Numerical studies of white dwarf explosions: type Ia supernova and tidal disruption events

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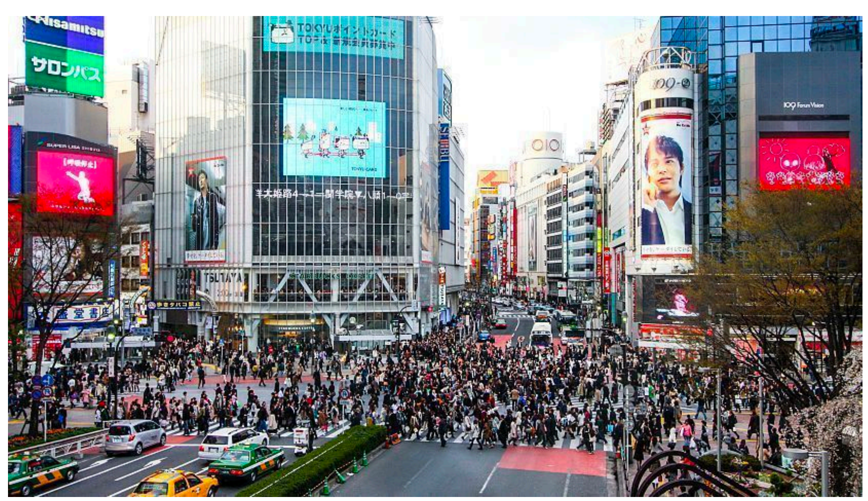
Kashiwa (e.g. Kavli IPMU)

Komaba



Shibuya

Contents

- Type Ia supernovae (SNe Ia)
- Tidal disruption events of white dwarfs (WD TDEs)

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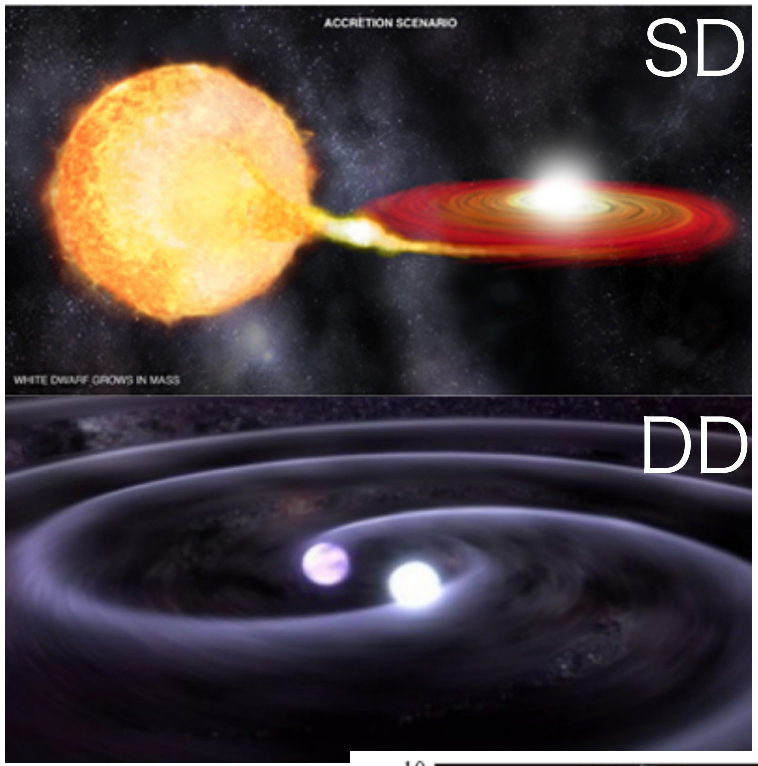
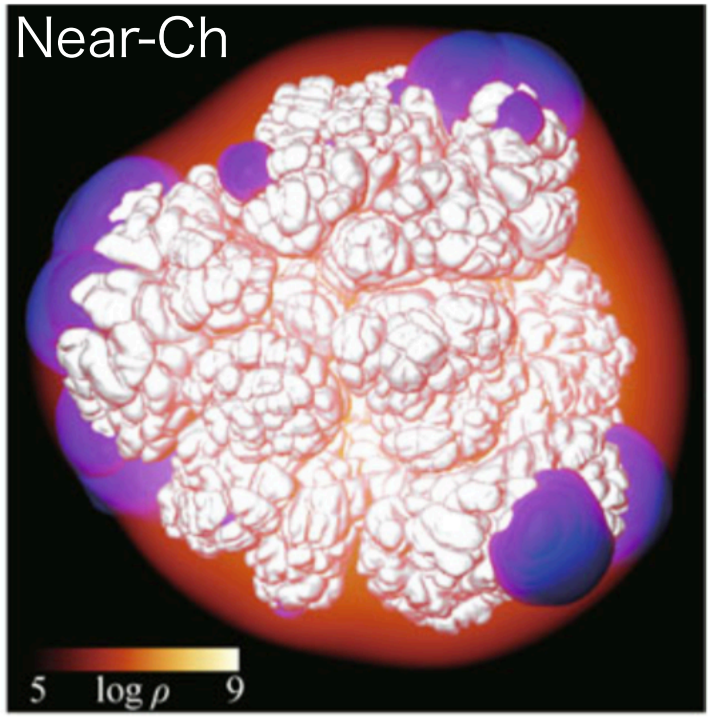
- Type Ia supernovae (SNe Ia)
- Tidal disruption events of white dwarfs (WD TDEs)

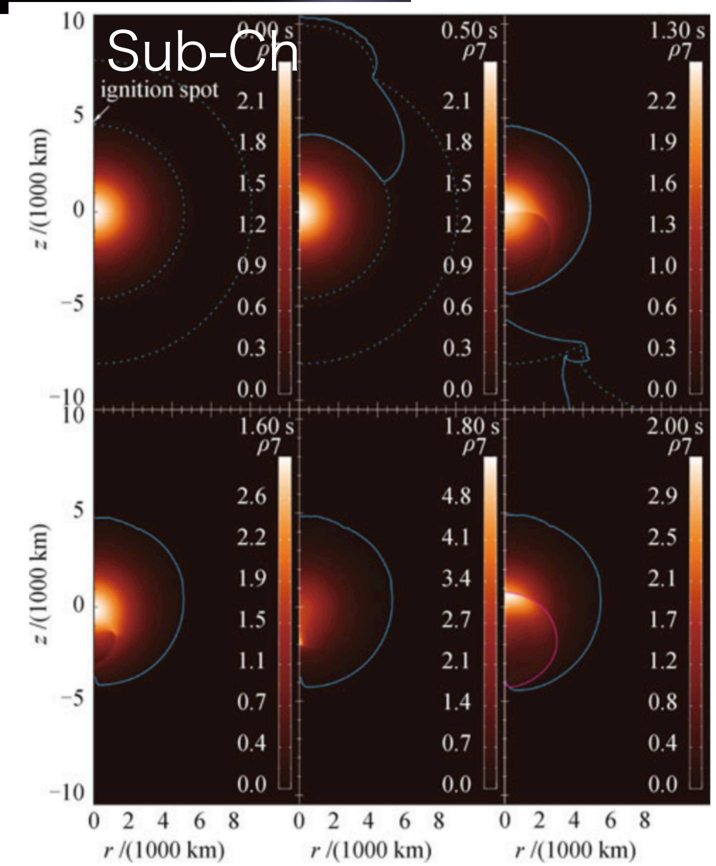
Type Ia supernovae

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





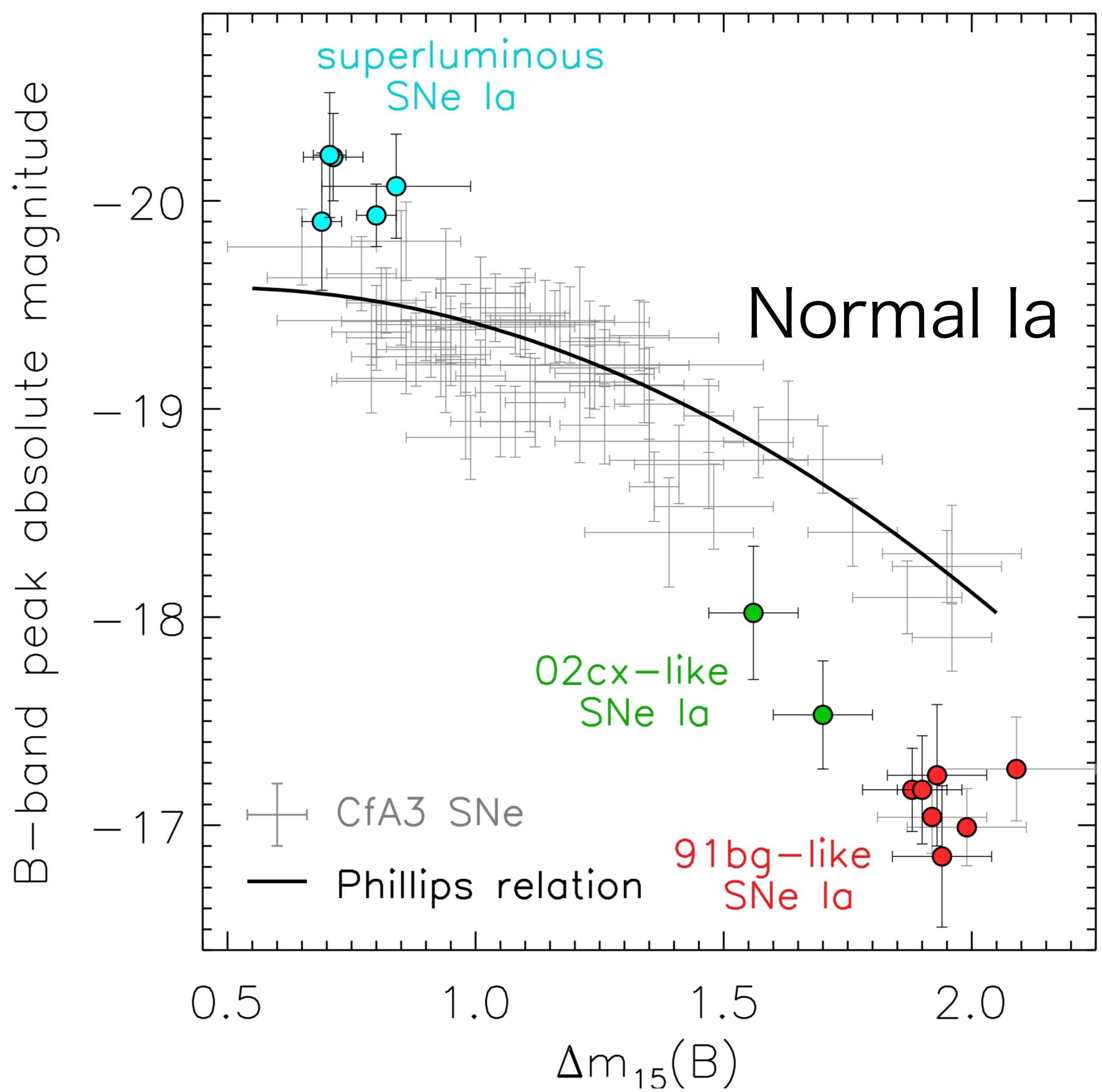
Seitenzahl et al. (2013)



Fink et al. (2010)

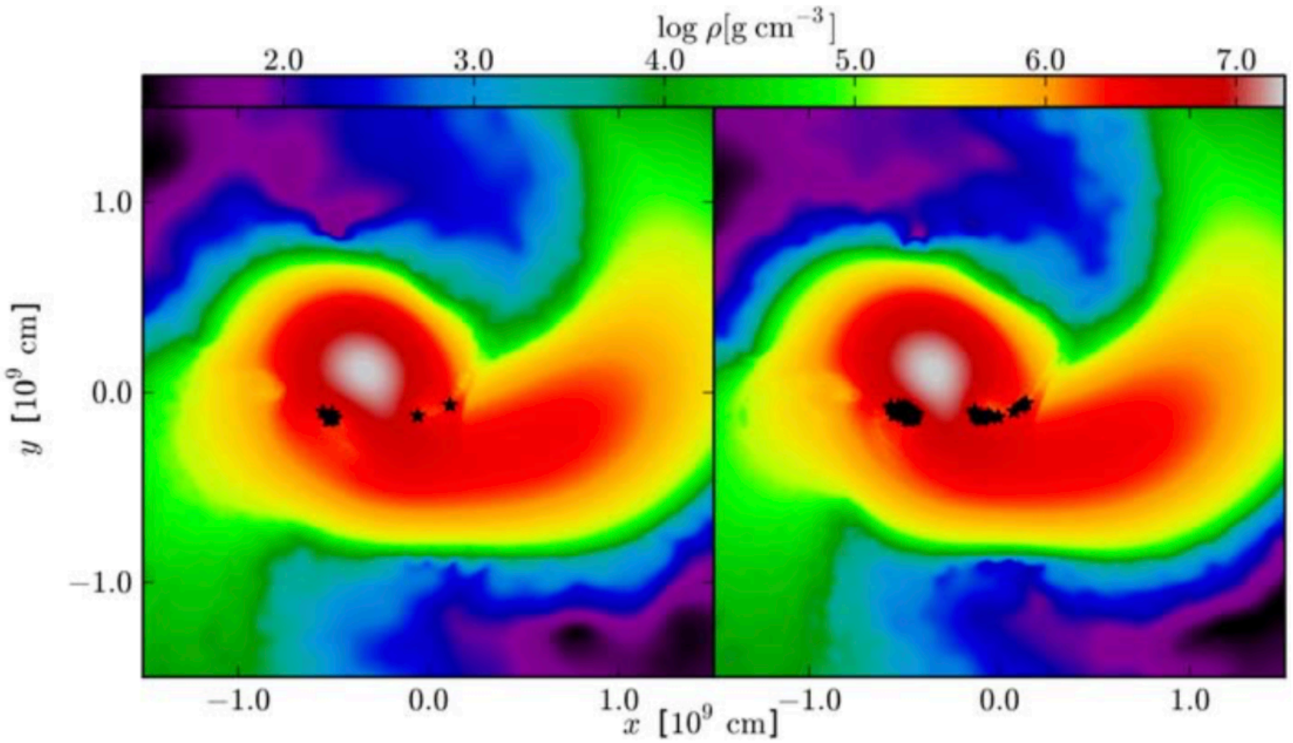
Normal & Peculiar SNe Ia

- 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

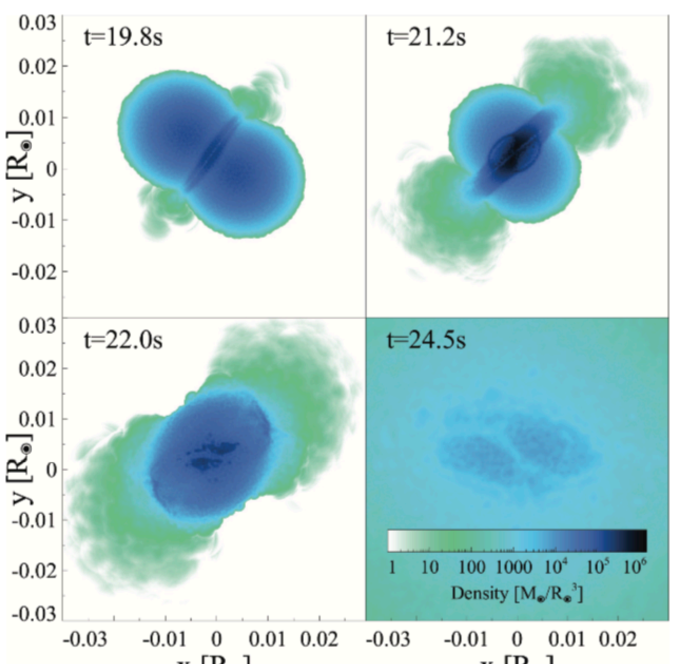


Hillebrandt+ (2013)

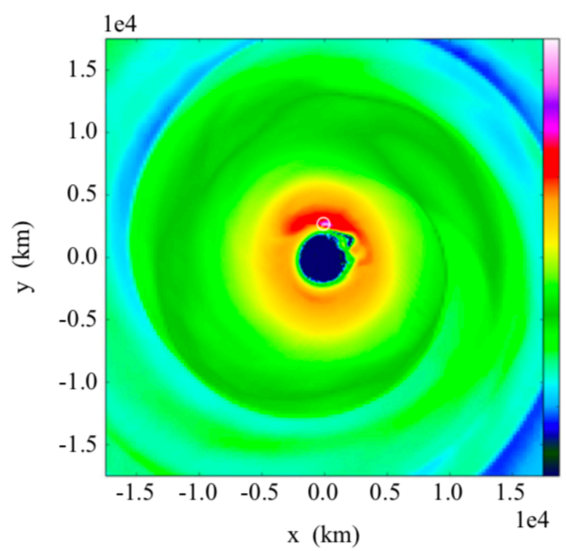
Sub-Ch DD Scenarios



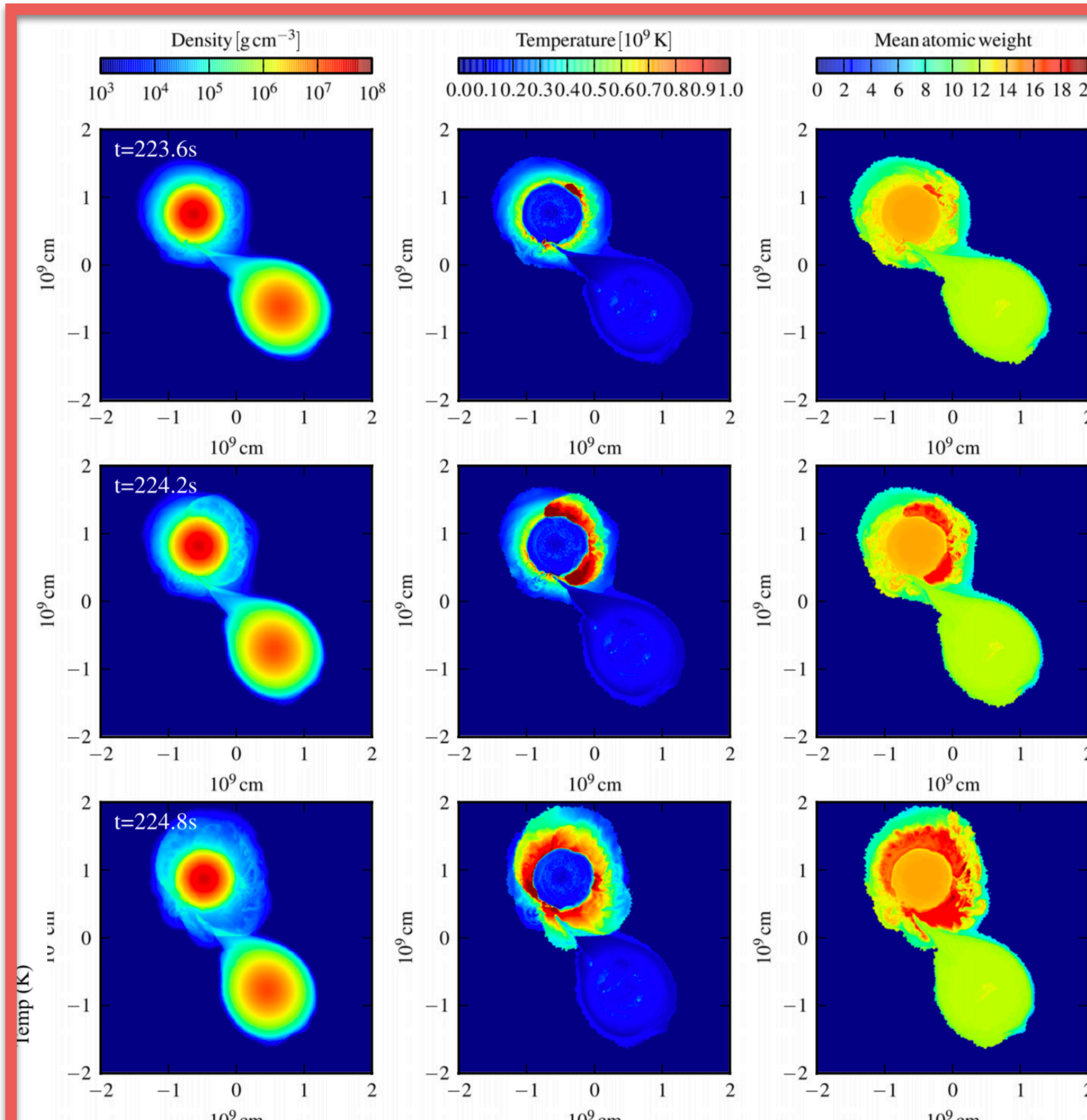
Violent merger (Pakmor+10; 11; 12; see also Tanikawa+15; Sato+15;16)



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



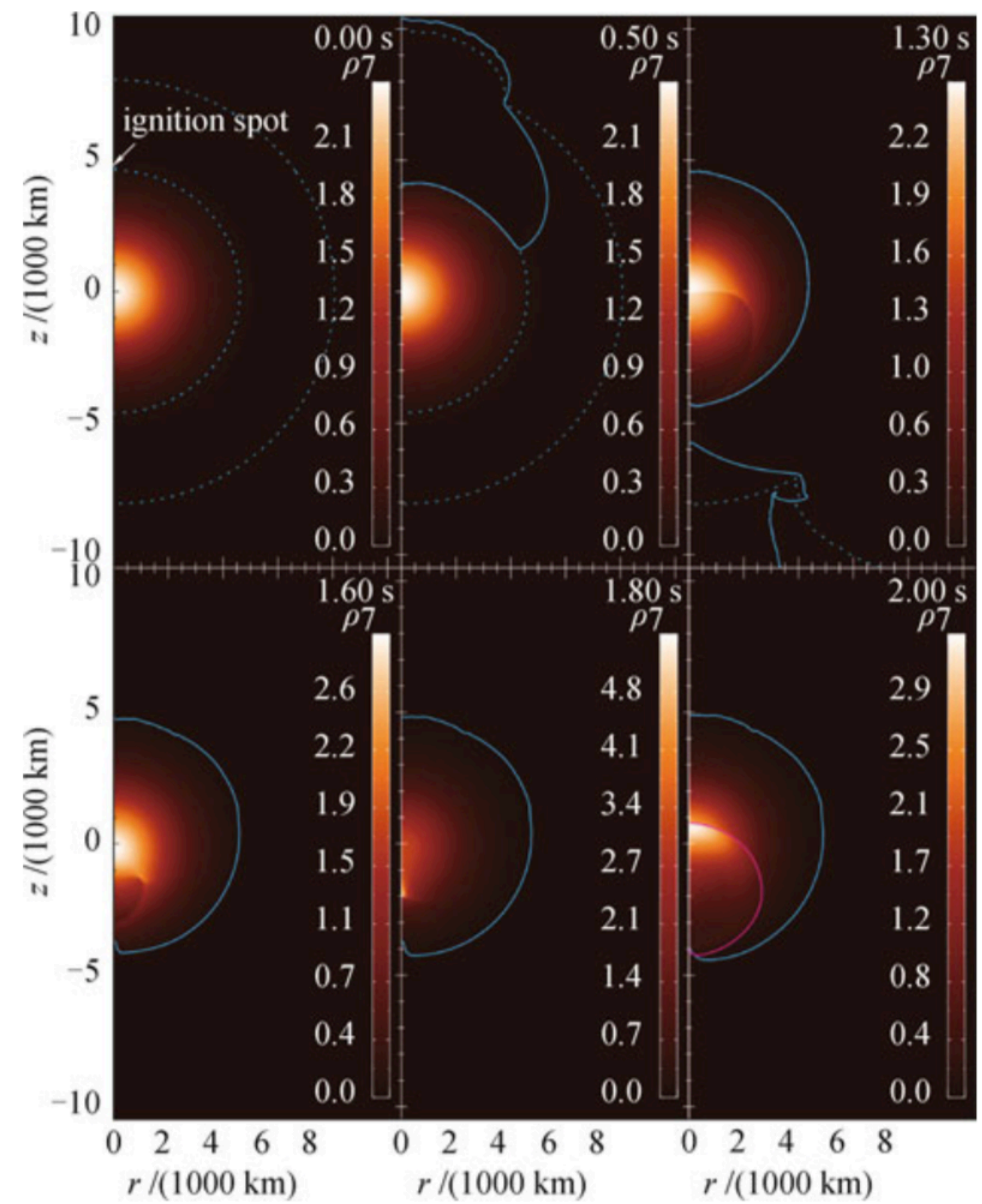
Spiral instability (Kashyap+15;17)



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

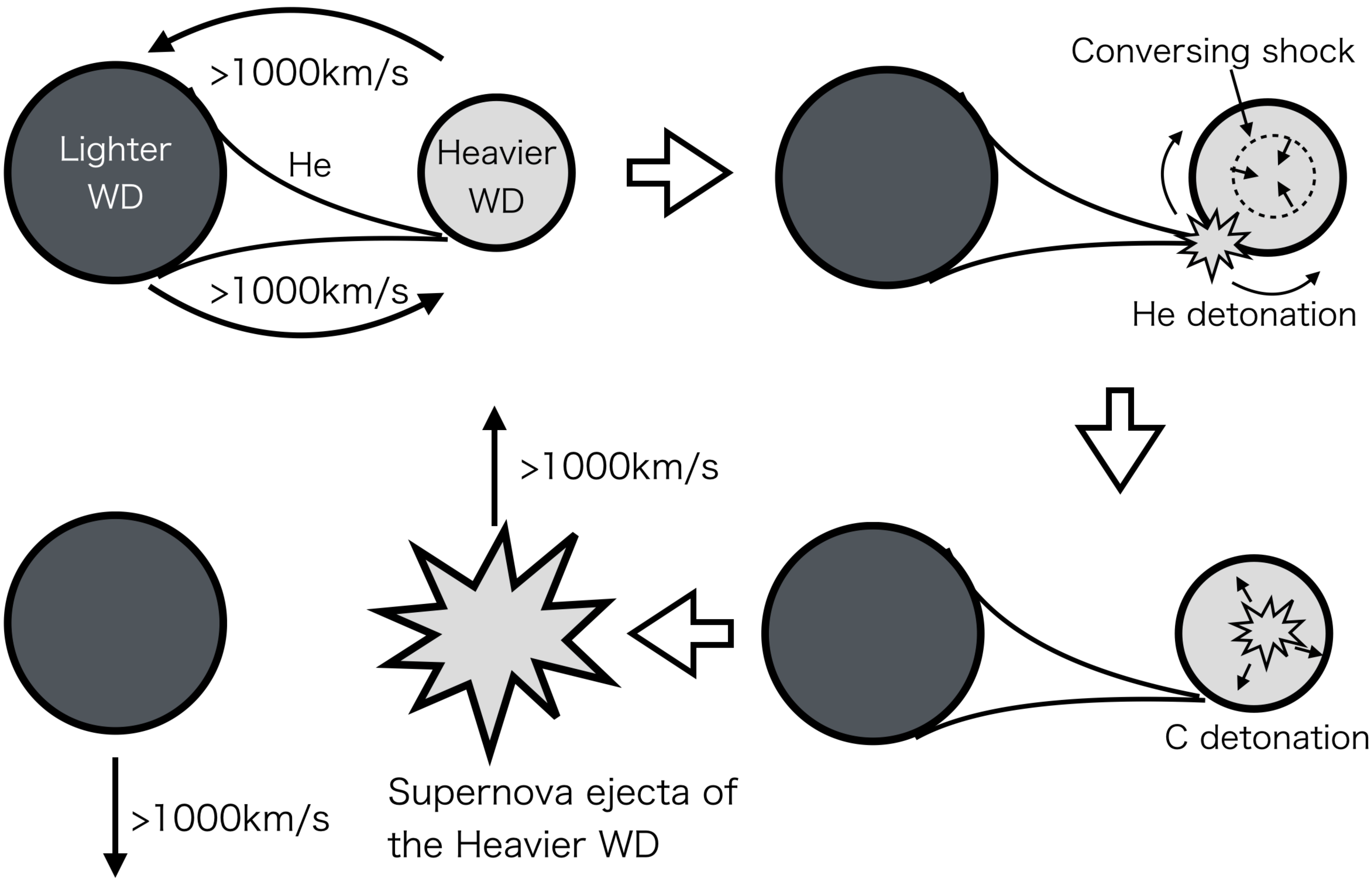
Double detonation

- Consider CO WD with a CO core and He outer shell.
- He detonation starts.
- The detonation
    - Propagates only in the He shell.
    - sends a shock separated from the detonation into the CO core.
- When the He detonation surrounds the CO core, the separated shock turns out to a converging shock.
- The conversing shock makes a hot spot to generate C detonation.
- The C detonation explodes the CO WD.



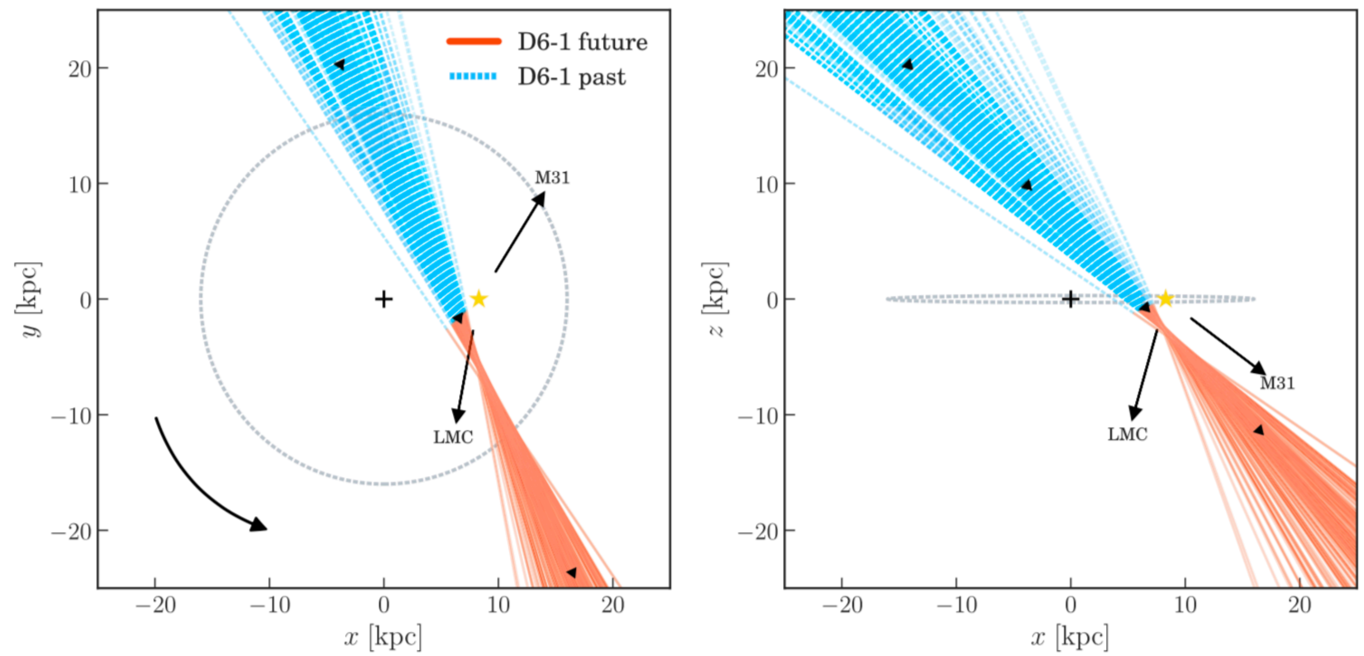
Fink et al. (2010)

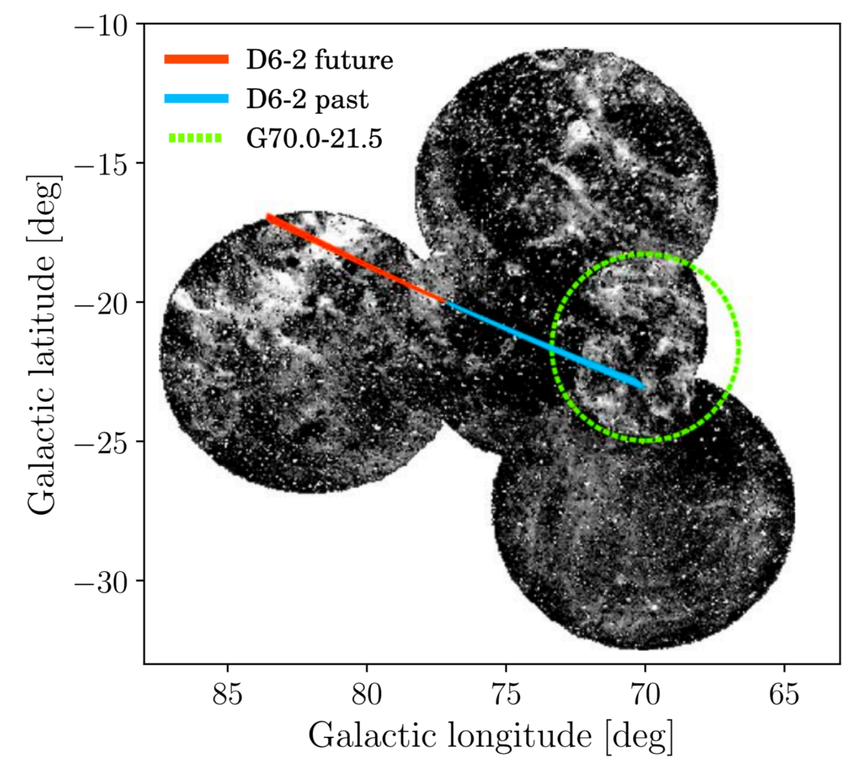
The D6 explosion



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

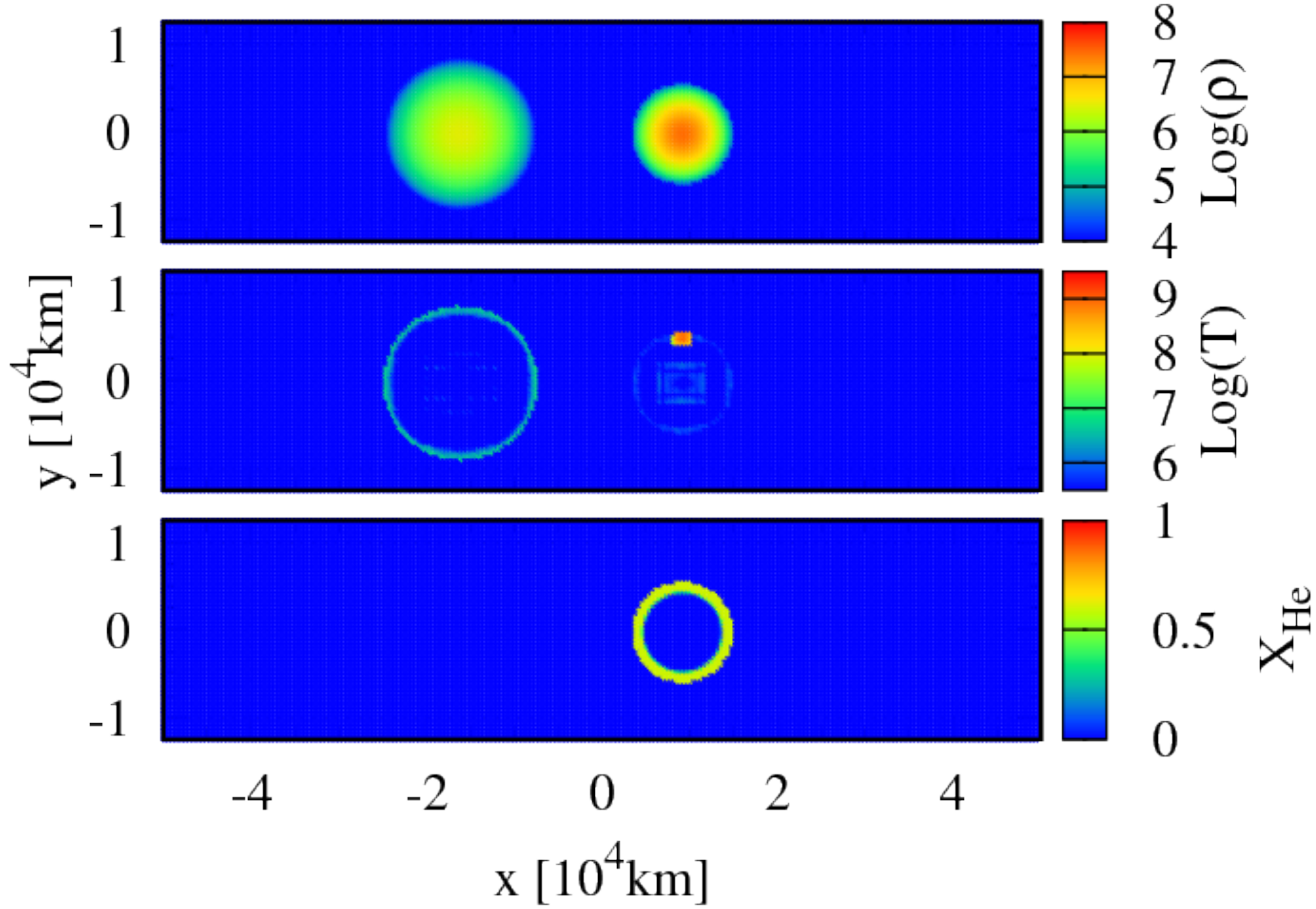
- The discoveries of these hypervelocity WDs make the D6 model promising.
- However, there is a possibility that the hypervelocity WDs are products of peculiar Ia.
- We reproduce D6 explosions, and investigate their features to assess whether they are consistent with normal Ia.

