Mixing Instabilities in CCSNe in 3D

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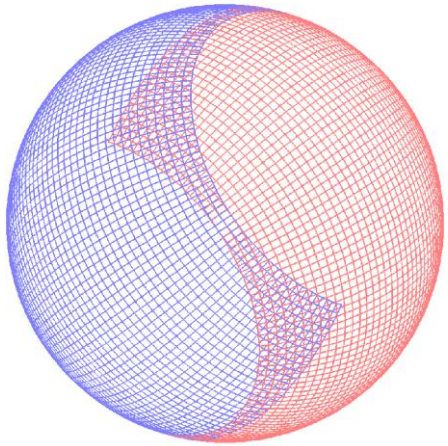
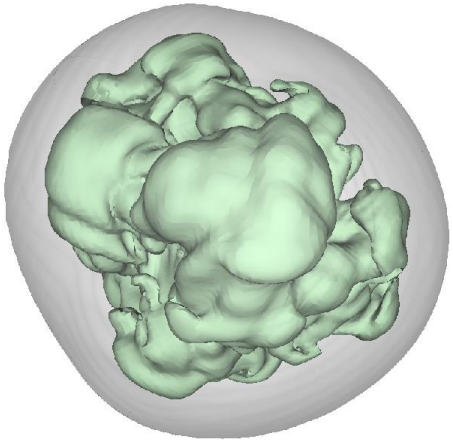
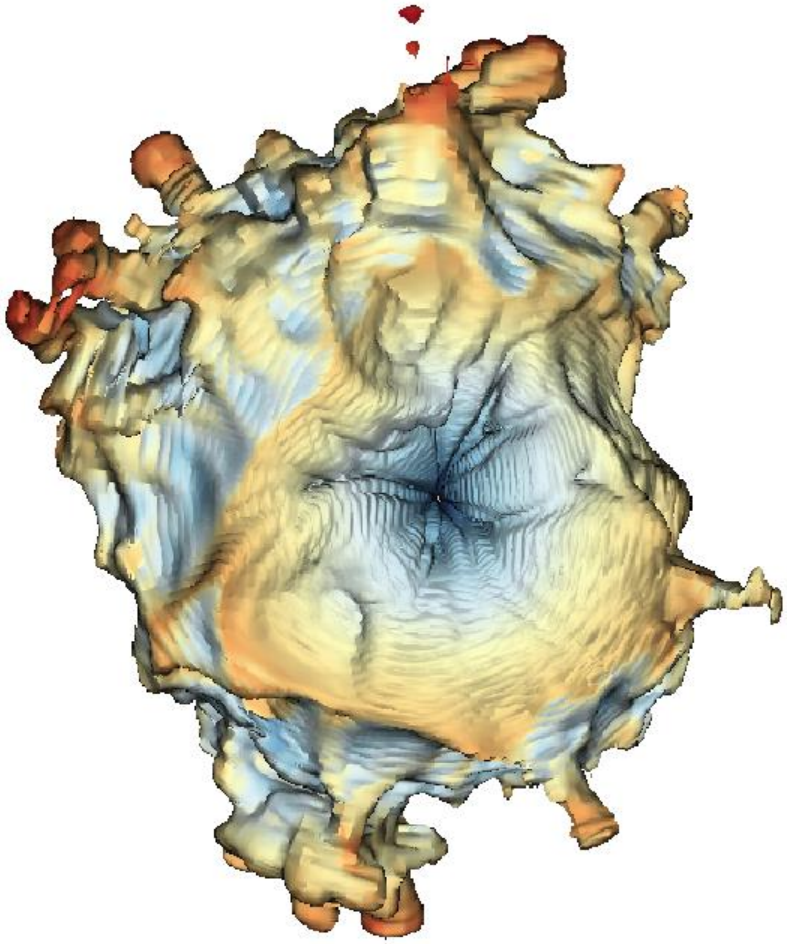






YIPQS workshop, Kyoto, 30 Oct 2013

Introduction

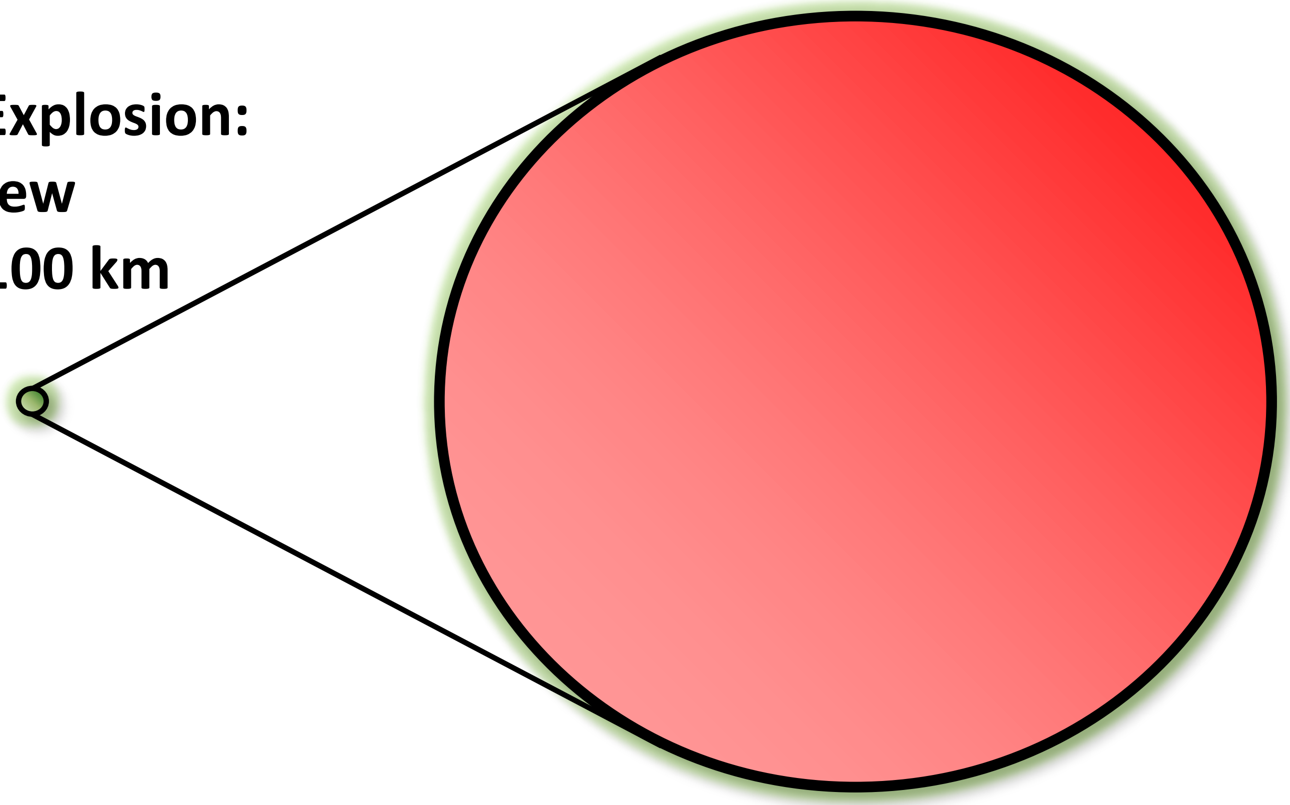
- Evidences of mixing from observations of SN1987A;

