Convective-reactive nucleosynthesis in low-mass and massive stars

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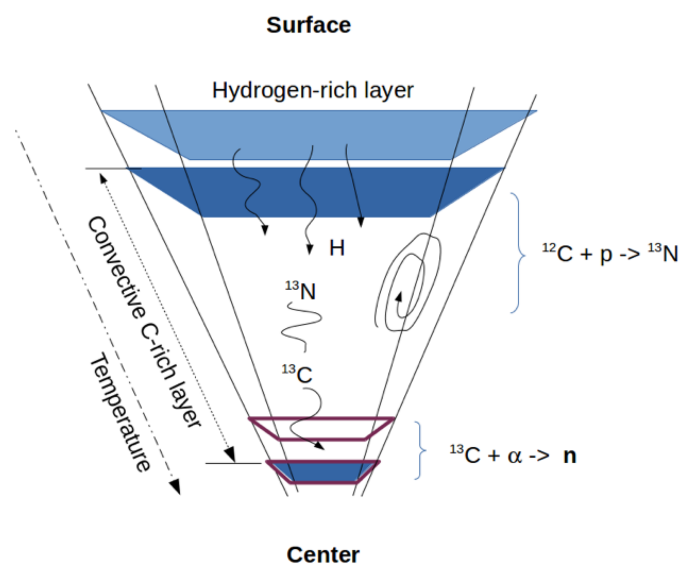
Summary

Convective-reactive events in stellar evolution may give rise to unusual and unique nucleosynthesis pathways. An example is the intermediate neutron-capture process (i process) that occurs in the convective-reactive ingestion of H into He-shell flash convection. These events require 3D simulations (Herwig+14). Here we describe a new advective-reactive 3D post-processing approach that allows to determine the detailed nucleosynthesis based on large nuclear networks. Another example of convective-reactive nucleosynthesis is the O-C shell merger in massive stars. Based on multi-zone nucleosynthesis models we find strong production of K, Cl and Sc. This hydrodynamic nuclear production could address the general deficiency of K and Sc in chemical evolution models. Like the H-ingestion phase 3D hydrodynamic simulations will eventually be required for realistic predictions.

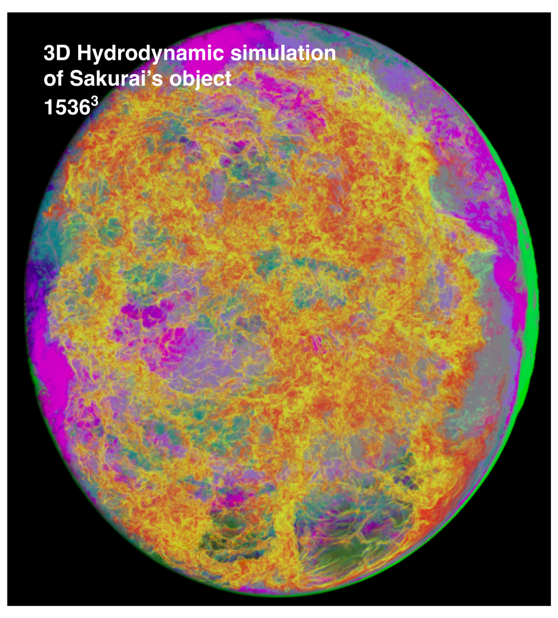
I process

i process signatures are observed in grains, CEMP-r/s stars, low-Z post-AGB stars (Jadhav+13, Dardelet +15, Lugaro+15). Proposed sites are He-core/shell flashes in low-mass stars (Campbell+10), SAGB stars (Jones+15) and rapidly accreting WDs (Denissenkov+16, in prep.). The interplay of mixing and burning is shown to the right.



