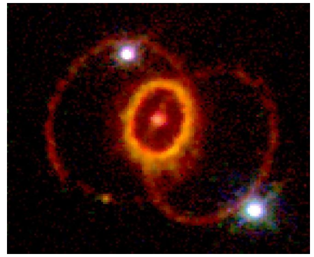

SUPERNOVA 1987A: ejecta mass and explosion energy

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SUPERNOVA 1987A: 20 YEARS AFTER
Supernovae and Gamma-Ray Bursters

Aspen, Colorado
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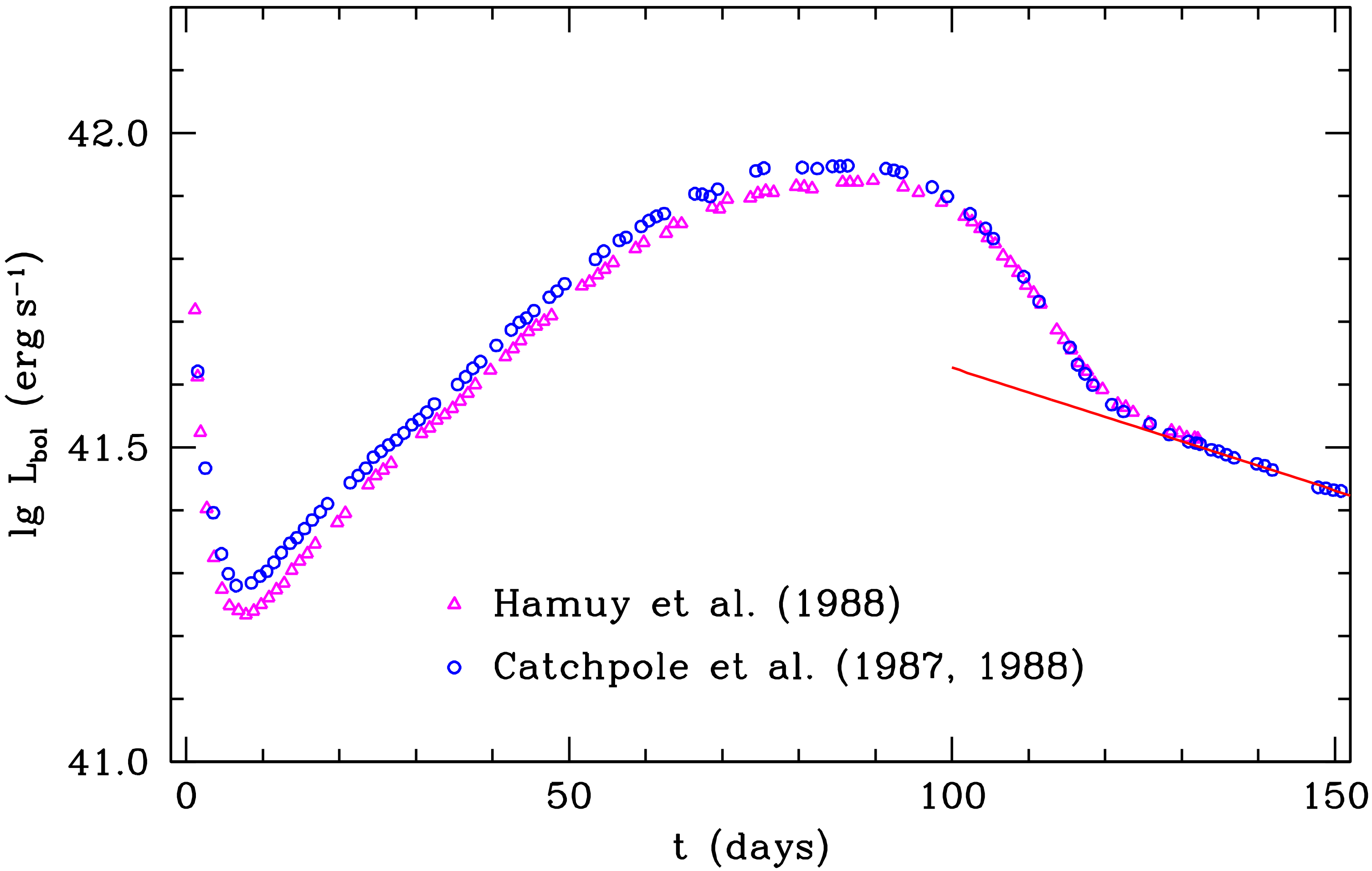
OUTLINE

- Motivation
- Presupernova models
- Effects of time-dependent ionization
- Ejecta mass and explosion energy
- Discussion
- Summary

