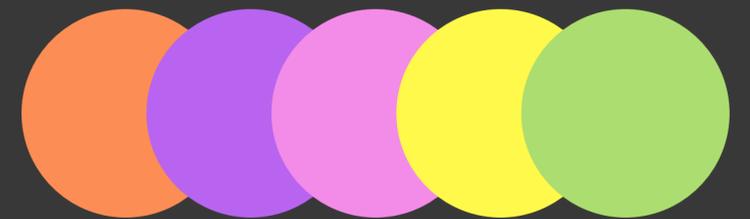
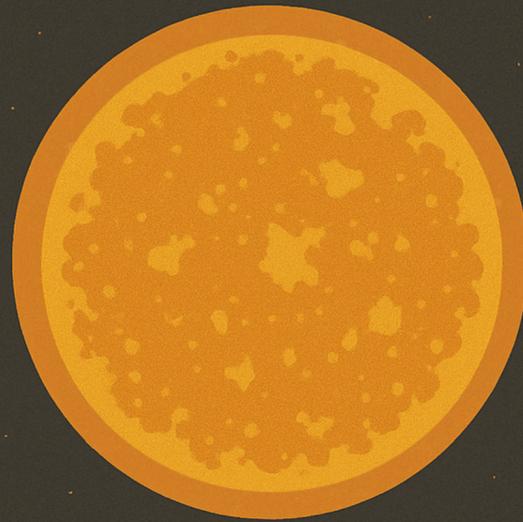


Haakon Andresen

Turbulence in Supernova Progenitors





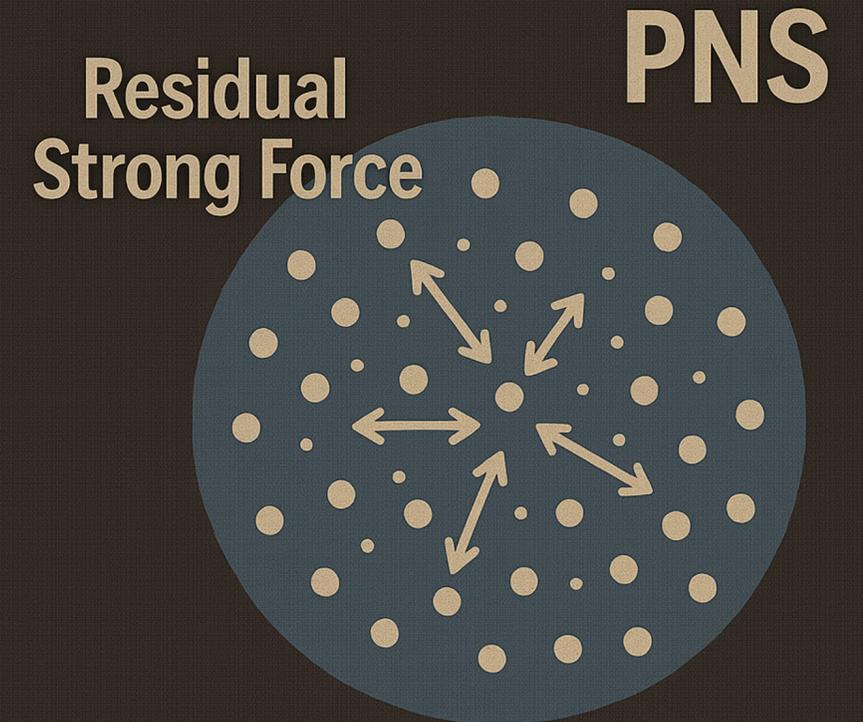
Massive Stars

About 10 times more massive than the sun.



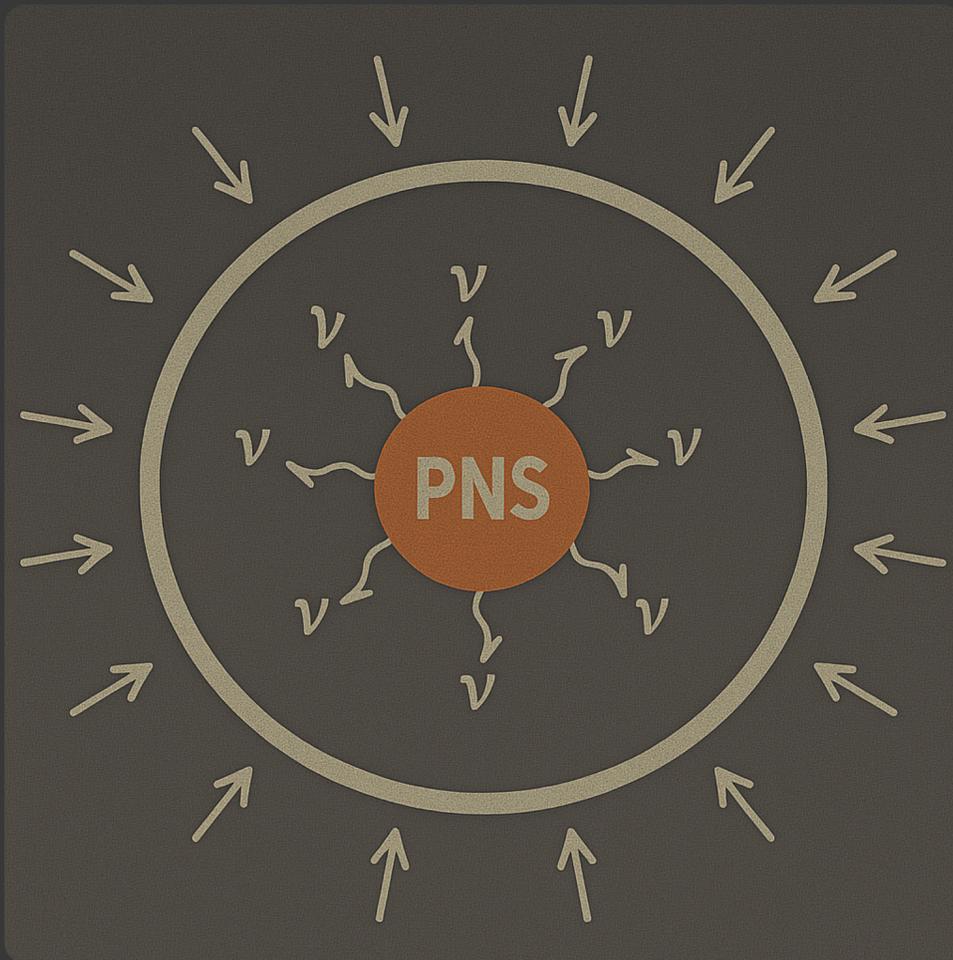
Shell Burning

Hydrogen depletion leads to the burning of heavier elements, which continues until an iron core is formed.



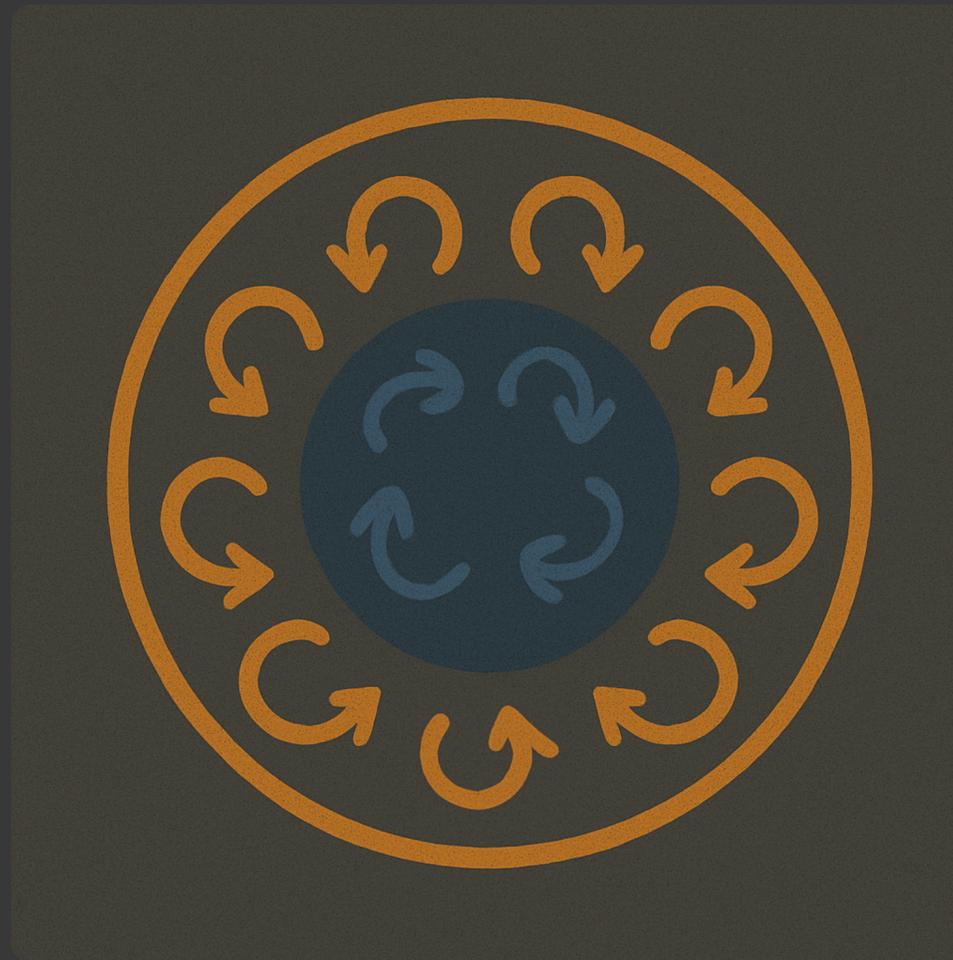
Core Collapse

The core surpasses its Chandrasekhar mass and collapses. The collapse is halted when the inner core reaches nuclear densities.



