Pulsing ULXs (PULXs): low-B, super-Eddington accretion

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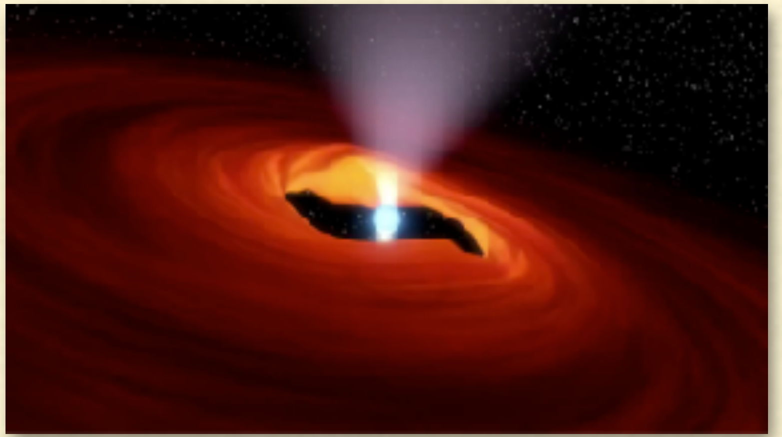
Collaborators: Andrew King, Włodek Kluźniak and Matt Middleton



Ultra-luminous X-ray pulsars

6 - 8 June 2018

European Space Astronomy Centre (ESAC)

Villafranca del Castillo, Madrid, Spain

Don’t be afraid of super-Eddington accretion !

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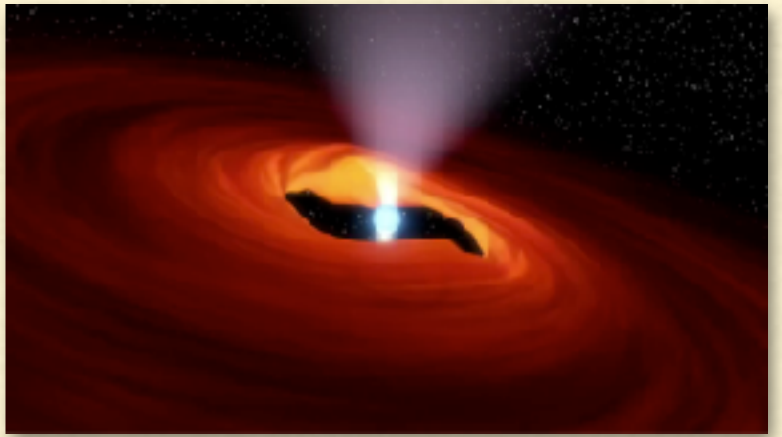

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Definitions:

$$L_{\rm Edd} = \frac{4\pi c G M}{\kappa} = 2.5 \times 10^{38} (1+X)^{-1} \left(\frac{M}{{\rm M}_\odot}\right) \, {\rm erg\,s^{-1}}$$

Solar composition:

$$L_{\rm Edd} = 1.5 \times 10^{38} \left(\frac{M}{{\rm M}_\odot}\right) \, {\rm erg\,s^{-1}}$$

Neutron-star mass:

$$L_{\rm Edd}({\rm N}*) = 2.1 \times 10^{38} \, {\rm erg\,s^{-1}}$$

Accretion rate:

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{0.1 c^2} = 1.6 \times 10^{18} m_1 \, {\rm g\,s^{-1}} = 2.5 \times 10^{-8} m_1 \, {\rm M_\odot\,yr^{-1}}$$

$$m_1 \equiv \frac{M}{{\rm M}_\odot}$$

$$\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\rm Edd}}$$

At least 6 neutron-star accreting systems (NGC2403 ULX, SMC X-3, NGC300 ULX1, NGC7793 P13, M82 X-2, NGC5907 ULX) are observed to have super-Eddington luminosities: from ~ 6 to ~ 476 $L_{Edd}(N_*)$.

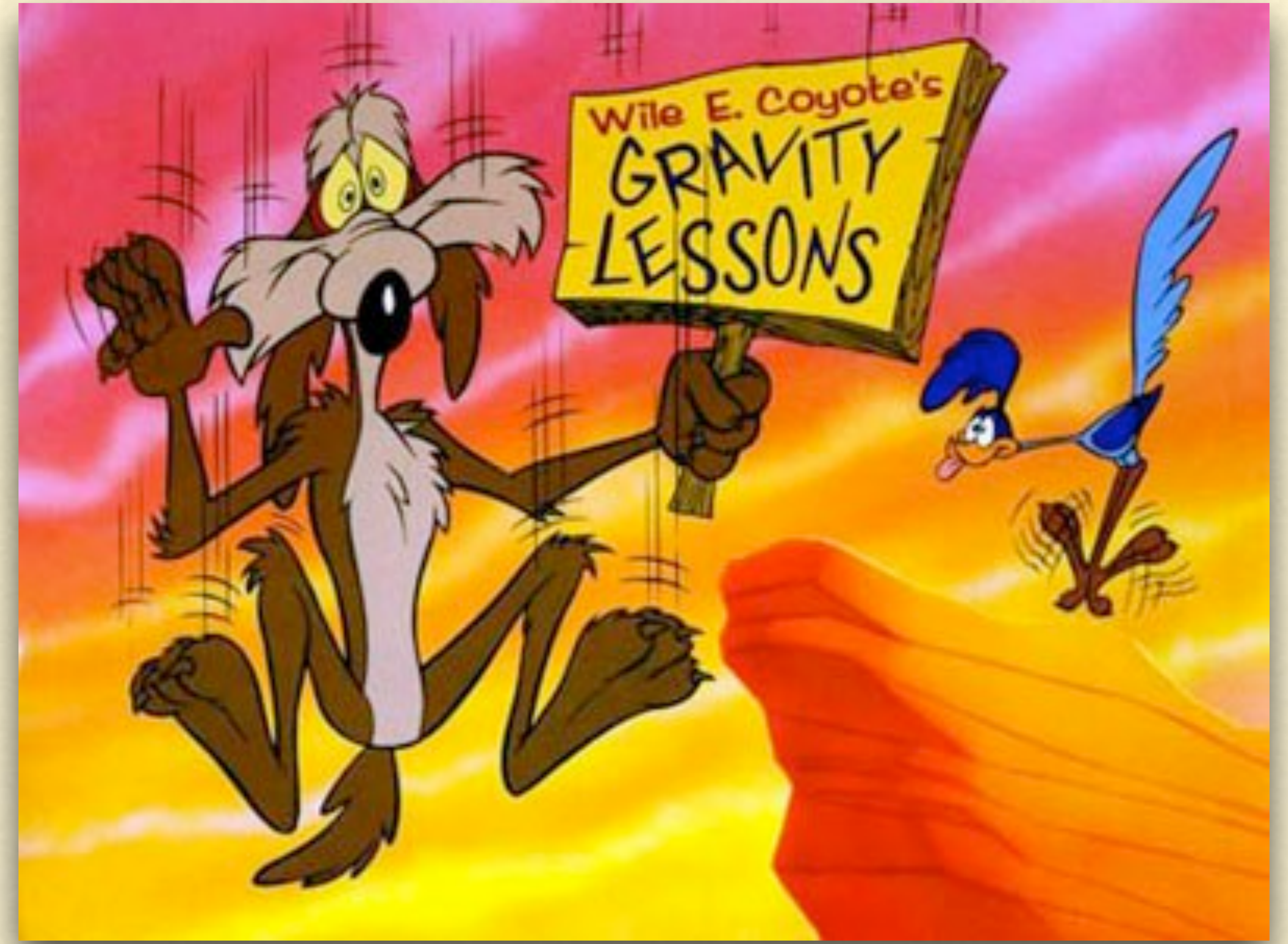
There is nothing (physically) wrong, with super-Eddington luminosities, or with super-Eddington accretion rates. The Eddington luminosity is a <u>critical</u>, not a <u>limiting</u> luminosity.

There is no limit on accretion rate onto a black hole (Begelman 1979): photons inside the <u>trapping radius</u>

$$R_{tr} \equiv \frac{\kappa_{es}\dot{M}}{4\pi c} = \frac{\dot{m}}{2} R_{Sch}$$

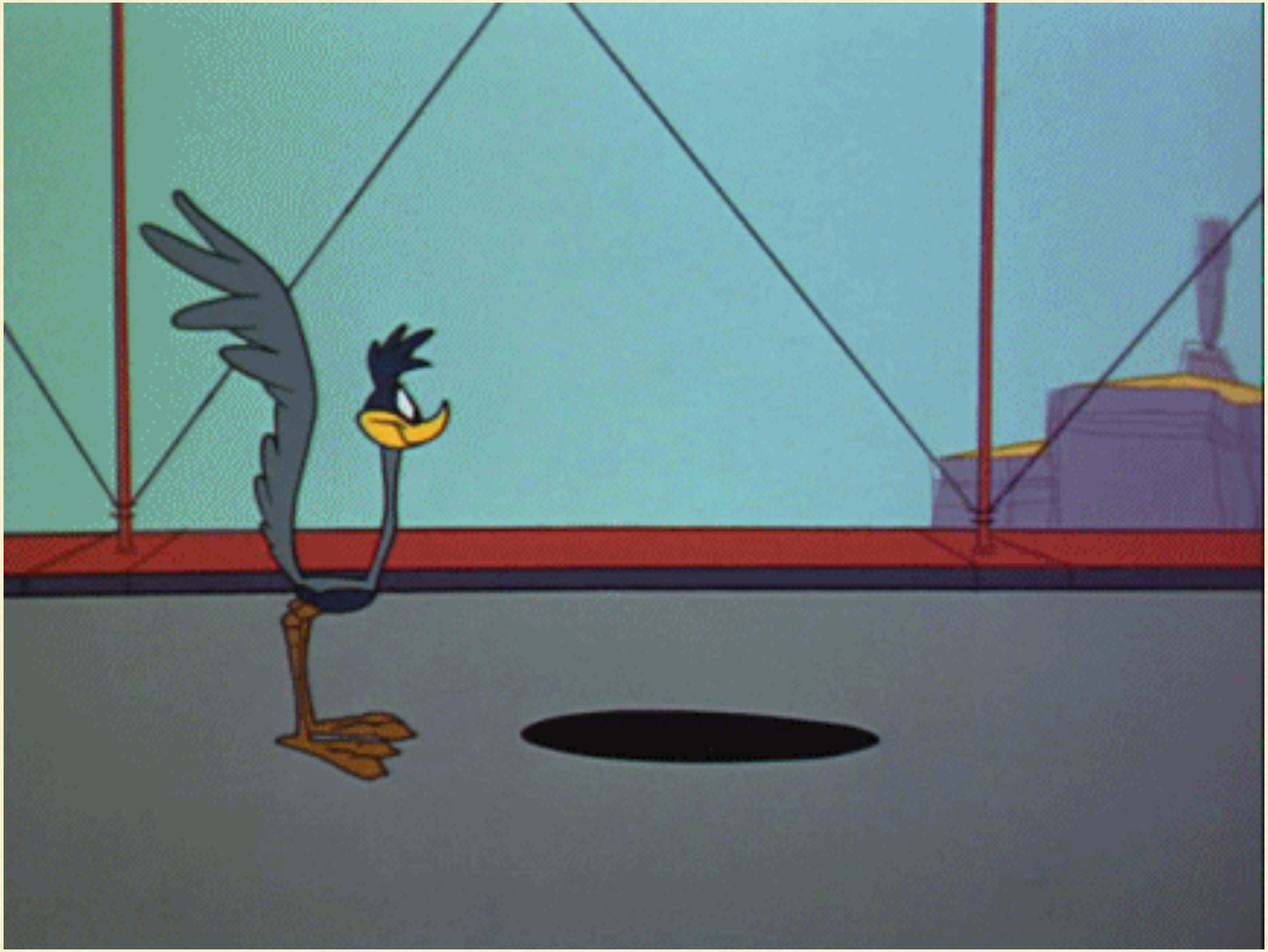
are trapped and advected into the BH.

