Journal Club

Core-collapse supernovae simulations with reduced nucleosynthesis networks

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The paper

Core-collapse supernovae simulations with reduced nucleosynthesis networks

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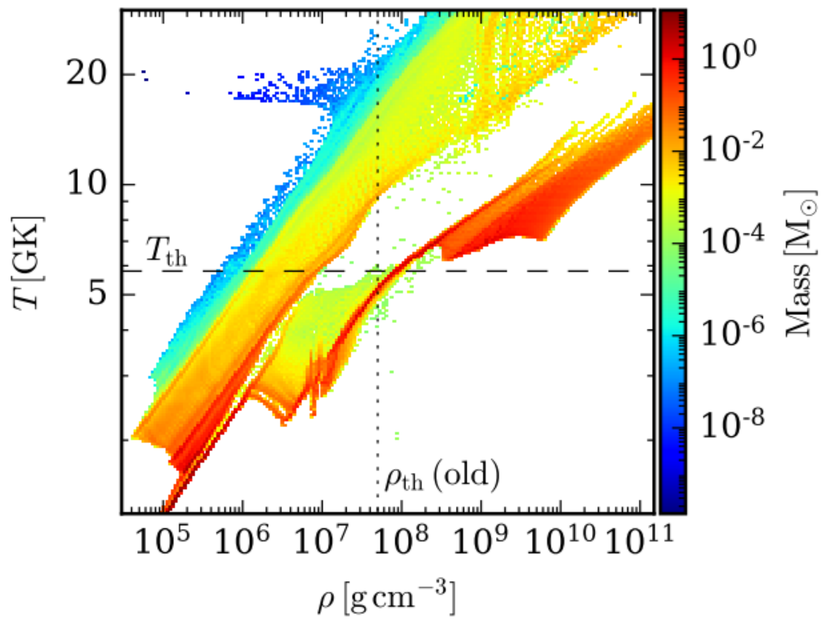


