Improved Nuclear Network for Studying the Convective Urca Process in Type Ia Supernova Progenitor

Brendan Boyd [1,2] Ferran Póca Amoros [1,2,3] Alan Calder [1,2] Dean Townsley [4] Michael Zingale [1]

[1]Department of Physics and Astronomy, Stony Brook University [2]Institute for Advanced Computational Science, Stony Brook University [3]Dept. Física i Enginyeria Nuclear, Univ. Politècnica de Catalunya, and Institut d'Estudis Espacials de Catalunya [4]Department of Physics and Astronomy, University of Alabama

Introduction

Type Ia Supernova Progenitor

Type Ia Supernovae (SNe Ia) are thermonuclear explosions of roughly a solar mass of white dwarf material. The exact progenitor system that leads to SNe Ia is not well understood. Proposed ideas include a white dwarf accreting material from a companion star to the point of carbon ignition in the core. This begins the simmering phase where carbon burning drives core convection for about 1,000 to 10,000 years before the thermonuclear explosion. The carbon burning alters the composition of the core region which in turn impacts the nucleosynthesis of the SNe Ia we observe.

Low-Mach Hydrodynamics: MAESTROeX

The convection in a simmering white dwarf is slow compared to the sound speed (Mach Number $\sim 10^{-3}$). To efficiently model this slow moving regime, we use the MAESTROeX low-Mach hydrodynamic code [1], which is specifically designed to model stellar interiors and atmospheres. MAESTROeX effectively filters out the sound waves while still accurately modeling the convection. Our simulations are full 3D and resolve the convective core to 5 km. We incorporate a reaction network to model the carbon burning and Urca reactions (See Fig. 2) The full source code for MAESTROeX can be found at github.com/AMReX-Astro/MAESTROeX.

Convective Urca Process

The Urca process is the combination of a beta-decay and electron-capture which connects a pair of nuclei, called an Urca pair. A relevant Urca pair to simmering white dwarfs is the A=23 pair:

$$\begin{aligned} {}^{23}\mathrm{Ne} &\rightarrow {}^{23}\mathrm{Na} + e^- + \bar{\nu}_e \\ {}^{23}\mathrm{Na} + e^- &\rightarrow {}^{23}\mathrm{Ne} + \nu_e \end{aligned} \tag{1}$$

The convective Urca process links the Urca reactions with convection creating a cyclical process. Convection transports material above and below the **Urca Shell, the region where the Urca reactions are in local equilibrium**. Material mixed below the shell will electron-capture while that mixed above will beta-decay. Since convective Urca can continue without additional fuel, only small fractions of Urca nuclei are needed to impact the white dwarf's evolution. Convective Urca results in local cooling (from emitted neutrinos) and compositional changes (particularly to Y_e) which impact buoyancy and convection itself [2, 3].

