Core-Collapse Supernova Explosion Models from 3D Progenitors

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The Supernova Problem

Supernova explosions, which mark the death of massive stars (>8 solar masses), are among the most spectacular events in the universe, and present one of the greatest challenges in computational astrophysics. After more than 40 years of modeling, the complex interplay of hydrodynamics, neutrino transport, general relativity and nuclear physics underlying the explosion mechanism is still not completely understood. Neutrino heating, hydrodynamical instabilities and magnetic fields are considered as possible factors that can play a role for the explosion [1,2]. While the complexity of the supernova problem presents a formidable challenge for numerical simulations, it also adds to its attractiveness: Because of its intimate links with many other areas of physics, a deeper understanding of supernova physics may shed light on many issues in nuclear an particle physics (nuclear equation of state, neutrino oscillations). In recent years, the supernova problem has been attacked using 3D simulations with multi-group neutrino transport with an ambiguous record of a few successful explosion models and a number of failures.

Robust Explosions from 3D Progenitor Models?

One of the keys to robust explosions as observed in nature could be initial asymmetries in massive stars at collapse [3,4], that naturally arise during convective shell burning shortly before the supernova. Such seed asymmetries could boost the activity of instabilities like convection behind the supernova shock and thereby help to drive it outwards and enhance neutrino energy deposition in the post-shock region. To test this hypothesis, 3D models of the final minutes of shell burning are required [5,6]. In [6], we performed the first 4π-3D simulation of oxygen shell burning up to collapse (Figure 1). We verified that the convective flow develops Mach $\mathrm{Ma}_\mathrm{prog}$ numbers of >0.1 as burning accelerates on the way to collapse, and that a quadrupolar (ℓ=2) flow mode emerges due to the thickness of the shell. $\mathrm{Ma}_\mathrm{prog}$ and ℓ agree well with the mixing-length theory of convection and linear perturbation theory, which allows us to estimate the properties of the convective flow in other progenitors.

