# INSTABILITIES IN 3D SIMULATIONS OF NEUTRINO-DRIVEN CCSNe FROM RSG PROGENITORS


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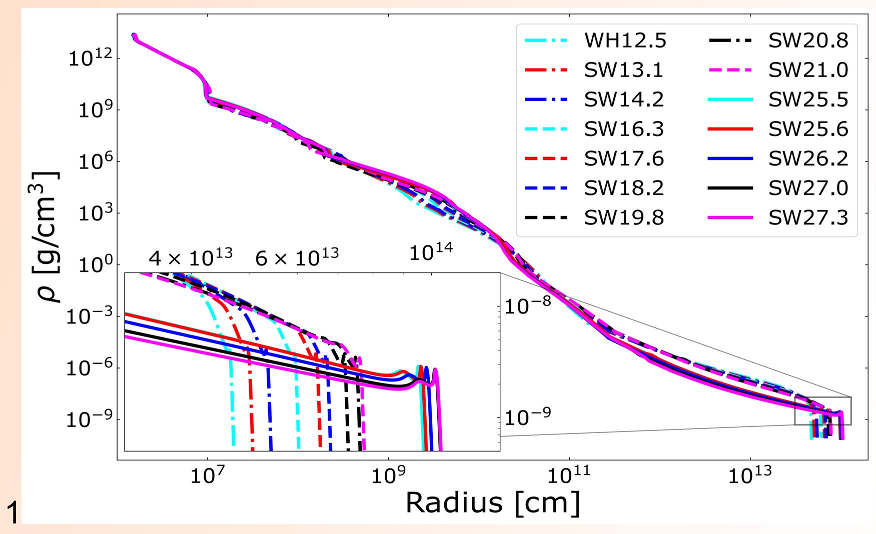
## INTRODUCTION

We simulate core-collapse supernova (CCSN) explosions of 14 red supergiant (RSG) progenitor stars. We use an approximated, gray, ray-by-ray neutrino transport for the first seconds, after which we switch to suitable boundary conditions to simulate further. This allows us to reduce the computational time due to the neutrino treatment and bring the simulations to late times. Moreover, the explosions have been calibrated over the known explosions of SN 1987A and that of the Crab nebula. Our focus lies on the effect caused by the growth of Rayleigh-Taylor intsabilities (RTIs), which mix heavy elements such as 56Ni into the outer layers of the progenitor star. In this study, we find a relation between the mixing of the heavy elements and the density structure of the progenitor star.

## PROGENITOR MODELS

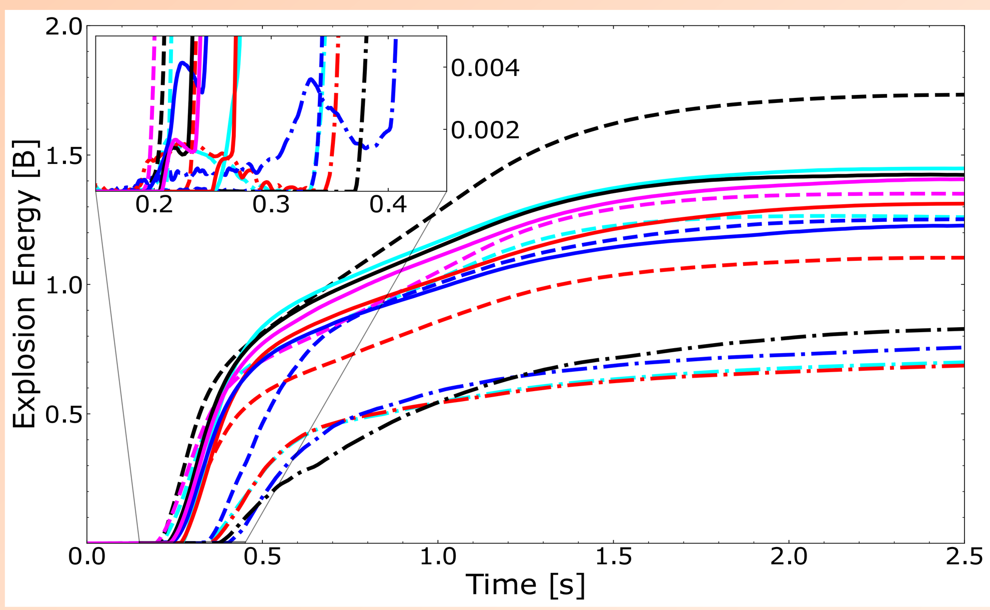
We evolve 14 red supergiant (RSG) progenitor models from [1,2,3] using the numerical code PROMETHEUS-HOTB [4,5].
The models are non-rotating 1D stars with solar composition and were chosen in the mass range between 12.5 and 27.3 solar masses.

