Heidelberg Institute for Theoretical Studies

A sub-Chandrasekhar mass white dwarf as possible progenitor for a thermonuclear explosion

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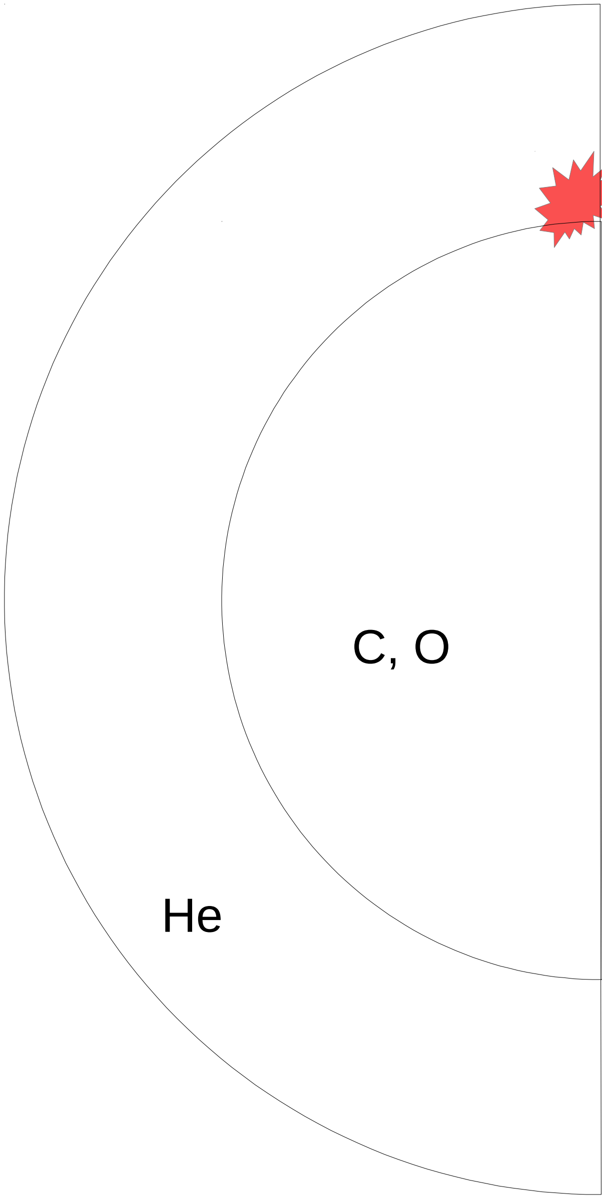
Introduction

- Latest results indicate detonations of sub-M_{Ch} WDs as promising SN Ia progenitor (e.g. Sim+ 2010, Goldstein+ 2018)
- Isolated sub-M_{Ch} WD stable
  → binary system
- Investigate double detonation scenario
  (e.g. Nomoto 1982)

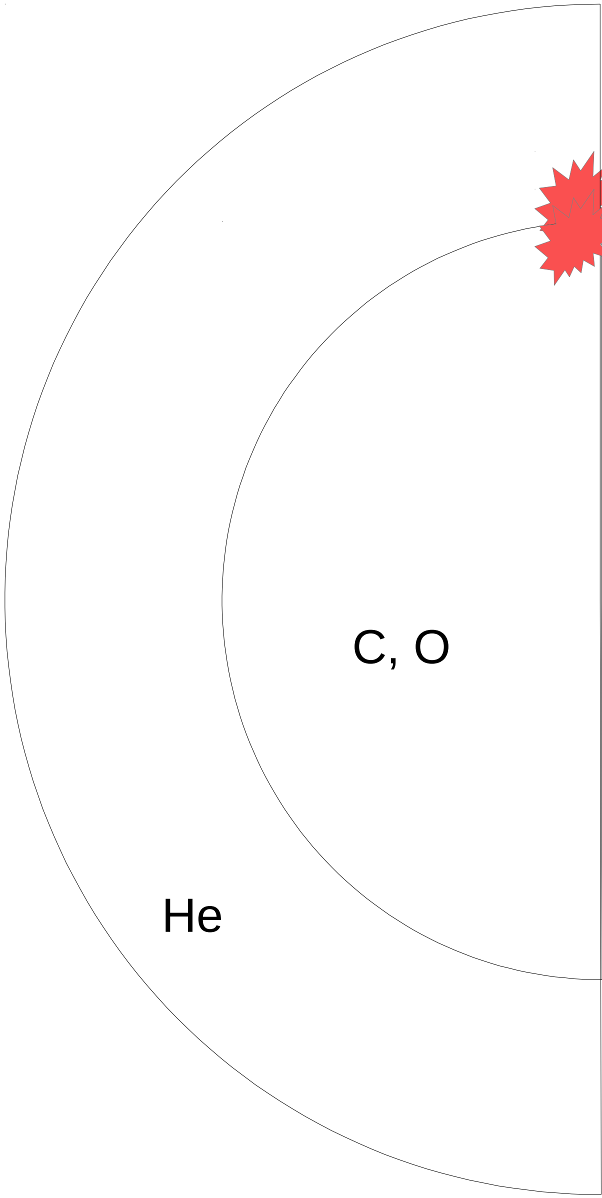
Theory: Double detonation scenario

- Assume: Detonation at base of He shell
  (Glasner+ 2018)
  - Accretion of He from companion
  - Thermal instability develops
  - Detonation



Theory: Double detonation scenario

- Assume: Detonation at base of He shell (Glasner+ 2018)
- Three possible outcomes:
  - 1st directly triggers 2nd detonation at surface of core: edge-lit mechanism (e.g. Livne & Glasner 1990, Sim+ 2012)



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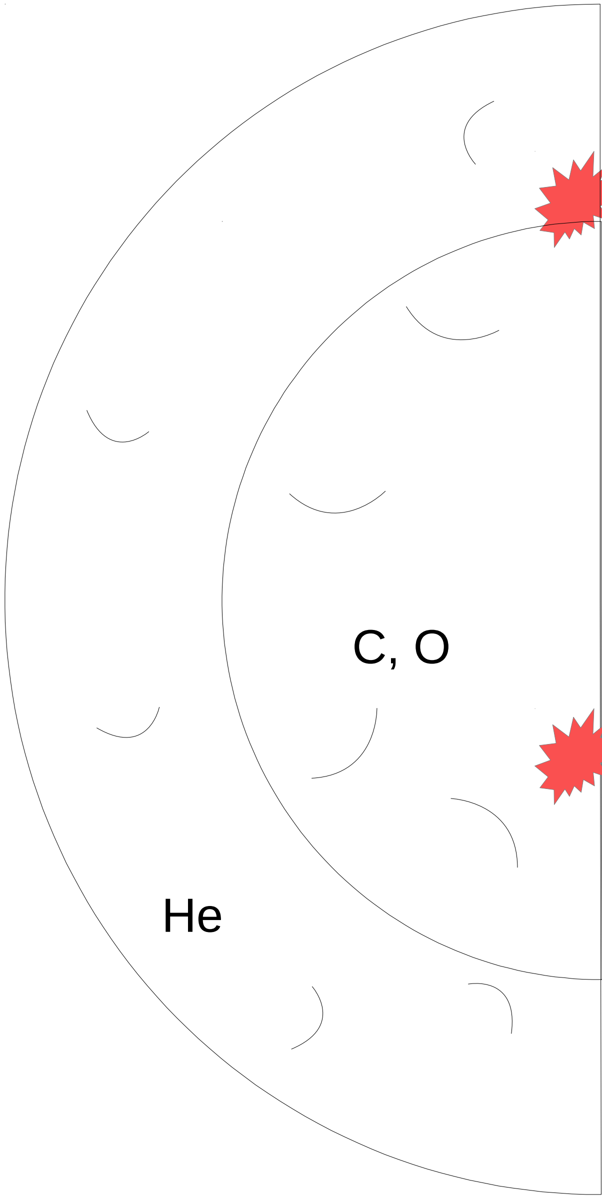
  - Shock and detonation waves initiated by 1st detonation converge off-center in core and trigger 2nd detonation: converging shock mechanism
    (e.g. Fink+ 2007, 2010; Moll & Woosley 2013)



