Supernova Progenitors and Their Binary Companions

Schuyler D. Van Dyk
IPAC/Caltech, USA

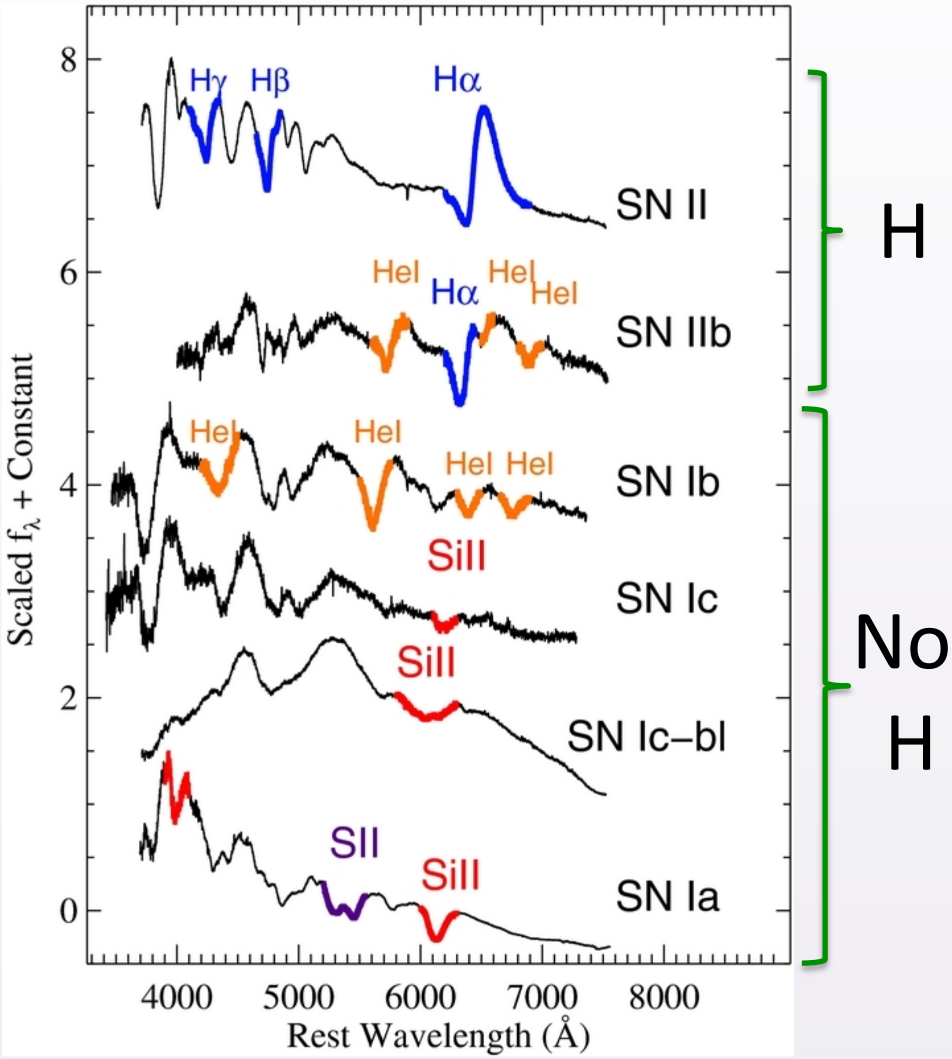
Before there were supernova remnants…

… there were supernovae.

Before there were supernovae…

… there were stars.

Supernova Taxonomy, I.



(Modjaz et al. 2014)

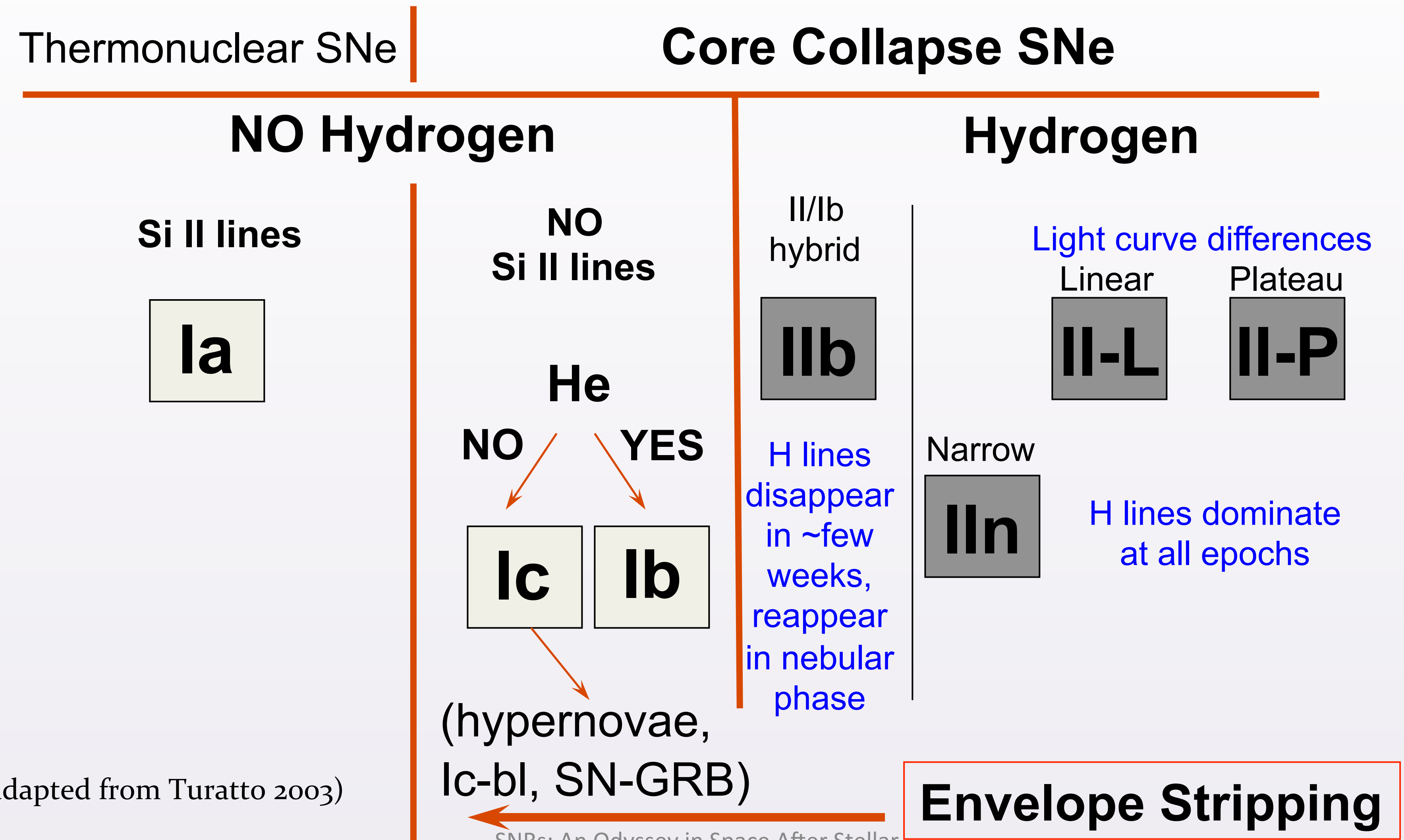
Core-collapse SNe

Massive stars with
$M_{ini} \geq 8$--$10\ M_{\odot}$

Thermonuclear SNe

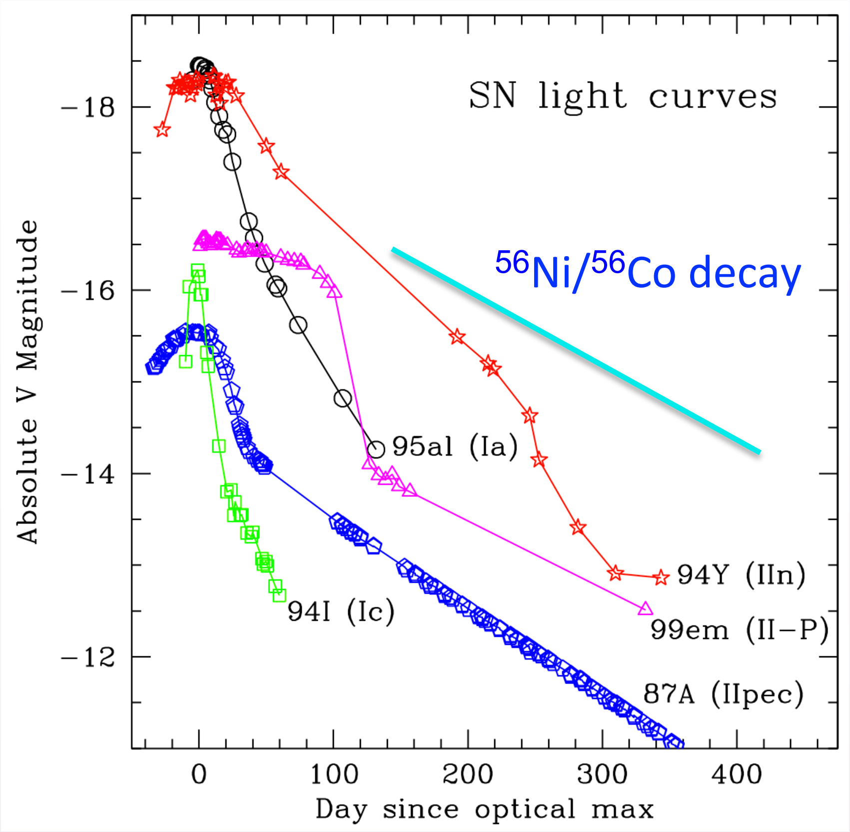
Deflagration/detonation
of a white dwarf

Supernova Taxonomy, II.



(adapted from Turatto 2003)

Supernova Light Curves

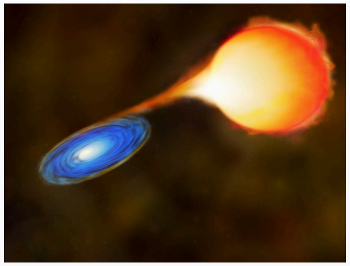


Mass of ^{56}Ni depends on the mass of core

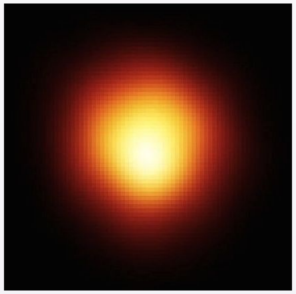
Progenitor Models

SNe Ia: **Single- or double-degenerate system**

(An accreting O-Ne-Mg white dwarf
vs.
Two merging C-O white dwarfs)



SNe II-P, II-L (?), IIn (??): **Single, massive supergiant**



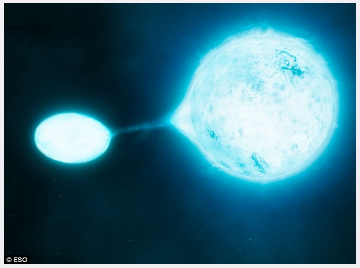
Betelgeuse (HST UV)

SNe IIb, Ib, Ic:
(stripped-envelope SNe)

WR 124/M1-67 (HST)