Simmering White Dwarf

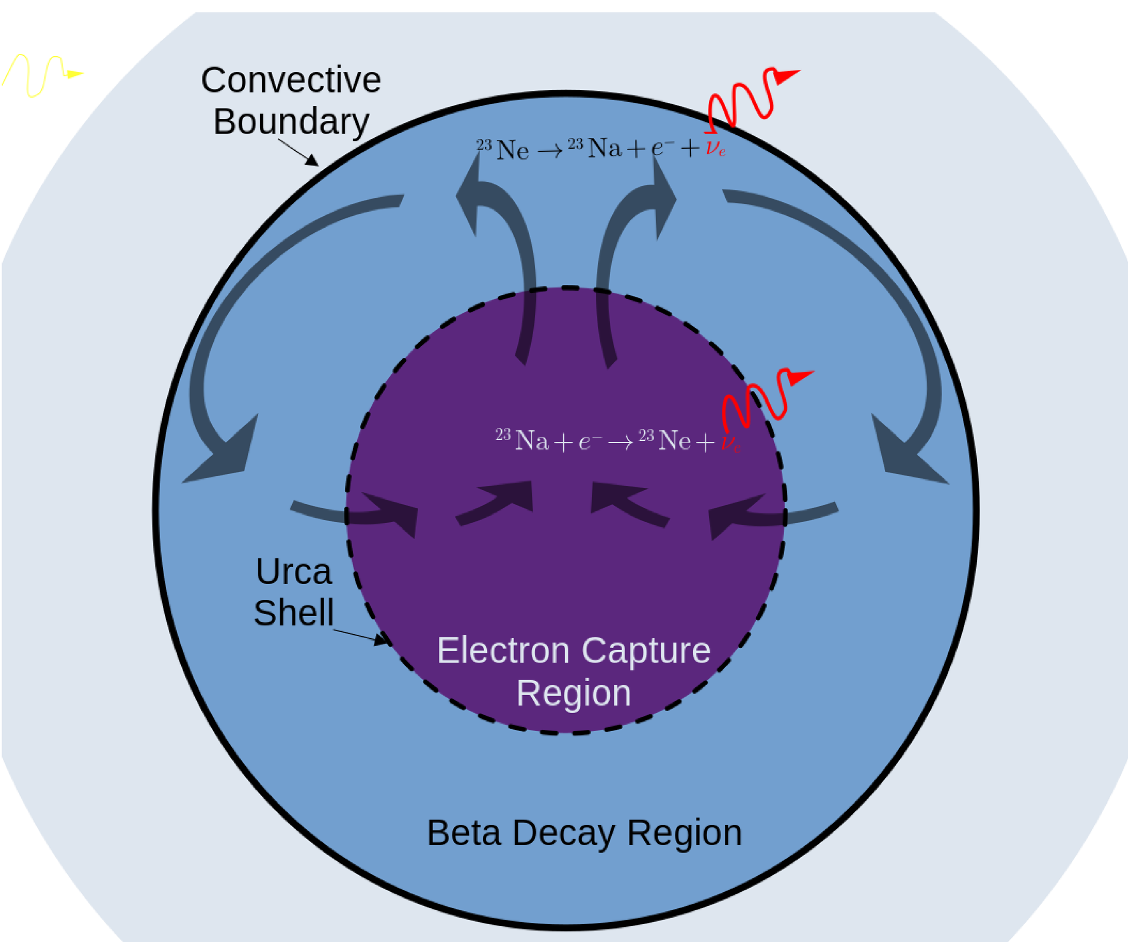

Figure 1. Cartoon of the interior of a convection white dwarf with the regions annotated with respect to the convective Urca process.

We set the initial state of our simulations to represent a 40% - 60% Carbon-Oxygen white dwarf with trace amounts of other nuclei informed by 1D stellar models [4]. We start with a central density $\rho_c = 4.5\times10^9$ g/cm^3 and temperature $T_c = 5.5\times10^8$ K. We integrate outward maintaing hydrostatic equilibrium with an isentropic core (reprenting the convection zone) and isothermal envelope. This setup was motivated by 1D stellar evolution models [5] and previous work including that by Don Willcox for his dissertation [6].

References

[1] D. Fan, A. Nonaka, A. S. Almgren, A. Harpole, and M. Zingale. *ApJ*, 887(2):212, December 2019.

[2] P. Lesaffre, Ph. Podsiadlowski, and C. A. Tout. *MNRAS*, 356(1):131–144, January 2005.

[3] J. Stein and J. C. Wheeler. *ApJ*, 643(2):1190–1197, June 2006.

[4] J. Schwab, H. Martínez-Rodríguez, A. L. Piro, and C. Badenes. *ApJ*, 851(2):105, December 2017.

[5] H. Martínez-Rodríguez, A. L. Piro, J. Schwab, and C. Badenes. *ApJ*, 825(1):57, July 2016.

[6] D. E. Willcox. PhD thesis, SUNY Stony Brook, 2018.

[7] B. Boyd, A. Calder, D. Townsley, and M. Zingale. *ApJ*, 979(2):216, February 2025.

[8] A. I. Smith, E. T. Johnson, Z Chen, K. Eiden, D. E. Willcox, B. Boyd, L. Cao, C. J. DeGrendele, and M Zingale. *ApJ*, 947(2):65, April 2023.