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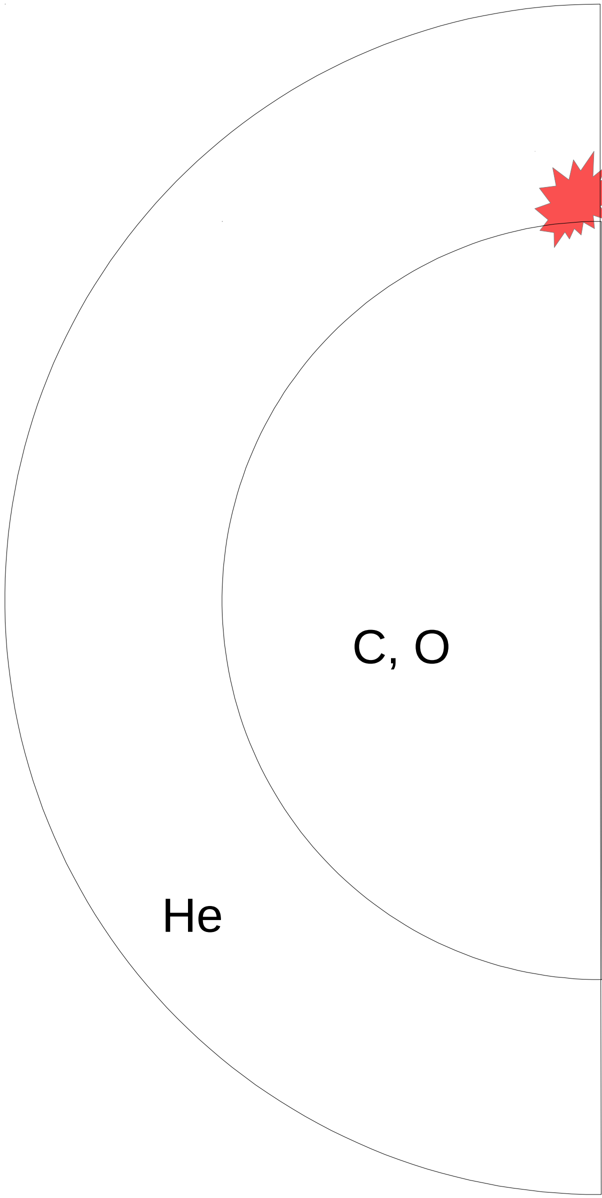
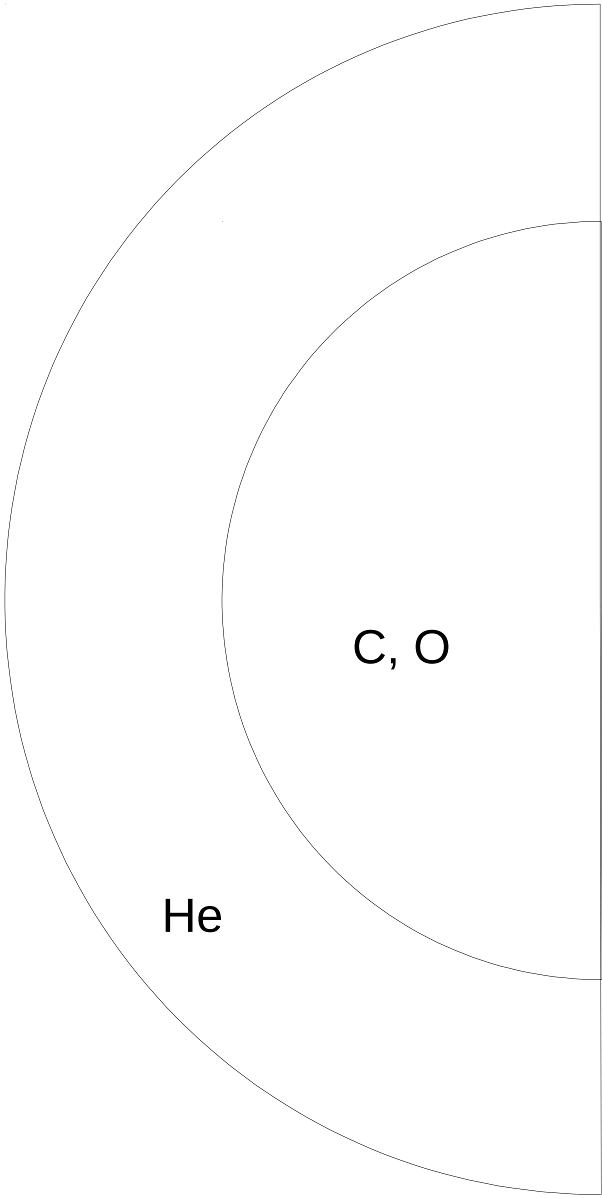
  - Shock and detonation waves initiated by 1st detonation converge off-center in core and trigger 2nd detonation: converging shock mechanism (e.g. Fink+ 2007, 2010; Moll & Woosley 2013)
  - No 2nd detonation: strictly no double detonation (e.g. Bildsten+ 2007)



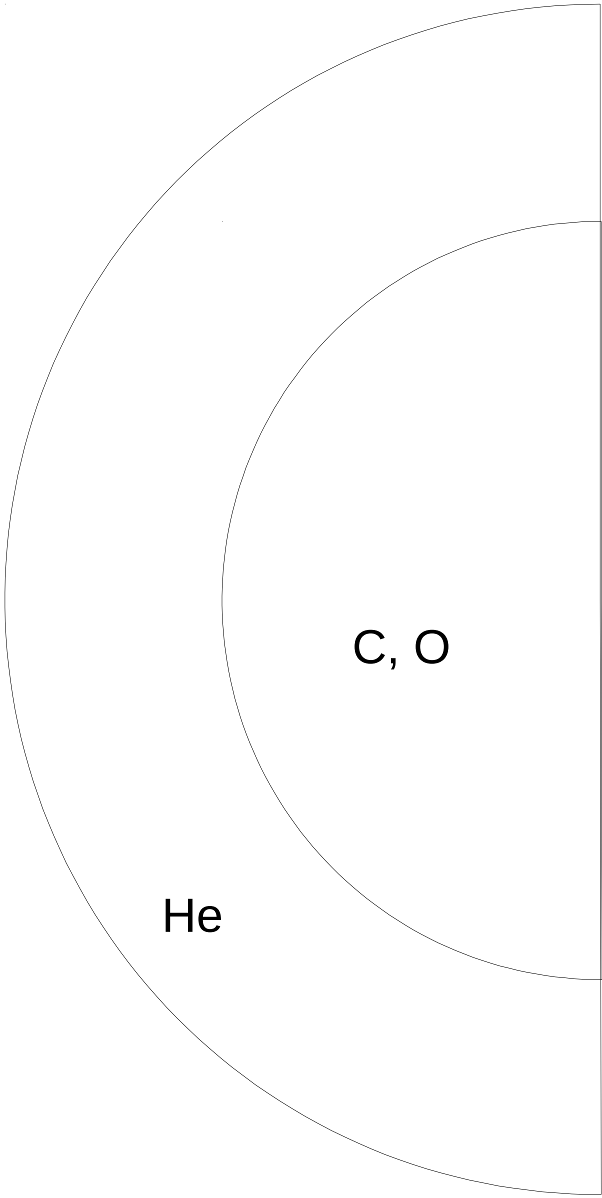
Approach

- Open questions:
  - He ignition (Glasner+ 2018)
  - Details of He detonation
    (e.g. Kromer+ 2010, Townsley+ 2012,2019)
  - C ignition
    (Röpke+ 2007, Seitenzahl+ 2009)



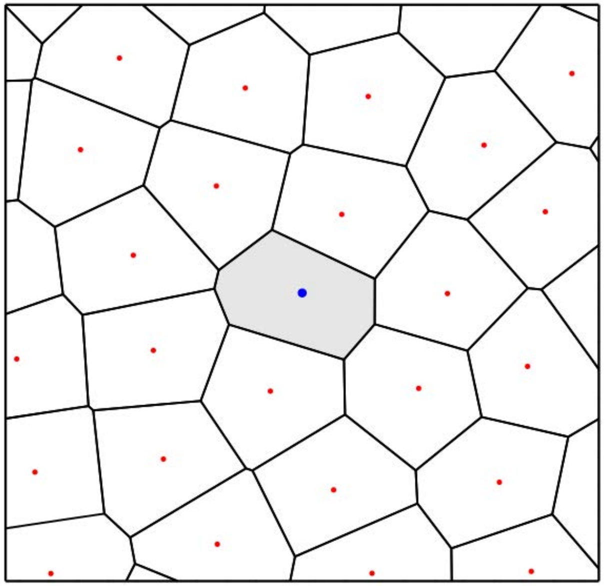
Approach

- Open questions:
  - He ignition (Glasner+ 2018)
  - Details of He detonation
    (e.g. Kromer+ 2010, Townsley+ 2012,2019)
  - C ignition
    (Röpke+ 2007, Seitenzahl+ 2009)
- Not completely answered in previous multi-D simulations
- Follow up with full 3D simulations



Approach

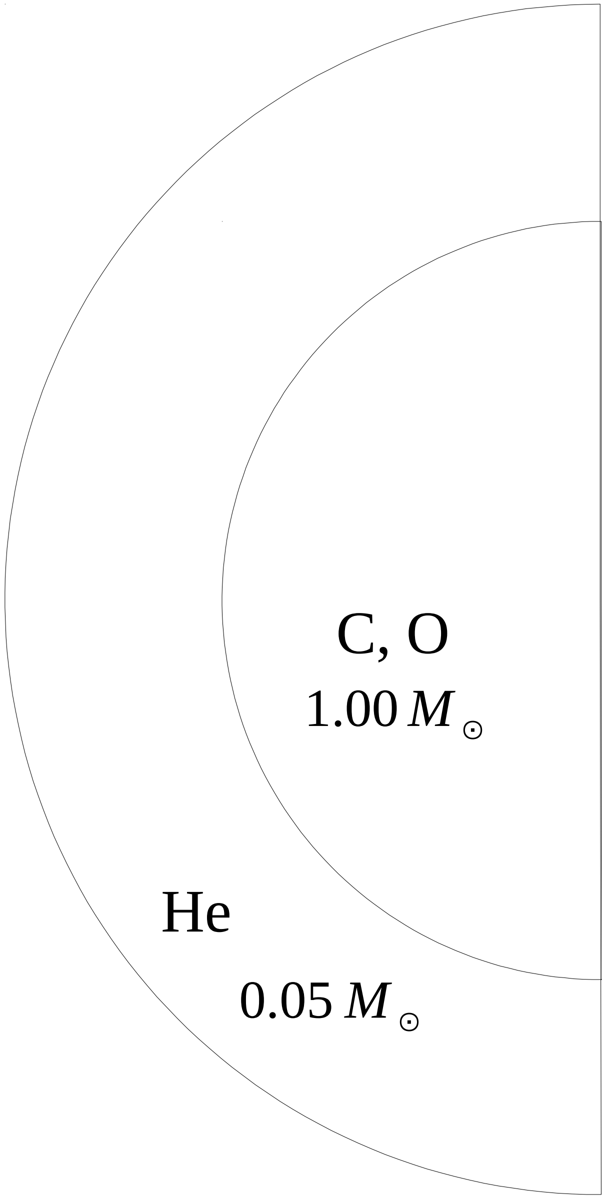
- AREPO code (Springel 2010)
- Moving unstructured mesh
- Second order finite volume scheme
- Explicit refinement and derefinement
- Nucleosynthesis consistent with hydrodynamics (Pakmor+ 2013)



Voronoi mesh (Springel 2010)