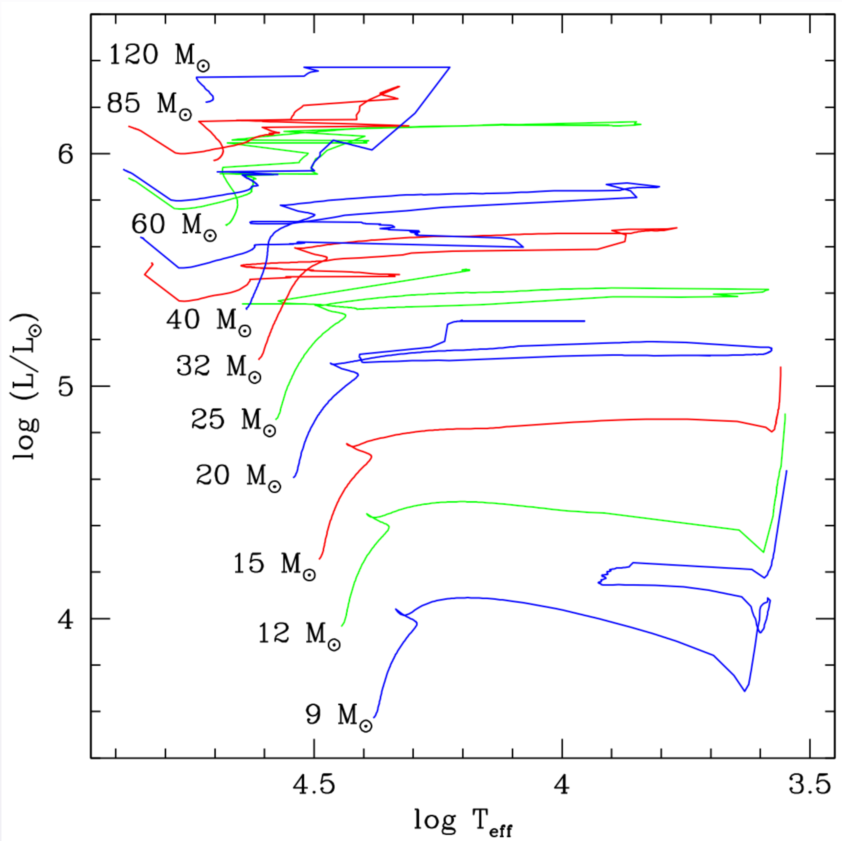
High-mass, windy single star

Massive binary system

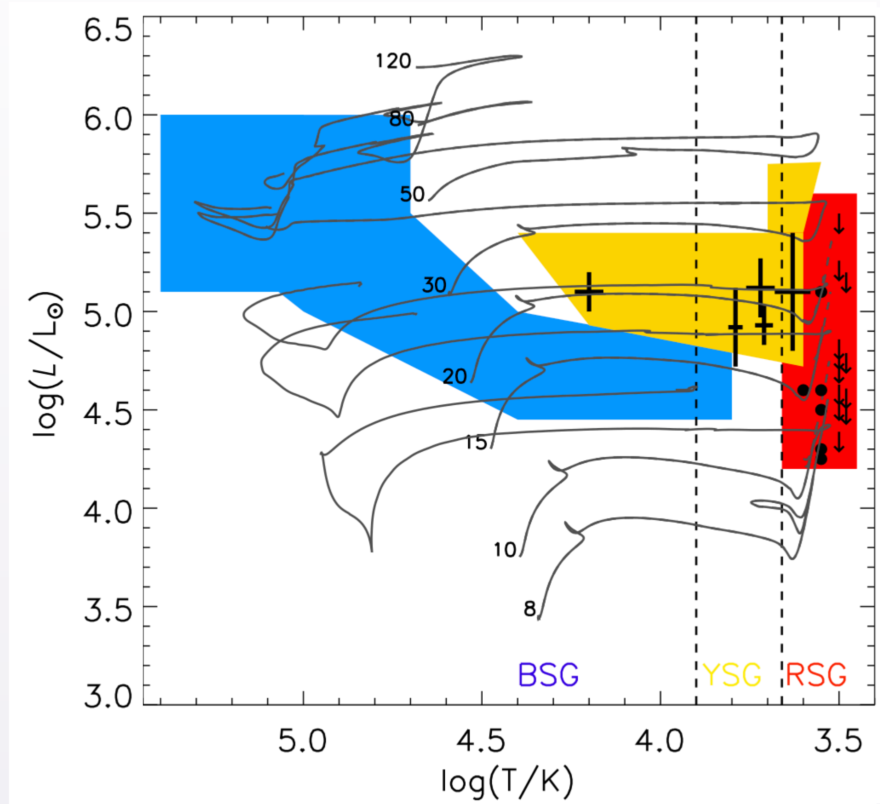


Sana et al. (2012)
(credit ESO)

Massive Star Evolution

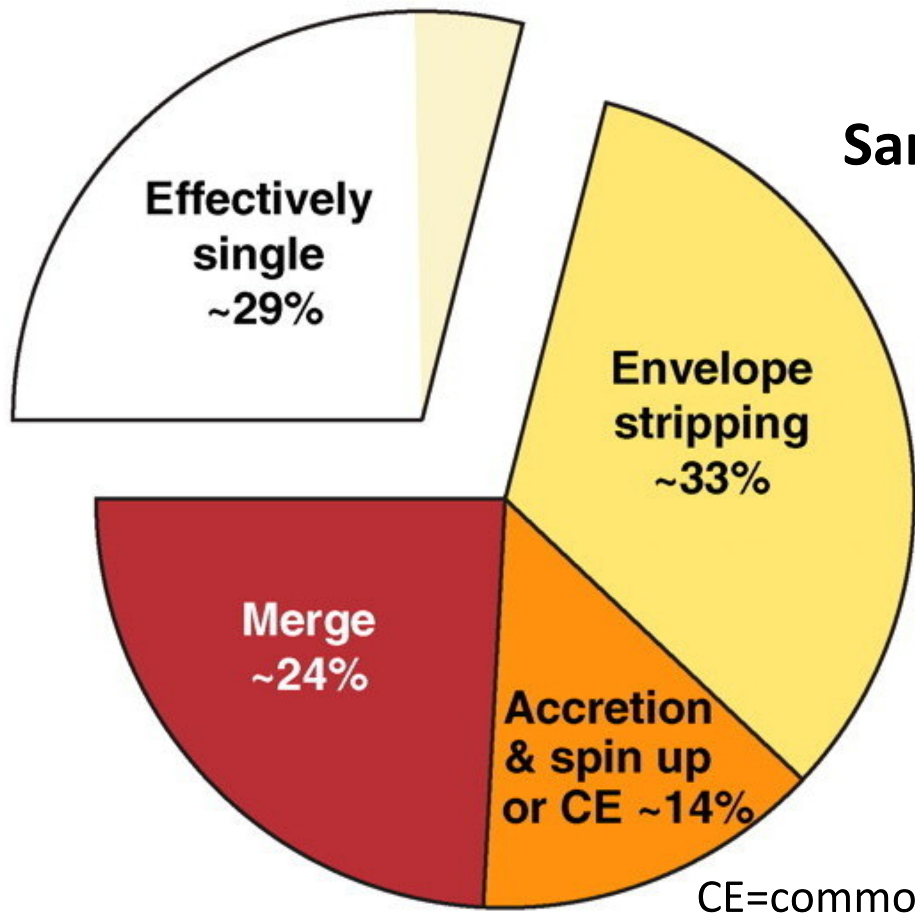


Geneva tracks for **SINGLE** stars
with rotation at solar metallicity
(Ekström et al. 2012)



Including **BINARY** stars
(Eldridge et al. 2013)

Odds are against massive stars dying alone

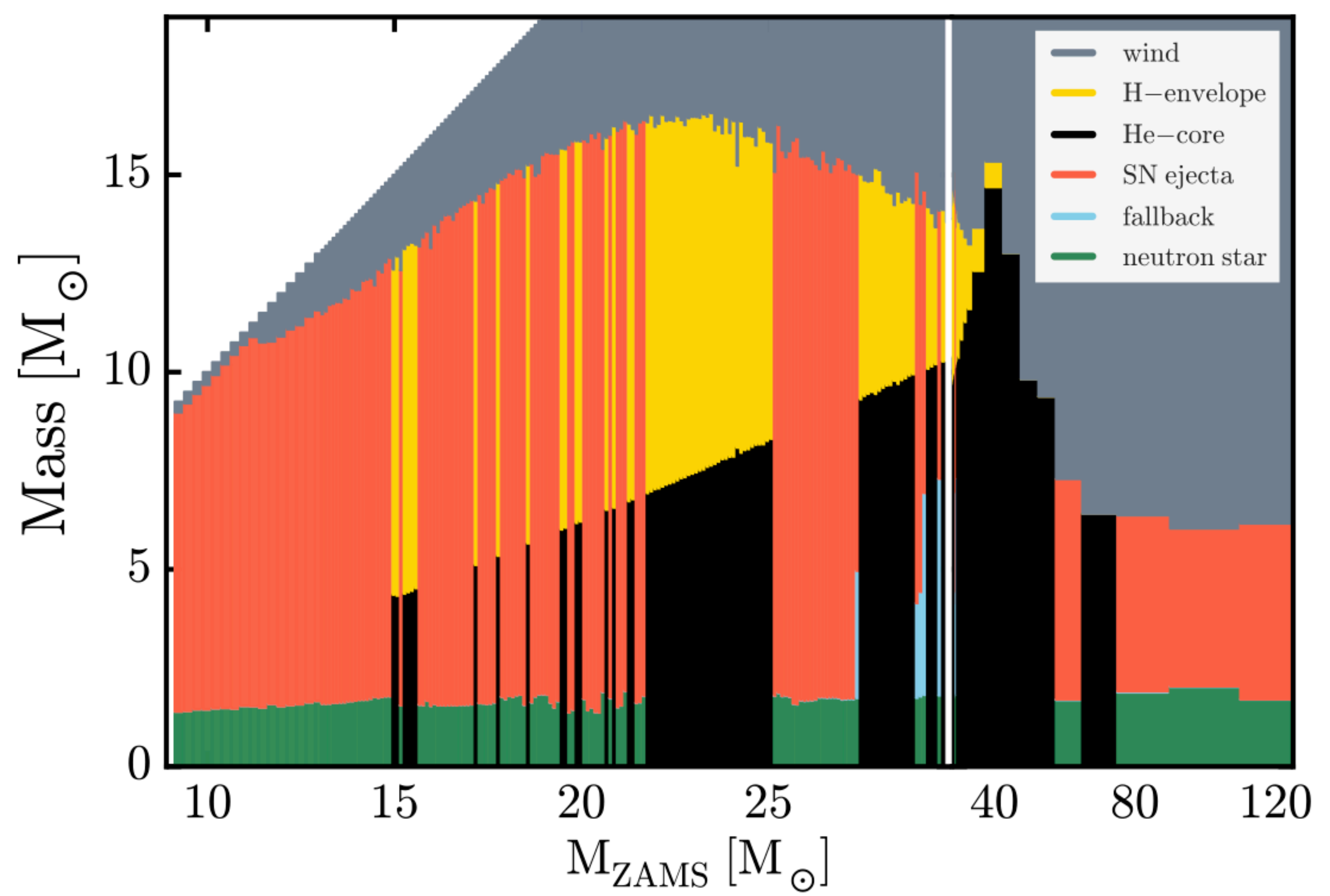


Sana et al. (2012)

CE=common envelope

Explosion Models

"Islands of 'explodability' in a sea of black hole formation"



1-D KEPLER and P-HOTB models (Sukhbold et al. 2016)

Determining the Progenitor

- Hydrodynamical simulations of the SN

  e.g., Bersten, Benvenuto, & Hamuy (2011); Dall'Ora et al. (2014)

- SN environmental analysis

  e.g., Van Dyk et al. (1999); Kelly et al. (2008); Williams et al. (2014)

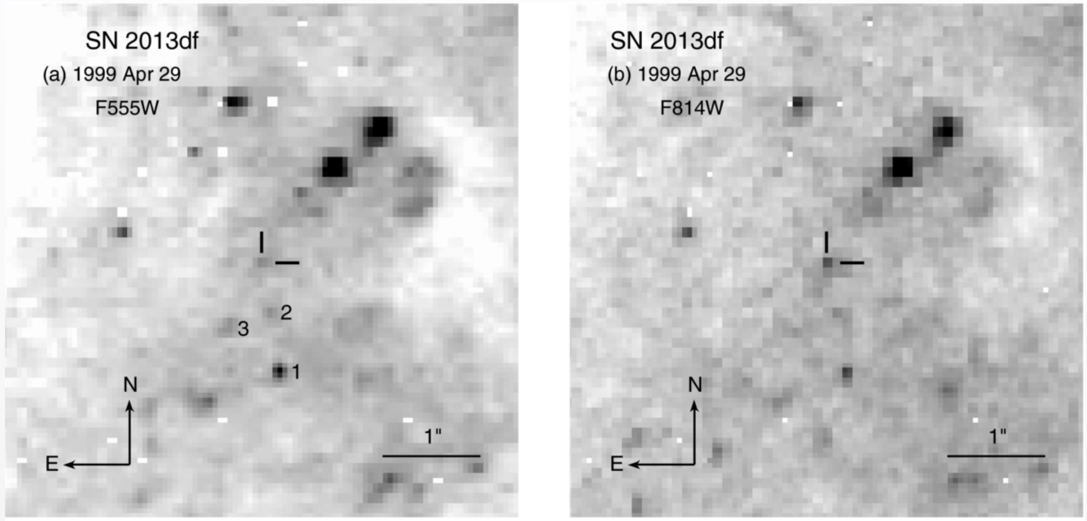
- Late-time nebular spectroscopy

  e.g., Jerkstrand et al. (2012); Kuncarayakti et al. (2015)

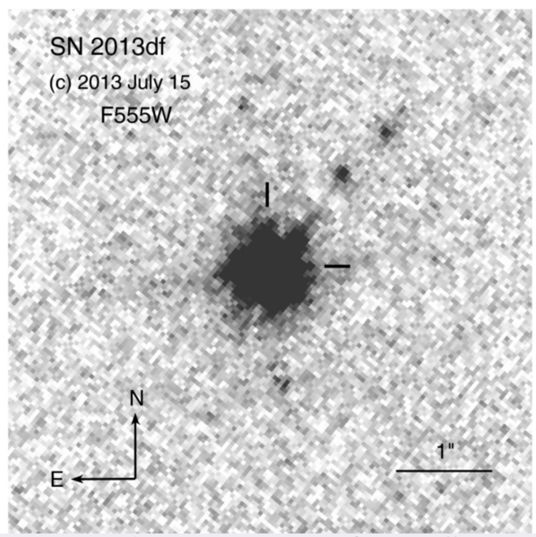
- **Direct identification in pre-SN images**

Identifying the Progenitor

Pre-SN
HST WFPC2



Post-explosion
HST WFC3/UVIS



So, do we see red supergiants as progenitors of Type II SNe?