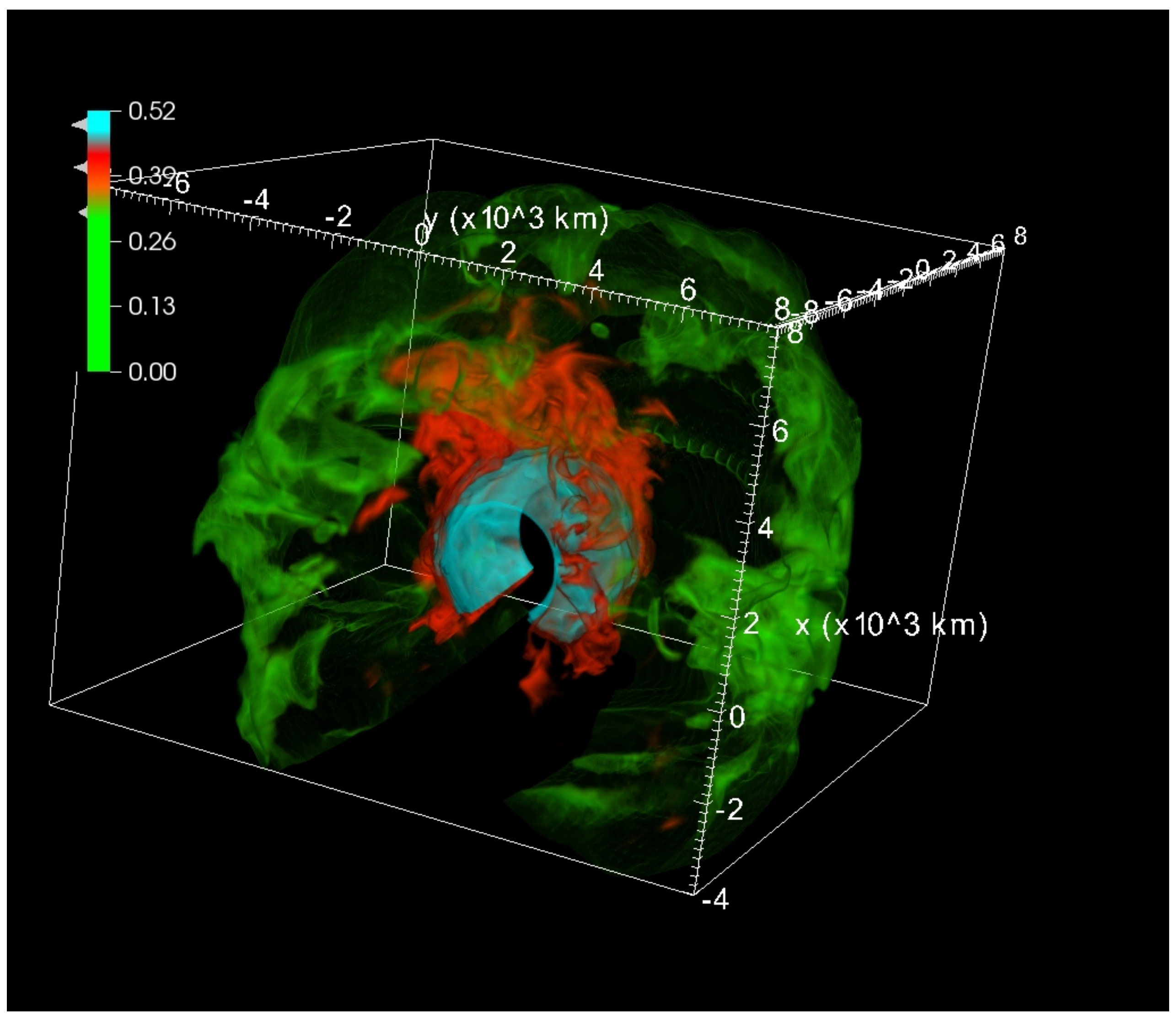

Fig. 1: Volume rendering of the mass fraction of silicon in a 3D simulations of oxygen shell burning in an 18 solar mass star at the onset of collapse. We show only one patch of the overset Yin-Yang grid in our model. Note the globally asymmetric distribution of fuzzy silicon-rich updrafts of hot ashes (red) and silicon-poor downdrafts of fresh fuel.The inner boundary of the oxygen shell (cyan) is relatively "hard" due to the strong buoyancy jump between the silicon and oxygen shell and therefore remains almost spherical.

References:
[1] Janka 2012, Annual Reviews of Nuclear and Particle Science, 62, 407
[2] Müller, arXiv e-print arXiv:1608.03274
[3] Müller & Janka 2015, MNRAS 448, 2141
[4] Couch & Ott 2013, ApJL, 778, L7
[5] Couch et al. 2015, ApJL, 799, L15
[6] Müller, Viallet, Heger & Janka 2016, ApJ accepted, arxiv:1605.01393

