# Binary Models for the Progenitors of "Peculiar" Supernovae

Philipp Podsiadlowski (Oxford)

- Binary evolution affects the final structure and fate of stars in many ways
  - ▷ appearance (envelope properties)
  - ▷ core properties → final fate (WD, NS, BH, GRB)

  → key in understanding the diversity of supernovae

**Question:** What is a peculiar supernova?

→ a well observed one!

- exceptions (homogeneous types)
  - ▷ SNe II-P (singles dominate)
  - ▷ bulk of typical SNe Ia
- for all supernova types except SNe II-P, binary evolution is important or essential

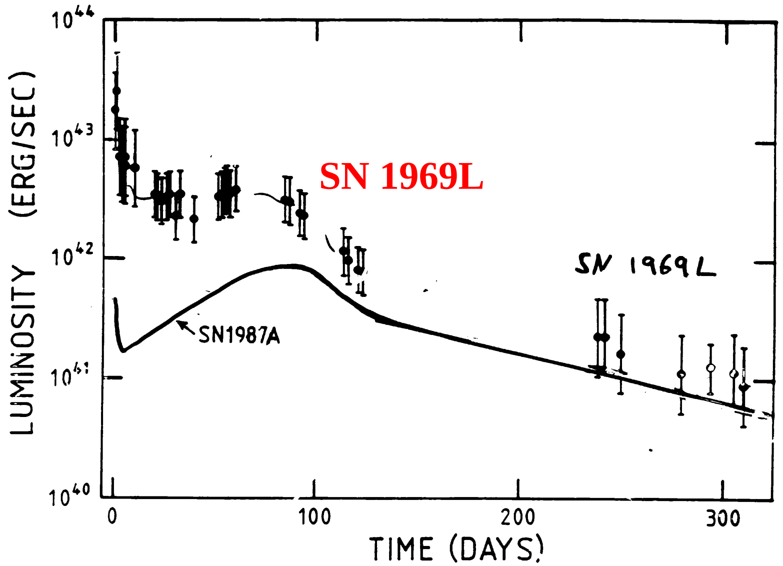
# Supernova Classification

- depends on three factors
  - ▷ explosion type
  - ▷ envelope/ejecta properties
  - ▷ circumstellar environemnt
- use for new classification scheme? (e.g. Gal-Yam)

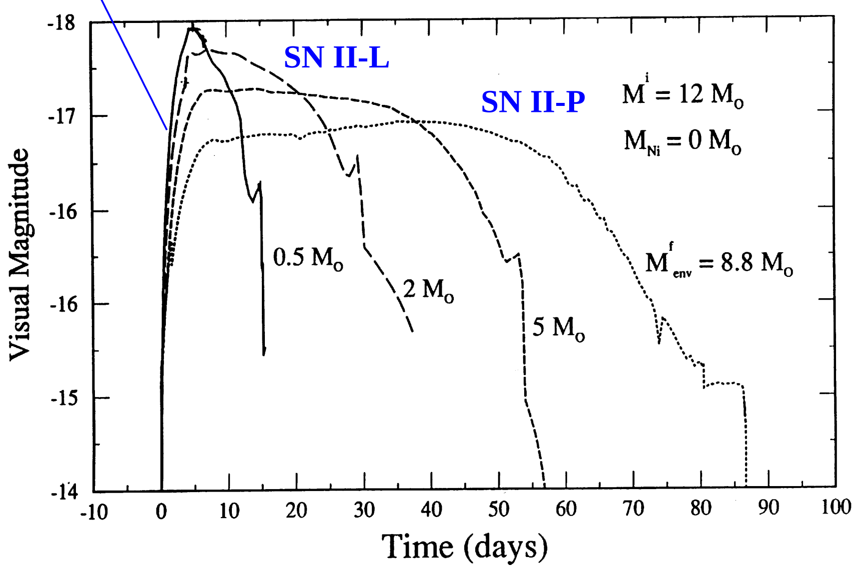
# Summary of Explosion Types

- **Neutron-star formation**
  - ▷ classical iron core collapse → typical core collapse: $10^{51}$ ergs (single and binary)
  - ▷ electron-capture supernova in degenerate ONeMg core (AGB, AIC, MIC) → faint core collapse (binary preferred)
- **Black-hole formation**
  - ▷ prompt collapse: → failed supernova
  - ▷ fall-back: → faint supernova
  - ▷ expected fate for most single WR stars (except at very high metallicity; see Heger, Meynet, Georgy)
  - ▷ with rapid rotation: collapsar/hypernova → energetic supernova (hypernova, GRB SN) (only 1 in $10^3$)
- thermonuclear explosion of Chandrasekhar-mass CO WD, binary
- He detonation on accreting CO white dwarf → explosive → supernova-like (faint SN Ia?)
- pair-instability supernova for very massive stars (low Z?) ($> 140\,M_\odot$): creation of electron/positron pairs → explosive nuclear burning → complete disruption of the star

Supernova lightcurves (core collapse)




SN II-b




Hsu, Ross, Joss, P.

## LIGHTCURVES OF CORE-COLLAPSE SUPERNOVAE

- central explosion may be very similar in all cases (with $E \sim 10^{51}$ ergs)
- variation of lightcurves/supernova subtypes mainly due to varying envelope properties
  - ▷ envelope mass: determines thermal diffusion time and length/existence of plateau
  - ▷ envelope radius: more compact progenitor $\rightarrow$ more expansion work required $\rightarrow$ dimmer supernova

Sequence: II-P $\rightarrow$ II-L $\rightarrow$ IIb $\rightarrow$ Ib $\rightarrow$ Ic

- mass loss by binary evolution and stellar winds

## Circumstellar Environment

- interaction driven supernovae
- SNe IIn
  - ▷ narrow emission lines from circumstellar material
  - ▷ phenomenon, unrelated (?) to explosion mechanism
- e.g. SN 2002ic
  - ▷ explosion type unclear: SN Ia or Ic
  - ▷ oddball (SN 1 1/2) or important clue?
  - ▷ symbiotic SN Ia
  - ▷ or extreme example of supersoft channel (delayed dynamical instability)

LBV supernovae

- not predicted by single-star theory
- change single-star theory? Or alternative solution

# Causes of Supernova Diversity

- binarity
  - ▷ supernova appearance (mass loss/accretion, merging)
  - ▷ core structure
- metallicity
  - ▷ appearance (mass loss, compactness)
  - ▷ core evolution
- rotation/magnetic fields
  - ▷ important in early evolutionary phases (only?), e.g. through mixing (magnetic fields prevent rapidly rotating evolved cores (Spruit))
- dynamical environment
  - ▷ e.g. in dense clusters → dynamical interactions → different final products (dynamical mergers → more HNe?)

