Three-dimensional simulations of double detonation explosions in double-degenerate systems for SNe Ia

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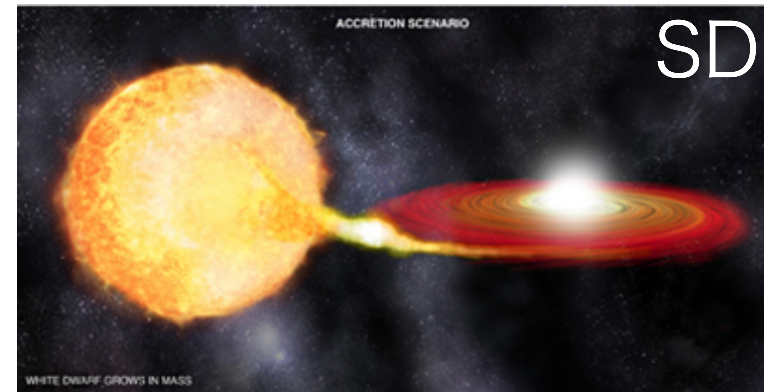
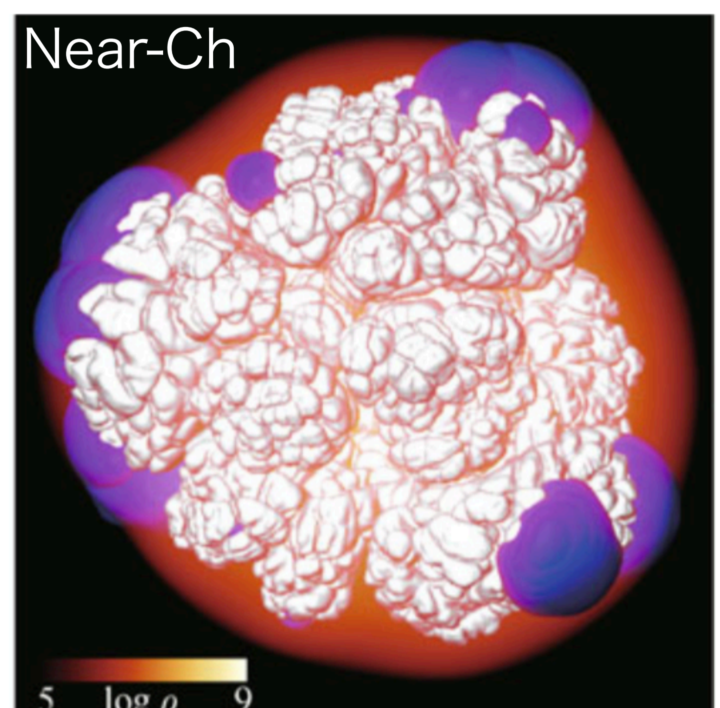
Progenitors of Type Ia Supernovae
Lijiang, 8th August 2019

Tanikawa, Nomoto, Nakasato (2018, ApJ, 868, 90)
Tanikawa, Nomoto, Nakasato, Maeda (submitted)

