〜 中性子星の観測と理論 〜 研究活性化ワークショップ
Aug. 10, 2021

Three-dimensional hydrodynamical simulations unravel the progenitor, supernova, and supernova remnant connection in SN 1987A

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PRACE

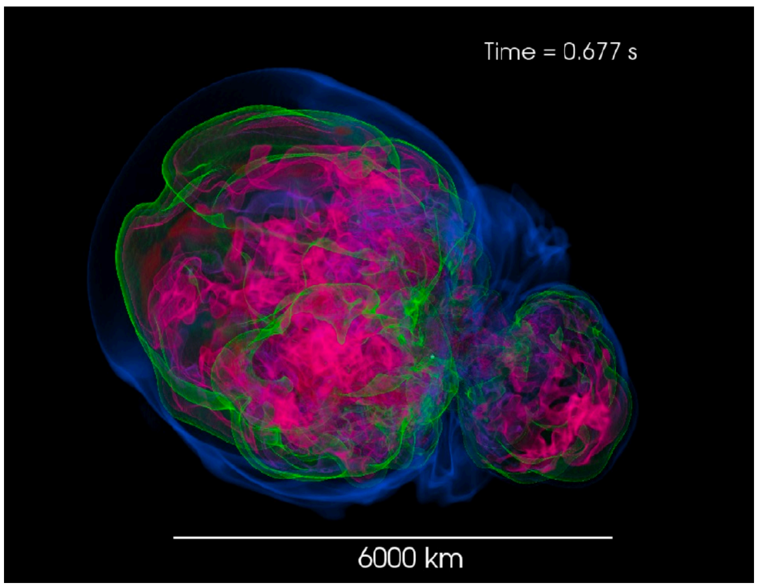
Outline

- Introduction of our SN-SNR project
- Recent application to Cassiopeia A supernova remnant

- Observational backgrounds of SN 1987A
- SN-SNR simulations for SN 1987A
  - 3D hydro simulations for SN phases (MO+20)
    - Progenitor model dependence on the matter mixing
  - 3D MHD simulations for early SNR phases (Orlando+20)
    - X-ray synthesis
- Constraints on the properties of the NS of SN 1987A
- (Molecule formation calculations (preliminary))

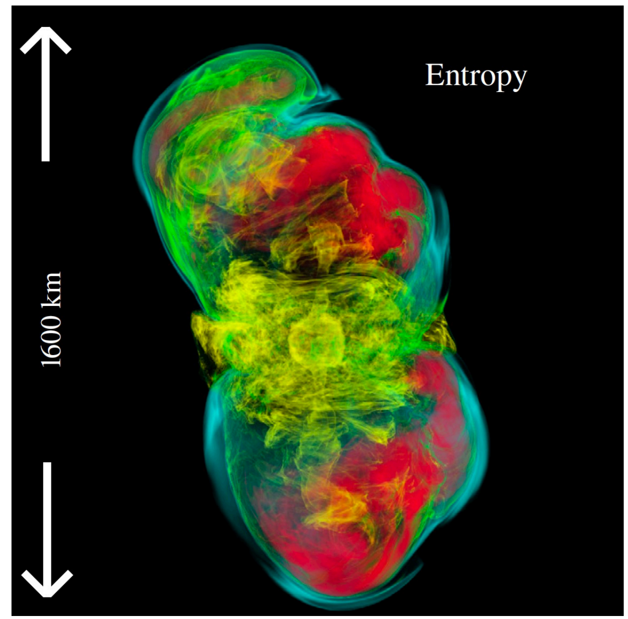
What are the explosion mechanism and morphology of core-collapse supernovae (CCSNe)?

Delayed neutrino heating mechanism aided by SASI and/or convection



Vartanyan+19, MNRAS, 482, 351

Magnetorotationally-driven explosion (and/or neutrino heating)



Mösta+14, ApJL, 785, L29

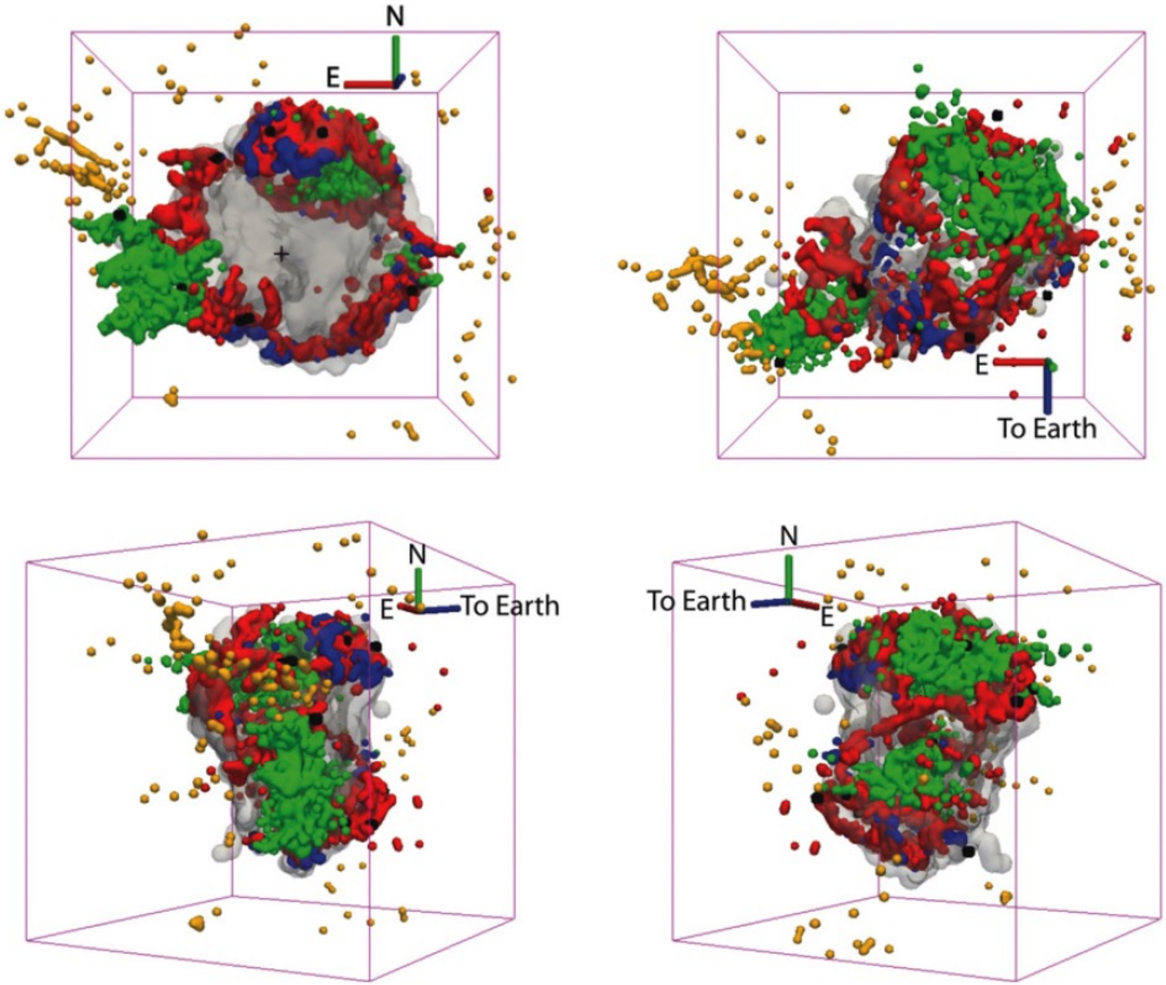
Volume rendered distributions of entropy

Core-collapse supernova explosions are essentially non-spherical?

3D structure of Cassiopeia A supernova remnant

Delaney et al. 2010

X-rays & Infrared observations



X-rays: Chandra

Infrared: Spitzer

Green: X-ray Fe-K

Black: X-ray Si XIII

Red: IR [Ar II]

Blue: high [Ne II]/[Ar II] ratio

Grey: IR [Si II]

Yellow: optical outer ejecta

Overturn of Fe and Si?

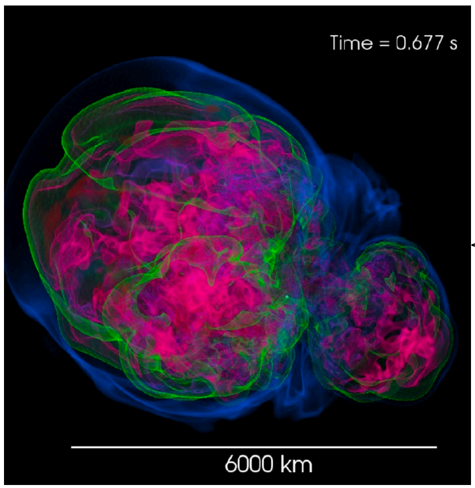
Supernova (SN) explosions to their supernova remnants (SNRs)

Supernova explosion $t < 1$ sec

Shock breakout $t < 1000$ sec

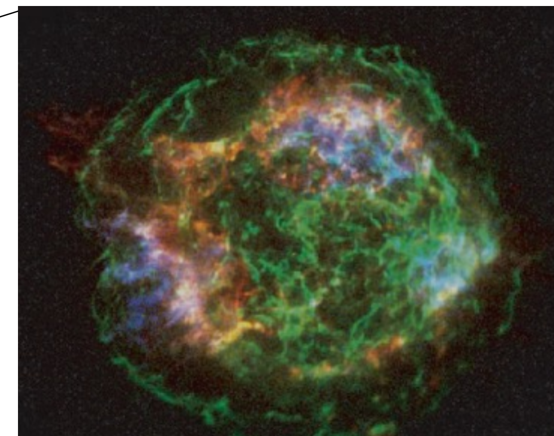
supernova $t < 1$ yr

Supernova remnant $t \sim 500$ yr



Vartanyan+19, MNRAS, 482, 351

Mixing?



Electromagentic signals

$10^7 - 10^9$ cm

Radius of the progenitor star

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

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 (SN1987A)

3D Hydro (HD) simulations of SNe

Nozawa, T.

Molecules/Dsut formation

Orlando, S.

3D HD/Magnetohydro (MHD) simulations of SNRs

Dohi, A.

Radiation hydro

Cooling model of NSs

Kozyreva, A.

X-ray emission

Miceli, M./Greco, E.

Optical light curves

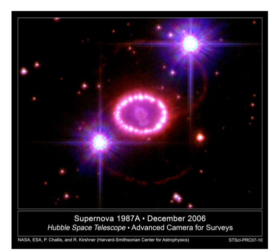
X-ray light curves/images

Vibration and/or rotational transitions of molecules

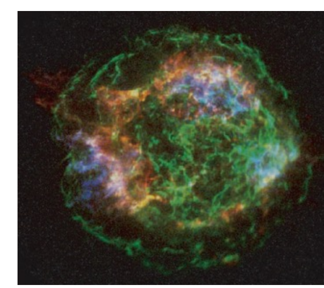
Observations to be comared

Comparison with observations

- Origin of asymmetries
- SN Explosion
- Progenitor star
- Neutron star (NS)



SN 1987A (> 30 yr)



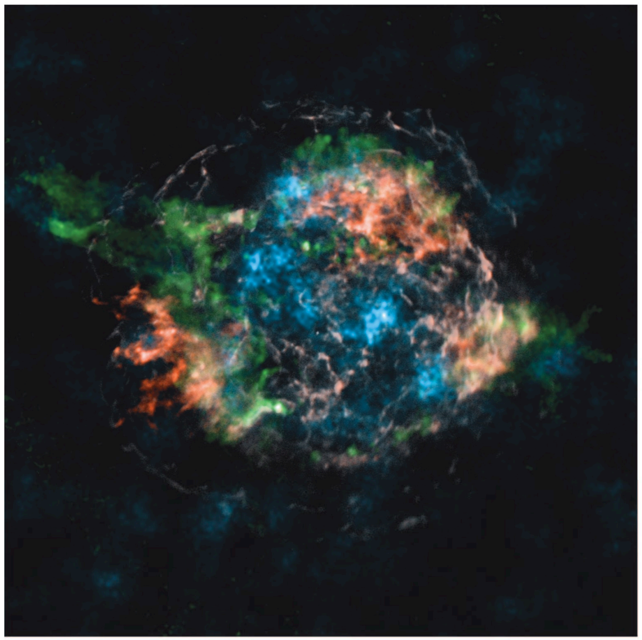
Cassiopeia A (> 330 yr)

Unraveling progenitor-SN-SNR connection

The case of Cassiopeia A supernova remnant

Asymmetries from gamma-ray emission of radioactive ^{44}Ti in Cassiopeia A (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
- $M(^{44}Ti) = (1.25 \pm 0.3) \times 10^{-4} M_\odot$

Radioactive decay

$$^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$$

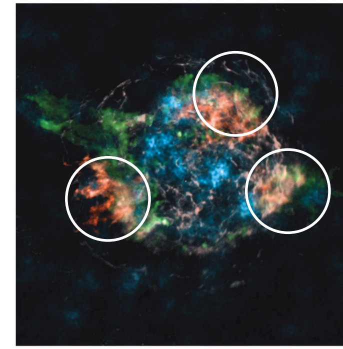
$\tau_{1/2} = 60$ yr $\tau_{1/2} = 4$ h

Distributions of Fe and ^{44}Ti are different!

