SILICON SHELL BURNING AND THE GROWTH OF THE IRON CORE

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TEAMS Meeting June 15-16, 2020

OUTLINE

- Introduction and Motivation
- Methodology
- Results
- Future Work

LIFETIME OF A MASSIVE STAR

- Main Sequence Hydrogen Burning
  - $\mathcal{O}(10^7$ years)
  - For the CNO-cycle $T > 1.7 \times 10^7\ K$
- Giant Branch (Advanced stages of nuclear burning)
  - He burning via triple-α process lasts on $\mathcal{O}(10^5$ years), $T > 1.5 \times 10^8\ K$
  - C,O,Ne core burning - duration $\mathcal{O}(10^3$ years), $T > 5 \times 10^8\ K$

SILICON SHELL BURNING (SISB)

- Final stage of nuclear burning before Iron core-collapse
  - Lasts for 1 hour to at most 1 day
  - Occurs just above the inert iron core
- Si burning is not $^{28}\mathrm{Si} + {}^{28}\mathrm{Si} = {}^{56}\mathrm{Ni}$
- Photodisintegration of ^{28}Si into nucleons and alpha particles which then capture onto other silicon nuclei, slowly increasing the mean atomic number
- Iron peak elements "rain" down onto the core slowly increasing the mass

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IRON CORE-COLLAPSE

- Iron ash continues to accumulate onto the core until it approaches the Chandrasekhar mass limit above which electron degeneracy pressure is no longer sufficient to prevent gravitational collapse $M_{ch} \simeq 5.76 Y_e^2 \sim 1.4 M_\odot$ $(Y_e = 0.5)$

- Contraction begins once $M \geq M_{ch}$, but is not instantaneous

- Collapse is defined: $v_{infall} = 1000$ km/s

- Collapse is accelerated by:

    - Electron capture onto iron peak nuclei increases density $\longrightarrow$ neutron rich environment which decreases $Y_e \longrightarrow$ more electron capture

    - Continued photodisintegration of iron peak species into alpha particles as temperature and density continue to increase

MOTIVATION

- Understanding the nucleosynthetic origins of the universe
- Understanding the structure of the core before collapse
- Asymmetries in outer core may make a difference in the
  - Most simulations are done in 1D
  - multi-D is needed in certain epochs because fluid instabilities like convection and turbulence are inherently 3D

WORK FLOW

MESA

1D Progenitor generation

Begin Pre-MS

Stop during SiSB

Stop at Fe-core infall

Polaris

Multi-D Progenitor Generation

Begin pre-collapse (SiSB)

Stop at Fe-core infall

Chimera

Multi-D CCSNe Simulation

Begin at Fe-core collapse

METHODOLOGY/CODES

Modules for Experiments in Stellar Astrophysics (MESA)

- Open source, easy access
- Modular in nature- useful for many different applications
- Modern techniques - Adaptive mesh refinement(AMR), large nuclear reaction network capabilities, multitude of stopping and starting conditions, modern equations of state

CHIMERA

- Neutrino Transport- Spectral Neutrino Transport with 20 logarithmically spaced energy groups (4-250 Mev), ray-by-ray
- Hydrodynamics- Lagrangian + remap (VH1) with Newtonian multipole expansion for gravity with GR monopole
- XNET- fully implicit thermonuclear reaction code (sn160)
- Modern Equations of State: SFHO and Helmholtz

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Polaris

- Neutrino Emission - neutrino cooling via emission prescription is from Itoh et al. 1996 + tabular electron capture LMSH 2003
- Hydrodynamics- Lagrangian + remap (VH1) with Newtonian multipole expansion for gravity with GR monopole
- XNET- fully implicit thermonuclear reaction code including electron capture
- Equations of State: SFHo (NSE) and Cooperstein (1985) + not (nuclei) (non-NSE)