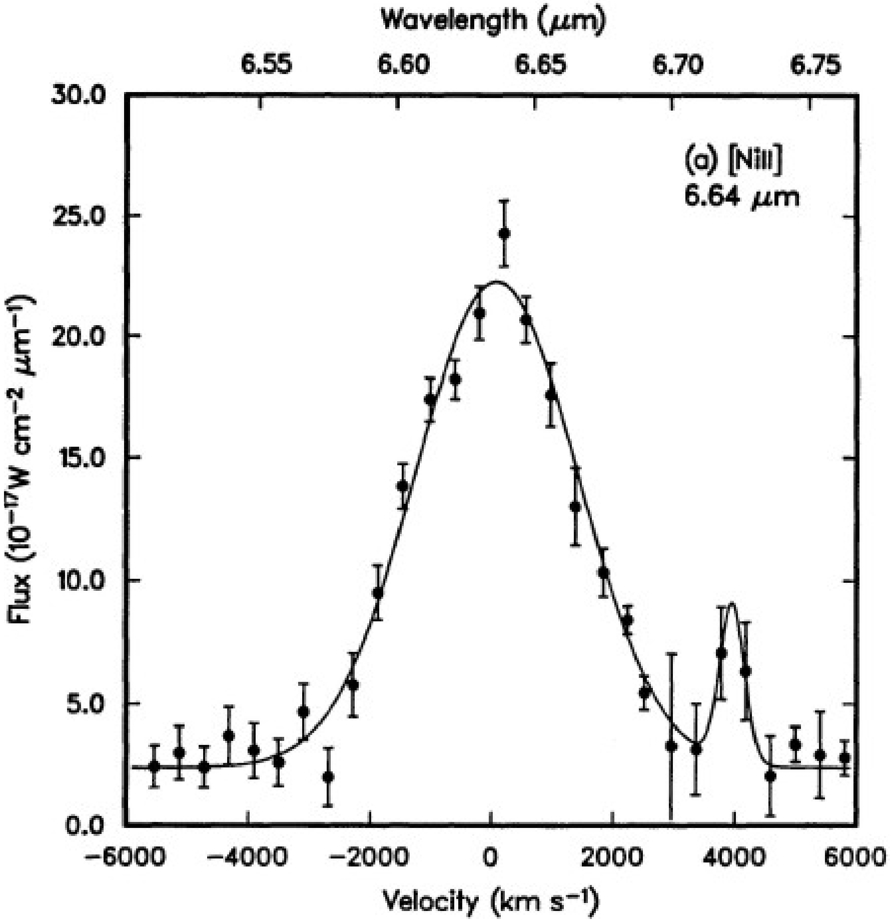
Bolometric light curve of SN 1987A



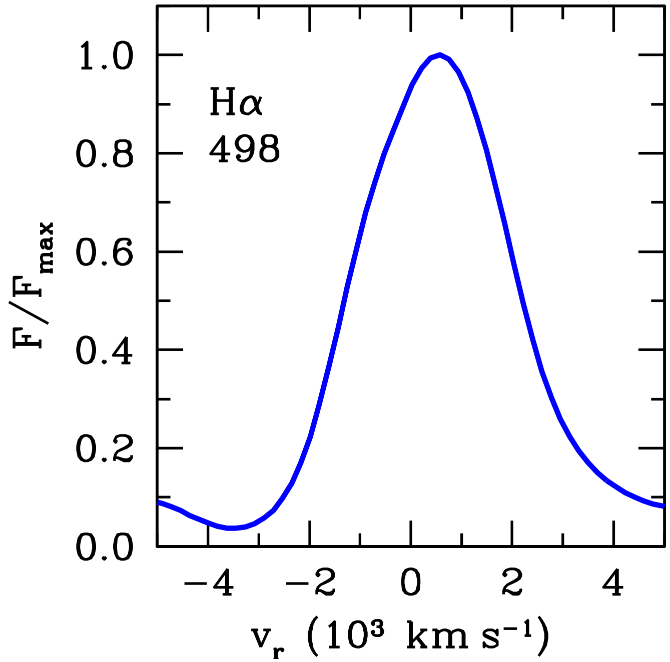
The total ^{56}Ni mass measured from the radioactive tail at D $= 50$ kpc is $\approx$ 0.072 $M_{\odot}$.

Observational evidence for H and ^{56}Ni mixing

A moderate ^{56}Ni mixing up to ~ 3000 km s^{-1}:
The [Ni II] 6.64 μm profile at day 640 gives $v_{\mathrm{FWHM}} = 3100$ km s^{-1} and its modelling results in $v_{max} = 2600$ km s^{-1} (Colgan et al. 1994).



A deep H mixing down to ~ 500 km s^{-1}:



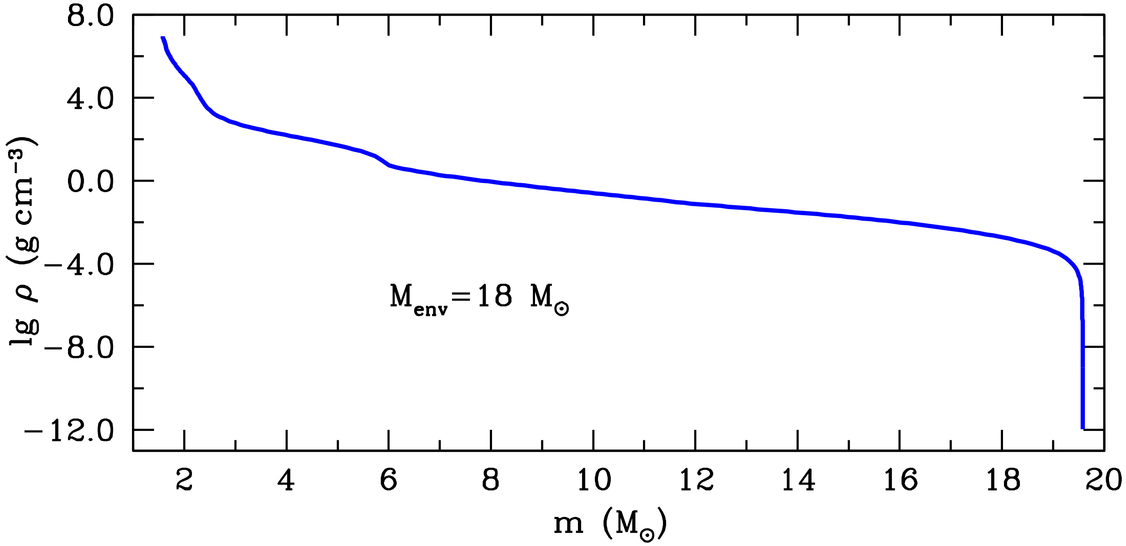
The fact that the Hα profile observed on day 498 (Phillips et al. 1990) is not flat-topped implies that there is no large cavity free of hydrogen at the center of the envelope.

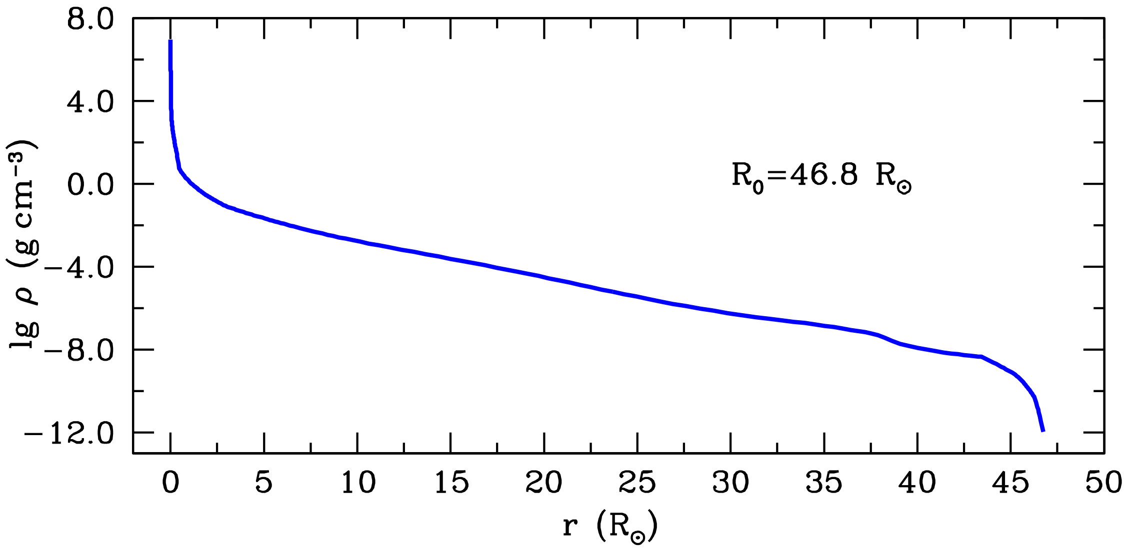
Hydrodynamic models based on photometric observations

Model	R_0 ($R_\odot$)	M_{env} ($M_\odot$)	E (10^{51} erg)	$M_{\rm Ni}$ ($M_\odot$)	$v_{\rm Ni}^{max}$ (km s^{-1})
Woosley (1988)	43.1±14.4	9.4–14.4	0.8–1.5	0.07	—
Shigeyama & Nomoto (1990)	35.9–50.3	11.4–14.6	1.0±0.4	0.075	4000
Utrobin (1993)	47	15–19	1.25–1.65	0.075	2500
Blinnikov et al. (2000)	48.5	14.67	1.1±0.3	0.078	4200
	28.7–57.5	9.4–19	0.6–1.65		

Utrobin & Chugai (2002) demonstrated that the time-dependent ionization played a crucial role in reproducing hydrogen lines of type IIP SNe.

