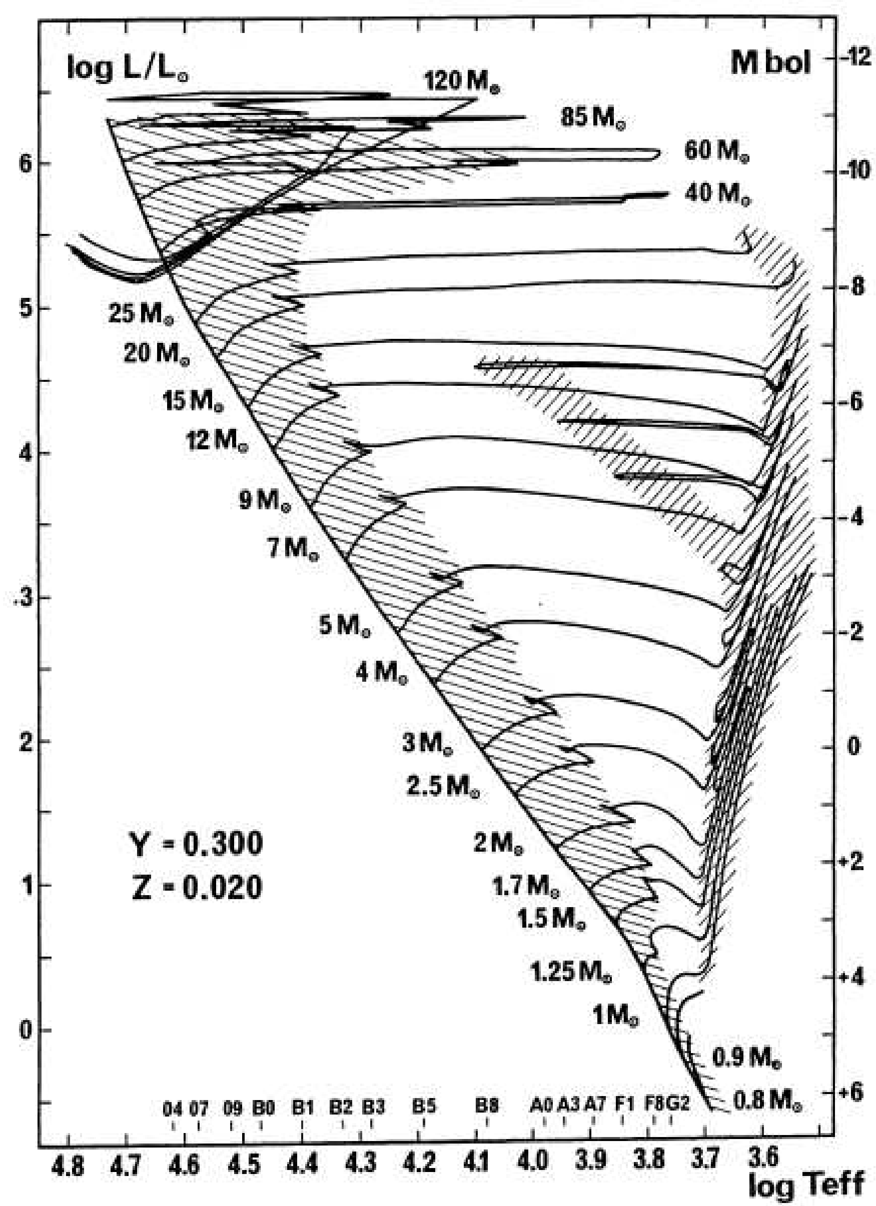
The Evolution of Massive Single and Binary Stars

Philipp Podsiadlowski (Oxford)

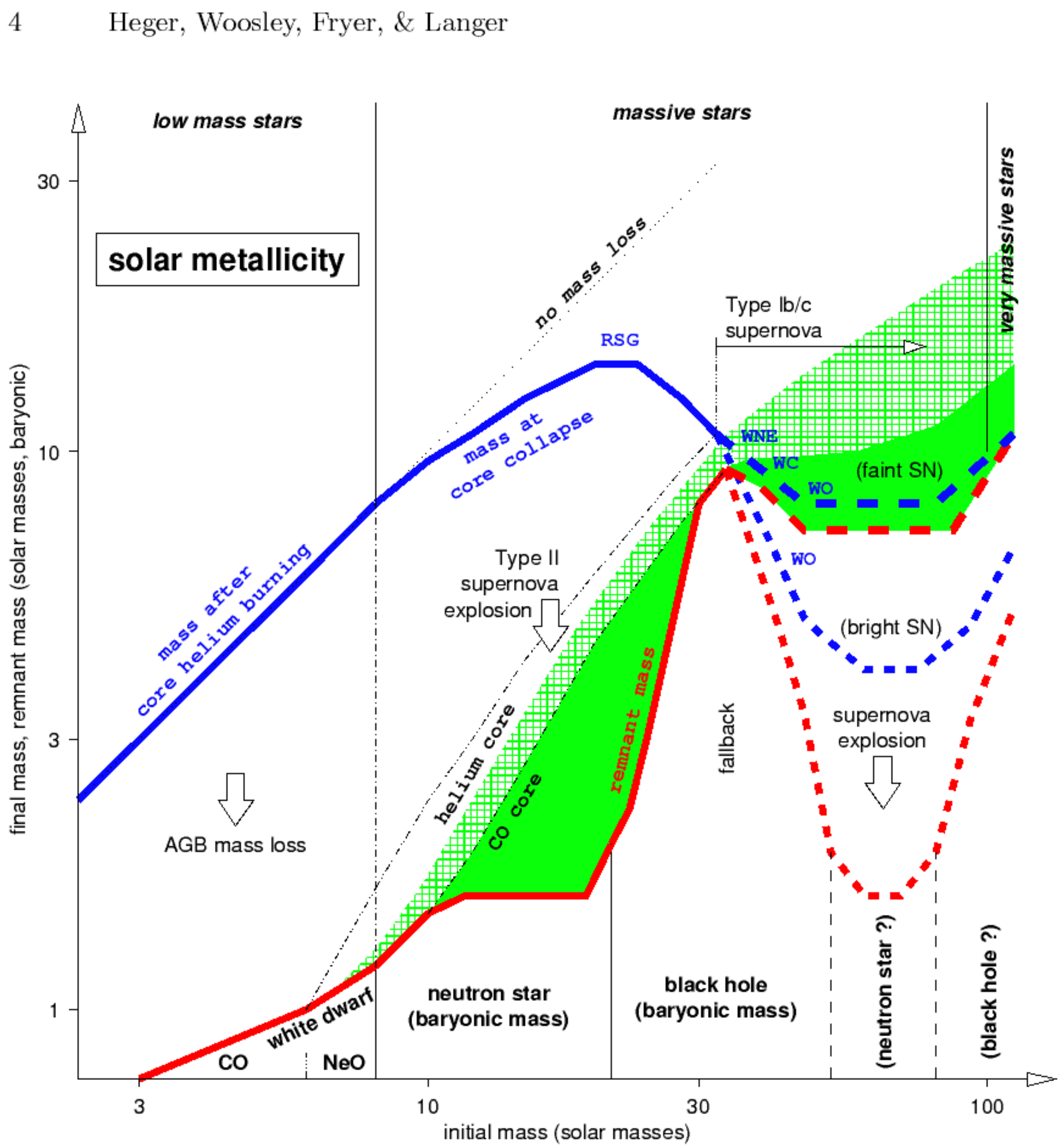
- large observed diversity of supernova types and sub-types

→ large diversity of evolutionary paths for massive stars?

- discuss the role of
  - ▷ metallicity and mass loss
  - ▷ rotation and magnetic fields
  - ▷ binary evolution
- for envelope evolution and core evolution and final fate

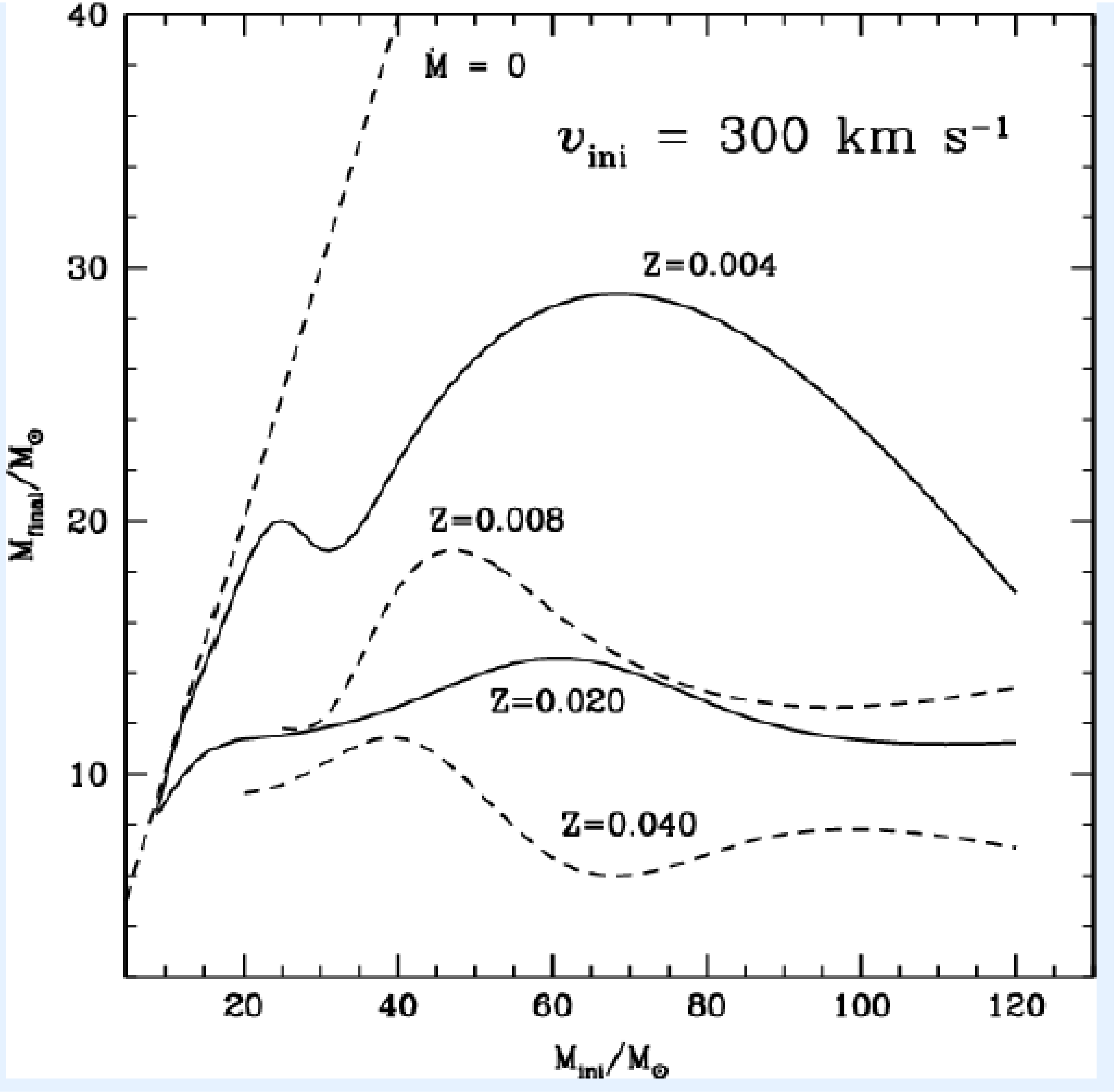


“Geneva models” (Schaller et al. 1992)

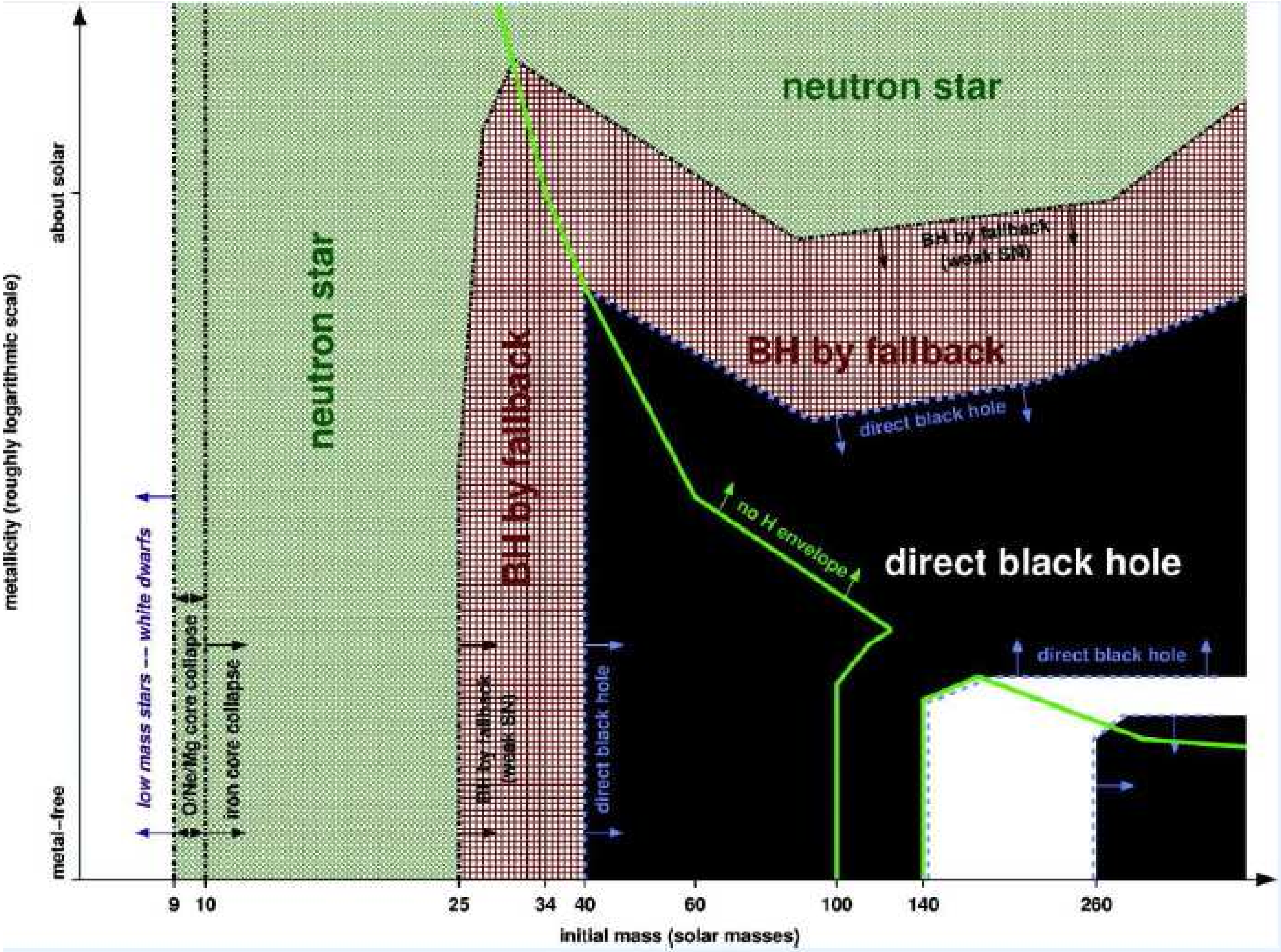


Heger et al. (2003)

Final Masses as a Function of Z



Meynet & Maeder (2005)

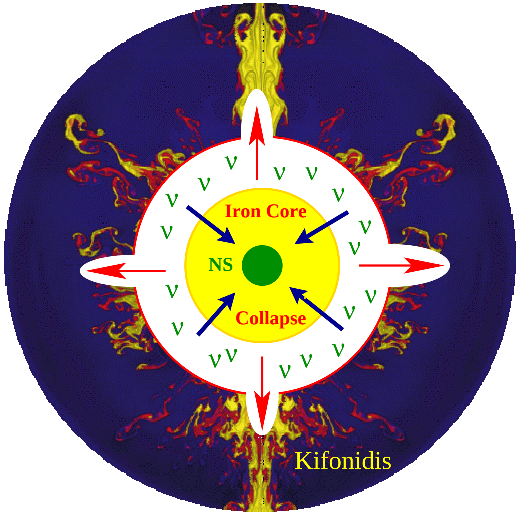


Heger et al. (2003)

Neutron Star Formation

Iron core collapse

- inert iron core ($> M_{\mathrm{Ch}}$) collapses
  - ▷ presently favoured model: delayed neutrino heating to drive explosion



Electron-capture supernovae

- occurs in degenerate ONeMg core
  - ▷ at a critical density ($4.5 \times 10^9\,\mathrm{g\,cm^{-3}}$), corresponding to a critical ONeMg core mass ($1.370 \pm 0.005\,M_\odot$), electron captures onto ^{24}Mg removes electrons (pressure support!)

