From GRBs To BH Binaries

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9/05/2012

Image credit: Zhang, Woosley

Outline

- Collapsar model (and its requirements)
- Binary evolution
- Energetics (Blandford-Znajek)
- BH binaries
- GRB relics & energies
- Massive BH binaries
- SASIs
- Conclusions

Collapsars

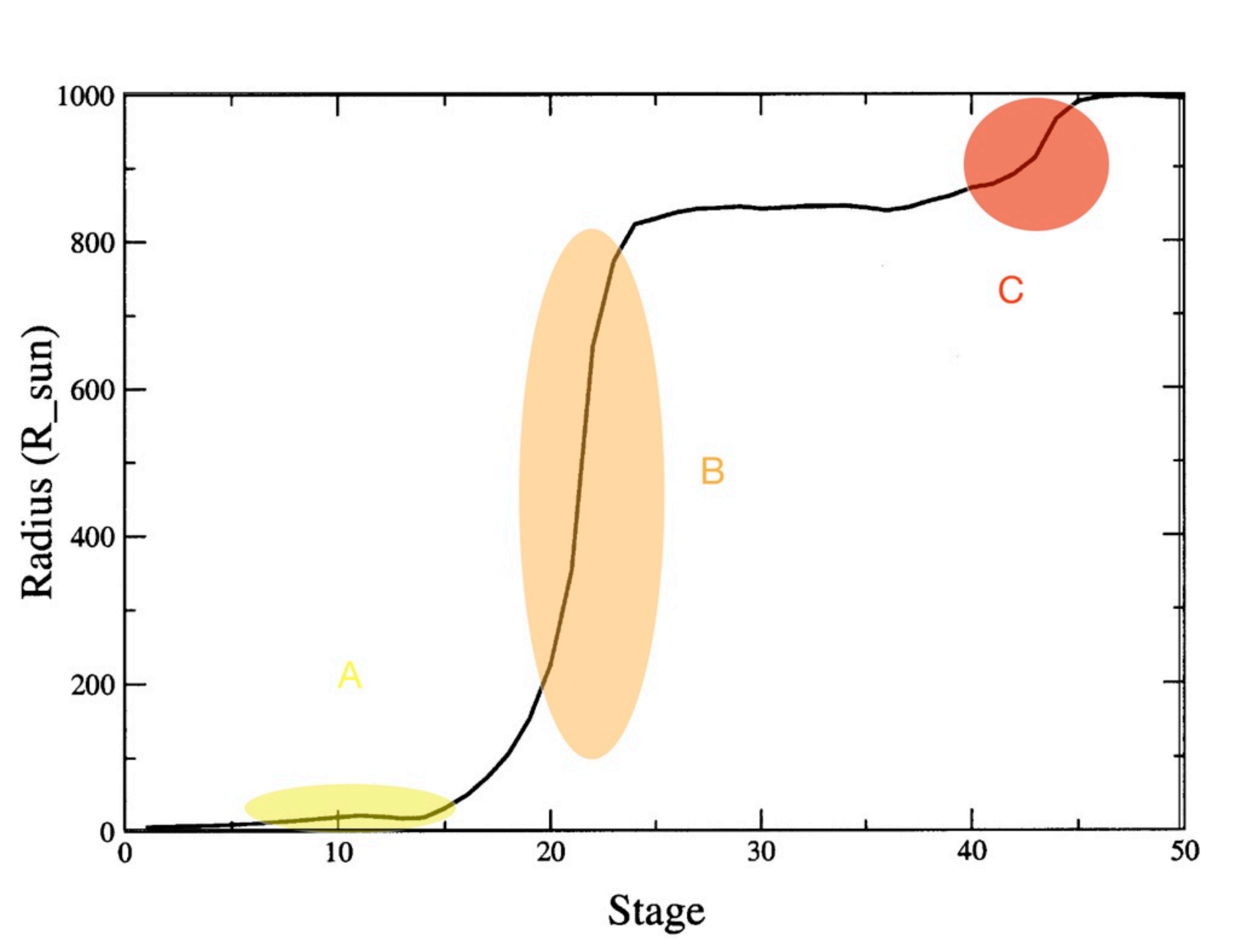
GRBs from Collapsars

- $E_{HN} \geq 30$ bethes
- $V_{HN} \sim 30{,}000$ km/sec
- Type Ic (bl) HN assoc. to GRBs
- Wolf-Rayet progenitor
- High angular momentum (to form accretion disk)
- Strong magnetic field

Binary evolution

Binary evolution

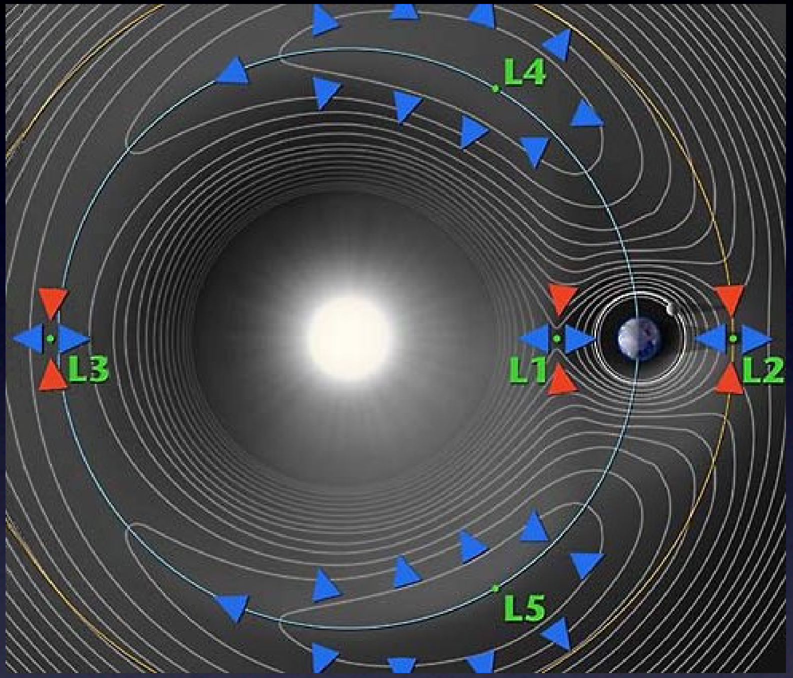
- BH Progenitor (primary): 20 Msun < Mzams < 40 Msun
- Let the star evolve as a single star, to guarantee a massive core ⇒ BH.