Super-Eddington accretion



(trapped photons = Wile E. Coyote)

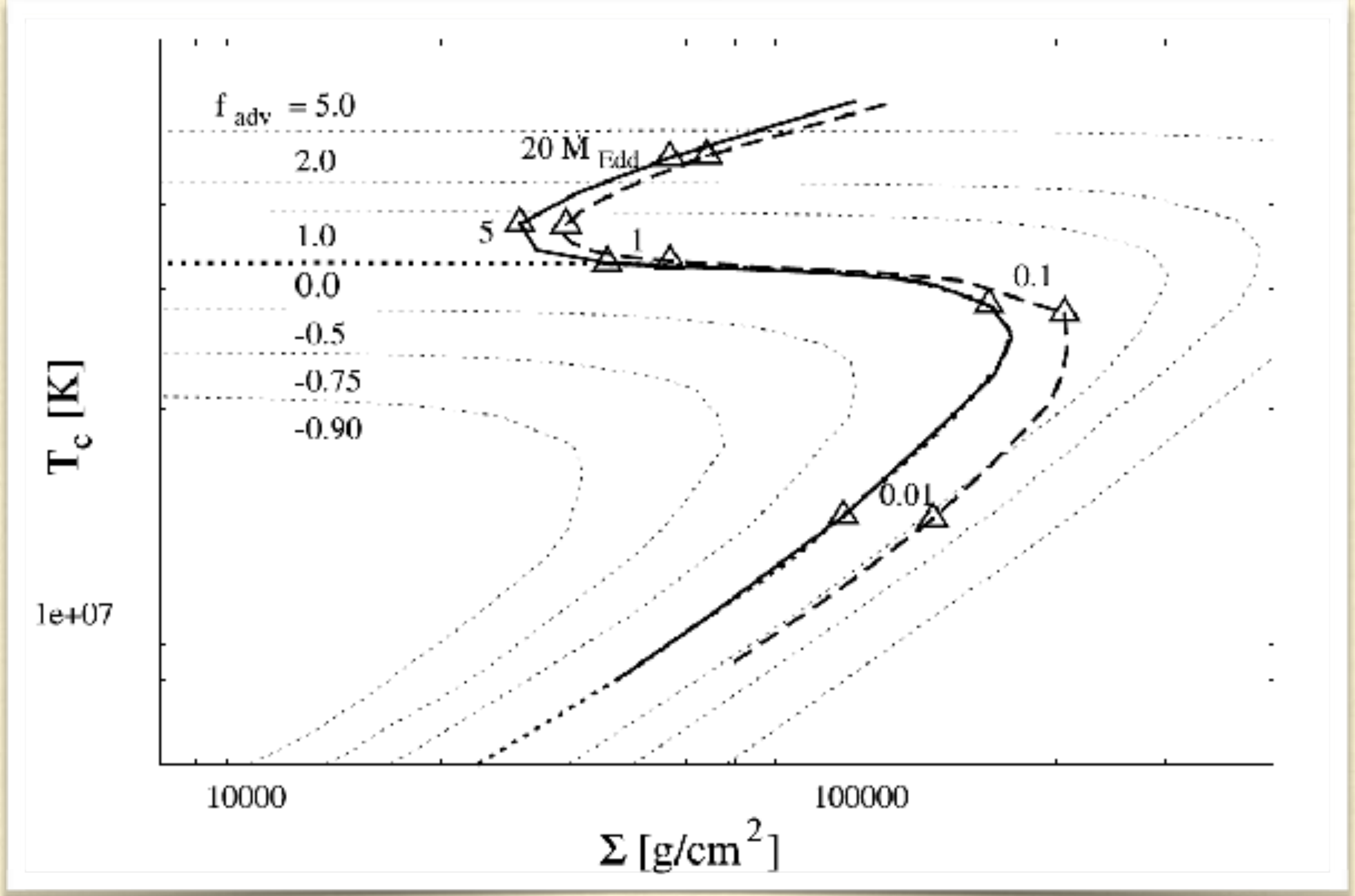
Black hole



Neutron star: more complicated because of hard surface

Btw, for radiative-pressure dominated flows, super-Eddington accretion is better understood than sub-Eddington accretion:
theory predicts violent instability at few % of Eddington accretion rate.
This instability is not observed.

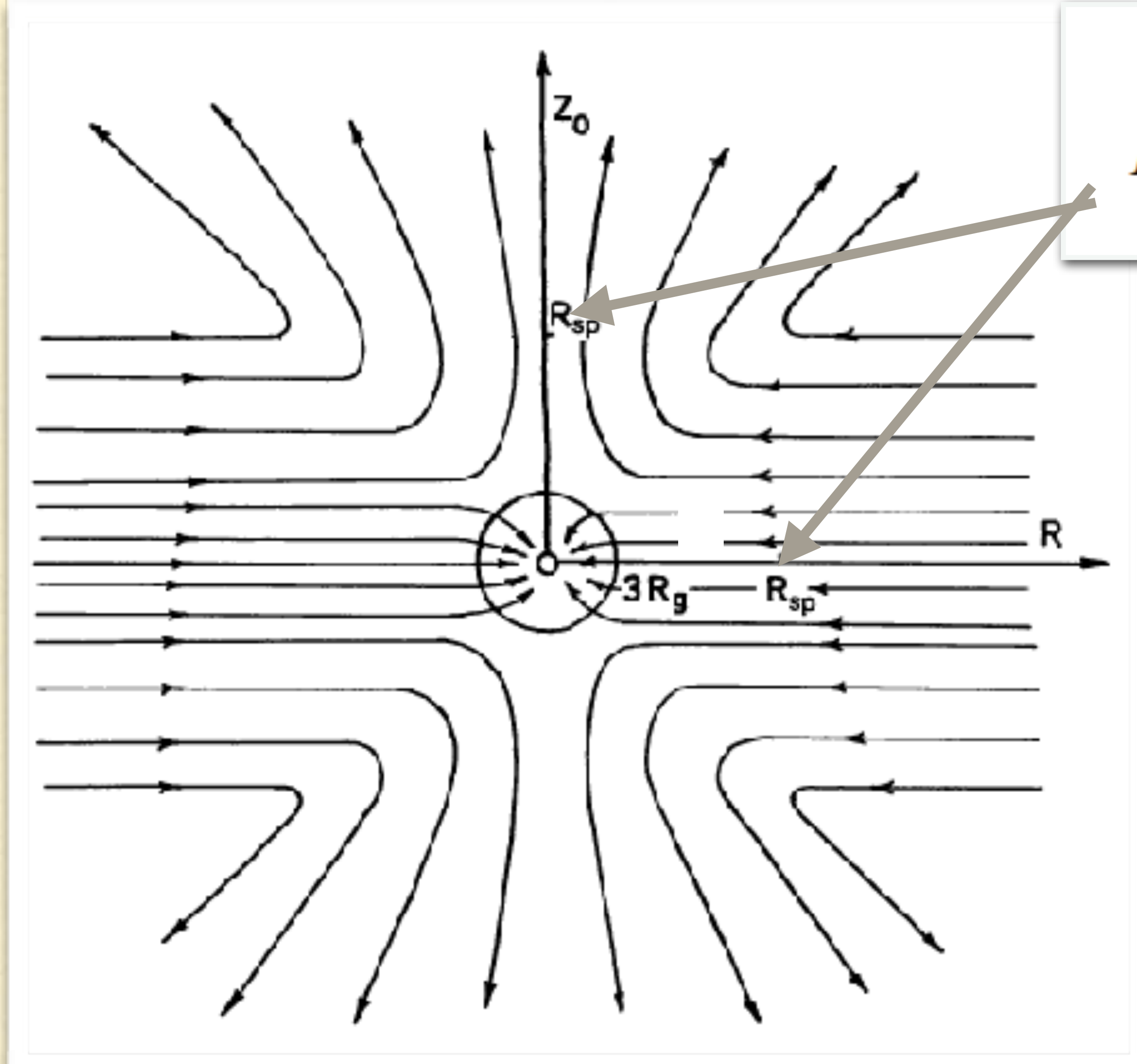
It gets suppressed by advection at super-Eddington rates.



Slim discs

Sądowski et al. 2011

Supercritical accretion generates outflows through radiative pressure (Shakura & Sunyaev 1973)



