4M-COCOS @ Fukuoka University
21 October, 2019

Three-dimensional simulations from supernovae to their supernova remnants: nucleosynthesis and molecule formation in the supernova ejecta of SN 1987A

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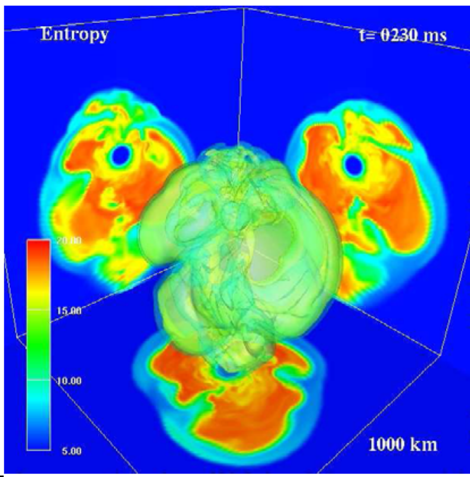
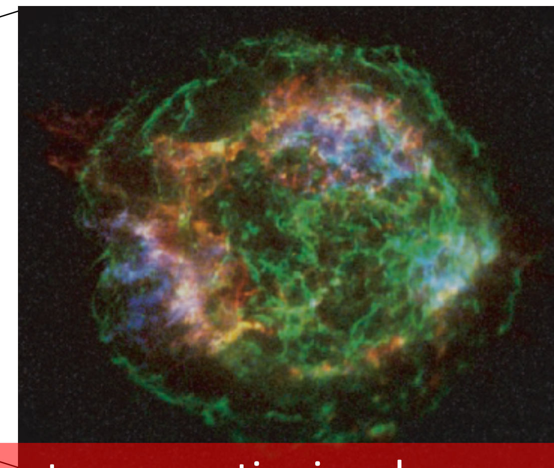
Supernova explosions to their supernova remnants (SNRs)

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

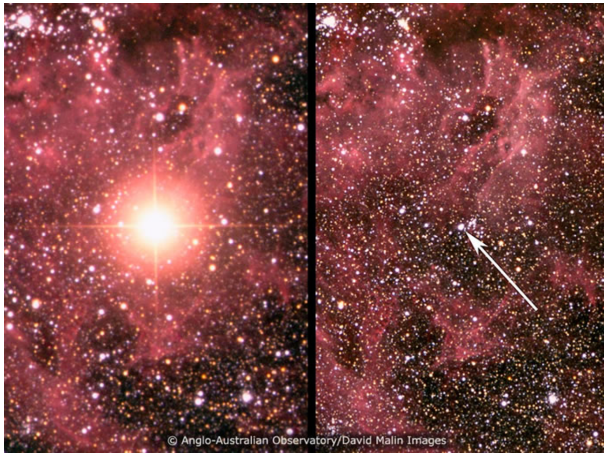
Formation of molecules and dust?

Asymmetric distribution of elements

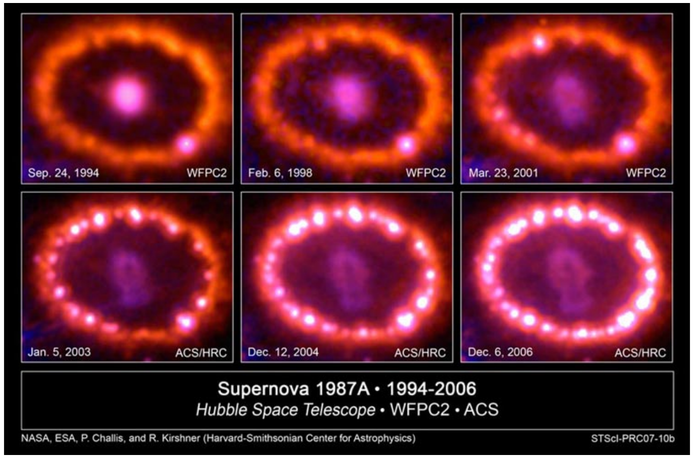
Chemical evolution (Nucleosynthesis/Molecule formation/dust formation) during the progenitor–SNe–SNRs sequence

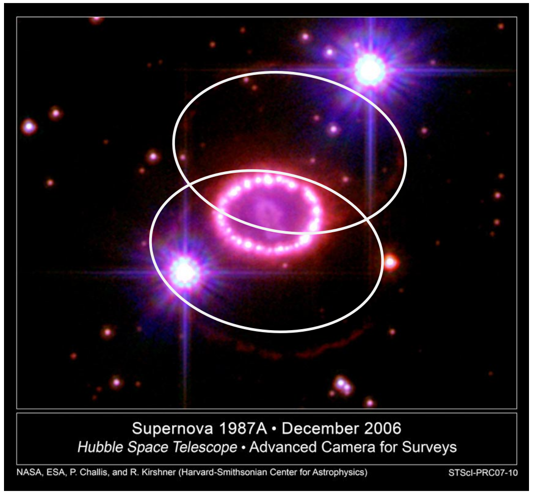
SN 1987A

Supernova 1987A (SN 1987A)

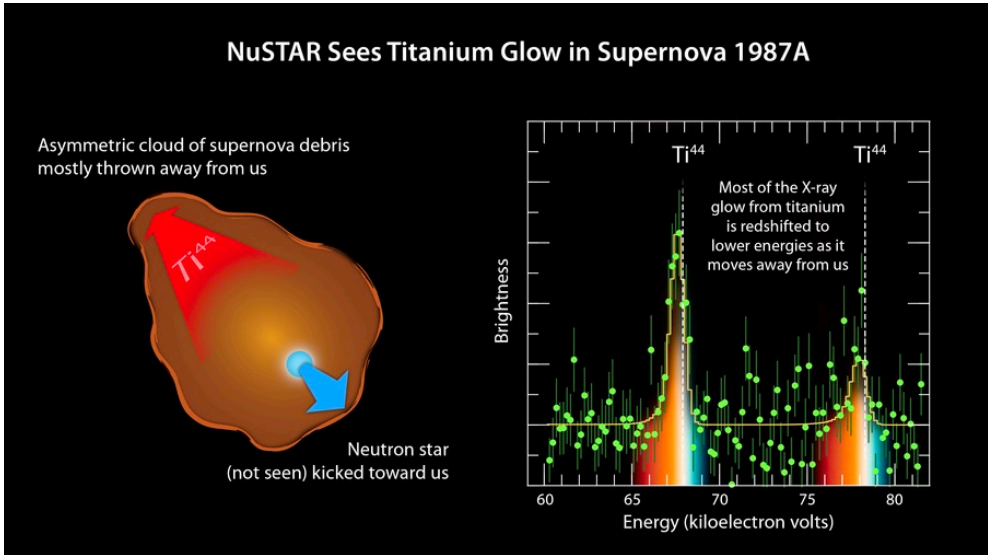


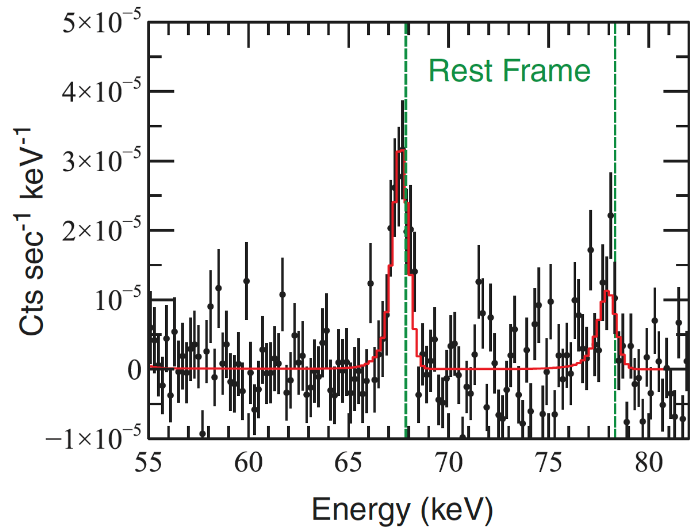
- Basic observational features of SN 1987A
  - SN @ LMC on 23 Feb., 1987
  - Neutrinos from the SN were detected by Kamiokande
  - Triple-ring nebula





^{44}Ti gamma-ray emission lines from SN 1987A 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