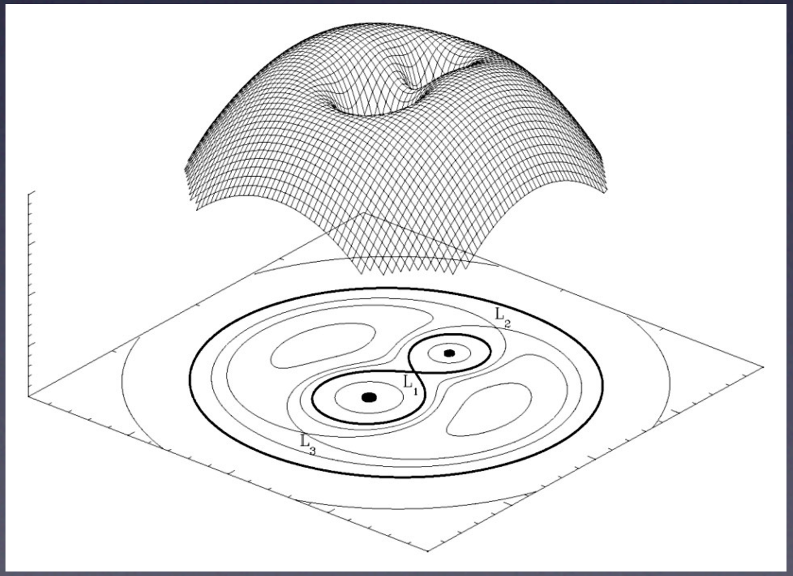


Case C mass transfer!

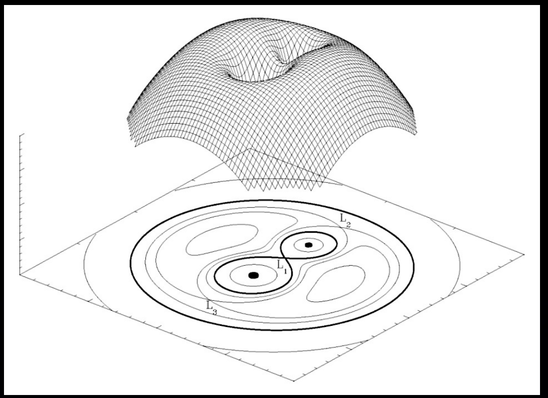
Roche Lobe Overflow

RLOF occurs when material from the star reaches the equipotential where the star's gravity is balanced by the companion's gravity and the centrifugal force.





Case C mass transfer



- RLOF ⇒ Common Envelope:

a_i ~ 1,500 R_{Sun} ⇒ a_f ~ few R_{Sun}.

- H envelope removed very late ⇒Massive WR star.

- Tidal synchronization provides a large amount of angular momentum late enough so it will not be lost to winds.
- Lower mass companions will fit in tighter orbits ⇒

more J into primary ⇒ large a_* BH.

Energetics

Energetics

- Spinning BHs contain a large reservoir of energy:

