FROM SLIM DISCS THROUGH ADAFs & HLXs TO THE PULXs

or my potholed road to super-Eddington reality

Jean-Pierre Lasota

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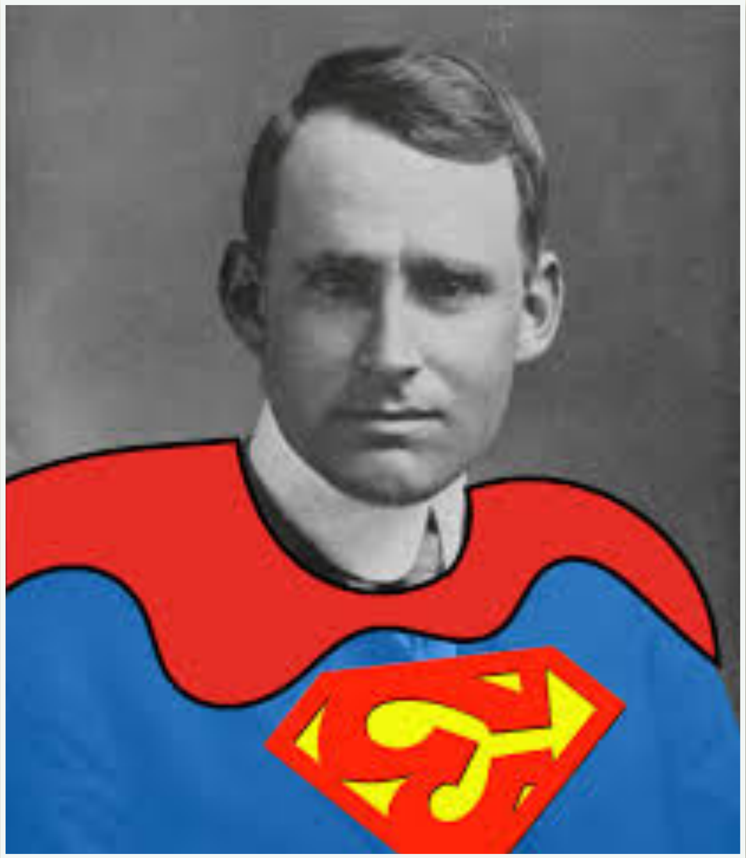


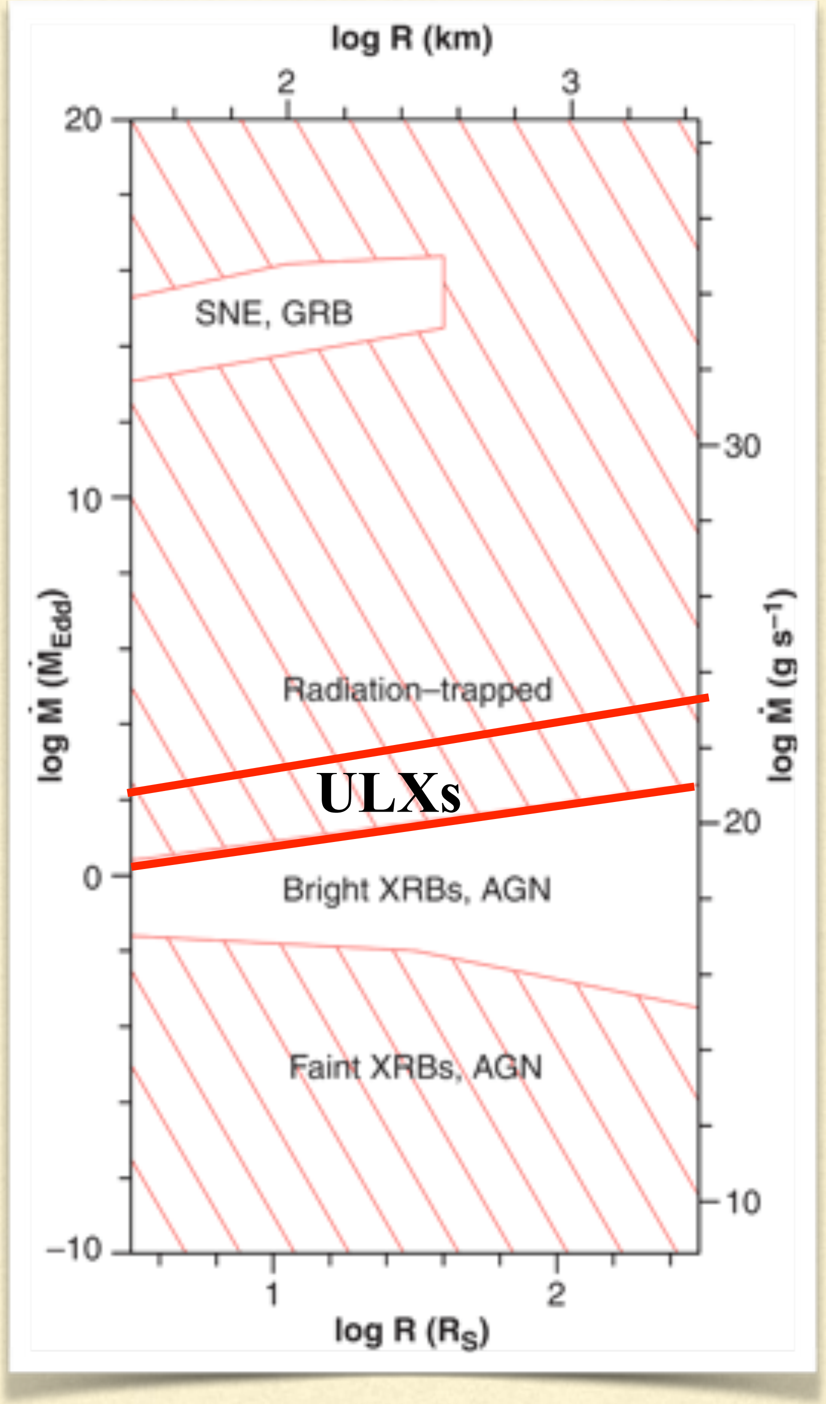
@supereddington2018

Slim accretion disk workshop

21 - 23 October 2018

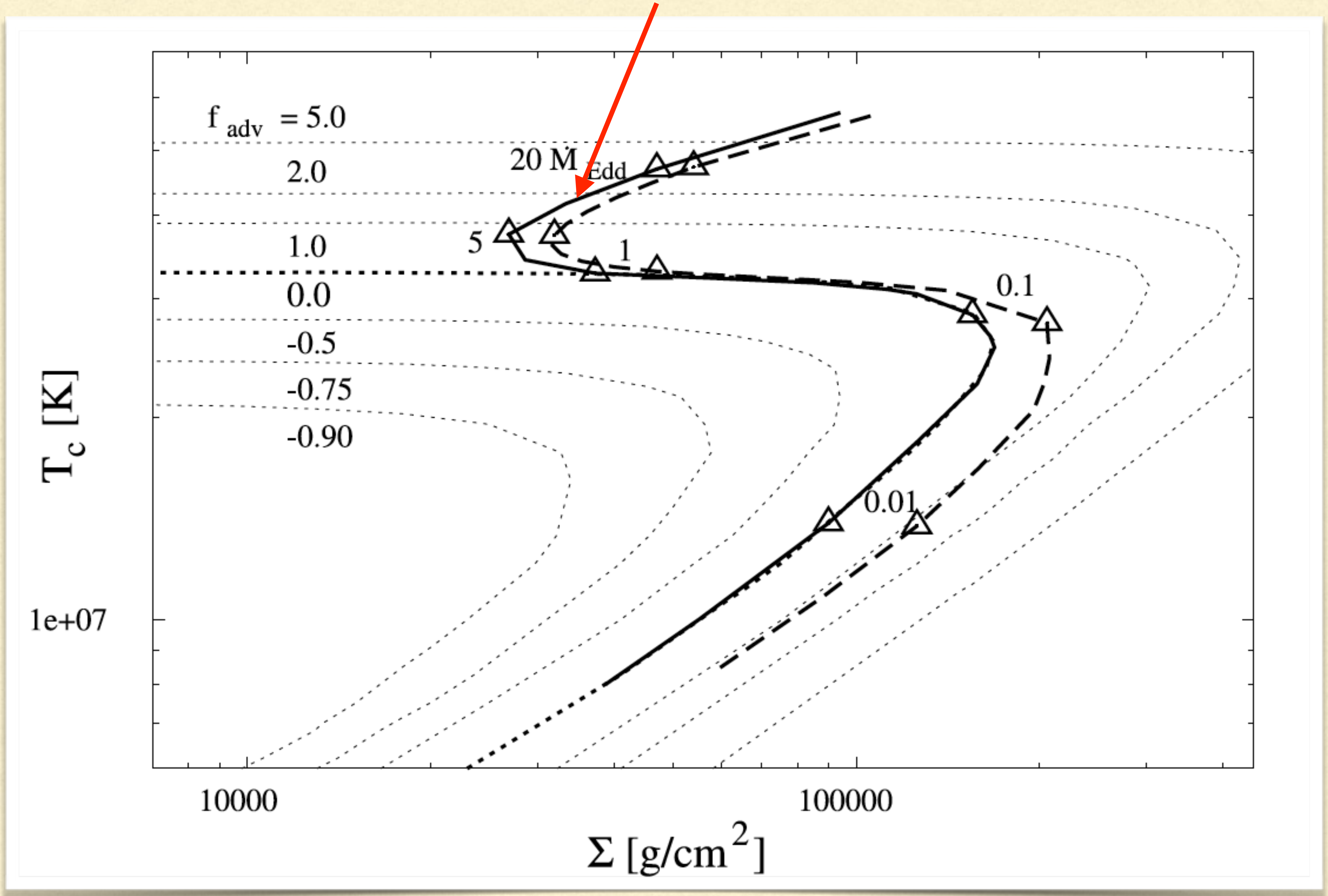
Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

Who needs slim discs anyway?



Narayan& Quataert 2005

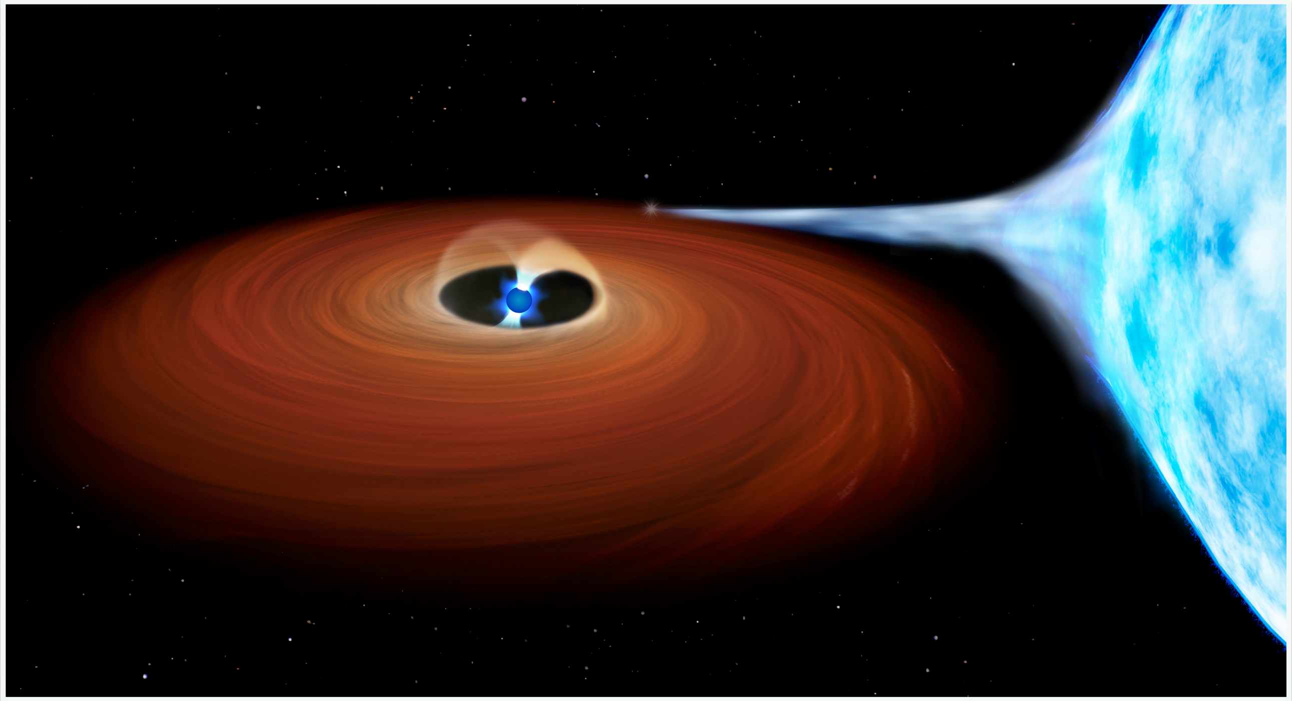
Slim discs



Sądowski et al. 2011

ULX pulsars - PULXs: $L > 10^{39}$ erg/s, hence super-Eddington

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 $L_{Edd}(N_*)$.



… unless $B > 10^{12}$ G,

$$L_{cr,M} = 2L_{Edd}\left(\frac{B}{10^{12}\,G}\right)^{4/3}$$ (Paczyński 1992)

Pulsing ULXs: PULXs

Name	M82 ULX2	NGC7793 P13	NGC5907 ULX1	NGC300 ULX1	NGC 2403 ULX
$L_X\,(\max)\;[\mathrm{erg\,s^{-1}}]$	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
$\dot{\nu}\;[\mathrm{s^{-2}}]$	10^{-10}	2×10^{-10}	3.8×10^{-9}	5.6×10^{-10}	3.4×10^{-10}
P_{orb} [d]	2.51 (?)	64	5.3(?)	> 8 (Be ?)	60 – 100 (?)
$M_2\;[\mathrm{M_\odot}]$	$\gtrsim 5.2$	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:

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

$B > 10^{13}\,\mathrm{G}$?

