Three dimensional simulations of D6 explosions for modeling type Ia supernovae

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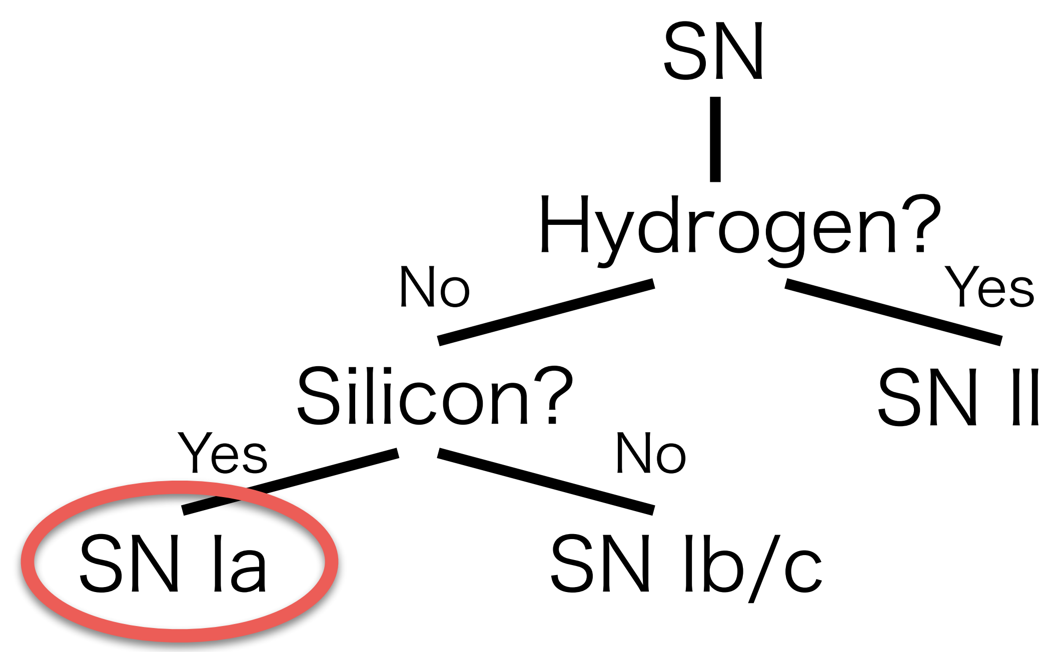
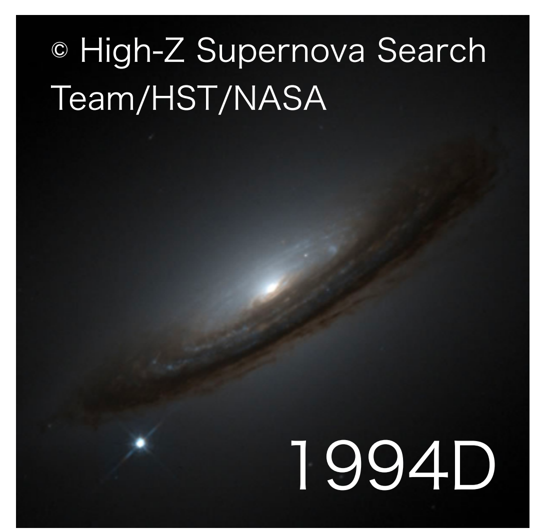
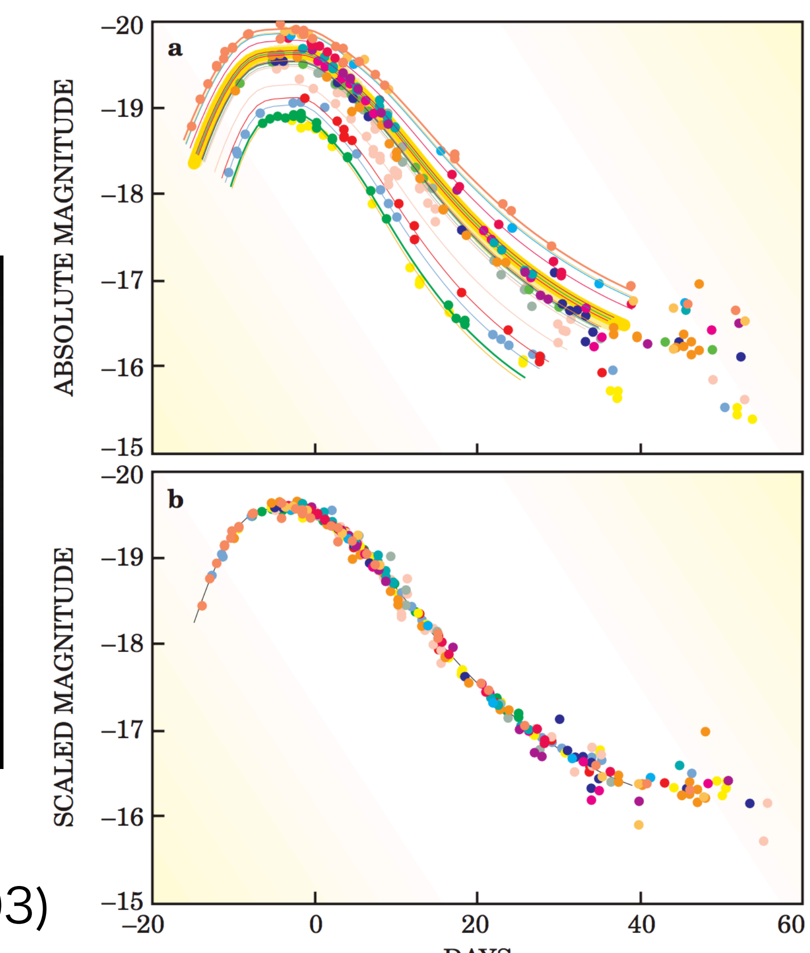
Komaba colloquium, 6th November 2019
AT, Nomoto, Nakasato (2018, ApJ, 868, 90)
AT, Nomoto, Nakasato, Maeda (2019, ApJ, 885, 103)

SNe Ia

- One of the brightest transients
- Spectra w/o H, and w/ Si
- Standard candle
- Dominant origin of iron peak elements



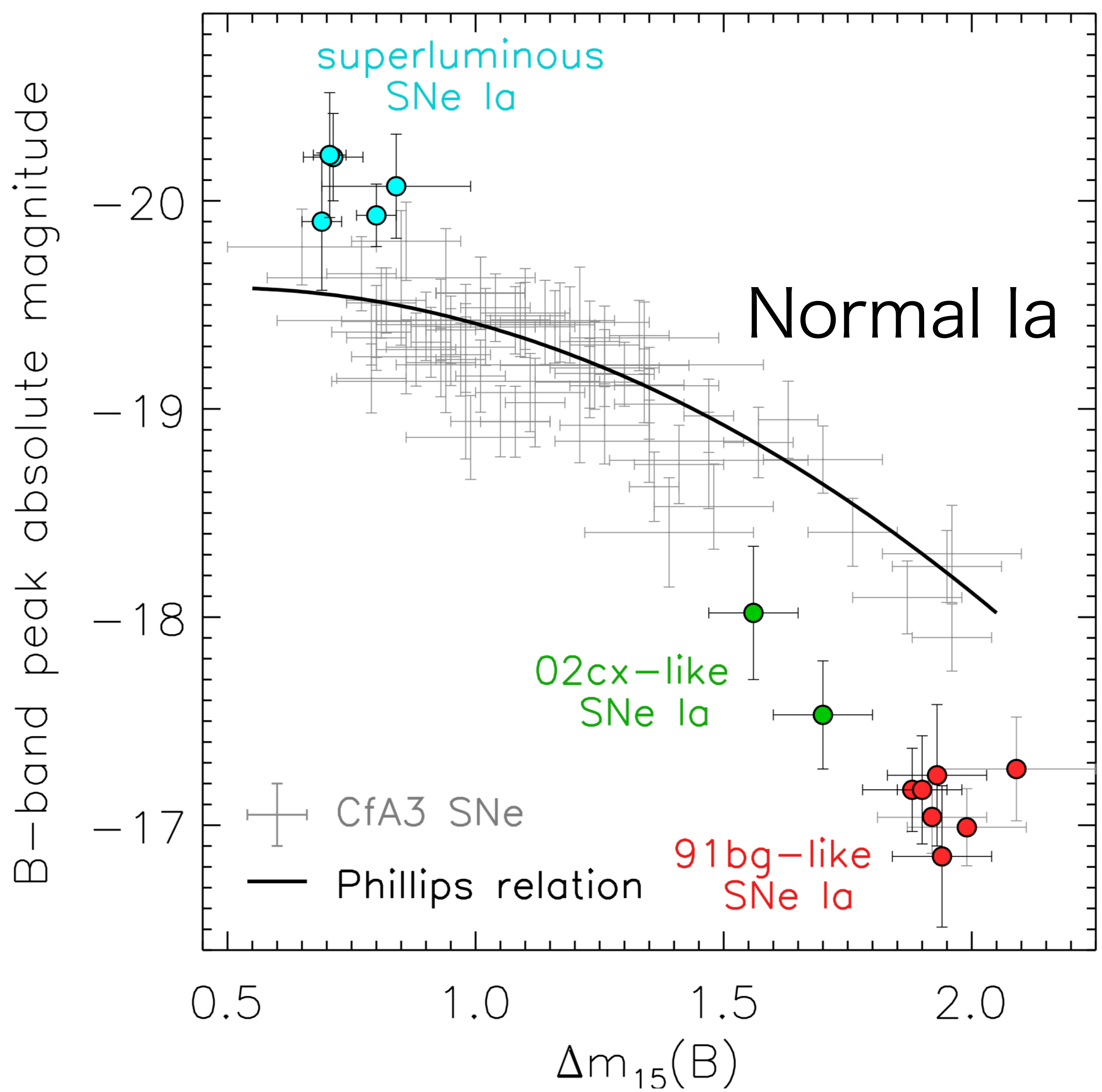




Perlmutter (2003)

Normal & Peculiar SNe Ia

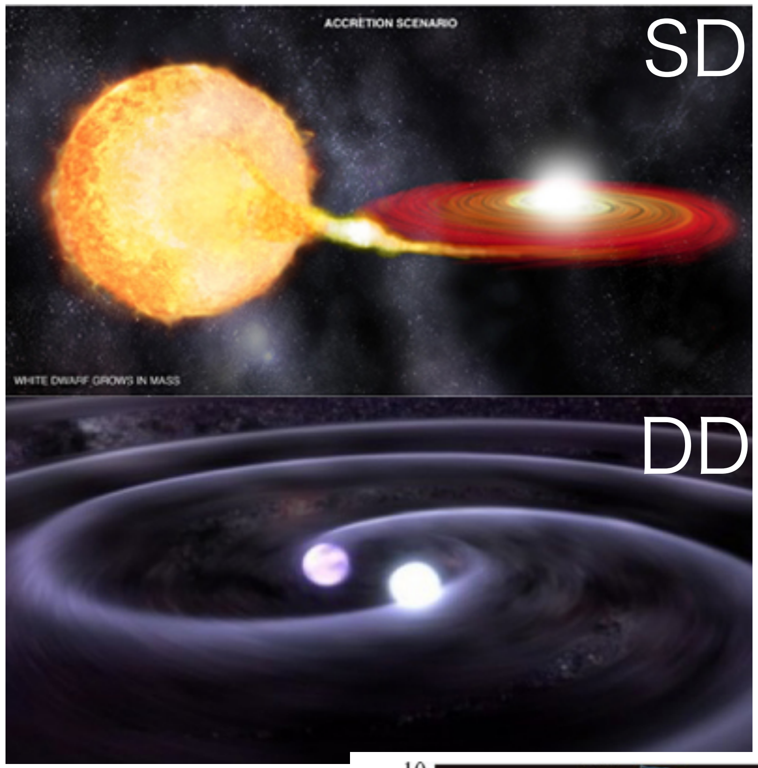
- Normal Ia
  - Standard candle
  - Dominant population (~50%)
- Peculiar SNe Ia
  - Sub-luminous Ia (e.g. 91bg-likes)
  - Type Iax, or 02cx-like
  - Over-luminous Ia (e.g. 91T-likes and 99aa-likes)
  - Super-Chandrasekhar Ia
- Discussion about the normal Ia

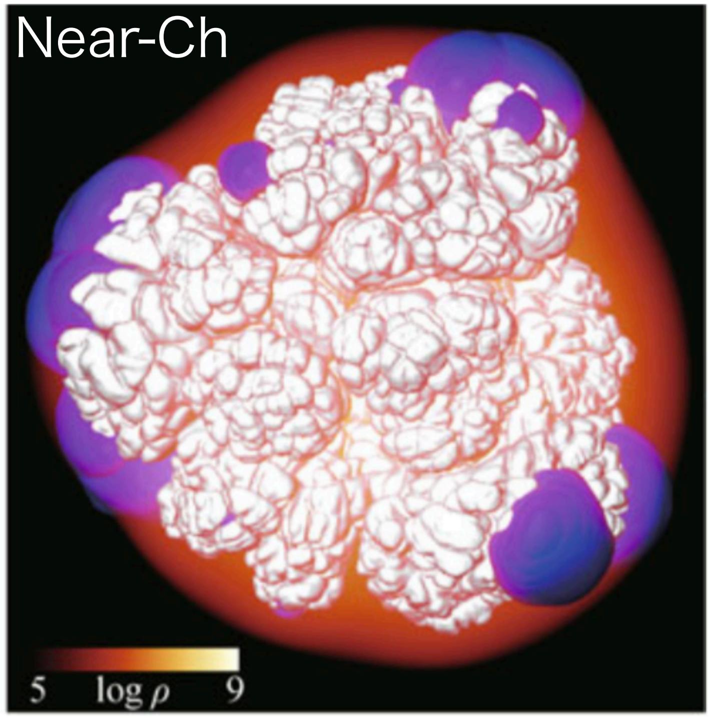


Hillebrandt+ (2013)

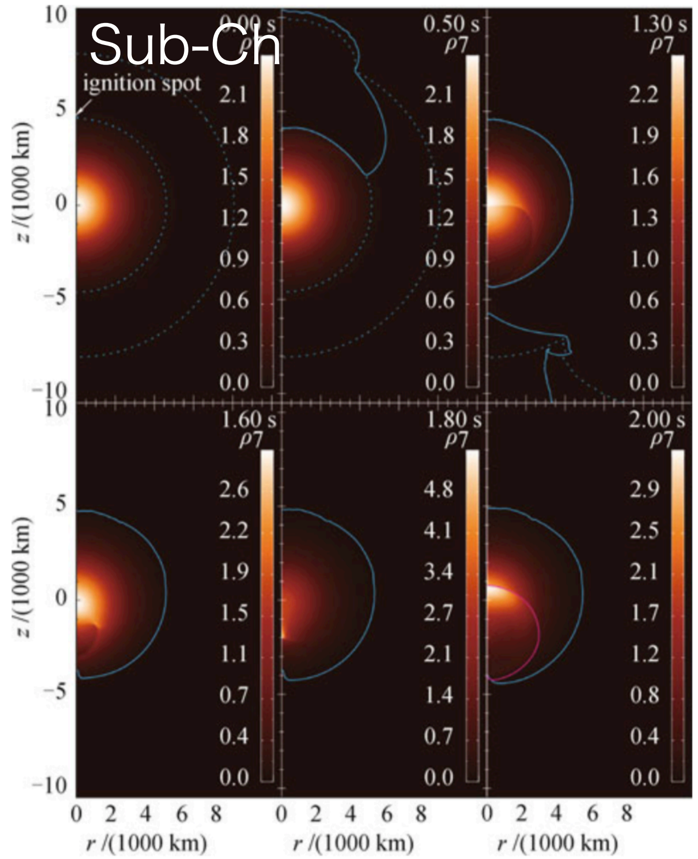
Progenitor models

- Thermonuclear explosions of Carbon-oxygen (CO) white dwarf (WD) in binary systems
- Radioactivity of ^{56}Ni
- Open questions
  - Single Degenerate (SD), Double Degenerate (DD)
  - Near-Chandrasekhar (Ch) mass or sub-Ch mass
- Near-Ch SD, near-Ch DD, sub-Ch SD, and sub-Ch DD





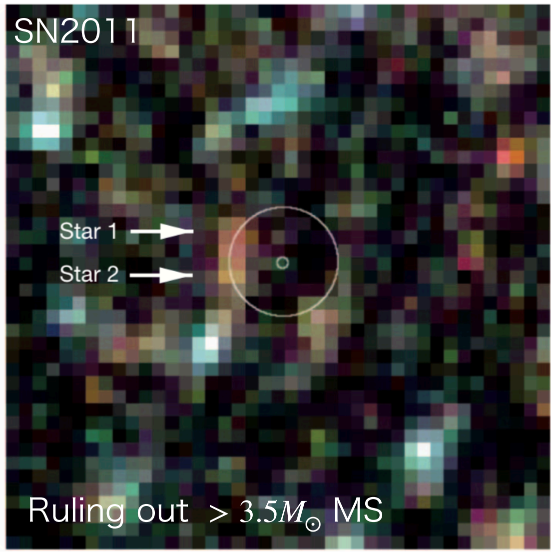
Seitenzahl et al. (2013)



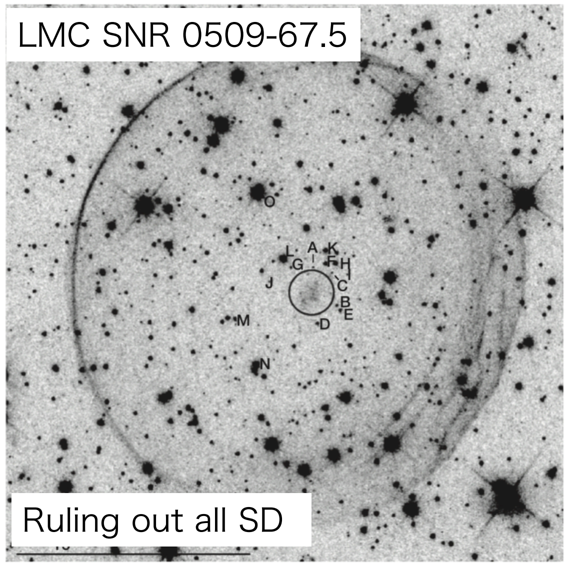
Fink et al. (2010)

Non-degenerate companion

- There are several problems in the near SD scenarios.
- Nearby SNe Ia have
  - No companion stars (Li+2011; Schaefer+12)
  - No circumstellar matter (CSM) (Maugutti+12; 14)
  - No hydrogen stripped from companion stars (Shappee+ 13)
- Some SNe Ia indicate the presence of non-degenerate stars, but
  - PTF11kx could be over-luminous (Dilday+12).
  - iPTF14atg is sub-luminous (Cao+15).

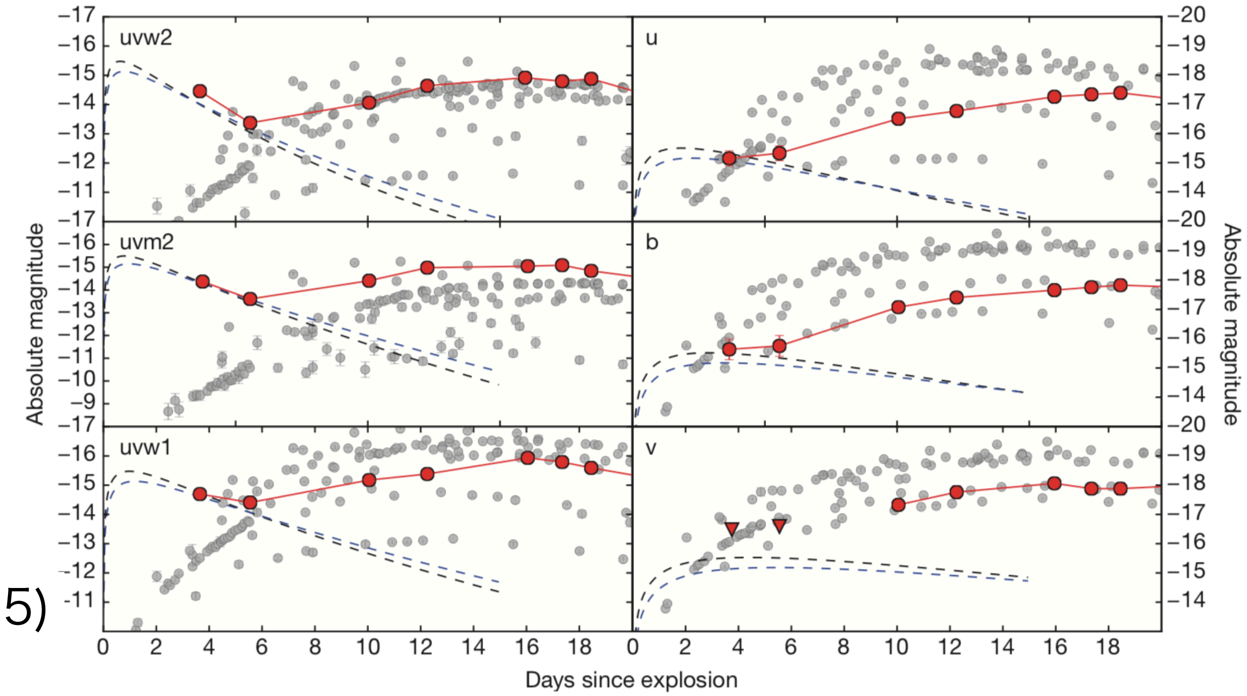


Li+ (2011)



Schaefer+ (2012)

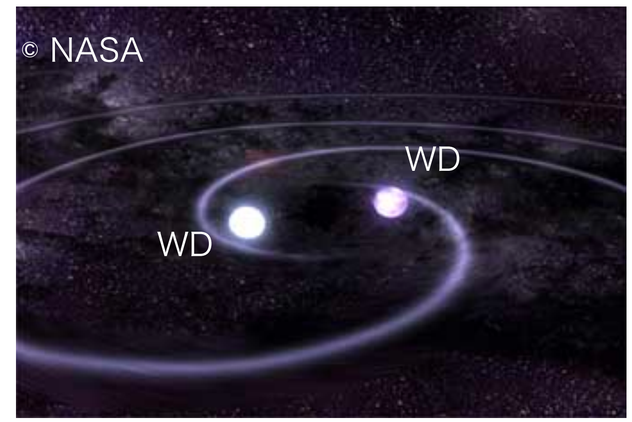
iPTF14atg (sub-luminous Ia)

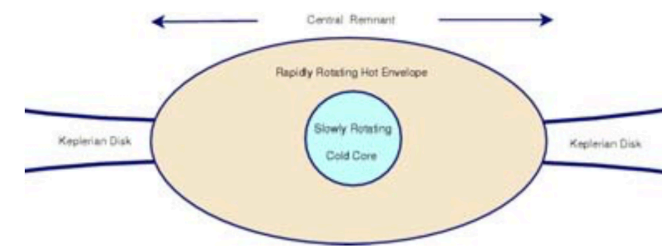


Cao et al. (2015)

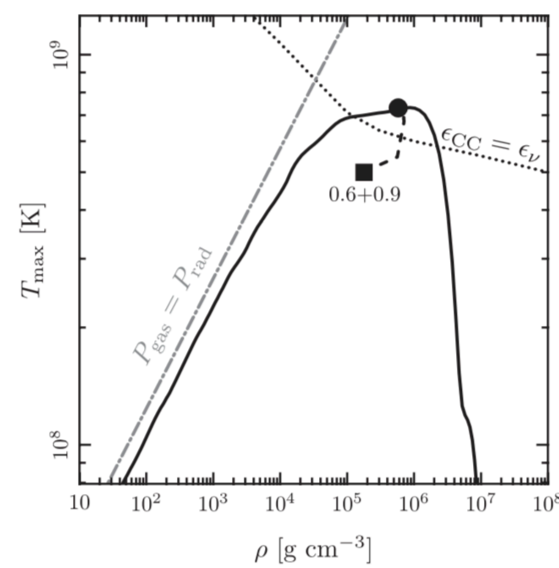
Near-Ch DD scenario

- Delayed detonation, but …
- Evolution of the near-Ch DD system
  - WD-WD merger
  - Merger remnant
    - Cold core (originally the heavier WD)
    - Debris (originally the lighter WD)
  - Rapid accretion of the debris due to magnetic viscosity
  - Ignition of slow (not explosive) C+C reactions
  - Conversion of the merger remnant from CO to ONeMg
  - Gravitational collapse to NS/BH
- A WD-WD merger ends with gravitational collapse unless some mechanism works before they completely merge.

