Core-Collapse Supernovae: A Day after the Explosion

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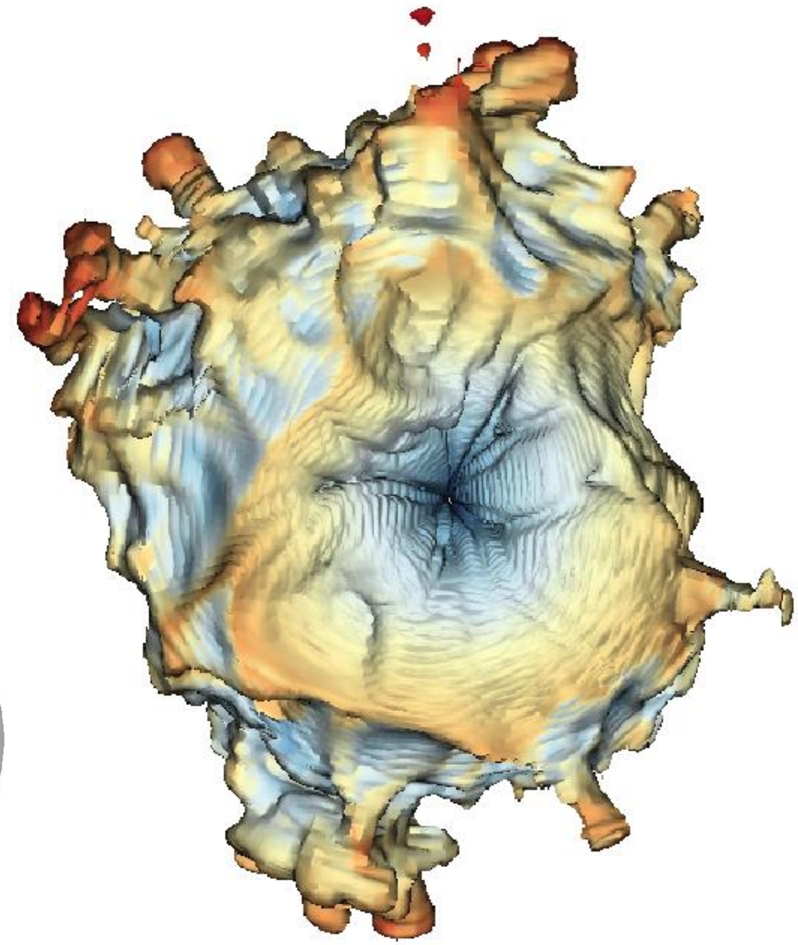
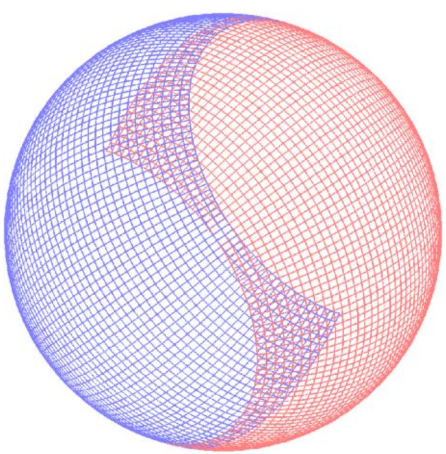
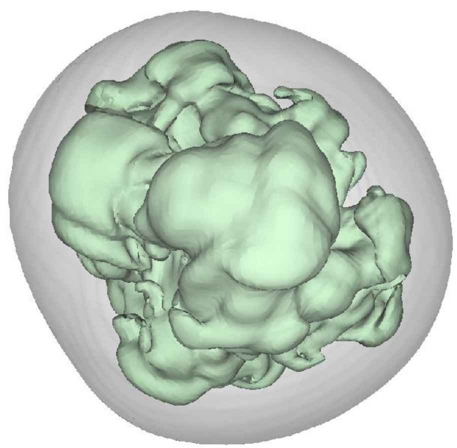
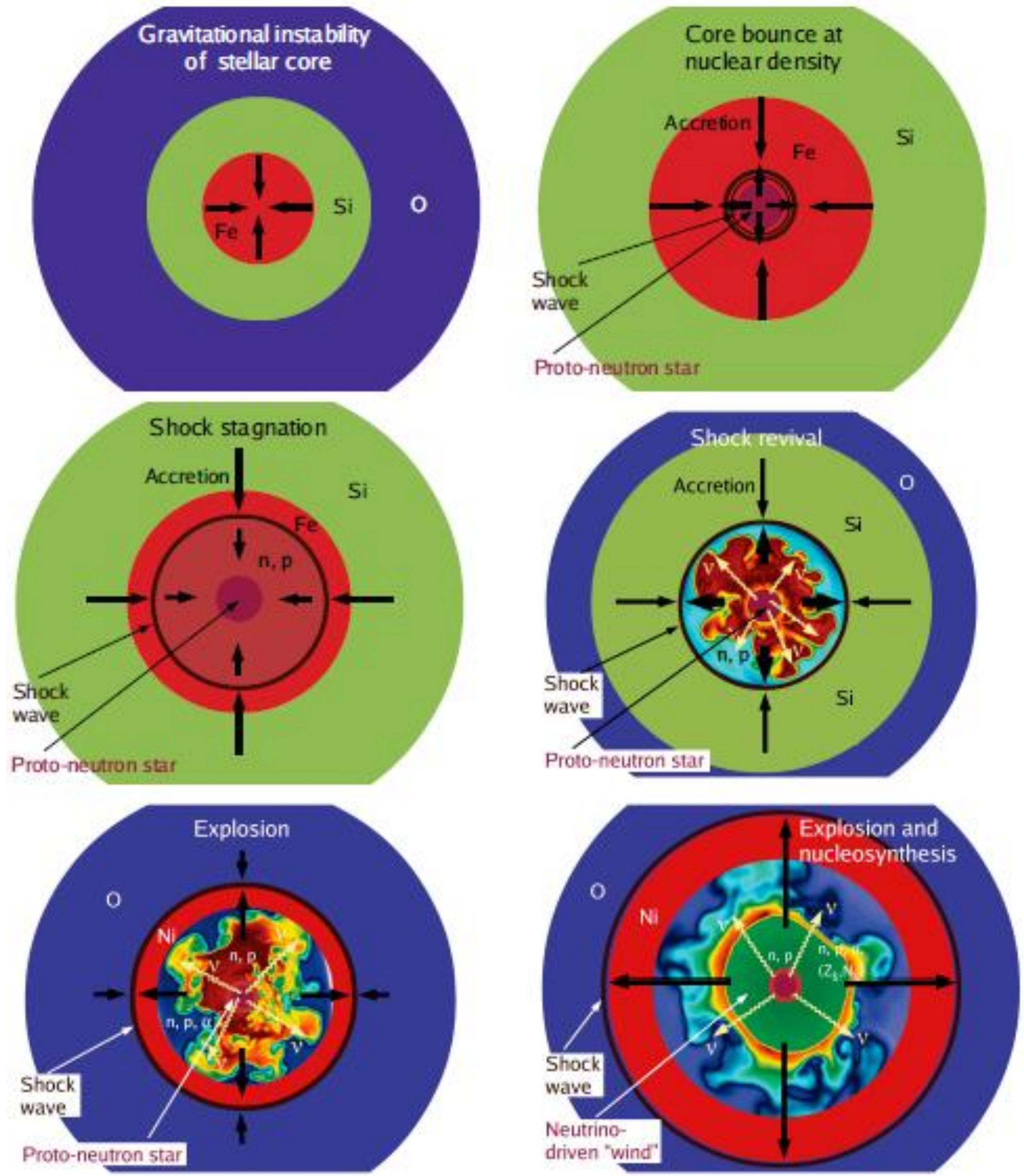






Introduction

Figure from Janka et al. (2012)



CCSNe = death of massive stars

collapse >> bounce >> shock formation >> stalled accretion shock

how to revive the stalled shock???

