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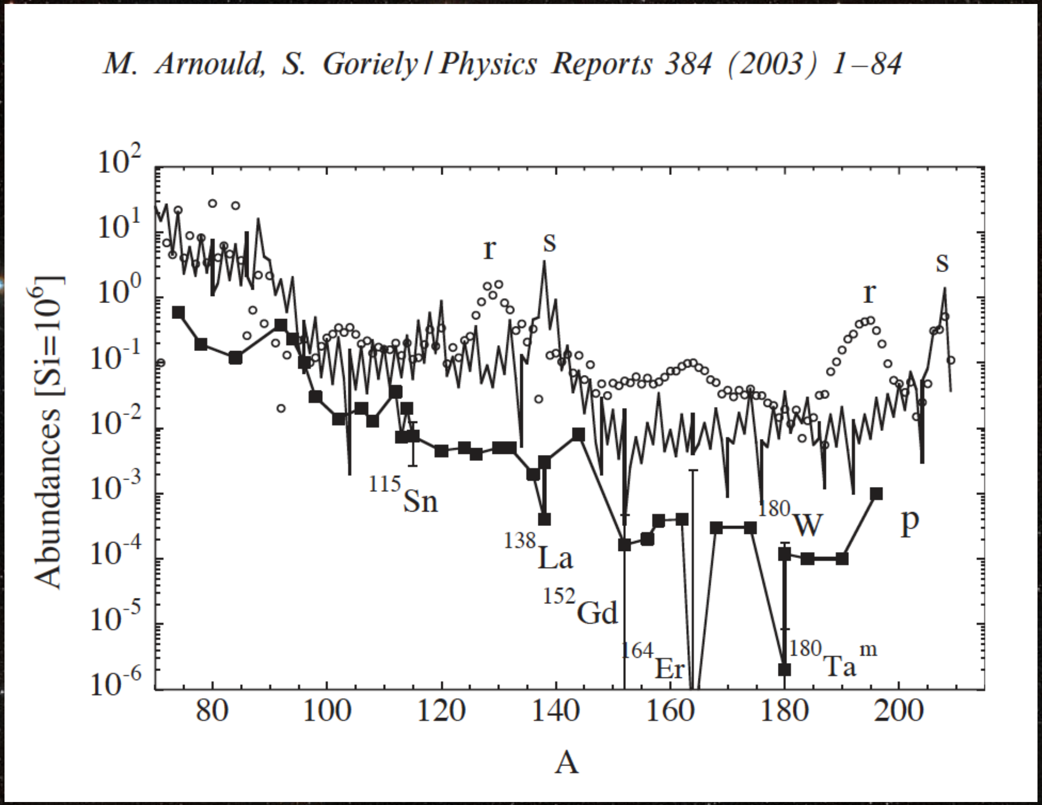
The p-process nucleosynthesis in core-collapse supernovae

L. Roberti, M. Pignatari, M. Lugaro, A. Psaltis, A. Sieverding, P. Mohr, Gy. Gyürky, and Zs. Fülöp

CSFK KONKOLY NUGRID RADIOSTAR erc OTKA

The p-rich nuclei



A small fraction of the total abundances of the elements beyond iron in the Solar System is made of proton-rich isotopes.

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.