SN II-P (pec) 1987A: The best progenitor detection

[David Malin]

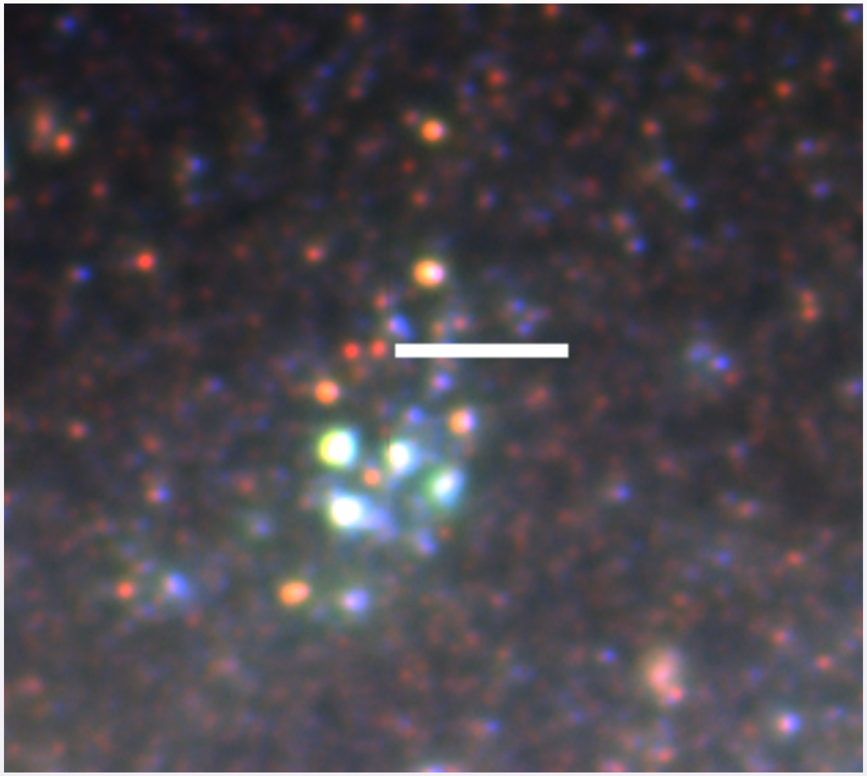
(initial mass ≈20 $M_{\odot}$
e.g., Arnett et al. 1989)

Sanduleak -69° 202
B0.7--B3 supergiant star
(Isserstedt 1975; Rousseau et al. 1978; Walborn et al. 1989)

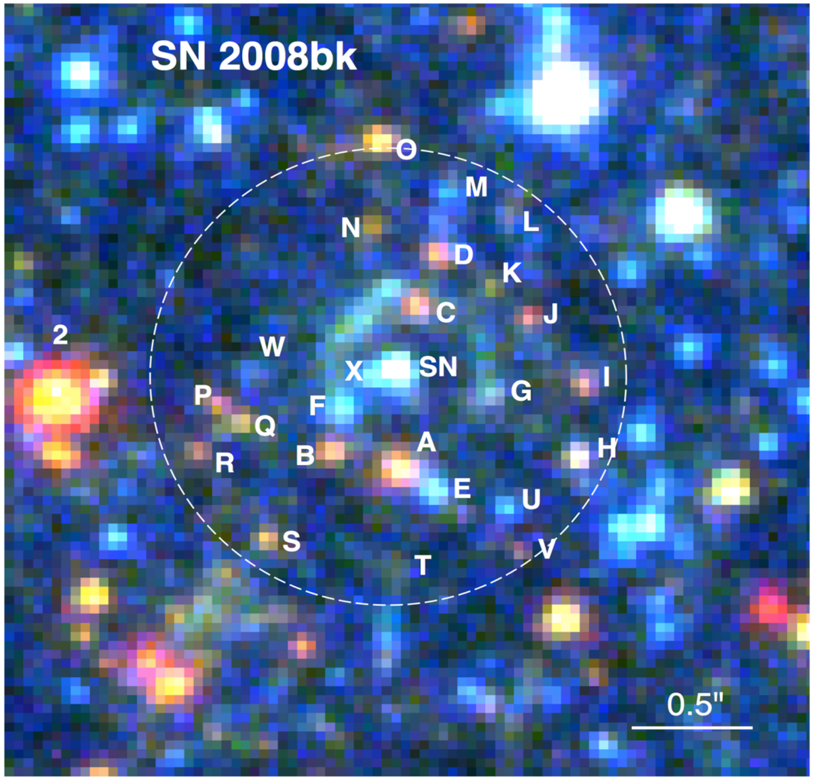
SN II-P 2008bk:
The *next* best progenitor detection

<u>A red supergiant</u>

Host: NGC 7793 (3.4 Mpc)



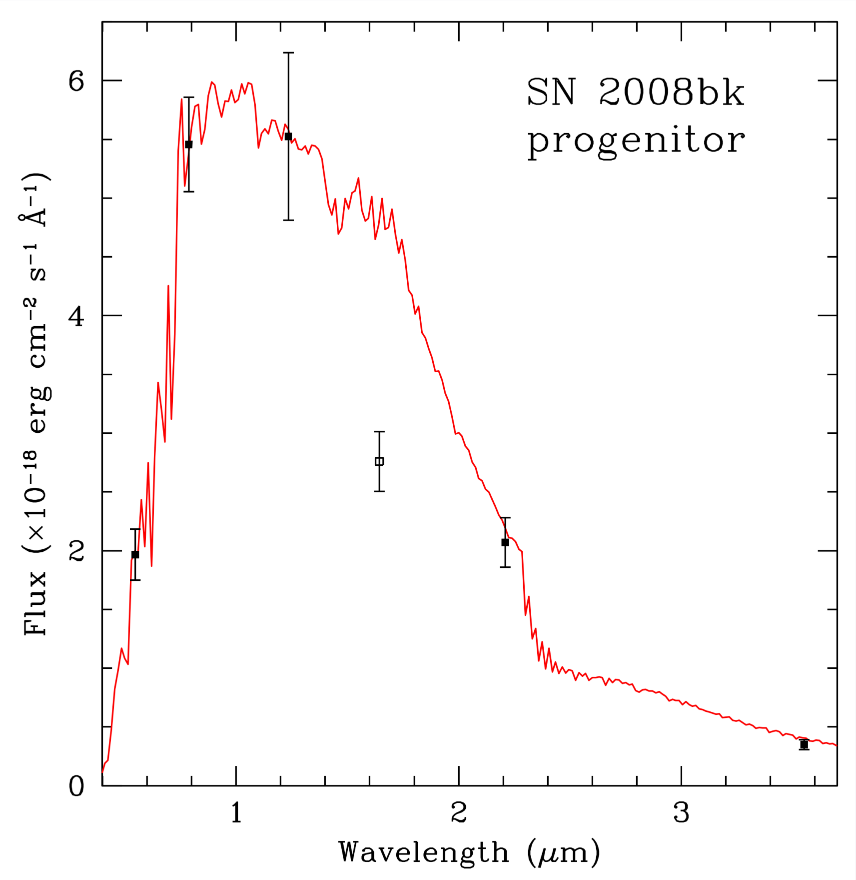
Gemini g’r’i’ from 2007
(Van Dyk et al. 2012a)

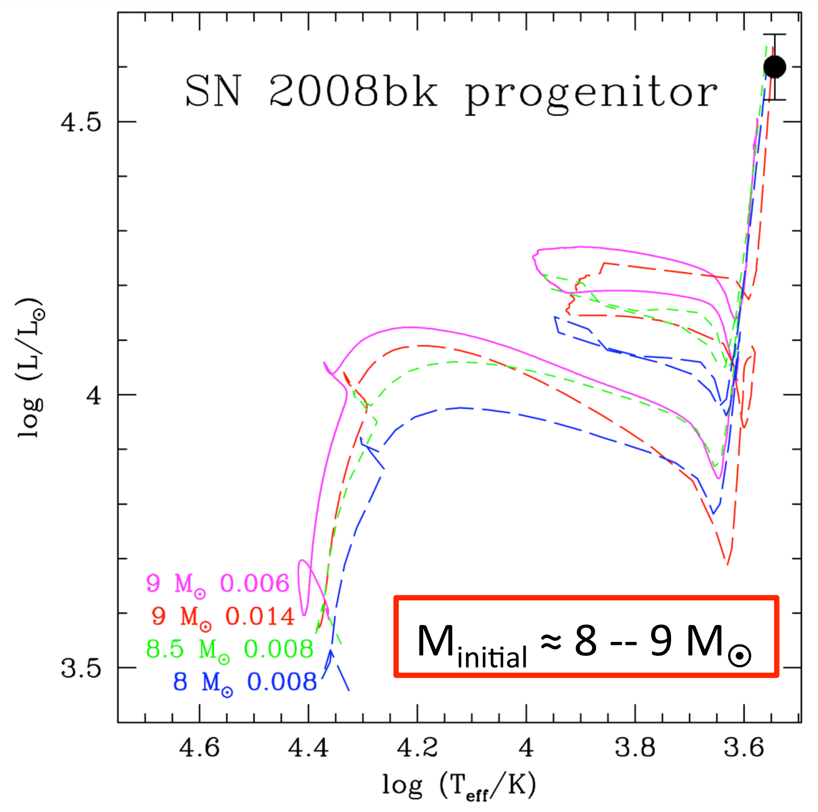


HST/WFC3 2011
(Echo: Van Dyk 2013)

The *next* best progenitor detection: SN 2008bk, a subluminous II-P

Spectral Energy Distribution (SED)





However, see Maund et al. (2014)

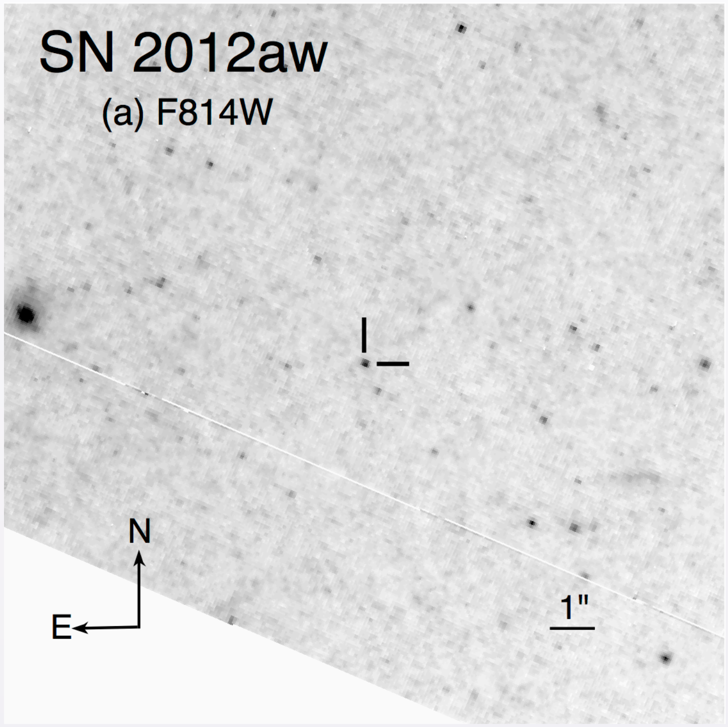
Magenta: Georgy et al. (2013; Z=0.006)
Red: Ekström et al. (2012; Z=0.014)
Green, blue: Cambridge STARS Z=0.008