$$R_{\rm sph} \simeq \frac{27}{4} \dot{m}_0 R_{\rm S}$$

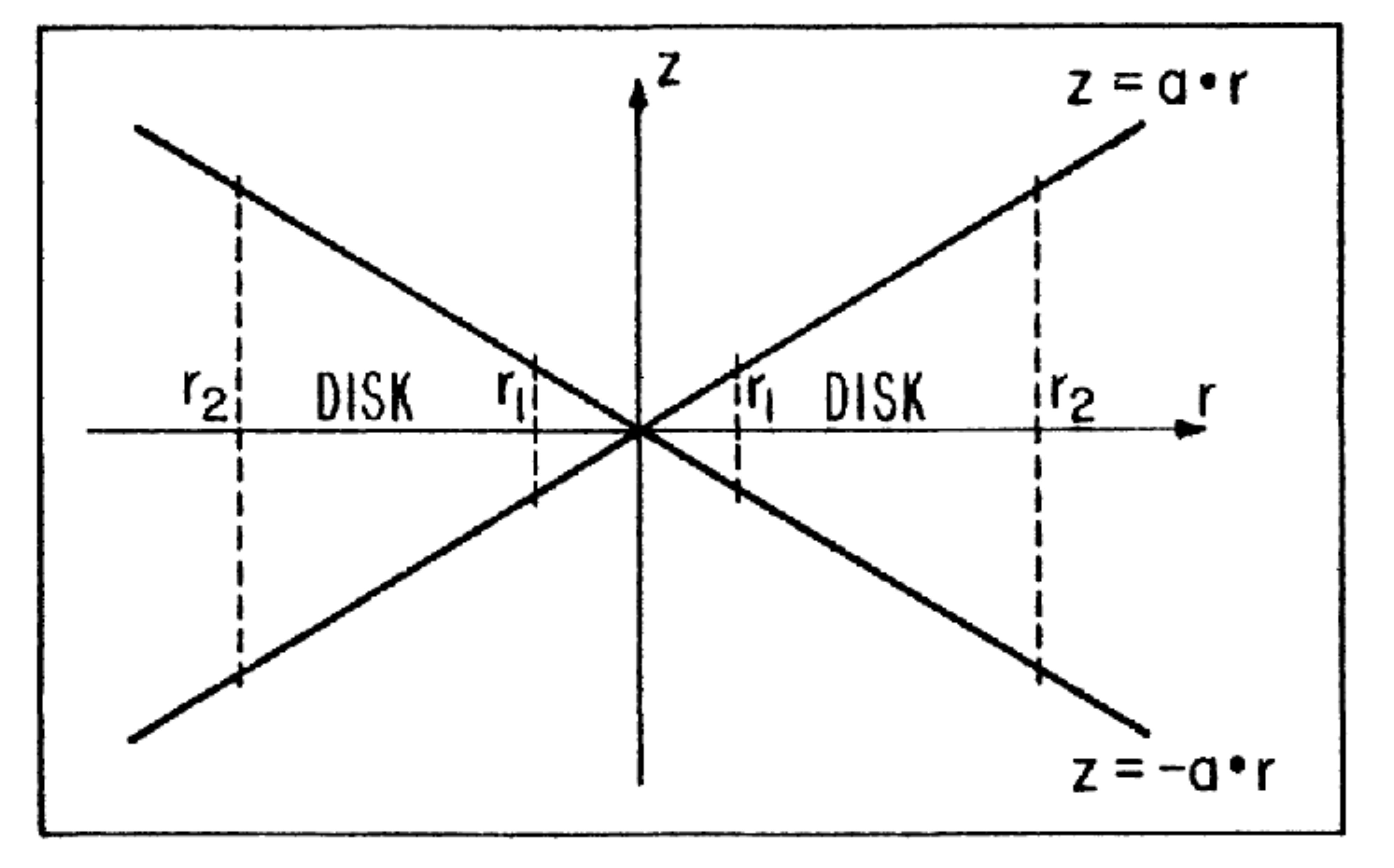
Outflow

$$\dot{M}(R) \simeq \frac{R}{R_{\rm in}} \dot{M}_{\rm Edd}$$

leads to

$$L_{\rm sph} \approx L_E [1 + \ln (1 + \dot{m})]$$

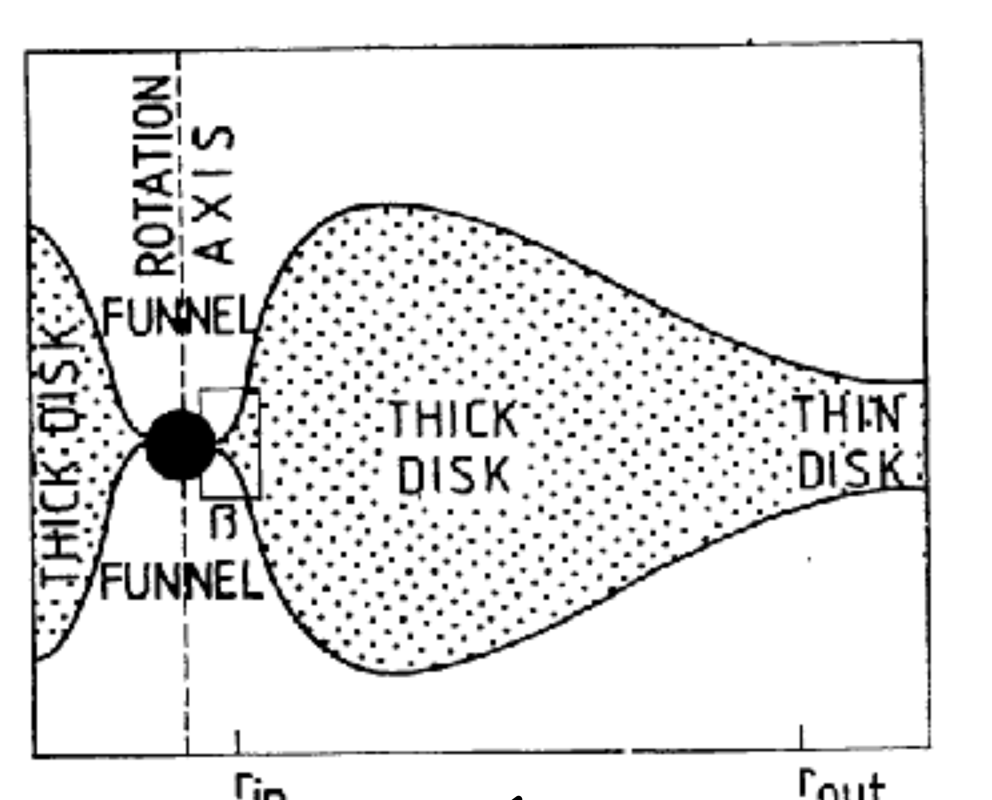
Paczyński 1980: "thick discs".



$$L = L_{cr}\, a(1 + a^2)^{-1/2} \ln(r_2/r_1)$$

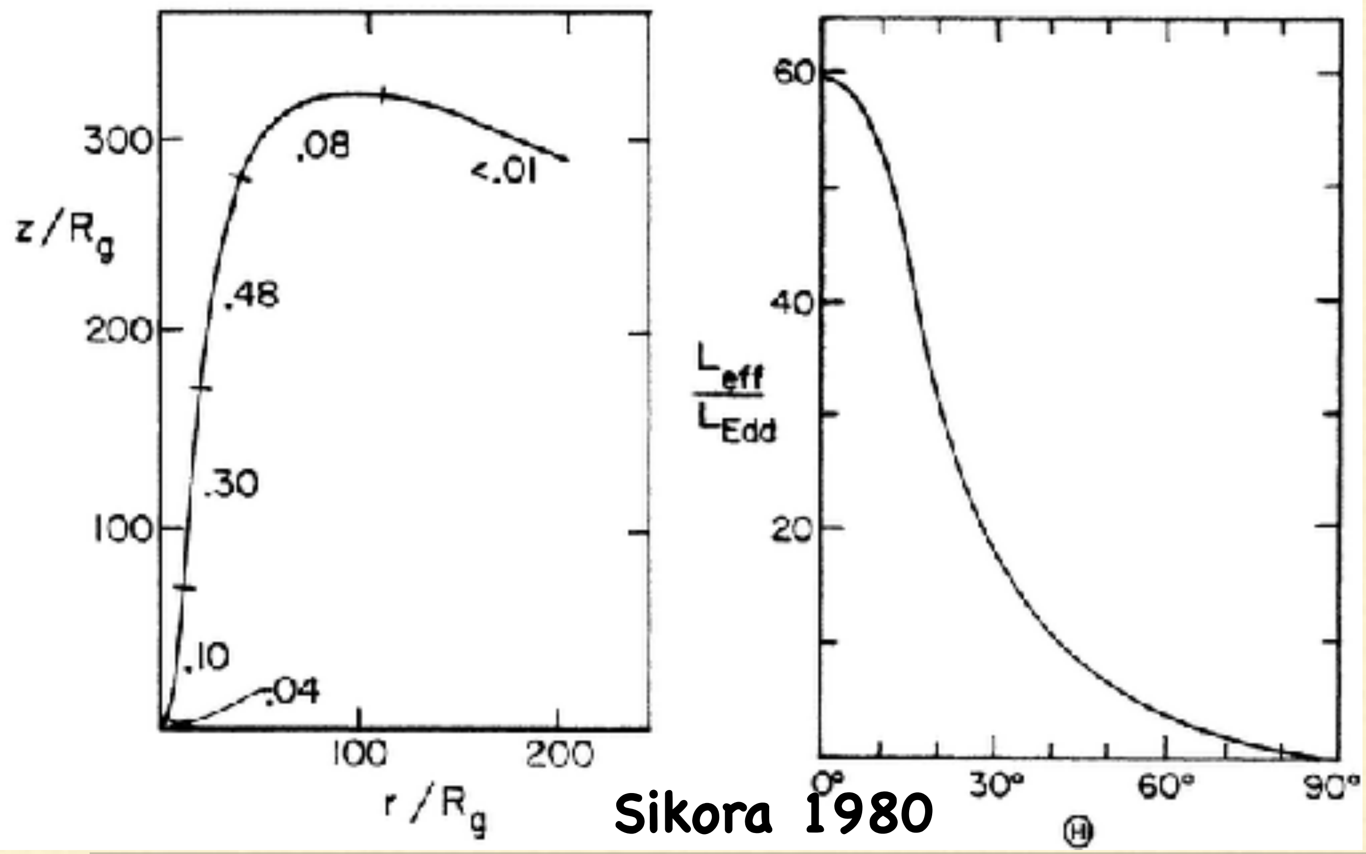
$$L/L_{cr} = 4.8 \log(\dot{M}/\dot{M}_{cr}), \text{ for } 5 < \dot{M}/\dot{M}_{cr} < 100$$

