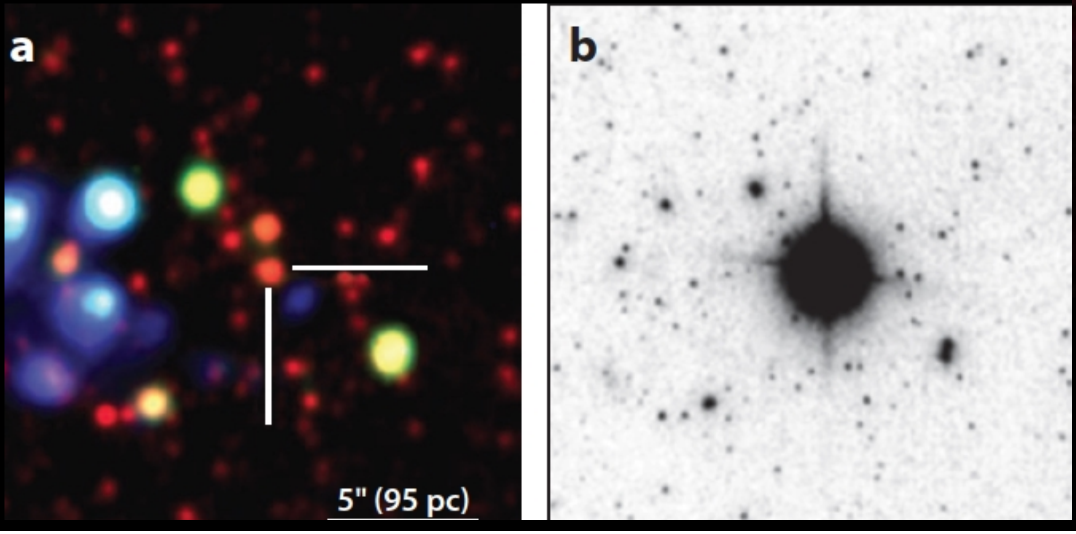
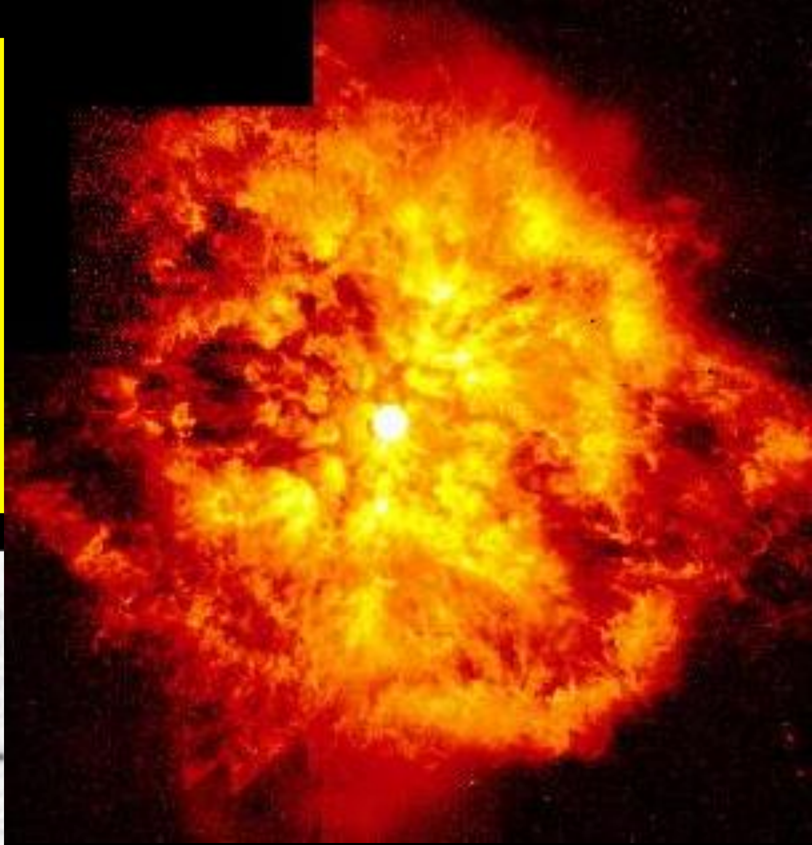
Massive Star Pre-Collapse Evolution

A Survey of Core-Collapse SNe




WR124: A stellar fireball (HST WFPC2, NASA)
Credit: Grosdidier (Uni. Montreal, CA)

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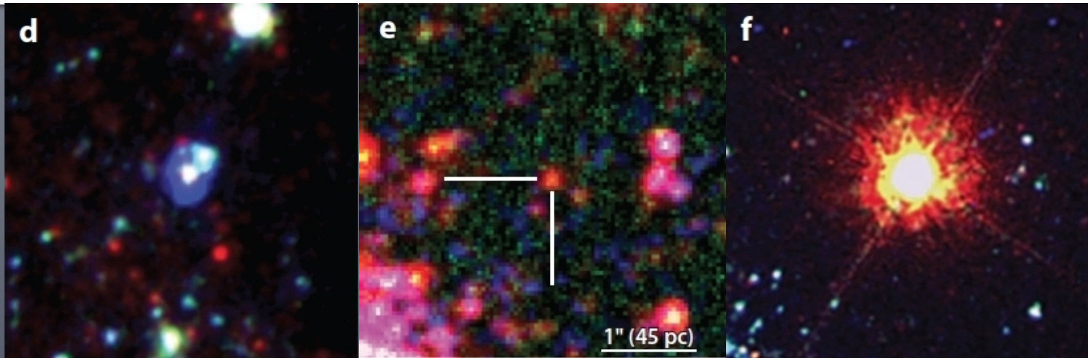


Outline

- The Latest SN statistics
- Stellar Evolutionary Scenarios vs. Initial Masses
- Progenitors of SN II
- Progenitors of Ib/c
- SN Impostors
- Conclusions

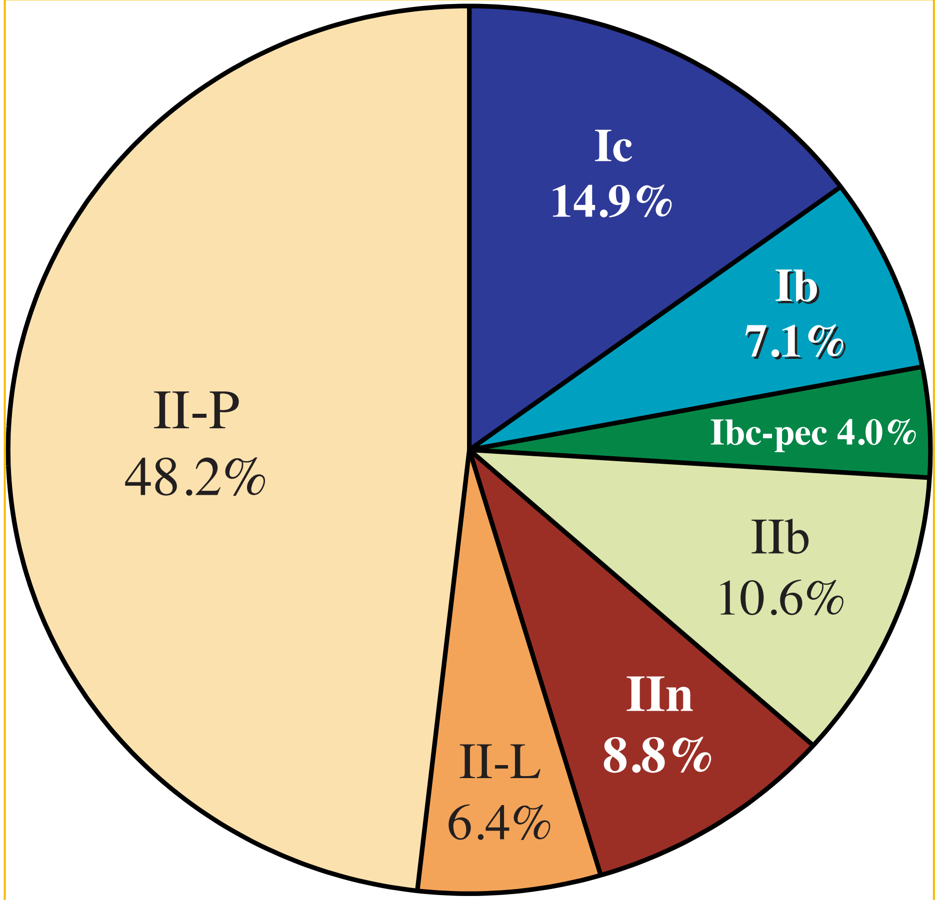
SN Statistics

Ref: Smith et al. (2011), see also Smartt et al. (2009)

- Hydrogen rich SNe:
  II-P, II-L, IIb, IIn, LBV
  ☑Red Supergiant

- Low Hydrogen SNe:
  Strong ^{4}He: Ib
  Weak ^{4}He: Ic
  ☑Wolf-Rayet Stars

- ^{1}H and ^{4}He free SNe:
  Strong ^{28}Si: Ia
  ☑White Dwarf+Giant



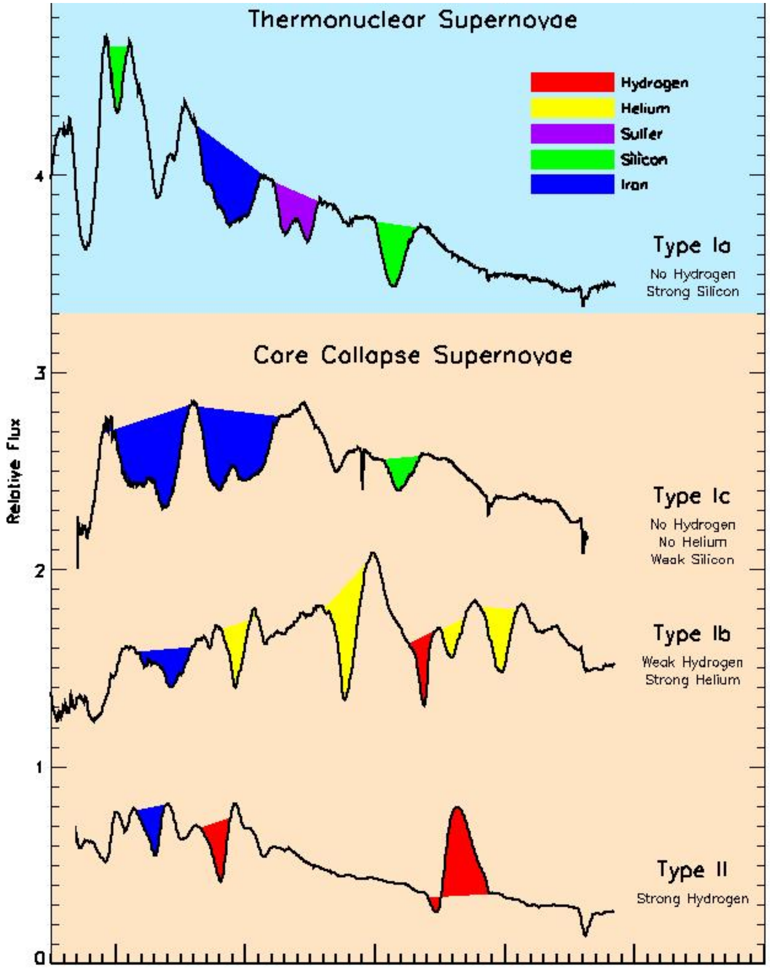
Core-Collapse SN Fractions

Type-Ib/Ic Supernovae

Ref: Smartt (2009, *ARA&A*), Smith et al. (2011)

- Type-Ib: Hydrogen-poor and Helium-rich.
- Progenitor?