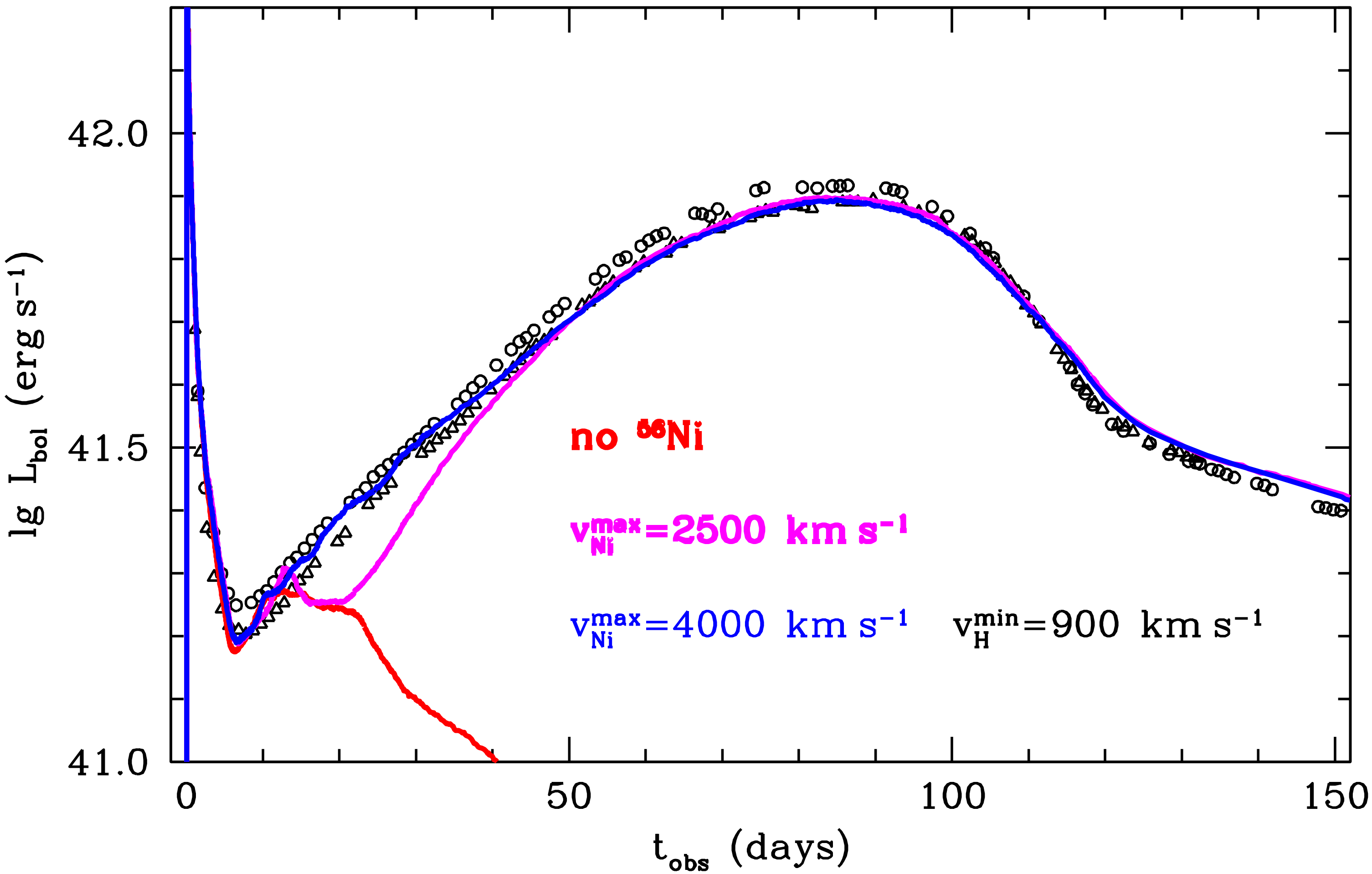
Evolutionary presupernova





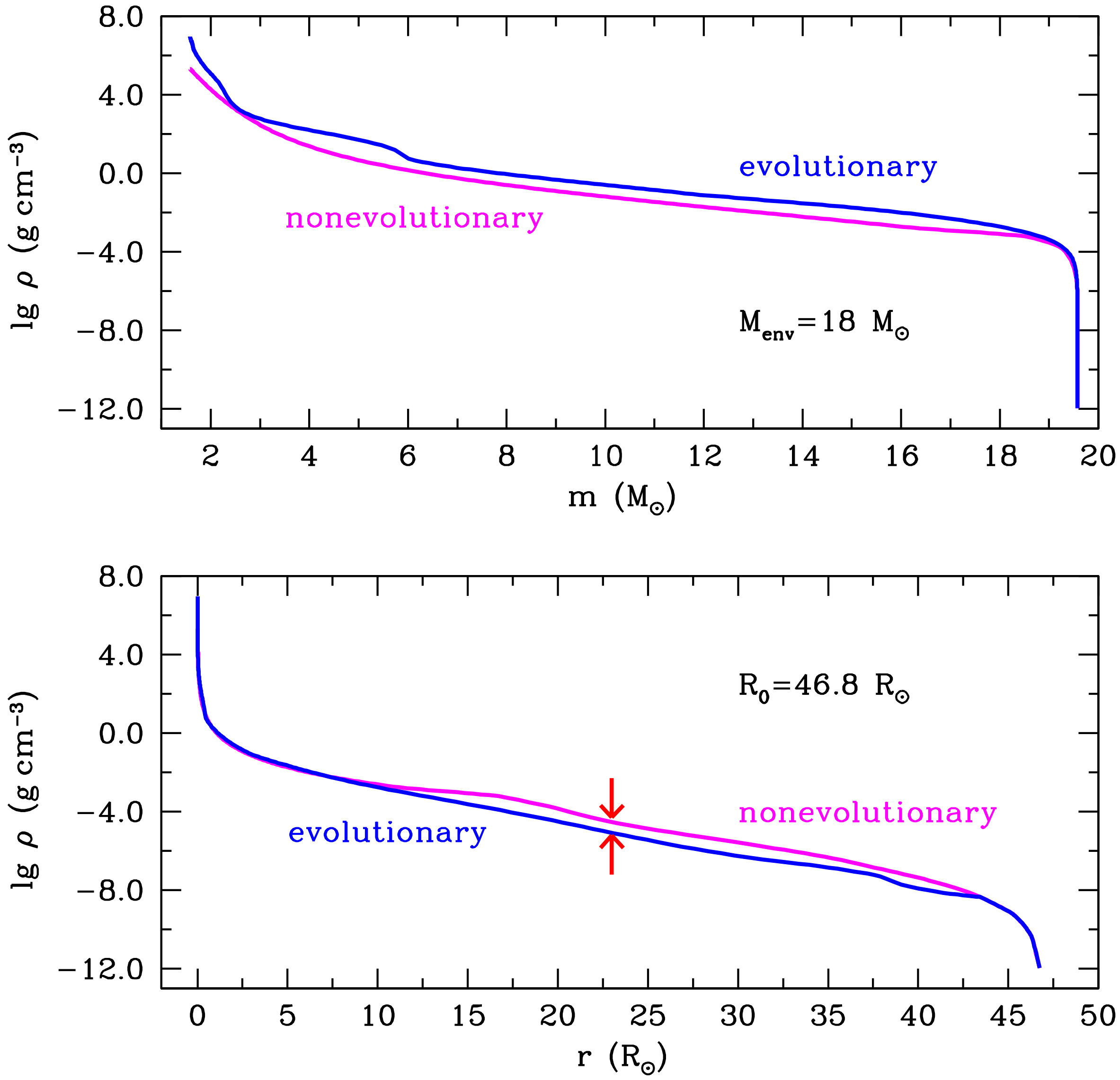
Woosley, Heger, Weaver, & Langer (1997)

