Identification of progenitors of core collapse supernovae

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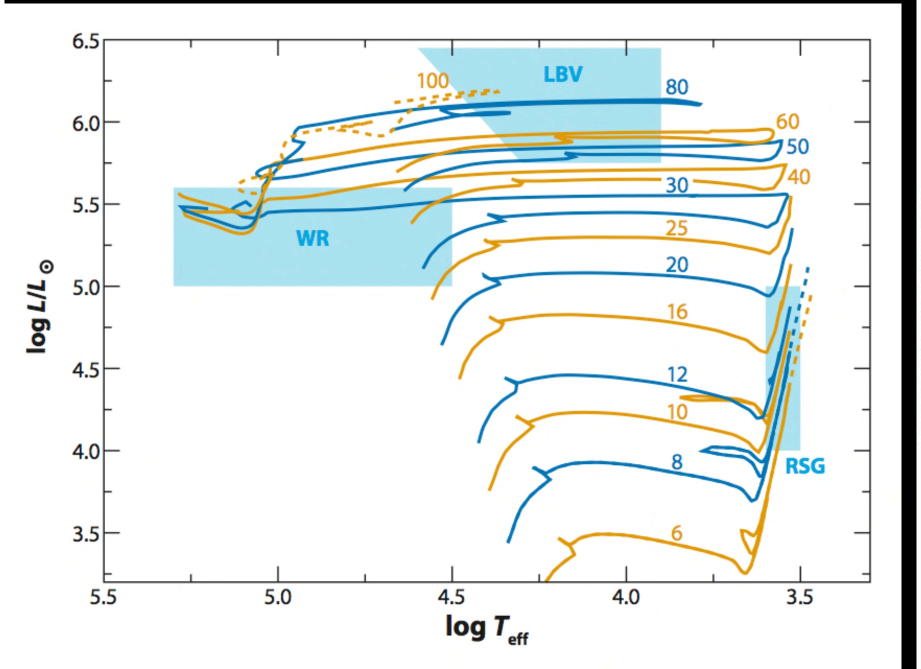
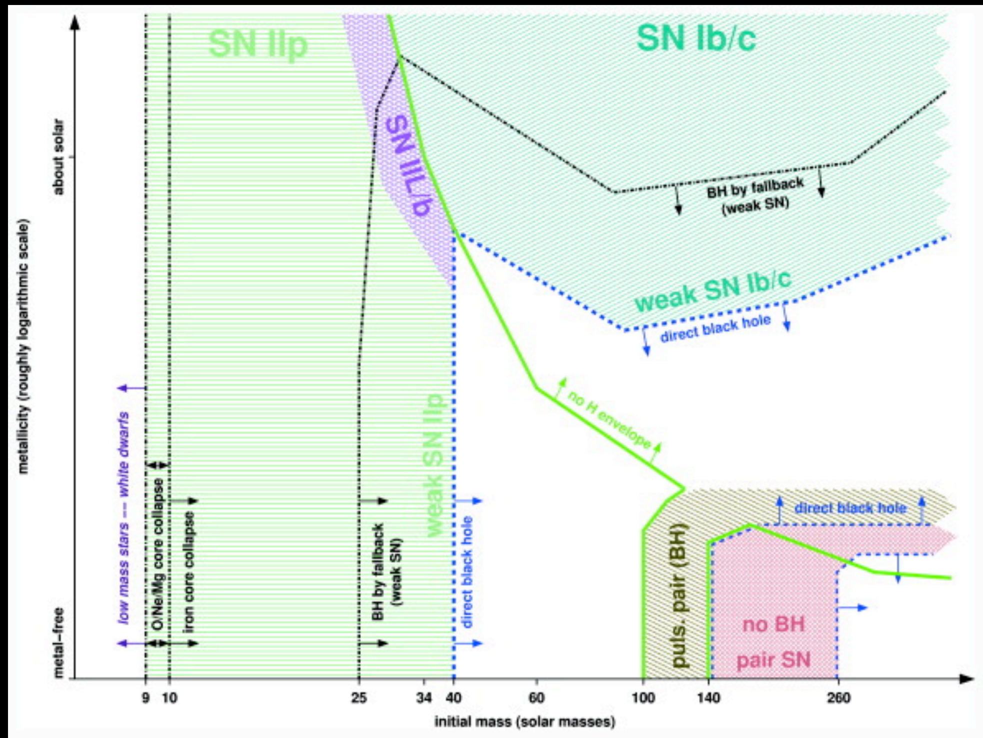
ESO VLT + NTT Large programme Collaboration : S. Bennetti, A. Pastorello, S. Valenti, J. Sollerman, M. Ergon, M. Botticella, R. Kotak, M. Turatto et al.

Overview and motivation

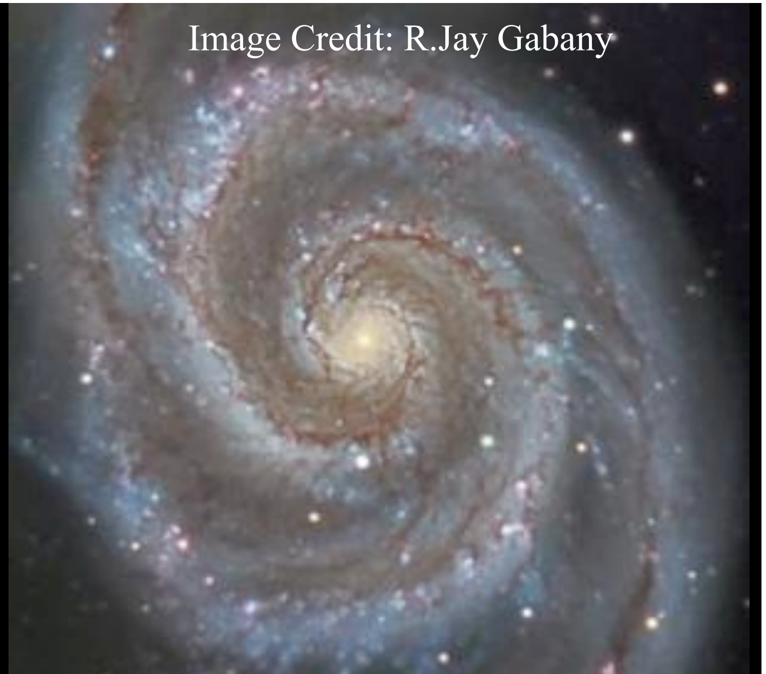
- Direct constraints on progenitor stars
- Test of final stages of stellar evolution
- Consistency with spectral and lightcurve modeling ?
- Range in energy and ejected masses : link to explosions ?
- Black hole and NS formation : which stars

Testing theory





Heger et al. (2003); Eldridge & Tout 2004 : now can place observational constraints



Nearby SNe discovered by amateur astronomers , LOSS (see recent astro-ph papers) and CHASE

Relative SN rates 10.5 yrs

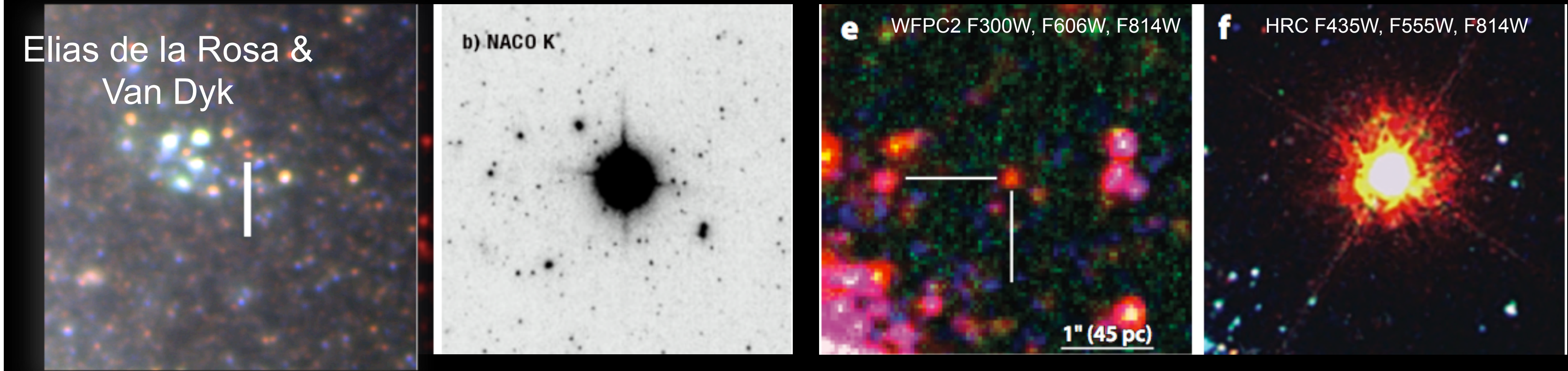
Smartt et al., 2009

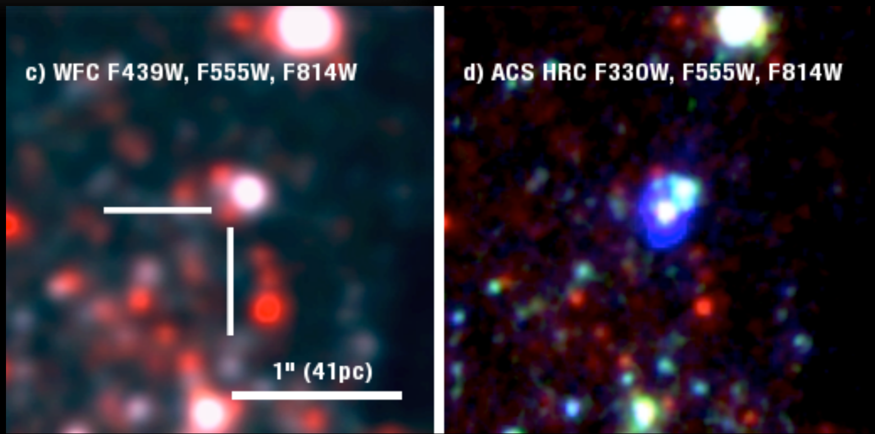
		Relative	Core-Collapse only
Type	No.	/ per cent	/ per cent
II-P	55	39.6	59.1
II-L	2.5	1.8	2.7
IIn	3.5	2.5	3.8
IIb	6	4.3	6.5
Ib	9	6.5	9.7
Ic	17	12.2	18.3
Ia	37	27.6	...
LBVs	7	5.0	...
Unclassified	2	1.4	...
Total	139	100	100
Total CCSNe	93	66	100