→ triggers collapse to form a low-mass neutron star

note: essentially the whole core collapses

→ easier to eject envelope/produce supernova

→ no significanct ejection of heavy elements

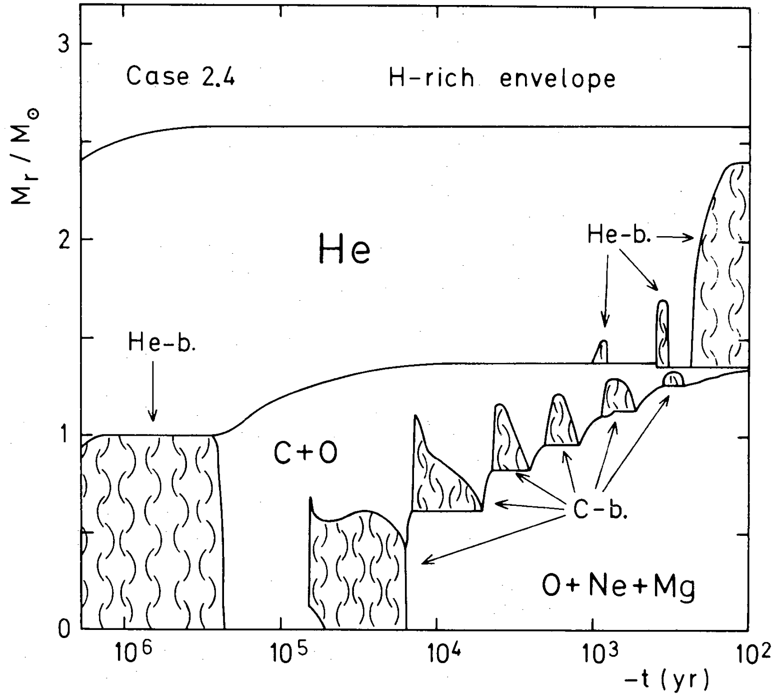
The Progenitors of E-capture Supernovae
(Nomoto 1982, 1984)

- He cores with $M_{He} = 2.0 - 2.5\,M_\odot$ lead to e-capture supernova ($M_{MS} = 8 - 10\,M_\odot$)
- significant fraction of neutron stars (NSs) produced in e-capture supernova
- Crab pulsar:
  - ▷ can explain low kinetic energy of ejecta ($\lesssim 10^{50}$ erg)

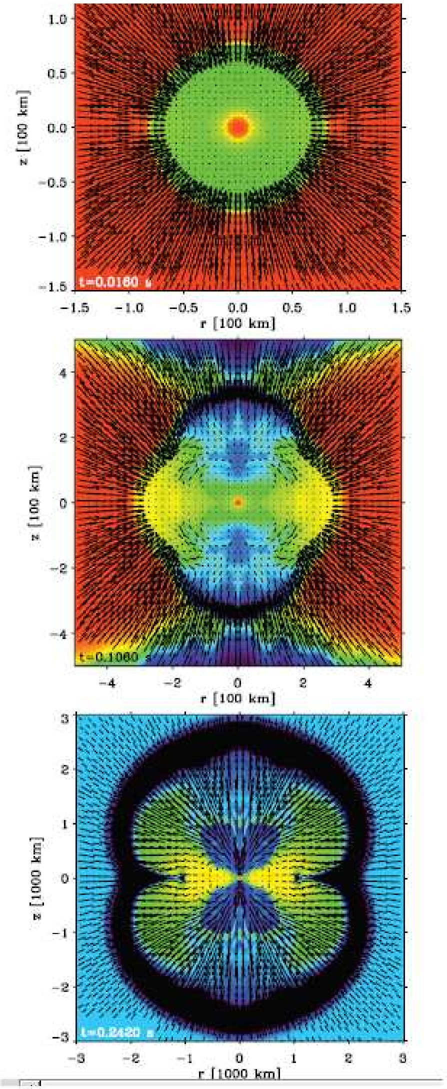
but: no hydrogen

→ loss of H-rich envelope by binary interaction?

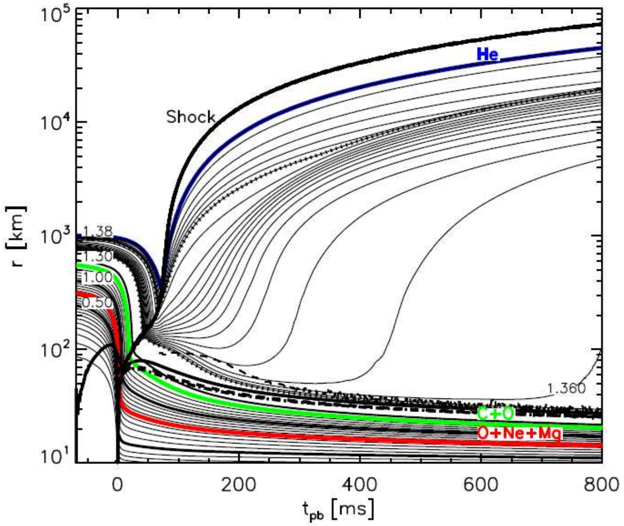
→ requires reverse evolution + binary break-up (→ space velocity?) (Pols, Nomoto)



Simulations of E-capture Supernovae



Dessart et al. (2006)



Kitaura, Janka, Hillebrandt (2006)

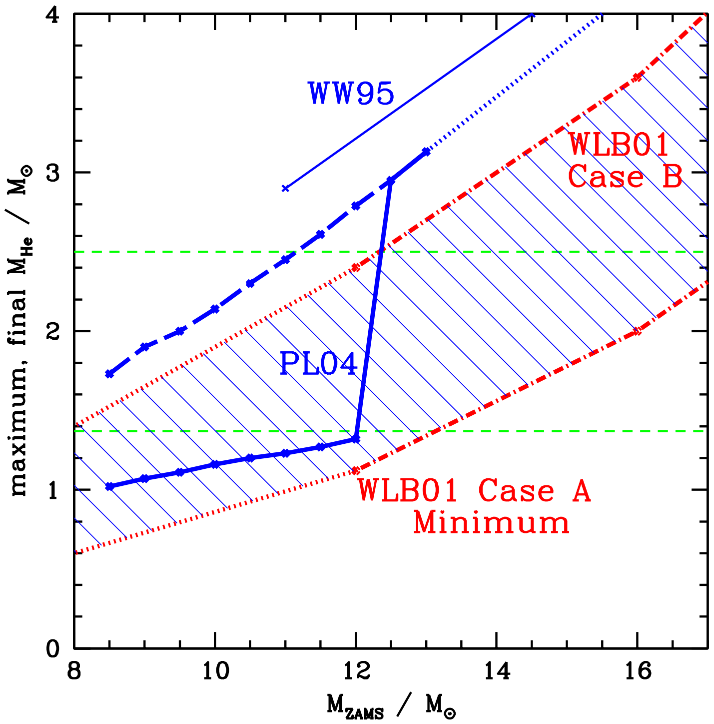
Recent simulations confirm

- successful explosion by delayed neutrino mechanism
- low explosion energy: $\sim$ few $\times\ 10^{50}$ erg (low binding energy; also Crab!)
- few metals ejected
- fast explosion: $100 - 200\,$ms

→ low neutron-star kick

▷ “best” present model for NS kick: standing accretion shock instability (Blondin, Mezzacappa, Foglizzo, Janka) requires slow explosion ($\gtrsim 500\,$ms) for instability to grow

Binary Evolution Effects



- dredge-up in AGB phase may prevent ONeMg core from reaching M_{crit} → ONeMg WD instead of collapse
- can be avoided if H envelope is removed by binary mass transfer

→ dichotomous kick scenario (P. et al. 2004)

- ▷ e-capture SN in close binaries → low kick
- ▷ iron core collapse → high kick

- can explain
  - ▷ all single pulsars seem to have received large kicks (Hobbs, Lyne, Lorimer)
  - ▷ but need low kicks in some X-ray binaries (e.g. X Per) with low eccentricity (Pfahl)
  - ▷ retention of neutron stars in globular clusters (Pfahl, Ivanova, Belczyński)
  - ▷ double neutron star properties (v.d. Heuvel, Dewi), specifically the double pulsar

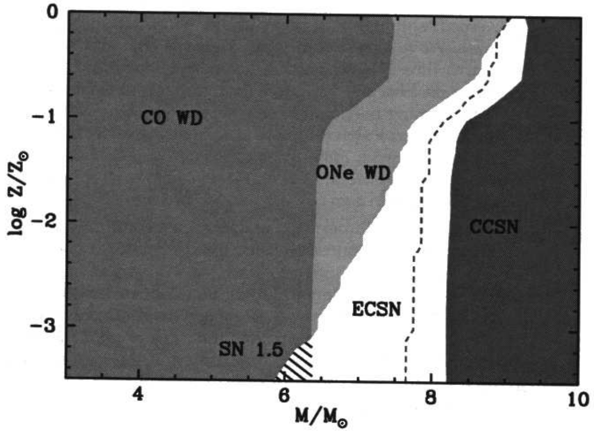
Recent Work

Arend Jan Poelarends (PhD Thesis):

- examined conditions for e-capture SNe on **metallicity, wind mass loss, dredge-up efficiency** in AGB stars
- **best model:** no e-capture SN at solar Z

Pols: mass transfer in He-star binaries may prevent e-capture SN → reduced parameter space

- **but:** possibility of binary break-up **(Crab?)**

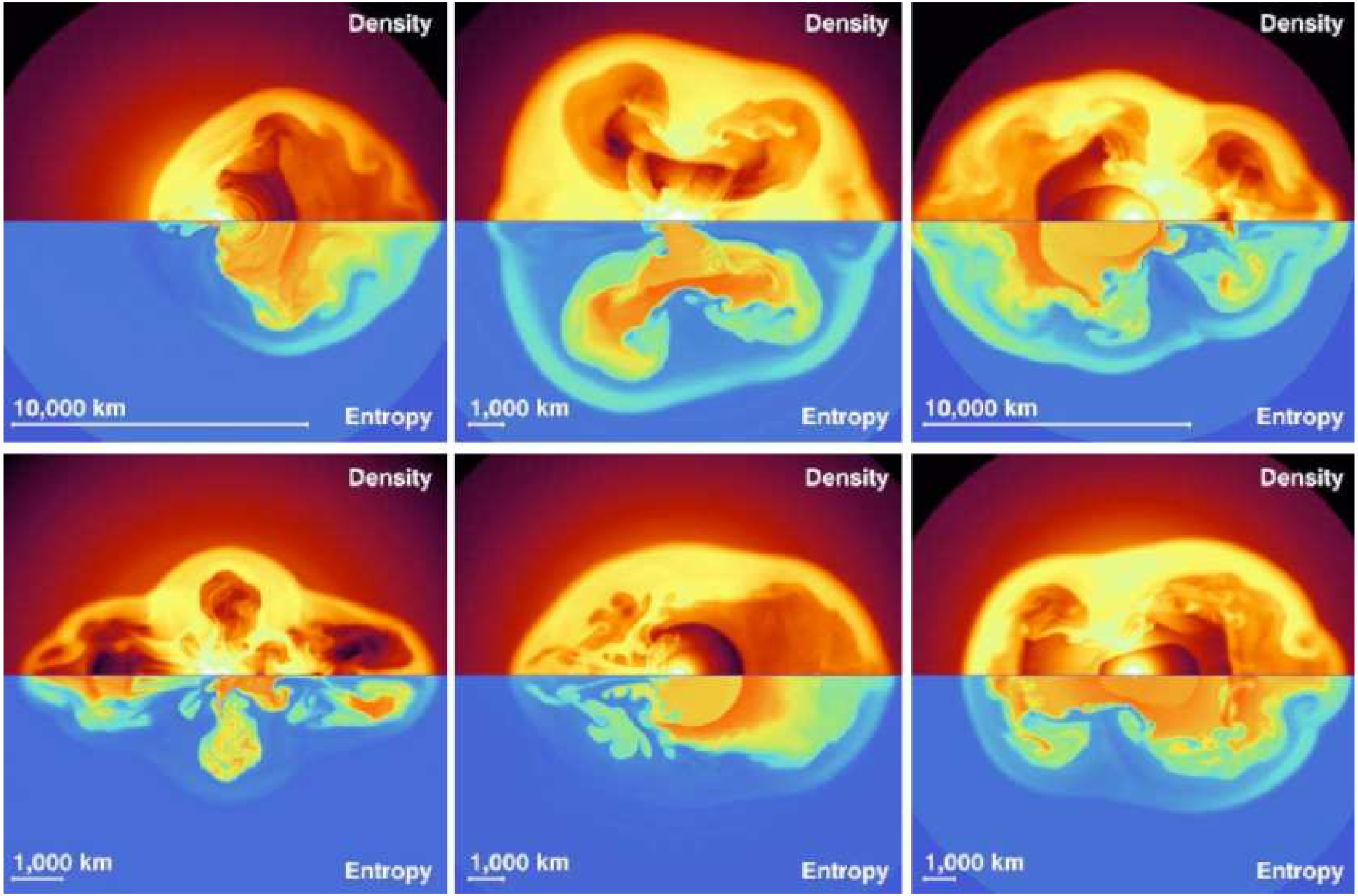


The origin of supernova kicks

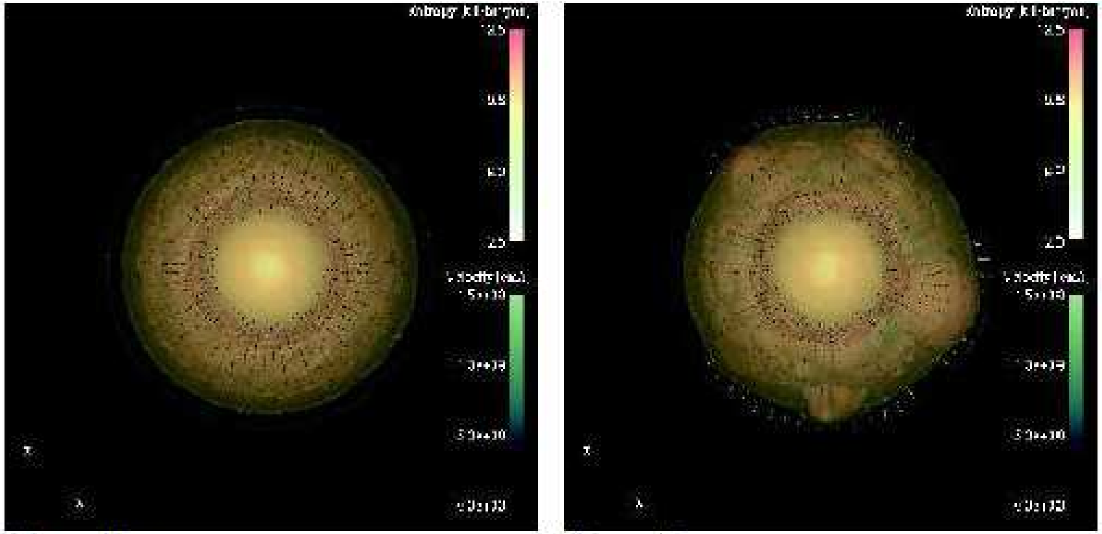
- dramatic recent progress in neutrino-driven core-collapse simulations
- supernova kicks produced by standing accretion shock instability (SASI) (Blondin, Mezzacappa, Foglizzo, Janka)
- driven by advective-acoustic instability
- $l = 1$ instability
- comes in two flavours:
  - ▷ sloshing instability ($m = 0$)
  - ▷ spiral mode ($m = \pm 1$)
- can produce kicks of a few $100\,\mathrm{km\,s^{-1}}$ if the collapse phase lasts $\gtrsim 500\,\mathrm{ms}$ (many growth timescale)
- can torque the proto-NS and produce the pulsar spin ($P_{\mathrm{spin}} \sim 100 - 200\,\mathrm{ms}$) (Blondin & Mezzacappa 2007)

Sloshing Instability

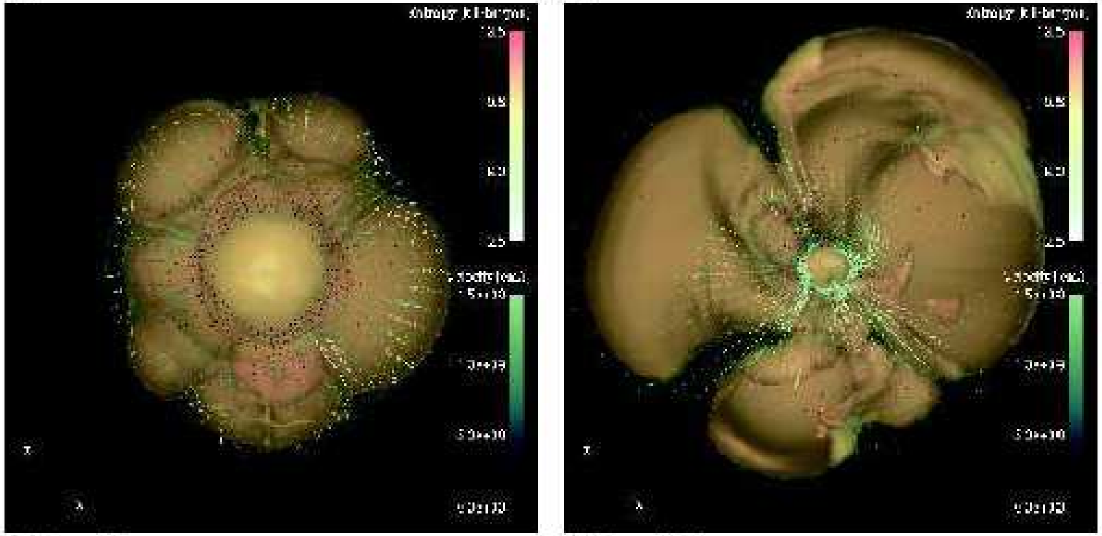
$(l = 1,\ m = 0)$



(Janka, Scheck, Foglizzo)



(a) $t = 40$ ms (b) $t = 70$ ms



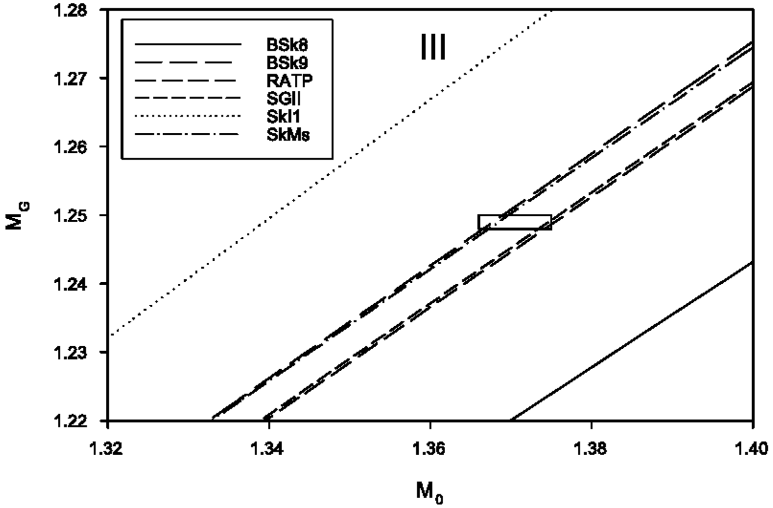
(c) $t = 80$ ms (d) $t = 350$ ms

Iwakami et al. (2008)

Testing the Equation of State of Nuclear Matter
(P. et al. 2005)

