Nuclear Physics in Astrophysics XI

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Rare nuclei production in core-collapse supernovae: the γ-process nucleosynthesis

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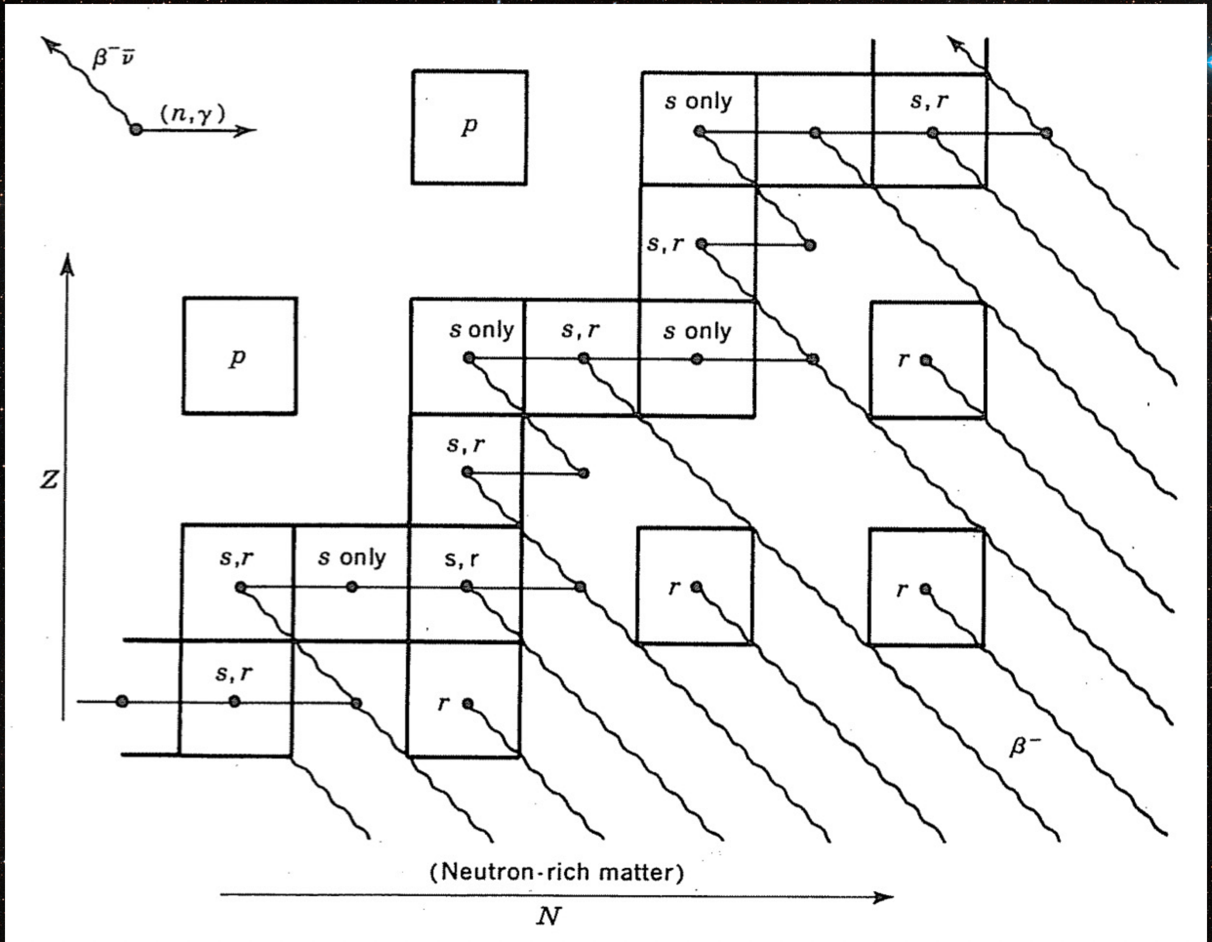
The γ-process nucleosynthesis in CCSNe



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

- 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).