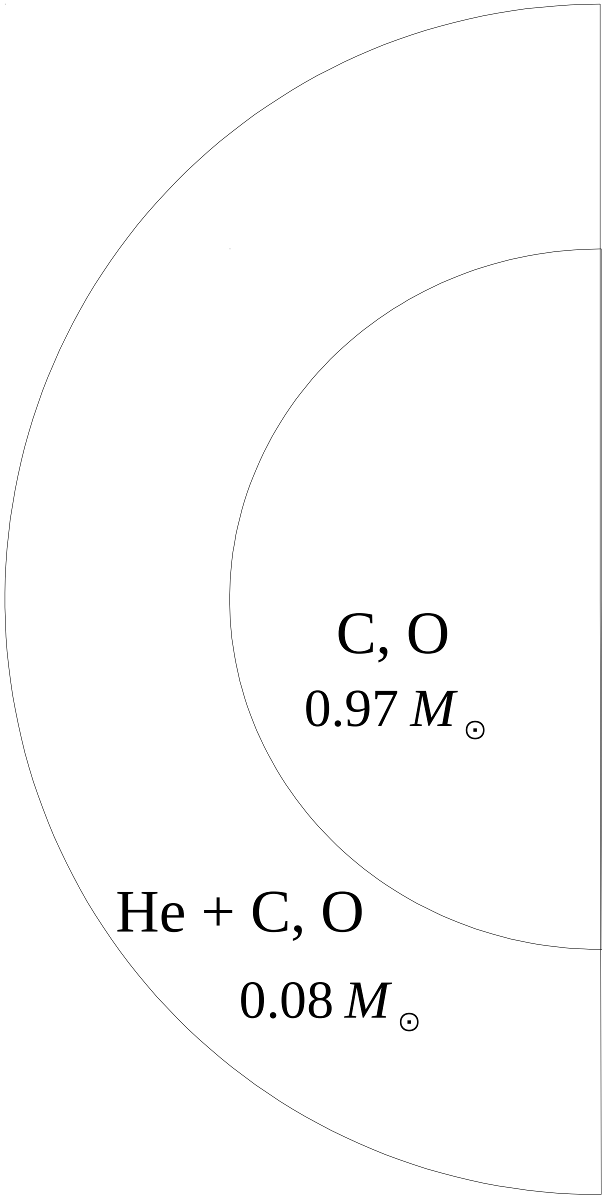
Model setup

- Here: sub-M_{Ch} CO white dwarf with He shell



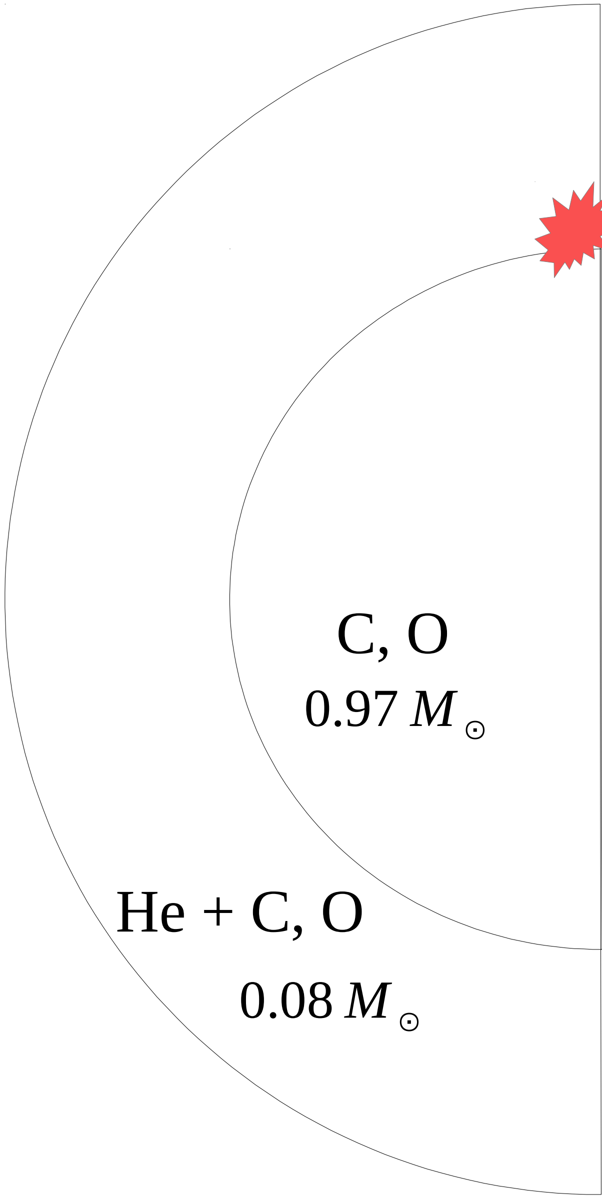
Model setup

- Here: sub-M_{Ch} CO white dwarf with He shell

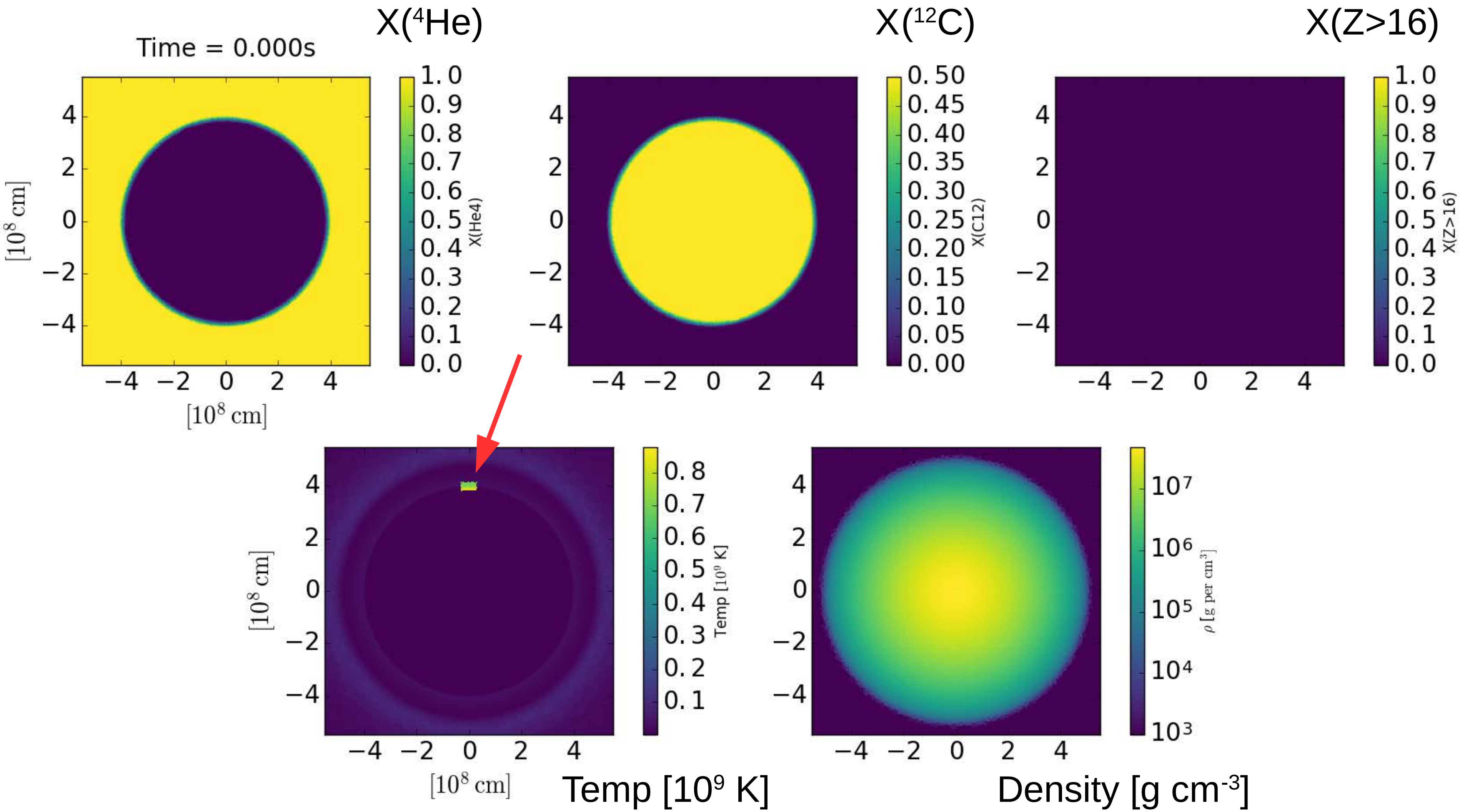


Model setup

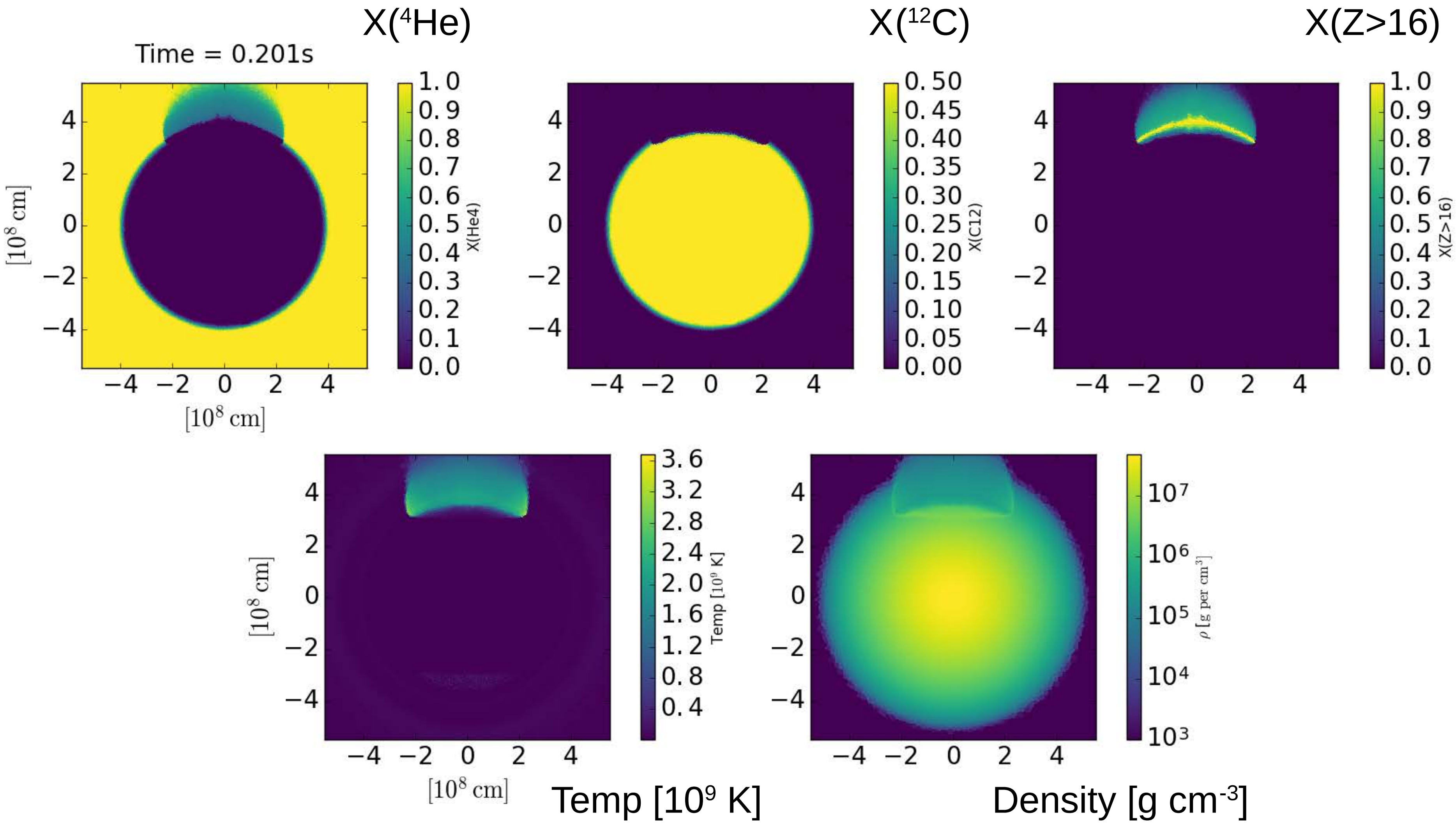
- Here: sub-M_{Ch} CO white dwarf with He shell
- 1st detonation is artificially ignited
- Follow evolution for $100\,\mathrm{s}$



