High-resolution numerical studies for tidal detonation of a white dwarf

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Tidal Disruptions in Kyoto: Confronting Theory with Observations
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Abstract

- A white dwarf (WD) may experience thermonuclear explosion in a TDE (tidal detonation).
- Numerical simulation of tidal detonation is much more difficult than thought usually.
- Careless simulation leads to incorrect tidal detonation due to numerically artificial heating.
- We will show WD explosion triggered by physical heating.

Contents

- Fundamentals of tidal detonation
- Tidal detonation in 1D simulation
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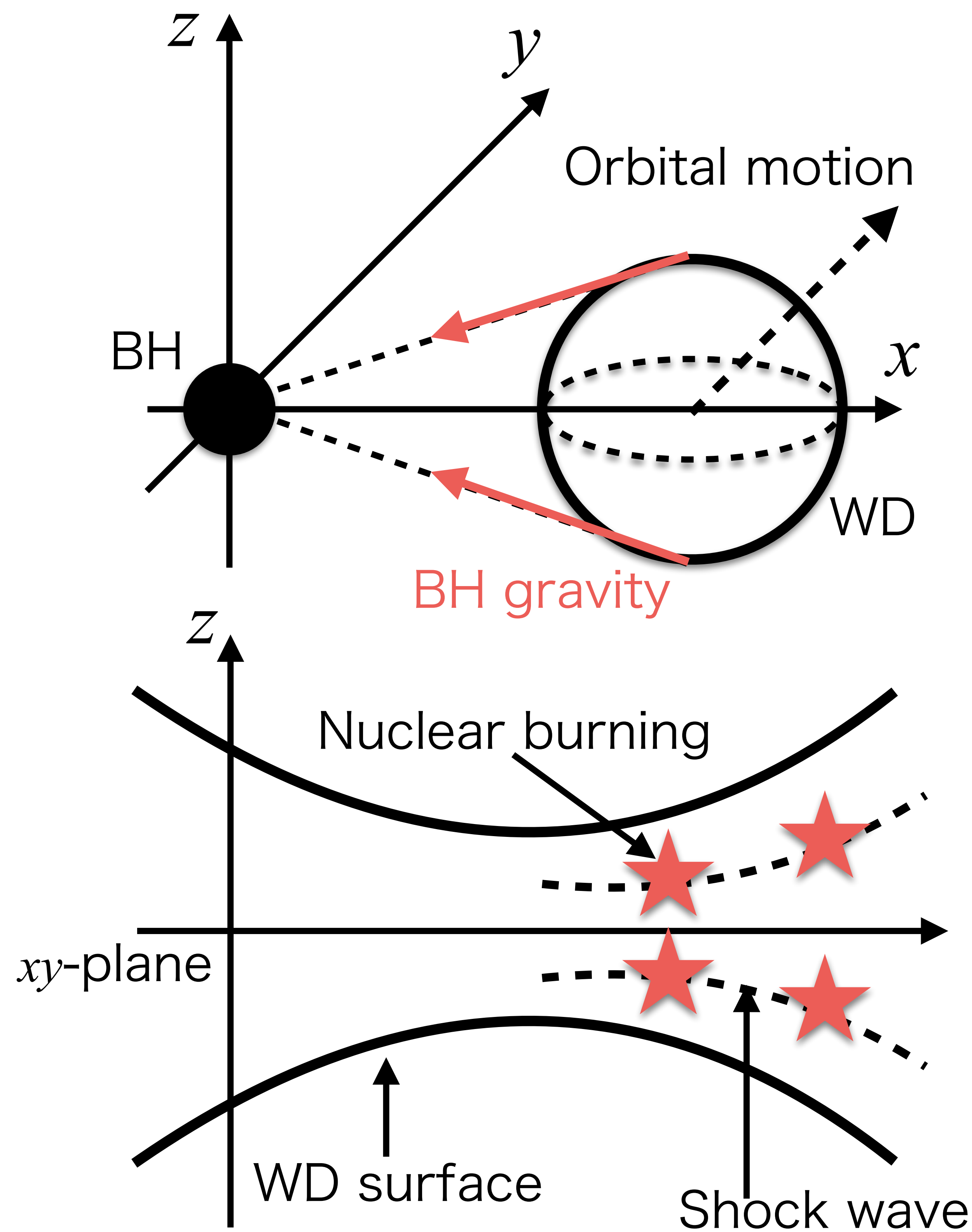
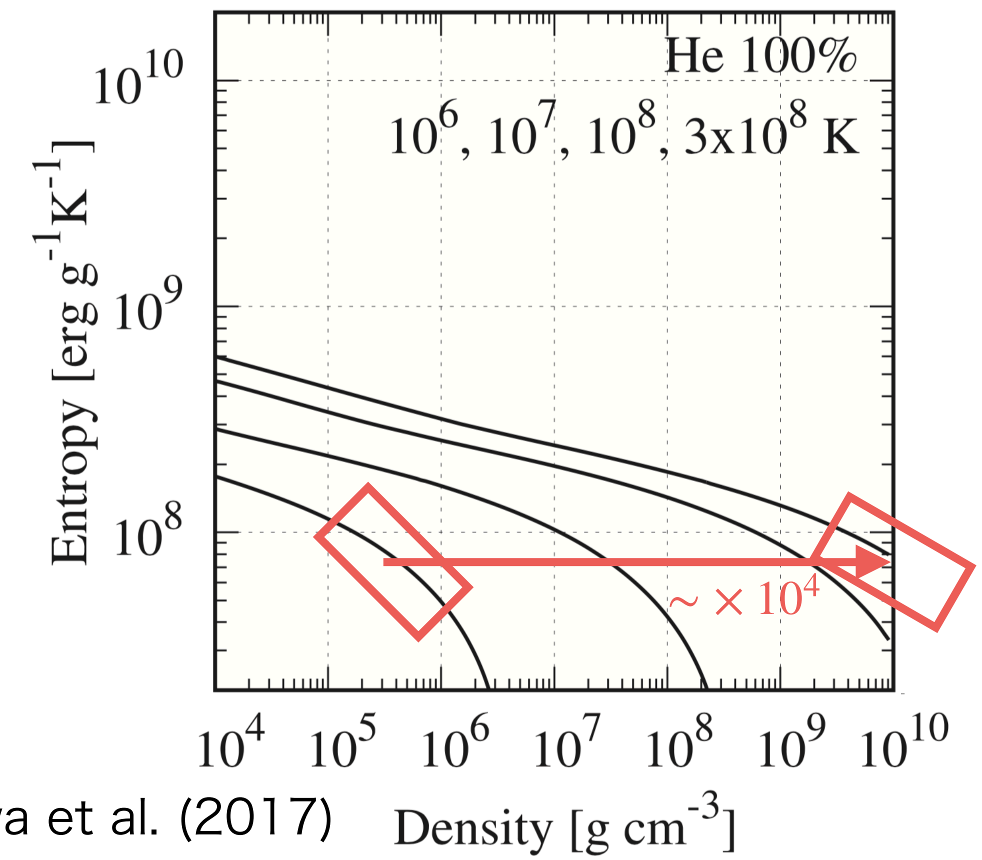
Tidal detonation

- The WD is compressed in z-direction.
- The compression induces a shock wave (nozzle shock).
- The shock wave triggers a detonation wave (tidal detonation).
- The detonation wave synthesizes ^{56}Ni.
- The WD TDE can be powered by ^{56}Ni, similarly to SNe Ia.

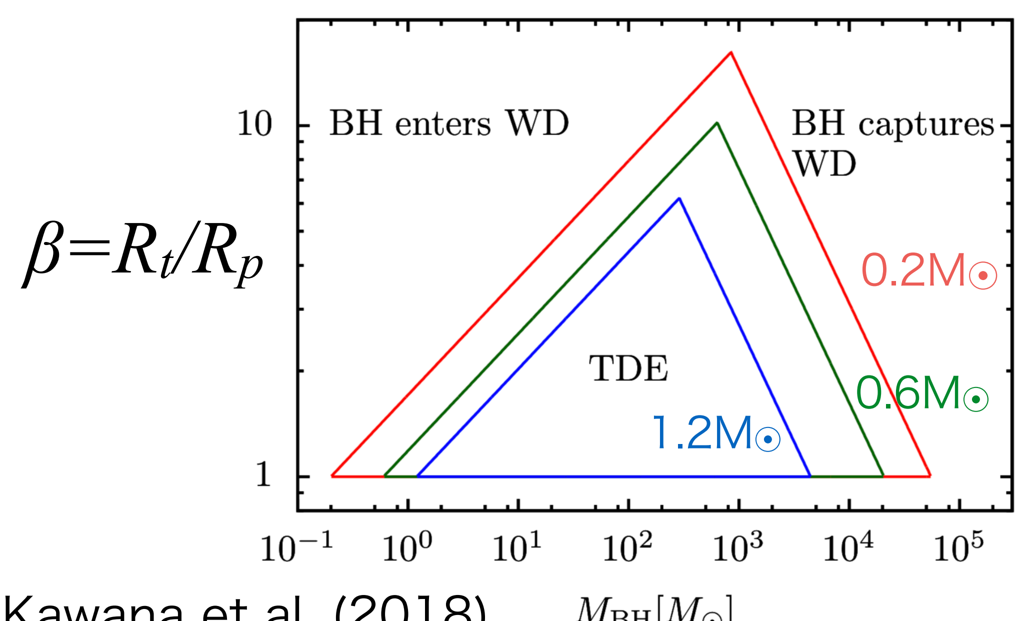


Adiabatic heating

- Adiabatic compression cannot ignite tidal detonation.
- A He WD (light WD) needs more than $\sim 10^4$ times compression for tidal detonation.
- But, even the deepest penetration ($\beta \sim 20$) achieves only $\sim 10^3$ times compression.
- CO and ONe WDs (heavy WDs) are much less compressed than He WDs.