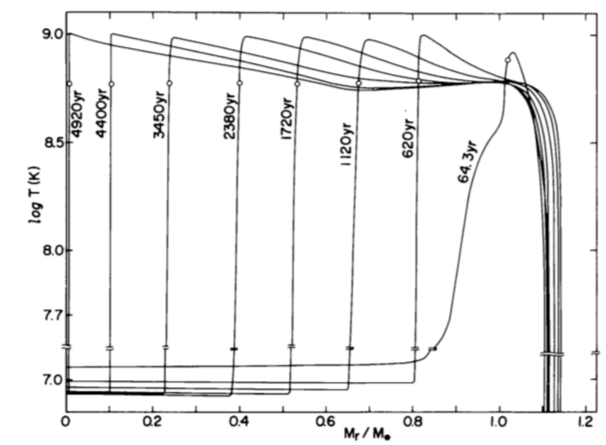




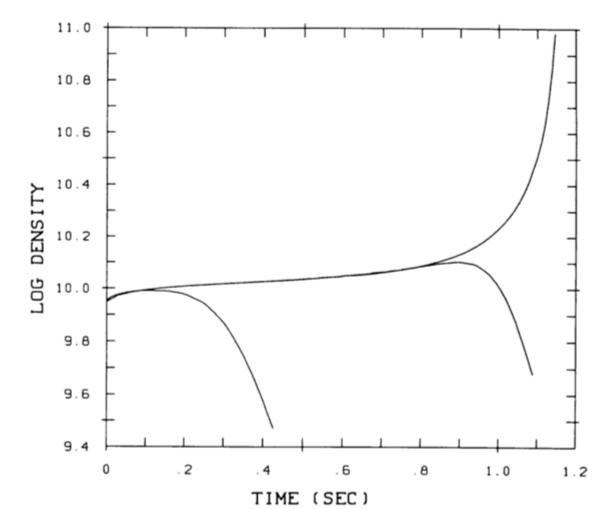
Yoon et al. (2007)



Schwab et al. (2012)

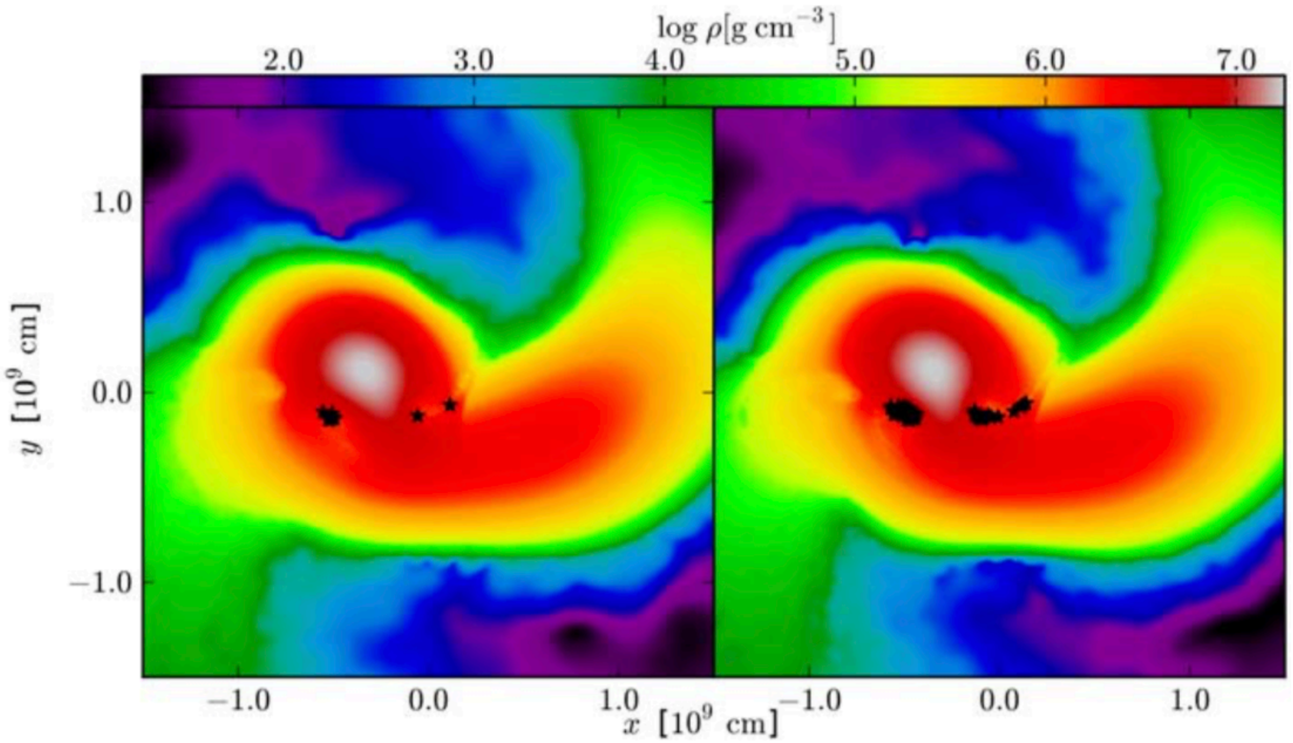


Saio, Nomoto (1985)

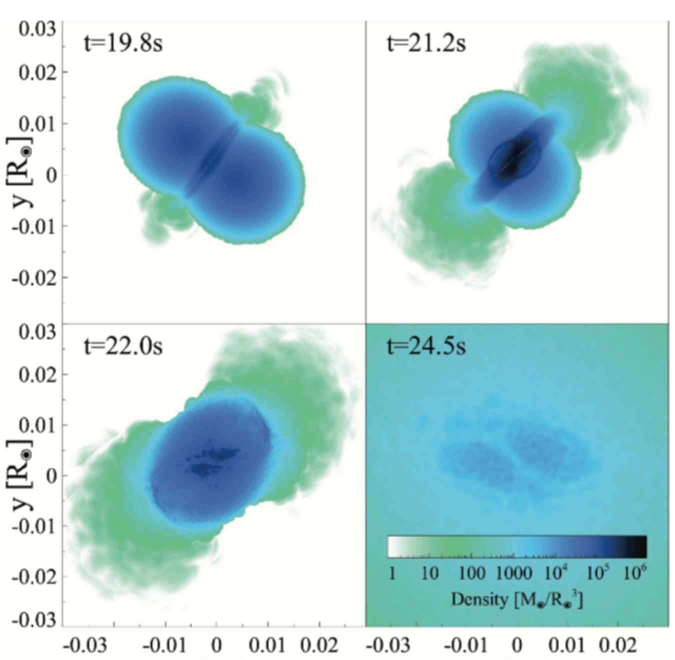


Nomoto, Kondo (1991)

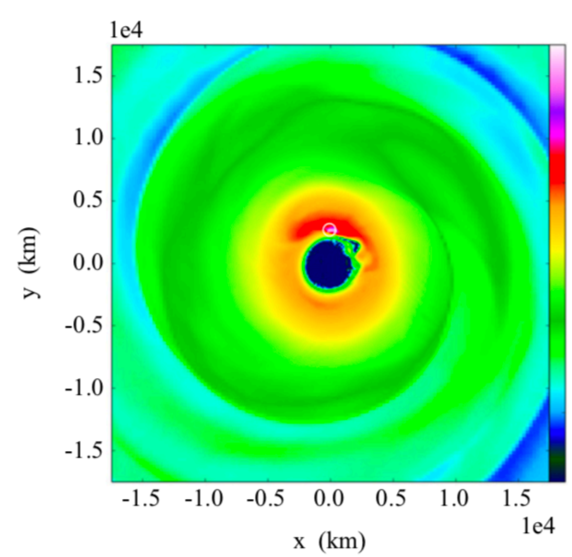
Sub-Ch DD Scenarios



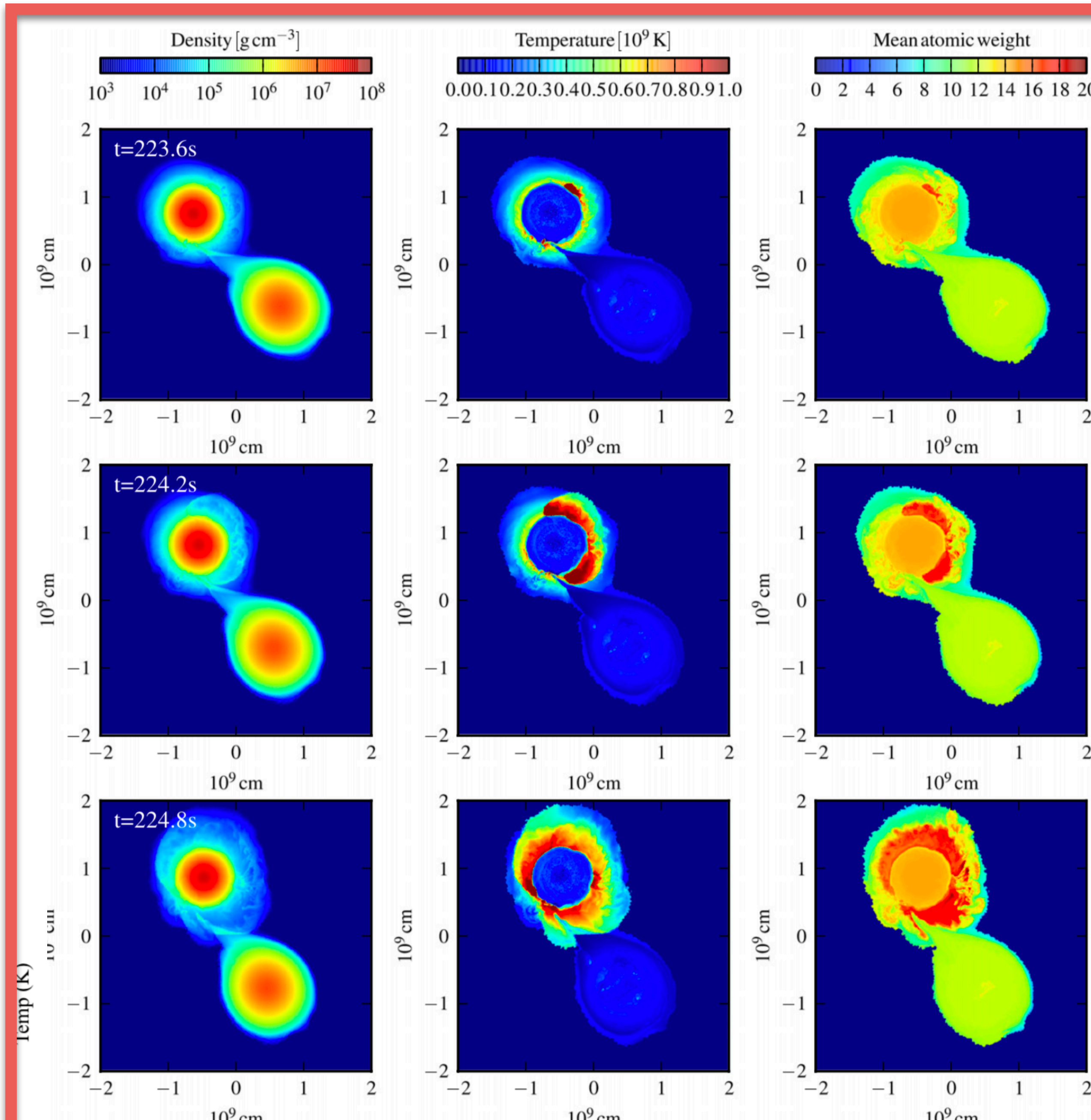
Violent merger (Pakmor+10; 11; 12;
see also Tanikawa+15; Sato+15;16)



Collisional scenario (Raskin+09; Rosswog+09; Loren-Aguilar+10; Dong+15; Isern's talk)



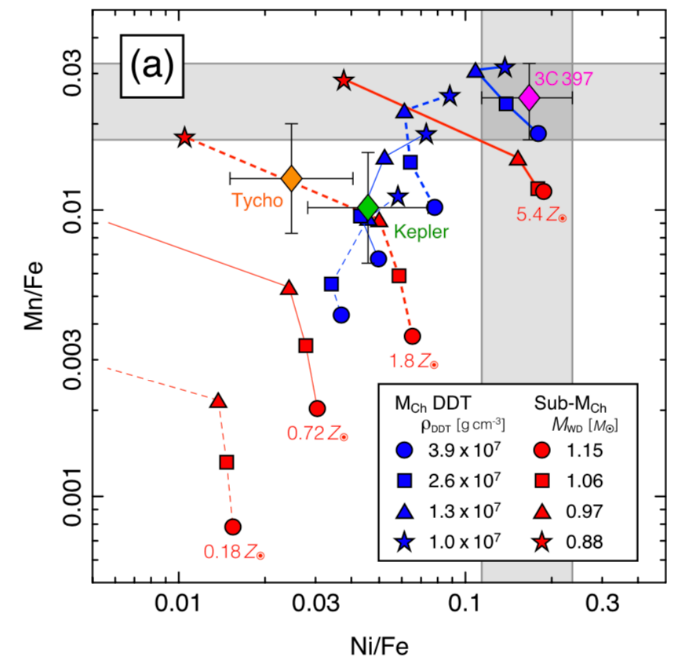
Spiral instability (Kashyap+15;17)



Helium-ignited violent merger or Dynamically-Driven Double-Degenerate Double-Detonation (D6) model(Guillochon+10; Pakmor+13)

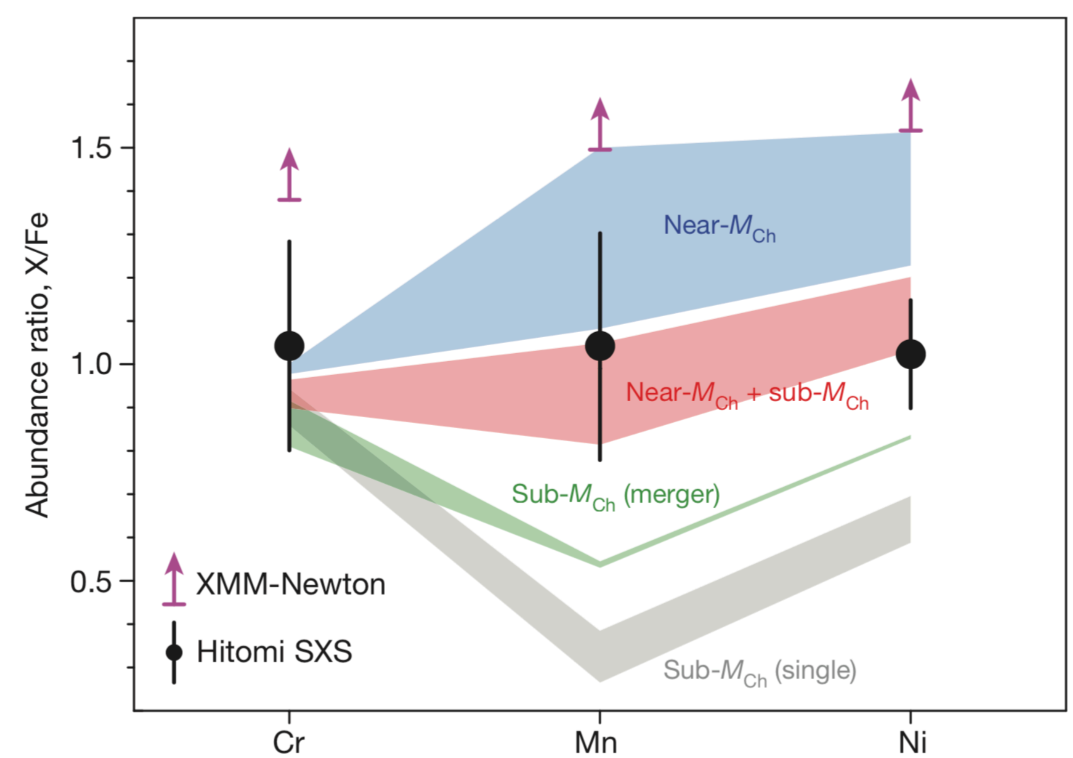
Multiple origins?

- Not all SNe Ia may be explained by the sub-Ch DD scenarios.
- Nucleosynthesis of the sub-Ch DD scenarios may not be consistent with abundance pattern of iron peak elements in SNR 3C 397.
- The abundance pattern of iron peak elements in the Perseus cluster needs both of the near-Ch and sub-Ch scenarios.
- SNe Ia may have multiple origins of near-Ch and sub-Ch mass WD.



3C 397

Yamaguchi et al. (2015)



Hitomi Collaboration (2017)

Short summary

- The sub-Ch DD scenarios
    - Nearby SNe Ia do not indicate the presence of non-degenerate companions.
    - The near-Ch DD scenario may not work well in theory.
- Combination of the sub-Ch DD and near-Ch SD scenarios
    - The abundance pattern of iron peak elements needs both the near- and sub-Ch mass explosions.
    - The SD scenarios are not necessarily ruled out for all the SNe Ia.
- We assess whether the sub-Ch DD scenario can be promising.

D6 model

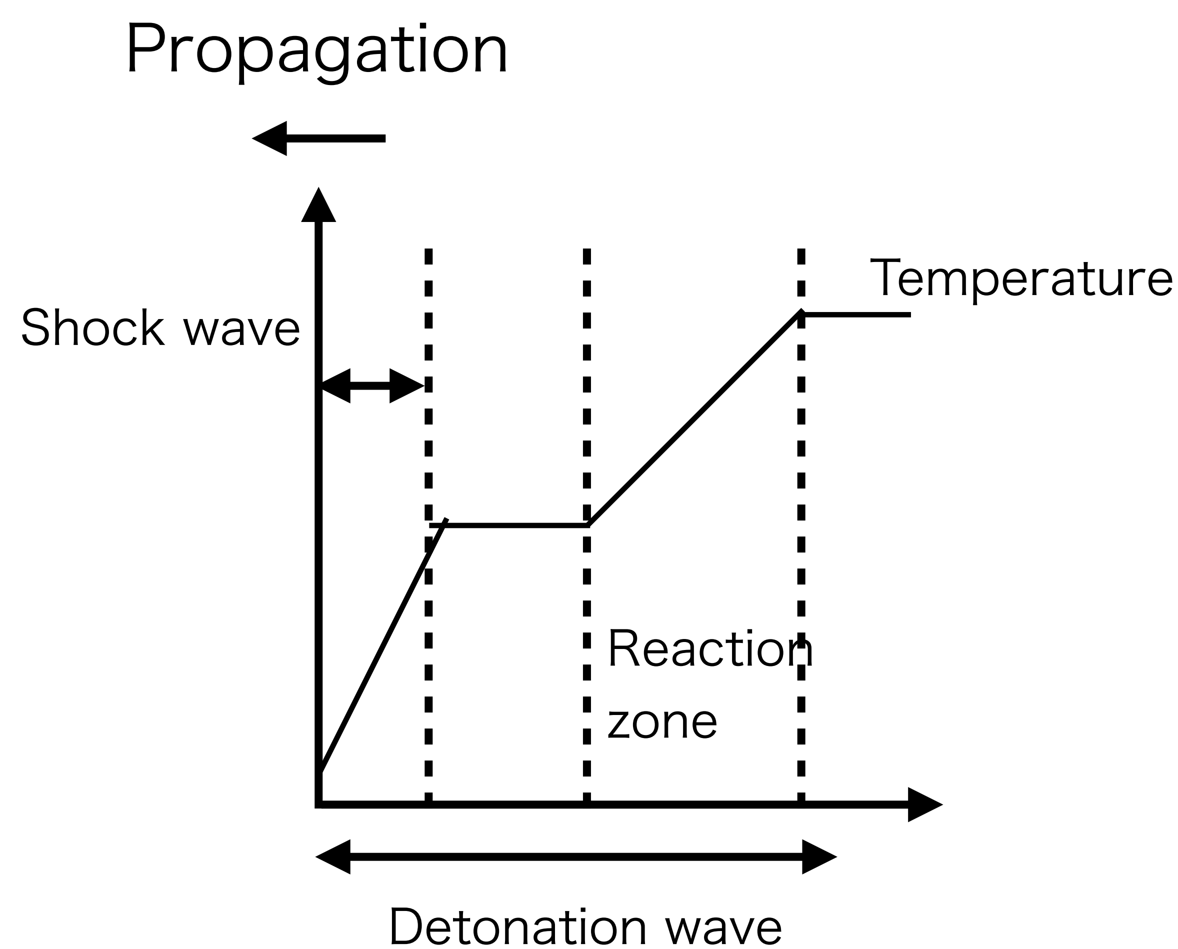
- Technical terms
- The D6 processes
- D6 Observations

Technical terms

- The D6 process
  - Double detonation model
    - Detonation
    - Conversing shock mechanism

