SN1987Aモデルの重力崩壊計算が示すコンパクト天体の性質

The compact remnant of SN1987A: implication from realistic CCSN simulations

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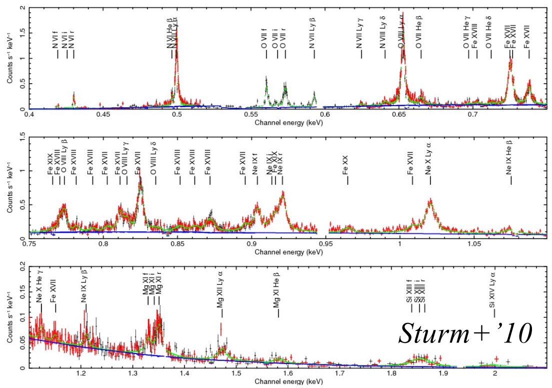
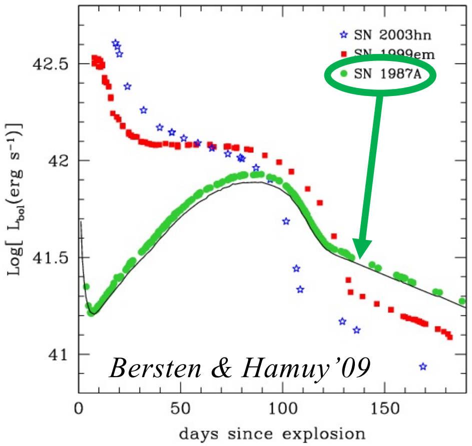
<u>SN 1987A - the most well observed supernova</u>

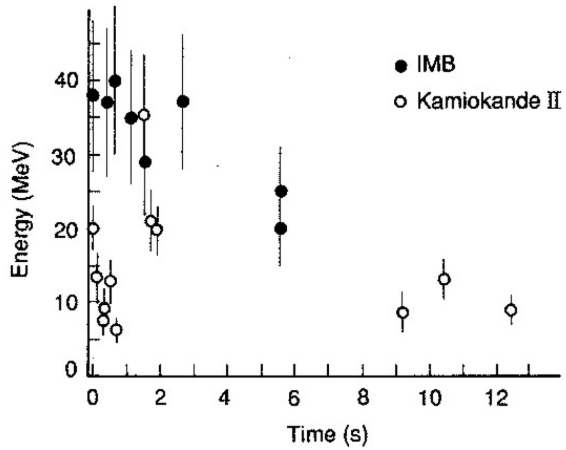
✓ emerged in LMC (D ~ 50 kpc)

✓ EM light curve & spectra
→ $E_{\rm exp}$ ~ 1.2 foe, $M_{\rm Ni}$ ~ 0.07 $M_{\rm sun}$

