



Queen's University  
Belfast

European Research Council



# Core-collapse supernovae, their progenitors and nucleosynthesis

S. J. Smartt<sup>1</sup>, A. Jerkstrand<sup>1</sup>, J. Maund<sup>1</sup>, C. Fransson<sup>2</sup>, J. Sollerman<sup>2</sup>, M. Fraser<sup>3</sup>, J.J. Eldridge<sup>4</sup>

<sup>1</sup>Queen's University Belfast

<sup>2</sup>Stockholm University

<sup>3</sup>University of Cambridge

<sup>4</sup>University of Auckland

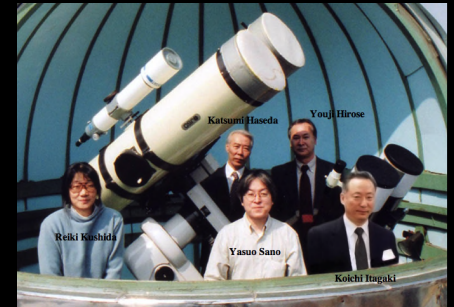
In collaboration with **PESSTO**  
<http://www.pessto.org>



Image Credit: NASA/Filippenko/Challis



Image Credit: R.Jay Gabany



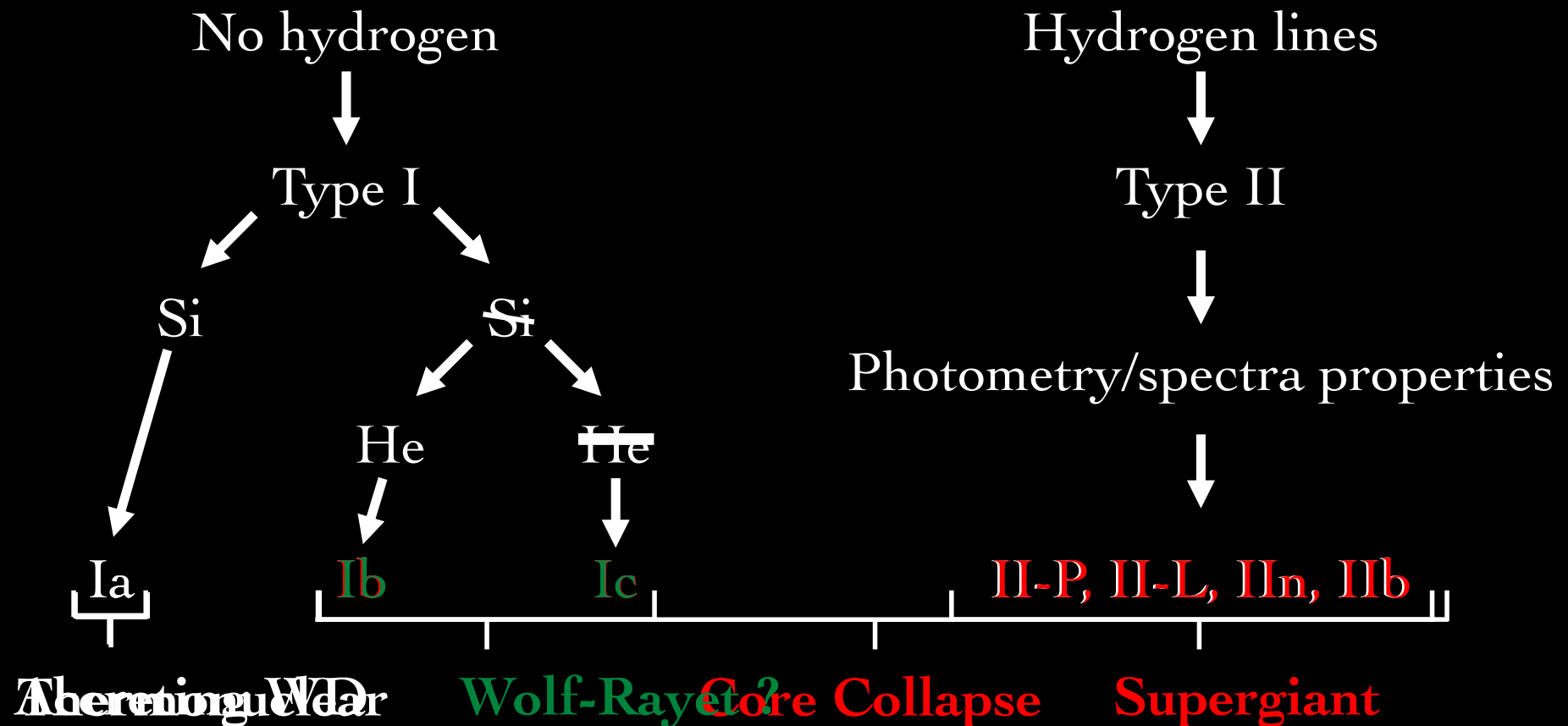
Nearby SNe discovered by amateur astronomers , and two professional search teams:  
North : LOSS (Filippenko & Li)  
South : CHASE (Pignata et al. )  
Also now Palomar Transient Factory (Kulkarni et al).



Tom Boles, Suffolk

# Supernova types

Supernovae are classified by their optical spectra

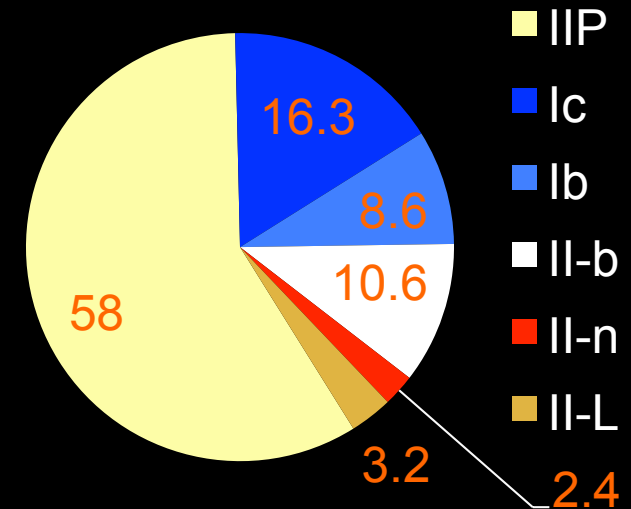


# Detected SN rates in Local Volume

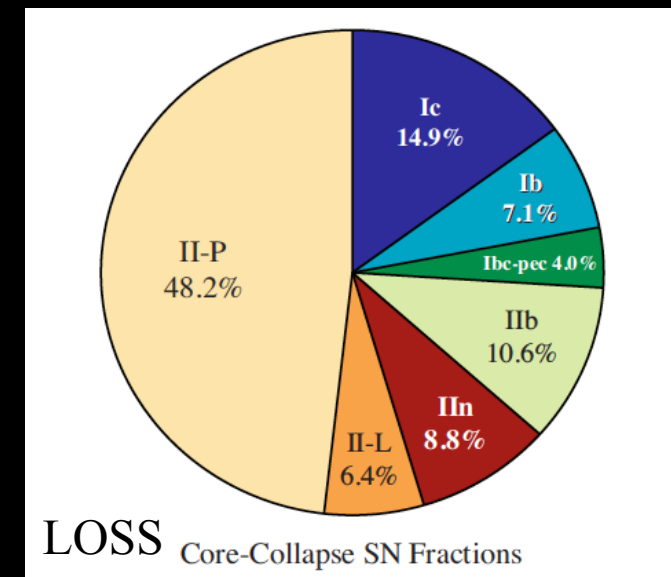
Smartt et al., 2009; Eldridge et al. 2012, in prep. (14.25yrs)

SN Type	Number	Relative rate (per cent)
IIP	55 (73.6)	$58.0 \pm 6.8$
III	3 (4)	$3.2 \pm 1.6$
IIn	3 (3)	$2.4 \pm 1.4$
IIf	11 (13.4)	$10.6 \pm 2.9$
IIfec (87A-like)	1 (1.3)	$1.0 \pm 0.9$
Ib	9 (10.9)	$8.6 \pm 2.6$
Ic	17 (20.7)	$16.3 \pm 3.6$
Total	99 (126.9)	

## 28Mpc rates



- 19980101-2012033121: 127 CCSNe discovered in galaxies with  $V_{\text{vir}} < 2000 \text{ km s}^{-1}$  (9 CCSNe  $\text{yr}^{-1}$ )
- LOSS : controlled, within  $\sim 60 \text{ Mpc}$ . Leaman et al, Li et al., Smith et al. 11