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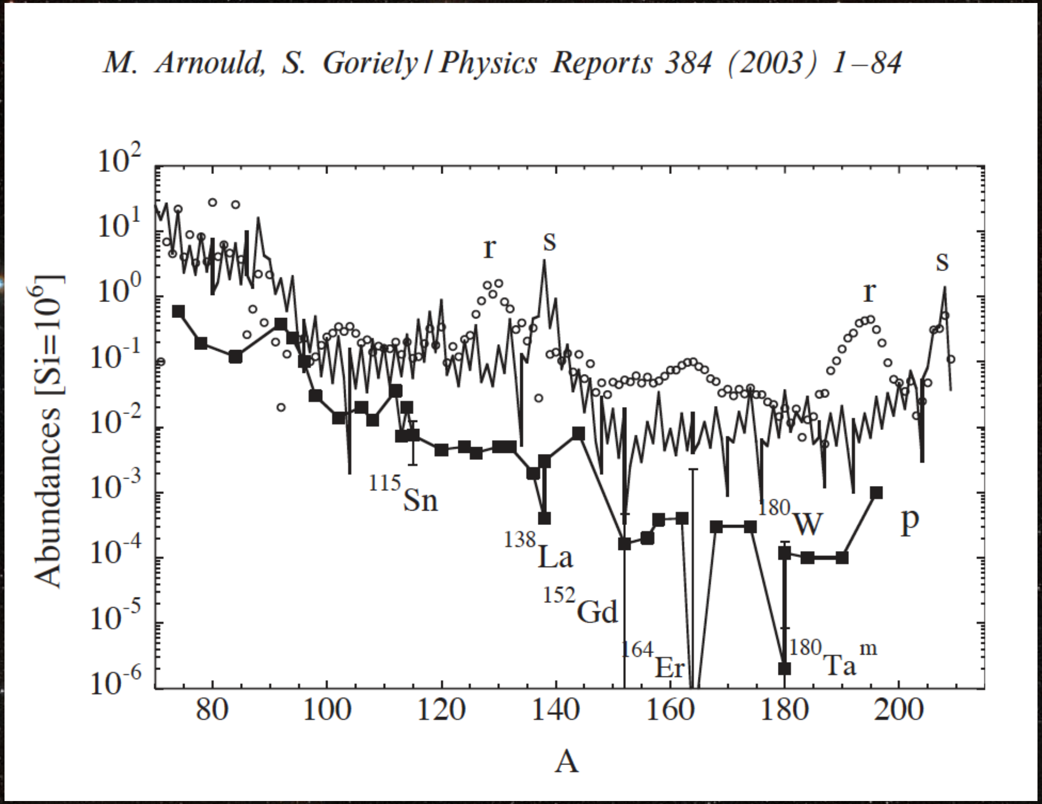

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See also:

F. G. Barba (Sn isotopes) **poster**

V. Vashi (^{115}In*) **talk**

A. Tsantiri (^{82}Kr+p) **talk**

… and talks later today!

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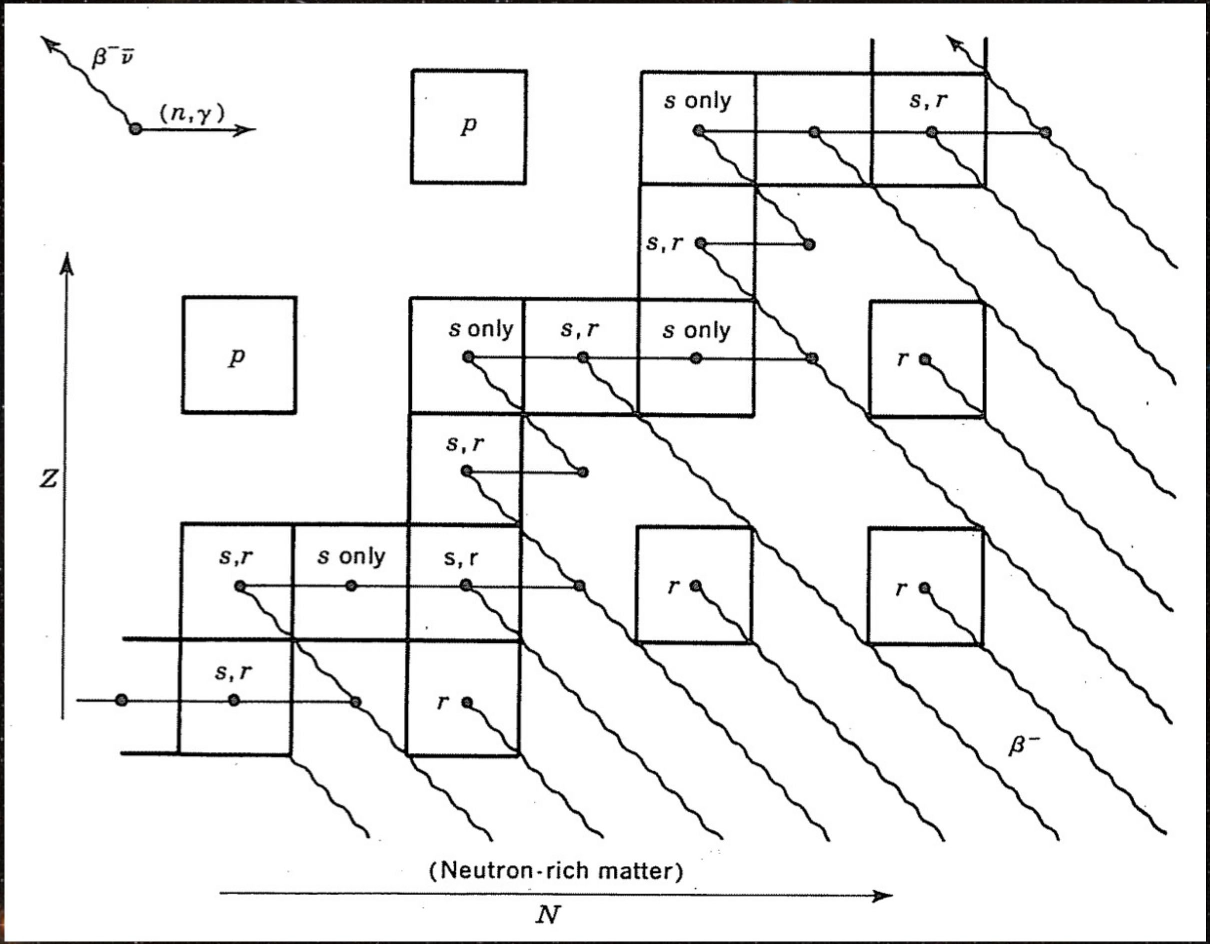