https://arxiv.org/pdf/2210.11848.pdf

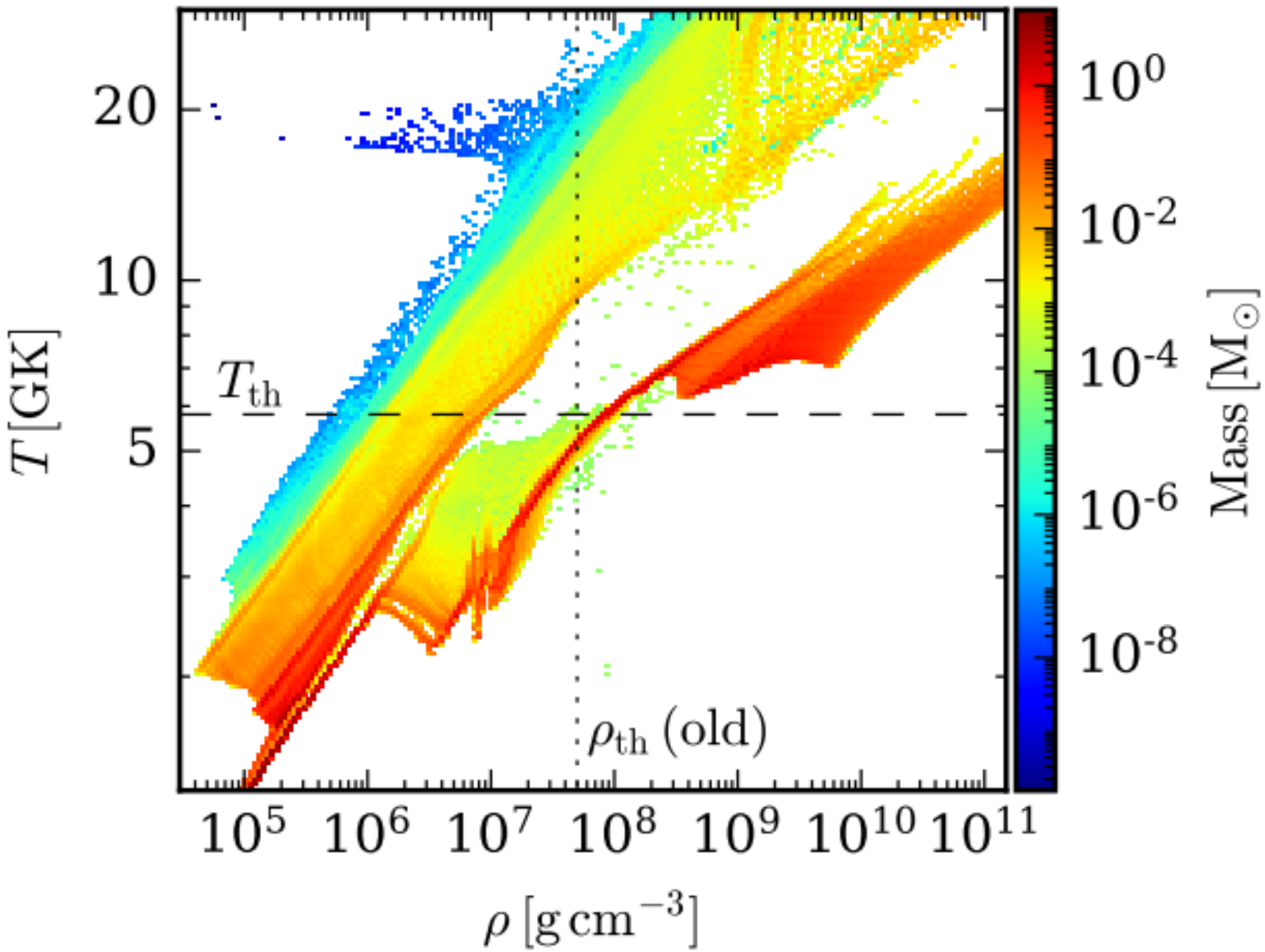
The abstract

ABSTRACT

We present core-collapse supernovae simulations including nuclear reaction networks which impact explosion dynamics and nucleosynthesis. The different composition treatment can lead to changes in the neutrino heating in the vicinity of the shock, by modifying the amount of nucleons and thus the ν-opacity of the region. This reduces the ram pressure outside the shock and allows an easier expansion. The energy released by the nuclear reactions during collapse also slows down the accretion, and aids the shock expansion. In addition, nuclear energy generation in the post-shocked matter produces more energetic explosions, up to 20 %. Nucleosynthesis is affected due to the different dynamic evolution of the explosion. Our results indicate that the energy generation from nuclear reactions helps to sustain late outflows from the vicinity of the proto-neutron star (PNS), synthesizing more neutron-rich species. Furthermore, we show that there are systematic discrepancies between the ejecta calculated with in-situ and ex-situ reaction networks. The mass fractions of some Ca, Ti, Cr, and Fe isotopes are consistently under-produced in post-processing calculations, leading to different nucleosynthesis paths. Therefore, large in-situ nuclear reaction networks are needed for a more accurate nucleosynthesis.

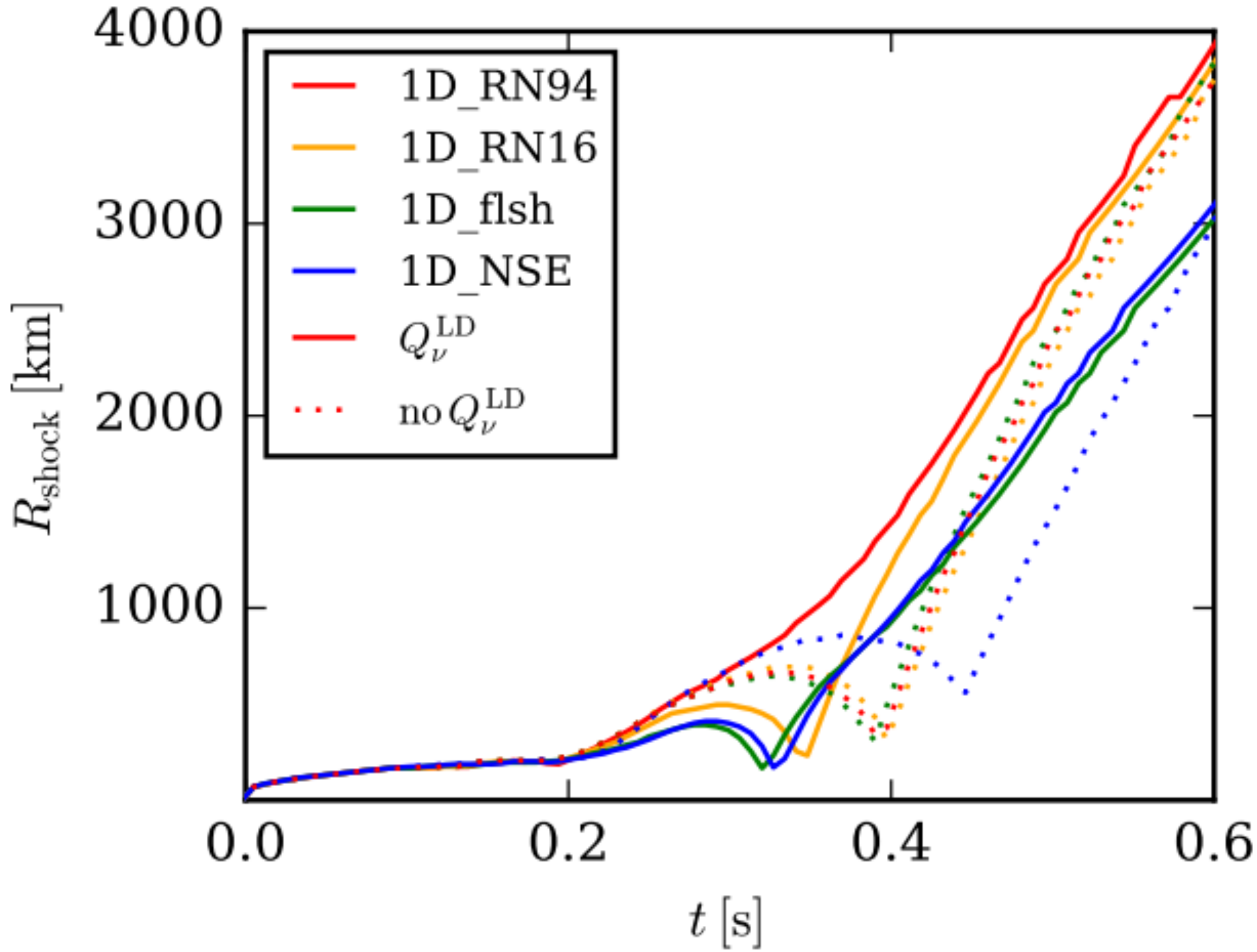
Keywords: Core-collapse supernovae(304) — Supernovae(1668) — Explosive nucleosynthesis(503) — Supernova dynamics(1664) — Astrophysical explosive burning(100) — Nuclear astrophysics(1129)