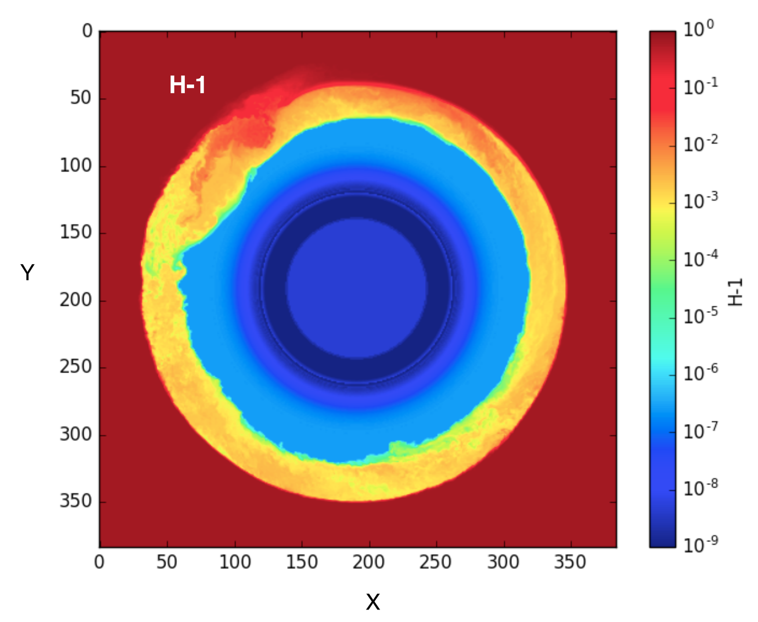
Burning & mixing in 3D

Predictions of heavy elements require to take into account the reactive-convective 3D nature of the i process. We develop a advective nucleosynthesis post-processing 3D (ANP3D) method in a JINA collaboration between UVic and the U. of Minnesota (P. Woodward). At each step nuclei are advected according to our 3D hydrodynamic simulation, followed by burning. A first application is the post-AGB star Sakurai's object (Herwig+11).