# Binary Interactions

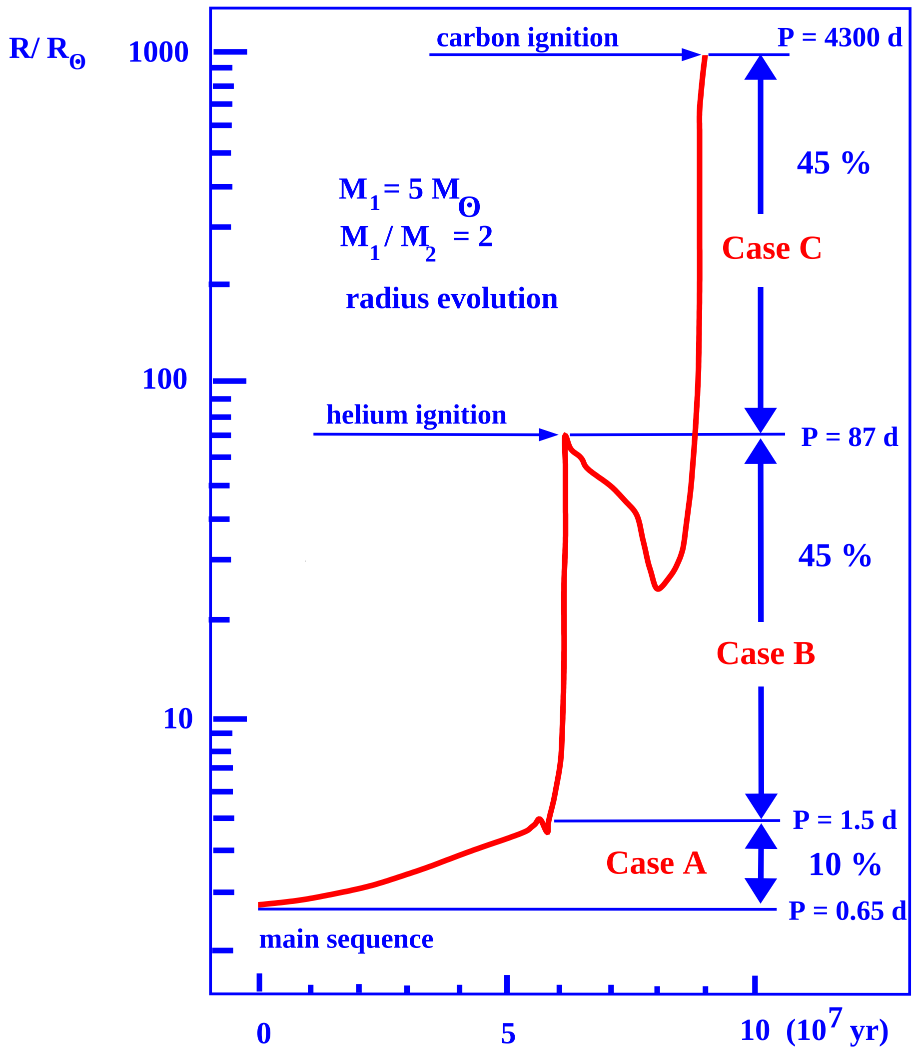
- most stars are members of binary systems
- a large fraction are members of interacting binaries ($30-50\,\%$)
- rule of thumb: each decade of log P contains $10\,\%$ of all stars (for P from $10^{-3}-10^{7}\,$yr)

$\rightarrow$ $50\,\%$ of all stars are in binaries with $P_{\rm orb} < 100\,$yr

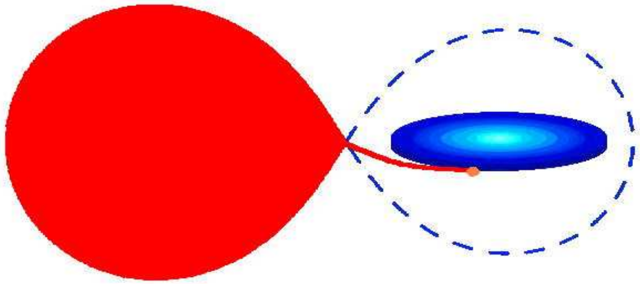
- note: mass transfer is more likely for post-MS systems
- mass-ratio distribution:
  - ▷ for massive stars: masses correlated
  - ▷ for low-mass stars: less certain
- binary interactions
  - ▷ common-envelope (CE) evolution
  - ▷ stable Roche-lobe overflow
  - ▷ binary mergers
  - ▷ wind Roche-lobe overflow

Classification of Roche-lobe overflow phases

(Paczynski)

