Three-dimensional simulations of double detonations in double-degenerate systems for type Ia supernovae

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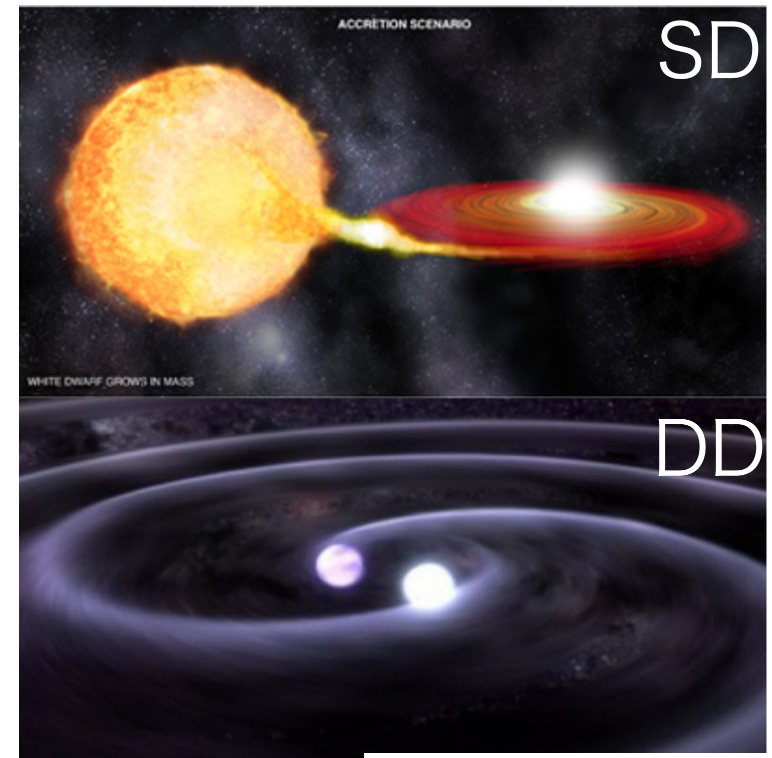
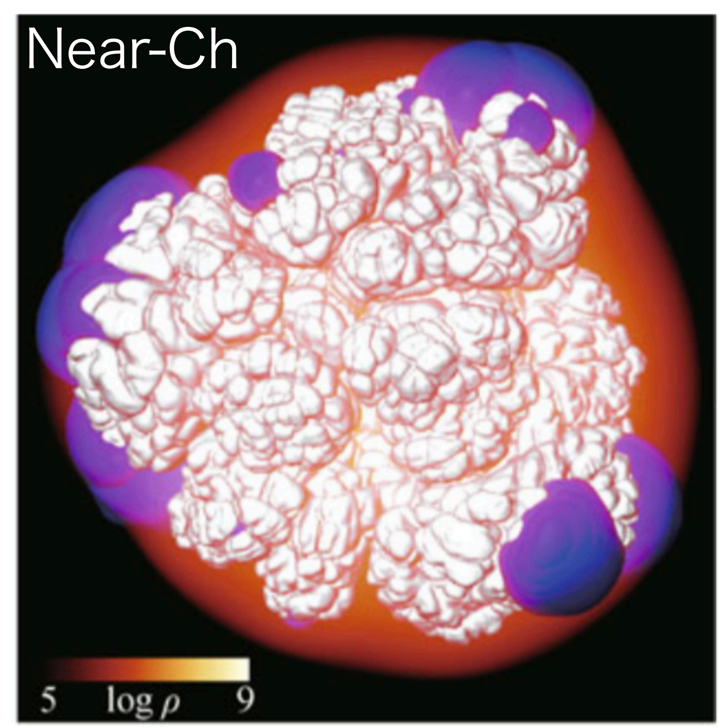
Tanikawa, Nomoto, Nakasato (2018, ApJ, 868, 90)

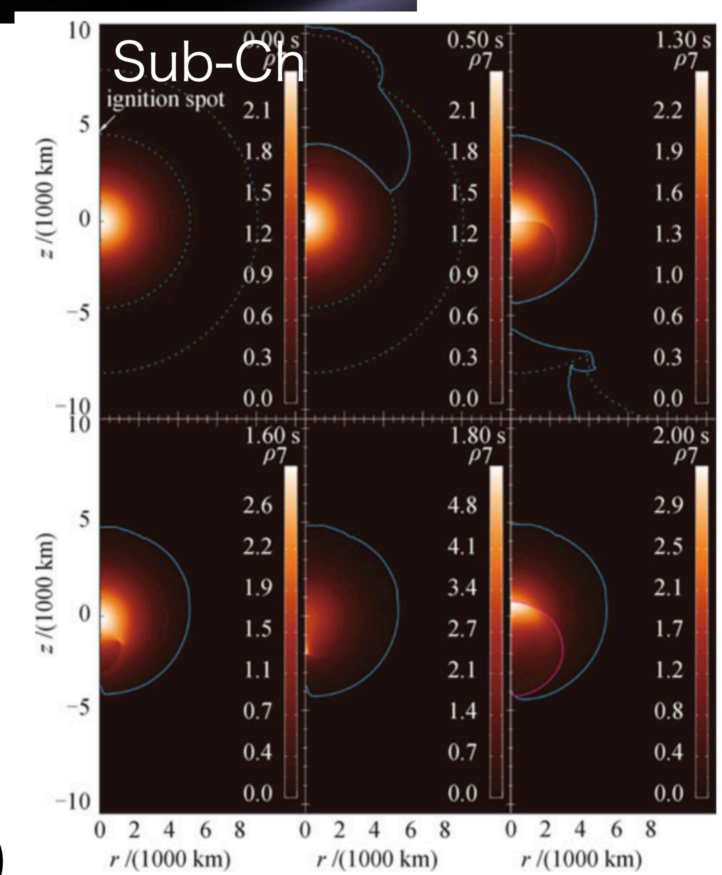
Type Ia supernovae

- One of the brightest and most common objects in the universe
- A cosmic distance indicator
- The origin of iron peak elements
- Thermonuclear explosions of white dwarfs (WDs)
- Unknown progenitor
    - Single Degenerate (SD) or Double Degenerate (DD)
    - Near-Chandrasekhar mass (Near-Ch) or sub-Chandrasekhar (sub-Ch) mass





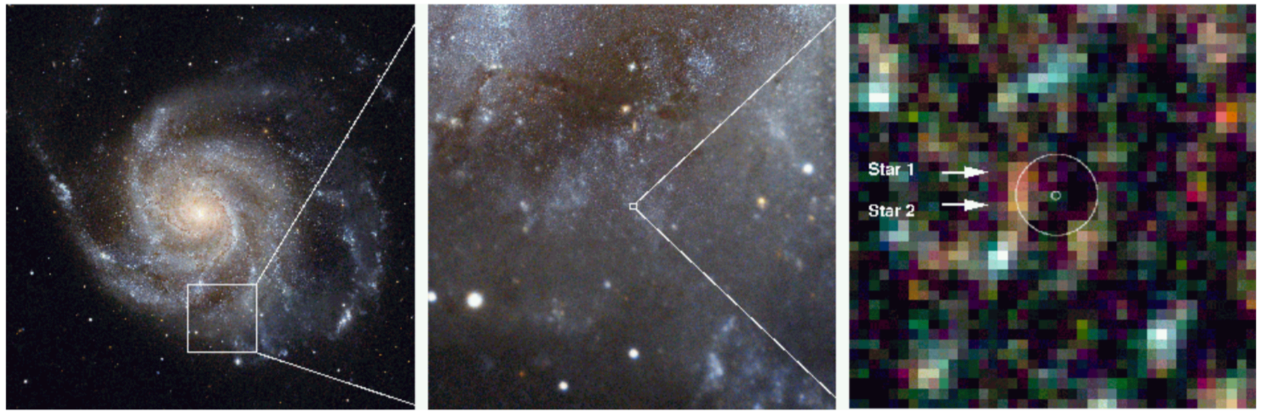
Seitenzahl et al. (2013)



