

Simulating X-ray Burst Flame Propagation: From Parallel Plane to Full Star

Zhi Chen¹ and Mike Zingale¹

¹Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA

INTRODUCTION

An X-ray burst (XRB) is a thermonuclear runaway caused by the ignition of the accreted fuel on the surface of a neutron star. The burst oscillation behavior observed during the rise-time of the burst and difference between the accretion and burst timescales both suggest that nuclear ignition is likely to begin in a localized region (hotspot), and spread to the rest of the neutron star. **The goal is to use numerical simulations to study the XRB flame dynamics:**

- 1) Study the effect of nuclear reactions on ⁴He flame propagation in a localized region on the rotating pole with 2D R-Z geometry.
- 2) Study the effect of variation in rotational forces on ⁴He flame as it spreads across the full star with 2D R-θ geometry.

INITIAL MODEL

- Corotating frame with consideration of rotating pseudo forces.
- Assumed a 1.4 M_⊙ NS with R = 11 km and Ω = 1000 Hz.
- Pure Helium-4 accretion layer for pure Helium XRB.
- Initial model is in hydrostatic equilibrium.
- Isothermal base with T = T_{*} and pure ⁵⁶Ni composition for 0 < z < H_{*} to represent the underlying neutron star.
- A transition phase with prescribed temperature and composition profiles that blend the base and atmosphere for H_{*} < z < H_{*} + 3δ_{atm}.
- Isentropic atmosphere with pure ⁴He composition for z > H_{*} + 3δ_{atm} to represent the accretion layer.
- A temperature perturbation on the left part of the domain to drive a rightward propagating flame, a spreading hotspot for our geometry.

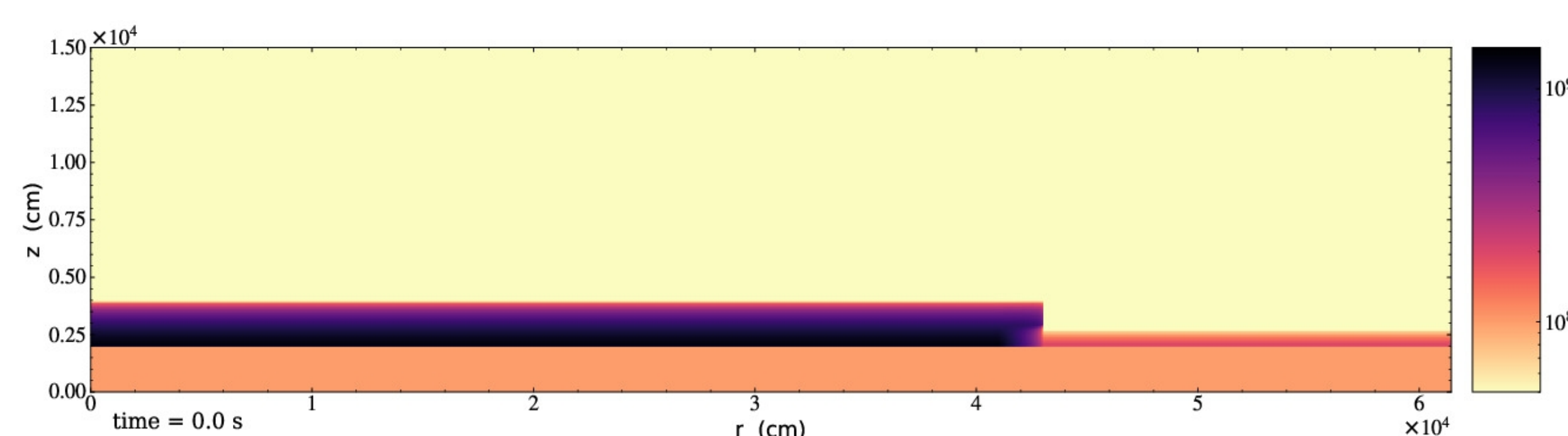


Fig: Zoom-in of the initial temperature profile. A temperature perturbation of 1.2 GK is set on the left edge of the domain to start the burning.