Clayton, D.D. (1968) Principles of Stellar Evolution and Nucleosynthesis. University of Chicago Press, Chicago.

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- 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 p/γ-process nucleosynthesis

- p-rich nuclei are (mostly) produced through 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);
- The typical γ-process yields from massive stars are underproduced by a factor of ~2-4 compared to the solar system abundances;
- ^{92,94}Mo and ^{96,98}Ru are underproduced by more than an order of magnitude compared to the other γ-process nuclei.

The p/γ-process nucleosynthesis

Main goals of the project:

- 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);
- Update of the nuclear reaction rates for the γ-process nucleosynthesis (in collaboration with ATOMKI);
- Production of new γ-process stellar yields through the NuGrid post-processing codes.

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The p/γ-process nucleosynthesis

The γ–process nucleosynthesis in core-collapse supernovae

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

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[2] INAF – Osservatorio Astronomico di Roma Via Frascati 33, I-00040, Monteporzio Catone, Italy
[3] NuGrid Collaboration, http://nugridstars.org
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[10] Institute for Nuclear Research (ATOMKI), H-4001 Debrecen, Hungary

The isotopic ratios

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

$$\frac{\left(\frac{X(A)_{\star}}{X(B)_{\star}}\right)}{\left(\frac{X(A)_{\odot}}{X(B)_{\odot}}\right)} = \frac{OP(A)}{OP(B)}$$

$X(A)_{\star}$ = model abundance in mass fraction of the isotope A

$X(A)_{\odot}$= solar abundance in mass fraction of the isotope A

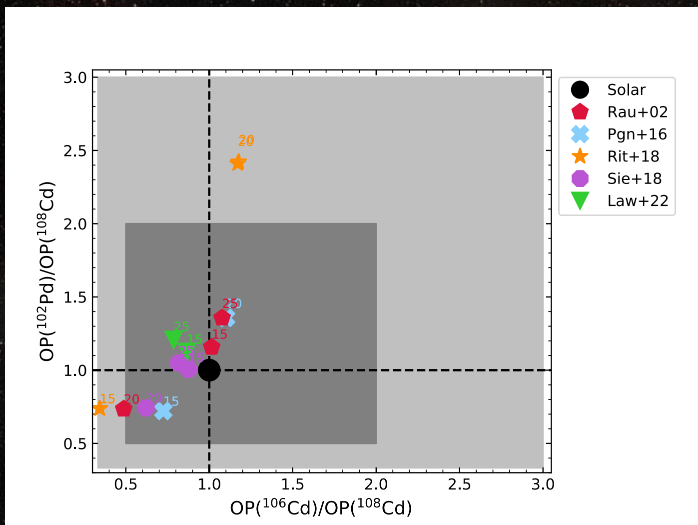
Ratios of p–nuclei close to each other in mass, normalized to the solar ratio, with the condition OP>2.