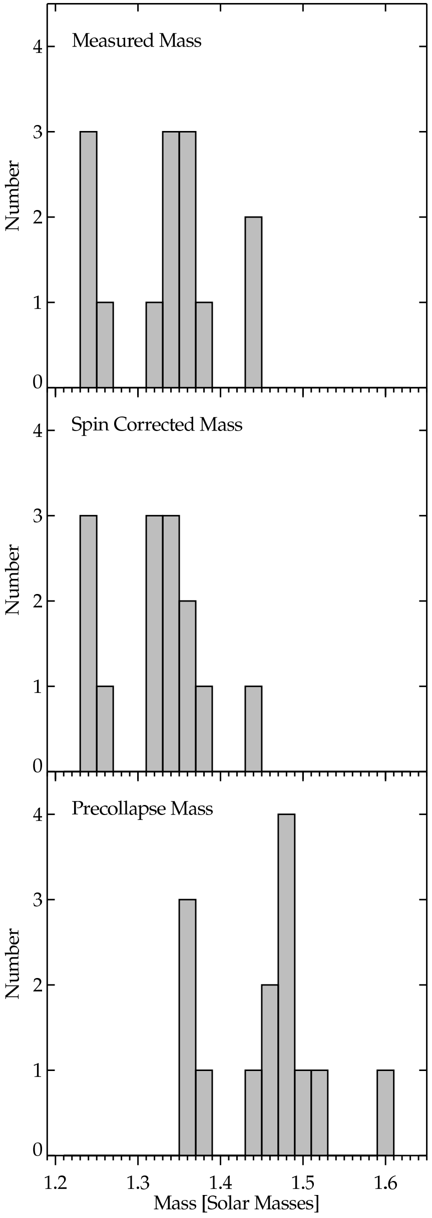
- critical density for e-capture in ONeMg core → critical collapse mass: $\mathrm{M_{crit}} = 1.370 \pm 0.005\,\mathrm{M_\odot}$ (Lesaffre) (no rotation!)
- post-SN NS mass = pre-collapse core mass − binding energy
- binding energy depends on the equation of state

complications: core mass loss in explosion (a few $10^{-3}\,\mathrm{M_\odot}$)



(Newton, Miller, Stone)

Schwab, Podsiadlowski & Rappaport (2010)



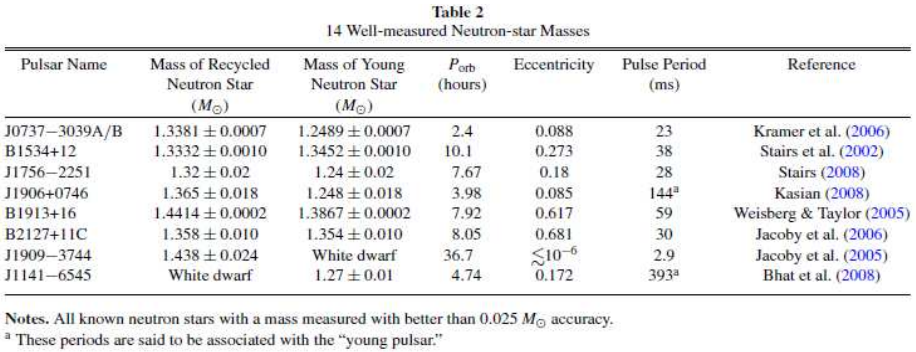


Table 2
14 Well-measured Neutron-star Masses

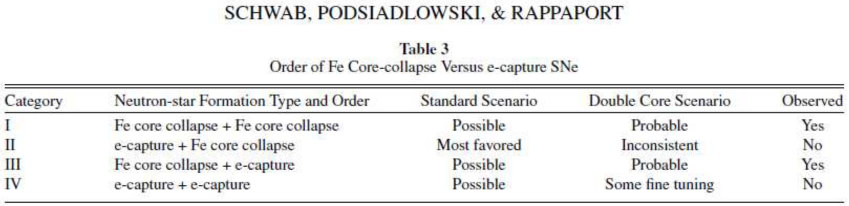
Pulsar Name	Mass of Recycled Neutron Star ($M_\odot$)	Mass of Young Neutron Star ($M_\odot$)	$P_{\rm orb}$ (hours)	Eccentricity	Pulse Period (ms)	Reference
J0737−3039A/B	1.3381 ± 0.0007	1.2489 ± 0.0007	2.4	0.088	23	Kramer et al. (2006)
B1534+12	1.3332 ± 0.0010	1.3452 ± 0.0010	10.1	0.273	38	Stairs et al. (2002)
J1756−2251	1.32 ± 0.02	1.24 ± 0.02	7.67	0.18	28	Stairs (2008)
J1906+0746	1.365 ± 0.018	1.248 ± 0.018	3.98	0.085	144[a]	Kasian (2008)
B1913+16	1.4414 ± 0.0002	1.3867 ± 0.0002	7.92	0.617	59	Weisberg & Taylor (2005)
B2127+11C	1.358 ± 0.010	1.354 ± 0.010	8.05	0.681	30	Jacoby et al. (2006)
J1909−3744	1.438 ± 0.024	White dwarf	36.7	$\lesssim 10^{-6}$	2.9	Jacoby et al. (2005)
J1141−6545	White dwarf	1.27 ± 0.01	4.74	0.172	393[a]	Bhat et al. (2008)

Notes. All known neutron stars with a mass measured with better than 0.025 $M_\odot$ accuracy.

[a] These periods are said to be associated with the "young pulsar."

- Schwab et al. (2010): looking only at NS with well-determined masses → bimodal NS mass distribution with e-capture and Fe core collapse peak

but prediction: first SN more likely to be e-capture → may disfavour standard model for double pulsars



SCHWAB, PODSIADLOWSKI, & RAPPAPORT

Table 3
Order of Fe Core-collapse Versus e-capture SNe

Category	Neutron-star Formation Type and Order	Standard Scenario	Double Core Scenario	Observed
I	Fe core collapse + Fe core collapse	Possible	Probable	Yes
II	e-capture + Fe core collapse	Most favored	Inconsistent	No
III	Fe core collapse + e-capture	Possible	Probable	Yes
IV	e-capture + e-capture	Possible	Some fine tuning	No

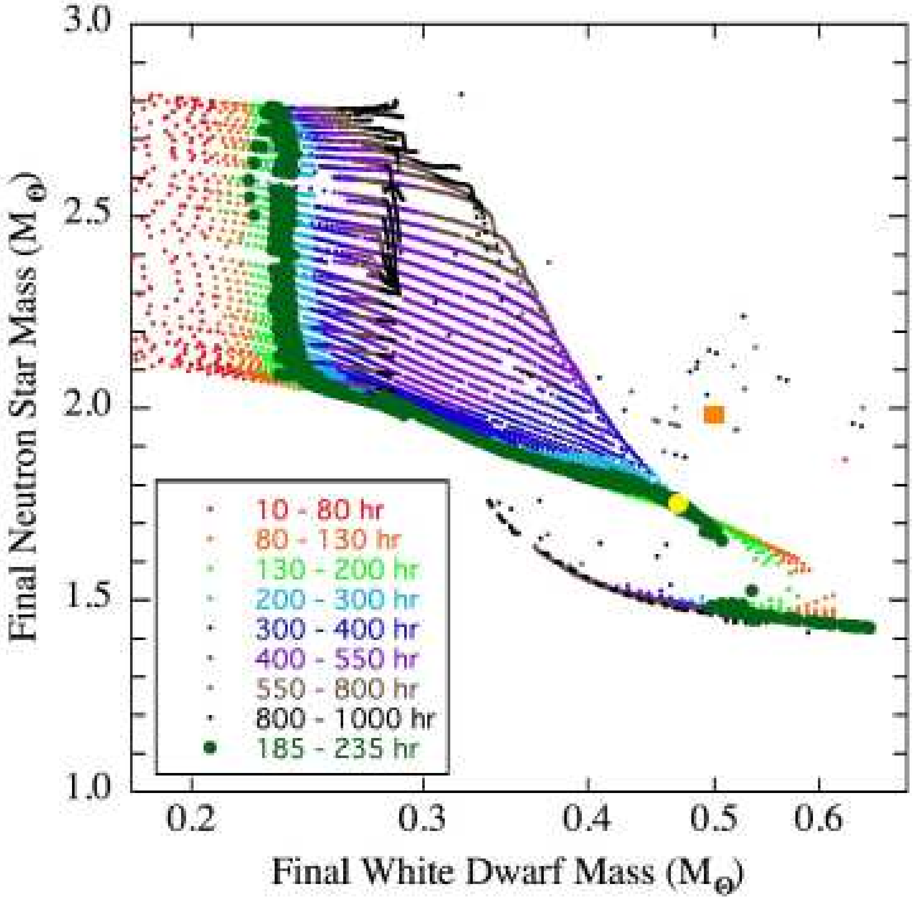
- is there a third peak in the NS mass distribution? (Timmes, van den Heuvel; Vela X-1?)

- Demorest et al. (2010): PSR 1614-2230
  - ▷ $M_{NS} = 1.97 \pm 0.04\,M_\odot$, $M_{WD} = 0.5\,M_\odot$
  - ▷ massive WD requires intermediate-mass progenitor (Li et al. 2011; Tauris et al. 2011)

→ relatively massive NS at birth ($> 1.6\,M_\odot$)

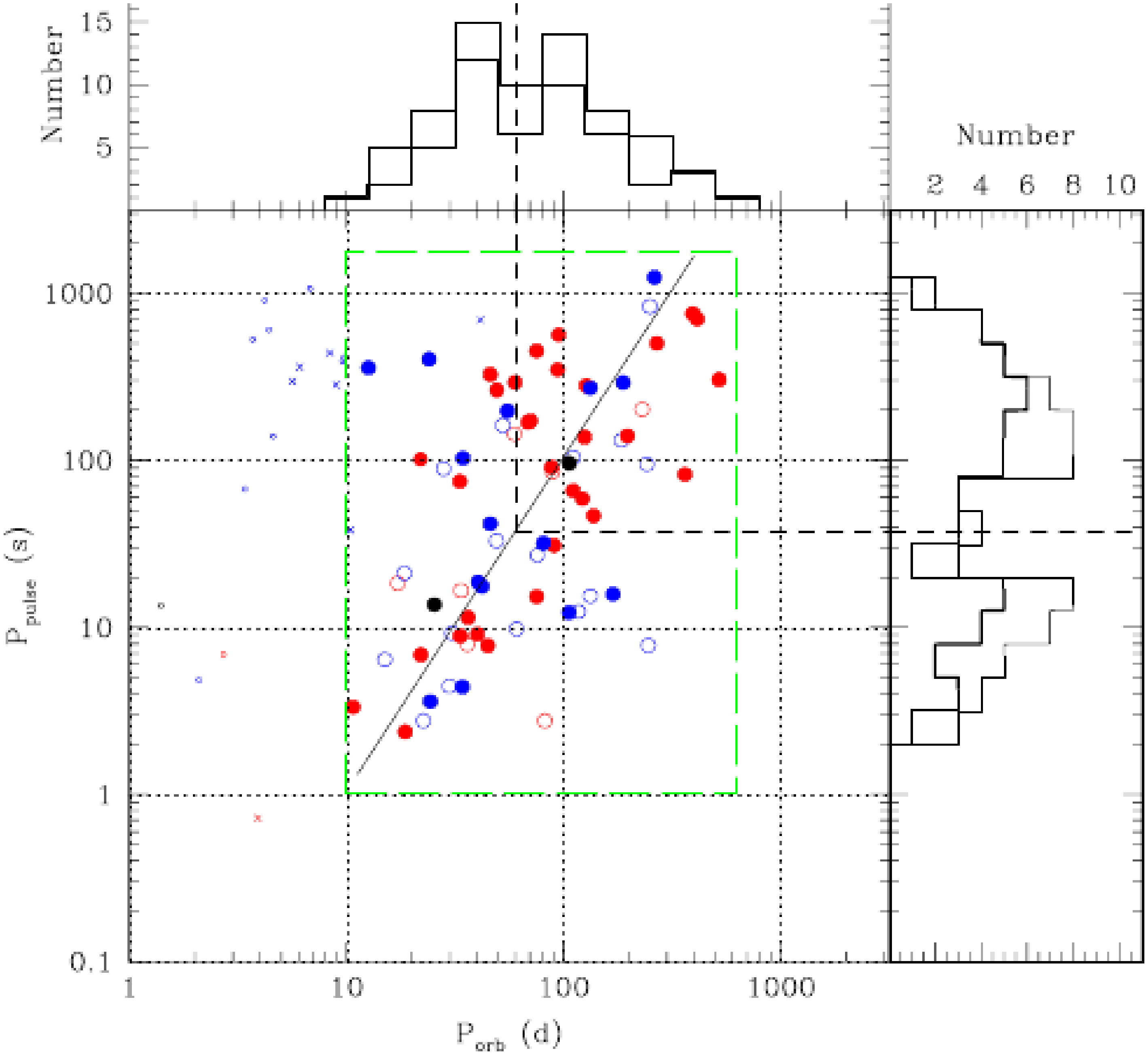
- Janssen et al. (2008): PSR J1518+4904
  - ▷ double-NS system with $M_1 < 1.17\,M_\odot$, $M_2 > 1.55\,M_\odot$
  - ▷ lowest NS mass (from direct collapse):

    Chandrasekhar mass for Fe core ($\sim 1.27\,M_\odot$) → $M_{NS}^{min} \sim 1.15\,M_\odot$

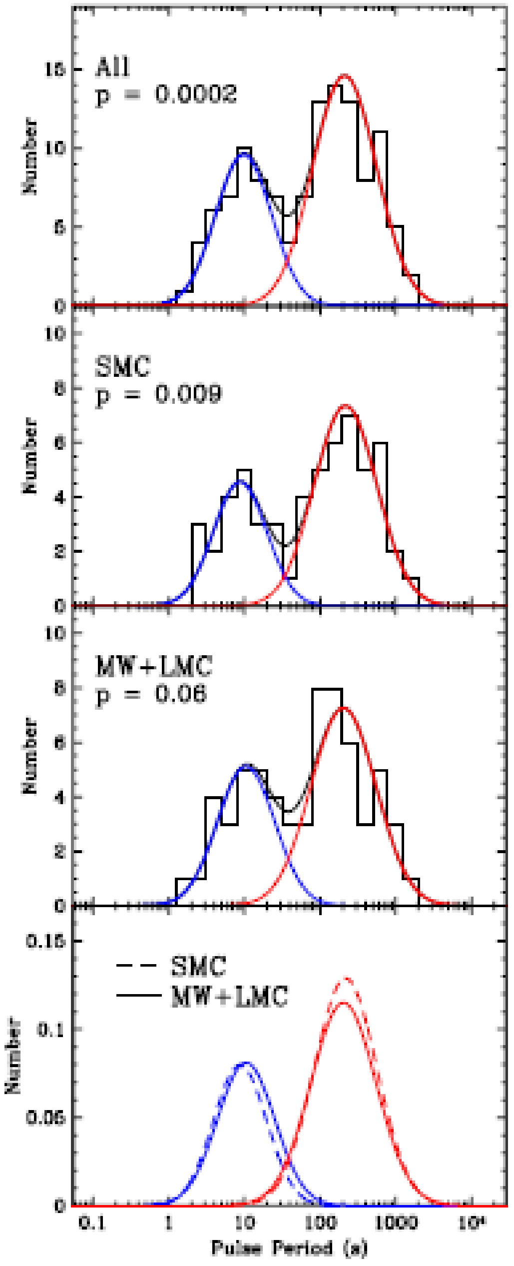


Li, Rappaport, Podsiadlowski (2011)

Knigge, Coe & Podsiadlowski (2011)



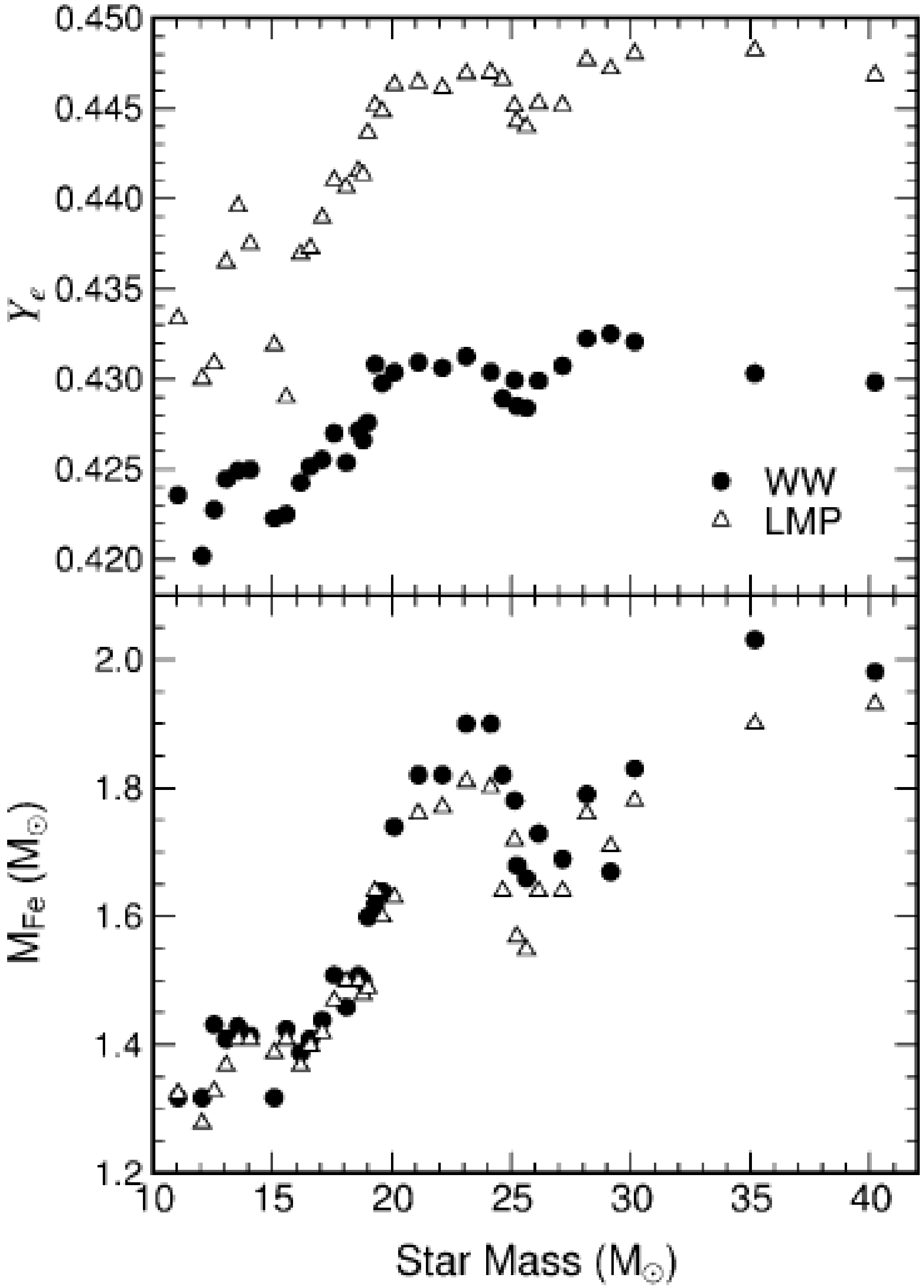
Knigge, Coe & Podsiadlowski (2011)