- Type-Ic: Hydrogen-Helium deficient, Metal-rich
- Progenitor?



Fate Scenarios For Massive Stars

Ref: Langer (1987, 2012)

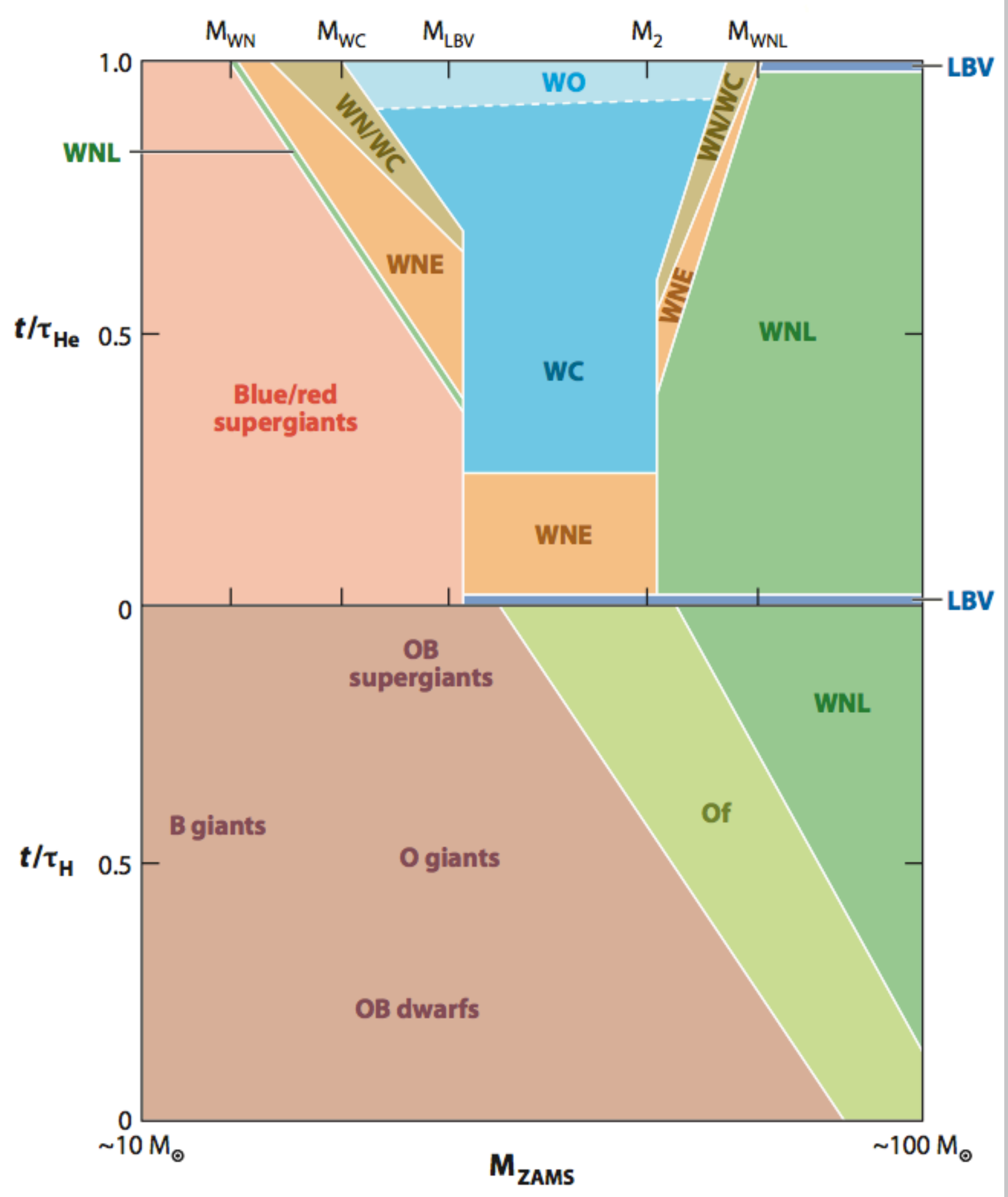
Stars more massive than ~ 25 $M_\odot$ enter the Wolf-Rayet phase.

They explode as Type Ib/c SNe, and probably form BHs. So, no neutrinos are expected from these to be detected.

Q: So, what is the favorable mass range for SNe that leave neutrino footprints along with photon signature?

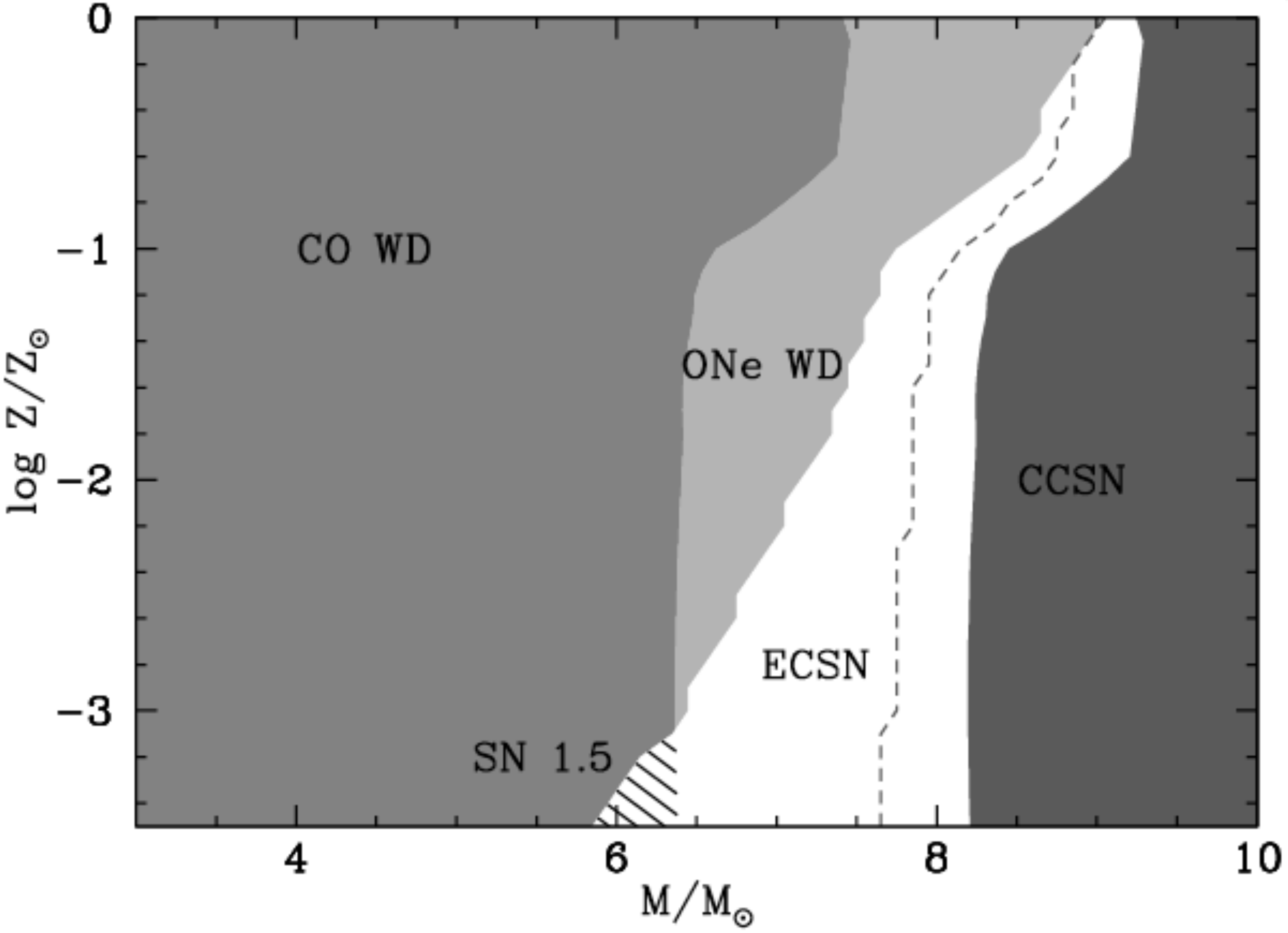
A: Depending on the metallicity of the host galaxy, it could be between 8 $M_\odot$ to 25 $M_\odot$.

Ref: Smartt (2009), Smith et al. (2011), Langer (2012).