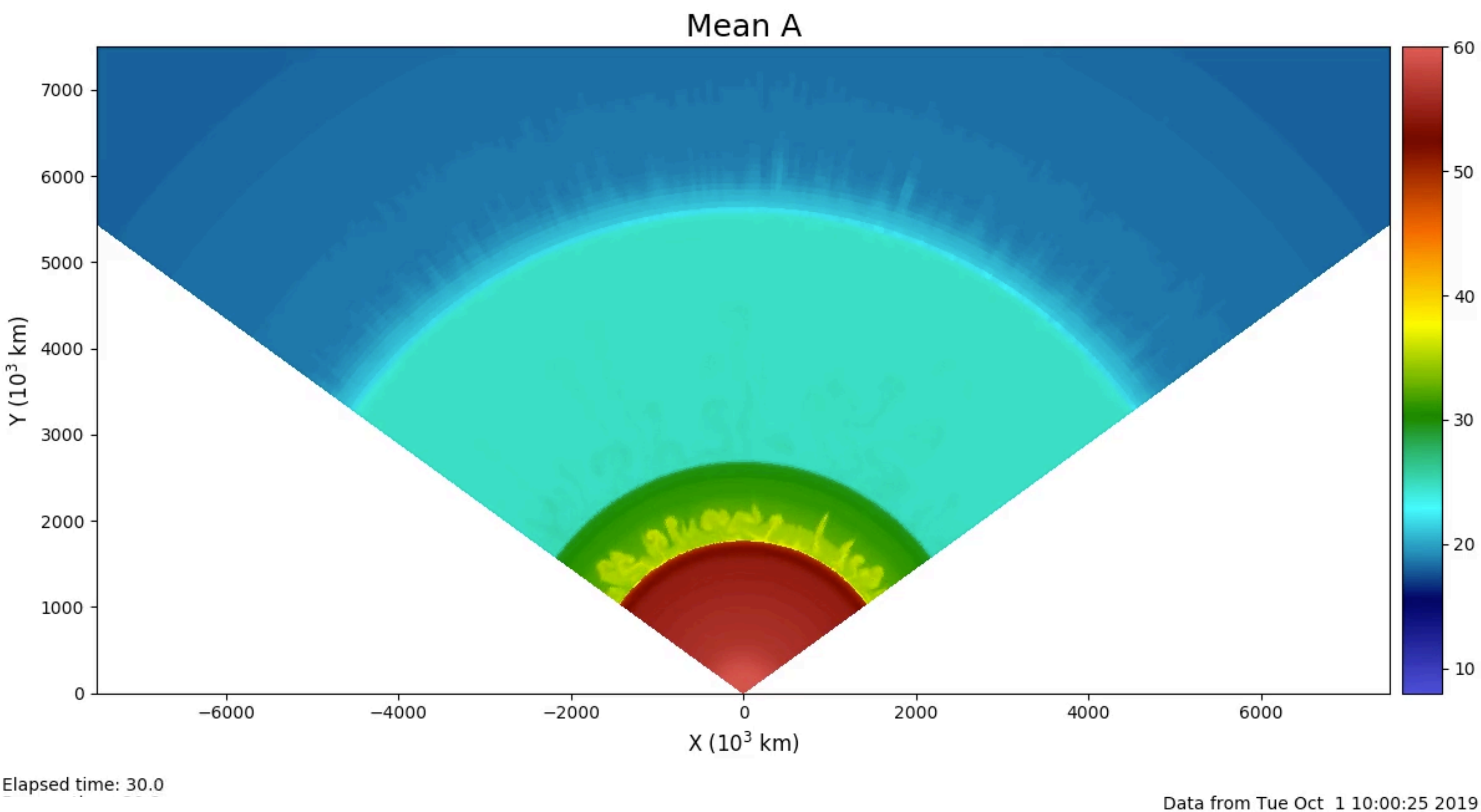
PROGENITOR SET-UP (MESA)

- Model begins at pre-main sequence to iron core infall
  - Rewound and stopped 270 sec before iron core infall
- Network: 204 species
- EoS: Helmholtz
- Revision 7623

MODEL SET-UP

- Initial Conditions: 15 $M_{\odot}$ 270 s from Fe-Core Collapse
- 2D Wedge with periodic boundary conditions
- Spherical Symmetry imposed on inner 360 zones (1 $M_{\odot}$)
- non-NSE EoS: BCK
- Network: sn160