See review of Hillebrandt&Höflich (1989)

- Mixing of hydrogen to inner core and Ni to hydrogen envelope
- Early appearance of hard X-rays and γ-rays
- Fe line profile suggests high velocities Ni (4000 km/s)
- Also in other CCSNe
- Complicated structures in SNRs; clumps, filaments, …
- Asphericity inferred from spectropolrimetric observations
- Connect explosion to remnant
- Multi-D multi-fluid simulations needed

Challenge

Explosion:
few
100 km



Star:
few 100
millions
km

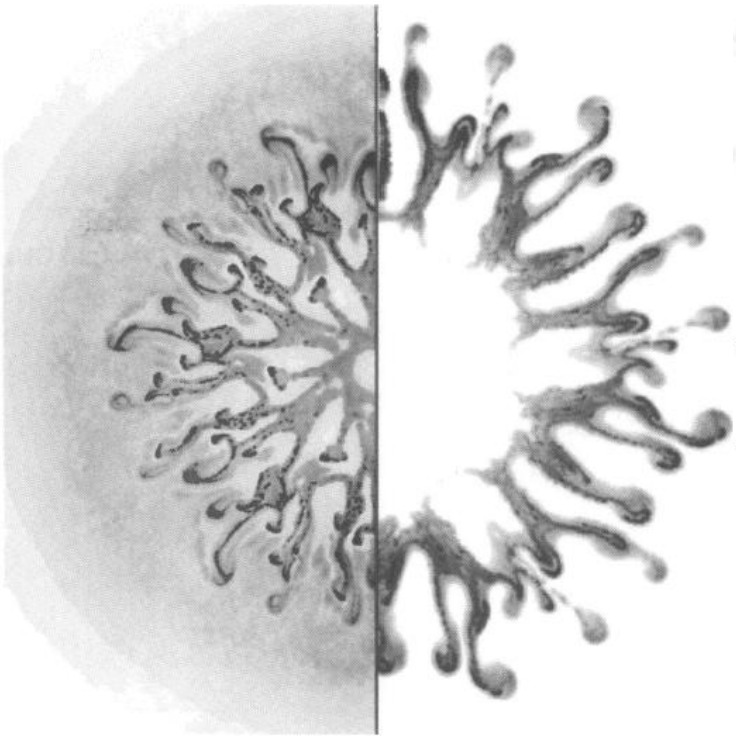
Remnants:
few 10
trillions
km

Time scale: ms >>> hours, day >>>>>>>>>>>>>>>>>>>>>>>> 100 years

Previous works

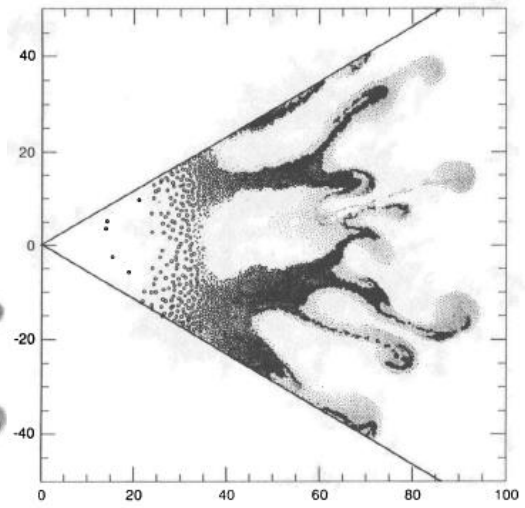
- Rayleigh-Taylor Instability is the main suspect
- layers in stars can become RT unstable due to shock passage (e.g. Chevalier 1979, Ebisuzaki+ 1989)
- works by many groups in 1990s; e.g., Arnett+ 1989, Fryxell+ 1991, Müller+ 1991, Hachisu+ 1990, Yamada&Sato 1990, Herant&Benz 1992, Herant&Woosley 1994, 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)
- Three important points learned

