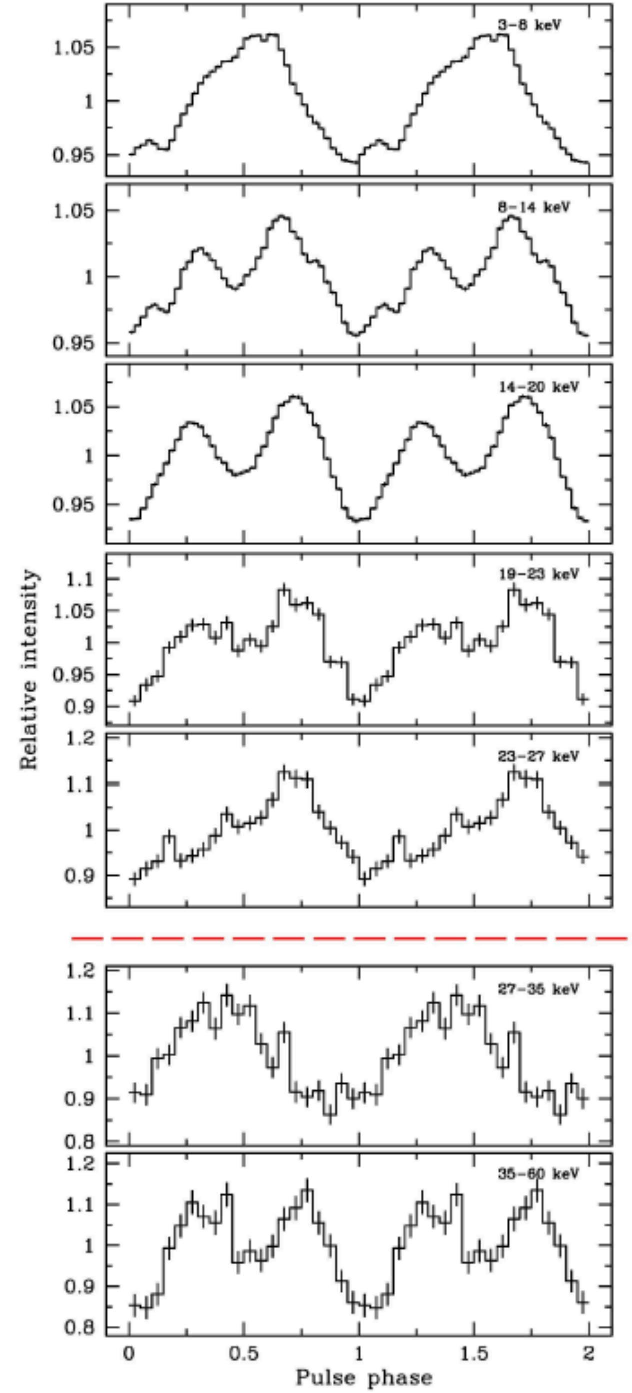
UNIVERSITY OF OXFORD



AM & Tsygankov, arXiv:2204.14185

Pulse Profiles in **V0332+53**: dependence on the energy range

L ~ 1.6×10^{38} erg/s



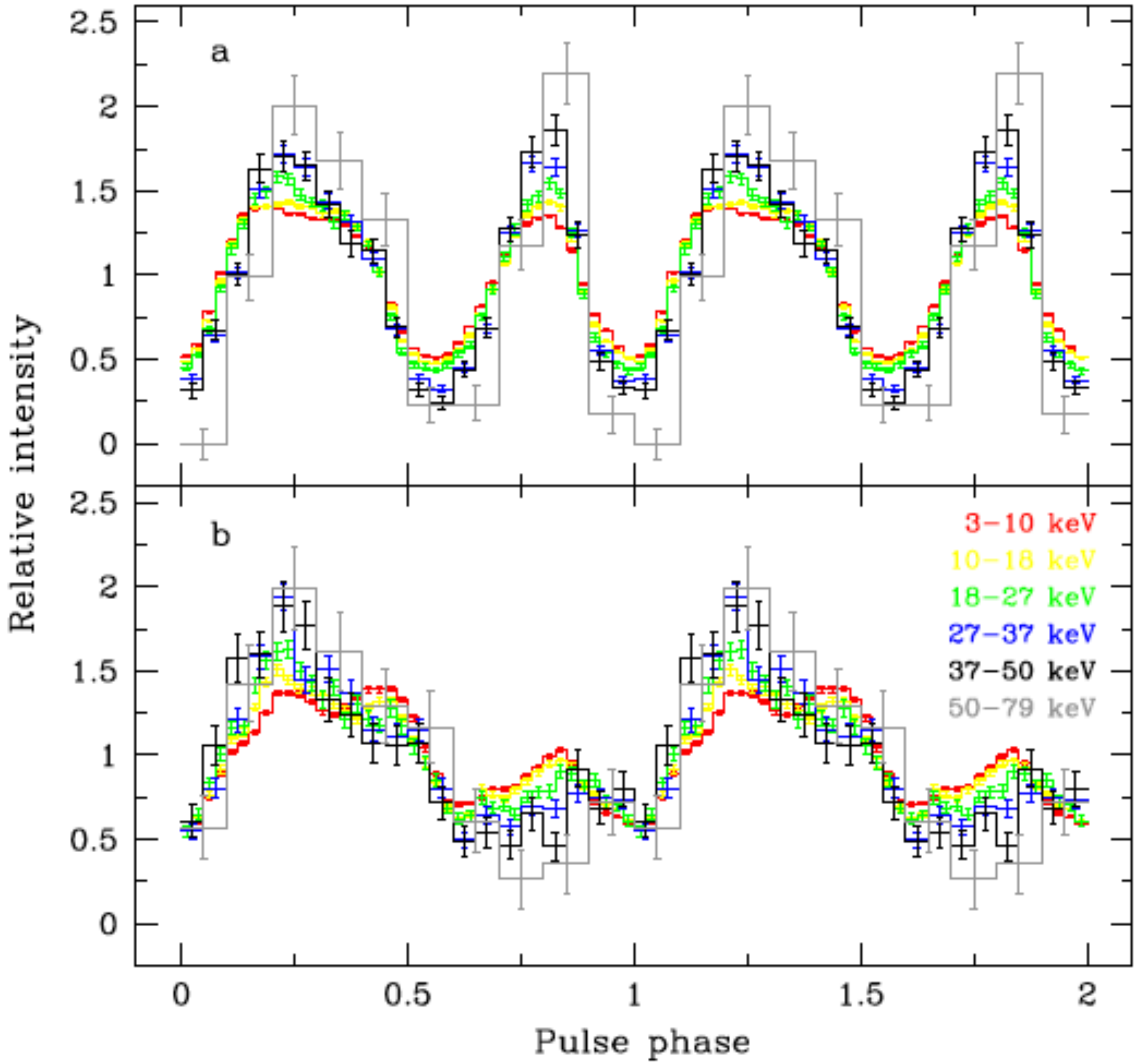
Tsygankov+, 2010, MNRAS, 401

Pulse Profiles in **SMC X-3**: dependence on luminosity

L ~ 10^{39} erg/s

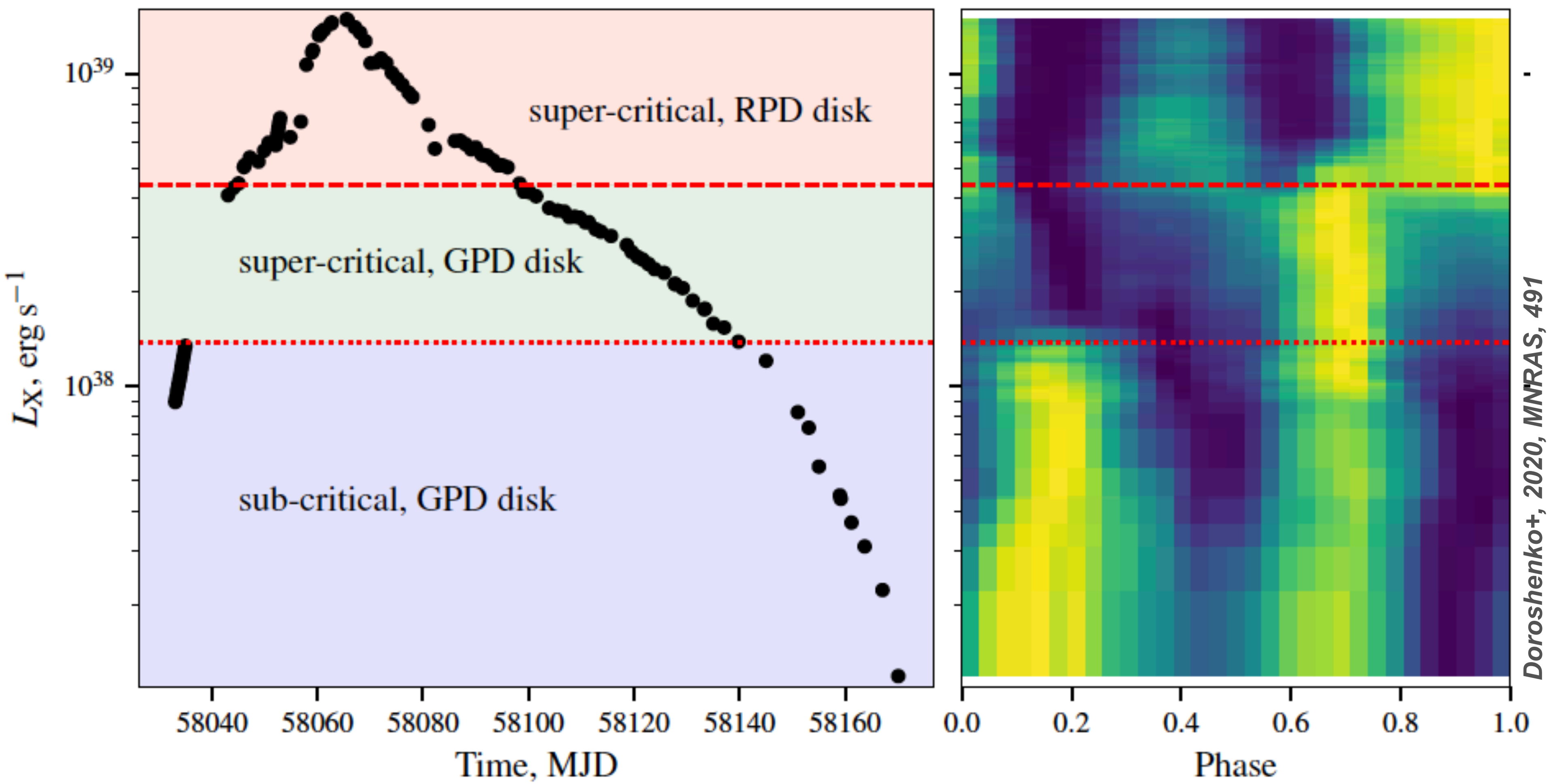
L ~ 1.9×10^{38} erg/s

Note: similar 2nd peak disappearance in Swift J0243 (?)



Tsygankov+, 2017, A&A, 605

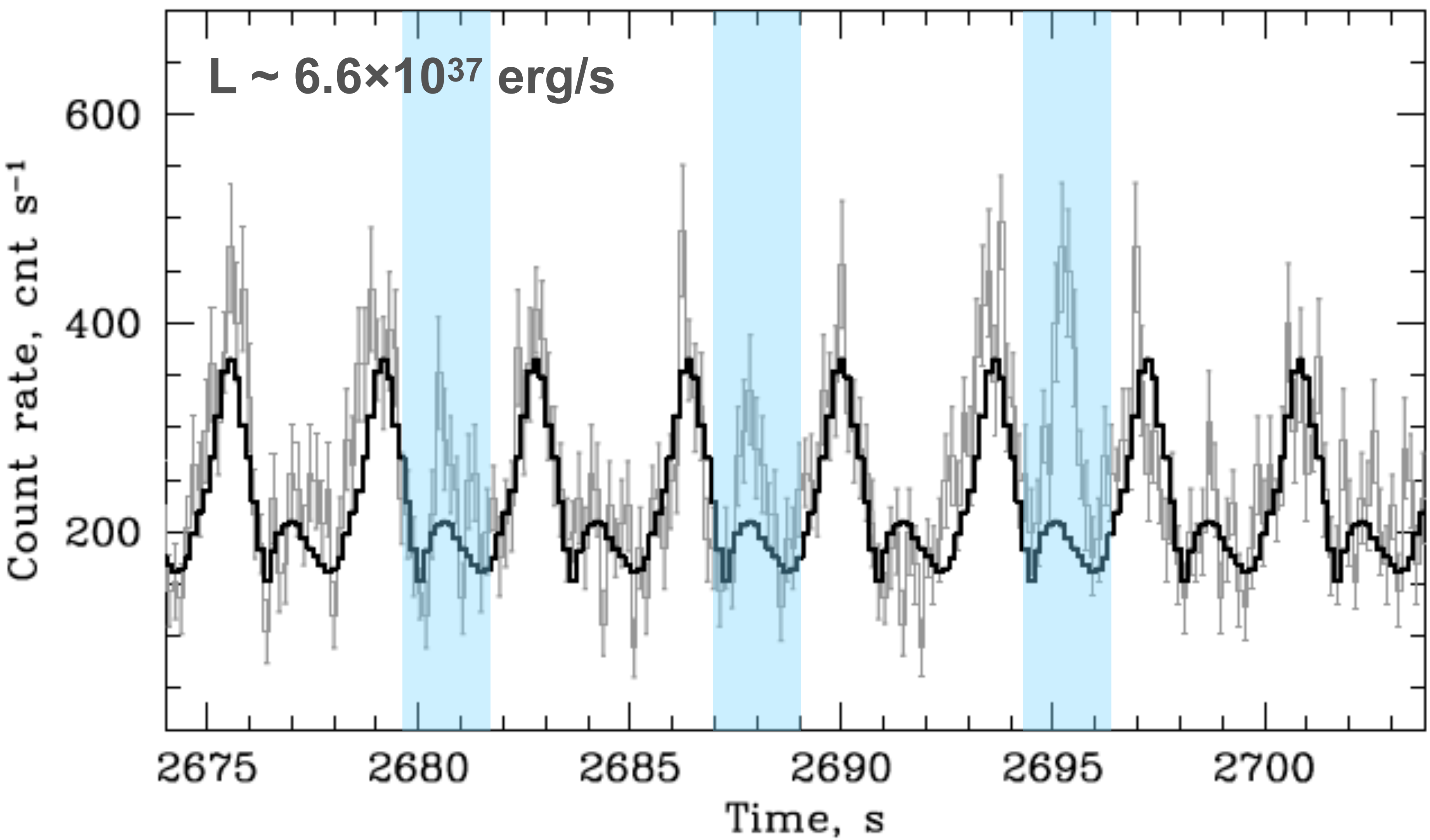
Pulse Profiles in **Swift J0243.6+6124**: dependence on luminosity