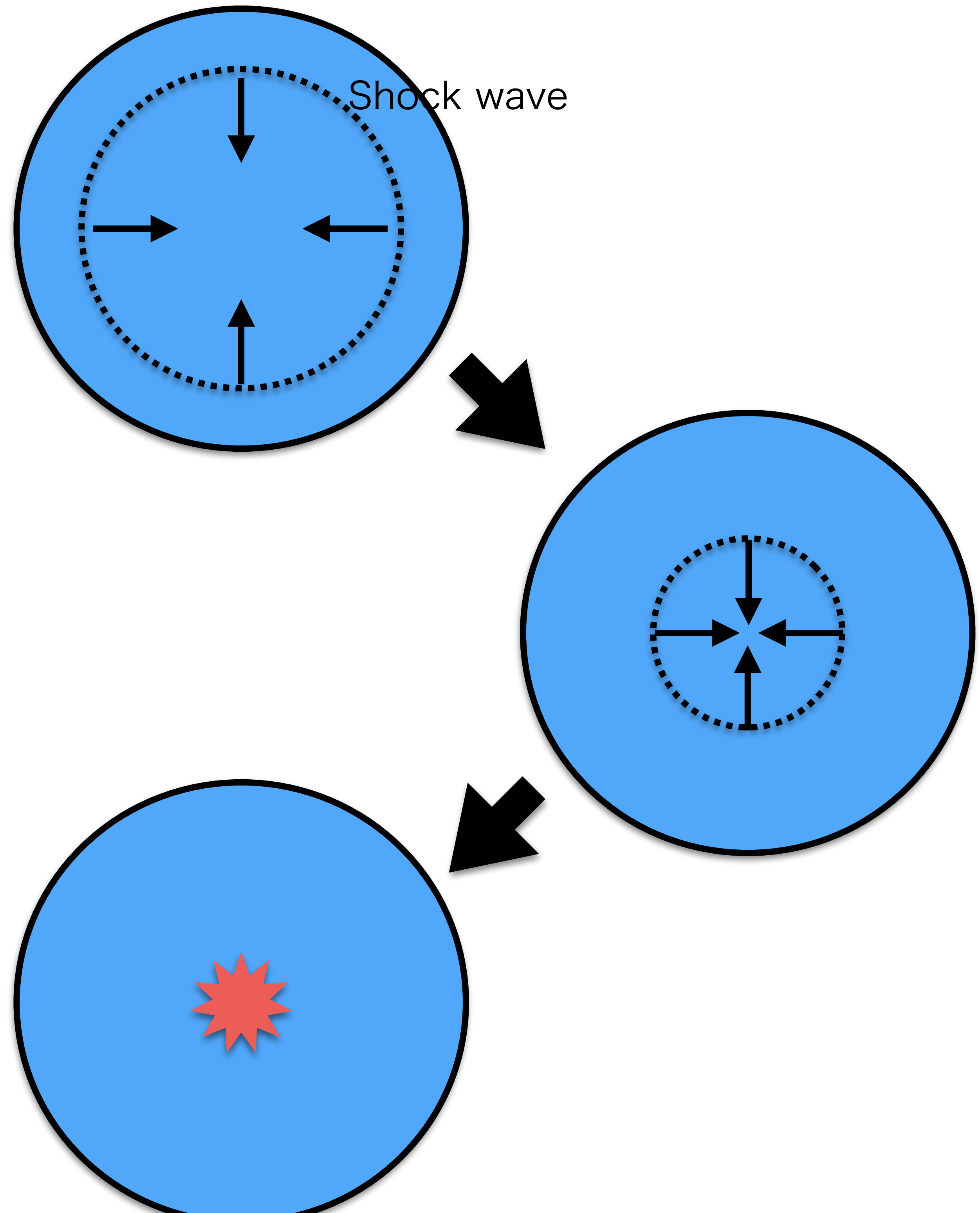
Detonation

- Supersonic combustion wave
- Process
    - Shock heating
    - Exothermic reactions
    - Fluid expansion due to the reactions
- Initiation
    - Hot spot
    - Preexisting or external shock
    - Deflagration-to-detonation transition



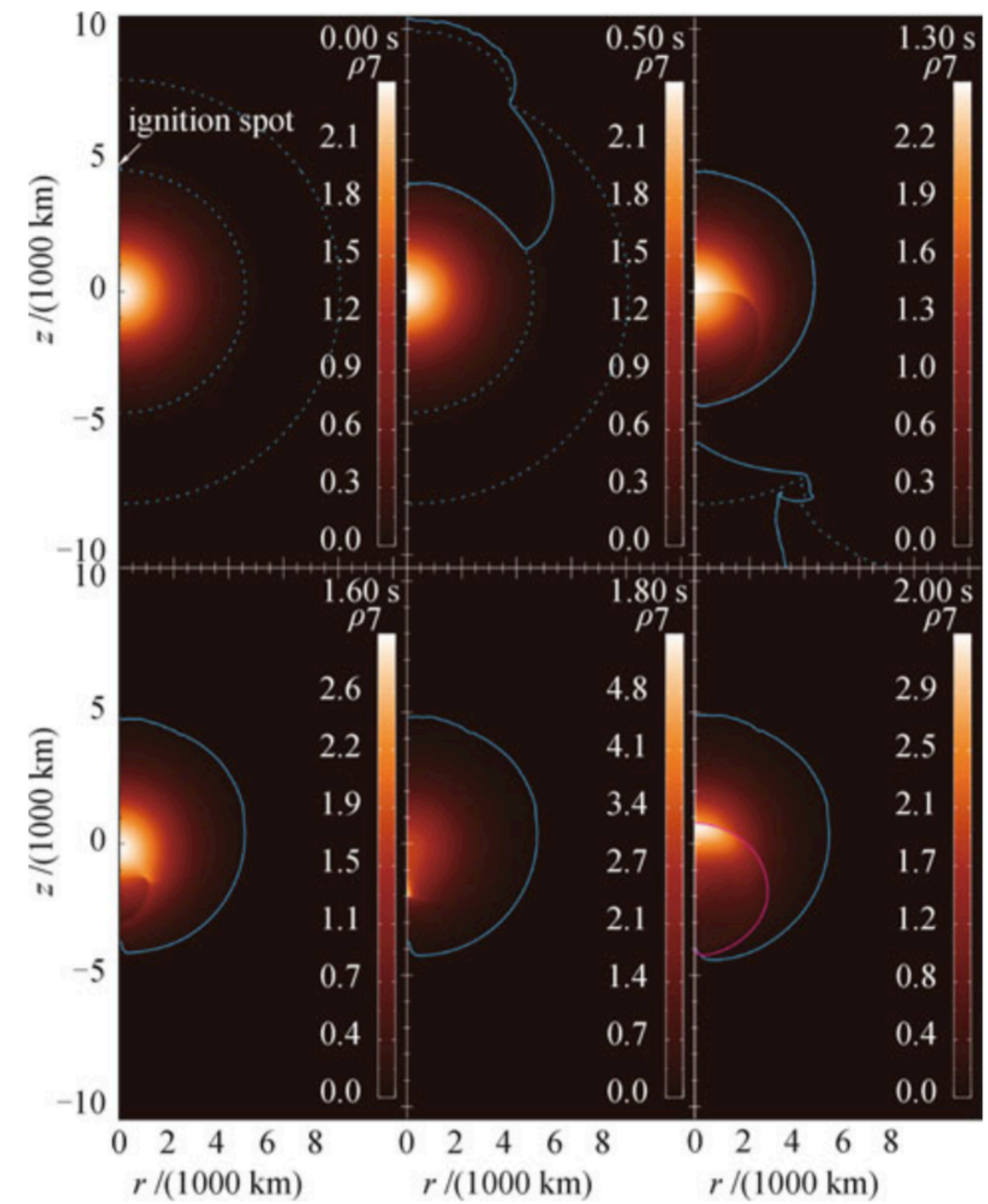
Conversing shock mechanism

- A shock wave surrounds a star for some reason.
- The shock wave converges at the center of the star.
- The shock wave strongly raises temperature.
- At the converging point, a hot spot emerges, and detonation stars from the hot spot.



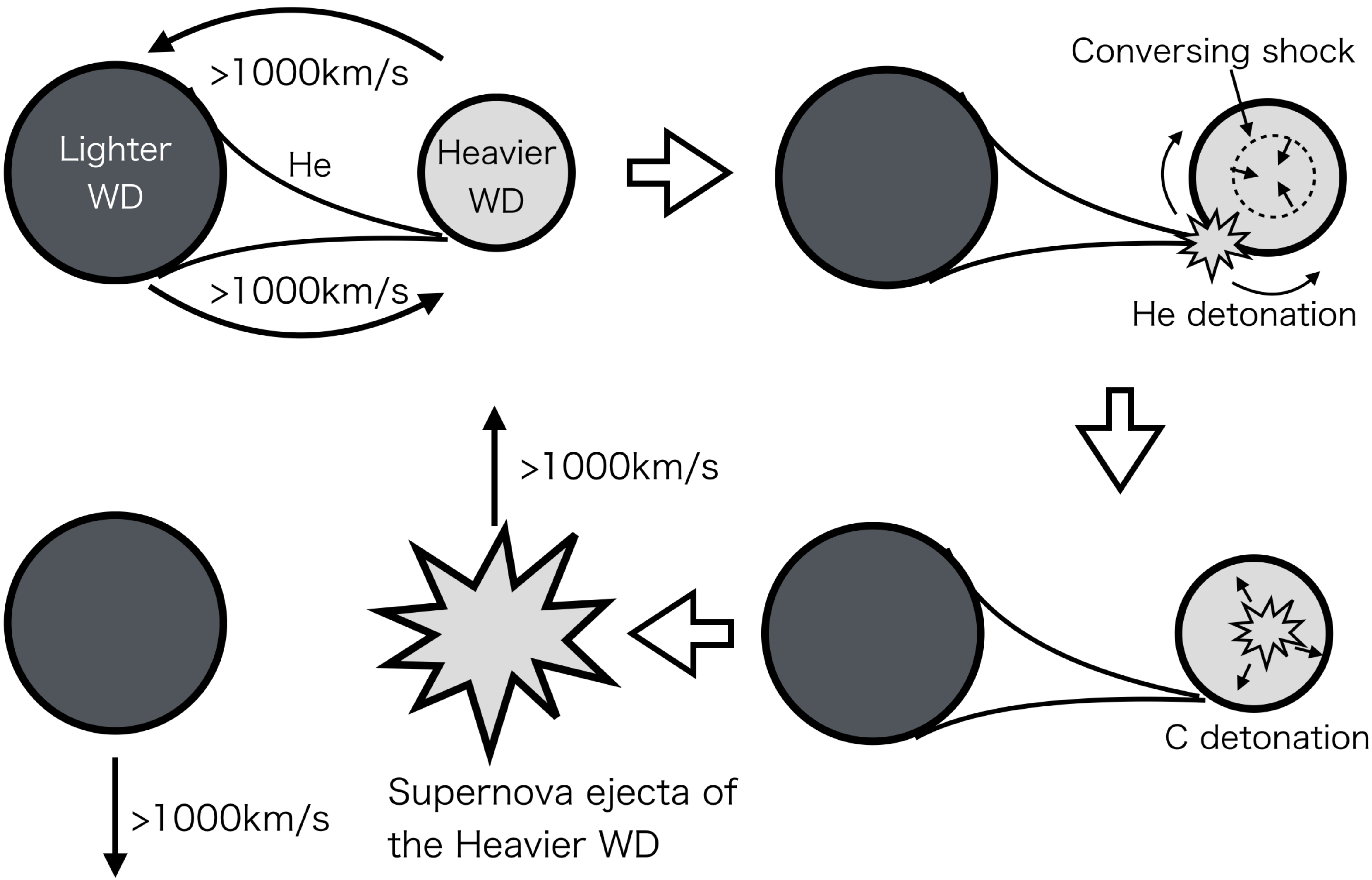
Double detonation model

- Consider CO WD with He outer shell.
- He detonation starts.
- The detonation
  - Propagates in the He shell.
  - Cannot invade into the CO core, but sends a shock wave separated from the detonation.
- A conversing shock wave appears when the He detonation surrounds the CO core.
- The conversing shock wave ignites C detonation.



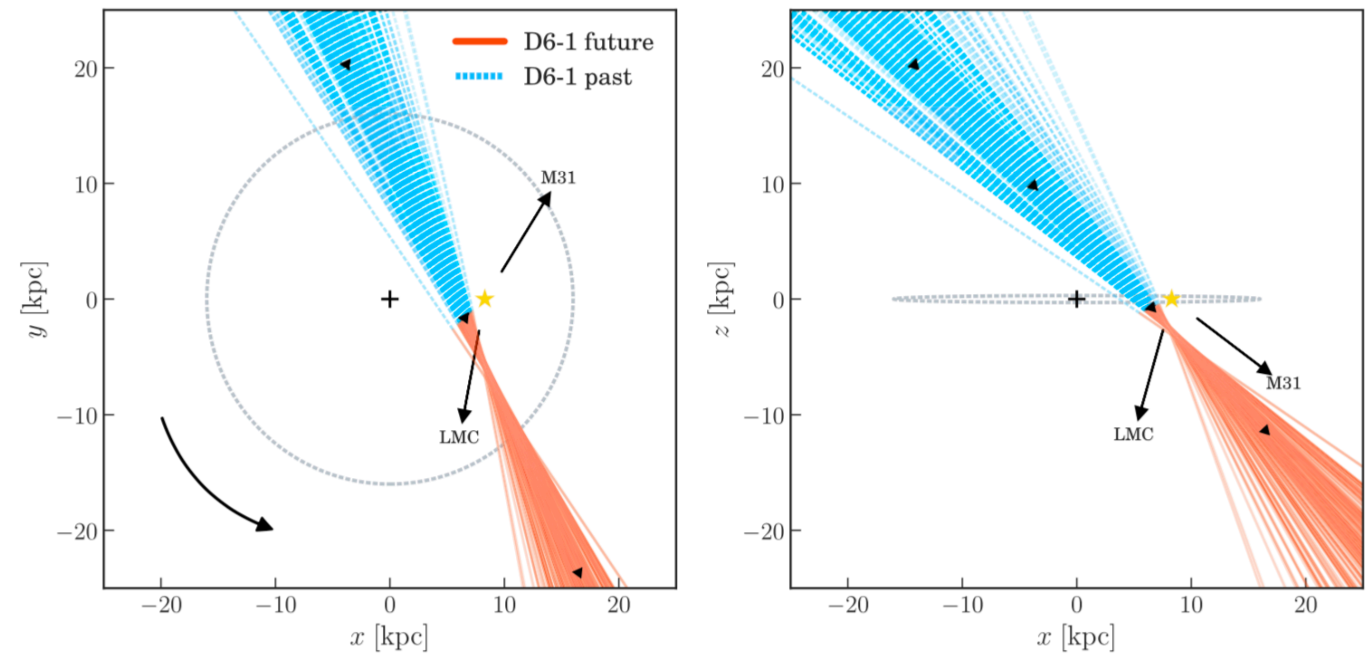
Fink et al. (2010)

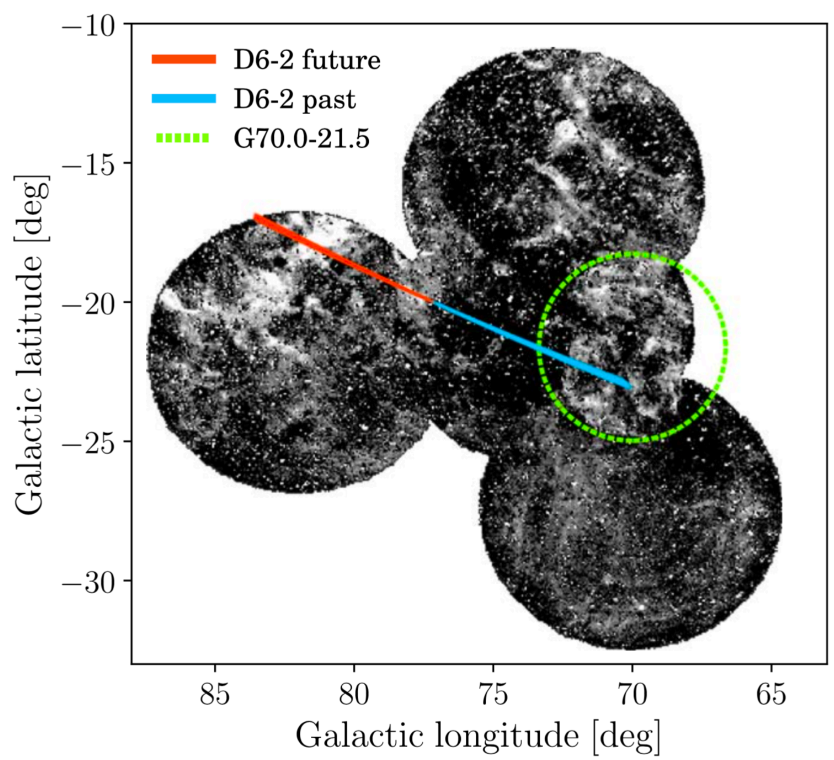
The D6 processes



Hypervelocity WDs

- Several hypervelocity WDs (>1000km/s) have been discovered from the Gaia's database (Shen+ 18).
- Their start points are NOT the Galactic center.
- One of them may start from a SNR.
- The D6 model is supported.
- Hypervelocity WDs are also formed from SNe Iax (e.g. Raddi et al. 2019)





Our study

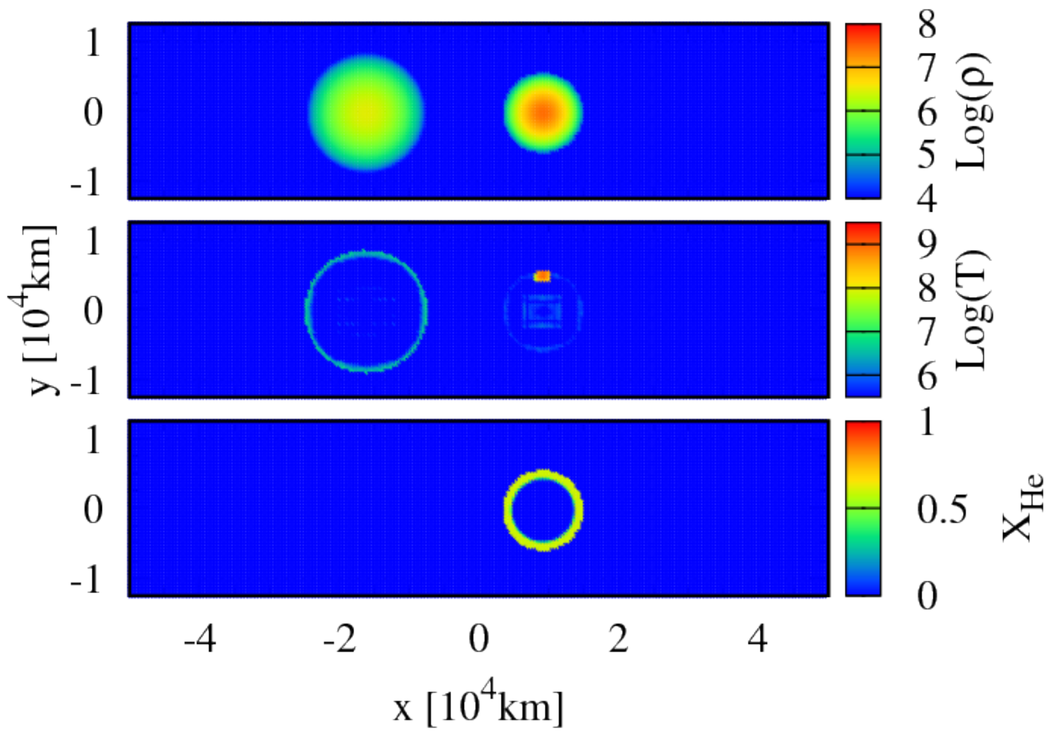
- The D6 model could be promising.
- However, it is unclear whether the hypervelocity WDs are products of normal Ia, or peculiar Ia.
- We reproduce D6 explosions, and investigate their features to assess whether they are consistent with normal Ia or peculiar Ia.
- We perform two simulations.
  - In the first case, the system experiences D6 explosion as predicted.
  - In the second case, the system indicates another explosion mode.

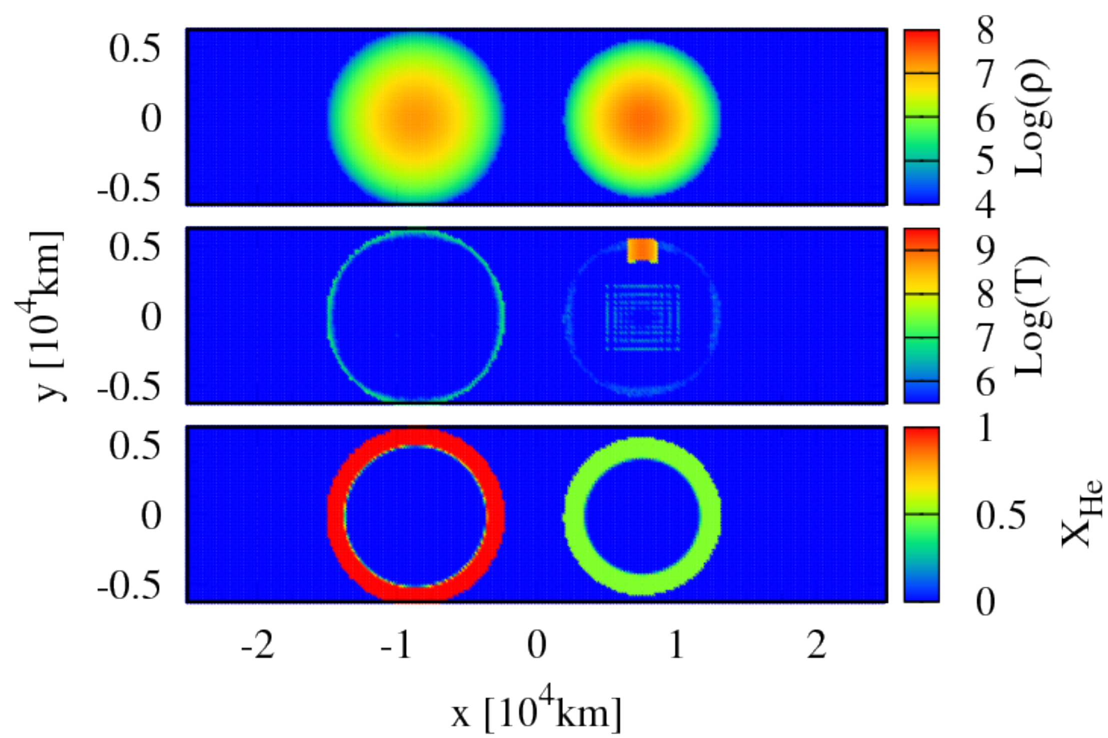
Simulation method

- 3D SPH method
  - Monaghan's artificial viscosity with Balsara switch (similar to GADGET)
  - Parallelized by FDPS (Iwasawa, AT+ 2016)
  - Vectorized by SIMD (e.g. AT+ 2012; 2013)
  - The number of SPH particles is 4 millions per $0.1M_{\odot}$.
- Helmholtz EoS (Timmes, Swesty 2000)
- Aprox13 nuclear reaction networks (Timmes et al. 2000)

