MIXING CONSTRAINTS ON THE PROGENITOR OF SUPERNOVA 1987A

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in collaboration with

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Workshop on “The Progenitor-Supernova-Remnant Connection”

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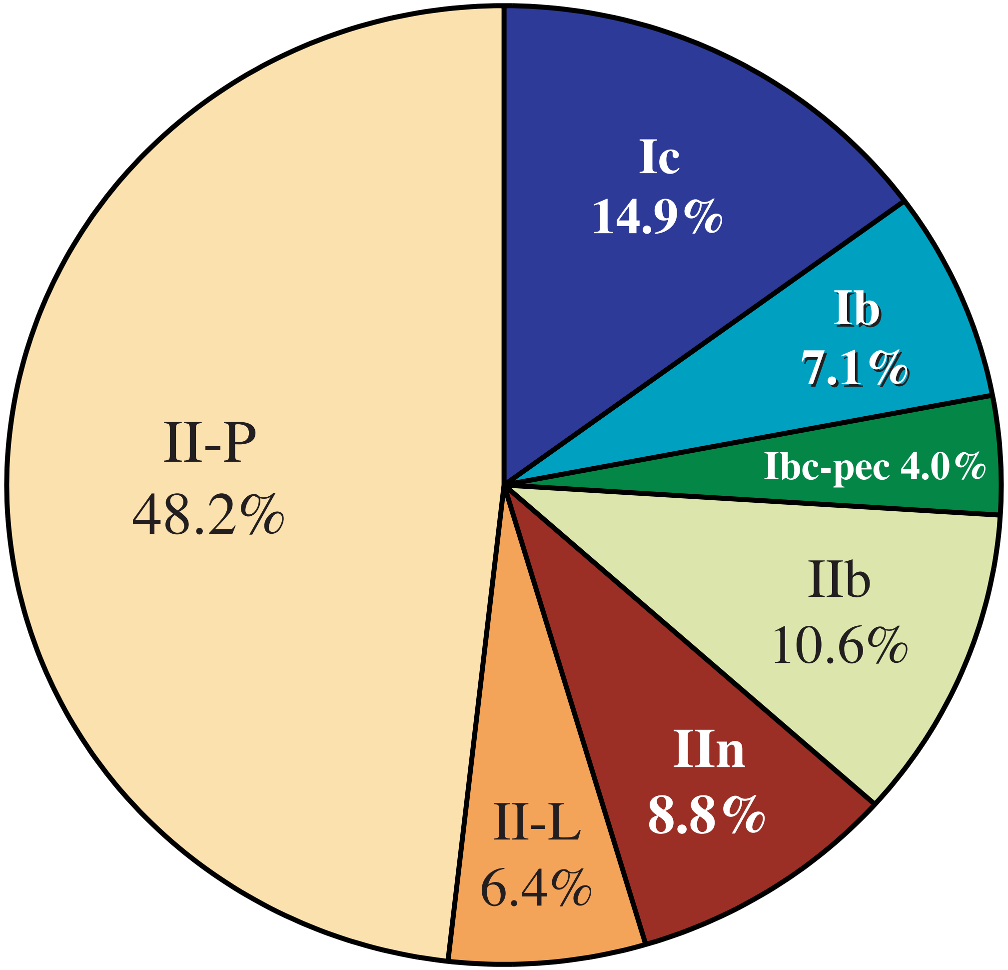
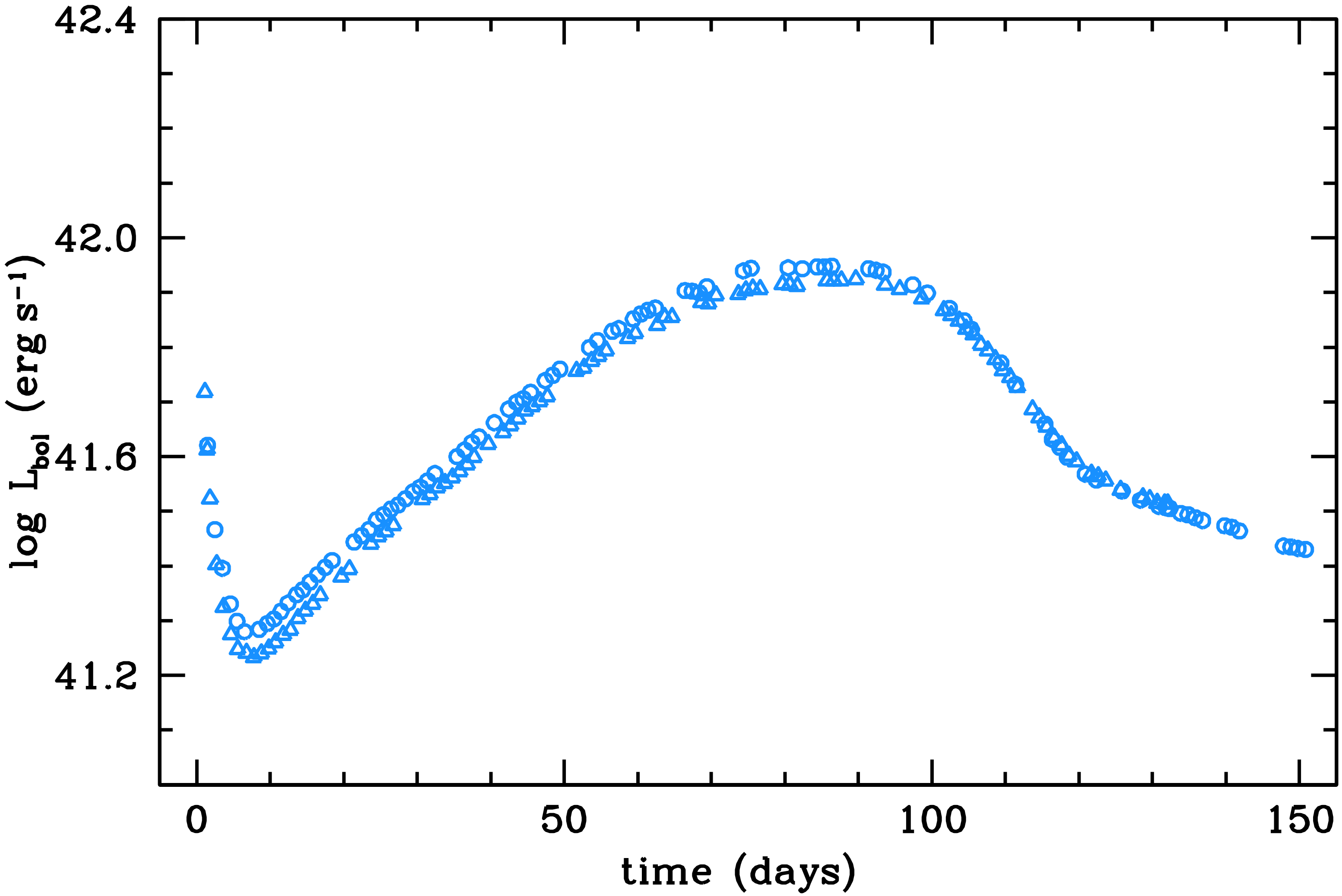
Core-Collapse Supernova Relative Fractions



ordinary SNe IIP $\sim$ 50%
(Li et al. 2011, Smith et al. 2011)

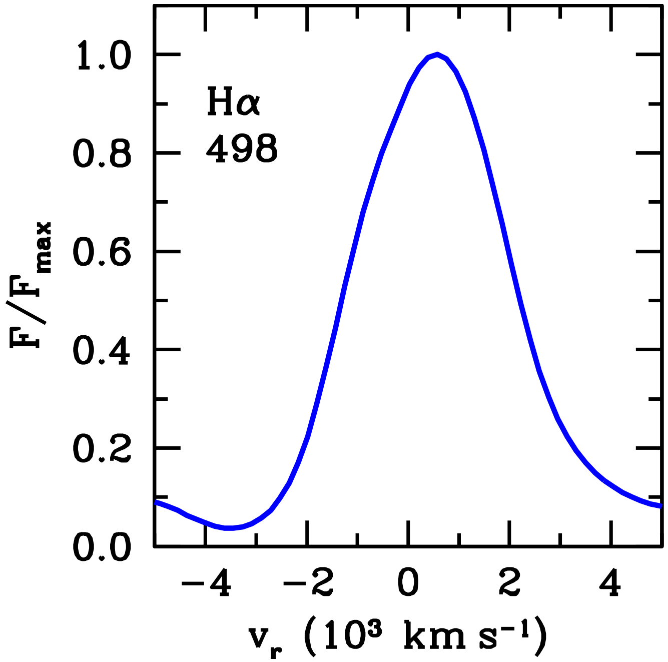
SN 1987A-like events 1–3%
(Pastorello et al. 2012)