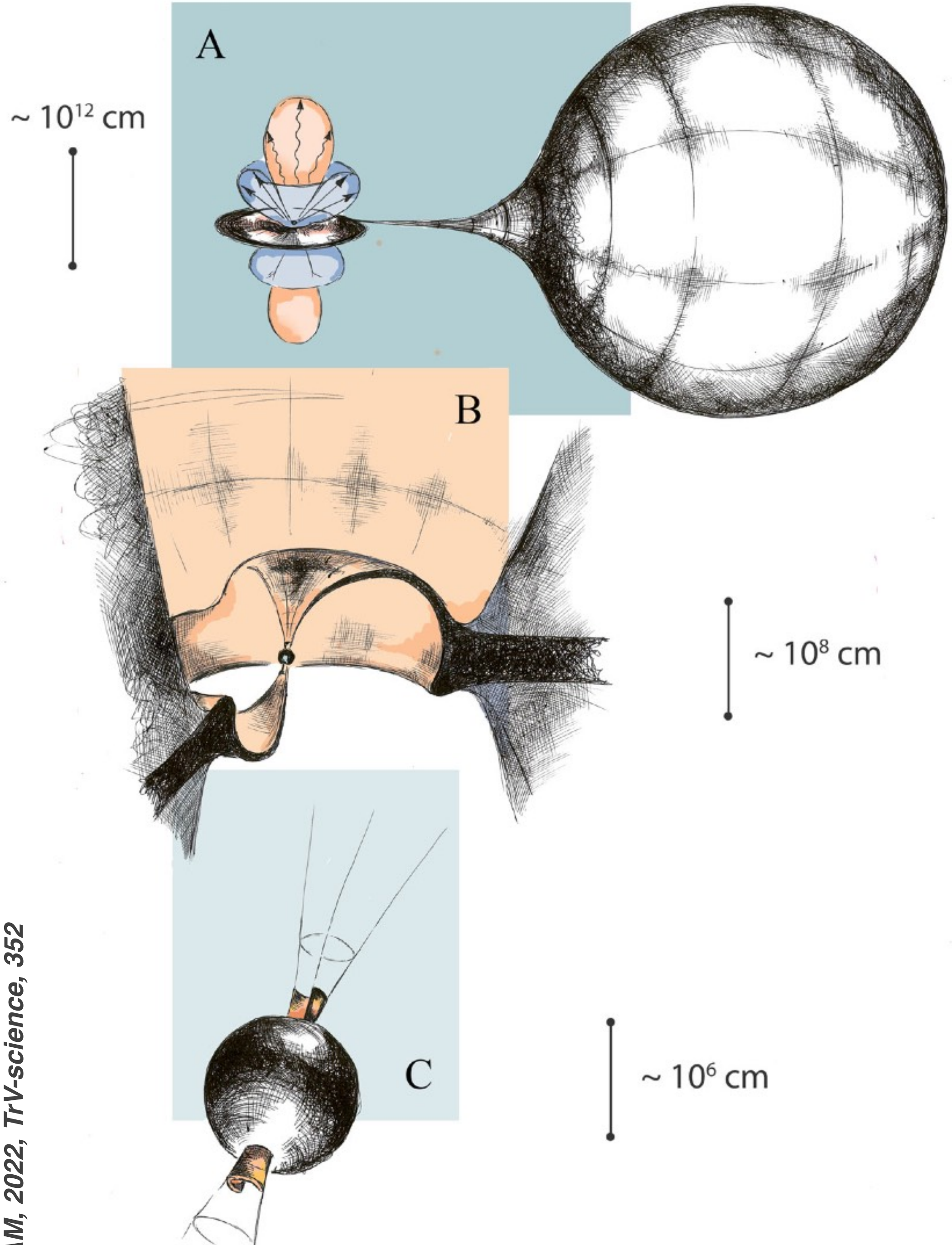
Recently, the similar phase shifts were detected in **SMC X-3** (Liu+, 2022, MNRAS) and **RX J0209.6+7427** (Hou+, 2022, ApJ) at **L > 10^{38} erg/s**.

Therefore, one can speculate that it is a typical feature at high mass accretion rates.

Pulse Profiles in **4U 0115+63**: stability



Tsygankov+, 2007, Ast.Let., 33

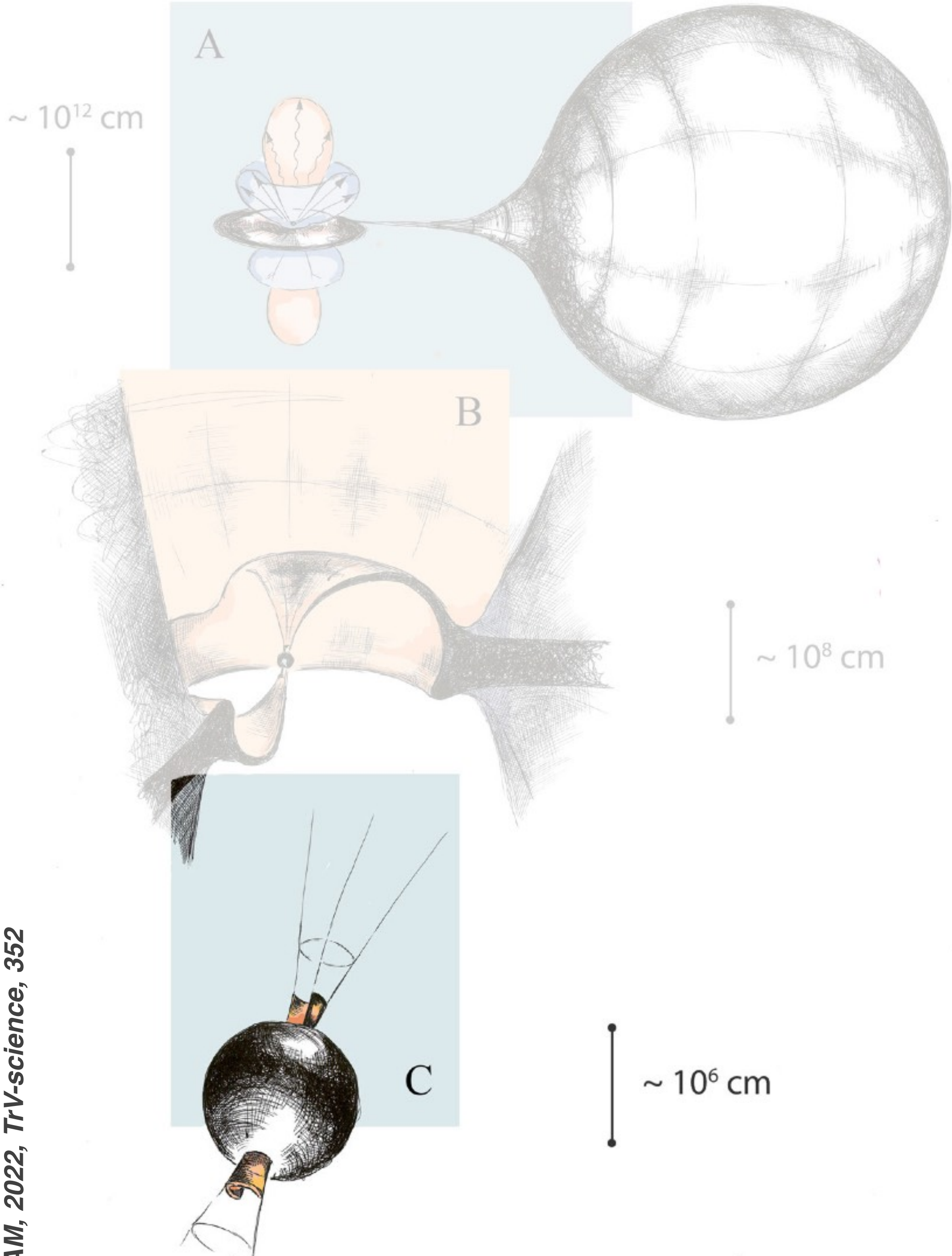


AM, 2022, TrV-science, 352

outflows from the disc

optically thick flow between the disc and NS surface

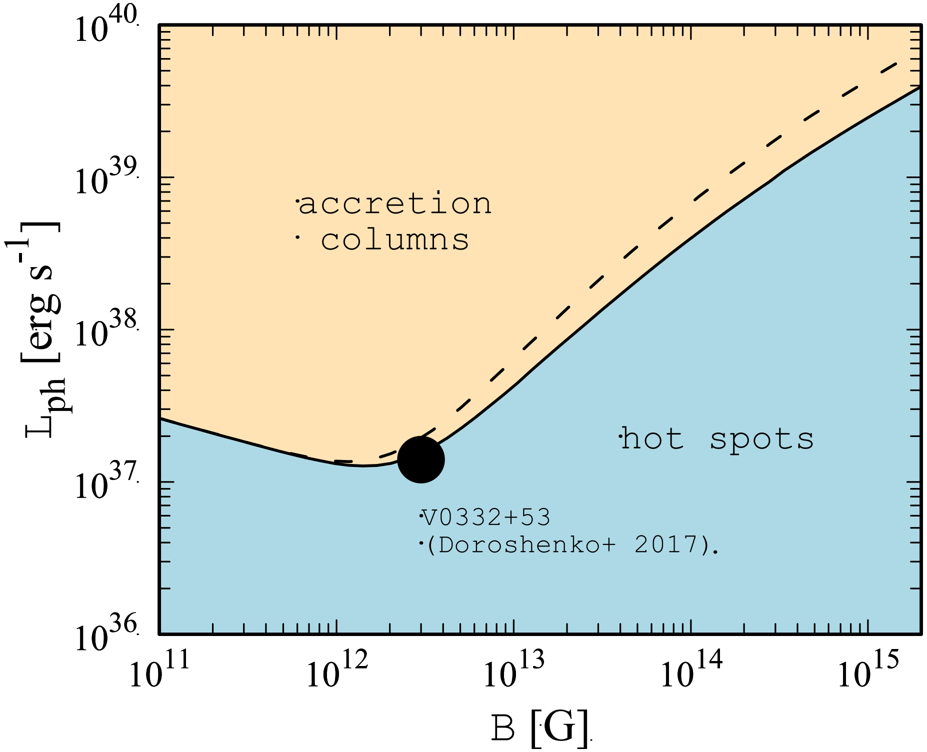
accretion column



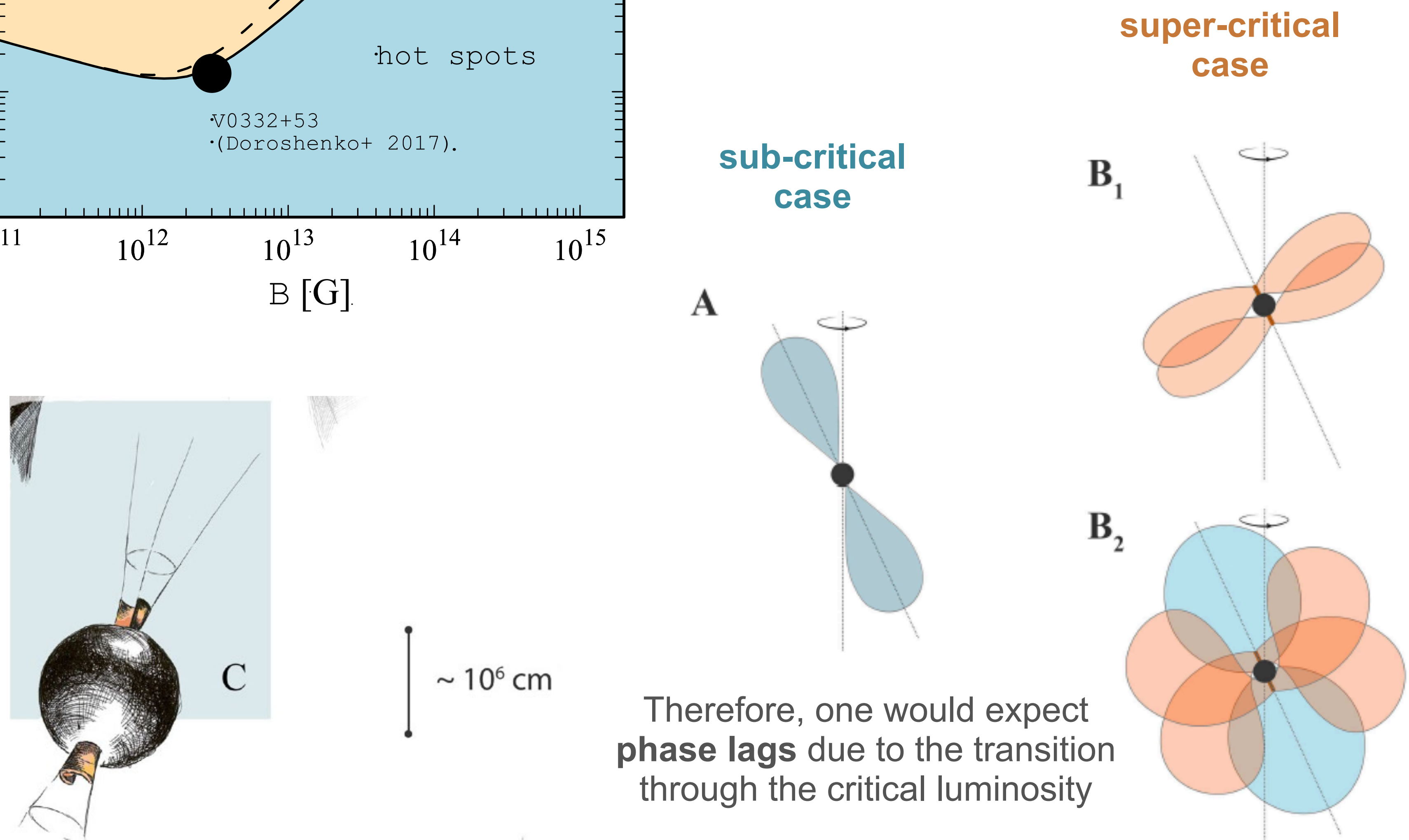
AM, 2022, TrV-science, 352

accretion column

Appearance of Accretion Columns

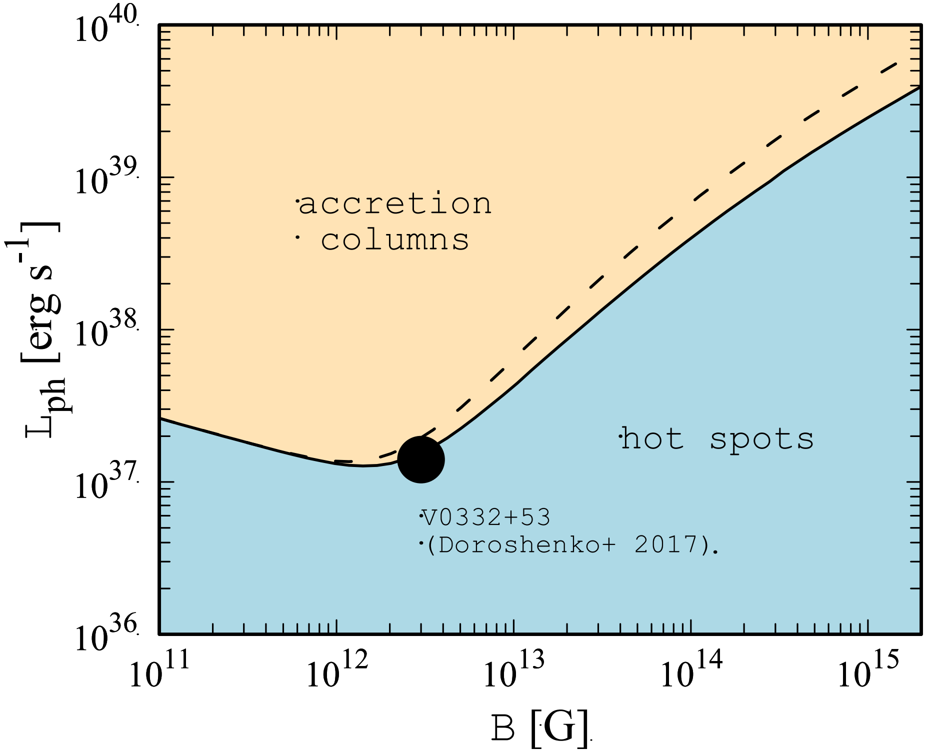


Different geometry of the emitting regions: **columns + reflection from NS surface.**