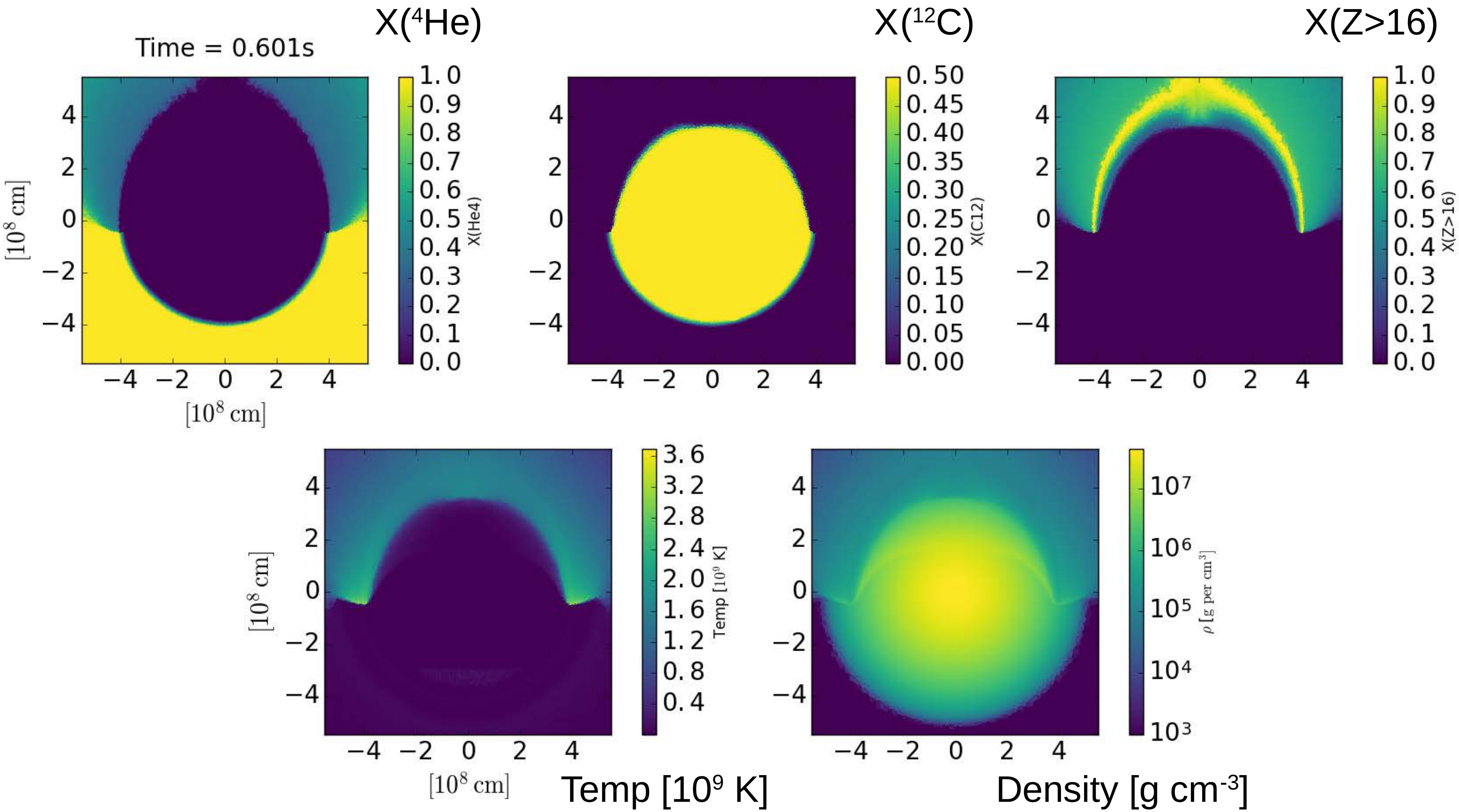
Detonation


X(^{4}He)
X(^{12}C)
X(Z>16)
Time = 0.000s
X(He4)
X(C12)
X(Z>16)
[10^8 cm]
Temp [10^9 K]
ρ [g per cm^3]
Temp [10^9 K]
Density [g cm^{-3}]

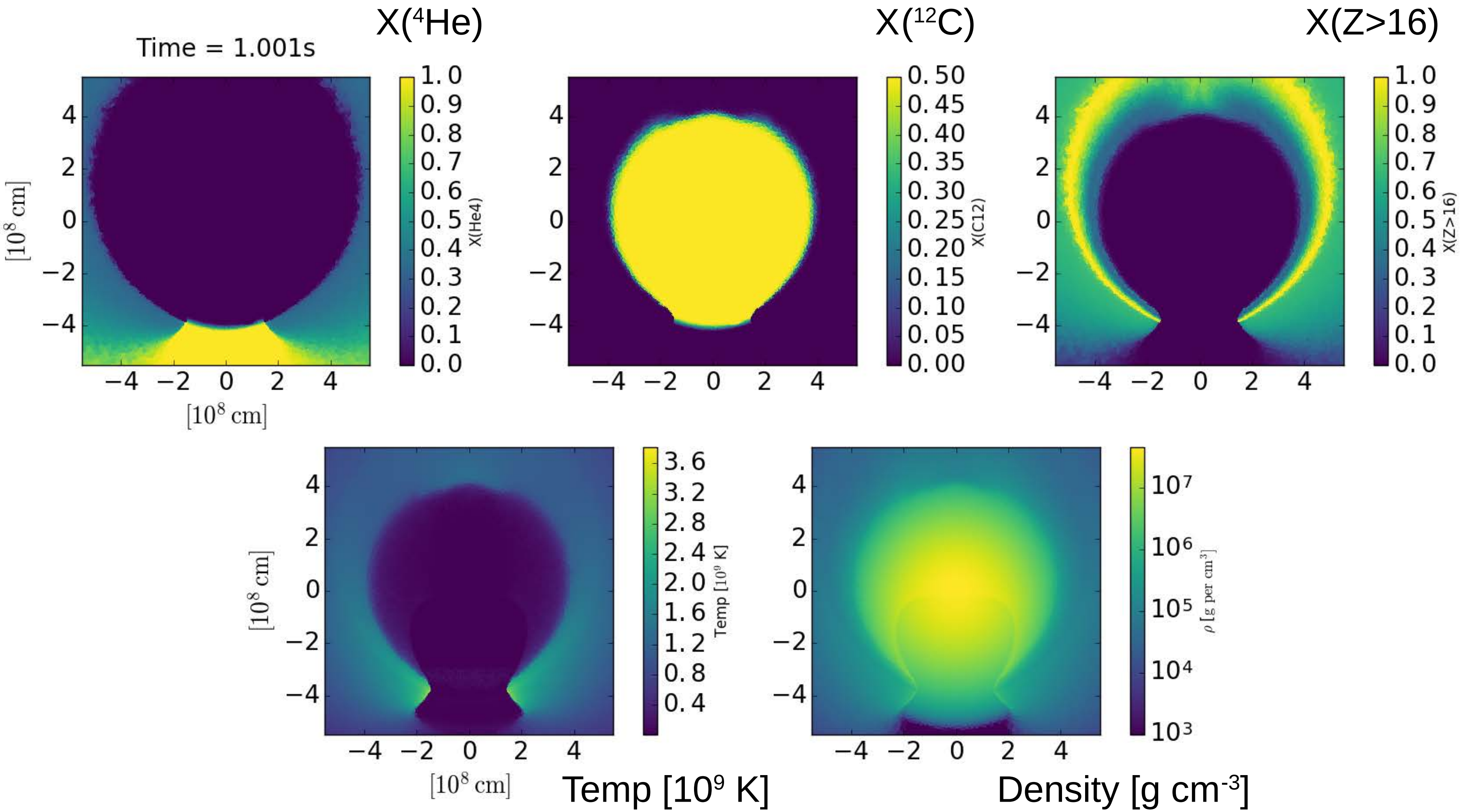
Detonation


X(⁴He)
X(¹²C)
X(Z>16)
Time = 0.201s
[10⁸ cm]
X(He4)
X(C12)
X(Z>16)
Temp [10⁹ K]
ρ [g per cm³]
Temp [10⁹ K]
Density [g cm⁻³]