CODE

Castro | <https://github.com/AMReX-Astro/Castro>
 Microphysics | <https://github.com/AMReX-Astro/Microphysics>
 Pynucastro | <https://github.com/pynucastro/pynucastro>



**New Contributions
Are Welcome!**

PARALLEL PLANE SIMULATION RESULTS

Plane Parallel Local Simulation:

- 9216 × 1536 zones or 20 cm resolution in finest grid
- **R** = [0, 1.843 × 10⁵ cm] and **Z** = [0, 3.072 × 10⁴ cm]
- ~ 3,000 GPU node hours to finish at t = 120 ms.
- Shows results between two networks: **aprox13** and **subch_simple**, they differ as **subch_simple** includes:

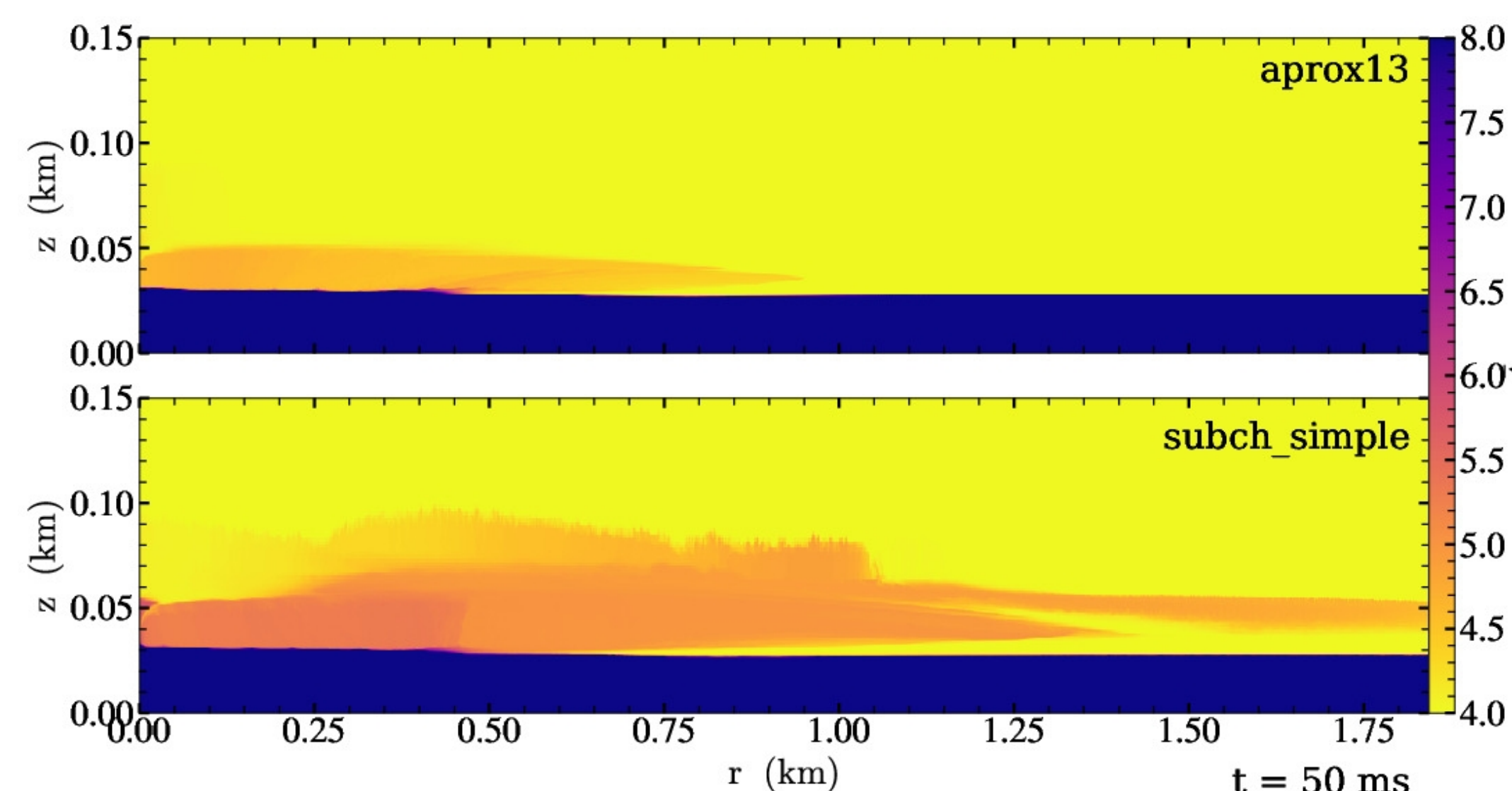


Fig: Slice plot showing average atomic weight at t = 50 ms.

