OMEG15 @ YITP, Kyoto University
4 July, 2019

Three-dimensional simulations from supernovae to their supernova remnants: the dynamical and chemical evolution of SN 1987A

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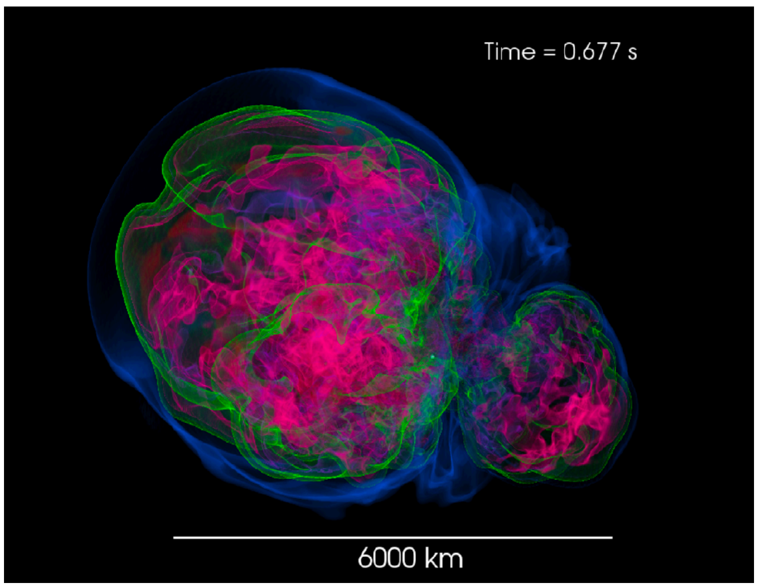
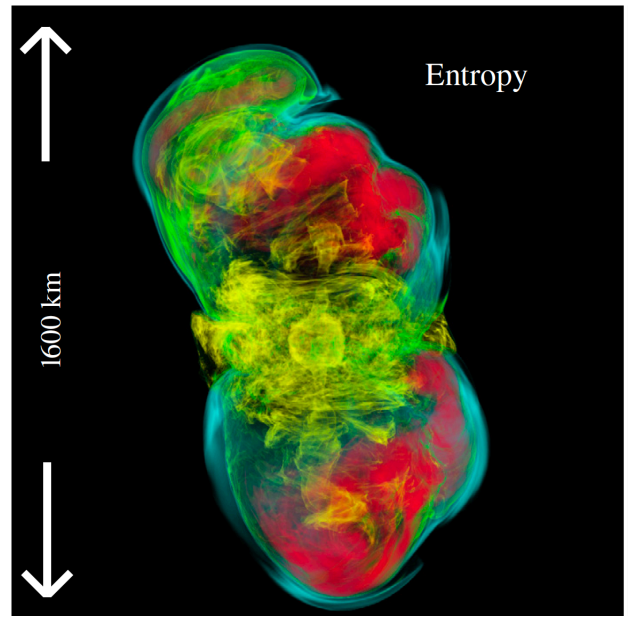
What are the explosion mechanism and morphology of core-collapse supernovae?

Delayed neutrino heating mechanism aid by SASI and/or convection



Vartanyan+19, MNRAS, 482, 351

Magnetorotationally-driven explosion (and/or neutrino heating)

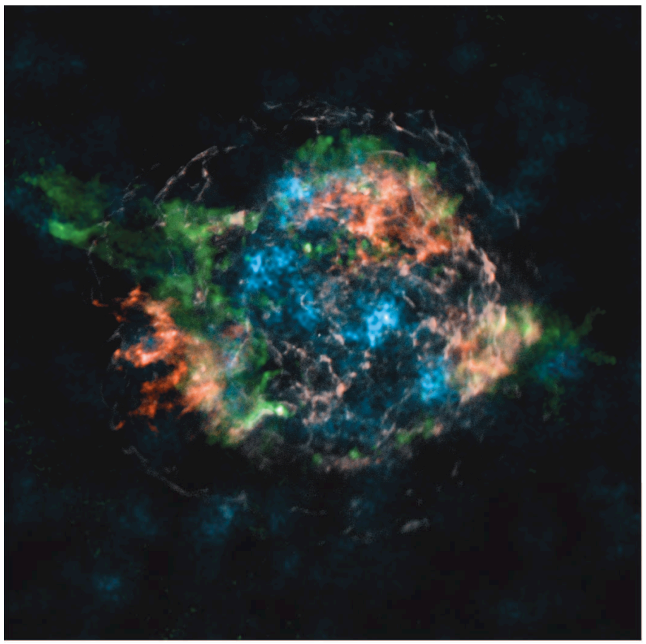


Mösta+14, ApJL, 785, L29

Volume rendered distributions of entropy

Asymmetries in core-collapse supernovae from maps of radioactive ^{44}Ti in Cas A

Cassiopeia A supernova remnant



Blue: ^{44}Ti

Green: Si/Mg band

Red: Fe (Chandra)

- Observations by the space-based Nuclear Spectroscopic Telescope Array (NuSTAR)
- Emission from the decay of ^{44}Ti
- M (^{44}Ti) = (1.25 ± 0.3) x 10^{-4} $M_{\odot}$

Distributions of Fe and ^{44}Ti are different

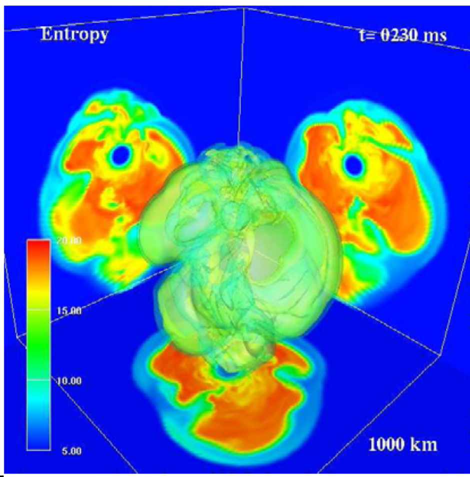
^{44}Ti -> ^{44}Sc -> ^{44}Ca

$\tau_{1/2}$ = 60 yr $\tau_{1/2}$ = 4 h

Grefenstette et al. 2014, Nature, 506, 339

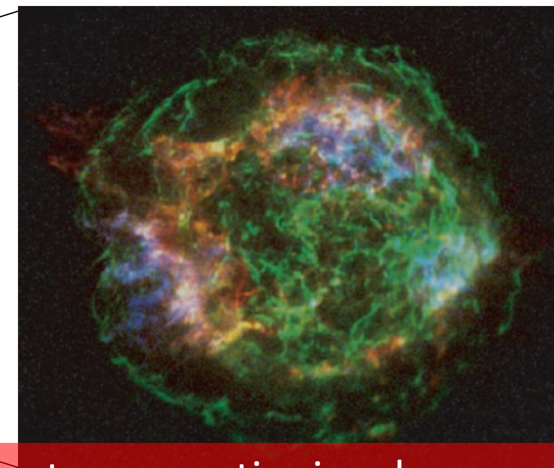
Supernova explosions to their supernova remnants (SNRs)

Supernova explosion	Shock breakout	supernova	Supernova remnant
$t < 1$ sec	$t < 1000$ sec	$t < 1$ yr	$t \sim 500$ yr



Takiwaki+14, ApJ, 786, 38

Mixing?



Radius of the progenitor star

Electromagentic signals

$10^7 - 10^9$ cm

$10^{12} - 10^{14}$ cm

$\sim 10^{18}$ cm (1 pc)

Stellar evolution of the progenitor star

Asymmetric explosion
Explosive nucleosynthesis

Matter mixing

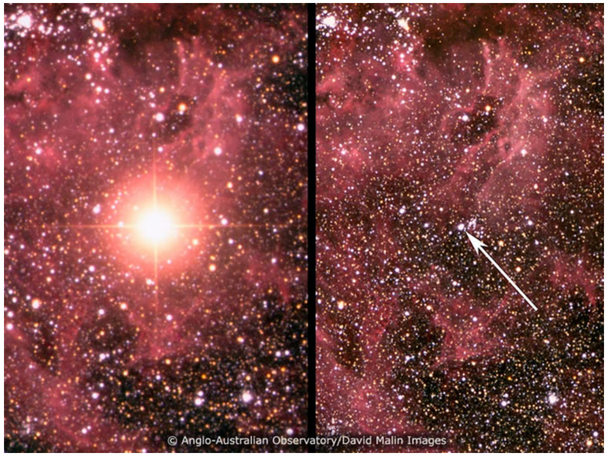
Formation of molecules and dust?

Asymmetric distribution of elements

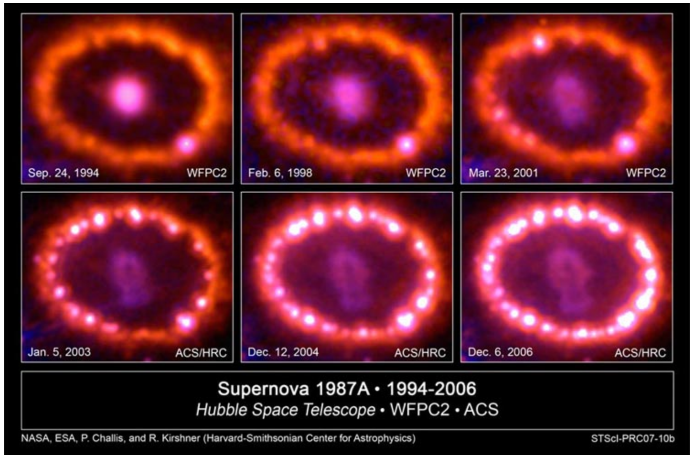
Chemical evolution (Nucleosynthesis/Molecule formation/dust formation) during the progenitor–SNe–SNRs sequence

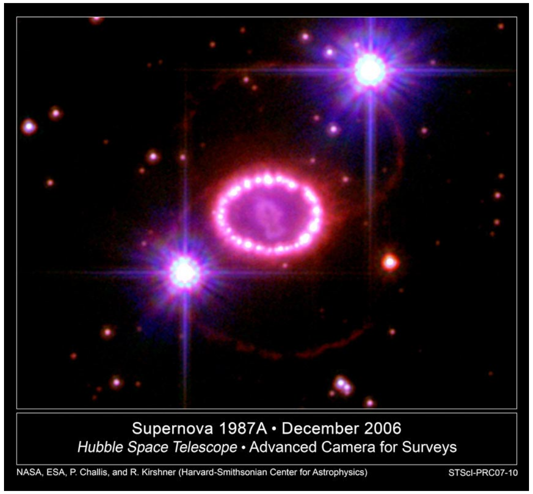
SN 1987A and matter mixing

Supernova 1987A (SN 1987A)



- Basic observational features of SN 1987A
  - SN @ LMC on 23 Feb., 1987
  - Neutrinos from the SN were detected by Kamiokande
  - Triple-ring nebula





