ASTRONUM 2024

Low Mach Simulations of the Convective Urca Process in a Type Ia Supernova Progenitor

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Type Ia Supernovae

- Extremely bright, with peak similar to a galaxy
- Thermonuclear explosions
  - powered by nuclear reactions
- Important to other areas of astronomy (e.g. cosmology)

High-Z Supernova Search Team/HST/NASA

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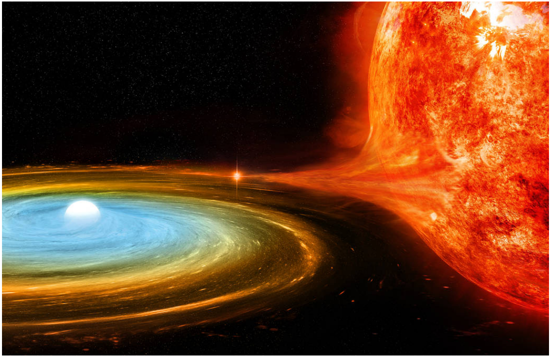
- **Exact origins are still unclear**
  - Sub-Chandrasekhar mass
  - Chandrasekhar mass

High-Z Supernova Search Team/HST/NASA

Chandrasekhar Mass Progenitor

- Mass transfer onto White Dwarf from companion
- More Mass == Hotter & Denser core
- Explosion due to runaway Carbon burning

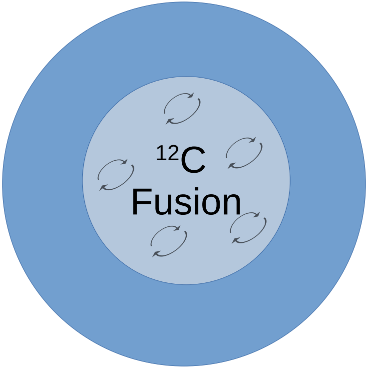


NASA/CXC/M. Weiss

Simmering Phase of White Dwarf

- Carbon starts burning slowly
- 1,000-10,000 years of convection, "simmering/smoldering"

ESA/Justyn Maund/Queens University Belfast

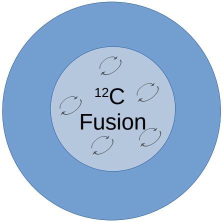


A Brendan Boyd Original

The Convective Urca Process

Convection

- Powered by carbon burning in core
- Mixes material across densities



Urca Process

- Relation between two weak reactions

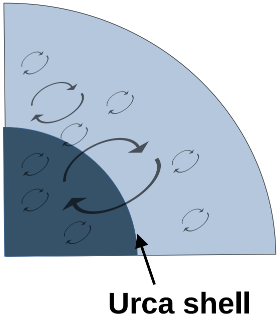
$$\begin{aligned} {}^{23}\mathrm{Ne} &\rightarrow {}^{23}\mathrm{Na} + e^{-} + \bar{\nu}_e \\ {}^{23}\mathrm{Na} + e^{-} &\rightarrow {}^{23}\mathrm{Ne} + \nu_e \end{aligned} \tag{1}$$

- Primarily density dependent reactions
- ν_e's free stream from star

The Urca Shell

$$
\begin{aligned}
{}^{23}\mathrm{Ne} &\rightarrow {}^{23}\mathrm{Na} + e^- + \bar{\nu}_e \\
{}^{23}\mathrm{Na} + e^- &\rightarrow {}^{23}\mathrm{Ne} + \nu_e
\end{aligned}
\tag{2}
$$

- Density where reactions are at equilibrium
- Keys to Convective Urca:
  - Cyclical, continuous reactions
  - Only need small amount of Urca pair
  - Urca reactions can impact convection