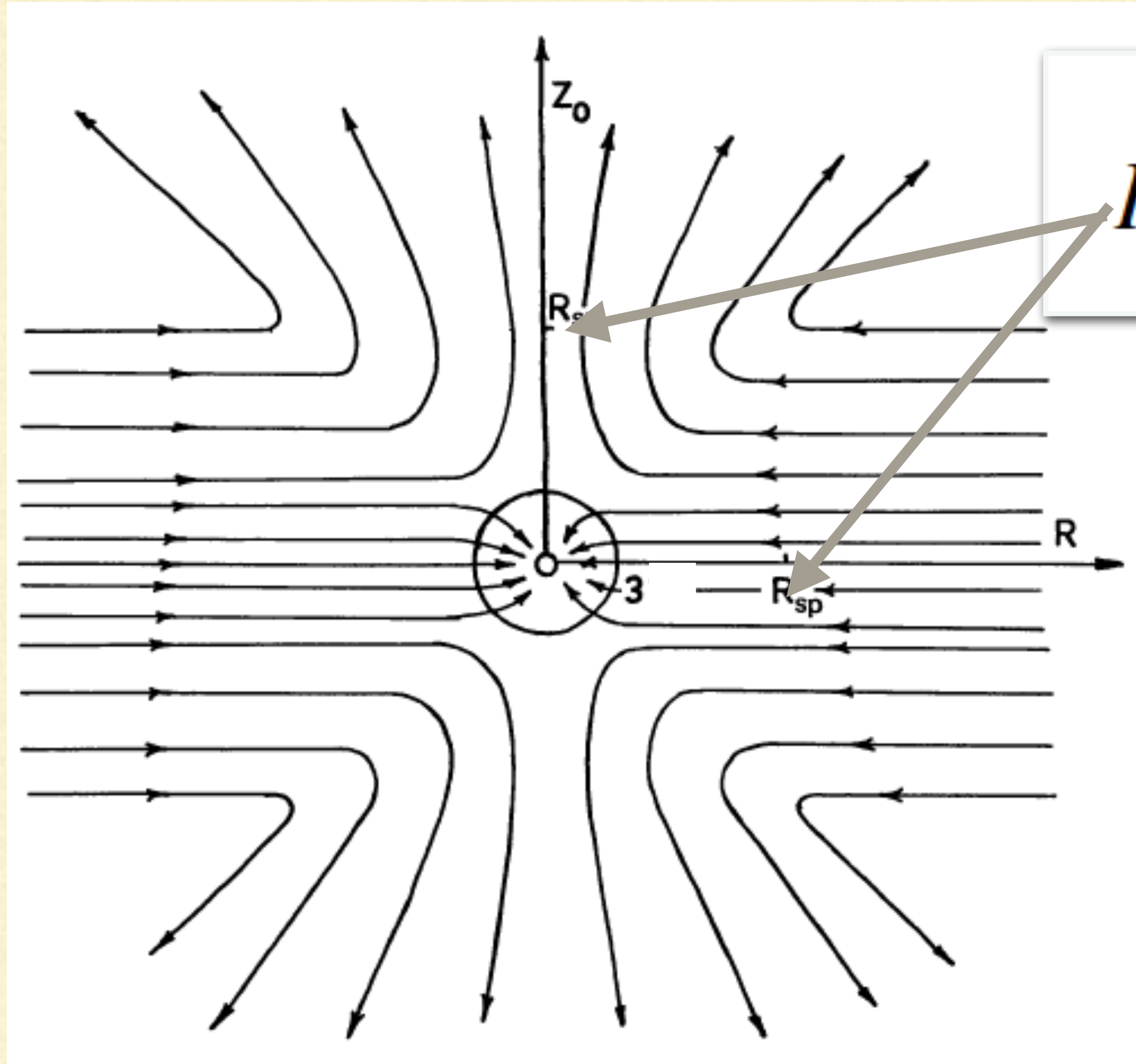
- ULX 8 in M51* and ULX1 in NGC 300†: $B \lesssim 10^{12}\,\mathrm{G}$
- Magnetars have never been observed in binary stars
- For $B \gtrsim 10^{14}\,\mathrm{G}$ magnetospheric radius close to light cylinder

* Middelton et al. 2018

† Walton et al. 2018

Geometrical beaming model for PULXs

(King & JPL, 2016; King, JPL & Kluźniak, 2017)



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

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

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

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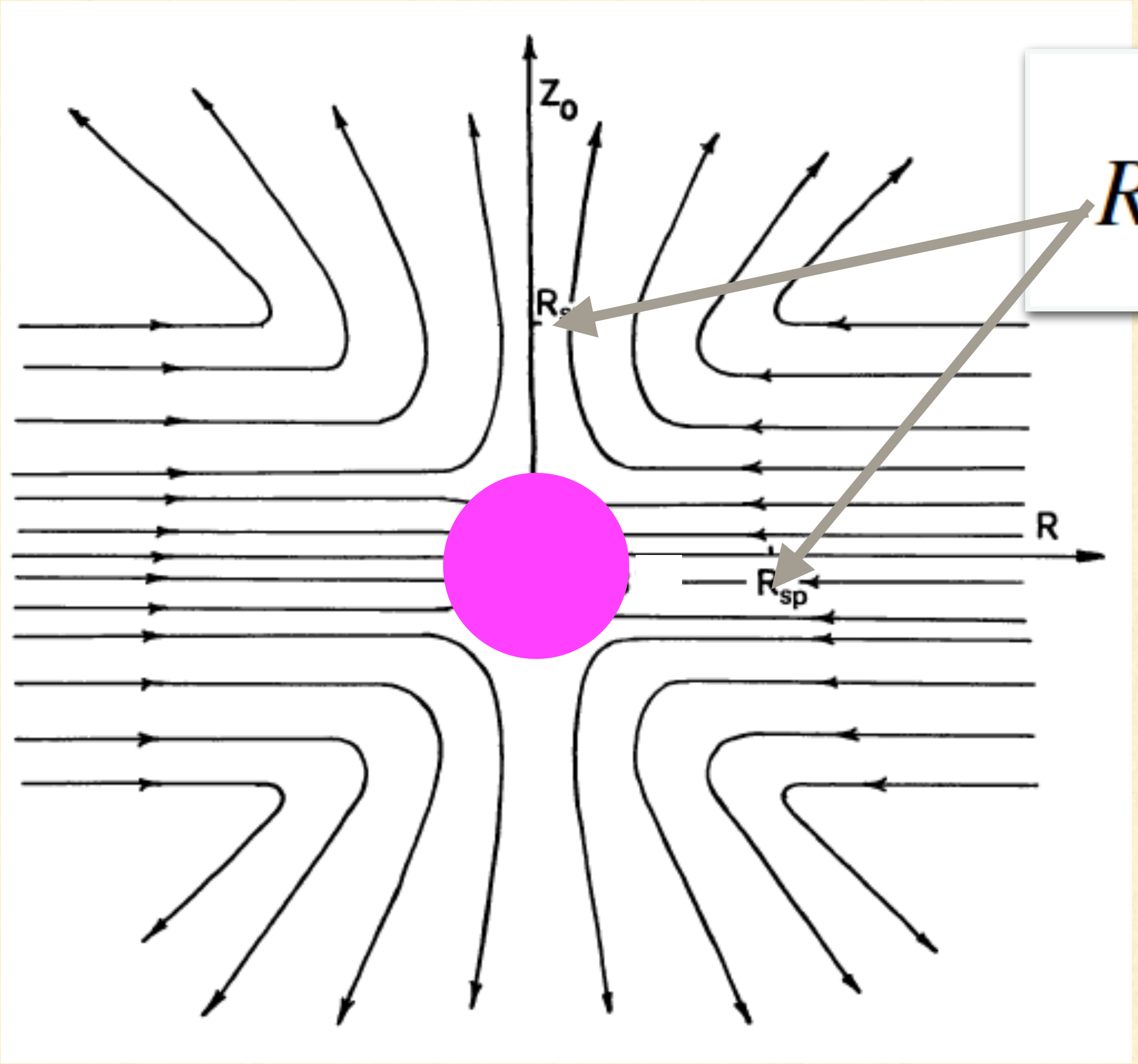

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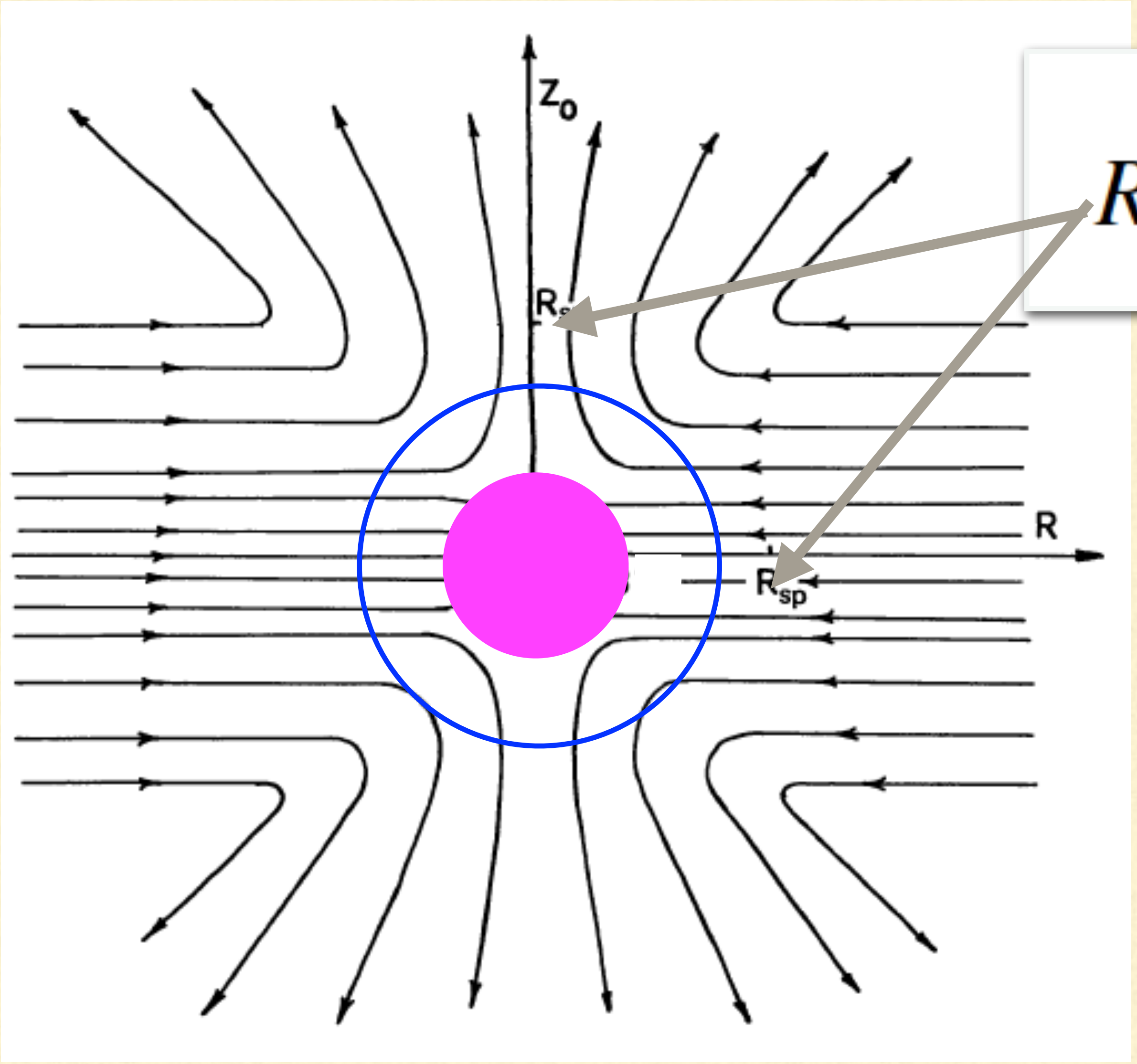

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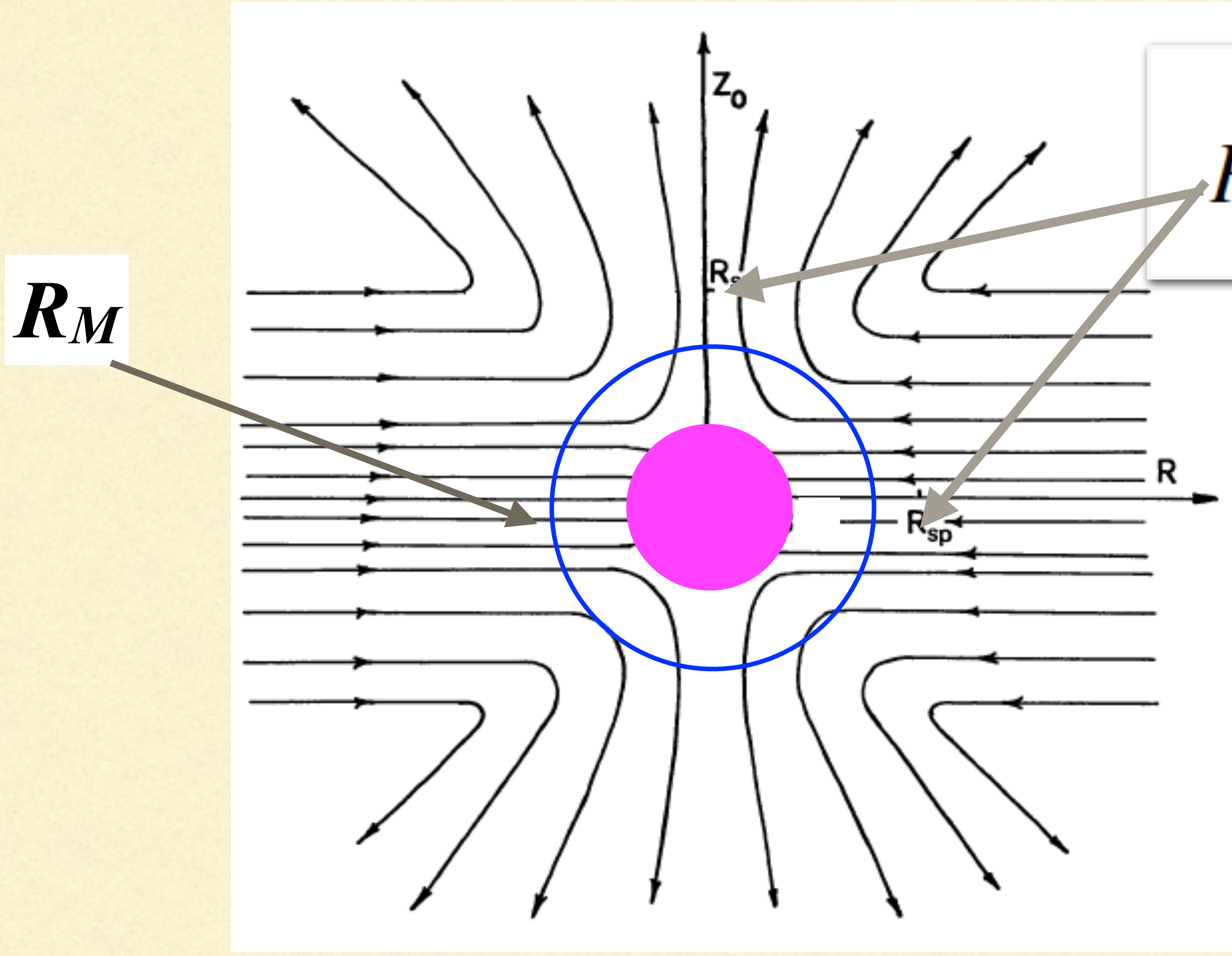