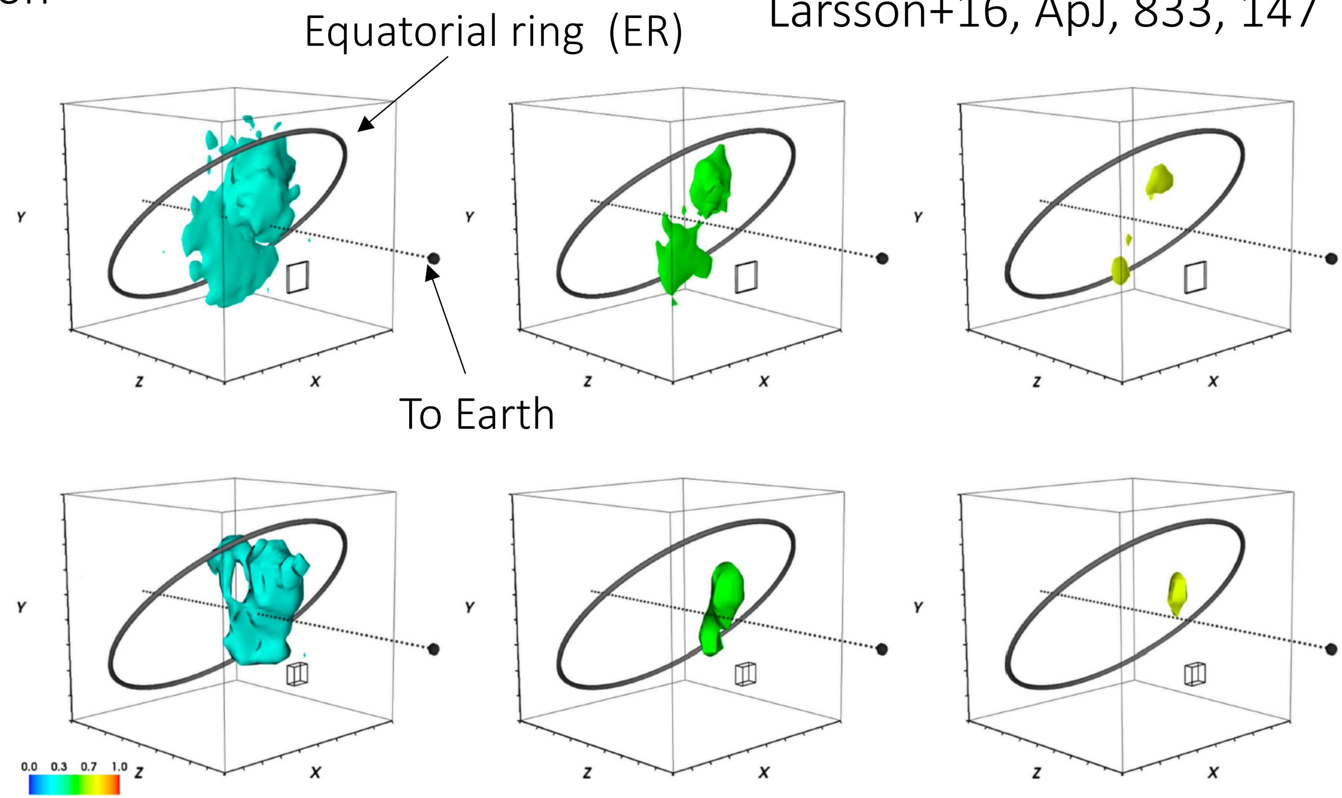
3D distribution of inner ejecta of SN 1987A

Observation from HST/STIS and VLT/SINFONI at 10,000 days after the explosion

Larsson+16, ApJ, 833, 147

Top: [Si I] + [Fe II] 1.644 μm

Bottom: H_α



Molecule distribution in 3D

Abellán et al. 2017, ApJ, 842, L24

ALMA observations of CO J = 2 -1, SiO J = 5 – 4, 6 -5 rotational transitions

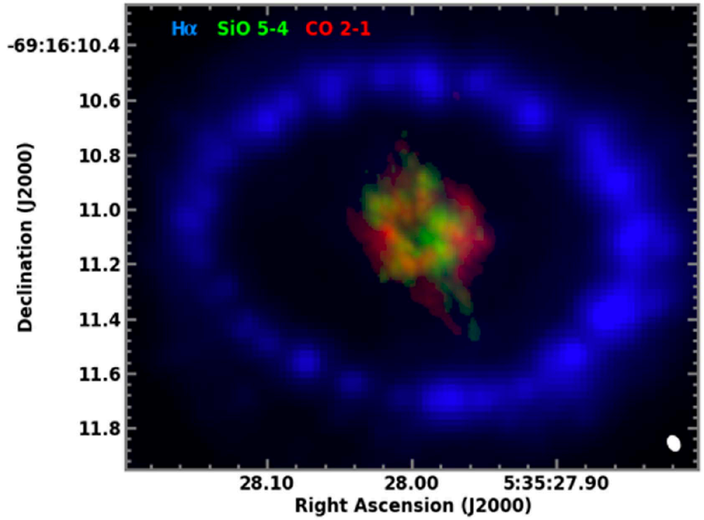


Figure 1. Molecular emission and Hα emission from SN 1987A. The more compact emission in the center of the image corresponds to the peak intensity maps of CO 2−1 (red) and SiO 5−4 (green) observed with ALMA. The surrounding Hα emission (blue) observed with *HST* shows the location of the circumstellar equatorial ring (Larsson et al. 2016).

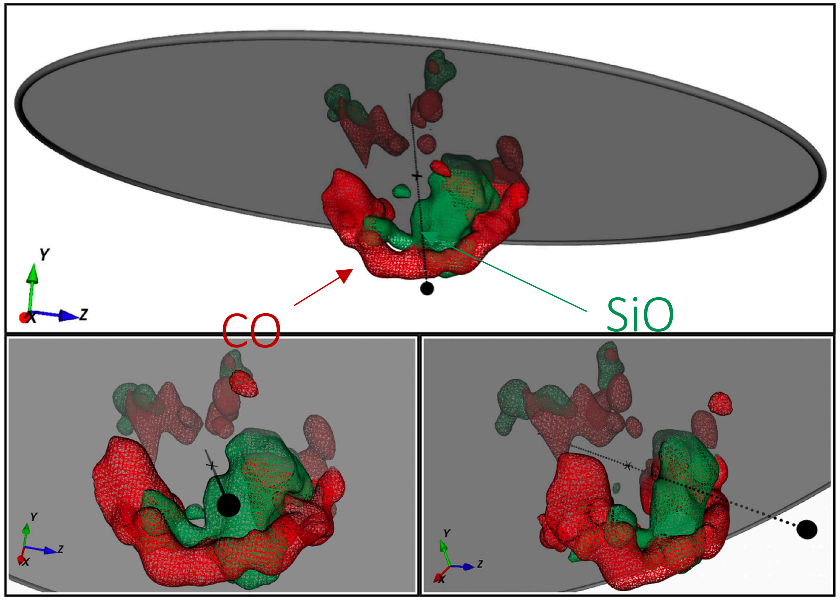
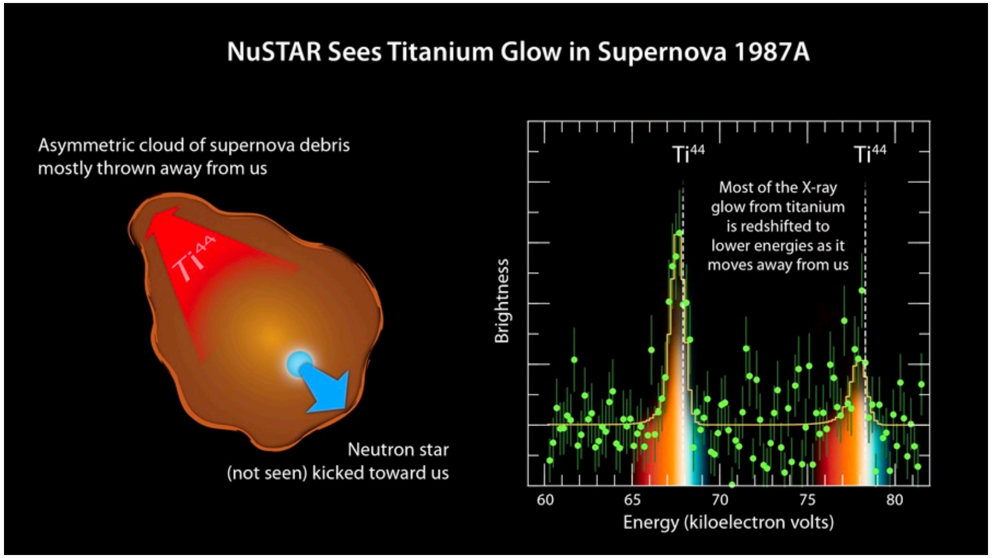
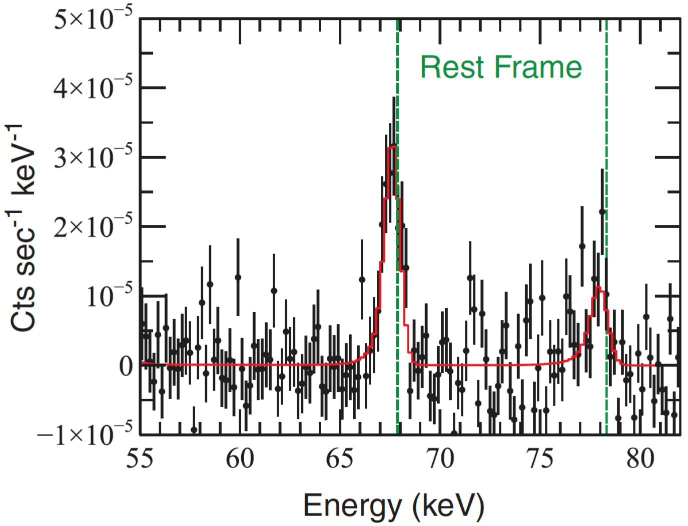


Figure 2. 3D view of cold molecular emission in SN 1987A. The CO 2−1 (red) and SiO 5−4 (green) emission is shown from selected view angles. The central region is devoid of significant line emission. The emission contours are at the 60% level of the peak of emission for both molecules. The black dotted line and black filled sphere indicate the line of sight and the position of the observer, respectively. The gray ring shows the location of the reverse shock at the inner edge of the equatorial ring (*XZ* plane). The black cross marks the geometric center.

(An animation of this figure is available.)

^{44}Ti gamma-ray emission lines from SN1987A reveal an asymmetric explosion





59-80 keV NuSTAR spectrum of SN1987A with detected ^{44}Ti emission lines.
[Credit: NASA/JPL-Caltech/UC Berkeley]

Figure from
https://nustar.ssdc.asi.it/news.php

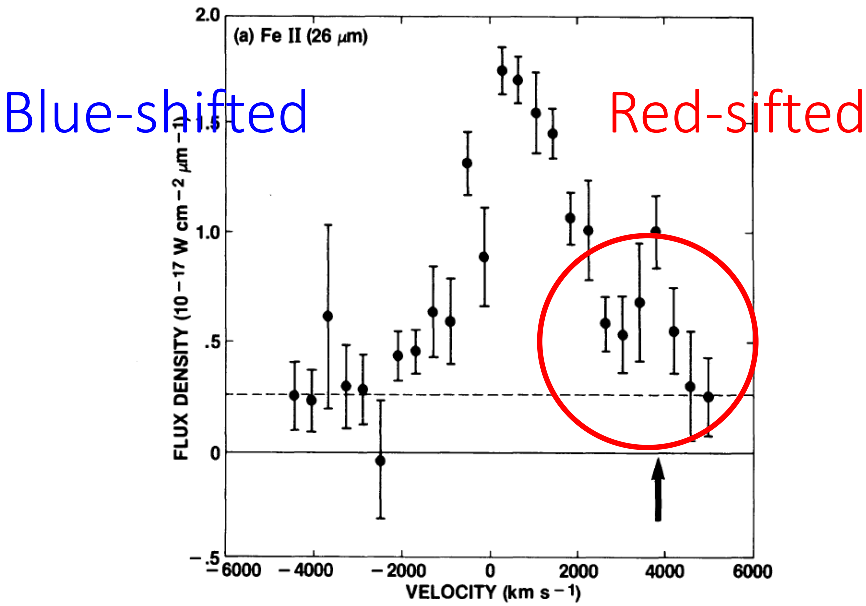
- Observations of ^{44}Ti lines by NuSTAR
- Lines are redshifted with a Doppler velocity of about 700 km/s
- An asymmetric explosion is invoked

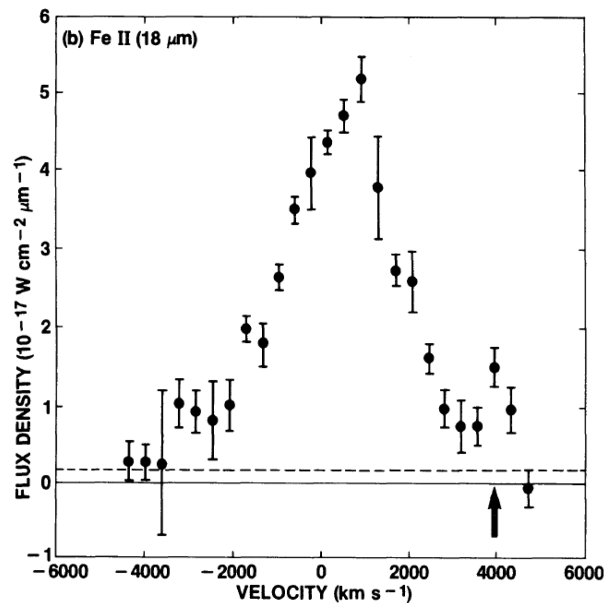
Boggs et al. 2015, Science, 348, 670

High velocity Fe : matter mixing?