Detonation

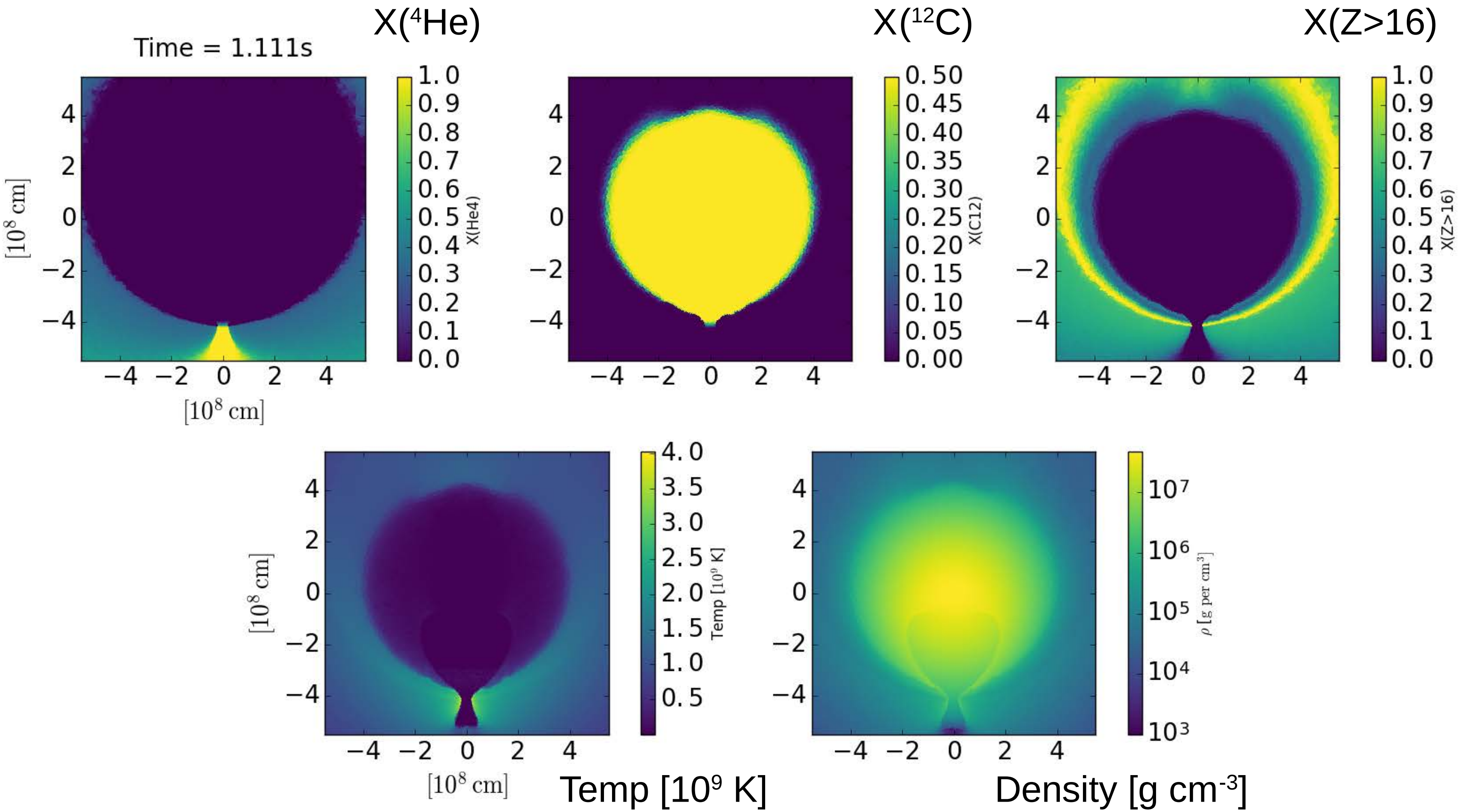

X(4He)
Time = 0.601s
X(He4)
[10^8 cm]
X(12C)
X(C12)
X(Z>16)
Temp [10^9 K]
Density [g cm^-3]
ρ [g per cm^3]
−4 −2 0 2 4
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
0.50 0.45 0.40 0.35 0.30 0.25 0.20 0.15 0.10 0.05 0.00
3.6 3.2 2.8 2.4 2.0 1.6 1.2 0.8 0.4
10^7 10^6 10^5 10^4 10^3

Detonation



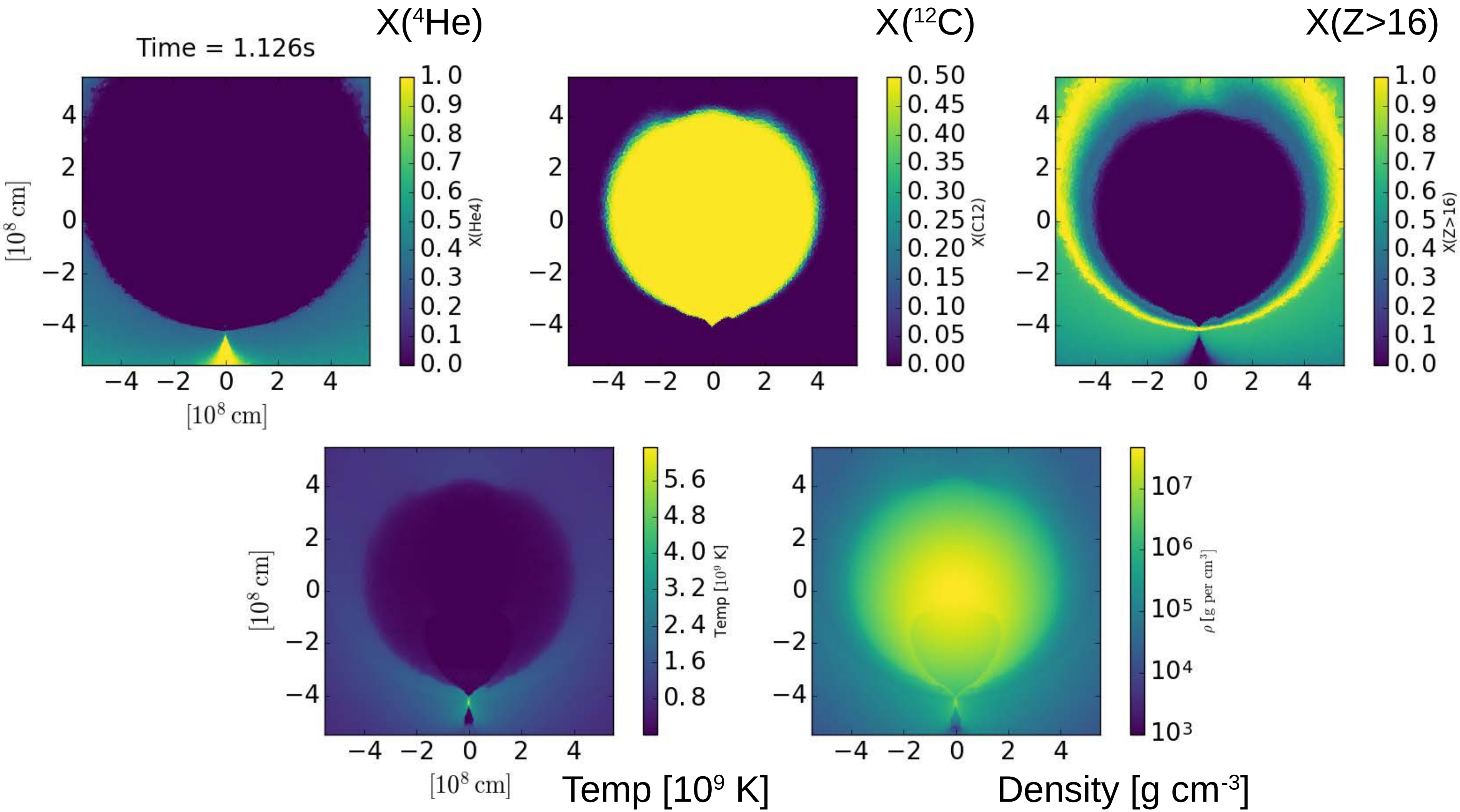
X(⁴He)
Time = 1.001s
X(He4)
X(¹²C)
X(C12)
X(Z>16)
X(Z>16)
[10⁸ cm]
[10⁸ cm]
Temp [10⁹ K]
ρ [g per cm³]
[10⁸ cm]
[10⁸ cm]
Temp [10⁹ K]
Density [g cm⁻³]

Detonation



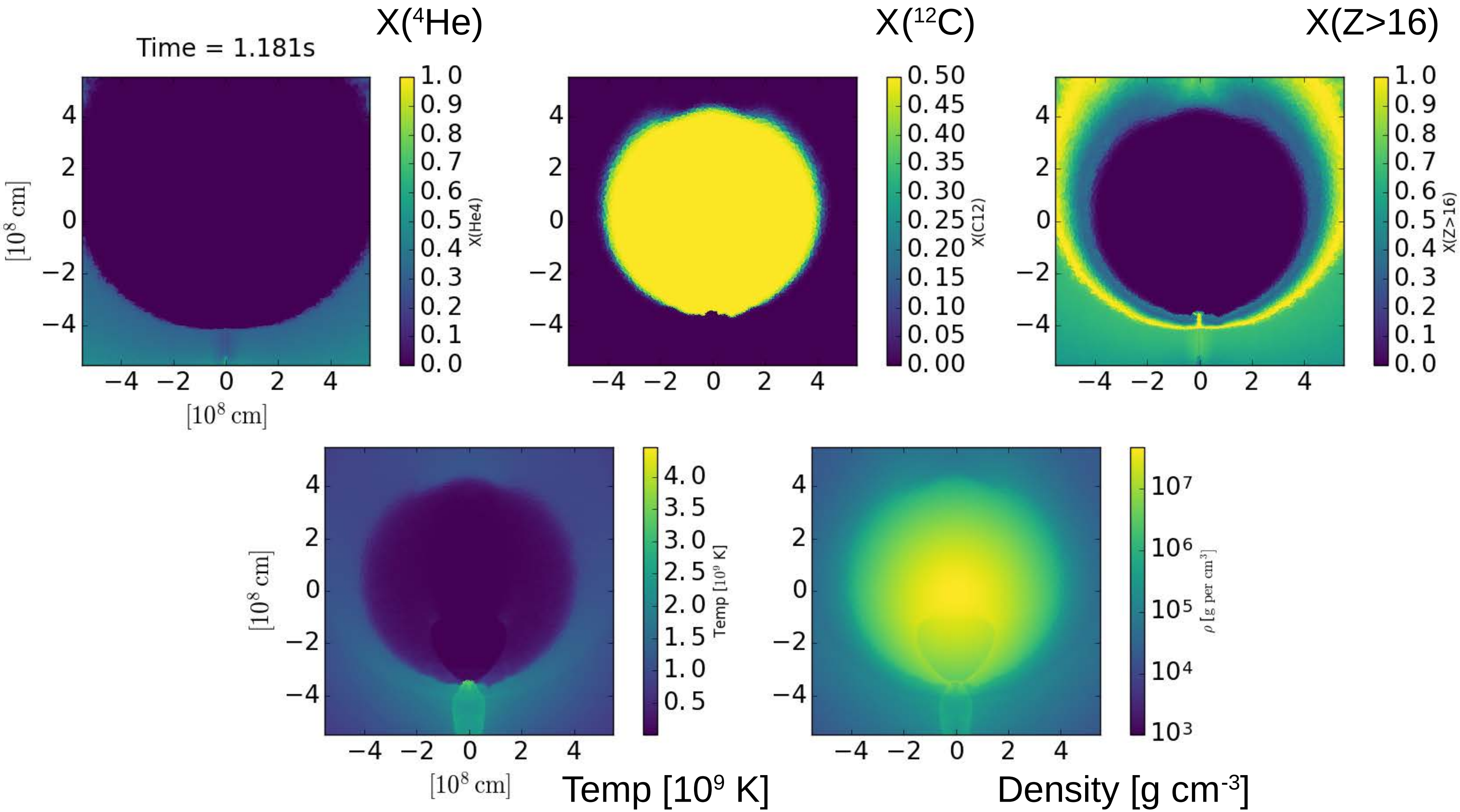
X(⁴He)
Time = 1.111s
X(He4)
X(¹²C)
X(C12)
X(Z>16)
[10⁸ cm]
Temp [10⁹ K]
Density [g cm⁻³]
ρ [g per cm³]