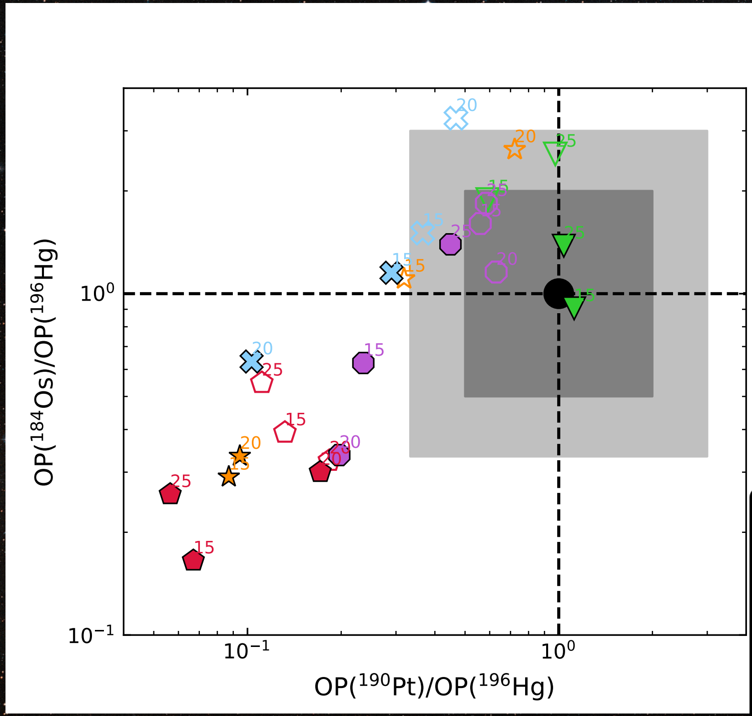
The γ-process nucleosynthesis in CCSNe

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.

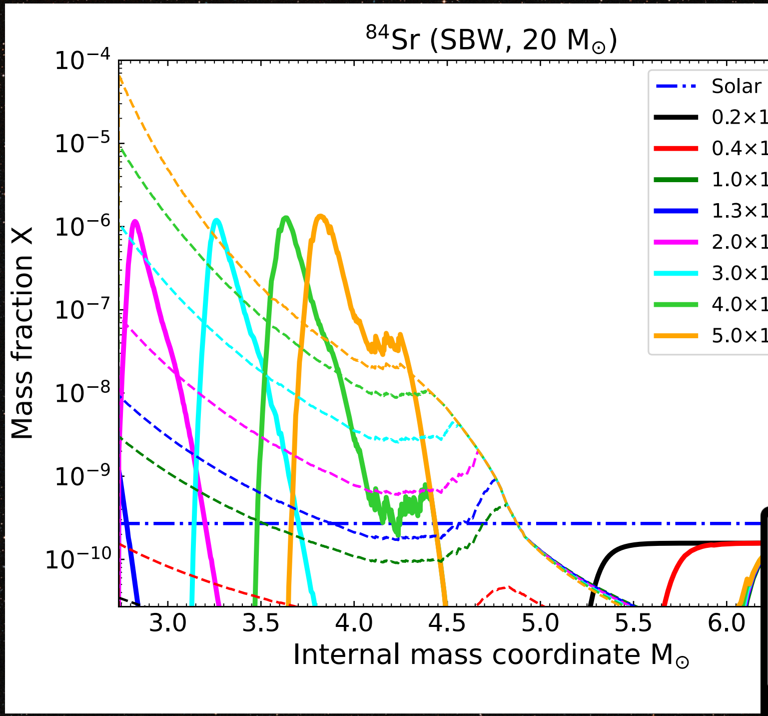
- Different explosive contributions (e.g., α- & νp-process, Woosley & Hoffman 1992, Froehlich et al. 2006, Arcones & Montes 2011, Sasaki et al., 2024);
- r-process contribution (Dillmann et al. 2008);
- neutrino capture (Goriely et al. 2001);
- s-process contribution (Bisterzo et al. 2011);
- s-process and neutrino capture (Bisterzo et al. 2011, Arnould & Goriely 2003).

The γ-process nucleosynthesis in CCSN models

- The **pre-supernova structure** of the model is crucial to determine the properties of the explosive O/Ne nucleosynthesis;
- The **explosion parametrization** affects the production of all p-nuclei;
- Different sets of **reaction rates** lead to significant differences in isotopic ratios.



