Nuclei in the Cosmos XVII

Institute for Basics Science
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The p-process nucleosynthesis in core-collapse supernovae

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The p(γ)-process nucleosynthesis

- The **γ-process:** a sequence of photodisintegrations (γ,n), (γ,p), and (γ,α) in O/Ne rich layers in CCSN explosions from massive star progenitors (e.g., Woosley & Howard, 1978; Rayet et al., 1995);
- Production of **p-nuclei**: 35 neutron-deficient isotopes of elements heavier than Fe;
- **Underproduction** of typical γ-process yields from massive stars (factor of ∼2-4) compared to the solar system abundances. **Larger underproduction** of ^{92,94}Mo and ^{96,98}Ru yields (∼1 order of magnitude).

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See also:

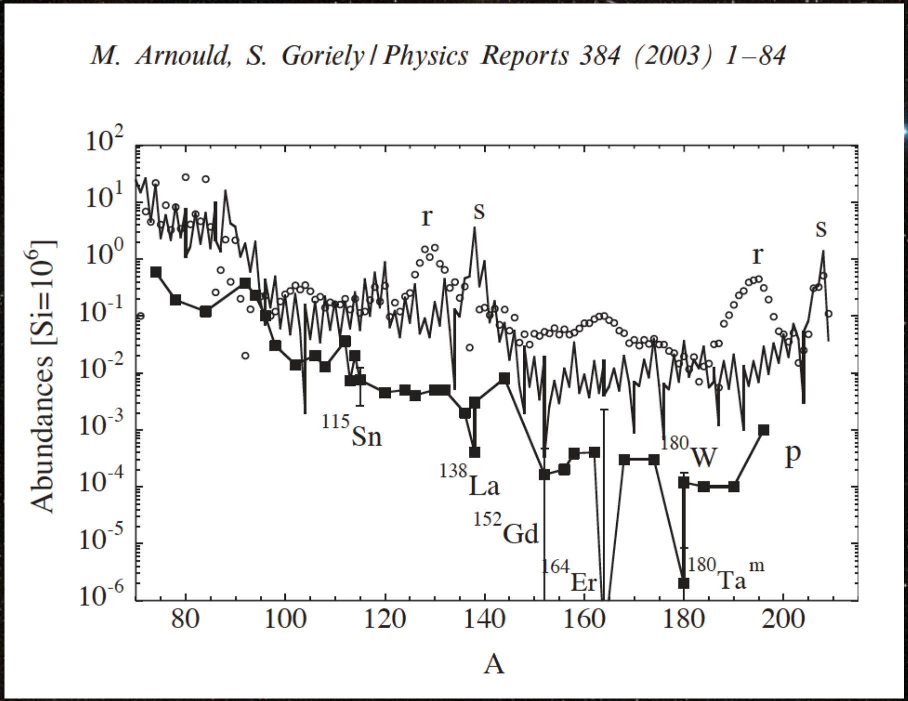
P-38: Riccardo Mucciola (^{94}Mo);

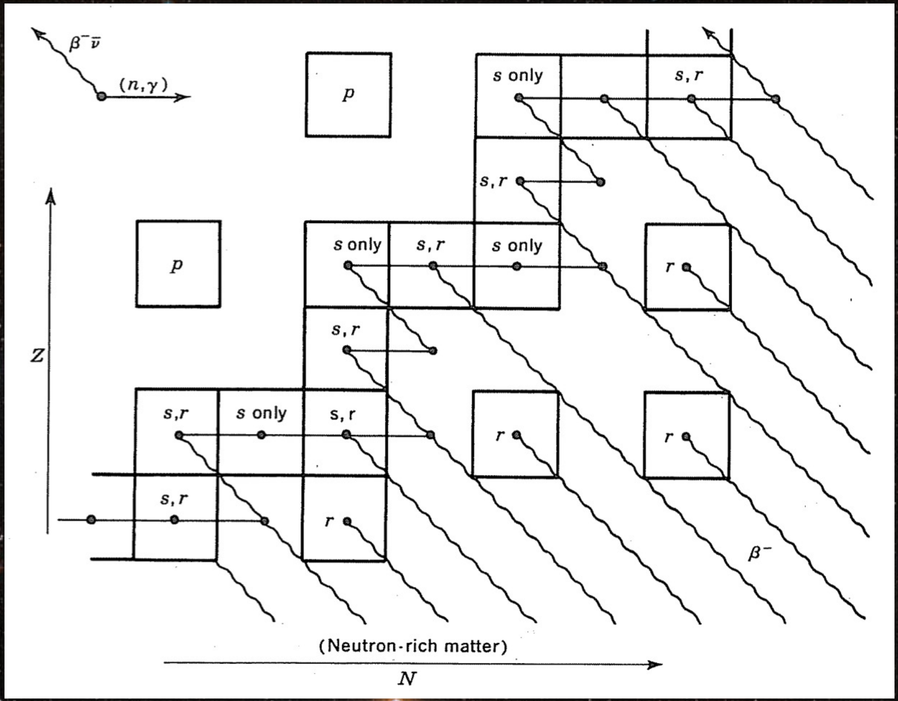
P-22: Fu-Long Liu (^{102}Pd);

