TYPE IIP SUPERNOVAE: HYDRODYNAMIC MODELS AND PROGENITORS

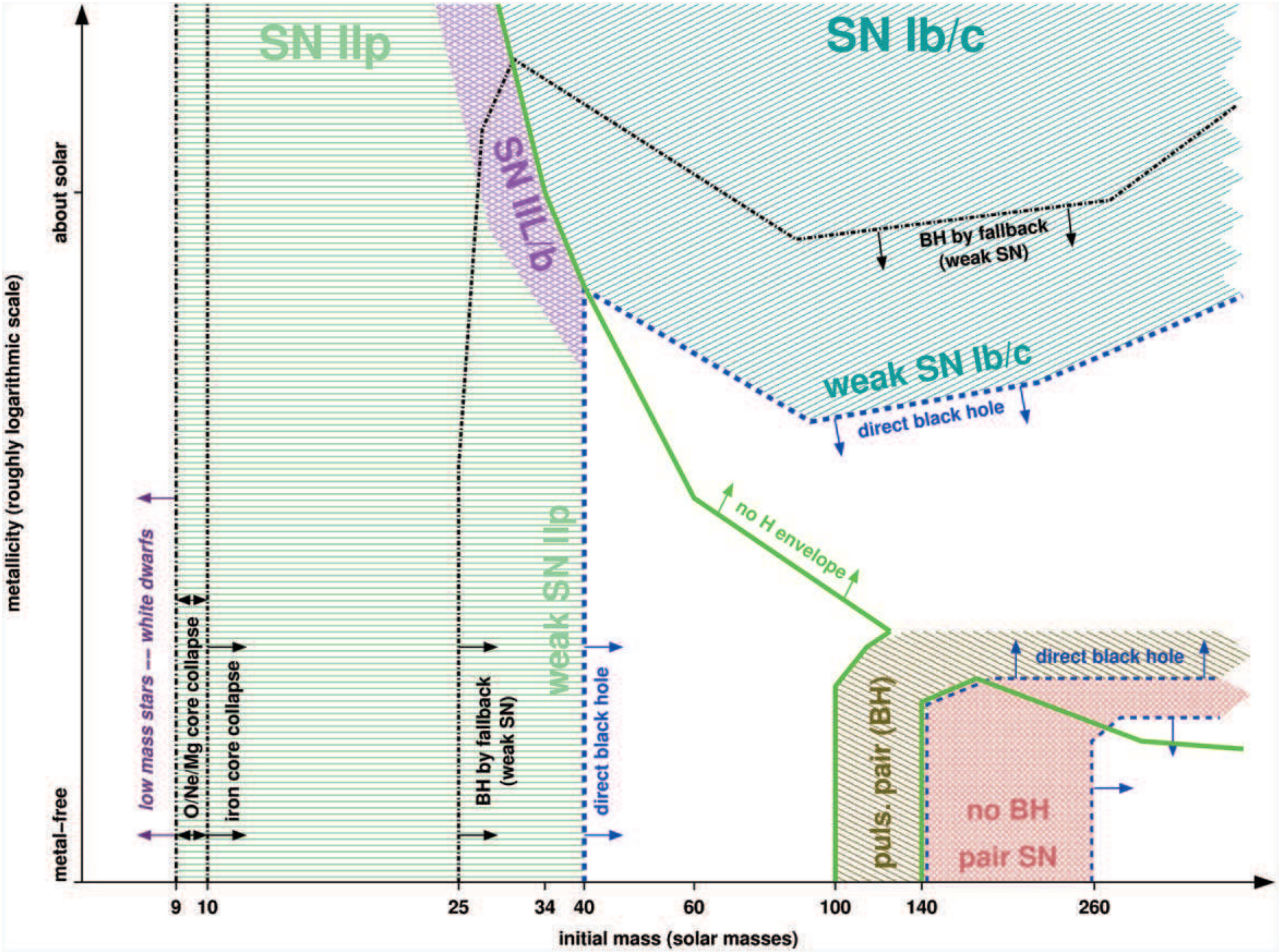
Victor Utrobin
ITEP, Moscow

in collaboration with:
Nikolai Chugai (INASAN), Ewald Müller (MPA), and Wolfgang Hillebrandt (MPA)

XXVIth IAP Annual Colloquium "Progenitors and environments of stellar explosions"