SCAN ME

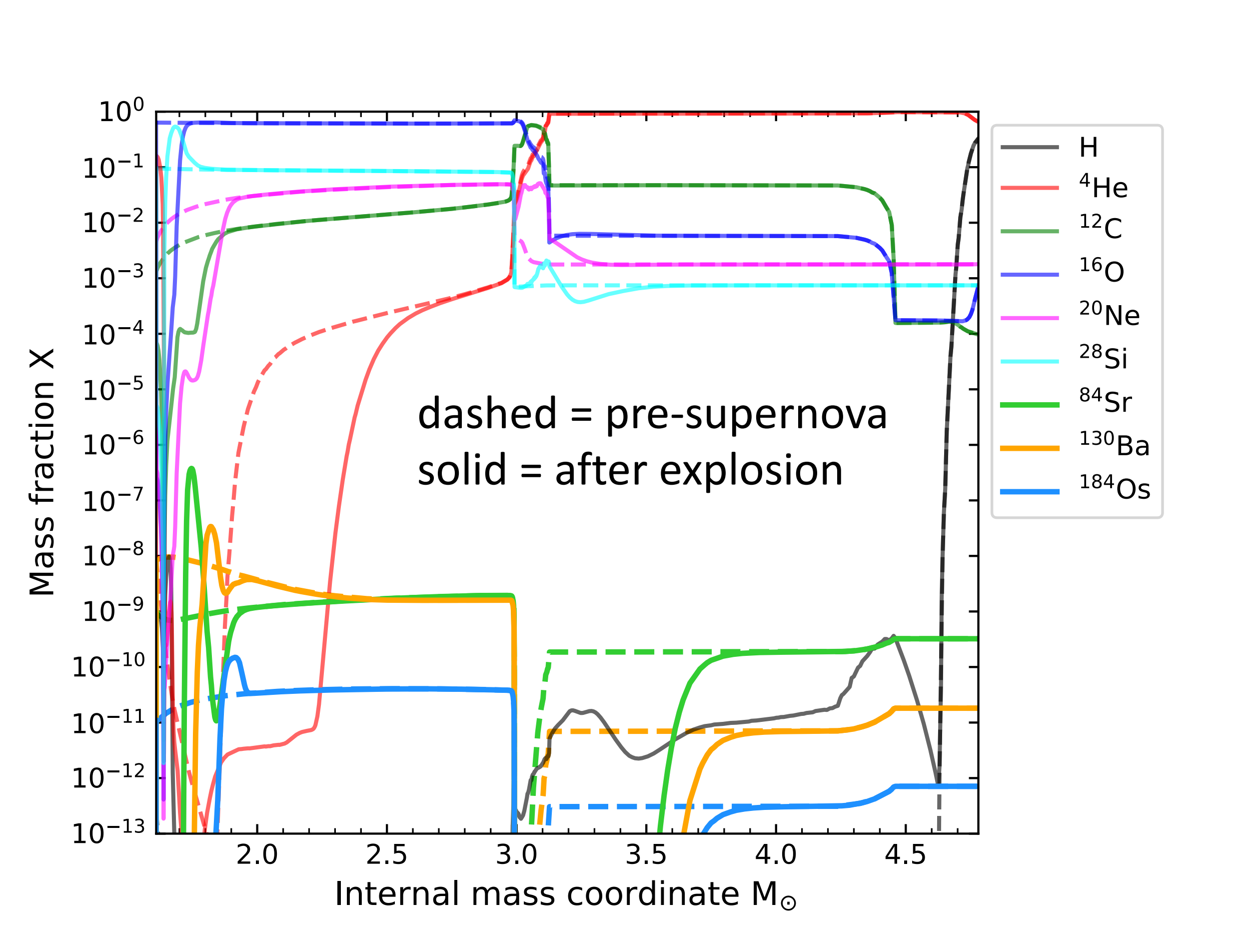


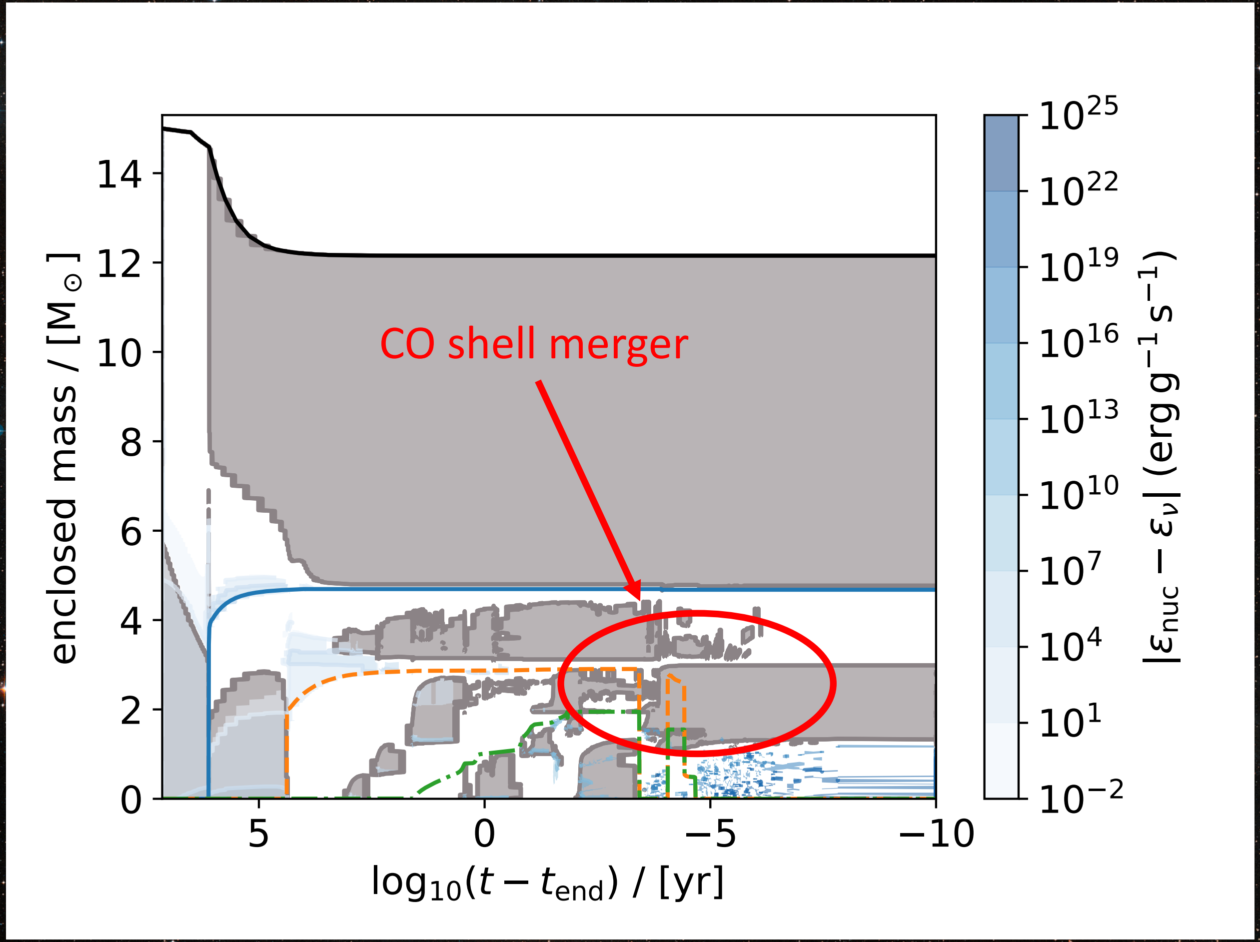
SCAN ME

Carbon-oxygen shell mergers in massive stars

- Ingestion of some C (and Ne) in the O burning shell during late stages of the evolution;
- Formation of an extended (both in mass and radius) mixed convective zone;