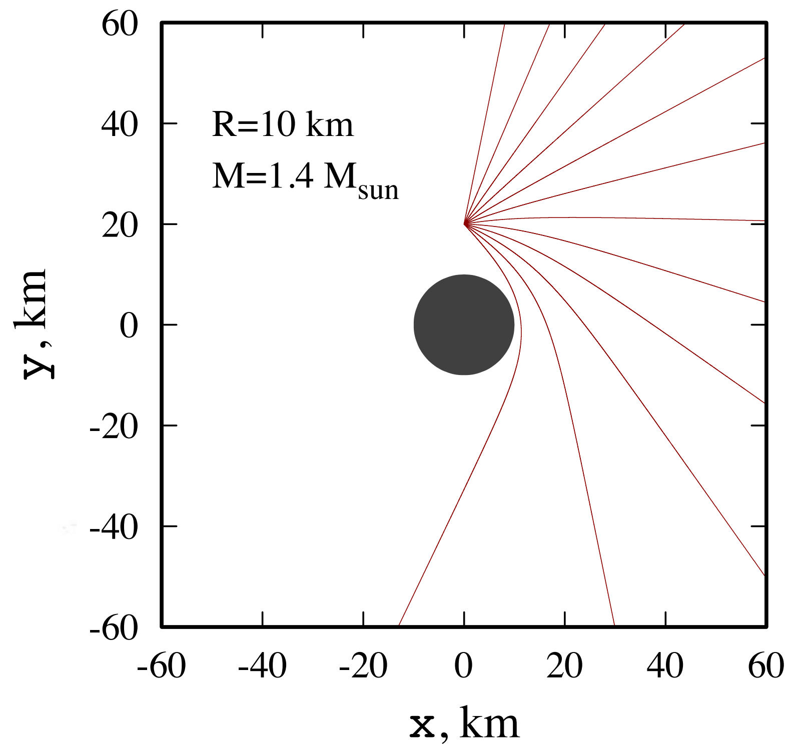
Therefore, one would expect **phase lags** due to the transition through the critical luminosity

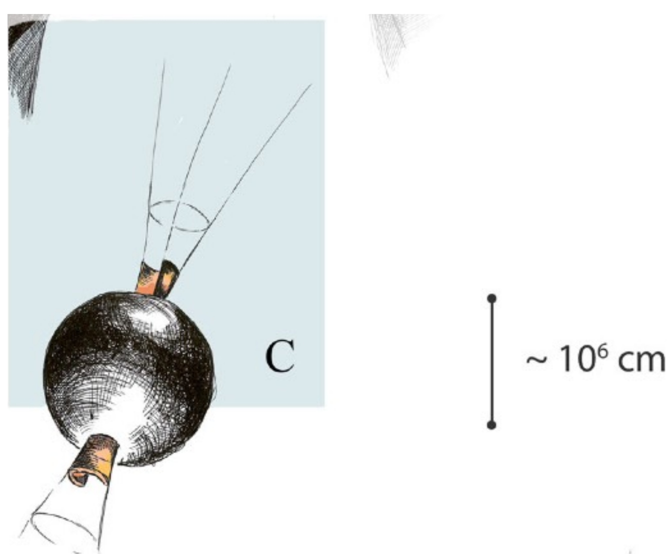
Appearance of Accretion Columns



Different geometry of the emitting regions: **columns + reflection from NS surface.**

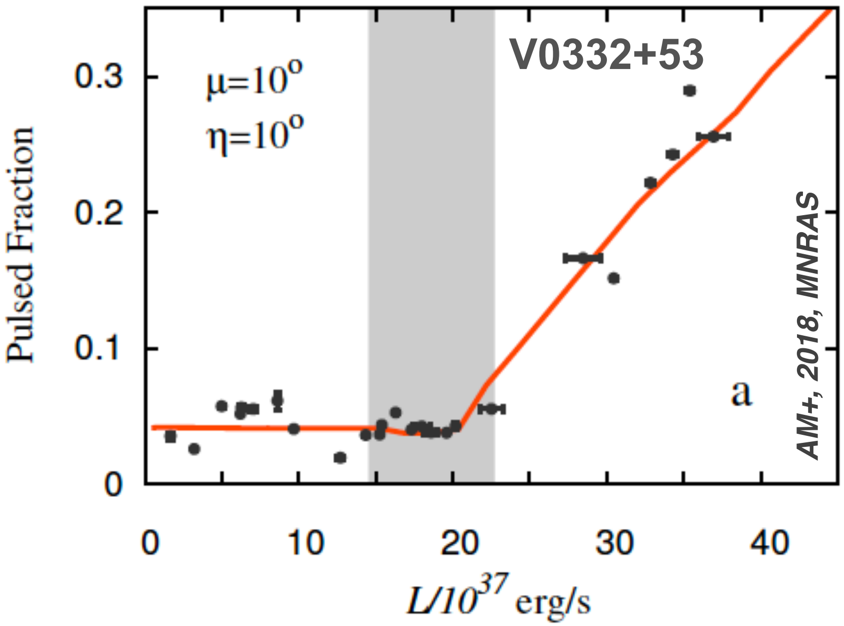
Columns are gravitationally lensed:



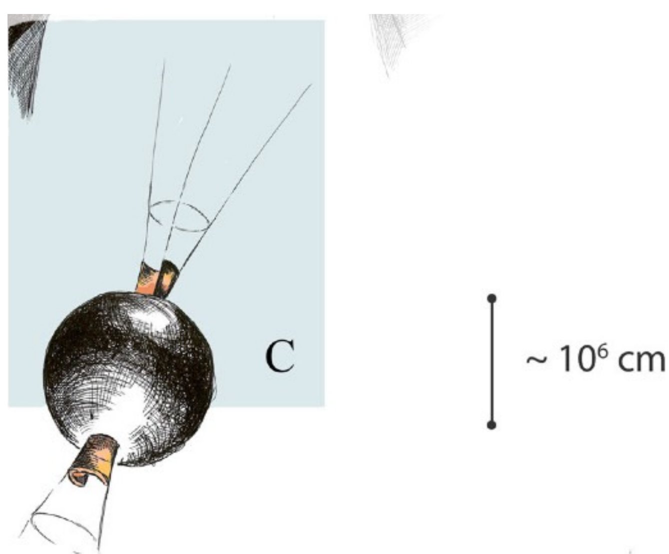


and their **height is fluctuating** with mass accretion rate

Appearance of Accretion Columns



Typical (theoretically) behaviour of PF



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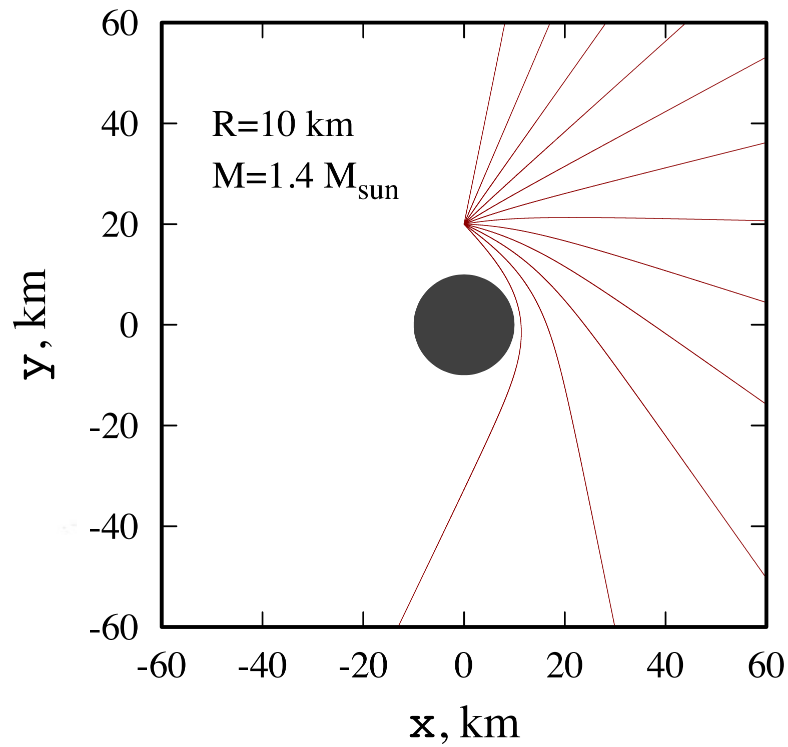

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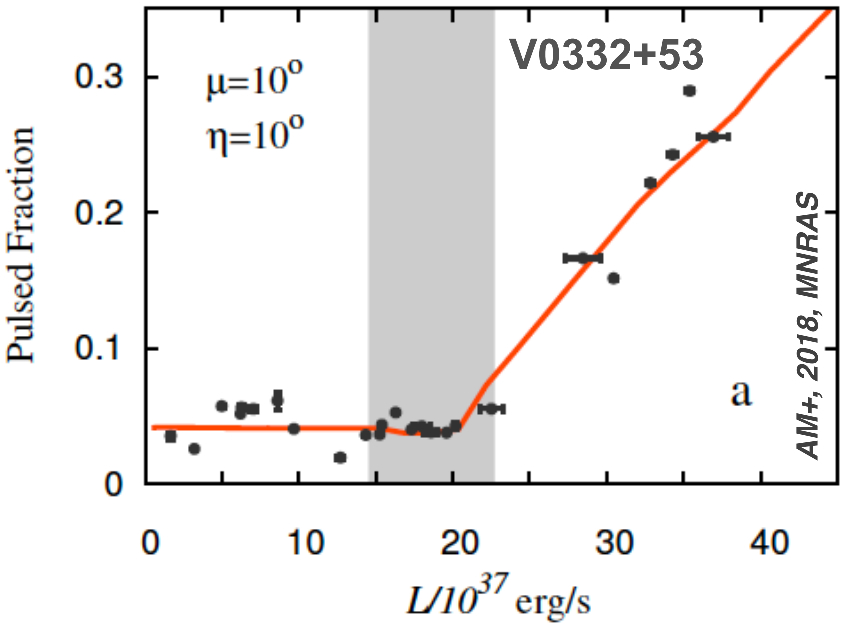

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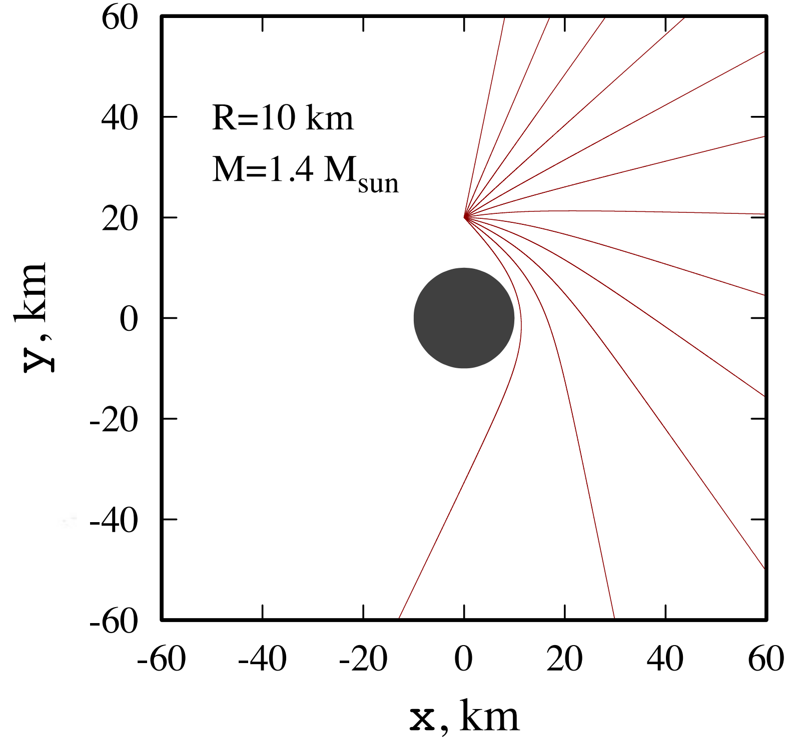