- spin period may be a better proxy for NS formation channel (?)
- comparable numbers of Fe core collapse and e-capture NSs
  - ▷ not consistent with simple BPS, but probably once case BB mass transfer is taken into account (work in progress)
- Be X-ray binaries may be useful for constraining NS formation and the formation of double NS binaries

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 in a binary (or inside AGB envelope at low Z?)
- He detonation on accreting CO white dwarf → explosive → supernova-like (faint SN Ia?)
- pair-instability supernova for very massive stars (low Z?) ($> 140\,\mathrm{M}_\odot$): creation of electron/positron pairs → explosive nuclear burning → complete disruption of the star

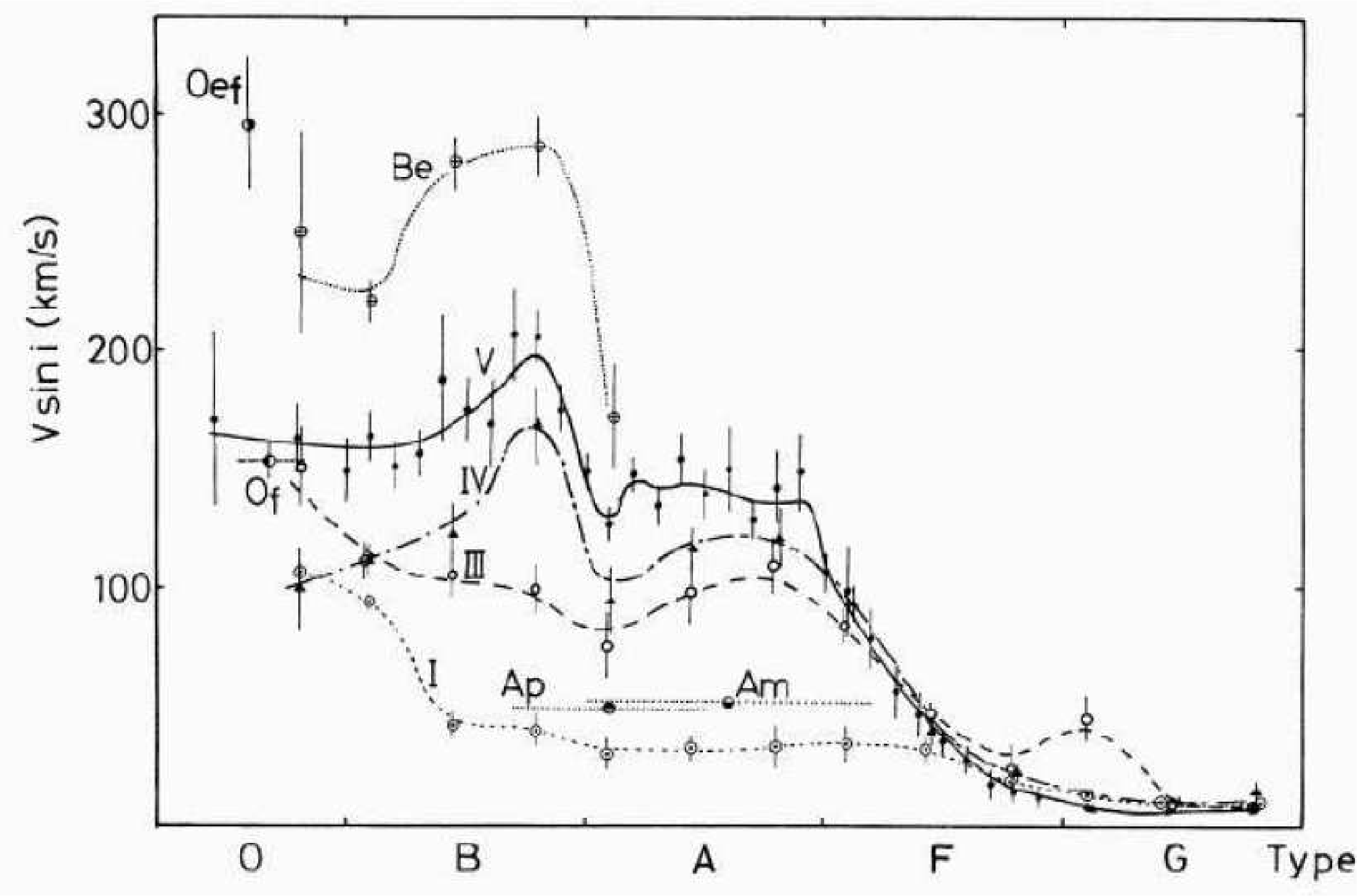


Heger et al. (2001)

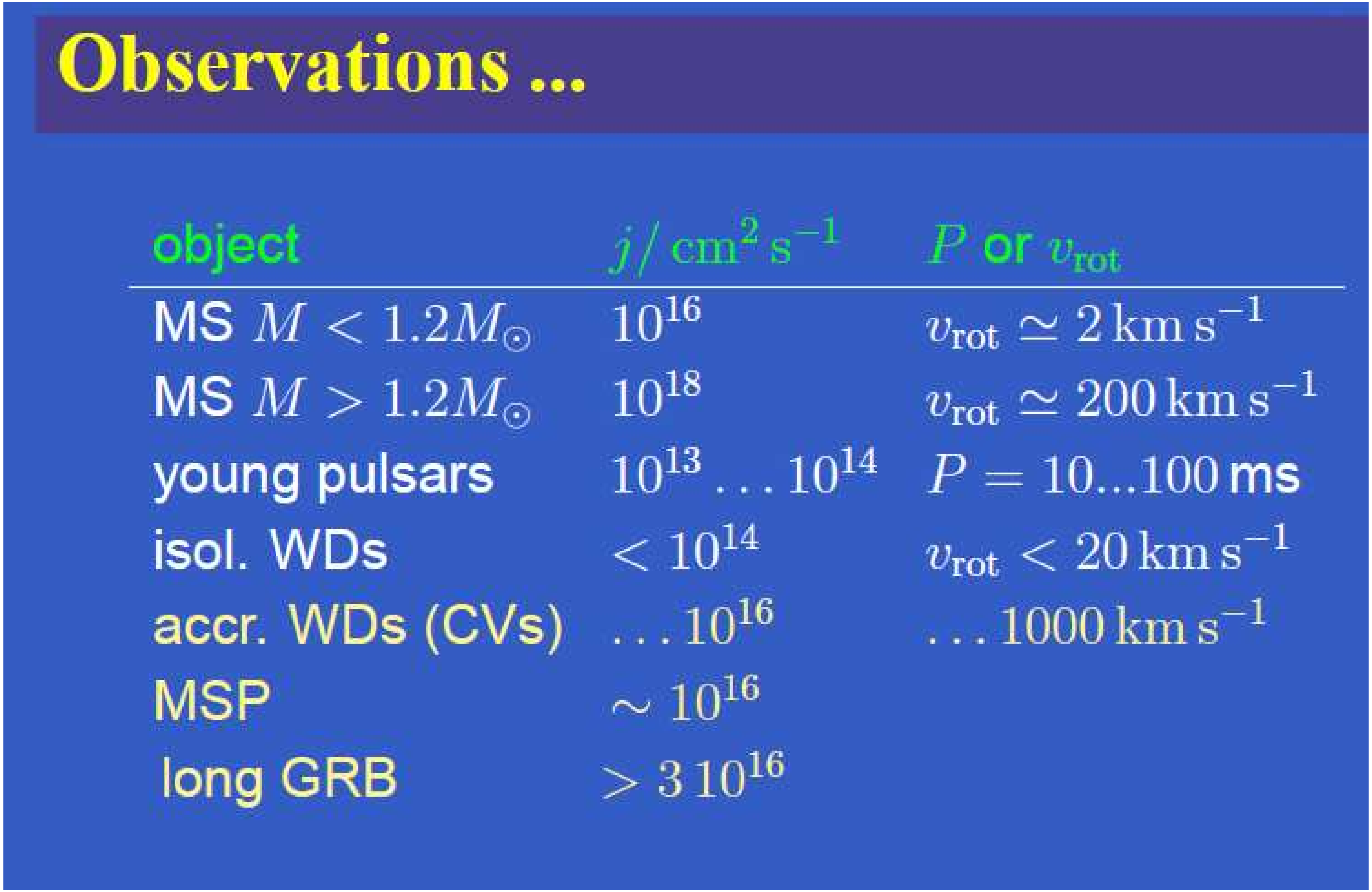
Causes of Massive Star/Supernova Diversity

- 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?)

Main-Sequence Rotation



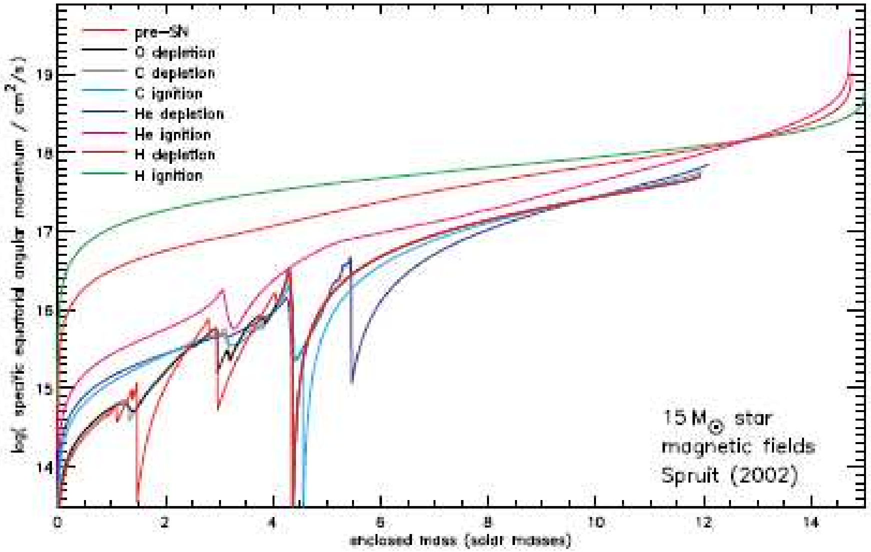
Fukuda (1982)

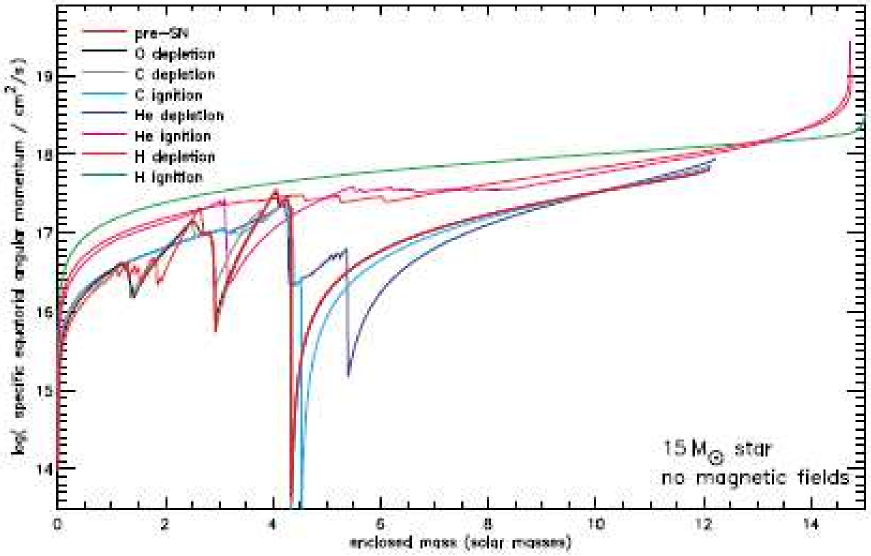


Observations ...

object	$j/\,\mathrm{cm^2\,s^{-1}}$	P or v_rot
MS $M < 1.2 M_\odot$	10^{16}	$v_\mathrm{rot} \simeq 2\,\mathrm{km\,s^{-1}}$
MS $M > 1.2 M_\odot$	10^{18}	$v_\mathrm{rot} \simeq 200\,\mathrm{km\,s^{-1}}$
young pulsars	$10^{13} \ldots 10^{14}$	$P = 10...100$ ms
isol. WDs	$< 10^{14}$	$v_\mathrm{rot} < 20\,\mathrm{km\,s^{-1}}$
accr. WDs (CVs)	$\ldots 10^{16}$	$\ldots 1000\,\mathrm{km\,s^{-1}}$
MSP	$\sim 10^{16}$	
long GRB	$> 3\,10^{16}$	

(from N. Langer)

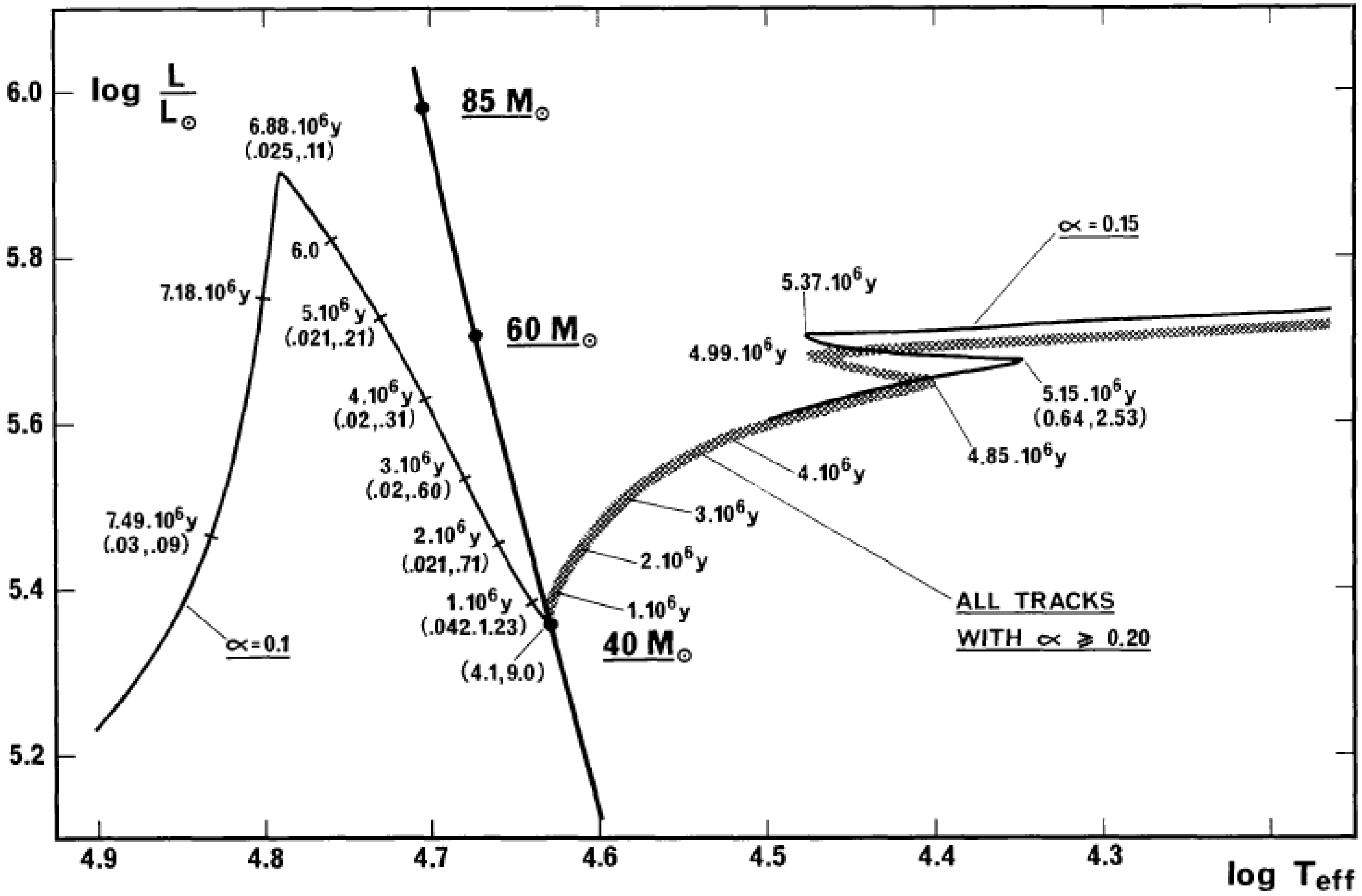




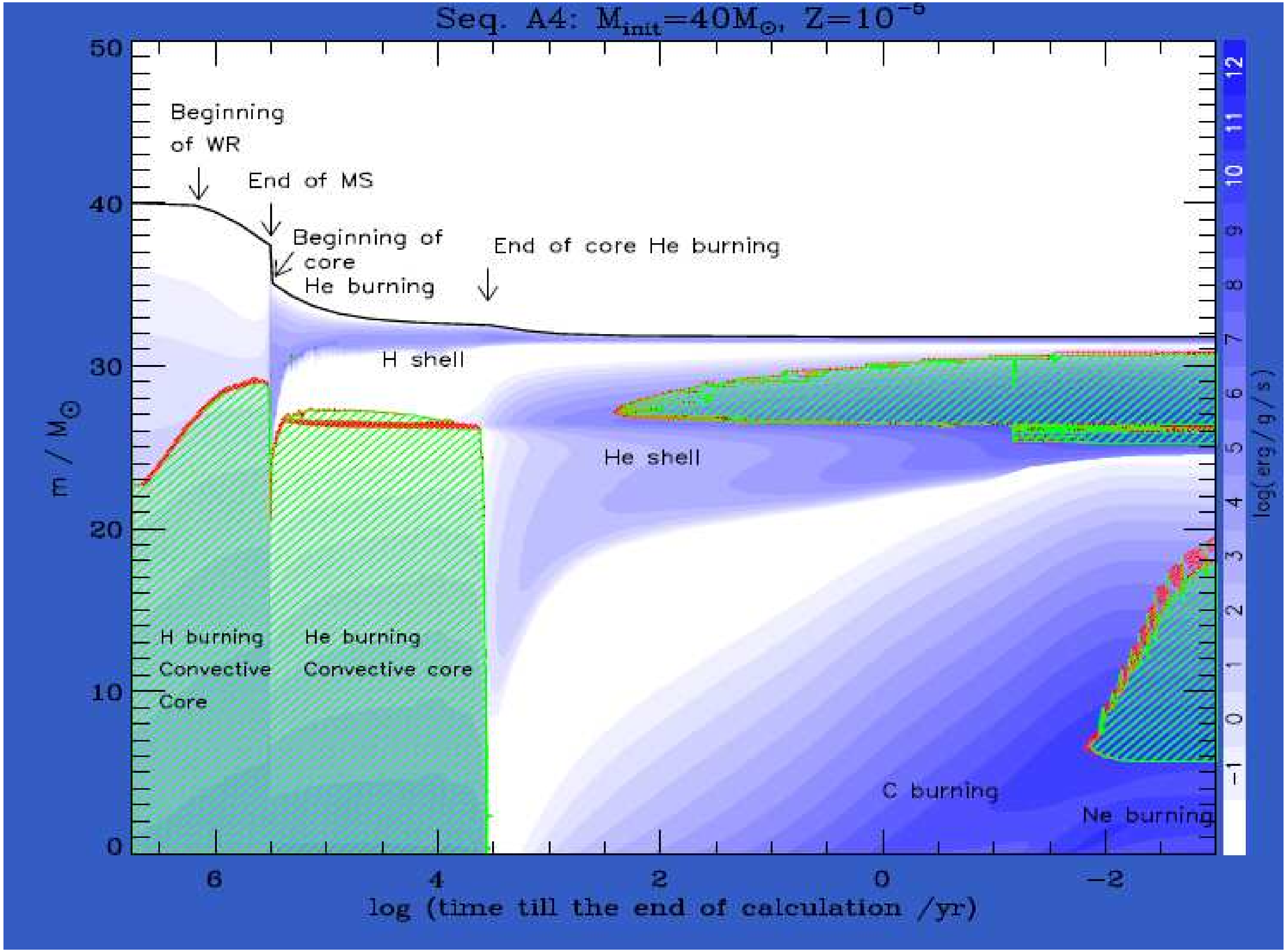
Heger et al. (2005)