MAESTROeX: Low Mach Reactive Hydrodynamics

- Typical Mach number of ∼0.005
- Finite Volume Method. Divide the volume into cells and construct fluxes between cells.
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$$\frac{\partial(\rho X_k)}{\partial t} = -\nabla \cdot (\rho X_k \boldsymbol{U}) + \rho\dot{\omega}_k, \tag{1}$$

$$\frac{\partial \boldsymbol{U}}{\partial t} = -\boldsymbol{U} \cdot \nabla \boldsymbol{U} - \frac{\beta_0}{\rho}\nabla\left(\frac{\pi}{\beta_0}\right) - \frac{\rho - \rho_0}{\rho} g \boldsymbol{e}_r, \tag{2}$$

$$\frac{\partial(\rho h)}{\partial t} = -\nabla \cdot (\rho h \boldsymbol{U}) + \frac{Dp_0}{Dt} + \rho H_{\text{nuc}}. \tag{3}$$

$$\nabla \cdot (\beta_0 \boldsymbol{U}) = \beta_0\left(S - \frac{1}{\overline{\Gamma}_1 p_0}\frac{\partial p_0}{\partial t}\right). \tag{7}$$

Reaction Network & Initial Model

Reaction Network

- Simple $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ burning (JINA REACLIB)
- $A = 23$ Urca reactions (Suzuki et al. 2016)

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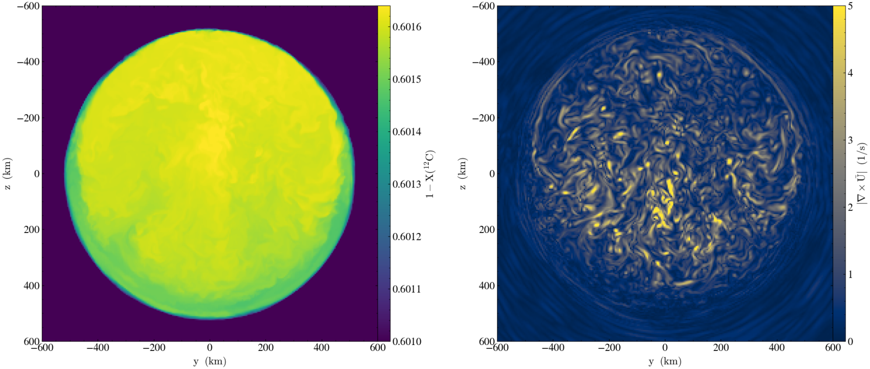
pynucastro

Initial Model

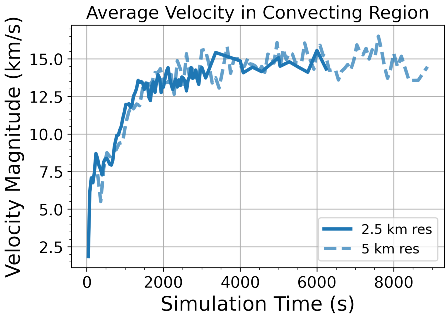
- $\mathrm{T_c} = 5.5 \times 10^8$ K
- $\rho_c = 4.5 \times 10^9 \; g/cm^3$
- Isentropic core ($0.5\,\mathrm{M}_\odot$). Stable envelope
- Composition:
  - $\sim$40% $^{12}\mathrm{C}$
  - $\sim$60% $^{16}\mathrm{O}$
  - 0.05% Urca pair

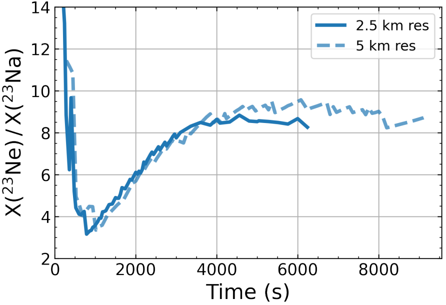
What the Convection looks Like?

- Full star 3D. Max refinement limited to convection zone



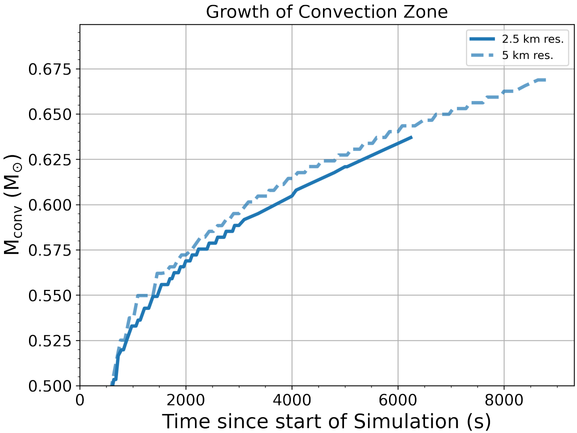
- Ideally want convection to reach a (quasi) steady state.





