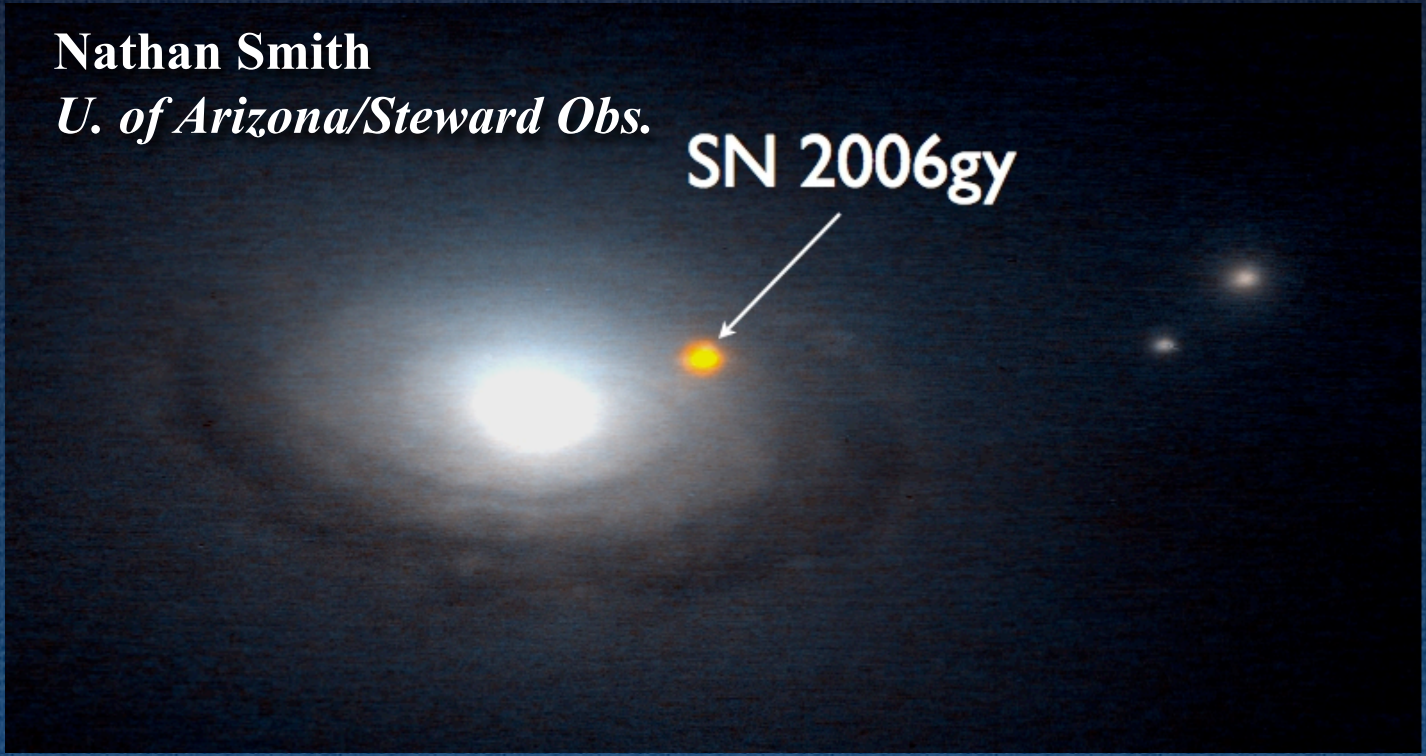
The Diverse Fates of Single and Binary Massive Stars



Main collaborators: A. Filippenko, W. Li, R. Chornock
and the Berkeley supernova search
(Smith et al. 2011, MNRAS, 412, 1522)

OUTLINE

INTRO: Massive stars and Diverse Explosions

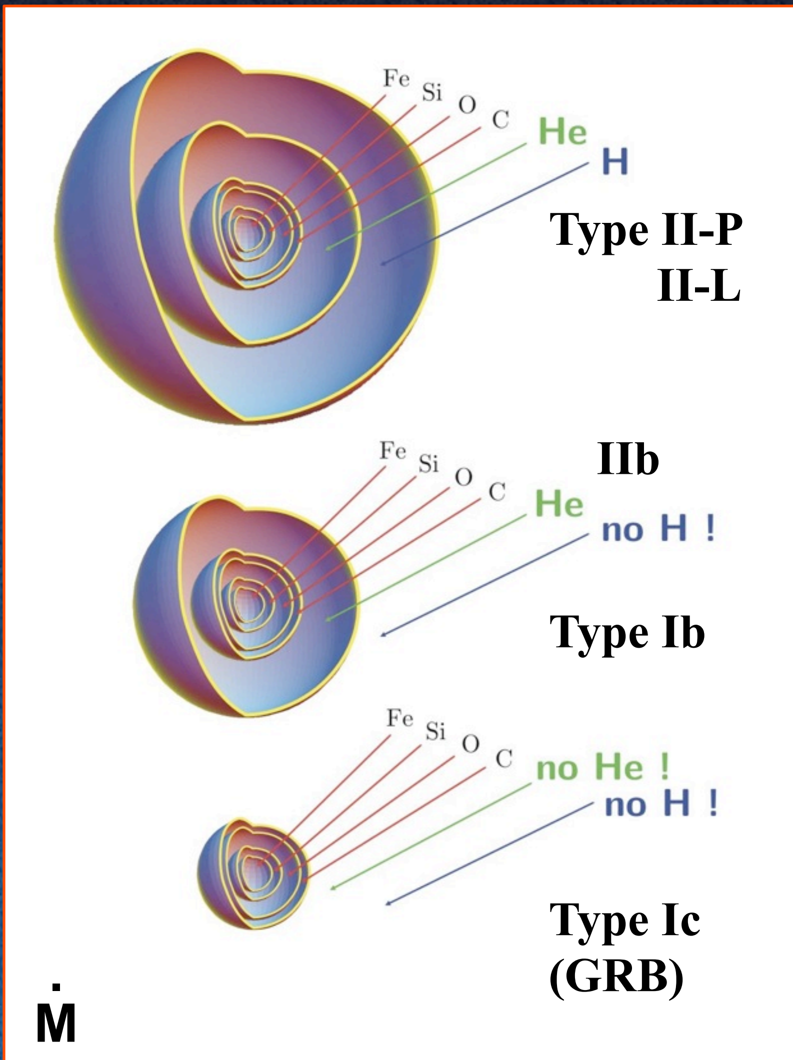
Observed Fractions of SN subtypes

Observations of Supernova Progenitors

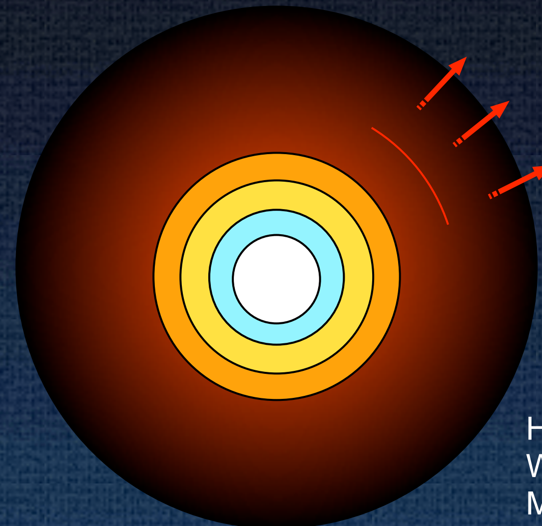
Type IIn Supernovae, Circumstellar Material, Luminous Blue Variables (LBVs), Pre-SN eruptions, close binaries, etc.

Implications for Massive Star Evolution

END FATES of MASSIVE STARS:
What type of supernova from which type of star?

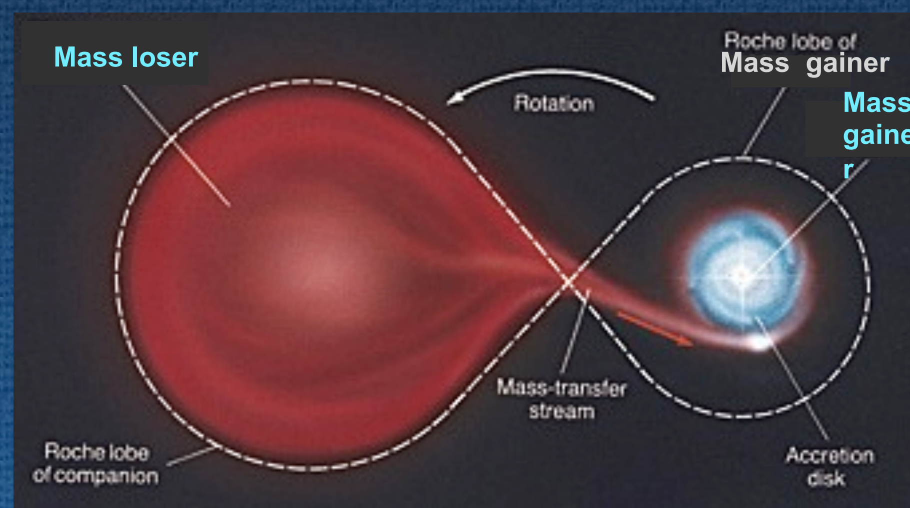


Single-star mass-loss
(*STELLAR WINDS and ERUPTIONS*)



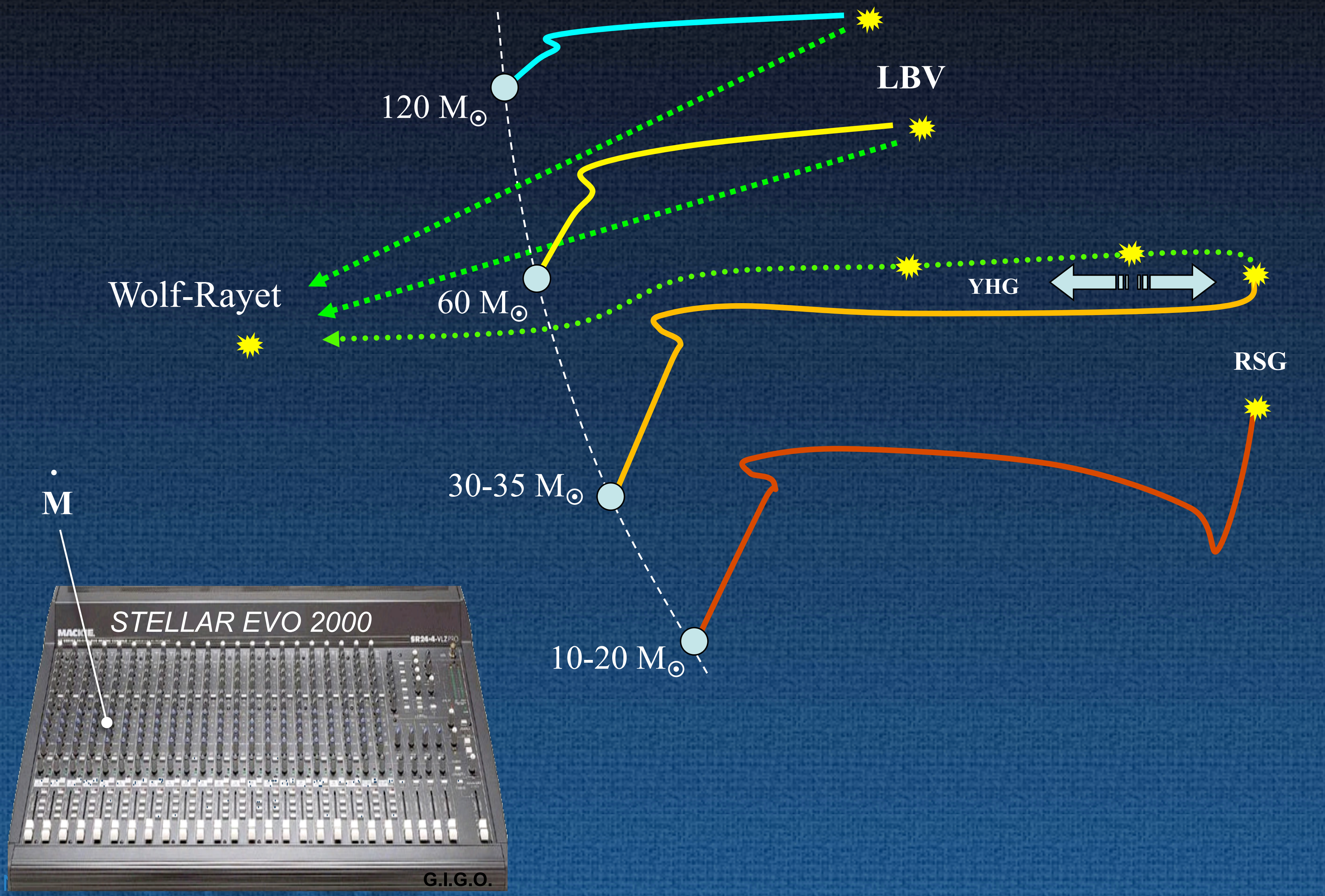
Heger et al.
Woosley et al.
Maeder & Meynet

Binary-star mass-transfer
(*ROCHE LOBE OVERFLOW*)



Paczynski et al. 67; Podsiadlowski et al. 92

Single-Star Evolution



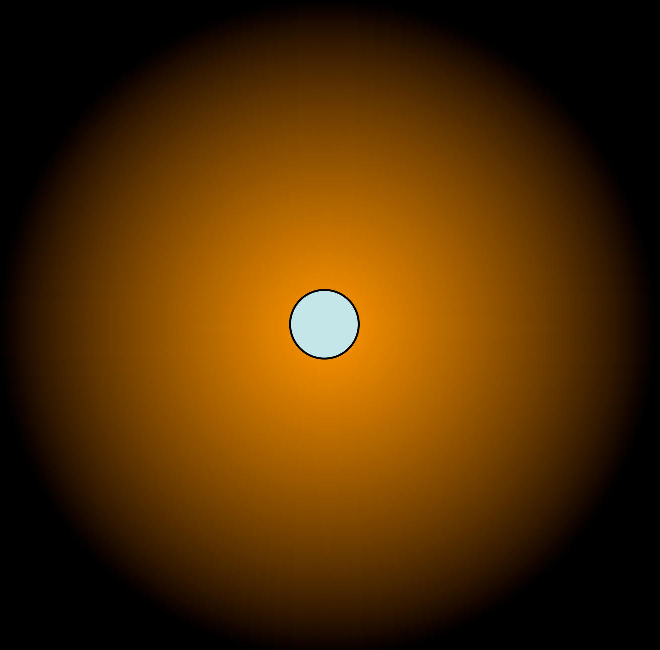
CLUMPING IN LINE-DRIVEN WINDS OF HOT STARS

Observational mass-loss rates come from Hα emission and IR/radio free-free. Both are sensitive to ρ^2.

If winds are highly clumped (F_C>>1)

$$F_c = \frac{<\rho^2>}{<\rho>^2}$$

Then $\dot{M}$ from Hα and free-free is ***much*** lower.



Examples:

- Fullerton et al. (2006); factors of 10-20 reduction in Mdot.
- Bouret et al. (2005); factors of >3.
- Puls et al. (2006); median of 5, but as much as 10x lower
- see also Crowther et al. 2003; Hillier et al. 2003; Massa et al. 2003; Evans et al. 2004.

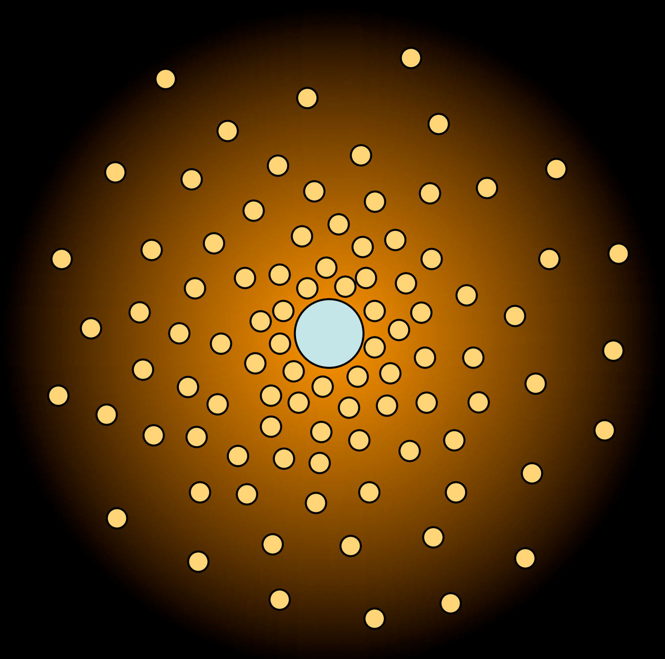
CLUMPING IN LINE-DRIVEN WINDS OF HOT STARS

Observational mass-loss rates come from Hα emission and IR/radio free-free. Both are sensitive to ρ^2.

If winds are highly clumped (F_C>>1)

$$F_c = \frac{<\rho^2>}{<\rho>^2}$$

Then $\dot{M}$ from Hα and free-free is ***much*** lower.