The role of rapid rotation

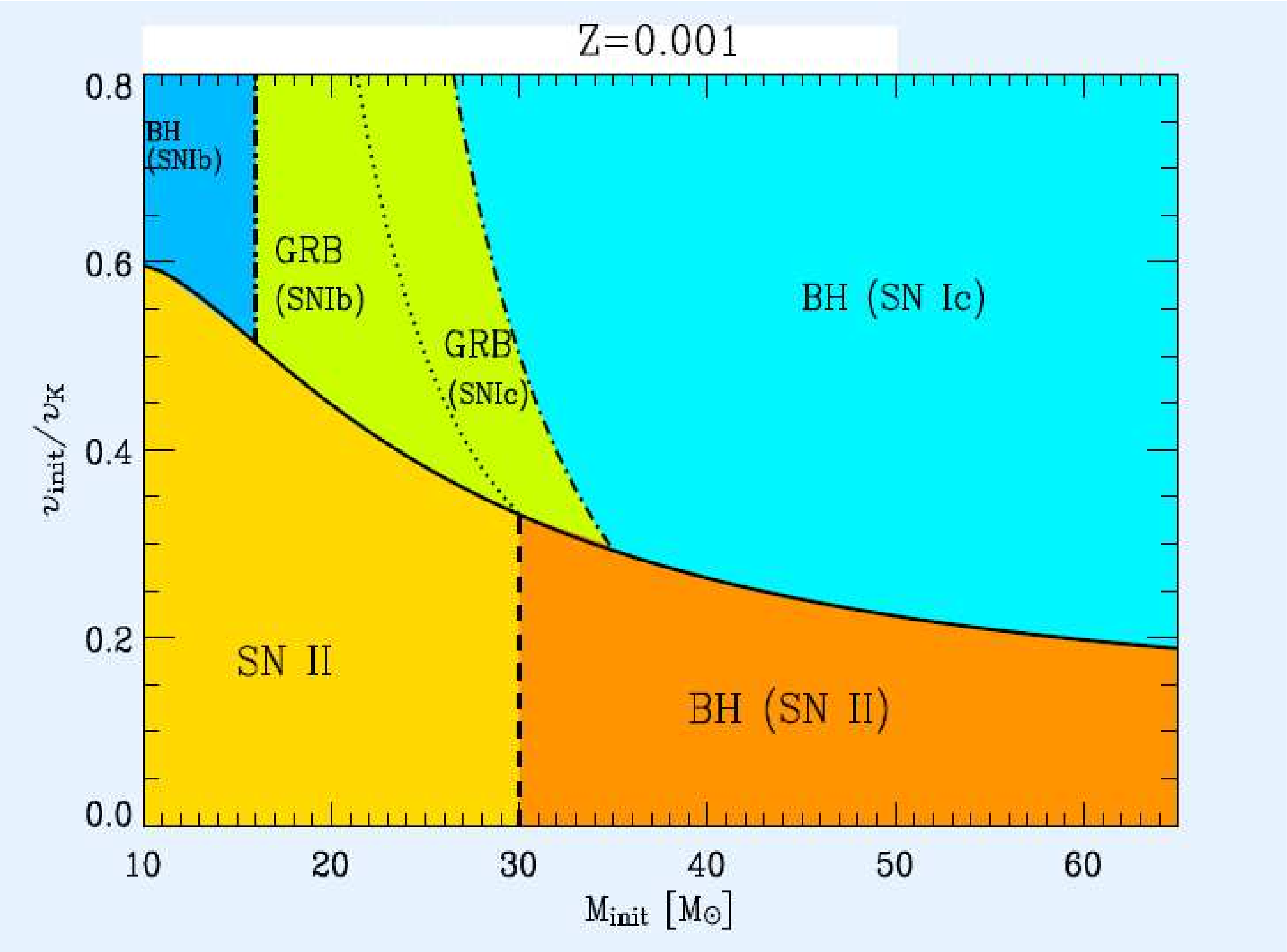
- homogeneous evolution for very rapily rotating MS stars
- stars evolve to the blue (i.e. skip red-giant phase)



Maeder (1987)



Yoon & Langer (2005) [also Woosley & Heger (2006)]



Yoon et al. (2006)

Binary Interactions

- most stars are members of binary systems
- a large fraction are members of interacting binaries (30 – 50 %)

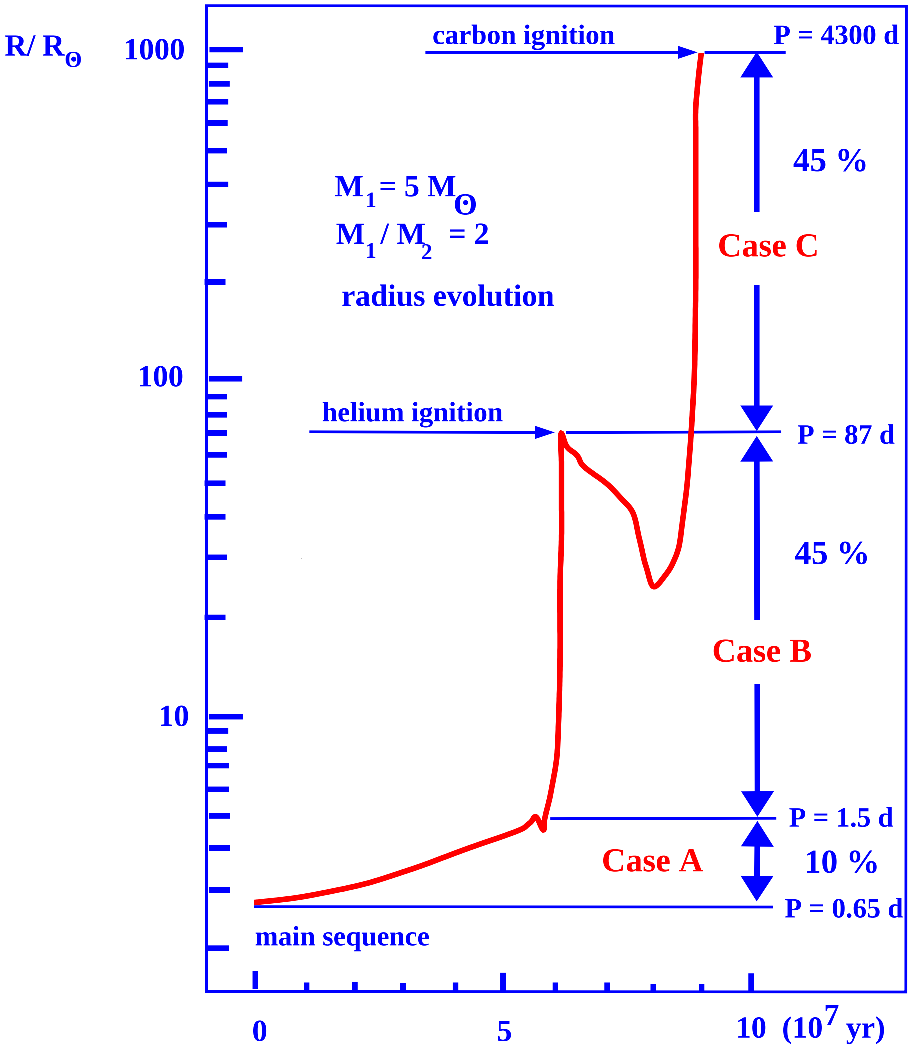
Sana et al. (2012):

$\boxed{75\,\%\ \text{for O stars with } M \gtrsim 15\,M_\odot}$

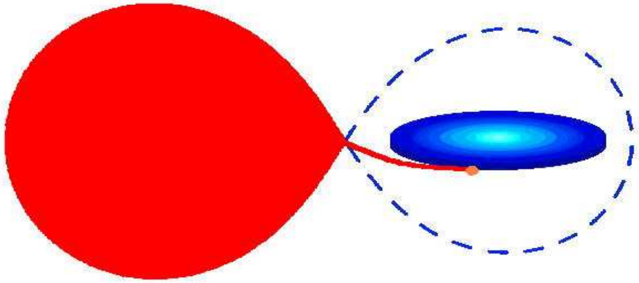
- note: mass transfer is more likely for post-MS systems
- mass-ratio distribution:
  - ▷ for massive stars: masses correlated
  - ▷ for low-mass stars: less certain
- binary interactions
  - ▷ common-envelope (CE) evolution
  - ▷ stable Roche-lobe overflow
  - ▷ binary mergers
  - ▷ wind Roche-lobe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

Classification of Roche-lobe overflow phases

(Paczynski)

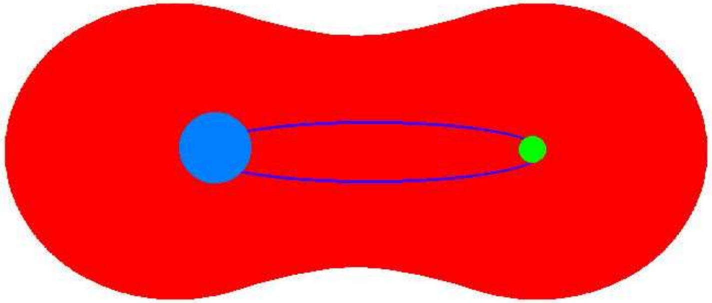


Stable Mass Transfer



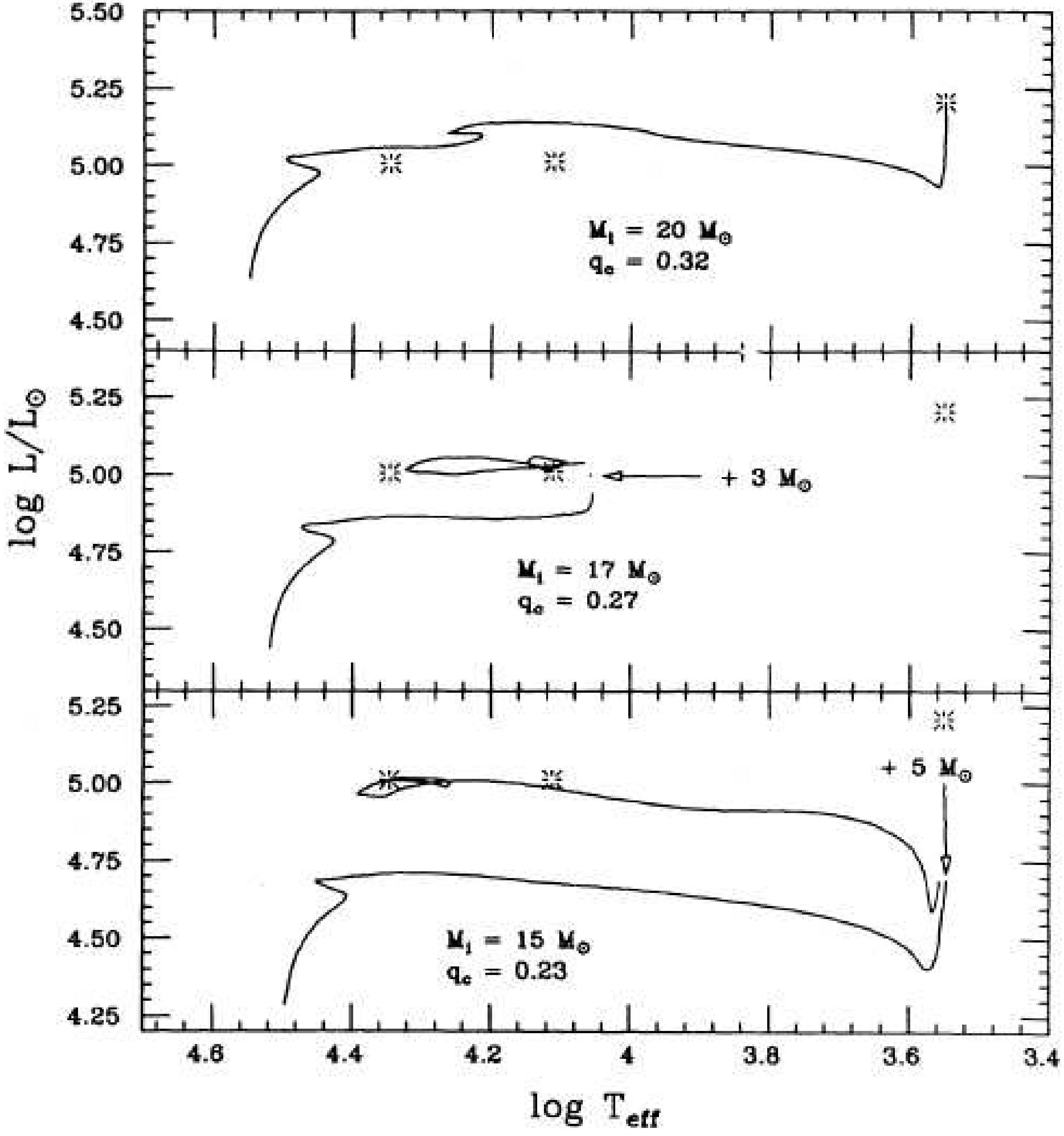
- mass transfer is **'largely' conservative**, except at very mass-transfer rates
- **mass loss + mass accretion**
- the mass loser tends to lose most of its envelope → formation of **helium stars**
- the accretor tends to be **rejuvenated (i.e. behaves like a more massive star with the evolutionary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



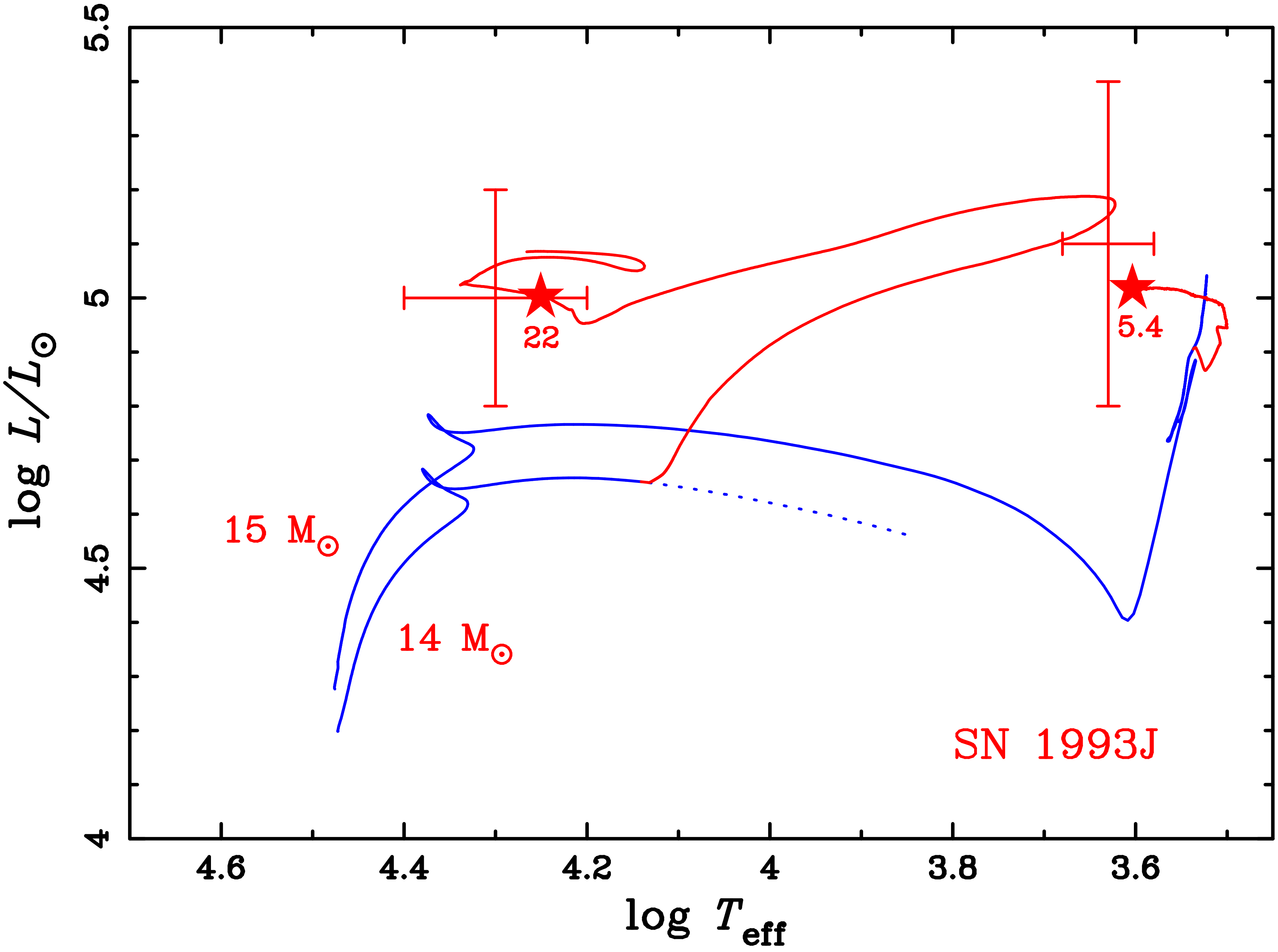
The Progenitor of SN 1993J

- 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 1993)
- 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?

