Evolutionary Channels for Gamma-Ray Burst Progenitors

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I. Progenitor Constraints

II. Single and Binary Progenitor Scenarios

III. Key Issues (and Tests)

Constraints (I)

Event Rates (for reference galaxy)

- LGRBs: $(10^{-6}-)10^{-5}\,\mathrm{yr}^{-1}$

  (faint GRBs: $\times\ 5 - 10$?)
- core-collapse supernovae: $\sim 10^{-2}\,\mathrm{yr}^{-1}$
- SNe Ib/Ic (normal!): $\sim 10^{-3}\,\mathrm{yr}^{-1}$ (mostly relatively low-mass binaries)
- SNe Ic (with engine): $\sim 10^{-5}\,\mathrm{yr}^{-1}$
- magnetar (= magnetic pulsar): $\sim 10^{-3}\,\mathrm{yr}^{-1}$
- "magnetar" (= engine): $\sim 10^{-5}$ (LGRB), $\sim 10^{-6}\,\mathrm{yr}^{-1}$ (SLSNe)

  ▷ GRBs are rare events!

  → GRBs require very special evolution/ circumstances (i.e. not just single massive stars, but stars that are special; i.e. rotation/low Z; binarity)

Constraints (II)

LGRB SNe are SNe Ic

- stripped stars that have lost their hydrogen (!) and helium (?) envelopes

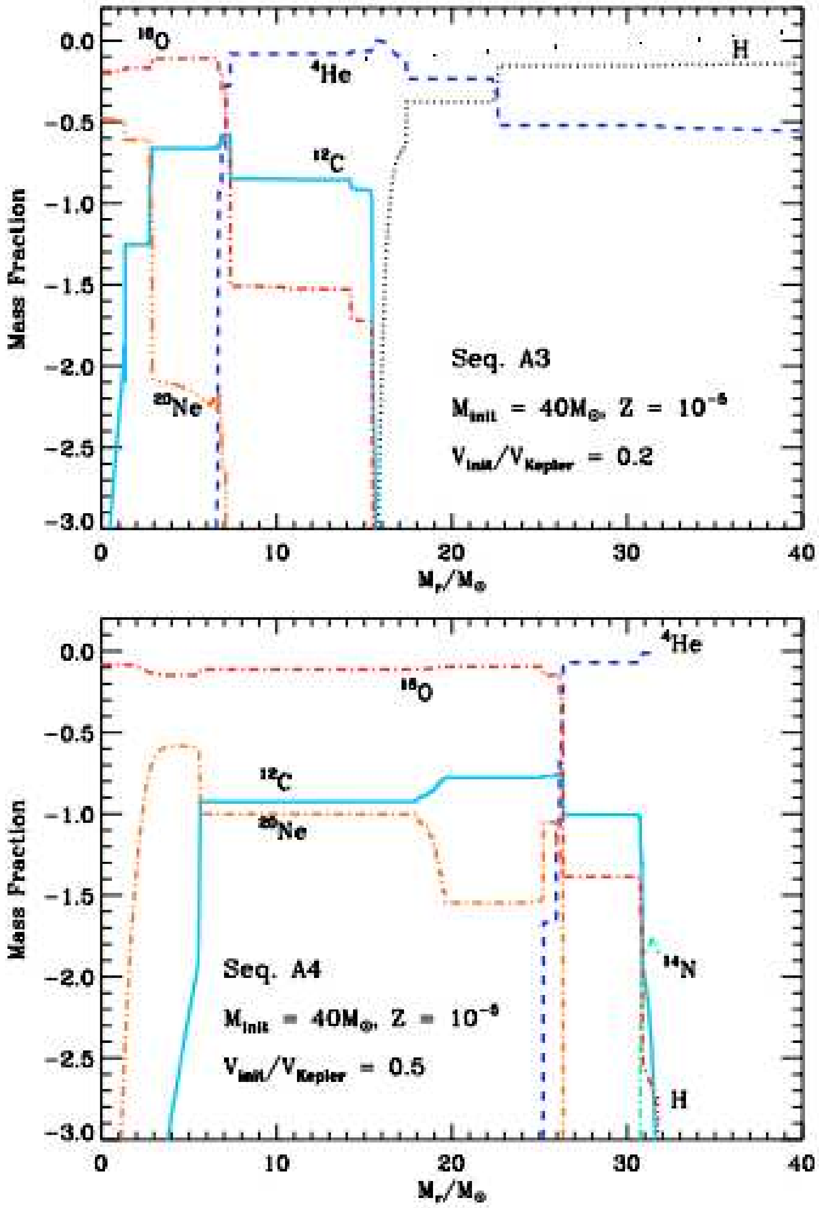
LGRBs prefer lower-metallicity environments

- mostly $Z < 1/2\,Z_\odot$ (but up to $\sim 2\,Z_\odot$)
- progenitor constraint or environment constraint (e.g. star formation)?

The progenitors are quite massive: $M_{MS} > 20\,M_\odot$ (unlike normal SNe Ib/c)

The progenitors have rapidly rotating "cores" (consensus)

- critical specific angular momentum (at $\sim 2\,M_\odot$)
  - ▷ models with disk: $j \sim 10^{16}\,cm^2\,s^{-1}$
  - ▷ magnetar: a bit less