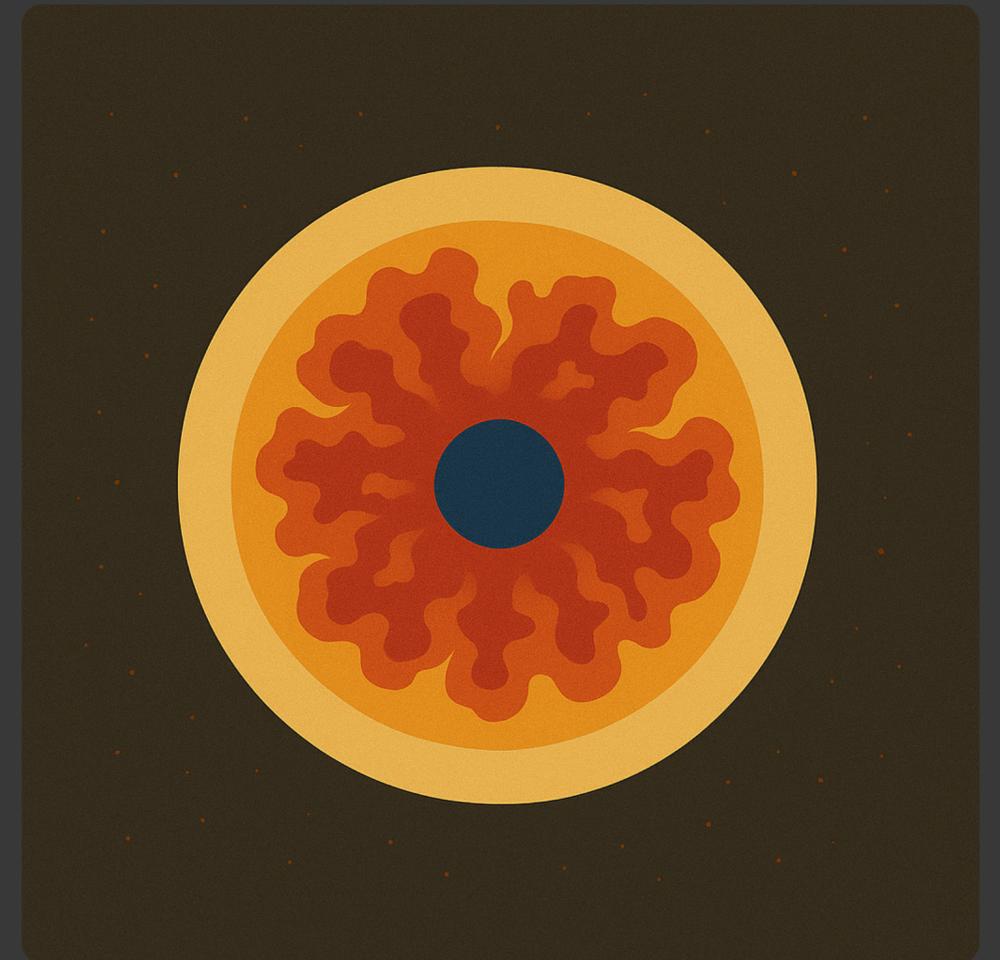
Proto-neutron star

A proto-neutron star is formed and a shock is launched. The shock stalls and is revived by neutrino heating.



Turbulence

Multi-dimensional effects are key to the success of supernovae. Importantly, the asymmetries sources gravitational waves.



Shock Revival

After a fraction of a second, the shock is revived. The shock then propagates through the star and disrupts the progenitor.



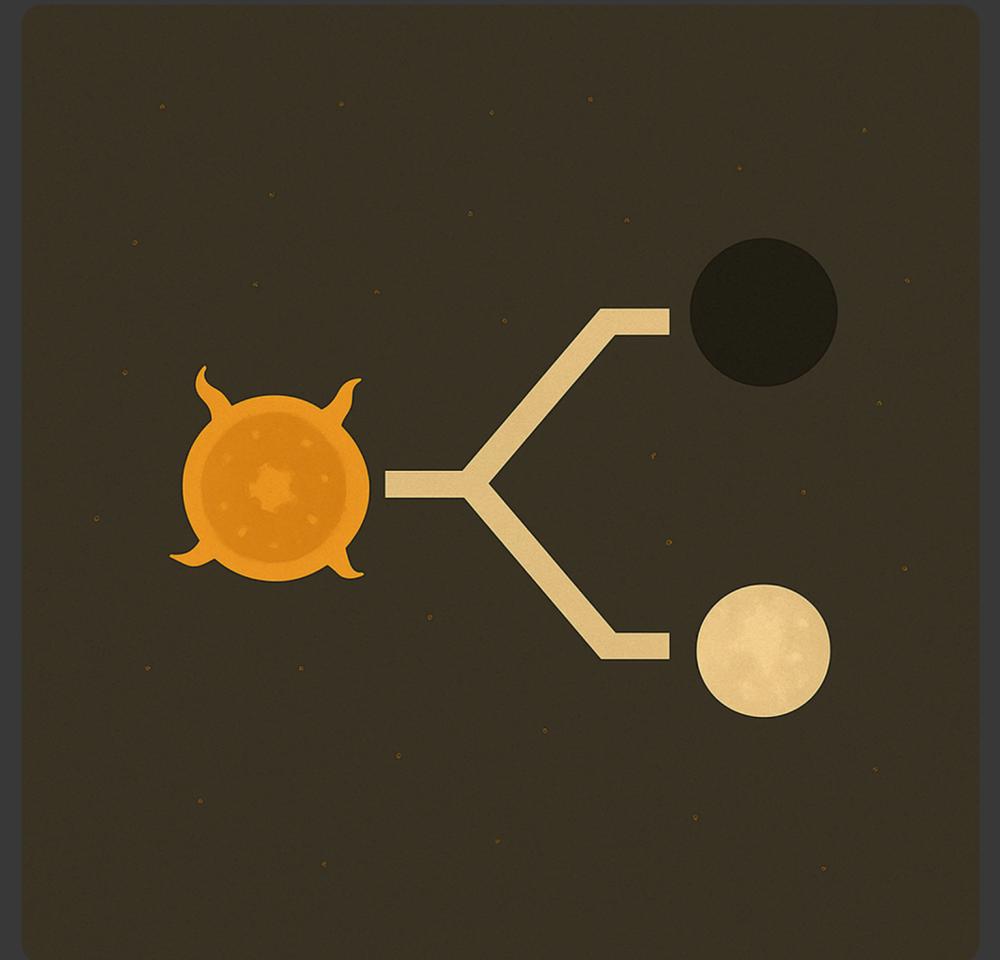
Which Stars?

The big question moving forward, which stars explode and what does the landscape of supernovae outcomes look like.



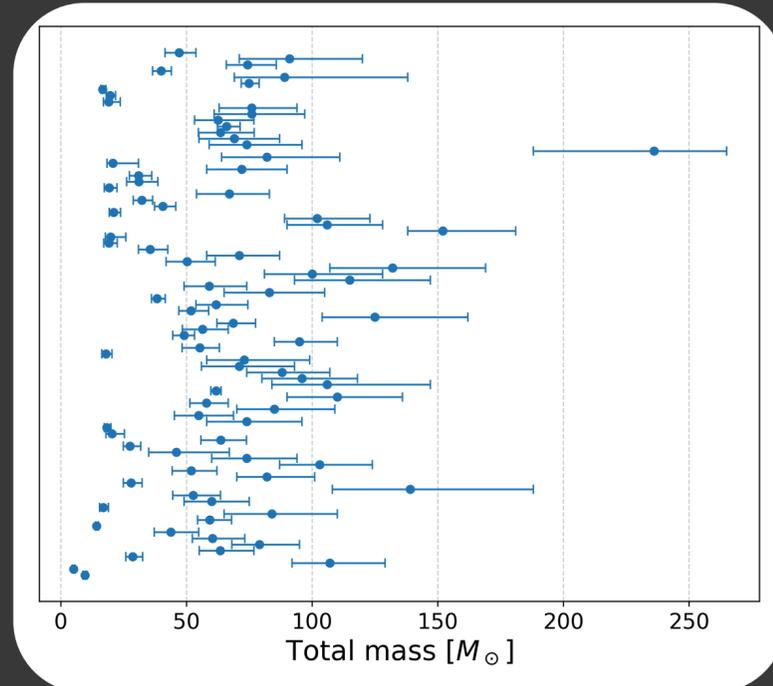
Progenitor

It is known that progenitor asymmetries are important (Müller+17, Fields+20, Varma+21)



Simulation Results

Beyond just explosion or not, the stellar progenitor influences the observables.