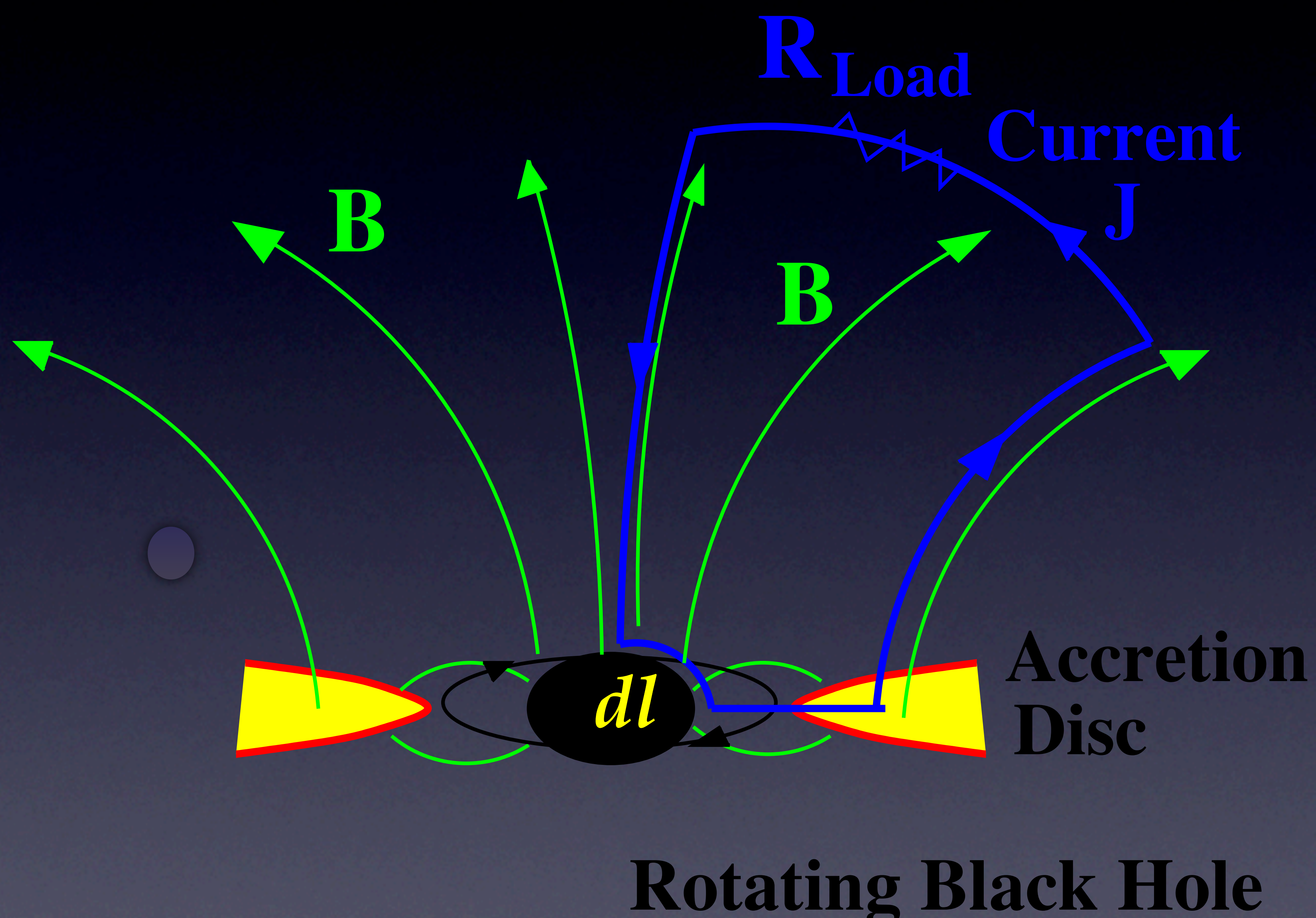
$$E_{rot} = f(a_*) M_{BH} c^2 ,$$

$$f(a_*) = 1 - \sqrt{\frac{1}{2}\left(1 + \sqrt{1 - a_*}\right)}$$

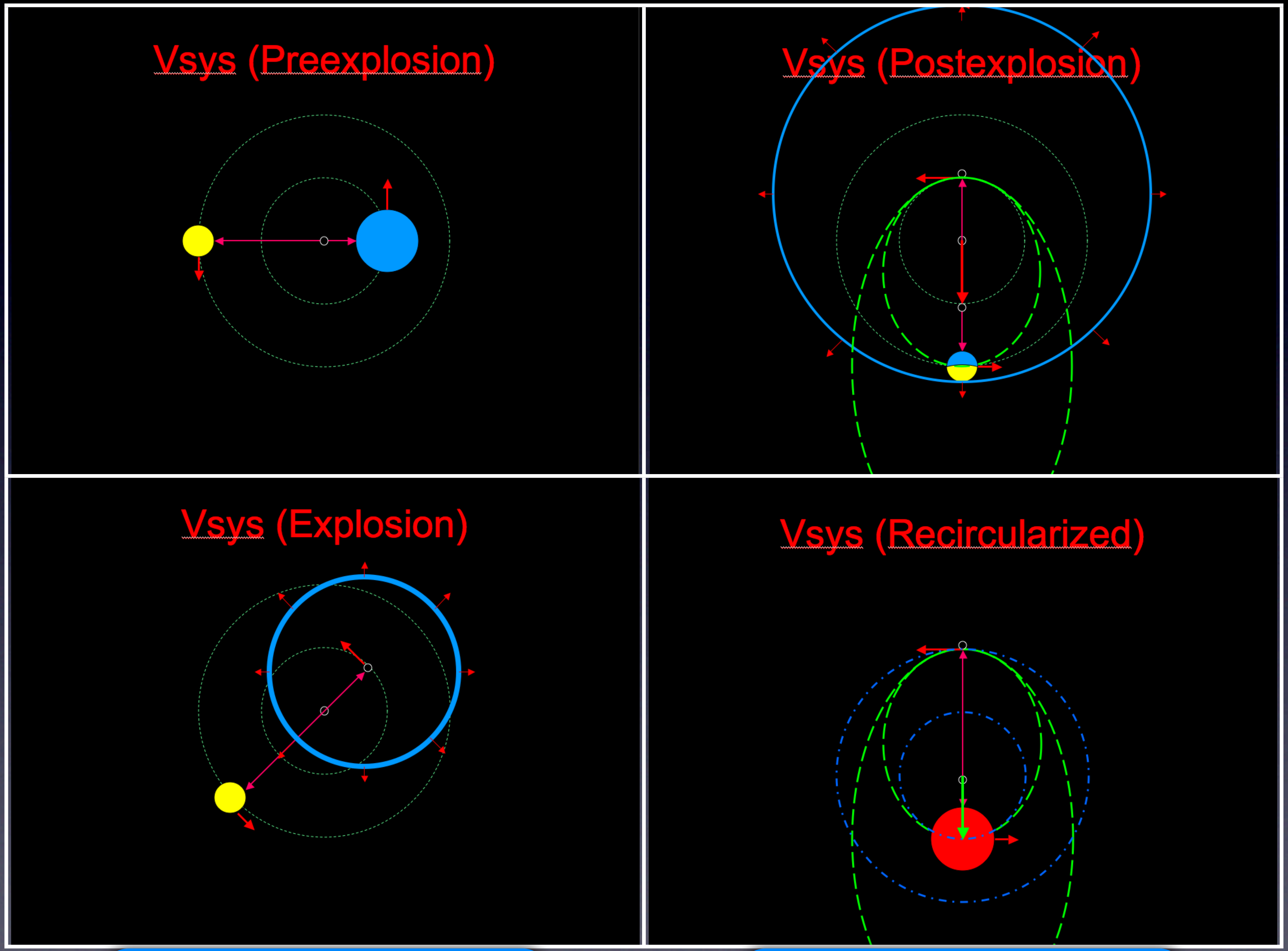
- GRBs, HNe, Jets can tap this energy through Blandford-Znajek mechanism:

$$E_{BZ} = \varepsilon_{\Omega} \frac{E_{rot}}{M_{\odot} c^2} \times 1{,}800 \ \textit{\textbf{bethes}}$$

Blandford-Znajek



Blaauw-Boersma Kicks



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

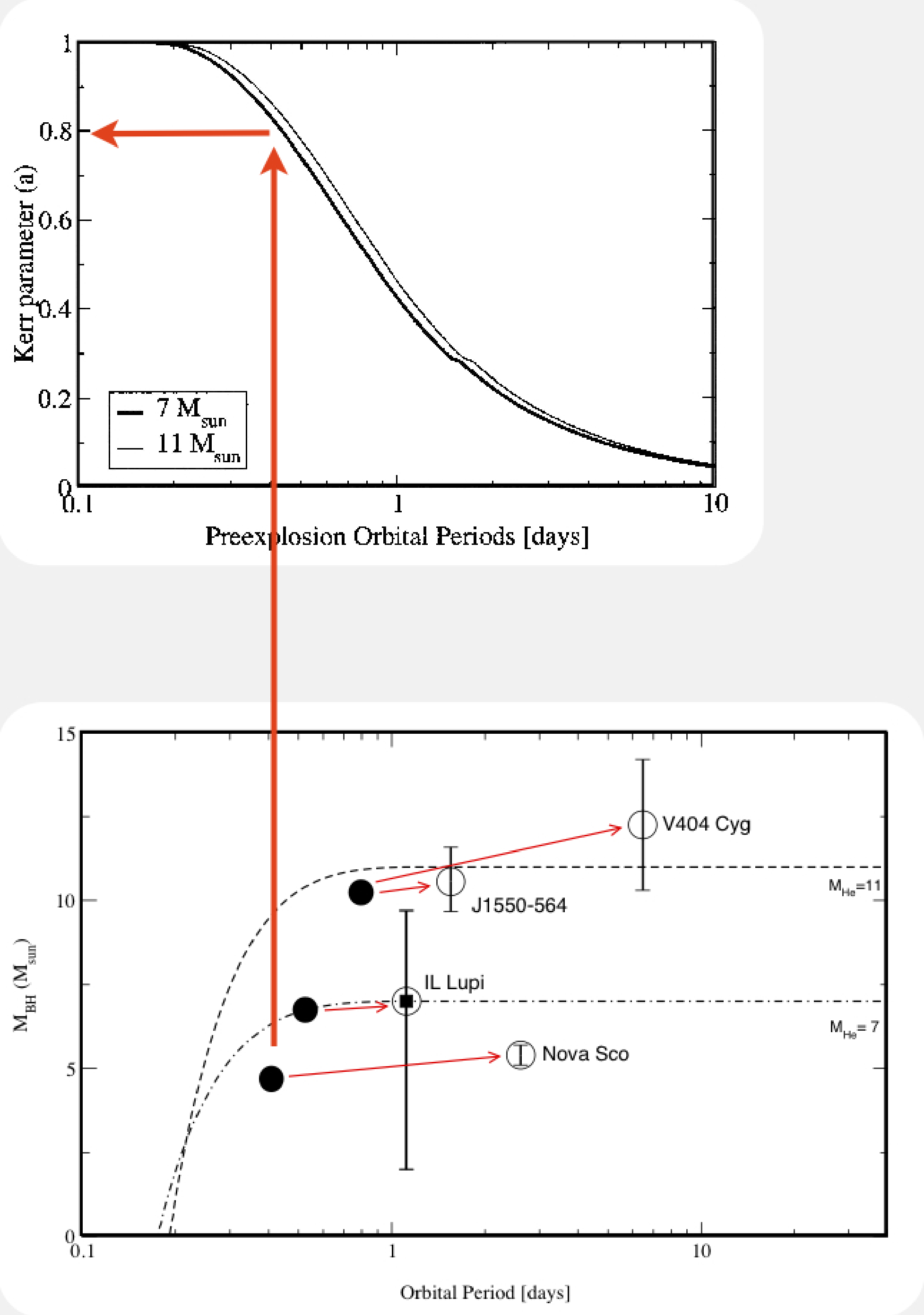
$$V_{Sys} = \left(\frac{\Delta M}{M_{BH} + m}\right) V_{He}$$