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

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

- 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

Evolution of X-ray images and light curves of SN 1987A

Frank et al. 2016, ApJ, 829, 40

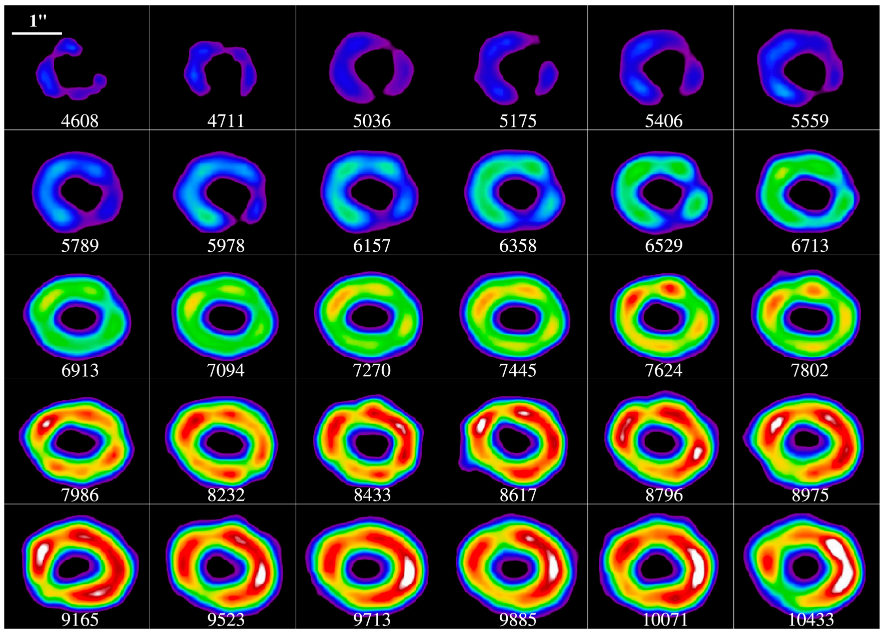
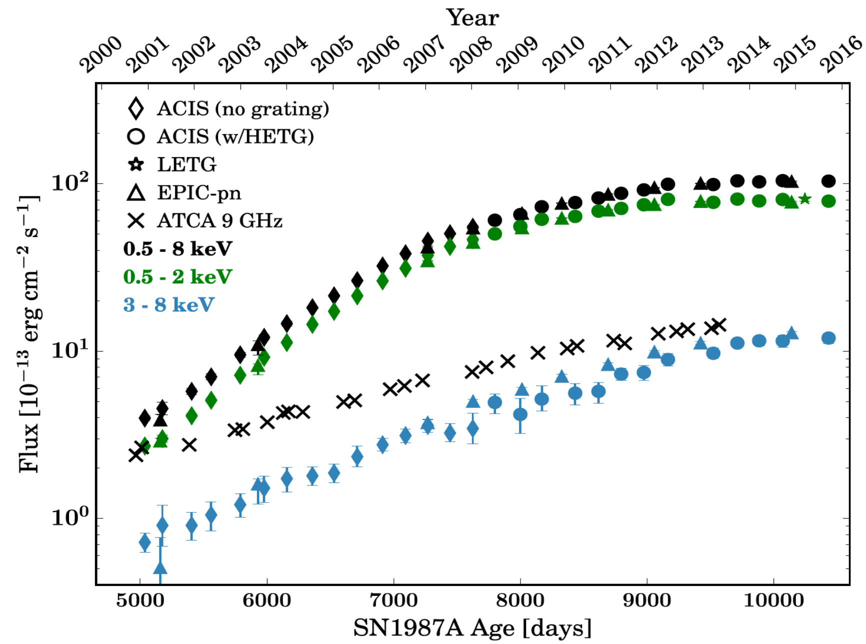


Figure 5. Deconvolved, smoothed 0.3–8.0 keV false-color images of SN 1987A covering days 4608–10433. Images use a square root scale and are normalized by flux. The age, in days since the supernova, is shown below each image. North is up and east is to the left.

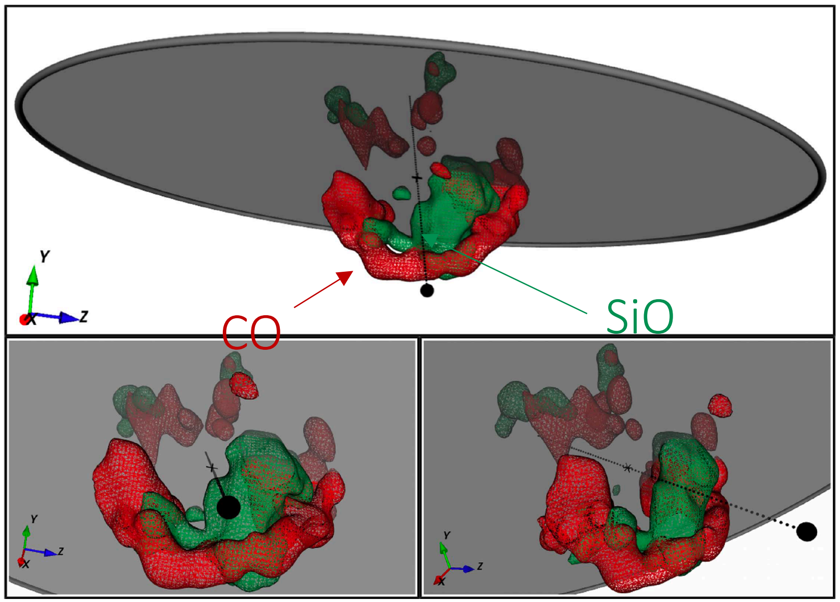


- X-ray emission first appeared on the eastern side of ER
- The eastern side began to fade (7000 days)
- E/W X-ray emission reversed during 7000 – 8000 days

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



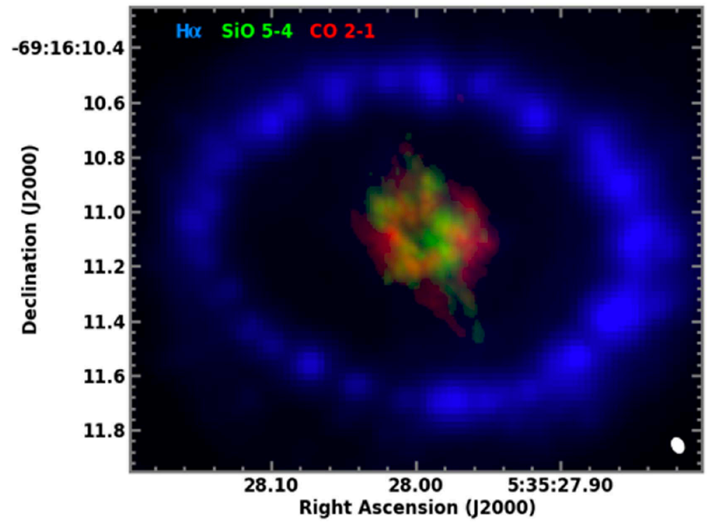


Figure 1. Molecular emission and Hα emission from SN 1987A. The more compact emission in the center of the image corresponds to the peak intensity maps of CO 2–1 (red) and SiO 5–4 (green) observed with ALMA. The surrounding Hα emission (blue) observed with *HST* shows the location of the circumstellar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

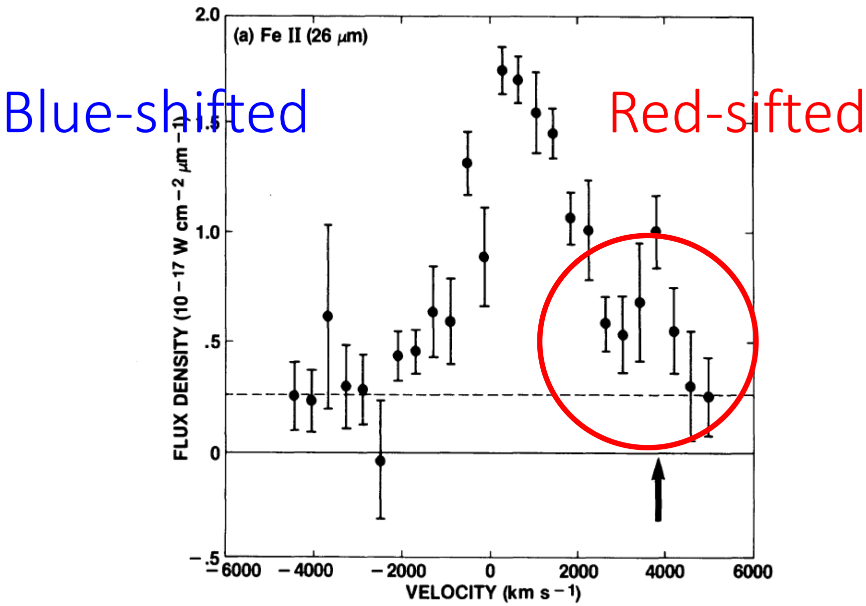
(An animation of this figure is available.)