Fates of Intermediate-Mass Stars

Ref: Poelarends (2007, PhD Dissertation)



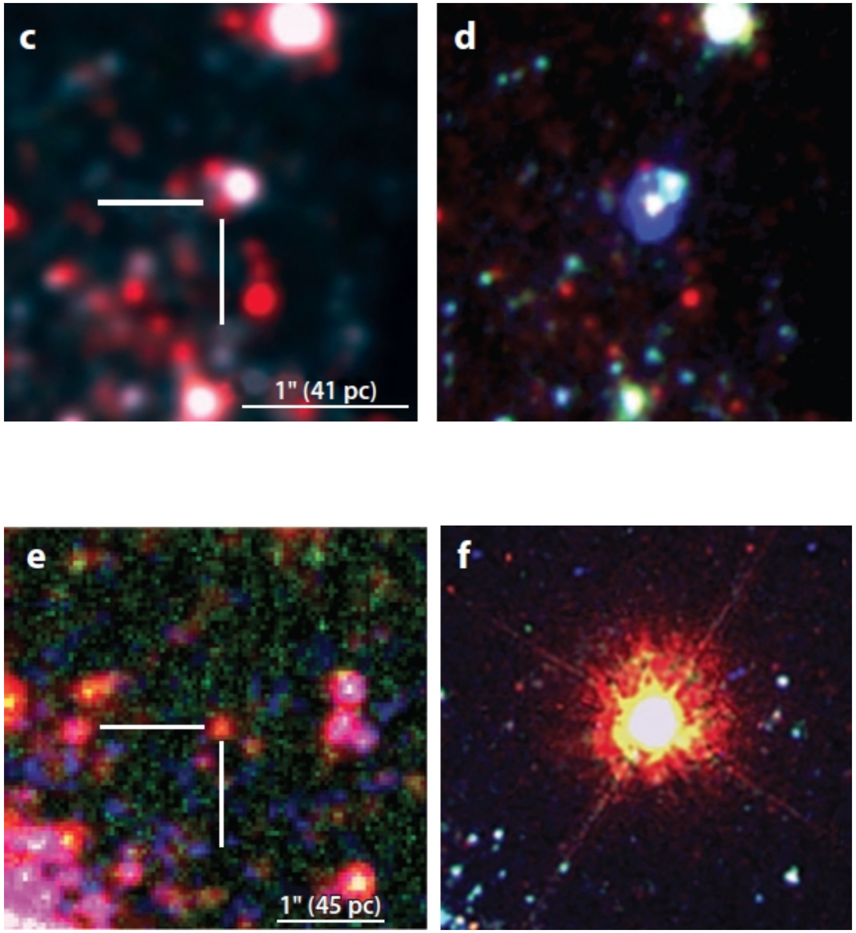
THE GOOD THE BAD AND THE UGLY

The Good: Type-II

Ref: Smartt(2009, *ARA&A*)

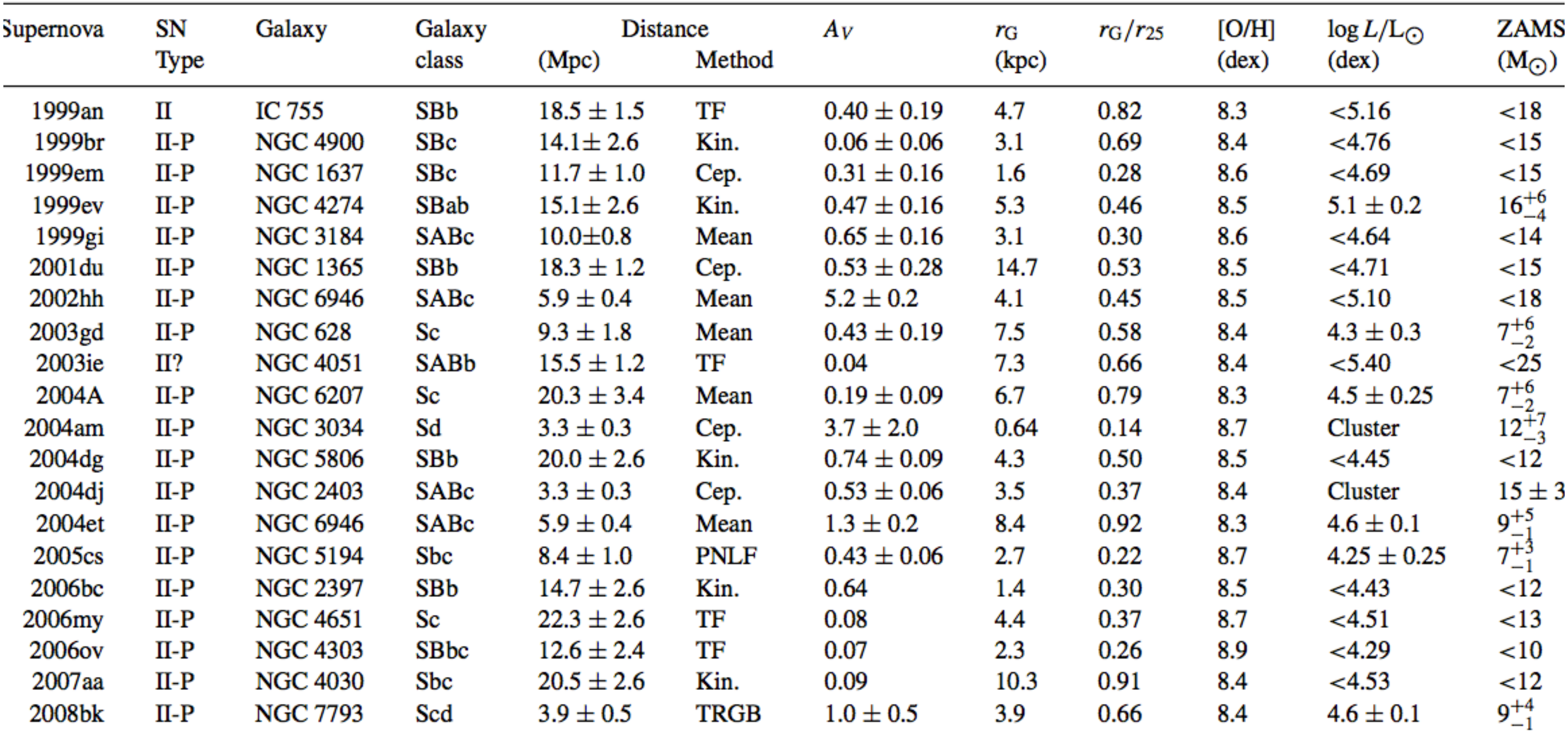
- They emerge from Red Supergiant Stars.
- Hydrogen-rich ejceta.

- INSIST THAT THESE SN EVENTS GENERATE NEUTRINO BURSTS ALONG WITH PHOTONS…
  It is of utmost interest if the location of the neutrino burst would coincide with SN flux sources.
- Binaries play no important role here.



Type IIp Supernovae Rosetta Stone

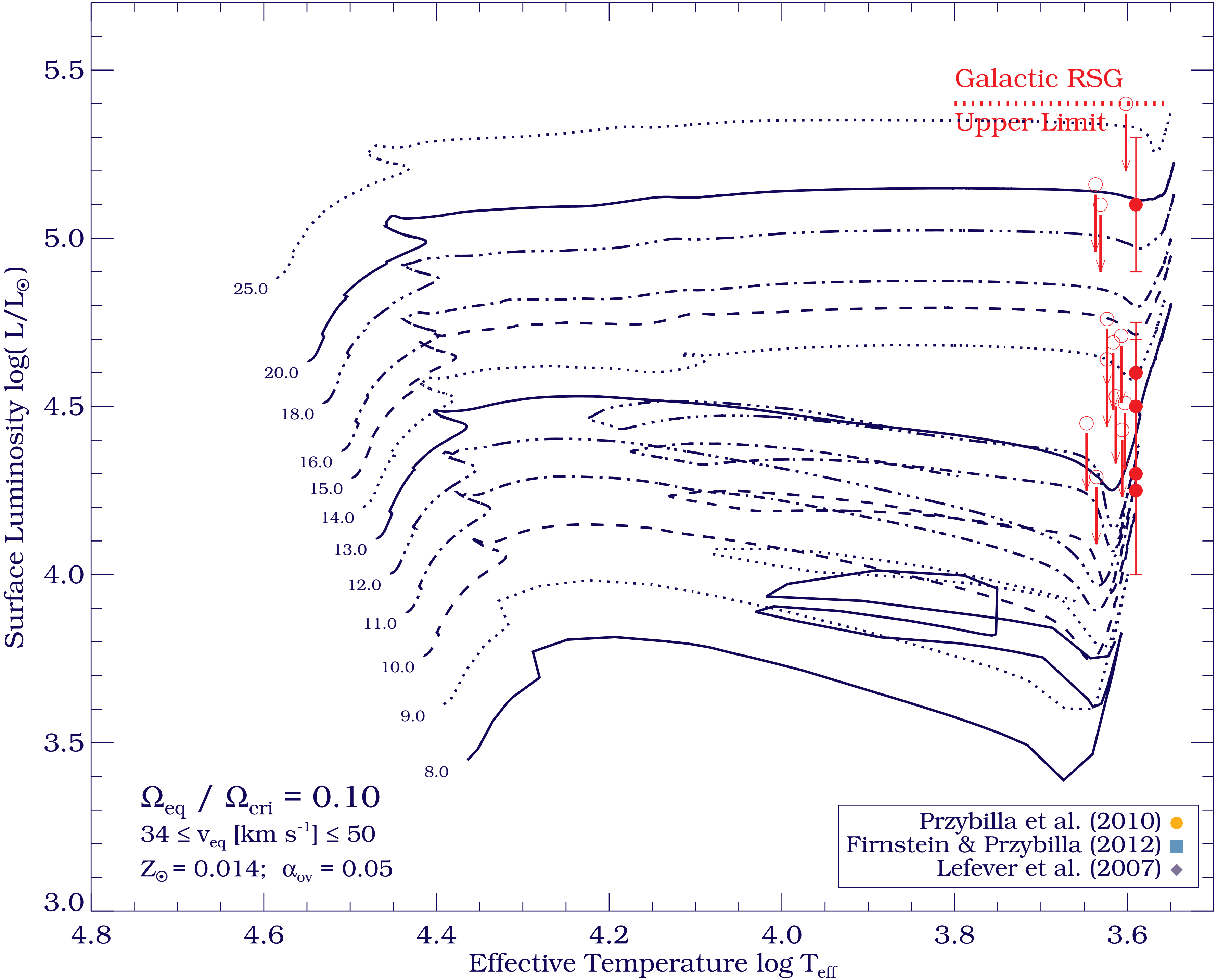
Ref: Smartt et al. (2009, MNRAS)