[Fe II] line profiles

Haas+90', ApJ, 360, 257
(observations at ～ 400 days after the explosion)





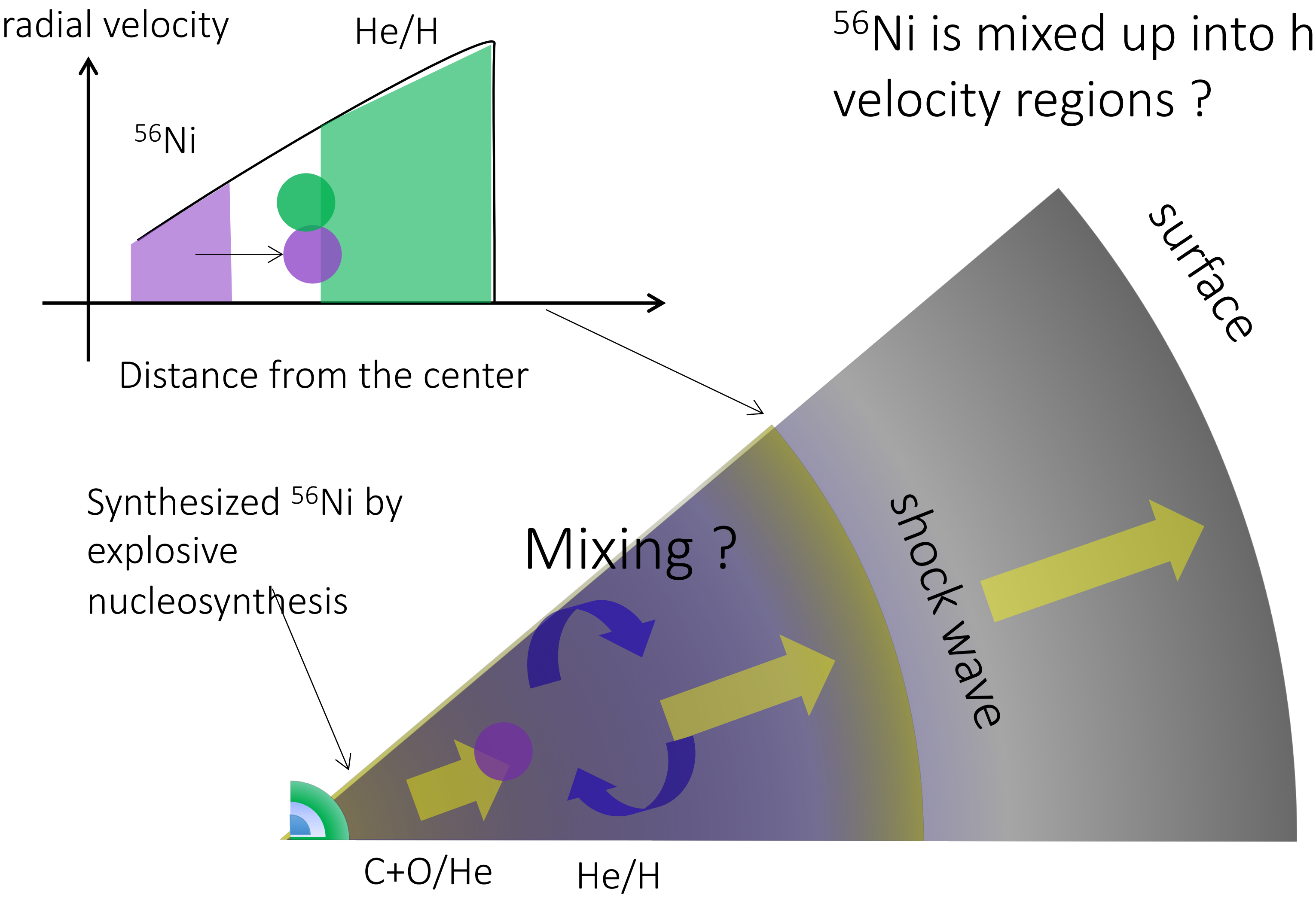
- High velocity tails of [Fe II] line profiles reach (> 4,000 km/s)

  Fast ^{56}Fe (^{56}Ni -> ^{56}Co -> ^{56}Fe) motion ー＞ Matter mixing？

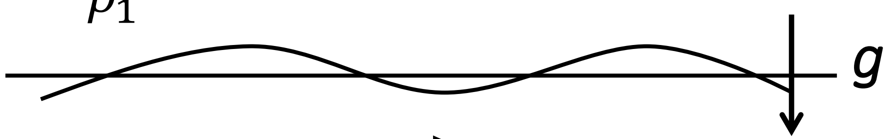
  Red-shifted side is dominated ー＞ Asymmetric explosion?

Matter mixing in supernova explosions

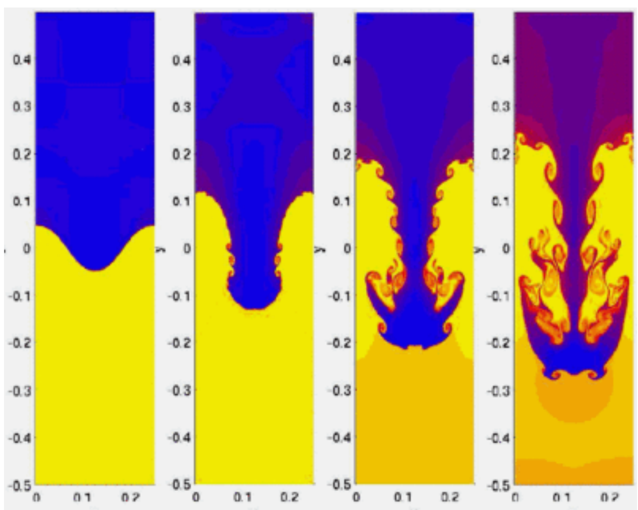
^{56}Ni is mixed up into high velocity regions ?



Rayleigh-Taylor (RT) instability



$\rho_1 > \rho_2$



Shengtai Li & Hui Li 2006

Self-similar solution (Sedov 1959)

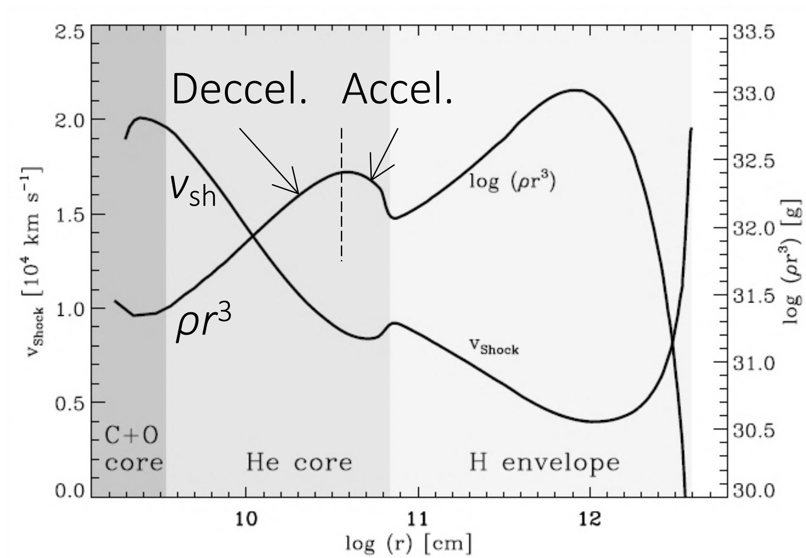
$$\rho(r) \propto r^{-\omega} \quad v_{\rm sh} \propto t^{(\omega-3)/(5-\omega)}$$

RT unstable condition

$$\nabla\rho \cdot \nabla P < 0$$ (Chevalier 1979)

$\rho\, r^3 \searrow \;\rightarrow$ accelerate

$\rho\, r^3 \nearrow \;\rightarrow$ decelerate

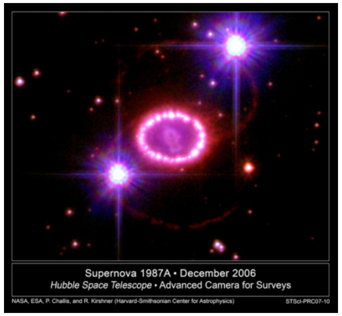


Density profile (ρ r^3) of a progenitor star

Figure is taken from Kifonidis et al. 2006

What is the progenitor of SN 1987A?

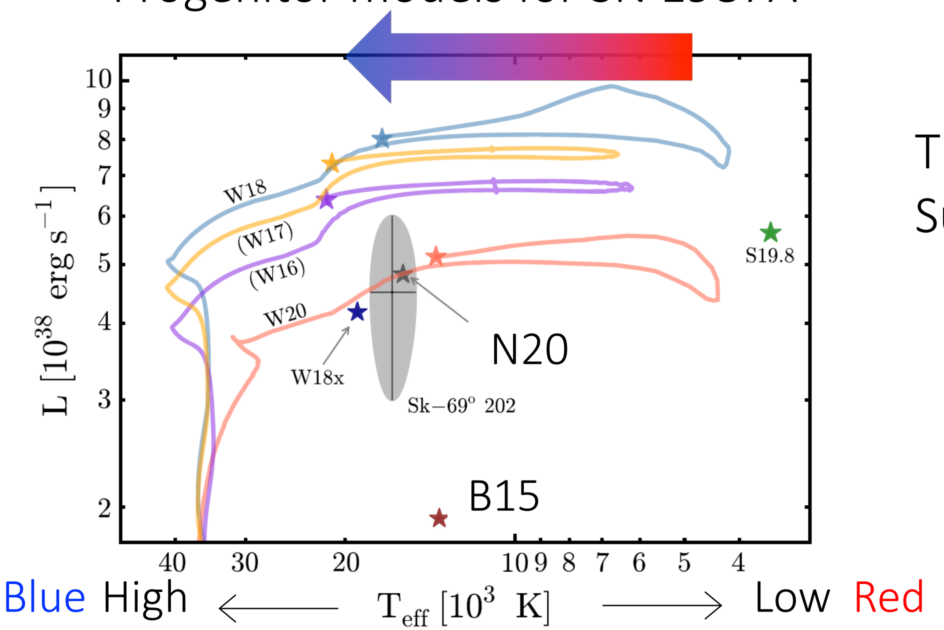
Properties of the progenitor of SN 1987A



- Observational features of Sk-69° 202 at LMC
  - Blue supergiant (BSG)
  - Triple ring structure
  - log ($L/L_\odot$) = 4.89 – 5.17 & $T_{\rm eff}$ = 15 – 18 kK [Woosley 1988]
  - log ($L/L_\odot$) = 4.90 – 5.11 & $T_{\rm eff}$ = 12 – 19 kK [Barkat & Wheeler 1989]
  - Red to Blue transition at least 2 x 10^4 yr ago [Crotts & Heathcote 1991]
  - Nebula abundance:
    He/H = 0.17 ± 0.06, N/C = 5 ± 2 [Lundqvist & Fransson 1996; Mattila et al. 2010]
    N/O = 1.1 ± 0.4 [Lundqvist & Fransson 1996]
    N/O = 1.5 ± 0.7 [Mattila et al. 2010]
- Preferable conditions for the progenitor star model [Arnett 1989, ARA&A, 27, 629]
  - helium core mass: 6 ± 1 $M_\odot$
  - Radius: (3 ± 1) x 10^{12} cm
  - Hydrogen envelope mass : about 10 $M_\odot$

