Binary Models for Long-Duration GRB Progenitors

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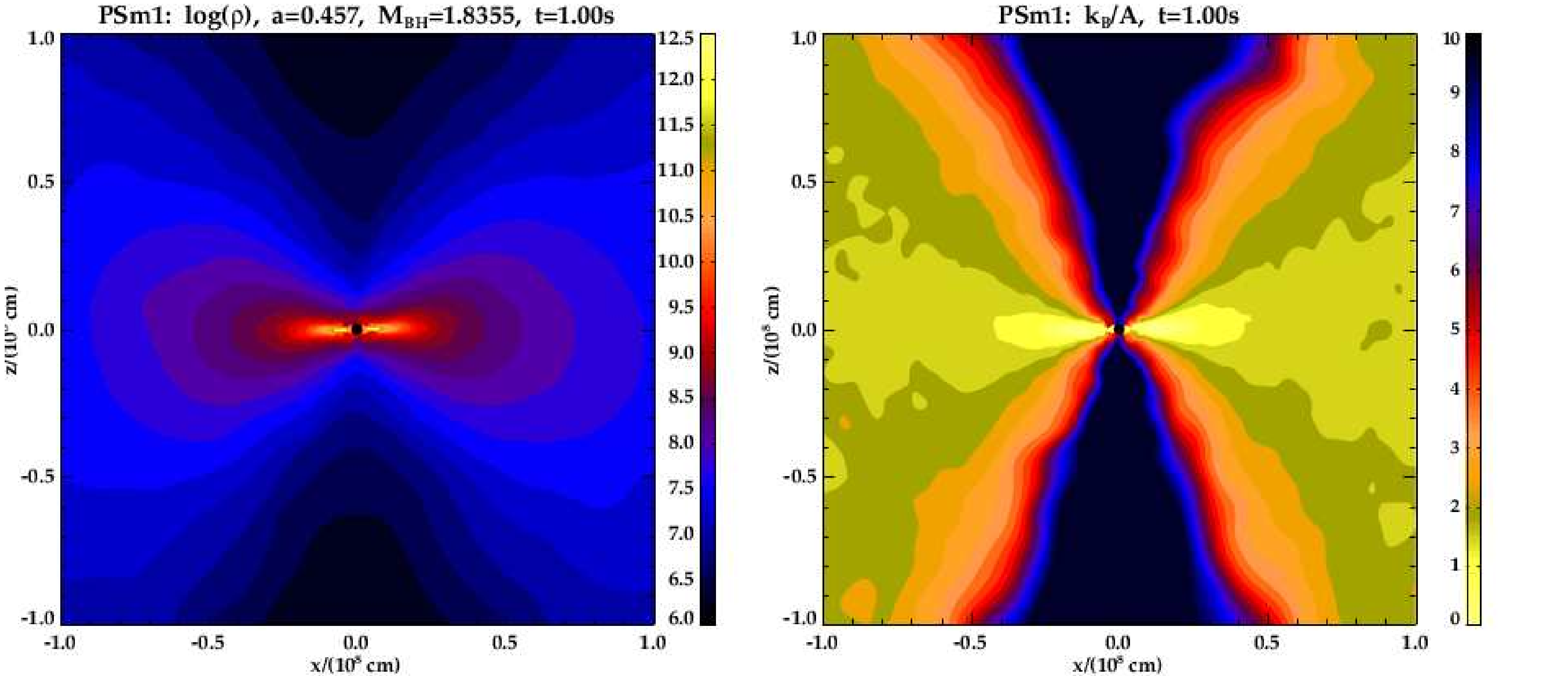
- Gamma-ray bursts (GRBs) are rare events that require a rare evolutionary channel
- the popular collapsar model requires rapidly rotating progenitors

→ binary evolution

The Collapsar Model

(Woosley 1993; MacFadyen & Woosley 1999)

- long-duration GRBs are associated with the collapse of a rapidly rotating core/star without hydrogen envelope
- efficiently extract rotational energy (i.e. BH/NS binding energy)
- key: rapid rotation
- also applies to magnetar spin-down models (e.g. Bucciantini, Quataert, Thompson 2008/09)



Taylor, Miller & Podsiadlowski (2010)