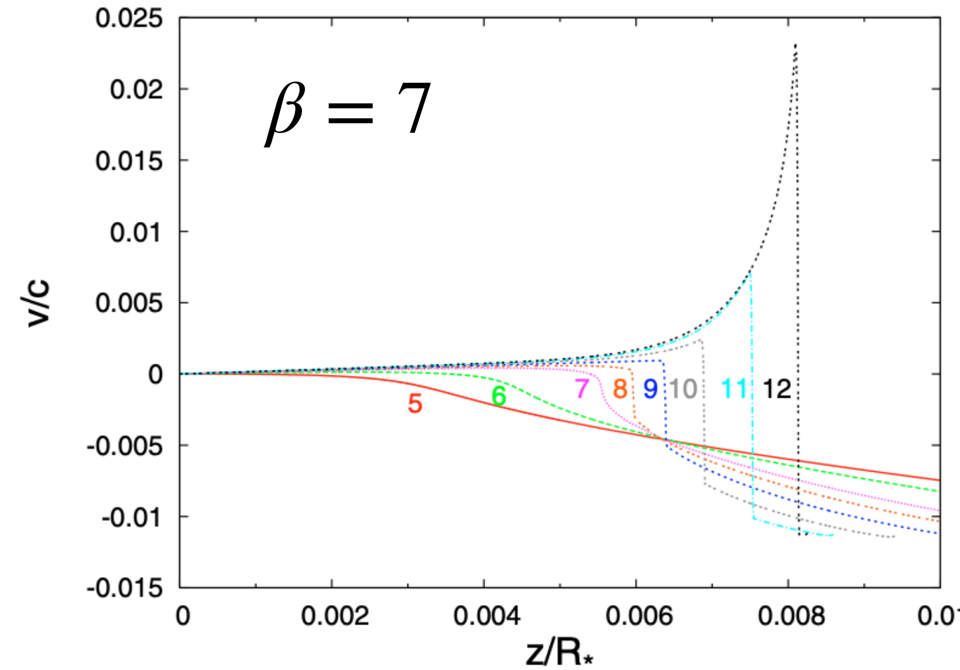
Tanikawa et al. (2017)



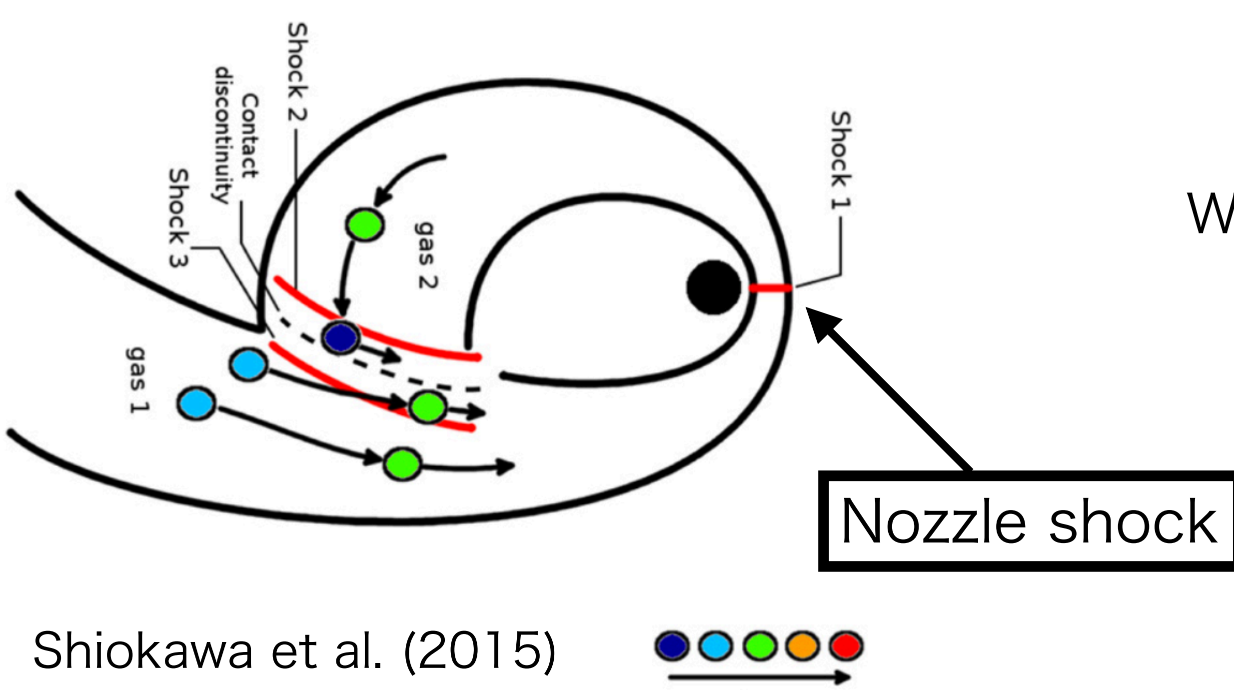
Kawana et al. (2018)

Shock heating

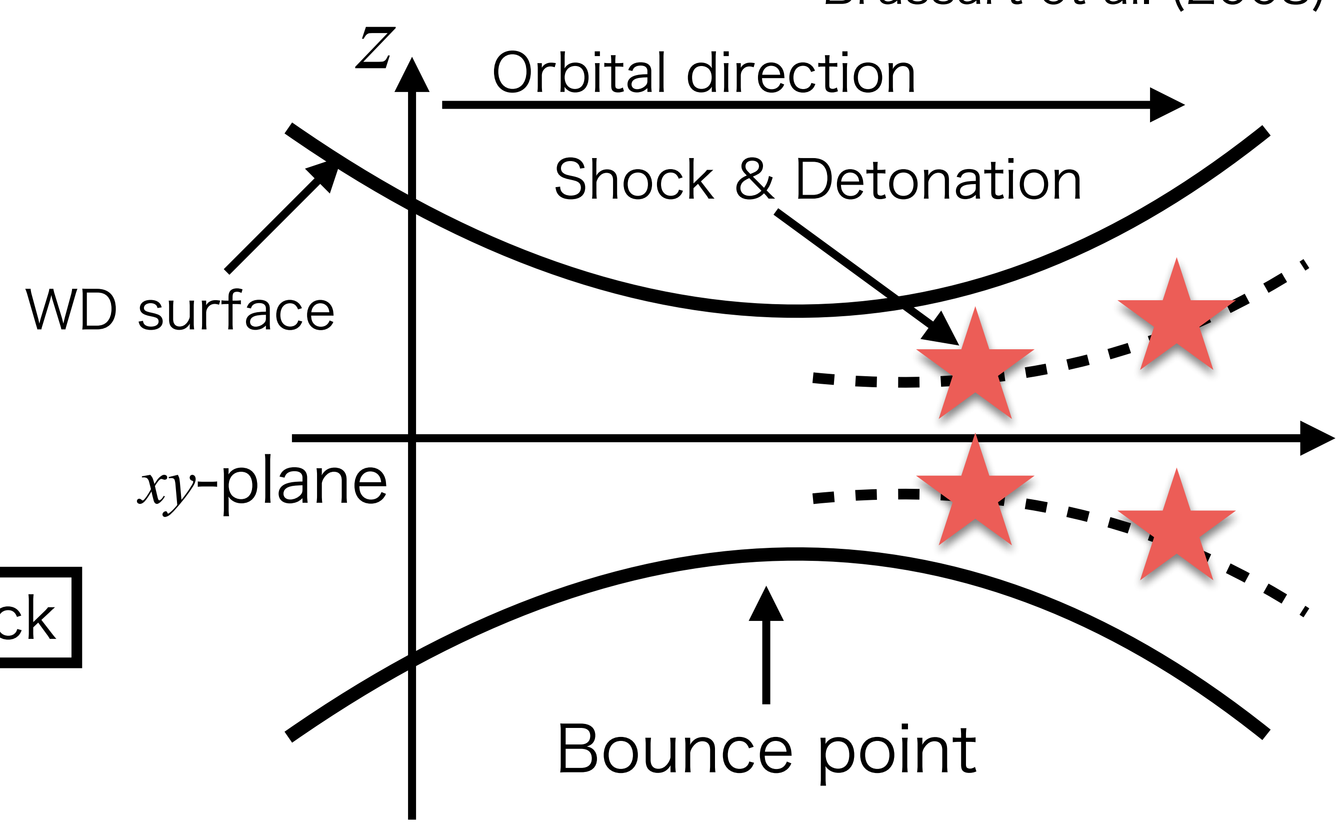
- Nozzle shock emerges
  - After bounce for typical WD TDE ($\beta \lesssim 10$).
  - Near the surface of a WD.
- A detonation wave is also generated near the surface after bounce.



Brassart et al. (2008)



Shiokawa et al. (2015)



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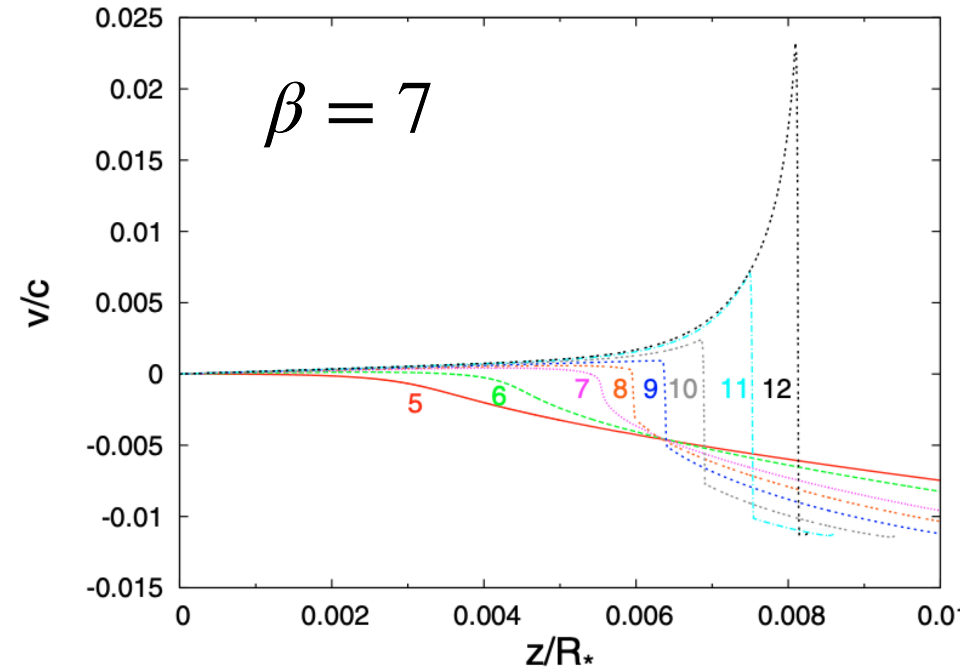
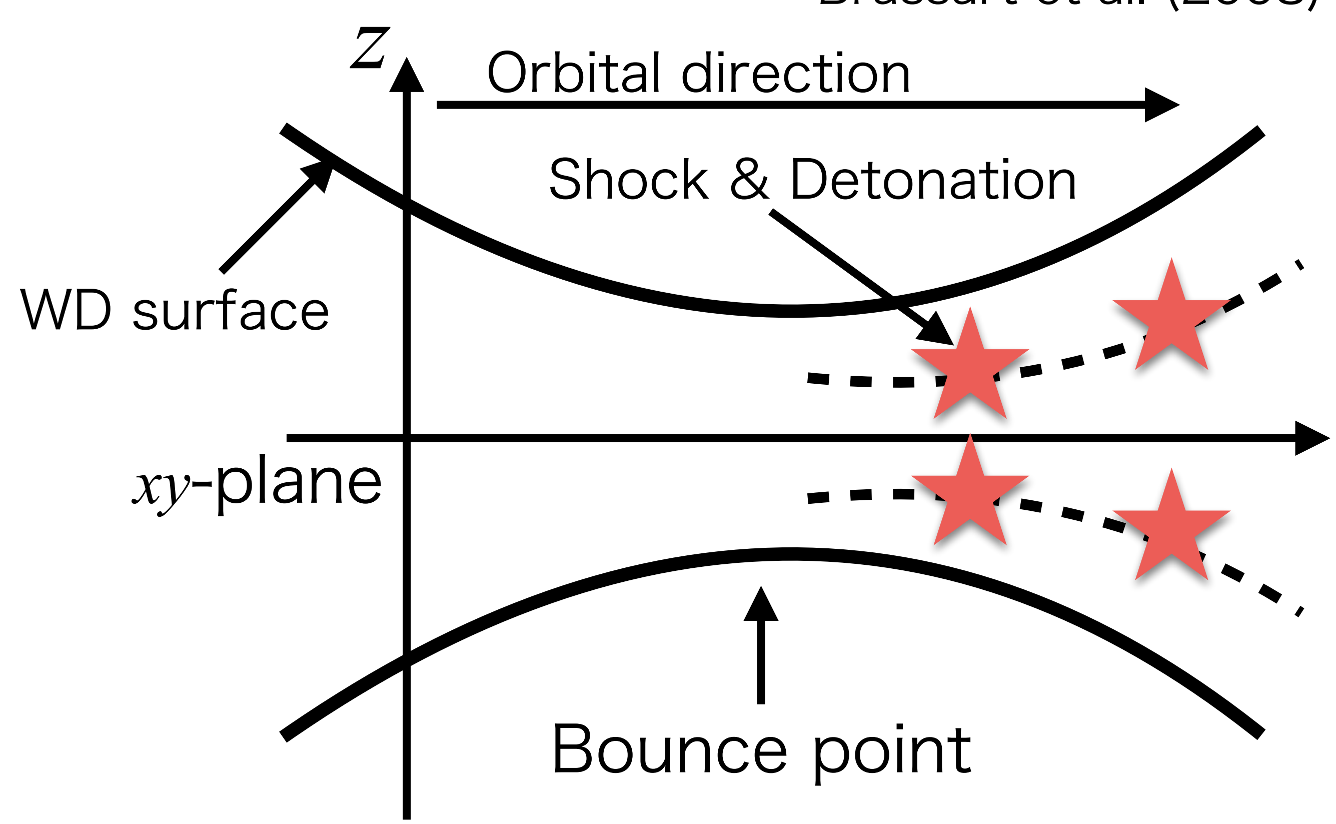