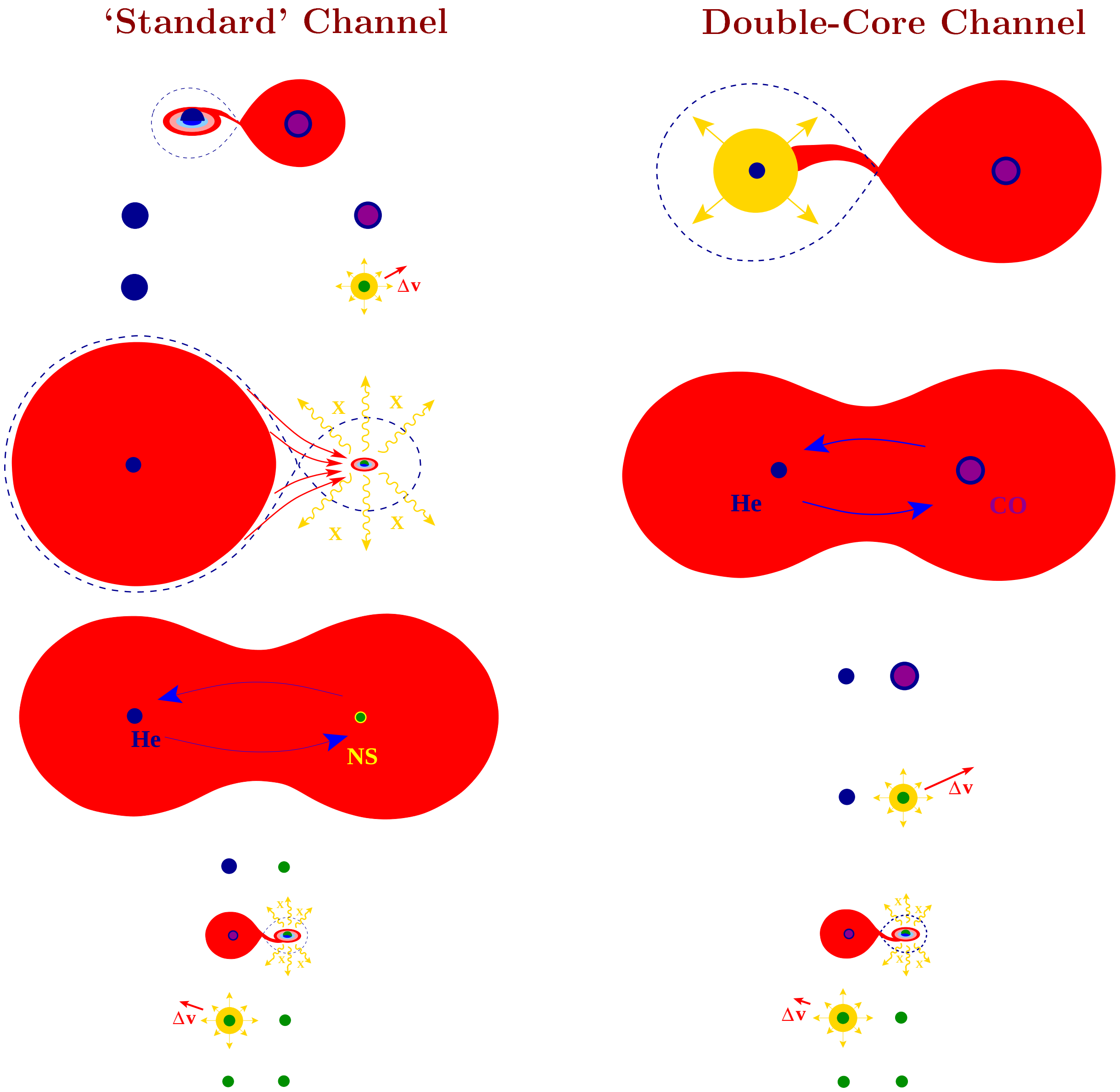
Maund et al. (2004)



The Double Pulsar (PSR J0737-3039)

- $P_{\rm orb} = 2.4\,{\rm h}$, $M_{\rm A} = 1.338\,M_\odot$ ($P_{\rm A} = 22.7\,{\rm ms}$), $M_{\rm B} = 1.249\,M_\odot$ ($P_{\rm B} = 2.77\,{\rm s}$)
- lower-mass pulsar formed in e-capture supernova?
- circumstantial evidence:
  - ▷ low mass of $1.249\,M_\odot$ close to expected mass from e-capture SN
  - ▷ evidence for low kick: low eccentricity, low space velocity, Pulsar A spin aligned with orbital axis (no geodetic precession)

note: Pulsar B not aligned if kicks induces torque (Blondin & Mezzacappa 2007)



Initial binary: $M_1 = 14\,M_\odot$, $M_2 = 9\,M_\odot$, $P_{\rm orb} = 190\,{\rm d}$

Stable non-conservative Case B mass transfer leaving a helium star with $M_{\rm He}^{\rm A} = 4\,M_\odot$ and $M_2' = 11\,M_\odot$, $P_{\rm orb} = 350\,{\rm d}$

After first supernova (with kick $v_{\rm kick} = 50\,{\rm km\,s^{-1}}$): $M_{\rm A}' = 1.337\,M_\odot$, $M_2' = 11\,M_\odot$, $P_{\rm orb} = 8.8\,{\rm yr}$, $e = 0.82$, $\Delta v_{\rm sys}^{\rm A} = 13\,{\rm km\,s^{-1}}$

High-mass X-ray binary phase leading to unstable mass transfer and a *common-envelope and spiral-in phase* and leaving $M_{\rm A}' = 1.337\,M_\odot$, $M_{\rm He}^{\rm B} = 2.4\,M_\odot$, $P_{\rm orb} = 2.8\,{\rm hr}$

Helium star mass transfer phase (+ spin-up of neutron star) leaving $M_{\rm A} = 1.338\,M_\odot$, $M_{\rm He} = 1.559\,M_\odot$, $P_{\rm orb} = 2.6\,{\rm hr}$

Immediately after second supernova: $M_{\rm A} = 1.338\,M_\odot$, $M_{\rm B} = 1.249\,M_\odot$, $P_{\rm orb} = 3.3\,{\rm hr}$, $e = 0.12$, $\Delta v_{\rm sys}^{\rm B} = 35\,{\rm km\,s^{-1}}$

Initial binary: $M_1 = 11.5\,M_\odot$, $M_2 = 11\,M_\odot$, $P_{\rm orb} = 3.1\,{\rm yr}$

Unstable Case C mass transfer: secondary expands to fill its Roche lobe

Double-core common-envelope and spiral-in phase leaving a CO star with $M_{\rm CO} = 3.0\,M_\odot$ and a He star with $M_{\rm He} = 2.4\,M_\odot$, $P_{\rm orb} = 3.8\,{\rm hr}$

After first supernova (with kick $v_{\rm kick} = 300\,{\rm km\,s^{-1}}$): $M_{\rm A}' = 1.337\,M_\odot$, $M_{\rm He}^0 = 2.4\,M_\odot$, $P_{\rm orb} = 3.3\,{\rm hr}$, $e = 0.33$, $\Delta v_{\rm sys}^{\rm A} = 230\,{\rm km\,s^{-1}}$

Helium star mass transfer phase (+ spin-up of neutron star) leaving $M_{\rm A} = 1.338\,M_\odot$, $M_{\rm He} = 1.559\,M_\odot$, $P_{\rm orb} = 2.6\,{\rm hr}$

Immediately after second supernova: $M_{\rm A} = 1.338\,M_\odot$, $M_{\rm B} = 1.249\,M_\odot$, $P_{\rm orb} = 3.3\,{\rm hr}$, $e = 0.12$, $\Delta v_{\rm sys}^{\rm B} = 35\,{\rm km\,s^{-1}}$

Case BB Mass transfer

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

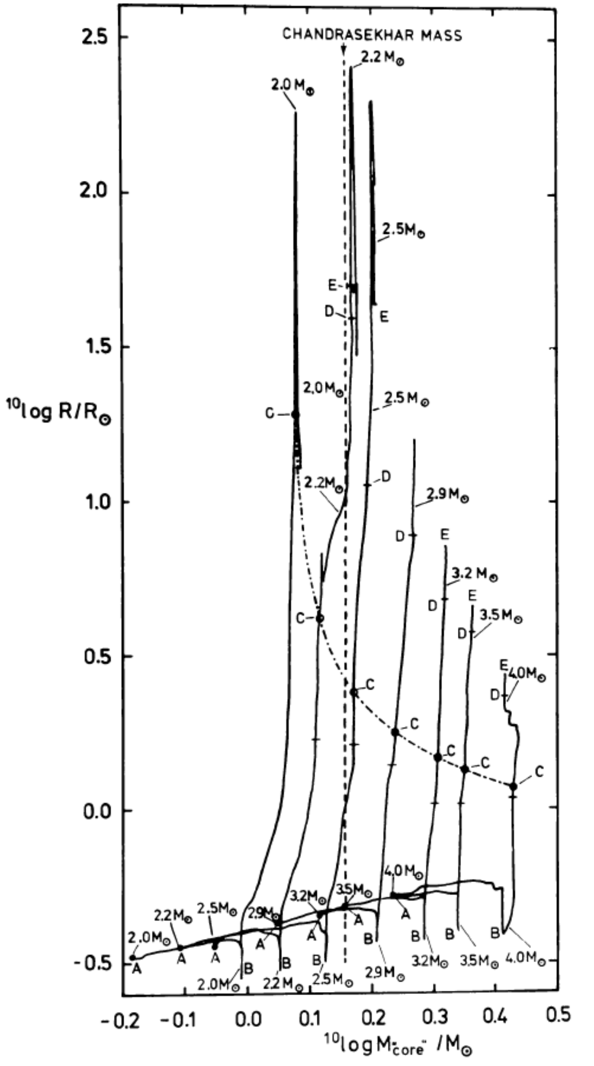
→ mass transfer from helium star to companion

→ 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

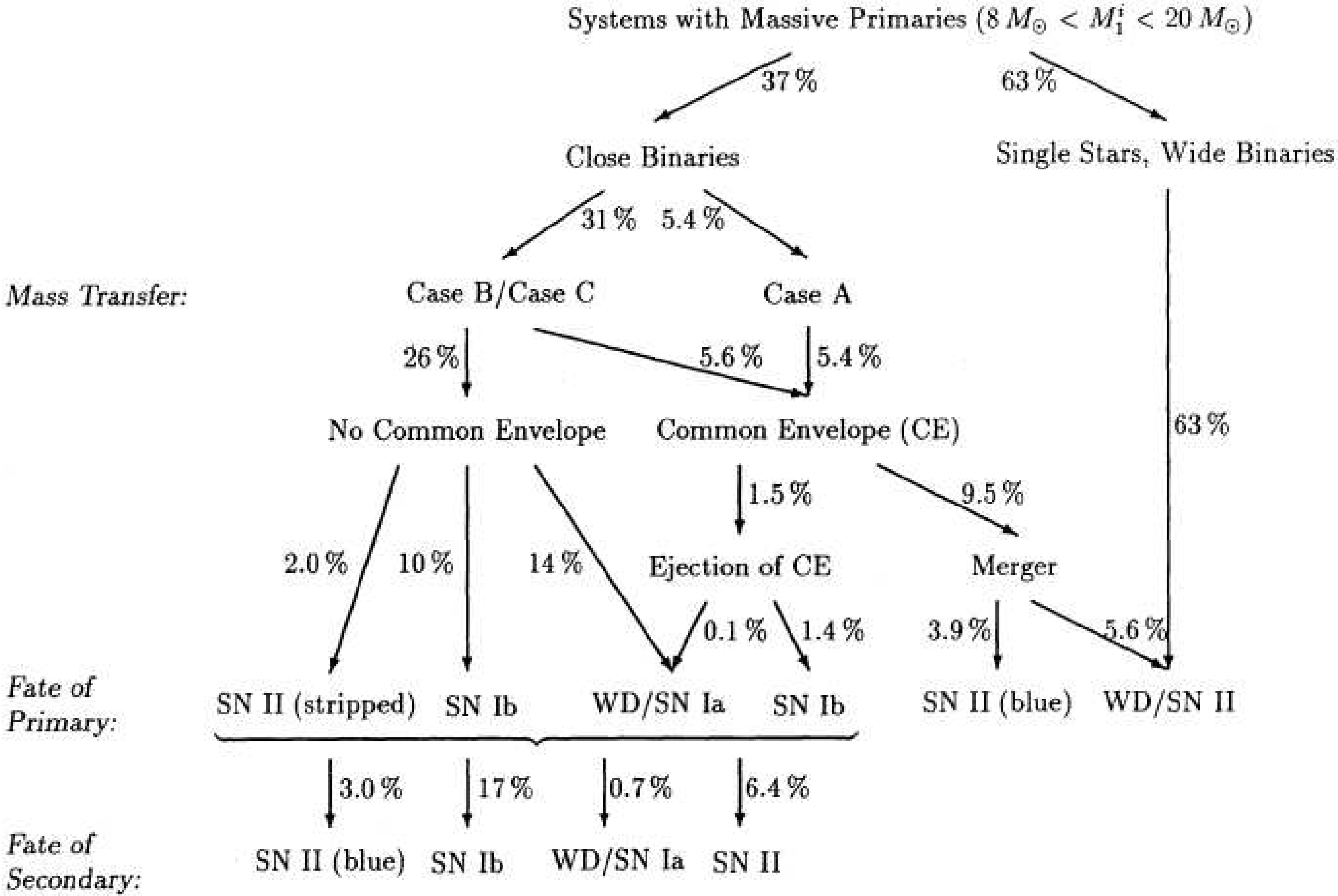
- one of the most important, but not well studied binary interactions
- **BPS:** ~ 10 % of all stars are expected to merge with a companion star → 1 binary merger in the Galaxy every 10 yr!
- efficient conversion of orbital-angular momentum to spin orbital-angular momentum
- if mergers occur early in the evolution → 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)

→ implications for GRB progenitors

→ 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 → no growth of the convective core) leading to smaller CO and finally smaller iron cores
  - ▷ stars in binaries up to $\sim 60\,\mathrm{M}_\odot$ may end as neutron stars rather than as black holes (Brown, Lee, Heger, Langer)
  - ▷ black-formation without rotation → faint supernova?

The Final Fates of Stars

- the effects of binary evolution

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

Note: (wide binary includes Case C mass transfer)

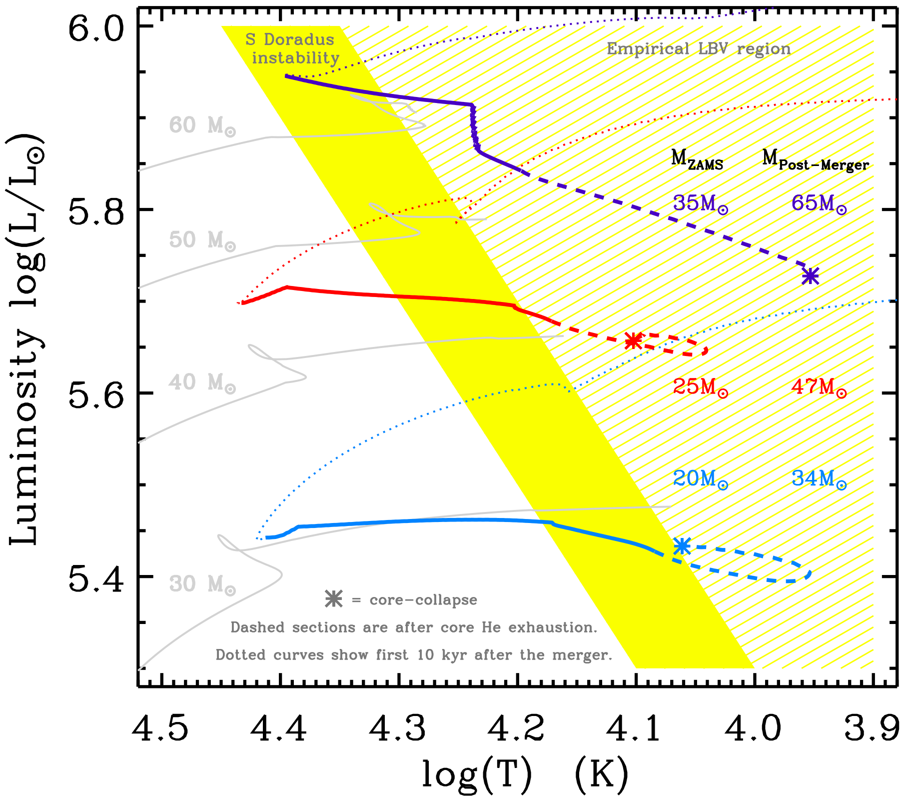
- the effects of metallicity
  - ▷ affects mass loss and compactness → supernova appearance (lower metallicity stars have less mass loss and are more compact)
  - ▷ affects core evolution (e.g. importance of CNO burning) and final core structure
  - ▷ example: the core structure of a $5\,\mathrm{M}_\odot$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