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Outflow $\dot{M}(R) \simeq \frac{R}{R_{\rm sph}}\dot{m}_0 \dot{M}_{\rm Edd}$ and beaming factor $b \simeq \frac{73}{\dot{m}_0^2}$:

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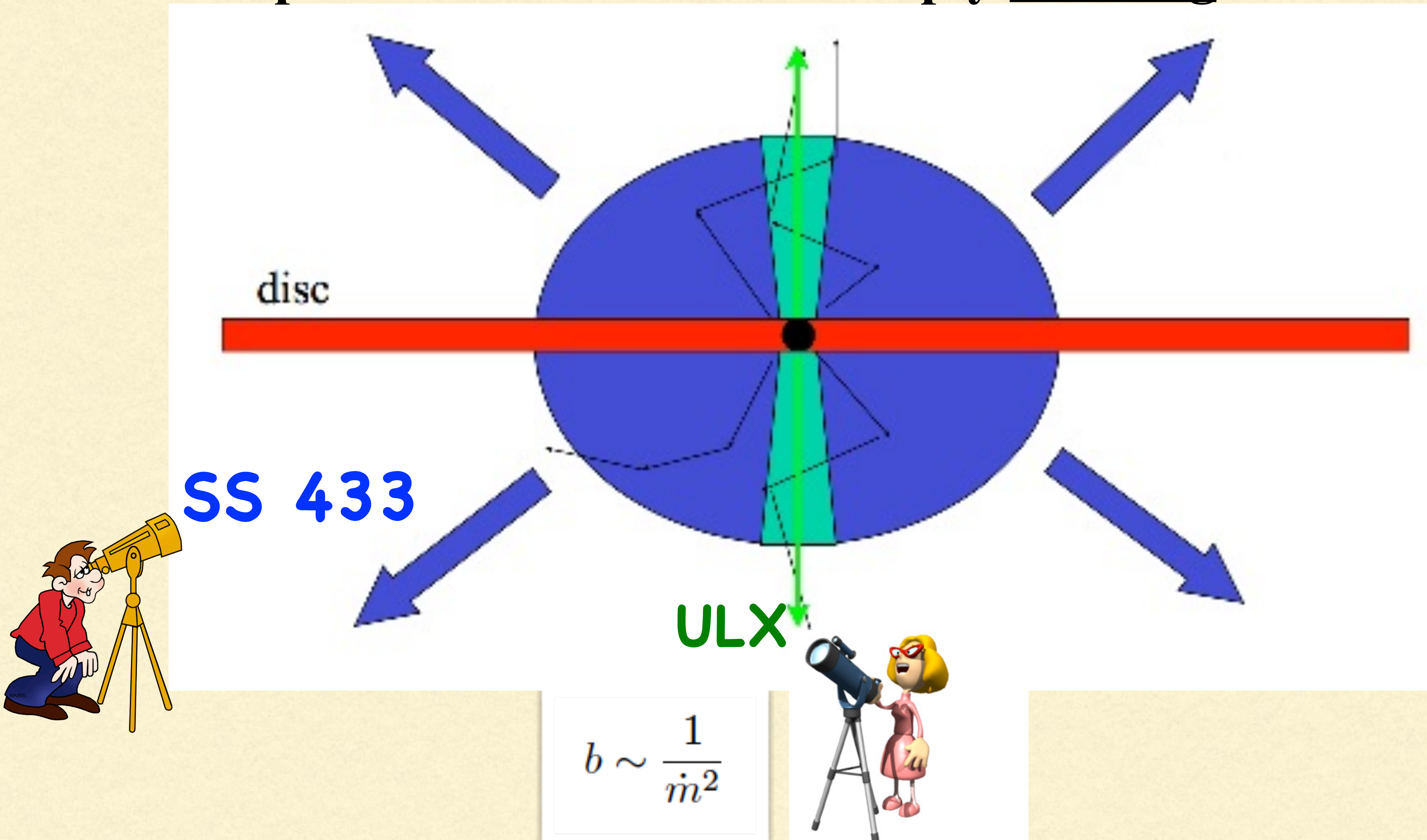
Super-critical luminosities imply **beaming**



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

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

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

King 2009

Results

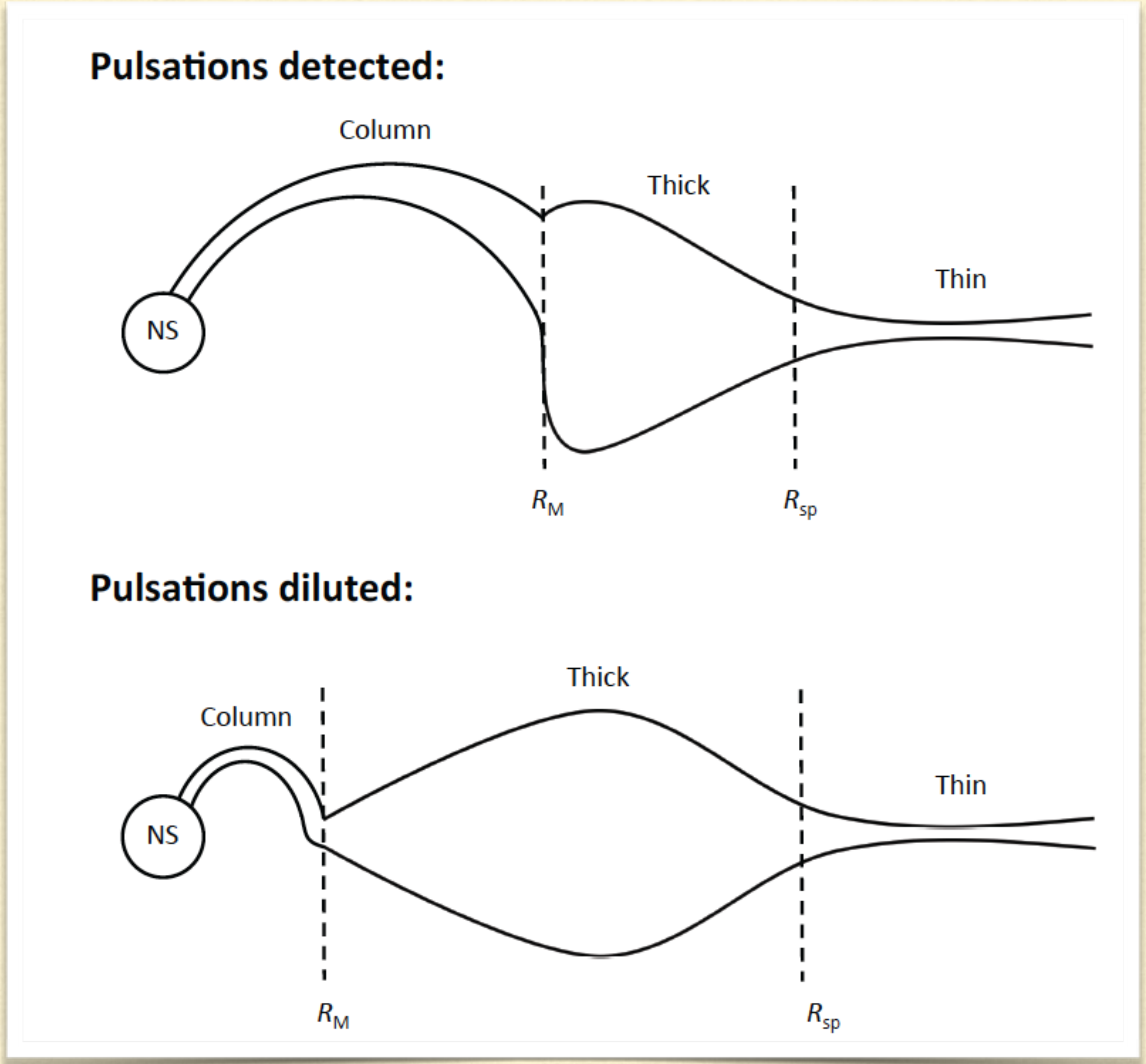
Name	M82 ULX2	NGC 7793 P13	NGC5907 ULX1	NGC300 ULX1	NGC 2403 ULX
$\dot{m}_0$	36	20	91	20	11
$\mu\, q^{7/4} m_1^{-1/2} I_{45}^{-3/2}$ [Gcm^3]	9.0×10^{28}	2.5×10^{29}	2.1×10^{31}	$1.2 \times 10^{30\,(i)}$	5.6×10^{29}
$R_{\rm sph} m_1^{-1}$ [cm]	7.2×10^7	4.1×10^7	2.6×10^8	4.1×10^7	2.2×10^7
$R_M m_1^{-1/3} I_{45}^{-2/3}$ [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

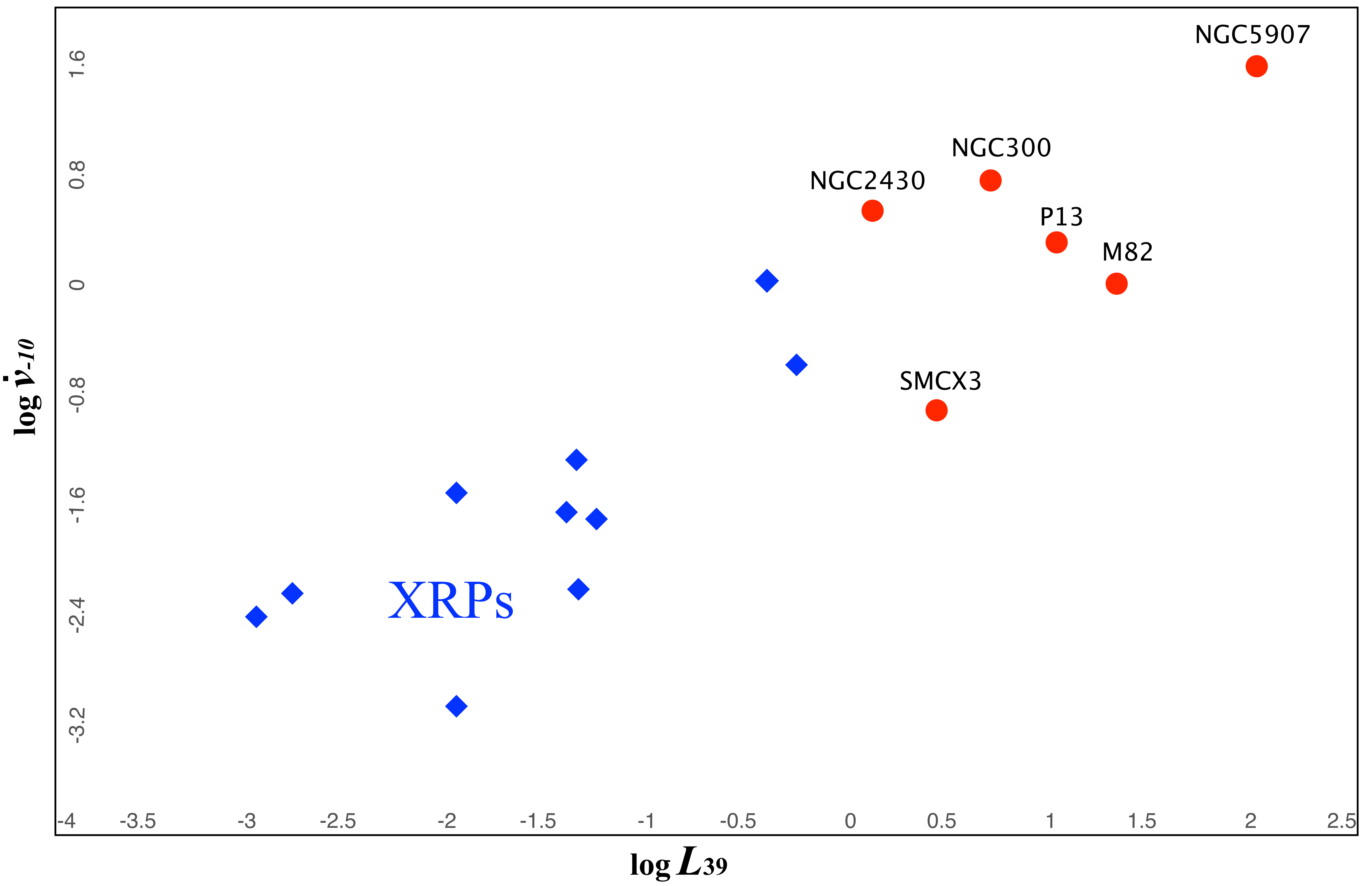
$\dot{\nu} = 5.2 \times 10^{-10} q^{5/6} m_1^{-1/3} \mu_{30}^{6/7} I_{45}^{-1}\ {\rm s}^{-2}$, which explains the high spin-ups.