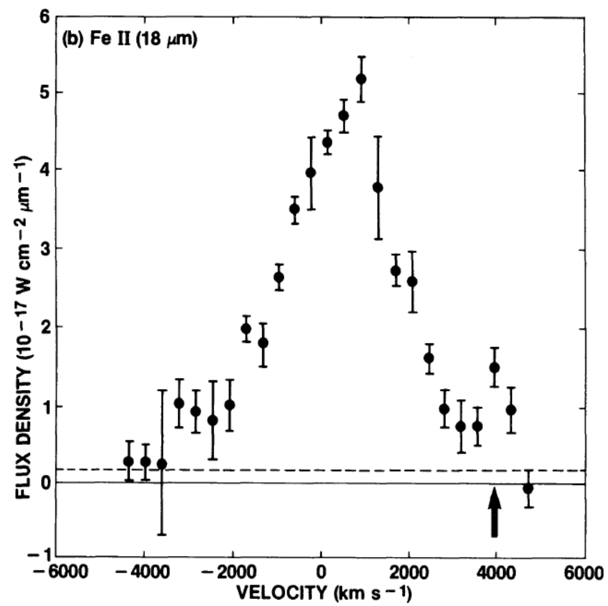
SN 1987A and matter mixing

SN 1987A: High velocity Fe : matter mixing?

[Fe II] line profiles

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





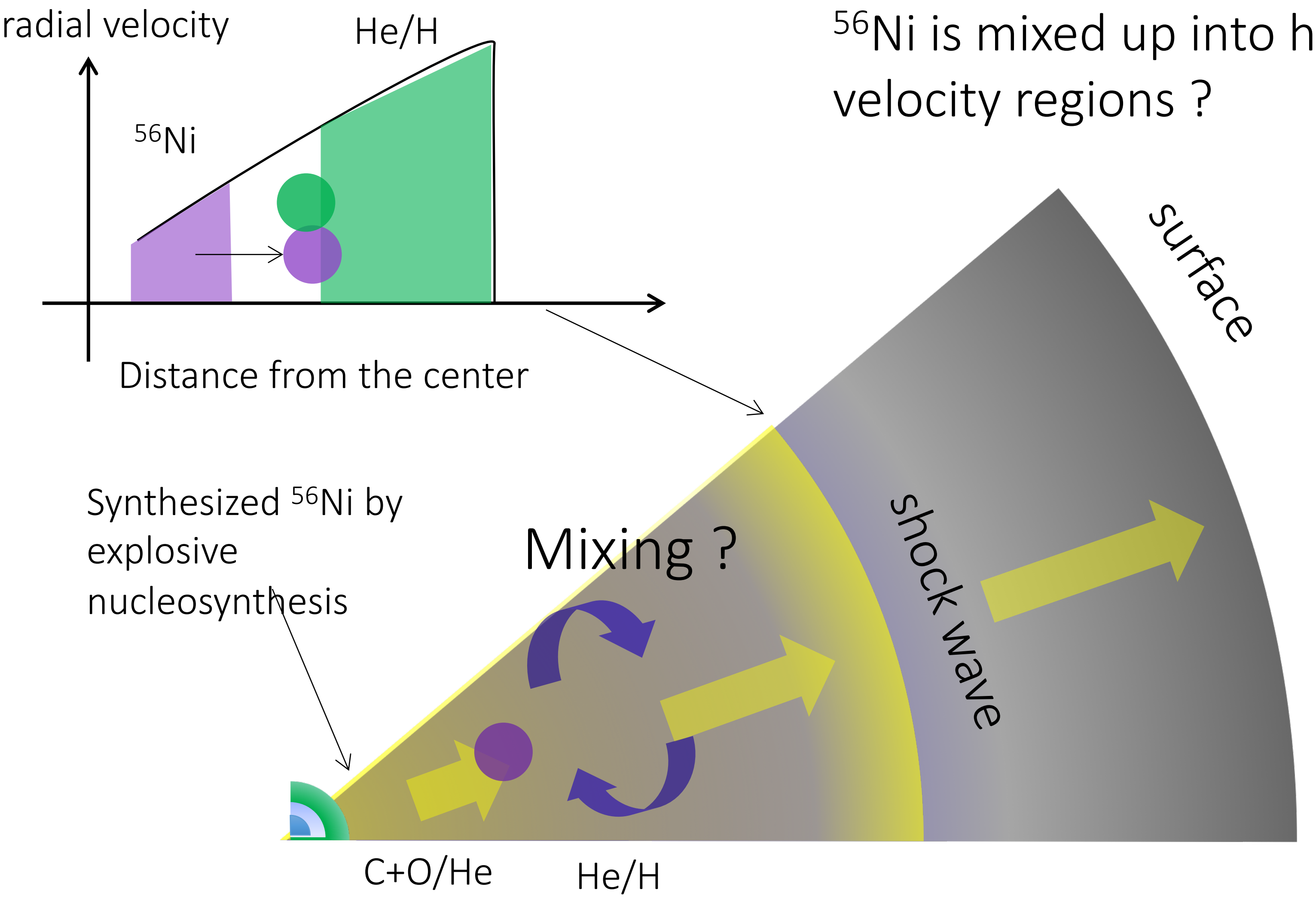
- High velocity tails of [Fe II] line profiles reach (> 4,000 km/s)

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

  Red-shifted side is dominated ー＞ Asymmetric explosion?

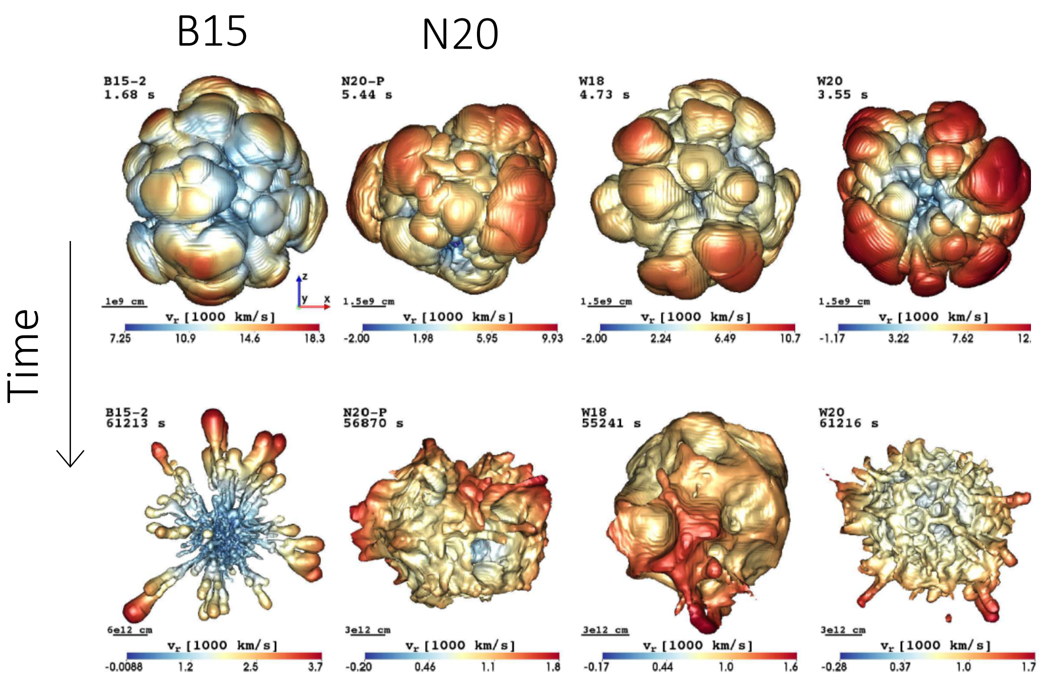
Matter mixing in supernova explosions

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

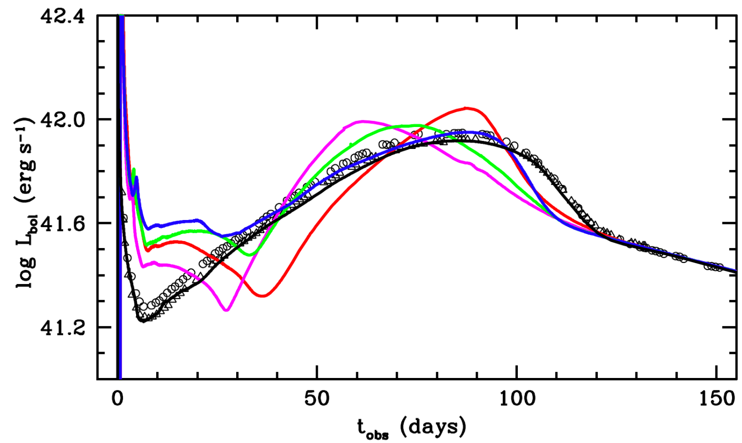


What is the progenitor of SN 1987A?