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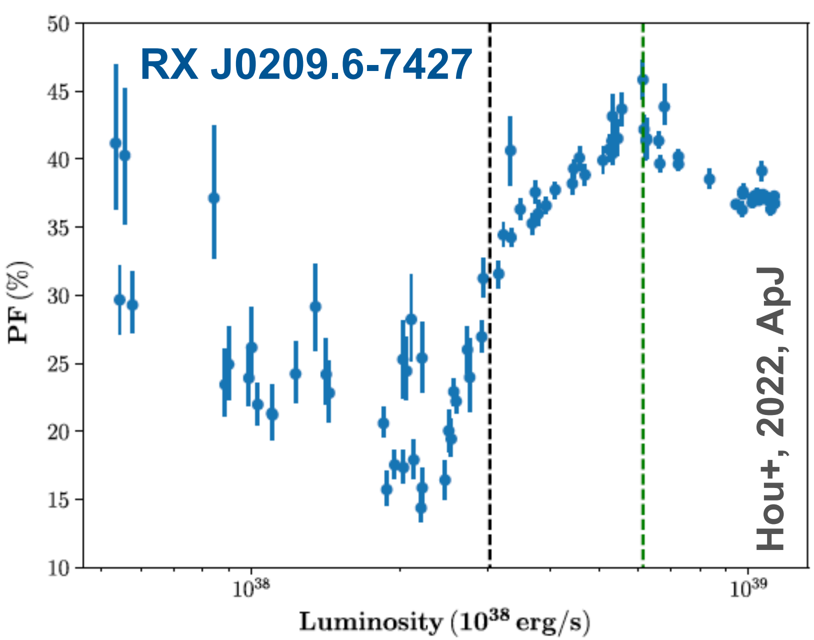
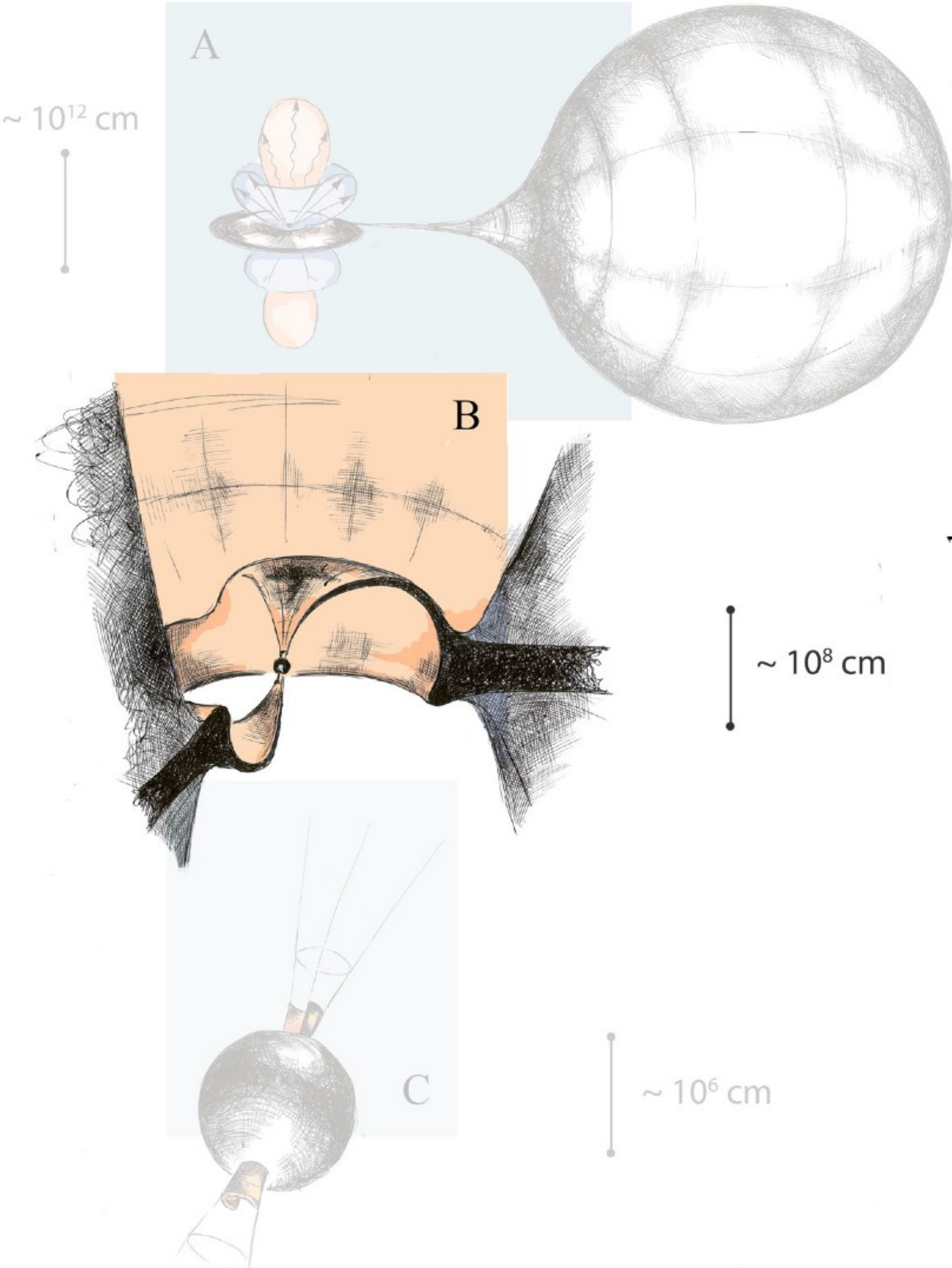
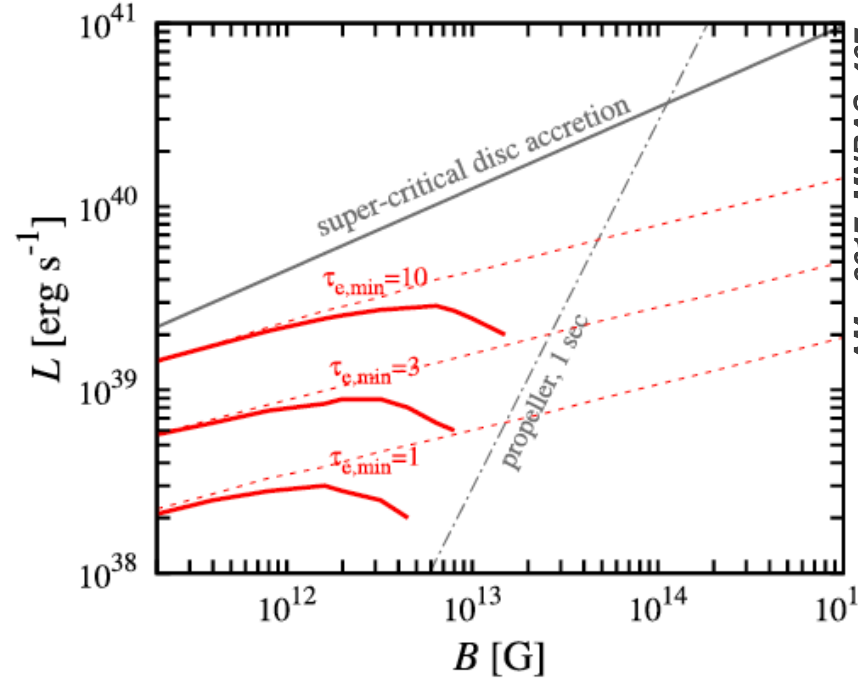


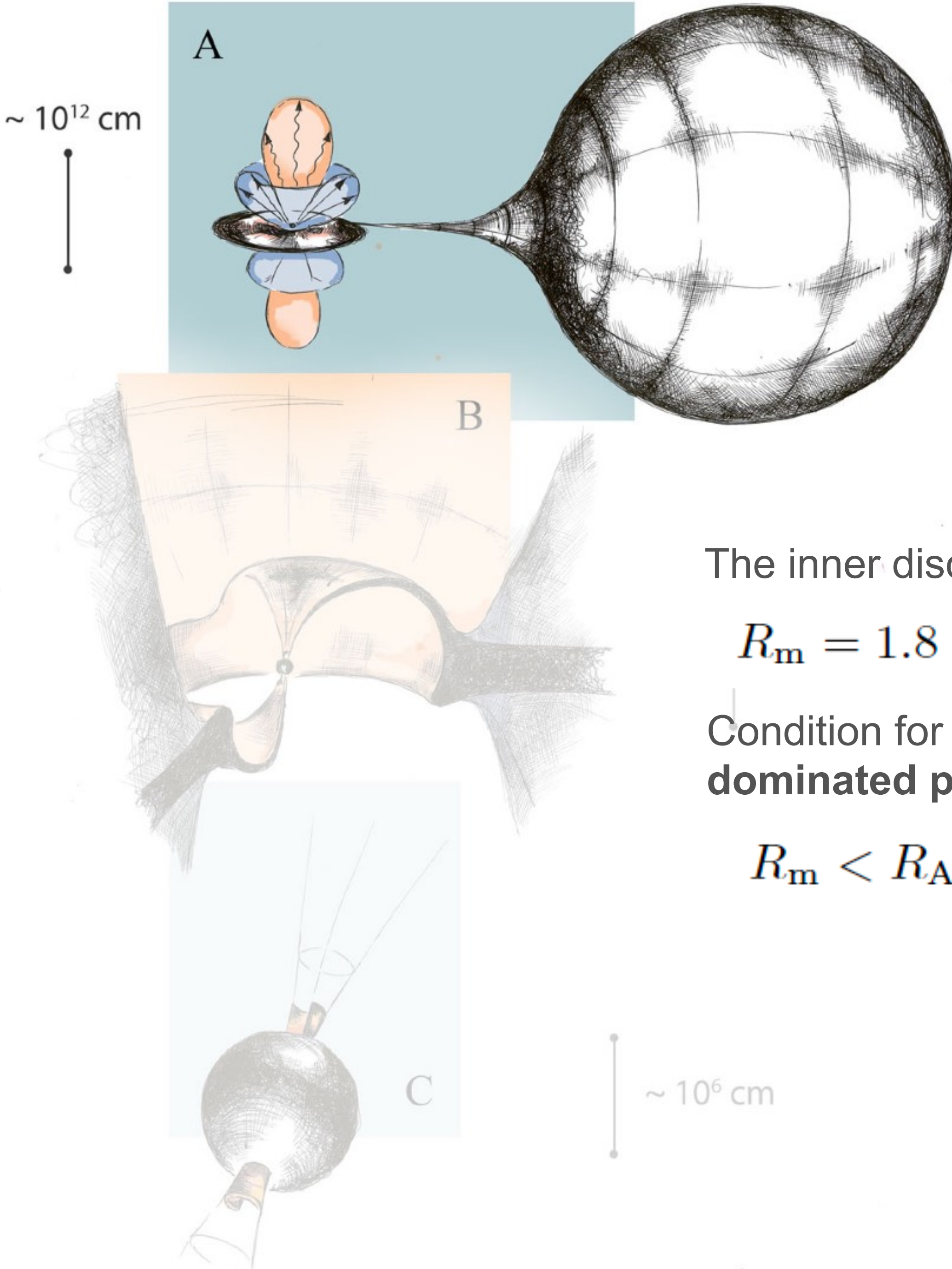




AM+, 2017, MNRAS, 467

At L > 2×10^{38} erg/s, the flow is optically thick already (if steady).

Outflows from accretion disc



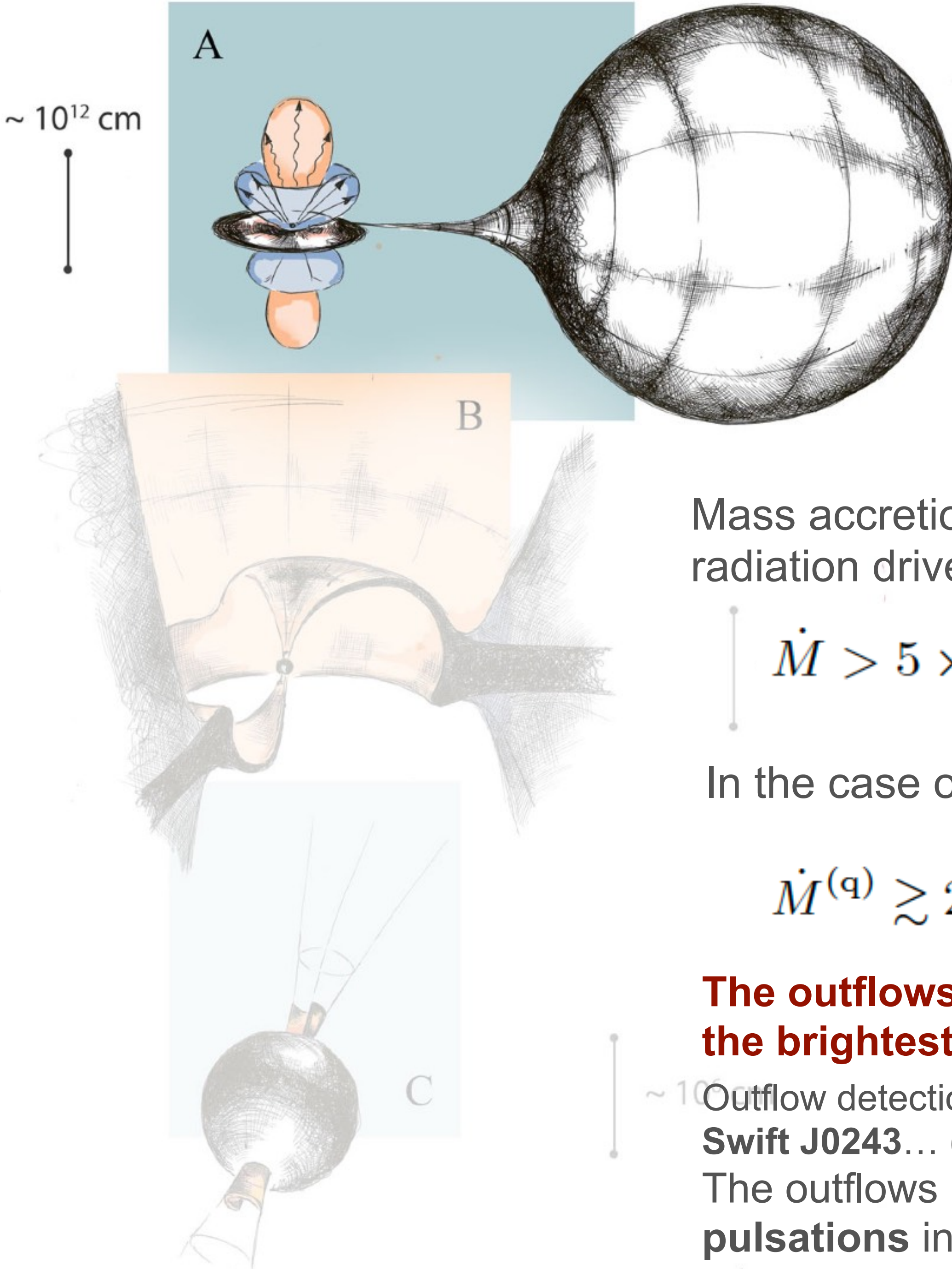
The inner disc radius:

$$R_{\rm m} = 1.8 \times 10^8 \, \Lambda B_{12}^{4/7} \dot{M}_{17}^{-2/7} m^{-1/7} R_6^{12/7} \ {\rm cm}$$

Condition for appearance of **radiation pressure dominated part**:

$$R_{\rm m} < R_{\rm A} \approx 2.7 \times 10^8 \, \dot{M}_{19}^{16/21} m^{7/21} \, {\rm cm}$$

Outflows from accretion disc



Mass accretion rate sufficient to launch radiation driven outflows:

$$\dot{M} > 5 \times 10^{19} \Lambda^{7/9} B_{12}^{4/9} m^{2/3} R_6^{4/3} \ \mathrm{g\,s^{-1}}$$

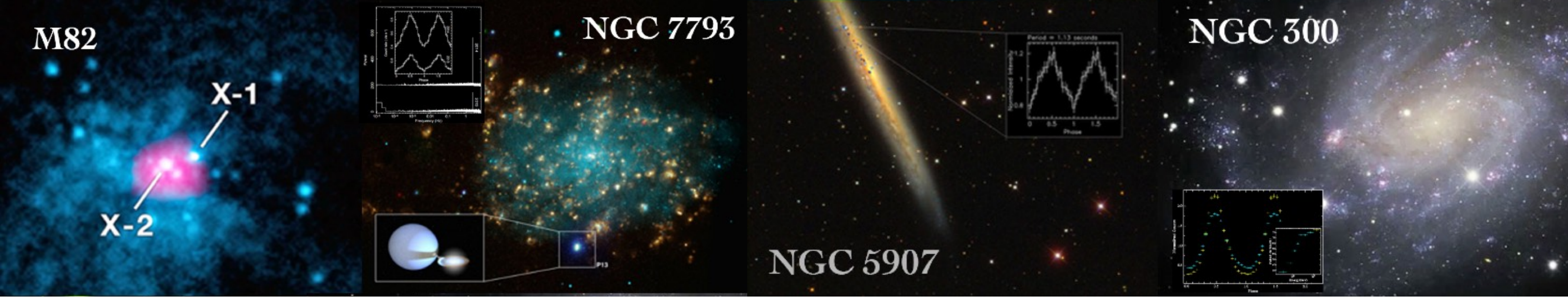
In the case of quadrupole B-field:

$$\dot{M}^{(\mathrm{q})} \gtrsim 2 \times 10^{19} \, B_{12}^{4/13} m^{12/13} R_6^{16/13} \ \mathrm{g\,s^{-1}}$$

The outflows are expected only in the brightest XRPs.