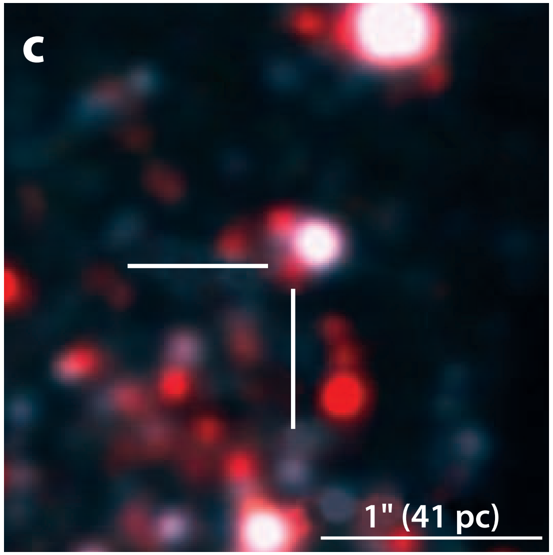
Paris, France
June 28 to July 2, 2010

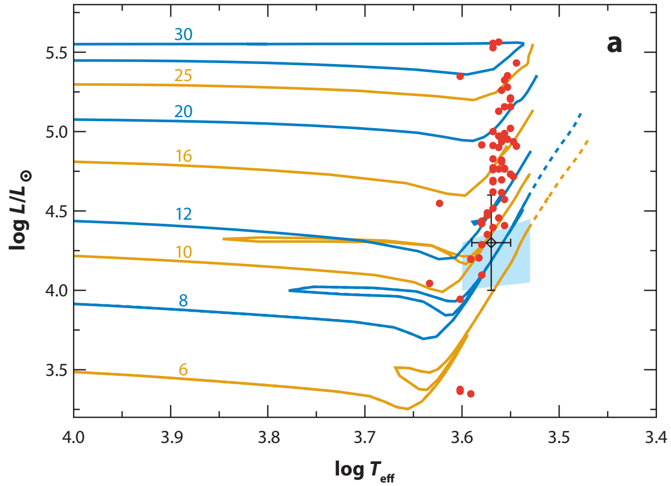
Death of Massive Stars



General paradigm: type IIP SNe originate from the 9–25 $M_{\odot}$ M-S stars (Heger et al. 2003).

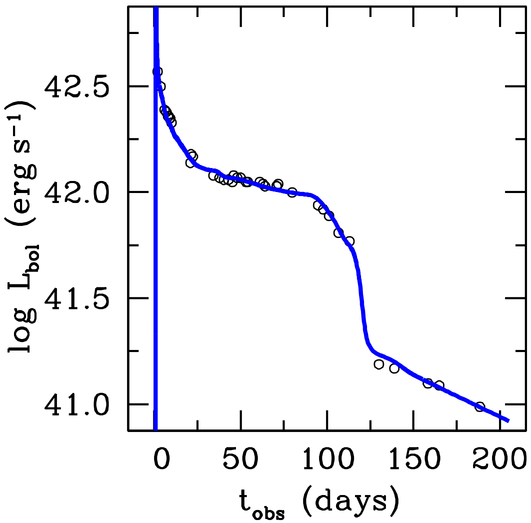
Two Methods to Estimate Mass of the Progenitor

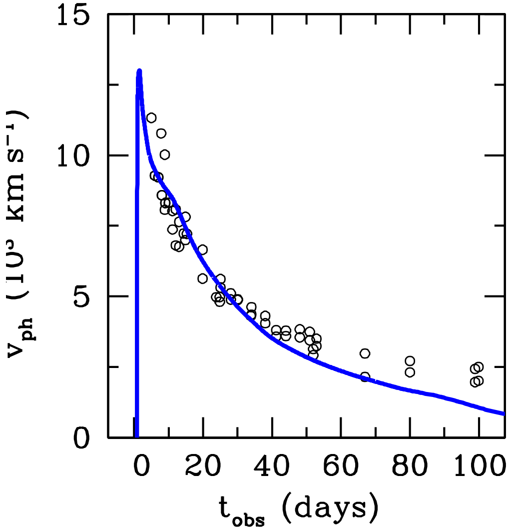




"Evolutionary mass"

The flux and the color index of detected pre-SN can be converted into M-S stellar mass using the stellar evolution models. Evolutionary mass is measured for 8 pre-SNe, and for 10 pre-SNe the upper limits are estimated (Smartt et al. 2009, Smartt 2009).