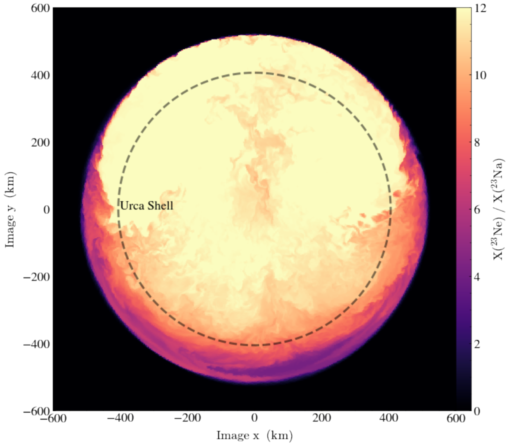
Convection Zone

- Ideally want convection to reach a (quasi) steady state.
- $\dot{M}_{\mathrm{conv}} \sim 0.03 - 0.05\ \mathrm{M}_{\odot}/\mathrm{hr}$



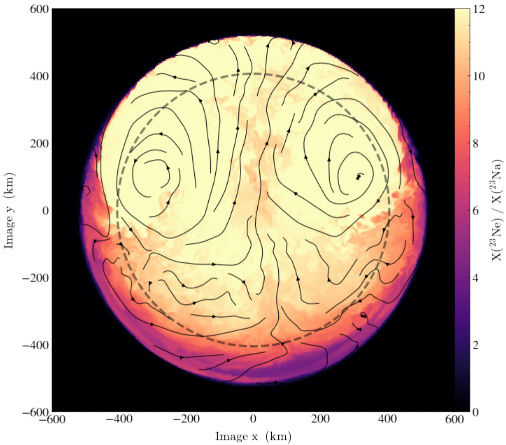
Distribution of Urca Pair

- Non-uniform mixing

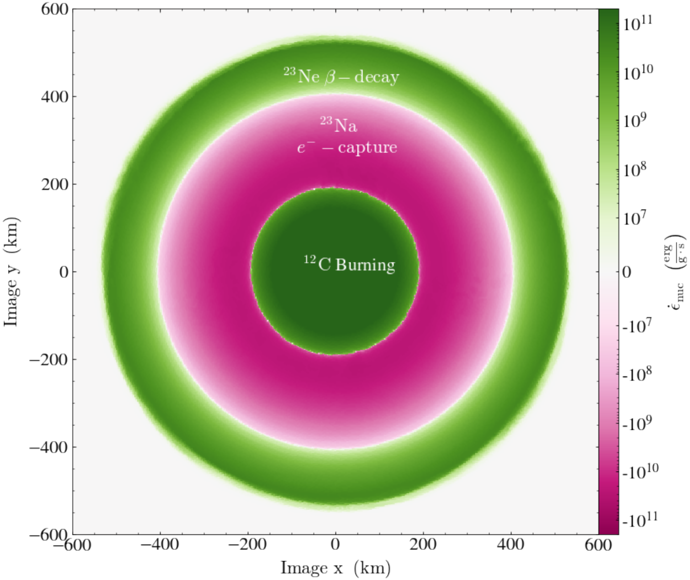


Distribution of Urca Pair

- Non-uniform mixing
- Dipole velocity structure
- Reaction timescale $\sim$1000 s
- Mixing timescale $\sim$100 s