SN 2012aw: A normal II-P

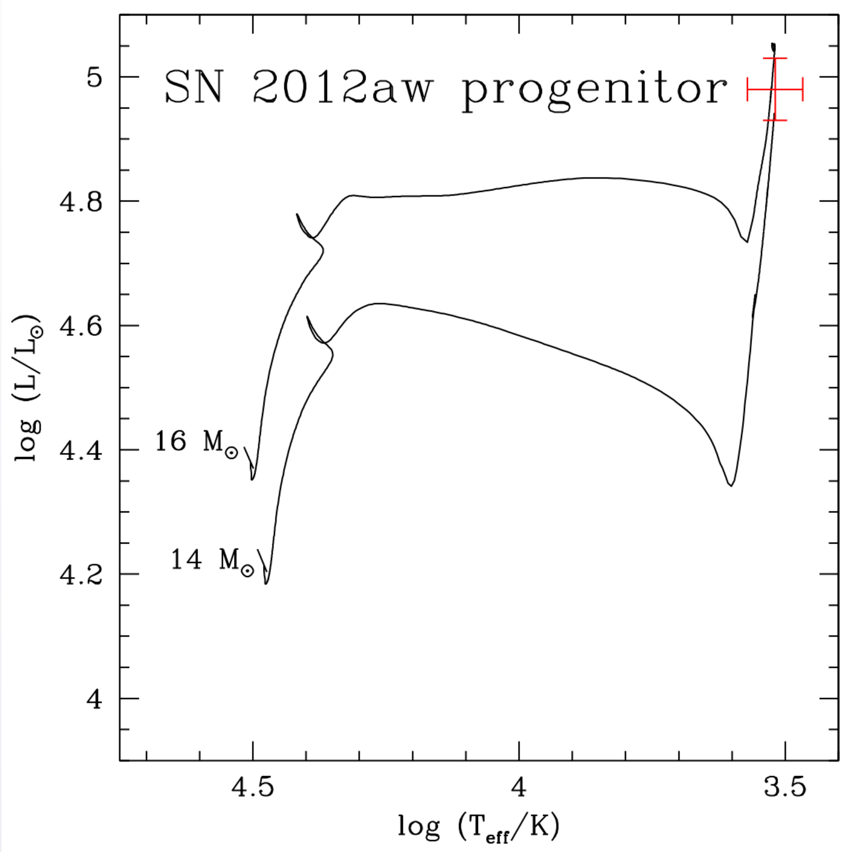
Host: M95 (10.0 Mpc)

- Red supergiant progenitor

$M_{initial} \approx 14\text{--}16\ M_{\odot}$



HST F555W & F814W from 1994
(Van Dyk et al. 2012b; Fraser et al. 2012)

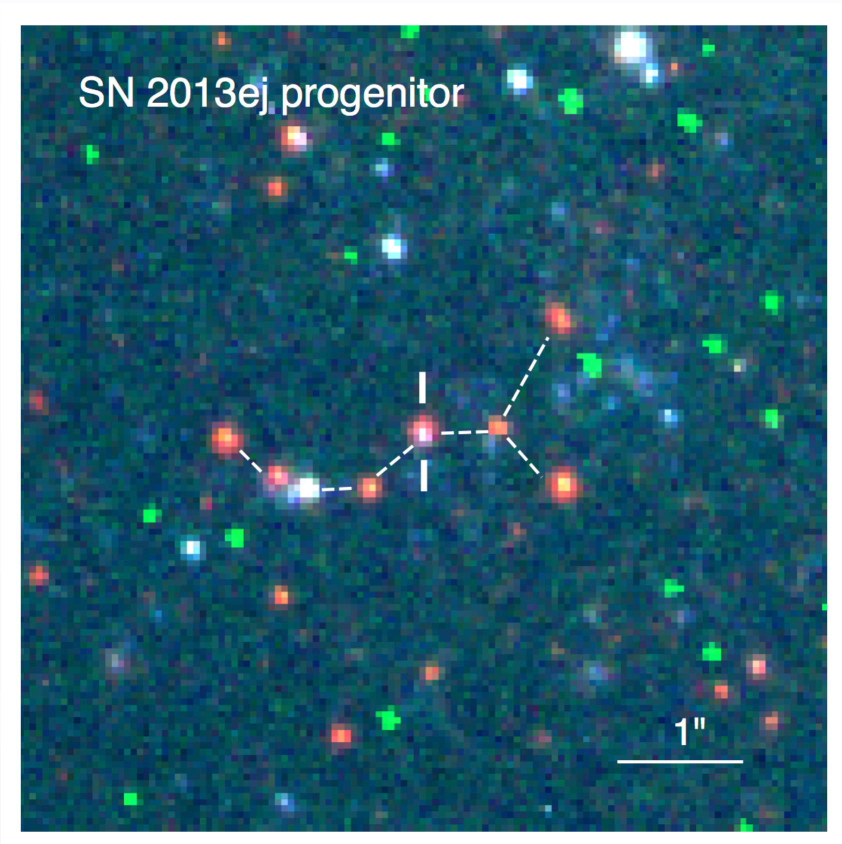


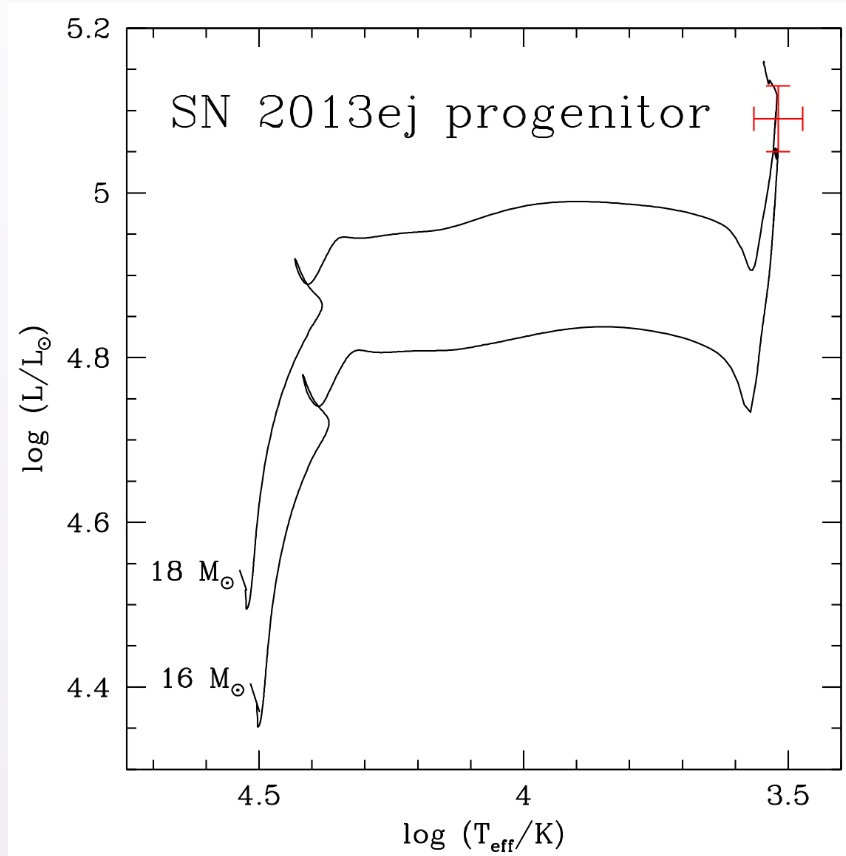
MIST solar metallicity tracks with rotation

SN 2013ej: A Type II-L?

Host: **M74** (10.2 Mpc)

$M_{initial} \approx$ 16--18 $M_\odot$

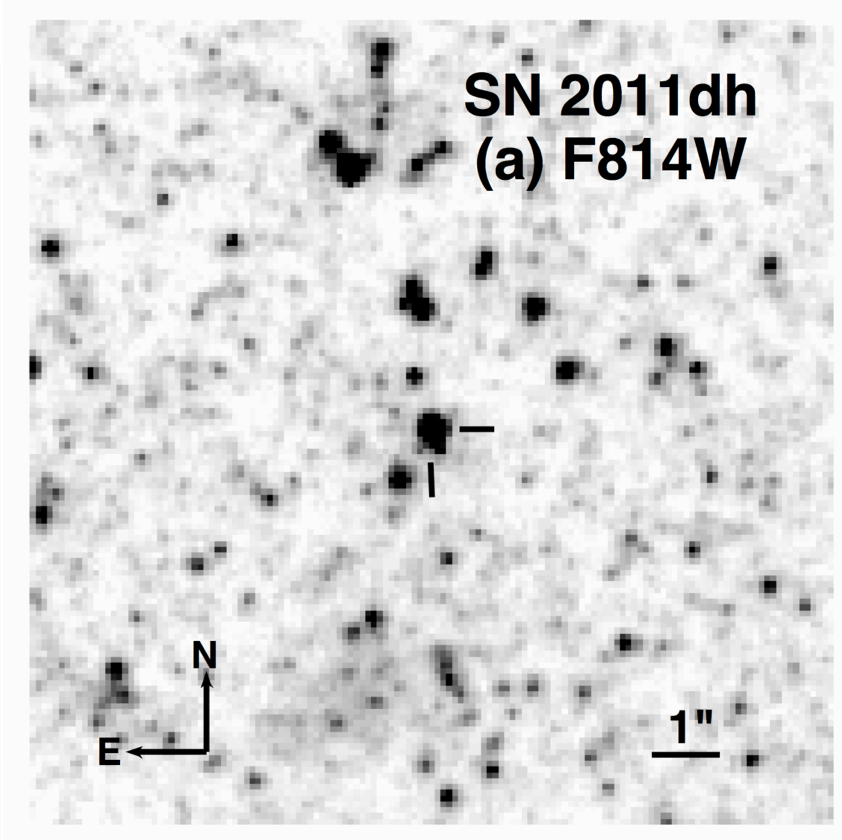




MIST solar metallicity tracks with rotation

But, what about the stripped-envelope SNe?

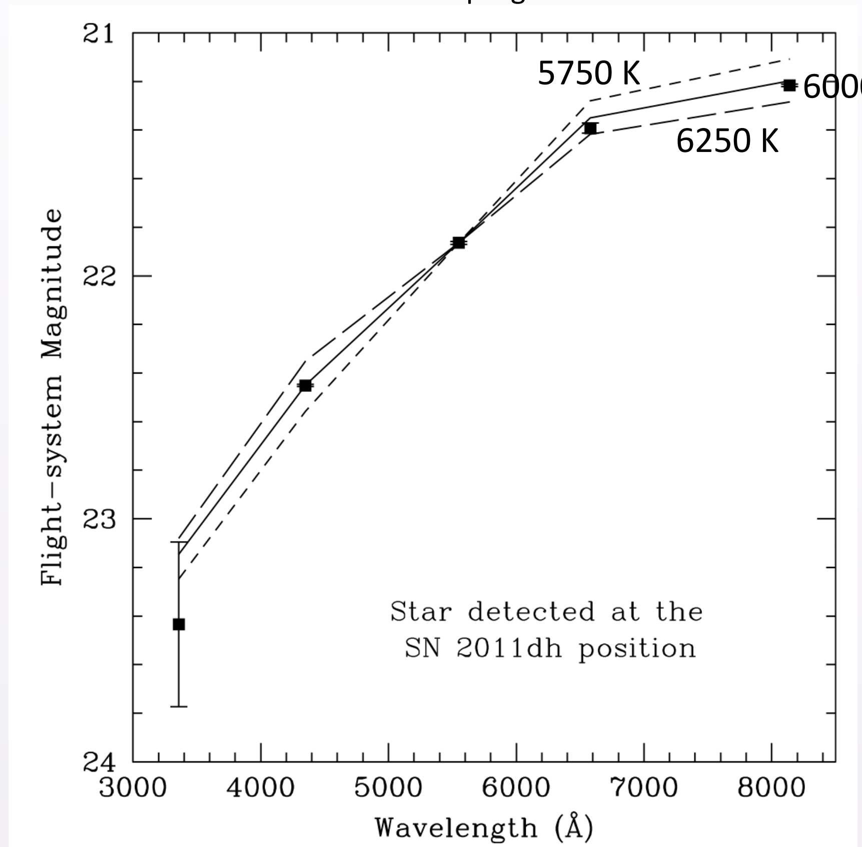
IIb: Yellow supergiant progenitors



Van Dyk et al. (2011), Maund et al. (2011)
HST/ACS data from 2005

Host: M51 (8.58 Mpc; McQuinn et al. 2016)