Caution: only shocked Fe can emit X-rays

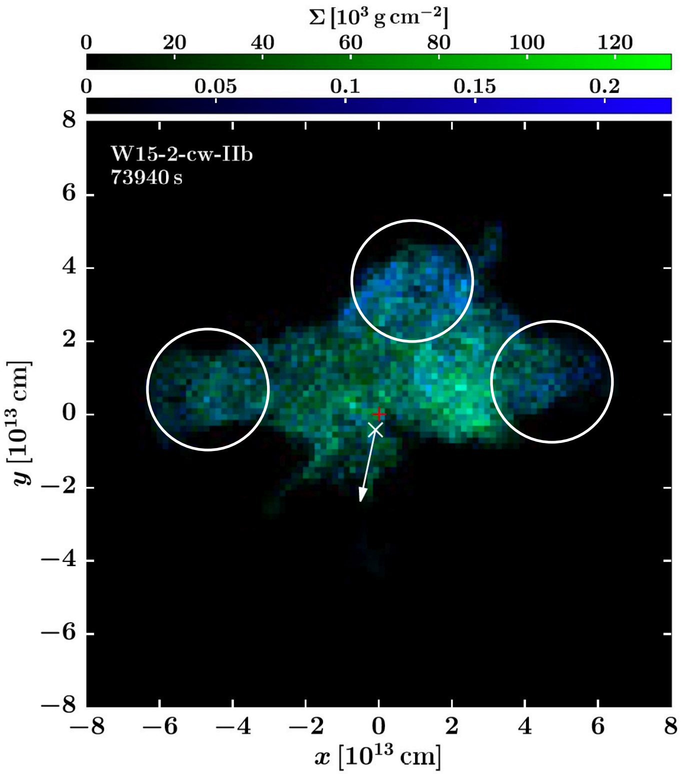
Grefenstette et al. 2014, Nature, 506, 339

3D CCSN model resembling Cassiopeia A

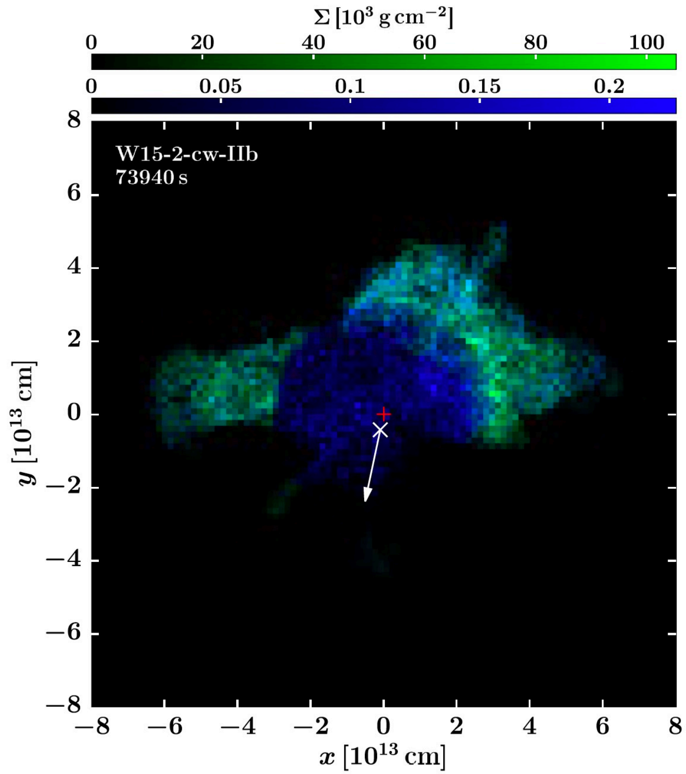


3D hydro simulation of a neutrino-driven CCSN

All ^{56}Ni and ^{44}Ti are shown



Inner ^{56}Fe (^{56}Ni) is hidden



^{56}Ni → ^{56}Co → ^{56}Fe

^{56}Ni (green)

^{44}Ti (blue)

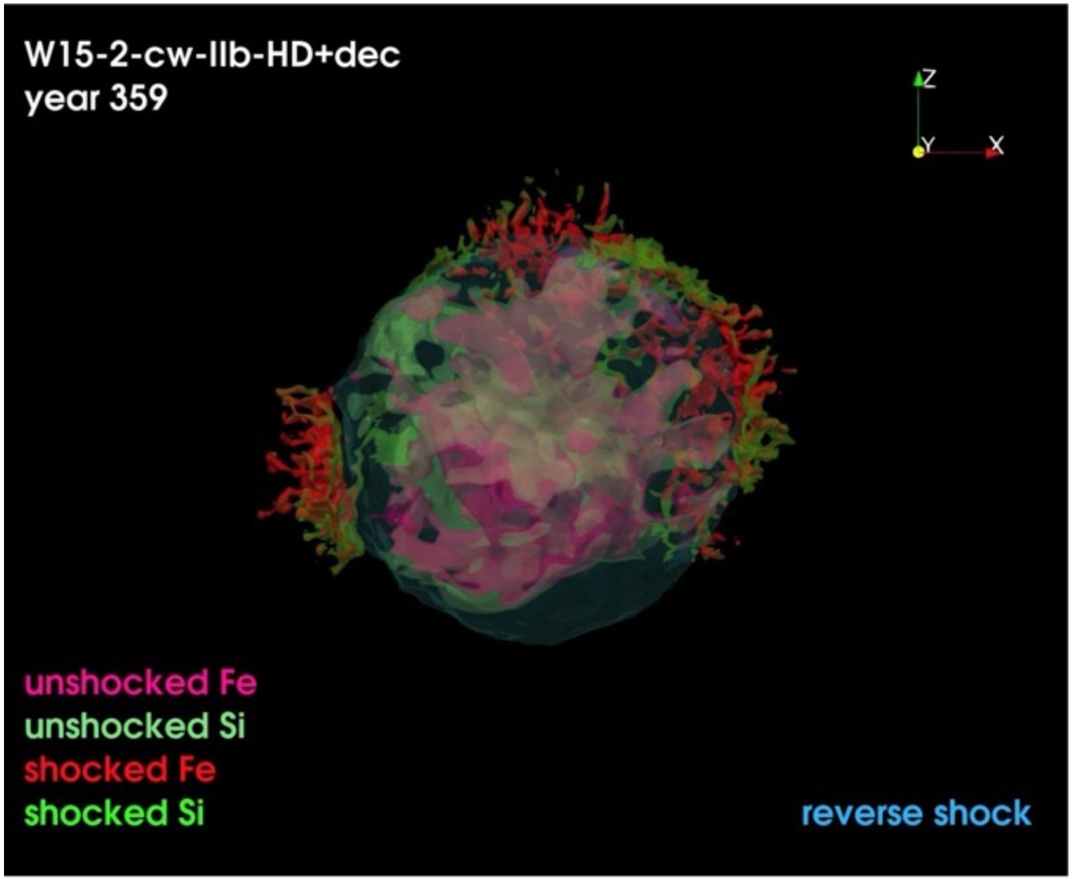
Wongwathanarat et al. 2017, ApJ, 842, 13

Wongwathanarat, A., Janka, H.-Th.

3D SN-SNR simulation for Cassiopeia A

Orlando, S.

Distribution of Fe and Si (Movie)

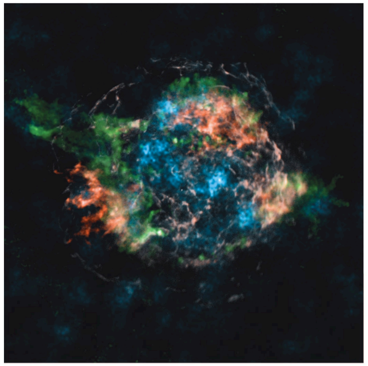


- Fe and Si rich ejecta is heated by the reverse shock of the SNR
- After the pass of the RS, instabilities develop
- Overturn of Fe and Si, crown-like structure or cavities are realized

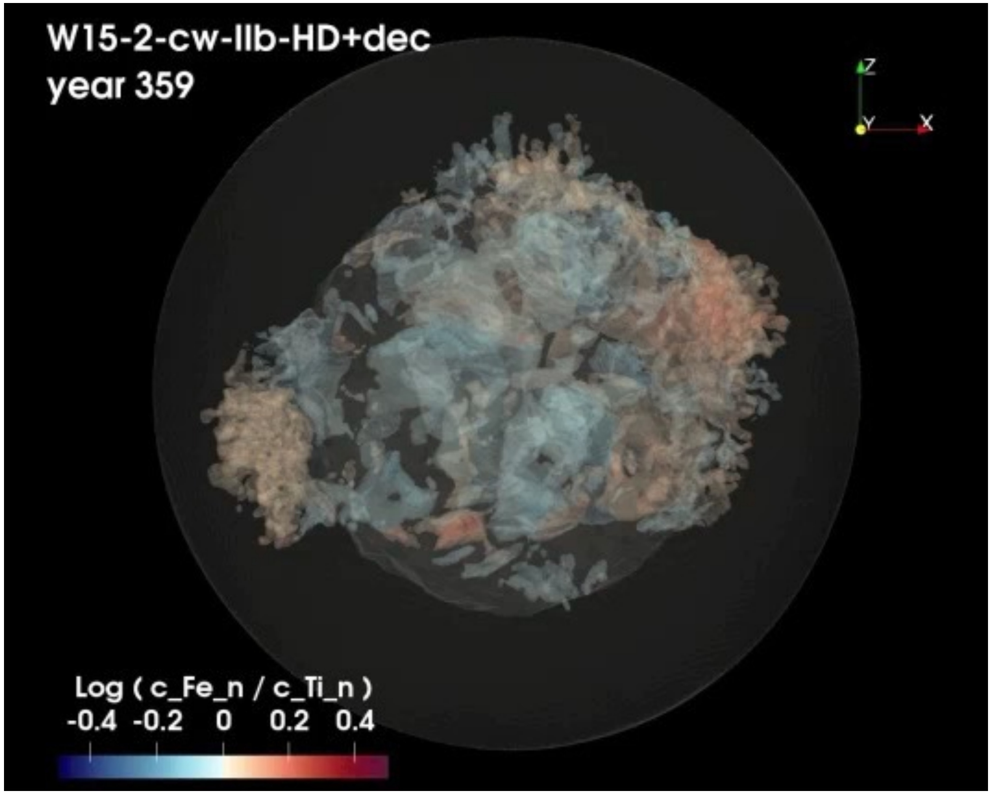
Orlando et al. 2021, A&A, 645, A66

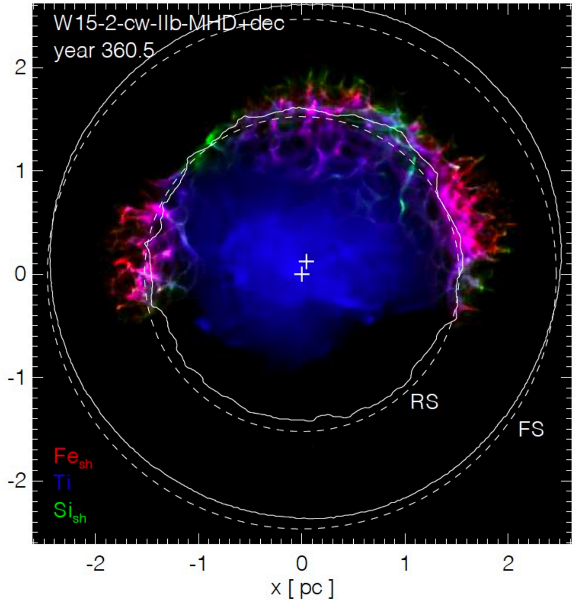
3D Sketchfab model https://skfb.ly/6UJYu

3D SN-SNR simulation for Cassiopeia A



$\log[(dM_{\mathrm{Fe}}/M_{\mathrm{Fe}})/(dM_{\mathrm{Ti}}/M_{\mathrm{Ti}})]$





$$\mathrm{EM} = \int_0^L n_e n_i dx$$

EM: Emission measure

Fe, Si: only for shocked ejecta

Ti: both shocked and unshocked ejecta

Orlando et al. 2021, A&A, 645, A66

Article

High-entropy ejecta plumes in Cassiopeia A from neutrino-driven convection

Sato et al. 2021, Nature, 592, 538

https://doi.org/10.1038/s41586-021-03391-9

Received: 15 July 2020

Toshiki Sato[1,2,3,4] ✉, Keiichi Maeda[5], Shigehiro Nagataki[6,7], Takashi Yoshida[8,9], Brian Grefenstette[10], Brian J. Williams[2], Hideyuki Umeda[8], Masaomi Ono[6,7] & John P. Hughes[11]