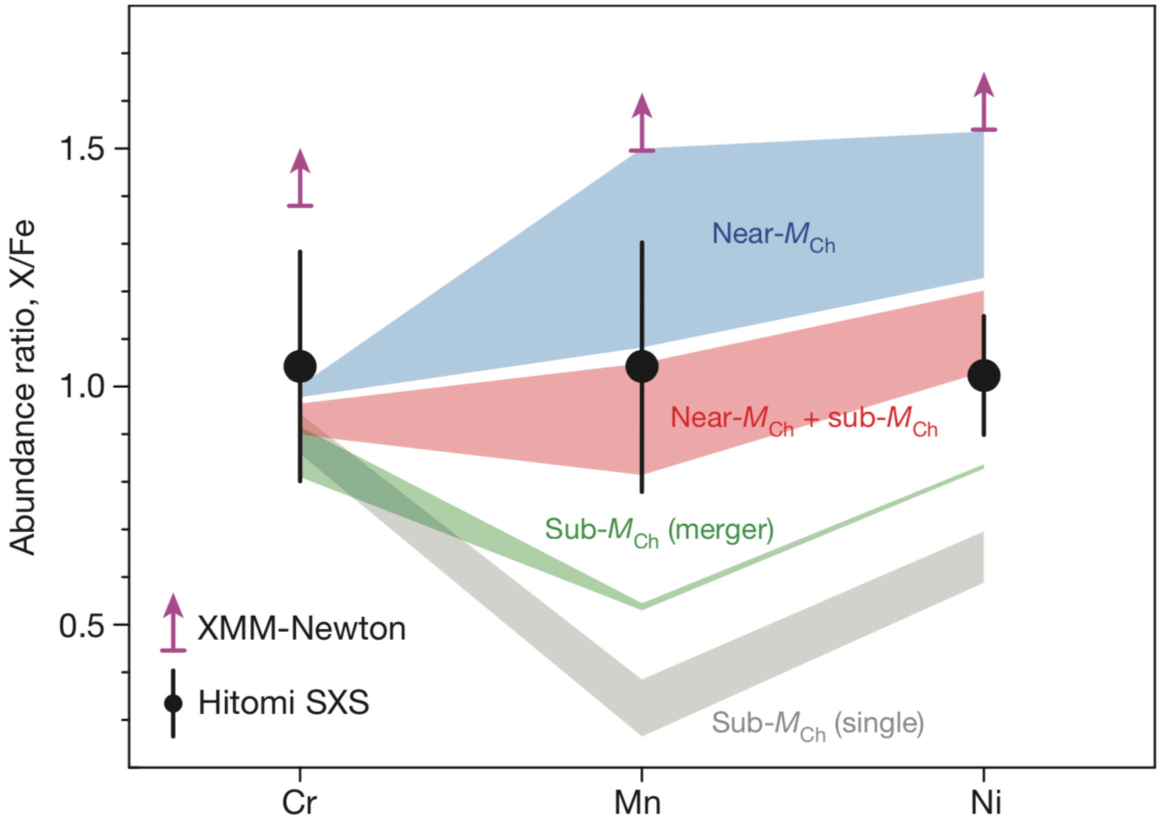
Fink et al. (2010)

Constraints on the progenitors

- SD or DD
  - Non detection of RG in the pre-explosion image of SN2011fe (e.g. Li et al. 2011)
  - Non detection of MS in LMC SNR 0509-67.5 (e.g. Schaefer, Pagnotta 2012)
  - But see spin-up/down model.
- Near-Ch or sub-Ch
  - Both required (Hitomi Collaboration 2017)
- Sub-Ch DD can be one of the progenitors



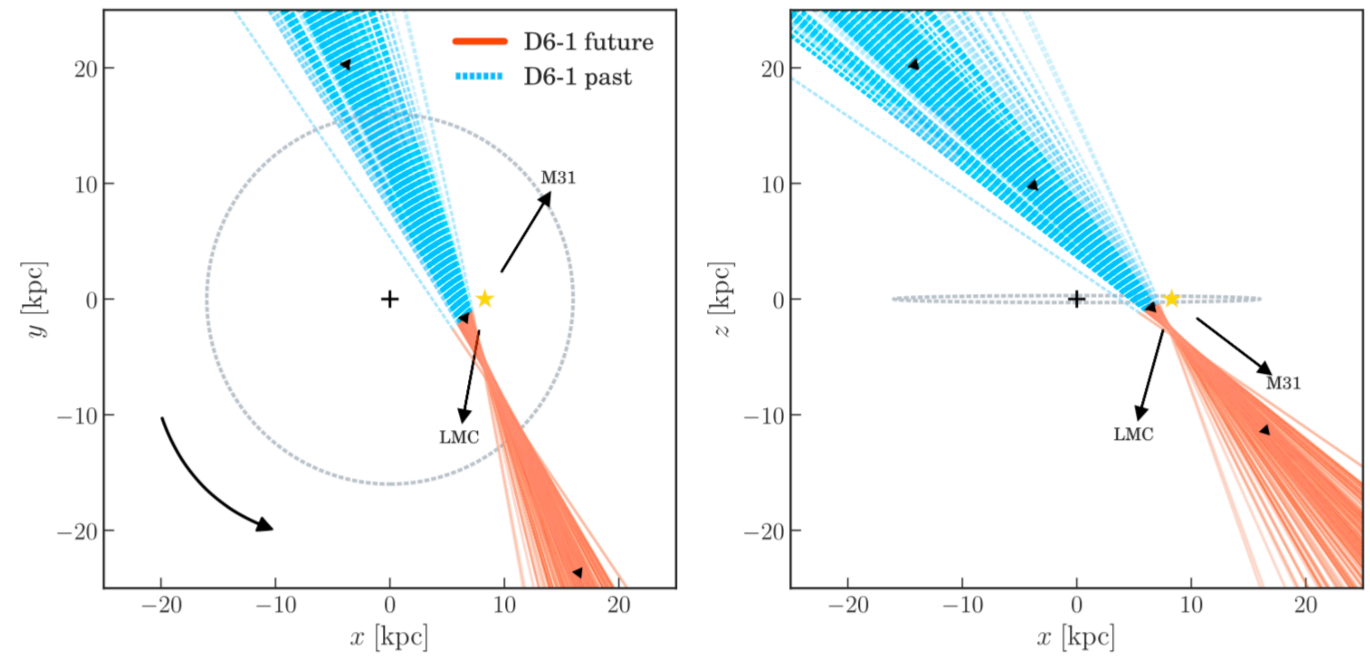
Li et al. (2011)