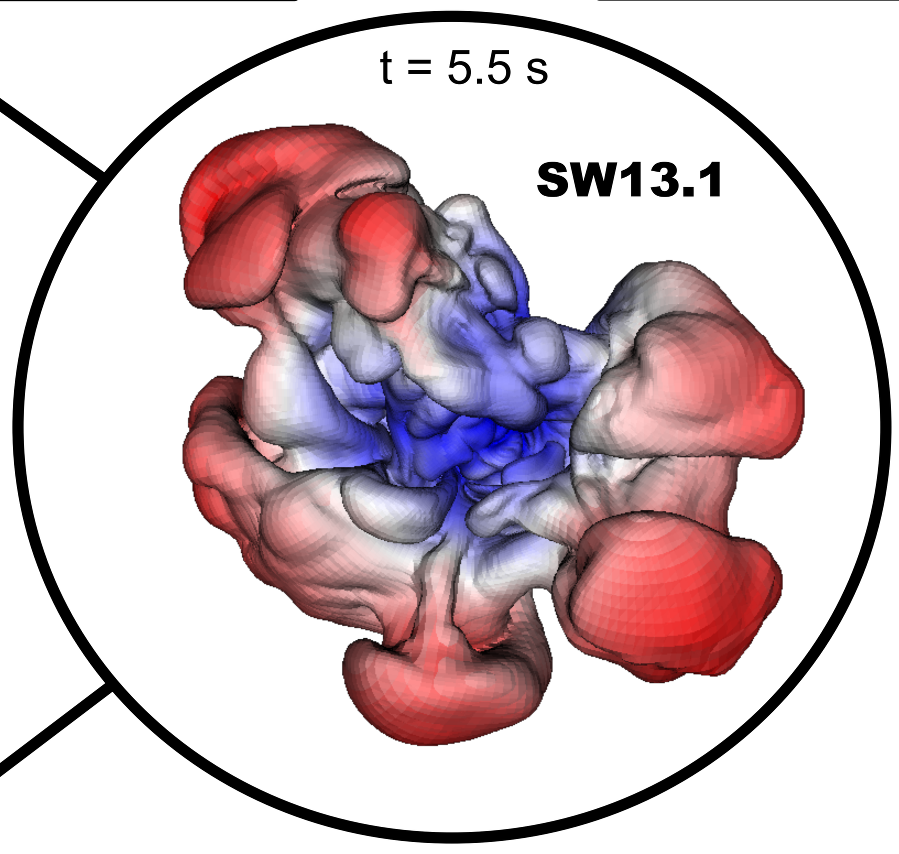
Figure 1

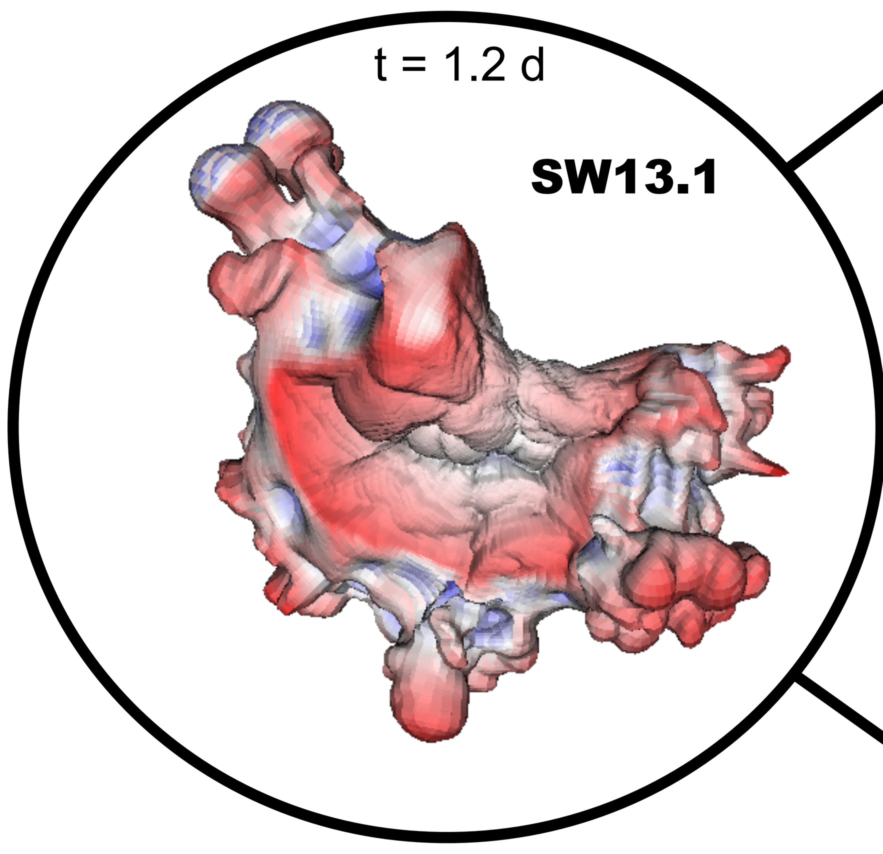



## THE FIRST FEW SECONDS

Figure 2



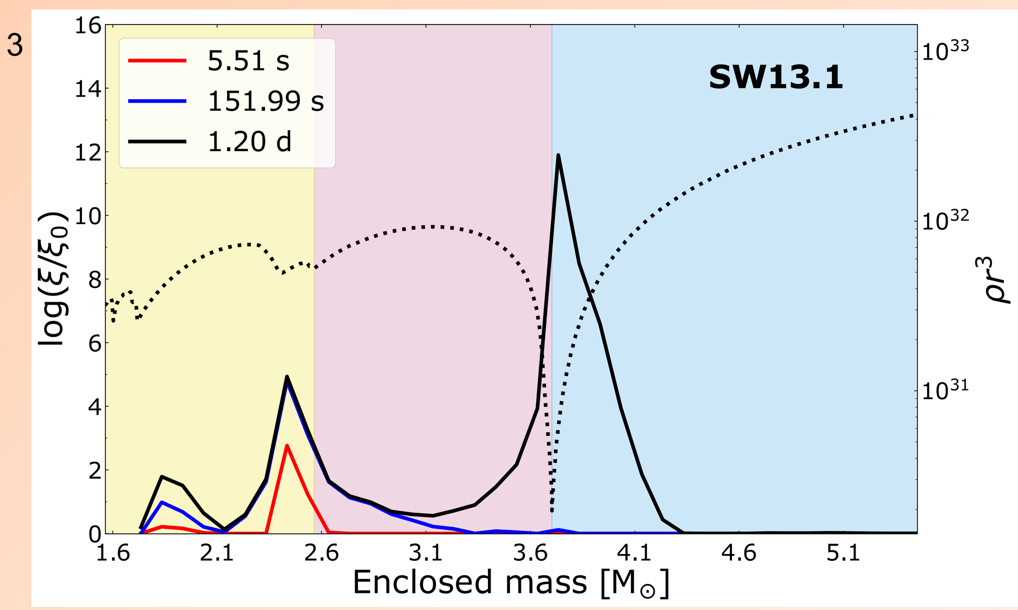




The first few seconds of a SN marking the onset of the explosion are a key moment. During the revival of the shock, instabilities such as convection, advection, and standing accretion shock instability (SASI) can develop. These hydrodynamic instabilities determine the early asymmetries of the matter at early stages and leave their imprint on the morphology of the ejecta even until the very later suernova remnant phase.
The global properties of our 14 explosion models lie in the ranges:

$$0.69\ \mathrm{B} \leq \mathrm{E_{exp}} \leq 1.73\ \mathrm{B}$$
$$0.059\ \mathrm{M_\odot} \leq \mathrm{M_{Ni}} \leq 0.110\ \mathrm{M_\odot}$$
$$1.35\ \mathrm{M_\odot} \leq \mathrm{M_{NS}} \leq 1.60\ \mathrm{M_\odot}$$
$$58.25\ \mathrm{km/s} \leq \mathrm{V_{NS}} \leq 680.6\ \mathrm{km/s}$$
$$0.32 \cdot 10^{46}\ \mathrm{g\ cm^2\ s^{-1}} \leq \mathrm{J_{NS}} \leq 14.42 \cdot 10^{46}\ \mathrm{g\ cm^2\ s^{-1}}$$

