

The 17th International Symposium on Origin of Matter and Evolution of Galaxies

Chengdu, Sep 10, 2024

The Role of Carbon-Oxygen Shell Interactions in the Nucleosynthesis and Final Fate of Massive Stars

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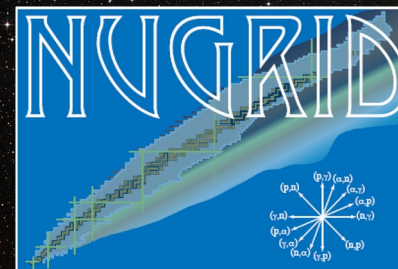
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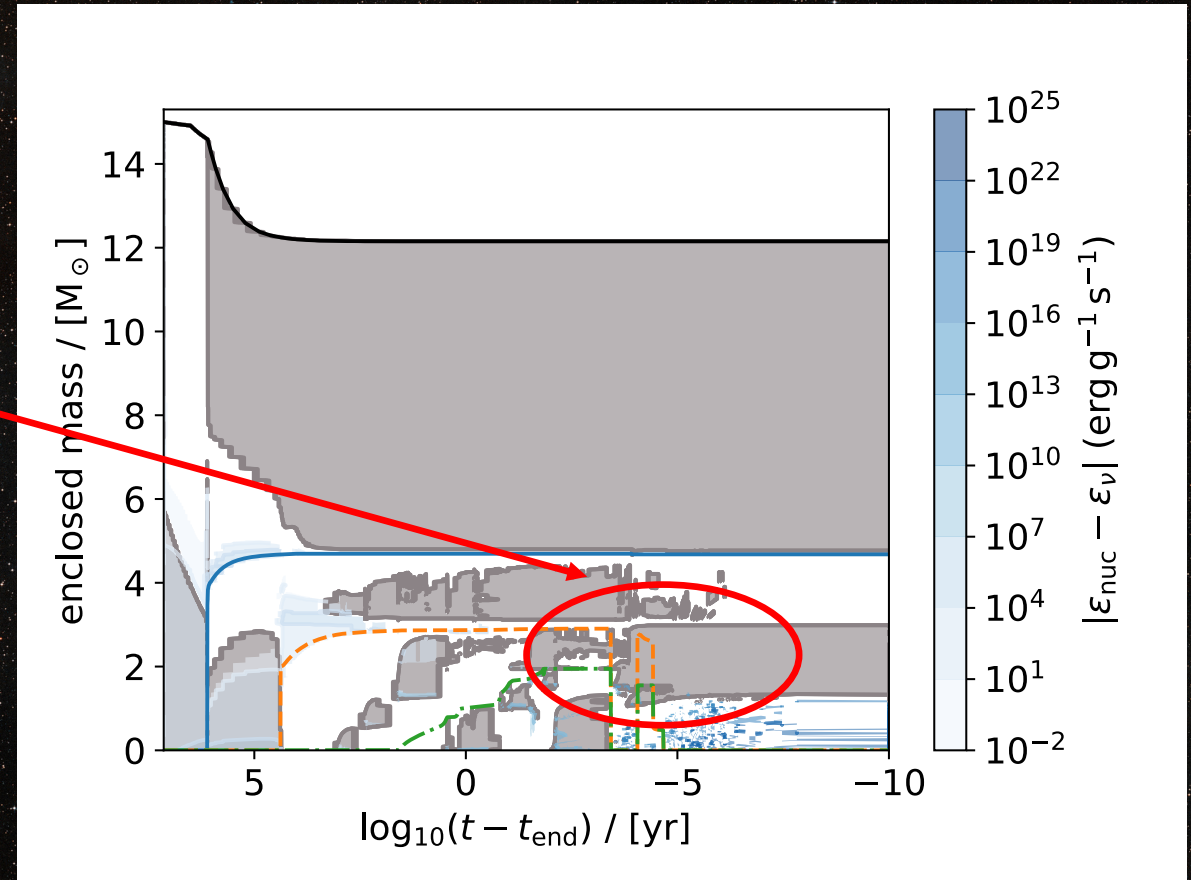
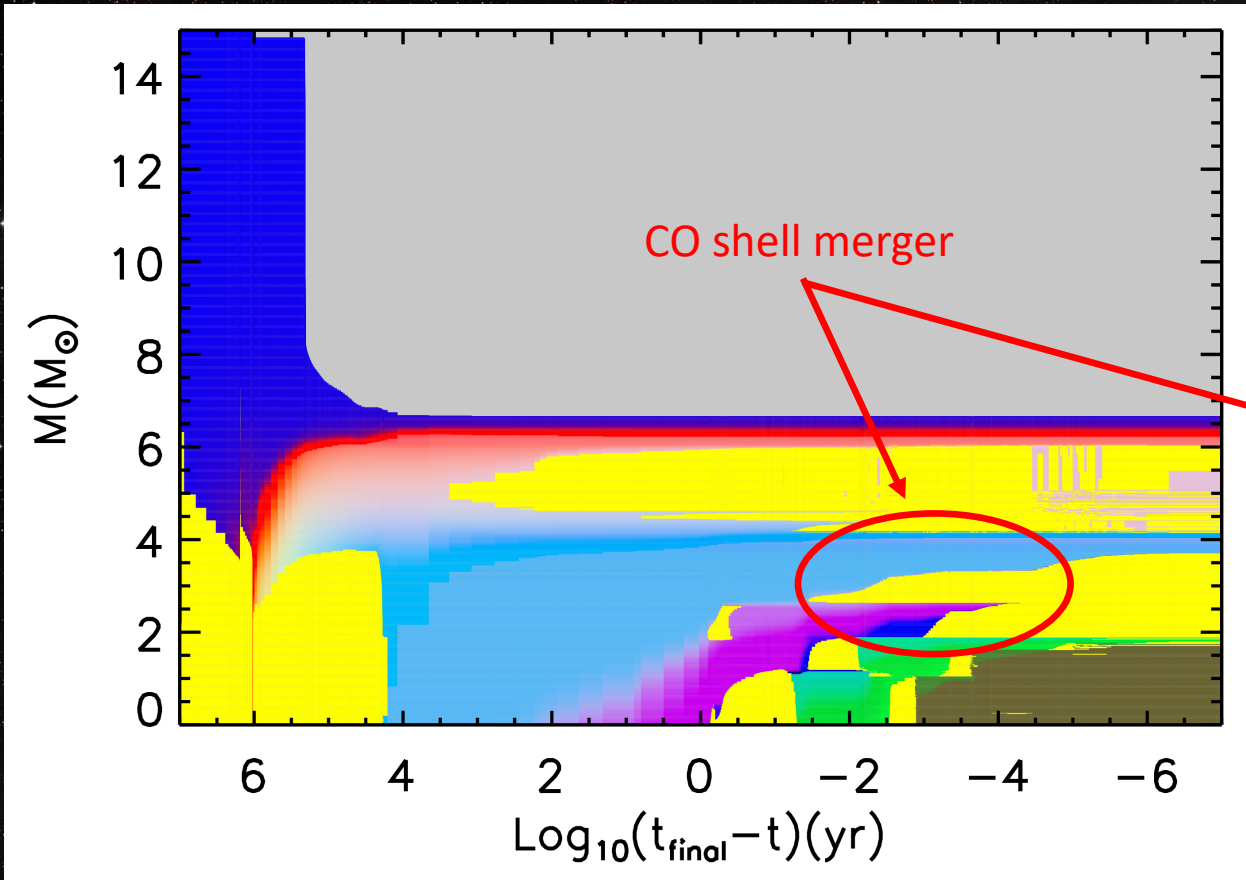
Advanced burning stages in massive stars