Light Curve of Peculiar Type IIP SN 1987A

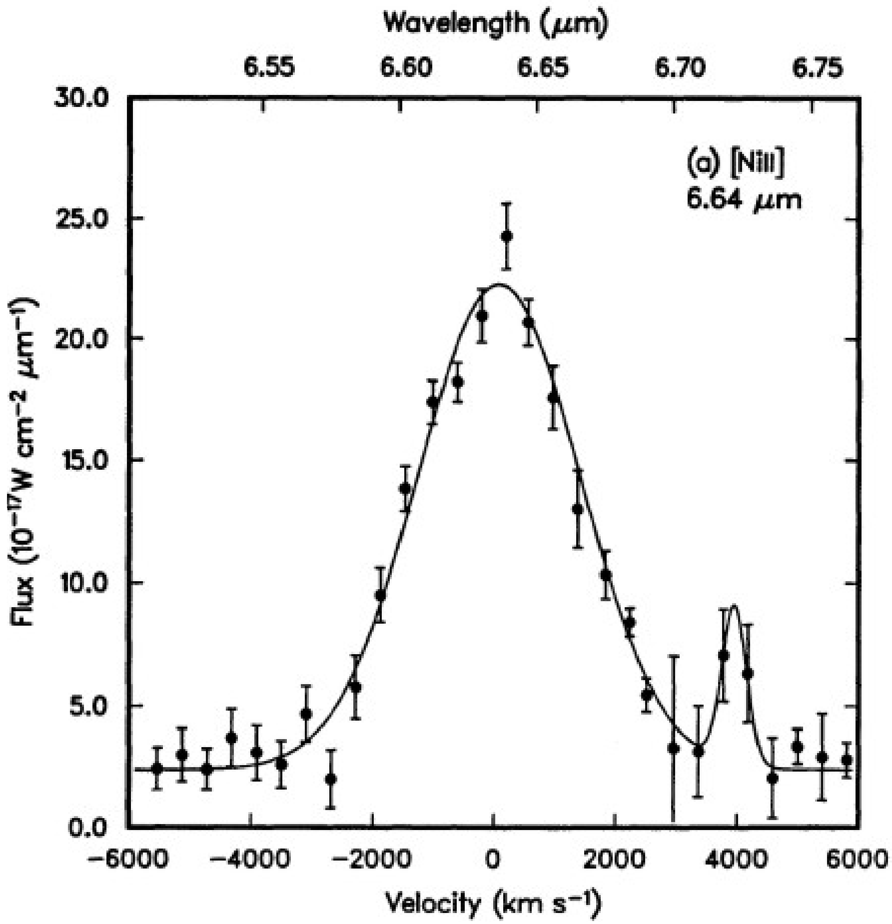


Open circles (Catchpole et al. 1987,1988); open triangles (Hamuy et al. 1988).

SN 1987A: Evidence for H and ^{56}Ni Mixing

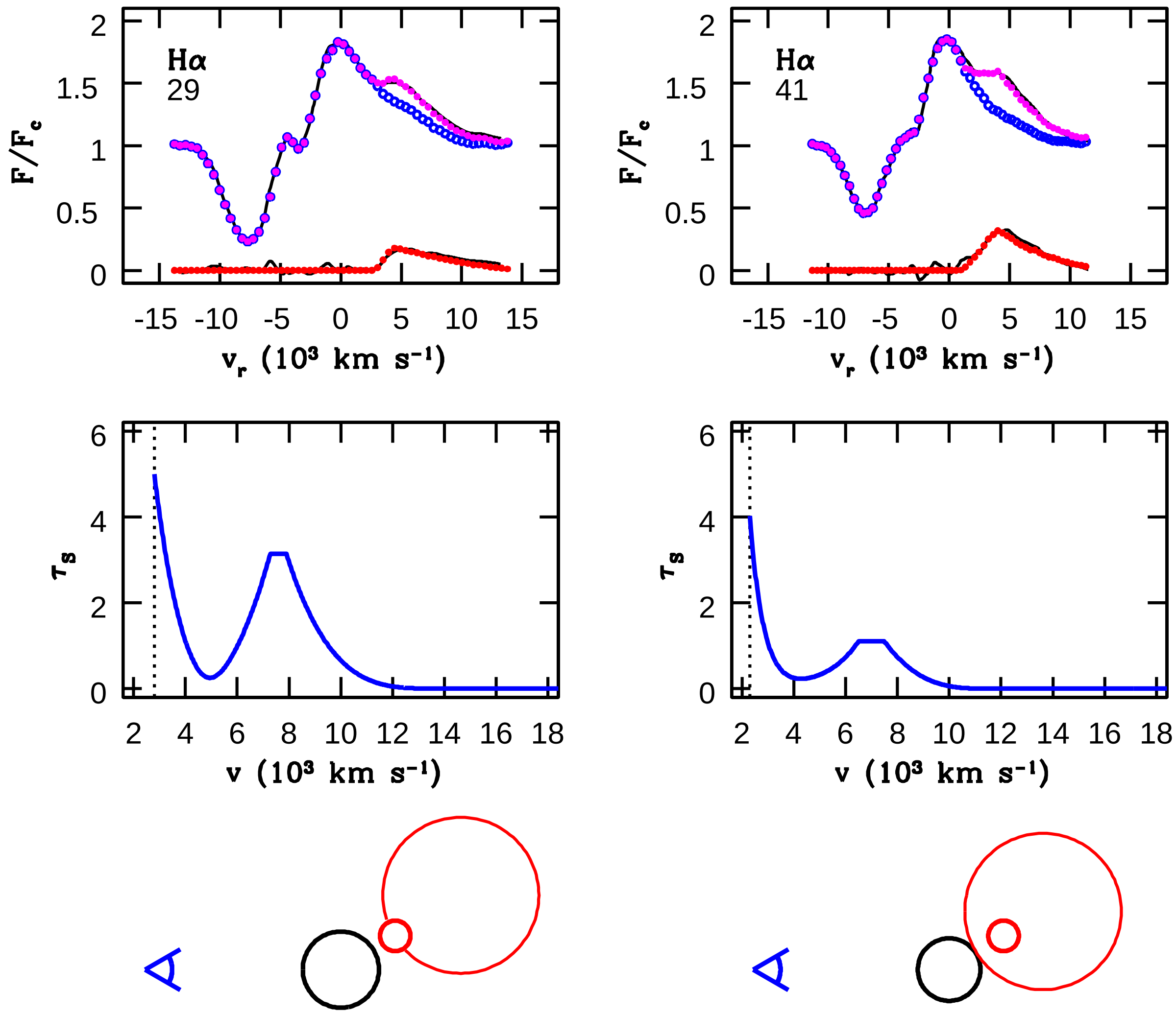


The [Ni II] 6.64 μm profile at day 640 gives $v_{\mathrm{FWHM}} = 3100$ km s^{-1} (Colgan et al. 1994).



Not flat-topped Hα profile on day 498 (Phillips et al. 1990) implies that there is no cavity free of hydrogen at zero velocity.

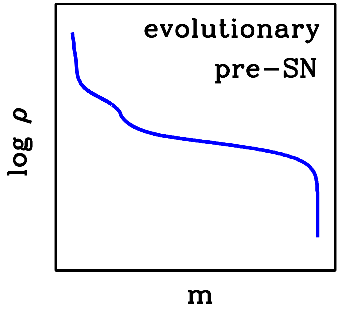
SN 1987A: Bochum Event and Fast ^{56}Ni Clump



Fast ^{56}Ni clump: $v_{3D} \approx 4700$ km s^{-1}, $M_{\rm Ni} \sim 10^{-3}\ M_\odot$ (Utrobin et al. 1995).

