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Predicting Gravitational Waves: from before collapse to after explosion

Part 1

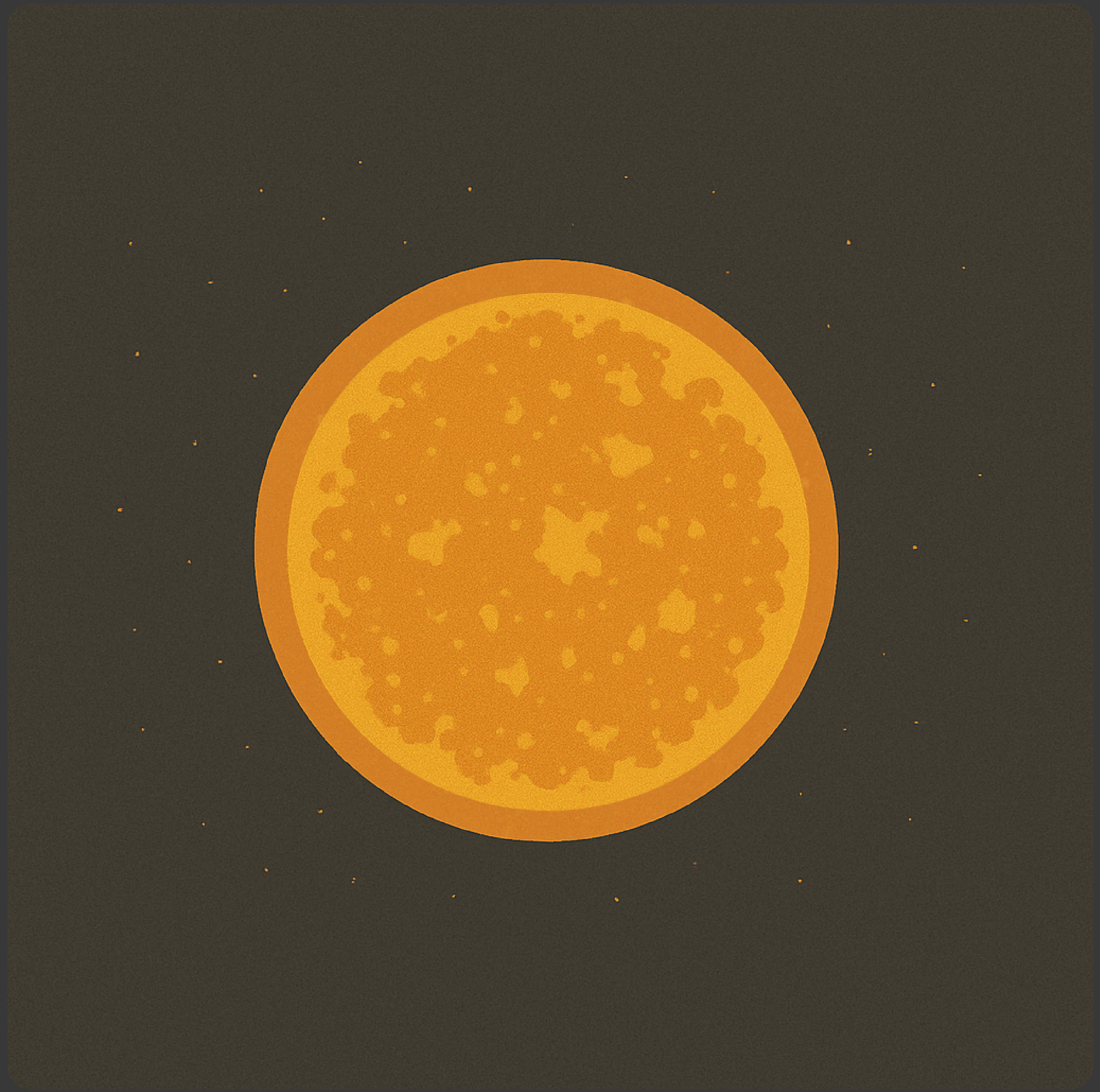
Stellar Evolution

Shell burning

Part 2

Late-time Gravitational Waves

Low-frequency emission

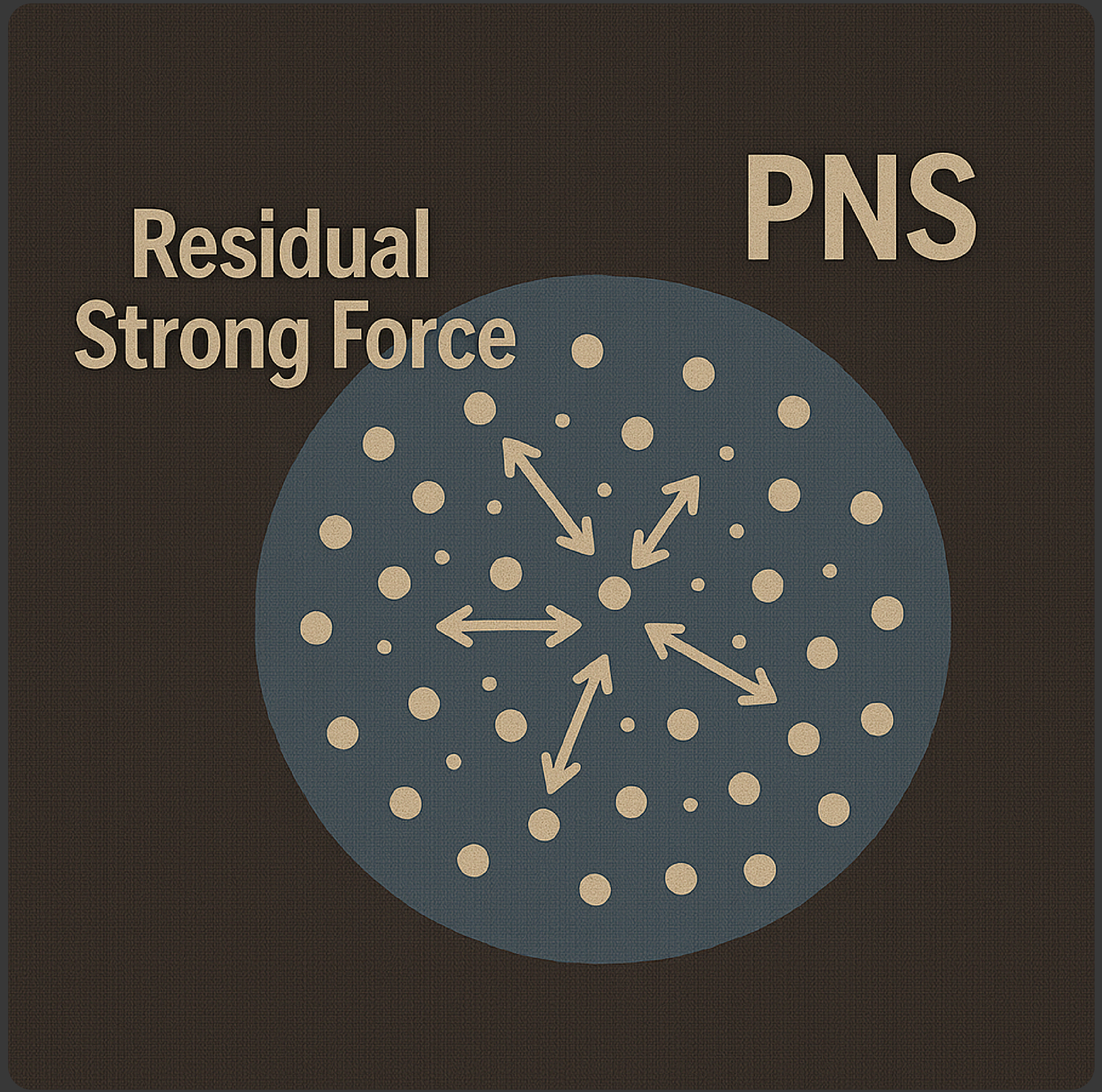


Massive Stars

About 10 times more massive than the sun.