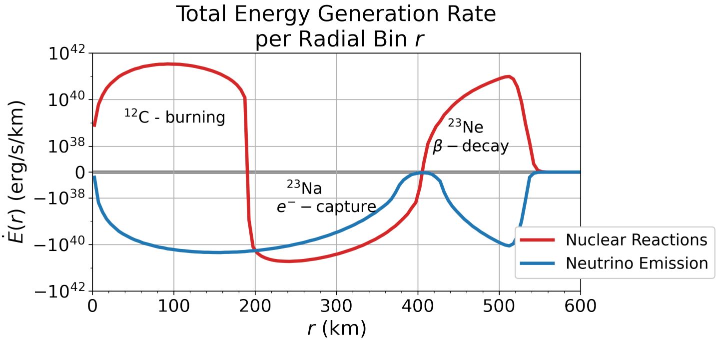


Energy Generation/Loss Rate



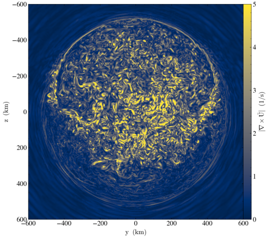
Neutrino Losses

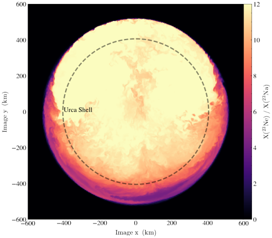
- Total Energy Generated: 3.32×10^{43} erg/s
- Total Energy loss to ν_e's: 4.18×10^{42} erg/s
- $\sim$ 12 % energy lost

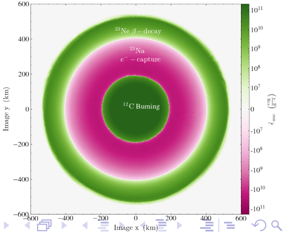


Summary of Results

- Mixing is non-uniform. Does not match a diffusive law (typical of MLT).
- Convective Urca does not slow convection to interior of shell.
  - more simulations/analysis needed to capture how significant the slowing is
- ν_e-losses are order magnitude smaller compared to $^{12}\mathrm{C}$-burning
- Future Work:
  - Larger Network
  - Earlier/later in simmering phase
  - different/more realistic progenitor (ie lower density, realistic composition)



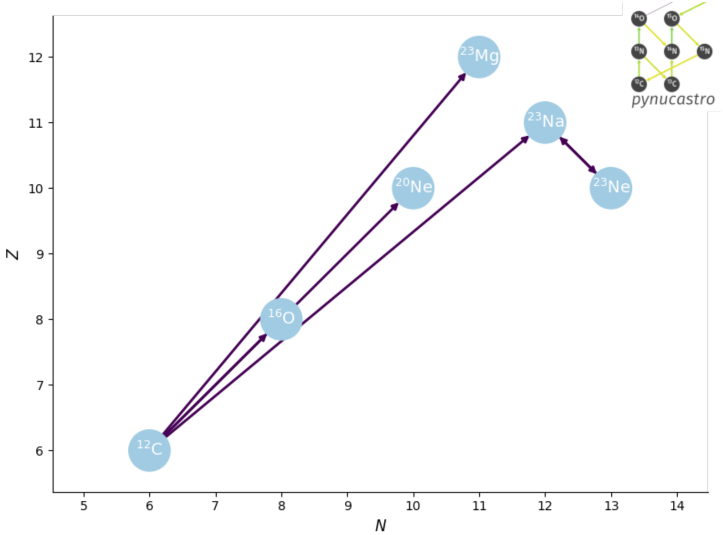




Thank You

Thank you for listening!

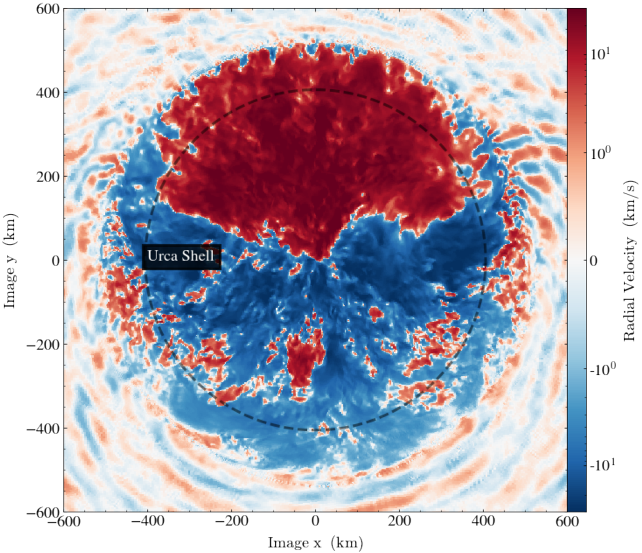
Reaction Network



Rates from JINA REACLIB and weak rates from Suzuki et al. 2016

Convection Zone

- Large Dipole
- Encompasses Urca Shell
- Turnover Time: 50-100 seconds.