- Computational Information:
  - Cori-KNL @ NERSC
  - 4 nodes- 45 processes/ node
  - 720 radial shells
  - 180 angular zones (36°-144°)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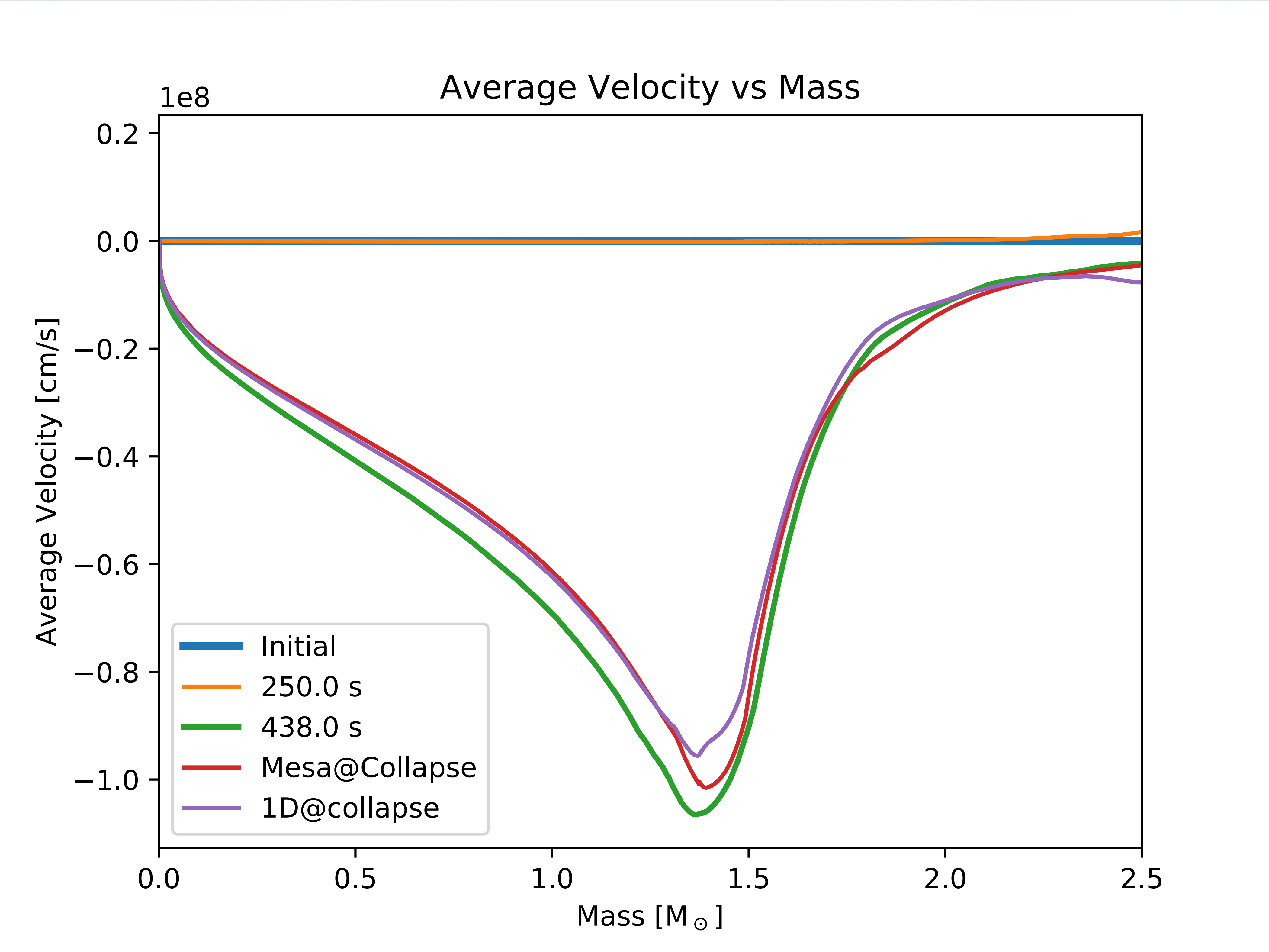