- After H and He burning phases, the evolution is controlled by CO core mass and ^{12}C mass fraction left by He burning;
- C, Ne, O, Si are progressively used as fuel for core and shell burning;
- After central Si depletion, a Fe core forms and begins to collapse;
- Core-collapse supernova (CCSN)?
- Evolution and development of convective shells impact the final M-R relation, density and entropy profiles.

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 $M_{\text{ini}} \leq 25 M_{\odot}$ (e.g., Rauscher+02, Ritter+18, Roberti+24).

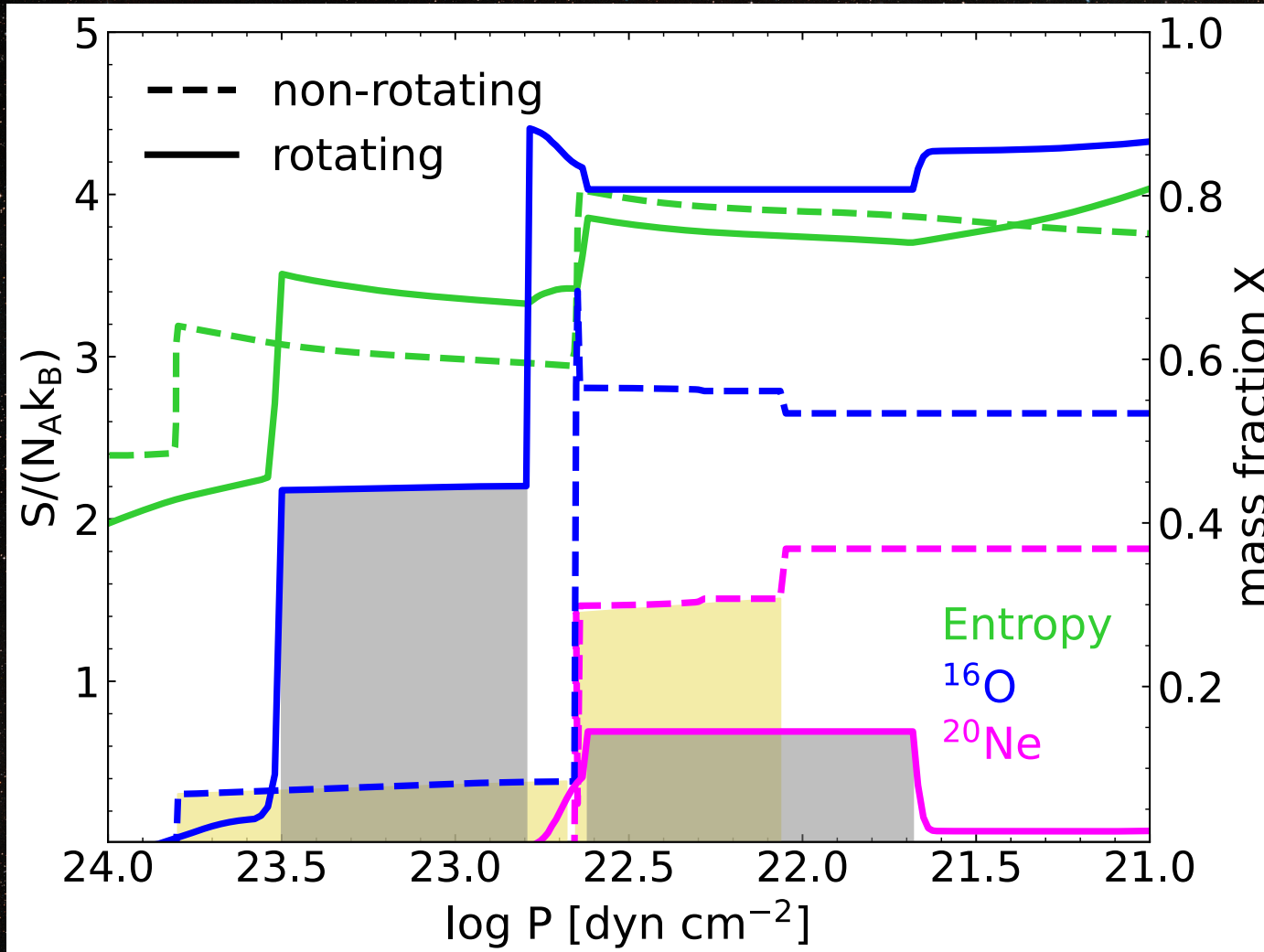
Carbon-oxygen shell mergers in massive stars