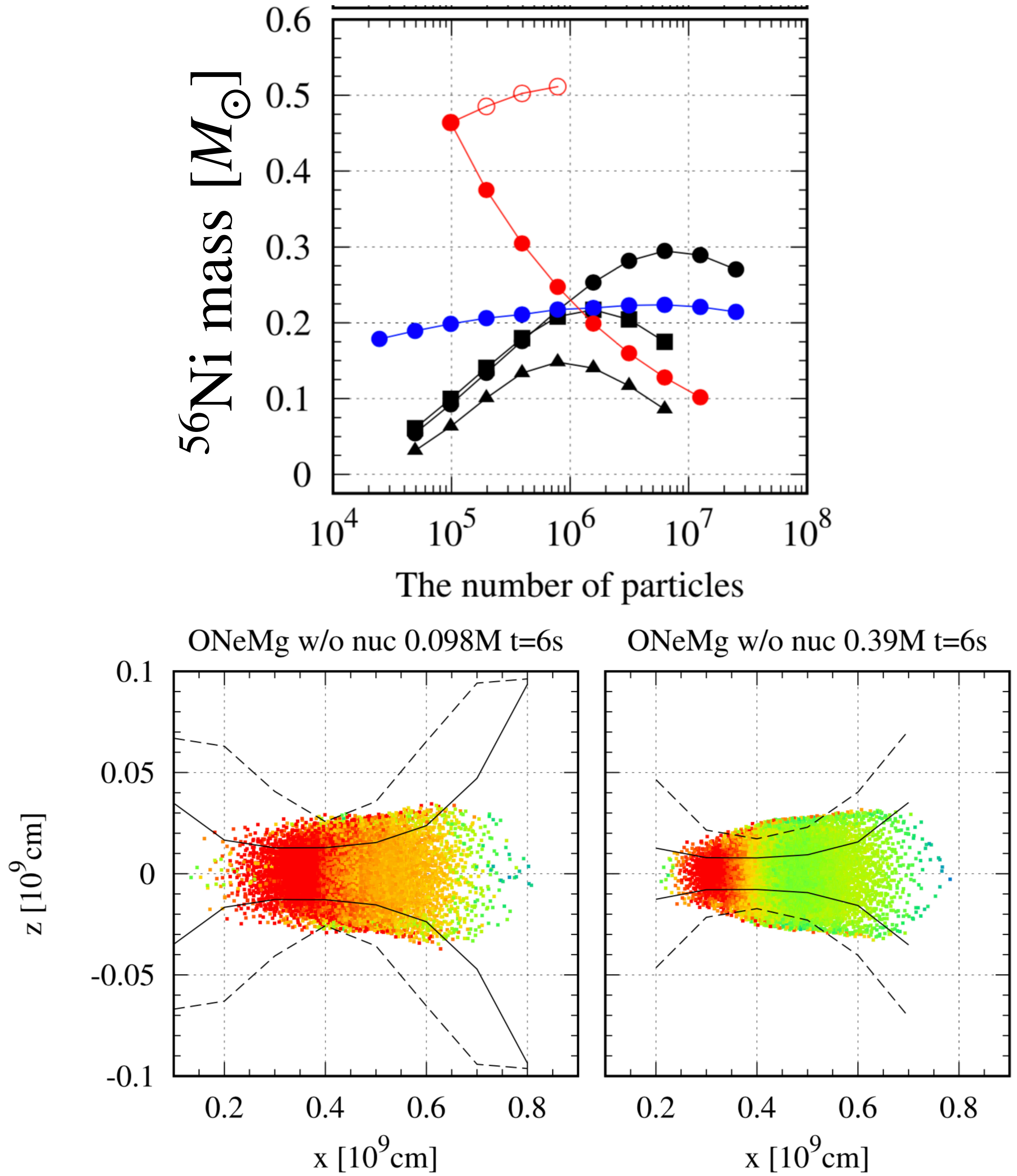
Brassart et al. (2008)

The first passage at the pericenter



Difficulty of WD TDE simulation

- No convergence of nucleosynthesis
- Overheating in the lower-resolution case due to numerically artificial heating
- Underheating in the higher-resolution case due to missing of shock generation
- The highest resolution among any studies for WD TDE SPH simulation



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

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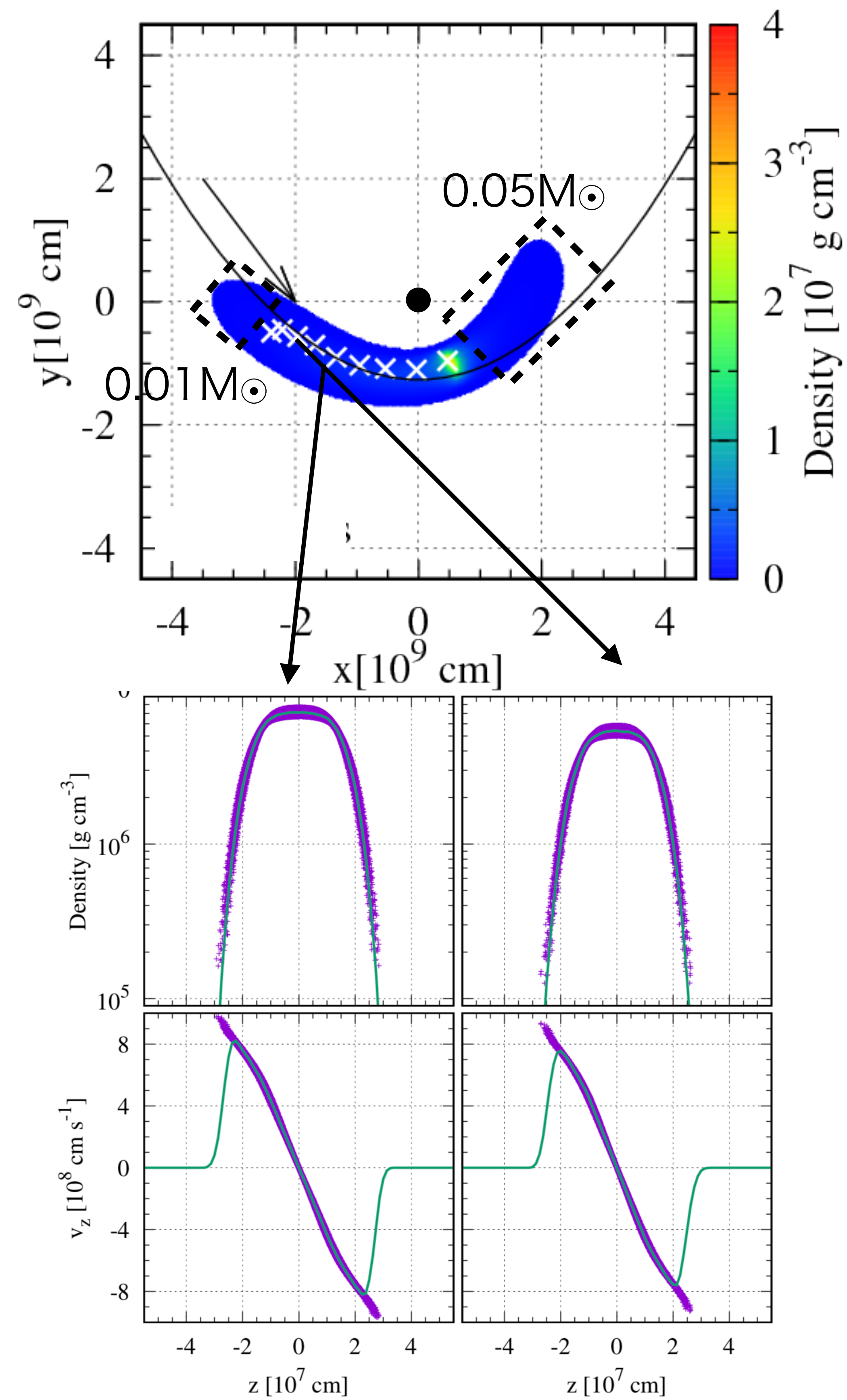
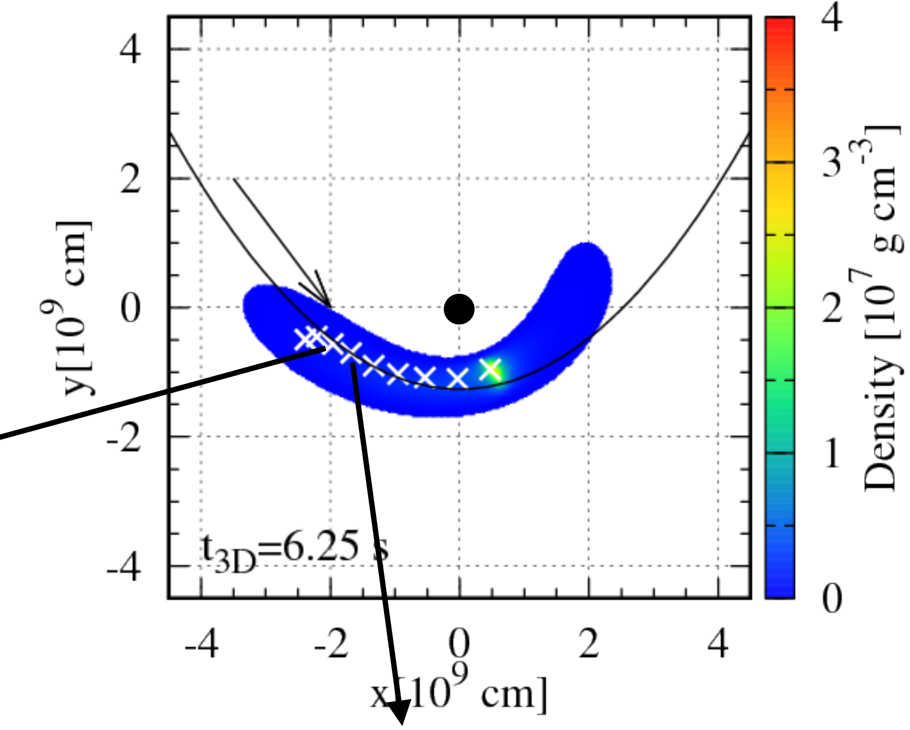
Switch 3D to 1D