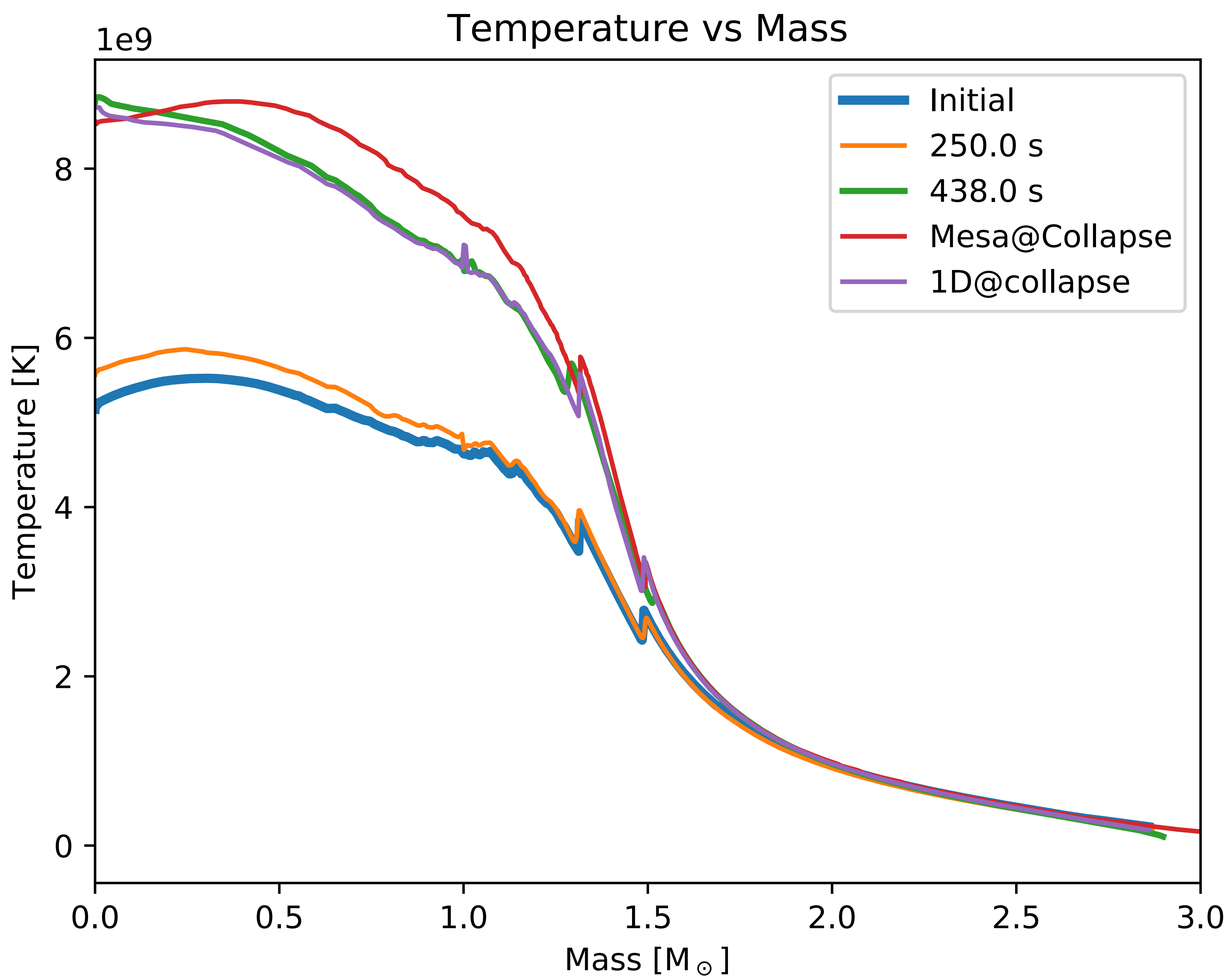
6000
5000
4000
3000
2000
1000
0
Y (10^3 km)
−6000
−4000
−2000
0
2000
4000
6000
X (10^3 km)
60
50
40
30
20
10
Elapsed time: 30.0
Data from Tue Oct 1 10:00:25 2019