BH binaries

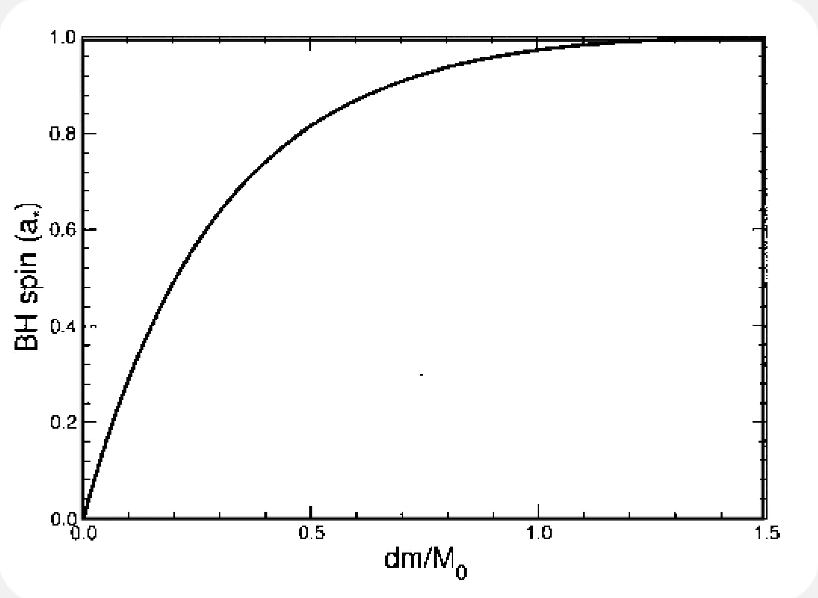
BH binaries

- ~ 15 "well known" Galactic sources.
- 3 extragalactic sources.
- 8 have Mstar < 1-Msun companions (hard to model).
- 7 have ~2-Msun companions (good candidates).
- 3 have Mstar > 10-Msun companions (little J).

Post SN Binary evolution



- 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.



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	$3 - 11$

GRB relics & energies

Some Galactic BHs

Name	M_{BH}	M_{Sec}	P_{orb}	a_*	E_{BZ}
4U 1543-47 Il Lupi	2-9.7	1.3-2.6	1.12	0.75-0.85	~430
GRO J1655-40 Nova Sco 94	5.1-5.7	1.1-1.8	2.61	0.65-0.75	~430
XTE J1550-564	9.7-11.7	0.96-1.64	1.55	0.3-0.6	~300
LMC X-3	5-11	4-8	1.70	~0.3	~150

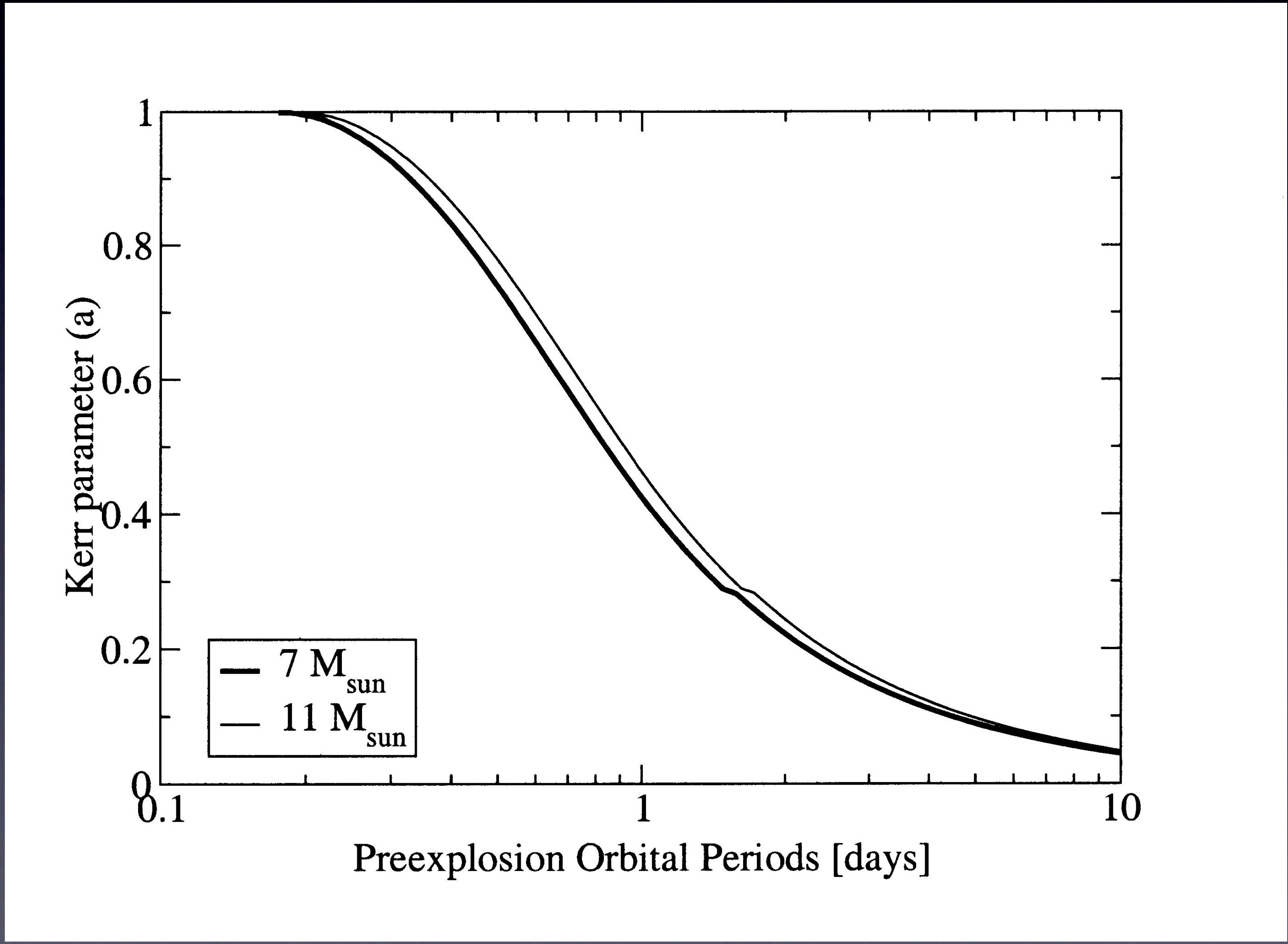
3 BHs where the spin has been measured and matches the predictions. Mass is expressed in Solar masses, orbital period in days, the Kerr parameter is unitless and the available Blandford-Znajek energy is in Bethes.