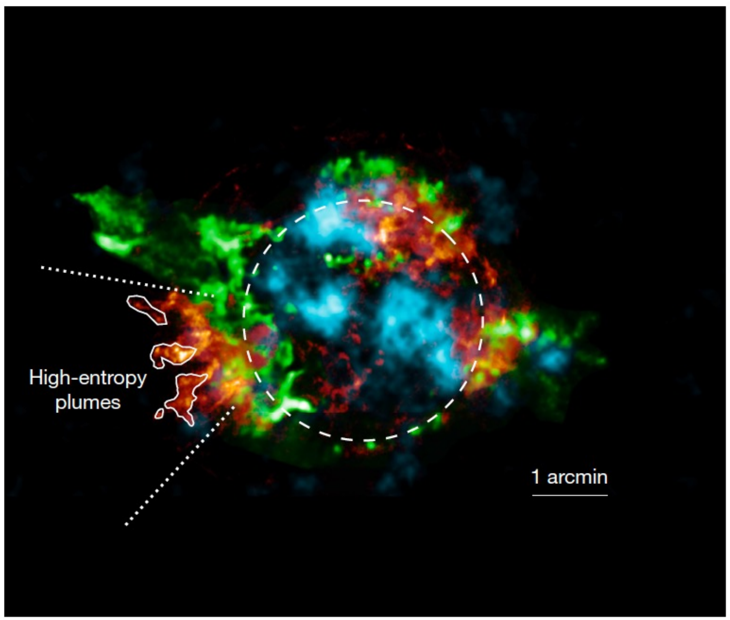
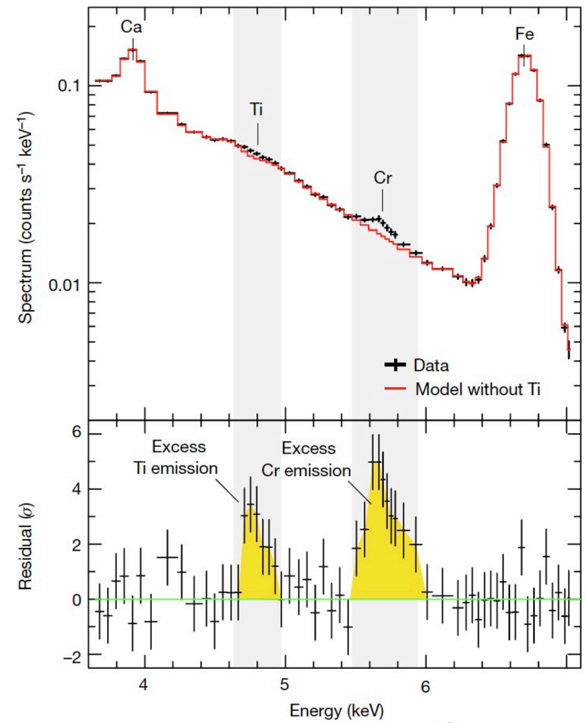


Fig. 1 | Asymmetric distribution of elements in Cassiopeia A supernova remnant. The Fe ejecta (red) are popping out in the southeastern direction. The Chandra ratio map of the Si/Mg band is shown in green where the jet structures can be seen at the northeastern and southwestern directions. The ^{44}Ti observed by NuSTAR[15,16] is shown in blue, which is concentrated in the central region. The dashed circle shows the mean location of the reverse shock[28]. From the white contour region, we extracted the X-ray spectrum in this study. At the southeastern Fe-rich region, the firm detection of ^{44}Ti has not been reported[16].

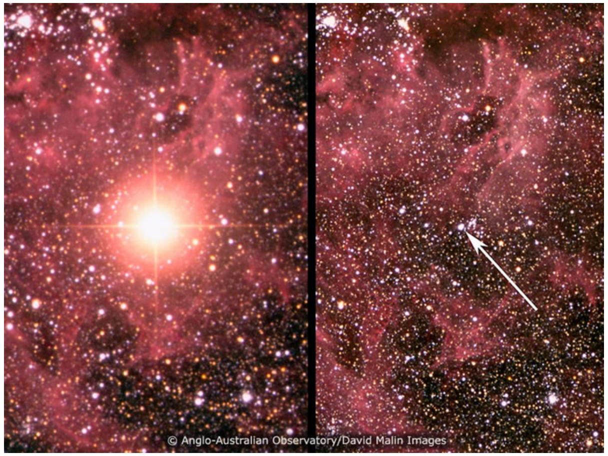


Detection of stable Ti (mainly ^{48}Ti) for the first time!

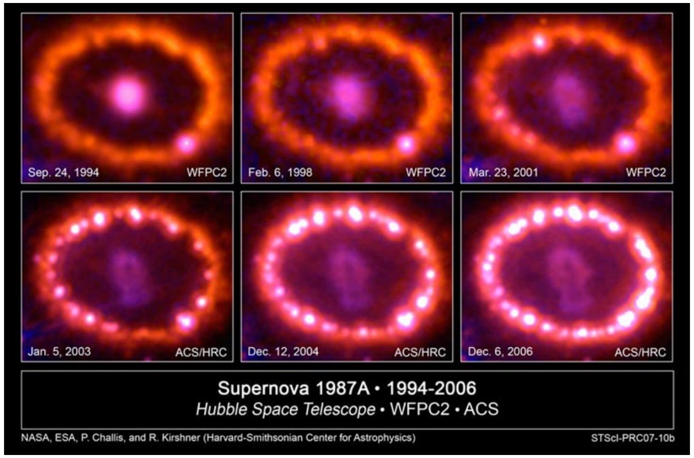
Observed abundance ratios (Ti/Fe, Cr/Fe) support a neutrino-driven explosion (nucleosyntheis in a high-entropy regime)

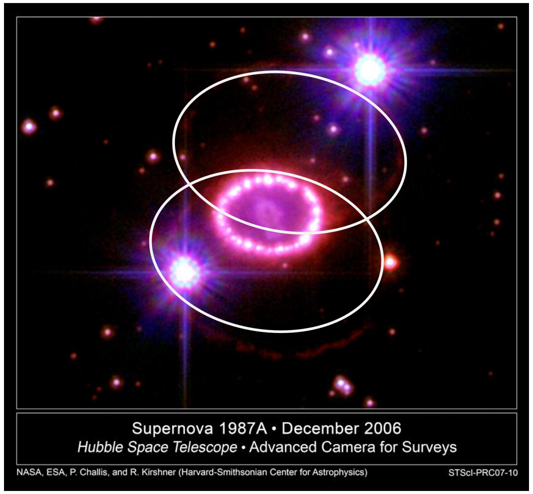
The case of SN 1987A: Observations of SN 1987A

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

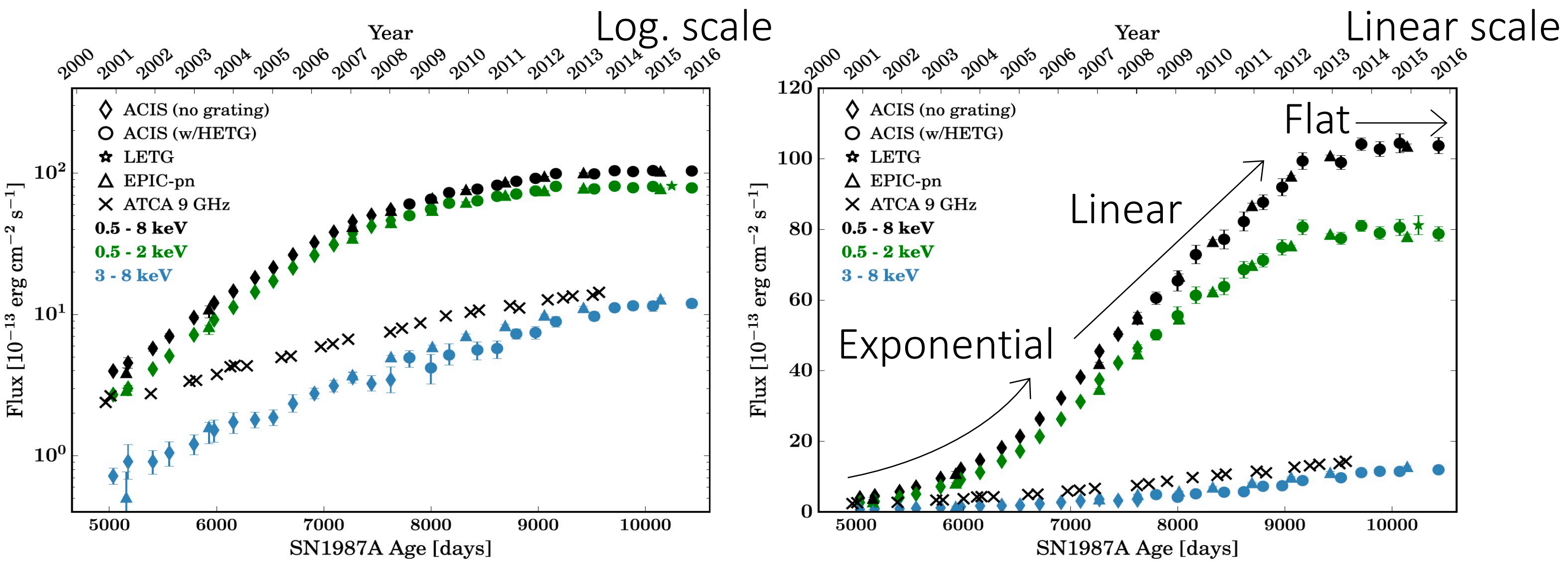




More than 30 years have passed from the detection;
SN 1987A has entered a phase of young SNR

X-ray light curves, covering late 16 years

Frank et al. 2016, ApJ, 829, 40

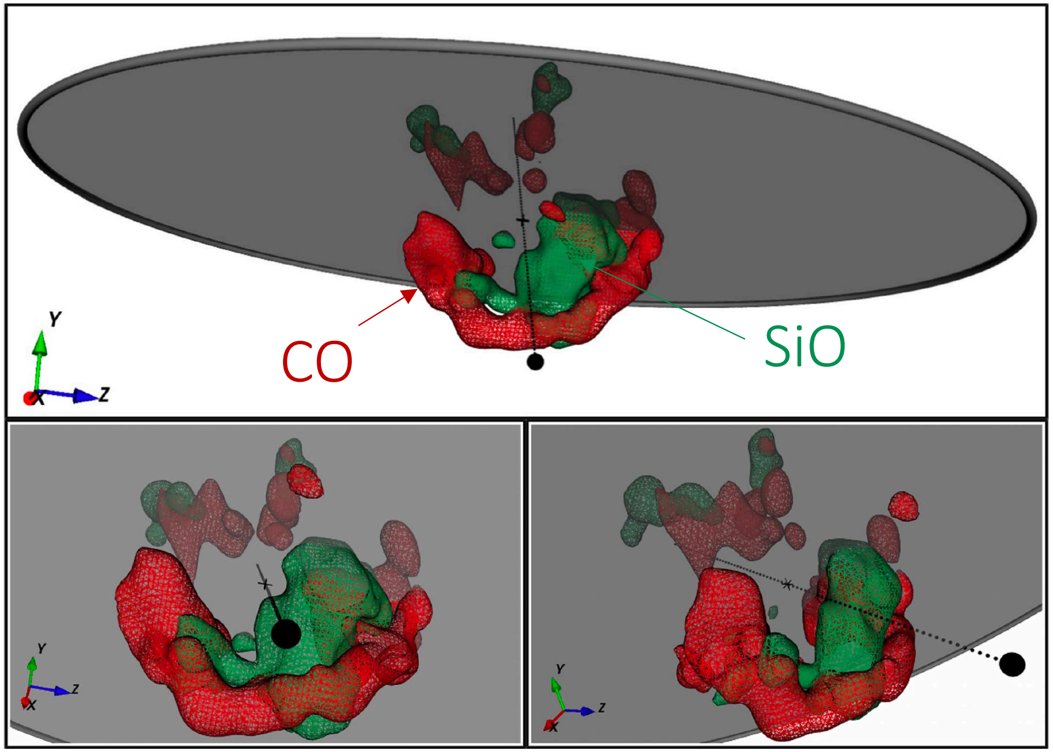


- Sharp upturn of soft components (6000 days): blast wave impacting ER
- Linear evolution (7000 - 8000 days): stop of density increase
- Nearly constant flux (9500 days): blast wave leaves the dens ER
- Hard component increases slowly: shocks moving lower density regions

Distribution of molecules seen in 3D!

