中間質量ブラックホールによる白色矮星の潮汐破壊中におこる熱核爆発に関する研究

谷川 衝 (東京大学総合文化研究科)

平成29年度CfCAユーザーズミーティング

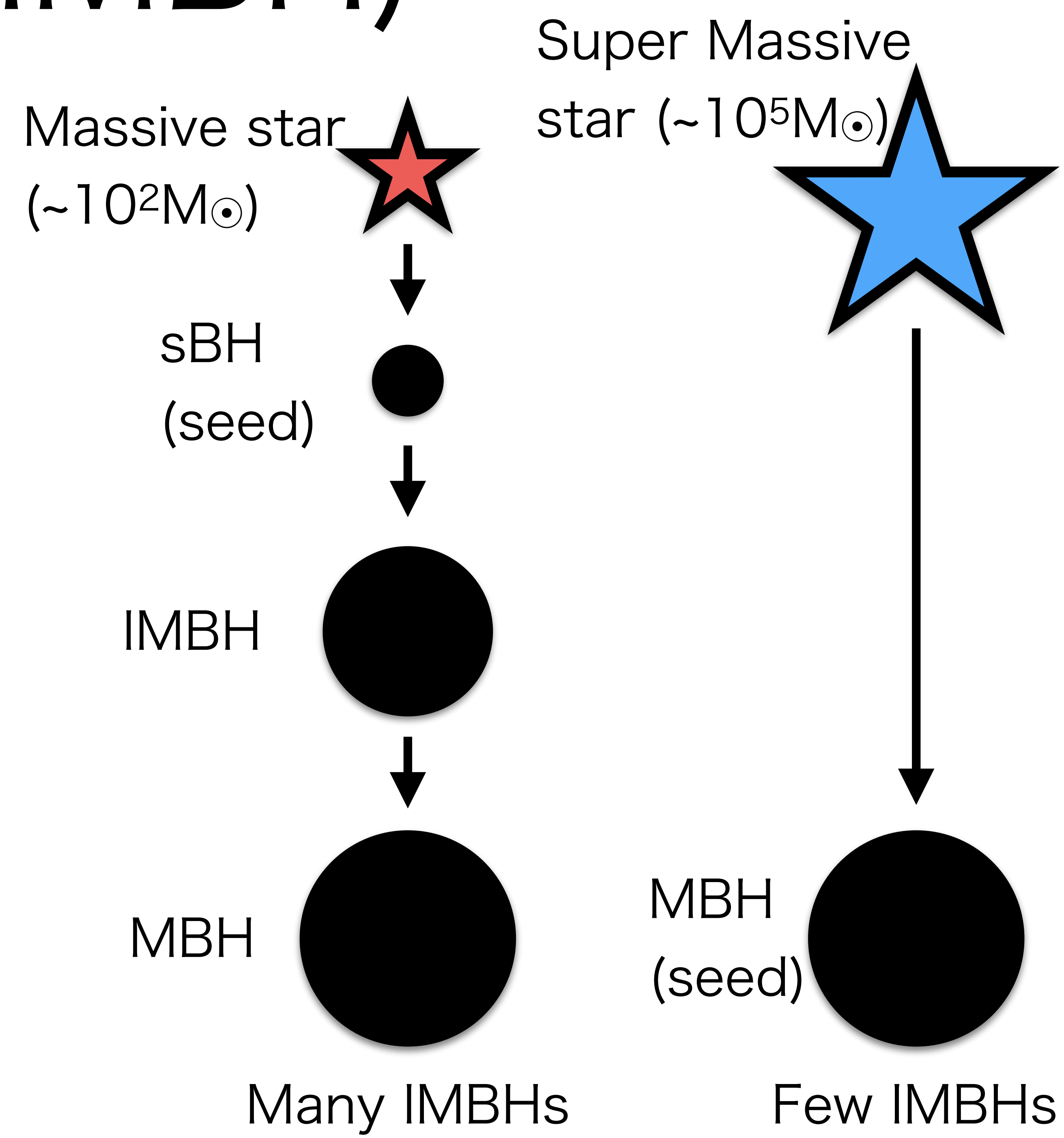
2017年11月28日 国立天文台三鷹

Contents

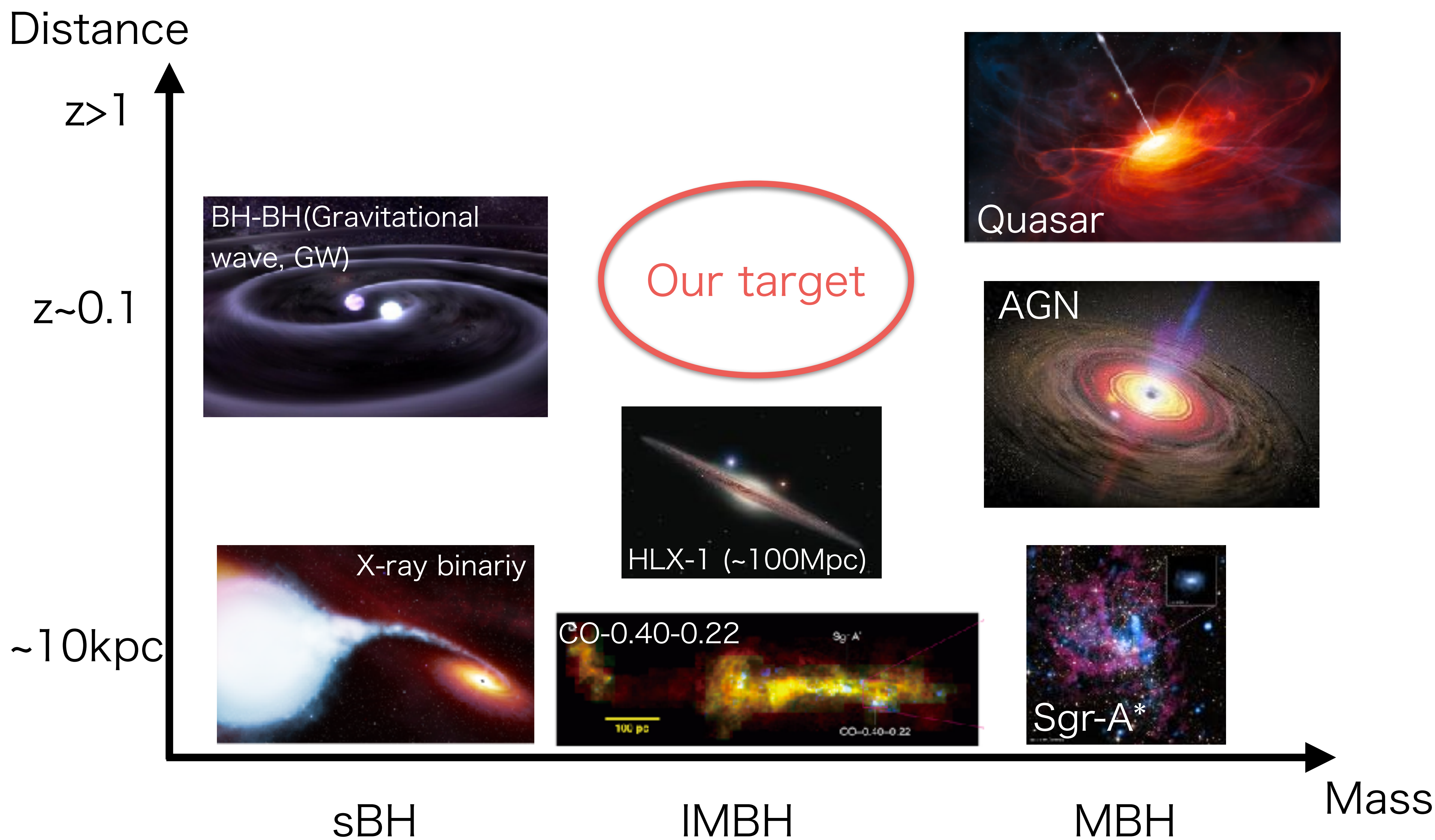
- Introduction of tidal detonation
- Spurious heating in SPH simulation (Tanikawa et al. 2017, ApJ, 839, 81)
- High resolution study of tidal detonation (Tanikawa 2017, arXiv:1711.05451)
- Tidal double detonation (Tanikawa 2017, arXiv: 1711.07115)

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

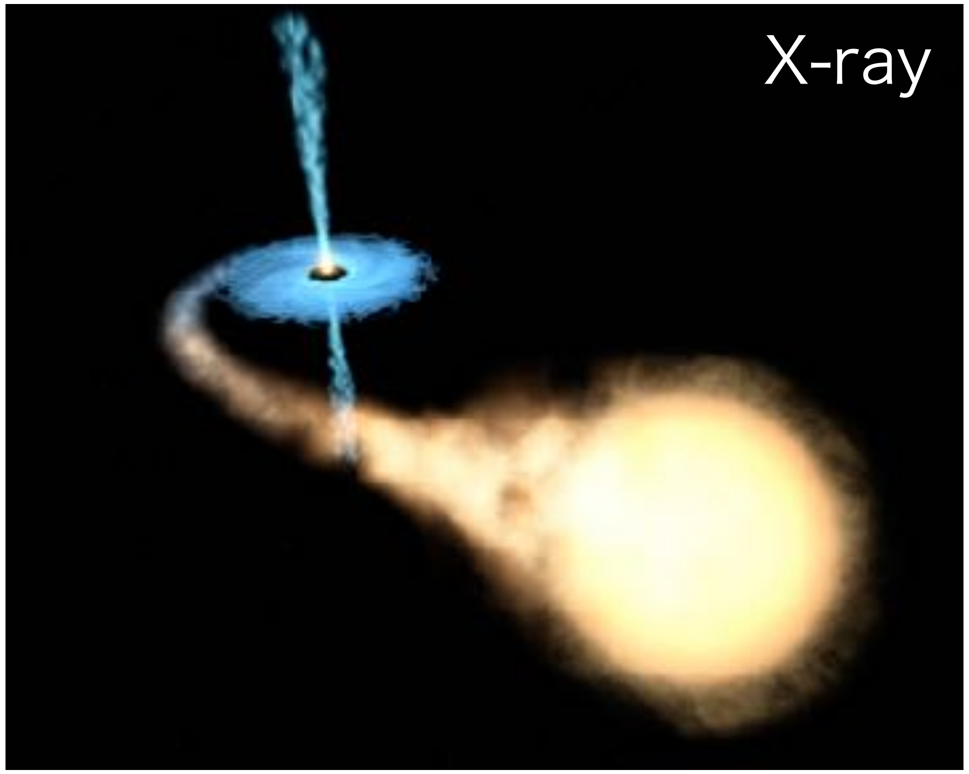


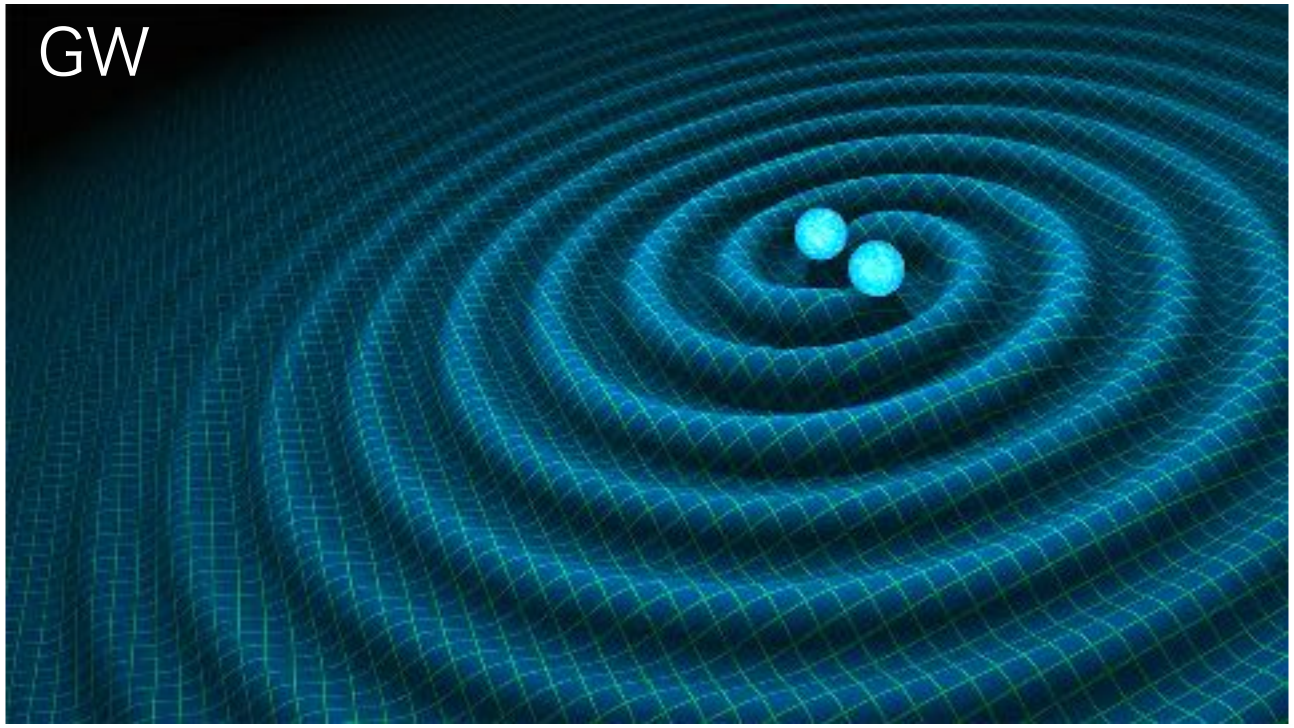
The current status of search for BHs



Strategies of IMBH survey

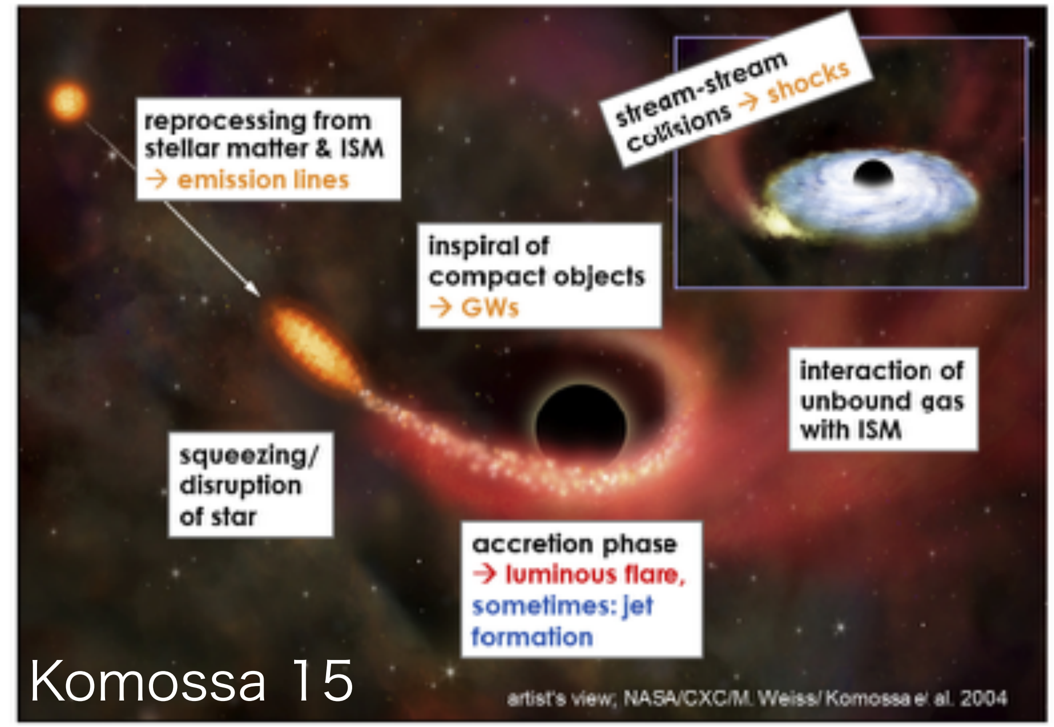
- Accretion disk (by X-ray observatory)
  - At most Eddington luminosity (not so luminous)
  - Super Eddington luminosity (strongly depending on line-of-sight directions)
- Inspiral of a BH (by GW observatory)
  - Space-based GW detector required (e.g. LISA, DECIGO)
    - LIGO, VIRGO & KAGRA are ground-based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