Bolometric light curve of evolutionary model

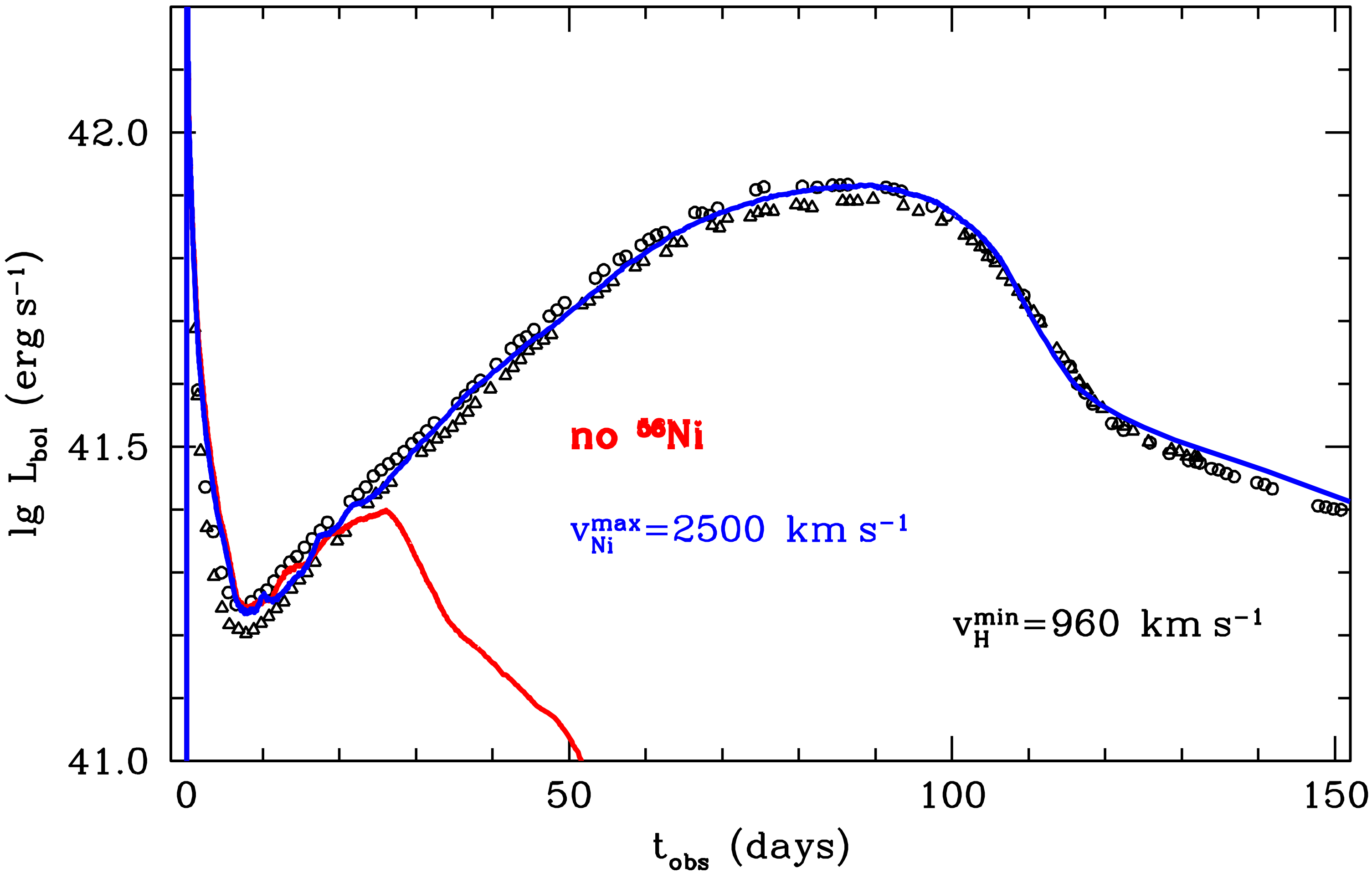


The explosion energy is 1.0×10^{51} erg.