The Progenitors of long-duration GRBs

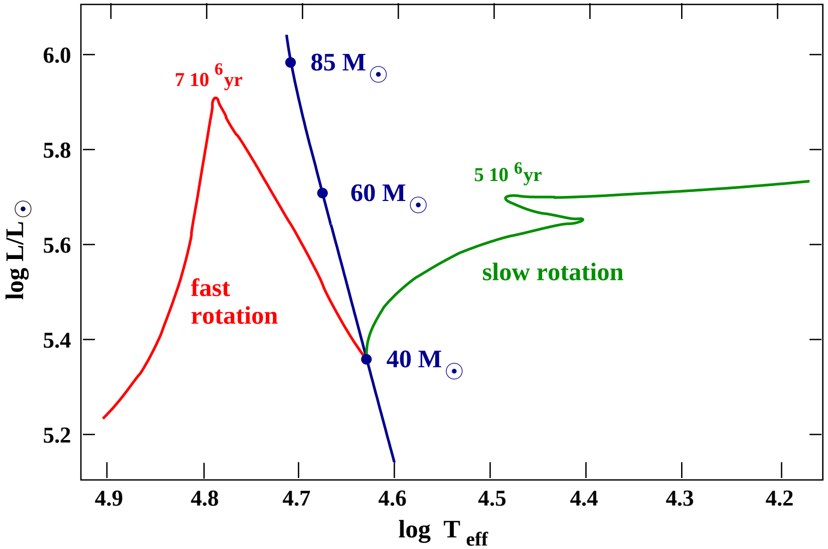
- GRBs are rare events! (Podsiadlowski et al. 2004)
  - ▷ rate of long-duration GRBs: $\sim 10^{-5}\,\mathrm{yr}^{-1}$/galaxy or 1 in 1000 core-collapse supernovae (cf. Ghisellini's talk)
  - ▷ comparable to hypernova (HN; broad-line SN Ic) rate!

  → GRBs require very special evolution/ circumstances (i.e. not just single massive stars, but stars that are special; i.e. rotation/low Z; binarity)
- the HN-GRB relation is not necessarily 1-to-1
  - ▷ failed jet break-out → HN without GRB
  - ▷ no radioactive Ni → GRB without HN
- all HNe to date are SNe Ic, i.e. have lost both their H and He envelopes (clue?)

The GRB Progenitor Problem

- most models require a rapidly rotating progenitor core
- massive stars lose angular momentum very efficiently by hydrodynamical (winds) and MHD processes
  - ▷ consistent with obervations of the Sun, young NSs/WDs
- possibe solutions: either find paths where stars keep their angular momentum or use other sources (binary orbital angular momentum!)
- low metallicity may be helpful in most models (weaker wind, case C mass transfer)
  - ▷ some weak evidence for metallicity dependence of GRBs (typical GRB host galaxy is the LMC with $Z = 1/2\,Z_\odot$; Fruchter 2006; Wolf & Podsiadlowski 2007)
  - ▷ NB: recent observations cast some doubt on this