3D simulation of neutrino-driven explosions: progenitor dependences



Utrobin, Wangwathanarat, Janka and Mueller 2015

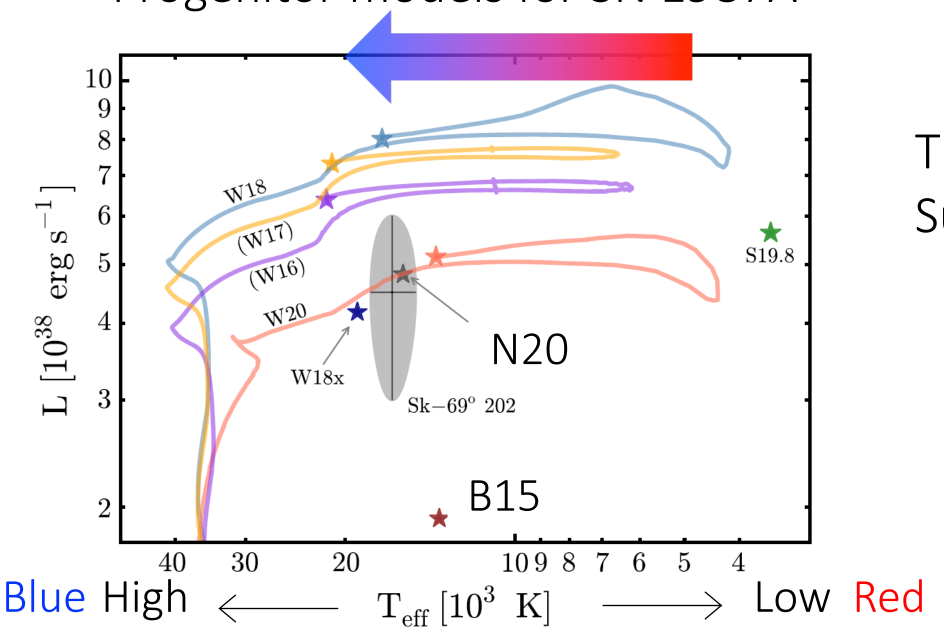


Model	$\langle v\rangle_{\rm Ni}^{\rm bulk}$	$v_{\rm Ni}^{\rm bulk}$ (km s^{-1})	$\langle v\rangle_{\rm Ni}^{\rm tail}$	$M_{\rm mix}$	$\delta M_{\rm H}$ ($M_\odot$)	$\langle X\rangle$
B15-1	921	3103	3241	11.45	0.111	0.040
B15-2	1222	3355	3490	11.20	0.172	0.062
B15-3	1807	4977	5678	12.31	0.329	0.118
N20-P	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

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

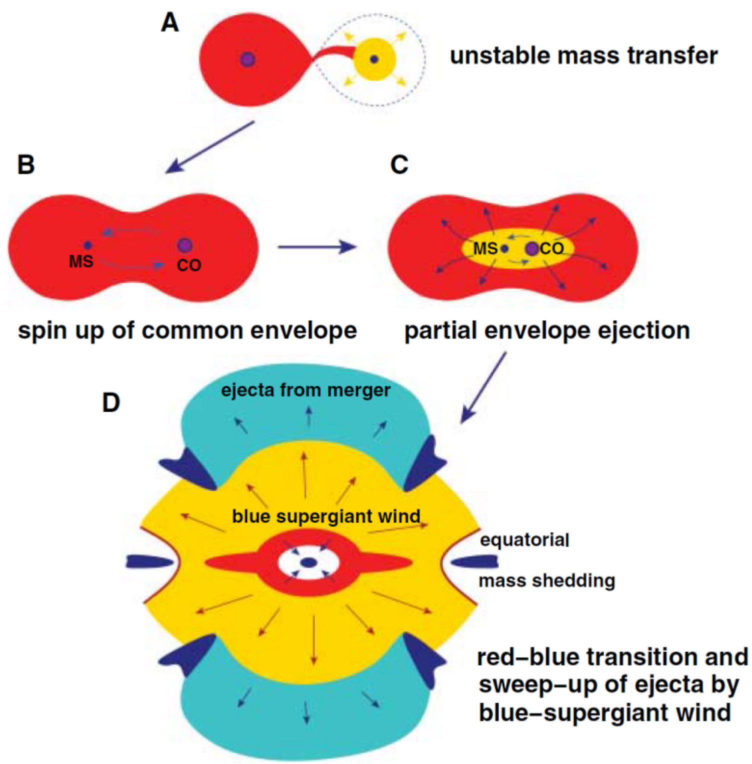
Table 1
SN 1987A Models

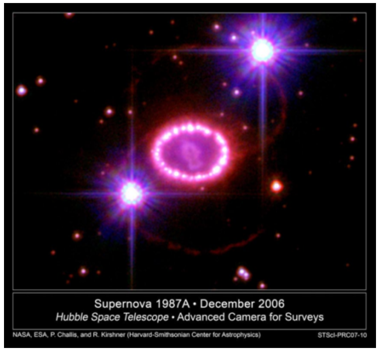
Model	$M_{preSN}/M_\odot$	$M_{He}/M_\odot$	$M_{CO}/M_\odot$	$L/10^{38}$ erg s^{-1}	T_{eff}	$\zeta_{2.5}$	$Z/Z_\odot$	Rotation
W18	16.93	7.39	3.06	8.04	18,000	0.10	1/3	Yes
N20	16.3	6	3.76	5.0	15,500	0.12	low	No
S19.8	15.85	6.09	4.49	5.65	3520	0.13	1	No
W15	15	4.15	2.02	2.0	15,300	…	1/4	No
W20	19.38	5.78	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

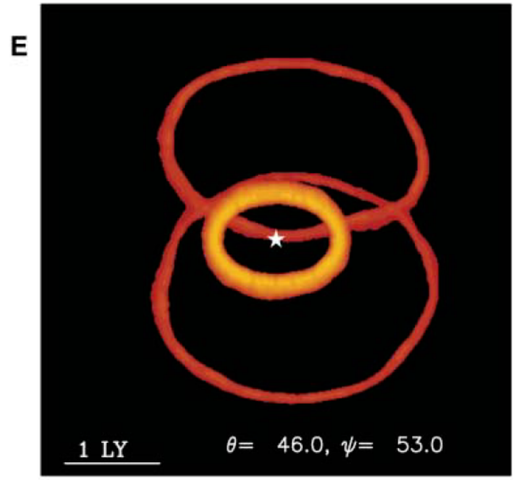
The progenitor of SN1987A was the outcome of a binary merger?