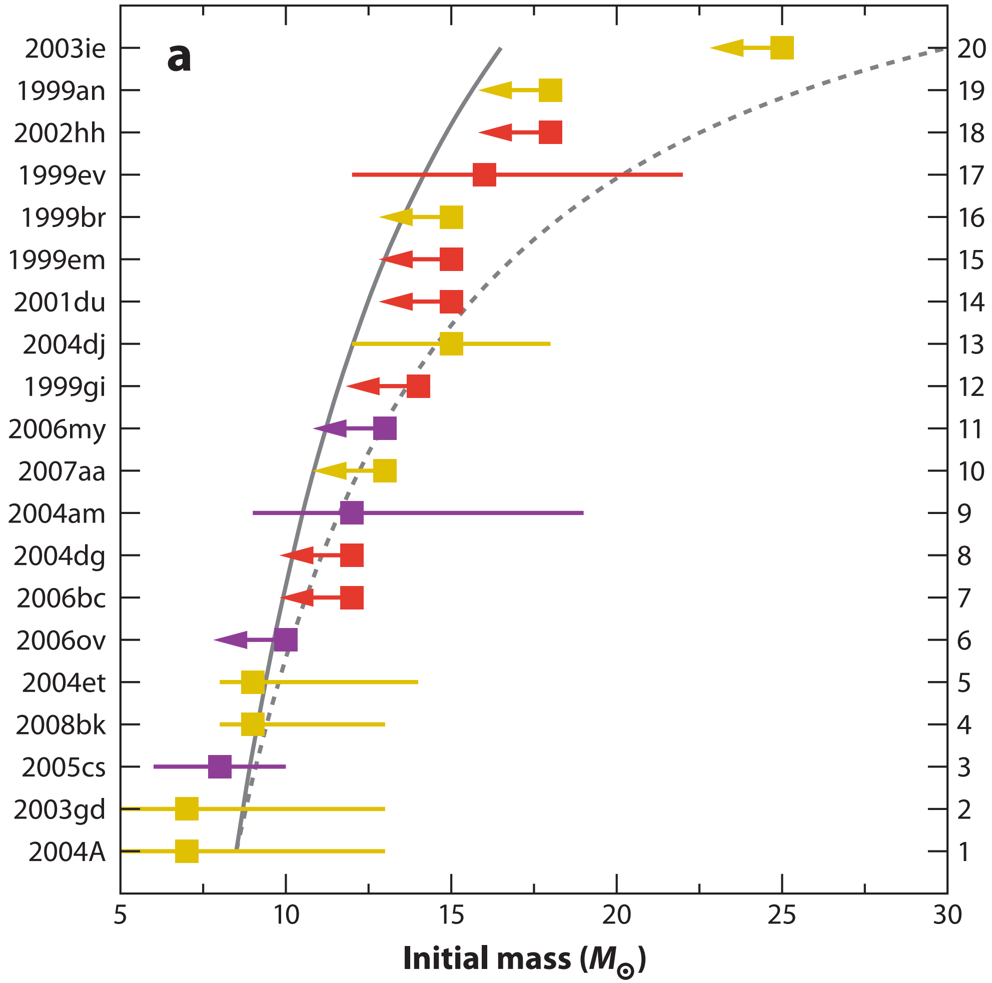




"Hydrodynamic mass"

Hydrodynamic modeling recovers the ejecta mass which, combined with NS mass, determines pre-SN mass. The latter and the mass lost by stellar wind give the mass estimate of M-S star. Hydrodynamic mass is measured only for 5 type IIP SNe.

Directly Detected Type IIP Pre-Supernovae

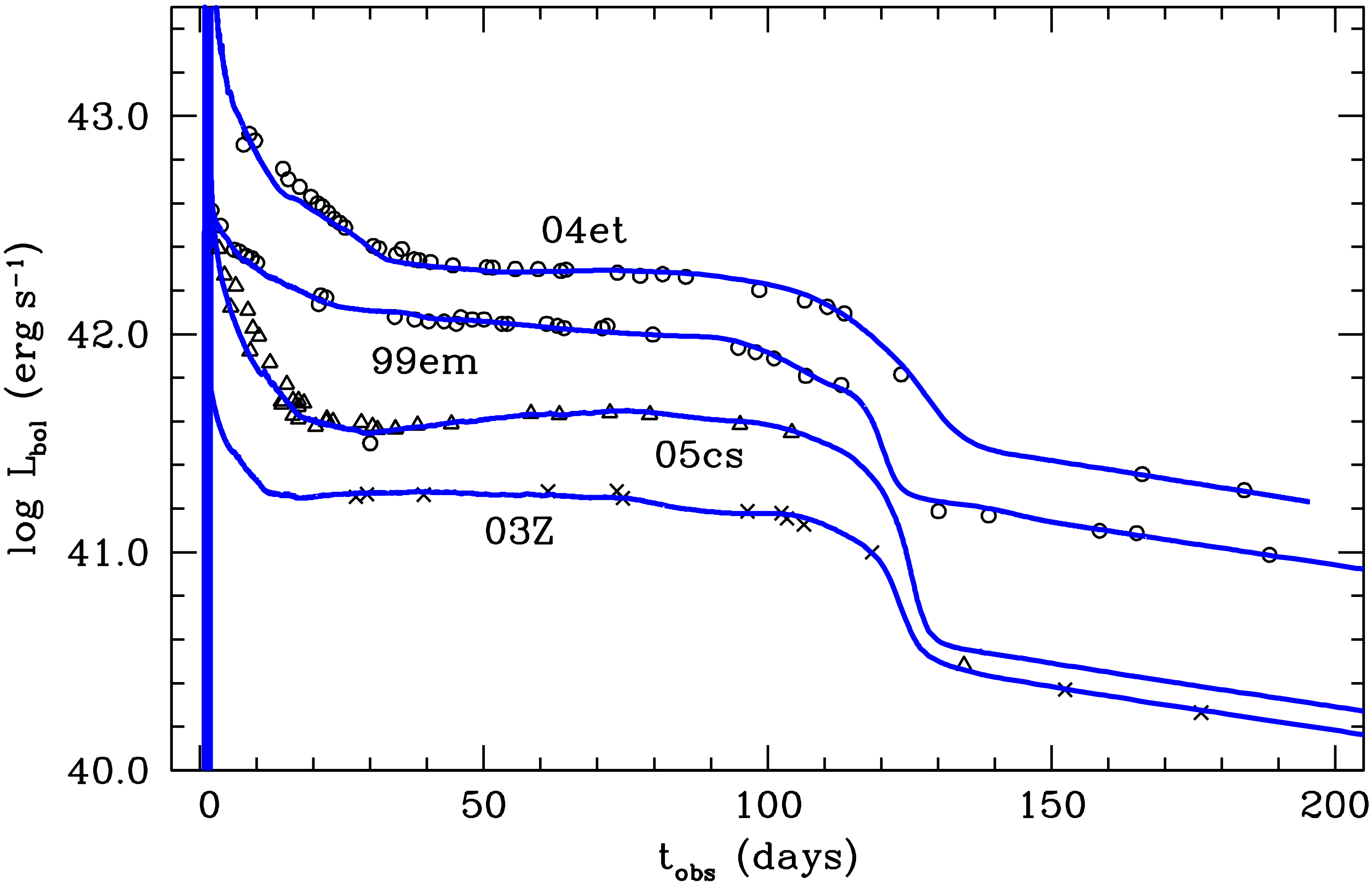


Smartt (2009) provides a brief summary for directly (non)detected pre-SNe:

- The type IIP pre-SNe were confirmed as red supergiants (as predicted by Grassberg, Imshennik & Nadyozhin 1971).
- The minimum initial mass that produces type IIP SN is converging toward $8 \pm 1 M_\odot$.
- A surprising lack of high-mass ($> 16 M_\odot$) type IIP progenitors was found (so called "Red Supergiant Problem").