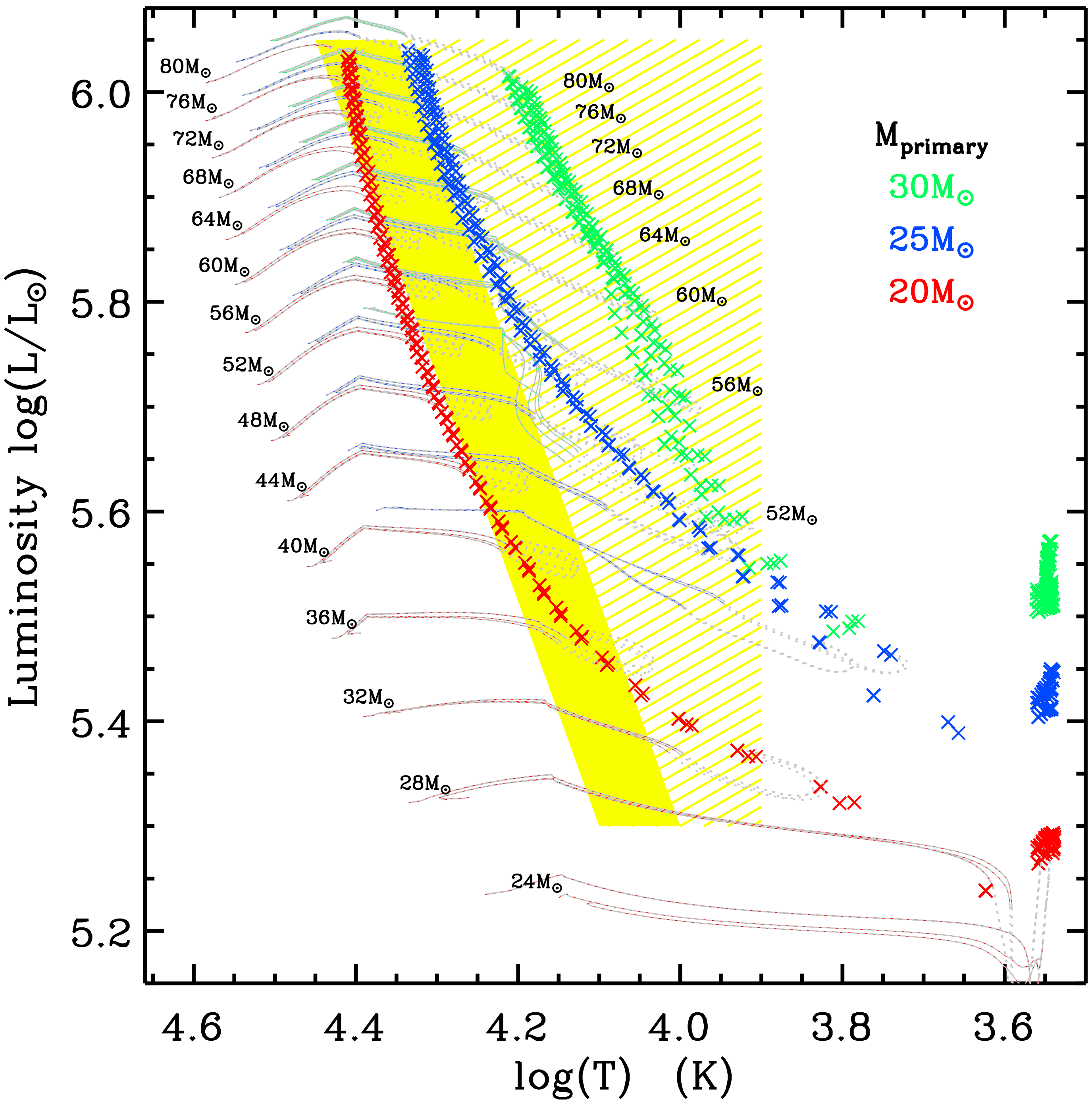
LBV Supernovae from Massive Binary Mergers

Justham, Podsiadlowski & Vink (2012)

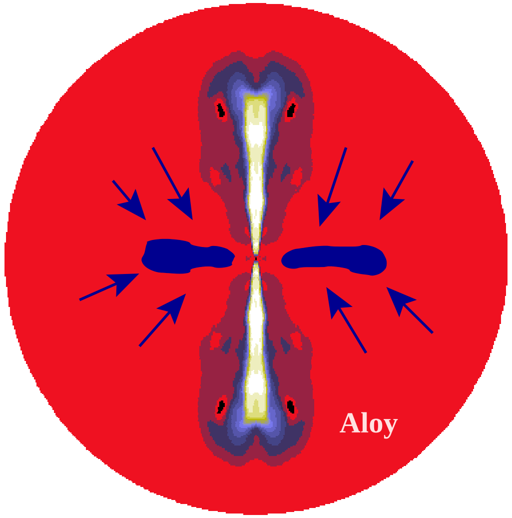
- large number of O-star binary mergers (Sana et al. [2012]: 20–30 %)
- for sufficiently small core mass fraction
  - ▷ He burning in blue-supergiant phase
  - ▷ with relatively low-mass loss rate
  - ▷ transition to the red only after He-core burning

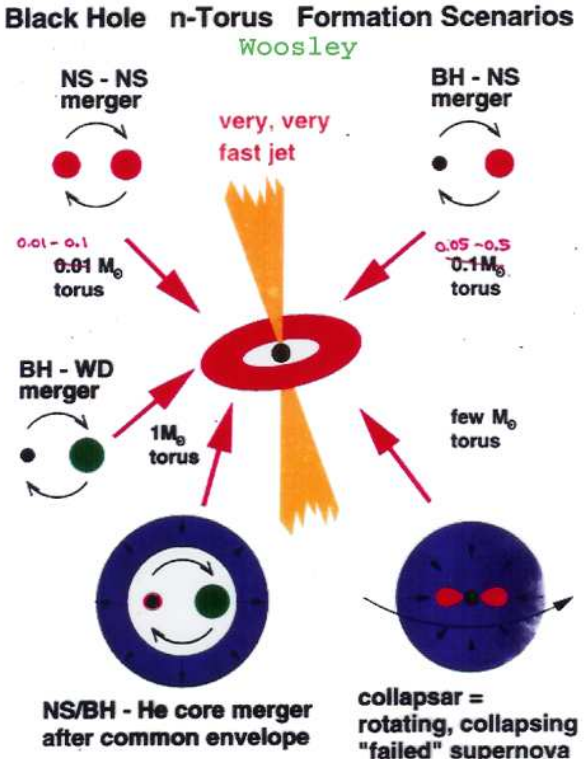
→ possibility of SN explosion in LBV phase
(with various amounts of H envelope masses)




Luminosity log(L/L☉)
log(T) (K)
6.0
5.8
5.6
5.4
5.2
4.6
4.4
4.2
4.0
3.8
3.6
80M☉
76M☉
72M☉
68M☉
64M☉
60M☉
56M☉
52M☉
48M☉
44M☉
40M☉
36M☉
32M☉
28M☉
24M☉
80M☉
76M☉
72M☉
68M☉
64M☉
60M☉
56M☉
52M☉
M_primary
30M☉
25M☉
20M☉

The collapsar model for long-duration GRBs



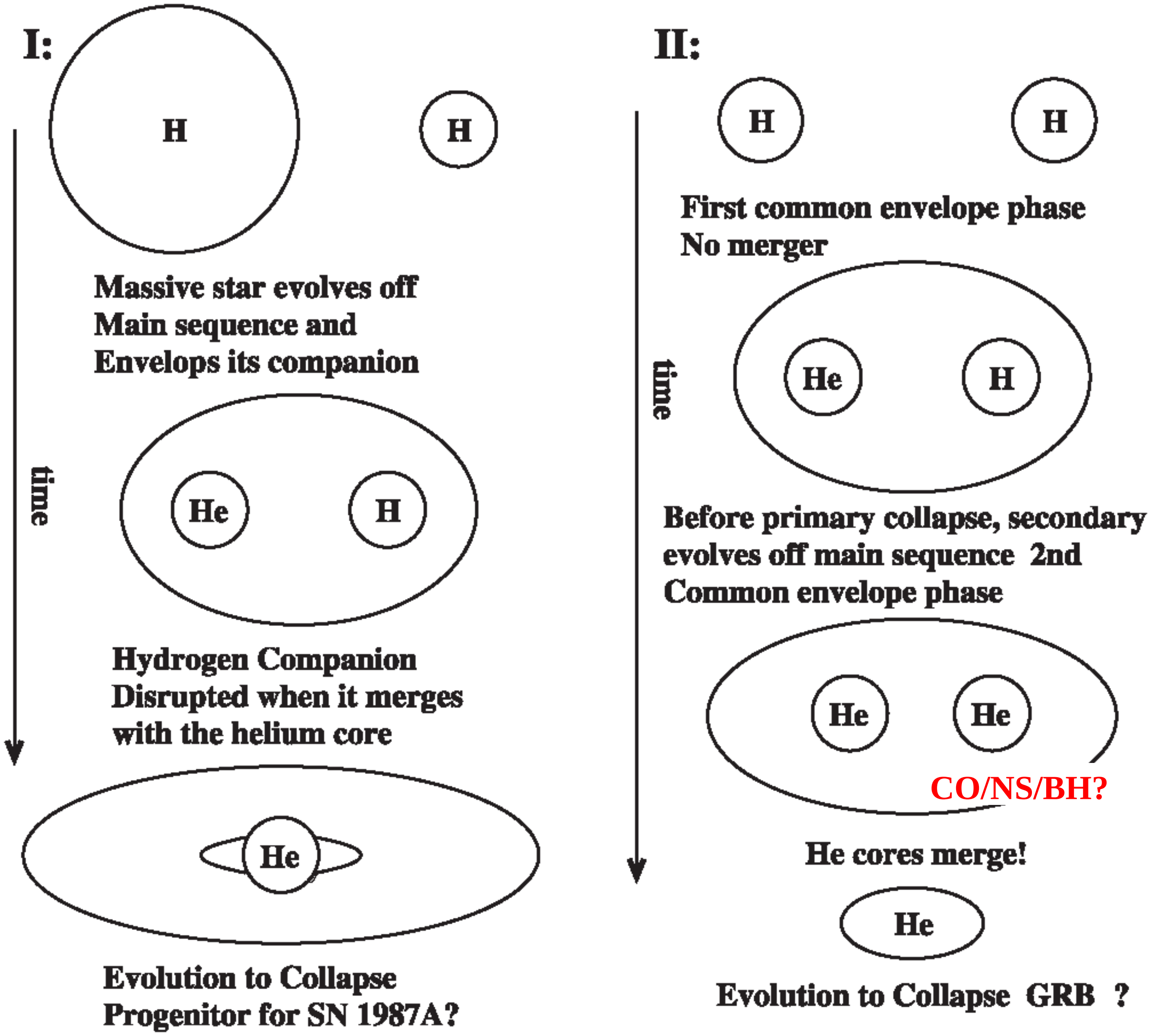


- **two-step black-hole formation:** neutron star, accretion from massive disk → black hole → relativistic jet → drills hole through remaining stellar envelope → escaping jet → GRB
- requires rapidly rotating He/CO star
- presently all hypernovae have been classified as SNe Ic (i.e., no H, He); only 1 in 100 Ib/Ic SNe are HNe
- HNe/GRBs are rare! $(10^{-5}\,\mathrm{yr}^{-1})$
- single star model: homogeneous evolution with low mass loss (Yoon & Langer; Heger & Woosley)
  - ▷ requires low metallicity $(< 0.2\,Z_\odot)$
  - ▷ not consistent with observations?
- binary channels? (e.g. mergers of a He + CO core in common envelope [CE]; explosive CE ejection)

Merger Ideas

(from Fryer & Heger)

COLLAPSAR ENGINES FROM BINARY MERGERS 303



Massive star evolves off
Main sequence and
Envelops its companion

Hydrogen Companion
Disrupted when it merges
with the helium core

Evolution to Collapse
Progenitor for SN 1987A?

First common envelope phase
No merger

Before primary collapse, secondary
evolves off main sequence 2nd
Common envelope phase

CO/NS/BH?

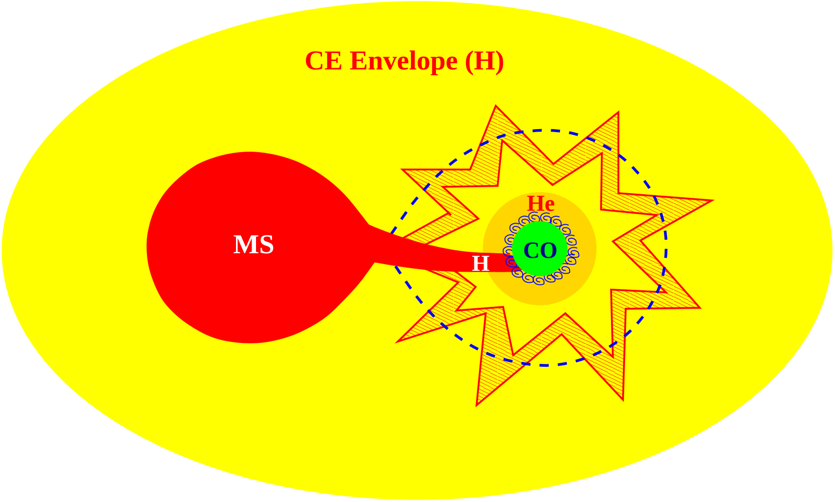
He cores merge!

Evolution to Collapse GRB ?

Explosive Common-Envelope Ejection

Podsiadlowski, Ivanova, Justham & Rappaport (2010)

- 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



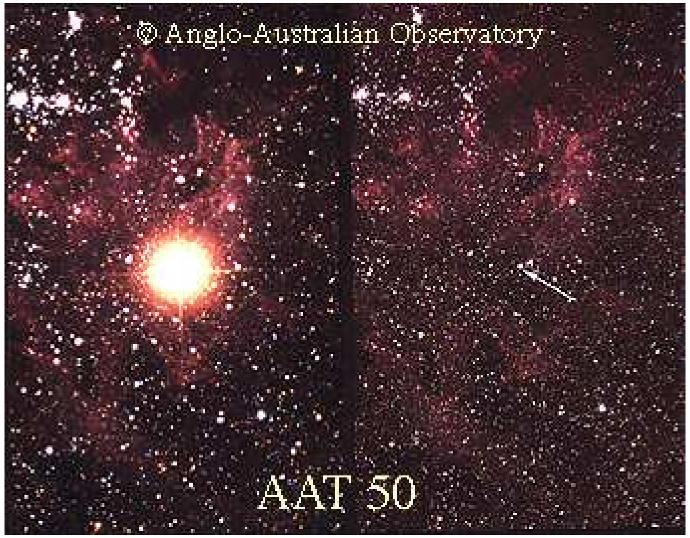
- energy source for CE ejection is nuclear energy (not orbital energy) → new CE ejection mechanism (application to short-period black-hole binaries, Nova Sco)
- works best for relatively low-mass companions ($\lesssim 3\,M_\odot$)

The Progenitor of SN 1987A

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

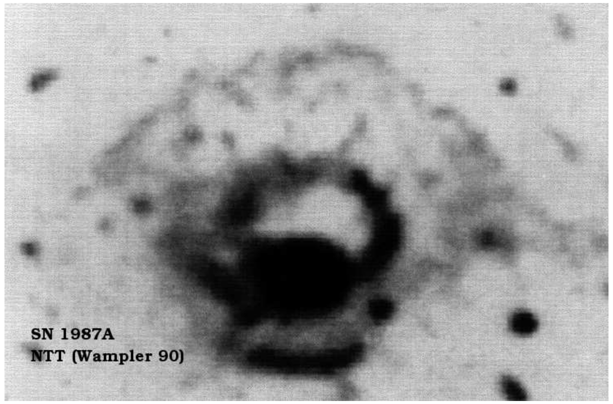
SN 1987A: an anomalous supernova

- progenitor (SK $-69^\circ 202$): **blue supergiant** with recent red-supergiant phase (10^4 yr)
- chemical anomalies:
  - ▷ **helium-rich** (He/H~ 0.25, N/C~ 5, N/O~ 1)
  - ▷ CNO-processed material, helium dredge-up
  - ▷ **barium anomaly** ($5-10$ solar)
- **the triple-ring nebula**
  - → axi-symmetric, but highly non-spherical
  - → signature of **rapid rotation**

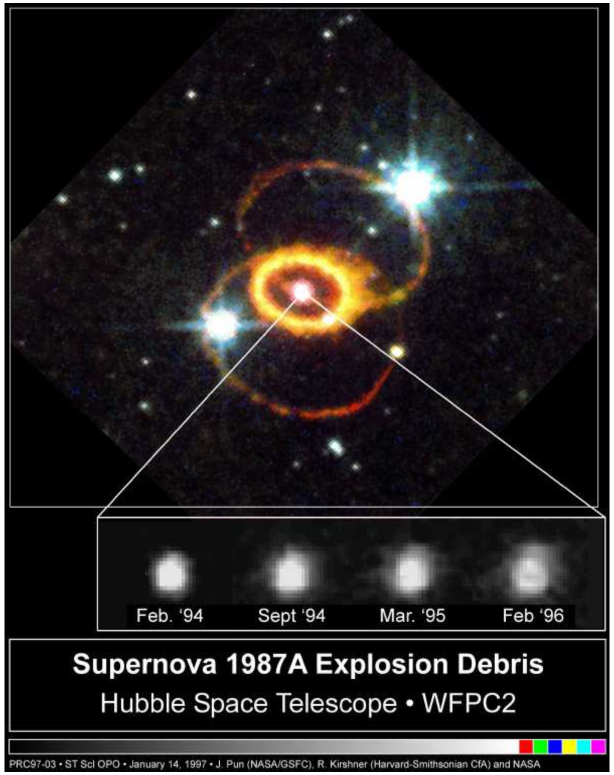


The Triple-Ring Nebula

- discovered with **NTT** (Wampler et al. 1990)



- HST image (Burrows et al. 1995)



PRC97-03 • ST ScI OPO • January 14, 1997 • J. Pun (NASA/GSFC), R. Kirshner (Harvard-Smithsonian CfA) and NASA