Figures



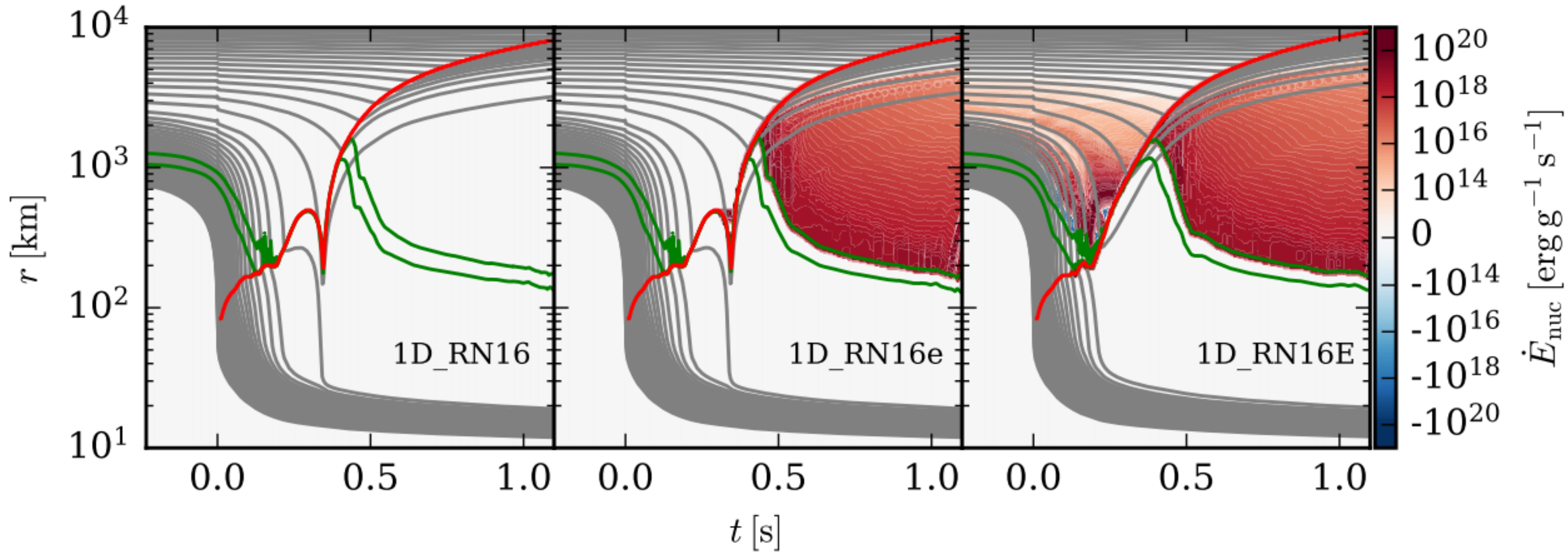
Density and temperature achieved in a characteristic CCSN simulation