Outflow detection: **ULX NGC300 X-1** (Kosec+, 2018), and in **Swift J0243**… (van den Eijnden+ 2019). **v~0.2c**

The outflows influence **apparent luminosity** and **pulsations** in XRPs.



Name	L_X (max) [erg s^{-1}].	P [s]	$\dot{P}$ [10^{-10} s s^{-1}]	PF %	P_{orb} [d]	M_2 [$M_\odot$]
M82 X-2	1.8×10^{40}	1.37	~ 2	> 20	2.52	> 5.2
NGC 7793 P13	5×10^{39}	0.42	~ 0.35	~ 20	64	$18 - 23$
NGC 5907 X-1	2×10^{41}	1.42	115	~ 15	5.3	?
		1.13	47	~ 15		
NGC 300 X-1	4.7×10^{39}	125	1.4×10^5	?	?	-
		31.5	5.5×10^3	~ 90		
		20	1.7×10^3	~ 90		
M51 X-7	7×10^{39}	2.8	$1.6 - 9.4$	$5 - 20$	~ 2	?
NGC 1313 X-2	2×10^{40}	1.5	?	$5 - 6.5$	?	< 12

Magnetic field strength and relation between **actual and apparent luminosity** are under debates.

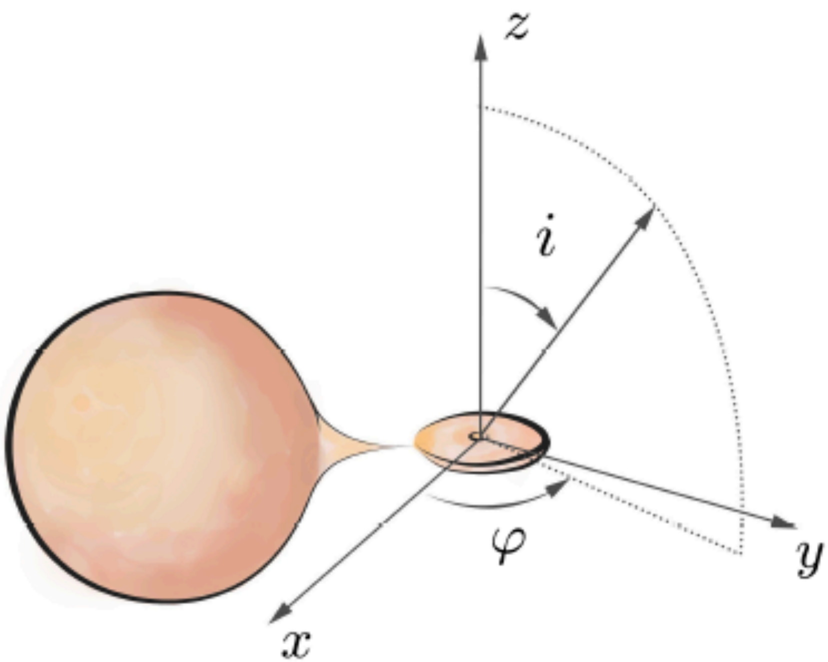
~ 300 ULXs known

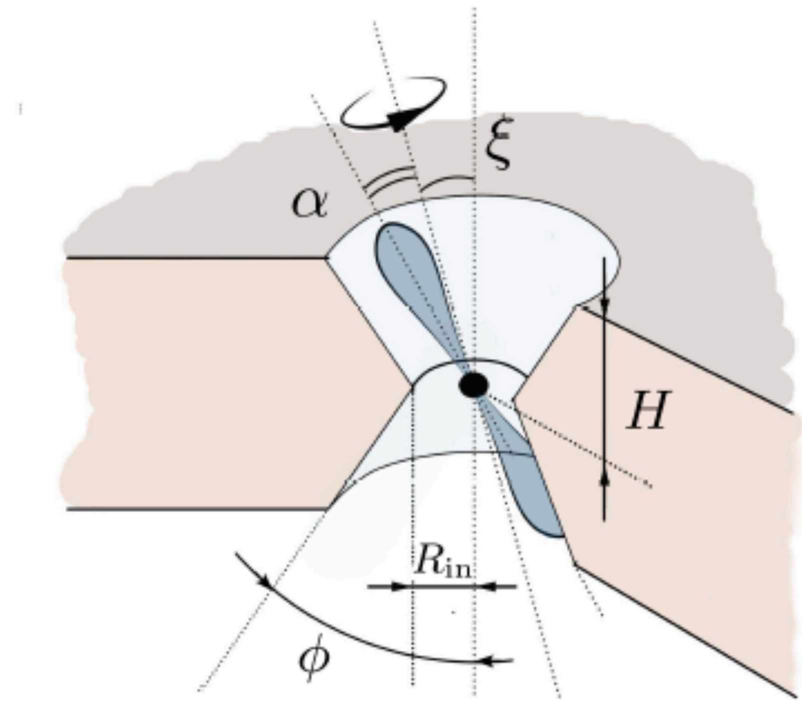
in **~ 15-20 ULXs** statistics of photons is high enough to detect pulsations

In **6 ULXs** pulsations are detected already

(Rodrigues Castillo+, 2020, ApJ, 895)

Geometrical Beaming vs. Pulsed Fraction

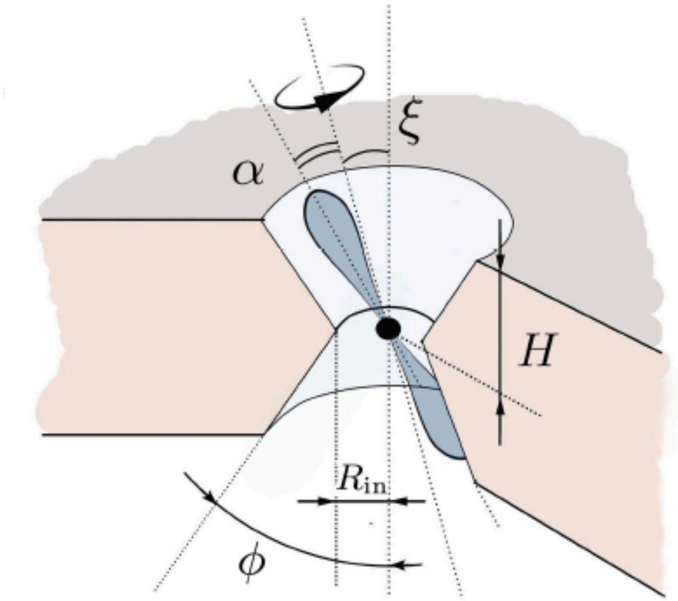




High Pulsed Fraction (>10 per cents) is a typical feature of ULX pulsars **(?)**

AM+, 2021, MNRAS, 501
AM & Portegies Zwart, arXiv:2211.08952

Outflows influencing apparent luminosity, pulse fraction and phase lags



$$L_{\rm app} = aL$$

Simulations account for:

1. Geometry of accretion cavity
2. Initial beam pattern (parameter n)

$$\frac{\mathrm{d}L(\theta)}{\mathrm{d}\cos\theta} \propto \cos^n\theta$$

3. Outflow velocity (v~0.2c)

Assumptions:

a. Conservative monochromatic scattering
b. No absorption
c. Typical photon travel inside the cavity is smaller than the spin period

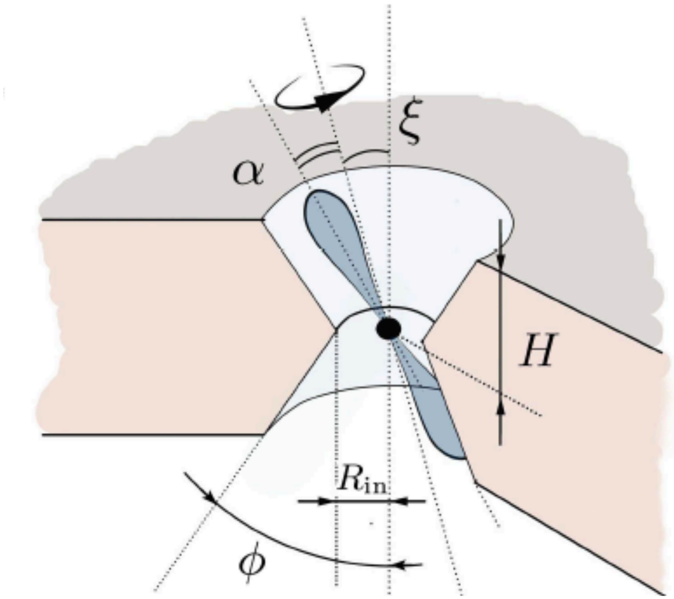
Simulations reproduce pulse profiles for different geometrical configurations of accretion flow and different relative displacement of the observers.

On the base of simulated pulse profiles **we get apparent luminosity** and **pulsed fraction.**

Note: Both of them are dependent on observer's viewing angle.

AM & Portegies Zwart, 2022

Outflows influencing apparent luminosity, pulse fraction and phase lags



$$L_{\rm app} = aL$$

Simulations account for:

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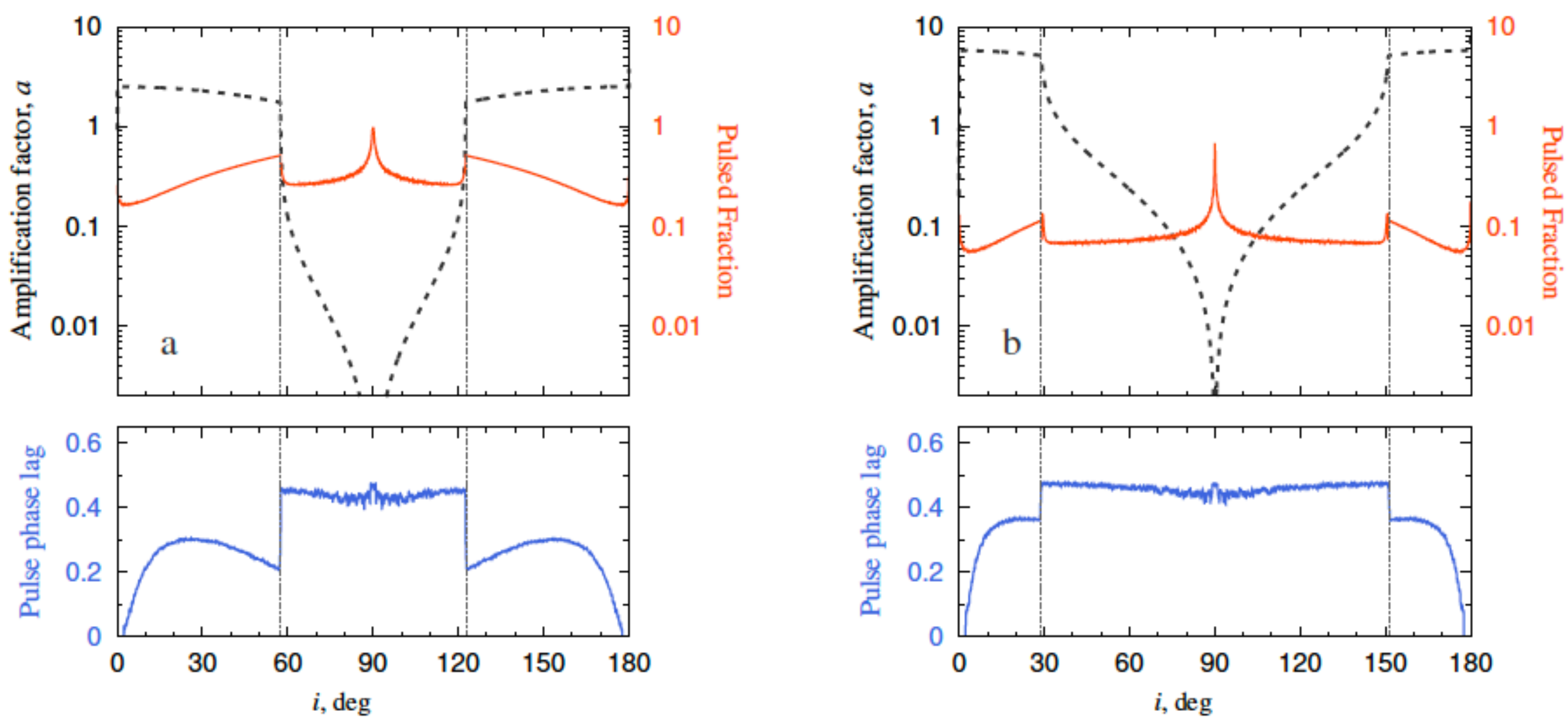
$$\frac{dL(\theta)}{d\cos\theta} \propto \cos^n\theta$$

3. Outflow velocity (v~0.2c)



AM & Portegies Zwart, arXiv:2211.08952

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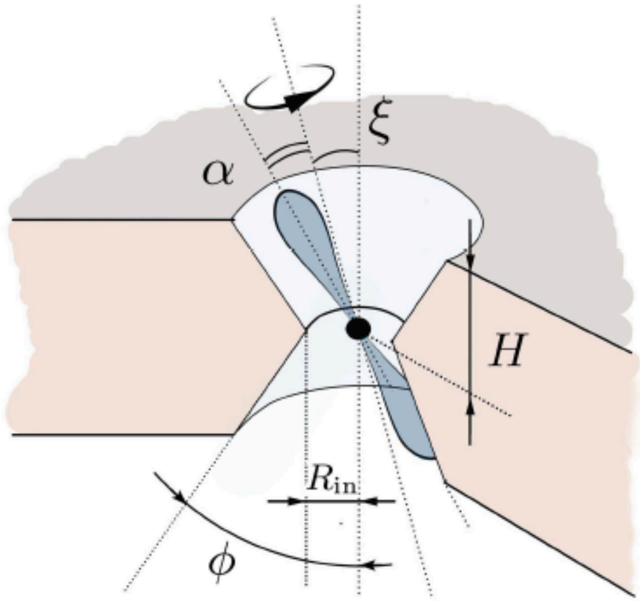