Simulation method

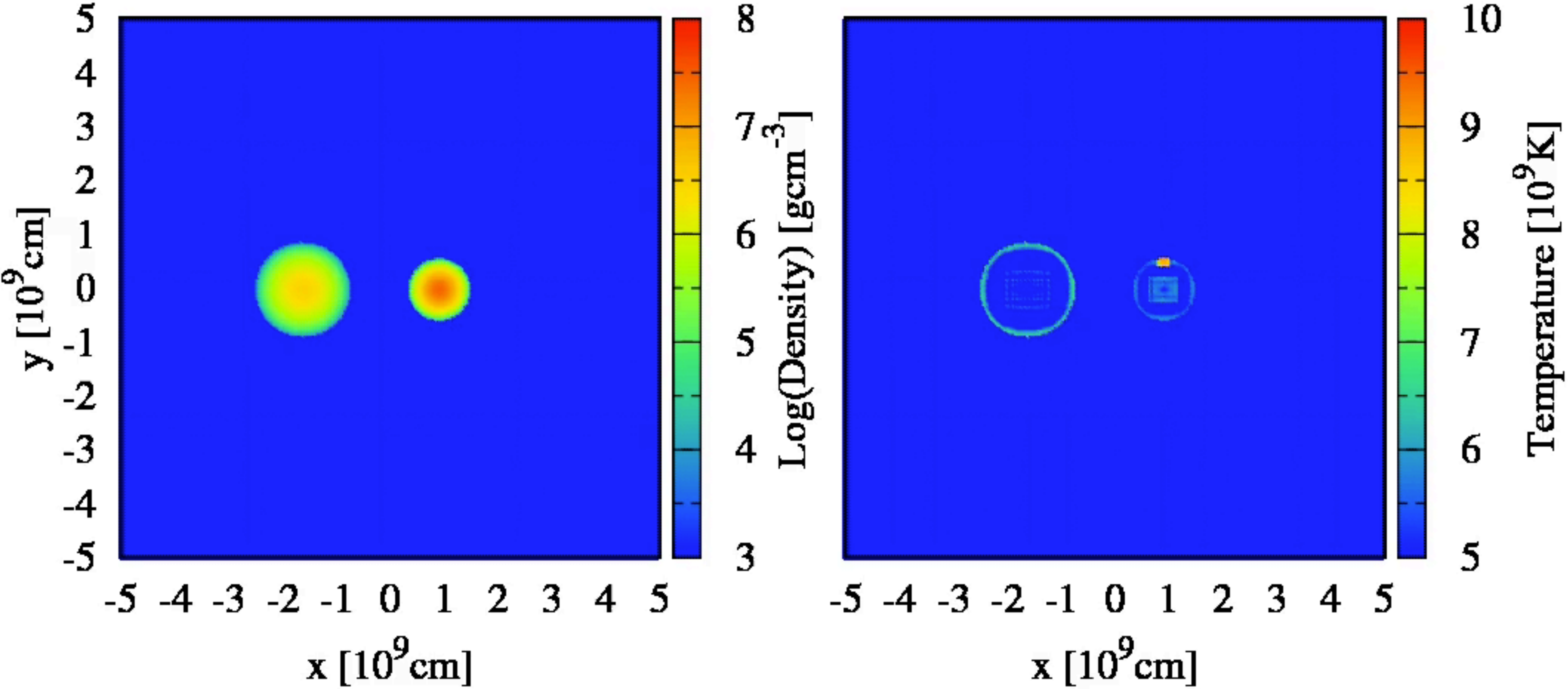
- 3D SPH method
    - Monaghan's artificial viscosity with Balsara switch (similar to GADGET)
- Optimization
    - Parallelized by FDPS (Iwasawa, AT+ 2016)
    - Vectorized by SIMD (e.g. AT+ 2012; 2013)
- Helmholtz EoS (Timmes, Swesty 2000)
- Aprox13 nuclear reaction networks (Timmes et al. 2000)

Initial condition

- $1.0M_{\odot}$ COWD
  - A He outer shell
  - A hot spot in the He shell
- $0.6M_{\odot}$ COWD
  - No He outer shell
- Separation
  - Just before Roche-lobe overflow



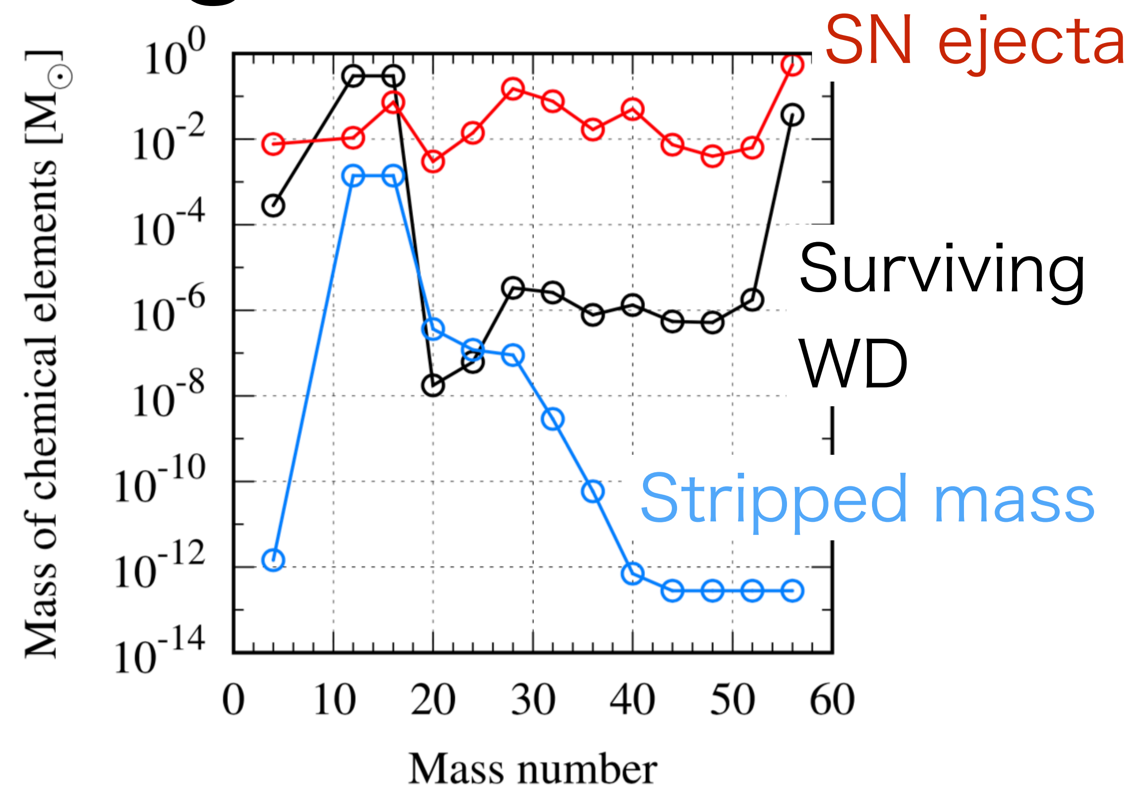
Animation

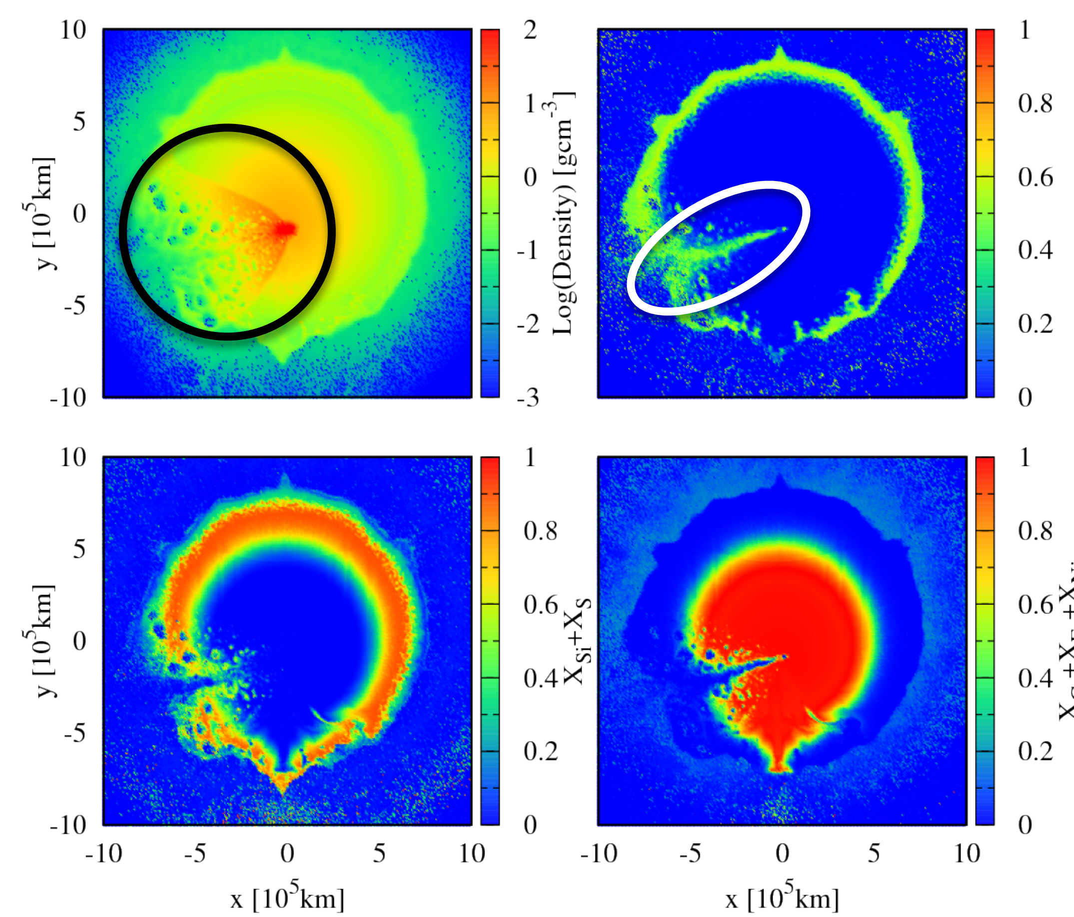


Tanikawa et al. (2018, ApJ, 868, 90)

Supernova ejecta

- ^{56}Ni mass is ~ 0.6 $M_\odot$
- SN ejecta with a shadow (see also Papish et al. 2015).
- Stripped materials from the lighter WD
  - $\sim 0.003 M_\odot$
  - Carbon and oxygen
  - Inner ejecta

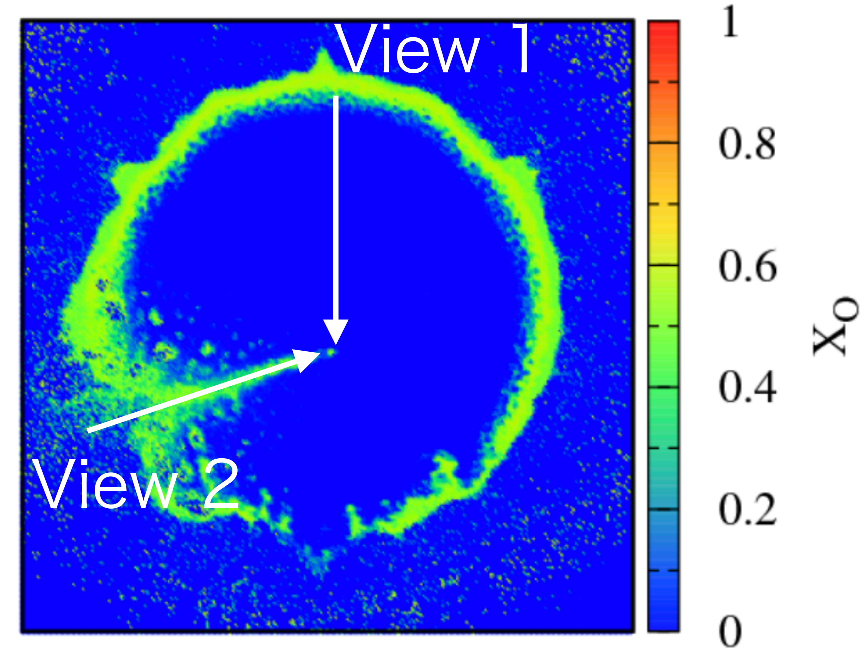




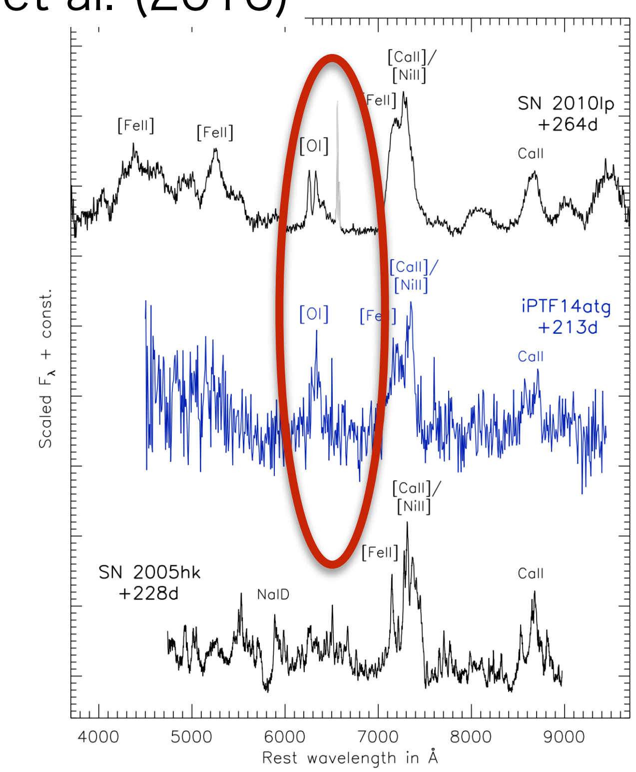
Tanikawa et al. (2018, ApJ, 868, 90)

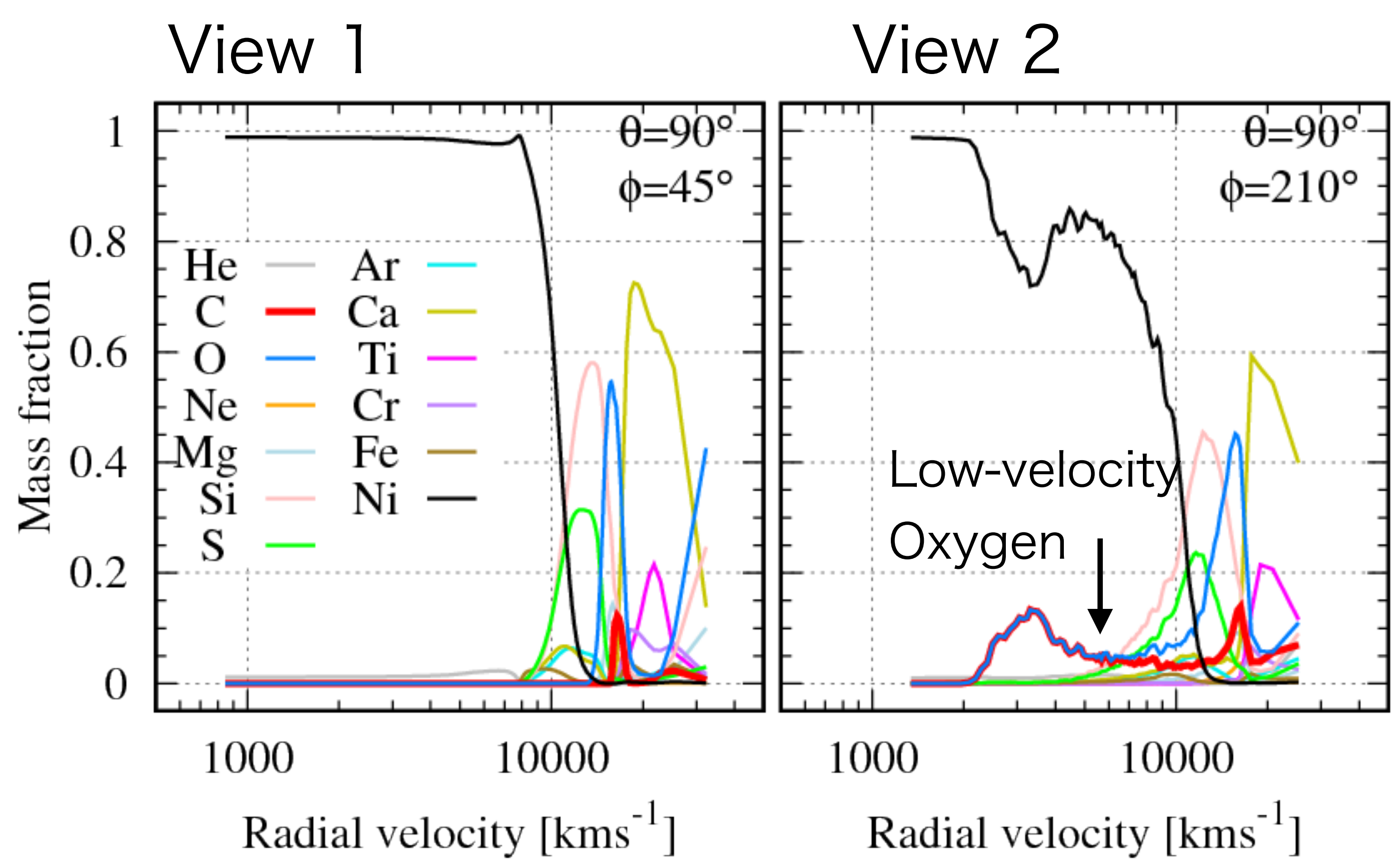
Inner carbon and oxygen

- The inner CO components could be a key to identify D6 explosions.
- Such low-velocity oxygen can explain nebular-phase spectra of some of sub-luminous SNe Ia.



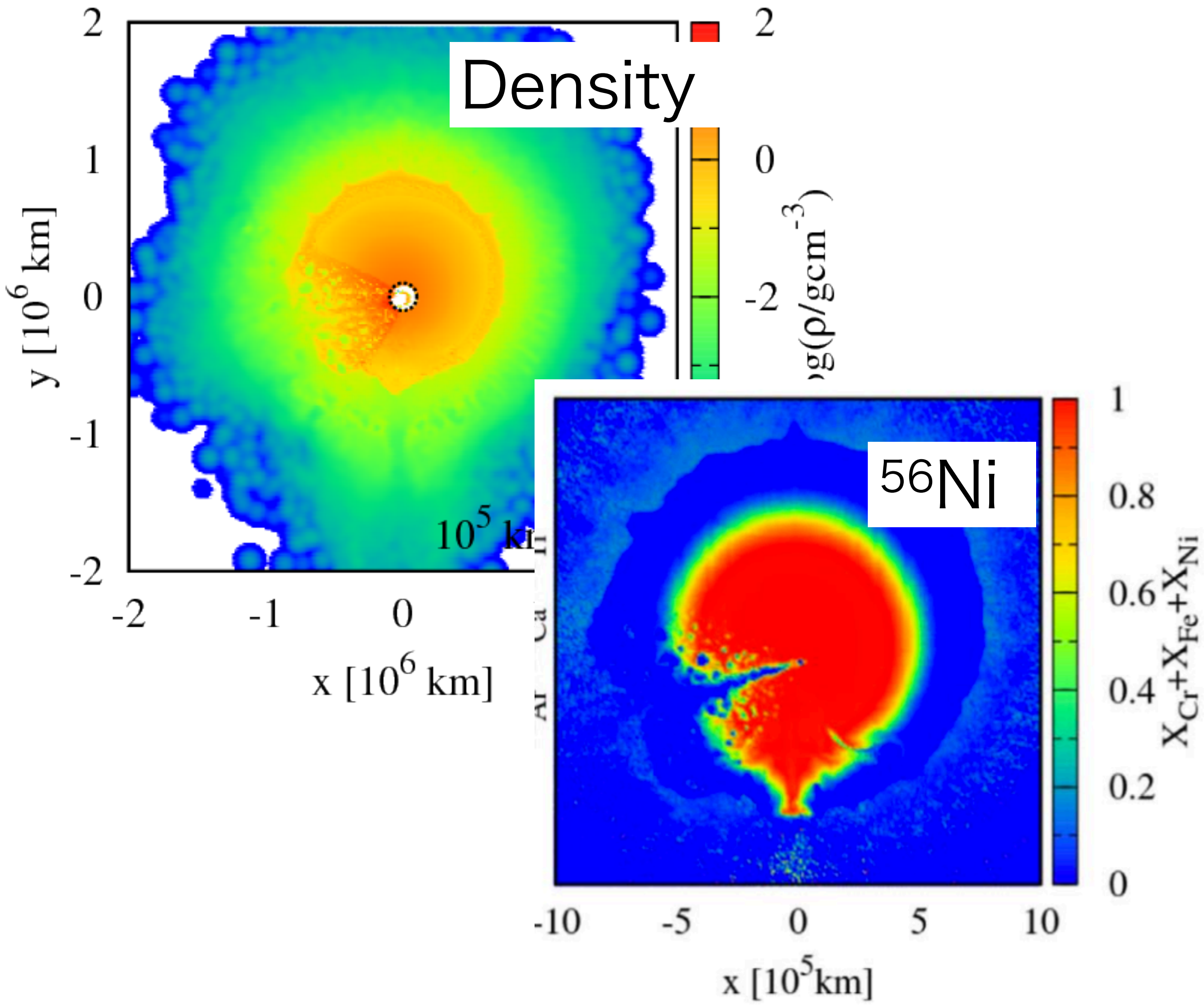
Kromer et al. (2016)





Tanikawa et al. (2018, ApJ, 868, 90)

Future plans



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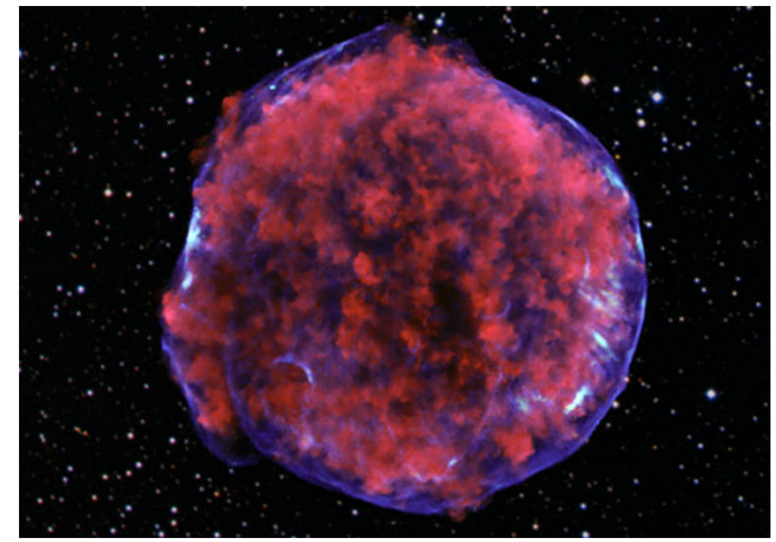
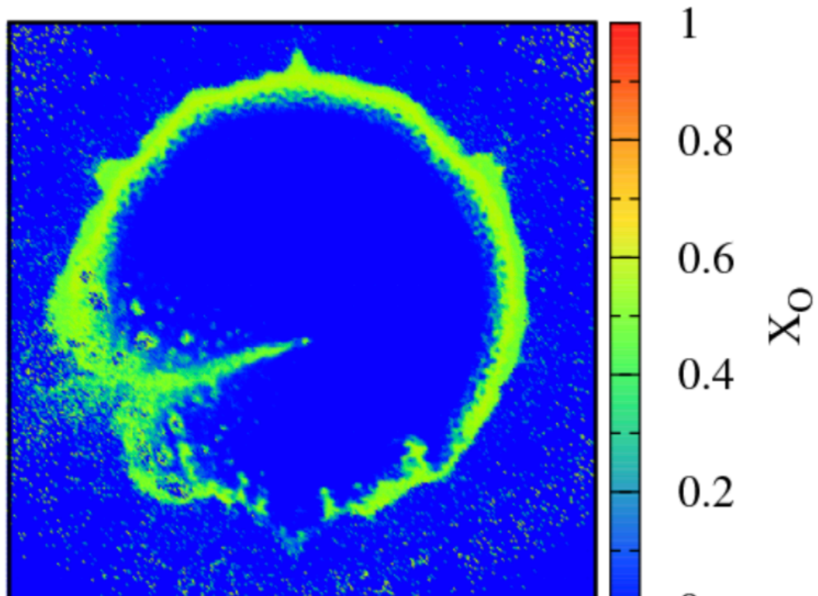


Collaboration with
G. Ferrand

Companion-
origin stream



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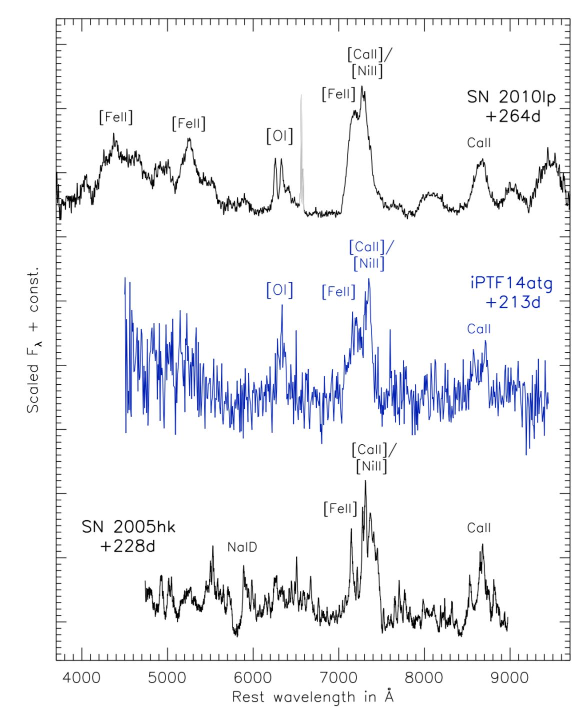


Kromer et al. (2016)

Short summary

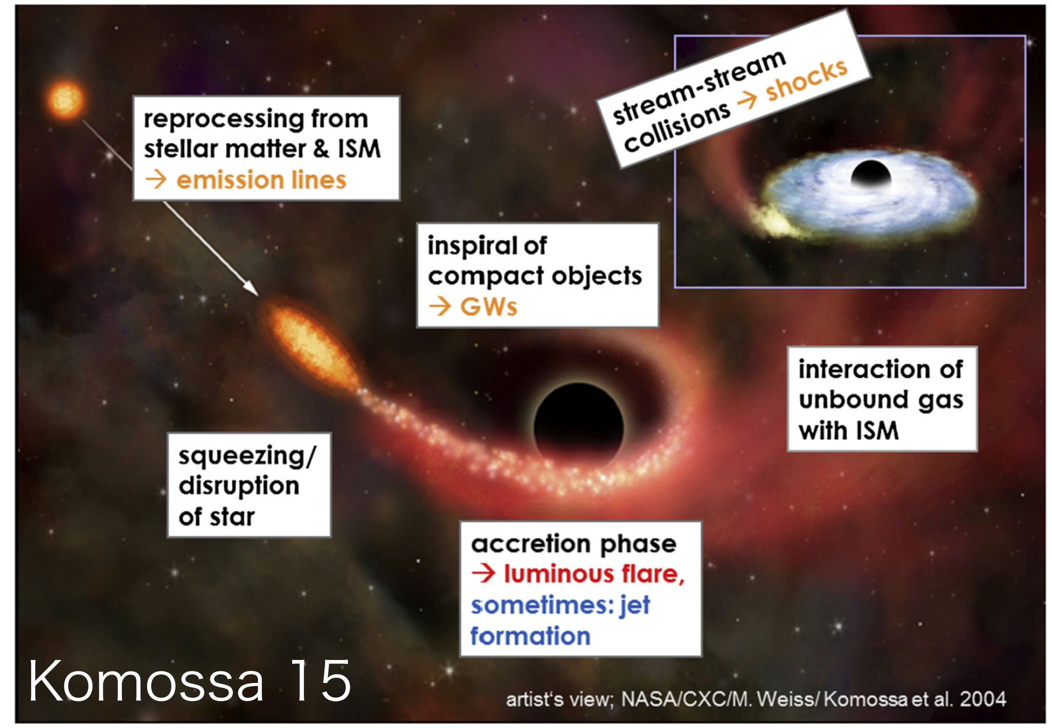
- SNe Ia can need the near-Ch SD and sub-Ch DD scenarios.
- We have assessed one of sub-Ch DD scenarios, the D6 model.
- We have found two potential discrepancies between the D6 model and normal Ia, the ejecta shadow and inner CO components.
- We will confirm whether these features can be observed or not.

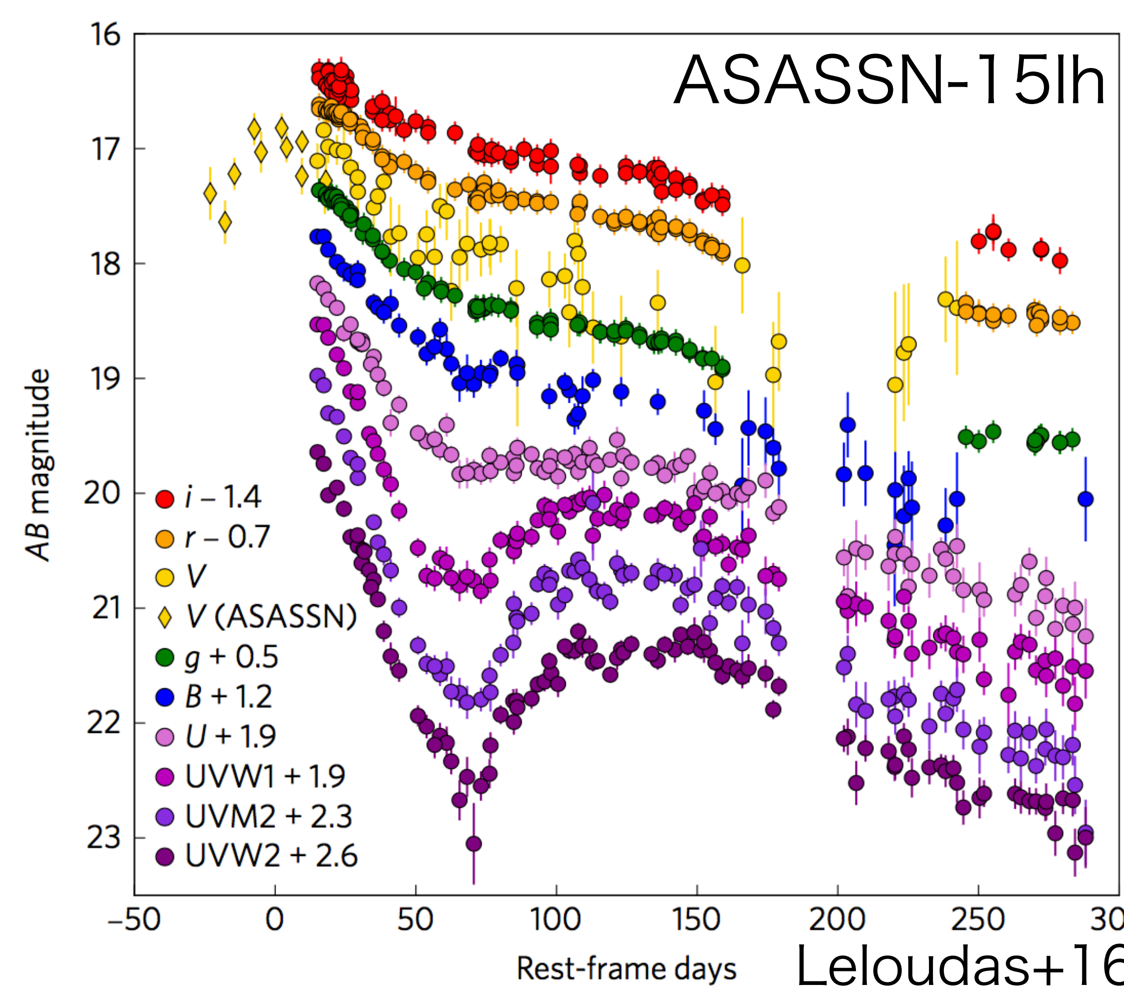
Contents

- Type Ia supernovae (SNe Ia)
- Tidal disruption events of white dwarfs (WD TDEs)

Tidal Disruption Event

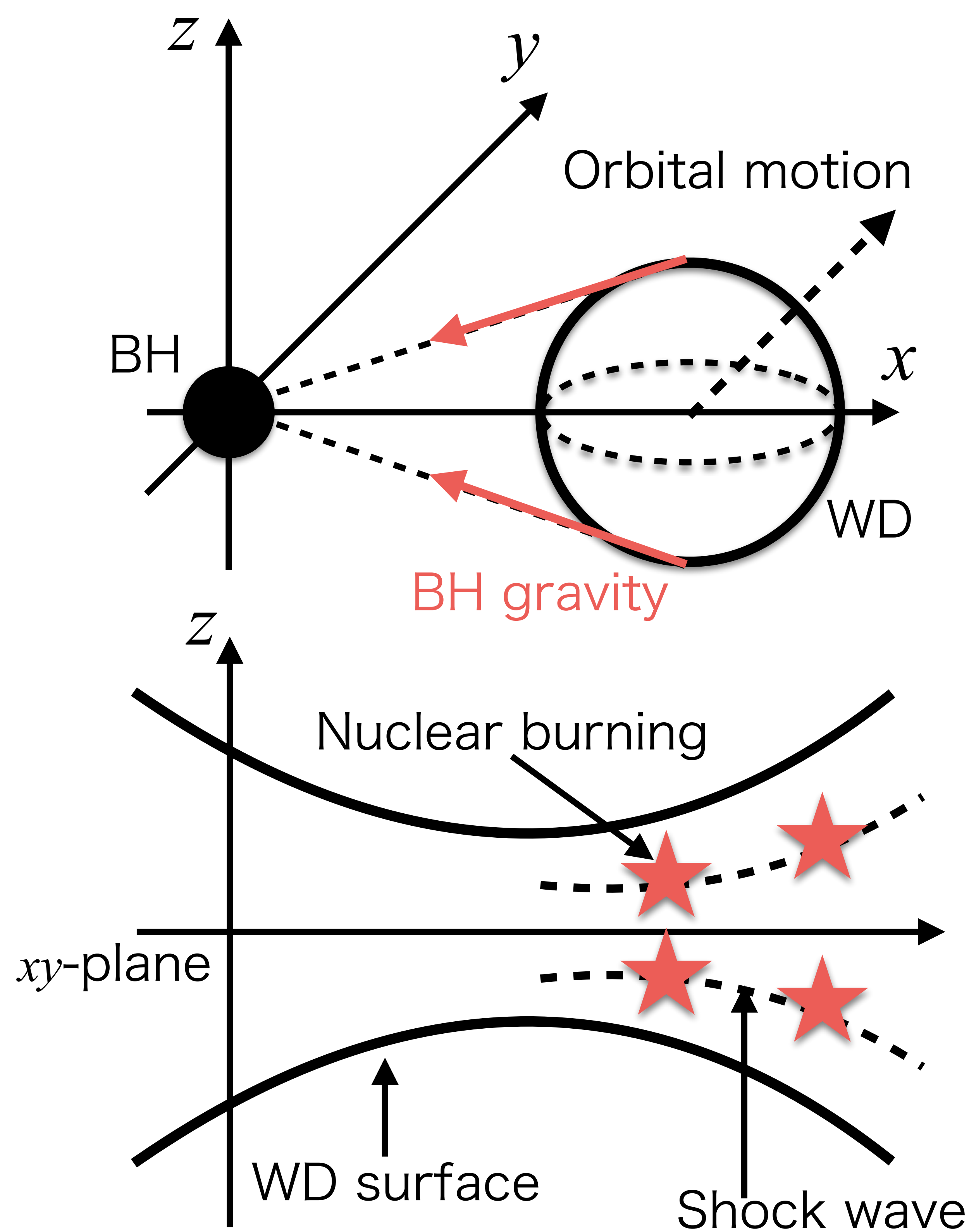
- Tidal disruption of a star (e.g. main sequence stars) by a BH
- Bright flare powered by accretion of the stellar debris
- Several ten candidates (Kommosa 2015)
    - TDEs of main sequence stars
    - No conformed WD TDEs





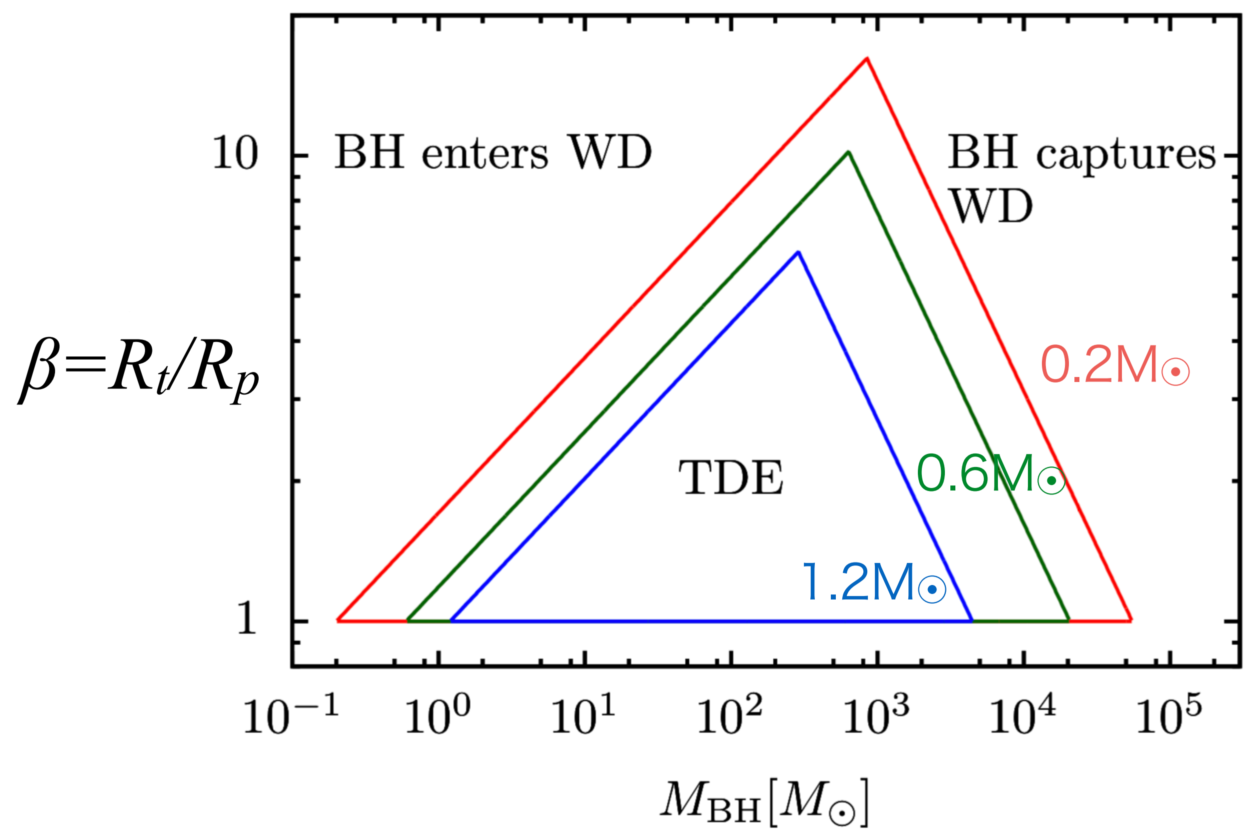
Tidal detonation

- Supersonic combustion induced by a tidal field of a BH
  - The WD is compressed in z-direction.
  - The compression induces a shock wave.
  - The shock wave triggers a detonation wave.
  - The detonation wave synthesizes ^{56}Ni.
  - The WD TDE can be powered by ^{56}Ni, similarly to SNe Ia.



Probe to search for Intermediate mass black hole

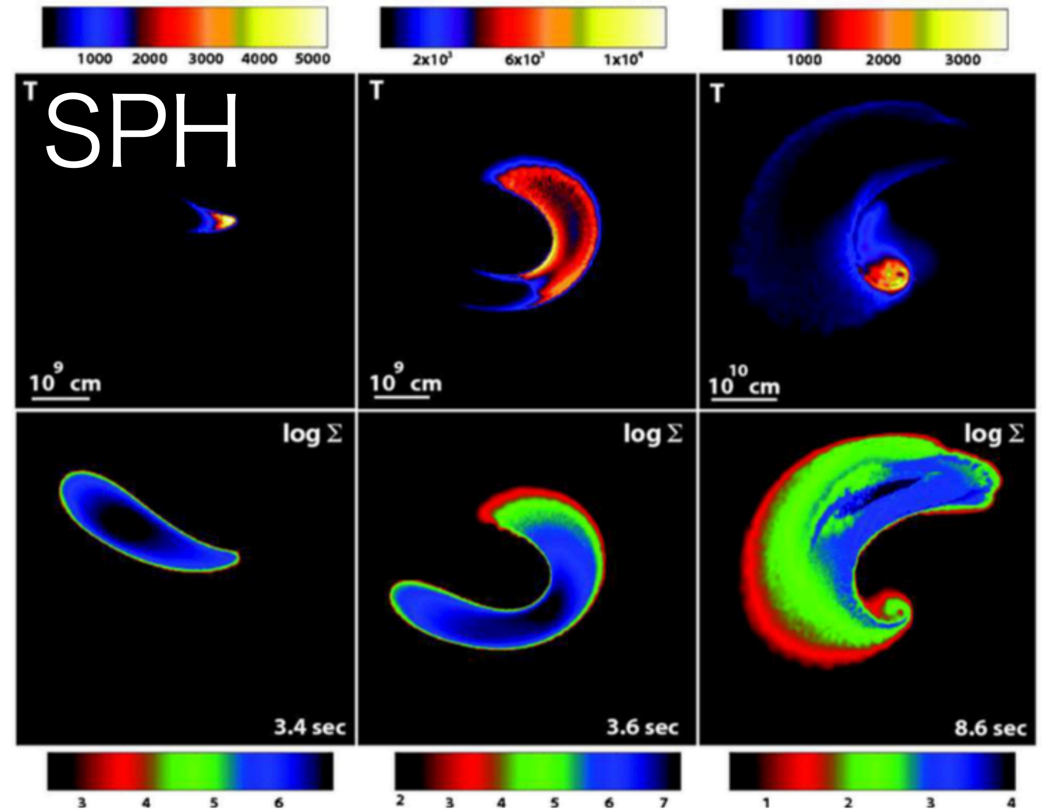
- Tidal detonation requires a WD TDE.
- A WD can be tidally disrupted only by an IMBH.
    - swallowing a stellar-mass BH.
    - swallowed by a massive BH.
- WD TDEs can illuminate only IMBHs.
- WD TDEs can be probes to search for IMBHs.



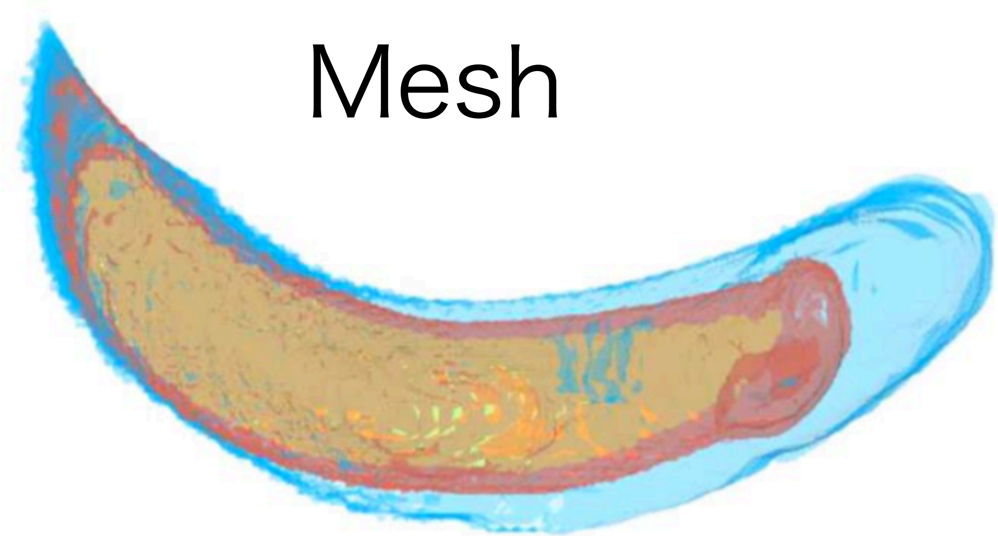
Kawana, AT+ 17 (see also Luminet, Pichon 1989 Rosswog et al. 2009; MacLeod et al. 2016)

Previous and our studies

- Previous studies
  - demonstrated tidal detonation by numerical simulations.
  - didn't explain the ignition mechanism explicitly.
- Our studies
  - make clear the ignition mechanism.
  - confirm tidal detonation.