Figures



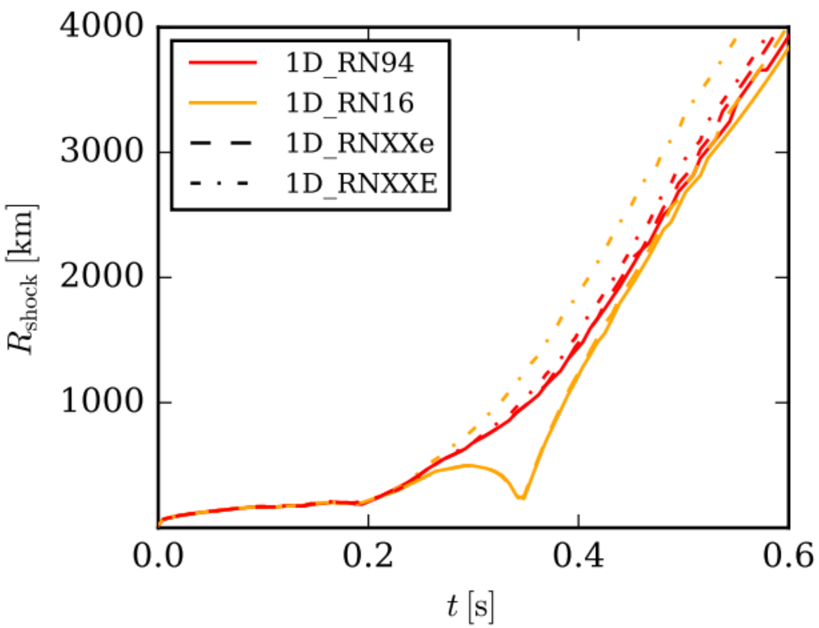
Shock evolution of models without E' nuc.