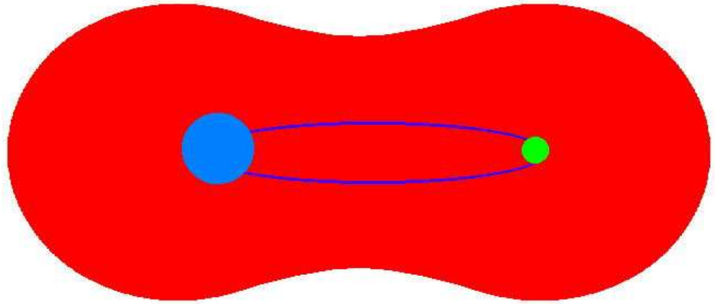


## Stable Mass Transfer



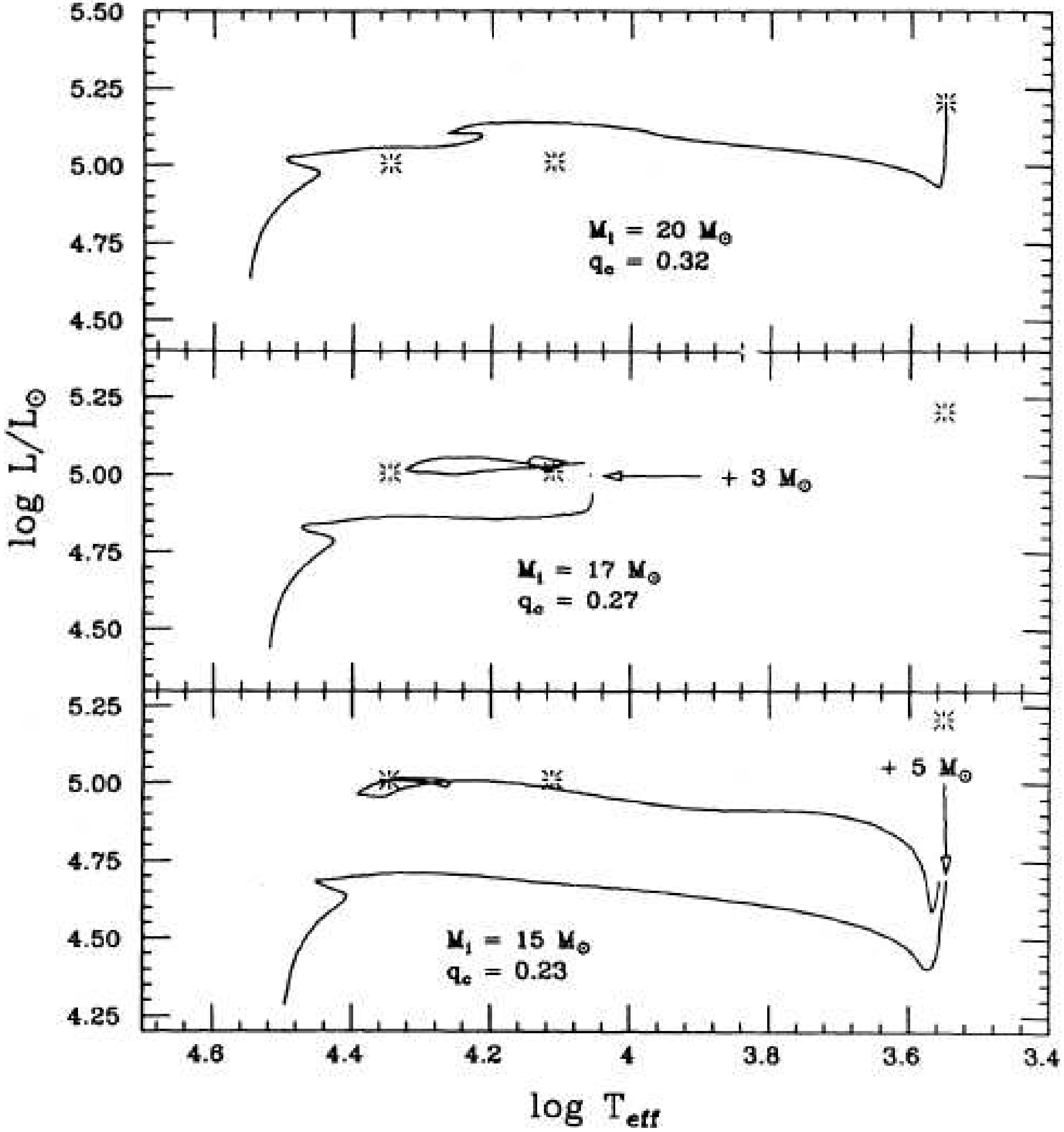
- mass transfer is 'largely' conservative, except at very mass-transfer rates
- mass loss + mass accretion
- the mass loser tends to lose most of its envelope → formation of helium stars
- the accretor tends to be rejuvenated (i.e. behaves like a more massive star with the evolutionary clock reset)
- orbit generally widens

## Unstable Mass Transfer



- dynamical mass transfer → common-envelope and spiral-in phase (mass loser is usually a red giant)
  - ▷ mass donor (primary) engulfs secondary
  - ▷ spiral-in of the core of the primary and the secondary immersed in a common envelope
- if envelope ejected → very close binary (compact core + secondary)
- otherwise: complete merger of the binary components → formation of a single, rapidly rotating star

PhP & Joss (1989)



# Case BB Mass transfer

- low-mass helium stars ($\lesssim 3.5\,M_\odot$) expand drastically after helium core burning

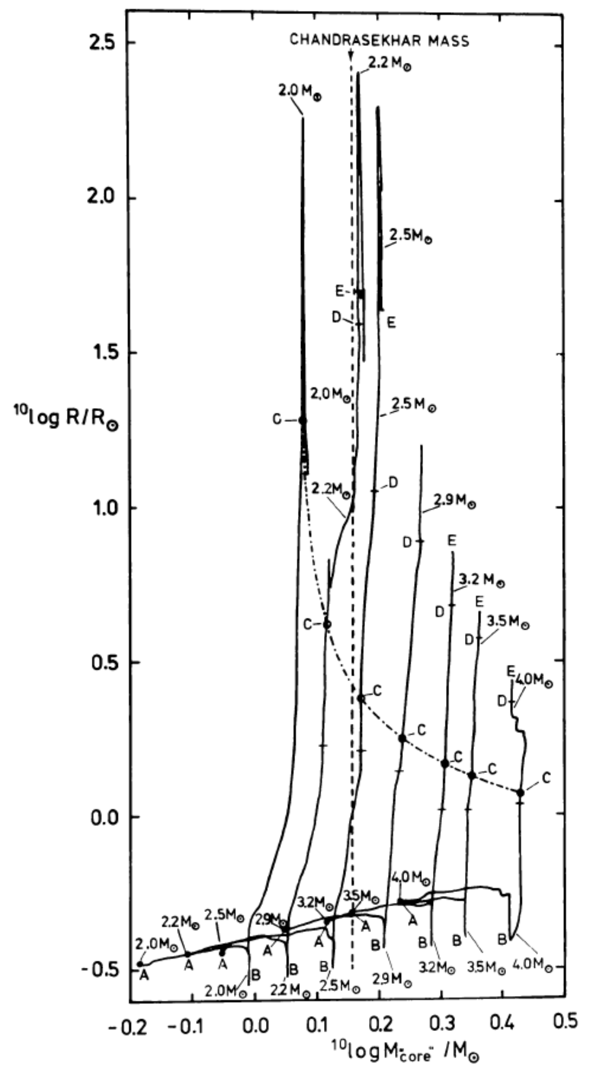
$\rightarrow$ mass transfer from helium star to companion