- 19980101-20080630
- 139 SNe discovered in galaxies with V_{vir}<2000 kms^{-1} (13.2 SNe yr^{-1})
- See Li, Filippenko et al. : LOSS results (astro-ph papers)

~26% SN-HST image coincidence rate

Detection of progenitors



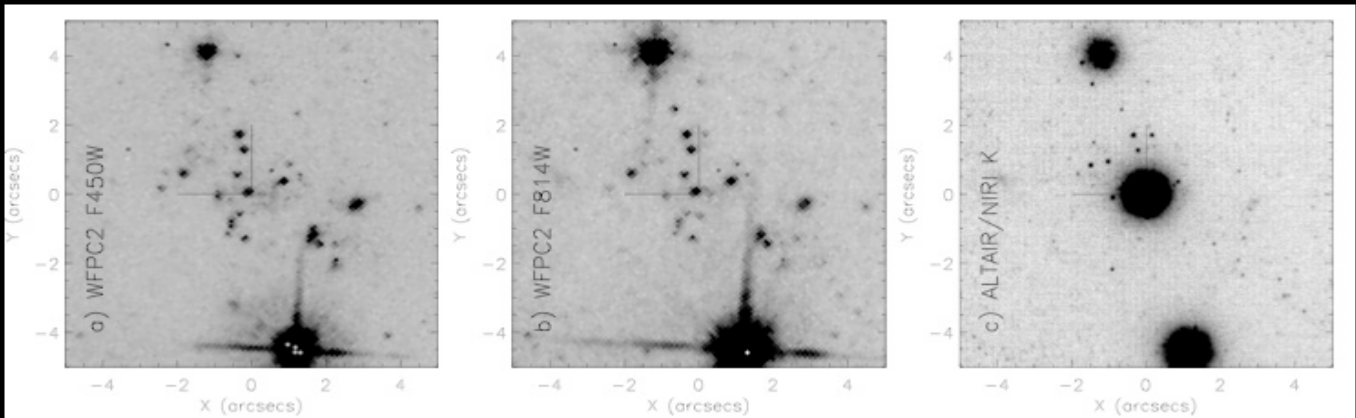


Figures from Smartt 2009 ARAA

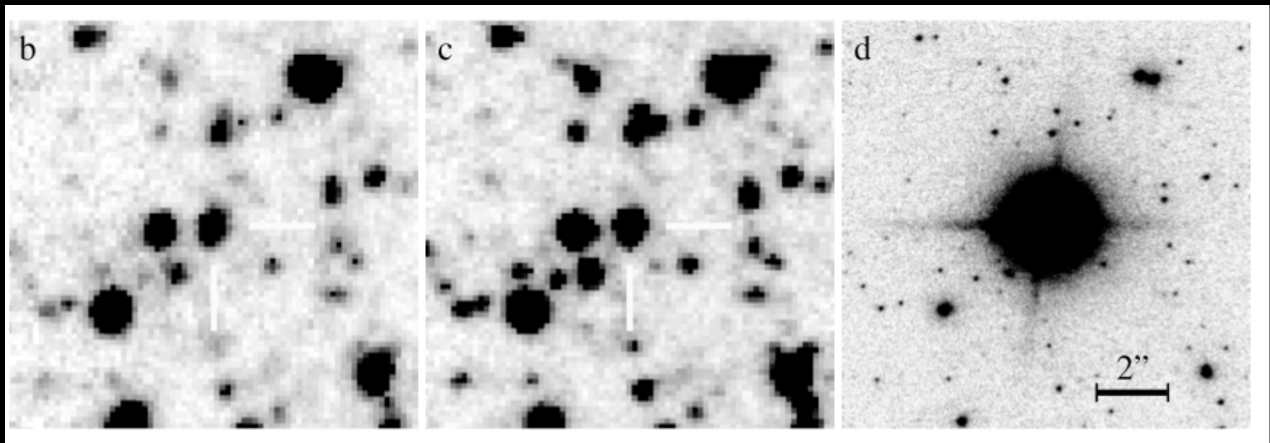
- Within the volume limited, 10.5 yr survey for progenitors : three “gold” events
- SN2008bk, SN2005cs, SN2003gd
- Red star identified coincident with all three.
- Typical magnitudes : M_V ~ -4.5 ; M_I ~ -6.5
- Discovery papers :

  Van Dyk et al. 03, Smartt et al. 04, Maund et al. 05, Li et al. 06, Mattila et al. 08.

8m AO imaging - new approach



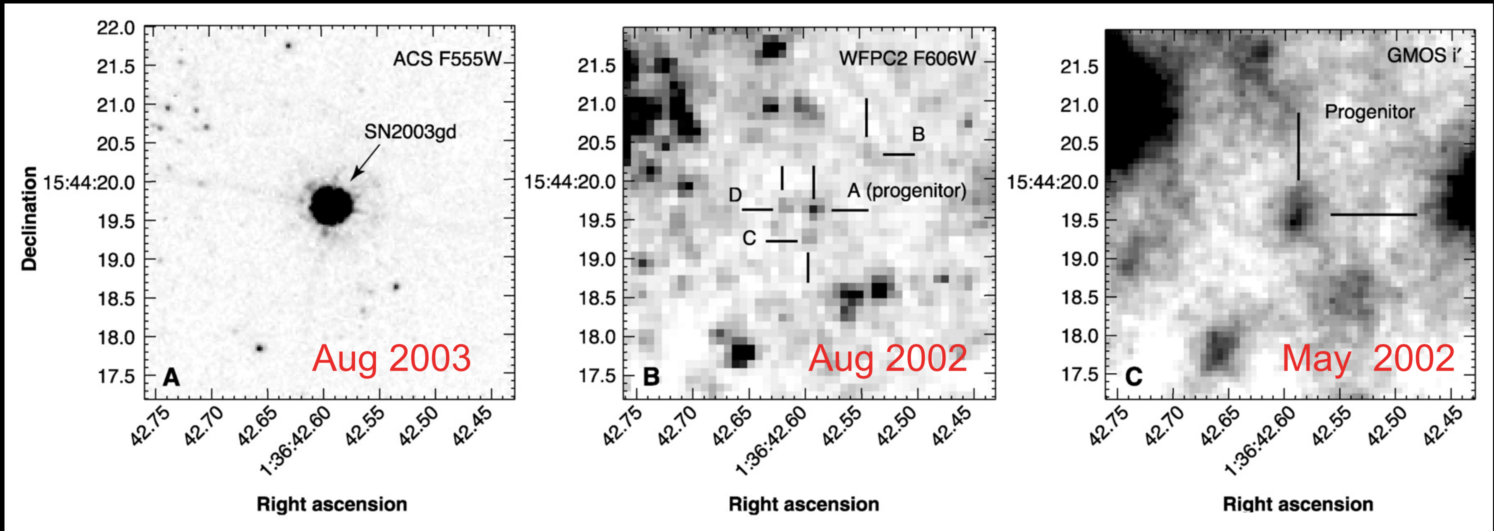
Gemini + Altair :
Crockett et al. 07



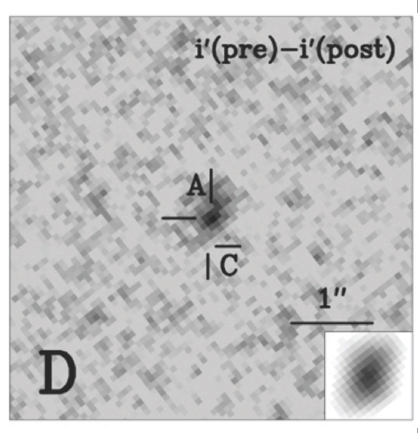
VLT + NACO :
Mattila et al. 08

Gal-Yam et al. 2006, Elias-Rosa et al. 2010
Gemini,VLT, Keck diffraction limited *K*-band AO images
0.08" and ~0.02" pixels = well sampled PSF
Differential astrometry ~ 20 milliarcseconds RMS