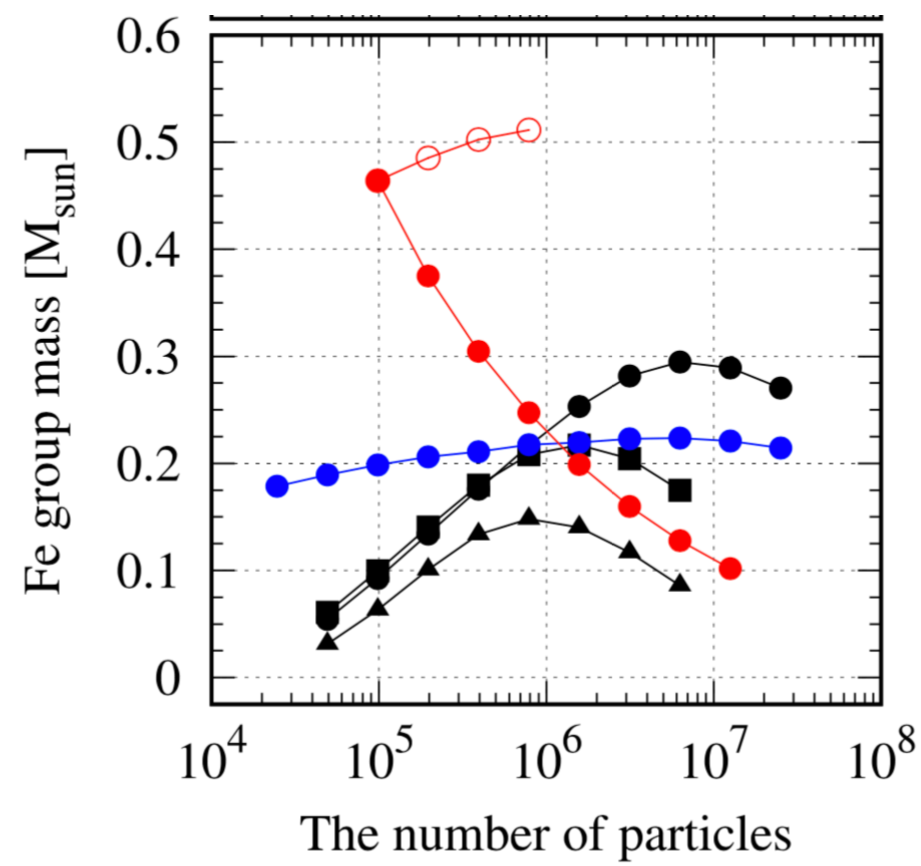
Rosswog et al. (2008; 2009)

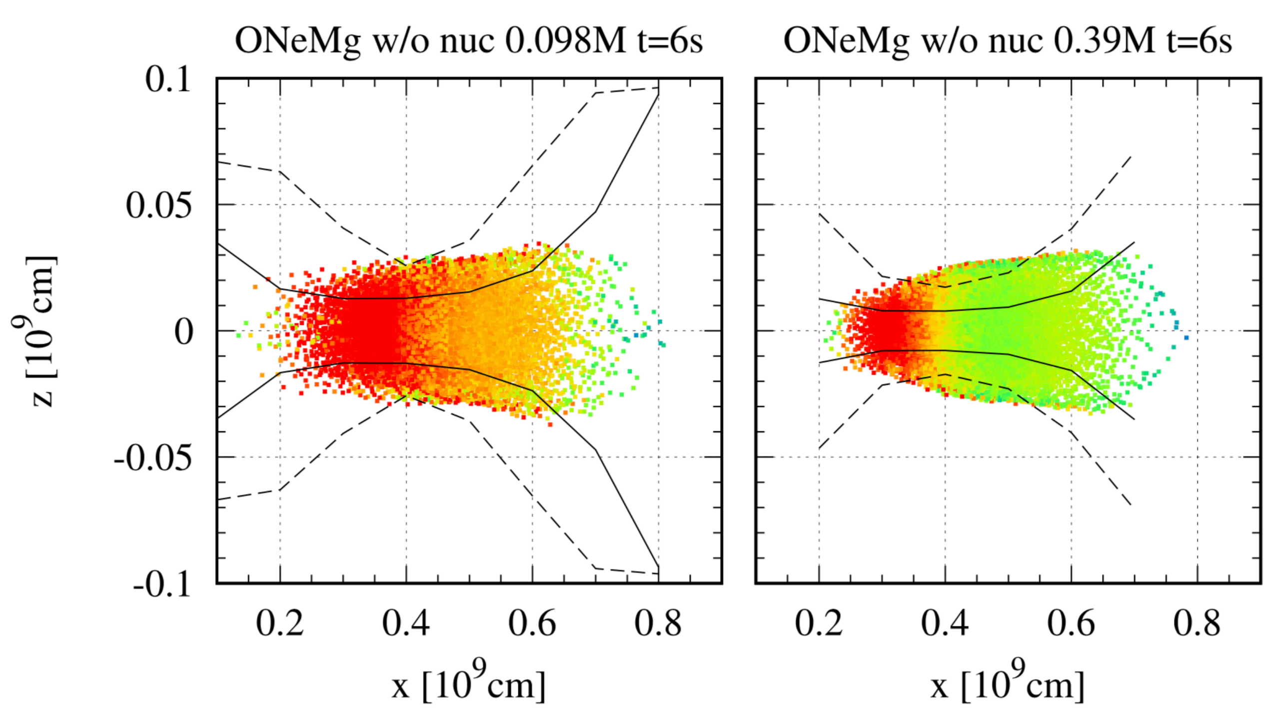


Anninos et al. (2018; 2019)

SPH simulation

- Mass of Yielded materials is not converged.
- ^{56}Ni yielded by spurious heating due to low resolution.
- Amounts of ^{56}Ni are decreased with resolution increasing.
- Does tidal detonation occur in reality?



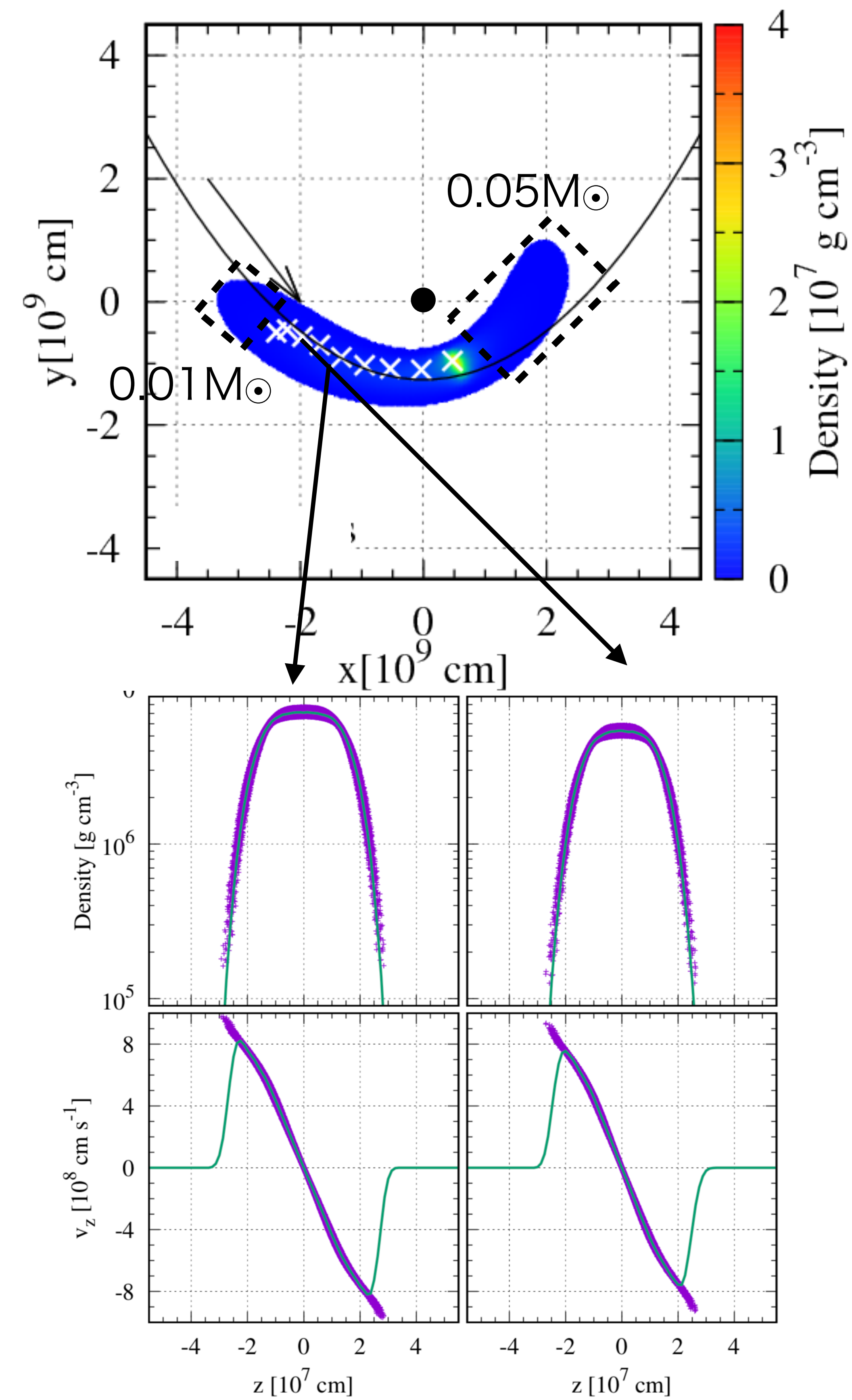


Tanikawa et al. (2017, ApJ, 839, 81)

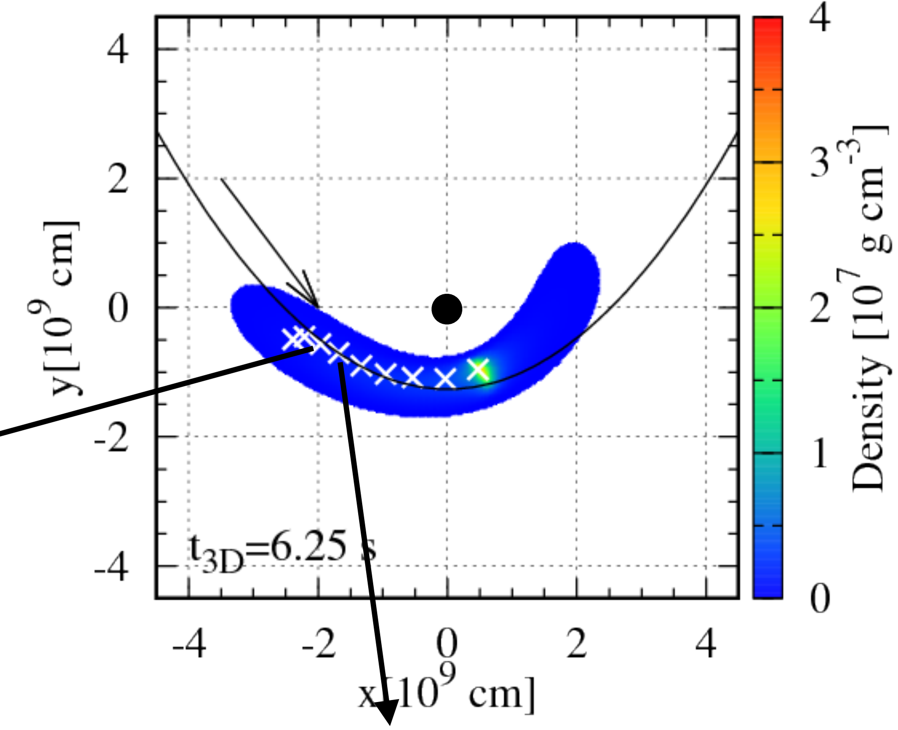
Switch 3D to 1D

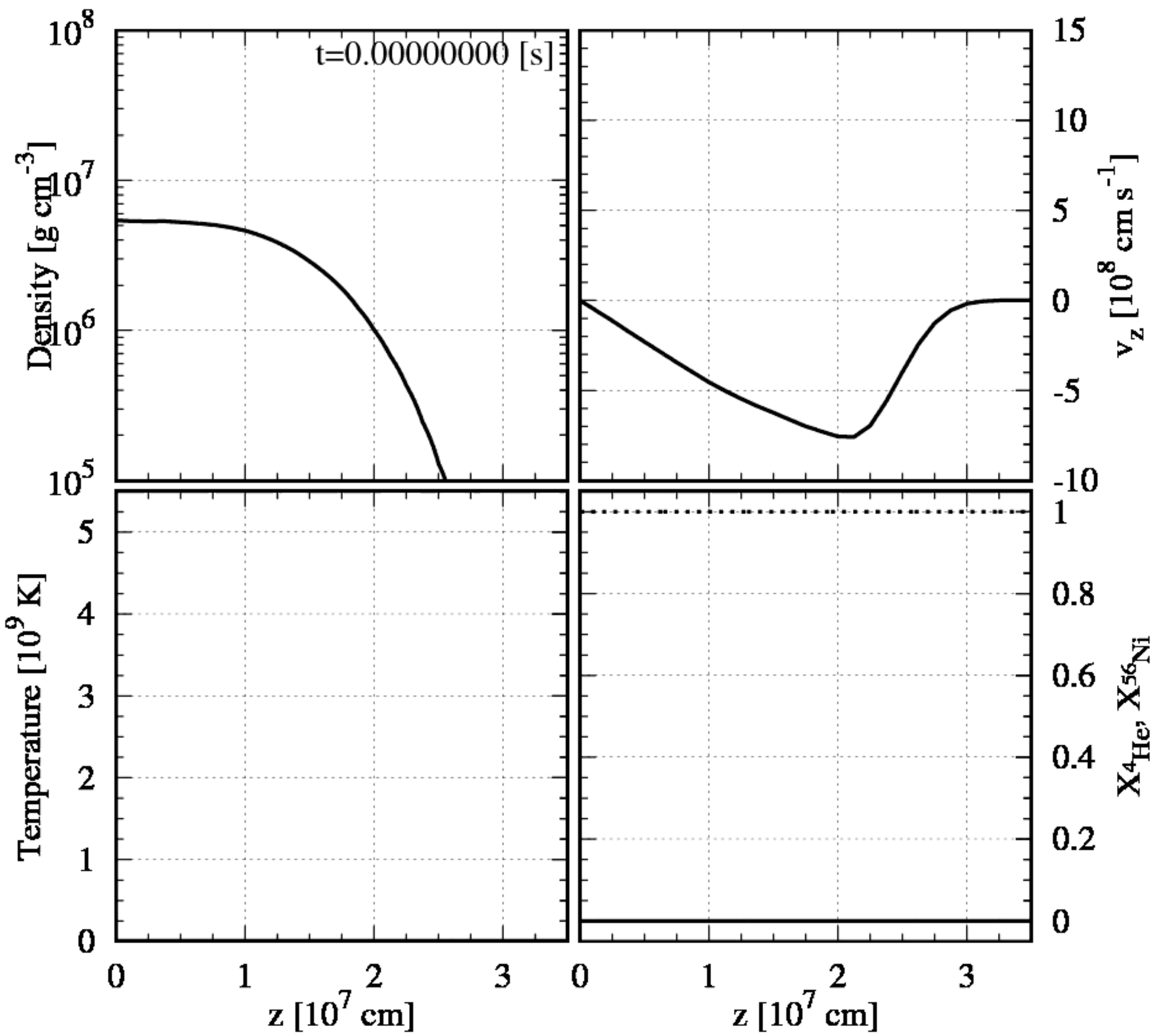
- 3D SPH simulation
    - 0.45M⊙ HeWD disrupted by 300M⊙ IMBH
        - N~3x10⁸ for the He WD
    - without nuclear reactions
- Extracting z-columns indicated by white crosses
- 1D mesh simulation
    - z-columns
    - with nuclear reactions

Tanikawa (2018, ApJ, 858, 26)



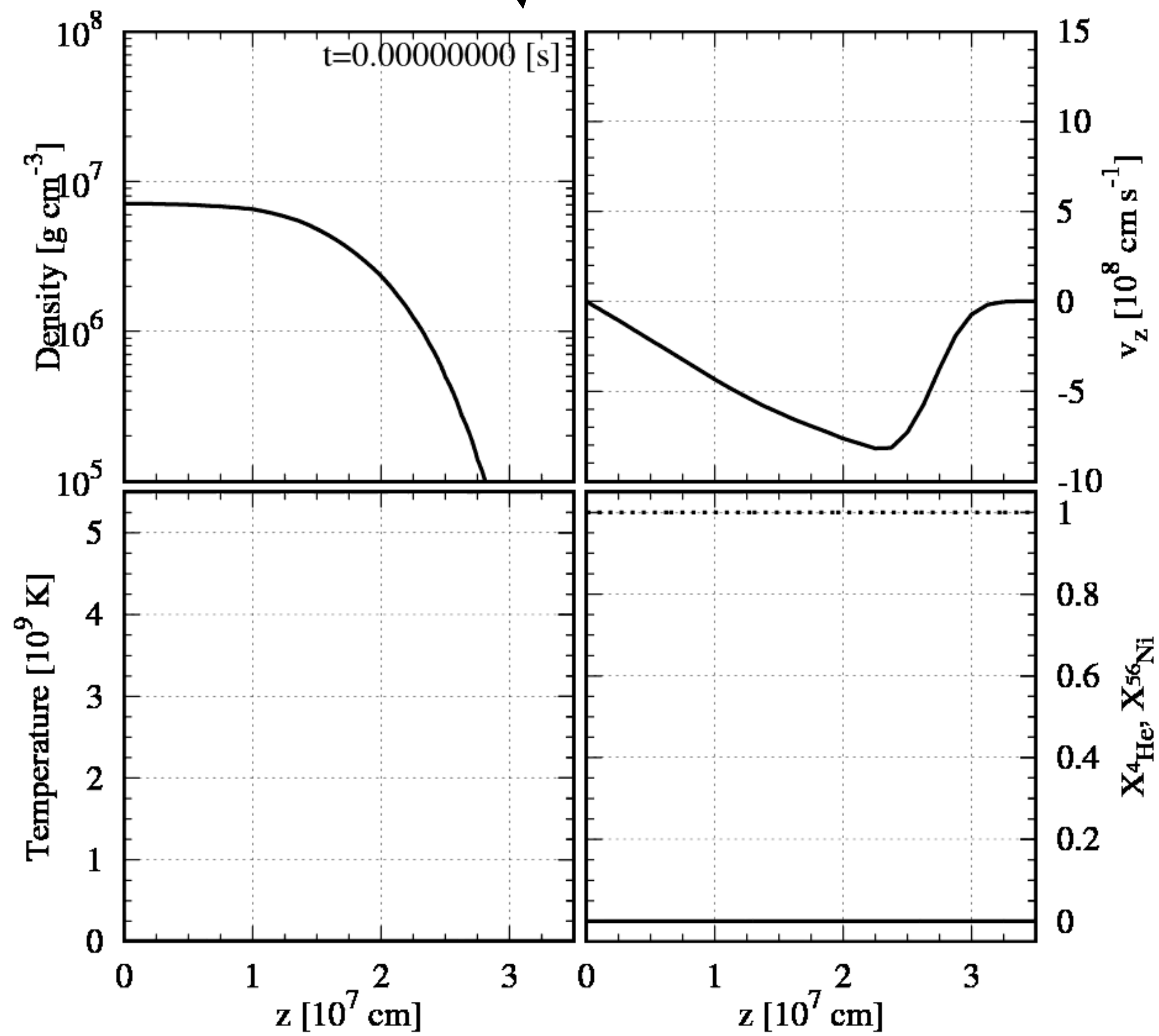
Movies





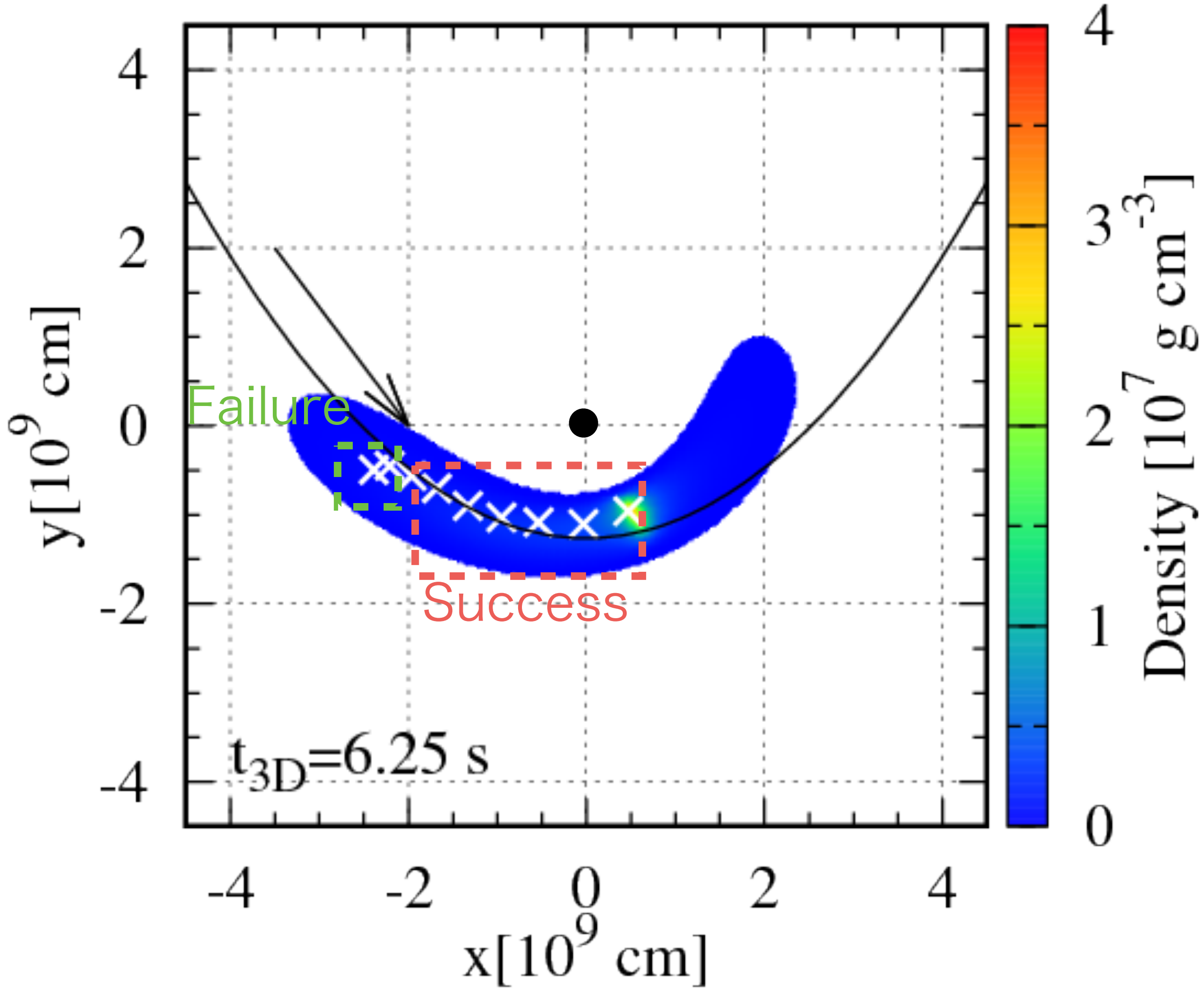
Failure case

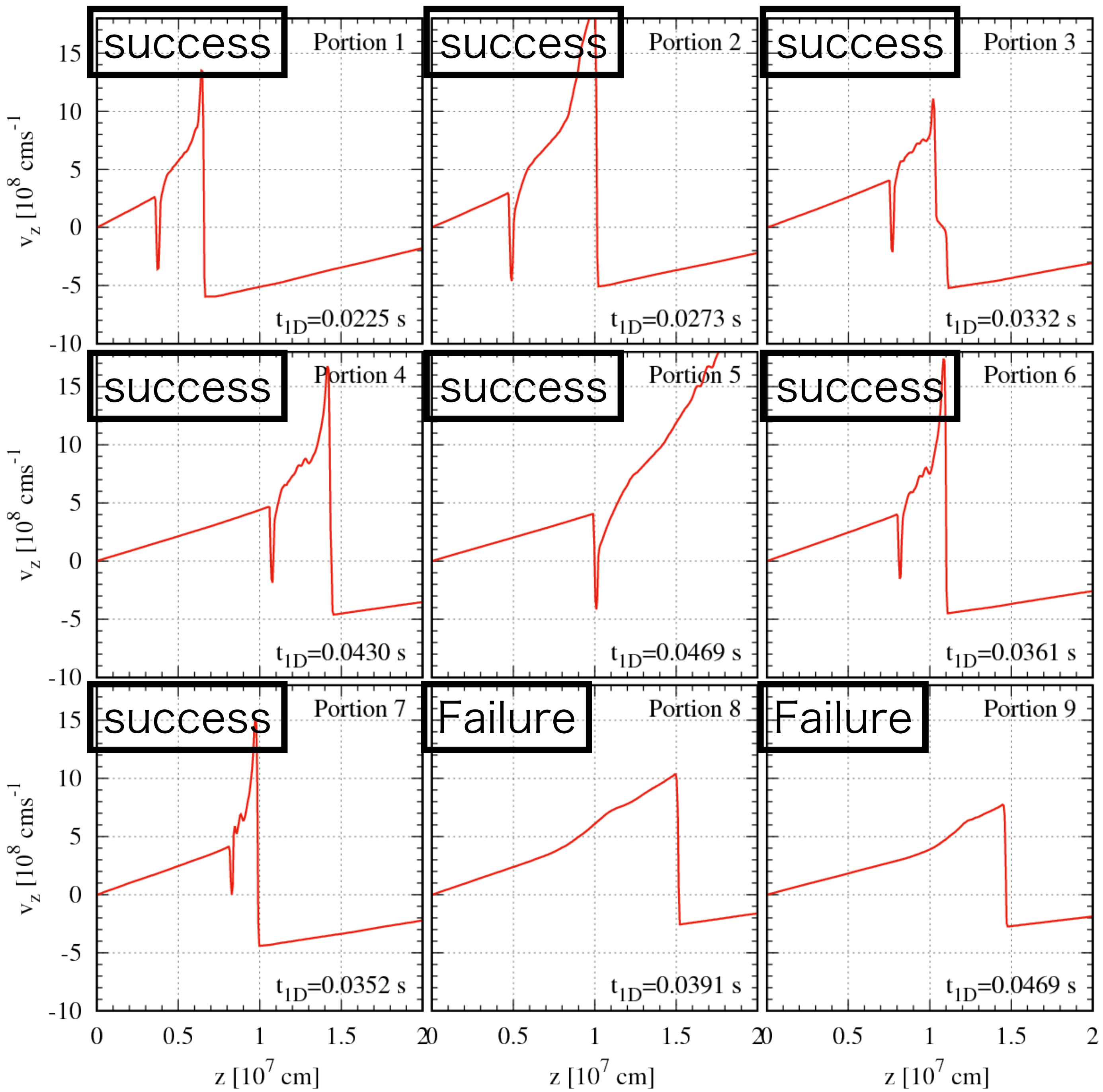
Tanikawa et al. (2018, ApJ, 858, 26)



Success case

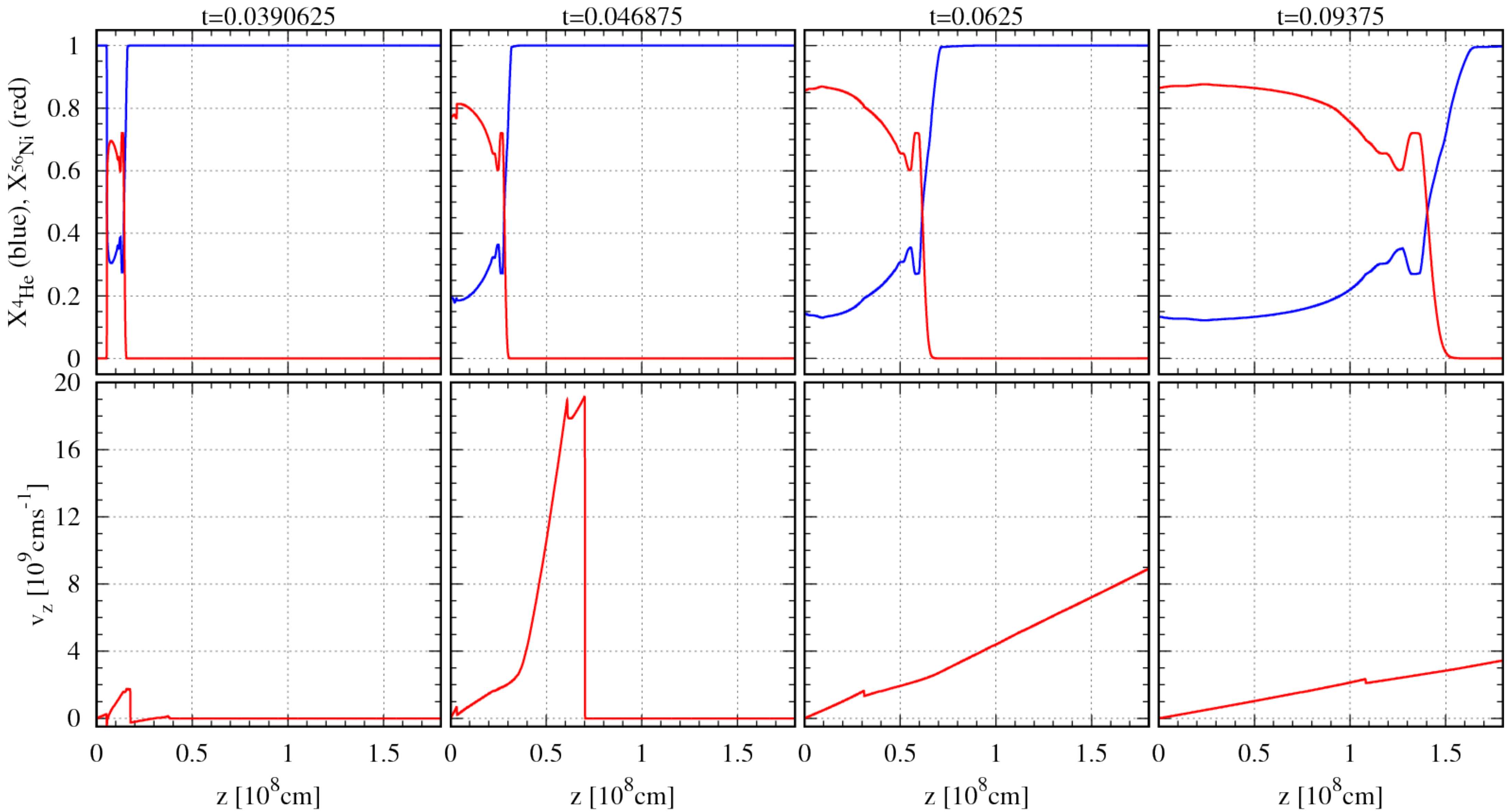
1D Results





Tanikawa (2018, ApJ, 858, 26)

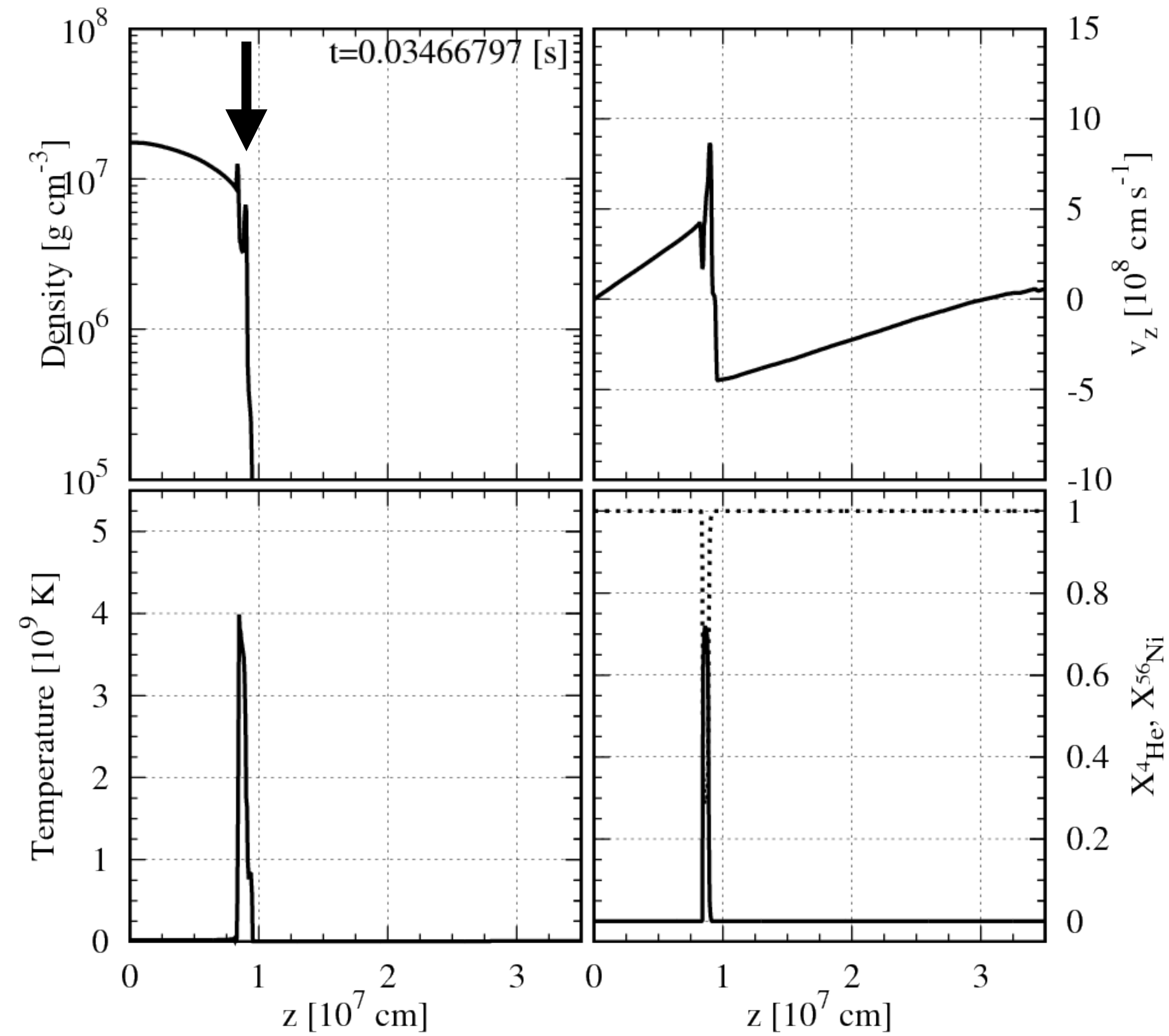
Nucleosynthesis



- The detonation wave leaves 20% ^{4}He and 80% ^{56}Ni.
- The detonated region has high density (>10^{6} gcm^{-3}).

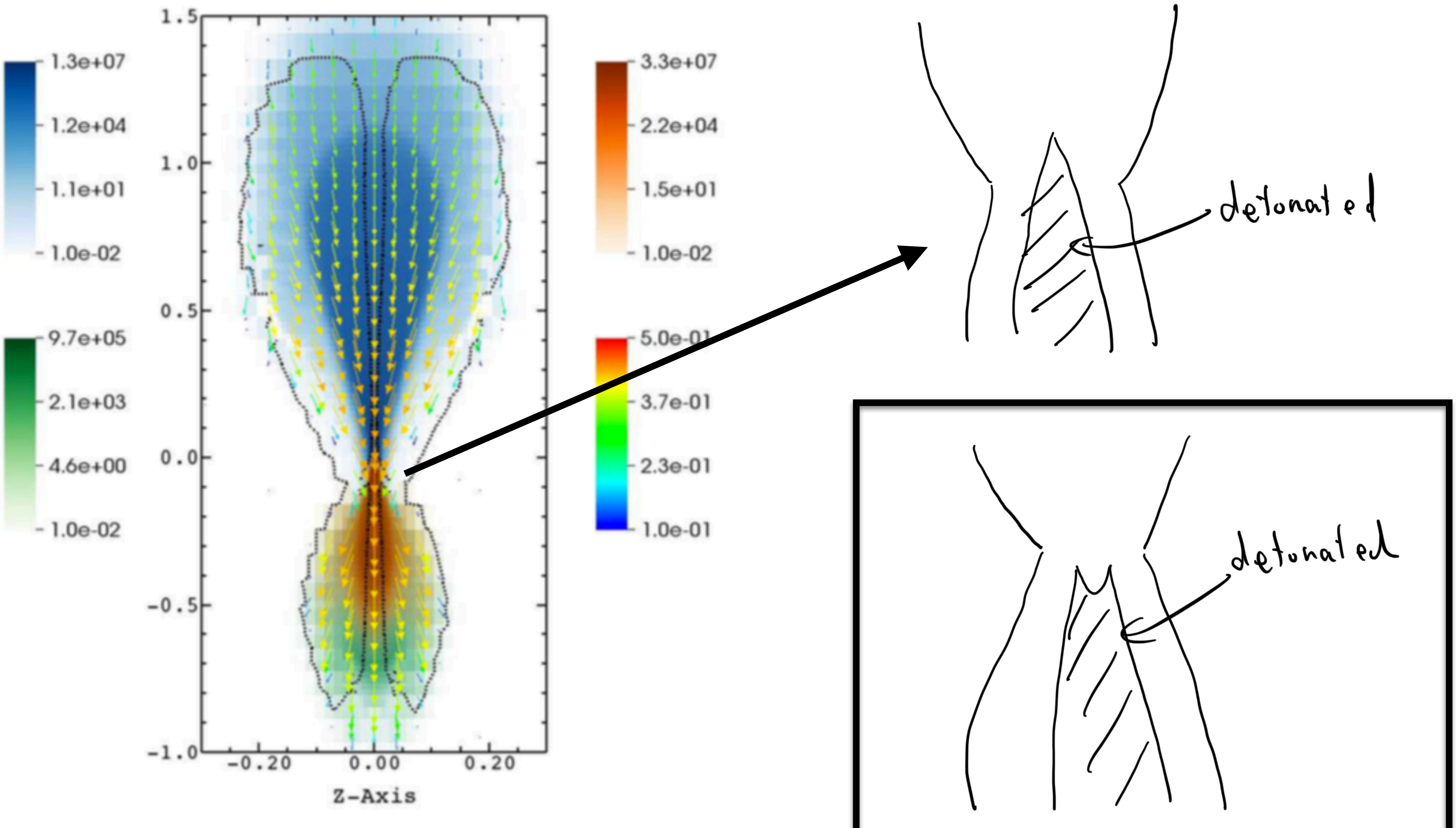
The beginning point of tidal detonation

- Tidal detonation starts from the edge of the white dwarf.
- A pressure wave steepens into a shock wave due to steep decrease of sound velocity at the edge.
- SPH method is not good at resolving the edges of any objects.