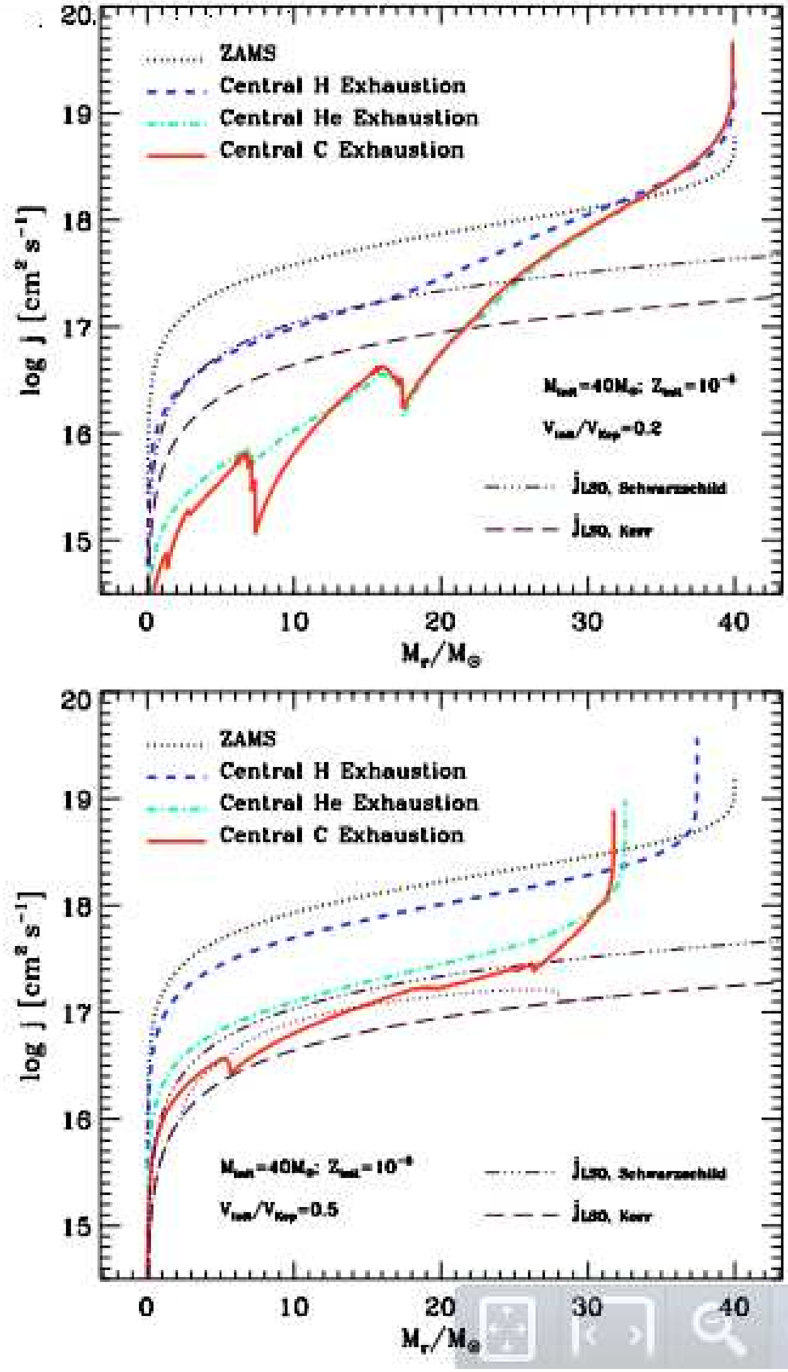


Fig. 4. *Upper panel*: mass fraction of chemical elements after core carbon exhaustion in Seq. A3, as a function of the mass coordinate. *lower panel*: same as in the upper panel, but for model Seq. A4.

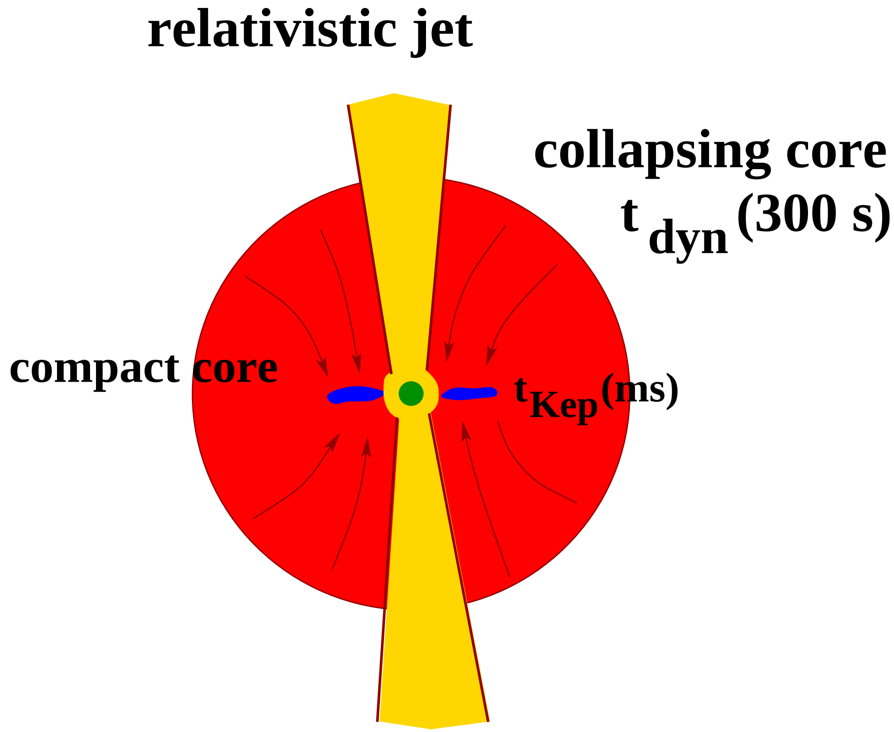
Yoon & Langer (2005)