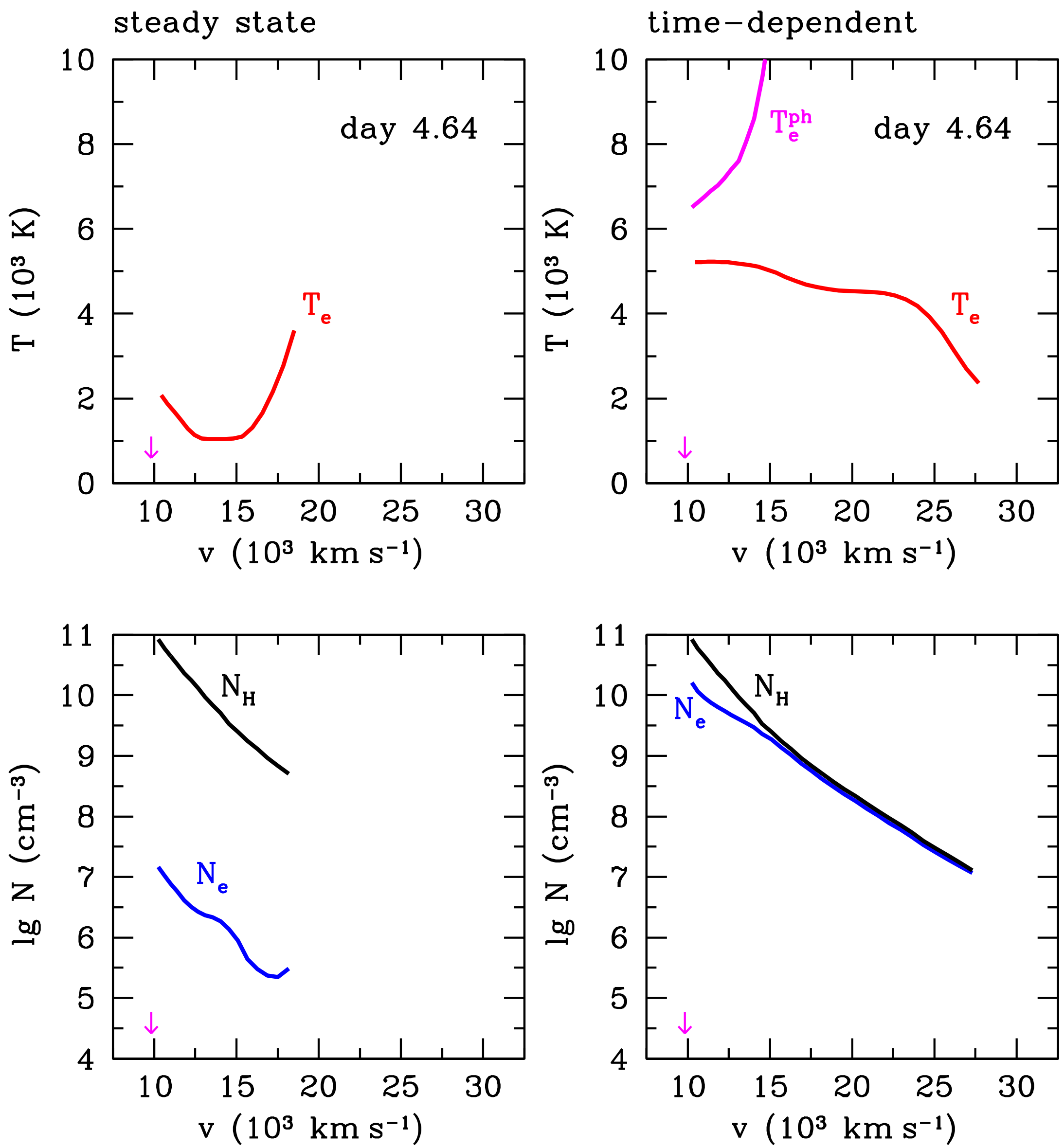
Evolutionary and nonevolutionary presupernovae



Bolometric light curve of nonevolutionary model

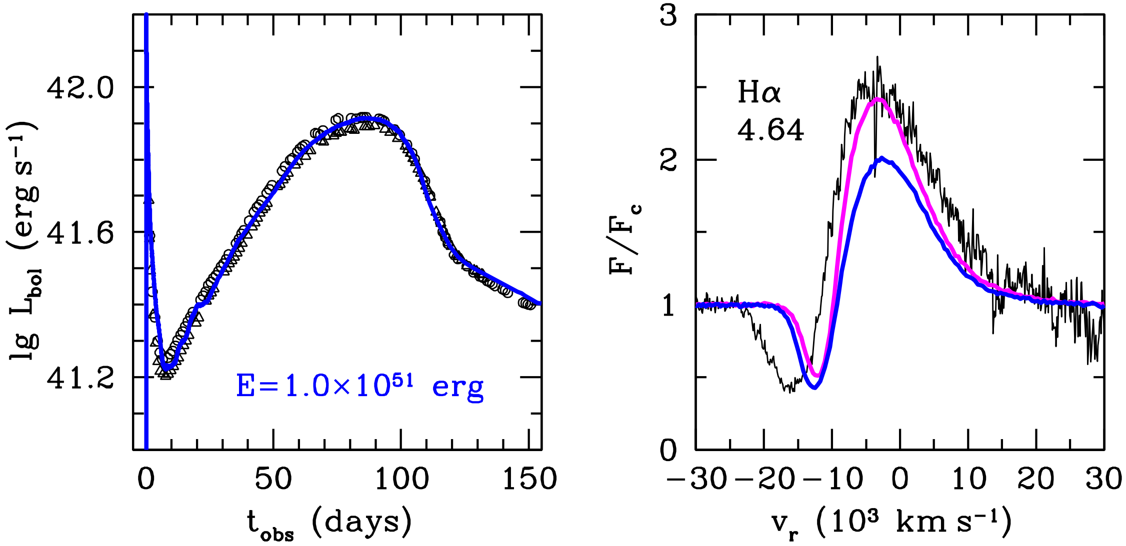


Ionization freeze-out effect at photospheric phase



Utrobin & Chugai (2005)

Hα on day 4.64 and hydrodynamic model



Utrobin & Chugai (2005):

