Theories of Astrophysical Big Bangs 2025@RIKEN
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Evolution of core-collapse supernova from explosion to supernova remnant: The case of SN 1987A

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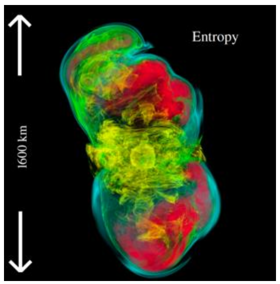
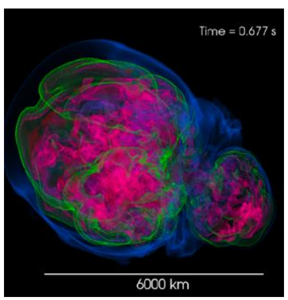
Supernova (SN) explosions to their supernova remnants (SNRs)

Magnetorotational vs Neutrino-driven?

Supernova explosion	Shock breakout	supernova	Supernova remnant
$t < 1$ sec	$t < 1000$ sec	$t < 1$ yr	$t \sim 500$ yr
$10^7 - 10^9$ cm	$10^{12} - 10^{14}$ cm		$\sim 10^{18}$ cm (1 pc)



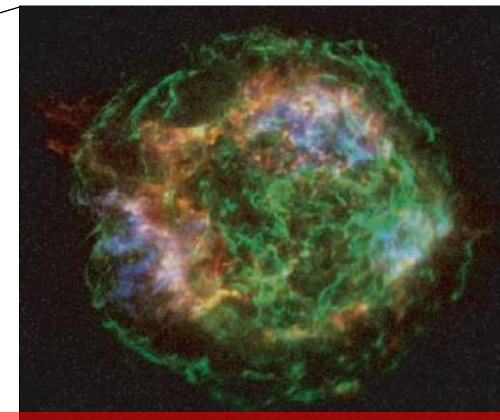
Mösta+14, ApJL, 785, L29



Vartanyan+19, MNRAS, 482, 351

Stellar Radius

Kifonidis+03, A&A, 408, 621



Electromagentic signals

Multi-dimensional effects
Explosive nucleosynthesis

Matter mixing

Formation of molecules and dust?

Destruction of part of the dust by the reverse shock?

Chemical evolution during the progenitor–SN–SNR sequence is unrevealed

Our SN-SNR project

Theoretical models

Umeda, H.
Yoshida, T.
Takahashi, K.

Progenitor models: Results of stellar evolution calculations

Wangwathanarat, A.
Janka, H.-T. (Cas A)

Explosive nucleosynthesis

MO (SN 1987A)

3D Hydro (HD) simulations of SNe

Nozawa, T.

Molecules/Dsut formation

Orlando, S.

3D HD/Magnetohydro (MHD) simulations of SNRs

Dohi, A.

Cooling model of NSs

Radiation hydro

Kozyreva, A.

X-ray emission

Miceli, M./Greco, E.

Optical light curves

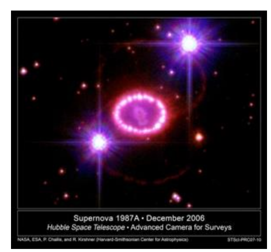
X-ray light curves/images

Vibration and/or rotational transitions of molecules

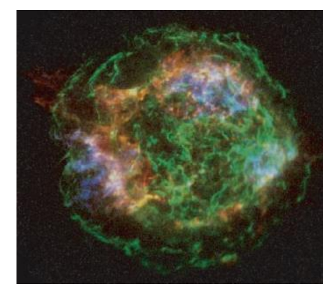
Observations to be compared

Comparison with observations

- Origin of asymmetries
- Mechanisms of explosions
- Progenitor stars
- Neutron stars (NSs)
- Circumstellar medium (CSM)



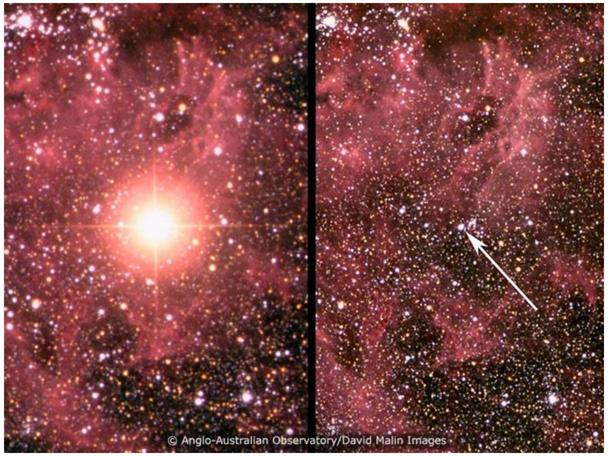
SN 1987A (> 30 yr)



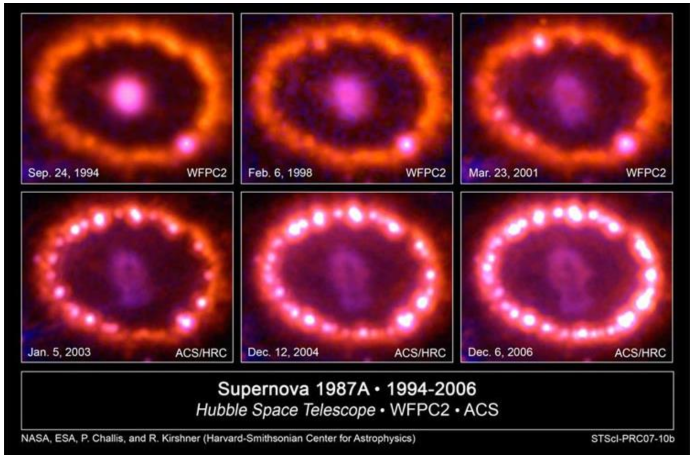
Cassiopeia A (> 330 yr)

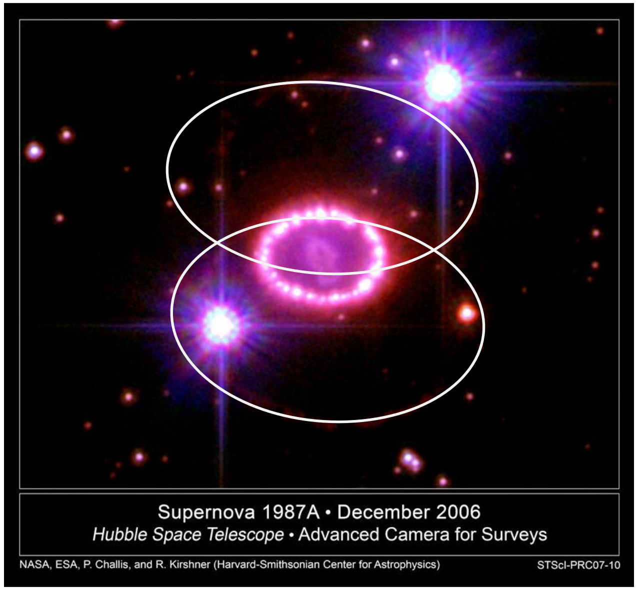
Unraveling progenitor-SN-SNR connection

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



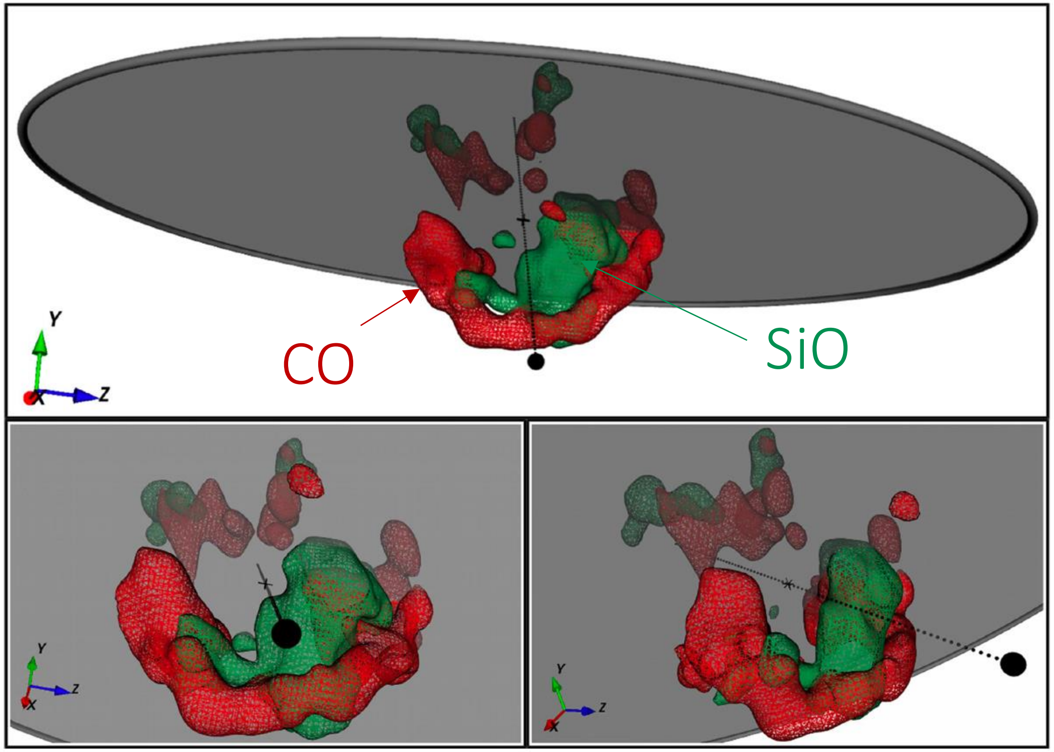


More than 30 years (～38 years) have passed since the discovery;
SN 1987A has entered a phase of *young SNR*

Distribution of molecular gas viewed in 3D

[Abellán+2017, ApJ, 842, L24]

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



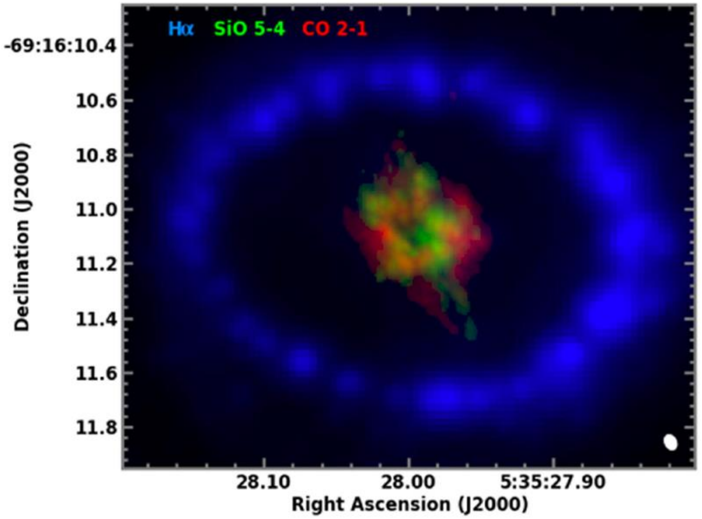


Figure 1. Molecular emission and Hα emission from SN 1987A. The more compact emission in the center of the image corresponds to the peak intensity maps of CO 2−1 (red) and SiO 5−4 (green) observed with ALMA. The surrounding Hα emission (blue) observed with *HST* shows the location of the circumstellar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

3D spatial distribution in a SN ejecta for the first time!