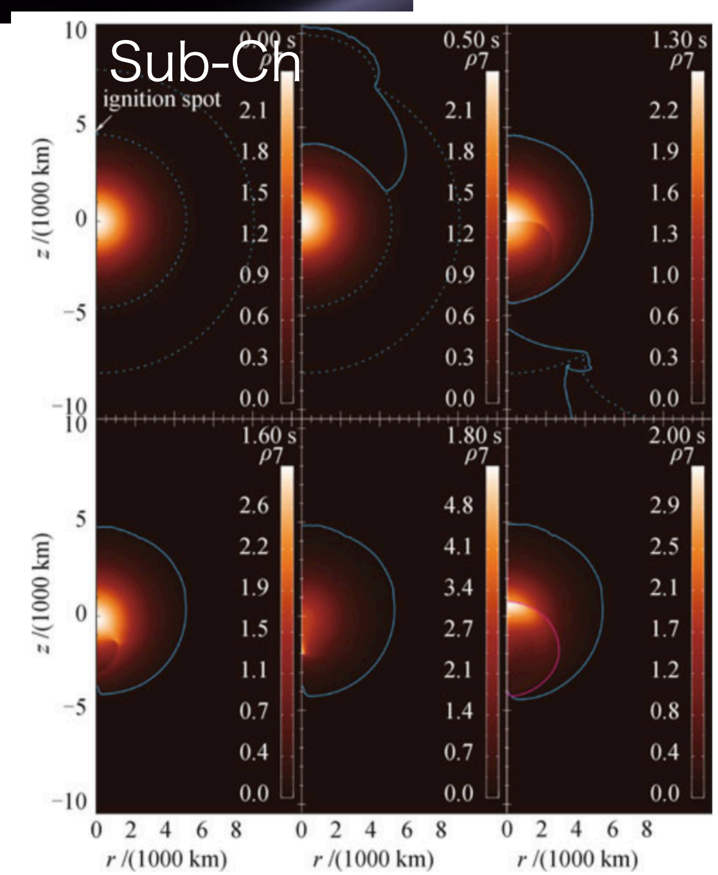
Type Ia supernovae

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





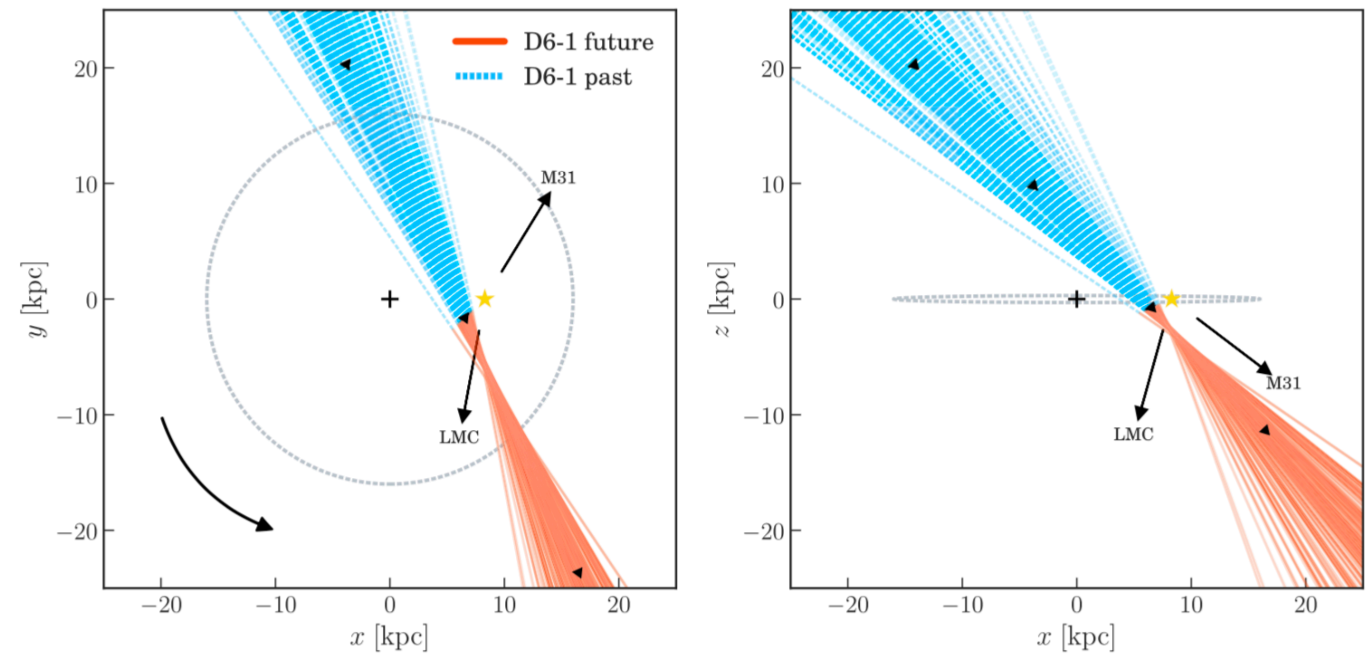
Seitenzahl et al. (2013)

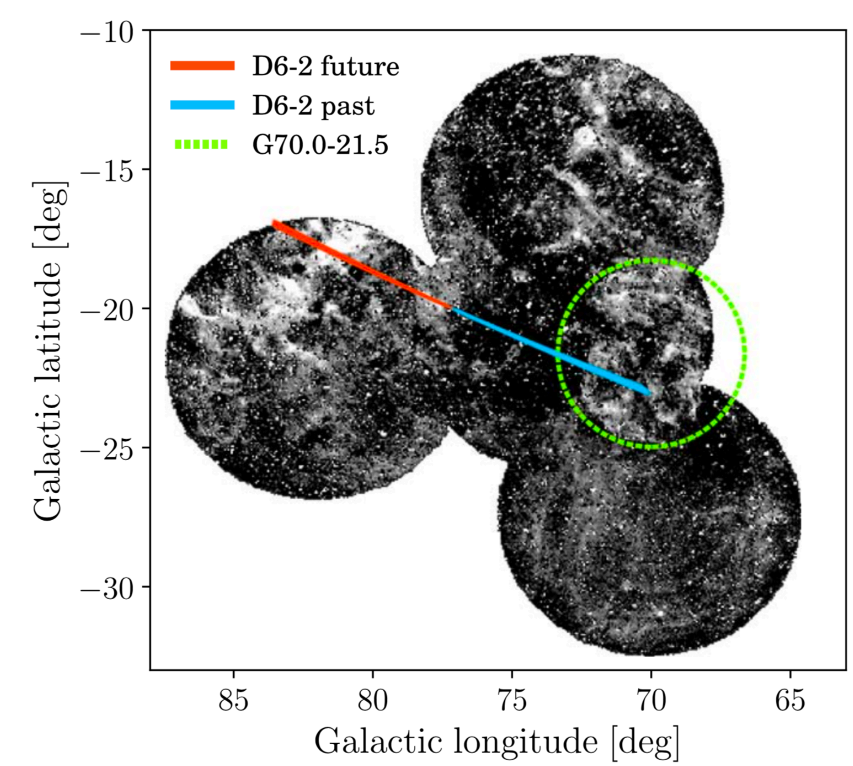


Fink et al. (2010)