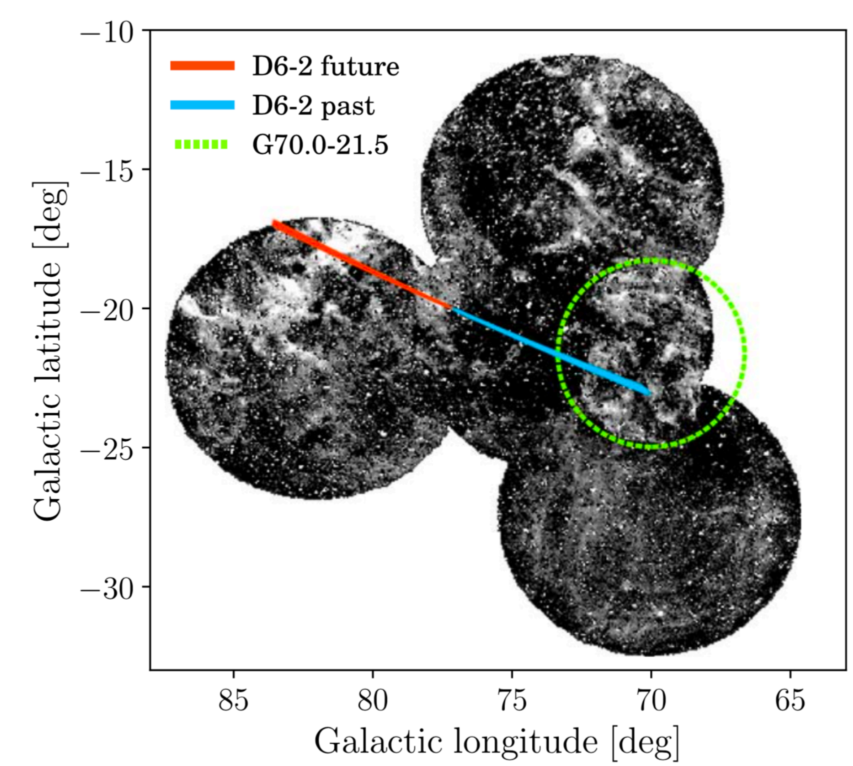


Hitomi Collaboration (2017)

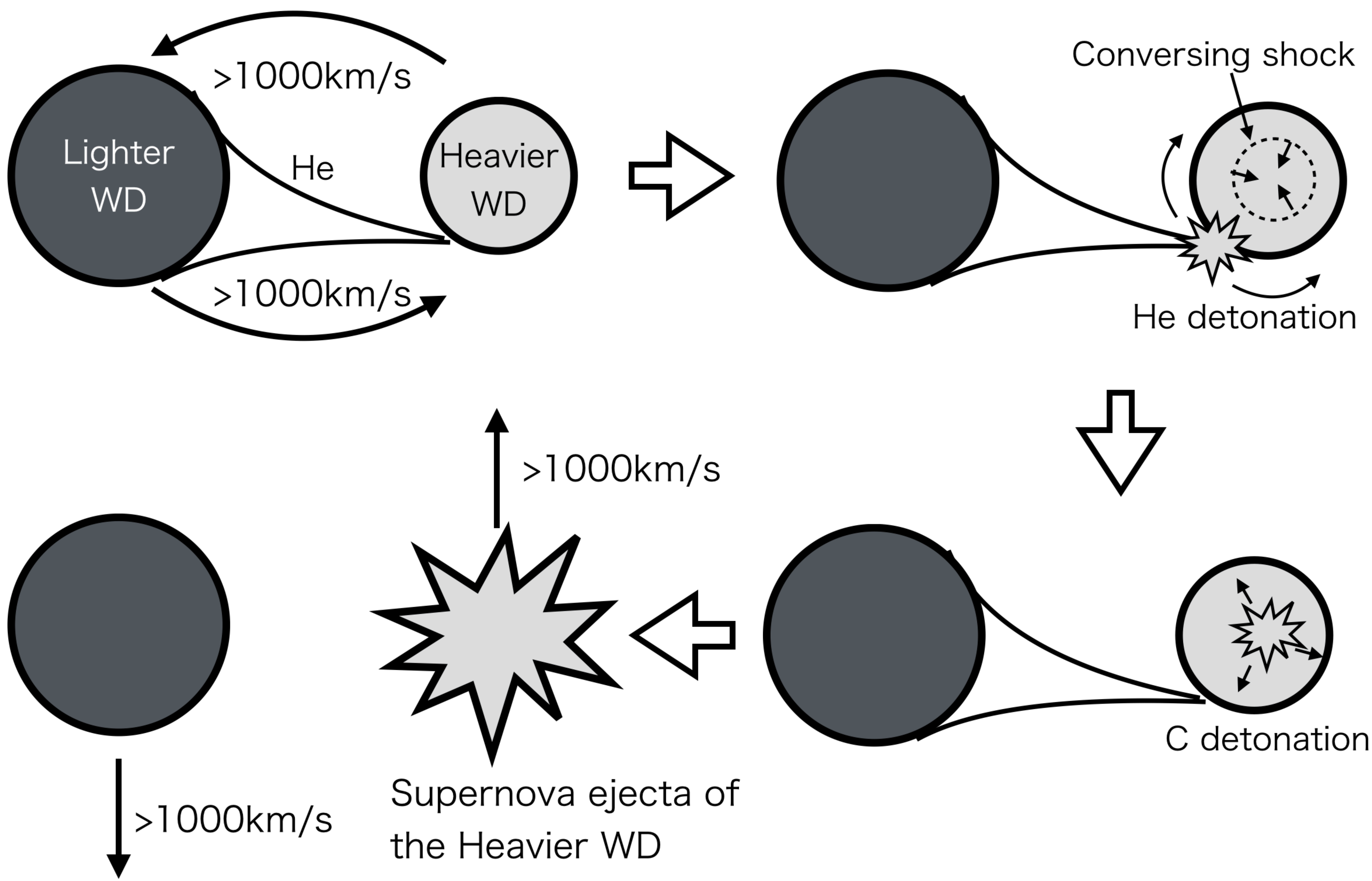
Hypervelocity WDs

- The discovery of hypervelocity (~1000km/s) WDs (Shen et al. 2018)
- Double detonations in a DD system (Guillochon et al. 2010; Pakmor et al. 2013)
- So-called Dynamically-Driven Double-Degenerate Double-Detonation (D6) explosion