a stronger Hα absorption at high radial velocities

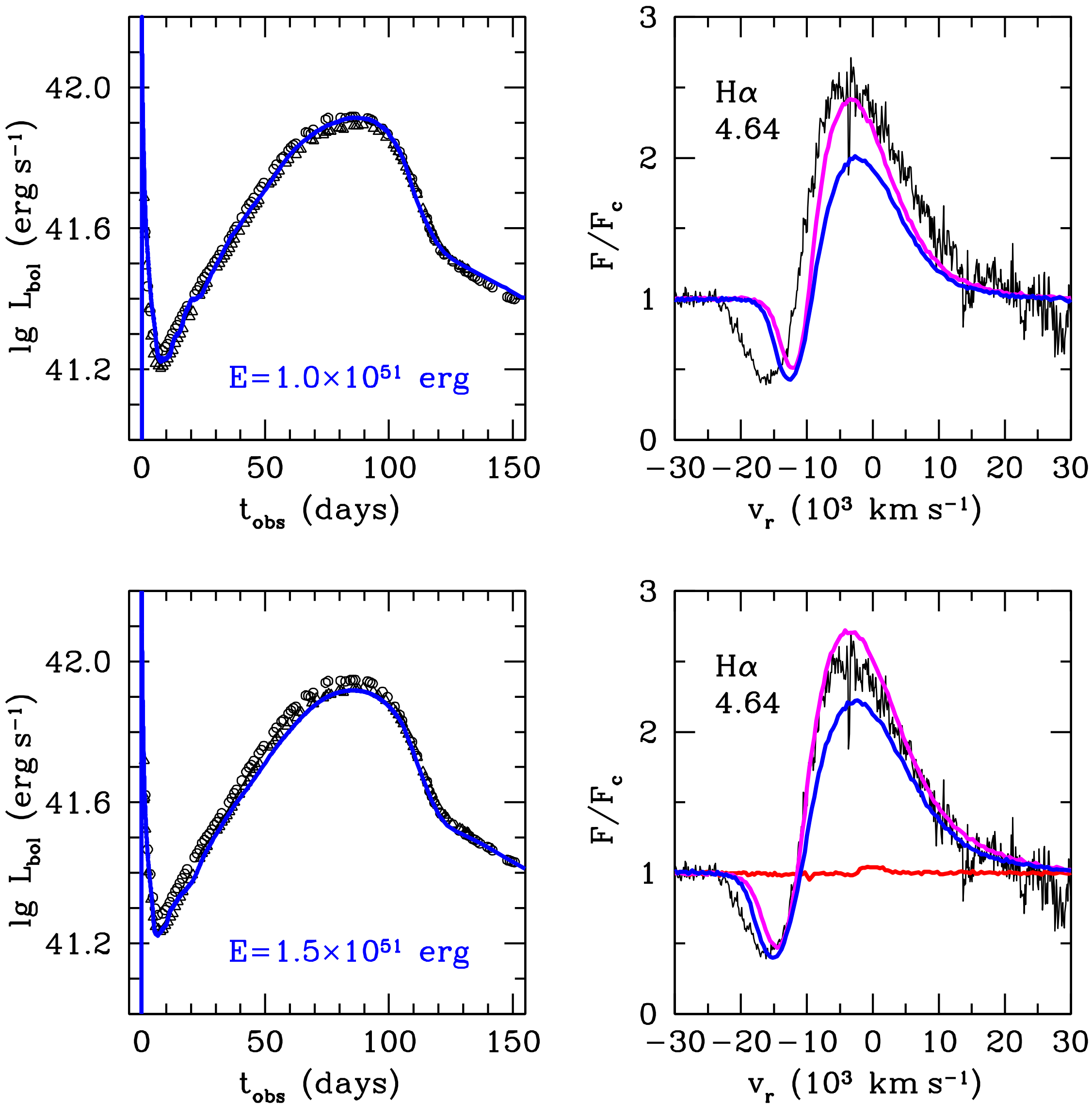
$\Downarrow$

a higher density in outer layers of the envelope

$\Downarrow$

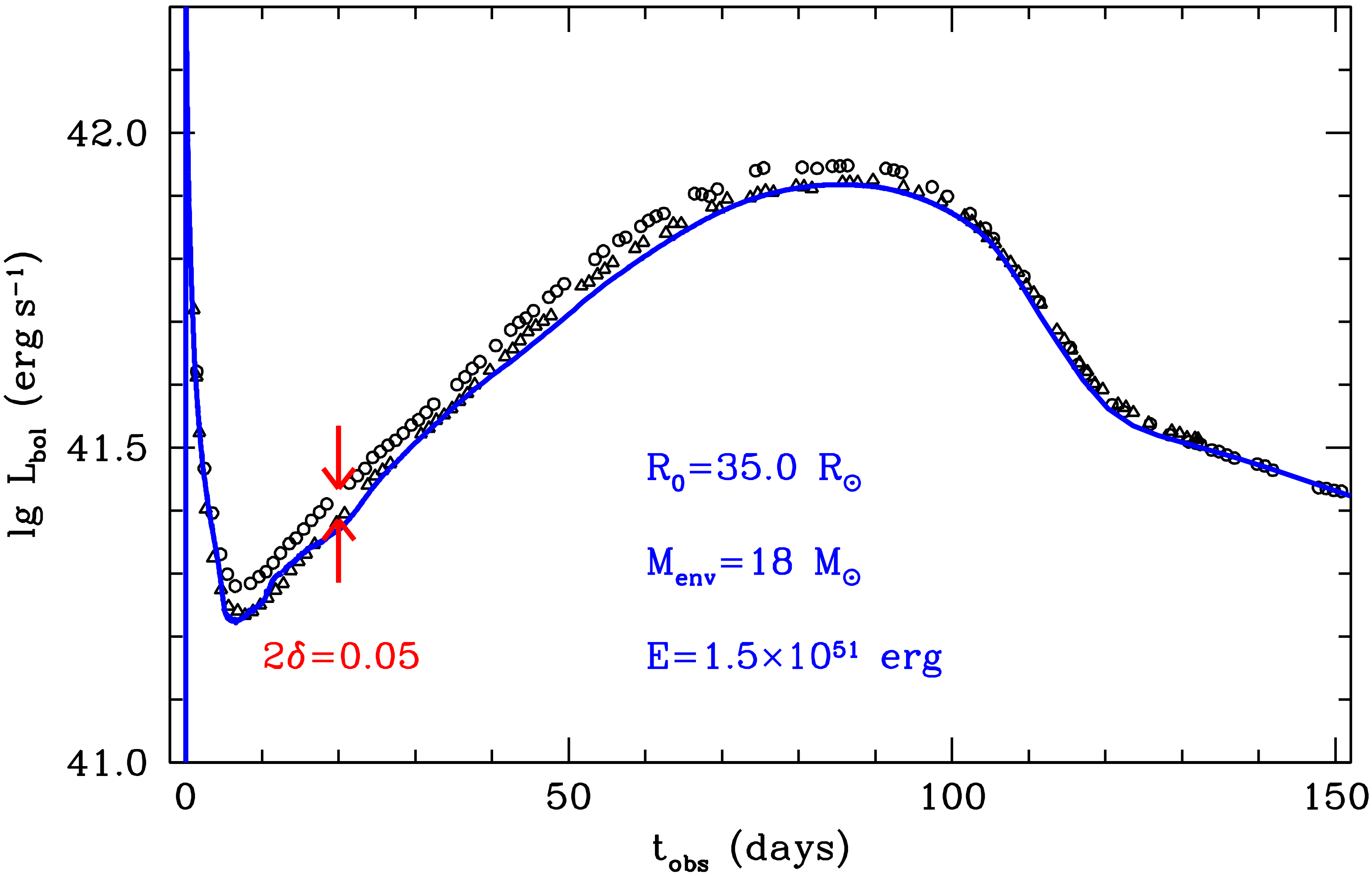
a higher explosion energy

Hα on day 4.64 and hydrodynamic model



A key ratio $E/M_{env} \approx 0.83 \times 10^{50}$ erg $M_{\odot}^{-1}$.