Comparing Nuclear Networks

Previous work used a very simple carbon burning network [7], which doesn't accurately model the energy generation and left out additional Urca pairs (A=21 and A=25). We vastly improve the nuclear network including **21 nuclei and 33 rates** (compared to 9 and 7 respectively). More complex networks have high computational costs for 3D simulations, though this can partially be offset with GPU acceleration. As shown in Fig. 7, we run simulations without the beta-decay rates to untangle the effects of the convective Urca process. All our networks are constructed using the `pynucastro` python package (**https://pynucastro.github.io**) [8].

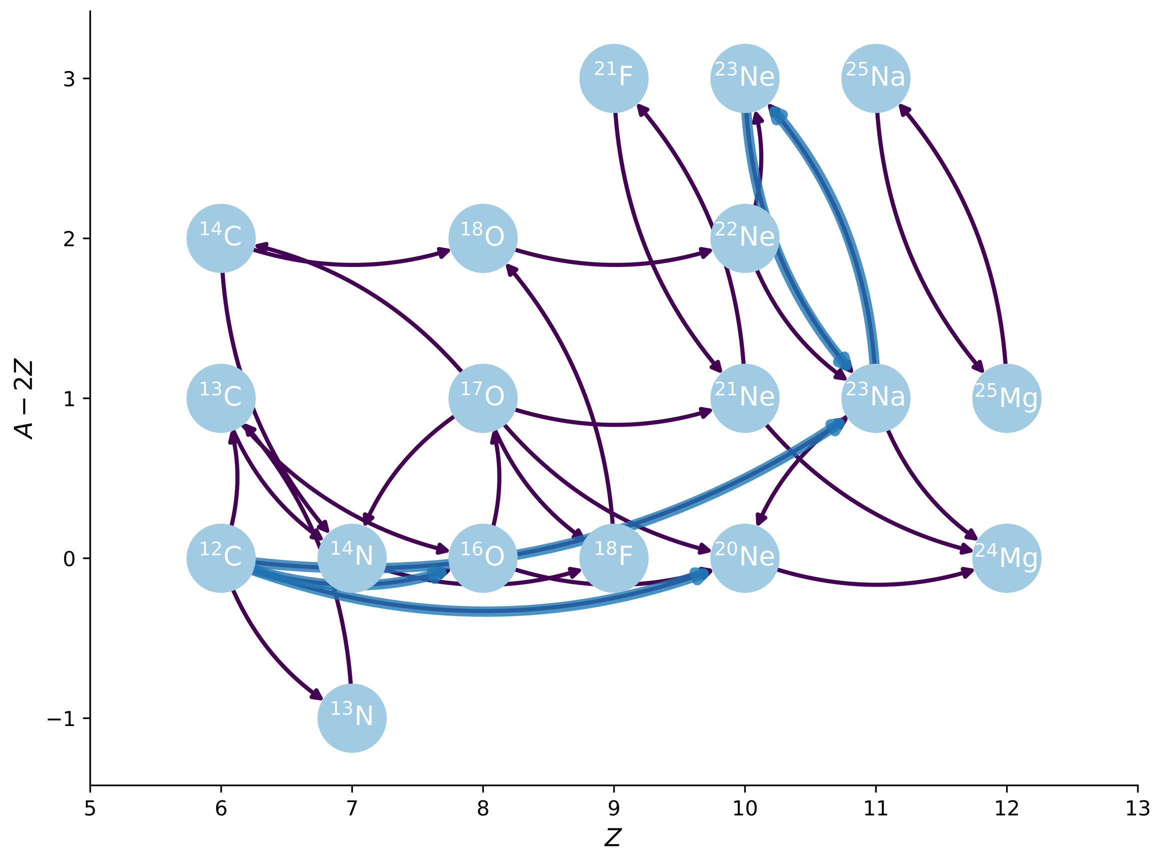

Figure 2. The proton number is shown on the x-axis, while the neutron-proton balance is displayed on the y-axis. Arrows indicate reaction rates w/ direction. Highlighted arrows indicate rates used in the "simple network". Note, n p and ^{4}He are not displayed but are included in the network.