# Neutrinos & Explosion Mechanism

Paradigm: Explosions by the convectively supported neutrino-heating mechanism

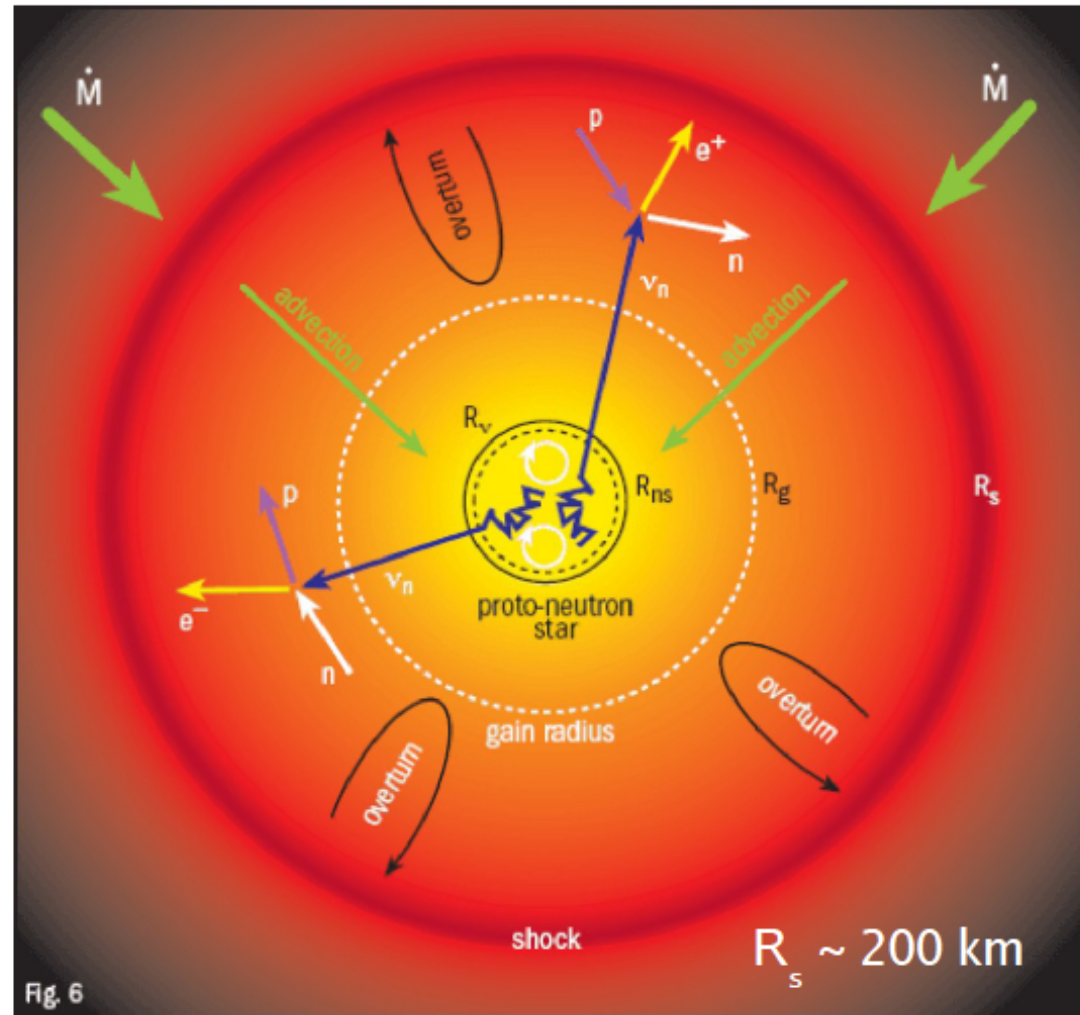


Fig. 6

- “Neutrino-heating mechanism”: Neutrinos ‘revive’ stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities enhance the heating mechanism (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Scheck et al. 2004,06,08).

Slide from H.T. Janka

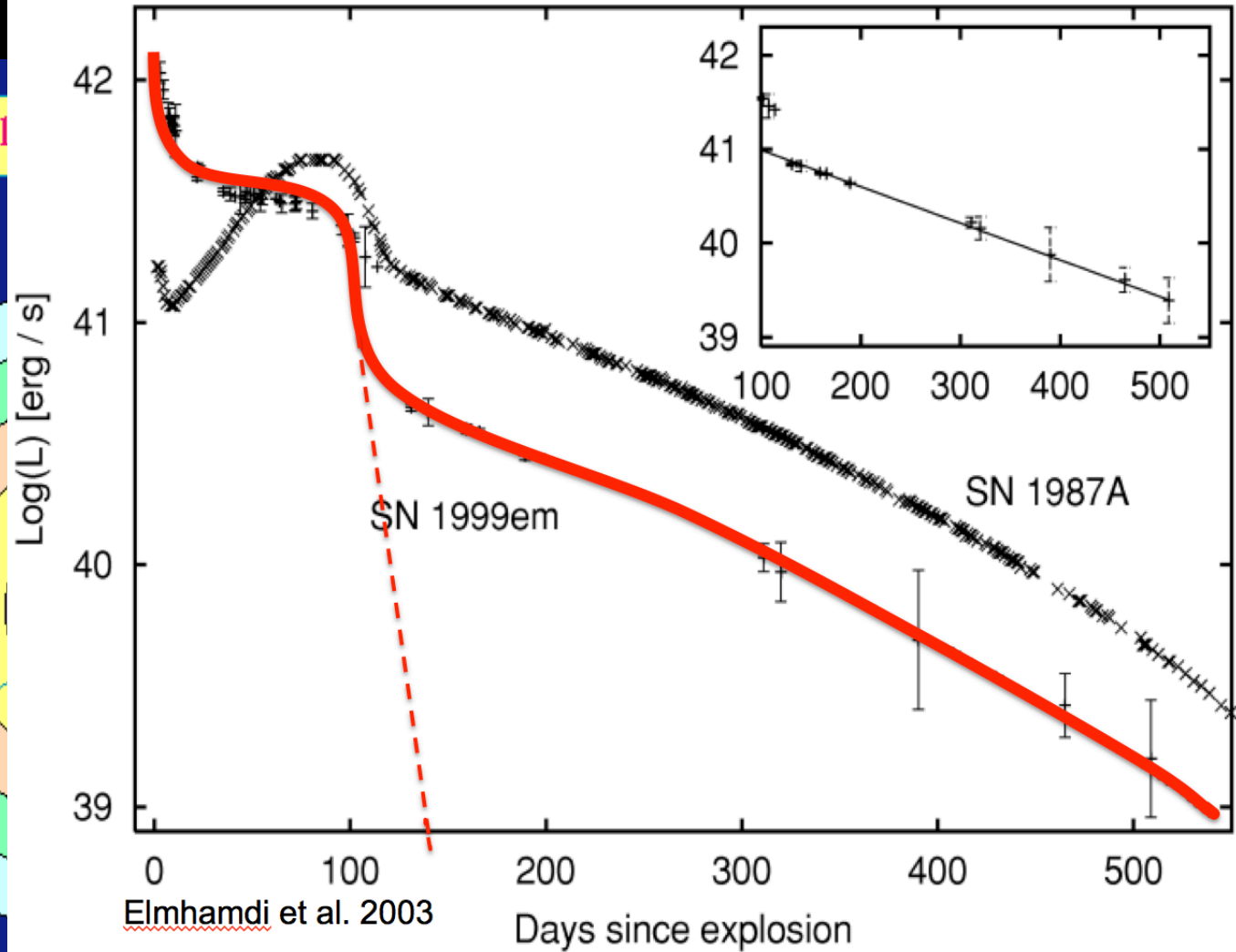
## Stellar Burning Shell

$$T = 2 \times 10^7 \text{ K}$$

$$\rho = 10^2 \text{ g / cm}^3$$

$$T = 4 \times 10^9 \text{ K}$$

$$\rho = 10^7 \text{ g / cm}^3$$



## Betelgeuse

Sun (1 pixel)

Jupiter is invisible at this scale

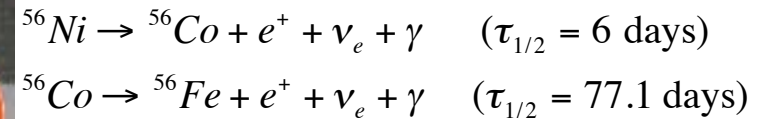
Sirius Pollux

Arcturus

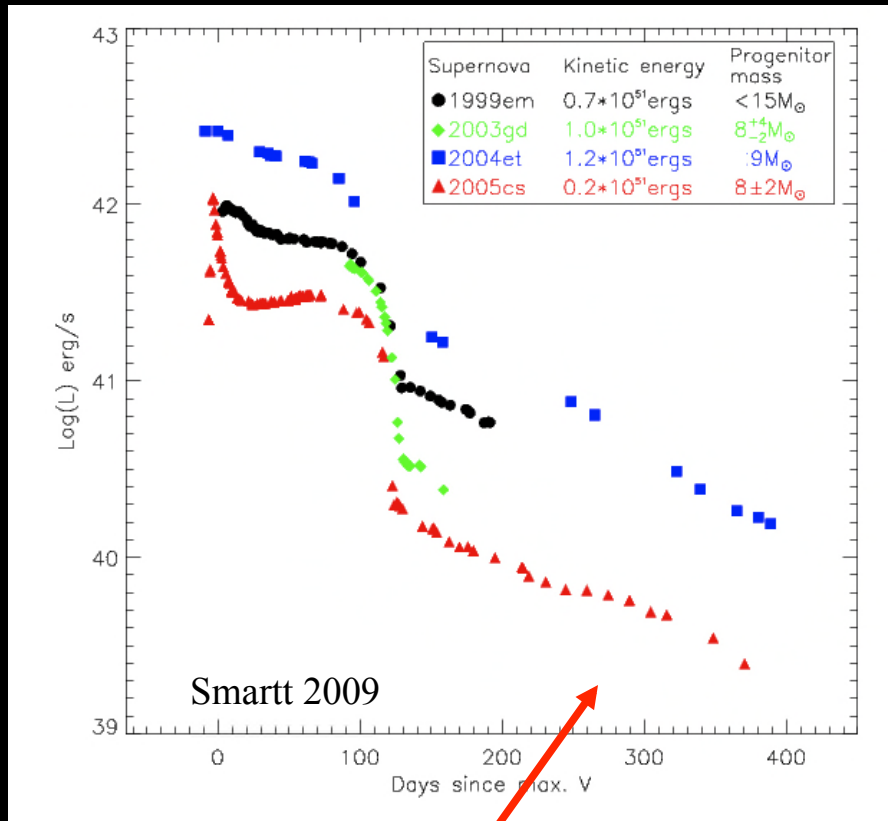


Rigel

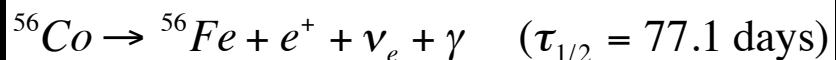
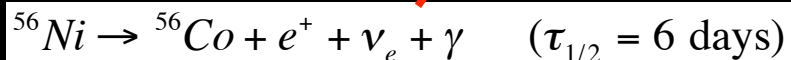
Aldebaran