Tanikawa (2018, ApJ, 858, 26)

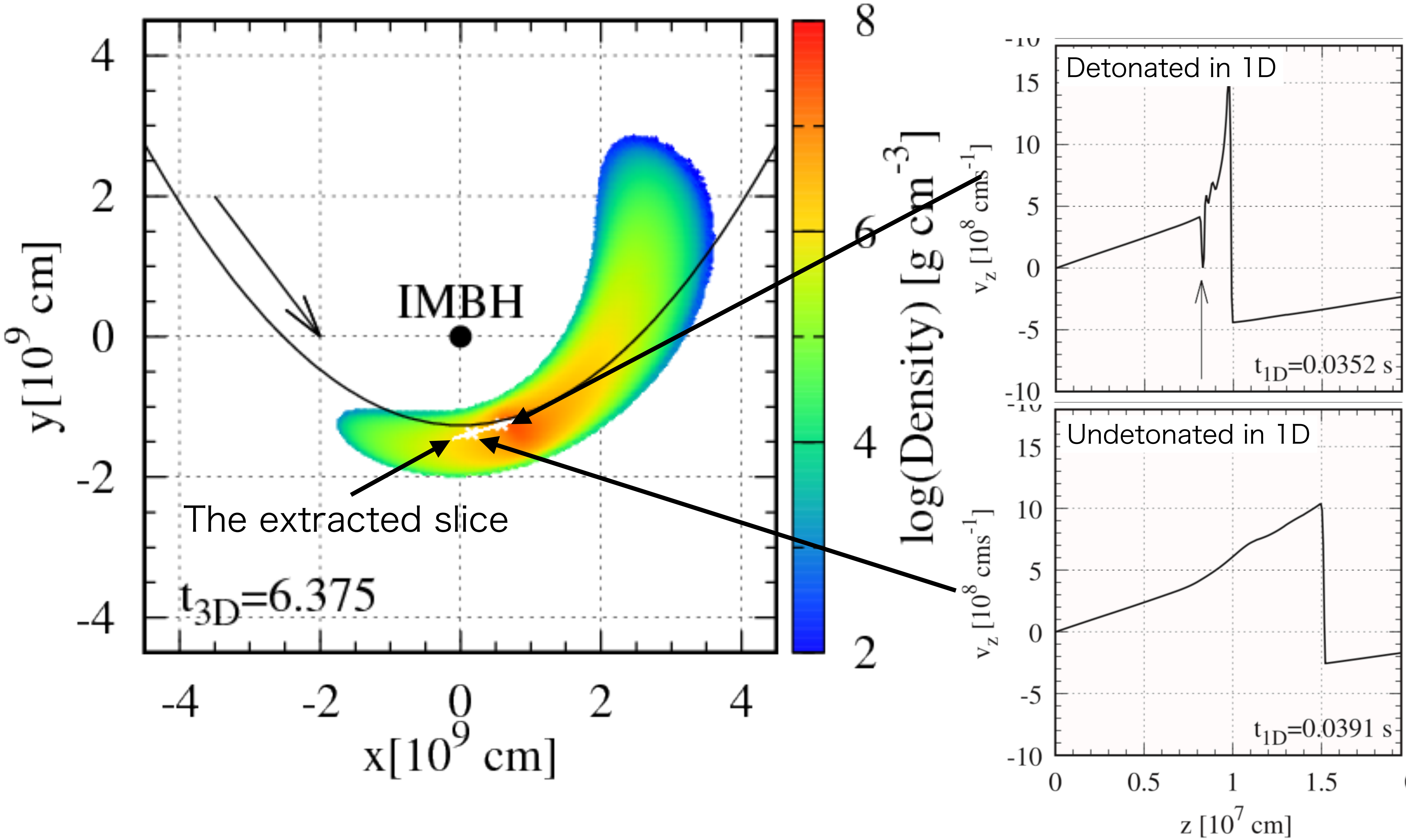
Mesh simulation?



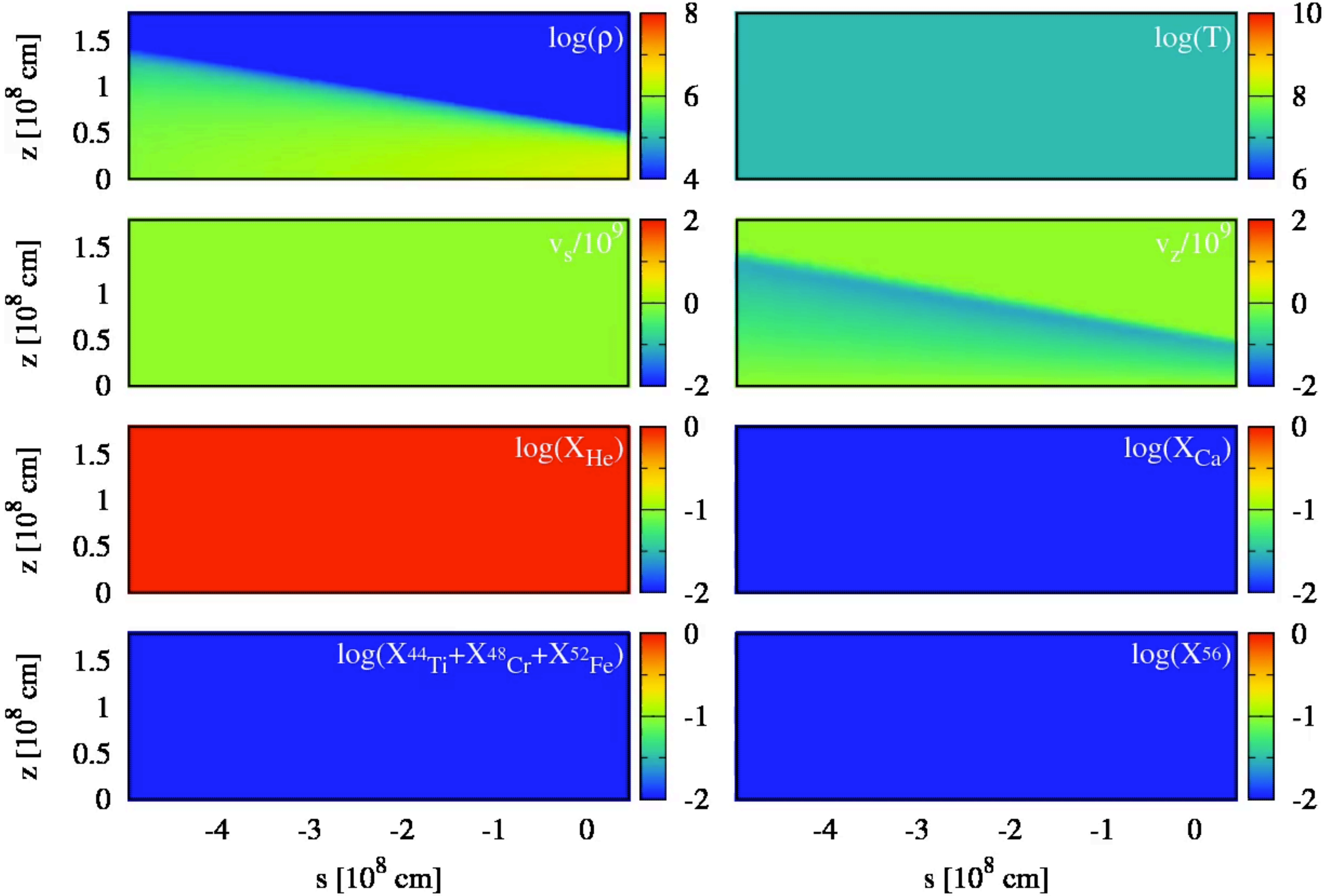
Anninos et al. (2018; 2019)

But, it should be like this.

2D simulation

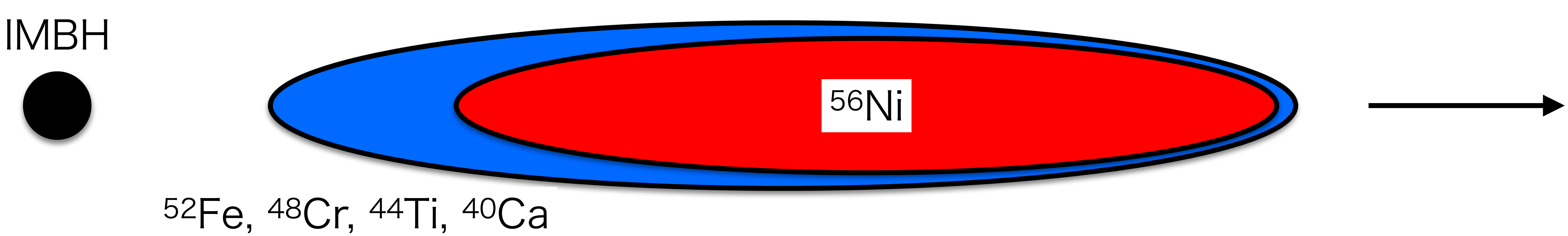


Simulation result



Short summary

- We confirm tidal detonation by extremely high-resolution simulations.
- ^{56}Ni are yielded around the ignition regions of tidal detonation.
- Elements lighter than ^{56}Ni (^{52}Fe, ^{48}Cr, ^{44}Ti, and ^{40}Ca) are yielded in the trailing part.
- We will investigate observational features of WD TDEs to help finding WD TDEs and IMBHs.



Summary

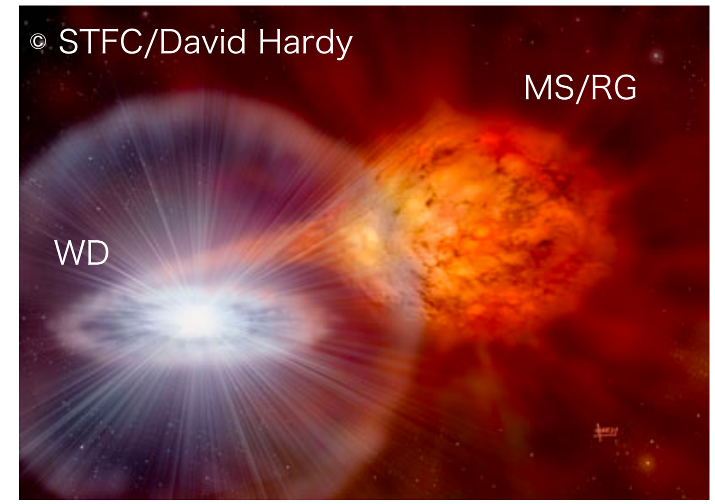
- SNe Ia
  - We perform D6 simulations.
  - We find two potential discrepancies.
- WD TDE
  - We confirm tidal detonation.
  - We find the ignition and propagation mechanism.

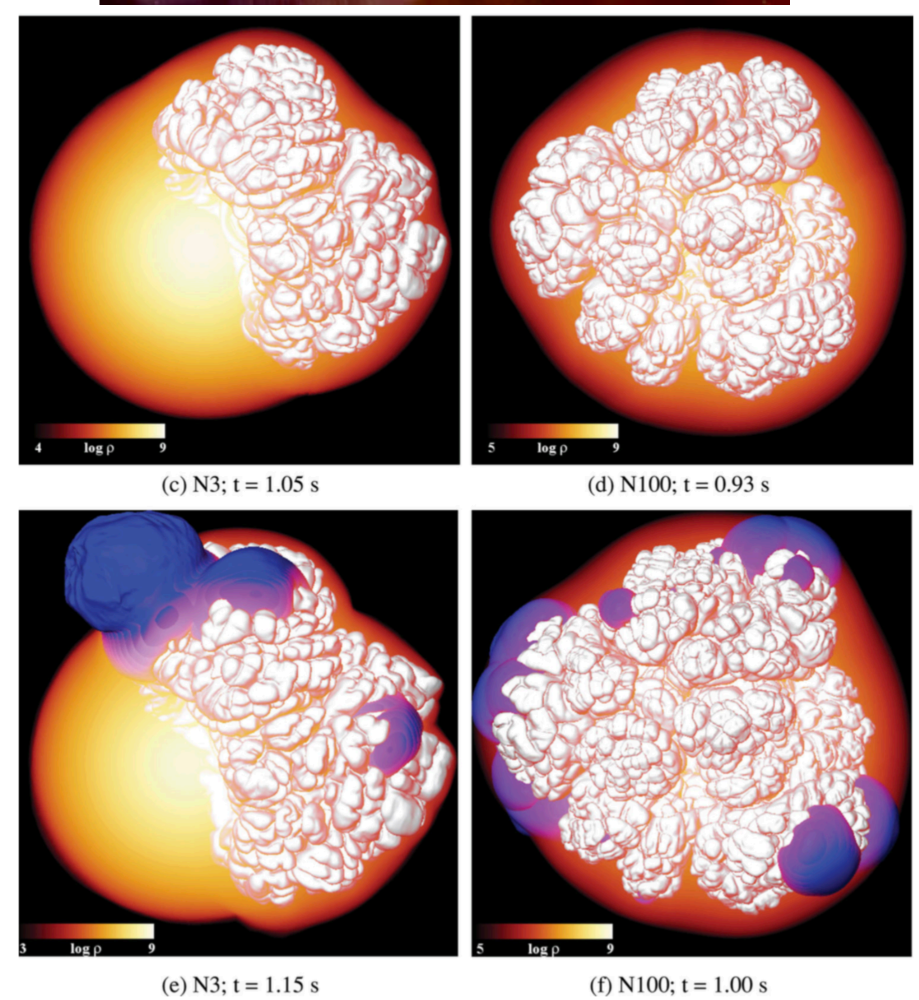
Backup slides

Type Ia supernovae

Near-Ch SD scenario

- Delayed detonation
  - A WD accretes materials from a non-degenerate companion star through Roche-lobe overflow.
  - The WD mass grows to near-Ch mass.
  - Thermonuclear runaway starts from deflagration (subsonic combustion wave).
  - It transitions to detonation (supersonic combustion wave)
- Successful light curve, and nucleosynthesis

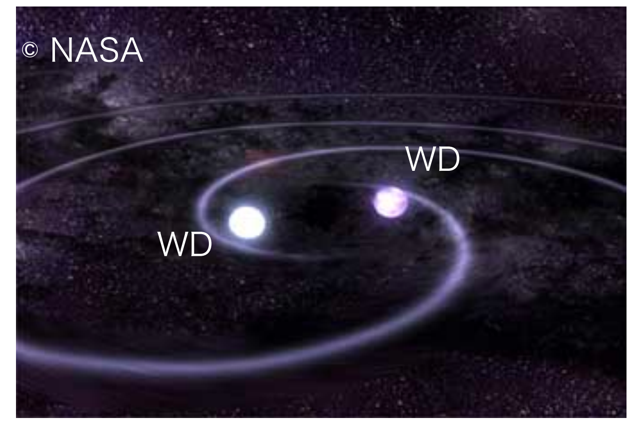


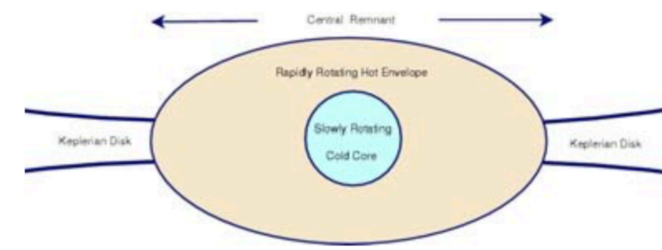


Seitenzahl et al. (2013)

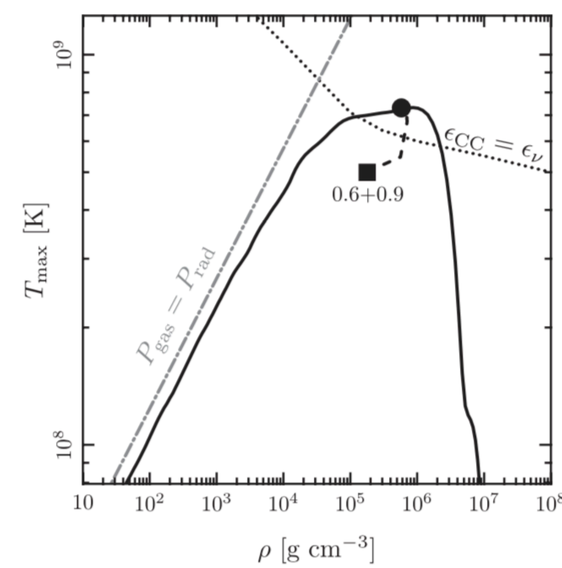
Near-Ch DD scenario

- 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.

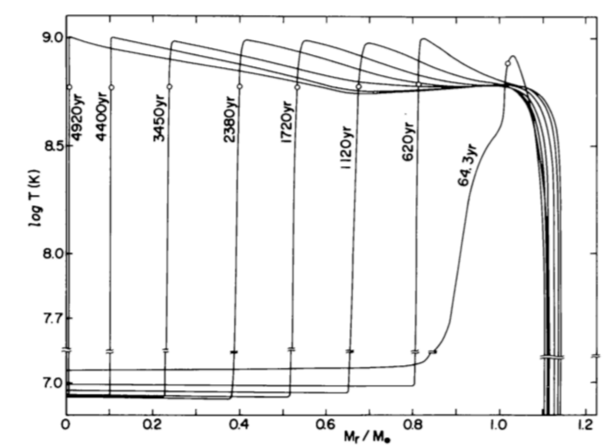




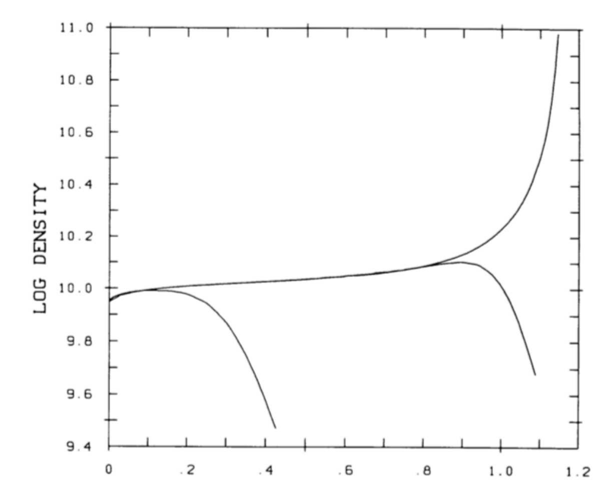
Yoon et al. (2007)



Schwab et al. (2012)



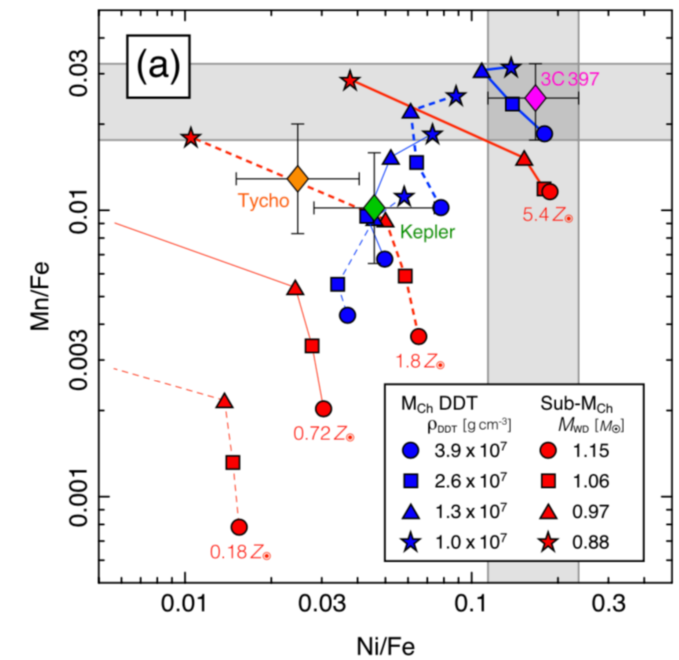
Saio, Nomoto (1985)



Nomoto, Kondo (1991)

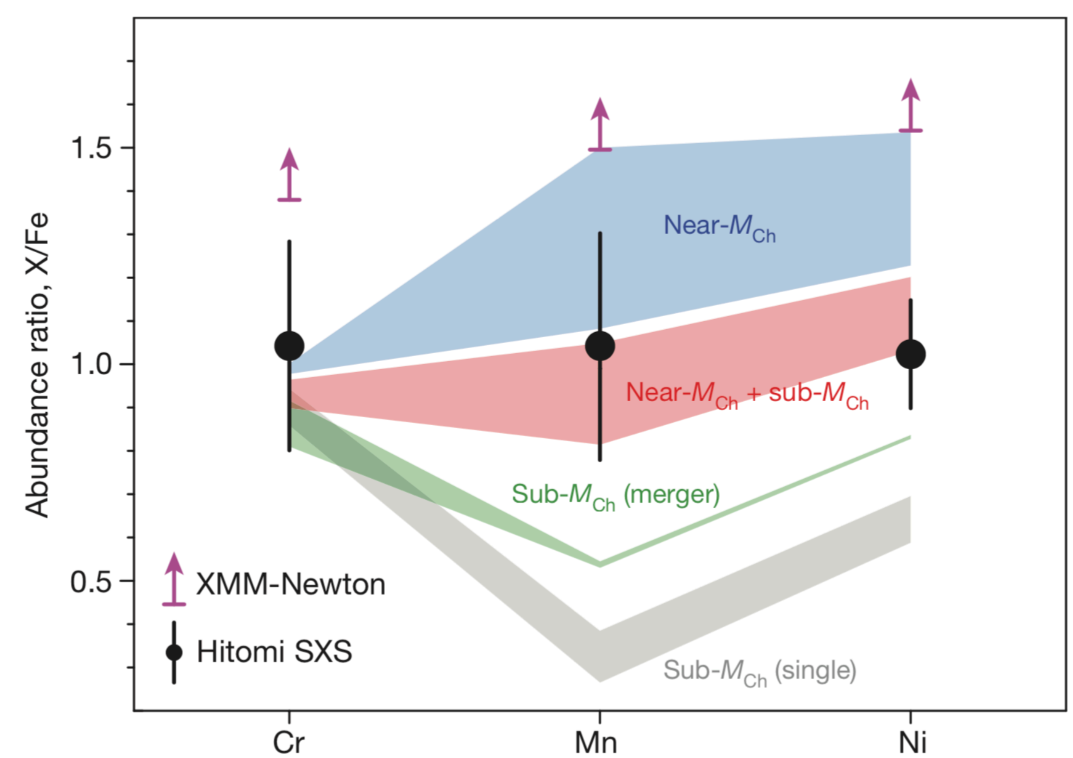
Multiple origins?

- 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)

D6 model

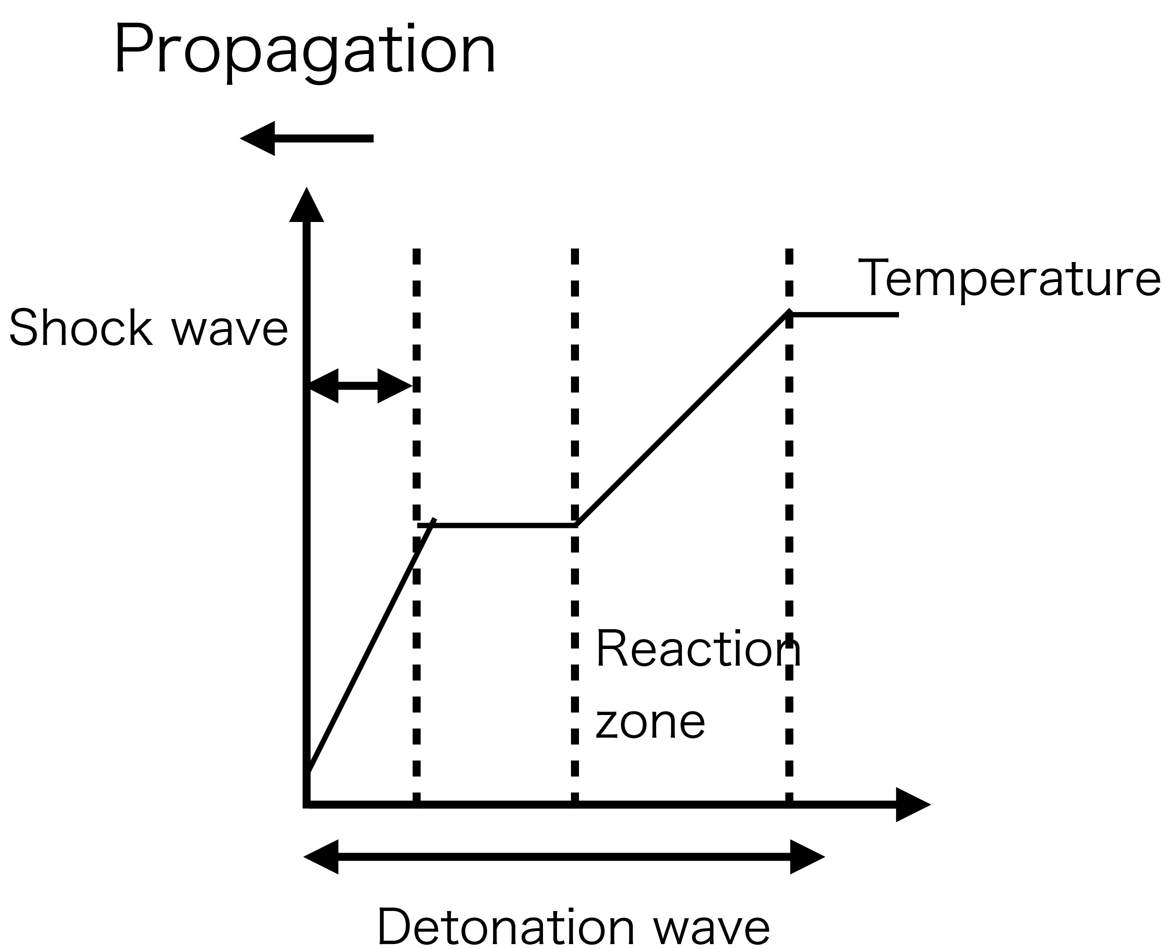
- Technical terms
- The D6 processes
- D6 Observations

Technical terms

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

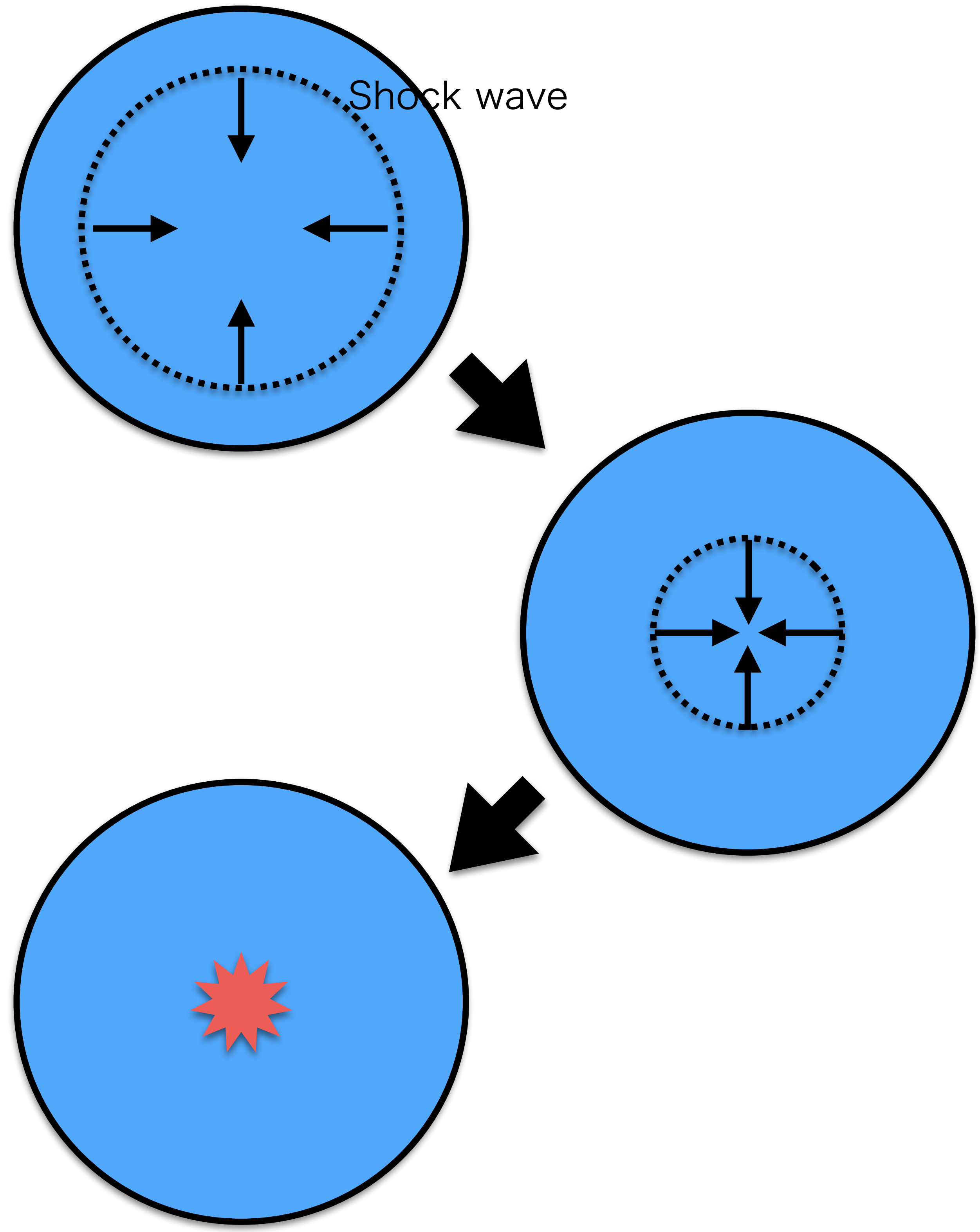
Detonation

- 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



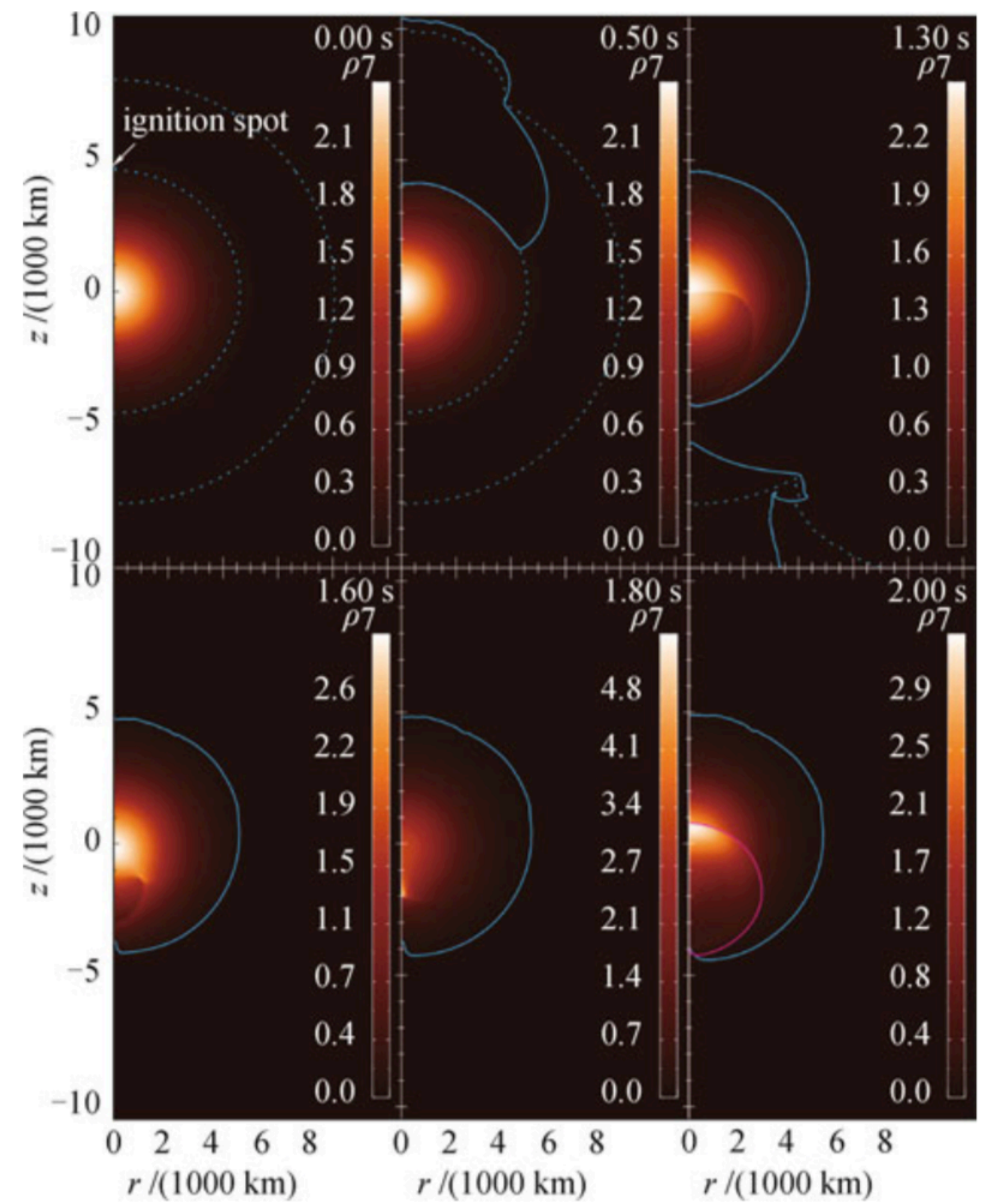
Conversing shock mechanism

- 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

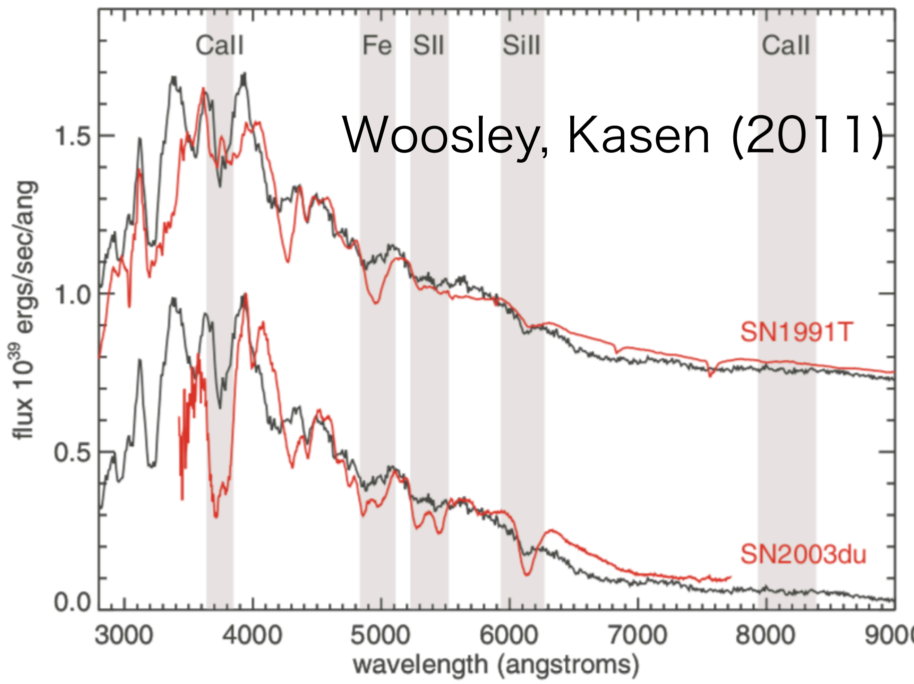
- Consider CO WD with He outer shell.
- He detonation starts.
- The detonation
  - Propagates in the He shell.
  - Cannot invade into the CO core, but sends a shock wave separated from the detonation.
- A conversing shock wave appears when the He detonation surrounds the CO core.
- The conversing shock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



Fink et al. (2010)

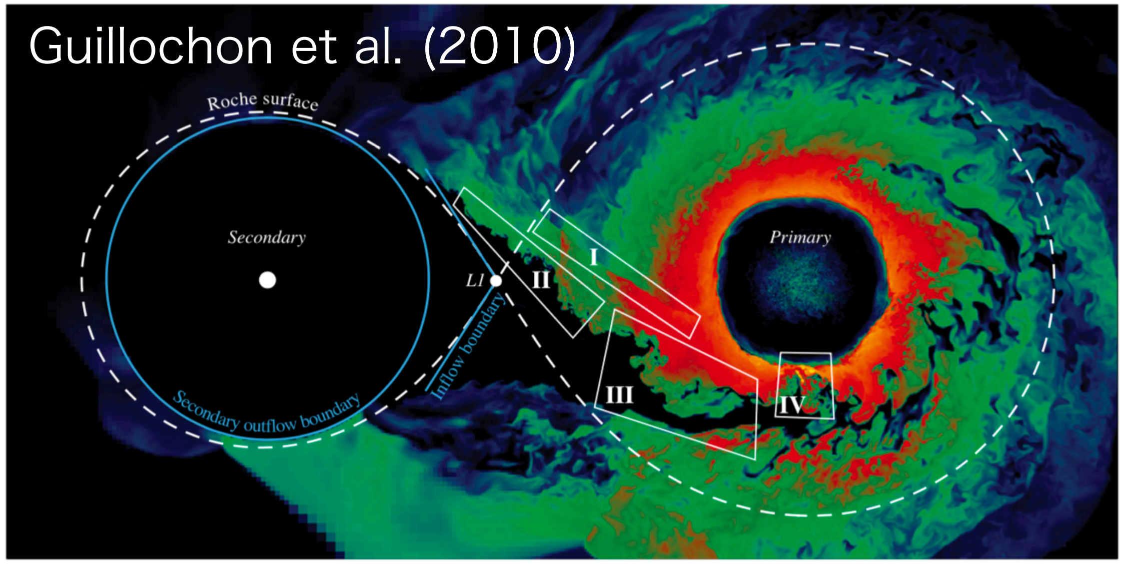
Double detonation problem

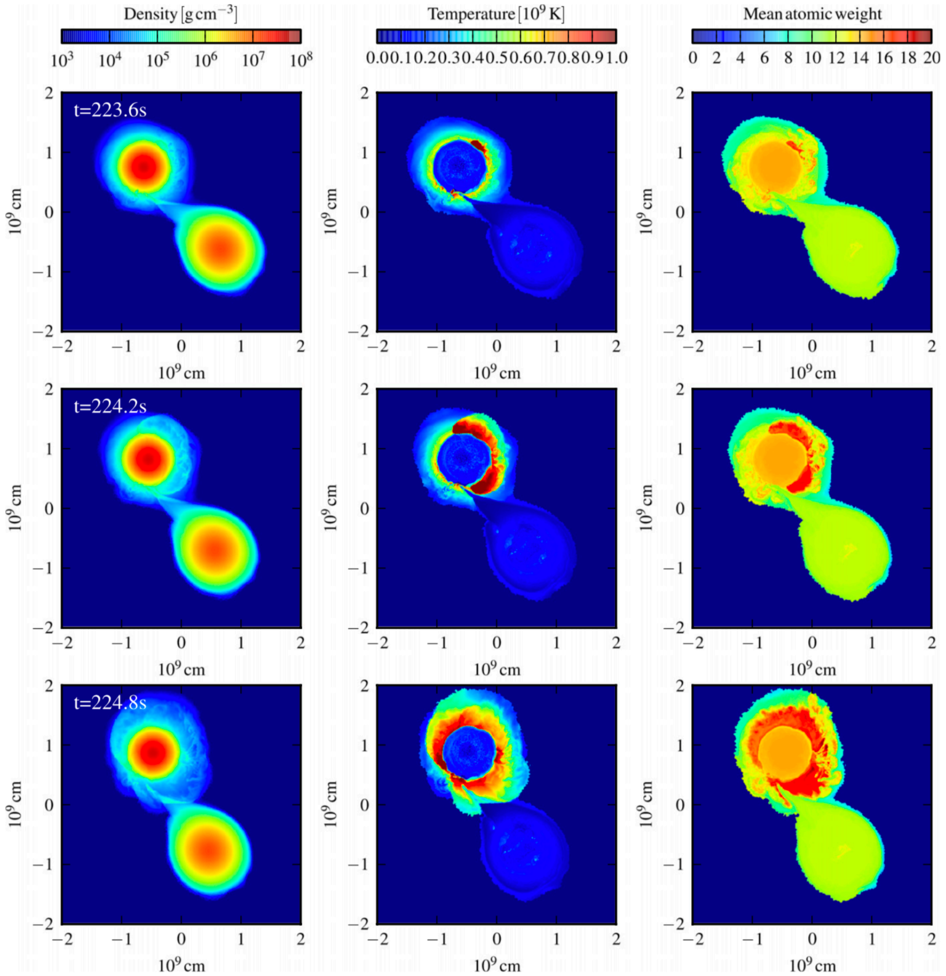
- Problem
  - Large He shell mass ($\sim 0.1 M_{\odot}$)
  - Featureless spectra due to radioactive nuclei yielded by He detonation



D⁶ feasibility

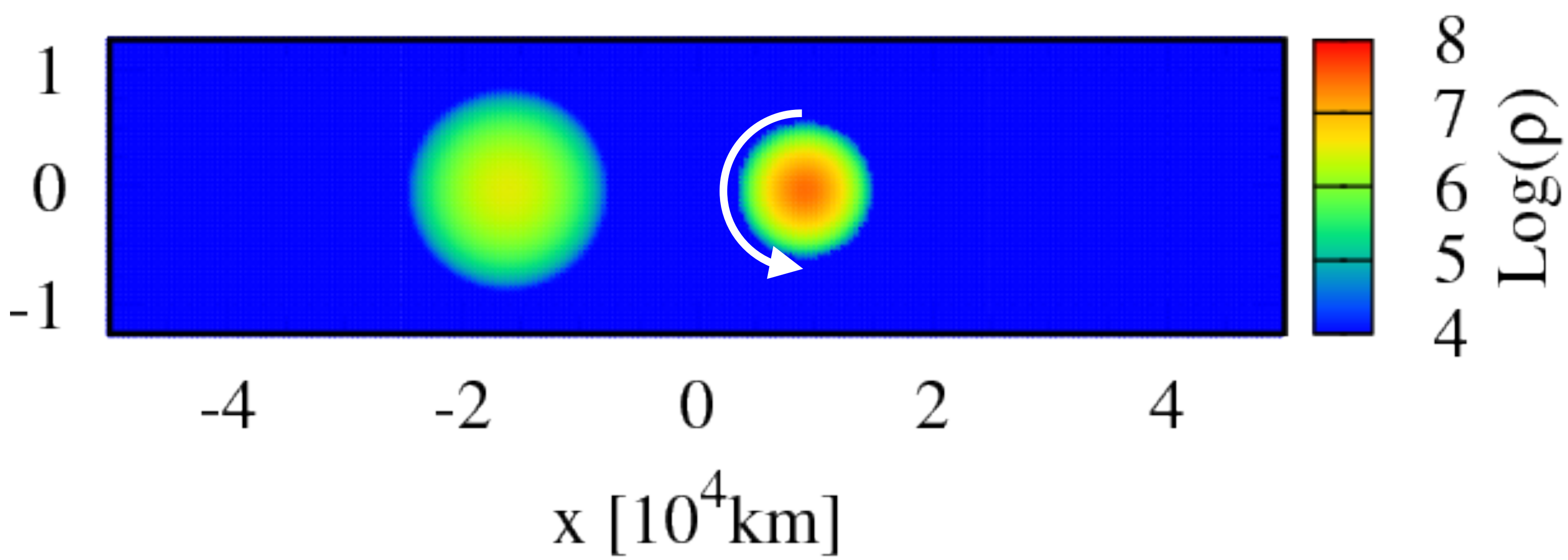
- Requisite: $M_{\rm He} \lesssim 0.05 M_\odot$
  - He detonation ashes make spectra featureless due to their opacity (e.g. Woosley, Kasen 2011)
- He detonation feasible for $M_{\rm He} \sim 0.01 M_\odot$
  - Hydrodynamical effects due to unstable mass transfer
  - C/O pollution (Shen, Moore 2014)
-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