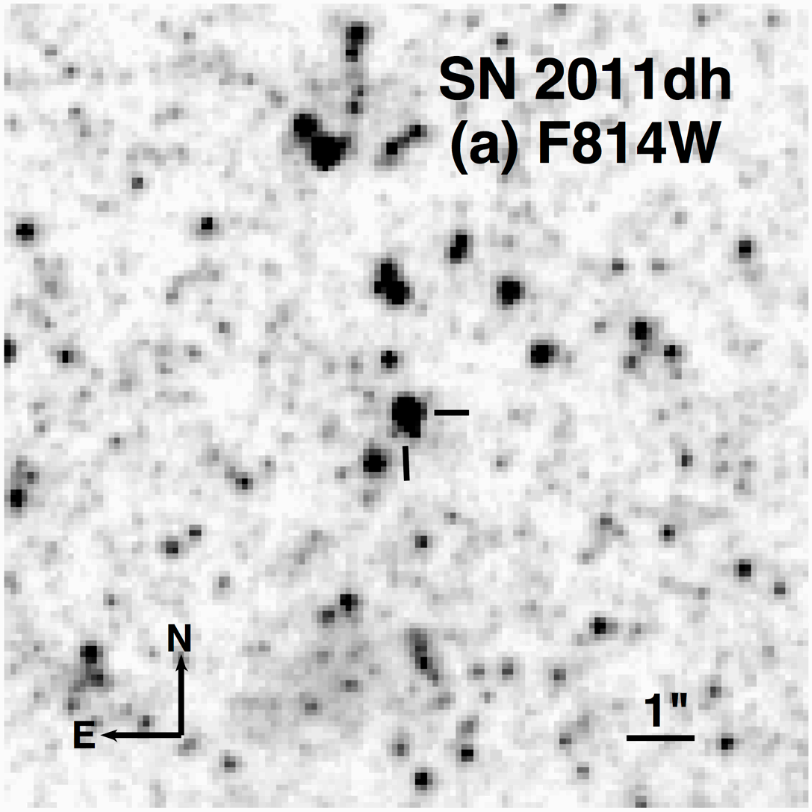
6000 ± 100 K, $R_{prog} \approx 200\ R_{\odot}$



Stripped H envelope: $\lesssim 0.1\ M_{\odot}$

He core ≈ 3--5 $M_{\odot}$

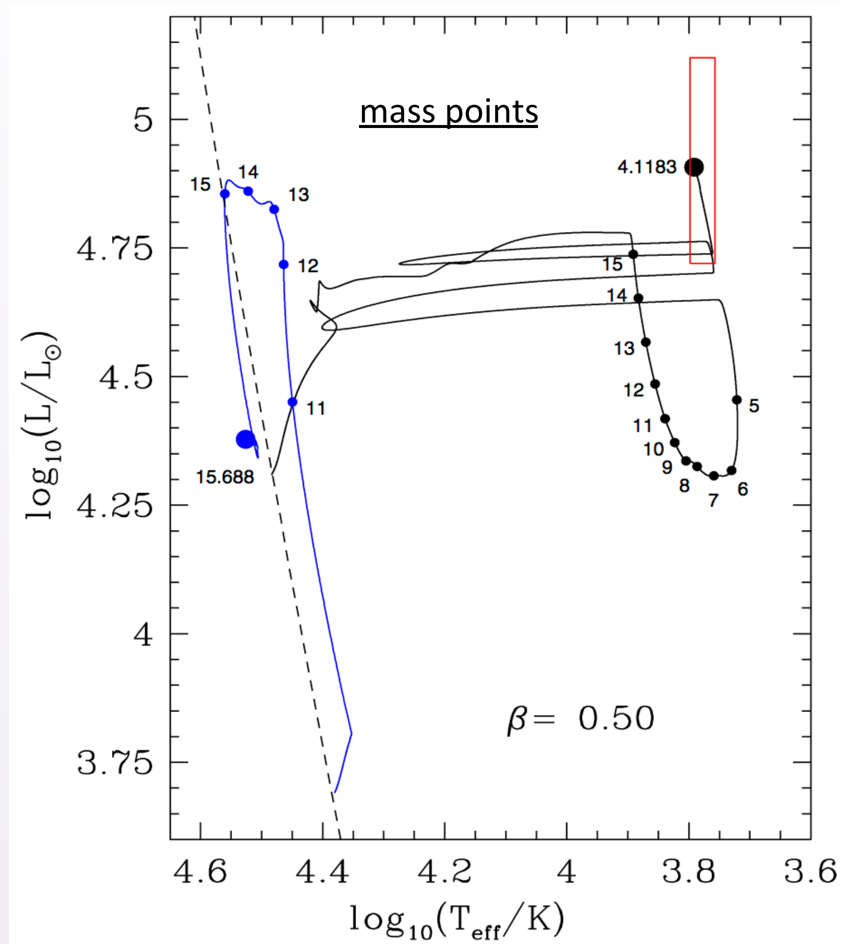
IIb: Yellow supergiant progenitors



Van Dyk et al. (2011), Maund et al. (2011)
HST/ACS data from 2005

Host: M51 (8.58 Mpc; McQuinn et al. 2016)

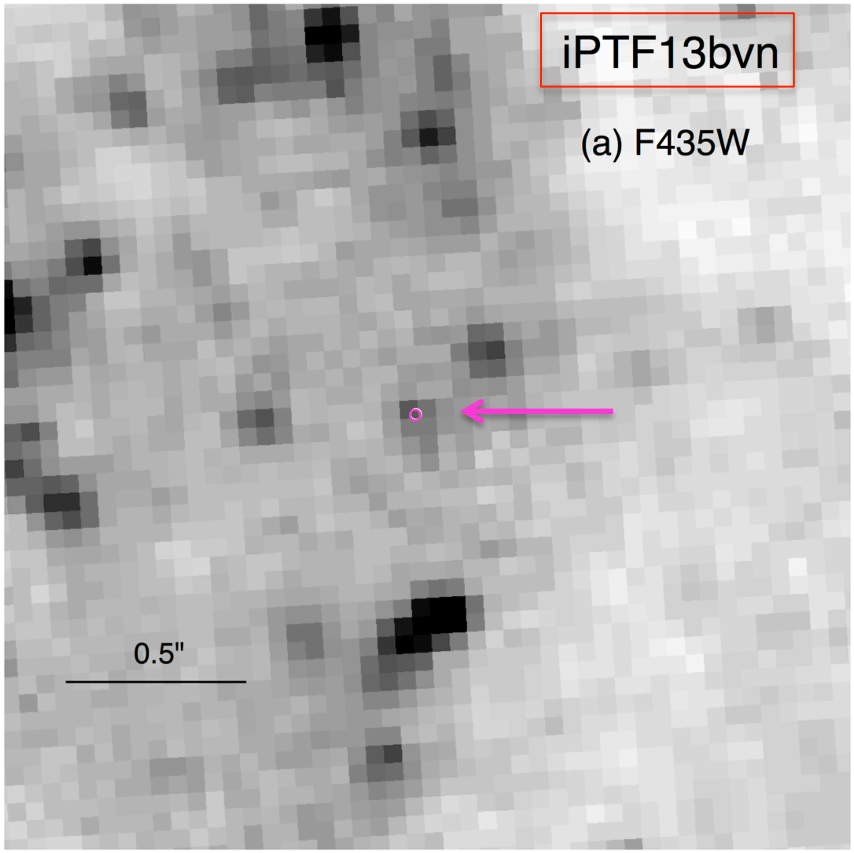
Model mass-transfer binary system



Bersten et al. (2012); Benvenuto et al. (2013)

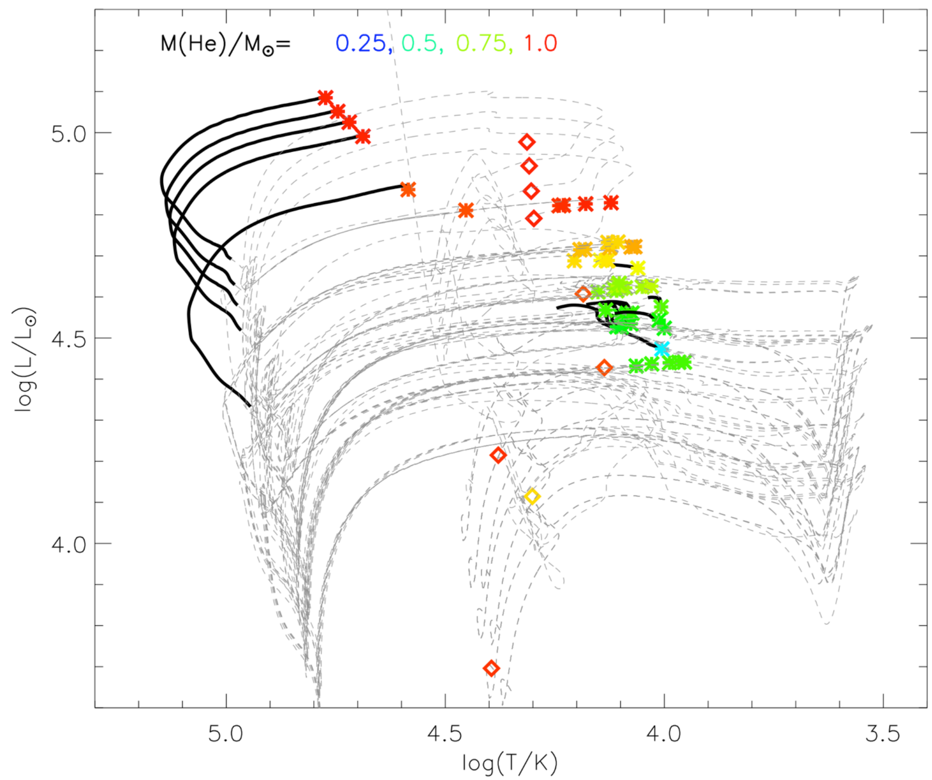
Confirmation of a Type Ib Progenitor !

Eldridge & Maund (2016); Folatelli, SVD, et al. (2016)



Cao et al. (2013): HST/ACS 2005
A Wolf-Rayet star??
(also Groh et al. 2013)

Host: NGC 5806 (22.5 Mpc)