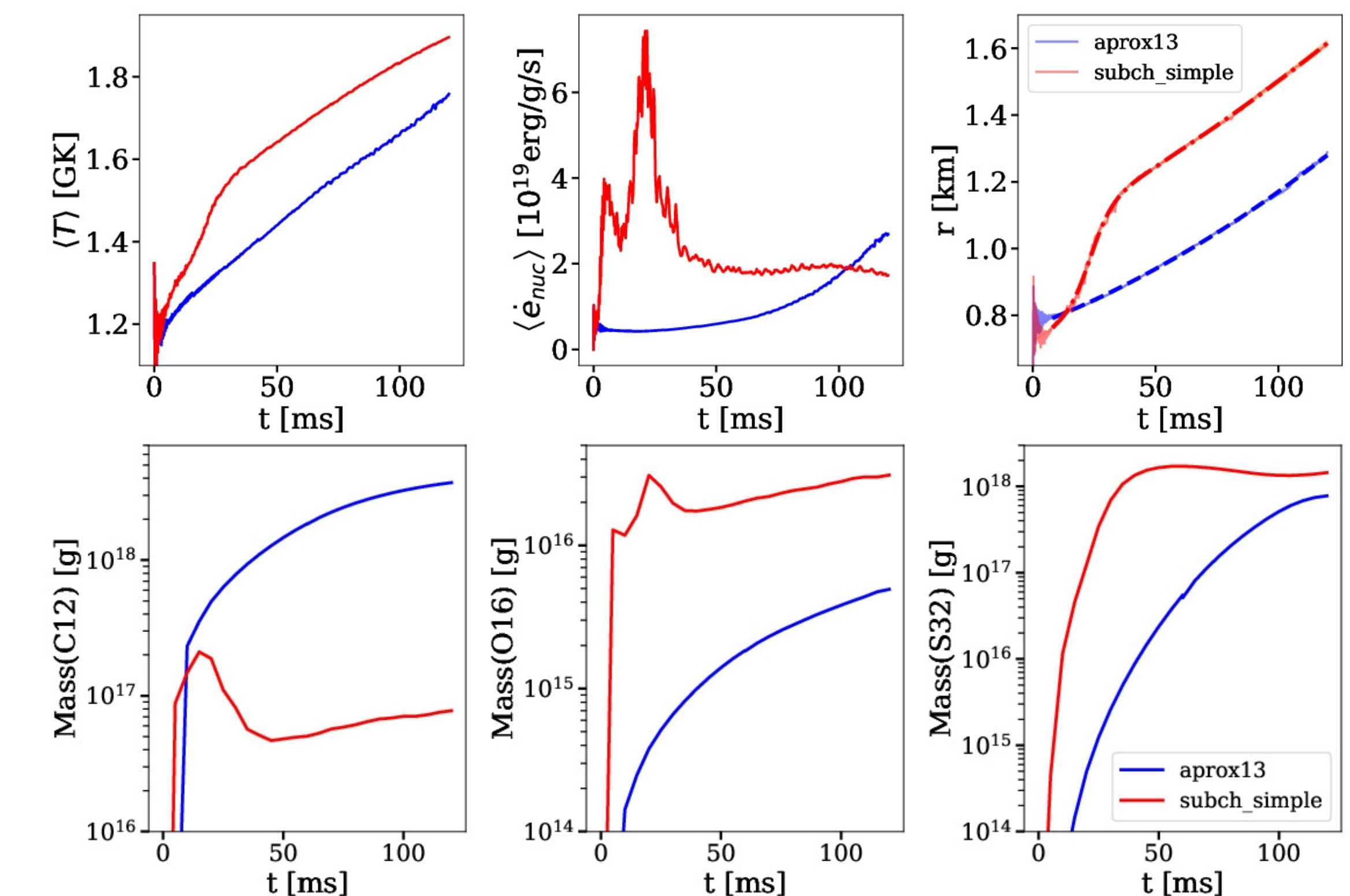


Fig: Top Panels: Time evolution of the density weighted T (left), nuclear energy generation rate (mid), and flame position (right).
 Bot Panels: Time evolution of total mass of ¹²C, ¹⁶O, and ³²S.