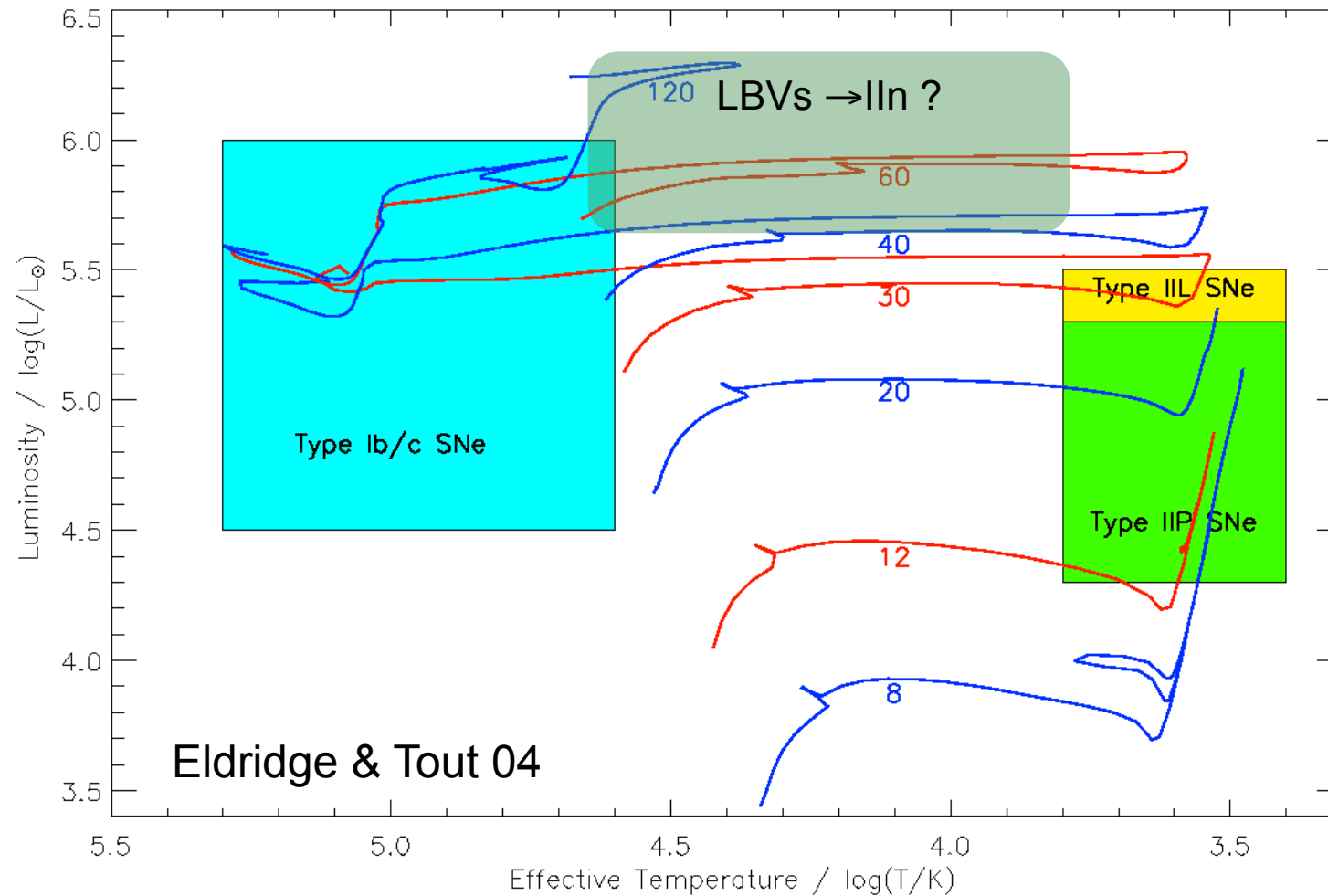
# II-P typical lightcurves



- Late time tail powered by radioactive  $^{56}\text{Ni}$
- $^{56}\text{Ni}$  explosively created from Si burning after core-collapse
- Direct probe of the explosion



# Theory HRD - STARS code



M101



**~26% SN-HST  
image  
coincidence rate**

Barred Spiral Galaxy NGC 1672



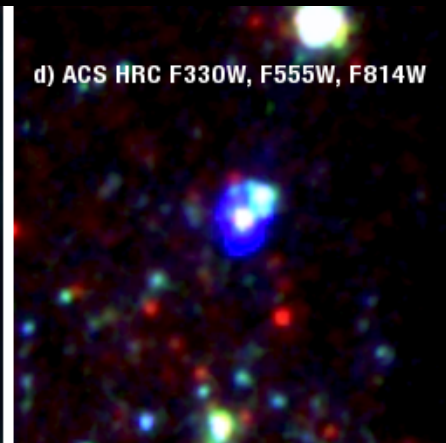
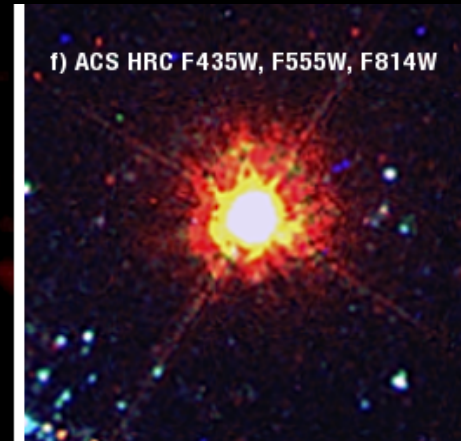
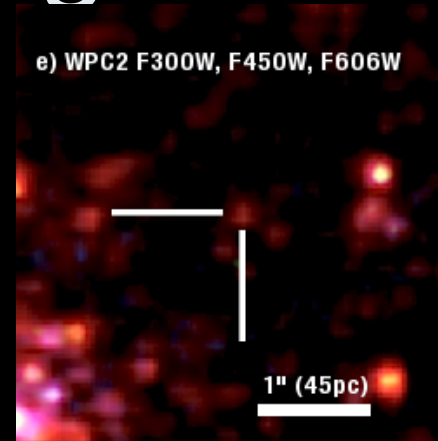
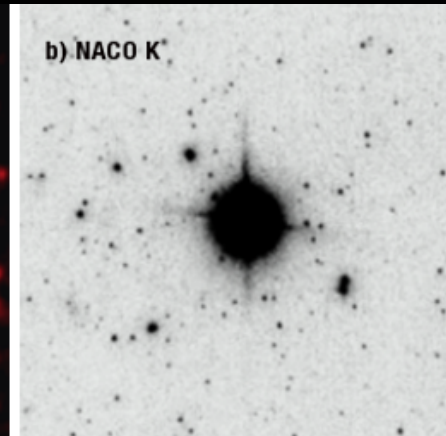
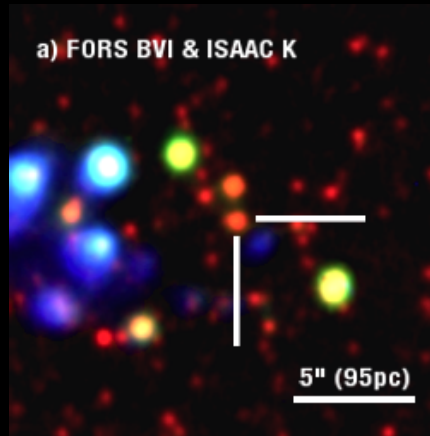
NGC3949



Hubble  
Heritage



# Detection of progenitors



- SN2008bk, SN2005cs, SN2003gd
- Red star identified coincident with all three.
- Typical magnitudes :  $M_V \sim -4.5$  ;  $M_I \sim -6.5$
- Review in Smartt 2009
  - Van Dyk et al. 2003, 2010, Li et al. 2006
  - Smartt et al. 2004, 2009, Maund et al. 2005, Mattila et al. 2008

