Progenitor with small reaction networks should not be used as initial conditions for core collapse

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ABSTRACT

Core collapse initial conditions are a bottleneck in understanding the explosion mechanism(s) of massive stars. Stellar evolution codes struggle after carbon burning, and either stop or adopt numerical simplifications missing crucial physics. The use of small nuclear reaction networks (NRN) that account for energy production but bypass weak reactions is typical, but insufficient to study the dynamics of the collapse. We advise against the use of progenitors computed with small NRN in expensive multi-dimensional simulations of core collapse, bounce, (jet formation), and explosion.

1. MODELING UNCERTAINTIES COMPOUND

Massive stars ($\gtrsim 7 - 10\,M_\odot$, Doherty et al. 2015; Poelarends et al. 2017) end their life collapsing and possibly exploding (e.g., Janka 2012; Burrows & Vartanyan 2021; Soker 2024). Although a consensus around the "neutrino-driven" paradigm is establishing (e.g., Wang & Burrows 2023; Nakamura et al. 2024), details remain debated (e.g., Shishkin & Soker 2022; Soker 2022), especially for magnetic fields and rotation (e.g., Symbalisty 1984; Mösta et al. 2015; Aloy & Obergaulinger 2021).

The collapse/explosion is sensitive to the initial conditions (e.g., Ott et al. 2018; Kuroda et al. 2018; Burrows et al. 2023; Nakamura et al. 2024), determined by the late core evolution. Only limited sets of nonrotating progenitors computed sufficiently late exhist (Woosley et al. 2002; Sukhbold et al. 2016; Farmer et al. 2016; Renzo et al. 2017; Wang et al. 2024) and even fewer include rotation (Heger et al. 2000; Aguilera-Dena et al. 2018).

Farmer et al. (2016) showed the impact of algorithmic choices on the final core of nonrotating stars, demonstrating that small (~ 20-isotope) NRN are insufficient to produce reliable initial conditions for multidimensional core collapse studies. These NRNs allow for deleptonization through one single compound reaction (e.g, $^{56}\mathrm{Fe} + 2e^- \rightarrow {}^{56}\mathrm{Cr} + 2\nu_e$). This predetermines Y_e *throughout* the core, thus the effective Chandrasekhar (1931) mass $\propto Y_e^2$, and ultimately the outcome of the collapse. This affects stellar evolution models computed with the `approx` family of nuclear reaction networks (Timmes et al. 2000). Here, we extend this result to fast rotating progenitors.

We ran two $40\,M_\odot$, Z=0.001 stars initially rotating at 60% of breakup with MESA (Paxton et al. 2013; Jermyn et al. 2023, r24.03.1). A reproducibility package is available at doi:10.5281/zenodo.11375523. The models differ only in the NRN, `mesa_128` (orange in Fig. 1), sufficient to follow the deleptonization (Farmer et al. 2016), and `approx21_plus_cr56` (blue). We include rotational mixing (Heger et al. 2000), magnetic torques (Spruit 2002), and hydrodynamics. We expunge spurious velocities in layers not in sonic contact with the innermost core (CO, Si, or Fe). We performed resolution tests (up to mesh sizes $\gtrsim 10\,000$), and found that numerical resolution affects convection in the inner $5\,M_\odot$ and consequently the inner structure (e.g., Sukhbold & Woosley 2014; Schneider et al. 2023). This emphasizes the importance of resolution tests (Farmer et al. 2016). The models we present have identical resolution requirements and are representative of the range of structures that can be obtained.

Both models experience blueward rotationally-induced chemically homogeneous evolution (e.g., Maeder & Meynet 2000) and are computed until the in-fall velocity exceeds $300\,\mathrm{km\ s^{-1}}$. Fig. 1 (right) shows the Hertzsprung-Russell diagram (HRD). The two tracks are observationally indistinguishable, with most differences confined to fast evolutionary phases: small NRNs are sufficient to simulate surface properties.

