中間質量ブラックホールによる白色矮星の潮汐破壊と熱核爆発

WD TDE and explosion by IMBH

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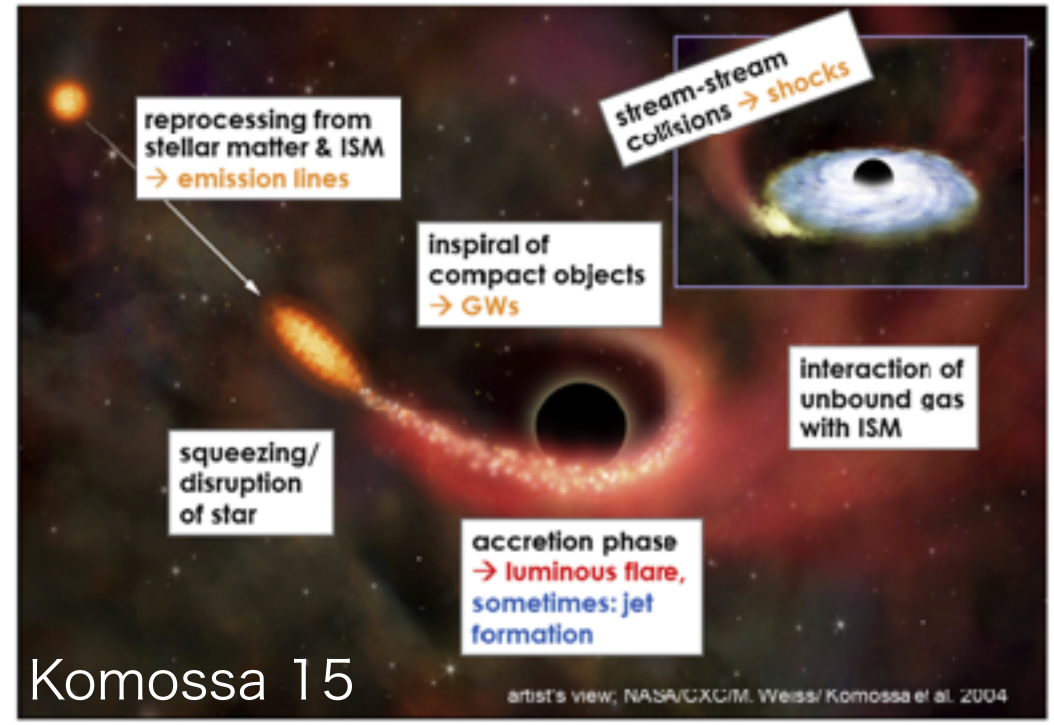
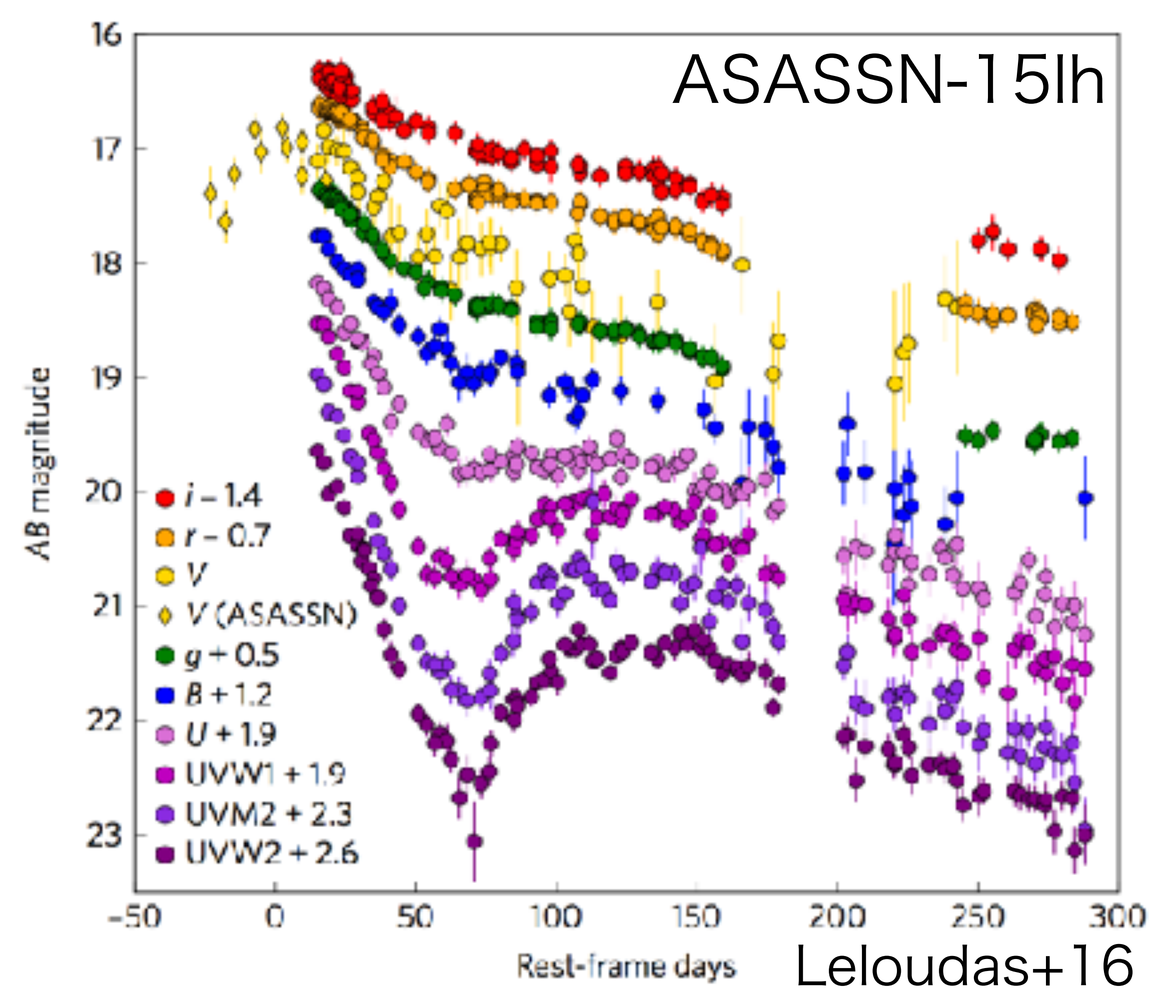
- Tanikawa et al. (2017, ApJ, 839, 81)
- Tanikawa (2018, ApJ, 858, 26)
- Tanikawa (2018, MNRAS, 475, L67)
- Kawana et al. (2018, MNRAS, 477, 3449)

Tidal Disruption Event

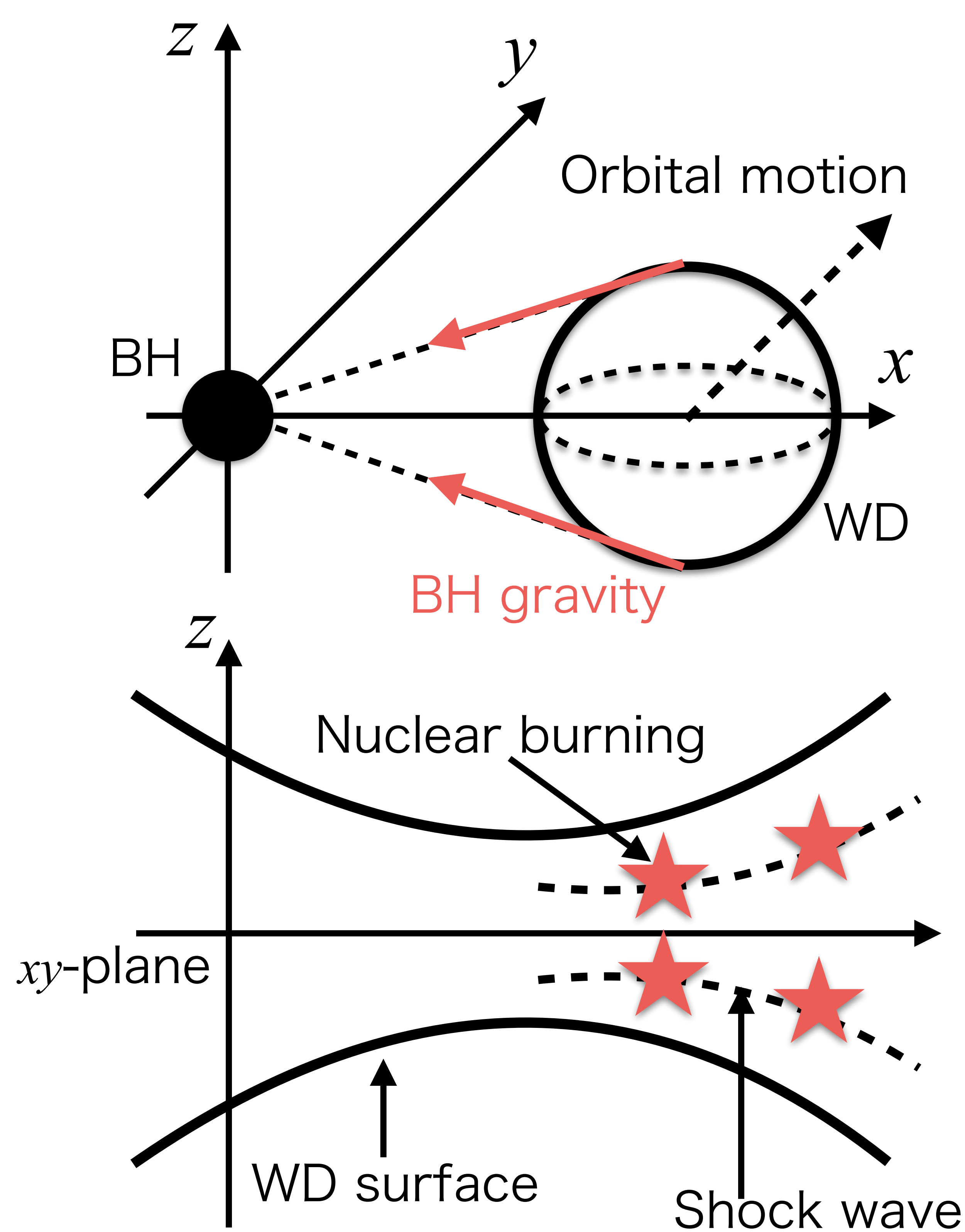
- Tidal disruption of a star (e.g. main sequence stars) by a BH
- Bright flare powered by accretion of the stellar debris
- Several ten candidates (Kommosa 2015)
  - TDEs of main sequence stars
  - Several candidates of WD TDEs (e.g. Ioka et al. 2016)





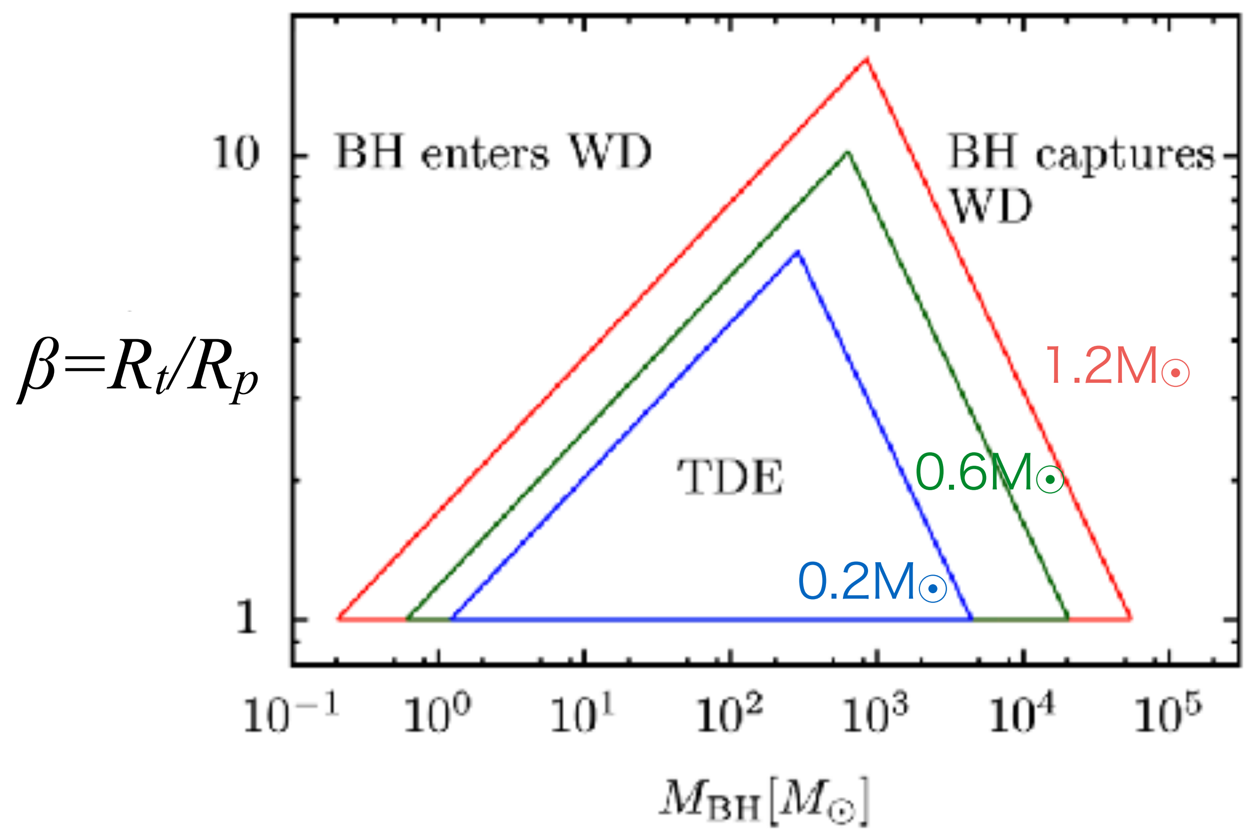
Tidal detonation

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



Probe to search for Intermediate mass black hole

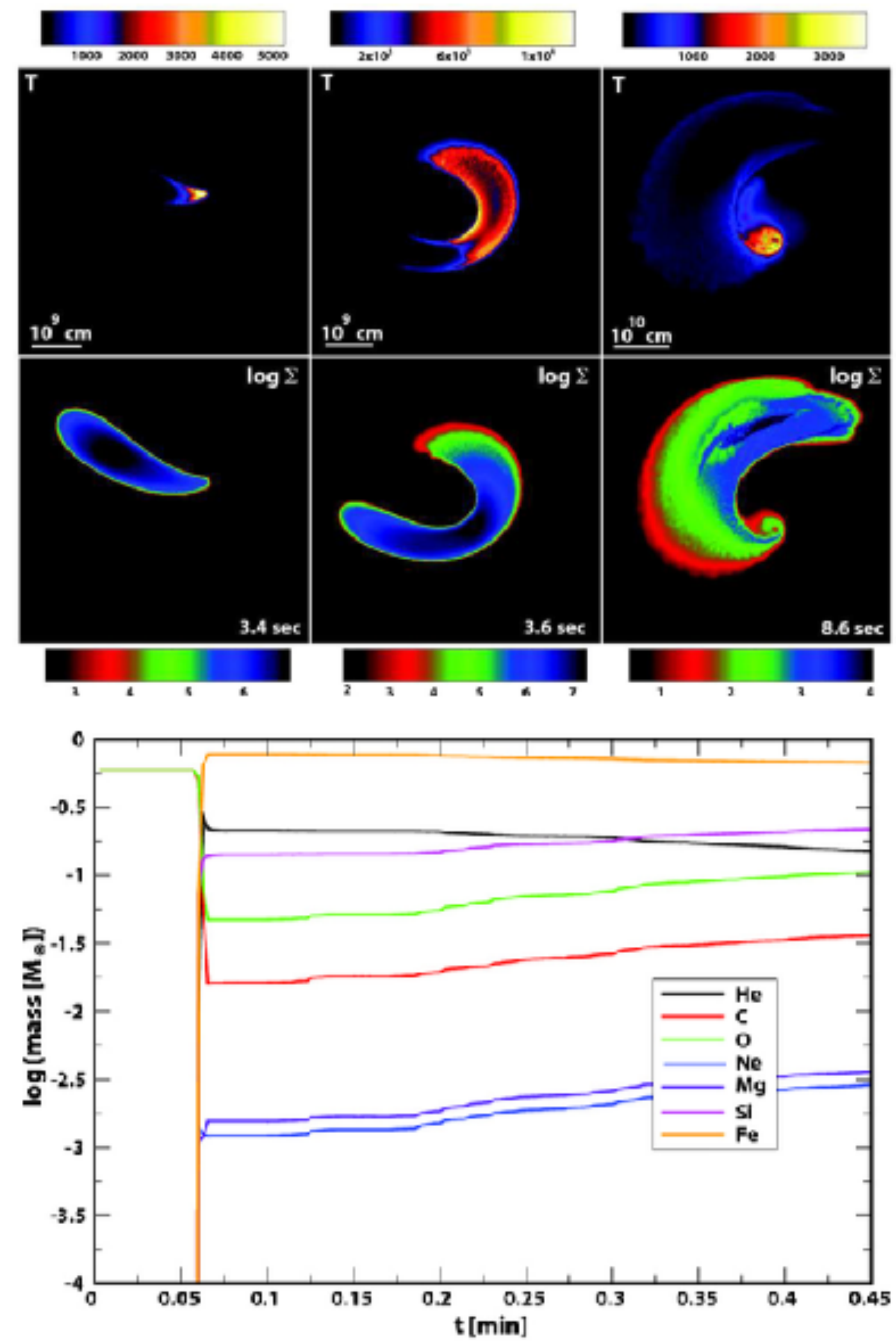
- Tidal detonation requires a WD TDE.
- A WD can be tidally disrupted only by an IMBH.
  - swallowing a stellar-mass BH.
  - swallowed by a massive BH.
- WD TDEs can illuminate only IMBHs.
- WD TDEs can be probes to search for IMBHs.