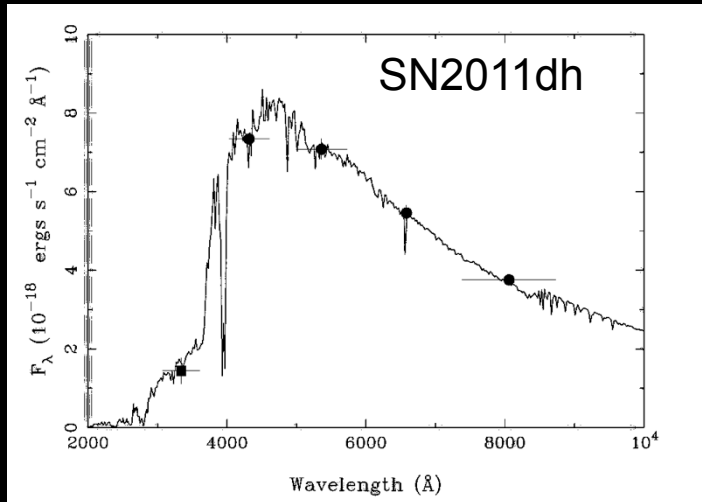
# NGC7793 with VLT FORS



SN2008bk ( $d=3.4\text{Mpc}$ ,  $\mu=27.68\pm 0.05$ )  
Pietrzynski et al. 2011 (Cepheids)



# Photometry and stellar SED

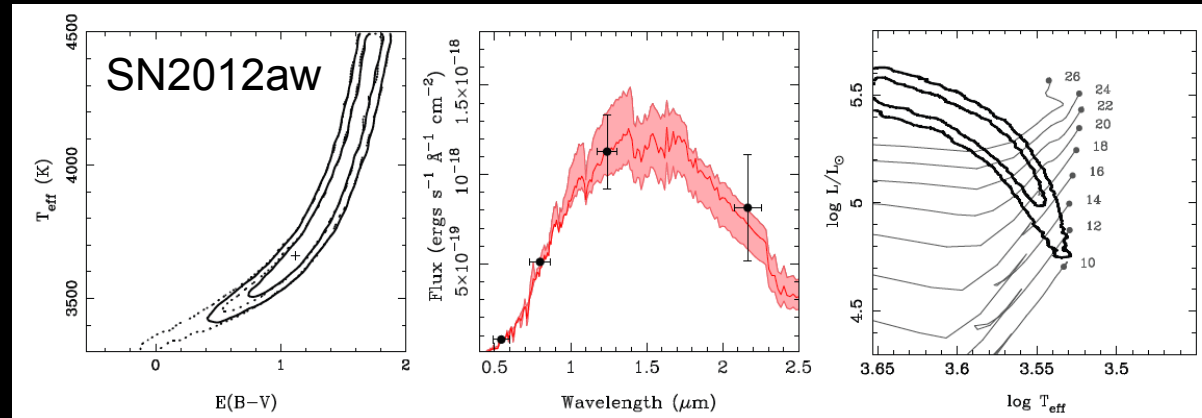


Maud et al. 11 ; Van Dyk et al. 11

Single stellar SED

$T_{\text{eff}} = 6000 \text{ K}$  ; F8 supergiant ;

$M_V = -7.5$



Fraser et al. 12 ; Van Dyk et al. 12 ; Kochanek et al. 12

*What is the extinction ?*

*Kochanek et al :  $R_V \neq 3.1$  , silicate dust*

*Log L < 5.0 dex*

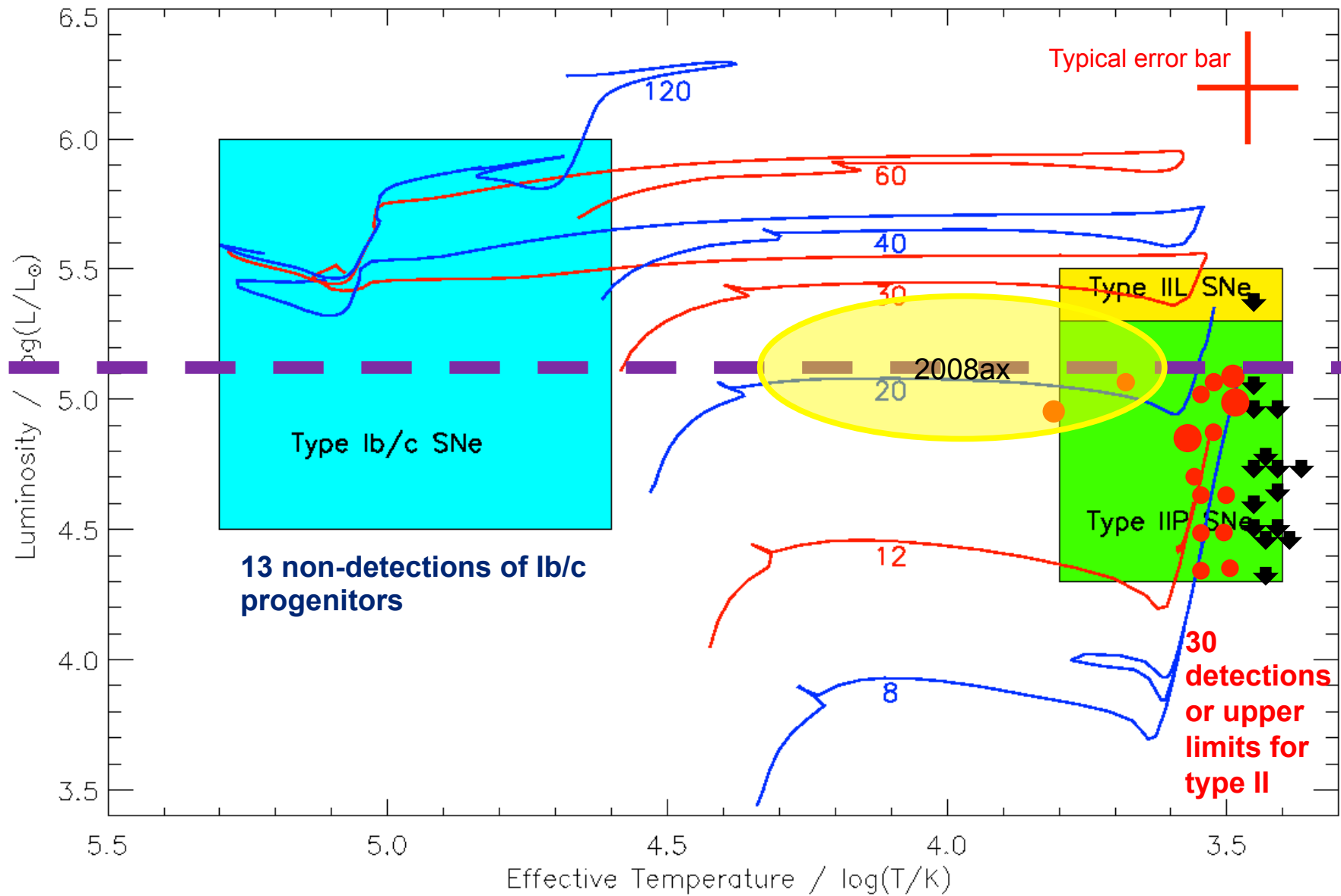
Dust extinction is largest uncertainty – CSM dominated ?

