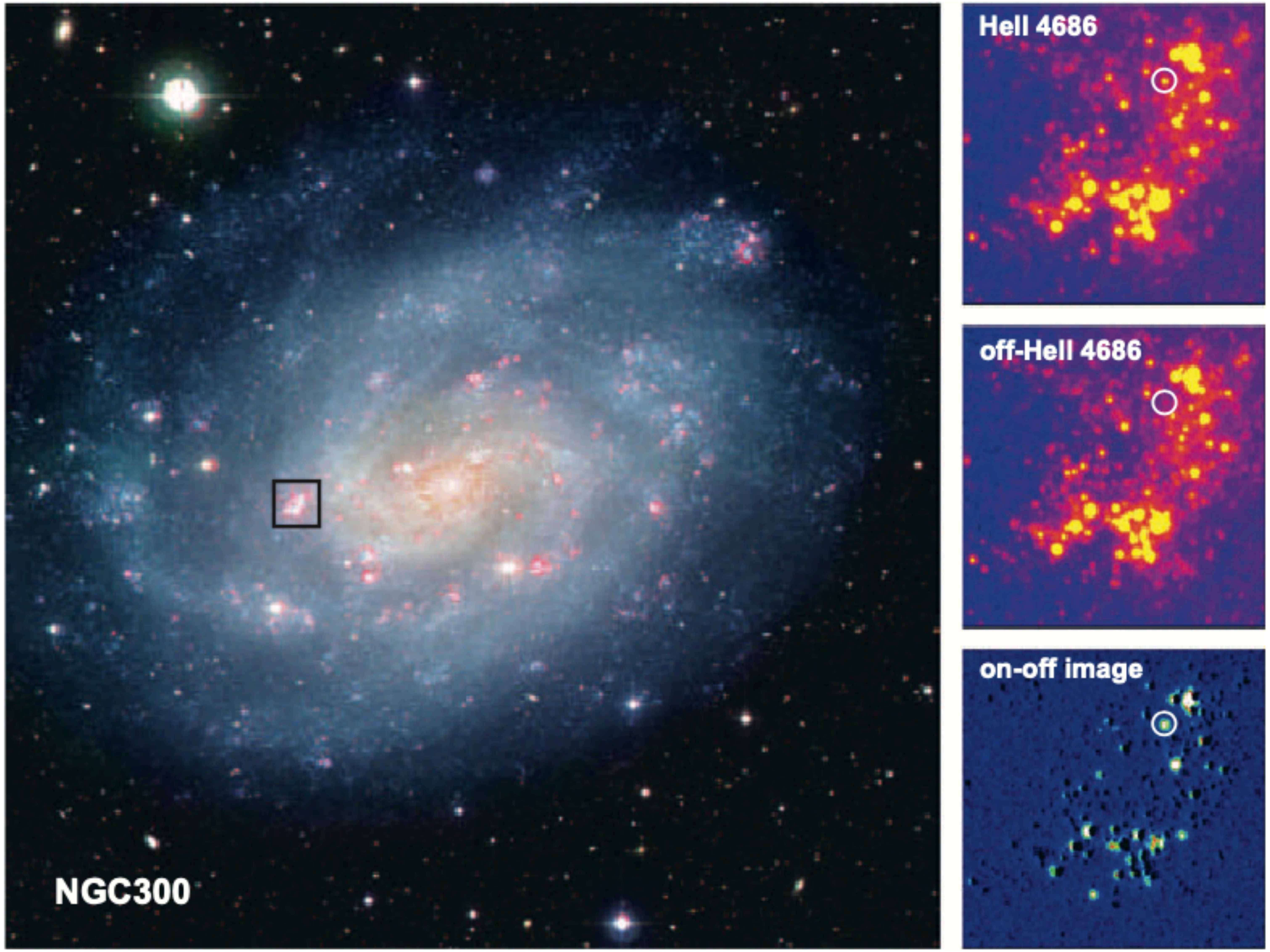
Part G

The most massive stars and their supernovae (or lack of)

Wolf-Rayet (WR) stars



Discovered 1867 by Wolf and Rayet: ***luminous (log L >~ 5.0), hot (log T >~4.6) stars whose spectra show <u>broad emission lines</u> (v ~2000 km/s) formed in a fast wind.***

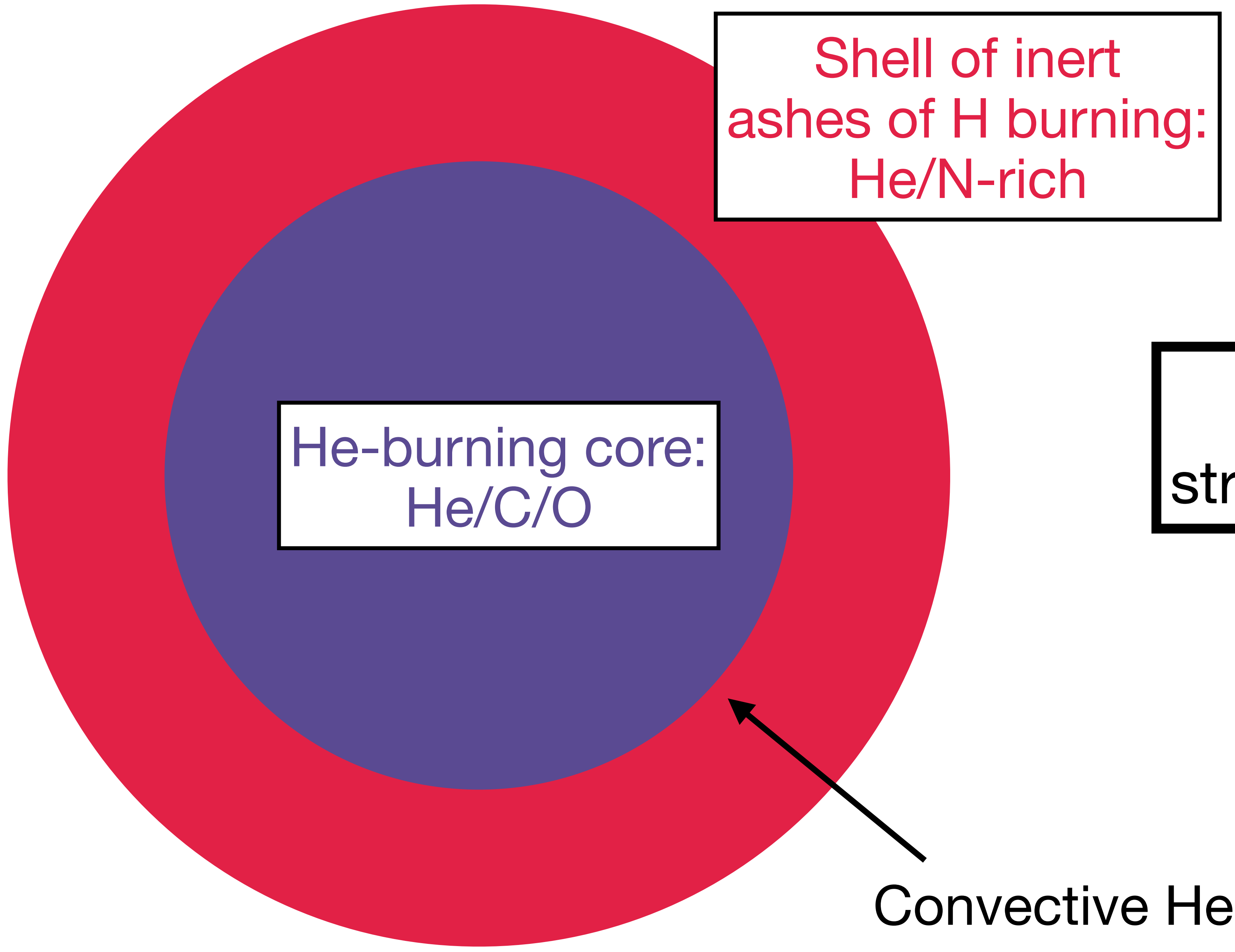
Strong emitters in certain lines like He II 4686.

The prevalence of WR stars is very **metallicity-dependent**: N(WR) / N(O) ~1/7 at solar metallicity, but only ~1/100 at Small Magellanic Cloud metallicity (about 5% of solar) —> <u>they form more easily at high metallicity.</u>

About 500 WR stars are known in the Milky Way.

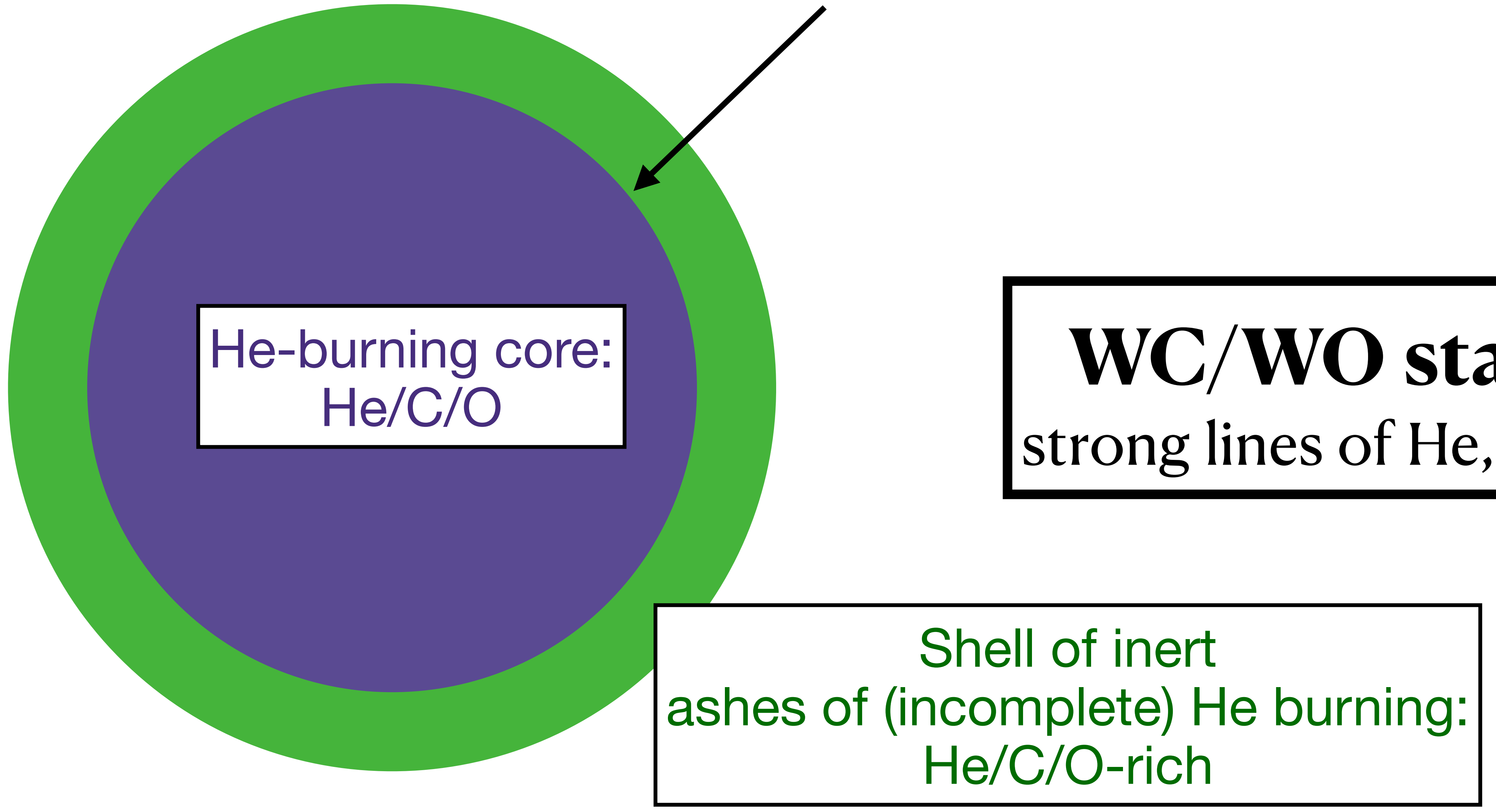
Crowther 2007

WR stars : Two main types : WN and WC/WO

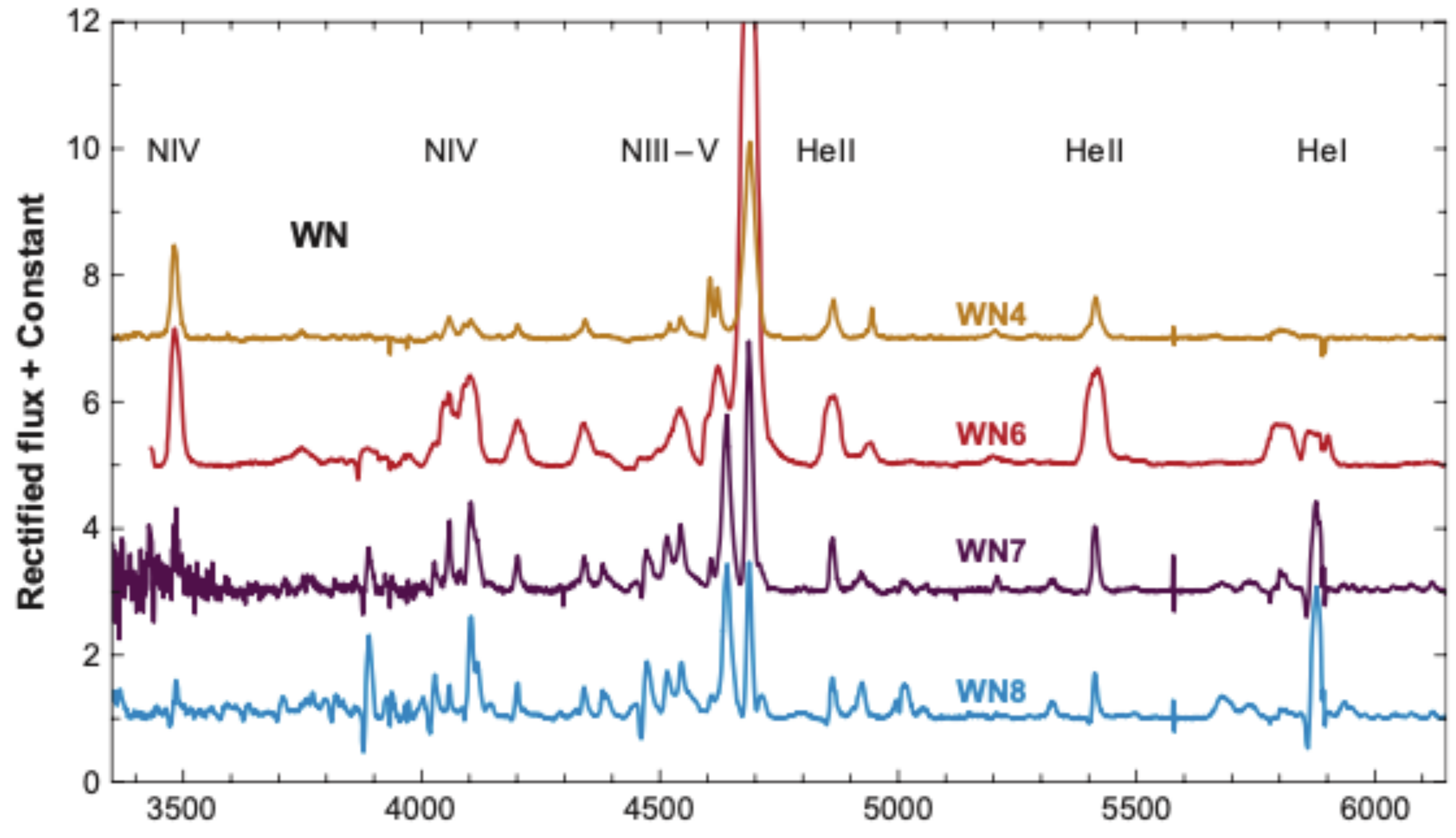


WN star :
strong lines of He, N

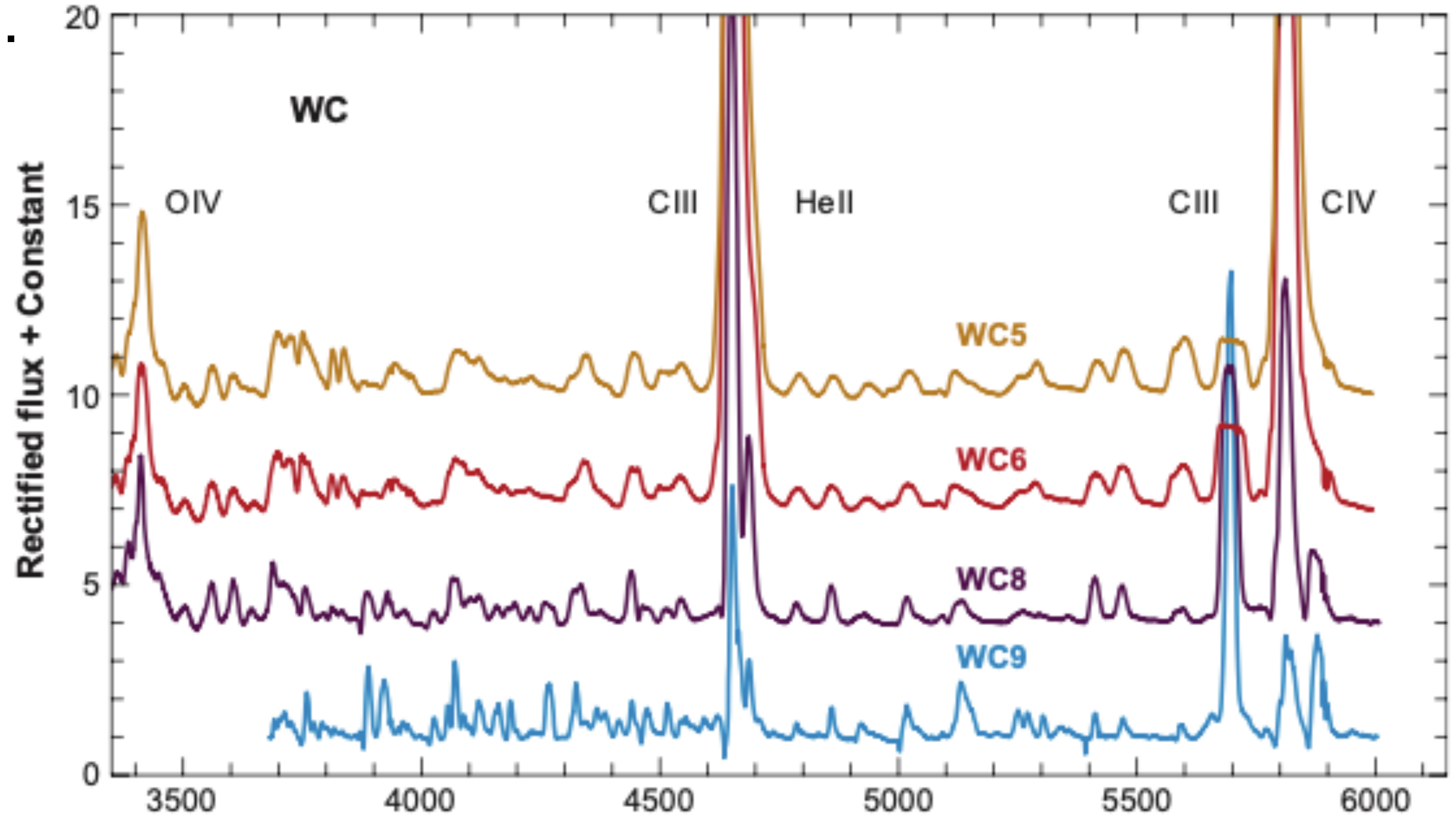
Convective He-burning core never reaches surface, retreats inwards as surface is peeled off by the wind.



WC/WO star :
strong lines of He, C, O



Spectra show broad emission lines from a fast wind

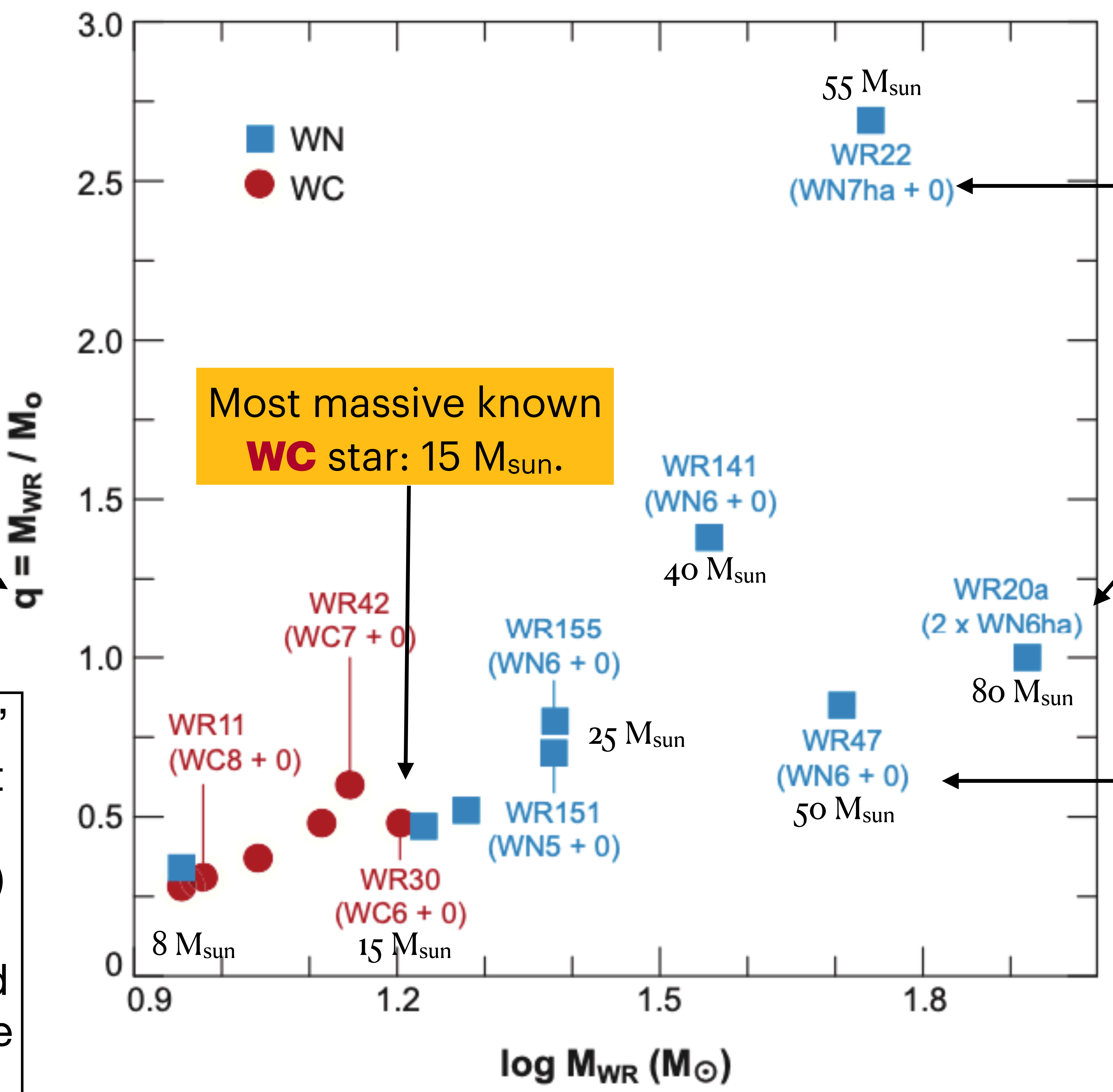


Very few WO stars known, order 10.