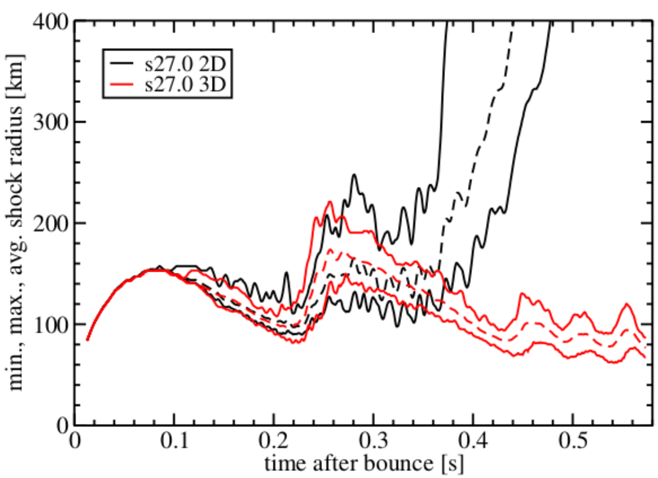
neutrino-driven mechanism

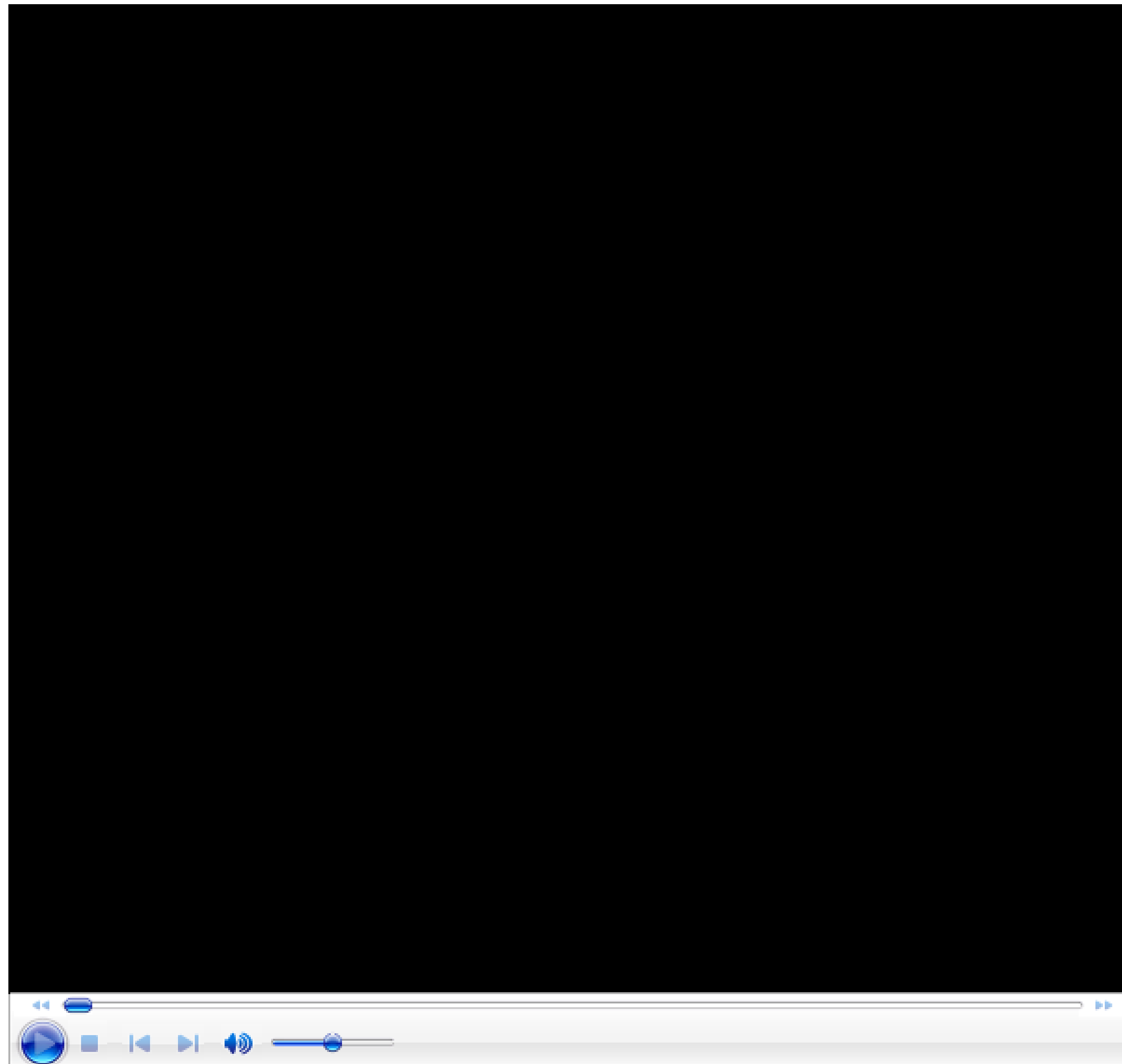
multi-D effects play important roles !!!

Introduction

3D self-consistent simulation by Florian Hanke (Hanke et al. 2013)

Development of convective instabilities and SASI





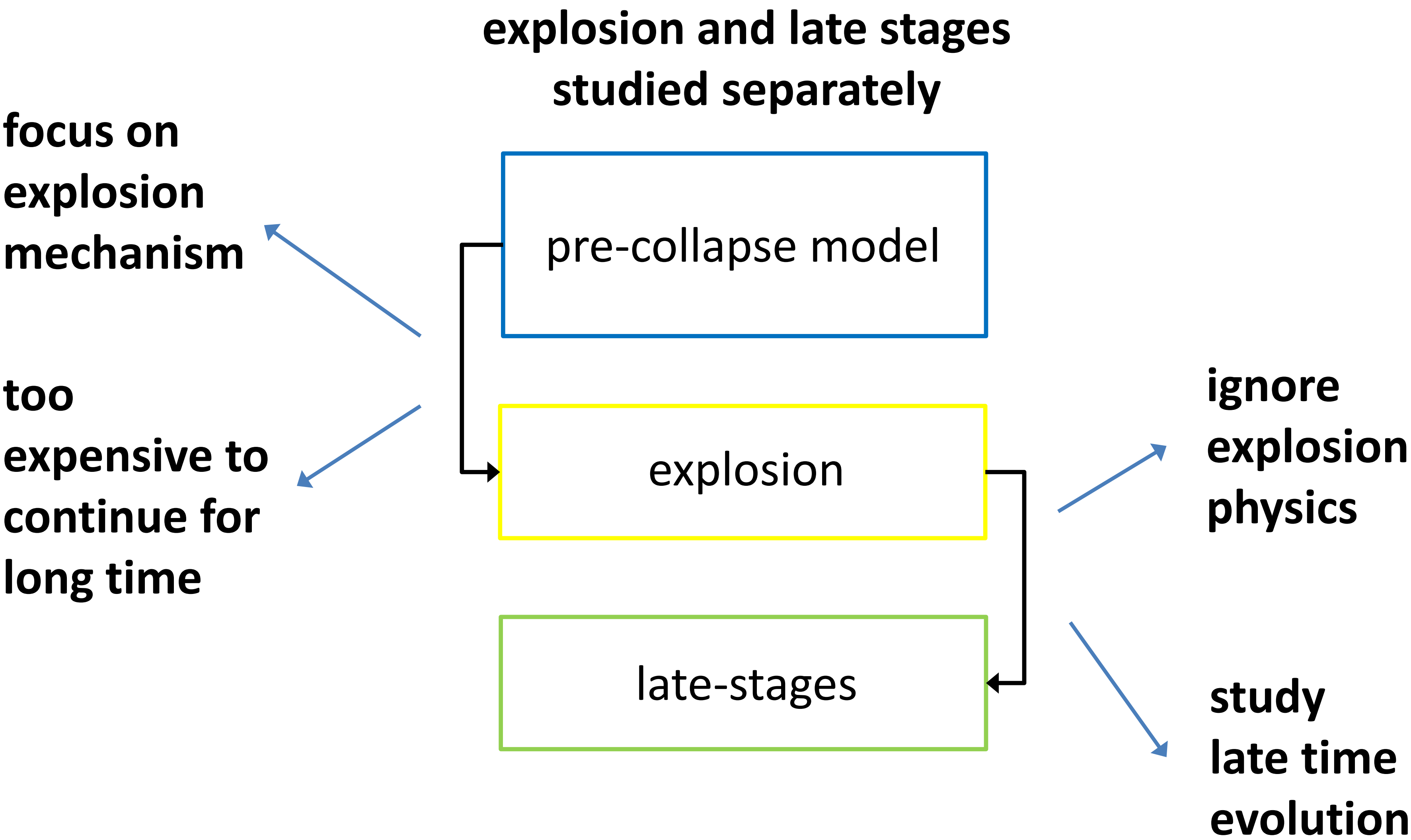
Introduction

- Evidences of mixing from observations of SN1987A;

See review of Hillebrandt&Höflich (1992)

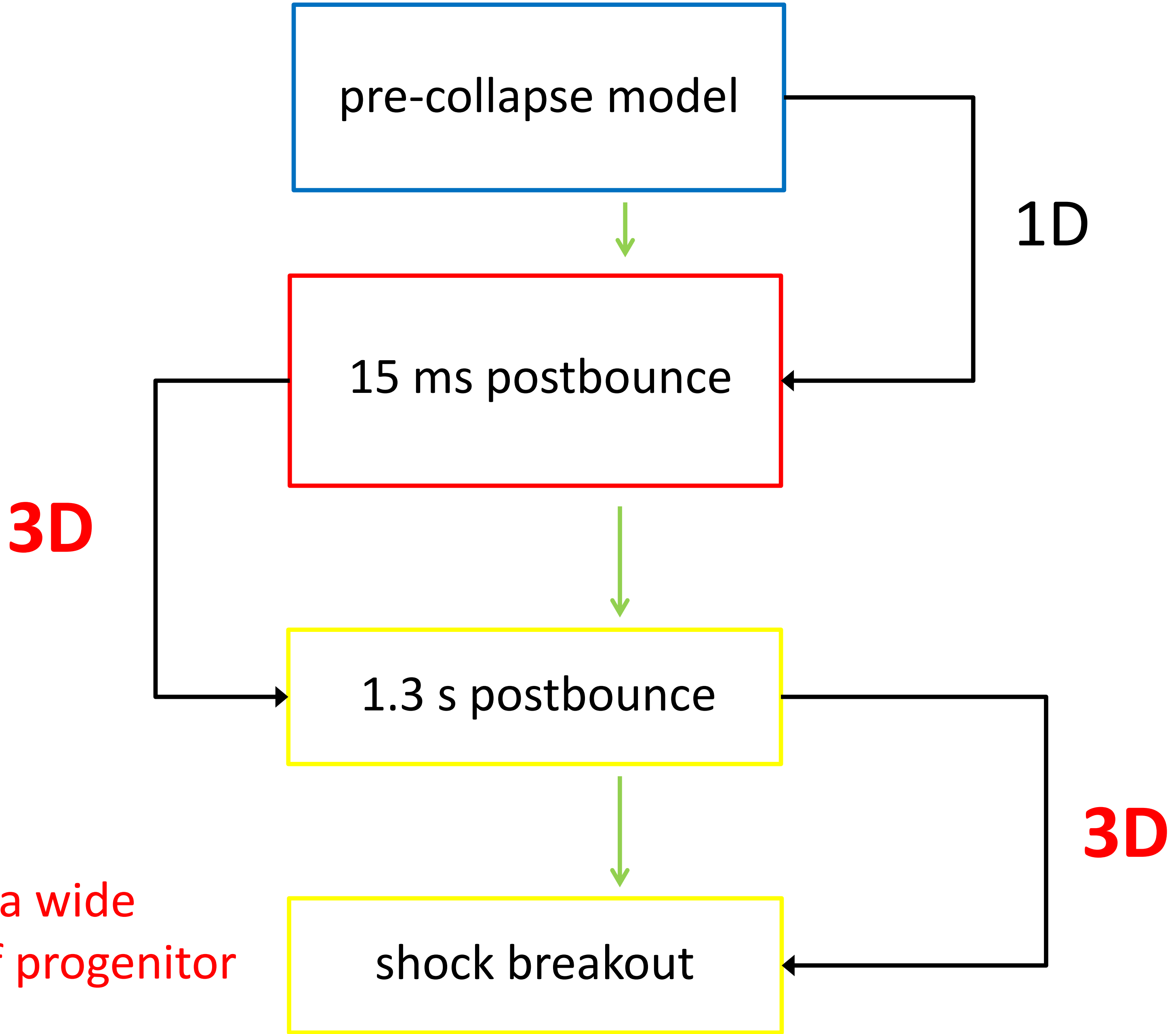
- Mixing of hydrogen to inner core and Ni to hydrogen envelope by light curve modelling (e.g., Utrobin 2004)
- Early occurrence of hard X-ray and γ –ray (e.g., Dotani+ 1987, Sunyaev+ 1987)
- High velocity feature of [FeII] line at 3900 km/s (Haas et al. 1990)
- Evidences of asymmetries in CCSNe
- Asphericity inferred from spectropolrimetric observations of SNIb/c & SNII-P (for review Wang&Wheeler 2008)
- large velocities of pulsar "kicks"
- Complicated structures in SNRs, e.g. Crab, Cas A
- Missing link between theories and observations