Energy Generation and Compositional Changes

To test the validity of our nuclear network, we use a toy model of convection. We track a fluid parcel which cyclically convects from the center of the white dwarf to the outer regions of the convection zone. We calculate the energy generation of this fluid as well as the changing composition over time. We compare the above "large network" to a "full network" which is made of 38 nuclei and 309 rates. The nuclear energy is generated primarily by the ^{12}C burning in the core with smaller contributions away from the core coming primarily from the A=23 Urca pair.

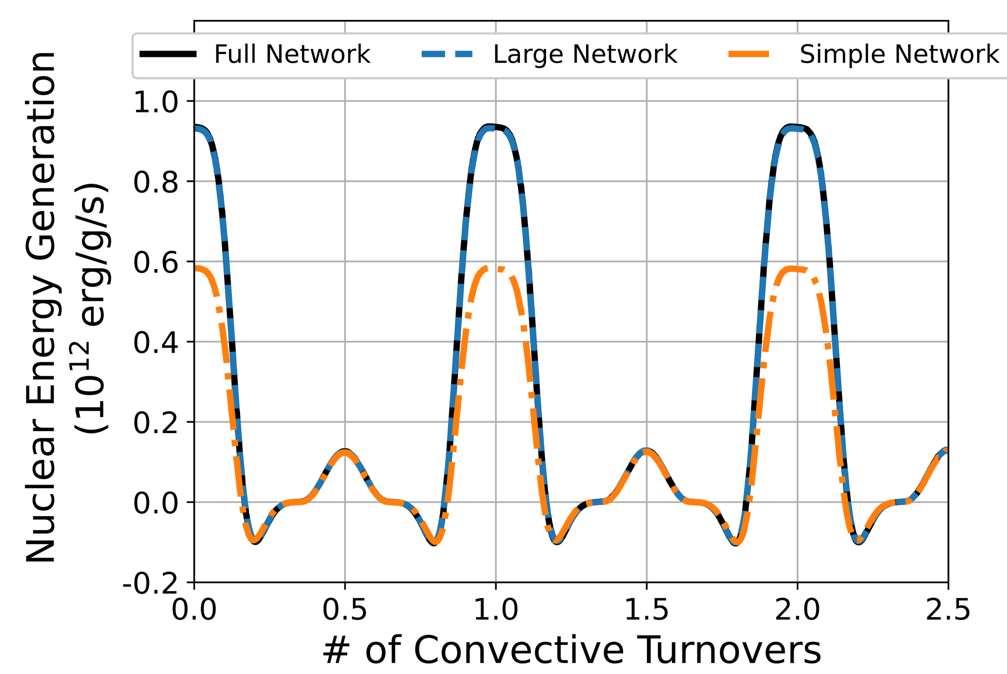

Figure 3. Time series of the specific energy generation rate from our test fluid. The three curves represent the three tested nuclear networks.

The compositional differences are smaller, but the states begin to diverge after just a few convective turnovers. Accurately modeling the electron fraction is important to the convective Urca process and understanding the final nucleosynthesis of the Type Ia explosion. Note, we evolve full simulations for order hundred convective turnovers.