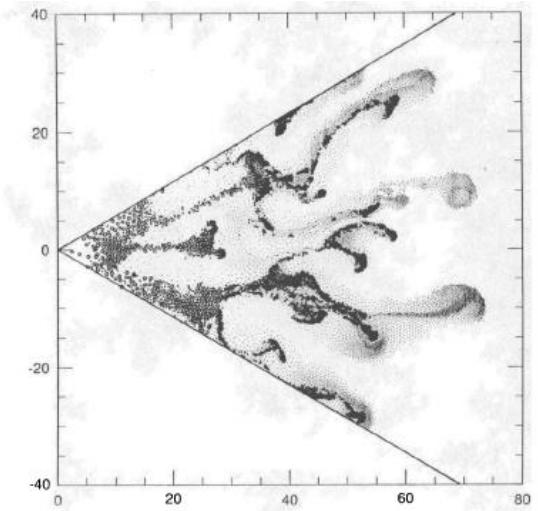
Progenitor

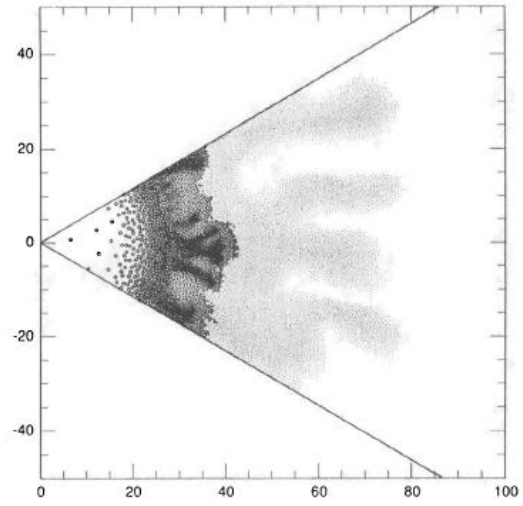


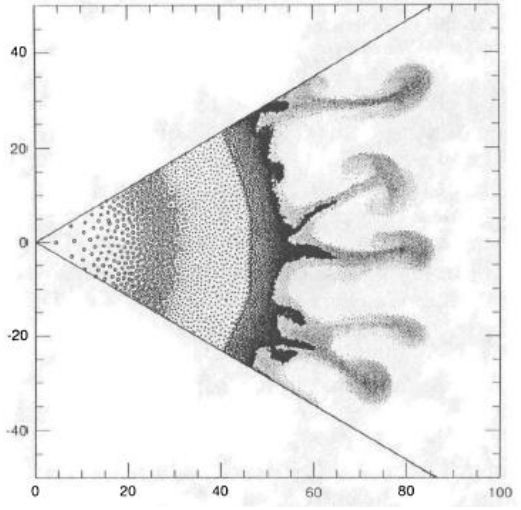
Herant&Benz 91

Herant&Benz 92





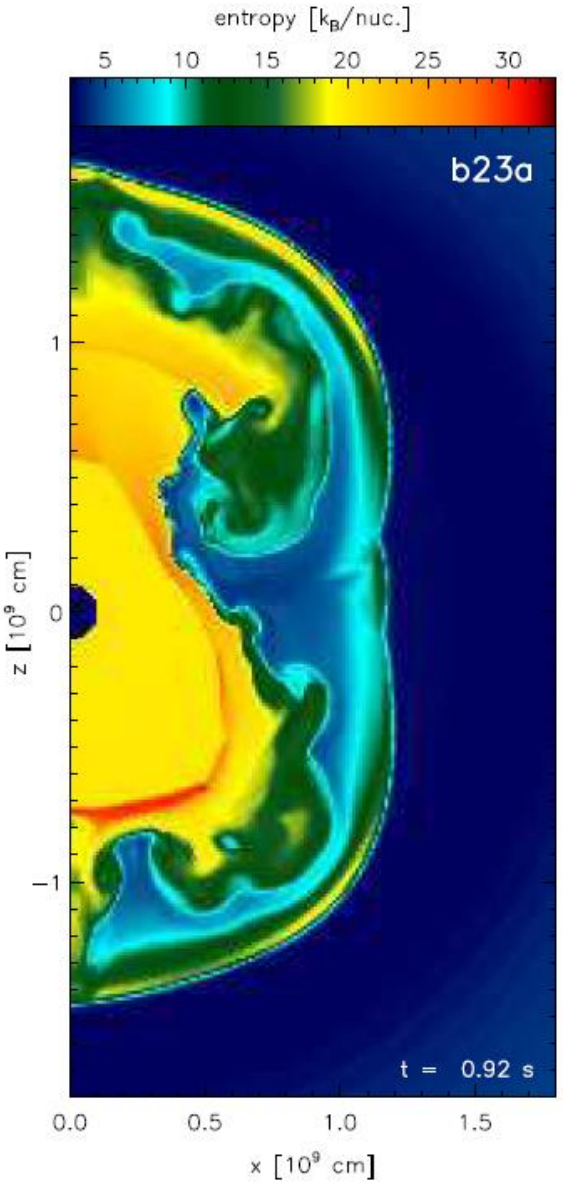


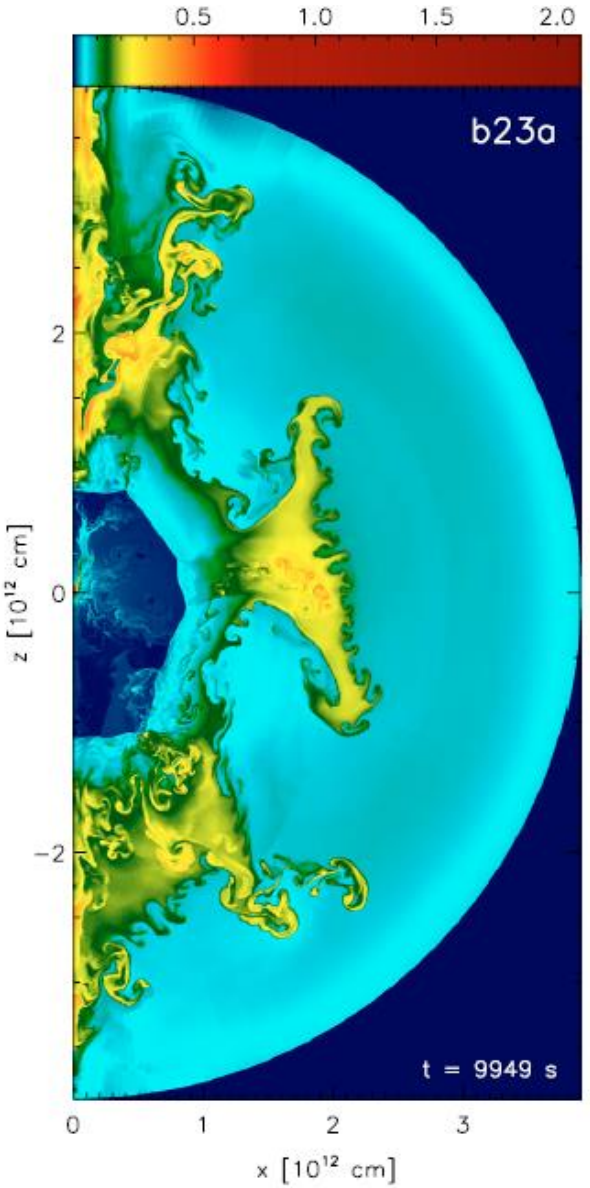


Different growth of RTIs depending on progenitor structure