VELOCITY PROFILE



THERMODYNAMIC PROFILES



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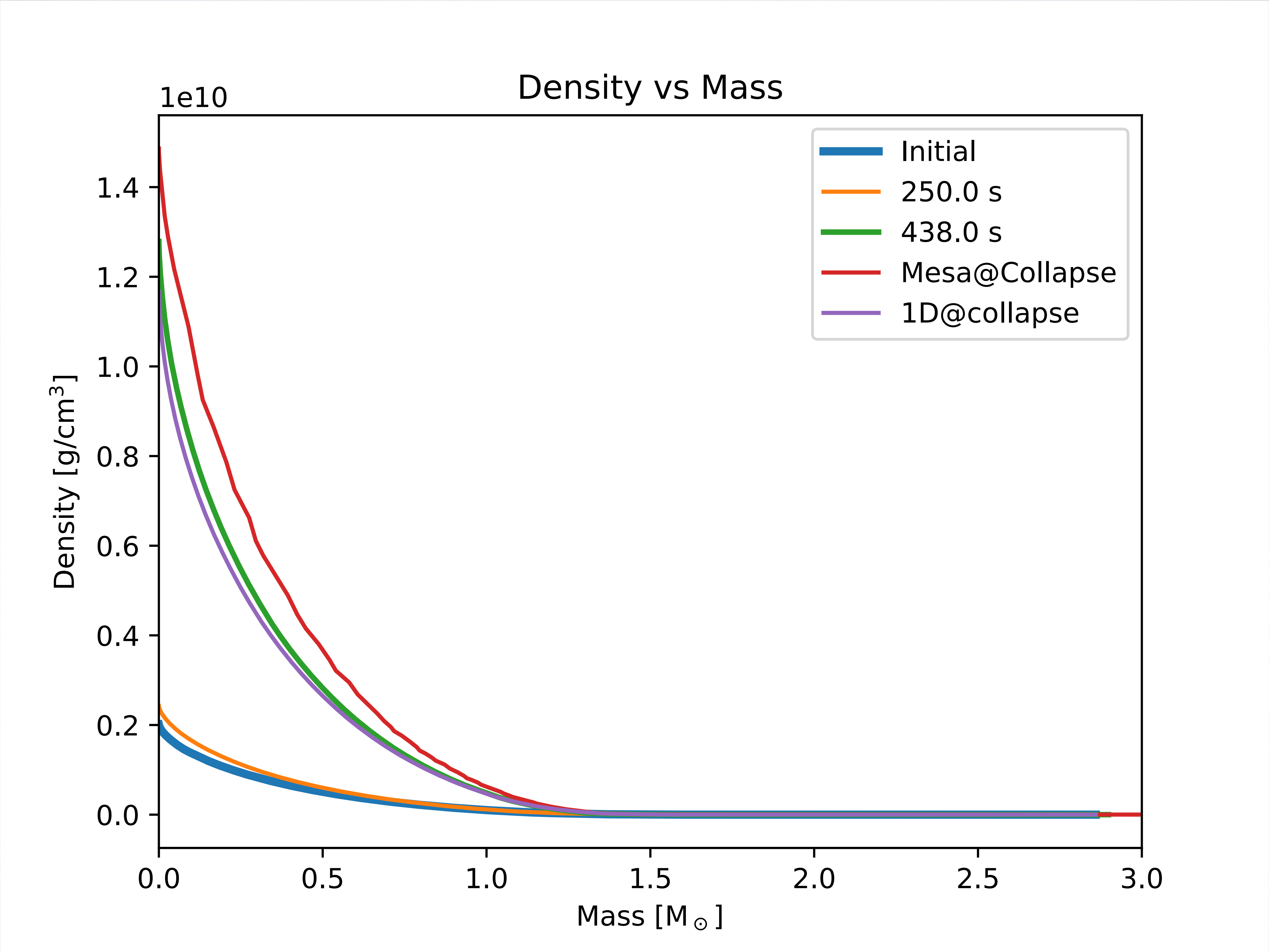