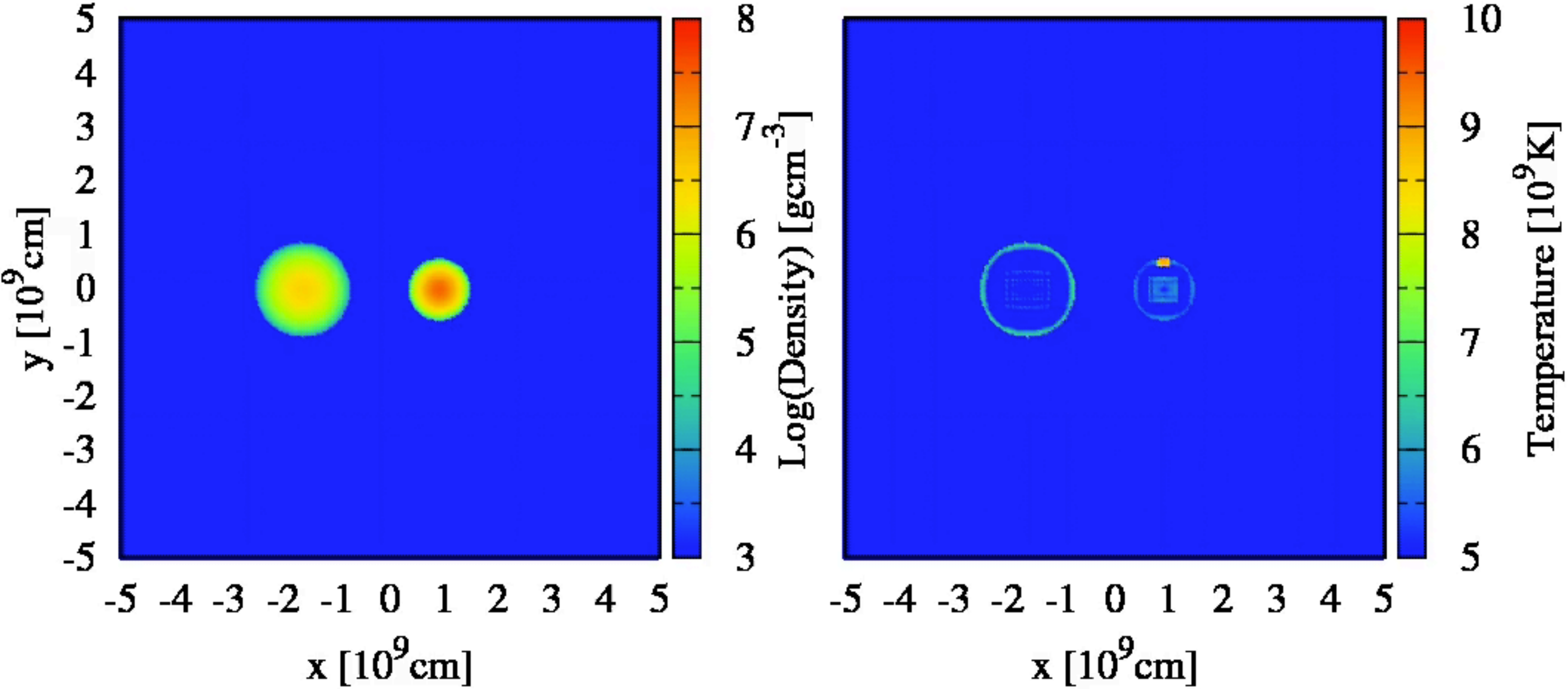
Initial conditions

- The first case
  - $1.0M_\odot$ COWD + $0.6M_\odot$ COWD
  - He outer shell on the heavier WD
  - No He outer shell on the lighter WD
- The second case
  - $1.0M_\odot$ COWD + $0.9M_\odot$ COWD
  - He outer shells on the heavier WD
  - Massive He outer shell on the lighter WD





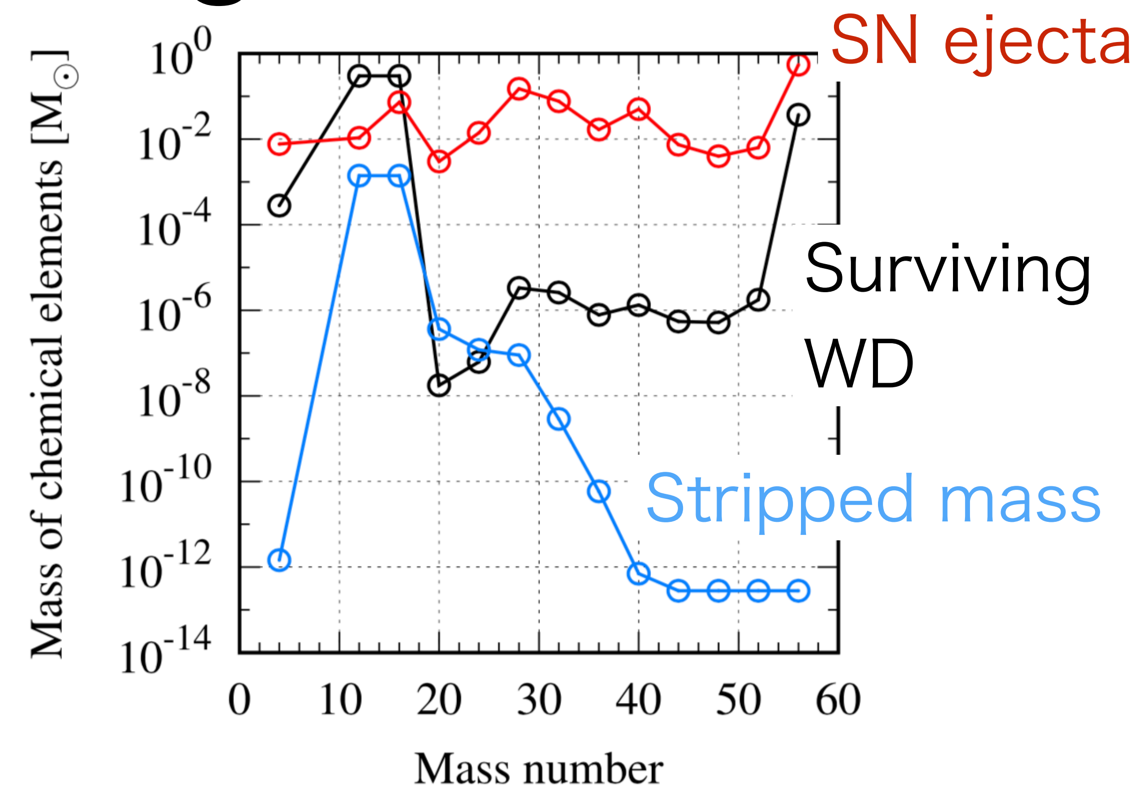
The first case

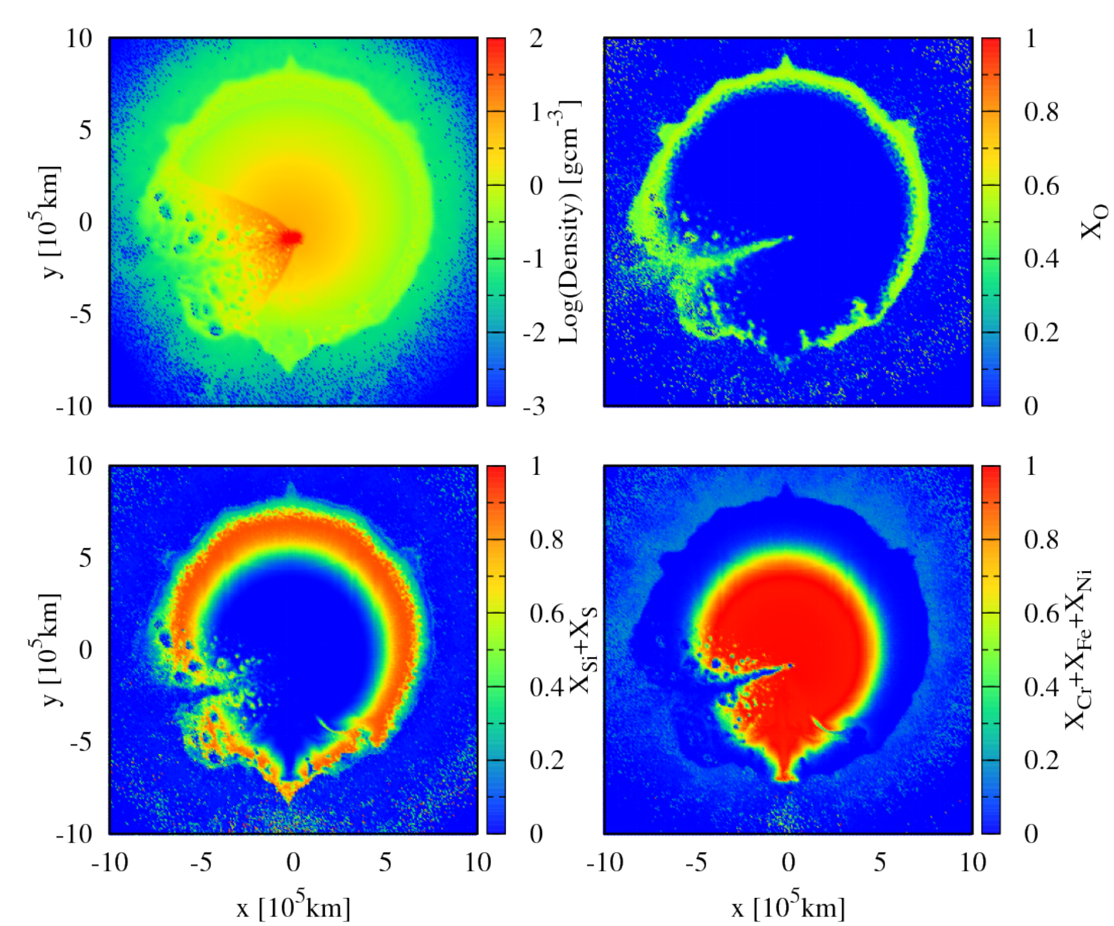


Tanikawa et al. (2018)

Supernova ejecta

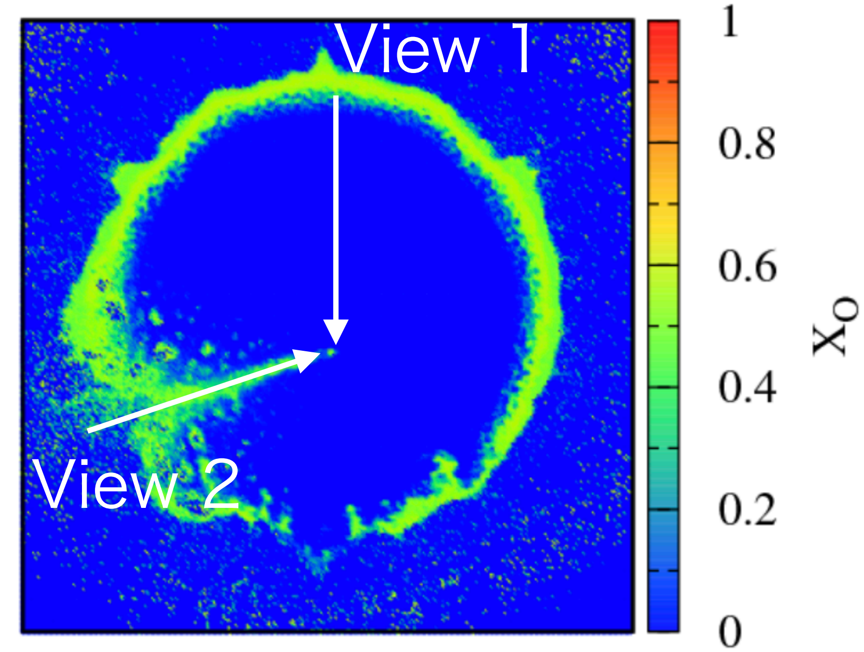
- ^{56}Ni mass is ~ 0.6 $M_\odot$
- Supernova ejecta have a shadow (Papish et al. 2015).
- Mass of materials stripped from the lighter WD is ~ 0.003 $M_\odot$
- The stripped materials consist of carbon and oxygen.
- Supernova ejecta have a stream consisting of the stripped materials (companion-origin stream).



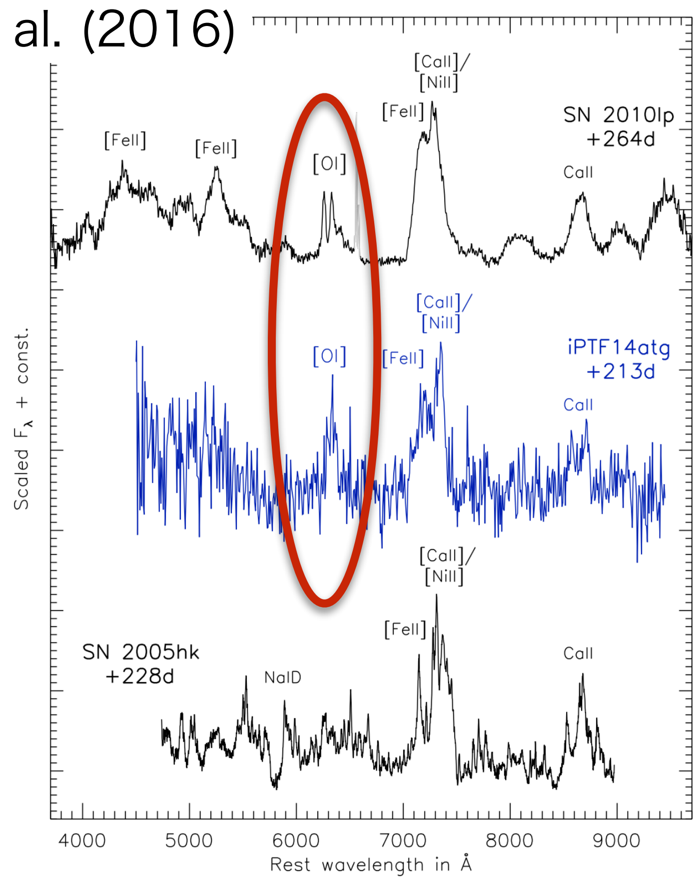


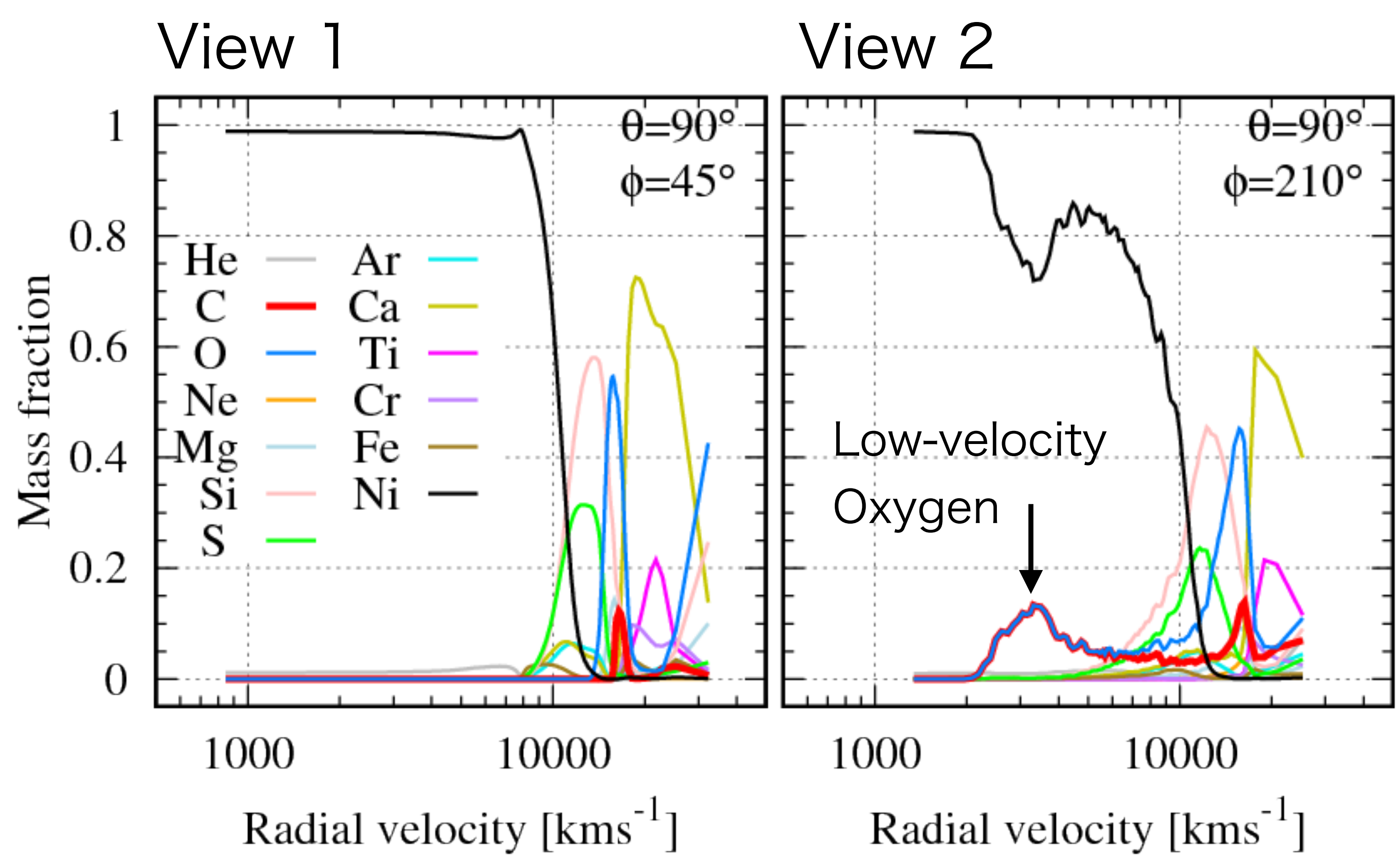
Low-velocity oxygen

- The companion-origin stream could be a key to identify D6 explosions.
- D6 explosions have low-velocity oxygen (~1000km/s) originating from the companion-origin stream.
- Such low-velocity oxygen can explain nebular-phase spectra of some of sub-luminous SNe Ia.
- We will investigate nebular phase spectra of D6 explosion by radiative transfer calculation in near future.

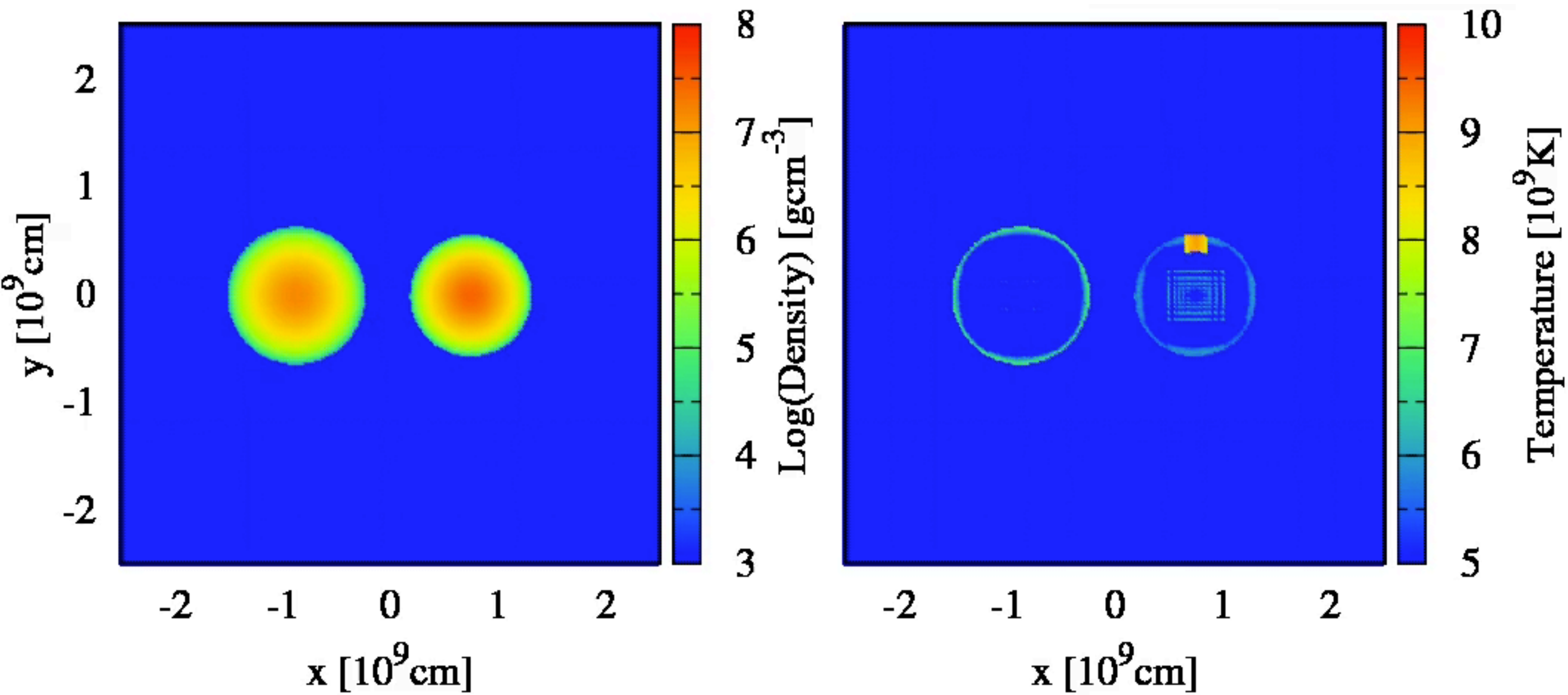


Kromer et al. (2016)

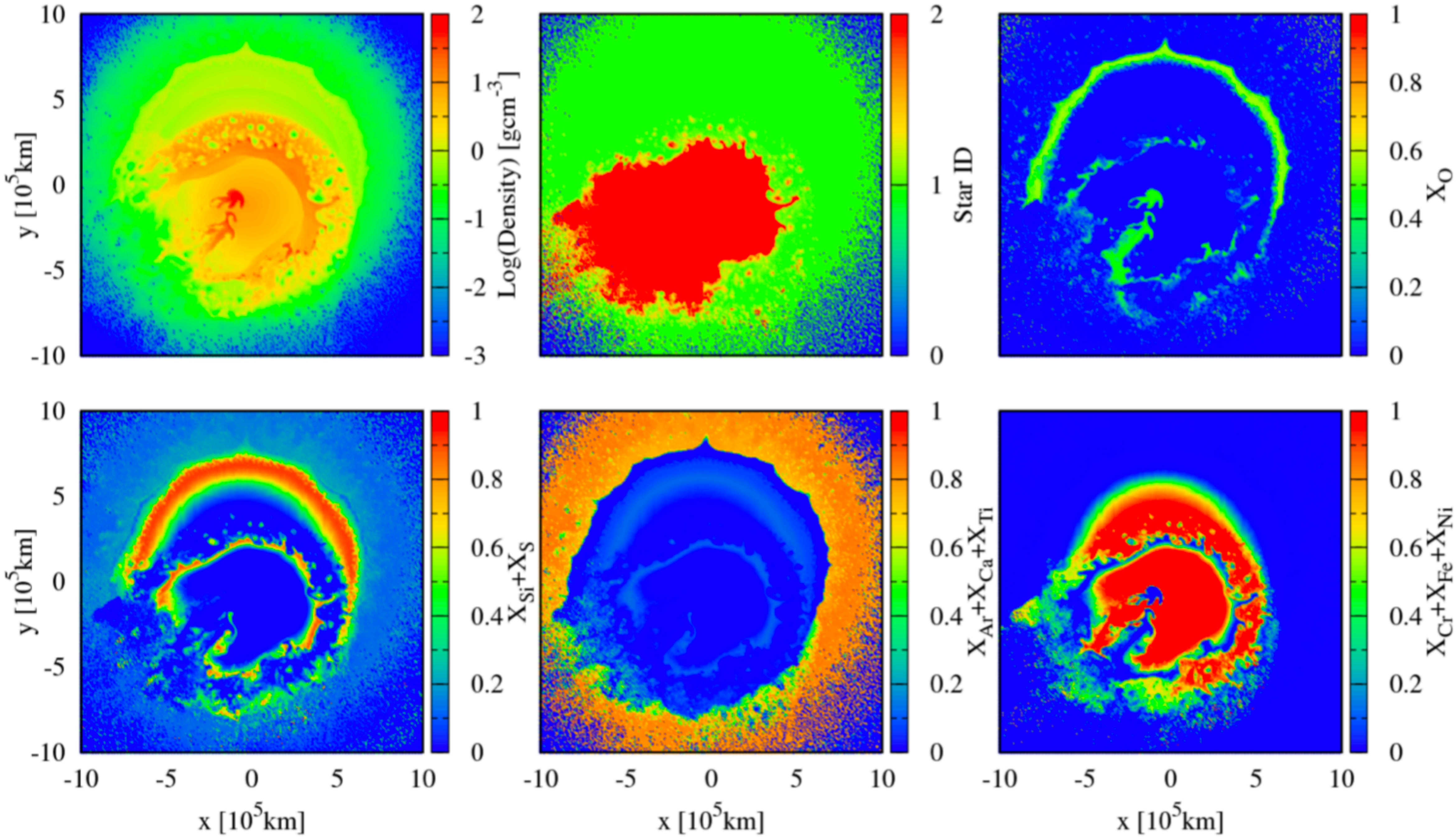




The second case



Chemical abundance



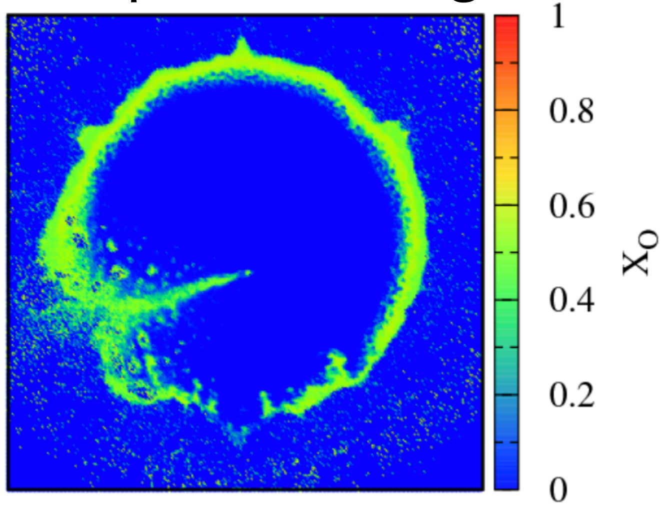
- ^{56}Ni mass is ~1.0Msun.
- SN ejecta have nested structure.