Agreement with solar if the ratio is within a factor of 3.

The isotopic ratios

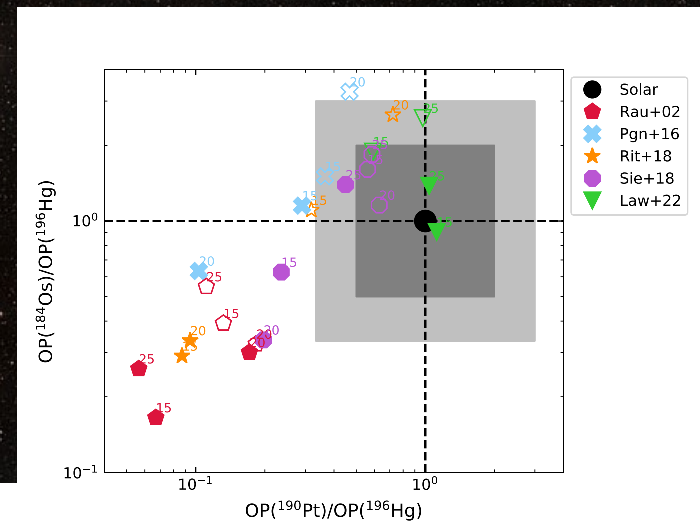
Plot	# isotopes	1st isotopic ratio	2nd isotopic ratio
1	3	$^{74}Se/^{78}Kr$	$^{84}Sr/^{78}Kr$
2	4	$^{92}Mo/^{94}Mo$	$^{96}Ru/^{98}Ru$
3	3	$^{102}Pd/^{108}Cd$	$^{106}Cd/^{108}Cd$
4	3	$^{112}Sn/^{114}Sn$	$^{113}In/^{114}Sn$
5	3	$^{112}Sn/^{114}Sn$	$^{115}Sn/^{114}Sn$
6	3	$^{120}Te/^{126}Xe$	$^{124}Xe/^{126}Xe$
7	4	$^{130}Ba/^{132}Ba$	$^{136}Ce/^{138}Ce$
8	3	$^{138}La/^{132}Ba$	$^{144}Sm/^{132}Ba$
9	3	$^{156}Dy/^{152}Gd$	$^{144}Sm/^{152}Gd$
10	4	$^{156}Dy/^{158}Dy$	$^{162}Er/^{164}Er$
11	4	$^{168}Yb/^{180}Ta$	$^{174}Hf/^{180}W$
12	3	$^{184}Os/^{196}Hg$	$^{190}Pt/^{196}Hg$