- 3D smoothed particle hydrodynamic (SPH) simulation

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





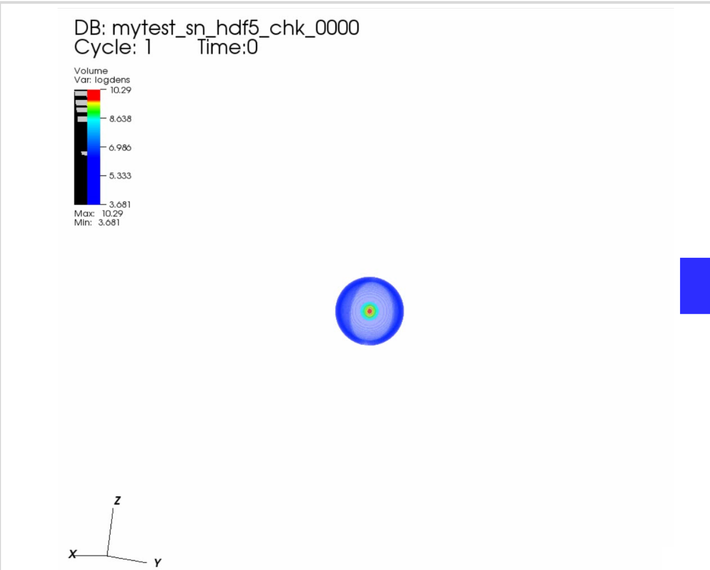


Morris & Podsiadlowsky 2007, Science, 315, 1103

3D hydrodynamic simulations of SN phases

3D simulation from Supernovae to Supernova remnants

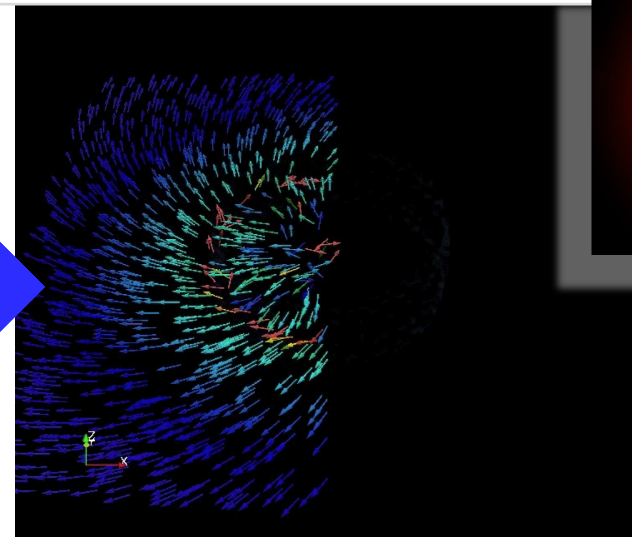
3D simulation of SNe

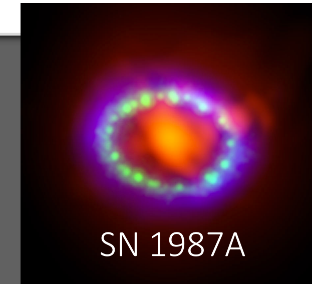


Aspherical explosion
Nucleosynthesis

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

PRACE project: Awarded and we got 6×10^7 CPU hours at a cluster of CINECA

RIKEN

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

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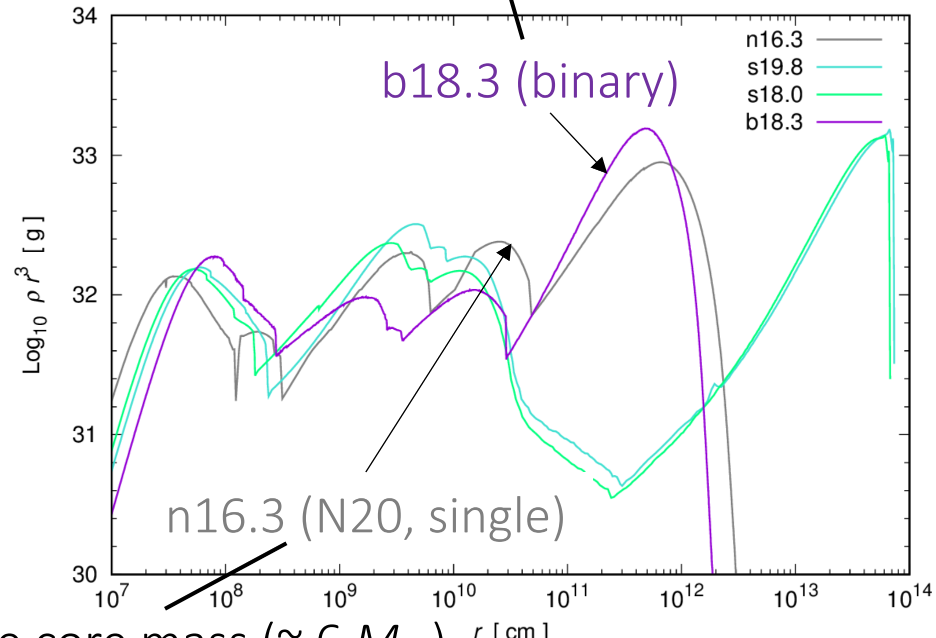
** Universita` di Palermo

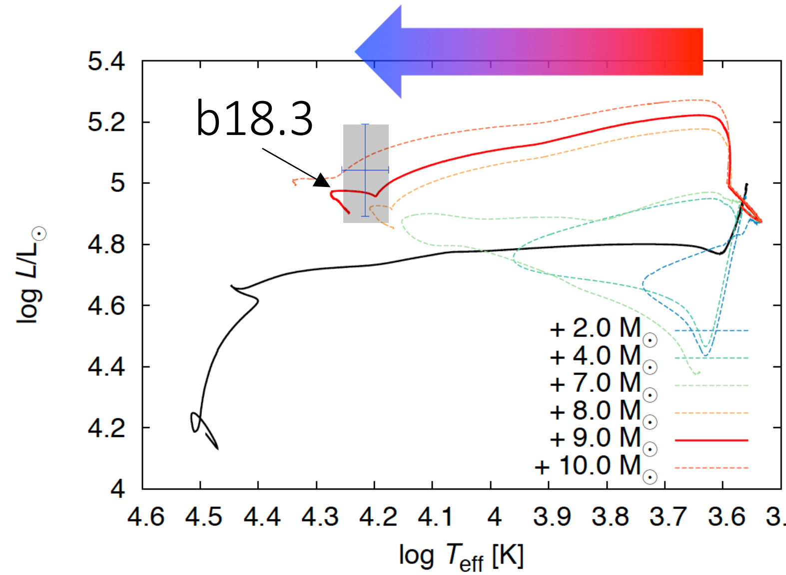
INAF

Density structures of two progenitor models used

Smaller He core mass (~ 4 $M_{\odot}$)



He core mass (~ 6 $M_{\odot}$)



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

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

If ω < 3 shock is decelerated

Initial setup: radial velocity distribution

Parameters

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

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

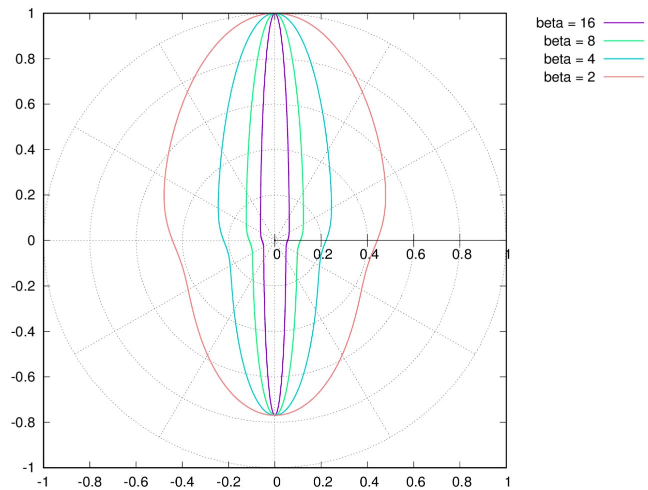
E_{in}: Injected energy

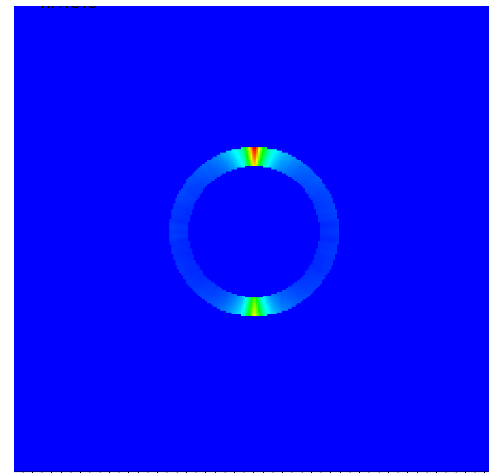
Ranges:

$E_{\mathrm{in}} = (1.5 - 3.0) \times 10^{51}$ erg

$\beta = 1.0 - 16.0$

$\alpha = (1.1 - 1.5)$





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

$$1 + \epsilon N \sum_n^4 \sum_m \frac{A^l_m(\theta,\phi)}{2^{n-1}} \qquad (l = n \cdot l_{\mathrm{base}})$$

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

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

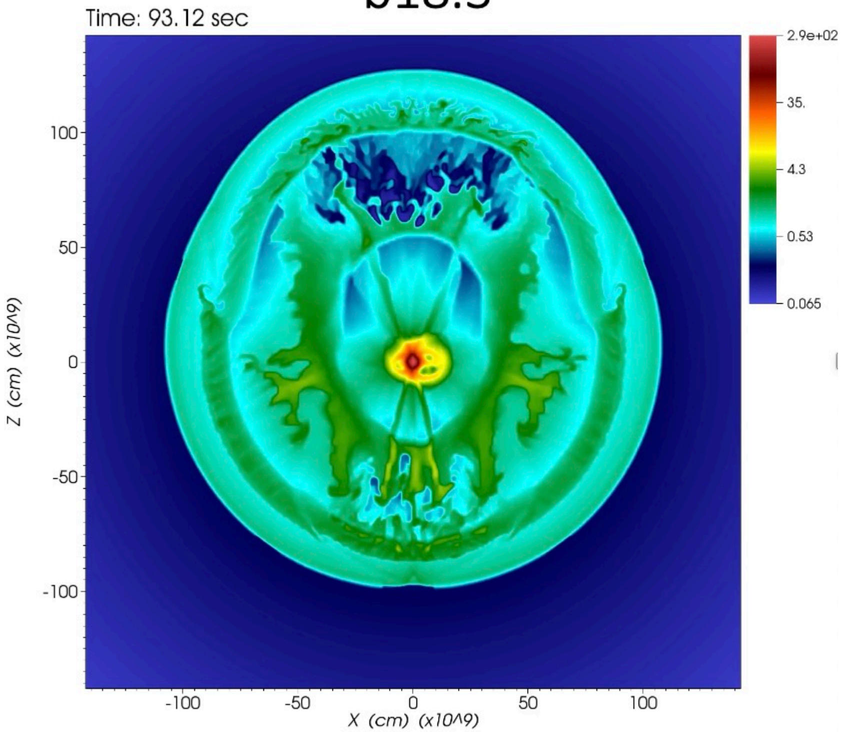
$$A^l_m(\theta,\phi) = \begin{cases} \begin{cases} Y^l_m(\theta,\phi) & (m = 1, -3, 5, -7, ..) \\ 0 & (\text{else}) \end{cases} & (l : \text{odd}) \\ \begin{cases} Y^l_m(\theta,\phi) & (m = 0, 2, -4, 6, ..) \\ 0 & (\text{else}) \end{cases} & (l : \text{even}) \end{cases}$$