Introduction



Previous works

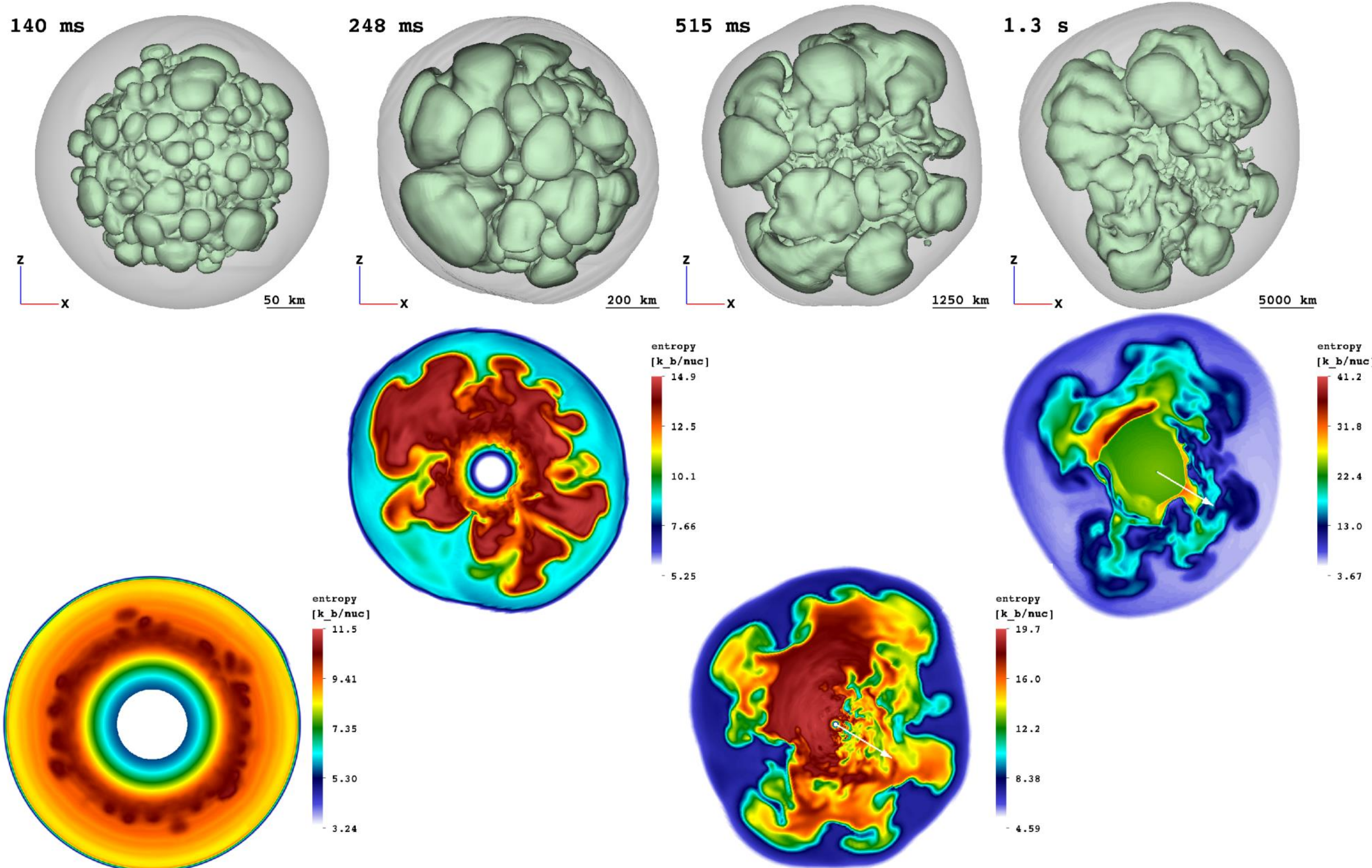
- late-time CCSN simulations
- works by many groups in 1990s; e.g., Arnett+ 1989, Fryxell+ 1991, Müller+ 1991, Hachisu+ 1990, Yamada&Sato 1990, Herant&Benz 1992, Herant&Woosley 1994, Shigeyama+ 1996, Iwamoto+ 1997, Nagataki+ 1998
- mostly in 2D; grid-based and SPH
- spherical symmetric explosion (thermal bomb) + random perturbation
- difficult to obtain fast (>2000 km/s) Ni
- more recent works in 2D & 3D (e.g., Hungerford+ 2003,2005, Kifonidis+ 2000,2003,2006, Joggerst+ 2009,2010, Couch+ 2009, Hammer+ 2010, Ellinger+ 2012,2013, Ono+ 2013)



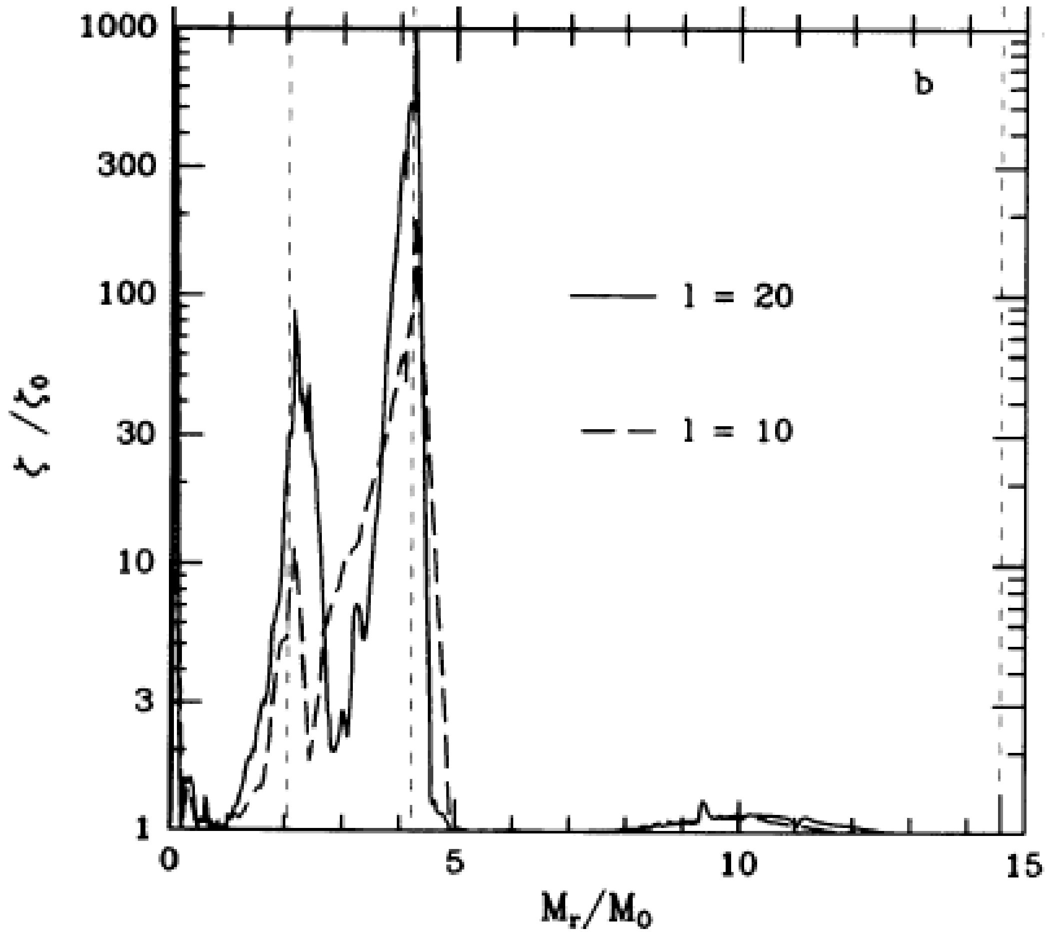
Explore a wide range of progenitor models