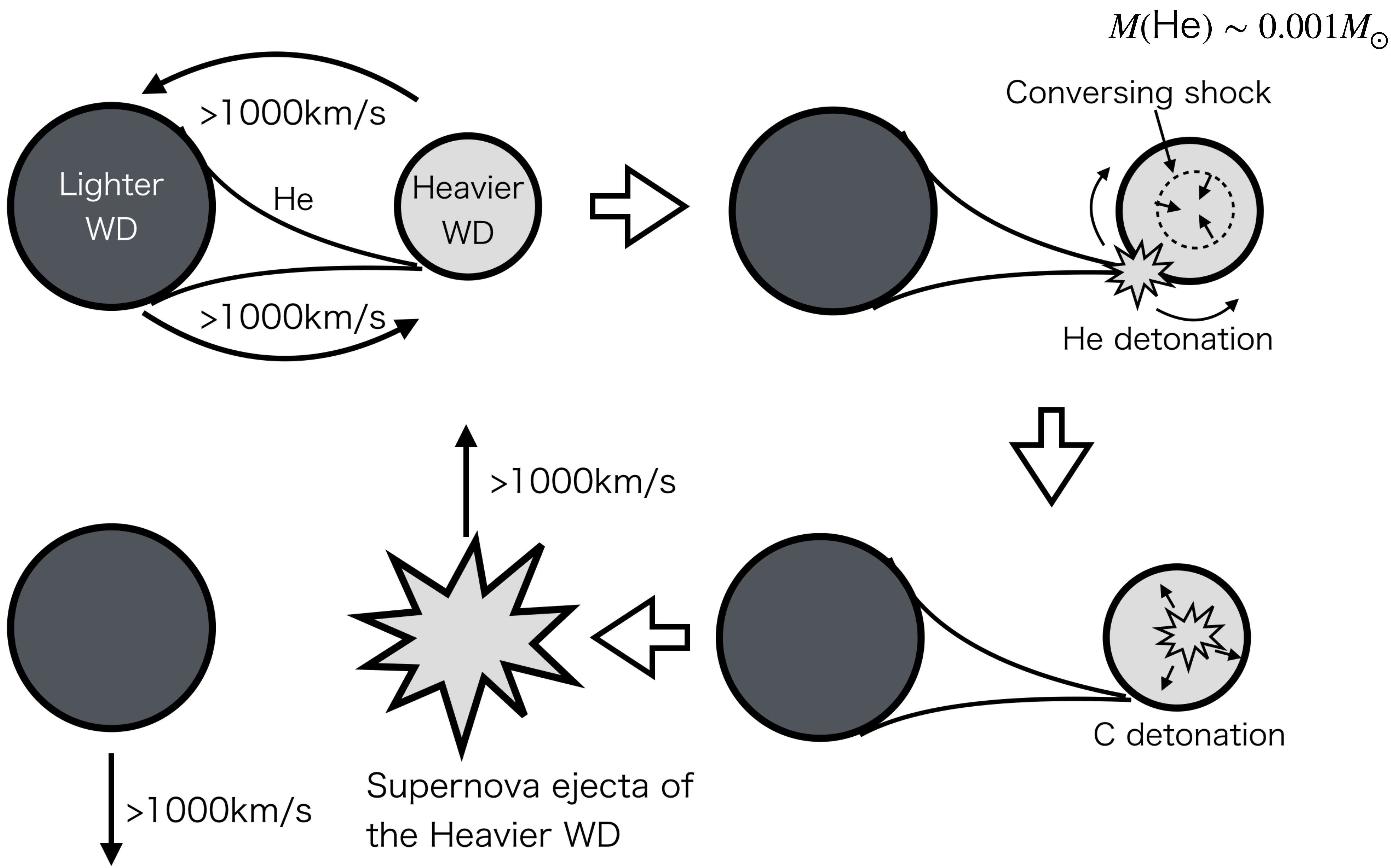
Hypervelocity WDs

- Several hypervelocity WDs 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 D^6 model is supported.



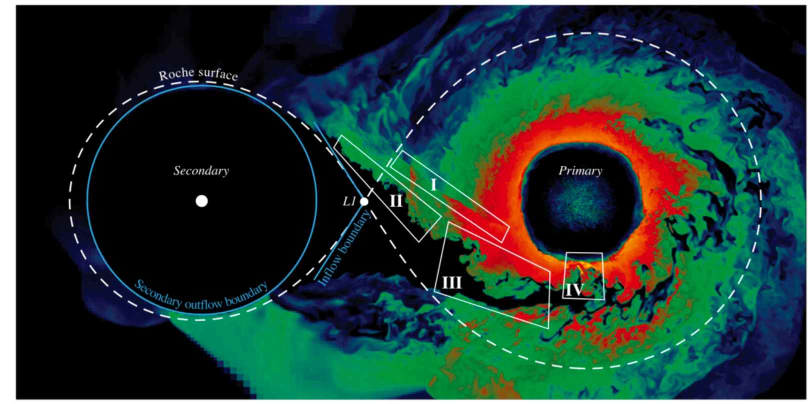


D[6] processes

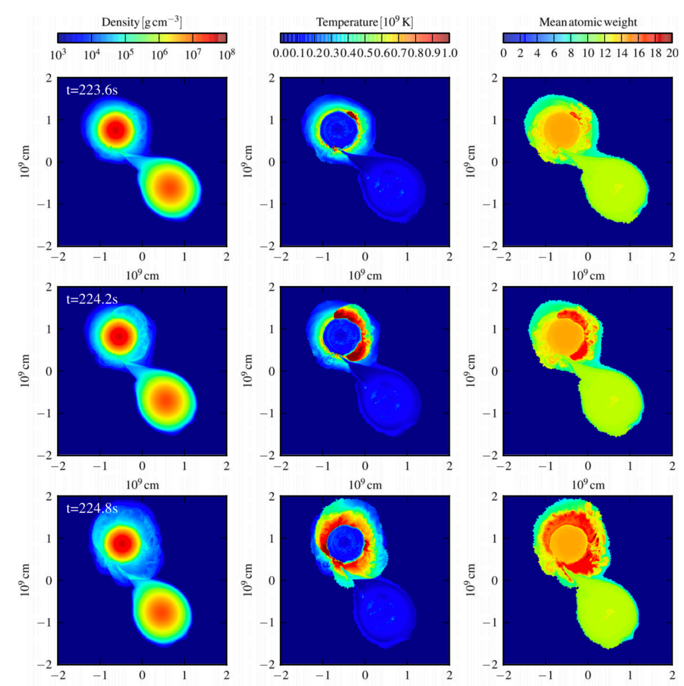


Previous and this studies

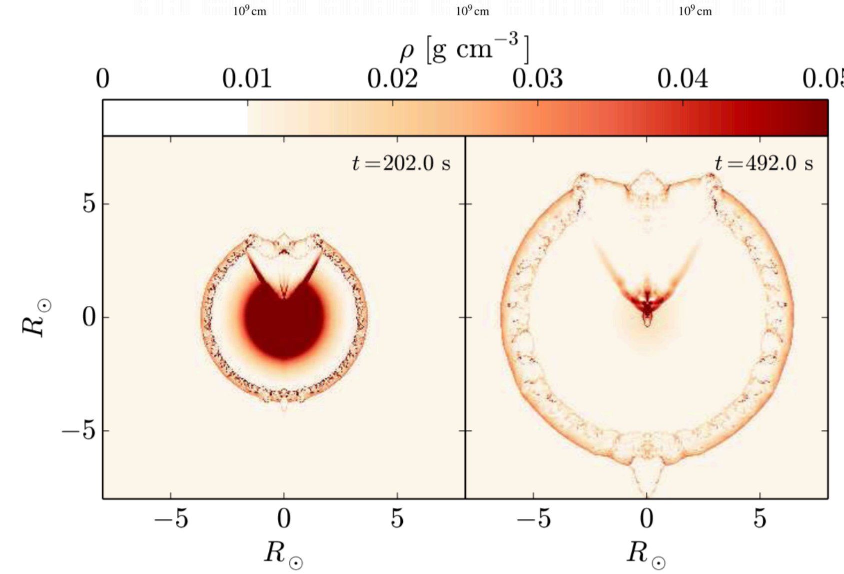
- Previous studies
  - Follow mass transfer and He detonation (Guillochon et al. 2010; Pakmor et al. 2013).
  - Follow interaction of SN ejecta with companion WDs (Papish et al. 2015).
- This study
  - Follows simple nucleosynthesis of D^6 explosions, and interaction of SN ejecta with companion WDs.
  - Explore signals of D^6 explosions to help SN Ia observations.