Single star progenitor models for SN 1987A

- Progenitor models for SN 1987A



Hertzsuprung-Russel diagram

Red to blue transition

The figure and Table are taken from Sukhbold et al. 2016

N: Nomoto & Hashimoto 1988

W: Woosely et al. 1988

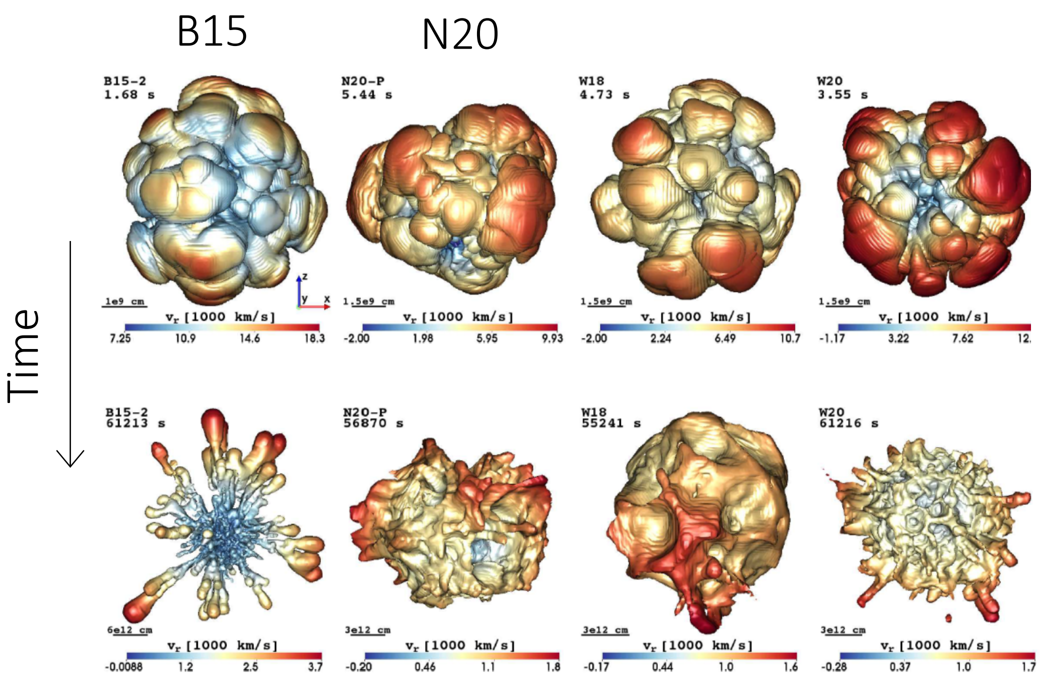
S: Sukhbold et al. 2016

Sukhbold et al. 2016

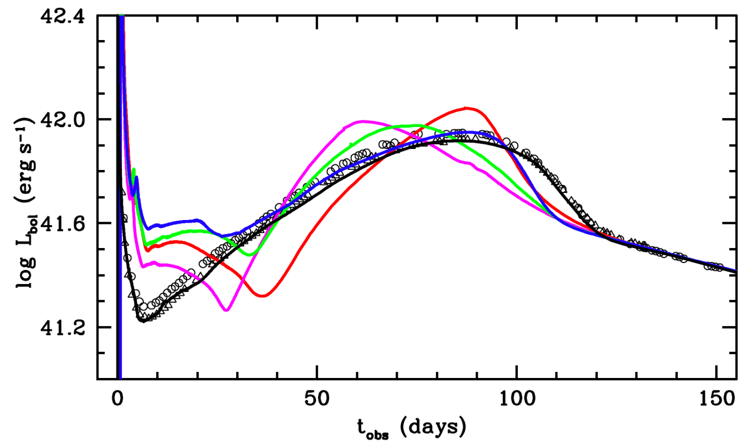
Table 1
SN 1987A Models

Model	$M_{\rm preSN}/M_\odot$	$M_{\rm He}/M_\odot$	$M_{\rm CO}/M_\odot$	$L/10^{38}$ erg s^{-1}	$T_{\rm eff}$	$\zeta_{2.5}$	$Z/Z_\odot$	Rotation
W18	16.93	7.39	3.06	8.04	18,000	0.10	1/3	Yes
N20	16.3	6	3.76	5.0	15,500	0.12	low	No
S19.8	15.85	6.09	4.49	5.65	3520	0.13	1	No
W15	15	4.15	2.02	2.0	15,300	…	1/4	No
W20	19.38	5.78	2.32	5.16	13,800	0.059	1/3	No
W16	15.37	6.55	2.57	6.35	21,700	0.11	1/3	Yes
W17	16.27	7.04	2.82	7.31	20,900	0.11	1/3	Yes
W18x	17.56	5.12	2.12	4.11	19,000	0.10	1/3	Yes
S18	14.82	5.39	3.87	4.83	3520	0.19	1	No

3D simulation of neutrino-driven explosions: progenitor dependences



Utrobin, Wangwathanarat, Janka and Mueller 2015



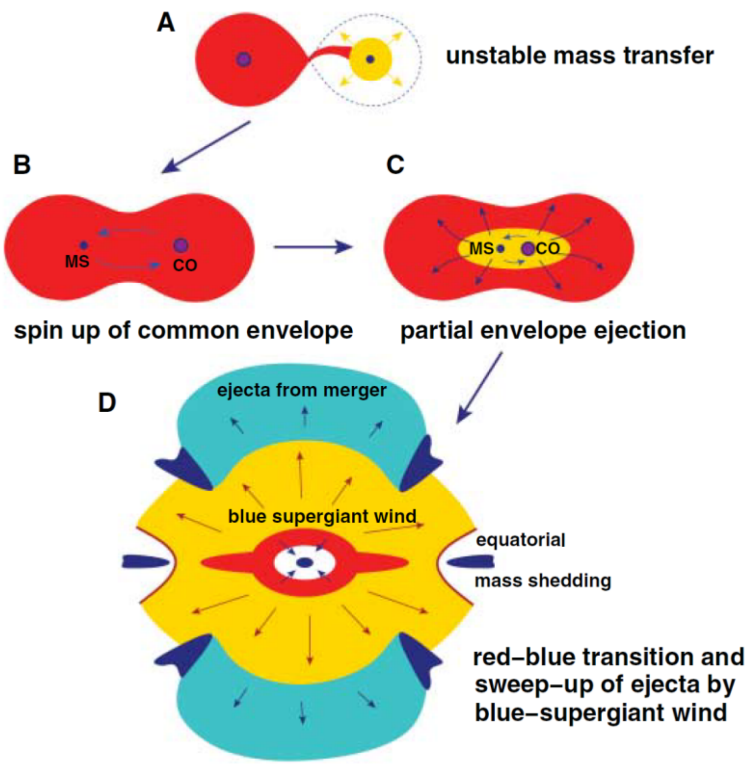
Model	$\langle v\rangle^{\rm bulk}_{\rm Ni}$	$v^{\rm bulk}_{\rm Ni}$ (km s^{-1})	$\langle v\rangle^{\rm tail}_{\rm Ni}$	$M_{\rm mix}$	$\delta M_{\rm H}$ ($M_\odot$)	$\langle X\rangle$
B15-1	921	3103	3241	11.45	0.111	0.040
B15-2	1222	3355	3490	11.20	0.172	0.062
B15-3	1807	4977	5678	12.31	0.329	0.118
N20-P	924	1635	1790	4.80	0.262	0.039
N20-C	930	1642	1797	4.79	0.375	0.052
W18	877	1395	1472	4.10	0.062	0.011
W20	783	1374	1482	5.32	0.083	0.012

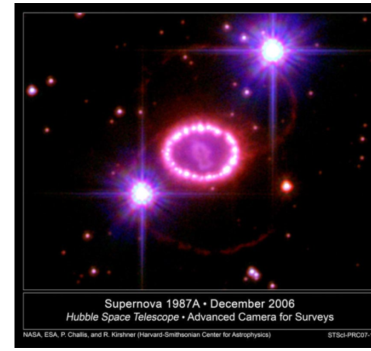
- B15-2 model seems to be good but...
  - He core mass (4.05 $M_\odot$) is quite different from the required value, 6 $M_\odot$
  - The synthesized the light curve

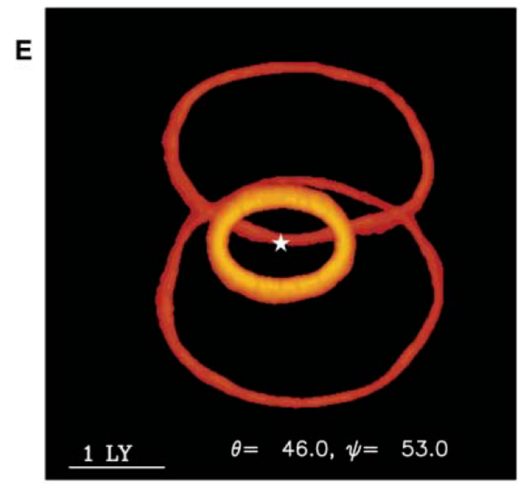
The progenitor of SN1987A was the outcome of a binary merger?

- 3D smoothed particle hydrodynamic (SPH) simulation

~ 15 $M_\odot$ RSG ~ 5 $M_\odot$ MS star





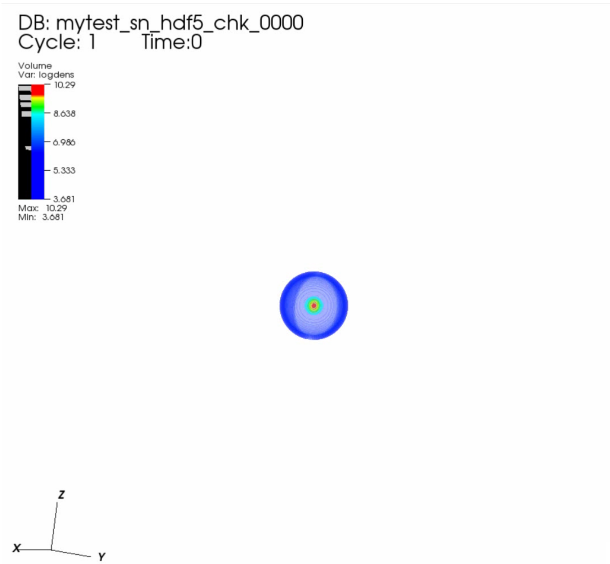


Morris & Podsiadlowsky 2007, Science, 315, 1103

3D hydrodynamic simulations of SN phases

3D simulation from Supernovae to Supernova remnants

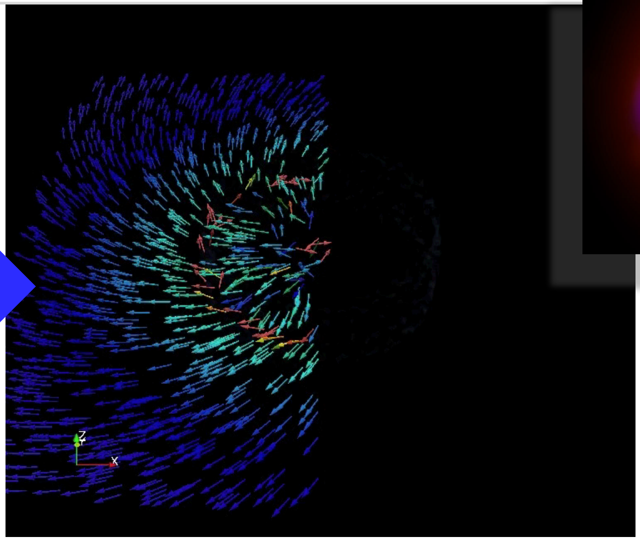
3D simulation of SNe

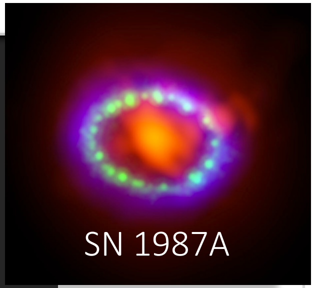


Aspherical explosion
Nucleosynthesis

1 sec,1000 km

3D MHD simulation of SNRs





X-ray light curve, X-ray Image,
Non-thermal emission

10 – 100 yr, 10^{12} – 10^{13} km

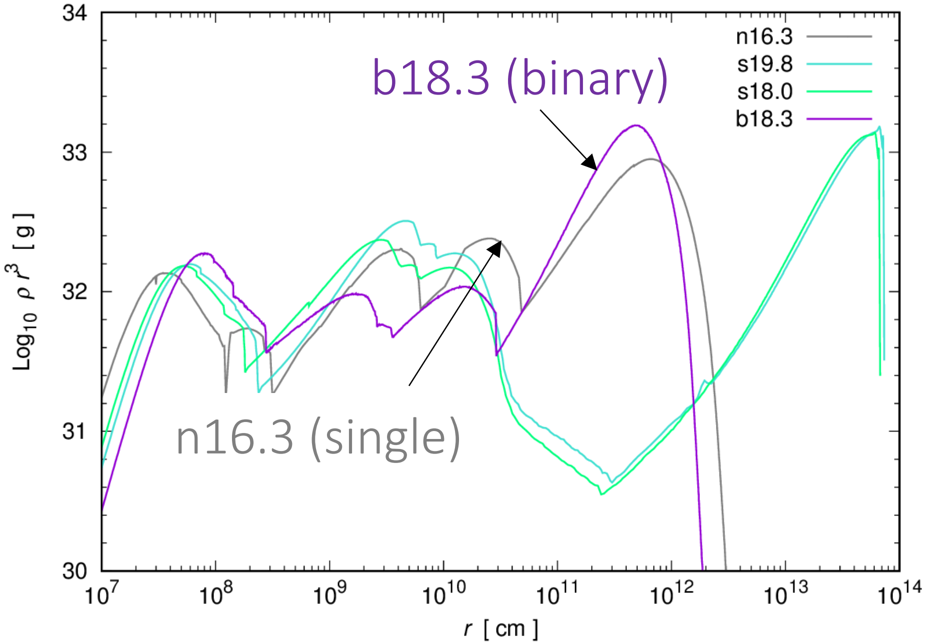
PRACE project: Awarded and we got 6x10^7 CPU hours at a cluster of CINECA

