連星進化モデルに基づく SN 1987Aの多次元数値シミュレーション

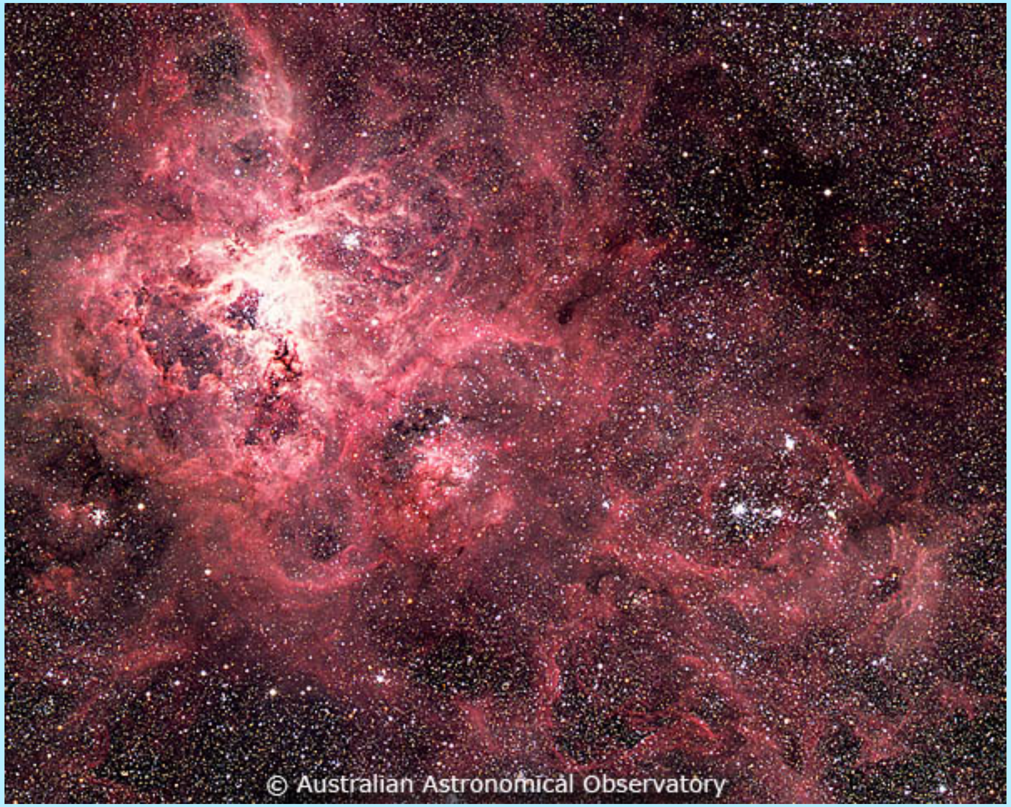
中村 航（福岡大学）

滝脇 知也（国立天文台）、固武 慶（福岡大学）

新学術「地下素核研究」 第5回超新星ニュートリノ研究会 @ NAOJ Jan. 7-8, 2019

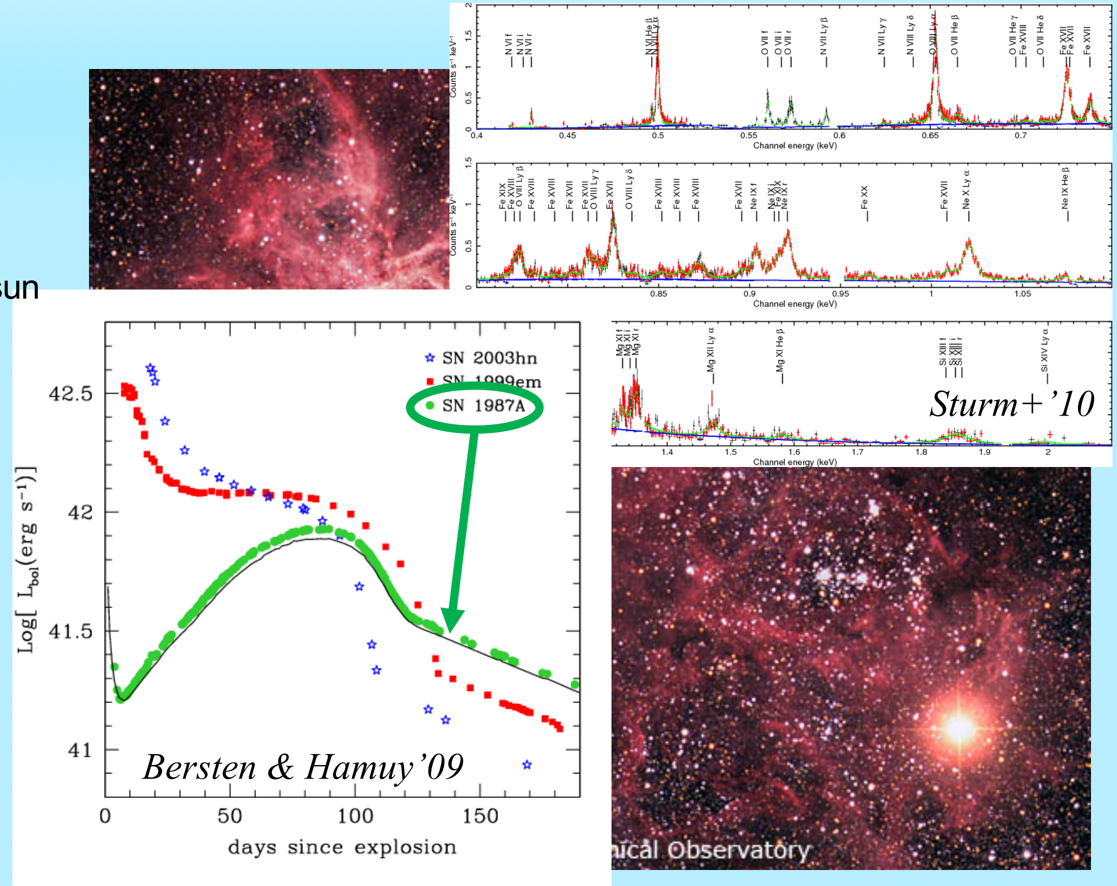
SN 1987A - the most well observed supernova

✓ emerged in LMC (D ~ 50 kpc)



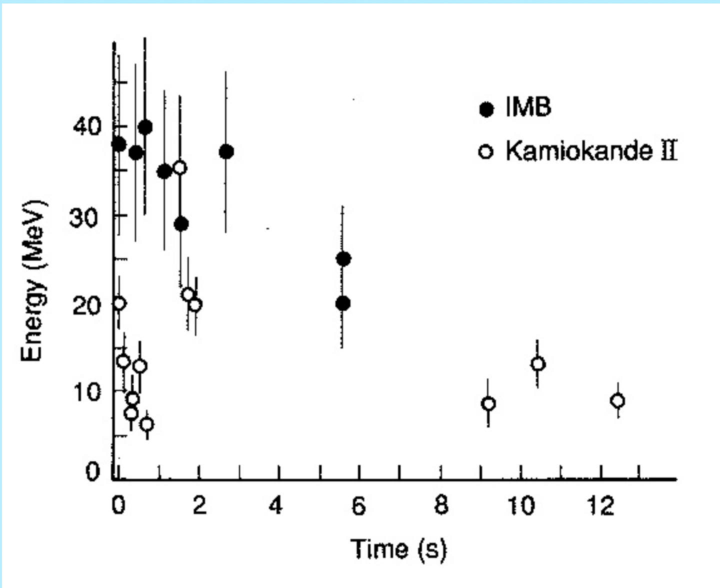
SN 1987A - the most well observed supernova