Nevertheless, the interior structure significantly different: the compactness parameter (O'Connor & Ott 2011) of the small (large) NRN model is $\xi_{2.5} = 0.376$ (0.262). The $\sim 44\%$ variation in $\xi_{2.5}$ is comparable to uncertainties introduced by numerical resolution (Farmer et al. 2016), mass loss (Renzo et al. 2017), and overshooting (Davis et al. 2019). No single parameter is sufficient to
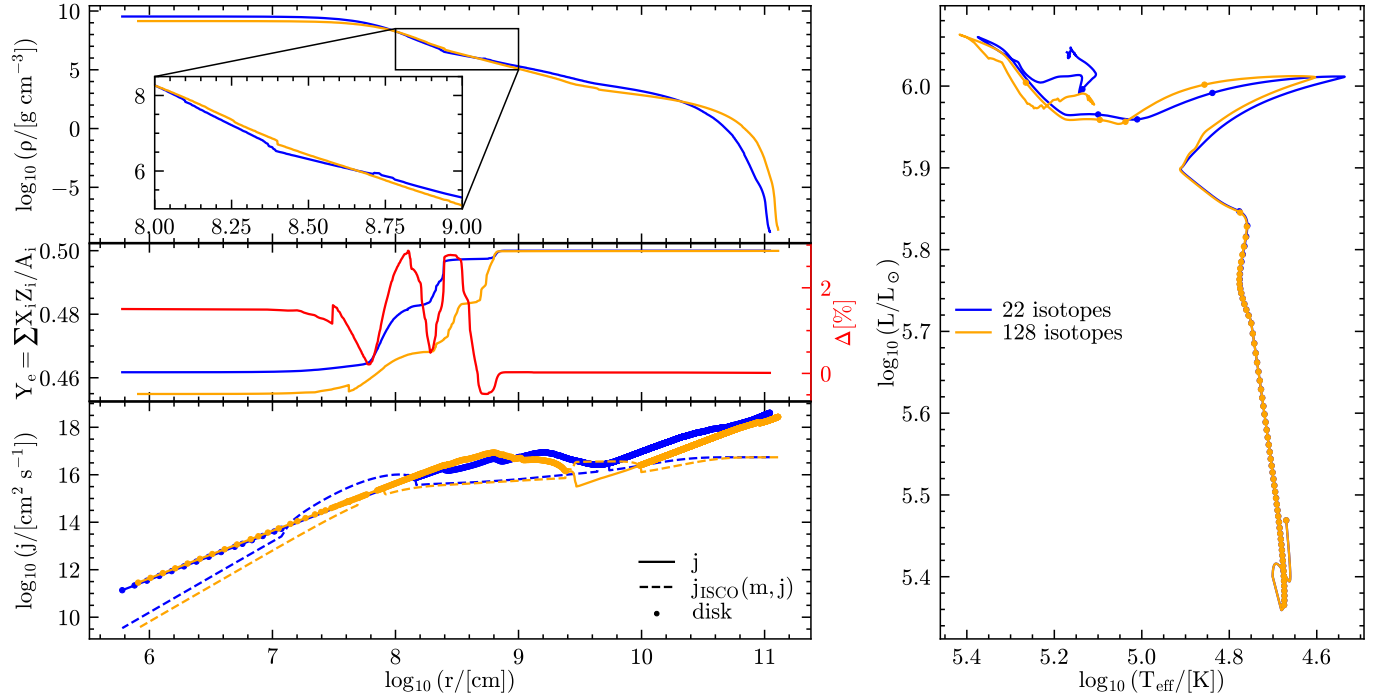
Figure 1. Comparison of chemically homogeneous models at the onset of core-collapse. Right: HRD (one dot every 10^5 years). Top left: density. Middle left: Y_e, relative difference in red (right vertical axis). Bottom left: specific angular momentum j. The dashed line shows $j_{\rm ISCO}$ assuming the accretion of the enclosed m and j. Dots correspond to regions that collapse forming a disk, $j \geq j_{\rm ISCO}$.

characterize "explodability" (e.g., Ertl et al. 2016; Vartanyan et al. 2021), and we show on the left of Fig. 1 the internal profiles.

The top panel shows the density profiles, with an inset focusing on the region where the success or failure of an explosion is decided (e.g., Ertl et al. 2016; Boccioli et al. 2023; Burrows et al. 2023).

The middle panel shows the Y_e profile. All the mass collapsing interior to 10^9 cm shows *structured* relative variations $\Delta = (Y_e^{\rm small~NRN} - Y_e^{\rm large~NRN})/Y_e^{\rm large~NRN} \simeq 1-3\%$ (red, righ vertical axis). The range of Y_e found at the onset of collapse is $0.4-0.5$, making this nonnegligible.

The bottom left panel shows the specific angular momentum (j, solid lines) and the innermost stable orbit angular momentum assuming accretion of the enclosed mass and j ($j_{\rm ISCO}$, dashed lines, Bardeen et al. 1972). Wherever $j \geq j_{\rm ISCO}$ an accretion disk has to form (thicker dots). In both cases the inner $\sim 10^7$ cm retain too much angular momentum to directly collapse, and we expect a proto-neutron-star phase. After the collapse of this material, the 128-isotope model shows the formation of a disk immediately, while the 22-isotope model only after $\gtrsim 1\,$s. From disk formation onwards the evolution will diverge because of feedback processes (disk wind, jet, etc., Gottlieb et al. 2022). This difference occurs because of the diverging evolution of the density and thus j caused by the treatment of nuclear physics.

Core collapse is a $\sim 1\%$ problem: only this fraction of the gravitational potential released needs to be "harvested" to produce a successful supernova. Predictive simulations require high accuracy initial conditions. Many uncertain processes occur in massive stars (e.g., Woosley et al. 2002; Langer 2012), and modeling choices matter, including resolution (Farmer et al. 2016), mass loss (Renzo et al. 2017), mixing (Davis et al. 2019), spurious envelope velocities (e.g., Farmer et al. 2016; Aguilera-Dena et al. 2018), and dimensionality of the simulations (e.g., Fields 2022). We advise against running expensive multidimensional simulations of core-collapse with initial conditions that are known to not include enough physics to address the questions motivating such simulations in the first place. This means not using models computed only until carbon depletion, models wiht small NRN, and/or underresolved models.

At fixed angular momentum transport, small NRN result in significantly different rotationally-powered explosions for the same core-collapse physics, making robust conclusions impossible.

Progenitors computed with small NRN remain useful for studying the outer layers of stars up to collapse, and possibly to make relative statements, but require care to

marginalize any conclusion against this large systematic modeling uncertainty in the progenitor.

<div style="text-align: center;">REFERENCES</div>

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