Examples:

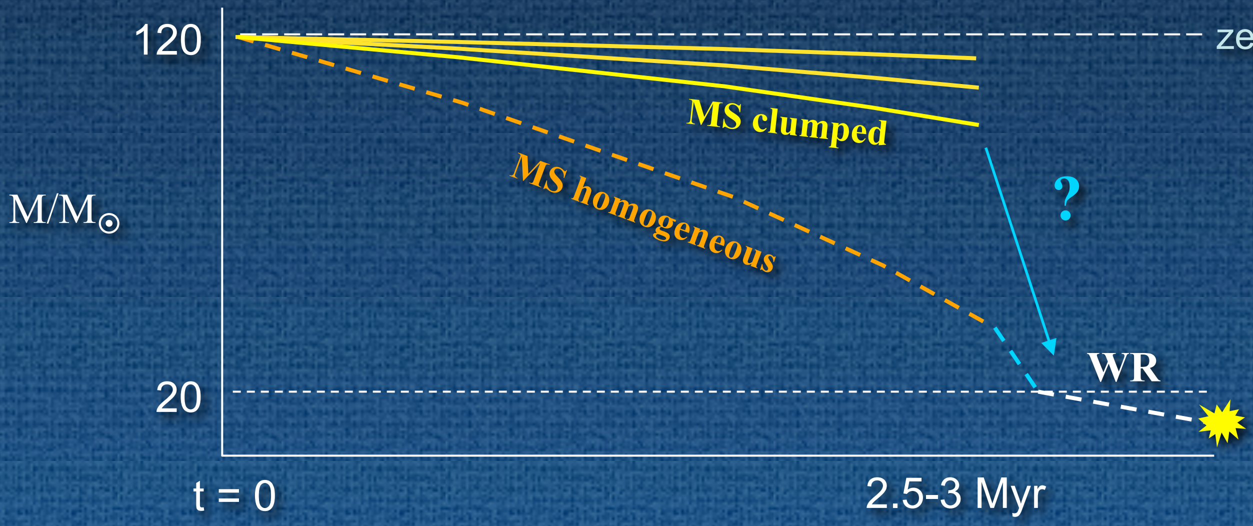
- Fullerton et al. (2006); factors of 10-20 reduction in Mdot.
- Bouret et al. (2005); factors of >3.
- Puls et al. (2006); median of 5, but as much as 10x lower
- see also Crowther et al. 2003; Hillier et al. 2003; Massa et al. 2003; Evans et al. 2004.

Single-Star Evolution

(consequences of overestimated mass loss rates)

- Evolutionary tracks for massive stars depend on adopted ***steady*** mass loss rates (e.g., Maeder & Meynet 1994, 2000, 2003; Heger et al. 2003).
- Problem: more recent modeling of spectra of O stars winds find ***LOWER*** mass-loss rates than "standard" by factors of 3-10 or more. (Factor of >3; Bouret et al. 2005; Factor of >10; Fullerton et al. 2005).

Why are O-star winds clumpy? See papers by Owocki & Rybicki



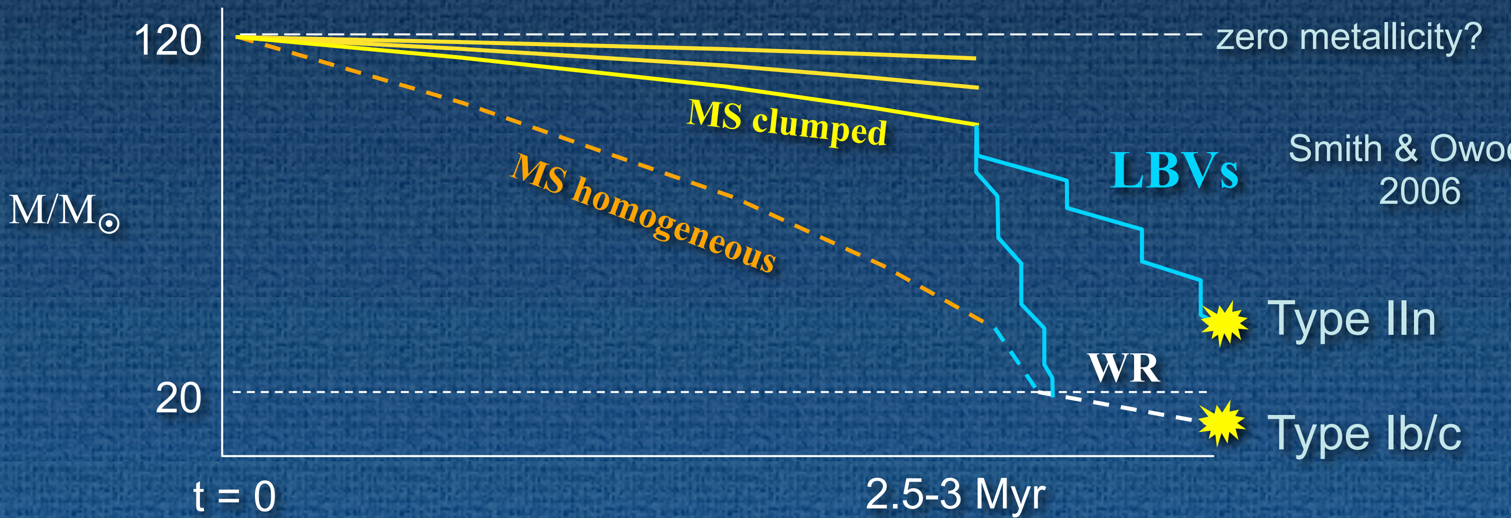
Smith & Owocki 2006

Single-Star Evolution

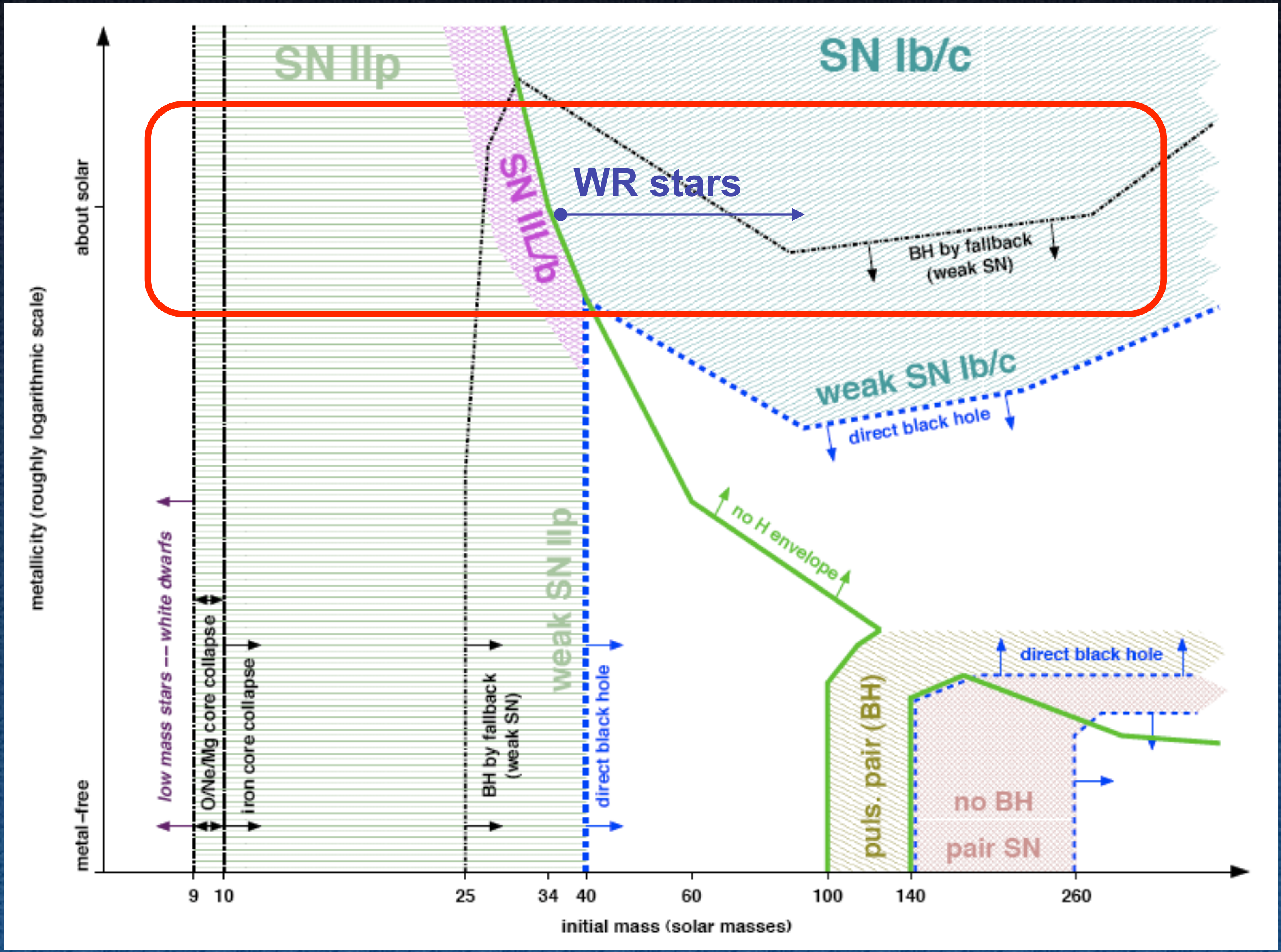
(consequences of overestimated mass loss rates)

- Evolutionary tracks for massive stars depend on adopted ***steady*** mass loss rates (e.g., Maeder & Meynet 1994, 2000, 2003; Heger et al. 2003).
- Problem: more recent modeling of spectra of O stars winds find ***LOWER*** mass-loss rates than "standard" by factors of 3-10 or more. (Factor of >3; Bouret et al. 2005; Factor of >10; Fullerton et al. 2005).

Why are O-star winds clumpy? See papers by Owocki & Rybicki



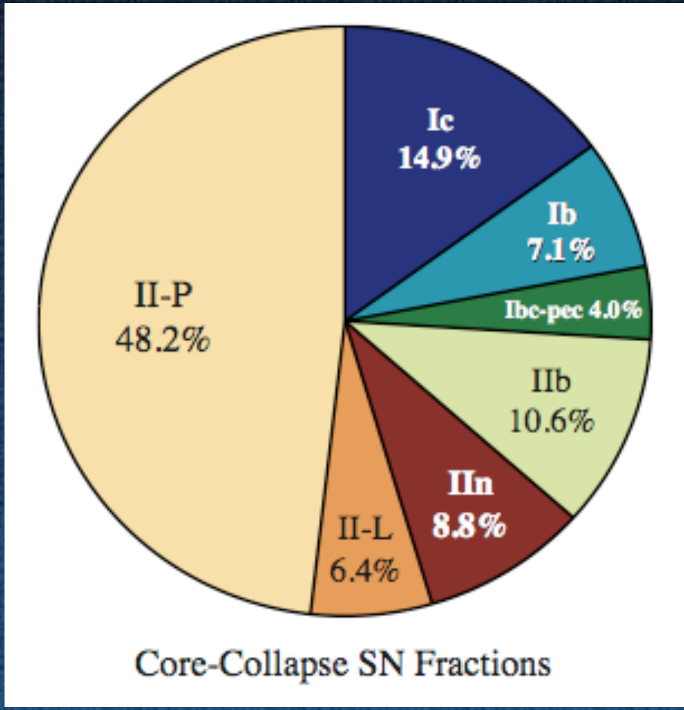
Single-Star Evolution



Heger et al. 2003

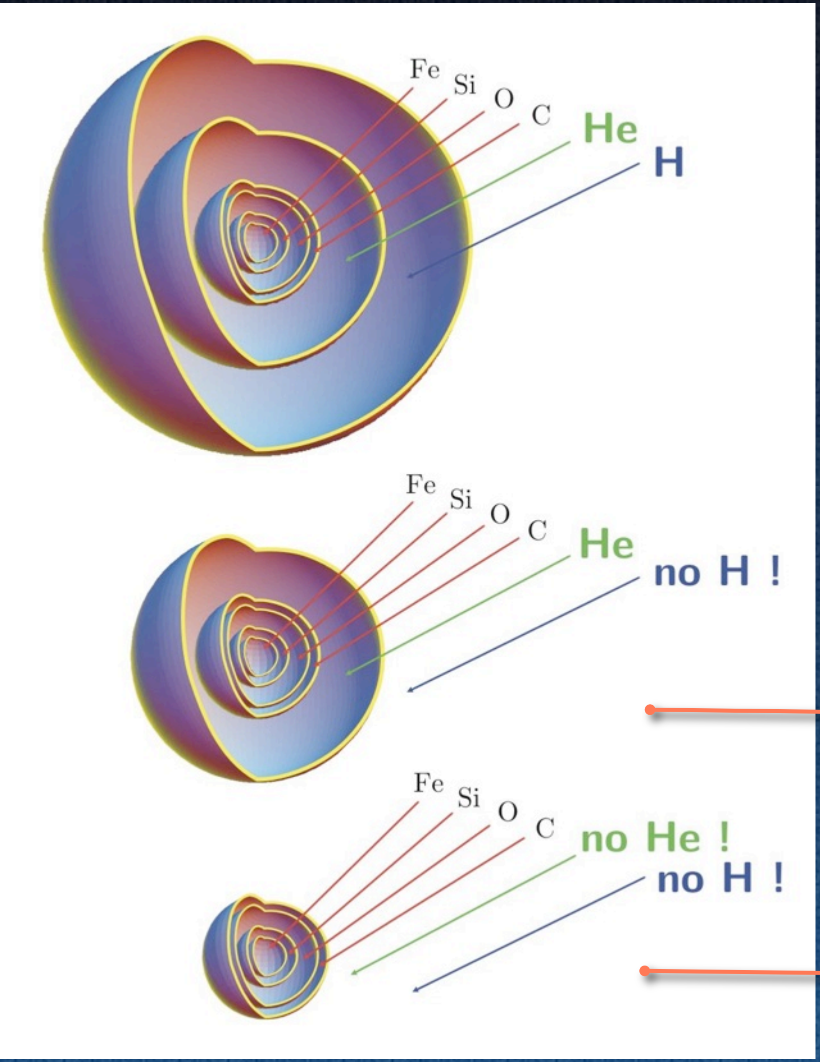
Note: adopted wind mass-loss rates are too high!

SN subtype fractions



Smith et al. (2011)
MNRAS, 412, 1522

Large galaxies, roughly $Z_{\odot}$



Type:

II-P
II-L

(IIn/Ibn)