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

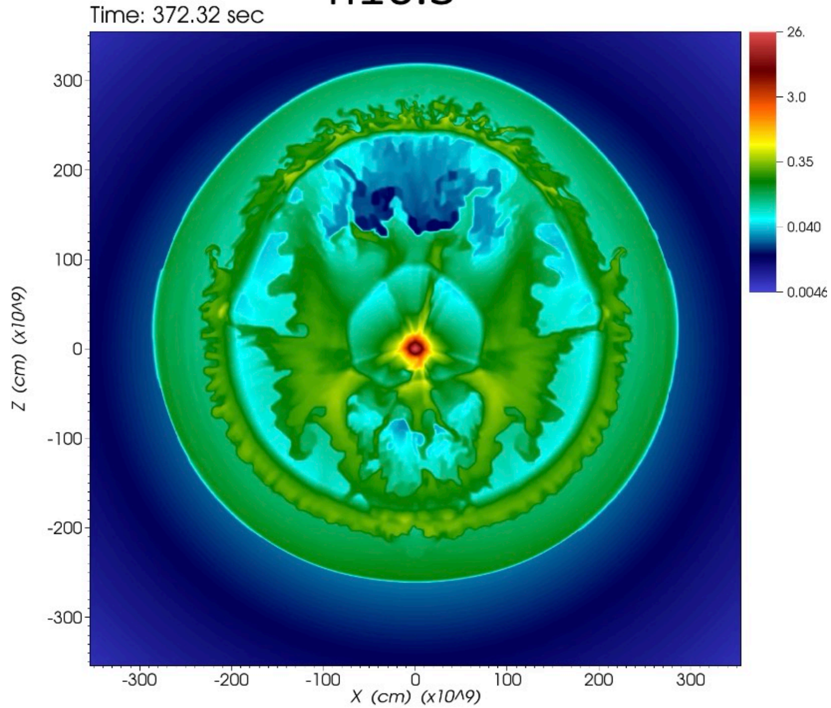
Time evolution of 2D slices of density : binary merger model vs single star model