The disappearance of 2003gd



SN2003gd:
V=25.8 ± 0.15
V–I=2.5 ± 0.2
Smartt et al. 04,
Van Dyk et al. 03

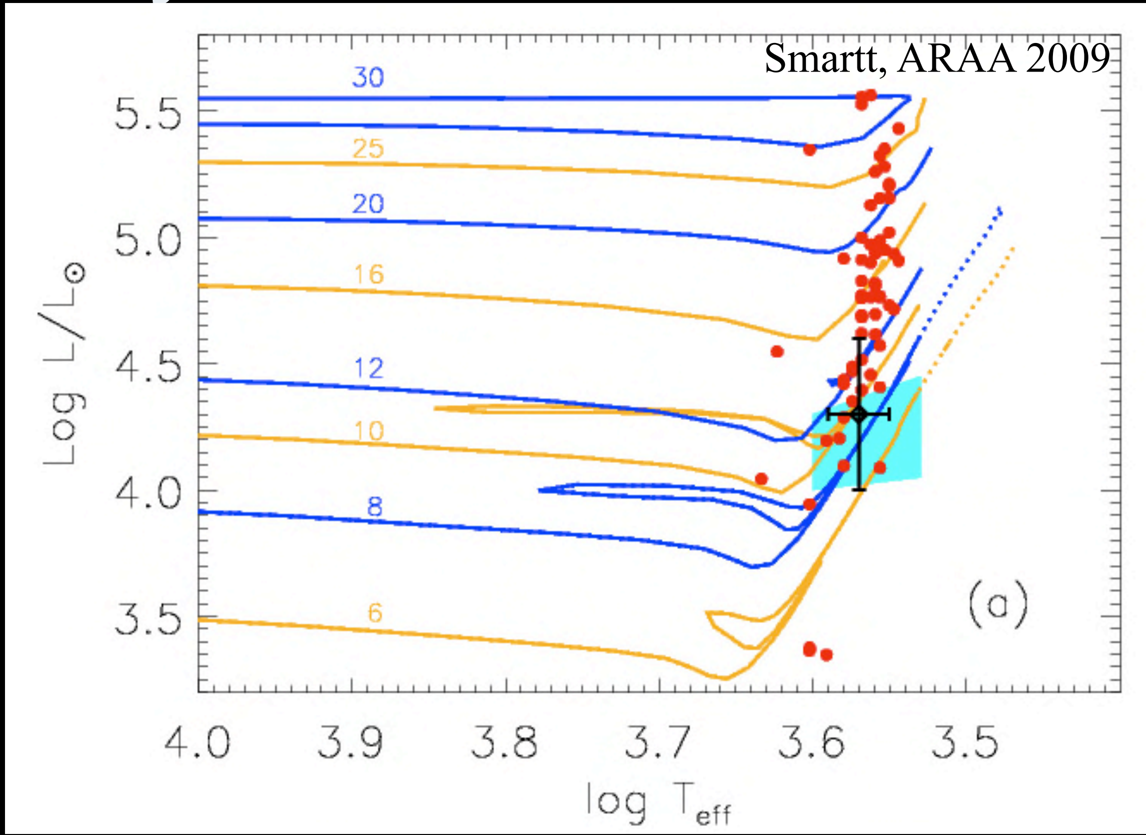


Maund & Smartt (2009)

Four confirmed cases of disappearance :
SN1987A , SN1993J, SN2003gd,

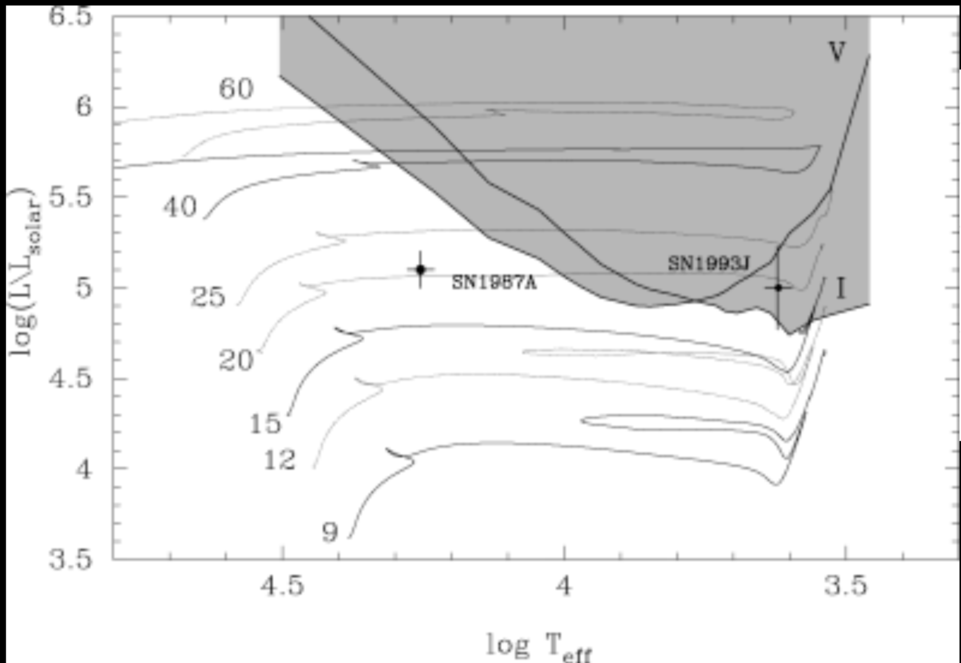
SN2005gl (Gal-Yam & Leonard 2009)

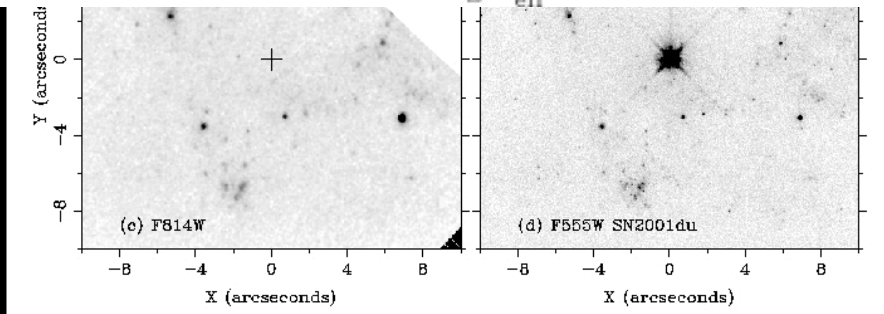
Mass estimates from stellar evolutionary tracks



Red points : Milky Way red supergiants (Levesque et al. 2005)
STARS stellar evolutionary tracks
SN progenitors : SN2003gd (black), SN2005cs (blue box)

Other examples: no detection





- **SN1999gi** in NGC3184,
- HST *U+V* pre-explosion
- D=11Mpc (Leonard et al. 2002)
- M ≤ 12 $M_\odot$

- **SN2001du** in NGC1365
- HST *UVI* pre-explosion
- D=17Mpc (Cepheid Key P.)
- M ≤ 15 $M_\odot$

Van Dyk et al 02, Smartt et al. 01,02,

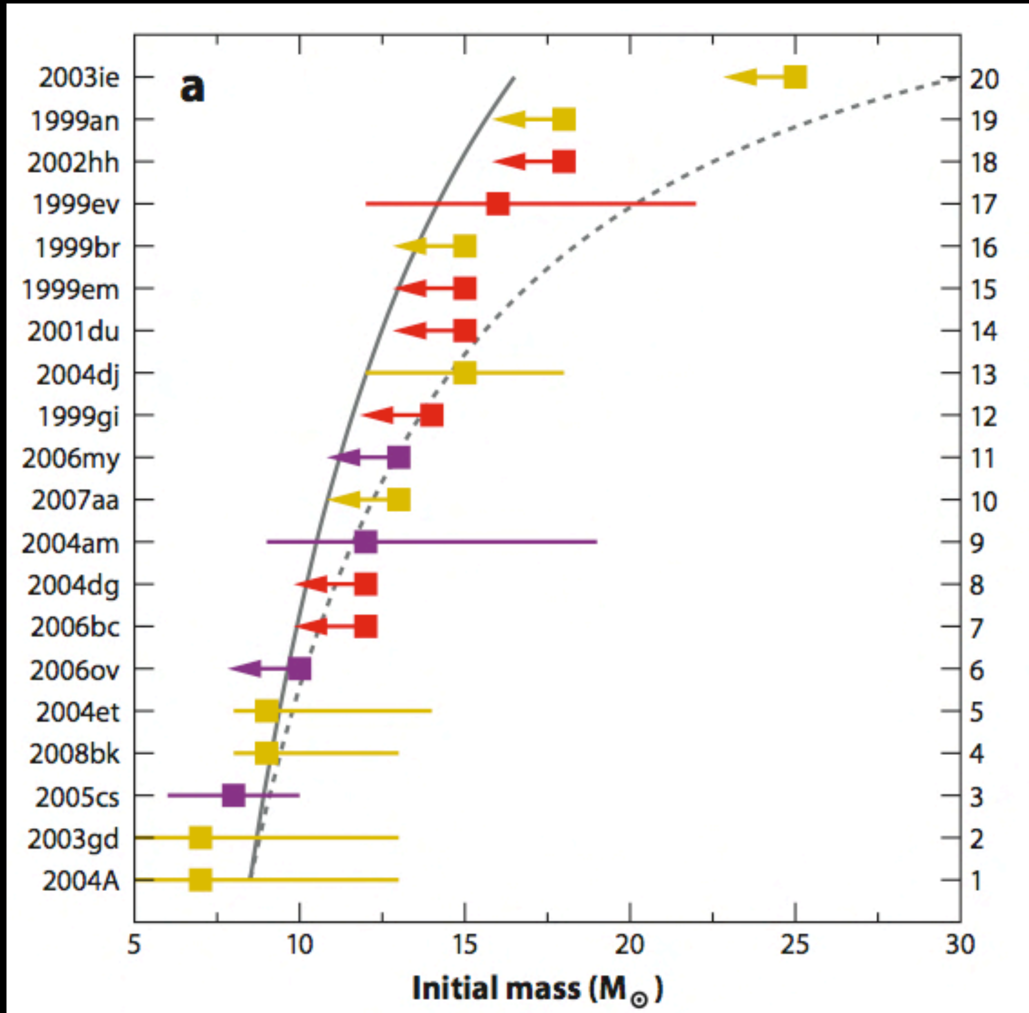
Summary of II-P progenitors : 10.5yr search