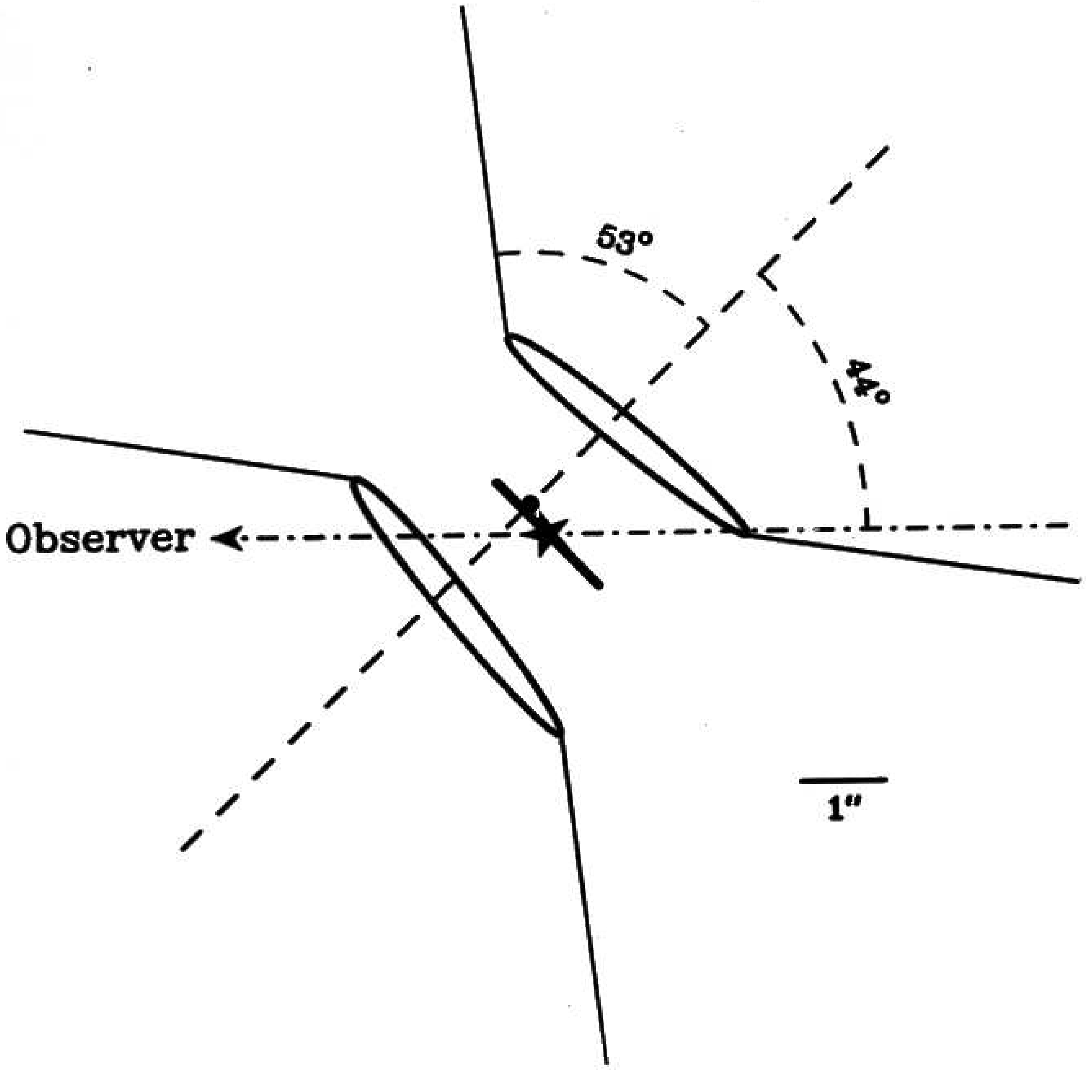
- not a limb-brightened hourglass, but physically distinct rings
- axi-symmetric, but highly non-spherical

  → 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 $10^4\,$yr ago, most likely the merger of two massive stars

Figure 2



Formation of the Triple-Ring Nebula

Morris and Podsiadlowski (Science 2007)

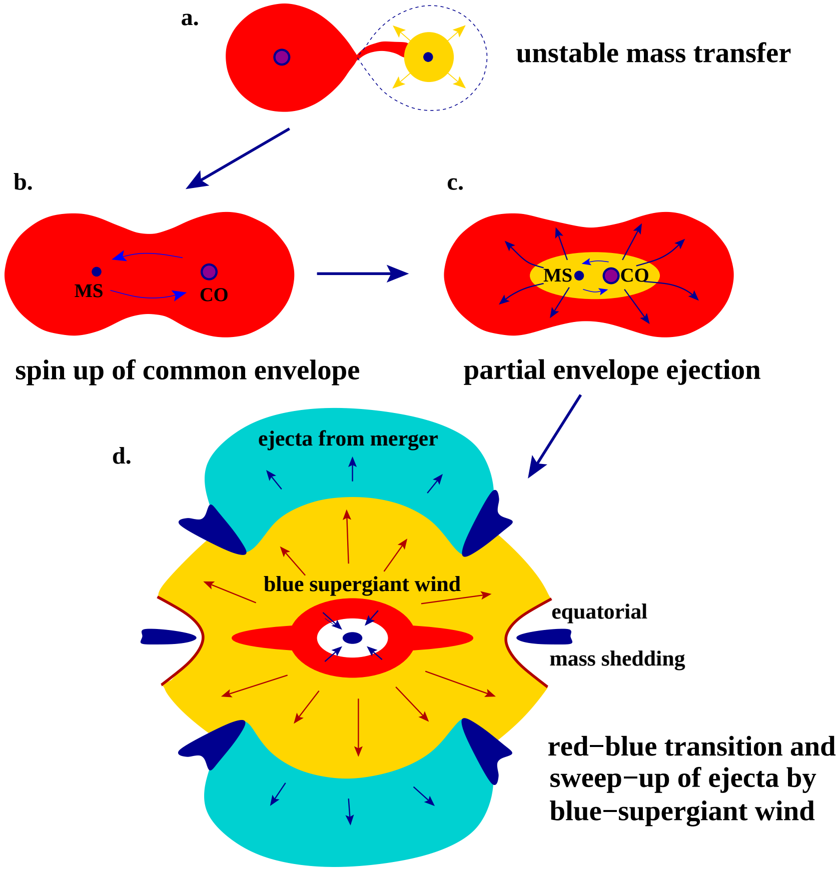
- 3-dim SPH simulations (GADGET; Springel)
- simulate mass ejection during merger and subsequent blue-supergiant phase
- angular momentum of orbit → spin-up of envelope

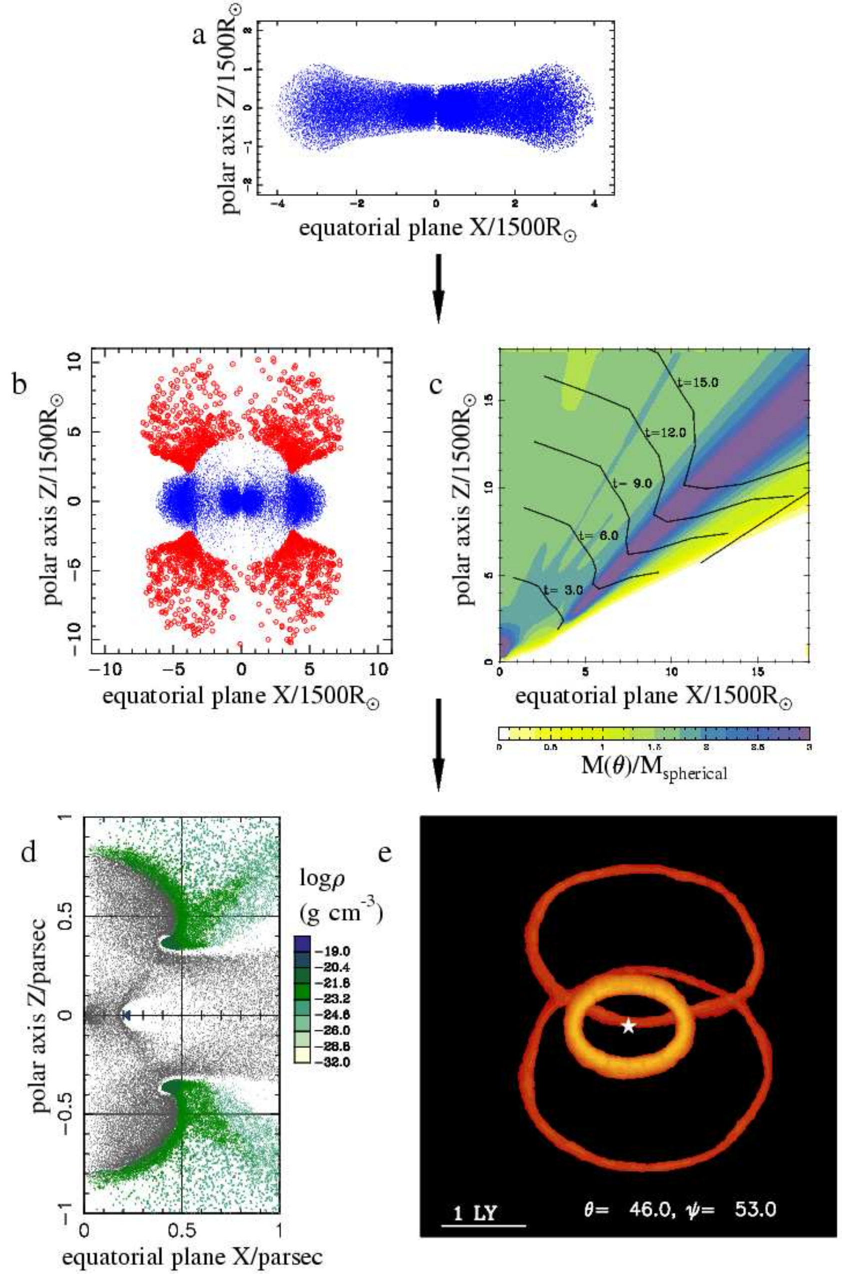
→ flattened, disk-like envelope

- energy deposition in rapid spiral-in phase $(\lesssim 1/3\mathrm{E}_{\mathrm{bind}})$

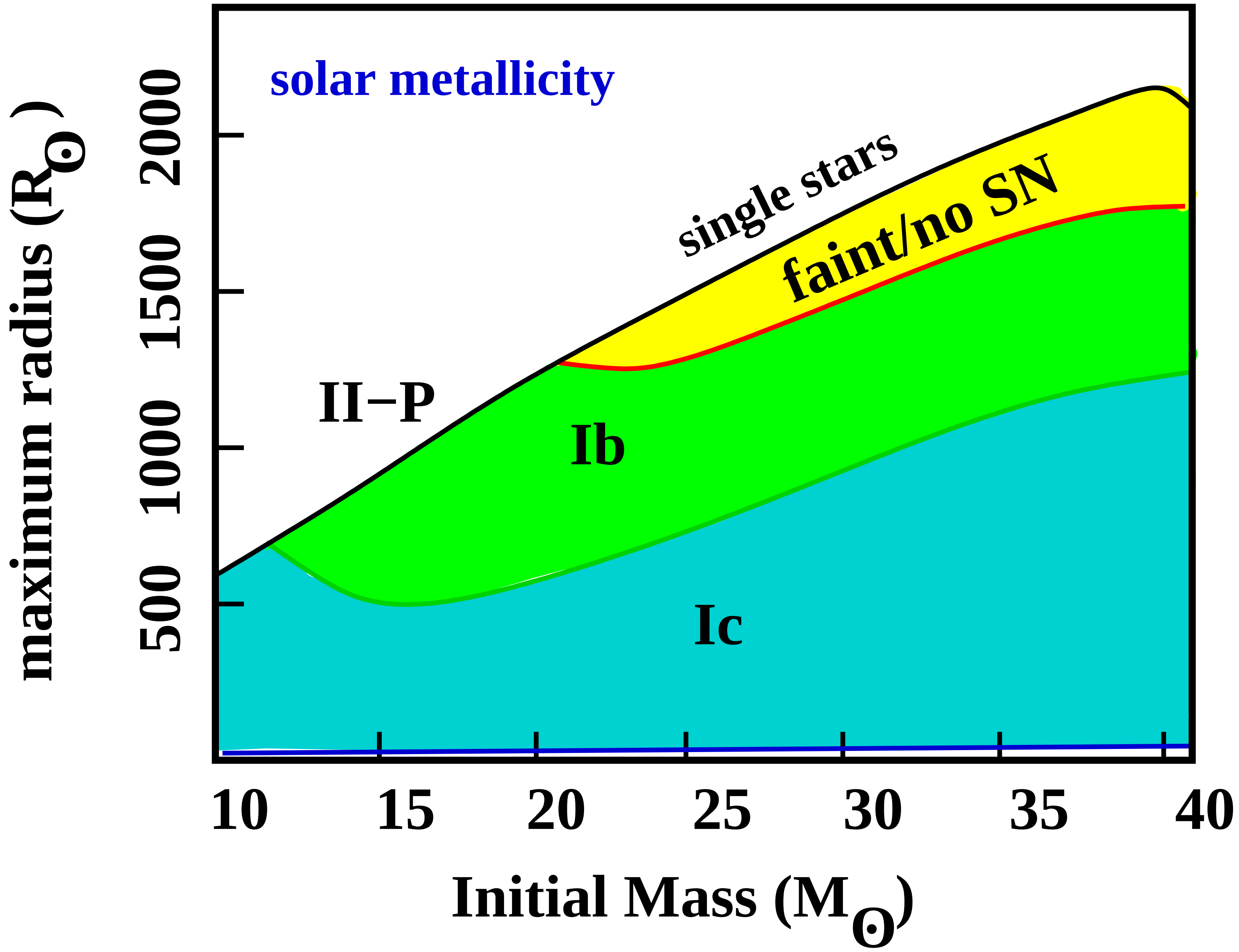
→ partial envelope ejection → outer rings, bipolar lobes

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




a
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
-4
-2
0
2
4
-2
-1
0
1
2
b
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
-10
-5
0
5
10
c
polar axis Z/1500R$_\odot$
equatorial plane X/1500R$_\odot$
t= 3.0
t= 6.0
t= 9.0
t=12.0
t=15.0
0
5
10
15
0
0.5
1
1.5
2
2.5
3
M(θ)/M$_{\mathrm{spherical}}$
d
polar axis Z/parsec
equatorial plane X/parsec
-1
-0.5
0
0.5
1
logρ
(g cm^{-3})
-19.0
-20.4
-21.8
-23.2
-24.6
-26.0
-28.8
-32.0
e
1 LY
θ= 46.0, ψ= 53.0

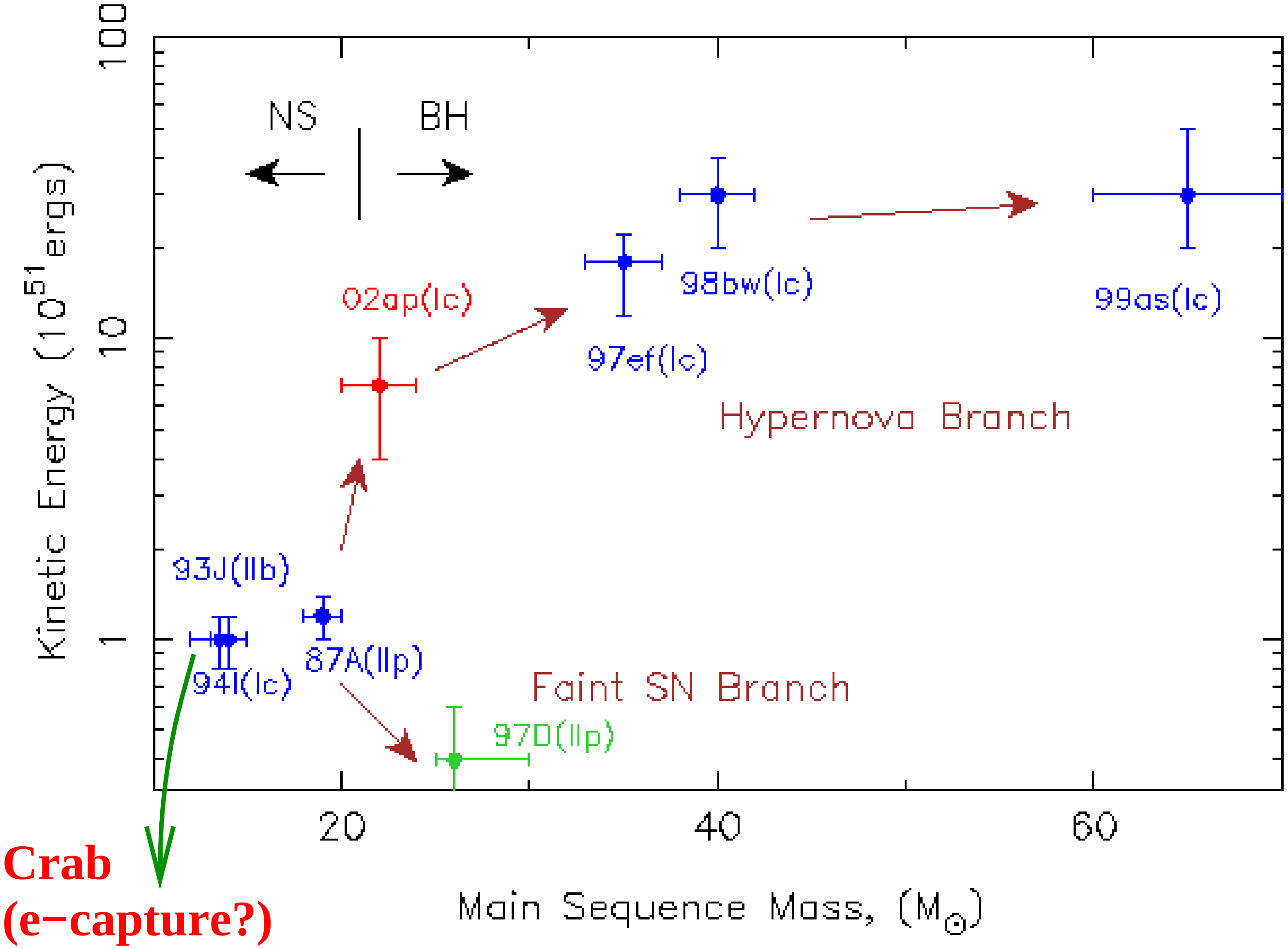
PhP, Mazzali, Justham (2009)



The Diversity of SNe Ic (II)

- **normal SNe Ic**
  - ▷ $M_{MS} \simeq 10 - 50/60\,M_\odot$ in close binaries
  - ▷ case B (BB) mass transfer
- **hypernovae/GRB supernovae**
  - ▷ $M_{MS} \simeq 23 - 40/50\,M_\odot$
  - ▷ late case C mass transfer (explosive CE ejection?)
- **faint SNe Ic (Ib?)**
  - ▷ $M_{MS} \gtrsim 23\,M_\odot$
  - ▷ 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



Crab
(e−capture?)