Abellán et al. 2017, ApJ, 842, L24

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



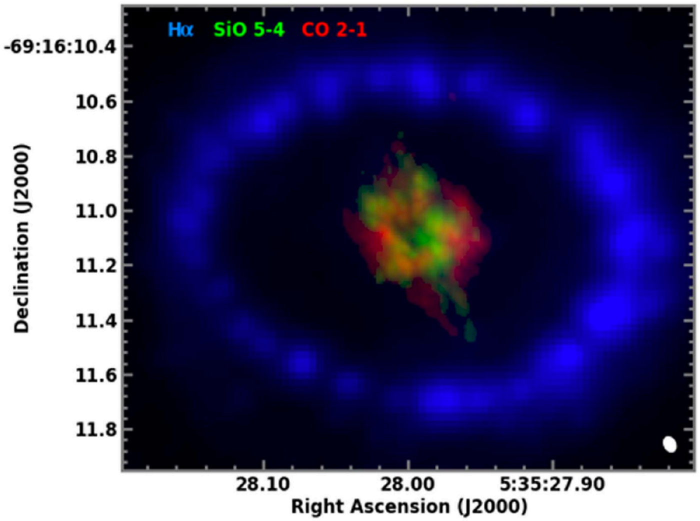


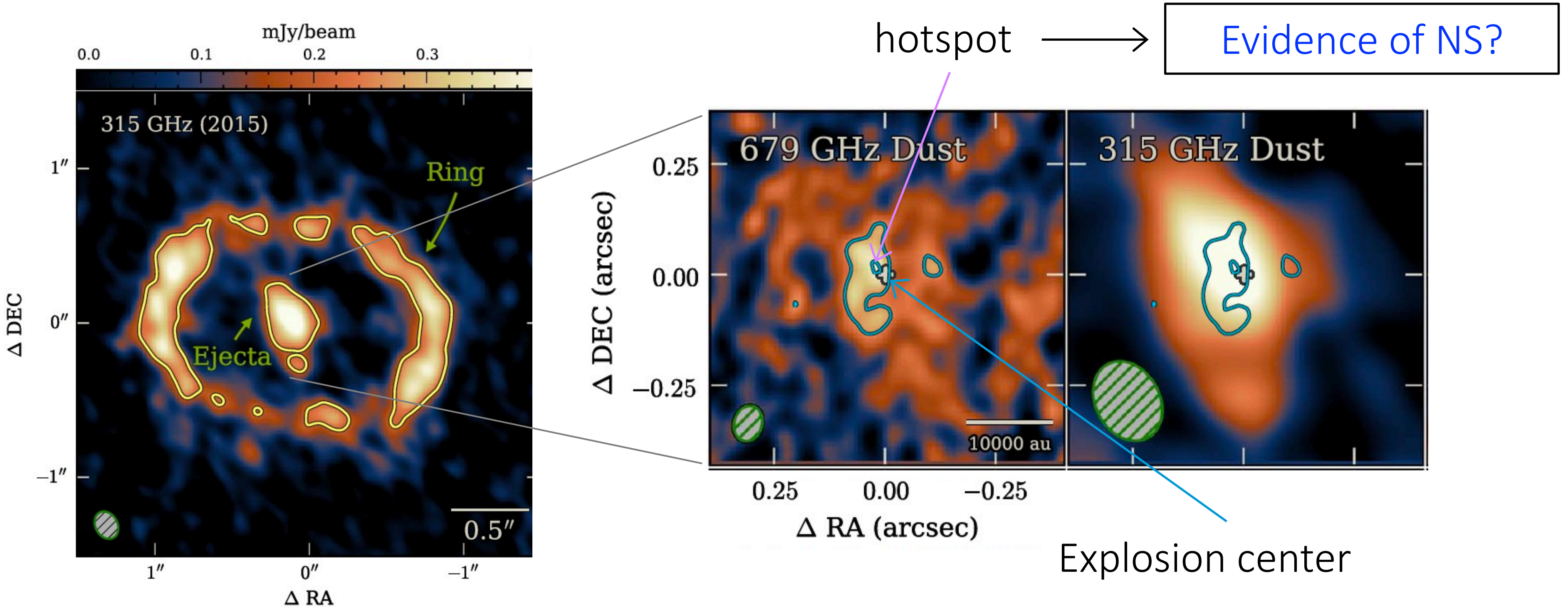
Figure 1. Molecular emission and Hα emission from SN 1987A. The more compact emission in the center of the image corresponds to the peak intensity maps of CO 2−1 (red) and SiO 5−4 (green) observed with ALMA. The surrounding Hα emission (blue) observed with *HST* shows the location of the circumstellar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

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

Cigan et al. 2019, ApJ, 886, 51

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

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



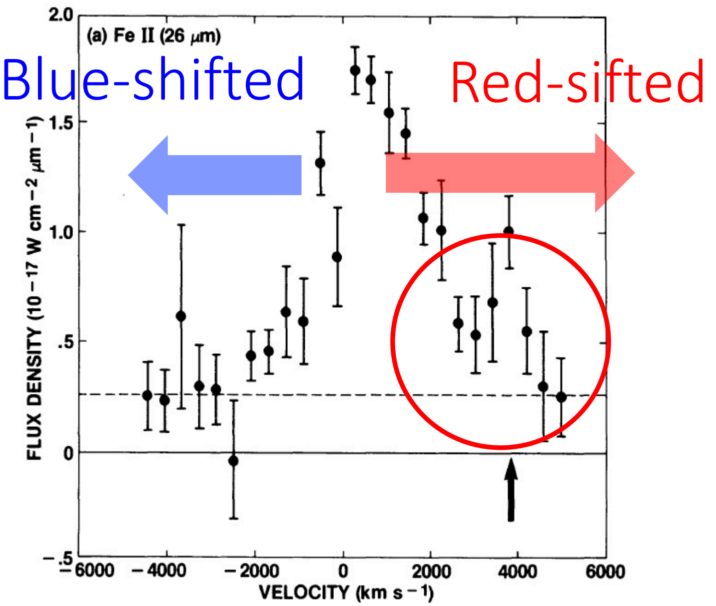
- The dust peak could be stemed from an additional heating by a compact souce of $L_{\text{bol, dust}} = (40\text{-}90)\ L_{\odot}$

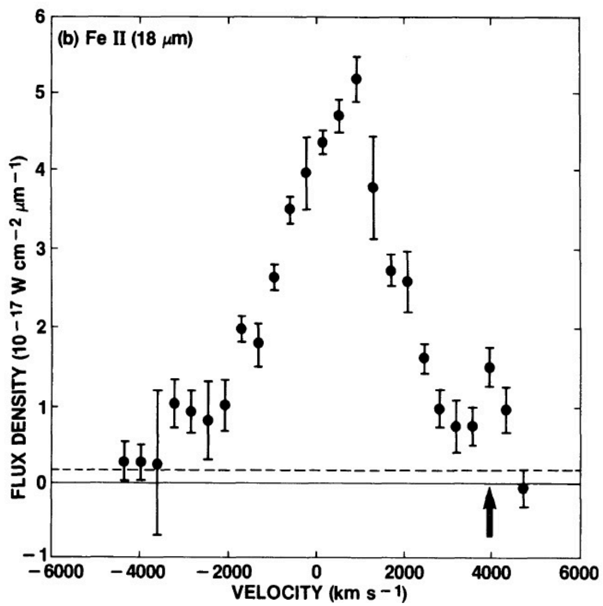
Matter mixing problem in SN 1987A

SN 1987A: High velocity Fe : matter mixing?

[Fe II] line profiles

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



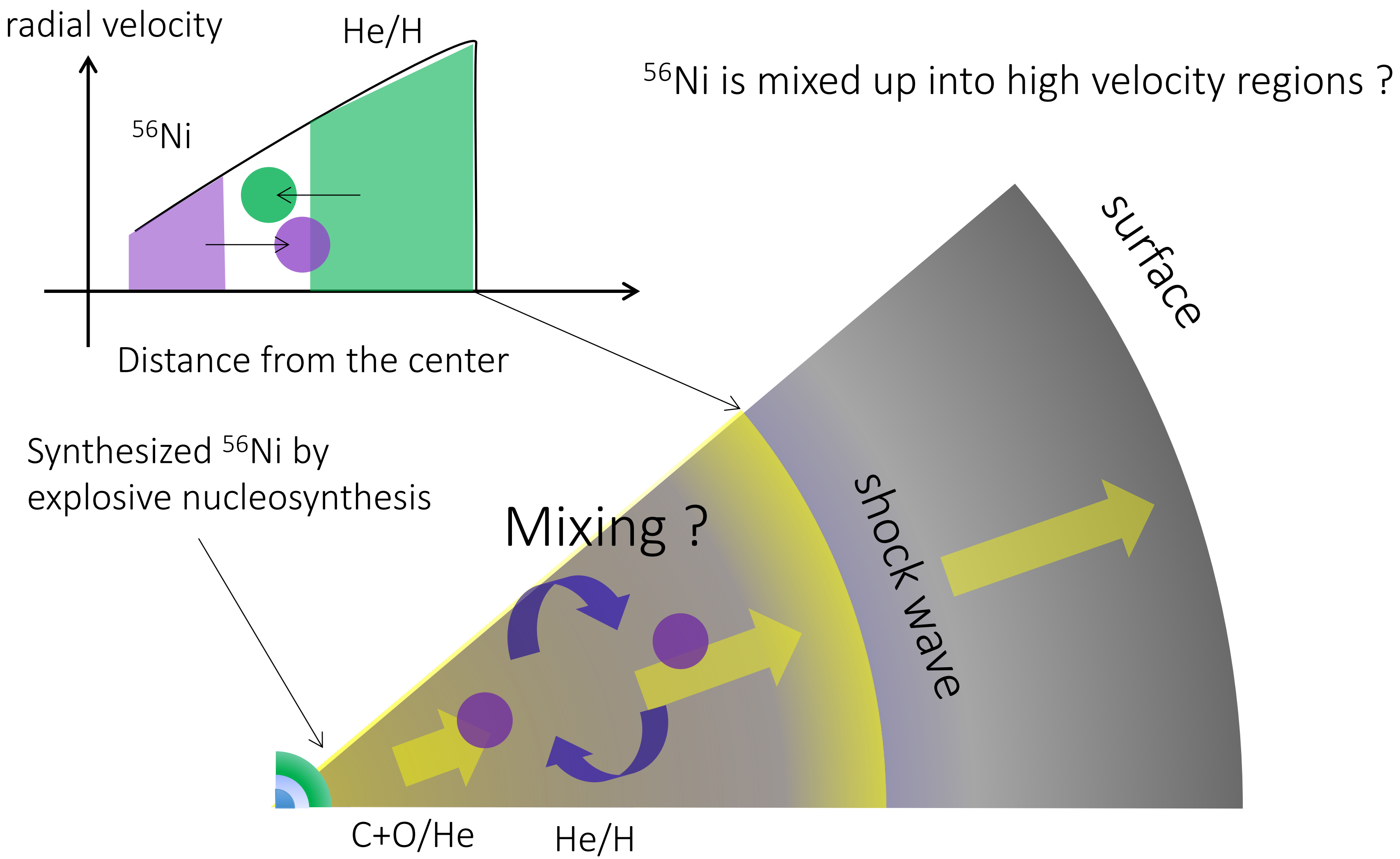


- High velocity tails of [Fe II] line profiles reach (> 4,000 km/s)

Fast ^{56}Fe (^{56}Ni → ^{56}Co → ^{56}Fe) motion → Matter mixing ?

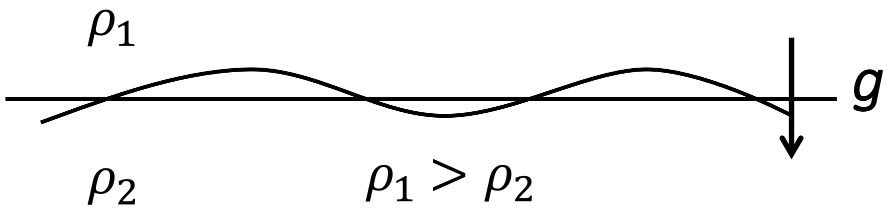
Red-shifted side is dominated → Asymmetric explosion?

Matter mixing in supernova explosions

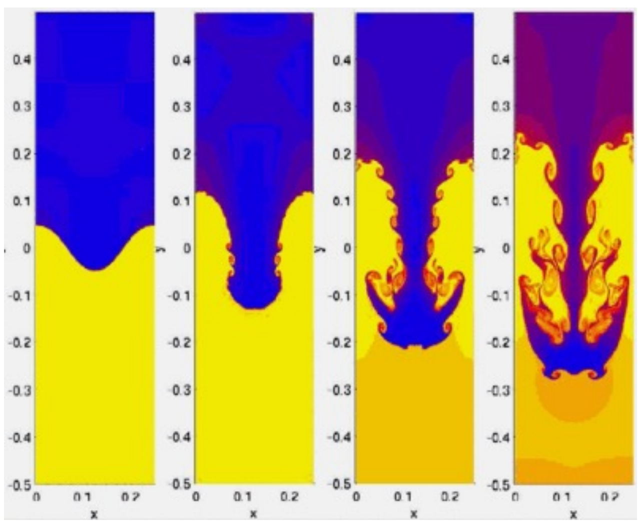


Mechanisms of mixing: Asymmetric explosion/ Fluid instabilities?

Rayleigh-Taylor (RT) instability



$\rho_1 > \rho_2$



Shengtai Li & Hui Li 2006

Self-similar solution (Sedov 1959)

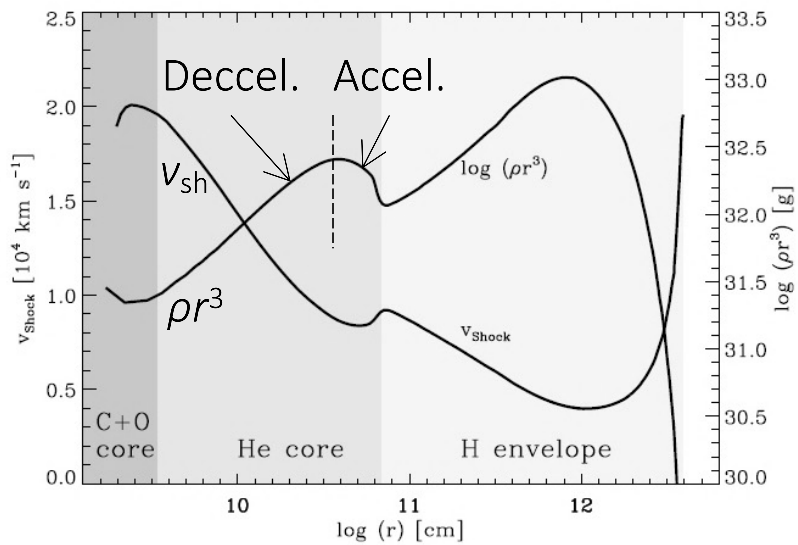
$$\rho(r) \propto r^{-\omega} \quad v_{\rm sh} \propto t^{(\omega-3)/(5-\omega)}$$