15 M_{\odot} , $Z=0$, $v_{\text{rot}}=300$ km/s at zero (Roberti et al., 2024, ApJS, 270, 28)

15 M_{\odot} , $Z=0.02$, $v_{\text{rot}}=0$ km/s at zero (Ritter et al., 2018, MNRAS 480, 538)

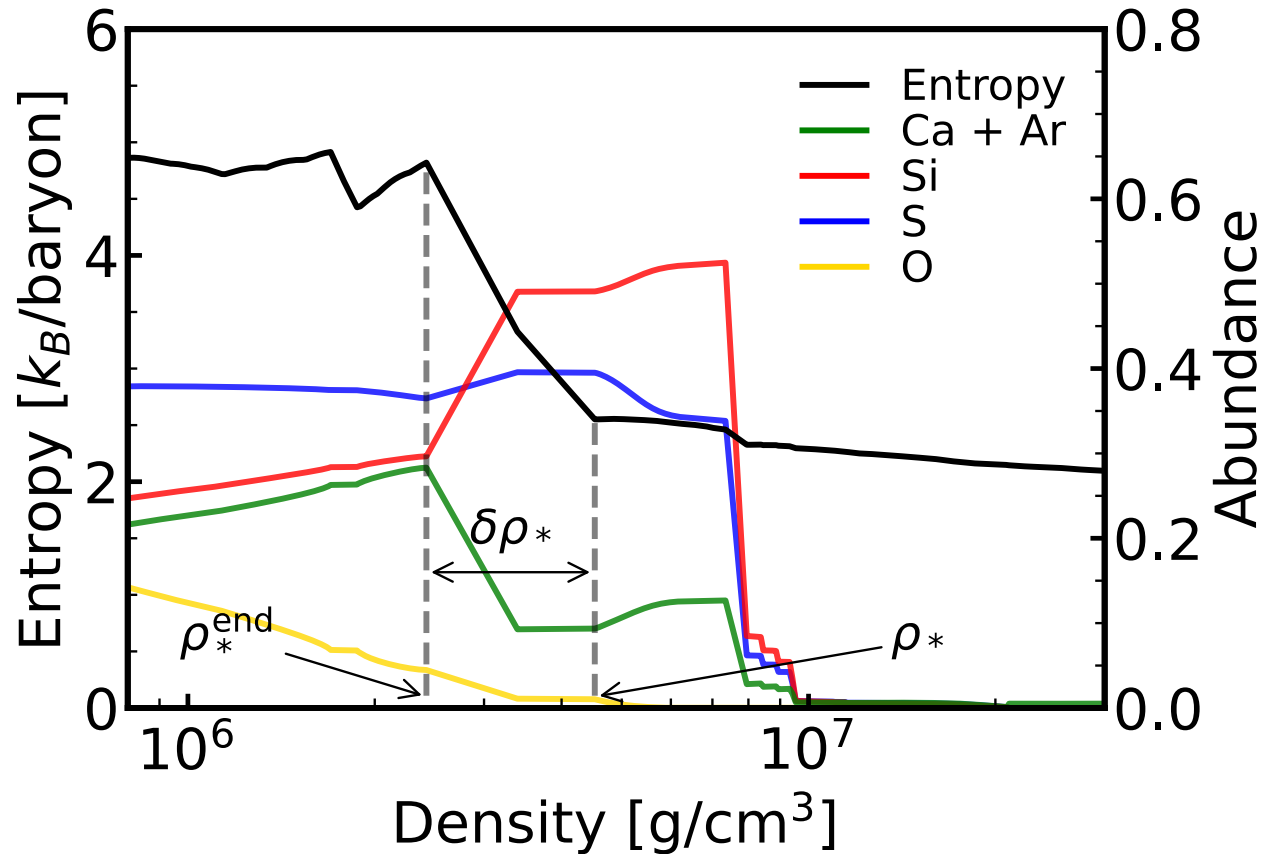
Carbon-oxygen shell mergers in massive stars



Low ¹²C left by He burning may favor C-O shell mergers, by decreasing the entropy barrier at the shell interface (Roberti+24, Roberti et al., in prep.).

Roberti et al., 2024, ApJS, 270, 28

Explodability of stars with a C-O merger?



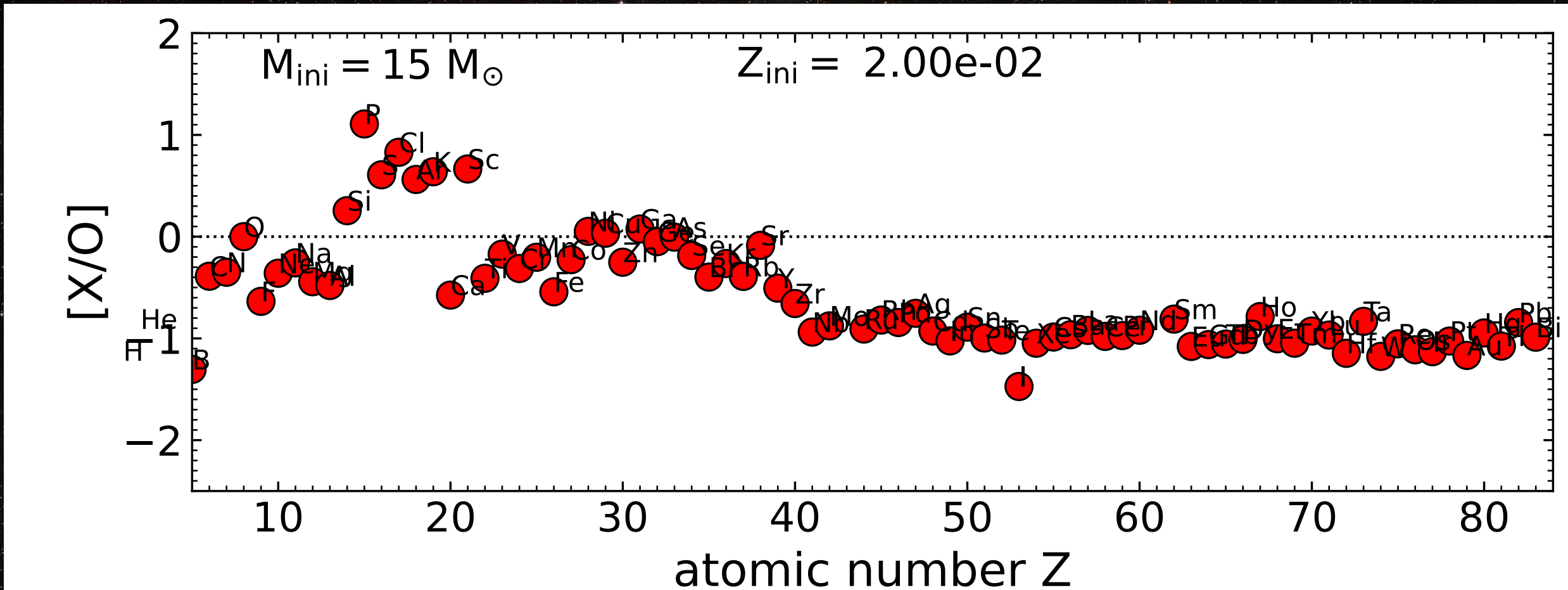
Large $\delta\rho/\rho$ at the Si/O interface help the CCSN explosion (Boccioli+23).
Massive stars with C-O shell mergers naturally meet this condition (Roberti&Boccioli, in prep.).