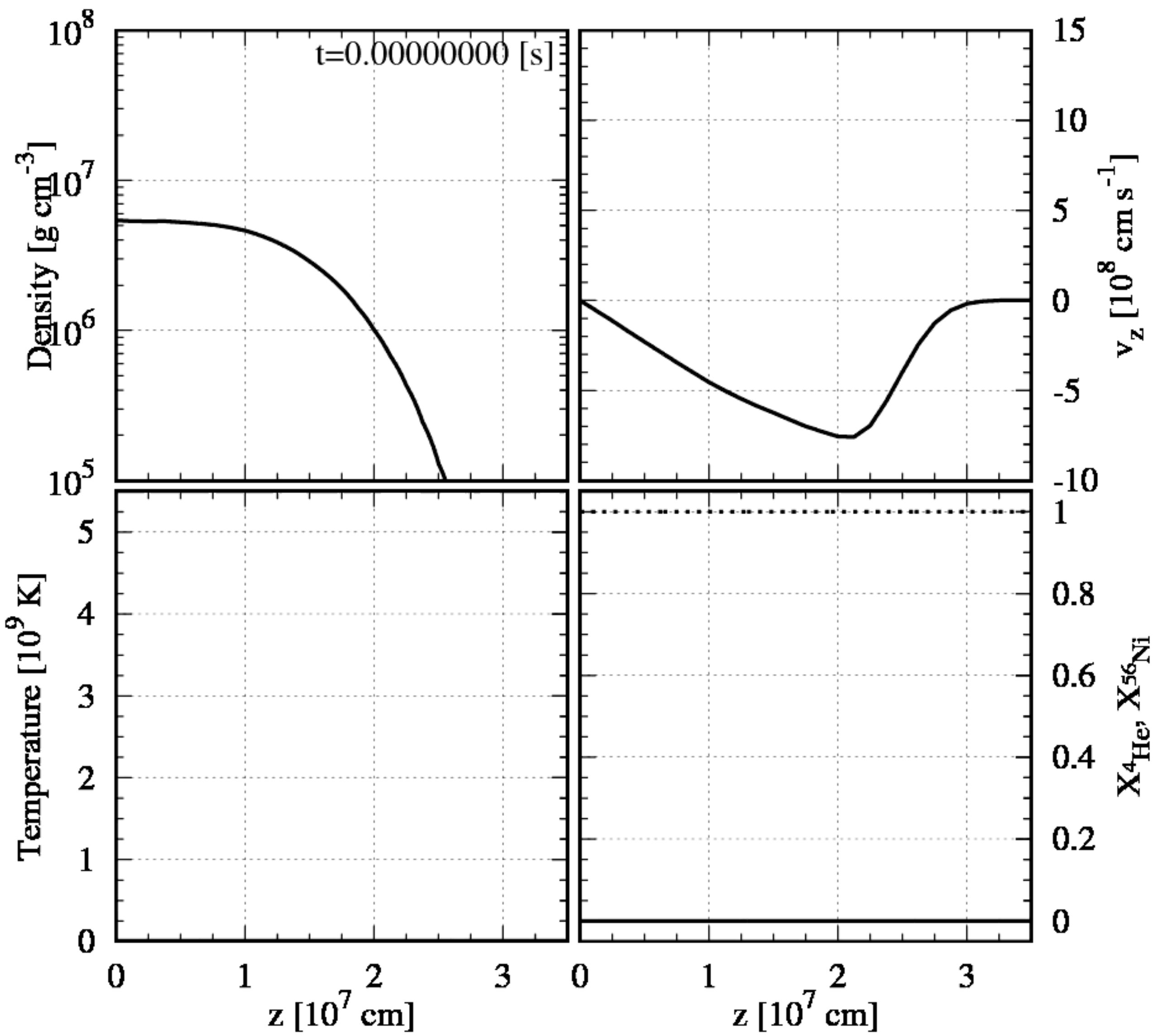
- 3D SPH simulation with high resolution enough to suppress overheating
  - 0.45M⊙ HeWD disrupted by 300M⊙ IMBH
  - N~3x10⁸ for the He WD
- Extracting z-columns indicated by white crosses
- 1D mesh simulation
  - z-columns
  - with nuclear reactions

Tanikawa (2018, ApJ, 858, 26)