RT unstable condition

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

$\rho\, r^3 \searrow$ → accelerate

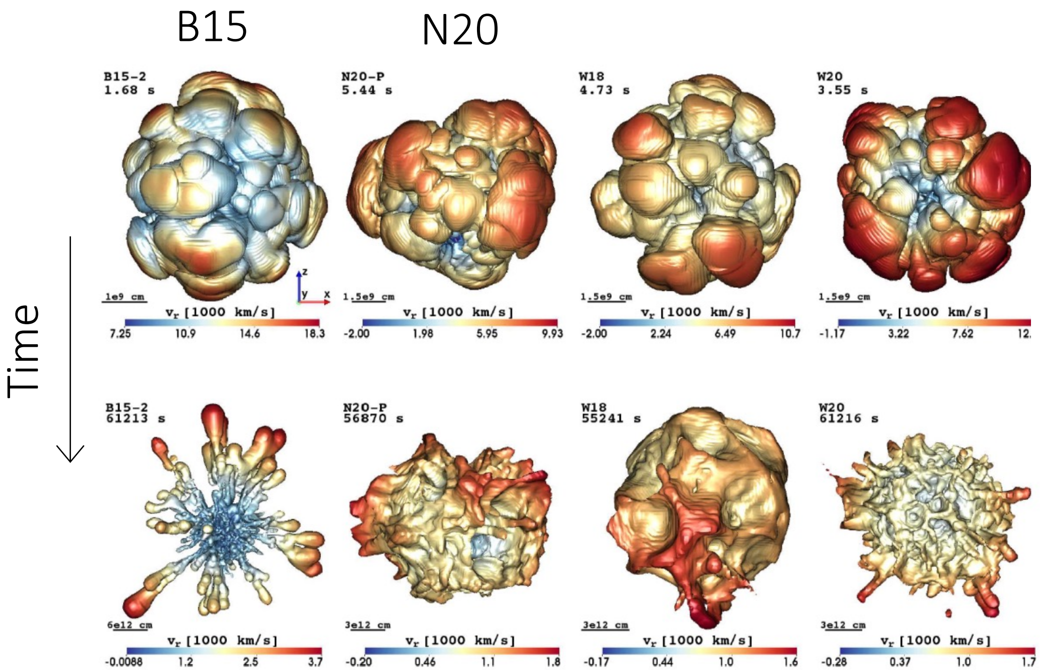
$\rho\, r^3 \nearrow$ → decelerate



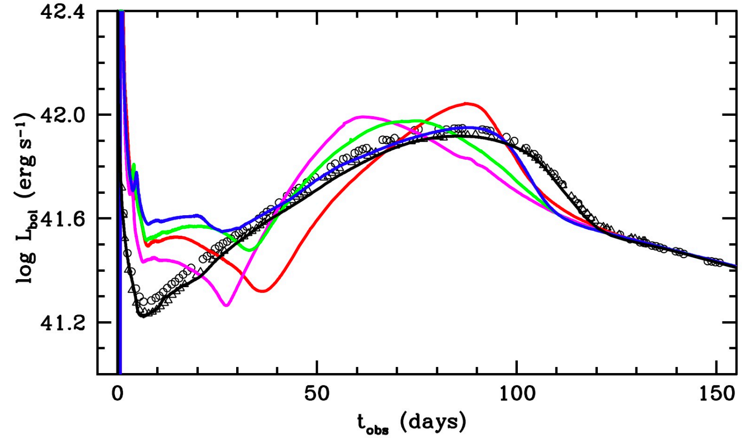
Density profile (ρ r^3) of a progenitor star

Figure is taken from Kifonidis et al. 2006

3D simulation of neutrino-driven explosions: Dependence of matter mixing on progenitors



Utrobin, Wangwathanarat, Janka and Mueller 2015



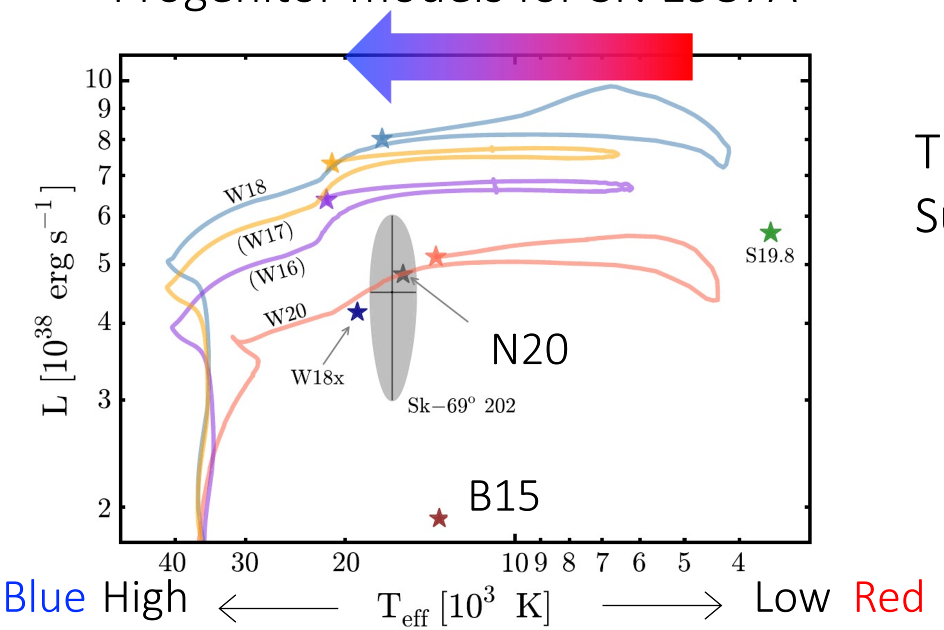
Model	$\langle v\rangle^{bulk}_{Ni}$	v^{bulk}_{Ni} ($km\,s^{-1}$)	$\langle v\rangle^{tail}_{Ni}$	M_{mix}	δM_H ($M_\odot$)	$\langle X\rangle$
B15-1	921	3103	3241	11.45	0.111	0.040
B15-2	1222	3355	3490	11.20	0.172	0.062
B15-3	1807	4977	5678	12.31	0.329	0.118
N20-P	924	1635	1790	4.80	0.262	0.039
N20-C	930	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 light curves (LCs) are not fully consistent with observed LCs

Progenitor models for SN 1987A

Single star progenitor models for SN 1987A

- Progenitor models for SN 1987A



Hertzsuprung-Russel diagram

Red to blue transition 2x10^4 yr ago

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

N: Nomoto & Hashimoto 1988

W: Woosely et al. 1988

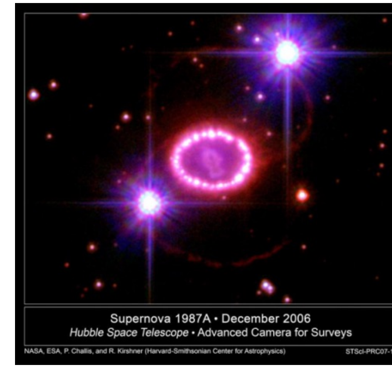
S: Sukhbold et al. 2016

Sukhbold et al. 2016

Table 1
SN 1987A Models

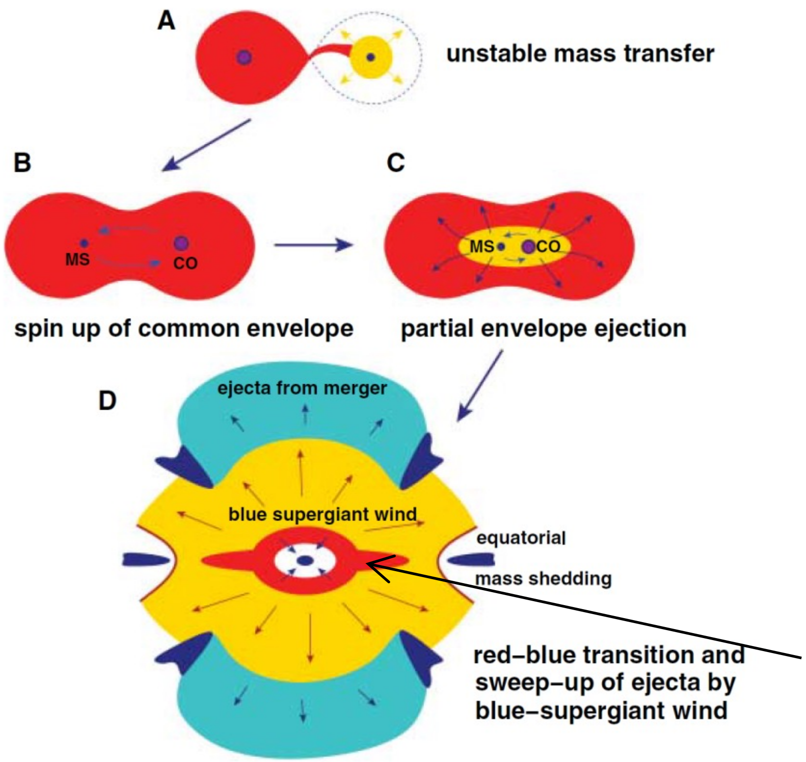
Model	$M_{preSN}/M_\odot$	$M_{He}/M_\odot$	$M_{CO}/M_\odot$	$L/10^{38}$ erg s^{-1}	T_{eff}	$\zeta_{2.5}$	$Z/Z_\odot$	Rotation
W18	16.93	7.39	3.06	8.04	18,000	0.10	1/3	Yes
N20	16.3	6	3.76	5.0	15,500	0.12	low	No
S19.8	15.85	6.09	4.49	5.65	3520	0.13	1	No
W15	15	4.15	2.02	2.0	15,300	...	1/4	No
W20	19.38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

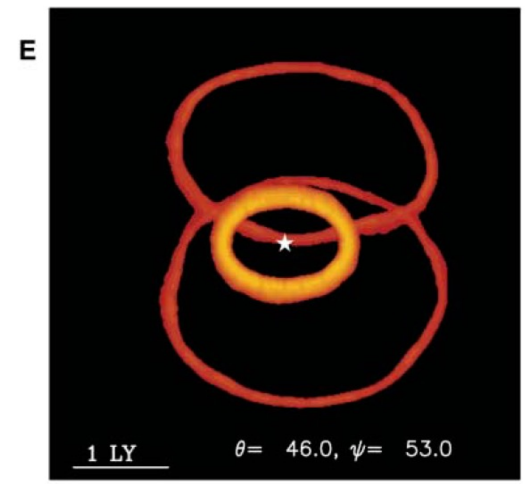
The progenitor of SN 1987A was the outcome of a binary merger?



- 3D smoothed particle hydrodynamic (SPH) simulations

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





A single blue supergiant (BSG)
just before the explosion

Morris & Podsiadlowsky 2007, Science, 315, 1103

3D hydro simulations of CCSN: Matter mixing in SN 1987A

Initial setup: radial velocity distribution

Parameters

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

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

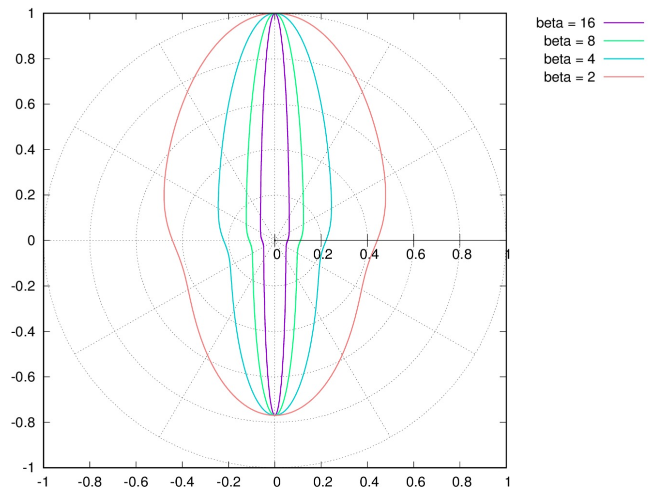
E_{in}: Injected energy

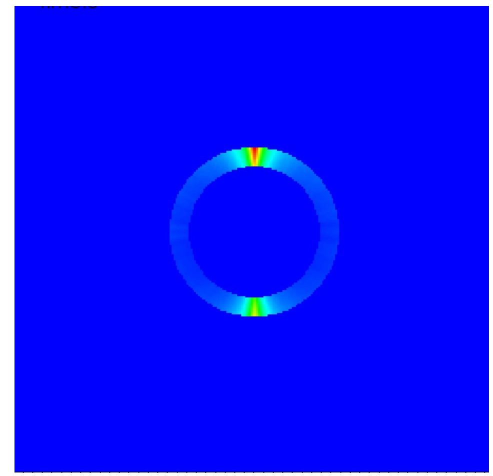
Ranges:

E_{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 : Normalization factor

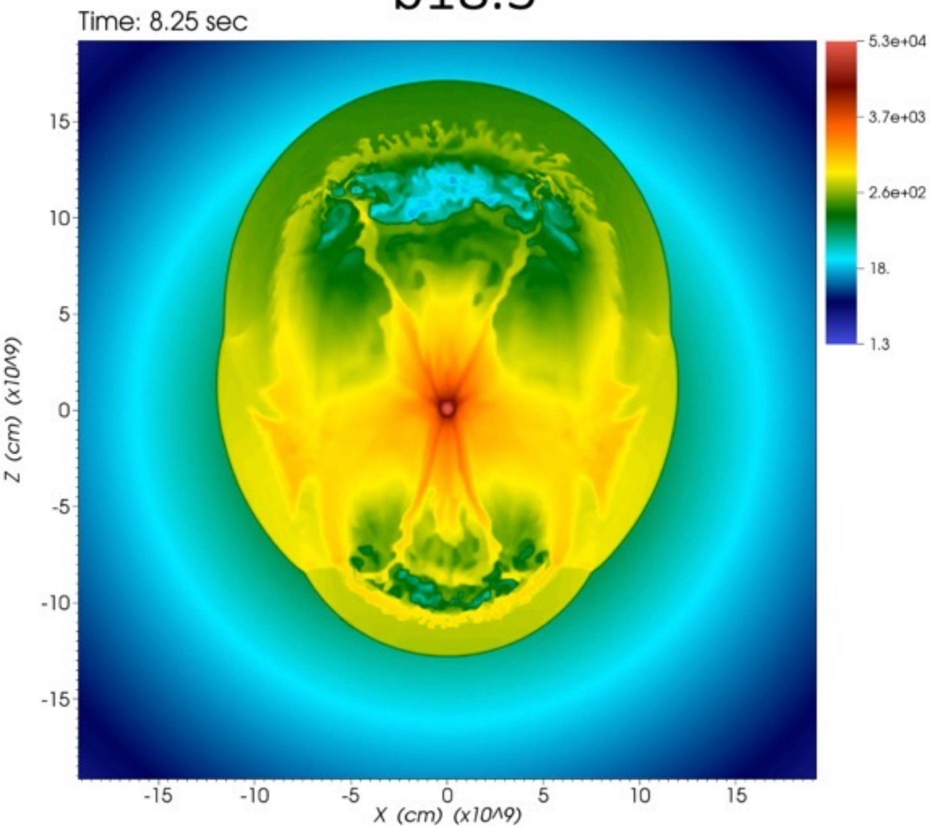
$$A_m^l(\theta,\phi) = \begin{cases} \begin{cases} Y_m^l(\theta,\phi) & (m = 1, -3, 5, -7, ..) \\ 0 & (\mathrm{else}) \end{cases} & (l : \mathrm{odd}) \\ \begin{cases} Y_m^l(\theta,\phi) & (m = 0, 2, -4, 6, ..) \\ 0 & (\mathrm{else}) \end{cases} & (l : \mathrm{even}) \end{cases}$$