✓ neutrino detection



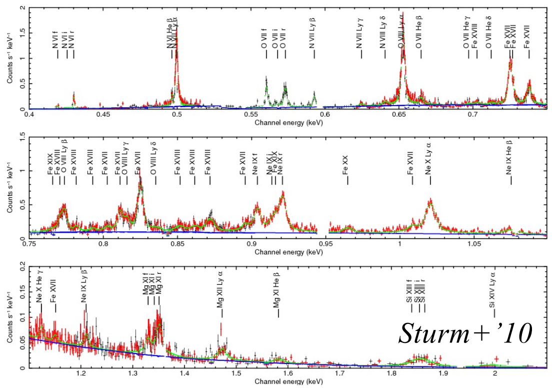


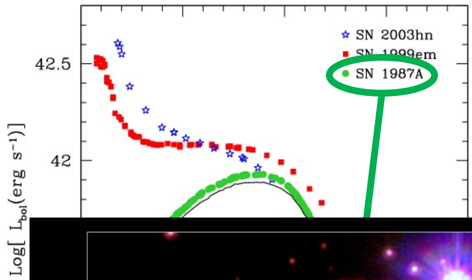


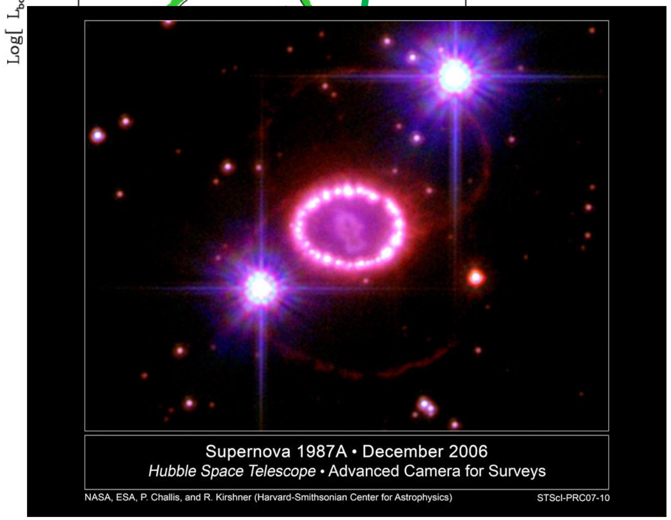
SN 1987A - an anomalous supernova

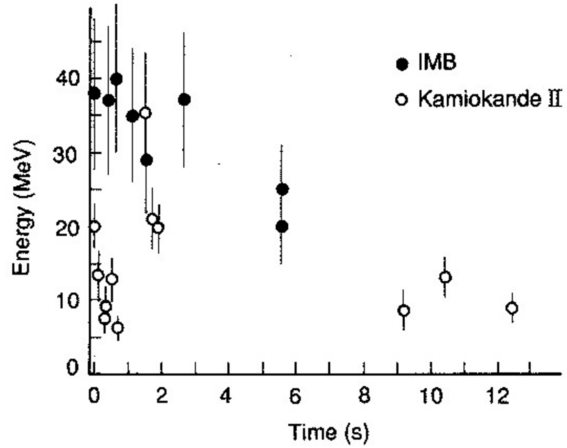
- ✓ emerged in LMC ($D \sim 50$ kpc)
- ✓ EM light curve & spectra
  → $E_{\mathrm{exp}} \sim 1.2$ foe, $M_{\mathrm{Ni}} \sim 0.07\ M_{\mathrm{sun}}$
- ✓ neutrino detection
- ✓ **red** → **blue** supergiant progenitor
  Sk - 69˚202
- ✓ chemical anomalies:
  He & N-rich (CNO process)
  Ba-rich (s-process)
- ✓ triple-ring nebula

✓ The central remnant (NS/BH) is not yet confirmed.









NEUTRON STAR IN SN 1987A

High Angular resolution Observation by ALMA

Cigan+'19 found clumpy dust emission in the ejecta of SN 1987A.

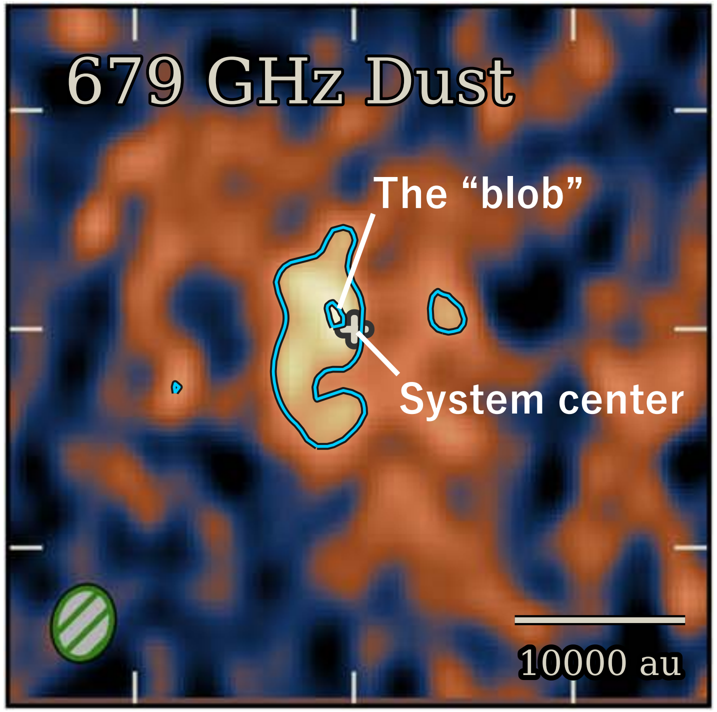
A dust peak (the "blob") could be due to

1) slow-moving reverse shock (unlikely),

2) heating from radioactive isotopes (unlikely),

3) heating from a compact source (the most likely).
   a) X-rays from a neutron star surface?
   b) synchrotron radiation (pulsar wind)?
   c) black hole jet?

If there is a neutron star in the blob,
the offset between the blob and the system center
suggests v_{NS} ~ **700 km/s**.



