Long GRBs from WR-HMXBs

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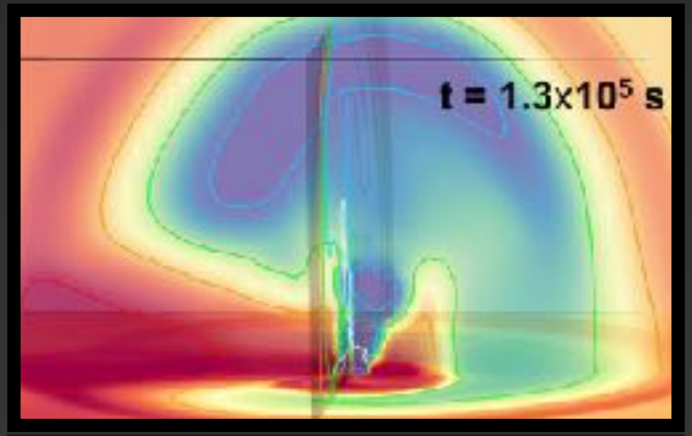
GRBs & Central Engone Powerwed Transients 2024
(Playa del Carmen, MX 2/XII - 6/XII, 2024)

Collaborators:
G.E. Brown, C.-H. Lee,
M. Cantiello,
F. De Colle, D. López Cámara,



Lo… WR-HMXBs

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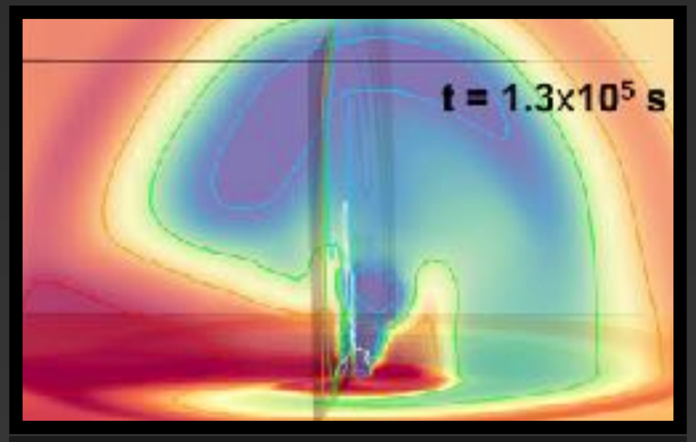

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Collapsar lGRBs

- $E_{HN,kin} \geq 30$ bethes (foes)
- $V_{HN} \sim 30{,}000$ km/sec
- Type Ic (bl) HNe
  asociated to GRBs
- Progenitors:
  Wolf-Rayet (He) stars
- Accretion disk formation required.
- Magnetic field:
  B ~ (10e15 G) ~ Magnetars ➪
- But… stellar winds remove L!!

NASA / SkyWorks Digital

ESO

Large-mass stars lose mass (winds) and angular momentum at a very large rate.

He-star stage is even worse.

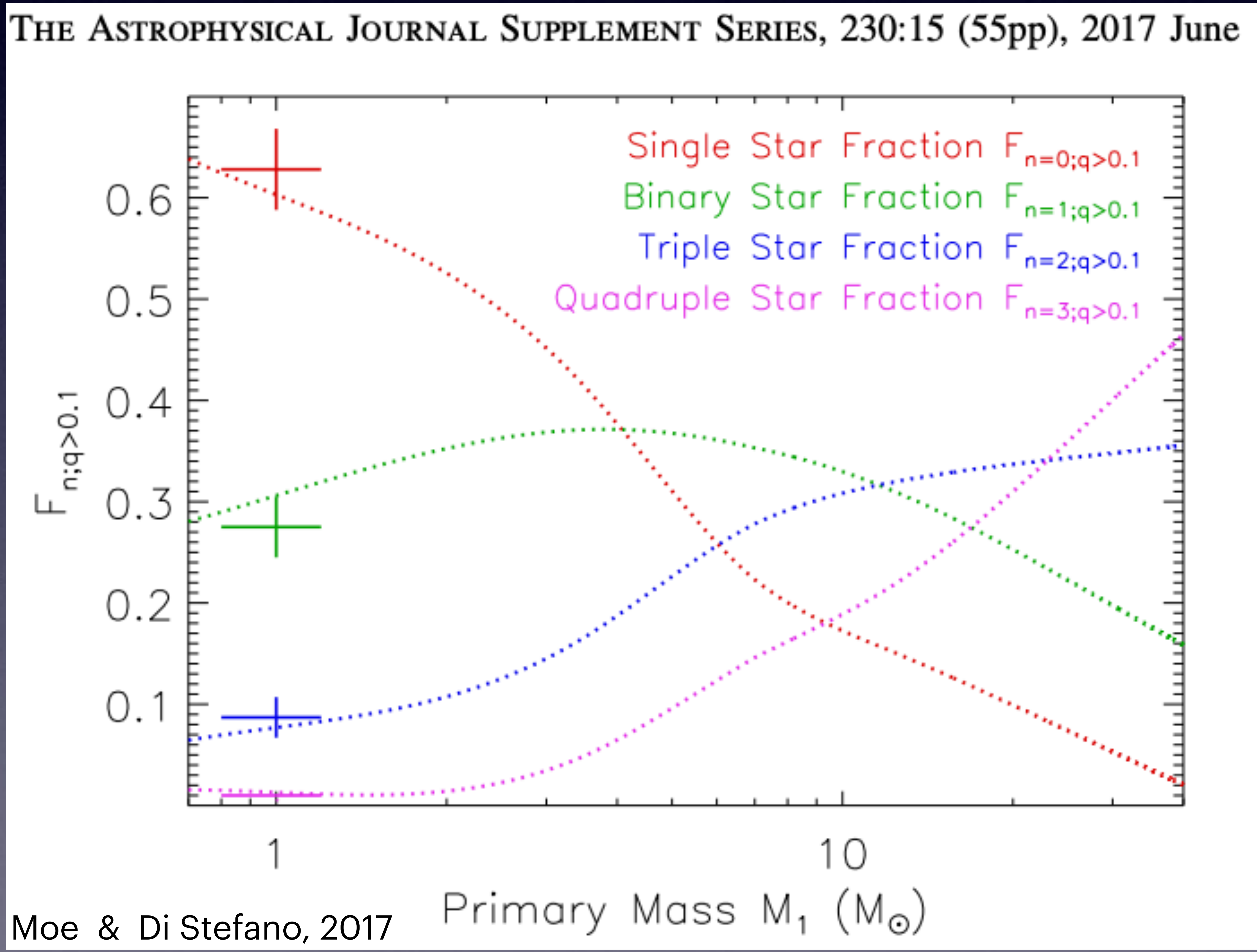
WR-phase does not help either.

I.e., not great for GRB progenitors.

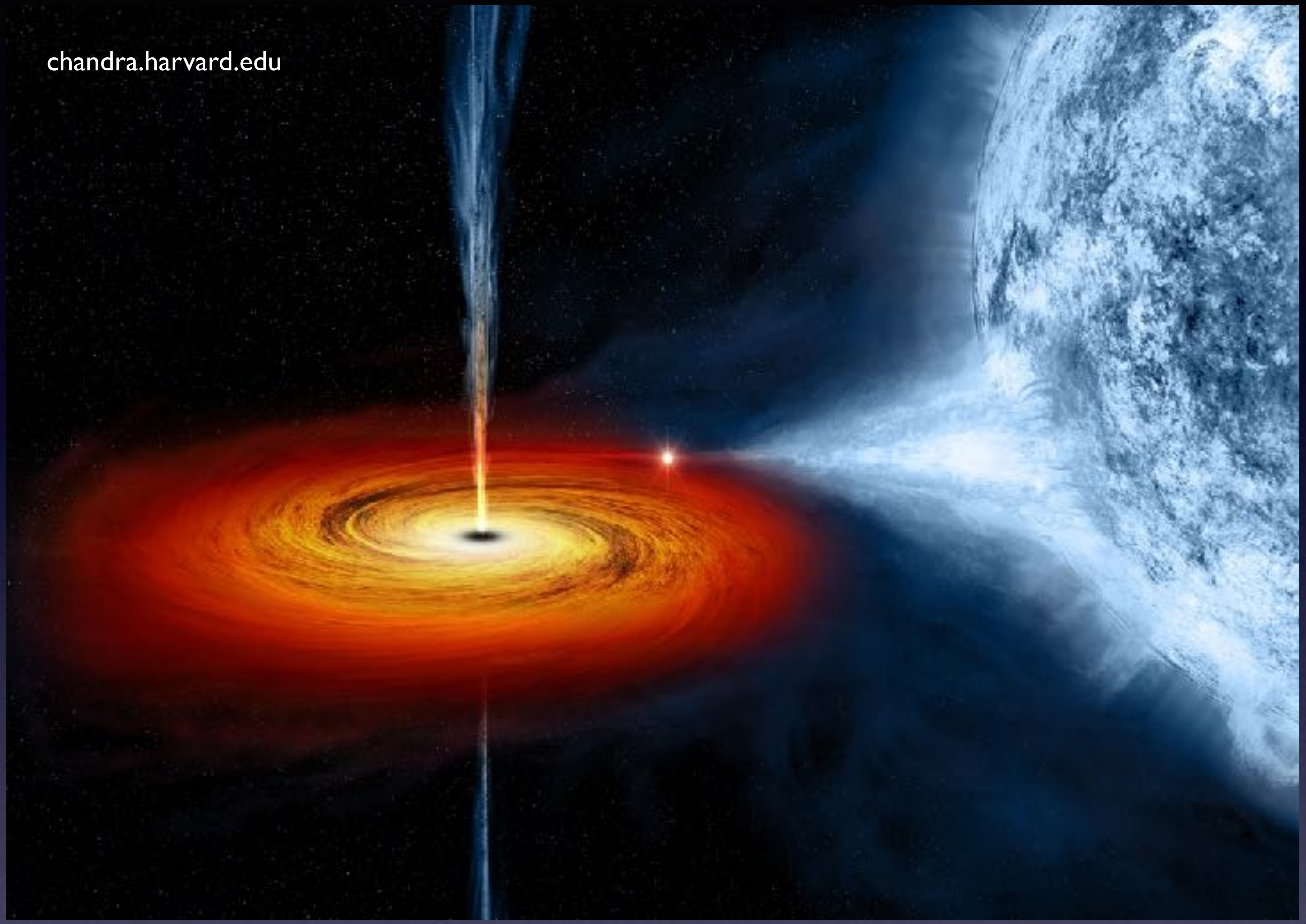
Binaries

- ~50% of visible stars are binaries.
- >71% of massive are binaries or multiples.