D6 processes



This study

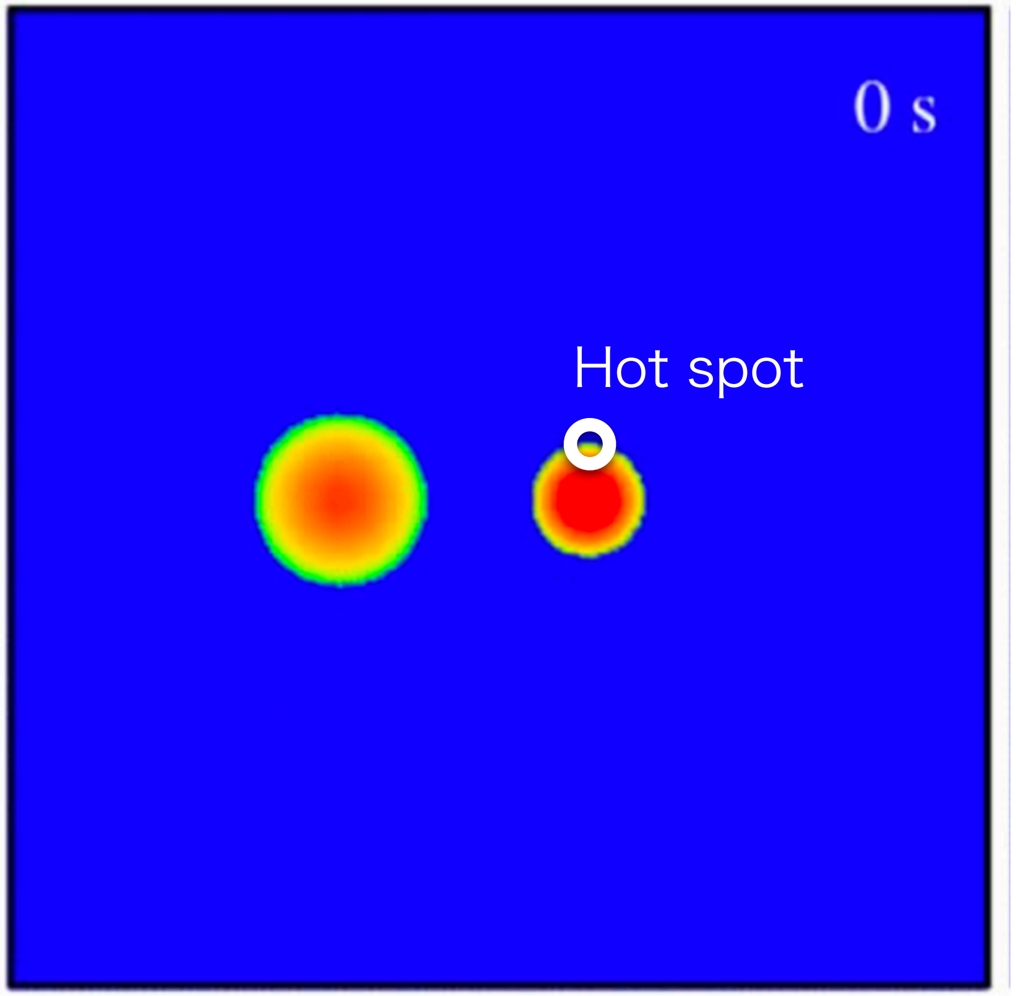
- We perform a SPH simulation of double detonations in a DD system.
- We explore signals of the progenitor model.
- We also investigate various combinations of WDs.

Method

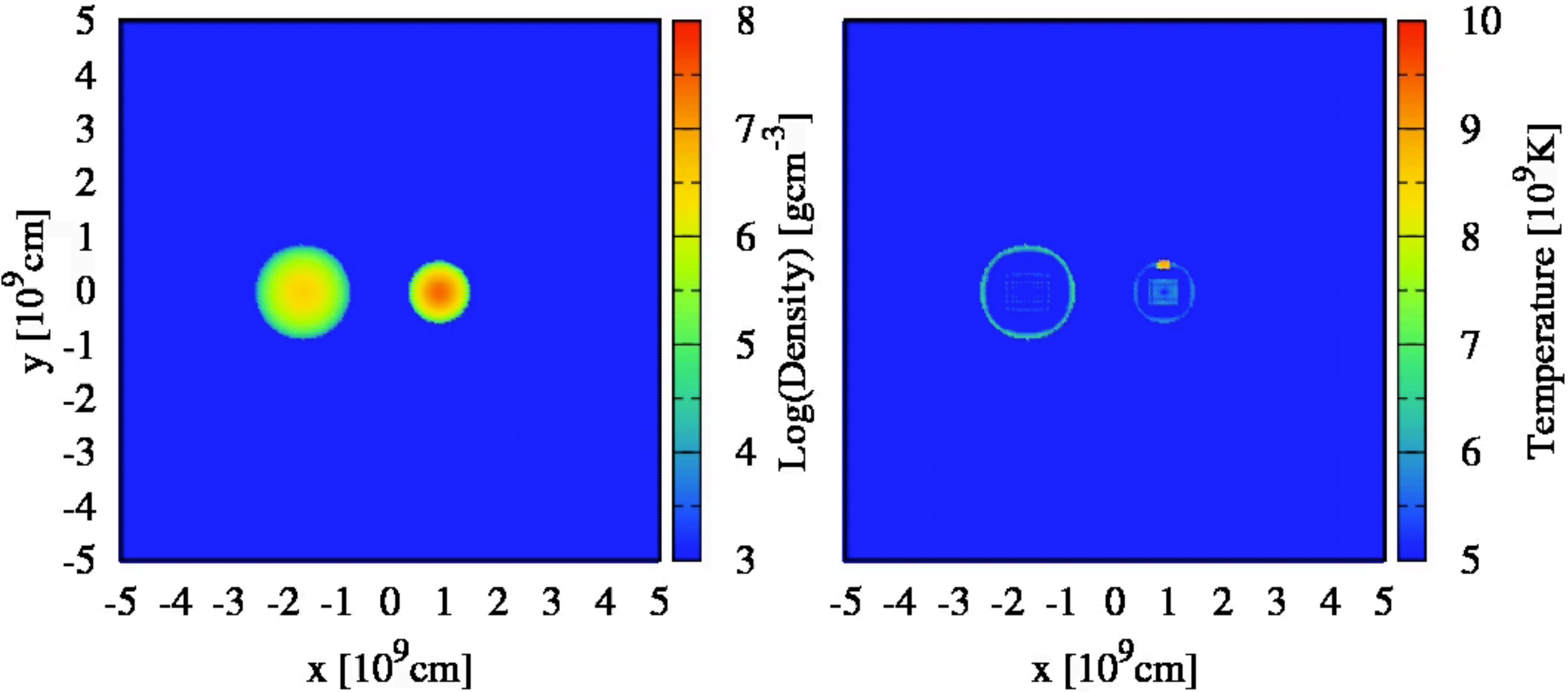
- 3D SPH method
  - Parallelized by FDPS (Iwasawa, AT+ 2016)
  - Vectorized by SIMD (e.g. AT+ 2012; 2013)
- Helmholtz EoS (Timmes, Swesty 2000)
- Aprox13 nuclear reaction networks (Timmes et al. 2000)

Initial condition

- Mass combinations
  - 1.0Msun + 0.6Msun COWDs
    - w/o a He shell of the lighter WD
  - 1.0Msun COWD + 0.45Msun HeWD
    - Impossibly small separation
  - 1.0 Msun + 0.9Msun COWDs
    - w/ a thick He shell of the lighter WD
- Hot spot in thick He outer shells