Kawana et al. 2017 (see also Luminet, Pichon 1989 Rosswog et al. 2009; MacLeod et al. 2016)

Previous and our studies

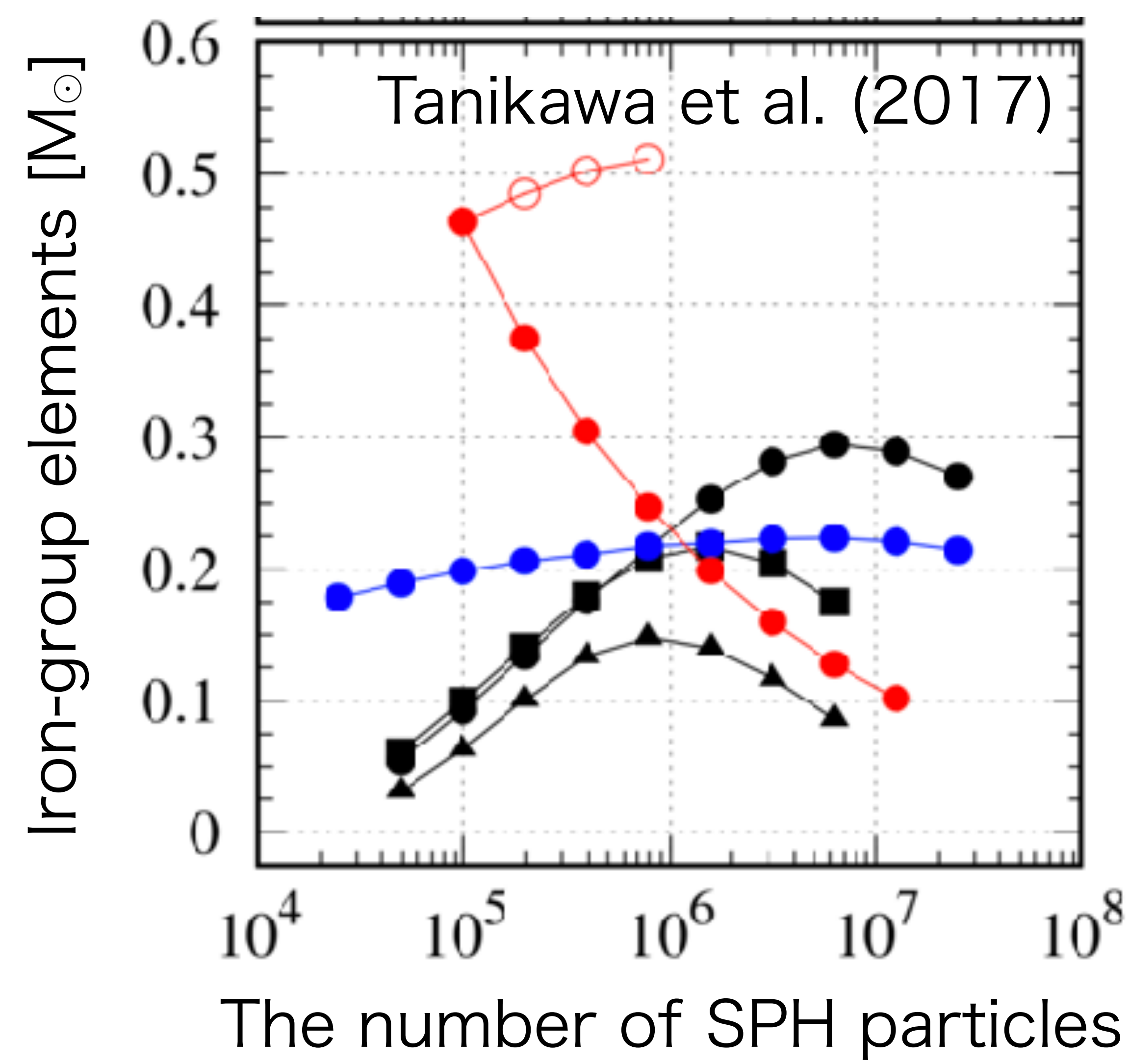
- Previous studies
  - Demonstration of large amounts of ^{56}Ni yielded
  - No convergence check about mass resolution
  - No demonstration of shock generation
- Our studies
  - Convergence check
  - Demonstration of shock generation



Rosswog et al. (2008; 2009)

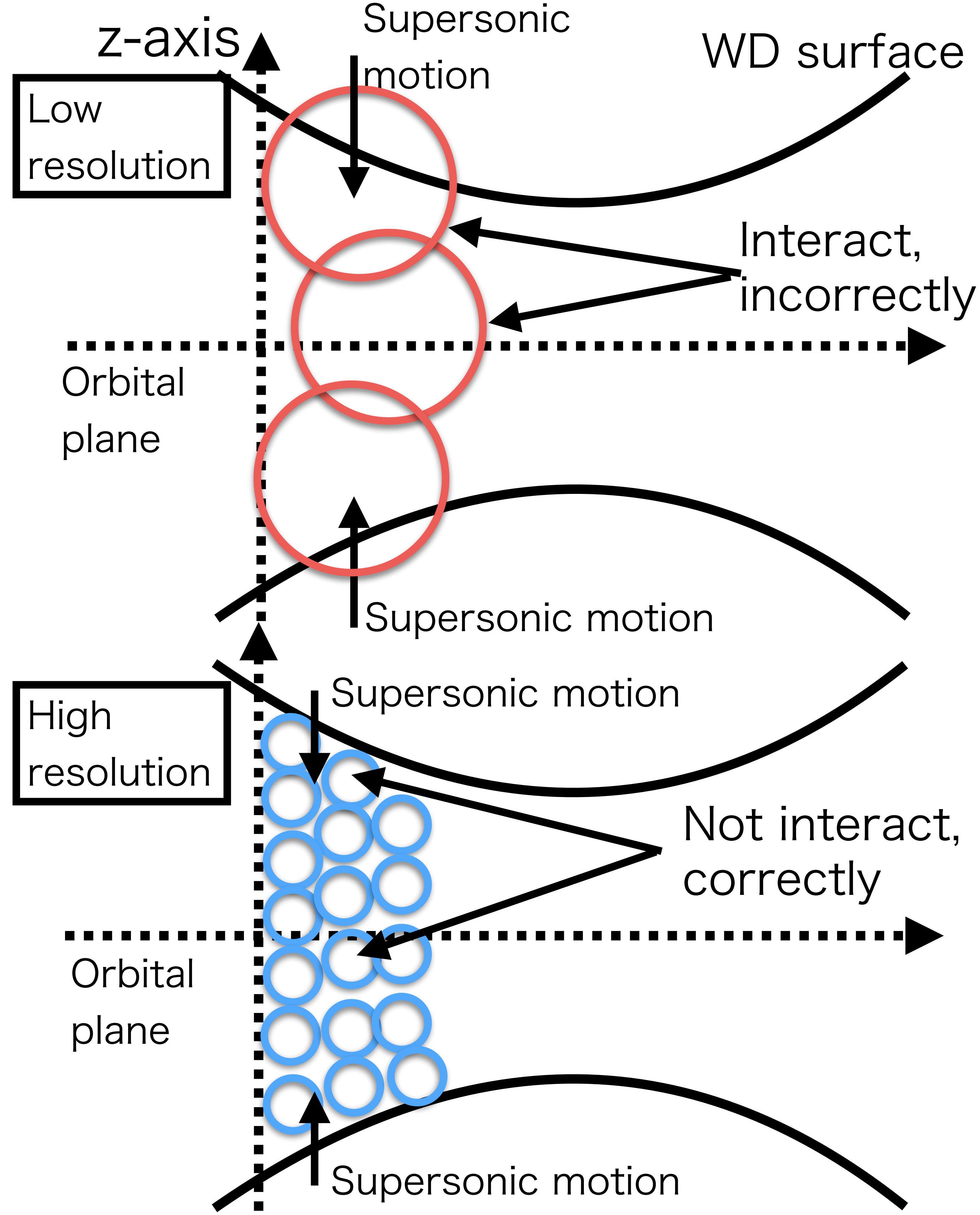
SPH simulation

- SPH simulation in the same way as in previous studies, but with higher-mass resolution
  - Massively-parallel 3D SPH simulation code
  - Helmholtz EoS
  - Aprox13 nuclear reaction networks
  - N >~ 10^7
- Ni yielded by spurious heating due to low resolution, not by a shock wave



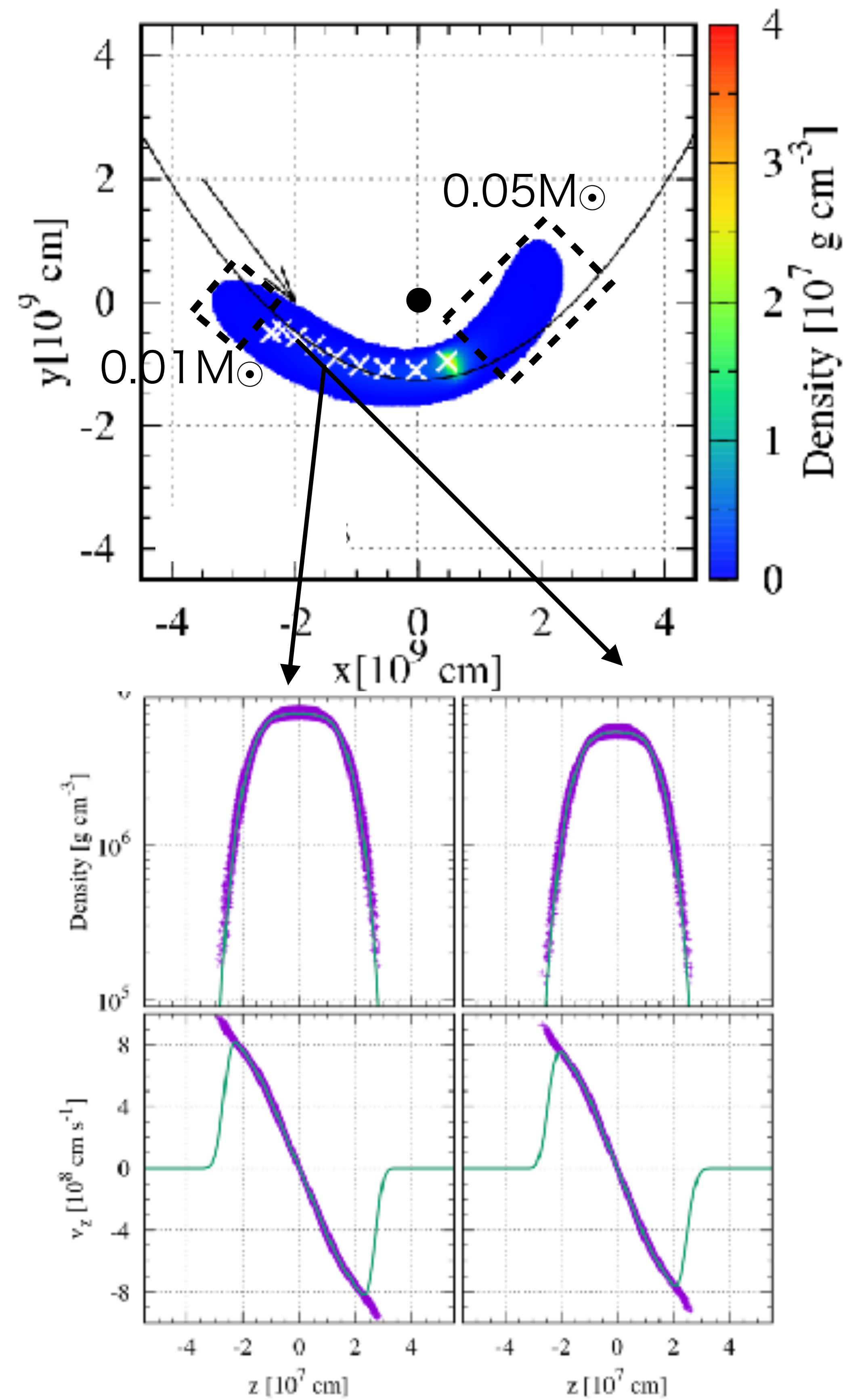
Spurious heating

- 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.

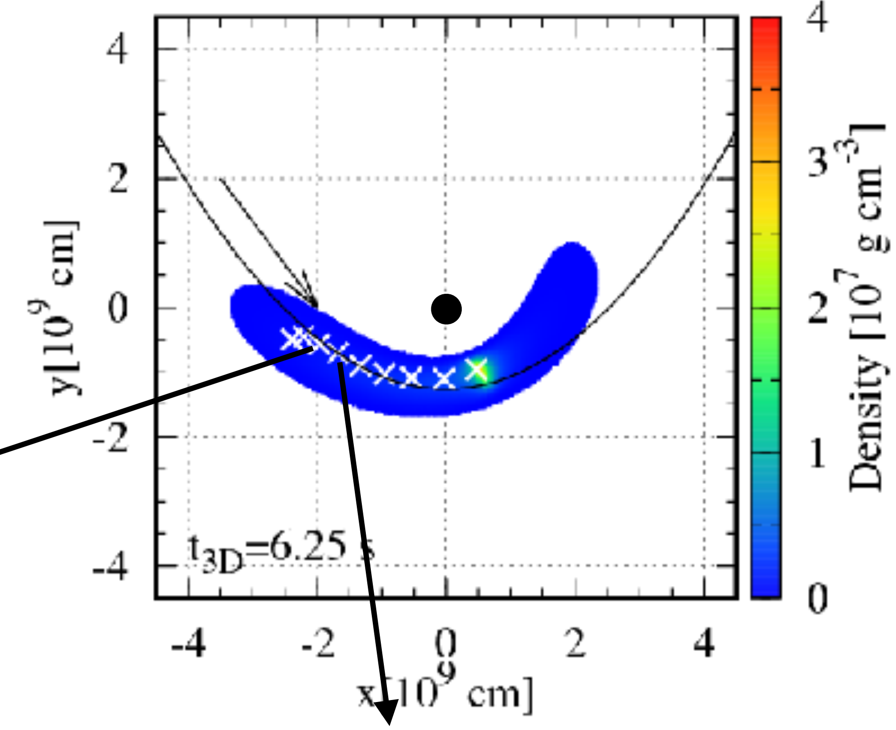


Switch 3D to 1D

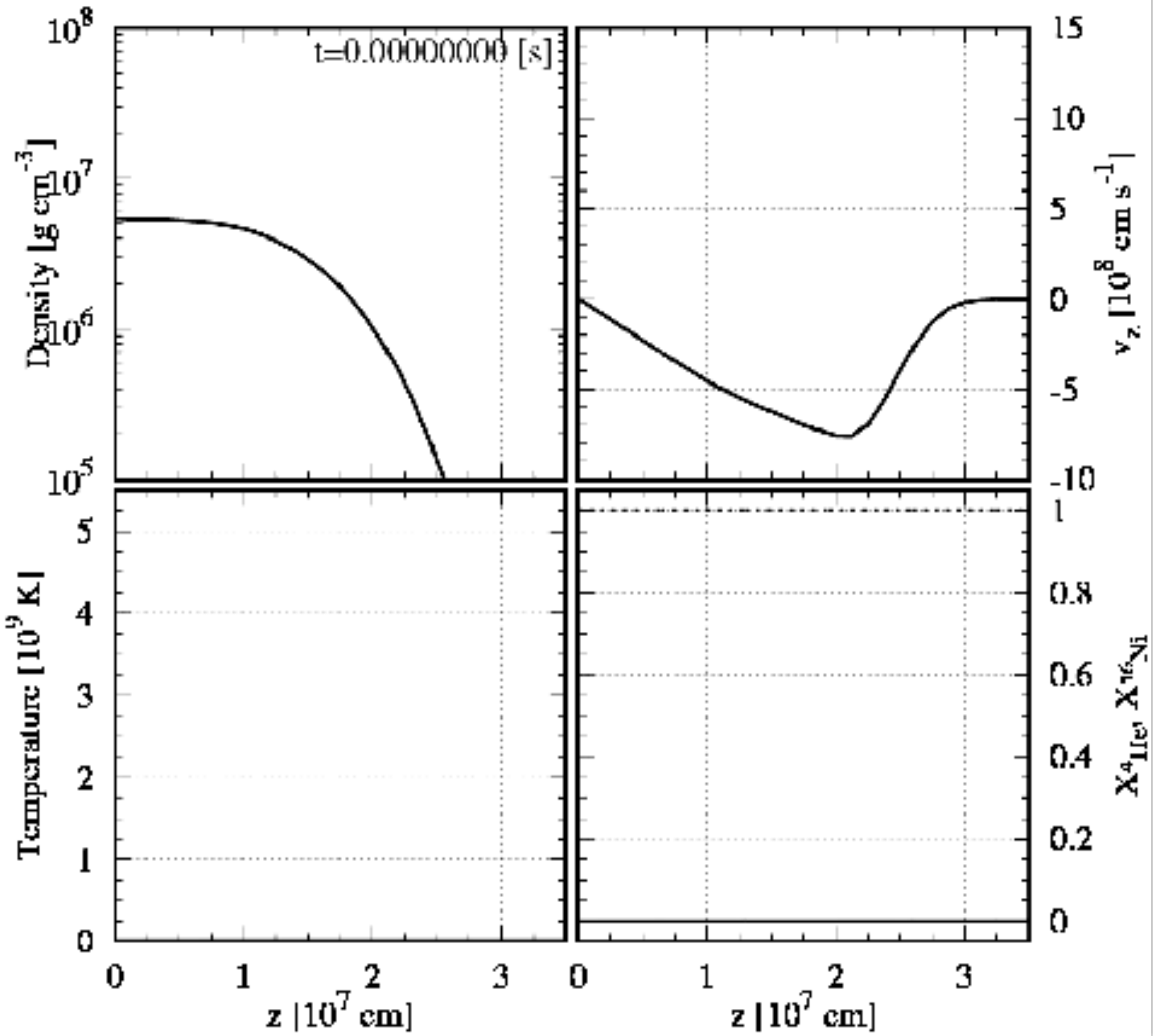
- 3D SPH simulation
  - 0.45M⊙ HeWD disrupted by 300M⊙ IMBH
    - N~3x10⁸ for the He WD
  - without nuclear reactions
- Extracting z-columns indicated by white crosses
- 1D mesh simulation
  - z-columns
  - with nuclear reactions