Massive BH binaries

When the stars don't fit in their orbit!

Name	M_{BH}	M_{Sec}	P_{orb}	a_*	E_{BZ}
Cyg X-1	14.8(1)	19.2(1.9)	5.60	>0.97	5-6
LMC X-1	10.8(.84)	30.6(3.2)	3.91	0.91(6)	<2
M33 X-7	15.6(1.4)	70(6.9)	3.45	0.84(5)	3-11

P_{orb} vs a_*

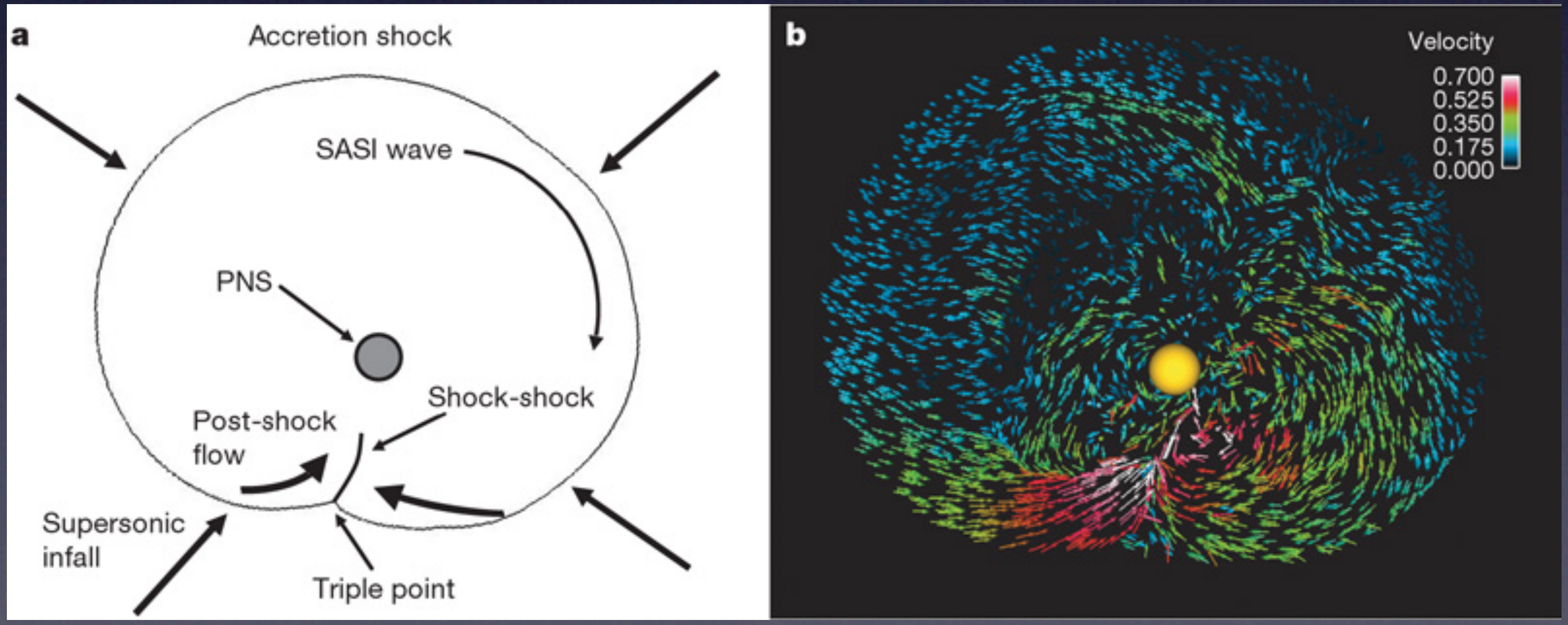


1
0.8
0.6
0.4
0.2
0
0.1
1
10
Kerr parameter (a)
Preexplosion Orbital Periods [days]
7 M_sun
11 M_sun

Alternative?

Kick the BH off center!

- 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.

Does it solve the problem?

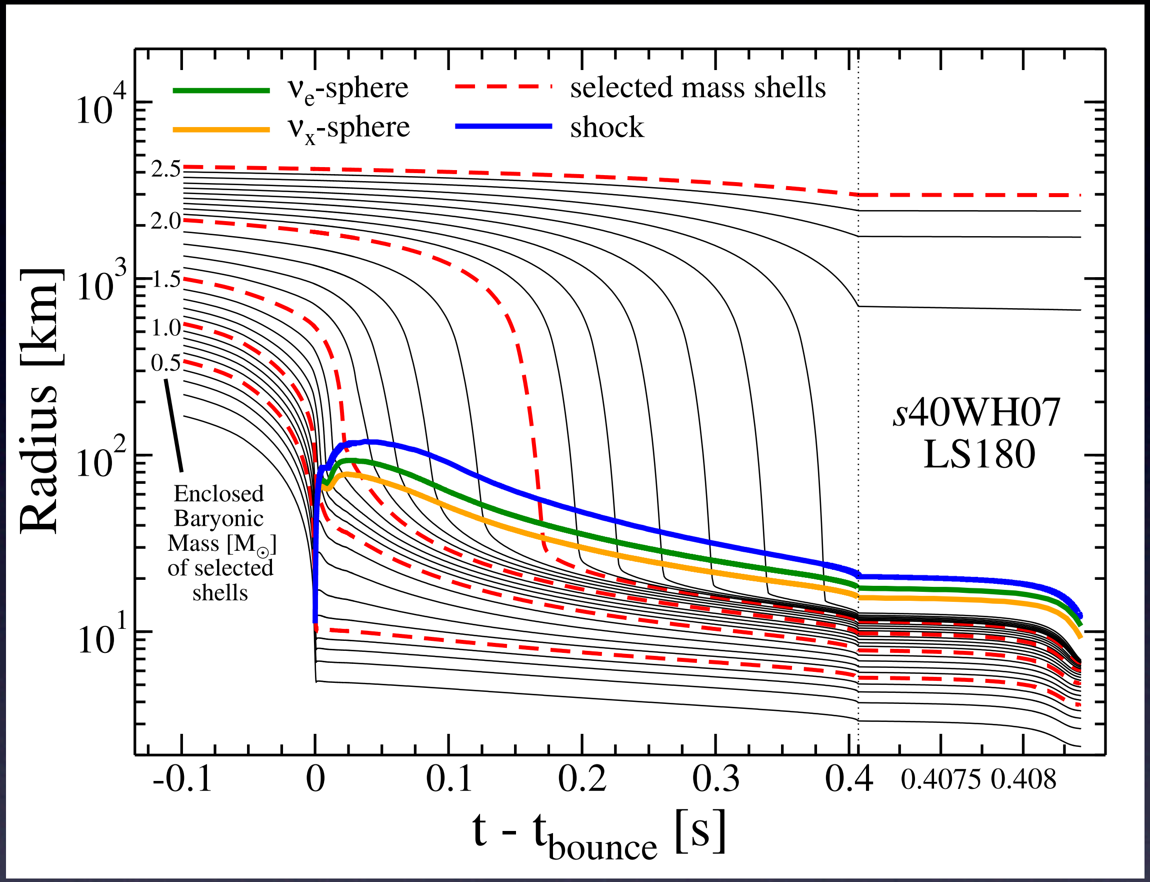
However...