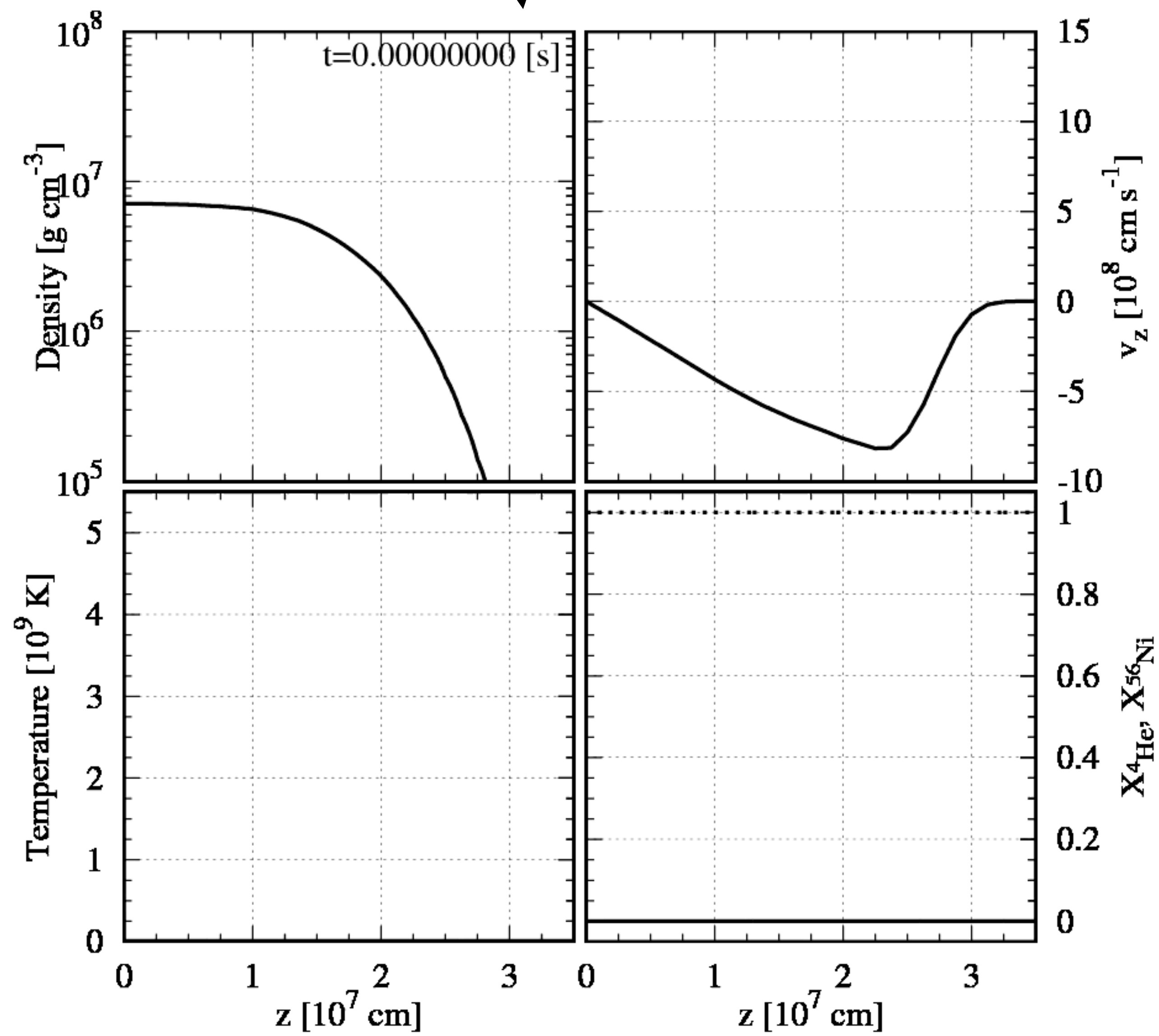
Movies





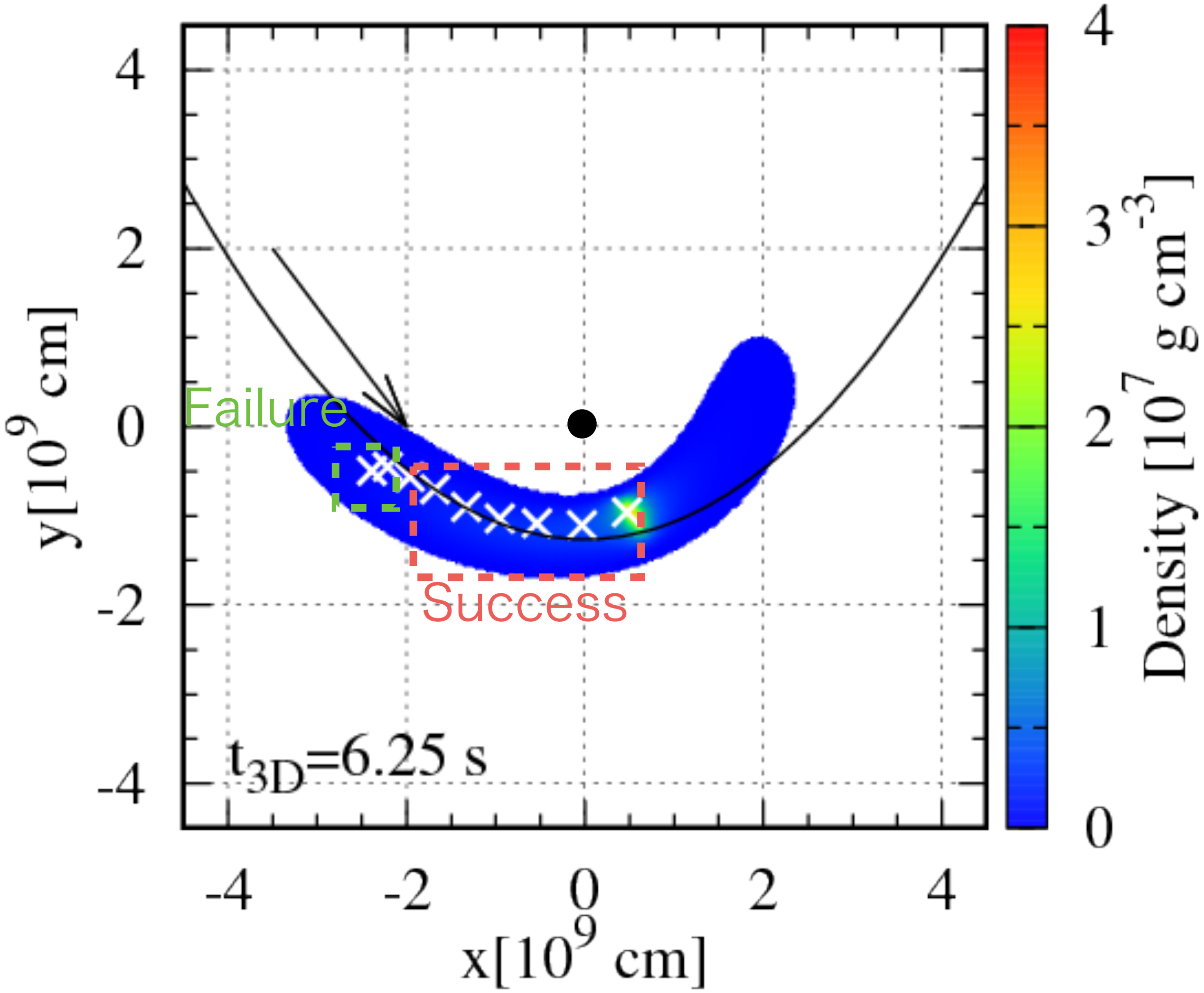
Failure case

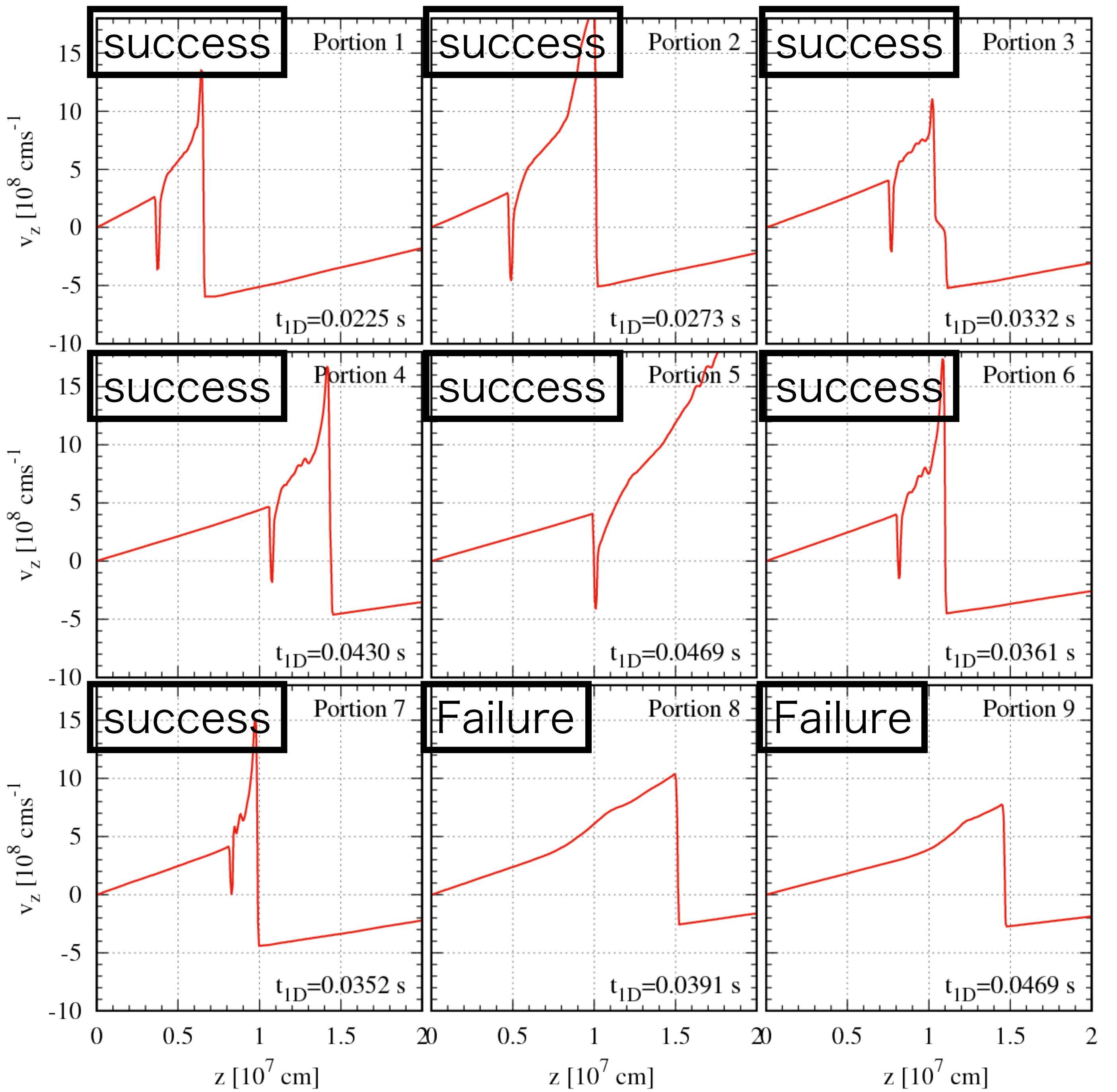
Tanikawa et al. (2018, ApJ, 858, 26)



Success case

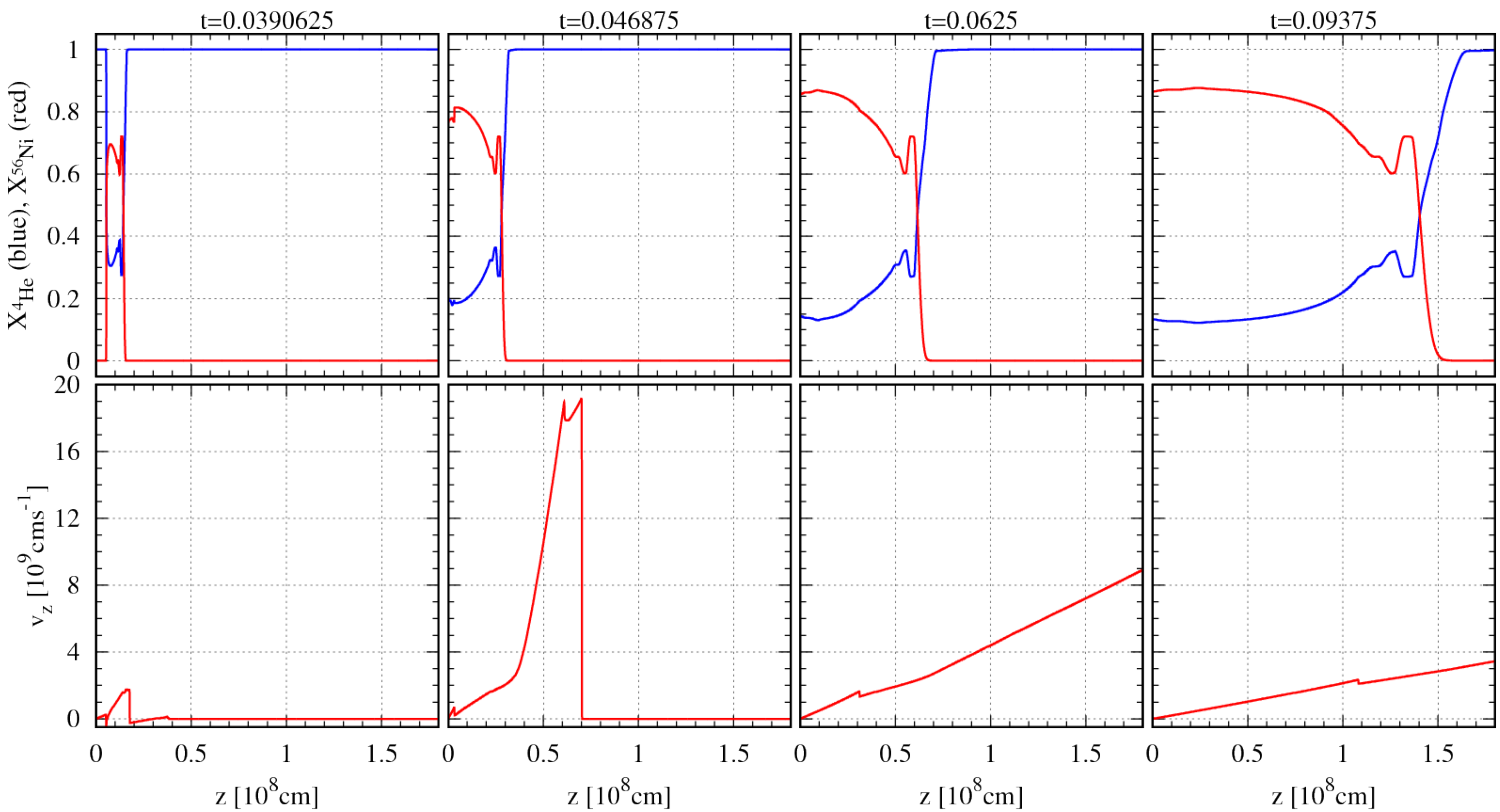
1D Results





Tanikawa (2018, ApJ, 858, 26)