Modeling of Supernovae: Three Approaches

First approach



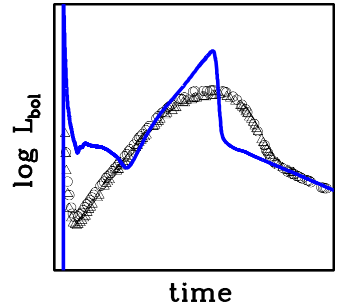
+

1D
piston or
thermal bomb

⇛

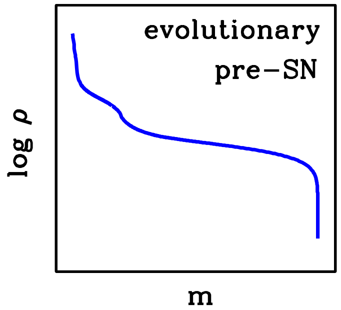
1D
hydrodynamics
code

⇛



No fit

Second approach



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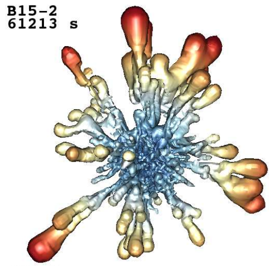
3D simulations



⇛

1D
hydrodynamics
code

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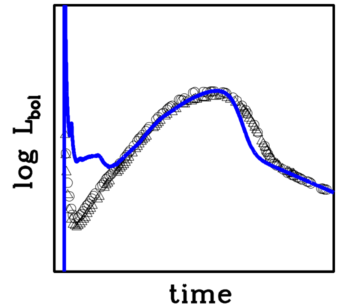
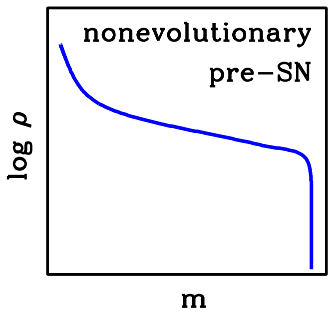


No fit

Third approach



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1D
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⇛

1D
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code

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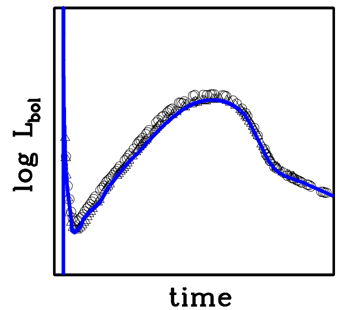
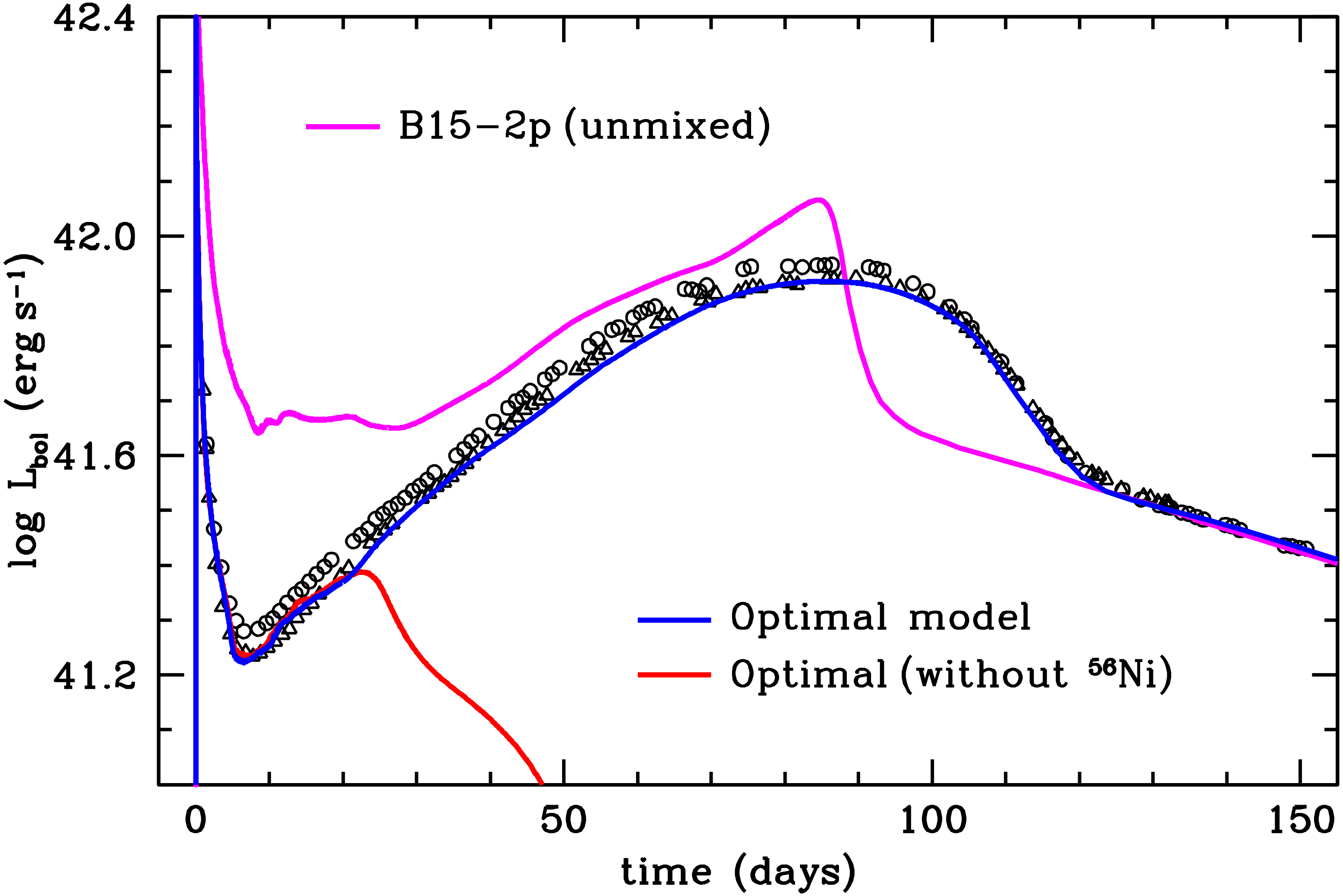


Fit

Light Curve: Radioactive ^{56}Ni and Mixing



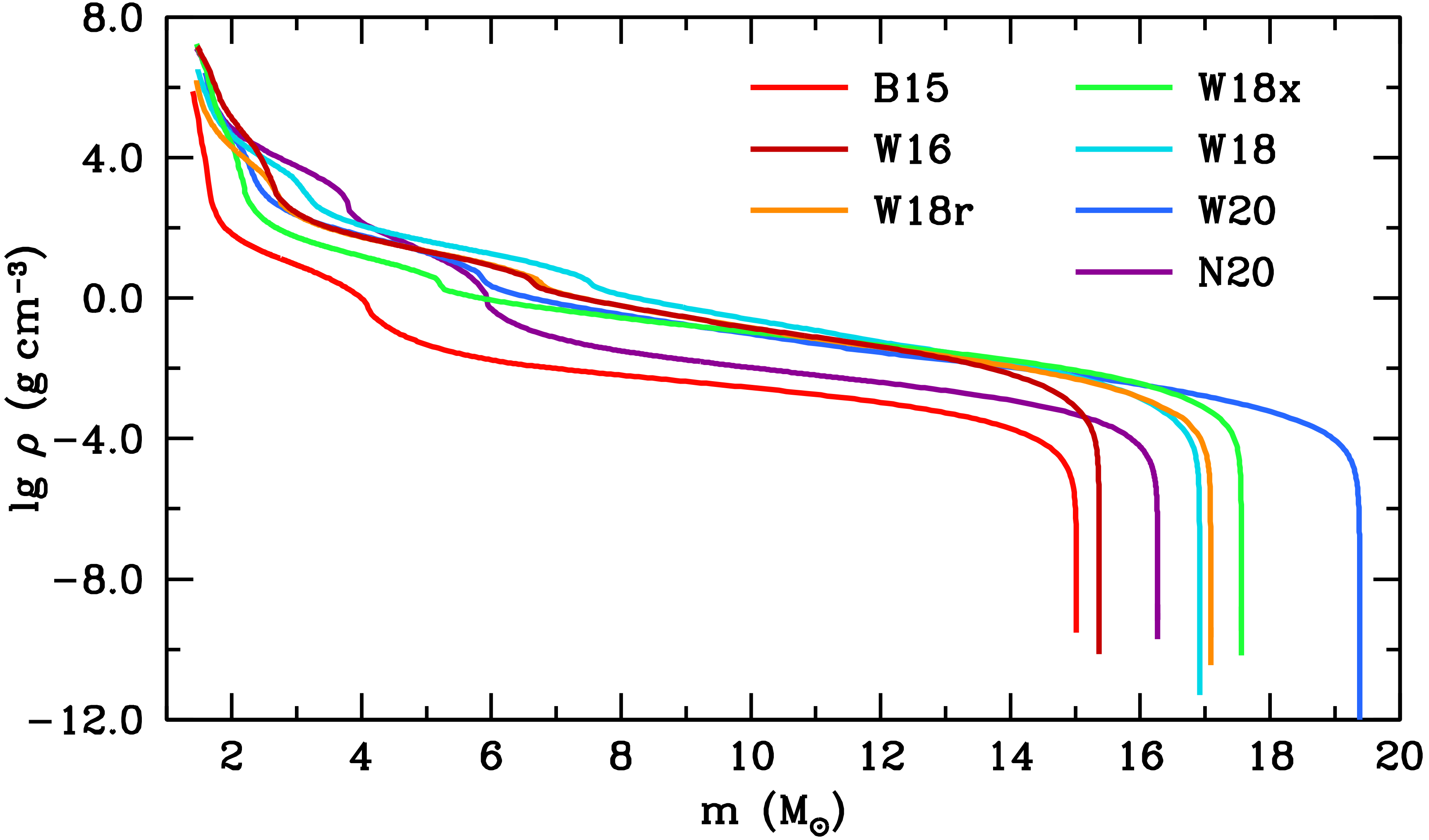
SN 1987A originates from BSG; its light curve is powered by radioactive decays.