One of multiwavelength views of the ejecta in SN 1987A. The cyan contours represent the 679 GHz dust emission at 3 σ and 5 σ. The small plus sign denotes the system center. The small 5 σ cyan contour just northeast of the center of the remnant is the so-called "blob."
(Fig 3a in Cigan+'19)

Summary of observational features

Progenitor model (stellar evolution) → CCSN model (core collapse and explosion dynamics) → Ejecta and CSM interaction (stellar environment)

Progenitor model

- ✓ emerged in LMC (D ~ 50 kpc)
- ✓ red → blue supergiant progenitor
  Sk - 69°202
- ✓ chemical anomalies:
  He & N-rich (CNO process)
  Ba-rich (s-process)

CCSN model

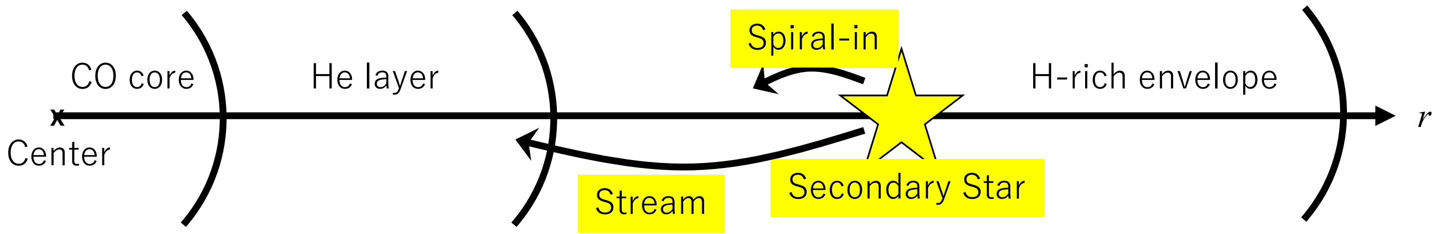
- ✓ EM light curve & spectra
  → E_{exp} ~ 1.2 foe, M_{Ni} ~ 0.07 M_{sun}
- ✓ neutrino detection
- ✓ The central remnant is a NS
  with v_{NS} ~ 700 km/s?

Ejecta and CSM interaction

- ✓ triple-ring nebula

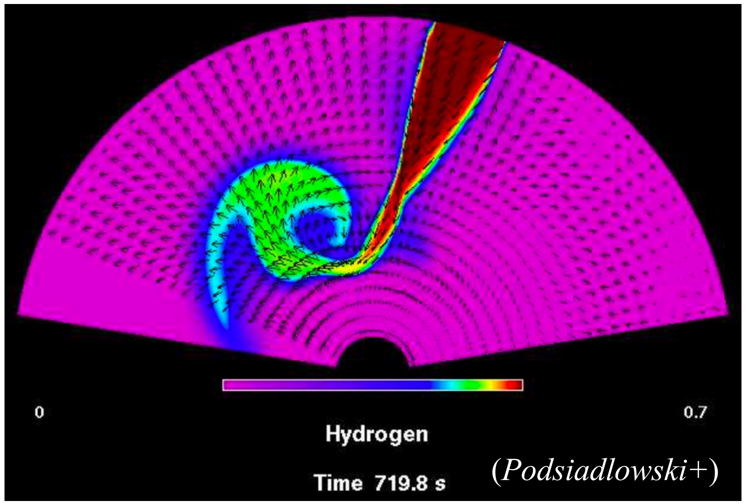
Slow Merger Scenario - new progenitor models

Urushibata+'18; Menon & Heger'17



fresh (H-rich) fuel
→ CNO cycle
→ **He & N production**

injection of angular momentum
→ partially stripped
→ **BSG**



(*Podsiadlowski+*)