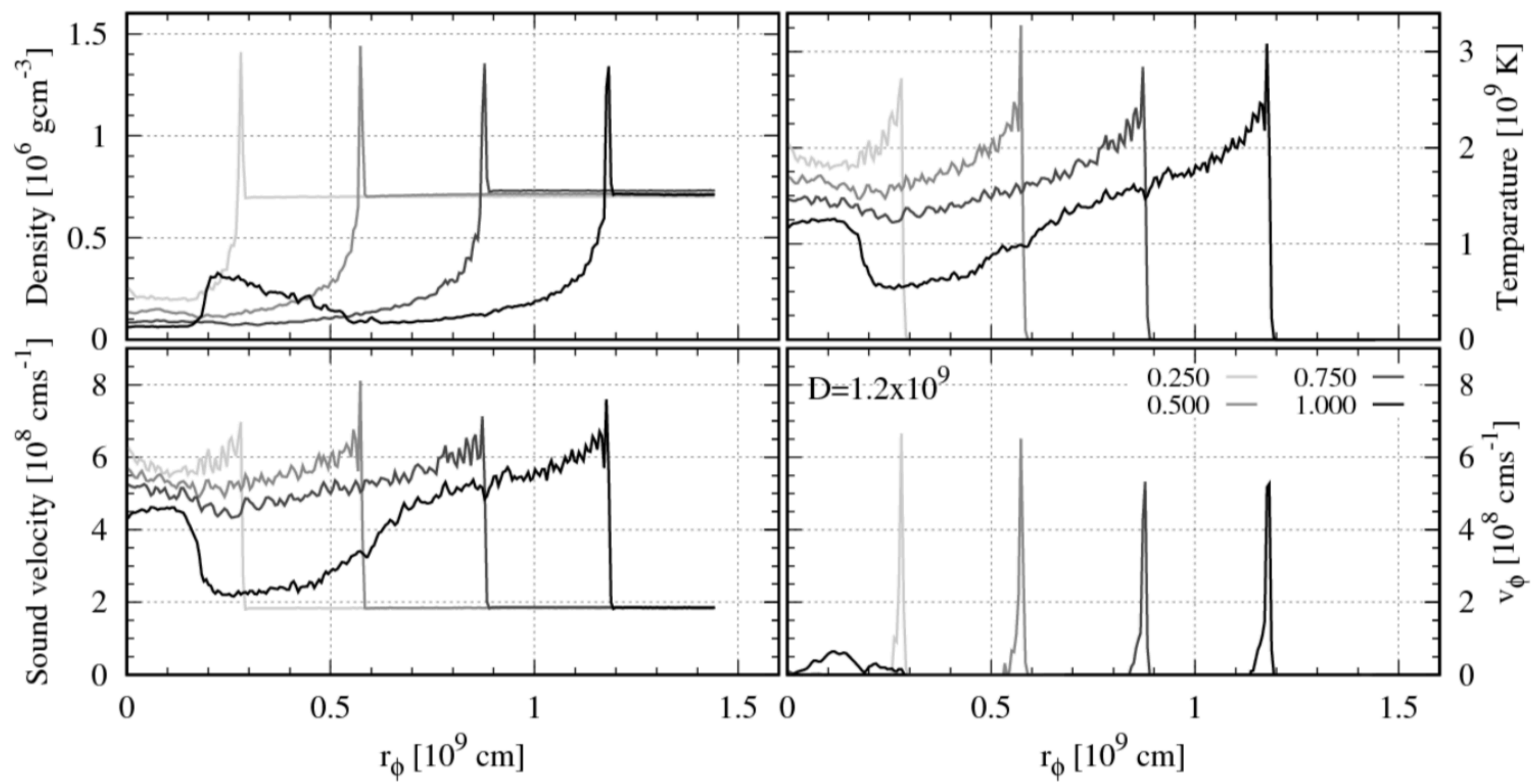




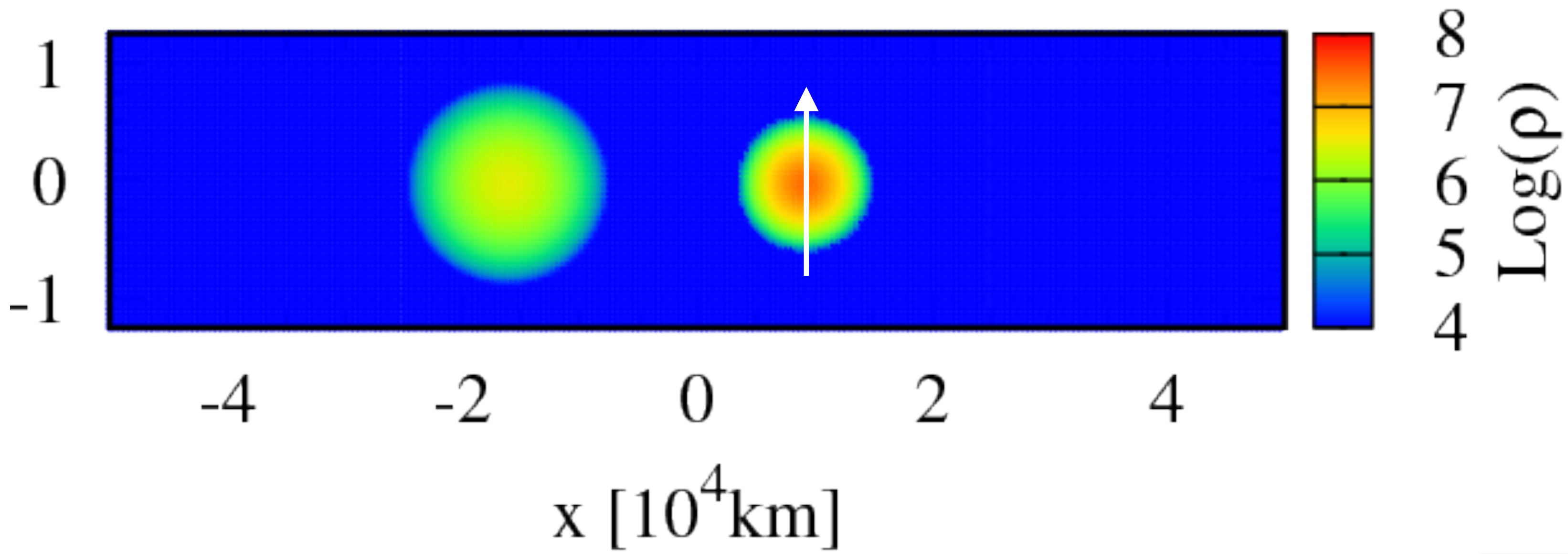
Pakmor et al. (2013)

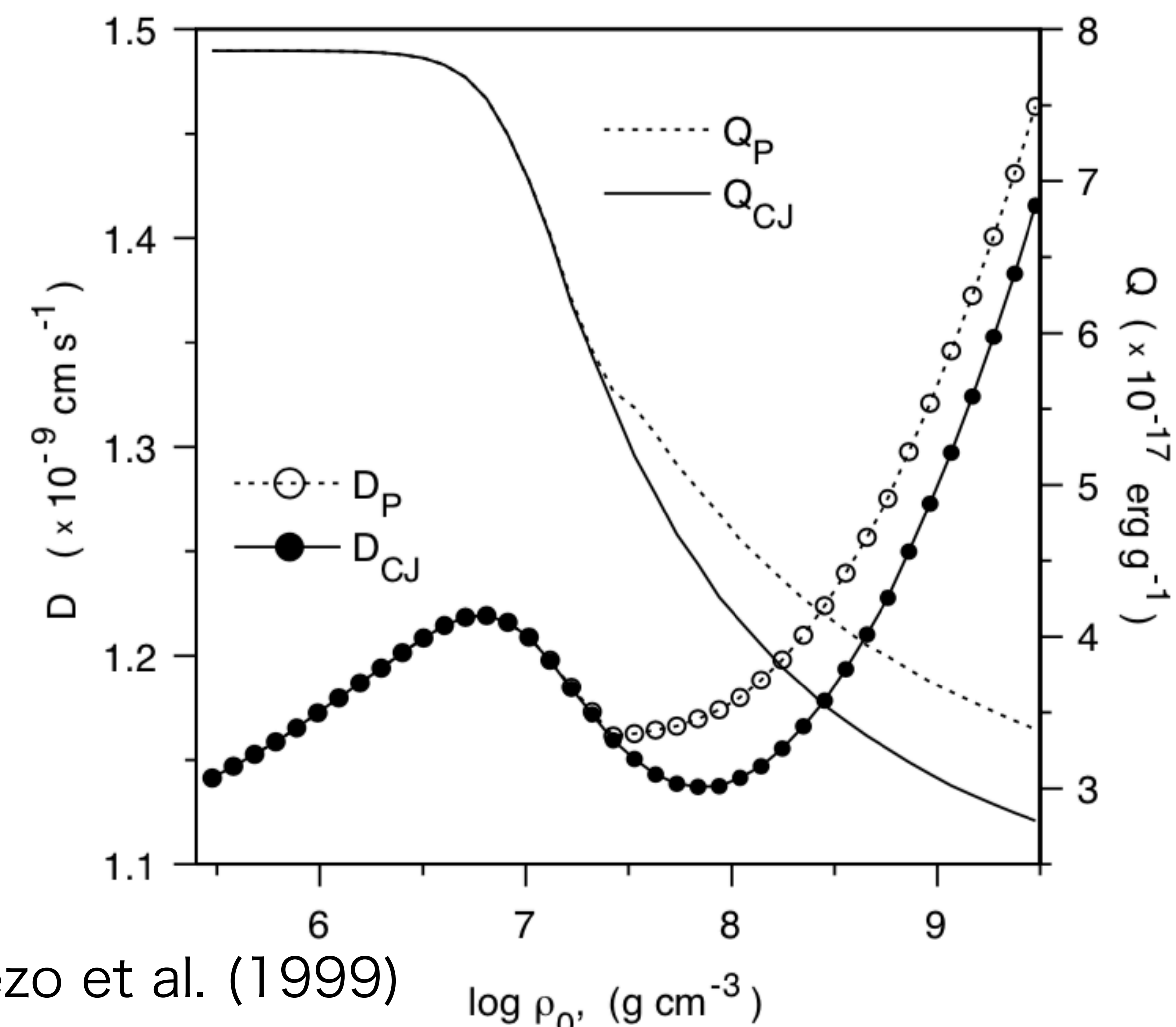
He detonation

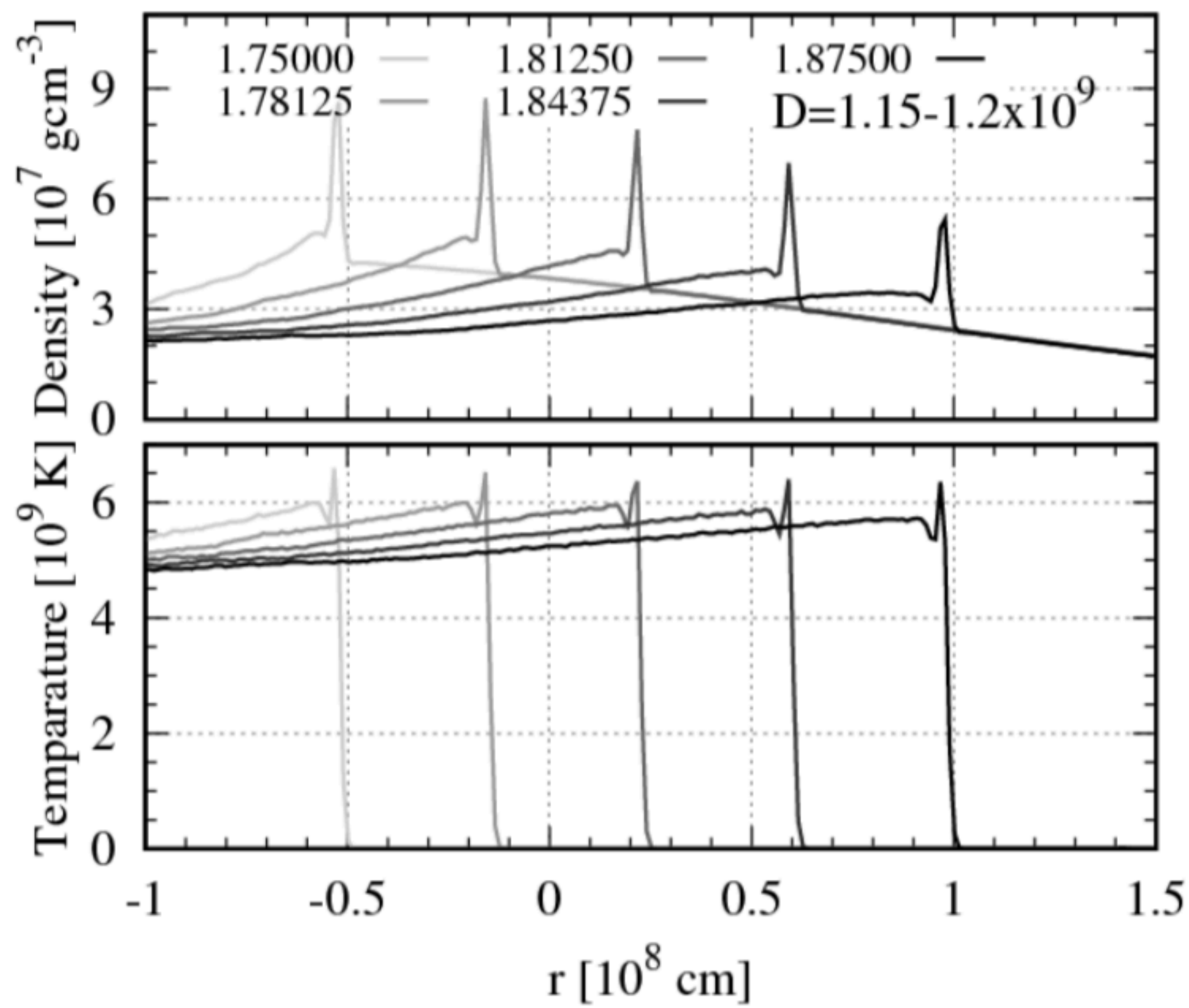




C detonation

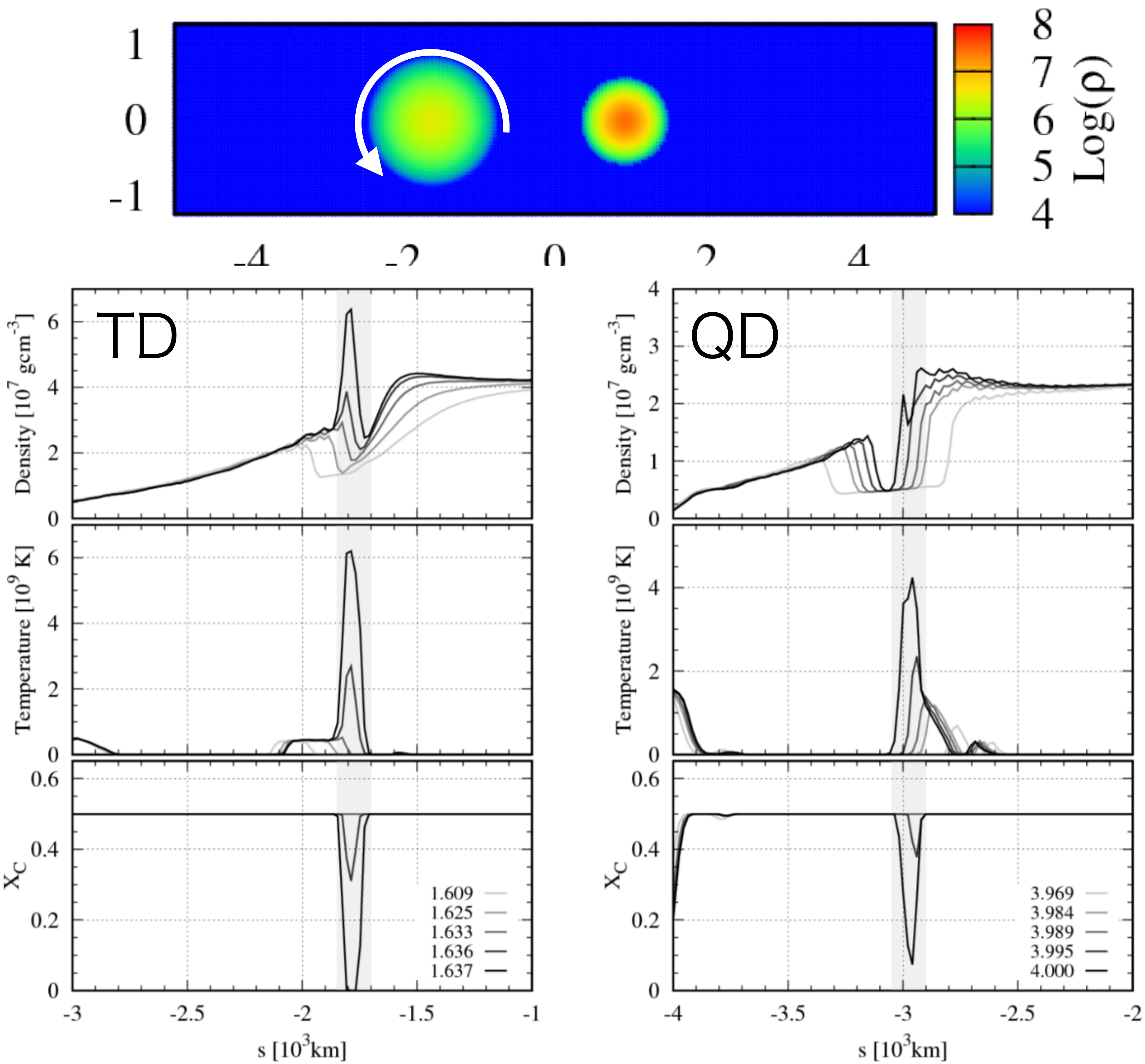




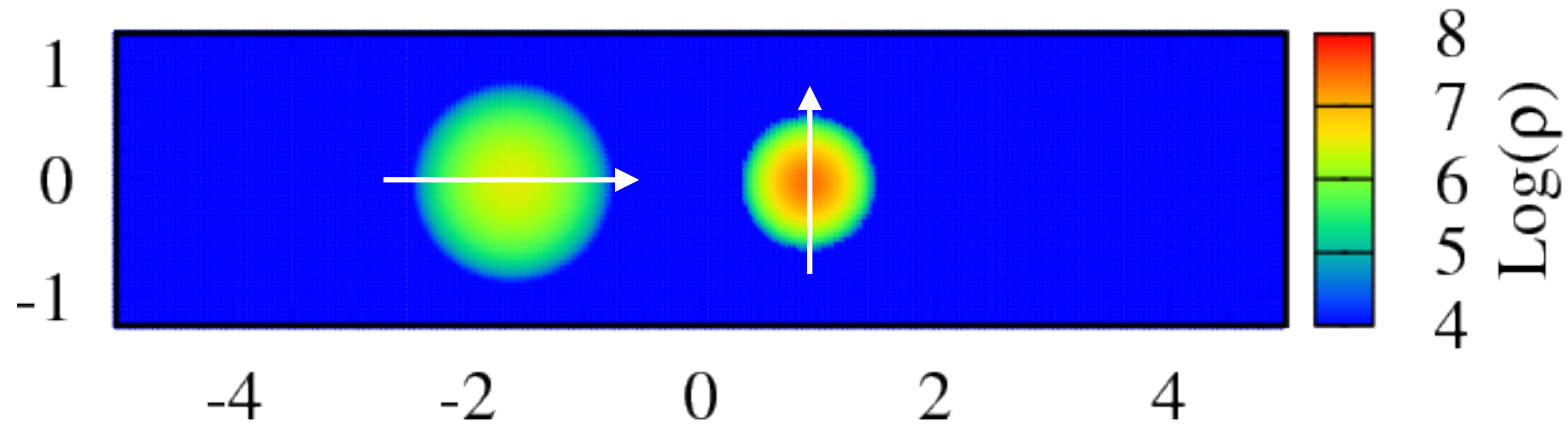


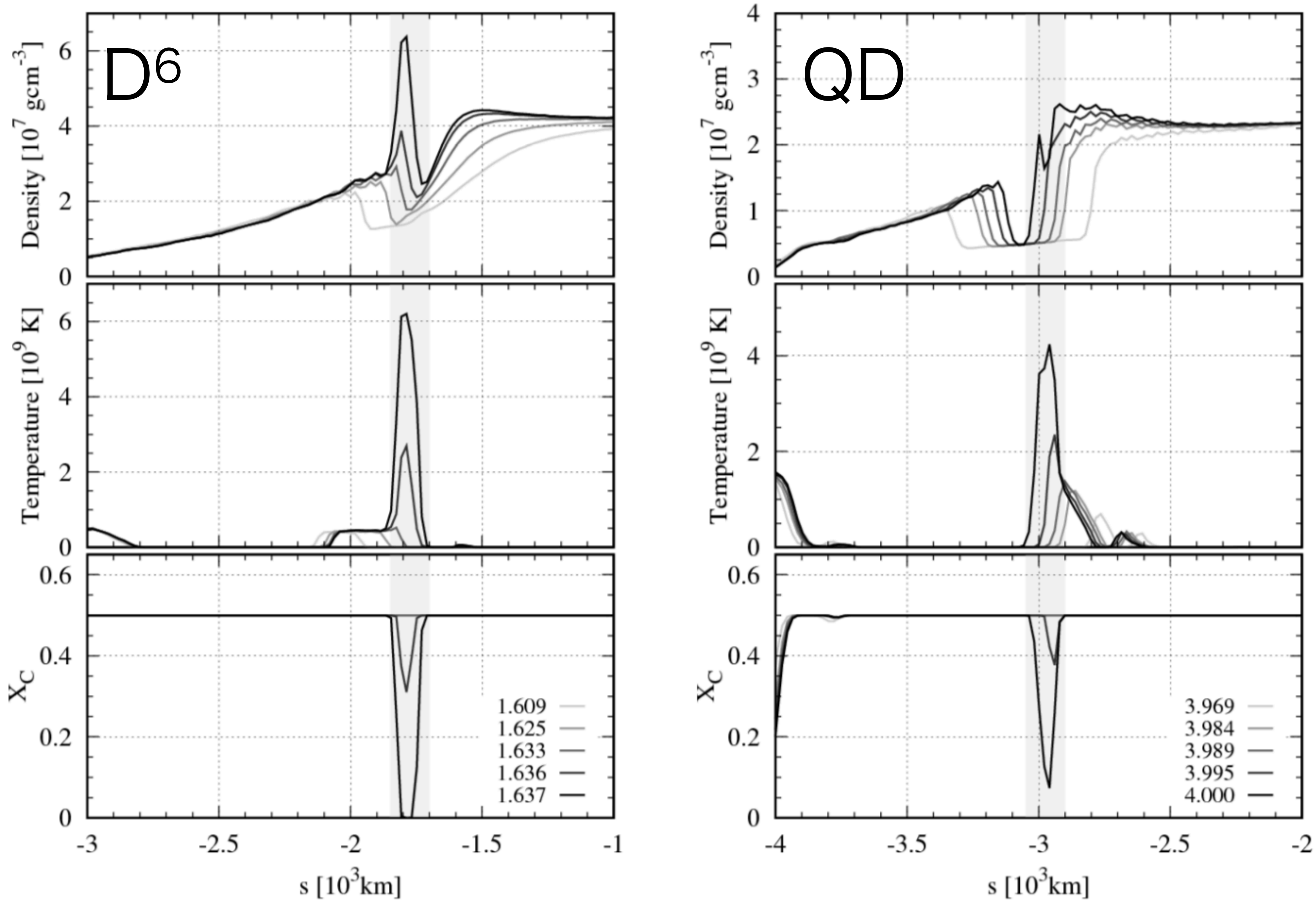
Gamezo et al. (1999)
(see also Sharpe 1999)

Hotspot for He detonation

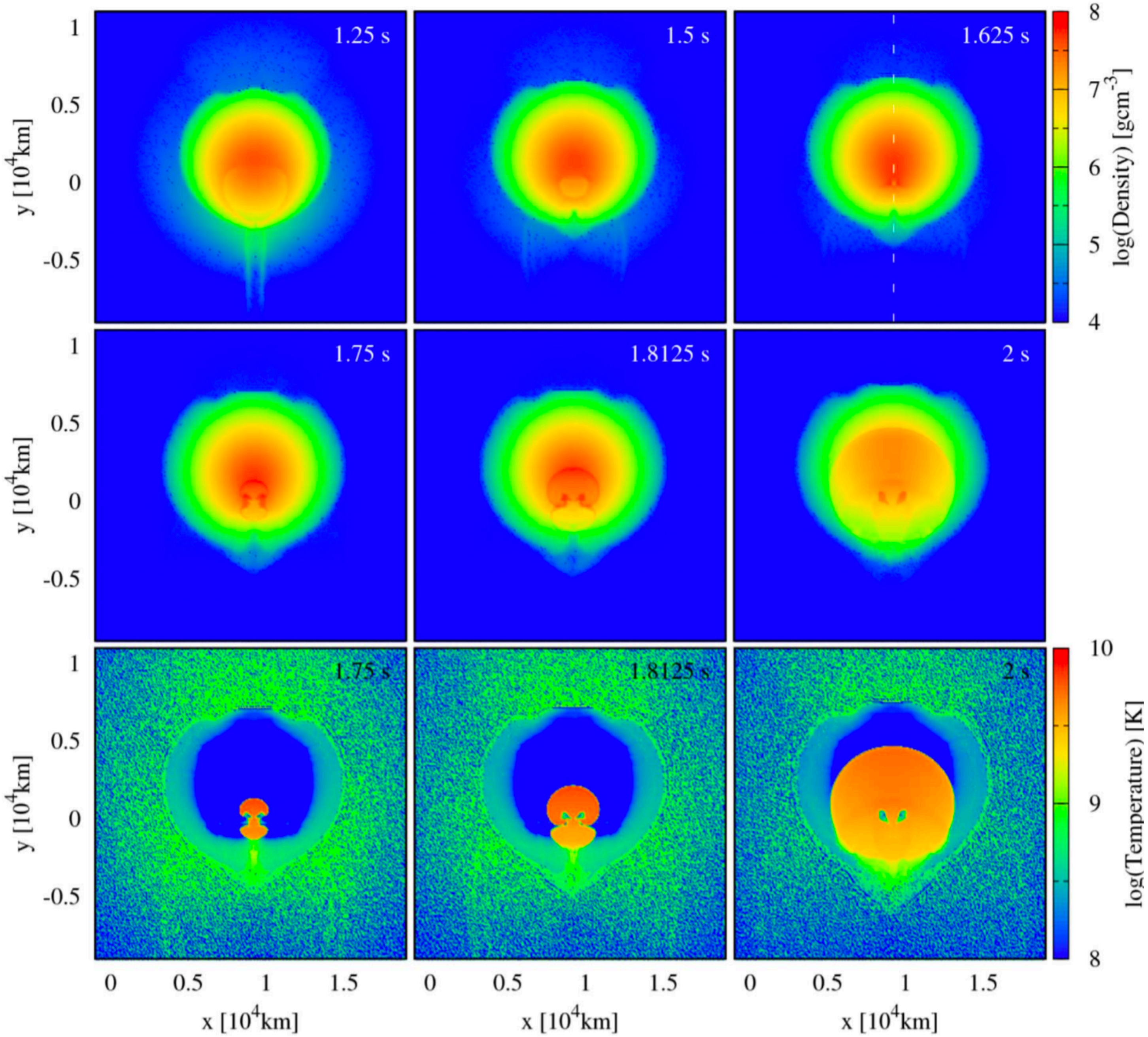


Hotspot for C detonation





Unburned materials



Tanikawa et al. (2018)

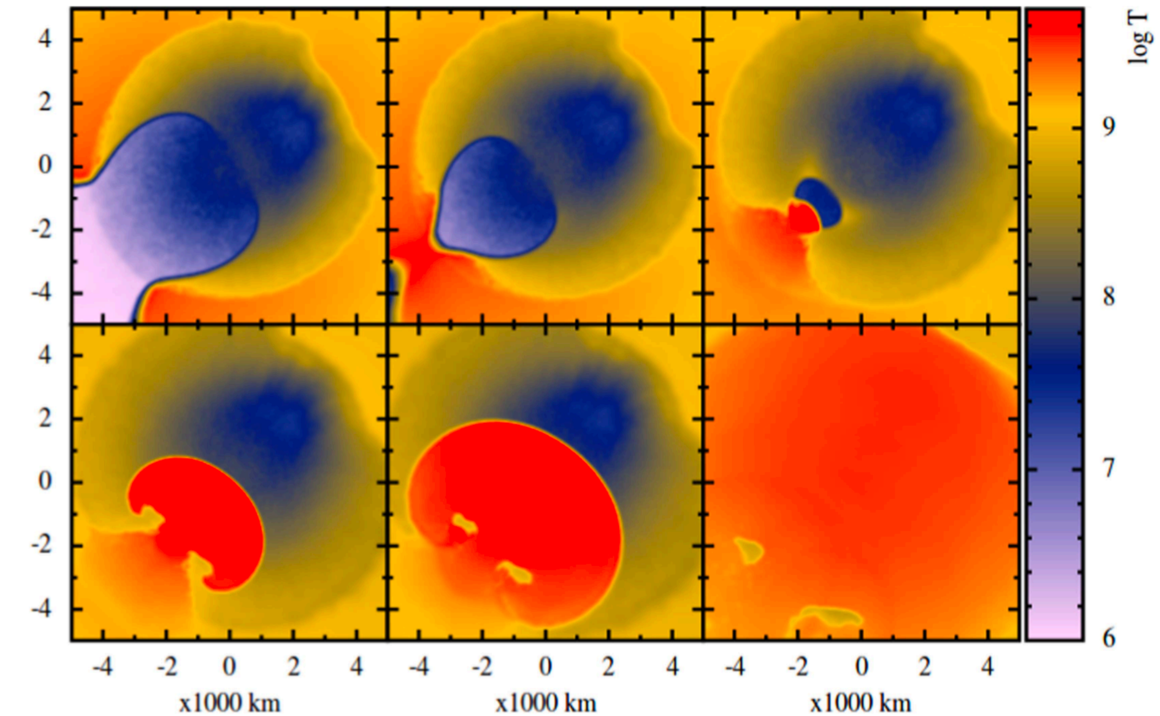


Figure 10. Colormap of temperature in a *YZ* (equatorial) slice, showing the core detonation of model B_6 in Table 1 at times t = 1.10, 1.22, 1.42, 1.62, 1.72, and 2.03 s, respectively. The box size is [−5:5] × 10^3 km in all directions.

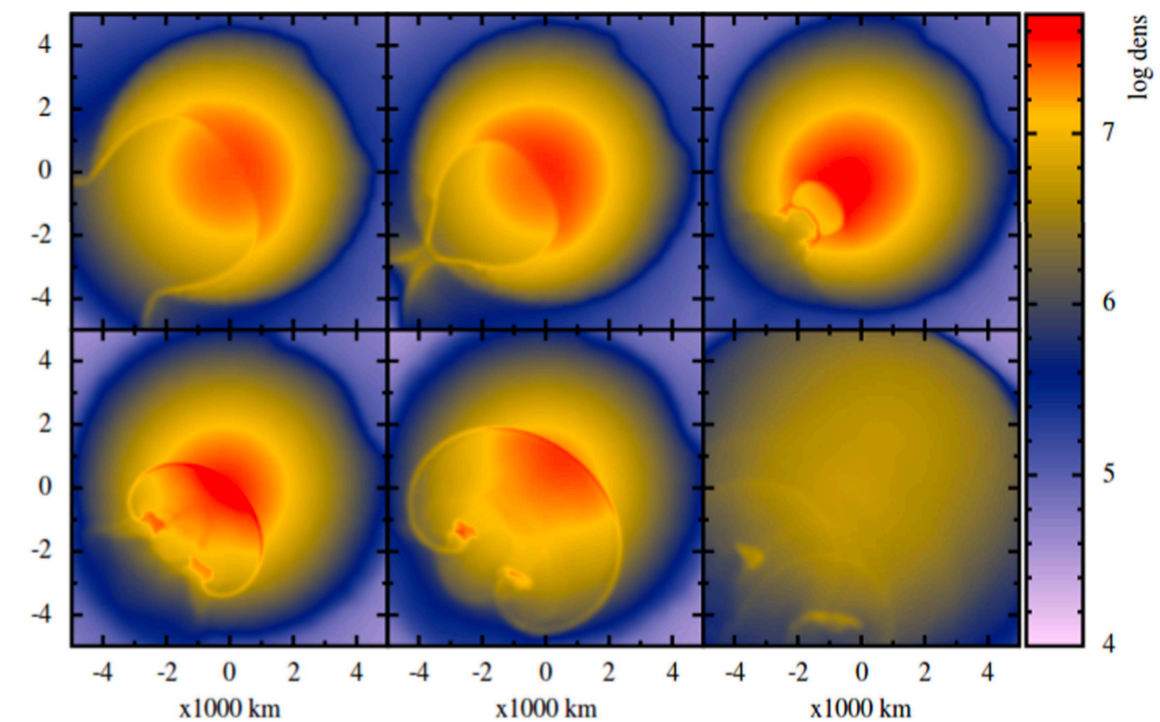
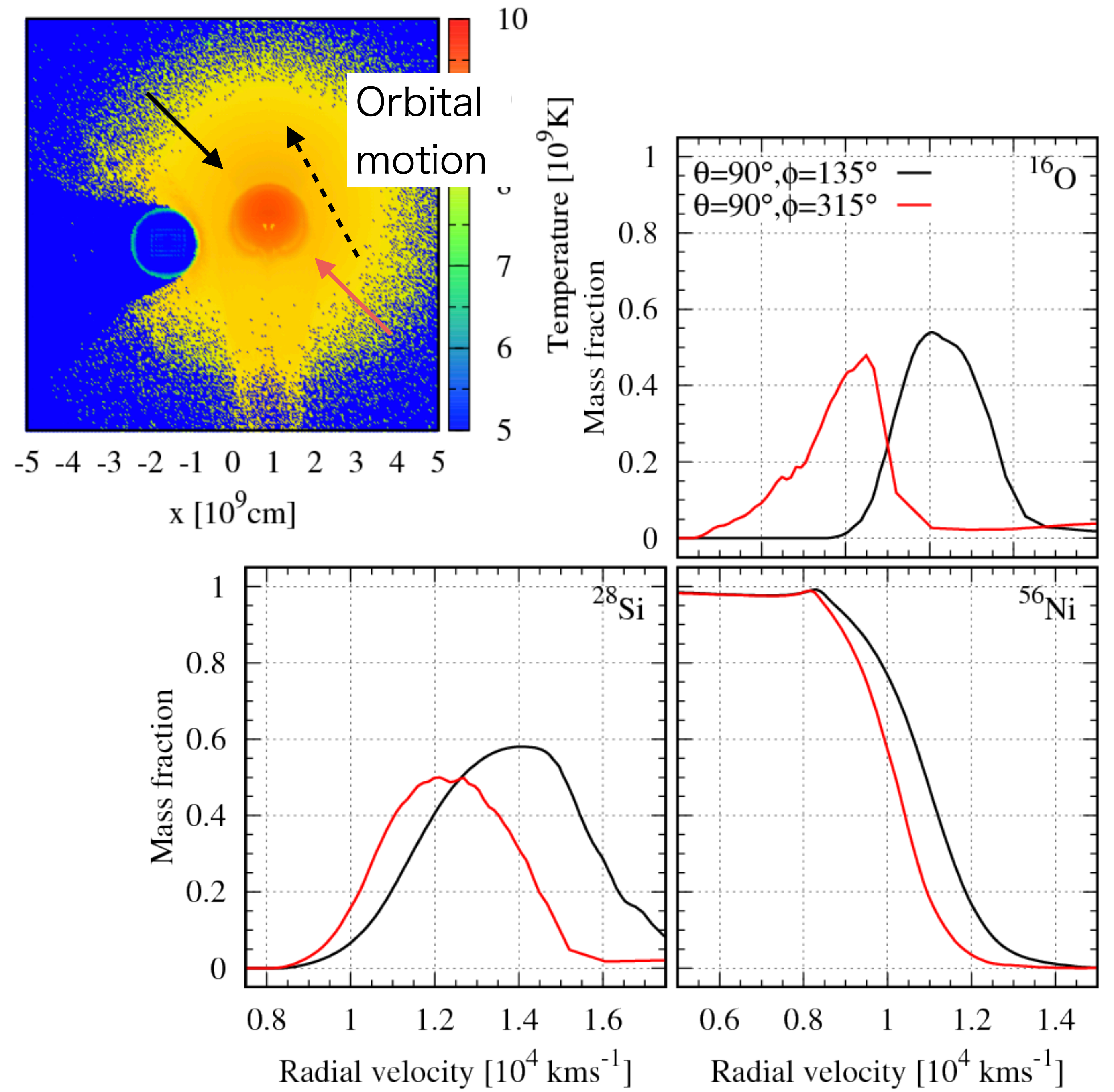


Figure 11. Same as Figure 10, but for density.

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.



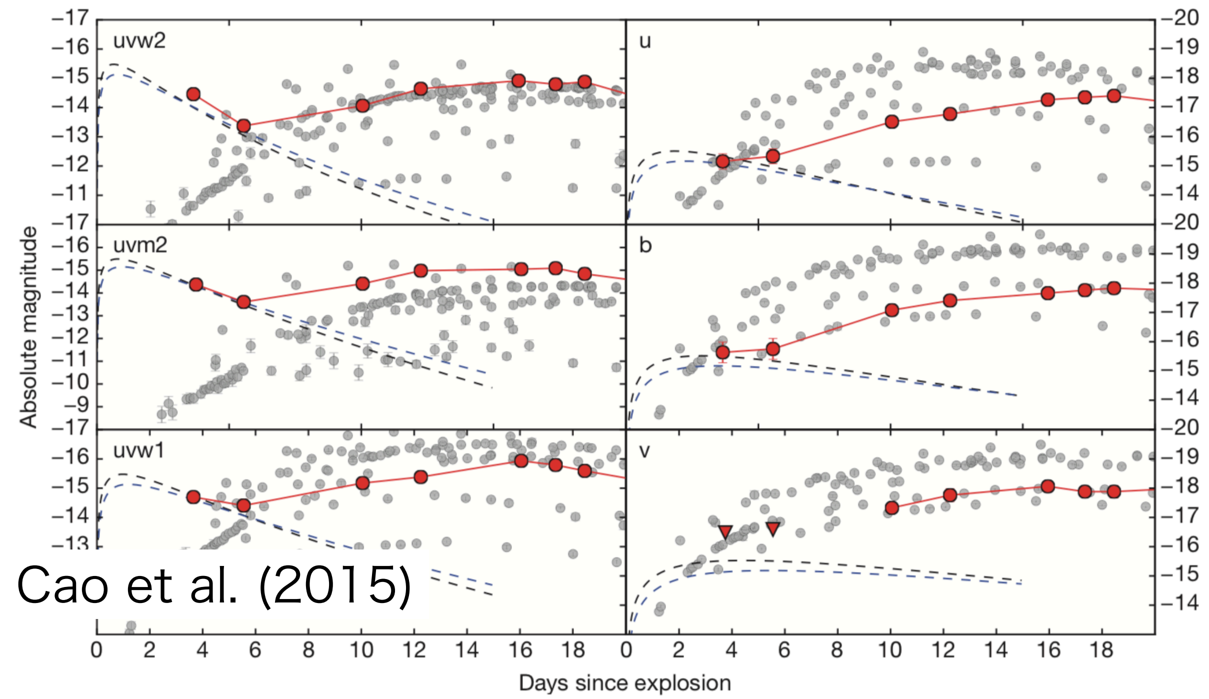
Possible counterpart

- iPTF14atg
  - Early flash

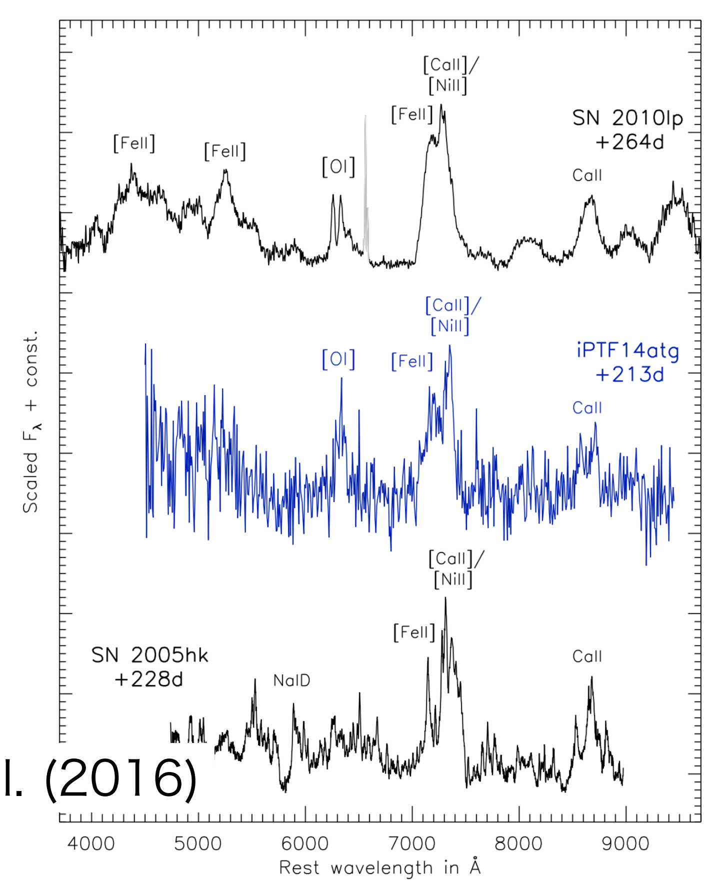
    ← He-detonation ash
  - Oxygen emission in nebular phase

    ← 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).