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}

Smartt et al. 2009,MNRAS : used Cambridge STARS code, homogeneous analysis, consistent luminosity and mass estimates

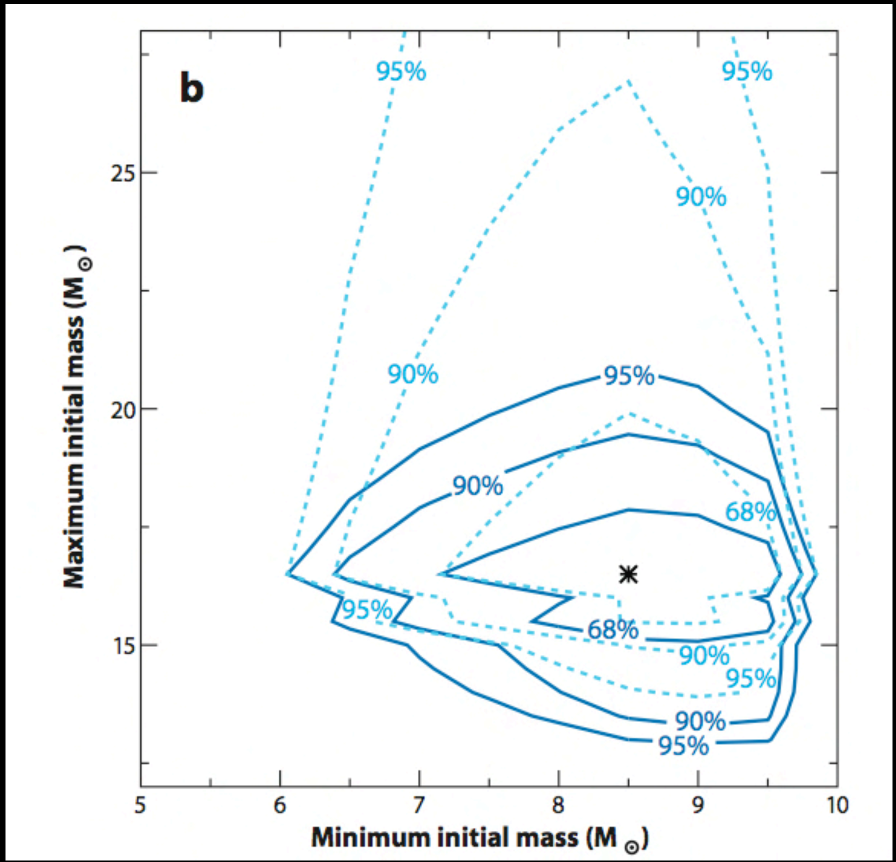
Does a Salpeter/Scalo IMF fit ?

- Solid : Salpeter IMF maximum mass of 16.5M$_\odot$
- Dashed : Salpeter IMF, maximum mass of 30M$_\odot$
- Lower mass limit from White dwarfs : >6-7M$_\odot$ (K. Williams et al 2009 : WD surveys)



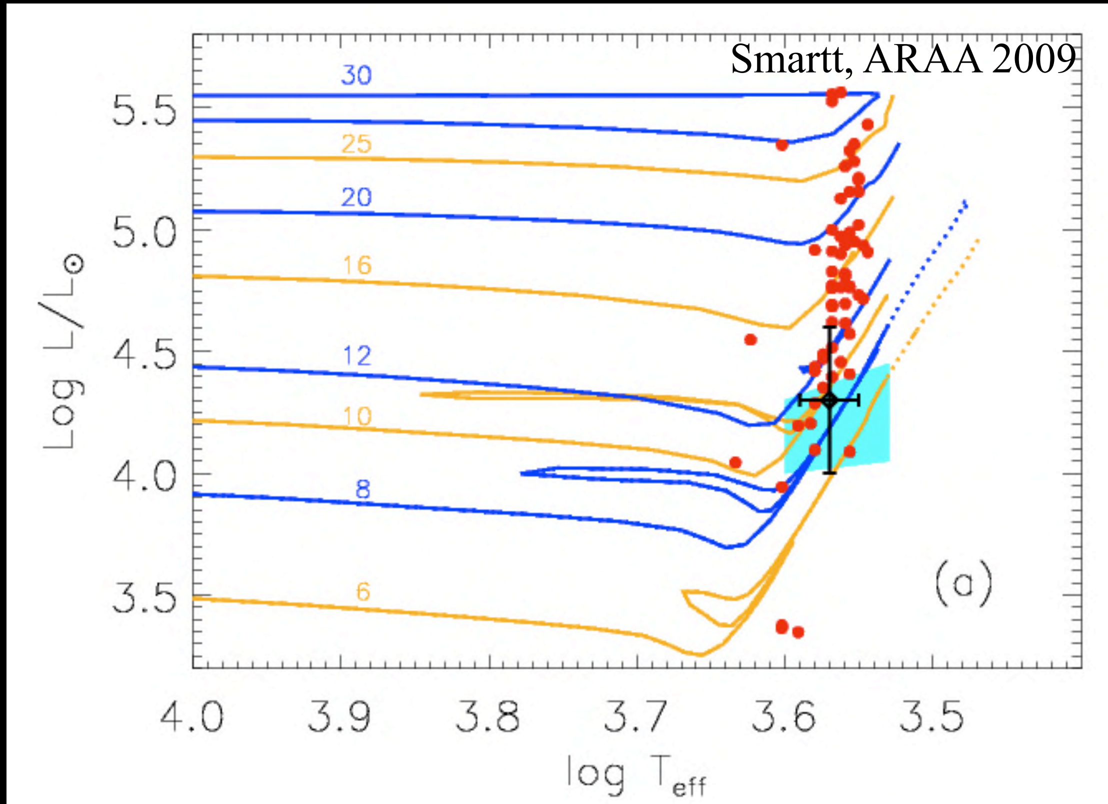
Maximum likelihood approach

- m_{min} : is better measured with the detections only. Unconstrained IMF if limits used.
- m_{max} : calculated using both detections and limits :
  - $m_{min} = 8^{+1}_{-1.5}\ M_{\odot}$
  - $m_{max} = 16.5 \pm 1.5\ M_{\odot}$



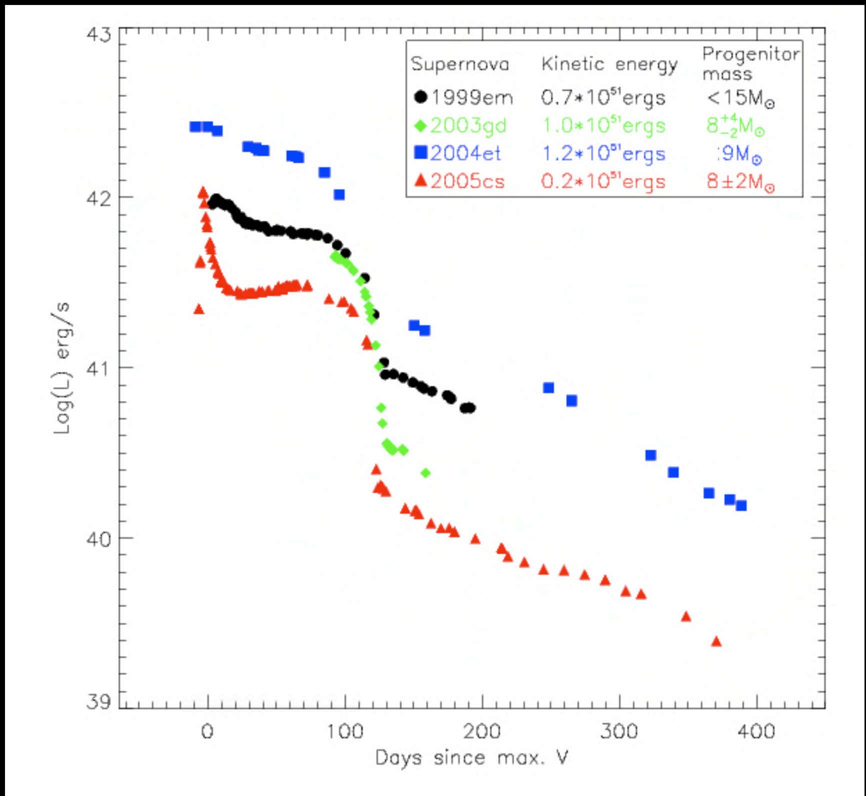
The “red supergiant problem”

- Most massive RSGs in MW and LMC are 25-30$M_\odot$
- Where are these progenitors ?
- Would be the easiest to detect in the pre-explosion images
- From Salpeter/Scalo IMF we would have expected 4-5 bright, massive progenitors
- Do they produce IIn and II-L ?