- Peculiar **nucleosynthesis** and impact on the **explodability**;
- Intrinsically 3D occurrence: studied by hydro simulations (e.g., Andrassy+20, Rizzuti+24);
- Found in several 1D stellar models with $M_{ini} \leq 25\ M_{\odot}$ (e.g., Rauscher+02, Ritter+18, Roberti+24).

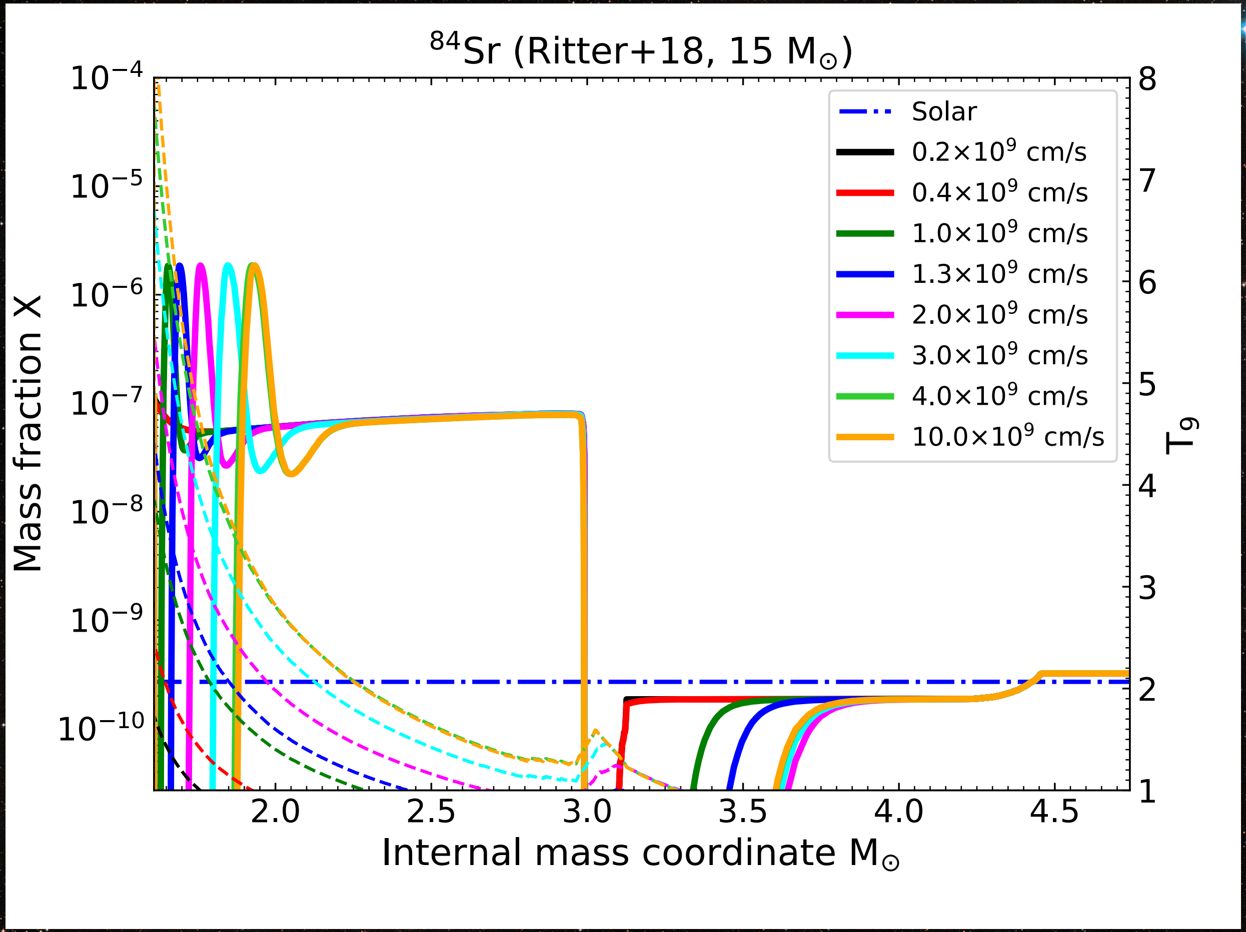
Carbon-oxygen shell mergers in massive stars