Guillochon et al. (2010)



Pakmor et al. (2013)



Papish et al. (2015)

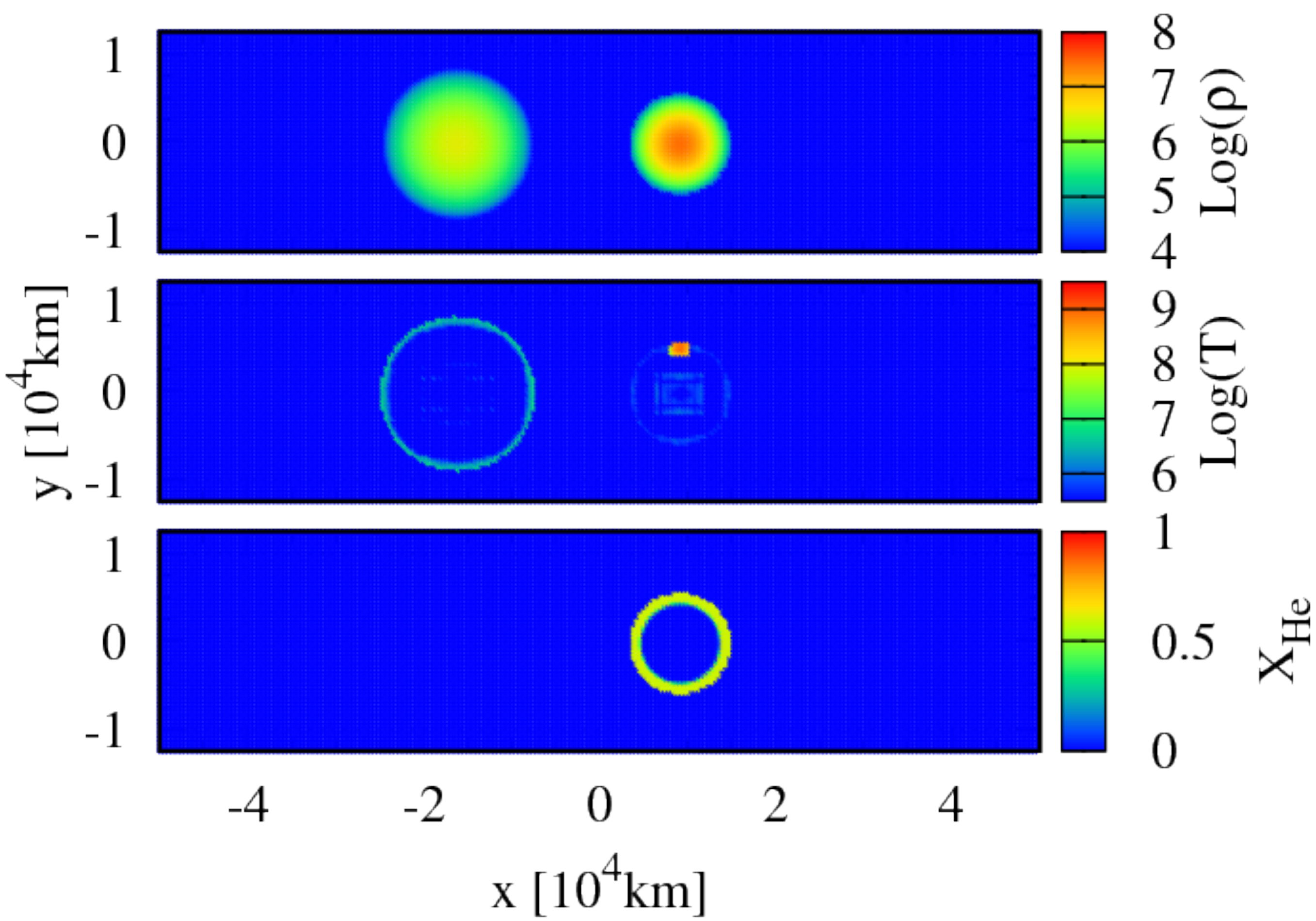
Method

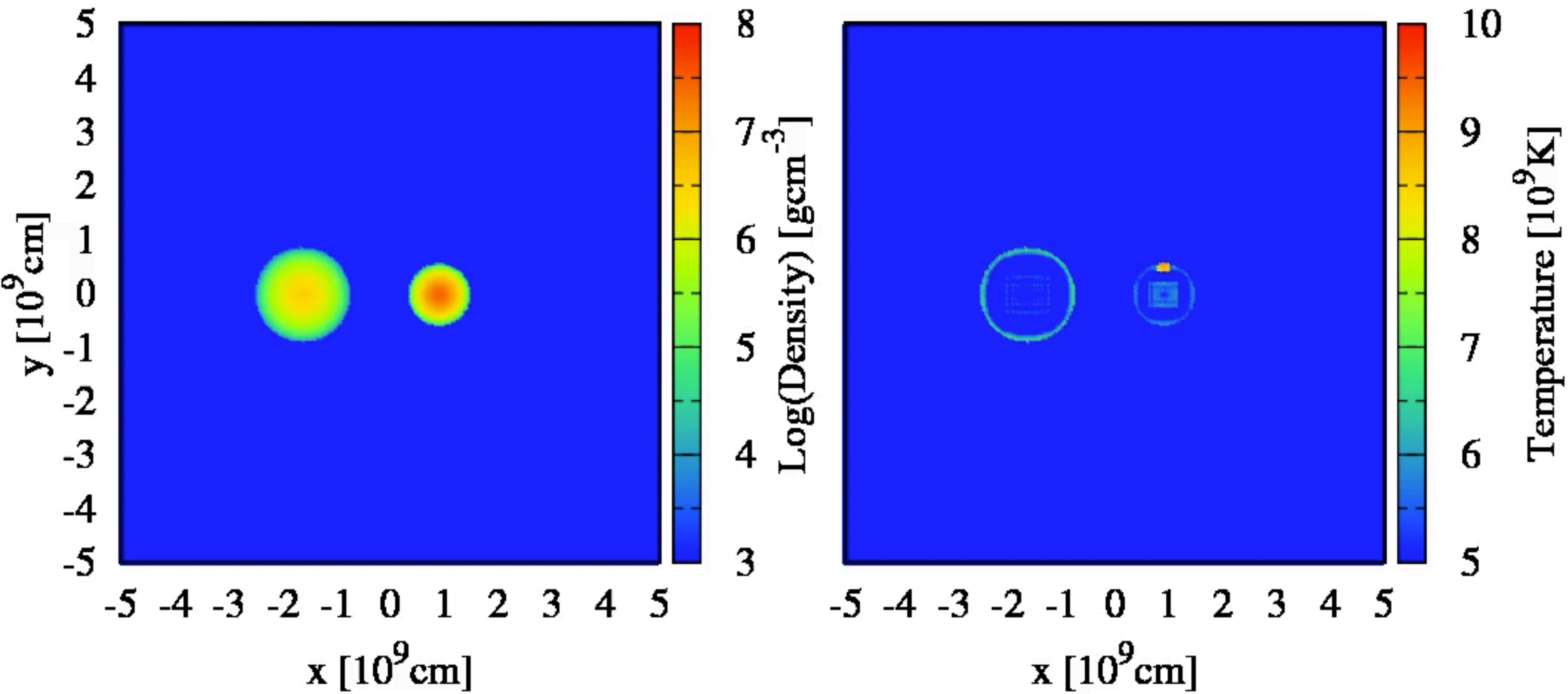
- 3D SPH method
  - Monaghan's artificial viscosity with Balsara switch (similar to GADGET)
  - Parallelized by FDPS (Iwasawa, AT+ 2016)
  - Vectorized by SIMD (e.g. AT+ 2012; 2013)
  - The number of SPH particles is 4 millions per $0.1M_{\odot}$.
- Helmholtz EoS (Timmes, Swesty 2000)
- Aprox13 nuclear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