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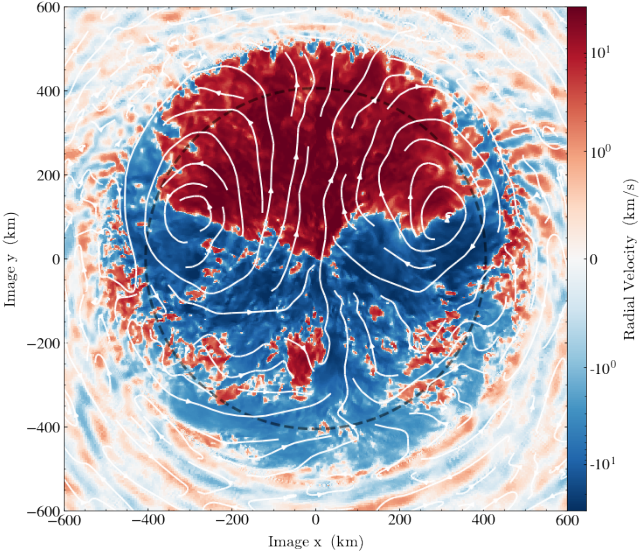
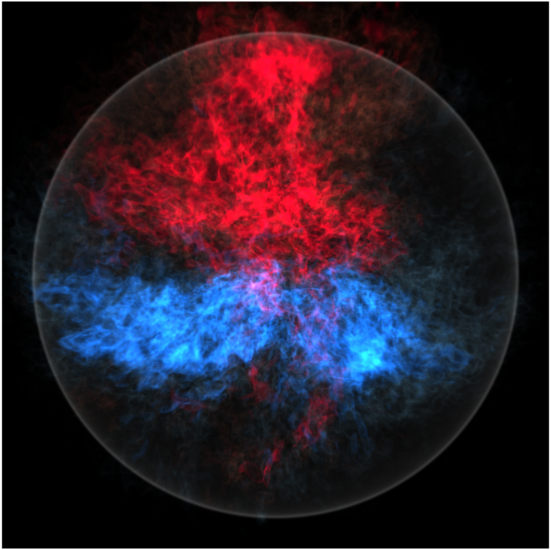
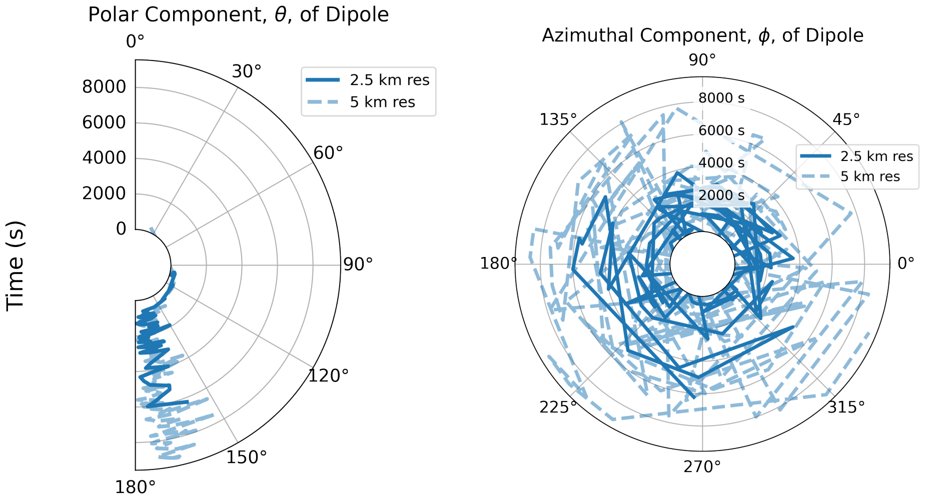