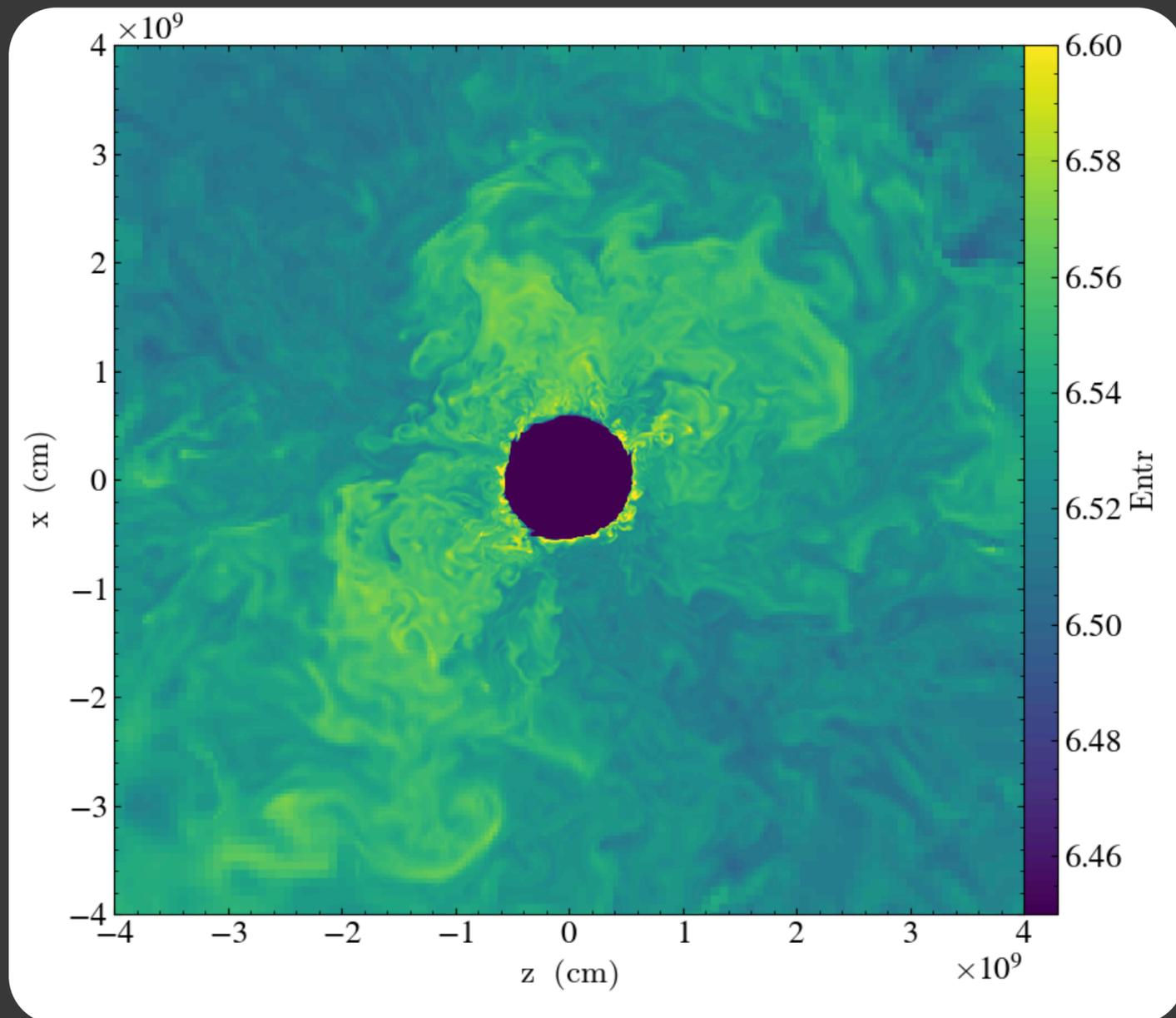
The devil is in the details

Will never get better than the initial conditions we start with



Atomic Number	17	35.45	Atomic Mass, u		13					
Name	Cl Chlorine Halogen			Symbol	B Boron Metalloid					
Chemical Group Block										
50.9415	V Vanadium Transition Metal	24 51.996 Cr Chromium Transition Metal	25 54.93804 Mn Manganese Transition Metal	26 55.84 Fe Iron Transition Metal	27 58.93319 Co Cobalt Transition Metal	28 58.693 Ni Nickel Transition Metal	29 63.55 Cu Copper Transition Metal	30 65.4 Zn Zinc Transition Metal	31 69.723 Ga Gallium Post-Transition M...	32
92.90637	Nb Niobium Transition Metal	42 95.95 Mo Molybdenum Transition Metal	43 96.90636 Tc Technetium Transition Metal	44 101.1 Ru Ruthenium Transition Metal	45 102.9055 Rh Rhodium Transition Metal	46 106.42 Pd Palladium Transition Metal	47 107.868 Ag Silver Transition Metal	48 112.41 Cd Cadmium Transition Metal	49 114.818 In Indium Post-Transition M...	50
180.9479	Ta Tantalum Transition Metal	74 183.84 W Tungsten Transition Metal	75 186.207 Re Rhenium Transition Metal	76 190.2 Os Osmium Transition Metal	77 192.22 Ir Iridium Transition Metal	78 195.08 Pt Platinum Transition Metal	79 196.96... Au Gold Transition Metal	80 200.59 Hg Mercury Transition Metal	81 204.383 Tl Thallium Post-Transition M...	82
268.1...	Db Dubnium Transition Metal	106 269.1... Sg Seaborgium Transition Metal	107 270.1... Bh Bohrium Transition Metal	108 269.1... Hs Hassium Transition Metal	109 277.1... Mt Meitnerium Transition Metal	110 282.1... Ds Darmstadtium Transition Metal	111 282.1... Rg Roentgenium Transition Metal	112 286.1... Cn Copernicium Transition Metal	113 286.1... Nh Nihonium Post-Transition M...	114
140.116	Ce Praseodymium Lanthanide	59 140.90... Pr Neodymium Lanthanide	60 144.24 Nd Promethium Lanthanide	61 144.91... Pm Samarium Lanthanide	62 150.4 Sm Europium Lanthanide	63 151.964 Eu Gadolinium Lanthanide	64 157.2 Gd Terbium Lanthanide	65 158.92... Tb Dysprosium Lanthanide	66 162.500 Dy Holmium Lanthanide	67

Stellar Evolution



Multi-dimensional effects

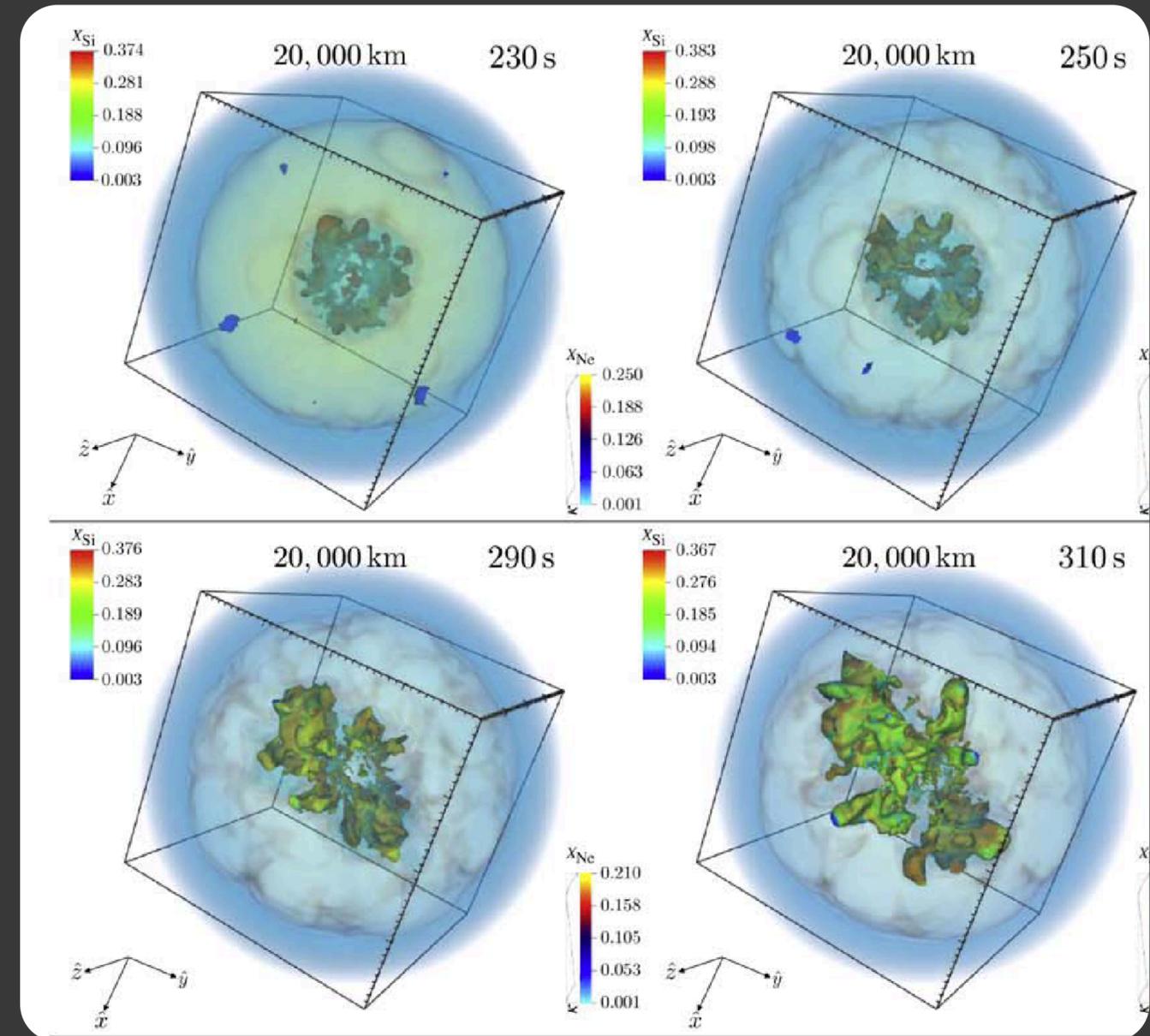
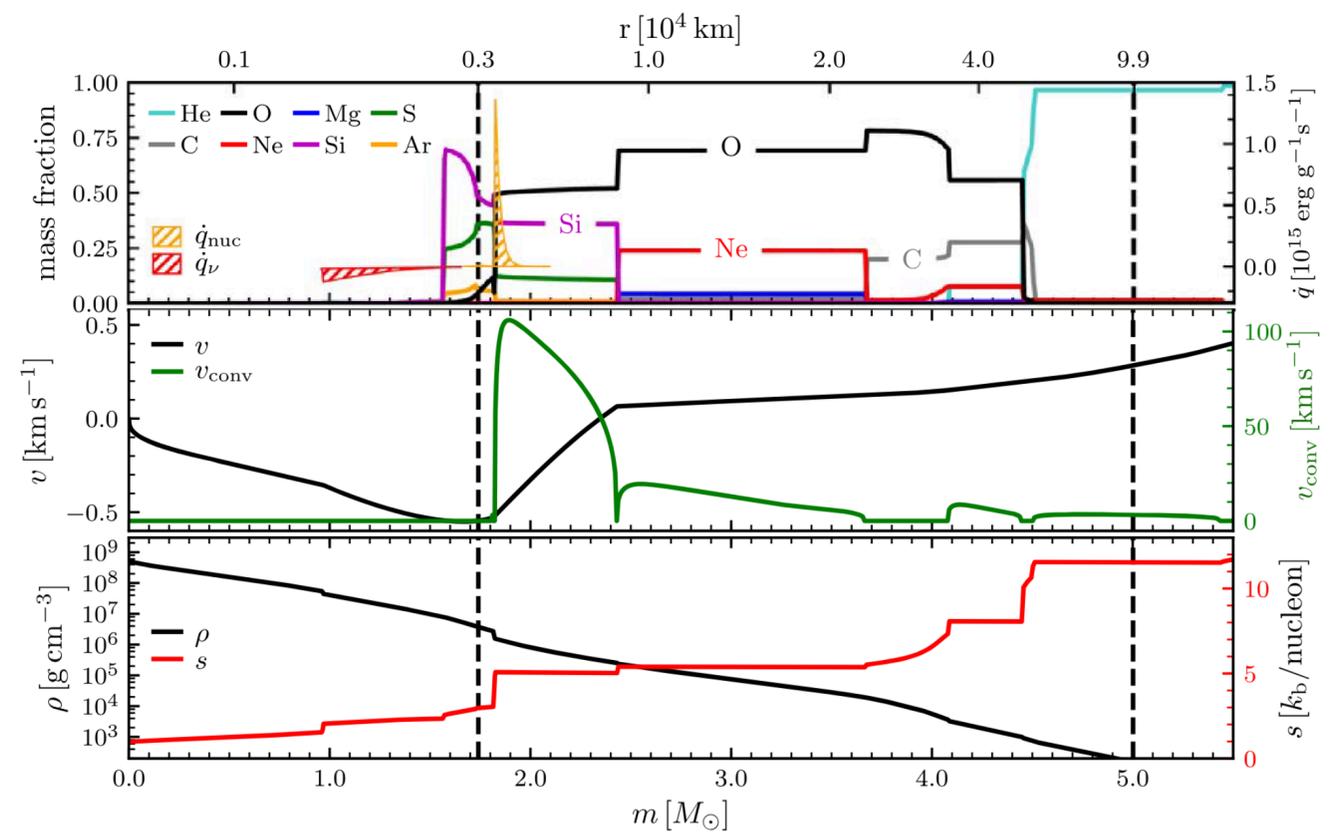
Stars are clearly not spherically symmetric and late stage burning can be convectively unstable.