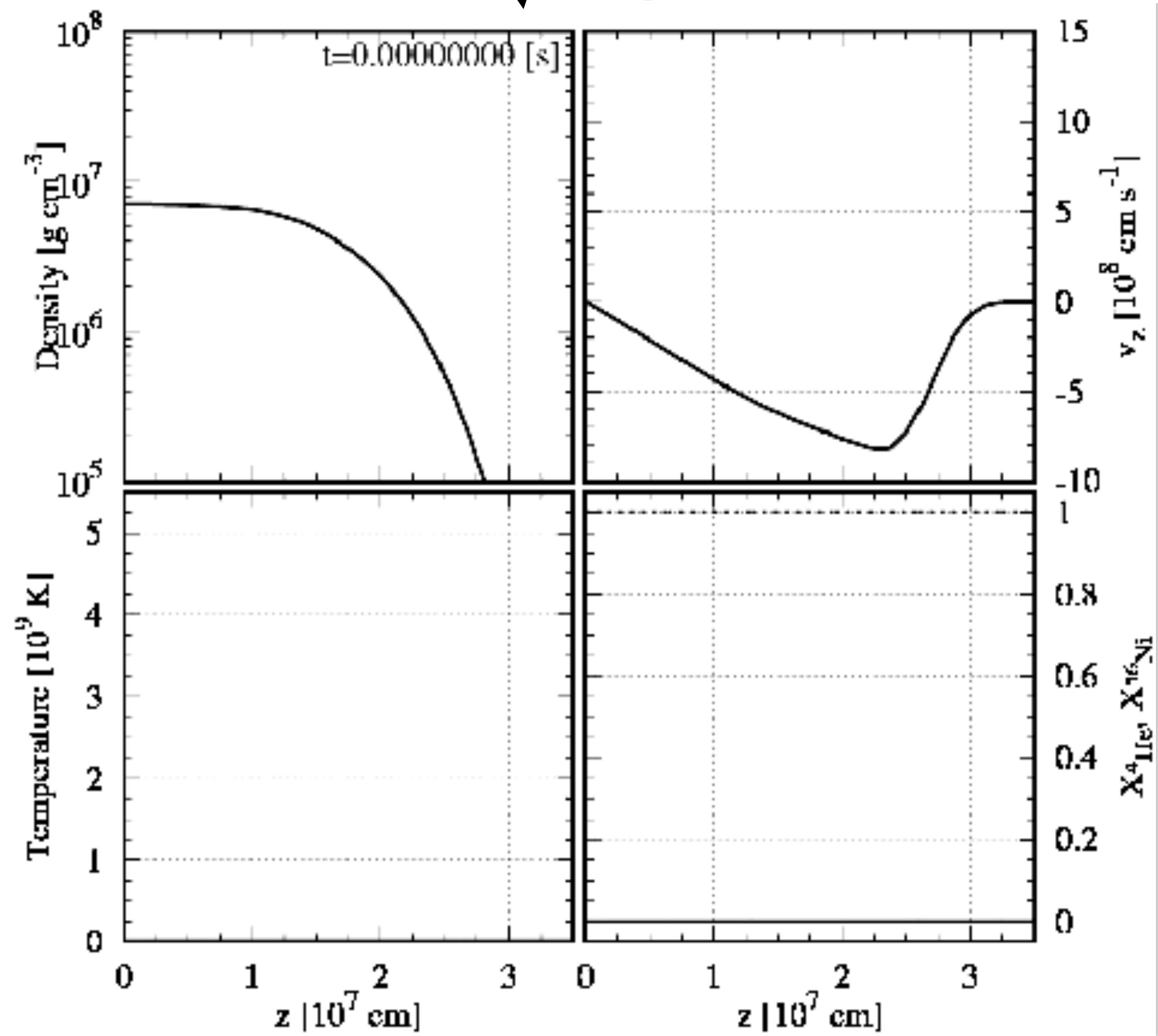
Movies



Tanikawa (2018, ApJ, 858, 81)

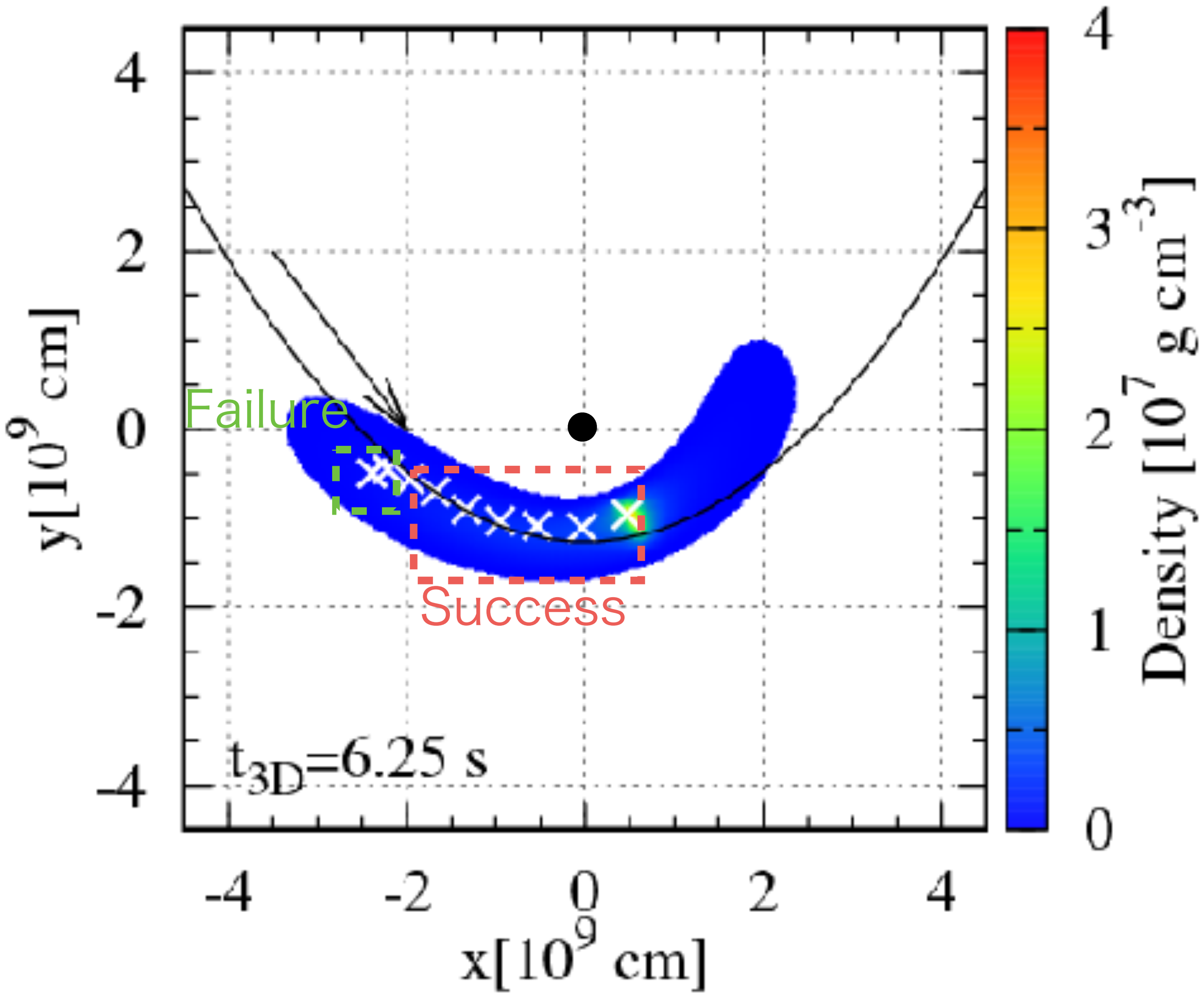


Failure case

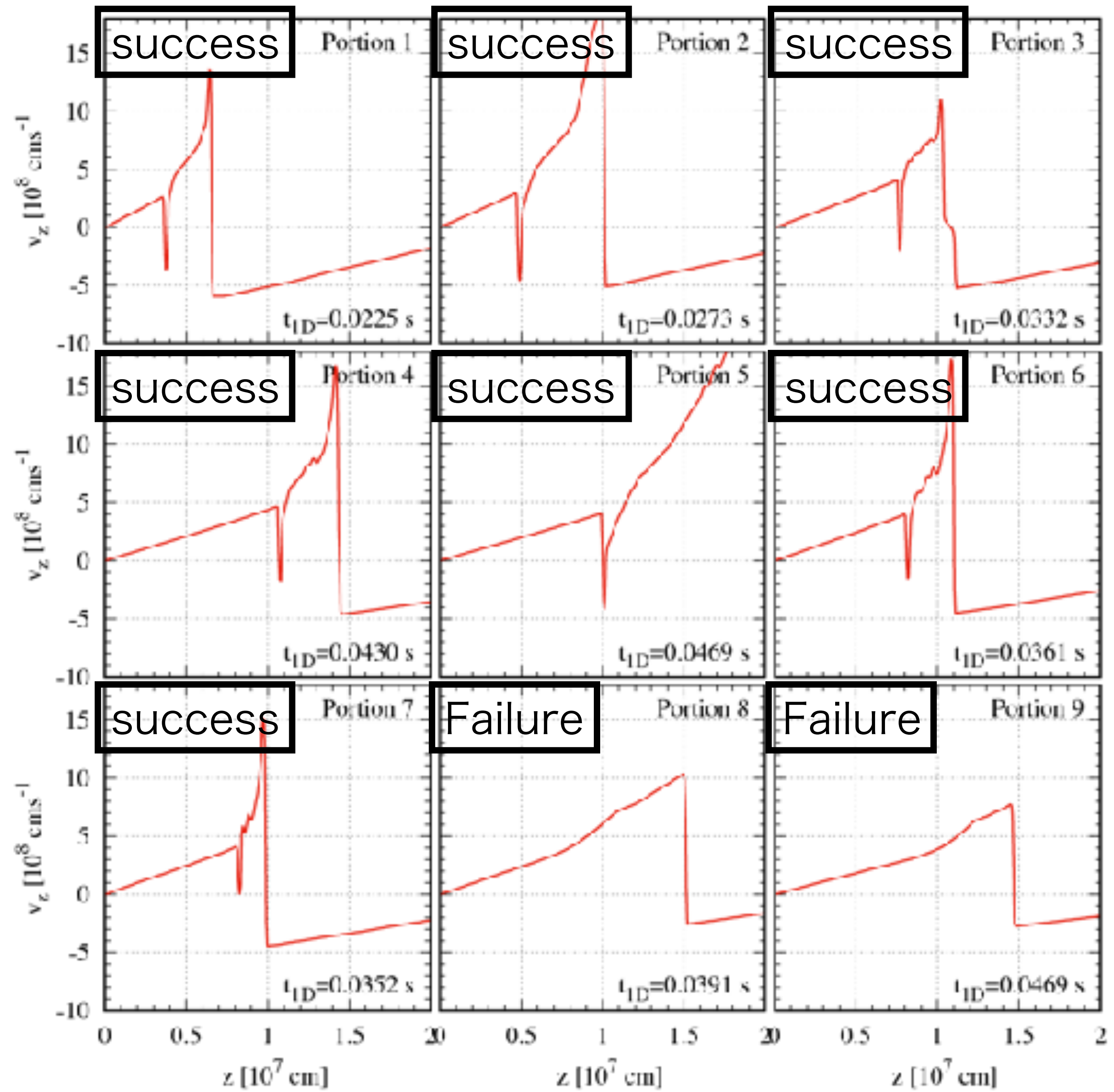


Success case

Results

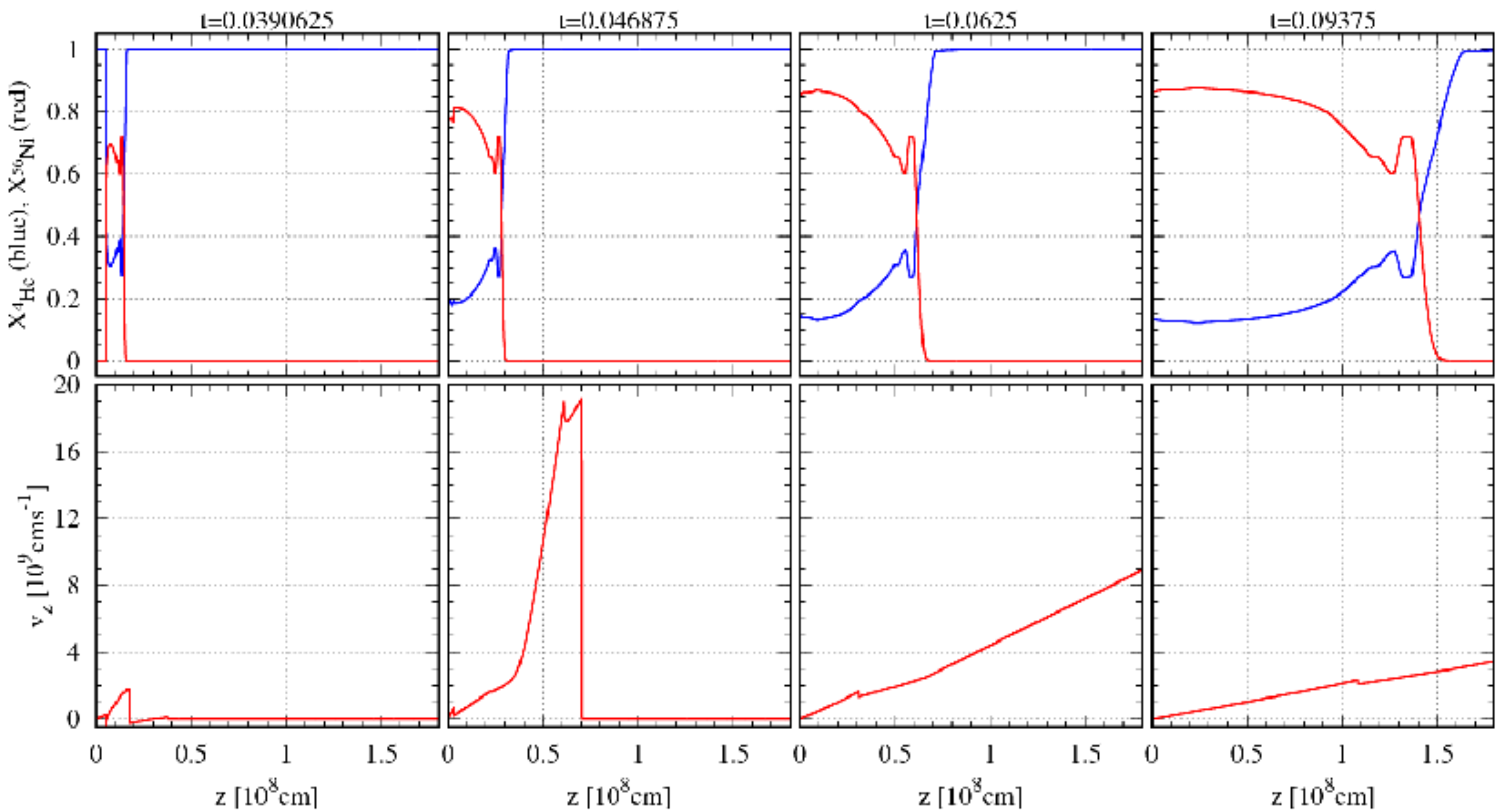


Failure
Success
t_{3D}=6.25 s
x[10^9 cm]
y[10^9 cm]
Density [10^7 g cm^{-3}]



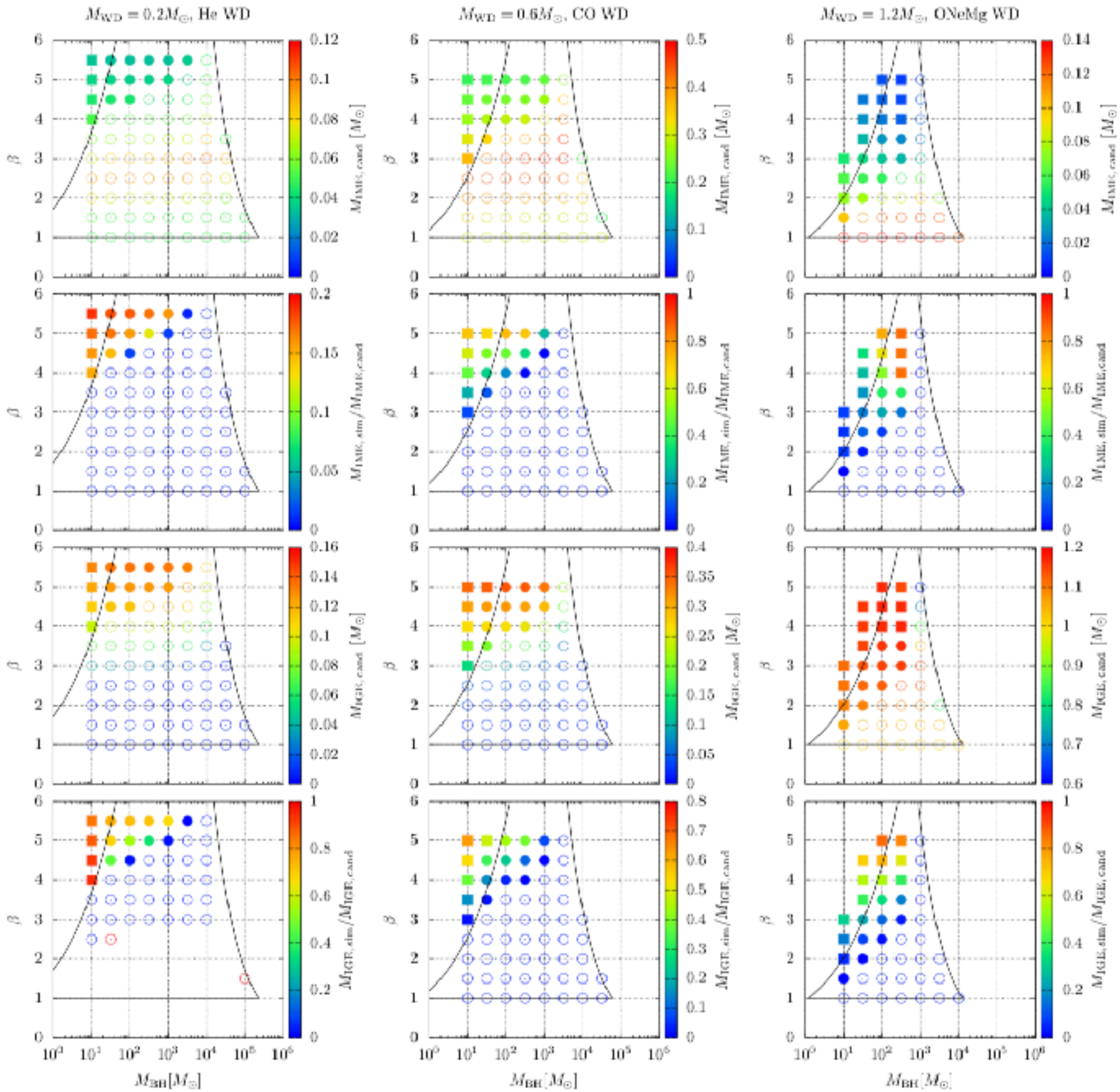
success
Portion 1
t_{1D}=0.0225 s
success
Portion 2
t_{1D}=0.0273 s
success
Portion 3
t_{1D}=0.0332 s
success
Portion 4
t_{1D}=0.0430 s
success
Portion 5
t_{1D}=0.0469 s
success
Portion 6
t_{1D}=0.0361 s
success
Portion 7
t_{1D}=0.0352 s
Failure
Portion 8
t_{1D}=0.0391 s
Failure
Portion 9
t_{1D}=0.0469 s
v_z [10^8 cm s^{-1}]
z [10^7 cm]

Nucleosynthesis



- The detonation wave leaves 20% ^{4}He and 80% ^{56}Ni.
  - The detonated region has high density (>10^6 gcm^{-3}).
- The total ^{56}Ni mass is about 0.3M$_\odot$, comparable to SNeIa.