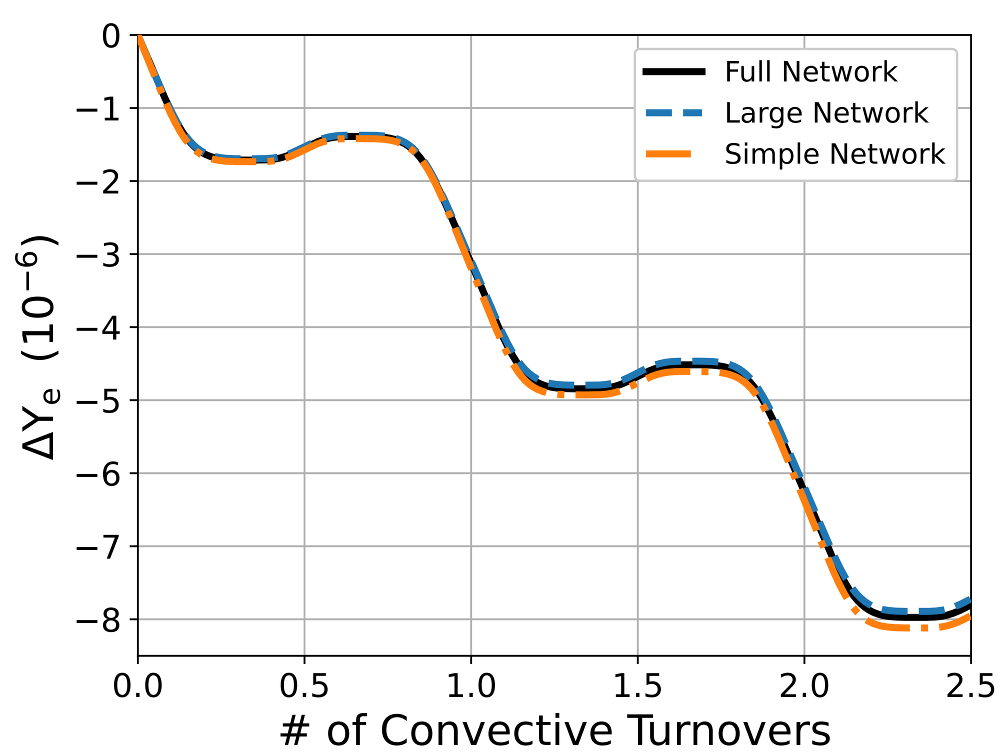

Figure 4. Time series of the change in electron fraction for our test fluid. Note the composition for each network is slightly different due to the differing sets of included nuclei. The three curves represent the three tested nuclear networks.

Full 3D Simulation Results

We present preliminary results of simulations using the network in Fig. 2. These simulations were evolved for about an hour which accounts for >100 turnovers. A key aspect of these simulations is the complex compositional mixing. We can visualize this by looking at a product of carbon burning (in this case ^{24}Mg) or the radial velocity (Fig. 6). Note, **the highly directional, "dipolar flow", makes this convection difficult to model in 1D.** Also, see in Fig. 7 that convection mixes material well past the multiple Urca shells.