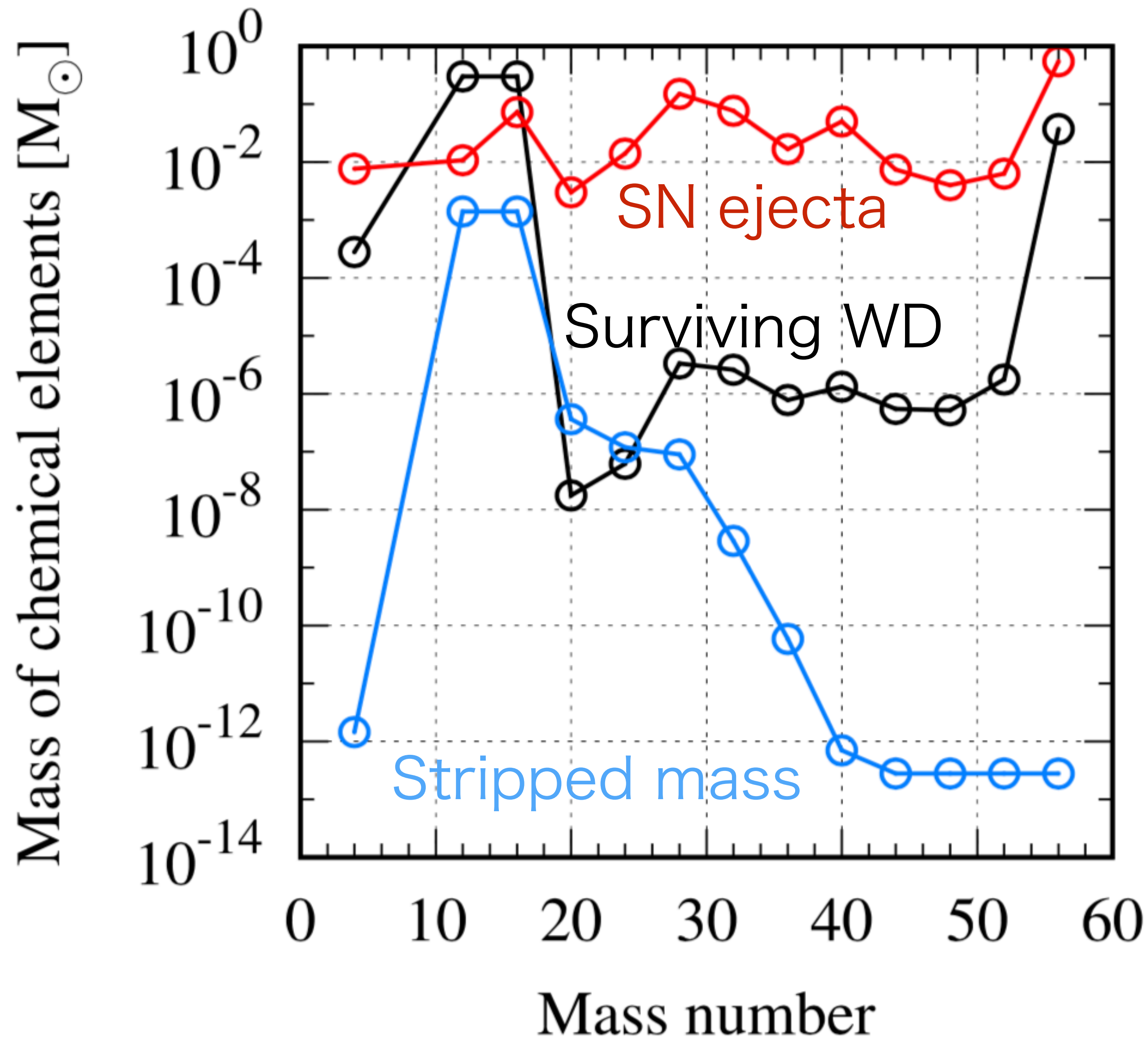


Animation
1.0 Msun+0.6 Msun COWDs



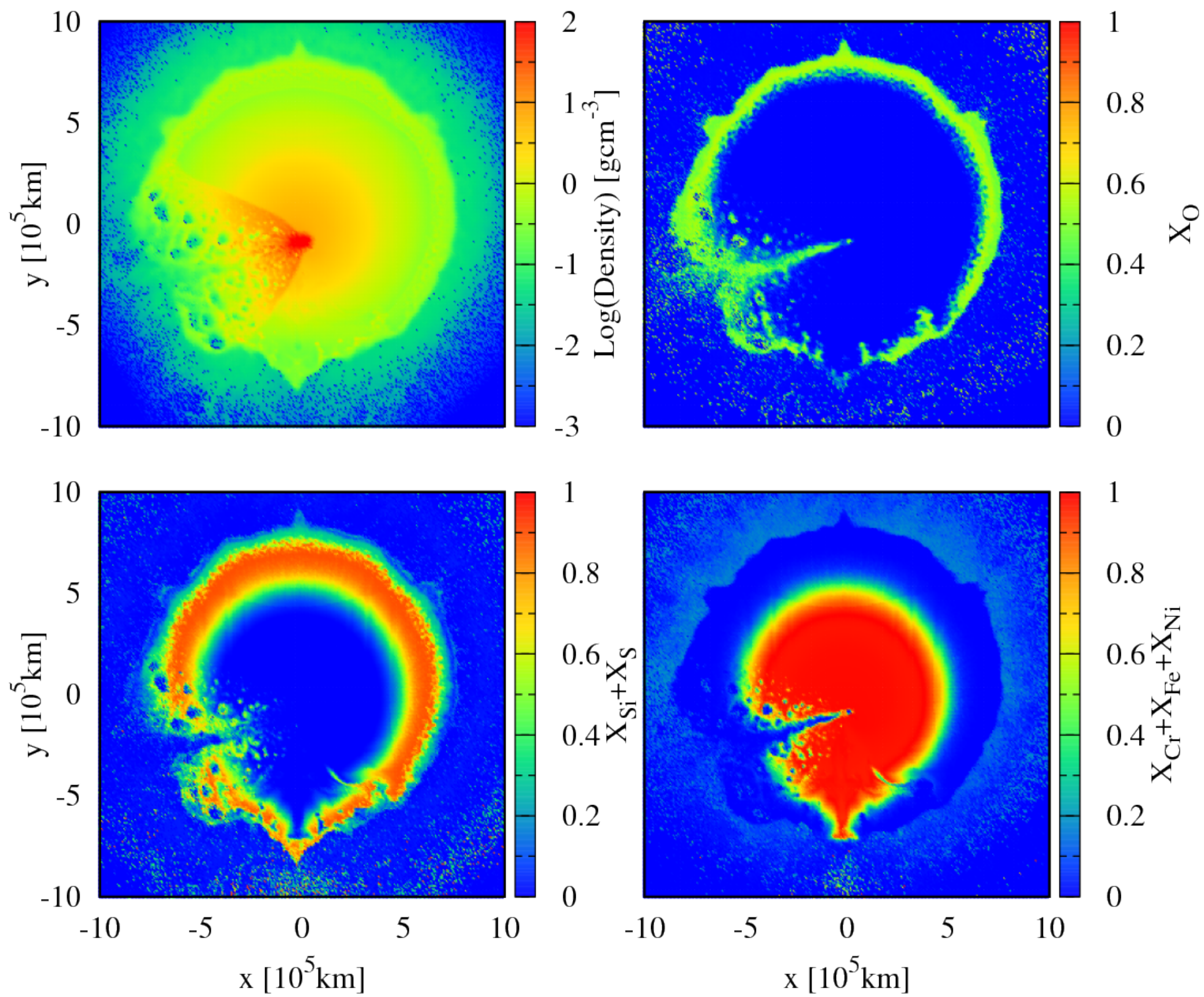
Outcome explosion

- Nuclear energy: 1.35x10^51 erg
- 56Ni: ~0.6Msun
- Stripped mass from the lighter WD: ~0.003Msun
- Captured mass by the lighter WD: ~0.03Msun