$\rightarrow$ transformation into a CO star (Dewi, Pols)

- produces "normal" SNe Ic (e.g. prototype SN 94I had a progenitor $\lesssim 18\,M_\odot$ [Sauer])

## Double Pulsar (PSR J0737-3039)

- pulsar B ($1.249\,M_\odot$) formed in a faint SN Ib
- with $0.2 - 0.3\,M_\odot$ of ejecta




Habets (1986)

# Binary Mergers

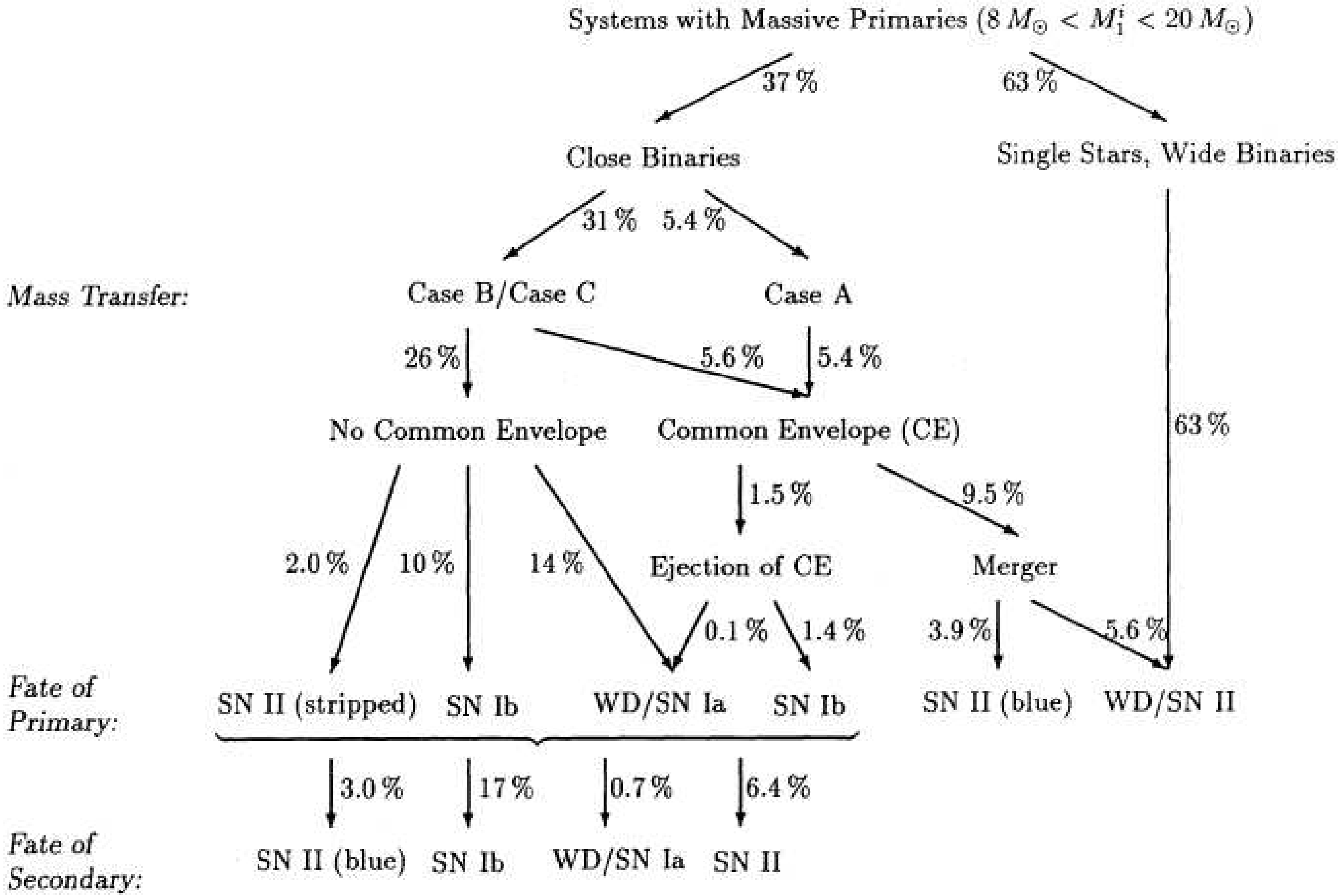
- one of the most important, but not well studied binary interactions
- BPS: $\sim 10\,\%$ of all stars are expected to merge with a companion star $\rightarrow$ 1 binary merger in the Galaxy every 10 yr!
- efficient conversion of orbital-angular momentum to spin orbital-angular momentum
- if mergers occur early in the evolution $\rightarrow$ subsequent spin-down just as for single stars
- late mergers to affect the nearby CSM and pre-SN structure (e.g. case C mass transfer)

note: case C mass transfer is more frequent at lower metallicity (Justham, PhP 2008)

$\rightarrow$ implications for GRB progenitors

$\rightarrow$ rapidly rotating core, short WR phase, circumstellar shell?

## PhP, Joss, Hsu (1989, 1992)



# Binary Evolution and the Final Fate of Massive Stars

**Recent: binary evolution affects not only the envelope structure, but also the core evolution**

- **generically:** after mass loss/accretion during an early evolutionary phase, a star behaves like a less/more massive star
- the core evolution is very different for stars that lose their hydrogen envelopes before helium ignition (no hydrogen burning shell during He core burning $\rightarrow$ no growth of the convective core) leading to smaller CO and finally smaller iron cores
  - ▷ stars in binaries up to $50/60\,M_\odot$ may end as neutron stars rather than as black holes (Brown, Lee, Heger, Langer)
  - ▷ black-formation without rotation $\rightarrow$ faint supernova?