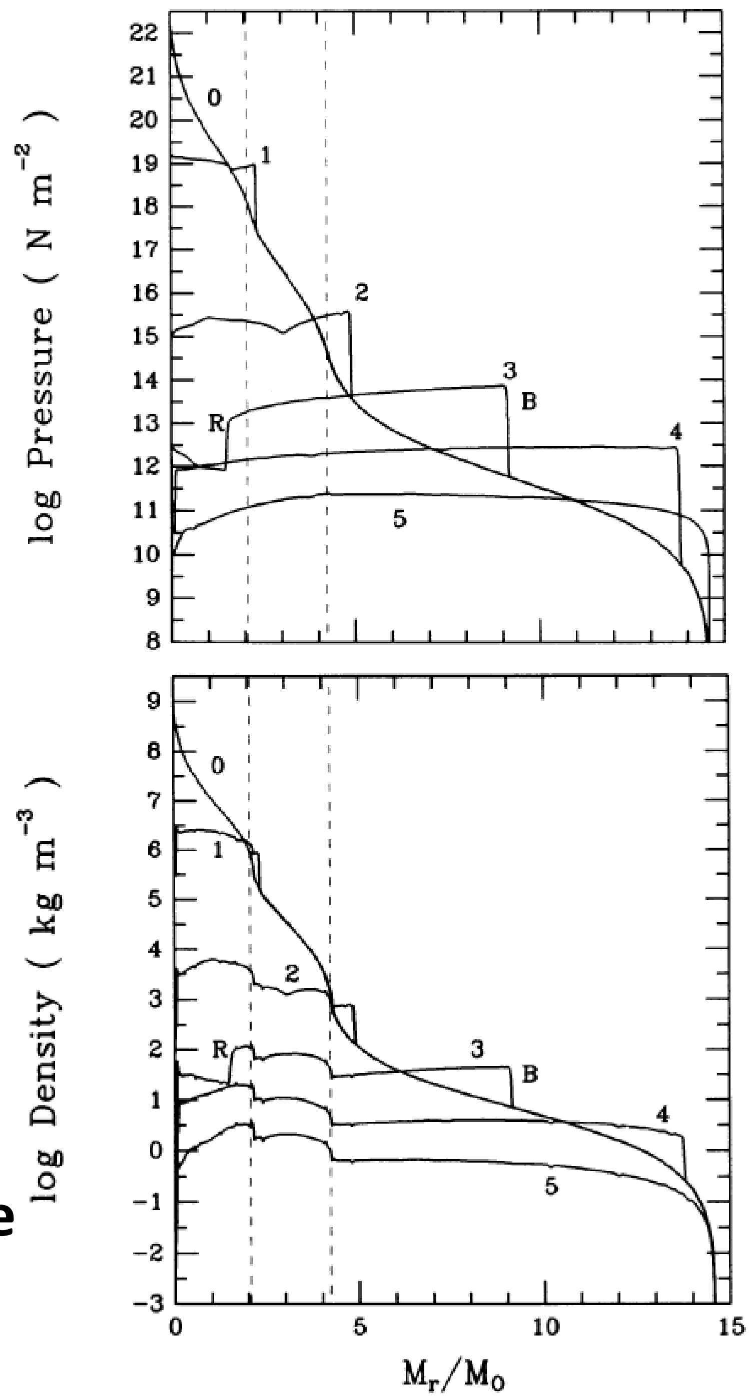
Results

Explosion simulation



Ebisuzaki et al. (1989)



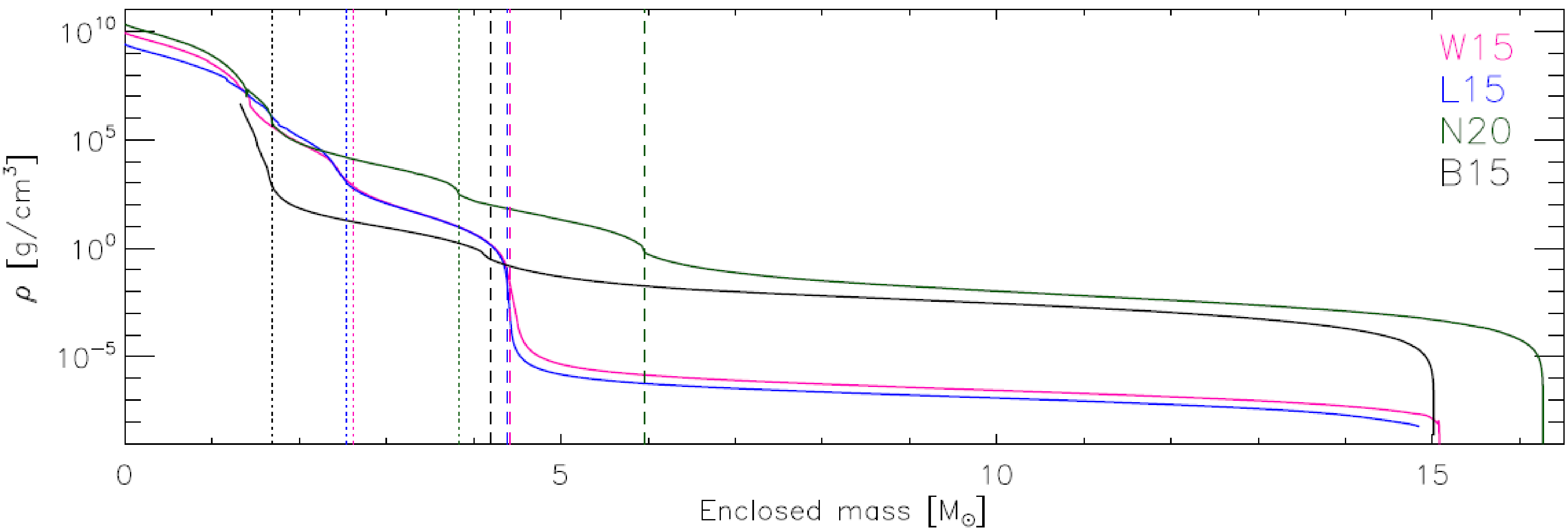


He/H and metals/He interface can become RT unstable due to gradients of pressure and density having opposite signs

Results

Wongwathanarat et al. (in prep.)

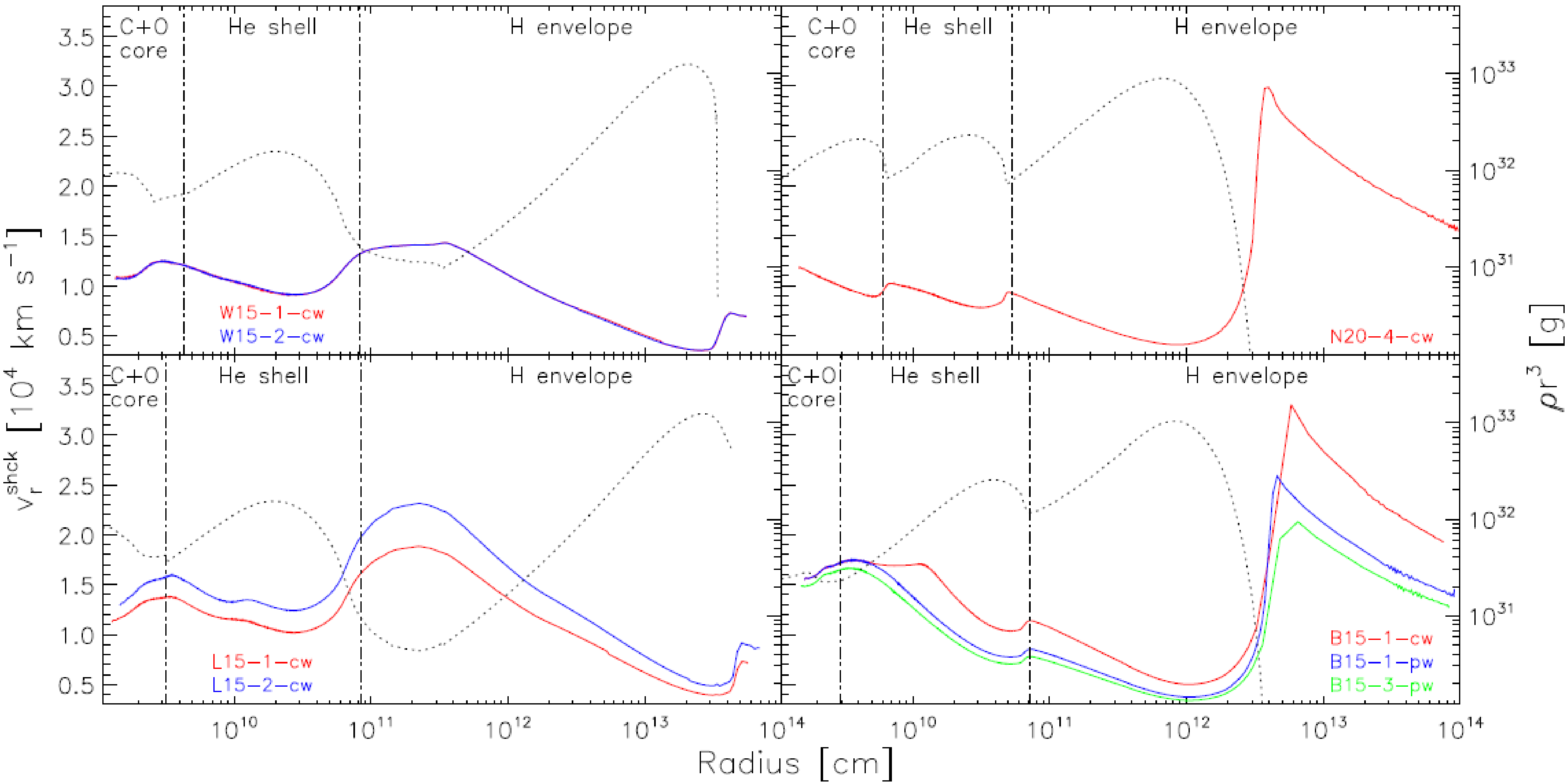
progenitor type	3D model	explosion model	time [s]	E_{exp} [B]	$\mathrm{avg}^{(max)}_{(min)}\ R_s$ [10^6 km]	M_{Ni} (M_{Ni+X}) [$M_\odot$]	v_{max}(Ni) [10^3 km s^{-1}]	$< v >_{1\%}$ (Ni) [10^3 km s^{-1}]
RSG	W15-1-cw	W15-1	84974	1.48	$389^{(443)}_{(355)}$	0.05 (0.13)	5.29	3.72
	W15-2-cw	W15-2	85408	1.47	$393^{(458)}_{(349)}$	0.05 (0.14)	4.20	3.47
	L15-1-cw	L15-1	95659	1.75	$478^{(530)}_{(448)}$	0.03 (0.15)	4.78	3.90
	L15-2-cw	L15-2	76915	2.75	$475^{(500)}_{(458)}$	0.04 (0.21)	5.01	4.51
BSG	N20-4-cw	N20-4	5589	1.65	$39.7^{(43.6)}_{(35.6)}$	0.04 (0.12)	2.23	1.95
	B15-1-cw	B15-1	5372	2.56	$41.5^{(43.6)}_{(39.5)}$	0.05 (0.11)	6.25	5.01
	B15-1-pw	B15-1	7258	1.39	$42.7^{(45.7)}_{(40.0)}$	0.03 (0.09)	3.34	3.17
	B15-3-pw	B15-3	8202	1.14	$48.1^{(51.1)}_{(44.7)}$	0.03 (0.08)	3.18	2.95