A cumulative frequency plot of the masses of type IIP progenitors and the Salpeter IMF.
Solid line: Salpeter IMF with $\alpha = -2.35$, $M_{min} = 8.5 M_\odot$, $M_{max} = 16.5 M_\odot$.
Dotted line: Salpeter IMF with $M_{max} = 30 M_\odot$ (Smartt 2009).

Light Curves of Well-Observed Type IIP Supernovae



The bolometric luminosity at the plateau varies by ~ 1.2 dex from the low-luminosity SN 2003Z to the luminous SN 2004et.

Hydrodynamic Models Versus Observed Progenitors

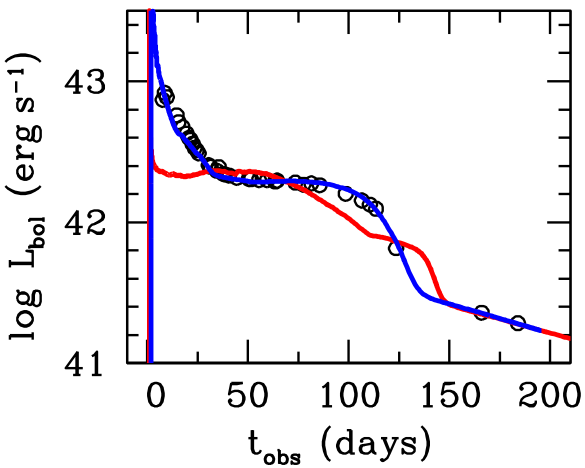
SN	M_{env} ($M_\odot$)	M_{NS} ($M_\odot$)	$M_{\rm pre-SN}$ ($M_\odot$)	ΔM_{lost} ($M_\odot$)	$M_{\rm ZAMS}^{hydro}$ ($M_\odot$)	$M_{\rm ZAMS}^{evol}$ ($M_\odot$)
SN 1987A	18.0	1.6	19.6	1.7	19.8–22.8	16–22[a], 18–22[b,c,d]
SN 1999em	19.0	1.6	20.6	1.6	21.0–23.4	15–25[e], < 15[f]
SN 2003Z	14.0	1.4	15.4	0.2–0.8	14.4–17.4	—
SN 2004et	22.9	1.6	24.5	1.4–3.4	25.0–29.0	8–14[g]
SN 2005cs	15.9	1.4	17.3	1.0	17.6–20.4	7–12[h], 7–13[i], 6–8[j]

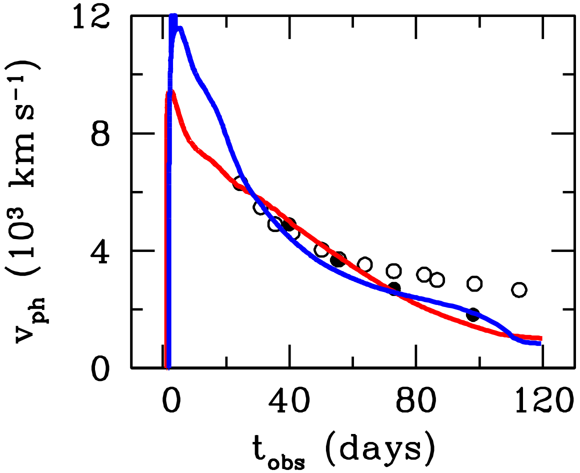
(a) Woosley (1988)
(b) Nomoto & Hashimoto (1988)
(c) Shigeyama & Nomoto (1990)
(d) Woosley et al. (1997)
(e) Leonard et al. (2003)
(f) Smartt et al. (2003)
(g) Smartt et al. (2009)
(h) Maund et al. (2005)
(i) Li et al. (2006)
(j) Eldridge et al. (2007)

- In sharp contrast with the progenitor masses estimated from the pre-explosion images, hydrodynamic modeling suggests that the $15 - 30\ M_\odot$ main-sequence stars are the progenitors of type IIP SNe.

