On the isotopic yields of thermonuclear explosions in non-accreting progenitors

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Introduction:

Type Ia supernovae (SNe Ia) are traditionally associated with thermonuclear explosions in binary star systems. Recent theoretical work (Antoniadis et al. 2020) challenges this paradigm by suggesting that SNe Ia-like explosions may also arise from non-accreting single-star progenitors. If substantiated, this alternative channel could affect the SNe Ia rate in star-forming galaxies. Building on the **1D stellar evolution models from Antoniadis et al. (2020) using MESA**, this study extends the investigation to **3D simulations of the explosion phase**.

Ignition of a (C)ONe White Dwarf:

- Stripped He star (2.5 $M_\odot$) develops a **CO core** during He burning
- C burning ignites off-center, and turbulent flame propagates inwards, forming a **ONe core**
- e^- -captures on **^{24}Mg → ^{24}Na → ^{24}Ne**.
- Releases heat, increasing core temperature.
- Leftover C burning initiates runaway O burning and a thermonuclear explosion.

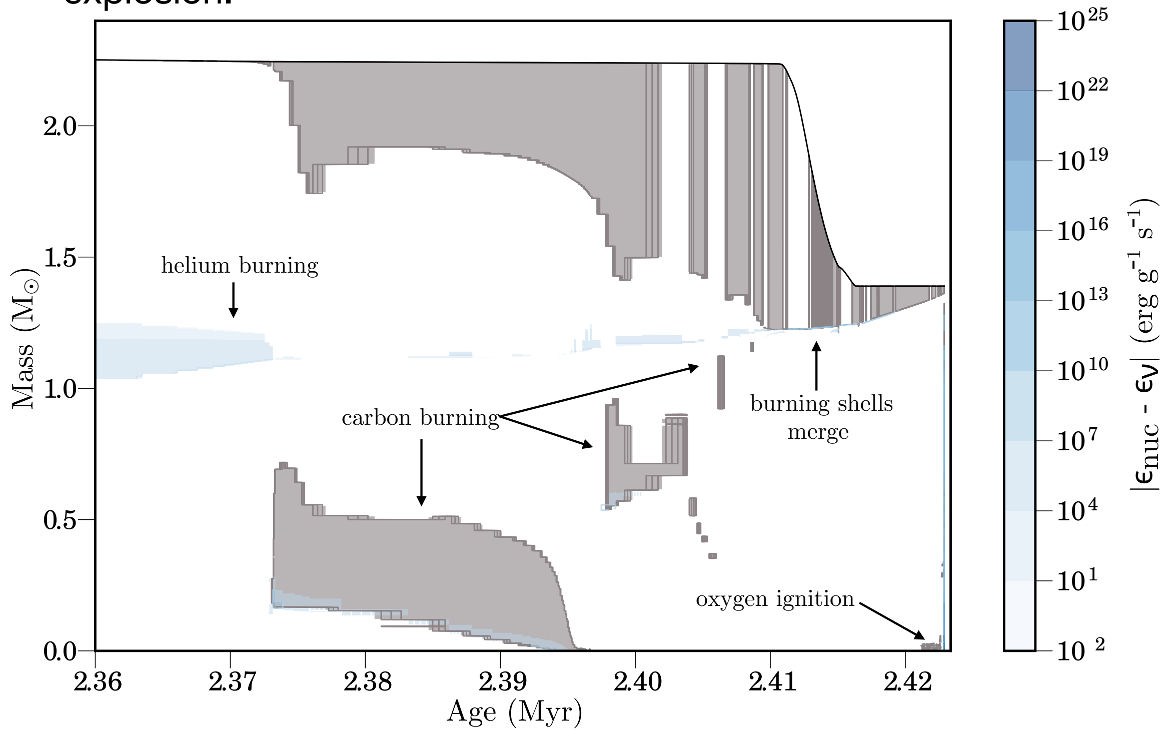

Figure: Kippenhahn diagrams following the evolution after core He depletion. Blue shaded areas indicate regions in which nuclear burning occurs, i.e. locations for which the nuclear energy ϵ_{nuc} exceeds energy losses due to neutrino emission, ν. Grey regions are subject to convective mixing. t = 0 corresponds to the onset of core He burning. Adapted from Antoniadis et al. (2020)

Core Evolution

- **Off-center C ignition** at **~0.3 $M_\odot$**
- Secondary burning episodes propagate inwards and outwards
- Core composition: **Ne, O, Mg**, with residual **C**