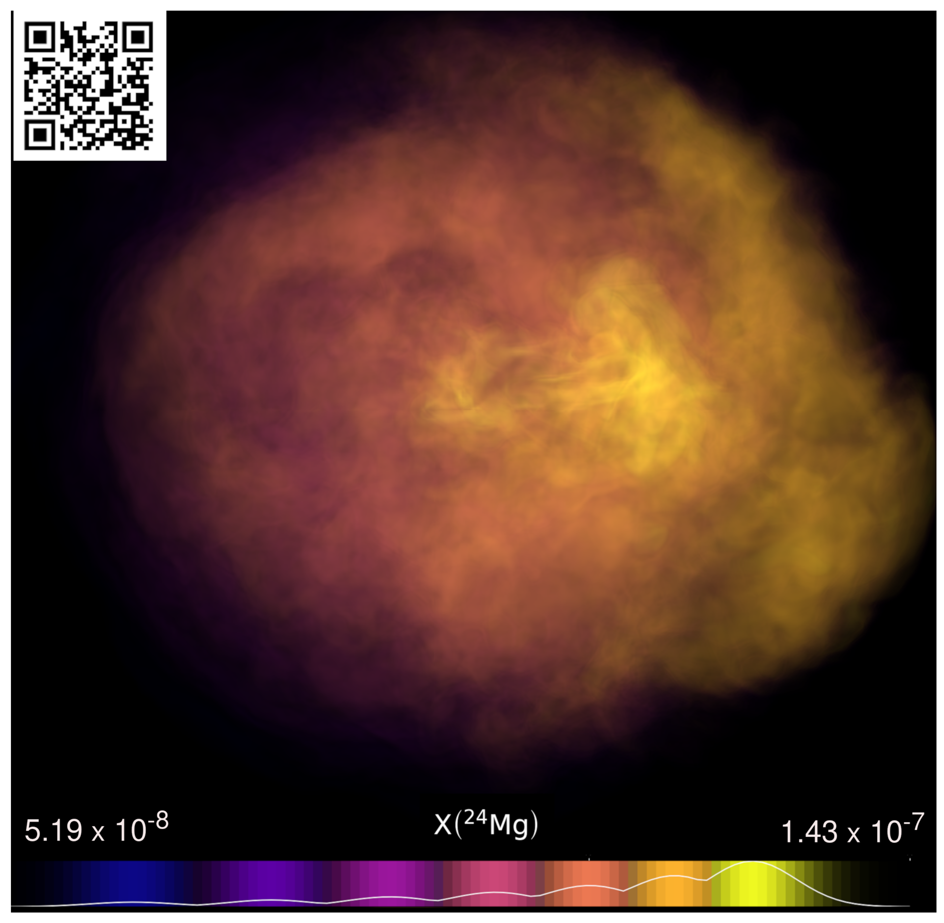

Figure 5. Volume Render of the X(^{24}Mg) in the convective core of the white dwarf. The orientation is the same as Fig. 6.

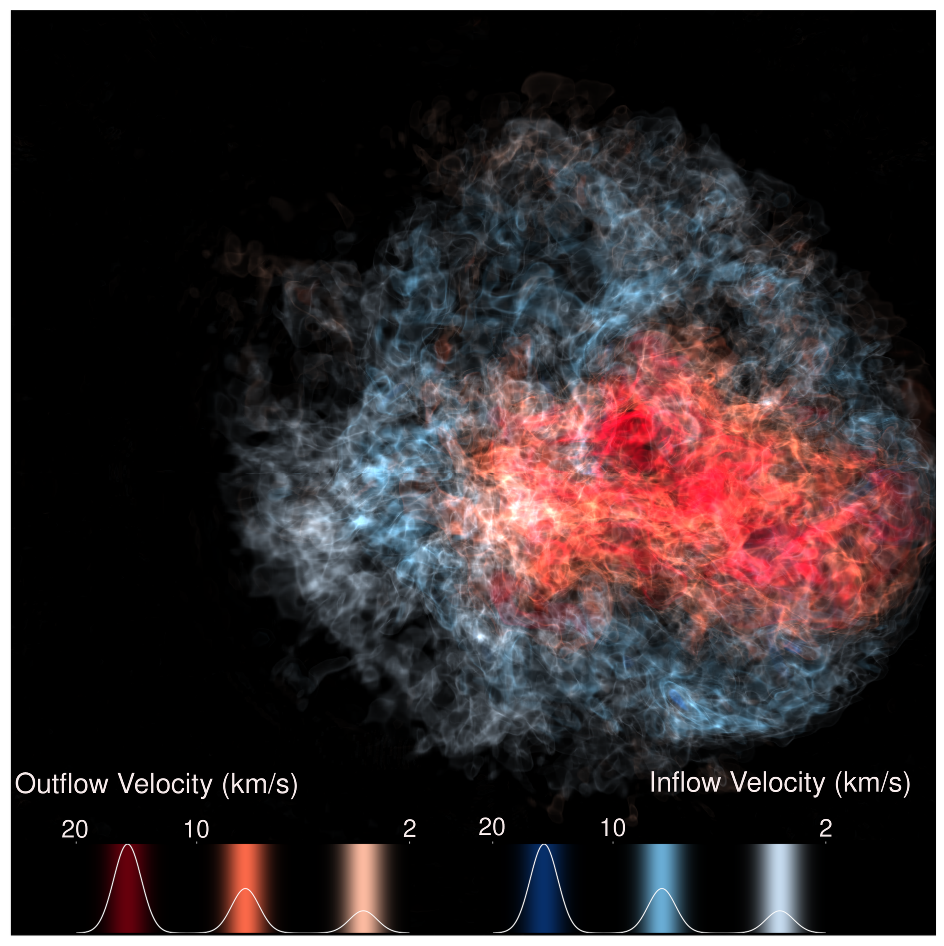

Figure 6. Volume render of the radial velocity. Red colored fluid indicates outflowing material, while blue indicates inflowing material. The orientation is the same as Fig. 5.