Comparison of Optimal and Evolutionary Models

SN 2004et





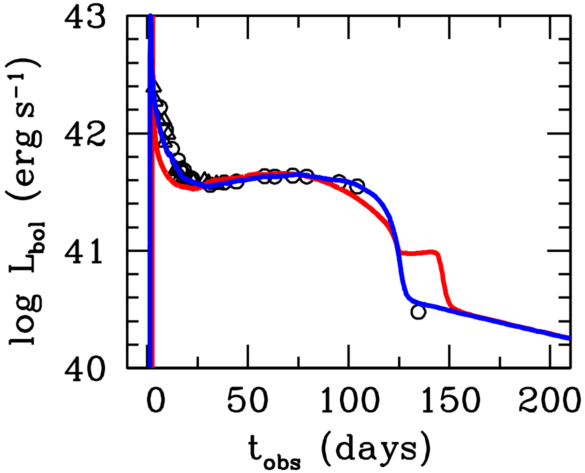
optimal / evolutionary

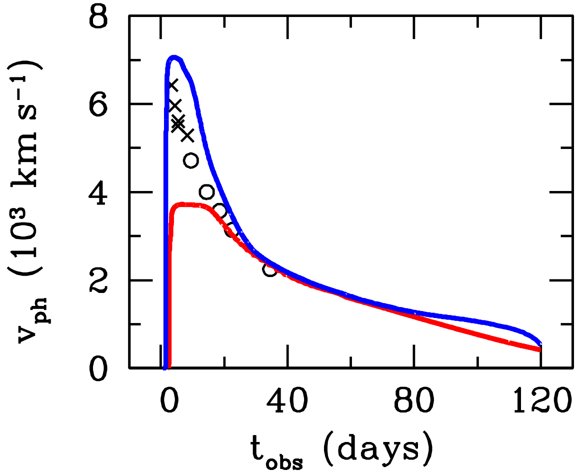
$R_0(R_\odot) = 1500/600$

$M_{env}(M_\odot) = 24.5/15.9$

$E(10^{51}\mathrm{erg}) = 2.3/1.3$

SN 2005cs





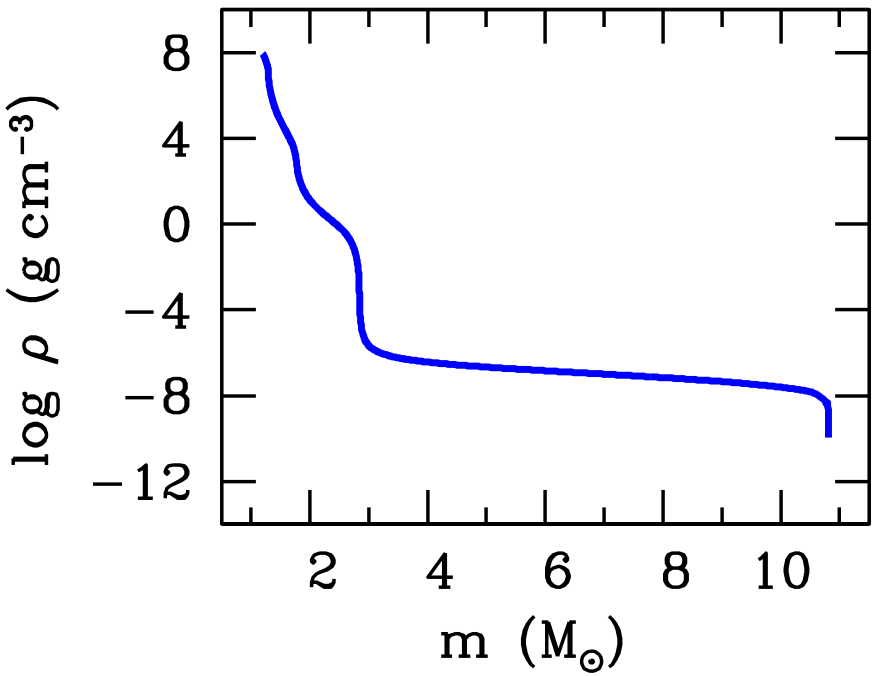
$R_0(R_\odot) = 600/700$

$M_{env}(M_\odot) = 15.9/7.8$

$E(10^{50}\mathrm{erg}) = 4.1/1.4$

Aspherical Explosion

- SN 2005cs: A kinetic energy excess of $\sim 10^{49}$ erg ($\sim 3\%$ of the explosion energy) in the outermost layers of $\sim 0.2 M_\odot$ is required to fit spectroscopic observations.
- Spectropolarimetry shows that asphericity of core-collapse SNe is more pronounced in the inner layers, implying that the explosion process is strongly aspherical (e.g. Leonard & Filippenko 2005; Wang & Wheeler 2008).
- A directed outflow as the aspherical energy input would produce the required kinetic energy excess in the outer layers.