Large scales and short times

The key problem is that stars evolve over long time-scales and that the evolution of stars is determined by physical processes on scales much smaller than the size of the star.

Stellar Evolution

Yadav+20



Stellar Simulations

Goal

Produce realistic initial conditions for our core-collapse simulations and study the impact of progenitor asymmetries

Initial data

MESA

Using approx 21
Up to 700-650 seconds before bounce

Simulation

FLASH

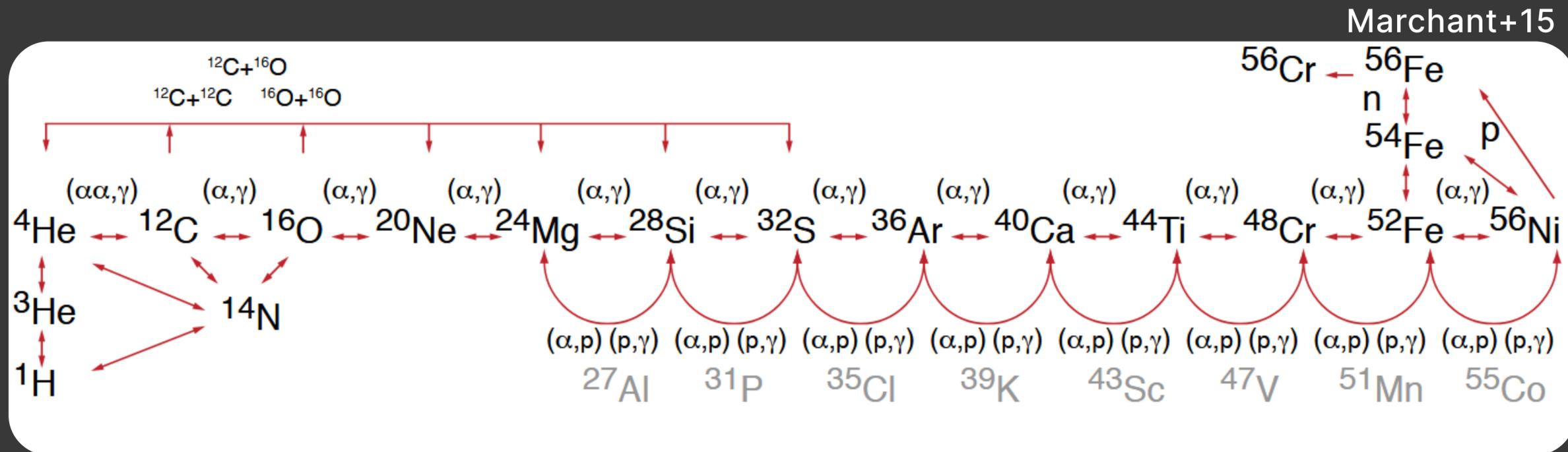
Approx 21
AMR, finest resolution ~ 19 km

The last 15 minutes

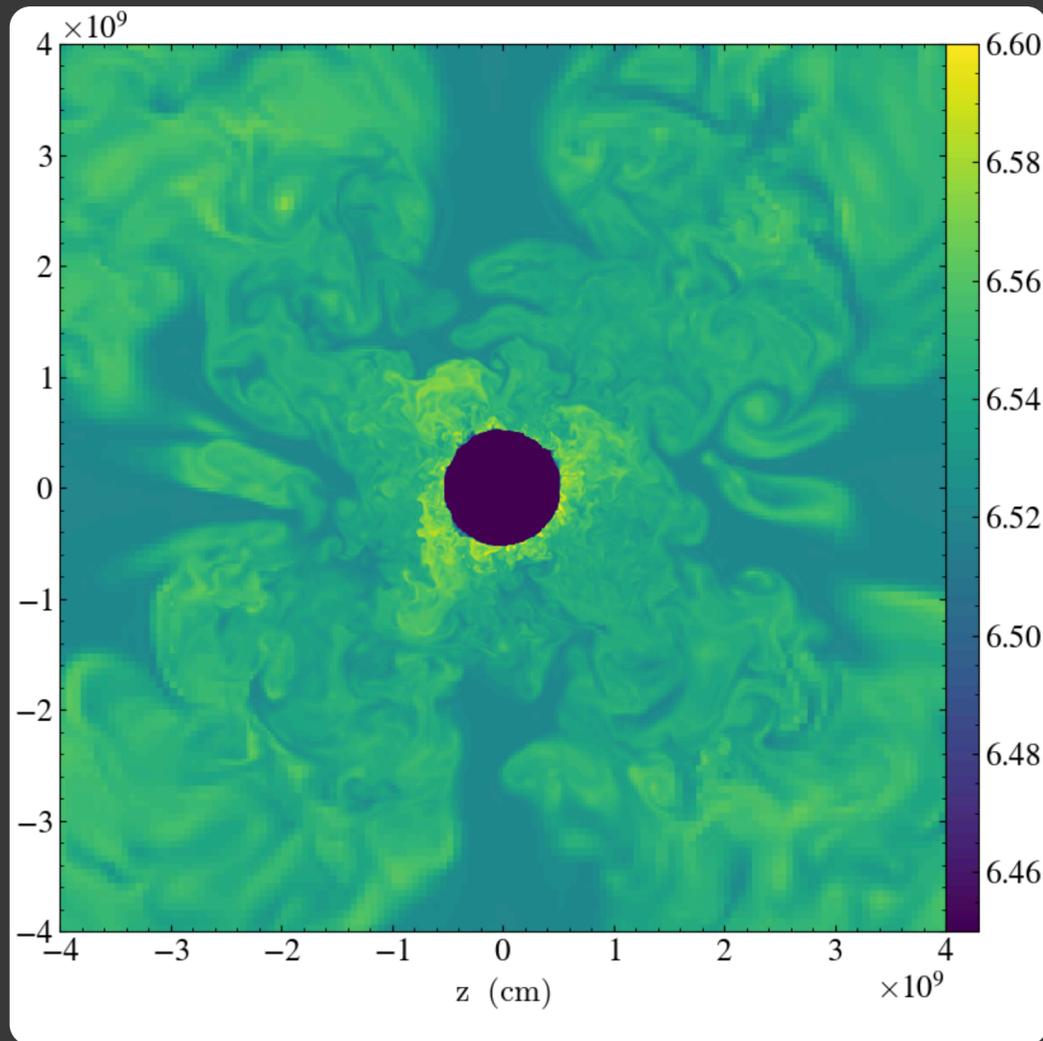
Woosley and Heger (2002)

Burning stage	Typical duration
Hydrogen burning	3 – 10 Myr
Helium burning	0.3 – 2 Myr
Carbon burning	0.5 – 3 kyr
Neon burning	0.03 – 1 yr
Oxygen burning	0.01 – 5 yr
Silicon burning	0.2 – few days