Optimal hydrodynamic model

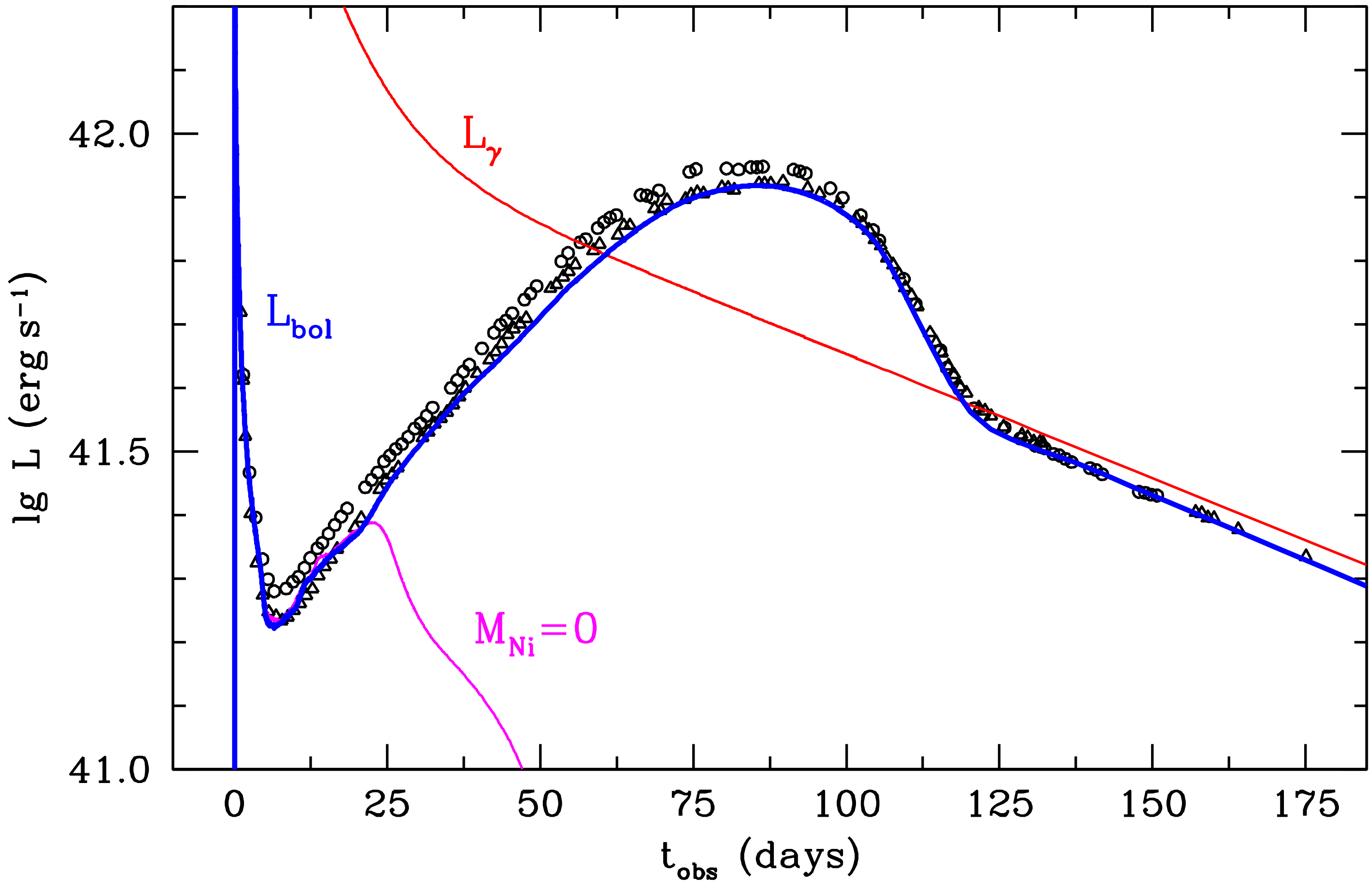


Hydrodynamic models of SN 1987A

Model	PSN	R_0 ($R_\odot$)	M_{env} ($M_\odot$)	E (10^{51} erg)	M_{Ni} ($M_\odot$)	v_{Ni}^{max} (km s^{-1})	E/M_{env} (10^{50} erg $M_\odot^{-1}$)
Woosley (1988)	evol.	43.1$\pm$14.4	9.4–14.4	0.8–1.5	0.07	—	$\sim$ 0.73
Shigeyama & Nomoto (1990)	evol.	35.9–50.3	11.4–14.6	1.0$\pm$0.4	0.075	4000	$\sim$ 0.76
Blinnikov et al. (2000)	evol.	48.5	14.67	1.1$\pm$0.3	0.078	4200	$\sim$ 0.75
Utrobin (1993)	nonev.	47	15–19	1.25–1.65	0.075	2500	$\sim$ 0.85
Utrobin (2005)	nonev.	35$\pm$5	18.0$\pm$1.5	1.50$\pm$0.12	0.0765	3000	$\approx$ 0.83

The last hydrodynamic model is based on both the photometric and spectroscopic observations.

Bolometric and γ-ray luminosities

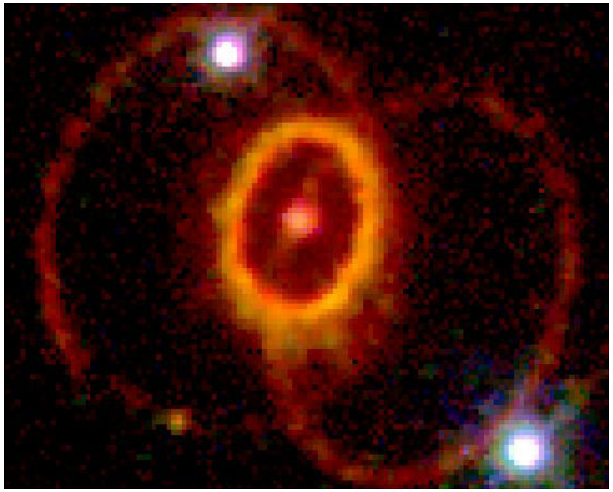


The total ^{56}Ni mass is 0.0765 $M_\odot$.

Indirect evidence for the moderate ^{56}Ni mixing

- Li, McCray, & Sunyaev (1993) developed a model that fitted the infrared Fe, Co, and Ni emission lines assuming that the newly formed ^{56}Ni was distributed in ~ 100 clumps throughout the volume within a velocity of 2500 km s^{-1}.
- Chugai (1991) interpreted the Bochum event as a result of the nonmonotonic, spherically symmetric distribution of H excitation and a local enhancement of H excitation from an asymmetric ^{56}Ni ejection in the far hemisphere. It implies that ^{56}Ni is distributed within $v_{ph} \sim$ 3000 km s^{-1} on day 30. An absolute velocity of the fast clump is $\sim$ 4700 km s^{-1} (Utrobin, Chugai, & Andronova 1995).
- The Monte Carlo calculations of X-ray emission required the ^{56}Co mixing up to a velocity of 3000 km s^{-1} (Pinto & Woosley 1988).
- The Monte Carlo simulations of γ-ray transport of the 847 and 1238 keV lines of ^{56}Co in the envelope showed that up to 50% of the total ^{56}Ni mass should remain below 1000 km s^{-1} (A. Burrows & Van Riper 1995) and the total ^{56}Ni mass within a velocity of 3000 km s^{-1} (Pinto & Woosley 1988).
- Kifonidis, Plewa, Scheck, Janka, & Müller (2006) have carried out 2-D simulations of strongly anisotropic supernova explosions in a self-consistent approach and obtained both final Fe-group velocities of 3300 km s^{-1} and H mixing downward to 500 km s^{-1}.