Polish doughnuts



Jaroszyński et al. 1980

Collimation: $$L_{\rm app} = \frac{1}{b} L_{\rm Edd} \ln \dot{m} \quad ?$$

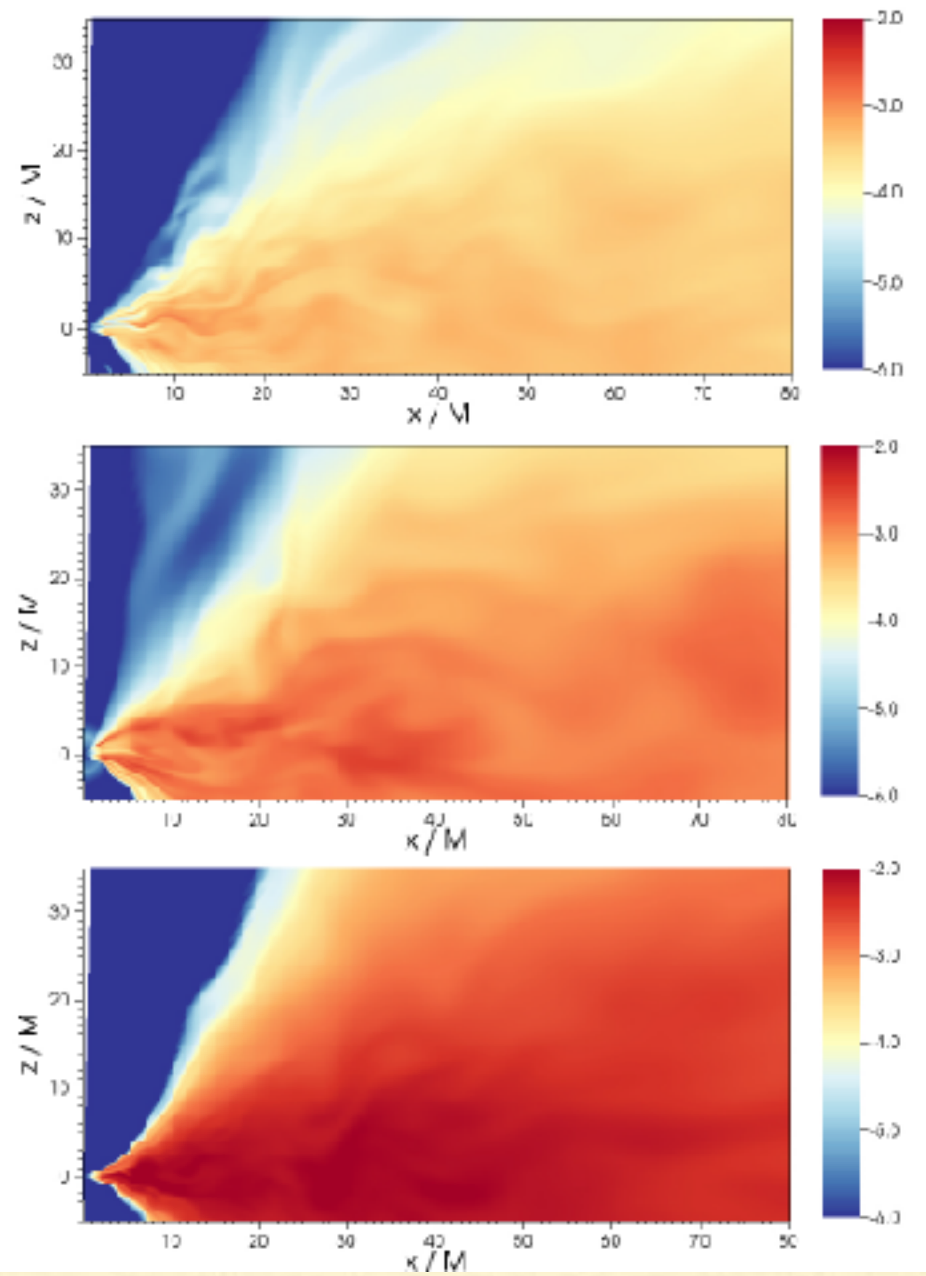


Sikora 1980

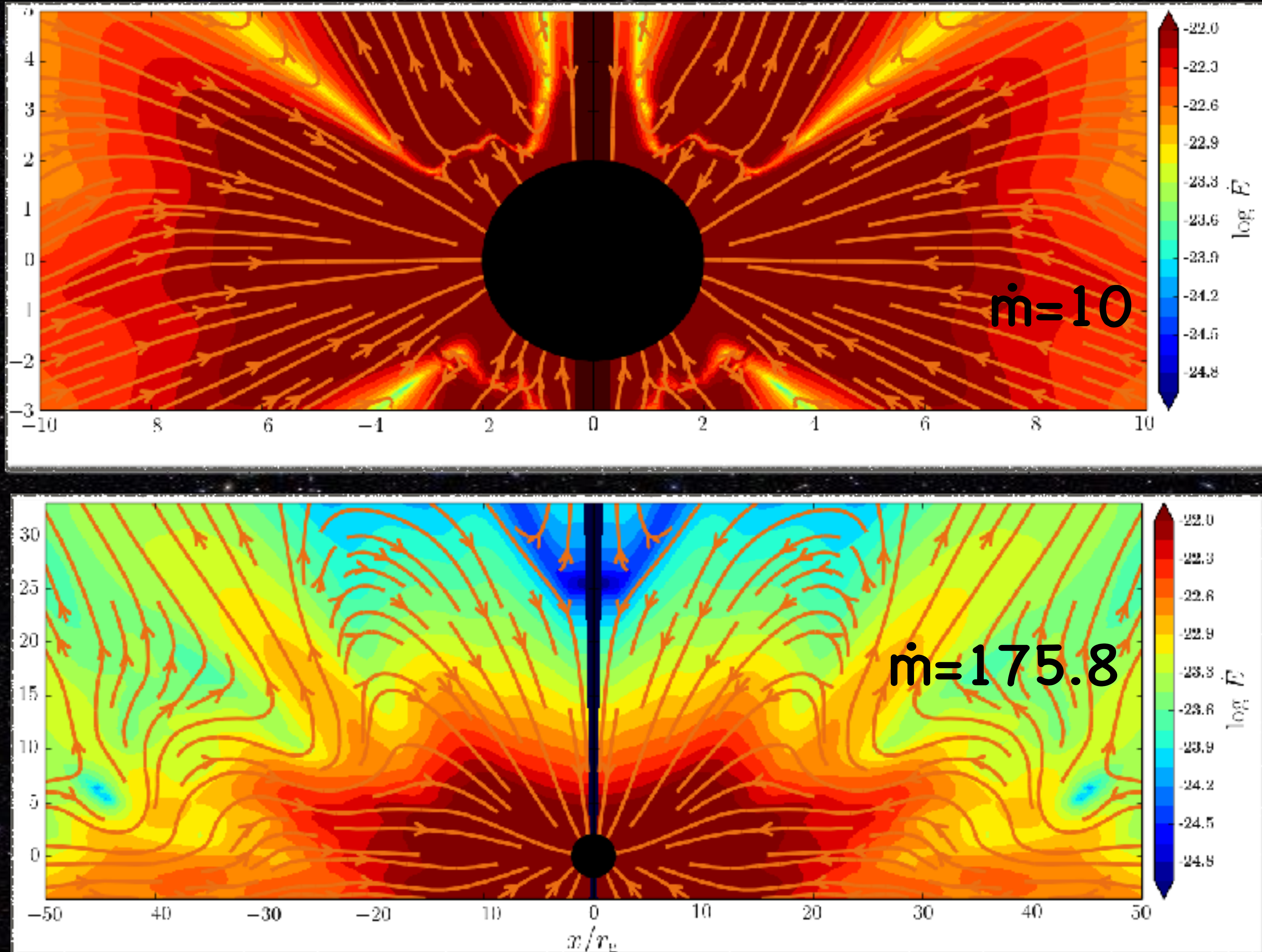
$\dot{m} = 9.6$

$\dot{m} = 24.3$

$\dot{m} = 73.1$



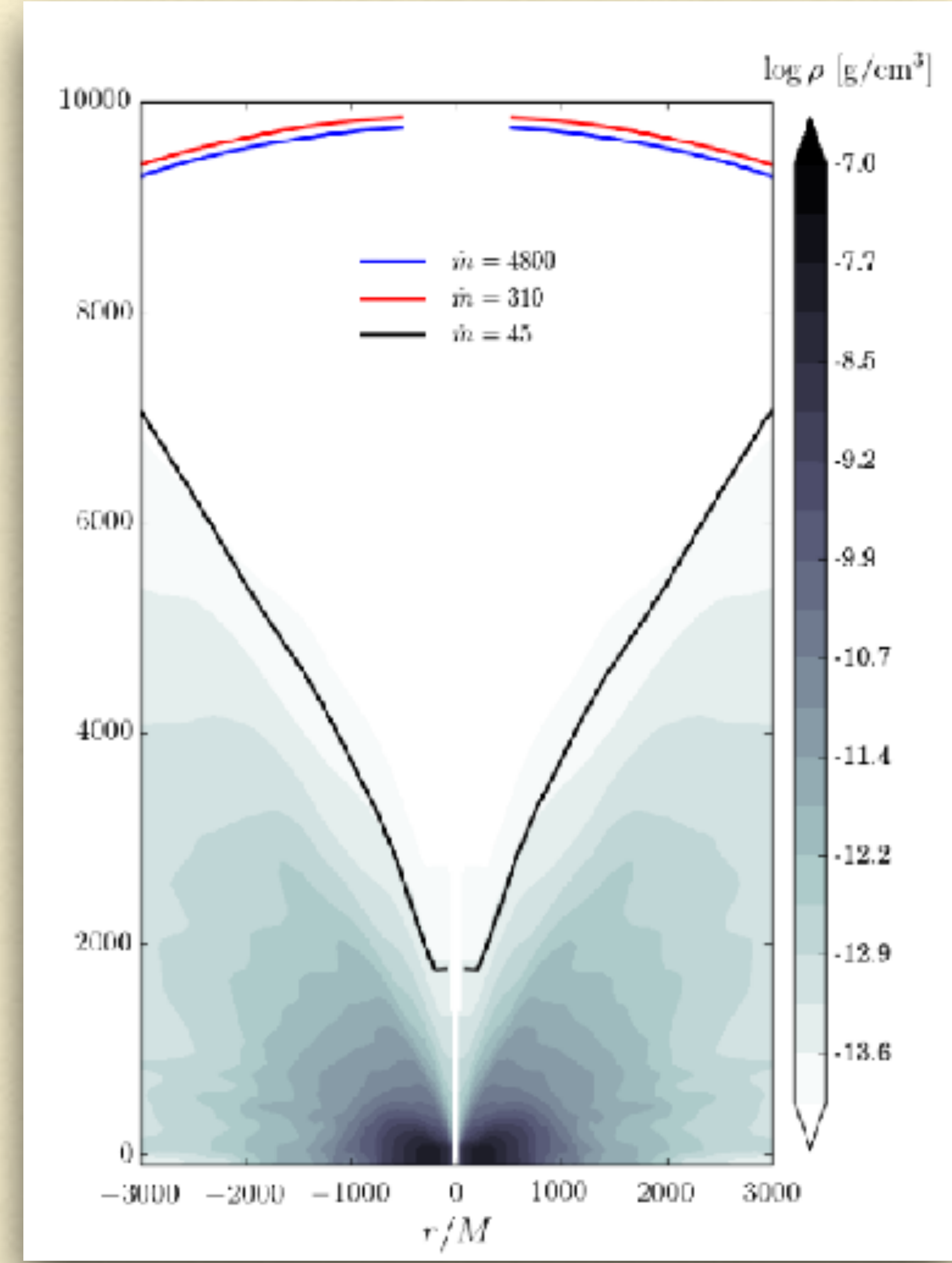
Lasota et al. 2016



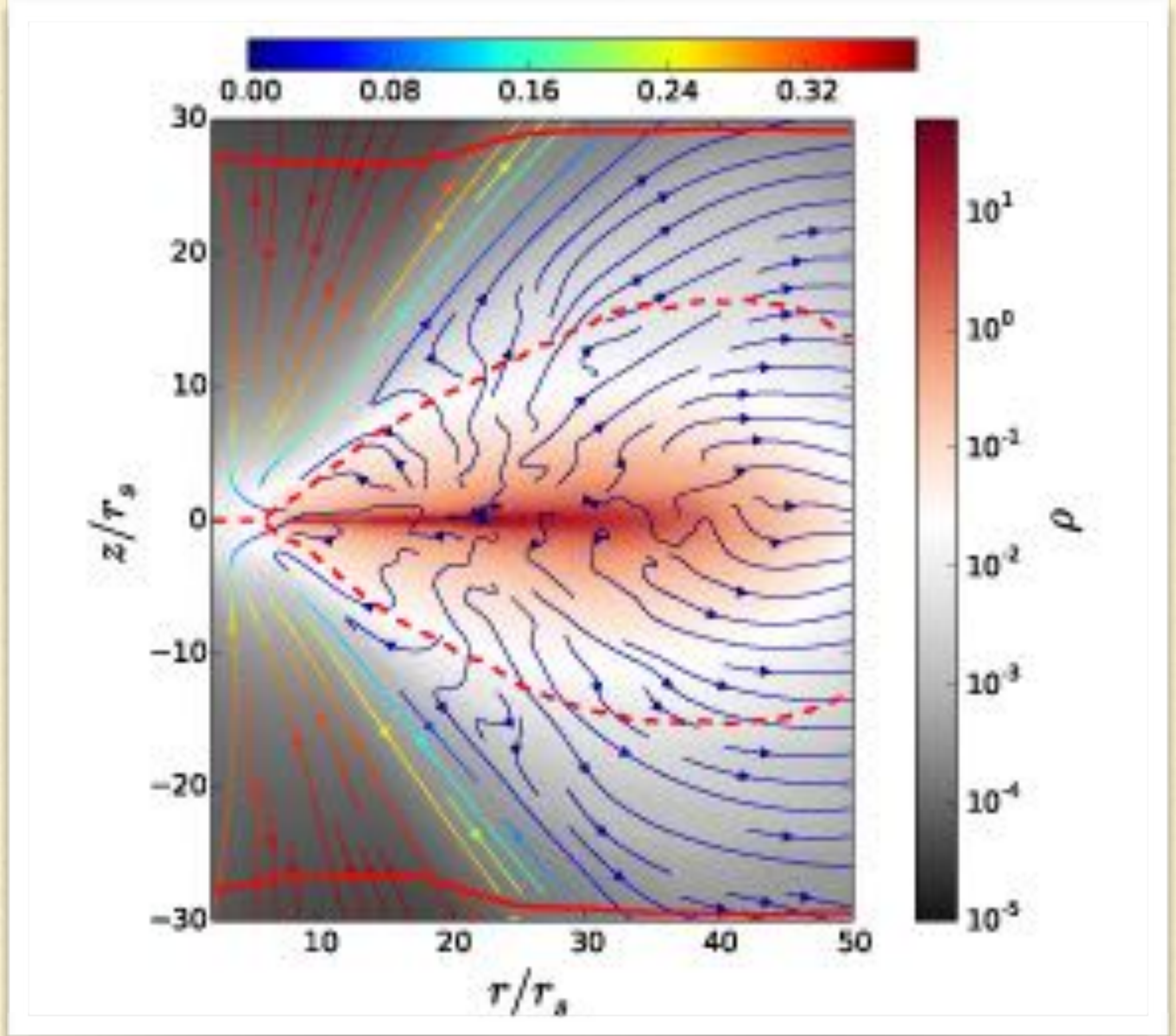
$$L_{\rm sph} \approx L_E\left[1 + \ln\left(1 + \dot{m}\right)\right]$$