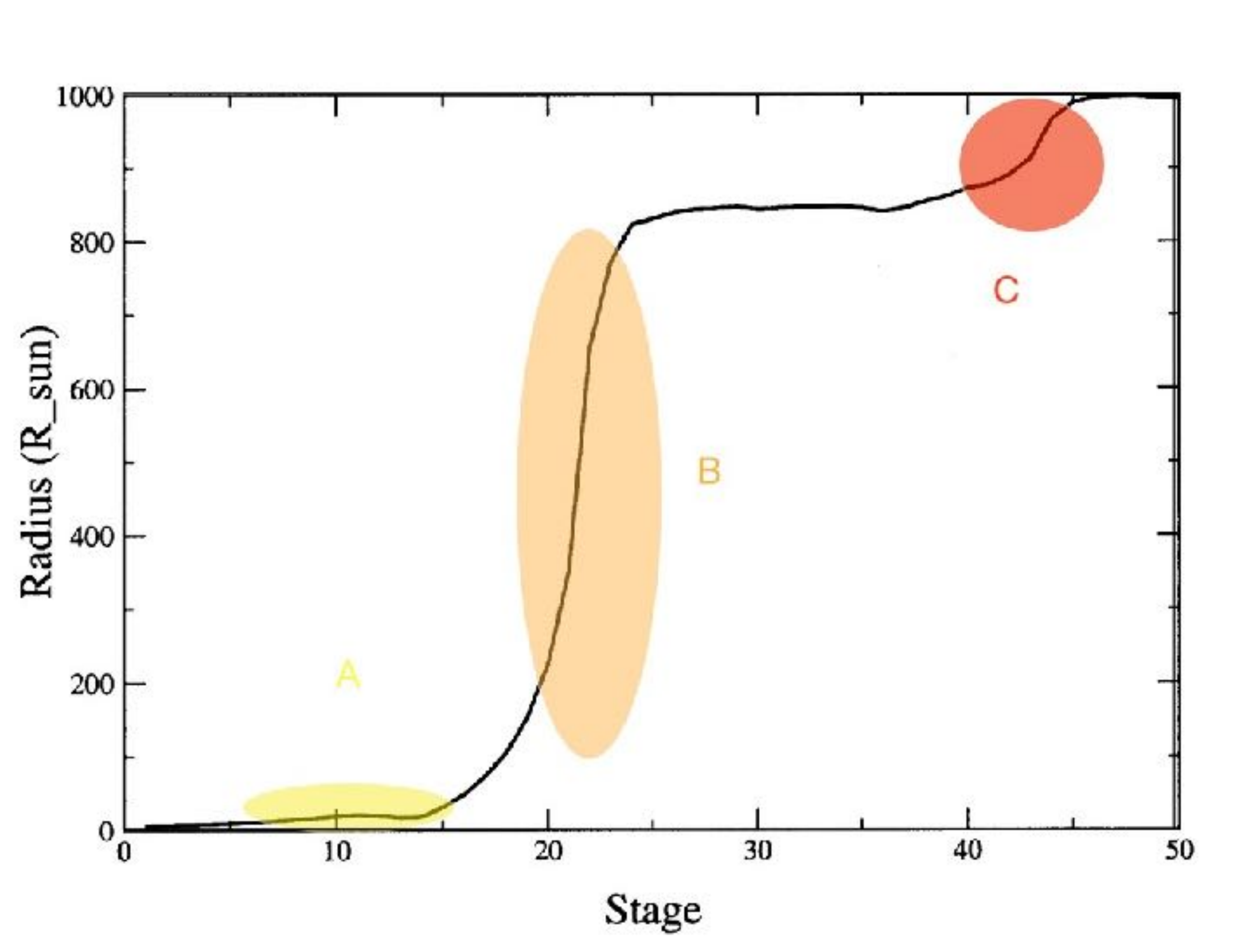
Sana et al. 2012



Evolution in contact binaries



- We need to prevent mass and angular momentum from being lost (Case B is out of the question)



- We need to allow for the He core to form so a CO is produced (Case A is out).

We are left with Case C mass transfer (and low Z)!

Tidal synchronization (or Spin-Orbit coupling; option 1)

- Equilibrium tide (turbulent discipation in convective envelopes; RSGs?):

$$t_{sync} = \frac{1}{6q^2k_2}\left(\frac{MR^2}{L}\right)^{1/3}\frac{I}{MR^2}\left(\frac{a}{R}\right)^6$$

- Dynamical tide (radiative damping; WRs? RGs?):

$$t_{sync} = \frac{2^{-5/3}}{5q^2(1+q)^{5/6}E_2}\left(\frac{R^3}{GM}\right)^{1/2}\frac{I}{MR^2}\left(\frac{a}{R}\right)^{17/2}$$

Zahn ’75, ’77

Alfven timescales

- Alfvén synchronization timescale

$$\tau_{\rm A} = \frac{L\sqrt{4\pi\rho}}{B}$$

- Average densities:

$$\rho_{\rm Fe} \simeq \frac{9}{4\pi} 10^9 {\rm g\,cm^{-3}}, \quad \rho_{\rm C} \simeq \frac{3}{4\pi} 10^7 {\rm g\,cm^{-3}}, \quad \rho_{\rm He} \simeq \frac{6}{4\pi} 10^4 {\rm g\,cm^{-3}}$$

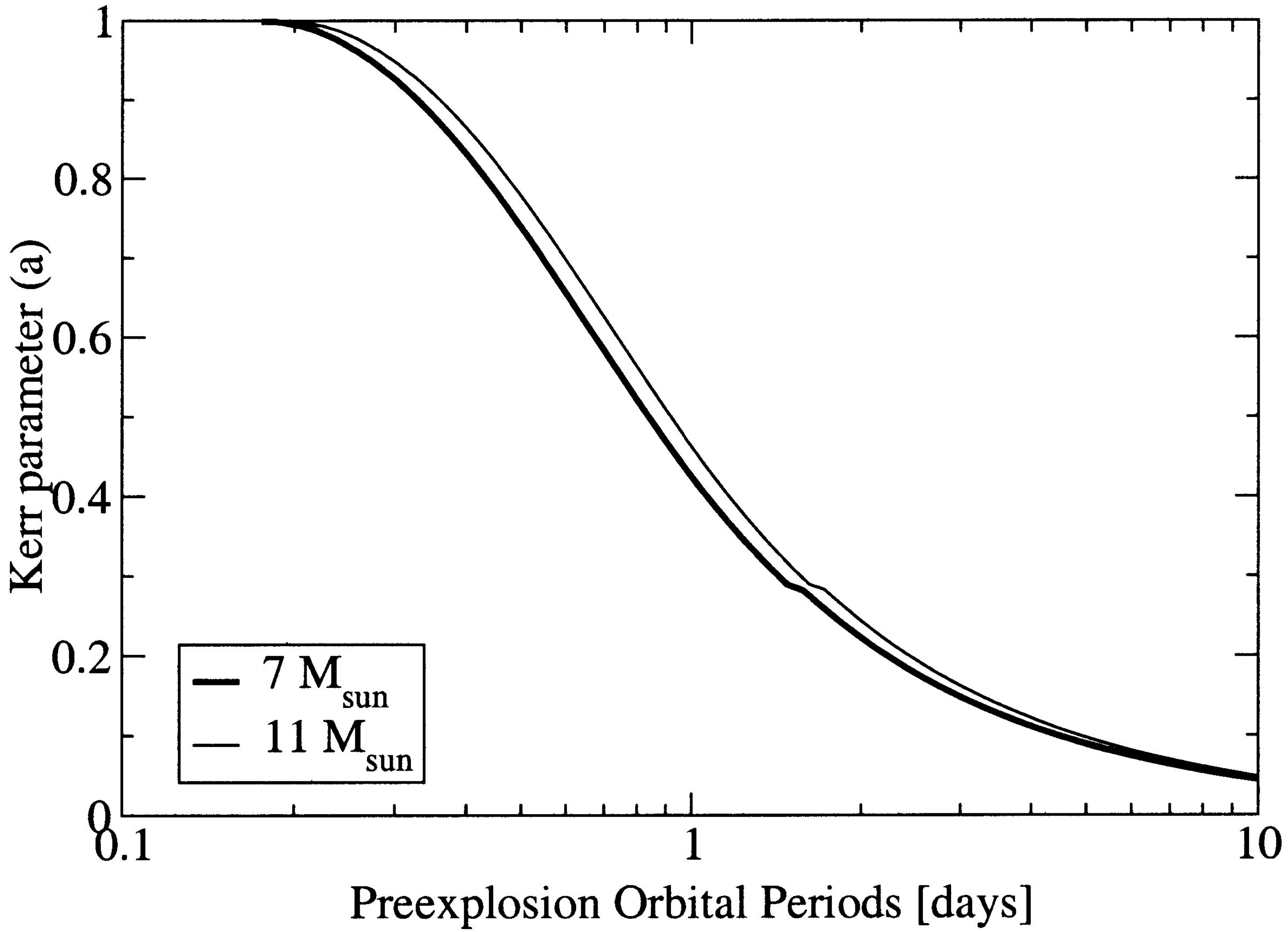
- Timescales:

Final Magnetic Field [Gauss]	$\tau_{\rm A,He}$ [Seconds]	$\tau_{\rm A,C}$ [Seconds]	$\tau_{\rm A,Fe}$ [Seconds]
10^{15}	2.5×10^5	5.5×10^3	10^2
10^{12}	2.5×10^8	5.5×10^6	10^5
10^{10}	2.5×10^{10}	5.5×10^8	10^7