- We're still missing E_{ring}.....
- E_{ring} depends on I_{ring} and ω^2.
- Material in the ring easily becomes relativistic if (a) the ring has little mass and if (b) its radius is small.

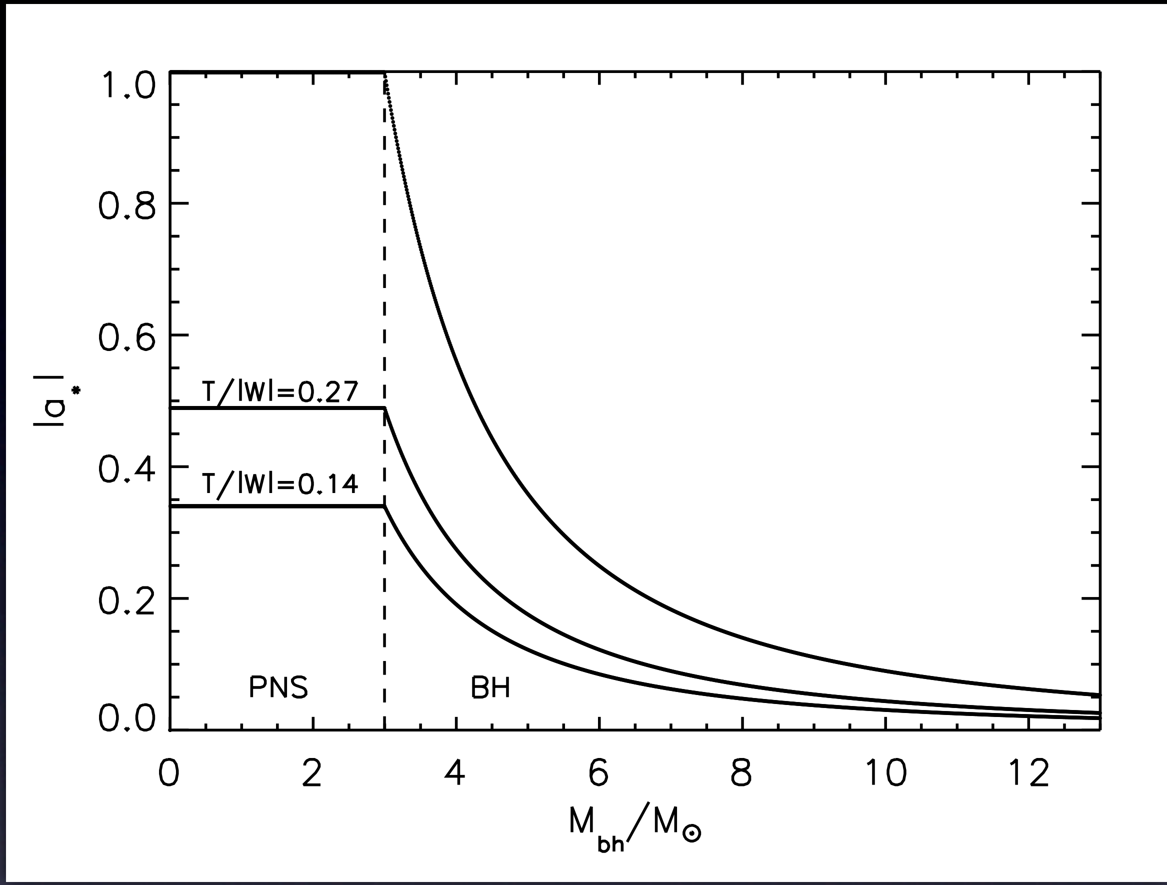
However # 2

- So far we have assumed 100% energy conversion efficiency!
- Unlikely.

Furthermore...



O'Connor & Ott, 2011



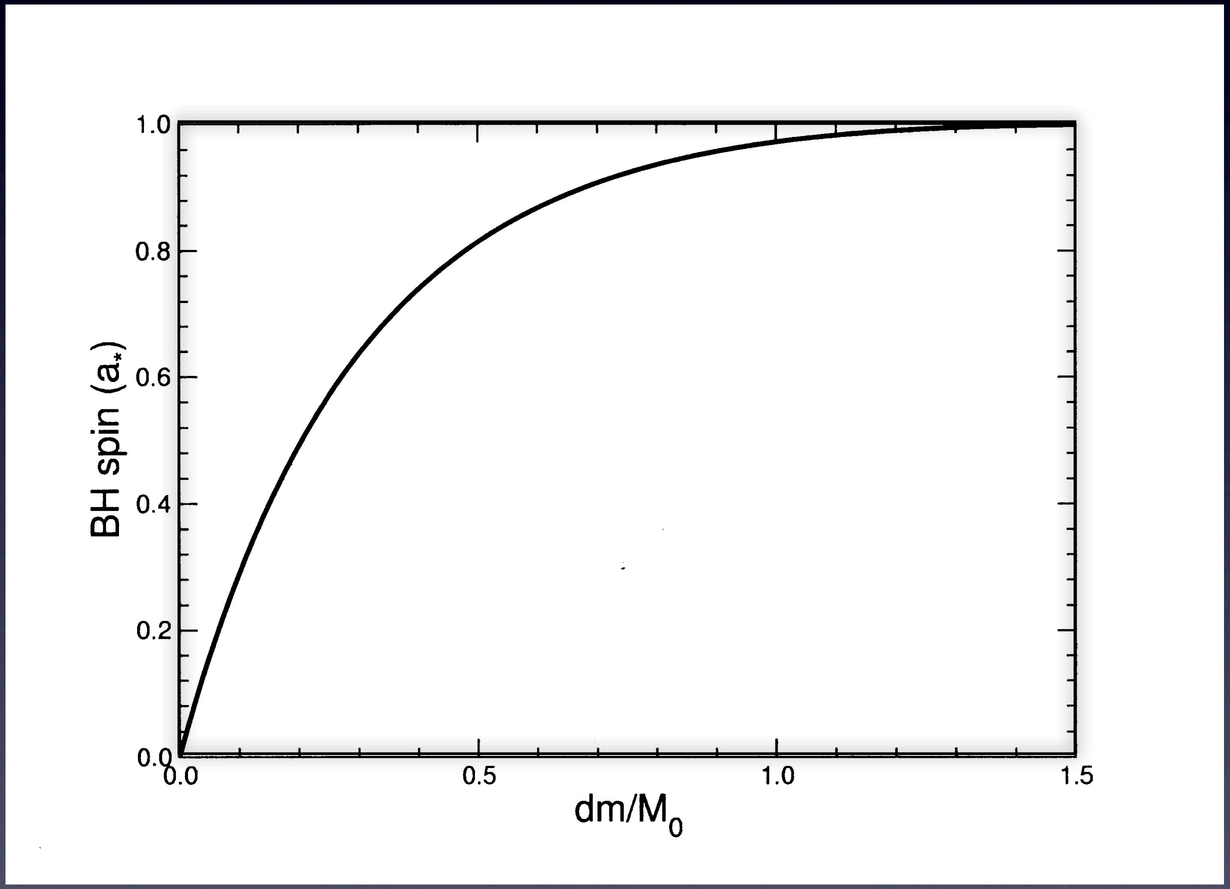
R_sasi~100 km, not a large lever arm

Further mass accretion lowers a*

Alternate alternatives...