Presupernova Models for Blue Supergiants

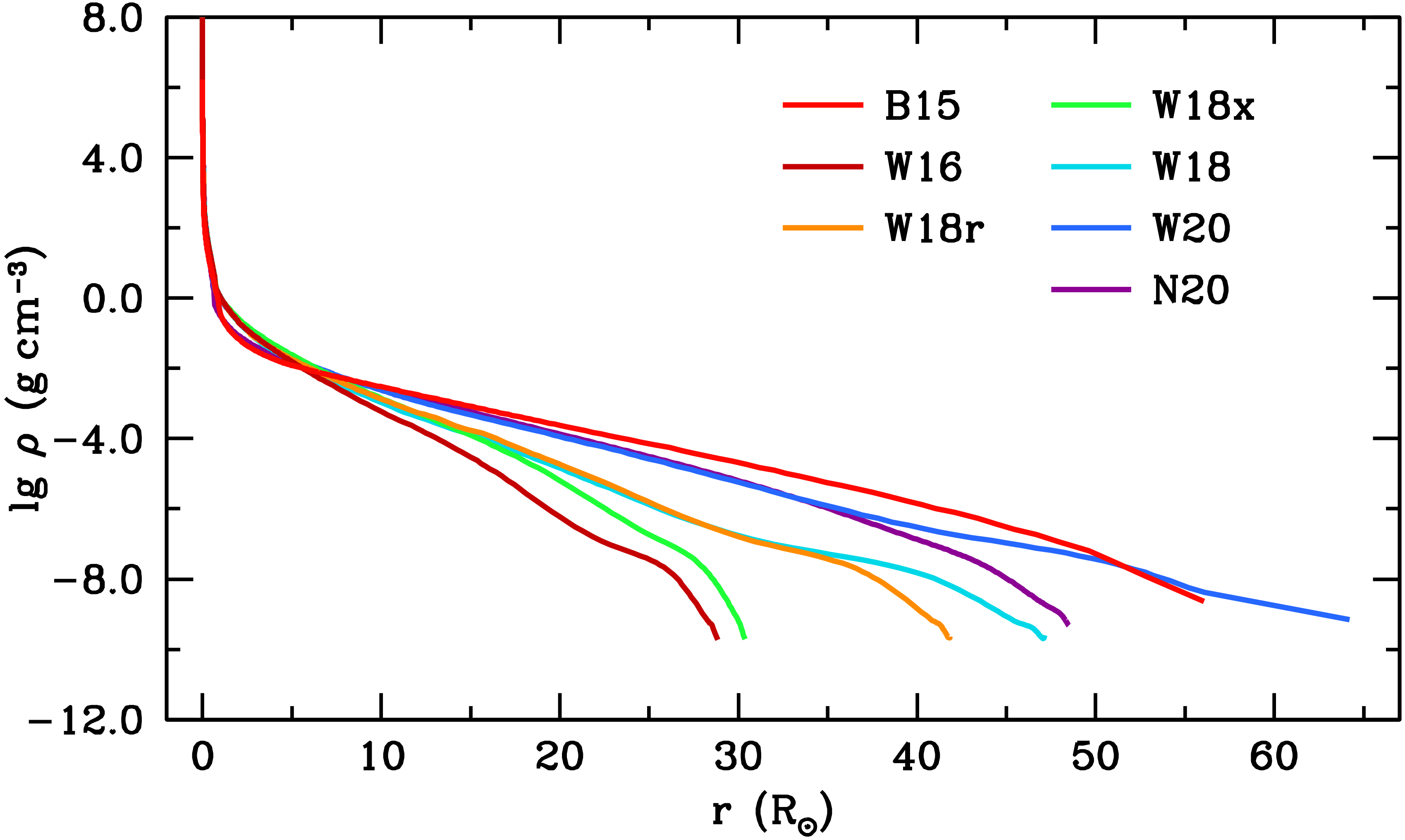
Model	$R_{\rm pSN}$ $(R_\odot)$	$M_{\rm He}^{\rm core}$	$M_{\rm pSN}$ $(M_\odot)$	$M_{\rm ZAMS}$	$X_{\rm surf}$	$Y_{\rm surf}$	$Z_{\rm surf}$ (10^{-2})	Rot.	Ref.
B15	56.1	4.05	15.02	15.02	0.767	0.230	0.34	No	1
W16	28.8	6.55	15.36	16	0.474	0.521	0.50	Yes	2
W18	46.8	7.40	16.92	18.0	0.480	0.515	0.50	Yes	2
W18r	41.9	6.65	17.09	18	0.542	0.453	0.50	Yes	3
W18x	30.4	5.13	17.56	18	0.713	0.281	0.60	Yes	2
N20	47.9	5.98	16.27	∼20.0	0.560	0.435	0.50	No	4
W20	64.2	5.79	19.38	20.10	0.738	0.256	0.56	No	5

(1) Woosley et al. (1988), (2) Sukhbold et al. (2016), (3) Woosley (priv. comm.), (4) Shigeyama & Nomoto (1990), (5) Woosley et al. (1997)

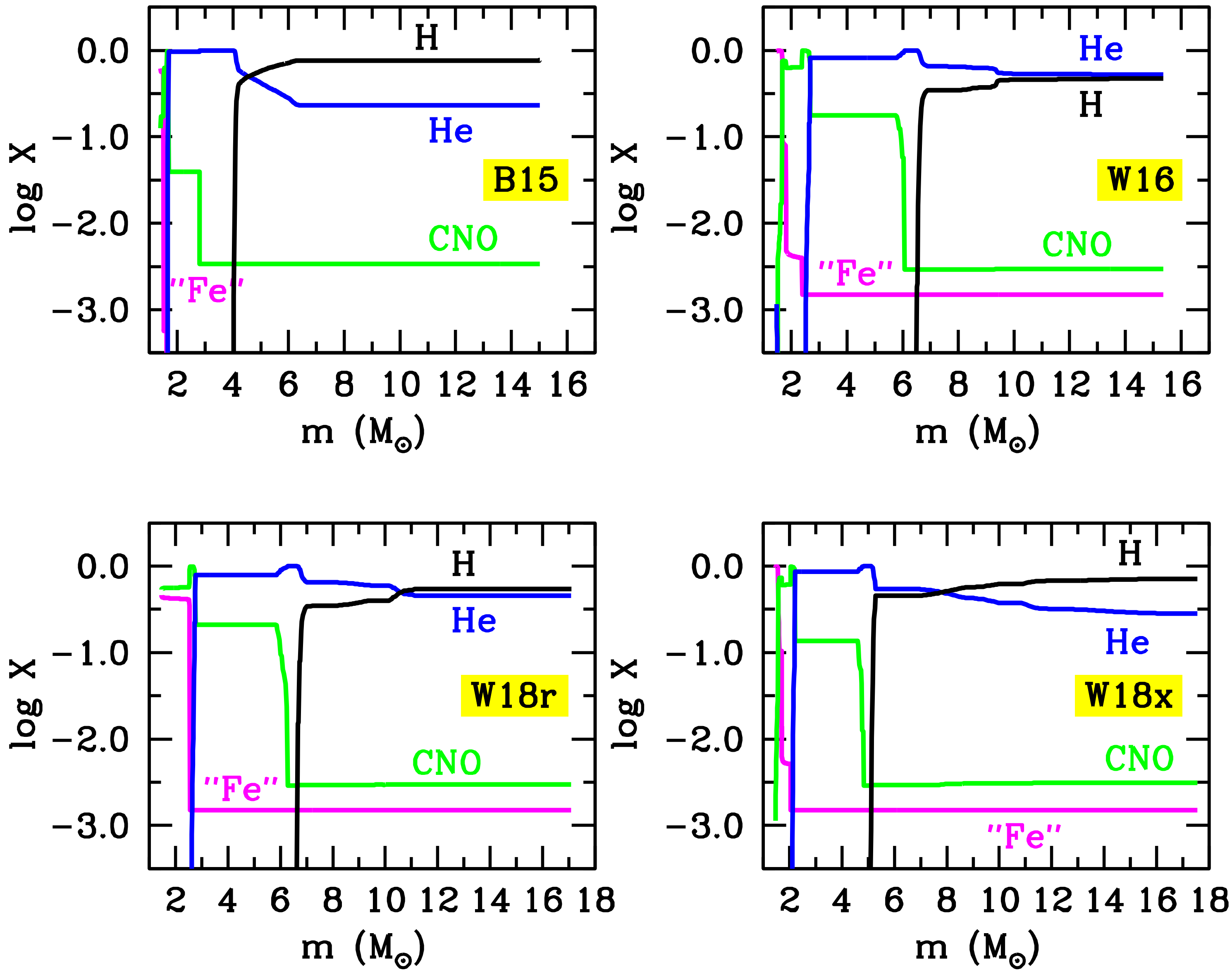
Presupernova Models: Density vs. Interior Mass