P-36: Anastasiia Chekhovska (^{113}In, ^{114}Sn);

Talk: Sophia Dellmann, Monday (^{120}Te, ^{124}Xe).

The p-nuclei





Clayton, D.D. (1968) Principles of Stellar Evolution and Nucleosynthesis. University of Chicago Press, Chicago.

35 stable proton-rich nuclei: ^{74}Se, ^{78}Kr, ^{84}Sr, ^{92,94}Mo, ^{96,98}Ru, ^{102}Pd, ^{106,108}Cd, ^{112,114,115}Sn, ^{113}In, ^{120}Te, ^{124,126}Xe, ^{130,132}Ba, ^{136,138}Ce, ^{138}La, ^{144}Sm, ^{152}Gd, ^{156,158}Dy, ^{162,164}Er, ^{168}Yb, ^{174}Hf, ^{180}Ta, ^{180}W, ^{184}Os, ^{190}Pt, and ^{196}Hg.

The γ-process in stellar models

A&A 677, A22 (2023)
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Astronomy & Astrophysics

The γ-process nucleosynthesis in core-collapse supernovae

I. A novel analysis of γ-process yields in massive stars

L. Roberti[1,2,3,⋆], M. Pignatari[1,2,4,⋆], A. Psaltis[5,6,⋆], A. Sieverding[7], P. Mohr[8],
Zs. Fülöp[8], and M. Lugaro[1,2,9,10]

Analysis of γ-process yields in 5 different existing sets of core-collapse supernova models (Rauscher+02, Pignatari+16, Sieverding+18, Ritter+18, Lawson+22);

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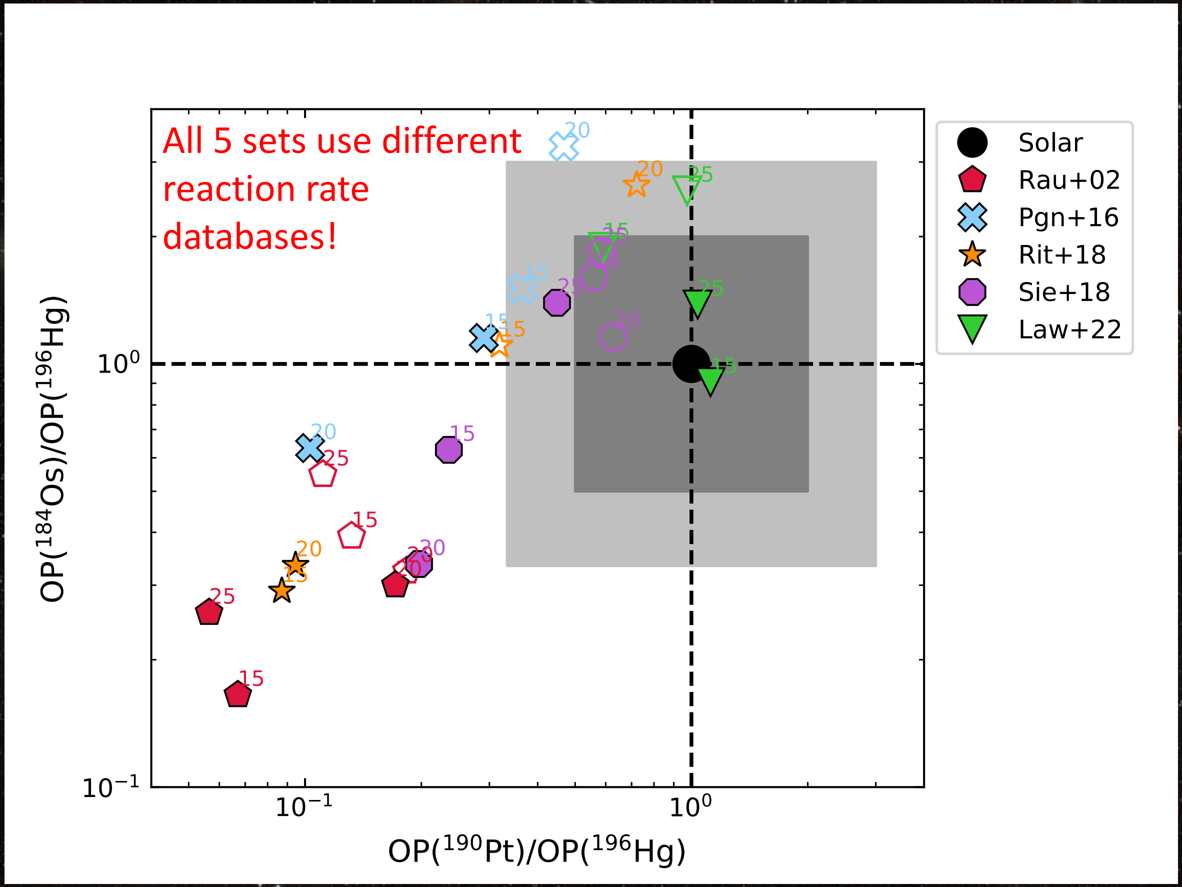
- **C-O shell interactions** before the explosion boost the production of all the nuclei with $A \gtrsim 110$;
- Different sets of **reaction rates** lead to significant differences in isotopic ratios.