Explosion physics

Kifonidis+ 2000, 2003, 2006 were first to consider explosions in Multi-D

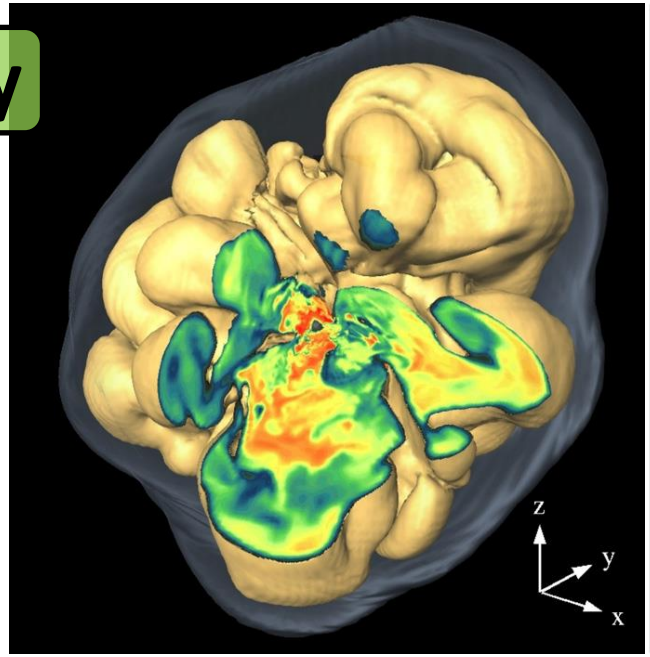


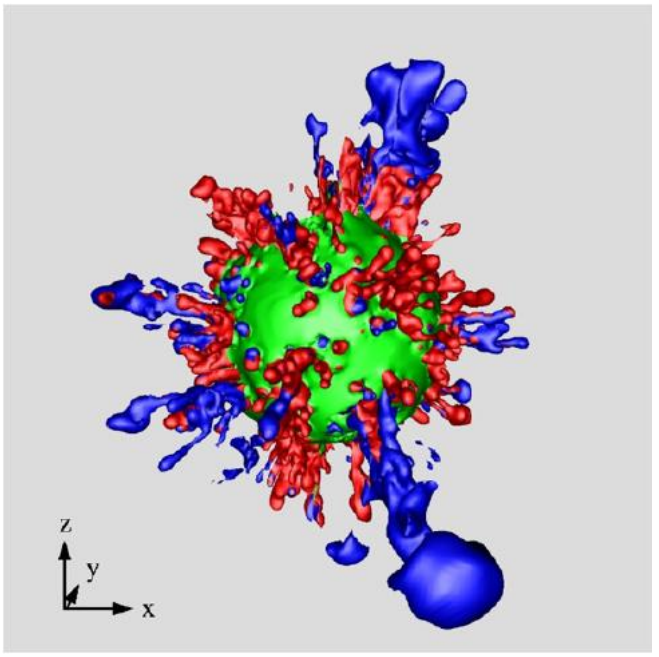


Dimensionality

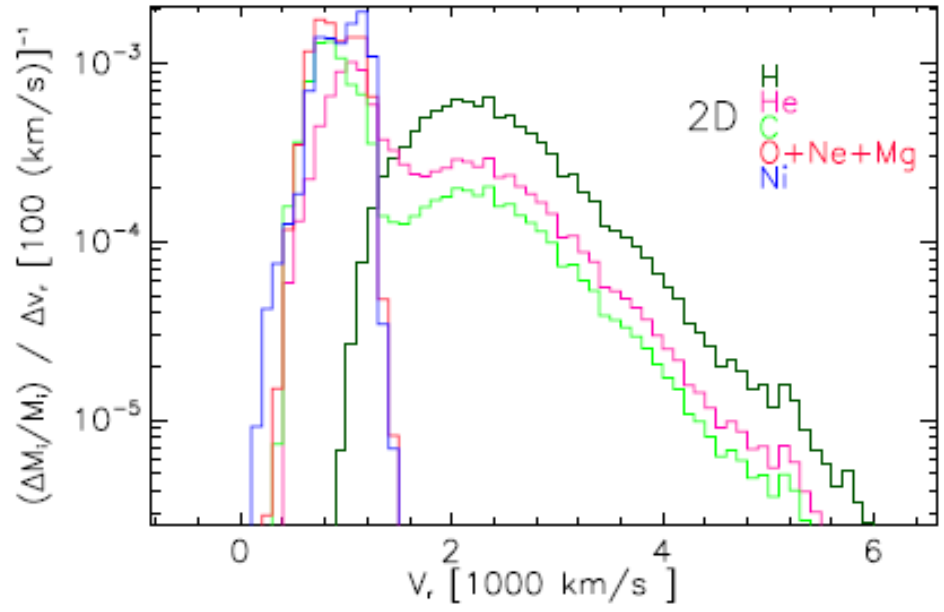
2D Vs 3D

Note: Joggerst+ 10 don't see difference; but different explosion physics and progenitor