Luminous SNe Ia?

- QD explosions have early emissions because of He detonation products.
- The colors of the early emissions may be consistent with those of Luminous SNe Ia, such as SN1991T and SN1999aa (Maeda et al. 2018).
- The colors of early emissions through interactions with non-degenerate companions and CSMs may be too blue (Hosseinzadeh et al. 2017; Maeda et al. 2018).
- Super-Chandrasekhar SNe Ia cannot be explained by QD explosions, since they have massive CSMs (Yamanaka et al. 2016).

Future plans

Companion-origin stream



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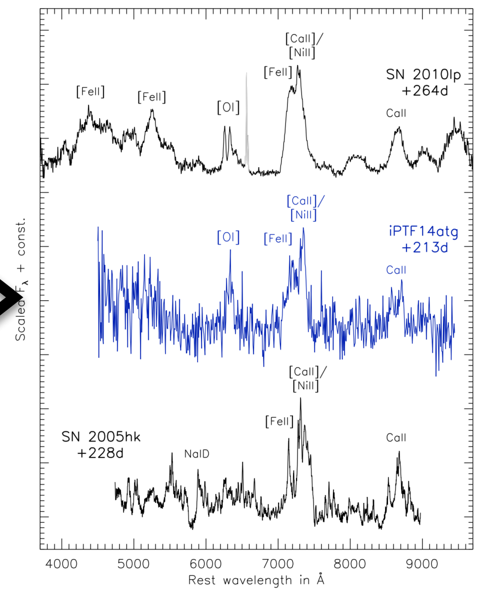
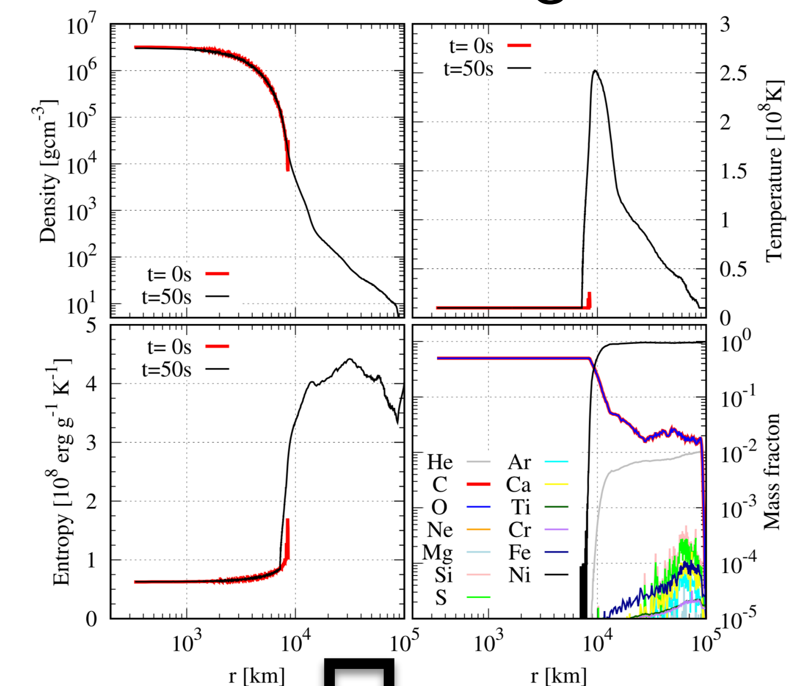


Kromer et al. (2016)

Surviving WD



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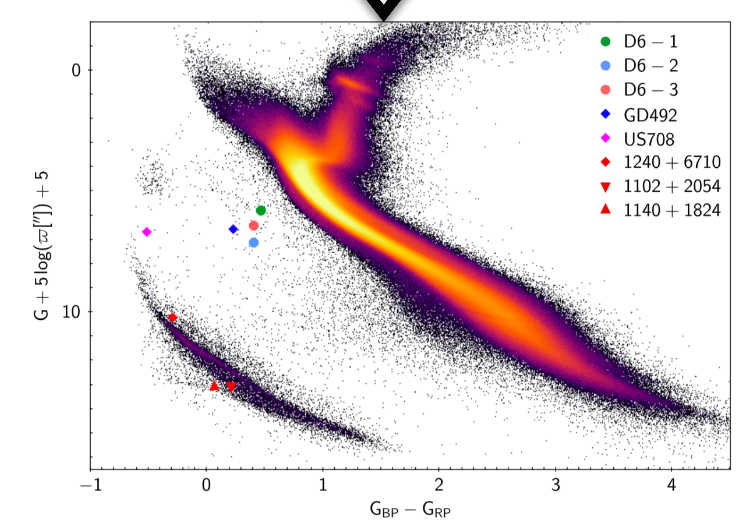
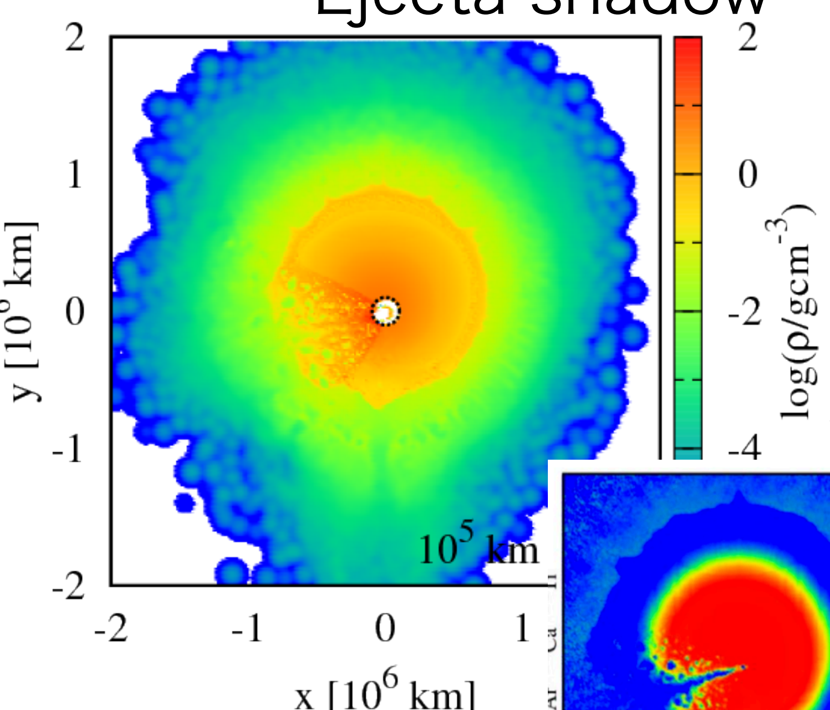


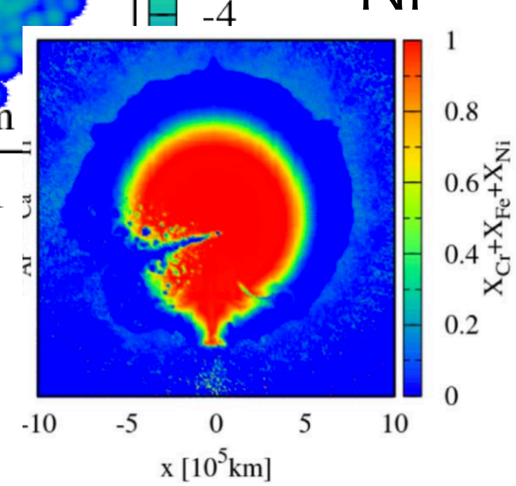
Collaboration with
Z. Liu

Ejecta shadow



Density

56Ni



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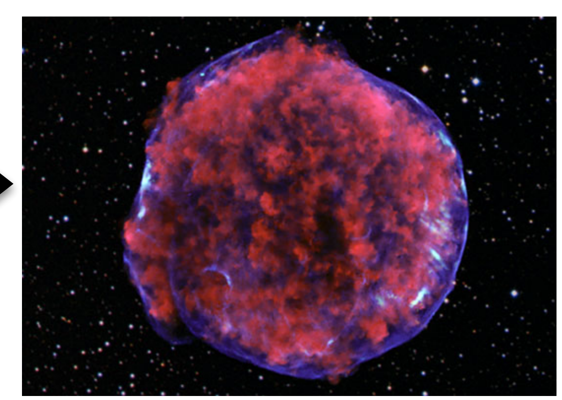


Collaboration with
G. Ferrand

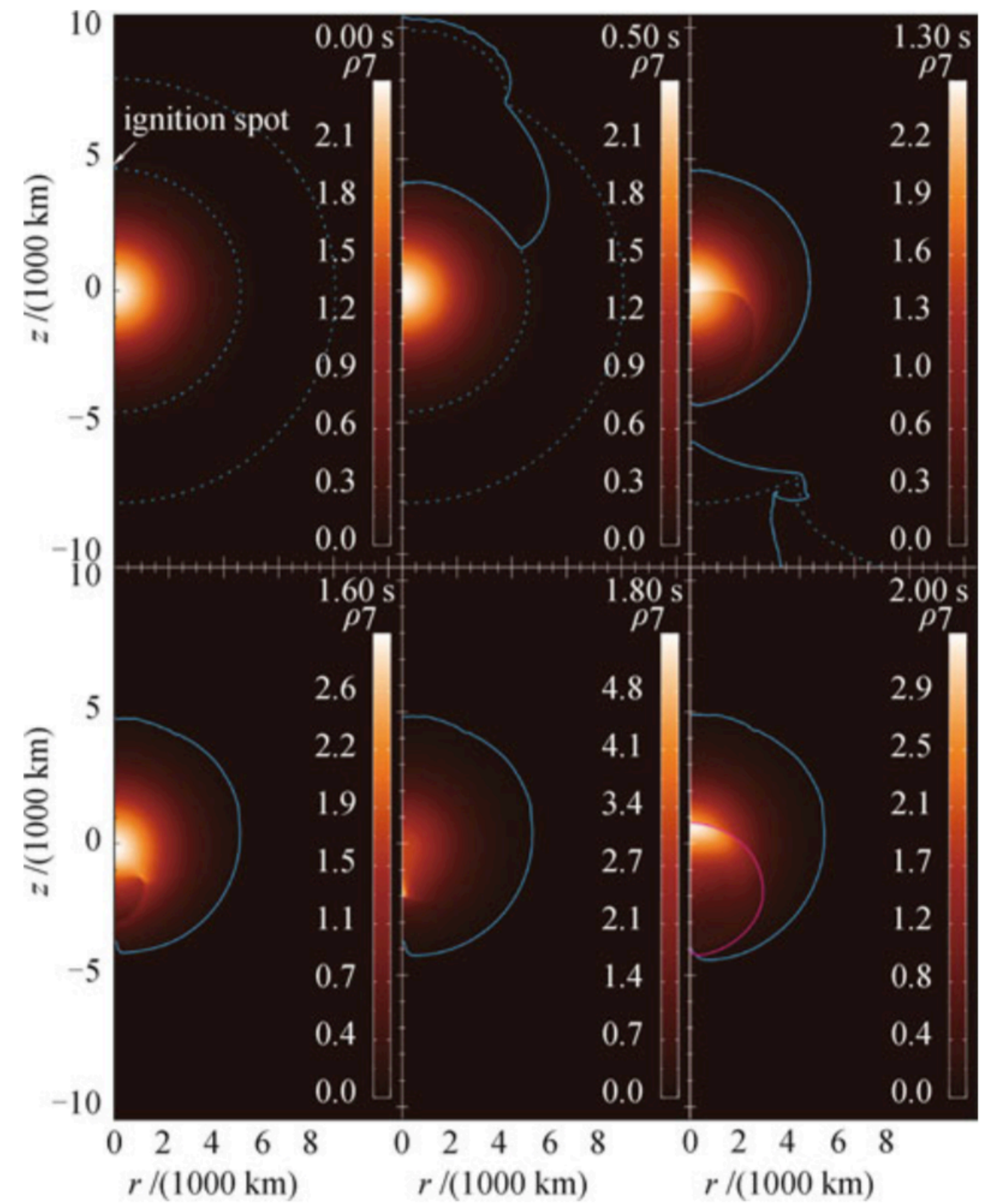
Summary

- SNe Ia can need the near-Ch SD and sub-Ch DD scenarios.
- We have assessed one of sub-Ch DD scenarios, the D6 model.
- The D6 model indicates several asymmetric features, such as the ejecta shadow, and companion-origin stream.
- The companion-origin stream can contribute to oxygen emissions in nebular phase spectra found in peculiar Ia.
- We will compare these asymmetric features with observations by detail calculations in the near future.

Backup slides

Double detonation mechanism

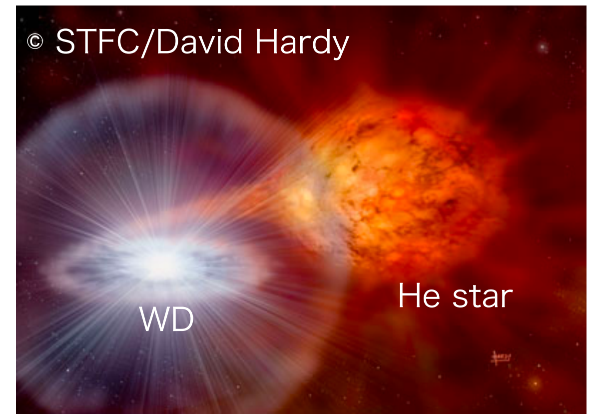
- Accreting He materials
- He detonation on the surface of a CO core
- Invasion of a converging shock wave into the CO core
- Ignition of CO detonation

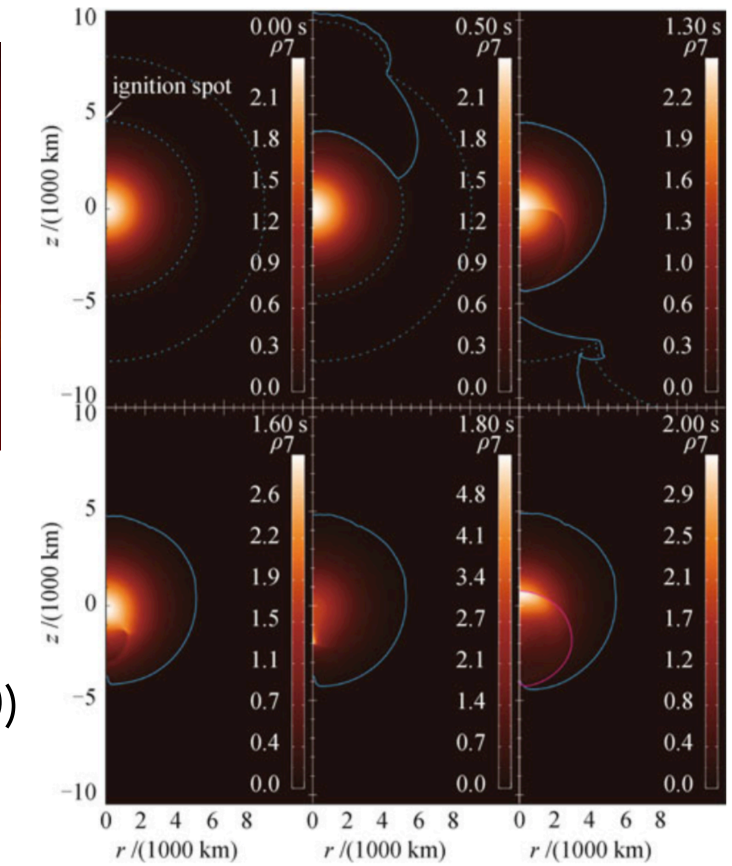


Fink et al. (2010)

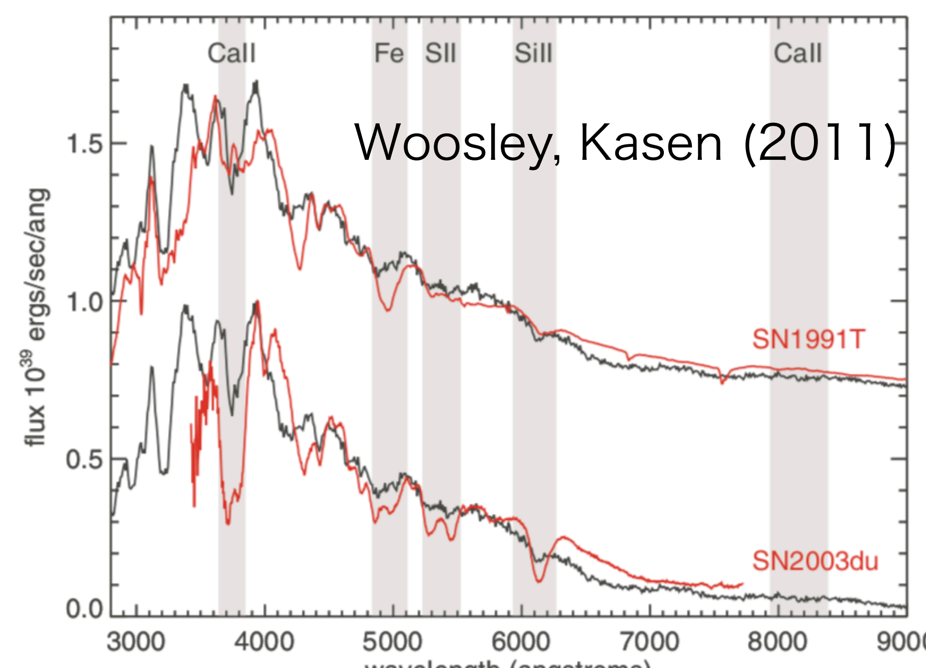
Double detonation

- The sub-Ch SD model
  - Accreting He materials
  - He detonation on the surface of a CO core
  - Invasion of a converging shock wave into the CO core
  - Ignition of CO detonation
- Problem
  - Large He shell mass ($\sim 0.1 M_{\odot}$)
  - Featureless spectra due to radioactive nuclei yielded by He detonation





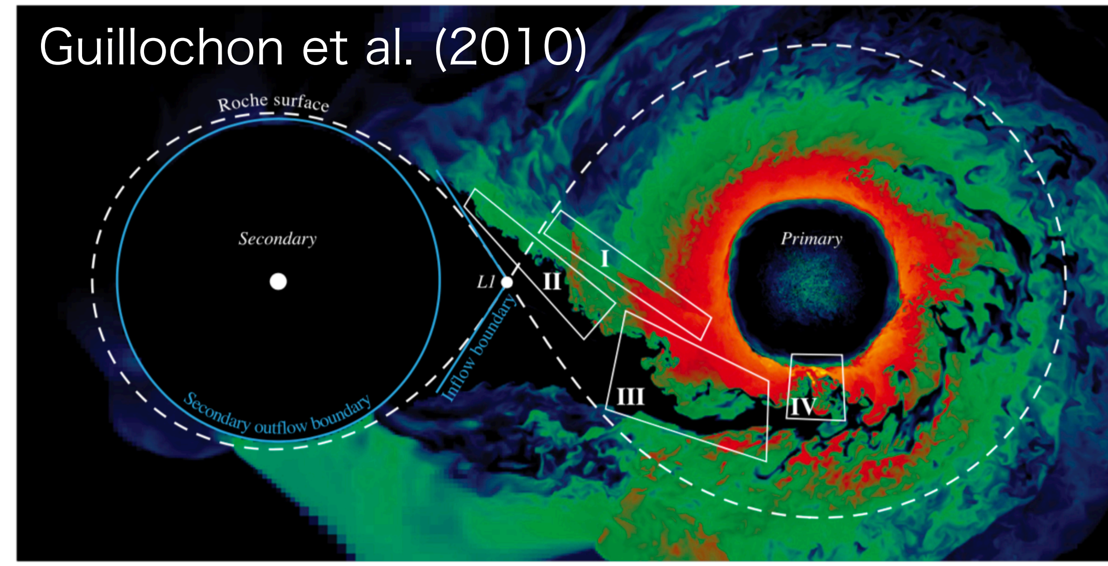
Fink et al. (2010)