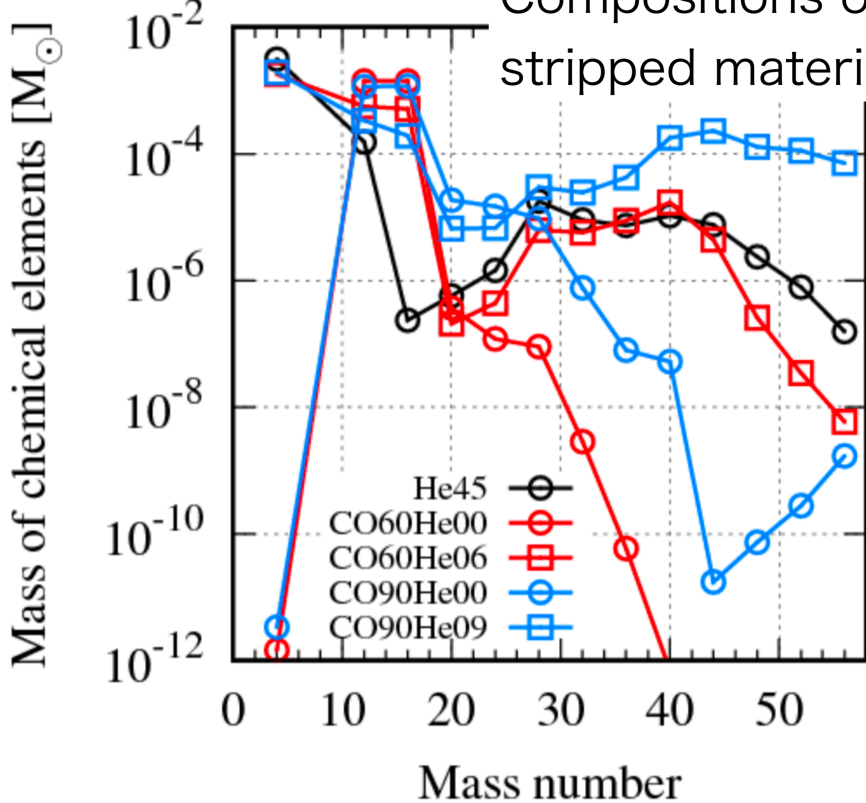
Cao et al. (2015)



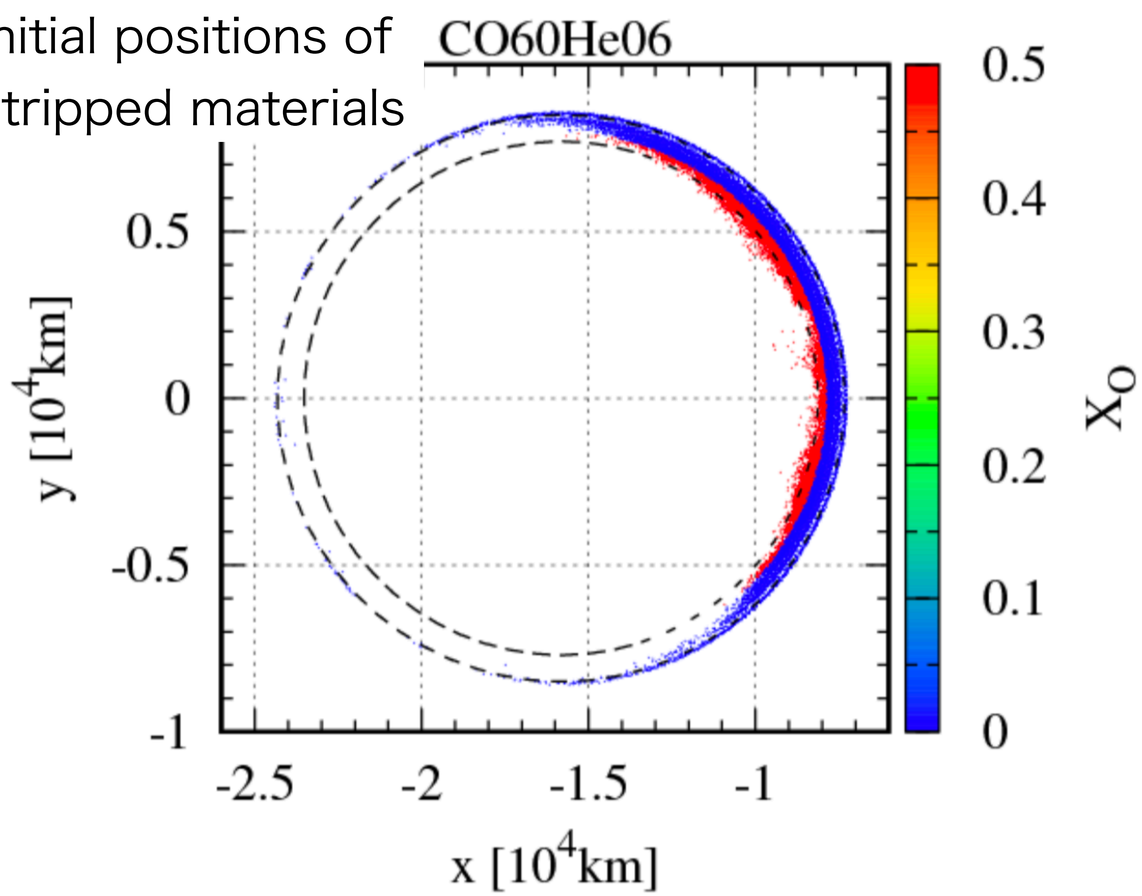
Kromer et al. (2016)

He shell on the companion

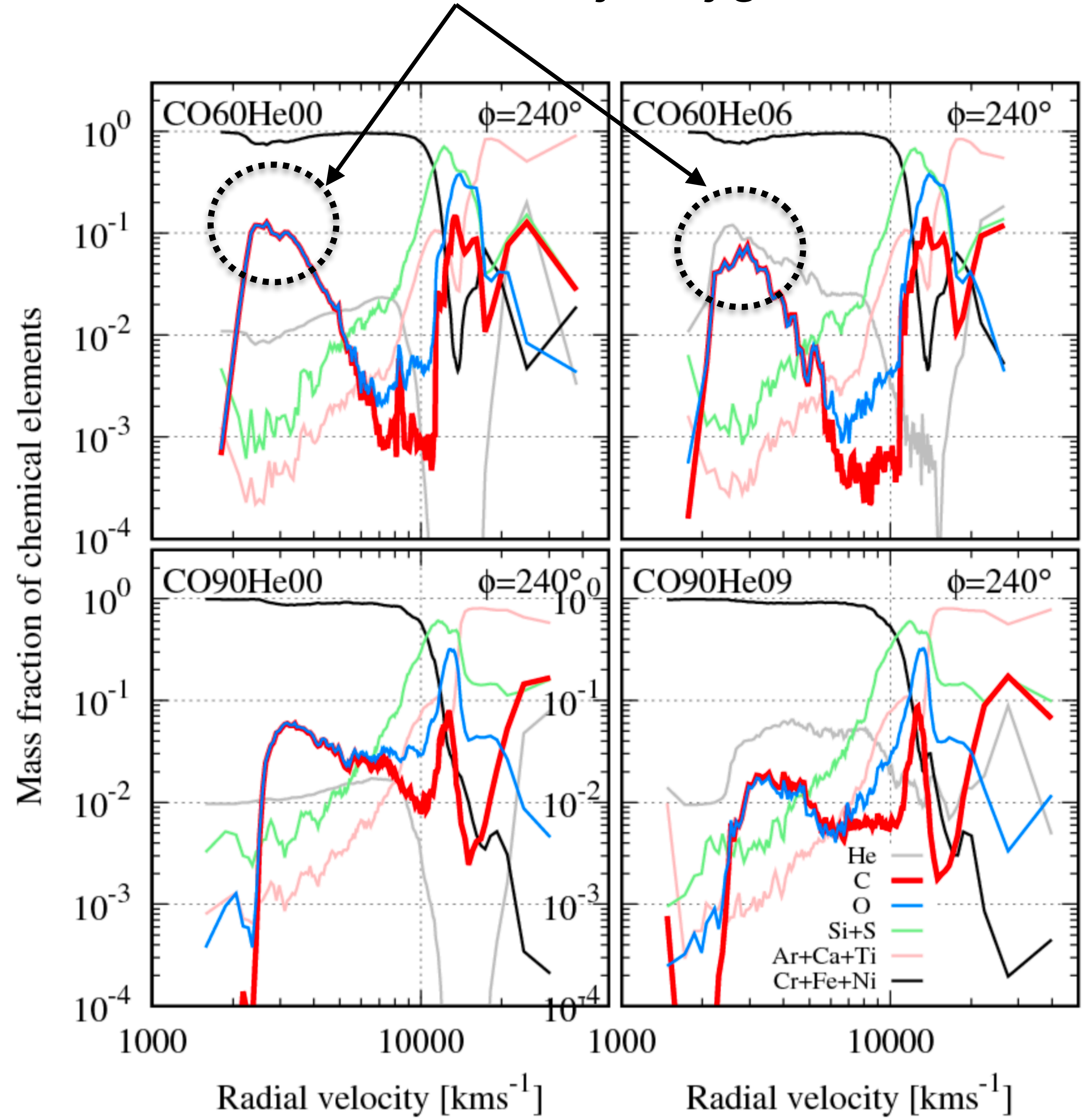
Compositions of stripped materials



Initial positions of stripped materials



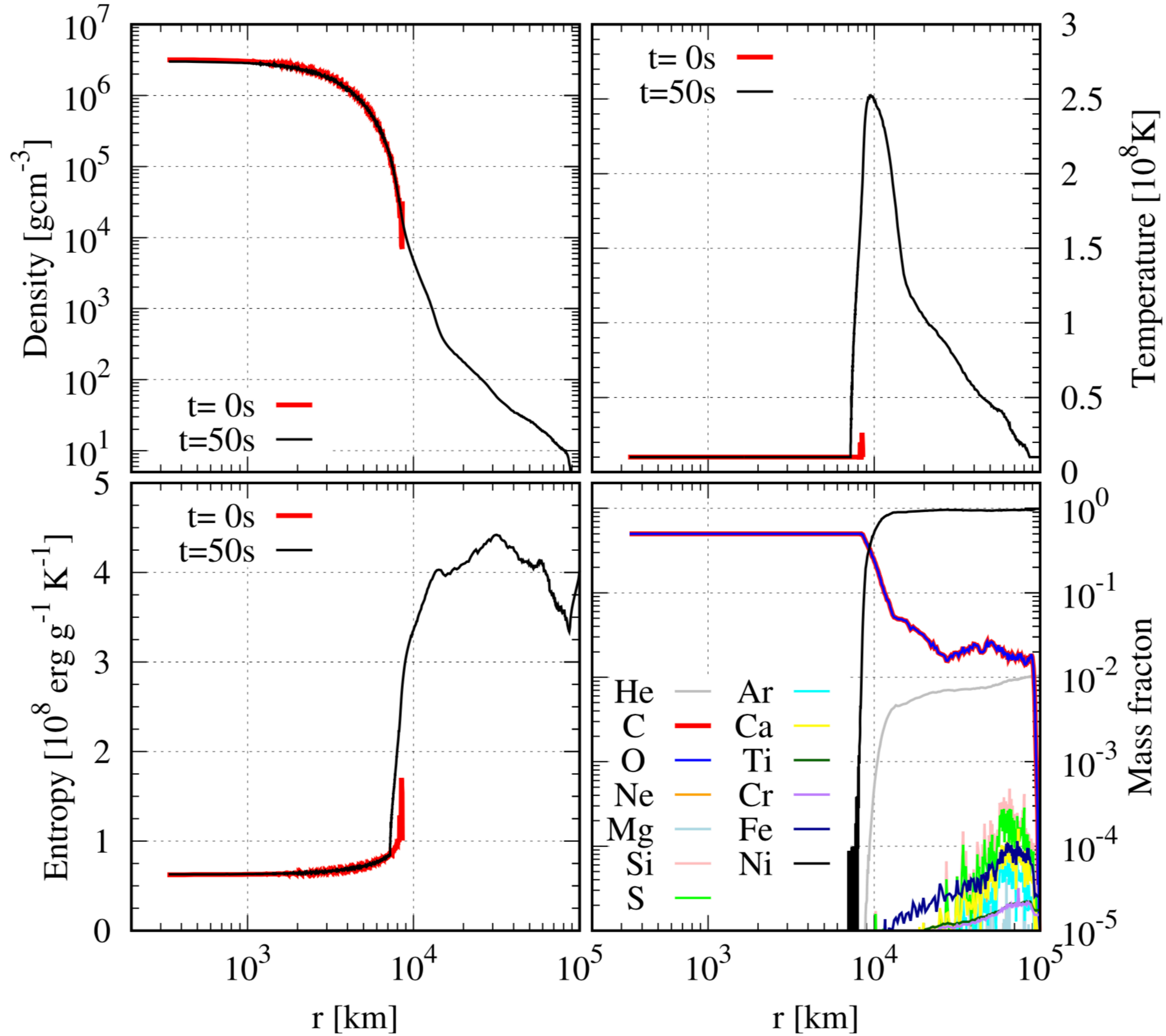
Low-velocity Oxygen



Comparison among sub-Chandrasekhar explosions in DD systems

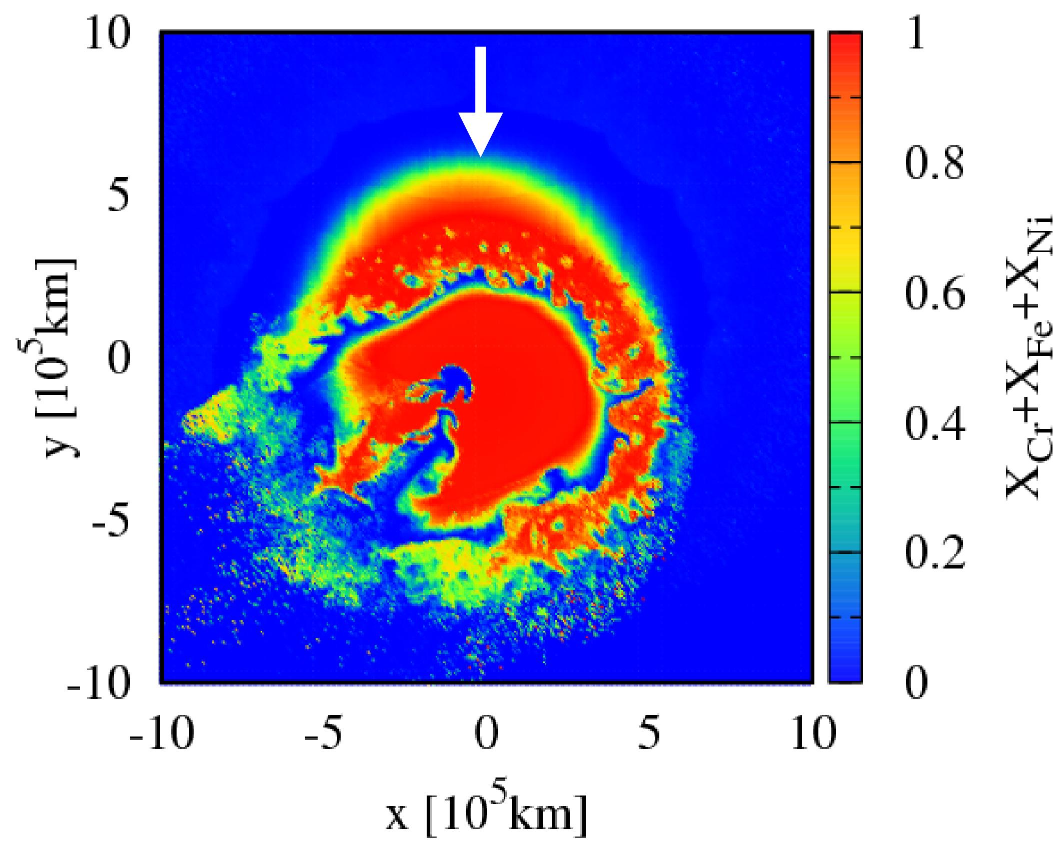
	D^6	Violent merger	Collision	spiral instability
Oxygen emission lines	✓	✓	×	×
Velocity shift (~1000km/s)	✓	×	×	×
Two ^{56}Ni components	×	×	✓	×
Surface radio activity	✓?	×	×	×

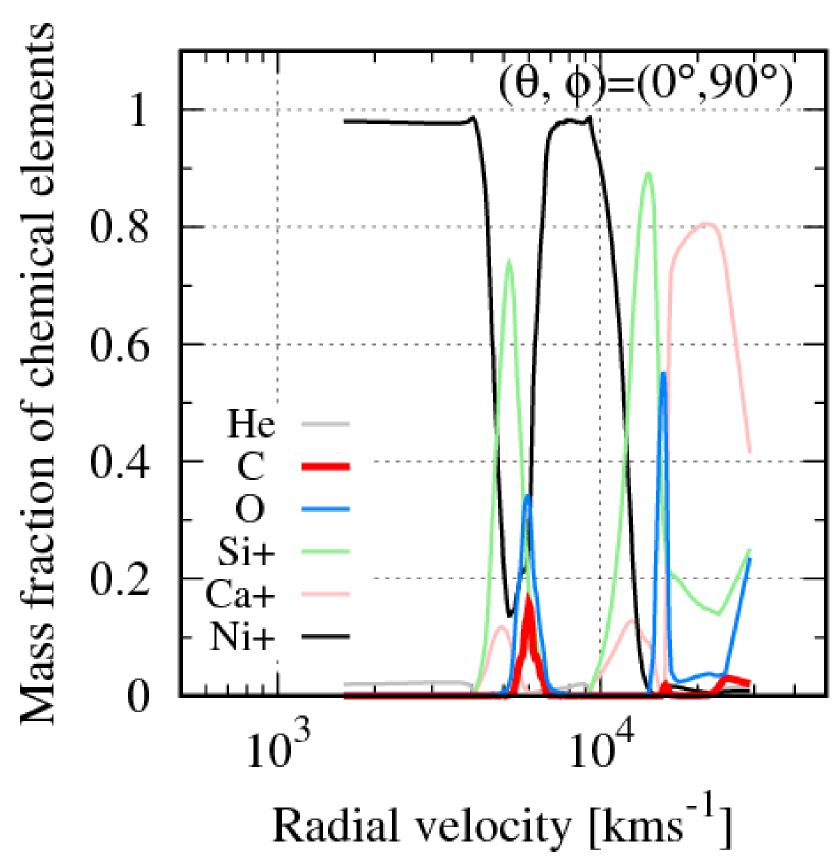
Surviving WD

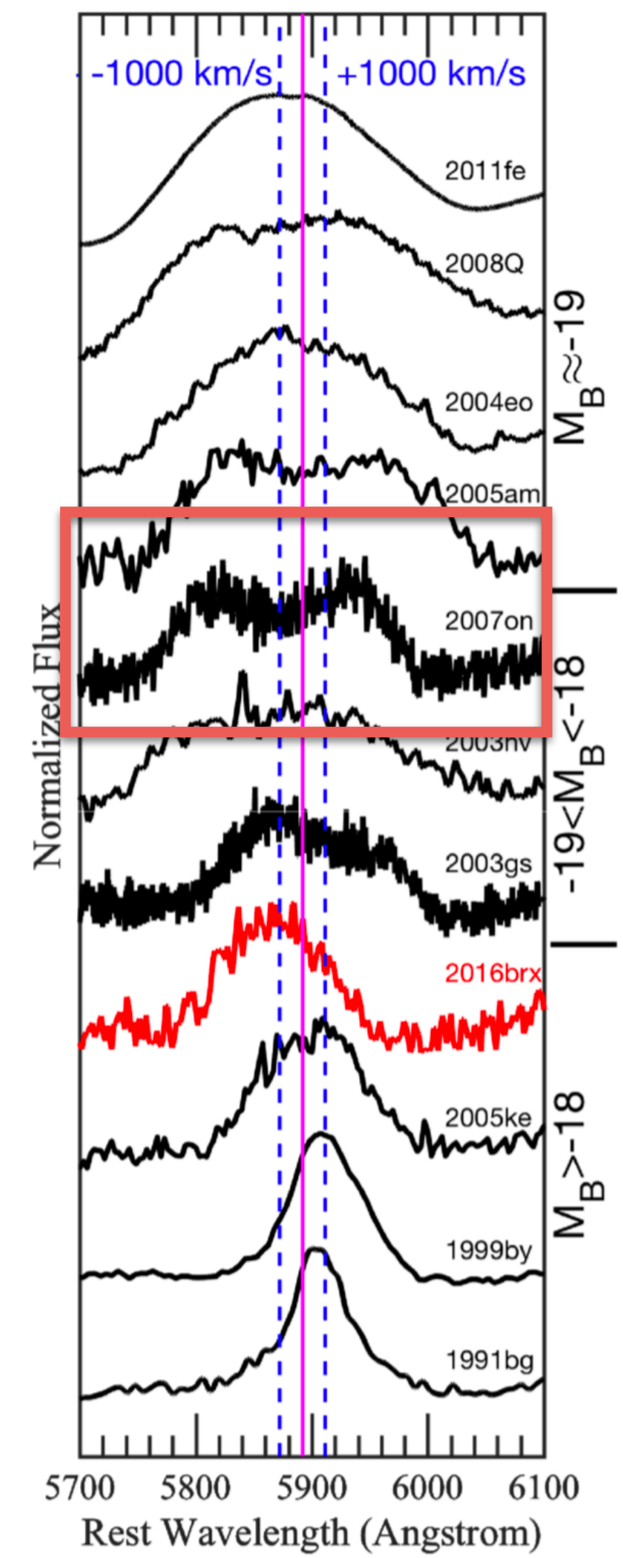


Two components of ^{56}Ni ?

- QD explosions have nested structure.
- The SN ejecta have two-component ^{56}Ni with ~3000km/s and ~8000km/s.
- The feature can be consistent with SN2007on.





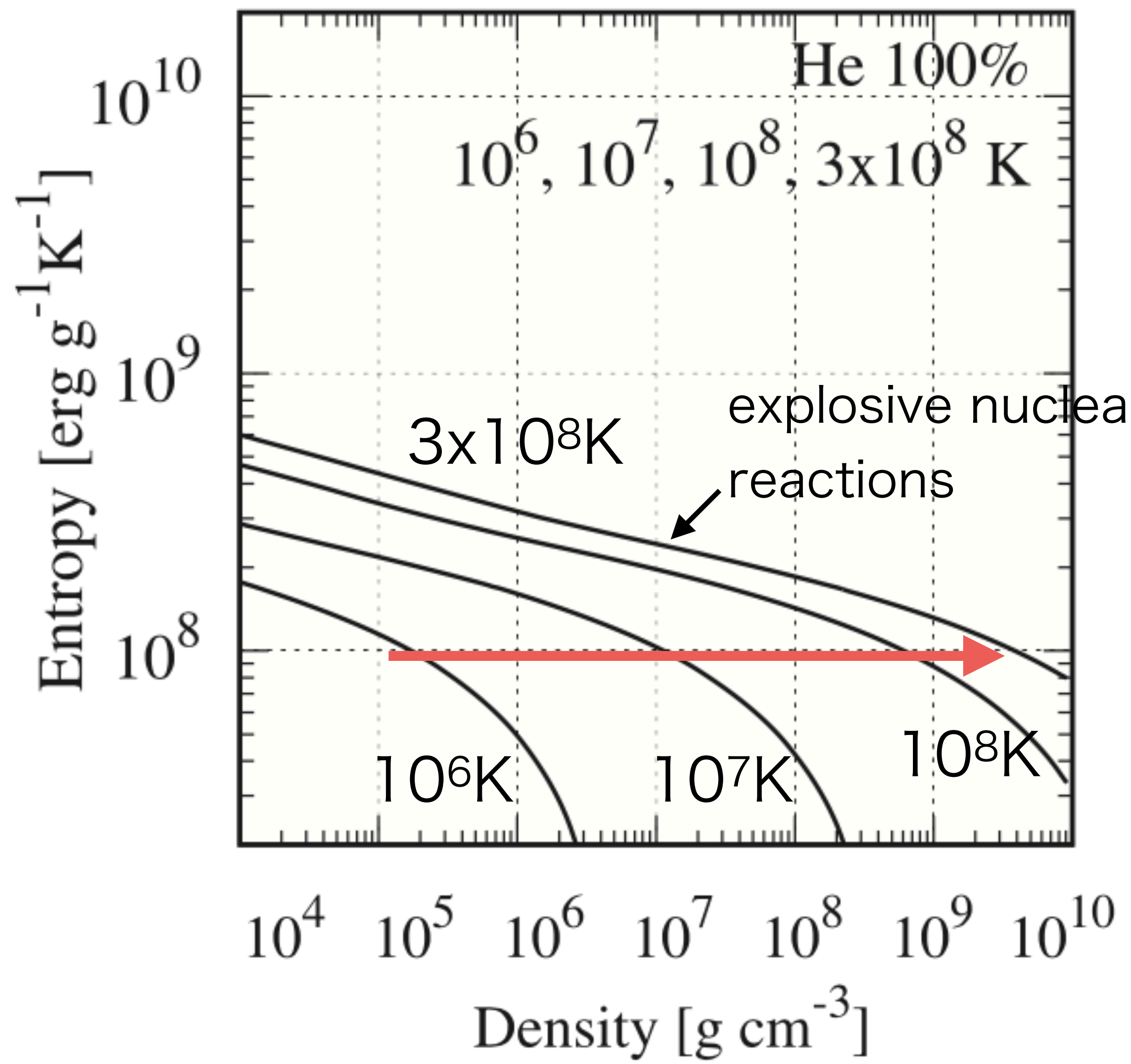


(Dong et al. 2018)

Tidal disruption event

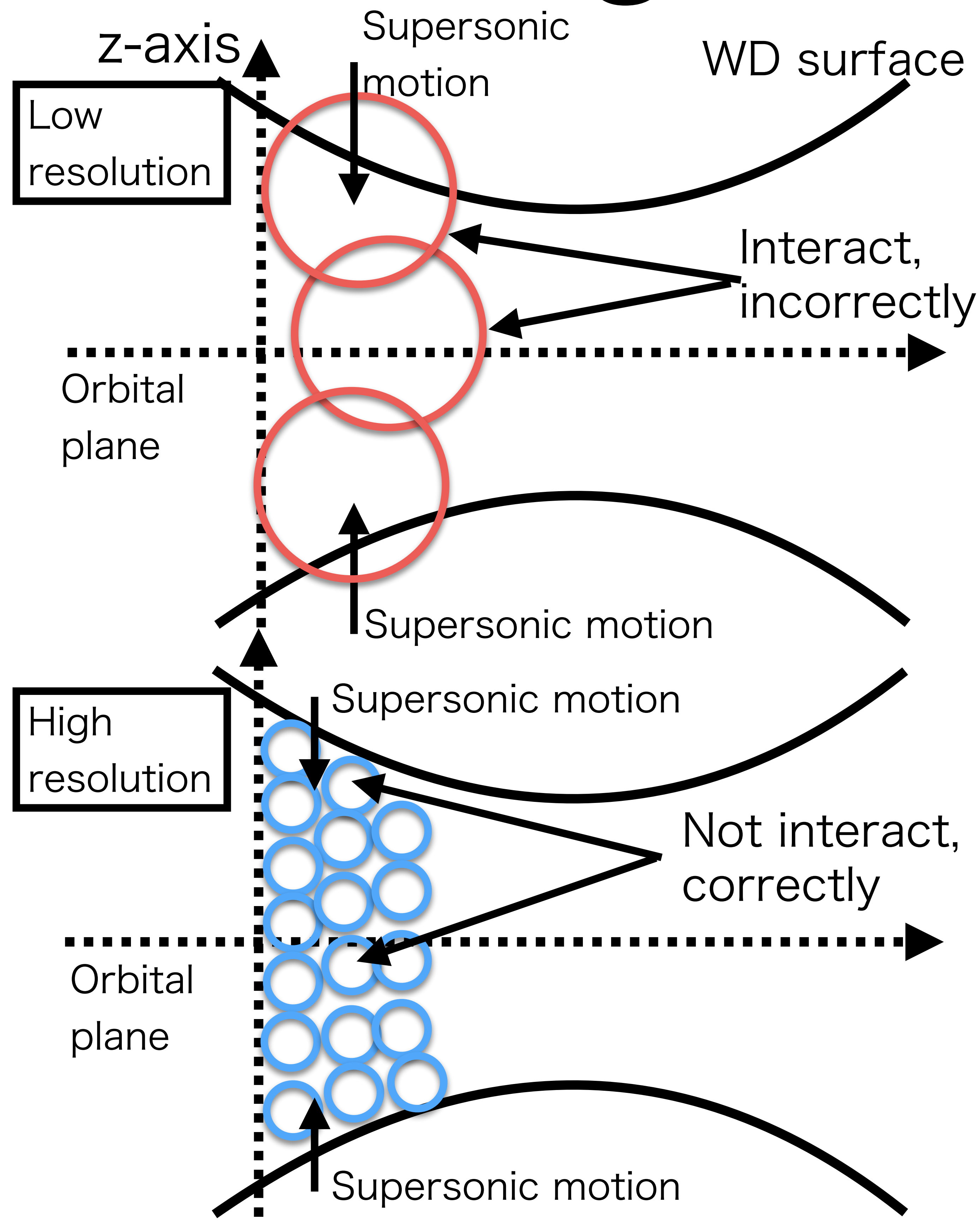
Adiabatic heating for tidal detonation

- Adiabatic compression is not sufficient for tidal detonation.
  - Density should be increased by 5 orders of magnitude, if temperature rises from 10^6 K to $3x10^8$ K
  - Such orbits are impossible.
- Shock compression is required.

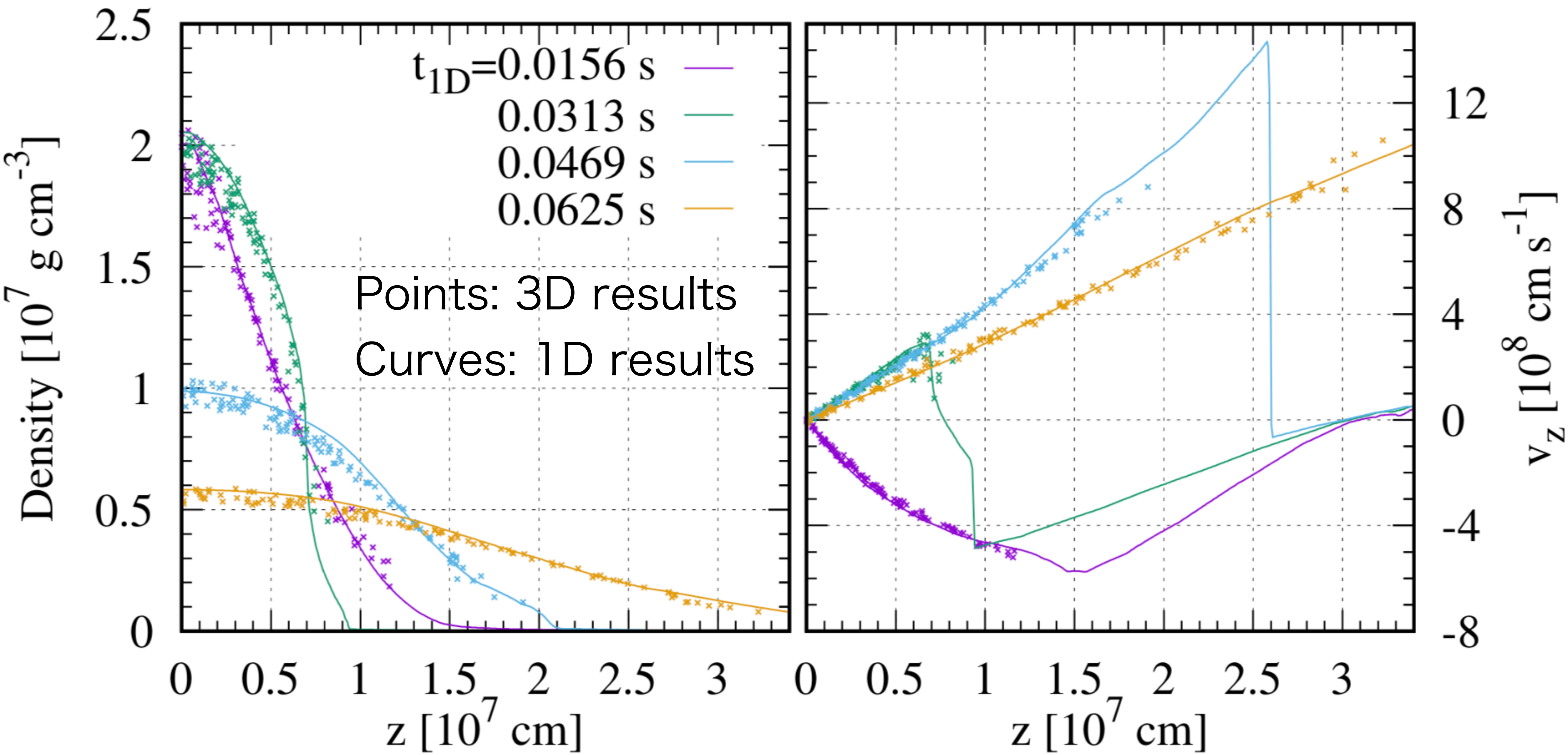


Spurious heating

- In small-N cases, the number of SPH particles is too few in z-direction.
- Distant particles interact incorrectly.
- Velocity gradient is overestimated.
- Overestimated velocity gradient falsely switches on artificial viscosity.
- The artificial viscosity raises spurious heating and false nuclear reactions.
- Note that artificial viscosity is correct, but velocity gradient is wrong.