Crowther 2007

WR star masses from binary orbits

q = mass ratio to companion O star:



Most massive known **WC** star: 15 M_{sun}.

WNha is a special WN subclass where also H lines are seen: still H-burning (MS) very massive O stars.

Most massive known **WN** star: 50 M_{sun}.

Lower-mass "bare He cores" may exist but may either not make WR-like winds or may not be detectable (in optical) compared to their companion stars (they would need a companion to remove their envelopes, see later).

WC and WO stars in the HR diagram

Observed WO stars are in tentative agreement with final appearance of model stars with M_{ZAMS} >~ 25-30 M_{sun}.

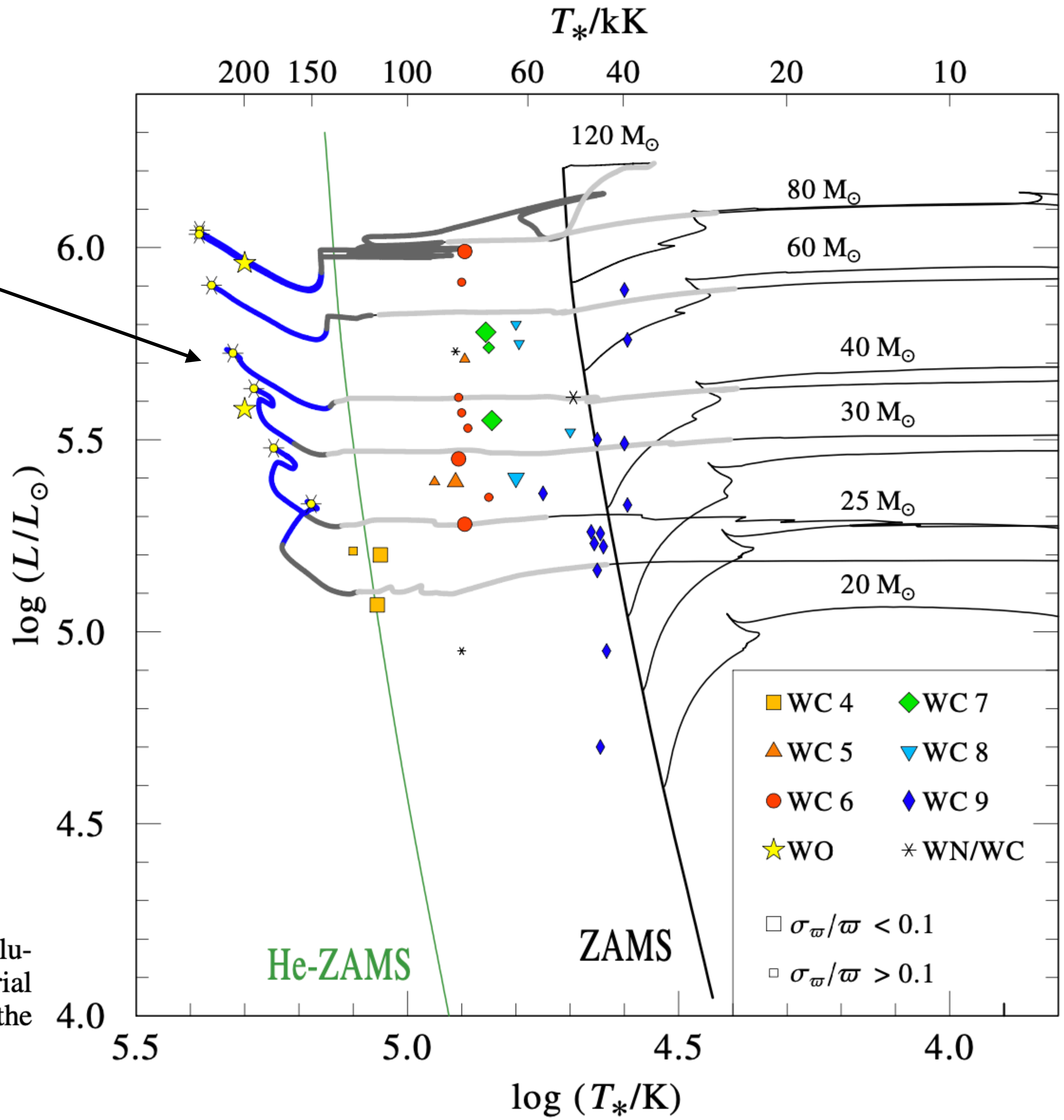


Fig. 12. HRD with the WC & WO star positions compared to the evolutionary tracks from Chieffi & Limongi (2013) with an initial equatorial rotational velocity of $\upsilon_{\mathrm{rot,ini}} = 300\,\mathrm{km\,s^{-1}}$. The thick lines indicate the WR phases of the tracks.

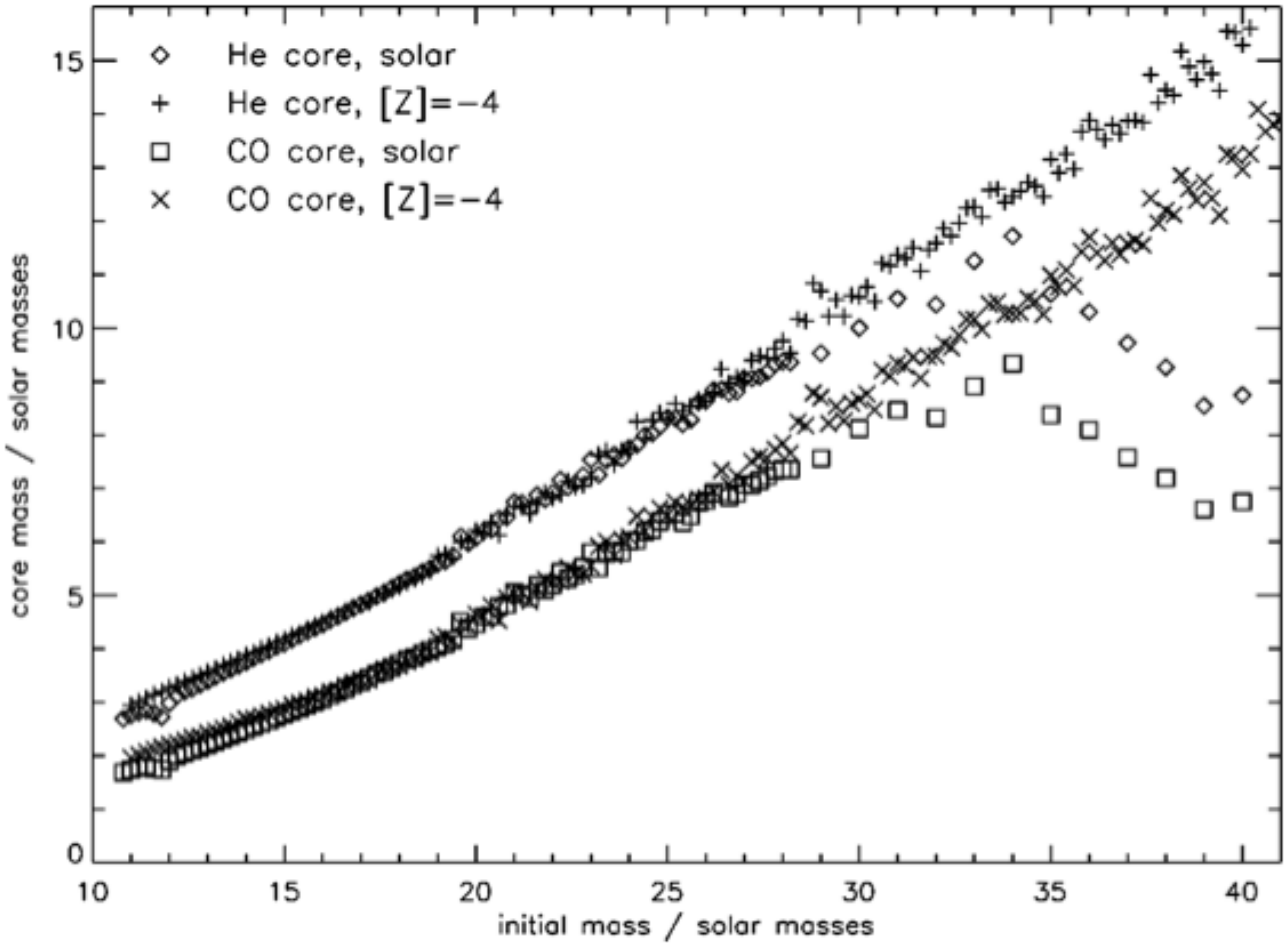
Sander 2019

WR masses from single star models

At solar metallicity, the maximum predicted He core masses are 10 - 12 M_{sun}. (Part B:26)

Lower metallicity allows for higher values.

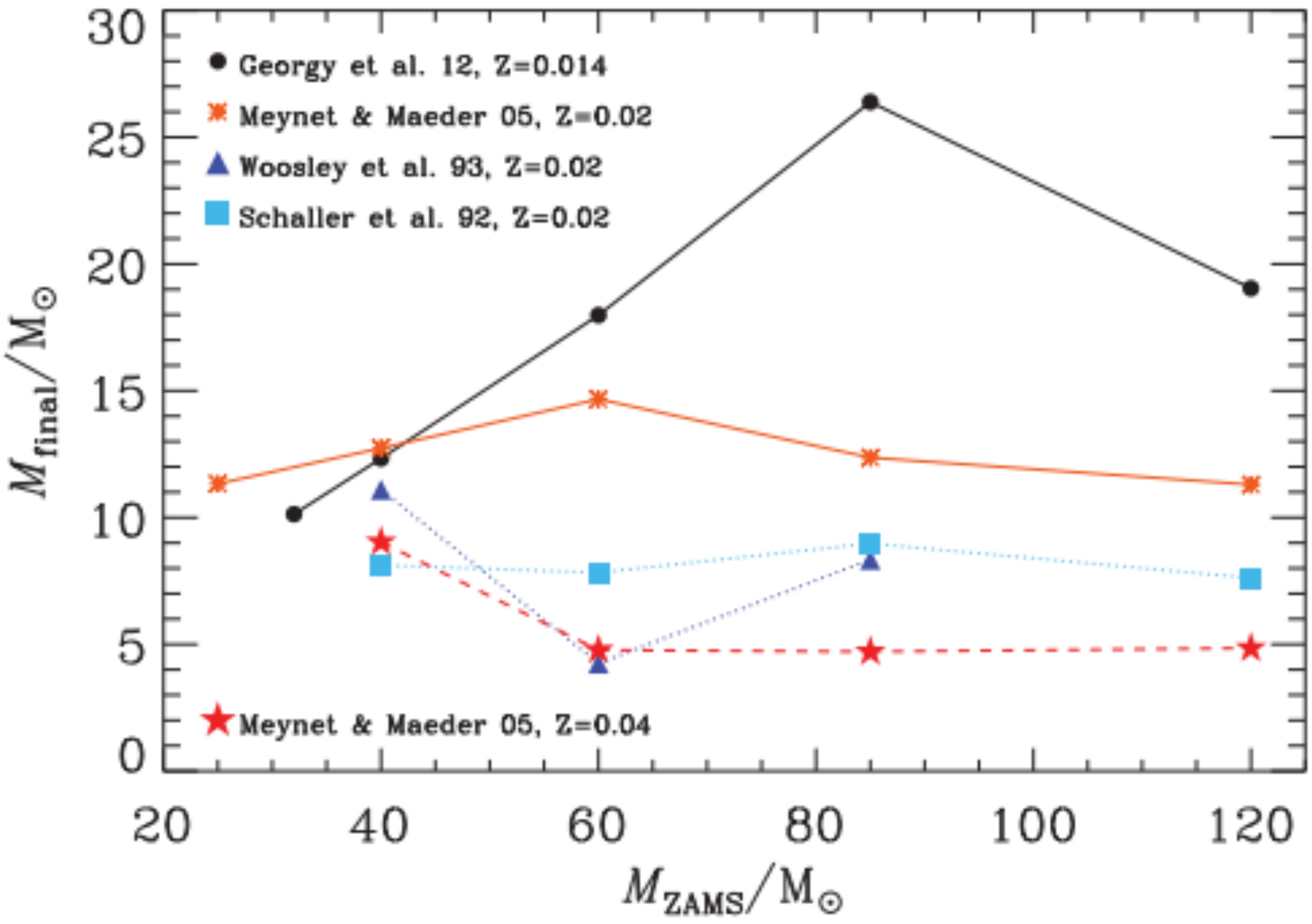
This matches the most massive observed WC/WO stars (~15 $M_{sun,}$ previous slide) quite well.



Woosley 2002

“Standard scenario” for massive star evolution at ~solar metallicity

Predicted final pre-SN masses for H-stripped stars at ~solar metallicity



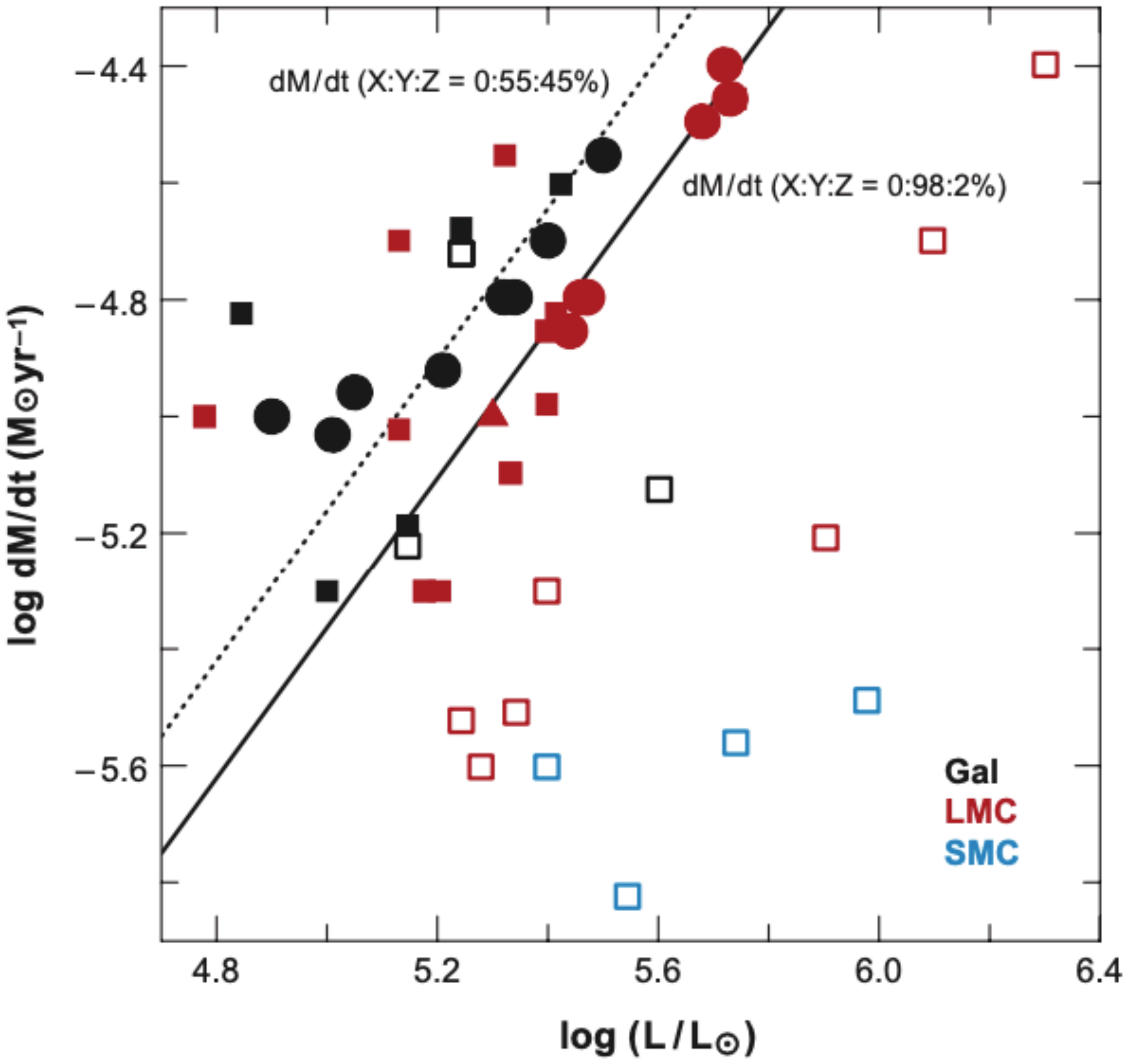
Combining all uncertainties in stellar evolution modelling, in particular regarding mass loss, ***one can end with final WR masses varying by a factor 5.***

Yoon 2015

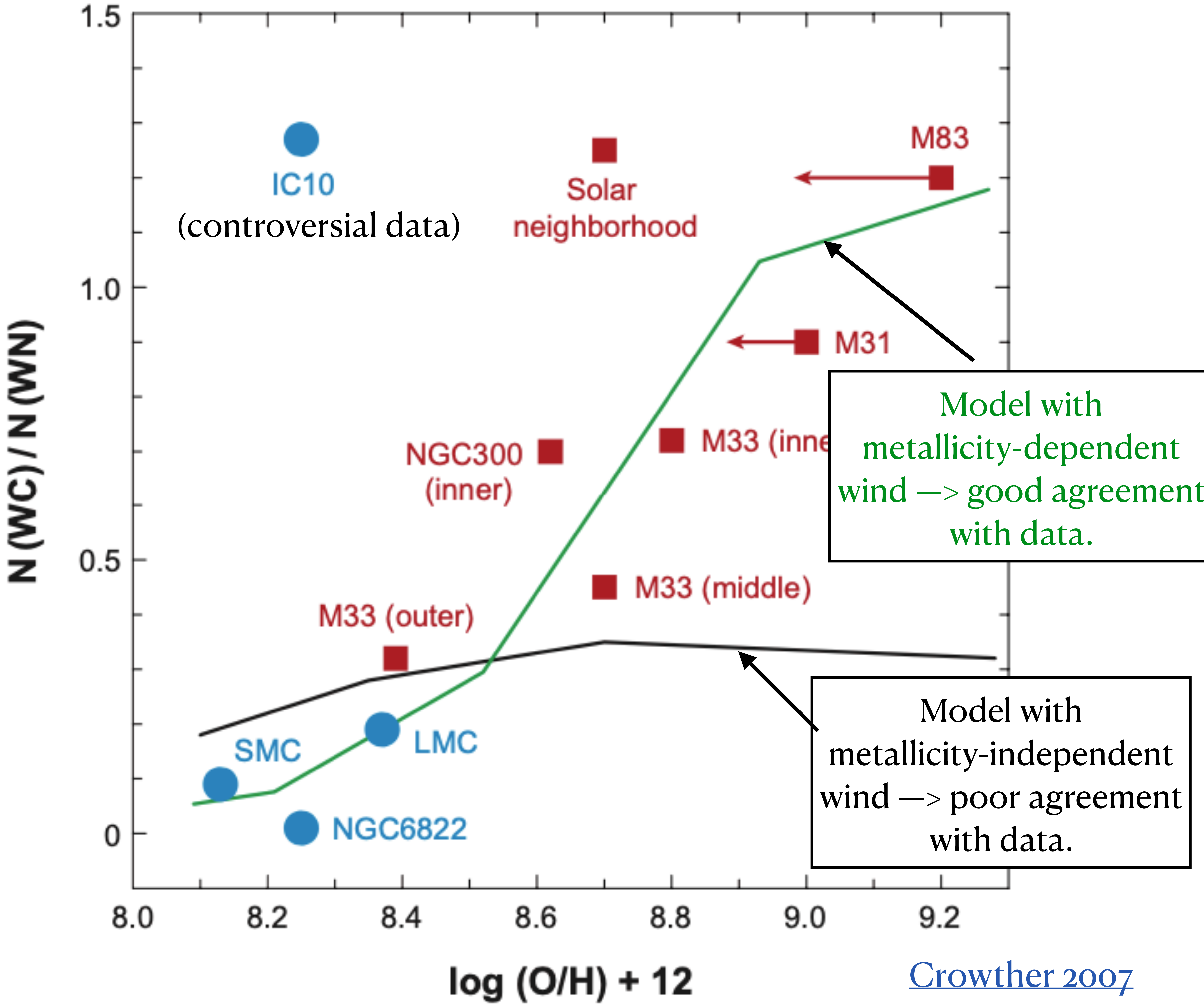
WR mass-loss

Observations show **significant metallicity-dependence**, as predicted by line-driven wind theory.