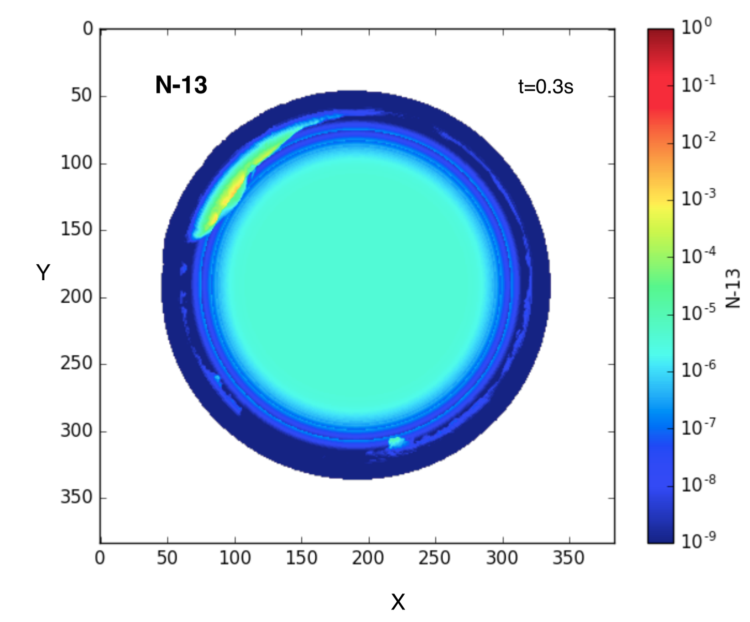


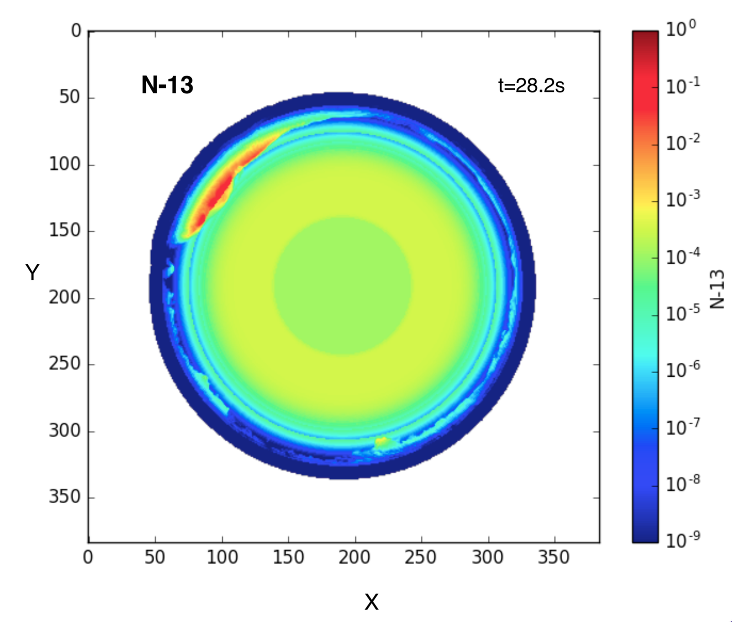
Nucleosynthesis

Post-processing of cartesian geometry of 1536^3-grid hydro simulations on a 384^3-grid with a 13-species network. The slice through the 4π sphere shows the H mass fraction during a violent GOSH event after 1434 minutes of H entrainment in the hydro simulations (Herwig+14). Mixing not applied yet.



Left panel: The entrained H is constrained by the output from the hydro simulation. It reacts via ^{12}C(p,g)^{13}N. **Panels to right:** ^{13}N mass fractions after 0.3s and 28.2s as shown the sphere slices. No advection is applied yet. The time step size are chosen to resolve the advection on the post-processing grid.



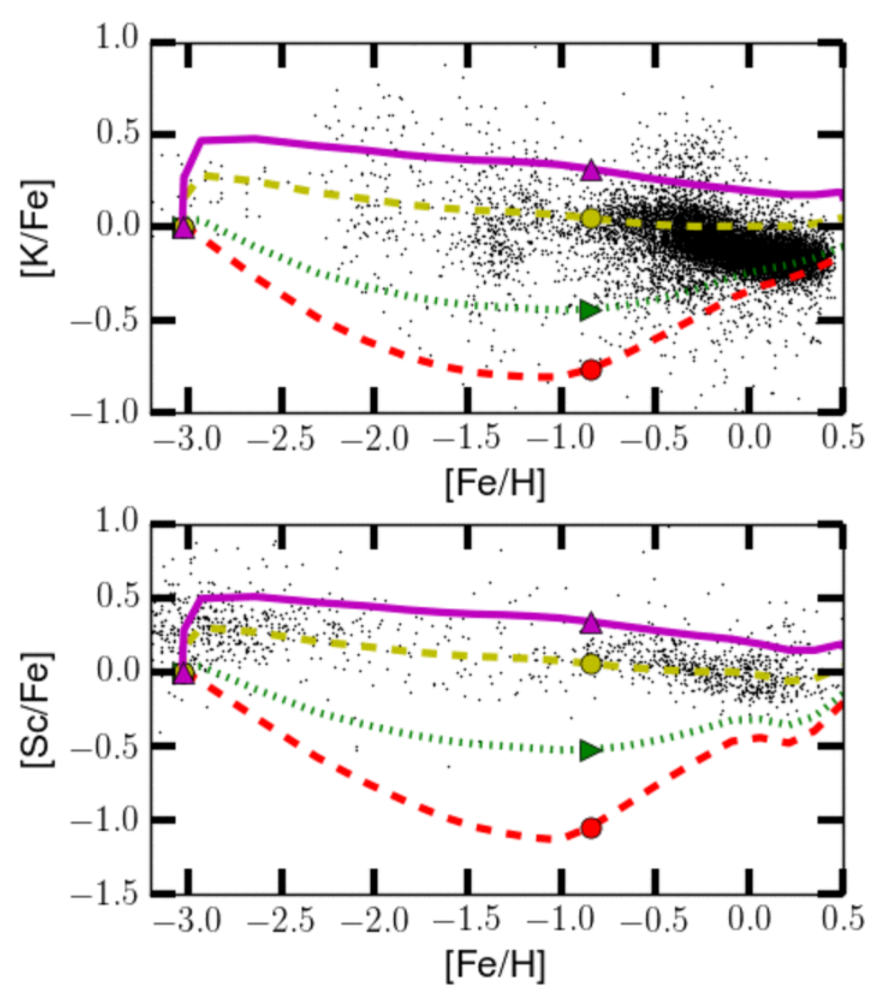


Origin of K and Sc in O-C shell merger?