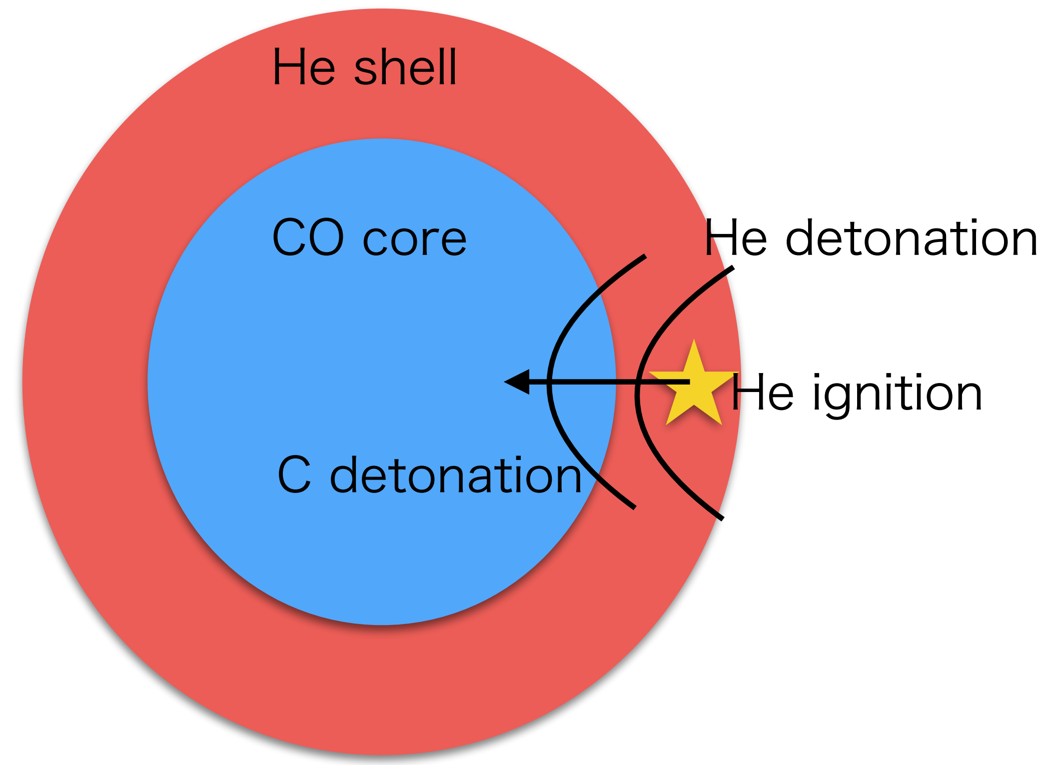
Variety of tidal detonation



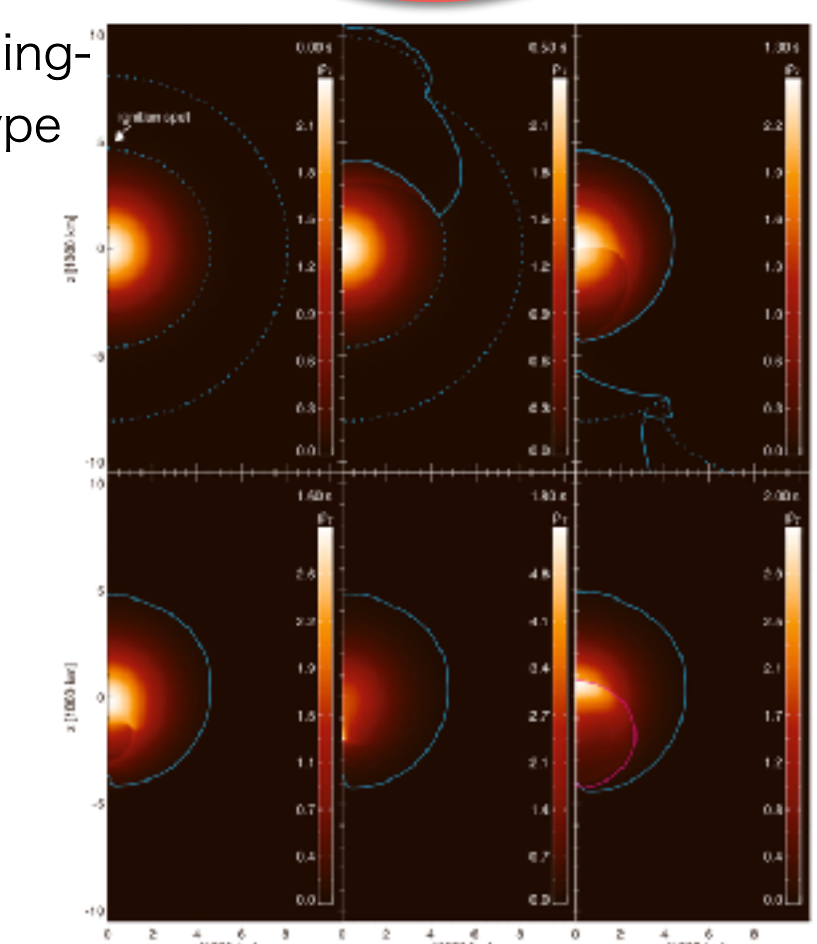
Kawana et al. (2018, MNRAS, 447, 3449)

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)



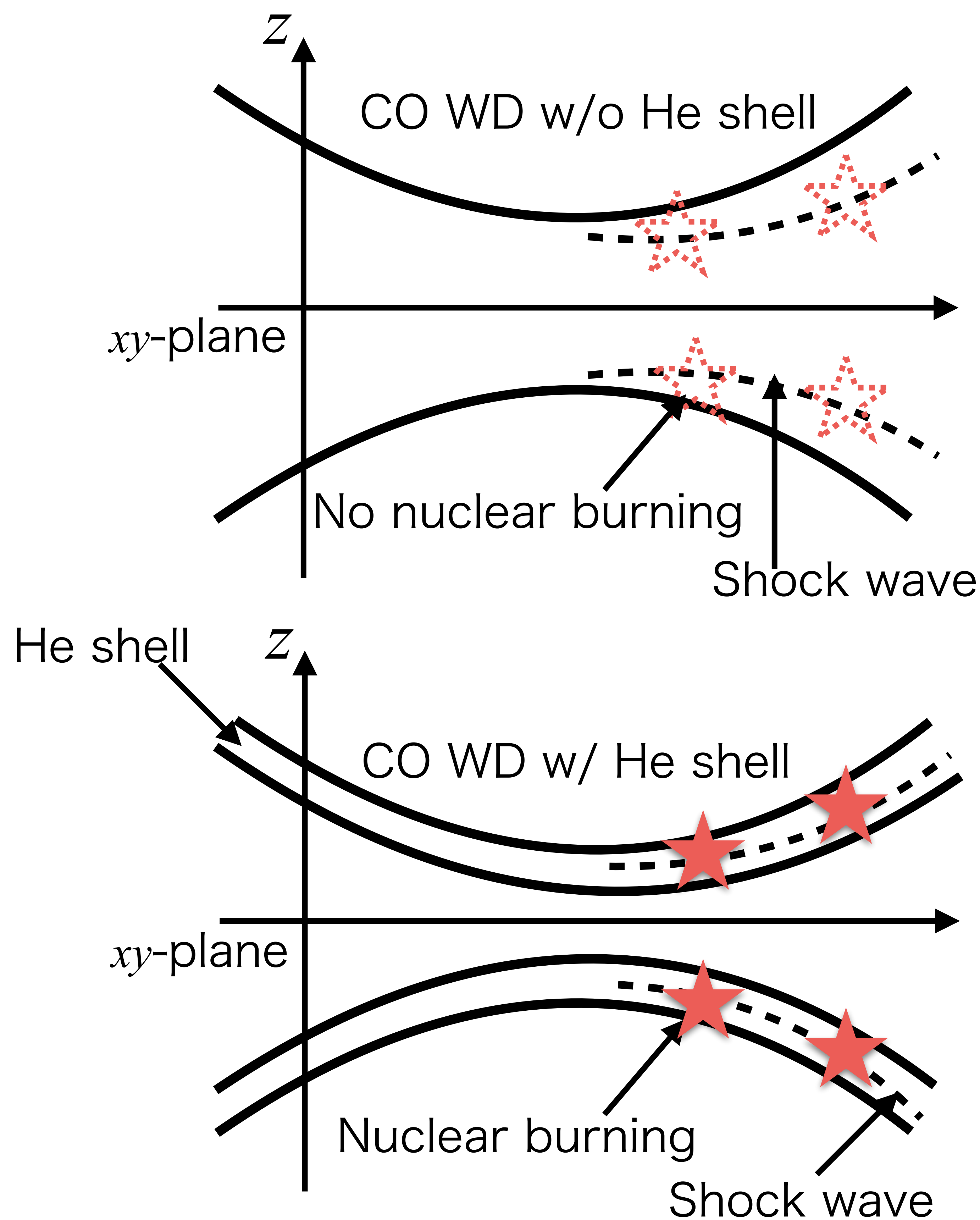
Converging-shock type



Fink et al. (2010)

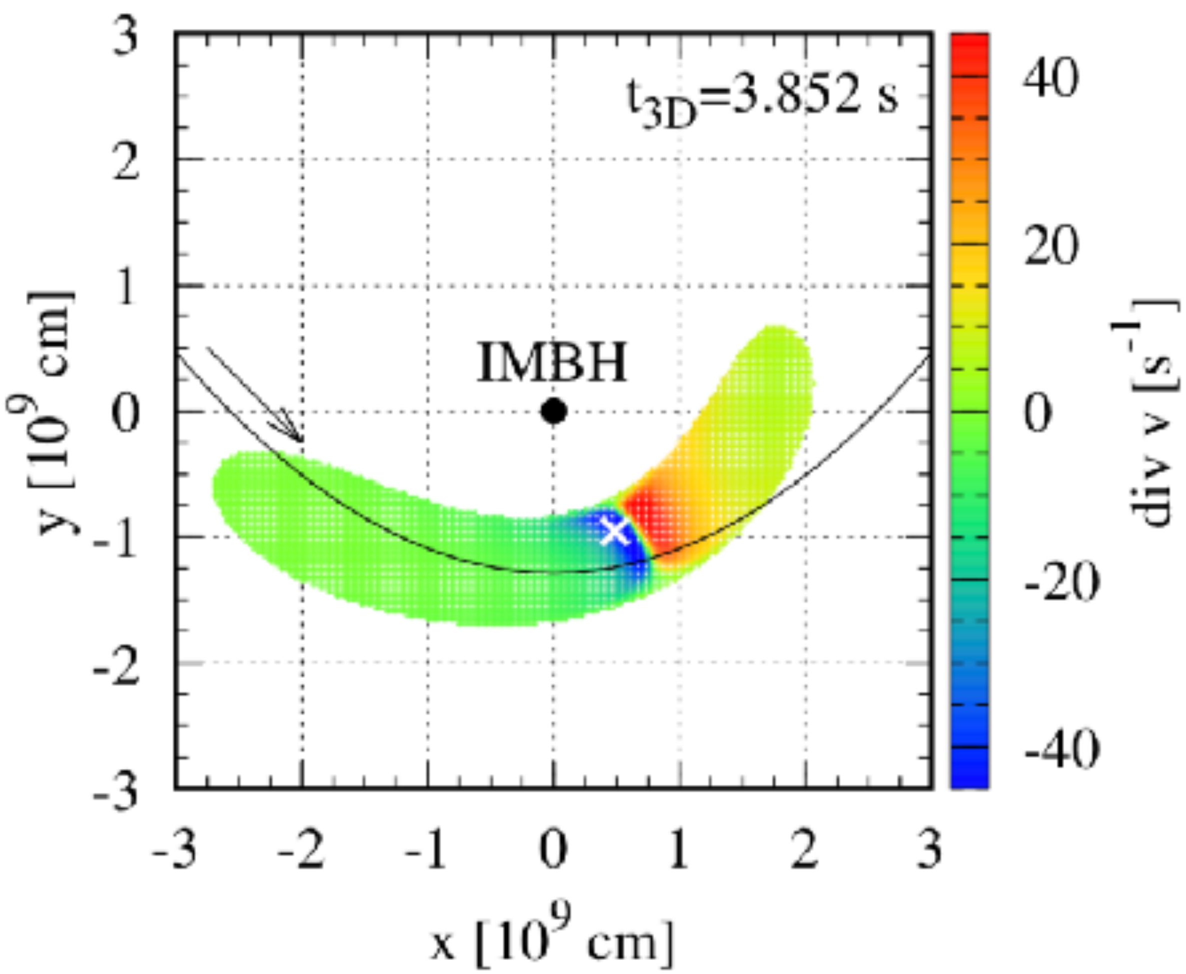
"Tidal" double detonation (TDD)

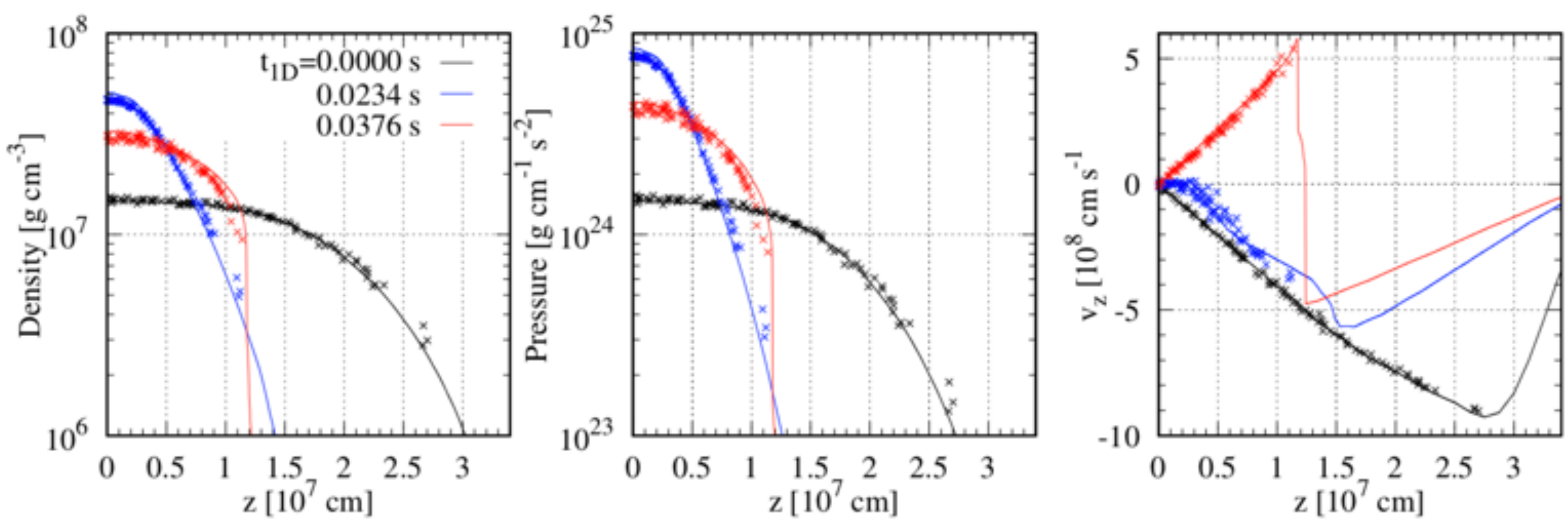
- A new explosion mechanism
- Helium detonation is ignited by tidal force, not by mass accretion.
- Tidal detonation is triggered by a shock wave in a He shell of a CO WD.
  - If there is no He shell, tidal detonation may not occur, since Carbon is harder to be ignited than Helium.
- TDD raises probability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



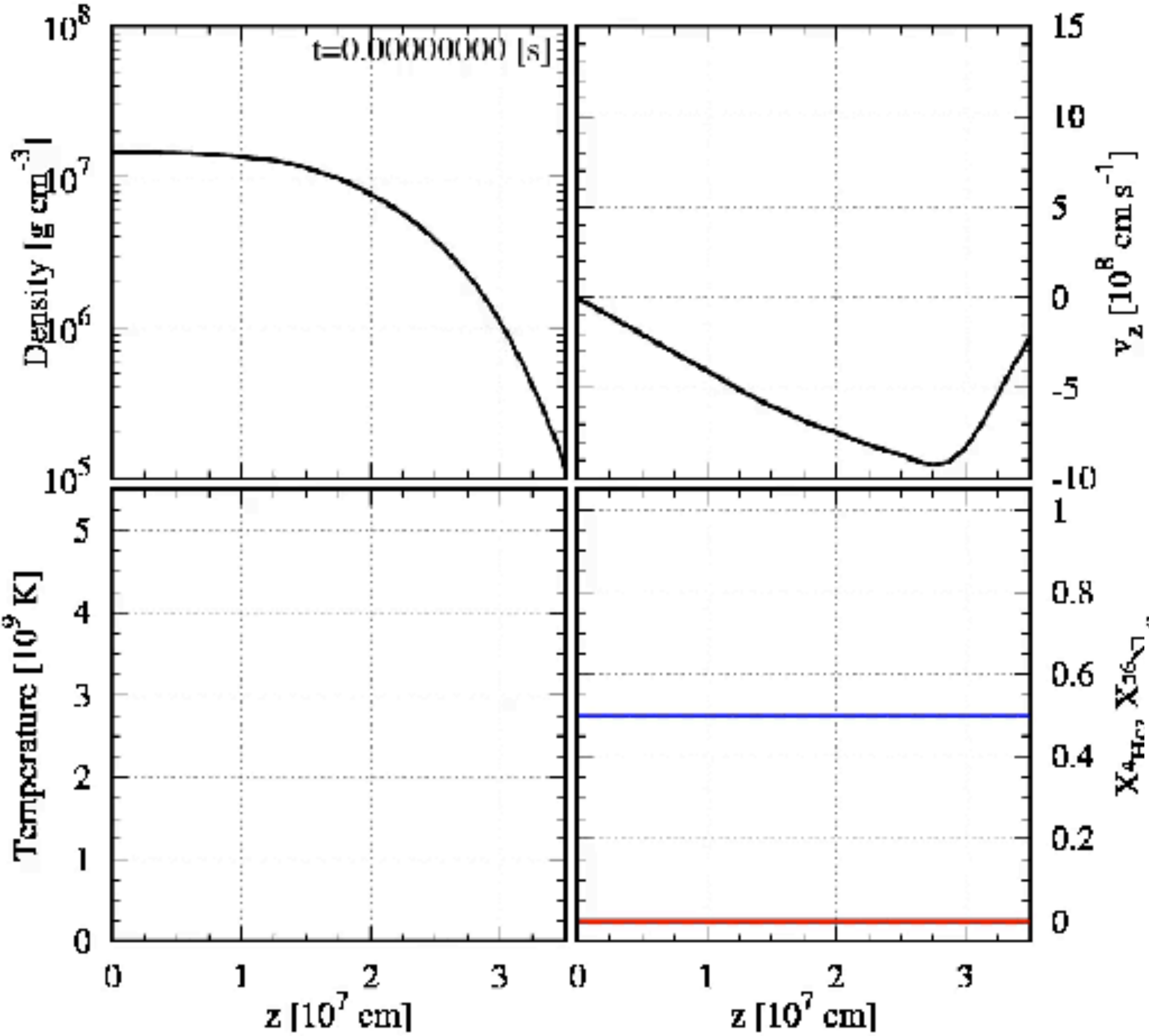
Initial conditions

- 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.