Final 5,000 years:

- Shell burning intensifies → **Envelope expands to ~900 $R_\odot$**
- Strong wind mass loss (~$10^{-2.8}$ $M_\odot$/yr) → **Complete He removal**
- Final pre-ignition mass: ~1.39 $M_\odot$

Acknowledgments

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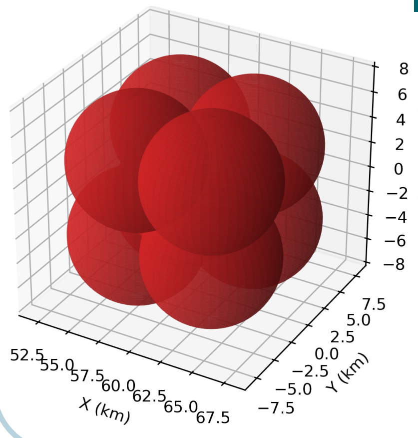
Model Setup:

- **Initial Composition**:

Species	^{16}O	^{20}Ne	^{24}Mg	^{12}C	^{23}Na	^{25}Mg
Mass Fraction	0.43	0.42	0.1	0.011	0.037	0.001

- Density: $\log_{10}(\rho_c/\mathrm{g\ cm^{-3}}) = 9.77$
- $Y_e = 0.496$
- Ignition at 60km off-centre

Ignition:



- In Leafs the flame is artificially ignited.
- The configuration employed consists of 9 overlapping bubbles, each of 5km, similar to Lach et. al. (2022)

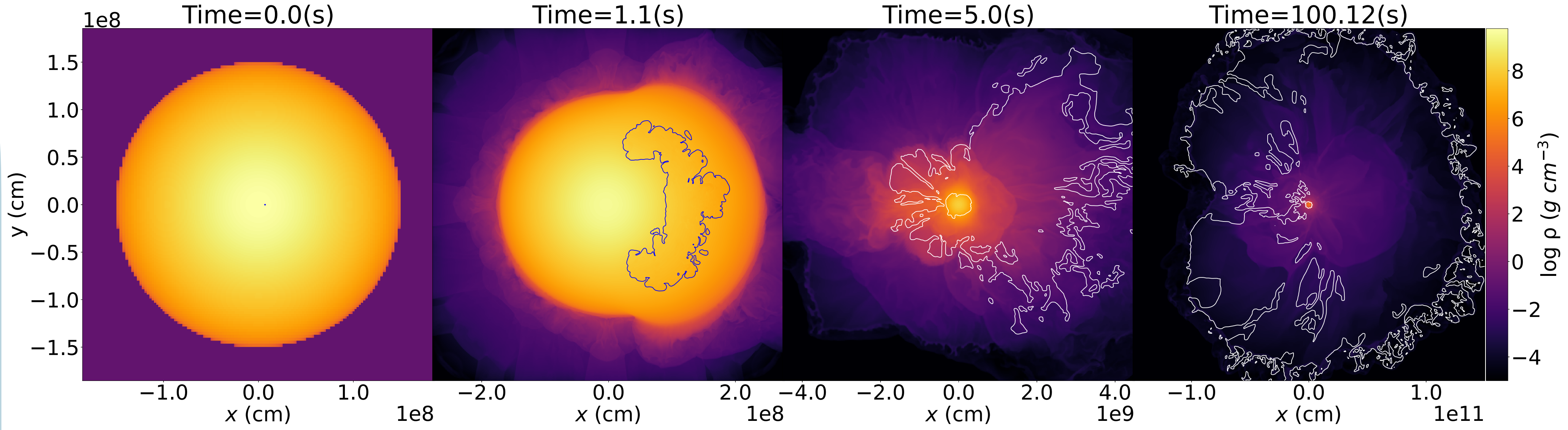


Figure: Leafs 3D simulation of the explosion showing the density distributions at different time steps

- **Ignition Phase** – Localized single spot ignition, starting laminar burning.
- **Turbulent Burning** – The flame front wrinkles due to turbulence, enhancing the burning rate.
- **Expansion Phase** – The white dwarf starts expanding as nuclear energy release drives the explosion ejecting material
- **Homologous Expansion** – The explosion reaches homologous expansion. Density is significantly lower, with turbulent structures persisting in the ejecta.