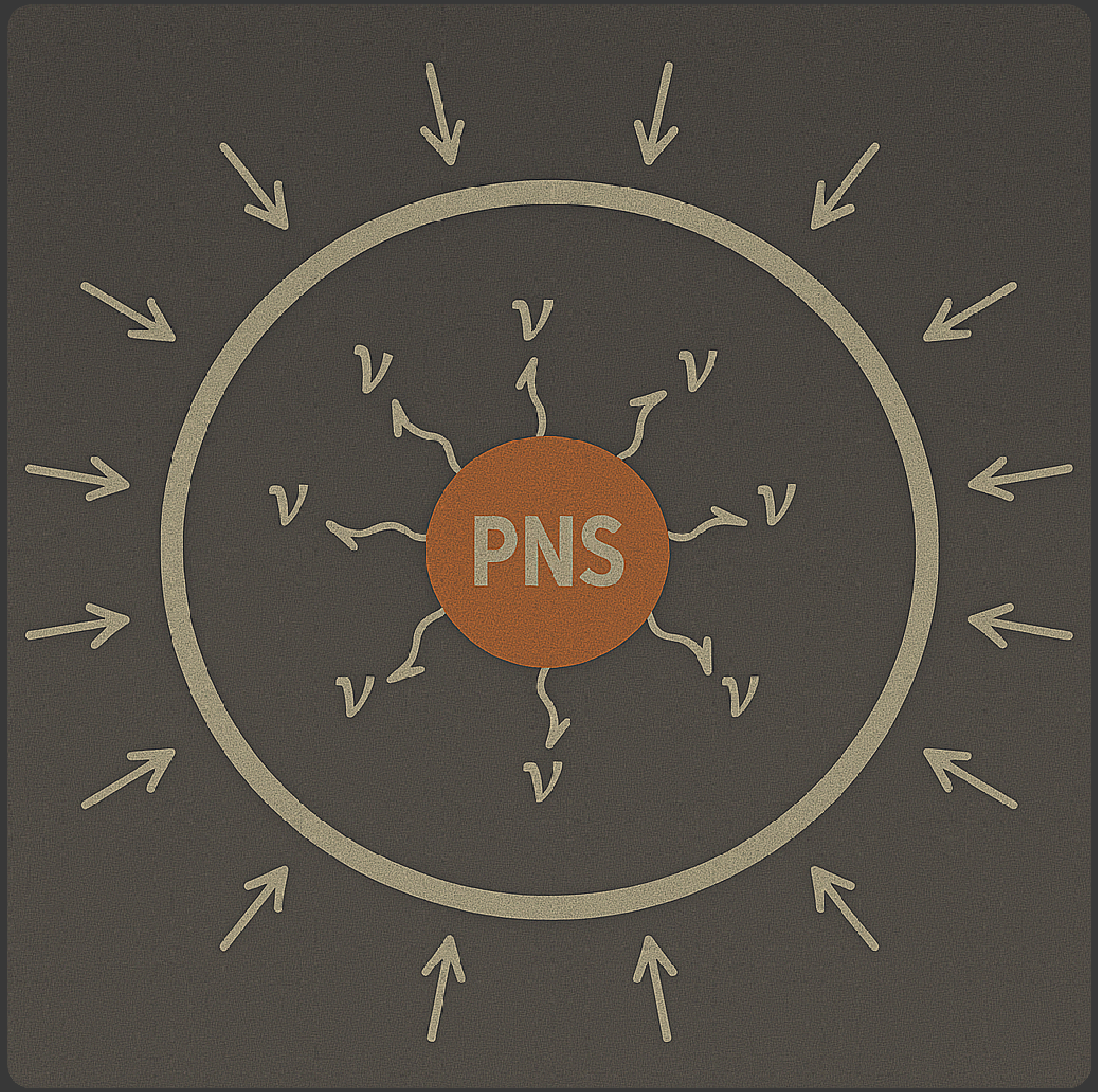
Shell Burning

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



Core Collapse

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

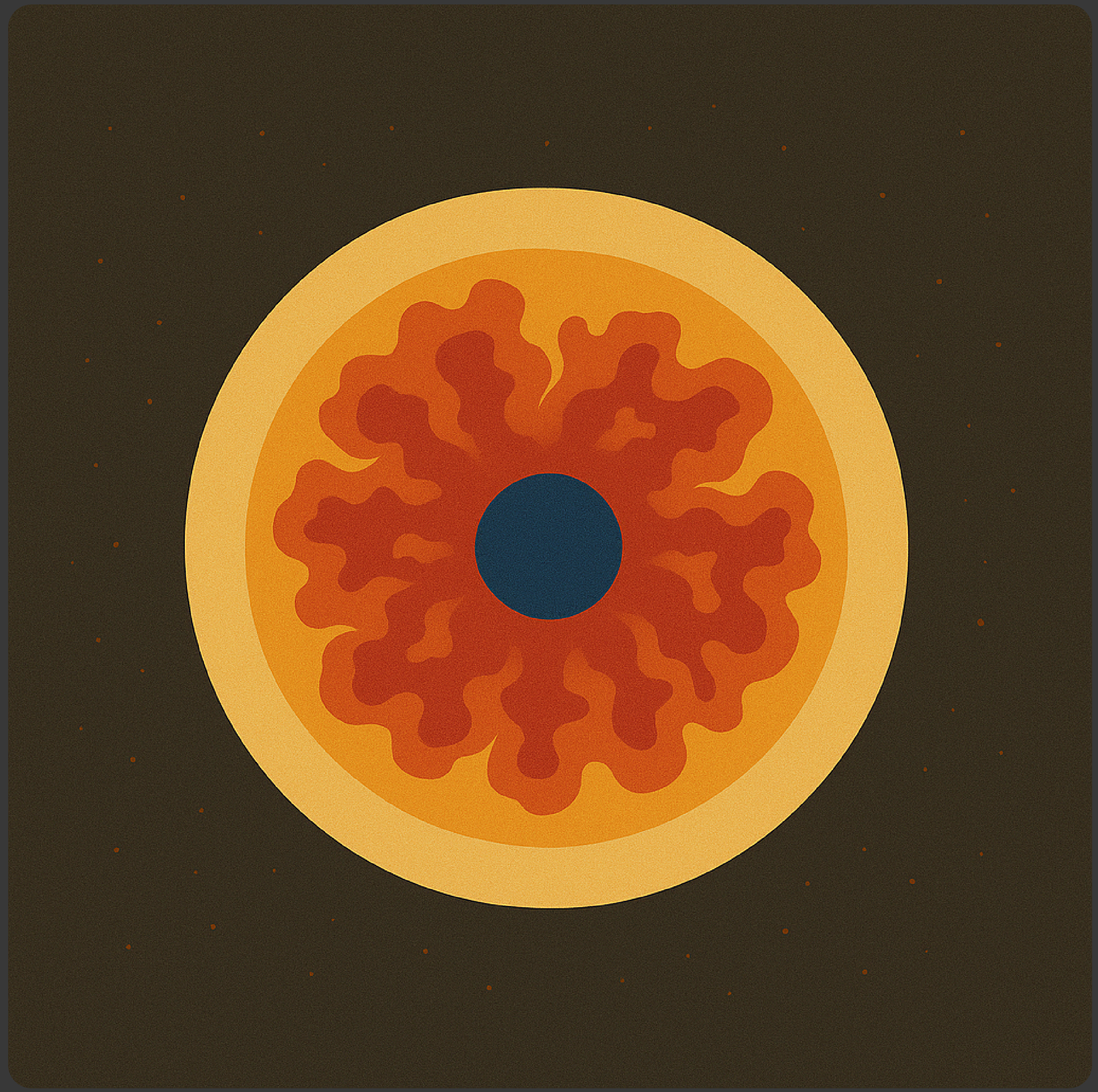


Proto-neutron star

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

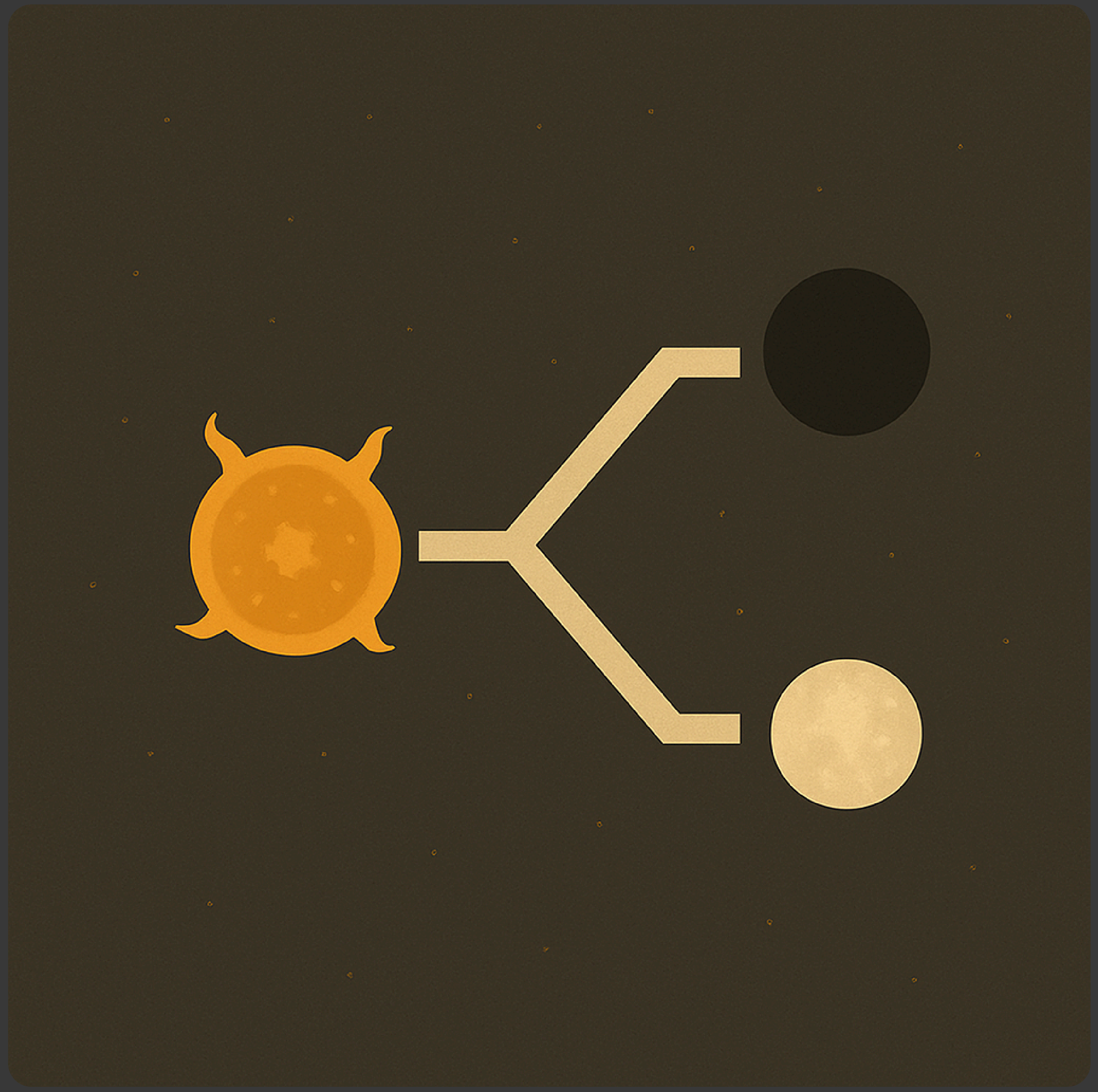
After a fraction of a second, the shock is revived. The shock then propagates through the star and disrupts the progenitor.

Which Stars?

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

Progenitor

This picture is clearly wrong and 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.

Stellar Evolution

Initial data

MESA

Using approx 21
Until 700-650 seconds before bounce.