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

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

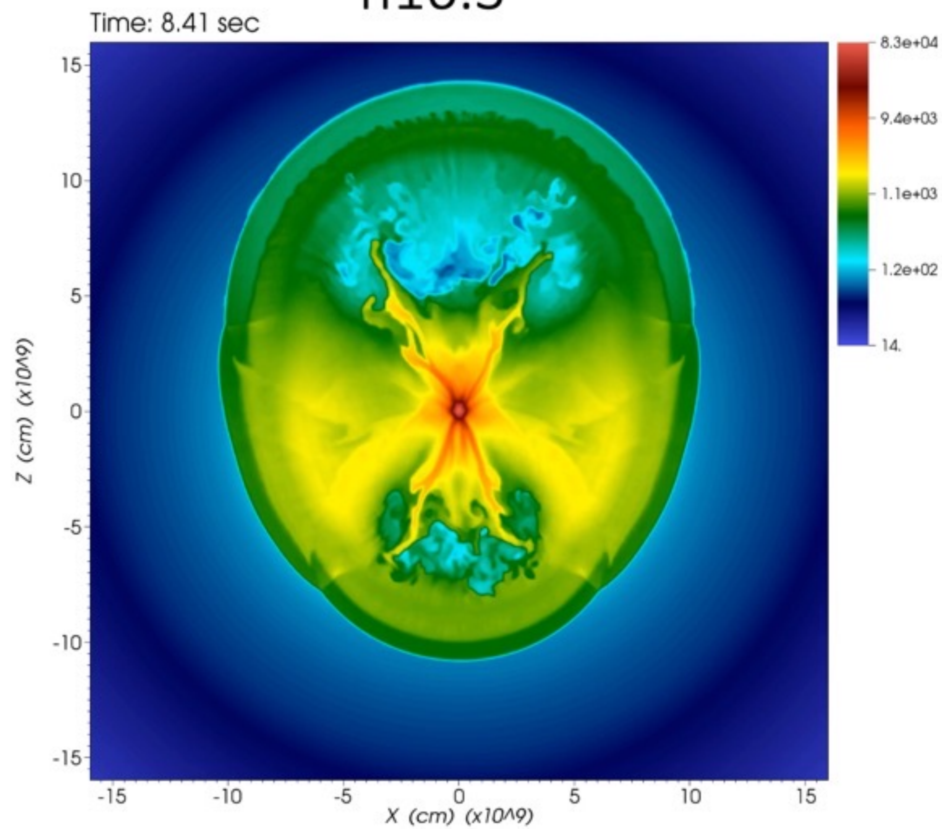
MO+20, ApJ, 888, 111

b18.3



Binary merger

n16.3

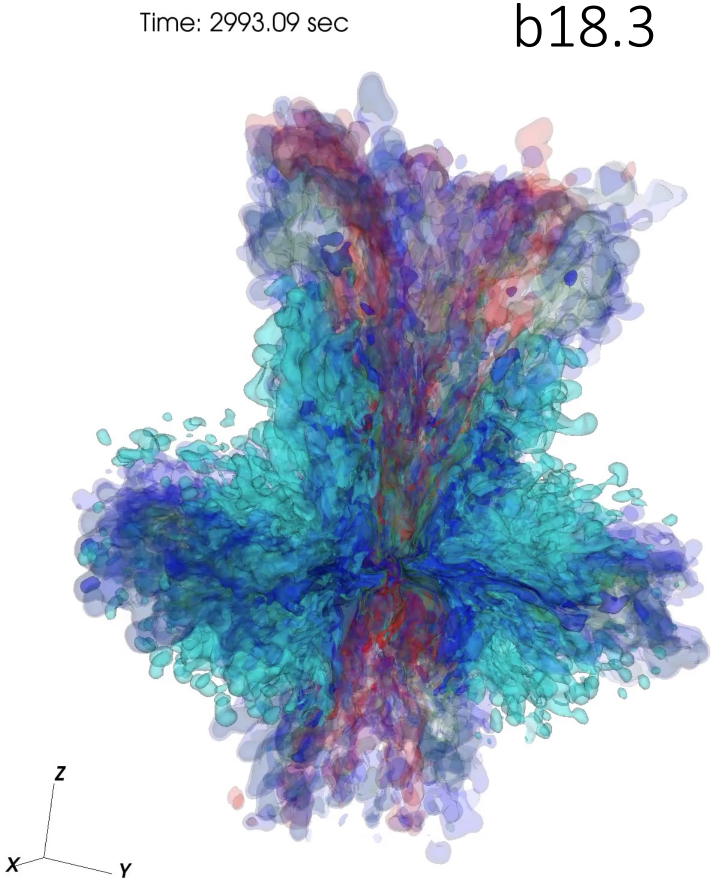


Single star

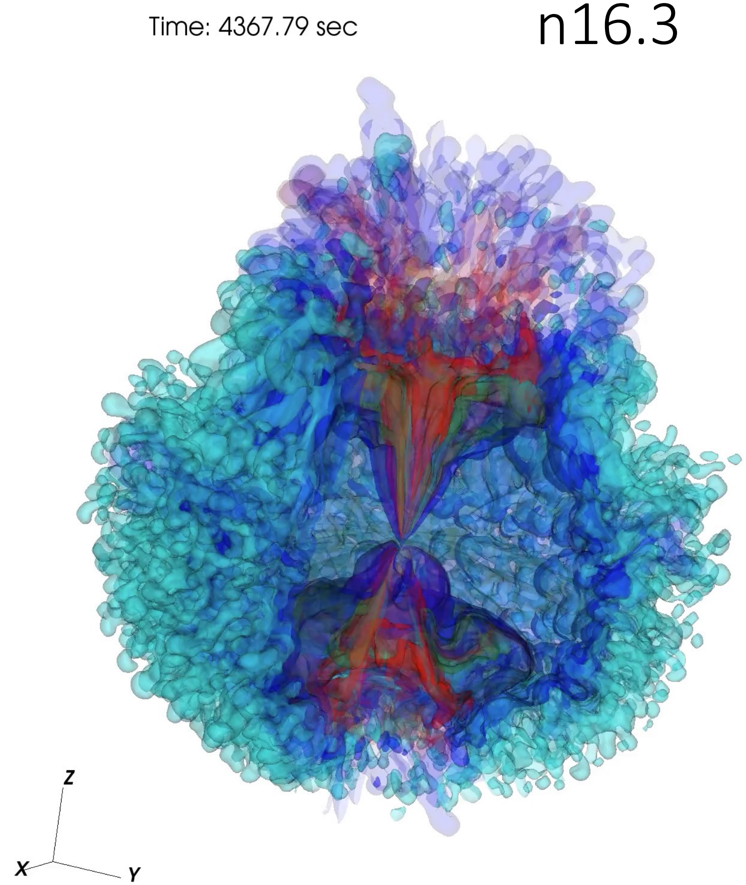
3D Sketchfab models for MO+20, ApJ, 888,111

b18.3 vs n16.3: distribution of elements

MO+20, ApJ, 888, 111



Binary merger

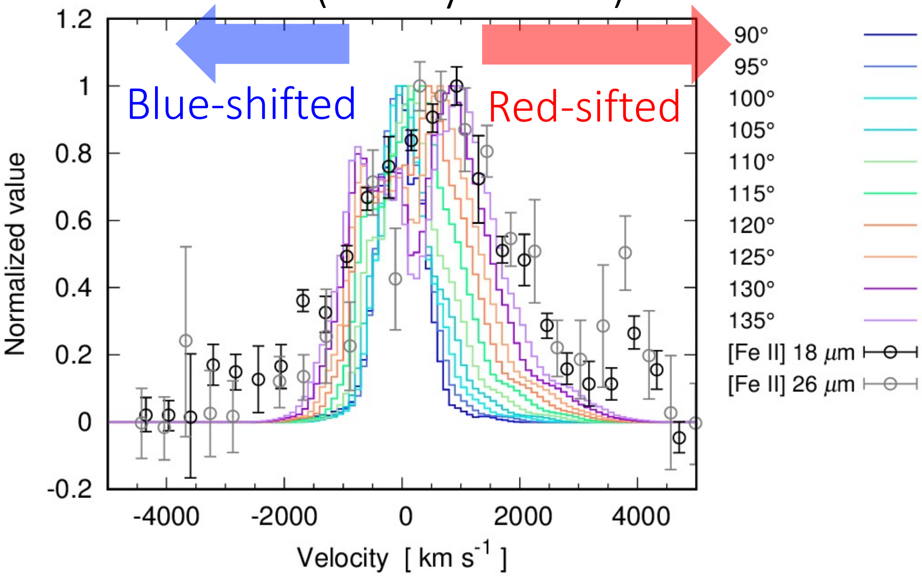


Single star

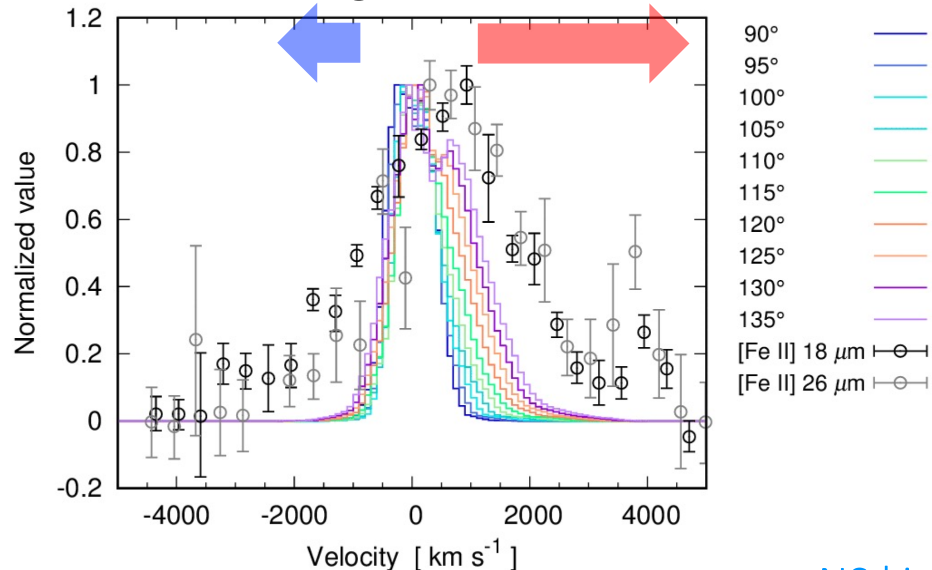
^{56}Ni (Red) ^{28}Si (Green) ^{16}O (Blue) ^{4}He (Sky blue)

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

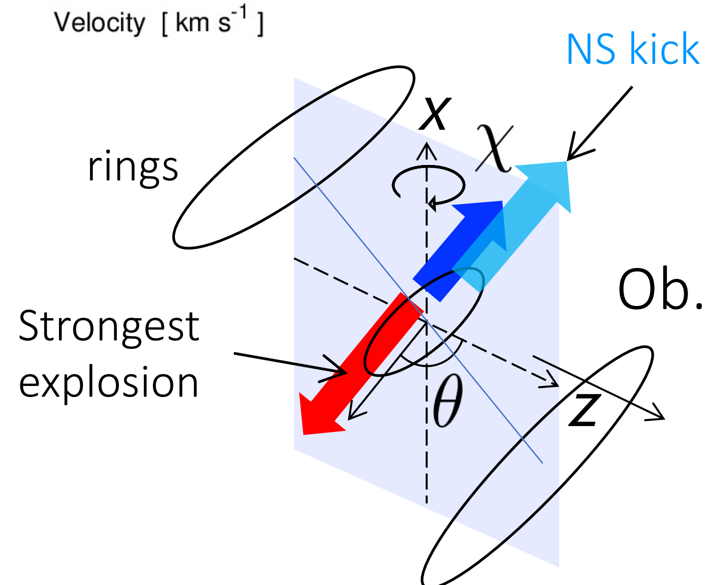
b18.3 (binary model)



n16.3 (single star model)