Supernova	SN Type	Galaxy	Galaxy class	Distance (Mpc)	Distance Method	A_V	r_G (kpc)	r_G/r_{25}	[O/H] (dex)	$\log L/L_\odot$ (dex)	ZAMS ($M_\odot$)
1999an	II	IC 755	SBb	18.5 ± 1.5	TF	0.40 ± 0.19	4.7	0.82	8.3	<5.16	<18
1999br	II-P	NGC 4900	SBc	14.1± 2.6	Kin.	0.06 ± 0.06	3.1	0.69	8.4	<4.76	<15
1999em	II-P	NGC 1637	SBc	11.7 ± 1.0	Cep.	0.31 ± 0.16	1.6	0.28	8.6	<4.69	<15
1999ev	II-P	NGC 4274	SBab	15.1± 2.6	Kin.	0.47 ± 0.16	5.3	0.46	8.5	5.1 ± 0.2	16^{+6}_{-4}
1999gi	II-P	NGC 3184	SABc	10.0±0.8	Mean	0.65 ± 0.16	3.1	0.30	8.6	<4.64	<14
2001du	II-P	NGC 1365	SBb	18.3 ± 1.2	Cep.	0.53 ± 0.28	14.7	0.53	8.5	<4.71	<15
2002hh	II-P	NGC 6946	SABc	5.9 ± 0.4	Mean	5.2 ± 0.2	4.1	0.45	8.5	<5.10	<18
2003gd	II-P	NGC 628	Sc	9.3 ± 1.8	Mean	0.43 ± 0.19	7.5	0.58	8.4	4.3 ± 0.3	7^{+6}_{-2}
2003ie	II?	NGC 4051	SABb	15.5 ± 1.2	TF	0.04	7.3	0.66	8.4	<5.40	<25
2004A	II-P	NGC 6207	Sc	20.3 ± 3.4	Mean	0.19 ± 0.09	6.7	0.79	8.3	4.5 ± 0.25	7^{+6}_{-2}
2004am	II-P	NGC 3034	Sd	3.3 ± 0.3	Cep.	3.7 ± 2.0	0.64	0.14	8.7	Cluster	12^{+7}_{-3}
2004dg	II-P	NGC 5806	SBb	20.0 ± 2.6	Kin.	0.74 ± 0.09	4.3	0.50	8.5	<4.45	<12
2004dj	II-P	NGC 2403	SABc	3.3 ± 0.3	Cep.	0.53 ± 0.06	3.5	0.37	8.4	Cluster	15 ± 3
2004et	II-P	NGC 6946	SABc	5.9 ± 0.4	Mean	1.3 ± 0.2	8.4	0.92	8.3	4.6 ± 0.1	9^{+5}_{-1}
2005cs	II-P	NGC 5194	Sbc	8.4 ± 1.0	PNLF	0.43 ± 0.06	2.7	0.22	8.7	4.25 ± 0.25	7^{+3}_{-1}
2006bc	II-P	NGC 2397	SBb	14.7 ± 2.6	Kin.	0.64	1.4	0.30	8.5	<4.43	<12
2006my	II-P	NGC 4651	Sc	22.3 ± 2.6	TF	0.08	4.4	0.37	8.7	<4.51	<13
2006ov	II-P	NGC 4303	SBbc	12.6 ± 2.4	TF	0.07	2.3	0.26	8.9	<4.29	<10
2007aa	II-P	NGC 4030	Sbc	20.5 ± 2.6	Kin.	0.09	10.3	0.91	8.4	<4.53	<12
2008bk	II-P	NGC 7793	Scd	3.9 ± 0.5	TRGB	1.0 ± 0.5	3.9	0.66	8.4	4.6 ± 0.1	9^{+4}_{-1}

Unambiguous Observation

Stellar Modeling



Galactic RSG
Upper Limit
25.0
20.0
18.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
$\Omega_{eq} / \Omega_{cri} = 0.10$
$34 \leq v_{eq}$ [km s^{-1}] ≤ 50
$Z_{\odot} = 0.014$; $\alpha_{ov} = 0.05$
Przybilla et al. (2010) ●
Firnstein & Przybilla (2012) ■
Lefever et al. (2007) ◆
Surface Luminosity log($L/L_{\odot}$)
5.5
5.0
4.5
4.0
3.5
3.0
Effective Temperature log T_{eff}
4.8
4.6
4.4
4.2
4.0
3.8
3.6

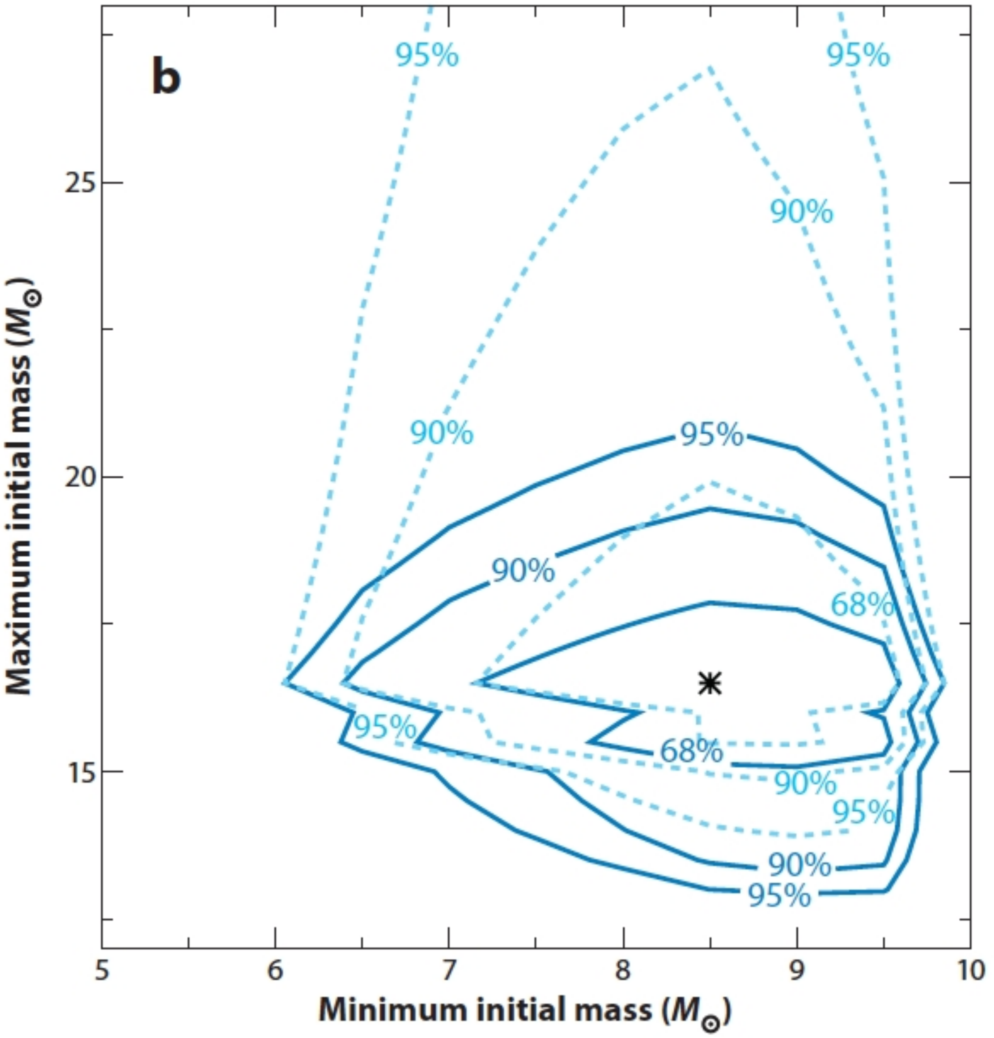
Initial Min/Max Masses

Ref: [1] Smartt (2009), [2] Smartt et al. (2009), [3] Lunardini & Tamborra (2012)

- **Method**: Maximum Likelihood.
- **PDF:** Salpeter (1955) Initial Mass Function: $\Psi_{\mathrm{IMF}} \approx m^{-1.35}$

$$P_i = \int_{m_{\min}}^{m_{i,\mathrm{limit}}} \frac{m^{\Gamma-1}}{(m_{\min}^{\Gamma} - m_{\max}^{\Gamma})} \mathrm{d}m,$$

- **Results:** Min. Initial Mass for SN-lip [1,2]: $M_{\min} = 8.5 \pm 1.5\ M_\odot$. These provide the bulk of *diffuse supernova neutrino background* [3].
- Max. Initial Mass for SN-IIp [1,2]: $M_{\max} = 16.5 \pm 1.0\ M_\odot$.



SN-2005gl (NGC 266, d=66 Mpc)

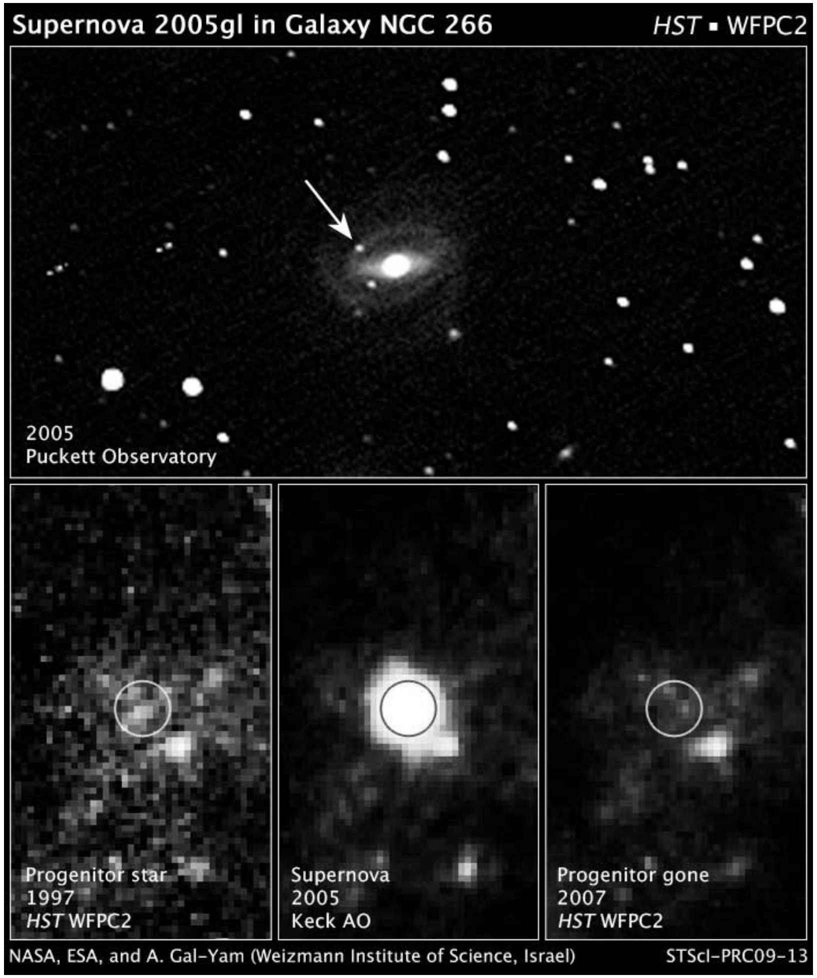
Ref: Gal-Yam & Leonard (2009, Nature)

- The only detection of Type-IIn supernova.
- Progenitor: A Luminous Blue Variable (LBV), with $M > 50\,M_\odot$.