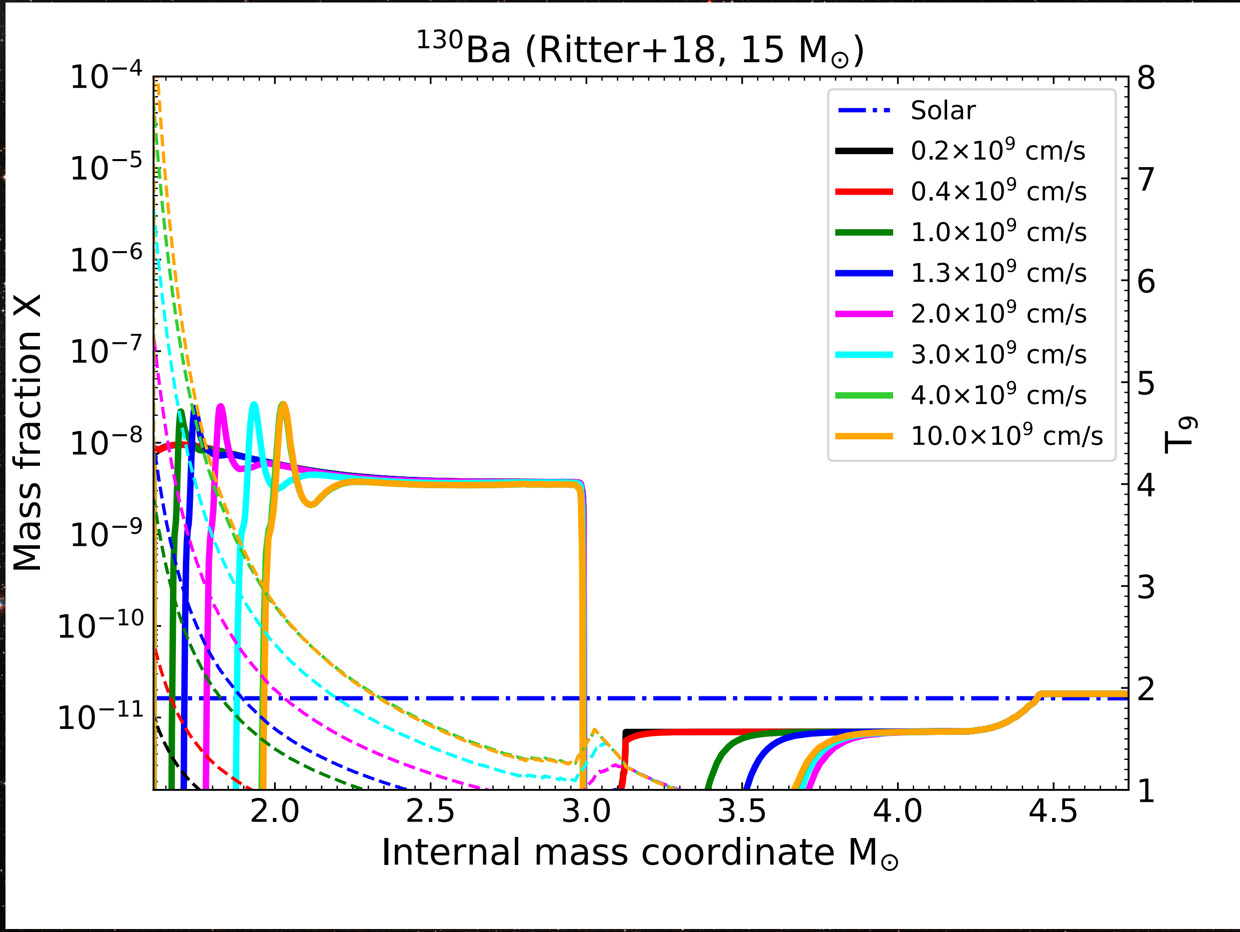




15 $M_\odot$ at Z=0.02 from Ritter et al., 2018, MNRAS 480, 538

The γ-process in C-O shell mergers





Summary and conclusions

- The production of p-nuclei in CCSNe depends on **progenitor evolution** → crucial having accurate and refined stellar models;
- Nuclear reactions affect the progenitor evolution and the nucleosynthesis;
- Different **explosion prescriptions** change the production of p-nuclei;
- The **C– O shell merger** dominates the production of p-nuclei heavier than Pd and it does not depend on the explosion energy;
- Frequency of C-O shell merger in a stellar population? Trend with mass/metallicity/rotation? Update GCE?