Boccioli et al., 2023, ApJ, 949,17

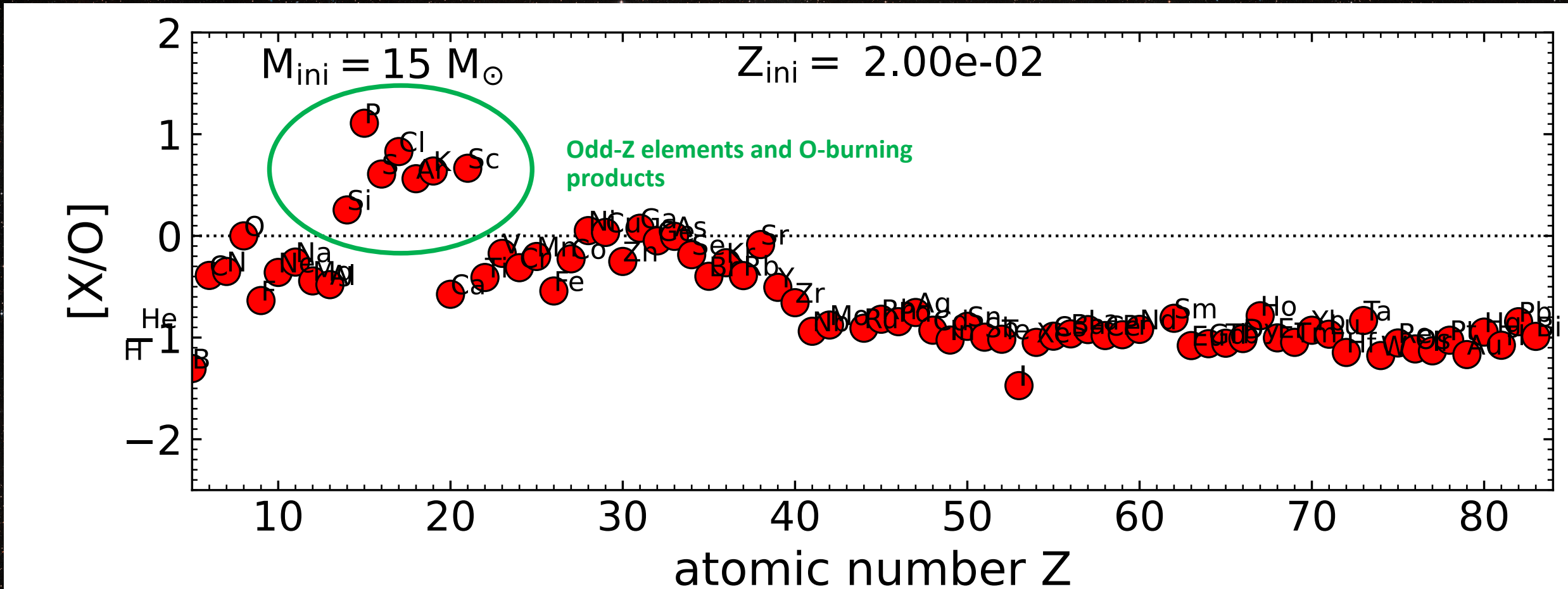
Nucleosynthesis in a C-O shell merger

- Enhanced O-burning products and production of odd-Z elements (P, Cl, K, Sc);
- Activation of the γ -process and production of the p-nuclei;
- Efficient photodisintegration of heavy elements and production of the weak s-process peak.

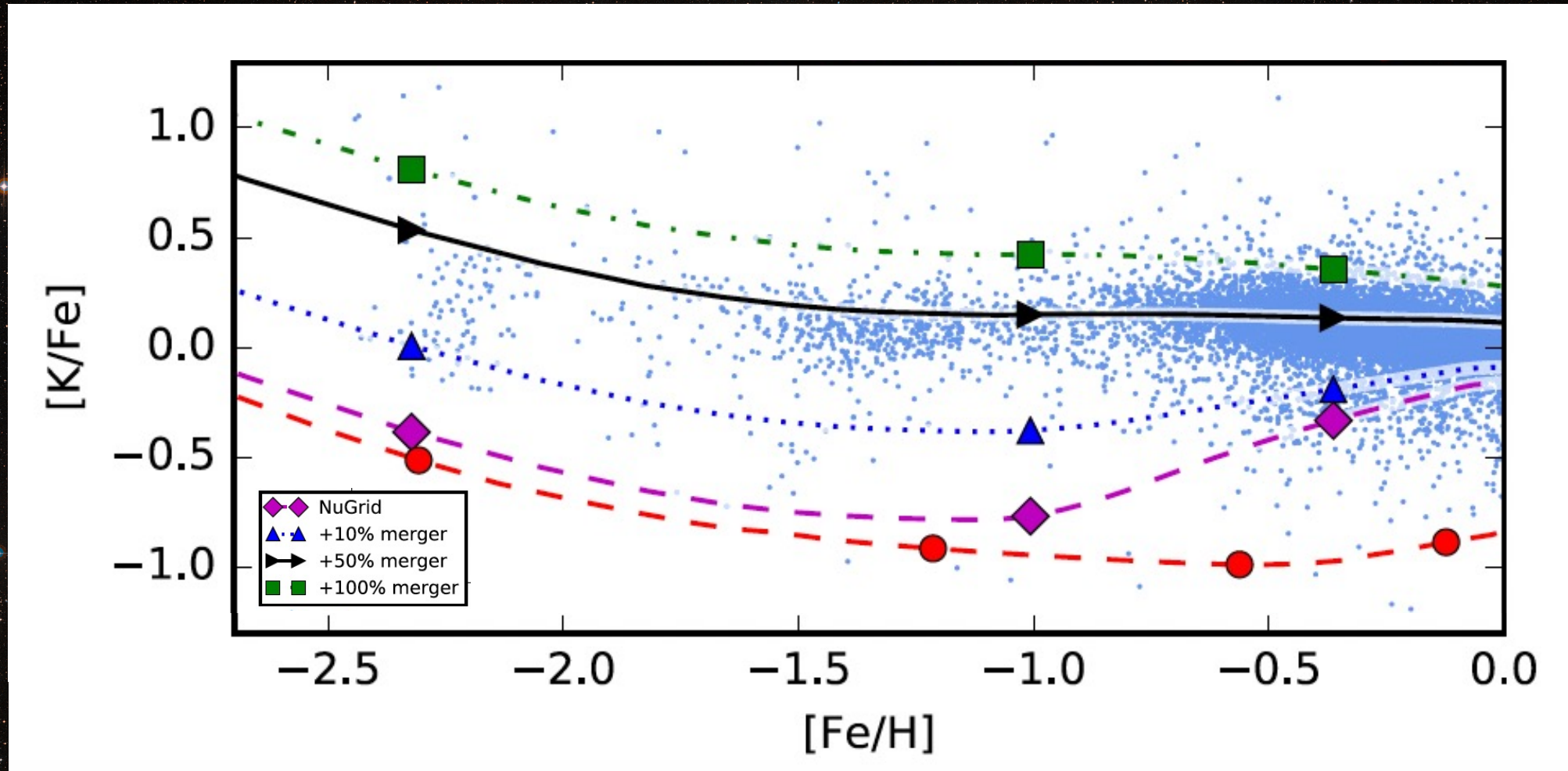
Nucleosynthesis: odd-Z element production