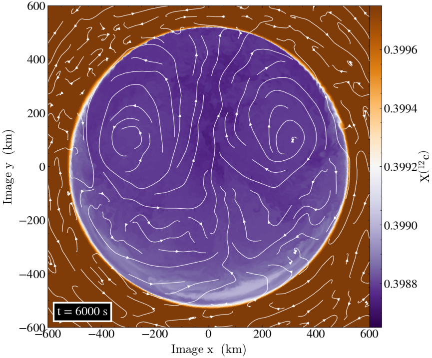
Convection Zone Volume Render

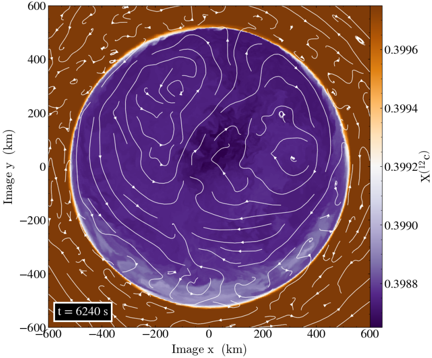


Direction of Dipole



Changing Structure





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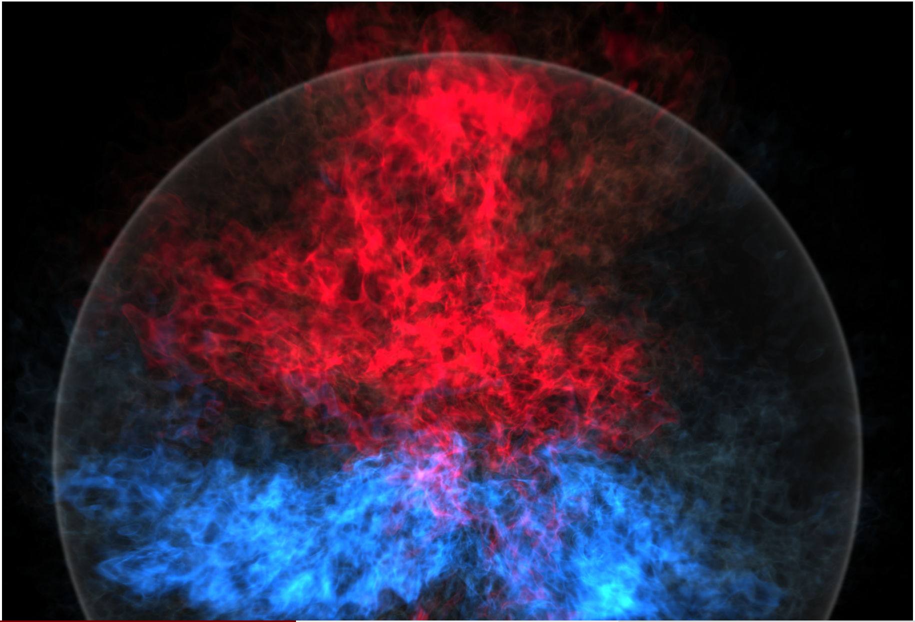
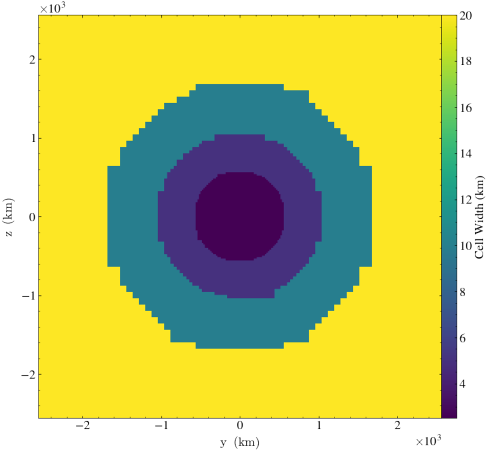


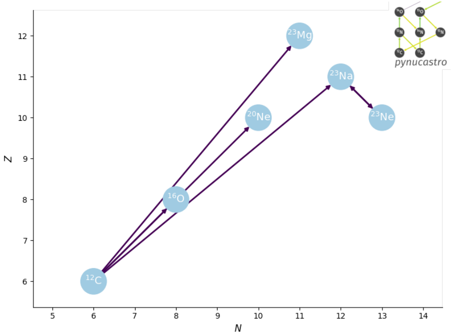
The Simulation: Grid

- 3D grid, 5,120 km
- 3-4 Layers of refinement. 2.5 km cell size
- map 1D initial models onto 3D grid