Short advertising!

We are organizing the

8th p-process workshop

@ Konkoly observatory in Budapest!

Save the date:

<u>16-18th October 2024</u>

https://indico.cern.ch/event/1389227/

8thpprocessworkshop@gmail.com

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Hope to see you in Budapest next October!

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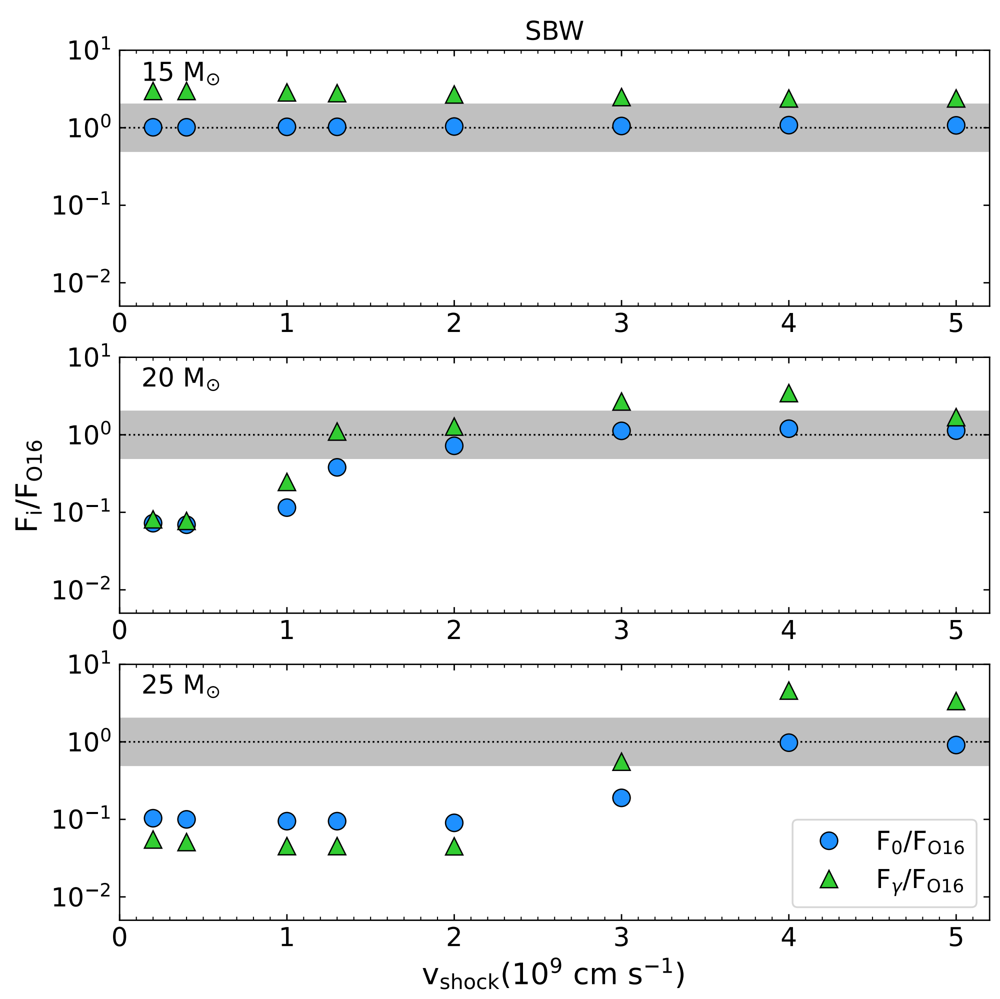
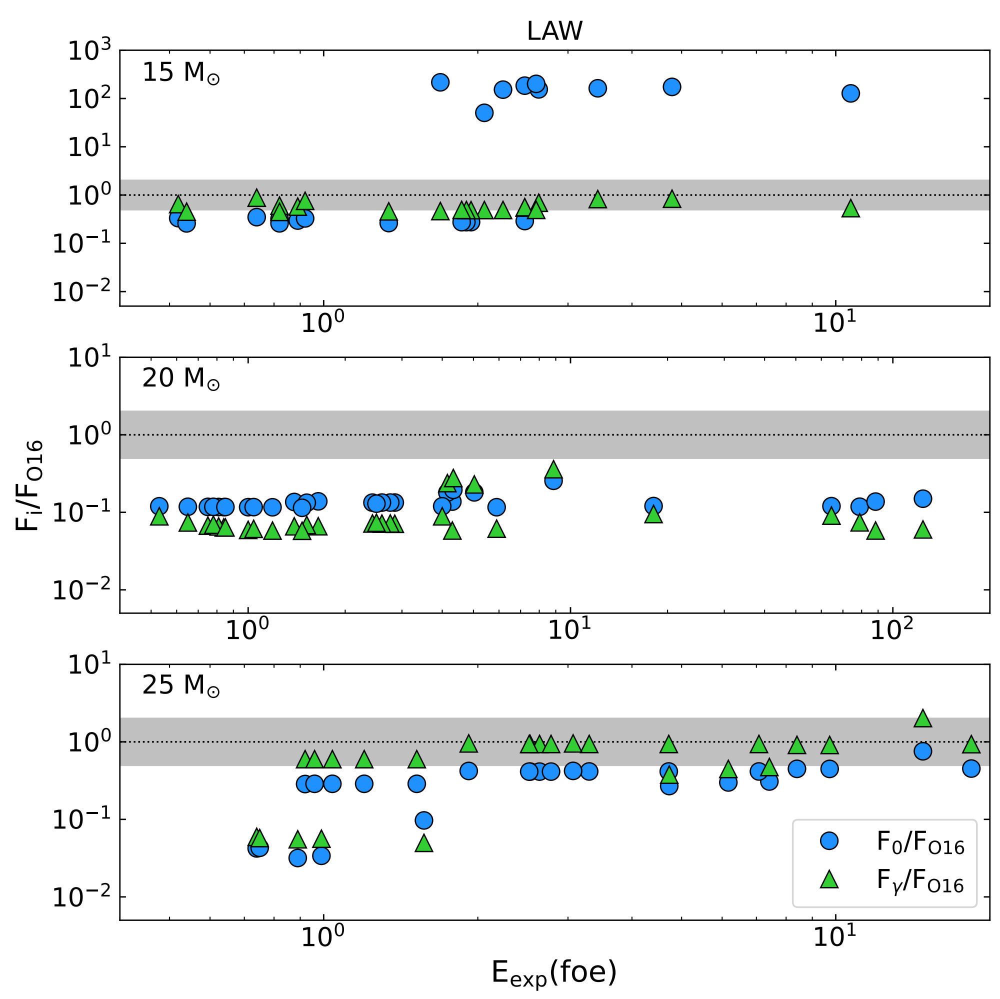
Impact of explosion models on the γ-process