## UP TO SHOCK BREAKOUT

Figure 3



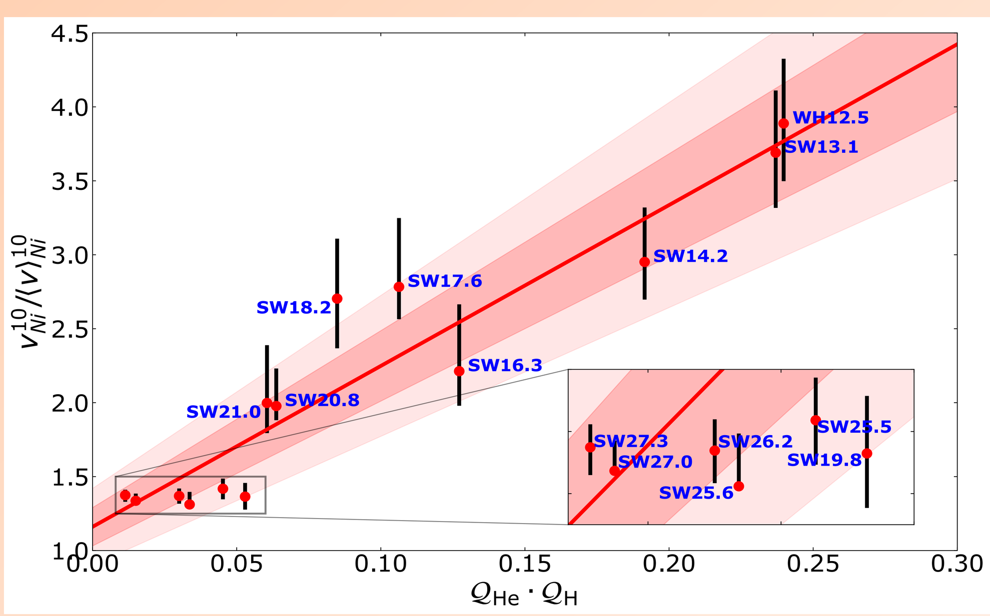

While the forward shock travels into the outer layers of the progenitor star, it encounters different density stratifications. Whenever the gradient of the density is steeper than $r^{-3}$ the shock accelerates, and it decelerates otherwise [6]. This change of density gradient can favor the development of Rayleigh-Taylor instabilities (RTIs). To measure the extent of RTI one can compute the time-integrated growth factor

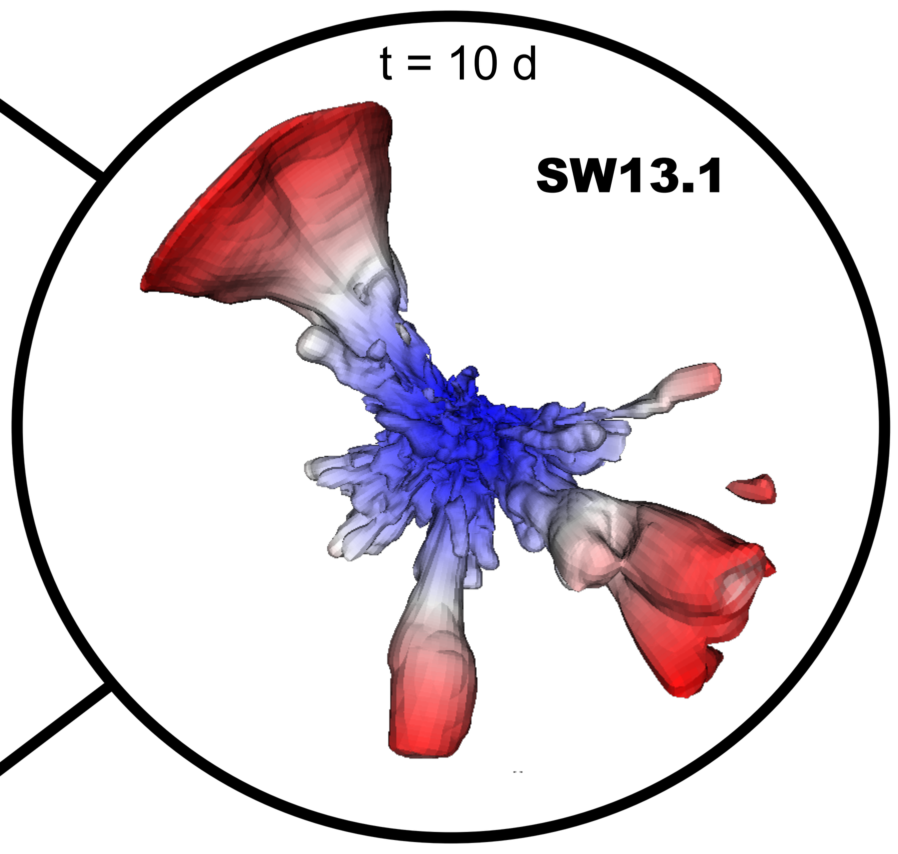
$$\frac{\xi}{\xi_0}(t) = \exp\left(\int_0^t \frac{1}{\rho}\sqrt{-\frac{\partial\rho}{\partial r}\frac{\partial p}{\partial r}}\,d\tau\right)$$