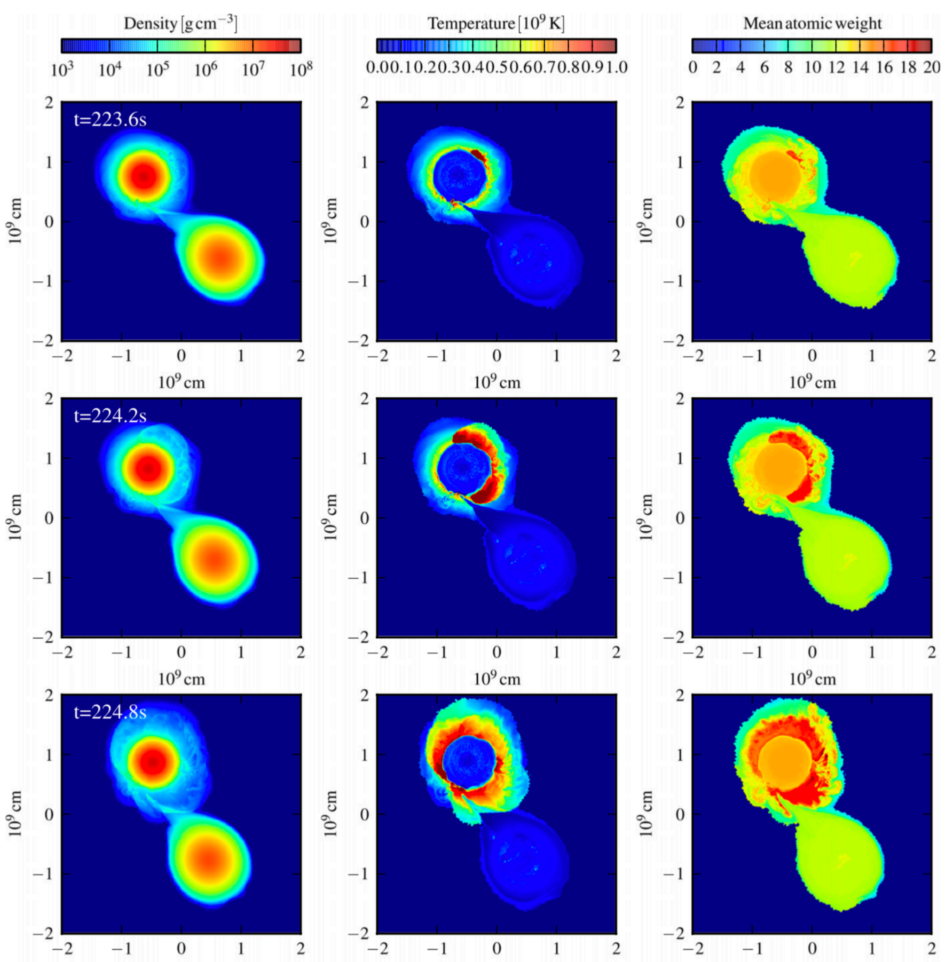


Woosley, Kasen (2011)

D⁶ feasibility

- Requisite: $M_{\mathrm{He}} \lesssim 0.05 M_{\odot}$
    - He detonation ashes make spectra featureless due to their opacity (e.g. Woosley, Kasen 2011)
- He detonation feasible for $M_{\mathrm{He}} \sim 0.01 M_{\odot}$
    - Hydrodynamical effects due to unstable mass transfer
    - C/O pollution (Shen, Moore 2014)
- Successful CO detonation unpublished

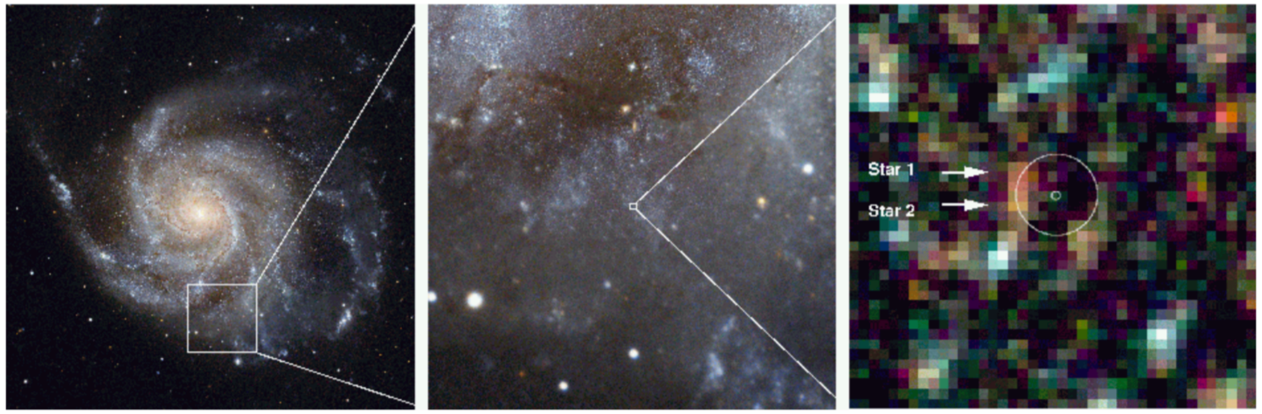




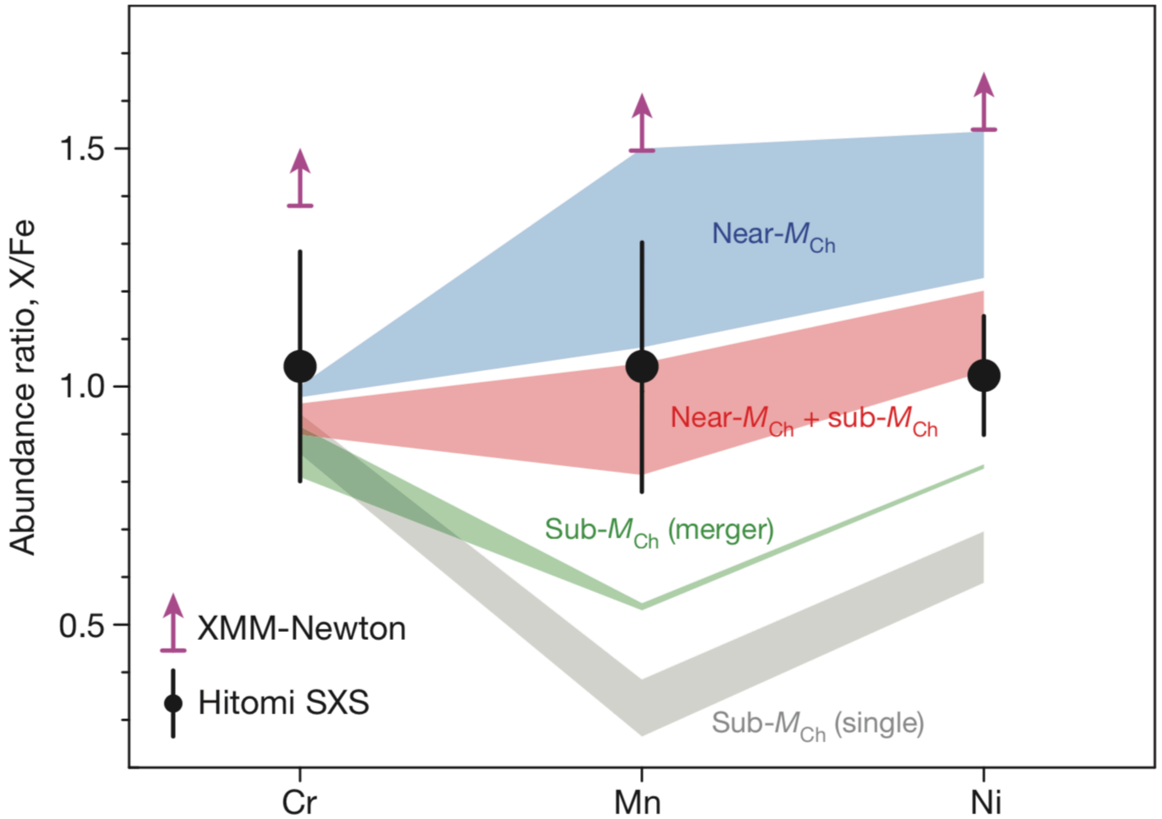
Pakmor et al. (2013)

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

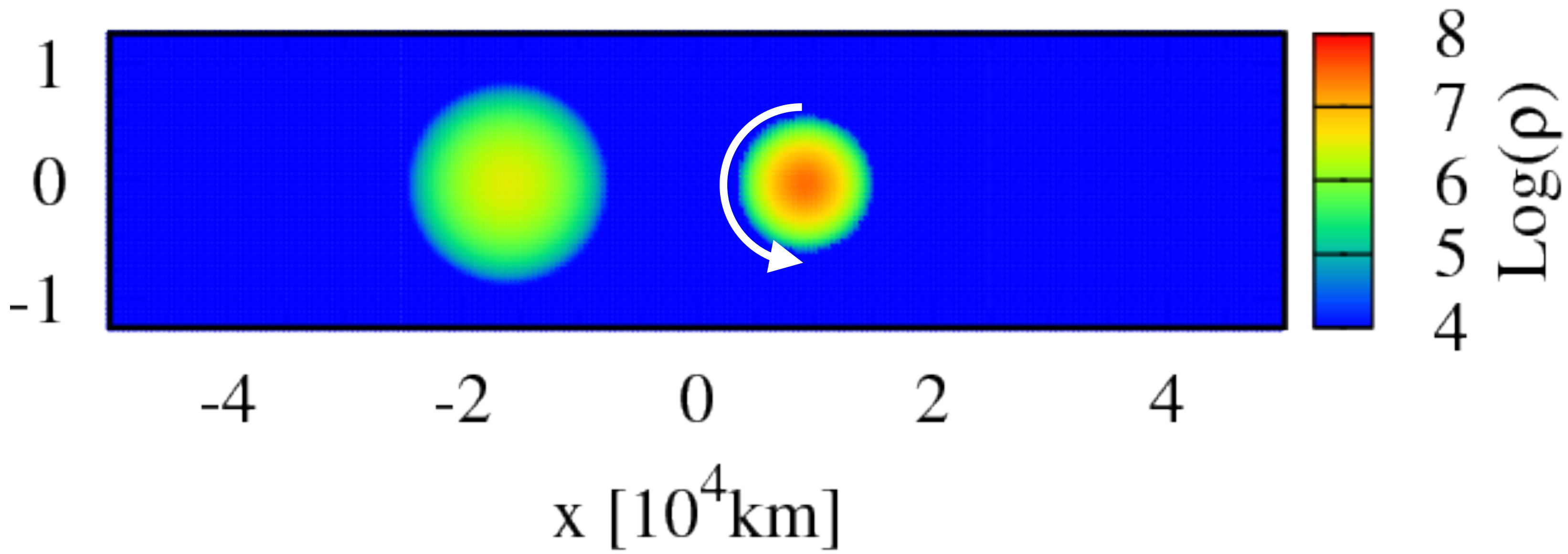


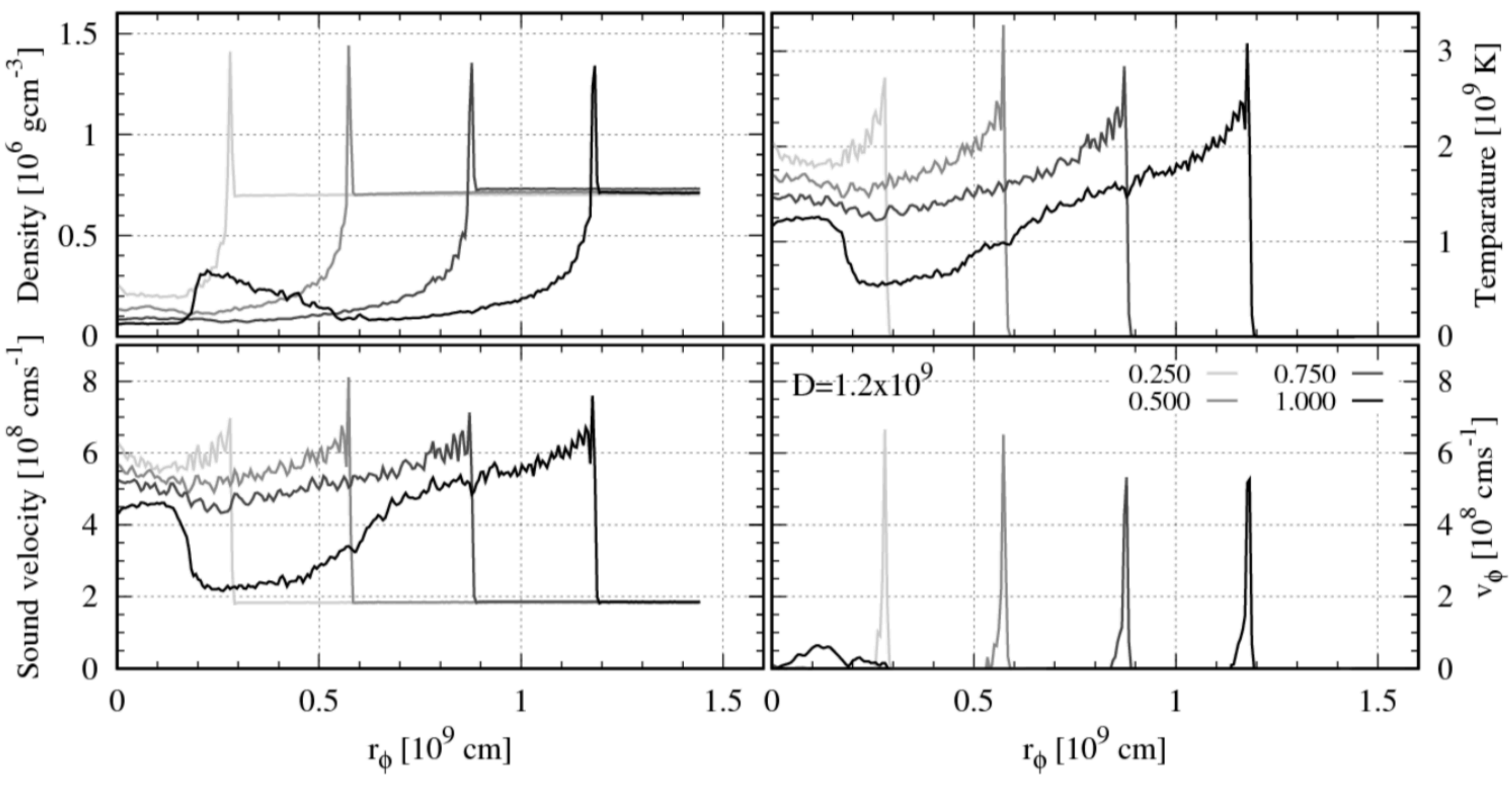
Li et al. (2011)



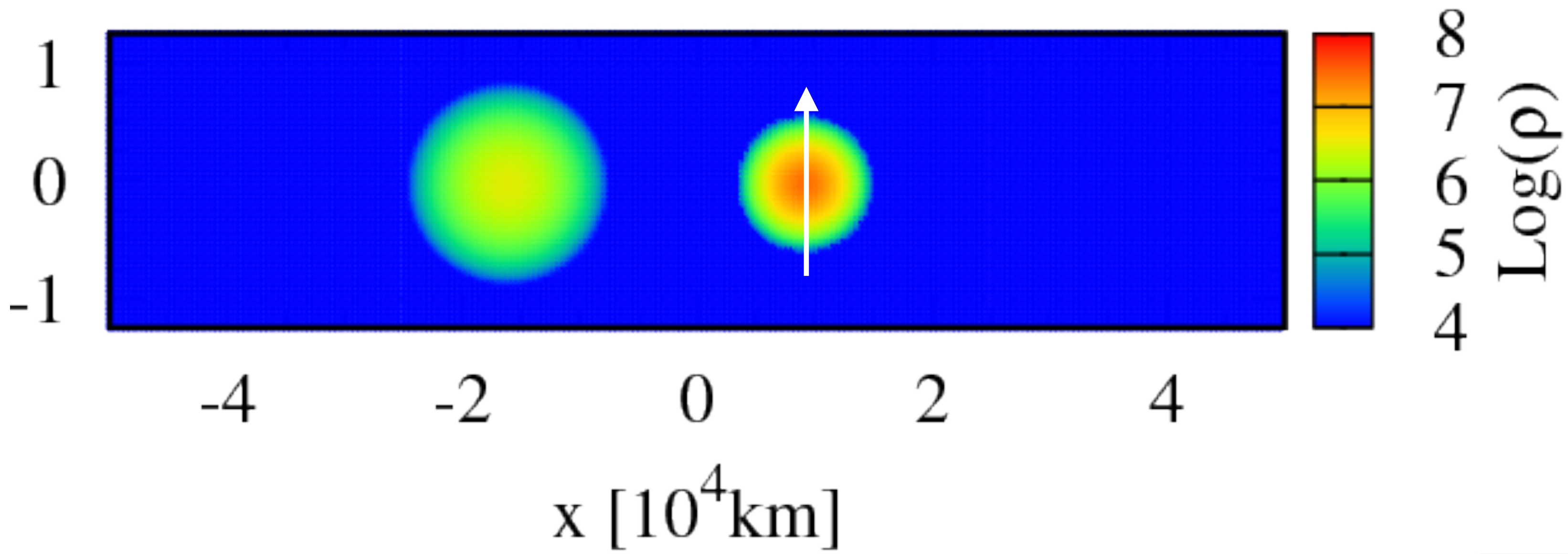
Hitomi Collaboration (2017)