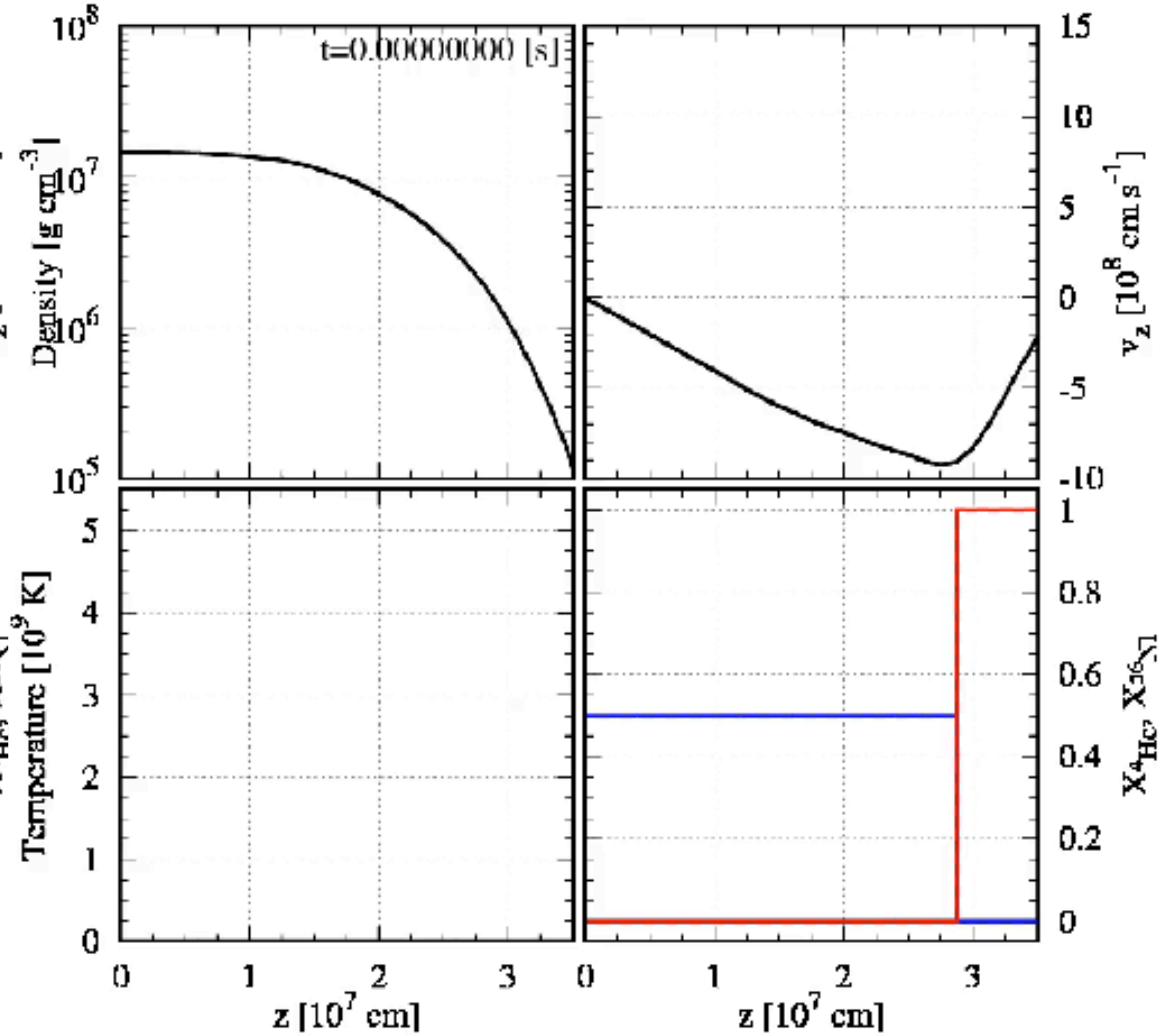




Results



w/o He shell



w/ 5% He shell

Tanikawa (2018, MNRAS, 475, L67)

Future work

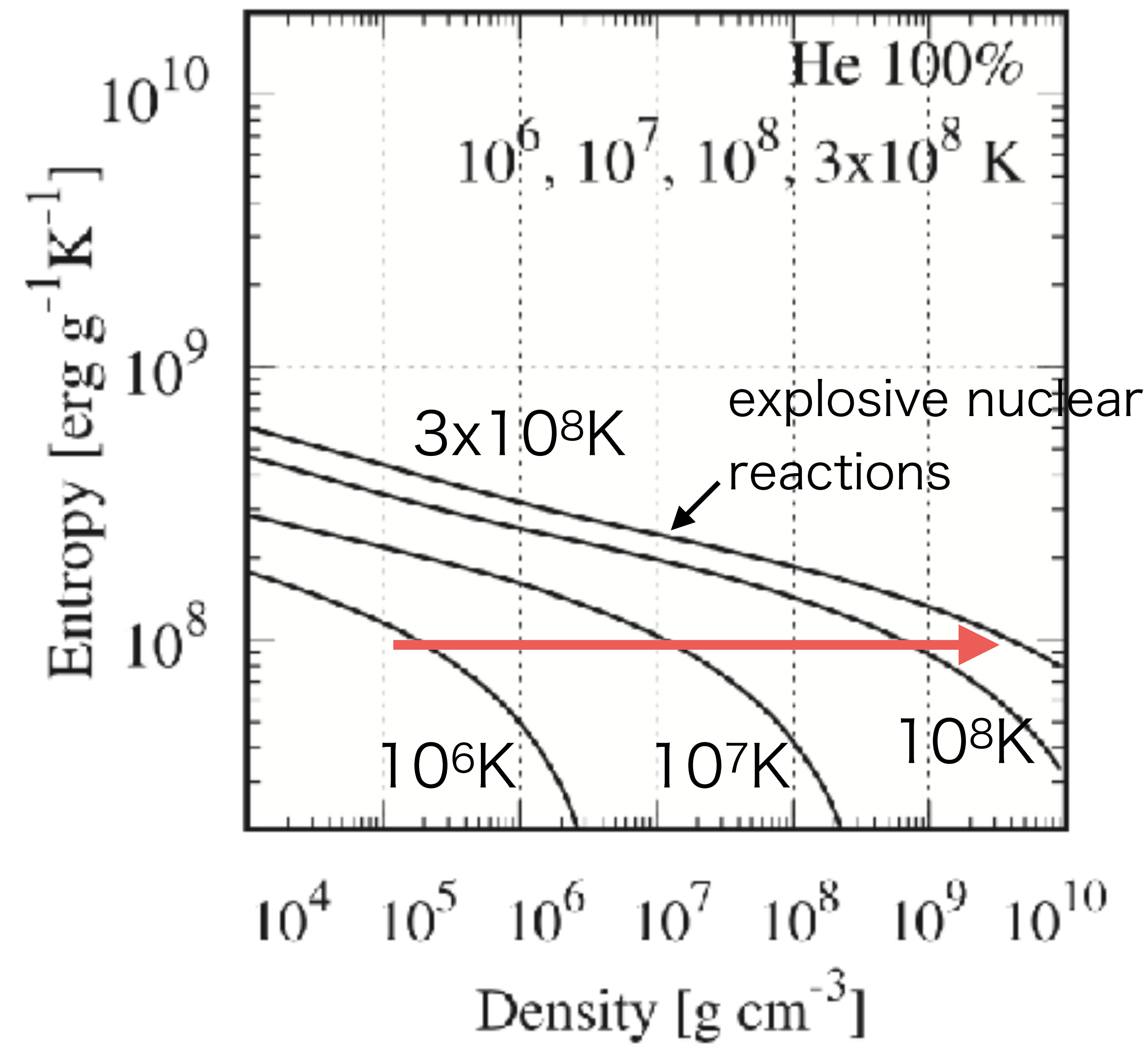
- Estimate of the event rate
- Radiative transfer calculation of WD TDEs
- WD mass function of TDEs
  - The same as that of single WDs?
  - Top-heavy mass function due to dynamical effects?

Summary

- We have studied tidal detonation of WDs.
- We should be careful of spurious heating in low-resolution SPH simulation (Tanikawa et al. 2017, ApJ, 839, 81).
- We have verified tidal detonation of WDs in the case of He WD with $0.45M_\odot$ in which large amount of ^{56}Ni ($\sim 0.3M_\odot$) is synthesized (Tanikawa 2018, ApJ, 858, 26).
- Helium shell helps tidal detonation (Tanikawa et al. 2018, MNRAS, 475, L67).
- We have investigated various tidal detonation (Kawana et al. 2018 MNRAS, 477, 3449).
- WD TDEs can be a clue to search for IMBHs.

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 $3\text{x}10^8$ K
  - Such orbits are impossible.
- Shock compression is required.

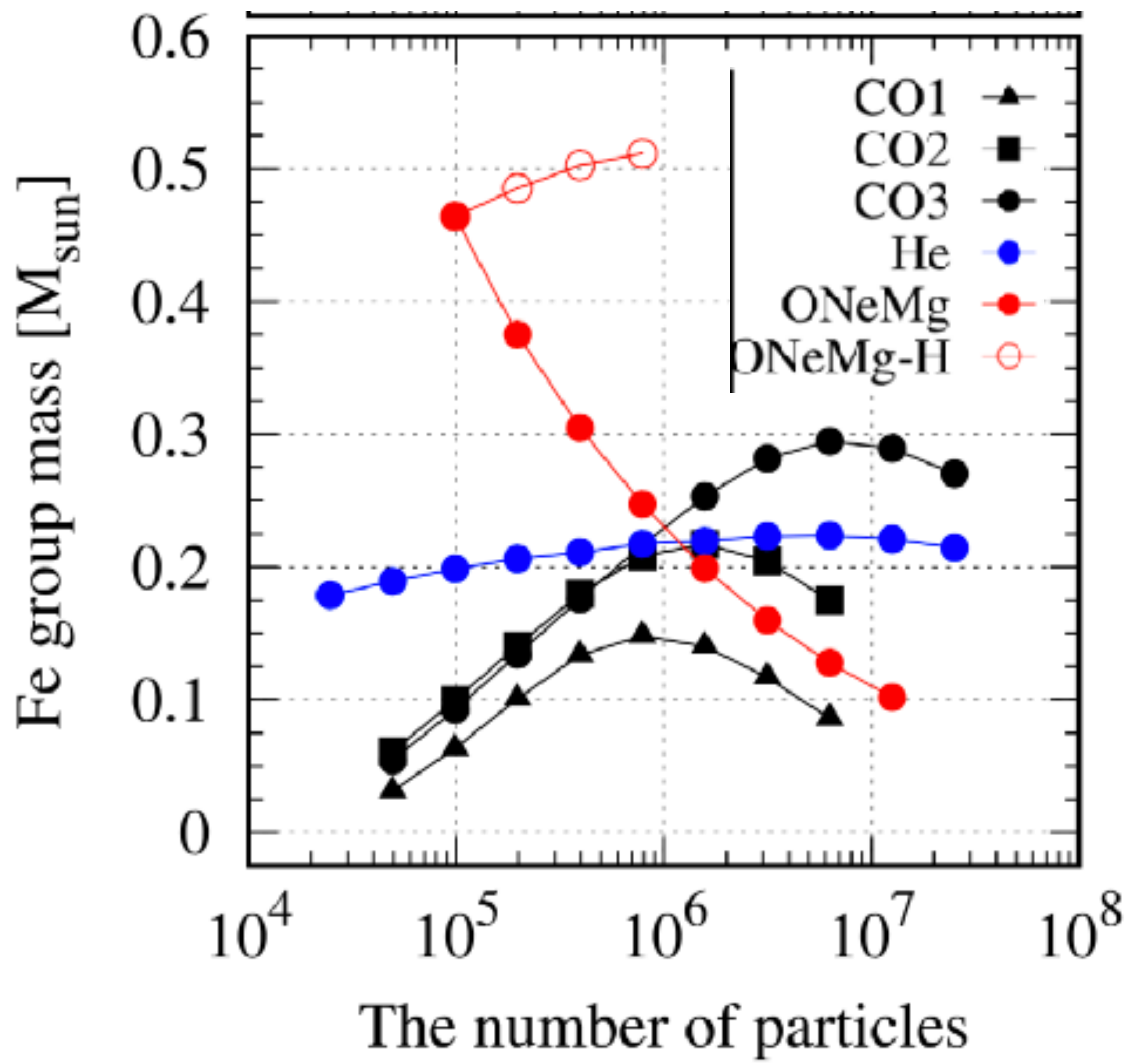


Initial conditions

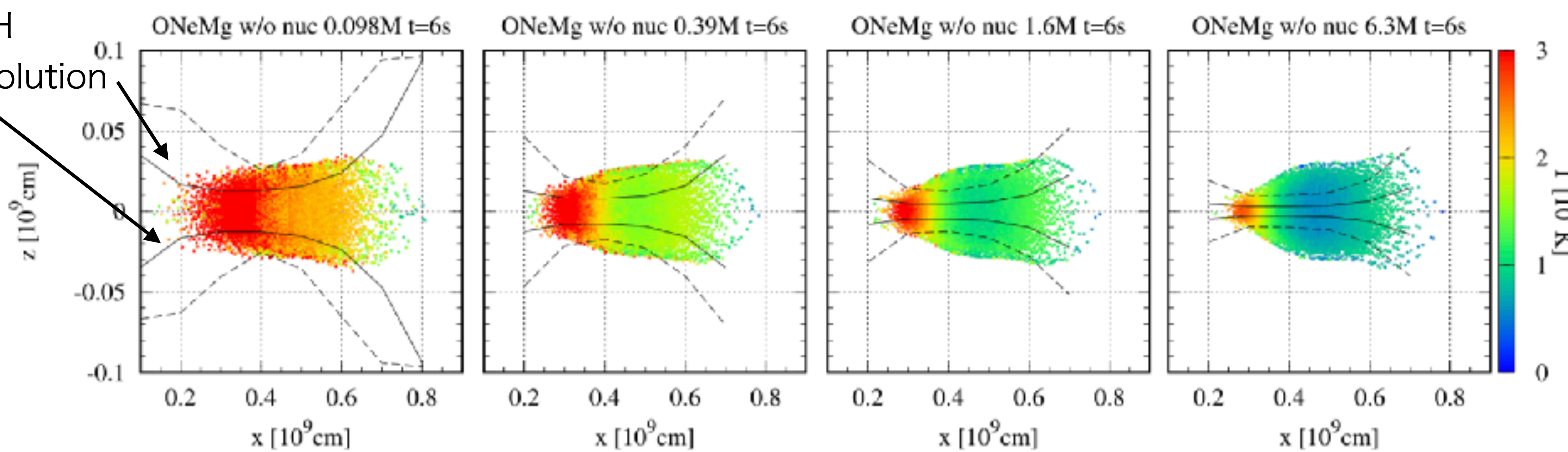
- WD-IMBH systems
  - 0.3 $M_\odot$ He WD (β=5, 500$M_\odot$ IMBH)
  - 0.6 $M_\odot$ CO WD (β=5, 500$M_\odot$ IMBH)
  - 1.2 $M_\odot$ ONeMg WD (β=3, 100$M_\odot$ IMBH)
- 10^4 - 10^7 SPH particles (N) for a WD
- The WDs have parabolic orbits.
- The WDs and IMBHs have no spin.