Presupernova Models: Density vs. Radius



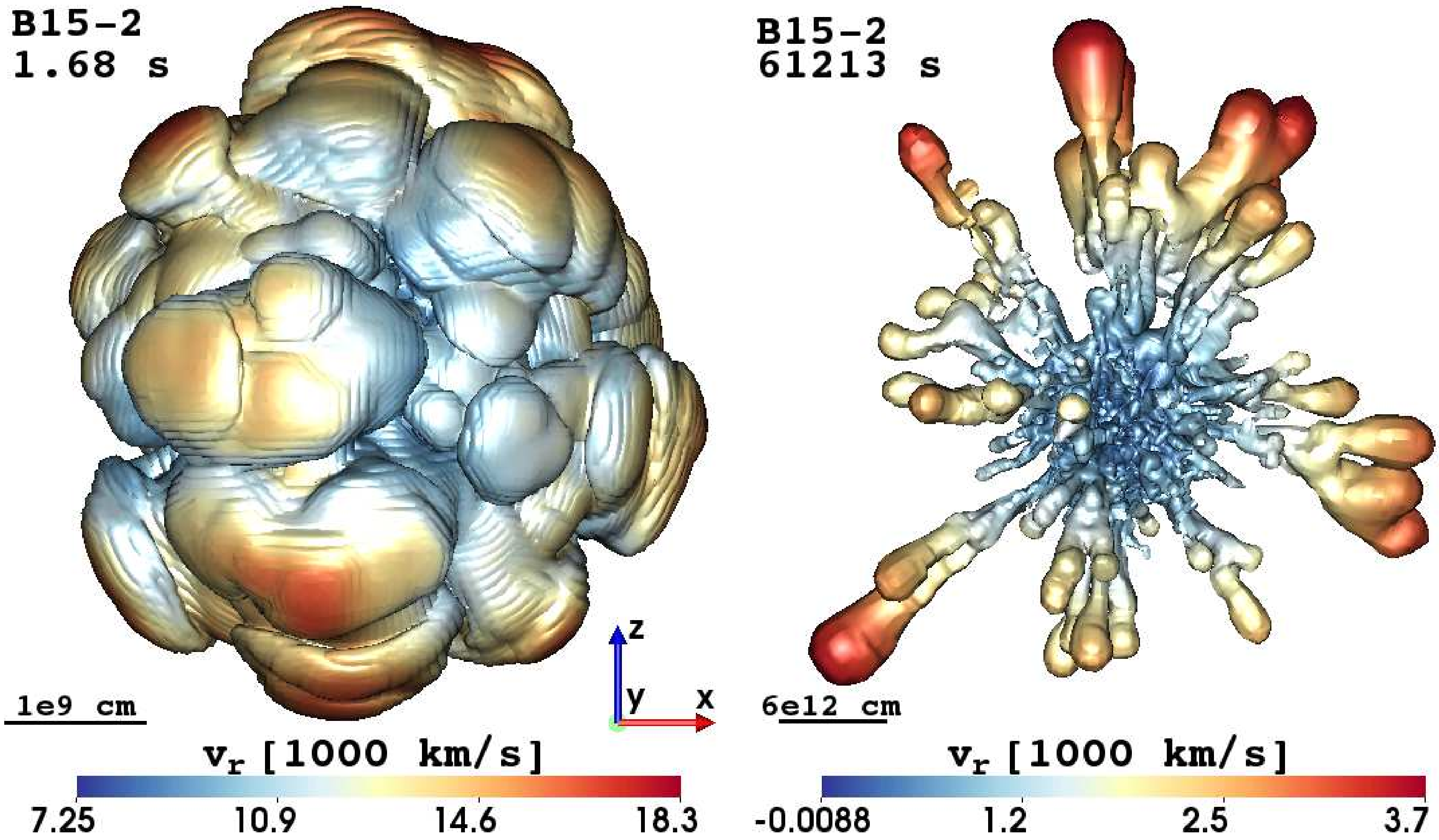
Pre-SN Models: Mass Fractions vs. Interior Mass