Moreno Méndez, 2014

Stellar spin up through tides

Lee et al. '02, Brown et al. '07, '08



XB properties

Name	$M_{BH,2}$ $[M_\odot]$	$M_{d,2}$ $[M_\odot]$	$M_{BH,now}$ $[M_\odot]$	$M_{d,now}$ $[M_\odot]$	Model $a_{\star,2}$	Measured $a_\star$	$P_{Orbit,now}$ [days]	$E_{\rm BZ}$ $[10^{51}$ ergs]
AML: with main sequence companion								
J1118+480	~ 5	< 1	$6.0 - 7.7$	$0.09 - 0.5$	0.8	-	0.169930(4)	~ 430
Vel 93	~ 5	< 1	$3.64 - 4.74$	$0.50 - 0.65$	0.8	-	0.2852	~ 430
J0422+32	$6 - 7$	< 1	$3.4 - 14.0$	$0.10 - 0.97$	0.8	-	0.2127(7)	$500 \sim 600$
1859+226	$6 - 7$	< 1	$7.6 - 12$		0.8	-	0.380(3)	$500 \sim 600$
GS1124−683	$6 - 7$	< 1	6.95(6)	$0.56 - 0.90$	0.8	-	0.4326	$500 \sim 600$
H1705−250	$6 - 7$	< 1	$5.2 - 8.6$	$0.3 - 0.6$	0.8	-	0.5213	$500 \sim 600$
A0620−003	~ 10	< 1	11.0(19)	0.68(18)	0.6	0.12 ± 0.19	0.3230	~ 440
GS2000+251	~ 10	< 1	$6.04 - 13.9$	$0.26 - 0.59$	0.6	-	0.3441	~ 440
Nu: with evolved companion								
GRO J1655−40	~ 5	$1 - 2$	$5.1 - 5.7$	$1.1 - 1.8$	0.8	$0.65 - 0.75$	2.6127(8)	~ 430
4U 1543−47	~ 5	$1 - 2$	$2.0 - 9.7$	$1.3 - 2.6$	0.8	$0.75 - 0.85$	1.1164	~ 430
XTE J1550−564	~ 10	$1 - 2$	$9.68 - 11.58$	$0.96 - 1.64$	0.5	0.49 ± 0.13	1.552(10)	~ 300
GS 2023+338	~ 10	$1 - 2$	$10.3 - 14.2$	$0.57 - 0.92$	0.5	-	6.4714	~ 300
XTE J1819−254	$6 - 7$	~ 10	$8.73 - 11.69$	$5.50 - 8.13$	0.2		2.817	$10 \sim 12$
GRS 1915+105	$6 - 7$	~ 10	14(4)	1.2(2)	0.2	> 0.98	33.5(15)	$10 \sim 12$
Cyg X−1	$6 - 7$	$\gtrsim 30$	~ 10.1	17.8	0.15	> 0.97	5.5996	$5 \sim 6$
Extragalactic								
LMC X−1	~ 40	~ 35	$8.96 - 11.64$	30.62 ± 3.22	< 0.05	$0.81 - 0.94$	3.91	< 2
LMC X−3	7	4	$5 - 11$	6 ± 2	0.43	~ 0.3	1.70	~ 155
M33 X−7	~ 90	~ 80	$14.20 - 17.10$	70.0 ± 6.9	~ 0.05	$0.72 - 0.82$	3.45	$3 - 11$

Lee et al. '02, Brown et al. '07, '08, Moreno Méndez '11.

On the HMXBs...

(1) HMXB	(2) $M_\star$ [$M_\odot$]	(3) M_{BH} [$M_\odot$]	(4) q	(5) P $_{orb}$ [days]	(6) $a_\star$	(7) E_{rot} [B]	(8) Refs.
M33 X-7	70.0 ± 6.9	15.65 ± 1.45	10→5	3.45	0.84 ± 0.05	3,400	i, ii, iii
Cyg X-1	40^{+2}_{-2}	21.2 ± 2.2	5→2	5.60	$> 0.9985(3\sigma)$	10,000	iv, v, vi
LMC X-1	31.79 ± 3.48	10.91 ± 1.41	7→3	3.90917	$0.92^{+0.05}_{-0.07}$	3,000	vii, viii
IC 10 X-1	$17 - 35$	$10 - 15(?)$	$2 \rightarrow 1(?)$	1.45175	$\gtrsim 0.8$	$> 1,300$	ix, x, xi
NGC 300 X-1	26(?)	$17 \pm 4(?)$	$? \rightarrow 1.5$	1.366	$> 0.8?$	$> 1,500?$	xii, xiii
Cyg X-3	$(8 - 15)(?)$	$\lesssim (5 - 10)(?)$	$? \rightarrow 1.5$	0.20	$\lesssim 1?$	$\sim 5,000?$	xiv

(9) Sp.T.	(10) L_X [10^{38} erg]	(11) e	(12) V_{pec} [km s^{-1}]	(13) E_{bubble} [erg]	(14) SNR?	(15) $J - S$	(16) Refs.
O(7-8)III	0.13-2.49	0.0185(77)	–	–	–	$\leq 3^o$	xv, xvi, xvii, xviii
O9.7Iab	0.05	0.0189	9 ± 2	7×10^{48}	Bubble	$(10 - 20)^o$	xix, xx, xxi, xxii
O7III	2.3	0.0256(66)?	–	–	–	–	xxiii, xxiv, xxv
WR	0.7	–	–	–	–	–	xxvi
WR	2.6(1)	–	–	–	–	–	xxvii, xviii
WN(4-7)	0.5	–	≥ 9	–	Yes	$(> 15^o)?$	xxix, xxx

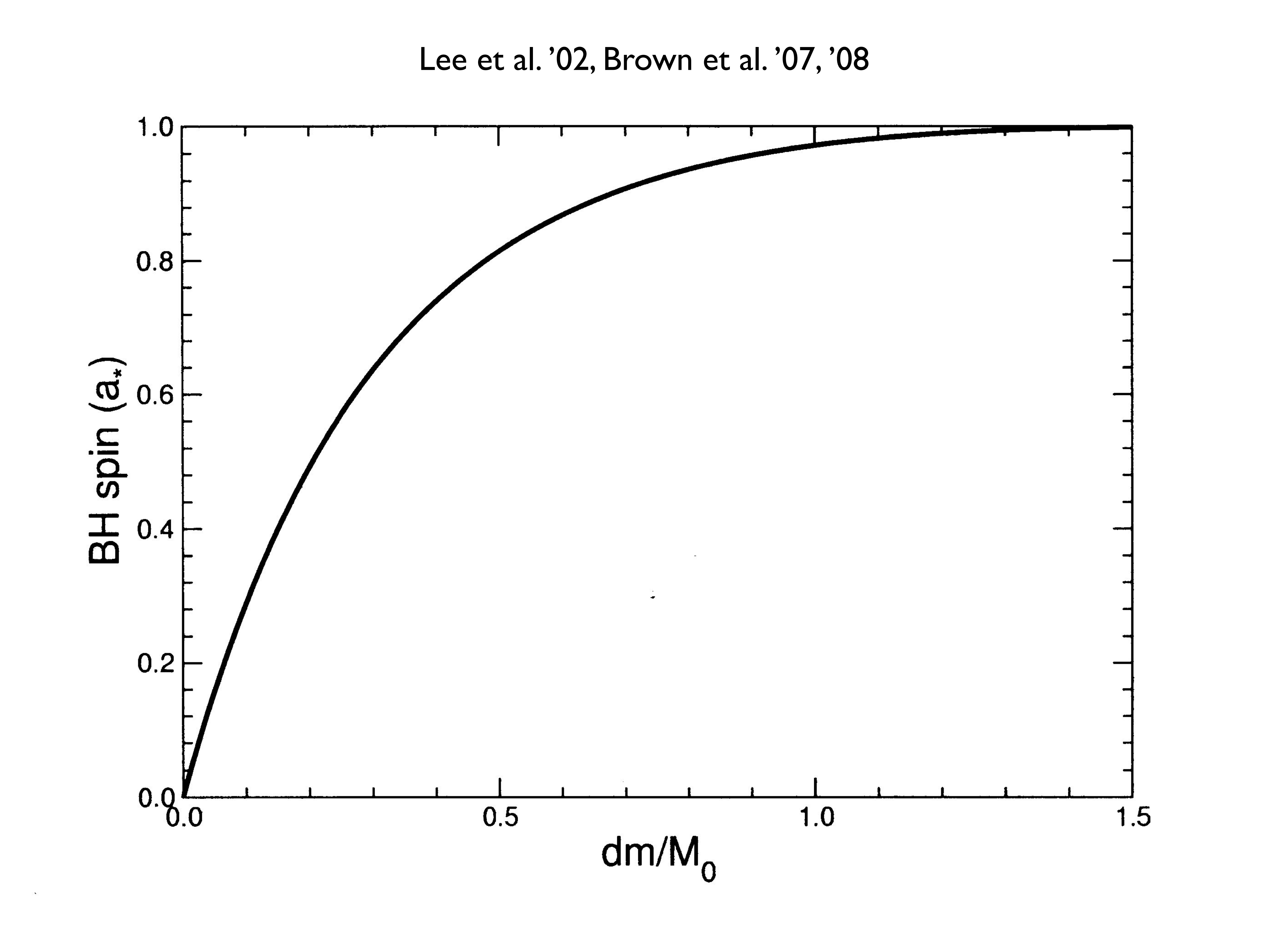
Moreno Méndez, 2022

Candidates for GRB central engines?

- Requisite: CE after Case C mass transfer.
- OK for Massive Stars with low-mass companion (i.e., up to ~2 Msun). But there might be too much energy and the central engine may blow itself apart (HN, type Ic bl) before a lGRB is produced.
- OK for Massive Stars with intermediate-mass stars (i.e., 2 to 8ish Msun).
- Not OK for Massive stars with massive companion.
  Typical BH spin: $a^* \sim 0.05$.