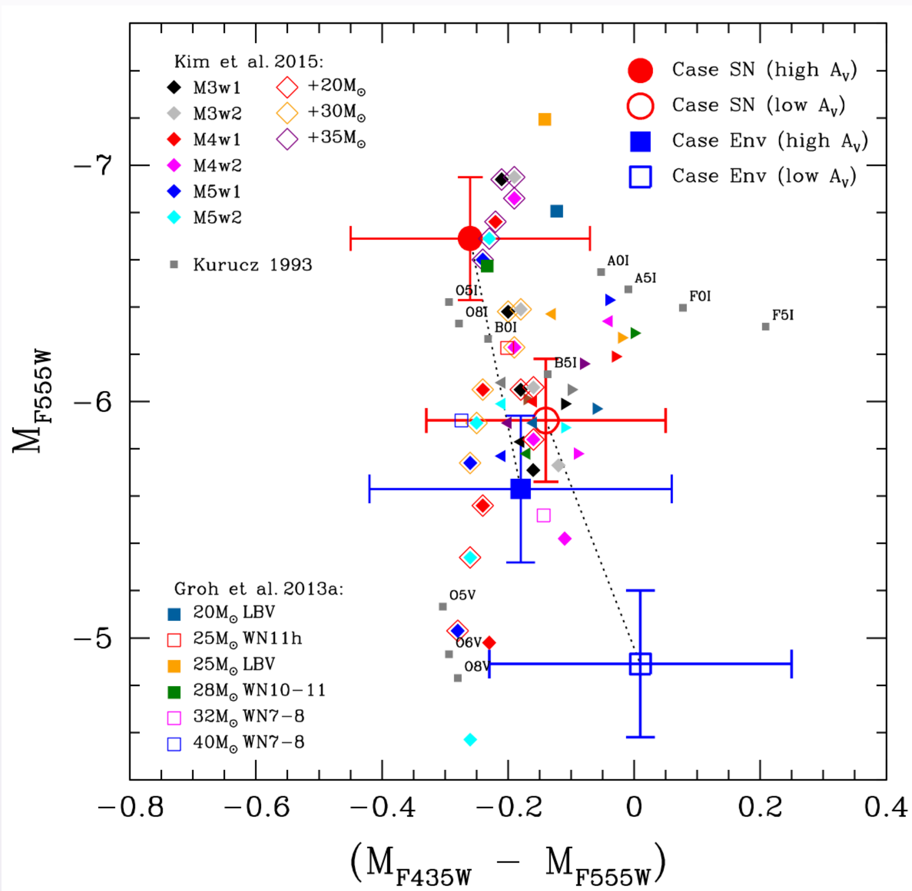


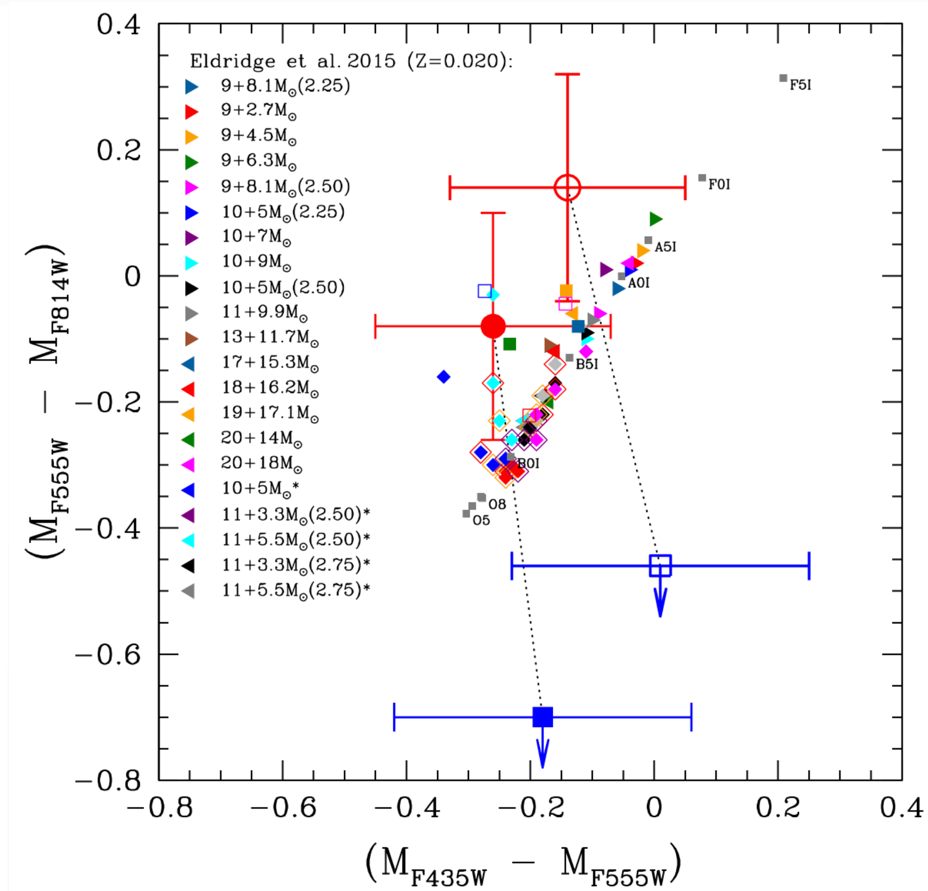
Range of 10-20 M$_\odot$ binary models

Eldridge et al. (2015)
(also Bersten et al. 2014, Fremling et al. 2014)

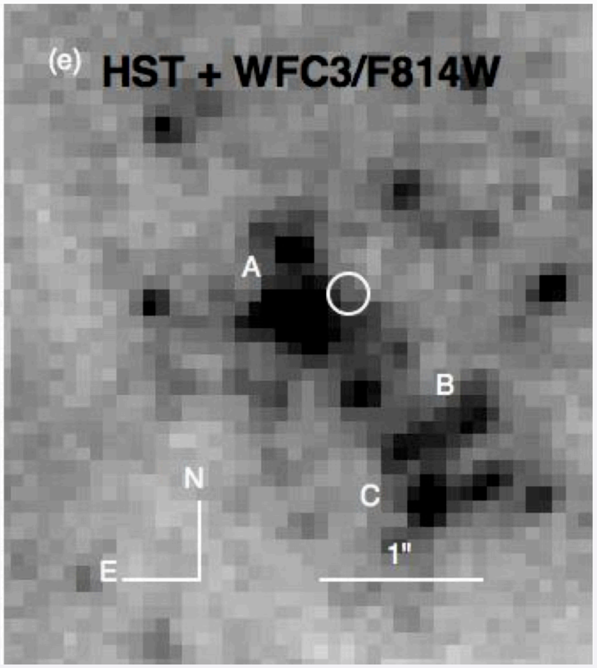
SN Ib iPTF13bvn

Folatelli, SVD, et al. (2016)





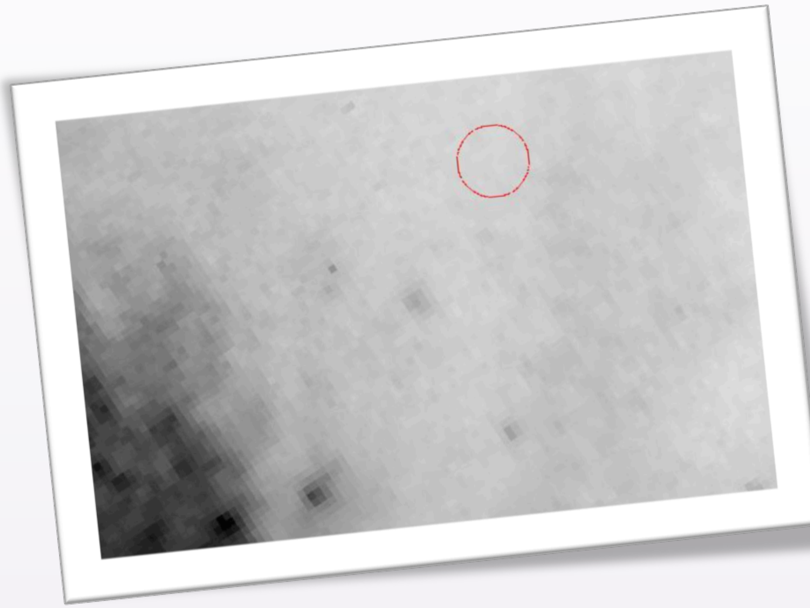
Type Ic SN environments complicate progenitor detection



SN Ic 2013dk
in the Antennae
(Elias-Rosa et al. 2013)

E(B-V) ≈ 0.49 mag

Generally,
are crowded
and/or dusty
E[B – V] ≥ 0.4 mag;
(Drout et al. 2011)



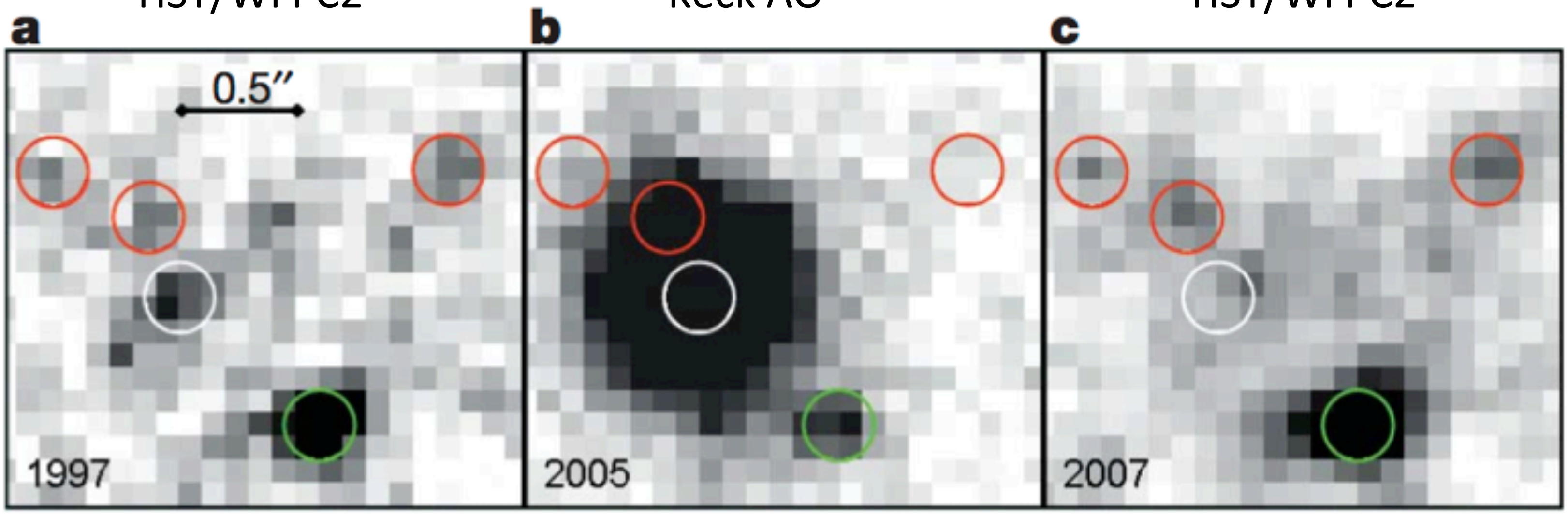
SN Ic 2003jg
in NGC 2997
HST ACS/HRC
(Eldridge et al. 2013)

E(B-V) ≈ 1.32 mag

SN IIn 2005gl: A LBV progenitor?

Very massive (>50 $M_{\odot}$) progenitor in luminous blue variable (LBV) phase

HST/WFPC2 | Keck AO | HST/WFPC2



BEFORE (F547M) | DURING (K-band) | AFTER (F547M)

$M_V \approx -10.3$ mag

Host: NGC 266 (66 Mpc)
A single WFPC2/WF pixel is ~32 pc

Gal-Yam et al. (2007); Gal-Yam & Leonard (2009)

DIRECT detections TO DATE

SN 1961V ? (“V”? IIn??)	SN 2004A (II-P)	SN 2008ax (IIb)	SN 2009md (II-P)	SN 2013df (IIb)
SN 1978K (IIn)	SN 2004et (II-P)	SN 2008bk (II-P)	SN 2010mc (IIn)	SN 2013ej (II-P)
SN 1987A (II-P pec)	SN 2005cs (II-P)	SN 2008cn (II-P)	SN 2011dh (IIb)	iPTF13bvn (Ib)
SN 1993J (IIb)	SN 2005gl (IIn)	SN 2009hd (II-L?)	SN 2011ht (IIn?)	ASASSN-14ha (II-P)
SN 1997bs (IIn?)	SN 2006jc (Ibn)	SN 2009ib (II-P)	SN 2012A (II-P)	SNHunt 275 (IIn?)
SN 1999ev (II-P?)	SN 2006my (II-P)	SN 2009ip (IIn?)	SN 2012aw (II-P)	SN 2016bkv (IIn?)
SN 2003gd (II-P)	SN 2006ov (II-P)	SN 2009kr (II-L?)	SN 2012ec (II-P)	

A few from the ground, but most identified with HST

DIRECT detections TO DATE

SN 1961V ? (“V”? IIn??)	SN 2004A (II-P)	SN 2008ax (IIb)	~~SN 2009md~~ (II-P)	SN 2013df (IIb)
SN 1978K (IIn)	SN 2004et (II-P)	SN 2008bk (II-P)	SN 2010mc (IIn)	SN 2013ej (II-P)
SN 1987A (II-P pec)	SN 2005cs (II-P)	SN 2008cn* (II-P)	SN 2011dh (IIb)	iPTF13bvn (Ib)
SN 1993J (IIb)	SN 2005gl (IIn)	SN 2009hd (II-L?)	SN 2011ht (IIn?)	ASASSN-14ha (II-P)
SN 1997bs (IIn?)	SN 2006jc (Ibn)	SN 2009ib (II-P)	SN 2012A (II-P)	SNHunt 275 (IIn?)
~~SN 1999ev~~ (II-P?)	SN 2006my (II-P)	SN 2009ip (IIn?)	SN 2012aw (II-P)	SN 2016bkv (IIn?)
SN 2003gd (II-P)	~~SN 2006ov~~ (II-P)	~~SN 2009kr~~ (II-L?)	SN 2012ec (II-P)	

Leonard (in prep.); Maund et al. (2014a, 2015).

*a red, not yellow, supergiant (Maund et al. 2015).