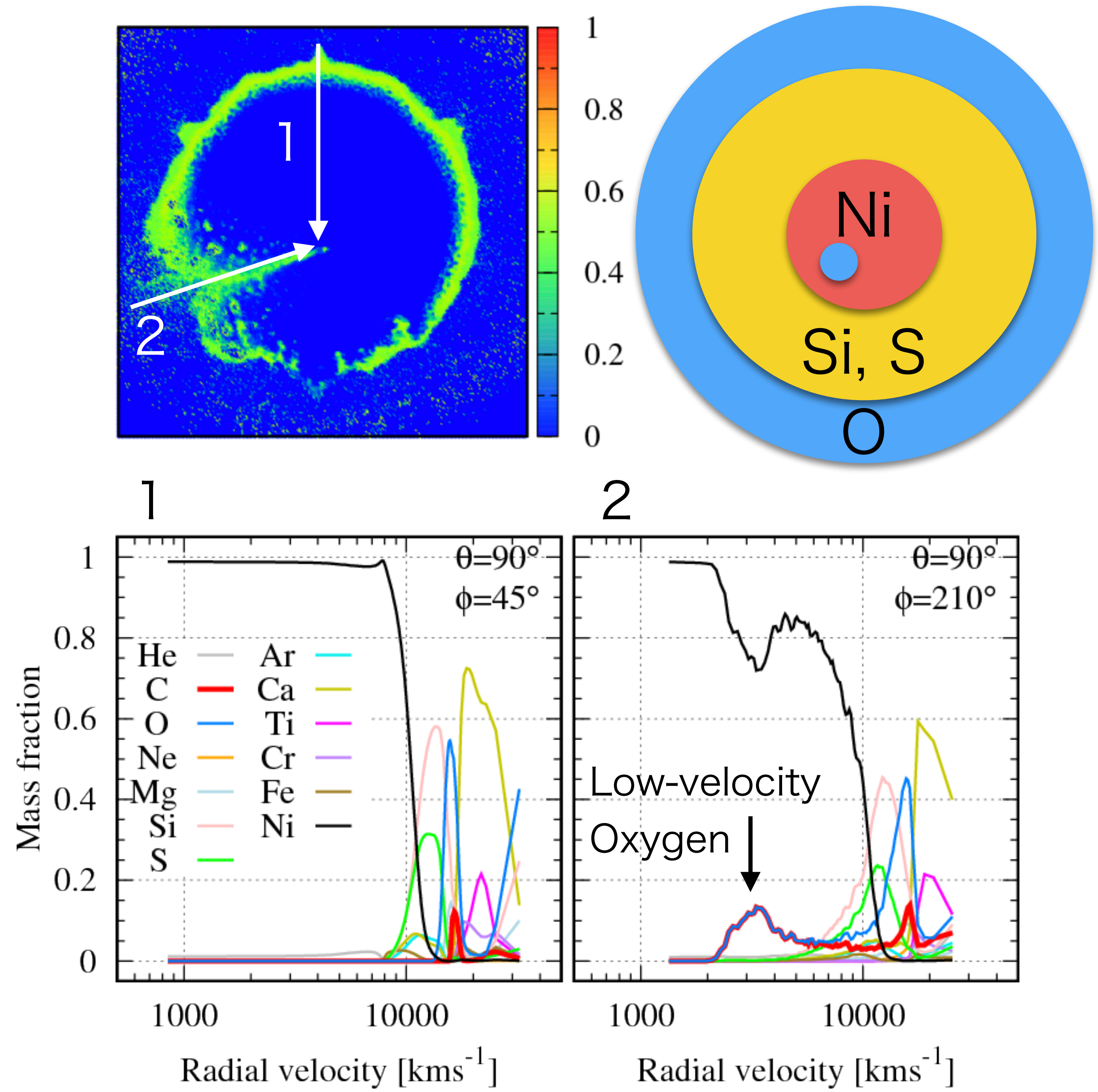
SN ejecta

- Almost spherically symmetric shape
  - An ejecta shadow formed by the lighter WD
- ^{56}Ni, Si+S, O, and C from inside to outside
  - Companion-origin stream stripped by the SN ejecta



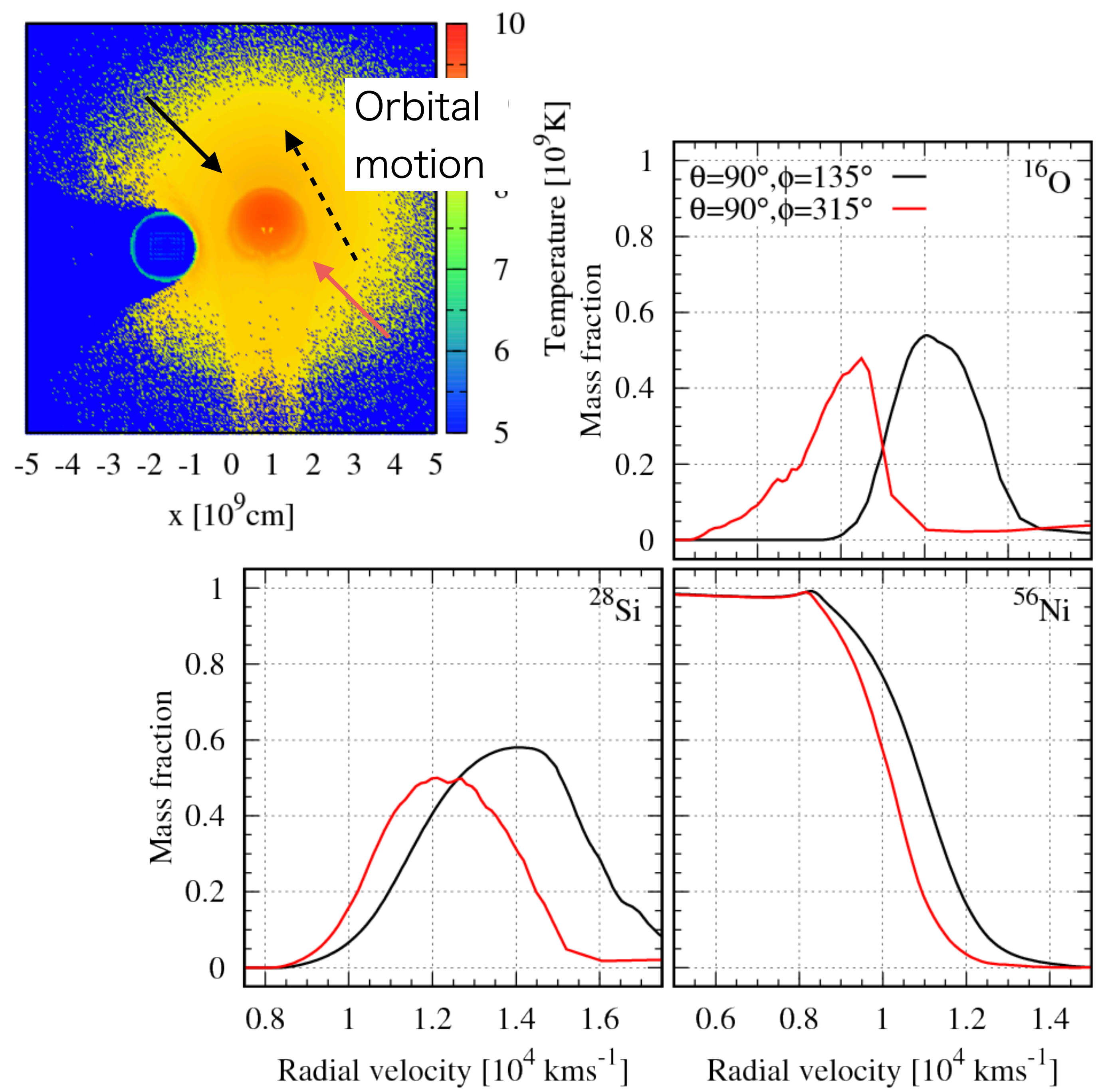
Low-velocity oxygen

- The companion-origin stream consists of carbon and oxygen.
- It contributes to low-velocity components, a few 1000 km/s.
- The D6 explosion has low-velocity oxygen.