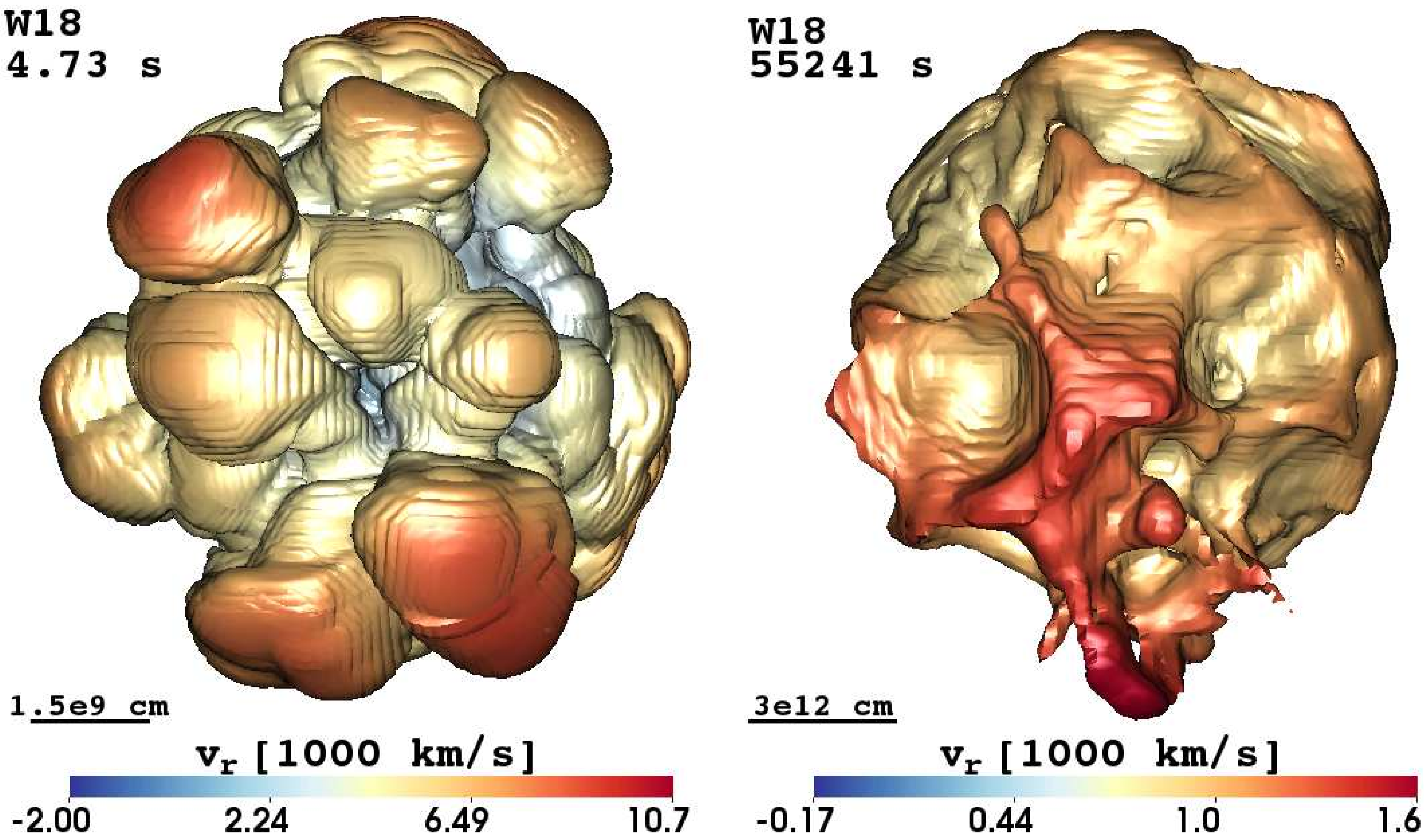
Hydrodynamic Models

Model	M_{NS}	M_{env}	E_{exp}	$M_{\mathrm{Ni}}^{\mathrm{min}}$	$M_{\mathrm{Ni}}^{\mathrm{max}}$	M_{Ni}	$v_{\mathrm{Ni}}^{\mathrm{bulk}}$	$\langle v \rangle_{\mathrm{Ni}}^{\mathrm{tail}}$
	$(M_\odot)$		(B)	$(10^{-2}\,M_\odot)$			(km s^{-1})	
B15-2	1.25	14.21	1.40	3.11	9.36	7.28	3355	3490
W16-1	1.97	13.38	1.13	3.43	8.24	7.32	2117	2222
W18	1.40	15.52	1.36	3.67	12.97	7.26	1395	1472
W18r-2	1.35	15.73	1.27	2.48	9.37	7.65	1088	1101
W18x-1	1.57	15.98	1.22	2.85	9.23	7.64	2247	2361
W18x-2	1.52	16.03	1.38	3.86	12.19	7.54	2436	2837
N20-P	1.46	14.72	1.67	4.16	12.11	7.23	1635	1790
W20	1.50	17.92	1.45	4.10	13.04	7.24	1374	1482

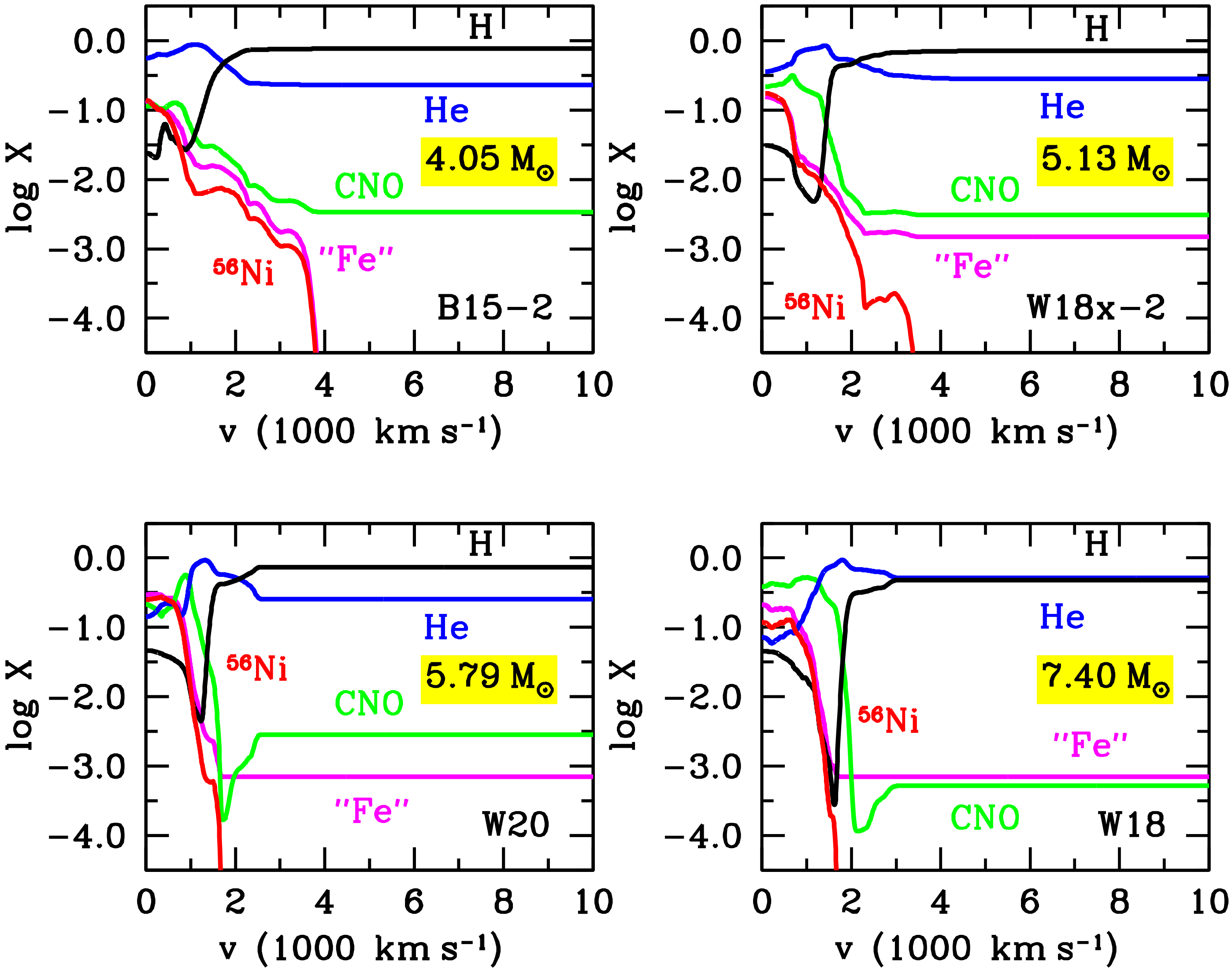
Morphology of ^{56}Ni-rich Matter in Model B15-2



Morphology of ^{56}Ni-rich Matter in Model W18



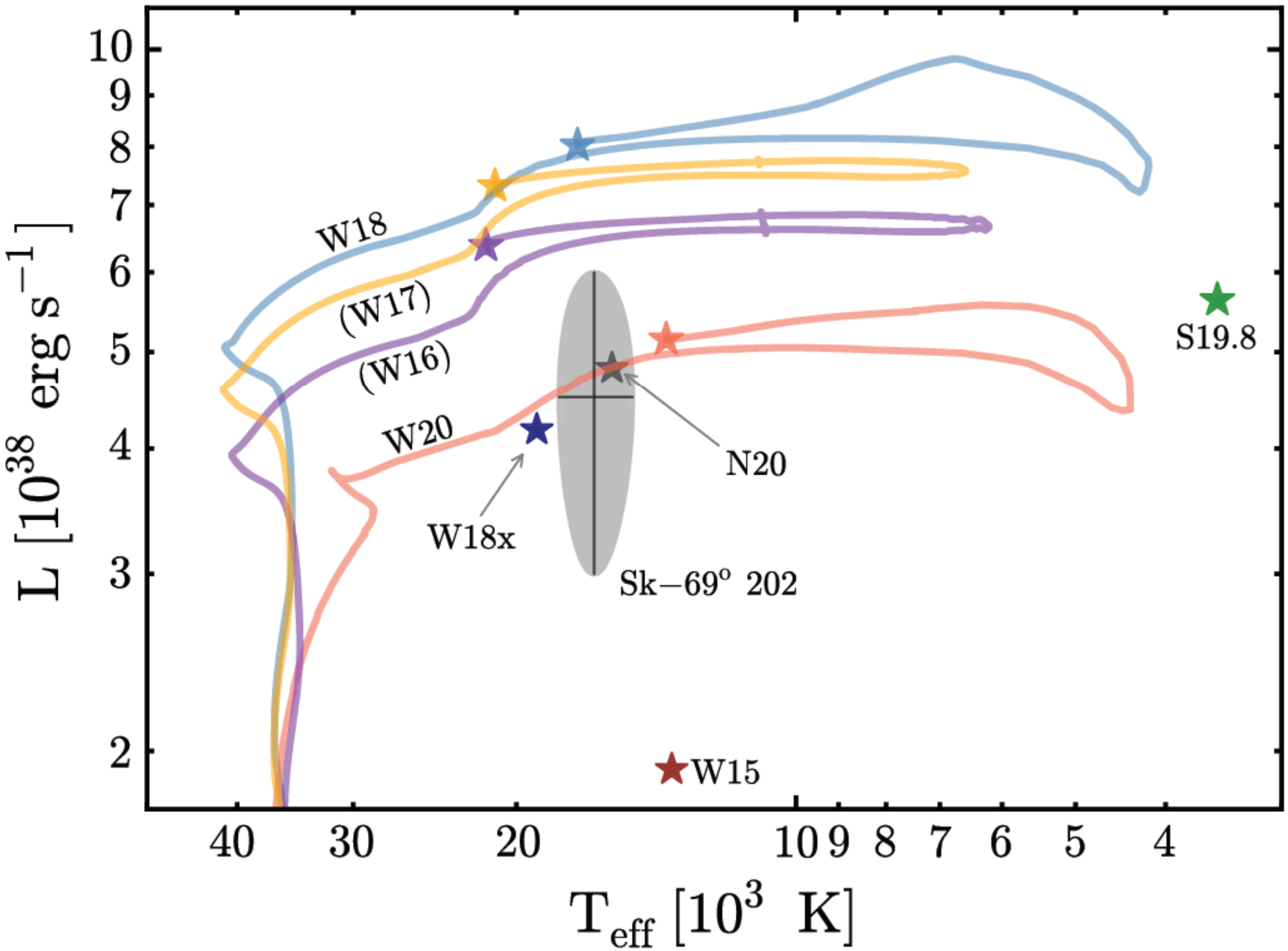
More Massive Helium Core, Lower ^{56}Ni Velocity



Only model B15-2 yields maximum Ni velocity consistent with the observations!