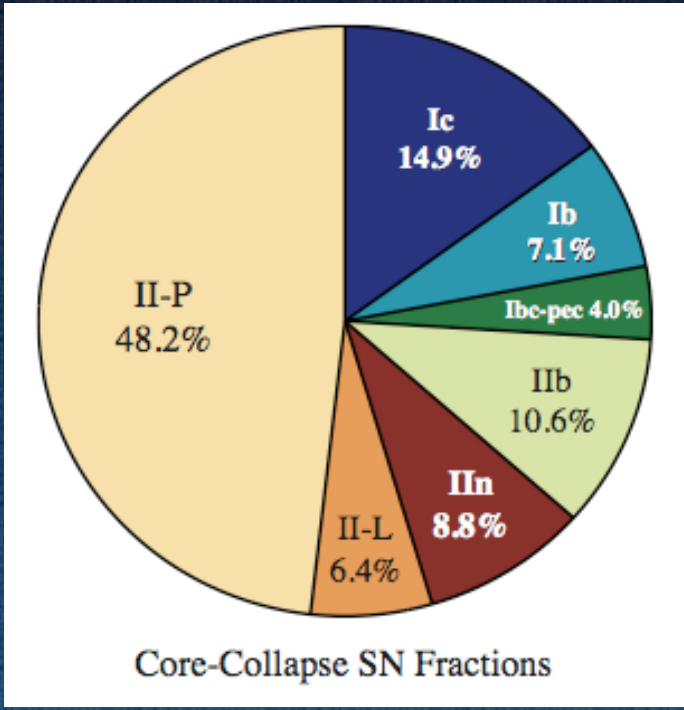
IIb

Ib

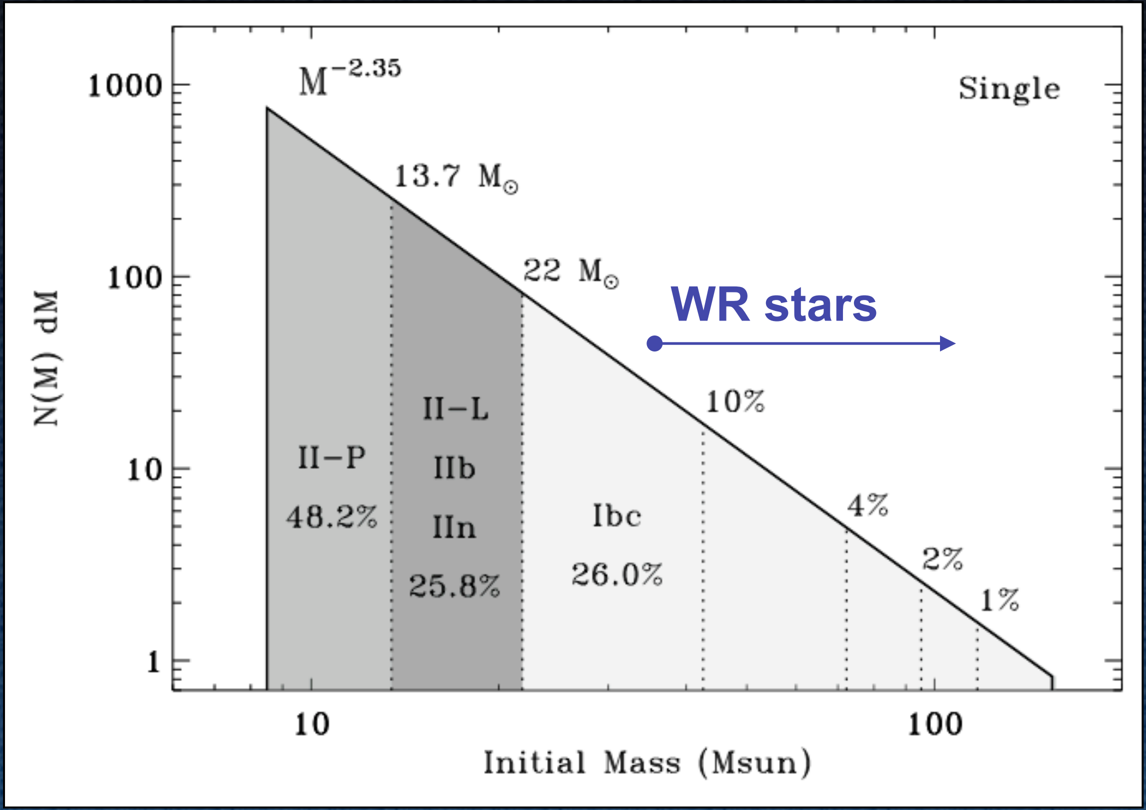
Ic

$\dot{M}$ determines SN type…

SN subtype fractions



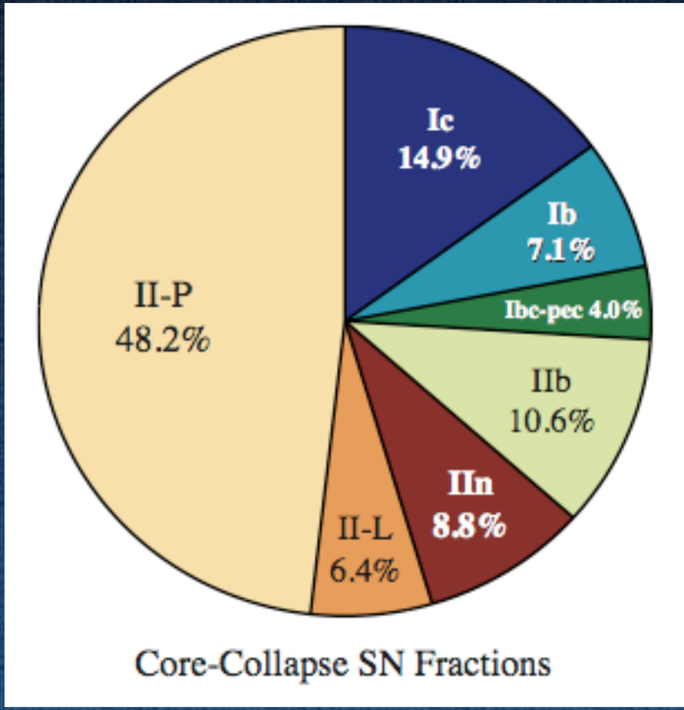
Smith et al. (2011)
MNRAS, 412, 1522



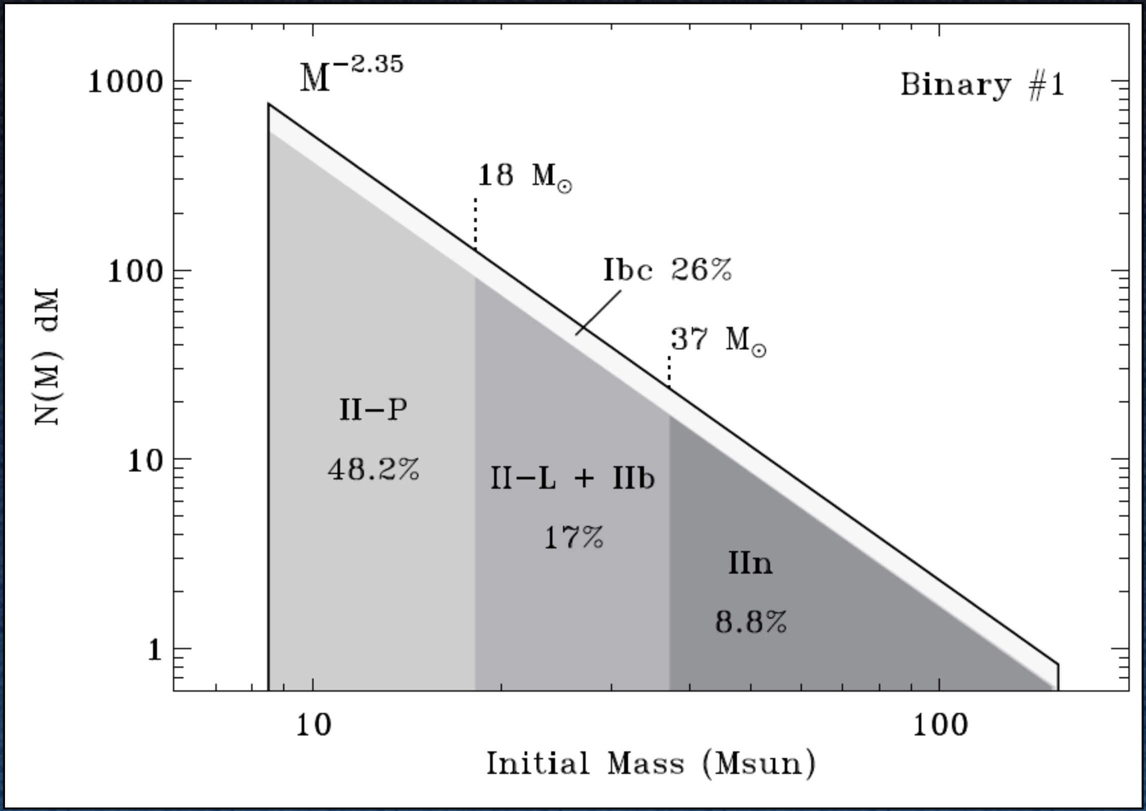
$\dot{M}$ determines SN type, due to:

- **Single star winds?**
- **Single star erruptions?**
- **Binary RLOF?**

SN subtype fractions



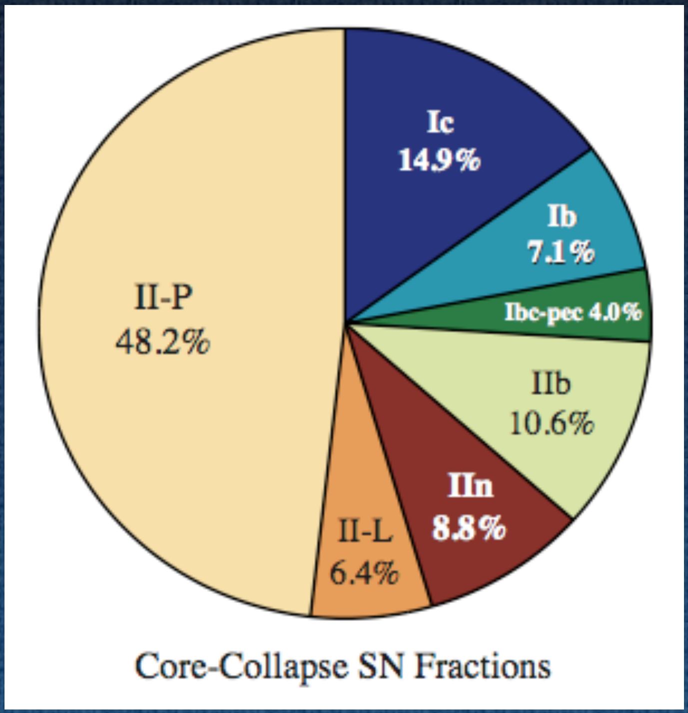
Smith et al. (2011)
MNRAS, 412, 1522



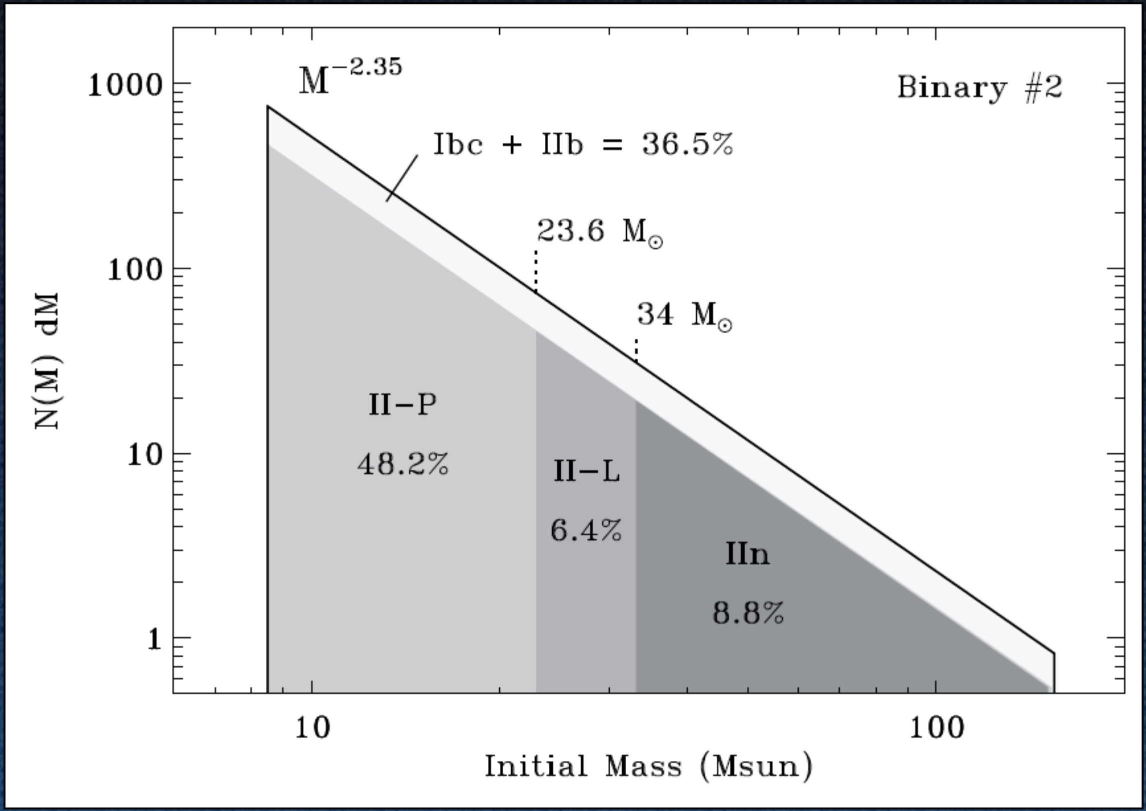
$\dot{M}$ determines SN type, due to:

- **Single star winds?**
- **Single star eruptions?**
- **Binary RLOF?**

SN subtype fractions



Smith et al. (2011)
MNRAS, 412, 1522

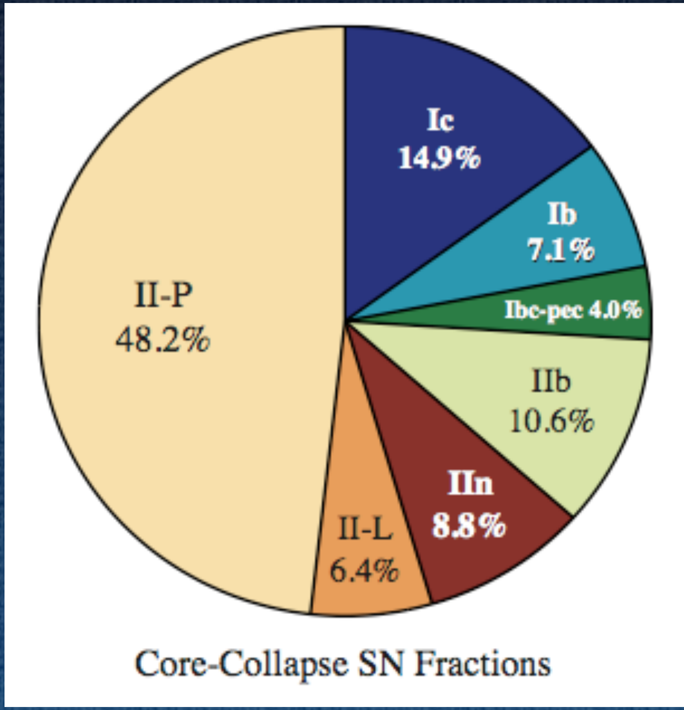


Type IIb = binary (see Claeys et al. 2011)

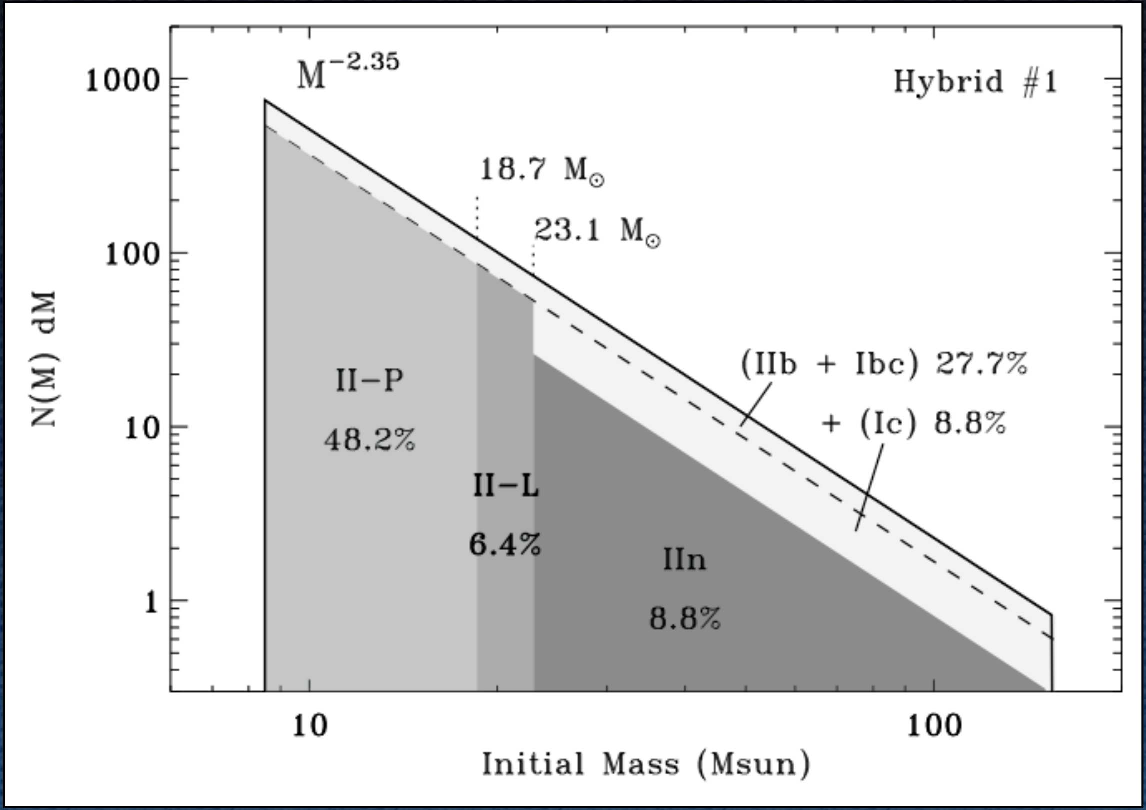
$\dot{M}$ determines SN type, due to:

- Single star winds?
- Single star eruptions?
- Binary RLOF?

SN subtype fractions



Smith et al. (2011)
MNRAS, 412, 1522

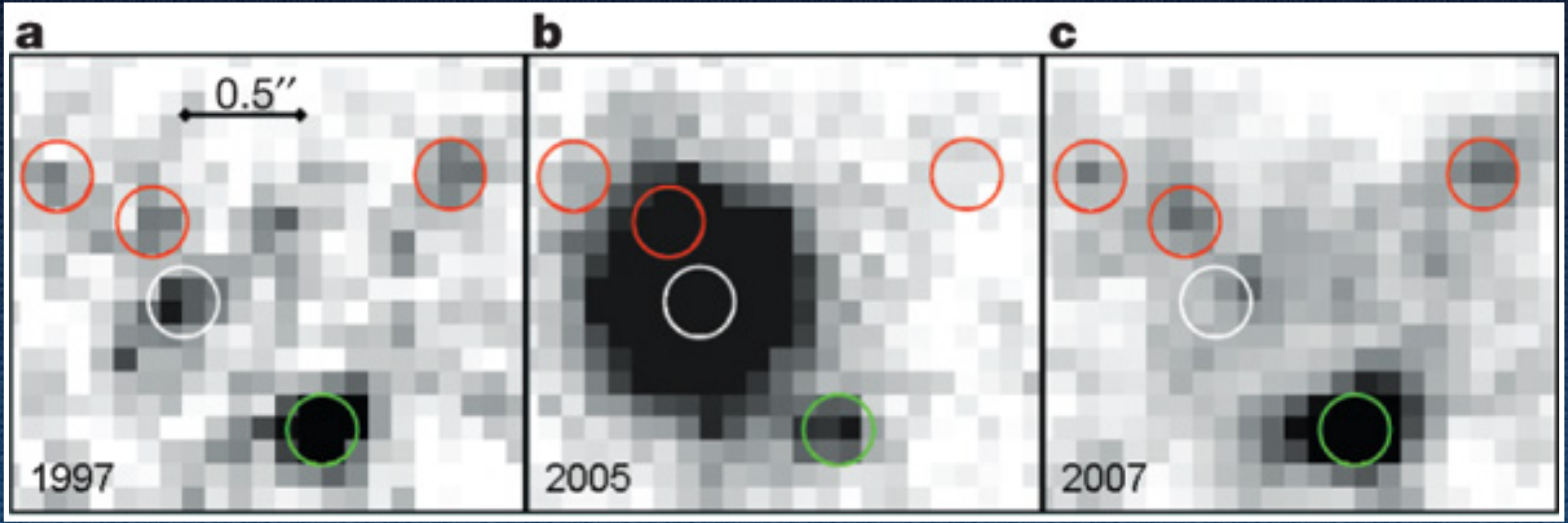


$\dot{M}$ determines SN type, due to:

- **Single star winds?**
- **Single star erruptions?**
- **Binary RLOF?**

CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

SN 2005gl (Gal-Yam & Leonard 2009)