Results

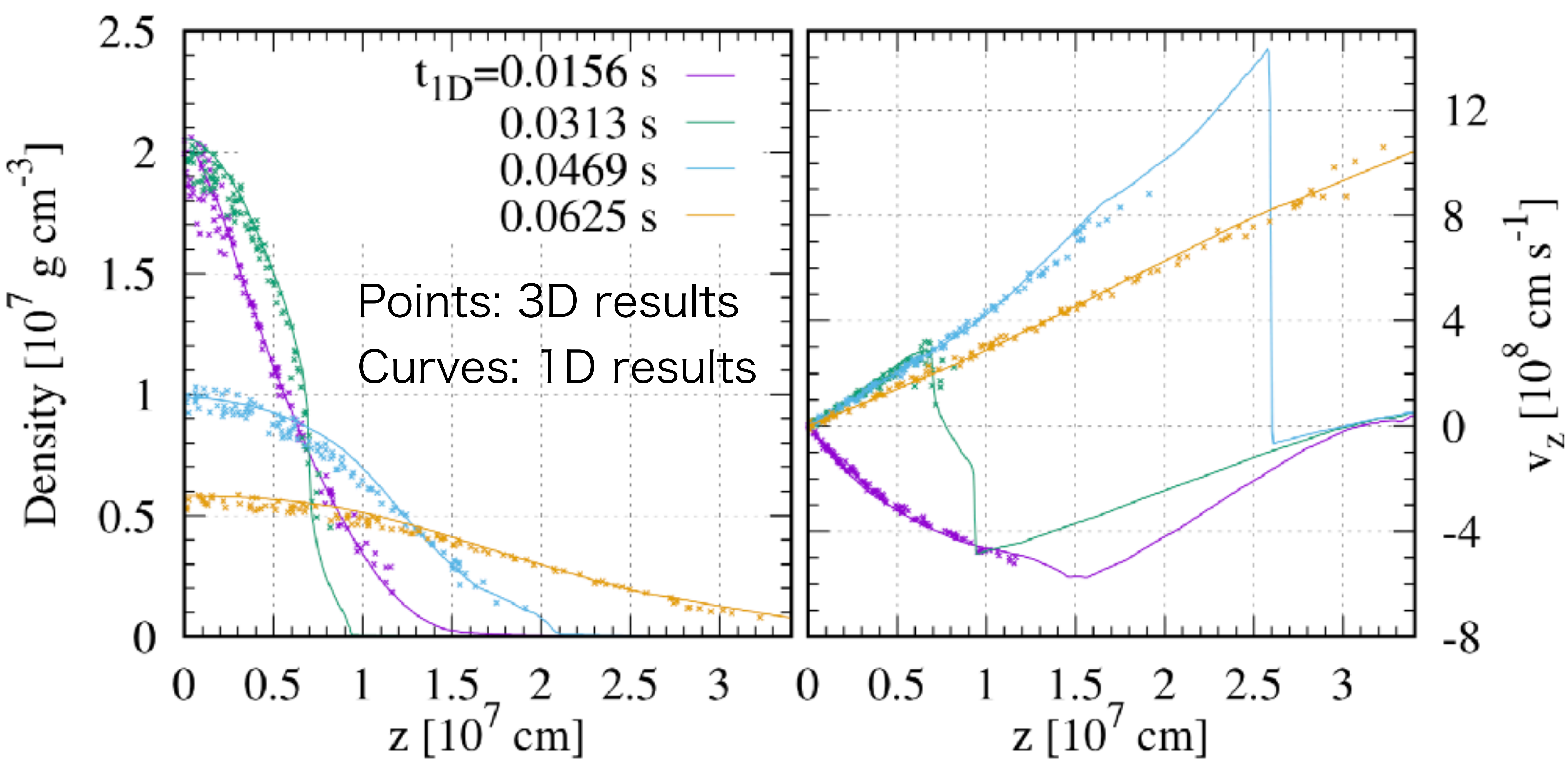
- Amounts of synthesized Fe group elements are not converged.
- These amounts become smaller with N increasing
- SPH simulations fail to resolve WD structure in z-direction.



SPH resolution

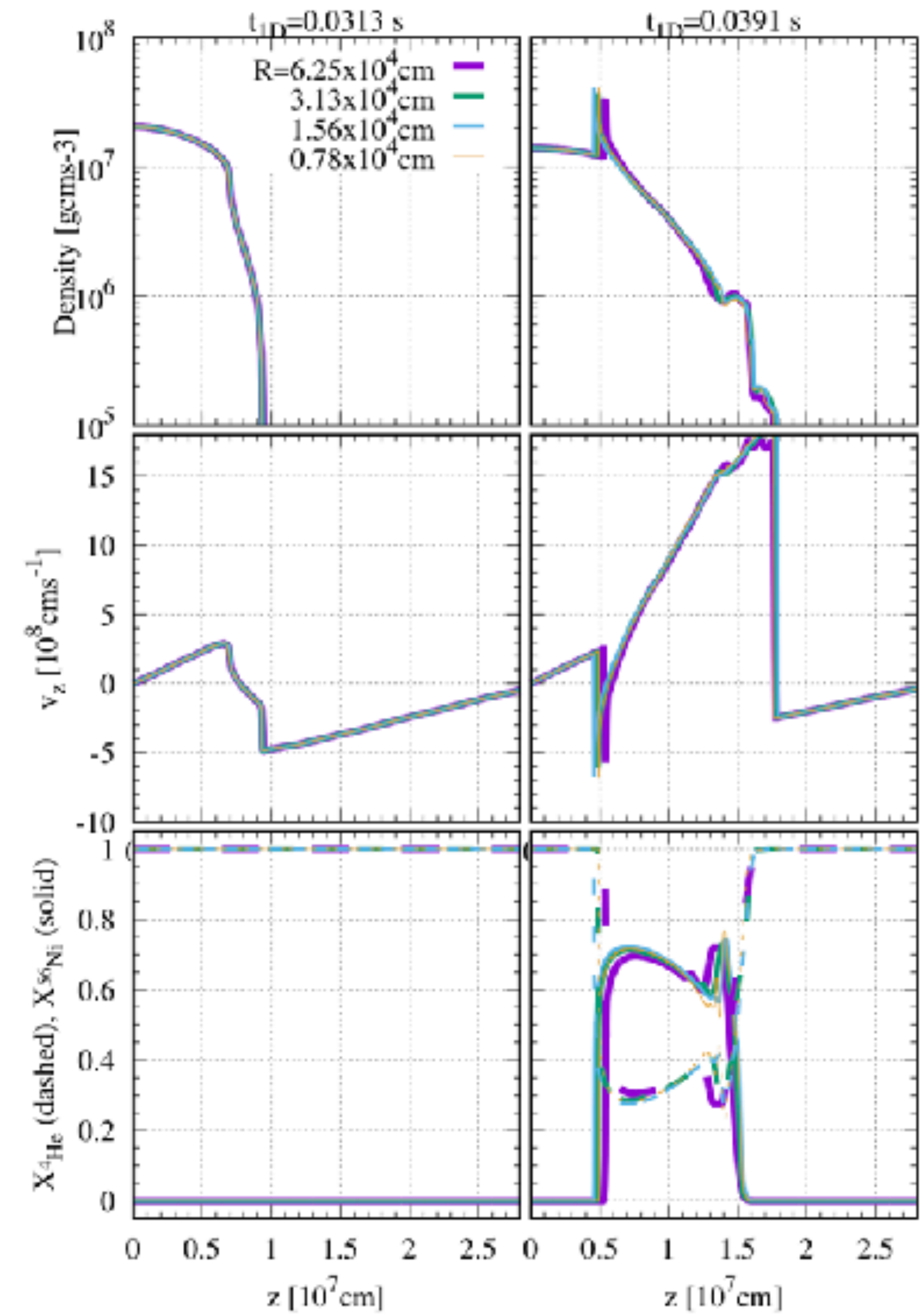


Comparison of 1D with 3D

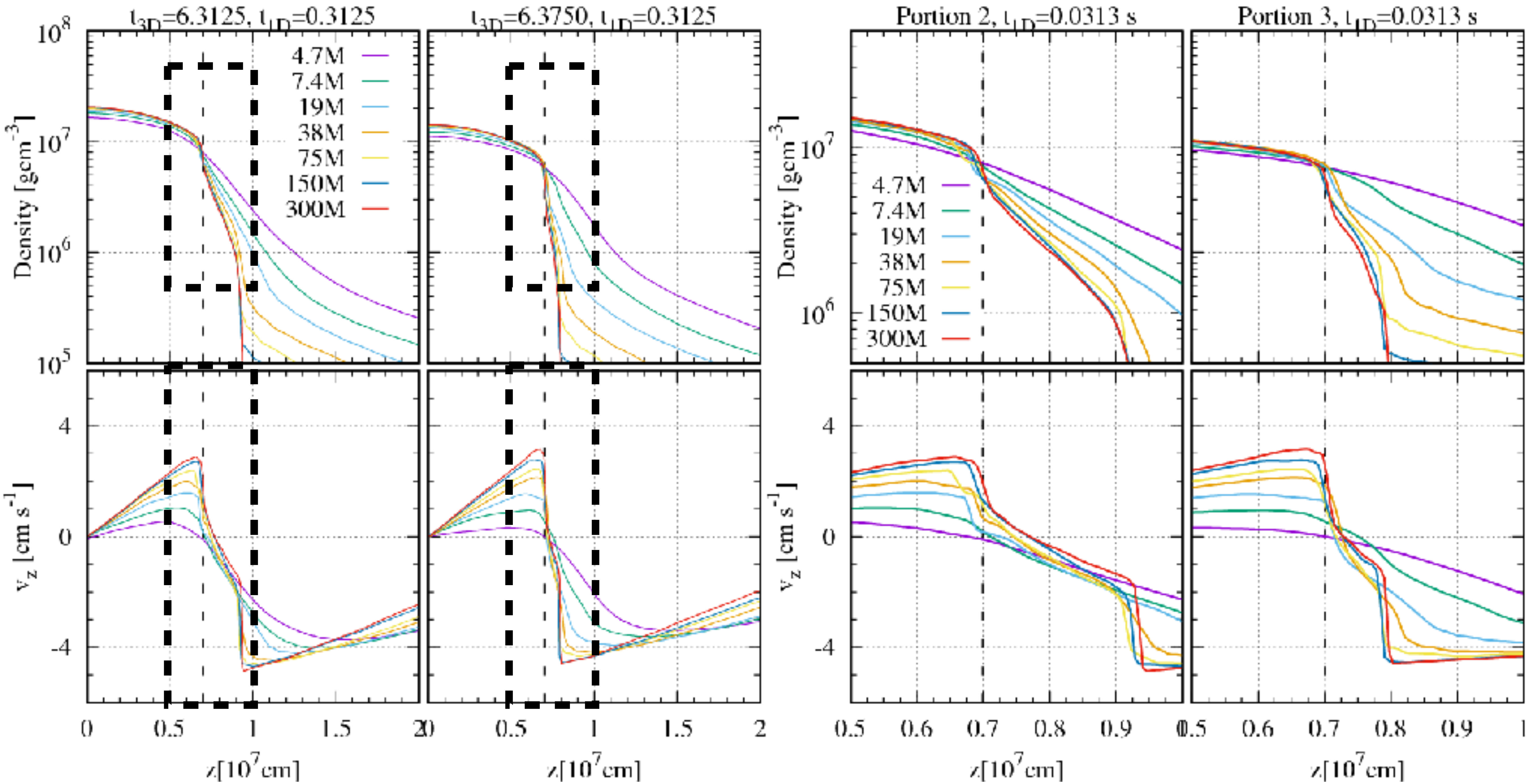


Convergence check of 1D resolution

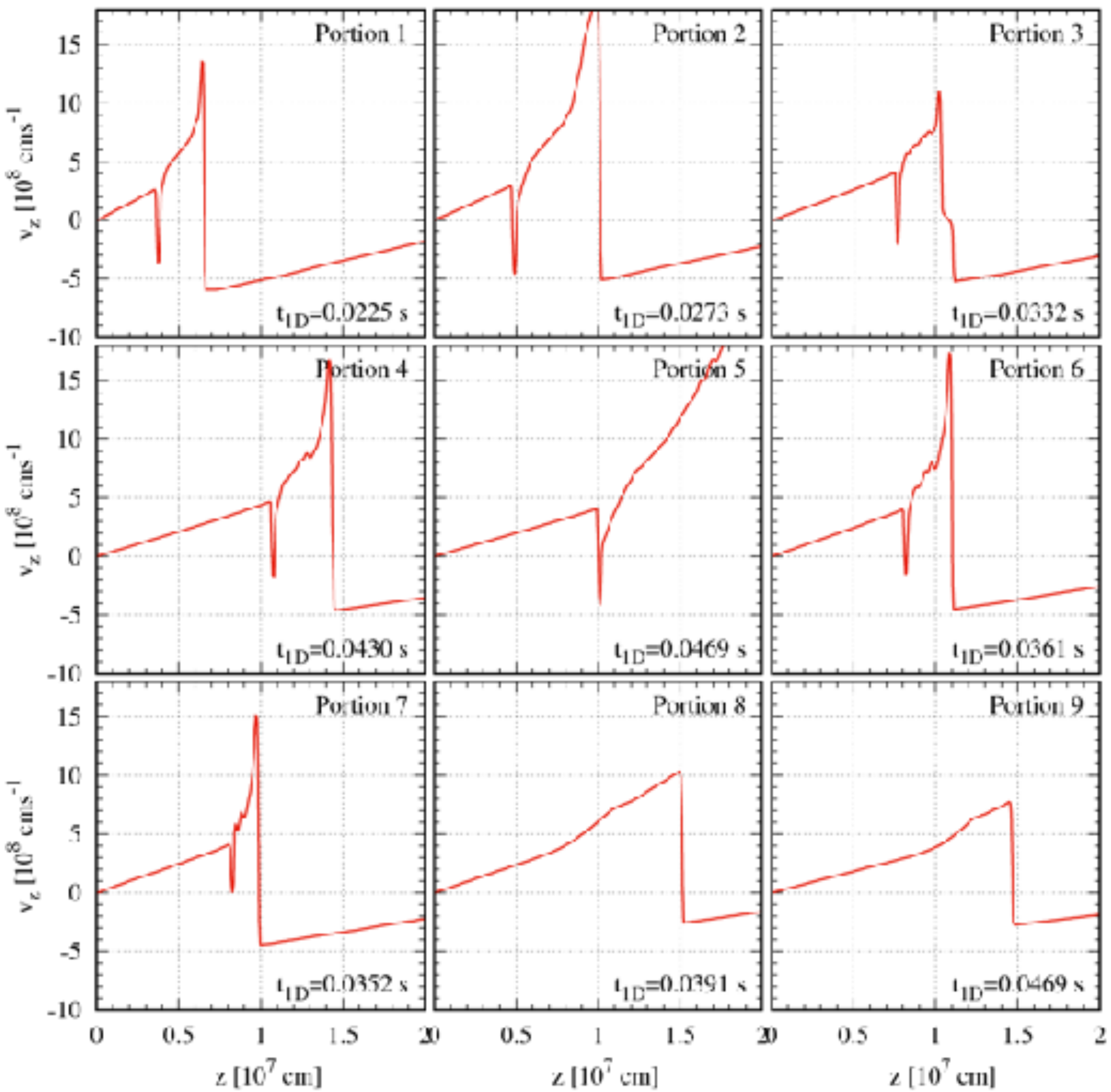
- Space resolution is changed by factors of 8.
- The evolution of density, z-velocity, and nuclear components is not changed as space resolution is changed.