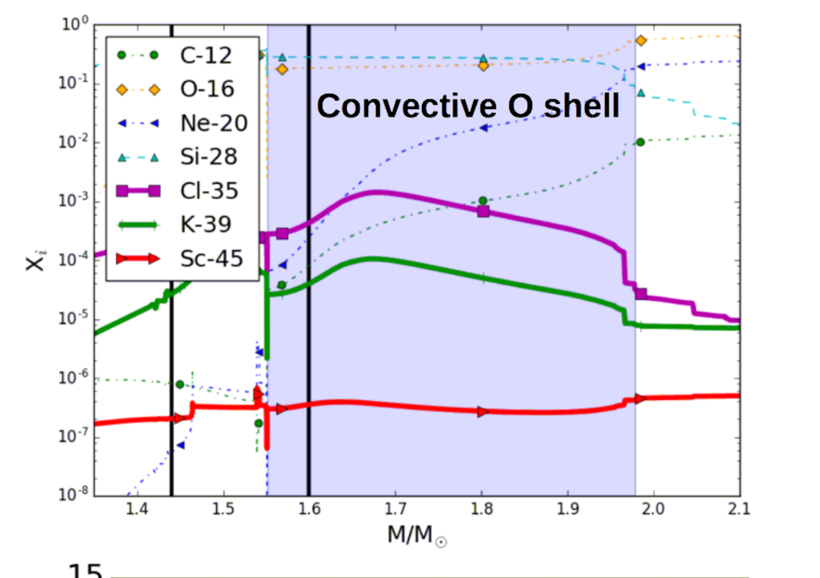
The amount of K and Sc observed in the Milky Way is underproduced with NuGrid yields when applied in a Milky Way model of the JINA pipeline (Benoit Côté, poster). This is visible for the default case in the comparison with Milky Way data. Jet-induced explosions or p-rich neutrino-driven winds are proposed to explain the deficiencies (Kobayashi+06, Nomoto+13). In the NuGrid massive star models we identify phases of ingestion of C and Ne into the convective O shell as part of O-C shell mergers (Rauscher+02, Tur+07). **Figure:** Scenarios in which a certain fractions (percentage) of material produced in the 15Msun, solar Z model is ejected by all massive stars in the Milky Way. This may solve the model underproduction of K and Sc of present models .

References to observations:

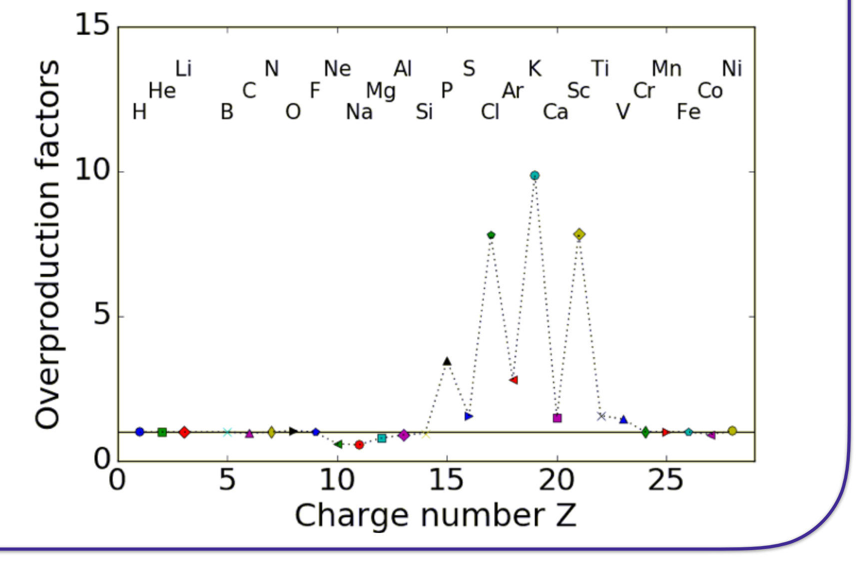
K	Sc
APOGEE (R12)	Frebel 2010
Hinkel et al. 2014	Hinkel et al. 2014
Andrievsky et al. 2010	Bonifacio et al. 2009
Cayrel et al. 2004	Cayrel et al. 2004
Reddy et al. 2003	Gratton et al. 2008
	Lai et al. 208
	Reddy et al. 2006
	Reddy et al. 2003



In the 15Msun solar Z model the entrained material of the C shell reaches sufficient depth and temperatures to produce large amounts of ^{35}Cl, ^{39}K and ^{45}Sc (profile to the right). Further studies require 3D hydrodynamic simulations of the reactive-convective flow (Herwig+14).