The γ-process in stellar models



Ratios of p–nuclei close to each other in mass, normalized to the solar ratio

$$OP(A) = X(A)/X(A)_{\odot}$$

☆ = undecayed yields

★ = undecayed yields + radiogenic contribution

Effect of different explosive prescriptions (preliminary)

Exploring the effect of explosion parametrization on γ-process:

- **2 sets of stellar progenitors**: Ritter+18, Lawson+22; 15, 20, and 25 $M_{\odot}$;
- 2 approaches: **semi-analytical explosions** (Ritter+18), **hydrodynamic simulations** mimicking a 3D convective engine (Lawson+22).

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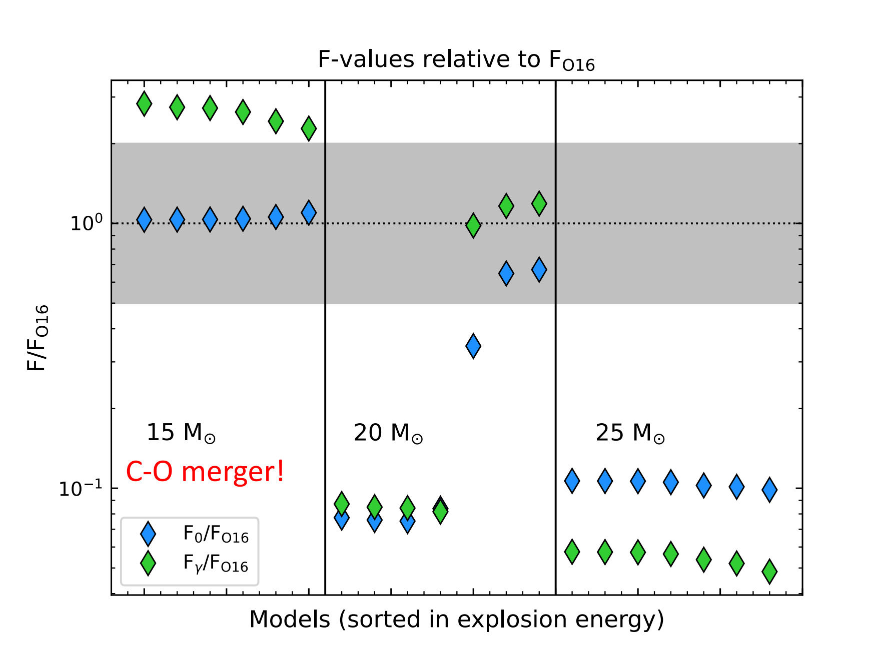
Main results:

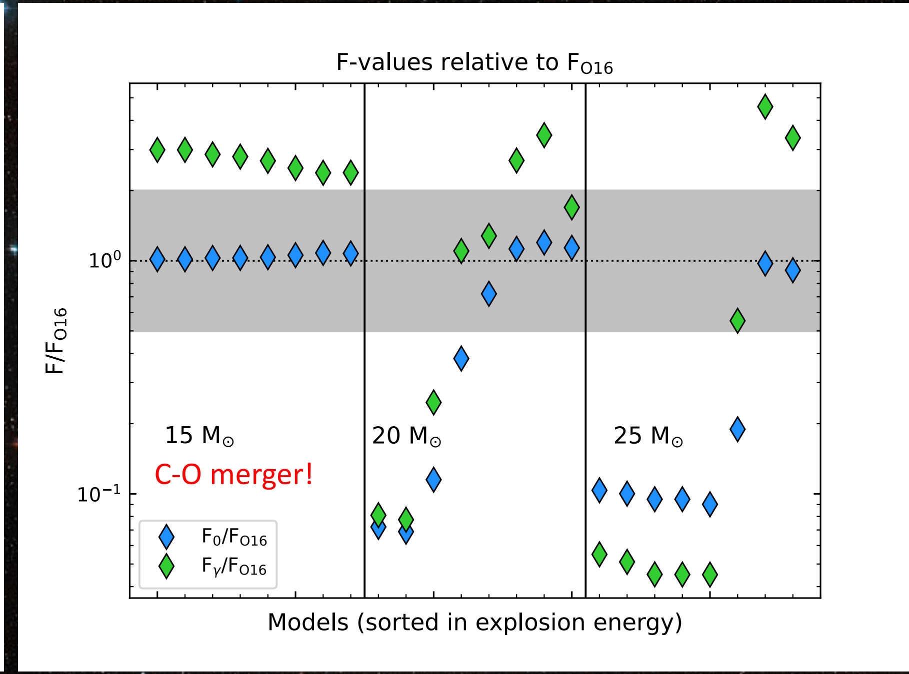
- The γ-process production site shifts in the structure by varying the explosion energy;
- More energetic explosions → more γ-process material escaped from the remnant;
- Less energetic explosions → more γ-process material locked in the remnant.