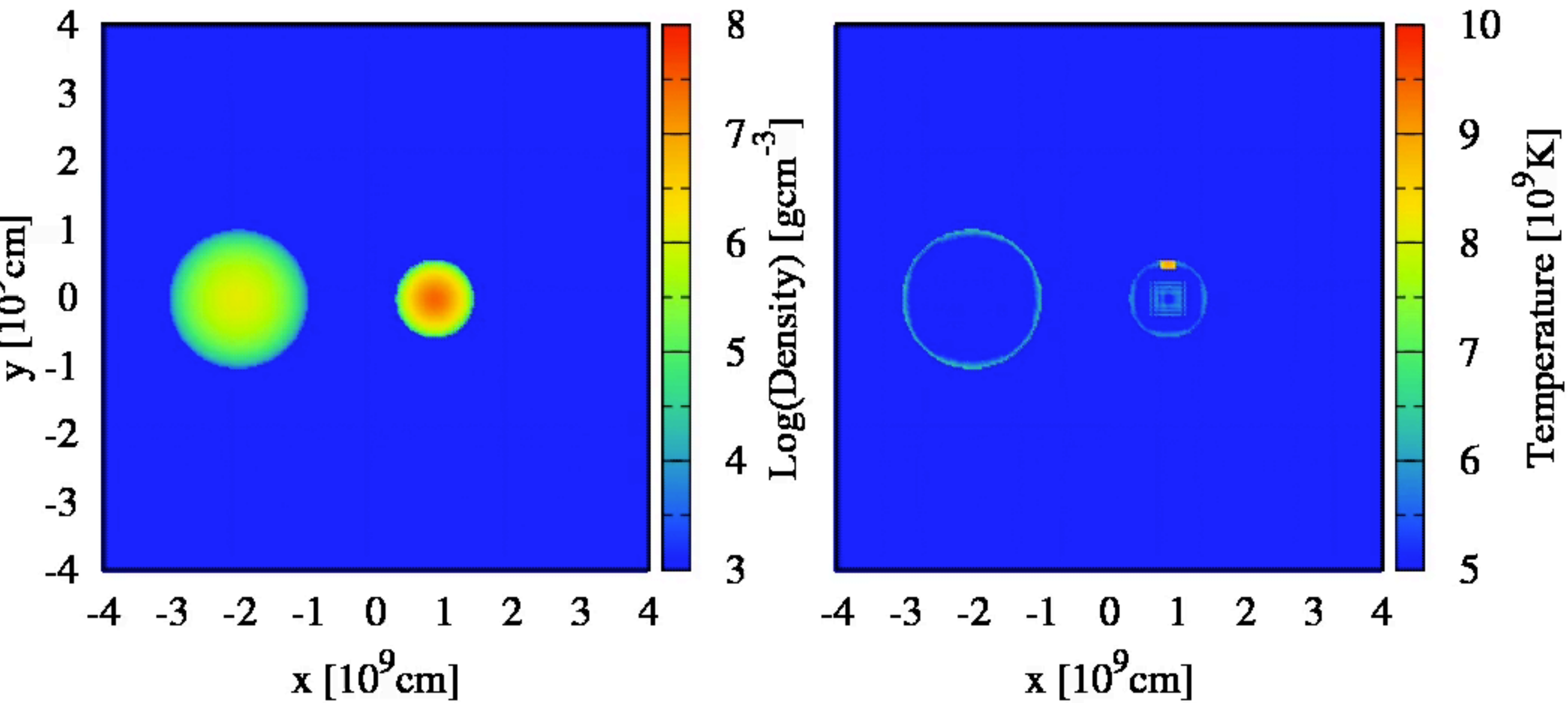


Velocity shift

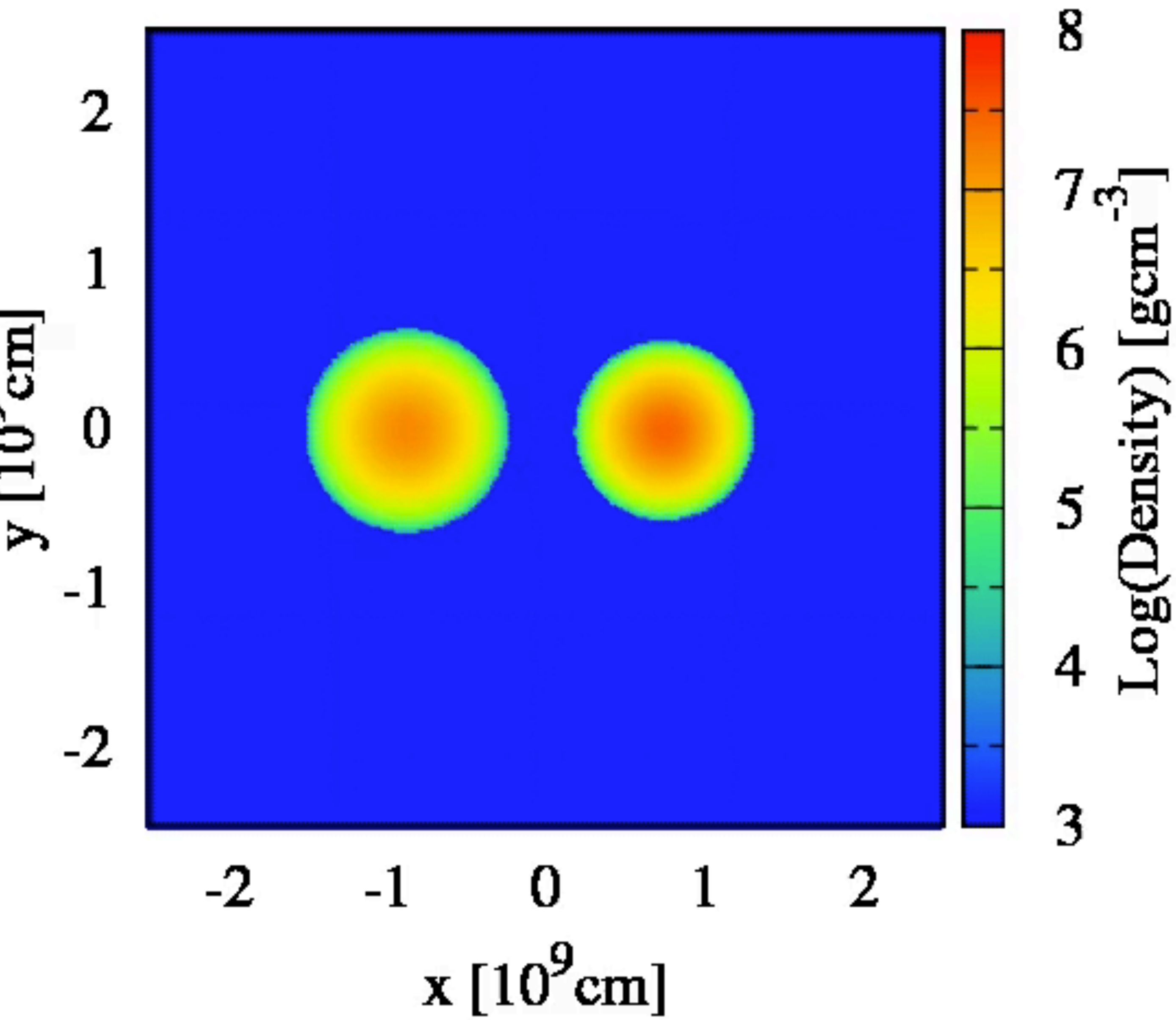
- Radial velocities of O, Si, and ^{56}Ni are systematically shifted by the orbital motion of the heavier WD.
- The velocity shift is about 1000km/s.
- This is not due to asymmetric explosion of double detonation.
  - Double detonation shifts velocities of O+Si and Ni in the opposite directions.