The Progenitor – LGRB Connection

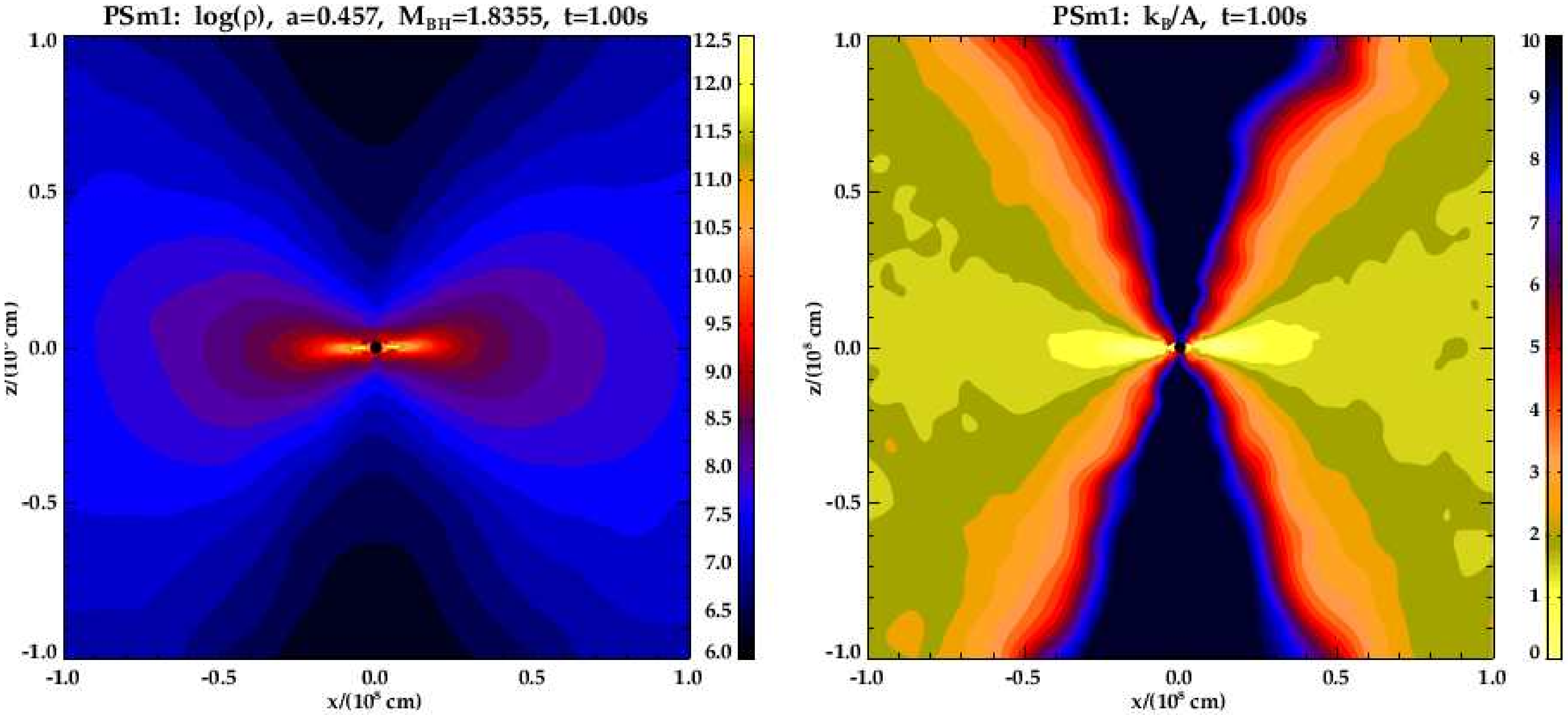
- popular working hypothesis: long-duration GRBs are associated with the collapse of a rapidly rotating core/star without hydrogen envelope ("collapsar" models [Woosley, MacFadyen])
- similar in magnetar scenarios?

Collapse timescales

- central (engine) timescale: $\sim 10^{-3}\,\mathrm{s}$
- core-collapse timescale: $\sim 100\,\mathrm{s}$ ($\rightarrow$ sets overall duration)