Pre-explosion archival HST images

Supernova position

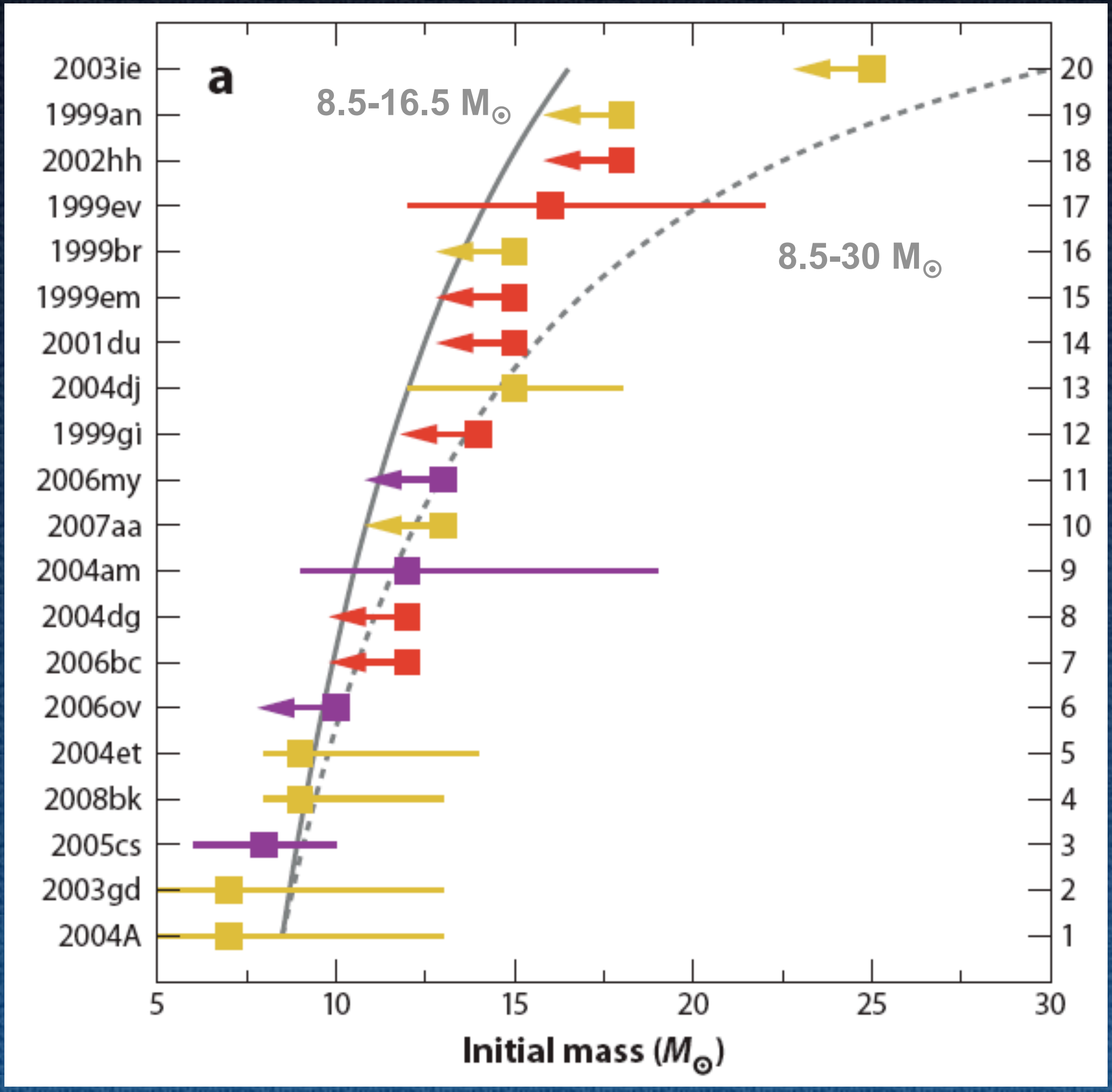
(ideally) Verify that candidate star disappears

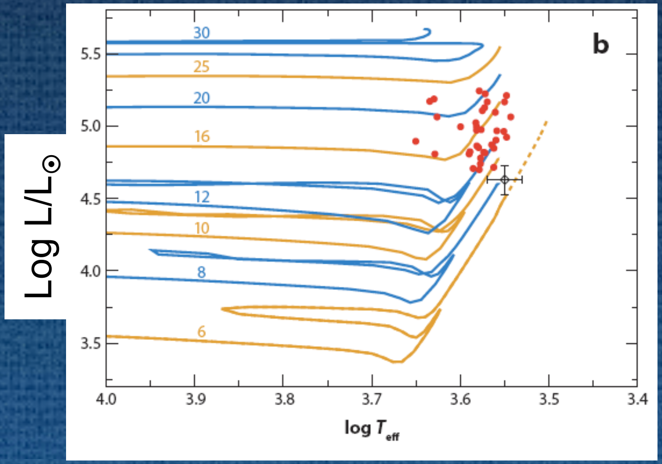
CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Type II-P

Red supergiants
With initial mass
8.5 - 16.5 $M_\odot$

(Smartt 2009, ARAA)



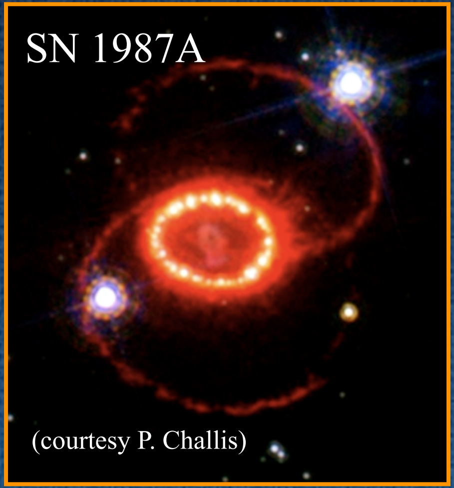


CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

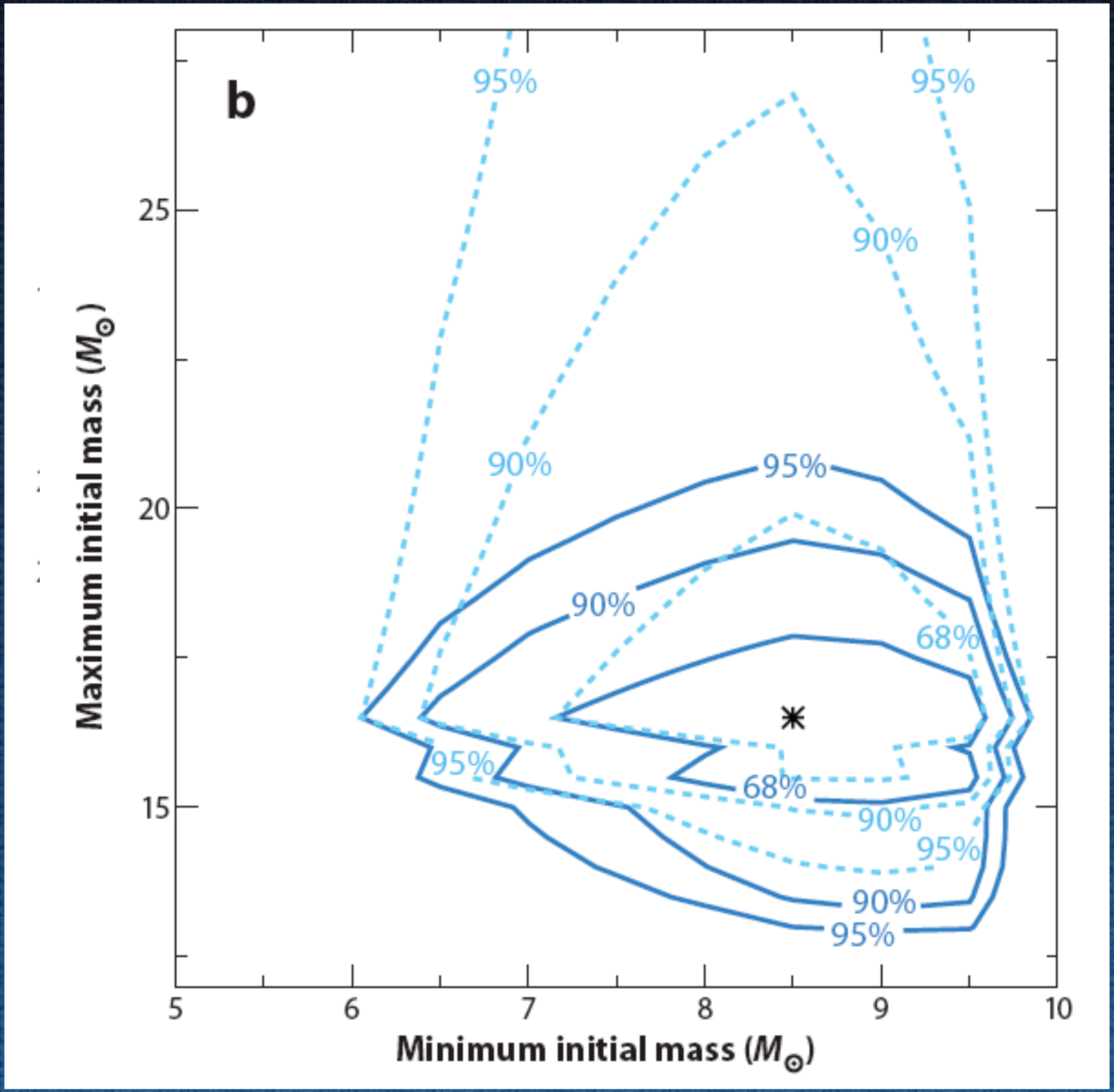
Type II-P

Red supergiants
With initial mass
8.5 - 16.5 $M_\odot$

(Smartt 2009, ARAA)



~18 $M_\odot$ blue supergiant
Progenitor (Arnett 1989)



CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Circumstellar dust as a solution to the red supergiant supernova progenitor problem

Joseph J. Walmswell ⋆, John J. Eldridge
Institute of Astronomy, The Observatories, University of Cambridge, Madingley Road, Cambridge, CB3 0HA

August 2011

ABSTRACT
We investigate the red supergiant problem, the apparent dearth of Type IIP supernova progenitors with masses between 16 and 30 $M_\odot$. Although red supergiants with masses in this range have been observed, none have been identified as progenitors in pre–explosion images. We show that, by failing to take into account the additional extinction resulting from the dust produced in the red supergiant winds, the luminosity of the most massive red supergiants at the end of their lives is underestimated. We re–estimate the initial masses of all Type IIP progenitors for which observations exist and analyse the resulting population. We find that the most likely maximum mass for a Type IIP progenitor is $21^{+2}_{-1}\,M_\odot$. This is in closer agreement with the limit predicted from single star evolution models.

Key words: stars: evolution – supernovae: general – stars: supergiants

Type II-P …including dust, perhaps initial masses are 8.5 – 20 $M_\odot$

CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Type II-P
RSGs with initial mass 8.5 – 17(20) $M_\odot$

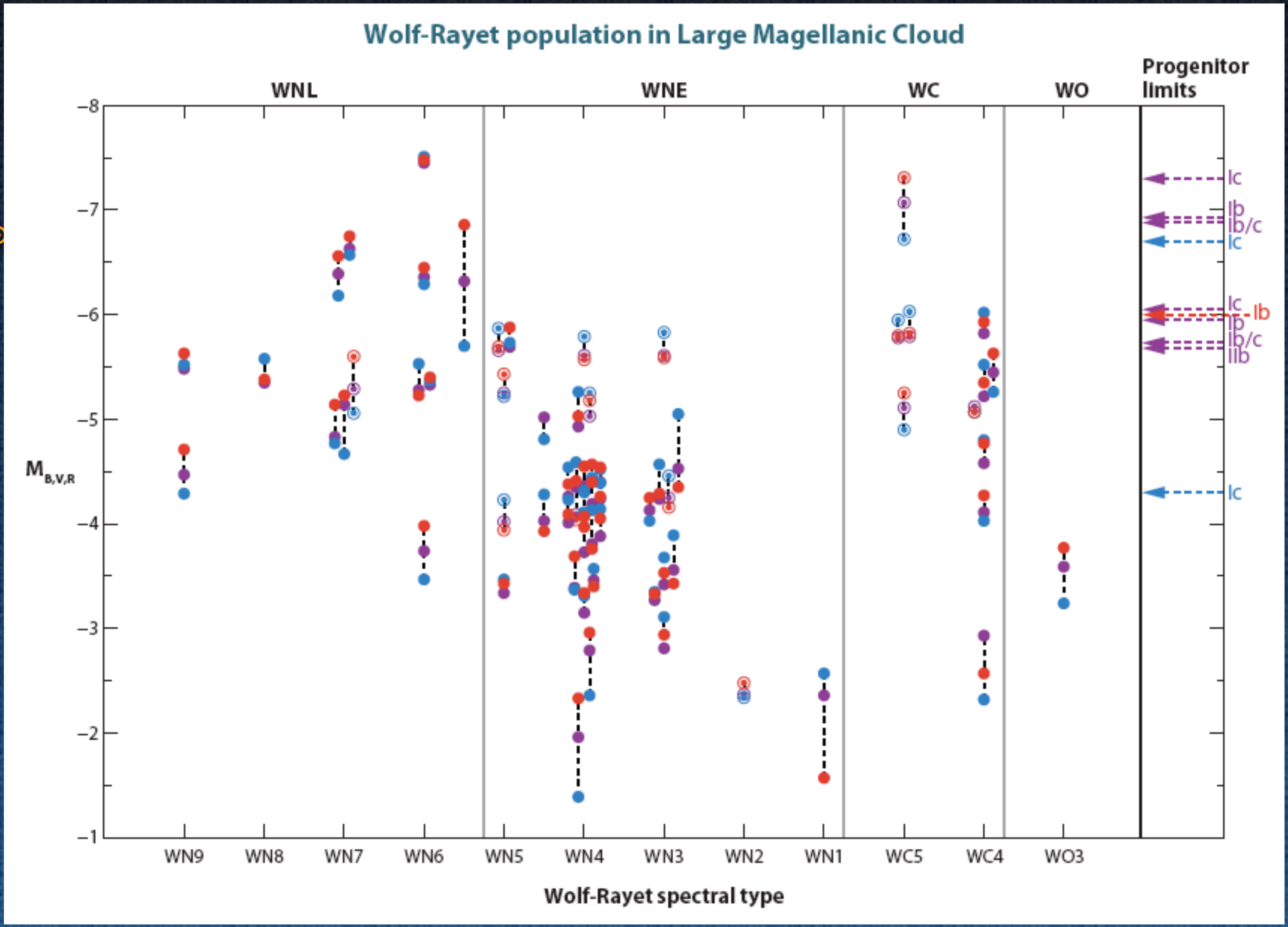
Type Ibc

Wolf-Rayet stars?

$M_0 > 35\ M_\odot$?

(Smartt 2009)

No Type Ibc progenitors detected yet



10% probably of not detecting a WR progenitor

CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Type II-P

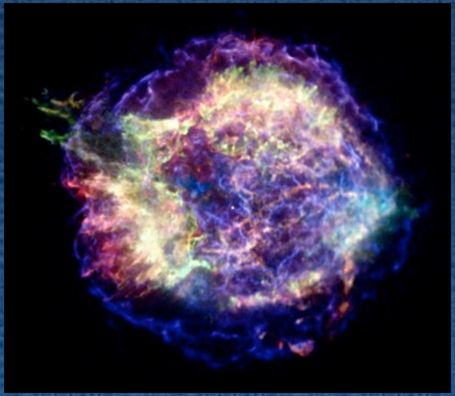
RSGs with initial mass 8.5 – 17/20 $M_\odot$ (20)

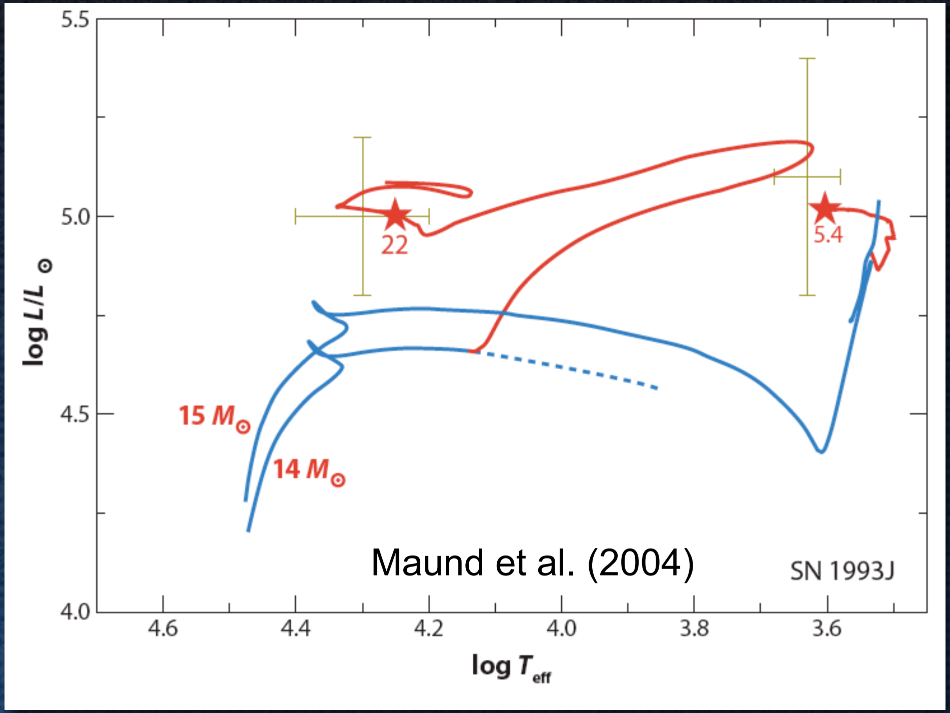
Type Ibc

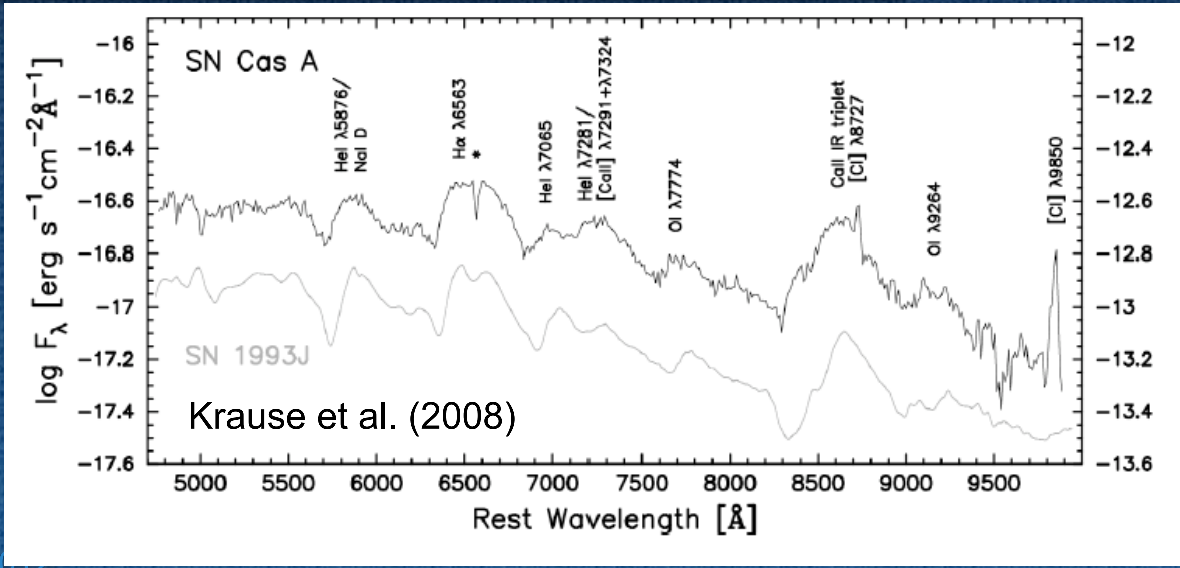
WR? Zero detections.