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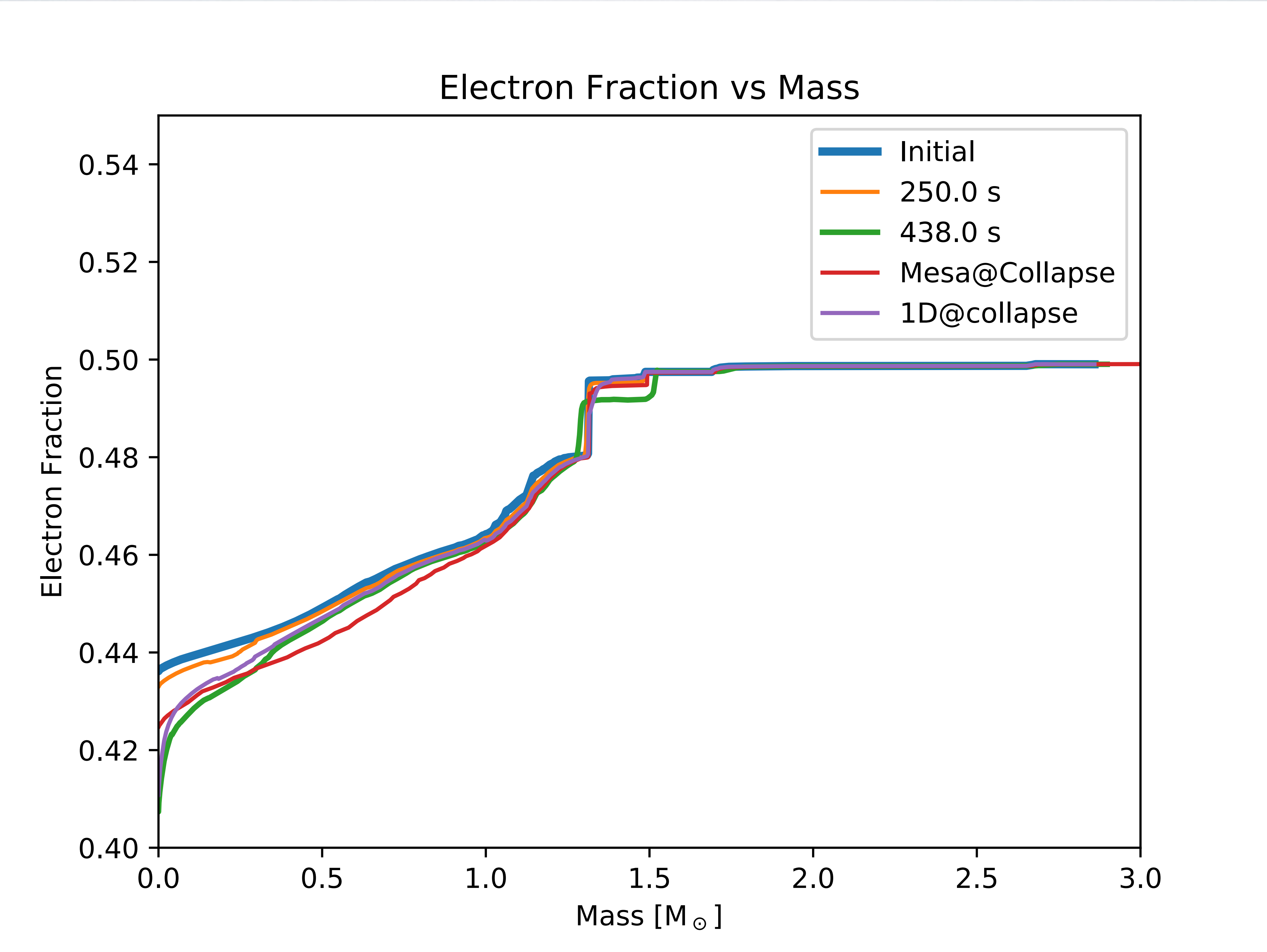