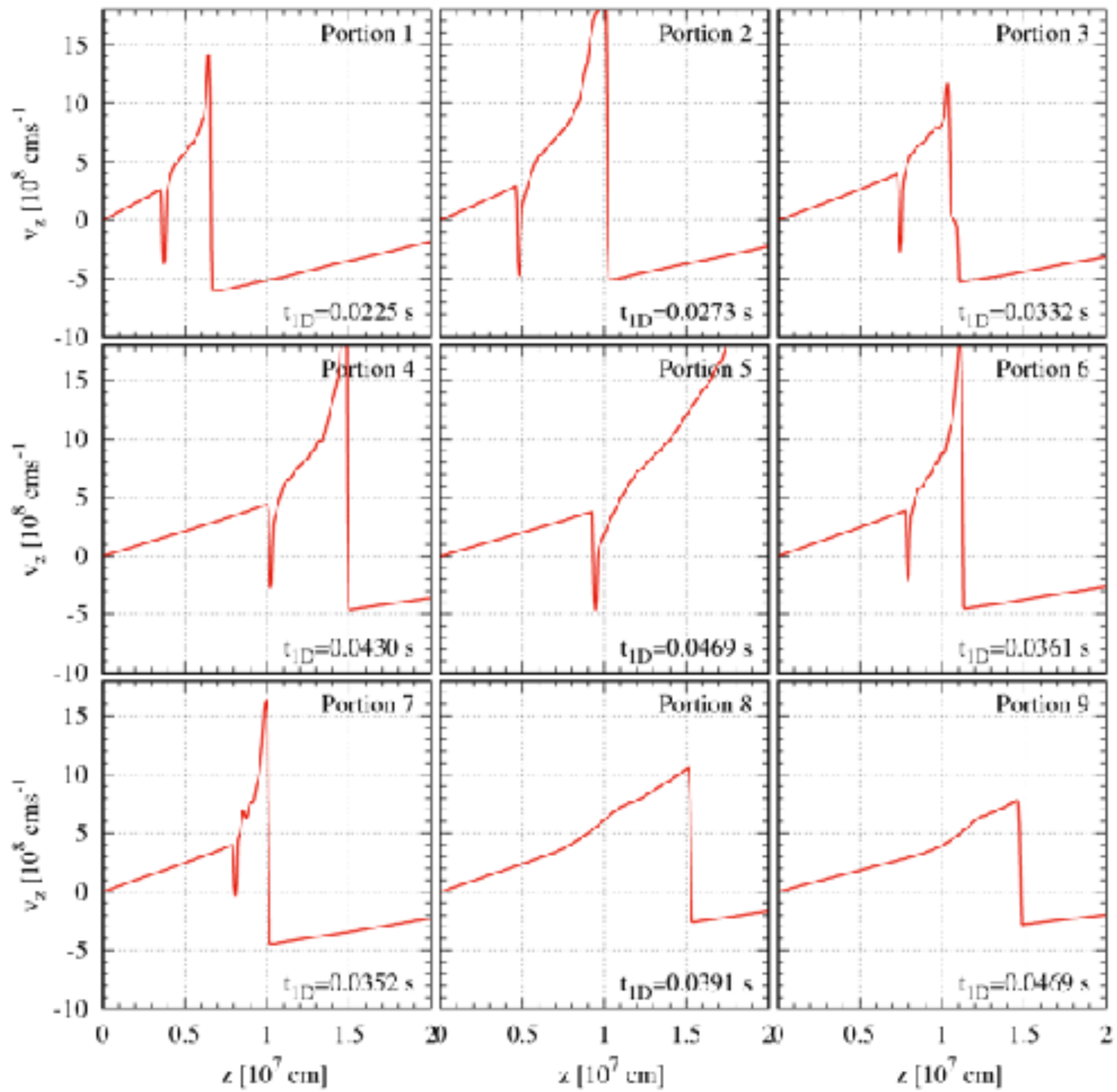
Convergence check of 3D SPH resolution



Tidal force (BH gravity) in z-direction



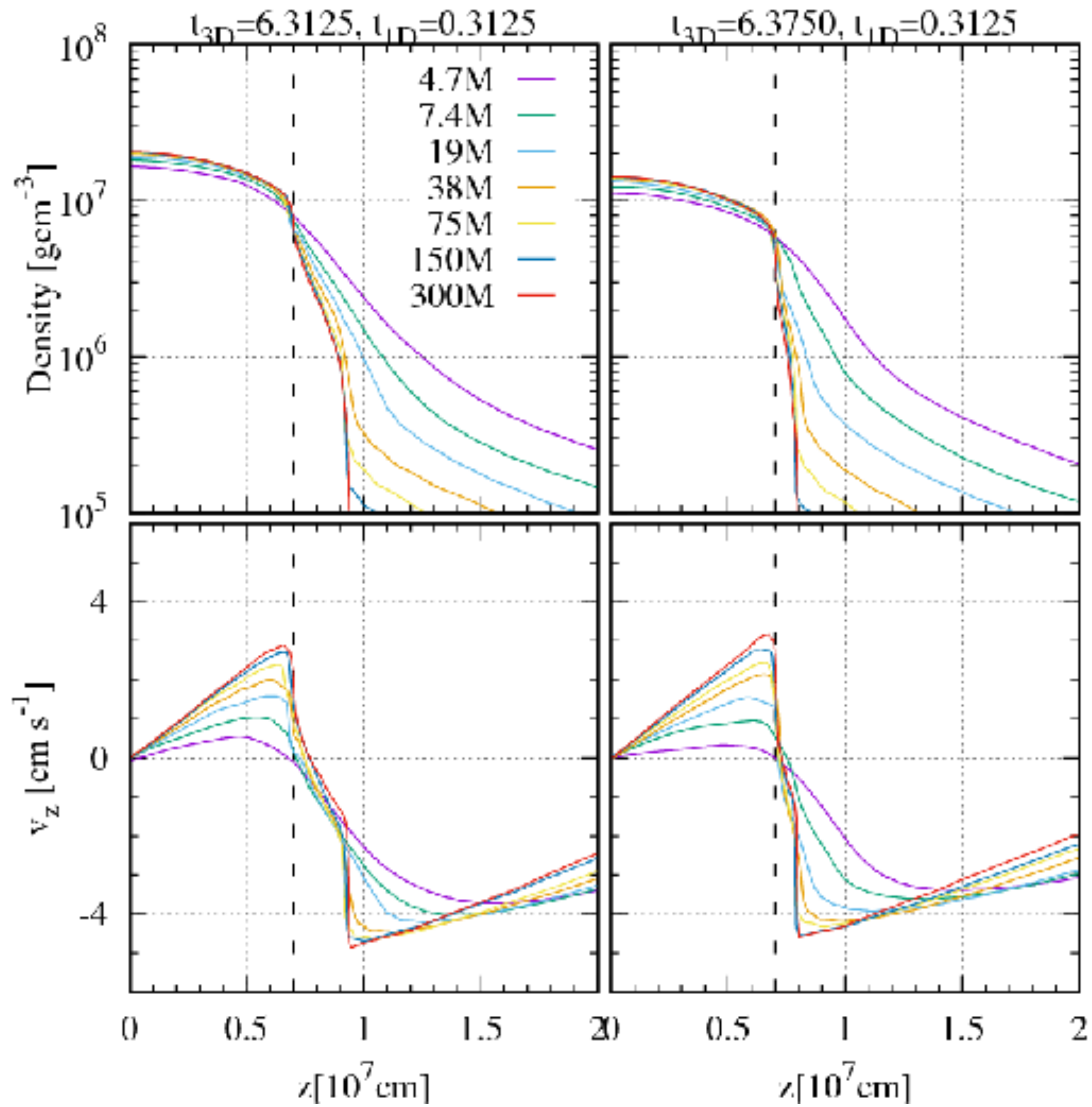
No BH gravity in z-direction



BH gravity in z-direction

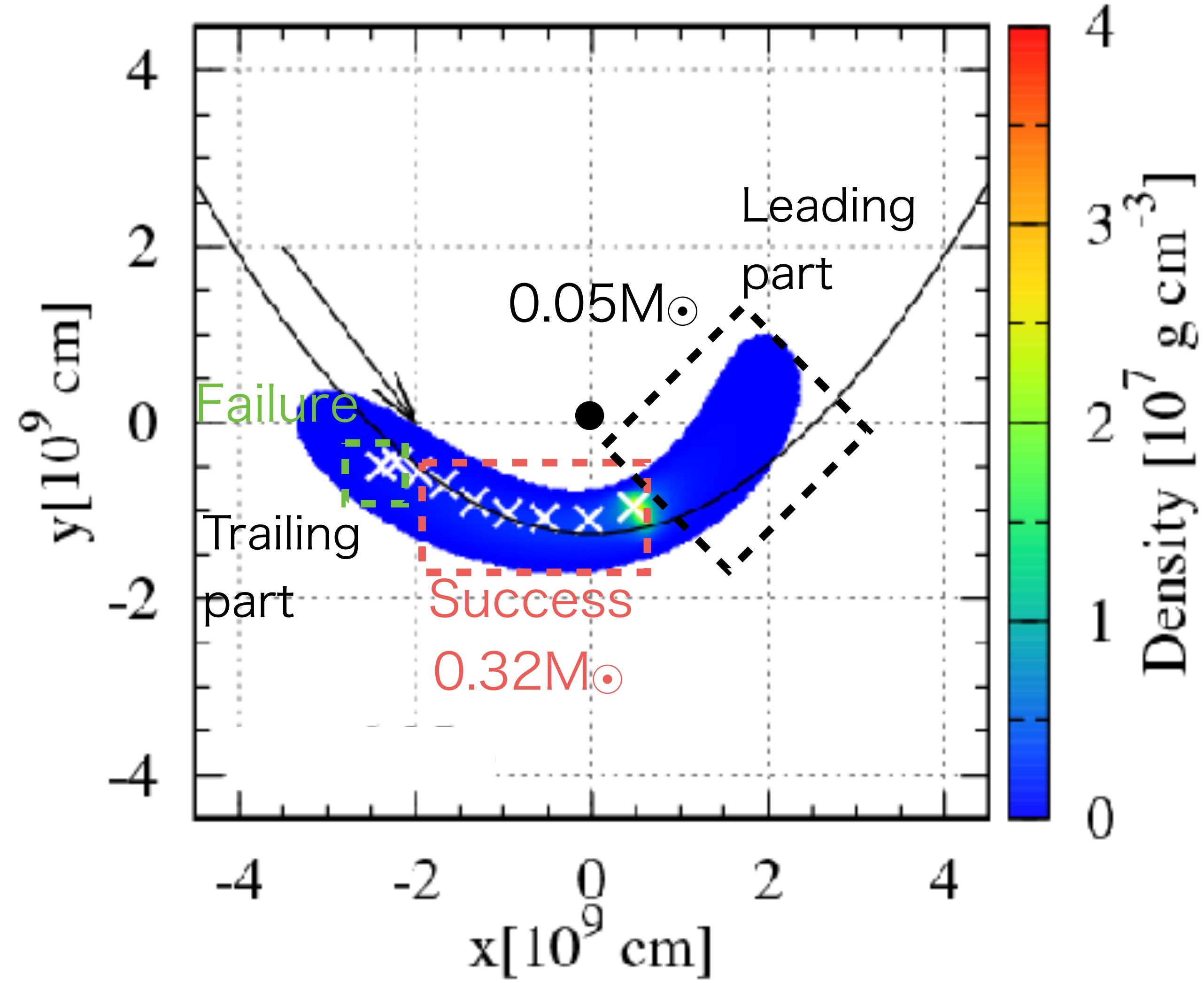
SPH VS mesh

- 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.



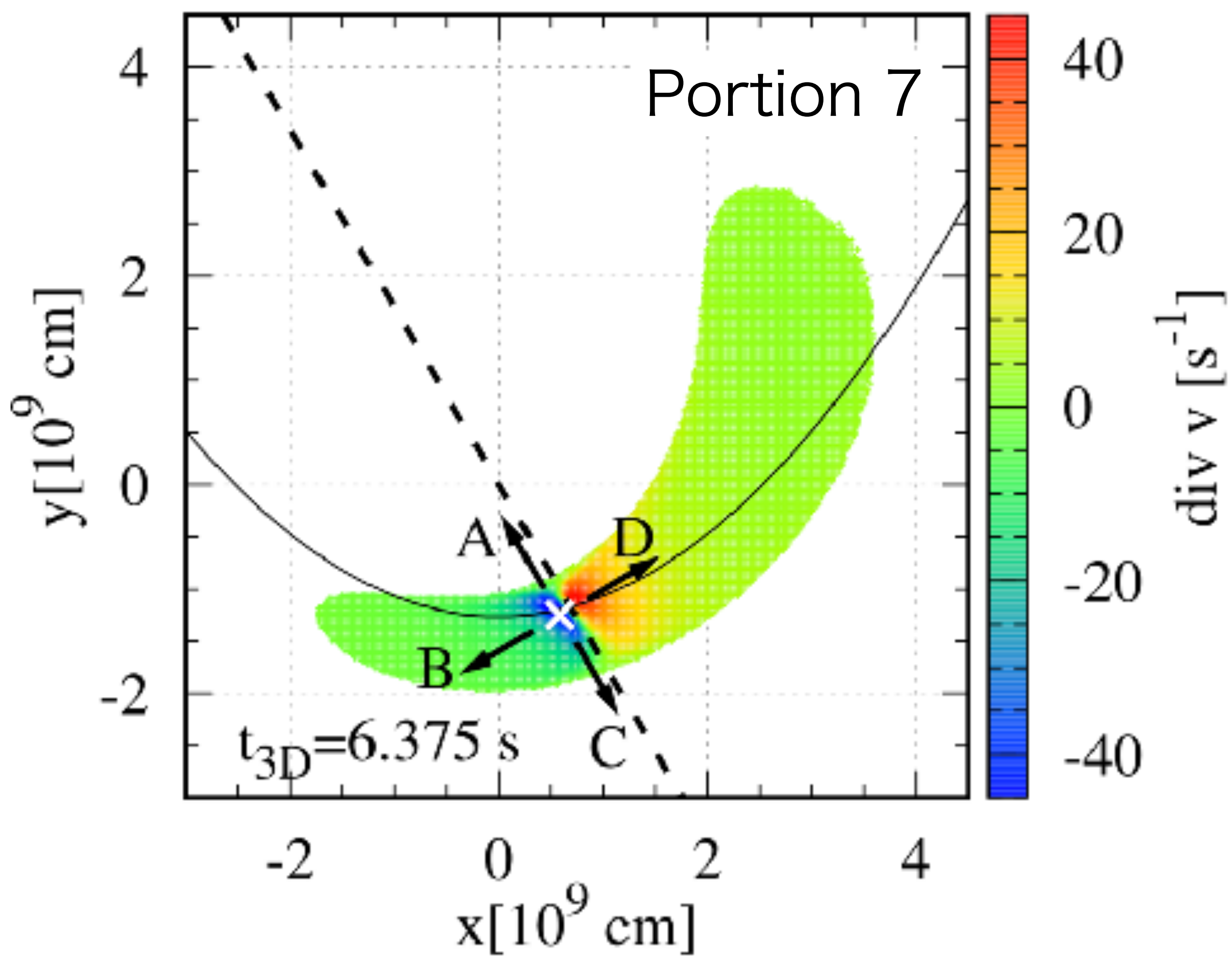
Difference between success and failure cases

- 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 $0.32M_\odot$, and at most $0.37M_\odot$.



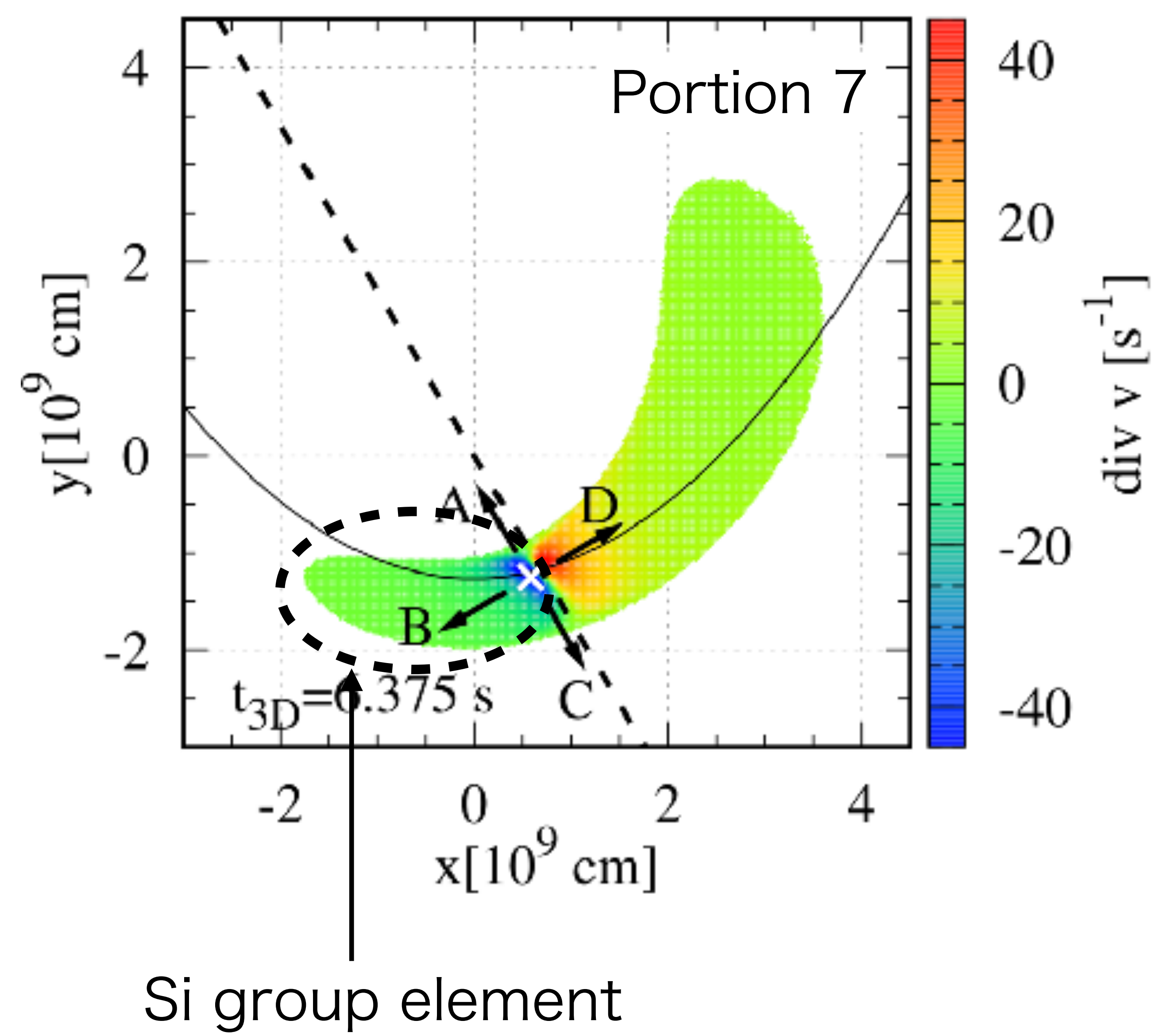
Interaction of z-columns

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



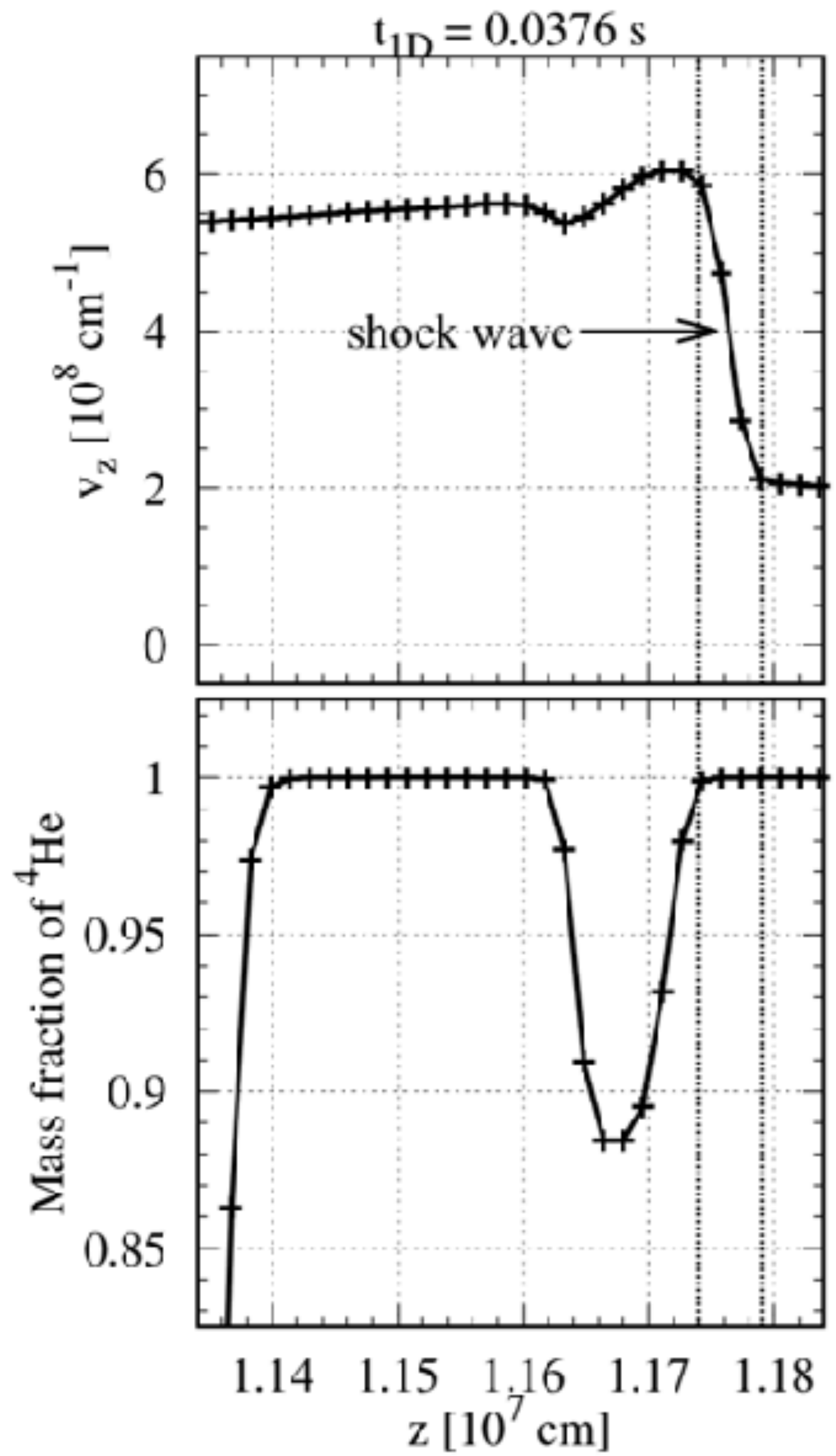
Detonation wave proceeding orbital plane

- 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.