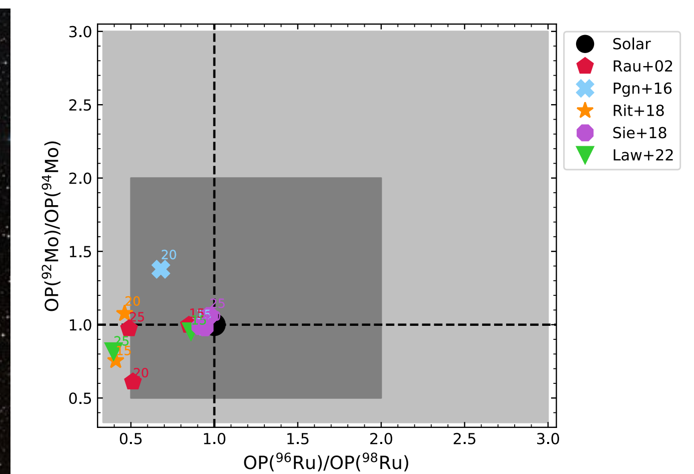
Results: agreement with solar



☆ = undecayed yields

★ = undecayed yields + radiogenic contribution





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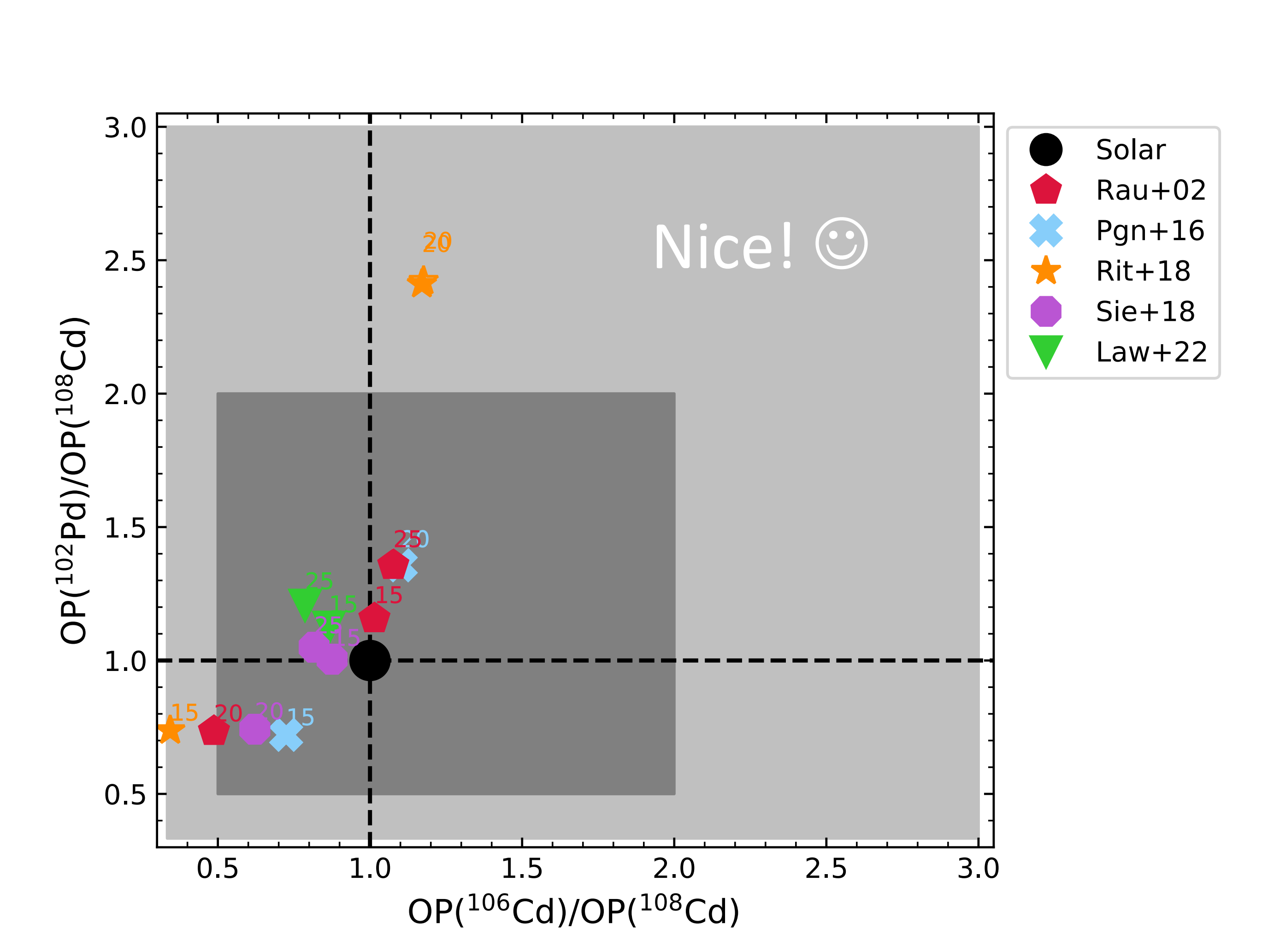