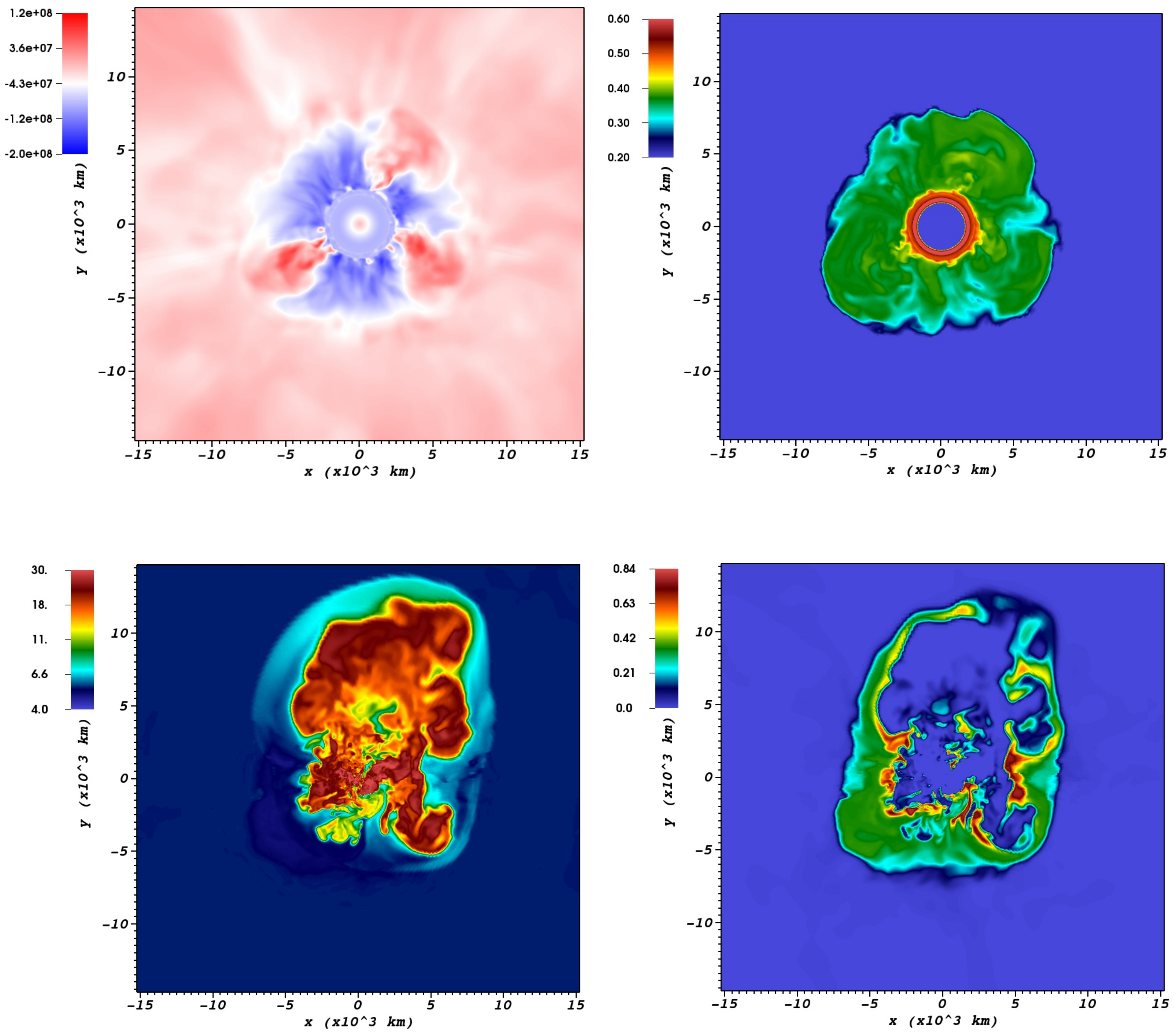

Fig. 2: Top row: Radial velocity in units of cm/s (top left) and mass fraction of Si (top right) at the onset of collapse in the 3D progenitor model of an 18 solar mass star. Bottom row: Entropy in units of k_b/nucleon (bottom left) and mass fraction of Si (bottom right) in the ensuing neutrino-driven explosion 1.43s after the formation of the neutron star. All plots show equatorial slices from the 3D simulation. It can be seen that the geometry of the initial conditions is still imprinted on the explosion to some extent with stronger shock expansion in the direction of updrafts of Si rich ashes in the O burning shell. This is a consequence of the forced deformation of the shock around the onset of the explosion.

A Perturbation-Aided Supernova Explosion

We investigated the impact of 3D initial seed perturbations from a simulation of shell burning in an 18 solar mass star [6] using multi-group neutrino transport [2]. 3D initial conditions qualitatively affect the outcome of the simulations: The delayed infall of convective updrafts creates asymmetries in the pre-shock ram pressure [3] that allow the shock to expand asymmetrically (Figure 2). Thanks to this "forced shock deformation", the model with 3D initial conditions stars to explode around 250ms after bounce, whereas a model started from 1D initial conditions does not undergo shock revival (Figure 3). The successful model has reached an explosion energy of $>5\times10^{50}$erg by the end of the simulation and is still growing at this point. This is the first time that a first-principle 3D model of a core-collapse supernova comes close to the typical observed explosion energies of type IIp supernovae.

It now remains to be demonstrated whether the perturbation-aided mechanism works for a wider range of progenitors. To this end, we formulated an analytic estimate for the reduction of the required neutrino heating to initiate an explosion [6]: Depending on the Mach number $\mathrm{Ma}_\mathrm{prog}$ of convection in the progenitor and the typical wave number ℓ, the critical neutrino luminosity L_crit for explosion is reduced by

$$\frac{\Delta L_\mathrm{crit}}{L_\mathrm{crit}} \sim \frac{(2\ldots4)\times\mathrm{Ma}_\mathrm{prog}}{\ell}.$$