Semi-analytical models

Pure RDA

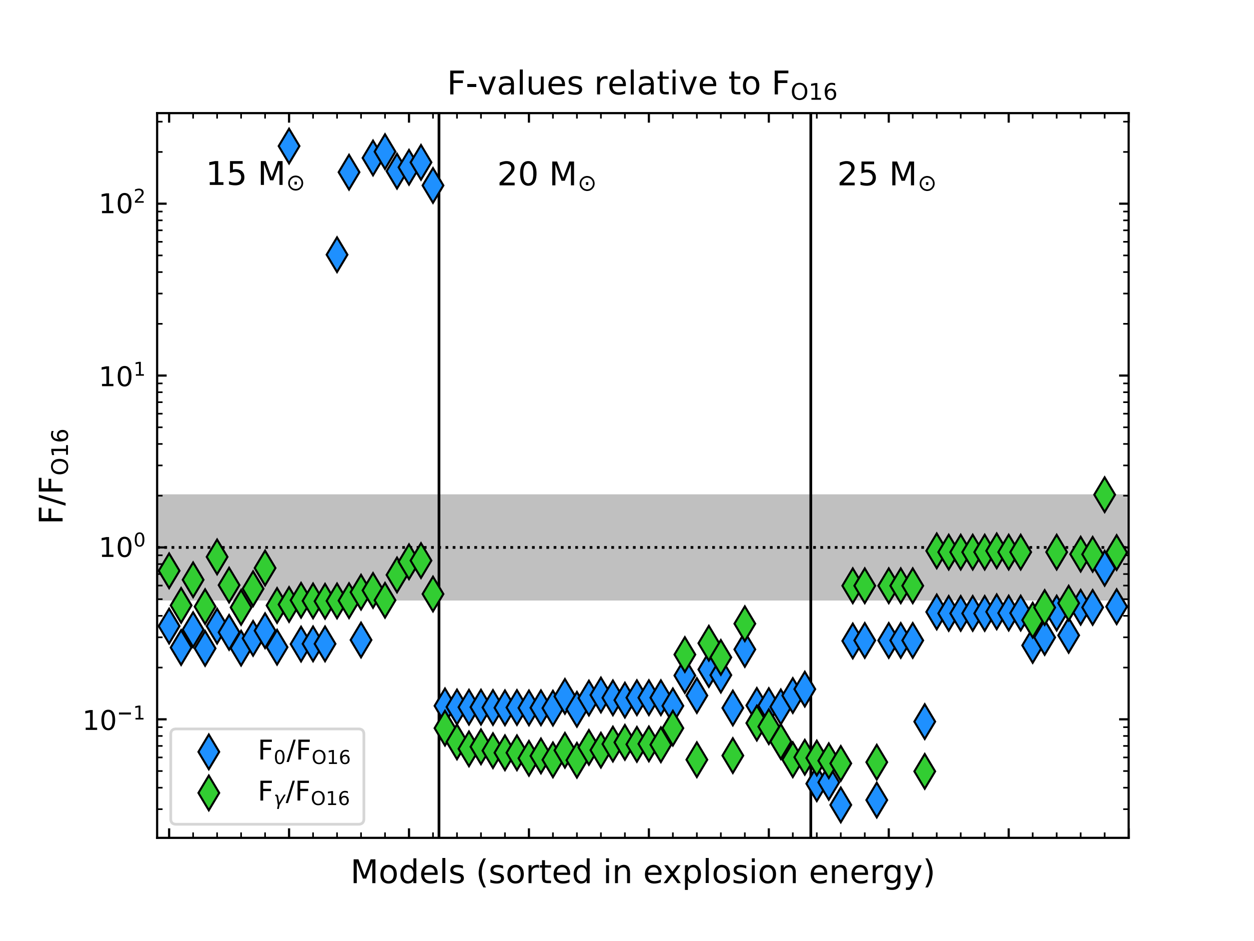


SBW propagation
(more energetic)



$F_0 = \frac{\sum_i^{35} F_i}{35}$; $F_\gamma = \frac{\sum_i^{3} F_i}{3}$ for 3 most produced γ-only nuclei

Full hydrodynamic models



Explosion models from Fryer, et al., 2018, ApJ, 856, 63; nucleosynthesis from Lawson, et al. 2022, MNRAS, 511, 886

Summary

- The production of p-nuclei is still unclear, therefore we aim to explore in more detail the CCSN scenario;
- The stellar structure at the onset of the Fe core collapse and the nuclear network play a crucial role in the production of p-nuclei;
- The C– O shell merger crucial for p-nuclei heavier than Pd.
- Next steps: radionuclides (^{92}Nb , $^{97-98}Tc$, ^{146}Sm), update of the nuclear network for the γ-process nucleosynthesis, production of new γ-process stellar yields.

- **Question for our experimental nuclear physics friends:** any new reaction rates for γ-process?