Simulation

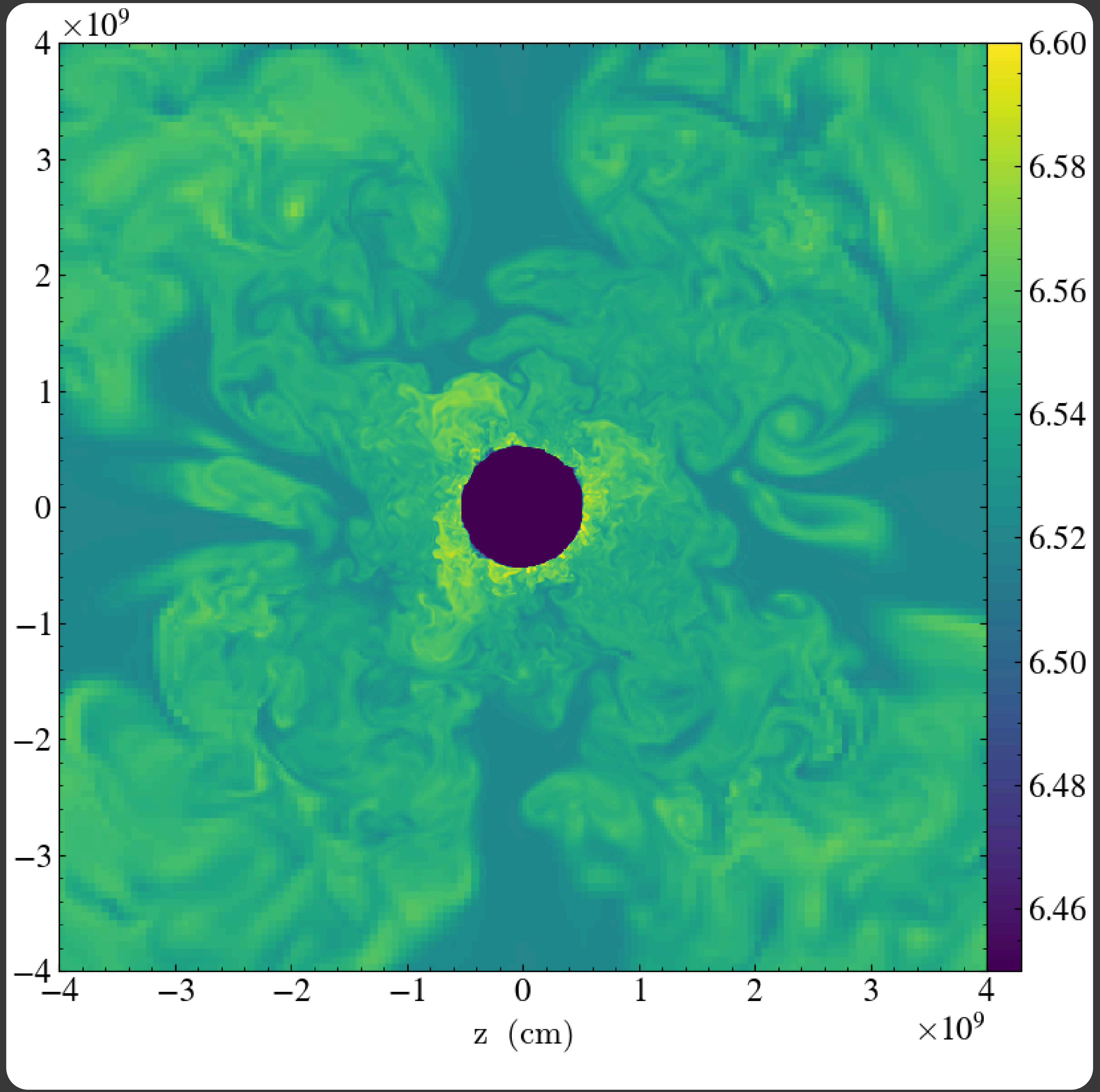
FLASH (Fields+20)