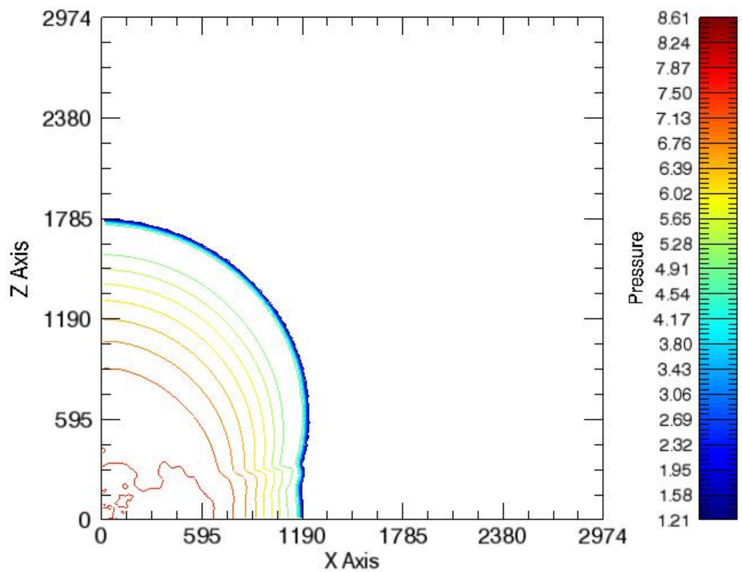


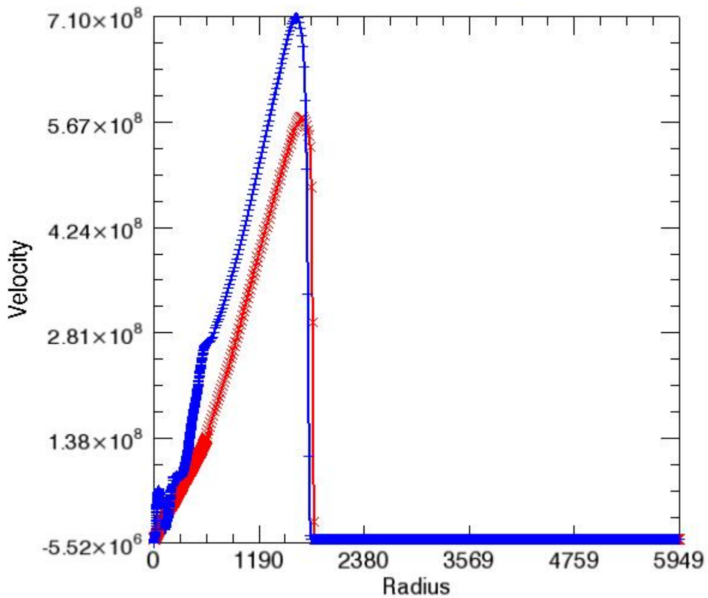
The pre-SN of Alex Heger
$R_0 = 600 R_\odot$
$M_{env} = 8 M_\odot$
$E = 10^{51}$ erg

2D simulations
hydro code PROMETHEUS
(Fryxell, Müller, & Arnett 1989)

A Failure of Aspherical Explosion

- Hydrodynamic modeling of the photospheric velocity for SN 2005cs gives $v_{max}(opt)/v_{max}(evol) \approx 1.75$.
- 2D simulations show that near polar direction $v_{max}(asph)/v_{max}(sph) \approx 1.25$ at terminal phase.
- Axis ratio of $\approx 3/2$ results in a linear polarization P $\approx 2\%$ (Höflich 1991).

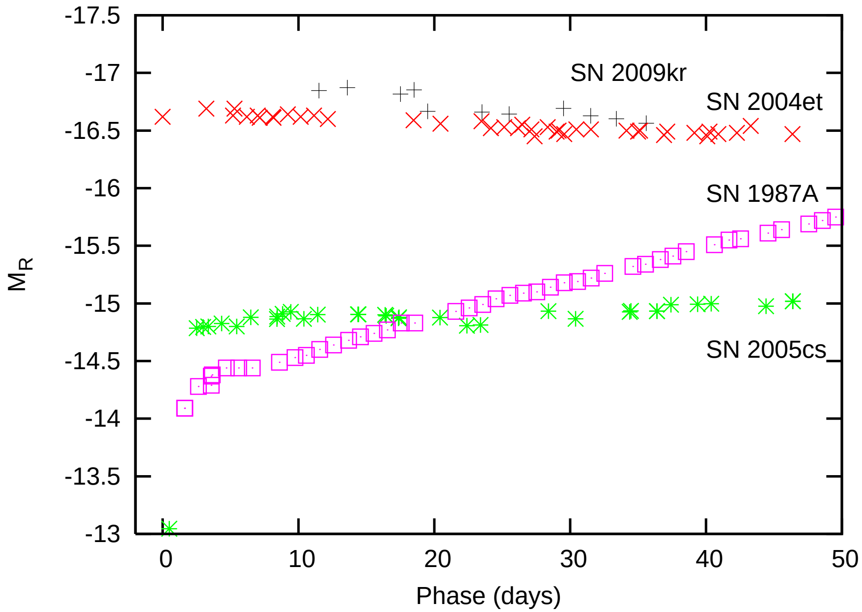




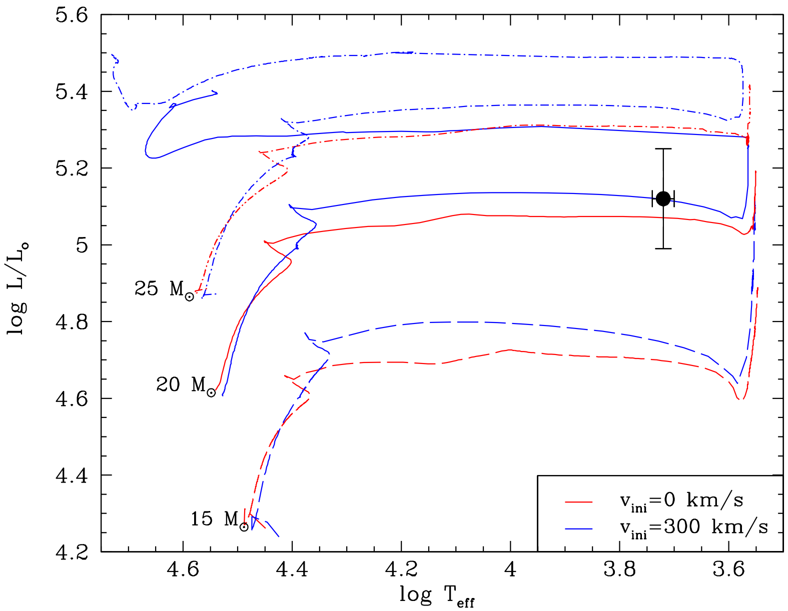
- Type IIP SNe at early-time phase: no event to show P $\geq 0.5\%$ (Leonard & Filippenko 2005).
- The required velocity excess of $50 - 75\%$ is inconsistent with polarimetric observations of type IIP SNe.
- An aspherical explosion fails to produce the required kinetic energy excess in the outer layers at the observed polarization.