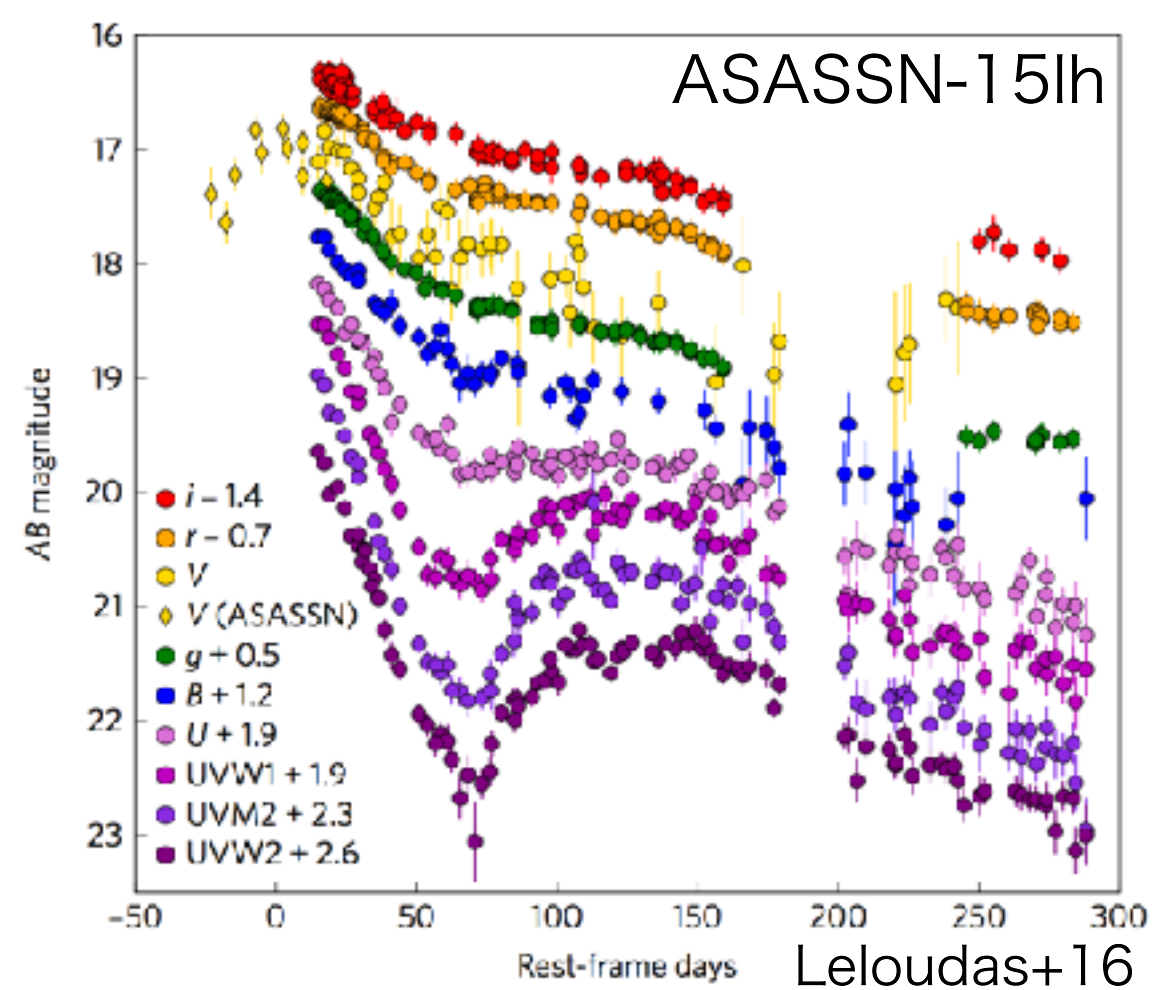




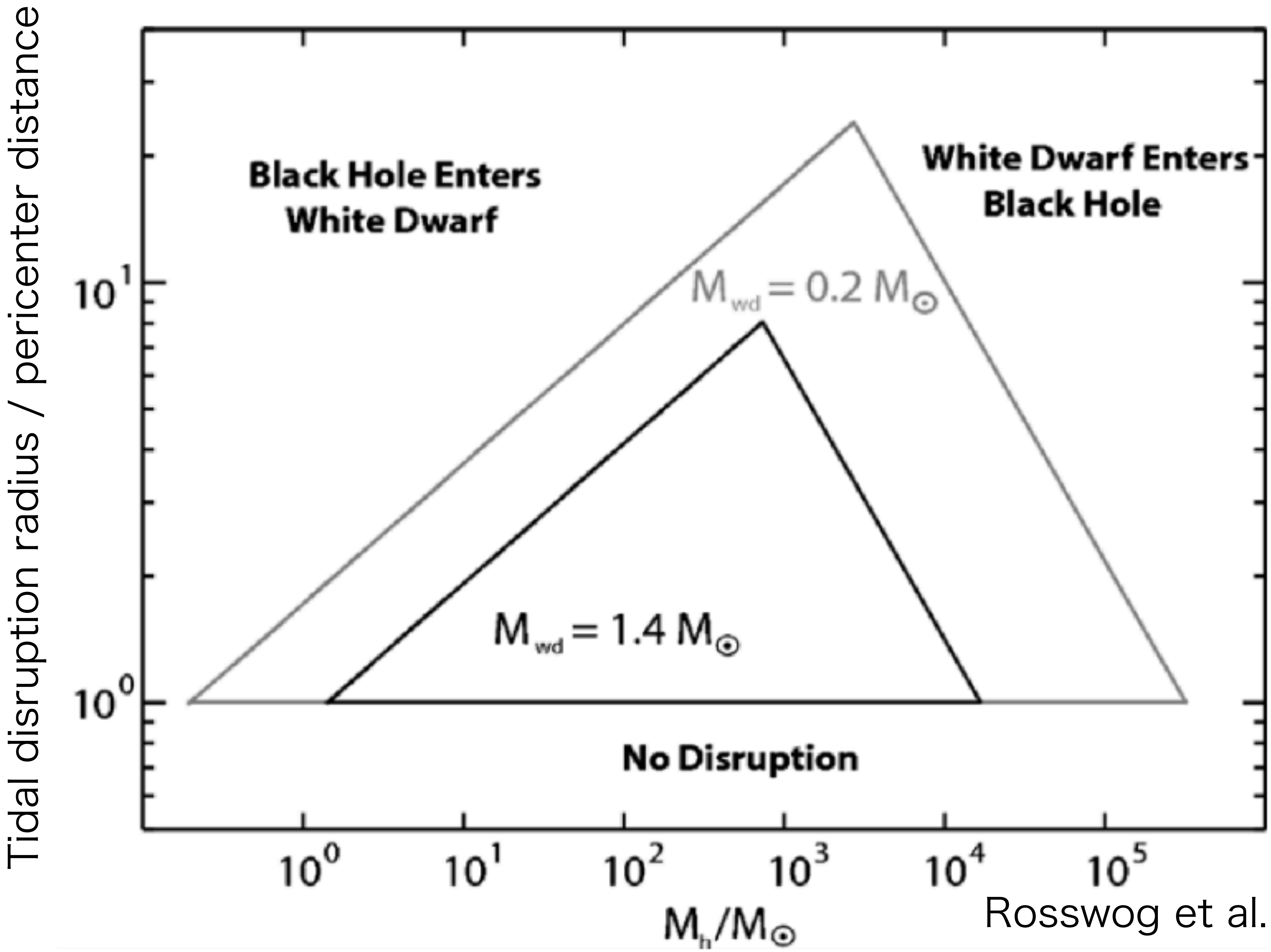
Tidal Disruption Events (TDEs)

- 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





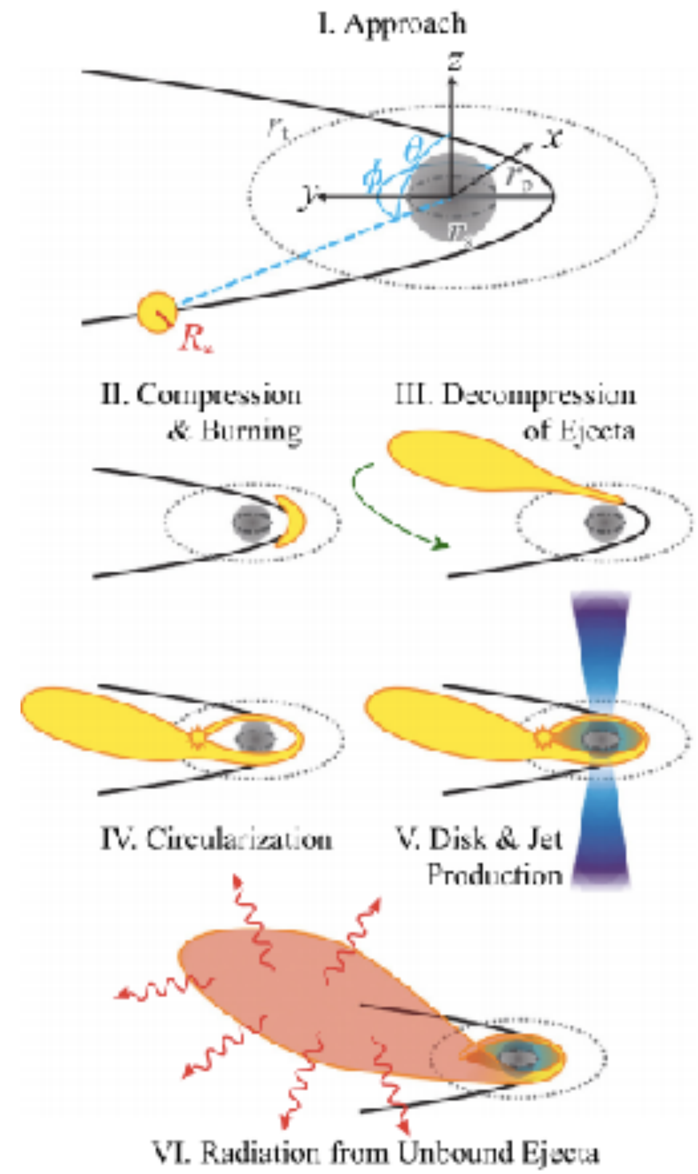
BH mass for WD TDE



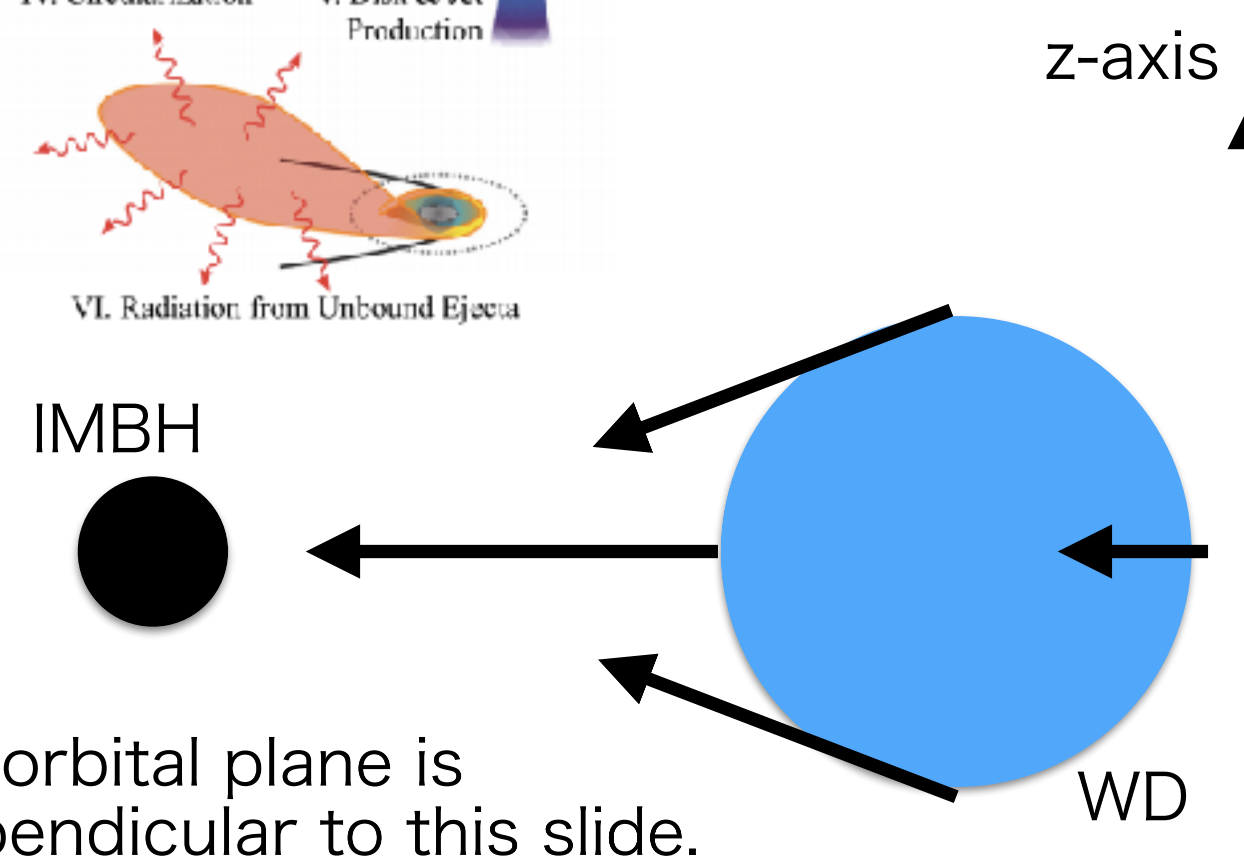
Rosswog et al. (2009)

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.