This figure shows that for a given luminosity, higher metallicity WR stars have higher mass loss rates.



This figure shows that higher metallicity galaxy regions have more WC stars per WN star.



Crowther 2007

Luminous Blue Variables (LBVs)

H-rich stars that are **luminous** (log L >~ 5.3), **blue** (T >~ 30,000 K), and have **strong and irregular mass loss**.

LBVs are 20 times more rare than WR stars —> only about 20 known.

Eruptions of two kinds: **Normal** and **Giant**.

Eta Carina ejected ~15 M_{sun} in its 1840 giant eruption!

Other galactic LBVs: P Cyg, AG Car, HR Car, HD 160529.

During giant eruptions, $\dot{M} \approx 0.01 - 1\ M_{\odot}$ yr^{-1} for a few decades.

The mechanism for this eruptive mass loss is unknown. One option (for massive LBVs) is that star oscillates between two Eddington limits as opacity varies.

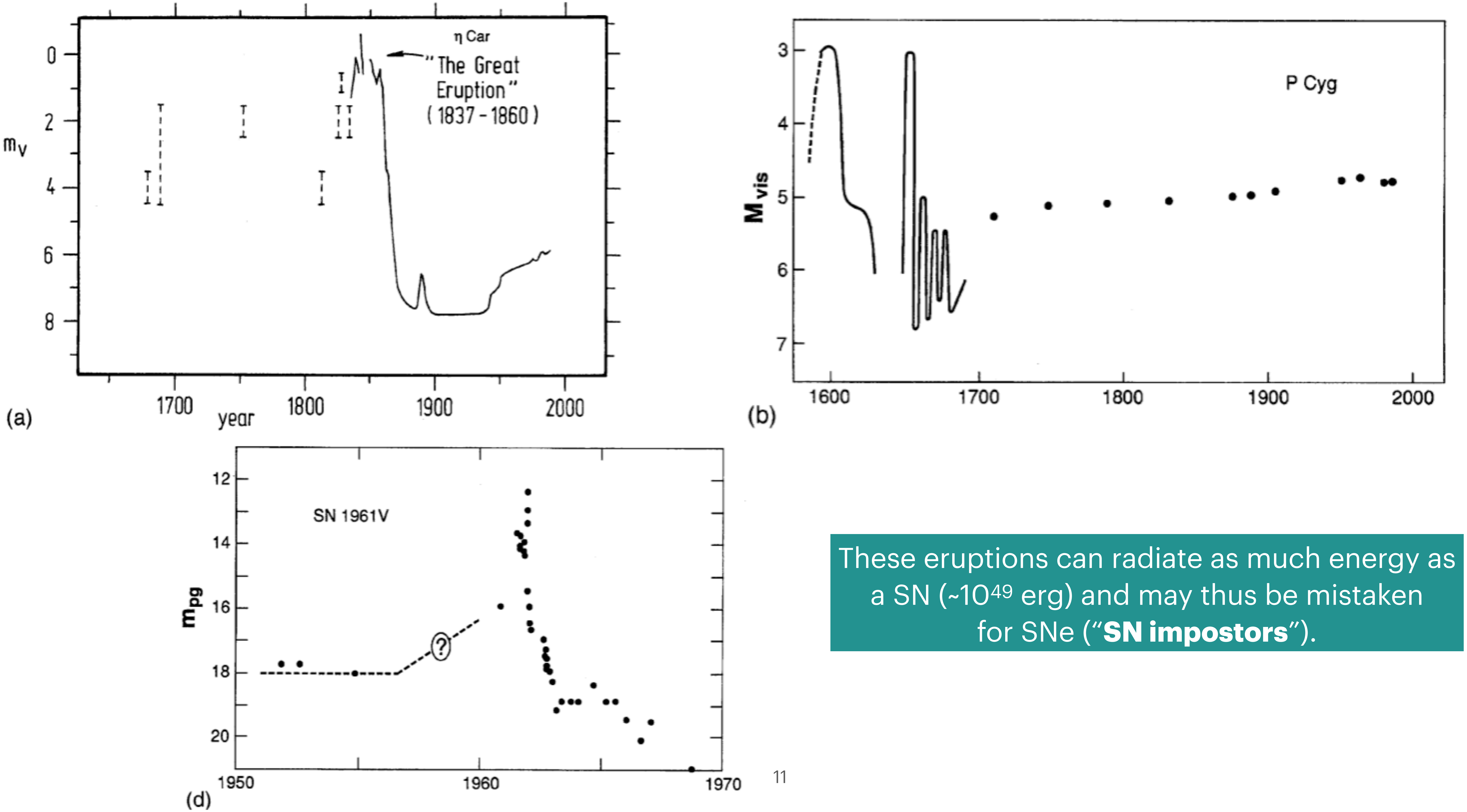
In the standard view, LBVs are late MS or early post-MS, pre-WR stars. However, there are plenty of other ideas/possibilities. There is some still controversial evidence that some LBVs can explode as SNe.

Reviews: Humphreys & Davidson 1994, Smith 2004, Smith 2014

Lobes of ~15 M_{sun} material ejected in 1840 : moves with up to 700 km/s.

Bipolar structure suggests that either rotation or binarity plays a role.

LBV giant eruptions



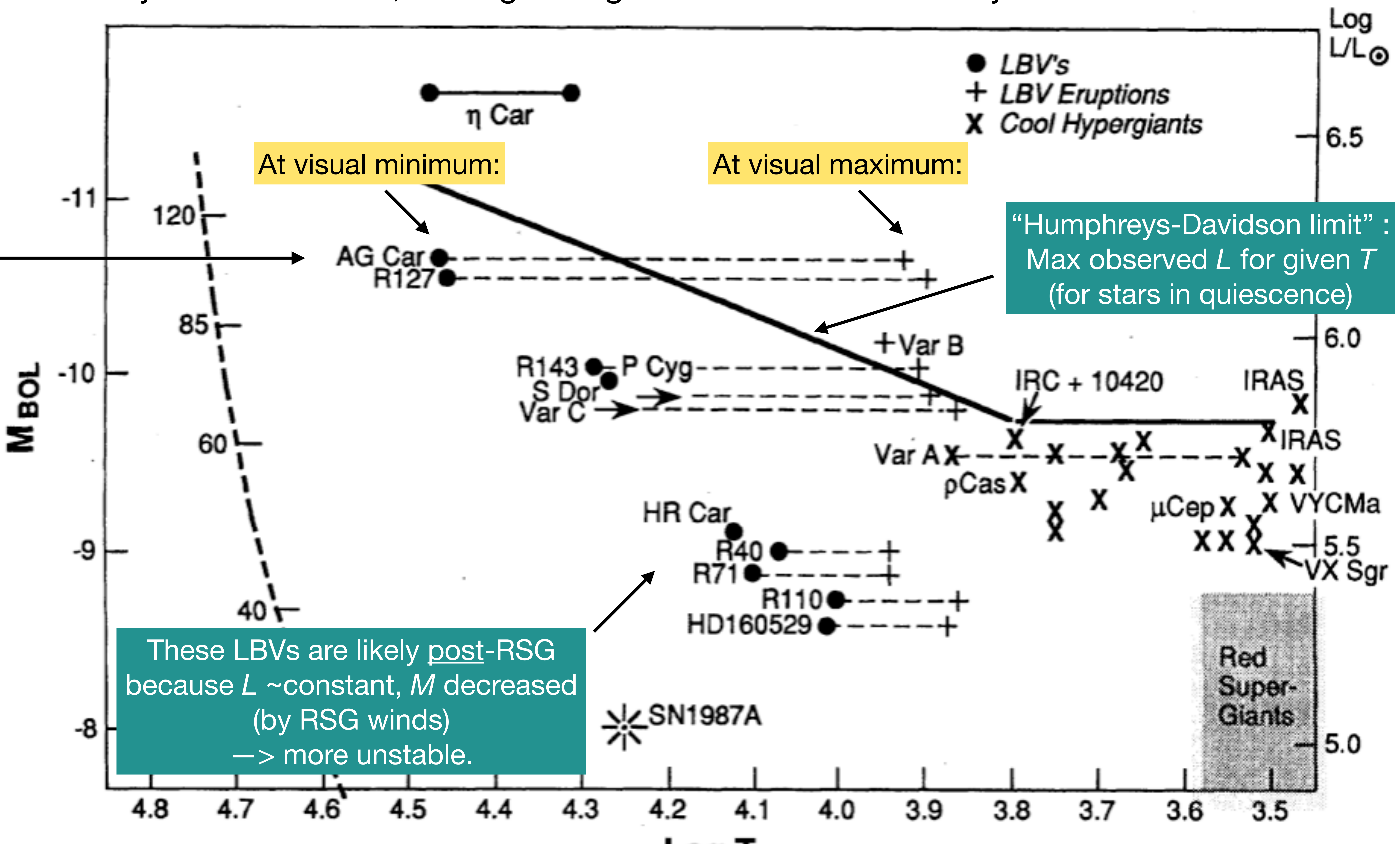
These eruptions can radiate as much energy as a SN (~10^{49} erg) and may thus be mistaken for SNe ("**SN impostors**").

LBVs in the HR diagram

Move horizontally back and forth, no big changes in absolute luminosity.

Bolometric luminosity does not change much as star burps and erupts.

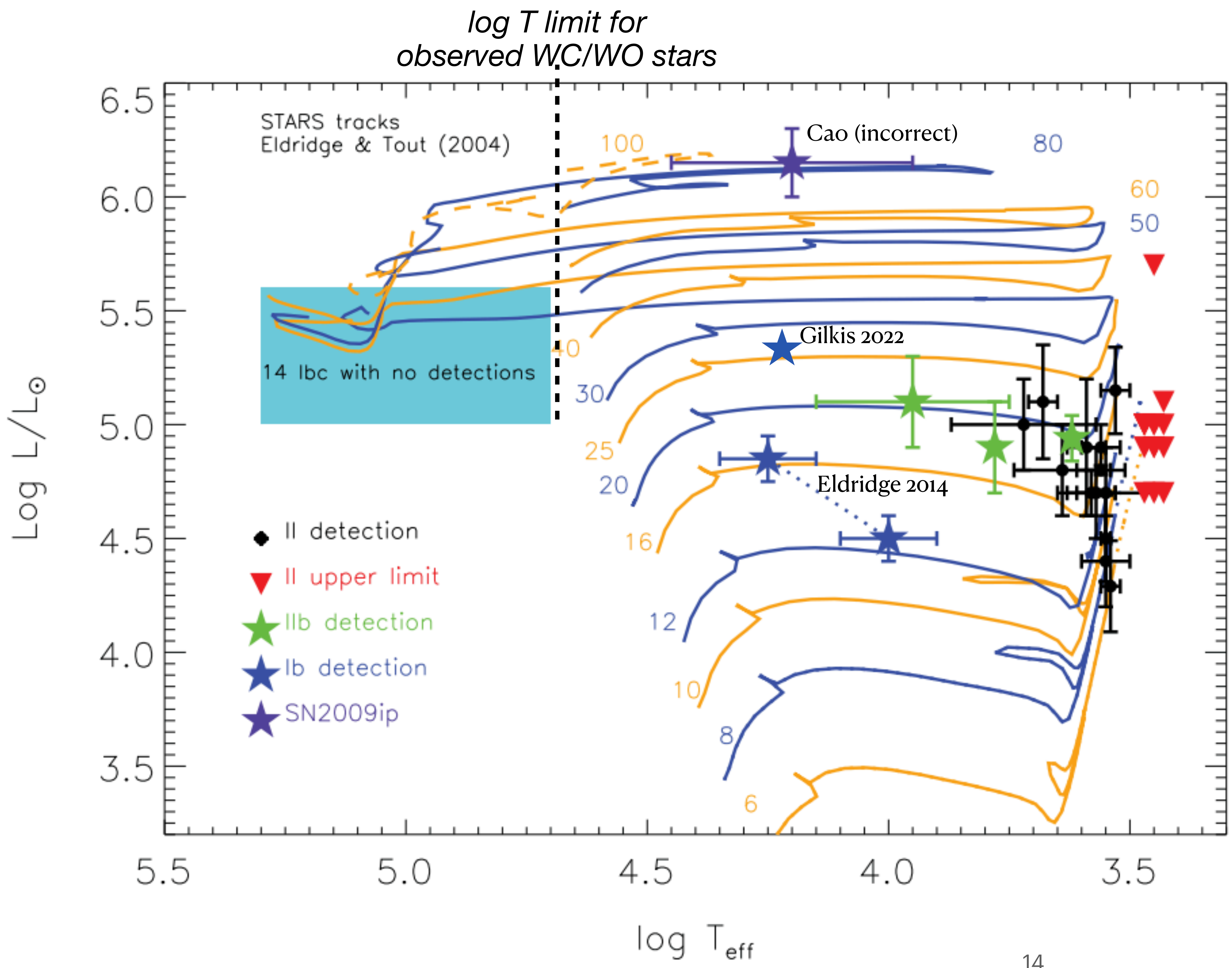
Expansion —> the SED peak shifts from UV (log T >~ 4.2) to optical/visual (log T <~ 4).



Humphreys & Davidson 1994

ARE WR STARS STRIPPED-ENVELOPE SN PROGENITORS?

Only one Type Ibc SN progenitor detected (iPTF13bvn)* : its HR position not in agreement with a WR star. Several limits on L_{bol} for other progenitors also in conflict.



Smartt 2015

The 14 upper limits (log L < 5 - 5.5) are in conflict with an hypothesis that WR stars (which are luminous) are SESN progenitors: some progenitors should then have been detected.

However, there is a caveat: some models predict that in the very late phases WR stars get much hotter and optically dimmer (and instead UV brighter), see e.g. Yoon 2012.

Normal observed WR stars would not be in this very late (and short) phase. If so, these detection limits would not strongly rule out WR stars.

However, several Type IIb progenitor detections (see Part F:20) are also in disagreement with WR stars.

Instead, **moderately luminous BSGs/YSGs are implicated.**

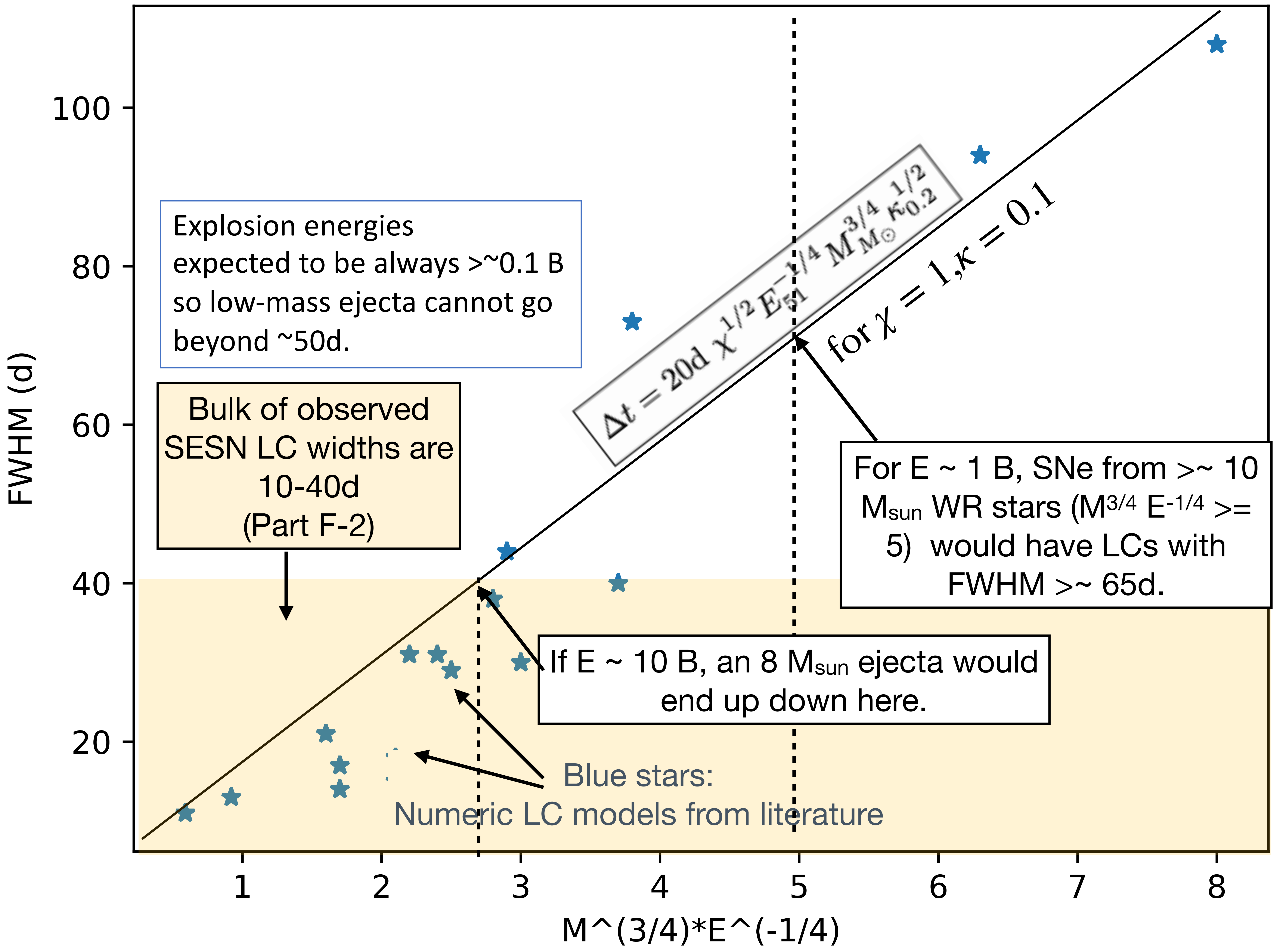
* The 2019ybr detection (PartF2 - slide 20) is still debated.

What SN light curves would exploding WR stars produce?

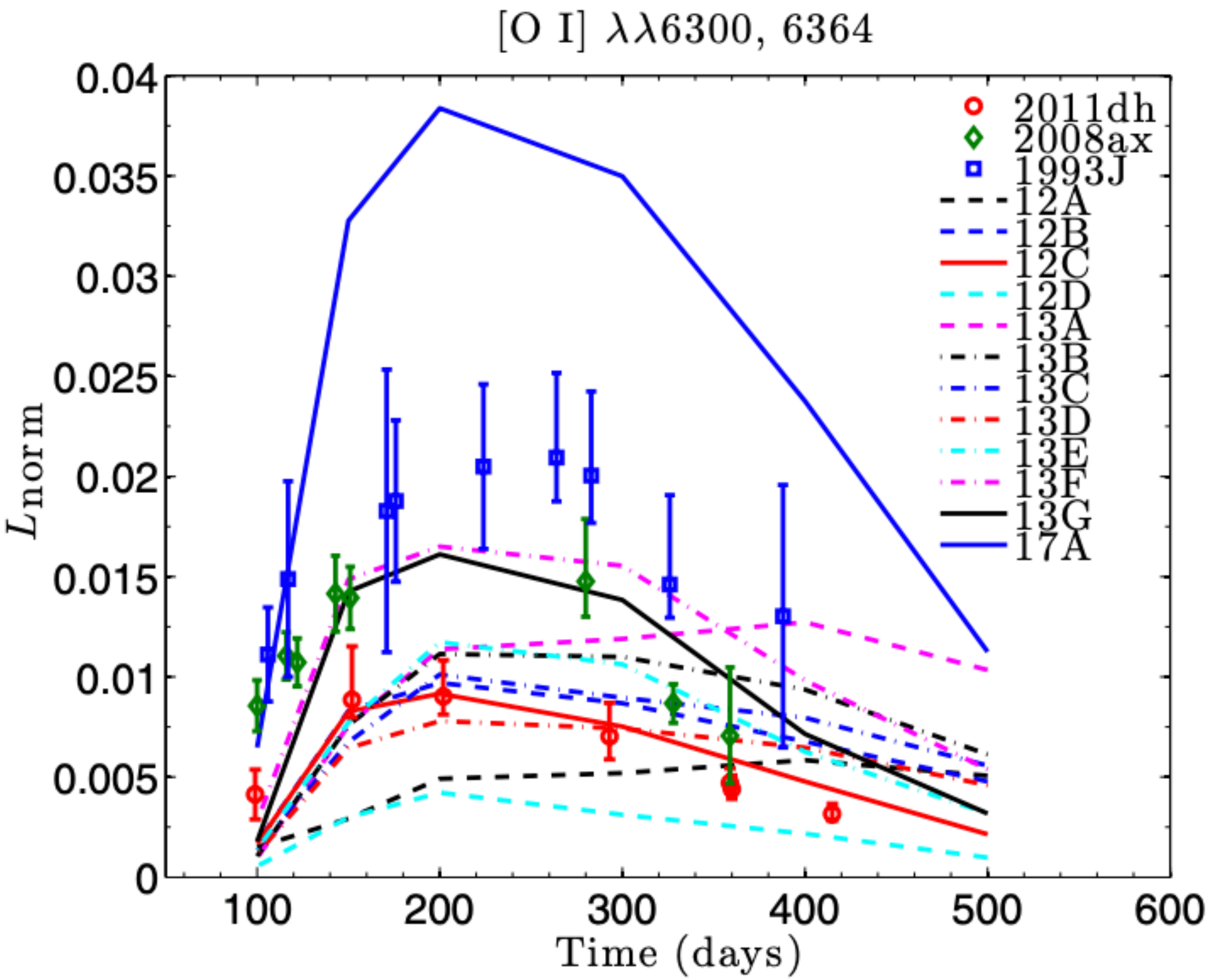
Forming both a BH <u>and</u> obtaining a successful SN explosion requires a lot of fine-tuning (Part D : e.g. slide 19): expect that either the whole He core collapses to a BH or that its inner region forms a NS and the rest is ejected in a SN.