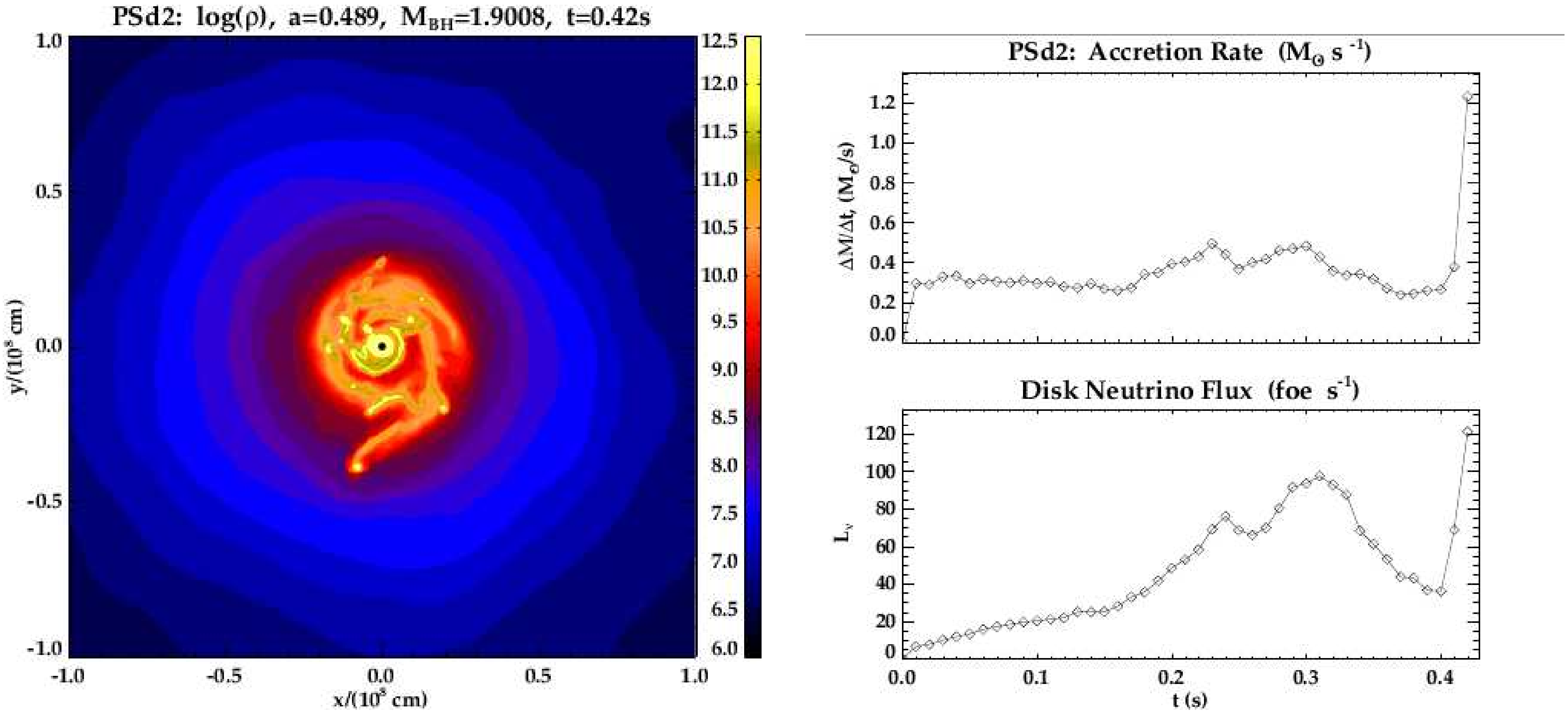


Taylor, Miller & Podsiadlowski (2010)



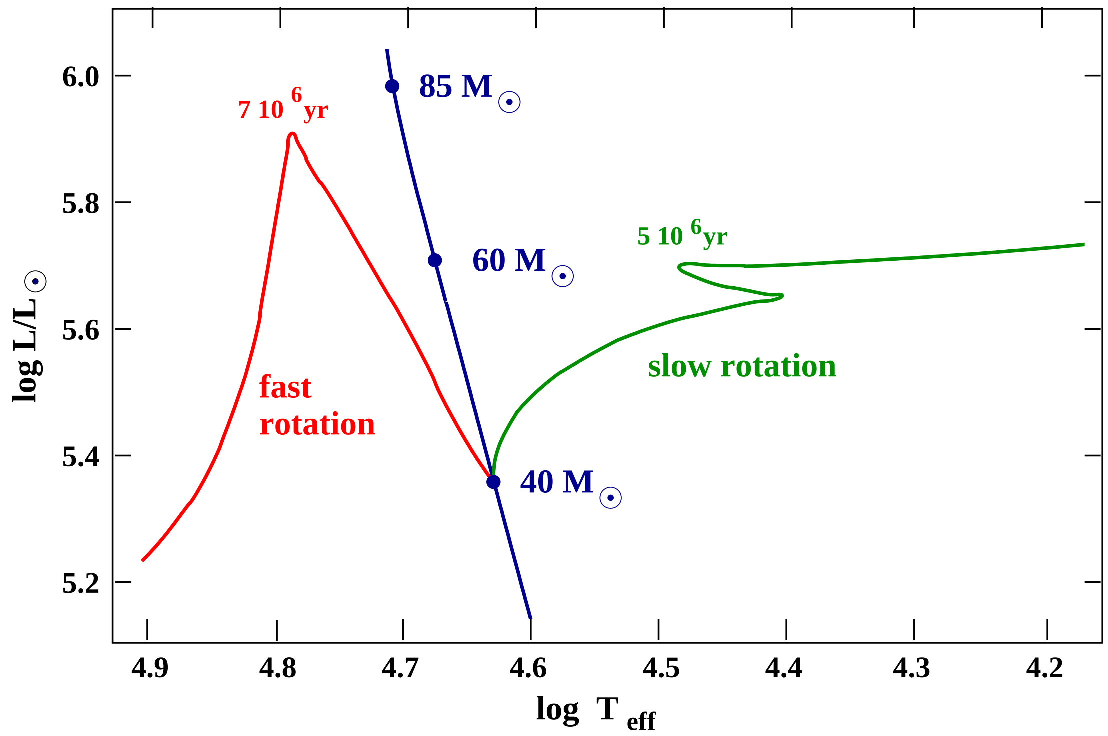
(using progenitor models from Fryer & Heger (2006))

Taylor, Miller & Podsiadlowski (2010)



Single Star Models

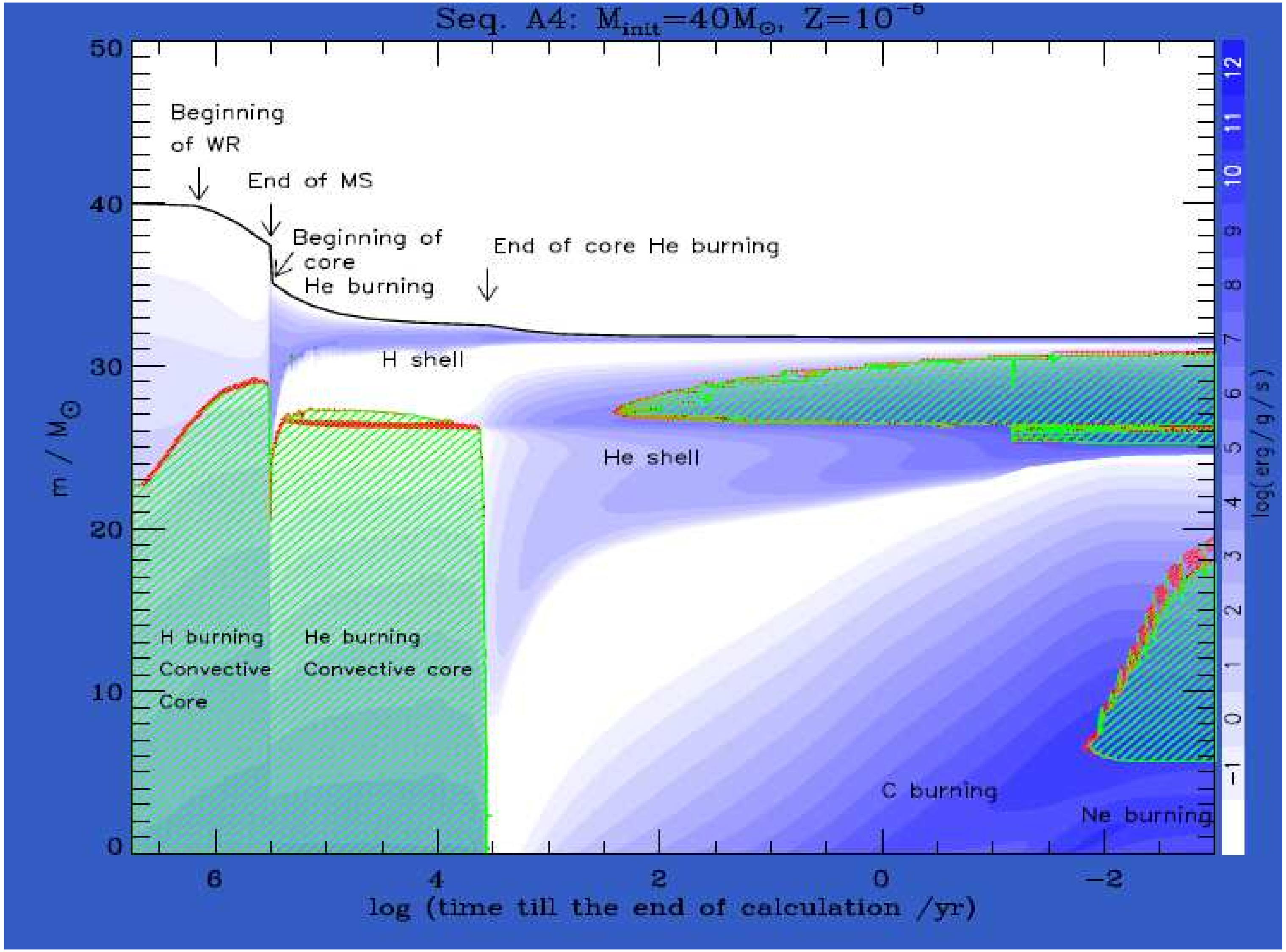
(Yoon & Langer 2005; Woosley & Heger 2006)