- Distributions are clumpy
- *CO distribution has a ring-like structure*

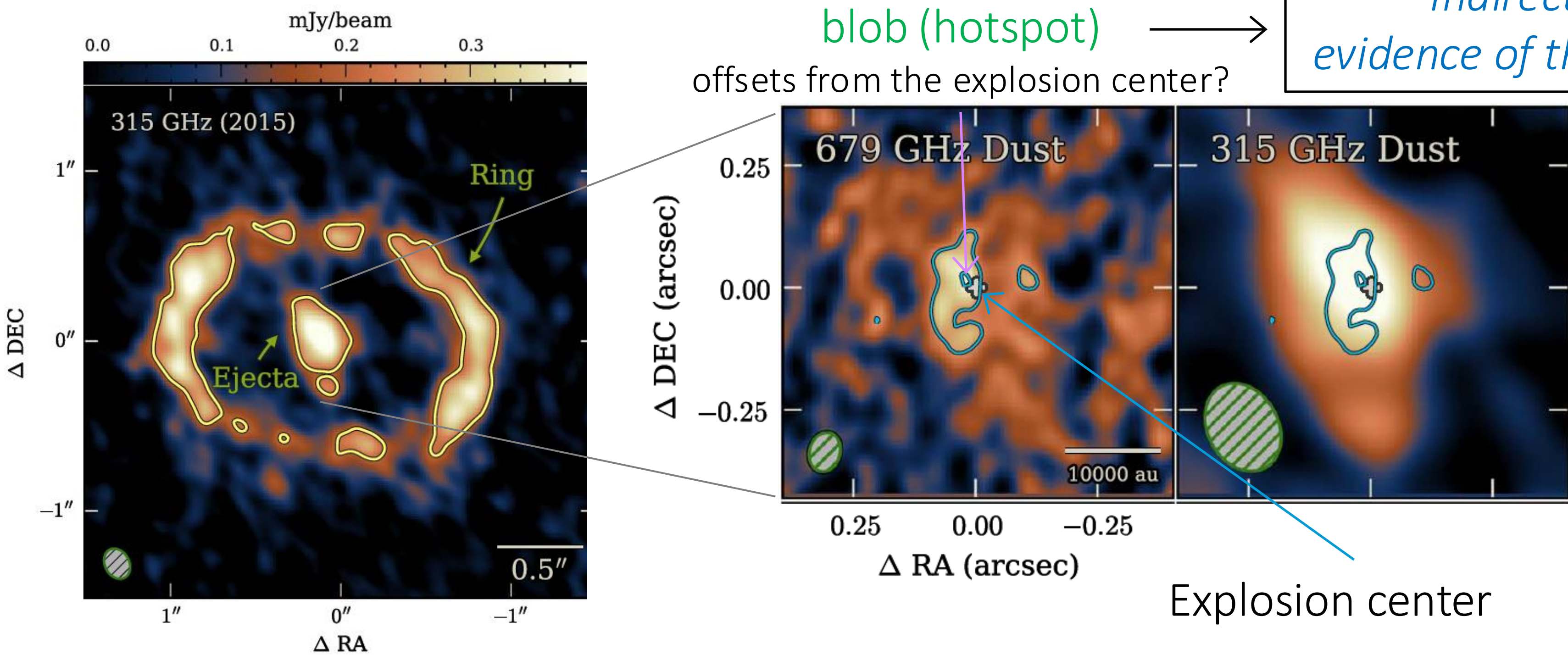
Emission from dust in the SN 1987A ejecta: Dust heated by a compact source (NS)?

[Cigan+2019, ApJ, 886, 51]

High angular resolution ALMA (Atacama Large Millimeter/submillimeter Array) images of dust in the ejecta of SN 1987A

blob (hotspot) → *Indirect evidence of the NS?*

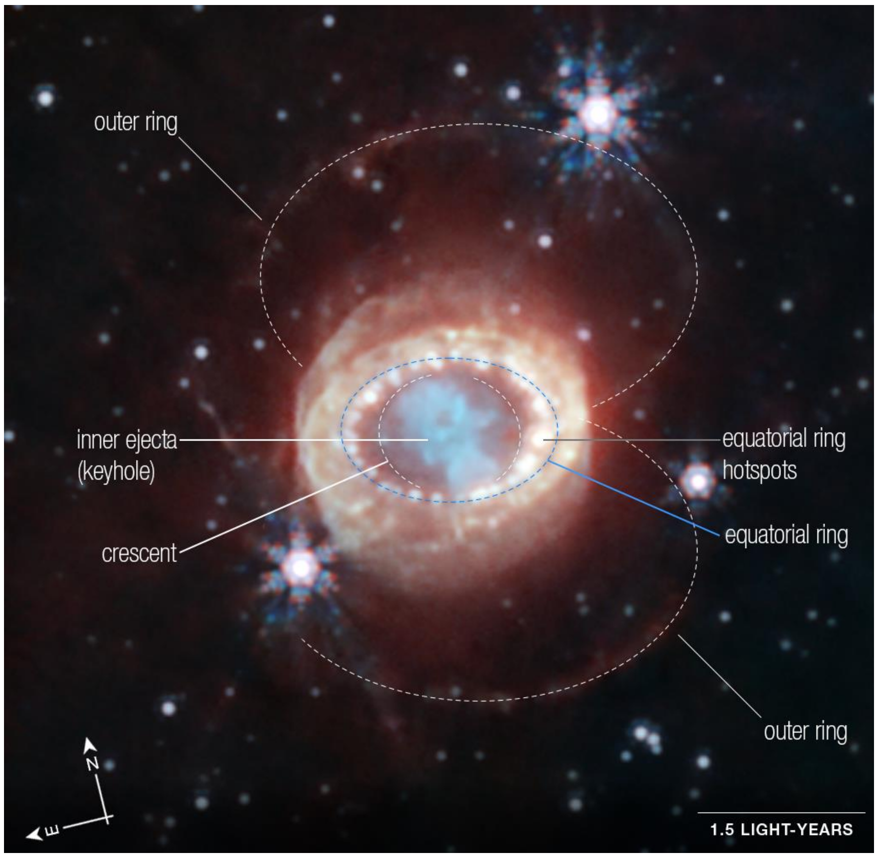
offsets from the explosion center?



Explosion center

- The dust peak could be stemed from an additional heating by a compact souce: 1-2 mJy @ 679 GHz corresponding to $L_{\mathrm{bol,\,dust}} = (40\text{-}90)\ L_\odot$

The latest image of the inner ejecta of SN 1987A by JWST



The recent image of SN 1987A provided by the newly launched JWST (James Webb Space Telescope)

JWST's NIRCam (Near-Infrared Camera)

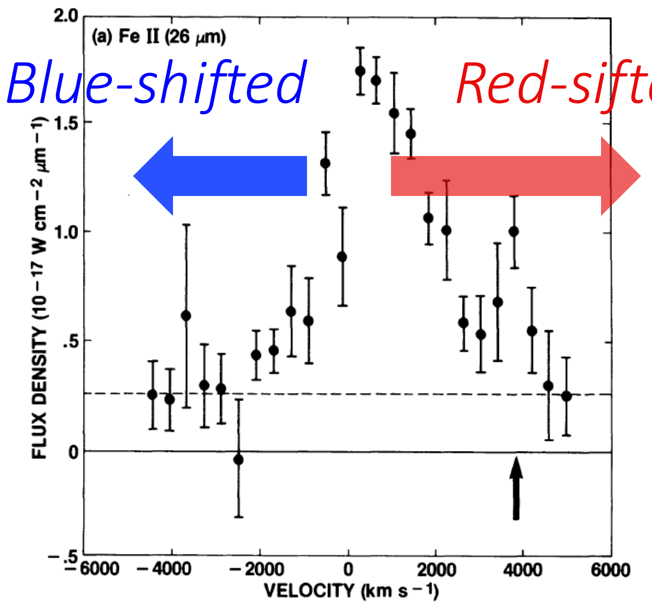
blue: 1.5 μm(F150W)
cyan: 1.64 and 2.0 μm (F164N, F200W)
yellow: 3.23 μm (F323N)
orange: 4.05 μm (F405N)
red: 4.44 μm (F444W)

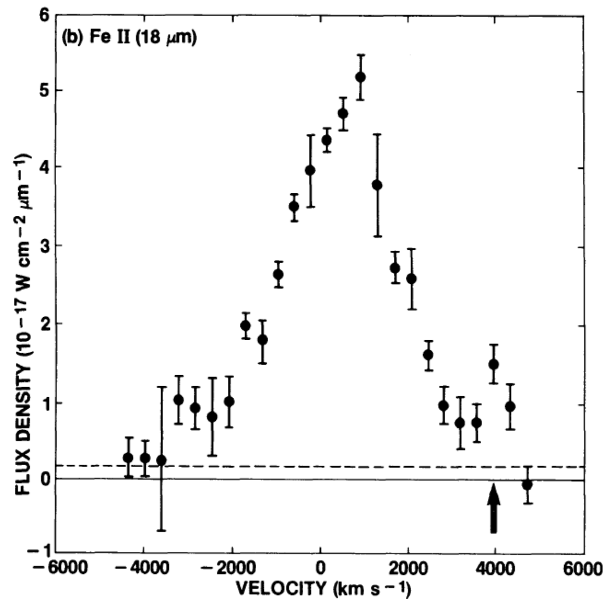
Credit: NASA, ESA, CSA, Mikako Matsuura (Cardiff University), Richard Arendt (NASA-GSFC, UMBC), Claes Fransson (Stockholm University), Josefin Larsson (KTH)

Evidence of matter mixing in SN 1987A: High velocity iron

[Fe II] line profiles

[Haas+1990, ApJ, 360, 257]
(observations at ～ 400 days after the explosion)





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

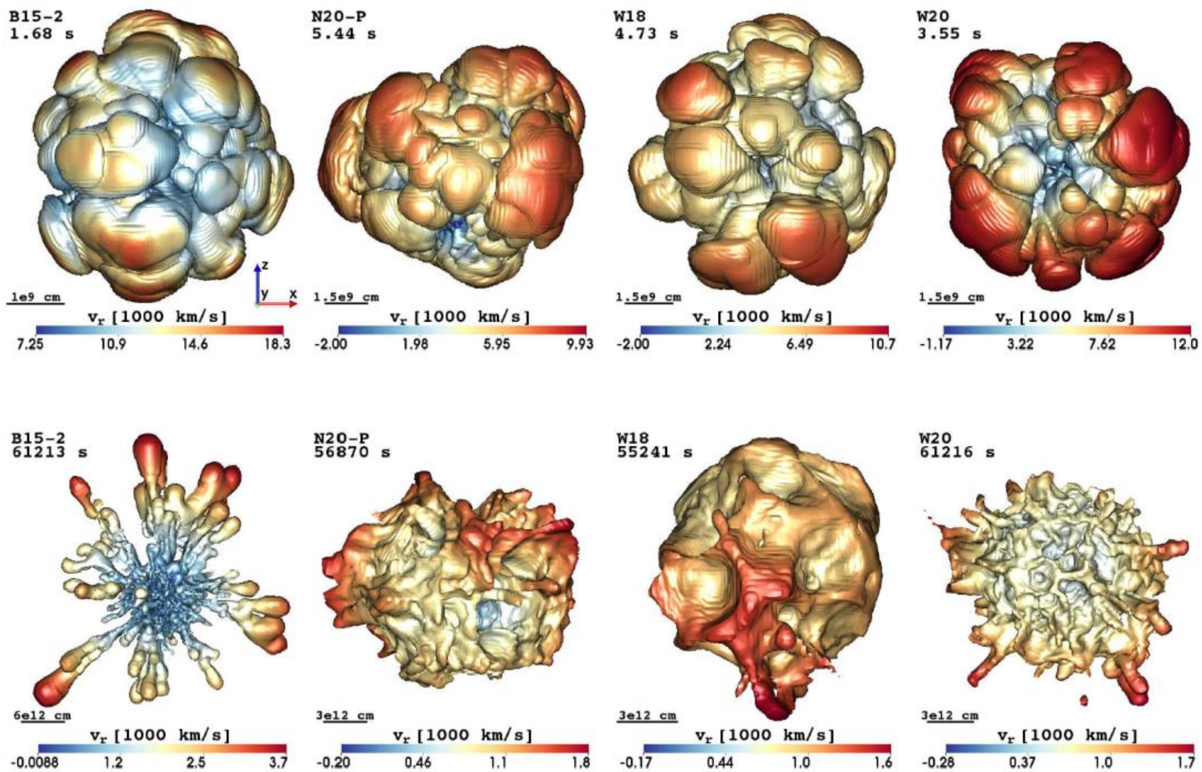
Fast ^{56}Fe (^{56}Ni → ^{56}Co → ^{56}Fe) motion → *Matter mixing?*
radio active decay

Red-shifted side is dominated → *Asymmetric explosion?*

3D neutrino-driven explosion models: Dependence of matter mixing on progenitor models

Different progenitor models

Time

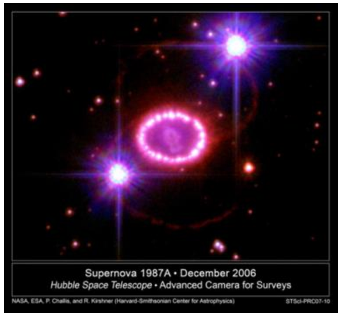


[Utrobin+2015, A&A, 581, A40]

Colors: velocity of ^{56}Ni

- The development of the finger-like structures made by Rayleigh-Taylor instability is *sensitive to the progenitor models*