Initial conditions

- Mass combinations
  - 1.0M$_\odot$ COWD + 0.6M$_\odot$ COWD
  - 1.0M$_\odot$ COWD + 0.6M$_\odot$ COWD
  - 1.0M$_\odot$ COWD + 0.45M$_\odot$ HeWD
- The primary WDs have He shells ($0.05M_\odot$).
- The companion WD in the 2nd combination has a He shell.
- The companion WDs nearly fill their Roche lobe.
- Hotspots are in the He shell of the primary WDs.

1.0M$_\odot$ COWD + 0.6M$_\odot$ COWD

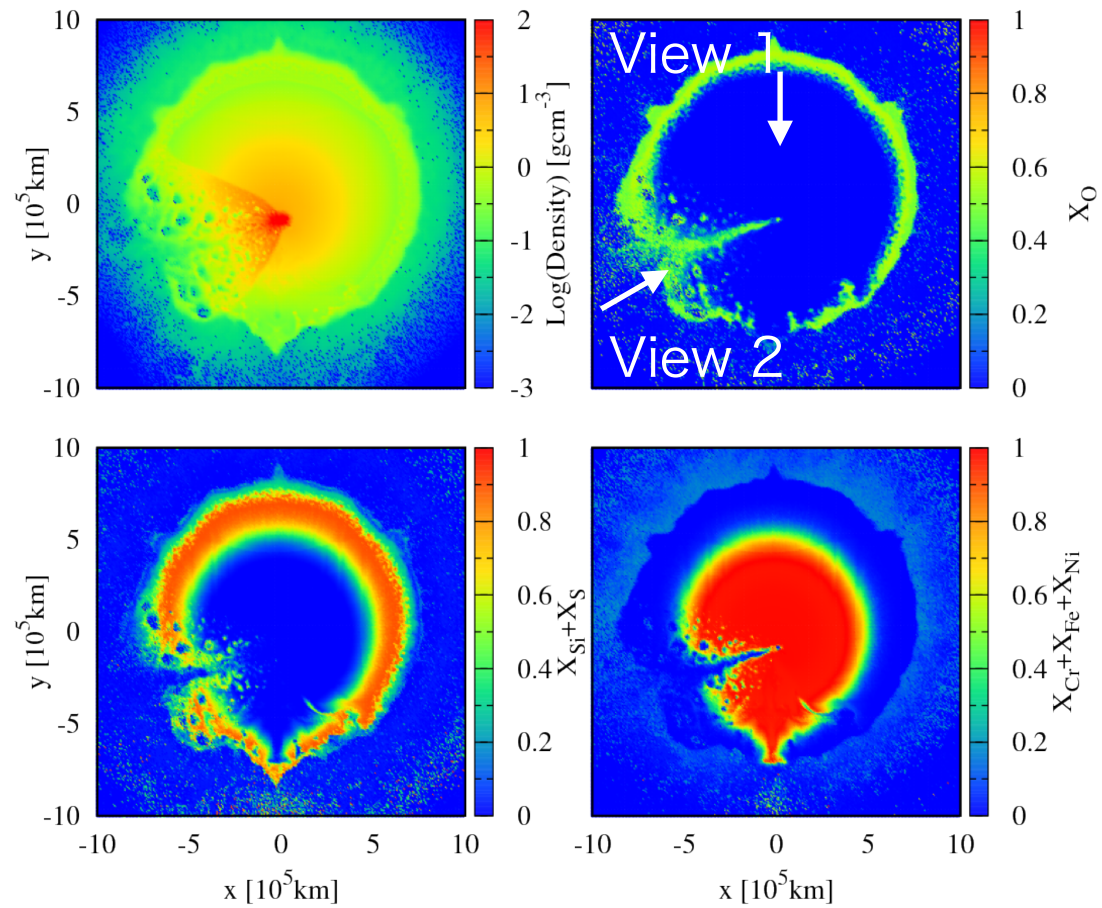


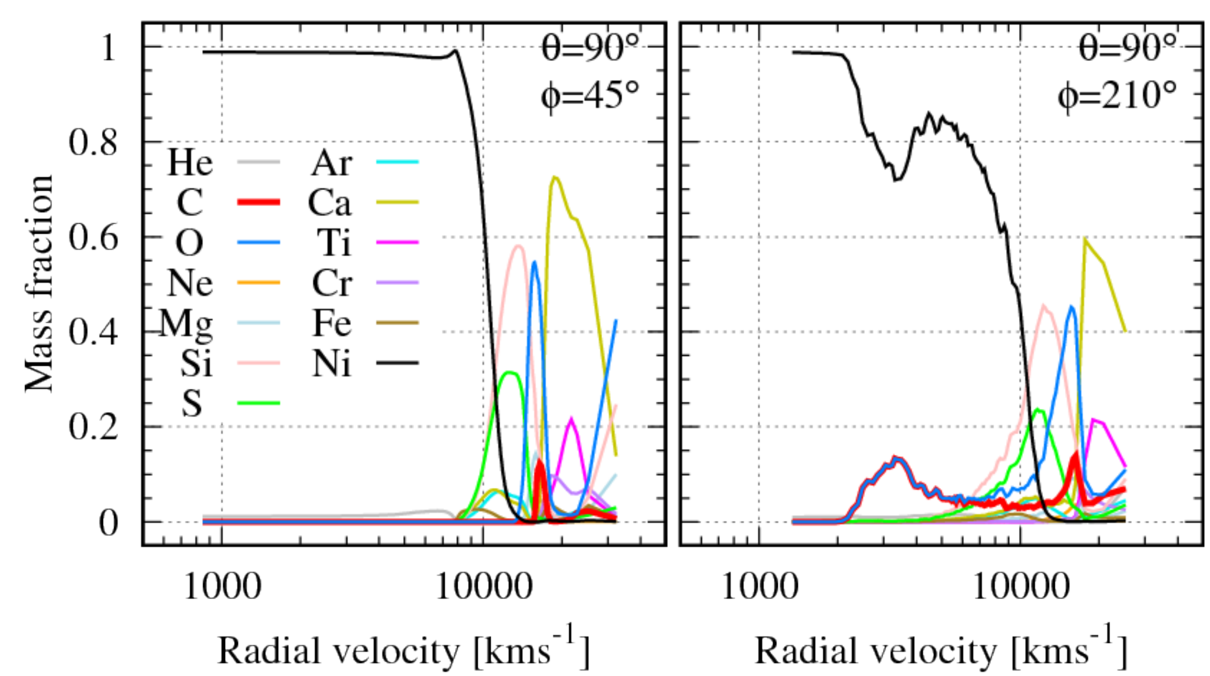


5
4
3
2
1
0
-1
-2
-3
-4
-5
y [10^9cm]
-5 -4 -3 -2 -1 0 1 2 3 4 5
x [10^9cm]
8
7
6
5
4
3