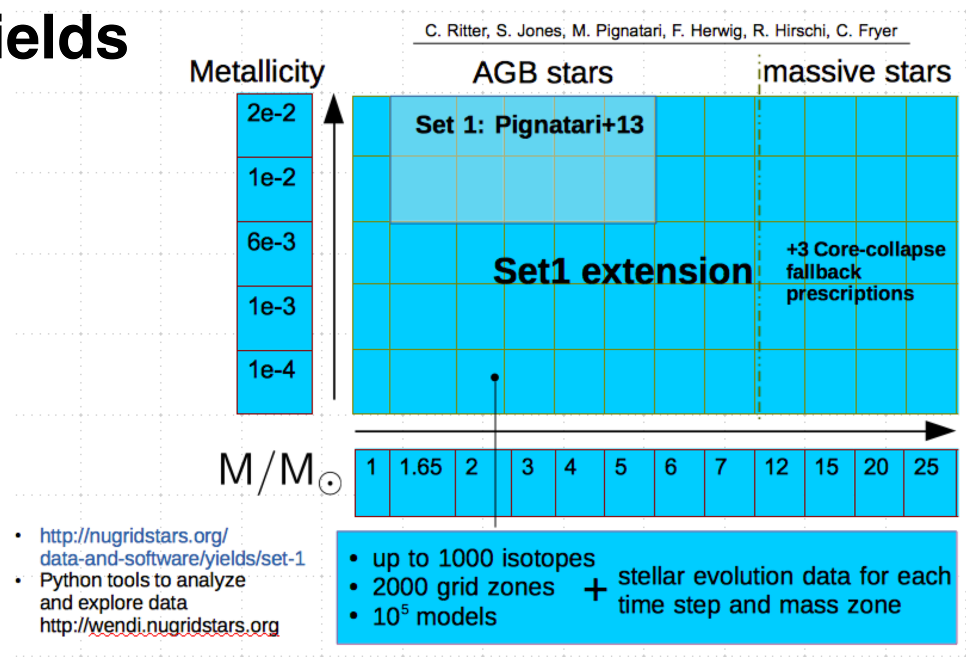


The overproduction factors of a model after a shell merger compared to a model before a shell merger indicate a distinct production of Cl, K and Sc only. We hypothesize a pre-SN source of K and Sc production which origins in C-O shell mergers of massive stars.



NuGrid/JINA stellar yields

Stellar yields depend critically on the choice of nuclear physics input and model assumptions (Gibson+02, Romano+ 10). The NuGrid yields include AGB stars and massive stars (+explosive nucleosynthesis) down to Z=10^{-4} calculated with consistent nuclear physics and with the same codes (Ritter+16, in prep.). The yields provide an an advanced post-processing scheme for heavy elements in hot-bottom burning.



Connecting Nuclear physics with observables

Nuclear Physics → Stellar yields →

What is the impact of **YOUR** nuclear physics proposal and/or measurement?

We have developed in collaboration with MSU (Benoit Côté, B. W. O'Shea, poster) the **JINA/NuGrid GCE pipeline** that connects nuclear physics with chemical evolution and observational data. We have used the pipeline to explore various aspects of GCE such as yield grid resolution and sensitivity of GCE parameter [*].