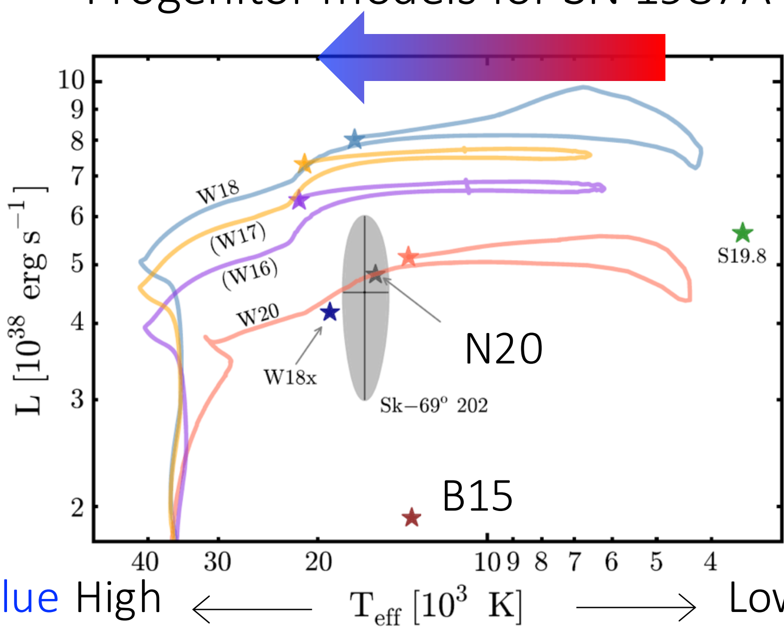
Properties of the progenitor of SN 1987A



- 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 2×10^4 years ago

The figure and Table are taken from Sukhbold+2016

N: Nomoto & Hashimoto 1988

W: Woosely et al. 1988

S: Sukhbold et al. 2016

To obtain a *single-star* model that fit the observations, *non-physical fine-tuning* is necessary

[Sukhbold+2016, ApJ, 821, 38]

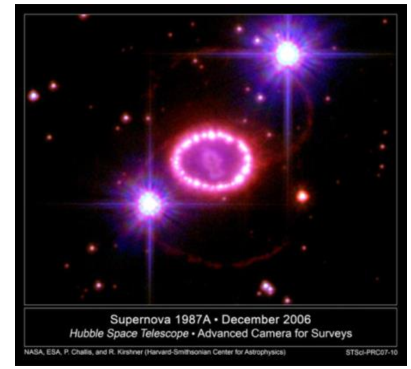
Table 1
SN 1987A Models

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

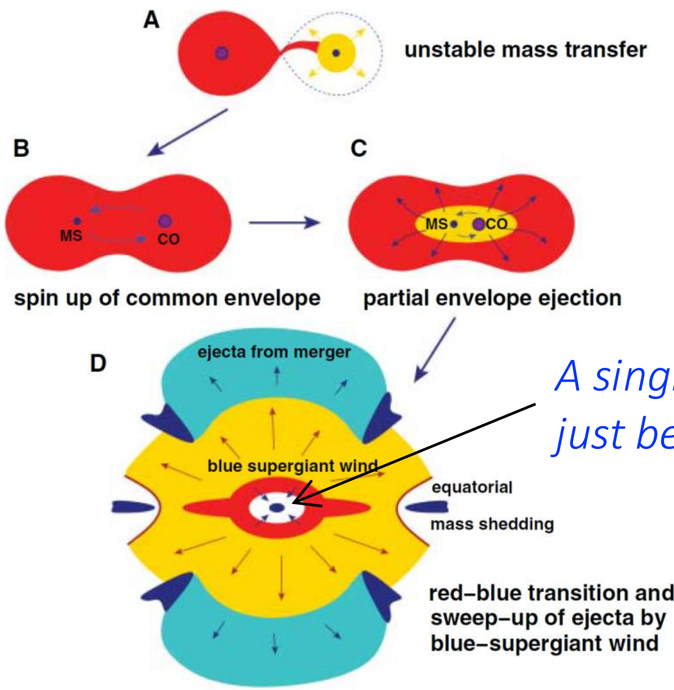
The progenitor of SN 1987A was made by a binary merger?

[Morris & Podsiadlowsky 2007, Science, 315, 1103]

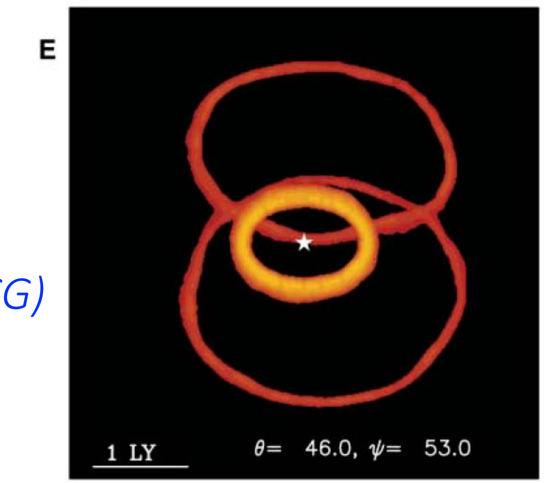
- 3D smoothed particle hydrodynamic (SPH) simulations



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



A single blue supergiant (BSG) just before the explosion



Triple ring-like structure reproduced

- A 18.3 $M_\odot$ binary merger progenitor model (14 $M_\odot$ + 9 $M_\odot$) (Urushibata+2018, MNRAS, 473, L101) is used in later simulation results

Initial setup: radial velocity distribution

Hydrodynamical code: FLASH (Fryxell+2000, ApJS, 131, 271)

Parameters

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

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

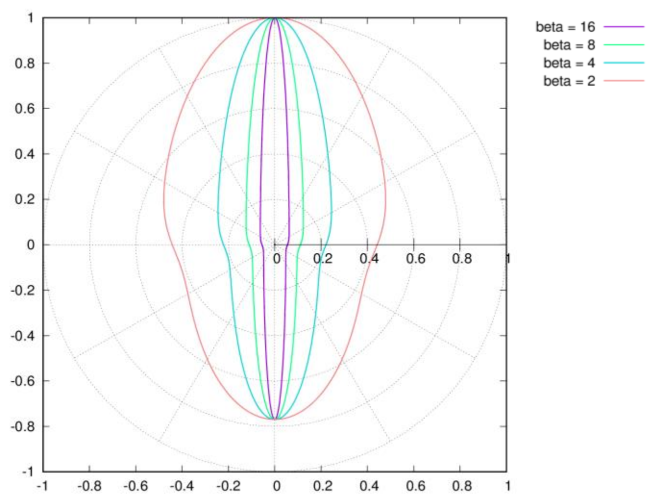
E_{in}: Injected energy

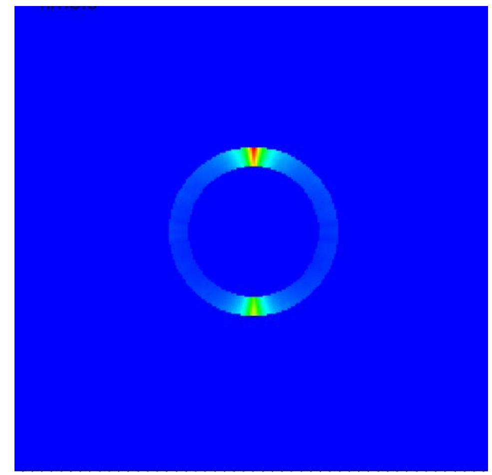
Ranges:

E_{in} = (1.5 – 3.0) x 10^{51} erg

β = 1.0 – 16.0

α = (1.1 – 1.5)





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

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

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

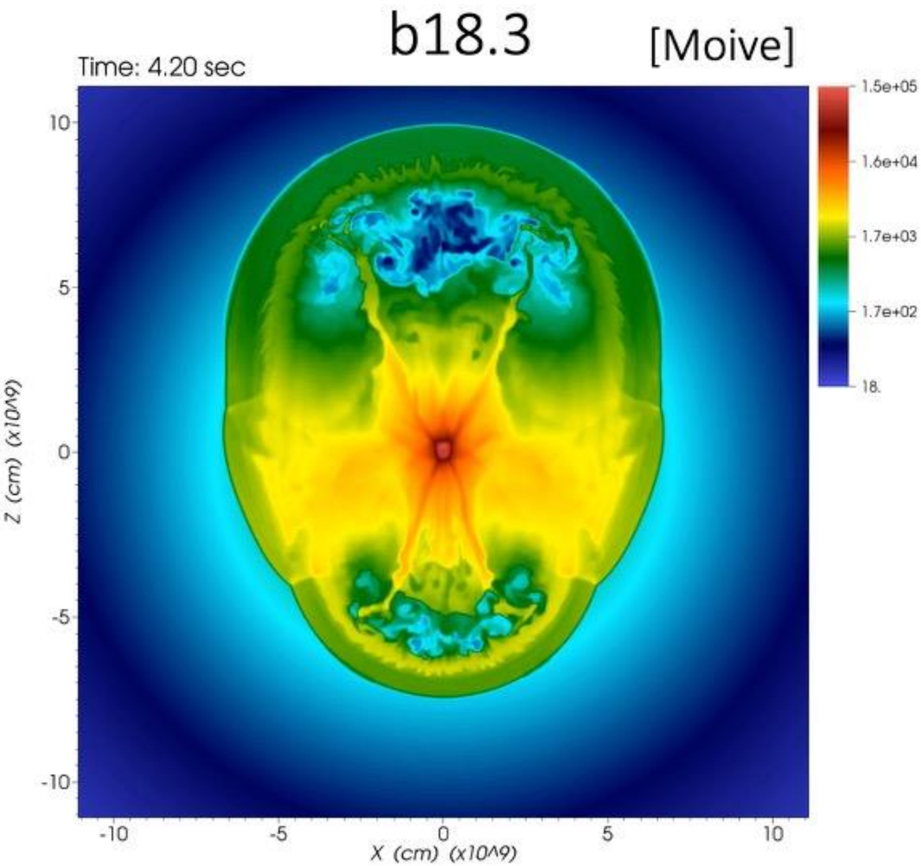
N : Normalization factor

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

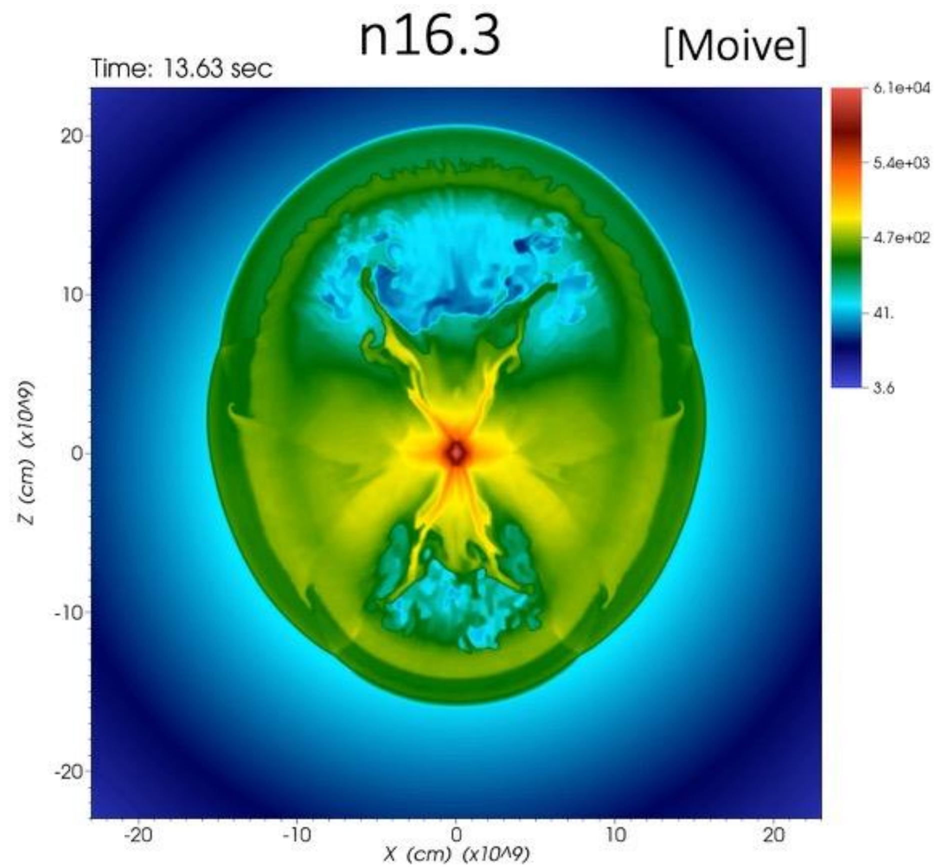
$$Y_m^l(\theta,\phi) = \begin{cases} \sqrt{2}\sqrt{\frac{2l+1}{4\pi}\frac{(l-|m|)!}{(l+|m|)!}}P_m^l(\cos\theta)\sin(|m|\phi) & (m < 0) \\ \sqrt{\frac{2l+1}{4\pi}}P_m^l(\cos\theta) & (m = 0) \\ \sqrt{2}\sqrt{\frac{2l+1}{4\pi}\frac{(l-|m|)!}{(l+|m|)!}}P_m^l(\cos\theta)\cos(m\phi) & (m > 0) \end{cases}$$