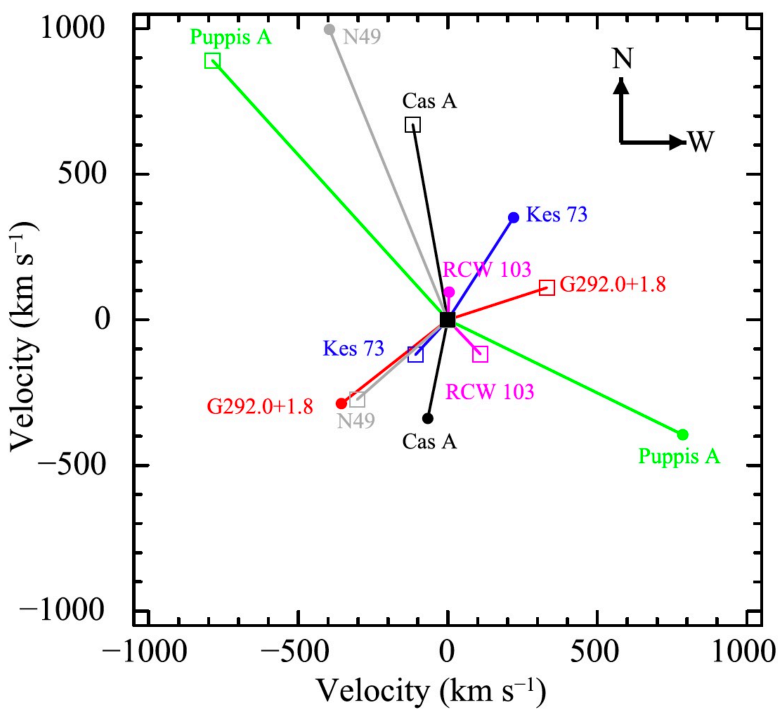
- The best model:
  - Progenitor model: b18.3 (binary merger)
  - (E_{in}, α, β) = (2.5 x 10^{51} erg, 1.5, 16.0)
  - θ = 130° , χ = 10°
  - Estimated NS kick velocity: 285 km s^{-1}
    (consistent with kick velocities
    of pulsars; e. g. Faucher-Giguère & Kapsi 2006)

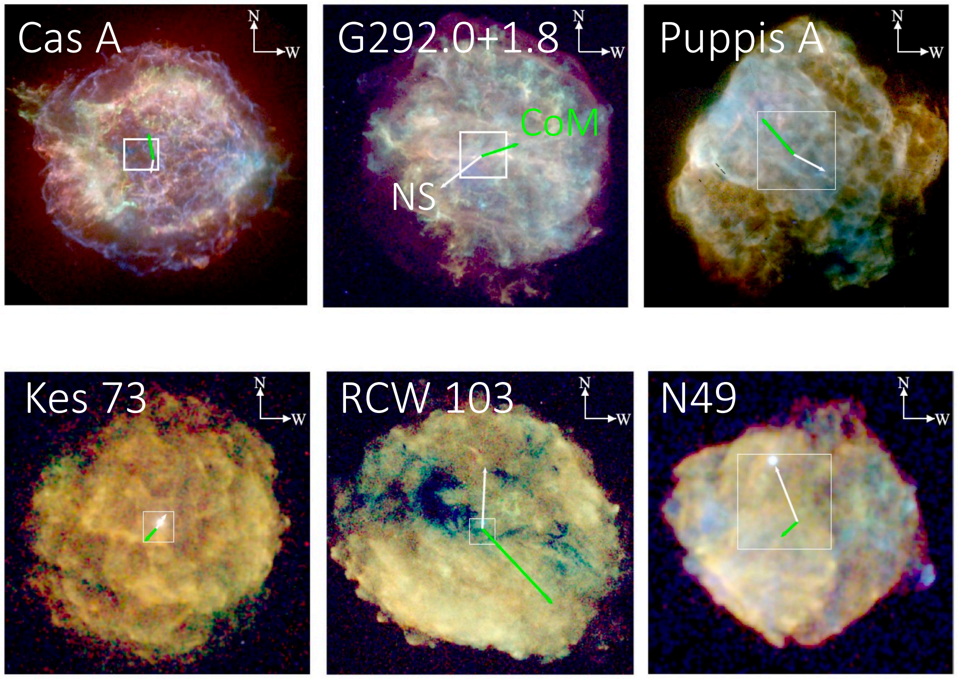


Origin of NS kicks inferred from X-ray SNR observations

Katsuda et al. 2018, ApJ, 856, 18

- Analysis of X-ray emission from six young supernova remnants
- NS kick velocities vs Center of Mass (CoM) velocities of intermediate mass elements





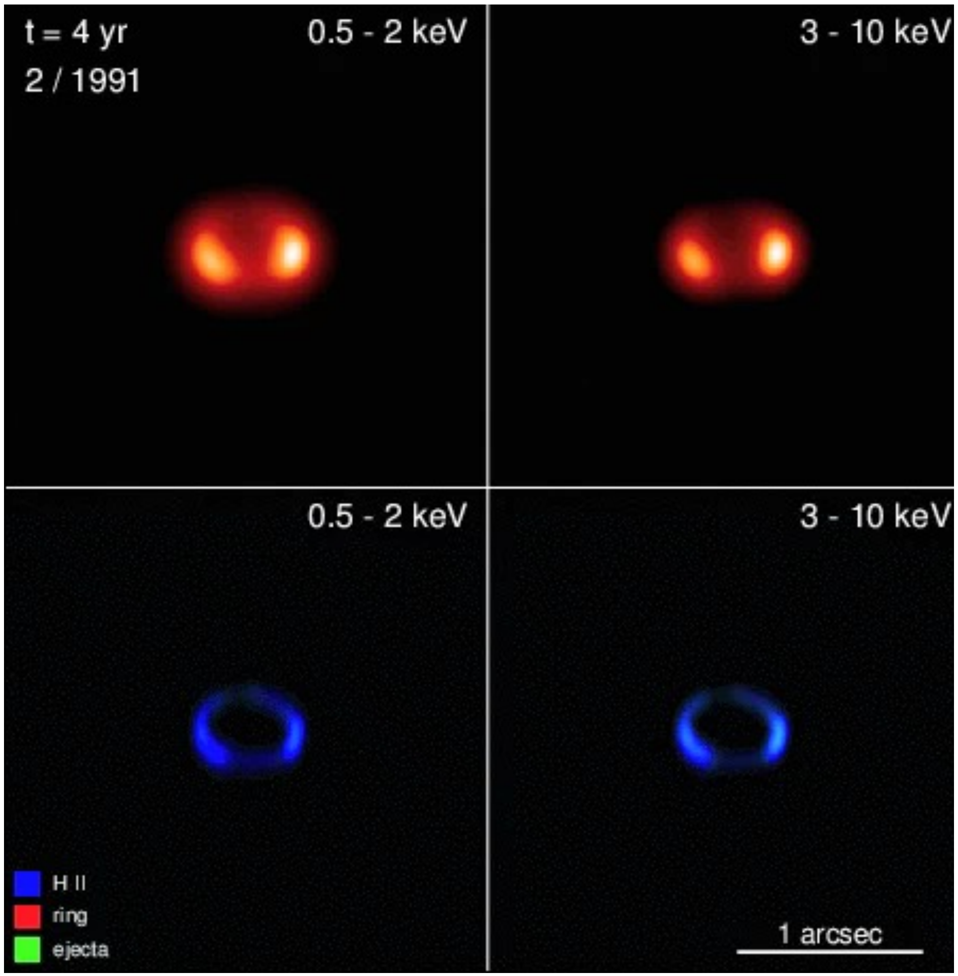
The analysis supports that the origin of NS kicks connected to asymmetric explosive mass ejection (Katsuda et al. 2018, ApJ, 856, 18)

Cf. Another possible origin: anisotropic neutrino emission (Fryer & Kusenko 2006)

The case of SN 1987A:
3D MHD simulations of SNR phases, X-ray synthesis

X-ray images and light curves

Evolution of synthetic X-ray emission map

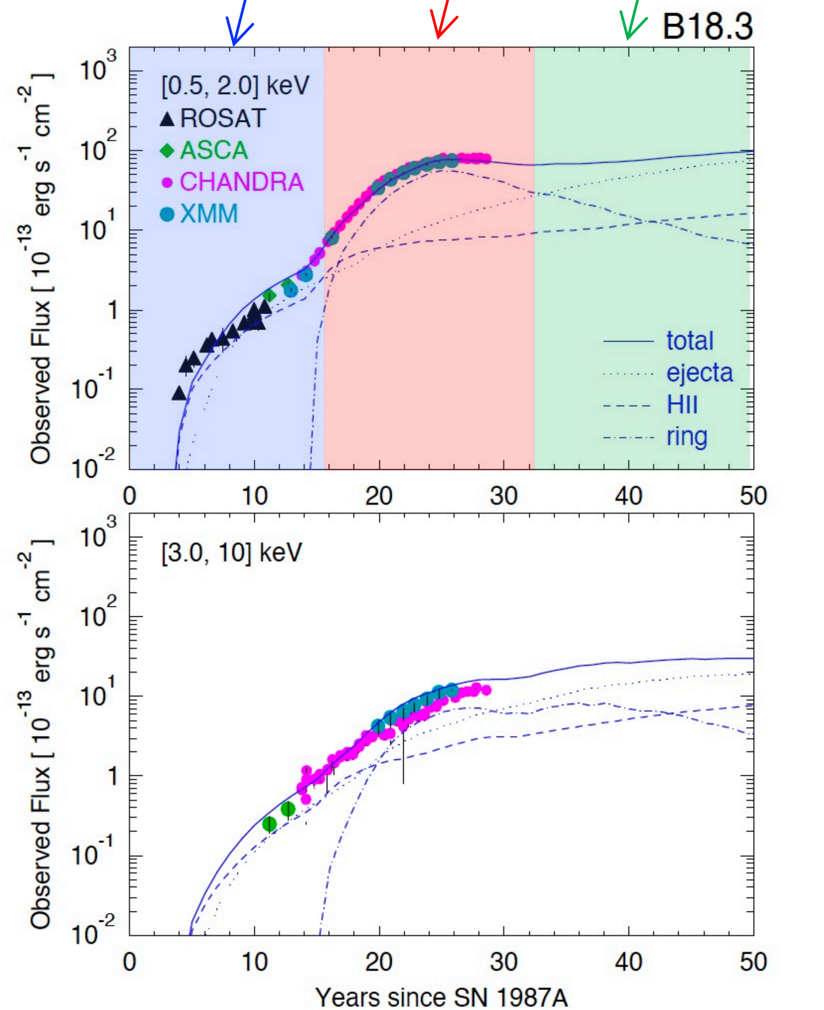


Orlando, MO+20, A&A, 636, A22

HII-region dominated

ring dominated

ejecga dominated

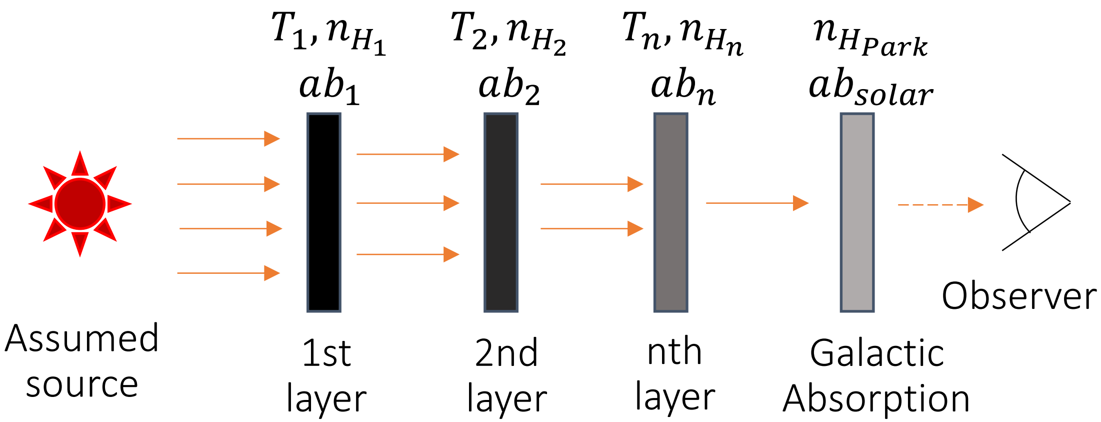


B18.3: Binary merger model

Constraints on NS properties of SN 1987A

Greco et al. 2021, ApJ, 908, L45

X-ray abosorption estimation with the 3D SN-SNR model



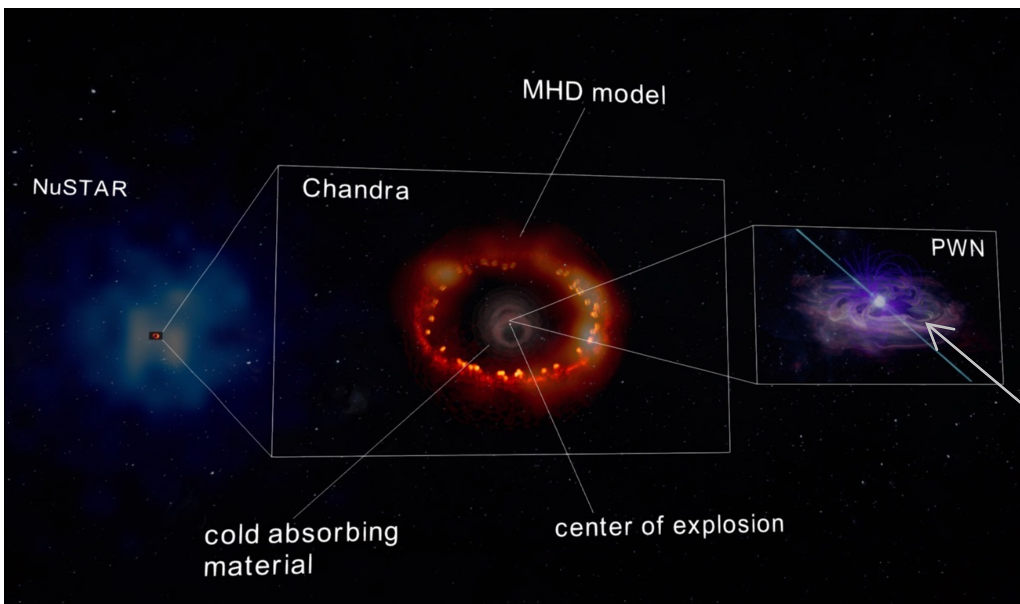
Greco, E./Miceli, M.