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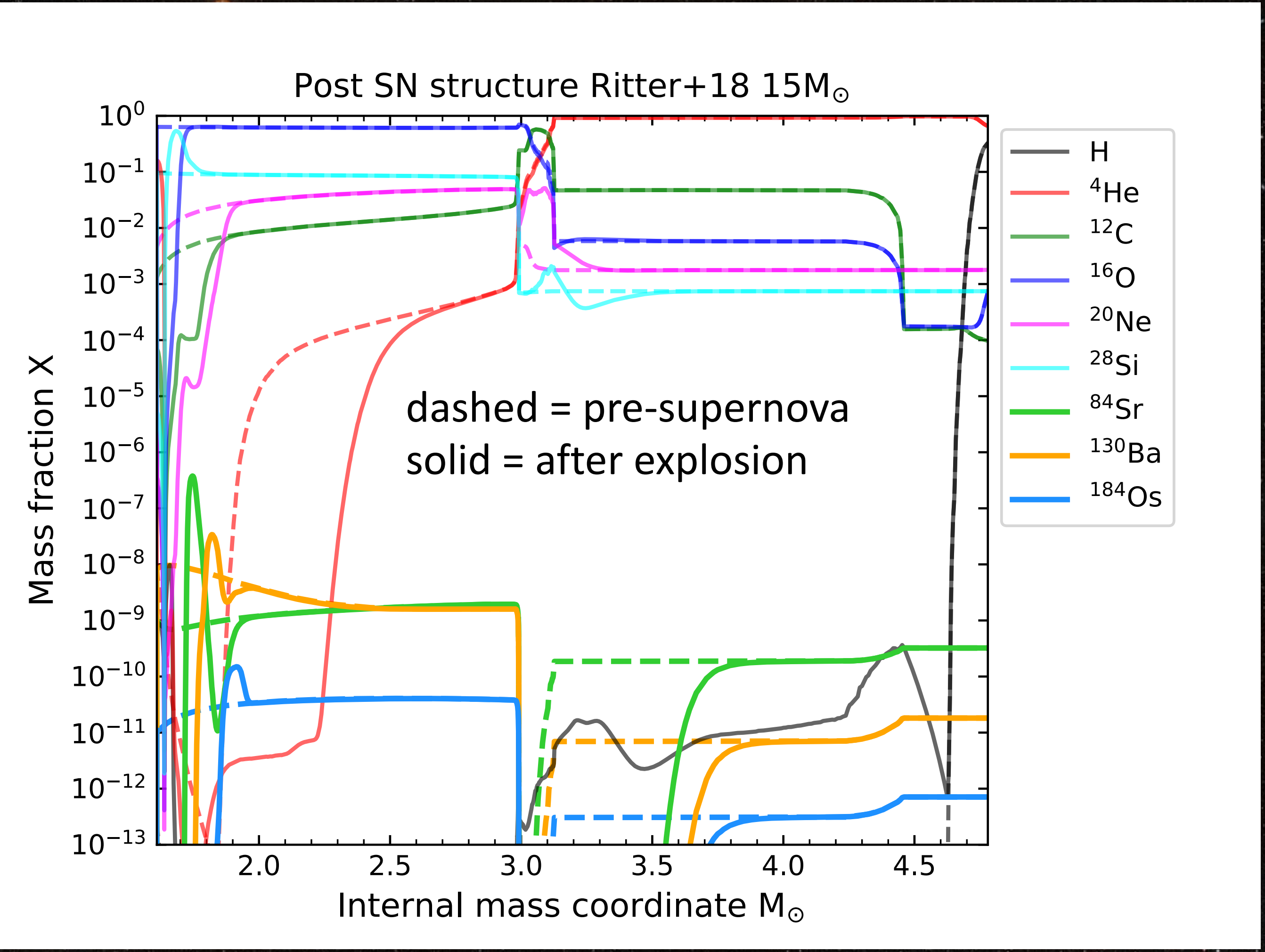
Backup slides

The p-(neutron deficient) nuclei

35 stable proton-rich nuclei: ^{74}Se, ^{78}Kr, ^{84}Sr, ^{92,94}Mo, ^{96,98}Ru, ^{102}Pd, ^{106,108}Cd, ^{112,114,115}Sn, ^{113}In, ^{120}Te, ^{124,126}Xe, ^{130,132}Ba, ^{136,138}Ce, ^{138}La, ^{144}Sm, ^{152}Gd, ^{156,158}Dy, ^{162,164}Er, ^{168}Yb, ^{174}Hf, ^{180}Ta, ^{180}W, ^{184}Os, ^{190}Pt and ^{196}Hg.

- Different explosive contributions (e.g., α- & νp-process, Woosley & Hoffman 1992, Froehlich et al. 2006, Arcones & Montes 2011);
- r-process contribution (Dillmann et al. 2008);
- neutrino capture (Goriely et al. 2001);
- s-process contribution (Bisterzo et al. 2011);
- s-process and neutrino capture (Bisterzo et al. 2011, Arnould & Goriely 2003).

The γ-process nucleosynthesis in C-O shell mergers



Different explosive prescriptions

- **Set 1**: Ritter+18 progenitors (MESA), Fryer+12 remnant mass, Sedov Blastwave (SBW) solution for propagation of shock wave, adiabatic exponential decay for temperature and density;
- **Set 2**: Ritter+18 progenitors (MESA), Fryer+12 remnant mass, pure radiation dominated approximation (RDA), adiabatic exponential decay for temperature and density;
- **Set 3**: Lawson+22 progenitors (Kepler), with hydrodynamic explosions from Fryer+18, mimicking the convection enhanced supernova engine in 1D, using a three-part parameterization for the energy injection (power, duration, and the extent of the energy injection region).

Different explosion energies