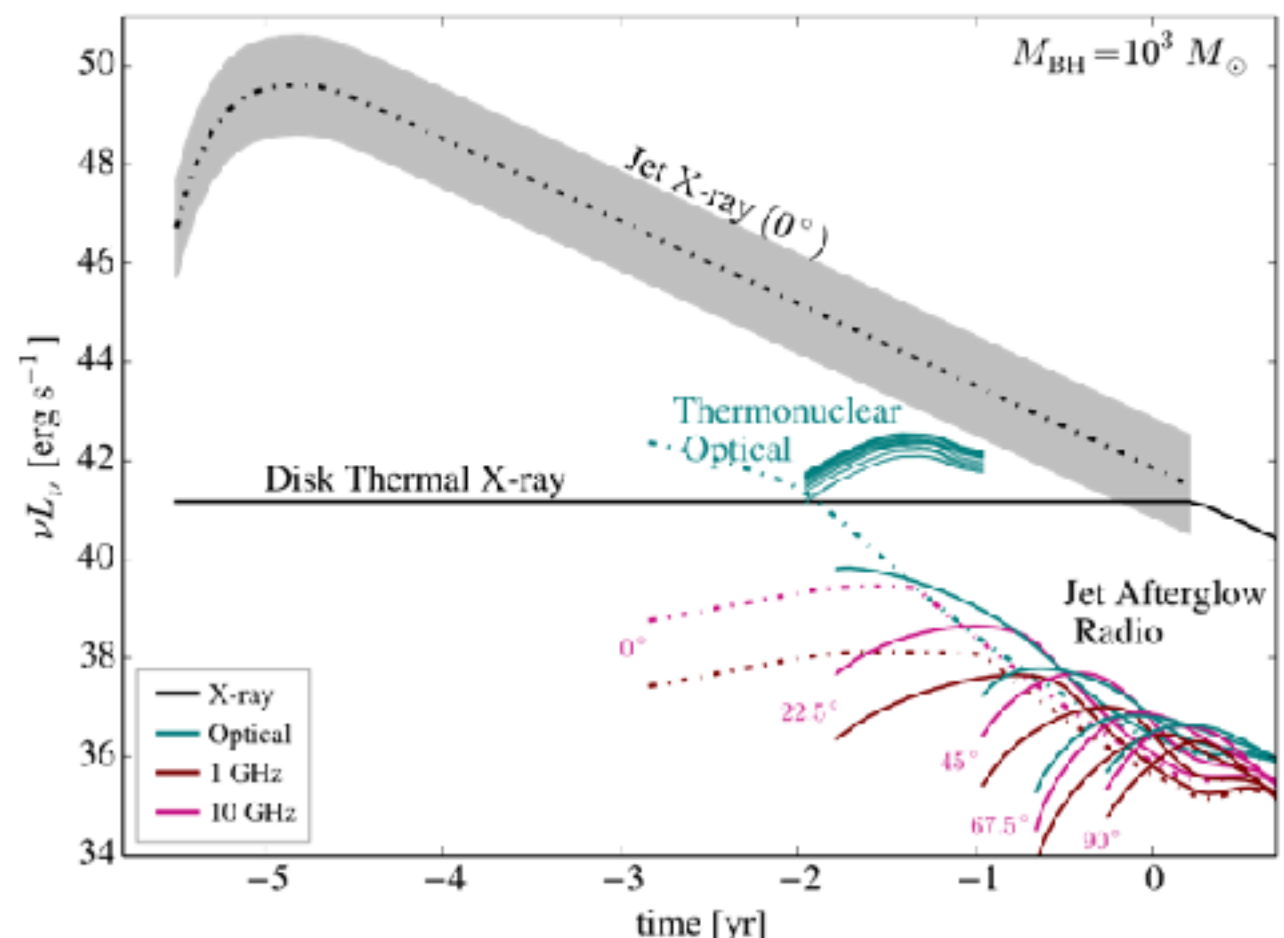
Mac Leod+16



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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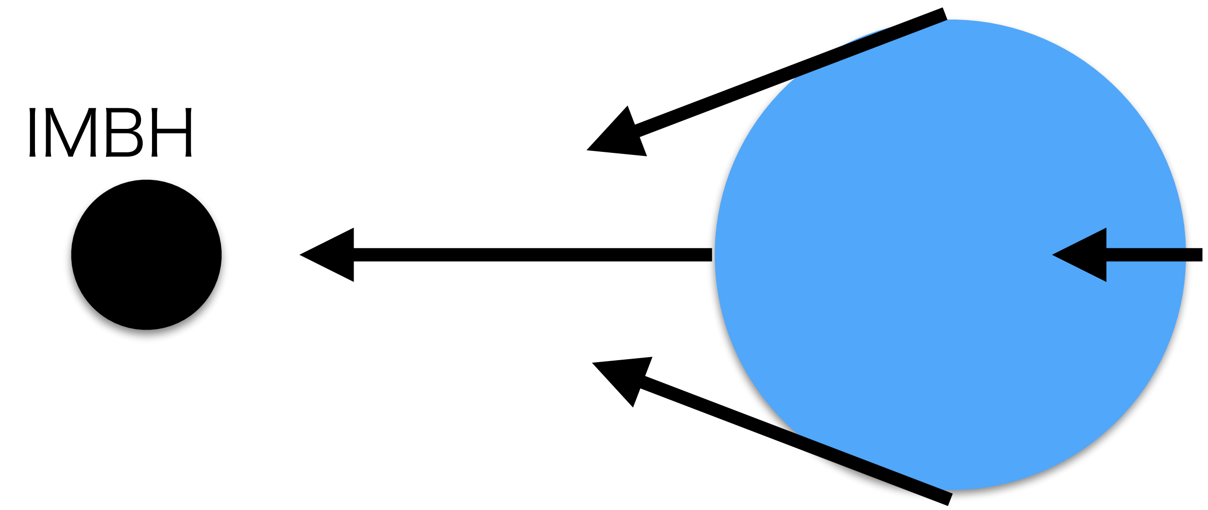
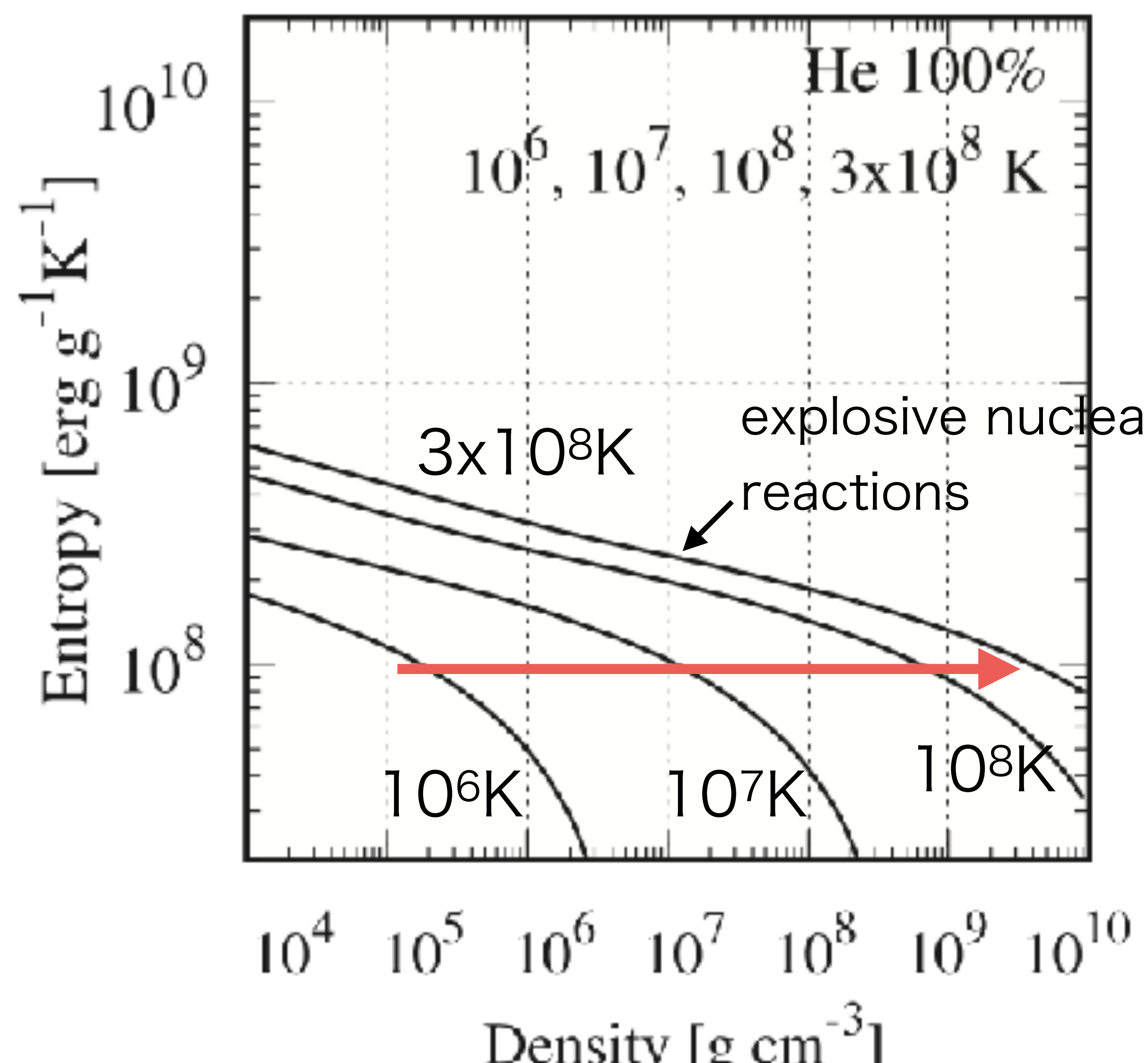
Optical surveys

- WD TDEs can be observed by optical observatories, similarly to SNe Ia.
- Many optical surveys are in progress and planning.
  - Current surveys: iPTF, HSC, etc.
  - Future surveys: ZTF, LSST, etc.
- WD TDEs may lurk in large archival data of current and future optical surveys.

Revisit of tidal detonation

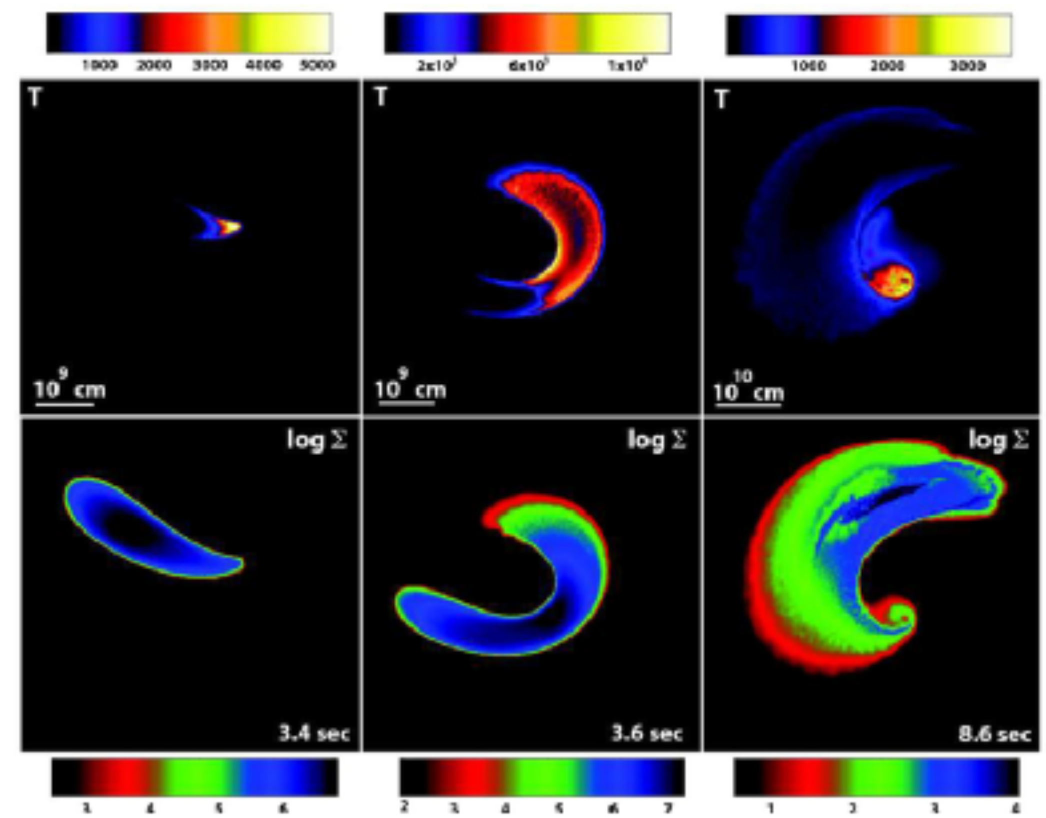
- What compression is required?
- Adiabatic compression is not sufficient for tidal detonation.
  - Density must be increased by five orders of magnitude.
  - Such orbits are impossible.
- Shock compression is required.

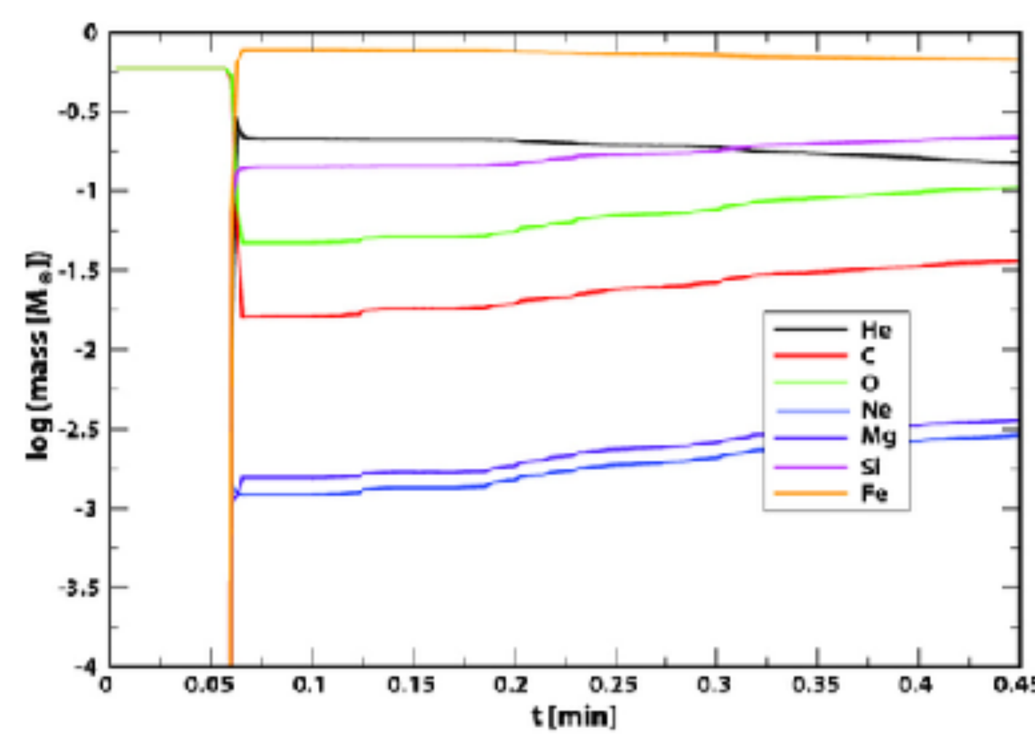




Previous study

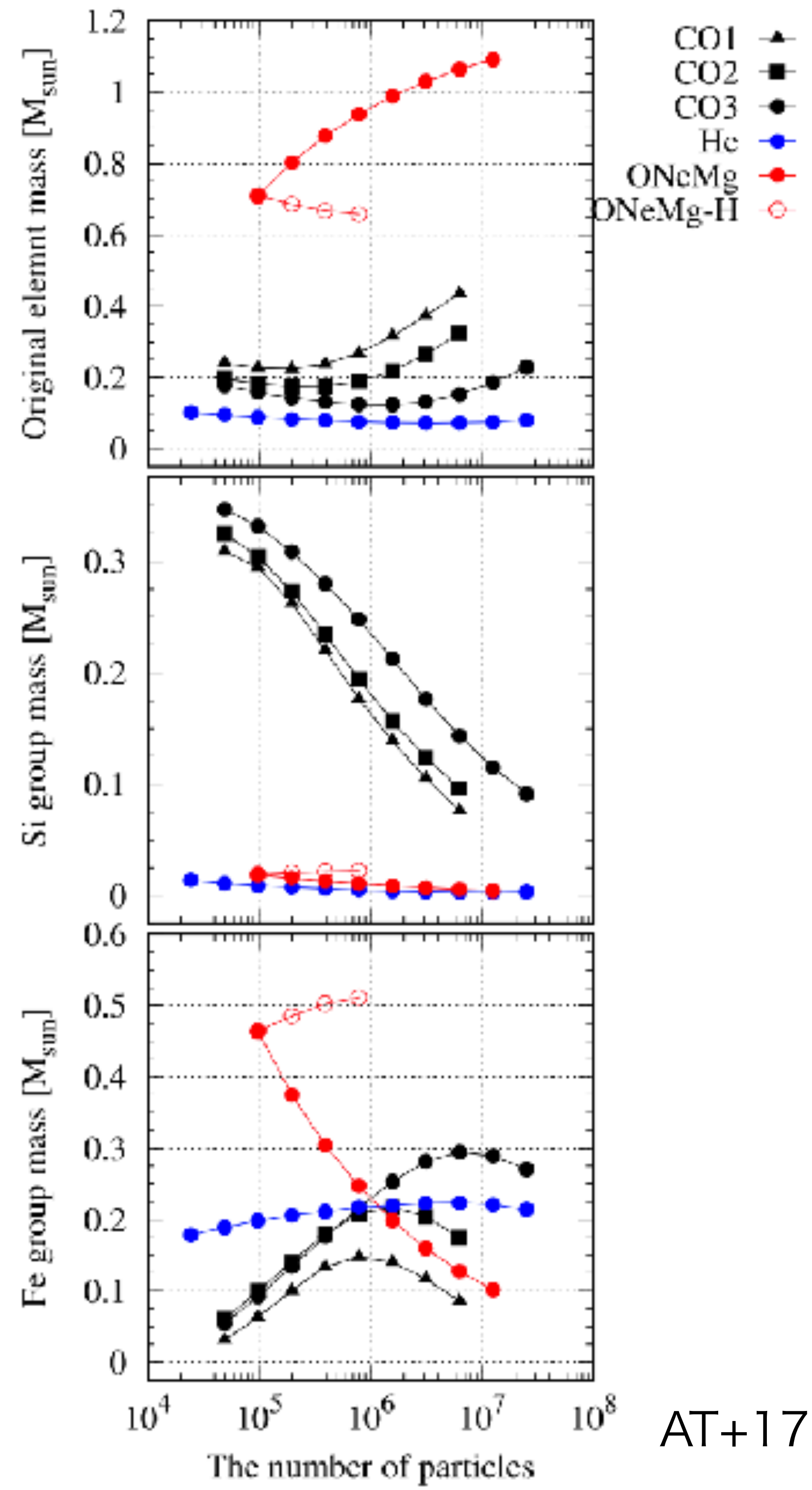
- Do previous studies follow shock compression?
- Rosswog et al. (2008; 2009)
  - Smoothed Particle Hydrodynamics (SPH) simulation of WD TDEs
  - A large amount of ^{56}Ni
  - SNeIa like transients
- But,
  - They didn't check convergence of mass resolution.
  - They didn't check the emergence of shock wave.