Slow Merger Scenario - new progenitor models

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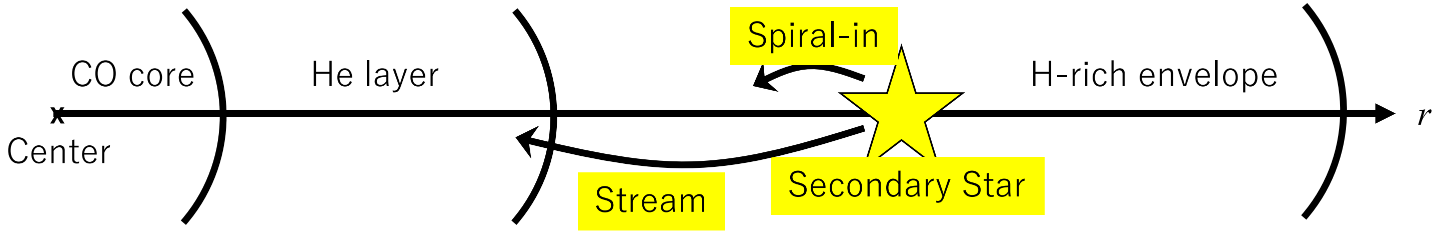
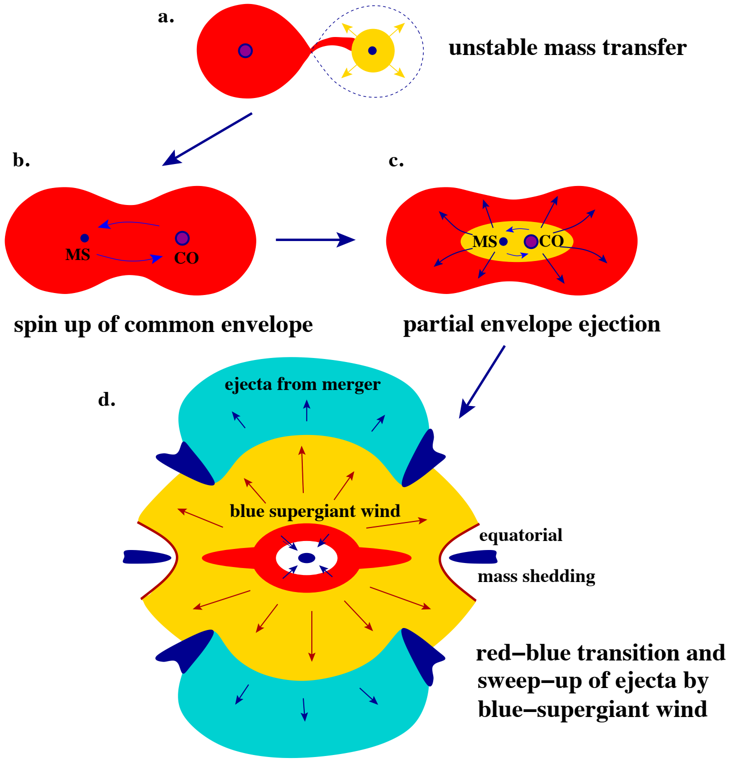


	Urushibata+'18	*Menon & Heger'17*
Red to blue evolution	Yes	Yes
Time to collapse	Yes	No
Origin of the rings	Yes	No
Anomalies of CNO-process elements	Yes	Yes
Anomalies of s-process elements	?	?

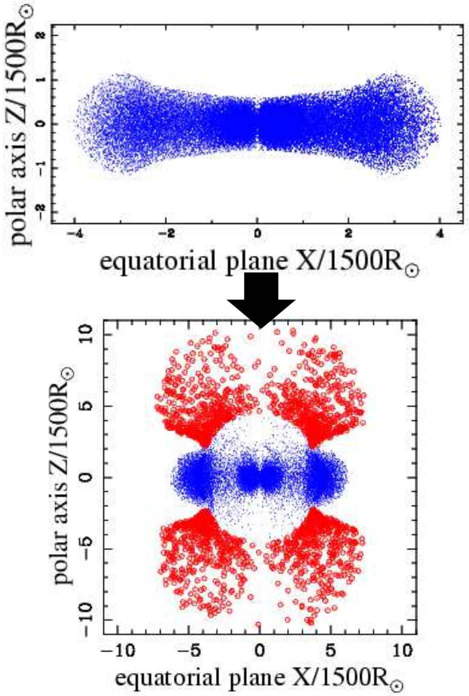
We use the best-fit model (14 + 9 Msun → 18.3 Msun) from *Urushibata+'18* for our core-collapse simulation.

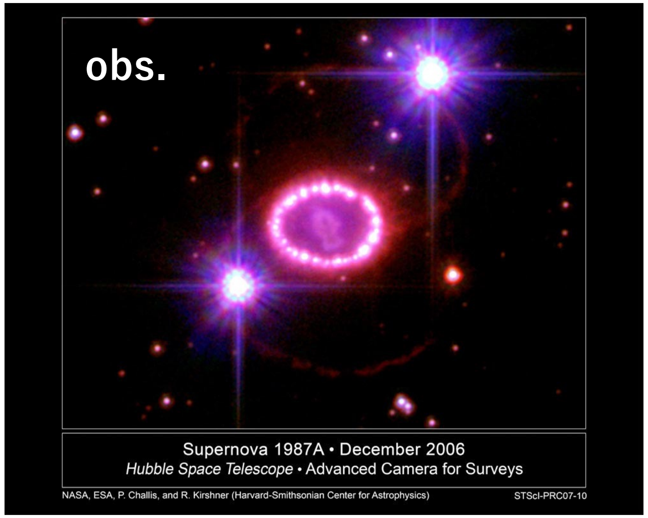
Slow Merger Scenario - the triple-ring nebula