Time evolution of 2D slices of the density : binary merger model vs single star model (Movies)

[MO+20, ApJ, 888, 111]



Binary merger progenitor



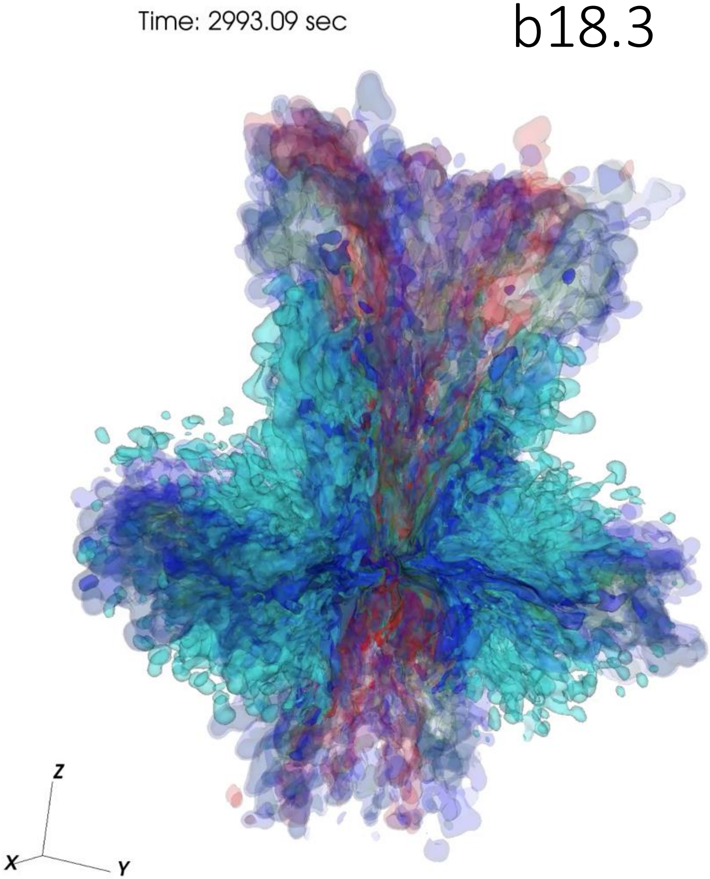
Single star progenitor

3D Sketchfab models for MO+20, ApJ, 888,111

b18.3 vs n16.3: distribution of elements (Movie)

[Moive]

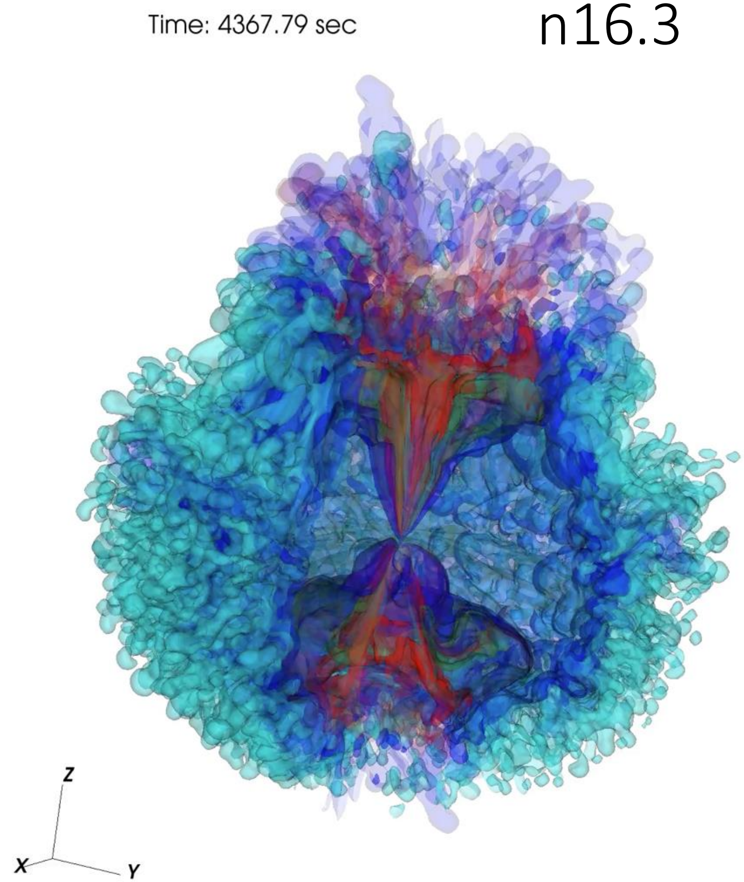
b18.3



Binary merger

[Moive]

n16.3



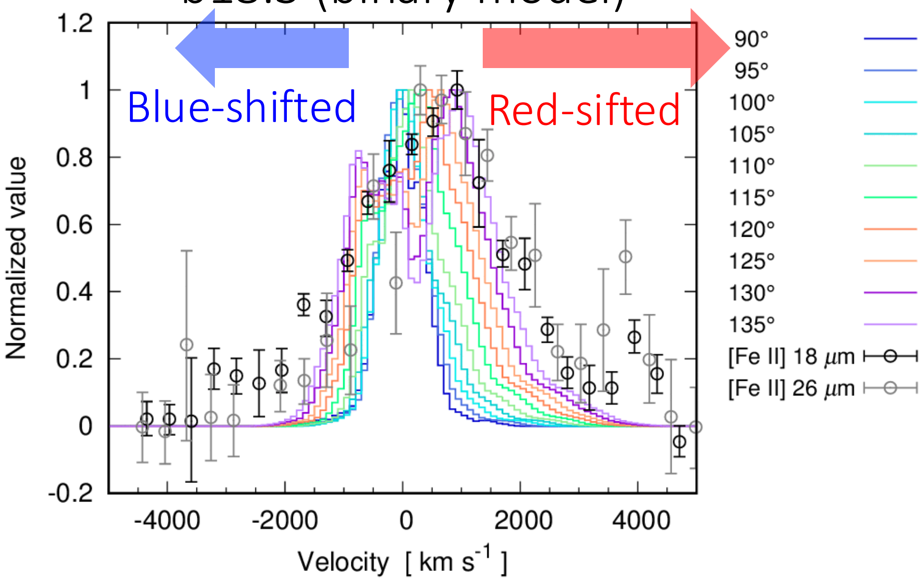
Single star

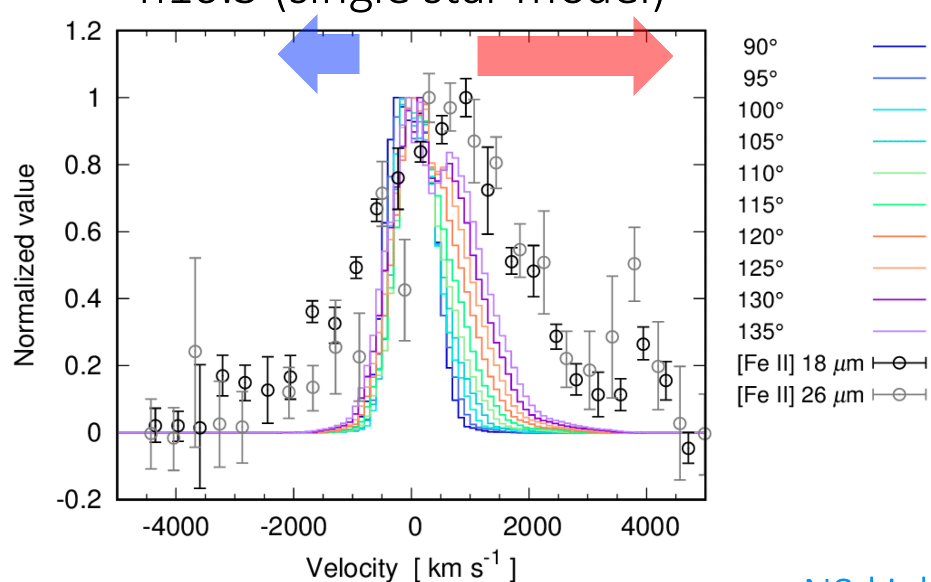
^{56}Ni (Red) ^{28}Si (Green) ^{16}O (Blue) ^{4}He (Sky blue)

[MO+20, ApJ, 888, 111]

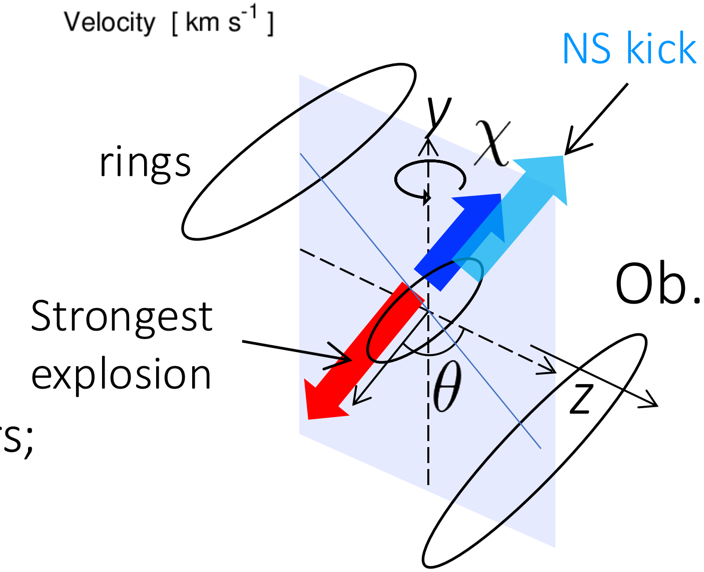
Line of sight (LoS) velocity distributions of ^{56}Ni

[MO+20, ApJ, 888, 111]





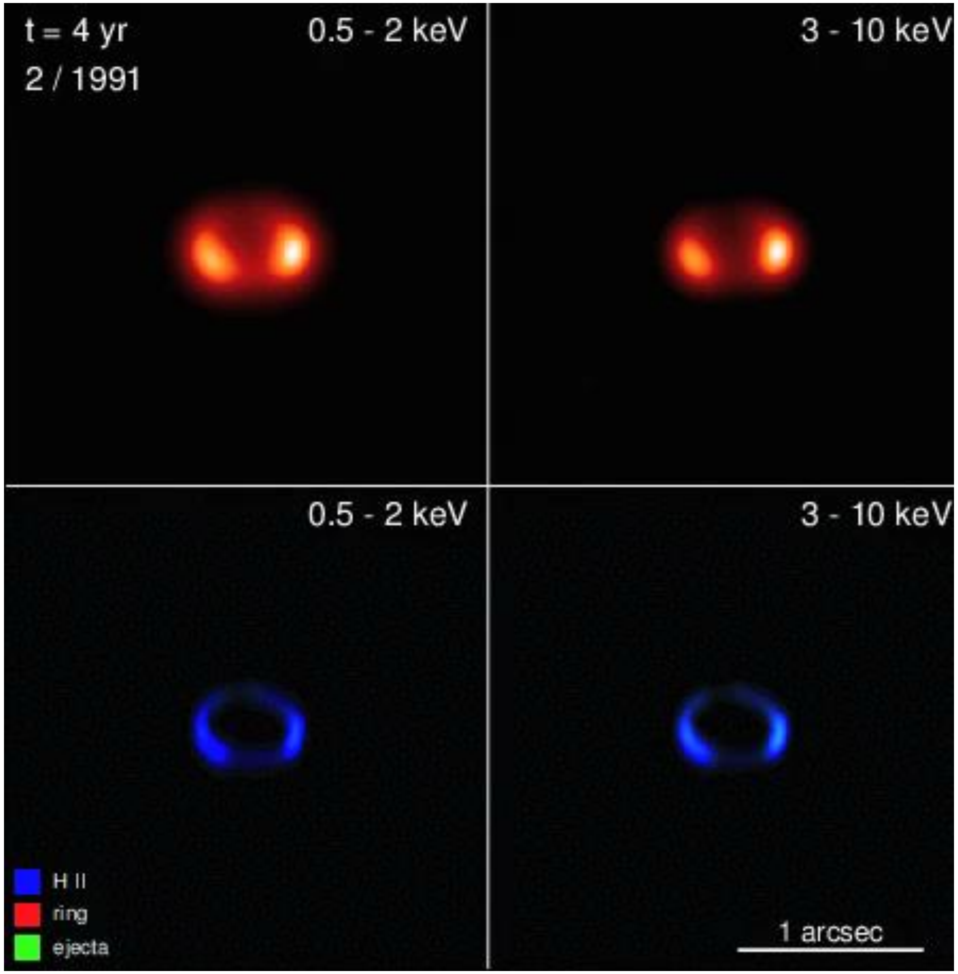
- The best model:
  - Progenitor model: b18.3 (binary merger)
  - (E_{in}, α, β) = (2.5 x 10^{51} erg, 1.5, 16.0)
  - θ = 130° ; χ = 10°
  - *Estimated NS kick velocity*: 285 km s^{-1} (consistent with kick velocities of young pulsars; e. g. Faucher-Giguère & Kapsi 2006)



Synthesized X-ray images and light curves

Orlando, S.