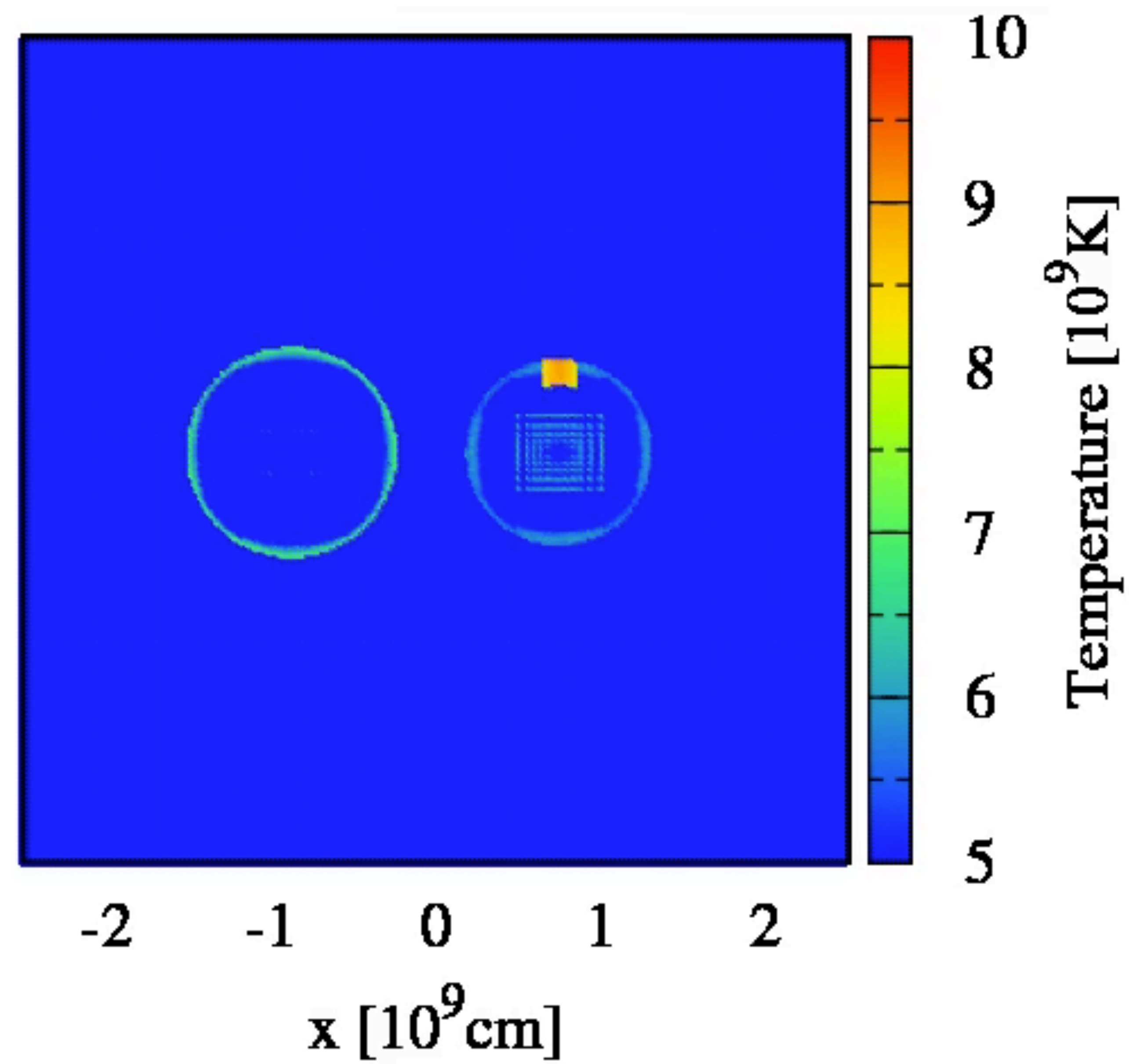


Triple detonations (TD)
1.0 CO + 0.45 He WD



Quadruple detonations (QD)
1.0CO + 0.9CO Msun w/ thick He shell of the lighter WD





Chemical abundance

Model	$M_{\rm p}$ $[M_\odot]$	$M_{\rm p,sh}$ $[M_\odot]$	$M_{\rm p,He}$ $[M_\odot]$	$M_{\rm c}$ $[M_\odot]$	$M_{\rm c,sh}$ $[M_\odot]$	$r_{\rm sep,i}$ [km]	Exp.	$M_{\rm ej}$ $[M_\odot]$	$M_{^{56}{\rm Ni}}$ $[M_\odot]$	$M_{\rm Si}$ $[M_\odot]$	$M_{\rm O}$ $[M_\odot]$	$M_{\rm cos}$ $[M_\odot]$	$E_{\rm nuc}$ [Foe]	$E_{\rm kin}$ [Foe]
He45R09	1.0	0.05	0.03	0.45	–	2.9	TD	1.45	0.81	0.15	0.08	–	2.3	2.0
He45	1.0	0.05	0.03	0.45	–	3.2	D^6	0.98	0.56	0.15	0.07	0.0033	1.4	1.1
CO60He00	1.0	0.05	0.03	0.60	0.000	2.5	D^6	0.97	0.55	0.15	0.07	0.0028	1.4	1.1
CO60He06	1.0	0.05	0.03	0.60	0.006	2.5	D^6	0.97	0.54	0.15	0.07	0.0029	1.3	1.1
CO90He00	1.0	0.10	0.05	0.90	0.000	1.6	D^6	0.93	0.51	0.14	0.06	0.0024	1.4	1.1
CO90He09	1.0	0.10	0.05	0.90	0.009	1.6	D^6	0.94	0.52	0.14	0.06	0.0033	1.4	1.1
CO90He54	1.0	0.10	0.05	0.90	0.054	1.6	QD	1.90	1.01	0.28	0.16	–	2.5	2.1

- Both TD and QD yield a large amount of 56Ni.
- Their feasibilities are unclear.
  - TD requires DD systems whose separation is impossibly small.
  - QD requires the lighter WD with thick He shells, ~0.06 Msun.

Summary

- We have performed a 3D simulation of the D6 model for type Ia supernova.
- CO materials are stripped by the SN ejecta, and compose low-velocity components.
- The SN ejecta have a velocity shift (~1000km/s) due to the binary motion of the progenitor system.
- We have demonstrated triple and quadruple detonations.