Then, if the WR star's mass is e.g. 10 M_{sun} at collapse, and a successful SN happens, the SN mass would be ~8 M_{sun} (NS mass <~2 M_{sun}). Fallback is mostly minor.

We can take E ~ 1 B: a significantly larger E is not supported by other observables such as velocities and ^{56}Ni masses. Such an ejecta would then have $M^{3/4}E^{-1/4} \approx 4.8$ and $\Delta t \sim$ 65d (for $\kappa = 0.1$), <u>much longer than observed</u>.



Nebular analysis of SESNe



Jerkstrand 2015

Finally, **nebular phase nucleosynthesis diagnosis also indicates quite low masses of oxygen** and other element sensitive to M_{ZAMS} —> low or moderate mass stars.

Combining

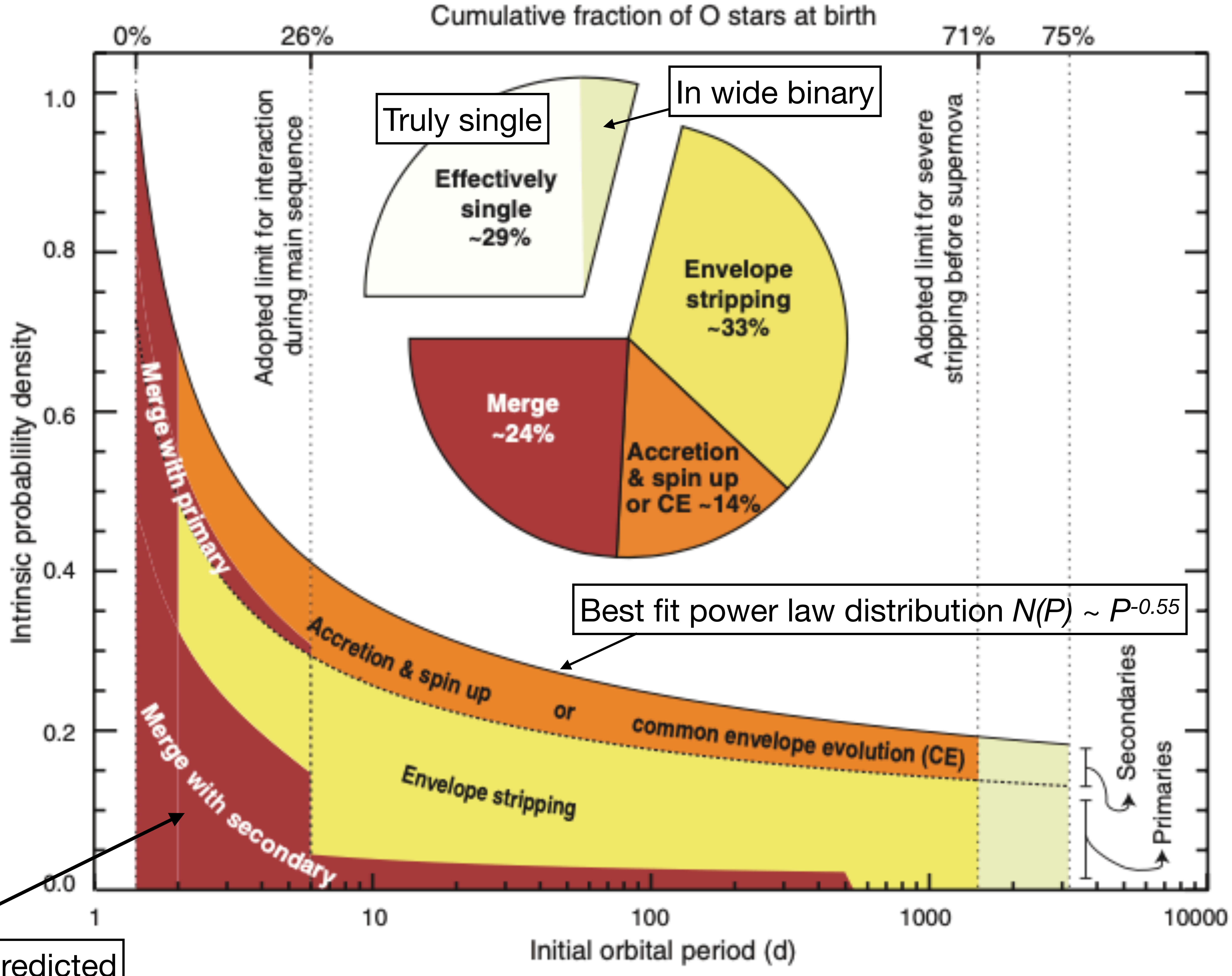
1. The lack of WR star progenitor detections
2. Disagreement on light curve widths
3. Low amounts of oxygen and other elements inferred from nebular spectra

we conclude that

Most SESNe are not WR star explosions unless WR stars lose much more mass than expected in their very late evolution.

BINARY MASS TRANSFER : THE ALTERNATIVE PATHWAY TO SESNe

Binaries are too common to ignore!



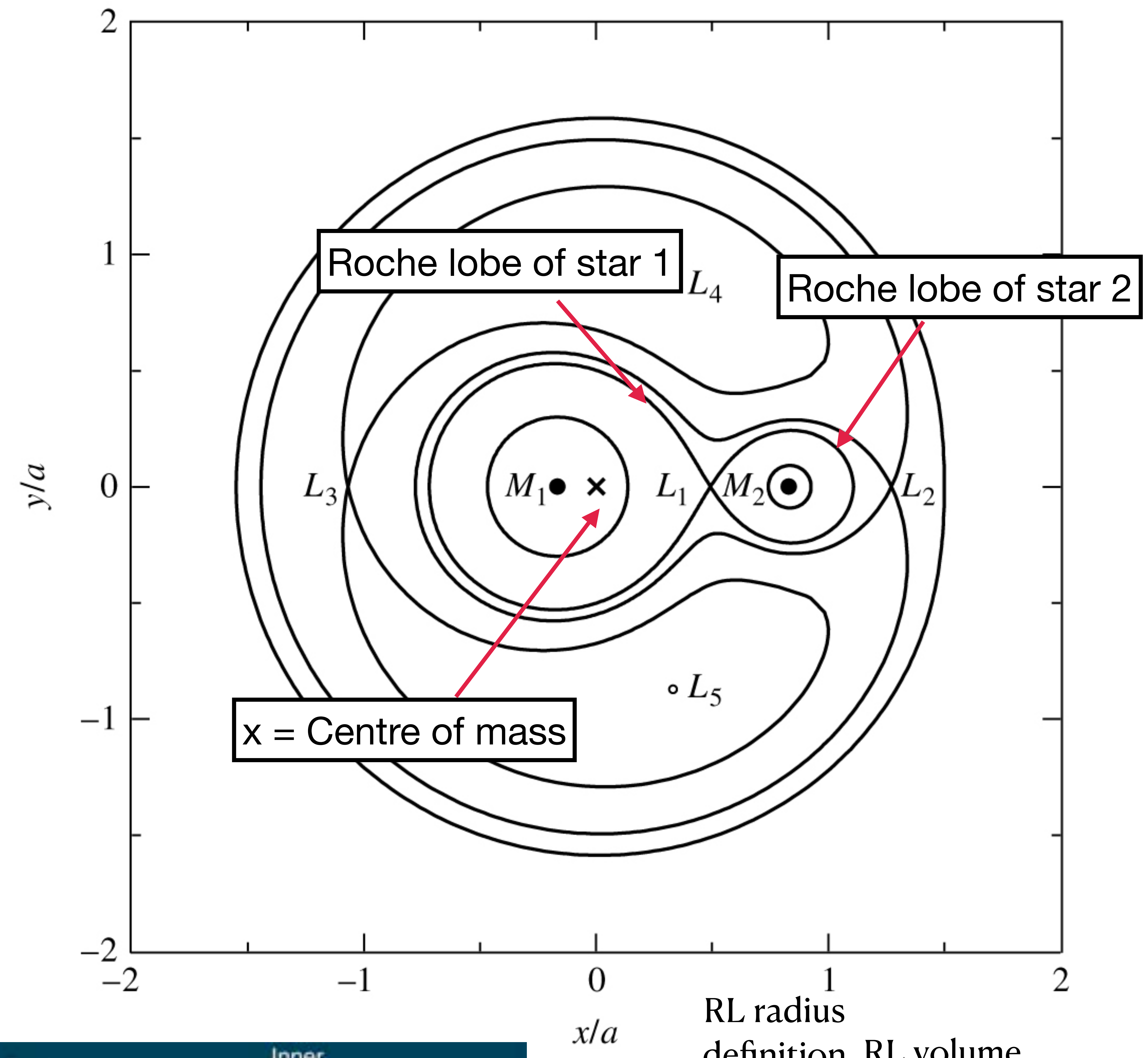
Most merger events predicted to occur on the MS

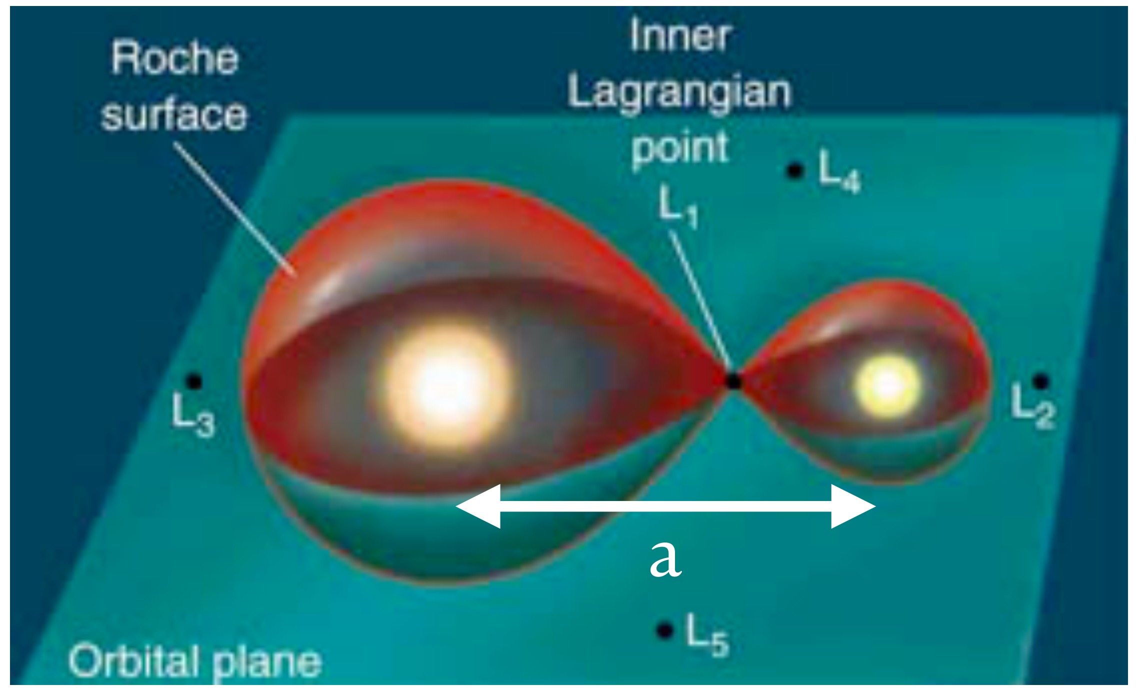
These data for O stars (M_{ZAMS} >~ 15 M_{sun})

Binary effects are somewhat less prominent for B stars (~8 - 15 M_{sun}), but still important (see e.g. Duchene 2013, Dunstall 2015.)

Sana 2012

Roche lobe overflow





RL radius definition RL volume

$$\frac{4\pi}{3}R_L^3 = V_L$$

Note $R_L^1 + R_L^2 < a$ ← separation between stars

In the co-rotating frame, there are surfaces of constant gravitational potential = isopotential surfaces.

The **Roche lobes** are the two lobes of the isopotential surface that passes through the L1 point (the point along the line between the stars at which the net force is zero).

At L1, a particle can transfer over to the other star with no energy cost.

If one of the stars expands to fill its Roche lobe, it will transfer mass to the companion star through L1, which acts like a nozzle.

In this process, mass can also be lost from the system rather than accumulated on the other star : this is called “non-conservative mass transfer”.

A **common envelope configuration** is possible when mass transfer is unstable: it can bring the stellar cores very close together and lead to merging.

Binary mass transfer

Two main properties of the transfer flow determine the outcome:

This online chapter by Onno Pols gives an excellent overview of binary mass transfer.

1) **Conservative** vs **non-conservative.**

Observationally, both cases appear to occur.

If conservative, mass transfer from the (initially) more massive primary leads to orbit shrinkage (and after reversal, to orbit growth).

If non-conservative: Much more complex situation with last least two more parameters:

β : Fraction of mass transferred that accretes onto companion ($1 - \beta$ is ejected).

γ : Angular momentum loss of the ejected matter. This depends on the mode of transfer (stable or unstable).

2) **Stable** vs **unstable.**

Which one happens depends on

- Radius response of the donor (which depends on e.g. whether its envelope is radiative or convective).
- Orbital response (which depends on whether conservative or non-conservative transfer).
- Companion response.

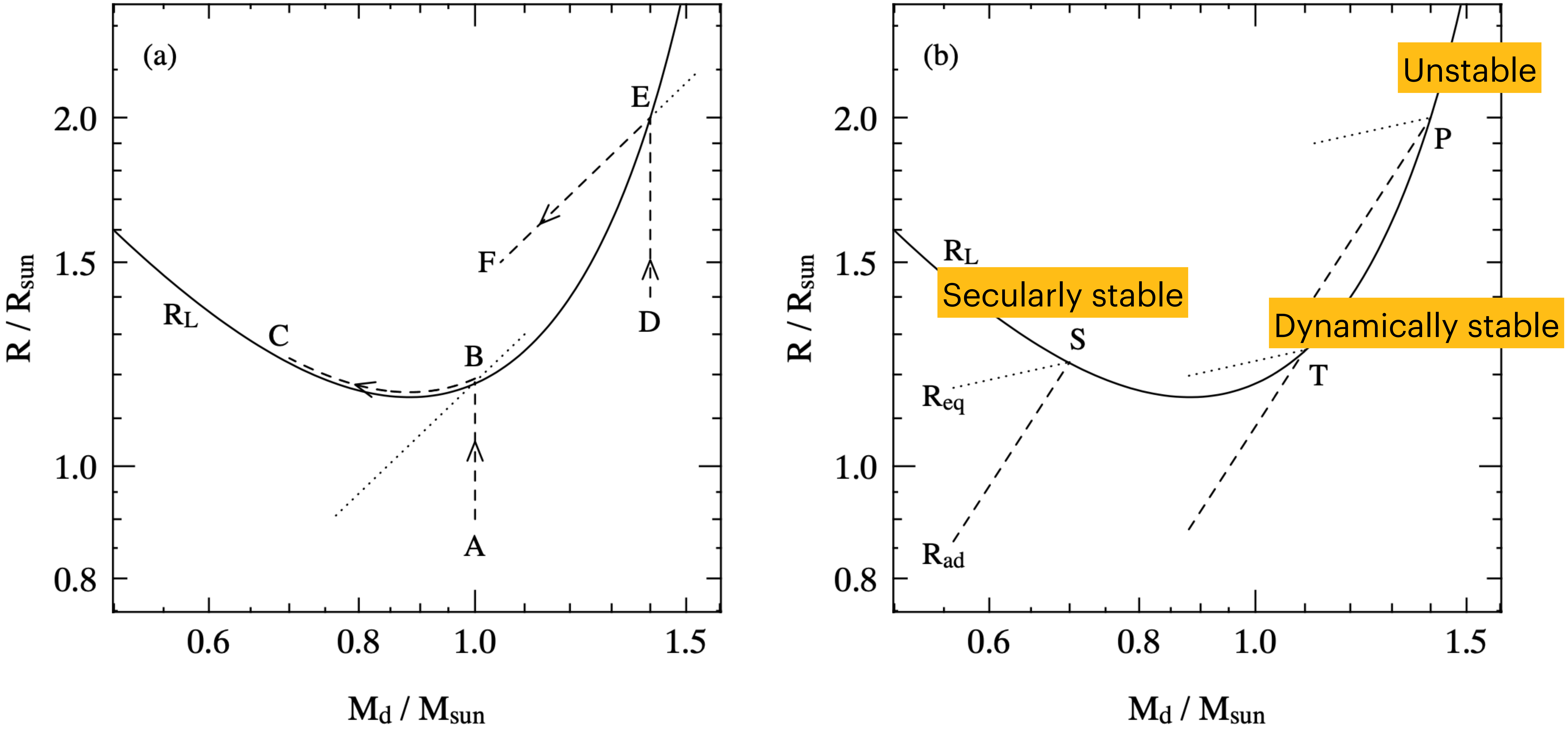
A. Secularly stable : Slow transfer on nuclear time-scale
B. Dynamically stable : Fast transfer on thermal time-scale
C. Unstable : Quickly leads to a common-envelope situation

Stability

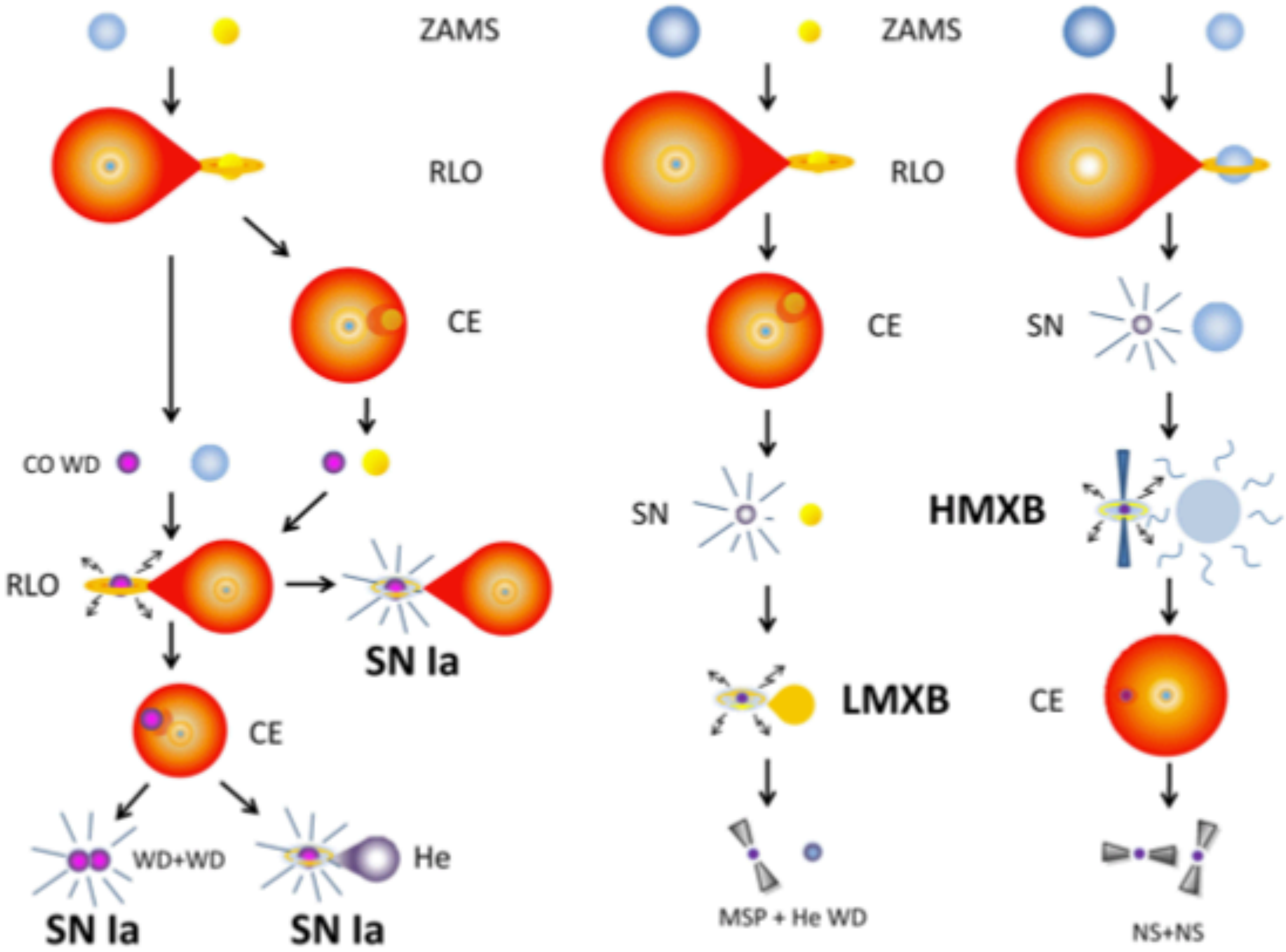
In this example, the total system mass is 2 M_{sun}.

Example 1: A 1.0 M_{sun} star, starts at **A.** When reaching **B**, responds with a *faster reducing radius than the Roche Lobe decreases* —> the star must re-expand to continue transfer —> transfer is **stable.**

Example 2: A1.4 M_{sun} star, starts **D.** When reaching **E**, responds with *slower reducing radius than the Roche Lobe decreases* —> transfer increases —> transfer is **unstable**.