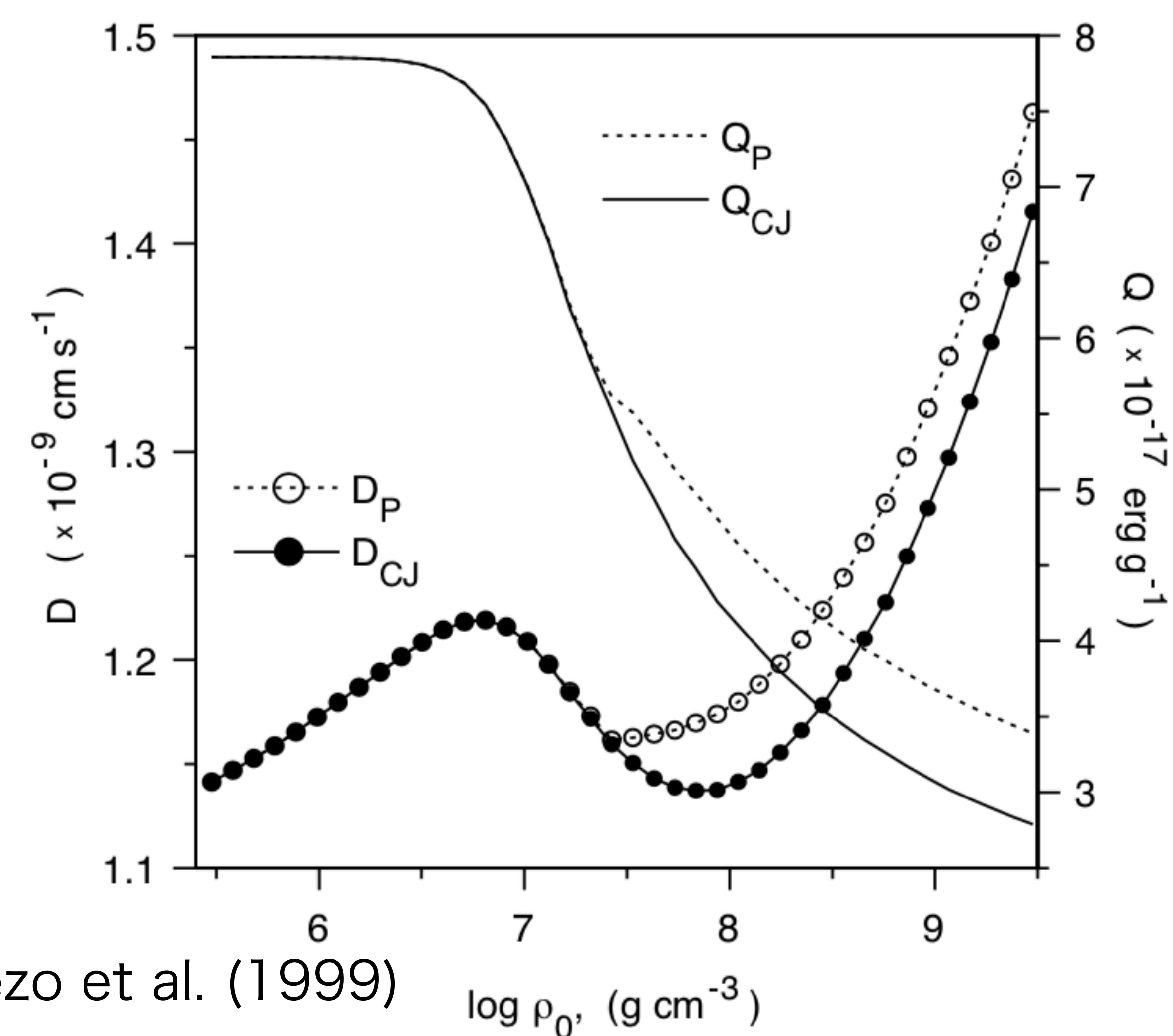
He detonation



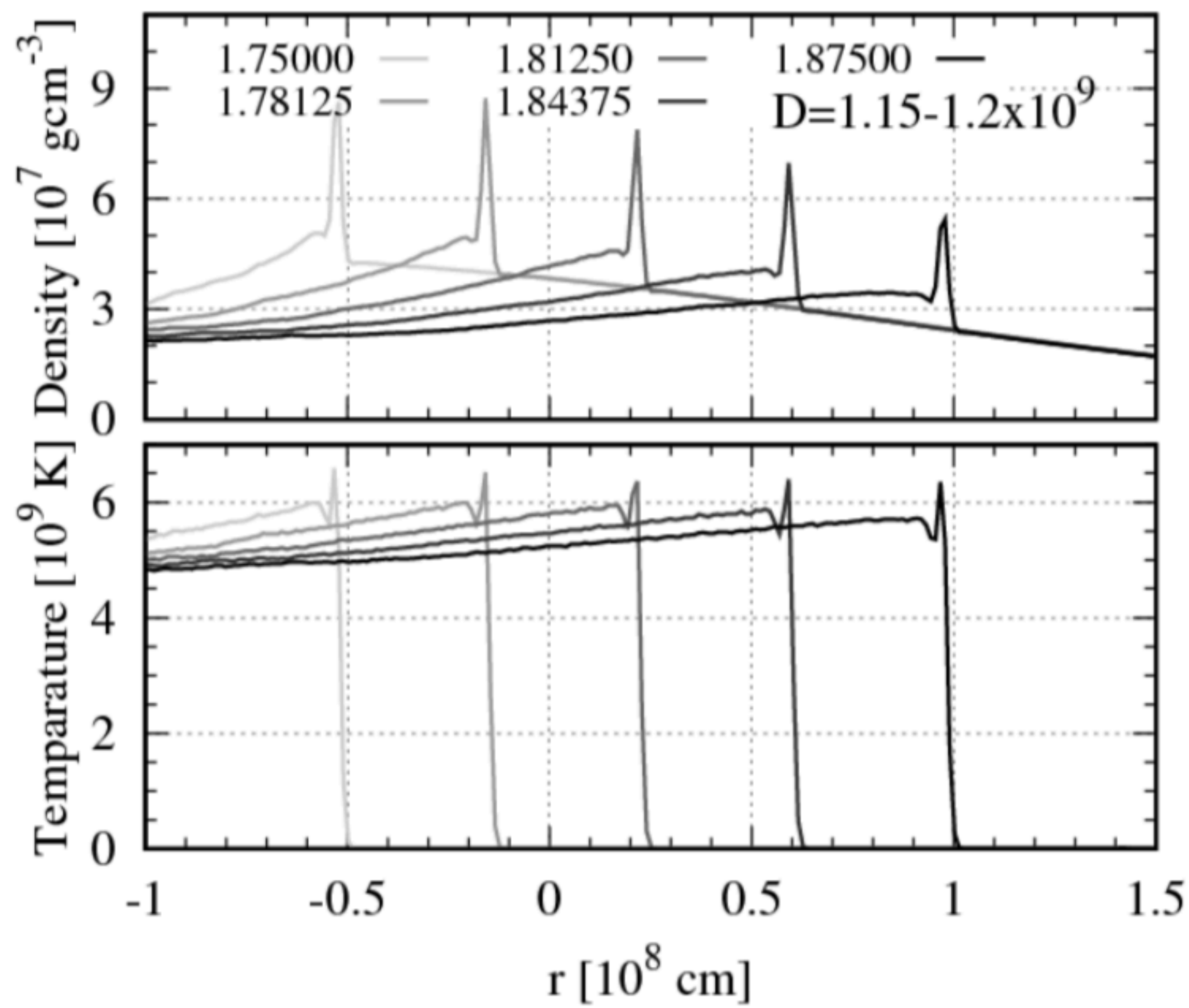


C detonation

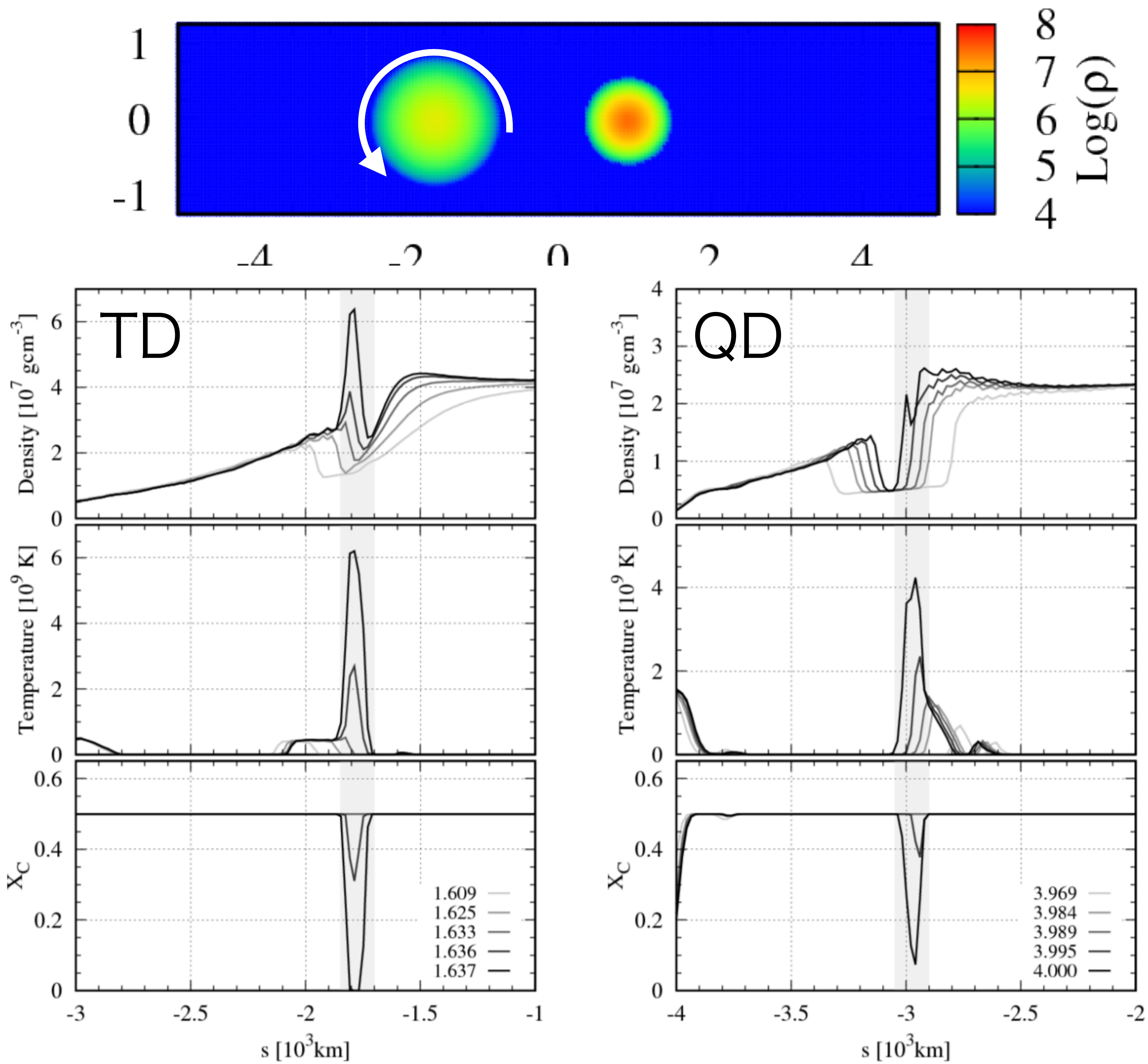




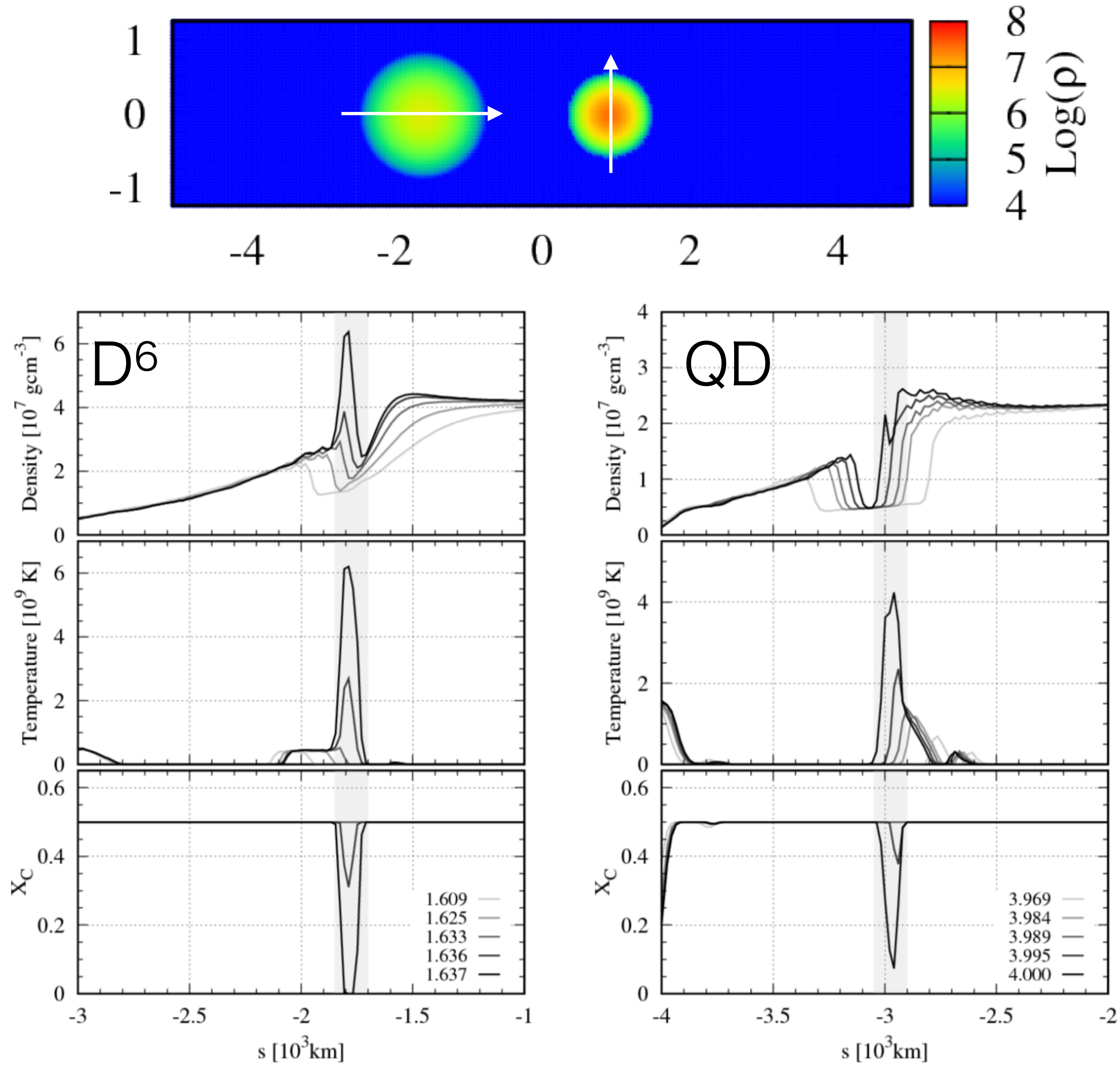
Gamezo et al. (1999)
(see also Sharpe 1999)



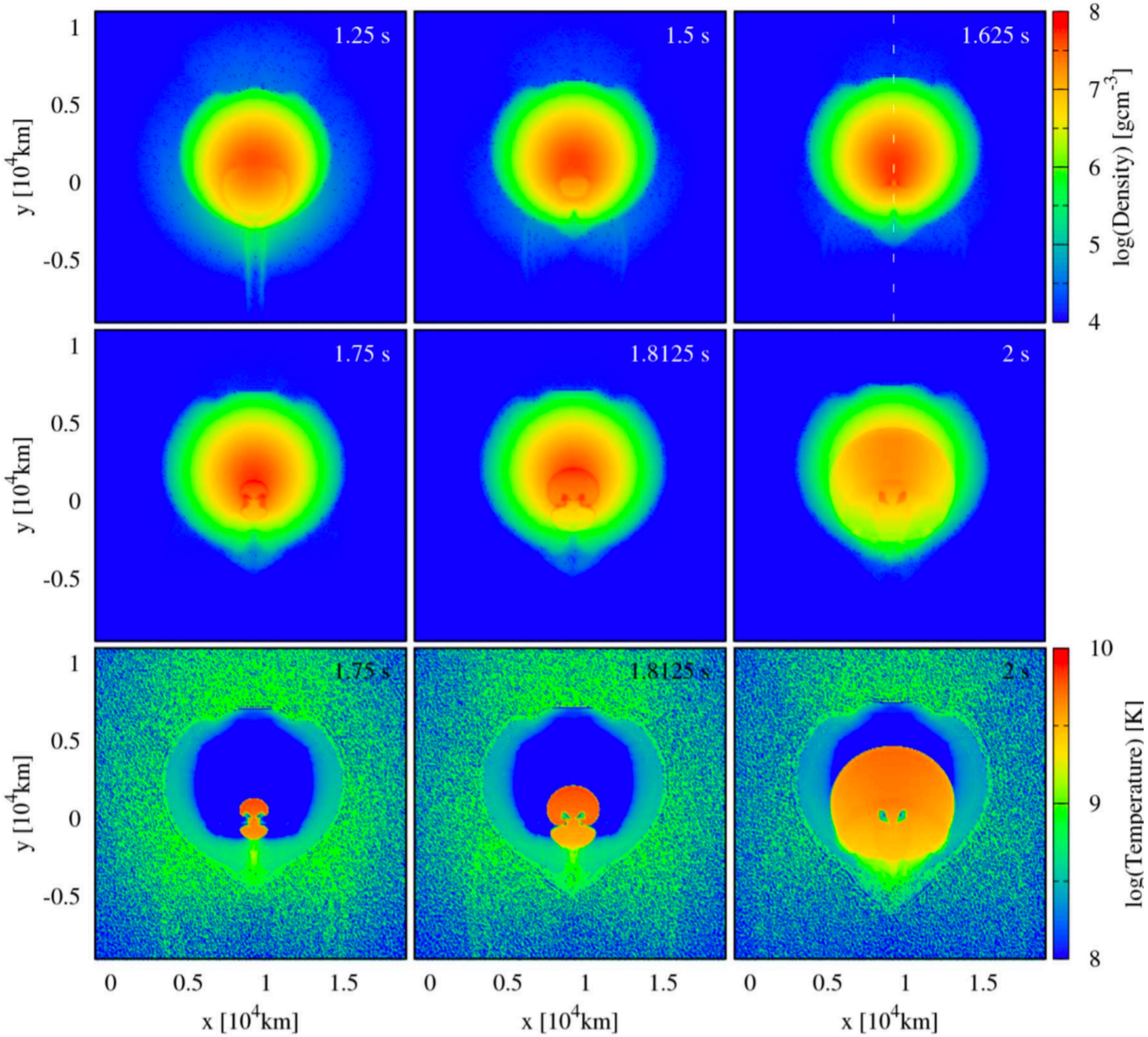
Hotspot for He detonation



Hotspot for C detonation



Unburned materials



Tanikawa et al. (2018)

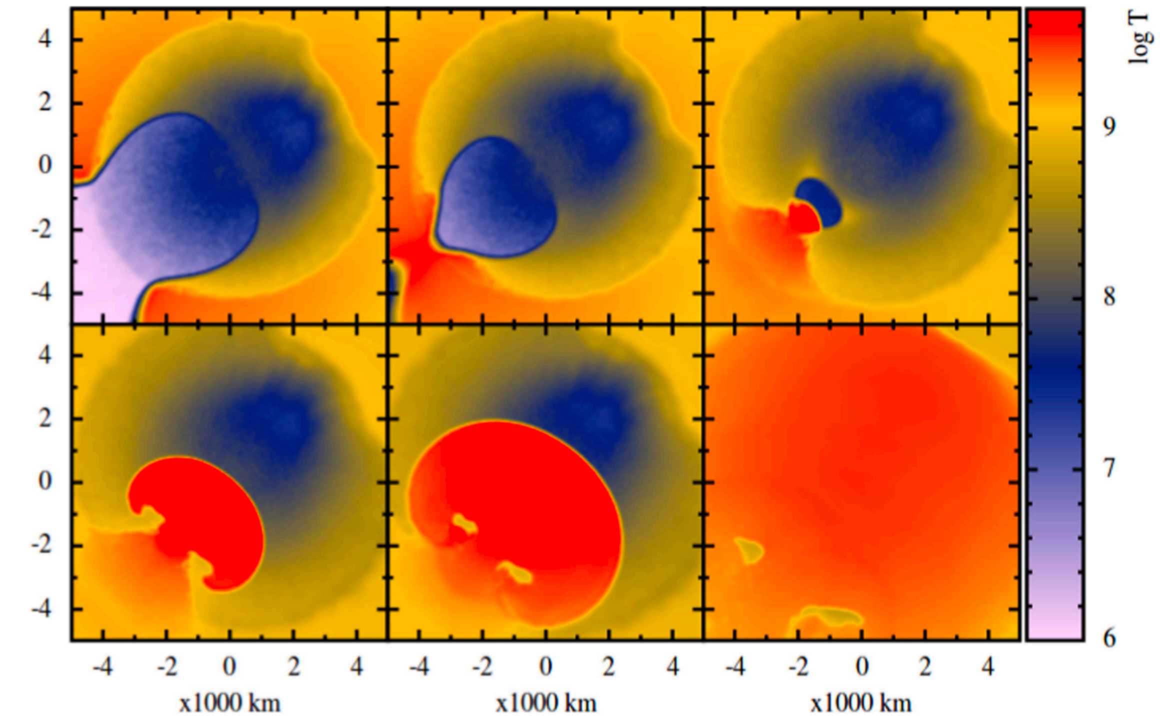


Figure 10. Colormap of temperature in a *YZ* (equatorial) slice, showing the core detonation of model B_6 in Table 1 at times t = 1.10, 1.22, 1.42, 1.62, 1.72, and 2.03 s, respectively. The box size is [−5:5] × 10^3 km in all directions.

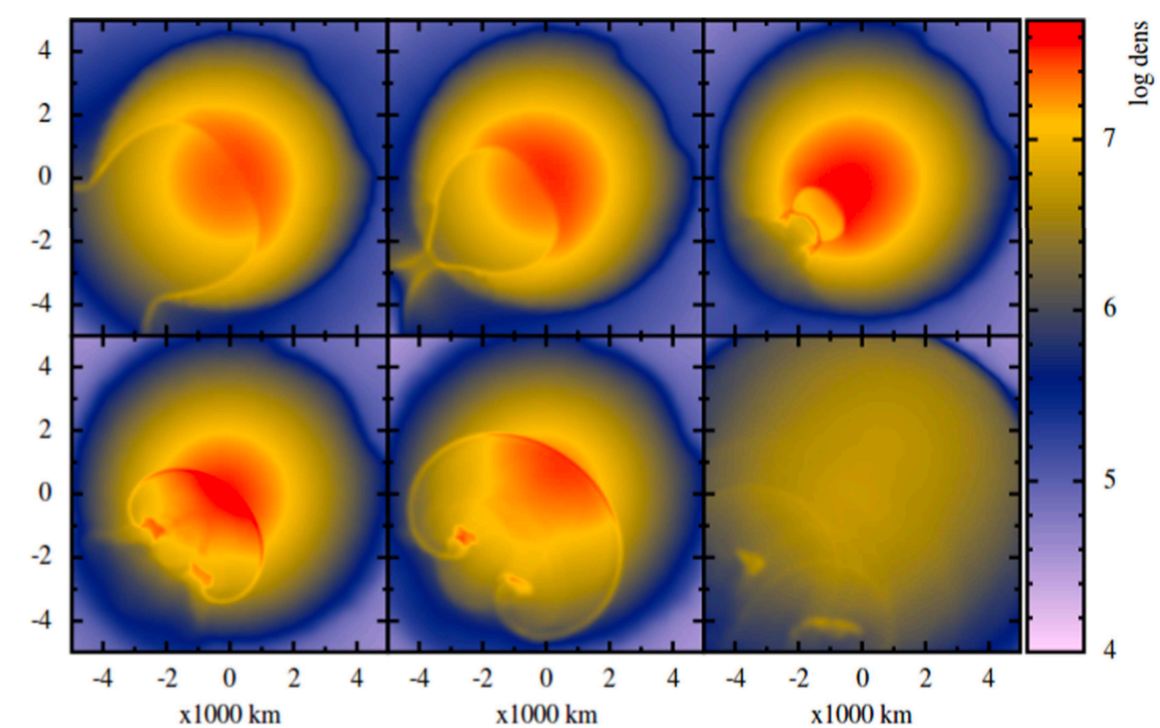
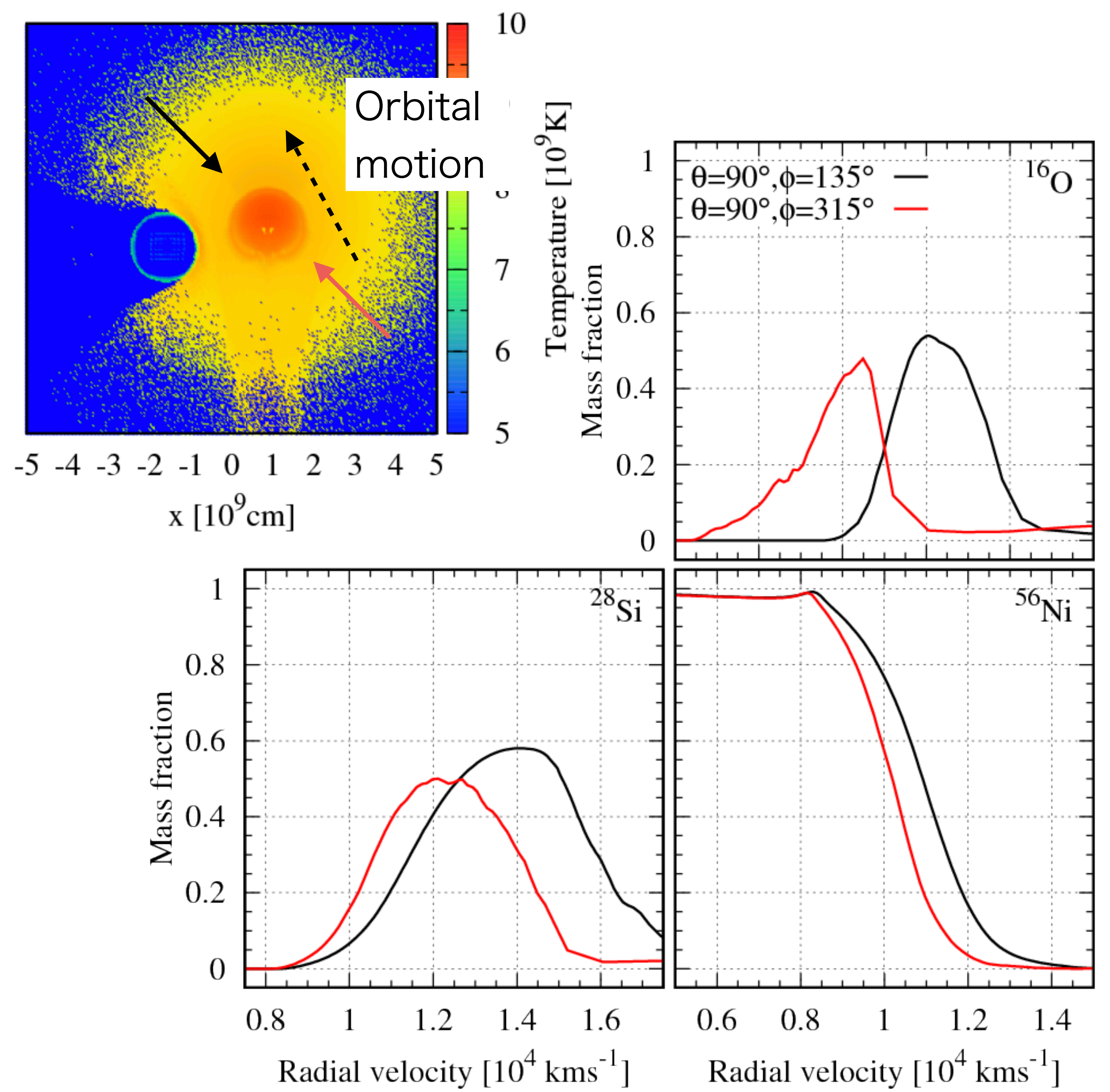


Figure 11. Same as Figure 10, but for density.

Garcia-Senz et al. (2018)

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.