Sądowski, Lasota, Abramowicz, Narayan 2016

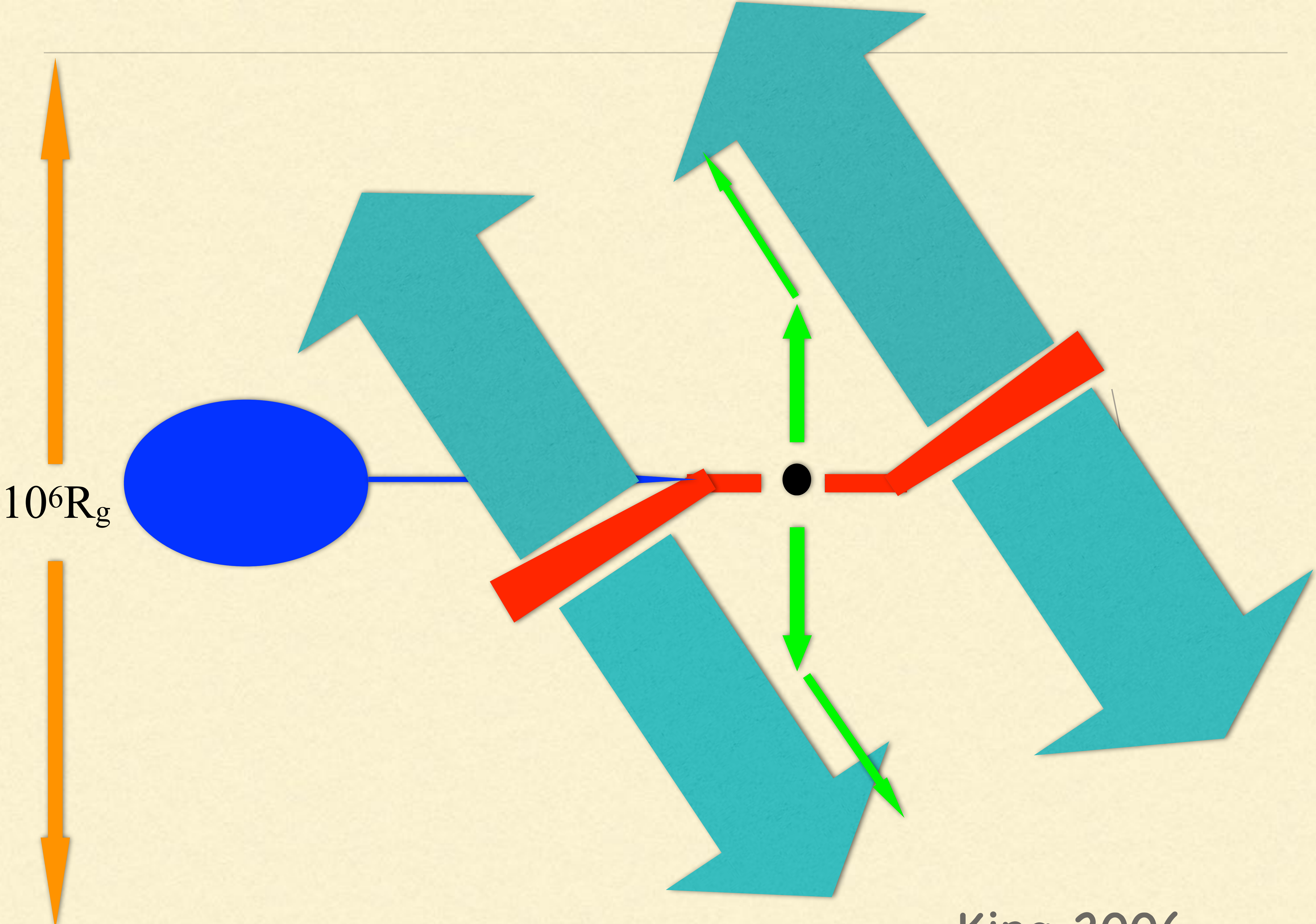
Problem: the photosphere



Sądowski & Narayan 2015



Jiang, Stone & Davis 2014

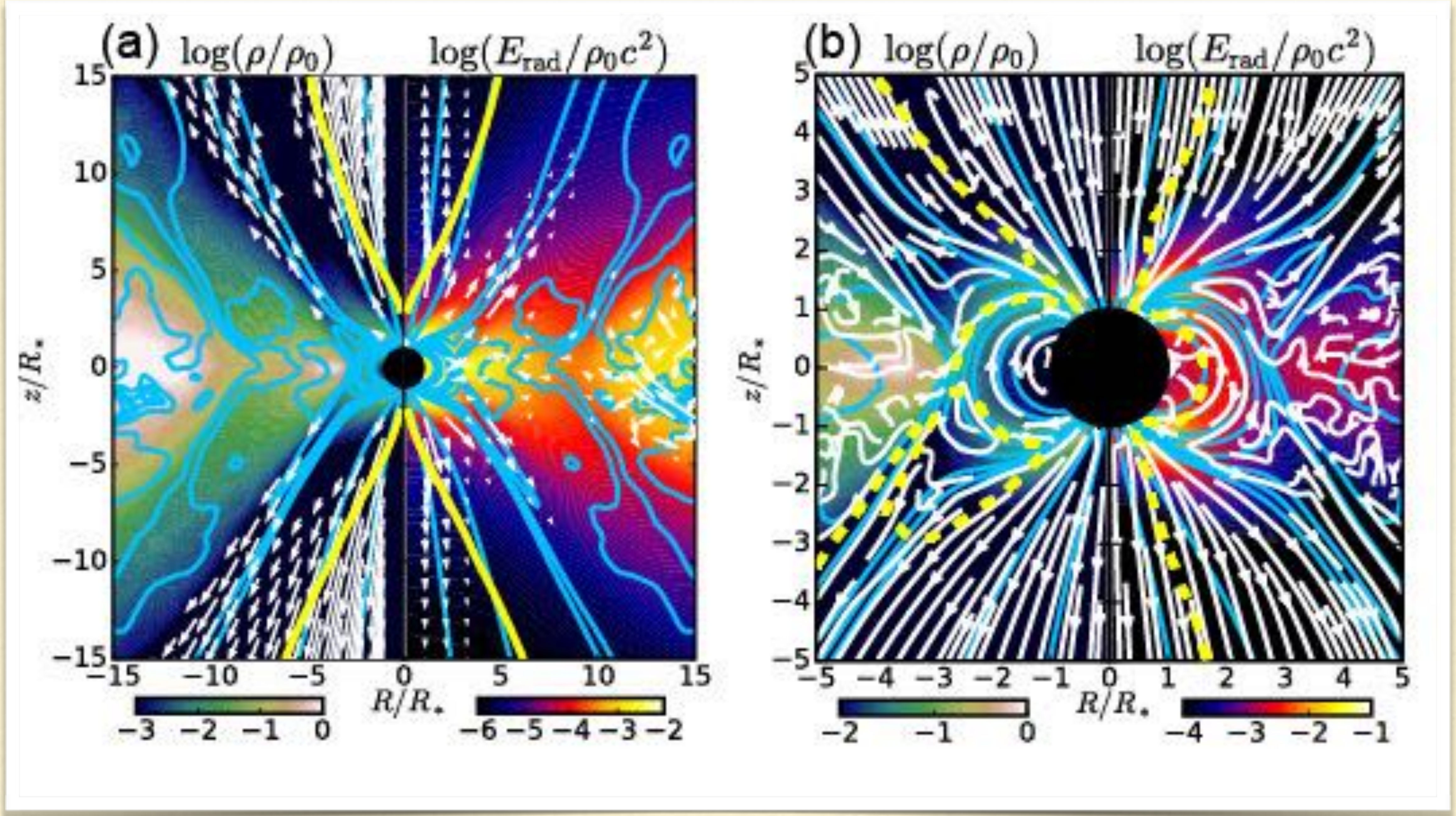


King 2006

Magnetised (10^{10} G) non-rotating neutron star

$L \sim 10\ L_{Edd}$

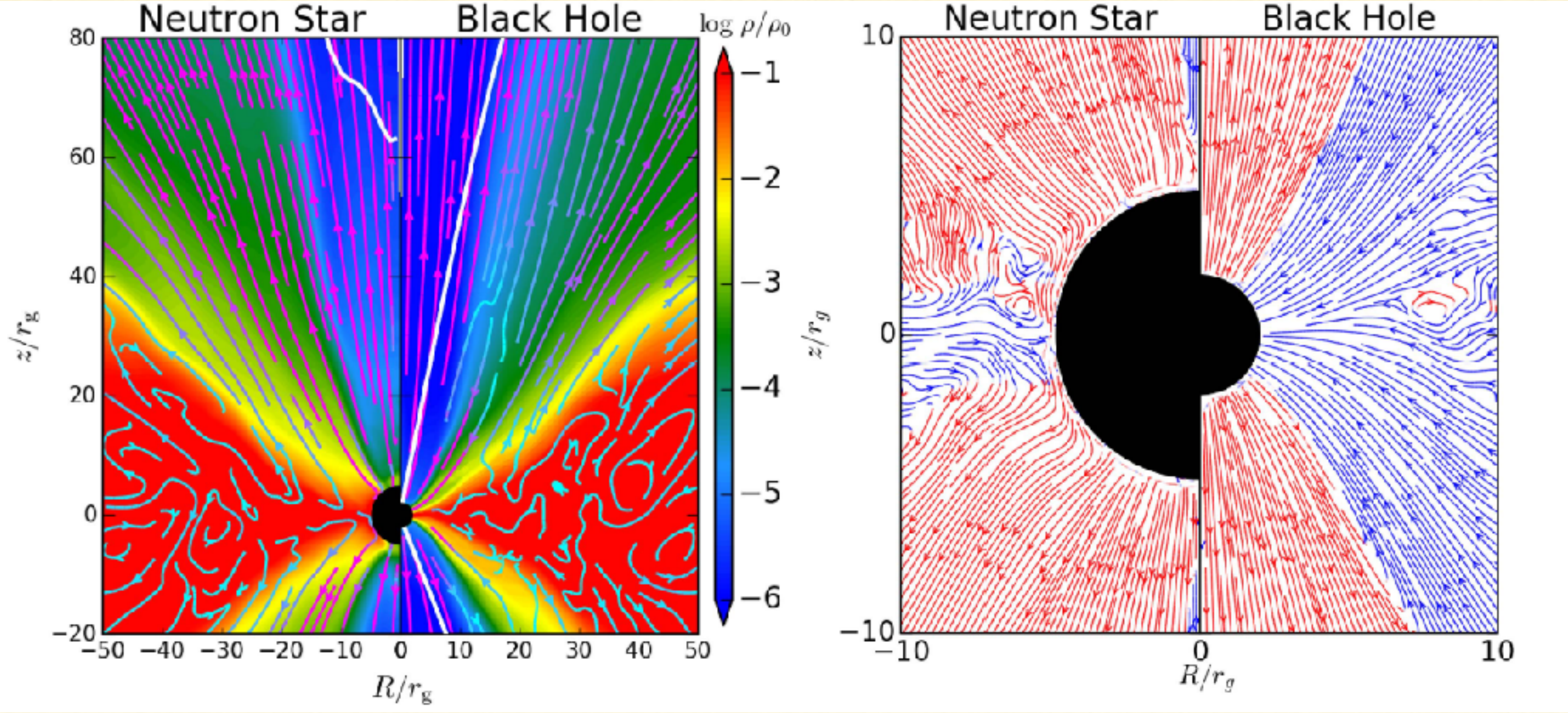
$\dot{M} \sim 66\ L_{Edd}/c^2$



Takahashi & Ohsuga 2017

Non-magnetised, non-rotating neutron star and black hole

"Supercritical Accretion onto a Non-magnetized Neutron Star: Why is it Feasible?"