Nucleosynthesis: odd-Z element production

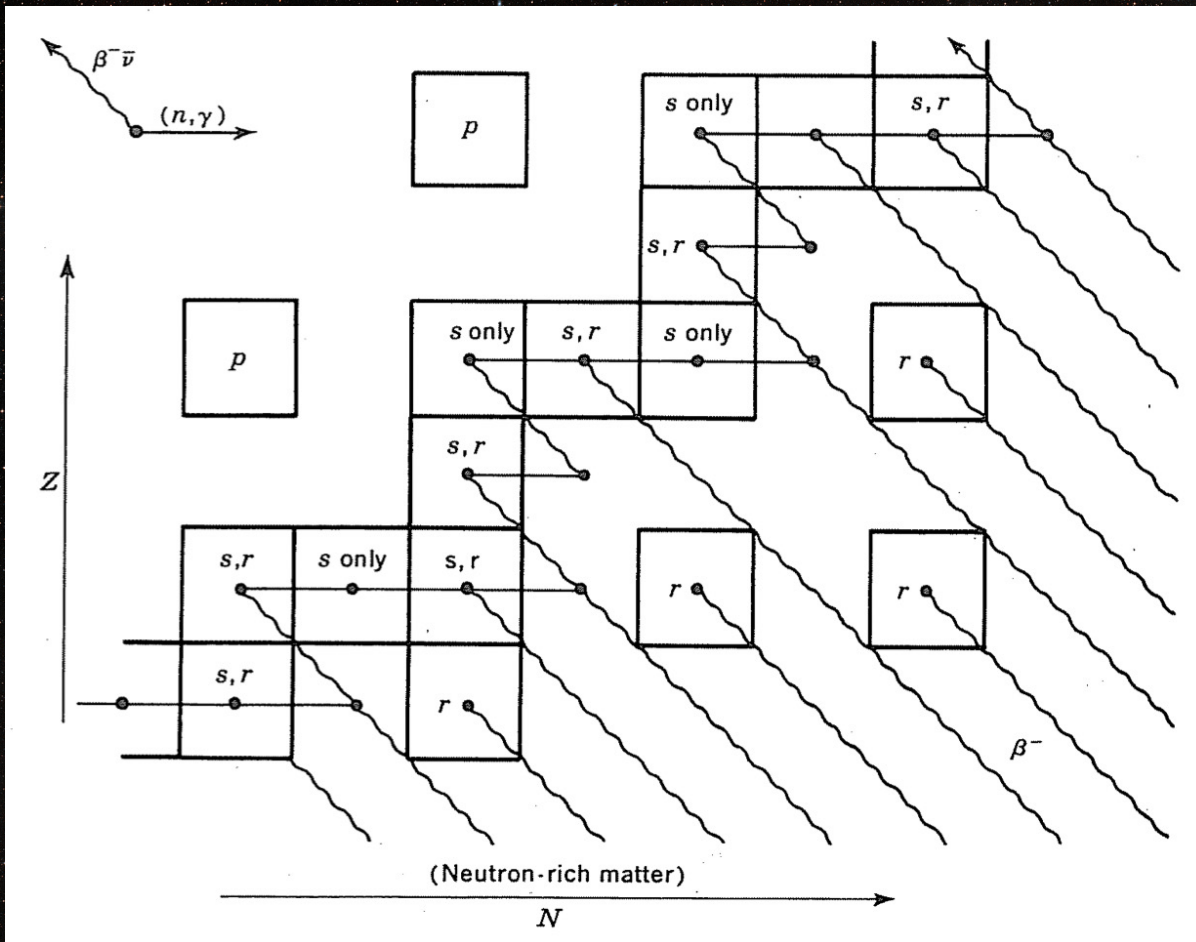


Nucleosynthesis: odd-Z element production



Ritter et al., 2018, MNRAS 474, L1

Nucleosynthesis: the γ -process



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

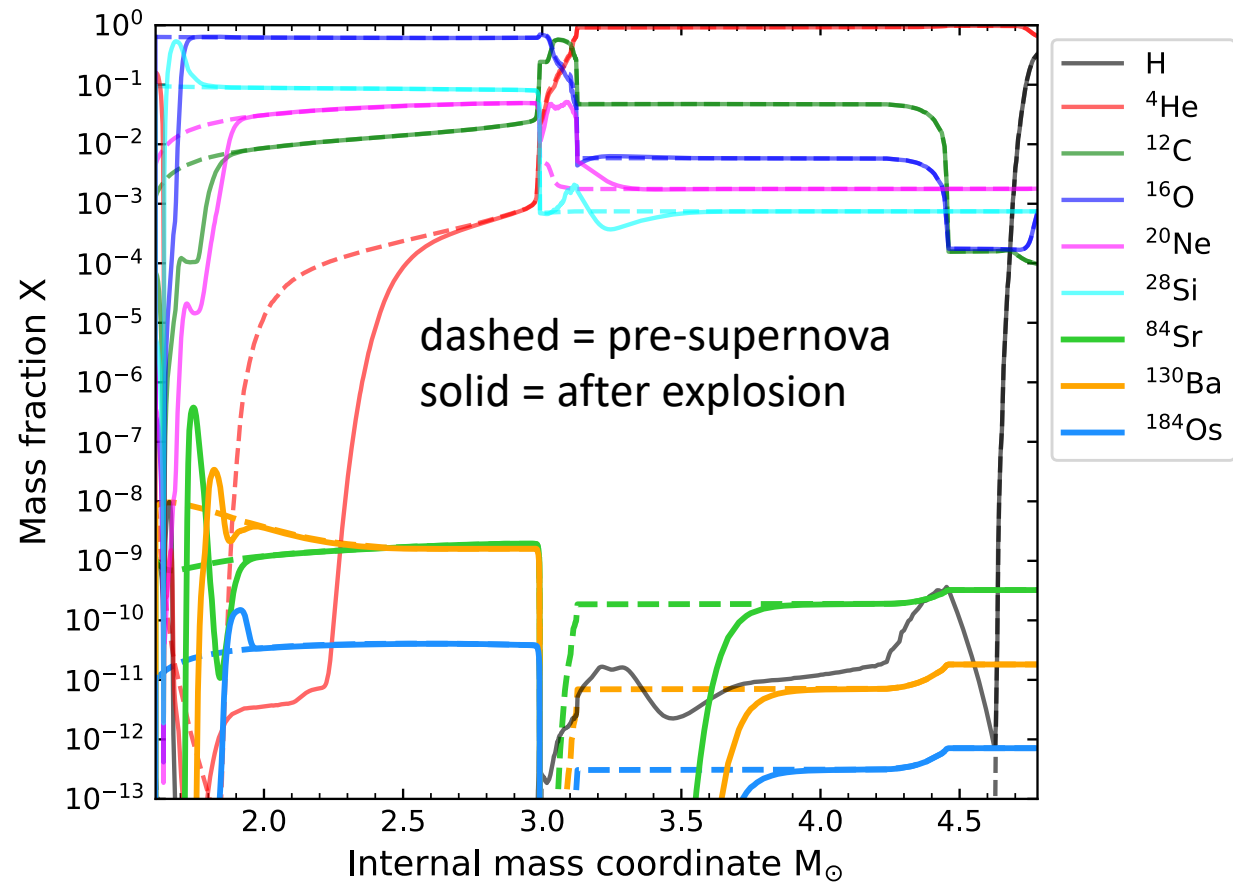
- The **γ -process**: a sequence of photodisintegrations (γ, n), (γ, p), and (γ, α) in O/Ne rich layers in CCSN explosions from massive star progenitors (e.g., Woosley & Howard, 1978; Rayet et al., 1995);
- Production of **p-nuclei**: 35 neutron-deficient isotopes of elements heavier than Fe;
- **Underproduction**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