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



Walton et al. 2018

PULXs: definition



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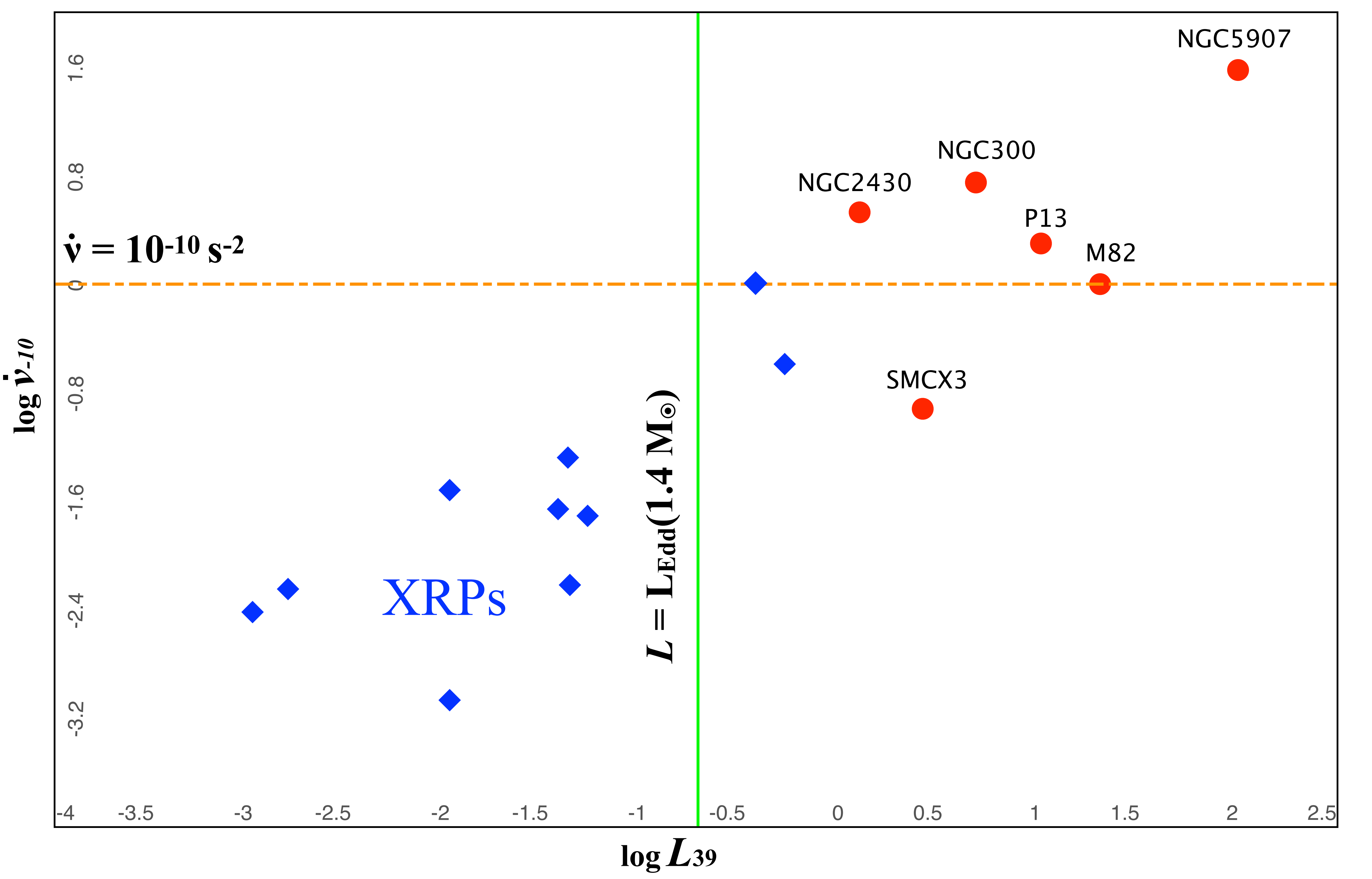

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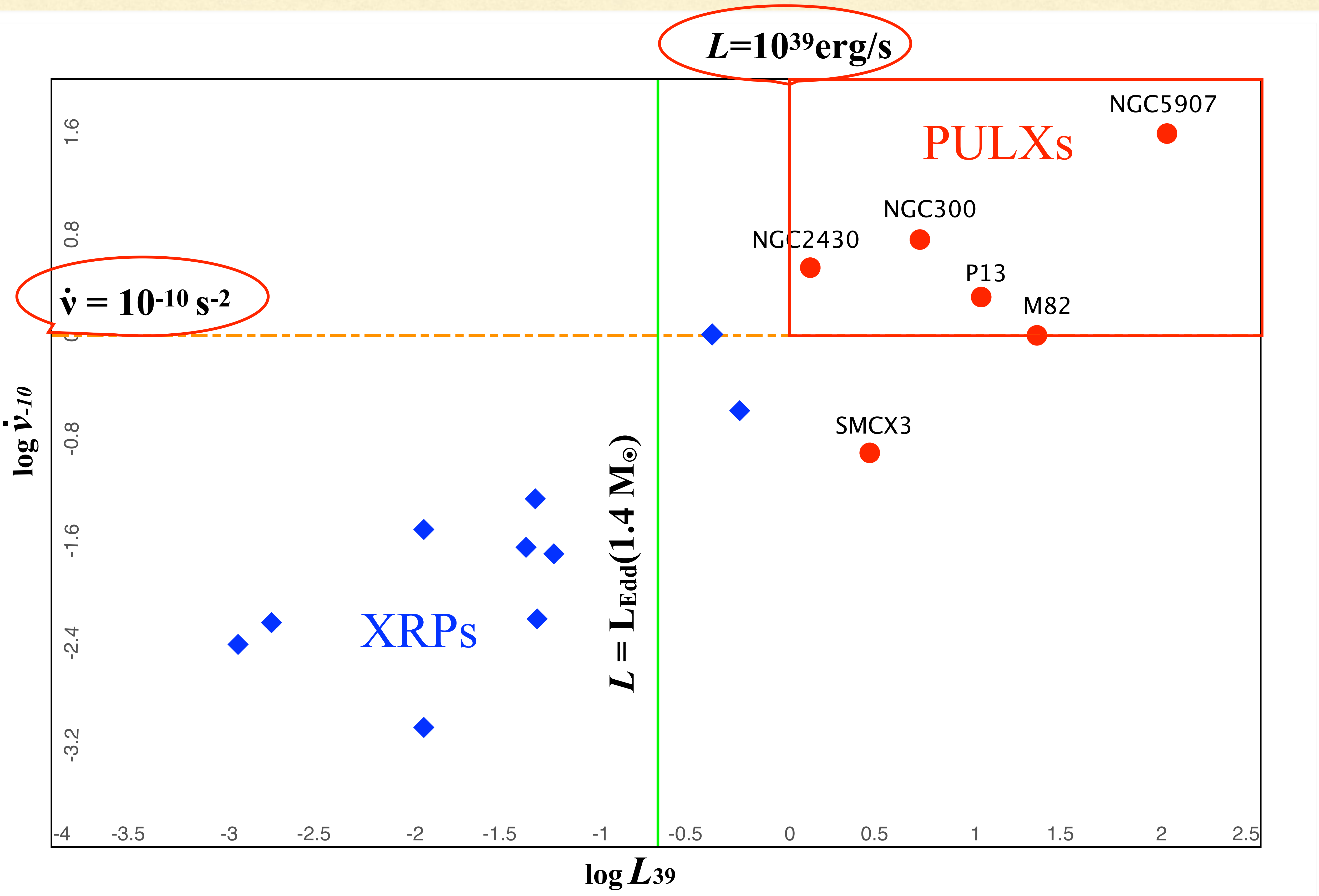
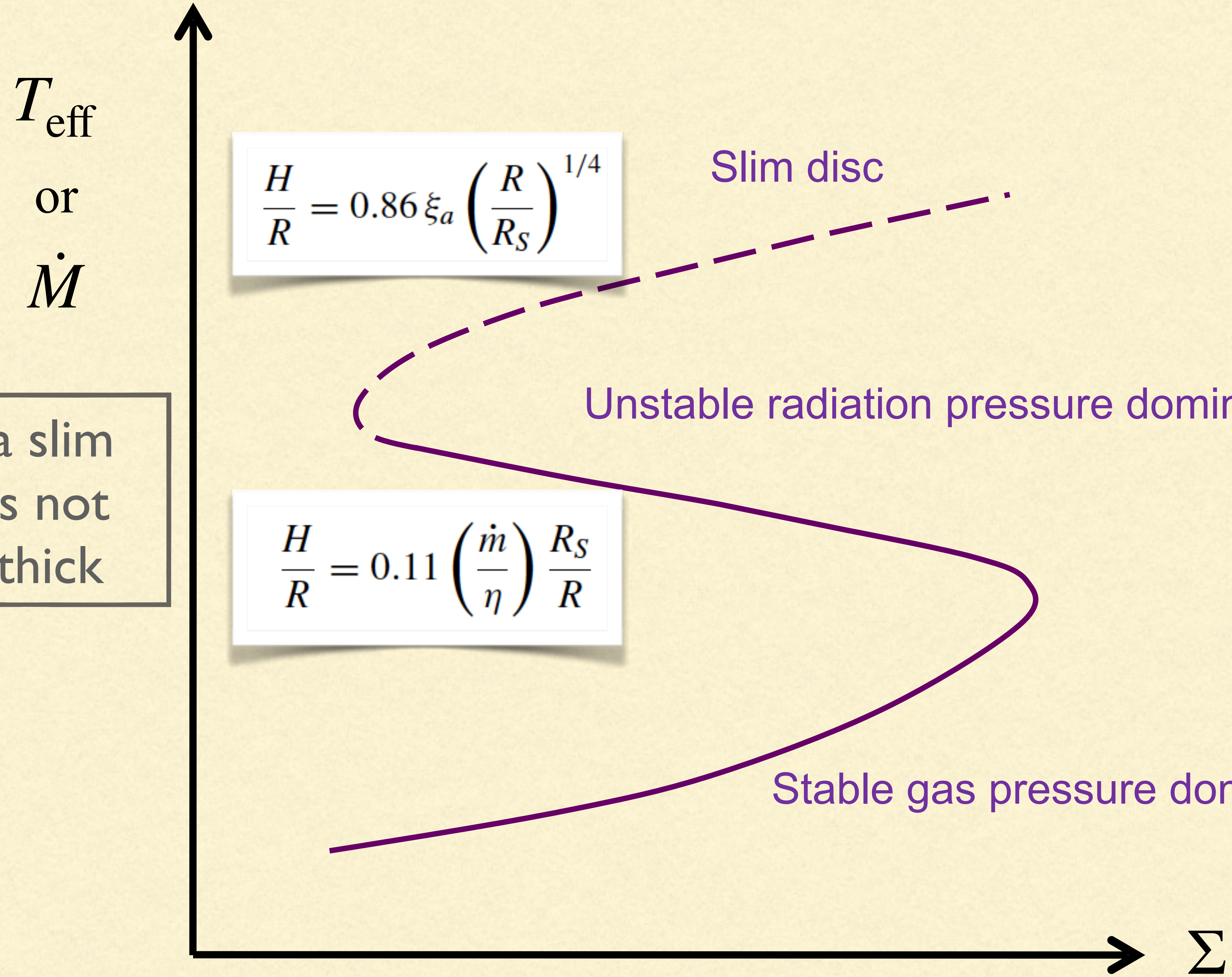


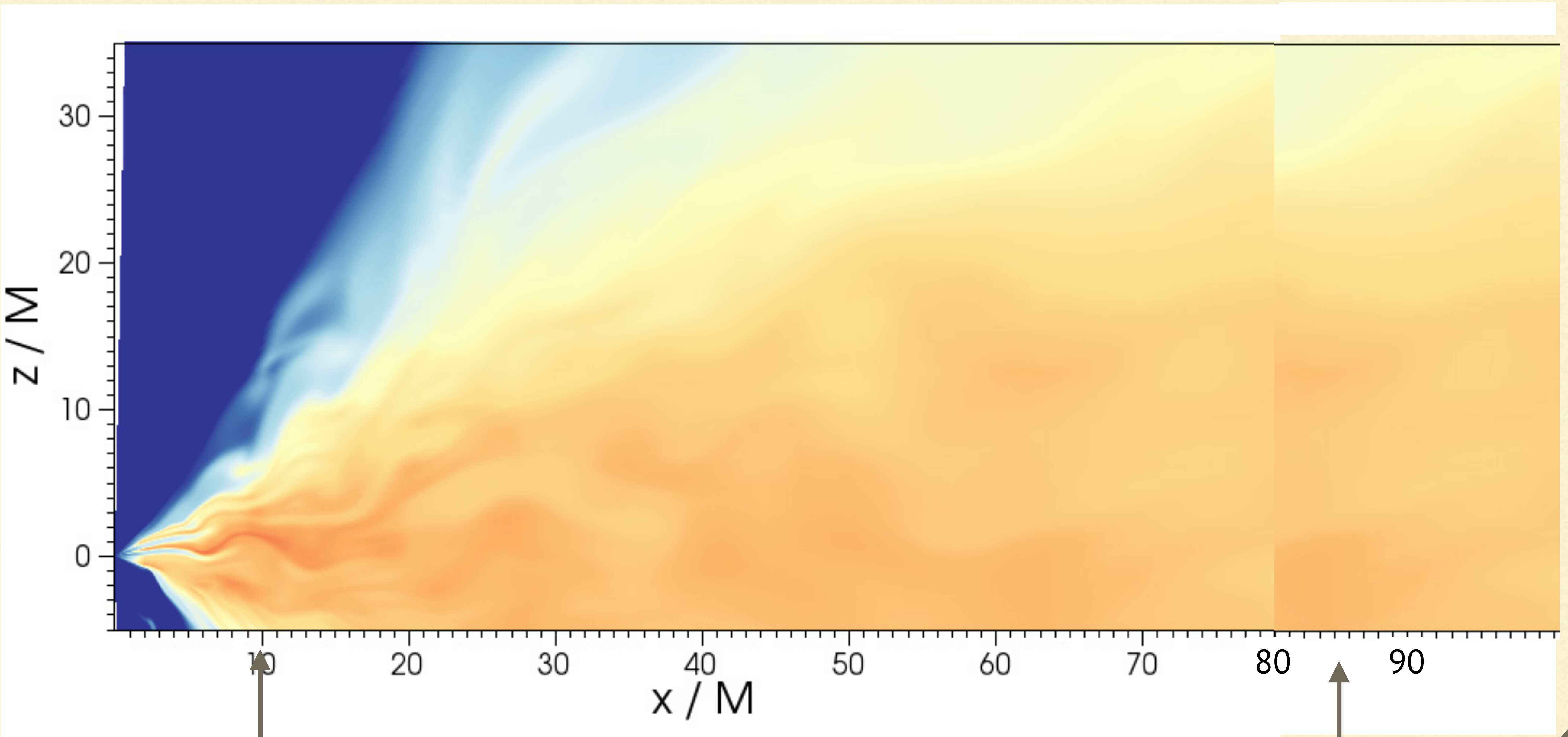
Slim discs in the context of (P)ULXs



Feeding a slim disc does not make it thick

There is NO observational evidence for the unstable behaviour!!!!!