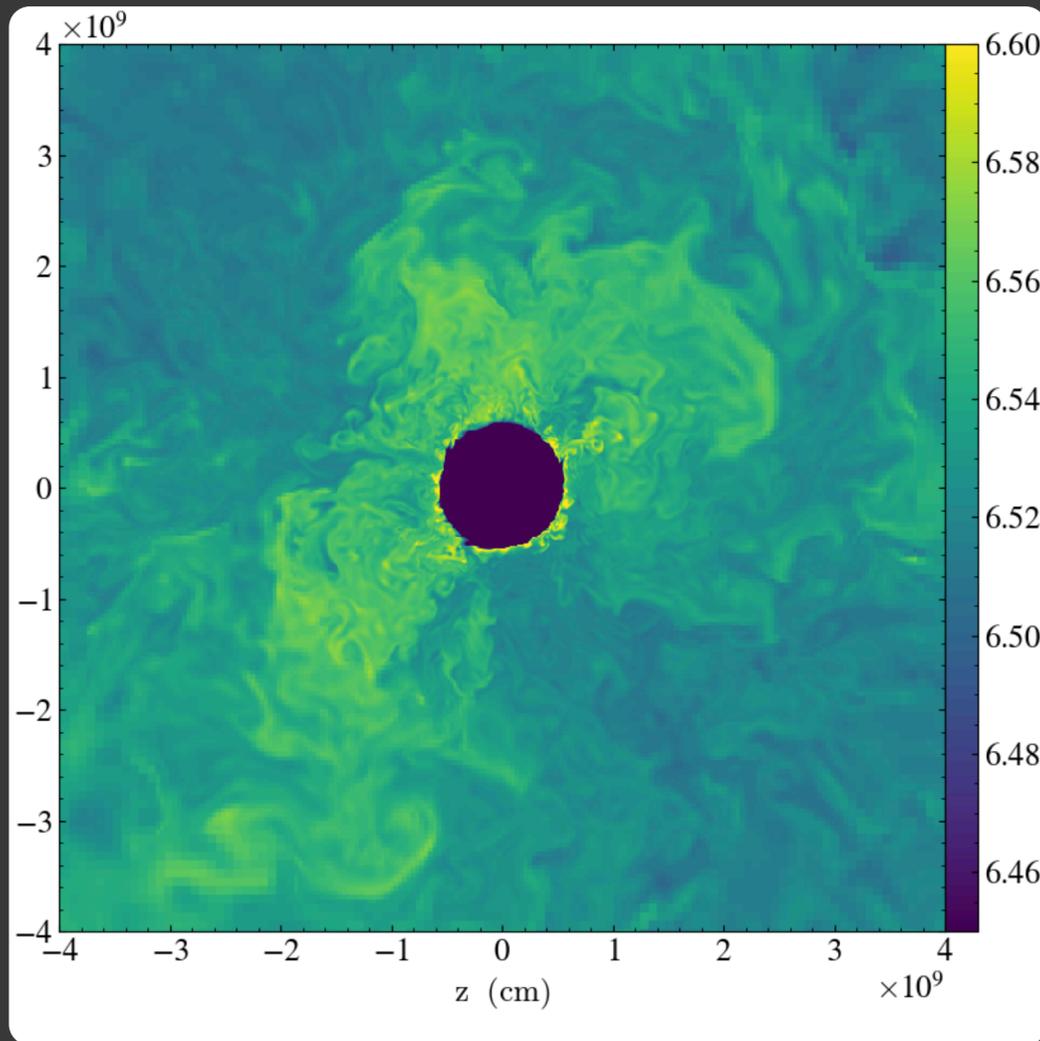
Nuclear Networks



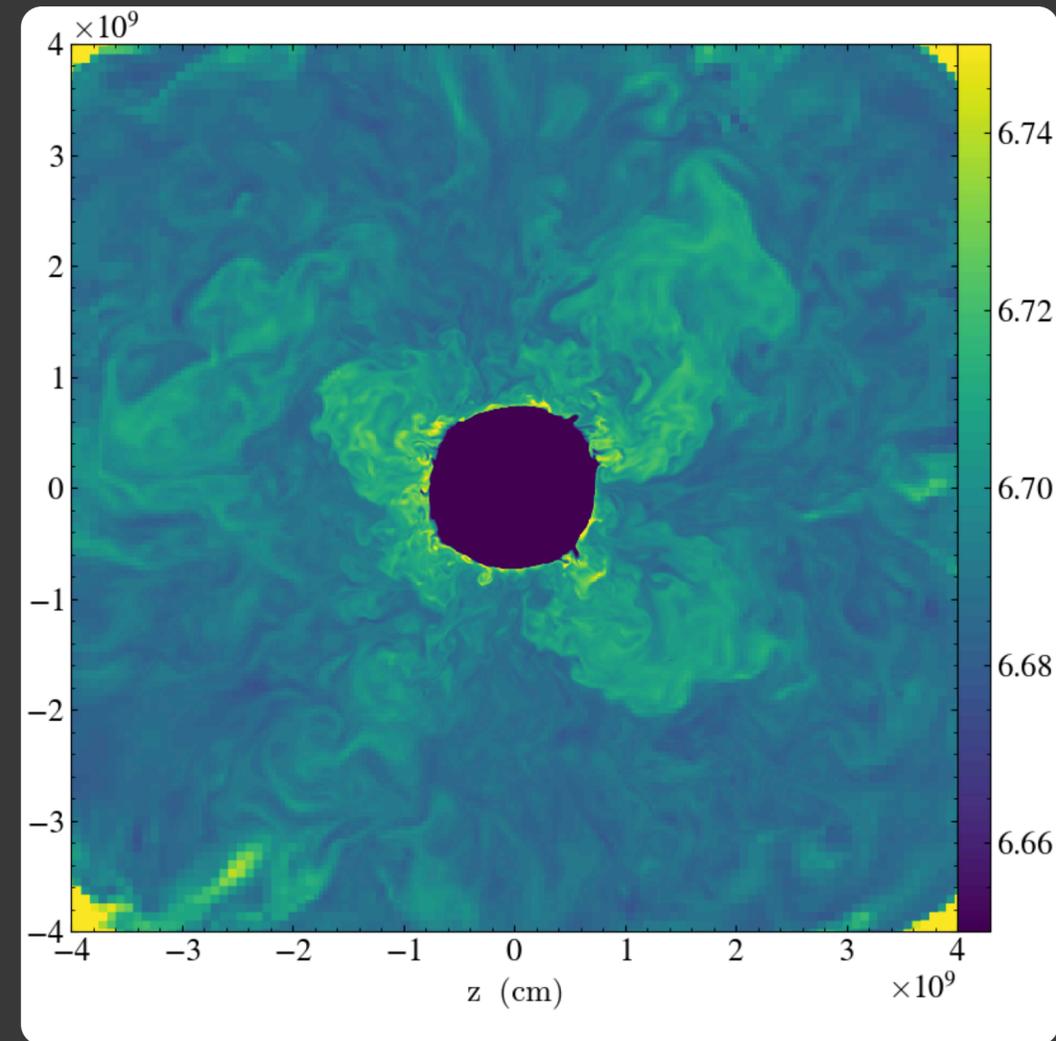
1. Weak reactions
2. Silicon burning
3. Core structure and mass(Grichener+25)



m24.5



m26.0



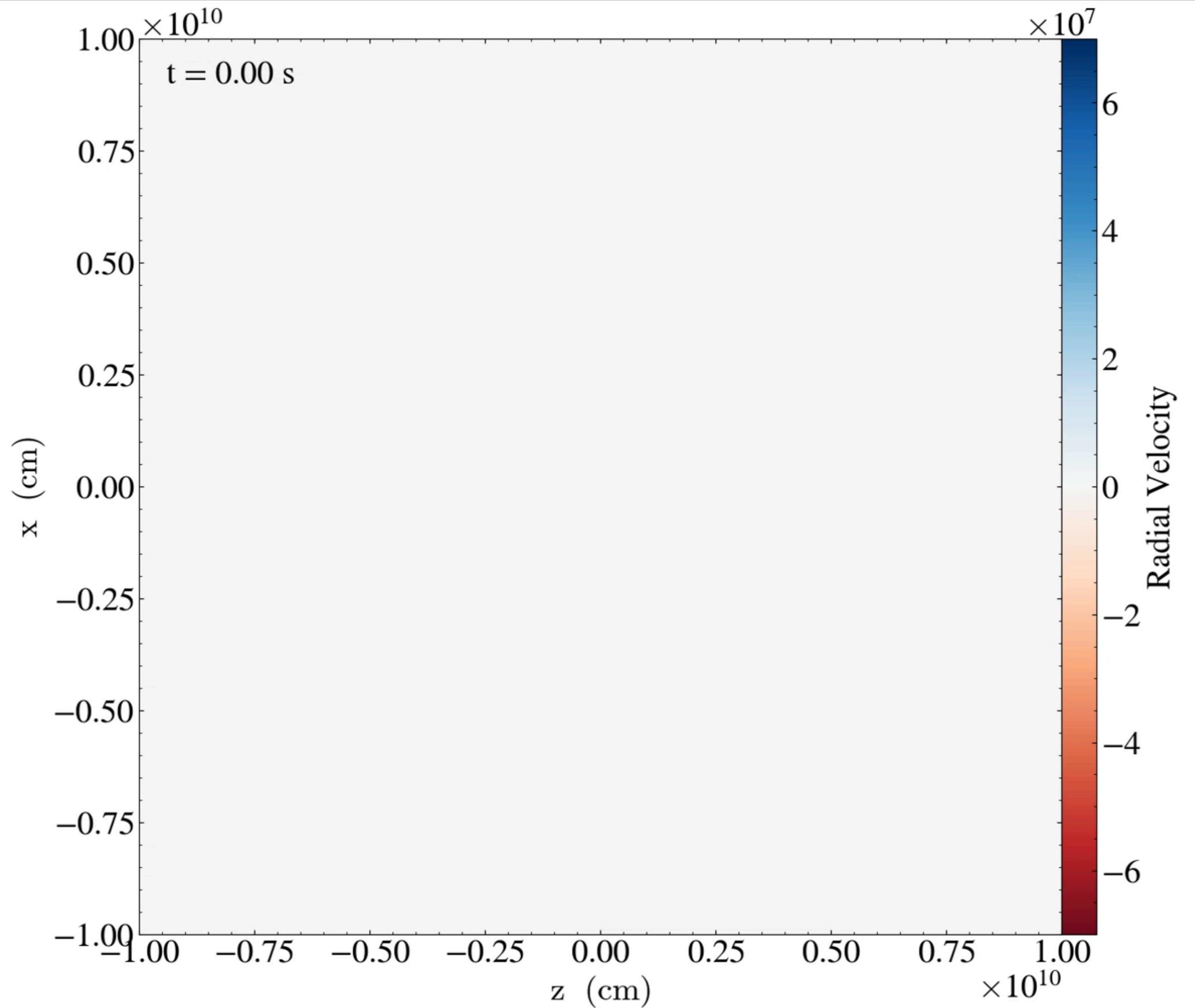
m29.0

Entropy

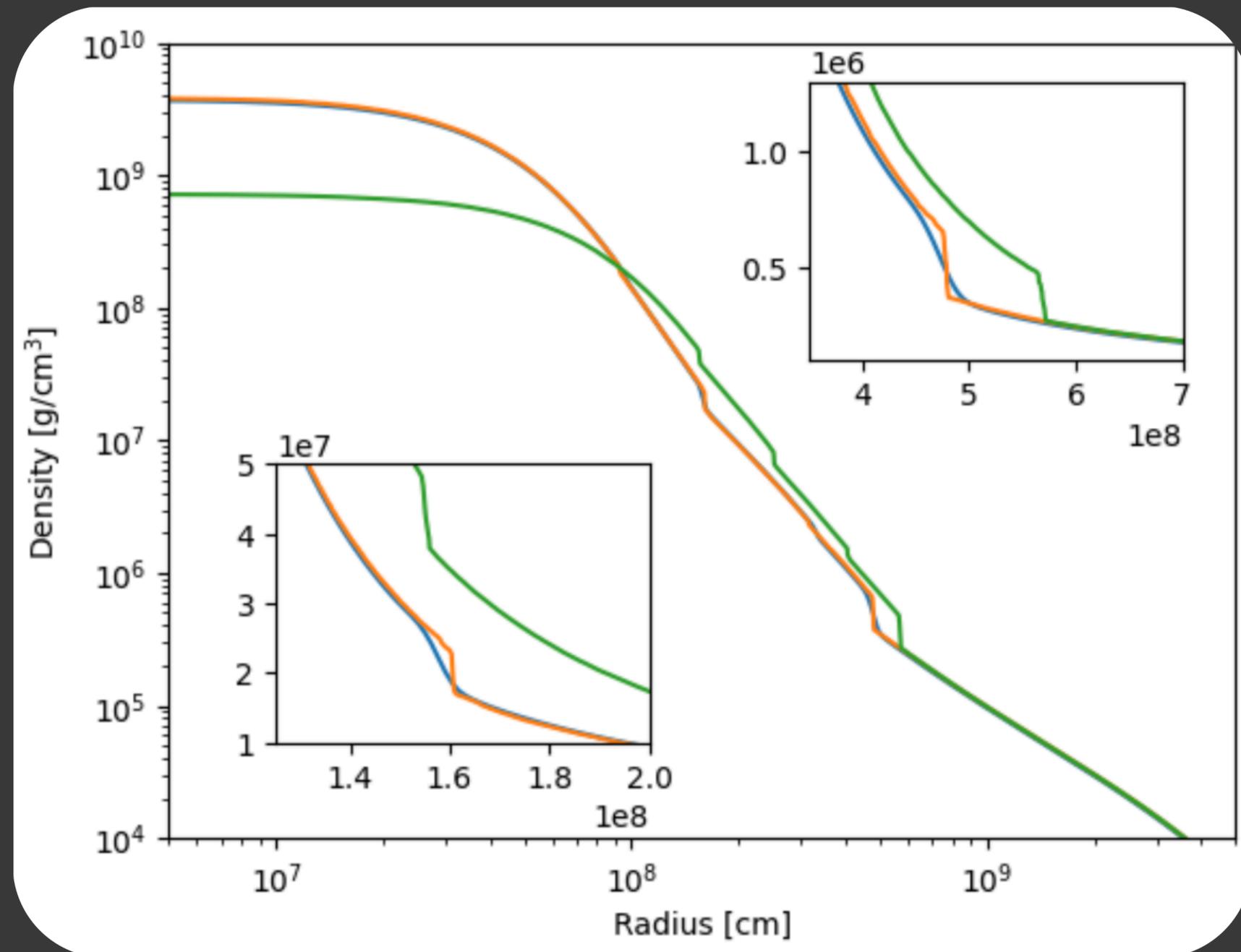
Slices in the xz plane of the simulations. Around 600 s into the simulation.