Accretion onto the BH

- Hypercritical accretion?
- Super-Eddington accretion?
- We need wRLOF mass transfer.



Wind RLOF

- If $M_{comp} > M_{BH}$, mass transfer shrinks a_{orb}. Also as the star losses mass, R_{comp} grows. RLOF leads to unstable mass transfer.
- Companion star filling large part of its RL.
- BH at $a_{orb} \lesssim 2\ R_{comp}$.
- Winds, not fully accelerated at RL surface ($V_w \lesssim 500$ km/s as opposed to $V_w \sim 3000$ km/s), become focused in L1 towards BH.
- $V_w \sim V_{orb}$ efficient wind RLOF mass transfer.

Eddington Limited Accretion

- Eddington luminosity for Bondi accretion (spherically symmetric):

$$L_{\mathrm{Edd}} = \frac{4\pi G M_{BH} m_p \mu_e c}{\sigma_T}$$

- Thus, a maximum accretion rate can be identified:

$$\dot{M}_{Edd} = \frac{L_{Edd}}{c^2} = \frac{4\pi c R}{\varkappa_{es}}$$

In general, if the accretion rate grows, L increases and self-regulates the accretion rate to a value below the Eddington limit.

- Hence, for a 10 M_{Sun} black hole we obtain:

$$\dot{M}_{BH,Edd} \approx \frac{10^{18}\ cm^2\ s^{-1}}{0.4\ cm^2\ g^{-1}} \approx 3 \times 10^{-8}\ \frac{M_{Sun}}{yr}$$

Hypercritical Accretion

- Dump material on desired BH.
- Trap photons emitted at R_{ph}.
- Form Standing Accretion Shock at $R_{sw} < R_{ph}$ with T~ 1 MeV.
- Photons are advected with mater, neutrinos remove energy.
- Accretion rate above: $\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{Edd}} \approx 3 \times 10^3$

Conclusions (1)

- Case C mass transfer seems to be essential for producing Collapsar GRBs (however see Case M).
- Tidal locking & strong B fields are necessary.
- BH binaries seem likely candidates of long GRBs (subluminous & cosmological)

Conclusions (2)

- 14 Galactic sources of subluminous lGRB / HN explosions.
- LMC X-3 likely formed from a cosmological lGRB / HN.
- 3 likely sources of "dark explosions".

Conclusions (3)

- SASIs do not seem to explain known spins of BHs in HMXBs.
- Neither do binary pre-BH-formation stellar evolution models.
- Evidence points to post-BH-formation spin up scenario.

Selected references

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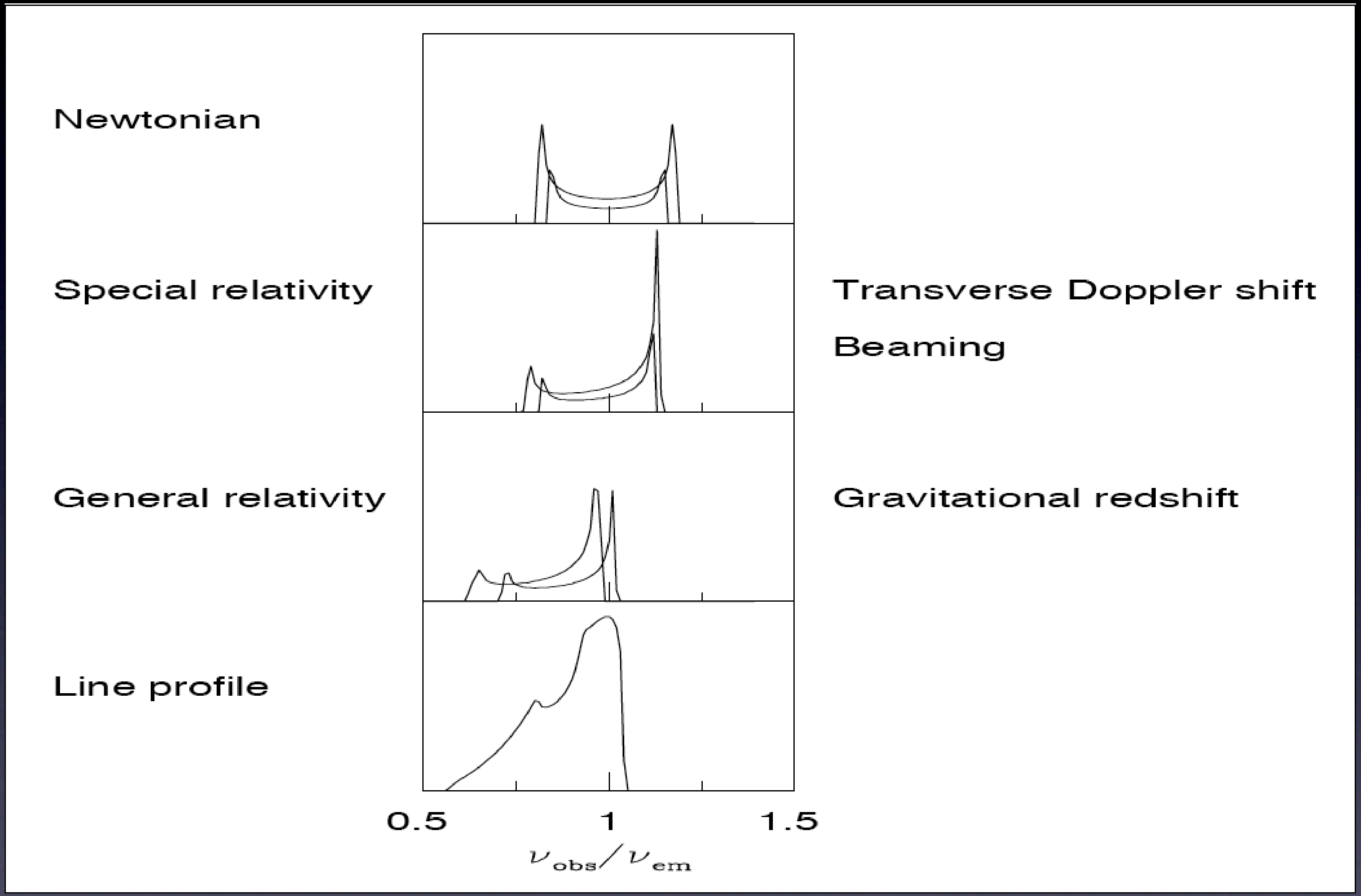
Measuring a*