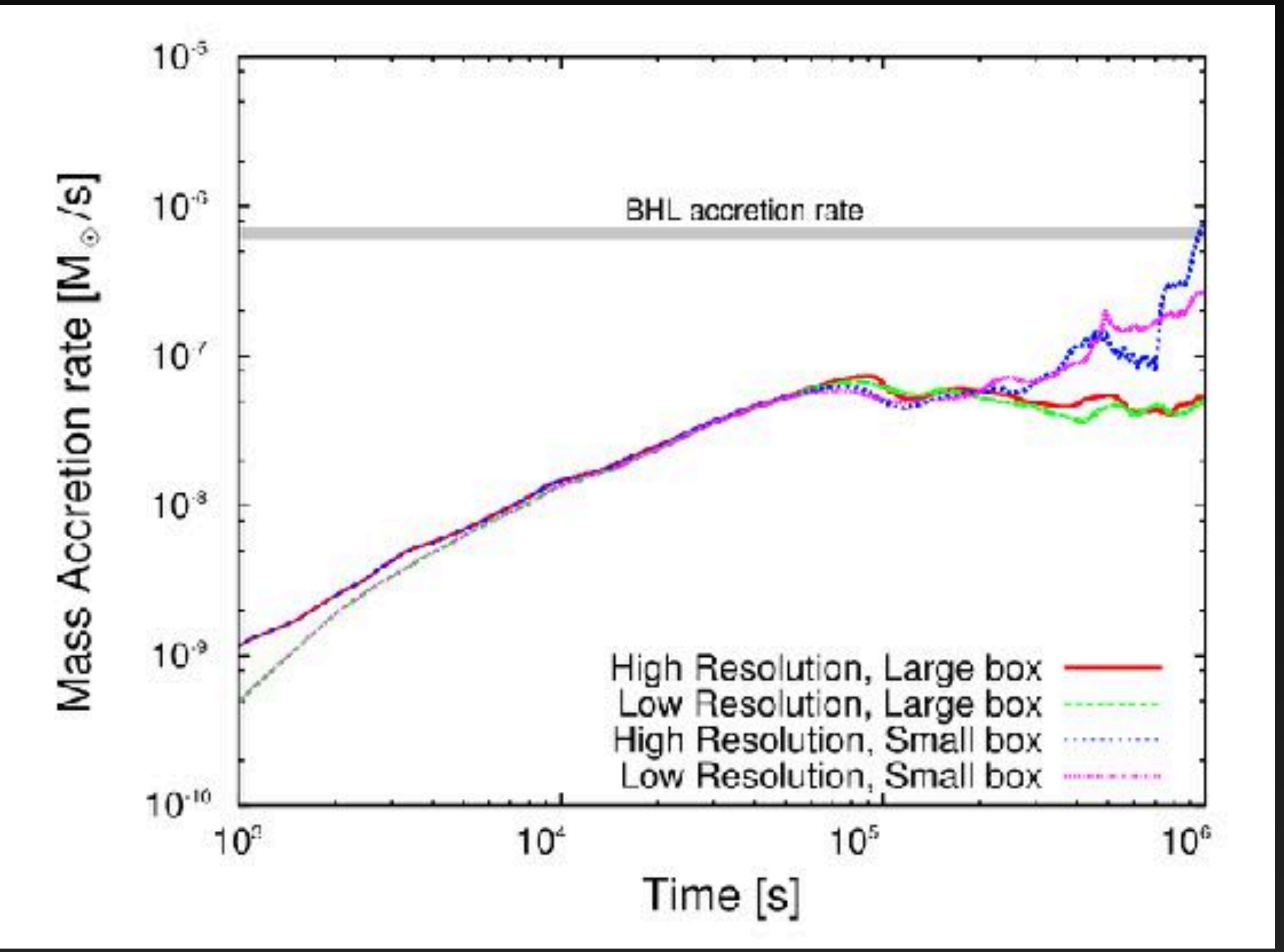
BH spin up through accretion (spin up, option 2)

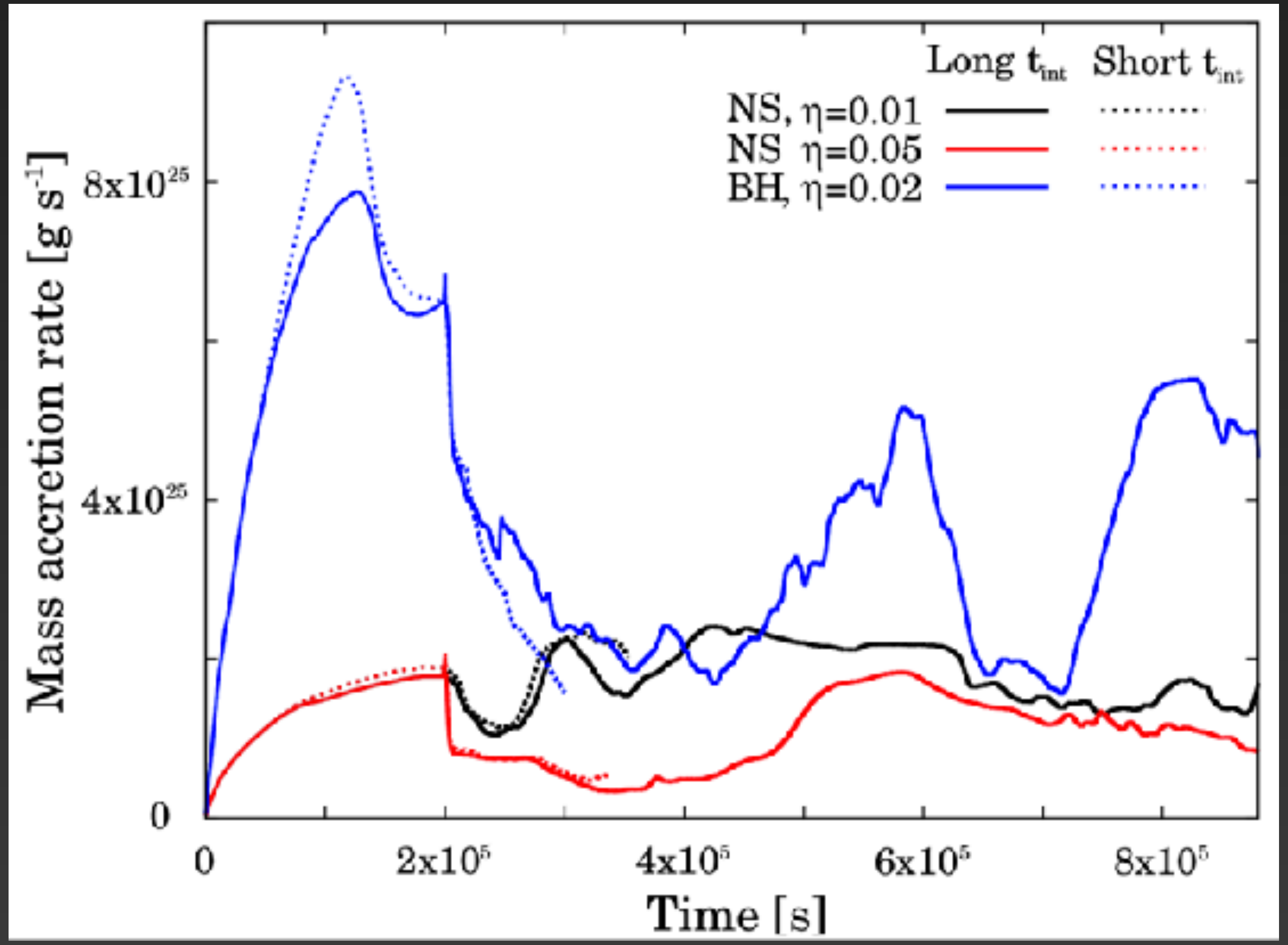
- Super Eddington or hypercritical accretion in HMXBs.
- Stable mass transfer needed (via RLOF? via wRLOF?)
- Obviously, too late for GRB central engine.