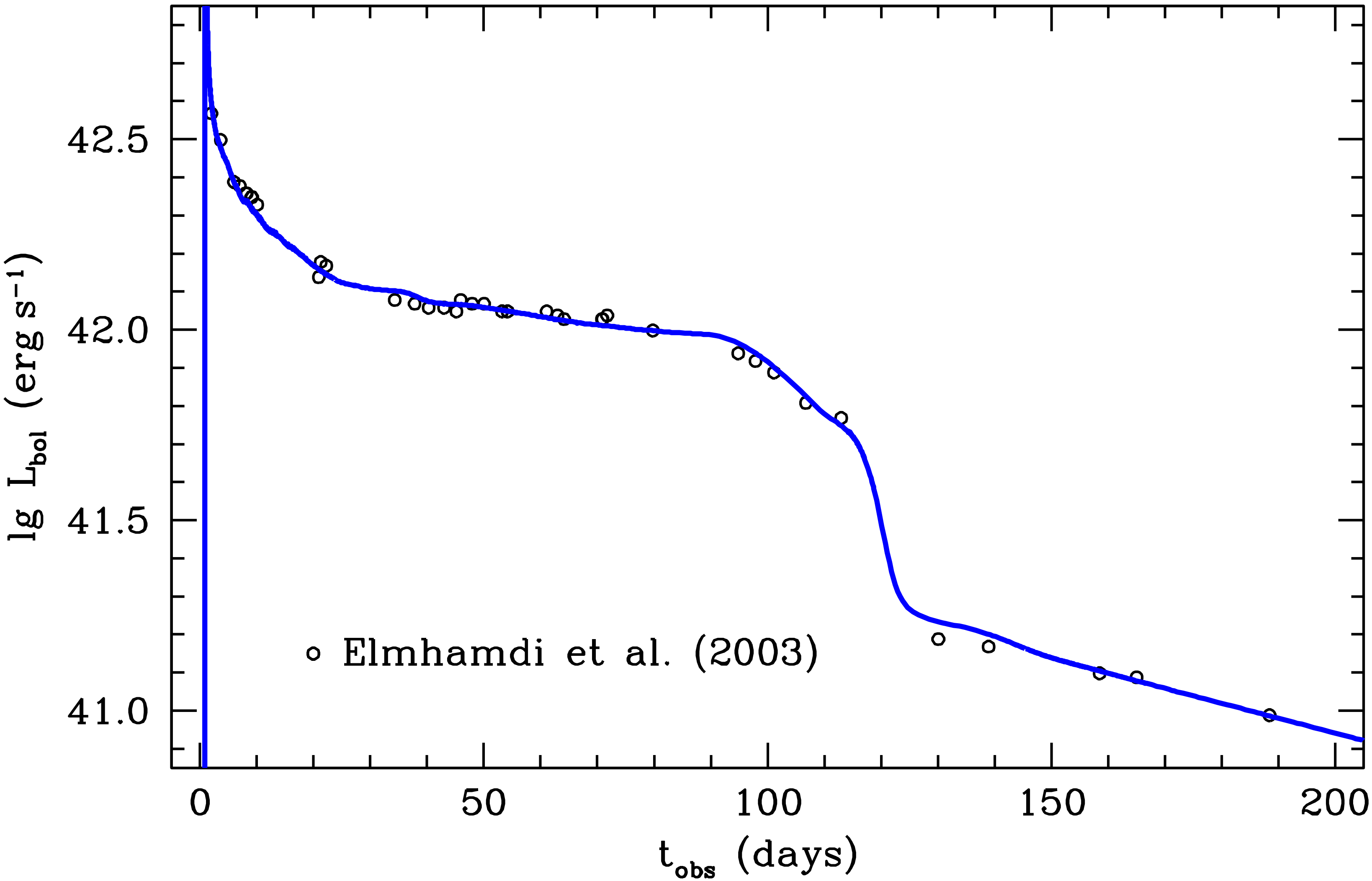
Triple ring nebula of SN 1987A



ESO NTT — Wampler et al. (1990);
NASA HST — Jakobsen et al. (1991),
C. Burrows et al. (1995).

- A single rotating star: Hydrodynamic formation of the rings due to the ionization and heating of the cool red giant wind (Meyer 1997, 1999).
- Binary system: An impulsive mass loss from the primary star, the formation of a thin, dense shell, and the subsequent expansion of two jets (Soker 2002).
- Binary mergers: The mass loss at mid-latitudes from a rotationally distorted envelope following the early, rapid in-spiral of a companion star inside a common envelope (Podsiadlowski 1992; Morris & Podsiadlowski 2006).

Hydrodynamic model for the normal type IIP SN 1999em



$R_0 = 500R_\odot$, $M_{env} = 19M_\odot$, $E = 1.3 \times 10^{51}$ erg, and $M_{Ni} = 0.036M_\odot$.

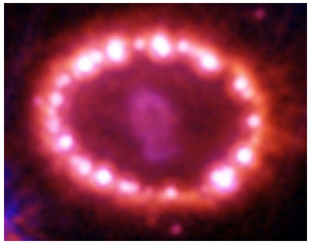
Comparison to the normal type IIP SN 1999em

SN	R_0 ($R_\odot$)	M_{env} ($M_\odot$)	E (10^{51} erg)	$M_{\rm Ni}$ ($10^{-2} M_\odot$)	Z	$v_{\rm Ni}^{max}$ (km s^{-1})	$v_{\rm H}^{min}$ (km s^{-1})
87A	35	18	1.5	7.65	0.006	3000	600
99em	500	19	1.3	3.60	0.017	660	700

- In the case of SN 1987A, a relative compactness of the pre-SN is a major factor in understanding the peculiar properties of this phenomenon. A difference between the explosions of the red and blue supergiants is radical, especially in the light curves.
- The optimal model for SN 1987A is characterized by a moderate ^{56}Ni mixing up to ~ 3000 km s^{-1} compared to a weaker ^{56}Ni mixing up to ≈ 660 km s^{-1} in SN 1999em, hydrogen being mixed deeply downward to ~ 650 km s^{-1}.
- The masses of He cores in the pre-SNe of SN 1987A and SN 1999em are close enough to suppose that nearly the same iron cores form within the pre-SNe. This fact and roughly the same explosion energies of SN 1987A and SN 1999em together imply a unique explosion mechanism for these core collapse SNe.

Conclusions

- The moderate mixing of ^{56}Ni at velocities ≤ 3000 km s^{-1} results in a more dense outer layers of the presupernova than in the evolutionary model of a single nonrotating star.
- The time-dependent ionization provides a sufficient population of excited hydrogen levels to account for the observed Hα line without invoking the external ^{56}Ni.
- The hydrodynamic and atmosphere modelling of the Hα profile on day 4.64 indicates $\boldsymbol{E/M_{env}} \approx \mathbf{0.83 \times 10^{50}}$ erg $M_{\odot}^{-1}$.
- The basic parameters of SN 1987A are $\boldsymbol{R_0 = 35.0 \pm 5R_{\odot}}$, $\boldsymbol{M_{env} = 18.0 \pm 1.5M_{\odot}}$, and $\boldsymbol{E = (1.50 \pm 0.12) \times 10^{51}}$ erg.
- A neutron star of $\approx \boldsymbol{1.6M_{\odot} + M_{env} = 18.0 \pm 1.5M_{\odot}} \Rightarrow$ the rotating presupernova mass of $\boldsymbol{19.6 \pm 1.5M_{\odot}}$. The complex structure around SN 1987A consists of gas and dust of $\sim \boldsymbol{1.7M_{\odot}}$ (Sugerman et al. 2005). Given this observed structure, a main-sequence star of at least $\boldsymbol{21.3 \pm 1.5M_{\odot}}$ corresponds to the SN 1987A phenomenon.
- Roughly the same explosion energies and masses of He cores of SN 1987A and SN 1999em together imply a unique explosion mechanism for these core collapse SNe.



THANK YOU.