Results

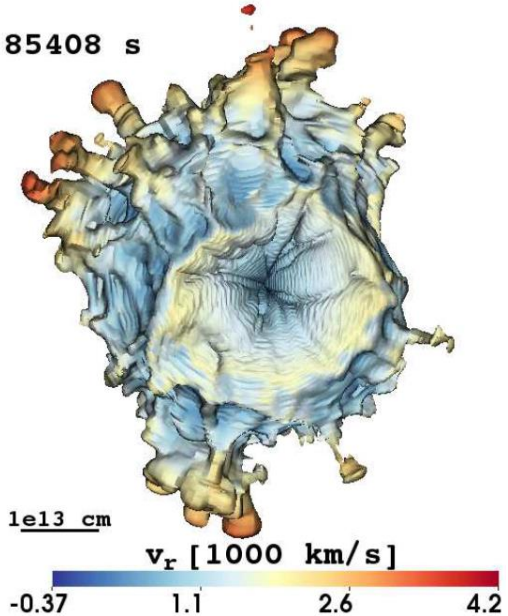
shock propagates according to blast wave solution (Sedov, 1959)

accelerates when ρr^3 decreases, and vice versa

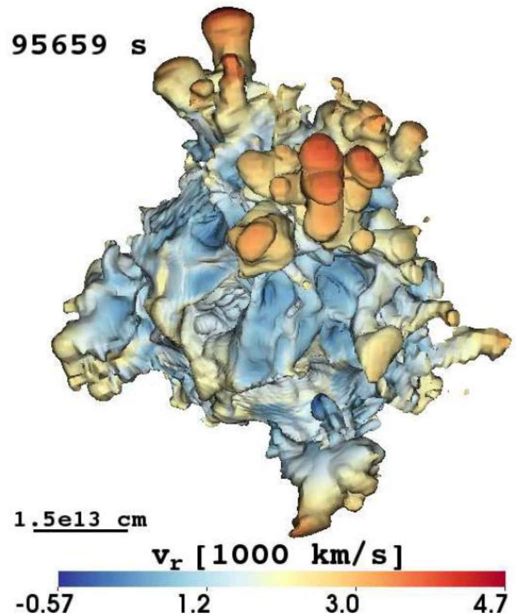


Results

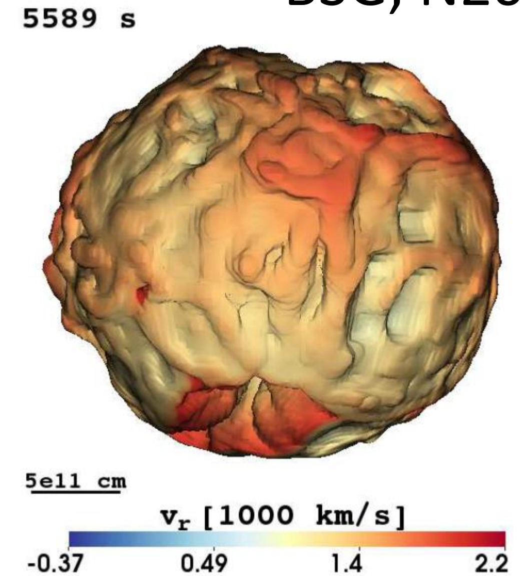
Shigeyama&Nomoto (1990)
BSG, N20



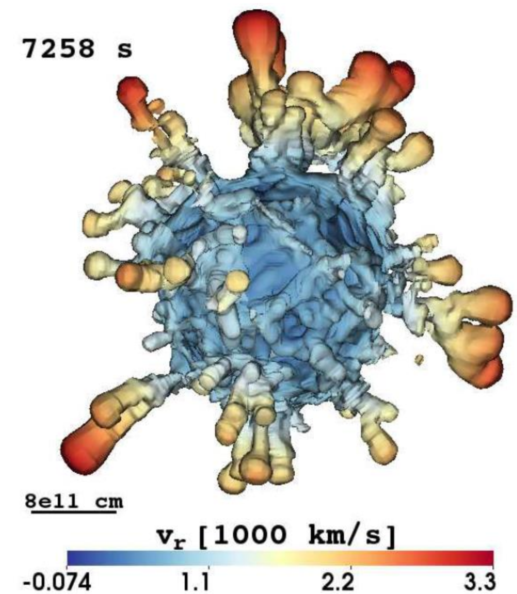
Woosley&Weaver (1995)
RSG, W15



Limongi+ (2000)
RSG, L15



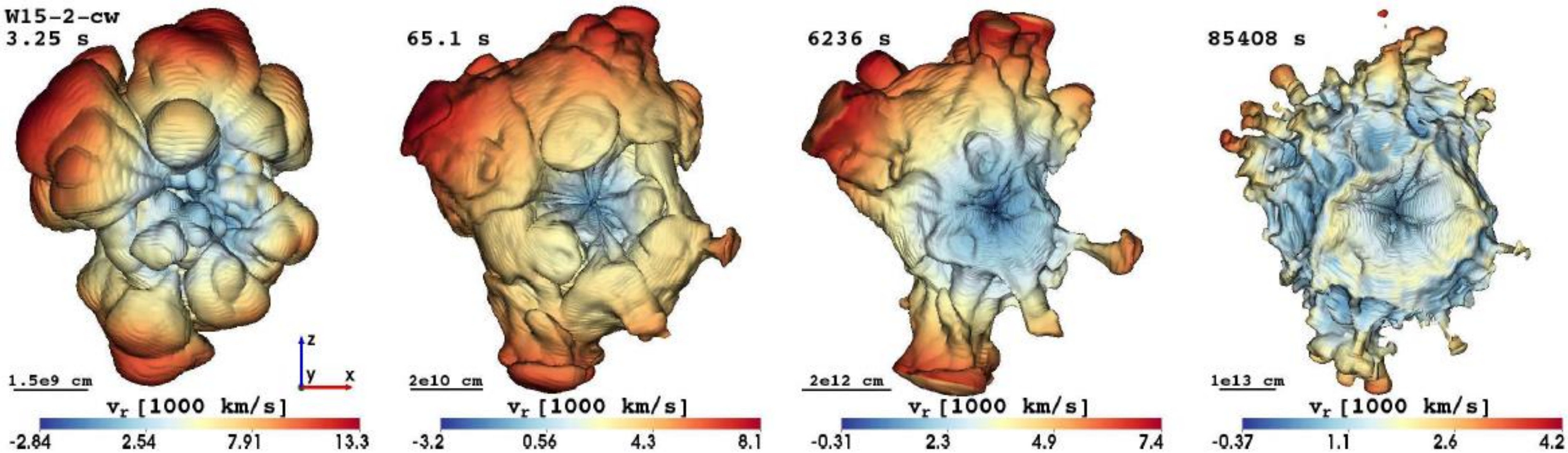
Nickel-rich ejecta at shock breakout



Woosley+ (1988) BSG, B15

Results

time evolution of propagation of nickel-rich ejecta