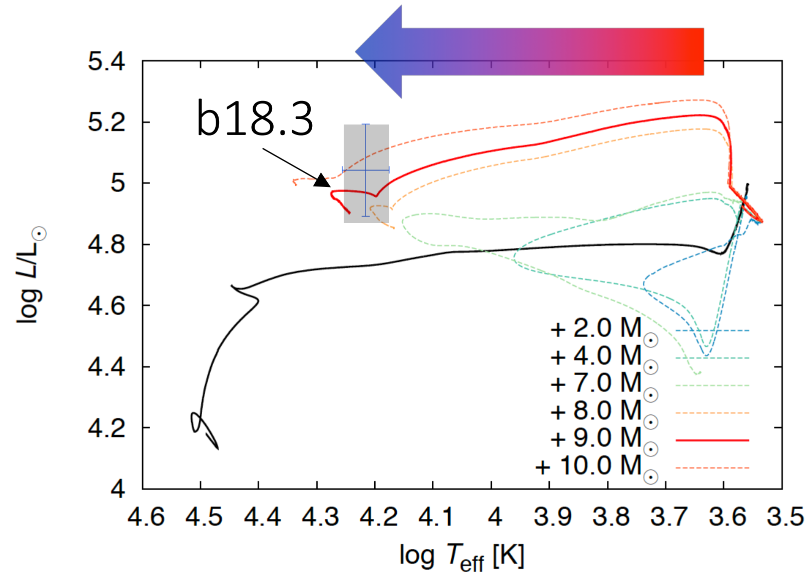
Masaomi Ono (ABBL, RIKEN, Japan)
Shigehiro Nagataki (ABBL, RIKEN, Japan)
Gilles Ferrand (ABBL, RIKEN, Japan)
Annop Wongwathanarat (ABBL, RIKEN, Japan)
Shiu-Hang Lee (Kyoto Univ., Japan)
Ko Nakamura (Fukuoka Univ., Japan)
Tomoya Takiwaki (NAOJ, Japan)

Salvatore Orlando (INAF – *, Italy)
Marco Miceli (**, Italy)
Oleh Petruk (INAF – *, Italy)
Giovanni Peres (**, Italy)

* Osservatorio Astronomico di Palermo
** Universita` di Palermo

Density structures of two progenitor models used





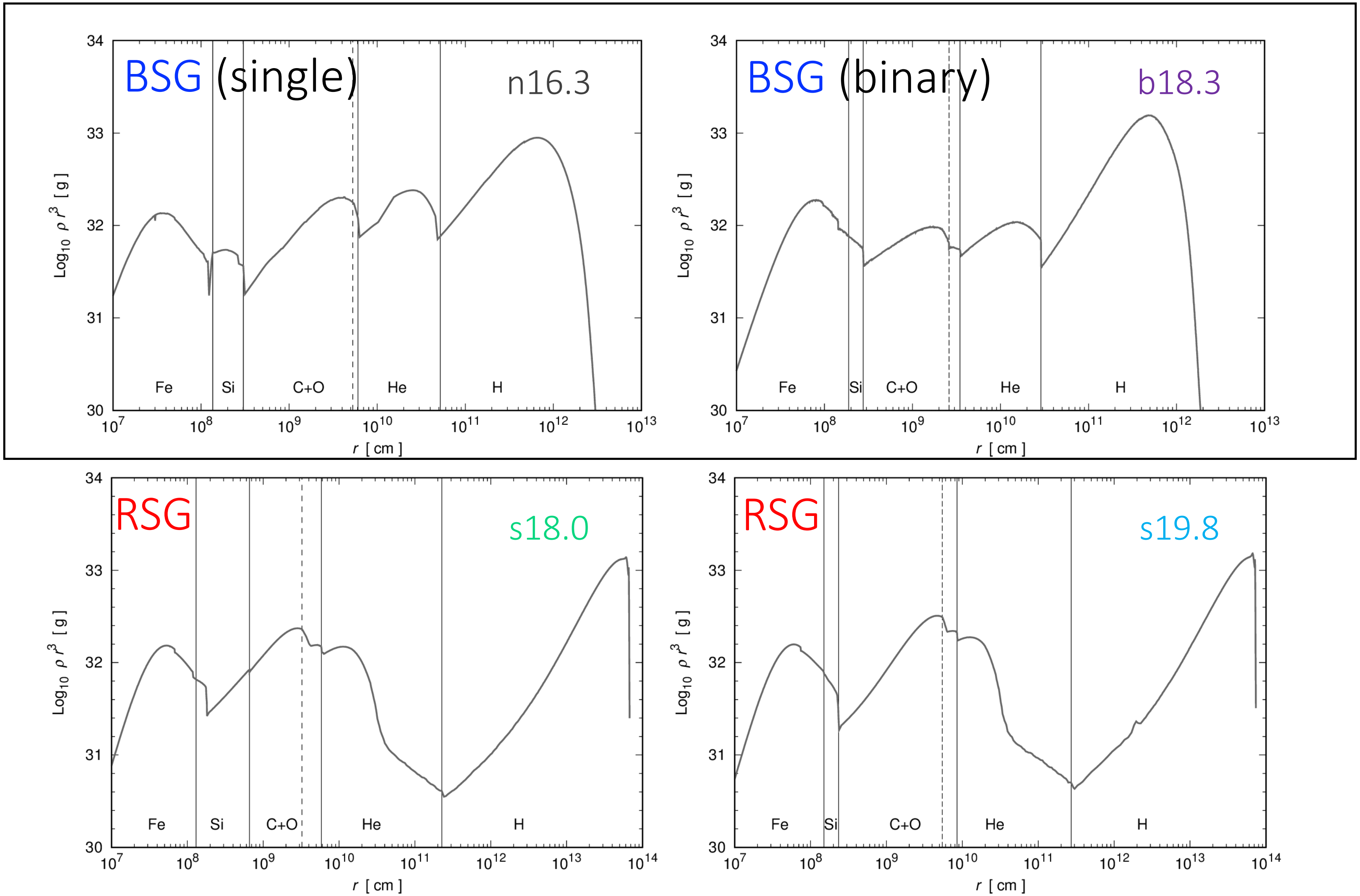
Slow binary merger scenario model

From the self-similar solution in the power law density medium

Urushibata, T., Takahashi, K., Umeda, H., & Yoshida, T. 2017, MNRAS, 473, L101

$\rho(r) \propto r^{-\omega}$ $\quad v_{\rm sh} \propto t^{(\omega-3)/(5-\omega)}$ If $\omega < 3$ shock is decelerated

Progenitor structures ($\rho\, r^3$ profiles)



Initial setup: radial velocity distribution

Parameters

β $= v_{\mathrm{pol}}/v_{\mathrm{eq}}$

α $= v_{\mathrm{up}}/v_{\mathrm{down}}$

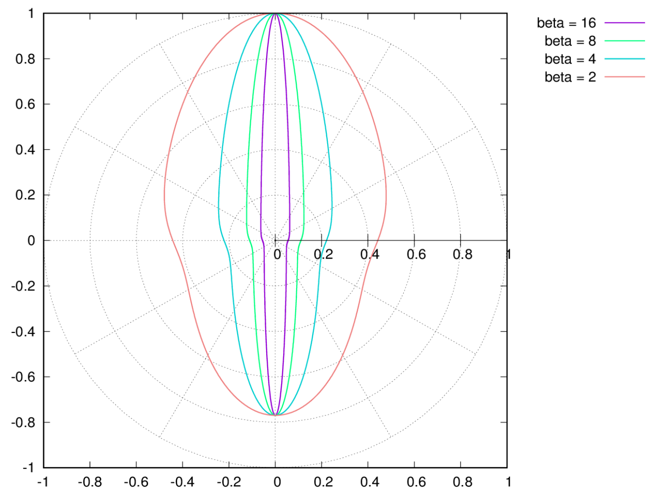
E_{in}: Injected energy

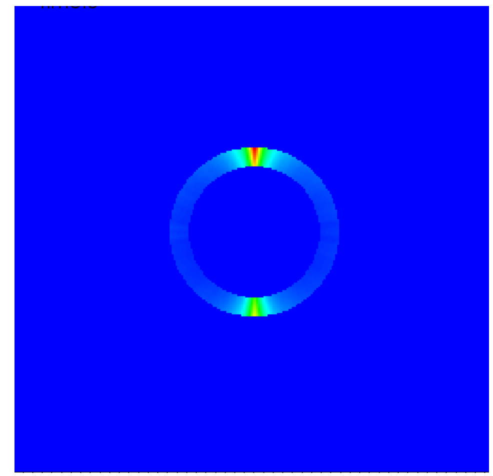
Ranges:

E_{in} = (1.5 – 3.0) x 10^{51} erg

β = 1.0 – 16.0

α = (1.1 – 1.5)





$$v_r \propto r \left(\beta^{-1}\cos^2\theta + \beta\sin^2\theta\right)^{-1/2}$$

$$1 + \epsilon N \sum_{n}^{4} \sum_{m} \frac{A_m^l(\theta,\phi)}{2^{n-1}} \qquad (l = n \cdot l_{\mathrm{base}})$$

$$\epsilon = 0.3,\ l_{\mathrm{base}} = 15$$

$$N : \text{Normalization factor}$$

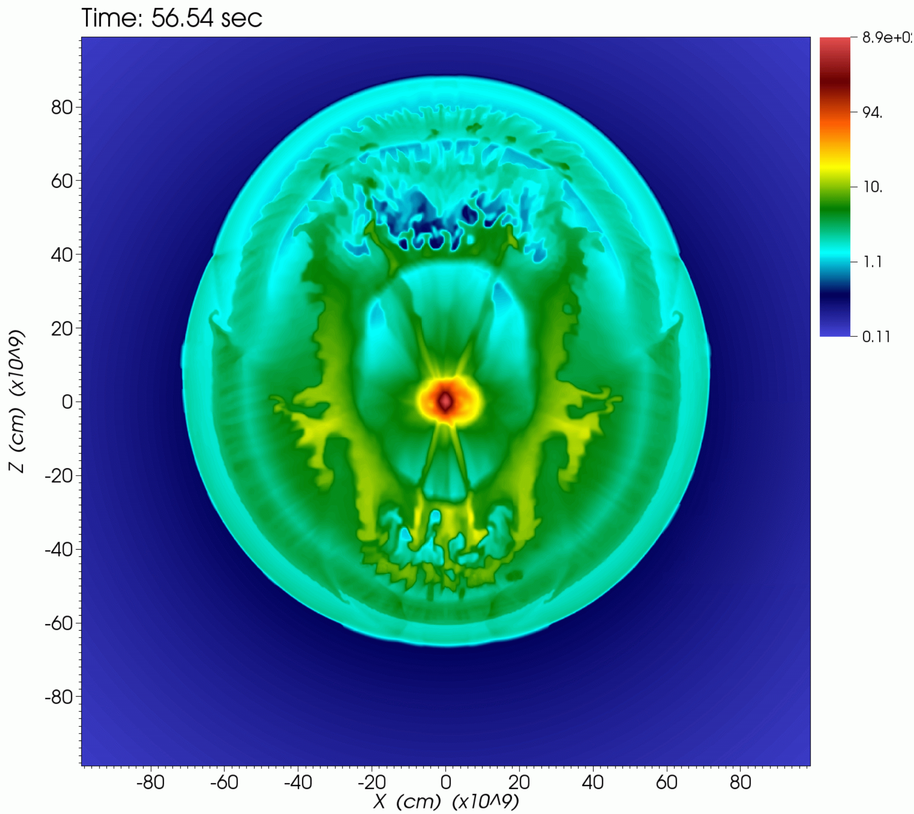
$$A_m^l(\theta,\phi) = \begin{cases} \begin{cases} Y_m^l(\theta,\phi) & (m = 1, -3, 5, -7, ..) \\ 0 & (\text{else}) \end{cases} & (l : \text{odd}) \\ \begin{cases} Y_m^l(\theta,\phi) & (m = 0, 2, -4, 6, ..) \\ 0 & (\text{else}) \end{cases} & (l : \text{even}) \end{cases}$$