Log(Density) [gcm^-3]
-5 -4 -3 -2 -1 0 1 2 3 4 5
x [10^9cm]
10
9
8
7
6
5
Temperature [10^9K]

Supernova ejecta

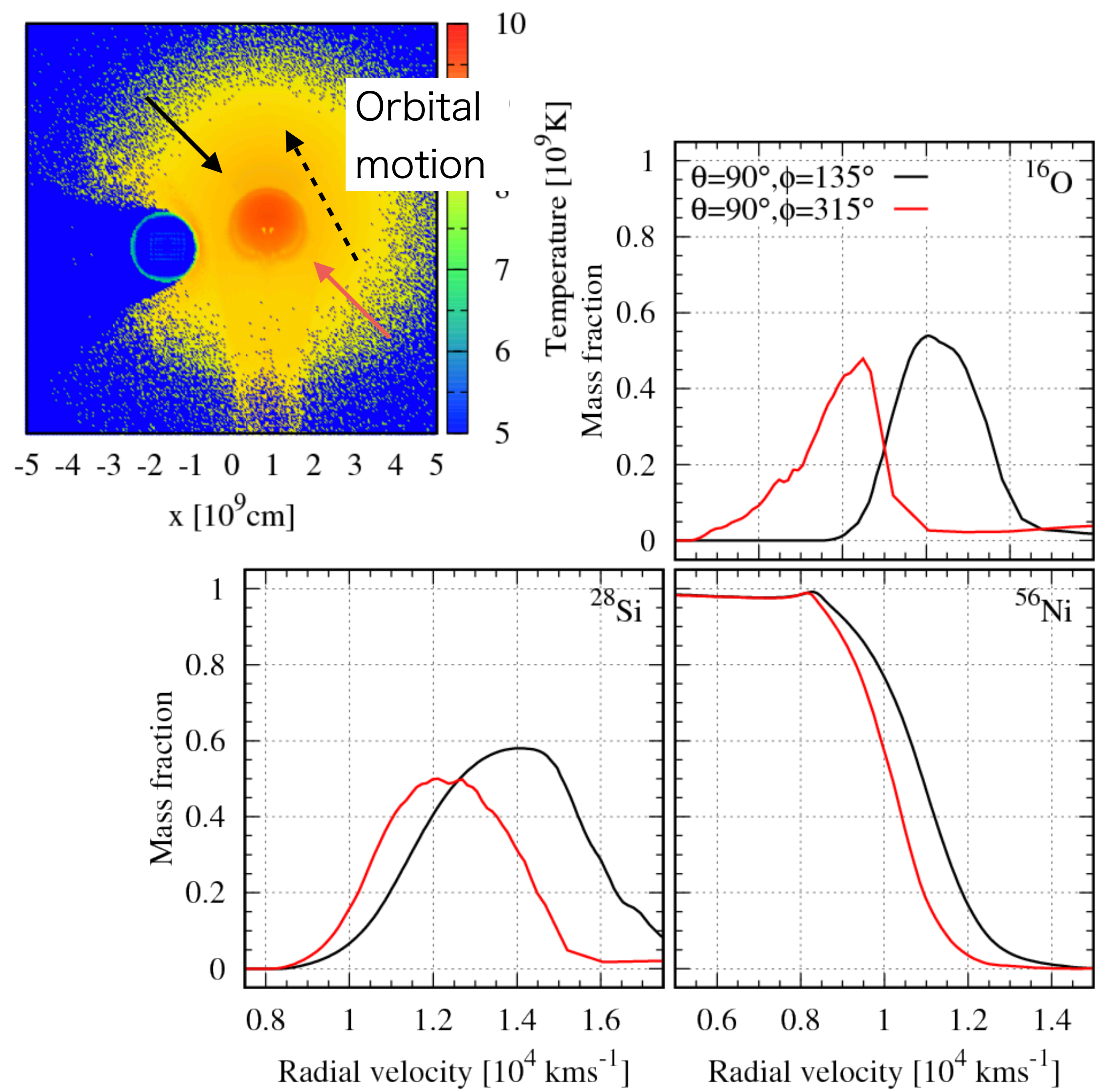
- ^{56}Ni mass: $\sim 0.6 M_\odot$
- Stripped CO materials: $\sim 0.003 M_\odot$
  - Stream structure (companion-origin stream)
  - Low-velocity ($\sim 10^3$ km/s) CO materials
- Dependence on companion WDs
  - He WD: $\sim$ few $\cdot\, 10^{-3} M_\odot$ He
  - CO WD w/ He shell ($6 \cdot 10^{-3} M_\odot$): $\sim$ few $\cdot\, 10^{-3} M_\odot$ He and $\sim$ few $\cdot\, 10^{-4} M_\odot$ CO





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.