Walmswell & Eldridge (2011) : underestimate  $A_{V,I}$

Kochanek et al. (2012) : overestimate  $A_{V,I}$

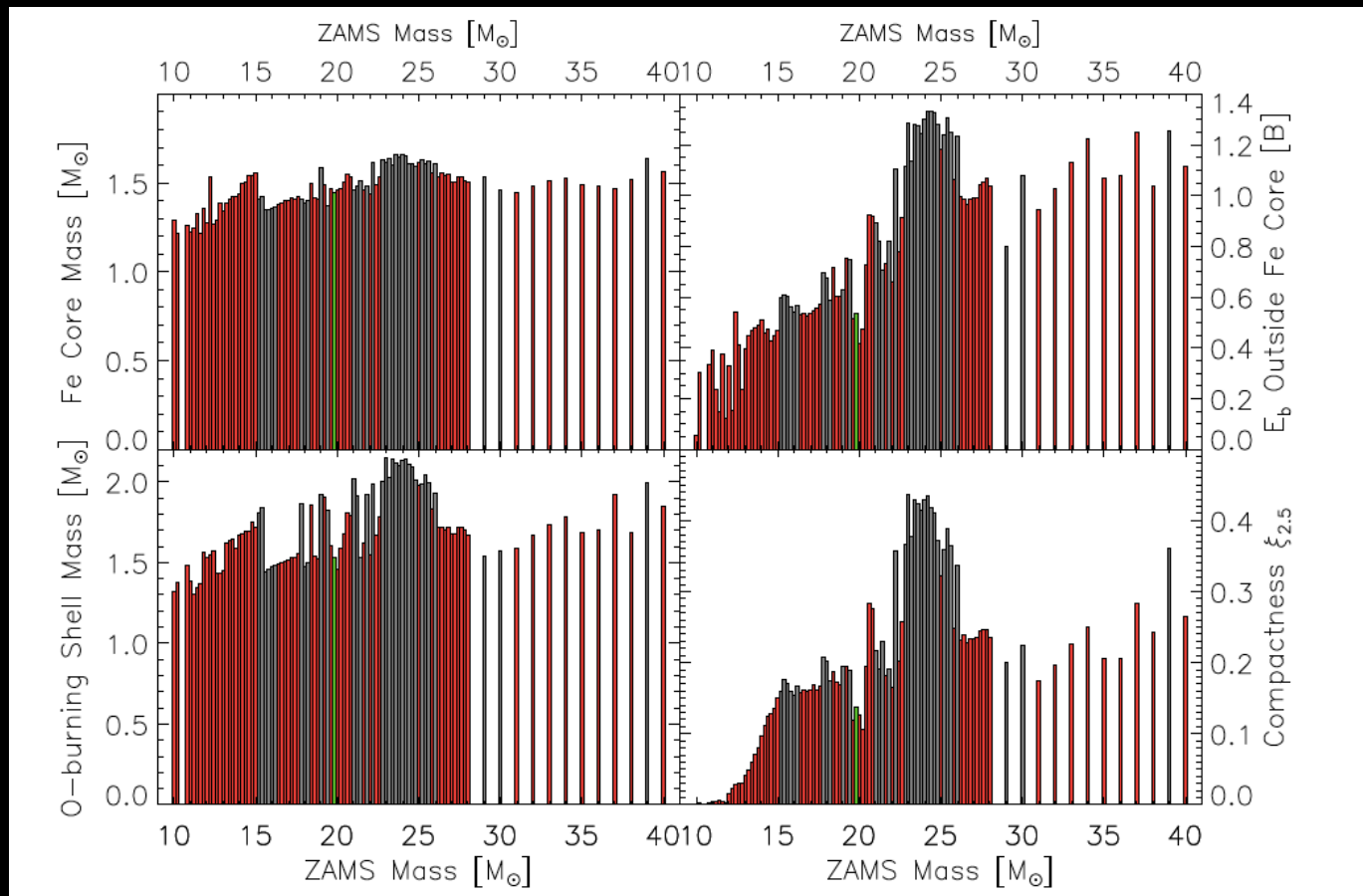
See also Elias-Rosa et al. 10, 11

# Results 1998 – 2013; within 28 Mpc (43 total)



For Salpeter IMF : 75% of 8-100 $M_{\odot}$  stars are 8-20 $M_{\odot}$  (14 “missing”)

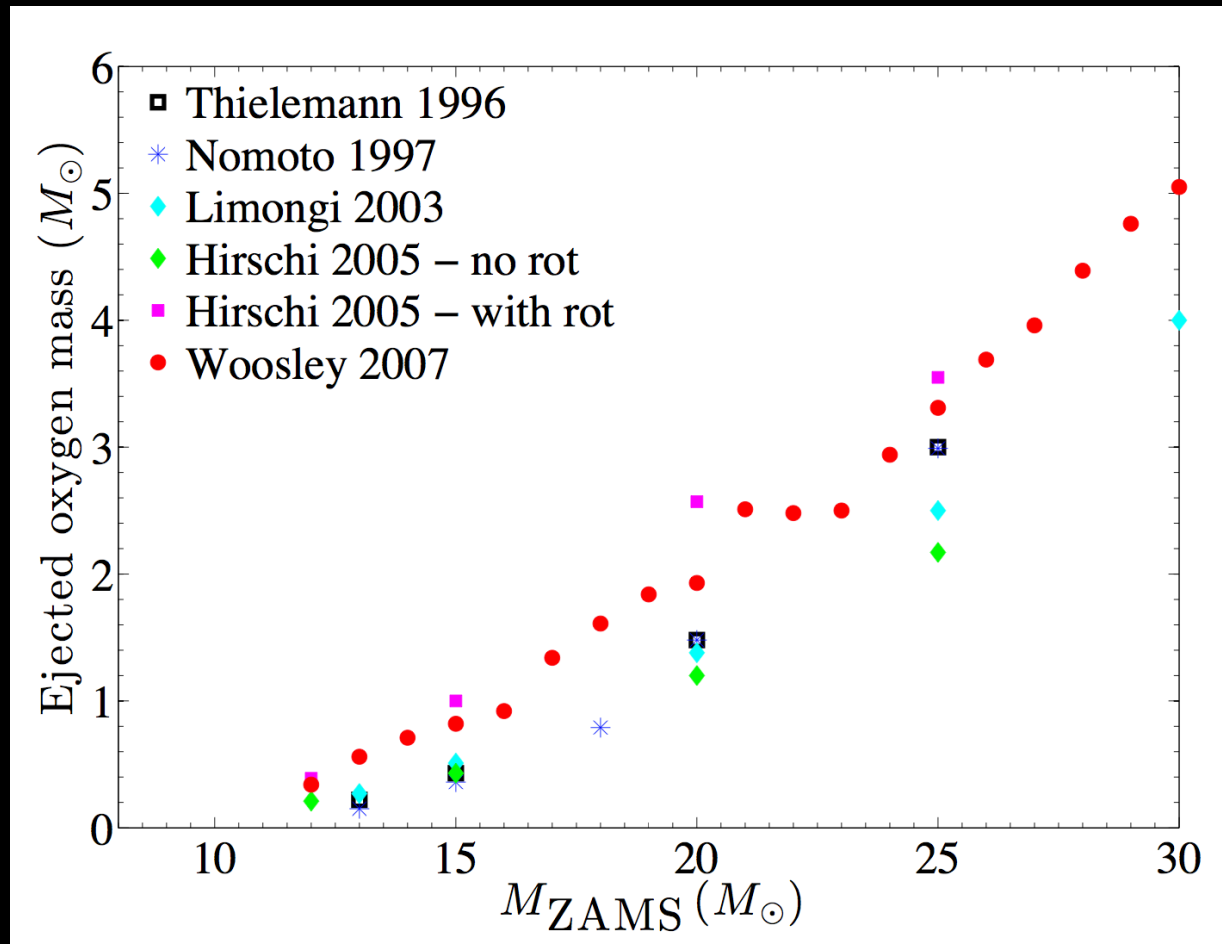
# Black hole formation



- Ugliano, Janka et al. 2012, arXiv1205.3657
- Neutrino driven explosions – no simple mass dependency
- Woosley : results show similar idea
- Compactness parameter : Ott & O'Connor



# Nucleosynthesis : oxygen mass as function of progenitor mass

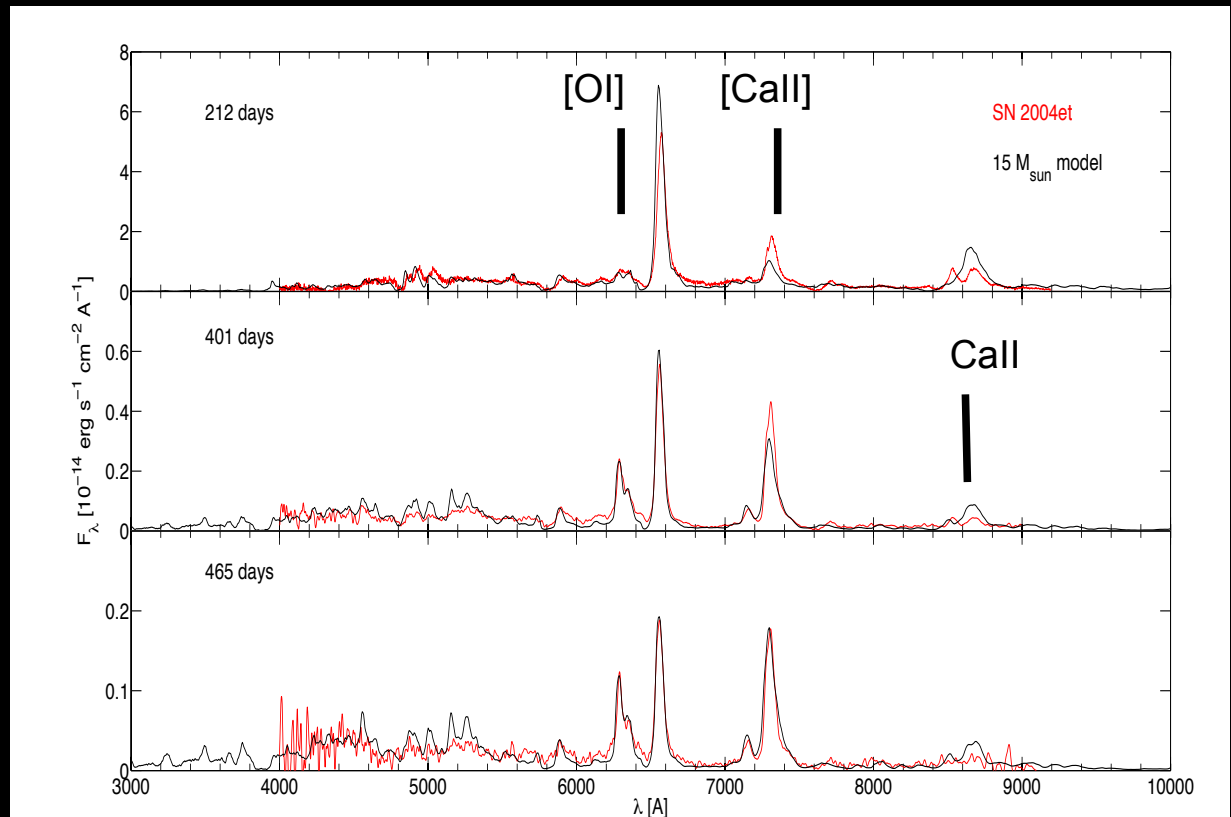
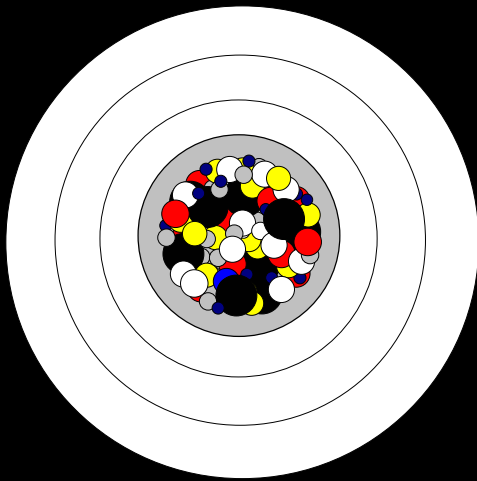