And, a number of upper limits

SN 1994I (Ic)	SN 2000ds (Ib)	SN 2003ie (II-P pec?)	SN 2004gn (Ic)	SN 2009H (II-P)	SN 2010jl (IIn)
SN 1999an (II-P)	SN 2000ew (Ic)	SN 2003jg (Ic)	SN 2004gt (Ic)	SN 2009N (II-P)	SN 2011am (Ib)
SN 1999br (II-P)	SN 2001B (Ib)	SN 2004am (II-P)	SN 2005V (Ib/c)	SN 2009jf (Ib)	SN 2011hp (Ic)
SN 1999em (II-P)	SN 2001du (II-P)	SN 2004cc (Ic)	SN 2006bc (II-P)	SN 2010O (Ib)	SN 2013dk (Ic)
SN 1999ga (II-L)	SN 2002ap (Ic-bl)	SN 2004dg (II-P)	SN 2007aa (II-P)	SN 2010P (Ib)	SN 2016adj (Ic??)
SN 1999gi (II-P)	SN 2002hh (II-P)	SN 2004dj (II-P)	SN 2007gr (Ic)	SN 2010br (Ib/c)	

(e.g., Smartt et al. 2009; Eldridge et al. 2013; Elias-Rosa et al. 2013; Kankare et al. 2014; Smartt 2014)

Look for the binary companion

Kochanek et al. (2009); Yoon et al. (2012); Eldridge et al. (2013)

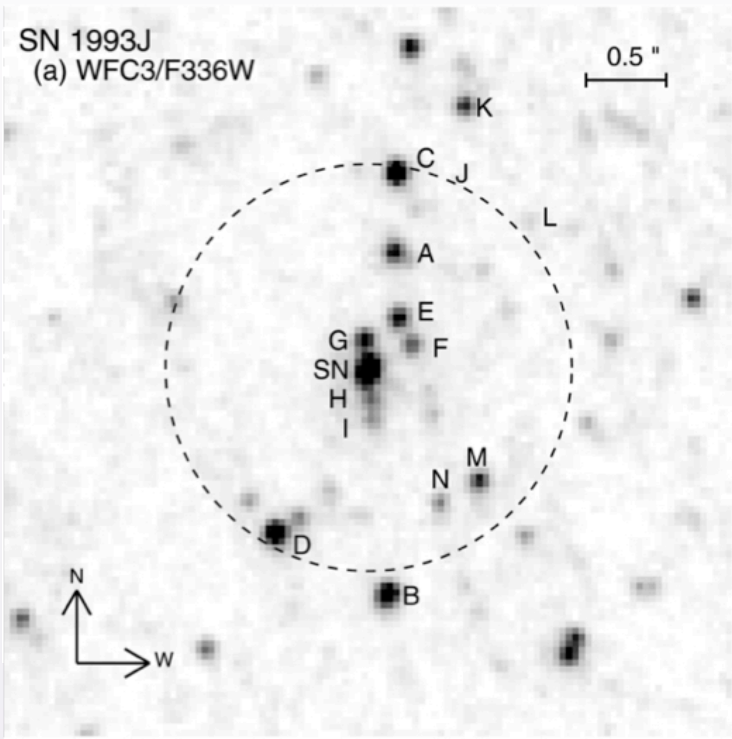
- Supernova must be old enough that it has faded from detectability, especially in the UV
- It must have been clearly detected in previous high spatial resolution imaging (with HST)
- It must have experienced low reddening
- It should have occurred in an uncrowded field
- Nearby host galaxy with low inclination

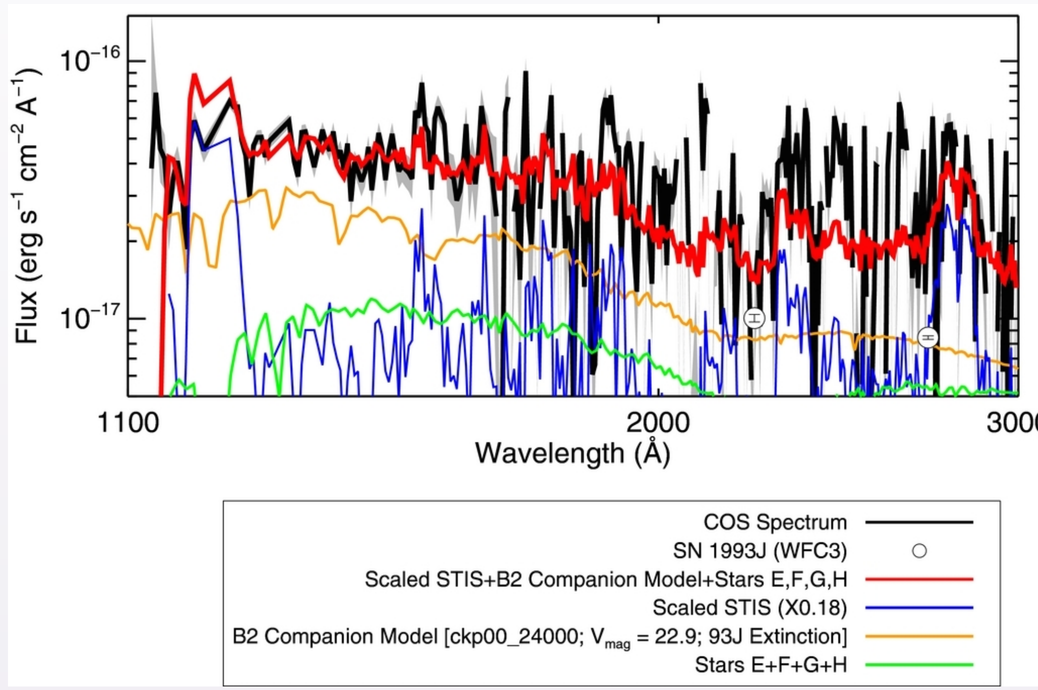
This is a short list

Companion to SN 1993J progenitor?

(Cas A echo spectra resemble SN 1993J)

Host: M81 (3.4 Mpc)

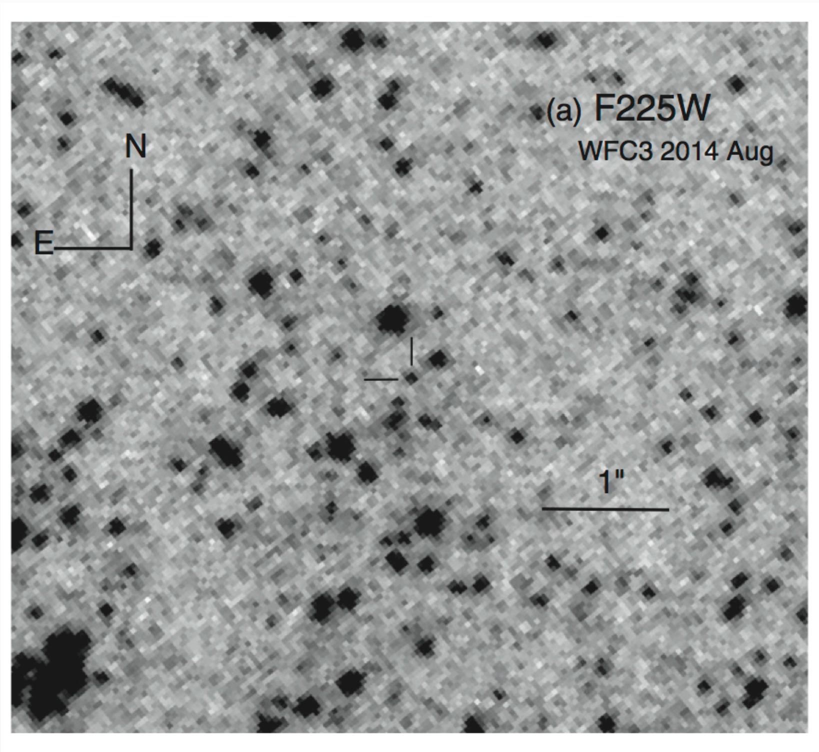




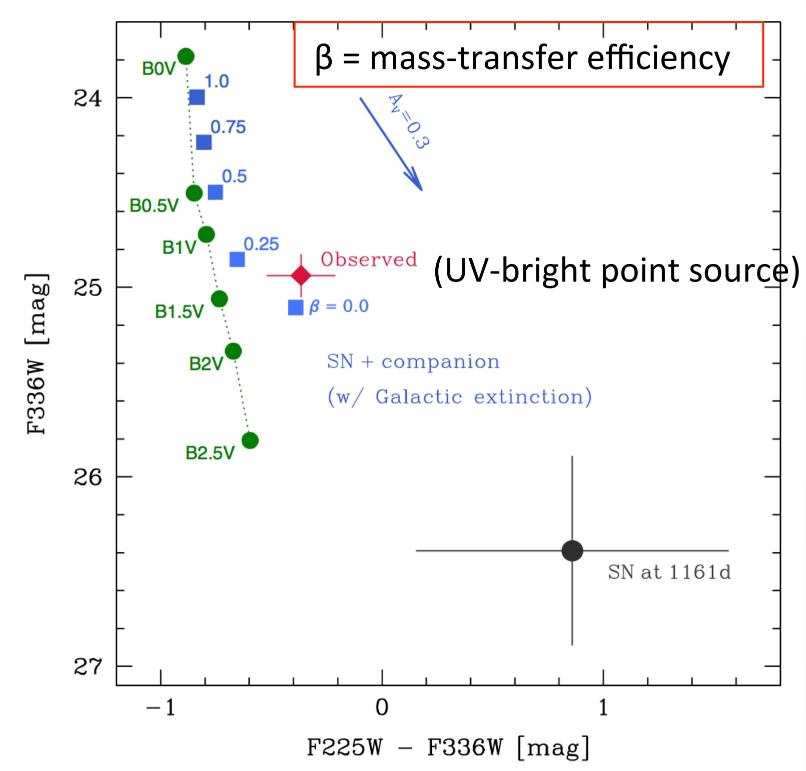
Fox et al. (2014): WFC3 and COS observations from 2012

Companion of SN 2011dh progenitor?

Host: M51 (8.58 Mpc)



Folatelli et al. (2014): WFC3 from 2014



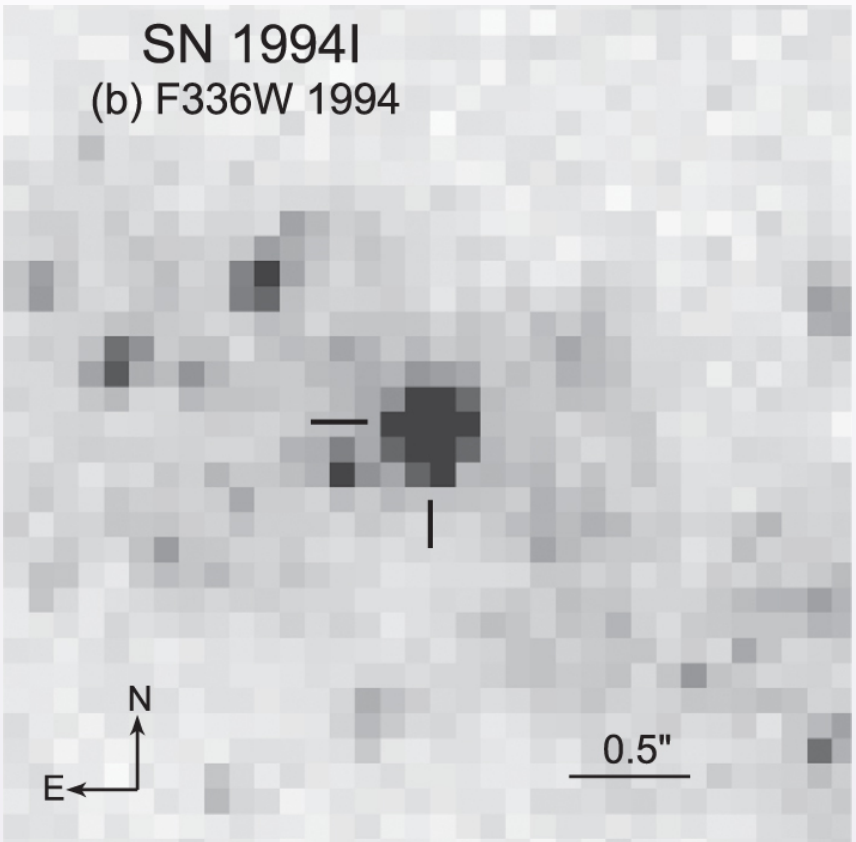
(UV-bright point source)

But, Maund et al. (2015) say, "not so fast…"

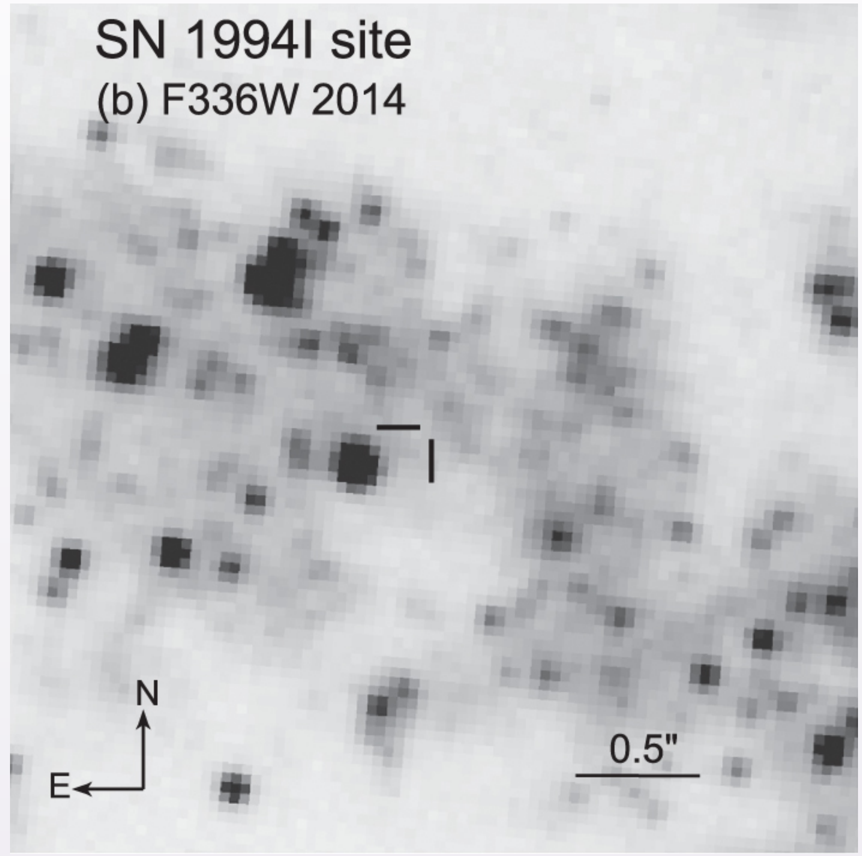
Companion to SN Ic 1994I progenitor?