Nucleosynthesis:

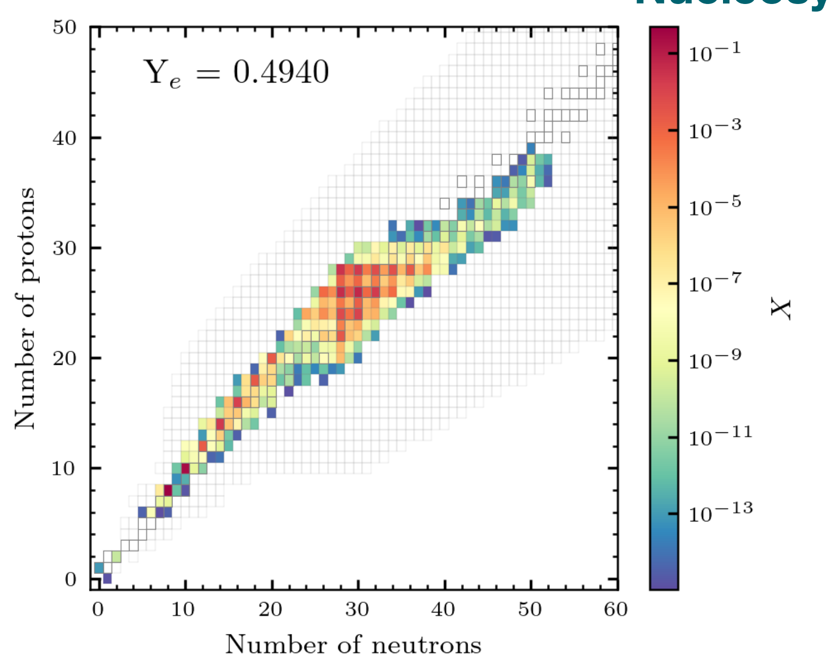


Figure: Isotopic abundances.

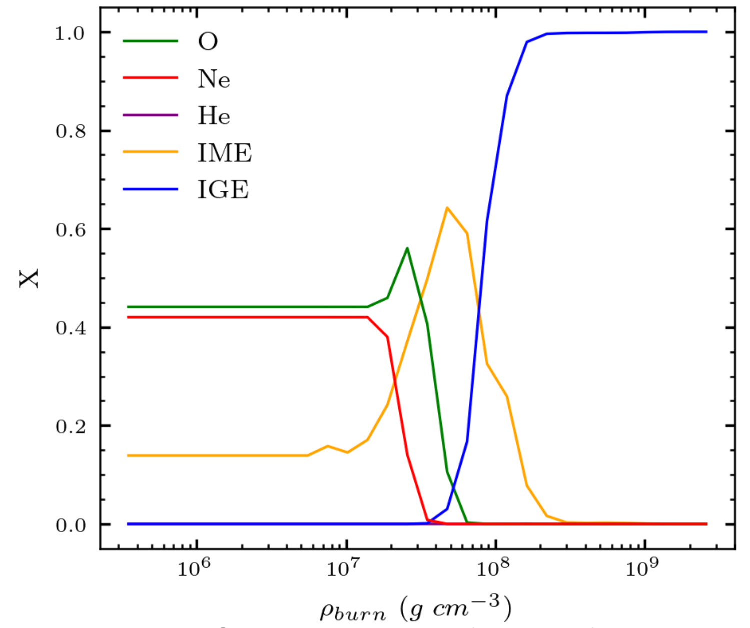


Figure: NSE composition as a function of density

- **Post-processing step**: Get detailed abundances → nuclear network
- Preliminary results: Production of Iron Group Elements (IGE) as well as some Intermediate Mass Elements (IME) due to incomplete Si burning
- Different burning stages can be distinguished. In high density regime $\rho_{burn} \gtrsim 10^8$ fuel is burnt to Iron Group Elements. For intermediate fuel densities $10^7 \lesssim \rho_{burn} \lesssim 10^8$, O and Ne burn to intermediate mass elements (IME: 11 ≤ Z ≤ 21). Below $\rho_{burn} \lesssim 10^7$ burning ceases.