Our previous study

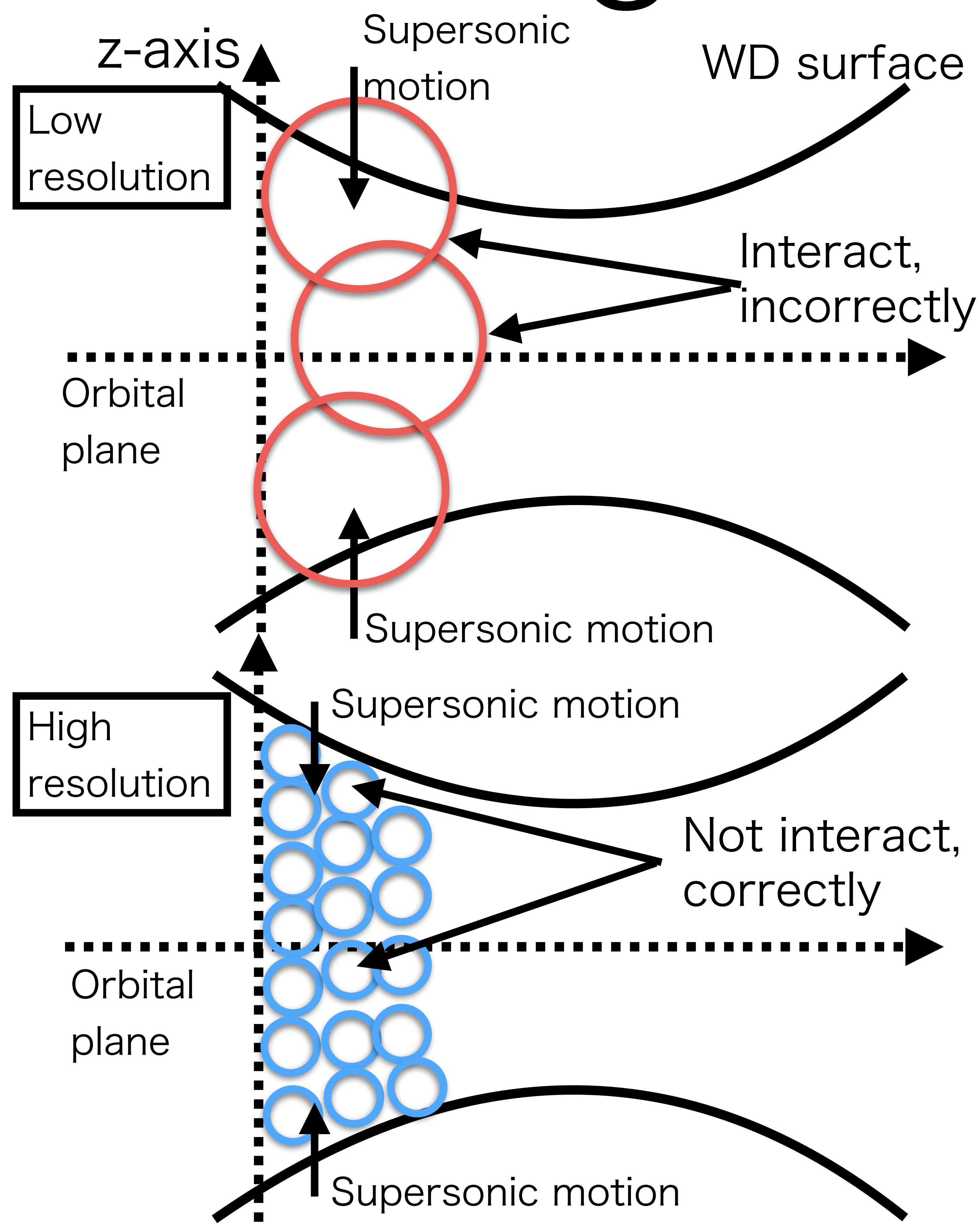
- SPH simulation in the same way as Rosswogs'
- Convergence check with the number of SPH particles $N=10^4$-10^7
  - Rosswog's N is $\sim10^6$
- Amounts of synthesized nuclear elements are not converged.
- These amounts become smaller with N increasing.



AT+17

Spurious heating

- Low resolution (small N)
  - Few particles in the direction perpendicular to the orbital plane
  - Incorrect interaction between distant particles
  - Heating due to their supersonic motion.
- High resolution (large N)
  - No interaction between distant particles
  - No heating even if these distant particles have supersonic relative velocity
- We made it clear that explosive nuclear reactions in Rosswog's simulation are due to spurious heating, not due to shock heating (physical heating).



Is tidal detonation false?

- The answer is “No. Not necessarily.”
- Rosswog’s results were incorrect.
- But, we didn’t deny the presence of tidal detonation.
- Tidal detonation could happen possibly.

High-resolution study

- We confirm whether tidal detonation occurs or not.

- We perform sufficiently high-resolution simulation, using 3D SPH and 1D mesh simulation technique, in order to capture genuine shock waves.

- We adopt an initial condition in which tidal detonation could occur easily.

Outline of our method

- Choose initial conditions: WD mass and composition, IMBH mass, and WD-IMBH orbit
- Perform 3D SPH simulation without nuclear reactions
- Extract data of flow structure in the z-axis direction from 3D SPH simulation as 1D initial conditions
- Perform 1D mesh simulation using the data as the initial conditions

Initial conditions

- WD mass and composition
  - WDs: 0.1-0.5$M_\odot$ HeWD, 0.5-1.1$M_\odot$ COWD, 1.1-1.4$M_\odot$
  - Our choice: 0.45$M_\odot$ HeWD
- IMBH mass
  - IMBHs: 10^2-$10^5 M_\odot$
  - Our choice: 300$M_\odot$
- WD-IMBH orbit
  - Parabolic orbit
  - Deep encounter ($\beta = R_t/R_p = 7$)

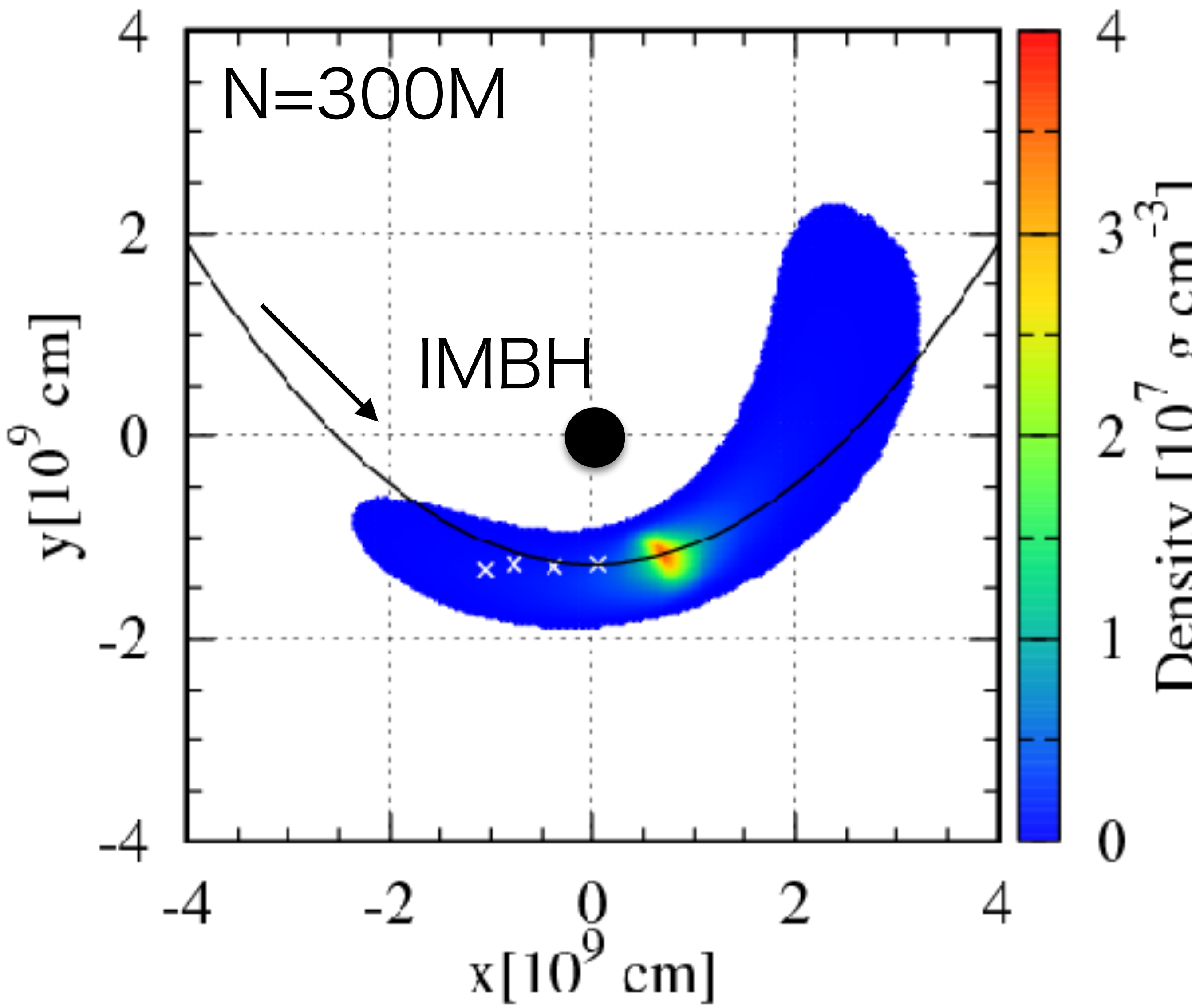
R_p: pericenter distance

R_t: tidal radius

$$R_{\rm t} = \left(\frac{M_{\rm WD}}{3M_{\rm IMBH}}\right)^{1/3} R_{\rm WD}$$

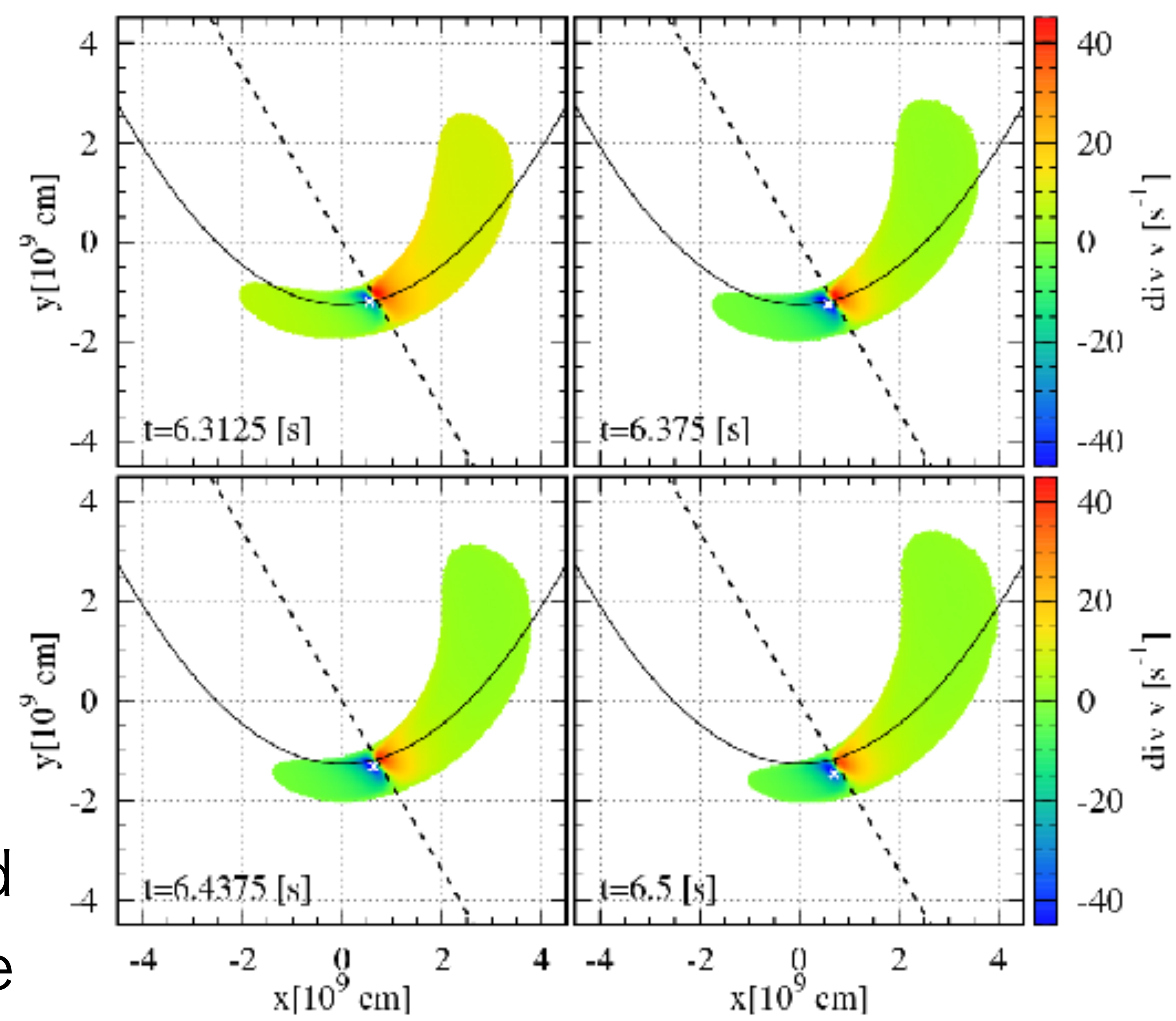
3D SPH simulation

- Our SPH code
  - The conventional algorithm, similar to GADGET
  - Using FDPS (Iwasawa, AT+16)
  - Optimization by SIMD(AT+12ab)
- Helmholtz EoS (Timmes, Swesty 2000)
- Oakforest-PACS (OfP) at JCAHPC, Kashiwa
- The number of SPH particles (N) for a WD: 4.7M-300M
- IMBH gravity: Newton gravity