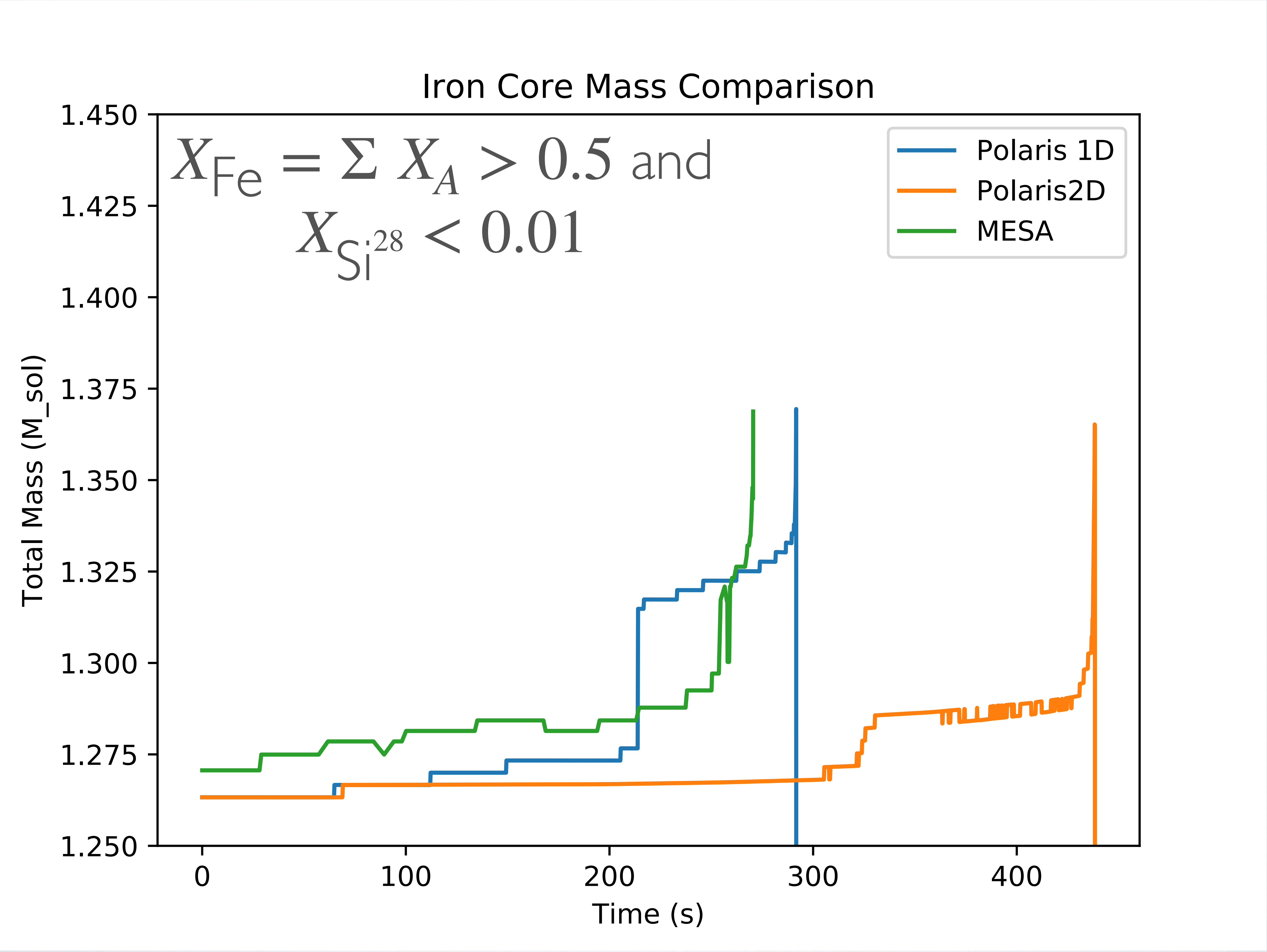
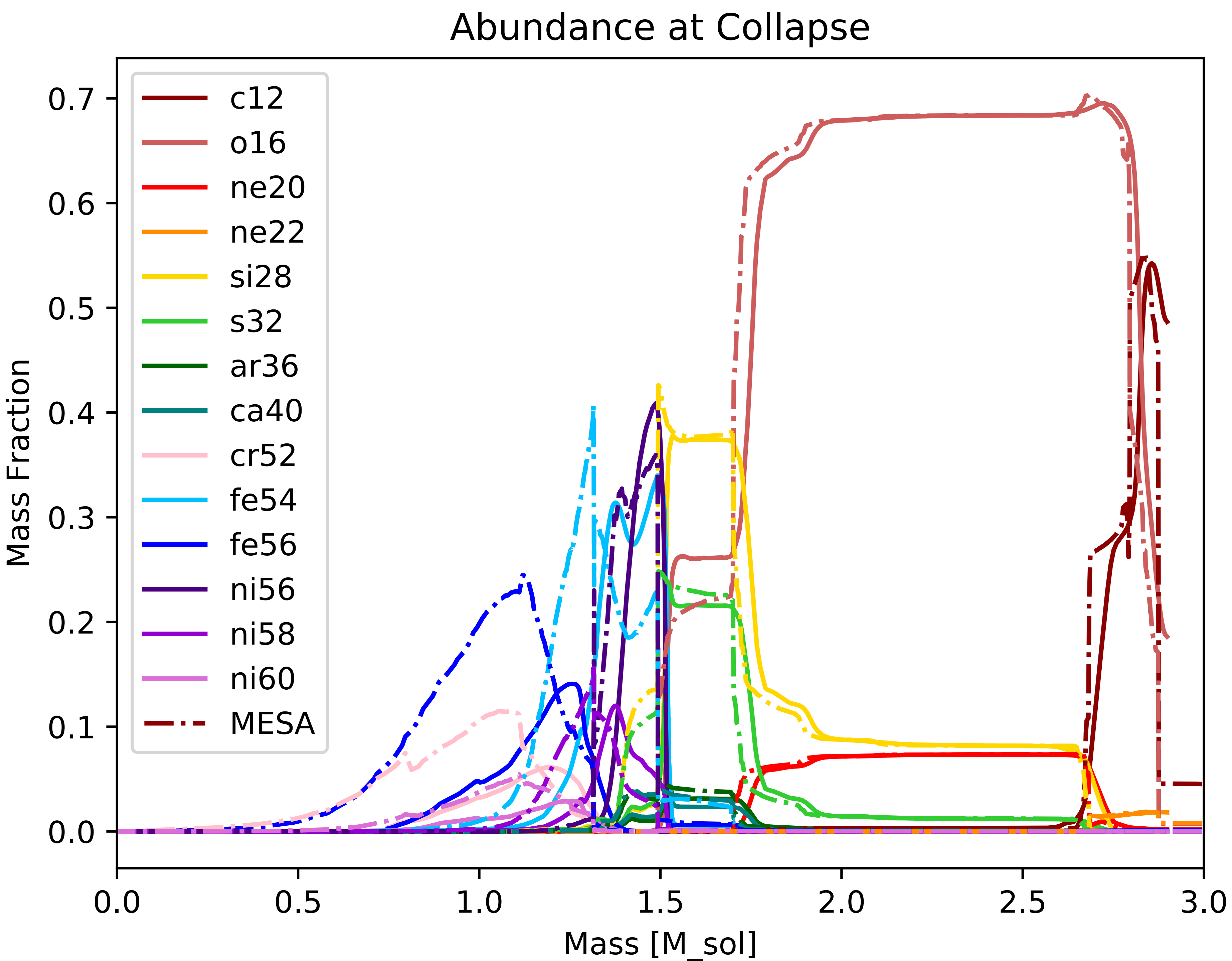