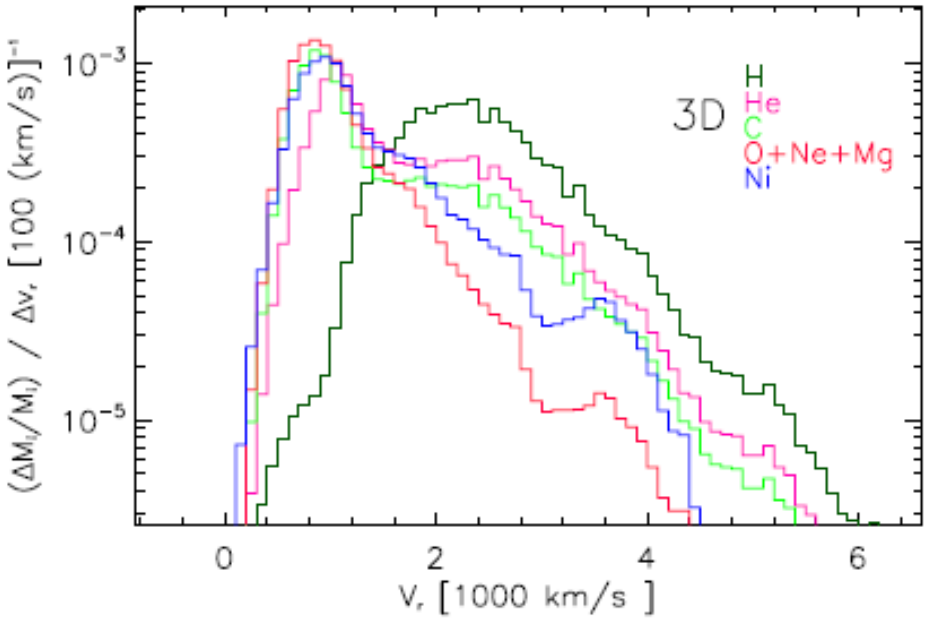




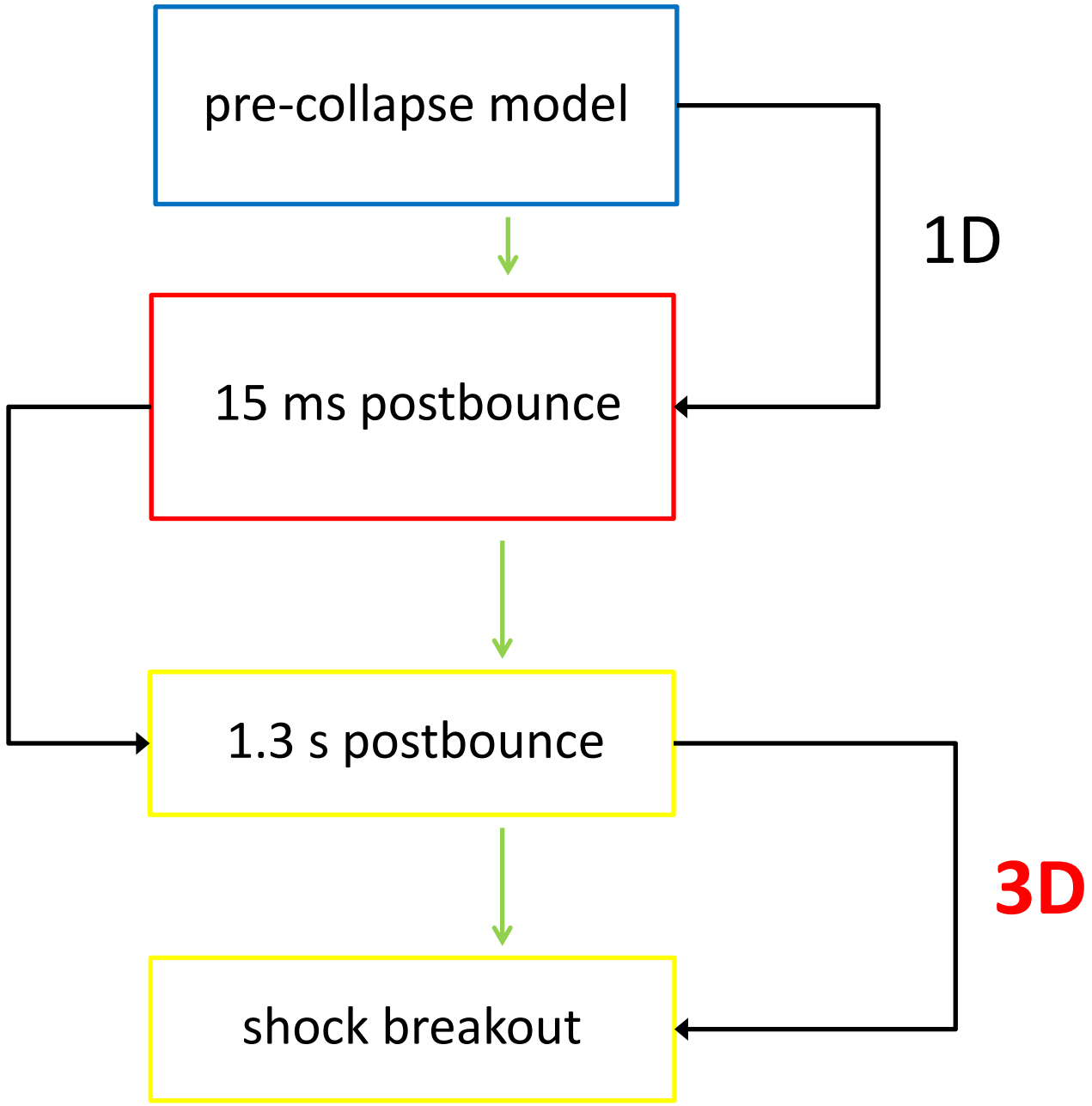
Scheck 2008



Hammer+ 2010

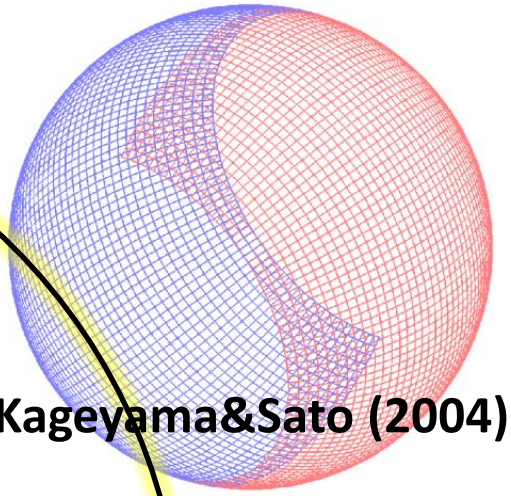


Different physics in each phase



Numerics

1D postbounce at 15 ms → 1.3 s later



Kageyama&Sato (2004)

3D Newtonian self-gravity

monopole GR correction

tabulated EOS by Janka & Müller (1996)

4 nuclear species in NSE (n, p, ^{4}He, ^{54}Mn)

14 species (^{4}He- ^{56}Ni+X) alpha-reactions network

ray-by-ray grey transport

L_ν

contracting inner grid

PNS
1.1 $M_\odot$

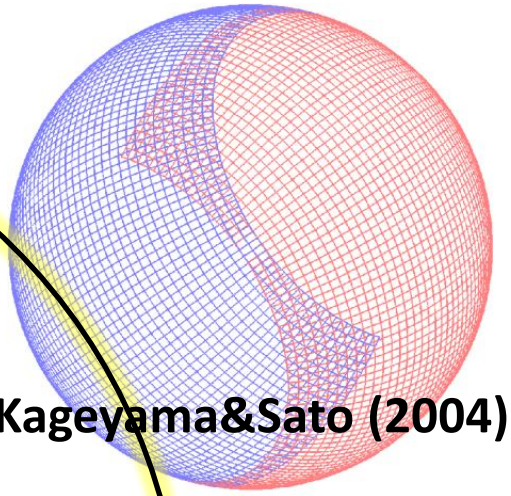
random perturbation of 0.1% amplitude

Numerics

1.3 s postbounce → shock breakout

3D Newtonian self-gravity

tabulated EOS by Timmes&Swesty (2000)



Kageyama&Sato (2004)