MO et al. 2019, ApJ, submitted

b18.3



n16.3

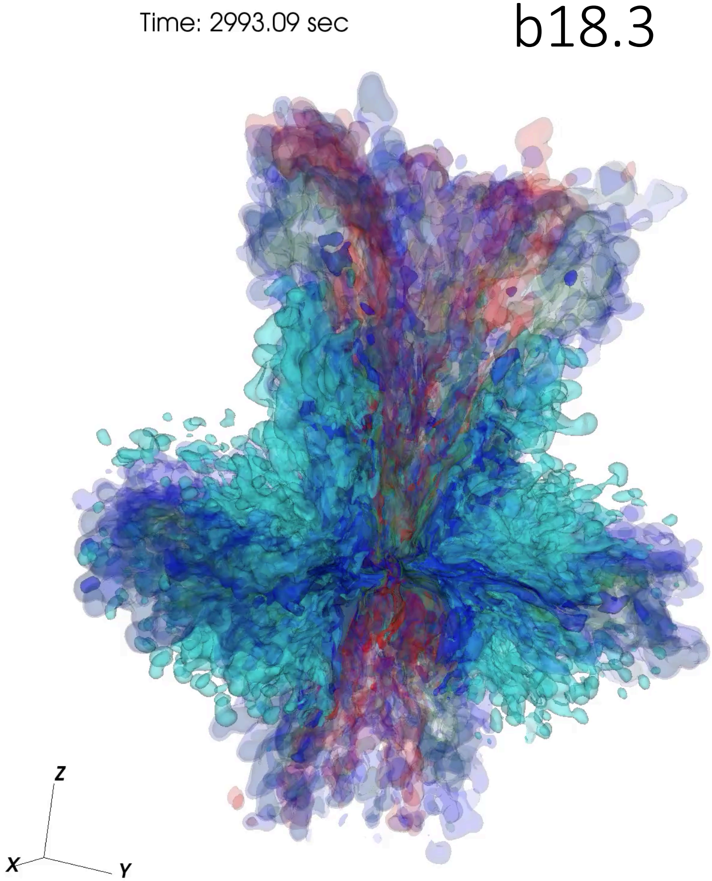


Binary merger

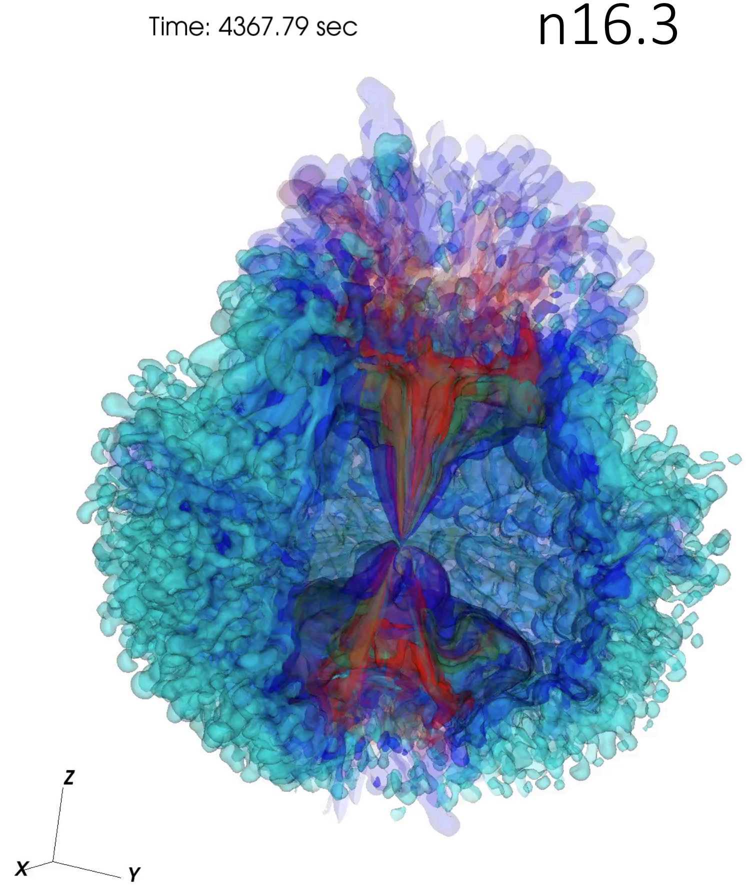
Single star

b18.3 vs n16.3: distribution of elements

MO et al. 2019, ApJ, submitted



Binary merger



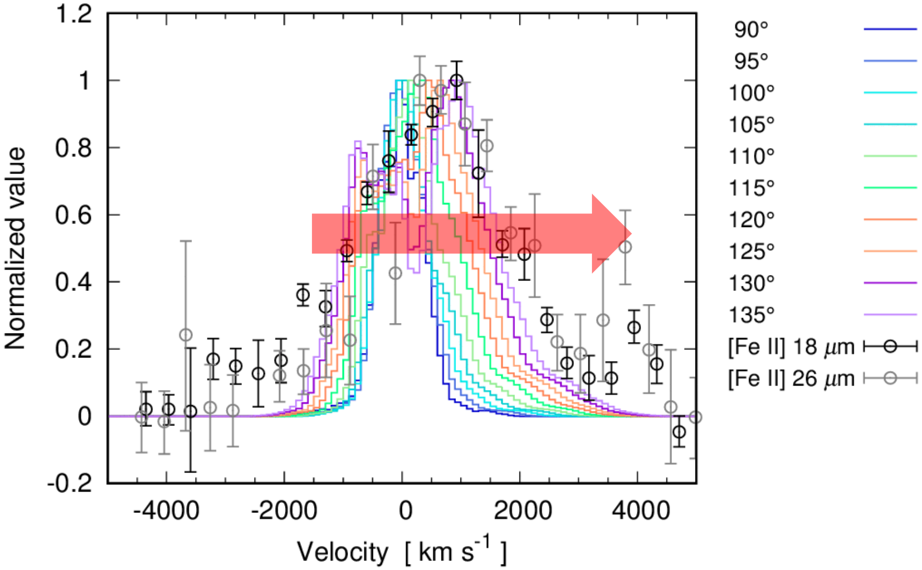
Single star

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

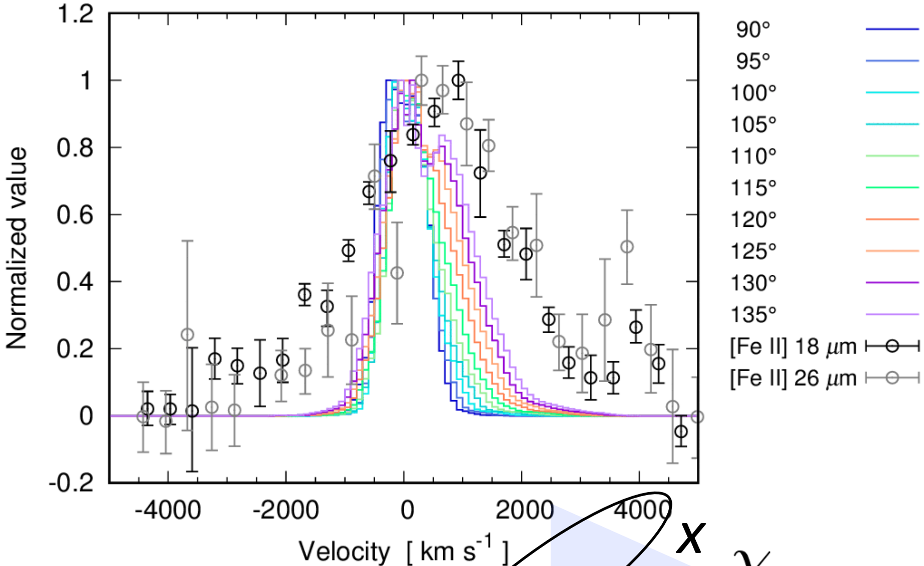
Line of sight (LoS) velocity distributions of ^{56}Ni

MO et al. 2019, ApJ, submitted

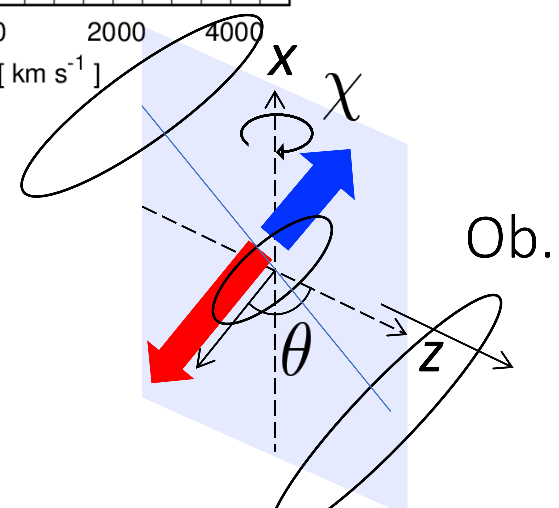
b18.3 (binary model)



n16.3 (single star model)

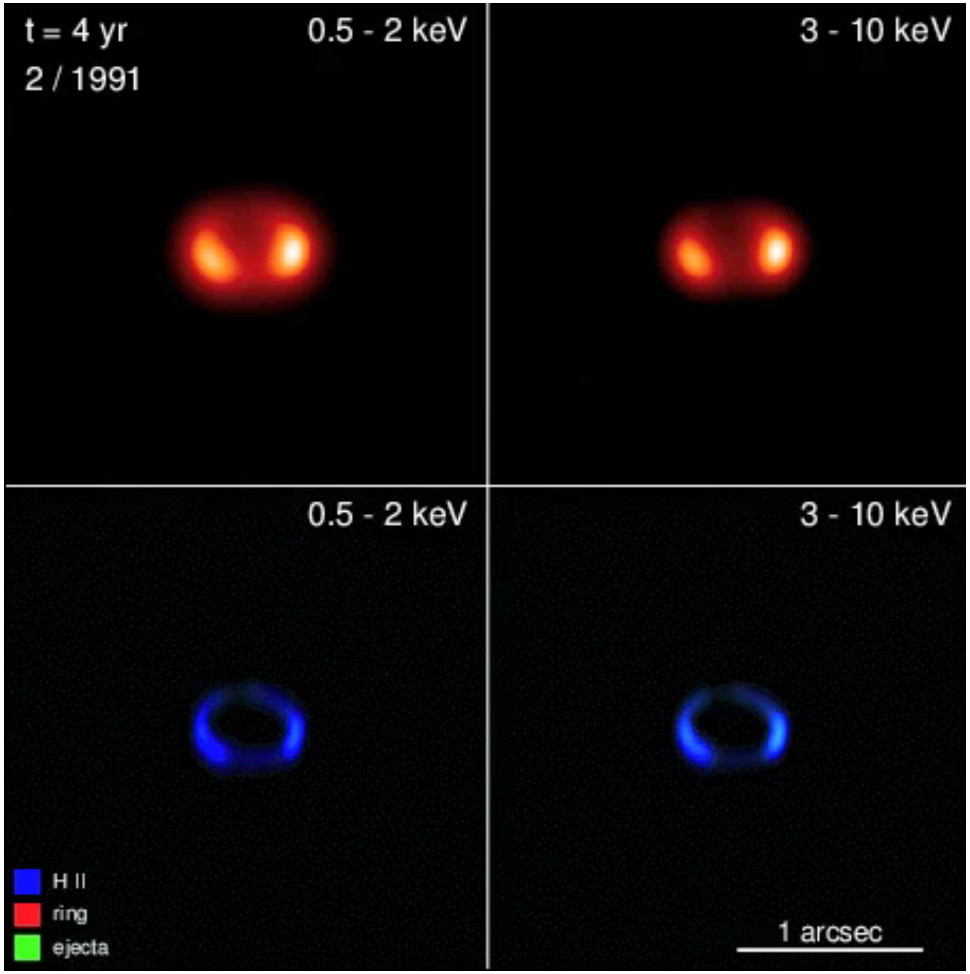


- The best model:
  - Progenitor model: b18.3 (binary merger model)
  - (E_{in}, α, β) = (2.5 x 10^{51} erg, 1.5, 16.0)
  - θ = 130° , χ = 10°

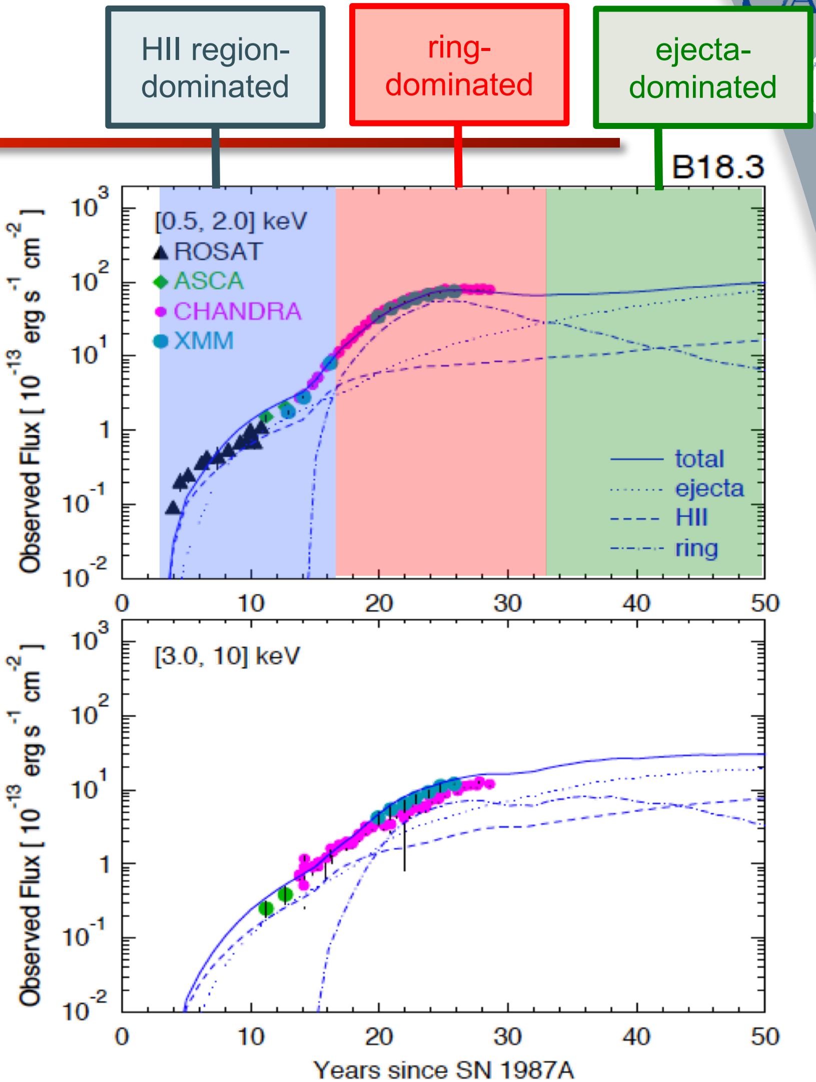


3D simulation of SNR phases

X-ray Lightcurves



Orlando, MO et al. 2019, A&A, submitted



Abundances from Zhekov+ (2009)