m24.5

- Time in after mapping
- Radial velocity
- xz plane



Similar Structure



The average structure of the progenitor is retained

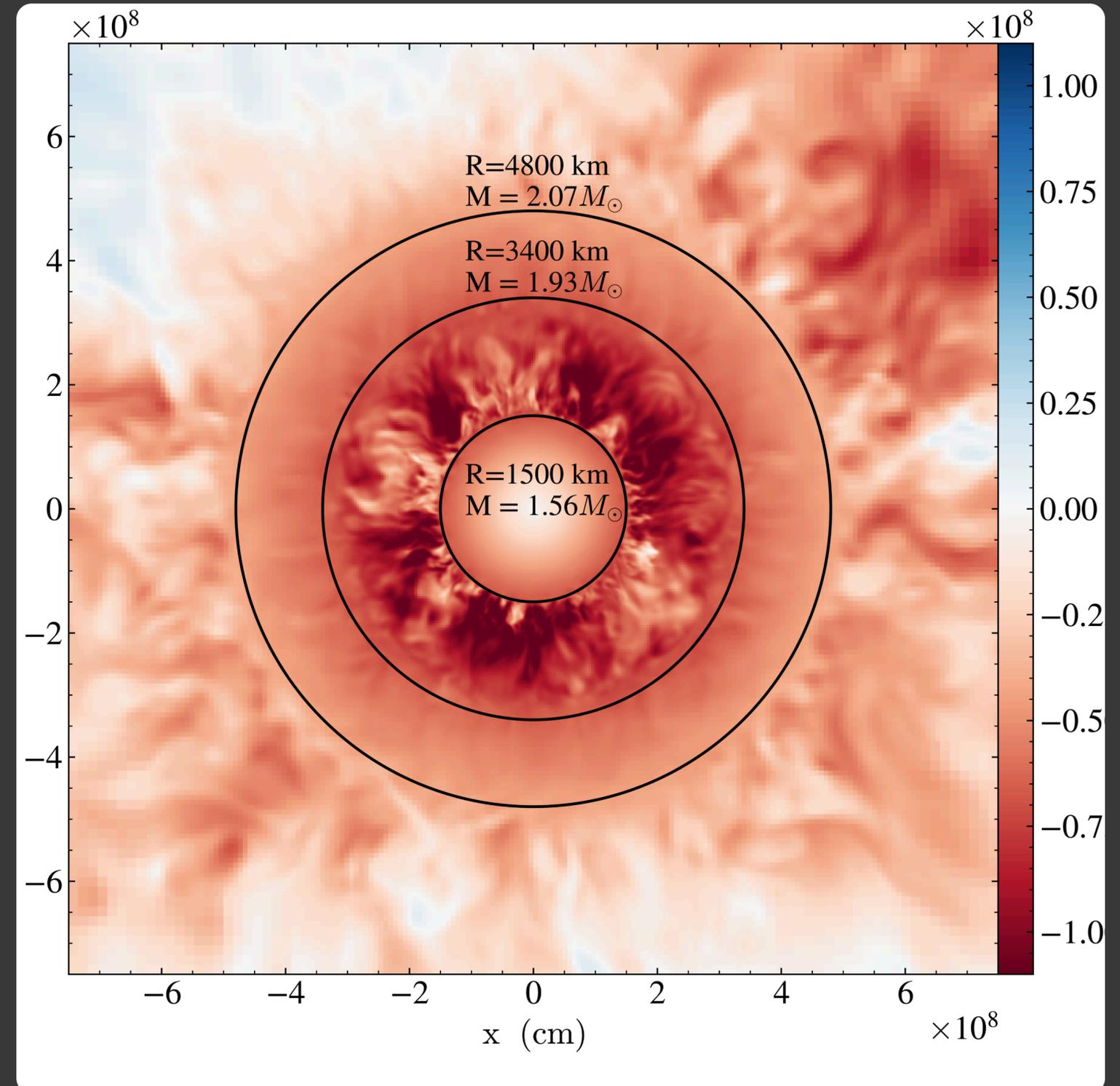
Green: Map from MESA
Blue: spherical average of last 3D snapshot
Orange: MESA at same central density

Core Collapse

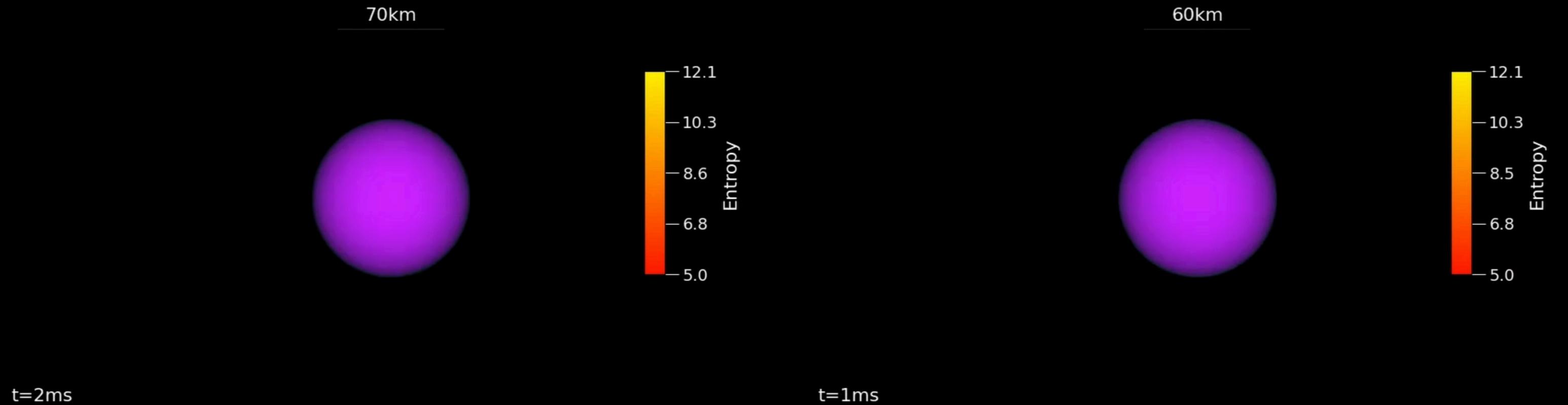
- Two simulations of the 24.5 solar mass progenitor
- Full 3D
- Neutrino transport

Core Collapse

- Two simulations of the 24.5 solar mass progenitor.
 - Full 3D
 - Neutrino transport
-
- Track when the active layers fall through the shock
 - Convective Si layer: ~ 60 ms