$$Y_m^l(\theta,\phi) = \begin{cases} \sqrt{2}\sqrt{\frac{2l+1}{4\pi}\frac{(l-|m|)!}{(l+|m|)!}} P_m^l(\cos\theta)\sin(|m|\phi) & (m < 0) \\ \sqrt{\frac{2l+1}{4\pi}} P_m^l(\cos\theta) & (m = 0) \\ \sqrt{2}\sqrt{\frac{2l+1}{4\pi}\frac{(l-|m|)!}{(l+|m|)!}} P_m^l(\cos\theta)\cos(m\phi) & (m > 0) \end{cases}$$

Time evolution of 2D slices of density : binary merger model vs single star model

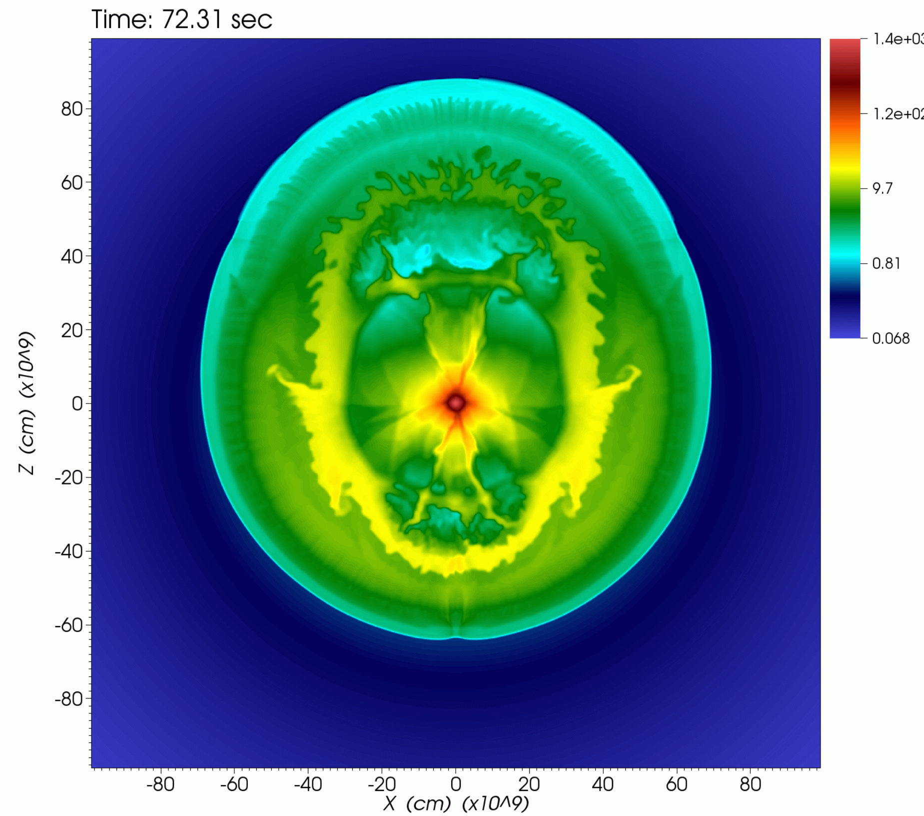
MO et al. 2019a, in prep.

b18.3



Binary merger

n16.3

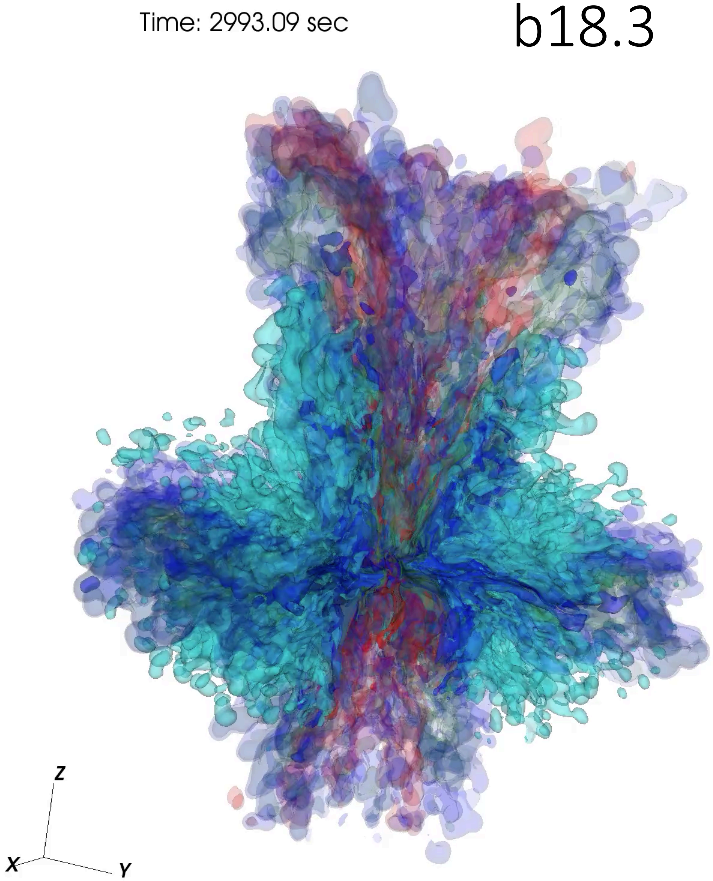


Single star

b18.3 vs n16.3: distribution of elements

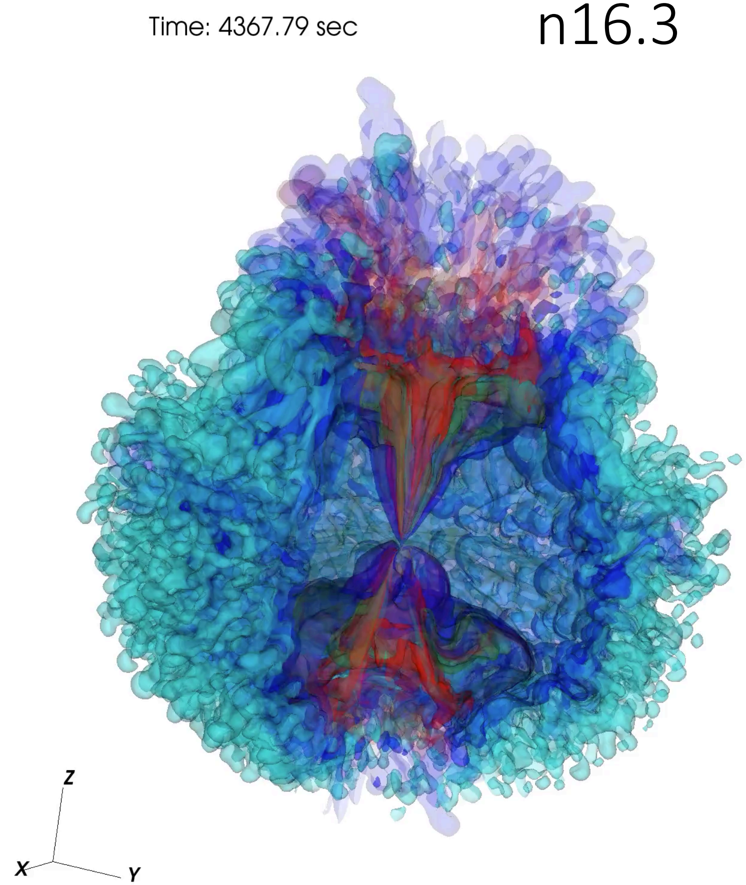
MO et al. 2019a, in prep.

b18.3



Binary merger

n16.3

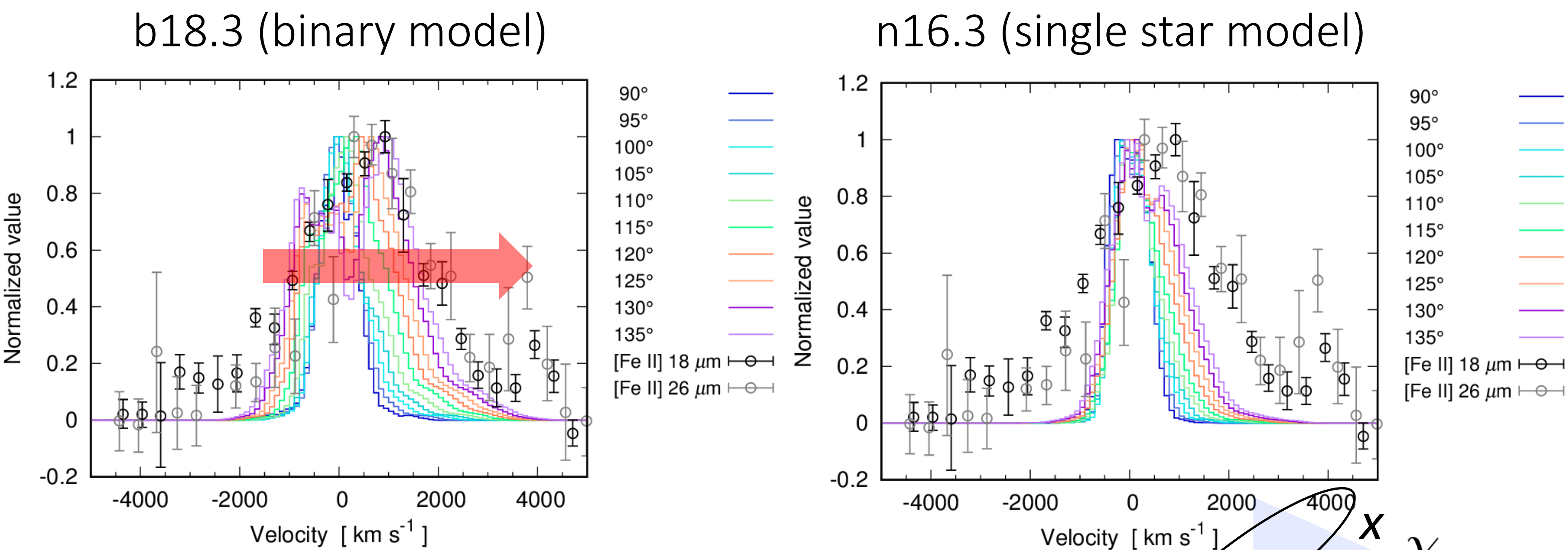


Single star

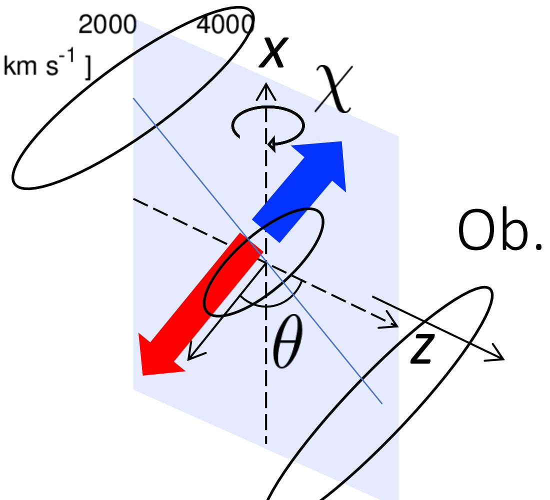
^{56}Ni (Red) ^{28}Si (Green) ^{16}O (Blue) ^{4}He (Sky blue)

Line of sight (LoS) velocity distributions of ^{56}Ni

MO et al. 2019a, in prep.