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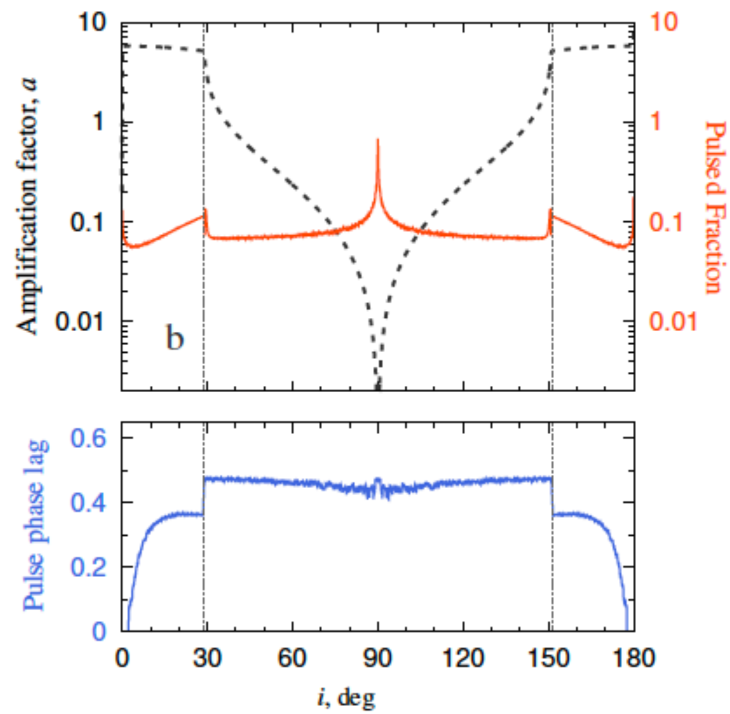
1. Geometry of accretion cavity
2. Initial beam pattern (parameter n)

$$\frac{\mathrm{d}L(\theta)}{\mathrm{d}\cos\theta} \propto \cos^n\theta$$

3. Outflow velocity (v~0.2c)

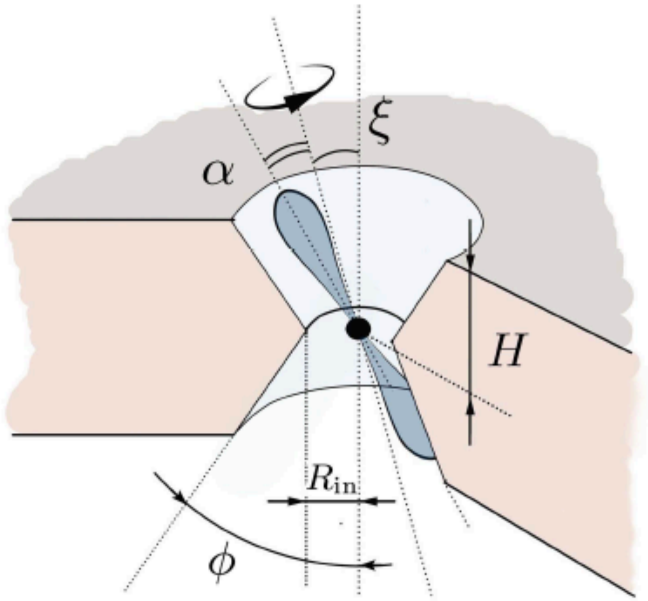
$$L_{\rm ULX} = \frac{2\pi}{\Omega_{\rm ULX}} L_{\rm X}$$

Numerical simulations give us the values that are a factor of few smaller.



AM & Portegies Zwart, arXiv:2211.08952

Outflows influencing apparent luminosity, pulse fraction and phase lags

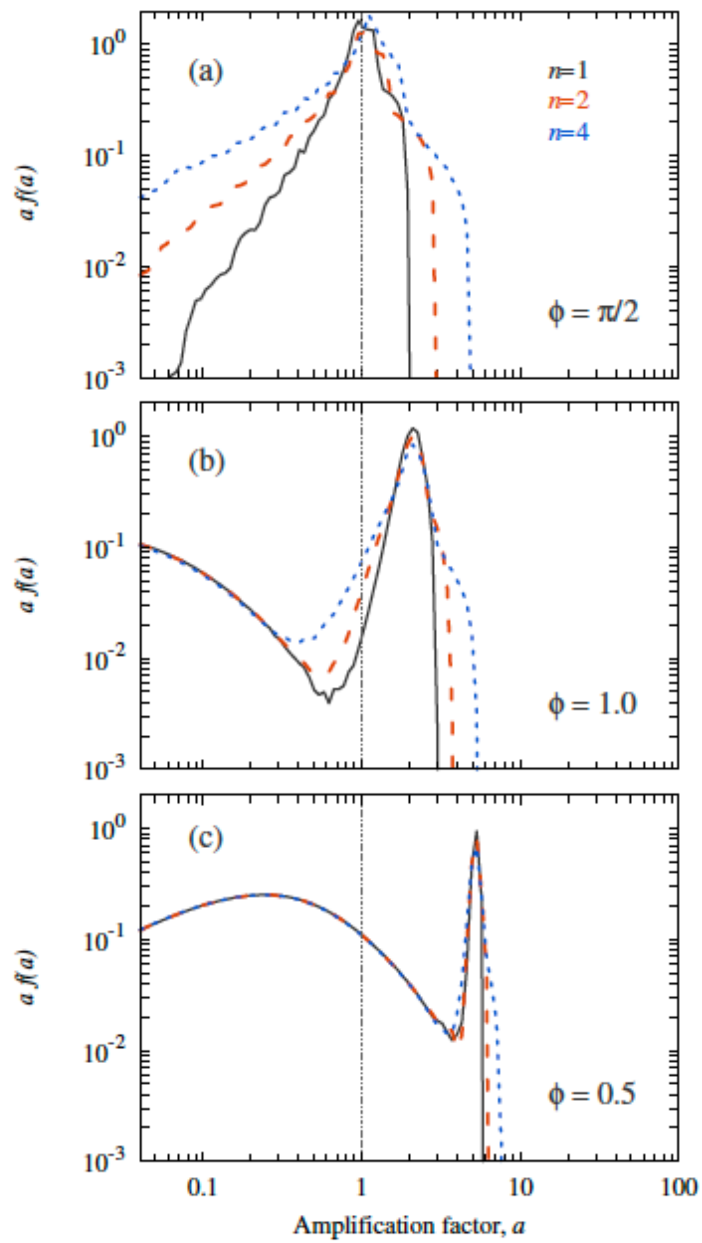


There is a difference between actual and apparent luminosity even in geometry without outflows.

Outflows can effectively amplify apparent luminosity.

What happens with the pulsed fraction?

H/R_{in}=100



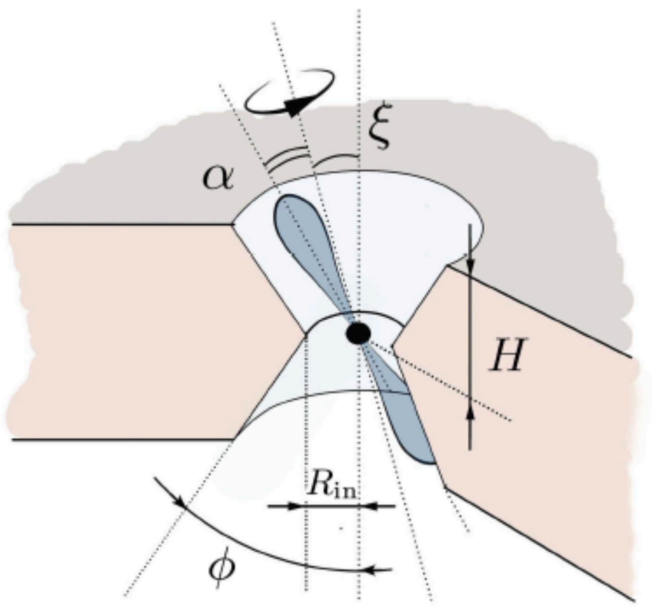
no beaming by the outflows

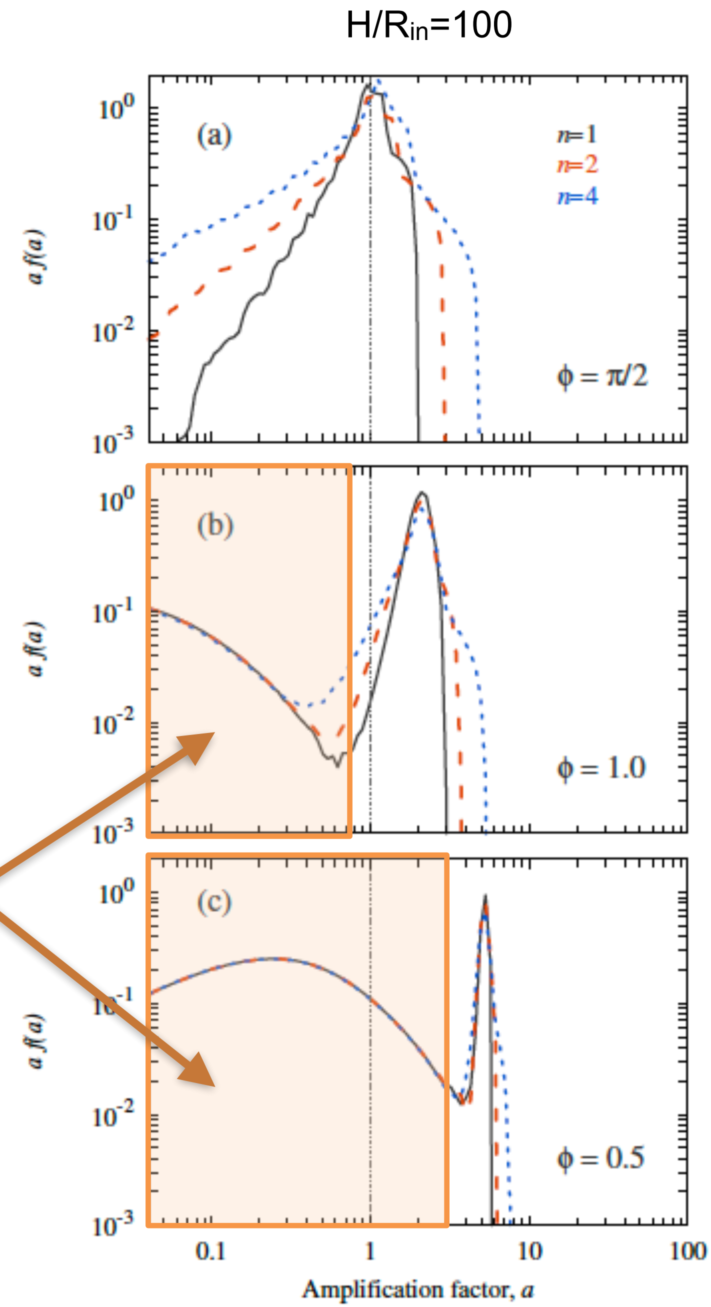
weak beaming

stronger beaming

AM & Portegies Zwart, arXiv:2211.08952

Outflows influencing apparent luminosity, pulse fraction and phase lags





no beaming by the outflows

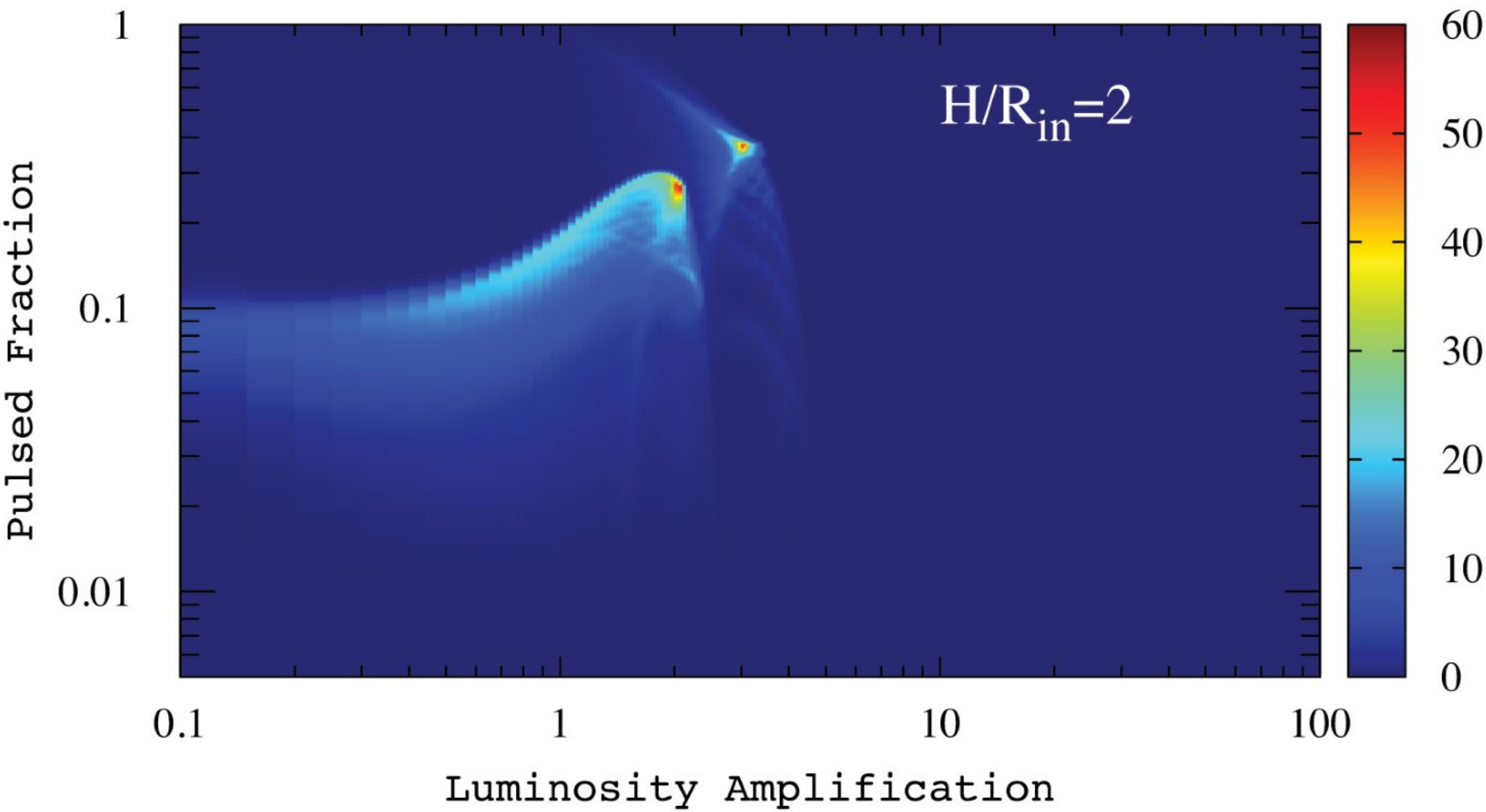
weak beaming

stronger beaming

Objects observed outside the opening angle of the cone.