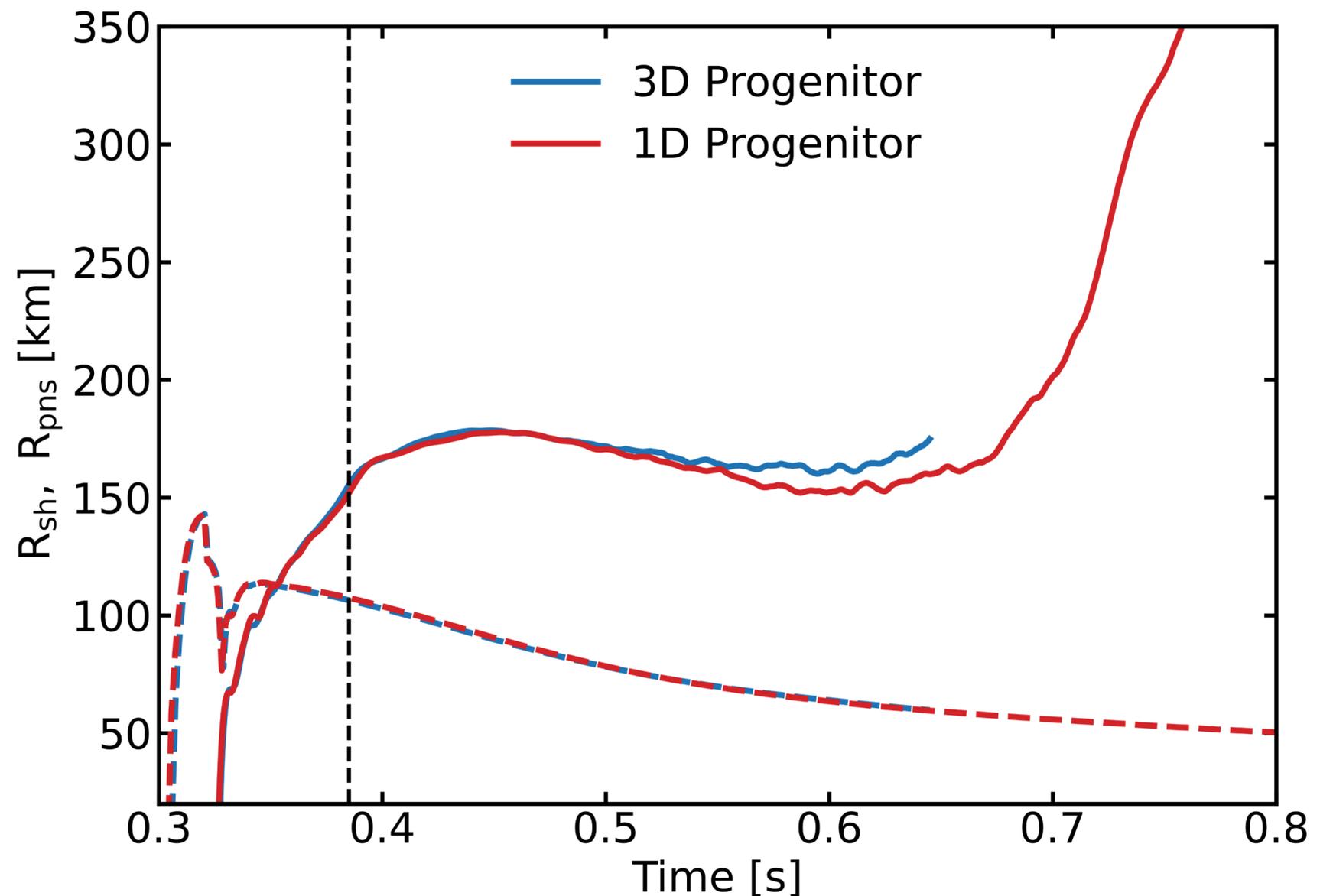


Core Collapse



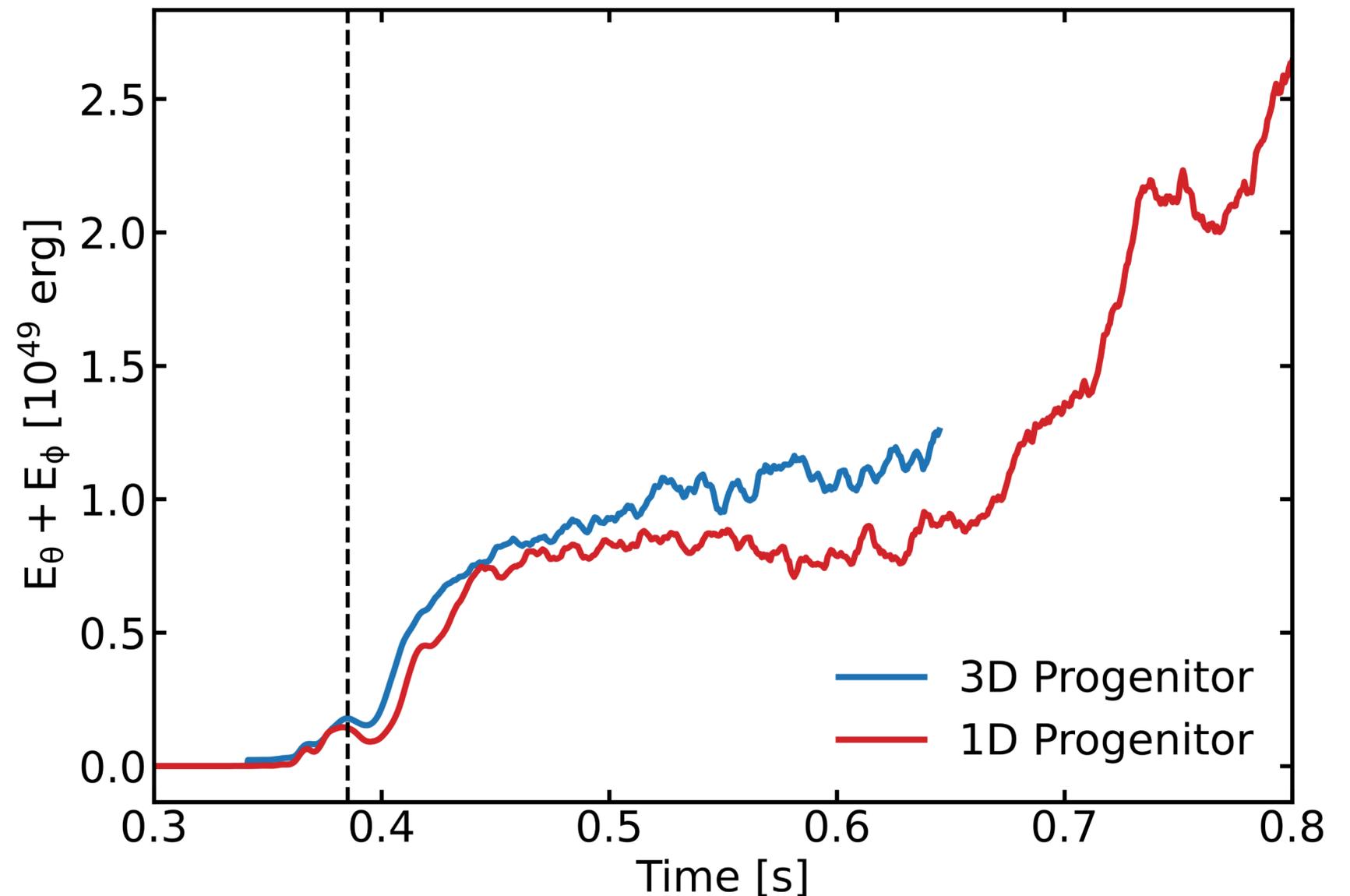
Core Collapse

- Small, but important difference in the shock radius

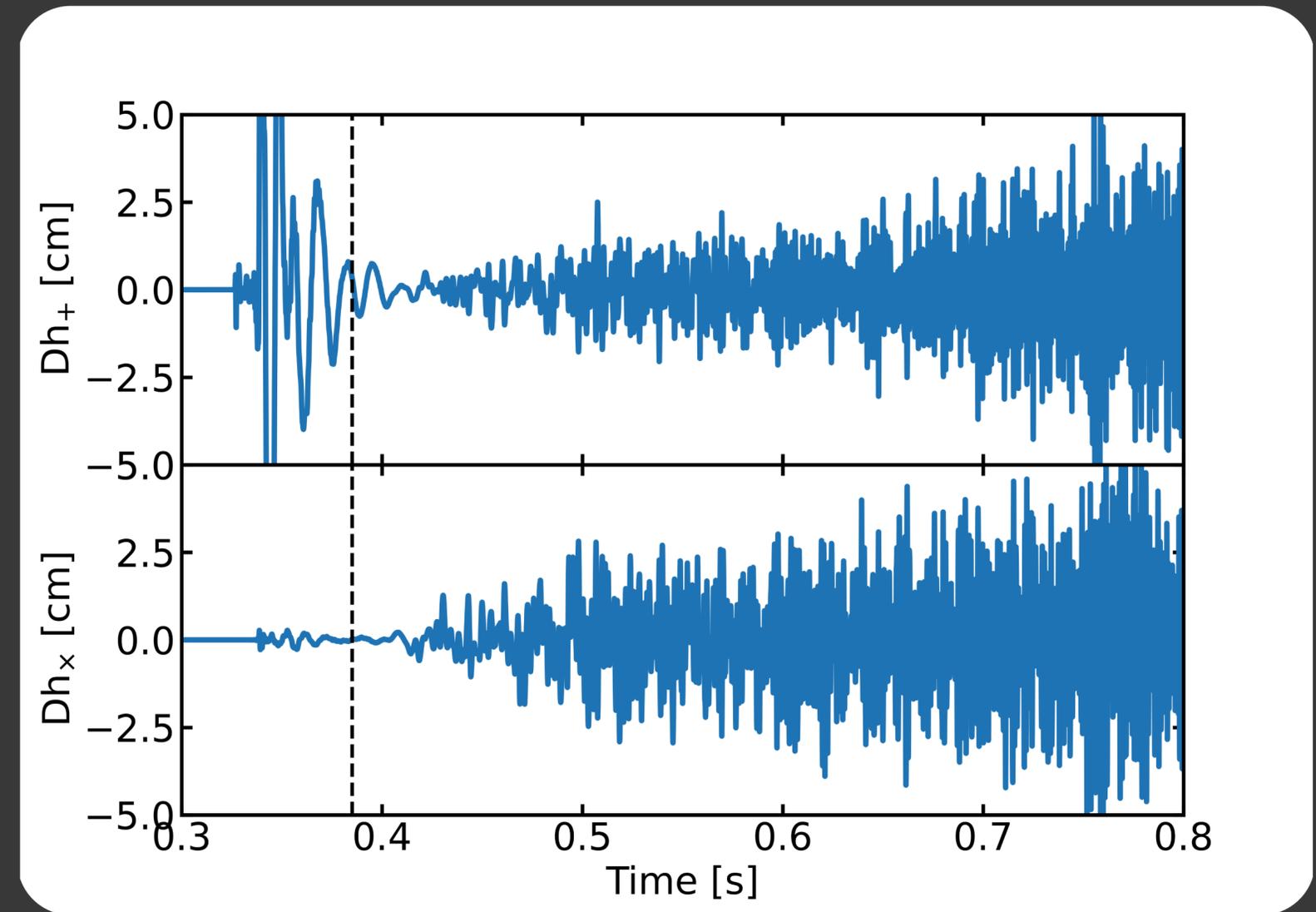
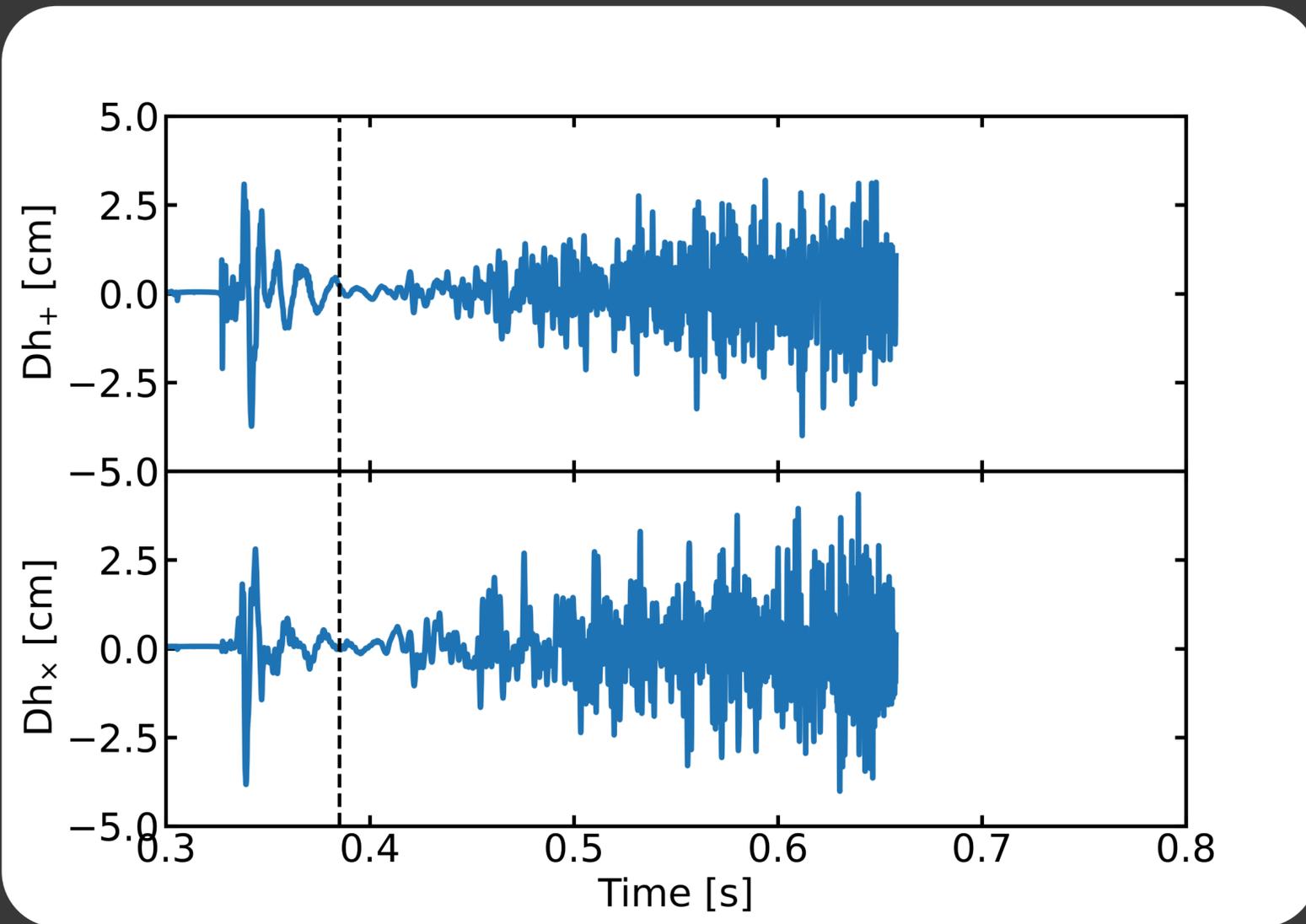