Hertzsprung-Russell Diagram for SN 1987A Progenitors.

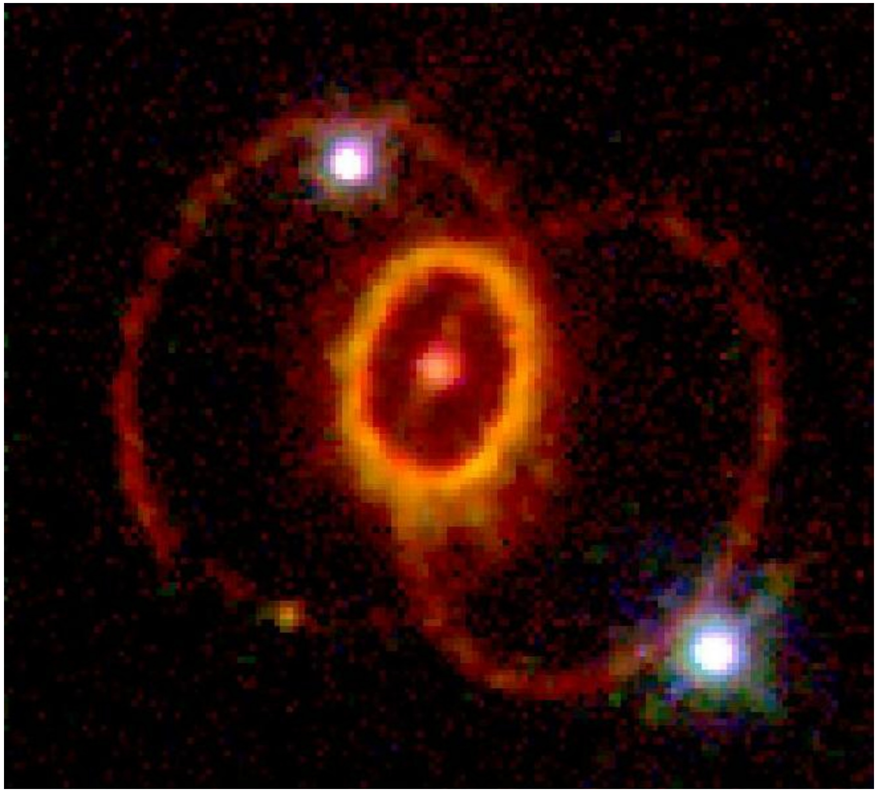
Single Star Scenario



Sukhbold et al. (2016)

Two Possible Solutions of The Problem

- A rapid rotation of Fe core producing more extent of Ni mixing.
- A binary evolution scenario for the BSG Sanduleak $-69^{\circ}202$.

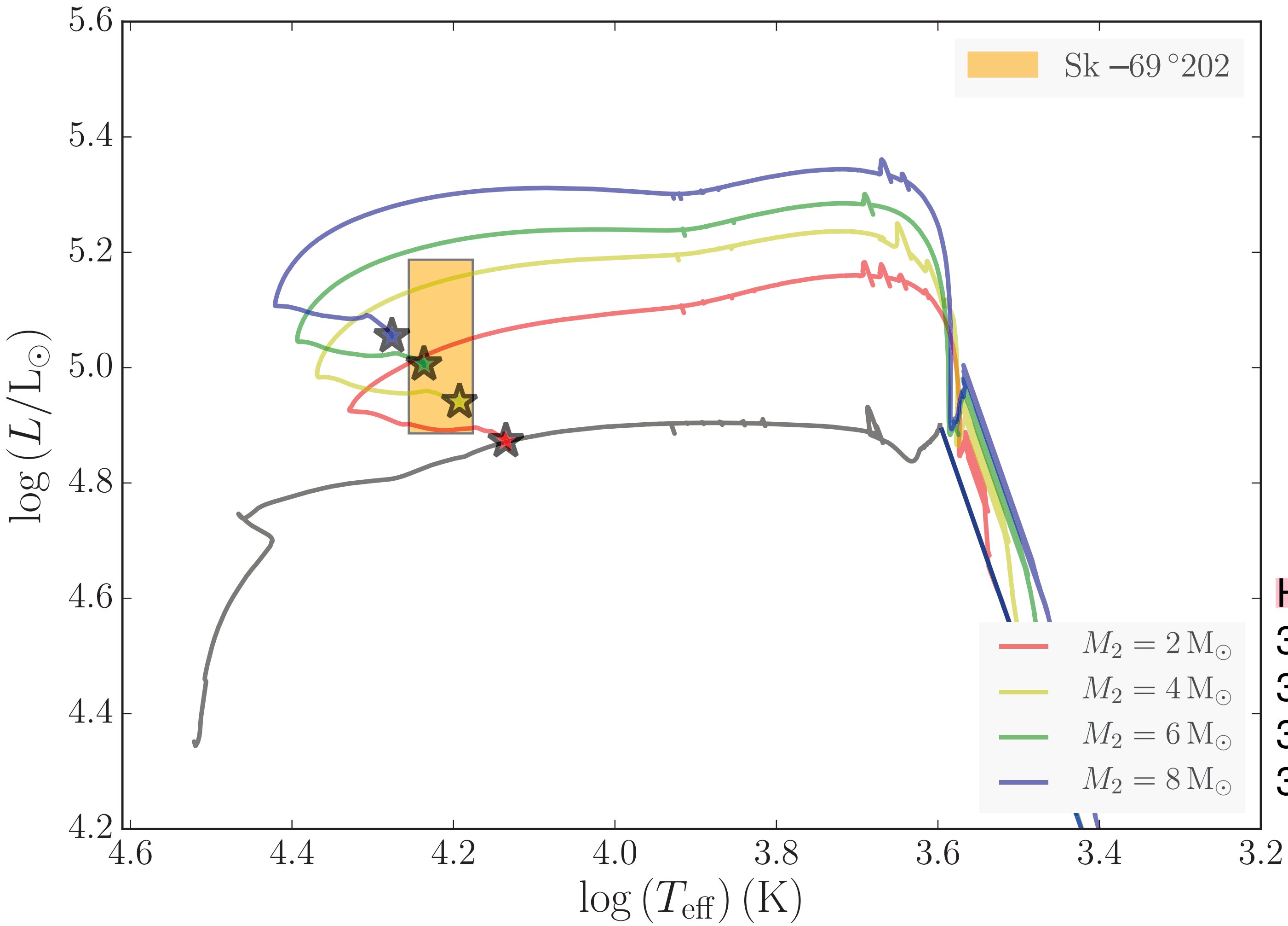


Credit: (ESA/STScI), HST, NASA

The triple-ring system was explained by Morris & Podsiadlowski (2009) in the scenario of a binary merger model.

Hertzsprung-Russell Diagram for SN 1987A Progenitors.