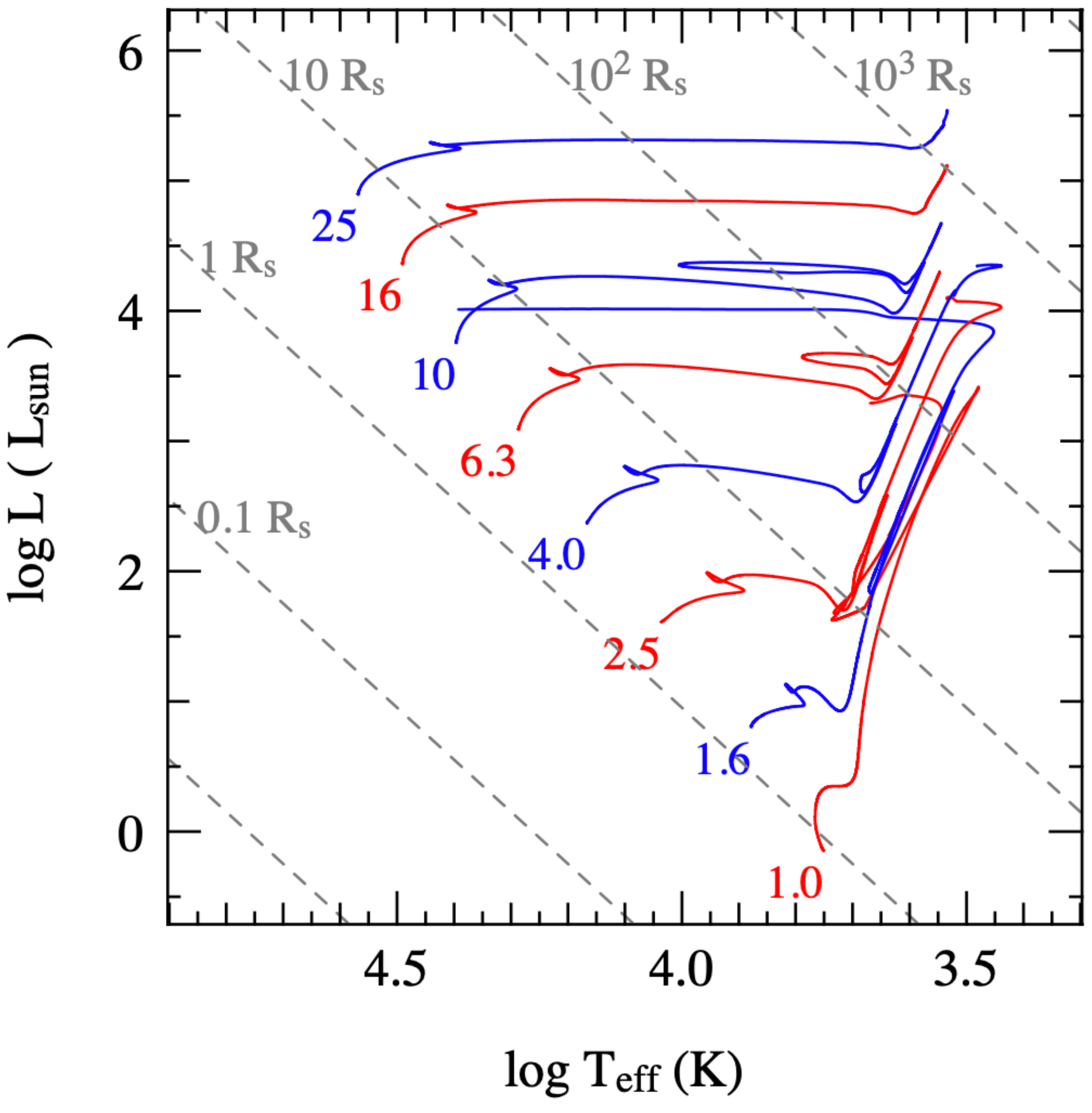


The many possible outcomes of binary interactions



Ivanova 2013

Binary mass transfer phases

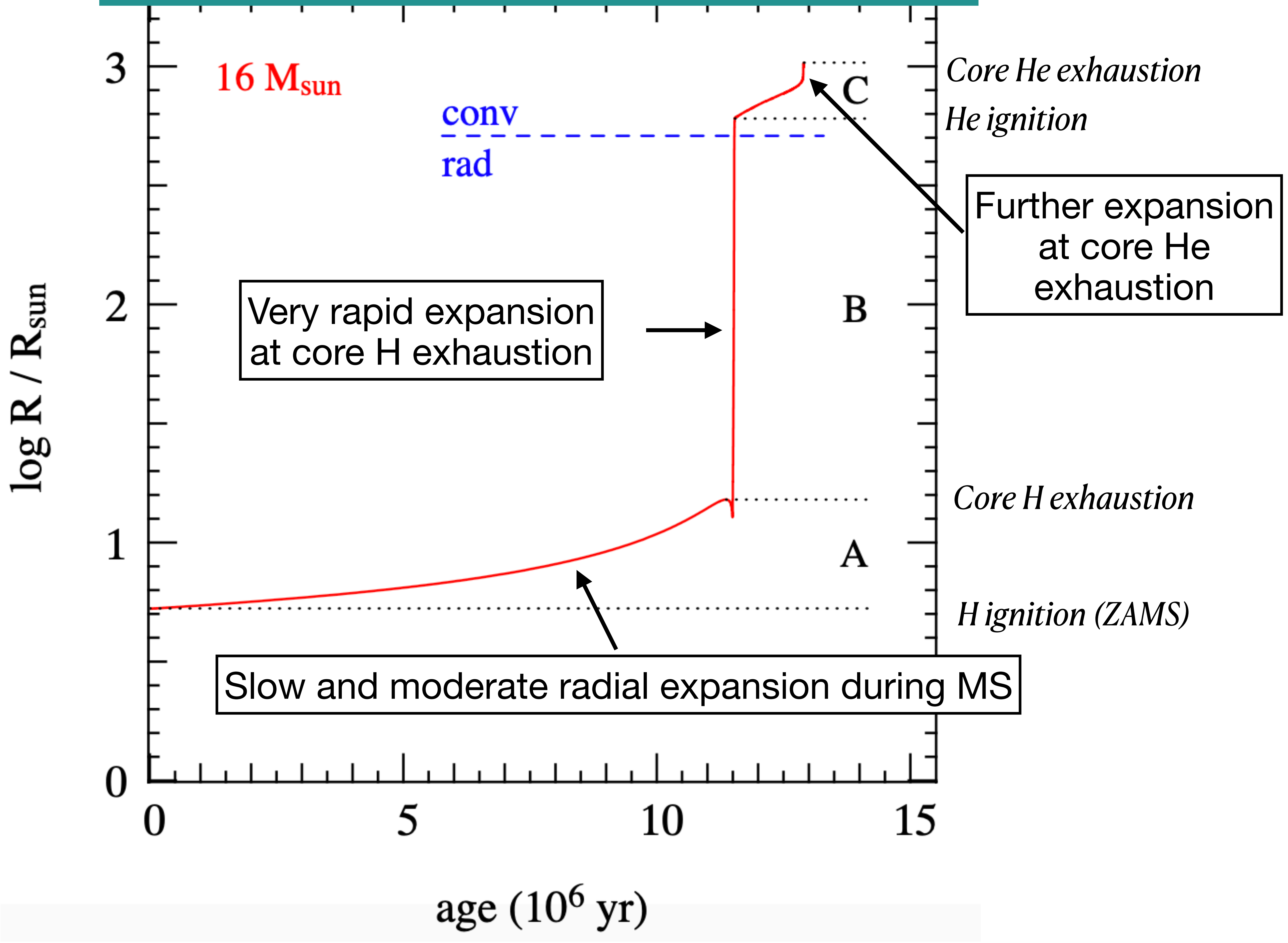


Case A : The primary expands to fill its RL during core H burning. (requires very close binaries).

Case B : The primary expands to fill its RL during H shell burning or core He burning.

Case C : The primary expand to fill its RL after core He burning.

Example of radius evolution in a 16 M_{sun} star



From **this online chapter** by Onno Pols

Binary mass transfer : an example model

Two limiting configurations in which transfer can occur on **thermal** or **nuclear** timescale**.**

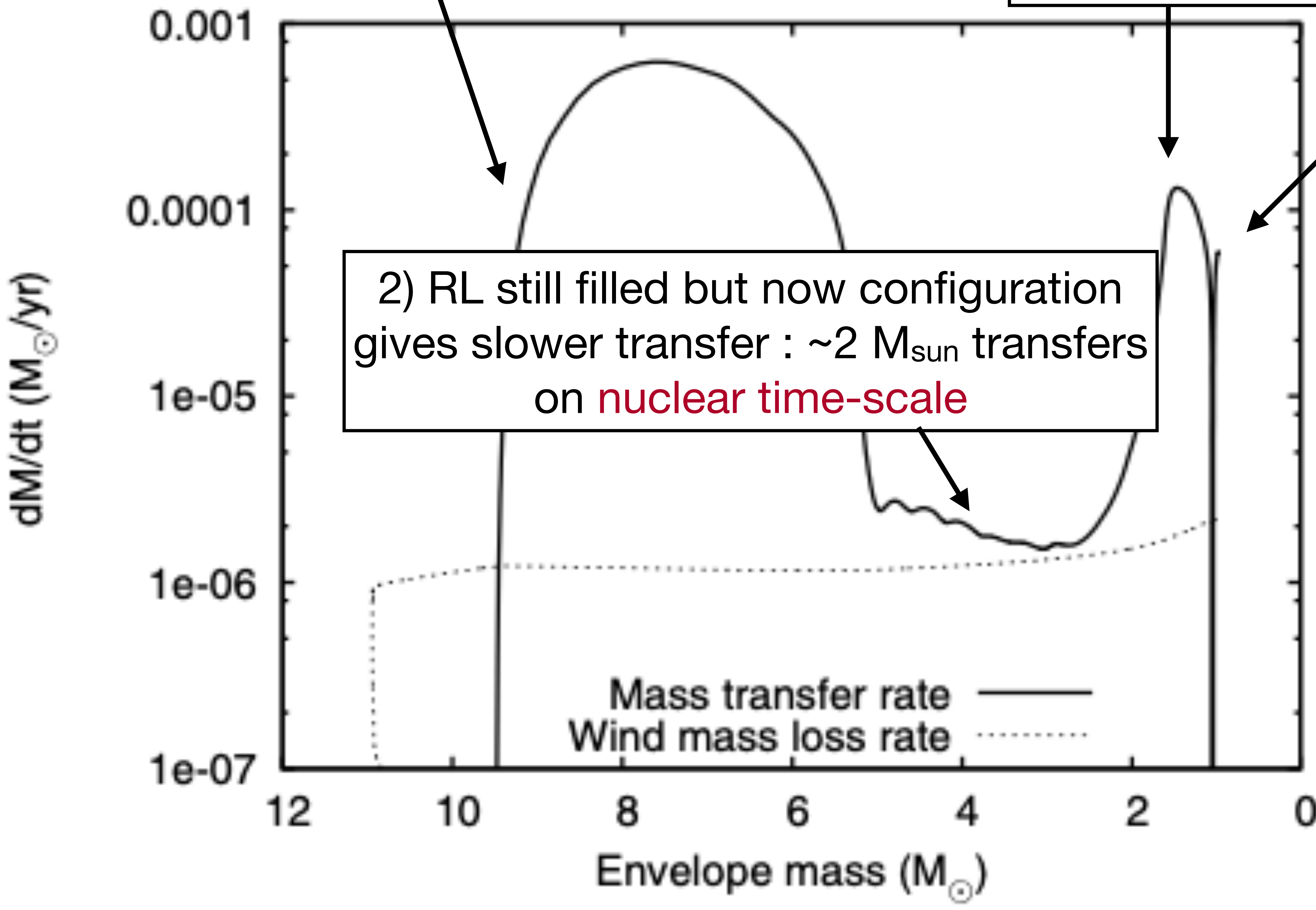
$$\dot{M}_{thermal} \approx \frac{M}{\tau_{KH}} \approx 0.01\ M_{\odot}/yr$$ **for a RSG**

$$\dot{M}_{thermal} \approx \frac{M}{\tau_{KH}} \approx 0.01\ M_{\odot}/yr$$ **for a RSG**

Which one happens depends (in a quite complicated way) on the primary star's envelope structure and the orbit:

1) Primary fills its RL in late core He burning (Case B): ~4 M_{sun} transfers on thermal time-scale

3) Star expands further at central He exhaustion (Case C): ~1 M_{sun} transfers on thermal time-scale



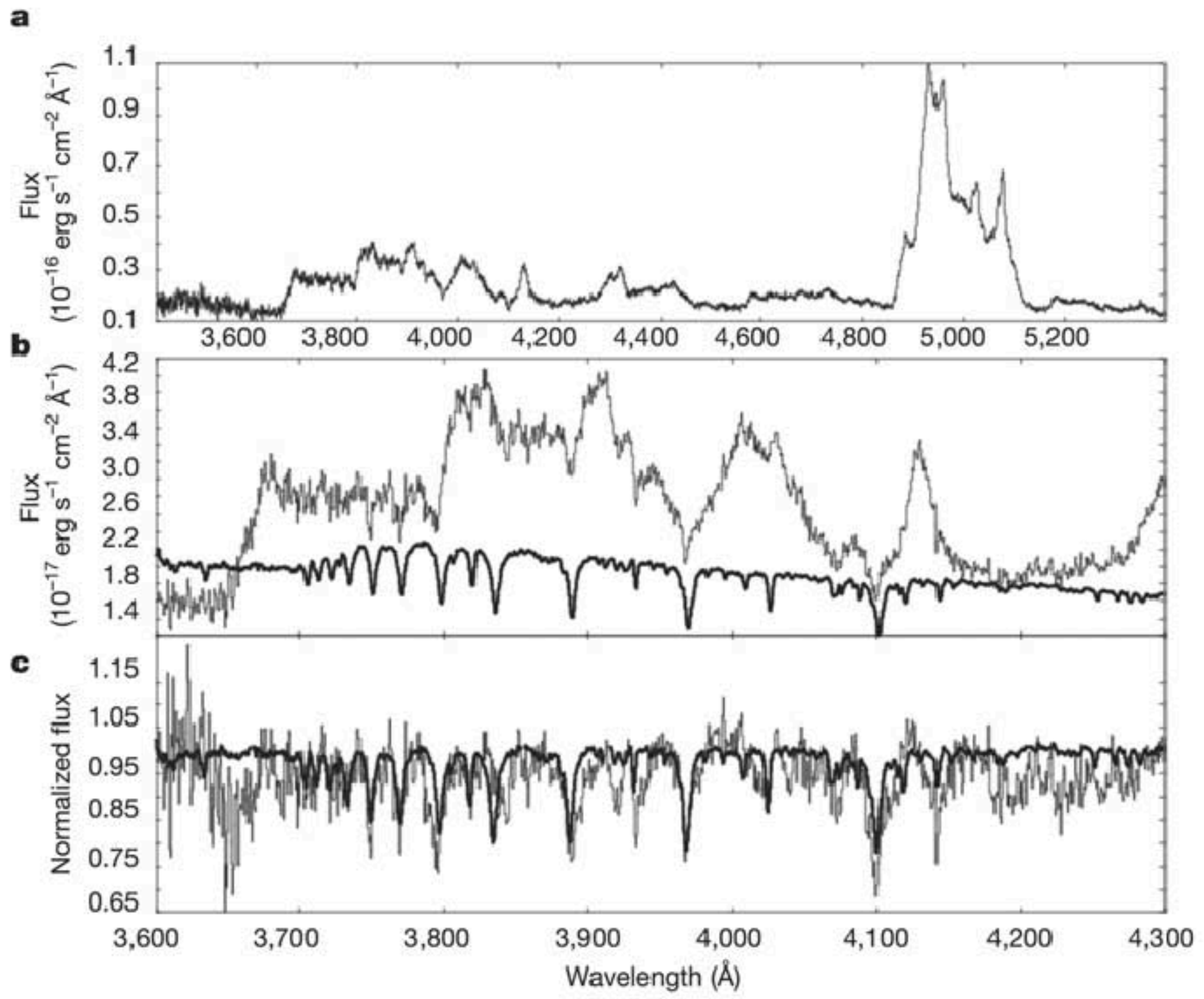
2) RL still filled but now configuration gives slower transfer : ~2 M_{sun} transfers on nuclear time-scale

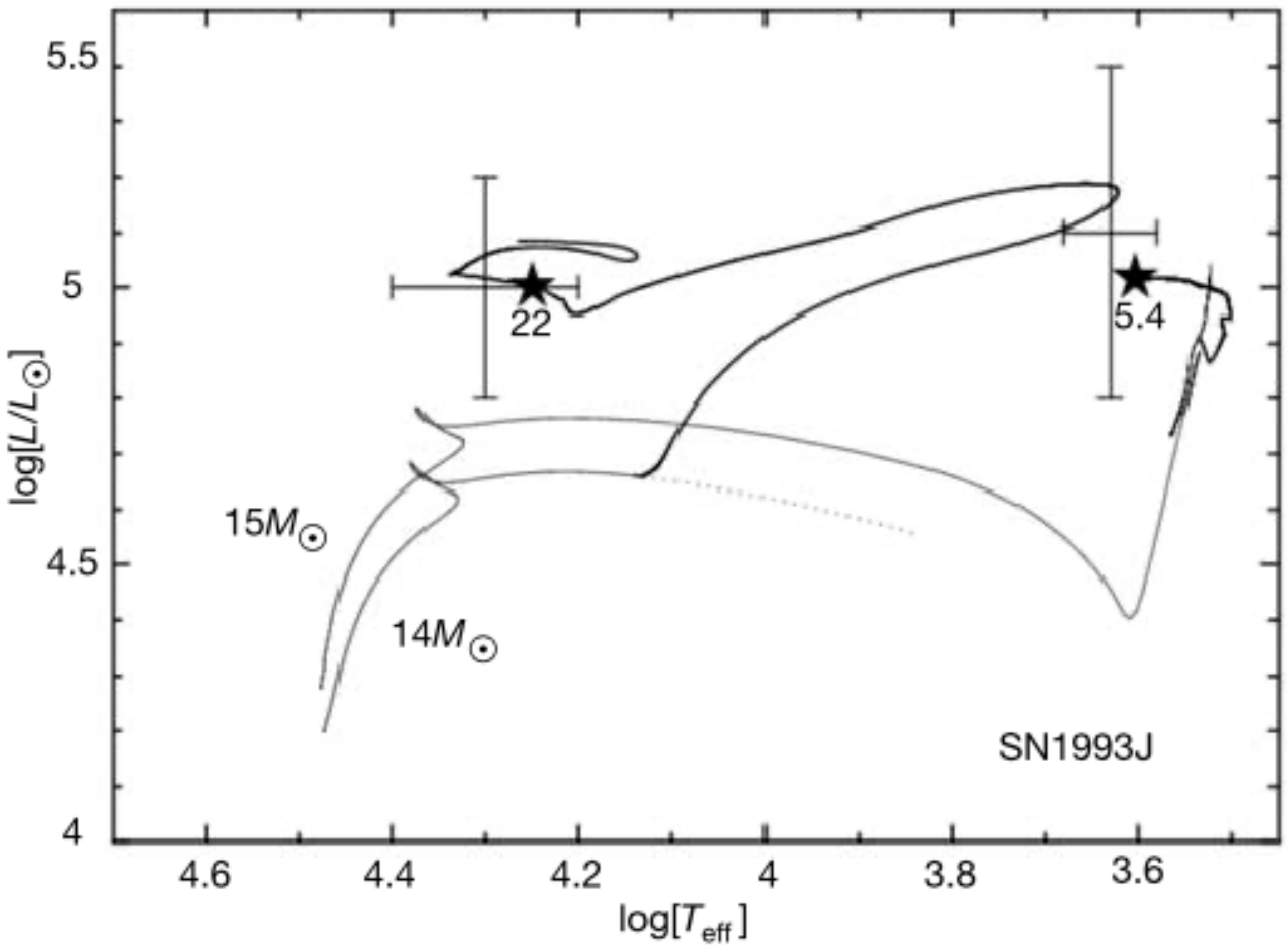
4) Simulation stopped but extrapolation —> ~0.4 M_{sun} of H left at collapse —> **IIb SN**

Claeys 2011: A M_{ZAMS} = 15 & 14 M_{sun} binary with initial orbital period 1500d.