Approx 21
AMR, finest resolution ~ 19 km

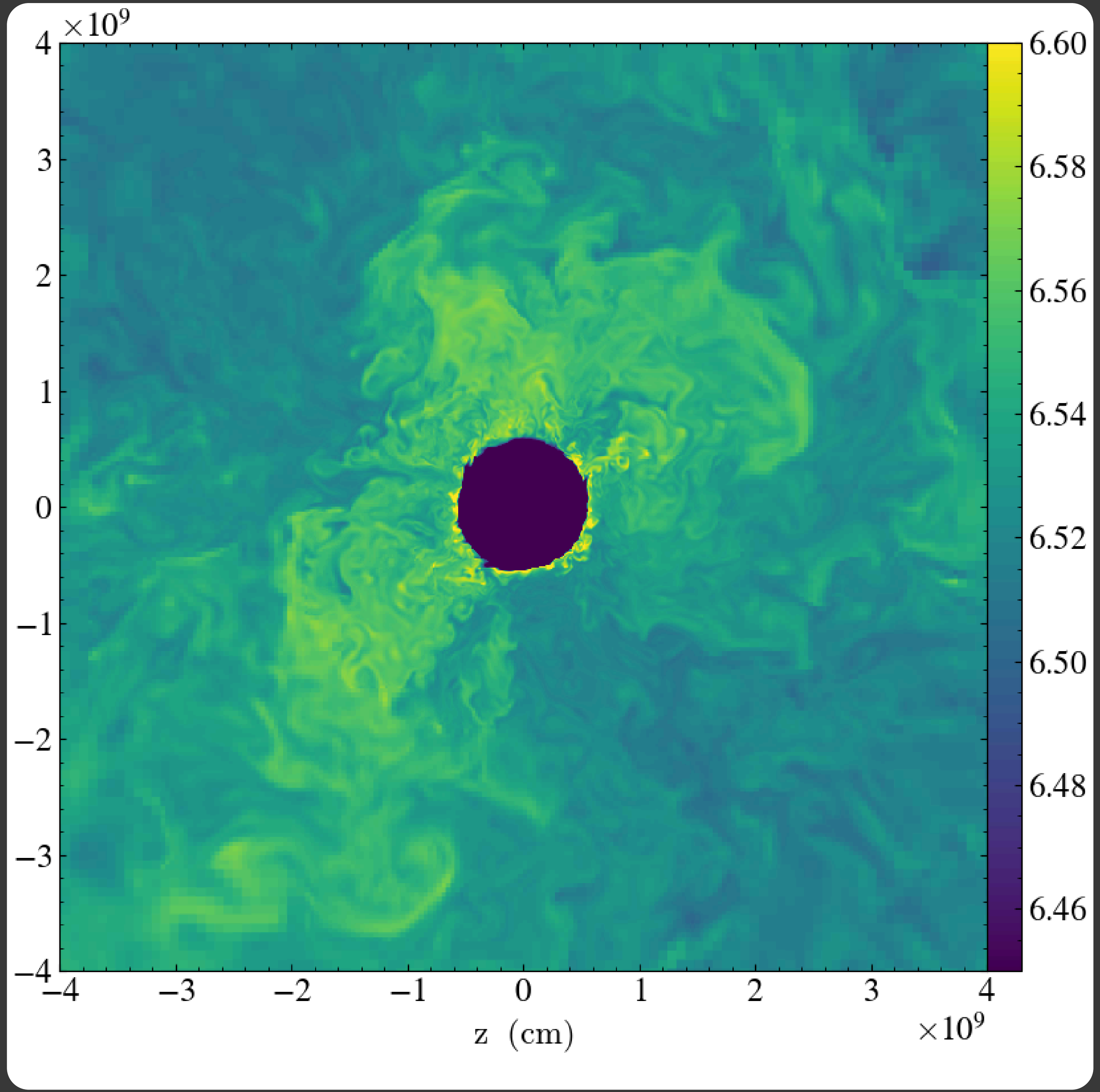
Potential Issues

Nuclear burning

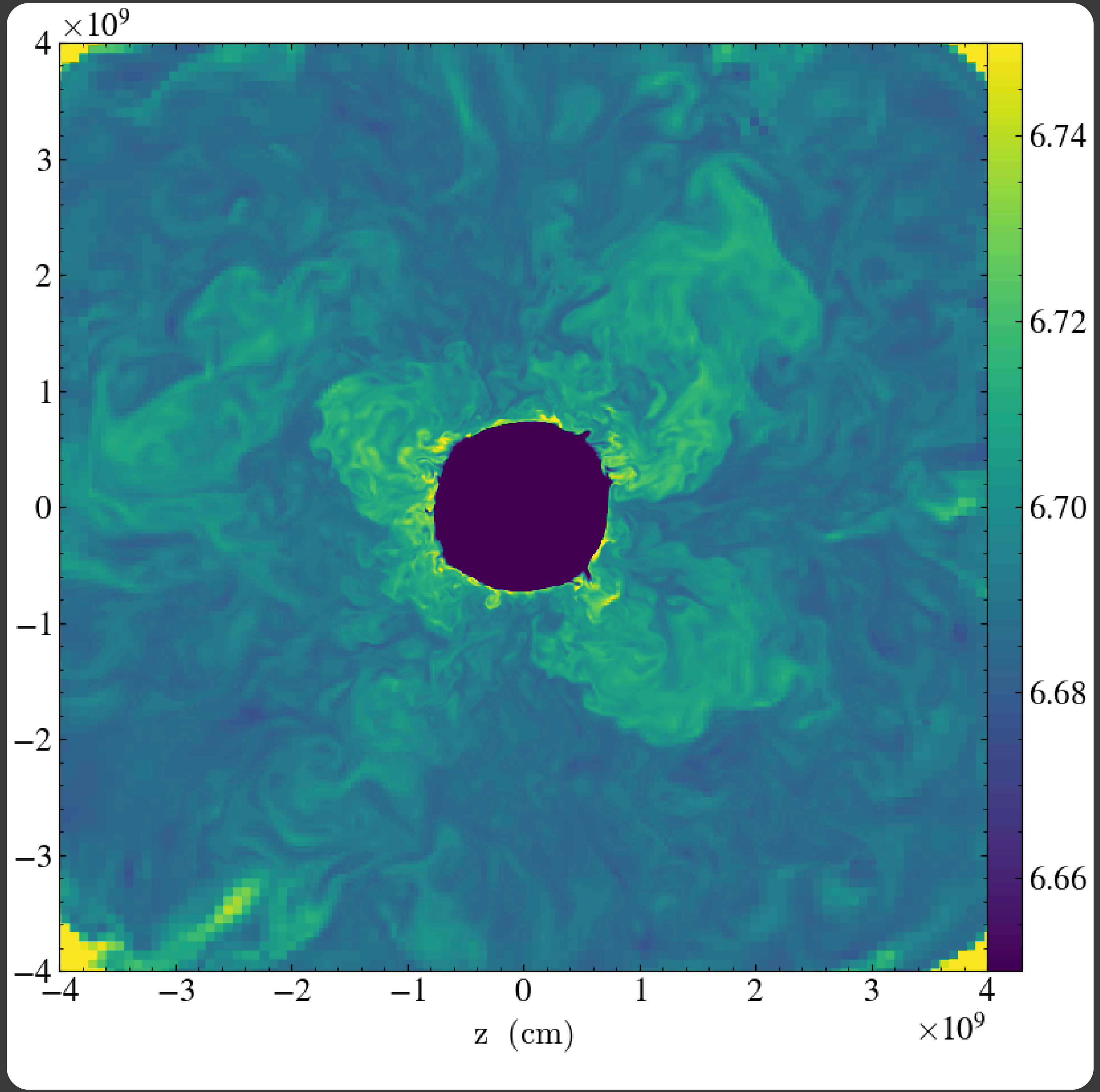
Si rates
Flash-X follow up



m24.5



m26.0

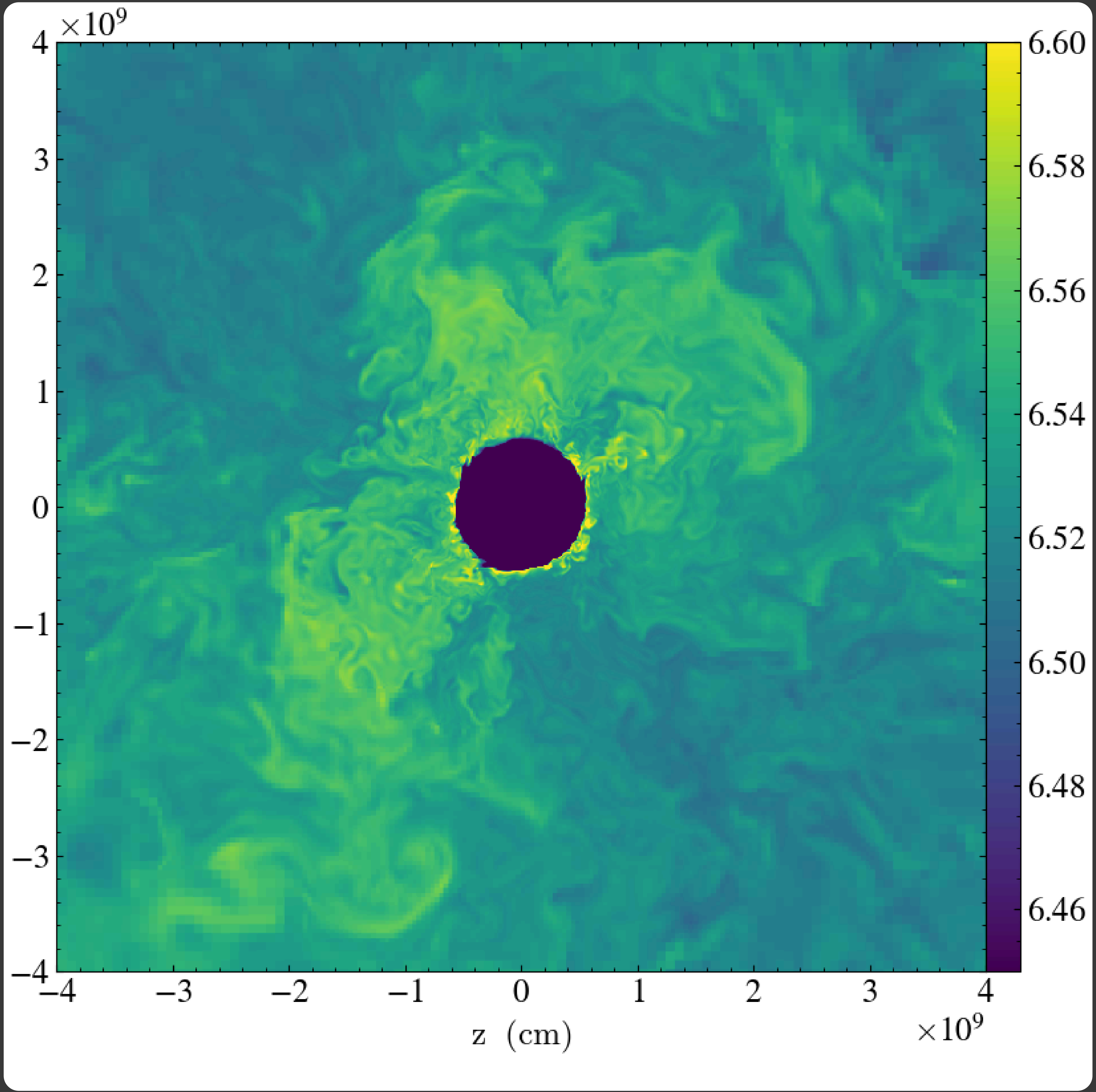


m29.0

Entropy

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

- Seed asymmetries
- 5-15 runs
- Comparison simulations in 3D
- Natural next step (Bollig+21)
- Late time gravitational wave emission