Type IIb

SN 1993J - binary
SN 2011dh - binary
Cas A light echo







CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Type II-P
RSGs with
initial mass
8.5 – 17/20 $M_{\odot}$ (20)

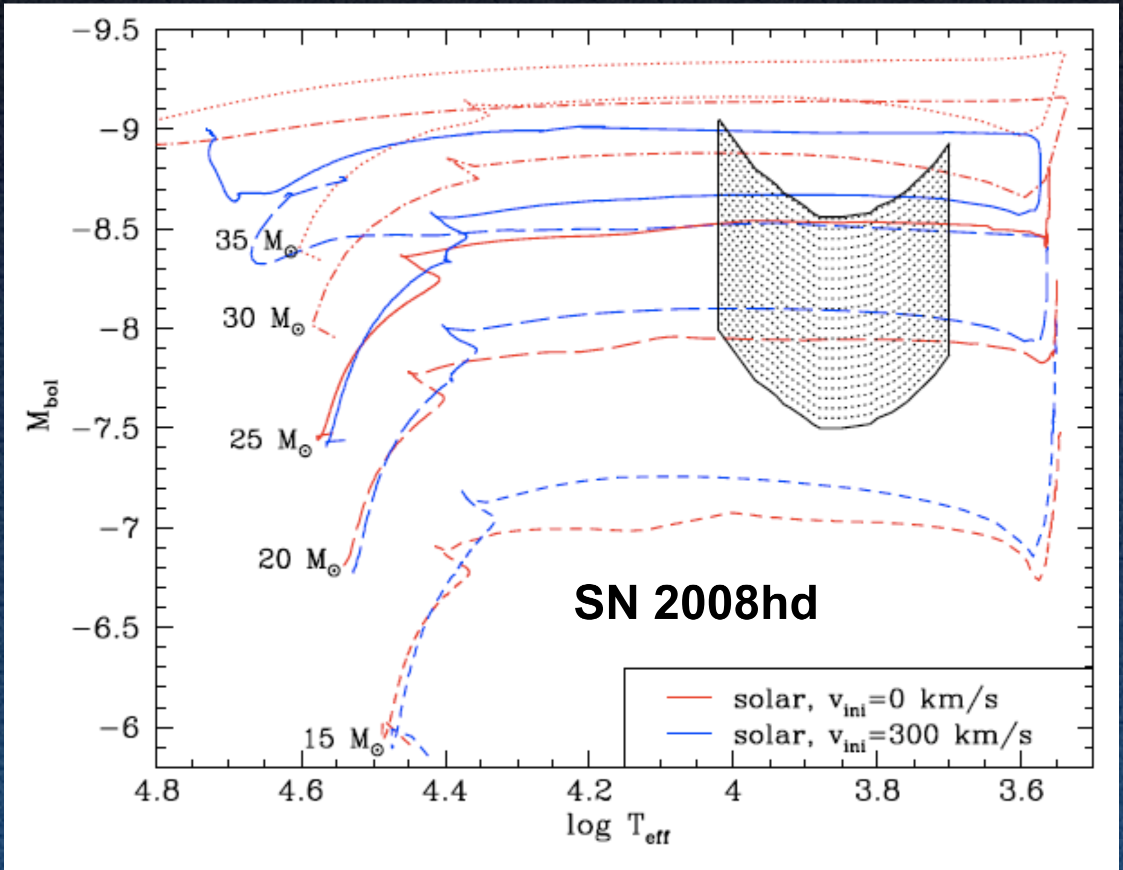
Type Ibc
WR? Zero detections.

Type IIb
13-15 $M_{\odot}$ binary? (2)

Type II-L

$M_0 \sim 18\text{-}25\ M_{\odot}$

2 detections
so far…



SN 2008hd … 20-25 $M_{\odot}$ yellow supergiant
(Elias-Rosa et al. 2010)

SN 2009kr … 18-24 $M_{\odot}$ yellow supergiant
(Fraser et al. 2010; Elias-Rosa et al. 2010)

CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

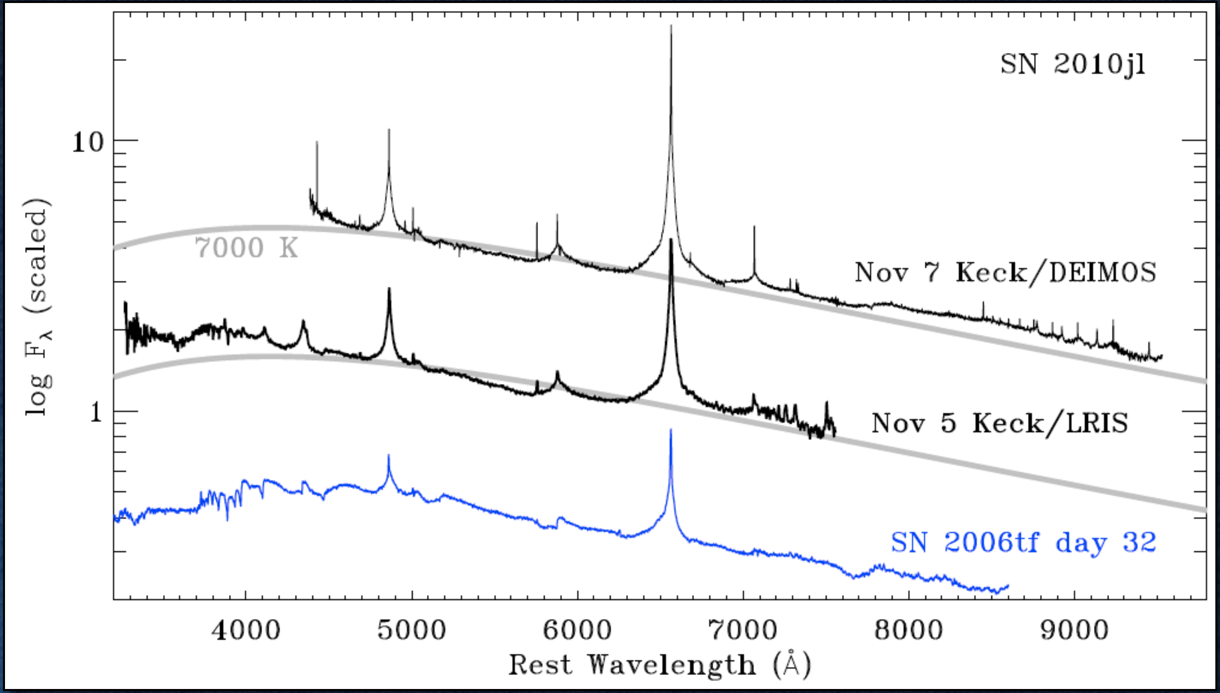
Type II-P
RSGs with initial mass 8.5 – 17/20 $M_\odot$ (20)

Type Ibc
WR? Zero detections.

Type IIb
13-15 $M_\odot$ binary (2)

Type II-L
18-25 $M_\odot$ (2)

Type IIn

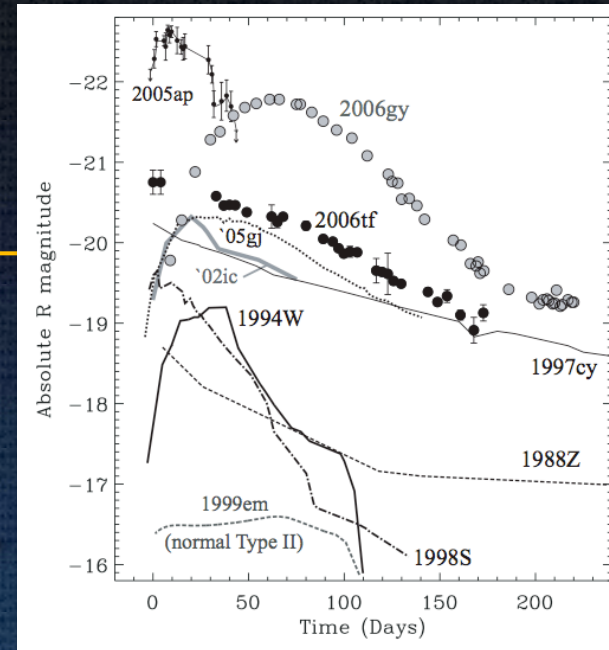


Type IIn supernova progenitors?

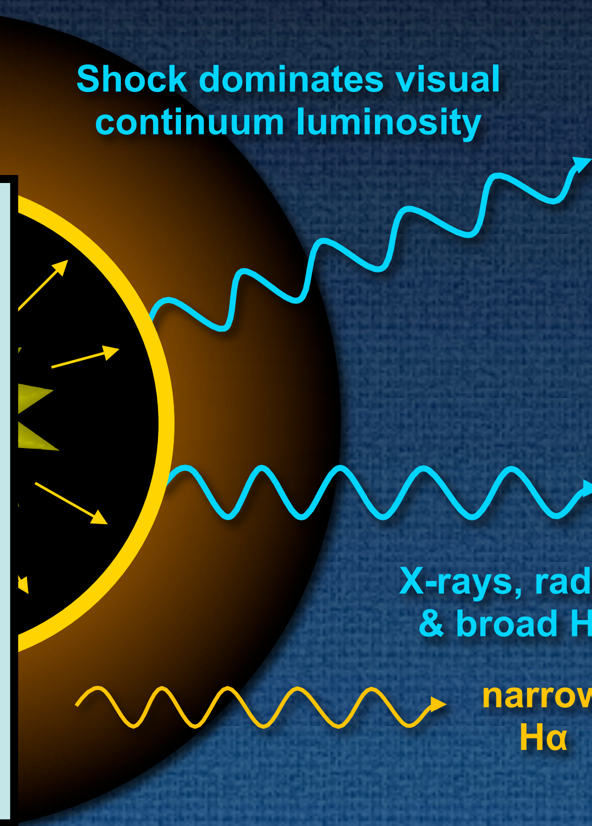
Type IIn supernovae:

Blast wave plows into dense circumstellar matter.

Smith et al. 2007, 2008, etc.



Efficient conversion of KE ⟹ Light



How dense is the CSM?

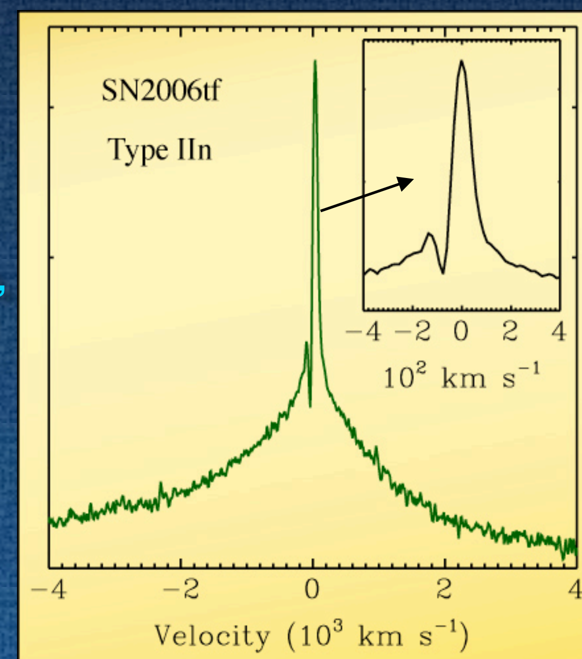
$$L_{SN} = \zeta \frac{1}{2} \dot{M} \frac{v_{SN}^3}{v_w}$$

$$\dot{M} = 0.04 \frac{M_{sun}}{yr} \left(\frac{L_9}{\zeta} \right)$$

(v_w=200 km/s, v_{SN}=4000 km/s)

see papers by N. Chugai et al.

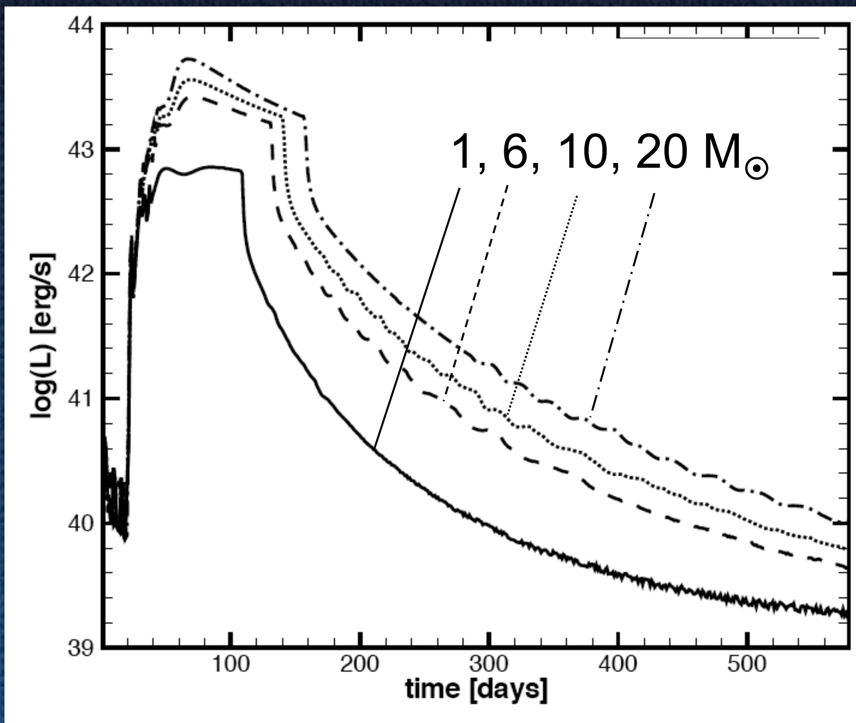
$\zeta \approx M_{shell}/(M_{shell} + M_{SN})$



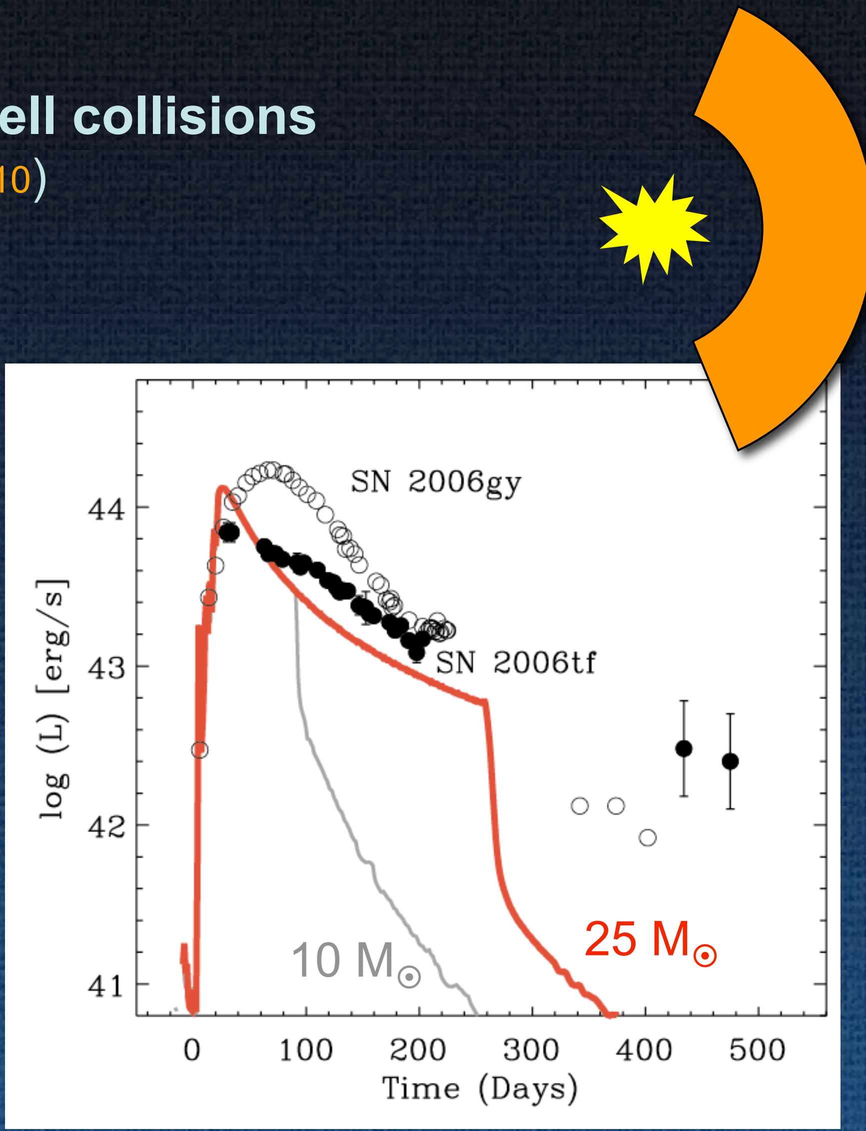
…need ***dense*** circumstellar gas within ~1000 AU of star.