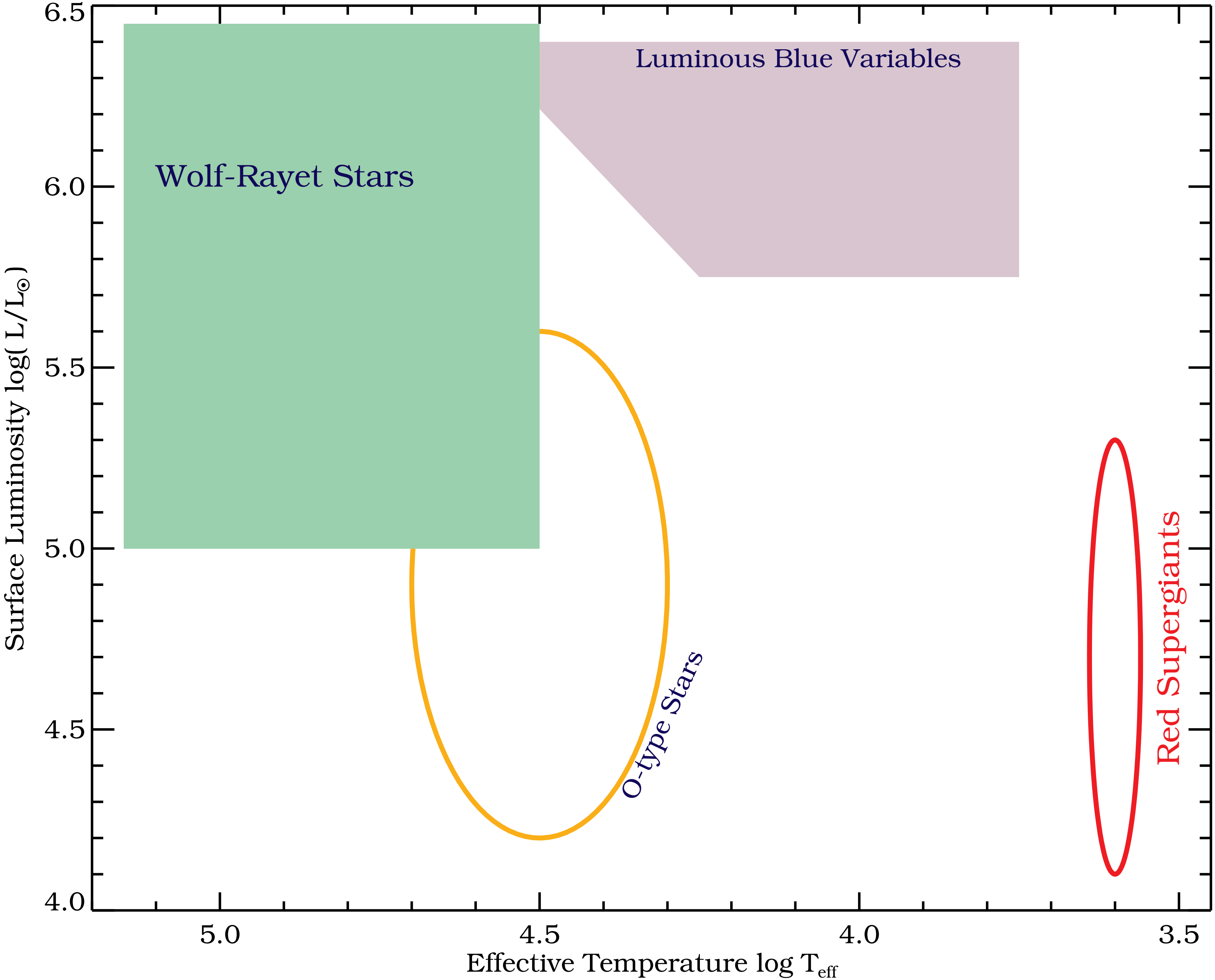
- 9 ± 3% of all detected SN.
- Progenitor mass $\geq 42\,M_\odot$.
- It means nearly 5% of all massive stars explode like this.
- Probably, leaves behind a BH.

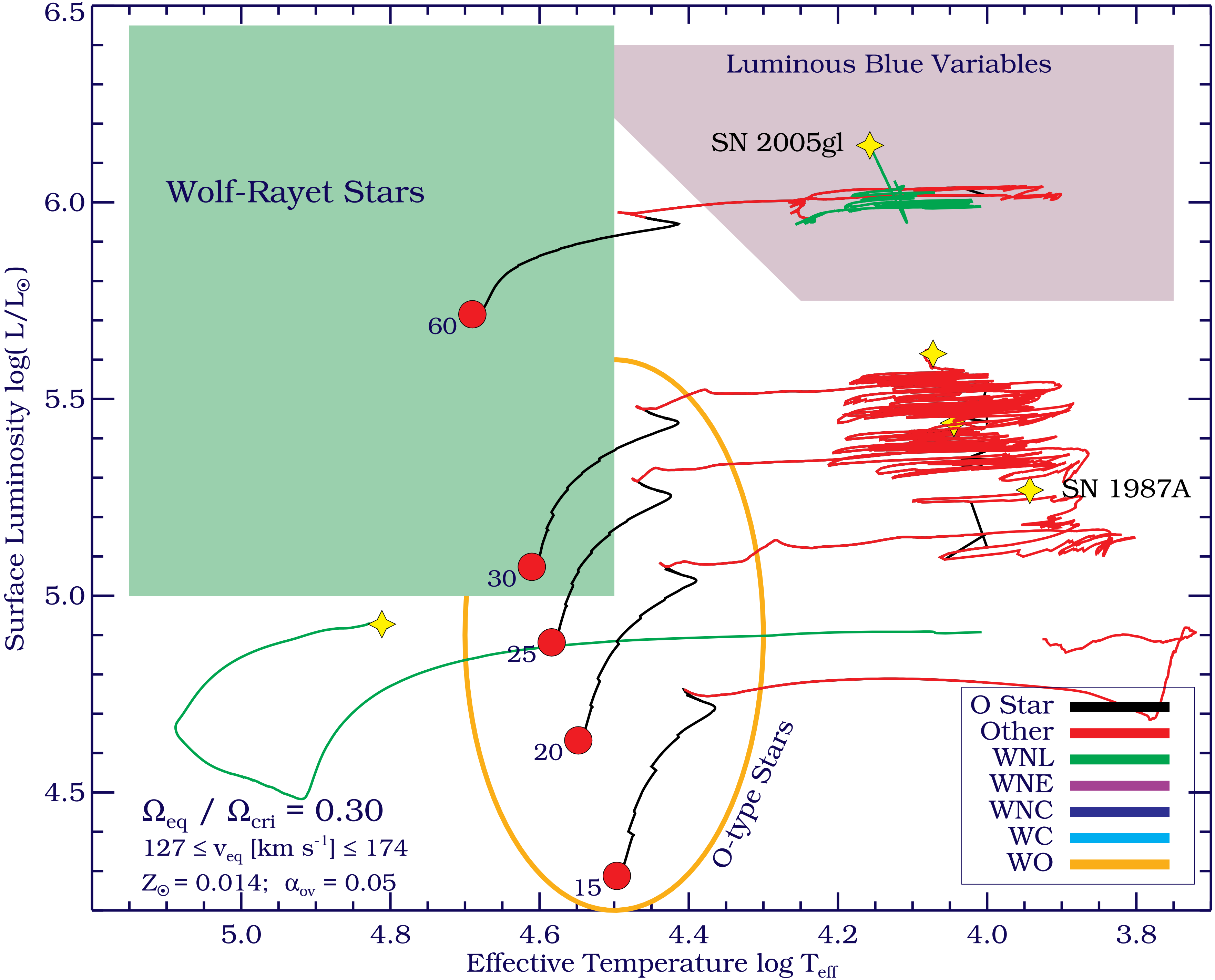
Ref: Smith et al. (2011), Langer (2012)

All our stellar structure and evolution modeling in this work is performed using the MESA code (Paxton et al. 2011)



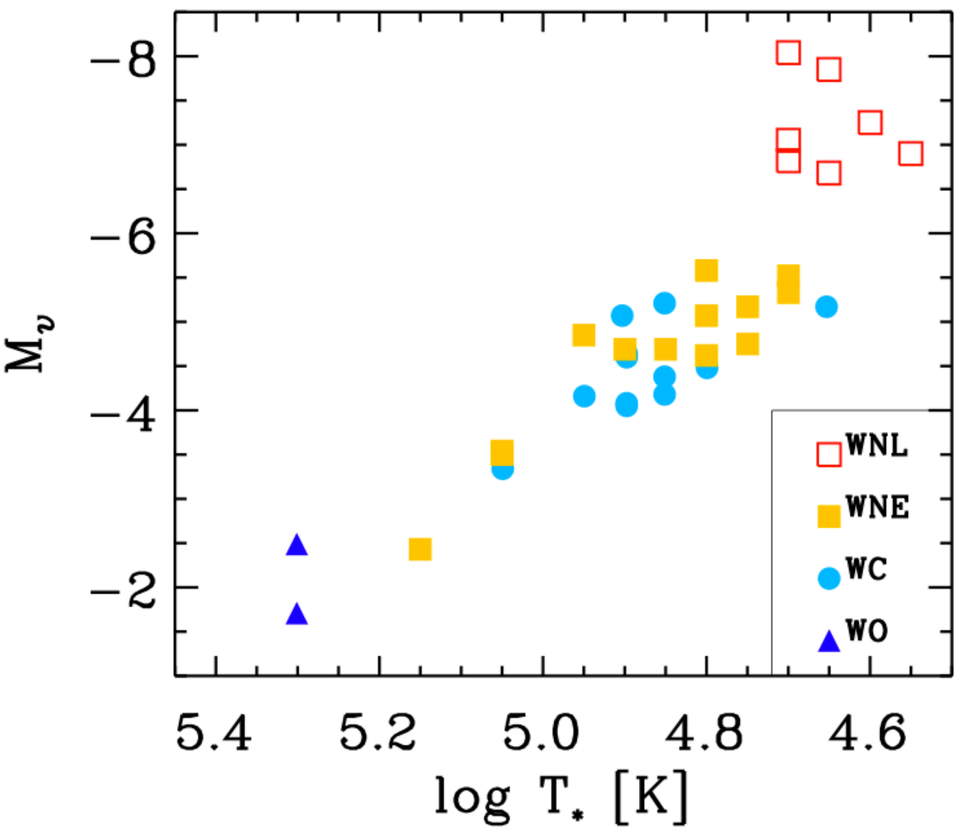
NASA, ESA, and A. Gal-Yam (Weizmann Institute of Science, Israel) STScI-PRC09-13


Luminous Blue Variables
Wolf-Rayet Stars
O-type Stars
Red Supergiants
Surface Luminosity log(L/L$_\odot$)
Effective Temperature log T$_{eff}$
6.5
6.0
5.5
5.0
4.5
4.0
5.0
4.5
4.0
3.5


Luminous Blue Variables
SN 2005gl
Wolf-Rayet Stars
SN 1987A
O-type Stars
60
30
25
20
15
O Star
Other
WNL
WNE
WNC
WC
WO
$\Omega_{eq} / \Omega_{cri} = 0.30$
$127 \leq v_{eq}$ [km s^{-1}] ≤ 174
$Z_{\odot} = 0.014$; $\alpha_{ov} = 0.05$
Surface Luminosity log($L/L_{\odot}$)
6.5
6.0
5.5
5.0
4.5
Effective Temperature log T_{eff}
5.0
4.8
4.6
4.4
4.2
4.0
3.8