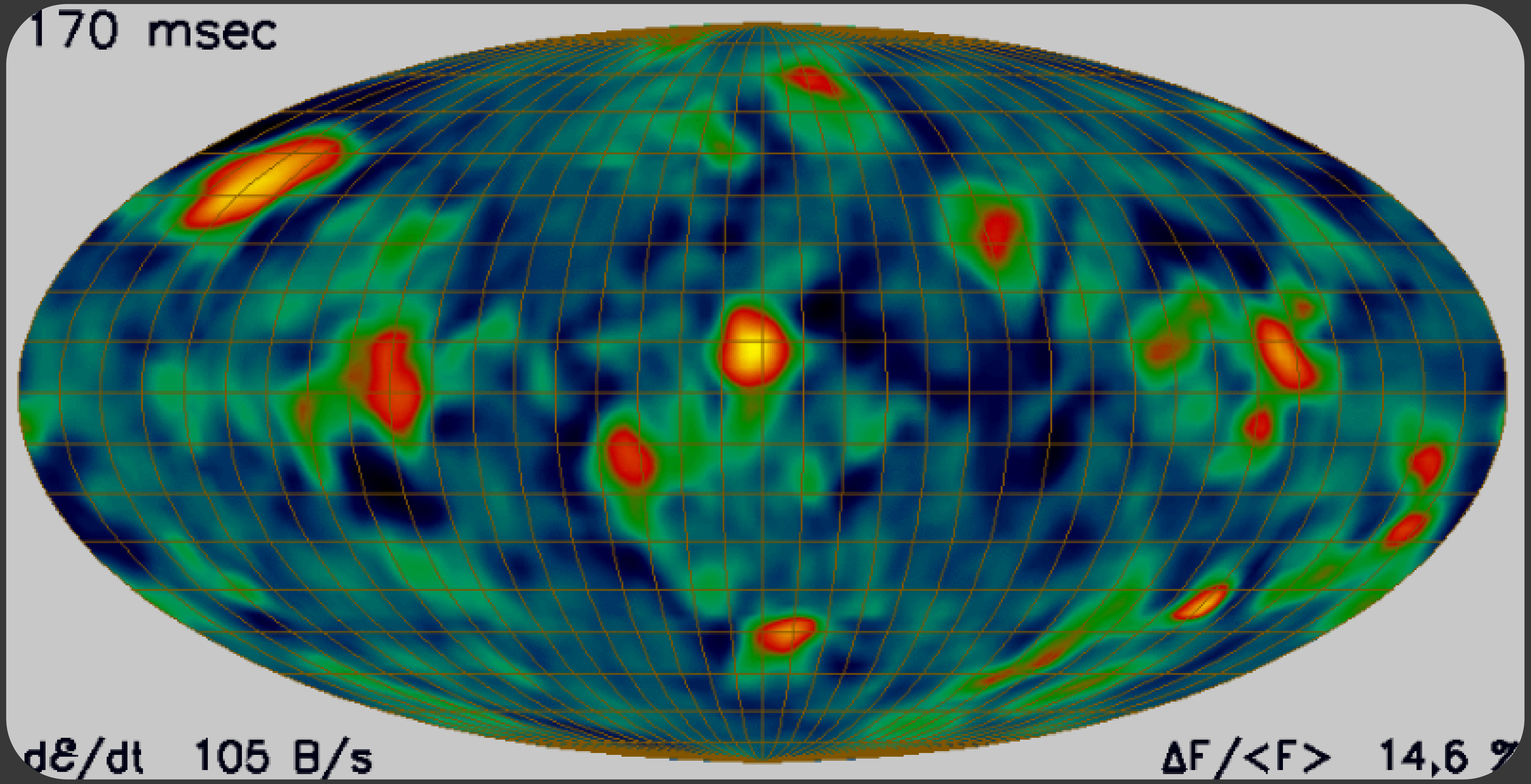


m26.0

Part 2

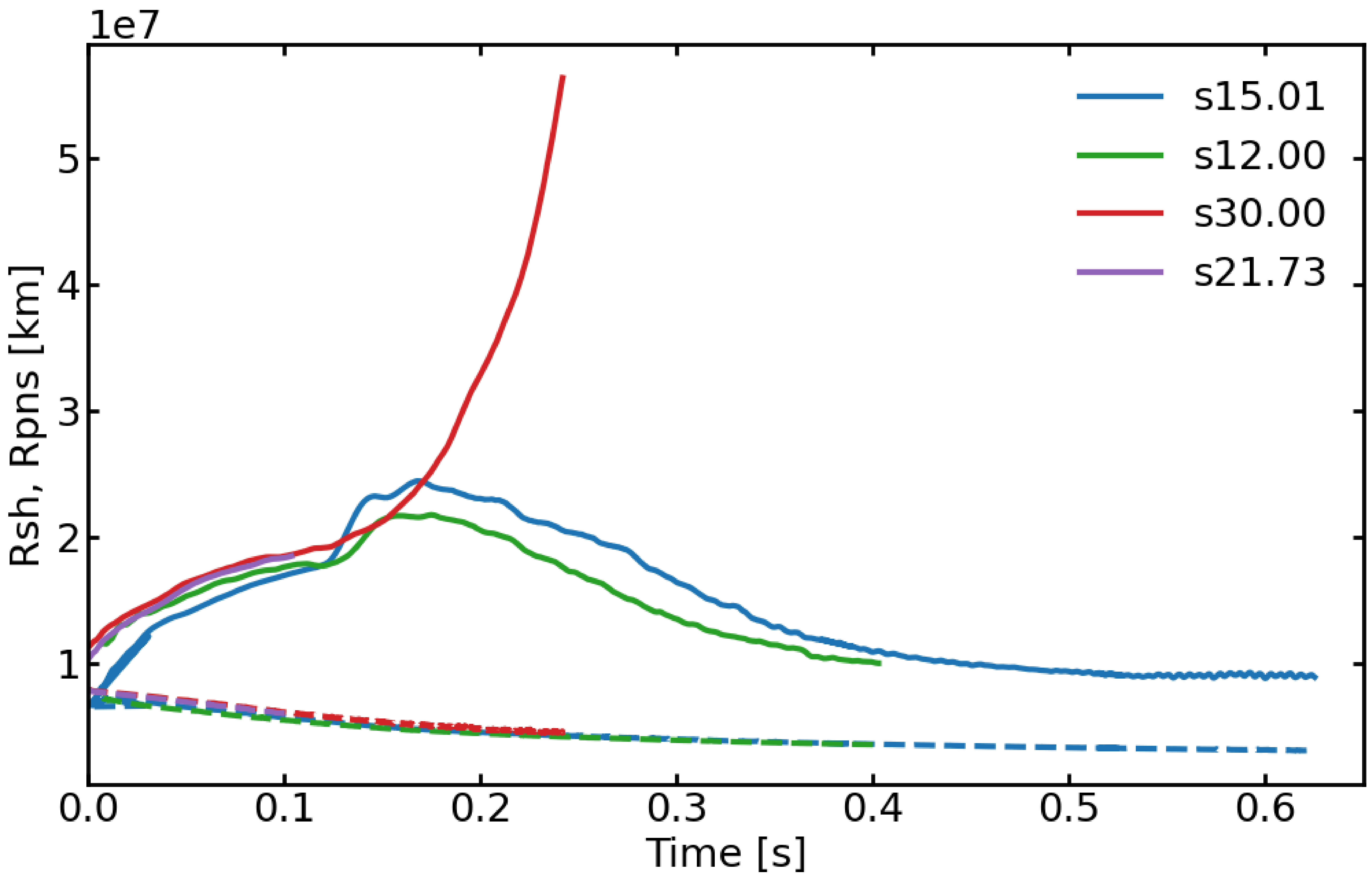
Late time gravitational wave emission

- Neutrino emission
- Shock propagation



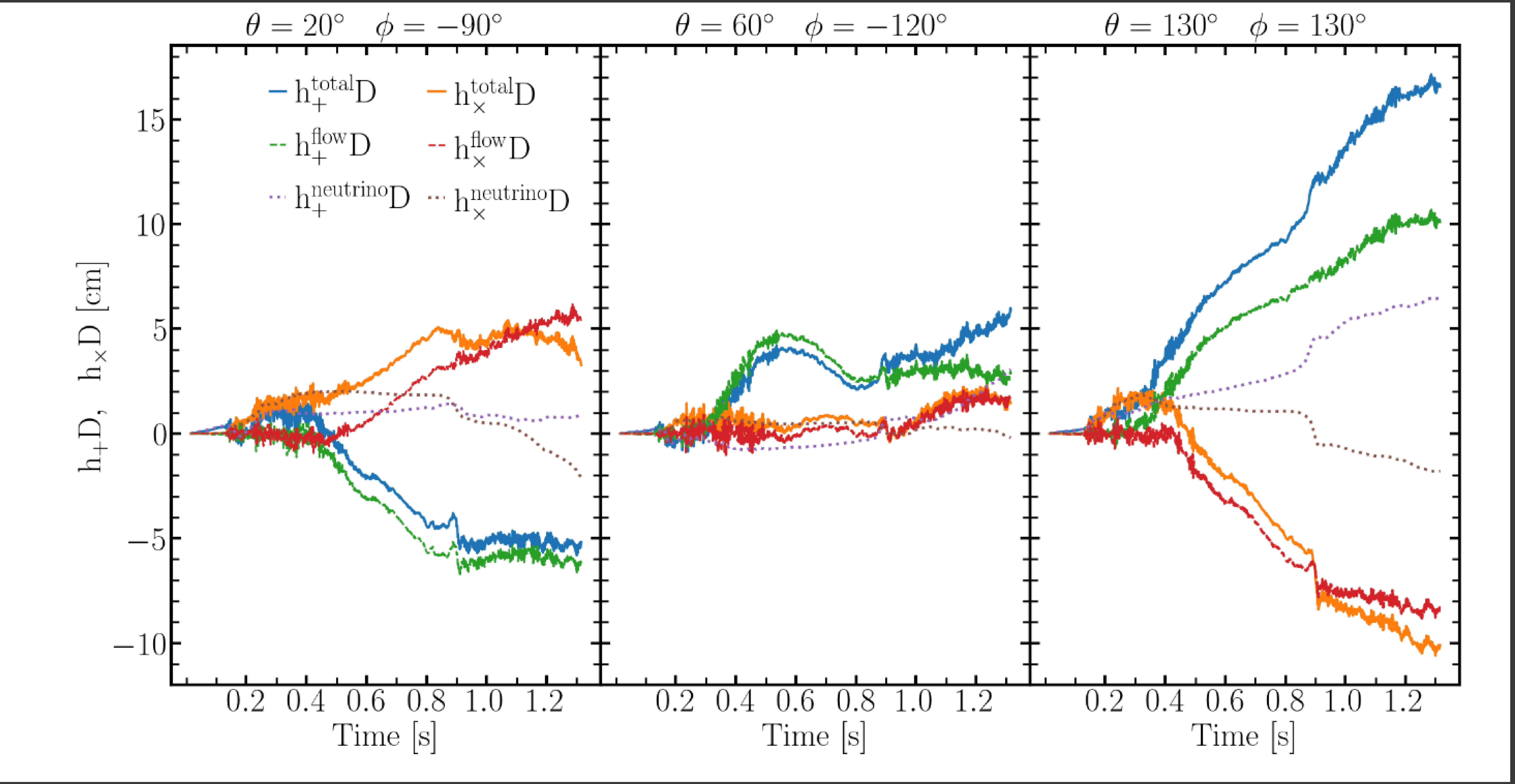
Long Simulations

- Perform five 3D simulations
- 1.5 - 2 seconds
- Late time emission



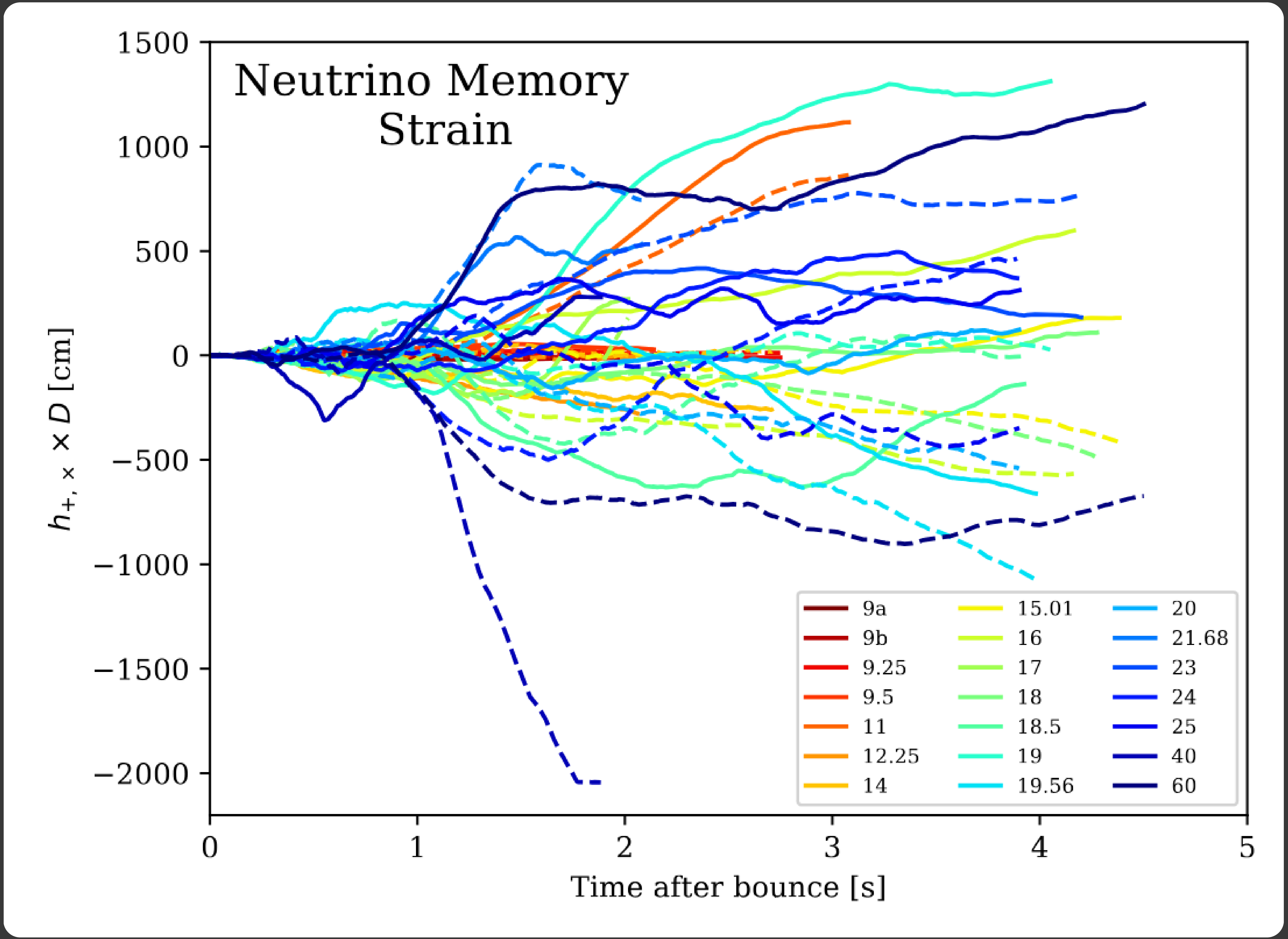
Motivation

Need for more predictions of the late-time emission



Choi et. al. 2024

- Rather large signals