$$F_0 = \frac{\sum_i^{35} F_i}{35}$$

$$F_\gamma = \frac{\sum_i^{3} F_i}{3}$$

for 3 most produced γ-only nuclei

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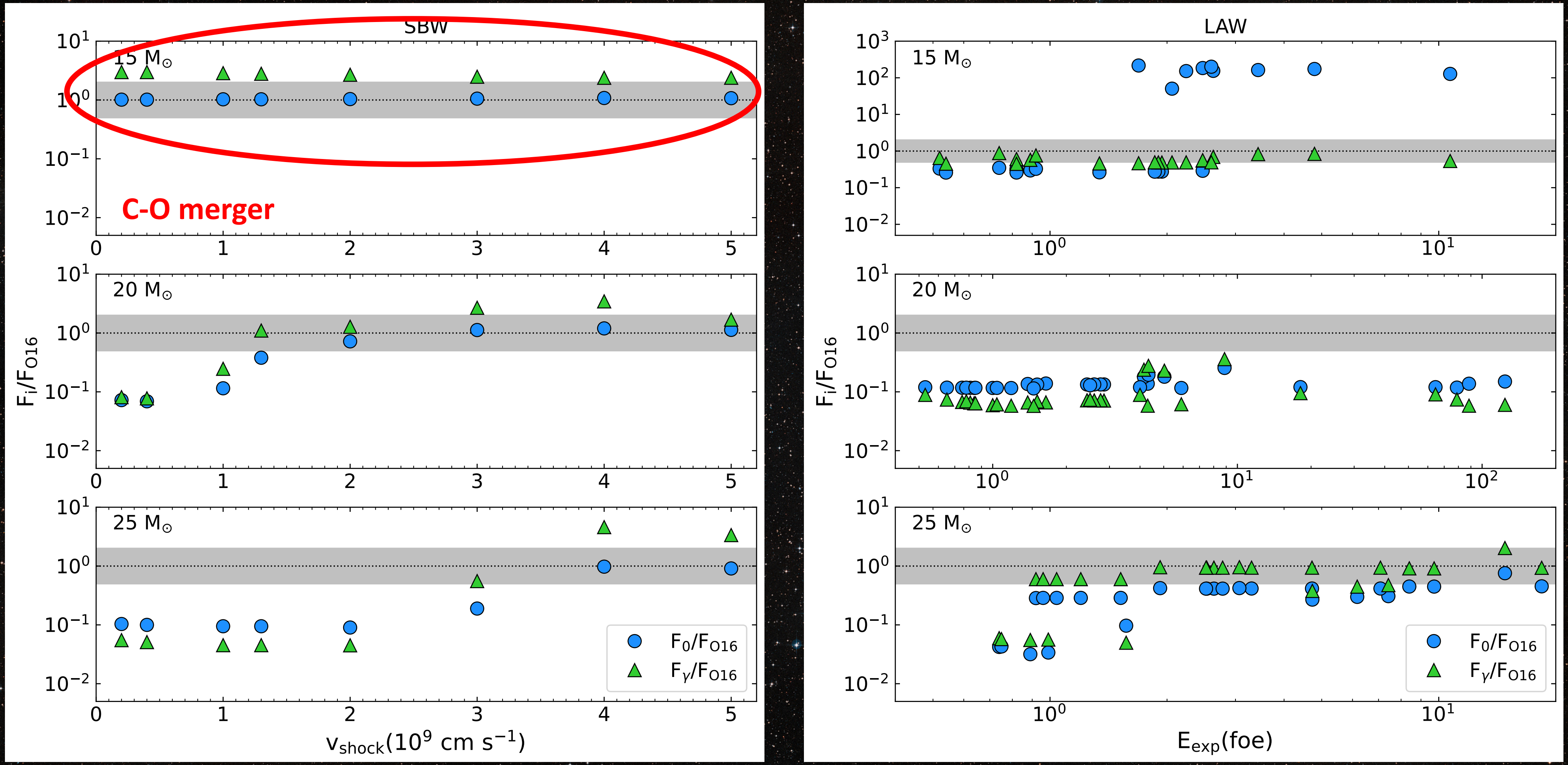