Example Light curves from SN/shell collisions

Simulations using ZEUS (van Marle et al. 2010)



increasing shell density (total mass) increases the peak luminosity



increasing the outer shell radius
(also increasing total M)
increases the duration

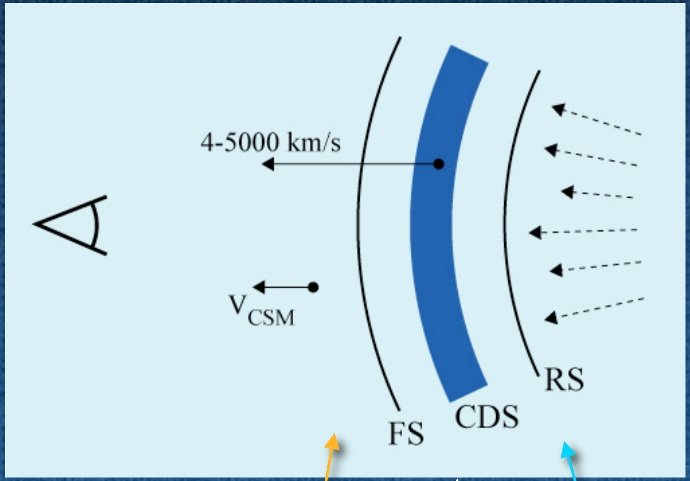
PROPERTIES OF SN2006gy's CSM

A Massive LBV-like Shell: Clues from Spectral Evolution

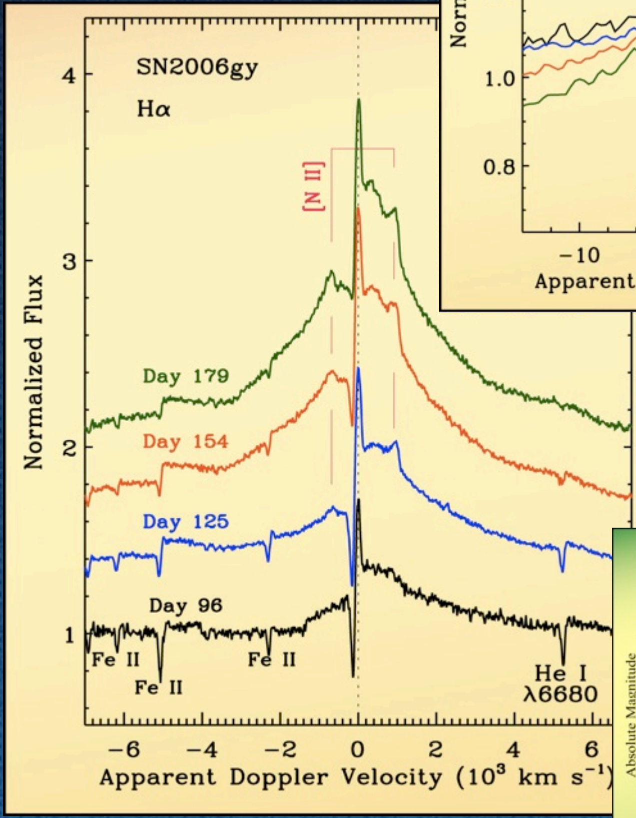
Time evolution of narrow Hα

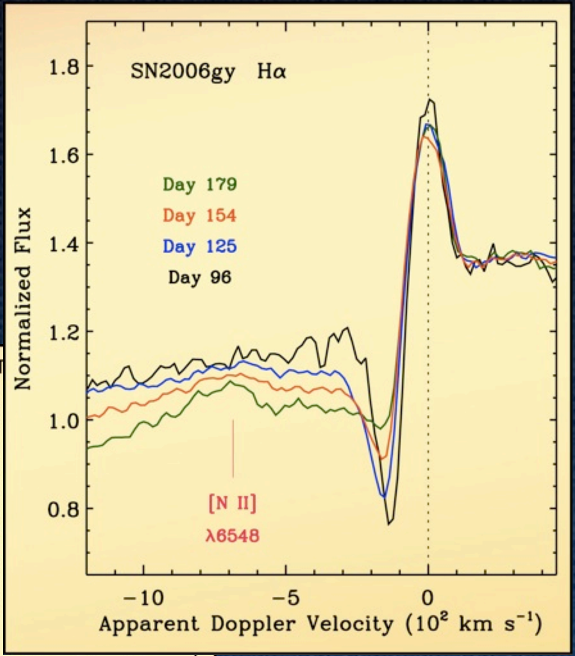
(Smith et al. 2010, ApJ, 709, 856)

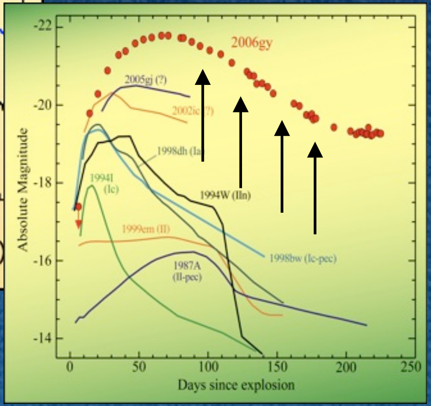
- Narrow absorption gets weaker...
  …running out of CSM?
- Narrow absorption gets broader...
  …faster CSM at larger radii?



Narrow Int. Broad







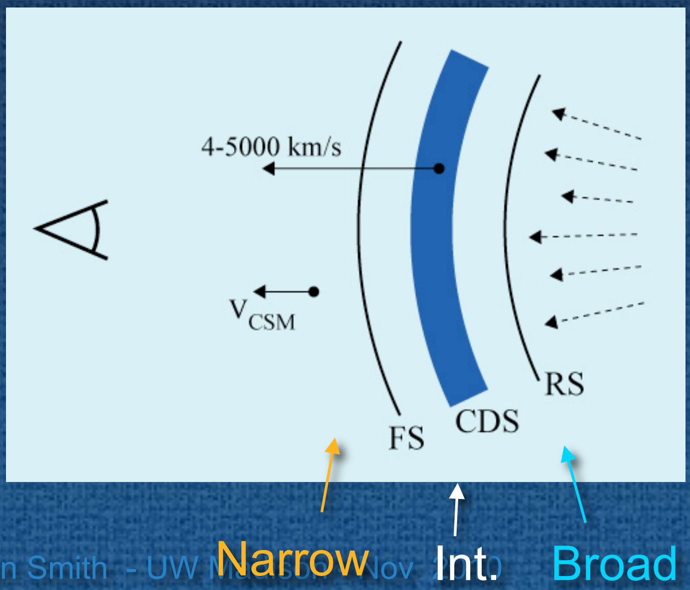
PROPERTIES OF SN2006gy's CSM

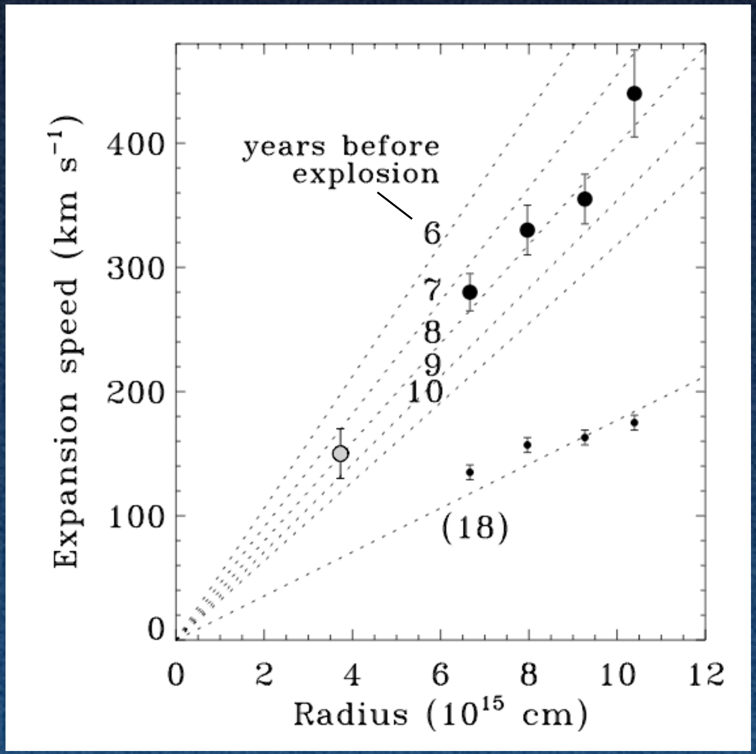
A Massive LBV-like Shell:
Clues from Spectral Evolution

Time evolution of narrow Hα

(Smith et al. 2010, ApJ, 709, 856)

- Narrow absorption gets weaker...
  …running out of CSM?
- Narrow absorption gets broader...
  …faster CSM at larger radii?





Hubble Flow at 150-500 km/s

Suggests ≥10^{49} erg ejection
~8 yr before SN (fall 1998)

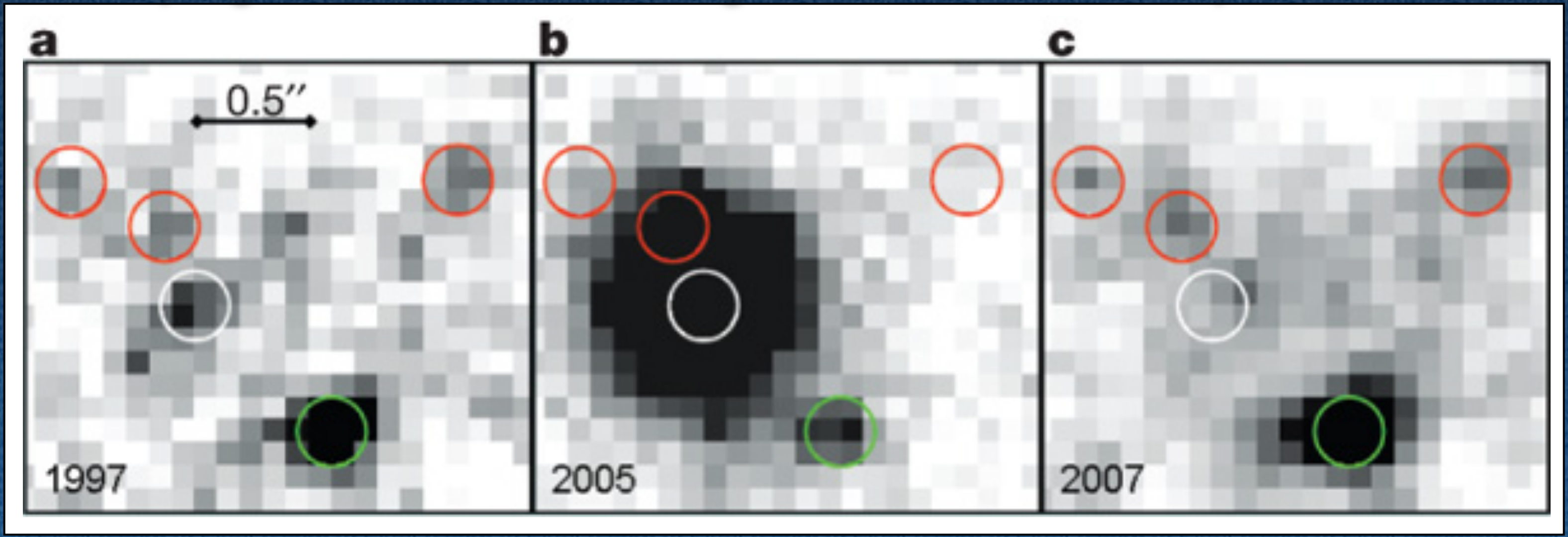
SN 2005gl

Moderate Luminosity Type IIn supernova: Narrow H lines

Progenitor star was very Luminous: $M_V = -10.3$ or $L = 1.1\times10^6\ L_\odot$
Implies $M_{ZAMS} \geq 50\ M_\odot$

Progenitor mass-loss rate about 0.03 $M_\odot$/yr: like P Cyg in 1600 AD

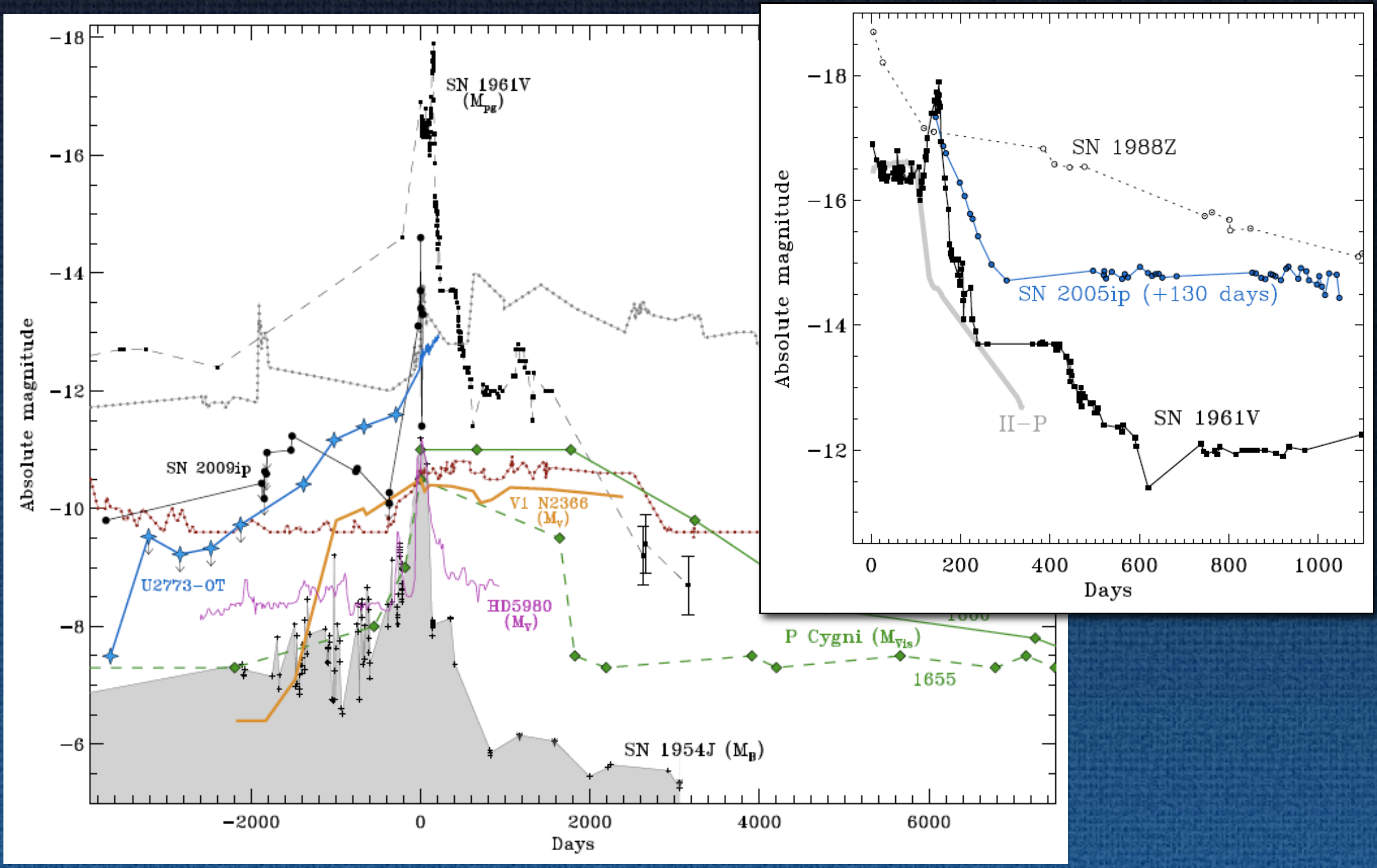
The progenitor star of SN 2005gl vanished after the supernova event.



Gal-Yam & Leonard *Nature* (2009)

SN 1961V

Minor tangent…
"SN impostors" or Luminous Blue Variables
(see Smith et al. 2011, MNRAS, 415, 773)

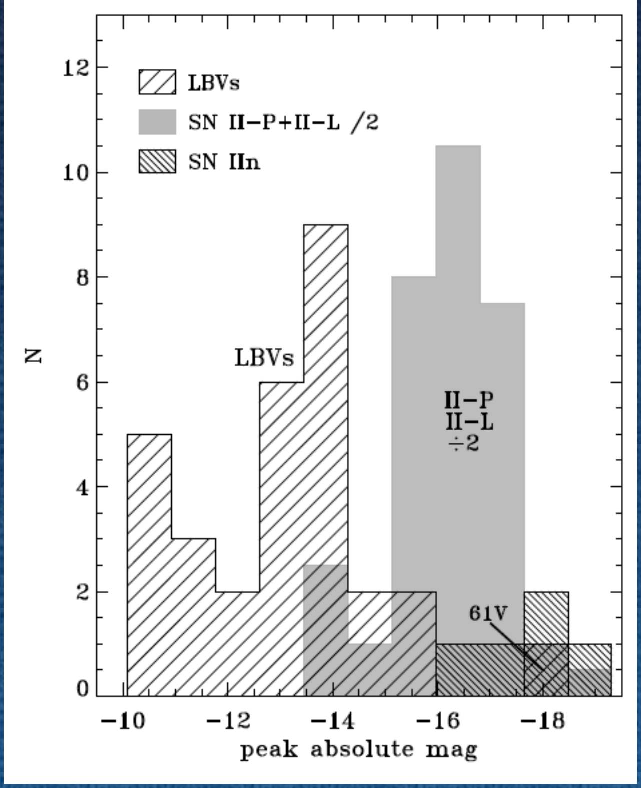


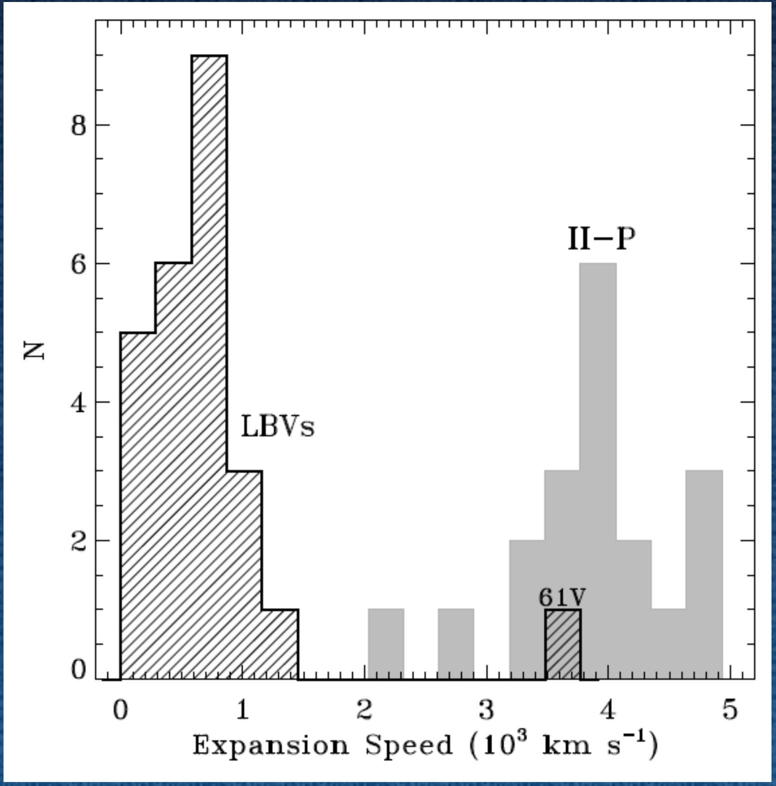
SN 1961V

Minor tangent…
"SN impostors" or Luminous Blue Variables
(see Smith et al. 2011, MNRAS, 415, 773)