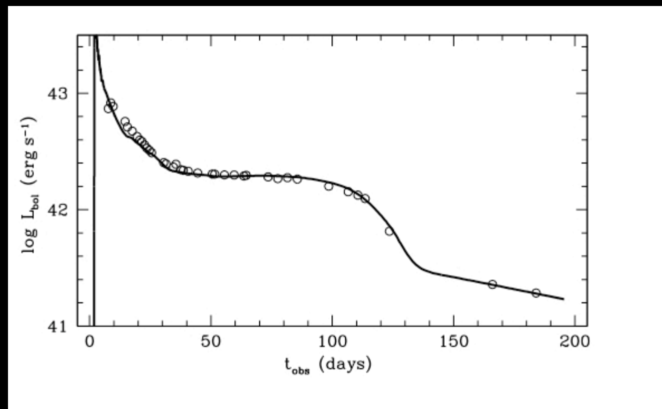


Levesque et al 05,06 : new Teff for RSGs

Probing the explosion

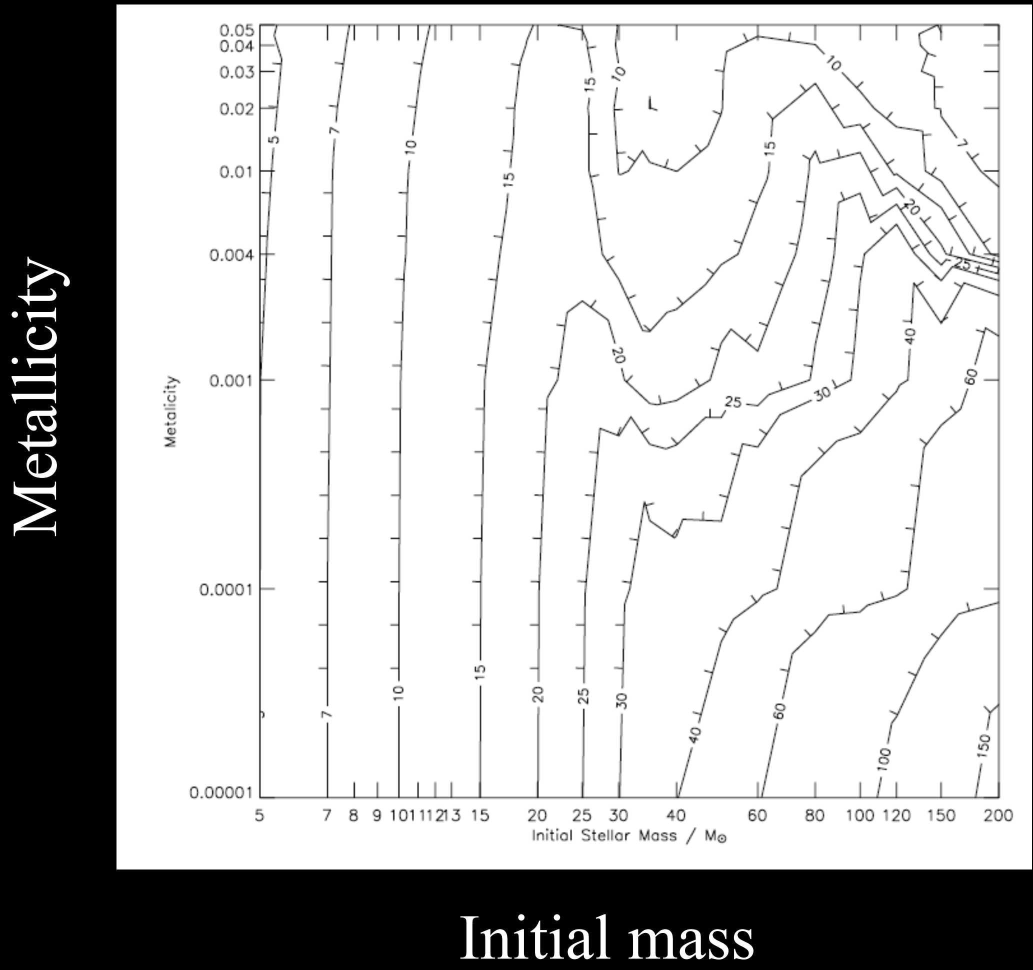


- Utrobin & Chugai : hydro models of LCs
- Factors of 2 -3 higher masses (2005cs, 2004et, 1999em…)



- With current mass-loss rates : difficult to get more than $15M_\odot$ of ejecta
- 20-25$M_\odot$ star : >5$M_\odot$ mass loss, 1.5$M_\odot$ remnant
- Maximum ejecta mass : $15M_\odot$ for a H-rich, RSG

Initial mass – final mass relation



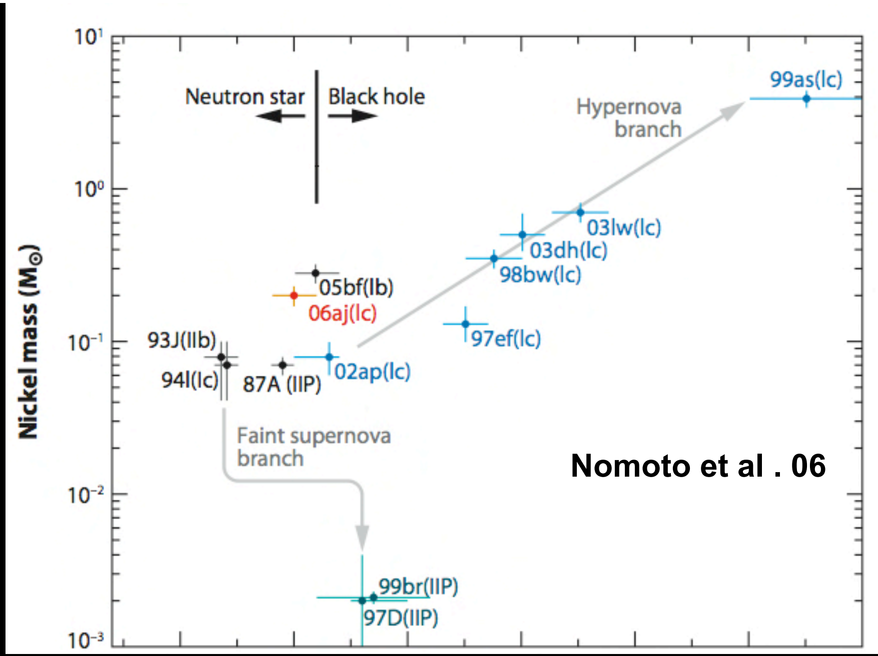
Eldridge & Tout 2004 : STARS Models

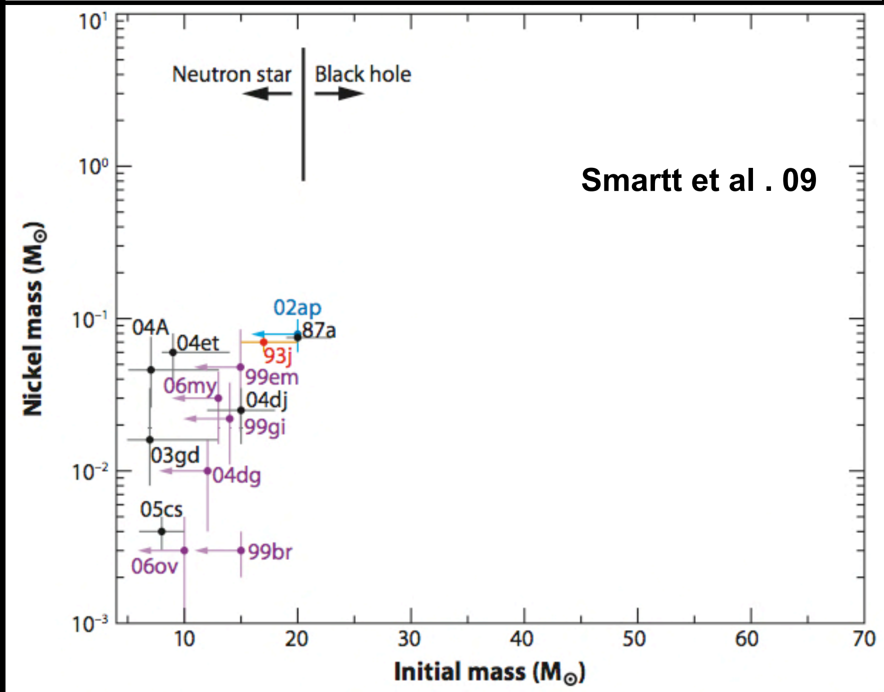
^{56}Ni mass *vs.* ejecta mass

- Nomoto et al. 2006 : ejecta mass from lightcurve and spectral models
  - Assume WR stars and use stellar evolution models to determine initial mass
  - Faint, ^{56}Ni poor branch : fall-back SNe from high mass stars