SVD, de Mink & Zapartas (2016)

Host: M51 (8.58 Mpc)



WFPC2

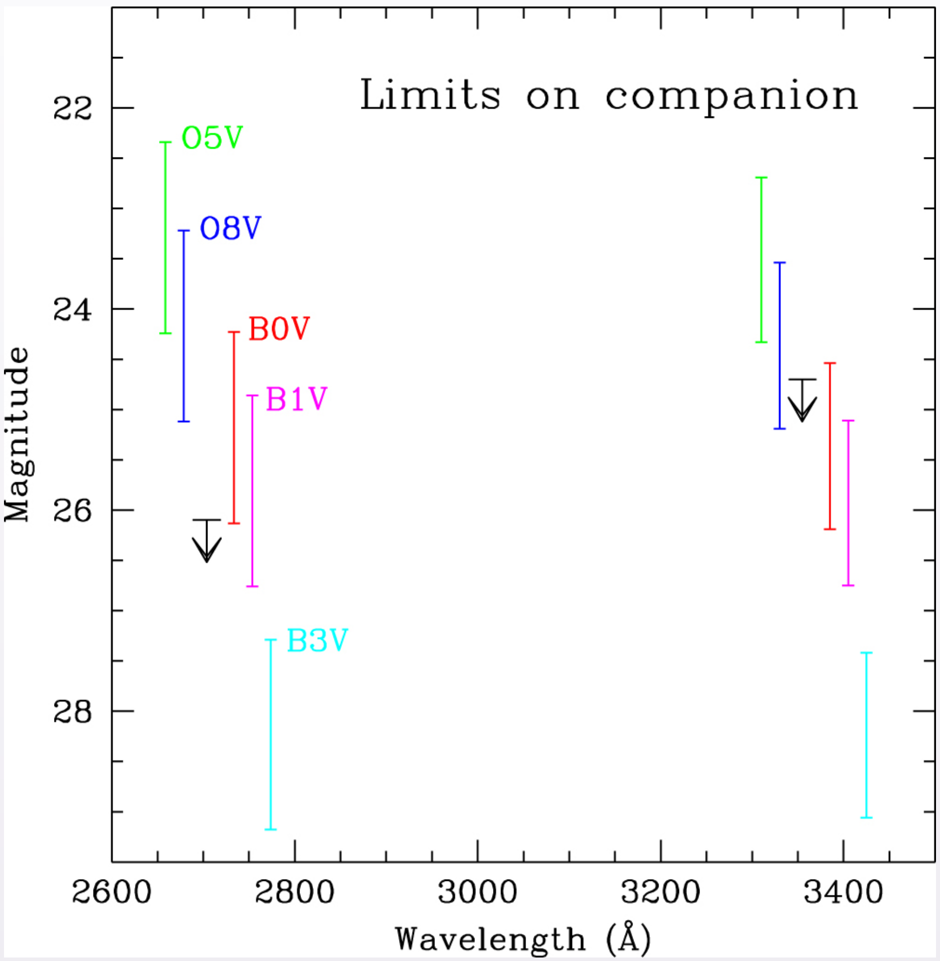


WFC3

(astrometry rms=13.9 mas)

Companion to SN Ic 1994I progenitor?

SVD, de Mink & Zapartas (2016)



We expect the companion to be hot
And equivalent to a main sequence star

M51 distance: 6.7—8.9 Mpc
E(B-V) = 0.25—0.45 mag

A star hotter than B2V
$T_{eff} \gtrsim 23000$ K
$L_{bol} \gtrsim 10^{3.6}\ L_\odot$
should have been detected

$M_{companion} \lesssim 10\ M_\odot$

Type Ic SN 1994I in Messier 51

SVD, de Mink & Zapartas (2016)

<u>Binary Population Synthesis</u>

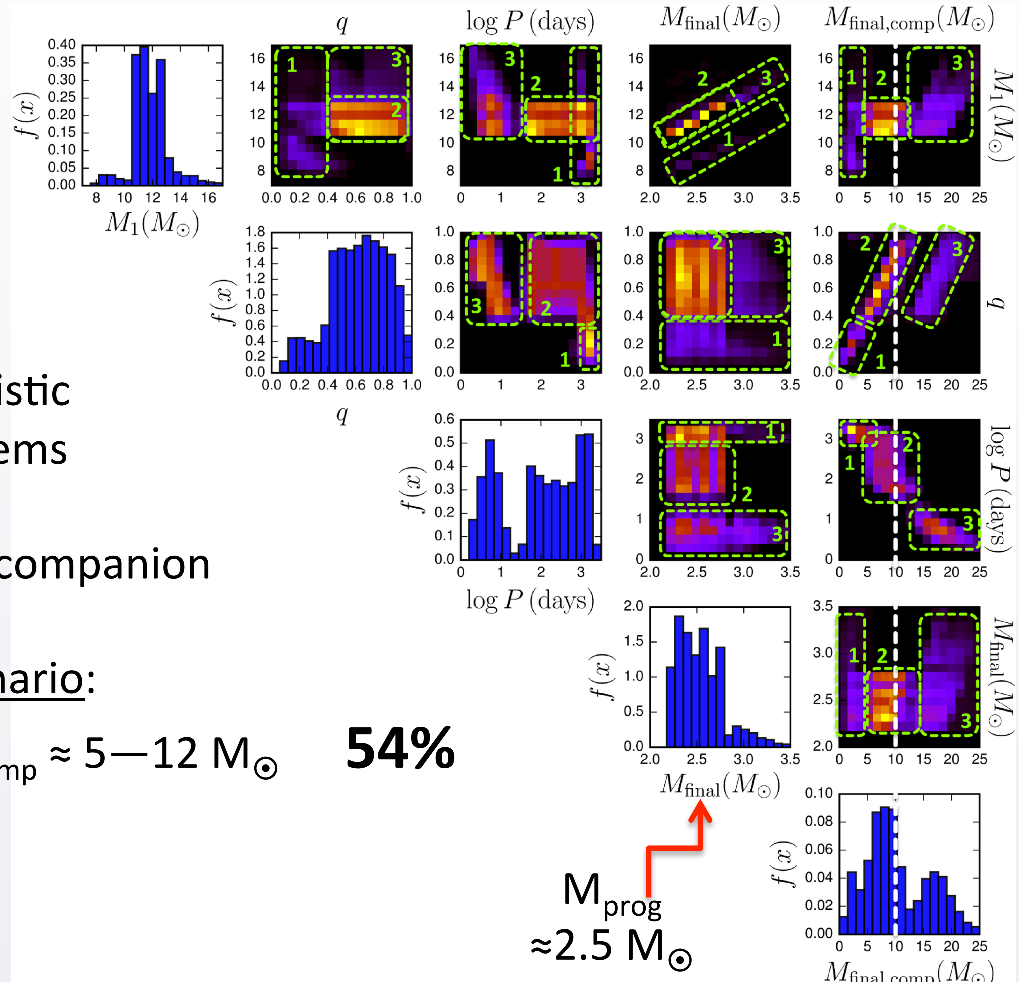
The code does not allow us to distinguish between Type Ib and Type Ic supernovae

Nonetheless, we produced realistic "SN 1994I-like" progenitor systems

99% of systems have a MS-like companion

<u>The most likely companion scenario</u>:

p ≈ 30-1000 days, $q \gtrsim 0.4$, $M_{comp} \approx 5$—$12\ M_{\odot}$ **54%**



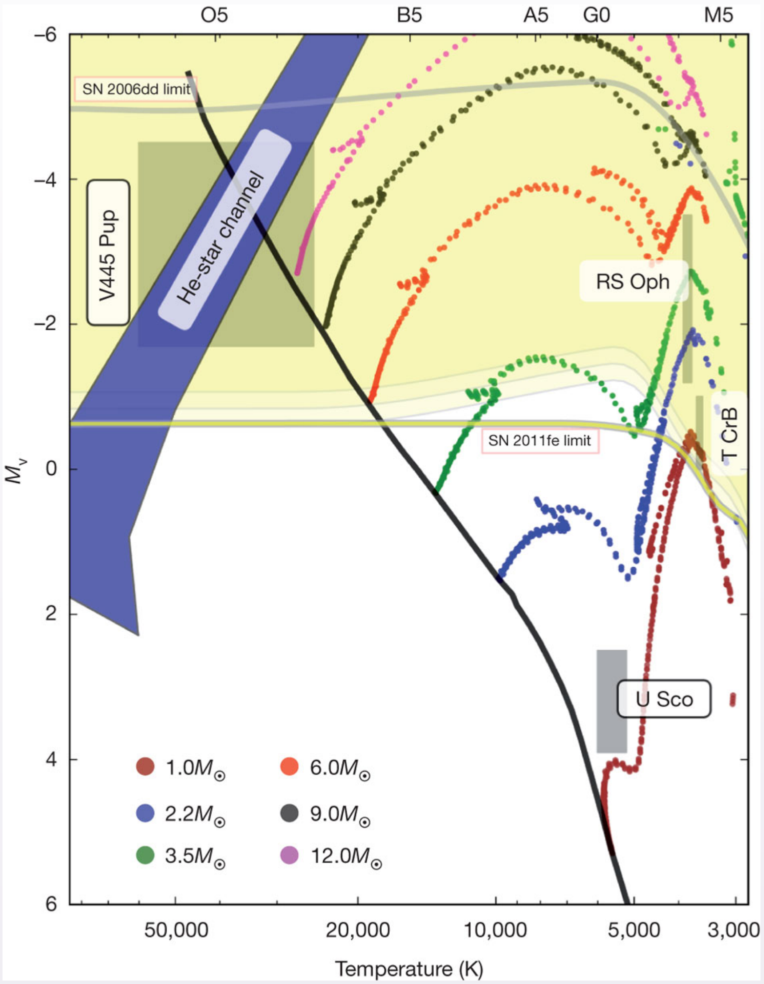
$M_{prog} \approx 2.5\ M_{\odot}$

$M_{comp} \lesssim 10\ M_{\odot}$

Searching for binary companions of stripped-envelope SN progenitors

- HST Cycle 23 program – PI: O. Fox
- Deep WFC3 imaging in F275W and F336W
  - SN Ic-bl 2002ap in M74 no detection
  - SN Ib/c 2010br in NGC 4051 no detection
  - SN IIb 2001ig in NGC 7424 **detection**

The best SN Ia progenitor constraint



SN 2011fe in M101

Deep **non-detection** in pre-SN HST images

Li et al. (2011)
(also Graur et al. 2014)

Eliminated RG companions
and
any star with M $\gtrsim$ 3.5 $M_\odot$

Rules out RS Oph-like, T CrB-like, and V445 Pup-like systems

Summary

Kurt Weiler
1943-2016

- SNe II-P from red supergiants
- SNe II-L from (more massive) red supergiants?
- Several SNe IIb from yellow supergiants (binaries?)
- He star progenitor for SN Ib iPTF13bvn ?
- No detection yet of a SN Ic progenitor
- SNe IIn from LBVs ?
- Hot companions detected for several SNe IIb?
- No detected companions for SNe Ic
- No companions detected for SN Ia 2011fe