IRON CORE GROWTH



COMPOSITION



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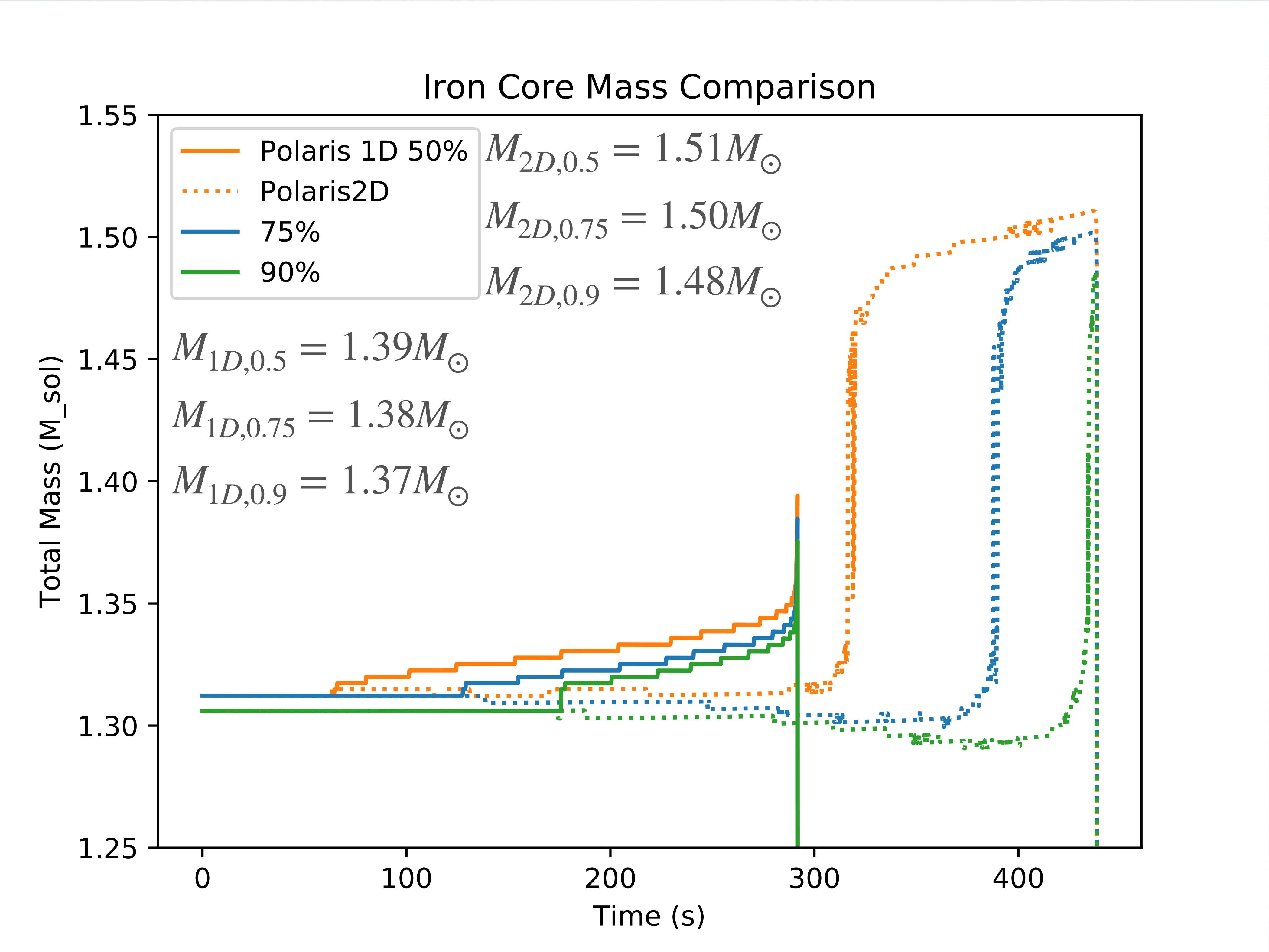

TAKE AWAYS

- Structural differences
- Sudden growth of the iron core then a slow growth until collapse
    - ~ 100 second delay in collapse
    - Lower Central Electron Fraction
- Larger iron core mass in 2D

FUTURE WORK

- Use current model to run in 3D
- Run a suite of 2D models with newer progenitors from MESA and updated EoSs in Polaris (Helmholtz)
- Run the same suite of 2D models in CHIMERA
  - Using 1D MESA at collapse as a starting point
  - Using 2D Polaris at collapse as a starting point

ACKNOWLEDGEMENTS

- NSF Grant - AST-1716134
- NERSC Allocation on Cori
- TACC Allocation on Frontera - for 3D model
- CHIMERA Team- Notably Eric Lentz and Raph Hix