Originally assumed to be a "SN impostor": Luminous Blue Variable

Progenitor star was extremely luminous: $M_V = -12$
Implies $M_{ZAMS} \geq 100\ M_{\odot}$ - like Eta Car



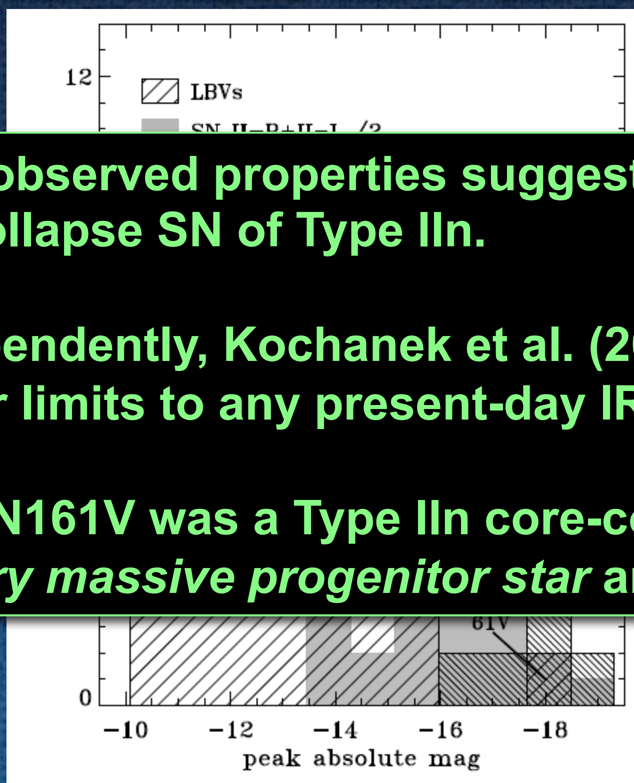


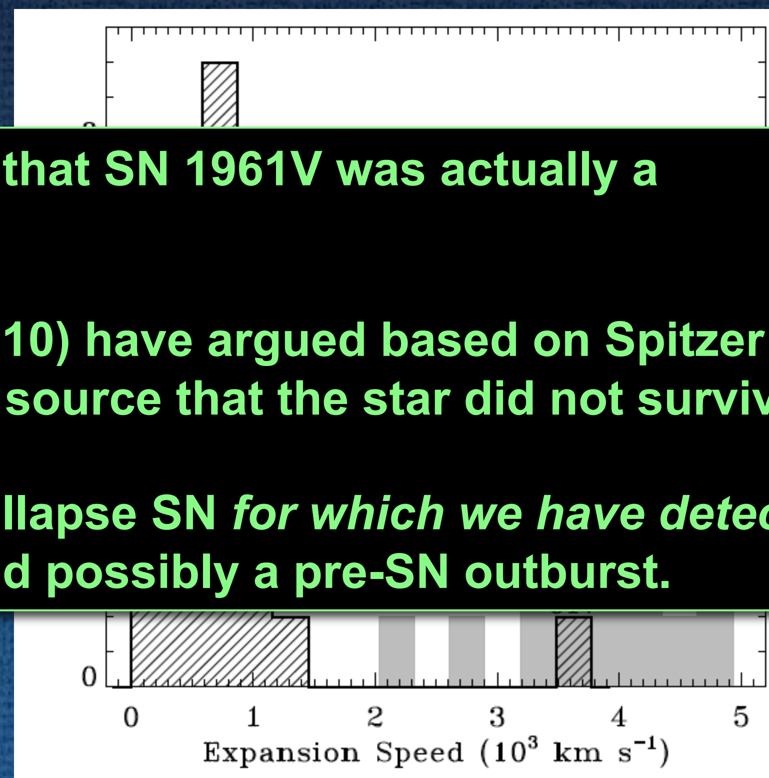
SN 1961V

Minor tangent…
"SN impostors" or Luminous Blue Variables
(see Smith et al. 2011, MNRAS, 415, 773)

Originally assumed to be a "SN impostor": Luminous Blue Variable

Progenitor star was extremely luminous: $M_V = -12$
Implies $M_{ZAMS} \geq 100\ M_{\odot}$ - like Eta Car





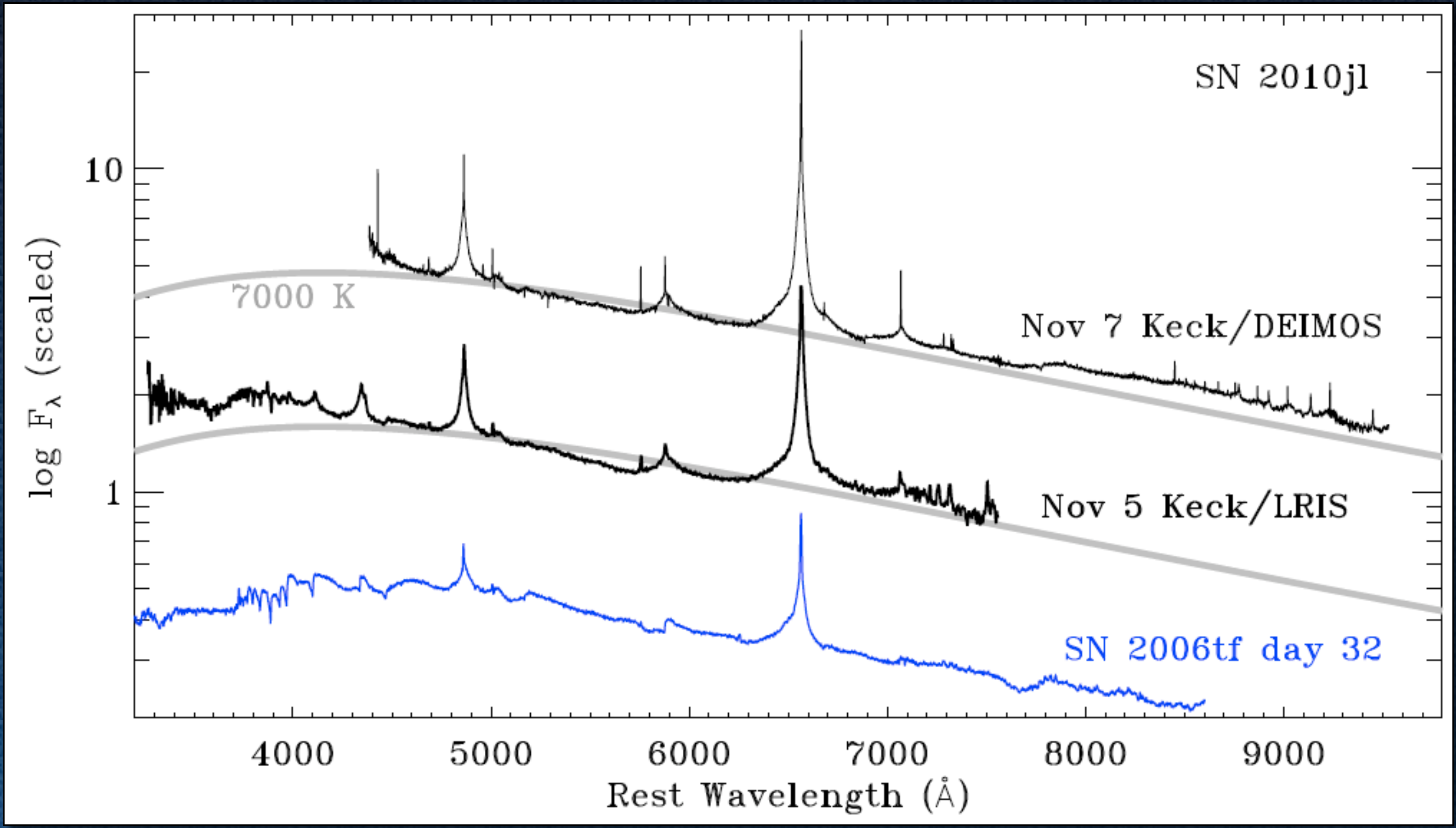
These observed properties suggest that SN 1961V was actually a core-collapse SN of Type IIn.

Independently, Kochanek et al. (2010) have argued based on Spitzer upper limits to any present-day IR source that the star did not survive…

…So SN161V was a Type IIn core-collapse SN *for which we have detection of a very massive progenitor star* and possibly a pre-SN outburst.

SN 2010jl

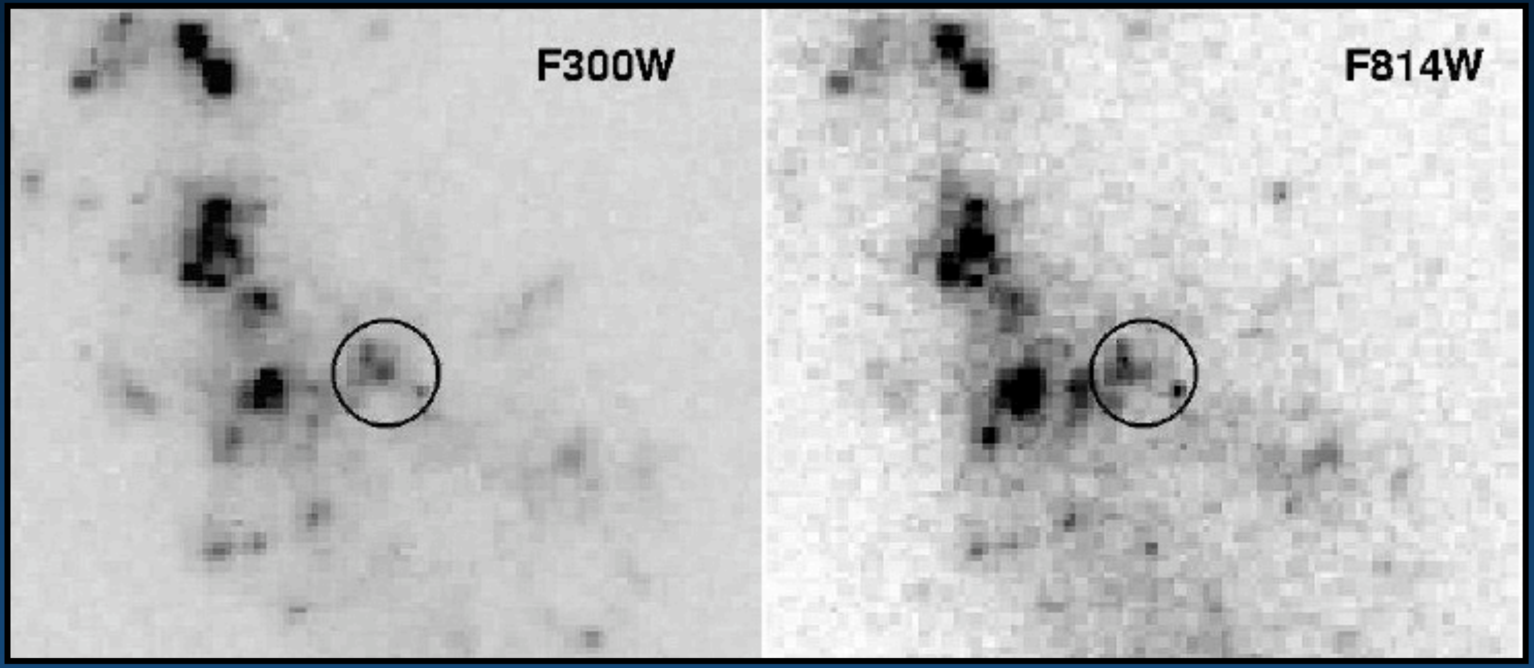
Very luminous Type IIn supernova: HST images from 10 yr ago



SN 2010jl (*a.k.a.* )

Very luminous Type IIn supernova (-20.something)
Bright blue source at SN position: $M_{F300W} = -12$
(either massive young cluster or very luminous progenitor star)

Implies $M_{ZAMS} \geq 30\ M_{\odot}$

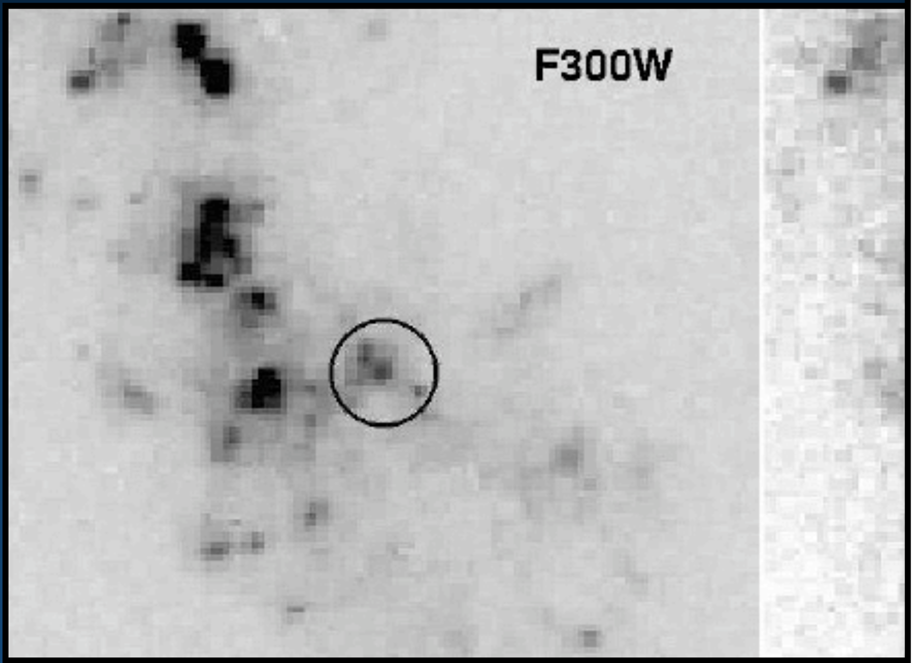


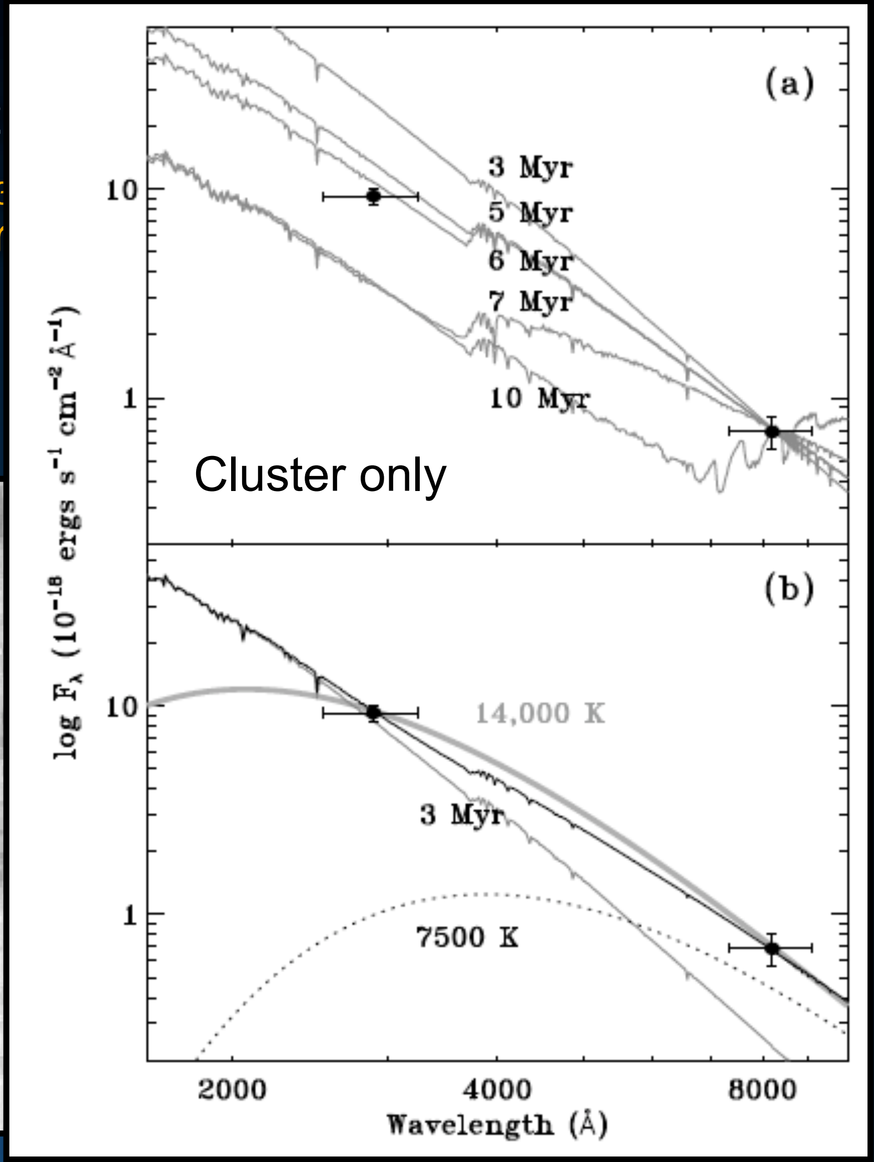
Smith et al. (2011)

SN 2010jl (*a.k.a.* )

Very luminous Type IIn supernova (-2
Bright blue source at SN position: M_{F3}
(either massive young cluster or ver

Implies $M_{ZAMS} \geq 30\ M_{\odot}$





Smith et al. (2011)

Type II-P
RSGs with initial mass 8.5 – 20 $M_\odot$ (20)

Type Ibc
WR? Zero detections.