The Bad: Faint Supernovae

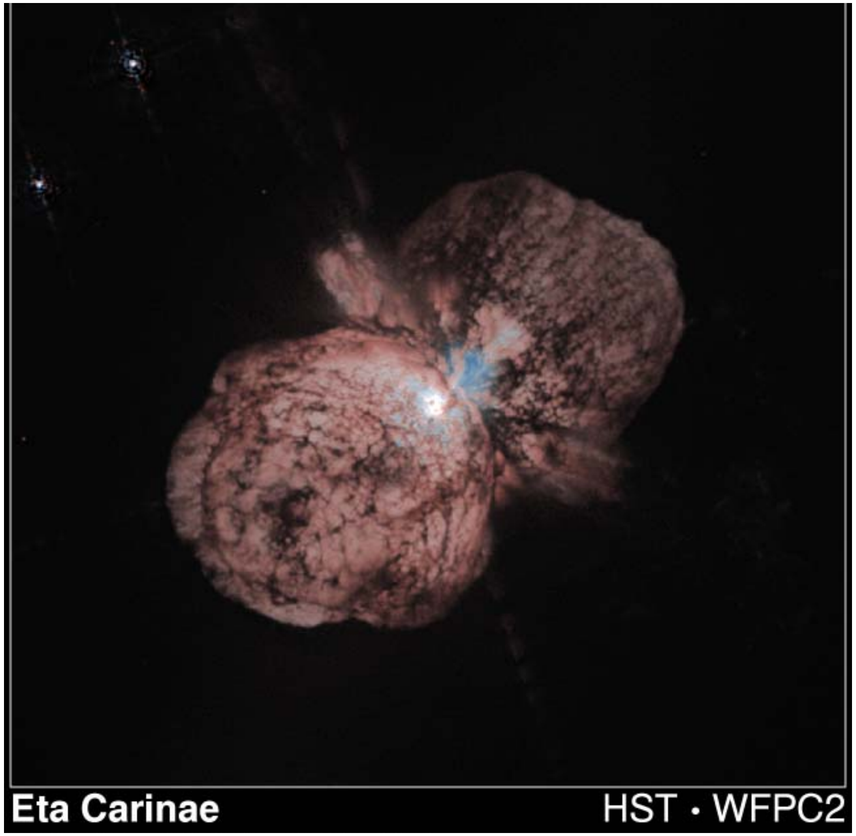
- SN Ib/c are optically faint (Yoon et al. 2012).
- **Hidden to Eyes, Naked to Neutrinos!**
  No progenitor of Type Ib/c SNe has been detected yet.
- Progenitors:
  1. Collapse of very massive stars which form BH,
  2. Wolf-Rayet stars.



Enigmatic Real-Life Examples!

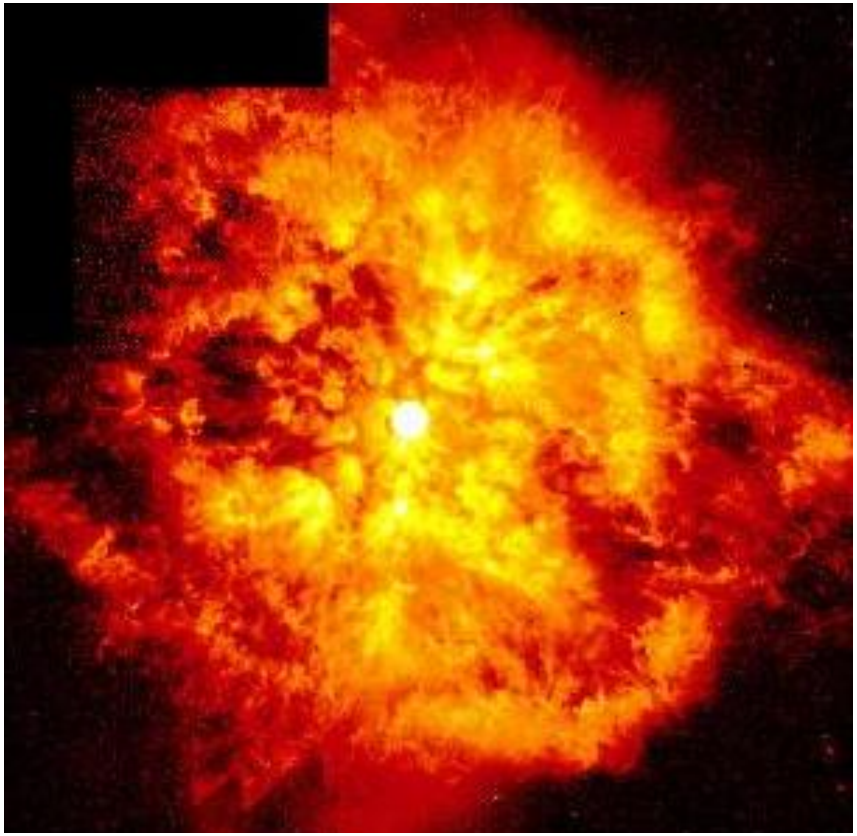
η Carinae:

A binary system ($120\ M_\odot$+ $30\ M_\odot$), last giant eruption in 1843.



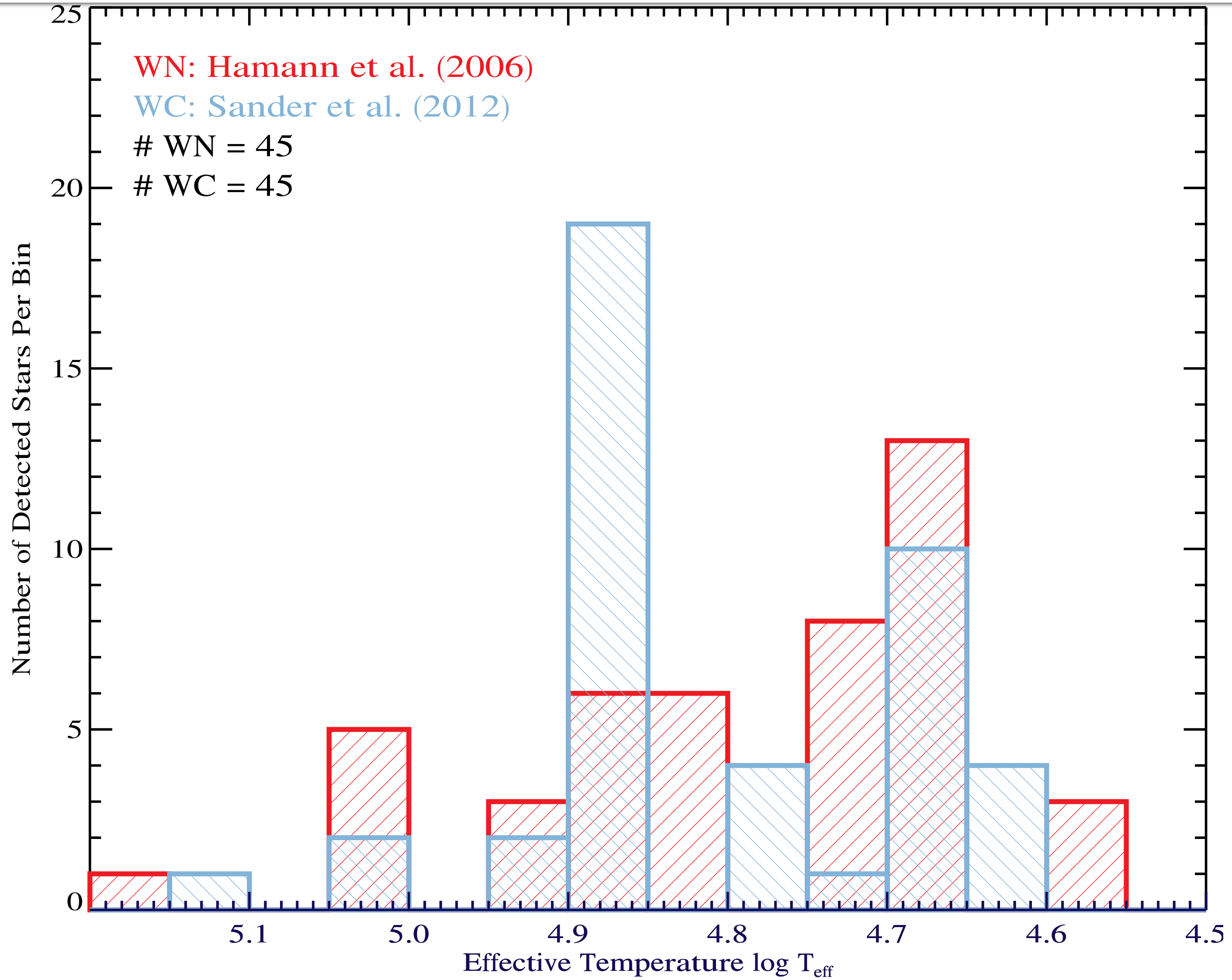
WR 124:

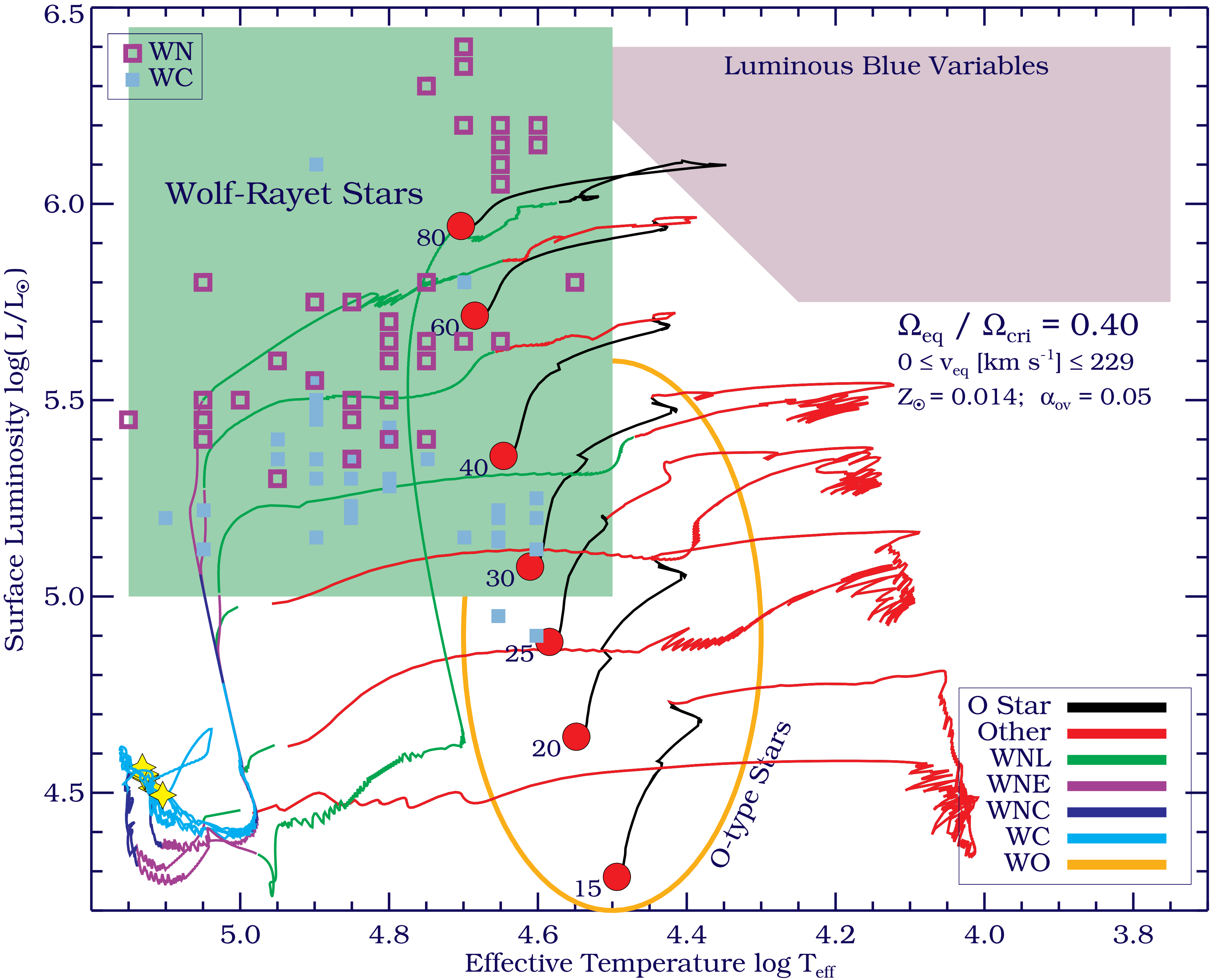
A $20\ M_\odot$ star in Sagittarius Constellation.
Credit: Grosdidier (Uni. Montreal, CA)



Galactic Wolf-Rayet Star Census

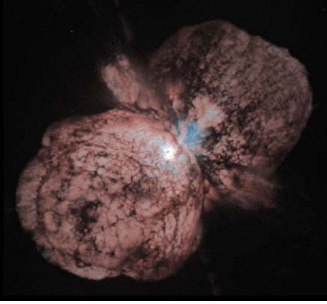
Ref: Hamann et al. (2006), Sander et al. (2012)




WN
WC
Luminous Blue Variables
Wolf-Rayet Stars
$\Omega_{eq} / \Omega_{cri} = 0.40$
$0 \leq v_{eq}$ [km s^{-1}] ≤ 229
$Z_\odot = 0.014$; $\alpha_{ov} = 0.05$
80
60
40
30
25
20
15
O-type Stars
O Star
Other
WNL
WNE
WNC
WC
WO
6.5
6.0
5.5
5.0
4.5
Surface Luminosity log($L/L_\odot$)
5.0
4.8
4.6
4.4
4.2
4.0
3.8
Effective Temperature log T_{eff}

The Ugly: SN Impostors

Ref: [1] Van Dyk (2007), [2] Kulkarni et al. (2007), [3] Bond et al. (2009), [4] Monard (2008), [5] Kitaura et al. (2006)



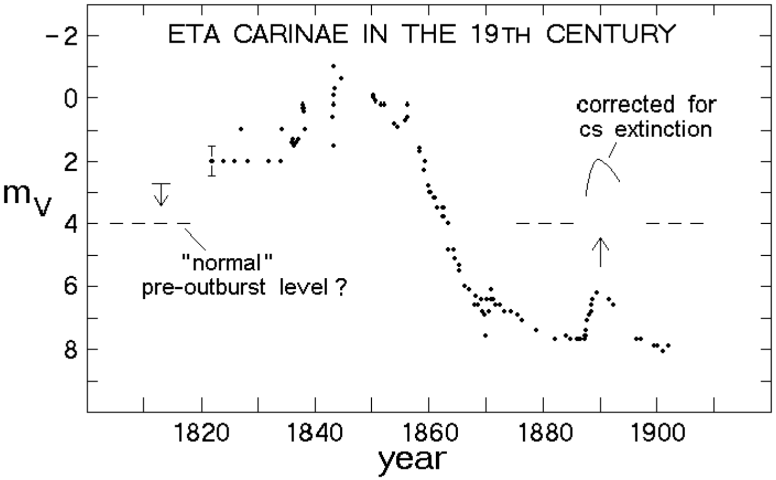
① Examples: SN 1954 J, SN 1961 V, SN 1997 bs, SN 2000 ch, SN 2002 kg, SN 2008 S [1]

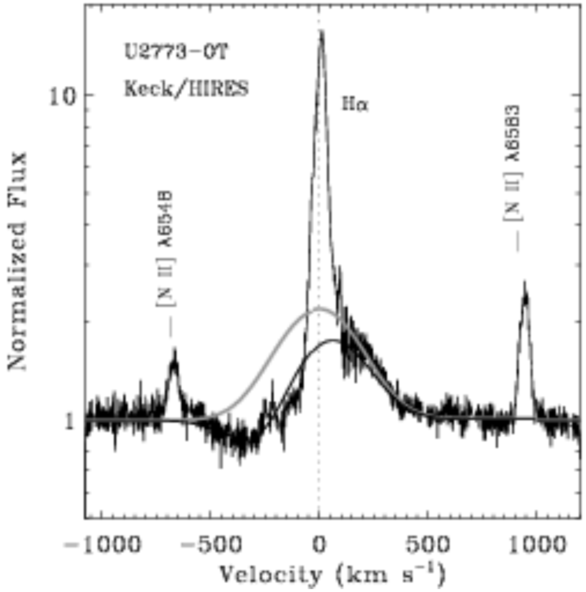
② Stellar merger? [2, 4]

③ Outburst of a massive OH/IR star? [3]

④ Collapse of massive stars enshrouded in thick dust shells? [4]

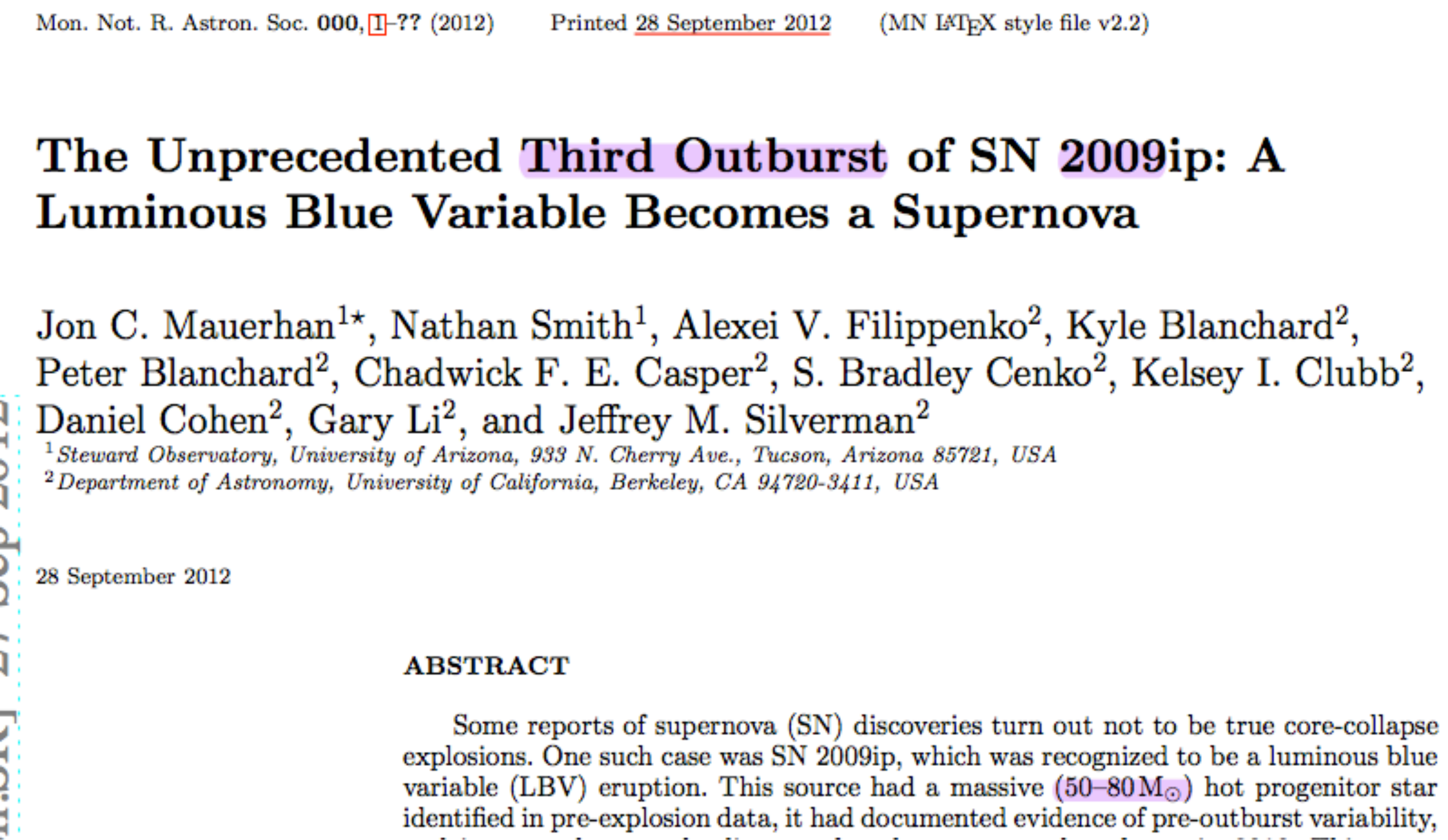
⑤ Electron-capture core collapse of Super-AGB stars (stars that ignite ^{12}C and form a O-Ne-Mg core)? [5]





Hot News: An Impostor Revealed!