AM & Portegies Zwart, arXiv:2211.08952

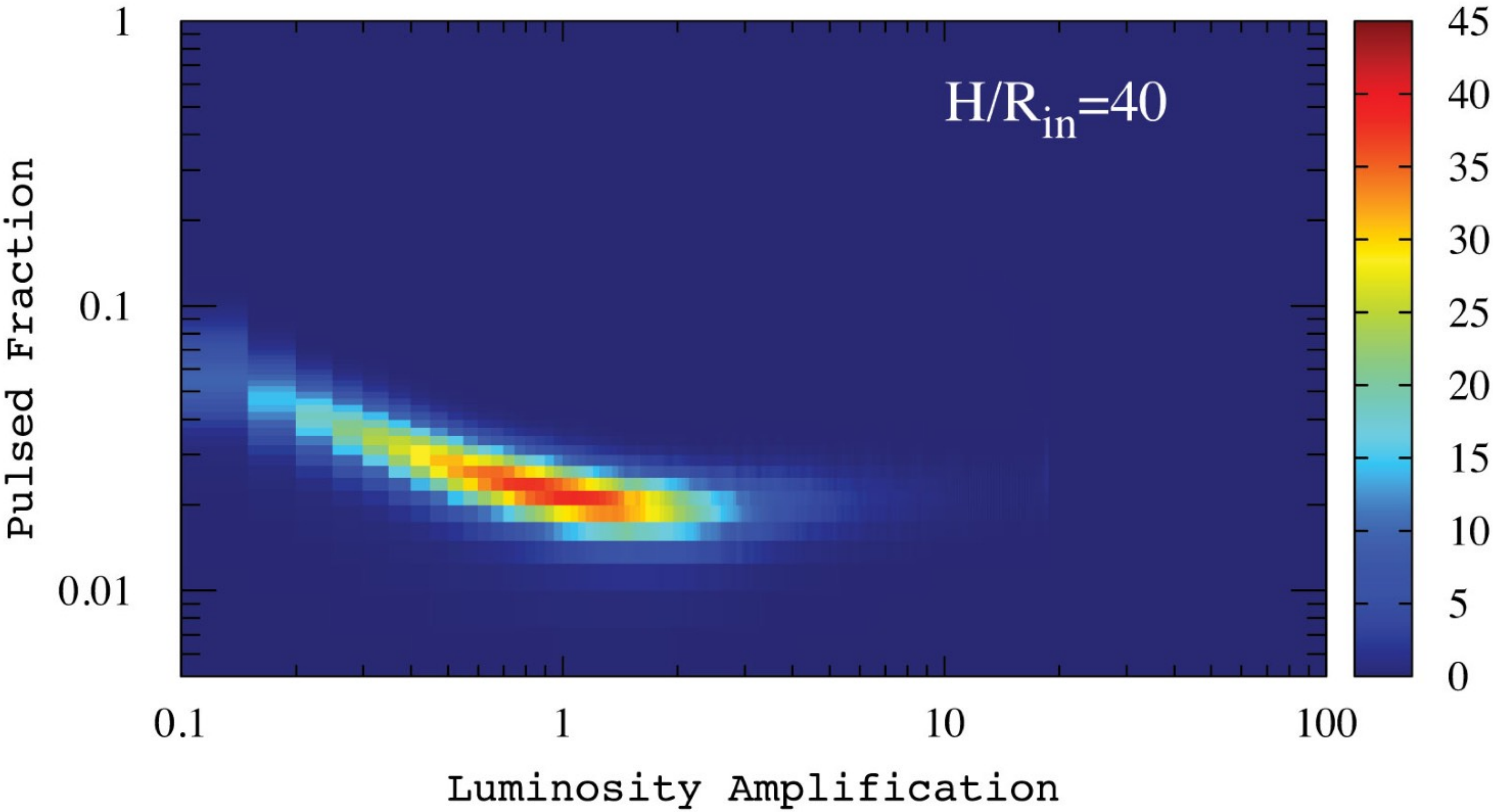
Outflows influencing apparent luminosity, pulse fraction and phase lags



Note: this simulations do not account for absorption!

AM+, 2021, MNRAS, 501

Outflows influencing apparent luminosity, pulse fraction and phase lags



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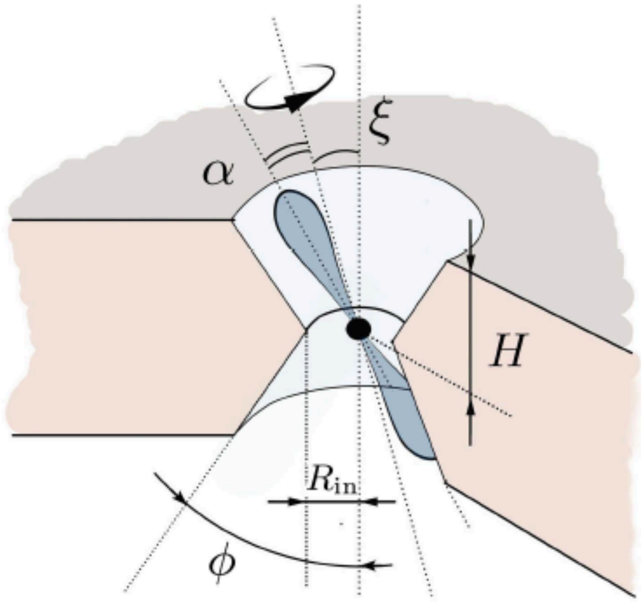
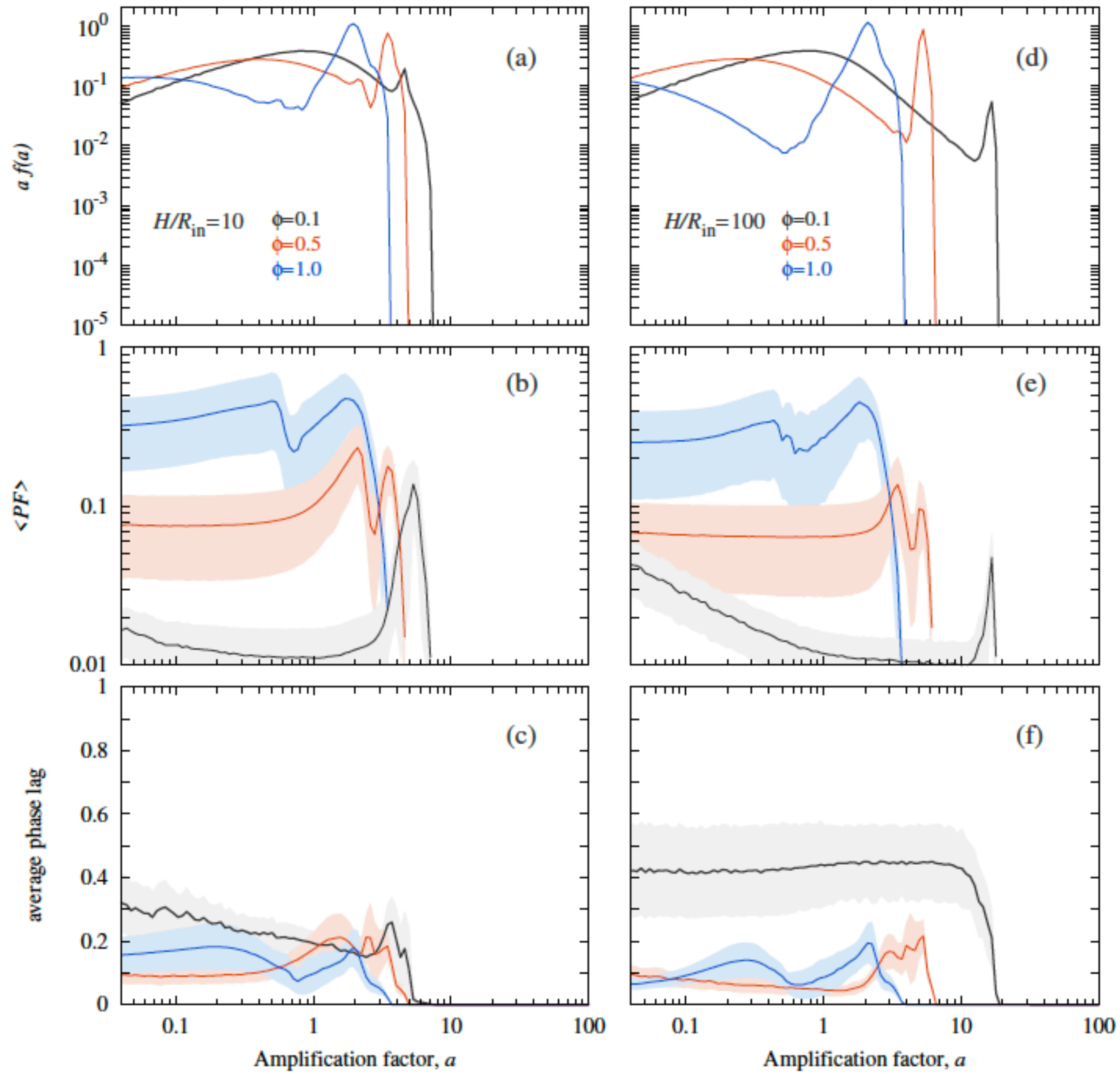
AM+, 2021, MNRAS, 501

Outflows influencing apparent luminosity, pulse fraction and phase lags



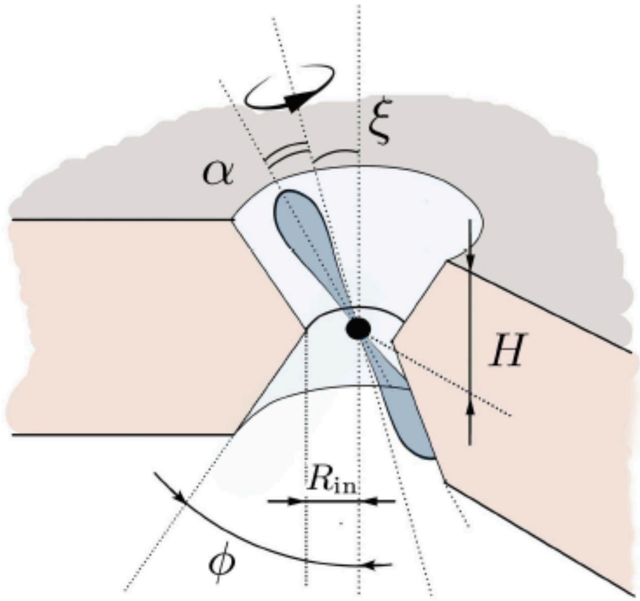


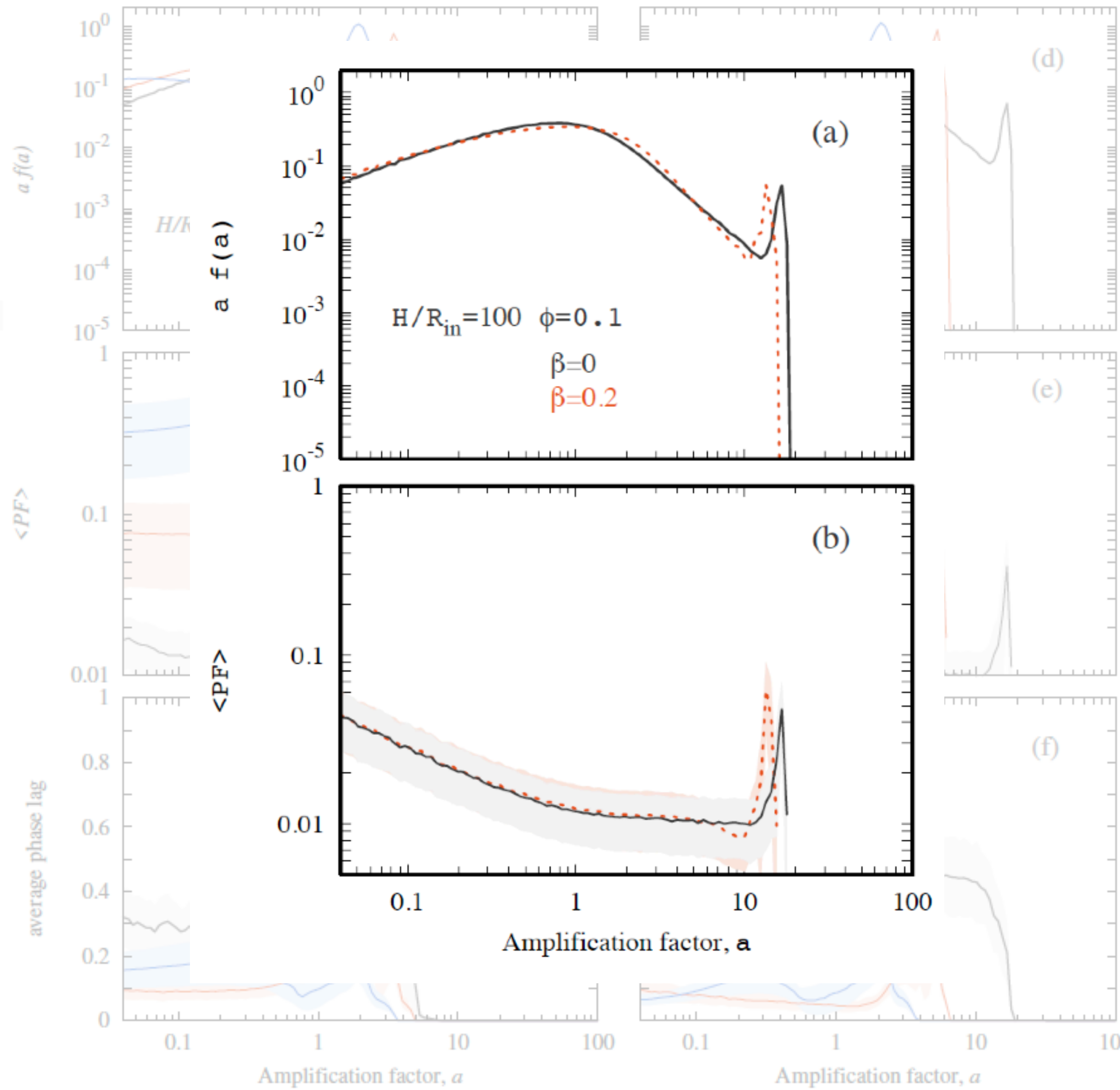
The outflows result in a phase lags of pulsations even in the case of weak luminosity amplification.

It should be detectable in **bright X-ray transients**.