$r_{adv} \sim r_{trapp} \sim \dot{m}$, $r_{sph} \sim 6.8\,\dot{m}$, $r_{pr} \sim 85\,\dot{m}^{16/21}$

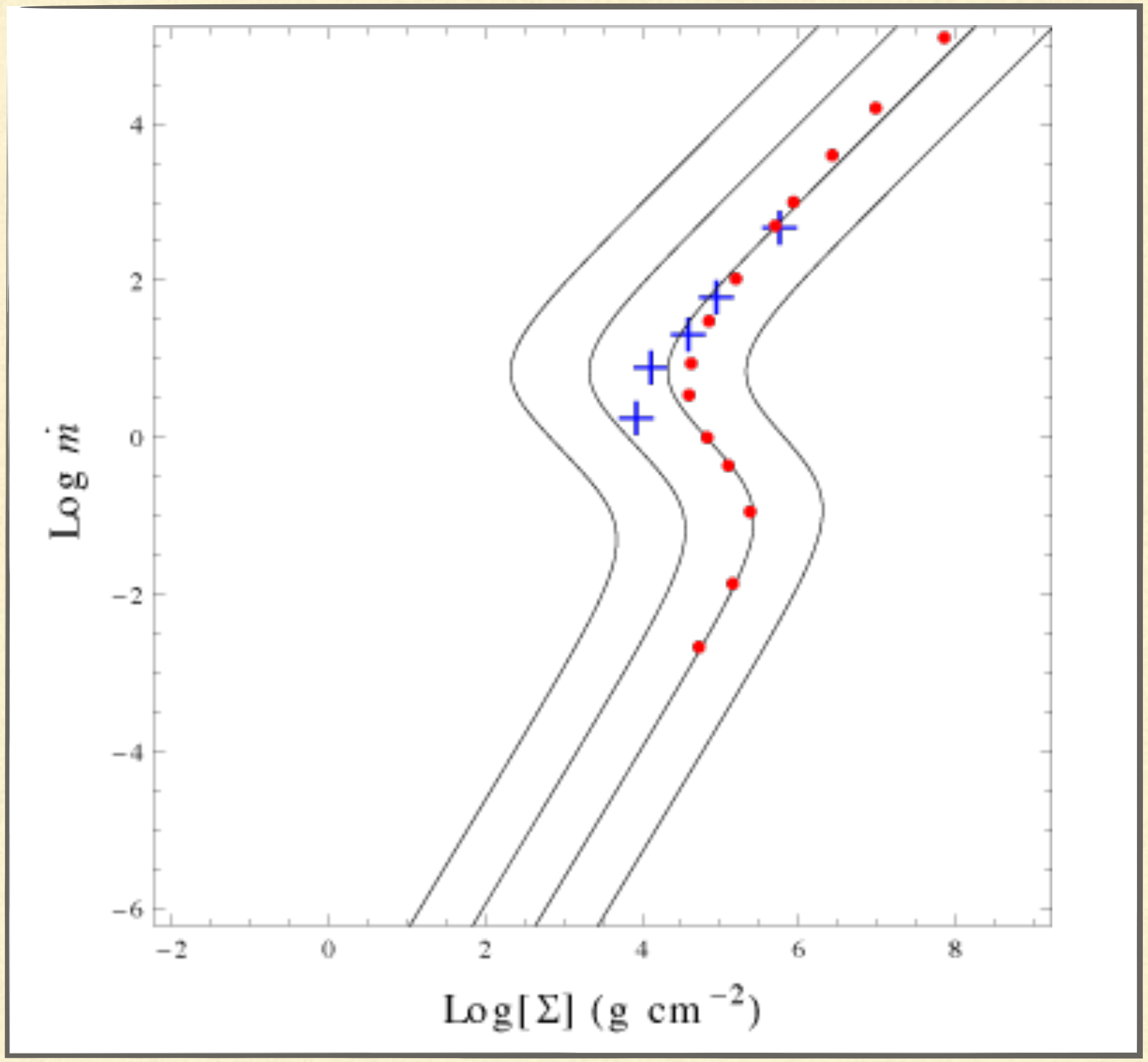


$\dot{m} = 10$

$r_{adv} \sim r_{trapp}$ r_{sph} r_{pr}

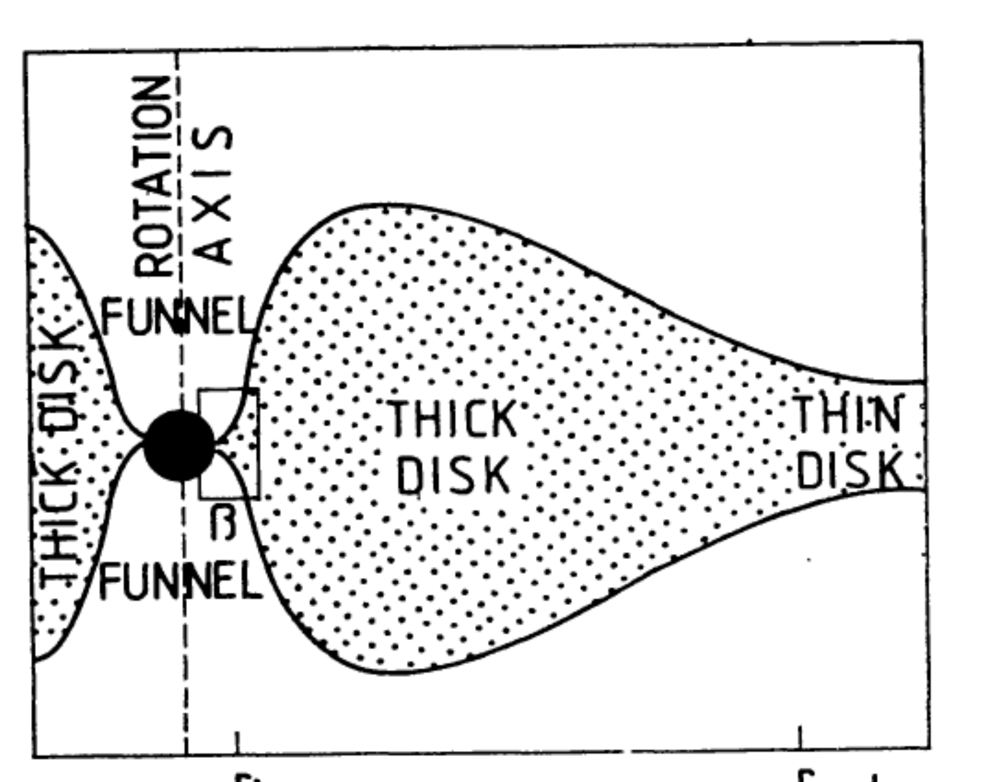
Lasota et al. 2016

Slim-disc models are quite a good approximation of (some) numerical simulations



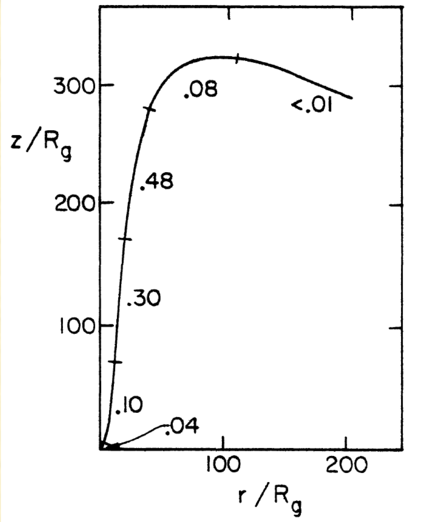
Lasota et al. 2016

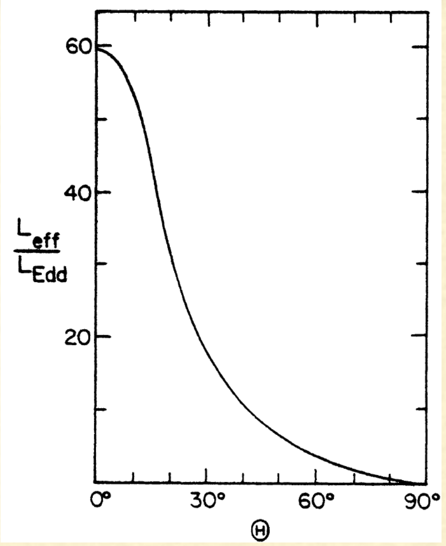
How to get beaming ?