Figures

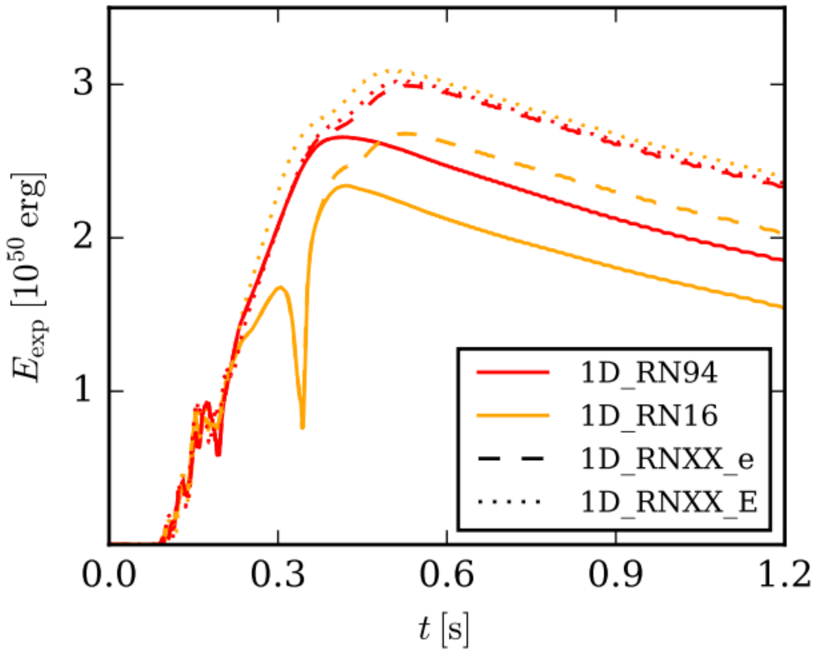


Mass shell evolution of 1D RN16, 1D RN16e and 1D RN16E models

Figures

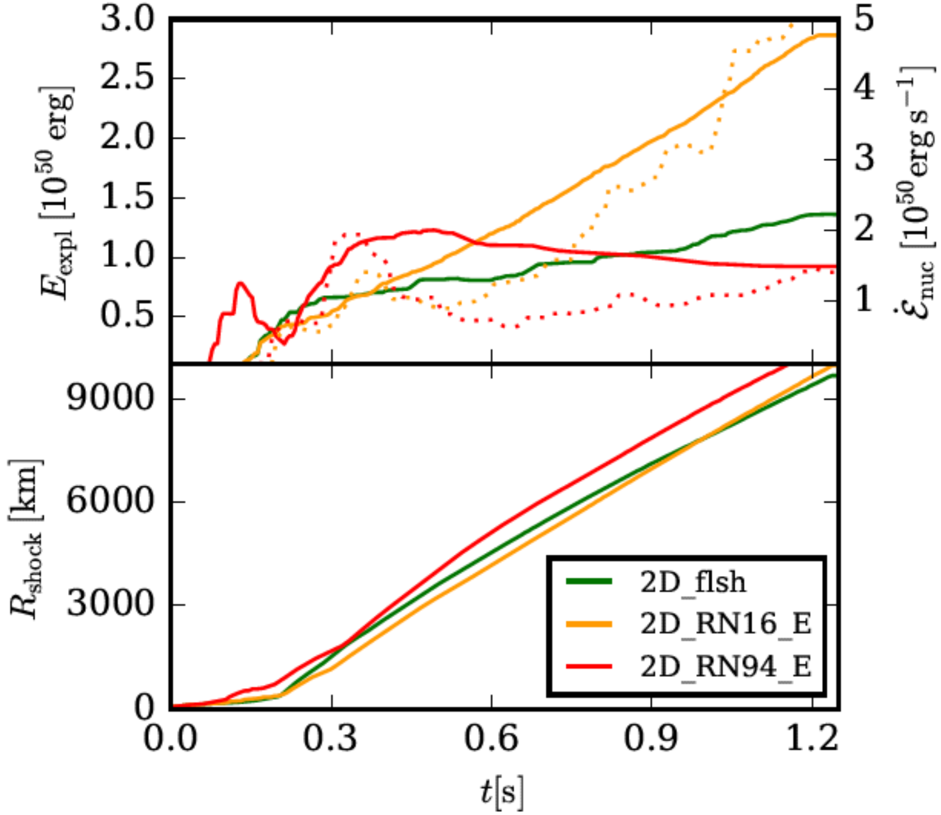


Shock evolution



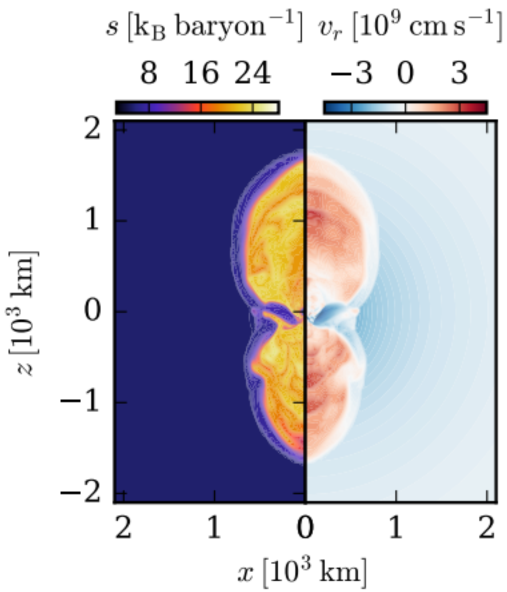
Explosion energy of the models with no E'nuc (solid), with E'nuc below the shock (dashed), and with E'nuc in the low density region

Figures

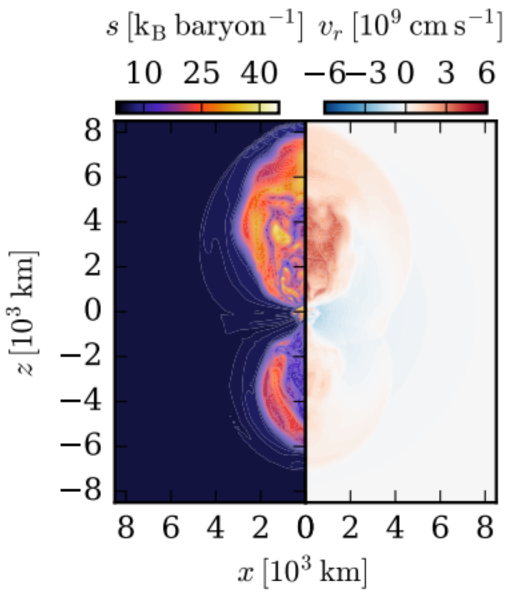


Evolution of the explosion energy (solid) and the nuclear energy generation (dotted) of the 2D models (upper panel) and the shock radius

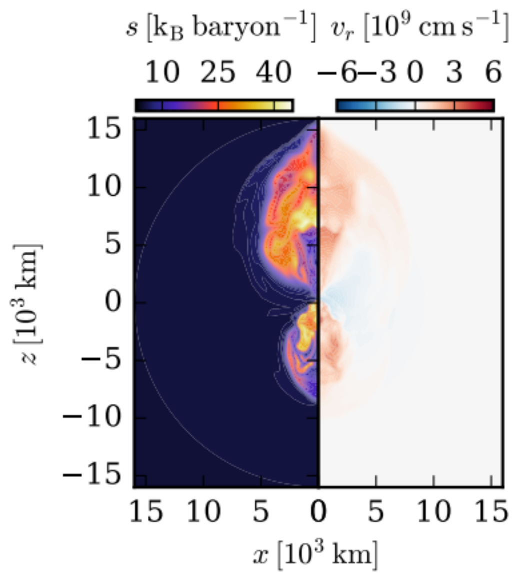
Figures



(a) 2D_flsh. $t = 500$ ms.