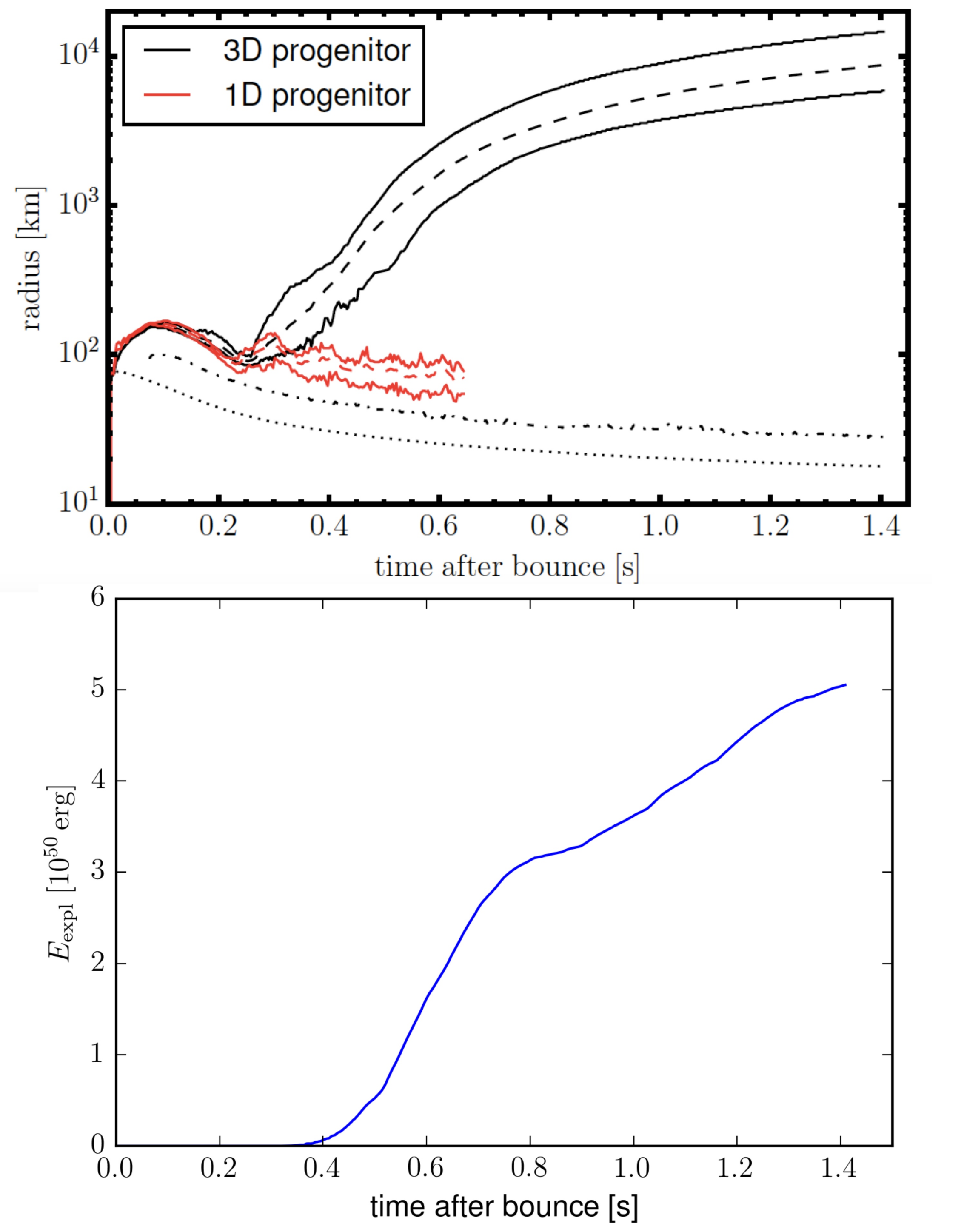

Fig. 3: Impact of pre-collapse asphericities on shock revival in 3D multi-group neutrino hydrodynamics simulations of an 18 solar mass progenitor. The **top panel** shows the minimum, maximum (solid lines) and average (dashed) shock radii for a model using 3D initial conditions (black) from the O shell burning simulation and a spherically averaged version of the same progenitor (red). The gain radius (dash-dotted) and the proto-neutron star radius (dotted, defined by a fiducial density of 10^{11}g/cm^3) are shown only for the model starting from 3D initial conditions; they are virtually identical for both models. A neutrino-driven explosion is triggered roughly 0.25s after bounce aided by the infall of the convectively perturbed oxygen shell in the model using 3D initial conditions. The simulation starting from the 1D progenitor model exhibits steady and strong SASI oscillations after 0.25s, but does not explode at least for another 0.3s. **Bottom panel:** Growth of the "diagnostic" explosion energy E_expl in the perturbed model.

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