Takahashi, Mineshige & Ohsuga 2018

Pulsing ULXs: PULXs

Name	M82 ULX2	NGC7793 P13	NGC5907 ULX1	NGC300 ULX1	NGC 2403 ULX
L_X (max) [erg s^{-1}]	2.0×10^{40}	5×10^{39}	$\sim 10^{41}$	4.7×10^{39}	1.2×10^{39}
P_s [s]	1.37	0.42	1.13	$\sim$31.5	$\sim$ 18
$\dot{\nu}$ [s^{-2}]	10^{-10}	2×10^{-10}	3.8×10^{-9}	5.6×10^{-10}	3.4×10^{-10}
$P_{\rm orb}$ [d]	2.51 (?)	64	5.3(?)	$>$ 8 (Be ?)	60 – 100 (?)
M_2 [M$_\odot$]	$\gtrsim$ 5.2	18–23		40 (Be ?)	(Be ?)

What is really characteristic of PULXs is their high spin-up rate:

$$\dot{\nu} \geqslant 10^{-10} \mathrm{s}^{-2}$$

which even for high B's implies super-Eddington accretion:

Spin-up rate at the magnetosphere radius:

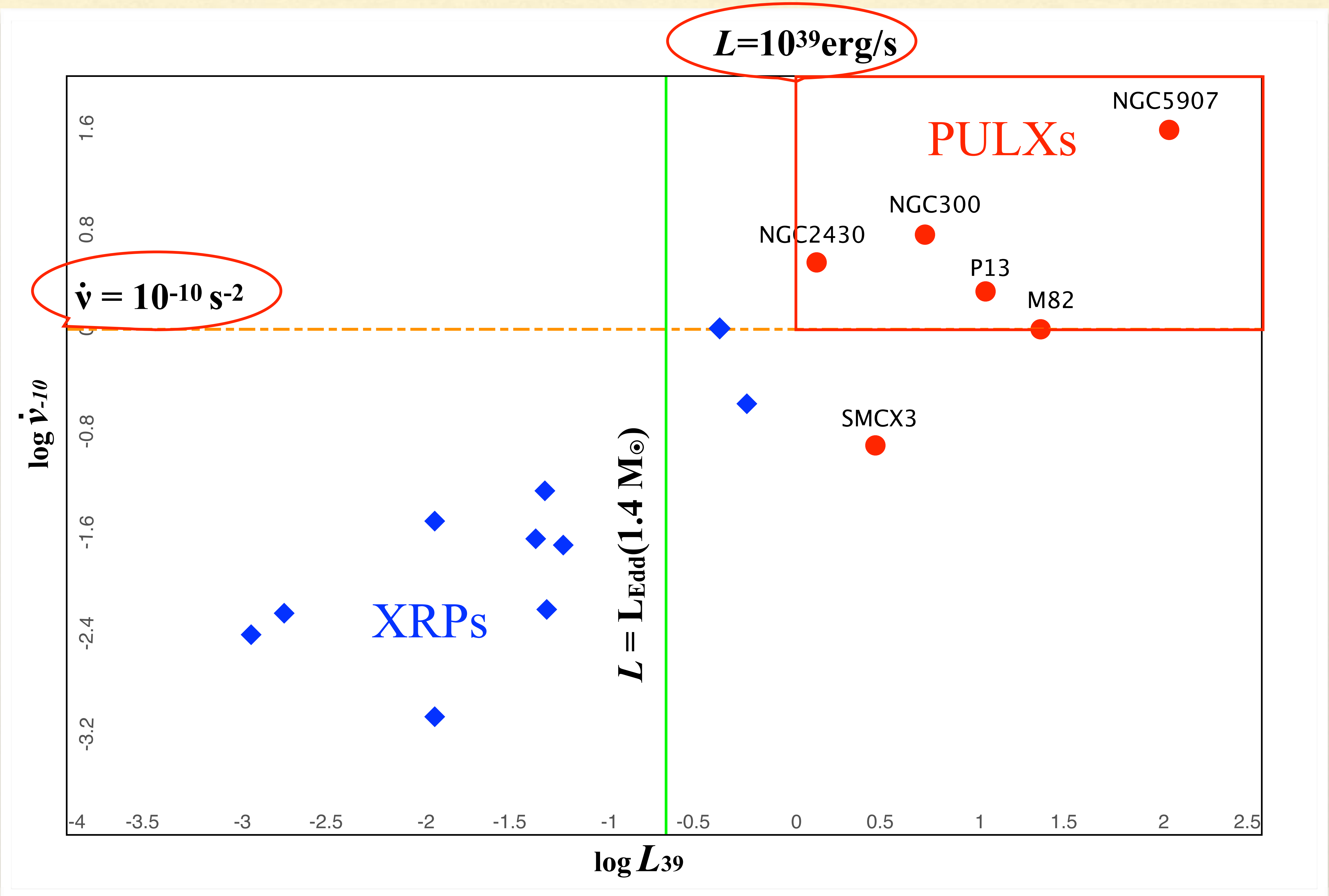
$$\dot{\nu} = \frac{\dot{J}(R_M)}{2\pi I}$$

$$\dot{\nu} = 3.1 \times 10^{-12} q^{1/2} \dot{M}_{17}^{6/7} m_1^{3/7} \mu_{30}^{2/7} I_{45}^{-1}\ \mathrm{s}^{-2}$$

$$\dot{m}(R_\mathrm{M}) = \frac{\dot{M}(R_\mathrm{M})}{\dot{M}_\mathrm{Edd}} = 5.8 \left(\frac{\dot{\nu}_{-10}}{q^{1/2}}\right)^{7/6} \mu_{30}^{-1/3}$$

Name	M82 ULX2	NGC 7793 P13	NGC5907 ULX1	NGC300 ULX1	NGC 2403 ULX
$\dot{m}(R_M)q^{7/12}$; $\mu_{30} = 1$	5.8	13.0	404	43.3	24
$\dot{m}(R_M)q^{7/12}$; $\mu_{30} = 1000$	0.6	1.3	40.4	4.3	2.4

PULXs: definition

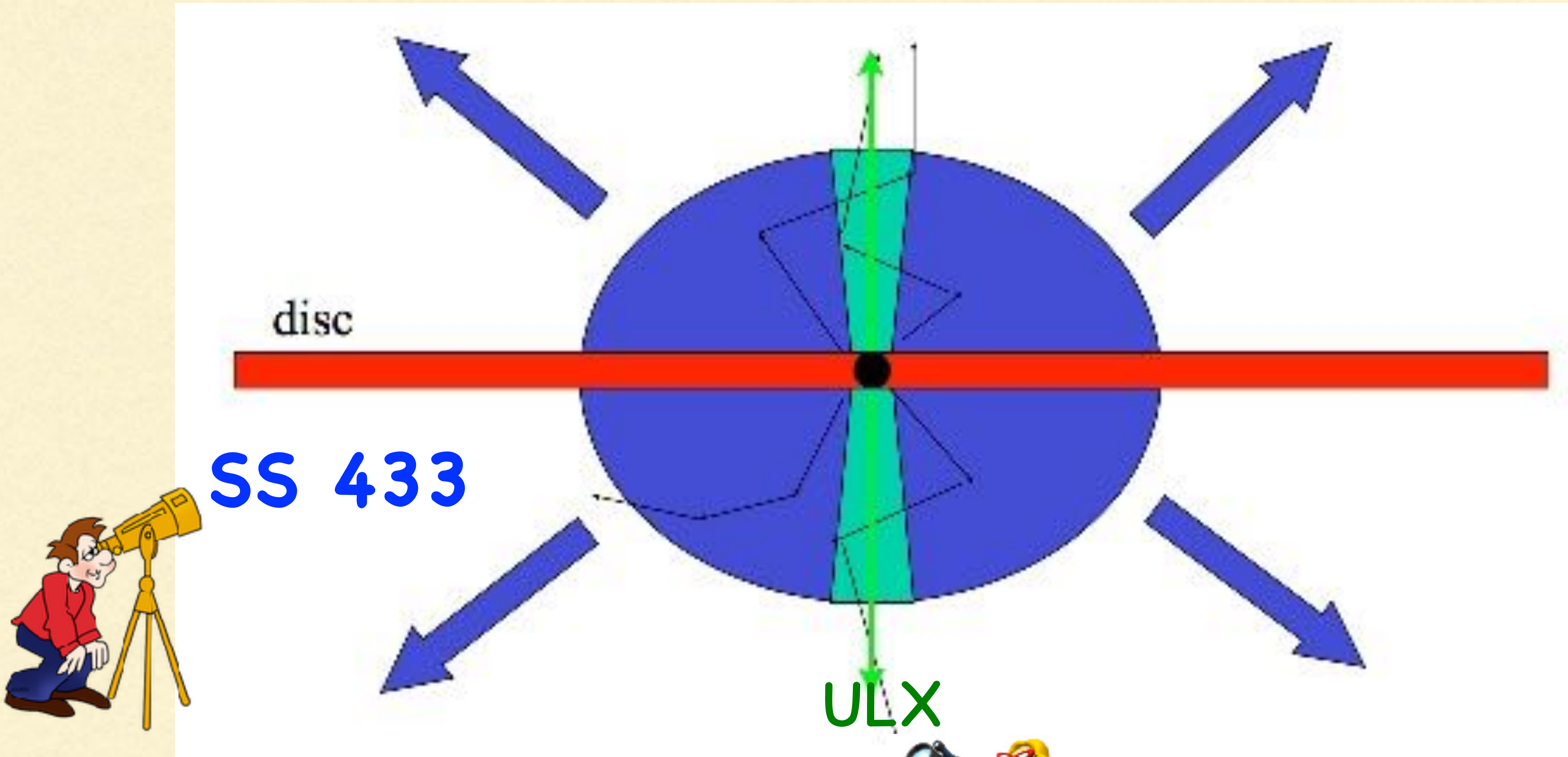


Why "low" magnetic fields and super-critical accretion rates?