"Red Supergiant Problem"?

- Type IIP SN 2009kr is probably the first evidence of high-mass progenitors. In *HST* pre-explosion images the pre-SN was identified as yellow SG with initial mass $\mathbf{11-20}M_{\odot}$ (Fraser et al. 2009; the evolutionary tracks of Eldridge & Tout 2004) and $\mathbf{18-24}M_{\odot}$ (Elias-Rosa et al. 2009; the evolutionary tracks of Hirschi et al. 2004).
- The progenitor mass for SN 2004et estimated with hydrodynamic modeling is in the range of $\mathbf{25-29}M_{\odot}$ (Utrobin & Chugai 2009).



Fraser et al. (2009)

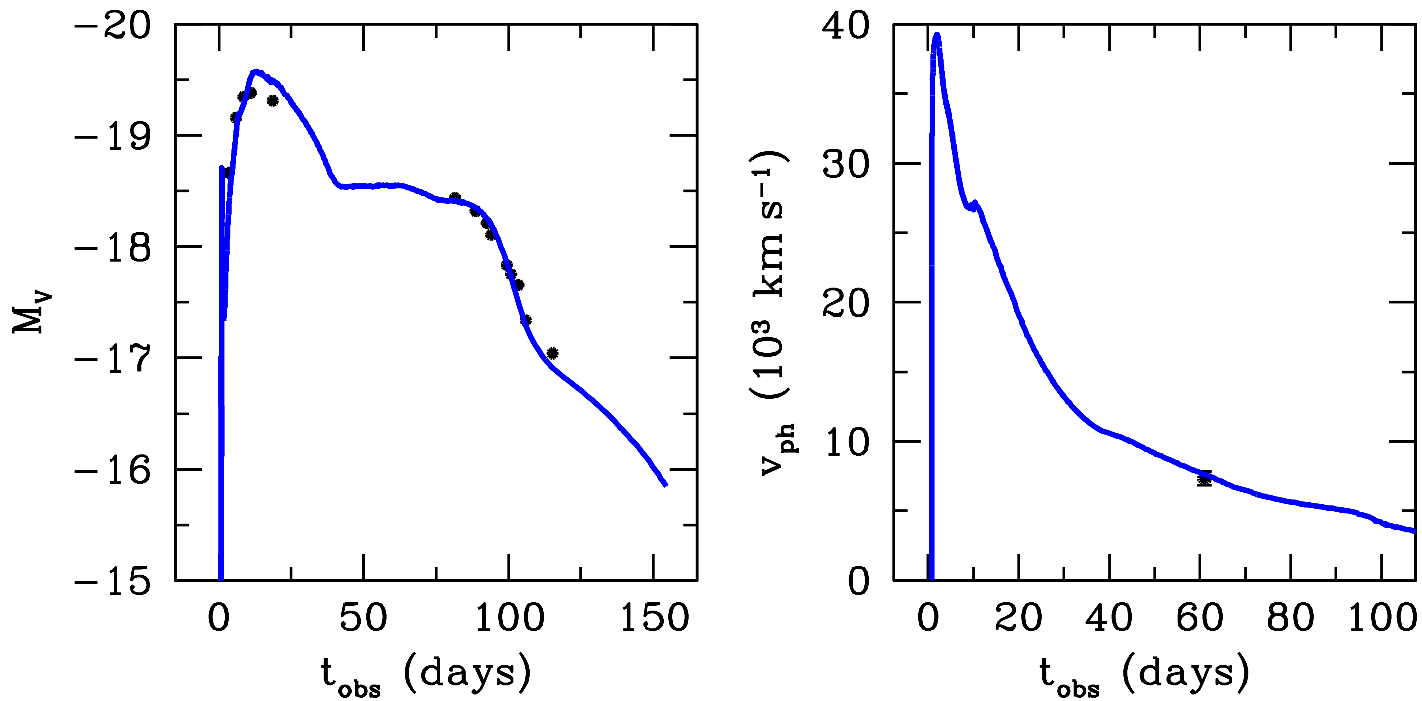


Elias-Rosa et al. (2009)