Data : stellar evolutionary calculations

Image credit : Anders Jerkstrand

# Stockholm : Radiative transfer model

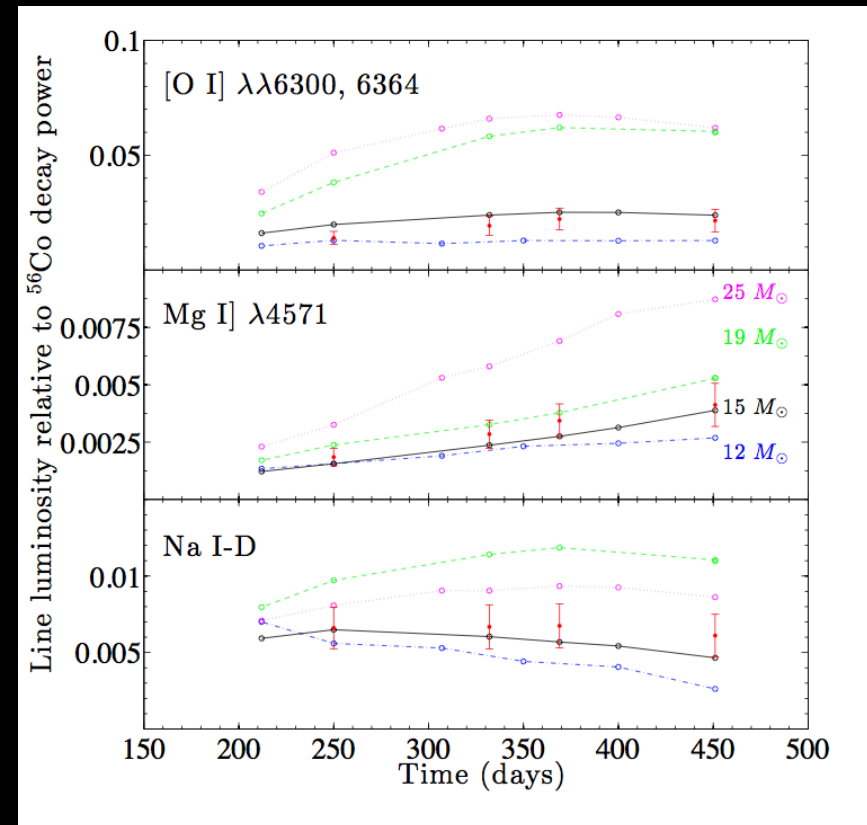
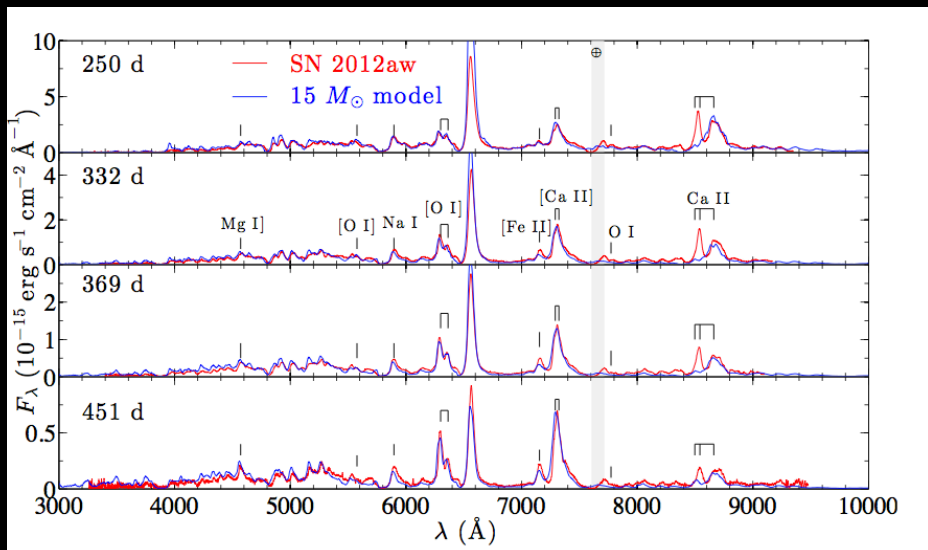
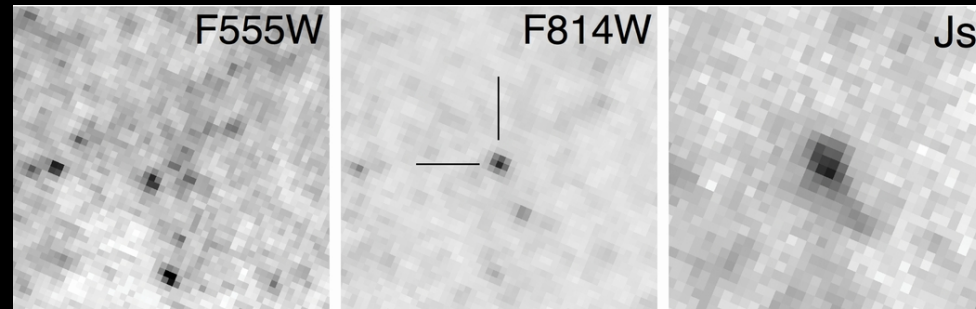
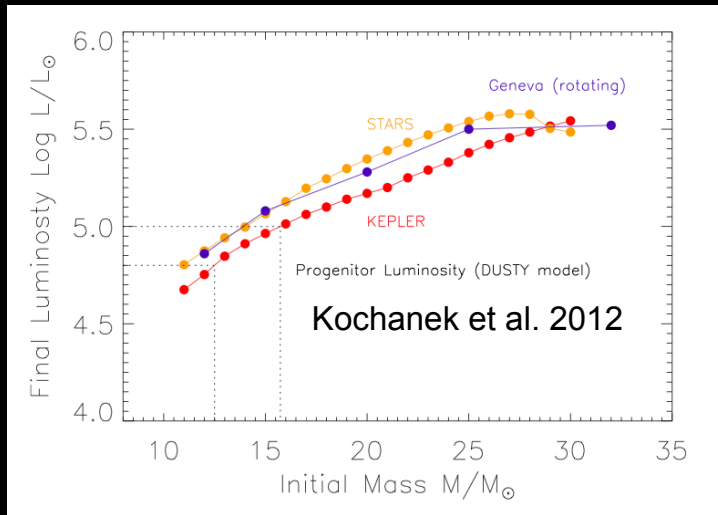
- Radioactivity
- Temperature, ionization and excitation solutions
- Radiative transfer
- Macroscopic mixing



SN 2004et compared to a  $15 M_{\text{sun}}$  model ( $\sim 0.5 M_{\text{sun}}$  oxygen)