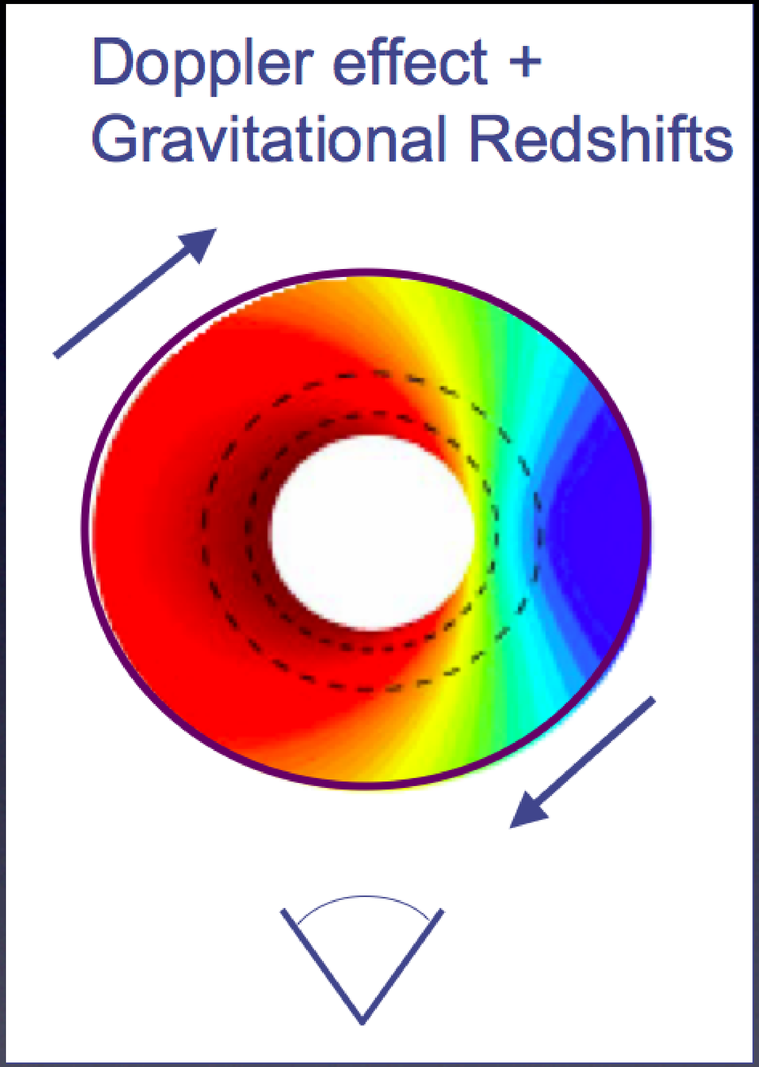
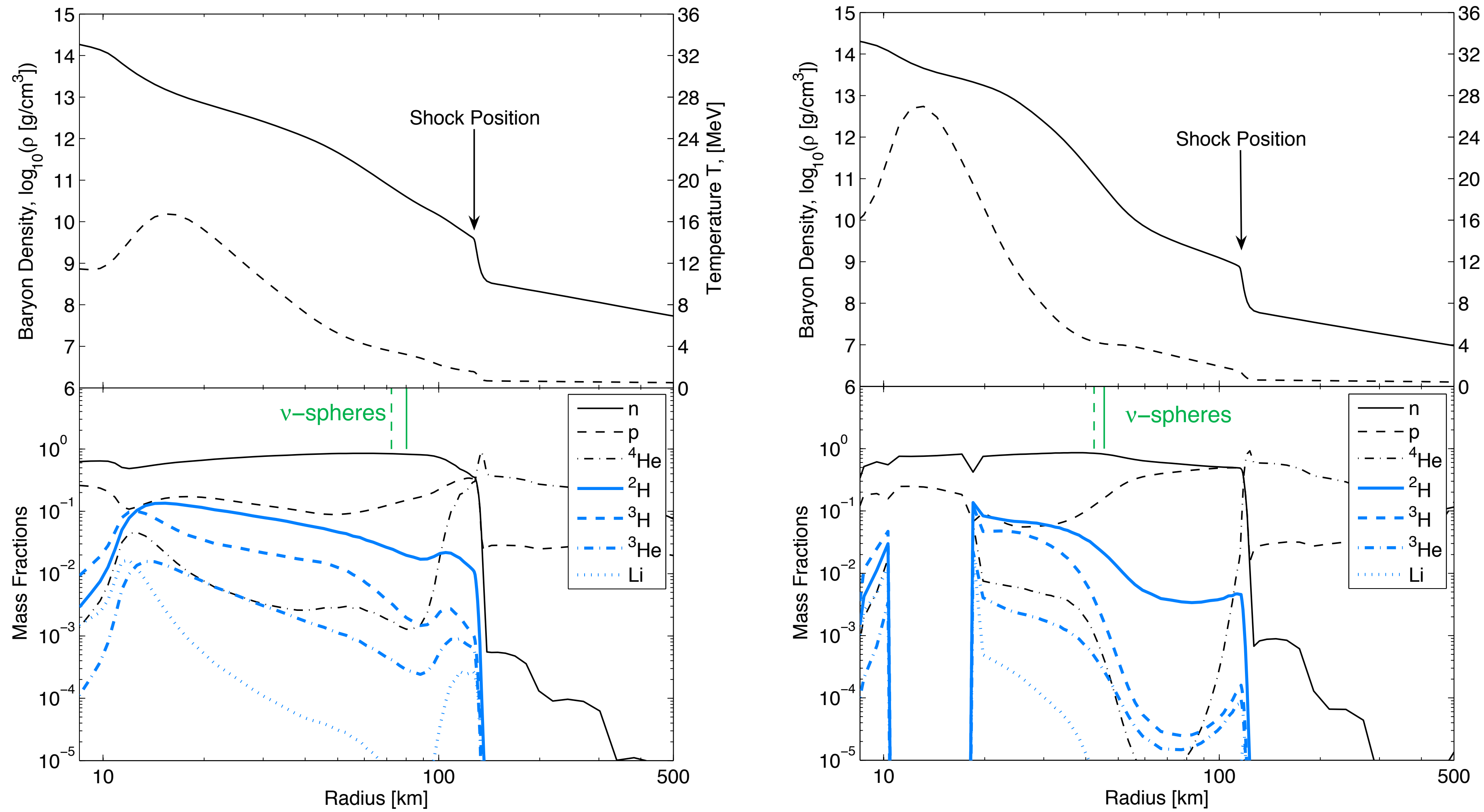


Image: Fabian & Miniutti, 2005, astro-ph/0507409v1.

Shock wave radii



(a) 50 ms post bounce (b) 200 ms post bounce

Radial profiles of the baryon density (solid lines) and the temperature (dashed lines) in the top panels and the corresponding NSE composition (bottom panels) at two selected post-bounce times for the 15 $M_\odot$ progenitor model from Woosley and Weaver (1995) using the HS (TM1) EOS. The green vertical lines denote the position of the neutrinospheres for ν_e (solid lines) and for $\bar{\nu}_e$ (dashed lines).

Hempel, Fischer, Schaffner-Bielich & Lienendoerfer 2011