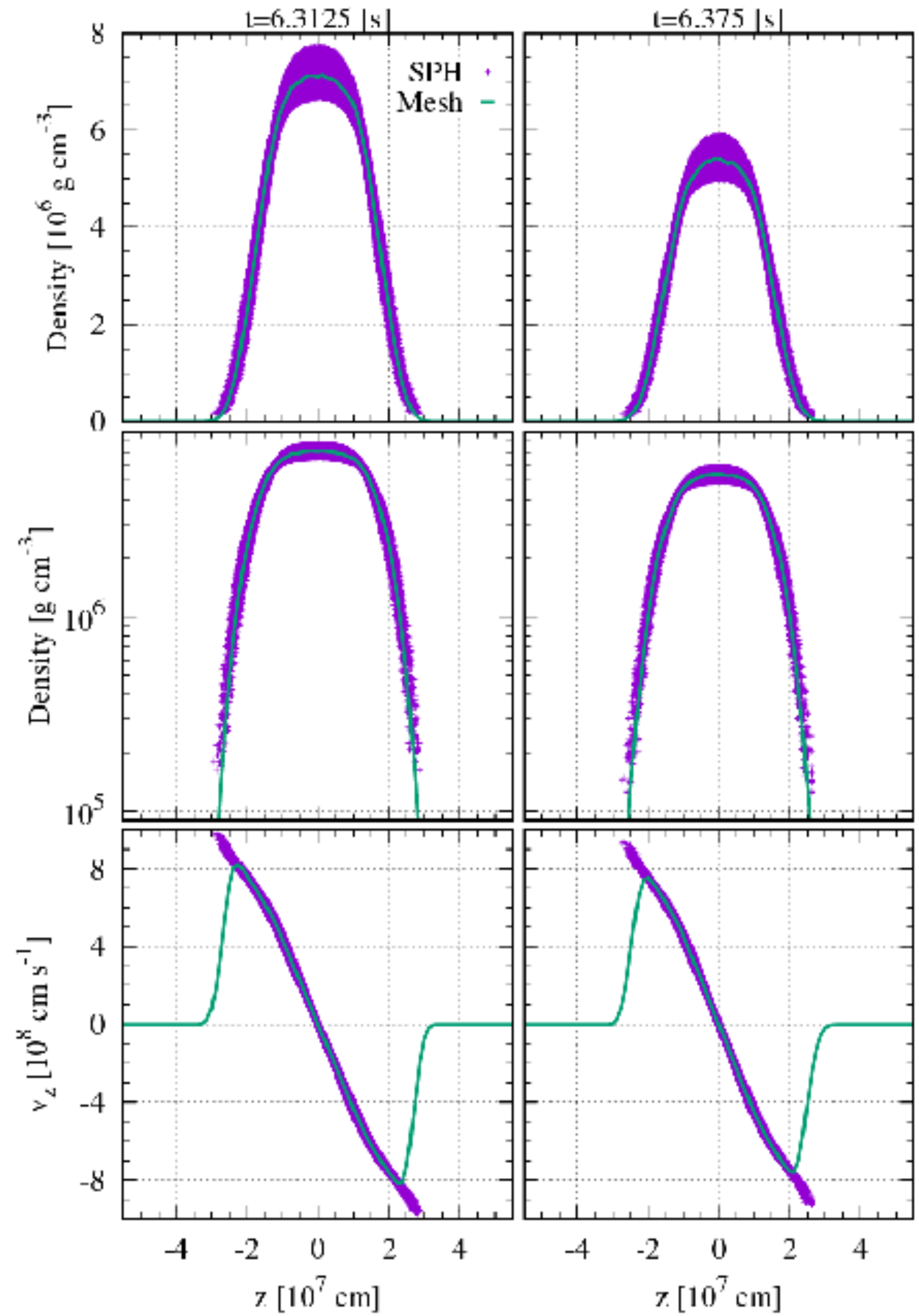
Extract 1D data from 3D data

- Intend to minimize 3D effects, e.g. tidal effect
- Extract portions just before bouncing back
- Extract a portion with the highest density among the above portions
- Use 3D data of density and v_z velocity, not temperature



Comparison of 1D with 3D

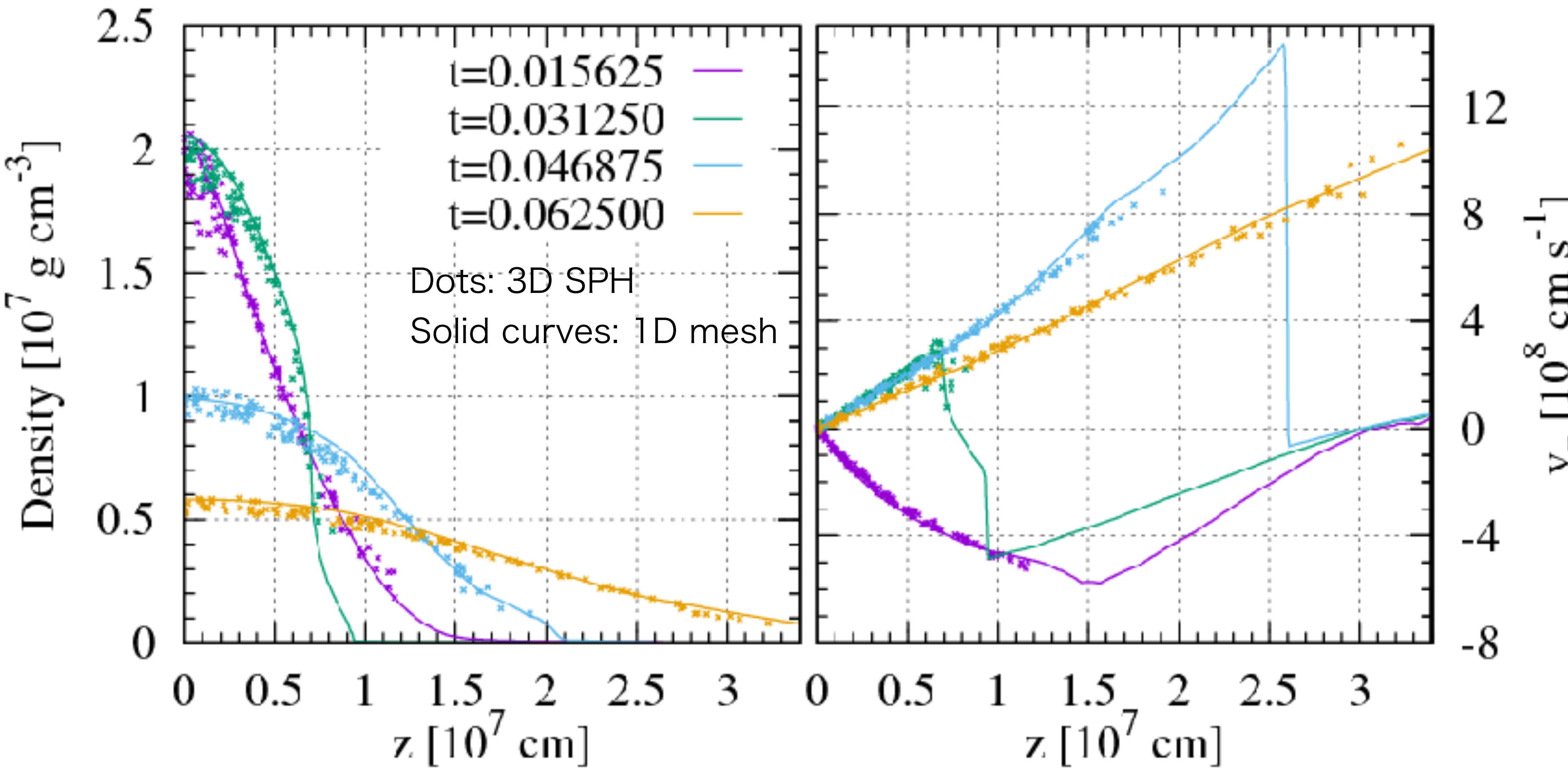
- Density profiles (>2x10^{5}gcm^{-3}) are in good agreement.
  - A shock wave at >10^{6}gcm^{-3} is important for the emergence of detonation.
  - Compression increases overall density by a factor of at most 5.
- Velocity profile is underestimated at the edge.
  - Disadvantage for the emergence of detonation



1D mesh simulation

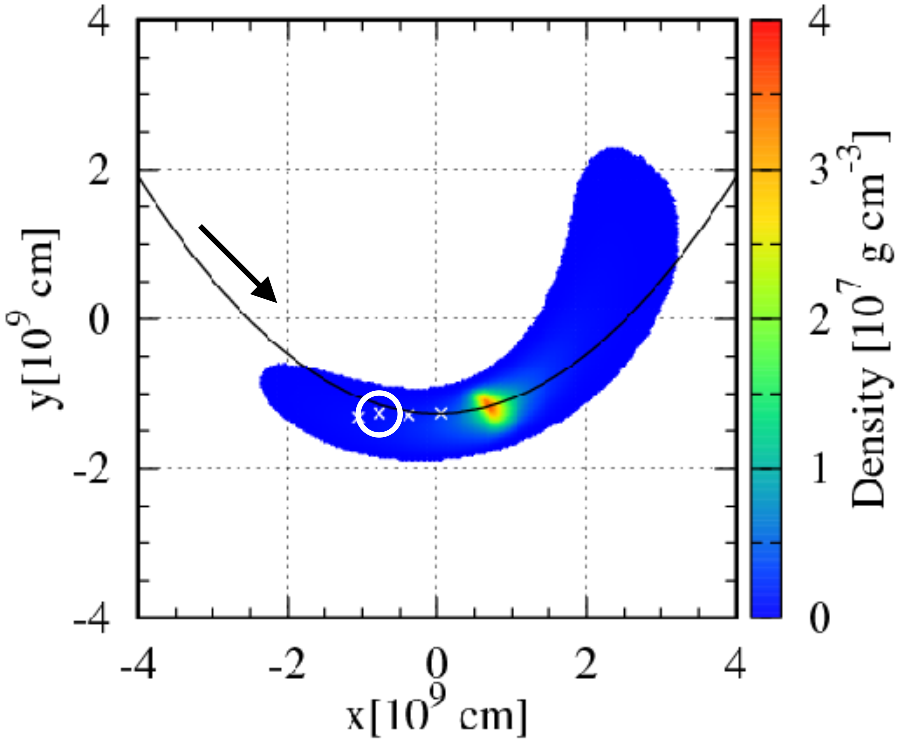
- FLASH code (Fryxell et al. 2000)
  - Equation of state routine “Helmholtz EoS”
  - Nuclear reaction network routine “Aprox13”
  - Neither self gravity nor IMBH gravity
- XC30 at CfCA, NAOJ

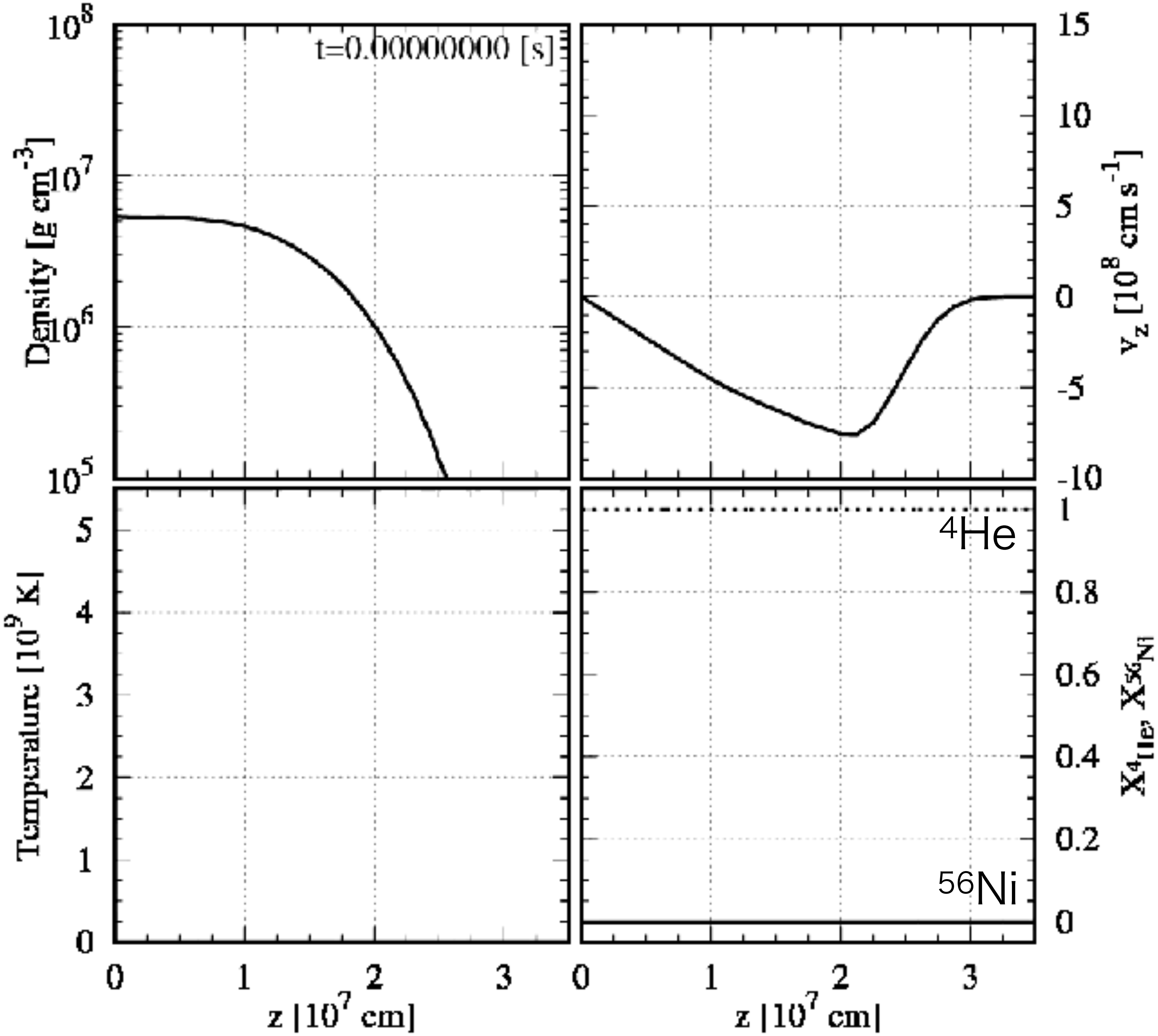
Comparison of 1D with 3D



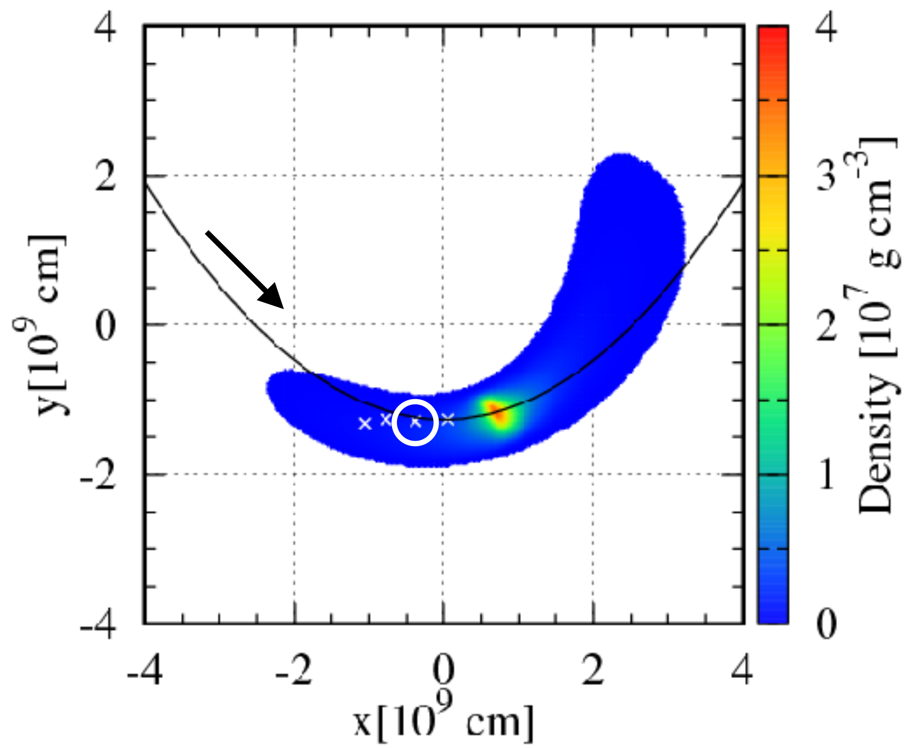
- We follow the record of sampling SPH particles at the extracted portion.
- We perform 1D simulation, turning off nuclear reaction network for this comparion.
- Density and v_z velocity are in good agreement between 3D and 1D simulations.
- 3D effects are not significant in this phase.