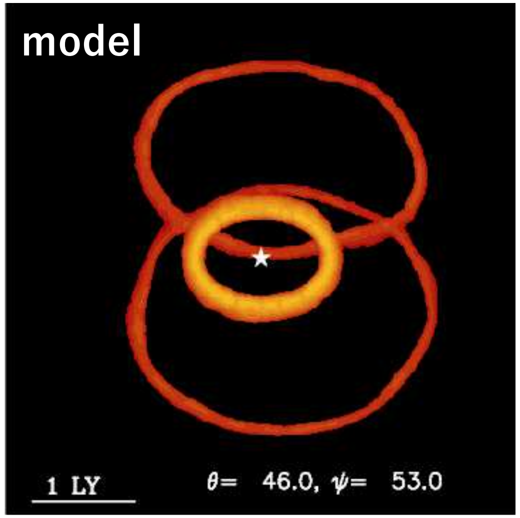
Ivanova+ '02; Morris and Podsiadlowski '07



3D SPH simulation with GADGET (10^6 particles)







Numerical Scheme for Core-Collapse Simulation

✓ **3DnSNe code** (*Takiwaki+'16,'18*) with some updates:

- updated • Isotropic Diffusion Source Approximation (IDSA; *Liebendoerfer+'09*) scheme for multi-energy 3-flavor (ν_e, $\bar{\nu}_e$, ν_x) neutrino transport.
- updated • state-of-the-art neutrino opacities (*Kotake+'18*).
- updated • effective GR potential.
- EoS: LS220 + Boltzmann gas.
- 13-α (He-Ni) nuclear network.
  → nucleosynthesis
  + energy feedback.

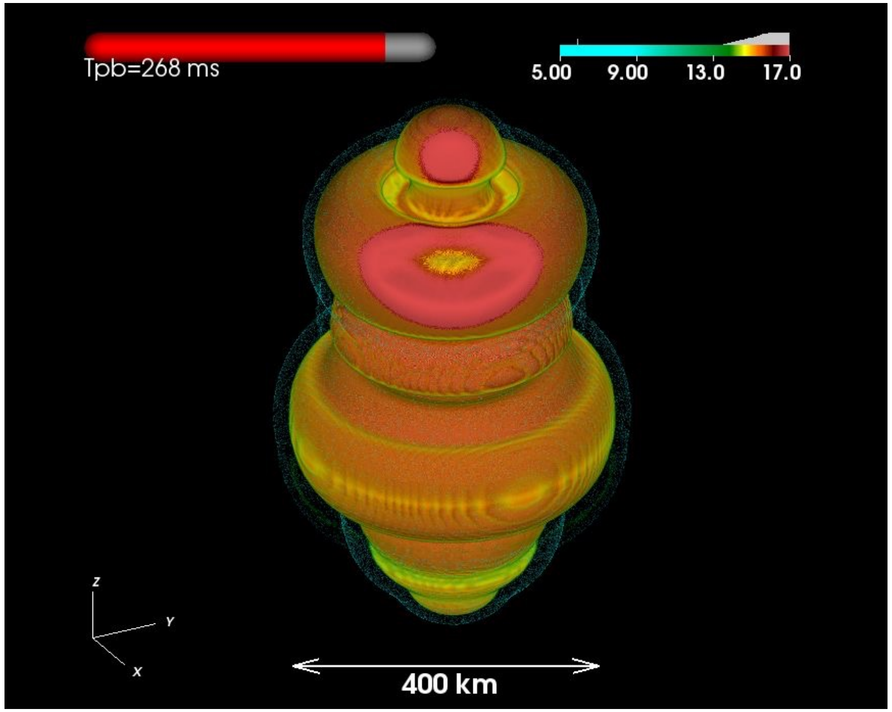
Model	Weak Process or Modification	References
set1	$\nu_e\, n \rightleftharpoons e^-\, p$	Bruenn (1985)
	$\bar{\nu}_e\, p \rightleftharpoons e^+\, n$	Bruenn (1985)
	$\nu_e\, A' \rightleftharpoons e^-\, A$	Bruenn (1985)
	$\nu\, N \rightleftharpoons \nu\, N$	Bruenn (1985)
	$\nu\, A \rightleftharpoons \nu\, A$	Bruenn (1985),Horowitz (1997)
	$\nu\, e^{\pm} \rightleftharpoons \nu\, e^{\pm}$	Bruenn (1985)
	$e^-\, e^+ \rightleftharpoons \nu\, \bar{\nu}$	Bruenn (1985)
	$N N \rightleftharpoons \nu\bar{\nu} N N$	Hannestad & Raffelt (1998)
set2	$\nu_e\, A \rightleftharpoons e^-\, A'$	Juodagalvis et al. (2010)
set3a	$\nu_e + \bar{\nu}_e \rightleftharpoons \nu_x + \bar{\nu}_x$	Buras et al. (2003); Fischer et al. (2009)
set3b	$\nu_x + \nu_e(\bar{\nu}_e) \rightleftharpoons \nu_x' + \nu_e'(\bar{\nu}_e')$	Buras et al. (2003); Fischer et al. (2009)
set4a	$\nu_e\, n \rightleftharpoons e^-\, p,\ \ \bar{\nu}_e\, p \rightleftharpoons e^+\, n$	Martínez-Pinedo et al. (2012)
set4b	$N N \rightleftharpoons \nu\bar{\nu} N N^*$	Fischer (2016)
set5a	$\nu_e\, n \rightleftharpoons e^-\, p,\ \ \bar{\nu}_e\, p \rightleftharpoons e^+\, n,\ \nu\, N \rightleftharpoons \nu\, N$	Horowitz (2002)
set5b	$m_N \to m_N^*$	Reddy et al. (1999)
set6a	$g_A \to g_A^*$	Fischer (2016)
set6b	$\nu\, N \rightleftharpoons \nu\, N$ (Many-body and Virial corrections)	Horowitz et al. (2017)
set6c	$\nu\, N \rightleftharpoons \nu\, N$ (Strangeness contribution)	Horowitz (2002)