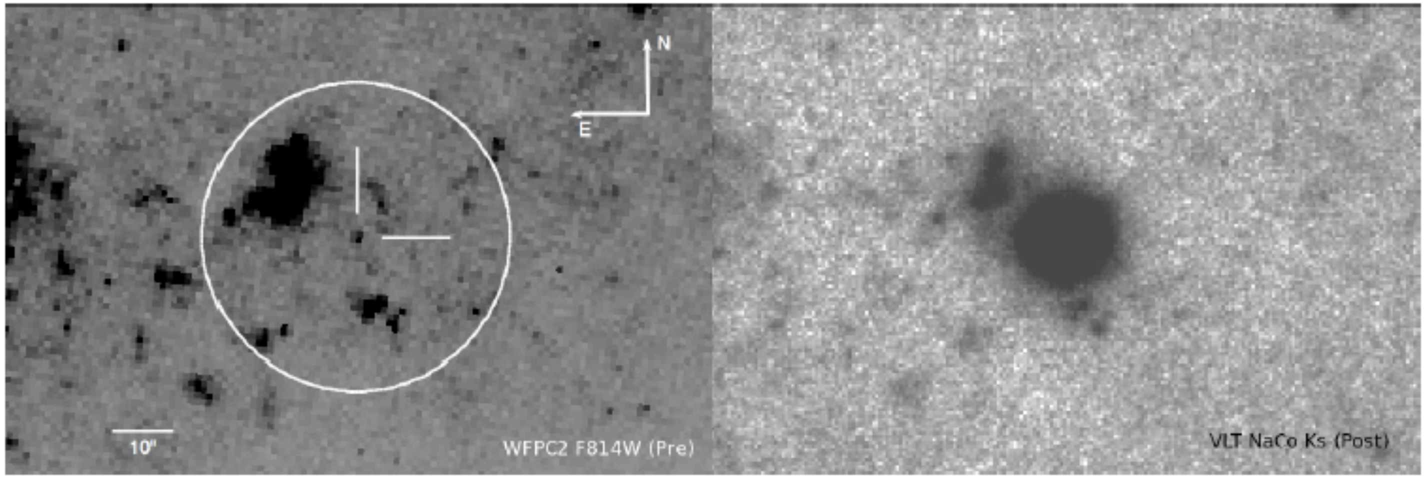
- Direct progenitor identification results :
  - All faint II-P, have low KE, and low ^{56}Ni
  - See talk by M. Fraser
  - No evidence of high mass progenitors
  - Large diversity in explosion energies between 7-16M$_\odot$

Faint IIP: Pastorello et al. 09, 06
Kitaura et al. 04, Wanajo et al. 09



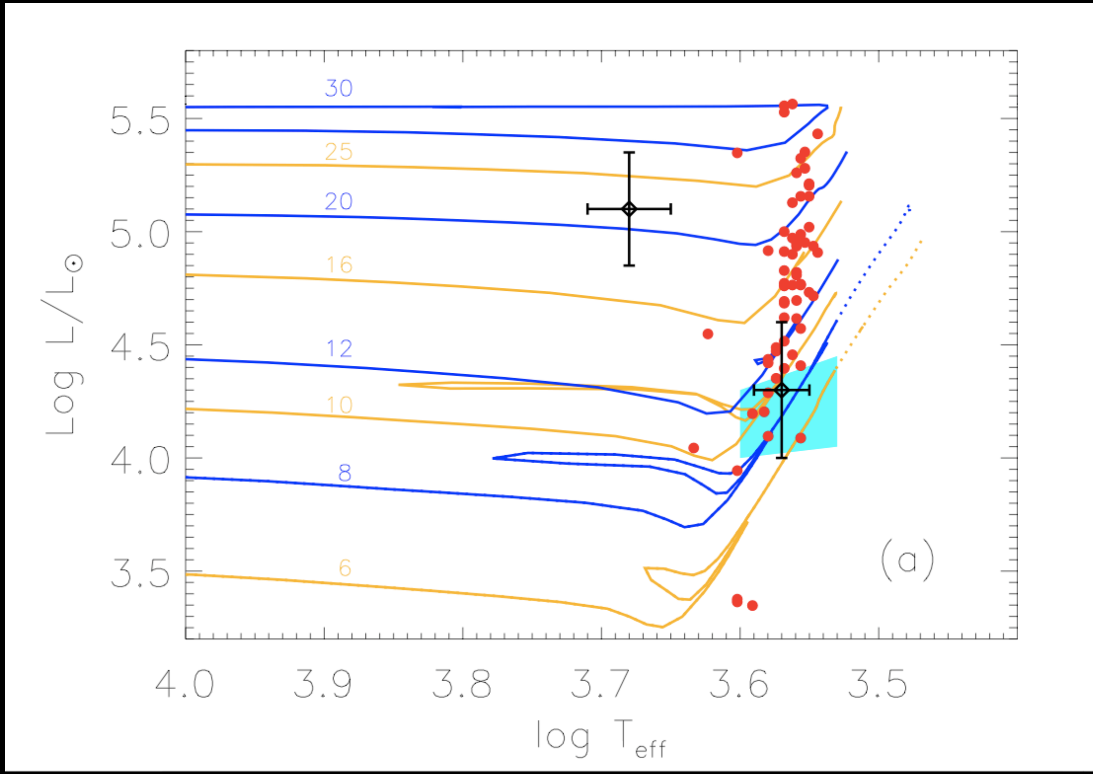


"Yellow supergiant" progenitors



- Elias-Rosa et al. 2009, 2010 ; Fraser et al. : SN2008cn, SN2009kr
- Relatively bright star SN2009kr: $M_V = -7.62 \pm 0.55$; $V - I = 1.13 \pm 0.2$
- How massive and what spectral type ?
- Solution to the Red supergiant problem ? (see last weeks paper by Smith et al. – astroph)

“Yellow” supergiant progenitors

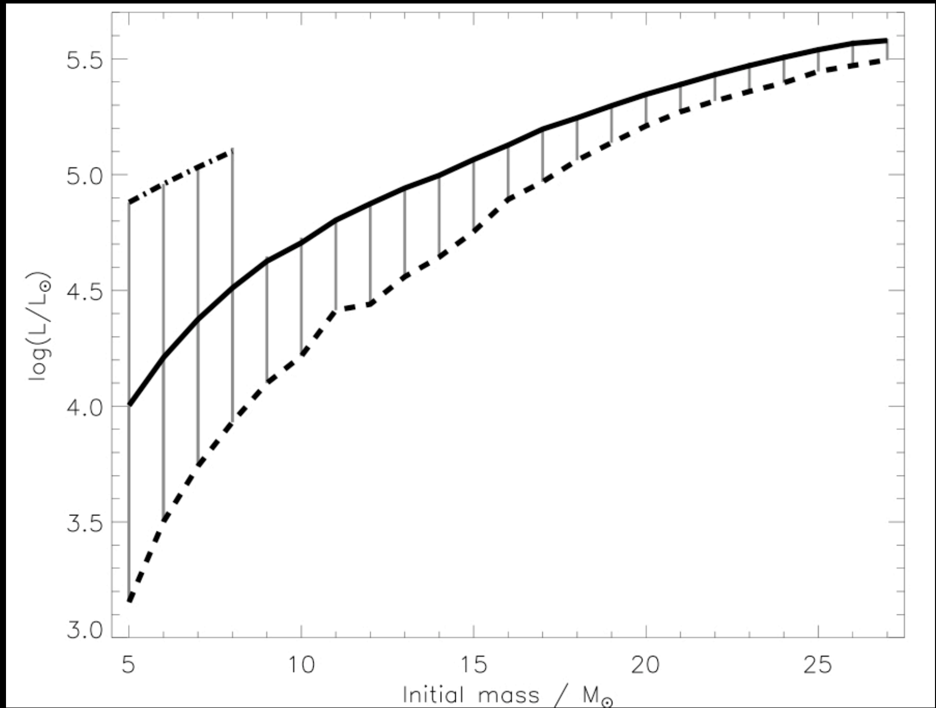


- G2 – K2 spectral type, log $L/L_{\odot}$ = 5.1
- What is the mass ?
- The “nearest” track is NOT a physically valid model – it is NOT a SN progenitor