Kozma & Fransson 1998  
Jerkstrand et al. 2014, 2012 ; 2010

# SN2012aw in M95 (10Mpc)

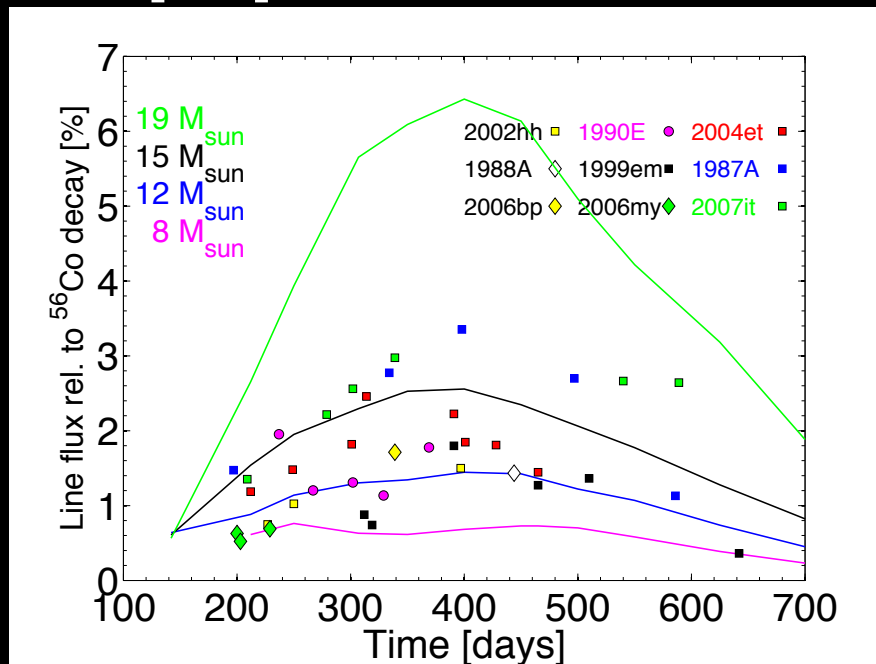


Jerkstrand, Smartt et al. 2014

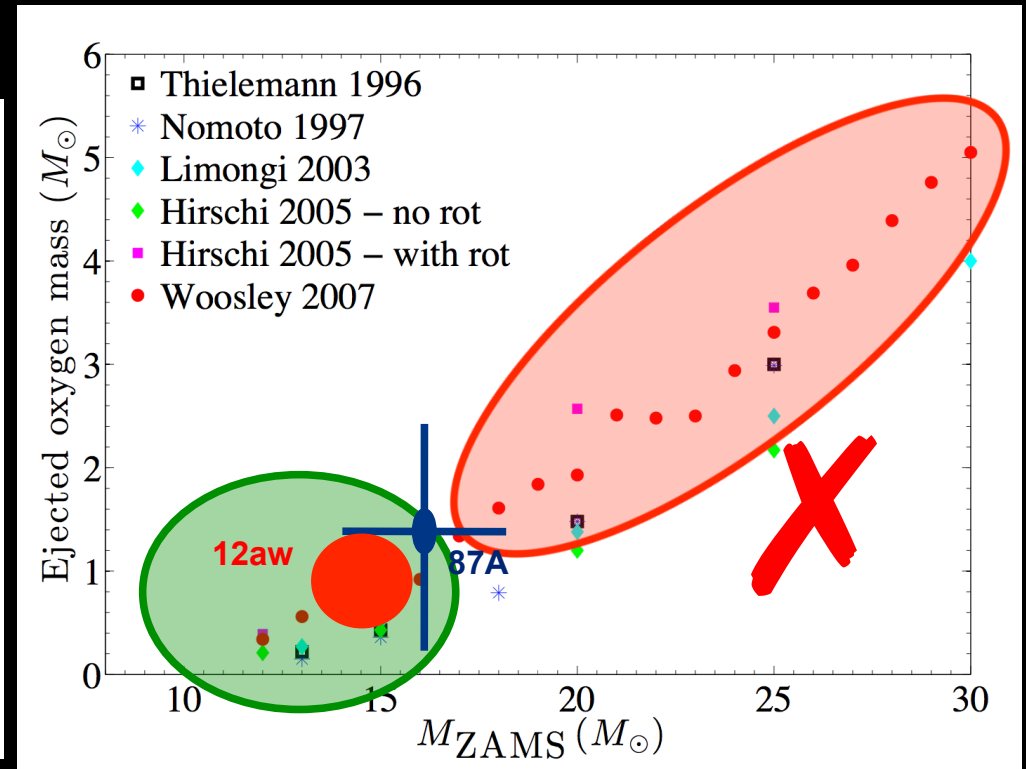
13-16  $M_{\odot}$  progenitor,  $0.6^{+0.3}_{-0.1} M_{\odot}$  of synthesised oxygen

# Type IIP SNe and oxygen production

[O I] 6300, 6364 Å

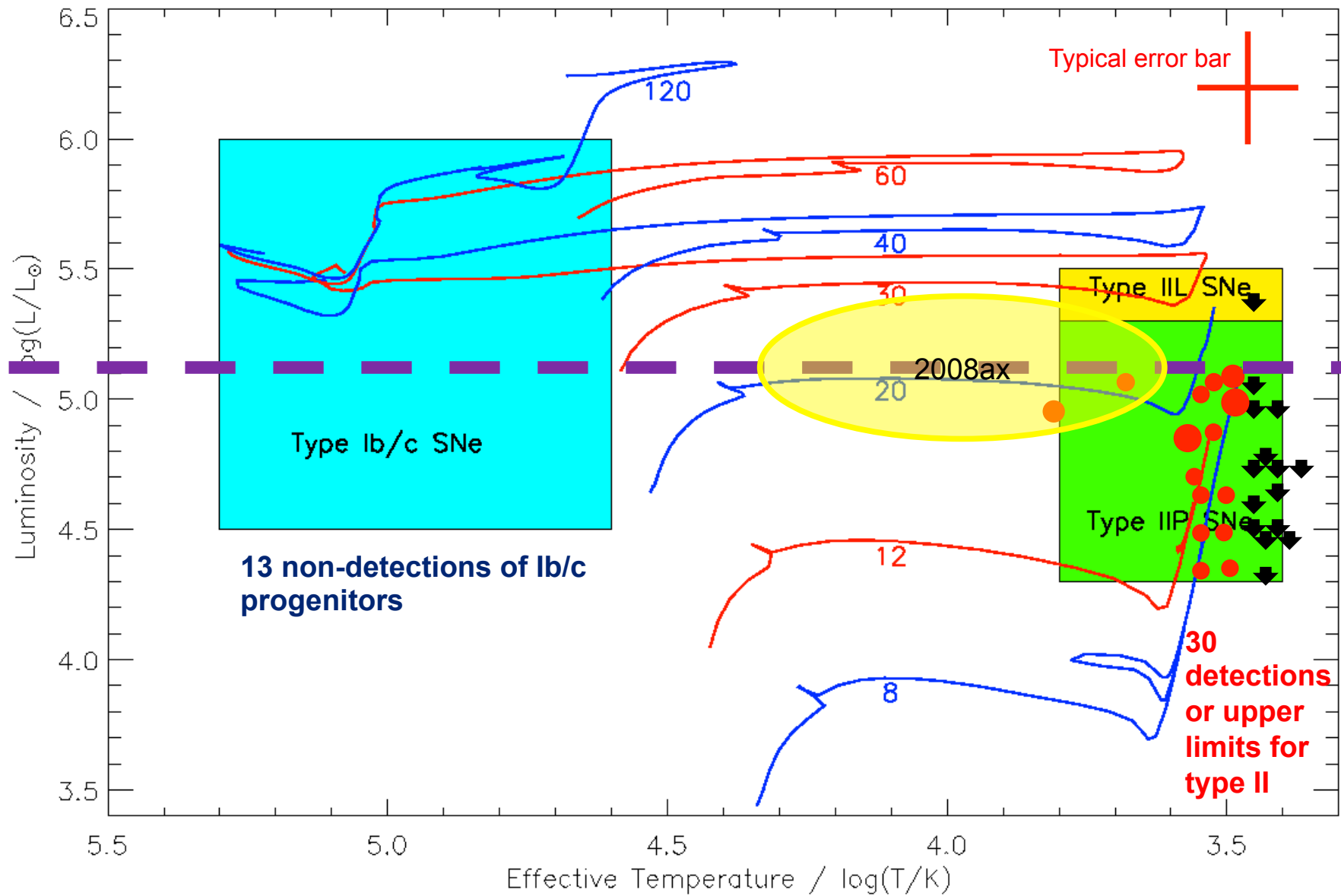


Jerkstrand et al. in prep  
Maguire et al. 2012



We haven't detected  
the cosmic oxygen  
producers

# Results 1998 – 2013; within 28 Mpc (43 total)



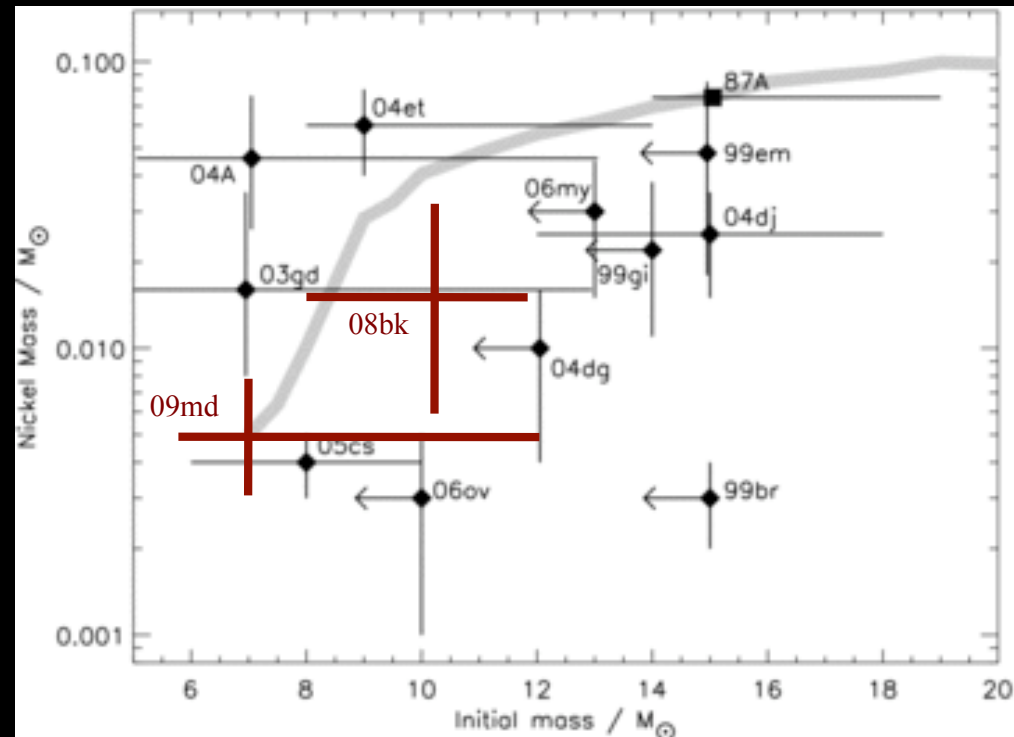
For Salpeter IMF : 75% of 8-100 $M_{\odot}$  stars are 8-20 $M_{\odot}$  (14 “missing”)