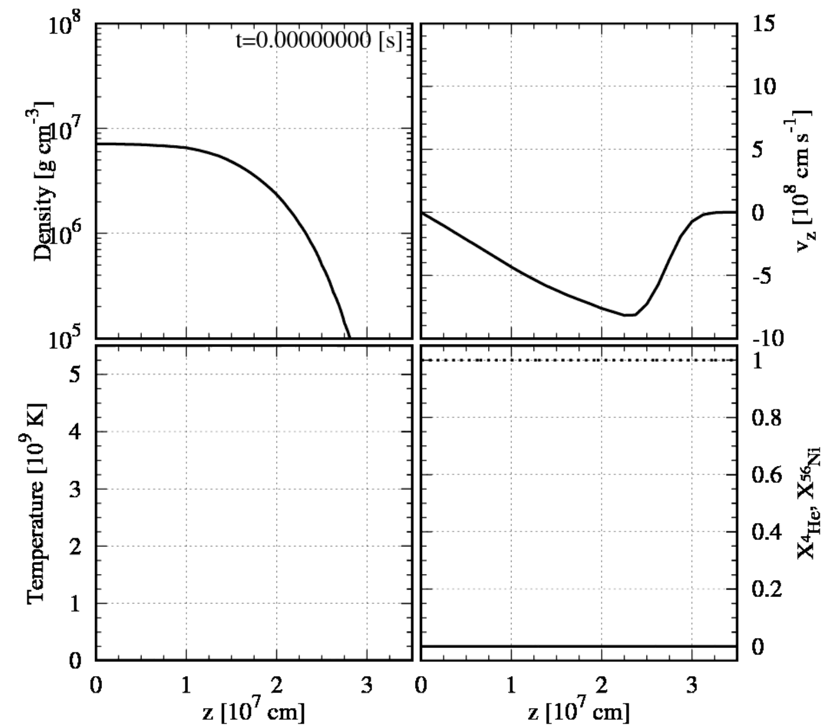
Nucleosynthesis

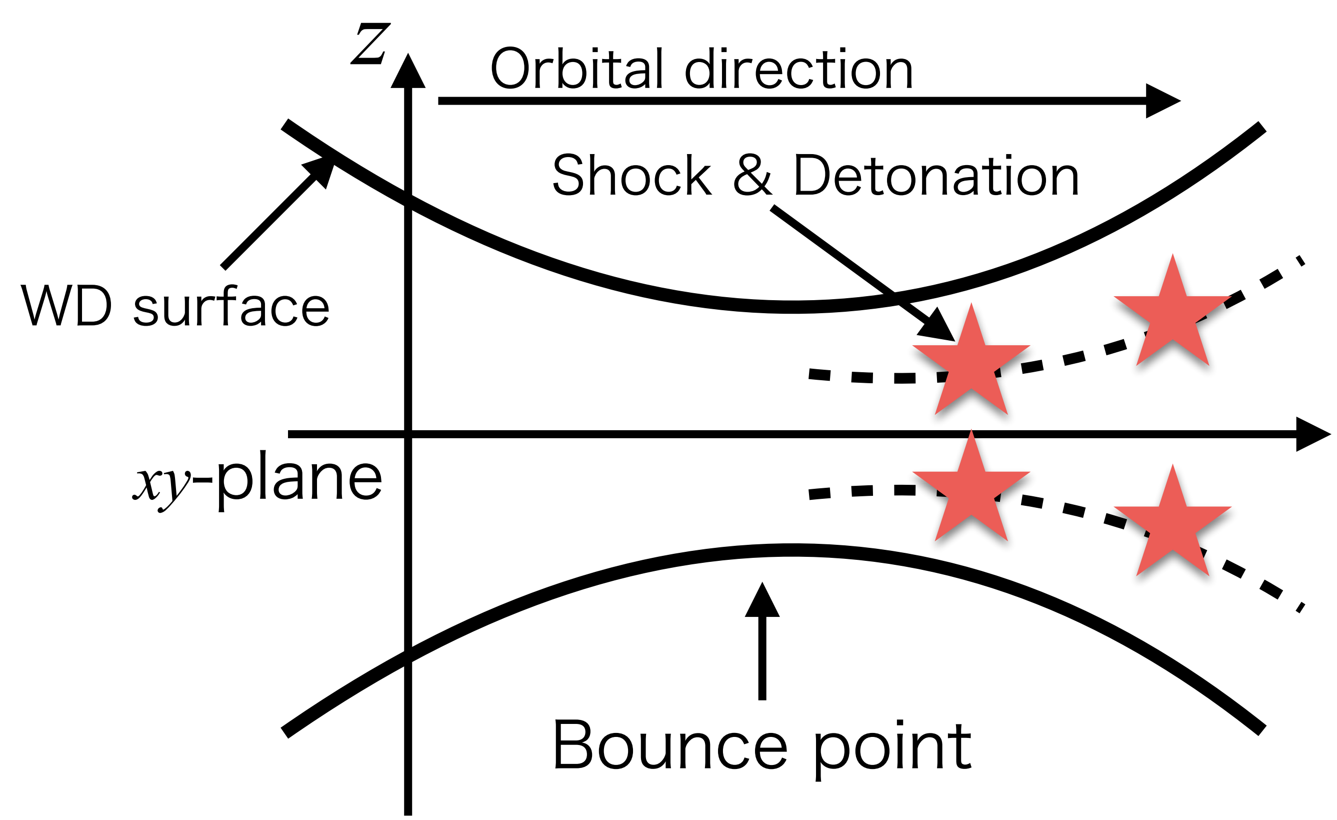


- The detonation wave leaves 20% ^{4}He and 80% ^{56}Ni.
- There is no intermediate mass element (IME) such as Ca.
- The detonated region has high density ($>10^6$ gcm^{-3}).

The important points

- Tidal detonation is triggered by a shock wave.
- The detonation starts after bounce near the surface.
- The detonation wave also incinerates the central region.





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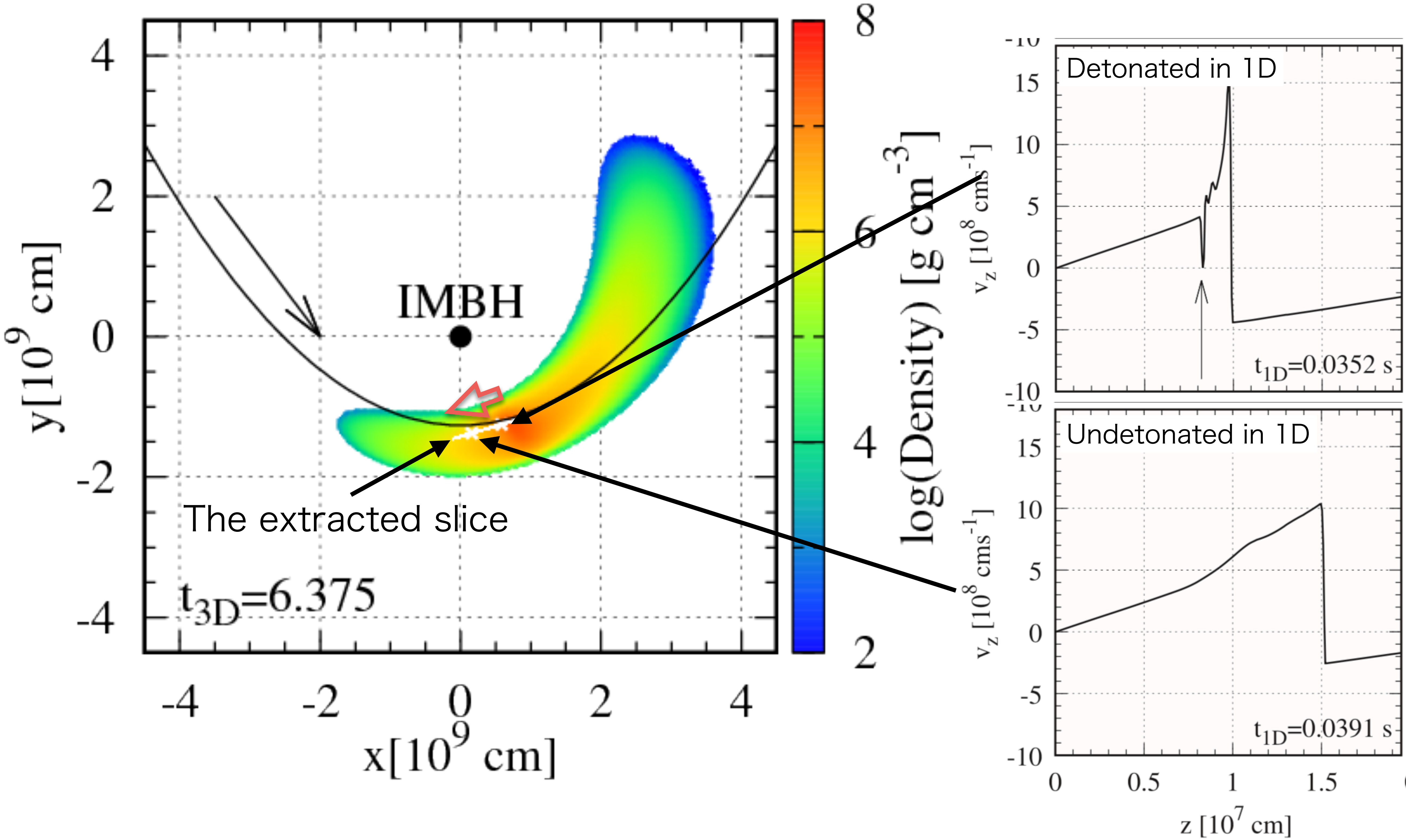
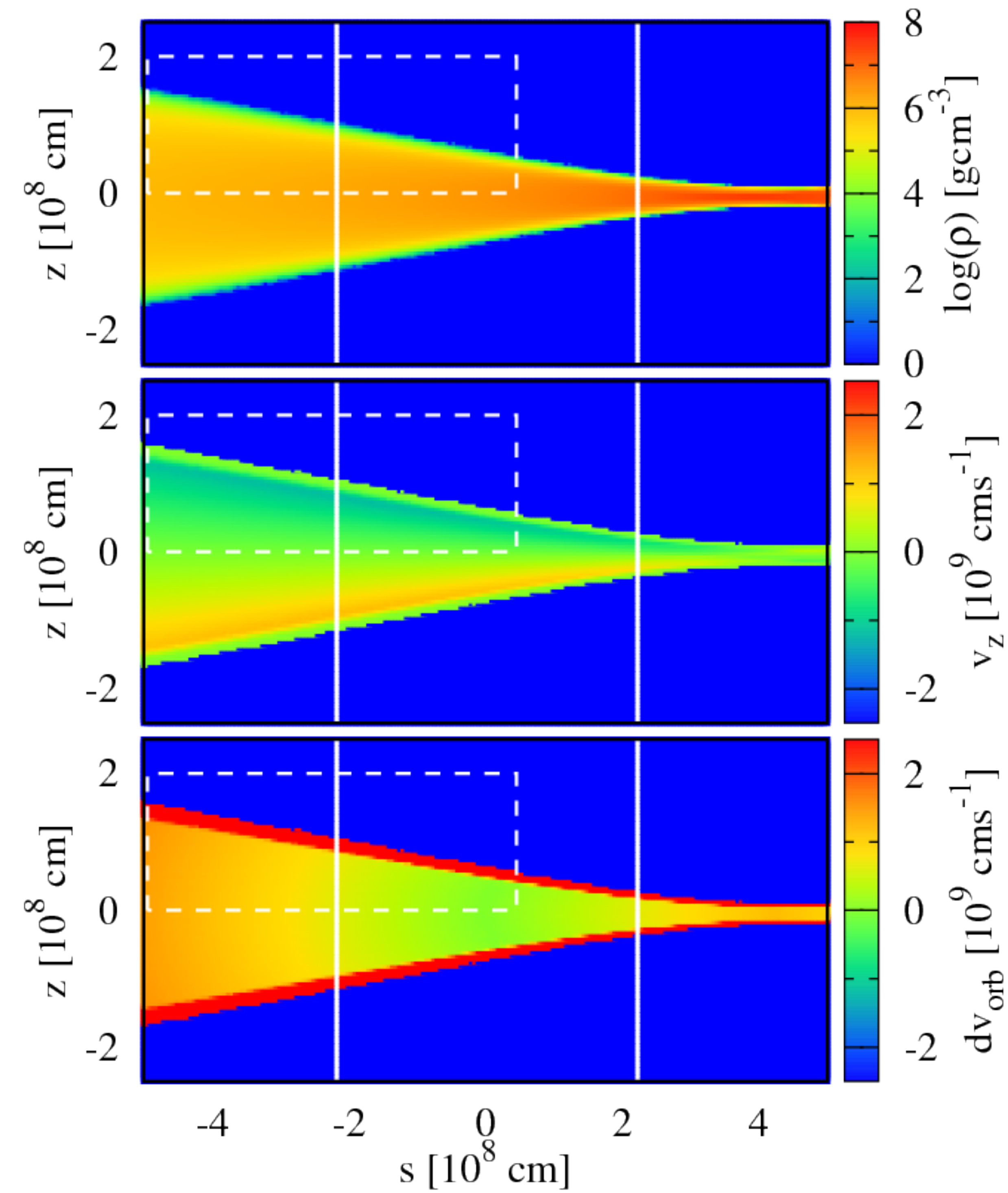
2D simulation