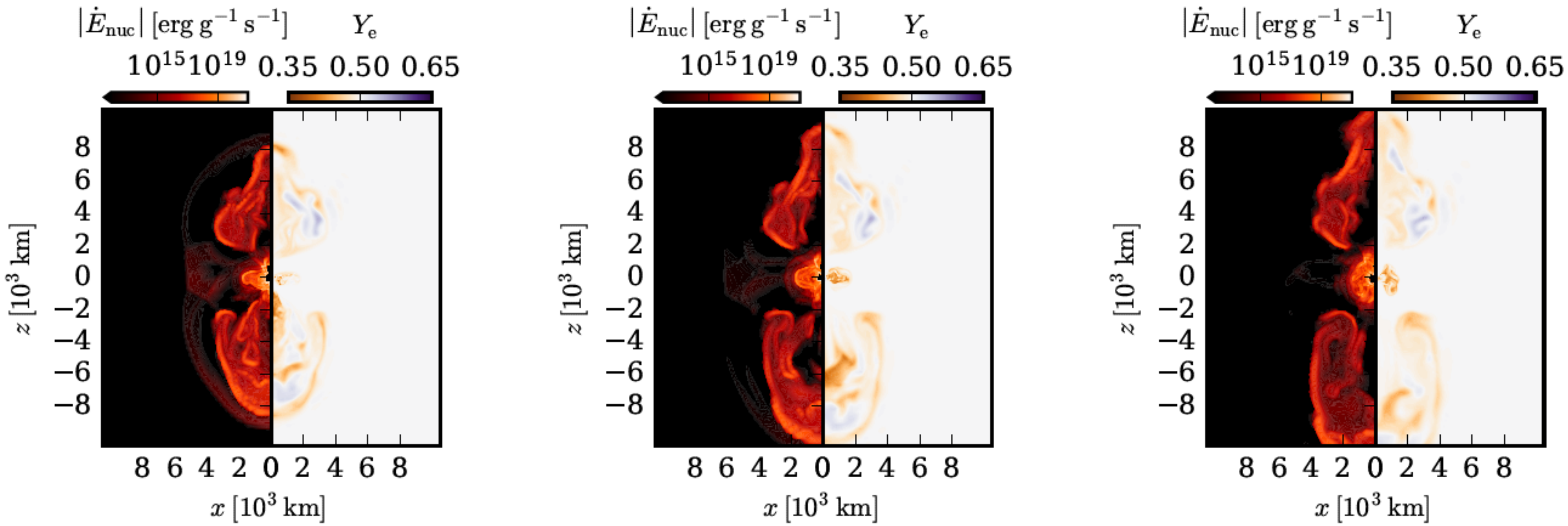
(b) 2D_flsh. $t = 1000$ ms.



(c) 2D_flsh. $t = 1500$ ms.