Some SESN companion stars have been detected, strengthening the binary mass loss hypothesis

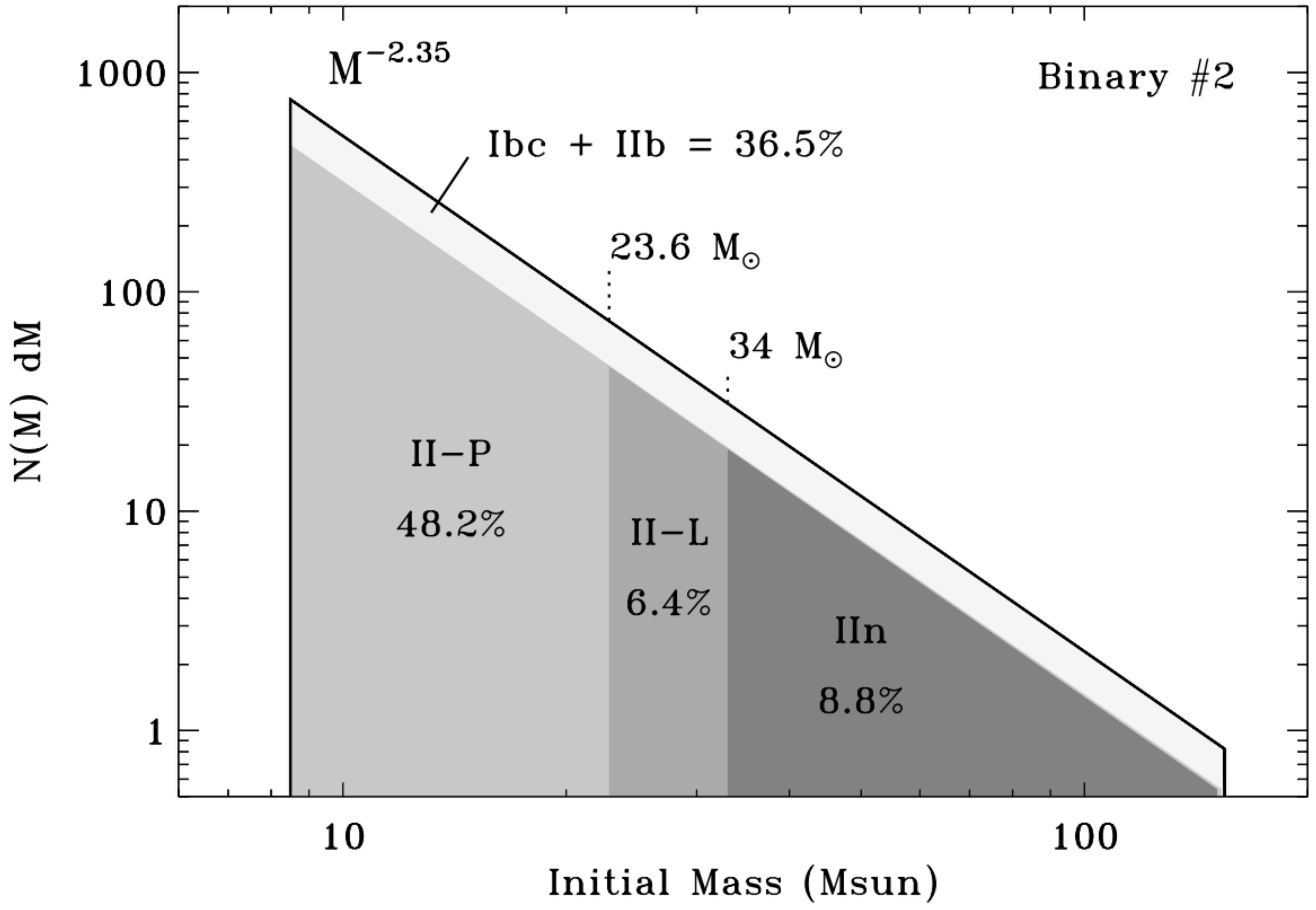
SN 1993J (Type IIb):

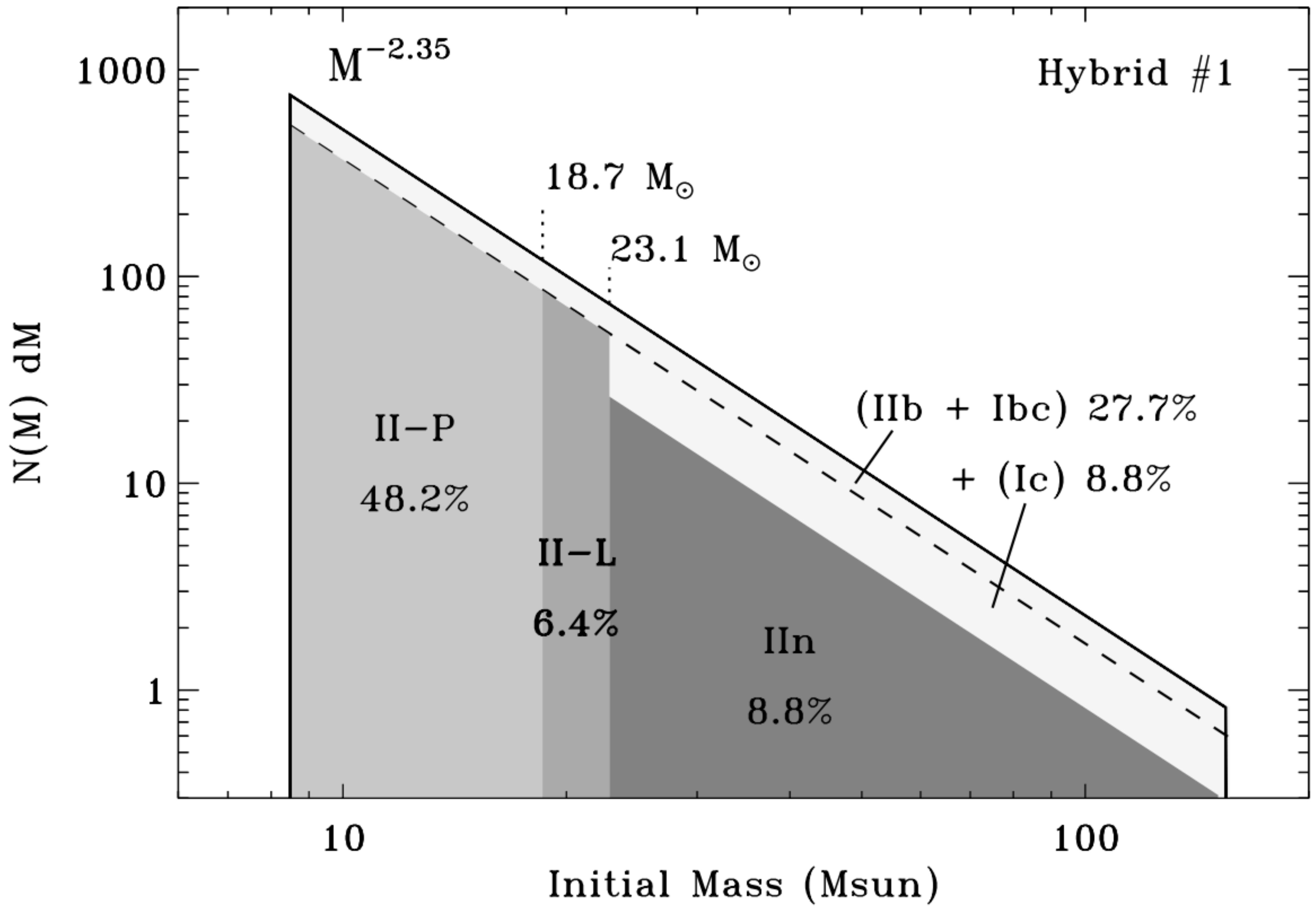




Maund 2004

Binary stellar systems can produce the lower-mass He star progenitors inferred for SESNe (because this mechanism allows also low-mass RSGs to lose their whole envelope), and can explain SN fractions quite well





Smith 2011

Rare SNe from WR stars

SESNe with broad light curve

Mostly Type Ic/Ic-BL

2011bm (Ic) Valenti 2012
Δt ~ 55d. M(^{56}Ni) ~ 0.7 M_{sun}

iPTF15dtg (Ic) Taddia 2016, 2019
Δt ~ 90d. M(^{56}Ni) ~ 0.4 M_{sun}

PTF11mnb (Ic) Taddia 2018
Δt ~ 65d. M(^{56}Ni) ~ 0.6 M_{sun}

→ More luminous than normal

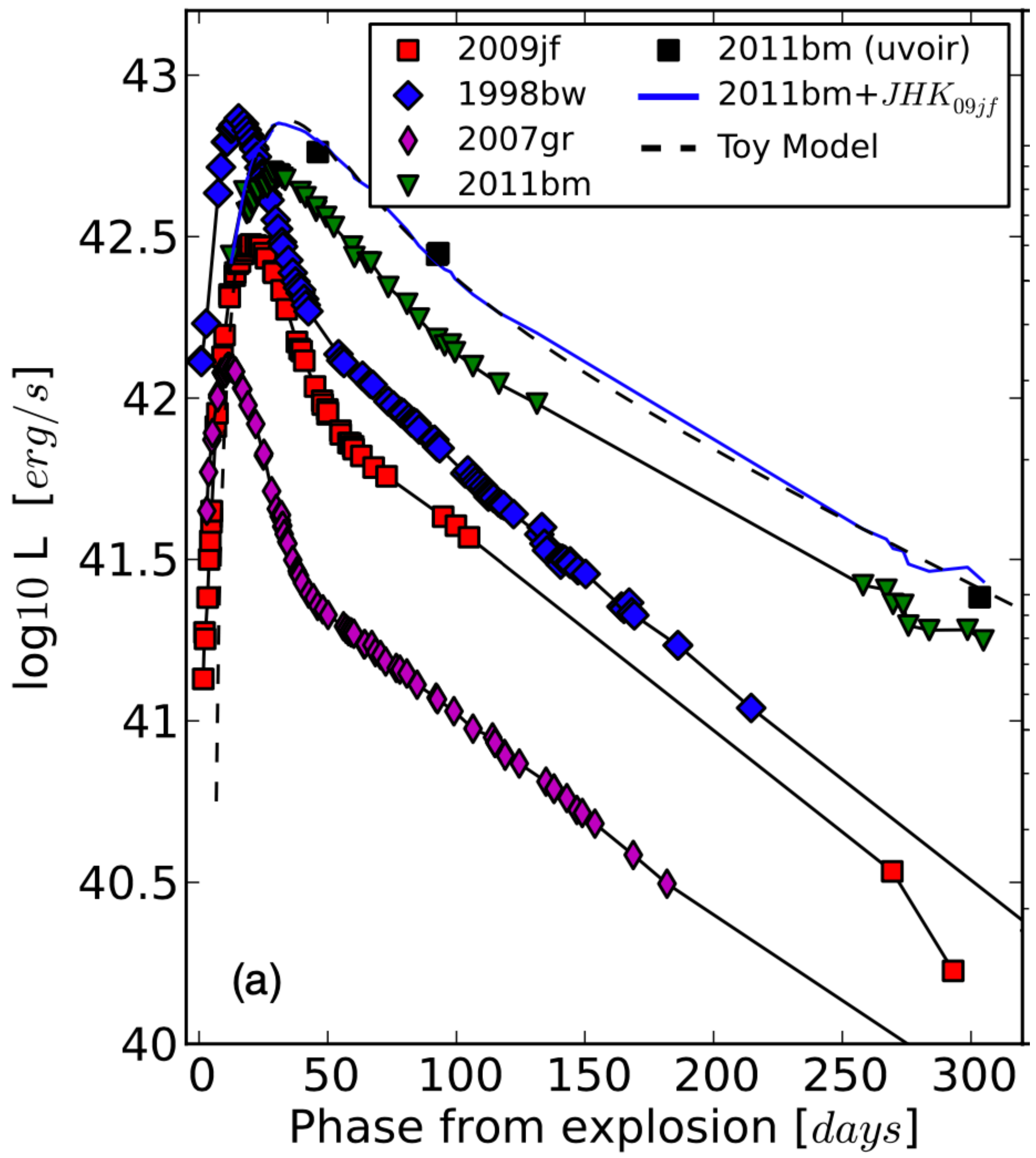
2007bi (Ic-BL) Gal-Yam 2009
No pre-peak data but slow decline.
M(^{56}Ni) >~ 3 M_{sun}

PTF12dam (Ic-BL) Chen 2015
Δt ~ 70d. M(^{56}Ni) >~ 3 M_{sun}

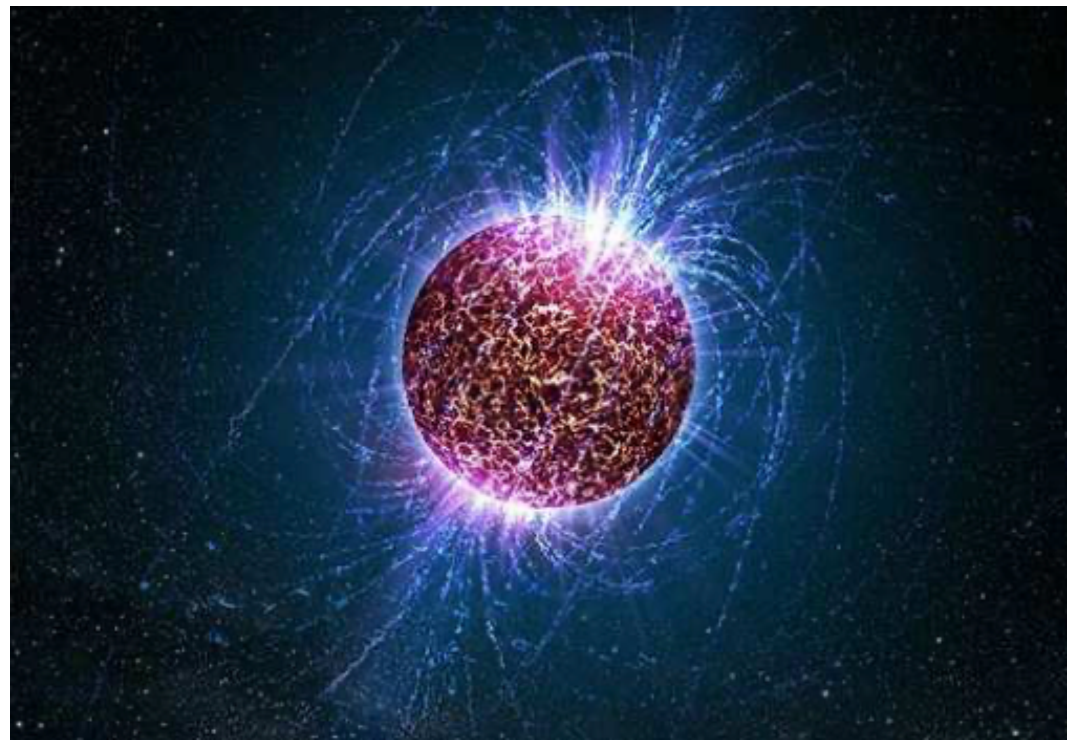
2015bn (Ic-BL) Nicholl 2016
Δt ~ 70d. M(^{56}Ni) >~ 3 M_{sun}

→ Much more luminous than normal —>"superluminous"

Valenti 2012



Superluminous supernovae

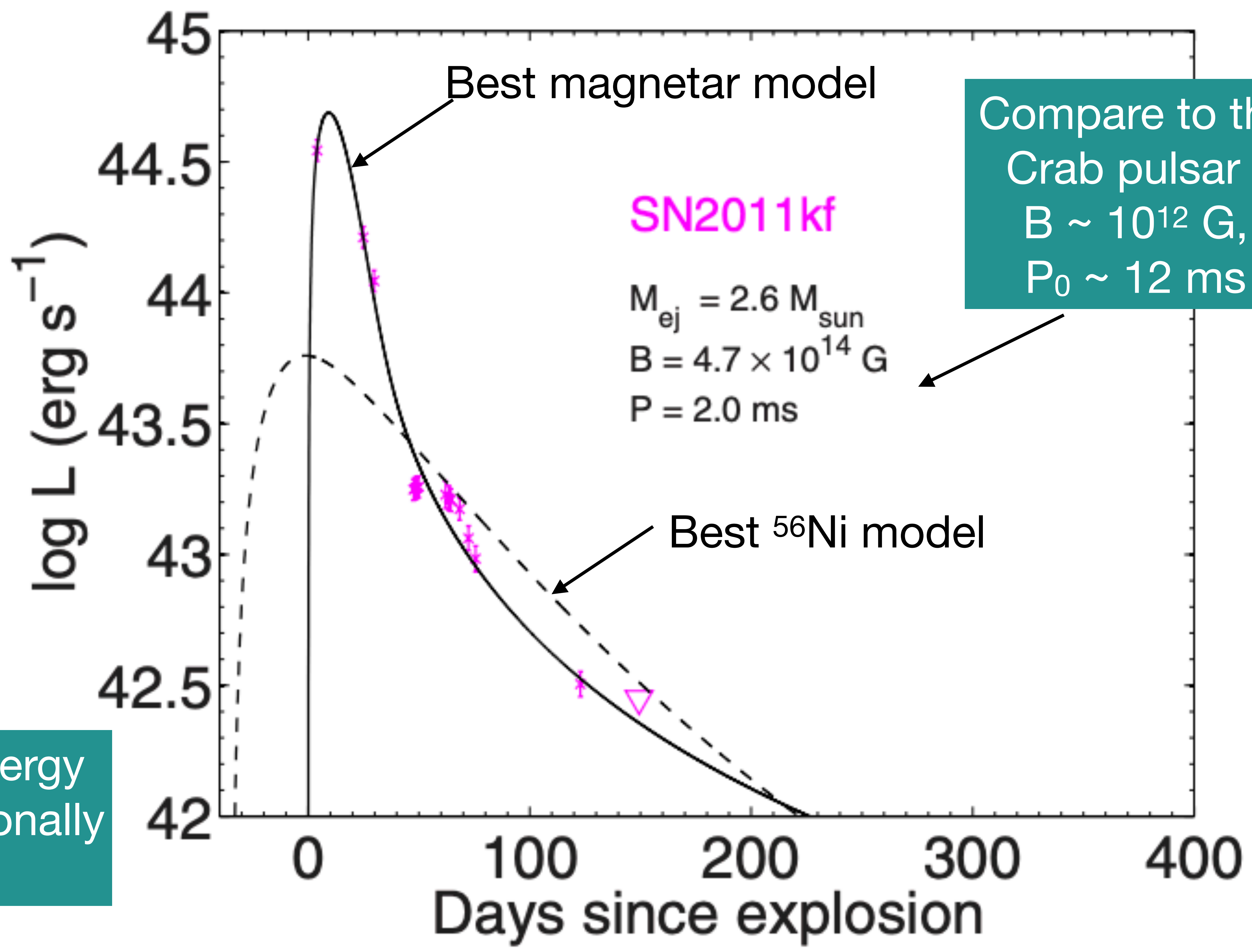


The brightest supernovae (original definition : peak mag > -21) are called **superluminous**.

The high luminosity typically requires some other energy source than radioactive decay by $^{56}Ni/^{56}Co$.

If there are no signs of circumstellar interaction from the spectra, power input by a rapidly rotating highly magnetized neutron star ("**magnetar**") is a popular model to explain a *S(t)* powering term apparently larger than what radioactivity can provide.

$$S(t)_{magnetar} = 5 \times 10^{46} B_{14}^{2} P_{0,ms}^{-4} \left(1 + \frac{t}{4.7\text{d}\ B_{14}^{-2} P_{0,ms}^{2}}\right)^{-2} \text{ erg s}^{-1}$$



Note the maximum possible rotation of a neutron star is about 1 ms. The energy reservoir stored in the NS rotation is

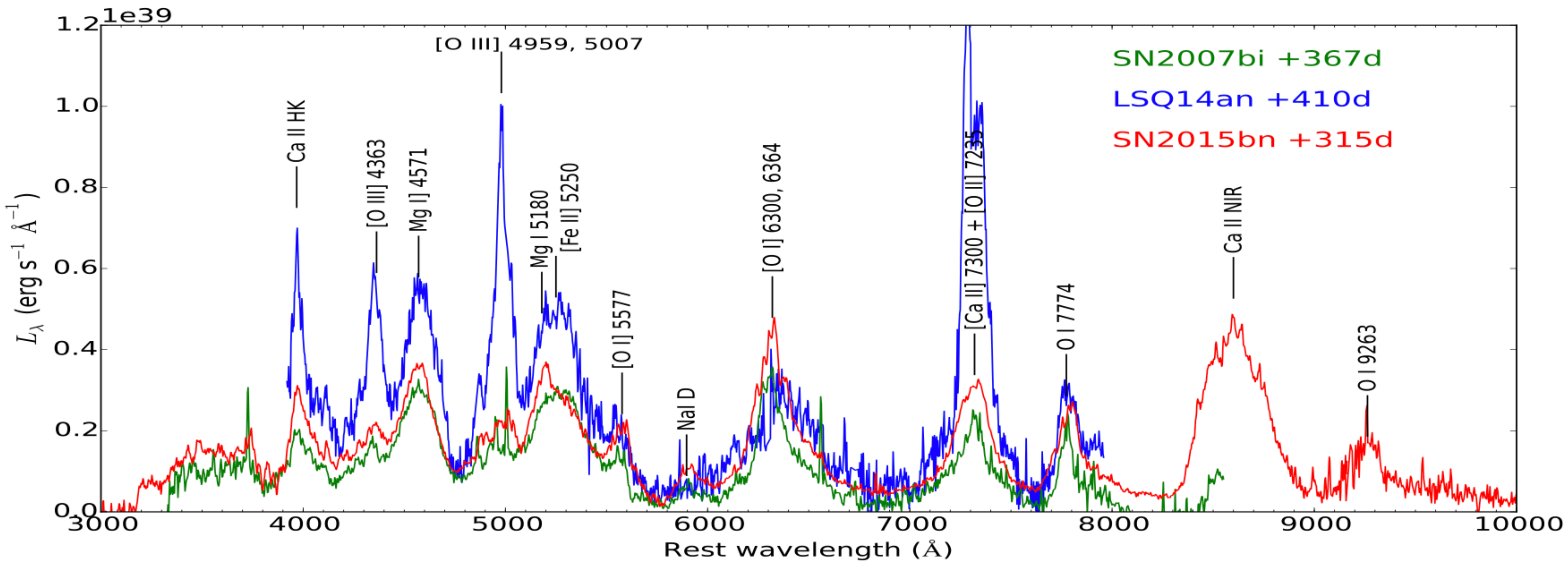
$$E_{rot} = \frac{1}{2} I_{ns} \Omega^2 = 2 \times 10^{52} P_{0,ms}^{-2} \text{ erg}$$

This energy comes ***not*** from rotation energy of the progenitor star but from gravitationally released energy in the collapse.