SPHERICAL POLAR SIMULATION RESULTS

Spherical Polar Local simulation:

- **R** = [11 km, 11.3072 km], **θ** = [0, 10°]
- 1536 × 9360 zones or 20 cm res
- ~ 2,000 node hours to reach 120 ms.
- A test run to demonstrate that the spherical-polar geometry is well behaved.

Full – Star simulation:

- **R** = [11 km, 11.3072 km], **θ** = [0, π]
- 1536 × 172,800 zones or 20 x 20 cm resolution
- Will need ~100,000 node hours to finish.
- **Ongoing simulation!**

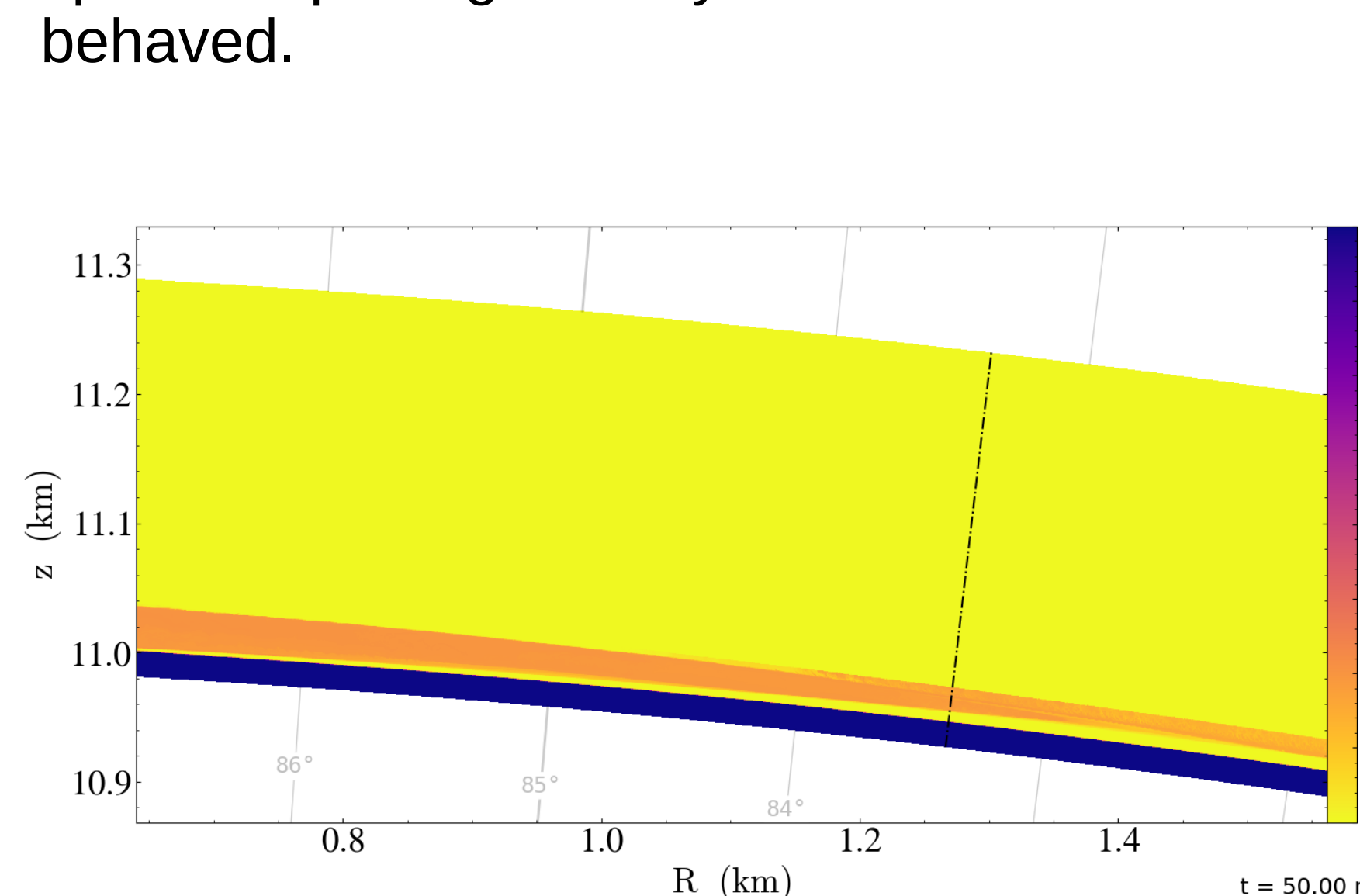


Fig: Slice plot showing average atomic weight at t = 50 ms. Black Dashed line indicates the flame front position, determined by the leading edge of the energy generation rate. Burning ash is more uniform compared to the plane-parallel run.