Detonation



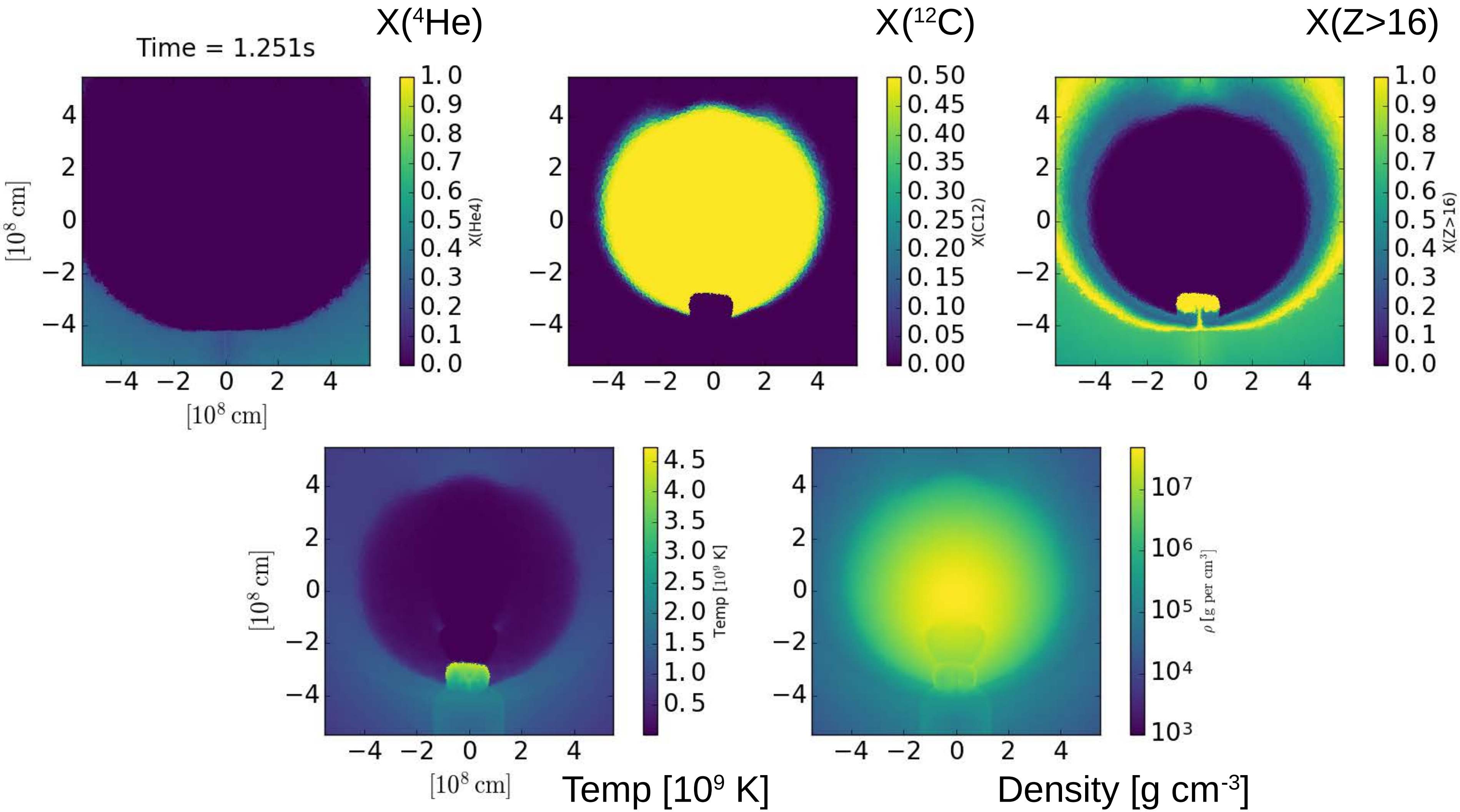
C detonation

Detonation



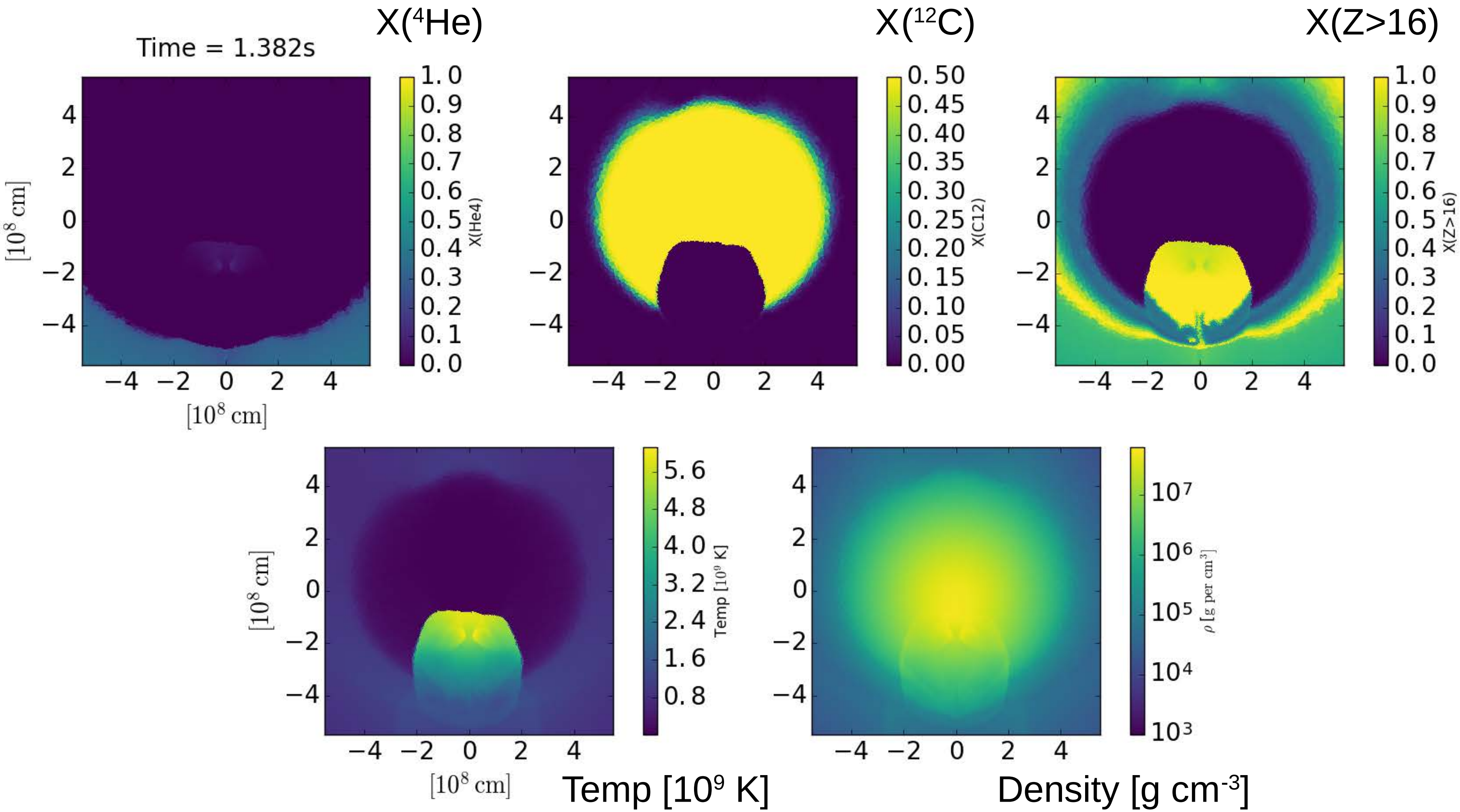
X(⁴He)
Time = 1.181s
X(He4)
X(¹²C)
X(C12)
X(Z>16)
[10⁸ cm]
Temp [10⁹ K]
ρ [g per cm³]
Temp [10⁹ K]
Density [g cm⁻³]