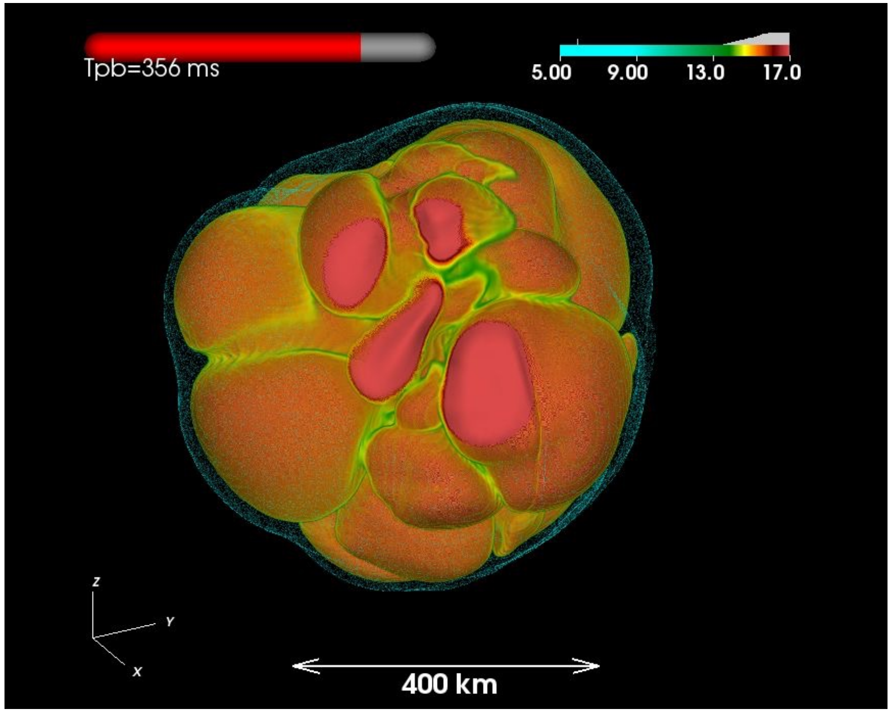
Table 1 in Kotake+'18

Comparison between 2D and 3D Simulations

2-dimensional simulation for SN 1987A progenitor.
(symmetry axis along the z-axis.)

3-dimensional simulation.
(no symmetry is assumed.)





Standing Accretion Shock Instability (SASI).
Very prolate.
Earlier shock expansion.

Convective motion.
Nearly spherical.
Slower evolution.