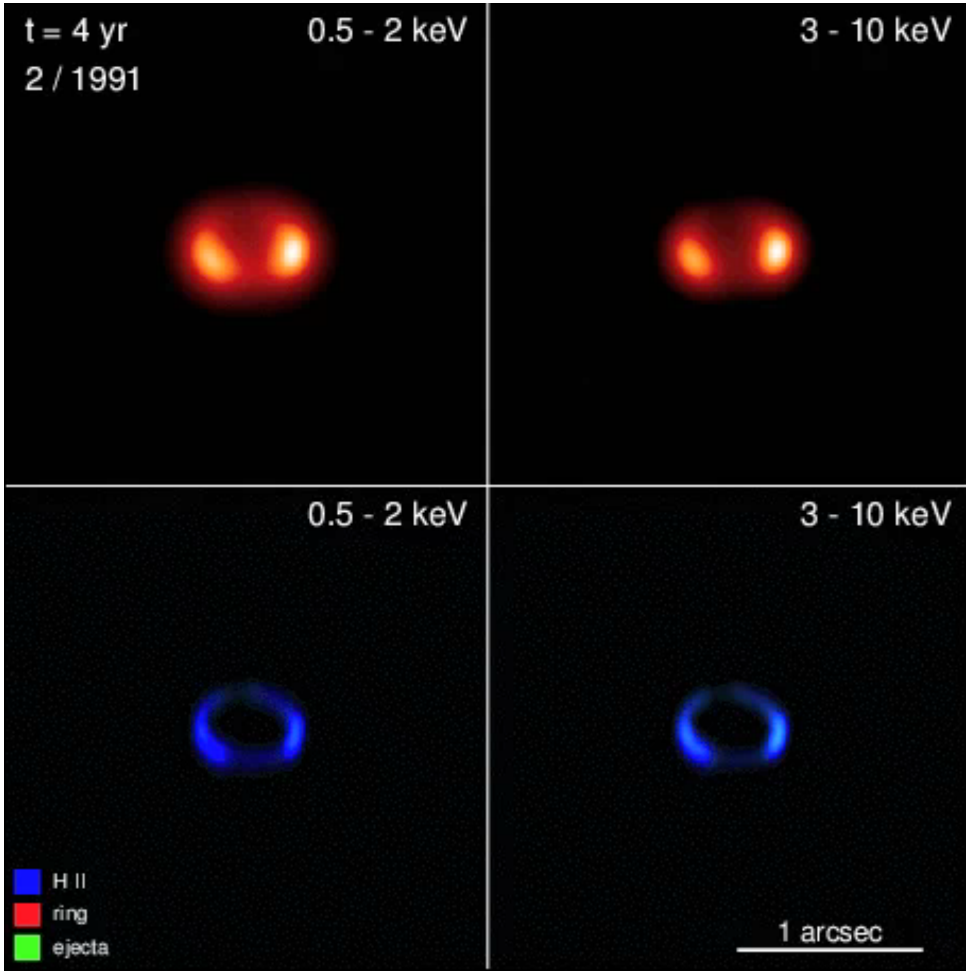


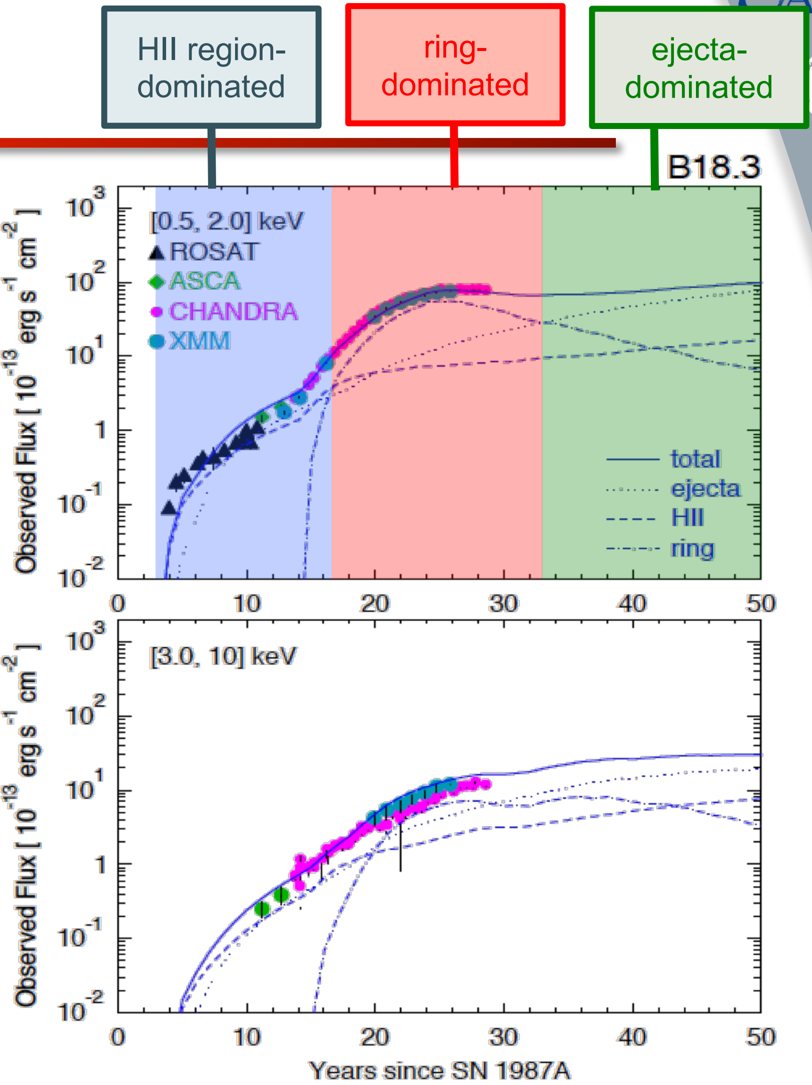
- The best model:
  - Progenitor model: b18.3 (binary merger model)
  - (E_{in}, α, β) = (2.5 x 10^{51} erg, 1.5, 16.0)
  - θ = 130°, χ = 10°



3D simulation of SNR phases

X-ray Lightcurves



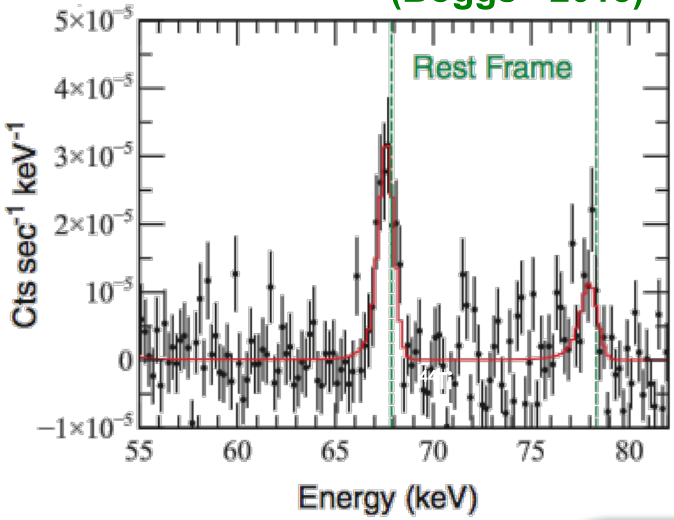


Orlando, MO et al. 2019, in prep.

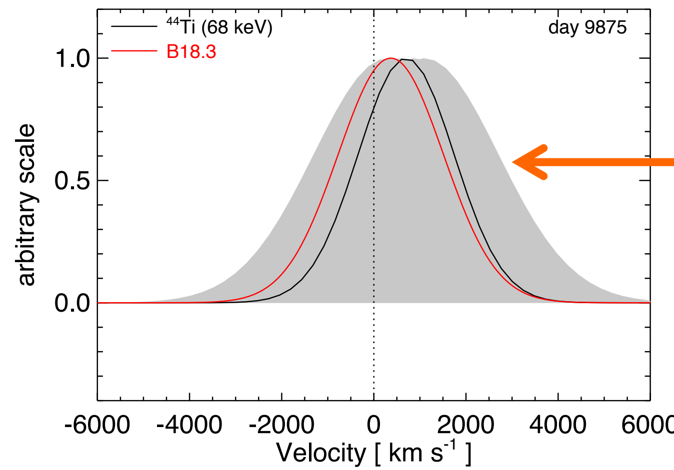
Abundances from Zhekov+ (2009)
ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)
Distance: 51.4 kpc (Panagia 1999)

Distribution of ^{44}Ti in the evolved SNR

(Boggs+ 2015)

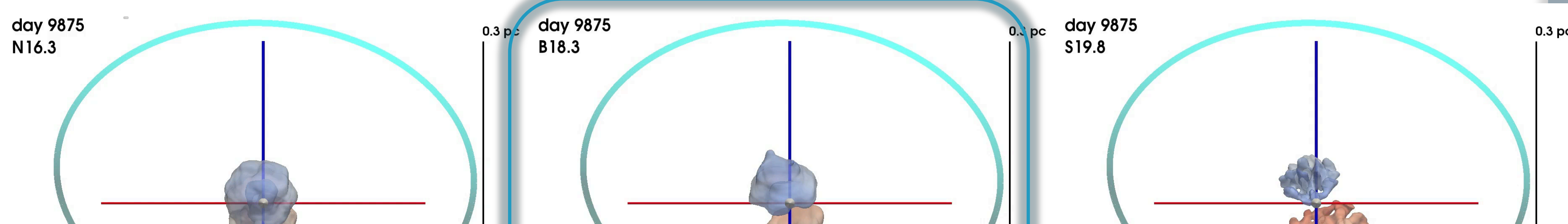


(Orlando+ 2019)



Orlando, MO et al. 2019, in prep.

90% confidence area for the position of the peak and for the width of the Gaussian



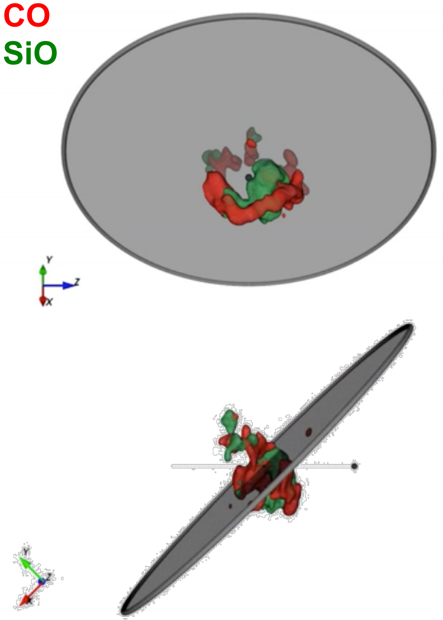
BSG

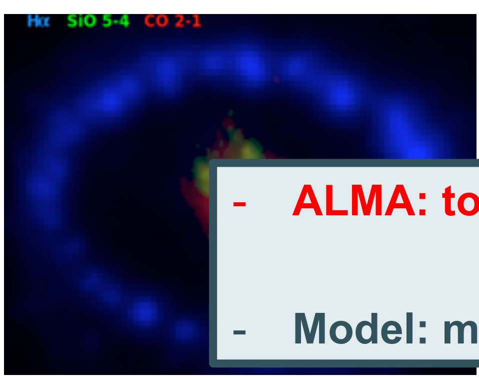
- **NuSTAR: ^{44}Ti lines redshifted with Doppler velocity ~ 700 ± 400 km/s (Boggs+ 2015)**
- **Model: Velocity along the LoS of ^{44}Ti ~ 400 km/s away from the observer**