Slices of entropy and radial velocity

Figures



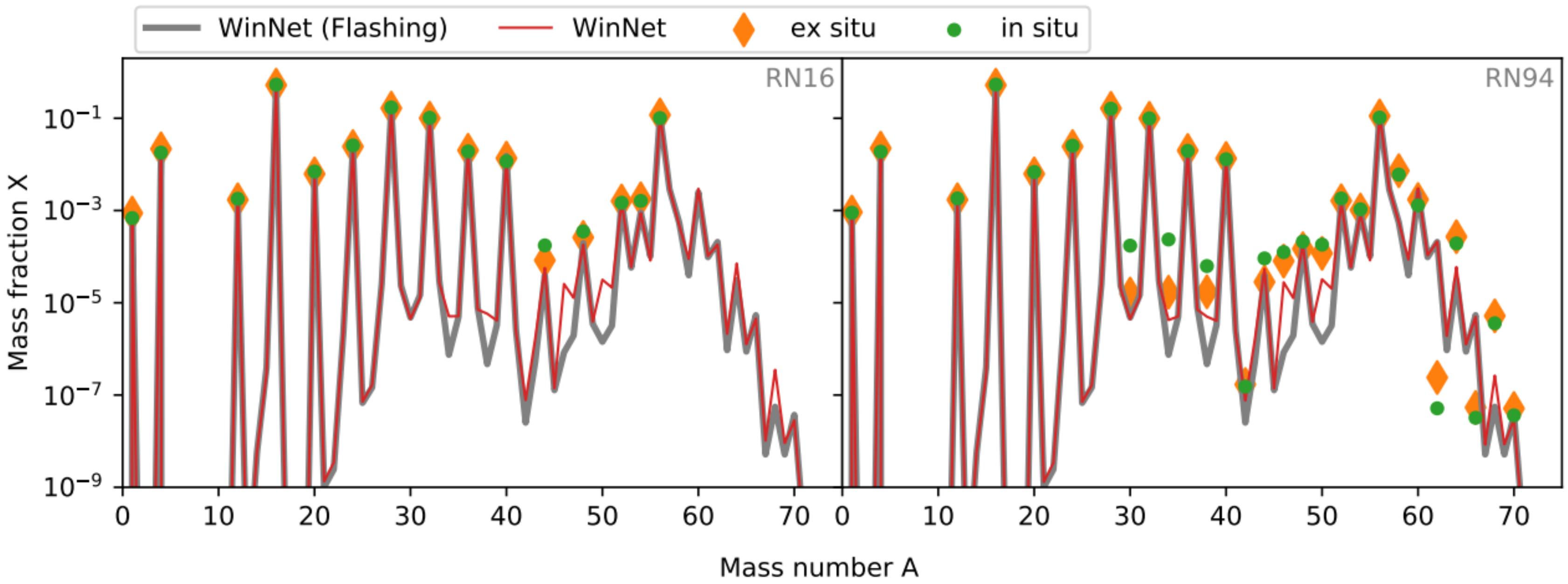
(a) $t = 1100$ ms.

(b) $t = 1250$ ms.

(c) $t = 1400$ ms.

Snapshots of the magnitude of E’nuc and Ye

Figures



Integrated final ejecta composition of the 1D models. Red lines correspond to the composition obtained in post-processing with the full network WinNet in the 1D RN16E (left) and 1D RN94E (right). The post-processing results for the 1D flsh are displayed in grey for comparison. Green dots stand for the values obtained from the network in situ, i.e. evolved in the simulation. The values obtained with the same reduced network in post-processing are depicted by orange diamonds