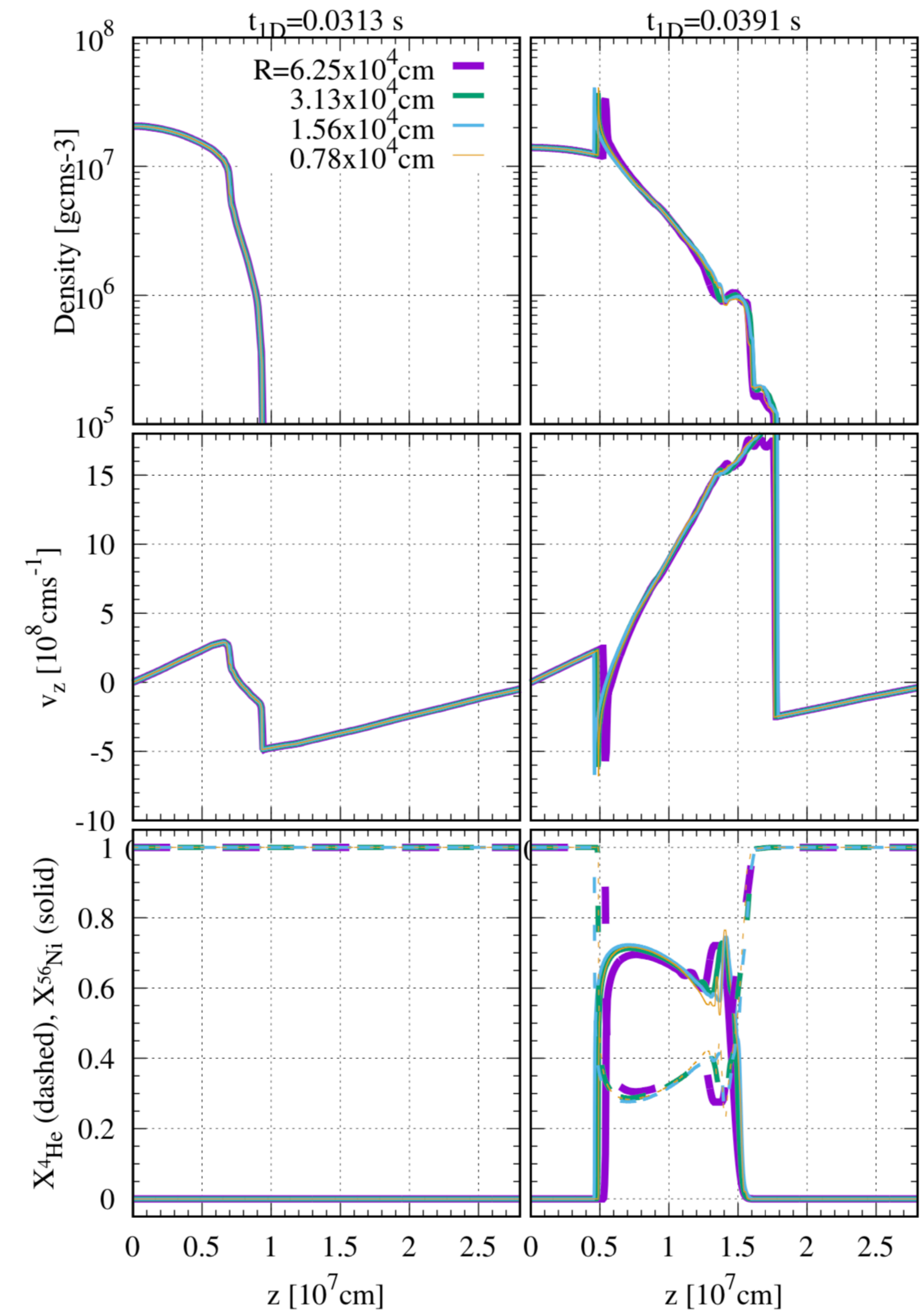


Comparison of 1D with 3D

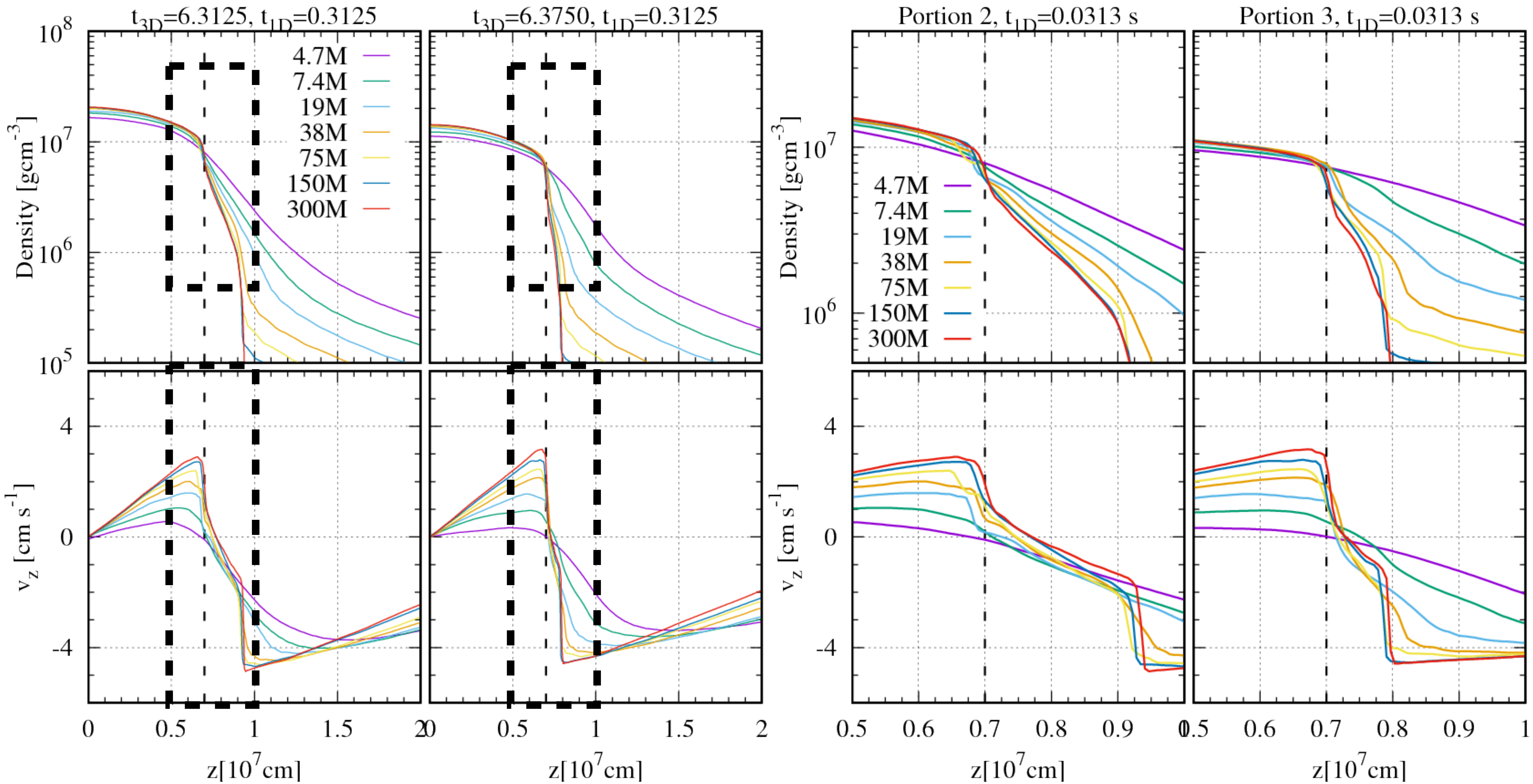


Convergence check of 1D resolution

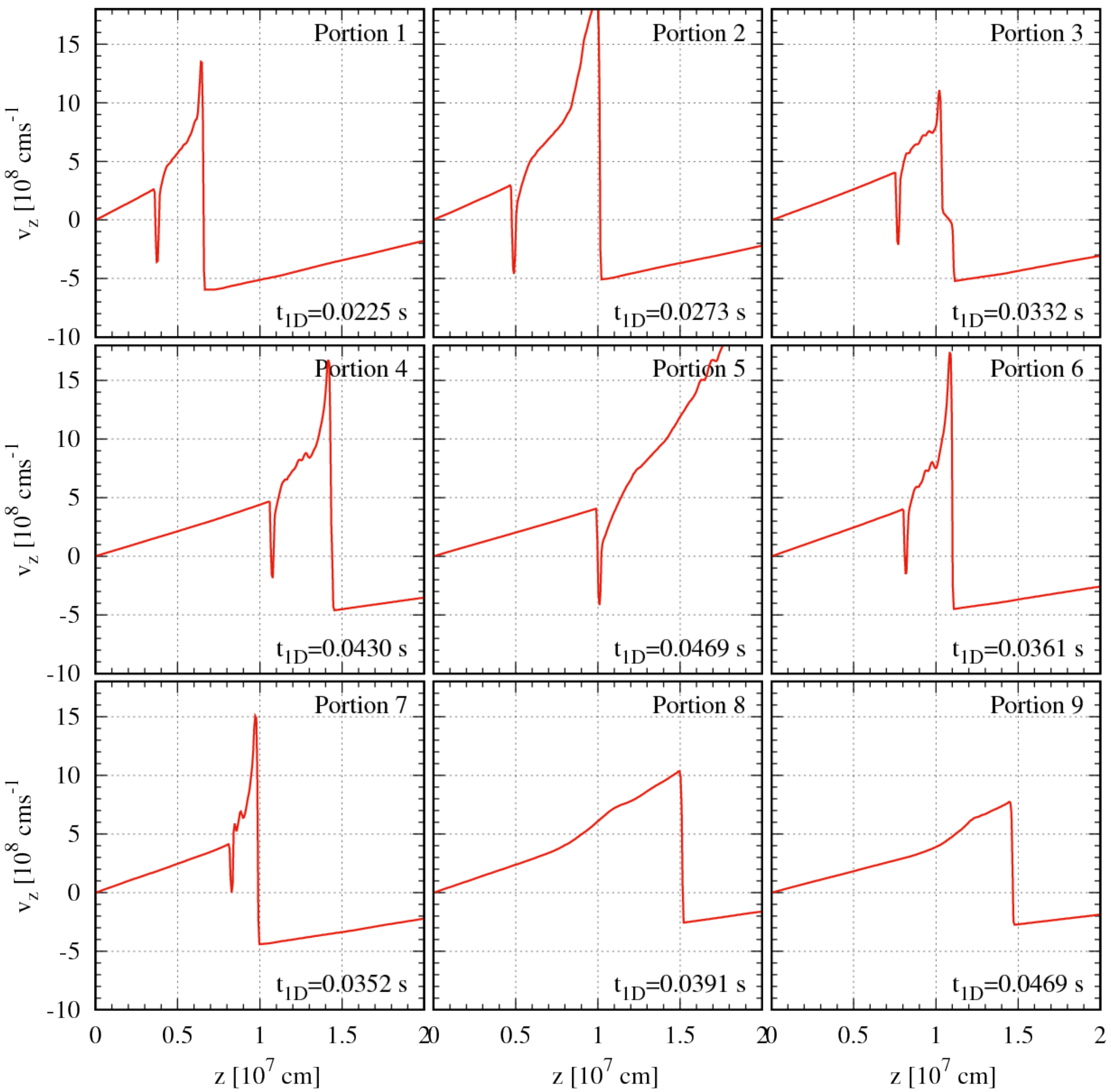
- Space resolution is changed by factors of 8.
- The evolution of density, z-velocity, and nuclear components is not changed as space resolution is changed.



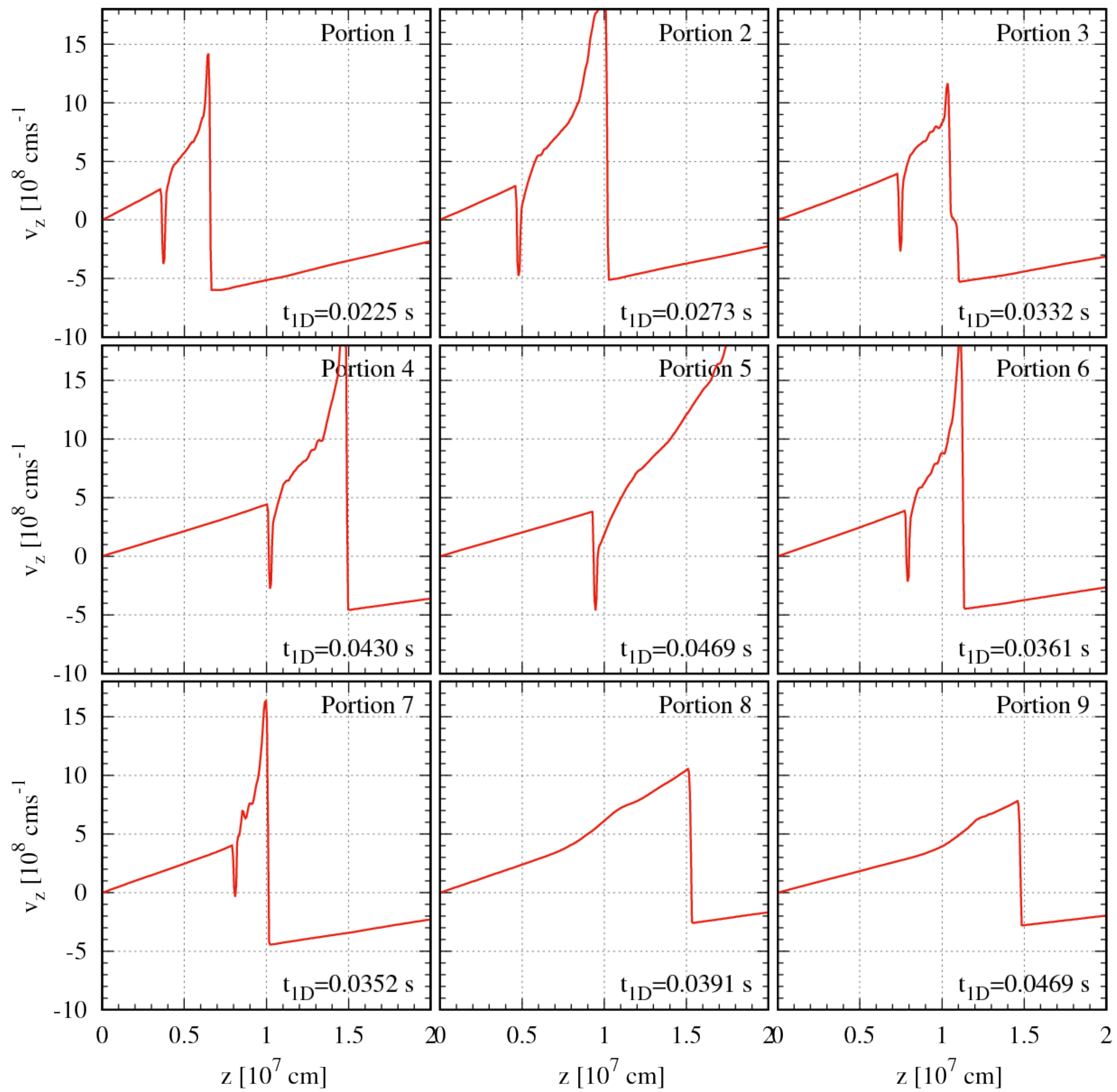
Convergence check of 3D SPH resolution



Tidal force (BH gravity) in z-direction



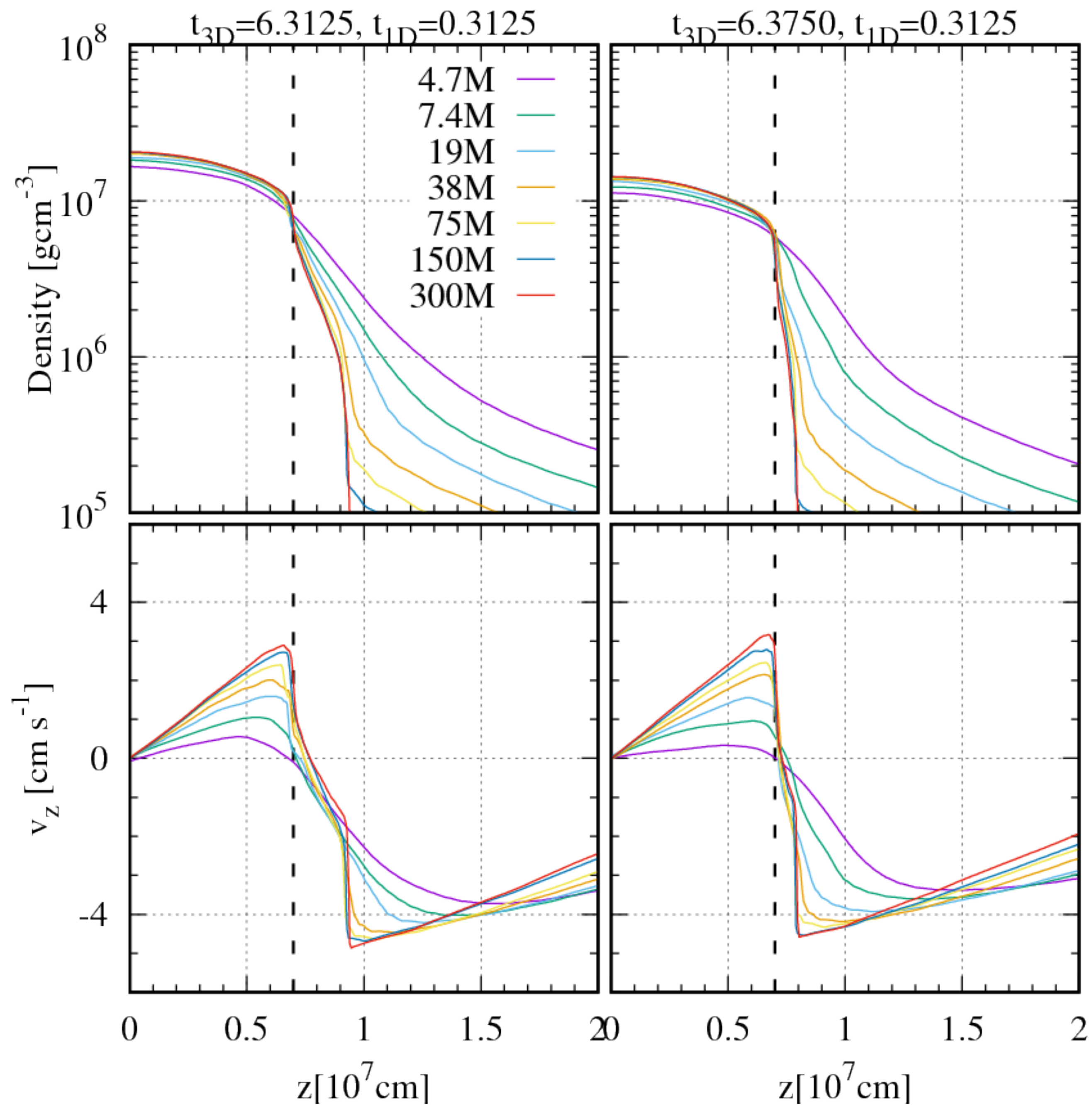
No BH gravity in z-direction



BH gravity in z-direction

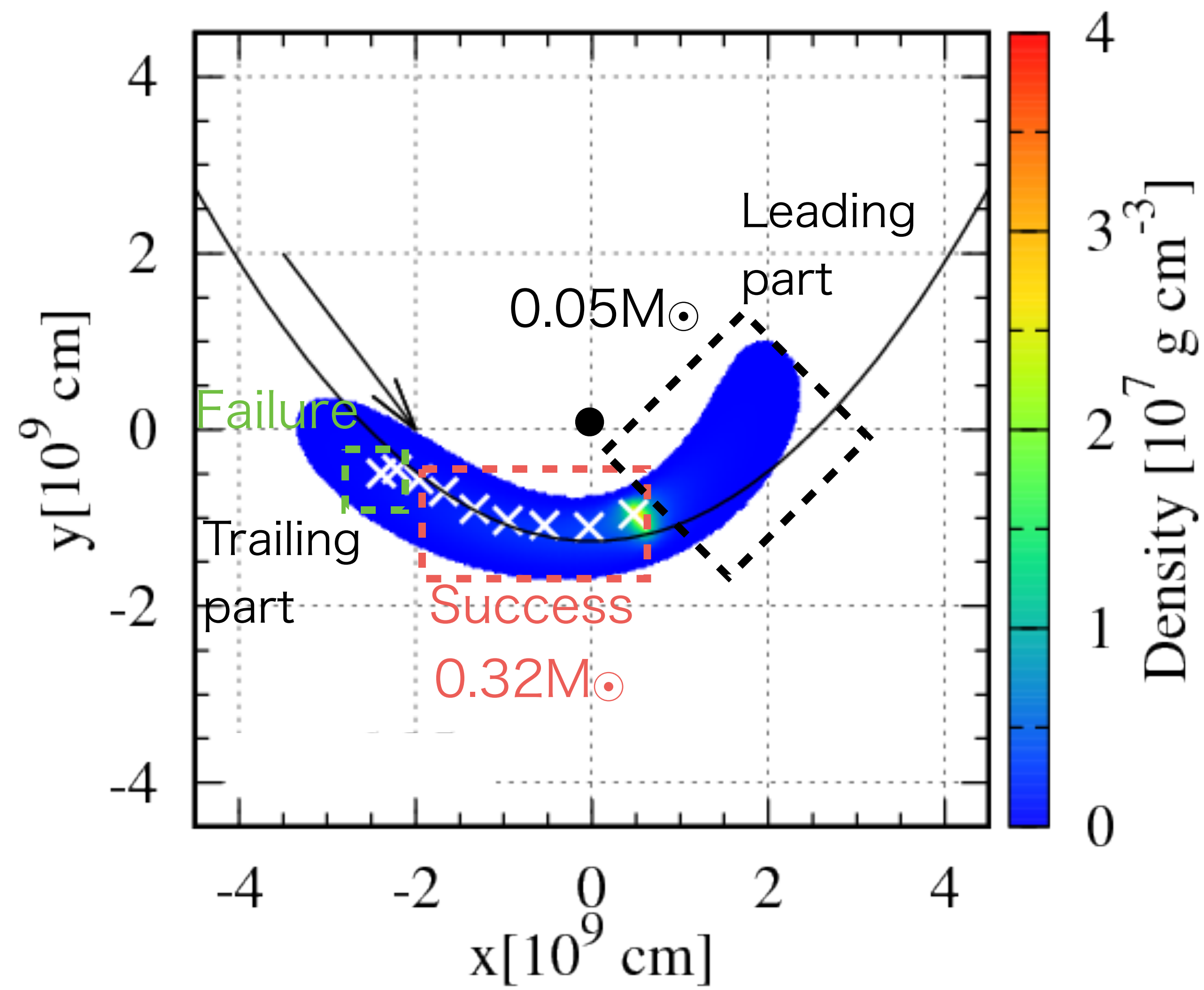
SPH VS mesh

- The shock wave appears near the surface of the WD.
- SPH simulation cannot resolve such thin layer, even if the number of particles is 300 million.
- SPH simulation cannot follow the emergence of the shock wave.



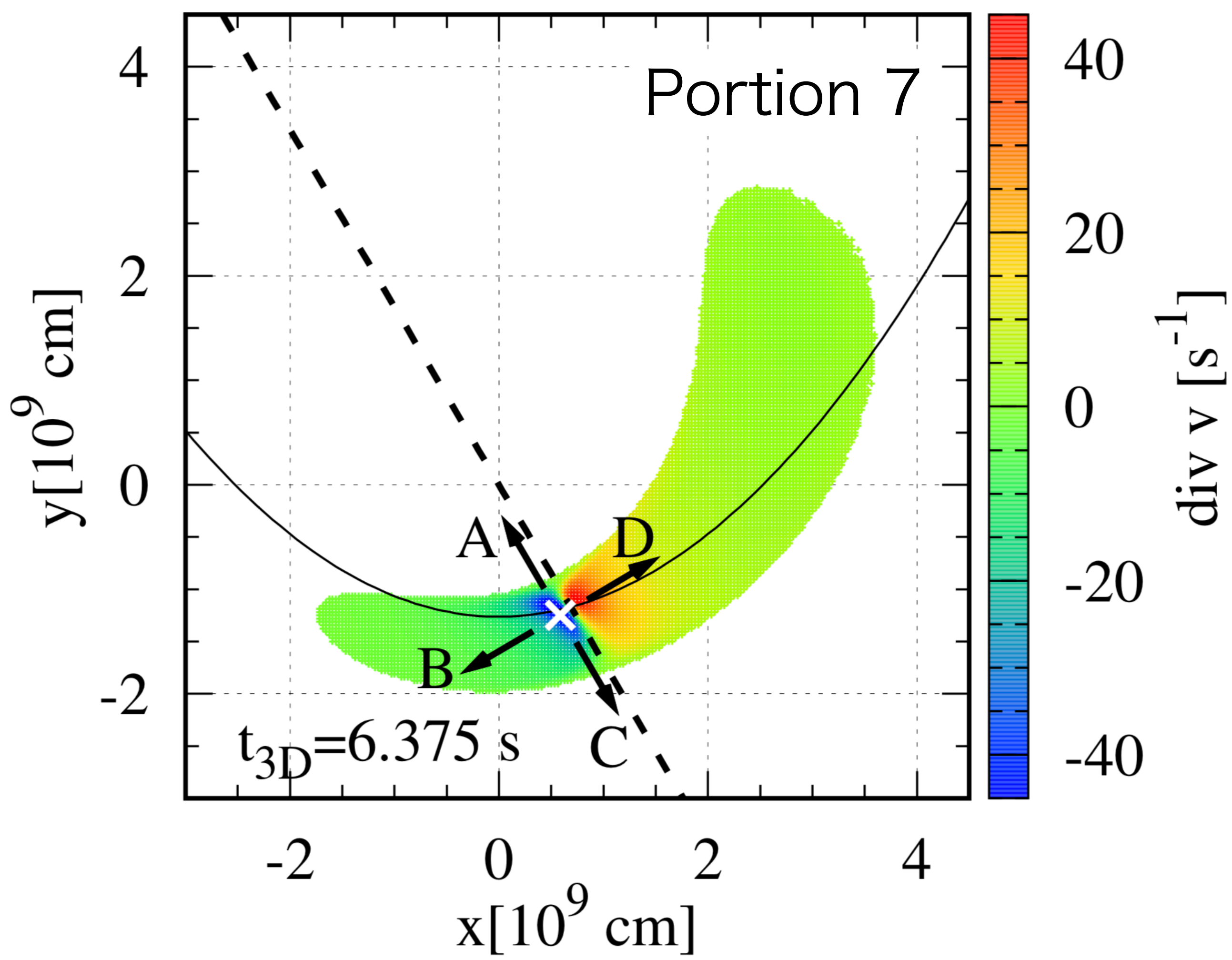
Difference between success and failure cases

- The detonated columns precedes the undetonated columns.
- A leading part of a WD passes closer to an IMBH than a trailing part.
- The leading part is more compressed, and easier to be detonated.
- The detonated mass is at least $0.32 M_\odot$, and at most $0.37 M_\odot$.



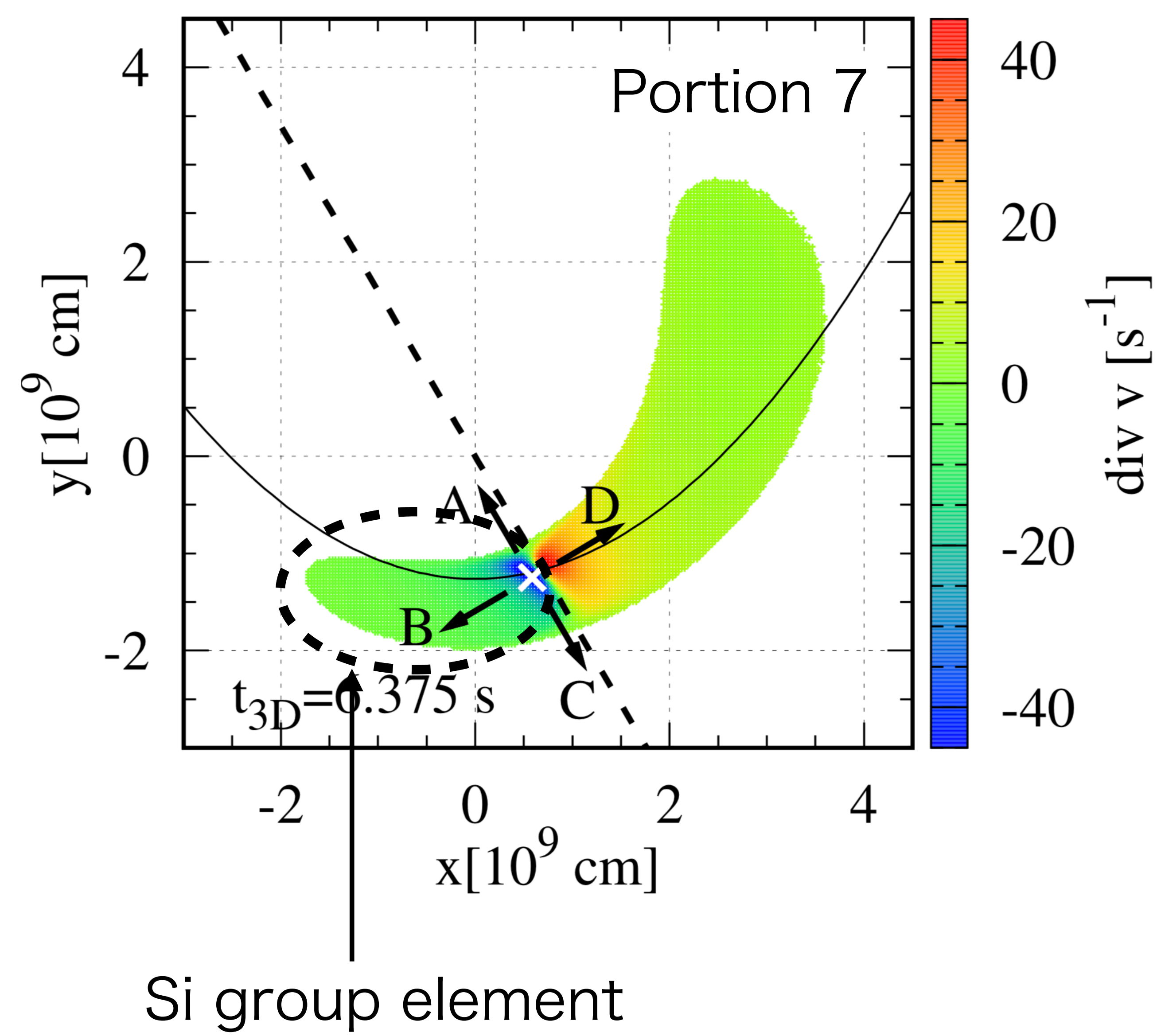
Interaction of z-columns

- Detonated z-columns do not interact with each other.
  - The velocity of the WD: ~10^{10} cms^{-1}
  - The velocity of detonation: ~10^{9} cms^{-1}



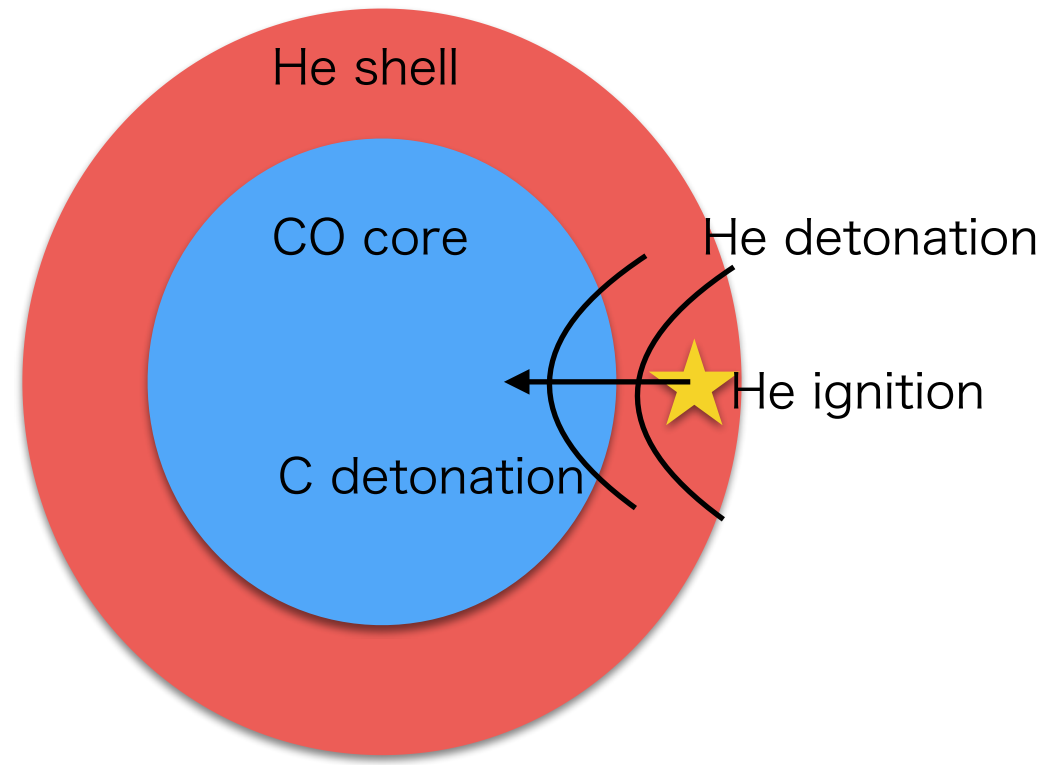
Detonation wave proceeding orbital plane

- In A- and C-directions, detonation does not proceed, since detonation occurs simultaneously.
- In D-direction, detonation does not proceed, since materials in D direction have been already detonated.
- In B-direction,
    - detonation does not proceed if detonation occurs from the materials.
    - detonation procees if not.
- Si group elements would be synthesized in the materials in B-direction, since detonation reaches when their density becomes low.

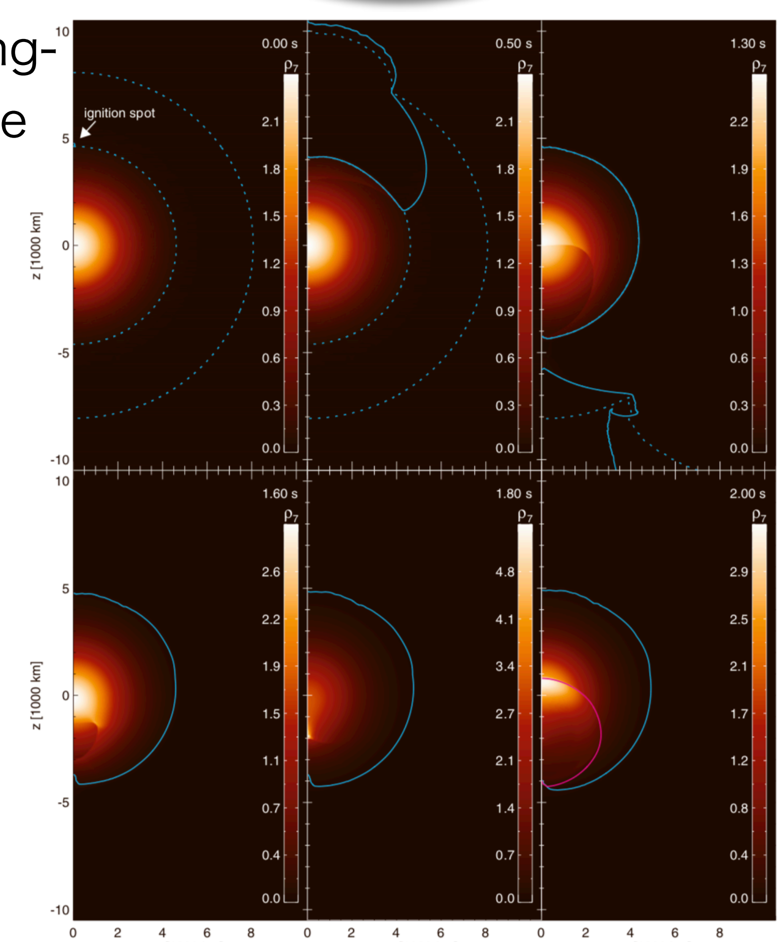


Double detonation

- One of explosion scenarios of SNeIa
- Explosion process
  - In a Helium shell, Helium detonation is ignited by mass accretion onto a WD from its companion star.
  - The Helium detonation drives Carbon detonation.
- Two types
  - Edge-lit type (Nomoto 1980; 1982; Woosley et al. 1980)
  - Converging-shock type (Livne 1990)



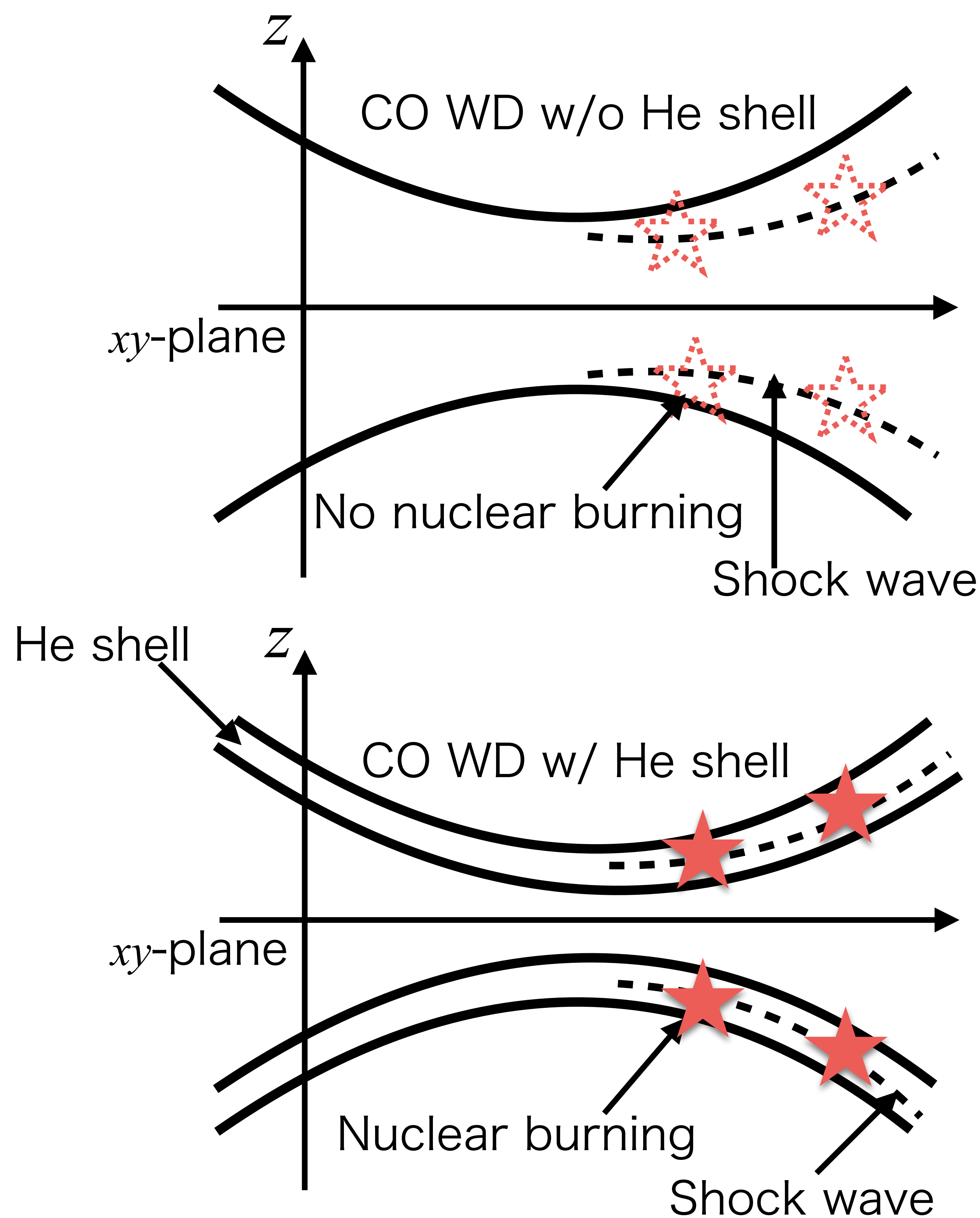
Converging-shock type



Fink et al. (2010)

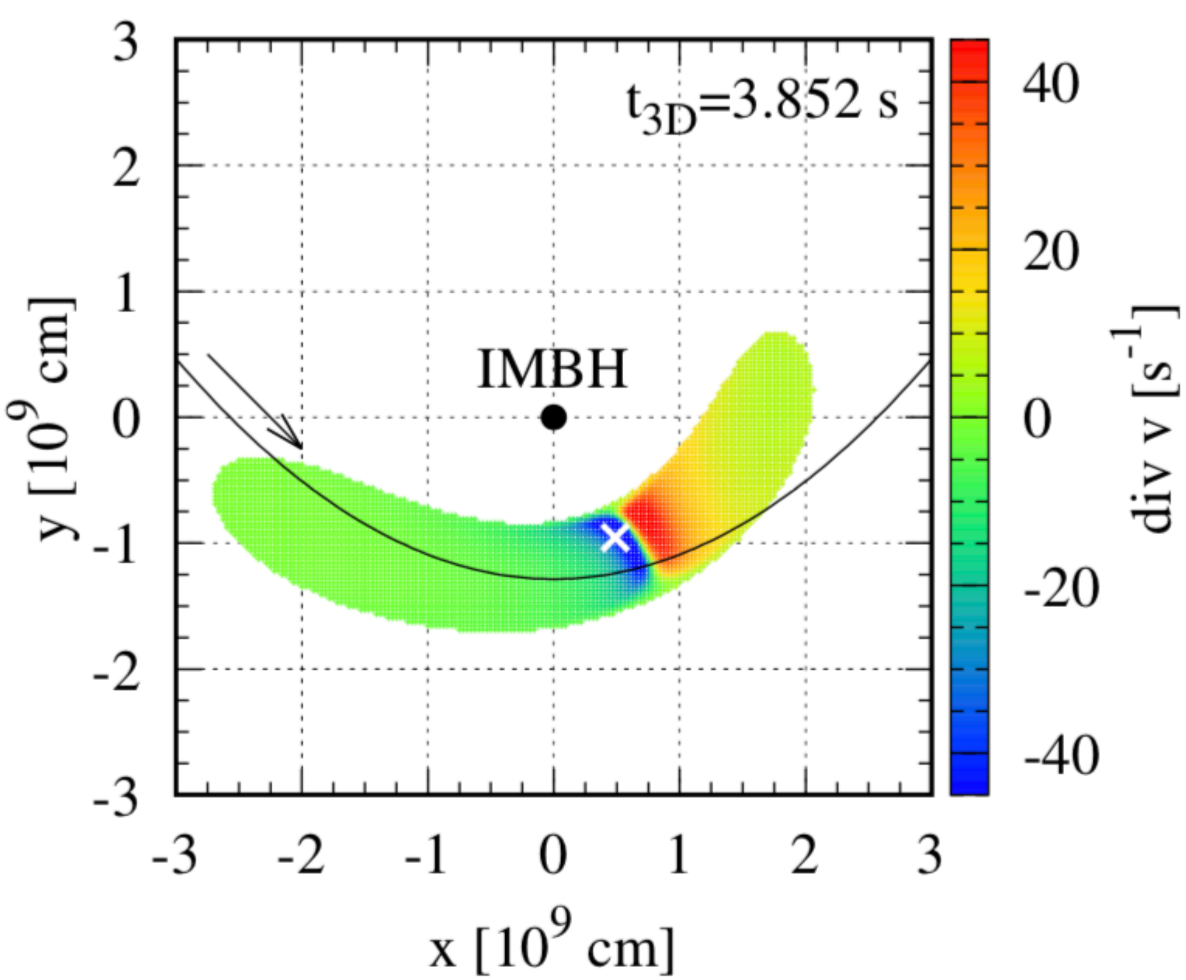
"Tidal" double detonation (TDD)

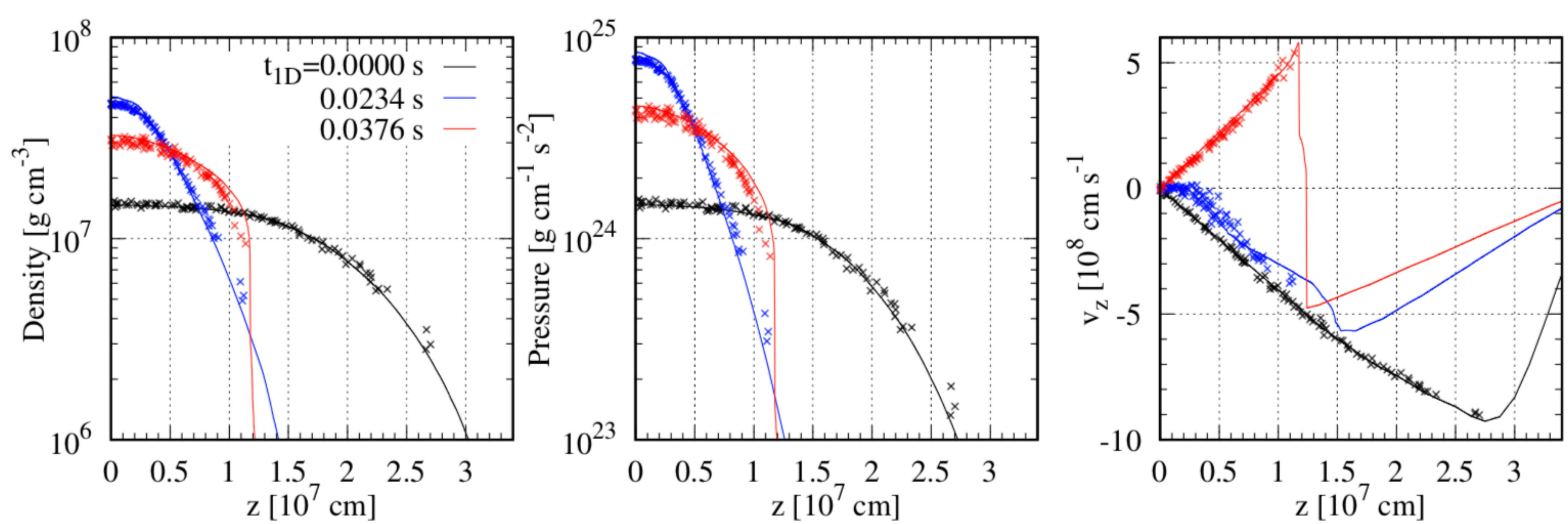
- A new explosion mechanism
- Helium detonation is ignited by tidal force, not by mass accretion.
- Tidal detonation is triggered by a shock wave in a He shell of a CO WD.
  - If there is no He shell, tidal detonation may not occur, since Carbon is harder to be ignited than Helium.
- TDD raises probability of illuminating IMBHs as thermonuclear transients.