Core Collapse

- Small, but important difference in the shock radius

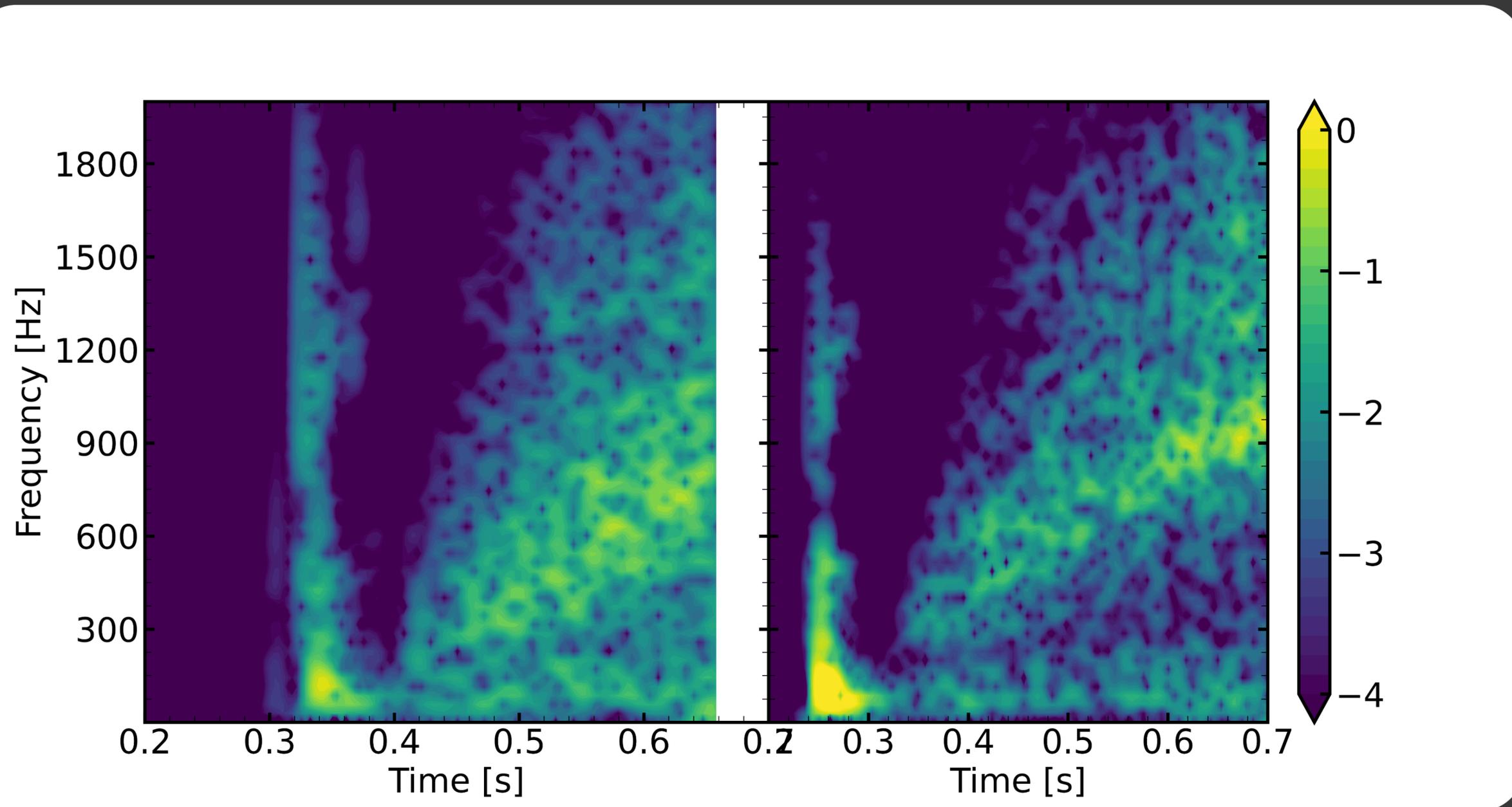


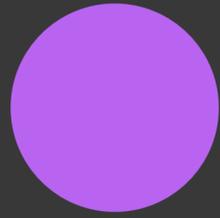
Core Collapse – GWs



For an observer along the z-axis of the simulation

Core Collapse – GWs

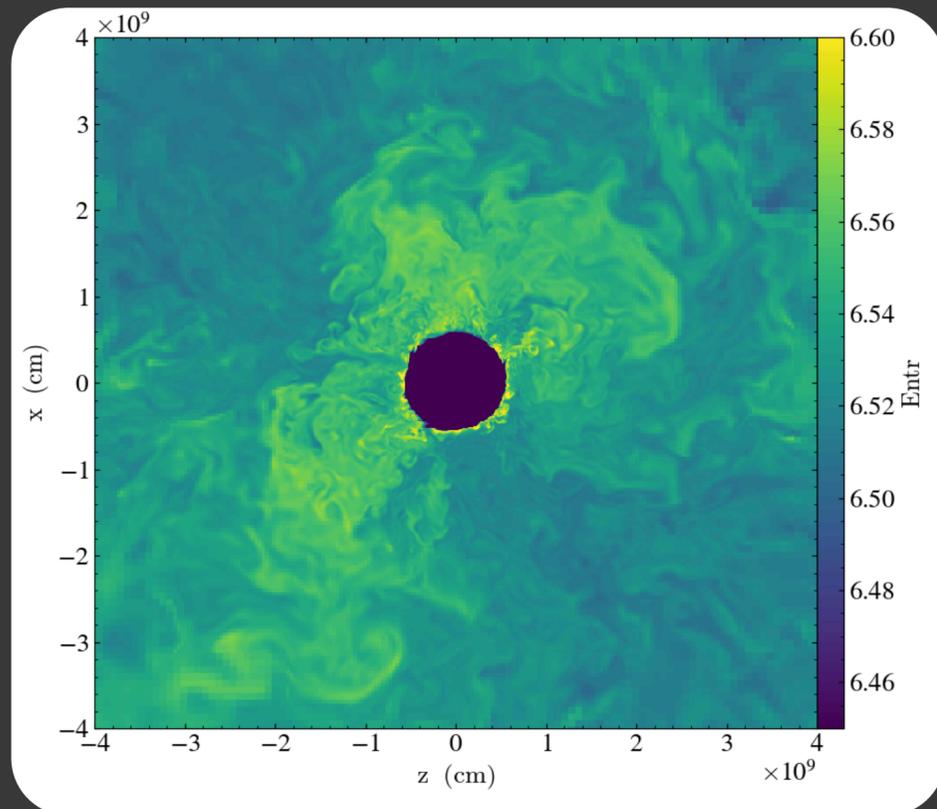




Summary

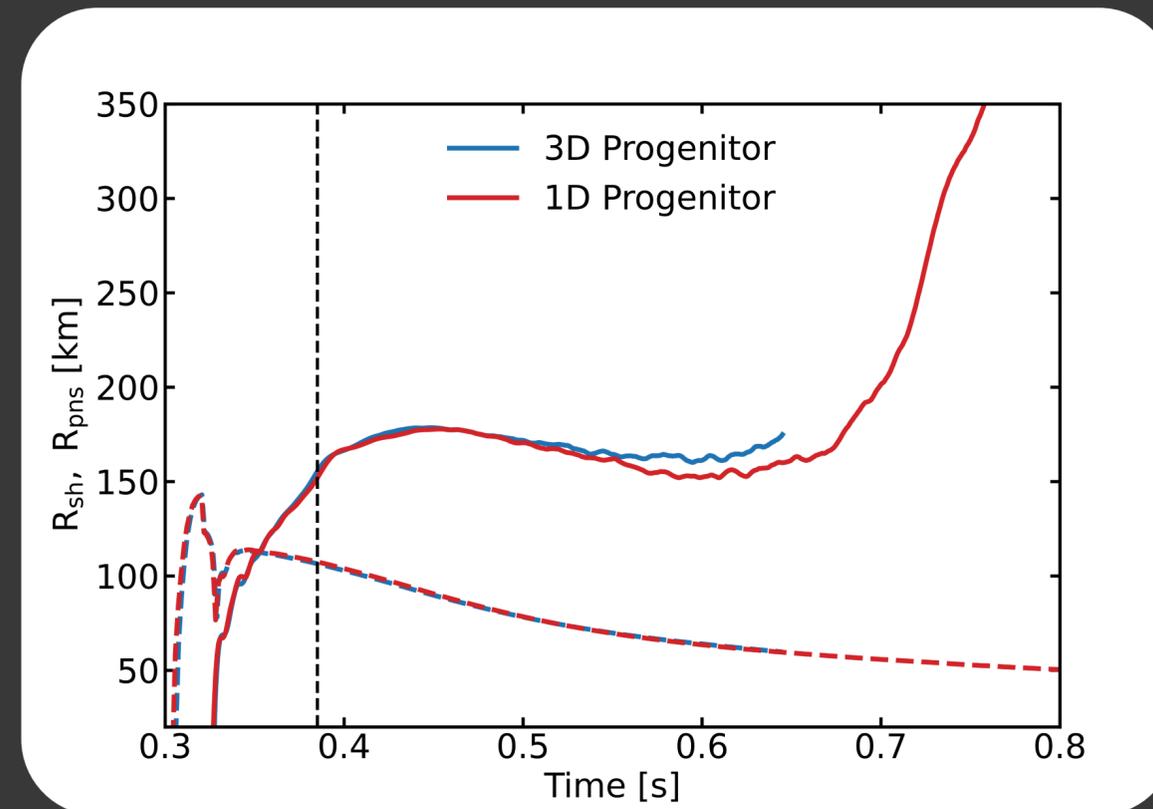
Stars

Large and small scale turbulence develops on several occasions during the life cycle of a star.



Core Collapse

Turbulence and asymmetries in the progenitor influences the explosion.



Observables

Impacts observable signals like the gravitational waves.