Detonation



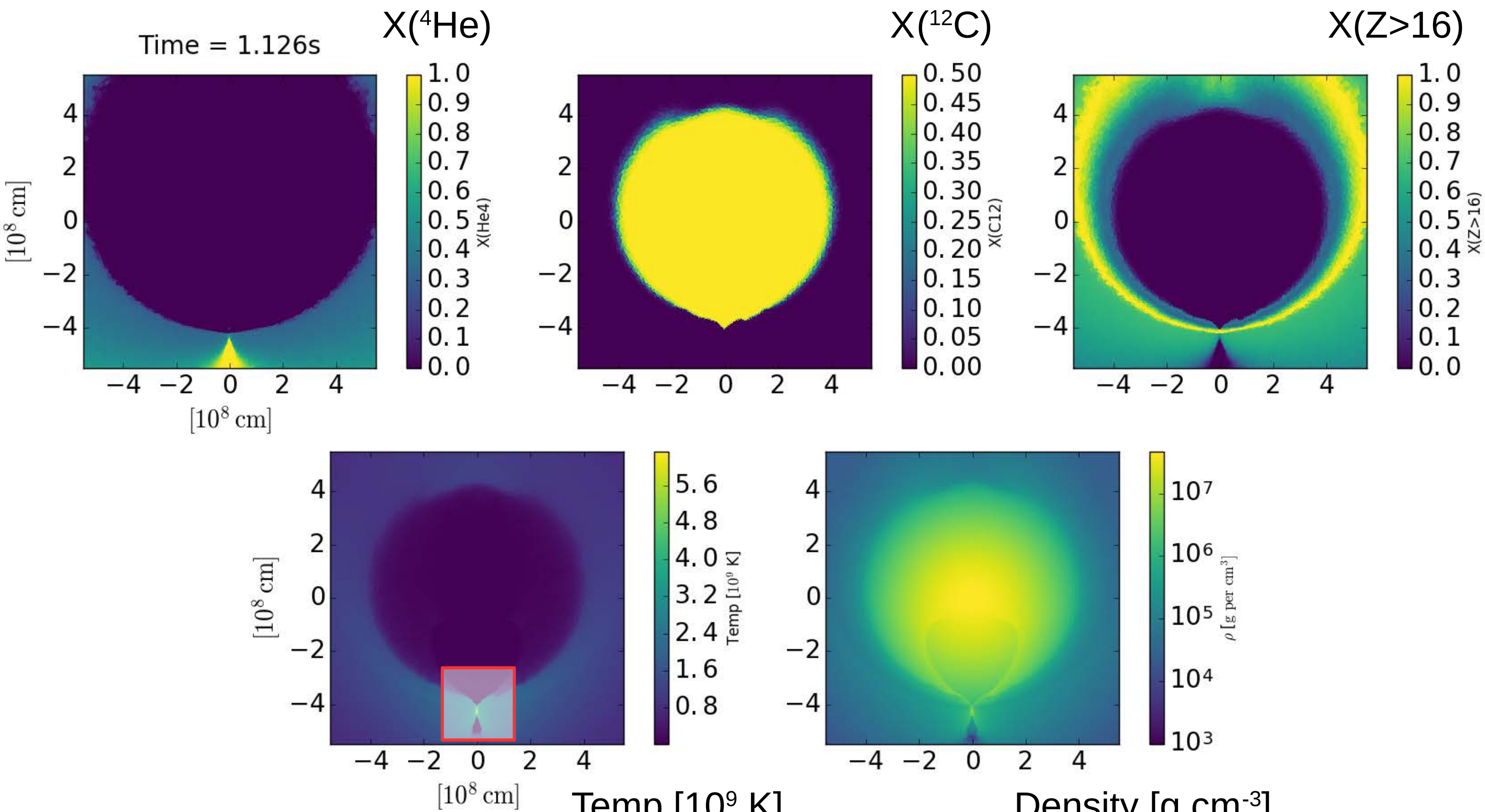
X(4He)
Time = 1.251s
X(He4)
X(12C)
X(C12)
X(Z>16)
X(Z>16)
[10^8 cm]
Temp [10^9 K]
Density [g cm^-3]
ρ [g per cm^3]

Detonation



X(⁴He)
X(¹²C)
X(Z>16)
Time = 1.382s
[10⁸ cm]
X(He4)
X(C12)
X(Z>16)
Temp [10⁹ K]
ρ [g per cm³]
Temp [10⁹ K]
Density [g cm⁻³]

Detonation



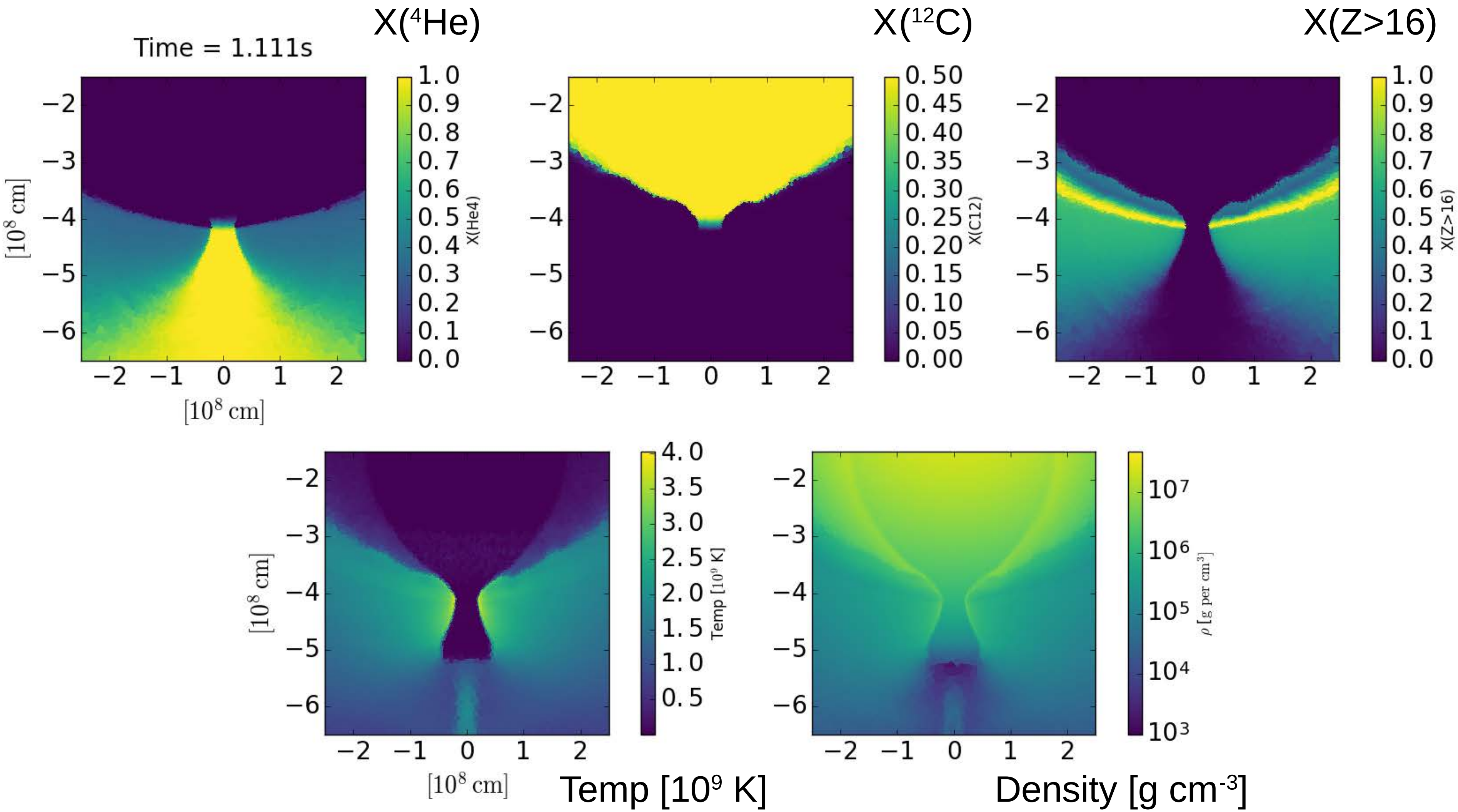
Temp [10^9 K]

Density [g cm^{-3}]

Zoom in

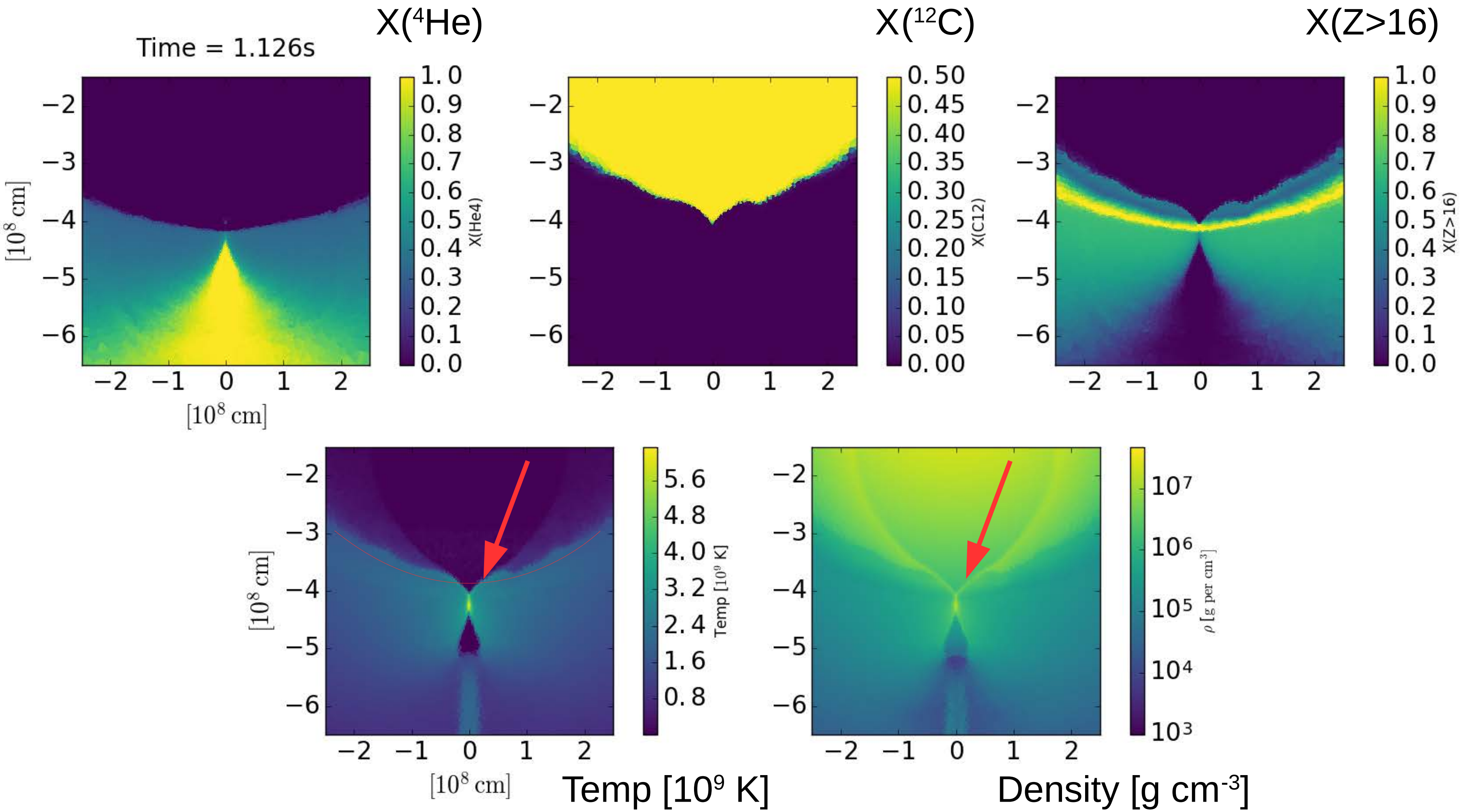
HITS

Detonation



X(⁴He)
X(¹²C)
X(Z>16)
Time = 1.111s
[10⁸ cm]
X(He4)
X(C12)
X(Z>16)
Temp [10⁹ K]
ρ [g per cm³]
Temp [10⁹ K]
Density [g cm⁻³]