Figures

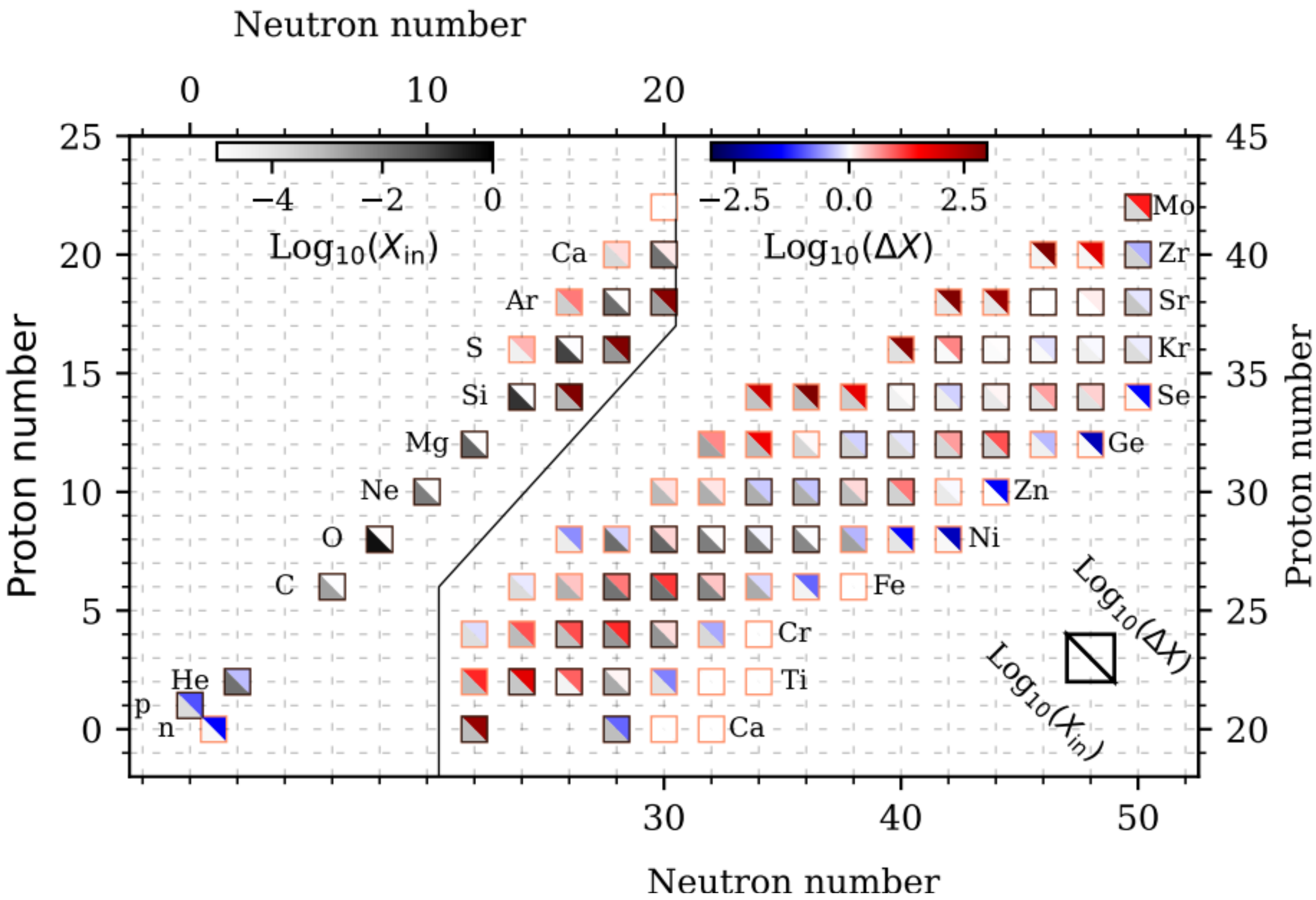


Figure 13. Chart with the RN94eq148 isotopes in boxes. Orange edges indicate unstable nuclei and black stable ones. Bottom half of boxes depict in situ integrated mass fractions for 2D_RN94E at the end of the simulation. Upper half show the differences with respect to ex situ mass fraction, defined as $\Delta X = \frac{X_{\mathrm{in}}}{X_{\mathrm{ex}}}$, for species with $X_{\mathrm{i}} > 10^{-5}$.

Conclusions

- We have presented a detailed study of how the treatment of the composition within CCSN simulations impacts the explosion dynamics and nucleosynthesis.
- We performed 1d and 2d CCSN simulations using the neutrino-hydrodynamics code Aenus-Alcar [..]
- So far, this code included the nuclear reactions outside the NSE regime only via the simplified flashing scheme, which gives neither accurate information on the composition nor accounts for the energy release by nuclear reactions.
- We used the reduced network module ReNet to replace the flashing scheme by a 16 α-chain and a 94 isotopes network.
- The latter is able to reproduce the main nucleosynthesis yields in standard CCSN explosions.
- In addition, thanks to the 148 nuclei considered in steady state approximation, RN94eq148 is the most extended network in the nuclear chart ever employed in state of-the-art hydrodynamic simulations

Conclusions

- Both in-situ networks return the composition of the gas and the rate at which nuclear reactions generate or consume internal energy.
- The different composition in the low-density region have an impact on the amount of nucleons, which can change the neutrino heating in the vicinity of the shock.
- This modifies the ram pressure outside it and, therefore, its evolution.
- We have demonstrated how the energy released in the nuclear reactions impacts the dynamics of the explosion. The energy generation in the pre-shocked collapsing matter decreases, again, the ram pressure outside the shock and allows it to expand easier.
- On the other hand, the nuclear energy released in the shocked region has a significant contribution, up to 20 %, to the total explosion energy. Differences between RN16 and RN94eq148 are small regarding the nuclear energy generation, where (α, γ) and (p, γ) are the main channels of production.
- While the models presented are not very energetic, we explored more energetic explosions and obtained similar impact.

Conclusions

- Finally, we obtained the detailed nuclear yields of the models by applying the nuclear network WinNet with 6545 isotopes in an ex-situ, post-processing step to Lagrangian tracer particles tracking the fluid flow.
- We compared its results among different models and to the in-situ networks.
- In 1d, the differences are small since the Ye involved are very similar among the models and close to 0.5. In 2D, the variation in abundances among different models get larger.
- The energy released in the nuclear reactions helps to sustain late neutron-rich outflows ejected from the vicinity of the PNS. The model 2D RN94E shows how this mechanism allows weak r-process to take place.
- Moreover, we have compared the final composition obtained in situ and ex situ making use of RN16 and RN94eq148.
- We find significant discrepancies mainly in products of the α-rich freeze out, since Lagrangian tracer particles involve larger uncertainties when tracking such regions.
- Also, we demonstrate how these differences can lead to variations on the nucleosynthesis path which alter the final yields. Thus, it is necessary to employ in situ realistic networks in CCSN simulations to obtain more accurate ejecta composition.