# The Final Fates of Stars

- the effects of binary evolution

| | single/wide binary | close binary |
|---|---|---|
| CO white dwarf | $< 7\,M_\odot$ | $< 7 - 17\,M_\odot$ |
| ONeMg white dwarf | $7 - 10\,M_\odot$ | $7 - 8\,M_\odot$ |
| Neutron star: | | |
| electron-capture | $\sim 10\,M_\odot$ | $7/8 - 10\,M_\odot$ |
| iron core collapse | $10 - 20/25\,M_\odot$ | $10 - 50/60\,M_\odot$ |
| Black hole: | | |
| two-step | $20/25 - 40(?)\,M_\odot$ | $> 50/60\,M_\odot$ |
| prompt | $> 40\,M_\odot(?)$ | |
| no remnant (Z?) | $> 140\,M_\odot$ | |

Note: (wide binary includes Case C mass transfer)

- the effects of metallicity
  - ▷ affects mass loss and compactness → supernova appearance (lower metallicity stars have less mass loss and are more compact)
  - ▷ affects core evolution (e.g. importance of CNO burning) and final core structure
  - ▷ example: the core structure of a $5\,M_\odot$ ($Z = 0.001$) is similar to the core structure of a $7\,M_\odot$ ($Z = 0.02$) star

## The Progenitor of SN 1987A

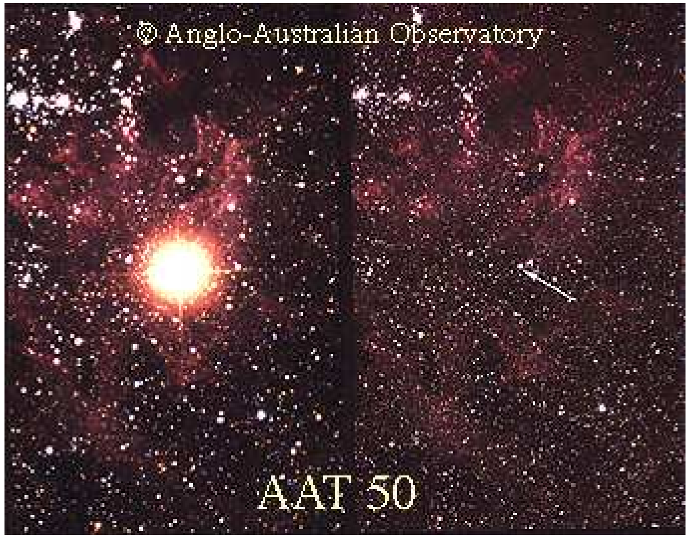
Thomas Morris (Oxford/MPA), Ph.P.

### SN 1987A: an anomalous supernova

- progenitor (SK $-69°202$): **blue supergiant** with recent red-supergiant phase ($10^4$ yr)
- chemical anomalies:
  - ▷ helium-rich (He/H$\sim 0.25$, N/C$\sim 5$, N/O$\sim 1$)
  - ▷ CNO-processed material, helium dredge-up
  - ▷ barium anomaly ($5 - 10$ solar)
- the triple-ring nebula

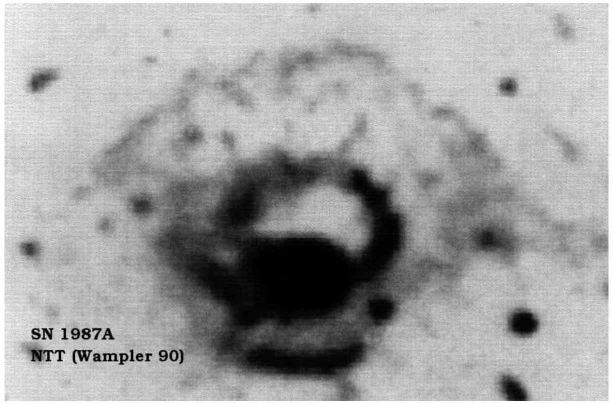
$\rightarrow$ axi-symmetric, but highly non-spherical

$\rightarrow$ signature of rapid rotation

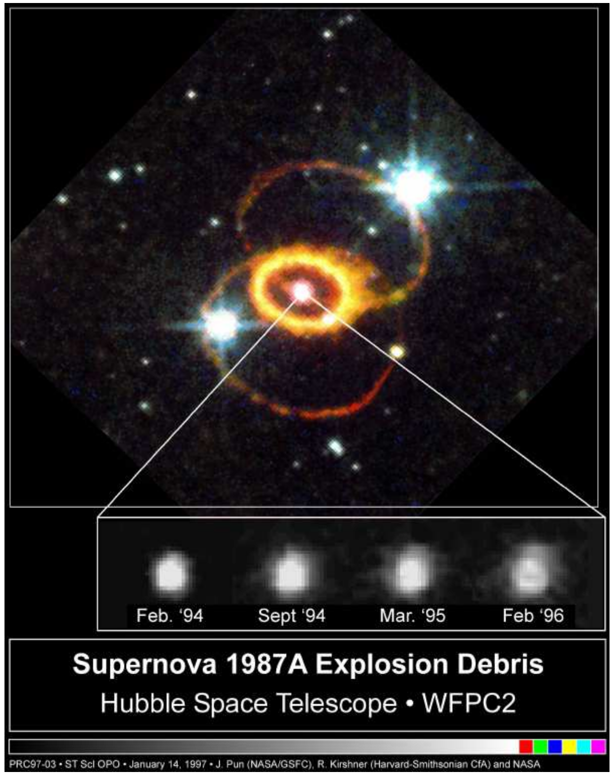
# The Triple-Ring Nebula

- discovered with NTT (Wampler et al. 1990)