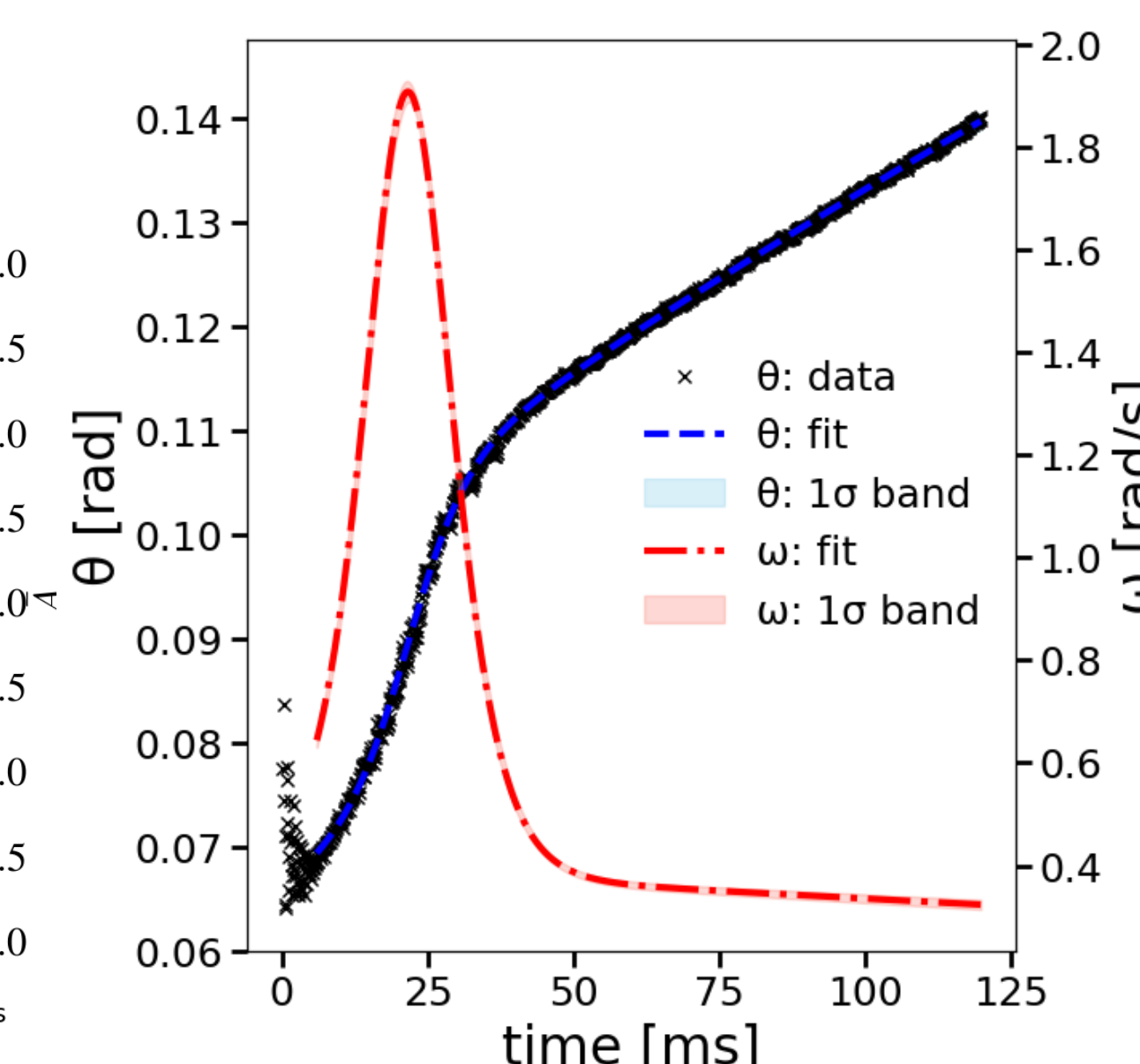


Fig: Time evolution of the flame front position with fitted curve shown in Blue. Derived fitted angular velocity shown in Red.