Single-Star Idea



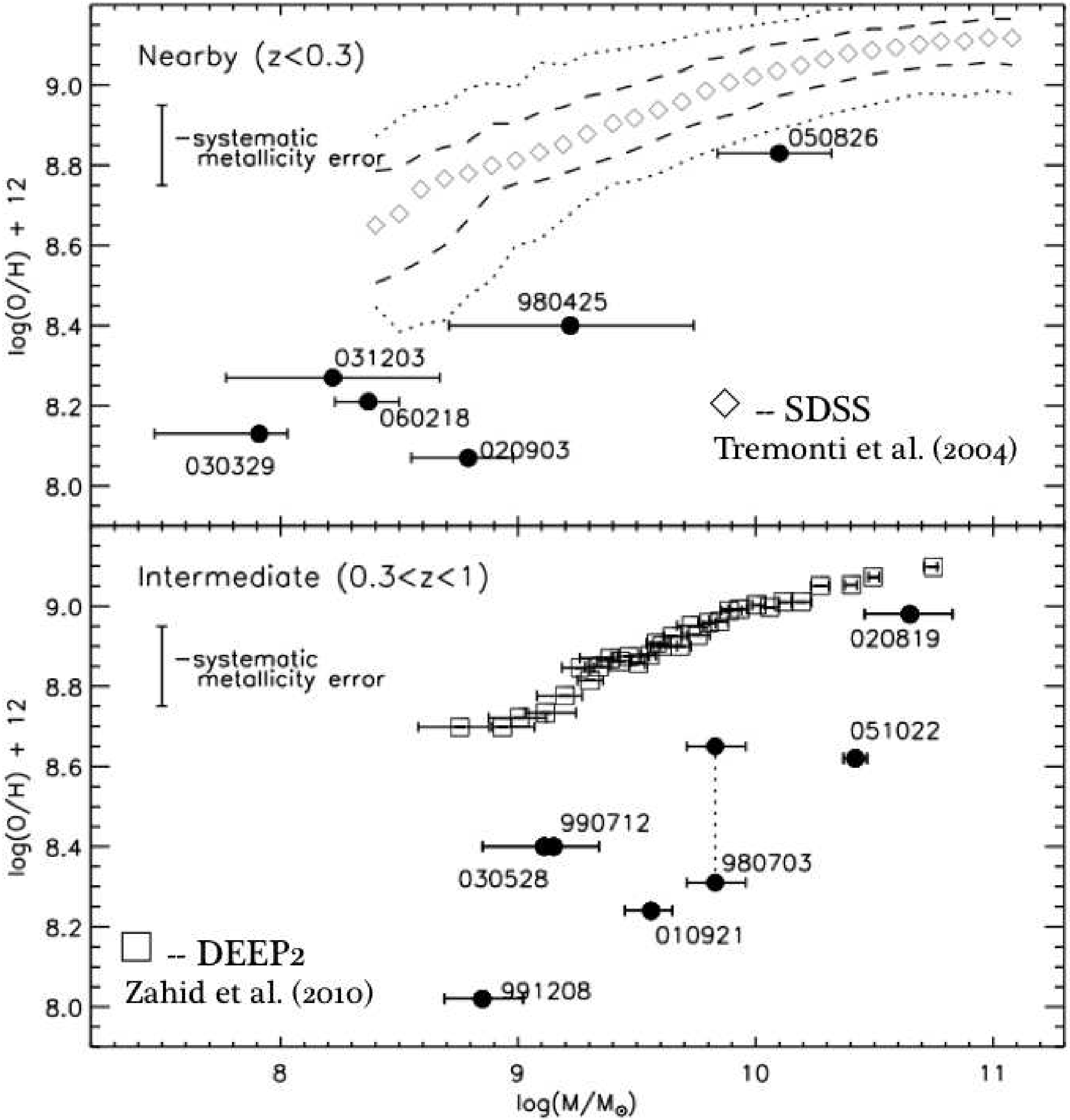
Maeder (1987)

- homogeneous evolution model (Yoon & Langer 2005; Woosley & Heger 2006)
- requires rapid rotation and low metallicity ($Z \lesssim 0.2\, Z_\odot$) $\rightarrow$ little mass loss $\rightarrow$ little angular-momentum loss
- fast rotation: models evolve homogeneously

$\rightarrow$ predicts: GRBs prefer low Z

Problems:

- GRBs are found in high-Z hosts (see talks by Elliott; Levesque)
- model predicts large amounts of He in ejecta: not observed (can rule out more than a few $0.1\, M_\odot$ of He; Hachinger, Mazzali, ... 2012)
- jet break-out in extended envelope?



Levesque (2010)

Binary Models

- most stars are members of binary systems
  - ▹ the majority of massive stars are members of interacting binaries

  Sana et al. (2012):

  75 % for O stars with $M \gtrsim 15\,M_\odot$

- the binary orbit provides a copious supply of angular momentum

Problems (similar to single stars)

- binaries are also subject to wind and angular-momentum loss (low Z preferred, though not necessary)
- removal of He easier, but not guaranteed

Solution?

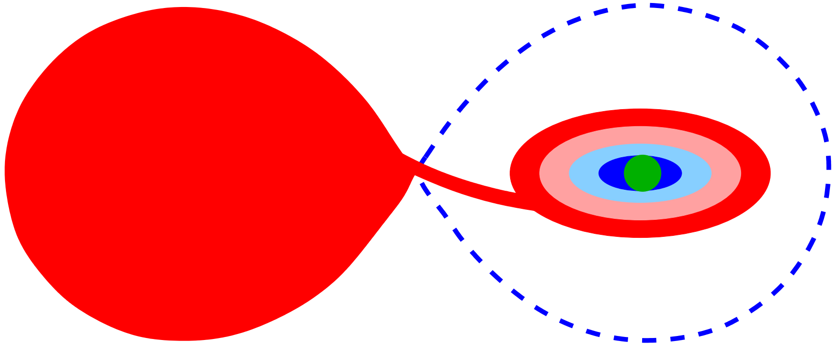
- late mass transfer preferred (after He core burning; case C)
  - ▹ little time ($\lesssim 10^4$ yr) to spin down after binary interaction