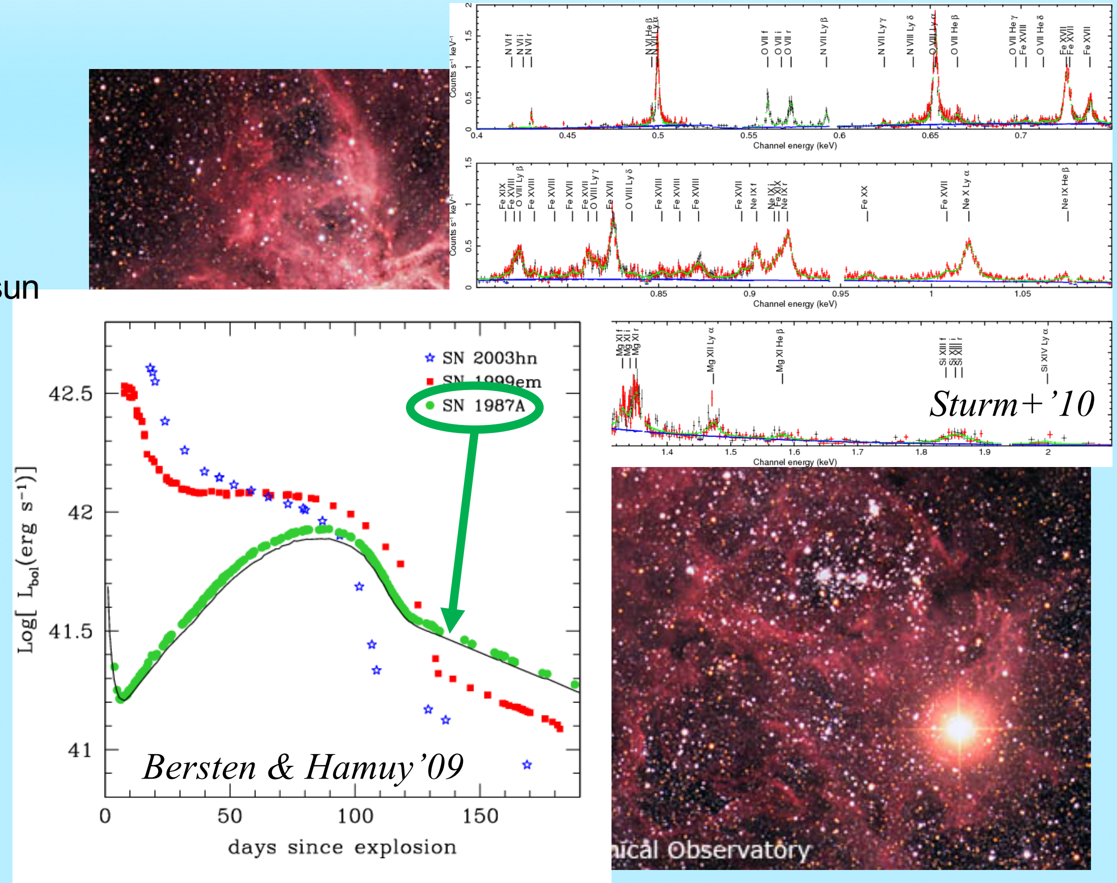
- ✓ emerged in LMC (D ~ 50 kpc)
- ✓ EM light curve & spectra
  $\rightarrow E_{\rm exp}$ ~ 1.2 foe, $M_{\rm Ni}$ ~ 0.07 $M_{\rm sun}$



SN 1987A - the most well observed supernova

- ✓ emerged in LMC (D ~ 50 kpc)
- ✓ EM light curve & spectra
  $\rightarrow E_{\rm exp}$ ~ 1.2 foe, $M_{\rm Ni}$ ~ 0.07 $M_{\rm sun}$
- ✓ neutrino detection!



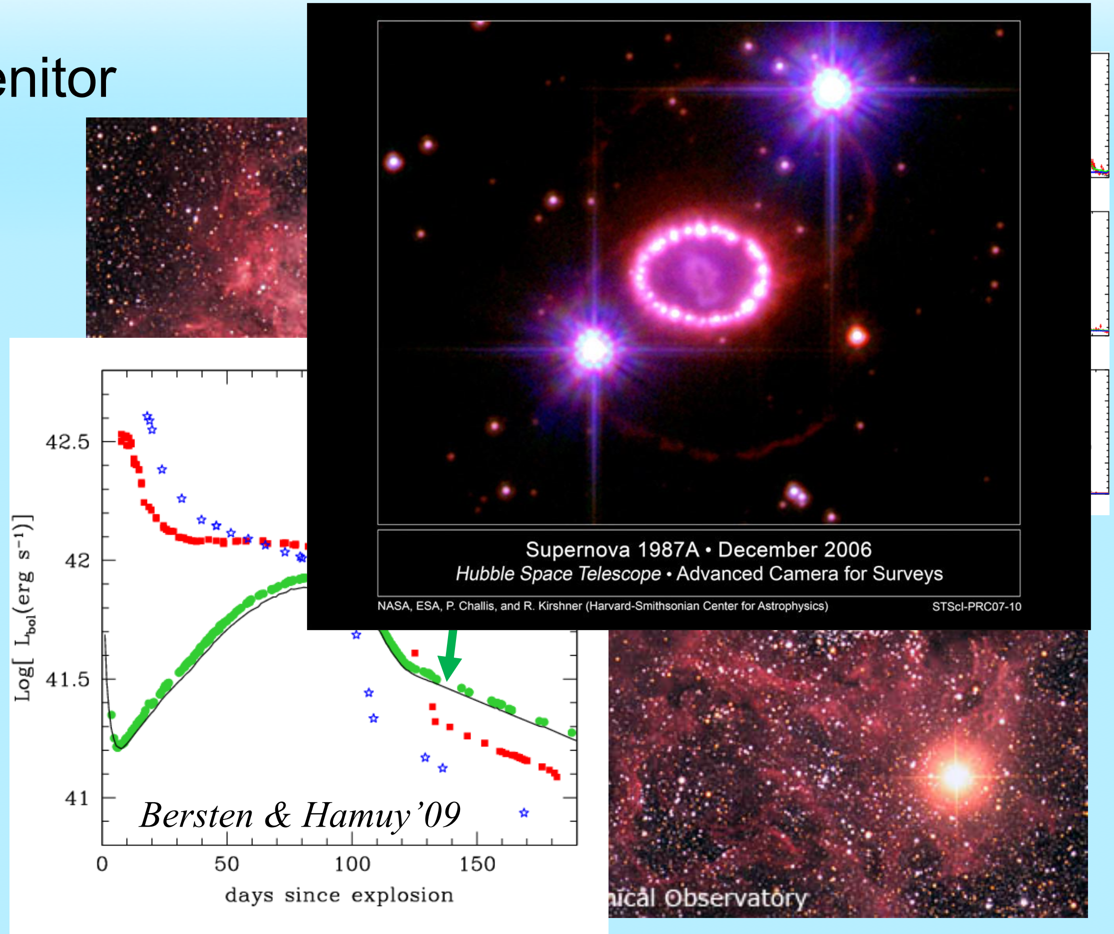


SN 1987A - an anomalous supernova

✓ red → blue supergiant progenitor
Sk - 69˚202

✓ chemical anomalies:
He & N-rich (CNO process)
Ba-rich (s-process)

✓ triple-ring nebula
→ signature of rotation?