at C+O/He interface

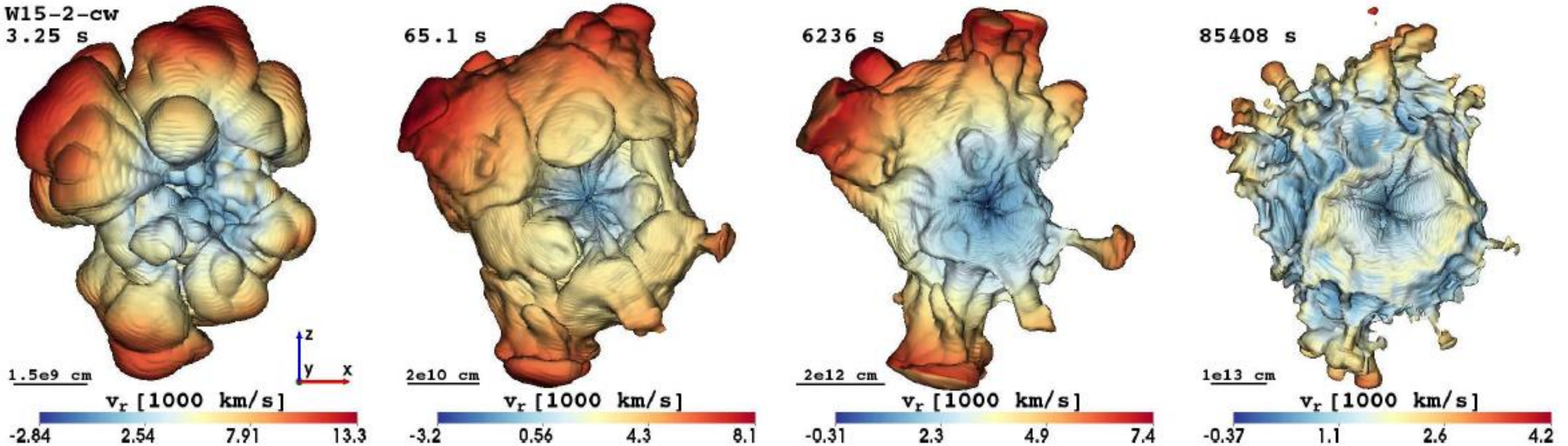
→ at He/H interface

→ meet reverse shock

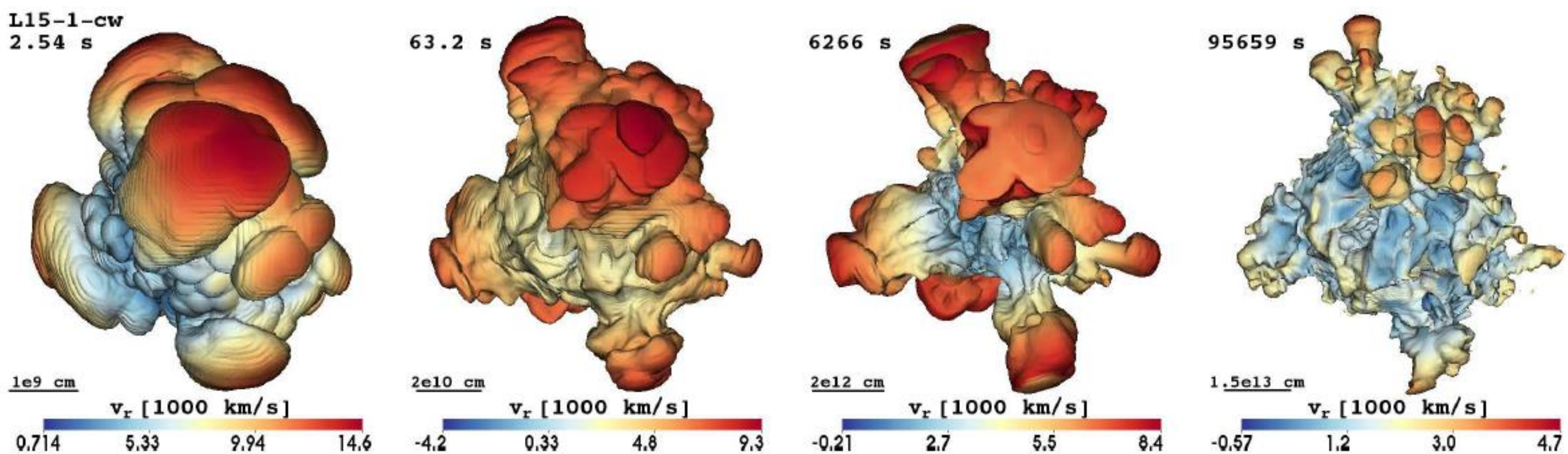
→ shock breakout

Results

RSG



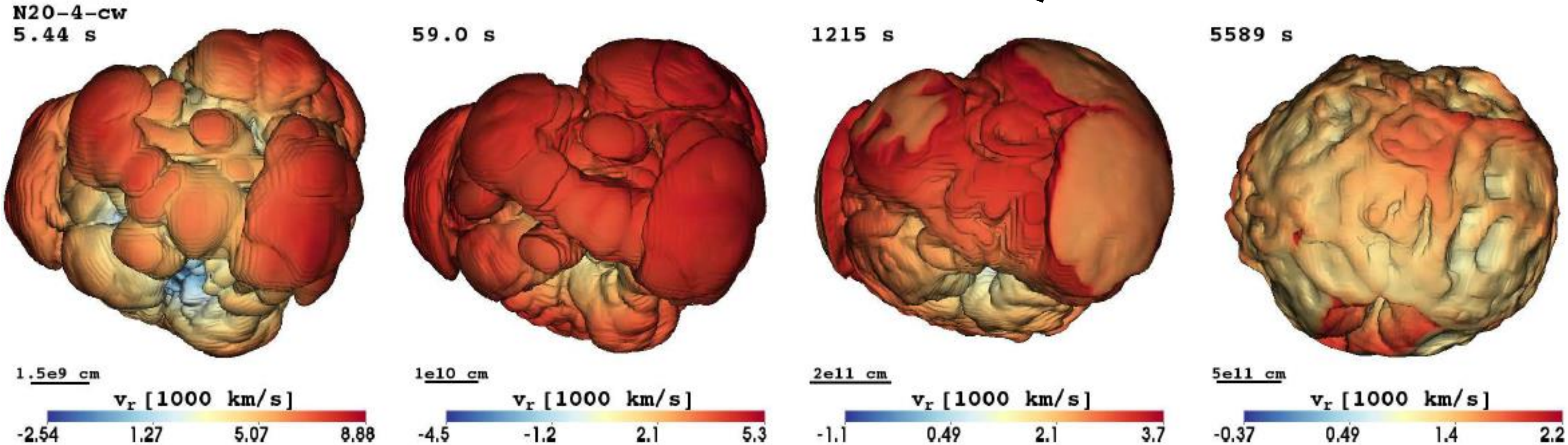
Similar evolution for both progenitors



Results

roundish structure

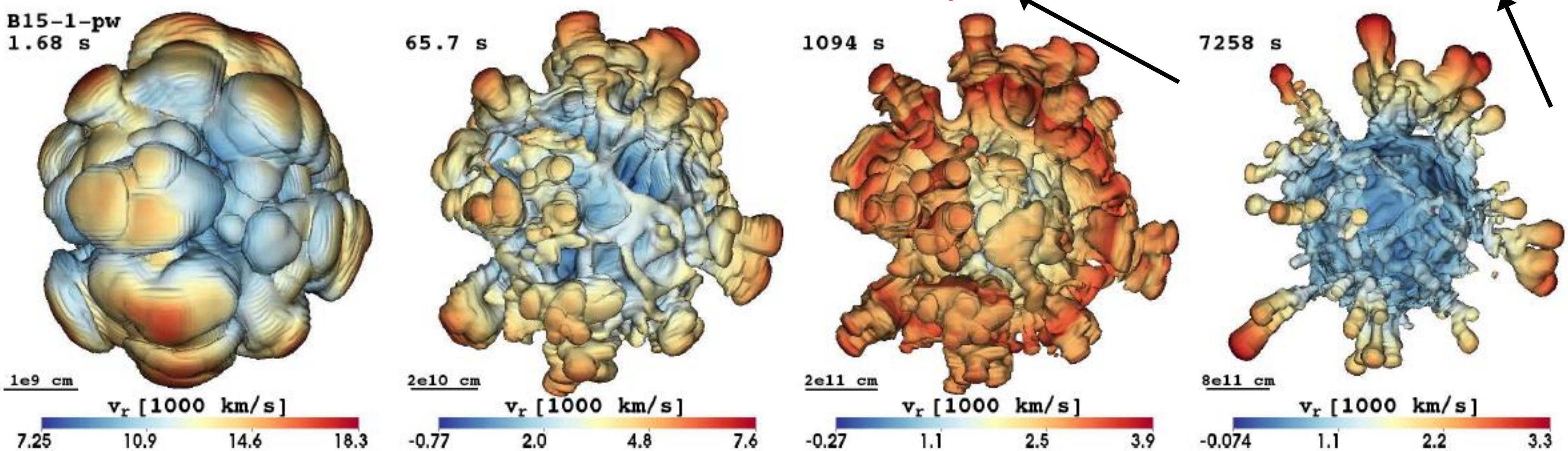
BSG



very different morphology
also different from RSG models

many RT fingers
into H-envelope

same progenitor as
Hammer+ (2010)



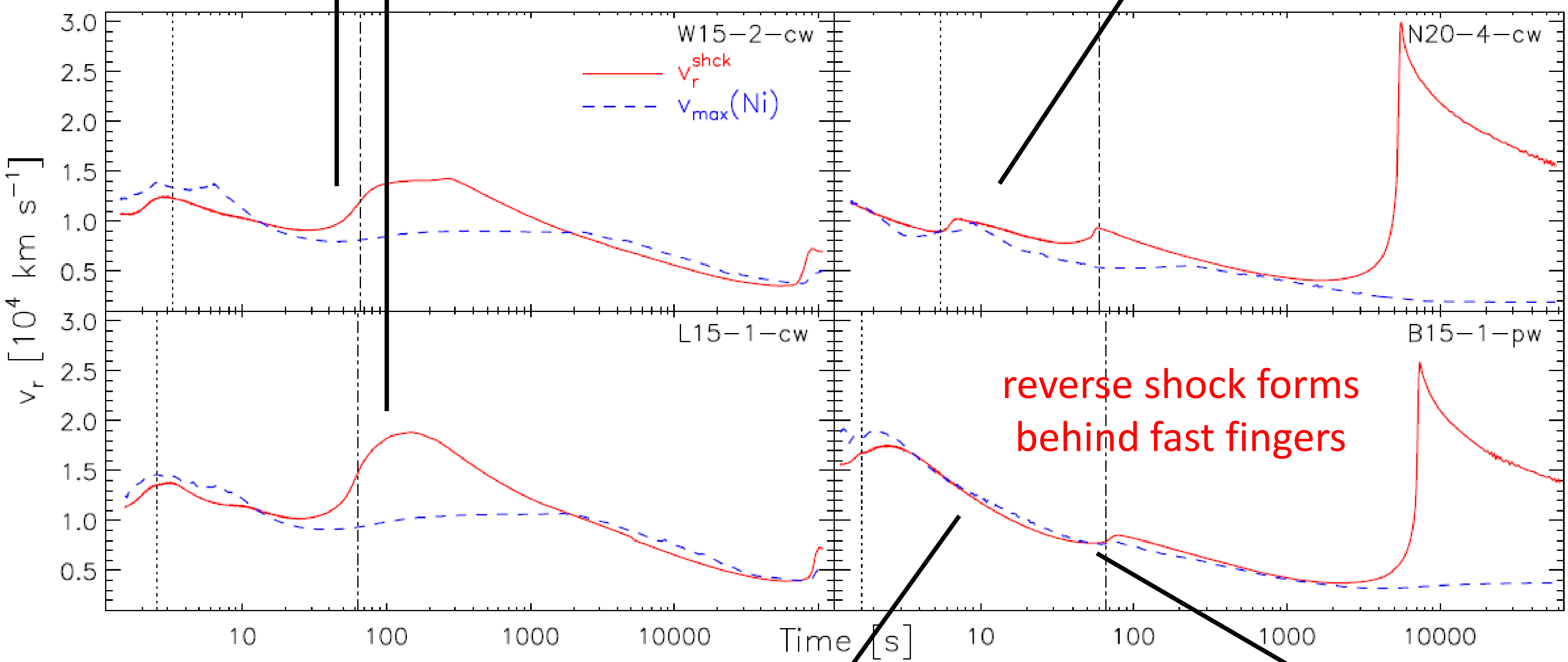
Results

What makes the difference?