Ref: Mauerhan et al. (2012)



Mon. Not. R. Astron. Soc. **000**, 1–?? (2012) Printed 28 September 2012 (MN LaTeX style file v2.2)

The Unprecedented Third Outburst of SN 2009ip: A Luminous Blue Variable Becomes a Supernova

Jon C. Mauerhan[1*], Nathan Smith[1], Alexei V. Filippenko[2], Kyle Blanchard[2], Peter Blanchard[2], Chadwick F. E. Casper[2], S. Bradley Cenko[2], Kelsey I. Clubb[2], Daniel Cohen[2], Gary Li[2], and Jeffrey M. Silverman[2]
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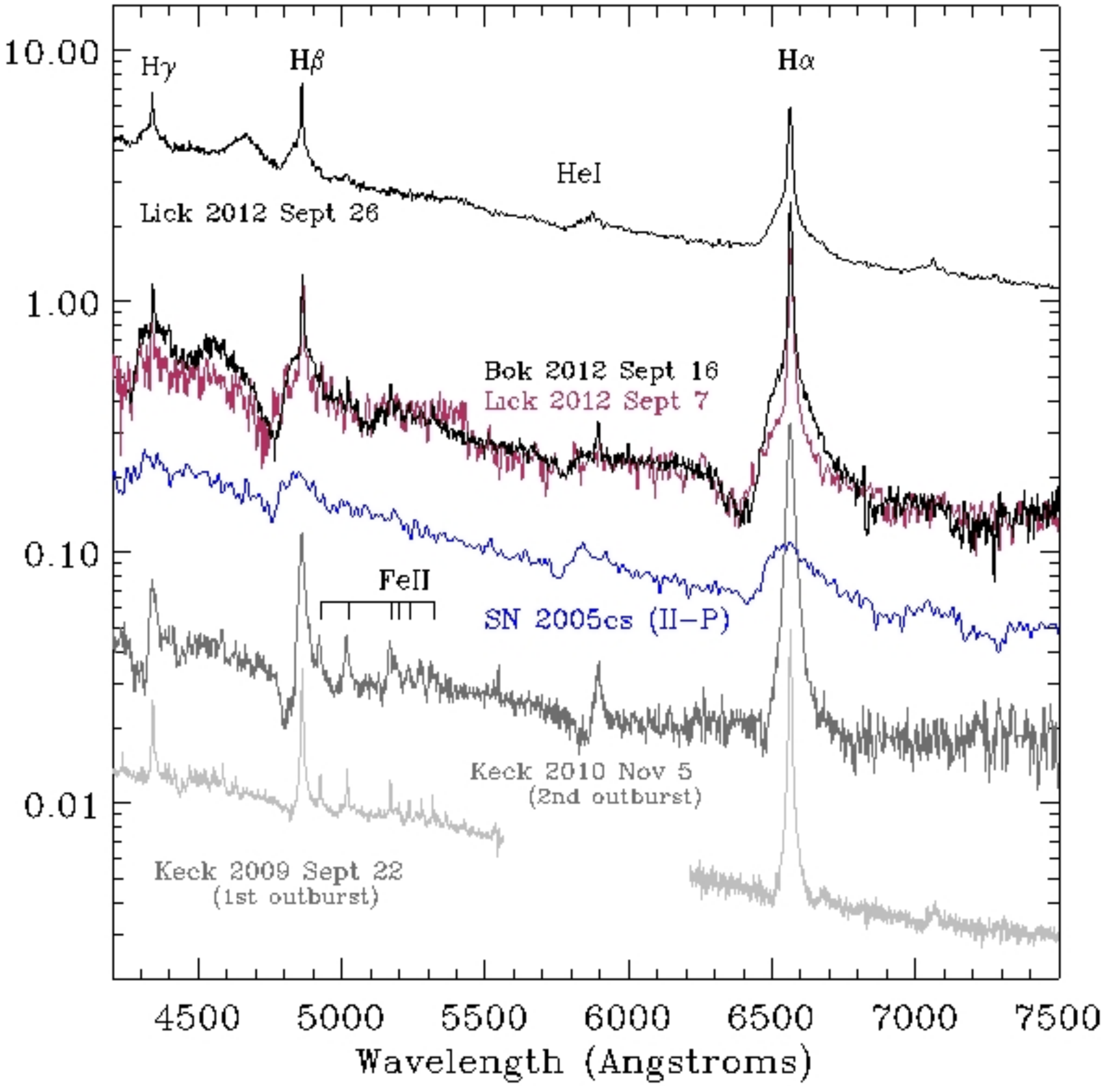
28 September 2012

ABSTRACT

Some reports of supernova (SN) discoveries turn out not to be true core-collapse explosions. One such case was SN 2009ip, which was recognized to be a luminous blue variable (LBV) eruption. This source had a massive (50–80 $M_\odot$) hot progenitor star identified in pre-explosion data, it had documented evidence of pre-outburst variability,

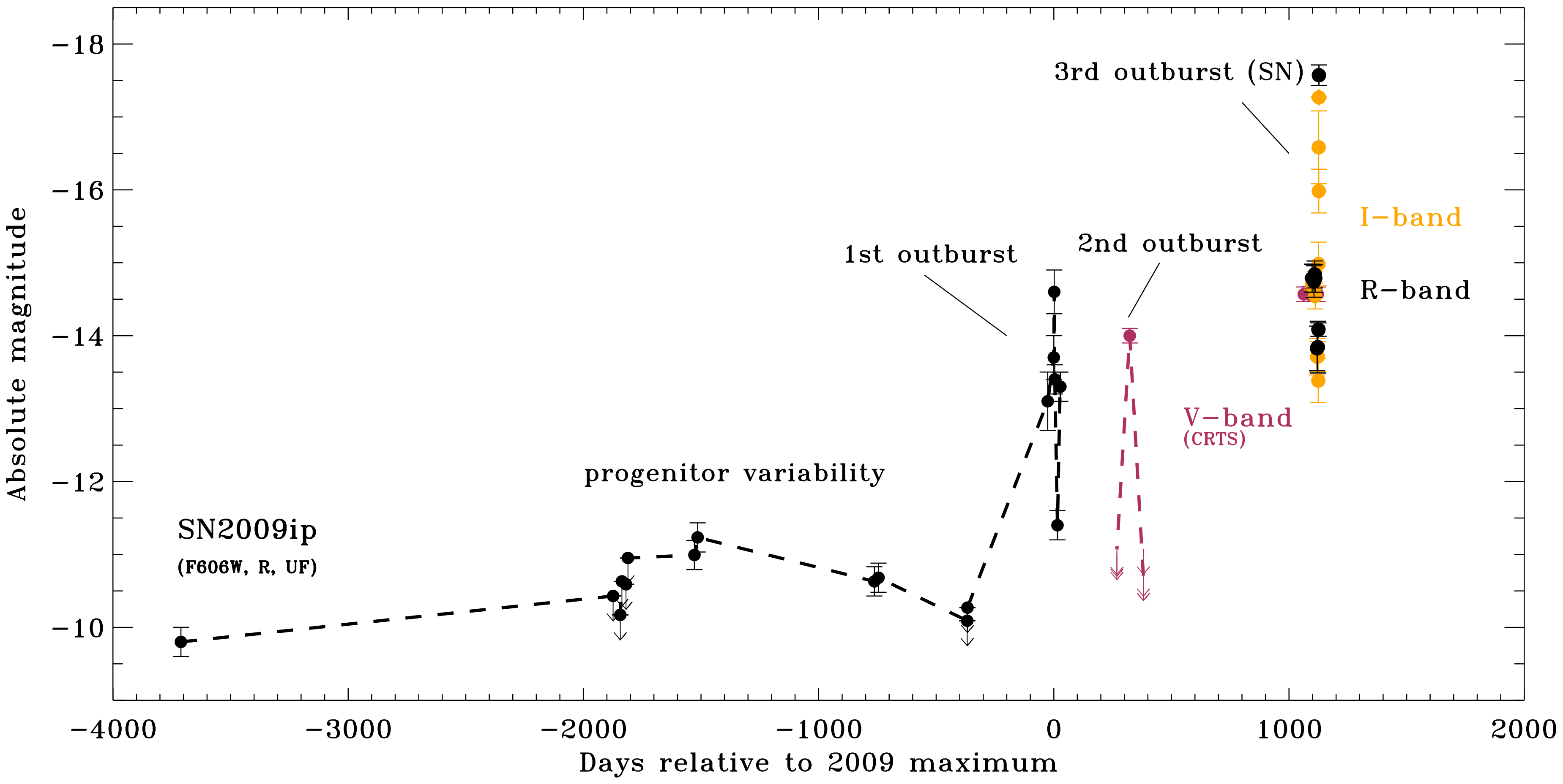
Time-Resolved Spectroscopy

Ref: Mauerhan et al. (2012)



Time-Resolved Photometry

Ref: Mauerhan et al. (2012)



Massive Star Birth – Fate Scenarios

Ref: Sander et al. (2012), Georgy et al. (2012)

Initial Mass [$M_\odot$]	Pre-Collapse Evolutionary Scenario	Fate	NS/BH?
8 - 15	OB → RSG ↔ [BSG?] →	SN IIP	NS
15 - 20	OB → RSG →	SN IIL	NS
20 - 45	O → RSG → WNE → WC →	SN Ib/c	BH
45 - 60	O → WNL ↔ [LBV?] → WNE? → WO →	SN Ib/c	BH
>60	O → WNL ↔ LBV →	SN IIn	BH

Complexities in Stellar Evolution:

- ✓ The Role of Metallicity,
- ✓ The Impact of Rotation,
- ✓ Accurate Mass-Loss Rates,
- ✓ Convective/Overshooting Mixing,
- ✓ The Binary System Influence.

The Critical Role of Mass Loss

Ref: [1] Nugis & Lamers (2000), [2] Maeder & Maynet (2000)

- ☐ There are **handful** of recipes for the mass loss rates (Mdot) at different evolutionary phases.
- ☐ E.g. Line-driven mass loss [1]

$$\log \dot{M} = -8.30 + 0.84 \log L + 2.04 \log Y + 1.04 \log Z$$

This varies between 10^{-6} to 10^{-3} $M_\odot\,\mathrm{yr}^{-1}$.

- ☐ Rotation enhances Mdot.
- ☐ There are some recent evidences that **we are overestimating Mdot**.
- ☐ Mass loss is one of the most critical ambiguities in contemporary stellar physics!

  This ambiguity directly translates to our understanding of the evolution of SN progenitors ☹

Conclusions

Ref: [1] Georgy et al. (2012), [2] Langer (2012), [3] Lunardini & Tamborra (2012), [4] Ugliano et al. (2012), [5] Ugliano et al. (2012) [6] Yoon & Langer (2010)

- Currently stars with $M \leq 35\ M_\odot$ collapse to form Neutron Stars [1]. So, they can be surveyed due to their photon and neutrino imprints.
- Those with $M \geq 30\ M_\odot$ end up as SN Ib/c. Their progenitors are faint (undiscovered) in the optical, but **not** in the neutrino channel.
- For uncertainties in *mass loss rates* and (convective+rotational +magnetic) mixings [2], we do not know the accurate core masses. The SN neutrino energy puts tighter constraints on this [3, 4].
- What is the fractional contribution of massive binary systems? Is this 50-50? [2, 6]
- **Direction-sensitive neutrino** detection helps distinguishing SN Impostors from real SN events. Identifying intrinsically faint/ obscured SNe.