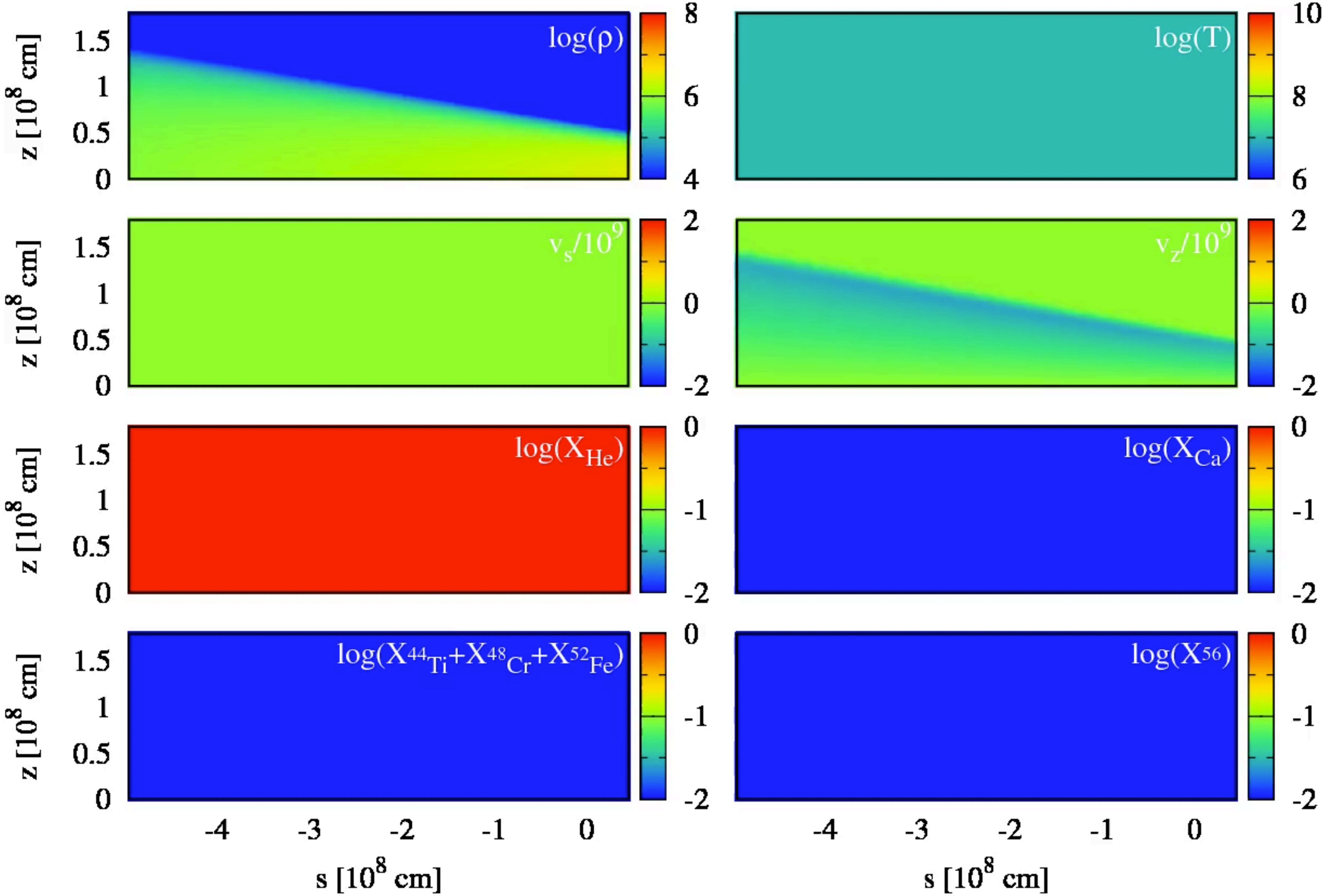


Edge-on view of the slice

- FLASH
- Helmholtz EoS
- Aprox13
- Mesh size $2.5 \cdot 10^5$ [cm]
- "Outflow" boundary condition at the s-edges and the upper z-edge.
- "Reflect" boundary condition at the lower z-edge.
- Oakforest-PACS (massive Xeon Phi cluster)

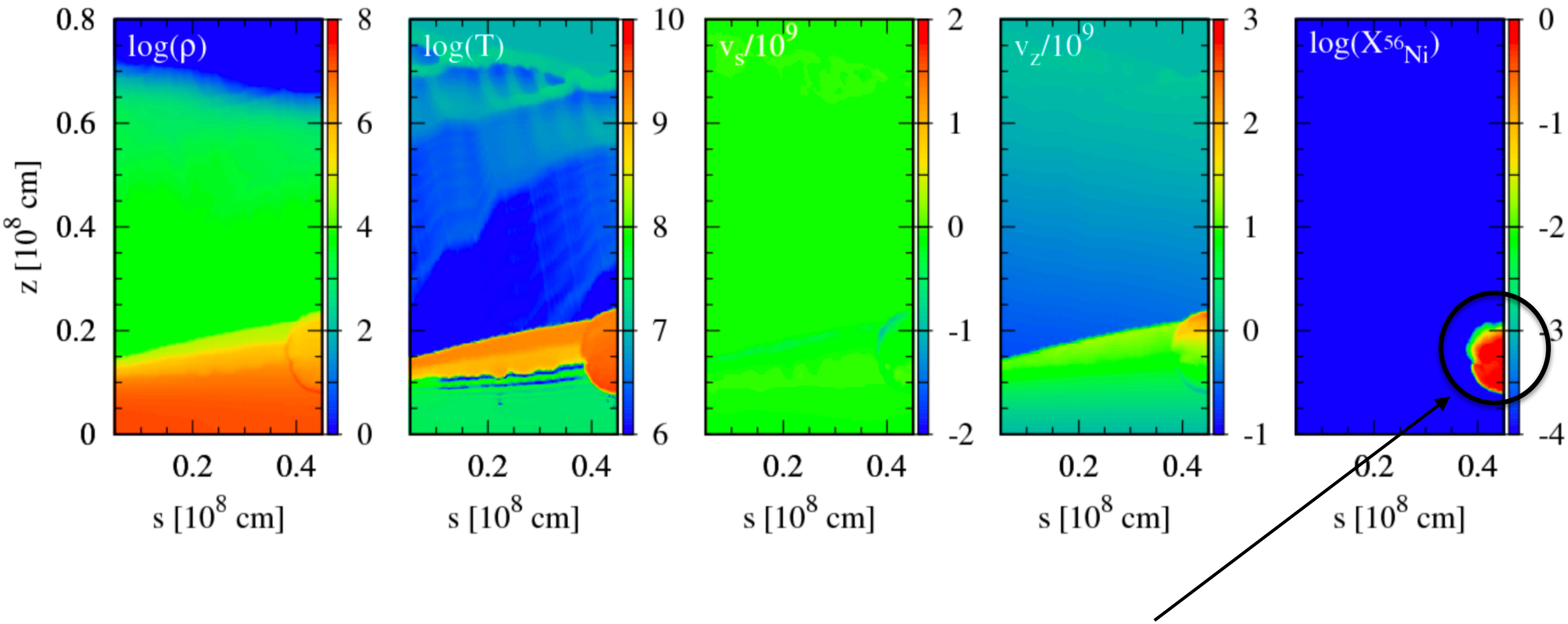


Movie



log(ρ)
log(T)
v_s/10^9
v_z/10^9
log(X_He)
log(X_Ca)
log(X44_Ti+X48_Cr+X52_Fe)
log(X56)
z [10^8 cm]
s [10^8 cm]

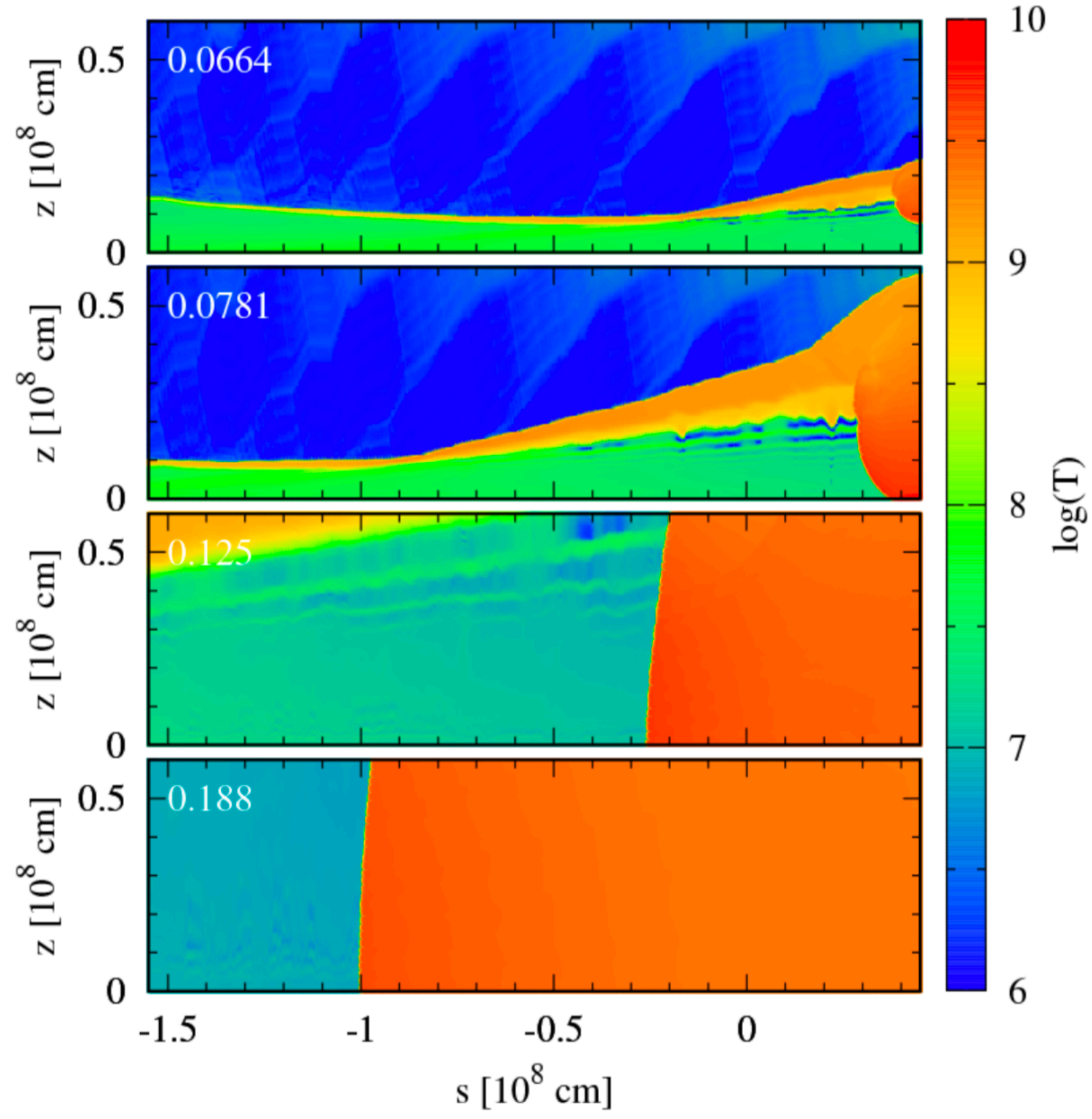
Ignition of detonation



- A detonation starts at an off-center region.
- This is consistent with 1D simulation.