Ray tracing method

- *T*, *n*, *ab* (abundance) from a 3D SN-SNR model (MO+20; Orlando+20)
- Comparison with Chandra + NuSTAR observations

Constraint on possible activities of NS 1987A?

Pulsar wind nebula (PWN) activities and/or thermal X-ray emission from NS 1987A?



Snapshot from the 3D Sketchfab model https://skfb.ly/6XZIU

Hard X-ray emission from SN 1987A: a pulsar wind nebula activity by NS 1987A?

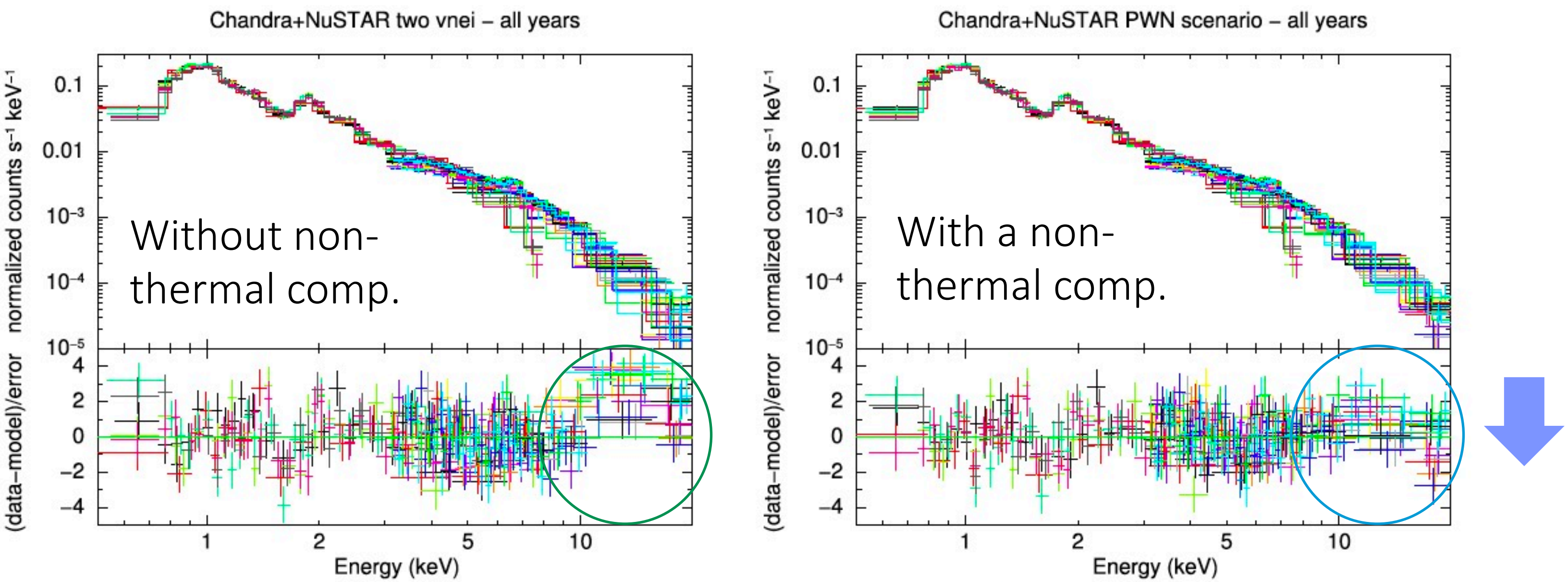


Figure 2. Spectra extracted in the 0.5–20 keV energy band from Chandra and NuSTAR in various years with the corresponding best-fit model and residuals. A different color is associated with each of the 20 data sets. On the left, the best-fit model is composed of two thermal components. On the right, the best-fit model also takes into account the emission coming from a heavily absorbed PWN. The spectra have been rebinned for presentation purposes.

- 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 (or diffused shock acceleration) is expected

Greco et al. 2021, ApJ, 908, L45

Comparison of NS cooling models with observed thermal X-ray emission

Preliminary

Calculated by
A. Dohi (iTHEMS, RIKEN)

The results are preliminary.
In case, figures in this slide are removed.

- The NS mass, envelope mass and compositions could be constrained

Greco et al. 2021, in prep.; Dohi et al. 2021, in prep.

Molecule formation calculations for SN 1987A

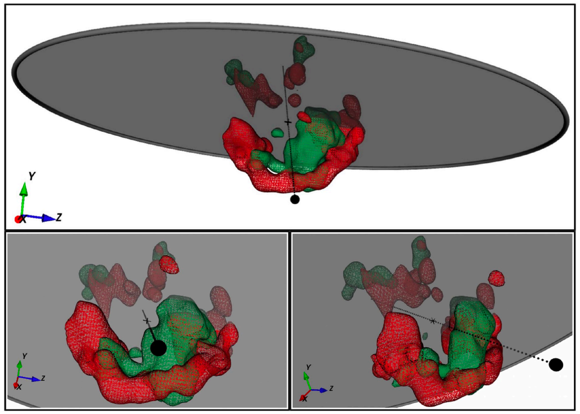
Assumption: Power law density /temperature evolution

Distribution of CO and SiO molecules

$$\rho(t) = \rho_0 \left(\frac{t}{t_0} \right)^{-3}$$

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

Observations by ALMA



Abellán+2017

Binary merger

Single star

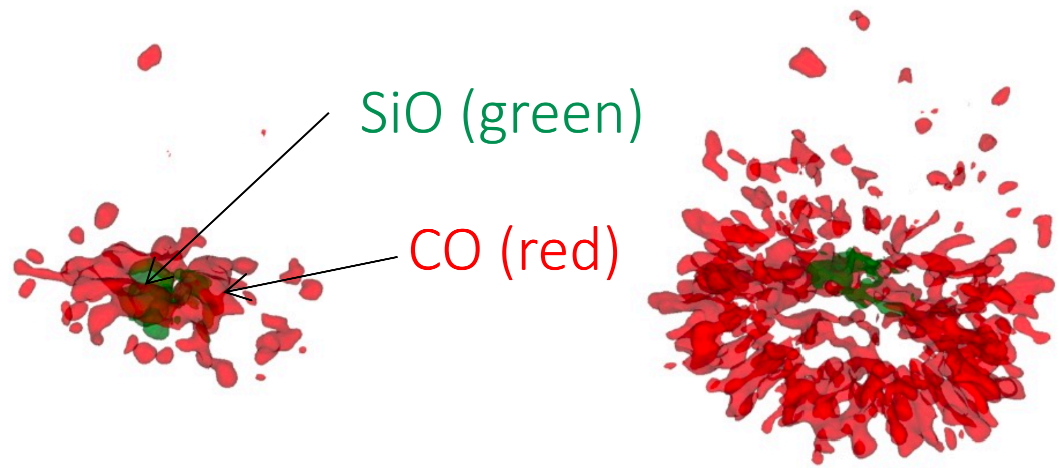
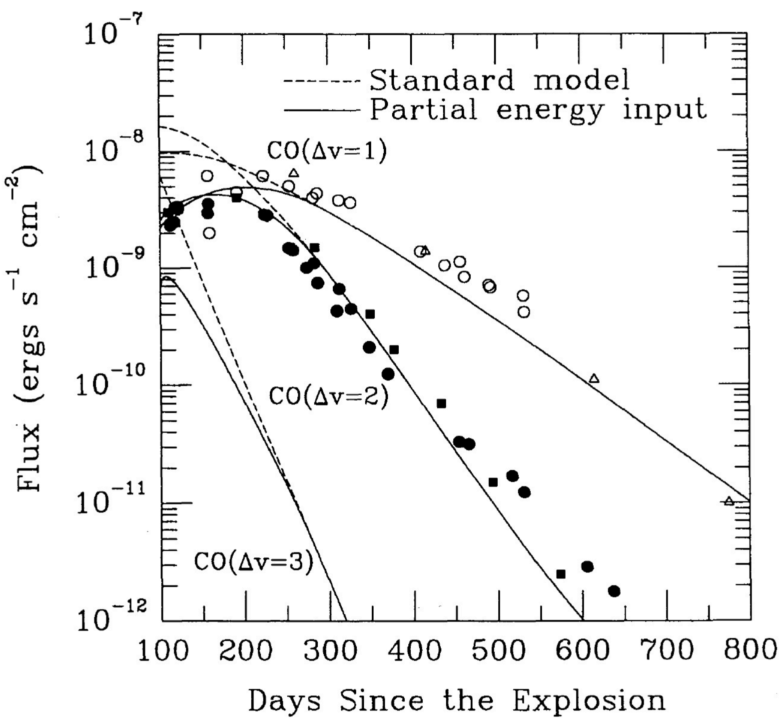
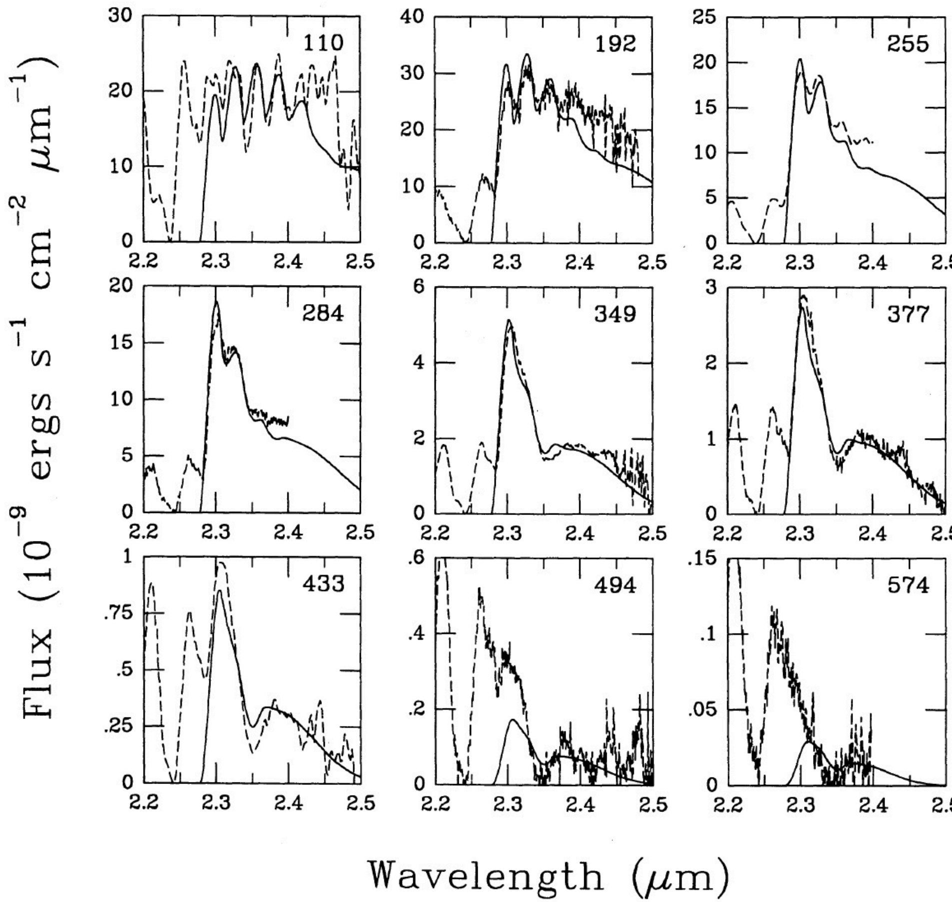


Fig. 3. Isosurfaces of number densities (30% of the maximum values) of CO (red) and SiO (green) molecules. Left (Right) is for the model with the binary merger progenitor model (single star progenitor model). The time is 30 yr after the explosion. By assuming a homologous expansion, the length scale of the distribution is approximately 10^{17} cm.

MO+20, JPS Conf. Proc., 31, 011029

Observed CO line emission in SN 1987A





Circles: Bouchet & Danziger+93

Triangles: Wooden+93

Squeres: Wooden+93

CO line emission could affectt as coolant of gas

Figures are taken from Liu & Dalgarno 1995, ApJ, 454, 472

Test spectral calculations of ro-vibrational transitions of CO

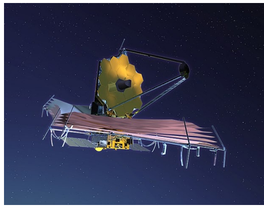
Preliminary

The results are preliminary.
In case, figures in this slide are removed.

- Test spectral calculation for each snap shot (under one-zone assumption)
- Here, CO mass, density, gas temperature, photospheric temperature, radial velocity, and ionization fraction are independent parameters

JWST (James Webb Space Telescope)
will be launched in Oct., 2021

A new tool for comparison with observations by coming JWST!



Summary

SN-SNR project for SN 1987A

- 3D HD/MHD simulations from CCSNs to SNRs
- Nucleosynthesis (coupled with the hydro simulation)
- Synthesis of X-ray emission (X-ray light curves + images)
- Constraints on the properties of NS 1987A by the estimation of X-ray absorption
- Molecule formation calculation (preliminary)
- Dust formation (future work)

Unraveling progenitor-SN-SNR connection

- Origin of asymmetries
- Mechanisms of CCSN
- Properties of progenitor stars
- Properties of neutron stars (NSs)