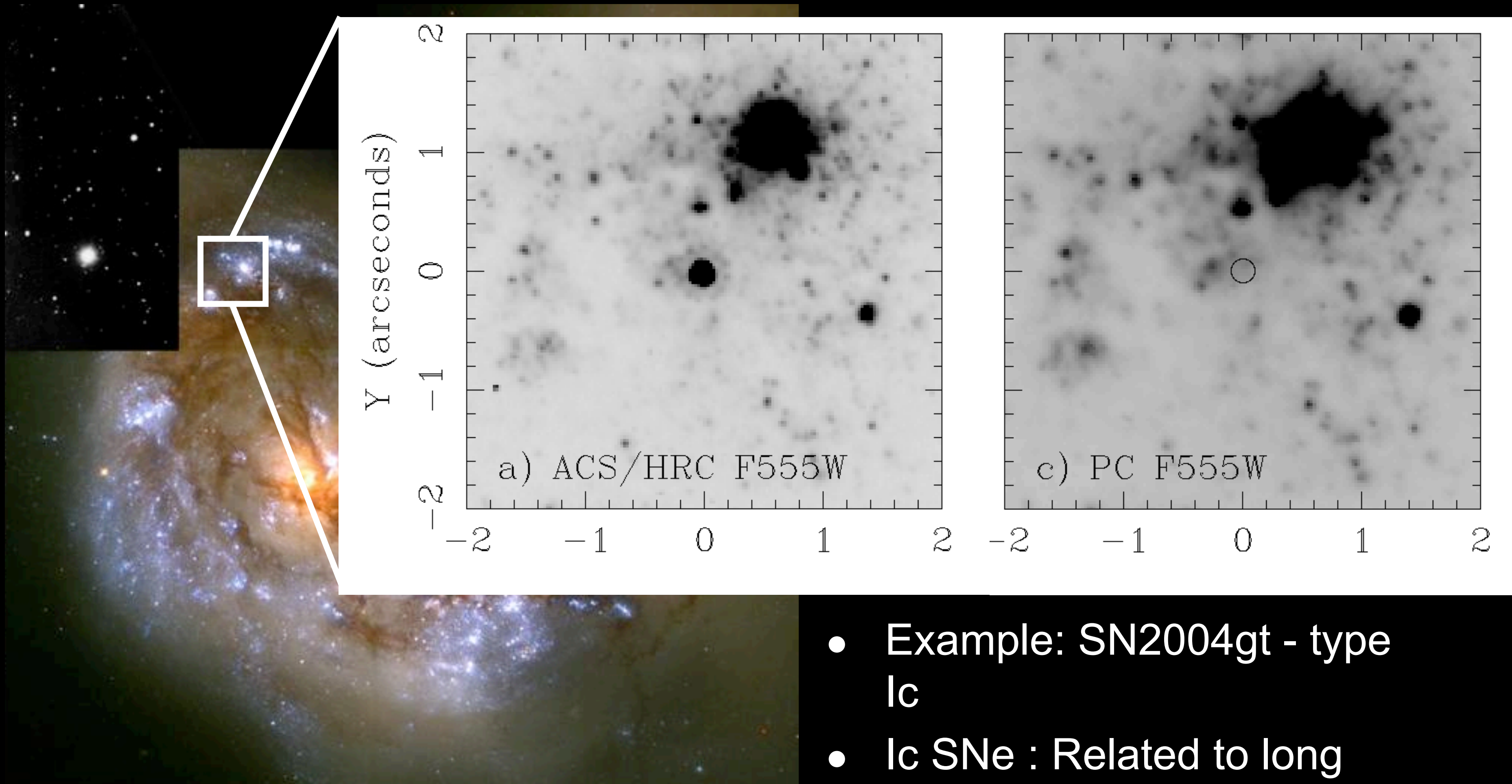
Initial-mass : final luminosity relations

- Stellar luminosity determined by the He-core luminosity
- SN progenitor model must have evolved core (end of C or O at least)
- Picking the "nearest" track is not valid for SN progenitors – OK for stable stars

- <u>Ideally : a model that produces Fe-core, *at that HRD position*</u>
- Next best : take the final luminosity as an initial mass guide



Constraints on Type SNe Ib/Ic

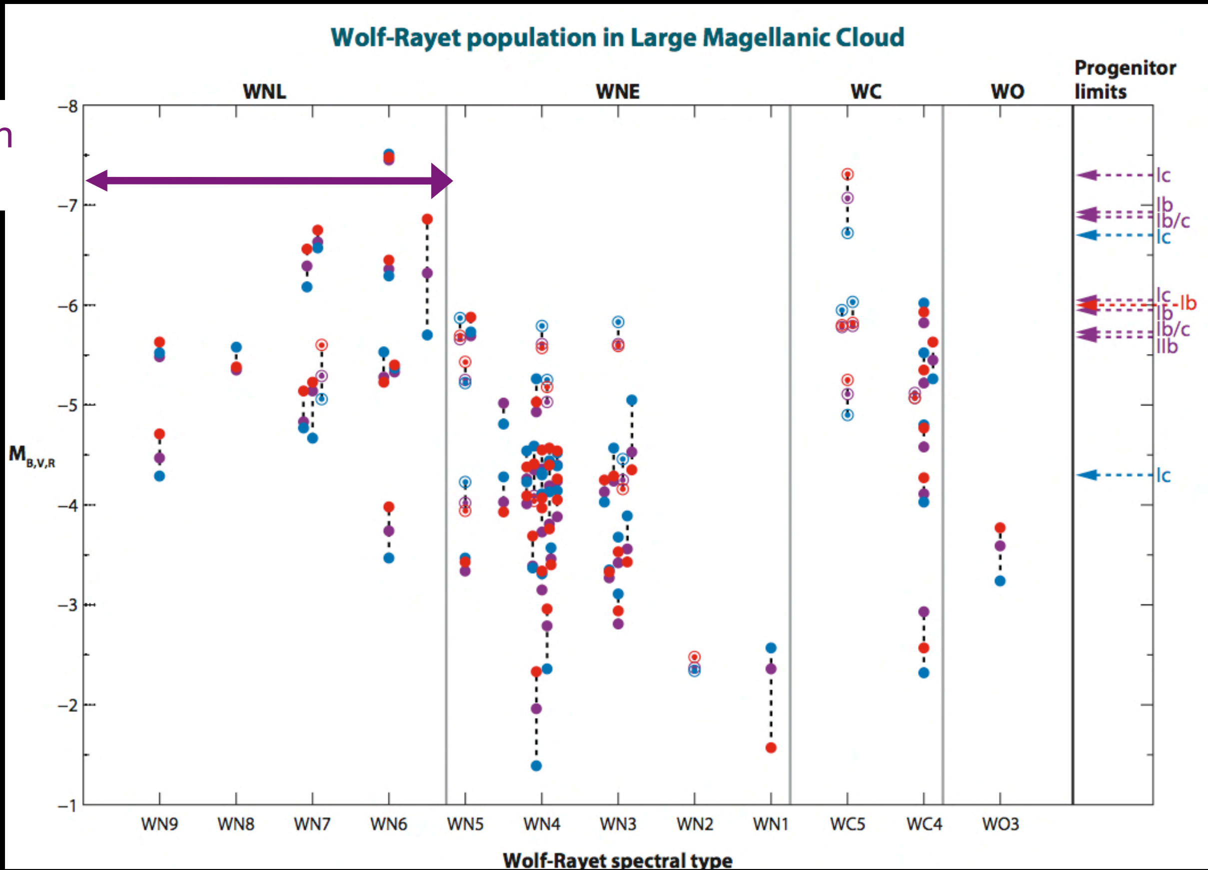


- Example: SN2004gt - type Ic
- Ic SNe : Related to long Gamma-ray burst

Maund et al. 2004, Gal-Yam et al. 2005

Wolf Rayet stars : not Ibc progenitors?