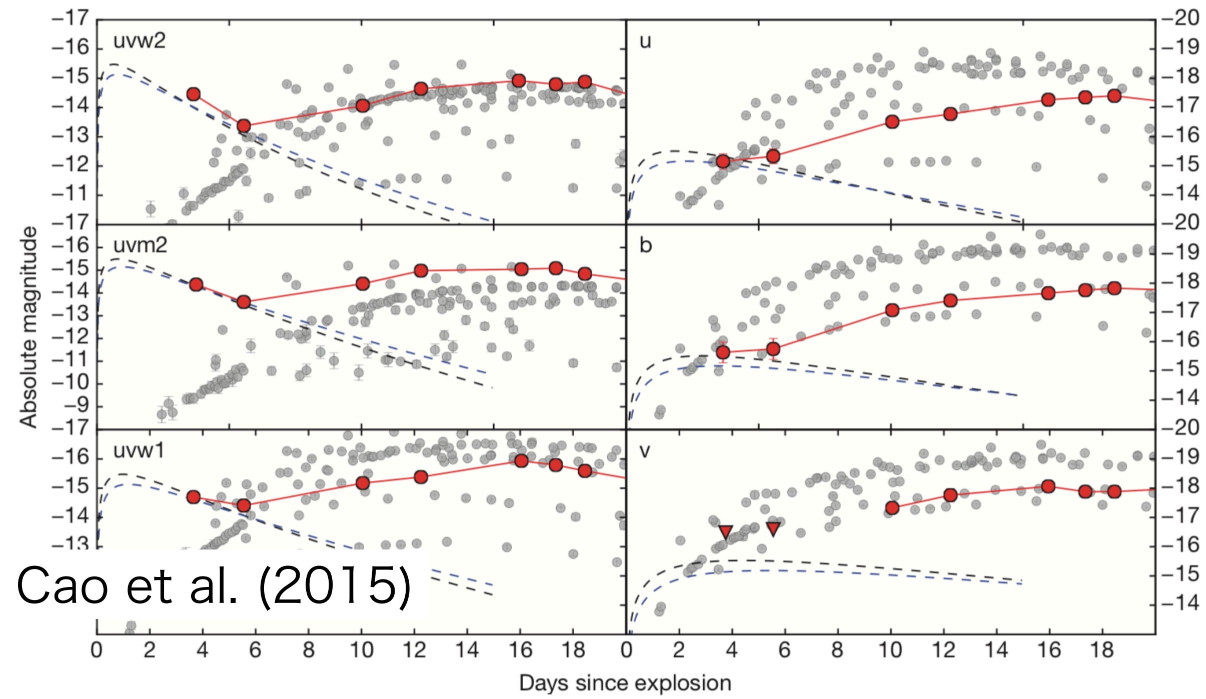
Possible counterpart

- iPTF14atg
  - Early flash

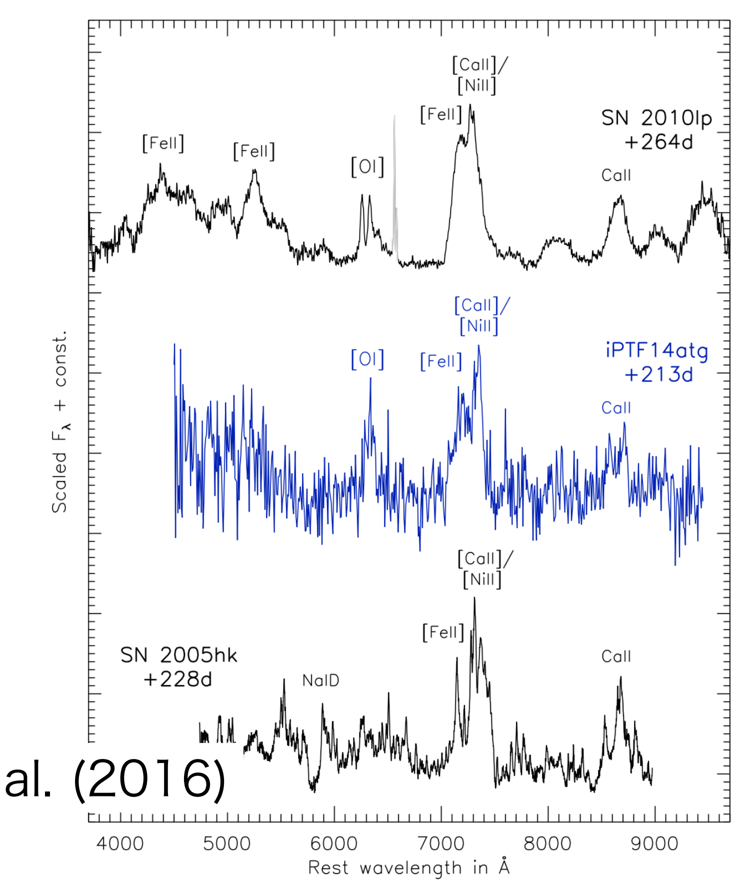
    ← He-detonation ash
  - Oxygen emission in nebular phase

    ← 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).



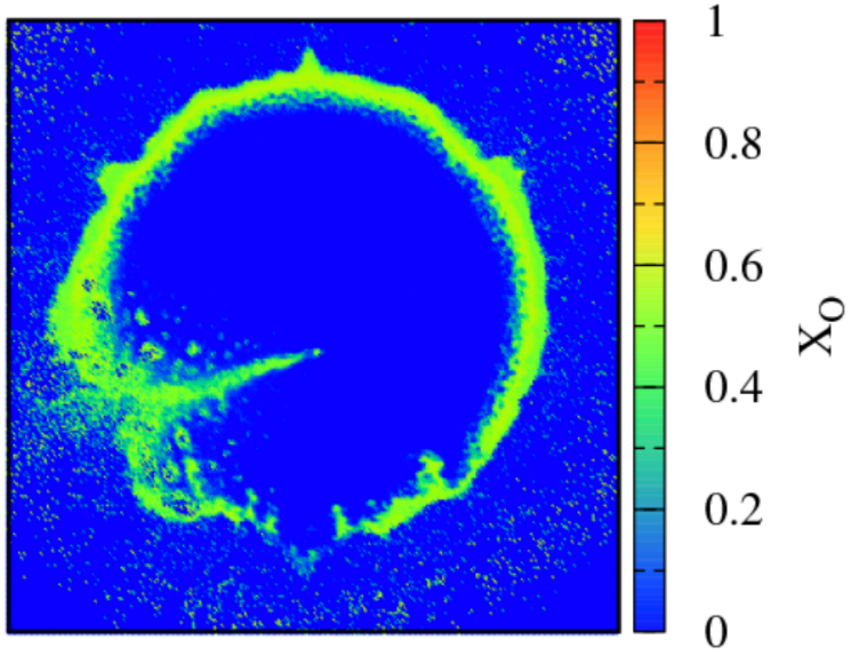
Cao et al. (2015)



Kromer et al. (2016)