Maeder (1987)

Basic Idea: Rapid Rotation

- homogeneous evolution for very rapily rotating MS stars
- stars evolve to the blue (i.e. skip red-giant phase) (Maeder 1987)



Yoon & Langer (2005)

- requires rapid initial rotation and low mass-loss rate to avoid spin down → low metallicity ($Z \simeq 1/4\,Z_\odot$)
- the progenitor retains a significant amount of helium

Binary Star Models

- orbital angular momentum provides a natural reservoir of angular momentum
- two types of binary models
- models that produce a "star" with a rapidly rotating core (similar to single-star models)
  - ▷ accretion models (+ supernova breakup) (e.g. Cantiello), main-sequence mergers, tidal spin-up models
- dynamical models (e.g. merger of He star with compact object)

$\rightarrow$ no extended envelope (flattened disk-like structure)

but: stars in binaries follow the same rules as single stars

- ▷ mass loss causes the loss of angular momentum $\rightarrow$ lower metallicity generally favoured
- ▷ late interaction often favourable (case C)
- ▷ most models contain helium

Tidal Spin-Up Models

- in a close binary, a massive companion can by spun up by tides (Izzard, Detmers, Yoon, van den Heuvel)
- requires relatively compact binary: $P_{crit} \leq 10\,hr$
- prototype: Cygnus X-3? (WR + NS/BH binary with $P_{orb} = 4.8\,hr$)

  Core spin-up?

  ▷ yes, in 10^4 yr (Spruit formalism) (Detmers et al. 2008)

but: at solar metallicity

  ▷ mass loss causes orbital widening ($t_{ML} < t_{spin-up}$) (and tidal spin-down!) or drasting orbital shrinking ($t_{ML} < t_{spin-up}$) and likely merger

- need to go to lower metallicity (lower mass loss) or later initial interaction (case C)
- channel to produce WR + NS/BH mergers (Fryer & Woosley 1998)