Jaroszyński et al. 1980

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



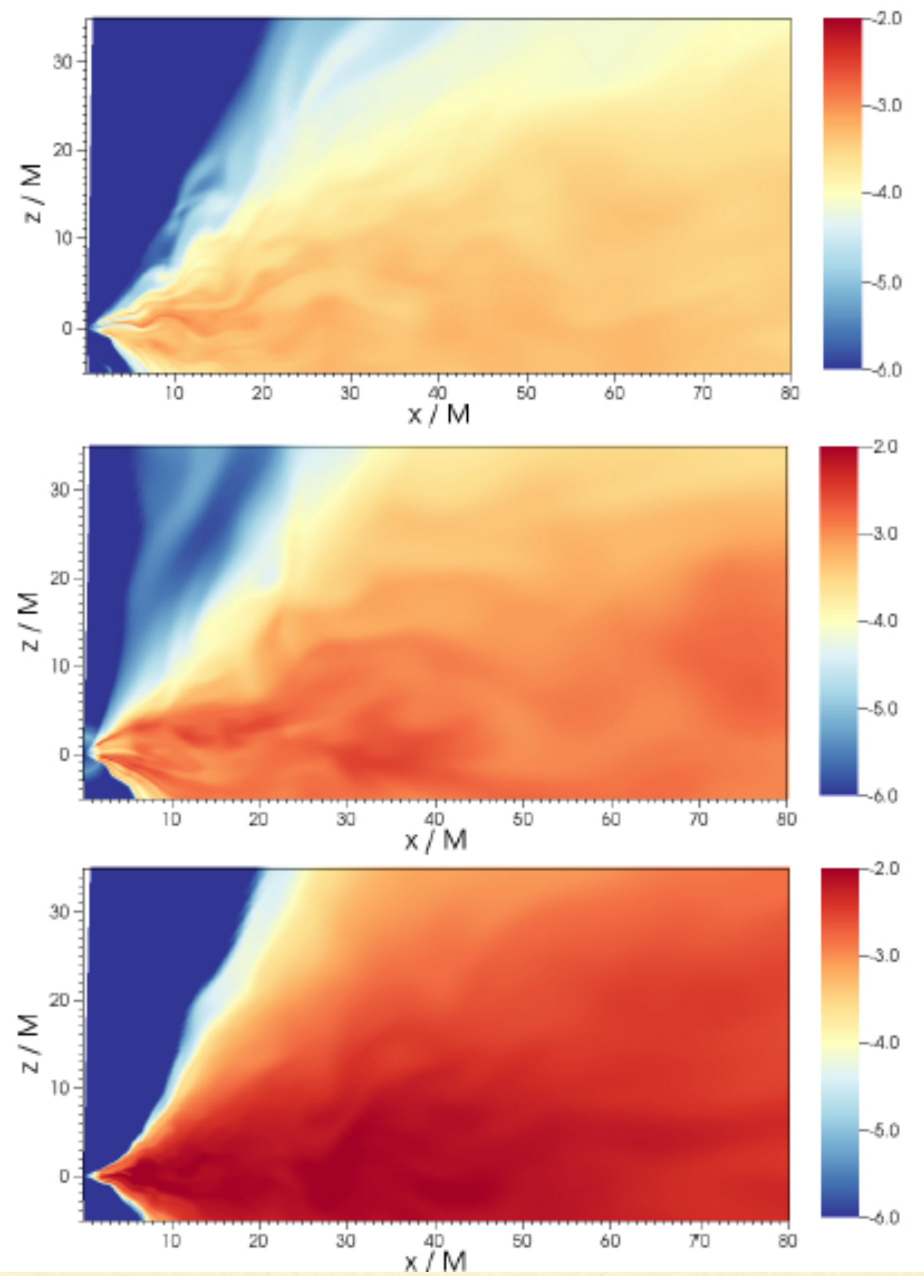


Sikora 1980

$\dot{m} = 9.6$

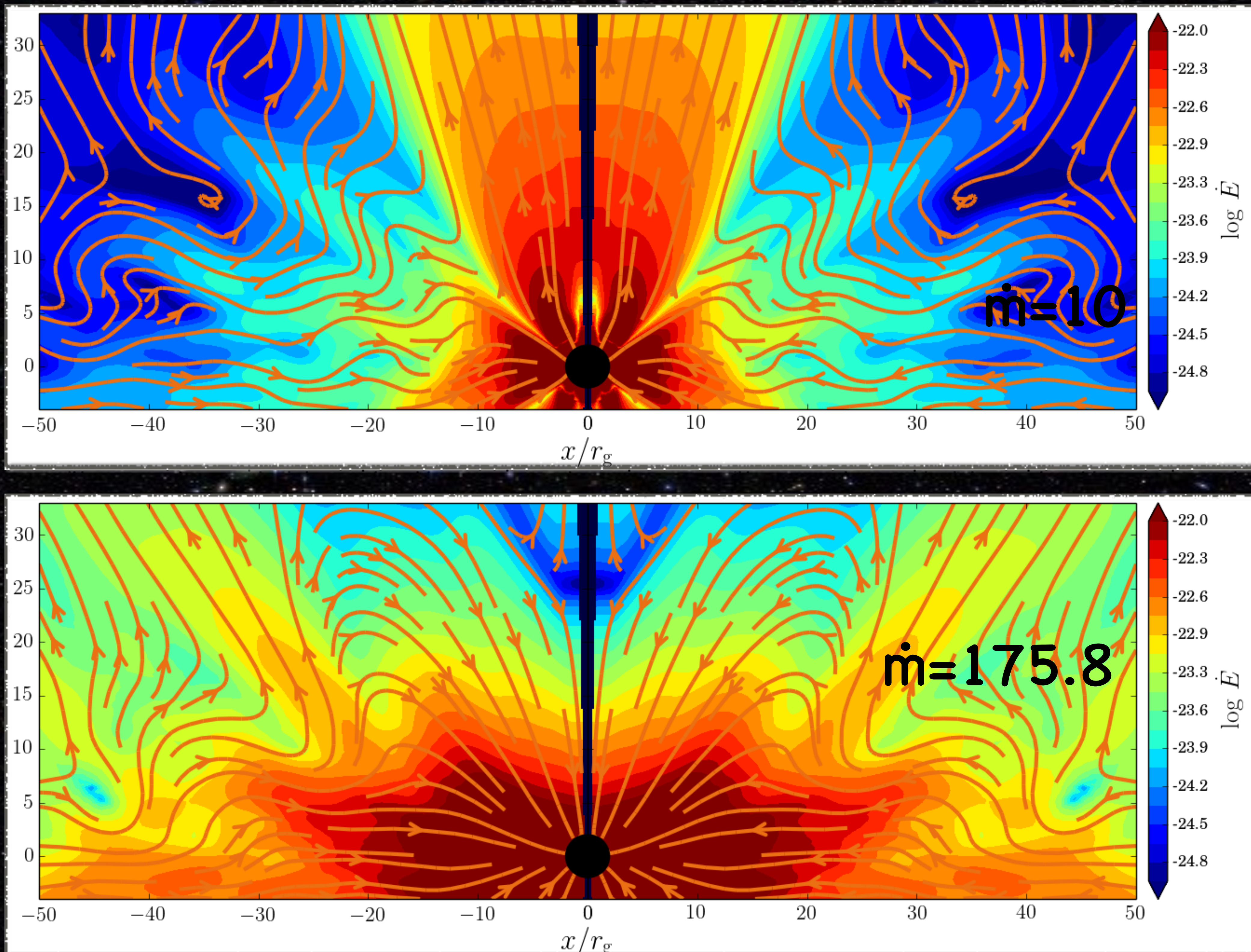
$\dot{m} = 24.3$

$\dot{m} = 73.1$

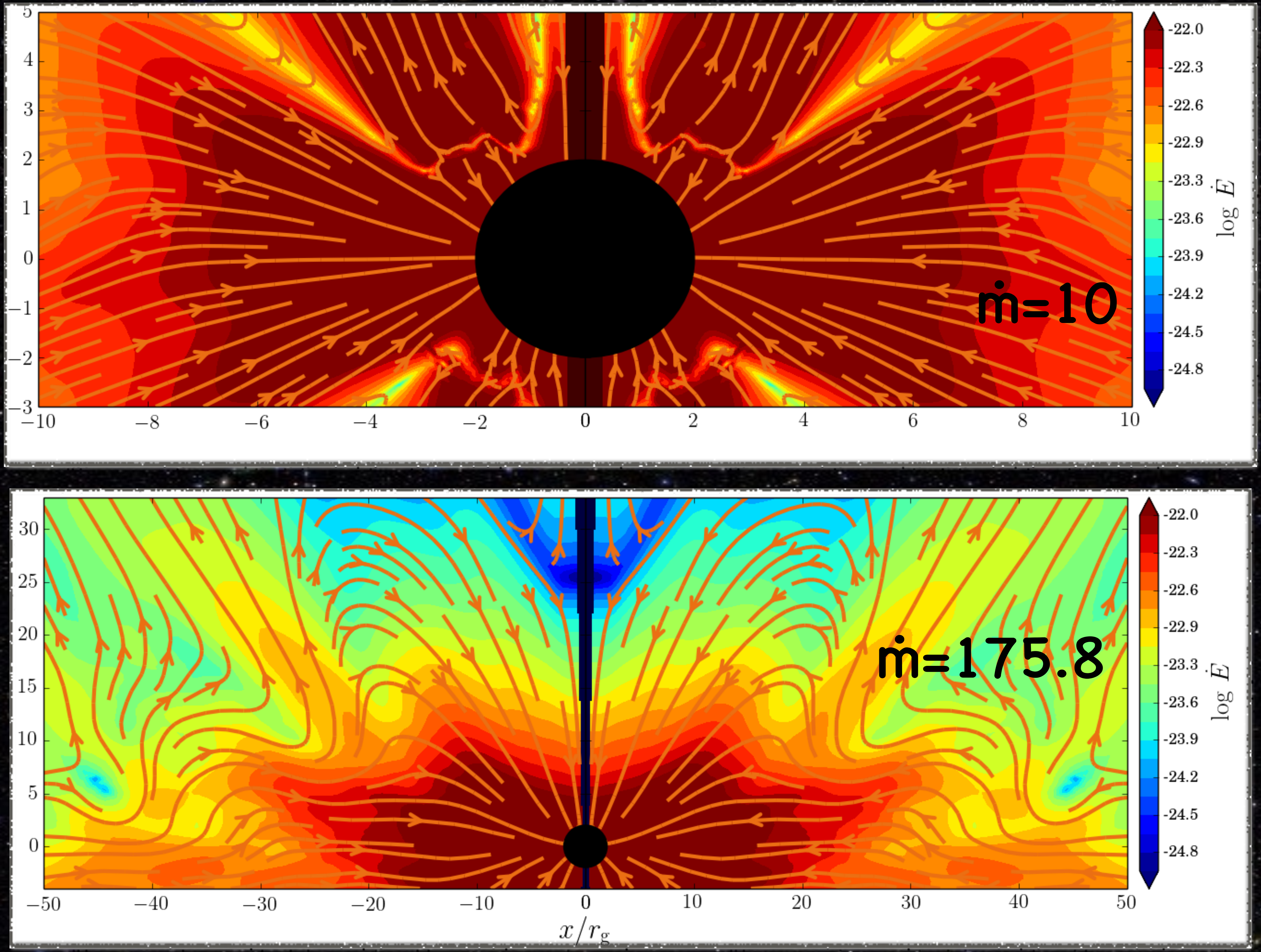


but slim discs are windy (Dotan & Shaviv 2011)

Lasota et al. 2016



Sądowski, Lasota, Abramowicz, Narayan 2016



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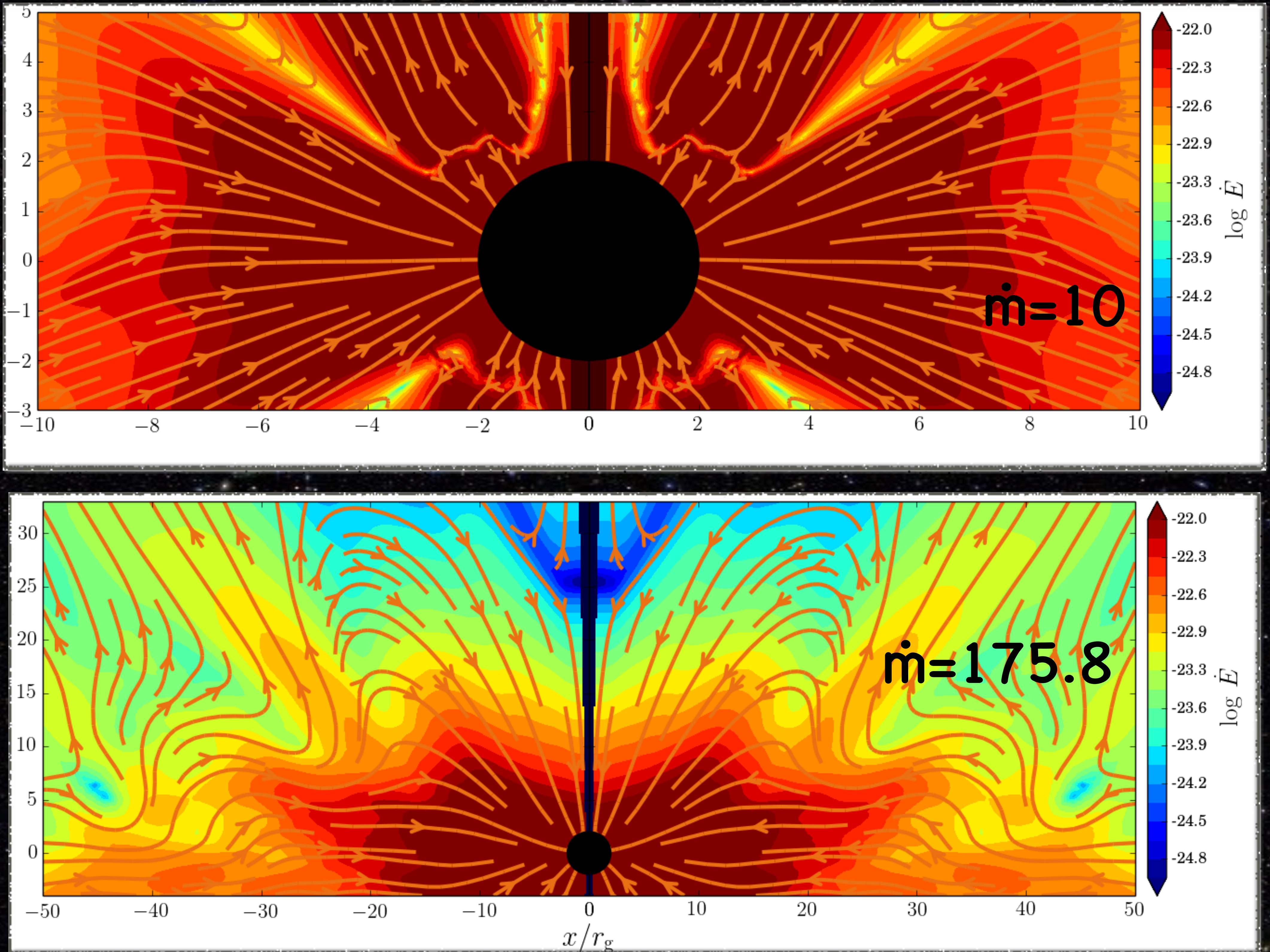
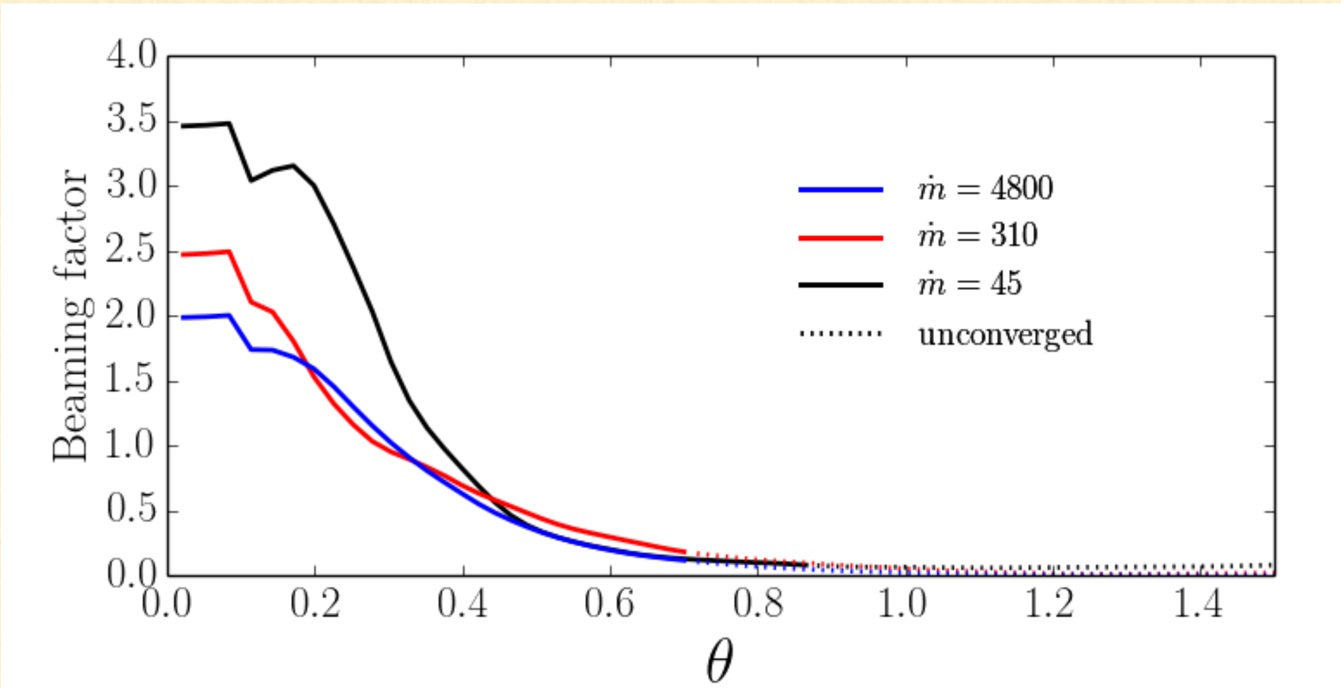
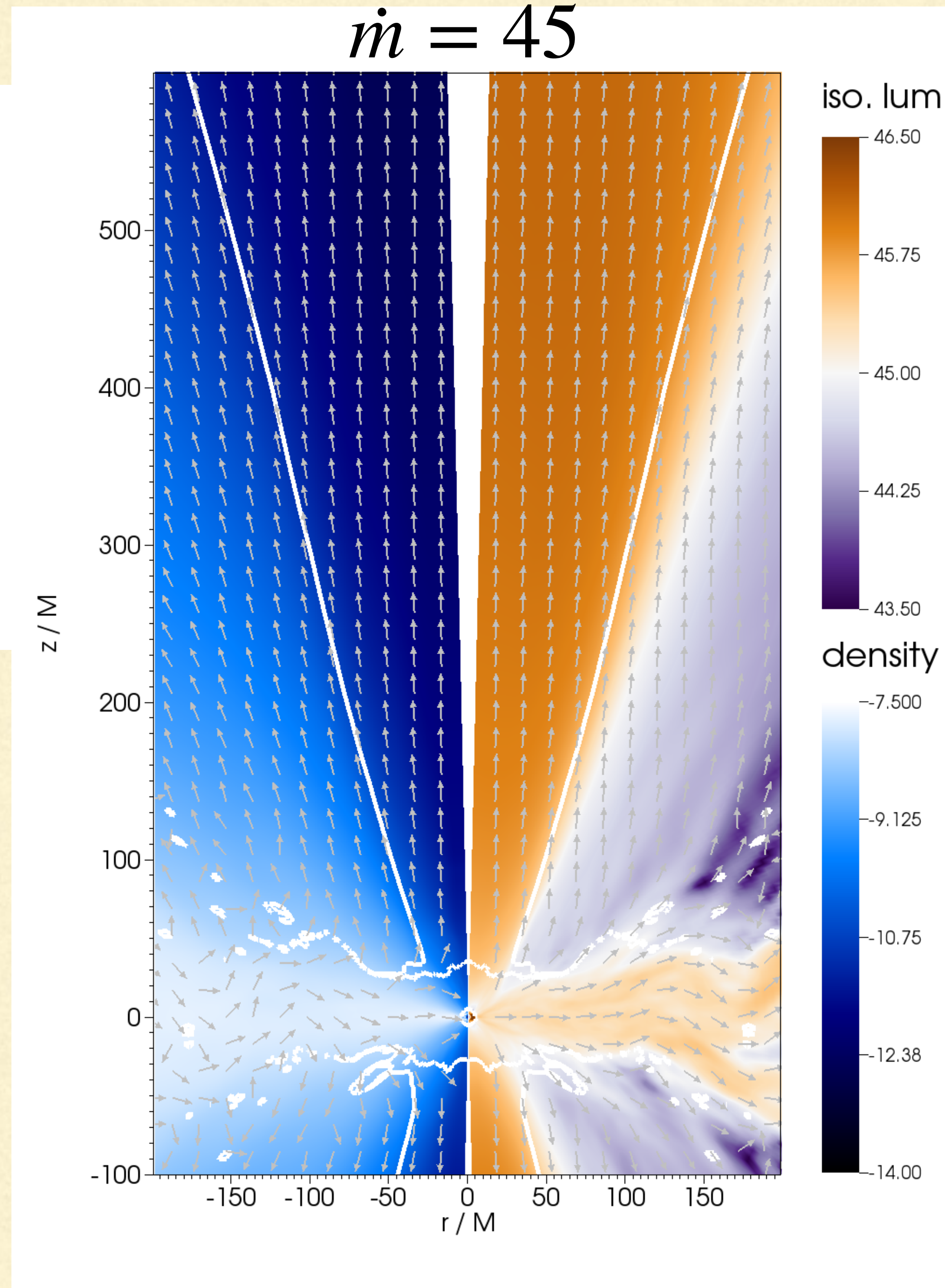