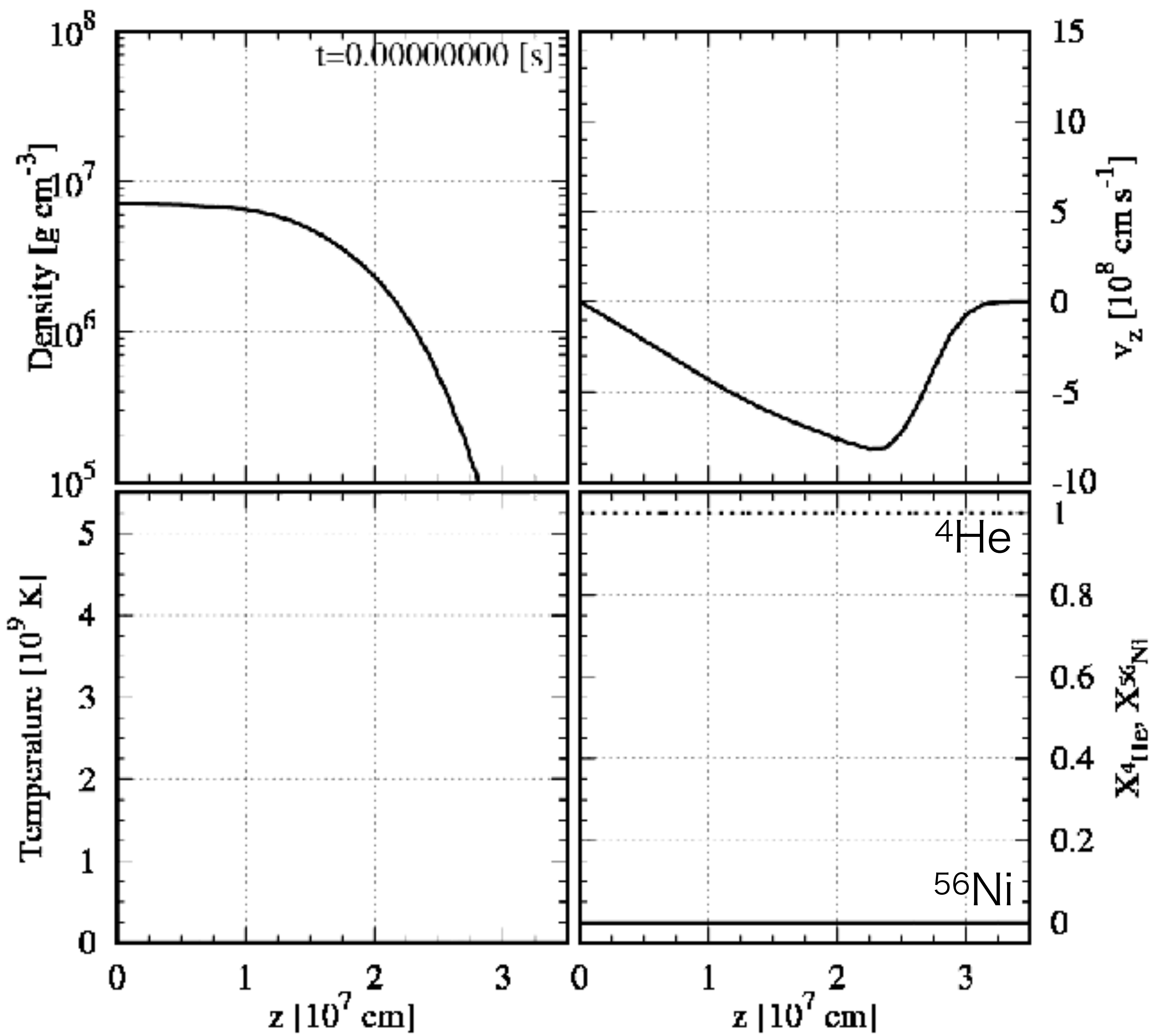
Failure case of detonation



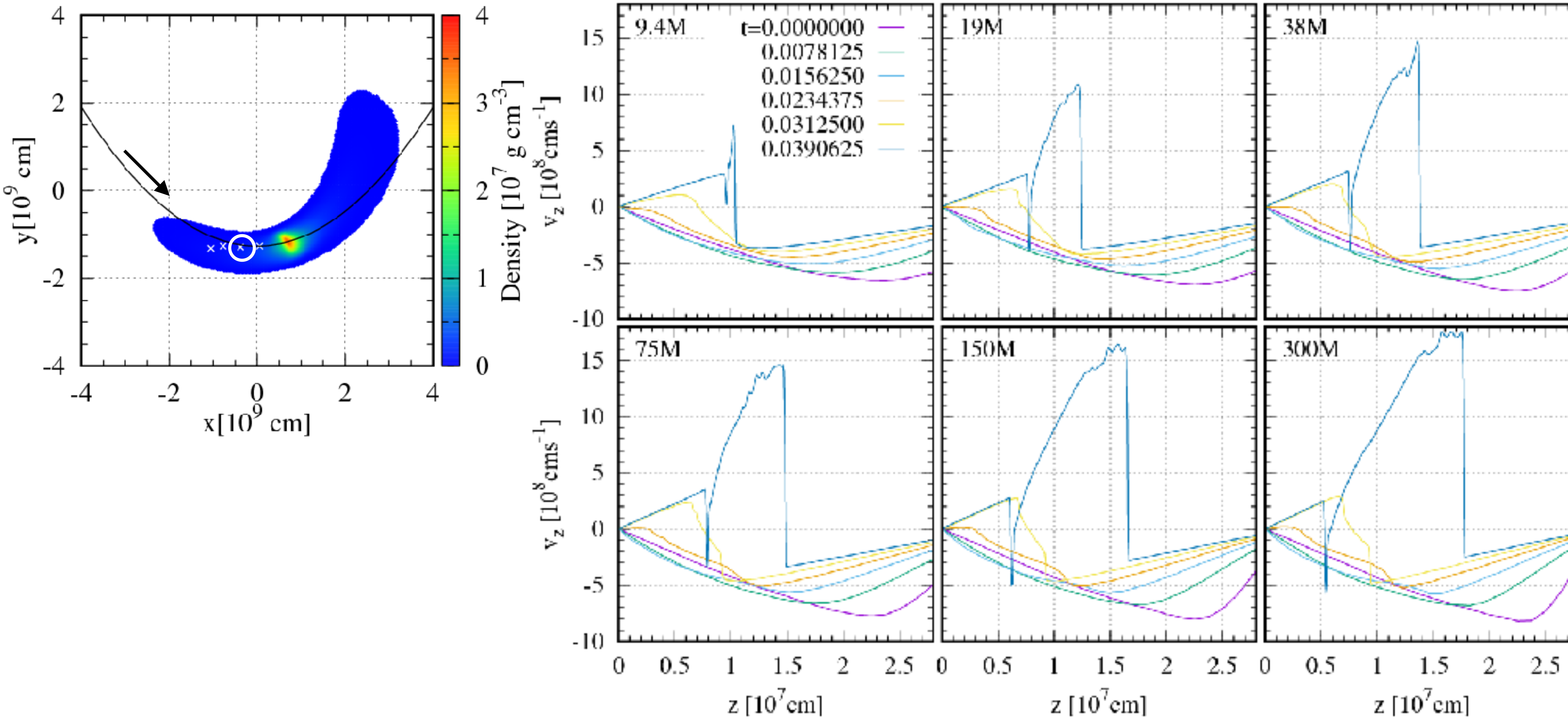


Success case of detonation



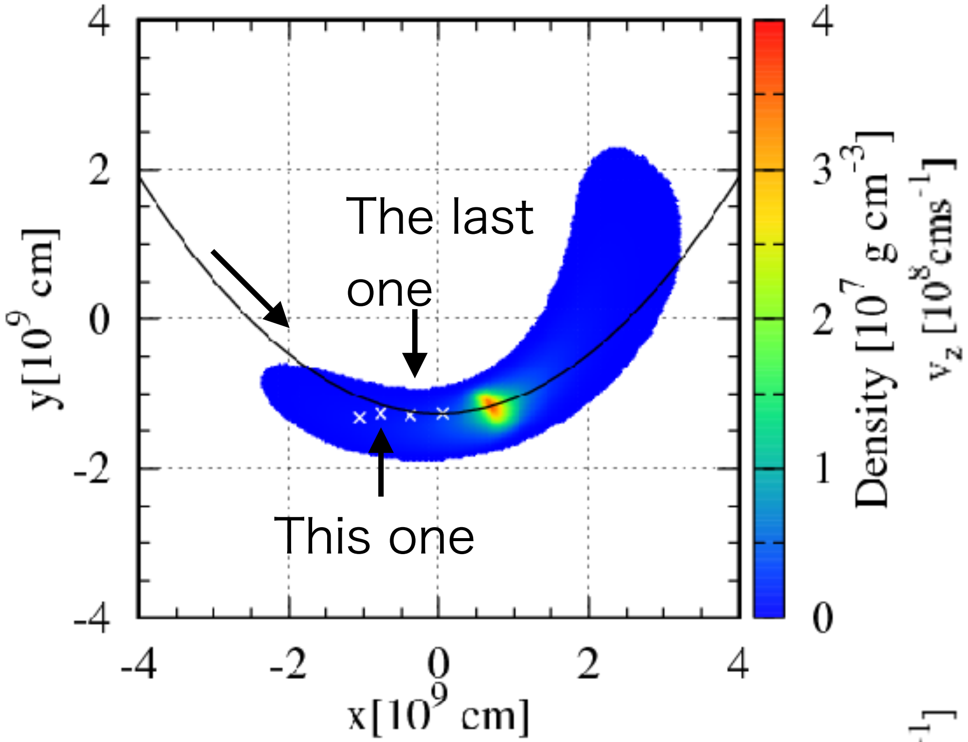


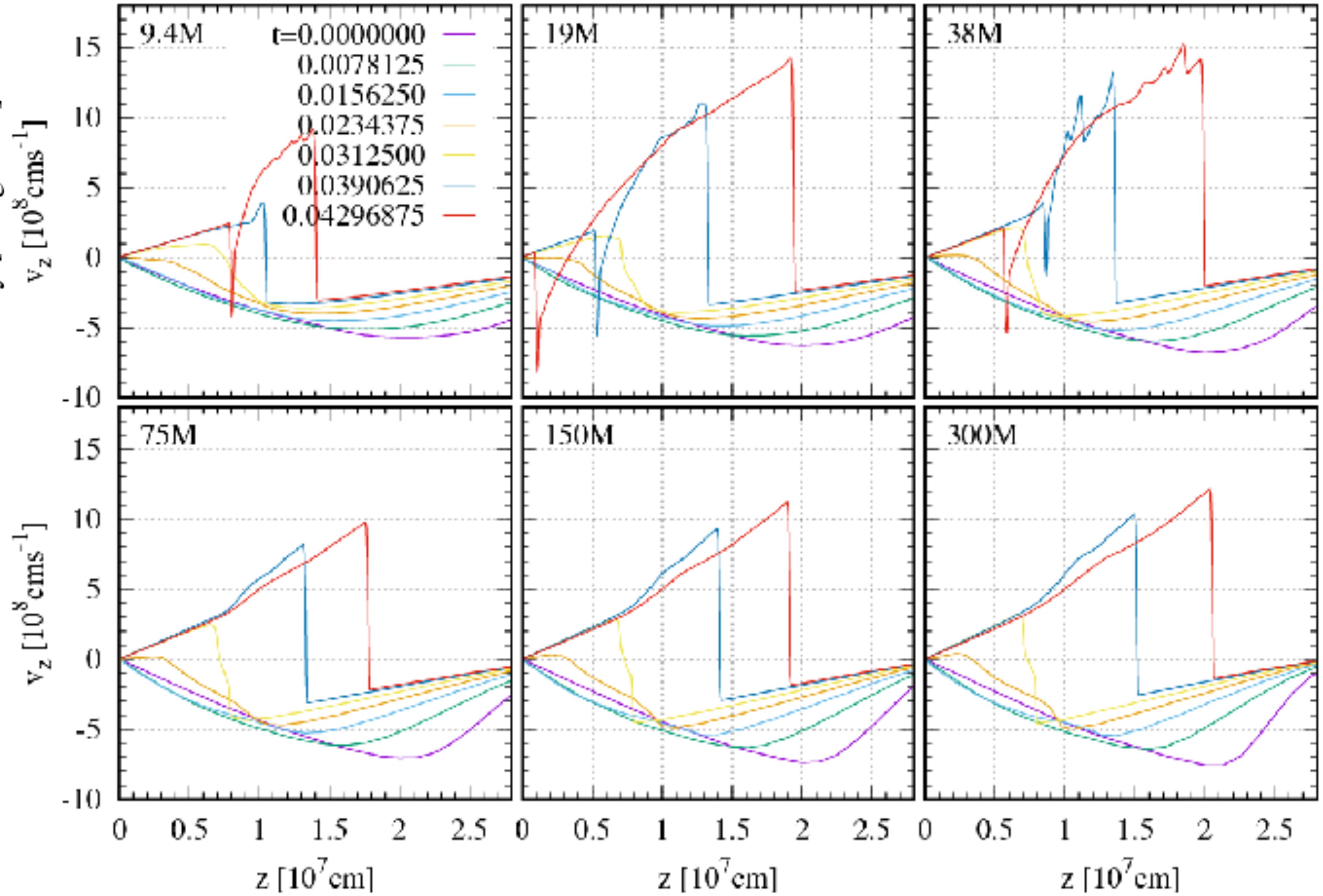
Convergence check 1



- This is convergence check of 1D results with different N in 3D SPH.
- This is NOT convergence check of 1D resolution.
- For all the N cases, detonation emerges.

Convergence check 2



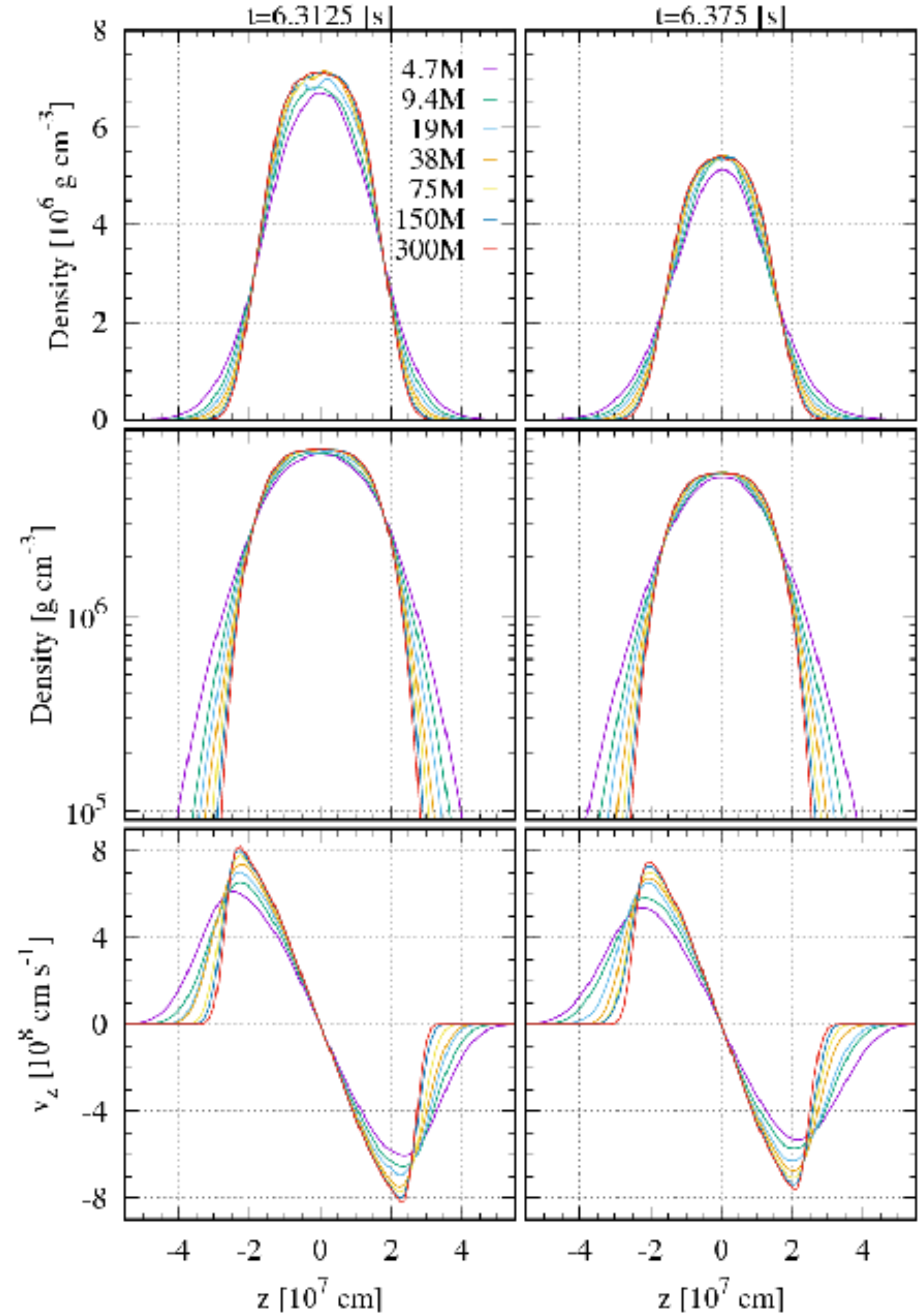


- This is a difference portion from the last slide
- For N<75M case, detonation appears.
- For N>=75M cases, detonation wave disappears.
- The results are not converged!