Nucleosynthesis: the γ -process

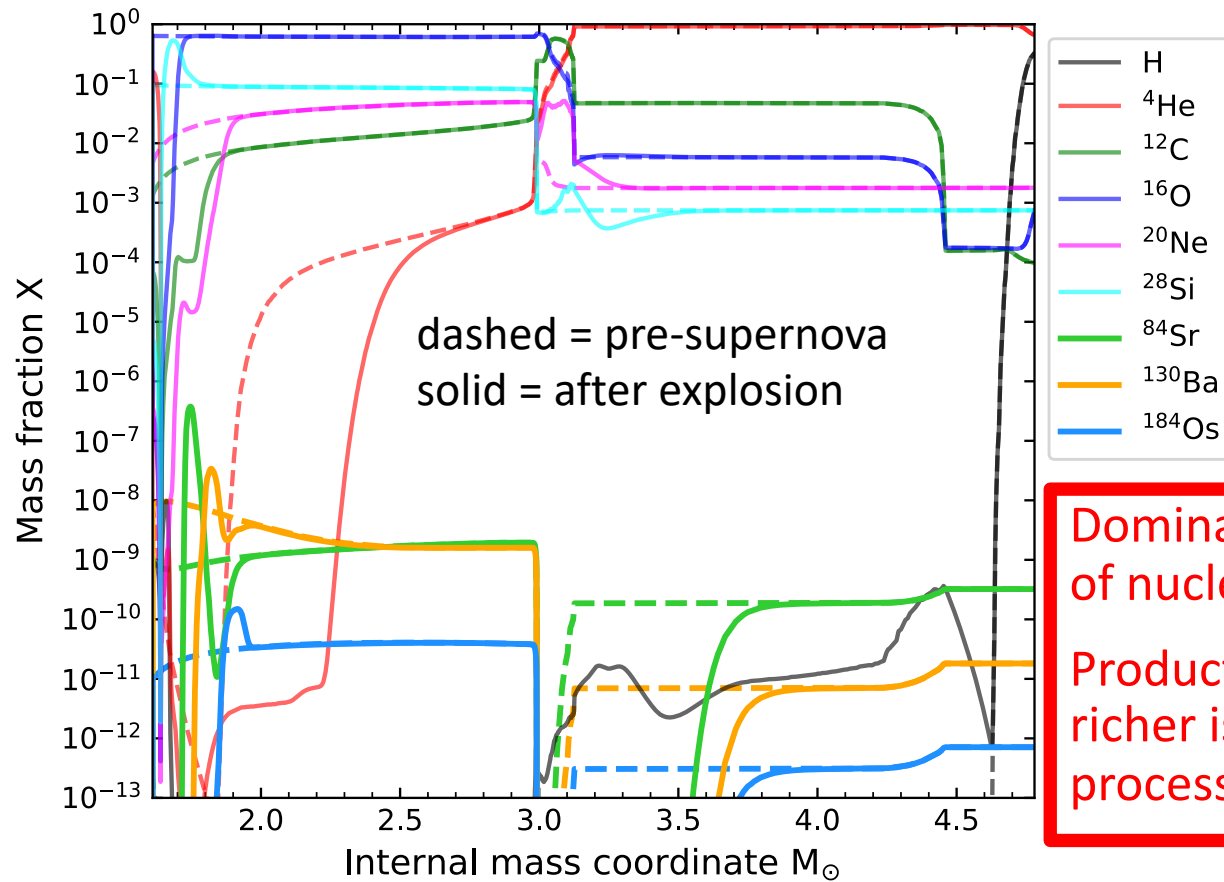
35 stable proton-rich nuclei: ^{74}Se , ^{78}Kr , ^{84}Sr , $^{92,94}\text{Mo}$, $^{96,98}\text{Ru}$, ^{102}Pd , $^{106,108}\text{Cd}$, $^{112,114,115}\text{Sn}$, ^{113}In , ^{120}Te , $^{124,126}\text{Xe}$, $^{130,132}\text{Ba}$, $^{136,138}\text{Ce}$, ^{138}La , ^{144}Sm , ^{152}Gd , $^{156,158}\text{Dy}$,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

- Different explosive contributions (e.g., α - & vp-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).