Future work

Companion-origin stream



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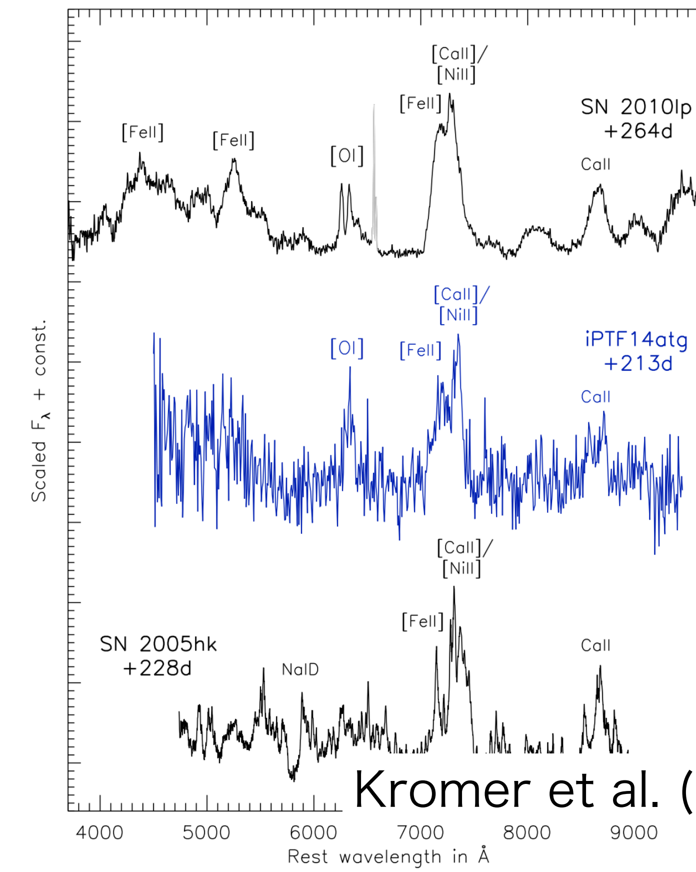
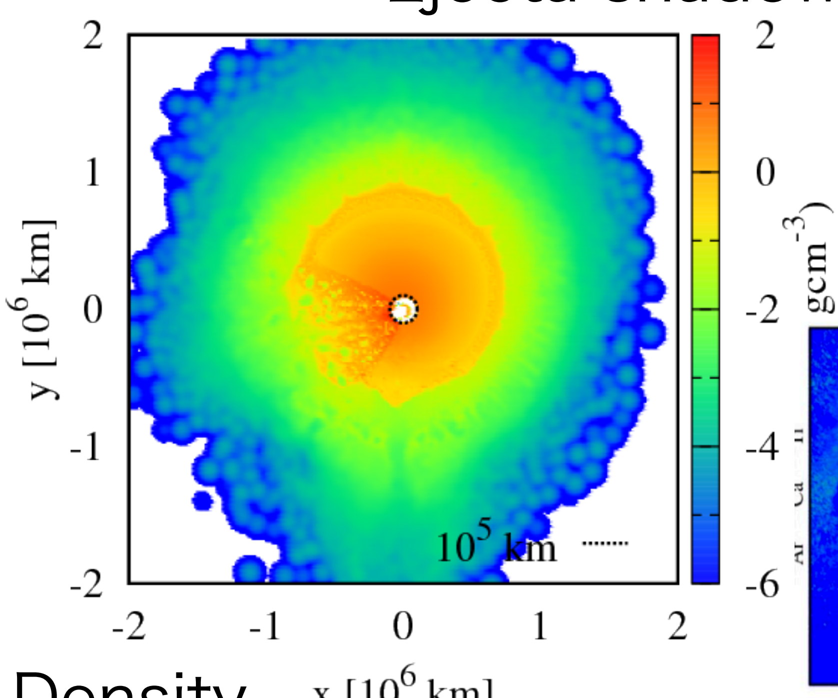


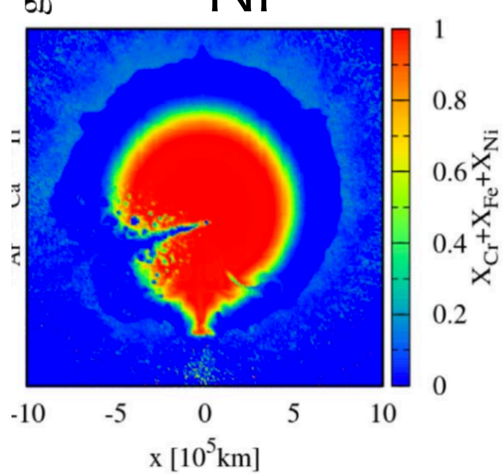
Kromer et al. (2016)

Ejecta shadow



Density

^{56}Ni



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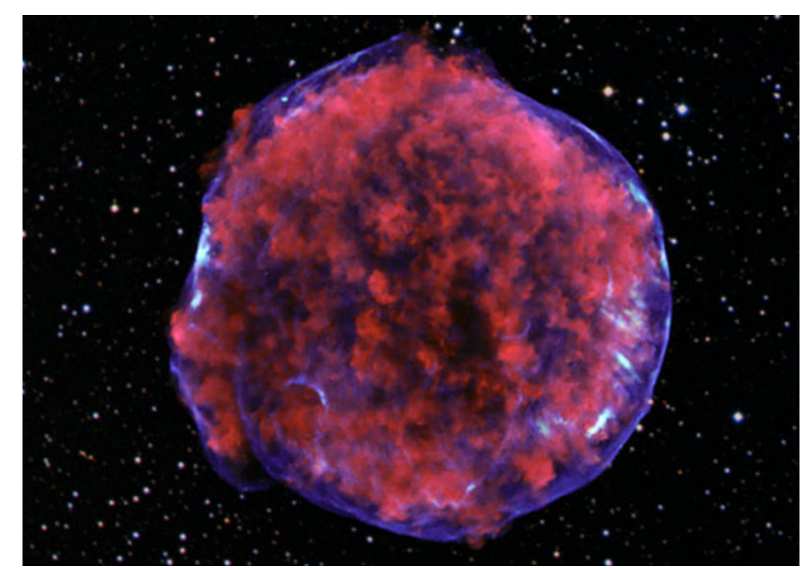

Collaboration with
G. Ferrand

Summary

- We reproduced D^6 explosions by 3D numerical simulations.
- D^6 explosions can contain materials stripped from companion WDs, and the stripped materials can contribute to low-velocity oxygen (and carbon).
- SN ejecta have velocity shift (~ 1000km/s) systematically for the same reason as hypervelocity WDs.
- iPTF14atg is a possible counterpart of D^6 explosion.