The reason for the disappearance (1)

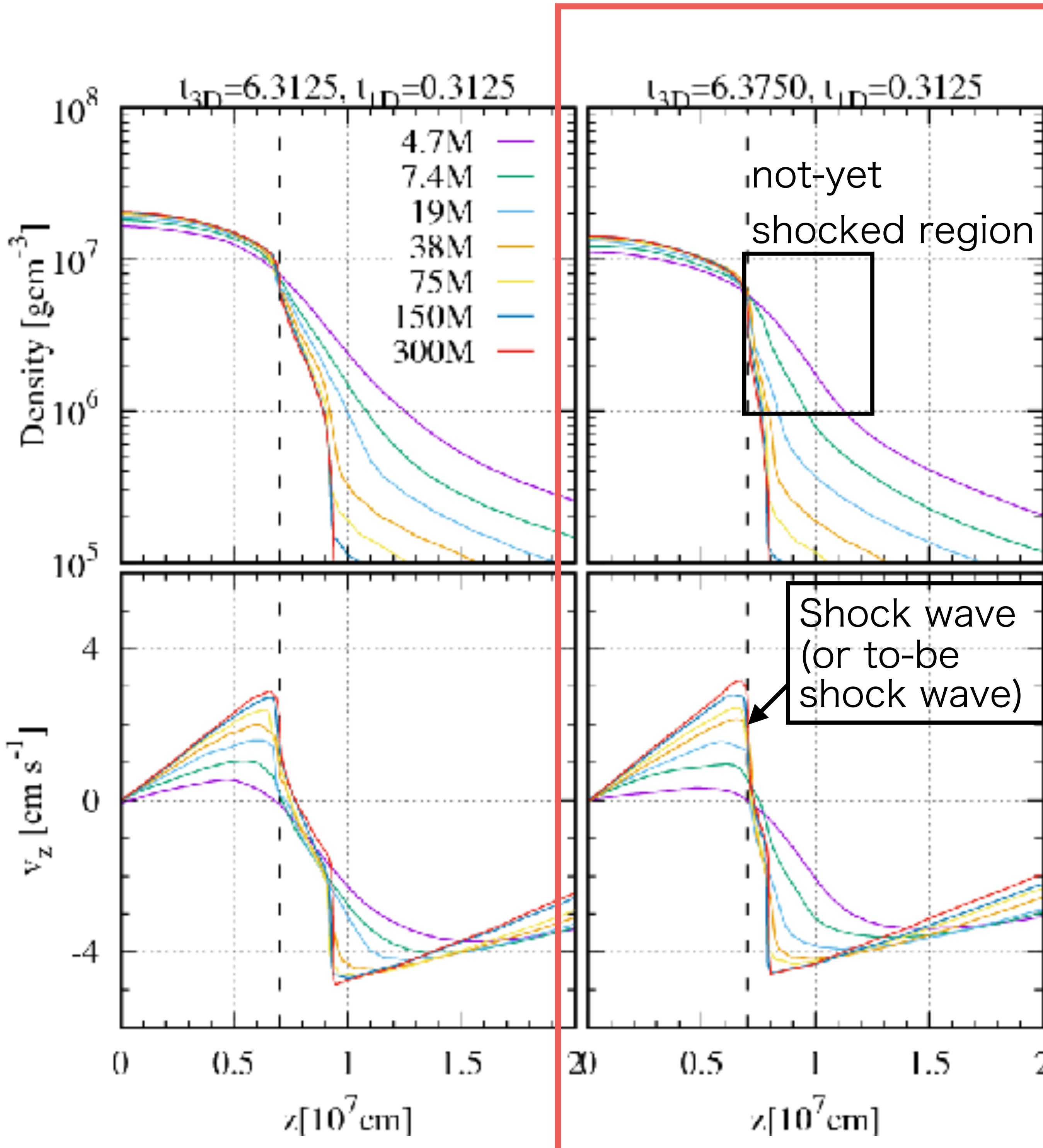
- 3D SPH simulation is not converged in N<75M, especially at the edge of the WD.
- The density at the edge is overestimated for small N cases.
- This is because SPH particles have large kernel lengths for small N cases.

1D initial conditions



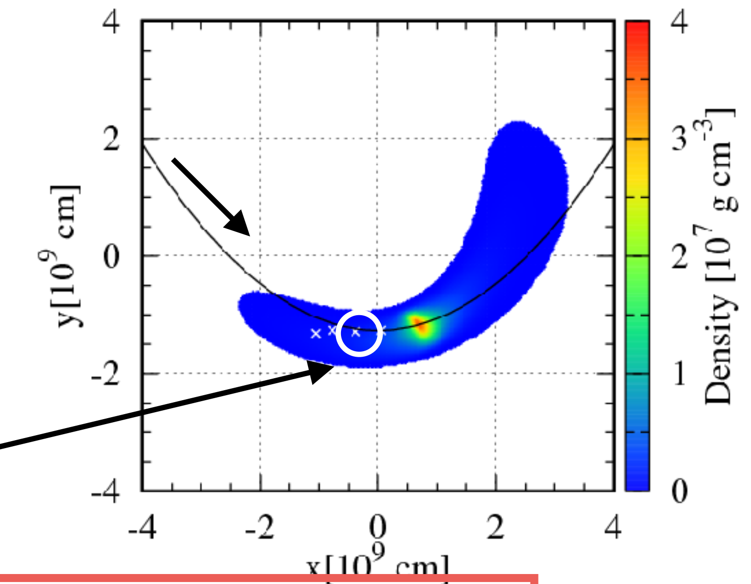
The reason for the disappearance (2)

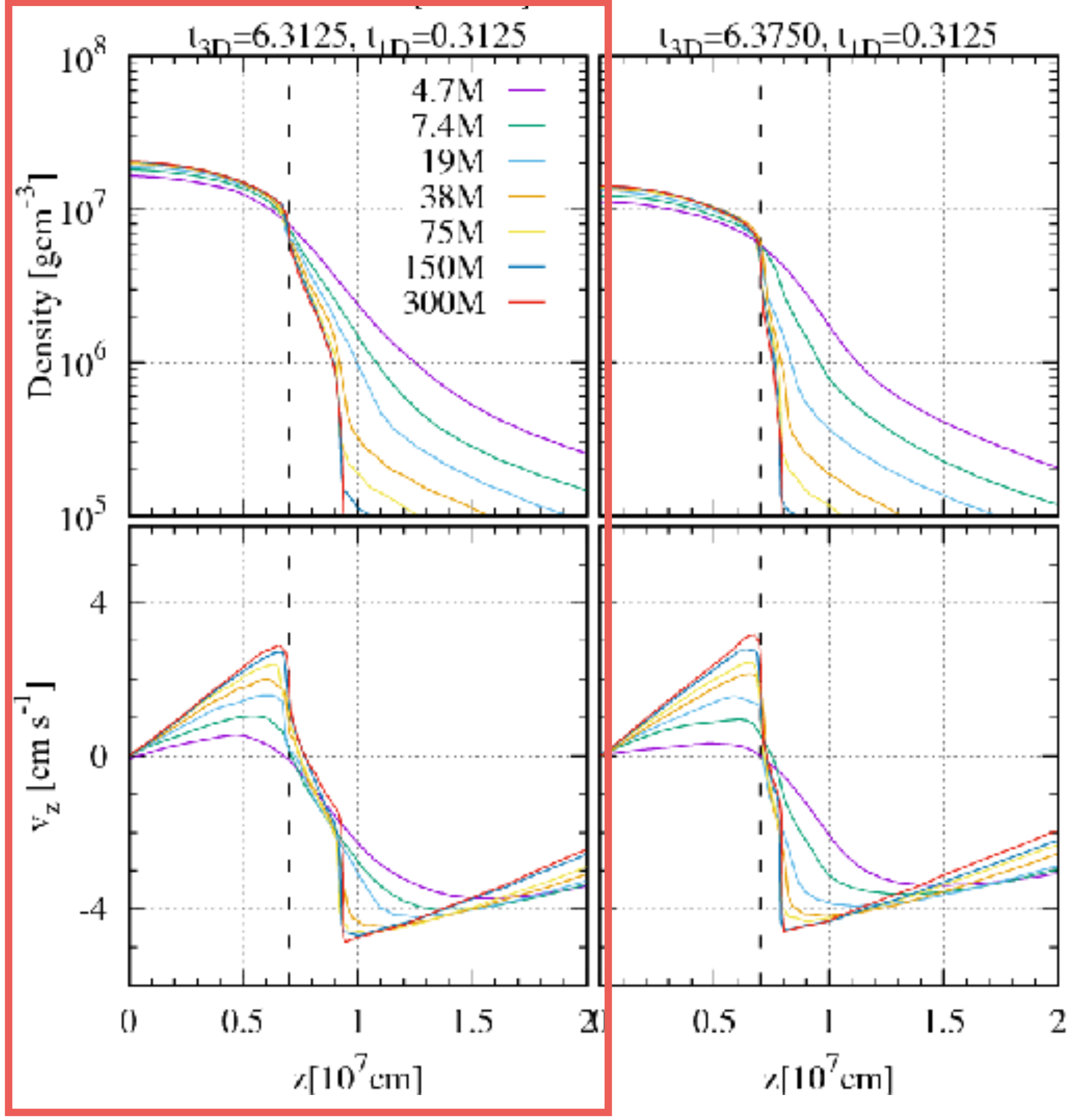
- Just before a shock wave emerges, not-yet shocked region has larger density for smaller N cases, if density is > 10^6 gcm^{-3}.
- Condition of initiation of detonation steeply depends on density (> 10^6 gcm^{-3}) at not-yet shocked regions.
- Detonation wave is easily generated for smaller N cases.



Is tidal detonation false again ?

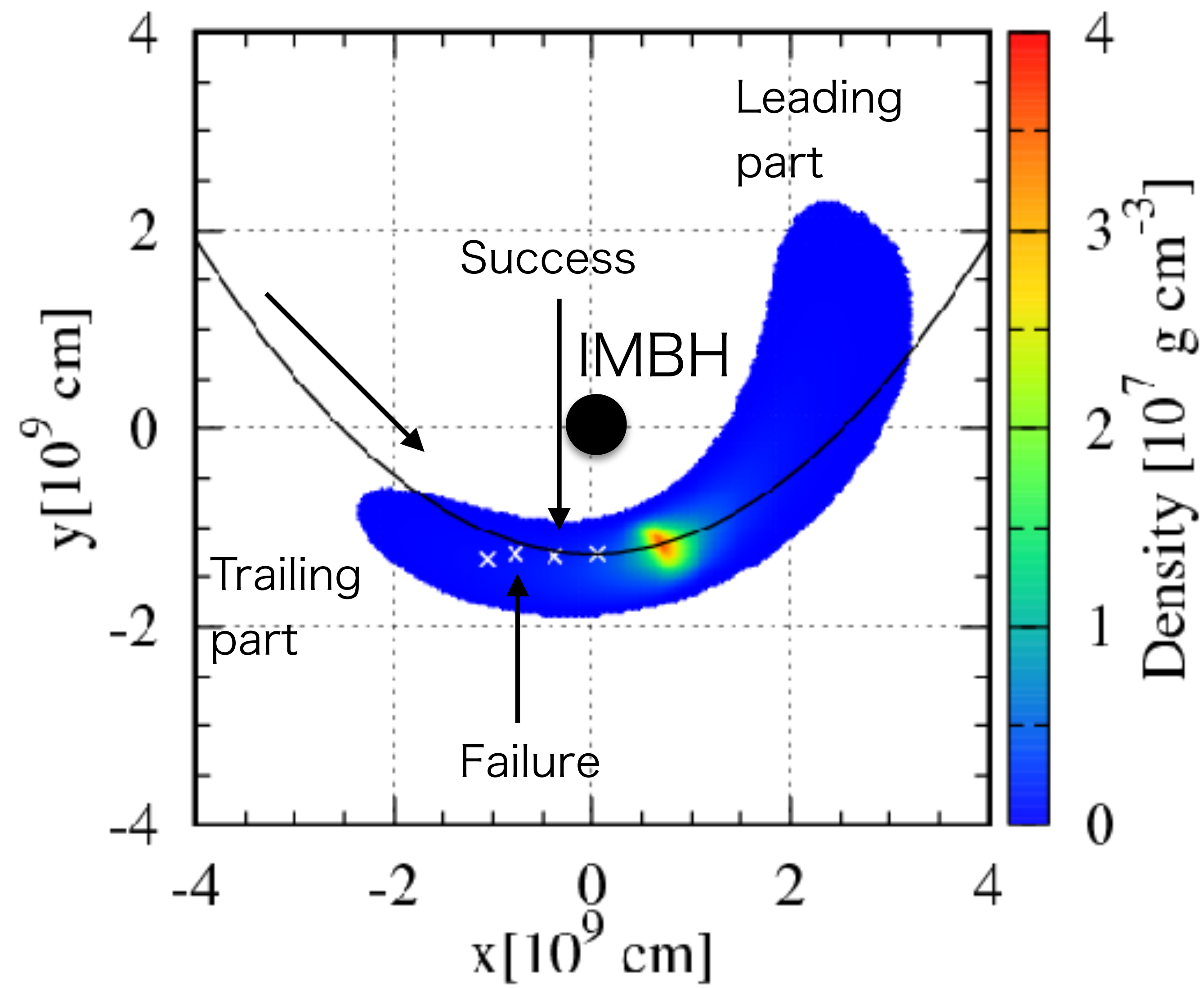
- The answer is "No".
- Detonation wave is still generated at this region even for N=300M.
- Density and v_z profiles are converged in the range of N=75M - 300M.
- Detonation will occur if N>300M.
- Tidal detonation is true!