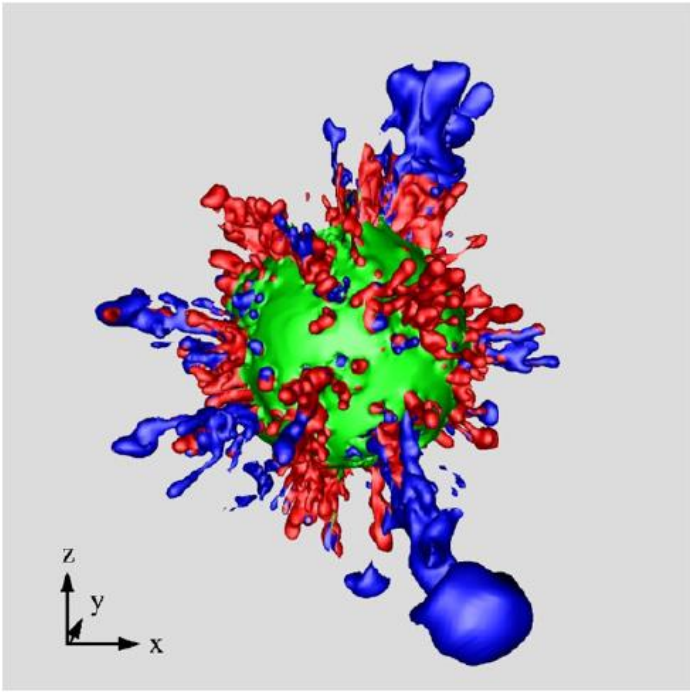
Neutrino-driven wind boundary condition

dynamic inner grid boundary

14 species (^{4}He- ^{56}Ni+X) alpha-reactions network

Test case

Comparison with Hammer+

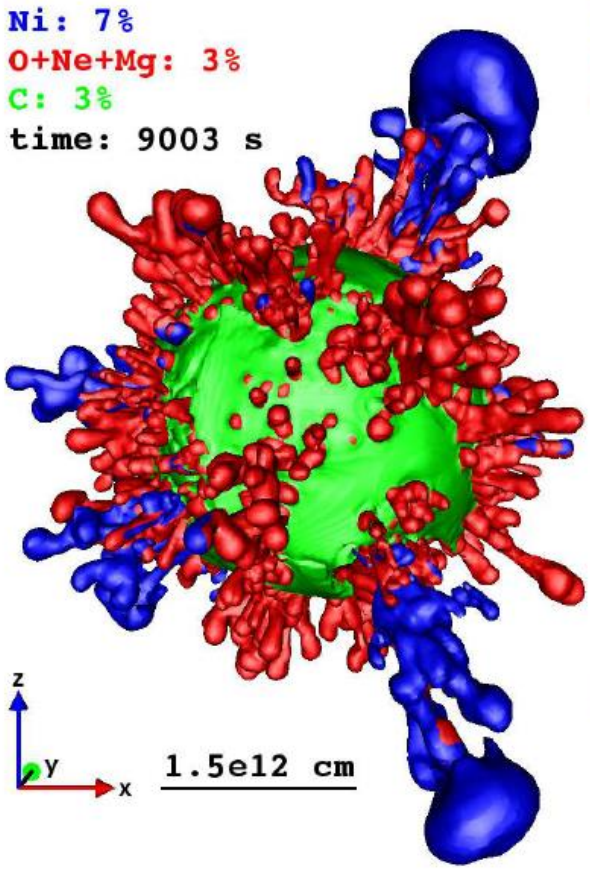


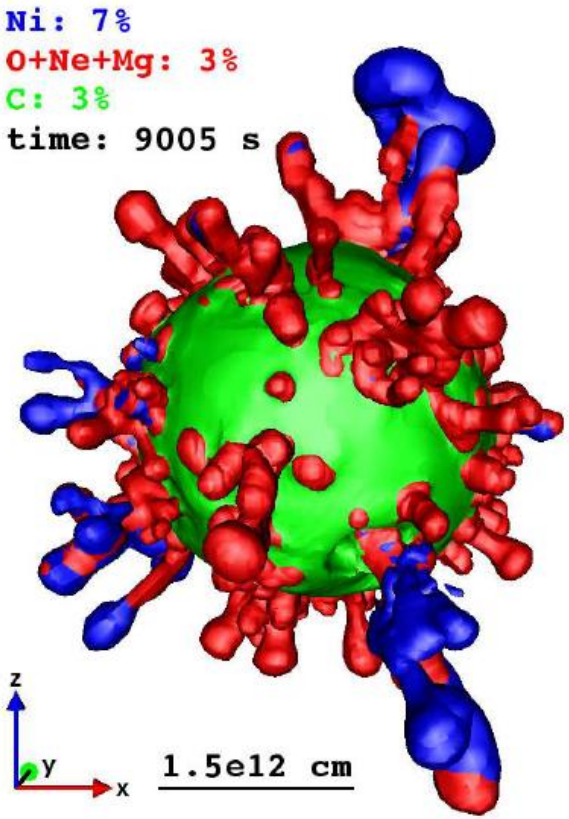
Hammer+ 2010

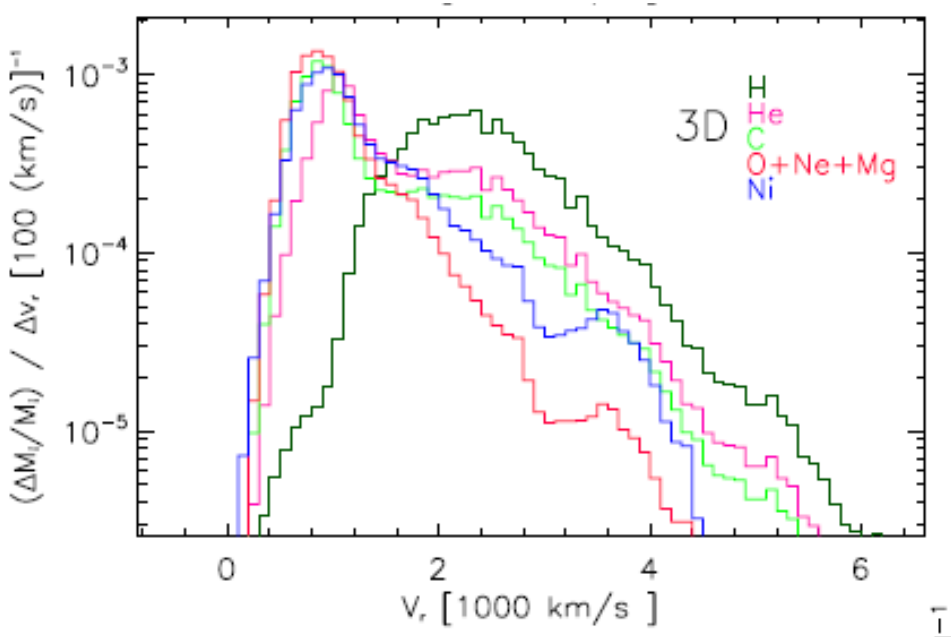
Spherical polar grid

Wongwathanarat+
(to be submitted)