Molecular structure in the evolved SNR

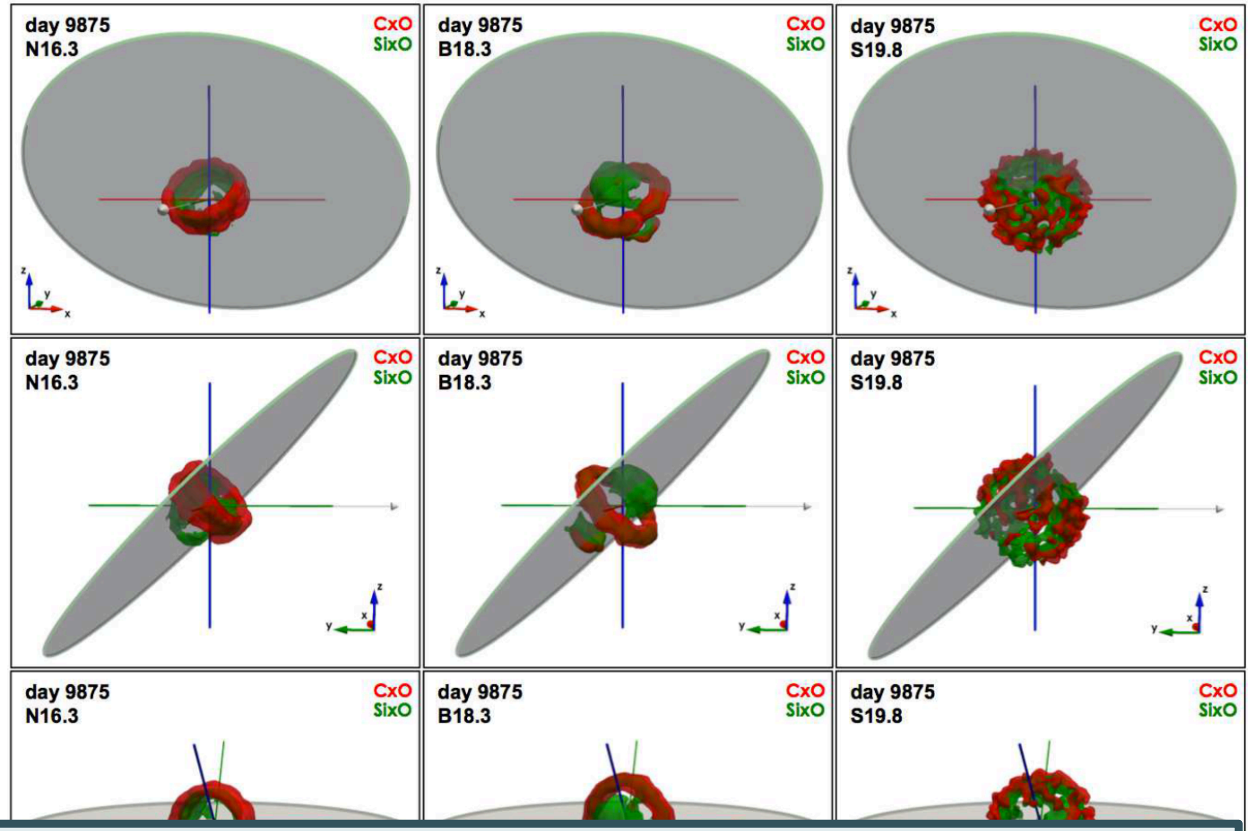
(Abellan+ 2017)

CO
SiO





BSG | BSG (merging) | RSG



- **ALMA: torus-like structure evident in SiO and CO**
  (Abellan+ 2017)
- **Model: modeled torus-like feature with similar orientation and size**
  (Orlando+ 2019)

Orlando, MO et al. 2019, in prep.

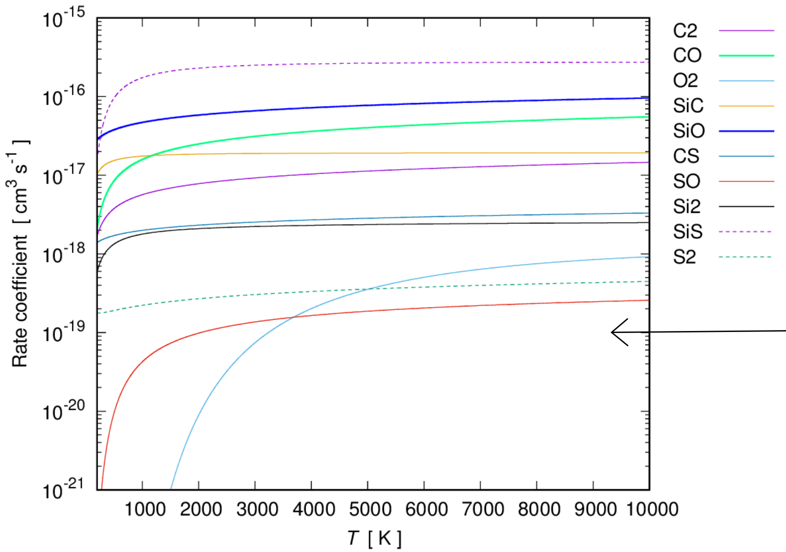
Molecule formation calculations

Molecule formation and destruction

Atoms: He, C, O, Ne, Mg, Si, S, Ar

Molecules: C_2, CO, O_2, SiC, SiO, CS, SO, Si_2, S_2

Formation rate coefficients



$$\frac{dc_i}{dt} = F_i - D_i$$

Formation

$k_i(T) c_k c_l$

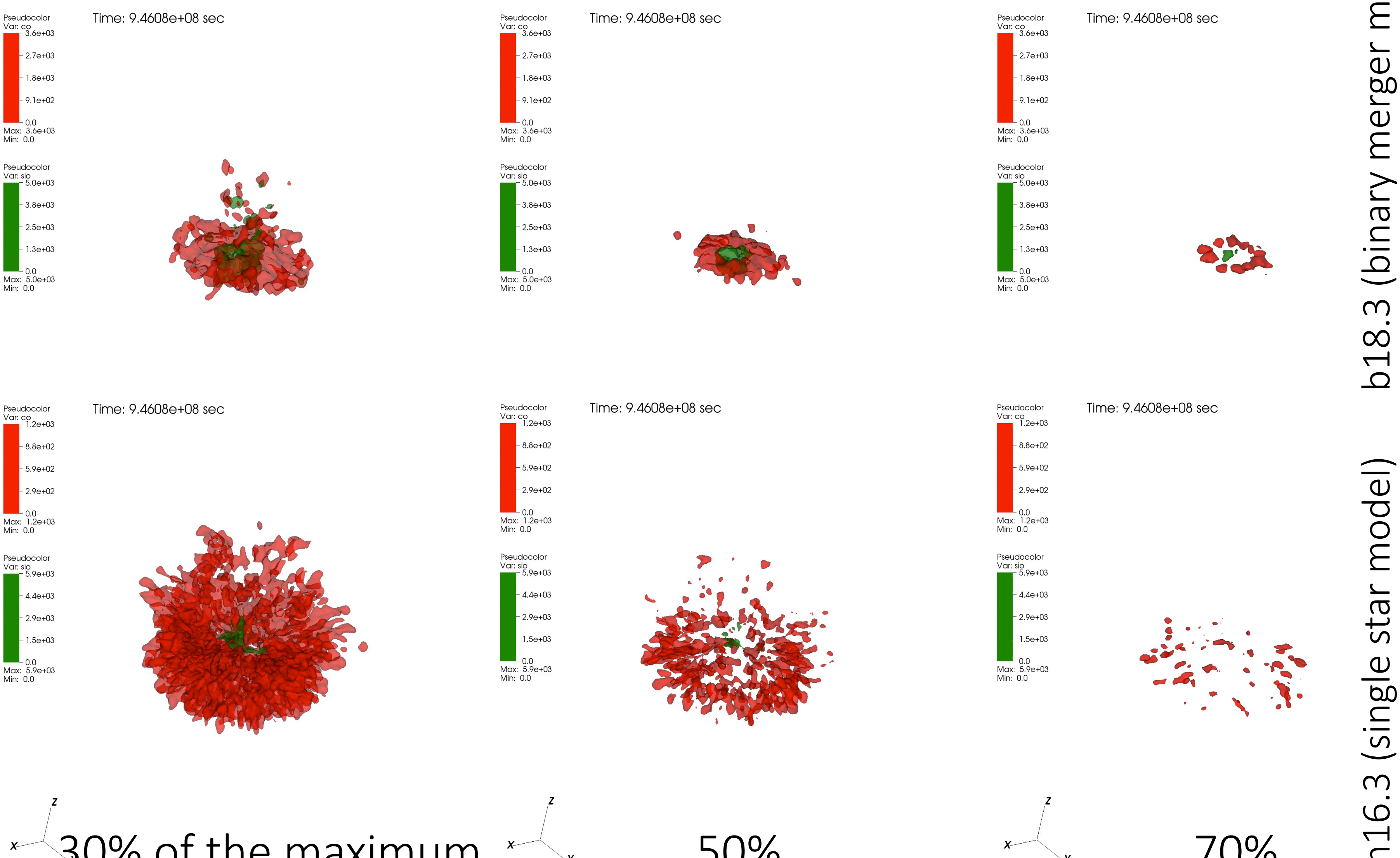
Destruction by the collision of particles

C_i: number density of *i* th molecules

Part of formulations are removed

MO et al. 2019b, in prep.

Number density of CO & SiO: γ = 5/3



MO et al. 2019b, in prep.

Calculated total masses of molecules

Assumed temperature evolution
γ: adiabatic index

$$T(t) = T_0 \left(\frac{t}{t_0}\right)^{-3(\gamma-1)}$$

	Binary merger			Single star		
	b18.3			n16.3		
Molecular species	Total mass $[M_\odot]$			Total mass $[M_\odot]$		
	$\gamma = 1.25$	$\gamma = 1.50$	$\gamma = 1.67$	$\gamma = 1.25$	$\gamma = 1.50$	$\gamma = 1.67$
C_2	3.38×10^{-4}	2.20×10^{-3}	4.07×10^{-3}	1.12×10^{-4}	2.40×10^{-3}	5.23×10^{-3}
CO	3.45×10^{-2}	2.80×10^{-1}	2.85×10^{-1}	4.49×10^{-2}	1.91×10^{-1}	1.96×10^{-1}
O_2	2.26×10^{-5}	3.25×10^{-4}	9.47×10^{-4}	2.73×10^{-4}	1.40×10^{-2}	3.74×10^{-2}
SiC	5.72×10^{-4}	1.15×10^{-3}	2.44×10^{-3}	4.87×10^{-5}	4.43×10^{-5}	8.91×10^{-5}
SiO	3.52×10^{-2}	2.85×10^{-1}	2.92×10^{-1}	3.46×10^{-2}	1.11×10^{-1}	1.12×10^{-1}
CS	7.17×10^{-5}	1.84×10^{-4}	1.32×10^{-4}	3.58×10^{-6}	4.70×10^{-6}	3.79×10^{-6}
SO	6.68×10^{-6}	7.72×10^{-4}	3.30×10^{-3}	4.64×10^{-6}	7.77×10^{-4}	2.71×10^{-3}
Si_2	1.81×10^{-5}	8.98×10^{-6}	4.81×10^{-5}	3.86×10^{-6}	6.95×10^{-6}	3.08×10^{-5}
SiS	7.67×10^{-3}	2.12×10^{-2}	1.11×10^{-2}	3.15×10^{-3}	7.01×10^{-3}	5.84×10^{-3}
S_2	5.85×10^{-7}	2.43×10^{-4}	1.33×10^{-3}	4.55×10^{-7}	1.06×10^{-4}	4.69×10^{-4}

- SiC molecules are produced much in b18.3 model with the aid of mixing
- Observations (Matsuura+17), CO (1.0 - 0.02 $M_\odot$) and SiO (2x10^{-3} – 4 x 10^{-5} $M_\odot$), suggest majority of SiO has gone to dust ?

Summary and future work

- 3D hydrodynamical/MHD simulation of SN 1987A from the explosion to an early phase of the supernova remnant
  - Outcomes sensitively depend on the density structure of the progenitor models
  - Line emissions, such as [Fe II] could be a good indicator to estimate the explosion morphology
- Molecule formation calculation
  - Distribution of CO and SiO looks like the recent observation of 3D distribution (perpendicular to ER)

Future work

- Molecule formation calculation based on realistic density and temperature histories
- Dust formation/destruction calculation