How can the nickel-rich ejecta escape the reverse shock?

strong acceleration at He/H interface >>> reverse shock forms ahead

slow nickel-rich ejecta >>> reverse shock forms ahead



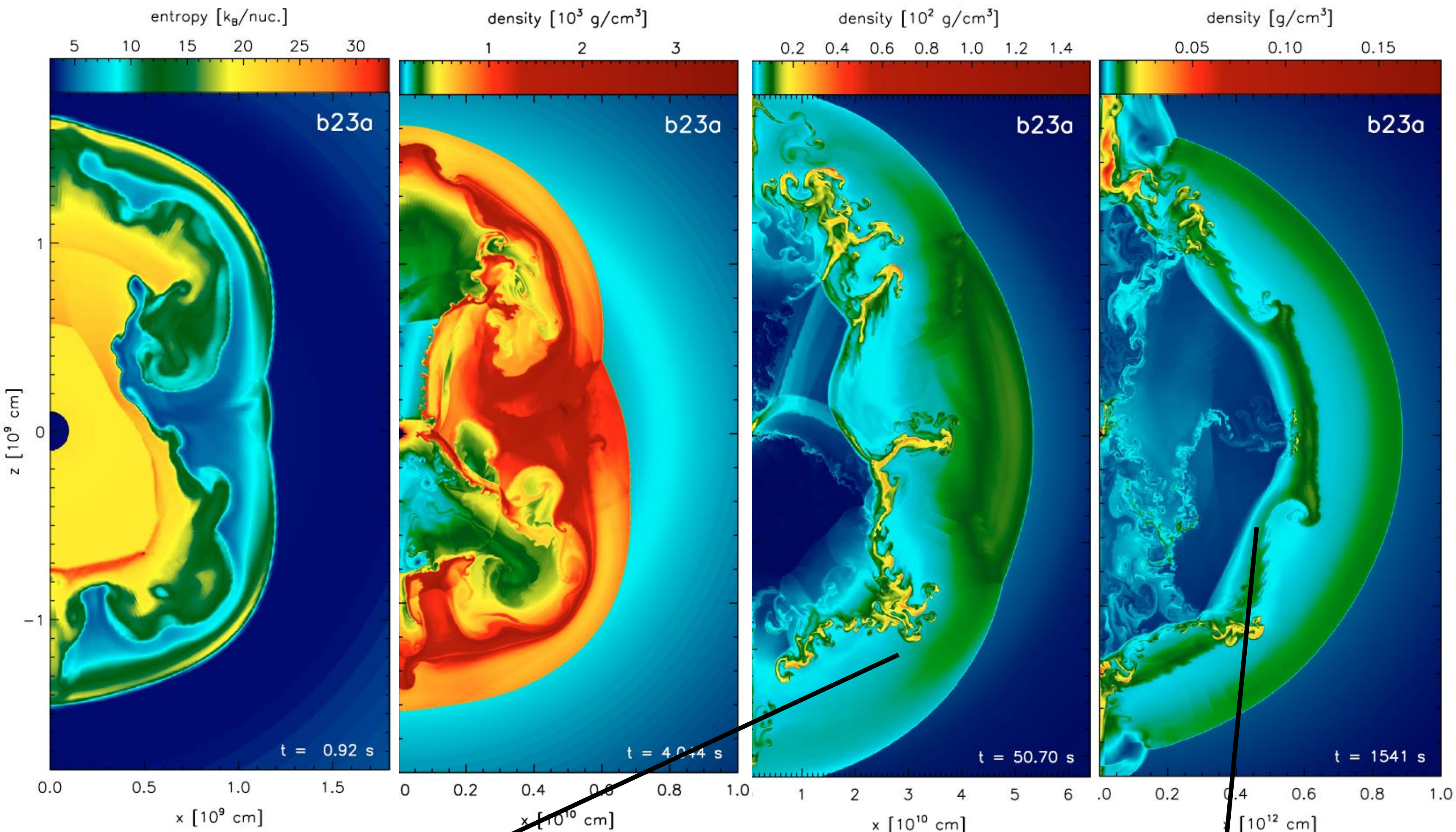
fast (relative to shock) nickel-rich ejecta

little acceleration at He/H interface

Results

How can the nickel-rich ejecta escape the reverse shock?

Kifonidis+ (2006)



fast fingers close to shock

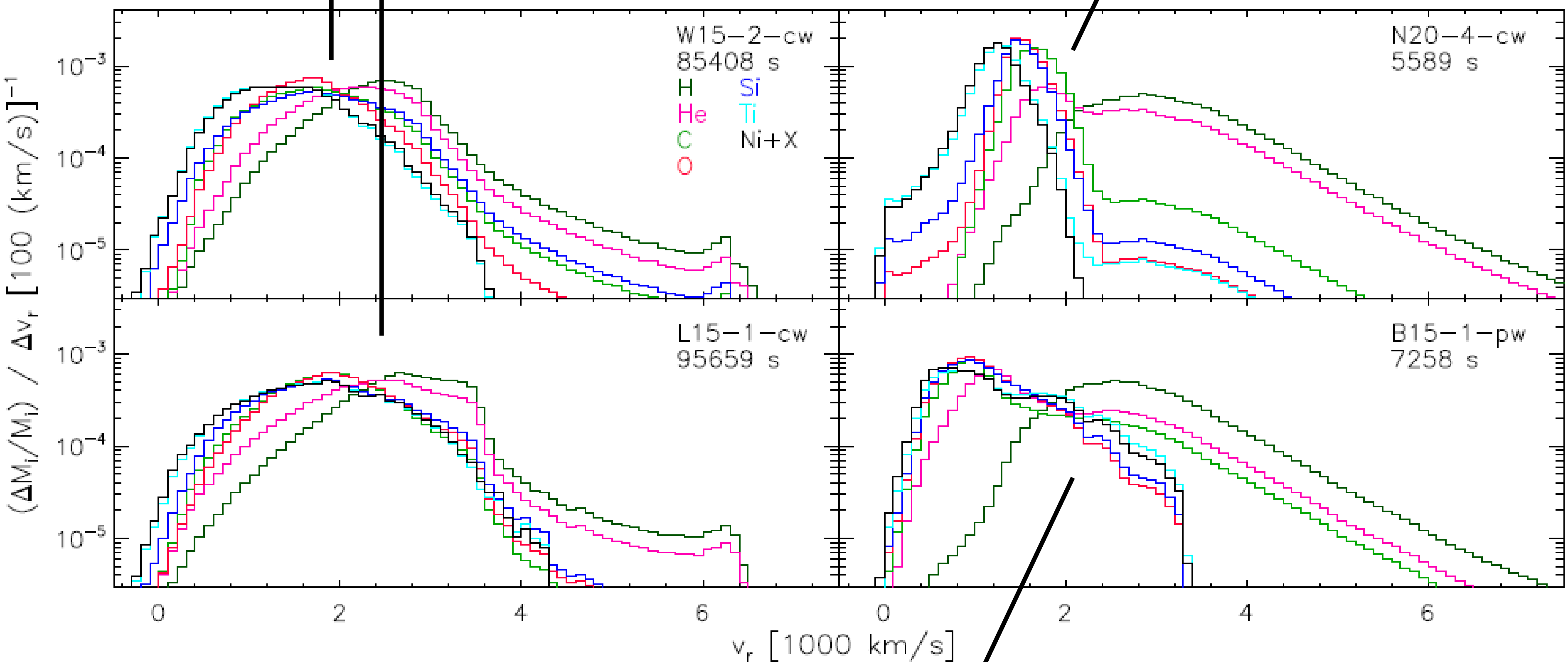
reverse shock behind fast fingers

Results

Distributions in velocity space

similar distribution for metals
vigorous mixing

narrow spread



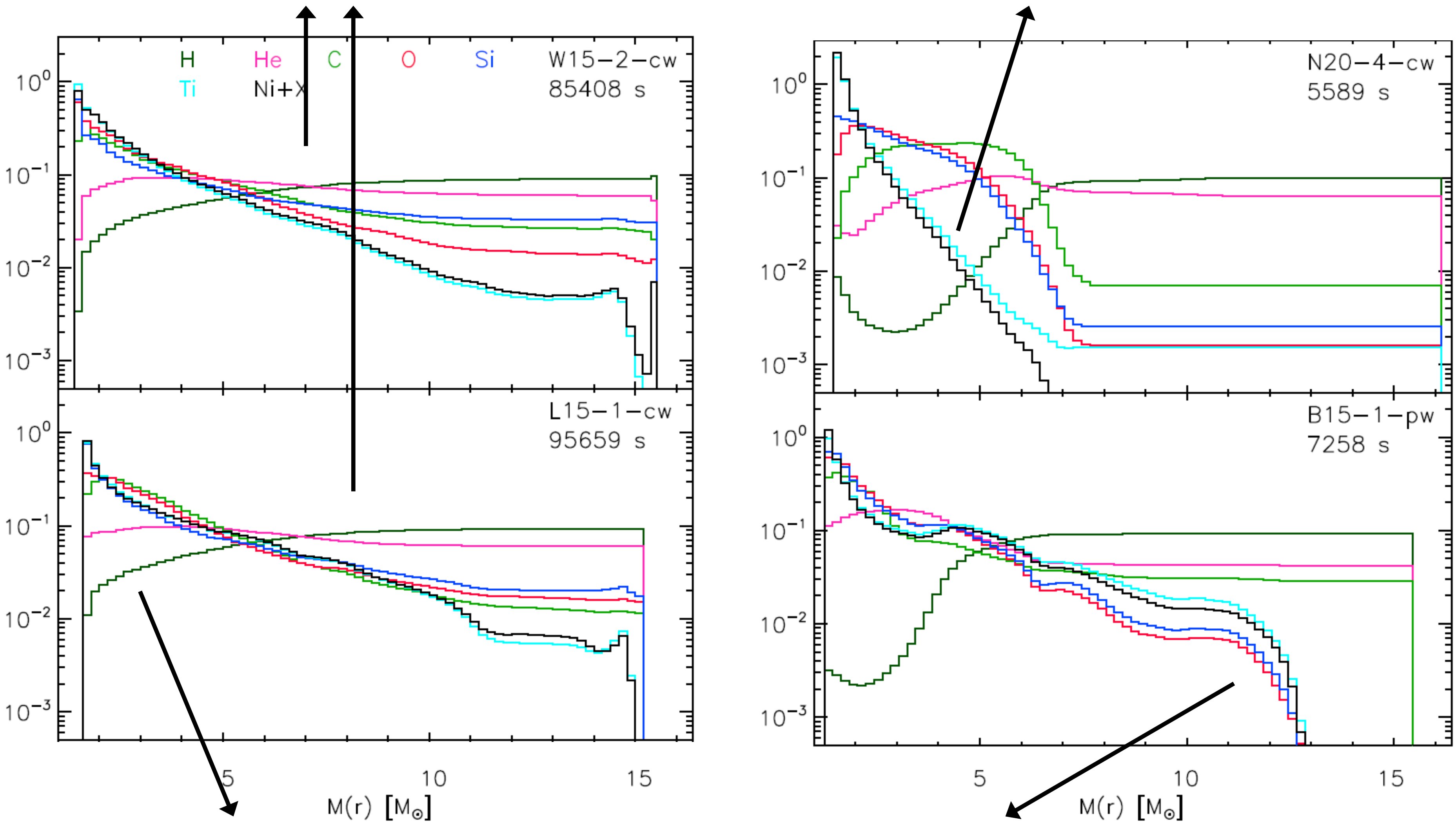
high velocity shoulder
two-components ejecta