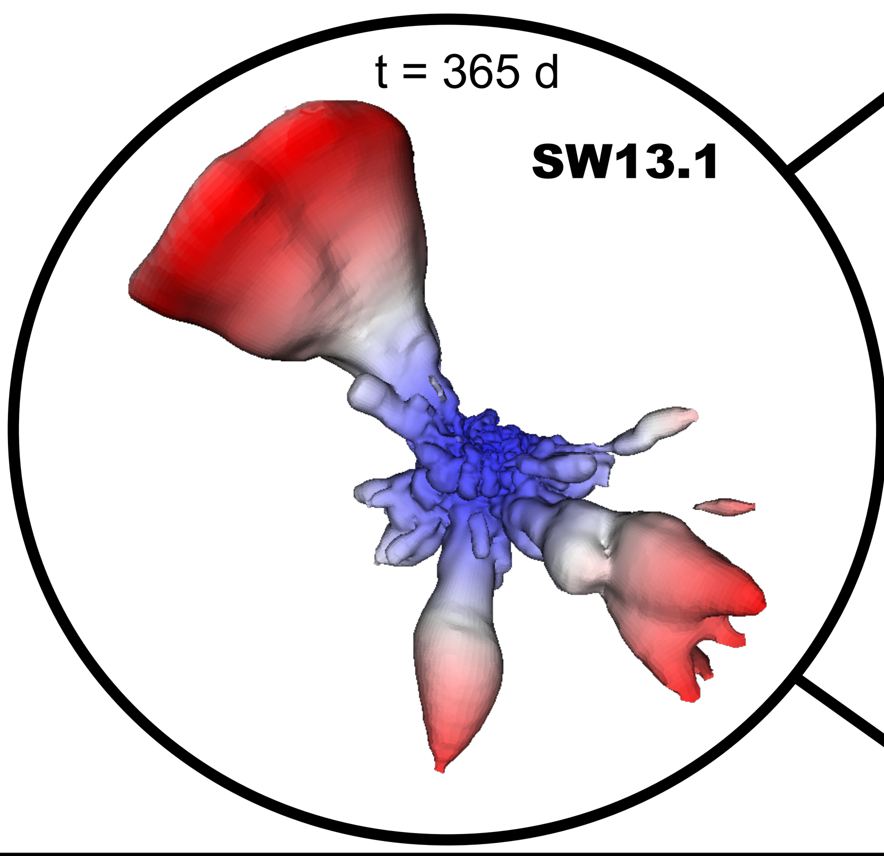
Depending on the progenitor, the interfaces of different shells are prone to the development of RTIs. For model SW13.1 (see figure) the growth factor has strong maxima between the C+O shell (yellow) and the He shell (violet), and between the He shell and the H shell (cyan).