- Extensive set of models
- Long duration simulations
- SNR of ~1000 at 10 Kpc



Choi+24

Simulation Setup

Initial data

1D profiles

Sukhbold models

Simulation

FLASH

Grey neutrino transport
AMR, finest resolution ~ 350 m

s15.01

Compare to Fornax

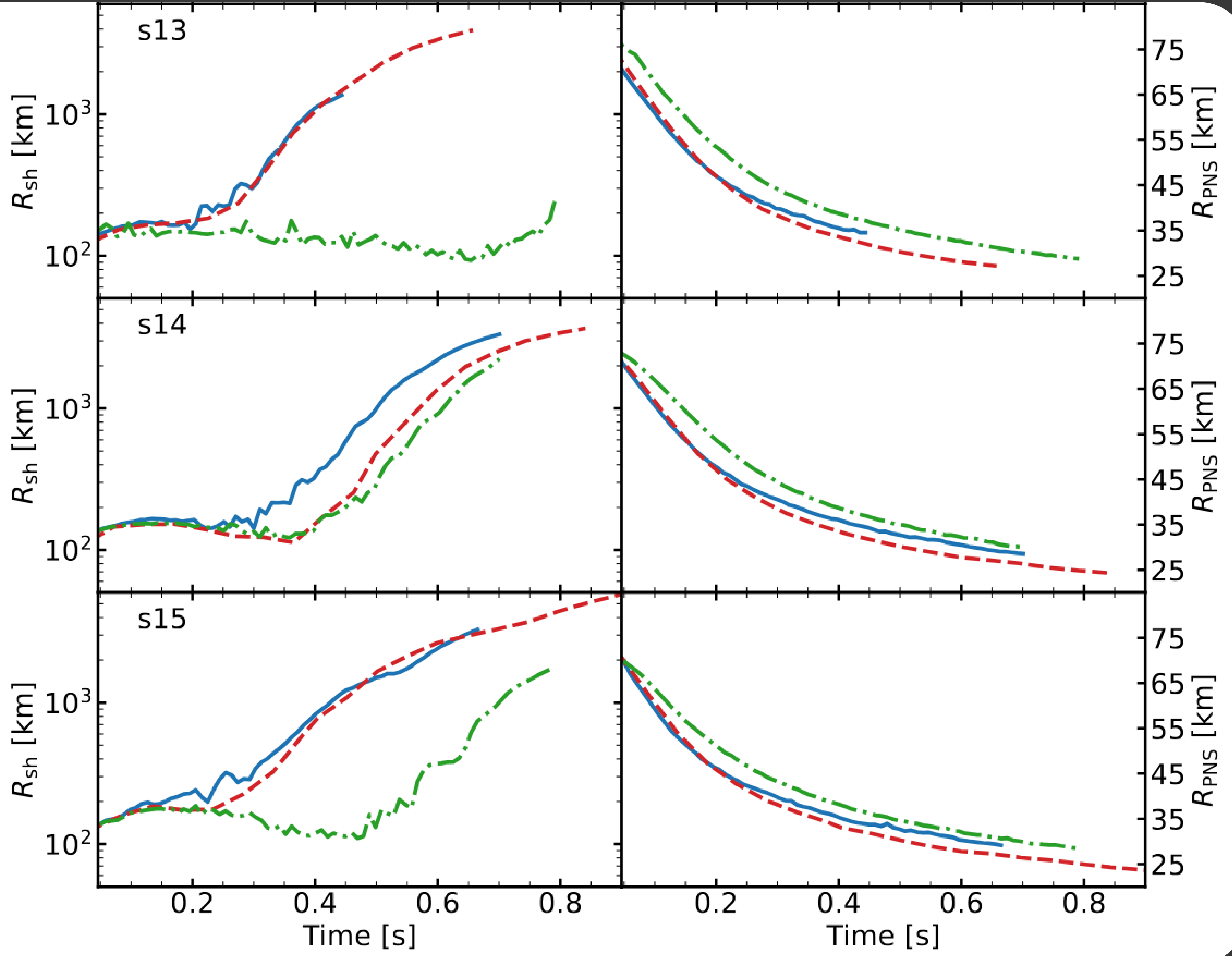
One model from the Fornax simulation set, s15.01.

Grey transport

Overall agreement with our energy-dependent transport, but some quantitative differences.