  → short WR phase

  → CSM: compact ionized wind bubble

- metallicity bias: rate of case C MT increases with lower Z! (Justham & Podsiadlowski 2012)

Tidal Spin-Up Models



- in close binaries, tidal interactions can spin up progenitor (e.g. Izzard et al. 2004; see talk by Church)
- requires $P_{orb} \lesssim 10\,\mathrm{hr}$
- primary most likely compact object (neutron star or black hole)
- system resembles Cyg X-3 ($P_{orb} = 4.8\,\mathrm{hr}$)
- characteristic rate: $10^{-5}\,\mathrm{yr}^{-1}$

Detmers, Langer & Podsiadlowski (2008):

- tidal spin-up of core possible

but: at solar Z: WR wind mass loss leads to widening of binary and subsequent spin-down of the companion

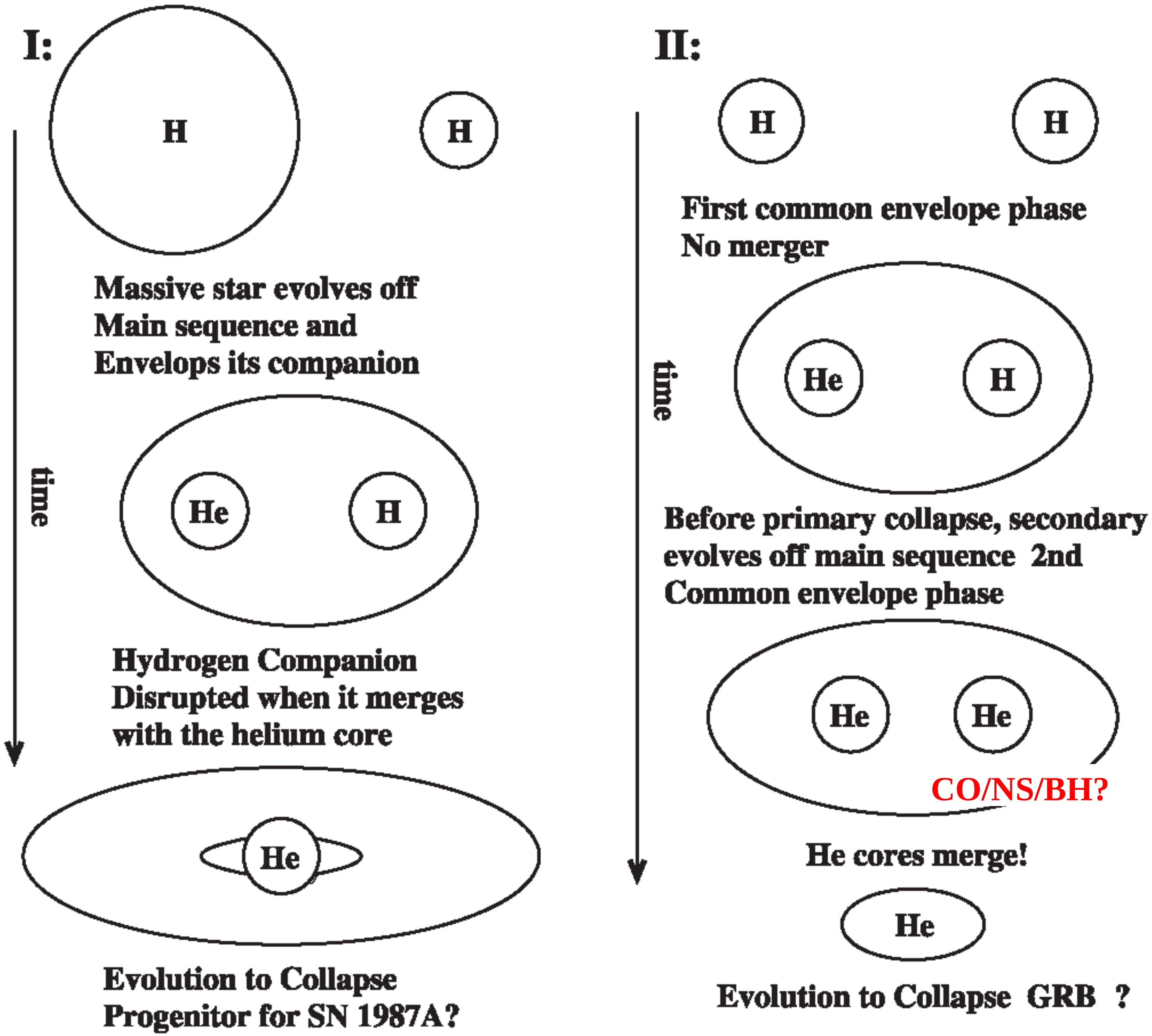
▷ need low wind-mass loss rate, low Z?