Evolution of synthetic X-ray emission map based on a 3D magnetohydrodynamical model with the successful model shown above

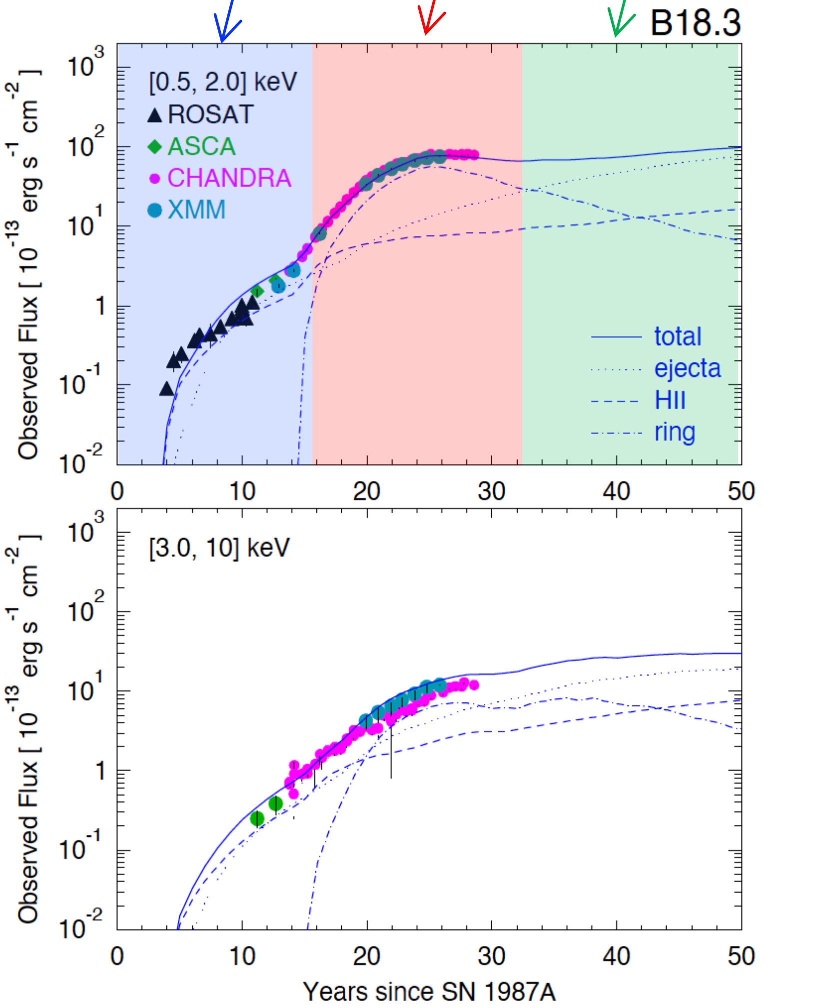


[Movie; Orlando+20, A&A, 636, A22]

HII-region dominated

ring dominated

ejecta dominated



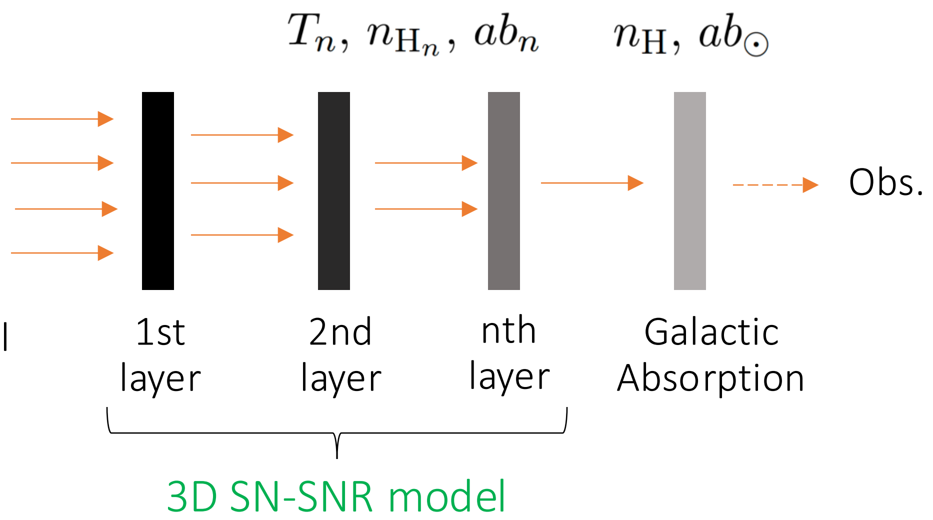
B18.3: Binary merger model

Spectral fitting with a non-thermal component with abosorption estimated byt the 3D SN-SNR model

Greco, E.

PWN?

Suppose a non-thermal component

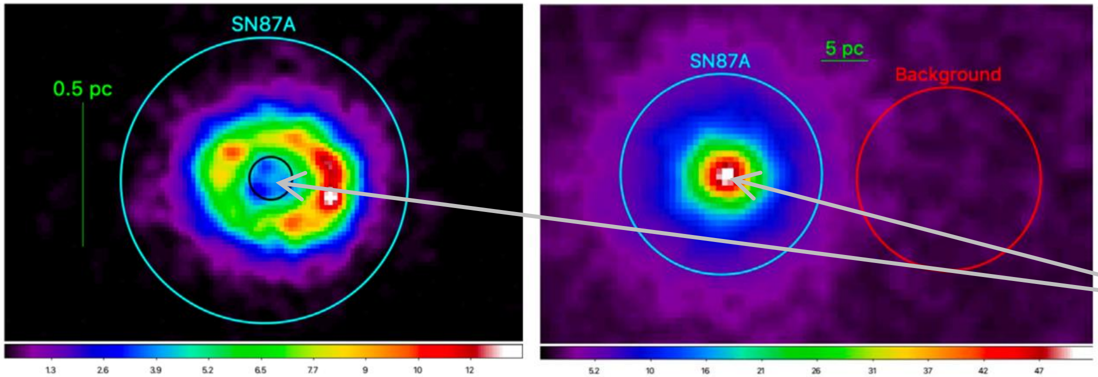


[Greco+2021, ApJ, 908, L45; 2022, ApJ, 931, 132]

A ray tracing method

- *T*, *n*, *ab* (abundance) from the 3D SN-SNR model [MO+20; Orlando+20]
- Spectral fitting of Chandra, XMM-Newton, and NuSTAR spectra

Count images of SN 1987A

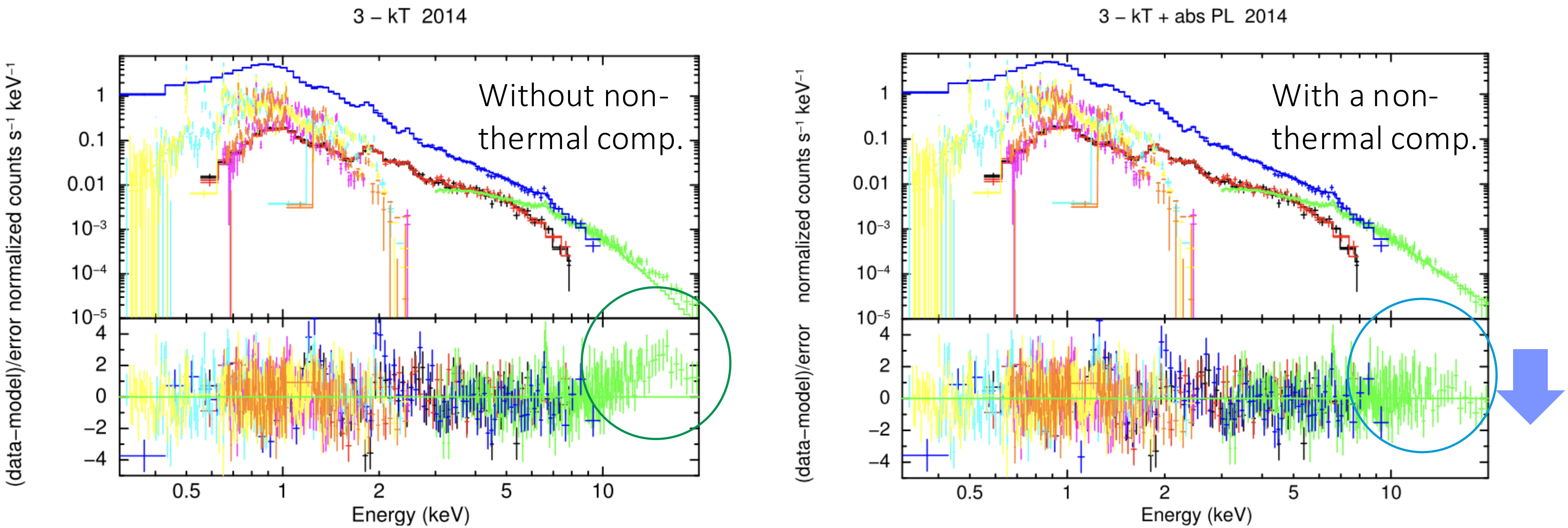


Chandra NuSTAR

Pulsar wind nebula (PWN) activities from the neutron star of SN 1987A?

Spectral fitting with or without a non-thermal component (PWN activity?)

Spectral fitting of SN 1987A observations by Chandra, XMM-Newton, and NuSTAR



- Inclution of non-thermal emission from a speculated position of NS 1987A make the residuals of the model be small
- A Pulsar wind nebula activity is expected

[Greco+2021, ApJ, 908, L45; 2022, ApJ, 931, 132]

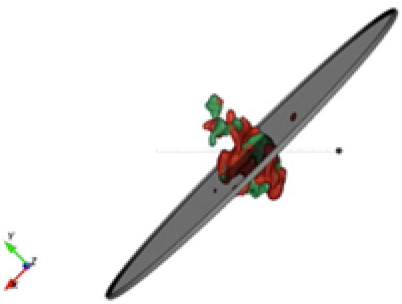
Distribution of molecules

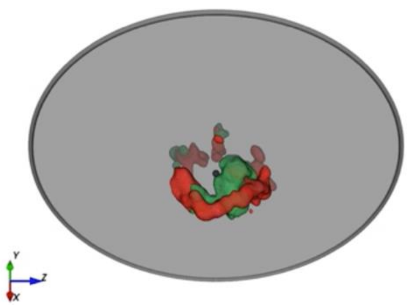
[Orlando+2020, A&A, 636, A22]

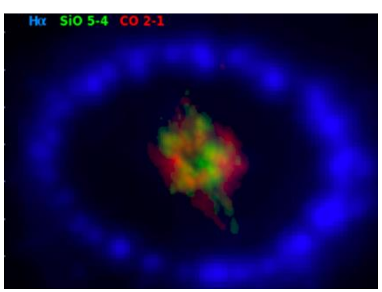
$$\mathrm{C} \times \mathrm{O} = \rho\sqrt{X_{^{12}\mathrm{C}} X_{^{16}\mathrm{O}}}$$

$$\mathrm{Si} \times \mathrm{O} = \rho\sqrt{X_{^{28}\mathrm{Si}} X_{^{16}\mathrm{O}}}$$