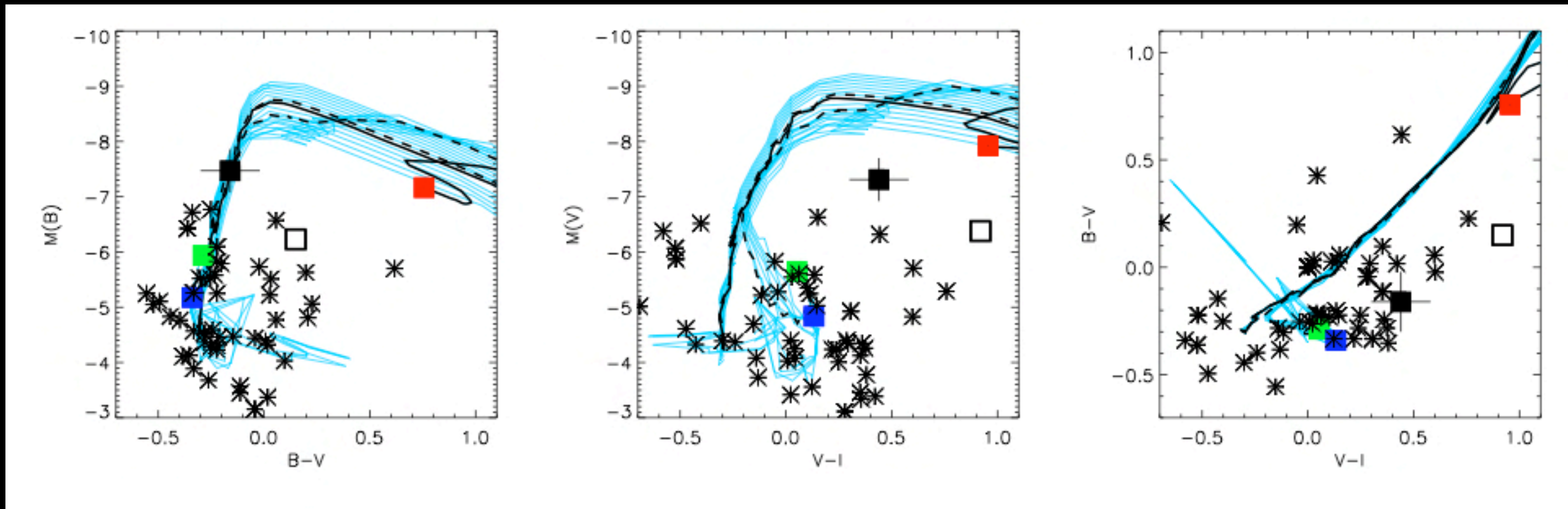
SN2008ax detection
M_V = -7.4

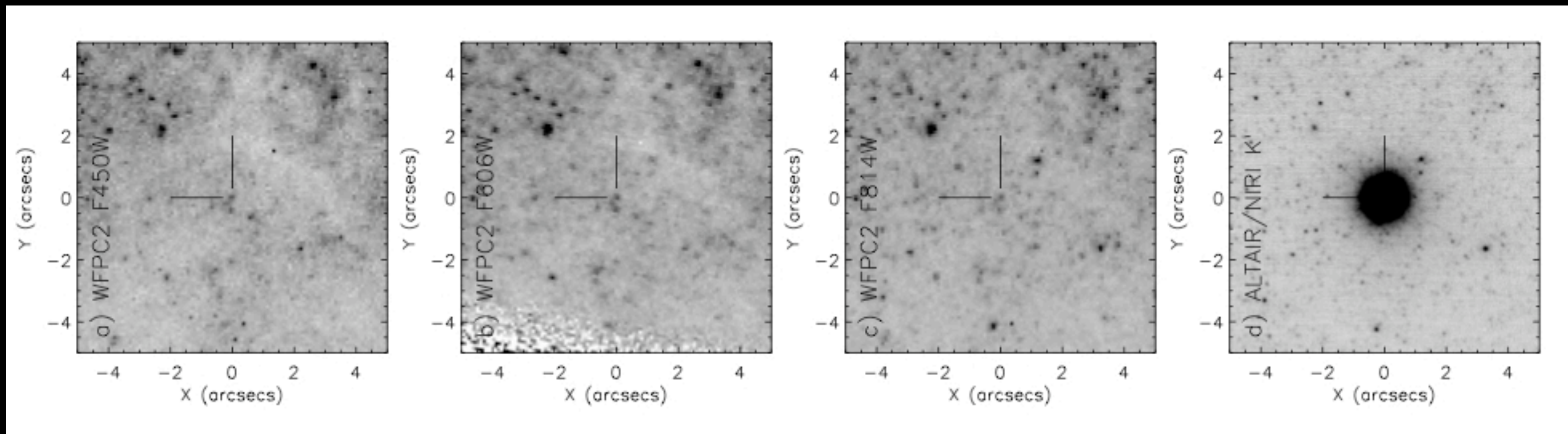


From Crockett 2009 (PhD Thesis),
See also
Van Dyk et al. 03
Maund & Smartt 05,
Maund et al. 05
Gal-Yam et al. 05

- LMC (or M31) WR magnitude distributions ⇒ ~5-10% probability we have had no detections by chance
- SN2008ax : detection of WNL progenitor of a IIb (Crockett et al. 08)

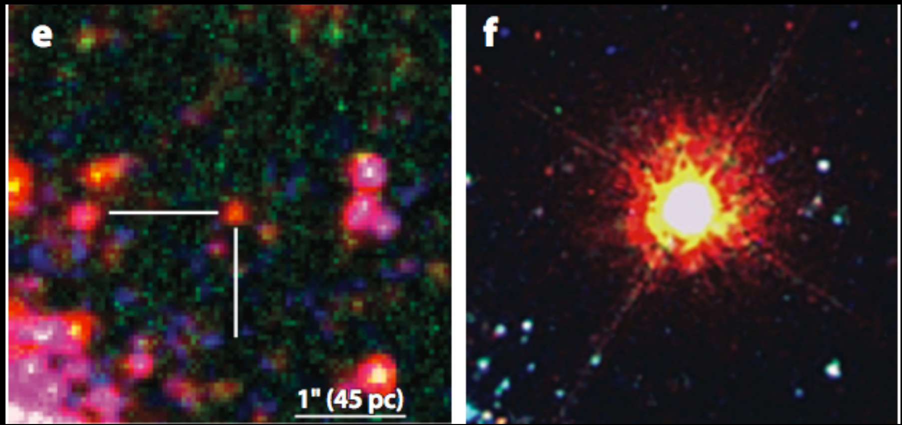
SN2008ax : IIb + WNL progenitor ?



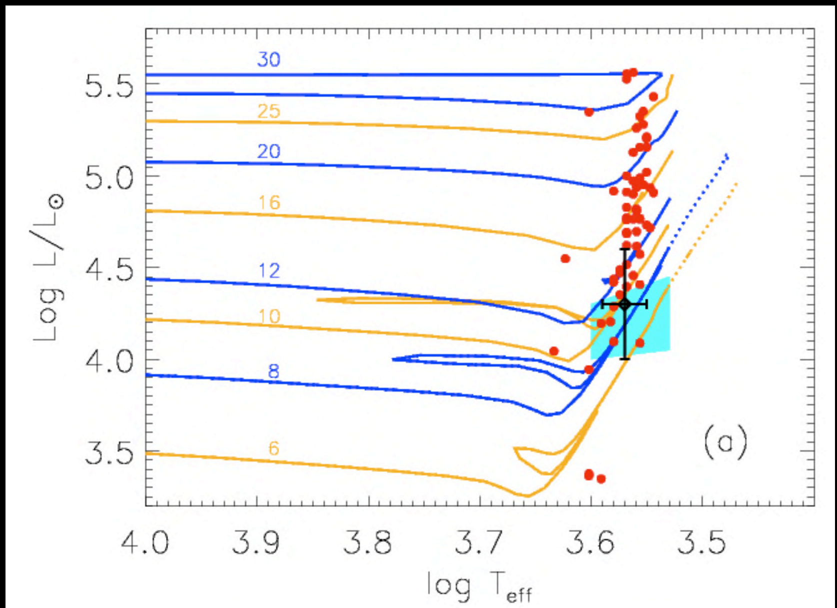


Crockett et al. 2008, Pastorello et al. 2008

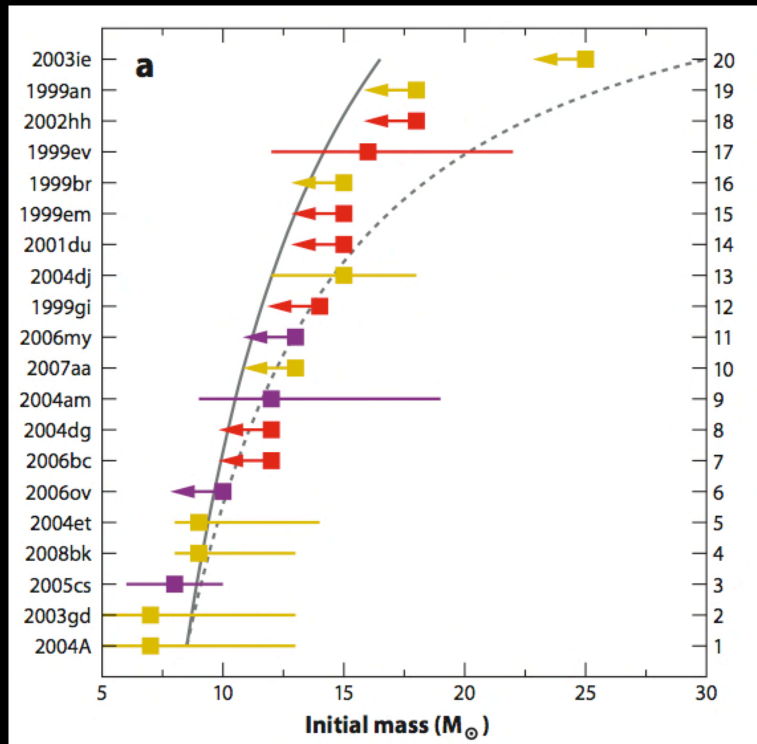
Summary



e
f
1" (45 pc)



30
25
20
16
12
10
8
6
5.5
5.0
4.5
4.0
3.5
Log L/L⊙
4.0
3.9
3.8
3.7
3.6
3.5
log Teff
(a)



a
2003ie
1999an
2002hh
1999ev
1999br
1999em
2001du
2004dj
1999gi
2006my
2007aa
2004am
2004dg
2006bc
2006ov
2004et
2008bk
2005cs
2003gd
2004A
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16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
5
10
15
20
25
30
Initial mass (M⊙)

Summary

- Red supergiants are progenitors of II-P Sne (as predicted by Chevalier, Falk & Arnett, and others …)
- Confident detections of 4 (+ several others) low luminosity progenitors : log L/L≈ 4.3± 0.3, colours imply M-type supergiants
- Suggests these stars *do NOT* go through 2nd dredge up

- Lower limit for core-collapse : no more than 7-8$M_{\odot}$
- Lack of high mass progenitors – statistically significant ?
- No detection of Ibc progenitors – the known massive WR population is not the progenitor population of Ibc SNe
- Massive stars collapse to black holes – we have not yet detected the SN ? $16 \rightarrow 60?\ M_{sol}$

Lessons Learned

- 10 years of searching – not as easy as first thought
- 93 CCSNe within 28Mpc : ~32 with good pre-explosion images
- 4 high significance, unambiguous detections. 3 questionable ones, plus 3 on unresolved host clusters
- 5-10% yield (but large number of upper limits restrictive)
- High resolution images (HST or 8m AO) crucial

The future :

- Extend to another ~10years
- Focus on the 10Mpc volume : large HST project (huge legacy science potential)
- Guaranteed ~15 CCSNe in 10 years. With full mosaic, deep WF3/ACS of the galaxies, discovery potential high

Comparison of codes