- Super-critical accretion is possible, so no need to reduce opacity.
- Even very high *B*'s require beaming in some cases (e.g., Abolmasov et al. 2017).
- Observations:
  - NGC 300 ULX1 – $B \sim 10^{12}$ G (Walton et al. 2018)
  - M51 ULX8 – ("… we rule out a very strong (10^{15} G) dipole field solution with either a sub- or super-critical flow. Instead we favour an upper limit on the dipole field of 10^{11} - 10^{12} G and a classical super-critical inflow, similar to that **inferred*** in other ULXs found to harbour neutron stars"; Middleton et al. 2018.)
  - Ultrafast winds (Pinto, Kosec), no magnetras in binaries (Rea).

*** how and by whom is the main subject of the present talk..**

Super-critical luminosities imply <u>beaming</u>



$$b \sim \frac{1}{\dot{m}^2}$$

King 2009

King et al. (2001): all ULXs are X-ray binaries with beamed emission caused by super-Eddington mass transfer rates.

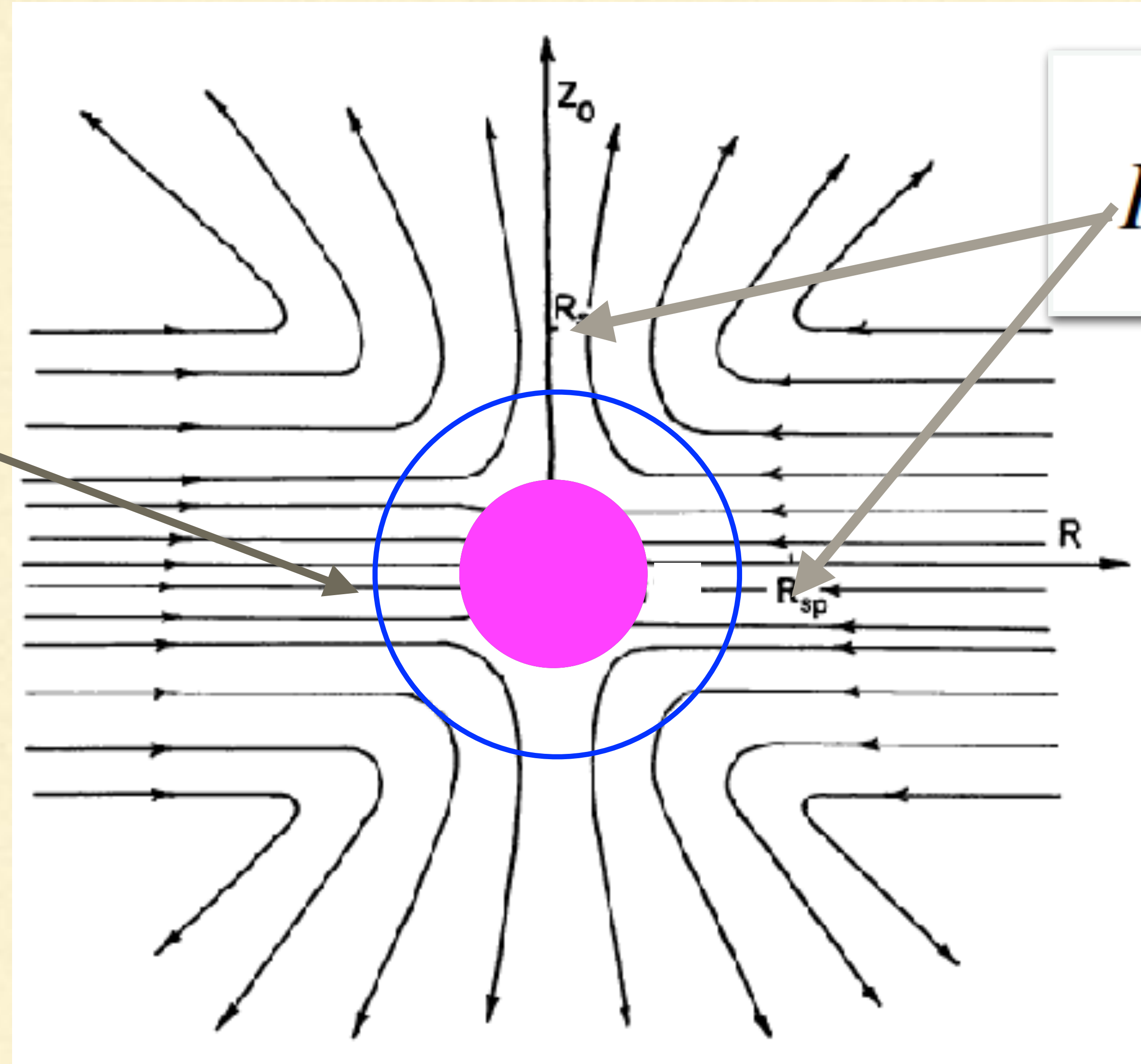
"A beaming factor […] $b \lesssim 0.01$ would bring *M* down to neutron star values. In addition, this kind of disk geometry, i.e., a thick disk with a central funnel, may actually radiate a total luminosity in excess of the Eddington limit (Jaroszyński, Abramowicz, & Paczyński 1980; Abramowicz, Calvani, & Nobili 1980). Thus, such modest *b* -values may allow quite large apparent luminosities for perfectly standard black hole or neutron star masses".

Caveat emptor: not all "formal" ULXs are necessarily beamed; e.g., in the King (2009) beaming model this is the case only for

$$\dot{m} \gtrsim \sqrt{73} \simeq 8.5$$

Geometrical beaming model for PULXs (King & JPL, 2016; King, JPL & Kluźniak, 2017; KLK)

R_M



$$R_{\rm sph} \simeq \frac{27}{4} \dot{m}_0 R_{\rm S}$$

Outflow $\dot{M}(R) \simeq \frac{R}{R_{\rm sph}} \dot{m}_0 \dot{M}_{\rm Edd}$ and beaming factor $b \simeq \frac{73}{\dot{m}_0^2}$:

$$L = \frac{1}{b} L_{\rm Edd} \left[1 + \ln \dot{m}_0\right]$$

In the main, people do not read; if they read, they do not understand. And those who understand forget.

Henry de Montherlant

Model

From equations:

$$R_M = 2.6 \times 10^8 q \dot{M}_{17}^{-2/7} m_1^{-1/7} \mu_{30}^{4/7} \text{ cm}$$

$$\dot{\nu} = 3.1 \times 10^{-12} q^{1/2} \dot{M}_{17}^{6/7} m_1^{3/7} \mu_{30}^{2/7} I_{45}^{-1} \text{ s}^{-2}$$

$$R_{\rm sph} \simeq \frac{27}{4} \dot{m}_0 R_S \simeq 2 \times 10^6 \dot{m}_0 m_1 \text{ cm}$$

$$\frac{R_{\rm sph}}{R_M} = \frac{\dot{M}_0}{\dot{M}(R_M)}$$

using observed spin-up rate and observed luminosity: $L_{40} \simeq 2.22 \times 10^{-4} \dot{m}_0^2 [1 + \ln \dot{m}_0] m_1$

one obtains:

$$\dot{M}_{17}(R_M) = 390\, q^{7/9} m_1^{-8/9} \mu_{30}^{4/9},$$

$$R_M = 1.6 \times 10^7 \dot{\nu}_{-10}^{2/3} m_1^{1/3} I_{45}^{2/3} \text{ cm},$$

$$\mu_{30} = 0.09\, q^{-7/4} \dot{\nu}_{-10}^{3/2} m_1^{1/2} I_{45}^{3/2},$$

where $\dot{\nu}_{-10} = \dot{\nu}/10^{-10} \text{ s}^{-2}$.

Results

Name	M82 ULX2	NGC 7793 P13	NGC5907 ULX1	NGC300 ULX1	NGC 2403 ULX
$\dot{m}_0$	36	20	91	20	11
$\mu\, q^{7/4} m_1^{-1/2} I_{45}^{-3/2}$ [Gcm^3]	9.0×10^{28}	2.5×10^{29}	2.1×10^{31}	$1.2 \times 10^{30\,(i)}$	5.6×10^{29}
$R_{\rm sph} m_1^{-1}$ [cm]	7.2×10^{7}	4.1×10^{7}	2.6×10^{8}	4.1×10^{7}	2.2×10^{7}
$R_M m_1^{-1/3} I_{45}^{-2/3}$ [cm]	1.6×10^{7}	2.5×10^{7}	1.8×10^{8}	5.0×10^{7}	1.1×10^{7}
$R_{\rm co} m_1^{-1/3}$ [cm]	1.9×10^{8}	8.4×10^{8}	1.6×10^{8}	1.5×10^{9}	1.1×10^{9}
$P_{\rm eq} q^{-7/6} m_1^{1/3}$ [s]	0.05	0.09	1.75	0.26	0.16
$t_{\rm eq}$ [yr]	6117	1385	0	2162	578

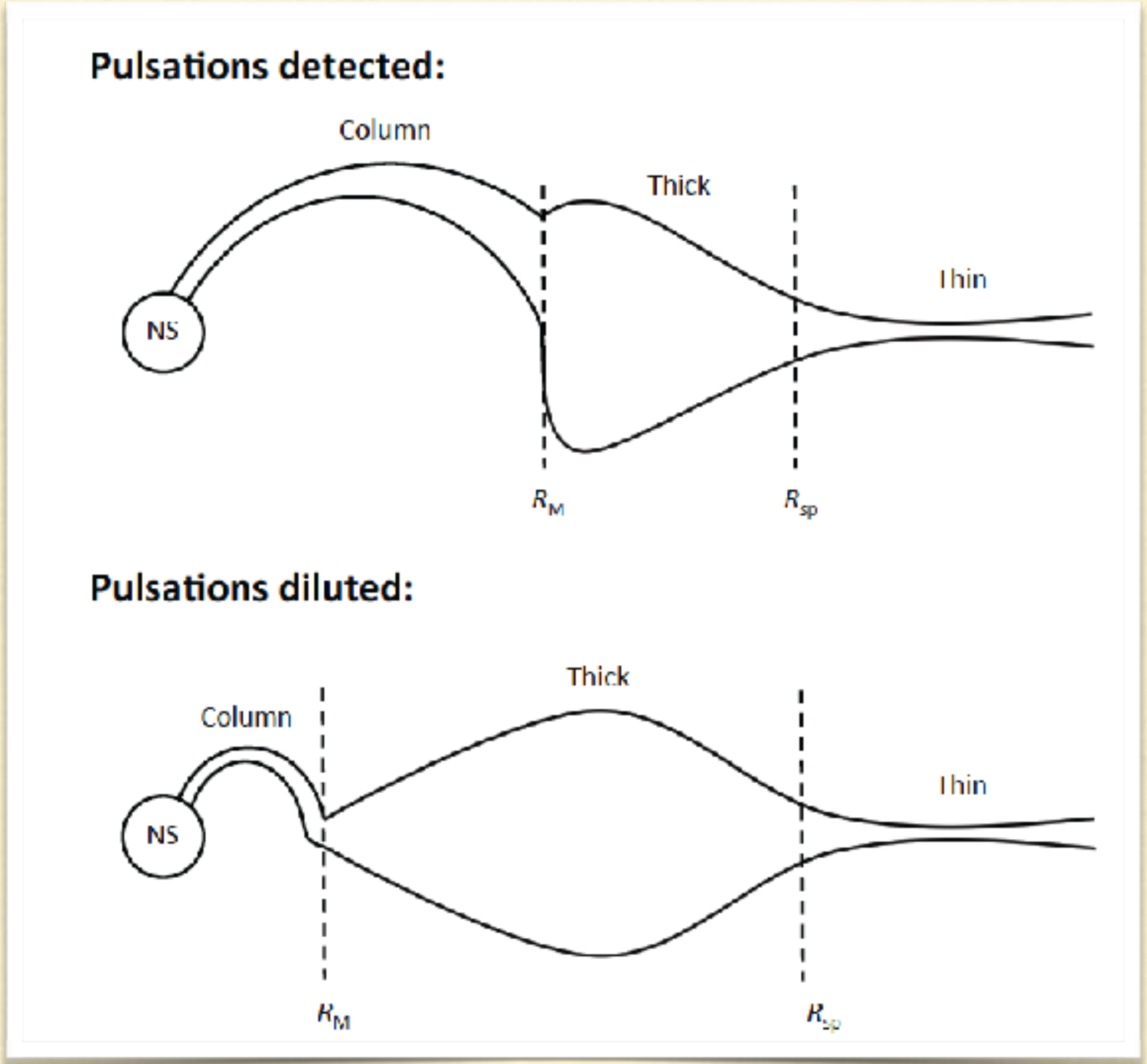
$^{(i)}$ – corresponding to $B \sim 10^{12}$G as measured by Walton et al. (2018c).