Results

Distributions in mass coordinates

very efficient mixing
metals close to shock

not so vigorous metal mixing



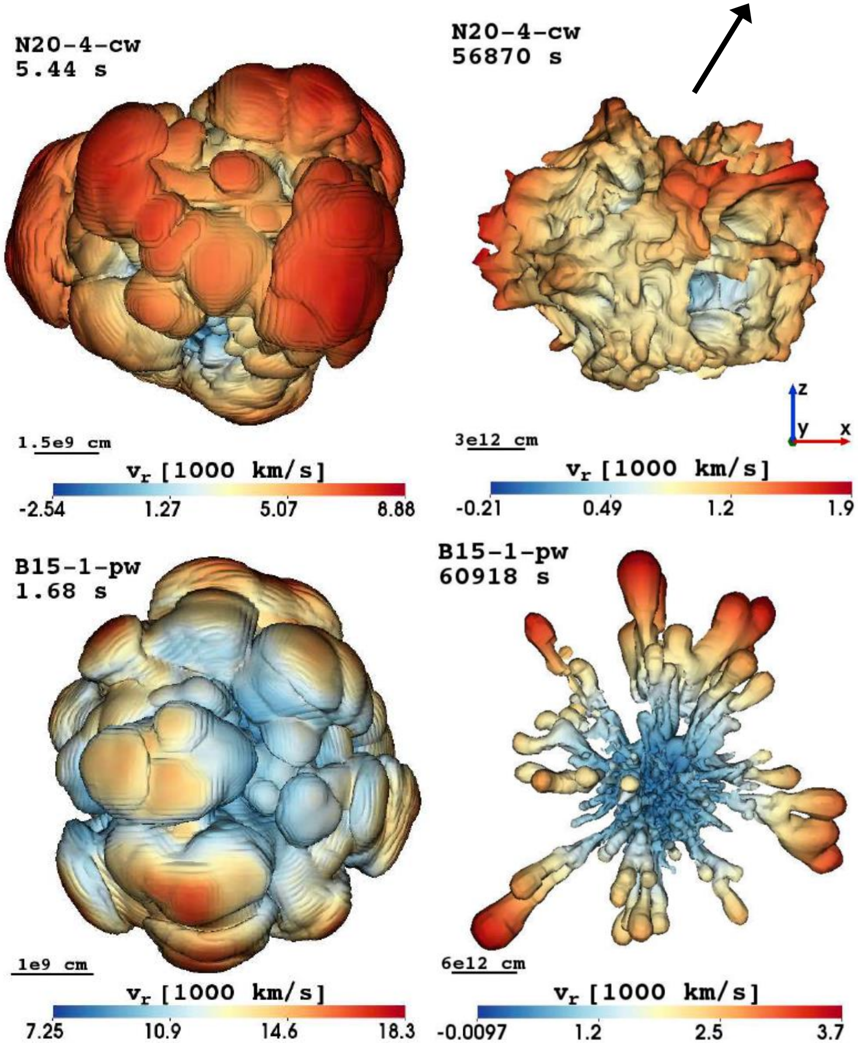
also very efficient inward mixing of H

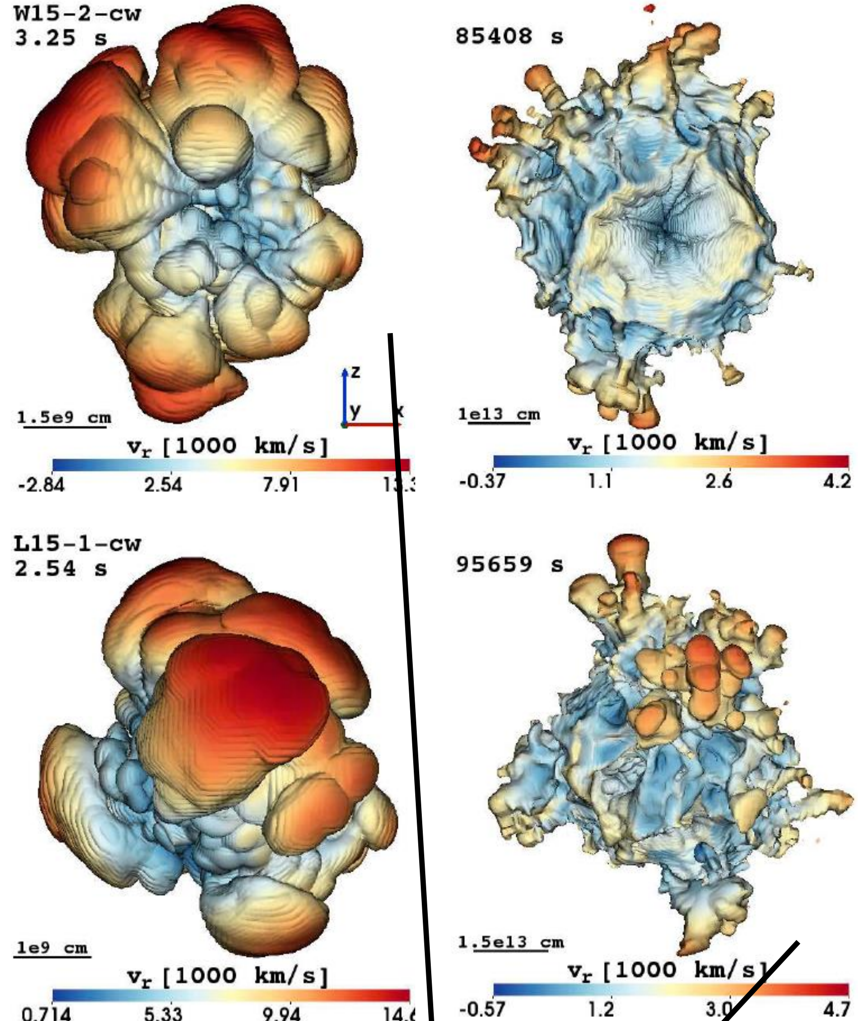
fast fingers into H-envelope

Results

Explosion vs. late-time asymmetries

not so clear??





clear correlation

Conclusions

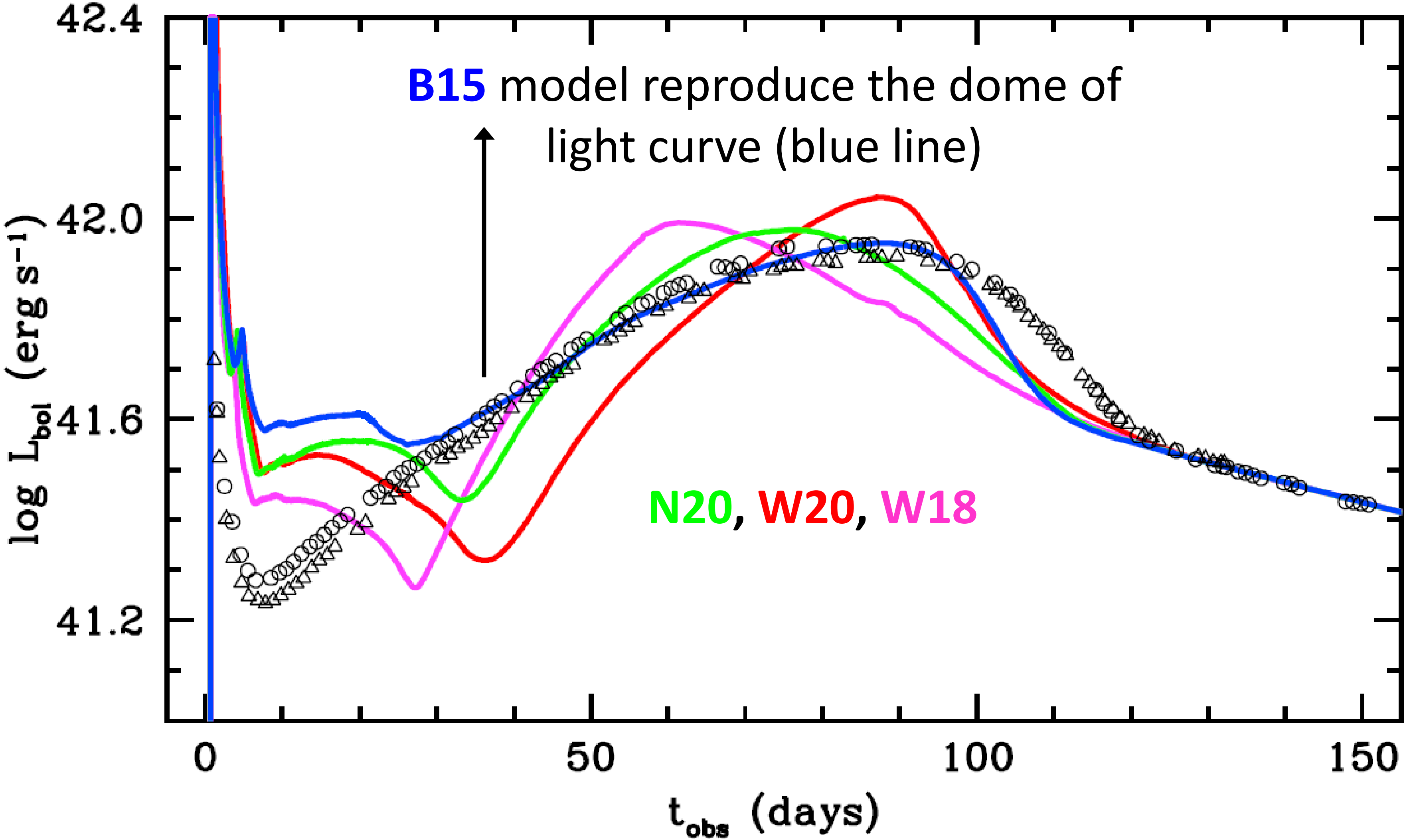
- perform 3D simulations of CCSN from shortly after core bounce until shock breakout
- evolution of early-time asymmetries associated with explosion mechanism depends on complex interplays between the asymmetries and the SN shock
- connects to the density structure of the progenitor star

Outlook

- more progenitors ??
- longer time evolution??

Outlook

comparison of bolometric light curve with SN1987A



Utrobin et al. (in prep.)