AM & Portegies Zwart, arXiv:2211.08952

Outflows influencing apparent luminosity, pulse fraction and phase lags





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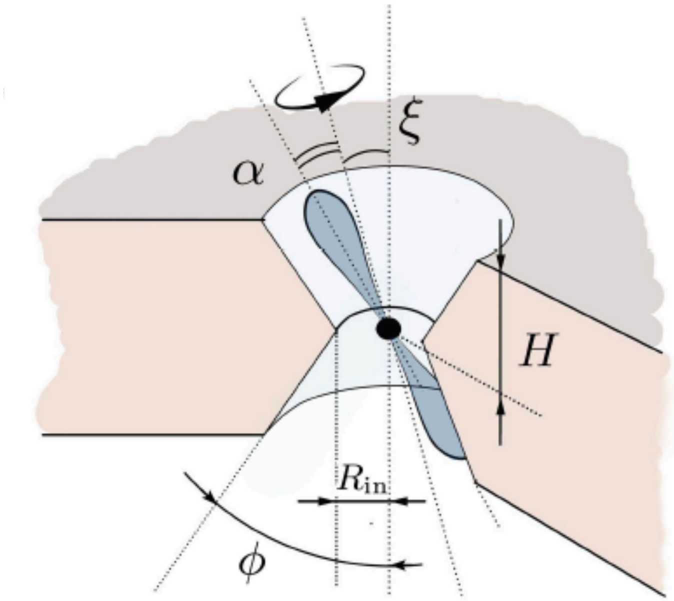

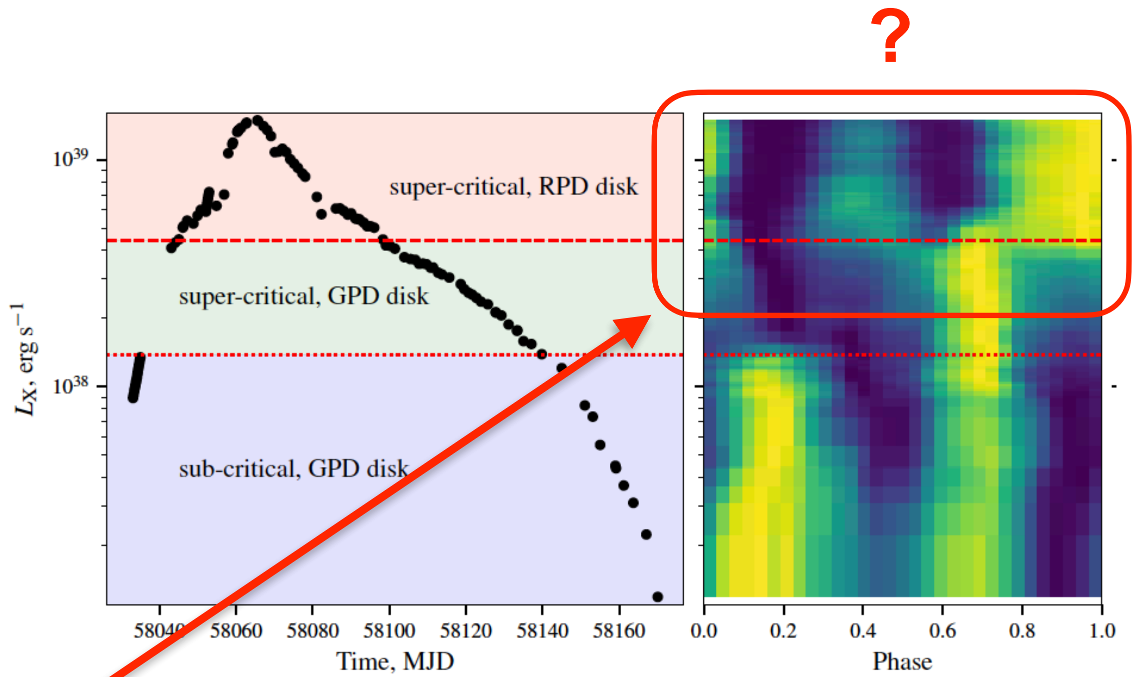

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Radiation pressure on the walls of accretion cavity

Total momentum carried by **X-ray photons** per unit of time:

$$\Upsilon_{X,0} = \frac{L}{c} = \frac{GM\dot{M}}{Rc} \gtrsim \frac{v_{\rm ff}^2}{c}\frac{\dot{M}_0}{2}$$

Total momentum carried by **the wind** per unit of time (*advective case, i.e. f<0.5*):

$$\Upsilon_{\rm wind} \lesssim \frac{\dot{M}_0}{2} 0.2c = \frac{\dot{M}_0 c}{10}$$

Fraction of material launched from the disc (**uncertain value**):

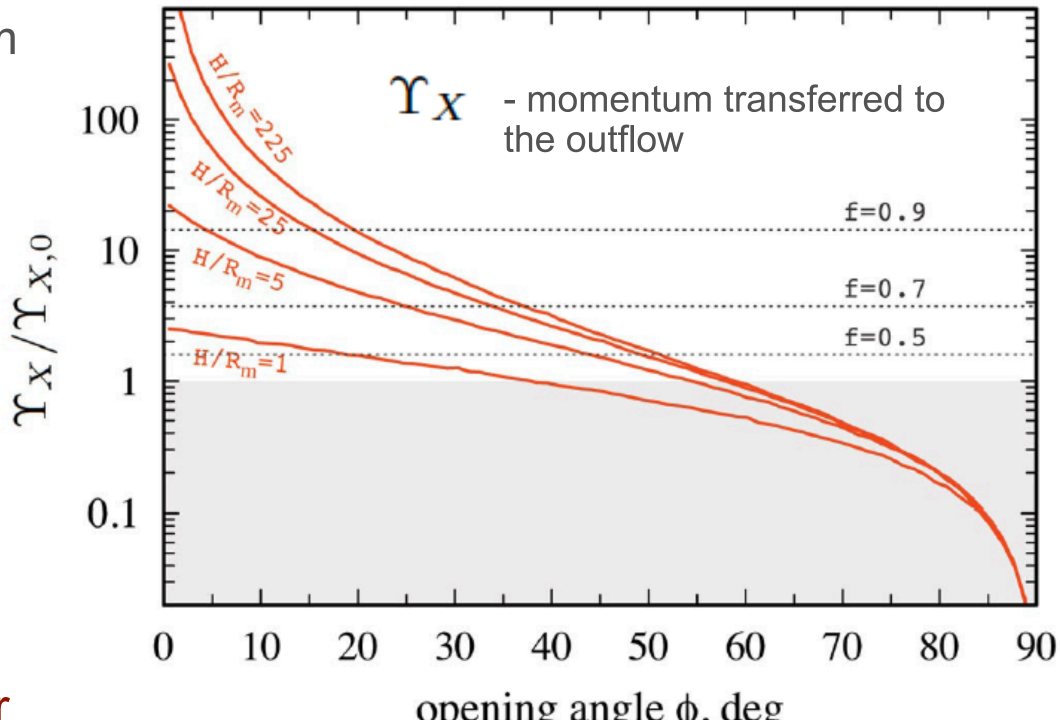
$$f = (\dot{M}_0 - \dot{M})/\dot{M}_0$$

$$\frac{\Upsilon_{\rm wind}}{\Upsilon_{X,0}} \approx \frac{8}{5}\frac{f}{1-f}$$

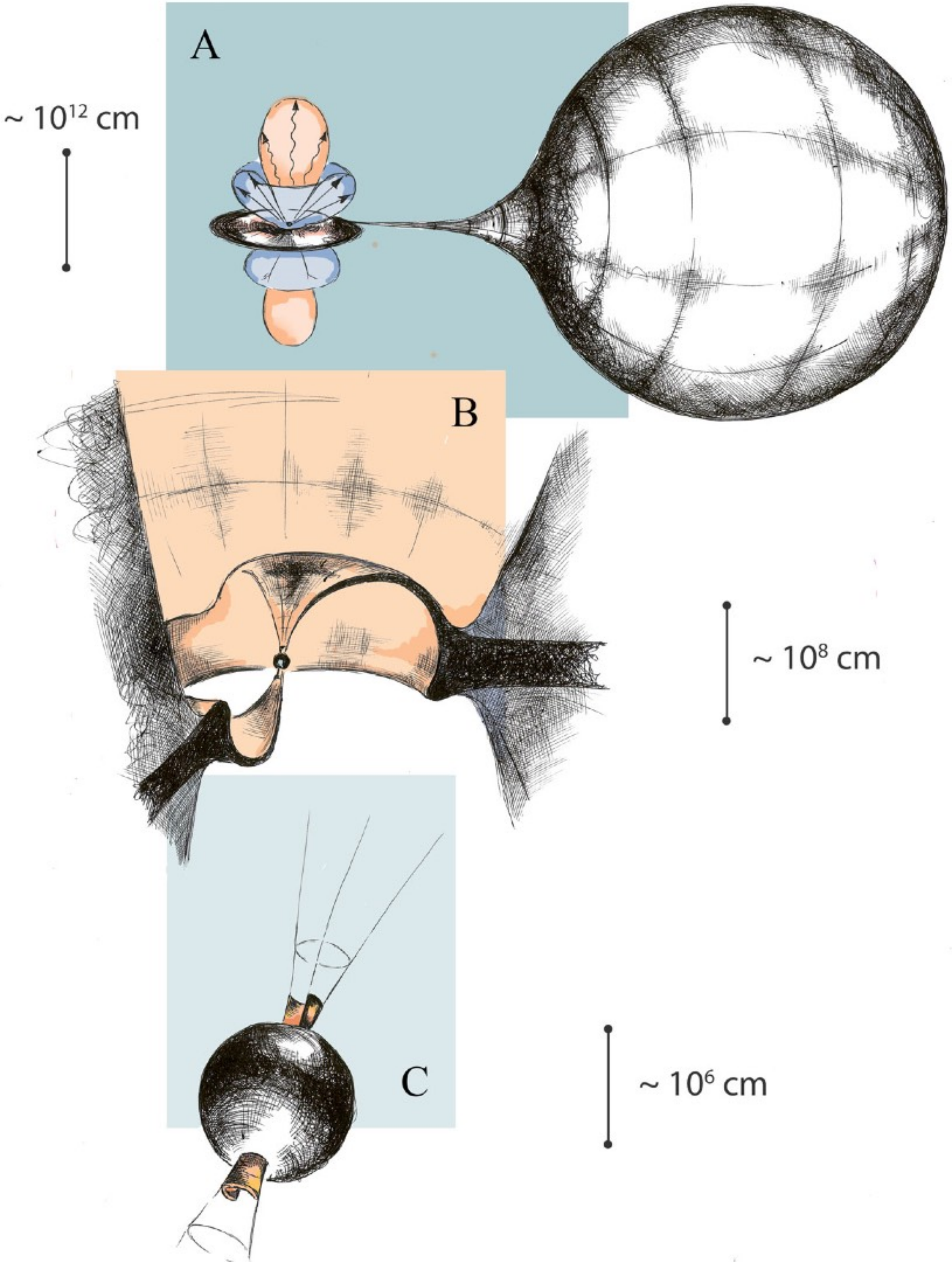
exceeds units at f>5/13 already

but

photons experience multiple reflections and are able to transfer their momentum more than once.



AM & Portegies Zwart, arXiv:2211.08952

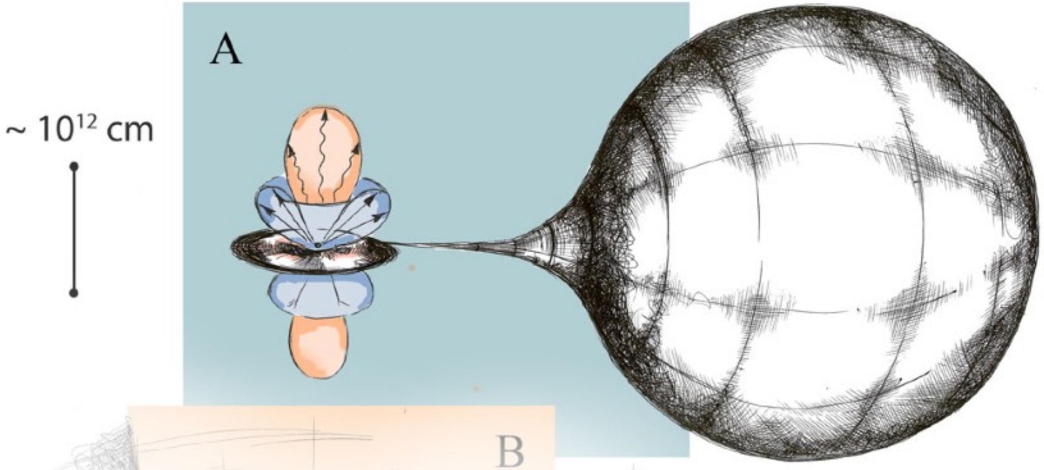


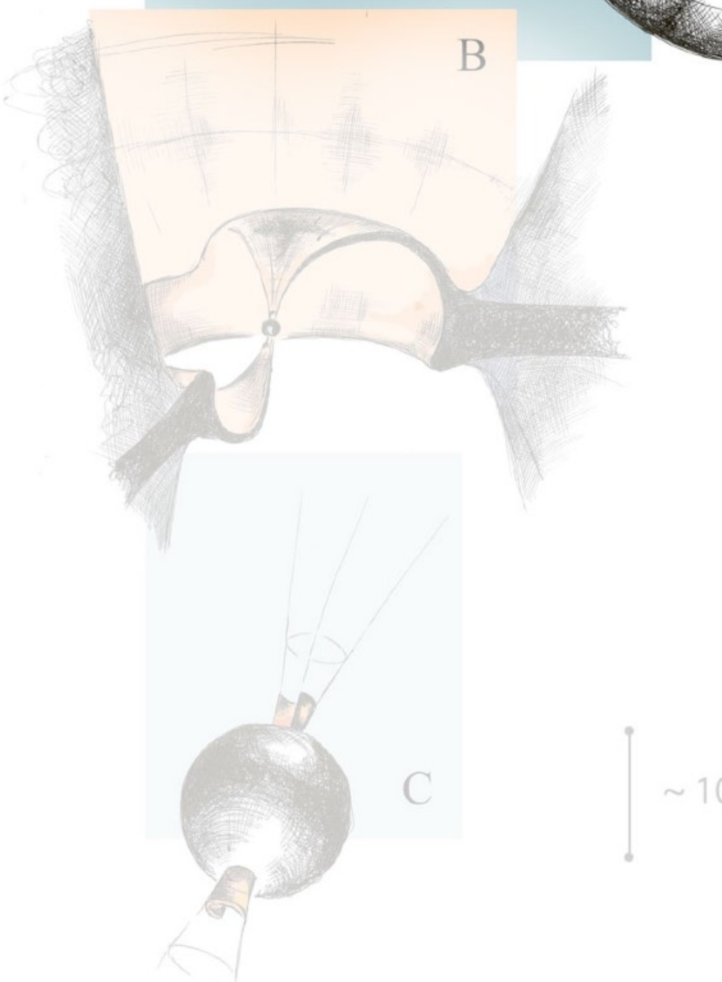
Summary

The **outflows** from the disc are expected at **L > few×10^{39} erg/s**. They influence apparent luminosity, PF and cause phase lags.

Optically thick magnetospheric **flow** is expected at **L > few×10^{38} erg/s**. It can cause strong variations of mass accretion rate onto the NS surface.

Accretion columns are expected at **L > few×10^{37} erg/s** (depending on B-field strength). The columns cause phase shift of pulsations and increase of PF with luminosity.





Summary

The **outflows** from the disc are expected at **L > few×10^{39} erg/s**. They influence apparent luminosity, PF and cause phase lags.

(A) Geometrical beaming results in a strong reduction of pulsed fraction

(B) Launch of the outflows influences apparent luminosity, pulsations (their shape and pulsed fraction) and phase lags.

(C) Accounting for effects of special relativity (at v~0.2c) does not influence much the results.

(D) Strong geometrical beaming leads to a significant radiative force on the walls of accretion cavity. Momentum transferred from photons can be comparable to the total momentum of the outflow. It may influence geometry of accretion cavity.

Next steps:

- Accounting for absorption and spectral changes
- Small spin periods
- Simulations of geometry of accretion cavity.