Nucleosynthesis: the γ -process



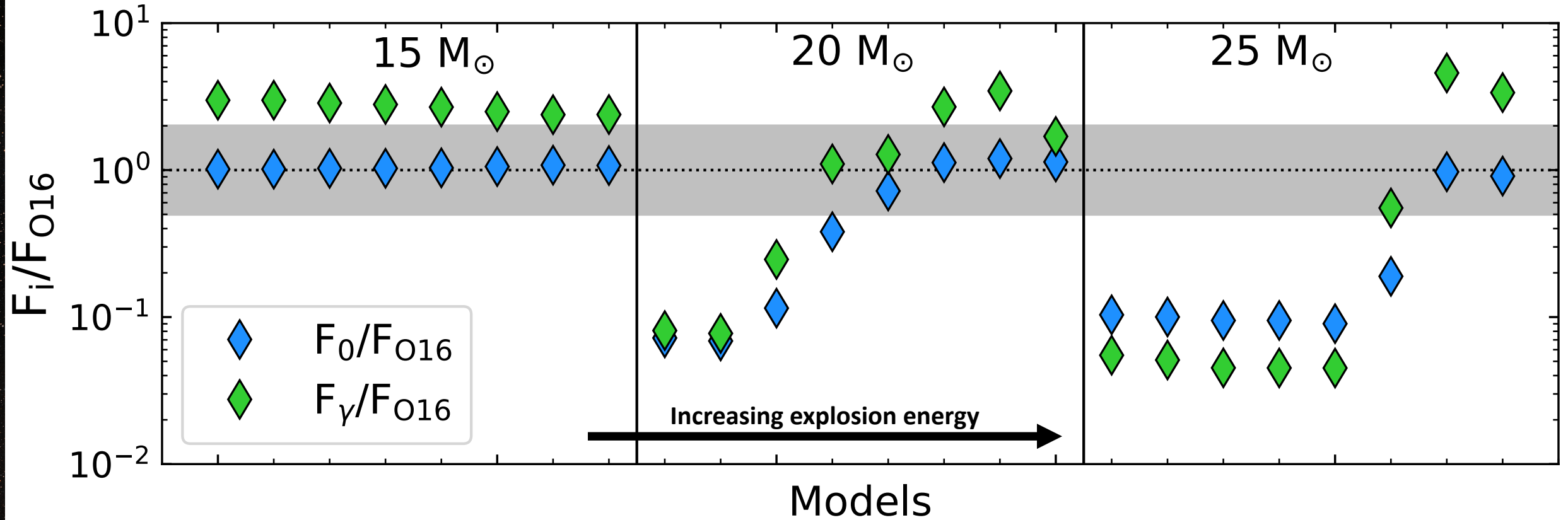
Nucleosynthesis: the γ -process



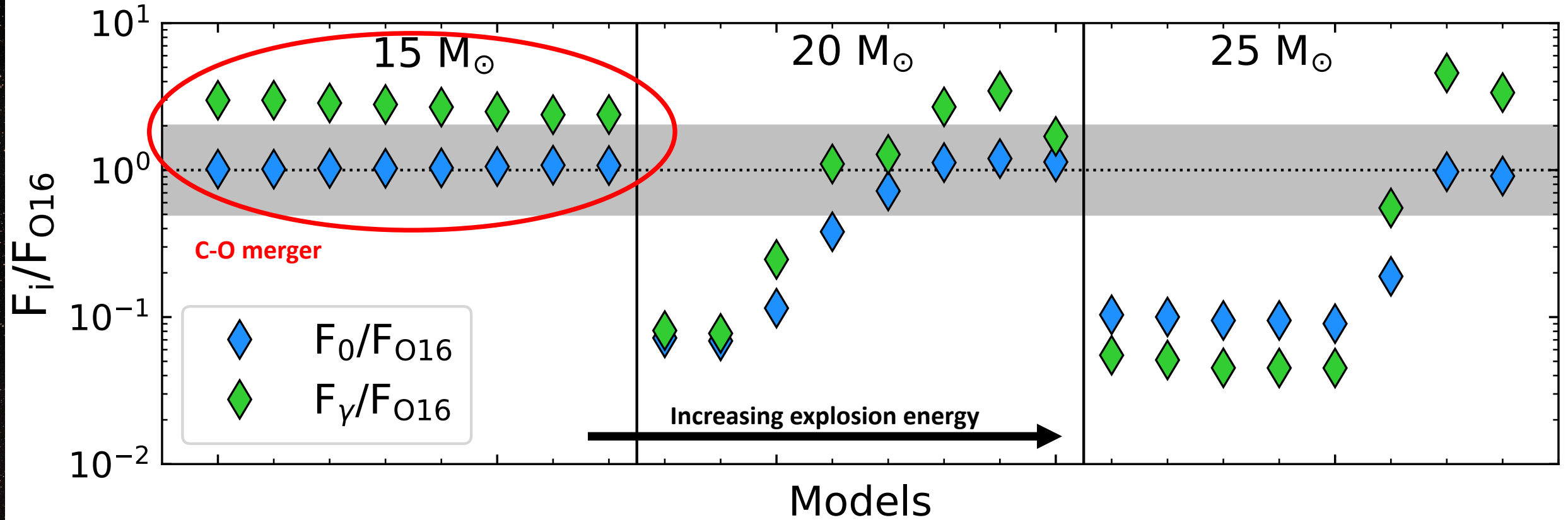
Dominant effect on yields of nuclei with $A \geq 110$.
Production of neutron richer isotopes (colder γ -process).