Leafs

- Eulerian finite volume hydro code
- Hybrid moving mesh
- Nuclear burning happens instantaneously at the burning front
- Burning fronts are treated as discontinuities with the **level set** approach
- A turbulence scheme is used to model the interaction of the flame with turbulence and propagate the flame

Importance of C:

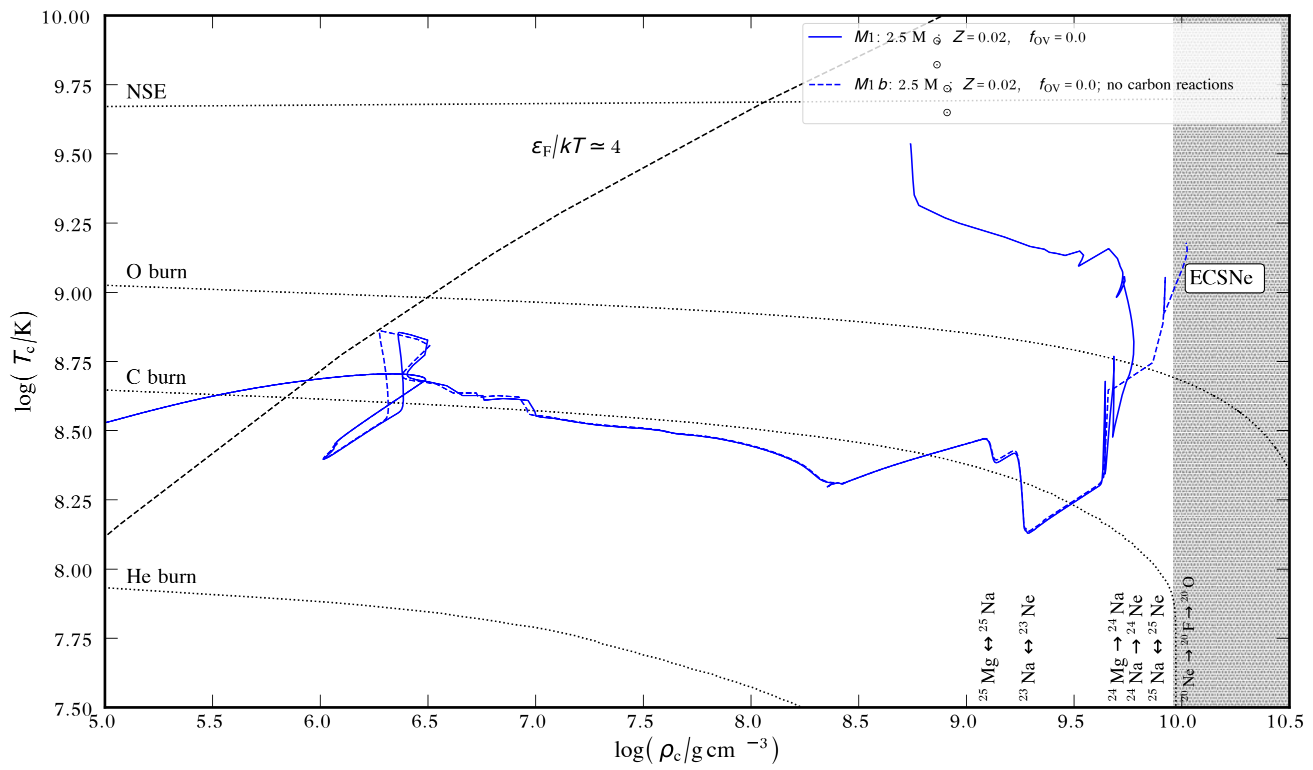


Figure: Core density and temperature evolution. The black dashed line shows the approximate boundary for electron degeneracy. The M1 model includes energy contribution from C burning. Adapted from Antoniadis et al. (2020)

- If the model does not include residual C, the core's density can increase enough that e^--captures on ^{20}Ne start taking place. This will lead to a core collapse ECSN
- If the model considers the energy released due to the residual C burning, then a thermonuclear explosion takes place before the core reaches the density needed for the e^--captures on ^{20}Ne.

Next Steps:

- How would these objects look observationally?
- The next objective is to create synthetic light curves and spectra through radiative transfer modeling.
- The radiative transfer should also potentially include interactions with the H envelope.

References:

Antoniadis, J., Chanlaridis, S., Gräfener, G., & Langer, N., Type Ia supernovae from non-accreting progenitors, A&A, 635 (2020), A72

F. Lach, F. P. Callan, D. Bubeck, F. K. Röpke, S. A. Sim, M. Schrauth, S. T. Ohlmann, M. Kromer, Type Iax supernovae from deflagrations in Chandrasekhar mass white dwarfs, A&A, 658 (2022) A179