Early Models of SN 1987A Progenitor

✓ **<u>Single star models</u>** :

- extreme-mass-loss models (*Maeder'87; Wood & Faulkner'88*)
- helium-enrichment models (*Saio+'88*)
- low-metallicity models (*Arnett'87; Hillebrandt+'87; Truran & Weiss'87*)
- rapid-rotation models (*Weiss+'88; Ramadurai & Wiita'89; Langer'91*)
- restricted-convection models (*Woosley+'88; Langer+'89; Weiss'89*)

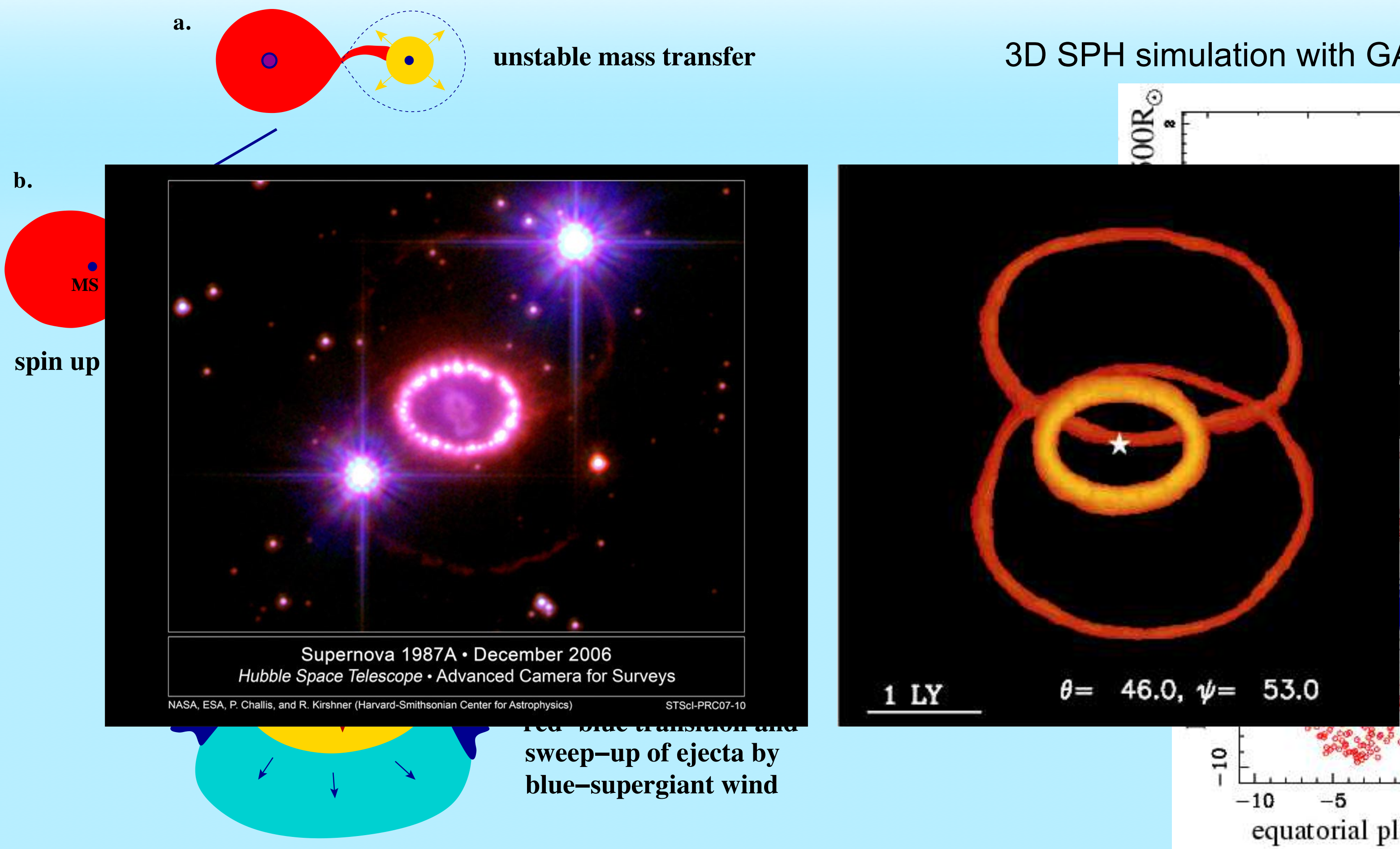
✓ **<u>Binary models</u>** :

- accretion models (*Maeder'87; Wood & Faulkner'88*)
- companion models (*Fabian+'87; Joss+'88*)
- merger models (*Barkat & Wheeler'89; Podsiadlowski & Joss'89; De Loor & Vanbeveren'92*)

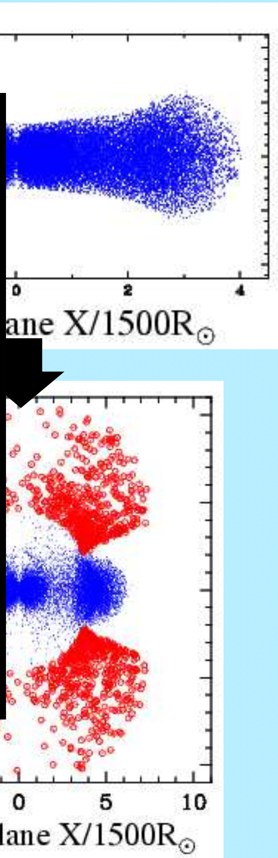
(see sec. 3 & 4 in *Podsiadlowski '92* for a review)

Slow Merger Scenario - the triple-ring nebula

Ivanova+ '02; Morris and Podsiadlowski '07

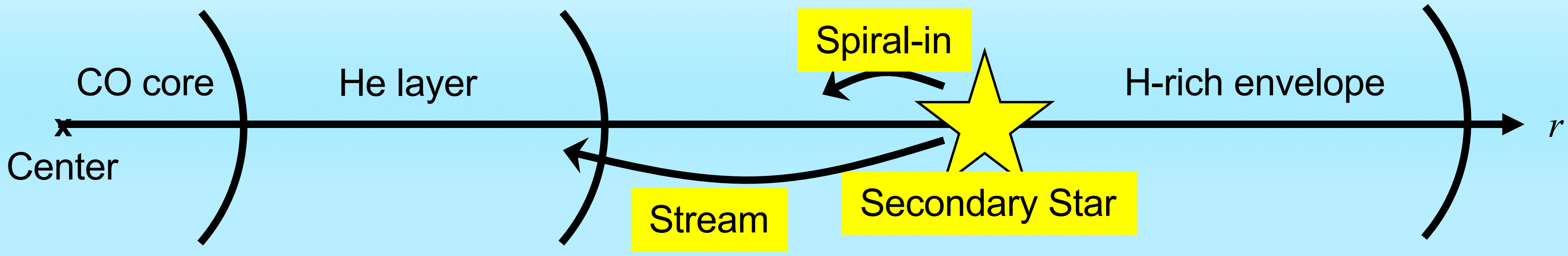


3D SPH simulation with GADGET (10^6 particles)