$$L_{\rm sph} \approx L_E\left[1 + \ln\left(1 + \dot{m}\right)\right]$$

Sądowski, Lasota, Abramowicz, Narayan 2016





$$b_{\rm SN} = 1/(\text{beaming factor})$$

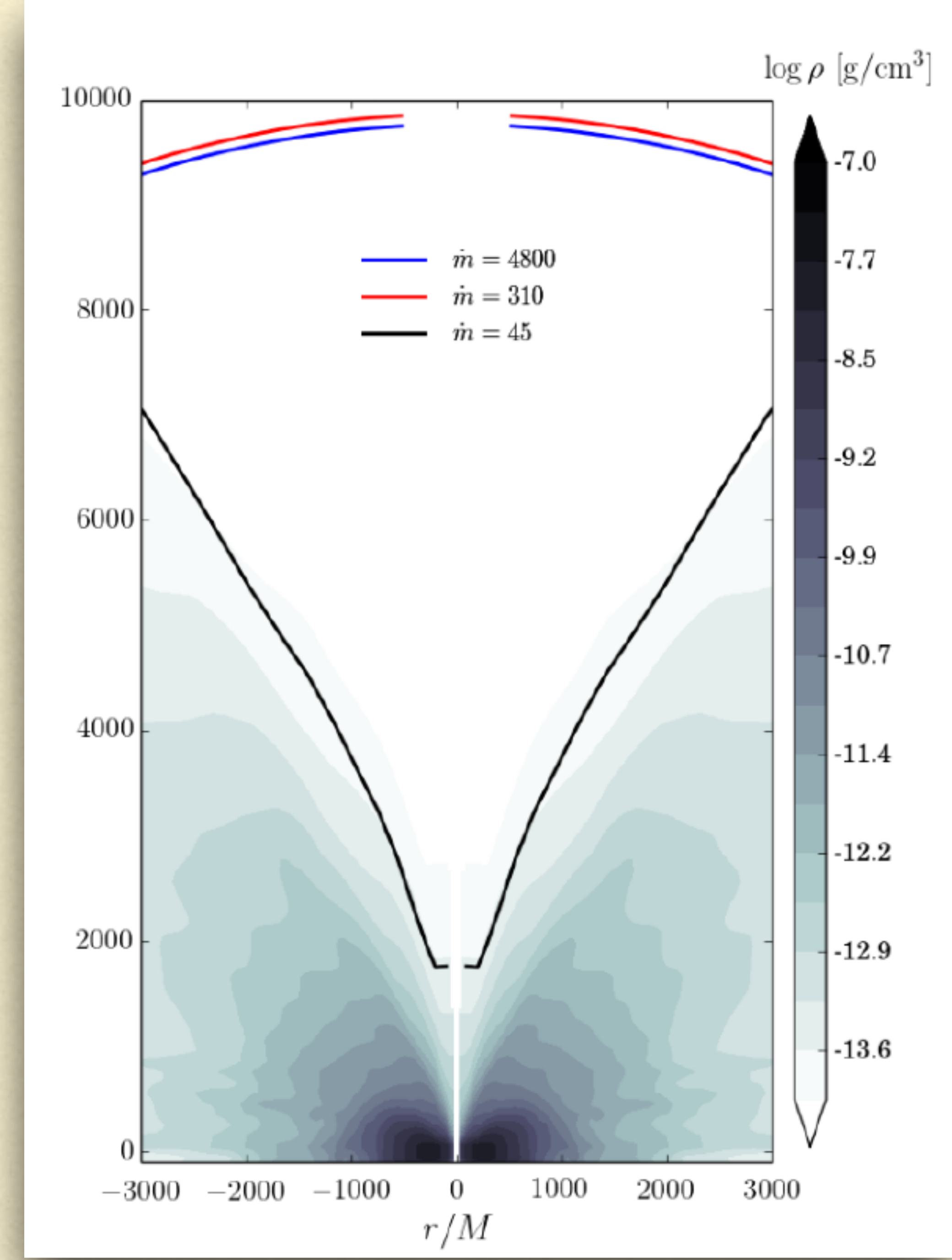
$$b \approx b_{SN} \frac{2(1+\ln \dot{m})}{\dot{m}}$$