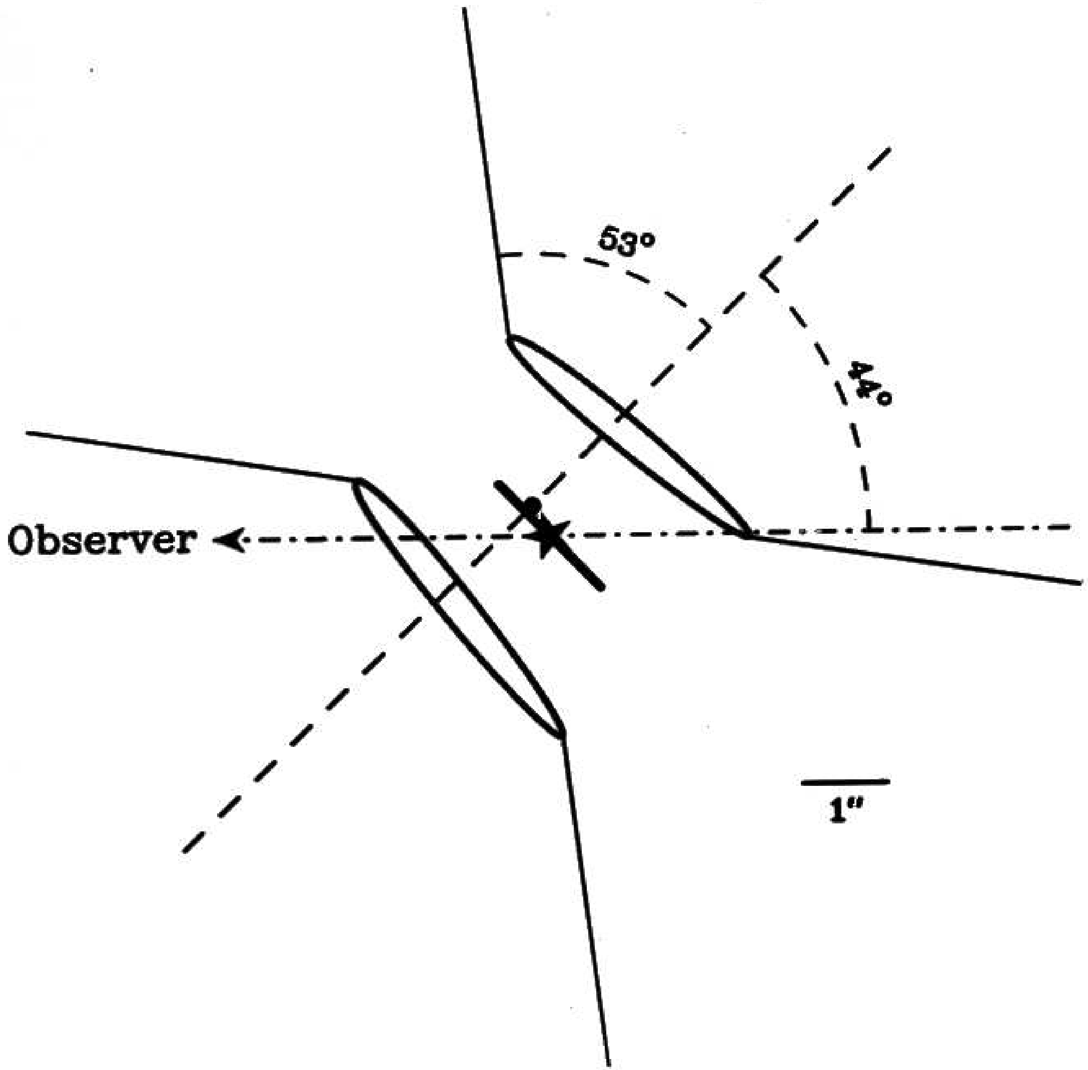

- HST image (Burrows et al. 1995)
- not a limb-brightened hourglass, but physically distinct rings
- axi-symmetric, but highly non-spherical

  → signature of rapid rotation?
  - ▷ not possible in simple single-star models (angular-momentum conservation!)
  - ▷ supernova is at the centre, but outer rings are slightly displaced
  - ▷ dynamical age: $\sim 20,000\,\mathrm{yr}$




all anomalies linked to a single event a few $10^4\,\mathrm{yr}$ ago, most likely the merger of two massive stars

Figure 2



# Formation of the Triple-Ring Nebula

## Morris and Podsiadlowski (Science 2007)

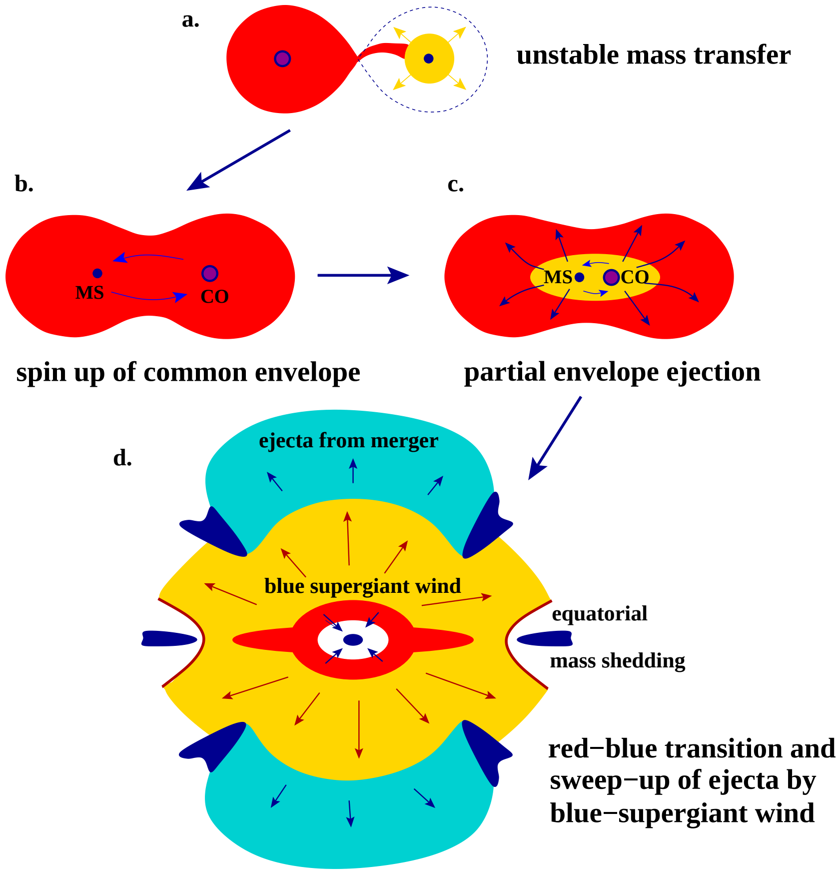
- 3-dim SPH simulations (GADGET; Springel)
- simulate mass ejection during merger and subsequent blue-supergiant phase
- angular momentum of orbit → spin-up of envelope