Axis-free Yin-Yang grid







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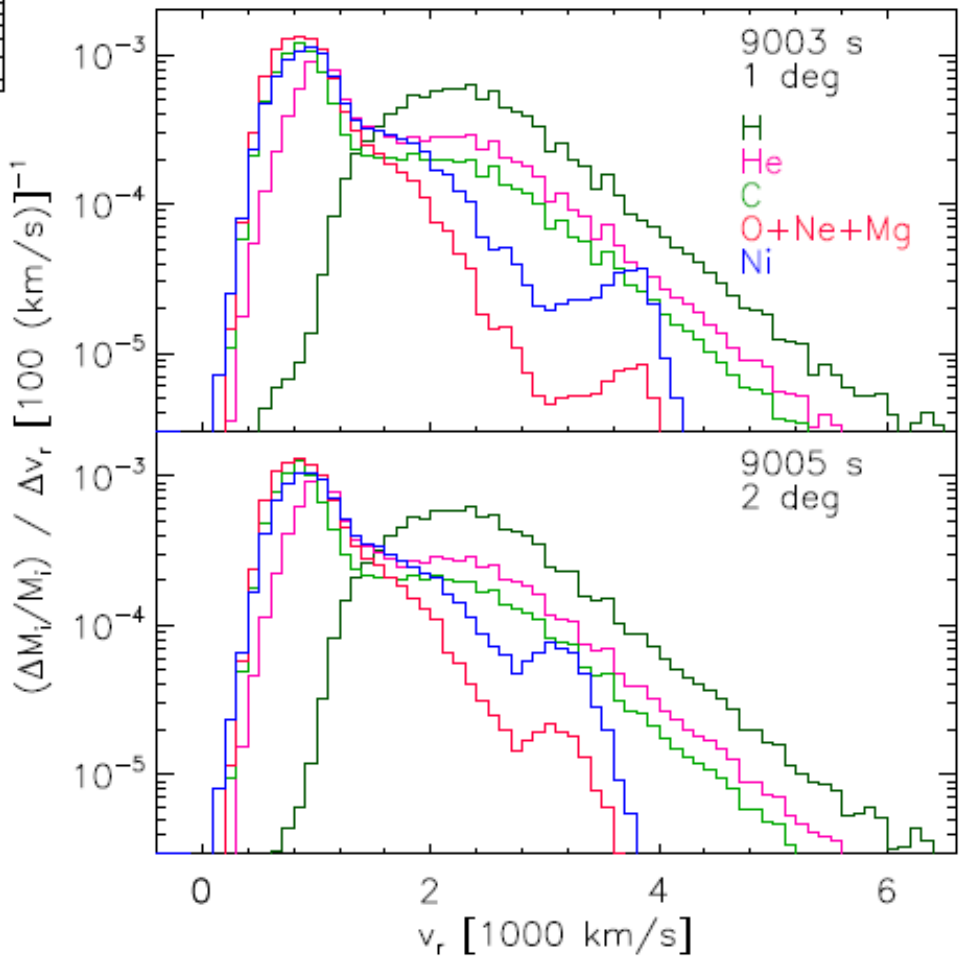
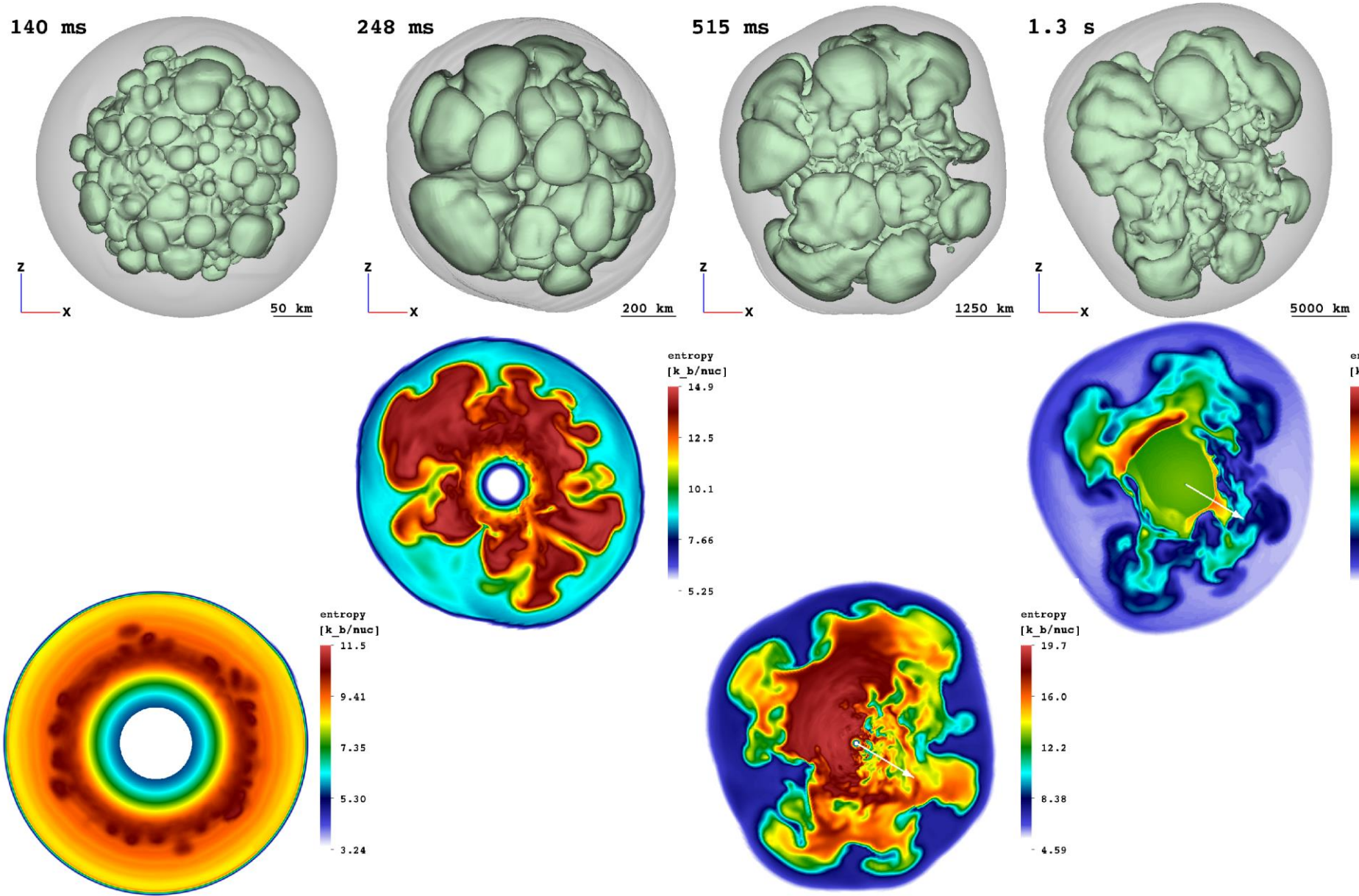