Slow Merger Scenario - new progenitor models

Urushibata+'17; Menon & Heger'17

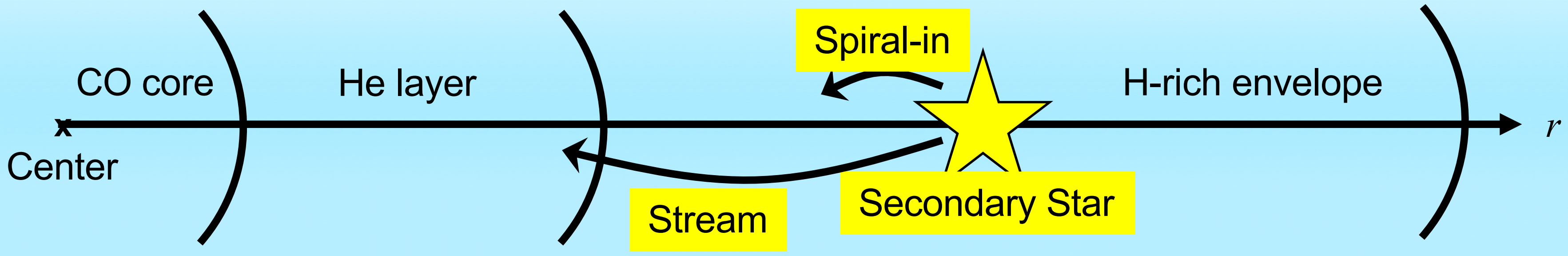


fresh (H-rich) fuel
→ CNO cycle
→ **He & N production**

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

Slow Merger Scenario - new progenitor models

Urushibata+'17; Menon & Heger'17

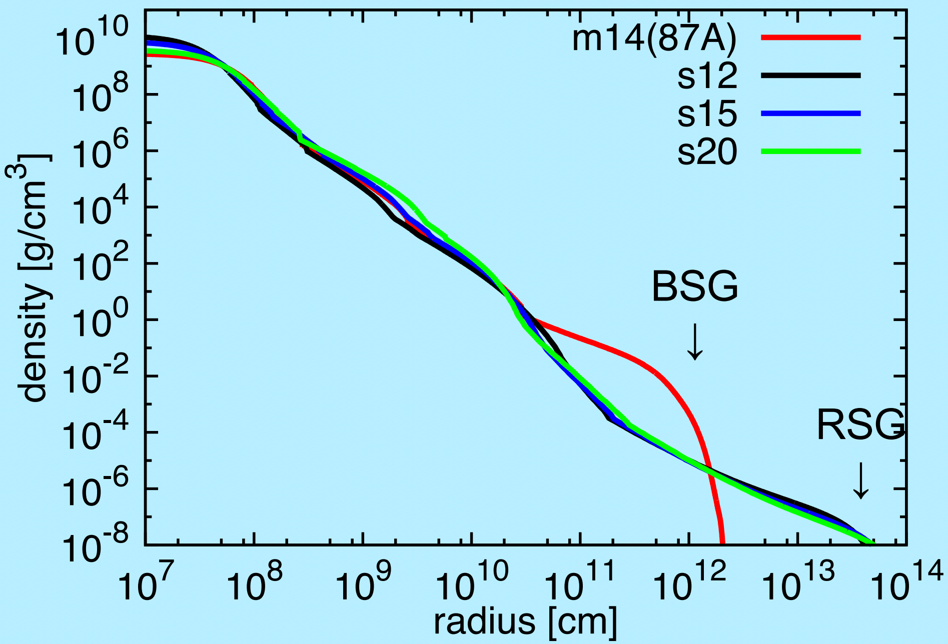


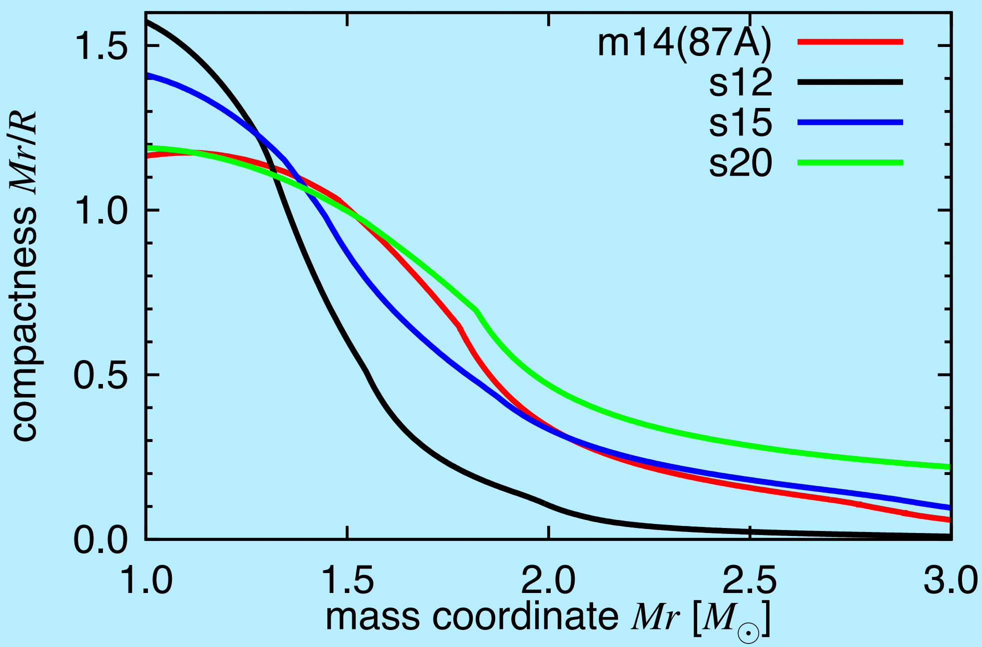
	Urushibata+'17	*Menon & Heger'17*
Red to blue evolution	Yes	Yes
Time to collapse	Yes	No
Origin of the rings	Yes	No
Anomalies of CNO-process elements	Yes	Yes
Anomalies of s-process elements	?	?

We use the best-fit model (14 + 9 Msun → 18.3 Msun) from *Urushibata+'17* for our core-collapse simulation.

Progenitor Model

✓ Density and "compactness" profiles
of our SN 1987A progenitor model (m14)
compared with 12, 15, and 20 *M*sun progenitors
from *Woosley, Heger, & Weaver'02*.





Numerical Scheme for Core-Collapse Simulation

✓ **<u>3DnSNe code</u>** (*Takiwaki+'12,'14,'18*) with some updates:

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

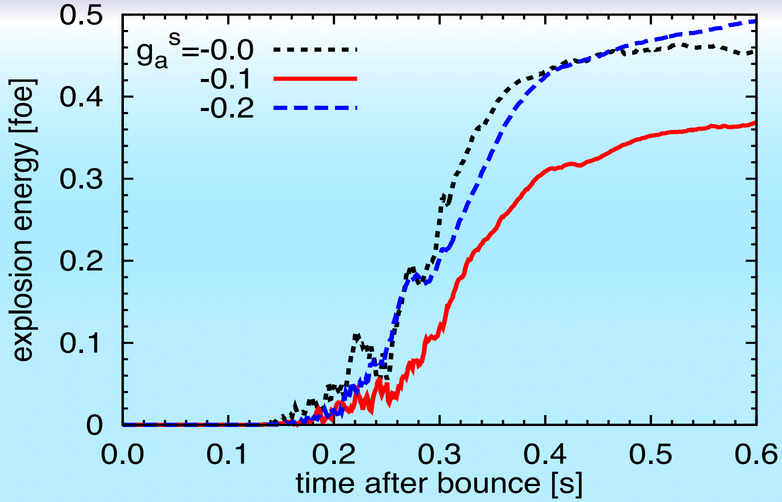
Model	Weak Process or Modification	References
set1	$\nu_e\, n \rightleftharpoons e^-\, p$	Bruenn (1985)
	$\bar{\nu}_e\, p \rightleftharpoons e^+\, n$	Bruenn (1985)
	$\nu_e\, A' \rightleftharpoons e^-\, A$	Bruenn (1985)
	$\nu\, N \rightleftharpoons \nu\, N$	Bruenn (1985)
	$\nu\, A \rightleftharpoons \nu\, A$	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	$m_N \rightarrow m_N^*$	Reddy et al. (1999)
set6a	$g_A \rightarrow g_A^*$	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)