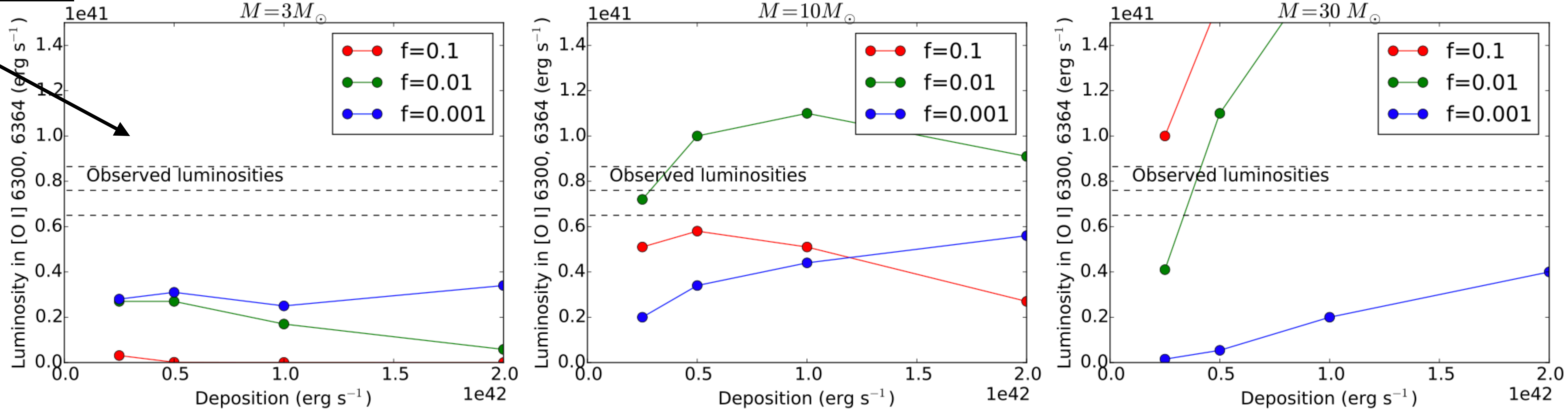
Compare this to the energy released by $^{56}Ni/^{56}Co$ decay : ~10^{49} erg for 0.1 M_{sun}.

Inserra 2013

Nebular spectra of Ic-BL SNe indicate >~ 5-10 M_{sun} of ejected oxygen and thereby support for a WR star origin



Models show low O mass (here 3 M_{sun}) cannot give bright enough emission lines to match observations



But, the extreme rarity of these kind of SNe (about 1 in every 10,000 event) probably means ***only a small/moderate fraction of WR stars explode!***

Jerkstrand 2017

(Semi)-agreed term in community:
“Very massive star (VMS)” means M_{ZAMS} > 100 M_{sun}.

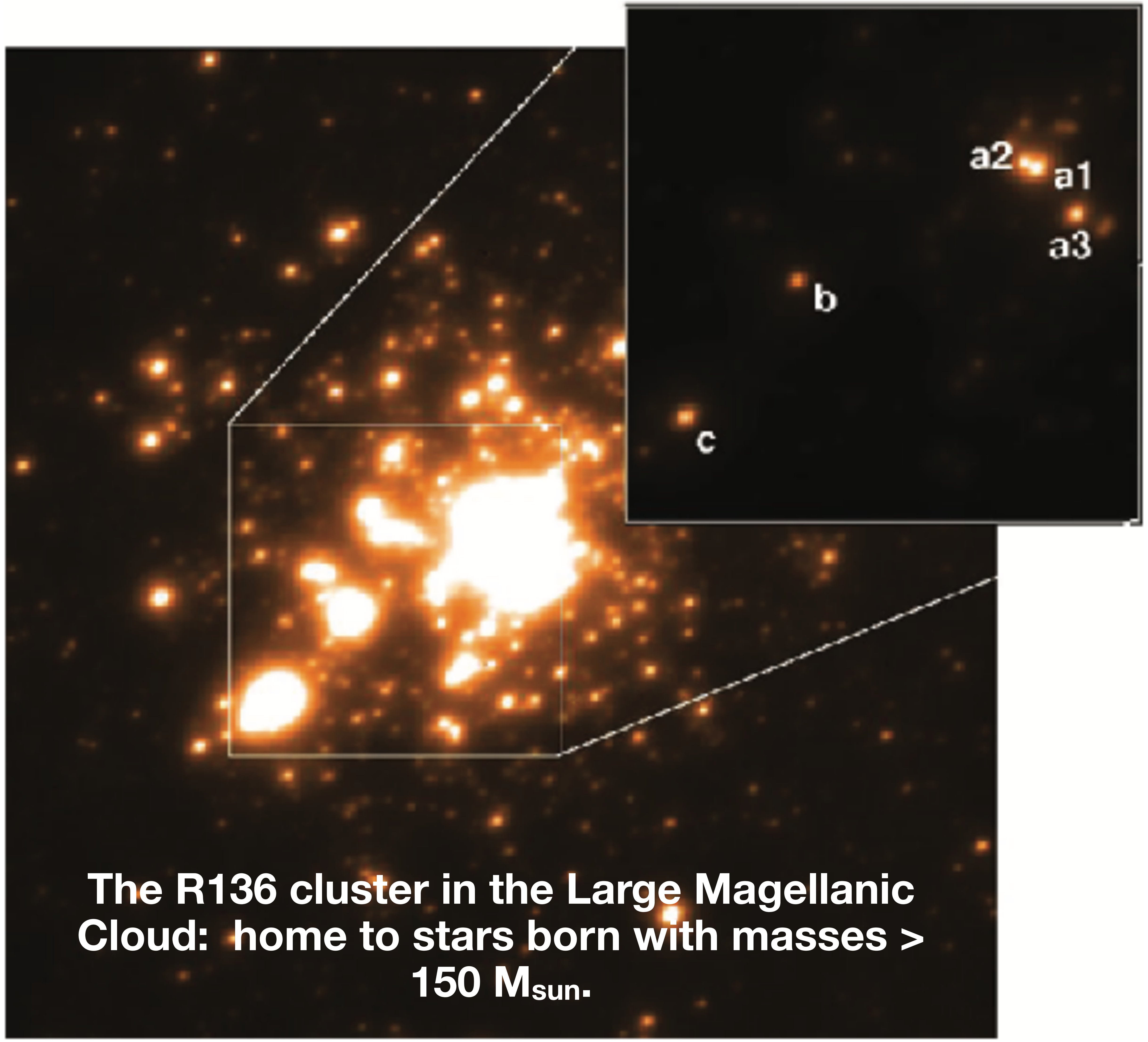
SNe from Very Massive Stars:
Pulsational Pair-Instability SNe
and Pair Instability SNe

Very massive stars are around us

Table 4. Physical properties of NGC 3603 WN 6h stars.

Name	A1a	A1b	B	C
T_* (kK)[a]	42 ± 2	40 ± 2	42 ± 2	44 ± 2
$\log(L/L_\odot)$	6.39 ± 0.14	6.18 ± 0.14	6.46 ± 0.07	6.35 ± 0.07
$R_{\tau=2/3}$ ($R_\odot$)	$29.4^{+10.1}_{-4.3}$	$25.9^{+7.2}_{-3.1}$	$33.8^{+2.7}_{-2.5}$	$26.2^{+2.1}_{-2.0}$
N_{LyC} (10^{50} s^{-1})	$1.6^{+0.8}_{-0.4}$	$0.85^{+0.54}_{-0.23}$	$1.9^{+0.3}_{-0.3}$	$1.5^{+0.3}_{-0.3}$
$\dot{M}$ (10^{-5} $M_\odot$ yr^{-1})	$3.2^{+1.2}_{-0.6}$	$1.9^{+0.9}_{-0.4}$	$5.1^{+0.6}_{-0.6}$	$1.9^{+0.2}_{-0.2}$
$\log \dot{M} - \log \dot{M}^c_{Vink}$	$+0.14$	$+0.24$	$+0.22$	-0.04
V_∞ (km s^{-1})	2600 ± 150	2600 ± 150	2300 ± 150	2600 ± 150
X_H (per cent)	60 ± 5	70 ± 5	60 ± 5	70 ± 5
M_{init} ($M_\odot$)[b]	148^{+40}_{-27}	106^{+23}_{-20}	166^{+20}_{-20}	137^{+17}_{-14}
$M_{current}$ ($M_\odot$)[b]	120^{+26}_{-17}	92^{+16}_{-15}	132^{+13}_{-13}	113^{+11}_{-8}
M_{K_s} (mag)[d]	-7.0 ± 0.3	-6.6 ± 0.3	-7.5 ± 0.1	-6.7 ± 0.1

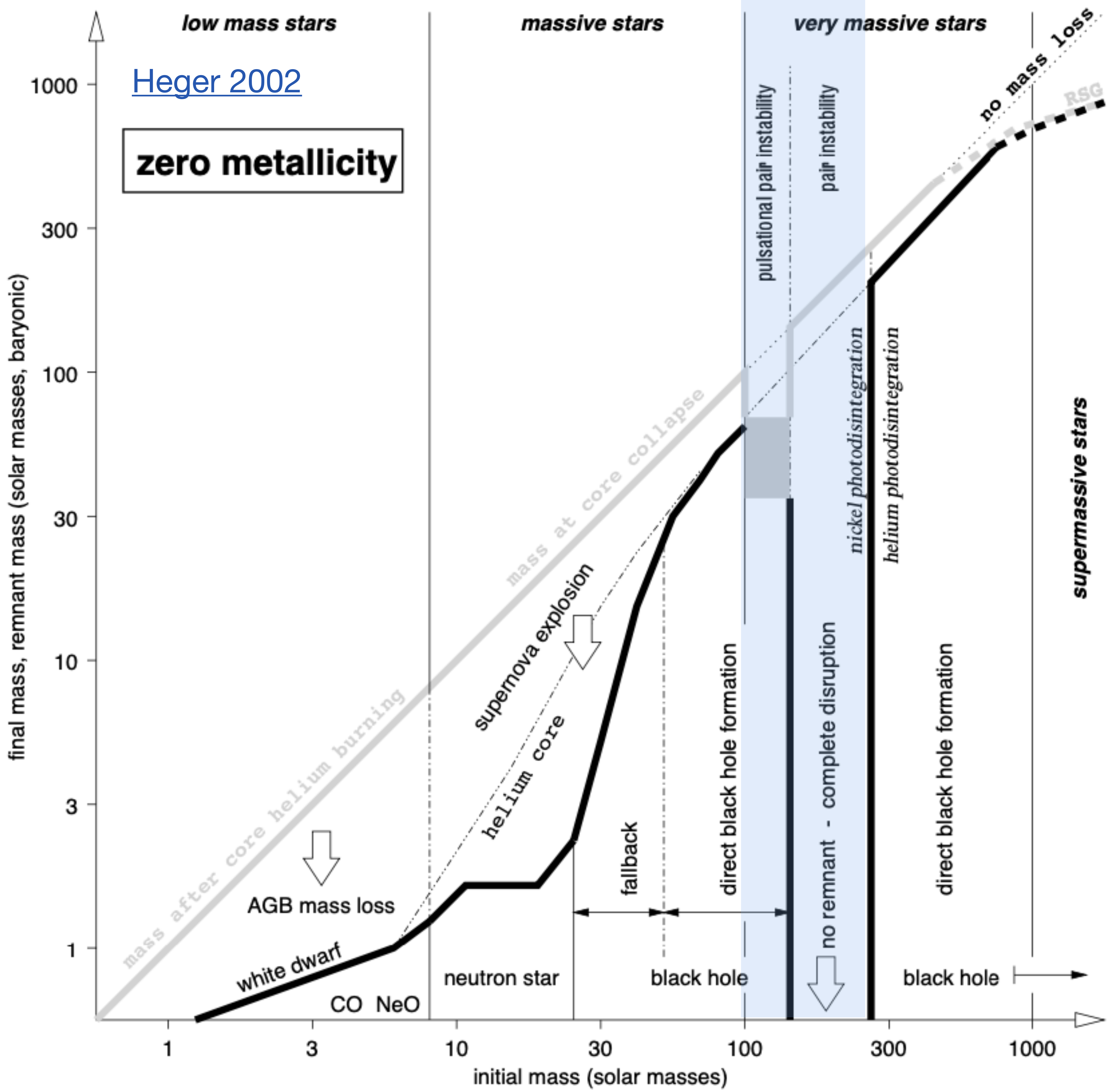
[a]Corresponds to the radius at a Rosseland optical depth of $\tau_{Ross} = 10$.
[b]Component C is a 8.9 d period SB1 system (Schnurr et al. 2008a).
[c]dM/dt_{Vink} relates to Vink et al. (2001) mass-loss rates for $Z = Z_\odot$.
[d]$M_{K_s} = -7.57 \pm 0.12$ mag for A1, for which we adopt $\Delta m = m_{A1a} - m_{A1b} = -0.43 \pm 0.30$ mag (Schnurr et al. 2008a). The ratio of their luminosities follows from their dynamical mass ratios together with $L \propto \mu M^{1.5}$ (and is supported by NICMOS photometry from Moffat et al. 2004).



The R136 cluster in the Large Magellanic Cloud: home to stars born with masses > 150 M_{sun}.

Crowther 2010

The fate of Very Massive Stars



If too strong mass loss is avoided (so low metallicity required), three possible fates:

1. **Pulsational Pair Instability SN** ($M_{ZAMS} \approx$ 100 - 140 M_{sun}, $M_{He\text{-}core} \approx$ 40 - 65 M_{sun}. *Star ejects mass in a series of pulses. A massive iron core eventually forms (maximum mass ~40-60 M_{sun}, e.g. Farmer 2019) and collapses to a BH.*

2. **Pair Instability SN** ($M_{ZAMS} \approx$ 140 - 260, $M_{He\text{-}core} \approx$ 65 - 130 M_{sun}). *Thermonuclear explosion of whole star, no remnant (similar to Type Ia SN).*

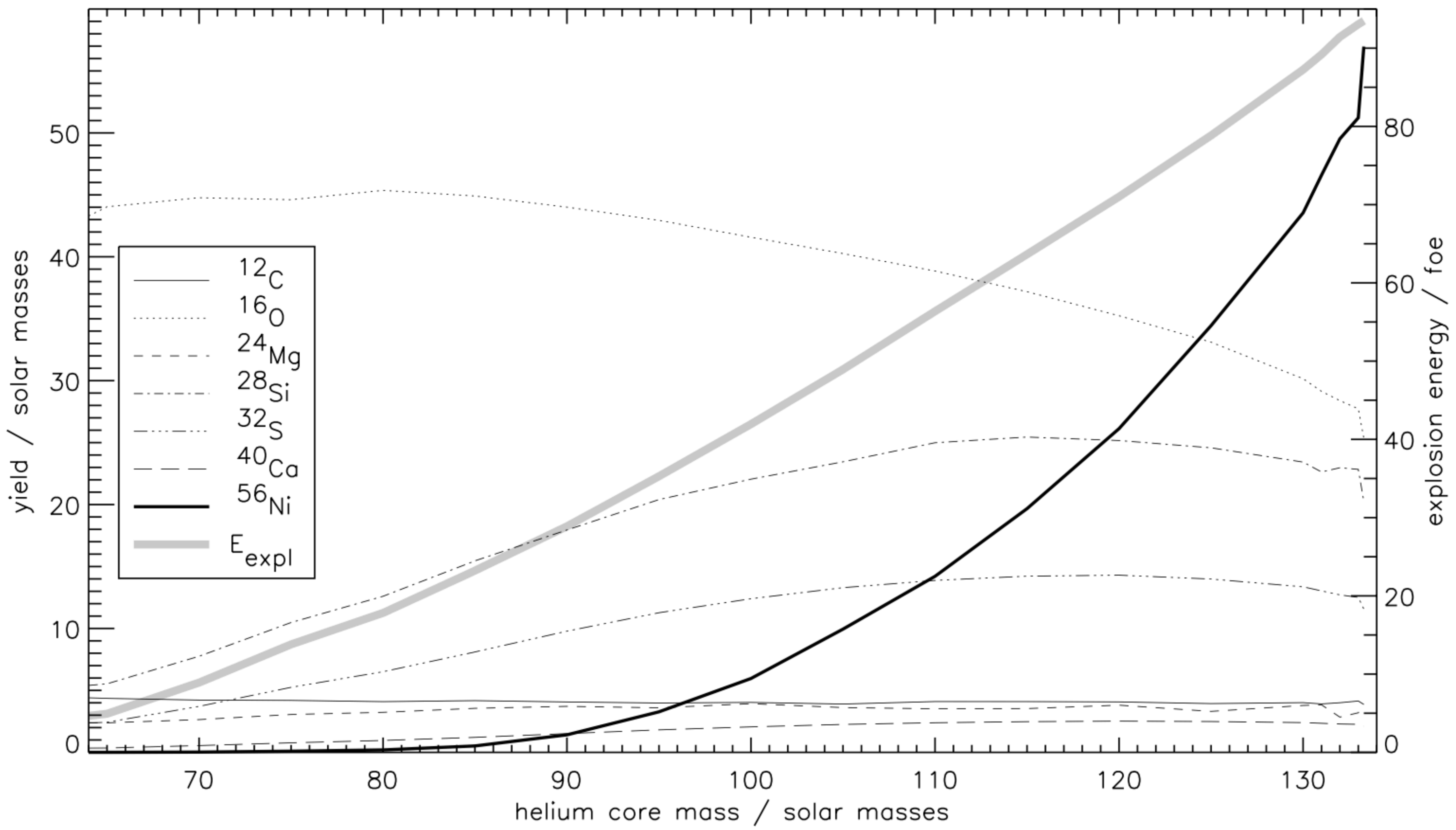
3. **Massive BH formation** (M_{ZAMS} > 260 M_{sun}, $M_{He\text{-}core}$ > 130 M_{sun}). *Can such massive stars exist (Exercise Set 1) ? If they can, what would be the BH masses?*

The pair-instability

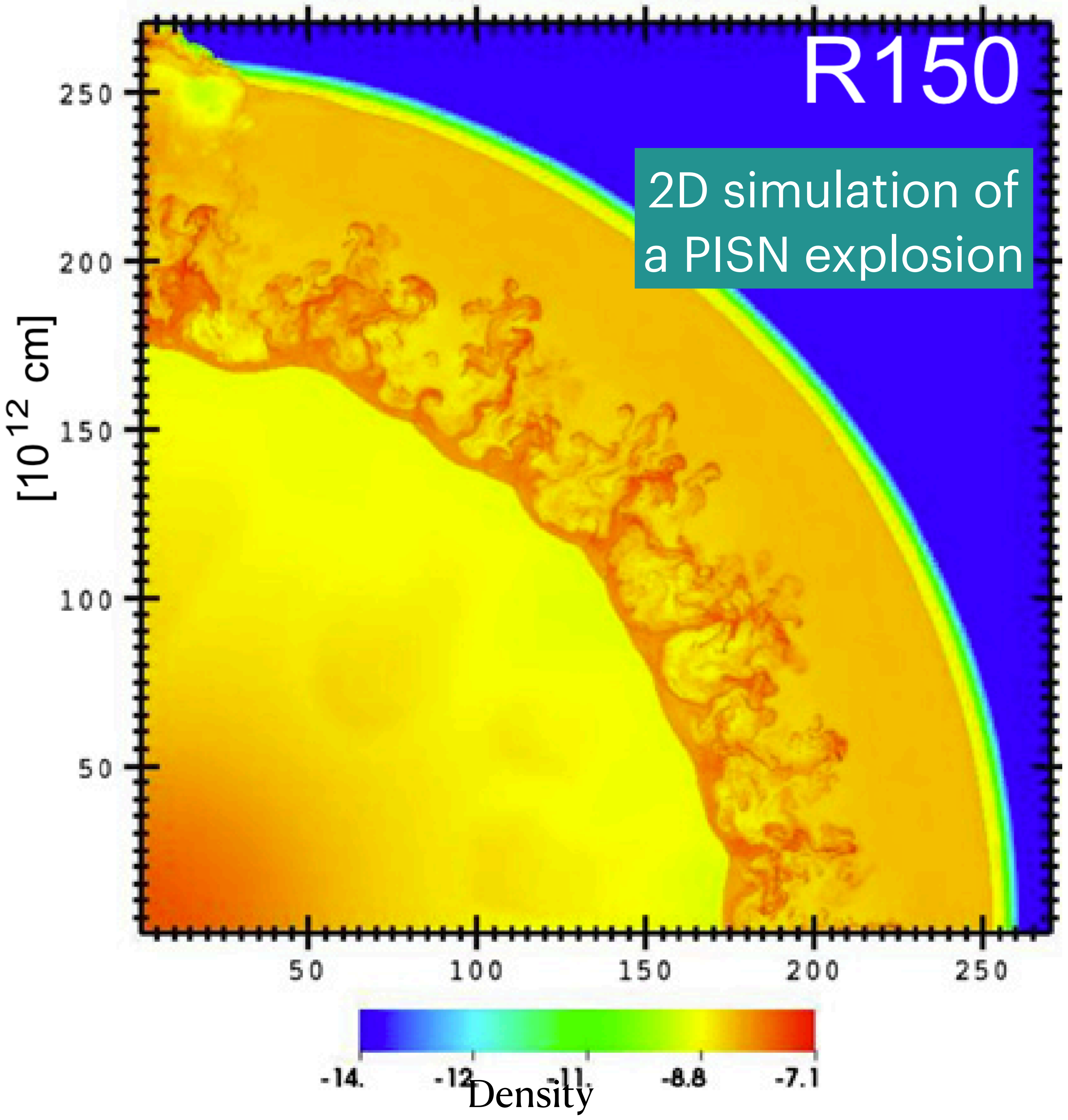
After central He burning is complete, radiation field in a >40 M_{sun} He core gets so hot that photons have enough energy to pair-produce.

Rapid loss of radiation pressure (massive stars are radiation pressure supported) —> collapse initiates. But large reservoir of oxygen burns up explosively in the infall —> **infall reverses to a thermonuclear explosion (same as Type Ia SNe)**.