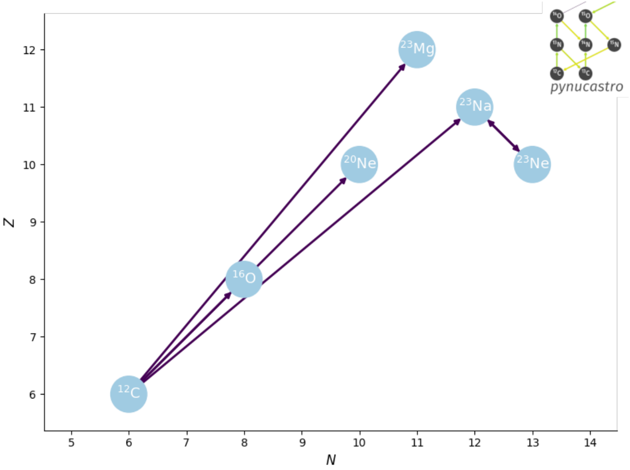


Reaction Network and pynucastro

- Construct a Reaction network with c12 burning and Urca reactions
- Pynucastro: python package (Clark et al. 2023)
  - Queries library of reaction rates (e.g. REACLIB)
  - Helps identify most important reactions
  - Writes C++ code to use reaction network



Future Work: Reaction Networks



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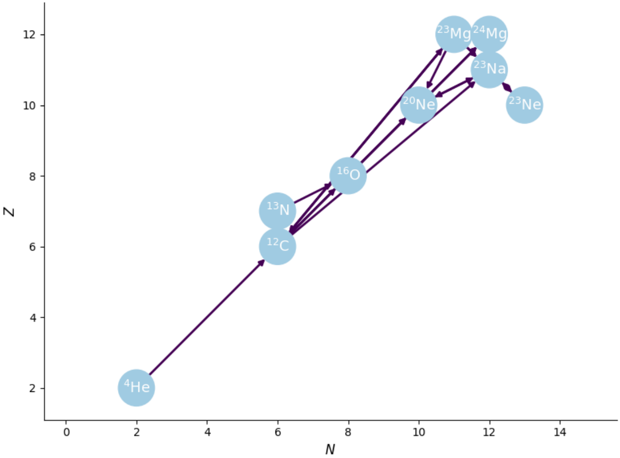
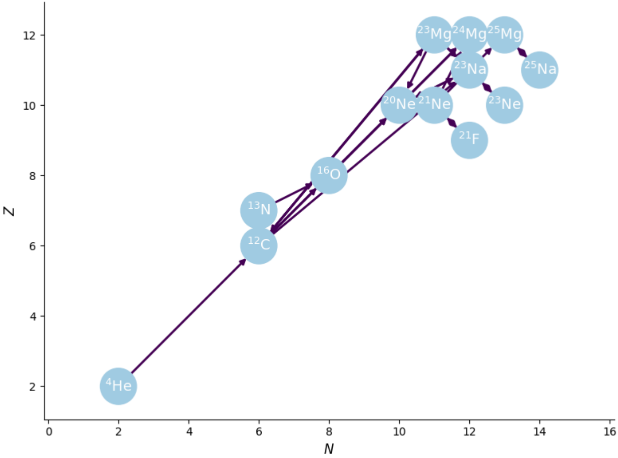
- Larger Network (more c12 burning)

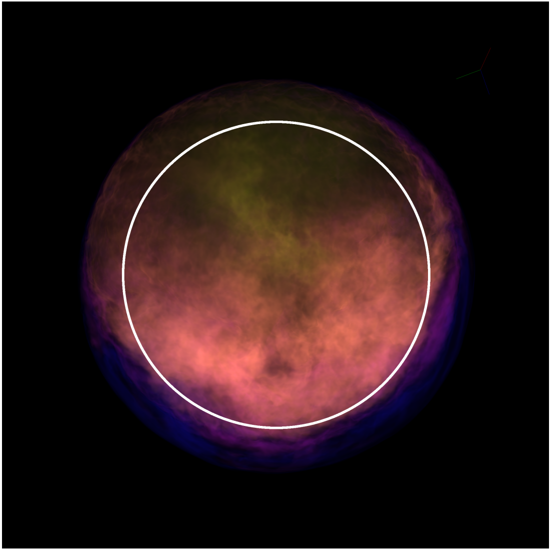


Future Work: Reaction Networks

- Larger Network (more c12 burning)
- Additional Urca pairs
  - ^{21}F-^{21}Ne
  - ^{25}Na-^{25}Mg



^{23}Ne Volume Render



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- Simulation w/o Urca process to better compare impacts.
- Investigate other densities and temperatures
- What happens at times closer to supernova?
    - Use this as "initial conditions"?

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