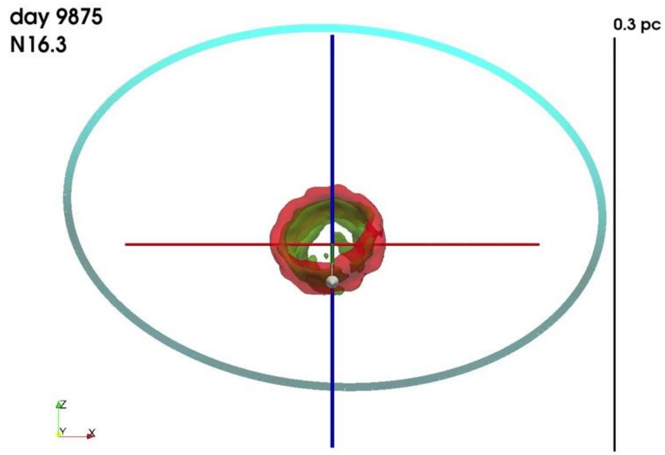
Observations by ALMA



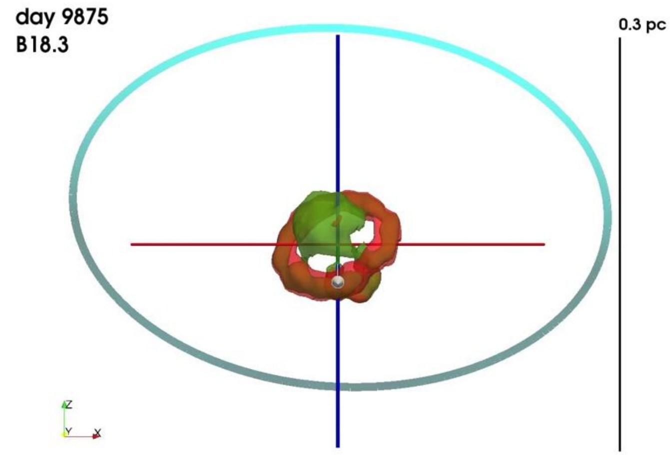




Abellán+2017



single star model



binary merger model

- Torus-like structure for CO seen in ALMA observations is similar with the models
- C x O and Si x O distributions in the models are just rough approximation

Although the simple assumption may qualitatively explain the observed features, *theoretical models for molecular formation are necessary*

[MO+2024, ApJS, 271, 33]

Calculations of molecule formation in the ejecta of SN 1987A — Impact of matter mixing on molecule formation —

There has been no numerical study on molecule formation in the core-collapse supernova ejecta based on 3D hydrodynamical models

This study — The impact of matter mixing on the molecule formation

- Ejecta models: one-zone/1D models based on 3D hydrodynamical models of the bipolar-like explosions [MO+2020, ApJ, 888, 111]
- Calculations of rate equations with a chemical reaction network
  - 75 species (11 atoms, 24 diatomic molecules, electron, and 39 ions)
- Calculations of rate equations for CO rotational-vibrational transitions
  - Contribute to the cooling of the gas
  - Diagnostic of the models through the comparison with observations
- Other effects taken into account
  - Heating of the gas due to the decay of ^{56}Ni and/or ^{56}Co
  - Ionizations and/or dissociation of atoms and molecules by Compton electrons from the decay of ^{56}Ni and/or ^{56}Co

Rate coefficients for available reactions from UMIST database for specified species

- UMIST database (RATE12) http://udfa.ajmarkwick.net/
  - In total 788 species (> 6000 reactions)

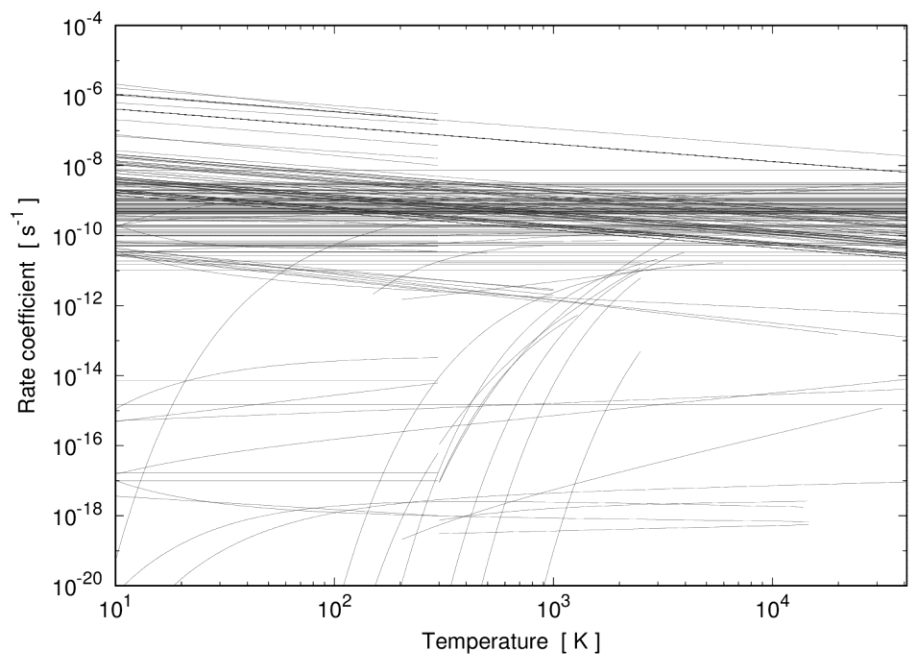
Reaction types and numbers of reactions

Code	Reaction type	Count
AD	Associative Detachment	132
CD	Collisional Dissociation	14
CE	Charge Exchange	579
~~CP~~	~~Cosmic-Ray Proton (CRP)~~	~~11~~
~~CR~~	~~Cosmic-Ray Photon (CRPHOT)~~	~~249~~
DR	Dissociative Recombination	531
IN	Ion-Neutral	2589
MN	Mutual Neutralisation	981
NN	Neutral-Neutral	619
~~PH~~	~~Photoprocess~~	~~336~~
RA	Radiative Association	92
REA	Radiative Electron Attachment	24
RR	Radiative Recombination	16

Atoms	H, He, C, N, O, Ne, Mg, Si, S, Ar, Fe
Diatomic molecules	H_2, CH, C_2, CN, CO, CS, NH, N_2, NO, OH, O_2, MgO, MgS, SiH, SiC, SiN, SiO, Si_2, SiS, SO, S_2, FeO, FeS, Fe_2
Ions	e^-, H^-, C^-, O^-, H^+, He^+, C^+, N^+, O^+, Ne^+, Mg^+, Si^+, S^+, Ar^+, Fe^+, H_2^+, HeH^+, CH^+, C_2^+, CN^+, CO^+, CS^+, NH^+, N_2^+, NO^+, OH^+, O_2^+, MgO^+, MgS^+, SiH^+, SiC^+, SiN^+, SiO^+, Si_2^+, SiS^+, SO^+, S_2^+, FeO^+, FeS^+, Fe_2^+

Arrhnius-type formula for two-body reactions

$$k_i(T) = A_i \left(\frac{T}{300\ \mathrm{K}}\right)^{\alpha_i} \exp(-\beta_i/T)$$

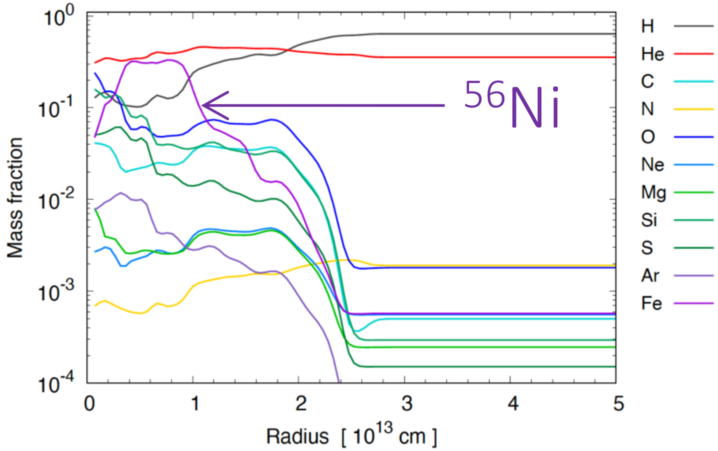


Calculations of different specified directions

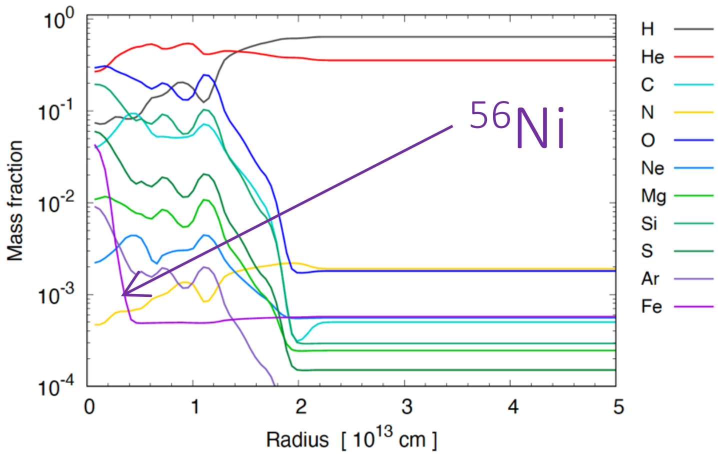
[MO+2024, ApJS, 271, 33]

- Dependence of molecule formation on directions for the binary merger progenitor model (b18.3-high: MO+2020)

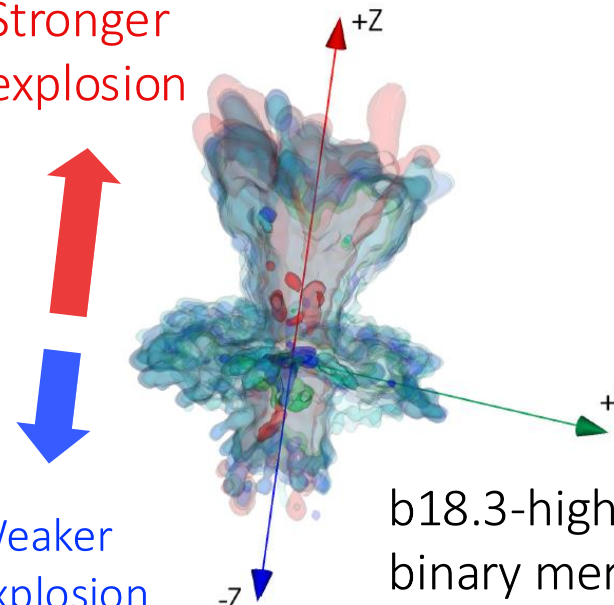
+Z



+Y



Stronger explosion



Weaker explosion

b18.3-high: binary merger progenitor case

^{56}Ni (red), ^{28}Si (green), ^{16}O (blue), ^{12}C (cyan)

Calculations of different specified directions

[MO+2024, ApJS, 271, 33]