Detonation



Critical values: $T \geq 2.22 \cdot 10^{9}\,\mathrm{K}$

$\rho \geq 1.41 \cdot 10^{6}\,\mathrm{g\,cm}^{-3}$

(Röpke+ 2007, Seitenzahl+ 2009)

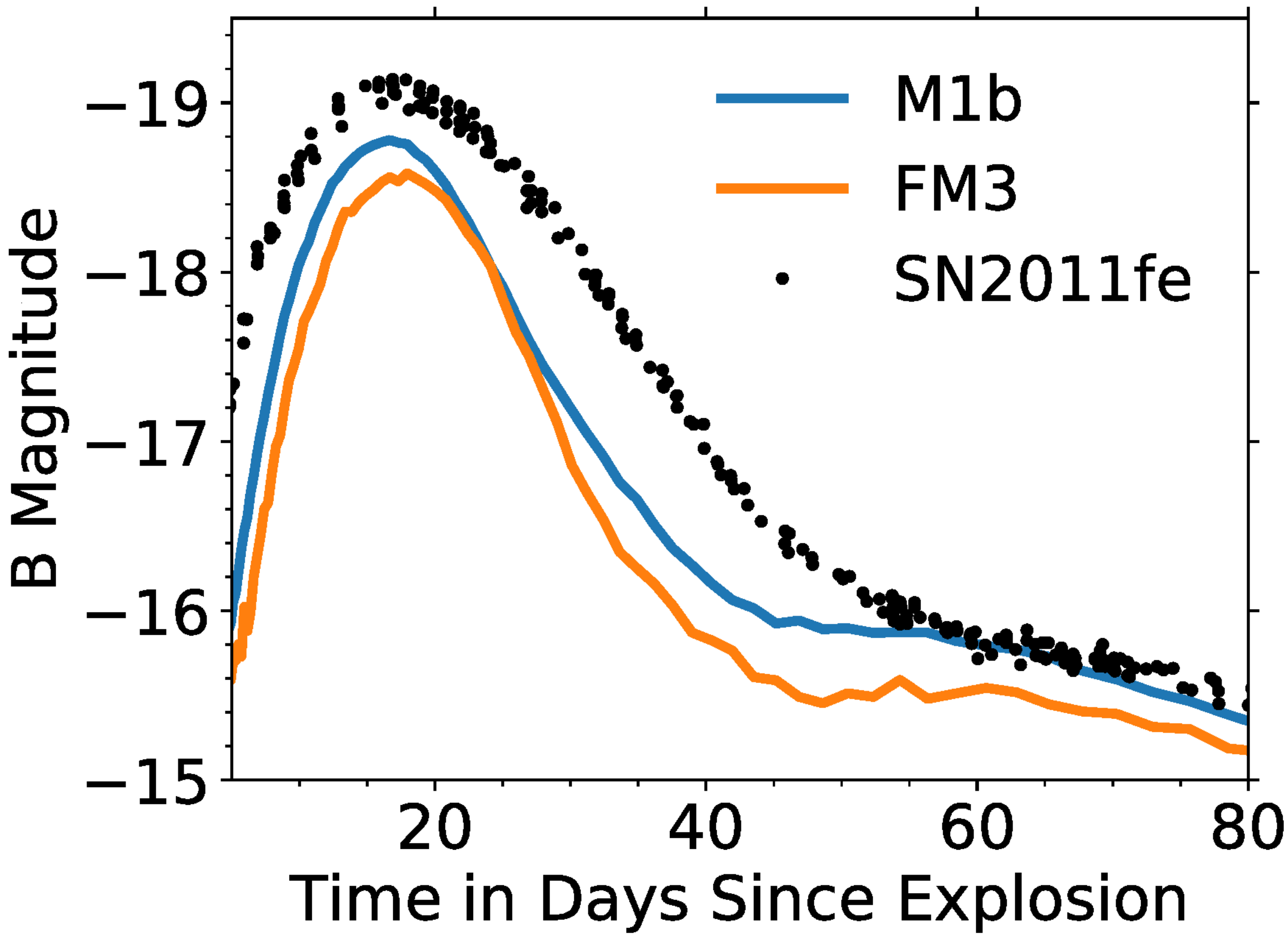
HITS

Nucleosynthesis yields

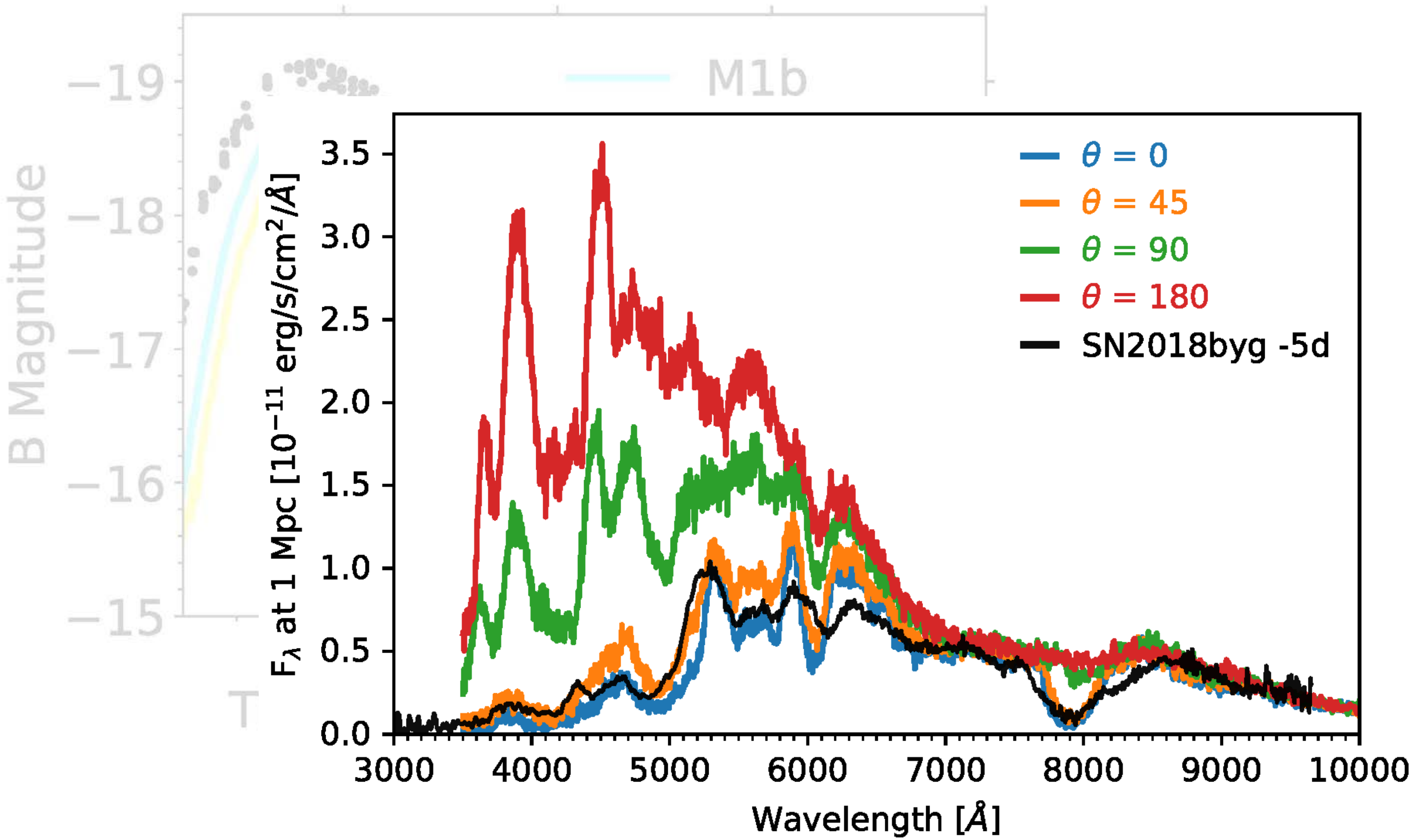
- Old simulations: burning products of He detonation have strong imprint on synthetic observables
  - Not observed
- Burning products depend on modeling of He burning
- Compare results to previous work:
  - Post-processing with large nuclear network
  - Obtain detailed chemical yields
- Results in expected range:

shell detonation			core detonation		
	We $[M_\odot]$	Fink+ 2010 $[M_\odot]$		We $[M_\odot]$	Fink+ 2010 $[M_\odot]$
^{4}He	2.6×10^{-2}	3.3×10^{-2}	^{12}C	4.8×10^{-4}	2.7×10^{-3}
^{44}Ti	6.6×10^{-4}	3.4×10^{-3}	^{16}O	4.9×10^{-2}	8.0×10^{-2}
^{56}Ni	1.8×10^{-2}	1.7×10^{-3}	^{56}Ni	5.7×10^{-1}	5.5×10^{-1}
IME	2.3×10^{-2}	5.3×10^{-3}	IME	3.7×10^{-1}	3.7×10^{-1}

Observables



Observables



Summary

- Double detonation scenario includes *four* different detonation mechanisms
  - convergence of He detonation waves strong enough
- Mechanism matches SN Ia observables as good as Fink+ 2010
- Spectra show necessity of multi-D simulations

HITS

Thank you!