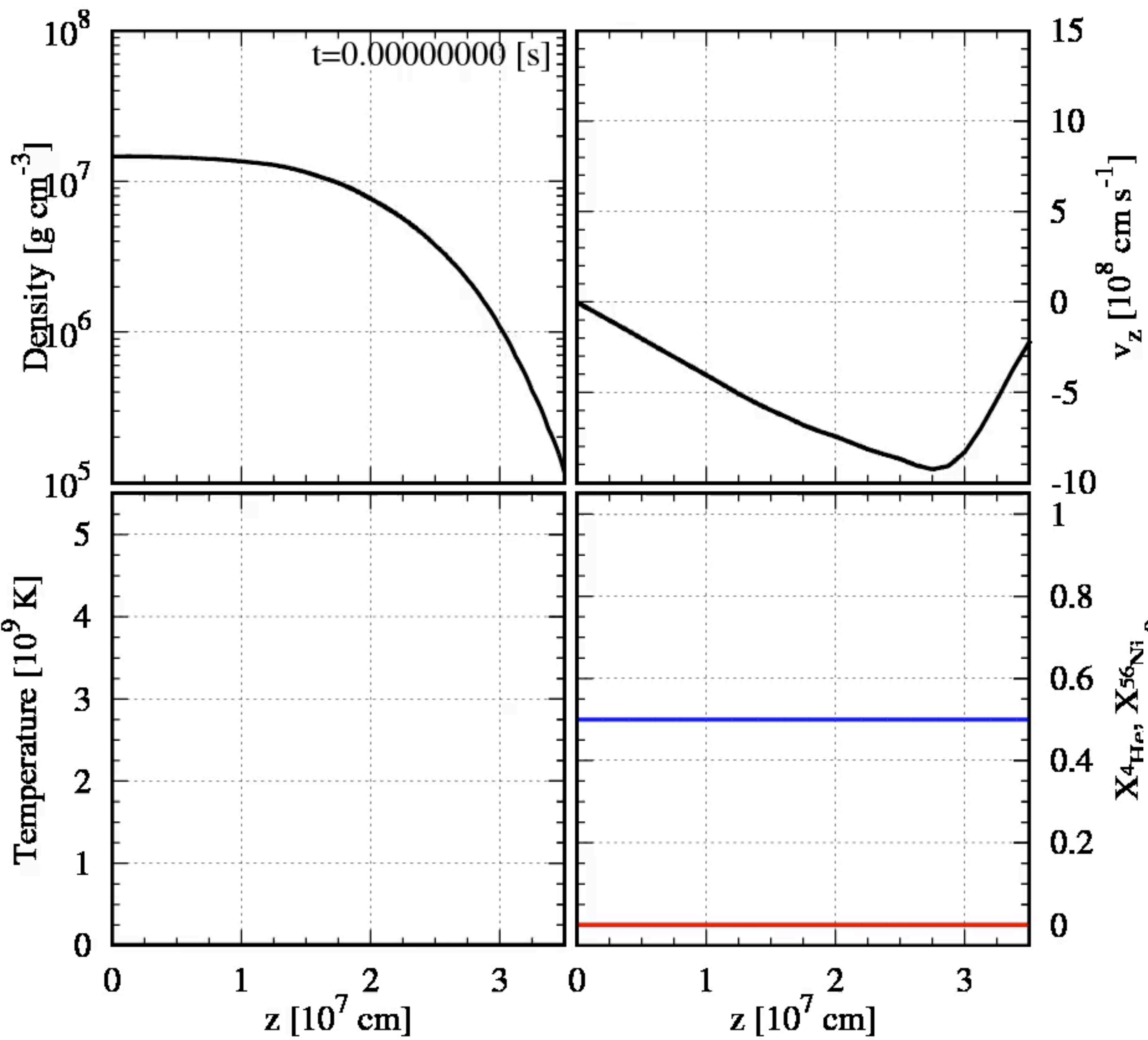
Initial conditions

- 0.6M⊙ CO WD (N~100 millions)
  - w/o He shell
  - w/ He shell (5 and 10% of total mass)
- 300M⊙ IMBH
- Parabolic orbit, β=5
- Simulation method is the same as the above.

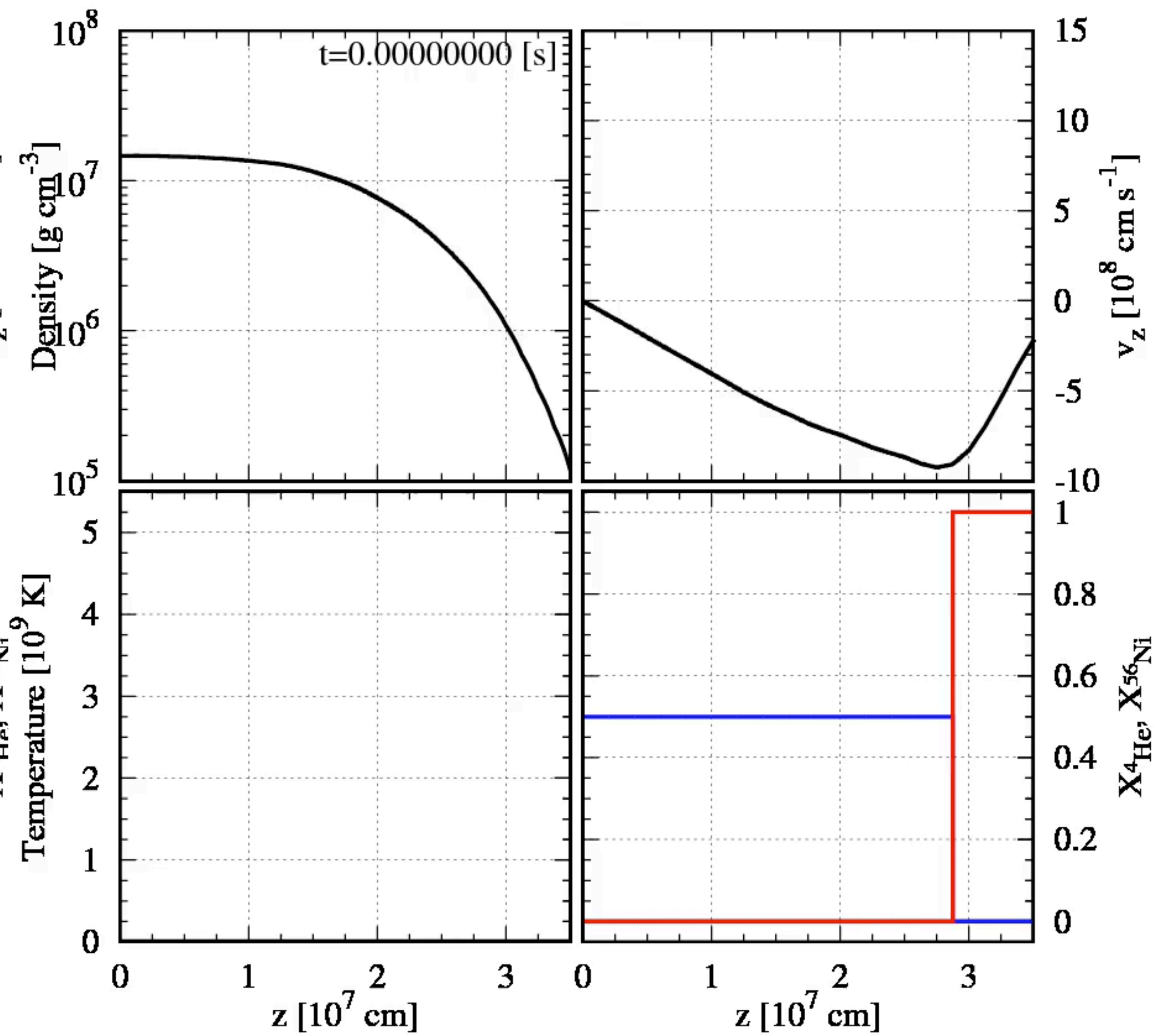




Results



w/o He shell



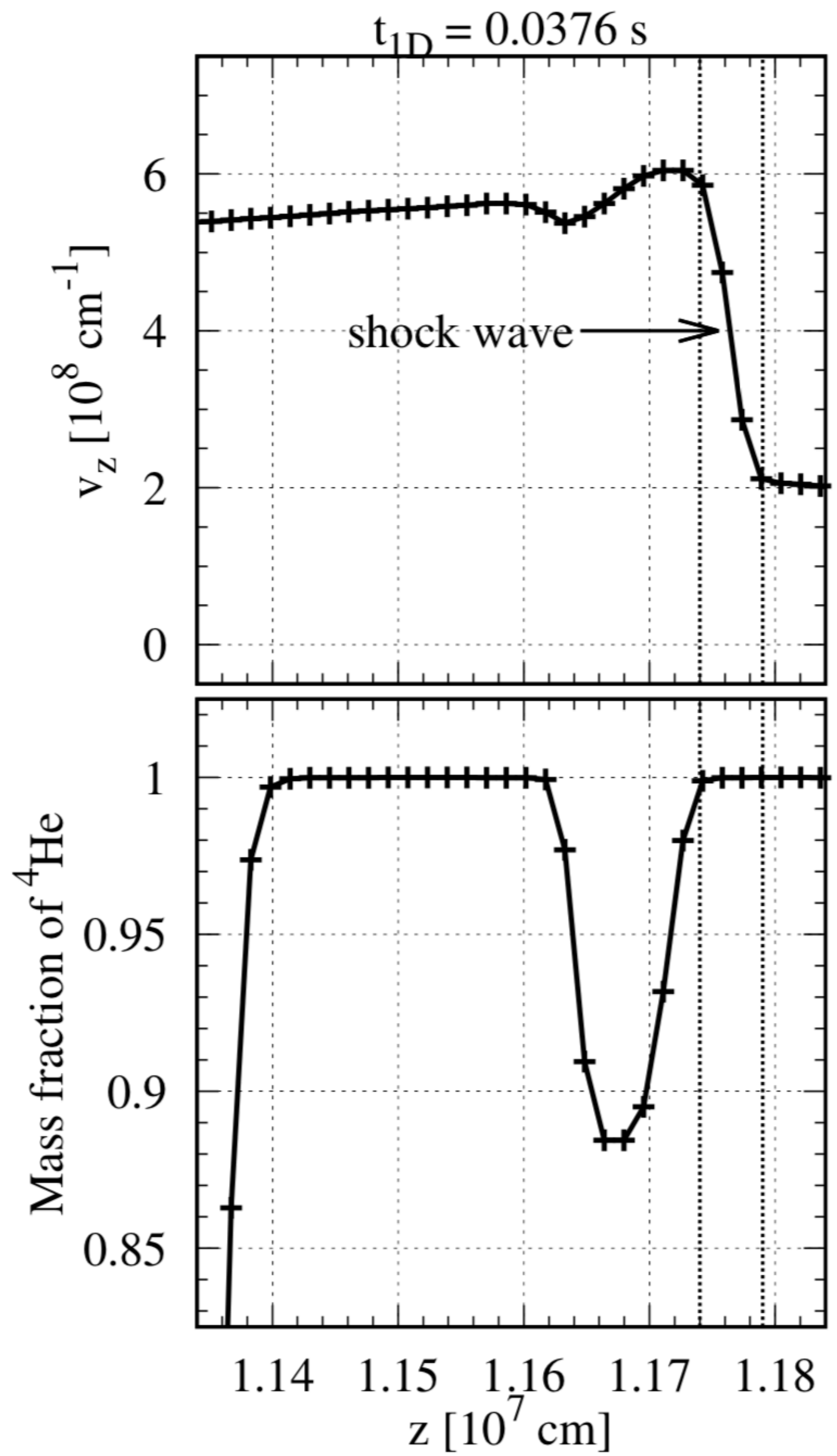
w/ 5% He shell

Signal of TTD

- Surface radioactivity
- Si group element, such as Calcium

Fine structure

- Detonation occurs in a He shell.
  - Although mixing occurs, it does not affect TDD.
- We suppress nuclear reactions in a shock layer, using a flag in FLASH code.

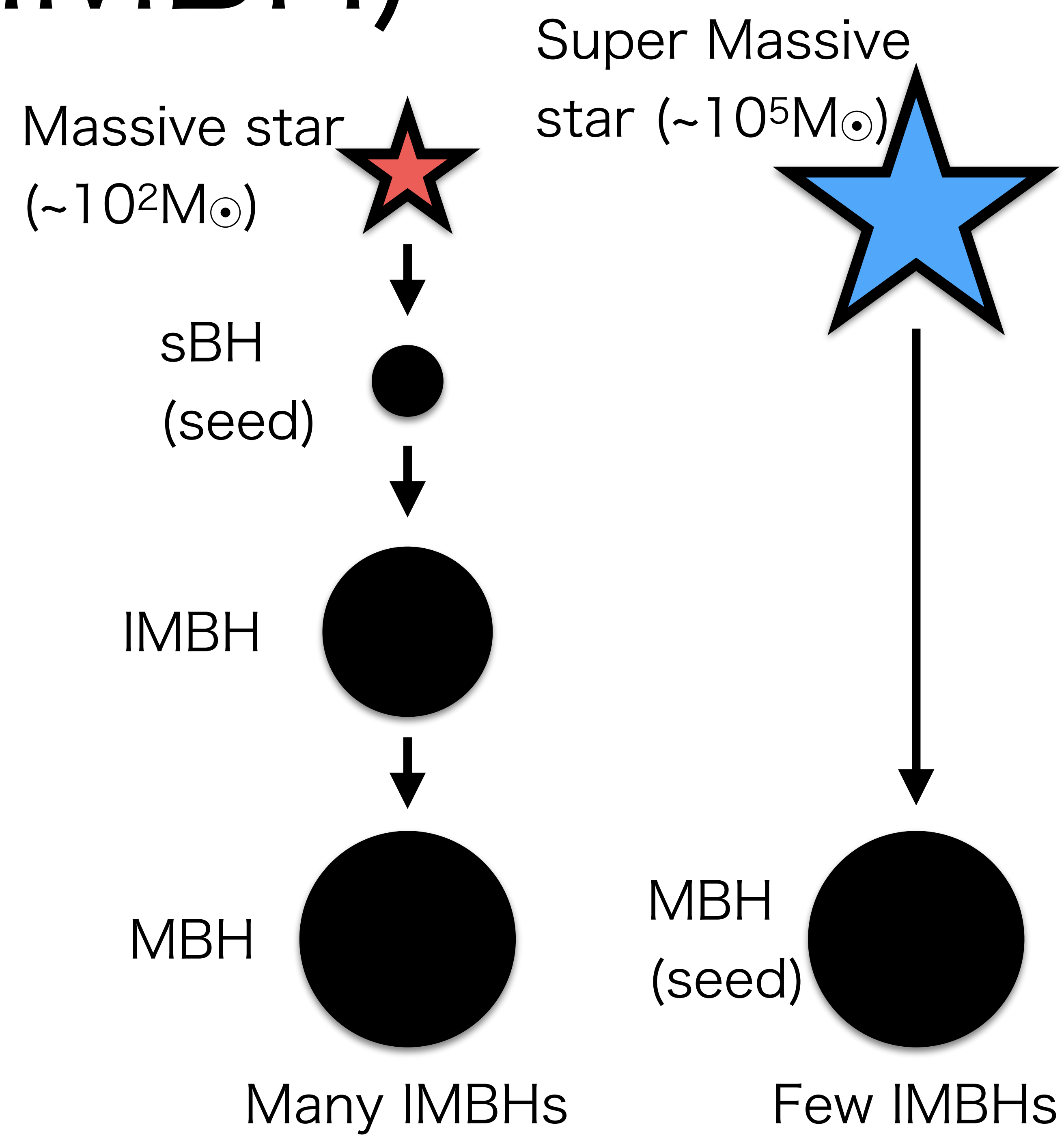


Summary

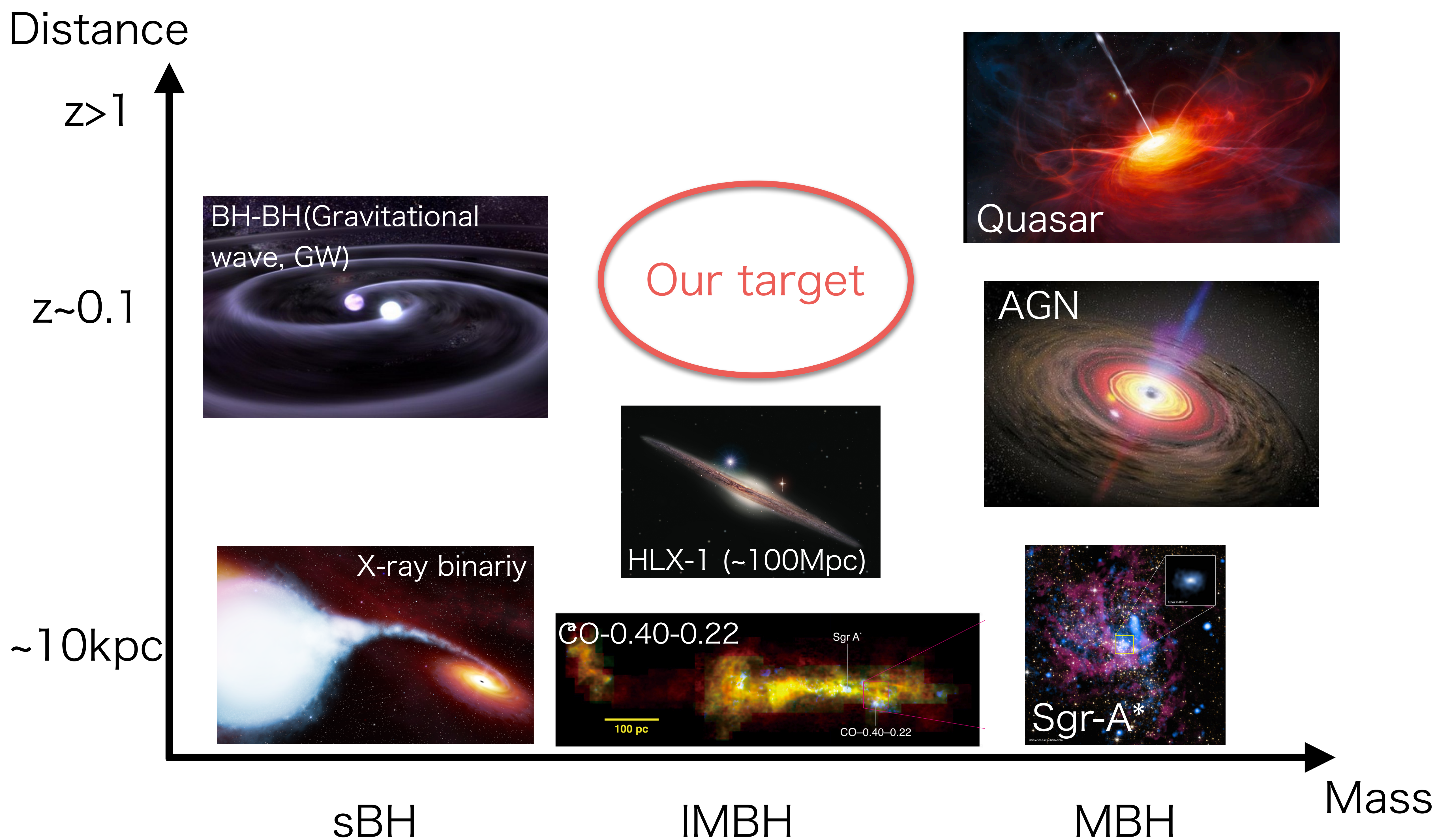
- We have studied tidal detonation of WDs.
- We should be careful of spurious heating in low-resolution SPH simulation.
- We have verified tidal detonation of WDs in the case of He WD with 0.45$M_\odot$ in which large amount of ^{56}Ni (~0.3$M_\odot$) is synthesized.
- We have suggested a new explosion mechanism of a WD: tidal double detonation (TDD).
- In future, we will devise a method for getting nucleosynthesis easily, because our current method is too time-consuming to investigate wide parameter ranges.

Intermediate Mass Black Hole (IMBH)

- Black hole (BH) with 10^2-$10^5 M_\odot$
  - Stellar-mass BH (sBH): $<10^2 M_\odot$
  - Massive BH (MBH): $>10^6 M_\odot$
- IMBH Candidates
  - M82 X-1 (Matsumoto et al. 2001)
  - HLX-1 (Farrell et al. 2009)
  - CO-0.40-0.22 (Oka et al. 2016)
  - IRS13E complex (Tsuboi et al. 2017)
- An important key to clarify the formation process of MBHs

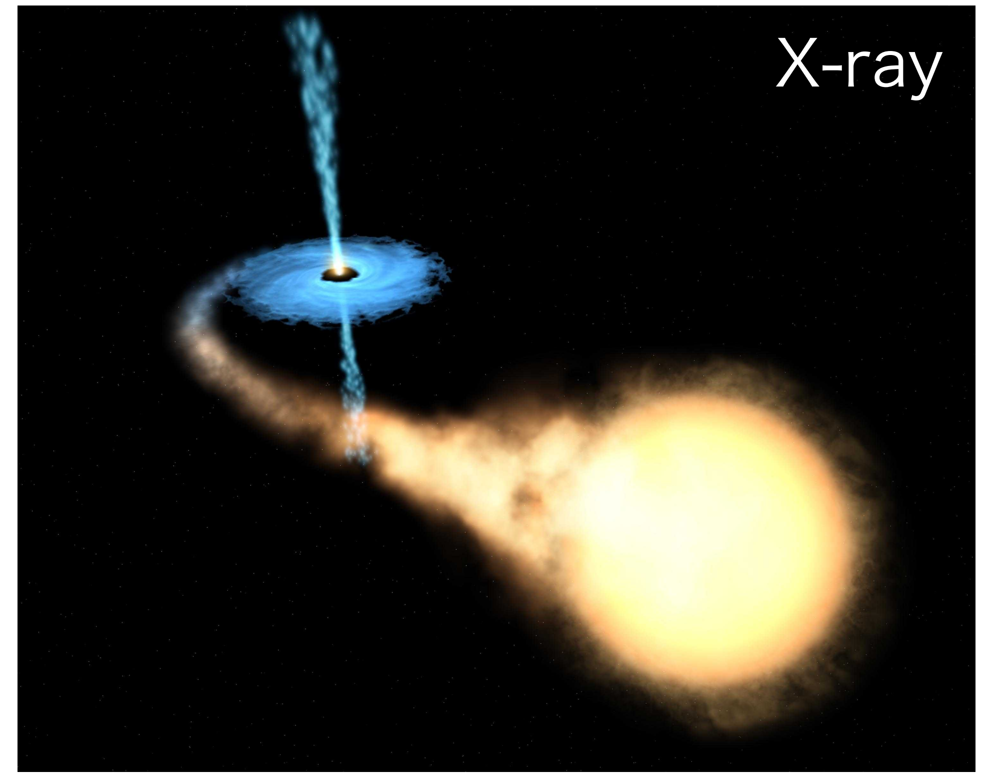


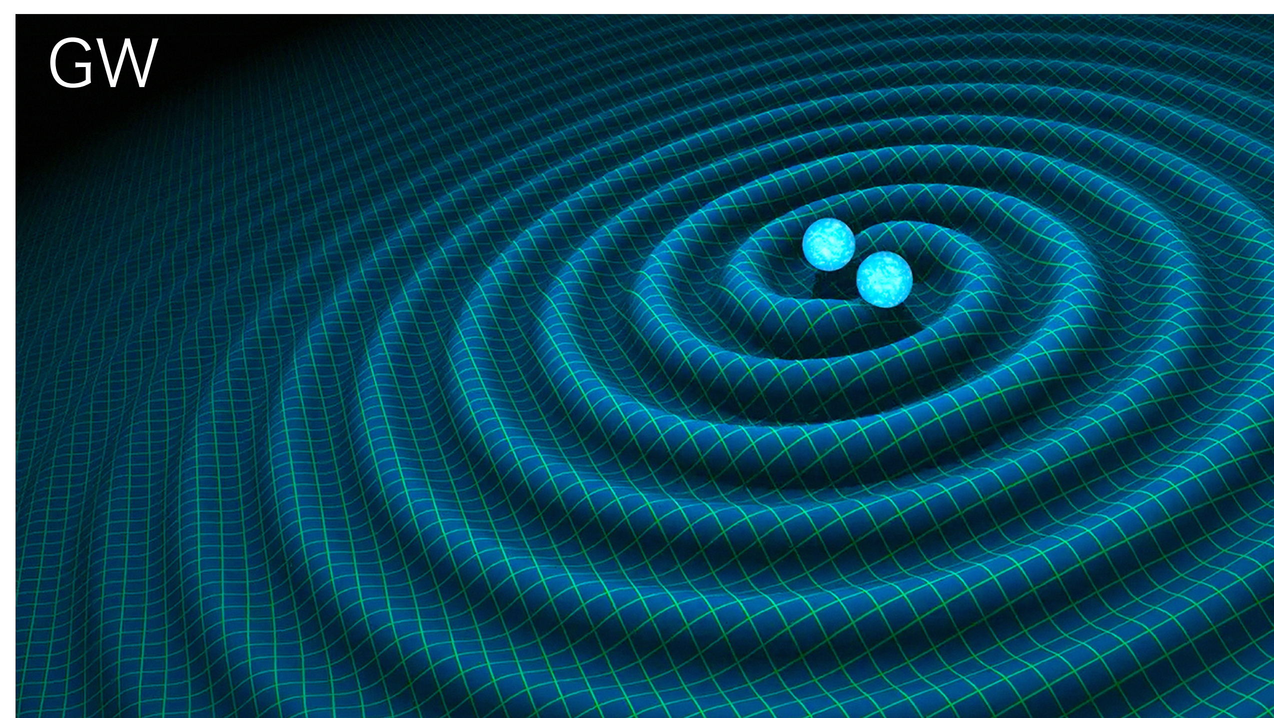
The current status of search for BHs



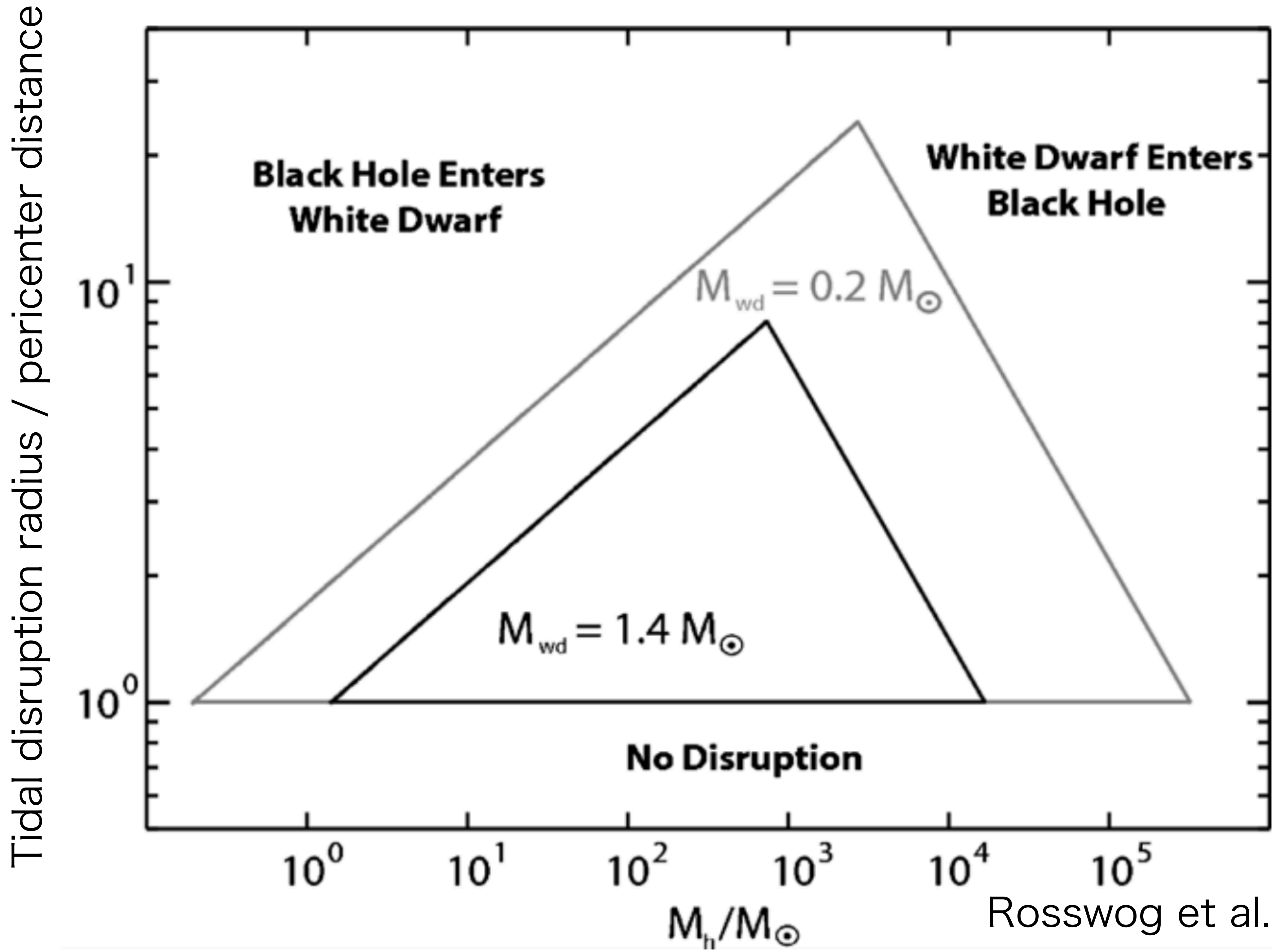
Strategies of IMBH survey

- Accretion disk (by X-ray observatory)
  - At most Eddington luminosity (not so luminous)
  - Super Eddington luminosity (strongly depending on line-of-sight directions)
- Inspiral of a BH (by GW observatory)
  - Space-based GW detector required (e.g. LISA, DECIGO)
    - LIGO, VIRGO & KAGRA are ground-based detectors.
  - Beyond 2030
- Tidal disruption events (TDEs) of white dwarfs (WD) (by optical observatory)





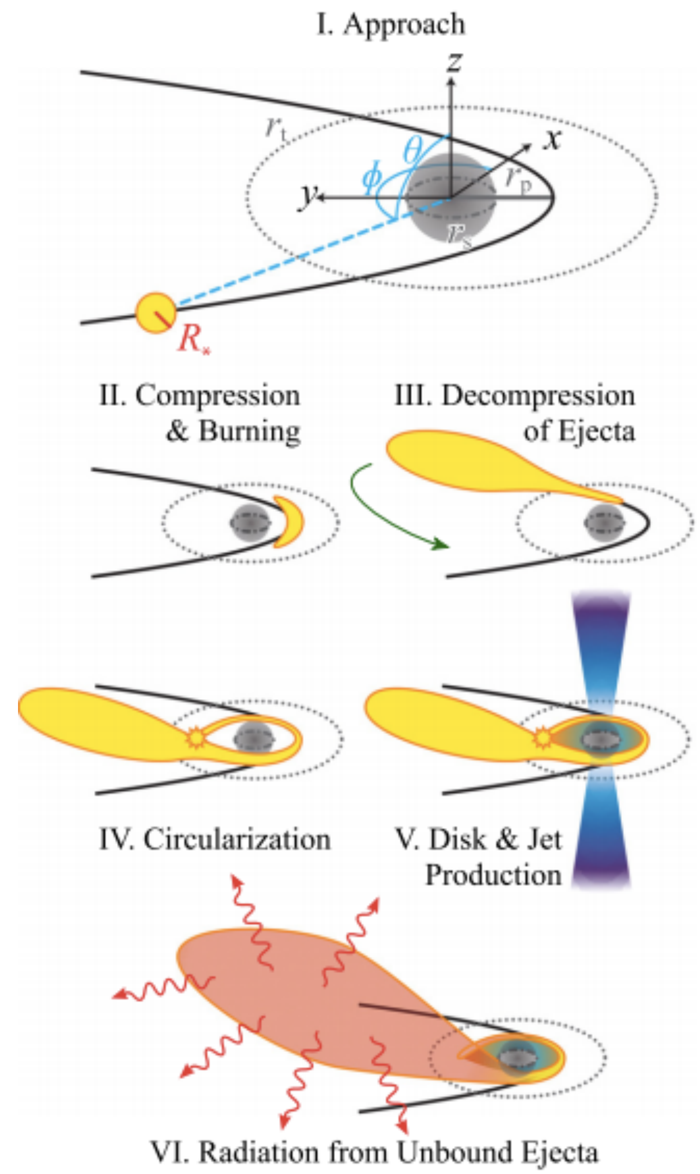
BH mass for WD TDE



Rosswog et al. (2009)

Tidal detonation in a WD TDE

- A WD approaches to an IMBH, and tidally disrupted.
- The WD is compressed in the direction perpendicular to the orbital plane.
- The WD is heated by the compression.
- The heating triggers explosive nuclear reactions (tidal detonation).
- The explosive nuclear reactions yield radioactive nuclei, such as ^{56}Ni.
- Radioactive decay of ^{56}Ni powers the emission from WD TDEs, similarly to type Ia supernovae (SNe Ia).
- WD TDEs at cosmological distance will be observed similarly to SNe Ia.



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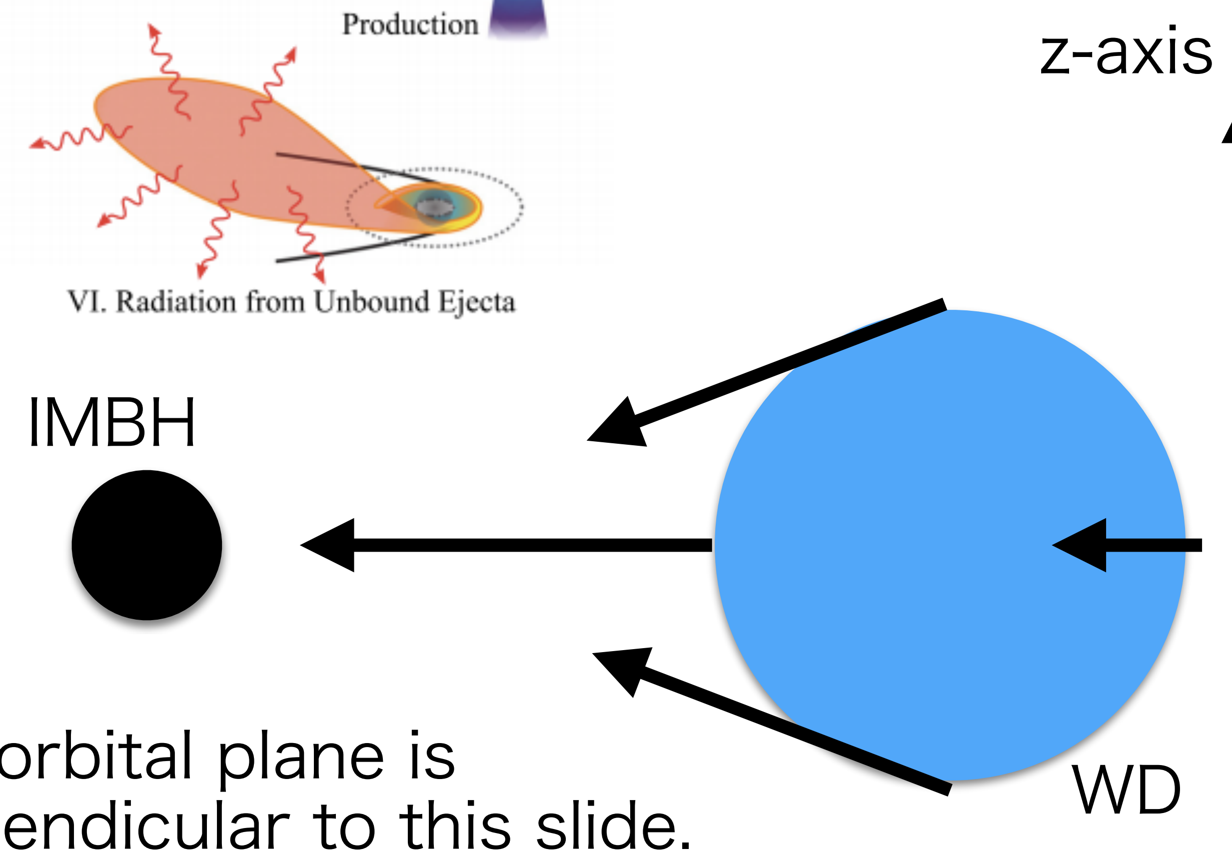
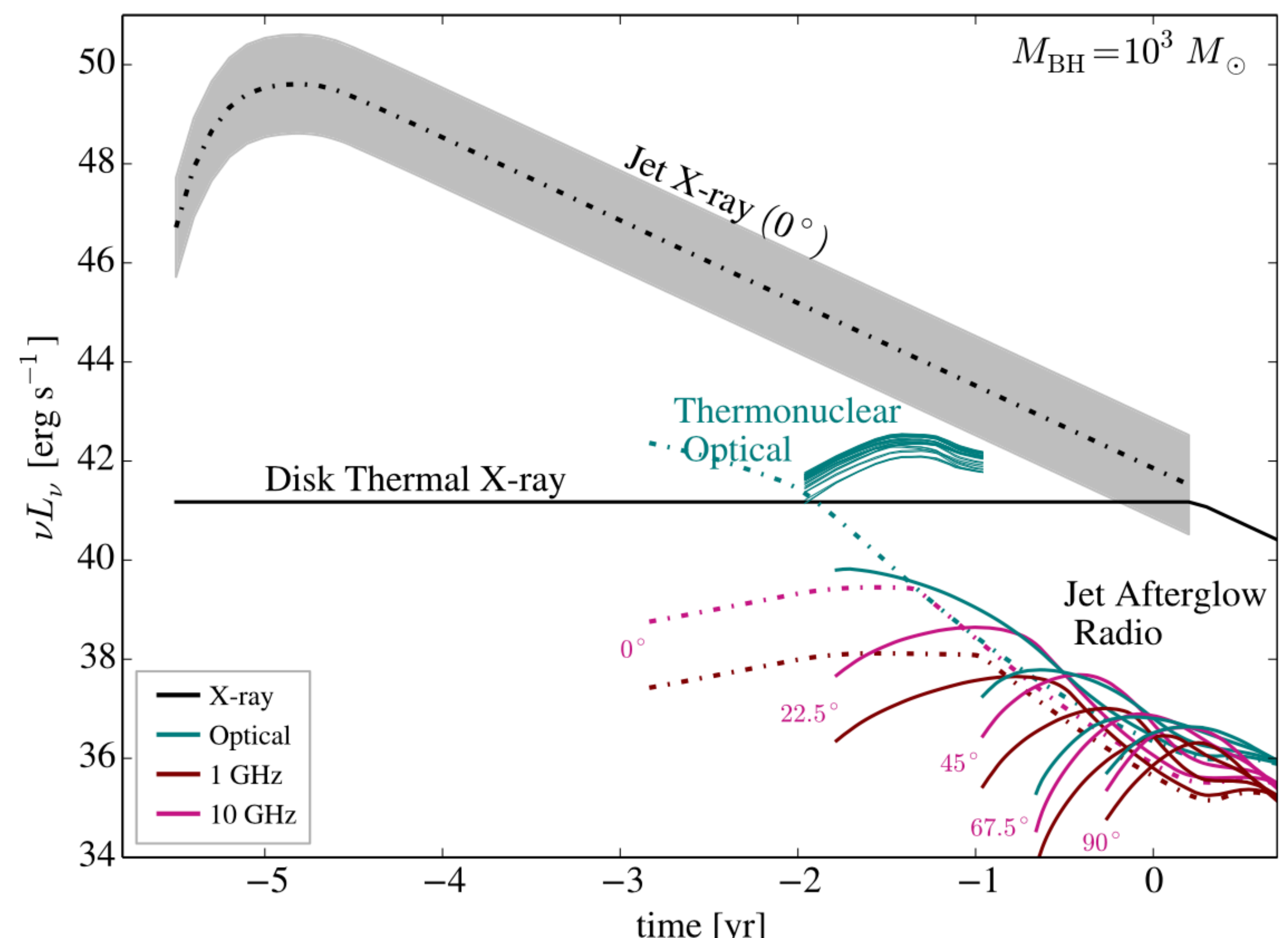


The orbital plane is perpendicular to this slide.

Estimated luminosity

- WD TDEs will be observed as thermonuclear transients powered by radioactive decay of ^{56}Ni.
    - Similar to SNeIa
- The estimated luminosity is larger than accretion-powered luminosity of the WD TDEs by two orders of magnitude.
- Jet luminosity would be much more luminous than the thermonuclear luminosity, but should have very small opening angle.



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