$$\dot{m} = 45, \quad b = 0.06$$

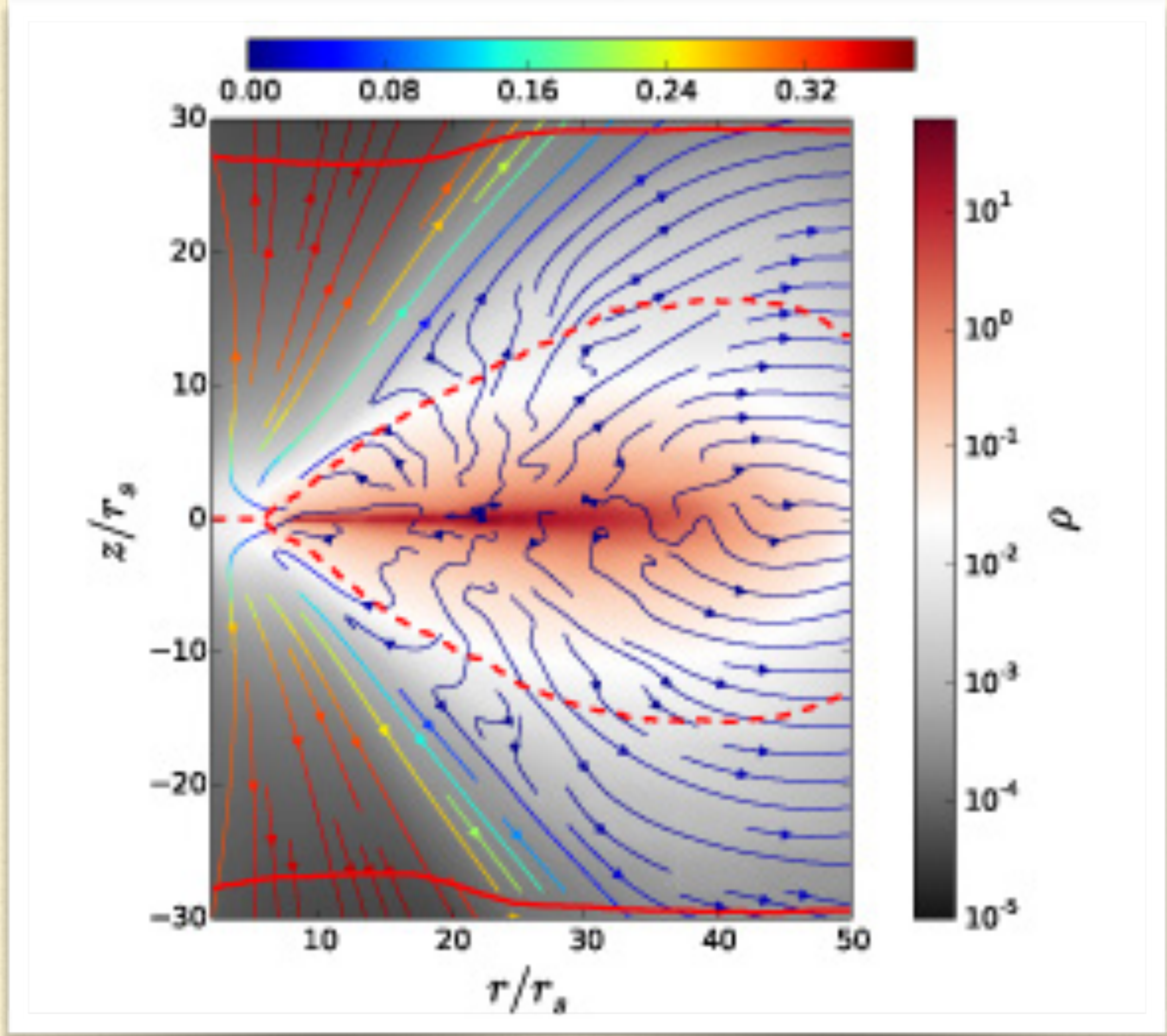
$$b_{\rm King} = 0.04$$

Sądowski & Narayan 2015

… but problem: the photosphere



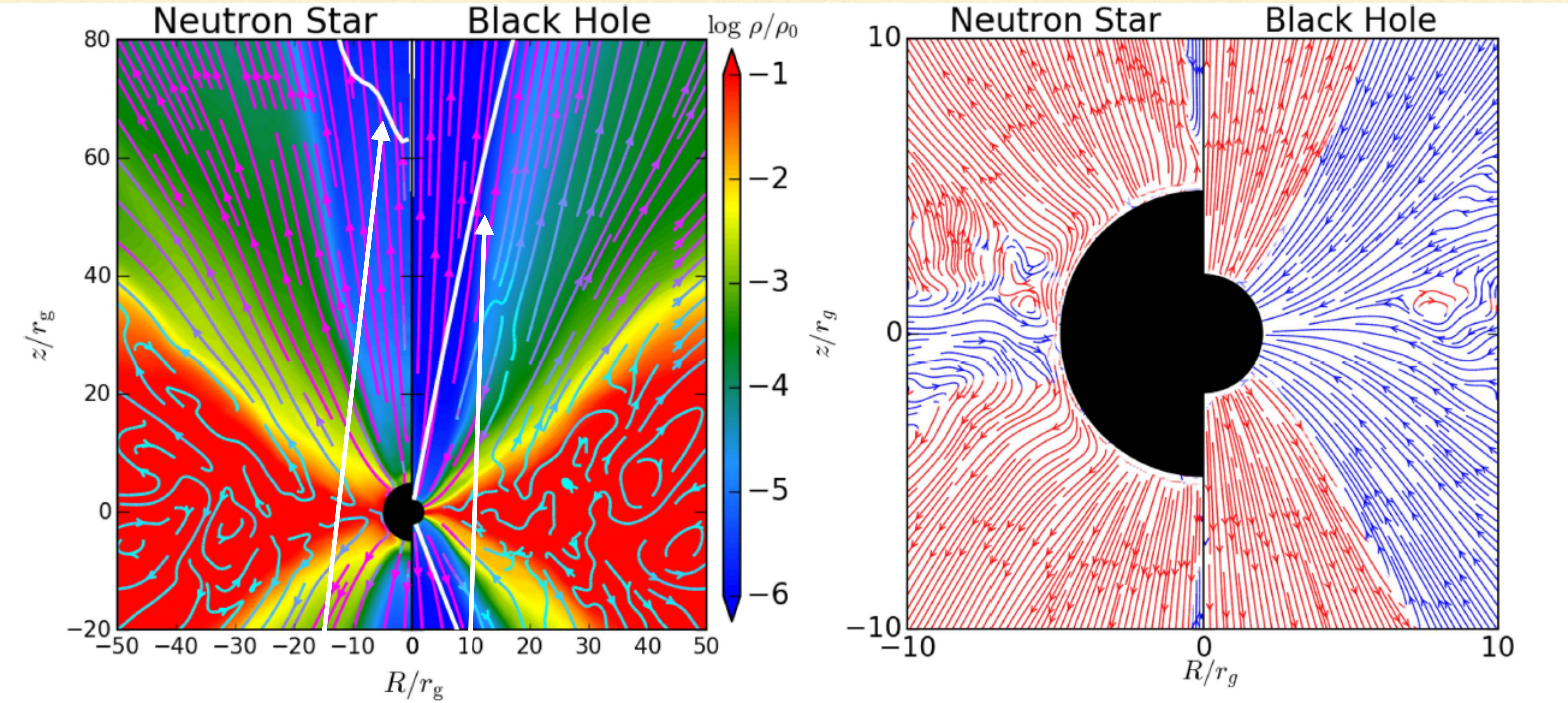
Sądowski & Narayan 2015



Jiang, Stone & Davis 2014

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

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

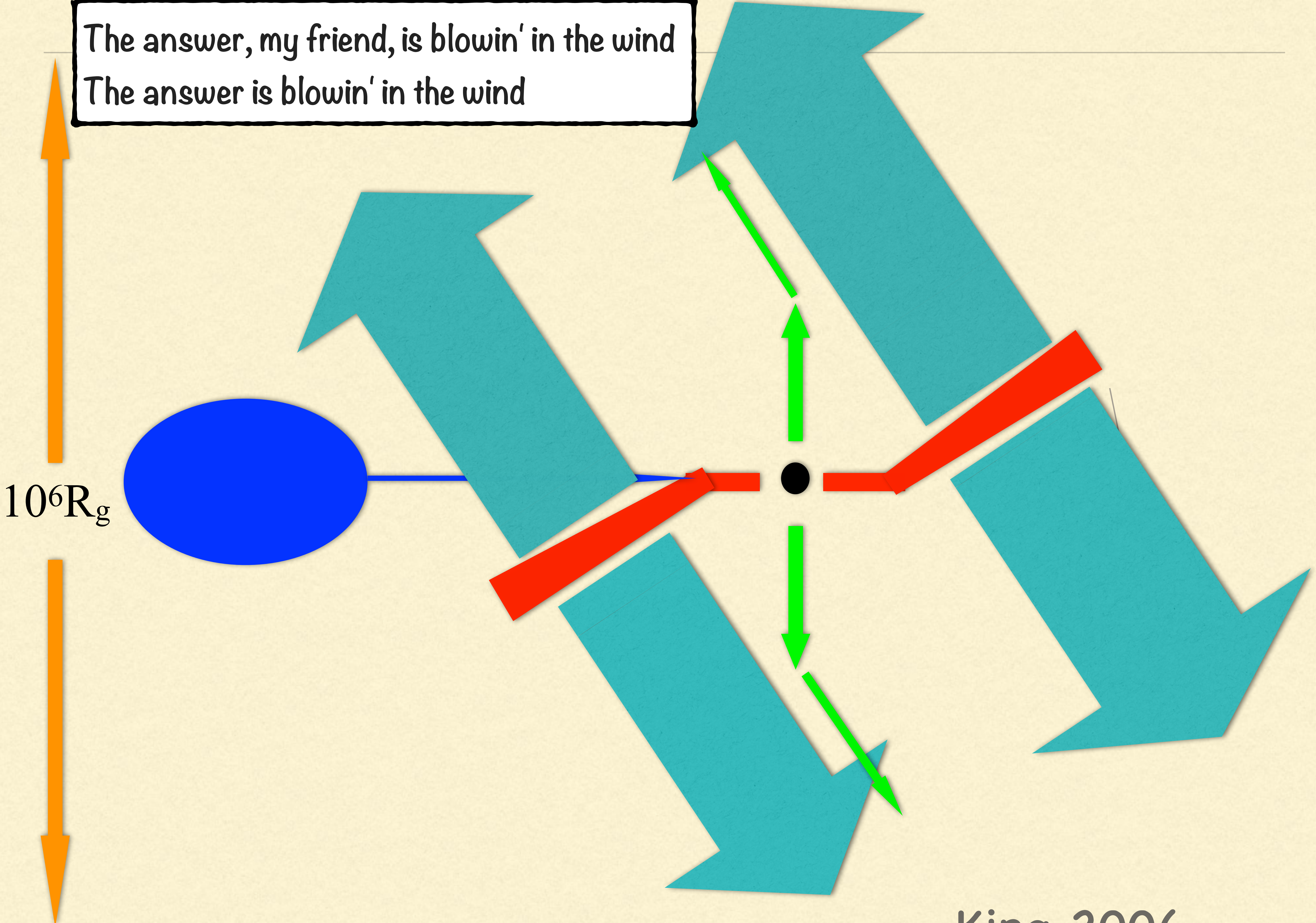


photosphere

Takahashi, Mineshige & Ohsuga 2018

So, for very high accretion rates, where is the beaming occurring ?

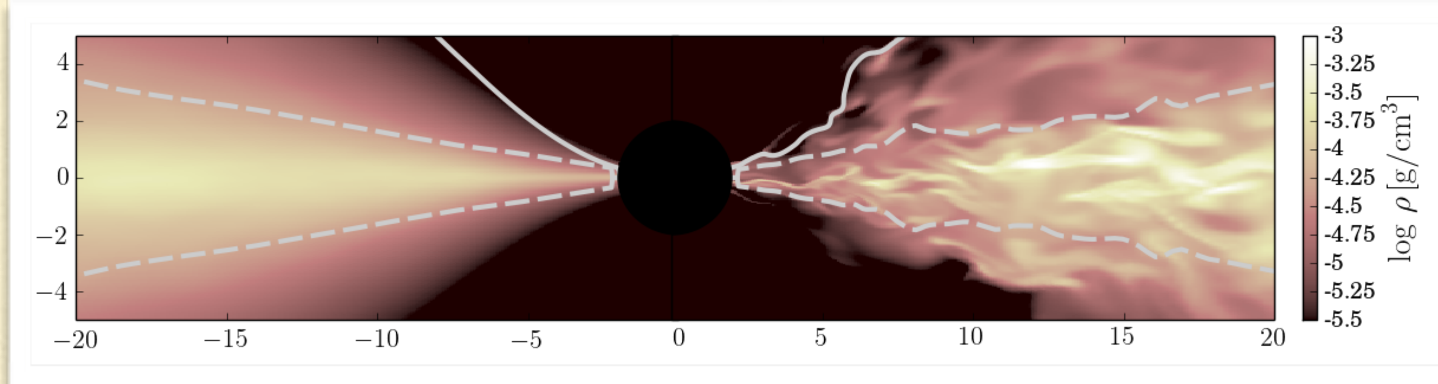
The answer, my friend, is blowin' in the wind
The answer is blowin' in the wind



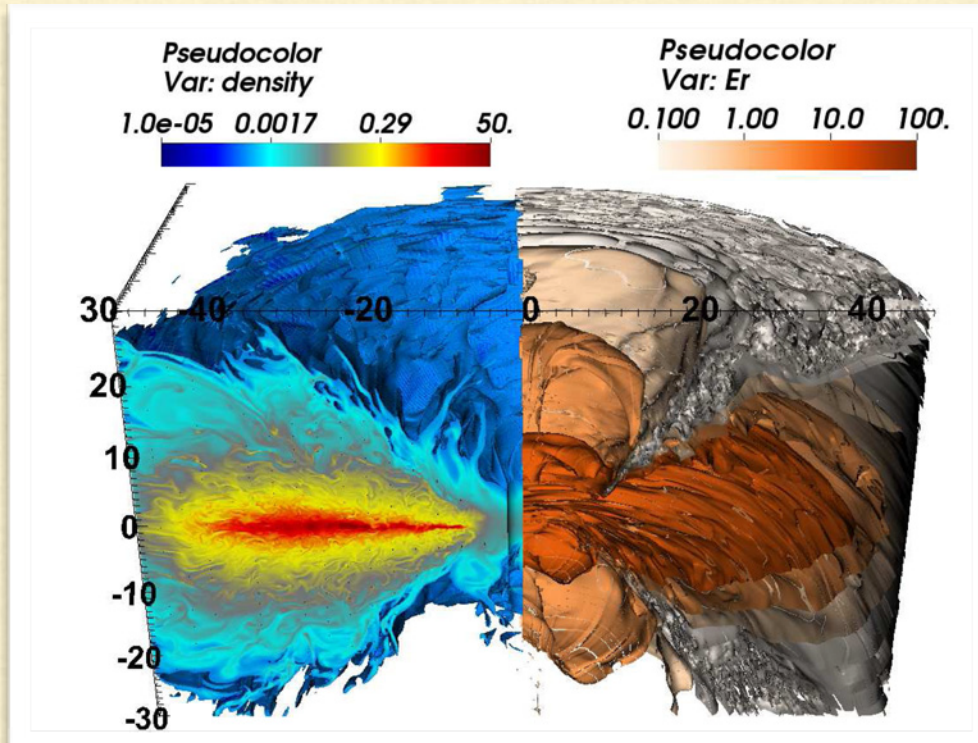
King 2006

And what about the radiation-pressure instability?

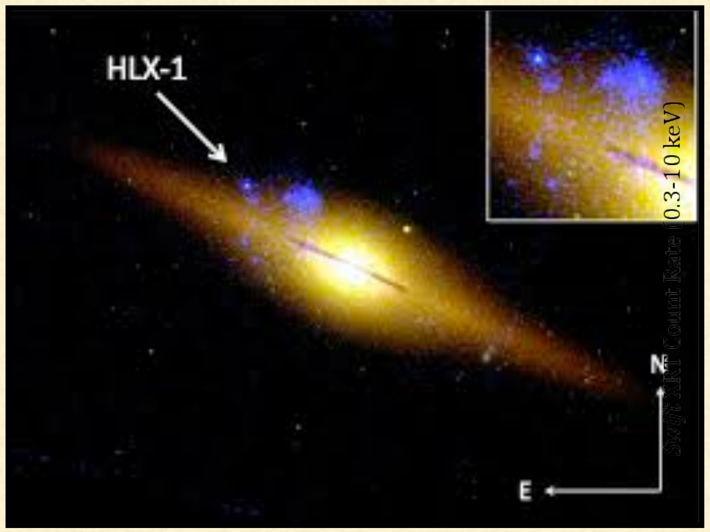
- Magnetic field ? (Sądowski 2016)

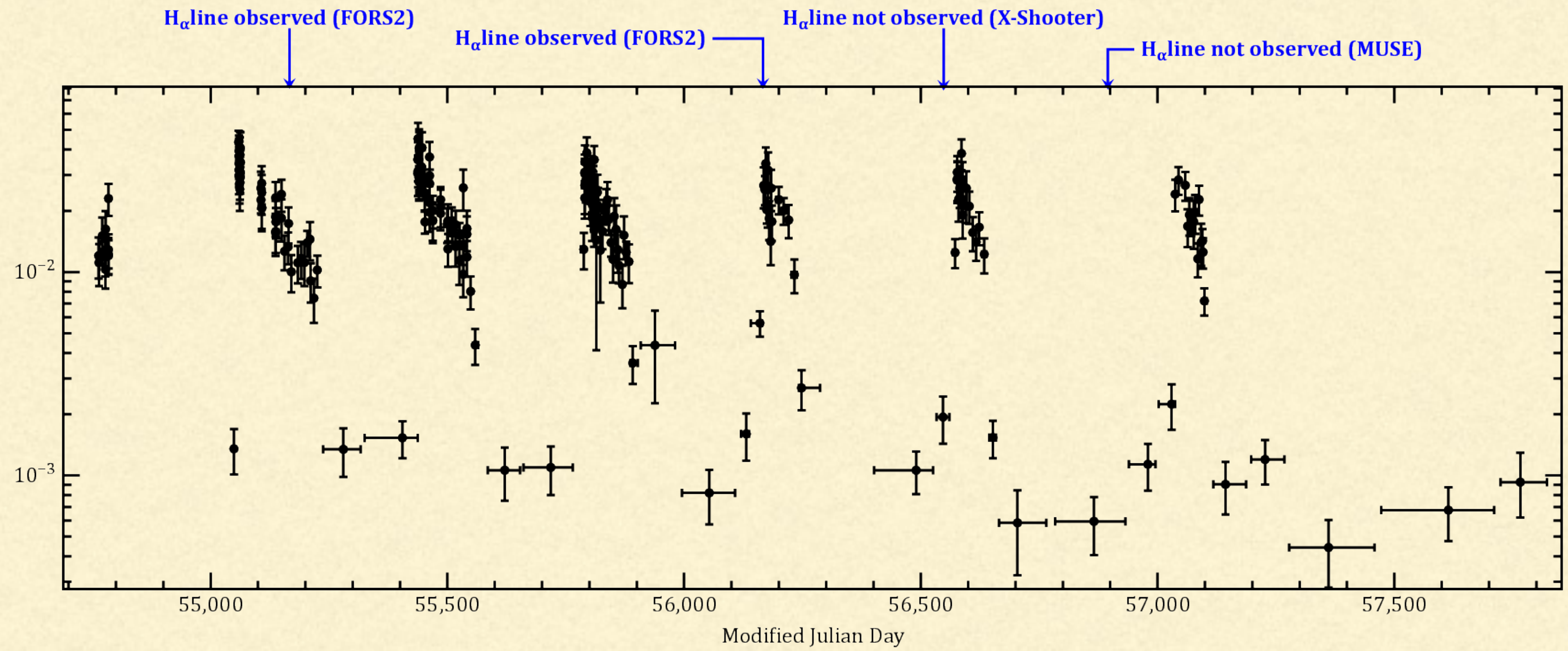


- Vertical advection ? (Jianng et al. 2014)



HLX-1 in ESO 249: $L_{\rm max} = 1.2 \times 10^{42}\,{\rm erg\,s^{-1}}$





Is it a super-Eddington source ?
"Consensus": $M \sim 10^4\,{\rm M}_\odot$

Dubus, King & Lasota: the outburst rise- and decay- times are <u>totally incompatible</u> with such a mass (especially in view of the observed 1-day optical - X-ray delay). HLX-1 is a $\sim 3\,{\rm M}_\odot$, $\dot{m} \approx 170$ system undergoing dwarf-nova-type instabilities. (see also Hameury's talk)