## 10 DAYS AFTER THE EXPLOSION

Figure 4



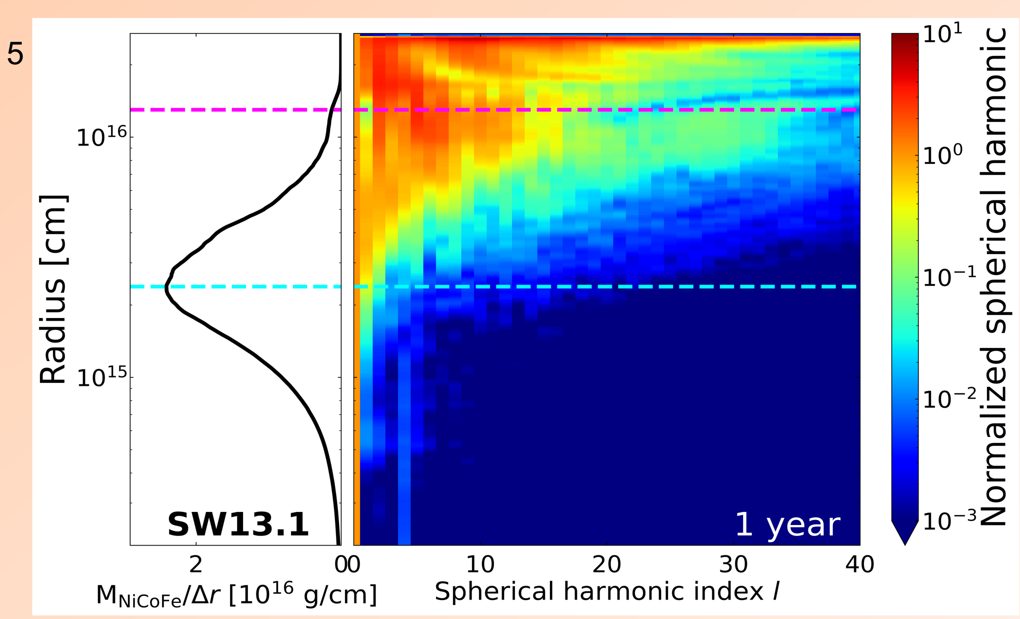

The radial distribution of the density in the progenitor star determines how strongly the $^{56}$Ni is mixed in the outer layers of the star.
In order to quantify the mixing, we consider the mass-weighted average velocity of the fastest 4% of $^{56}$Ni, $v^{10}_{Ni}$, divided by the average velocity of the bulk $\langle v\rangle^{10}_{Ni}$. The rescaling by the bulk velocity reduces the dependency on the explosion energy of the model and allows for a better comparison of models with different explosion energies. We find a linear relation between the extent of $^{56}$Ni mixing and the properties of the He and H shell in the progenitor star

$$Q_{\rm He} \equiv \frac{\int_{R_{\rm (C+O)/He}}^{R_{\rm He/H}} \rho r^3 dr}{\Delta R_{\rm He} \times (\rho r^3)|_{\rm (C+O)/He}} \qquad Q_{\rm H} \equiv \frac{\int_{R_{\rm He/H}}^{2R_{\rm He/H}} \rho r^3 dr}{\Delta R_{\rm H} \times (\rho r^3)|_{2R_{\rm He/H}}}$$

that are measures of how pronounced the maxima in the distribution of $\rho r^3$ are with respect to a flat distribution. The larger Q, the larger the maxima of $\rho r^3$ , hence, the larger the corresponding gradients.

## 1 YEAR AFTER THE EXPLOSION

Figure 5




The spherical harmonics decomposition is a powerful tool to quantify the asymmetries of $^{56}$Ni ejecta in the late phases of a SN [5]. The bulk of $^{56}$Ni has a more spherical shape and hence the l=0 mode dominates in the decomposition. Depending on the model, the distribution of $^{56}$Ni at outer radii can vary. In particular, very asymmetric models, like the one shown in the figure, show a dominance of low modes (0<l<15) if elongated RTI finger-like structures are present. These fingers are seeded by the asymmetries set by early-time hydrodynamic instabilities. More spherical explosions show a dominance of the mode l=0 for all the radii, with some deviations due to the production of small RTI fingers during later stages.

## SUMMARY

Hydrodynamic instabilities play a crucial role in the evolution of the ejecta of SN explosions. Understanding how they form and how they develop can prove to be a fundamental element in connecting properties of the explosions to properties of the originating progenitor stars. Indeed, we find that the mixing of heavy elements, here exemplary $^{56}$Ni, is determined by the development of RTIs, which in turn are related to the particular stratification of the outer layers of the progenitor star. We can identify 3 groups: i) explosions with low energies (i.e. < 1 B) and strong mixing, top right models in Figure 4; ii) explosions with high energies generated by medium-low mass stars which have intermediate mixing and $0.05 < Q_{He}Q_H < 0.15$; iii) explosions with high explosion energies generated by high-mass stars which have minimal mixing (see inlet in Figure 4). Studying the 3D distribution of elements which is determined by the hydrodynamic instabilities in different phases of a SN explosion can be a starting point to bridge the gap in the connection between SNe and their progenitors.

## REFERENCES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