Type IIb
13-15 $M_\odot$ binary (1)

Type II-L
18-25 $M_\odot$ (2)

Type IIn

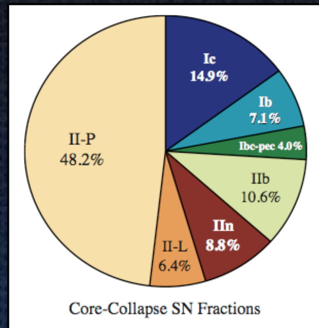
Type IIn supernovae progenitors: summary

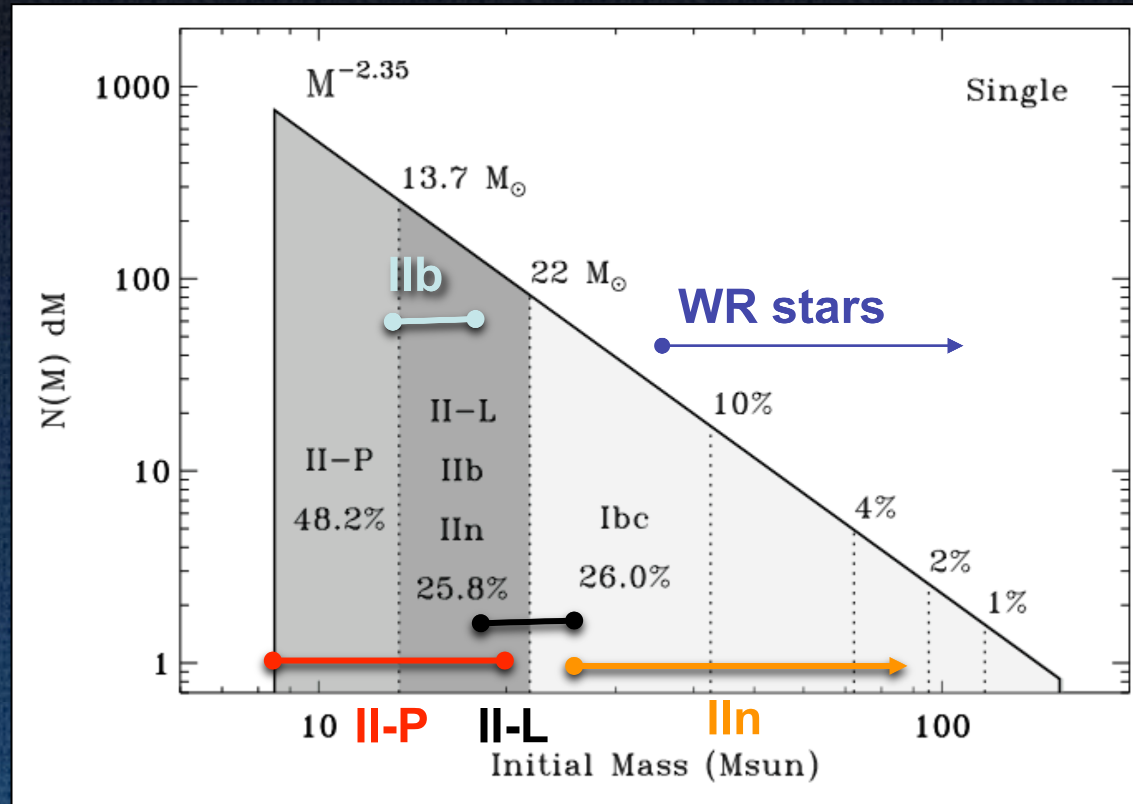
- Very luminous SNe IIn require high mass of CSM
  - some require >10 $M_\odot$ ejected in decade before core collapse.
  - high eruptive mass-loss rates resemble LBVs, suggesting $M_0 > 25\ M_\odot$
- Velocities and densities of CSM resemble LBVs
- 3 detections of SN progenitors (or host cluster)
  - SN 2005gl $M_0 \sim 60\ M_\odot$
  - SN 1961V $M_0 \sim 100\ M_\odot$
  - SN 2010jl $M_0 > 30\ M_\odot$ (cluster or progenitor)

Suggests that Type IIn supernovae come from very massive stars $M_0 > 25\ M_\odot$

CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Smith et al. (2011)
MNRAS, 412, 1522





Type II-P

RSGs with initial mass 8.5 – 20 $M_\odot$ (20)

Smartt (2008) ARAA

Type Ibc

Zero detections.

Type IIb

13-18 $M_\odot$ binary (2)

Type II-L

18-25 $M_\odot$ (2)

Type IIn

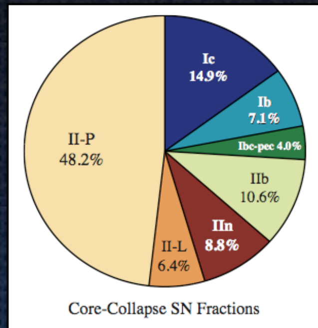
>25 $M_\odot$ (3+)

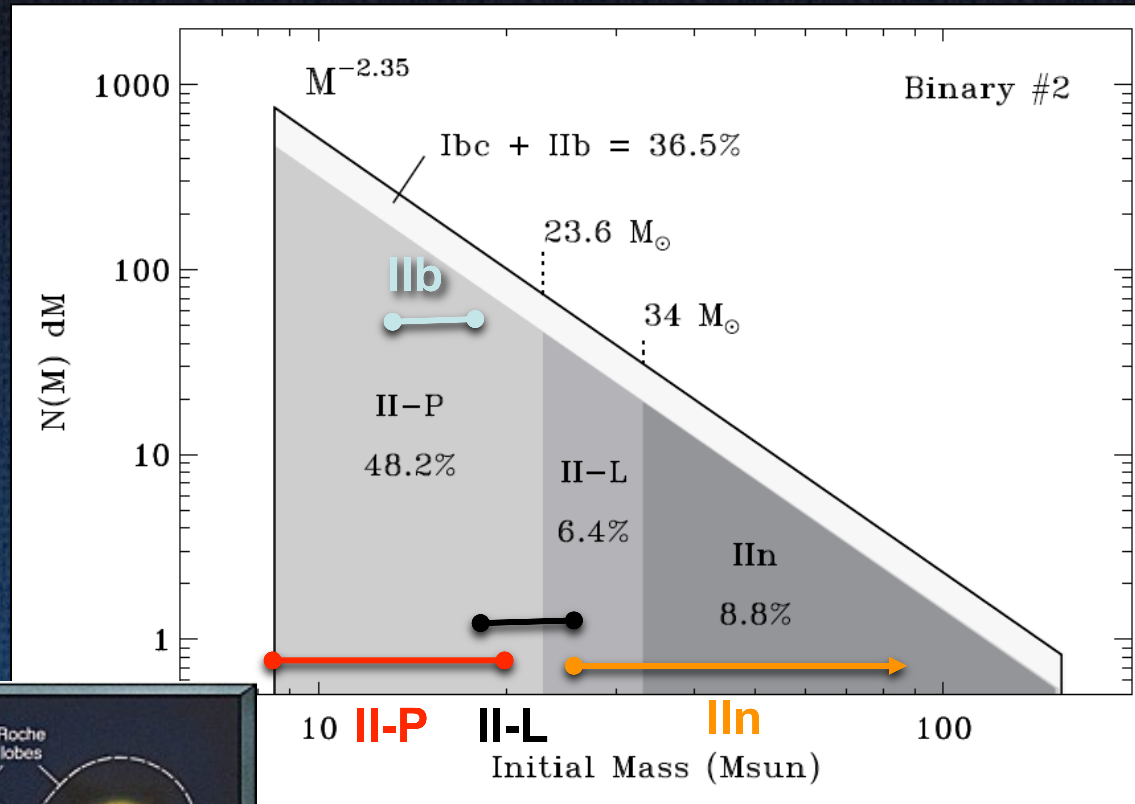
Steady winds do not dominate the H envelope removal of massive stars.

Assuming that ALL massive stars explode as visible SNe…
(including quiet collapse to black holes makes agreement worse)

CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Smith et al. (2011)
MNRAS, 412, 1522





Type II-P

RSGs with initial mass
8.5 – 20 $M_\odot$ (20)

Type Ibc

Zero detections.

Type IIb

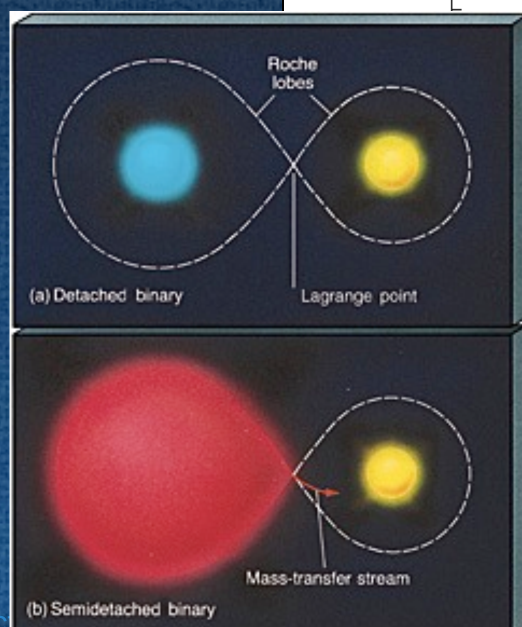
13-15 $M_\odot$ binary (2)

Type II-L

18-25 $M_\odot$ (2)

Type IIn

>25 $M_\odot$ (3+)

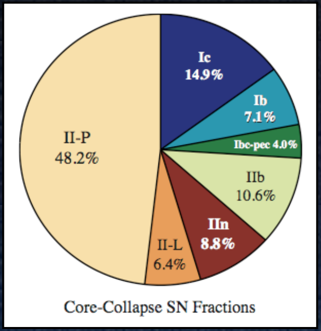


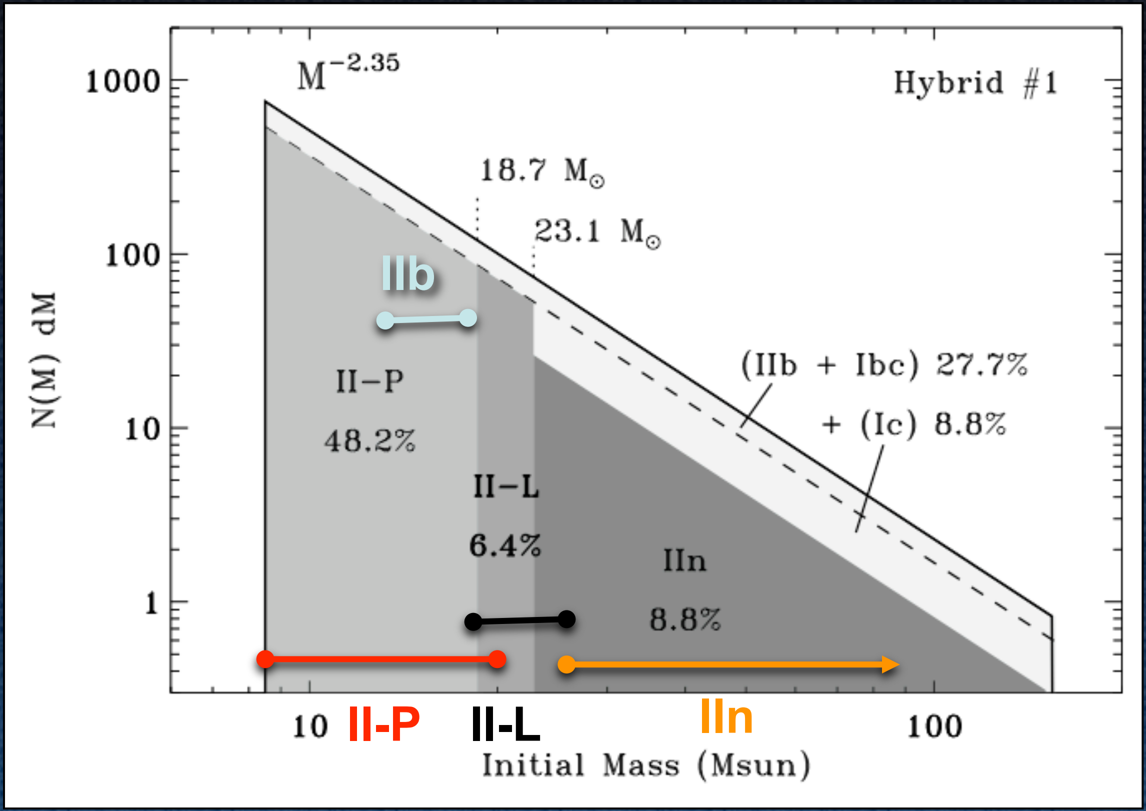
More consistent with low ejecta masses in SNe Ibc

Dessart et al. 2011
Hachinger et al. 2012
(more than 0.1-0.2 $M_\odot$ of He is easily seen in SNe Ic)

CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS

Smith et al. (2011)
MNRAS, 412, 1522





Type II-P

RSGs with initial mass
8.5 – 20 $M_\odot$ (20)

Type Ibc

Zero detections.

Type IIb

13-18 $M_\odot$ binary (2)

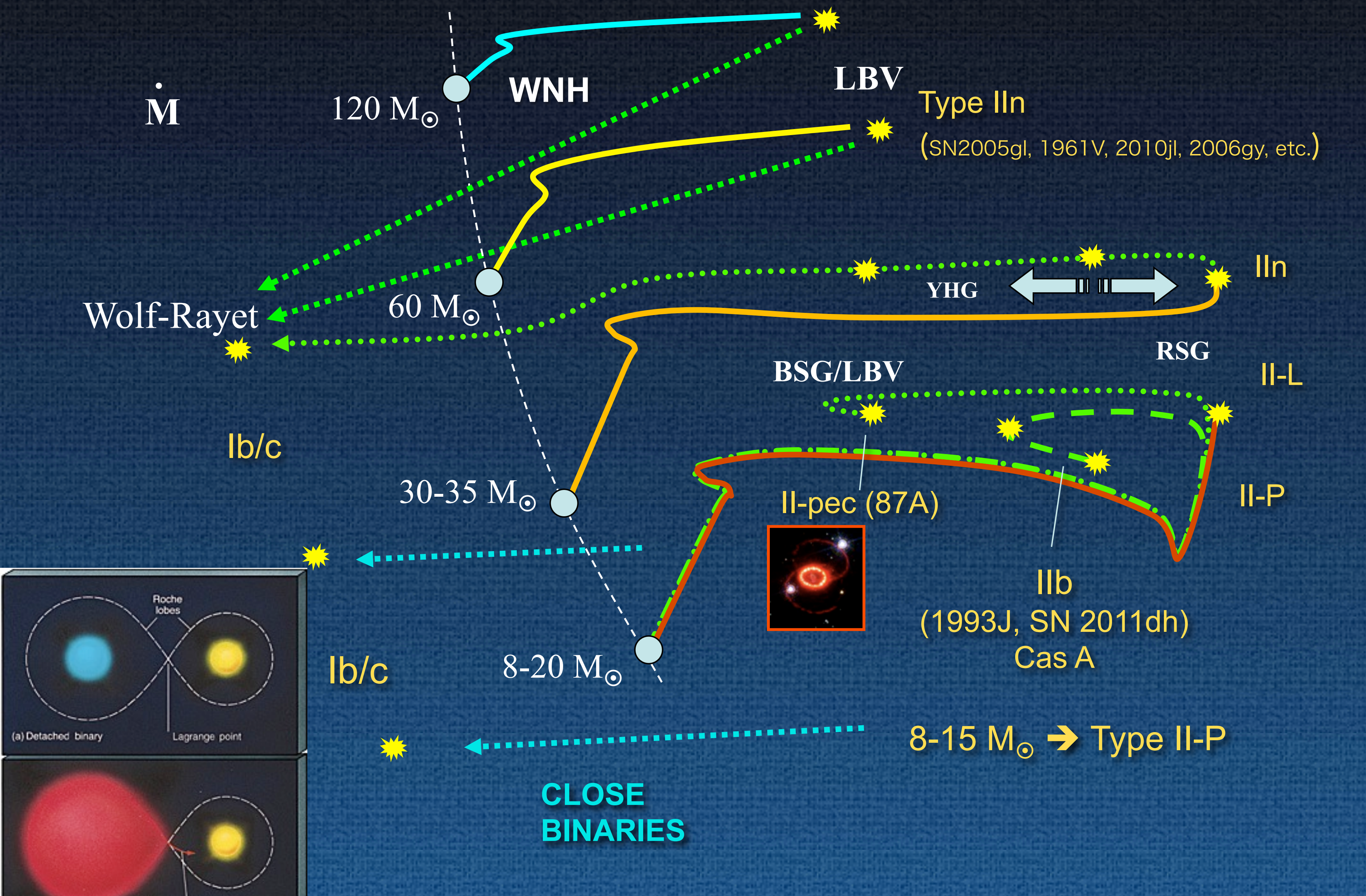
Type II-L

18-25 $M_\odot$ (2)

Type IIn

>25 $M_\odot$ (3+)

What about binary fraction as function of mass?
(SNe Ibc preferentially associated with clusters?)



Ṁ
120 M☉
WNH
LBV
Type IIn
(SN2005gl, 1961V, 2010jl, 2006gy, etc.)
Wolf-Rayet
60 M☉
YHG
IIn
RSG
II-L
BSG/LBV
Ib/c
30-35 M☉
II-pec (87A)
II-P
IIb
(1993J, SN 2011dh)
Cas A
Roche lobes
(a) Detached binary
Lagrange point
Mass-transfer stream
(b) Semidetached binary
Ib/c
8-20 M☉
8-15 M☉ ➔ Type II-P
CLOSE
BINARIES

CONCLUSIONS/DISCUSSION TOPICS

1. Observed fraction of Type Ibc is too high to be explained by massive single WR star progenitors.
   Only the most massive stars (> 40-50 $M_{\odot}$) can shed H envelopes via winds and/or eruptions, but these are too rare for all SNe Ibc.

2. Instead, stripped-envelope SNe (Types Ib, Ic, IIb) may be dominated by close binaries, so RLOF may dominate removal of H envelope in general.
   Which SNe IIb, Ib, Ic come from the lower mass range?
   What fraction of classical WR stars form this way?

3. Metallicity and cluster membership can still play an important role:
   Star formation (binaries), mass loss after RLOF, IIb/Ib/Ic ratio, etc.
   …GRBs? Quiet collapse to BH?

4. What about mass-gainers in RLOF systems?
   Some might still be there after SN – are they detectable?
   also, Rapid/critical rotation, thermal instability, high luminosity?