Very Luminous Type IIP SN 2009kf

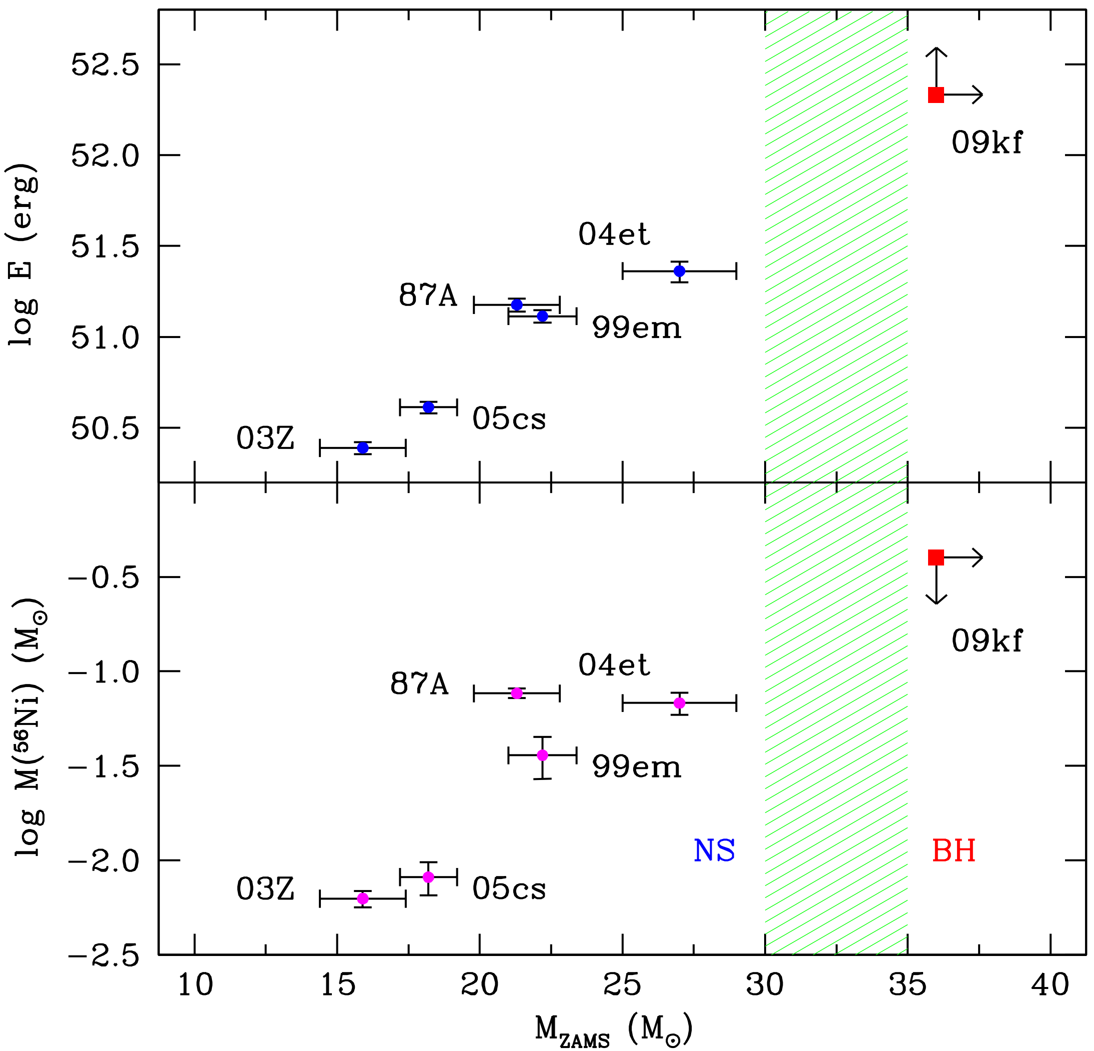
- Botticella et al. (2010): SN is extremely luminous both in the optical and NUV and has a large expansion velocity of $\sim$ 9000 km s^{-1} on day 61. The upper limit luminosity at $\sim$ day 234 suggests $M_{\rm Ni} < 0.4 M_\odot$. It may be interpreted with explosion energies $> 10^{52}$ erg or pre-SN radii $> 1000 R_\odot$, or interaction of the ejecta with a surrounding shell.

- Utrobin, Chugai, & Botticella (2010): It is the first energetic type IIP SN and its high explosion energy implies that this event is associated with a formation of BH (e.g. jet-powered explosion) rather than NS (e.g. neutrino-driven or magnetohydrodynamical mechanism).



$R_0 = 2000 R_\odot$, $M_{env} = 28.1 M_\odot$, $E = 2.15 \times 10^{52}$ erg, $M_{\rm Ni} = 0.4 M_\odot$, $M_{\rm BH} = 4.5 M_\odot$

Explosion Energy and ^{56}Ni Mass Versus Progenitor Mass



SN 2009kf

Its high explosion energy manifests that the event is powered by an accretion into BH.

Single star scenario (Collapsar)

It implies that a border between the NS and BH formation lies in the range of 30 to $35M_\odot$.

Binary scenario (Merger)

In this case a term ”progenitor” loses its original sense. For example, the required pre-SN could be produced by a $25M_\odot + 20M_\odot$ close binary at the ZAMS.

Final Comments and Conclusions

- Evolutionary mass
  The mass distribution of detected type IIP progenitors can be fitted with a Salpeter IMF of a slope $\alpha = -2.35$, assuming a minimum mass of $8.5M_{\odot}$ and a fixed maximum mass of $16.5M_{\odot}$ (Smartt 2009).
- Hydrodynamic mass
  Hydrodynamic modeling suggests that the $15-30M_{\odot}$ main-sequence stars are the progenitors of type IIP SNe.
- Aspherical explosion
  An aspherical explosion cannot reduce the ejecta mass measured from hydrodynamic modeling of type IIP SNe.
- ”Red Supergiant Problem”
  Type IIP SN 2009kr, the pre-SN of which was discovered on the pre-explosion images, is probably the first evidence of high-mass progenitors.
- Black hole formation in type IIP SN
  The very luminous SN 2009kf is the first energetic type IIP SN associated with a formation of BH (e.g. jet-powered explosion) rather than NS (e.g. neutrino-driven or magnetohydrodynamical mechanism).