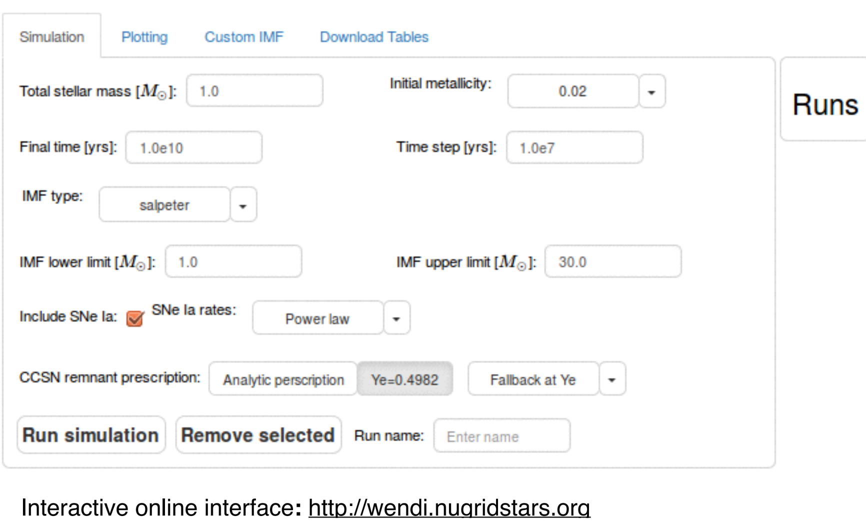
NUPYCEE
Chemical evolution suite

- Explore impact on simple stellar populations (SYGMA)
- Galactic chemical evolution (OMEGA+)
- Comparison with vast stellar data base
- Simple, interactive analysis in python framework
- Simple, interactive python interface

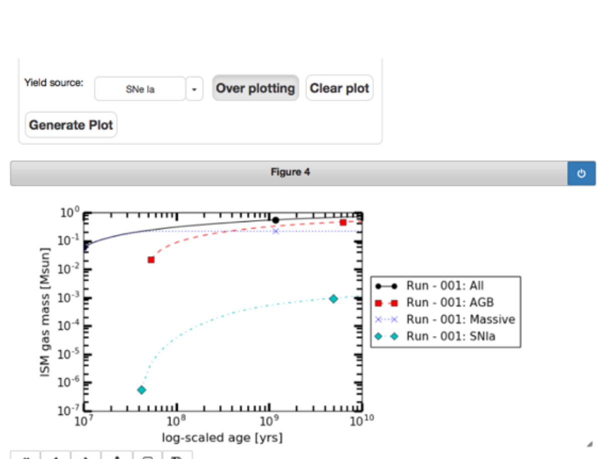
SYGMA: Simple stellar populations

Simple stellar populations (SSP) as the basic blocks of galaxy models allow to identify nucleosynthesis signatures which is often independent of chemical evolution model assumptions such as the 1-box assumption (see poster of Benoit Côté). SYGMA provides input tables for chemical enrichment and feedback in hydrodynamical simulations and semi-analytical models.We provide an interface to download SSP ejecta and other stellar feedback parameter in tabulated form (Ritter+16, in prep.).

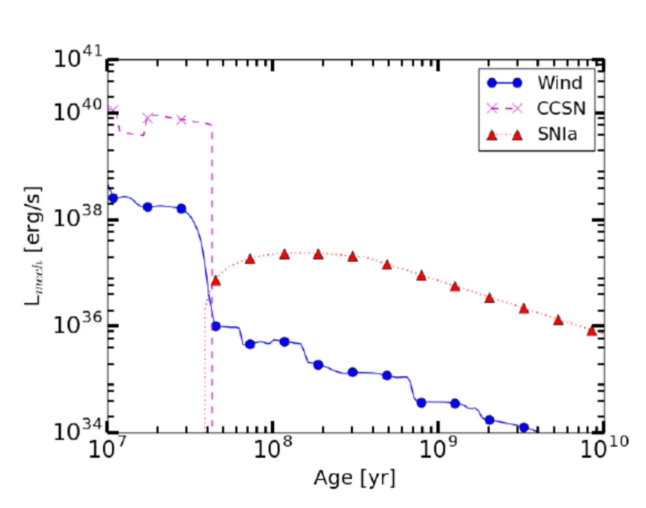
Input parameter



Analysis



Stellar feedback



Interactive online interface: http://wendi.nugridstars.org

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