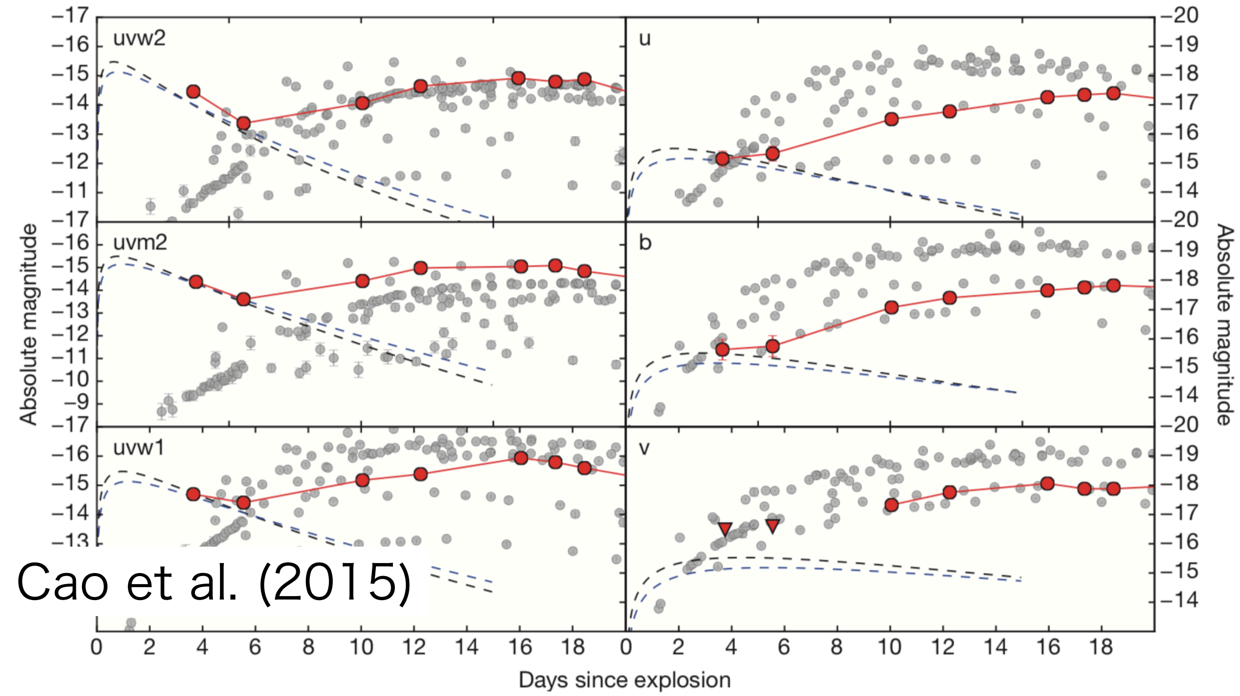
Possible counterpart

- iPTF14atg
  - Early flash

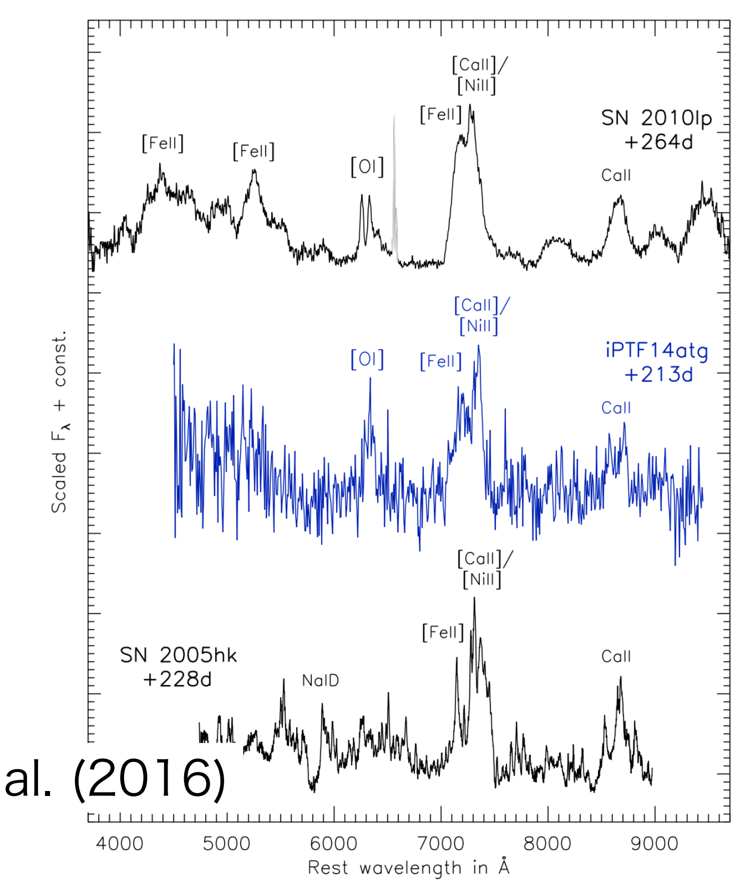
    ← He-detonation ash
  - Oxygen emission in nebular phase

    ← Stripped oxygen (but not confirmed)
  - Sub-luminous SN Ia

    ← Primary COWD with ~ 0.8 or $0.9 M_\odot$
- But, D[6] explosion could not explain early flash and spectral features at maximum luminosity consistently (Maeda et al. 2018).



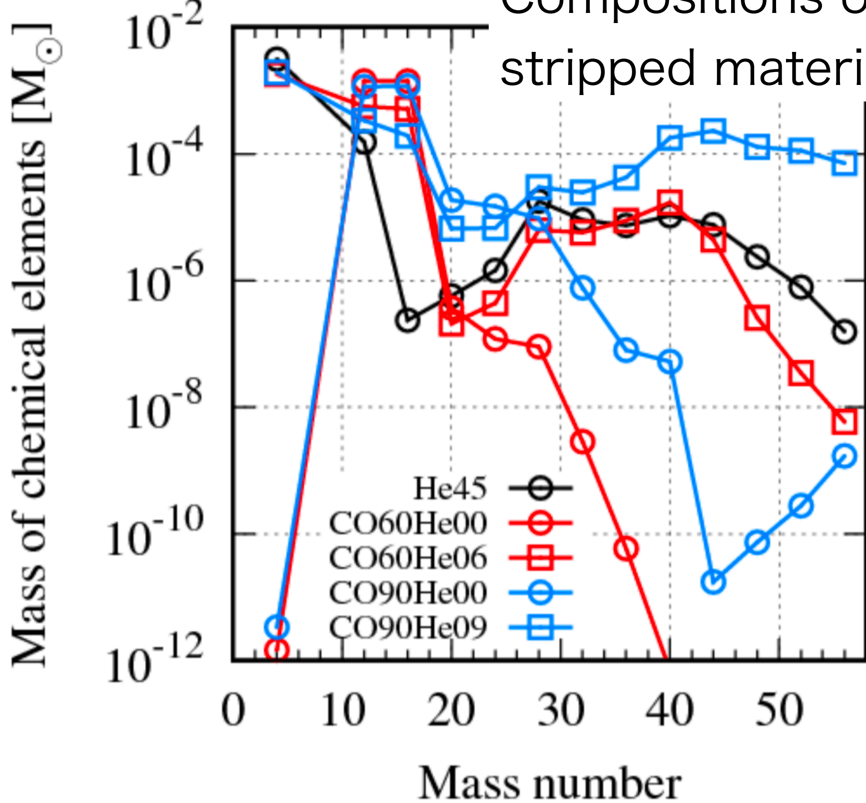
Cao et al. (2015)



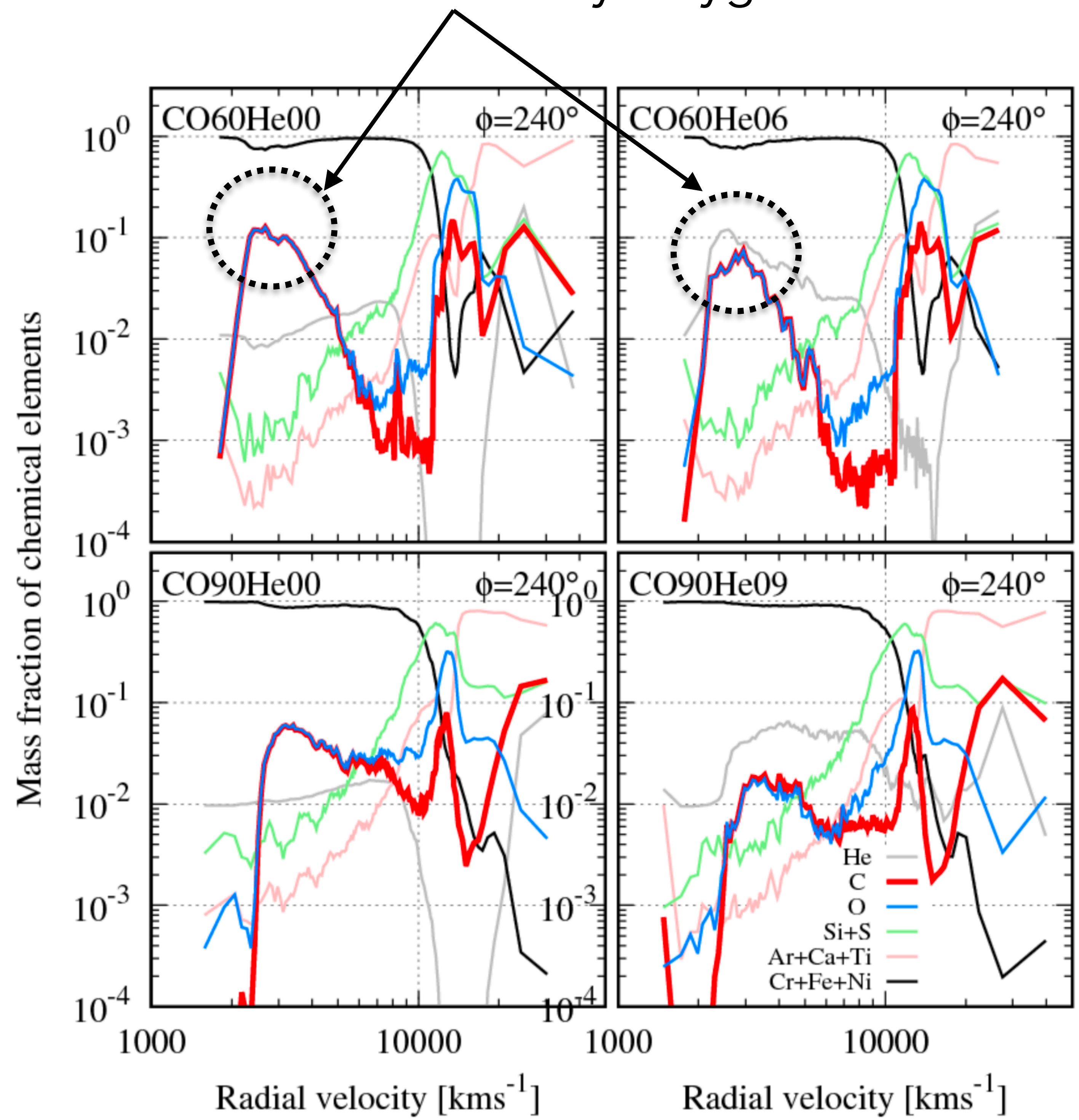
Kromer et al. (2016)

He shell on the companion

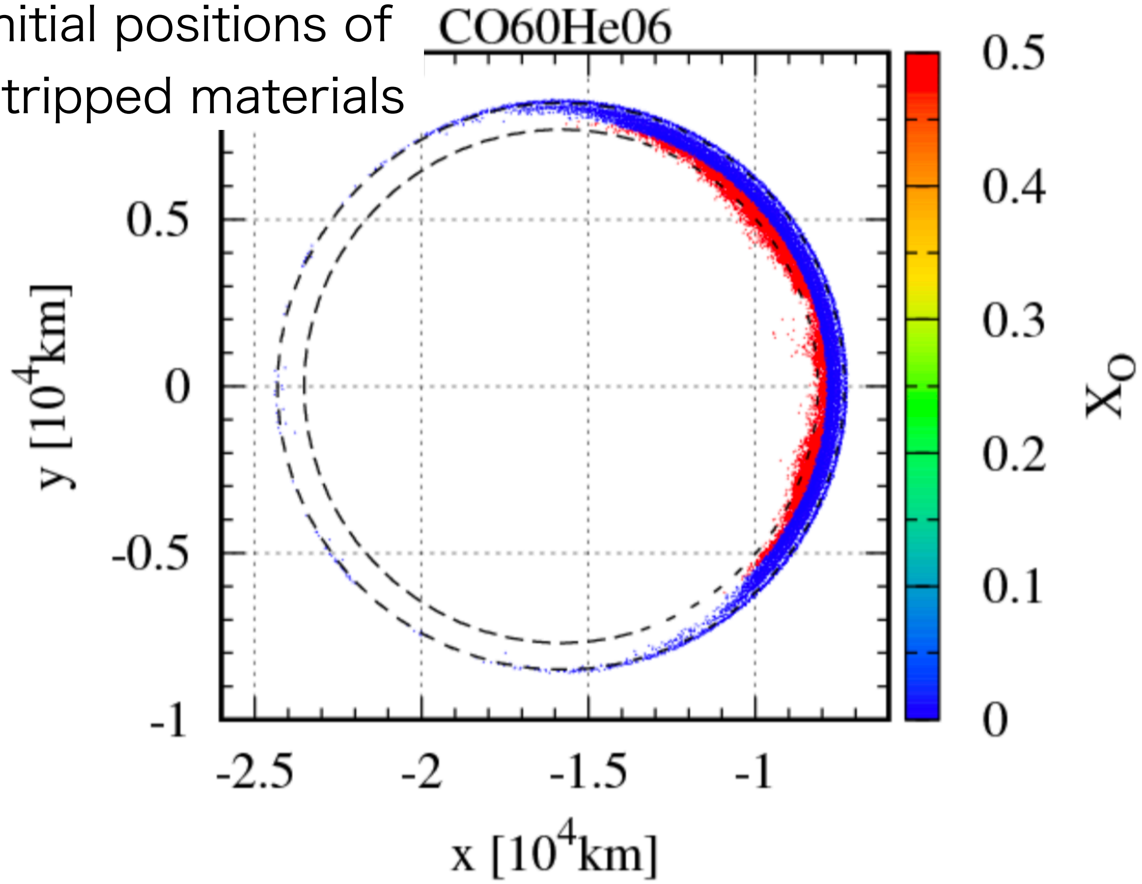
Compositions of stripped materials



Low-velocity Oxygen



Initial positions of stripped materials

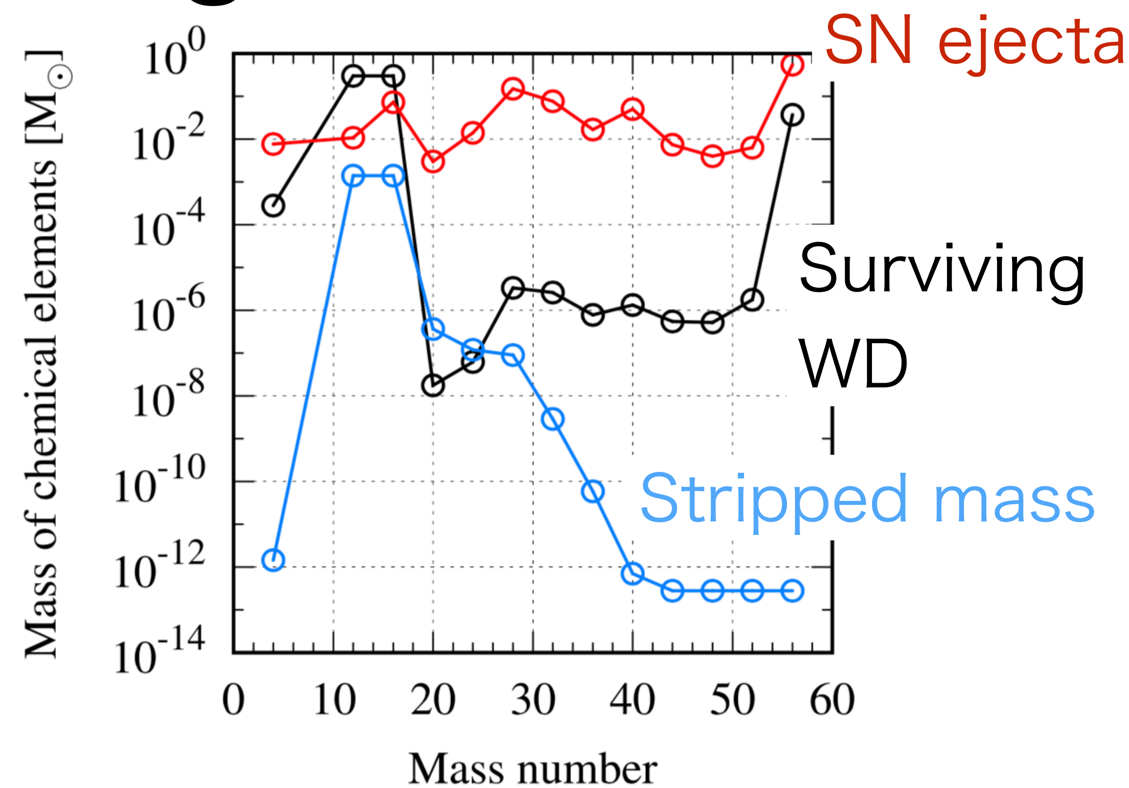


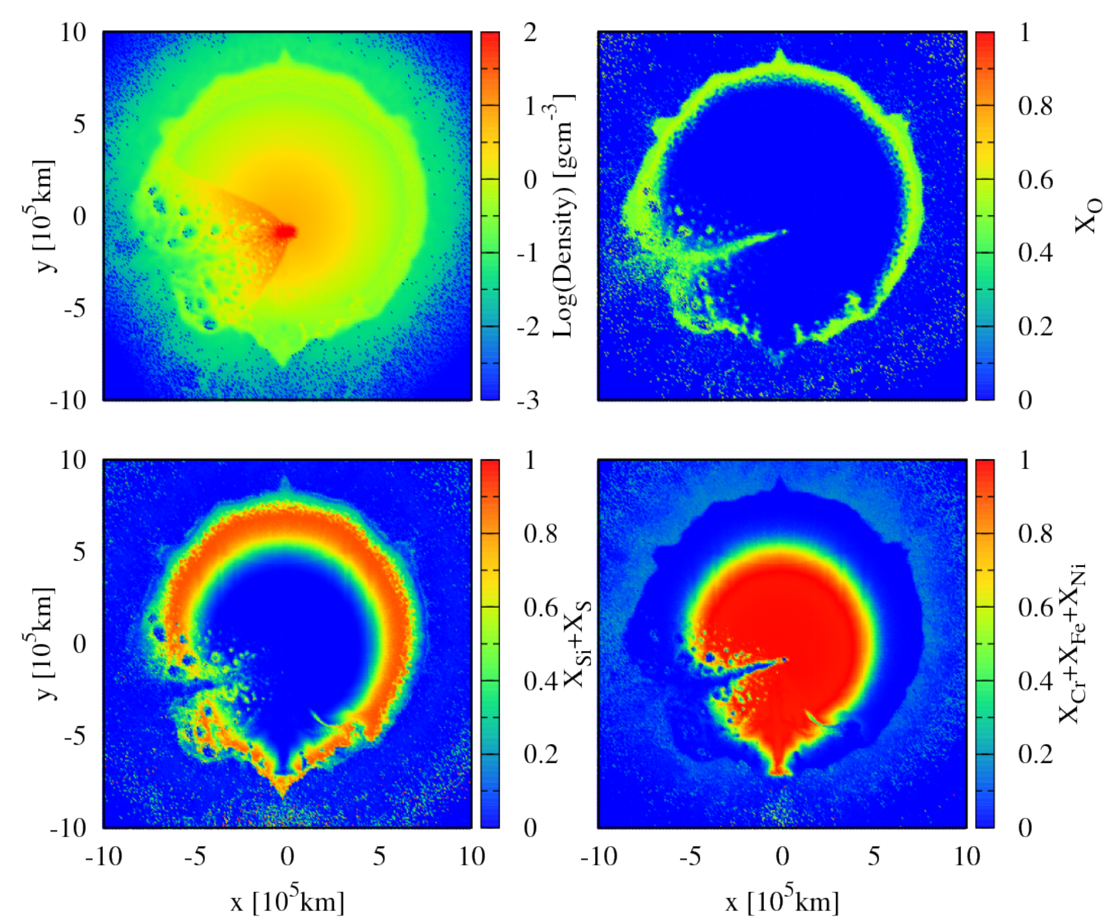
Comparison among sub-Chandrasekhar explosions in DD systems

	D^6	Violent merger	Collision	spiral instability
Oxygen emission lines	✓	✓	×	×
Velocity shift (~1000km/s)	✓	×	×	×
Two ^{56}Ni components	×	×	✓	×
Surface radio activity	✓?	×	×	×

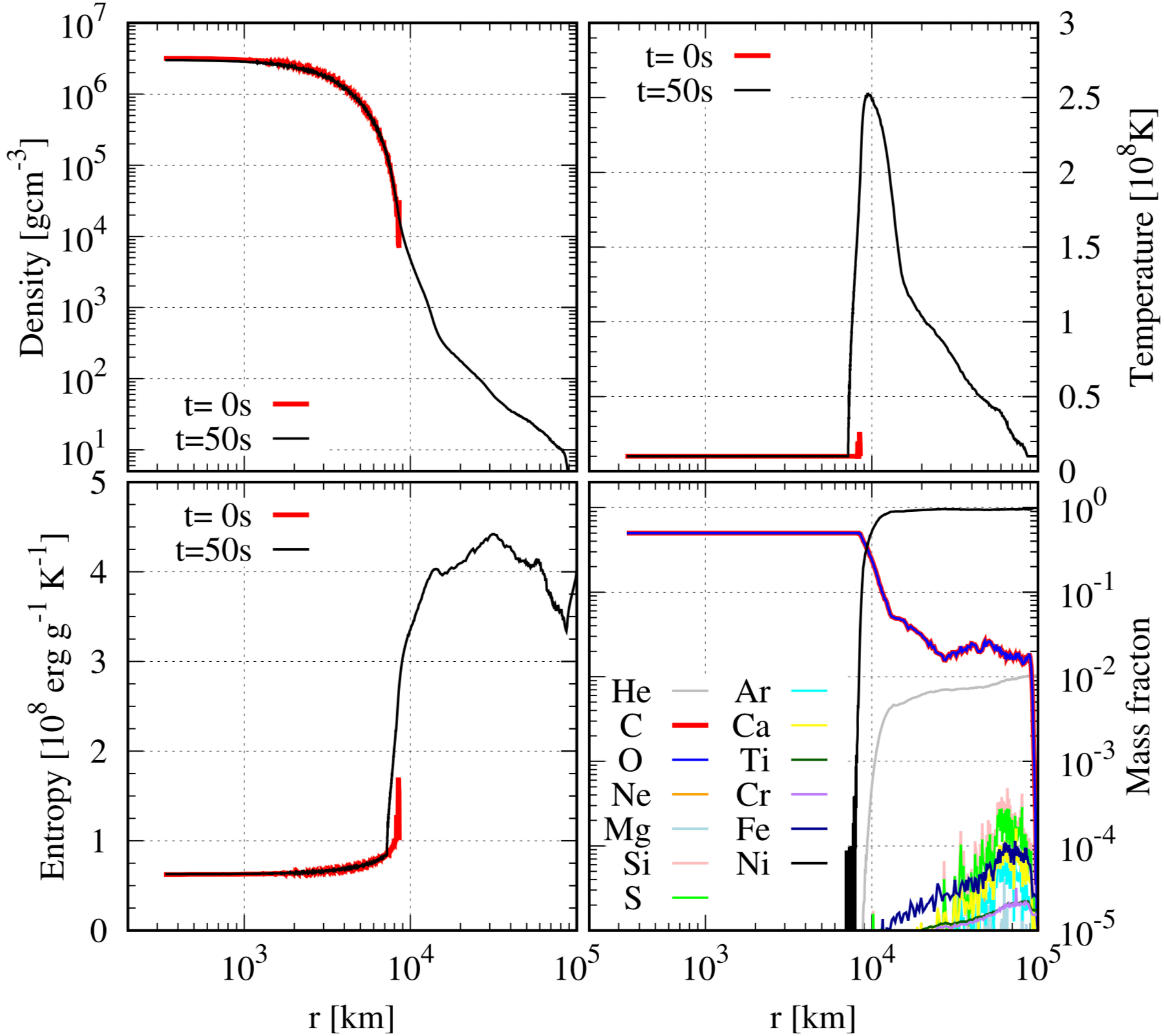
Supernova ejecta

- ^{56}Ni mass is ~ 0.6 $M_\odot$
- Mass of materials stripped from the companion WD is ~ 0.003 $M_\odot$
- The stripped materials consist of carbon and oxygen.
- Supernova ejecta have a shadow (Papish et al. 2015).
- Supernova ejecta have a stream consisting of the stripped materials (companion-origin stream).





Surviving 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	$\rm D^6$	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	$\rm D^6$	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	$\rm D^6$	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	$\rm D^6$	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	$\rm D^6$	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.