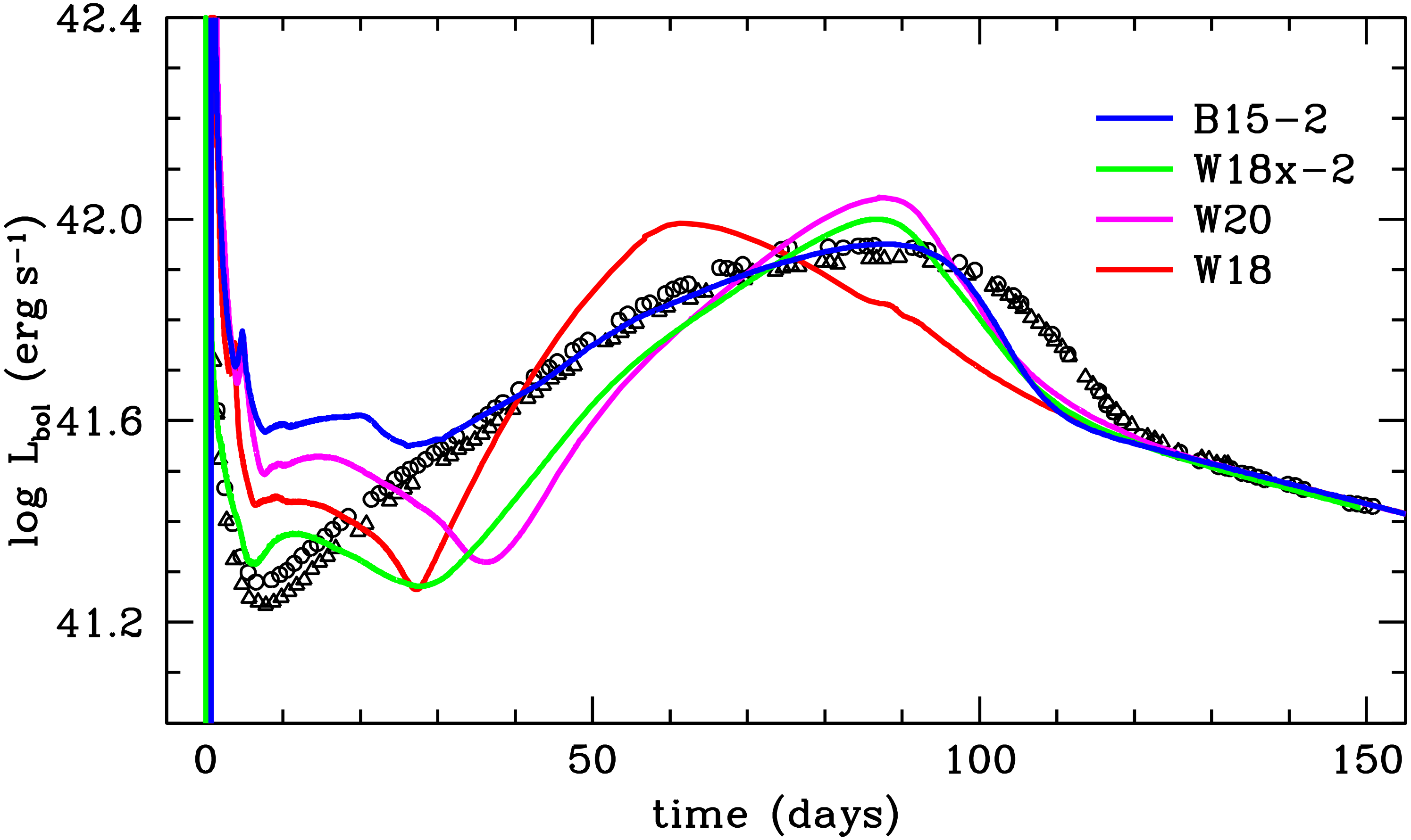
Binary Merger Scenario



He core
$3.73\,M_\odot$
$3.63\,M_\odot$
$3.61\,M_\odot$
$3.52\,M_\odot$

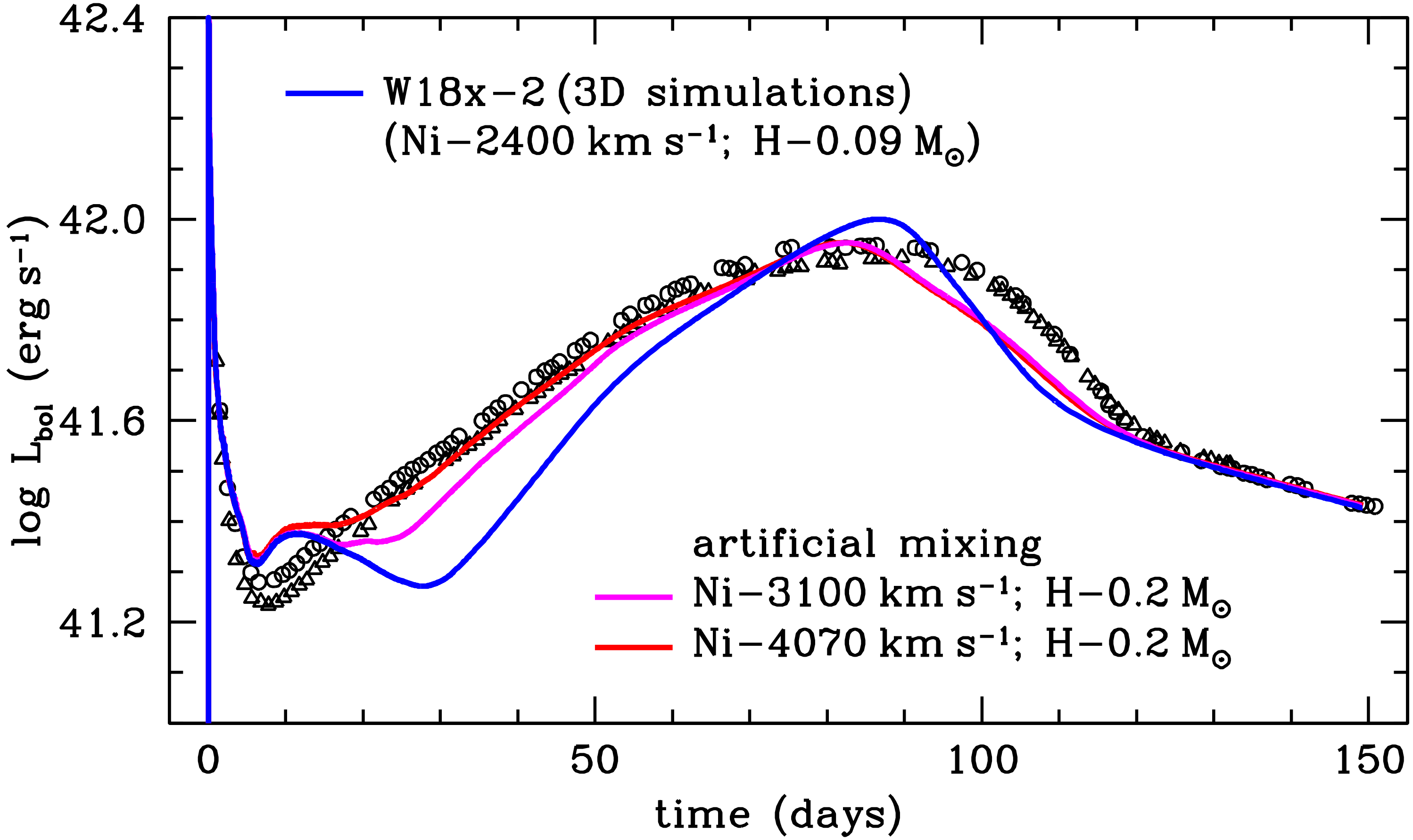
$\mathbf{M_1 = 16\,M_\odot}$ Menon & Heger (2017), see also A. Menon's talk.

Bolometric Light Curves



The total ^{56}Ni mass is scaled to fit the observed luminosity in the radioactive tail.

Light Curves: Artificial Mixing



The total ^{56}Ni mass is scaled to fit the observed luminosity in the radioactive tail.

Summary

- 3D neutrino-driven explosion simulations of SN 1987A are able to synthesize the ^{56}Ni mass estimated from the observed luminosity in the radioactive tail.
- The extent of outward ^{56}Ni mixing in the framework of the 3D simulations decreases with He-core masses of the corresponding progenitor models.
- In 3D simulations only the model with He-core mass of $4\,M_{\odot}$ yields a maximum velocity of the bulk of ^{56}Ni consistent with SN 1987A observations.
- In a single star scenario Sk $-69°202$ seems to require a progenitor with a $\sim 6\,M_{\odot}$ He core, and a $4\,M_{\odot}$ He core is not able to explain the color-luminosity properties before collapse.
- Rapid rotation of the iron core might lead to more mixing. Investigations are needed.
- Binary progenitor models with $\sim 4\,M_{\odot}$ He cores can account for the color-luminosity properties of Sk $-69°202$ (see A. Menon's talk). But do they yield the extent of mixing to explain SN 1987A observations?
- Inward hydrogen mixing leads to minimum velocities of H-rich matter of less than 100 km s^{-1} in a good agreement with SN 1987A observations.

Future

- 3D neutrino-driven explosion simulations on the basis of binary merger models of Menon & Heger (2017) for the progenitor of SN 1987A.