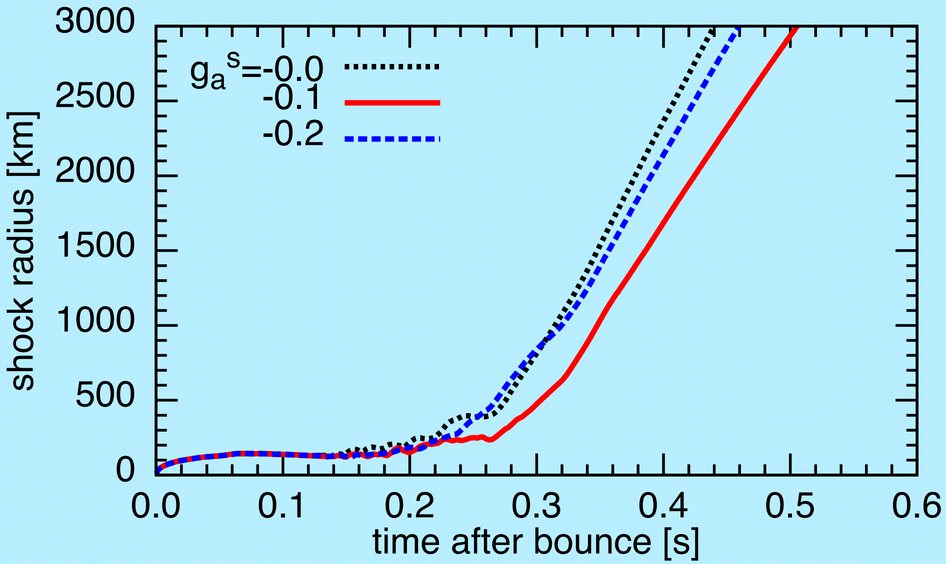
Results of 2D Simulations

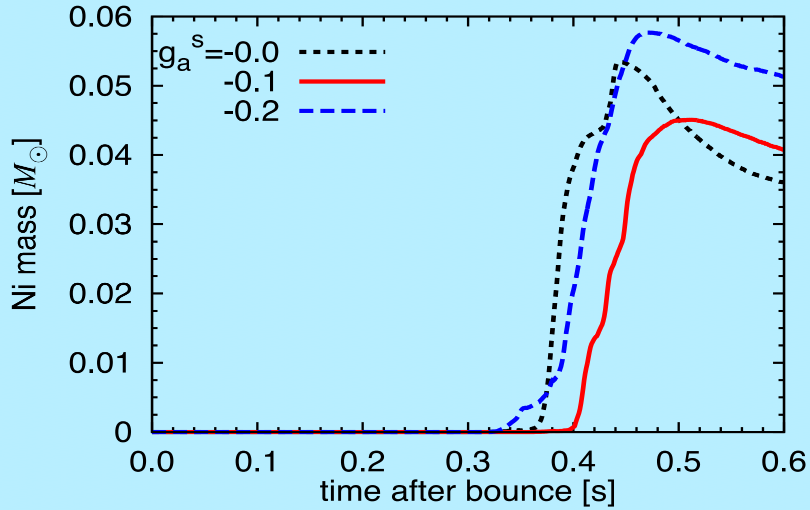
- ✓ Slightly different results
  between models with different input of microphysics
  (e.x., strangeness contribution).

- ✓ Successful shock revival at ~0.25 s.

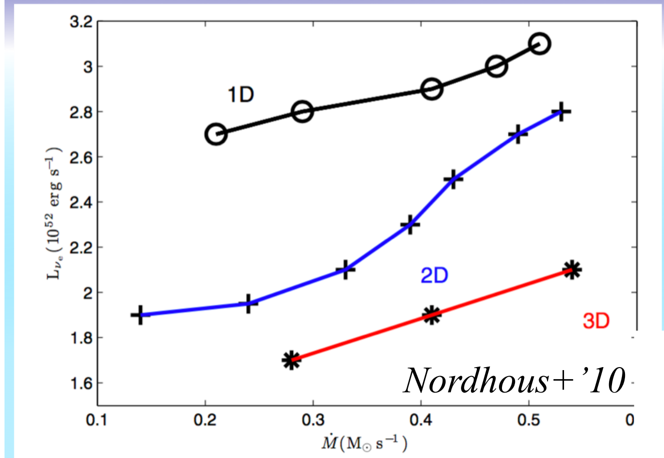
- ✓ E_{exp} ~ 0.36-0.5 foe, M_{Ni} ~ 0.035-0.05 M_{sun}
  (obs: E_{exp} ~ 1.2 foe, M_{Ni} ~ 0.07 M_{sun}).