- Dependence of molecule formation on directions

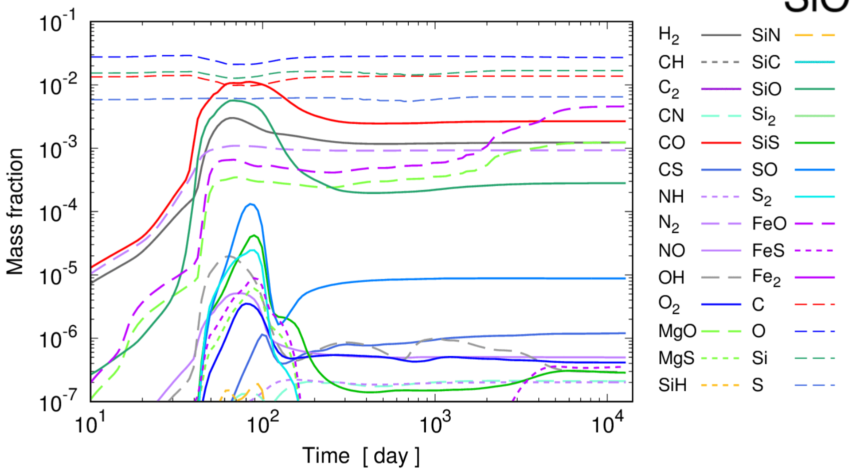
Evolution of mass fractions of moleules

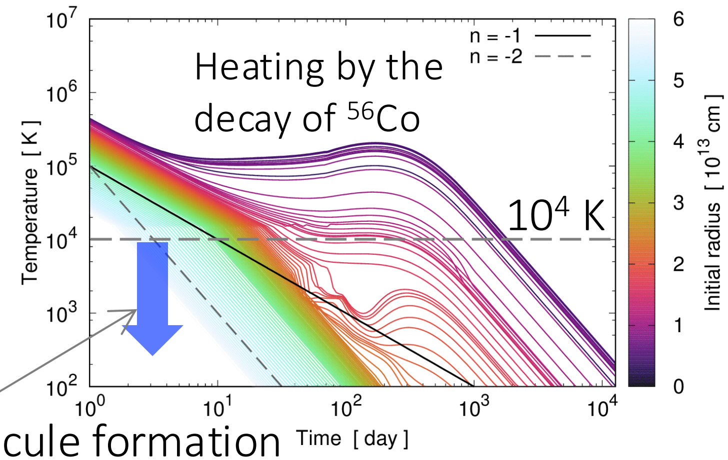
CO

SiO

Evolution of temperatures of gas

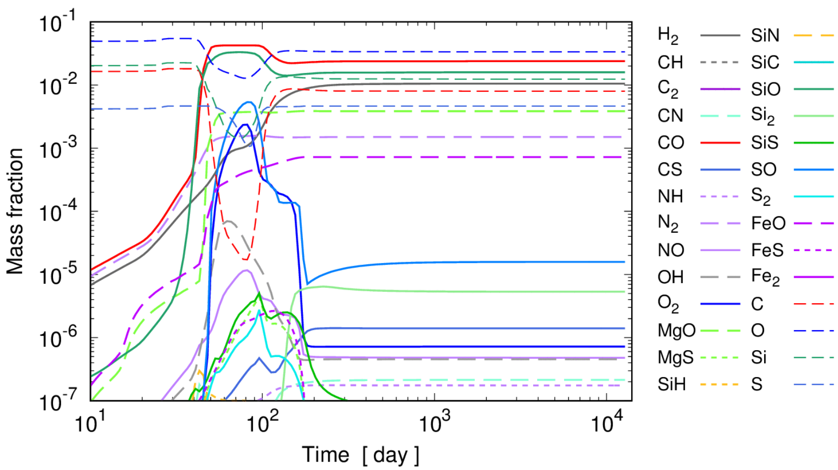
+Z

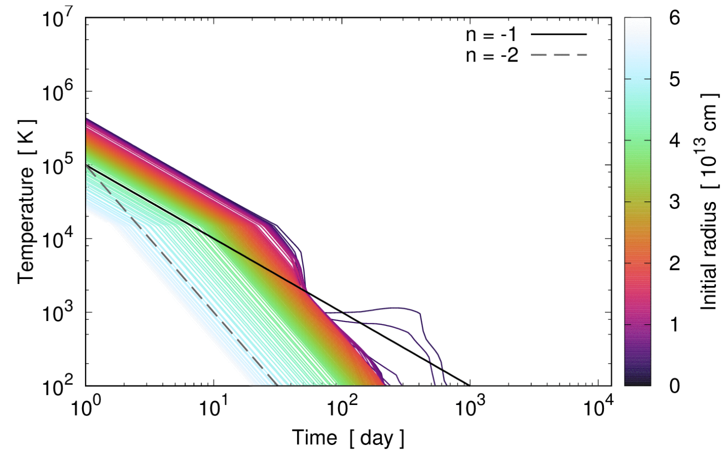




molecule formation

+Y



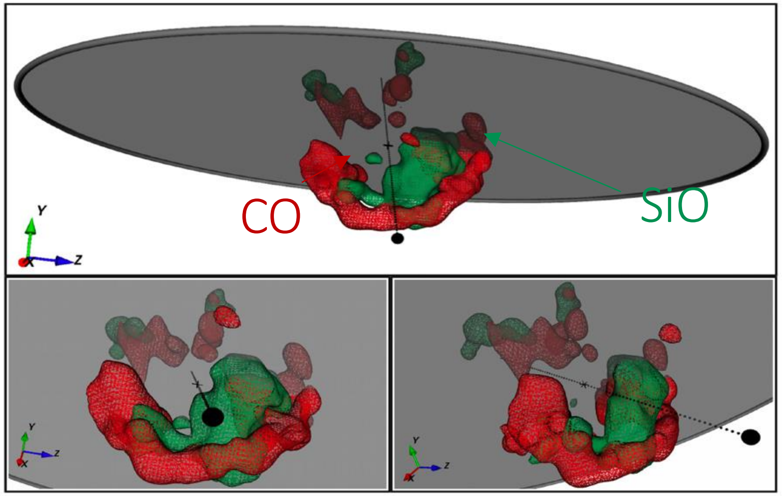


Comparison with the CO and SiO distribution by ALMA observations

[MO+2024, ApJS, 271, 33]

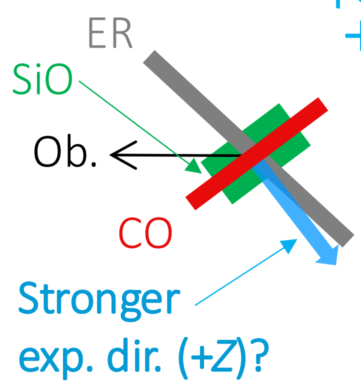
- Comparison of calculations for specified directions with the ALMA observations

ALMA observations

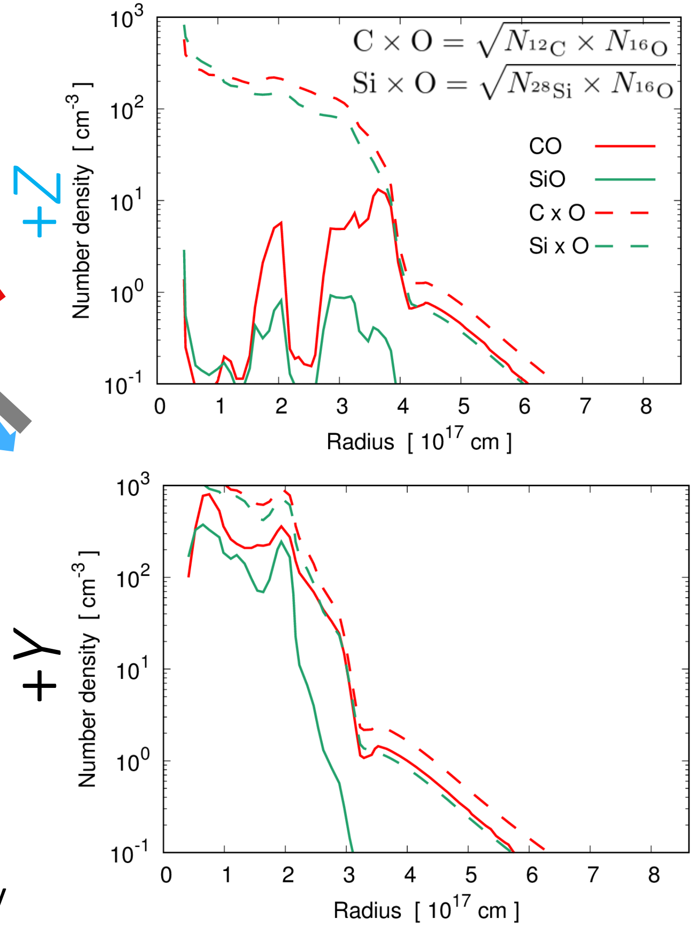


[Abellán+2017, ApJ, 842, L24]

Expected configurations (side view)



Calculation results



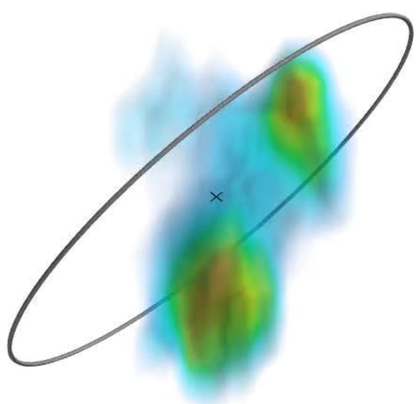
- Calculated CO distribution *may look like a ring*; more direct applications to 3D models are necessary
- The observed ring-like structure *may be a support for a bipolar-like explosion*

3D distribution of iron in the ejecta of SN 1987A by JWST NIRSpec observations

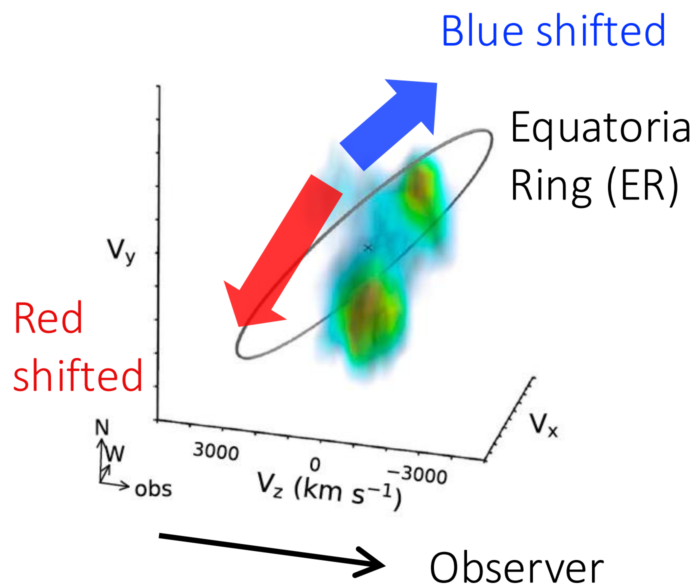
[Larsson+2023, ApJ, 949, L27]

- JWST (James Webb Space Telescope) was newly launched on 25 Dec. 2021
- Structure of the inner ejecta of SN 1987A traced by [Fe I] emission
- *Broken dipole-like* distribution?

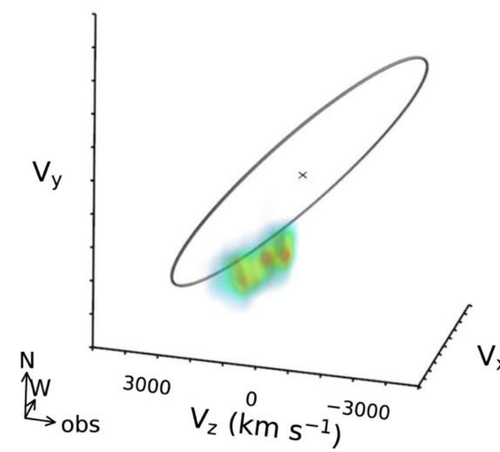
Movie



[Fe I] 1.443 μm



[Fe II] 1.644 μm: $v_z > 1{,}500$ km/s

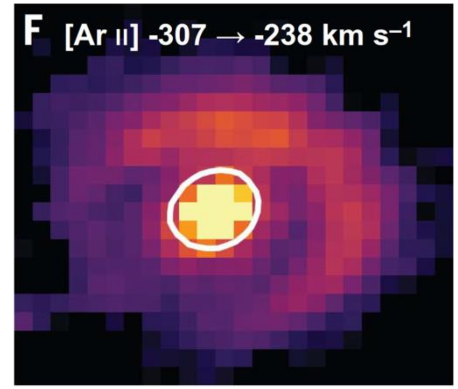


Q: neutrino-driven explosion? magnetorotational explosion? or ?

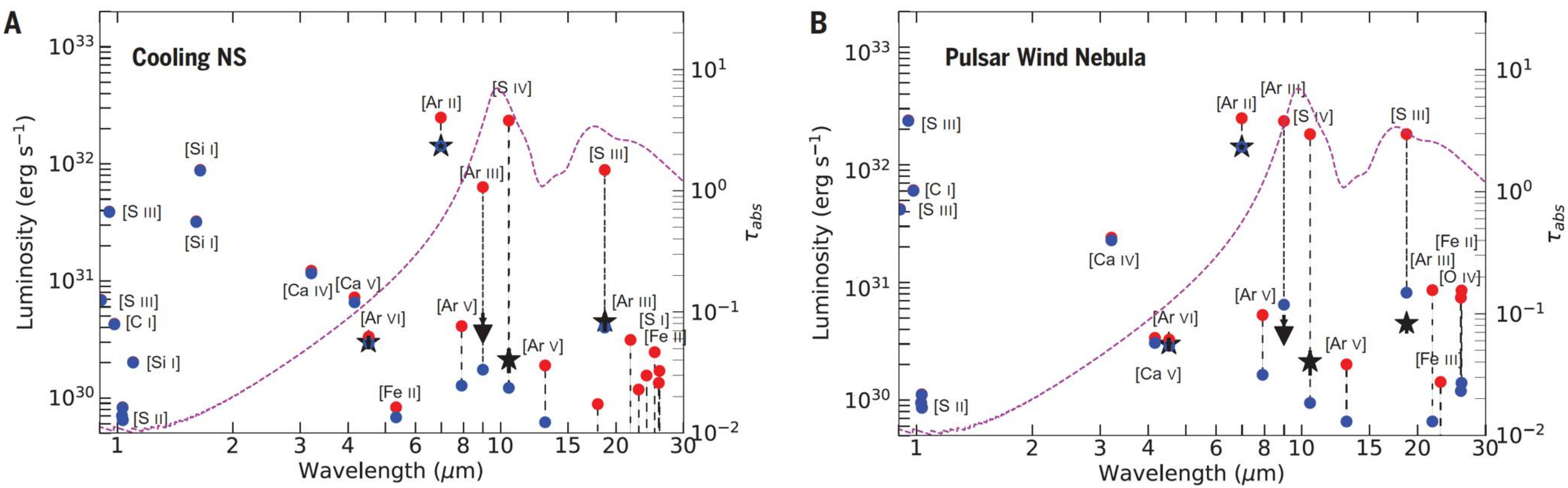
SUPERNOVAE Fransson *et al.*, *Science* **383**, 898–903 (2024) 23 February 2024 [Fransson+24, Science, 383, 898]

Emission lines due to ionizing radiation from a compact object in the remnant of Supernova 1987A

C. Fransson[1*], M. J. Barlow[2†], P. J. Kavanagh[3,4†], J. Larsson[5†], O. C. Jones[6], B. Sargent[7,8], M. Meixner[9], P. Bouchet[10], T. Temim[11], G. S. Wright[6], J. A. D. L. Blommaert[12], N. Habel[9], A. S. Hirschauer[7], J. Hjorth[13], L. Lenkić[14], T. Tikkanen[15], R. Wesson[16], A. Coulais[10,17], O. D. Fox[7], R. Gastaud[18], A. Glasse[6], J. Jaspers[3,4], O. Krause[19], R. M. Lau[20], O. Nayak[21], A. Rest[7,8], L. Colina[22], E. F. van Dishoeck[23,24], M. Güdel[19,25,26], Th. Henning[19], P.-O. Lagage[10], G. Östlin[1], T. P. Ray[4], B. Vandenbussche[27]



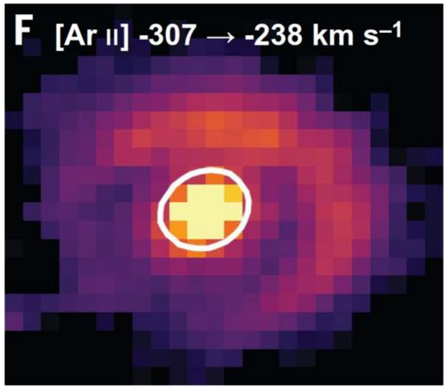
- JWST spectroscopic observations (narrow infrared lines of argon and sulfur) have revealed the *existence of the neutron star (NS) of SN 1987A*?