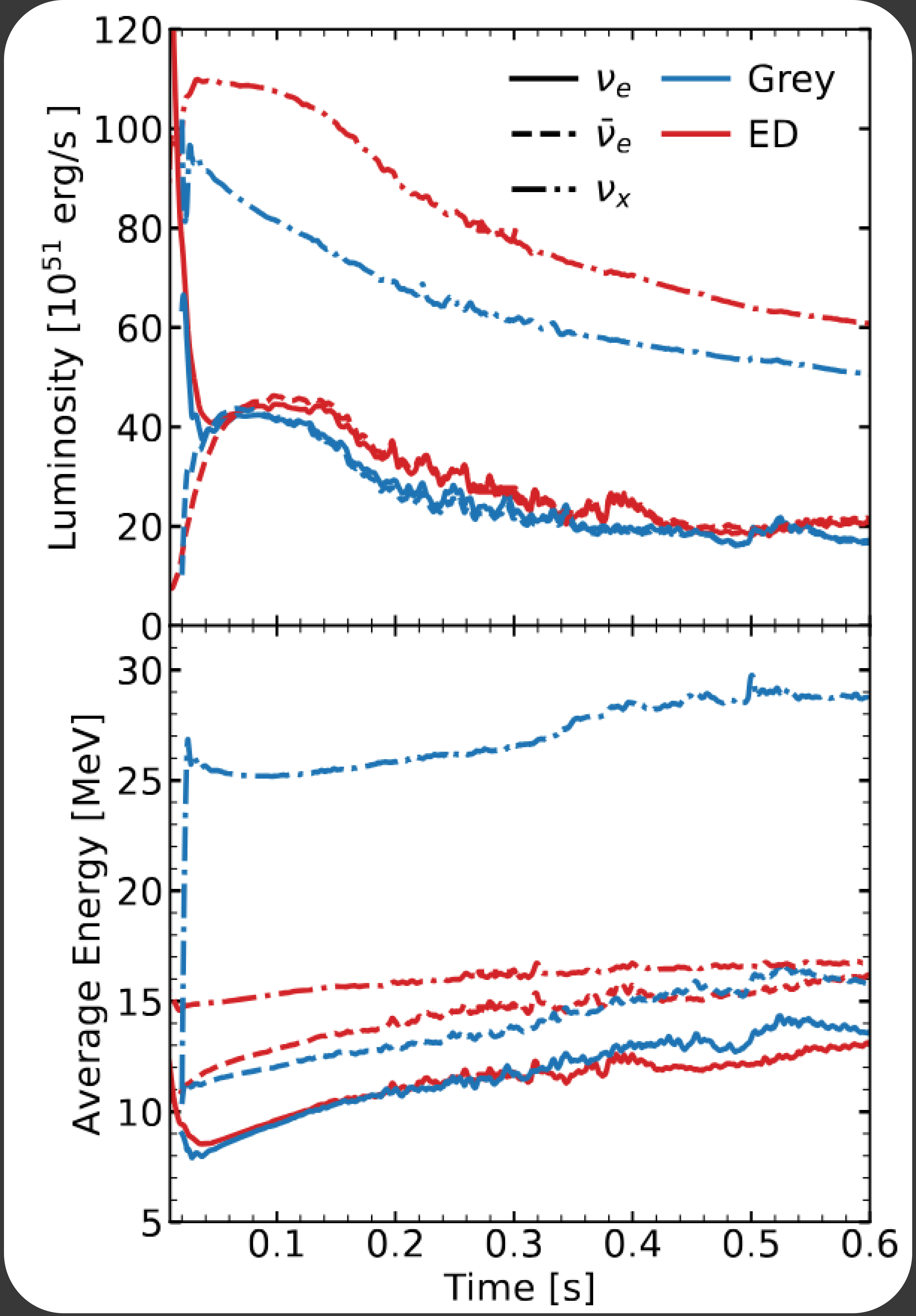
Explodes easier in 2D

See Andresen+24



Grey transport

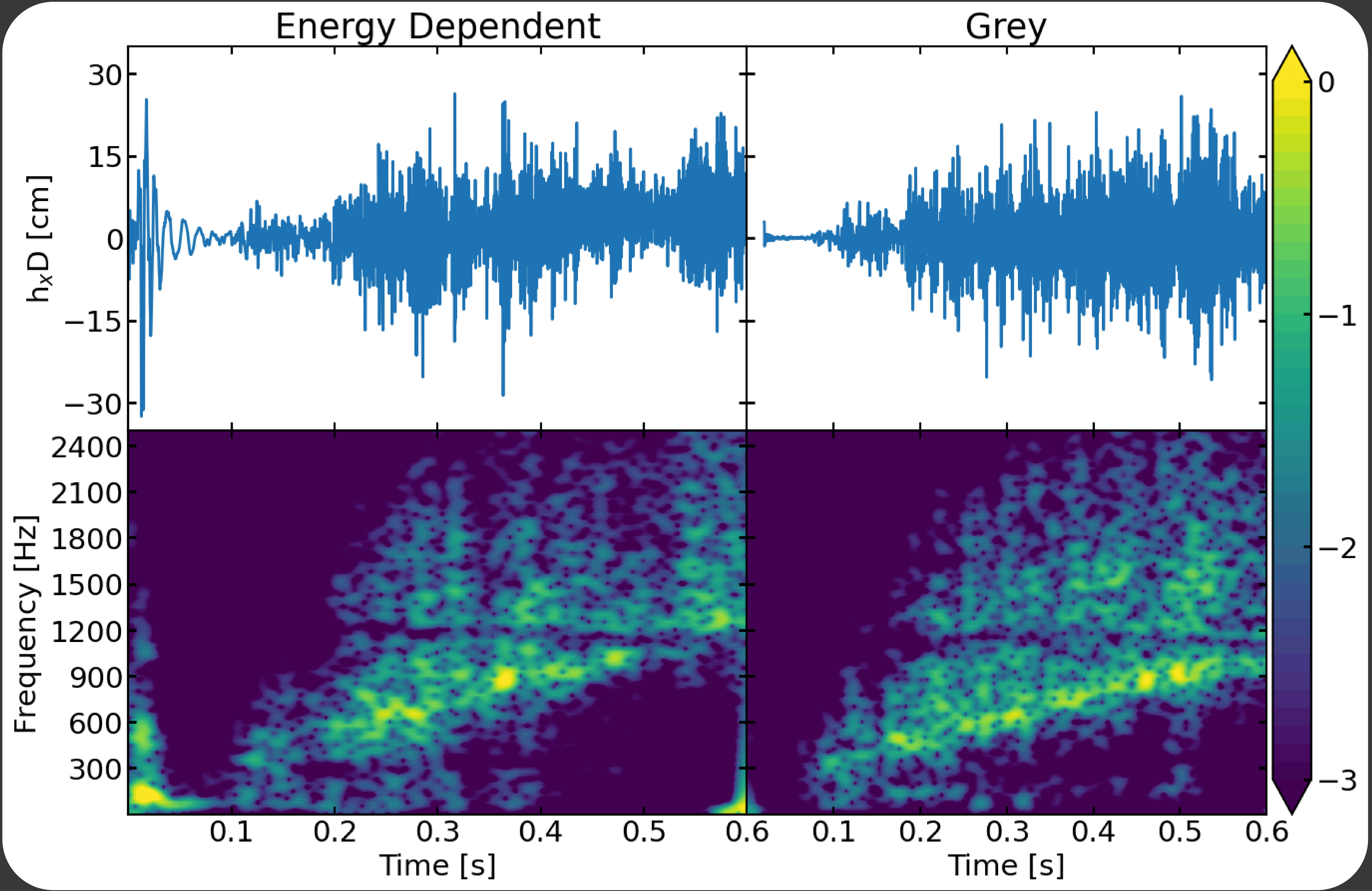
Heavy neutrinos
Scattering



Grey transport

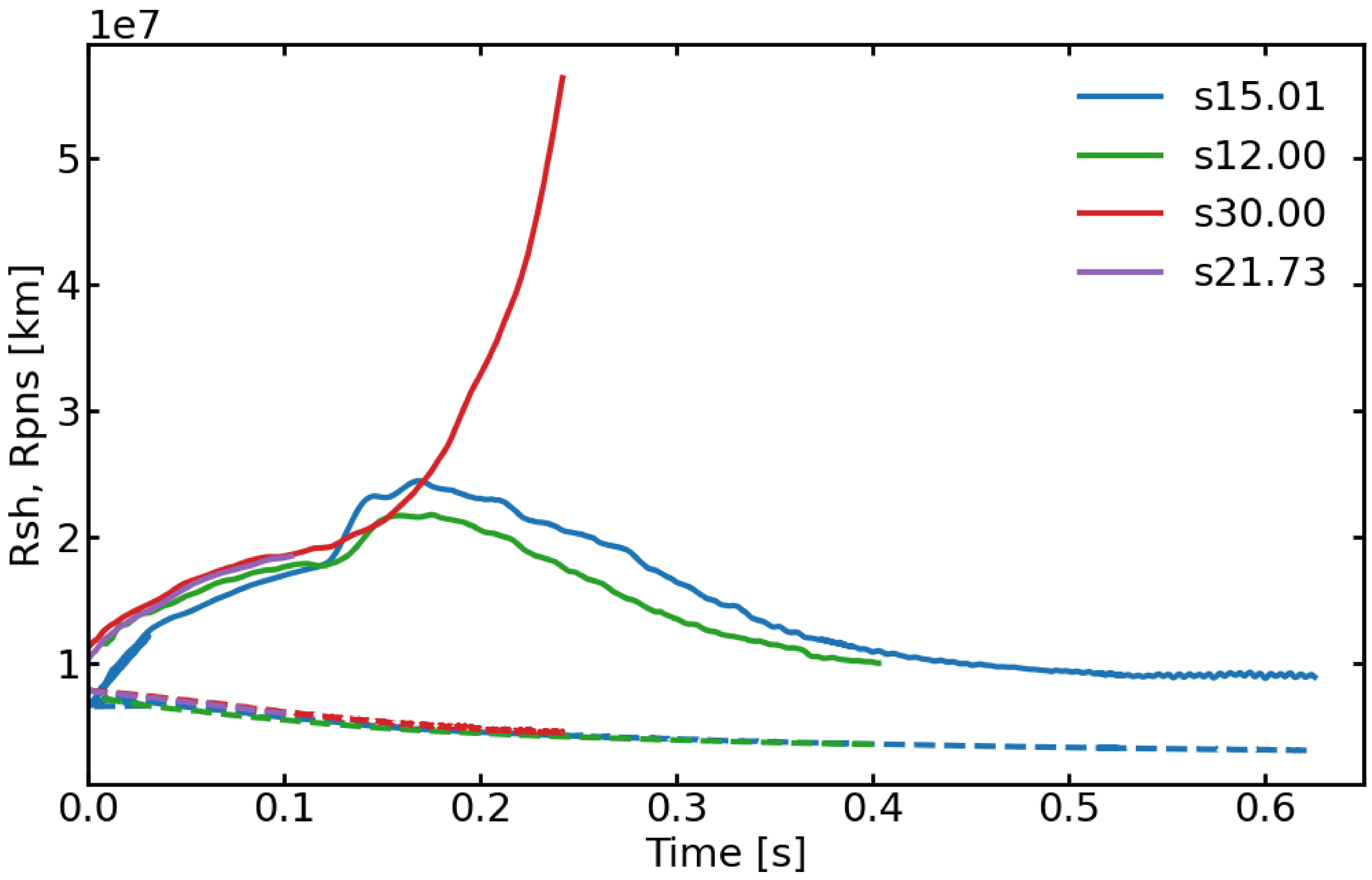
Slightly lower frequencies, this is due to the larger PNS.