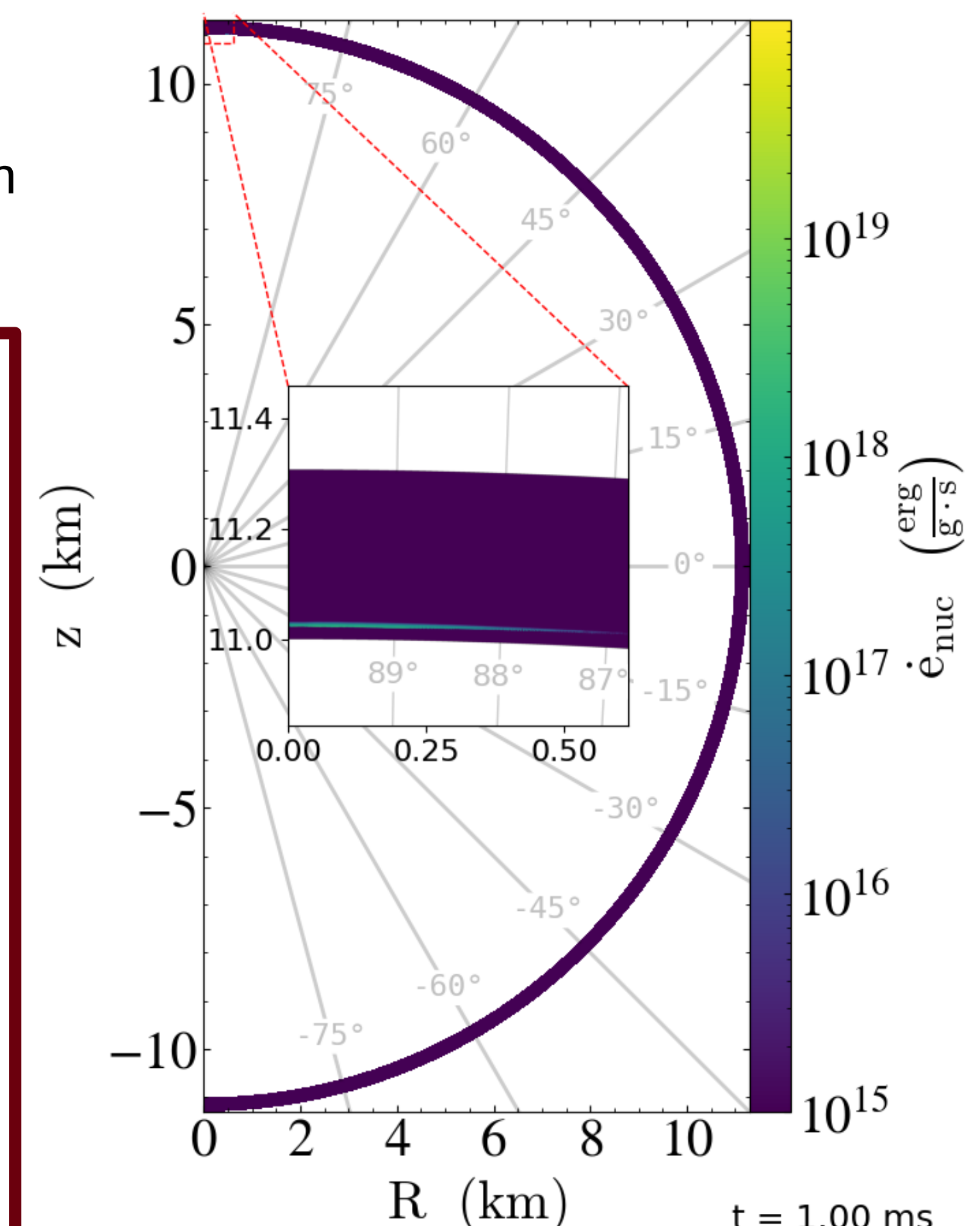


Fig: Full Star slice plot with zoom-in shown in the center, showing nuclear energy generation rate.