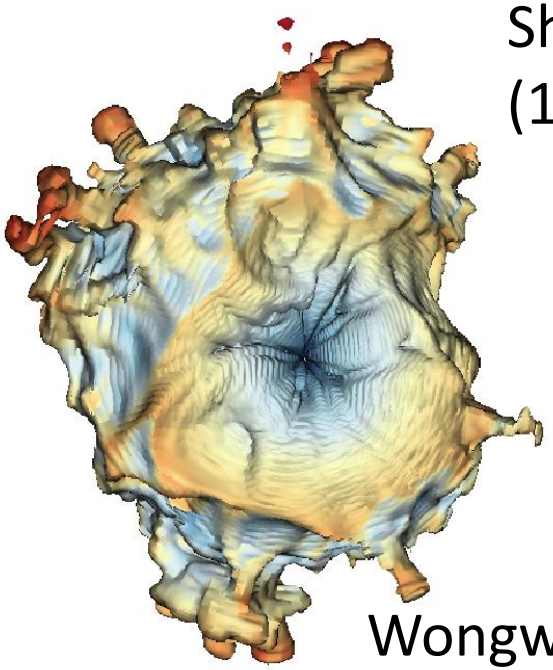
Wongwathanarat+ 2010,2013

Studied NS kick by gravitational tug-boat mechanism

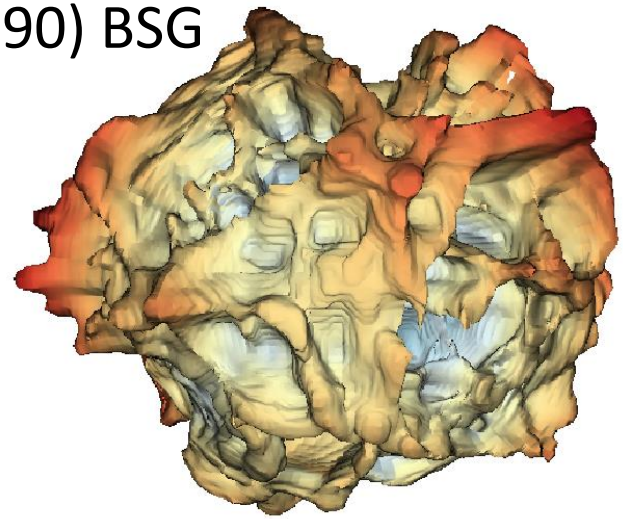


4 different progenitors

Woosley&Weaver (1995) RSG

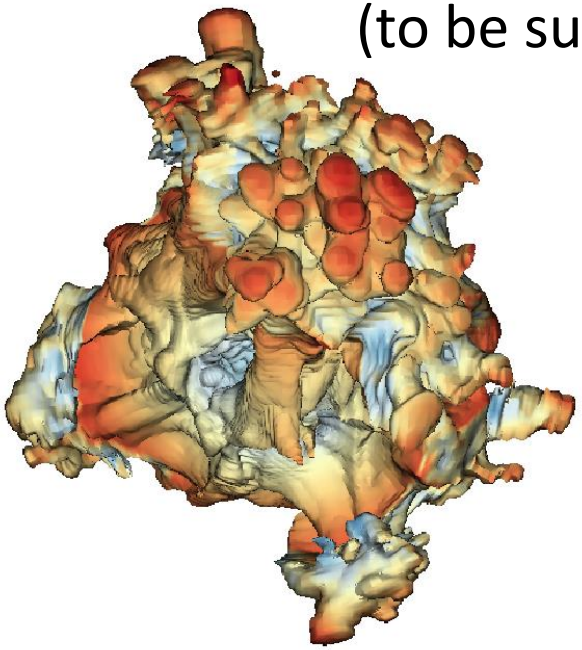


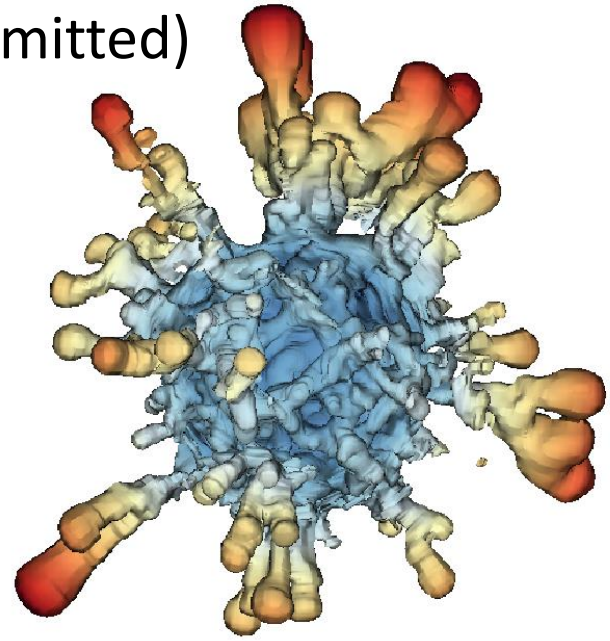
Shigeyama&Nomoto (1990) BSG



Wongwathanarat+ (to be submitted)

Limongi+ (2000) RSG





Woosley+ (1988) BSG

Conclusions

- long-time CCSN simulations linking explosions to observations are challenging
- Three important points to consider; explosion physics, progenitor structure, dimensionality
- Simulations considering shock revival all the way to young remnant phase in 3D required !!!
- Wongwathanarat+ (to be submitted)
- comparison with Hammer+ gave excellent agreement
- follow CCSN evolution from 15 ms postbounce to shock breakout
- consider 4 different progenitors; both BSG and RSG
- Please stay tune !!!