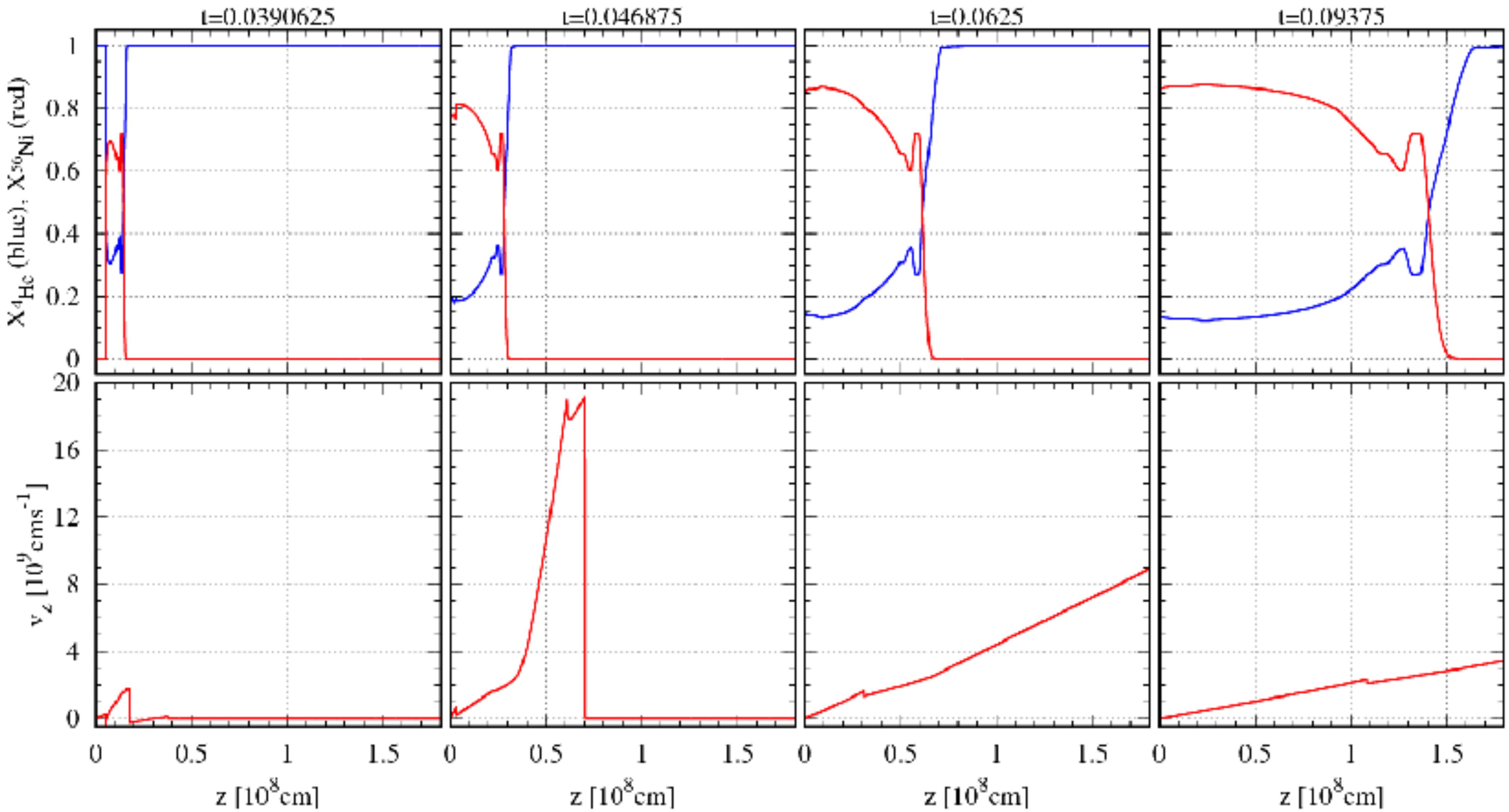


What makes the two portions different?

- The detonated portion precedes the undetonated portion.
- Generally, a leading part of a WD passes closer to an IMBH than a trailing part.
  - Closer parts are more compressed by the IMBH.
- All the parts preceding the detonated portion could be detonated.
  - The expected mass is $0.37 M_\odot$.



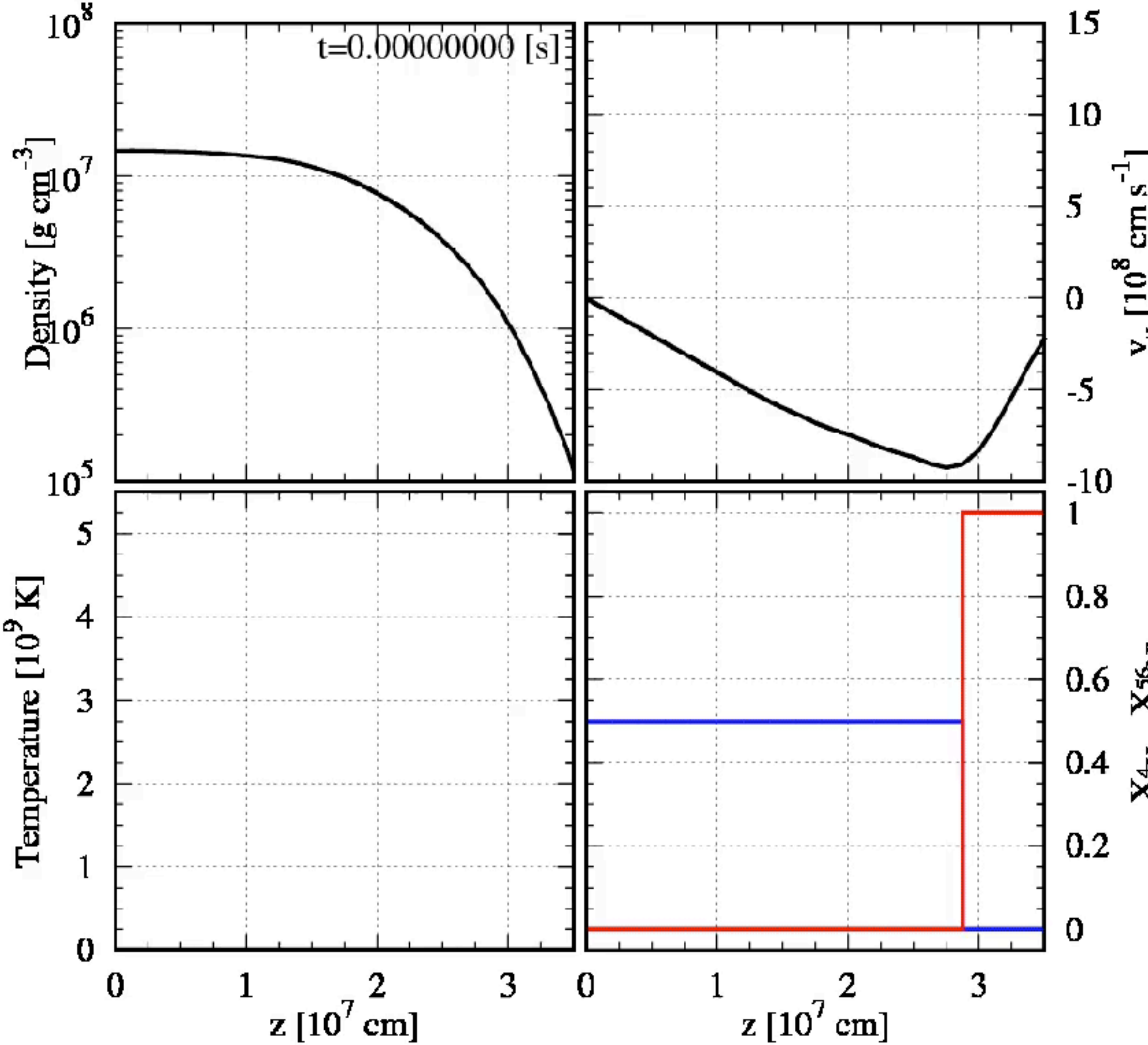
Nucleosynthesis



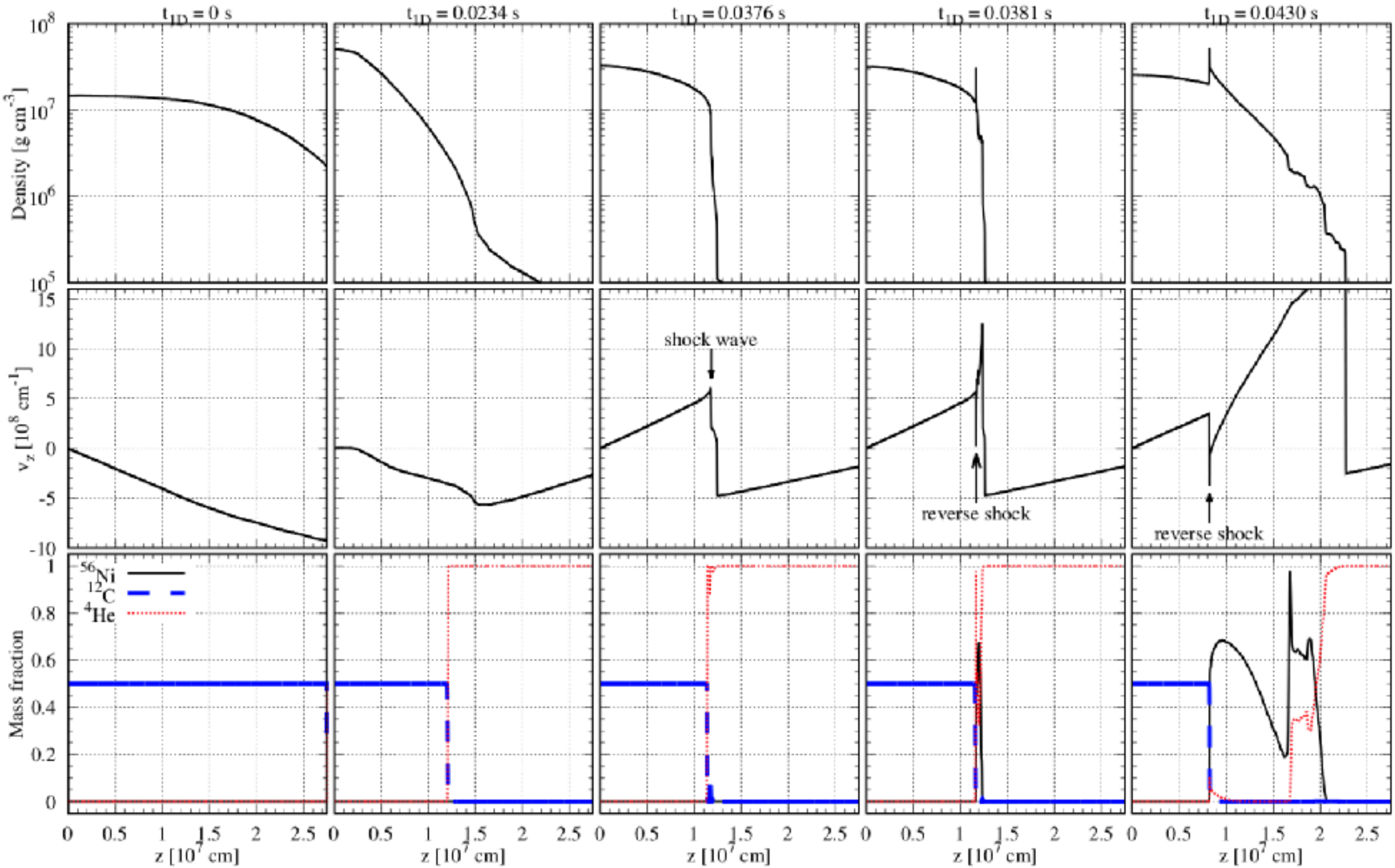
- The detonation wave leaves 20% ^{4}He and 80% ^{56}Ni.
- The detonated region has high density (>10^{6} gcm^{-3}).
- There are very small amounts of light elements, such as ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, and ^{44}Ti.
- This WD TDE cannot be observed as Ca-rich transients, despite of the expectation of Sell et al. (2015), unfortunately.

Tidal double detonation

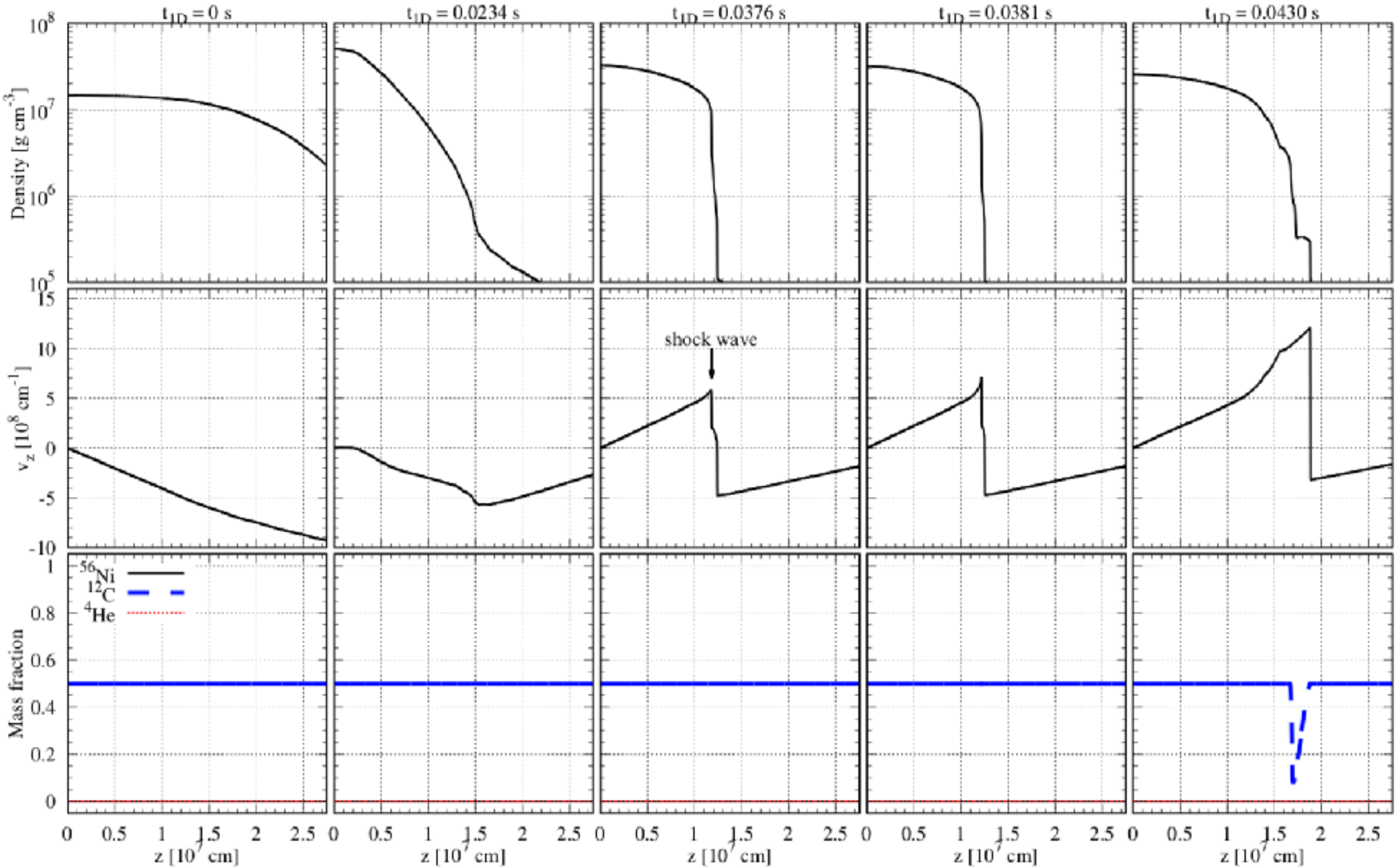
- The explosion mechanism is as follows.
  - A WD with a CO core and a He shell is tidally disrupted.
  - A shock wave generated in the He shell triggers a He detonation wave.
  - The He detonation wave invades into the CO core.
  - A CO detonation wave occurs.
- We name this explosion mechanism after the double detonation scenario in the context of type Ia supernovae.



t=0.00000000 [s]
Density [g cm^{-3}]
10^8
10^7
10^6
10^5
v_z [10^8 cm s^{-1}]
15
10
5
0
-5
-10
Temperature [10^9 K]
5
4
3
2
1
0
$X_{^4He}$, $X_{^{56}Ni}$
1
0.8
0.6
0.4
0.2
0
z [10^7 cm]
0
1
2
3
z [10^7 cm]
0
1
2
3



t1D = 0 s
t1D = 0.0234 s
t1D = 0.0376 s
t1D = 0.0381 s
t1D = 0.0430 s
Density [g cm-3]
vz [10^8 cm-1]
Mass fraction
shock wave
reverse shock
reverse shock
56Ni
12C
4He
z [10^7 cm]



t1D = 0 s
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t1D = 0.0430 s
Density [g cm-3]
vz [10^8 cm-1]
Mass fraction
shock wave
56Ni
12C
4He
z [10^7 cm]

Summary

- We study tidal detonation of a WD by an IMBH.
- We should be careful of spurious heating in low-resolution SPH simulations.
- We show the tidal detonation can occurs true in high-resolution numerical simulations.
- We suggest tidal double detonation of a WD with a CO core and He shell.
- In future, we will devise a method to follow nucleosynthesis of tidal detonation easily for pseudo-observation of WD TDEs by radiative transfer calculation.