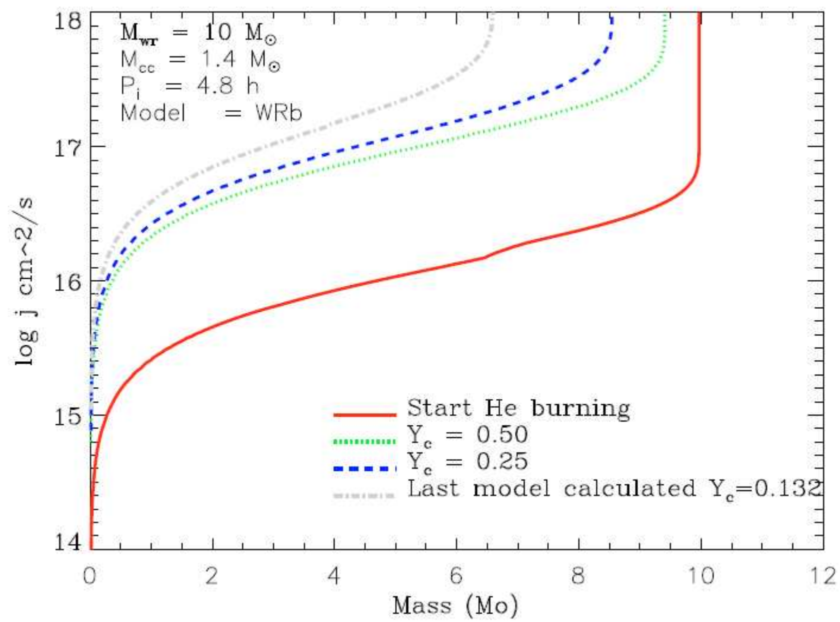
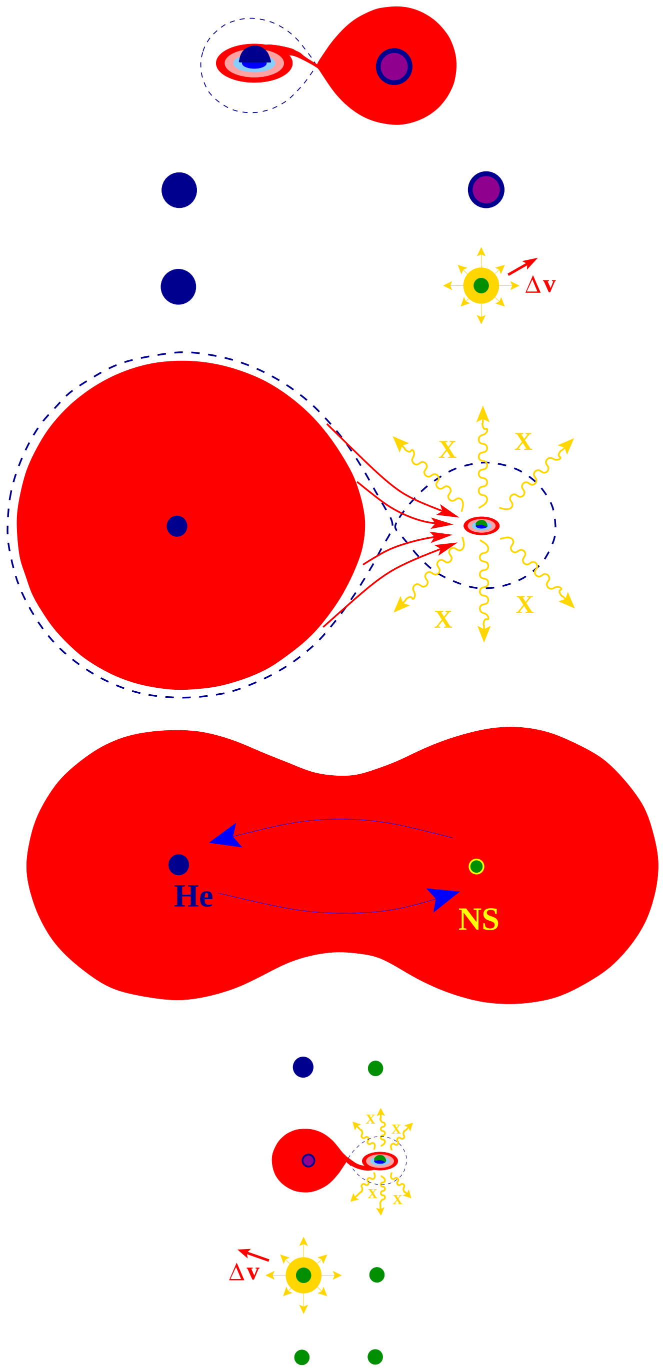


Table 2. Formation rates for each possible GRB progenitor type, for $\lambda = 0.5$.

Scenario	Type	Fate	Birthrate [yr^{-1}]
A	He-shell RLOF	CO-BH merger	5.64×10^{-6}
B	pre He-shell RLOF	He-BH merger	3.83×10^{-5}
C	CO + BH	collapsar?	1.39×10^{-7}

Detmers et al. (2008)



Δv
X
X
X
X
X
X
He
NS
x
x
x
x
Δv

Binary Merger Scenarios

Types (I)

A. mergers of compact objects (NS/BHs) with less compact objects (WD, He star, CO star)

→ trigger GRB

▷ potential problem: too much angular momentum

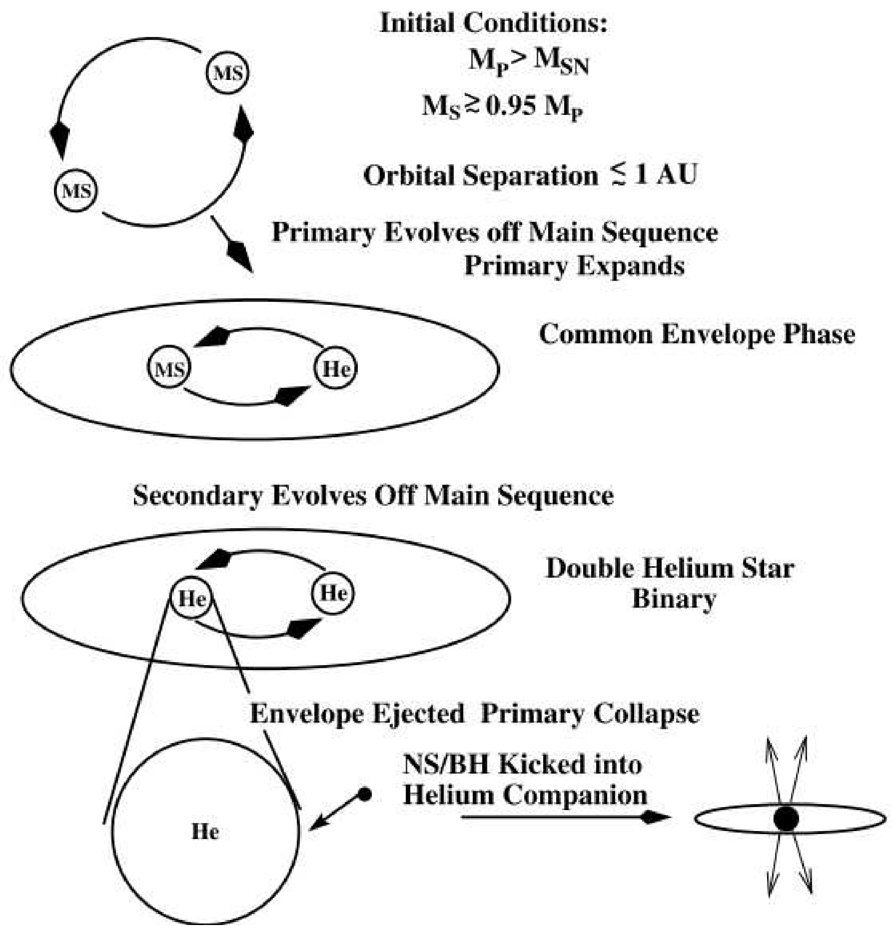
B. mergers of non-compact objects

→ rapidly rotating massive star (similar to single-star model)

Types (II)

1. merger driven by unstable mass transfer or caused by supernova kick
2. merger inside common envelope

▷ Issue: how to merge and eject common envelope?