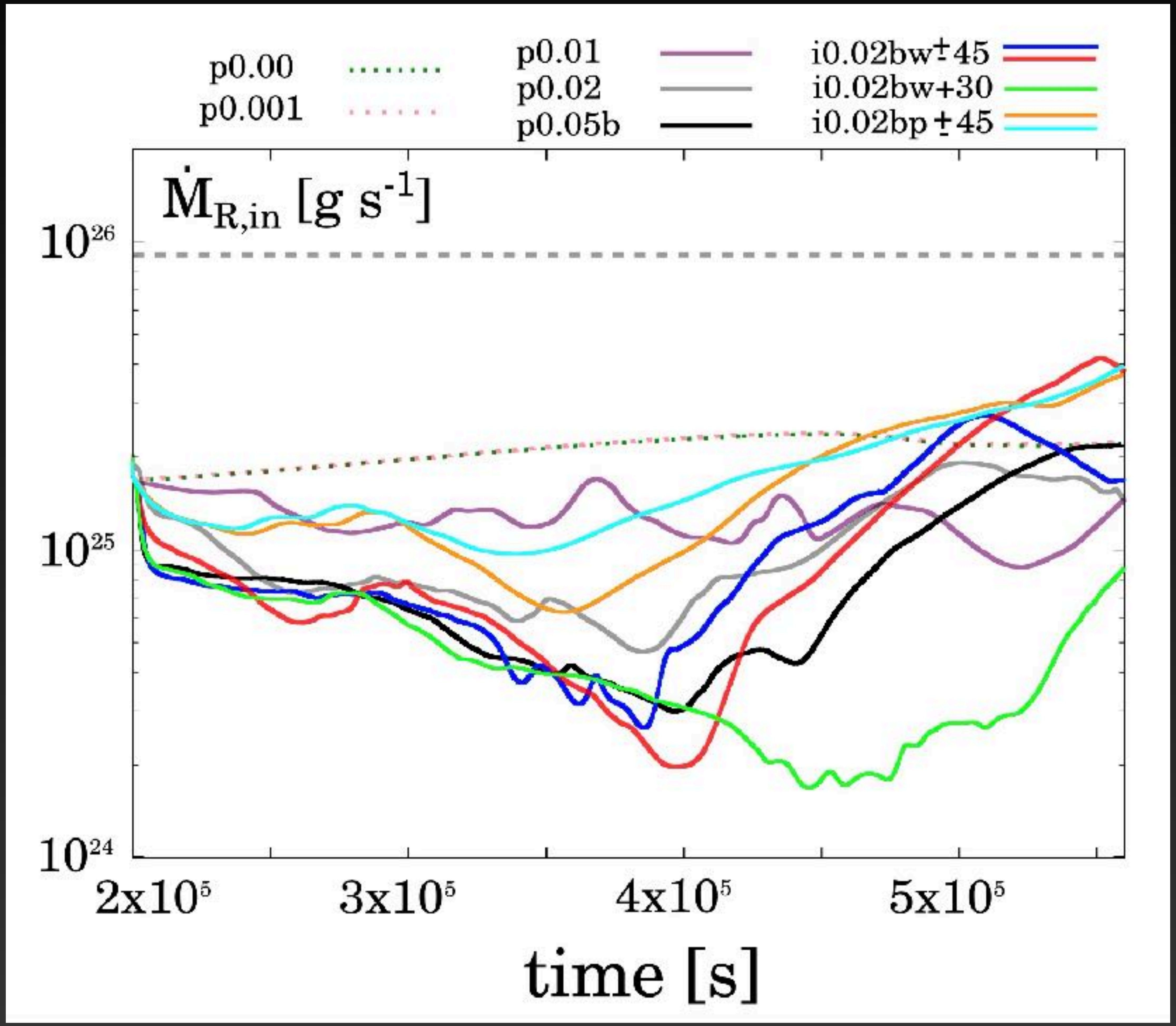


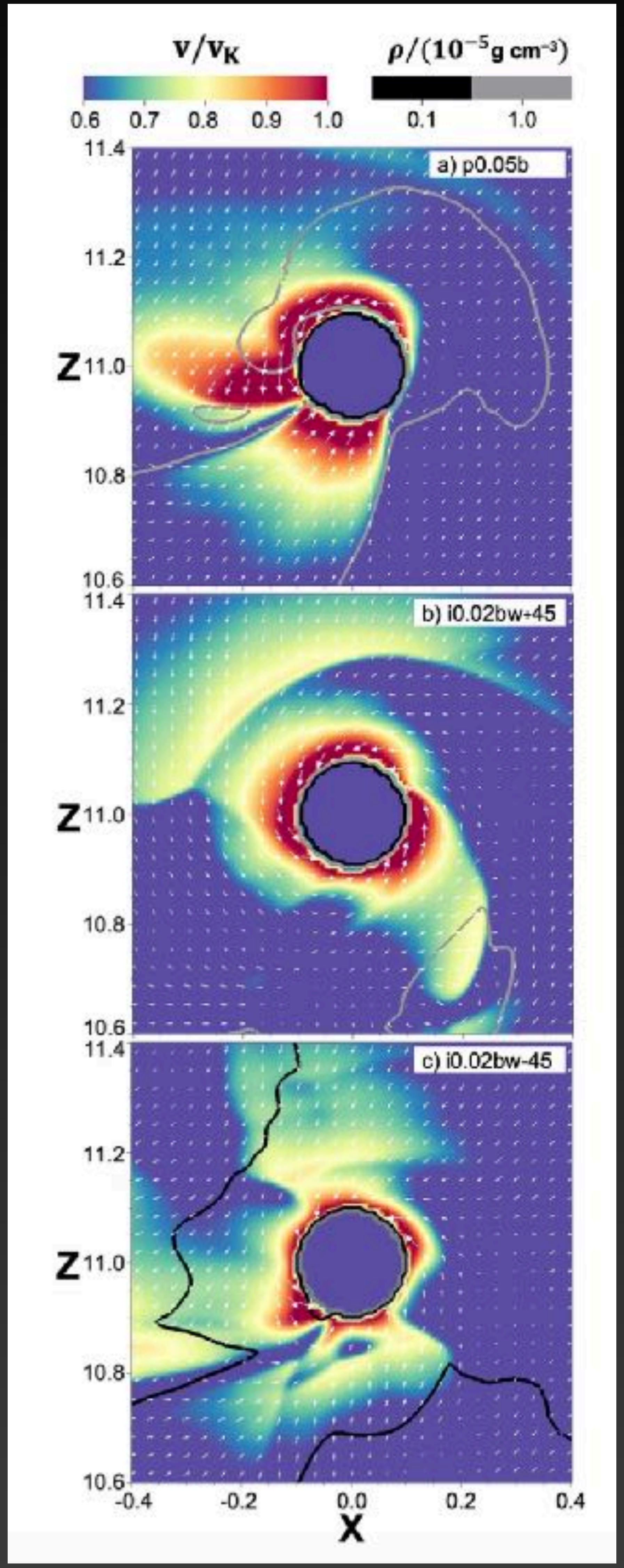
Hypercritical Accretion onto BHs!

CE/GE with BHL accretion with SR Jets, Coriolis, Gradients...



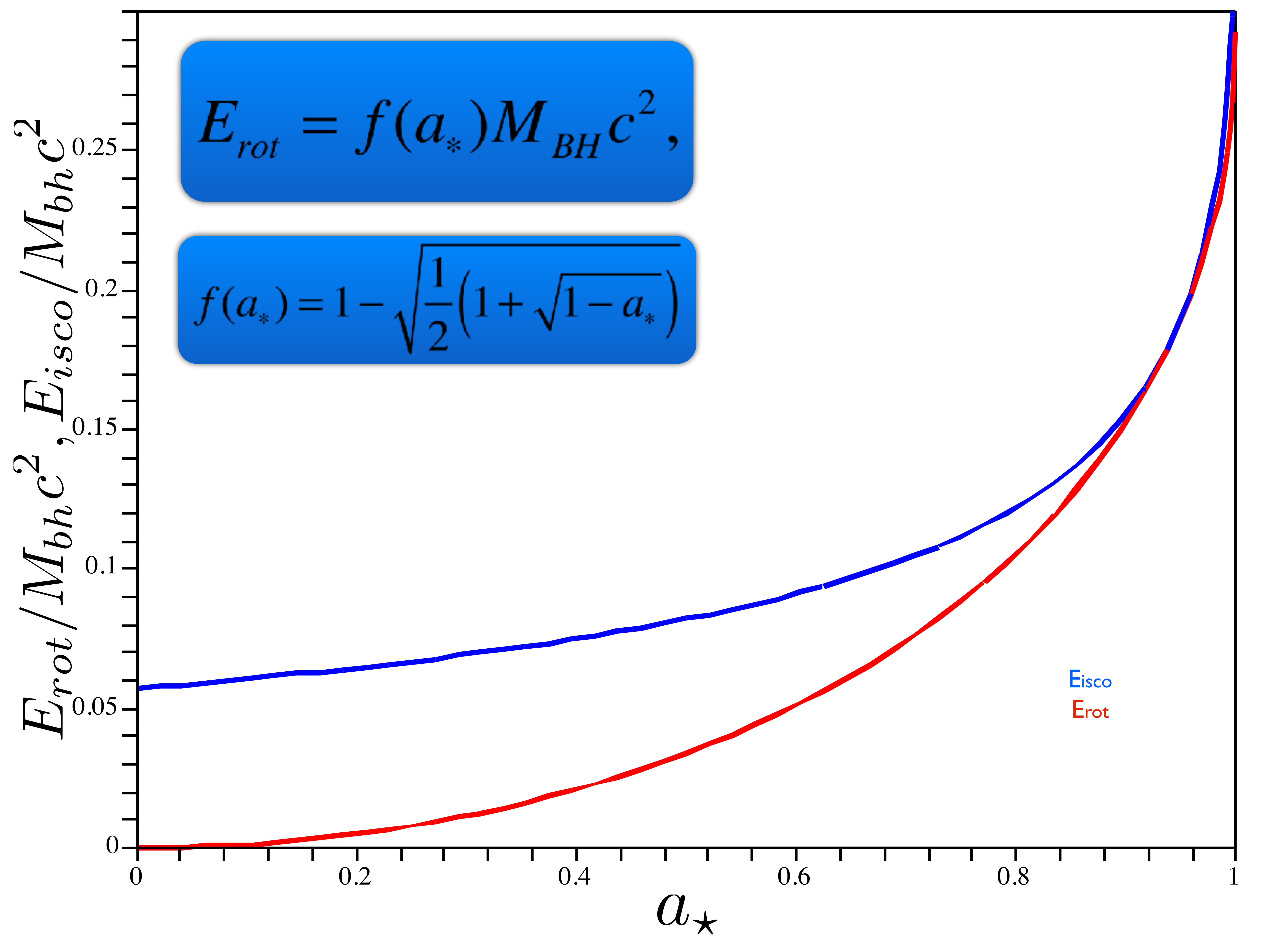




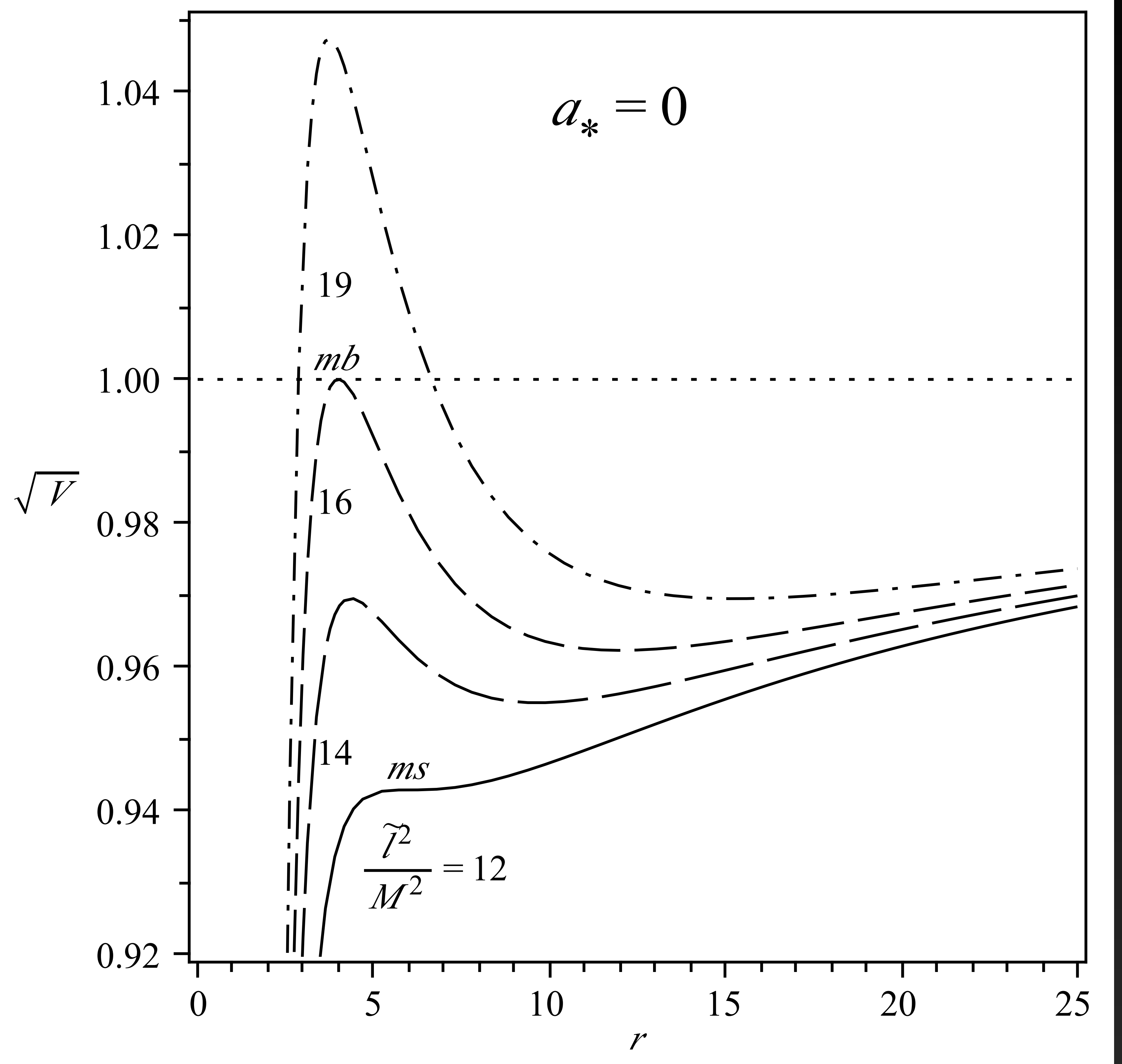


Moreno Méndez, López Cámara, De Colle, MNRAS 470, 2929, 2017
López-Cámara, De Colle, Moreno Méndez, MNRAS 482, 3646, 2019
López-Cámara, Moreno Méndez, De Colle, MNRAS 497, 2057, 2020