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

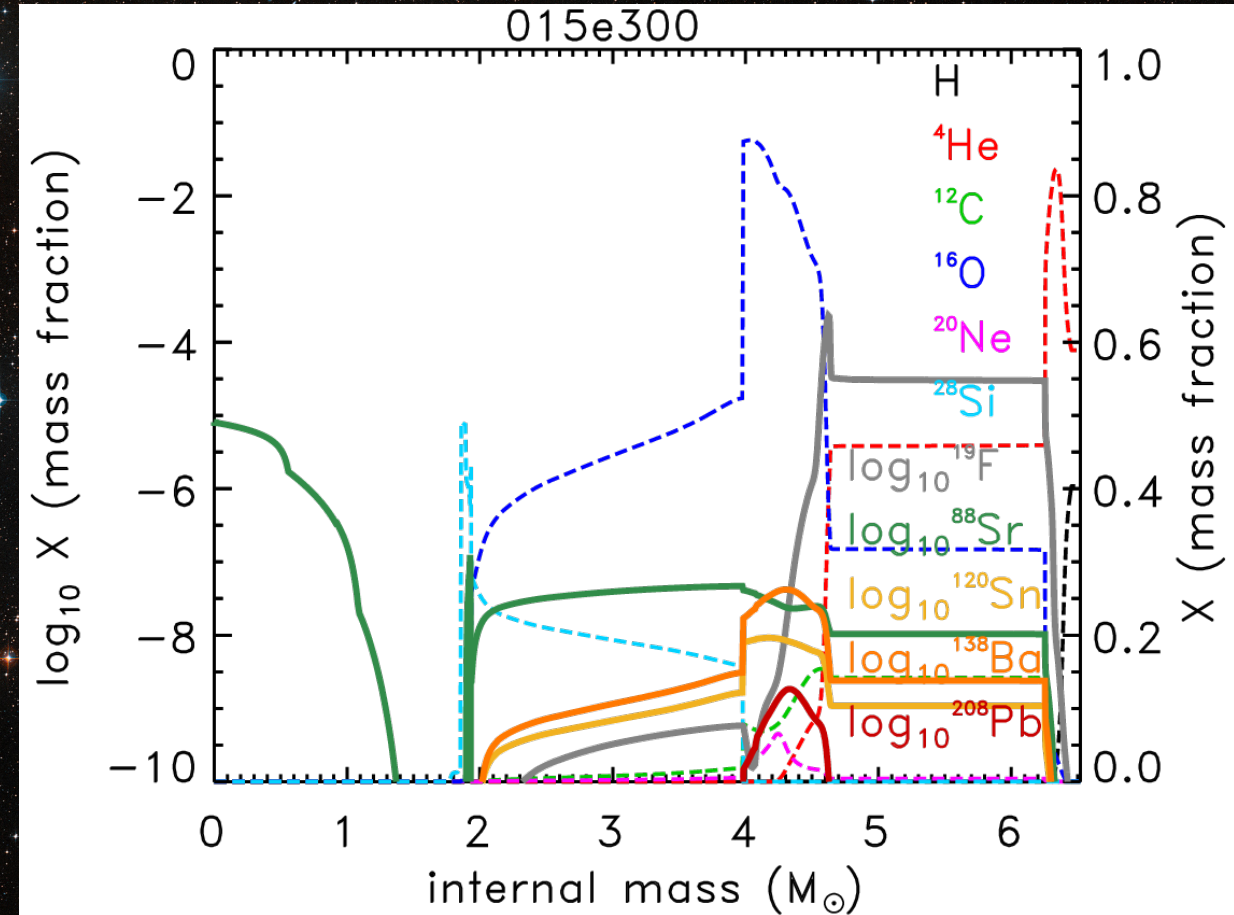
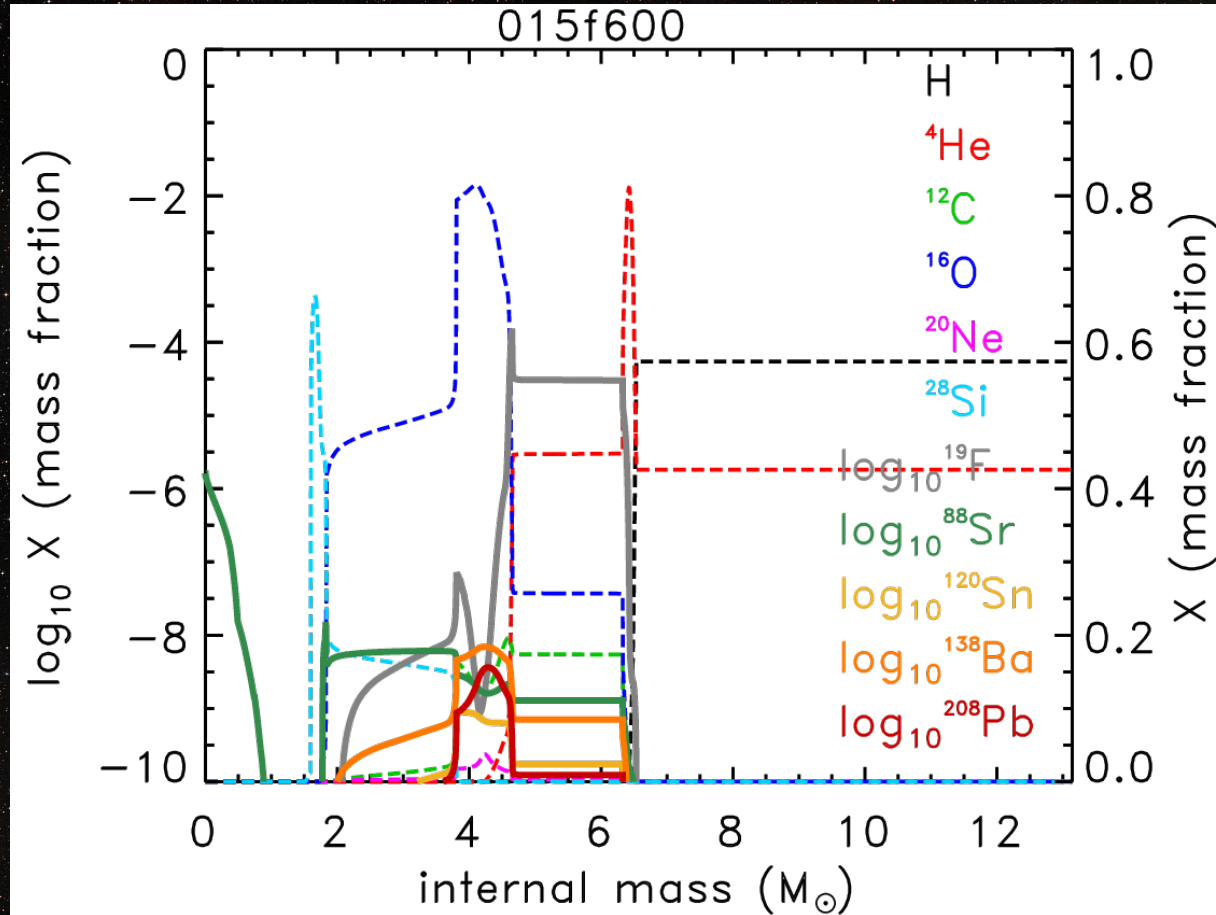
Nucleosynthesis: the γ -process



Nucleosynthesis: the γ -process



Nucleosynthesis: the weak s-process component



Roberti et al., 2024, ApJS, 270, 28

Summary and conclusions

- Carbon-oxygen (C-O) shell mergers in massive stars have a crucial impact on the explosion and on the ejecta composition of CCSNe;
- Indication from 3D modeling seem to confirm their existence;
- Large density jump at the Si/O interface because of the extended mixed convective region: easier explosion? In progress, stay tuned!
- Production site for odd-Z elements, p-nuclei, weak s-process component;
- Question: frequency? Trend with mass/metallicity/rotation?

THANK YOU!

Short advertising!



We are organizing the
8th p-process workshop
@ Konkoly observatory in Budapest!

Save the date:
16-18th October 2024

[https://indico.cern.ch/event/1389227/
8thprocessworkshop@gmail.com](https://indico.cern.ch/event/1389227/8thprocessworkshop@gmail.com)



Hope to see you in Budapest next October!

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THANK YOU!