Fryer (2006)

Helium (CO) Star Mergers

(Fryer & Heger 2006)

- near equal-mass binary components

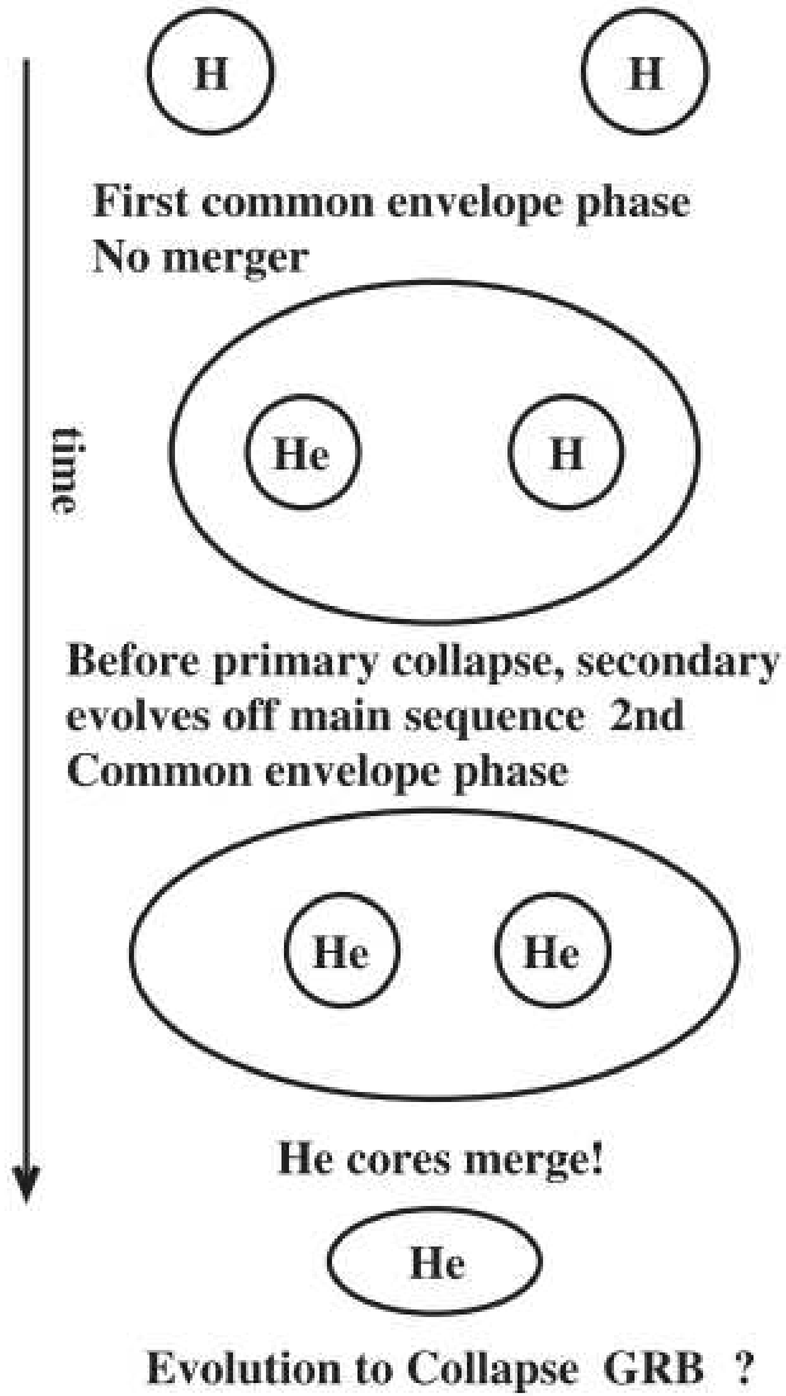
→ secondary evolves off the main sequence before binary interaction

- merger in common envelope → rapidly rotating helium star

but: long WR phase → slow-down?

better (and more probable!) merger of star with CO core and helium star (i.e. case C)

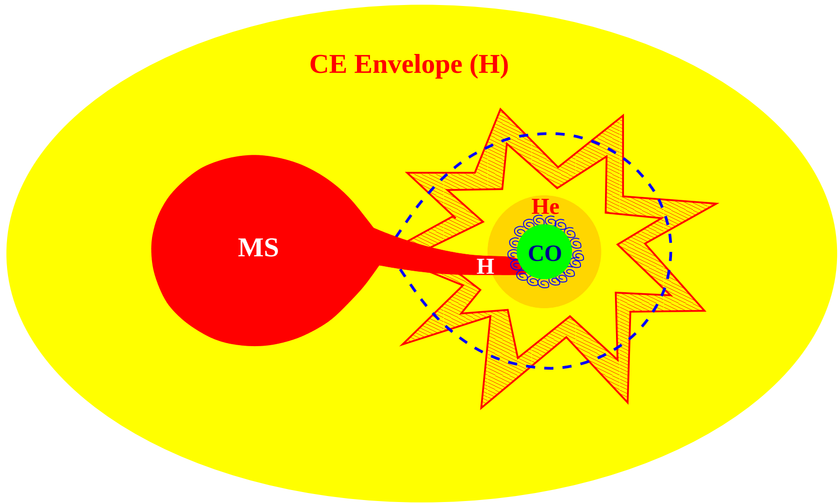
▷ short remaining lifetime → no spin-down



Fryer & Heger (2006)

Explosive Common-Envelope Ejection

- 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
- 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