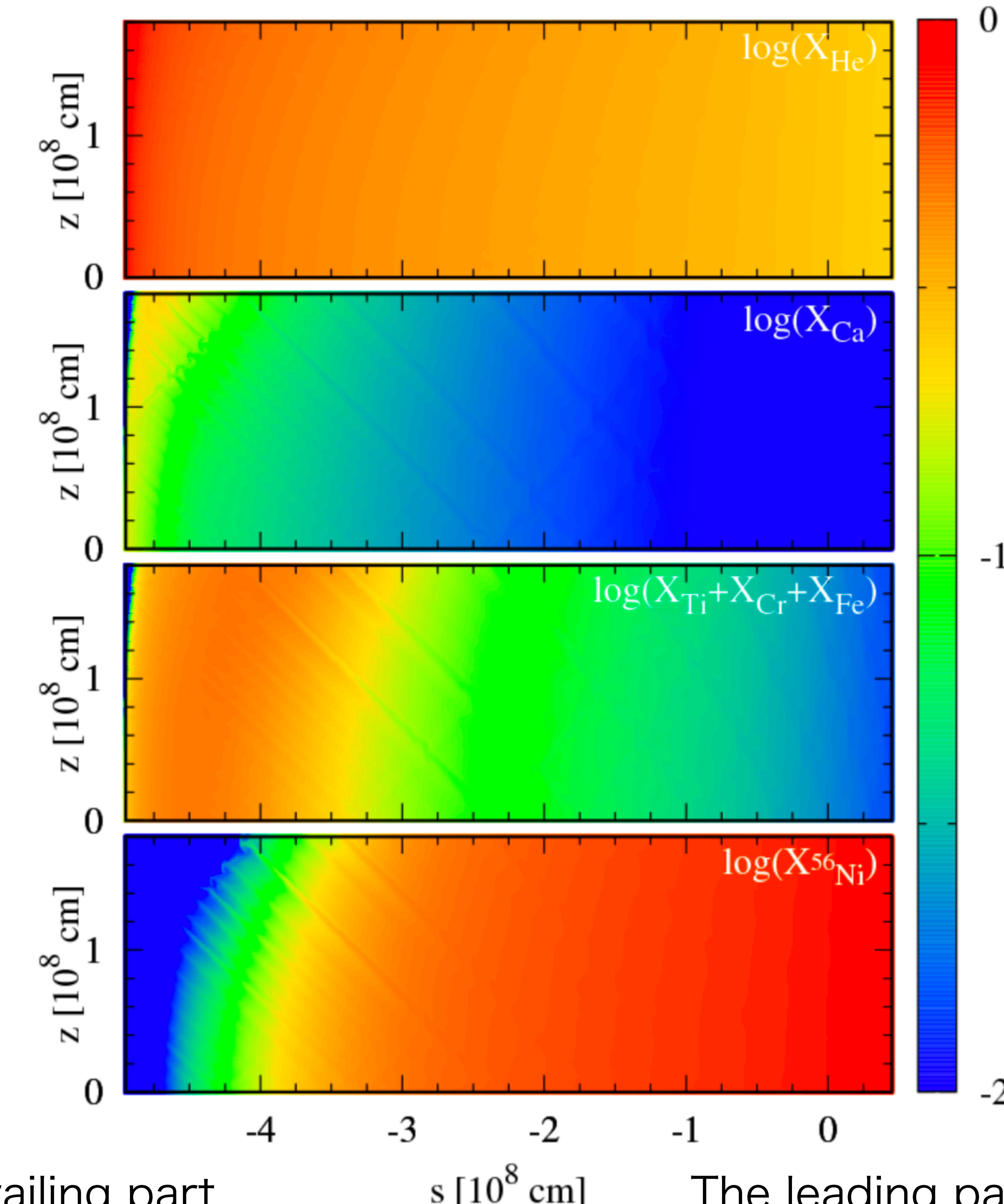
Propagation of detonation

- Detonation incinerates not only materials in the z-direction, but also materials in the orbital plane.



Nucleosynthesis

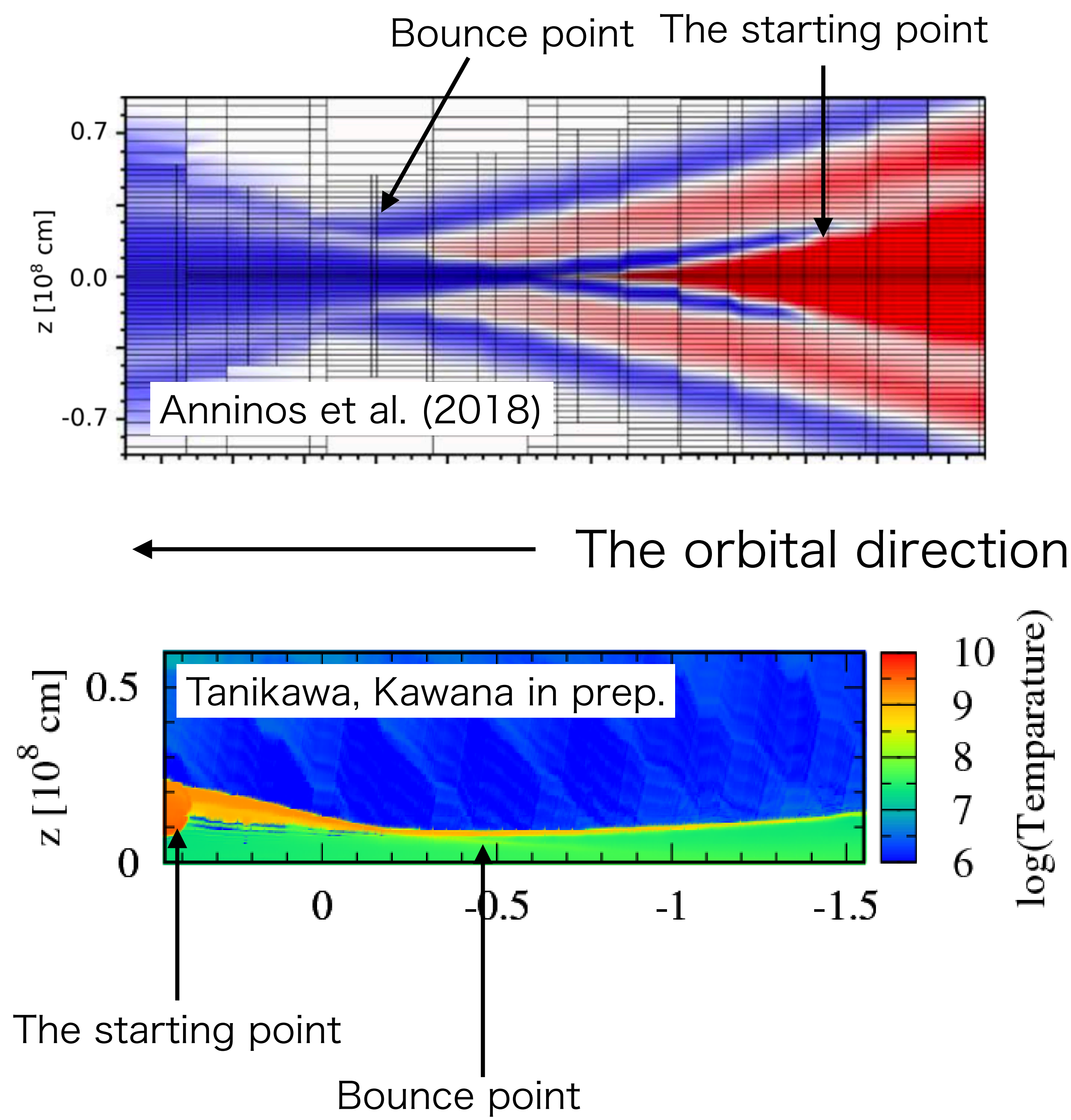
- In the leading part, only ^{56}Ni is yielded, the same as the 1D framework.
- IMEs are yielded in the trailing part.
- The trailing part receives detonation when their density becomes low ($\lesssim 10^6 \mathrm{g cm^{-3}}$).



The trailing part The leading part

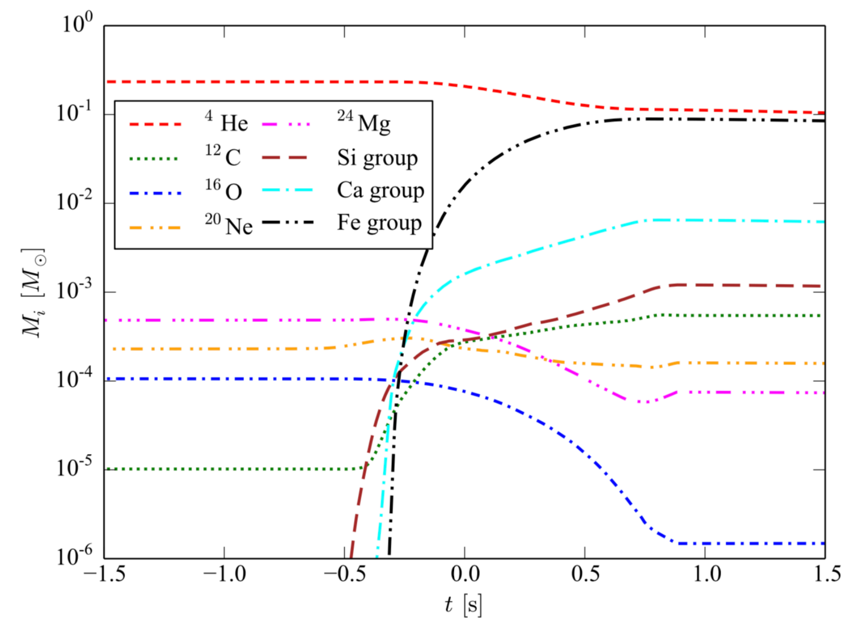
Comparison with 3D mesh simulation (1)

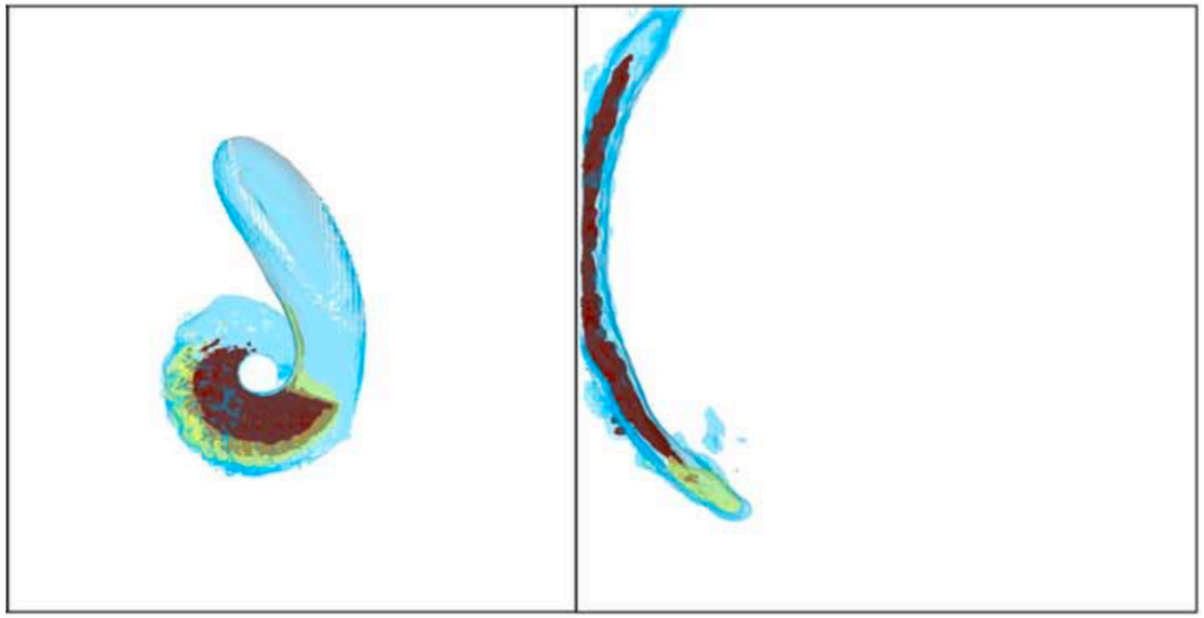
- The starting point of the detonation is different.
- The ignition process is unclear in Anninos's simulation (Anninos et al. 2018; 2019)
- The situation is extremely hard for mesh simulation, since kinetic energy is much larger than internal energy.



Comparison with 3D mesh simulation (2)

- Our simulation
  - ^{56}Ni is first yielded, and next IMEs
- Anninos's simulation
  - IMEs are first yielded, and next ^{56}Ni.
  - IMEs are converted into ^{56}Ni.
- Anninos's simulation may underestimate IME mass.





Anninos et al. (2018)

Summary

- Careless simulation of a WD TDE leads to numerically artificial detonation.
- If detonation is physically ignited,
  - It starts from the surface after the bounce.
  - ^{56}Ni is first yielded, and IMEs are next.
- Recent 3D mesh simulations are not consistent with the above results.
- We should fix this discrepancy to predict observations of WD TDEs.