Arguing that to see a PULX one needs $R_{\rm M} \sim f R_{\rm sph}$ (f=0.3 - 1), one obtains

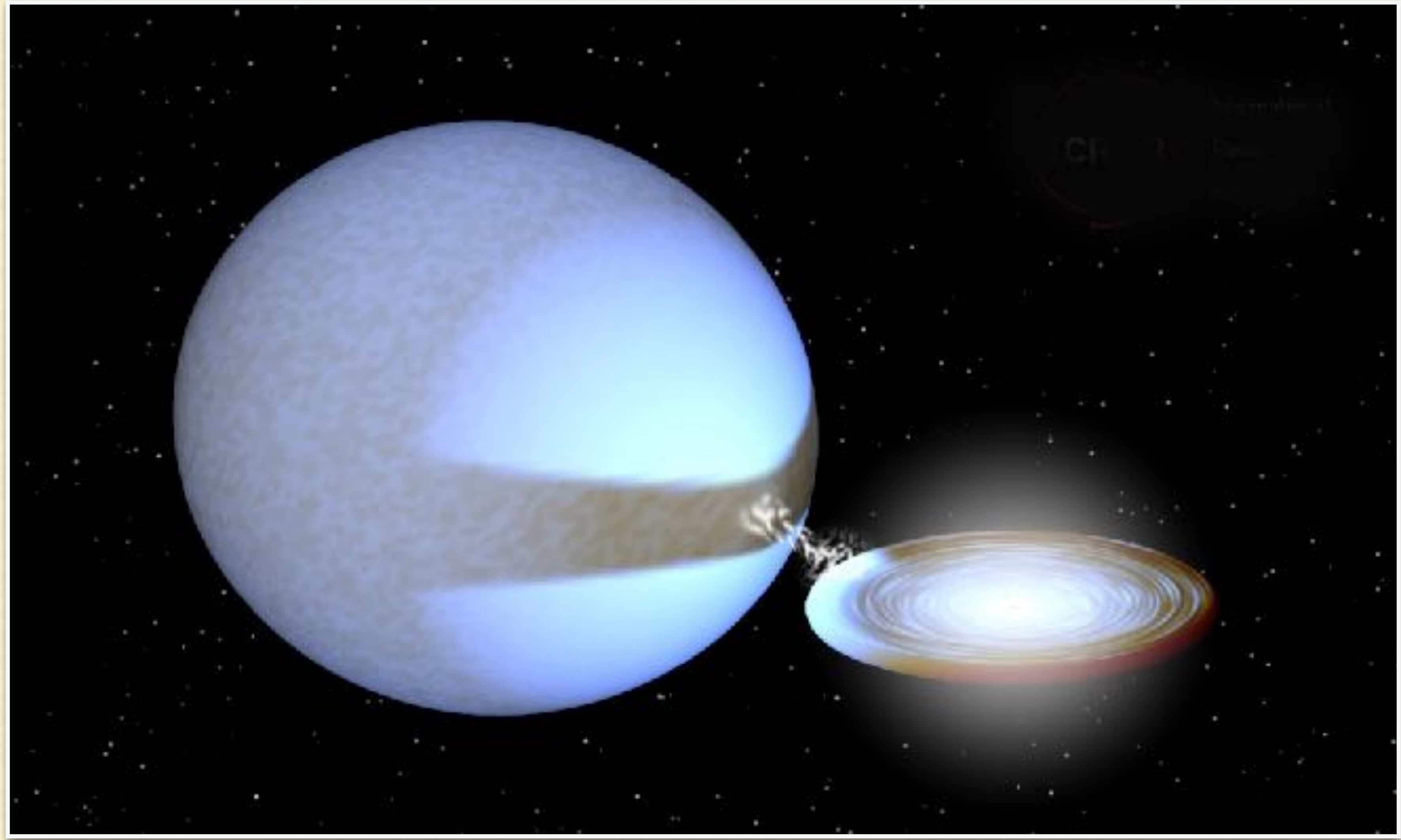
$$\dot{\nu} = 5.2 \times 10^{-10} q^{5/6} m_1^{-1/3} \mu_{30}^{6/7} I_{45}^{-1}\ {\rm s}^{-2}$$

, which explains the high spin-ups.

$R_M \sim R_{sph}$ from observations:



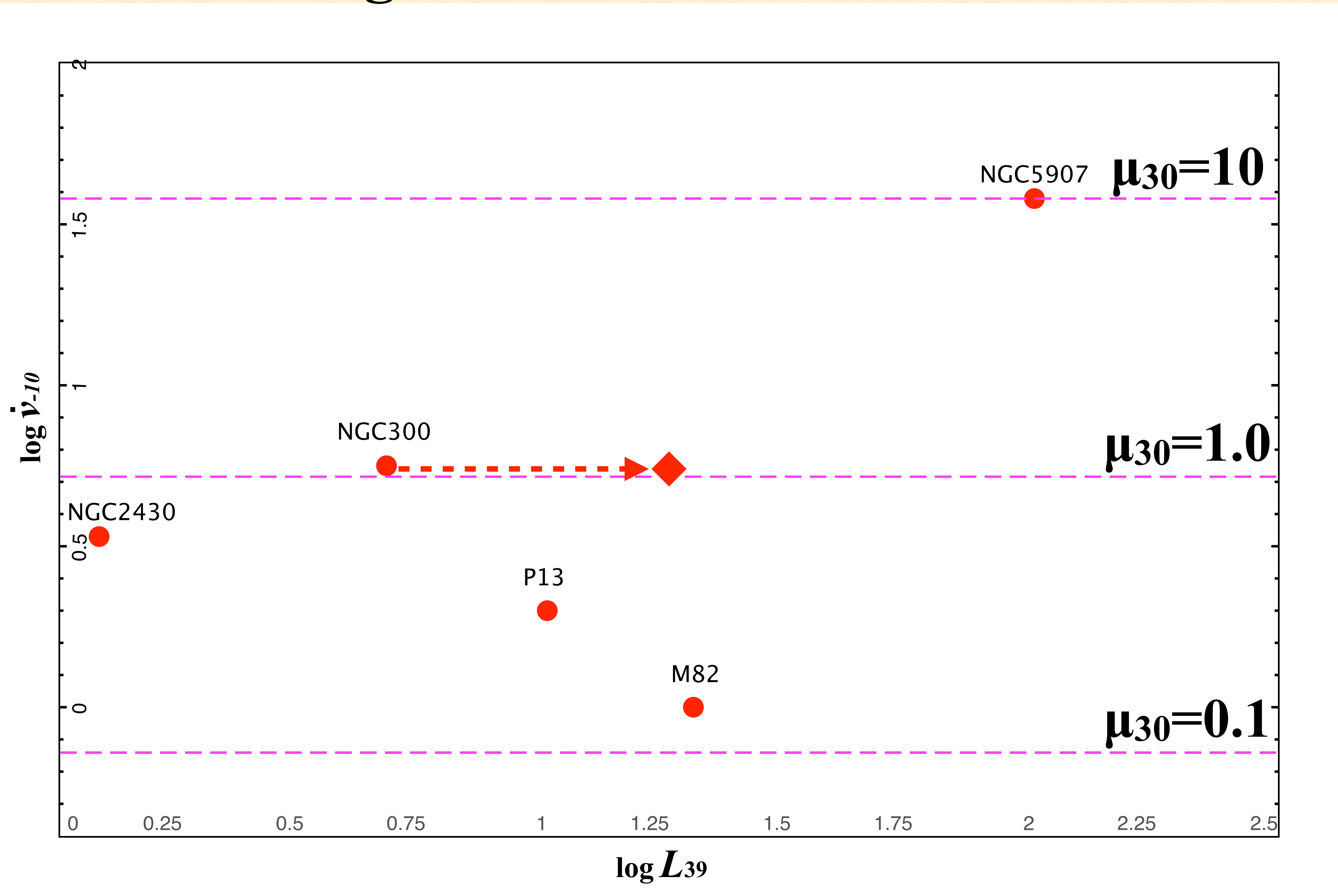
Walton et al. 2018



Christian Motch about P13: "X-ray are somewhat beamed".

<u>KLK Model: b=0.18</u>

PULX magnetic fields: B ~ 10^{11} - 10^{13} G.



NGC300 ULX1: probably some luminosity missing (much higher than usual pulse fraction).

NGC2430 ULX: not beamed (low luminosity)?

M51 ULX8: with its B-field and luminosity it could (should) have R_M~R_{sph}, but is not seen pulsing. Pulses are too weak to be seen (pulse fraction < 45%)?

- the "low-B" PULX model gives an explanation for very high spin-up rates.
- is the obvious option if ULXs represent a short-lived but common stage in the evolution of of X-ray binaries.
- "low" Bs are confirmed by two CSCFs observed in ULXs.

- in the "low-B" model the inner magnetospheric flow is not described … but Ohsuga, Abarca, Parfrey etc. are working.

- decay of magnetic field because of very high accretion rate?
- PULXs with very low field with R_{sph} >> R_M, which makes difficult observing pulses?
- neutron-star ULXs are likely to have higher apparent luminosities than black hole ULXs for a given mass transfer rate, as their tighter beaming outweighs their lower Eddington luminosities (observed luminosity $L \propto \frac{C - \ln m_1}{m_1}$).

Predictive power of the weak magnetic-field model:

Kluźniak & Lasota 2015: "... one needs to entertain the possibility that **other ULXs may be pulsars**. [...] Another ULX, in NGC 7793 [P13], has an upper limit to the mass of the compact object of <15 $M_\odot$, with allowed solutions in the neutron star mass range ..."

King & Lasota 2016: "[...] we suggest that a significant fraction of all ULXs may actually contain **neutron star accretors rather than black holes,** reflecting the neutron-star fraction among their X-ray binary progenitors."

Given the very short spin-up time-scales $\mathbf{t}_{eq}$, it seems very unlikely that we observe these systems during their only approach to spin equilibrium. Instead, they are all probably close to $\mathbf{P}_{eq}$ with alternating spin-up and spin-down phases. We can only see these systems during spin-up phases (so that $\boldsymbol{\nu}$ has its maximum value) because centrifugal repulsion during spin-down presumably reduces the accretion rate and so the luminosity.