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The γ-process in C-O shell mergers

Dominant effect on yields of nuclei with A≥ 110.

Production of neutron richer isotopes (colder γ-process).

isotope	explosive (%)	merger (%)	envelope (%)	explosive (%)	merger (%)	envelope (%)
		RIT15			RAU20	
^{74}Se	**74.1**	14.9	10.9	47.3	49.0	3.6
^{78}Kr	**82.1**	5.9	11.9	**62.1**	28.8	9.1
^{84}Sr	**70.5**	11.5	17.4	42.7	**53.2**	4.0
^{92}Mo	6.4	8.4	**85.2**	10.5	15.0	**74.5**
^{94}Mo	2.8	27.4	**69.7**	5.9	45.6	48.3
^{96}Ru	8.2	4.3	**87.5**	12.1	2.4	**85.5**
^{98}Ru	13.1	49.6	37.2	16.7	37.9	45.3
^{102}Pd	36.4	40.2	23.3	45.1	25.6	29.2
^{106}Cd	34.6	22.5	43.0	**53.5**	9.2	37.3
^{108}Cd	11.4	**63.4**	25.1	19.1	46.2	34.6
^{112}Sn	34.6	35.5	29.8	47.0	16.9	36.1
^{114}Sn	20.7	**71.0**	8.2	18.0	**68.7**	13.0
^{115}Sn	0.3	**64.9**	34.8	1.3	**61.7**	36.8
^{113}In	5.4	42.5	**52.0**	8.5	46.6	44.7
^{120}Te	8.2	**62.5**	29.3	43.0	29.6	27.3
^{124}Xe	22.0	**59.9**	18.1	**70.3**	8.9	20.8
^{126}Xe	7.0	**87.4**	5.5	40.1	**54.1**	5.6
^{130}Ba	35.0	**61.0**	3.7	**66.6**	24.1	9.3
^{132}Ba	1.8	**95.9**	2.2	18.6	**78.9**	2.2
^{136}Ce	40.4	**51.0**	8.5	42.6	39.0	18.4
^{138}Ce	8.3	**84.7**	6.8	20.7	**74.4**	4.6
^{138}La	0.0	**82.9**	17.0	2.0	**91.6**	6.2
^{144}Sm	12.6	**84.0**	3.2	16.3	**80.6**	2.9
^{152}Gd	0.0	3.9	**96.1**	0.5	13.1	**86.1**
^{156}Dy	0.6	**93.7**	5.7	7.7	**89.5**	2.3
^{158}Dy	0.0	**84.4**	15.5	1.8	**95.8**	1.9
^{162}Er	0.3	**97.2**	2.4	3.6	**95.0**	1.0
^{164}Er	7.5	39.1	**53.3**	16.4	**70.7**	12.7
^{168}Yb	2.4	**94.4**	3.2	3.8	**95.1**	0.7
^{174}Hf	3.7	**87.5**	8.6	6.7	**92.2**	1.4
^{180}Ta	0.0	**98.3**	1.7	0.9	**94.7**	4.2
^{180}W	18.1	**70.7**	10.2	35.0	**61.8**	3.1
^{184}Os	0.9	**88.9**	10.2	0.8	**96.8**	2.3
^{190}Pt	1.2	**58.4**	40.3	3.5	**91.4**	4.8
^{196}Hg	12.1	**84.4**	2.7	14.9	**84.2**	0.6