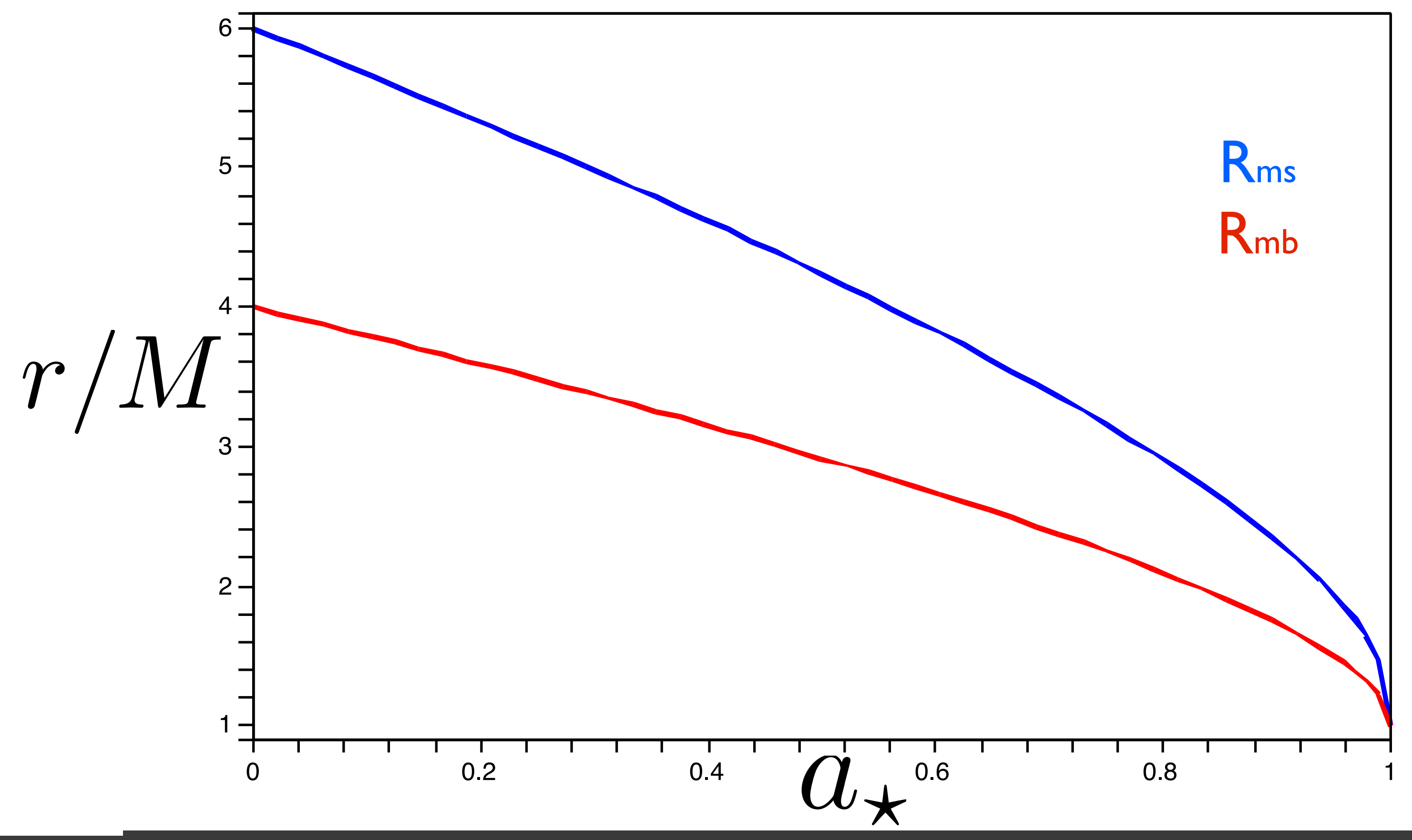
BH Energy



$E_{rot} = f(a_*) M_{BH} c^2,$
$f(a_*) = 1 - \sqrt{\frac{1}{2}\left(1 + \sqrt{1 - a_*}\right)}$
$E_{rot}/M_{bh}c^2, E_{isco}/M_{bh}c^2$
$a_\star$
Eisco
Erot



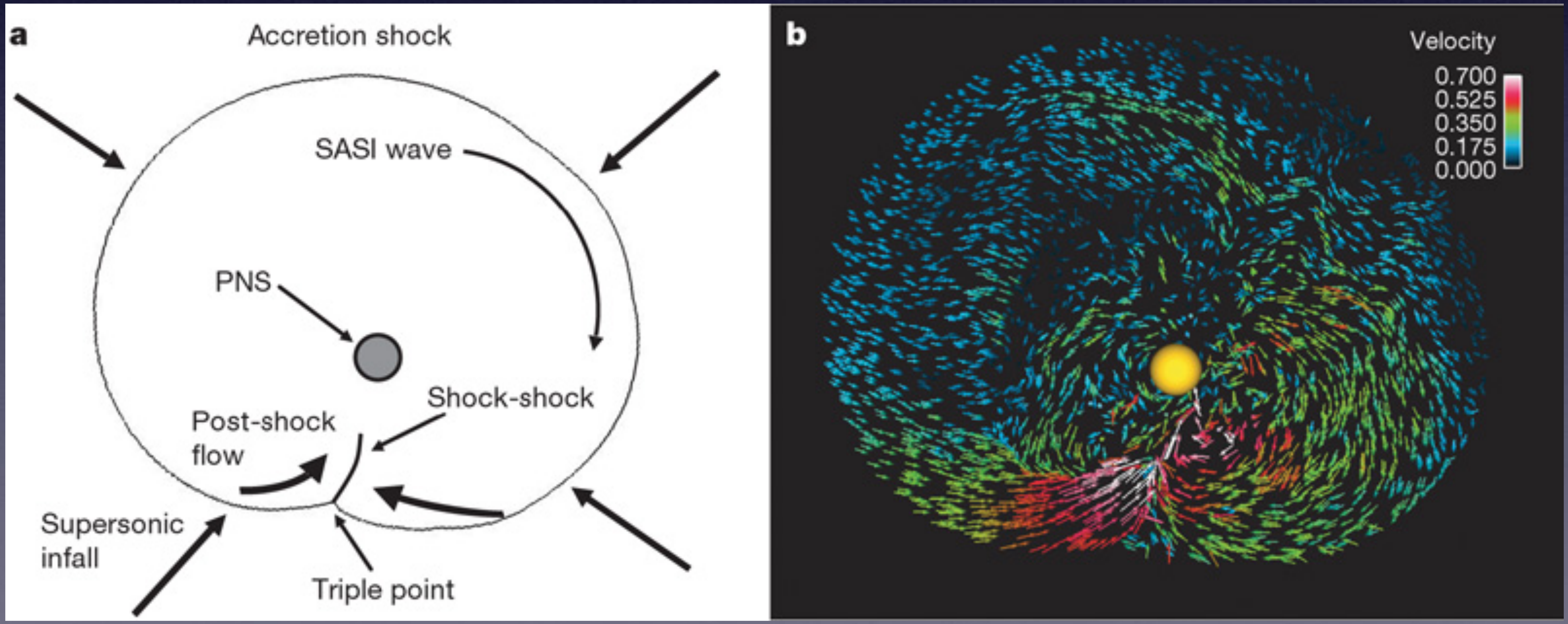
$a_* = 0$
$\sqrt{V}$
r
19
mb
16
14
ms
$\frac{\tilde{l}^2}{M^2} = 12$



r/M
$a_\star$
R_{ms}
R_{mb}

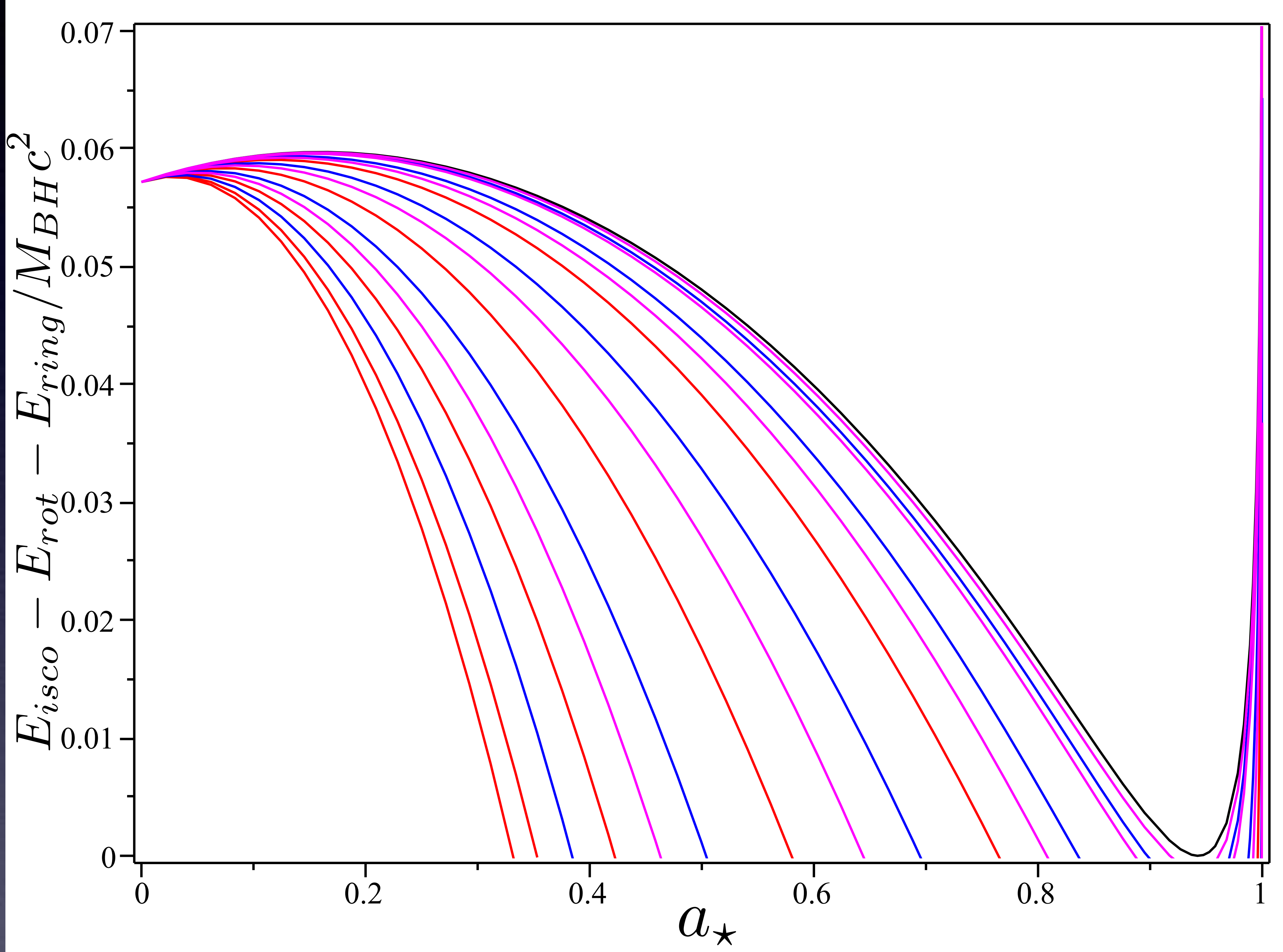
Kick the BH off center! (spin up, option 3)