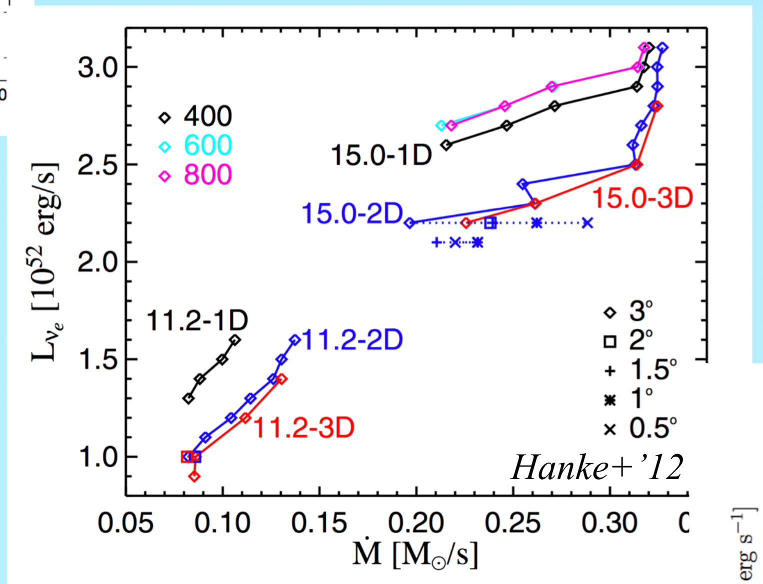


2D/3D CCSN simulations - previous works

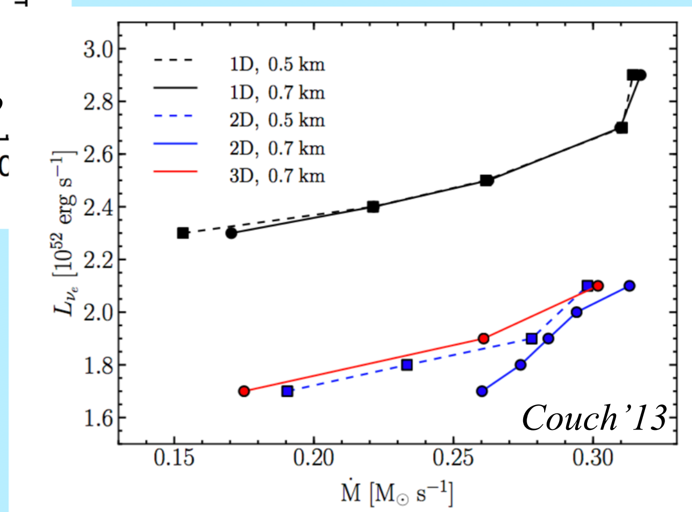


1D < 2D < 3D

1D < 2D ~ 3D



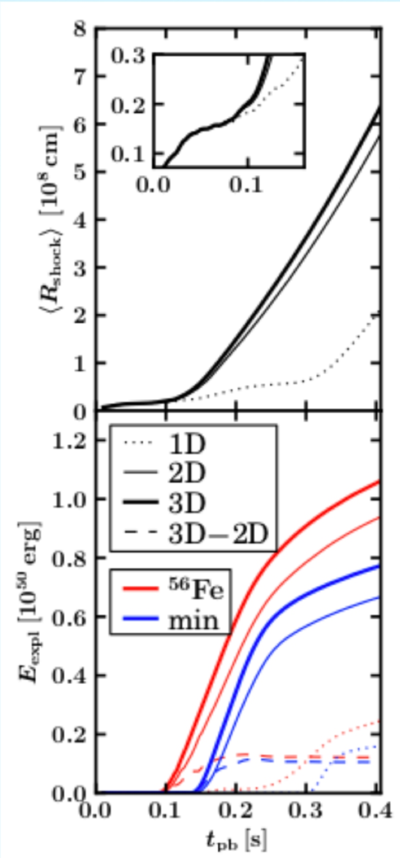
1D < 3D < 2D



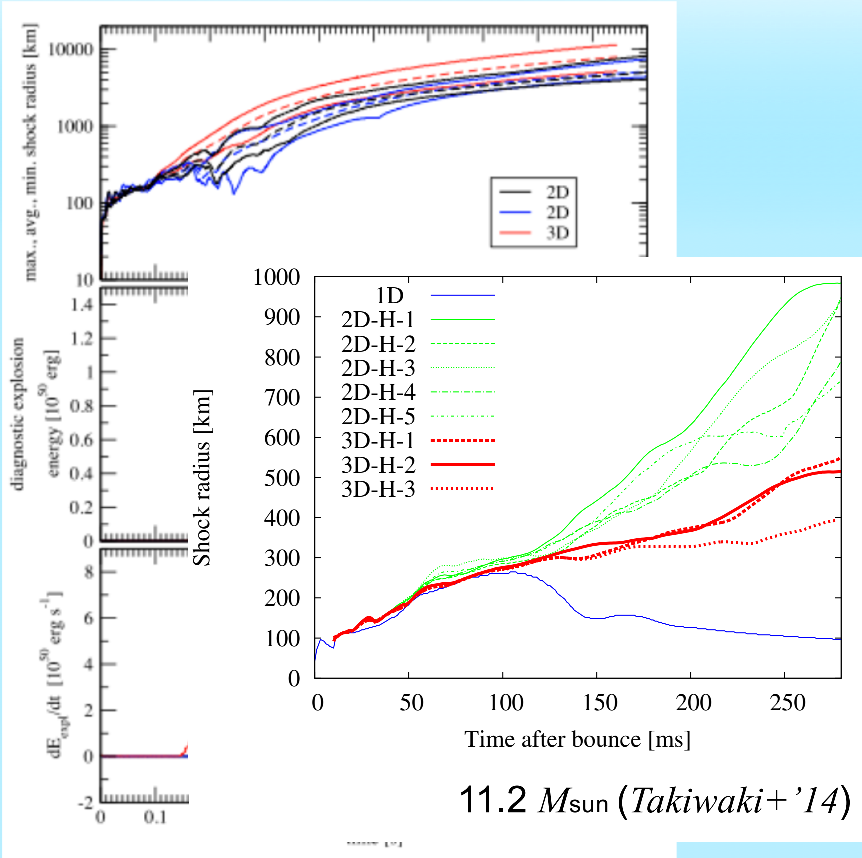
Critical curve:

neutrino luminosity ($L\nu$) necessary to make explosions as a function of mass accretion rate ($\dot{M}$).

2D/3D CCSN simulations - previous works

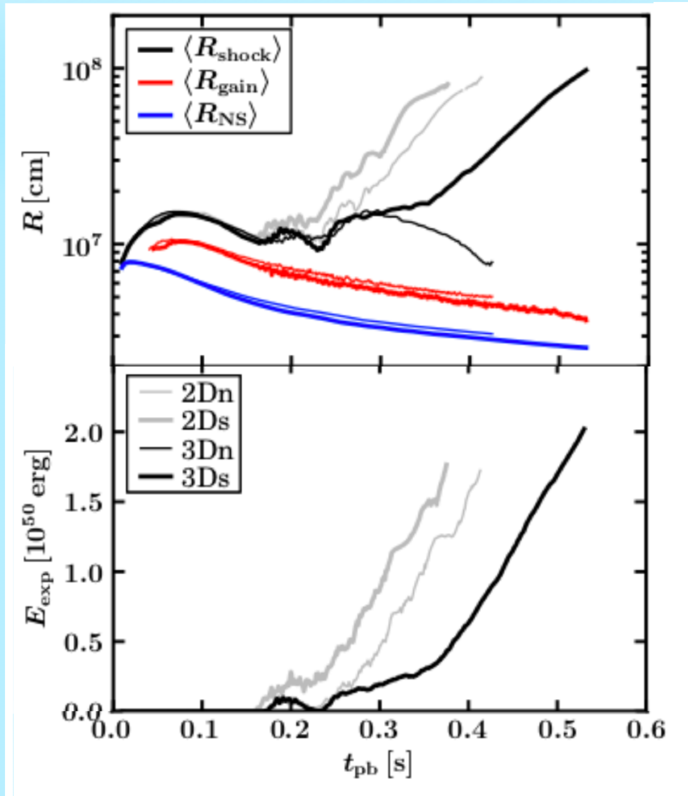


9.6 Msun (*Melson+'15a*)



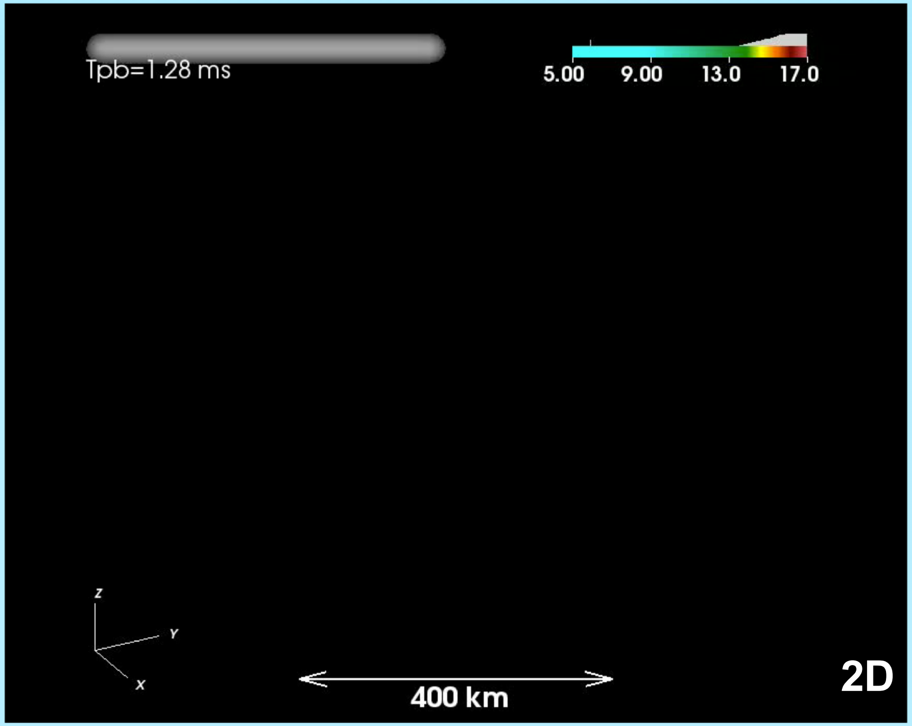
11.2 Msun (*Takiwaki+'14*)

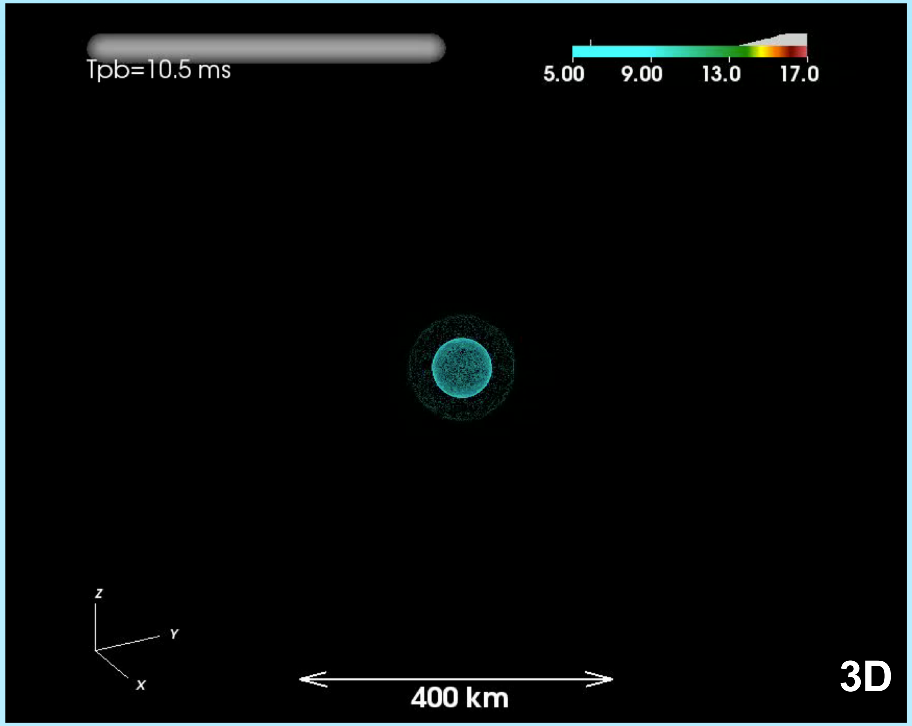
11.2 Msun (*Mueller'15*)