Urca vs No Urca

Understanding the Urca process is difficult due to the highly nonlinear nature of the nuclear burning, and turbulent convection. To help our analysis, we run a simulation without the convective Urca process to compare. Preliminary results from this work indicate **the convective Urca process slows/limits the size of the convection zone**, though the effect is smaller than some theoretical predictions. See Ferran Póca Amoros's poster *"3D Simulations of the Convective Urca Process in Type Ia Supernova Progenitor"* for further investigation of this phenomena.

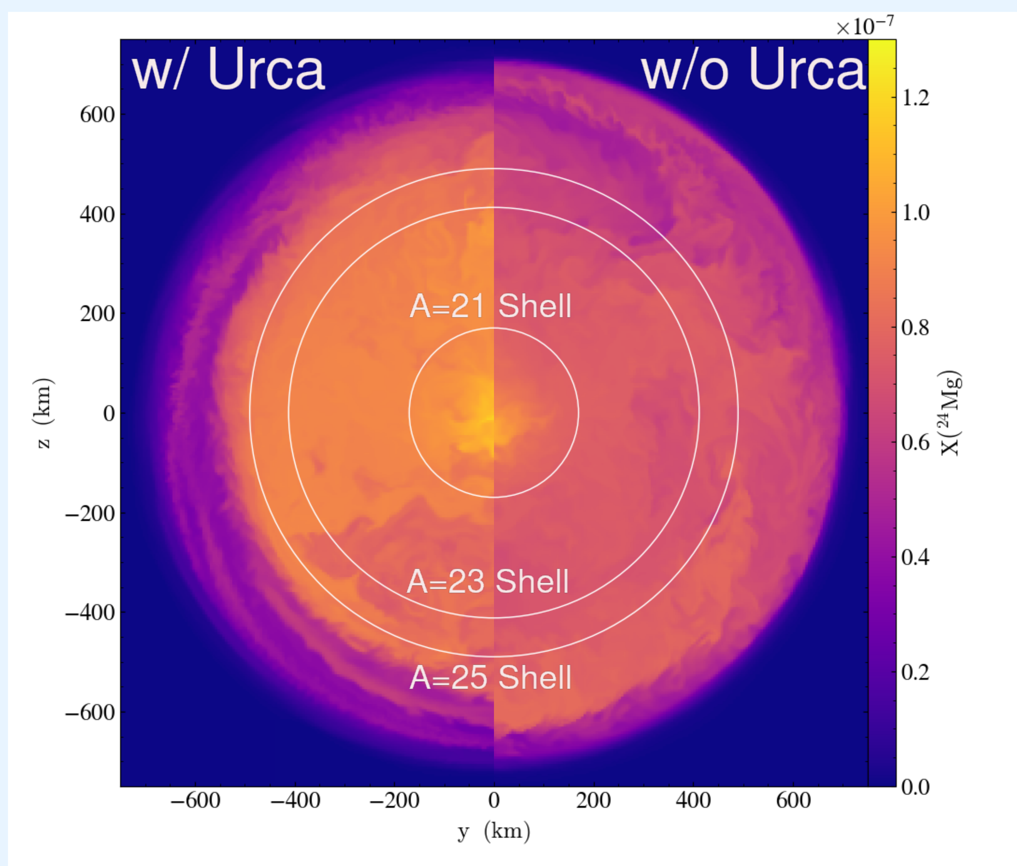

Figure 7. Slice through the core of the white dwarf showing X(^{24}Mg). The left half is from a simulation with the convective Urca process, using the network in Fig. 2. The right half is from a simulation without the convective Urca process, i.e. missing the beta-decay rates. The white circles mark the location of the three Urca shells.

boyd.brendan@stonybrook.edu NIC 2025 This research was supported in part by the US Department of Energy (DOE) under grant DE-FG02-87ER40317