# Summary

- Direct detections of progenitors – now routine
- Attempting to be complete within fixed volume, as far as data allows (16 yrs+)
- Statistical dearth of progenitors above luminosity  $\text{Log } L/L_{\odot} \sim 5.1$  dex
- No SN with ejected oxygen mass  $> 1M_{\odot}$
- Implication : most, but not all, stars  $M_{\text{zams}} > 20M_{\odot}$  make black holes and no (or faint) SNe
- Future :
  - progenitor model consistent with pre-discovery  $\log(L/L_{\odot})$  and ejected O mass
  - Find the cosmic oxygen producers
  - Directly Measure O/Fe as a function of stellar mass

# $^{56}\text{Ni}$ mass vs. ejecta mass

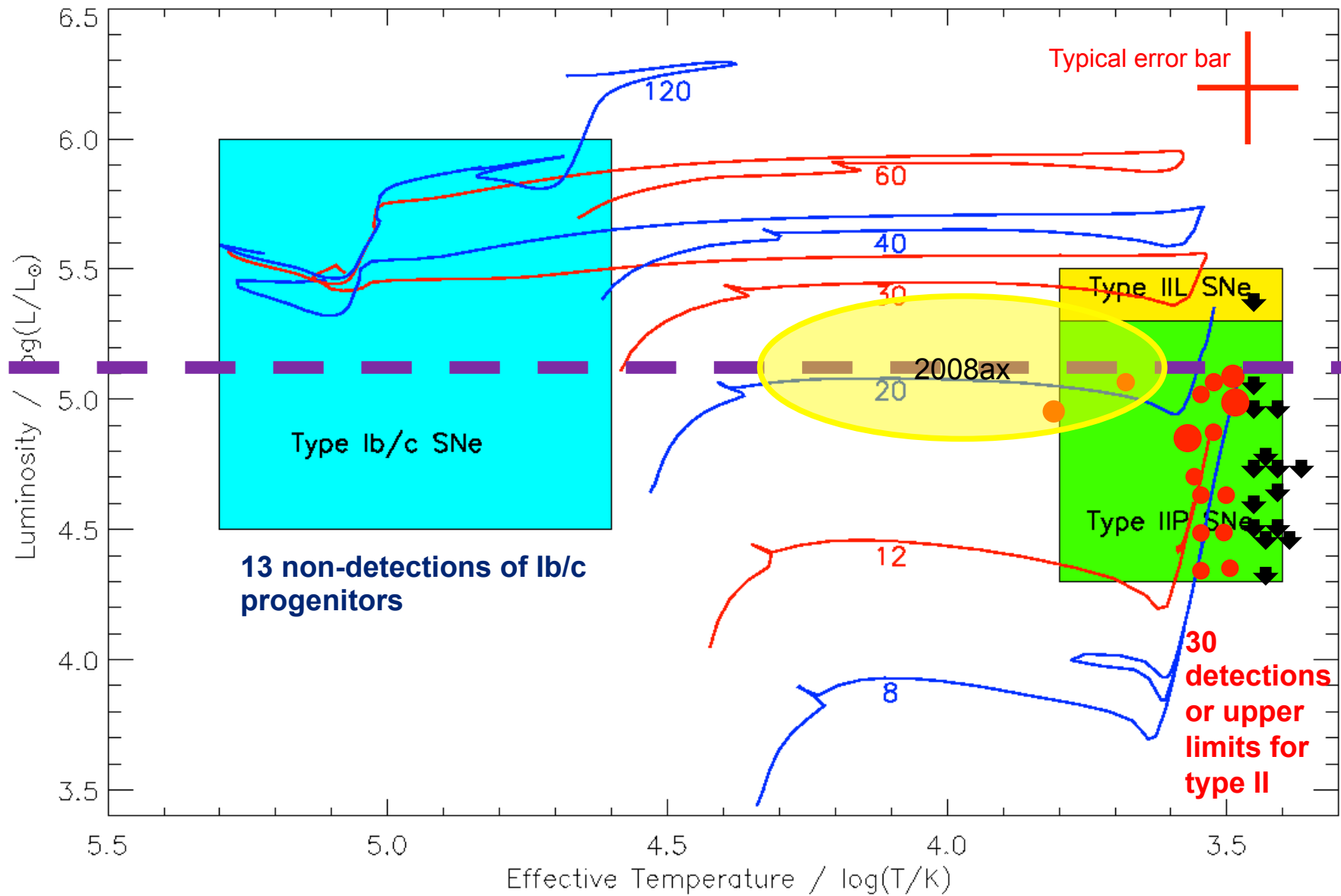
- Lower mass progenitors produce lower amounts of  $^{56}\text{Ni}$
- Grey line – relative mass of O-core/He-core
- Perhaps due to steep density gradient in inner regions ?
- The low luminosity, low KE, II-P SNe come from low mass progenitors
- E-capture explosions ?



Smartt et al. 2009

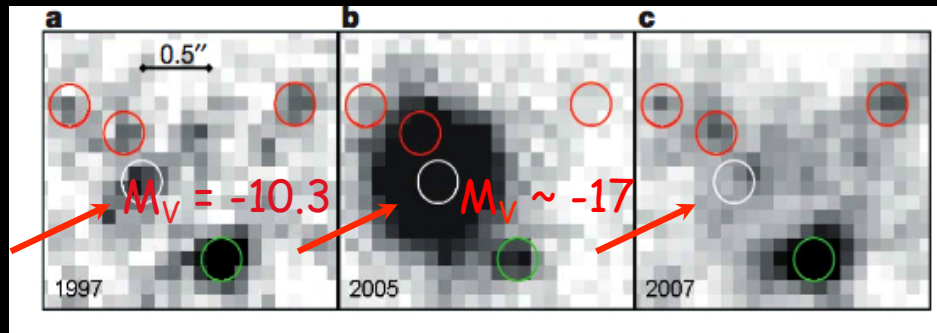
Faint IIP: Pastorello et al. 09, 06  
Kitaura et al. 04, Wanajo et al. 09

# Results 1998 – 2013; within 28 Mpc (43 total)

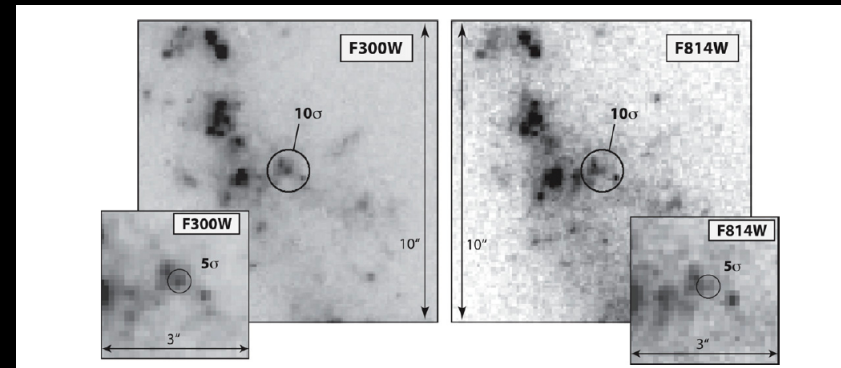


For Salpeter IMF : 75% of 8-100 $M_{\odot}$  stars are 8-20 $M_{\odot}$  (14 “missing”)

# What of the LBV-like progenitors ?

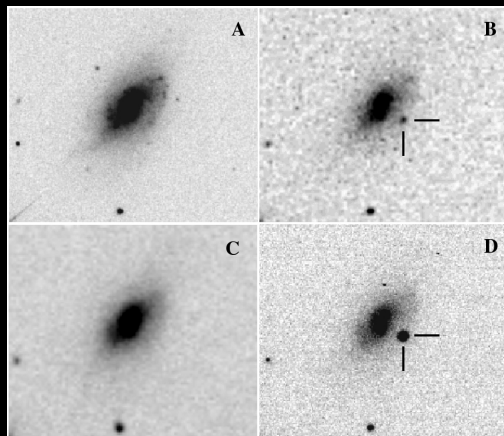


- SN 2005gl (~66Mpc) Progenitor gone
- Gal-Yam & Leonard 09



- SN2010jl (~50Mpc) - either massive young cluster, or LBV
- Suggests  $M_{ZAMS} > 30M$
- Smith et al. 2011

But both  $d > 50\text{Mpc}$ , can they be common enough to account for the “missing” high mass progenitors ?



- SN2006jc : LBV-like outburst detected (Pastorello et al. 07 Foley et al. 07)
- SN2009ip !