20 Msun (*Melson+'15b*)

Comparison between 2D and 3D Simulations

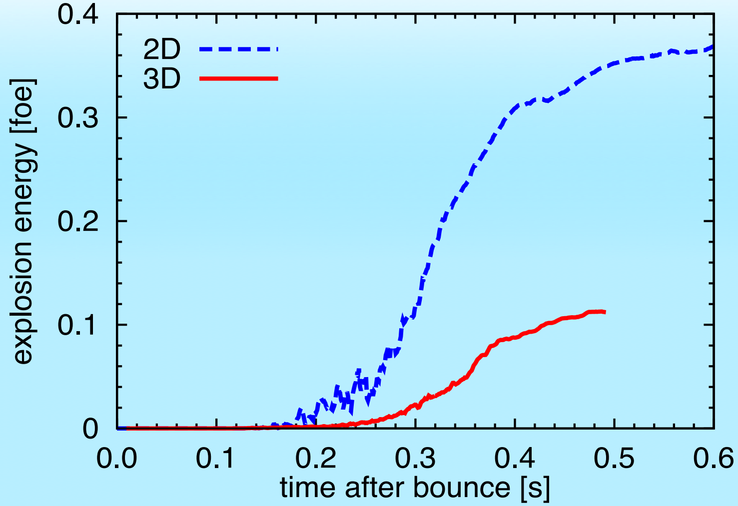


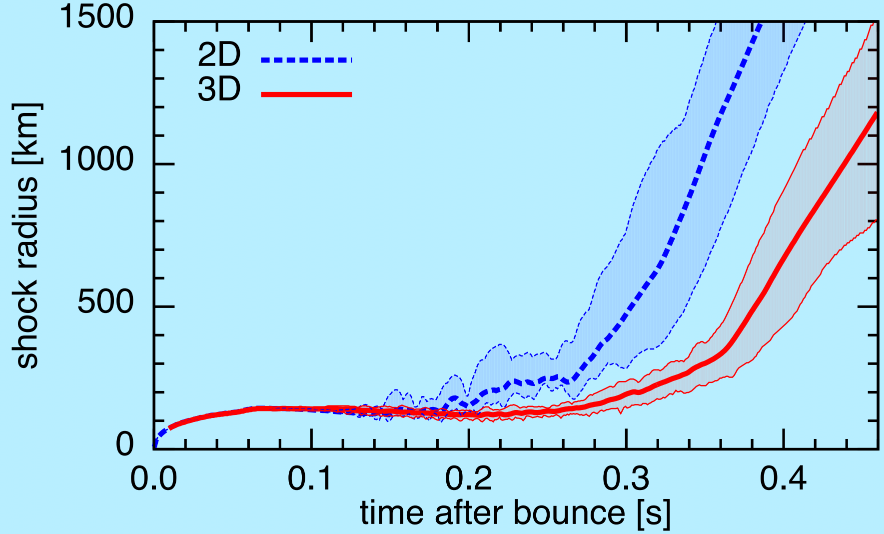


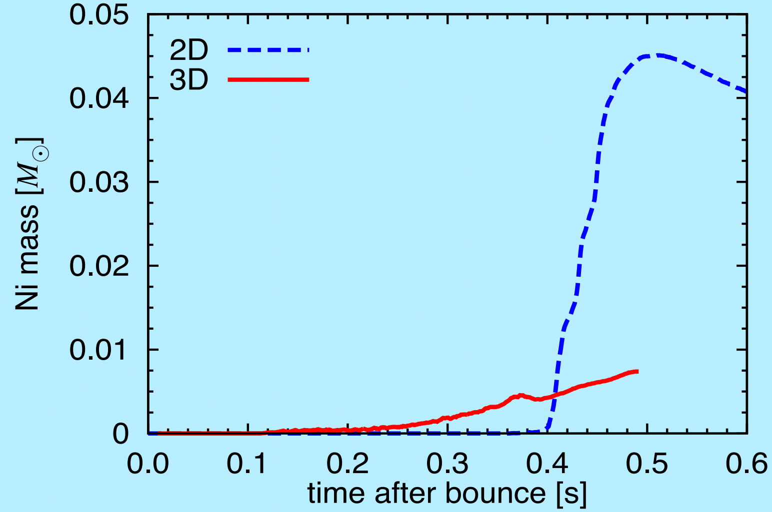
Comparison between 2D and 3D Simulations

✓ 2D model: shock revival aided by strong SASI (sloshing) motion.

✓ 3D model: nearly spherical shock structure. Unfortunately, the explosion is very weak ($E_{\rm exp}$ ~ 0.12 foe and $M_{\rm Ni}$ < 0.01 $M_{\rm sun}$ at 0.5 s after bounce).

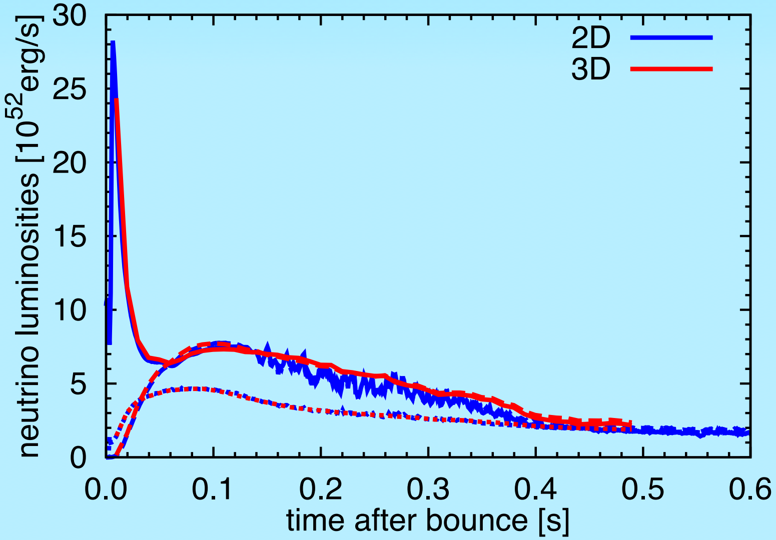


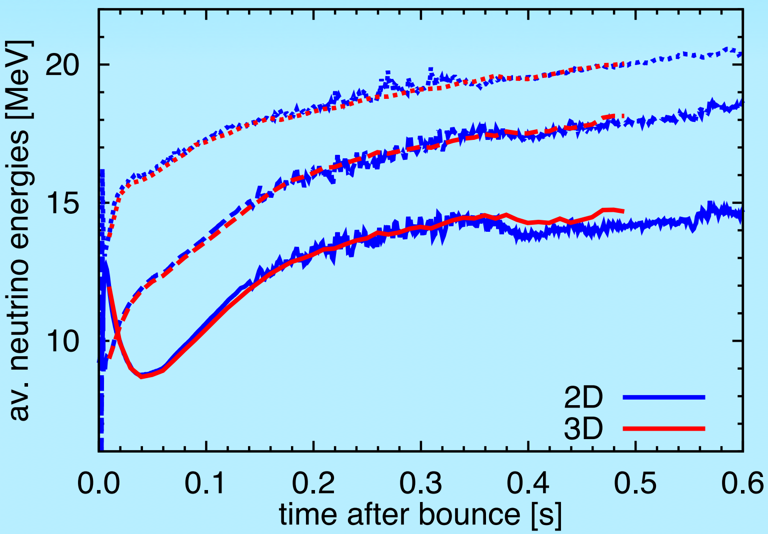




What makes the *weak* explosion in 3D?

✓ Neutrino luminosity and average energy?