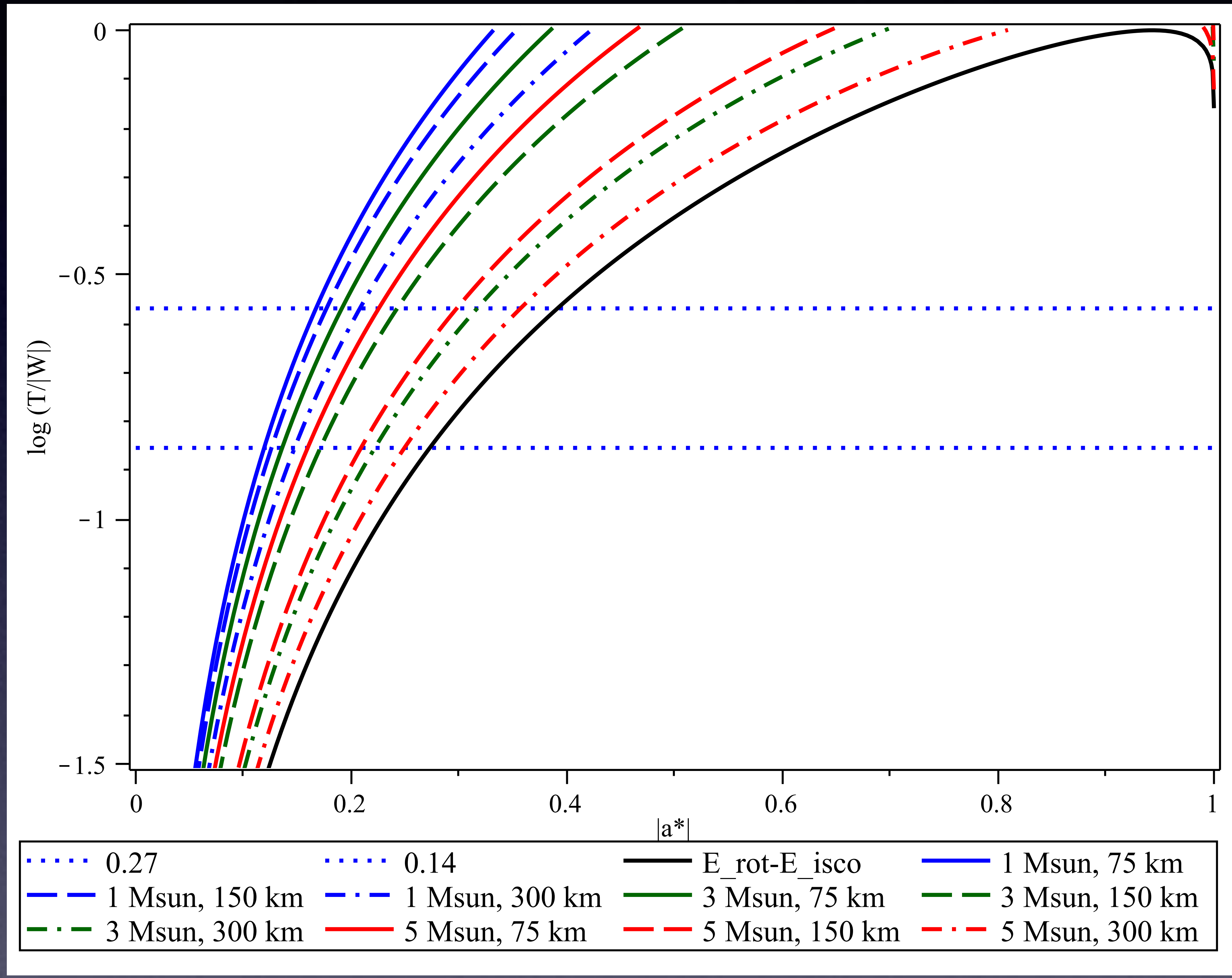
- A series of kicks? (Seems to work for NSs)
- A long single kick: SASI with m=1
- Conservation of E, J (It's a massive BH!)



Blondin & Mezzacappa, 2007.

Energy necessary to spin up a BH during CC with a SASI:

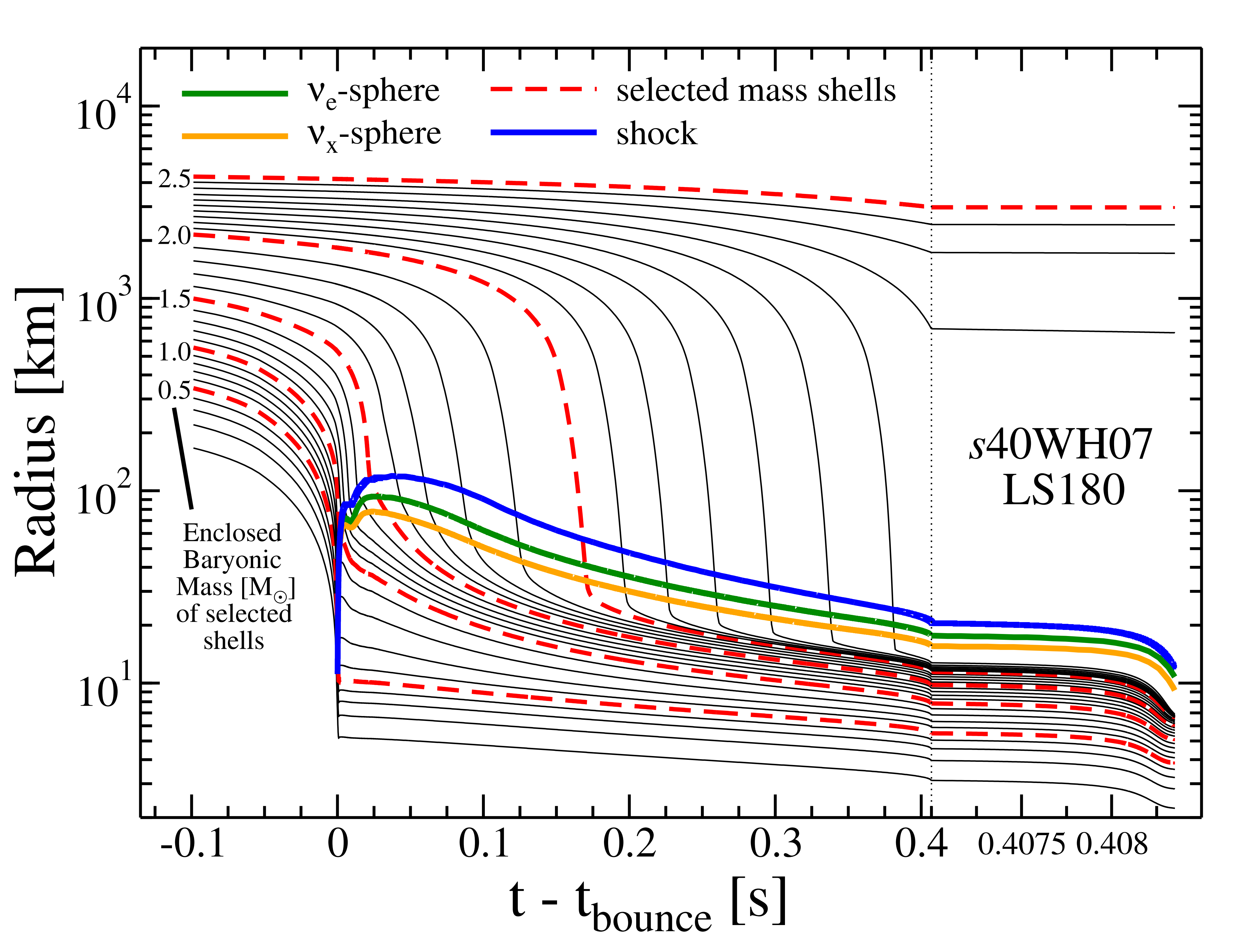




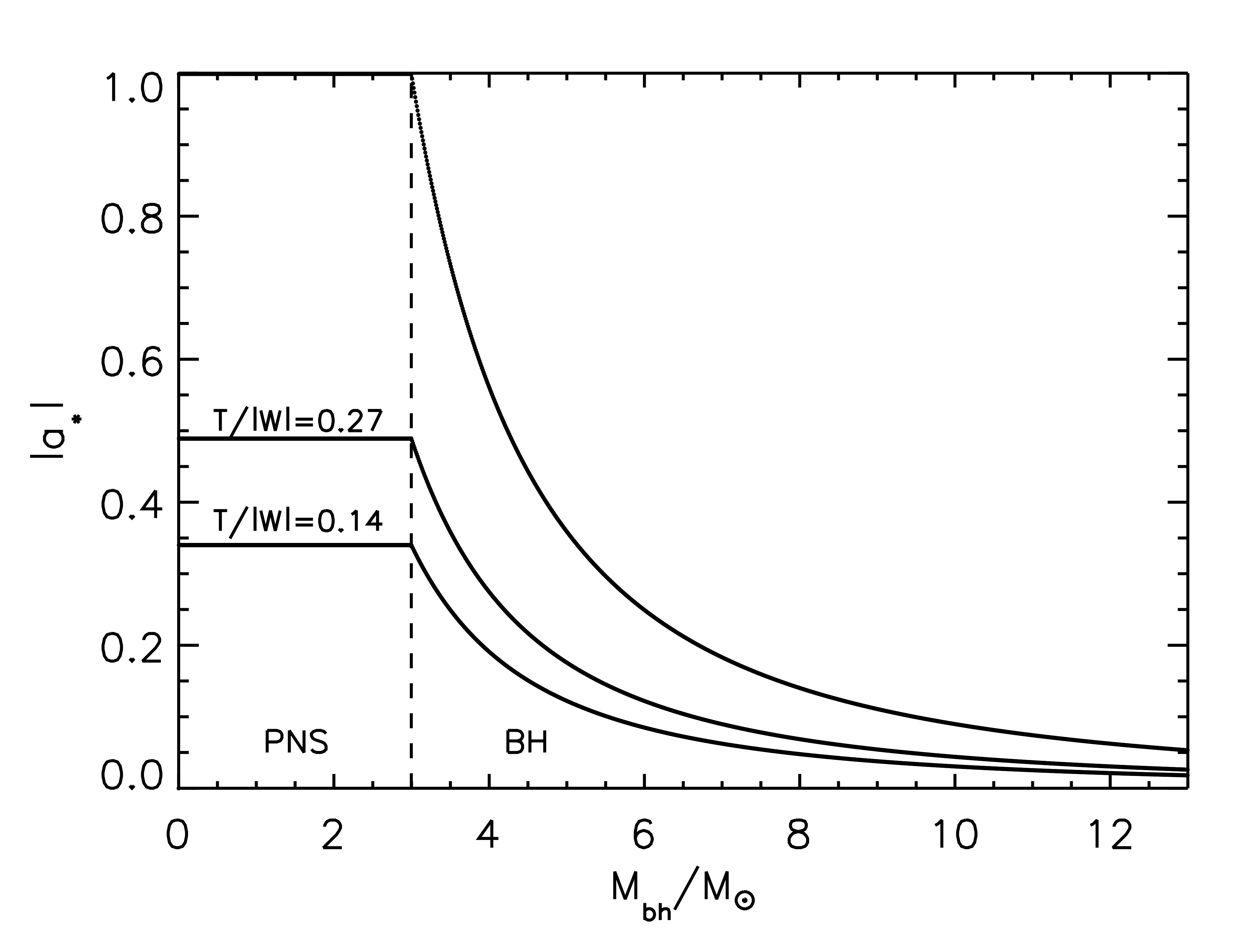
Moreno Méndez & Cantiello, 2016

- Discipation by GW production.
- T/|W| ~ 0.14 (secular instabilities) or
- T/|W| ~ 0.27 (dynamical instabilities).

Yet even more important...



O'Connor & Ott, 2011



Moreno Méndez & Cantiello, 2017

R_sasi ~100 km, is not a large lever arm.

Accretion after core collapse rapidly decreases a*.

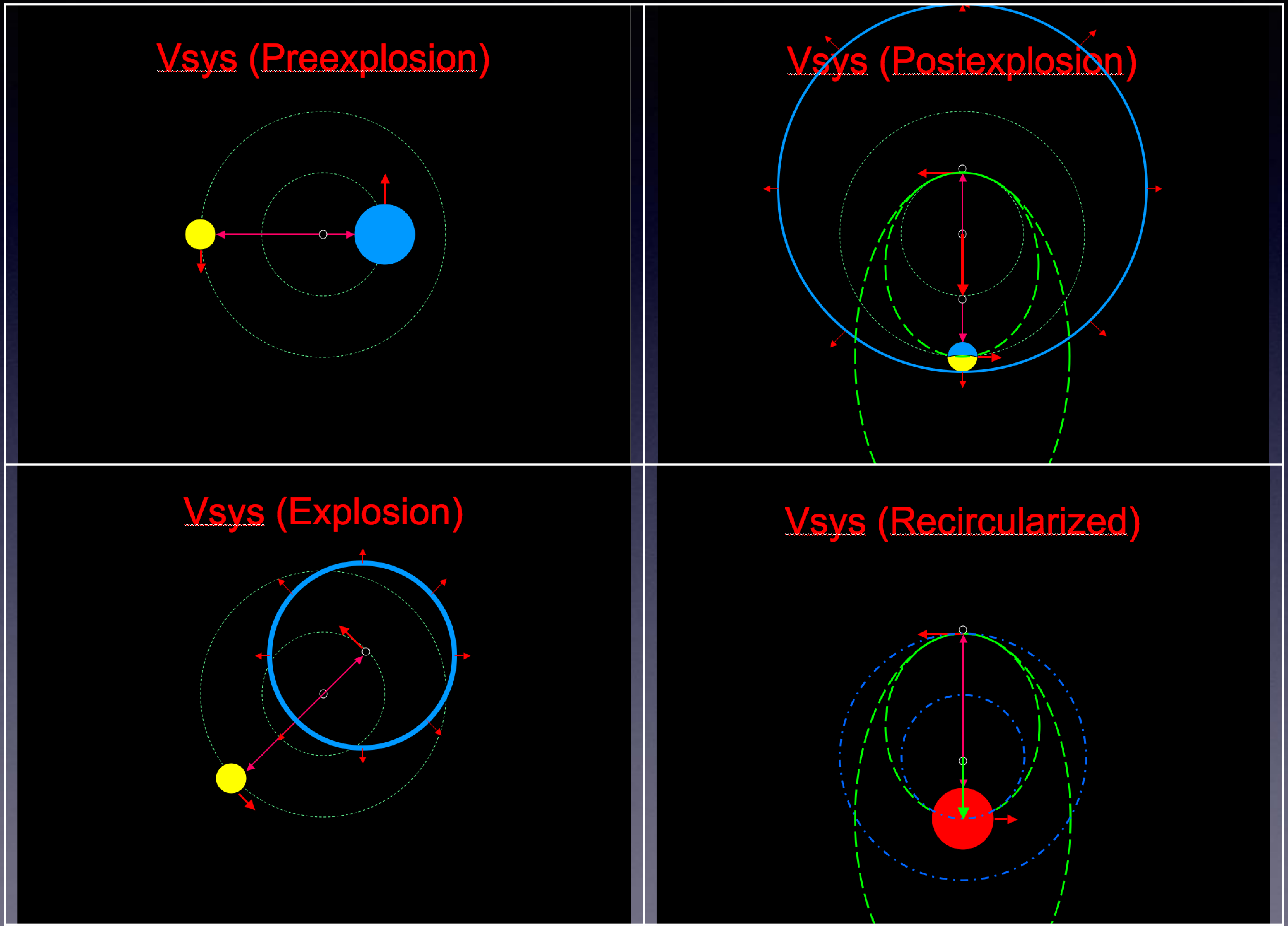
ULXs/HLXs

- RLOF, CE, and/or Grazing Envelope (GE) stages could radiate away with extreme luminosities (10e40 to 10e46 erg/s).
- This is the ULX or even HLX range.
- Most likely intermittent as the MT material is accreted or ablated away.
- A few months after 2207.14765 (MM 2022), confirmation came of Cyg X-3 being an off axis ULX (2303.01174; Veledina et al. 2023).

Observed dynamical properties of Cyg X-3

Parameter	Value	Relevant references
Distance	9.7 kpc	Reid & Miller-Jones 2023
L_X (ULX!)	$\sim 10^{40}$ erg/s	* MM 2022, Veledina et al. 2023
WR type	WN 4-5	Koljonen & Maccarrone 2017
WR mass *	$\sim$(11 - 14) $M_\odot$	Koljonen & Maccarrone 2017
BH mass	$<$10 $M_\odot$	Koljonen & Maccarrone 2017
P (days)	~ 0.2	Bhargava et al. (2017)
$\dot{P}$	$\sim 5.4 \times 10^{-10}$	Bhargava et al. (2017)
v_{pec}	$\lesssim 20$ km/s	Reid & Miller-Jones 2023

Blaauw-Boersma kick



$$P_2 = \left(1 + \frac{\Delta M}{M_{BH} + m}\right)^2 P_1$$

$$V_{Sys} = \left(\frac{\Delta M}{M_{BH} + m}\right) V_{He}$$

Dynamical properties of Cyg X-3

Parameter	Value	Relevant references
Distance	9.7 kpc	Reid & Miller-Jones 2023
L_X (ULX!)	$\sim 10^{40}$ erg/s	* MM 2022, Veledina et al. 2023
WR type	WN 4-5	Koljonen & Maccarrone 2017
WR mass *	$\sim$(11 - 14) $M_\odot$	Koljonen & Maccarrone 2017, MM 2024
BH mass	$\sim$14 $M_\odot$	MM 2024
P (days)	~ 0.2	Bhargava et al. (2017)
$\dot{P}$	$\sim 5.4 \times 10^{-10}$	Bhargava et al. (2017)
v_{pec}	$\lesssim 20$ km/s	Reid & Miller-Jones 2023
$a_\star$	~ 1	MM 2024
E_{rot}	$\sim$5,000 bethe	MM 2024

Work in progress: MM 2024

Conclusions:

- Mass loss to 1st SN restricted to less than a couple solar masses.
- 1st-BH in Cyg X-3 mass more than doubled, spin brought from $a^* \sim 0$ to $a^* \sim 1$ by accretion.
- WRs are expected to form a 2nd BH with $a^* > 0.5$: lGRB/HN !!
- Binaries could survive HN explosion if 1st BH is, indeed, massive and $P << 1$ day; if so, GW merger candidates.
- WR-HMXBs are likely progenitors of lGRB/HN if $P < 1.5$ day.
- Goldilocks: Probably luminous to sub-luminous.
- 3 to 4 known candidates nearby.

Work in progress: MM 2025

Thanks!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- Reconstructing the pre-explosion orbits in BH binaries allows for an estimation of the Kerr parameter of the BH at the time it was formed.

- Angular momentum extracted to power a GRB/HN may reduce this value.

- Accreting mass from the companion may increase the observed value.