Additional indirect evidence of the NS of SN 1987A

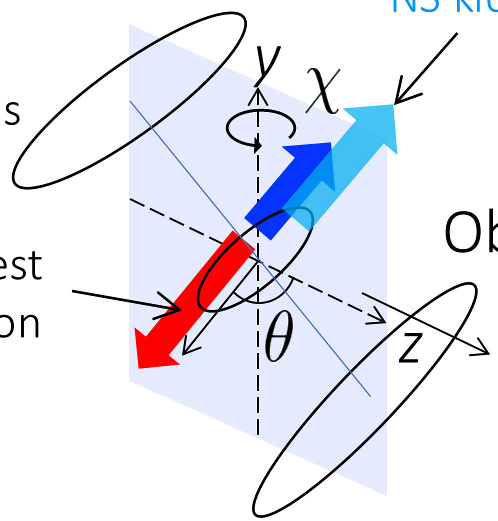
Inferred neutron star (NS) kick velocity

[Fransson+24, Science, 383, 898]



lines are blueshifted

- From the blue-shifted lines
  - *Line of sight* kick velocity: -259.6 ± 0.4 km s^{-1}
- From the position of the line in the sky
  - The kick velocity *on the sky*: 324 ± 206 km s^{-1}
- *Total kick velocity*: **406 ± 206 km s^{-1}**



[MO+2020, 888, 111]

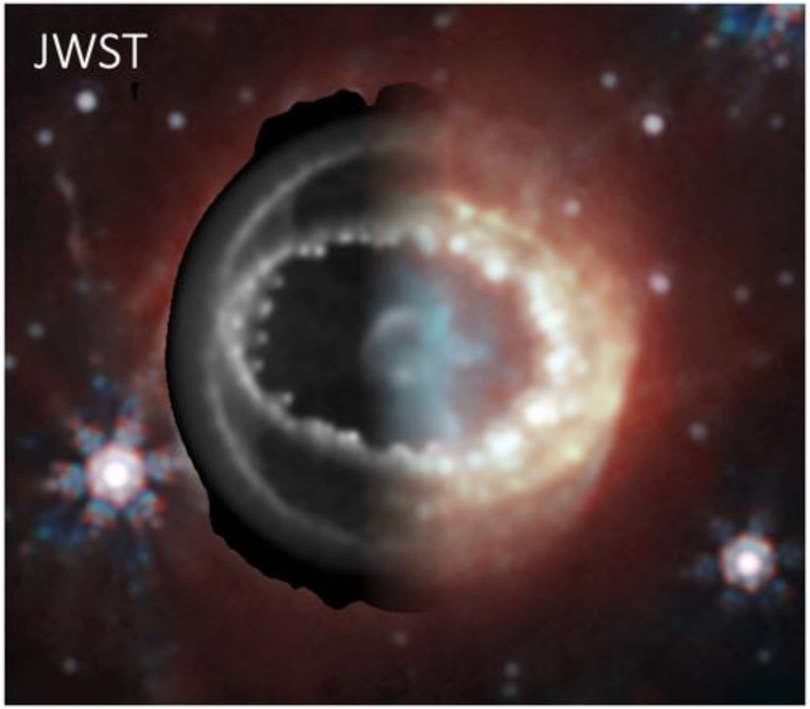
- From our 3D hydrodynamical model [MO+20]
  - Kick velocity: ∼300 km s^{-1}
  - From momentum conservation

$$\boldsymbol{v}_{\rm NS} = -\boldsymbol{P}_{\rm gas}/M_{\rm NS} = -\frac{1}{M_{\rm NS}}\int \rho \boldsymbol{v} dV$$

- *JWST observations (broken dipole iron dist.) may suggest the situation is not so simple*

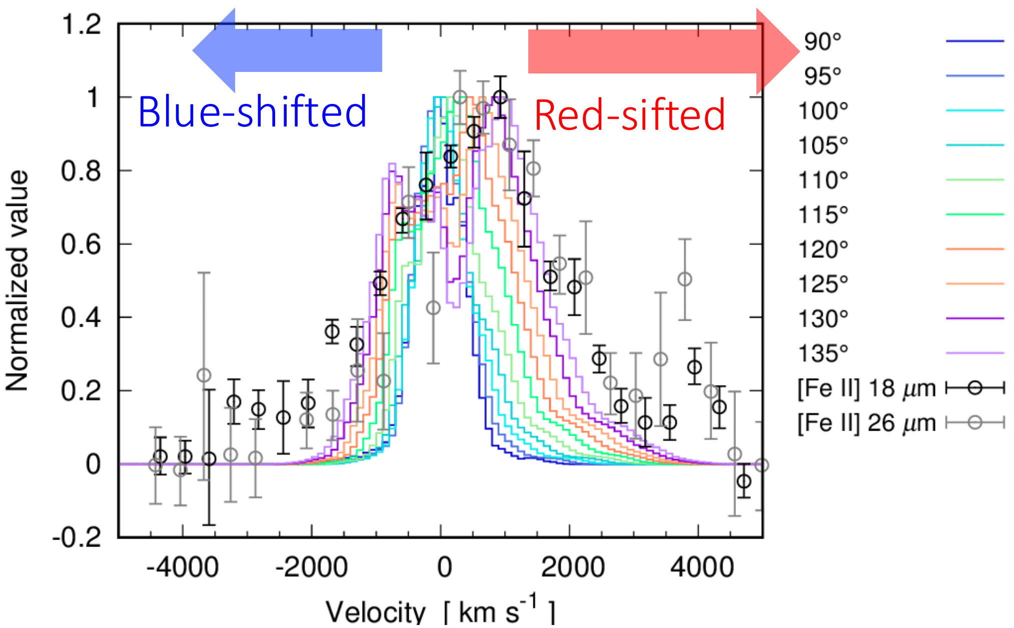
Defects in the current models

Comparison with JWST image and our model [MO+20; Orlando+20]



Courtesy of S. Orlando

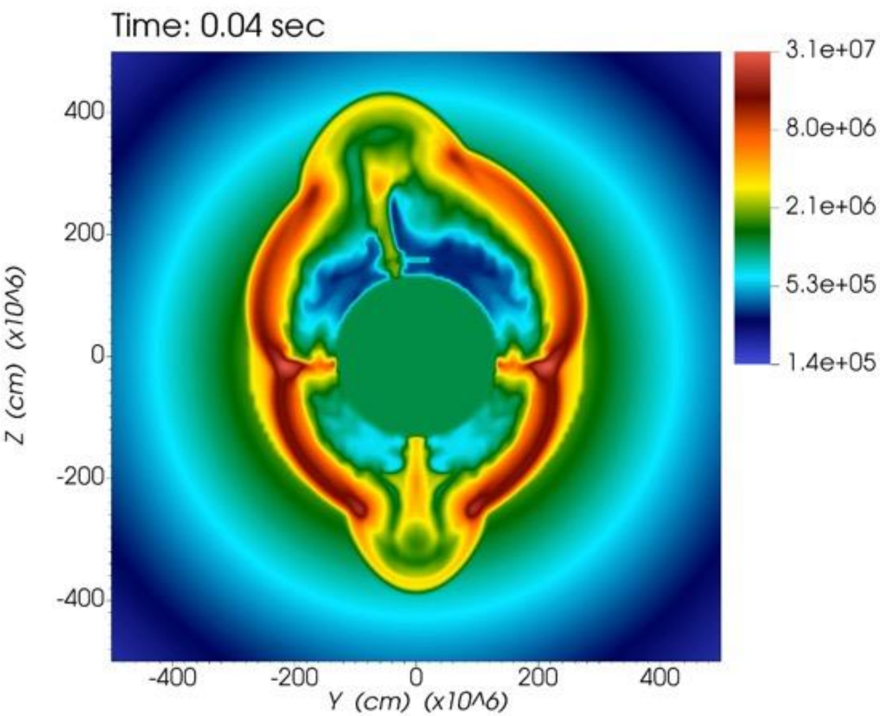
b18.3 (binary model) [MO+20]

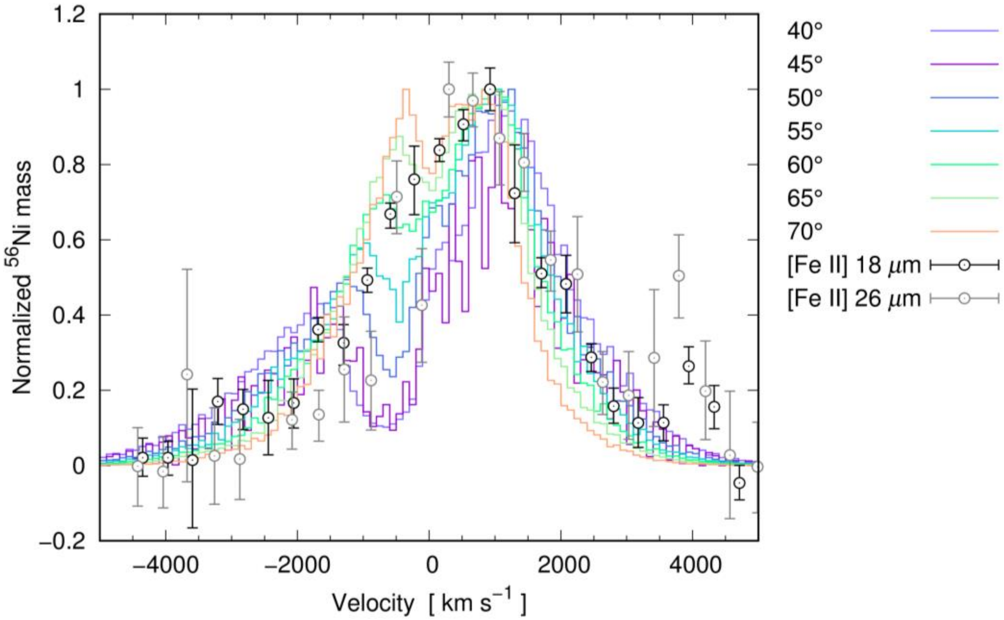


- There are several discrepancies between the models and observations
- *Further study may shed light on the open questions, e.g., the explosion mechanism*

Revisiting 3D hydro modeling of SN 1987A

One of the *preliminary* results [MO et al., in prep.]





- Simulations with more general/flexible injection of energy (injection by energy, momentum, and mass fluxes with finite timescales at the effective inner boundary) compared with MO+20

Summary

- SN 1987A is an ideal object to understand the *early evolution of core-collapse supernovae from the explosion to its supernova remnant*

- An *asymmetric bipolar-like explosion* with a *binary merger* progenitor model better explains several observations (iron lines, X-ray light curves, the triple-ring structure)

- We conducted the *first molecular formation calculations based on global 3D hydro models*, which may qualitatively reproduce the observed CO ring-like distribution by ALMA

- Recent *JWST observations* of SN 1987A further motivate us to study this object for interpreting those properly and addressing open questions, e.g., what is the explosion mechanism of SN 1987A