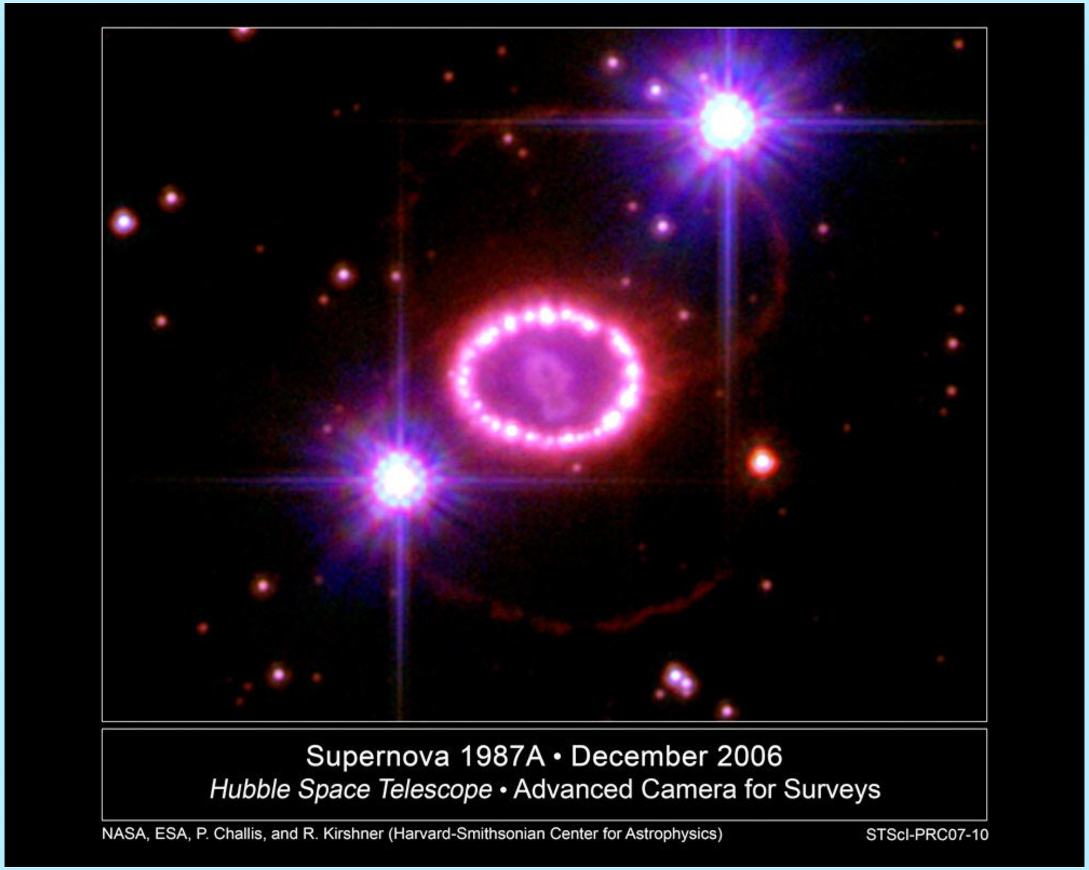


*Δt = 10 ms for 3D analysis.

✓ Spatial resolution?

n(θ) = 128 in 2D, n(θ)*n(φ) = 64*128 in 3D

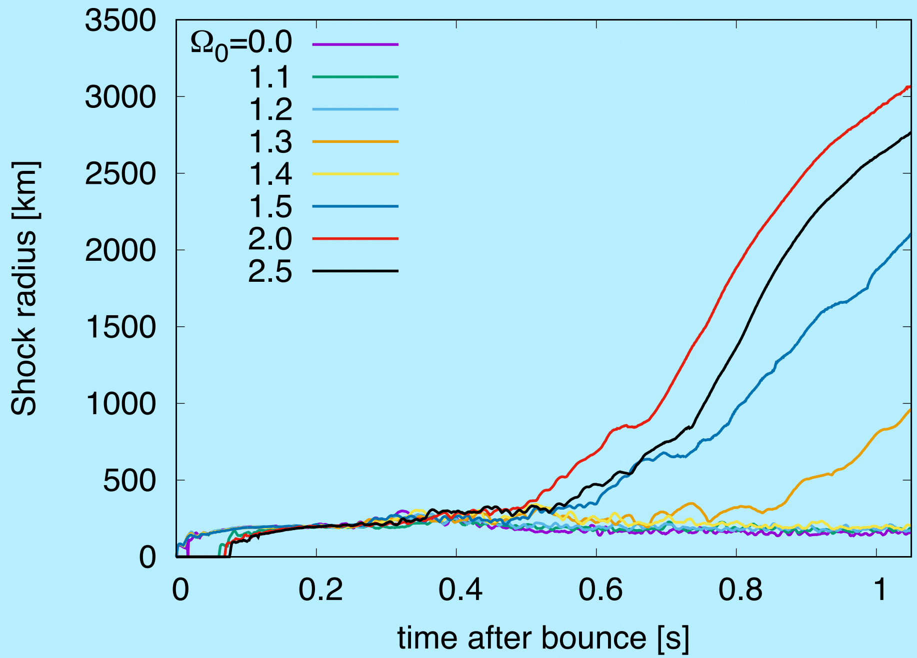
Rotation?

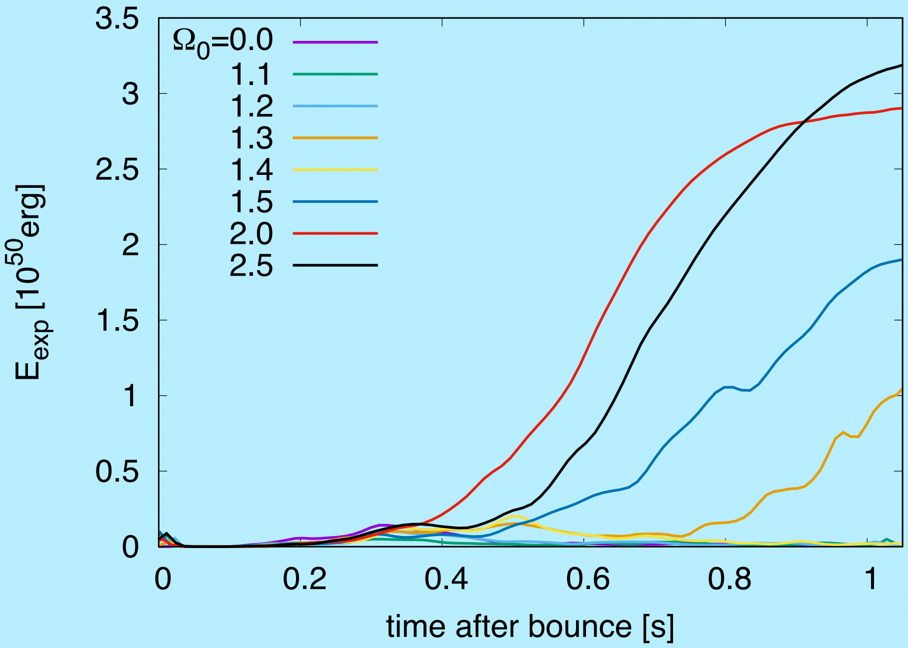

Supernova 1987A • December 2006
Hubble Space Telescope • Advanced Camera for Surveys
NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)
STScI-PRC07-10

Rotation?

✓ Our progenitor model is rotating very slowly (Ω_0~0.02 rad/s in the Fe core).

✓ 2D simulations for s20.0 progenitor with a variety of core rotation present more energetic explosions for more rapidly rotating models.





Summary

✓ SN 1987A:

- a peculiar core-collapse supernova
- red to blue evolution, chemical anomalies, and the triple-ring nebula
- E_{exp} ~ 1.2 foe, M_{Ni} ~ 0.07 M_{sun}

✓ A progenitor model from *Urushibata+'17*:

- based on slow-merger scenario
- well reproduces observational features

✓ Self-consistent 2D & 3D simulation:

- 3DnSNe code with state-of-the-art inputs
- both 2D & 3D models successfully revive shocks
- E_{exp} ~ 0.36-0.5 foe, M_{Ni} ~ 0.035-0.05 M_{sun} in 2D (relatively strong)
- E_{exp} ~ 0.12 foe and M_{Ni} < 0.01 M_{sun} (weak)

✓ What is missed?

- rotation? spatial resolution?