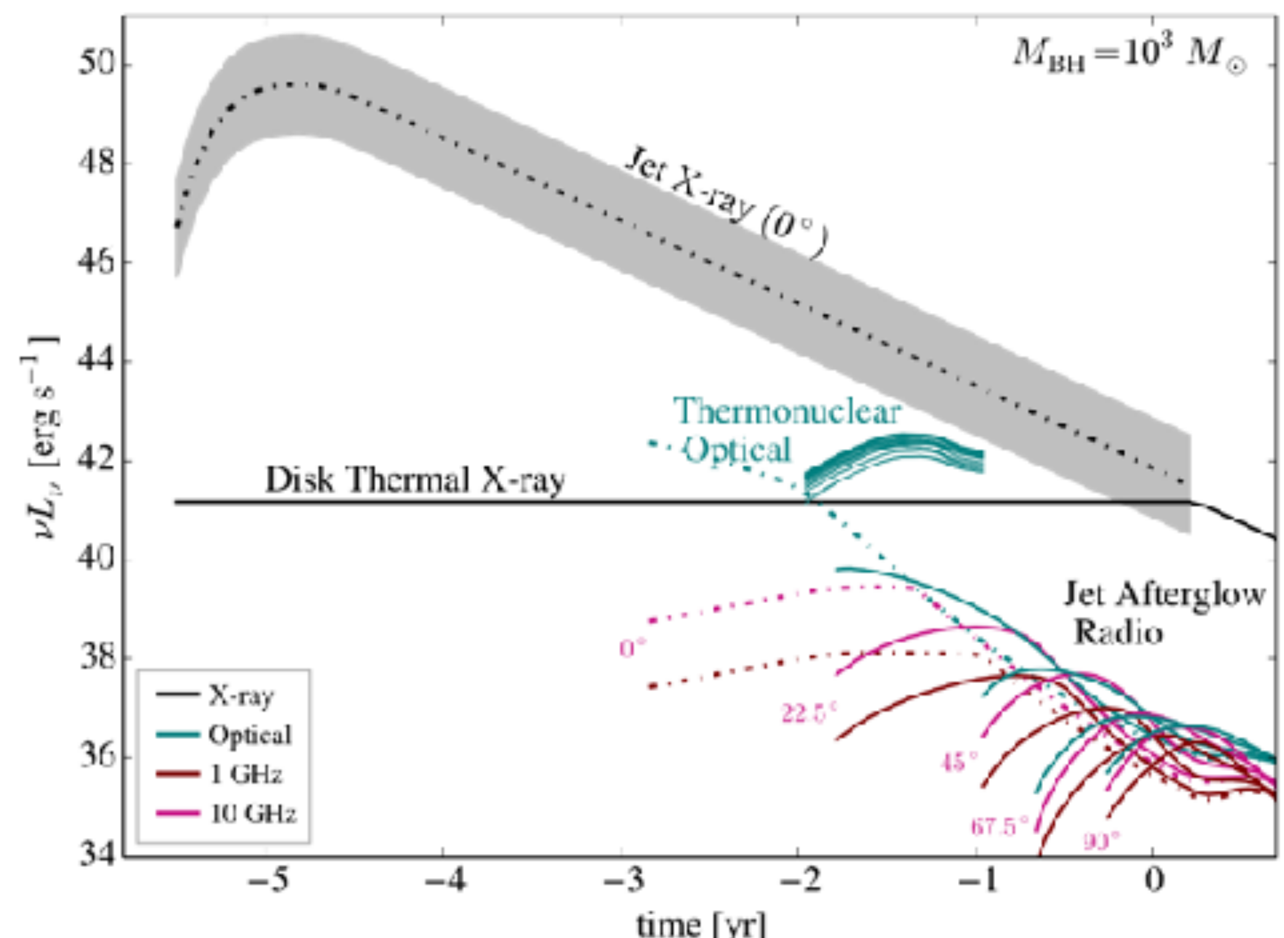
Fine structure

- 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.



Estimated luminosity

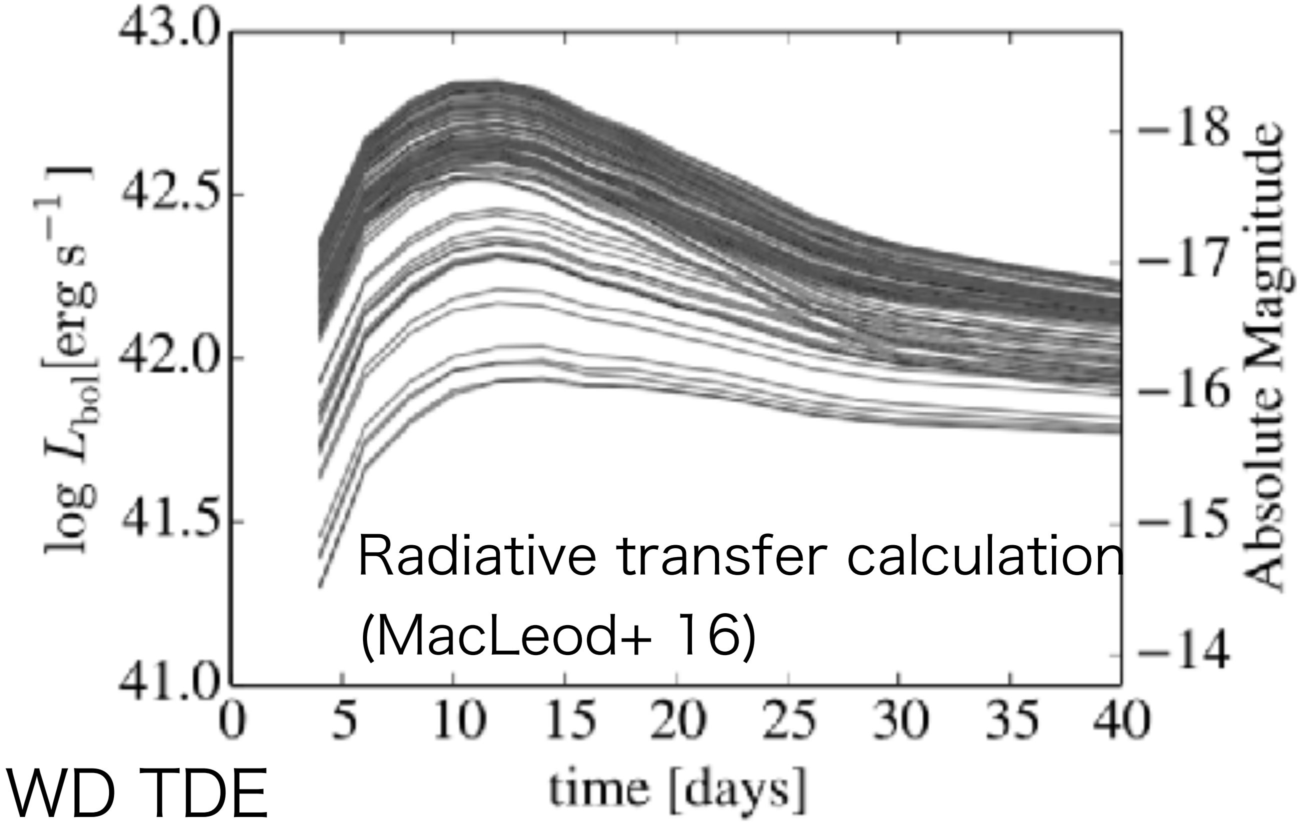
- WD TDEs will be observed as thermonuclear transients powered by radioactive decay of ^{56}Ni.
  - Similar to SNeIa
- The estimated luminosity is larger than accretion-powered luminosity of the WD TDEs by two orders of magnitude.
- Jet luminosity would be much more luminous than the thermonuclear luminosity,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



Mac Leod+16

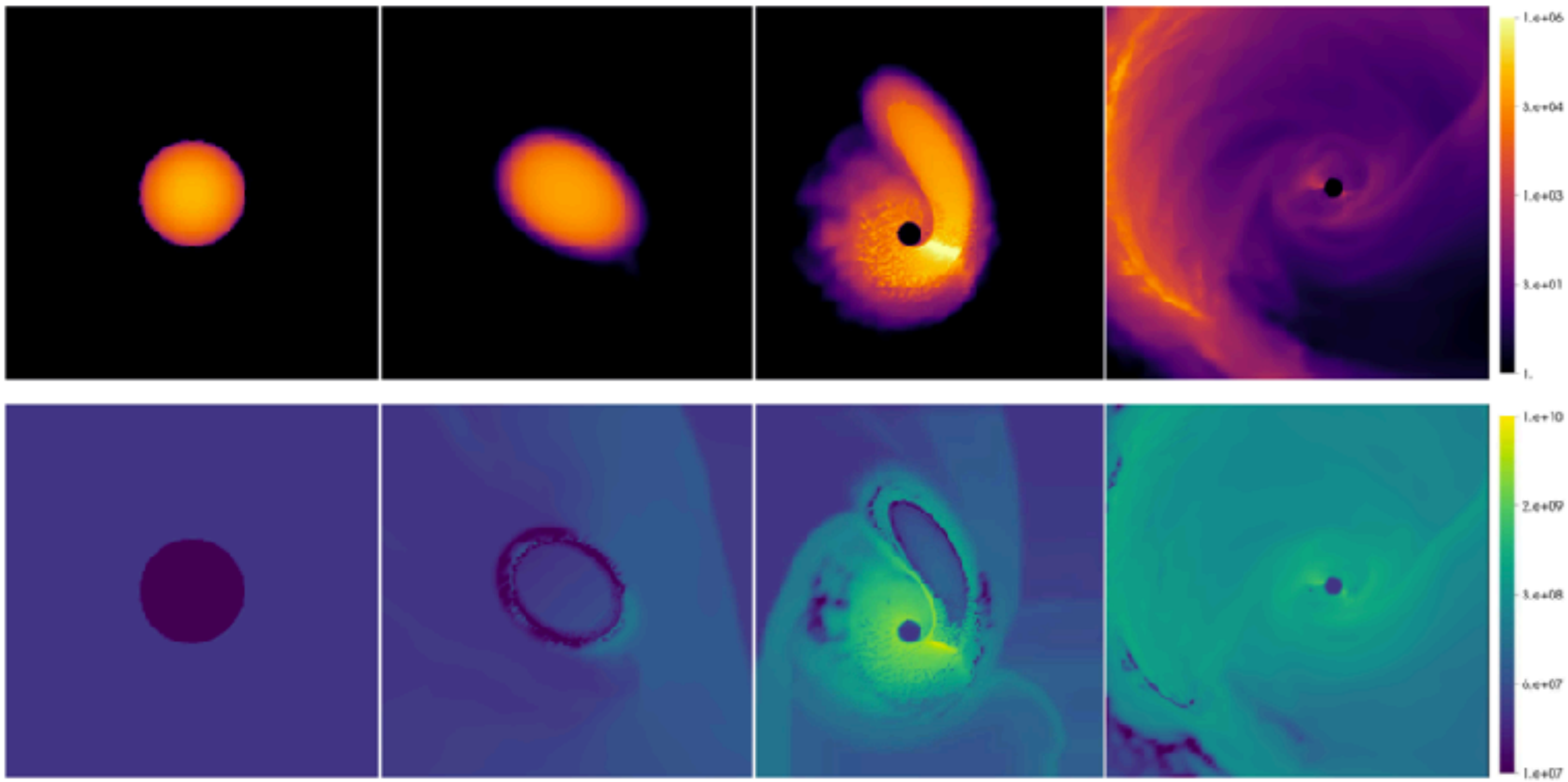
Difference from SNe Ia

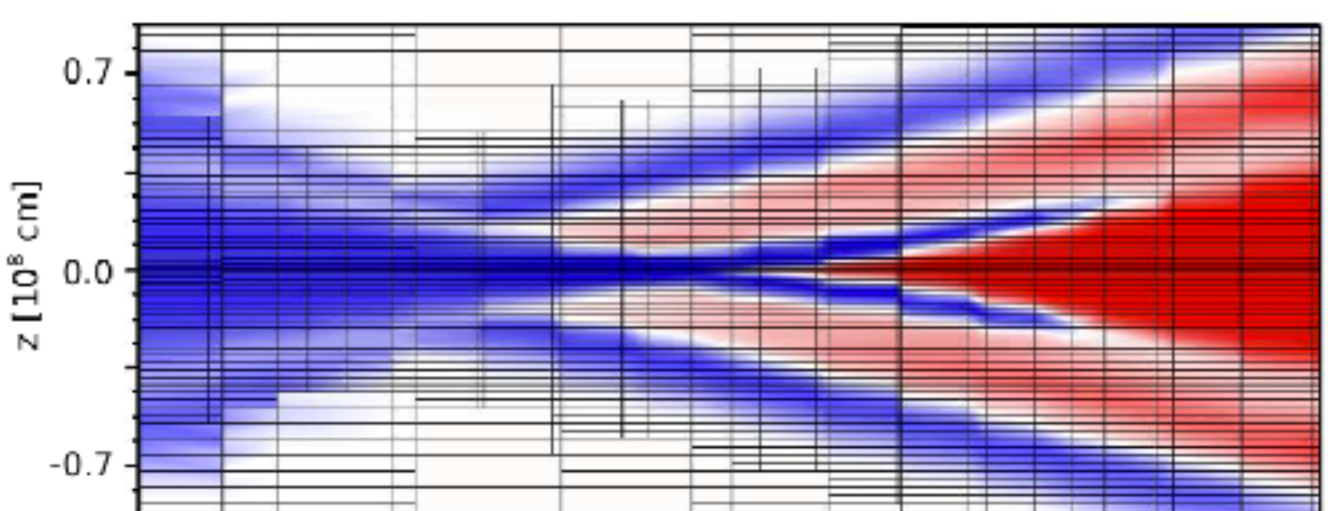
- Rapid light-curve evolution (~10 days) due to small ejecta mass (~ 0.6M$_\odot$)
- Large velocity shift due to orbital motion around IMBHs (~ 10^4 km/s)

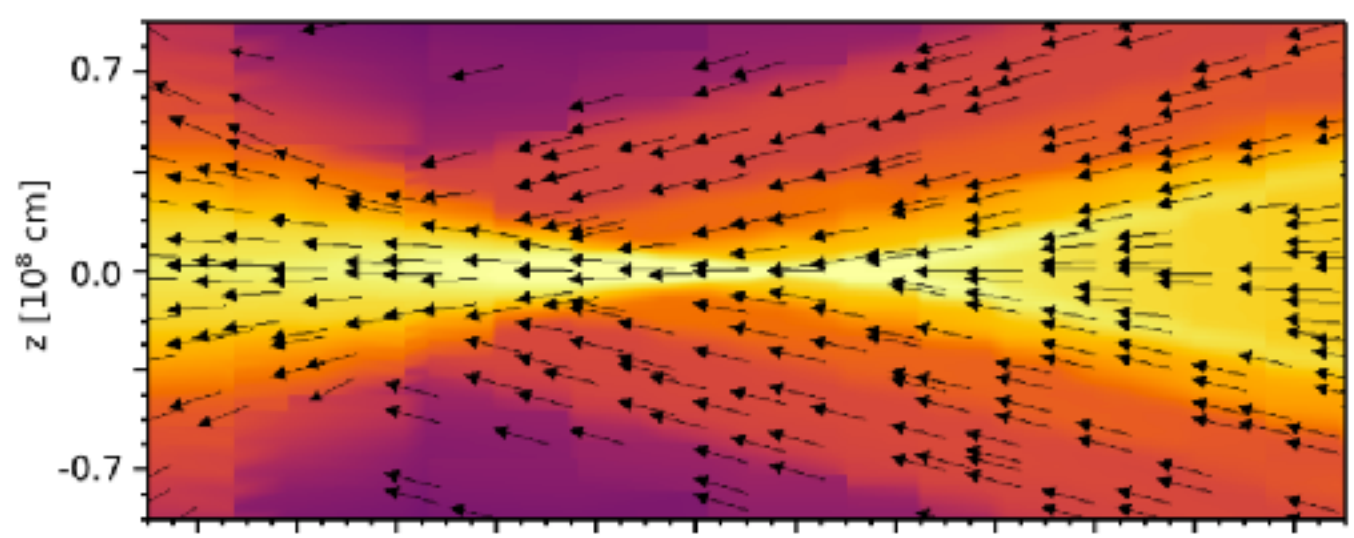


WD TDE

3D GR for WD TDE







Anninos et al. (2018)