- many systems expected to merge

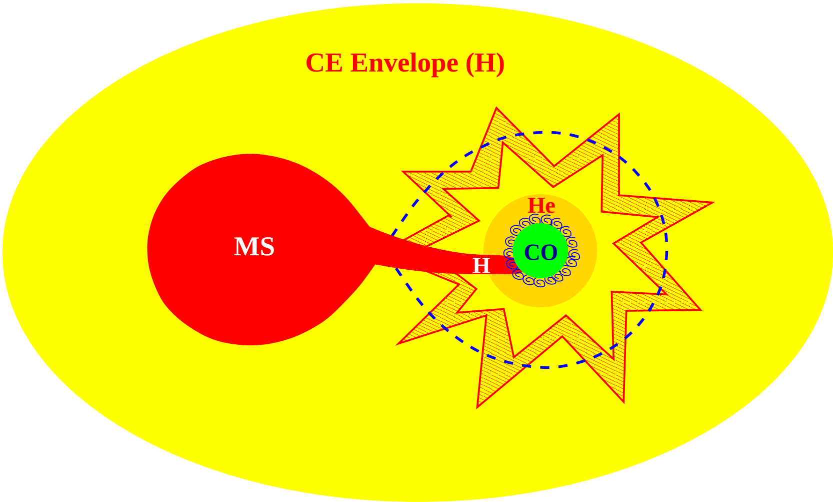
→ merger of WR star with compact star (Fryer & Woosley 1998)

Merger Ideas

(from Fryer & Heger)

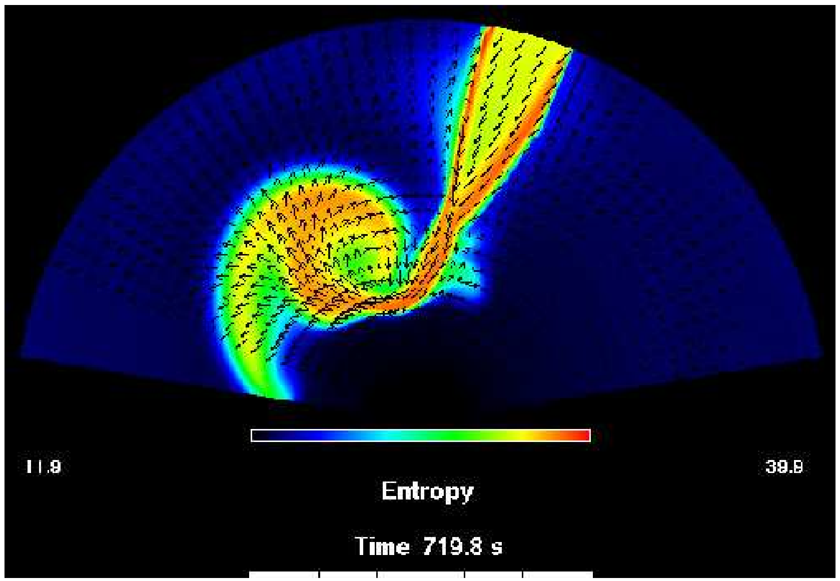


Explosive Common-Envelope Ejection
Podsiadlowski, Ivanova, . . . (2010)



- for large mass ratio:
  - → sudden mixing of H into very hot layer (few 10^8 K) → nuclear runaway (hot CNO cycle)
  - → rapid expansion of He layer and ultimate ejection of He-rich shell and rest of envelope

- discovered by Natasha Ivanova when studying the slow merger of massive stars
- spiralling secondary fills its Roche lobe inside common envelope (CE)
  - → mass transfer from secondary to the core of the supergiant
  - → H-rich stream penetrates helium core



Ivanova, Podsiadlowski & Spruit (2002)

Conclusions

- binary interactions provide a variety of promising paths to produce rapidly rotating collapsar/magnetar progenitors
- require special circumstances, but consistent with observed rates
- in many models, lower metallicity is preferred, but not a requirement