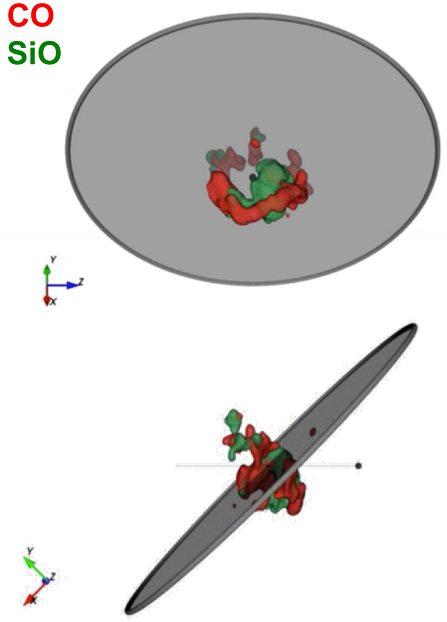
ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

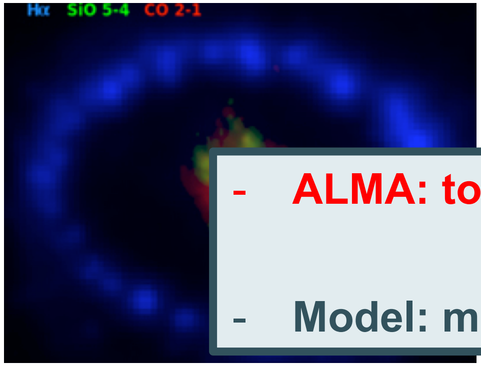
Distance: 51.4 kpc (Panagia 1999)

Molecular structure in the evolved SNR

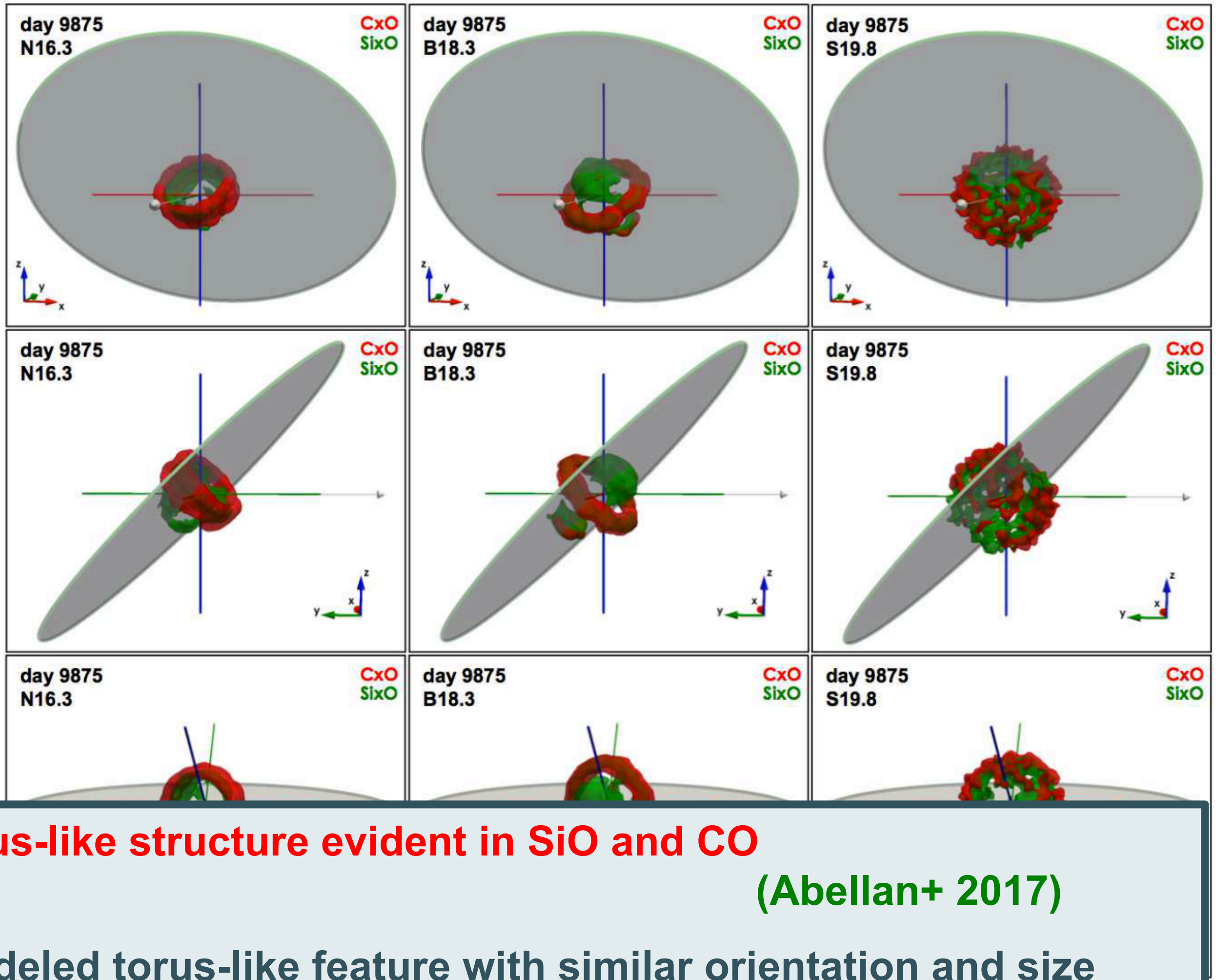
(Abellan+ 2017)

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, A&A, submitted

Molecule formation calculations

Molecule formation calculation

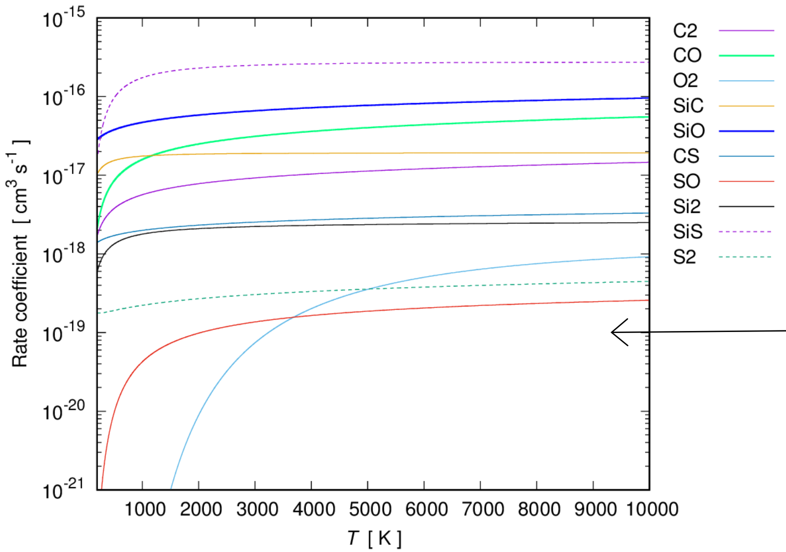
- Molecule network calculation is done based on the SN simulation results (1 day after the explosion) for each Eulerian grid

- Temperature and density evolutions 1 day after the explosion are assumed as power laws

$$\rho(t) = \rho_0 \left(\frac{t}{t_0} \right)^{-3} \qquad T(t) = T_0 \left(\frac{t}{t_0} \right)^{-3(\gamma-1)}$$

Molecule formation and destruction

Formation rate coefficients



$$k_i(T) = A_i \left(\frac{T}{300\ \mathrm{K}}\right)^{\alpha_i} \exp(-\beta_i/T) \quad [\mathrm{cm^3\,s^{-1}}]$$

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

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

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

C_i: number density of *i* th molecules

Formation

$$k_i(T) c_k c_l$$

Destruction by the collision of particles

$$D_i(T) = c_i \sum_k \frac{1}{1+\delta_{ik}} c_k \, S_{ik} \, G_{ik}(T)$$

$$S_{ik} = \pi(a_{0,i} + a_{0,k})^2$$

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 (smaller He core mass in the binary merger model is preferred)
    - 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 to some extent (ring-like CO distribution?)

Future work

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