See Andresen+24



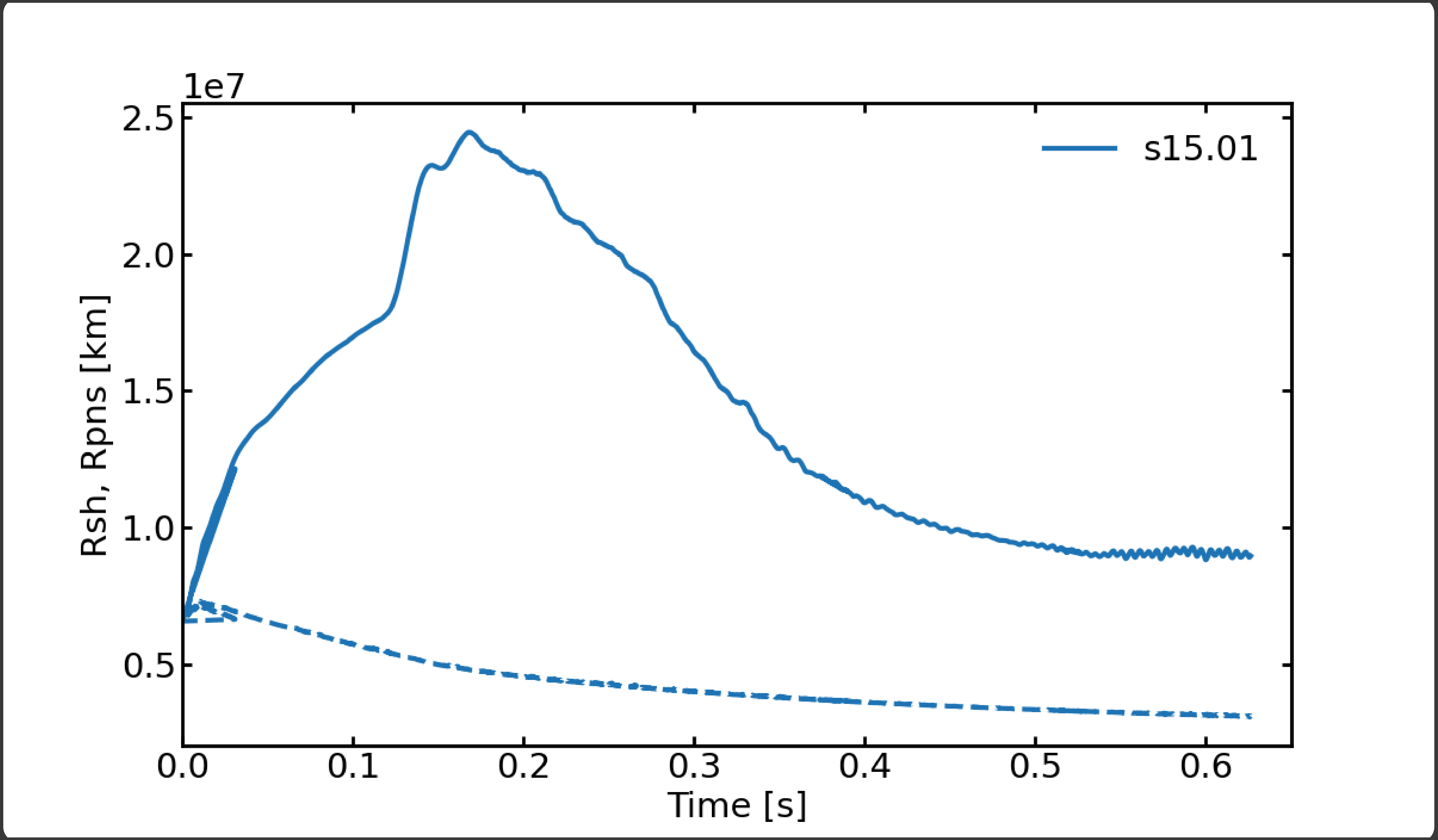
Long Simulations

- s15.01 has not exploded
- s30 looks good
- s21.73 might explode



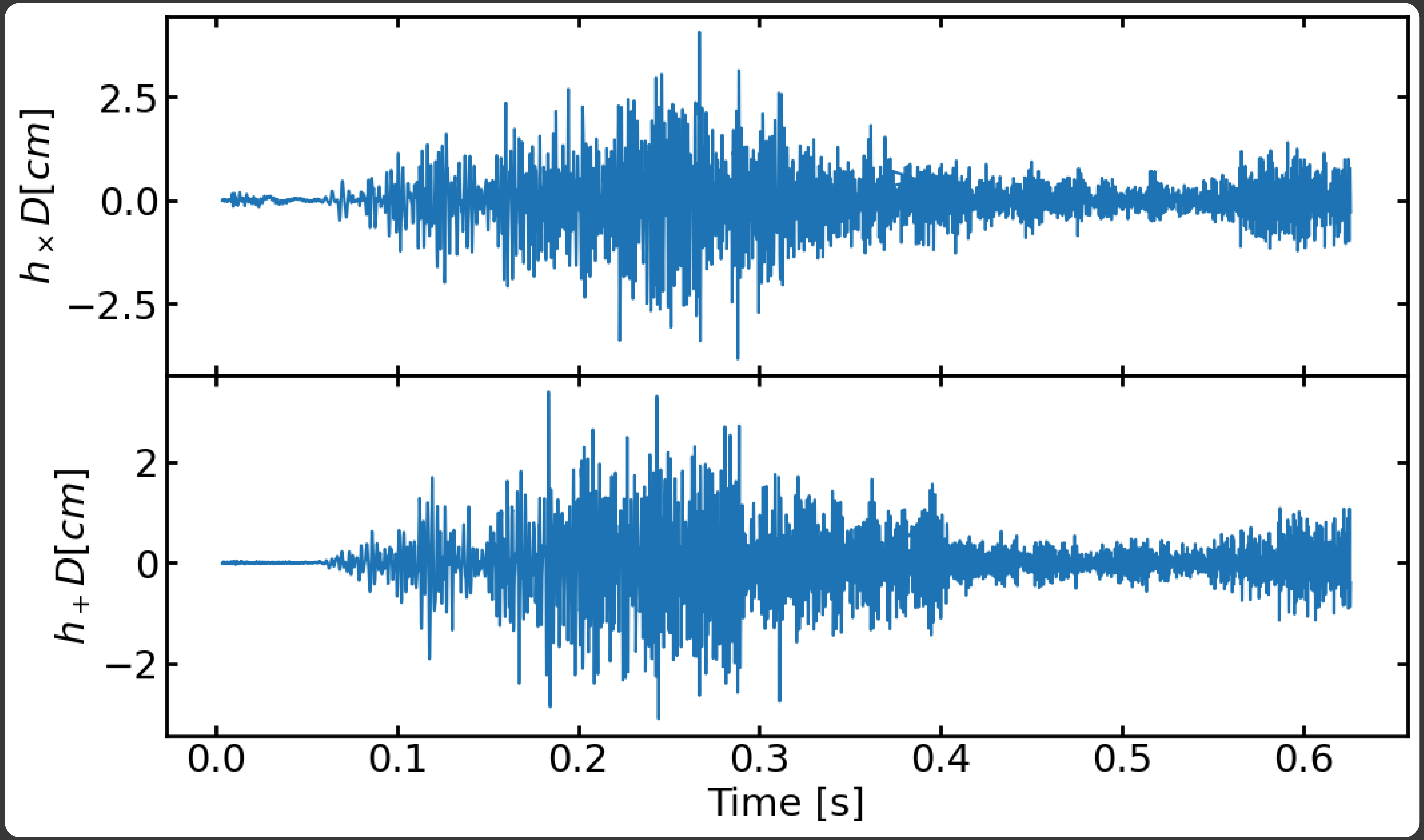
s15.01

- Si-O interface
- No sign of explosion
- Hard to compare



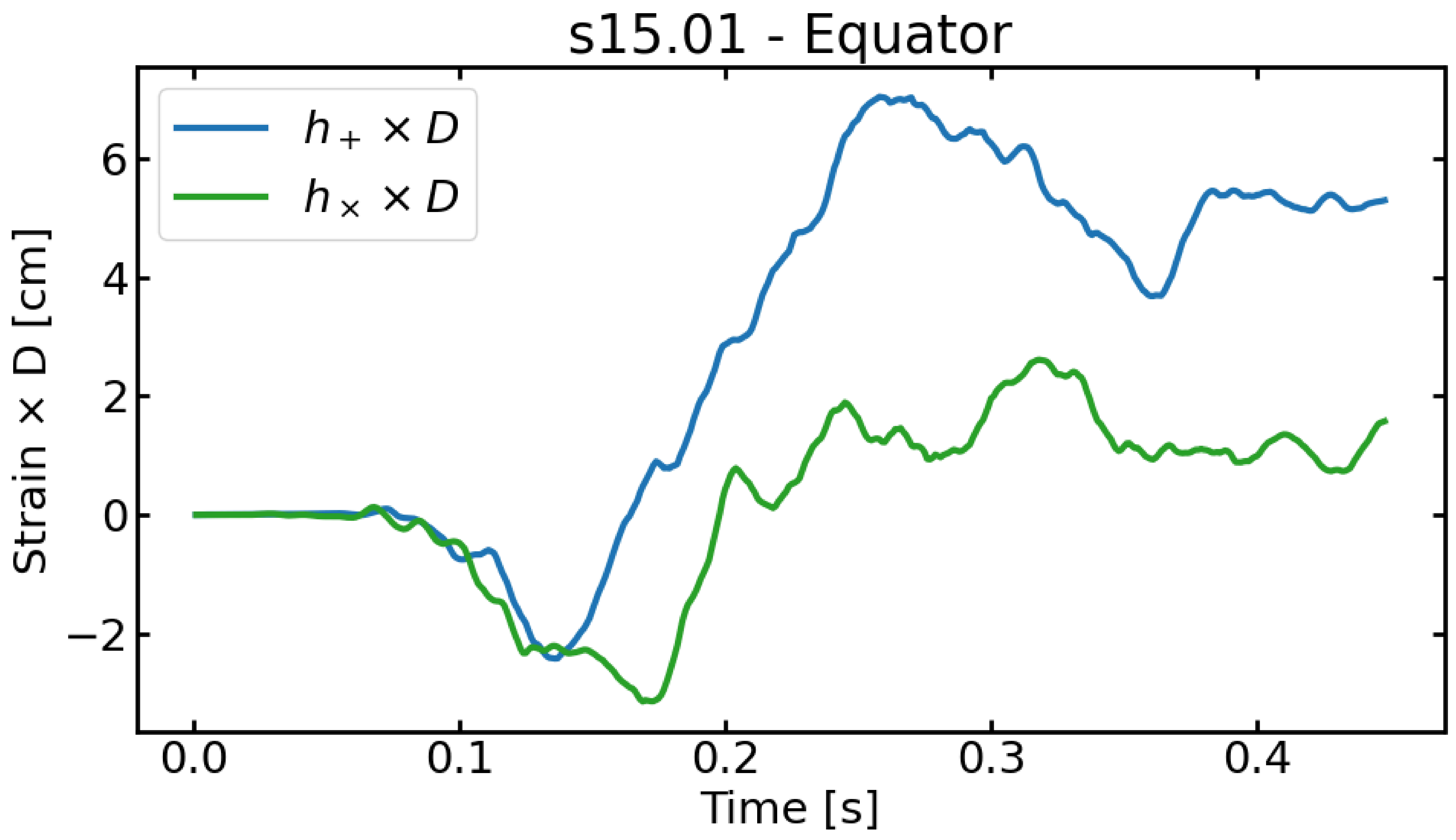
s15.01

- Typical signal



s15.01

Amplitude of a few centimeters, comparable with results from the literature.



Summary

3D progenitors

Several simulations underway. A clear need for better initial conditions. Stay tuned for comparison simulations and data release.

Gravitational Waves

Simulations are progressing, but few explosions as of now. We have not yet been able to confirm recent promising results.