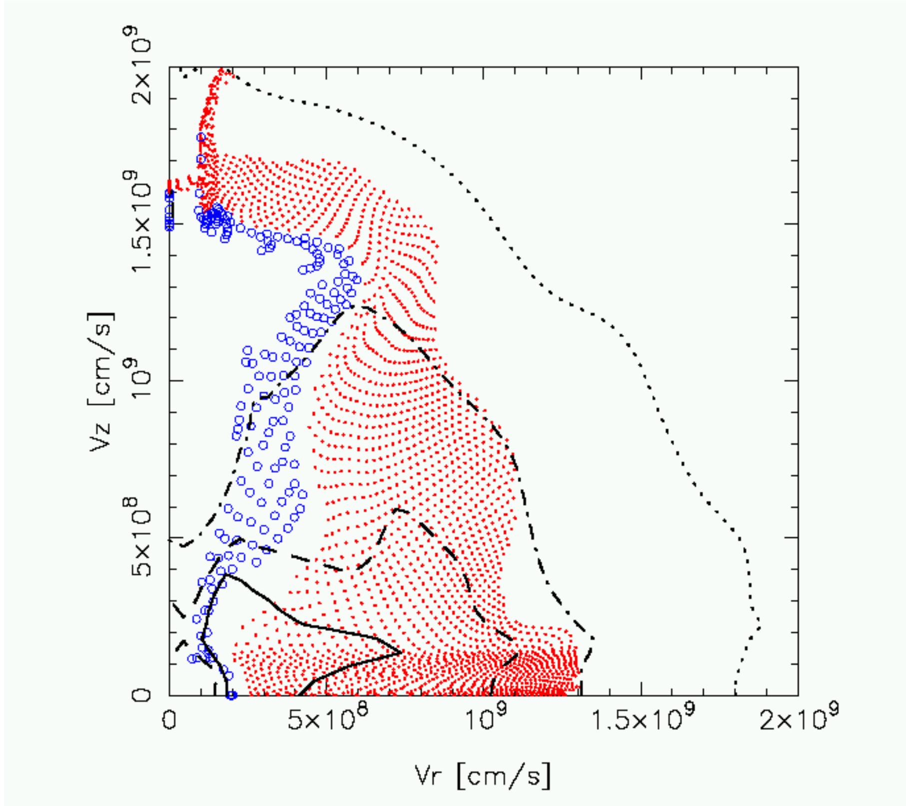
- energy source for CE ejection is nuclear energy (not orbital energy) → new CE ejection mechanism (application to short-period black-hole binaries, Nova Sco)
- works best for relatively low-mass companions ($\lesssim 3\,M_\odot$)

Metallicity Effects

- **basic principle:** lower metallicity $\rightarrow$ lower wind mass loss $\rightarrow$ less spin down
- helpful in most models, but to different degrees
  - ▷ **homogeneous, single-star models:** essential ($Z \leq 1/4\, Z_{\odot}$)
  - ▷ **most binary models:** useful/favoured (also case C more frequent at low Z)
  - ▷ **dynamical mergers with compact components:** not directly important

The Type Ic Problem

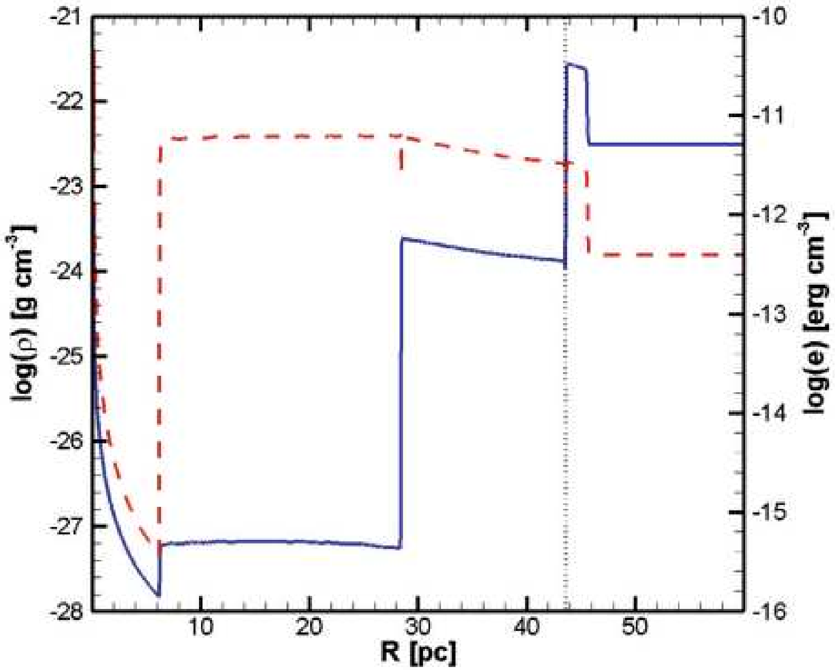
- most models predict significant amounts of helium at the time of explosion (except ECEE model, CO + compact mergers)
- how much helium can be hidden in a SN Ic?
- helium is excited non-thermally
- key: location of helium relative to radioactive decay products



Nomoto et al.

The Circumstellar Medium Structure

- different models make different predictions on the CSM
  - ▷ single-star models reflects full evolution history
  - ▷ case C binary models: recent CE ejection (10^{18} cm), short Wolf-Rayet phase → hot wind bubble (constant ρ?)
  - ▷ compact mergers: little CSM?



van Marle & Langer (2008)

A Unified Model (for discussion)

Supernovae with Engines (no normal GRB; faint GRB?)

- collapsar engine, but jet fails to get out

some issues :

  - ▷ reason for failure: envelope mass/structure? Models with or without envelope?
  - ▷ Why are they more common at larger Z? (more mass loss, lower rotation?)
  - ▷ Different energetics?

GRBs with Supernovae

- collapsar with successful GRB jet
- progenitors have relatively massive rapidly rotating CO cores (more massive stars)

some issues :

  - ▷ What ejects the envelope? (supernova mechanism)
  - ▷ Where is the Ni produced?

Type I Superluminous Supernovae with Fast Decays

- similar to above, but with lower-mass final cores

→ form magnetar rather than black hole