Explosion energies up to 10^{53} erg achievable! But because the SN mass is so large (>100 M_{sun}), the velocities are not that different from normal SNe, and can be even lower. ^{56}Ni masses can be up to 50 M_{sun}.



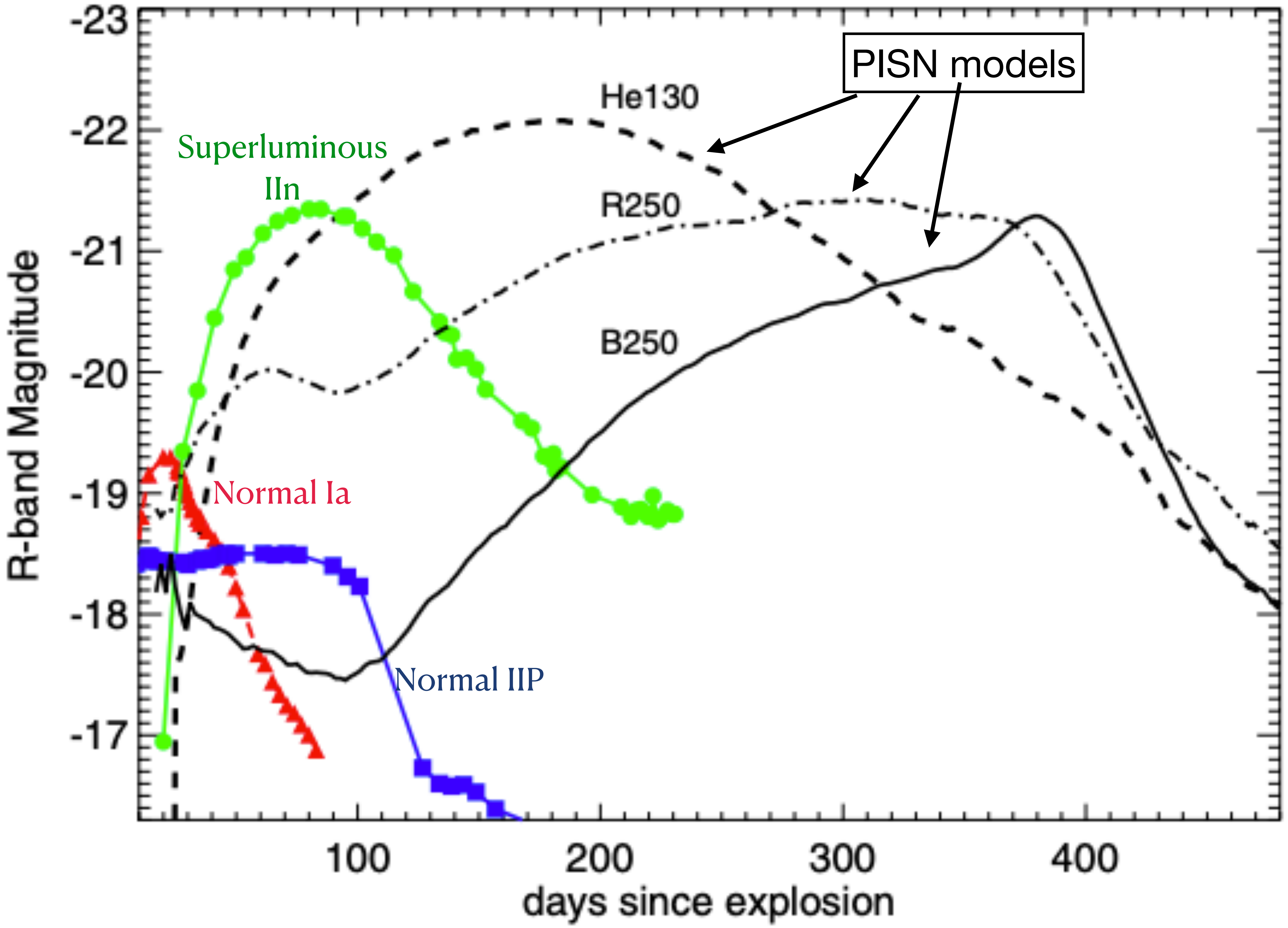
Heger 2003



Chen 2014

Pair-instability supernovae : predicted light curves

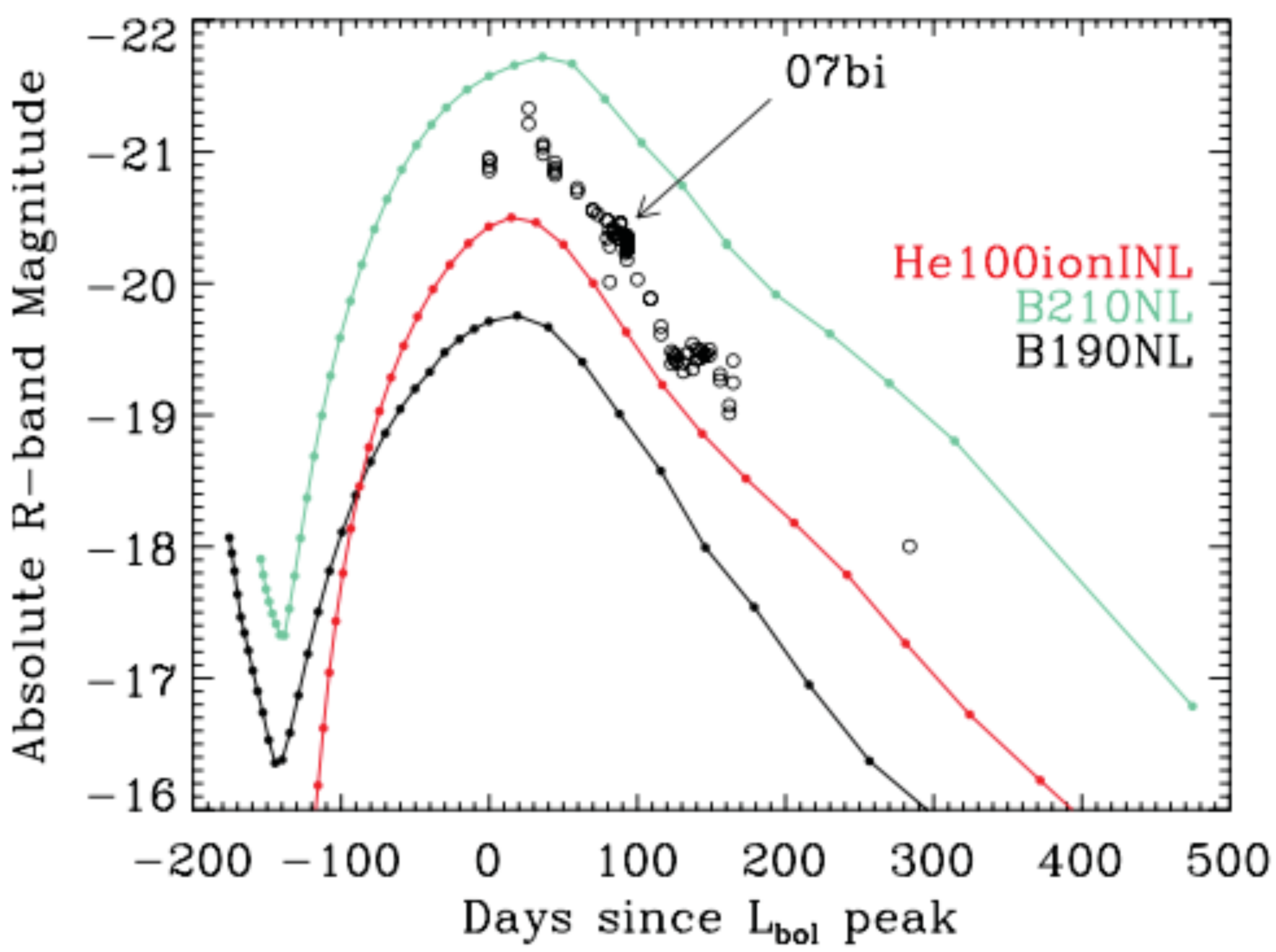
Enormous ejecta and ^{56}Ni masses give **broad and bright light curves.**

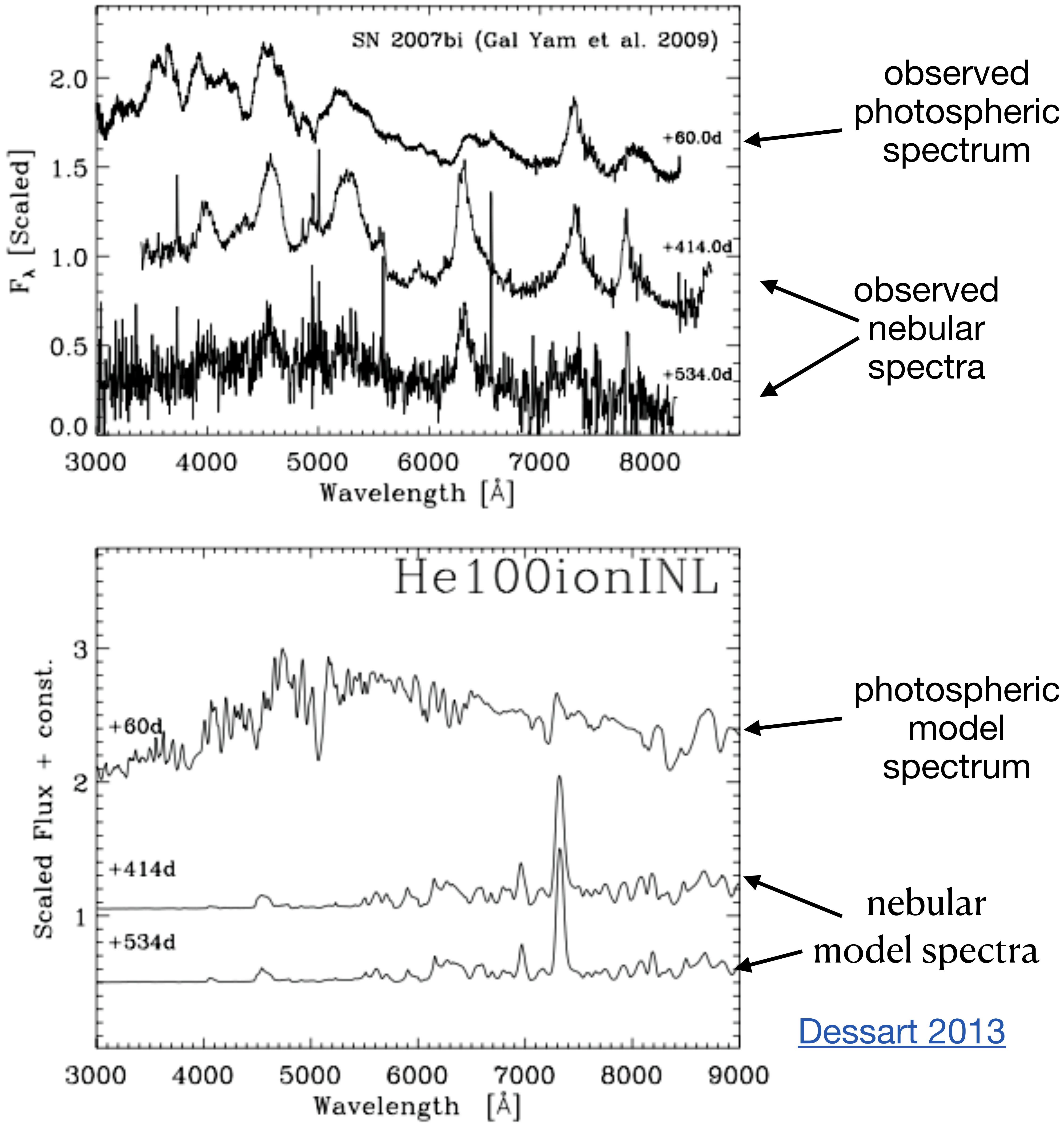


Kasen 2011

There have been some PISN candidates: but none match predicted spectra well

SN 2007bi was the first suggested candidate (Gal-Yam 2009).

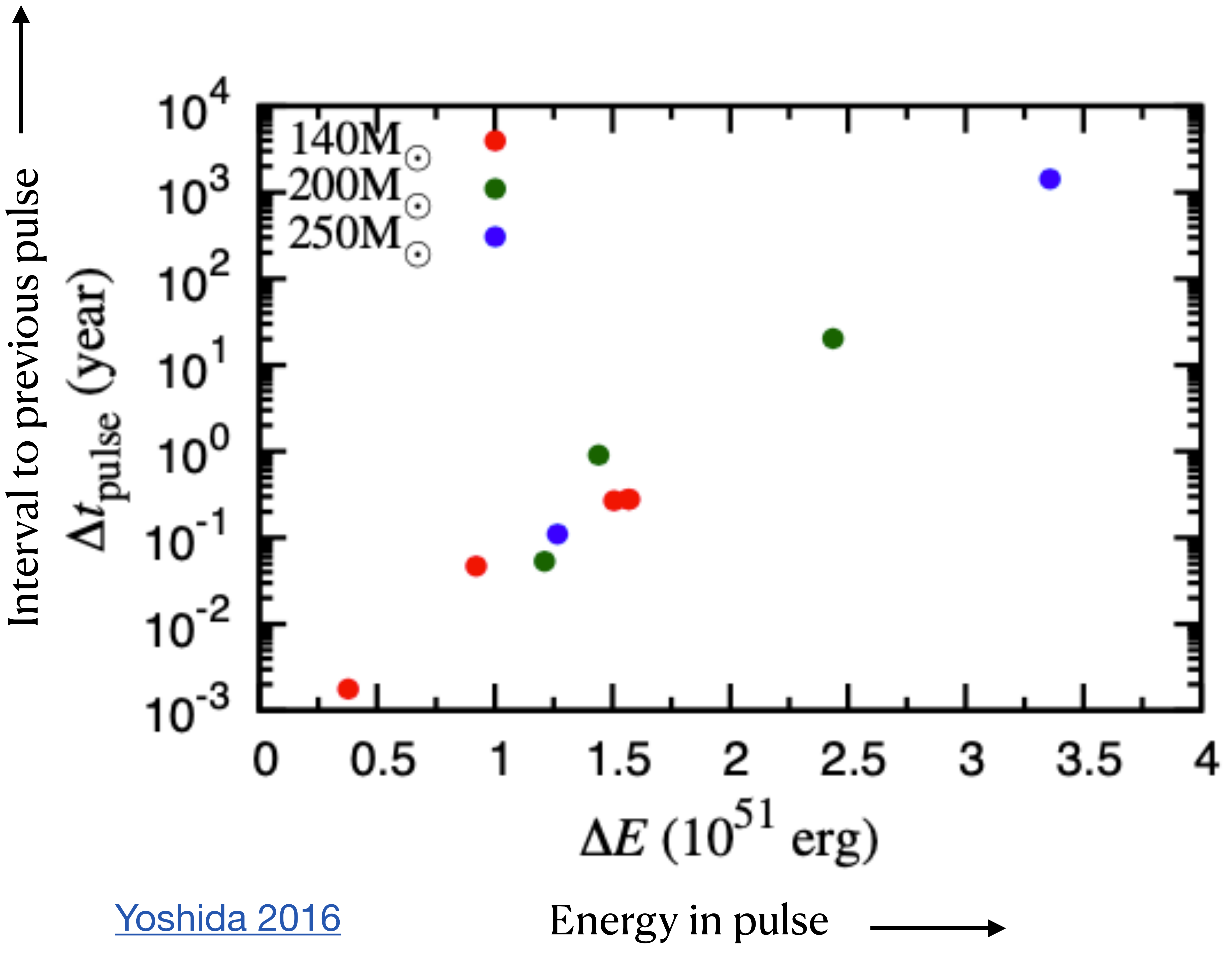




Dessart 2013

Pulsational PISNe

In 40-65 M_{sun} He cores, the pulsations are not strong enough to disrupt the whole star : instead pulses repeat several times, each time ejecting a large amount of stellar mass. Intervals days - decades.



Yoshida 2016

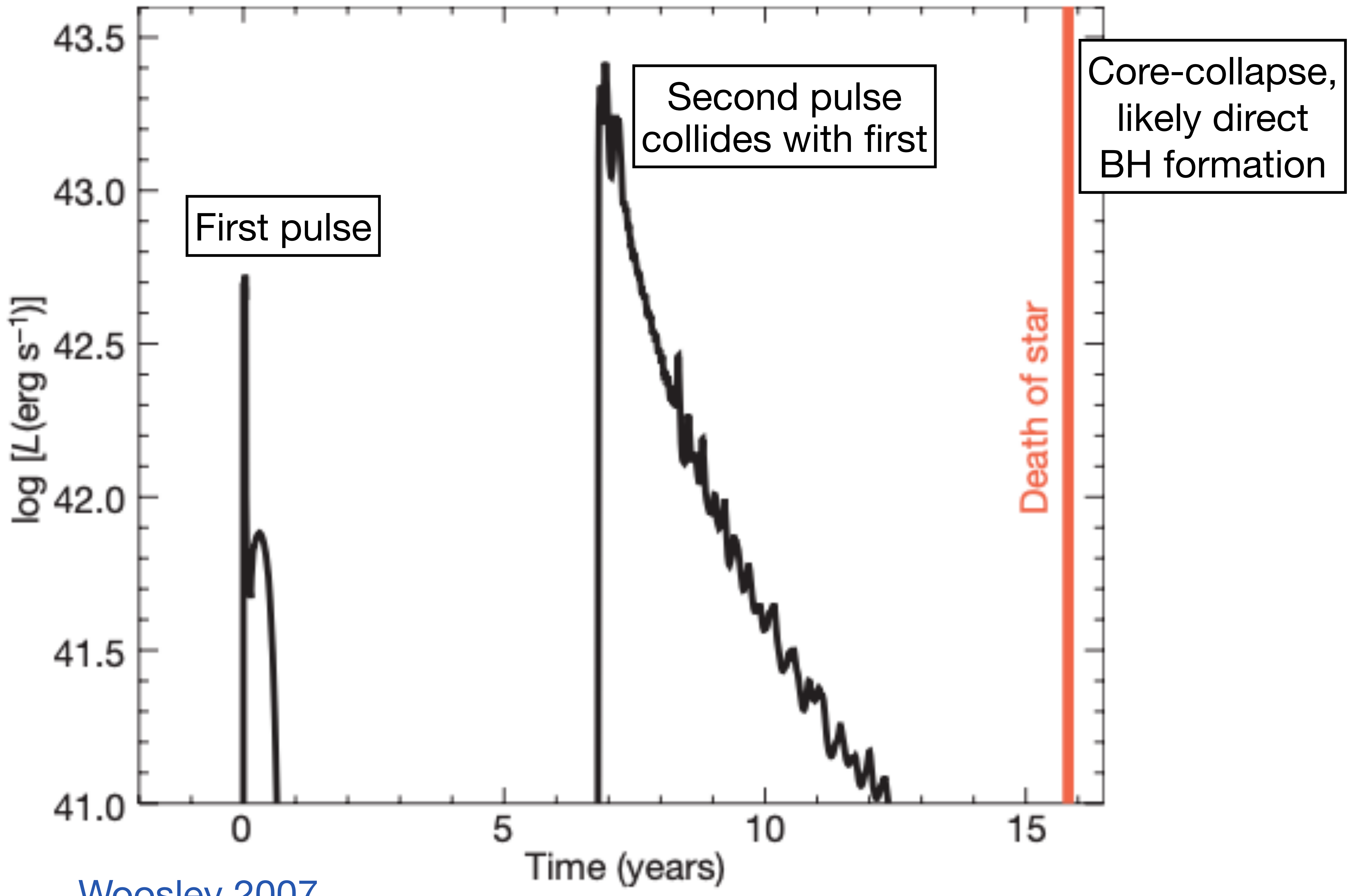
Table 1

Woosley 2007

He Mass ($M_\odot$)	Pulse	KE_1 (10^{50} erg)	ΔM ($M_\odot$)	T_c (10^9 K)	ρ_c (10^5 g cm^{-3})	interval (sec)
48	1	0.048	0.11	1.48	1.68	7.34(5)
	2	0.92	0.57	1.57	2.02	4.31(5)
	3	2.20	1.19	1.31	1.34	2.77(6)
	4	3.09	1.64	1.38	3.00	2.02(6)
	5	4.41	1.84	1.32	3.40	8.33(6)
	6	3.02	2.42	1.86	28.6	7.43(5)
51	1	0.26	0.44	1.17	0.67	1.02(7)
	2	2.70	1.55	1.30	1.80	2.72(6)
	3	4.49	1.99	1.06	1.66	2.74(7)
	4	7.56	3.68	1.22	3.77	2.53(7)
52	1	0.85	1.13	1.01	0.40	6.32(7)
	2	1.46	0.94	1.57	5.02	4.58(5)
	3	4.27	1.90	1.16	2.74	8.10(6)
	4	7.29	3.12	1.09	2.68	9.56(7)
54	1	3.11	3.23	0.71	0.14	6.13(9)
	2	2.51	2.09	1.57	14.6	8.85(5)
	3	5.33	2.68	1.01	3.33	3.73(8)
56	1	2.44	2.71	0.74	0.15	3.47(9)
	2	1.45	1.34	1.57	8.7	4.32(5)
	3	6.12	3.33	1.03	3.02	1.44(8)
58	1	13.3	9.39	0.24	0.0072	1.24(11)
	2	4.00	2.39	1.46	6.08	2.10(6)
	3	7.78	3.06	1.07	3.31	1.61(8)
60	1	20.6	17.6	0.087	0.0004	1.86(11)
	2	1.17	0.78	1.77	10.2	2.90(5)

Pulsational PISNe : light curves

Collision of subsequent pulses can give bright SN-line transients. In the collision, part of the the kinetic energy is converted to radiation.



Woosley 2007

As with PISNe, there are some candidate events but none yet unambiguously identified as a PPISN.