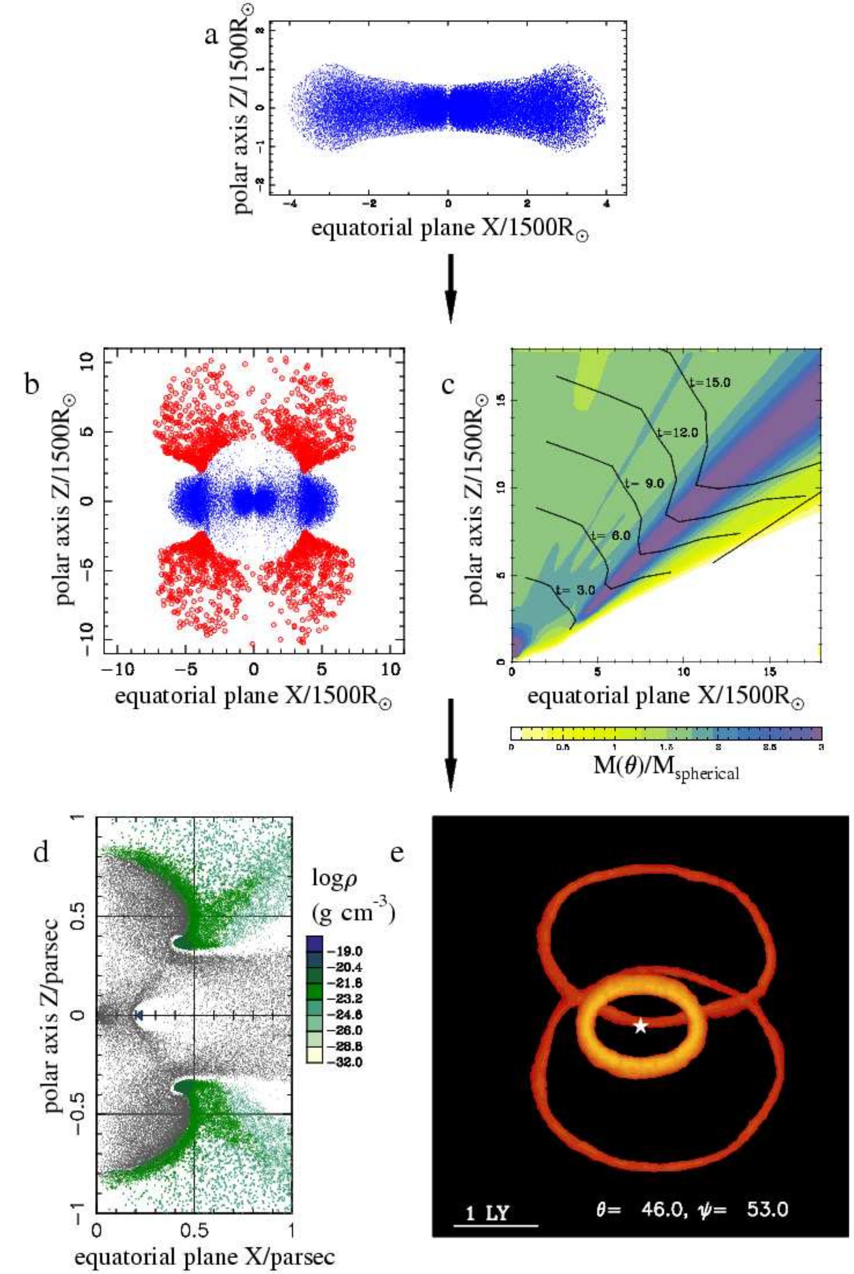
→ flattened, disk-like envelope

- energy deposition in rapid spiral-in phase ($\lesssim 1/3 E_{\rm bind}$)

→ partial envelope ejection → outer rings, bipolar lobes

- equatorial mass shedding during red-blue transition → inner ring




a
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
b
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
c
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
t=15.0
t=12.0
t= 9.0
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M($\theta$)/M$_{\rm spherical}$
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polar axis Z/parsec
equatorial plane X/parsec
log$\rho$
(g cm$^{-3}$)
-19.0
-20.4
-21.8
-23.2
-24.6
-26.0
-28.8
-32.0
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$\theta$= 46.0, $\psi$= 53.0

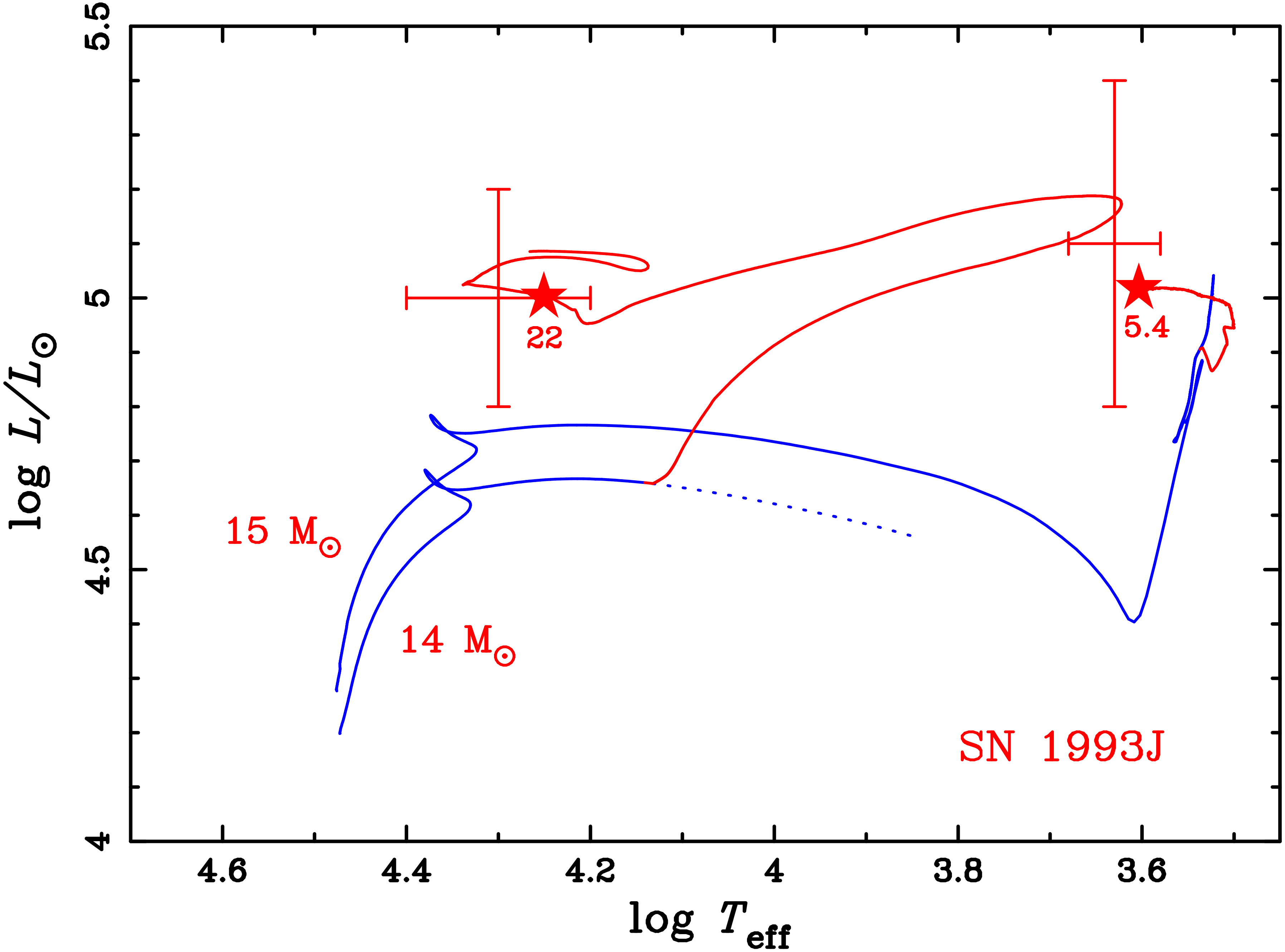
# The Progenitor of SN 1993J

- prototype SN IIb
- progenitor: stripped K supergiant ($< 0.5\,M_\odot$ envelope)
- initial mass: $\simeq 15\,M_\odot$
- most likely due to late binary interaction (Joss et al. 1988; Podsiadlowski; Nomoto; Woosley)
- predicted companion star has been found (Maund et al. 2004)

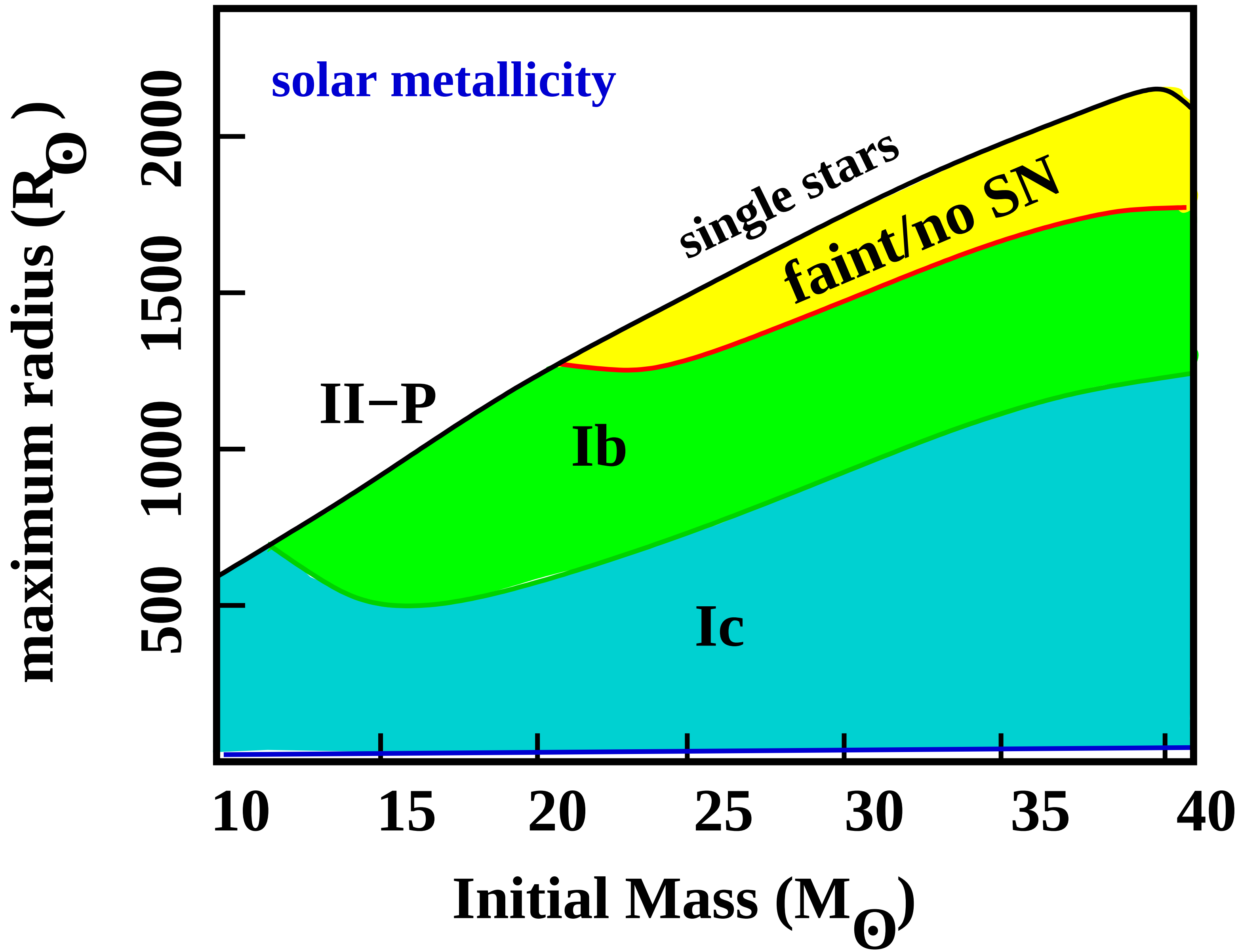
Potential Problem: predicted rate too low to explain all IIb? (PJH 1992; Claeys 2009)

- other channel or clue to binary evolution?

Maund et al. (2004)



PhP, Mazzali, Justham (2009)



## The Diversity of SNe Ic (II)

- **normal SNe Ic**
  - ▷ $\mathbf{M_{MS} \simeq 10 - 50/60\,M_\odot}$ **in close binaries**
  - ▷ **case B (BB) mass transfer**
- **hypernovae/GRB supernovae**
  - ▷ $\mathbf{M_{MS} \simeq 23 - 40/50\,M_\odot}$
  - ▷ **late case C mass transfer (explosive CE ejection?)**
- **faint SNe Ic (Ib?)**
  - ▷ $\mathbf{M_{MS} \gtrsim 23\,M_\odot}$
  - ▷ **single, slowly rotating stars**
- **also at low Z: homogeneous evolution → rapidly rotating single stars → energetic SNe Ib/Ic (Yoon & Langer; Heger & Woosley)**

# Nomoto Fork Plot