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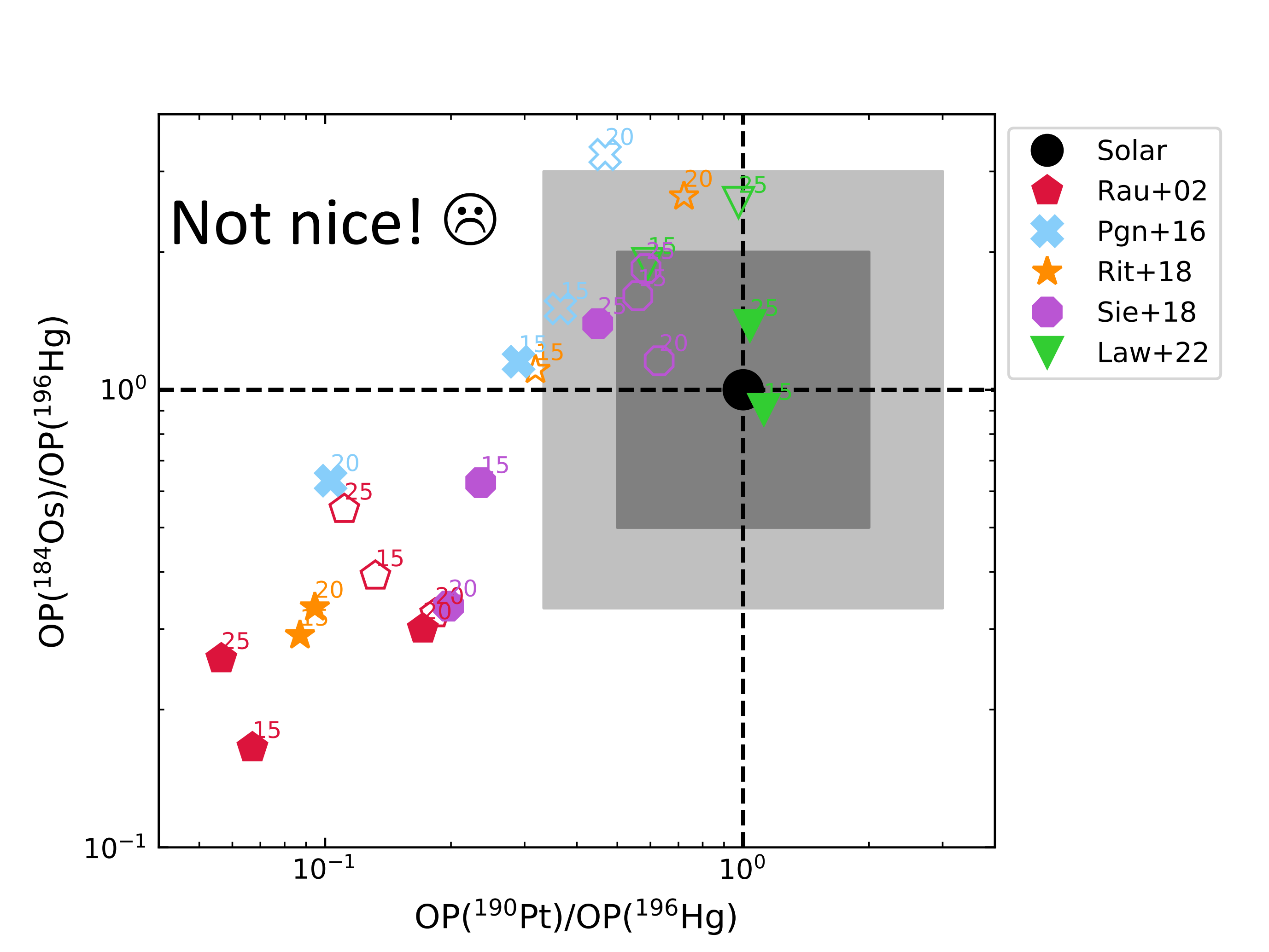

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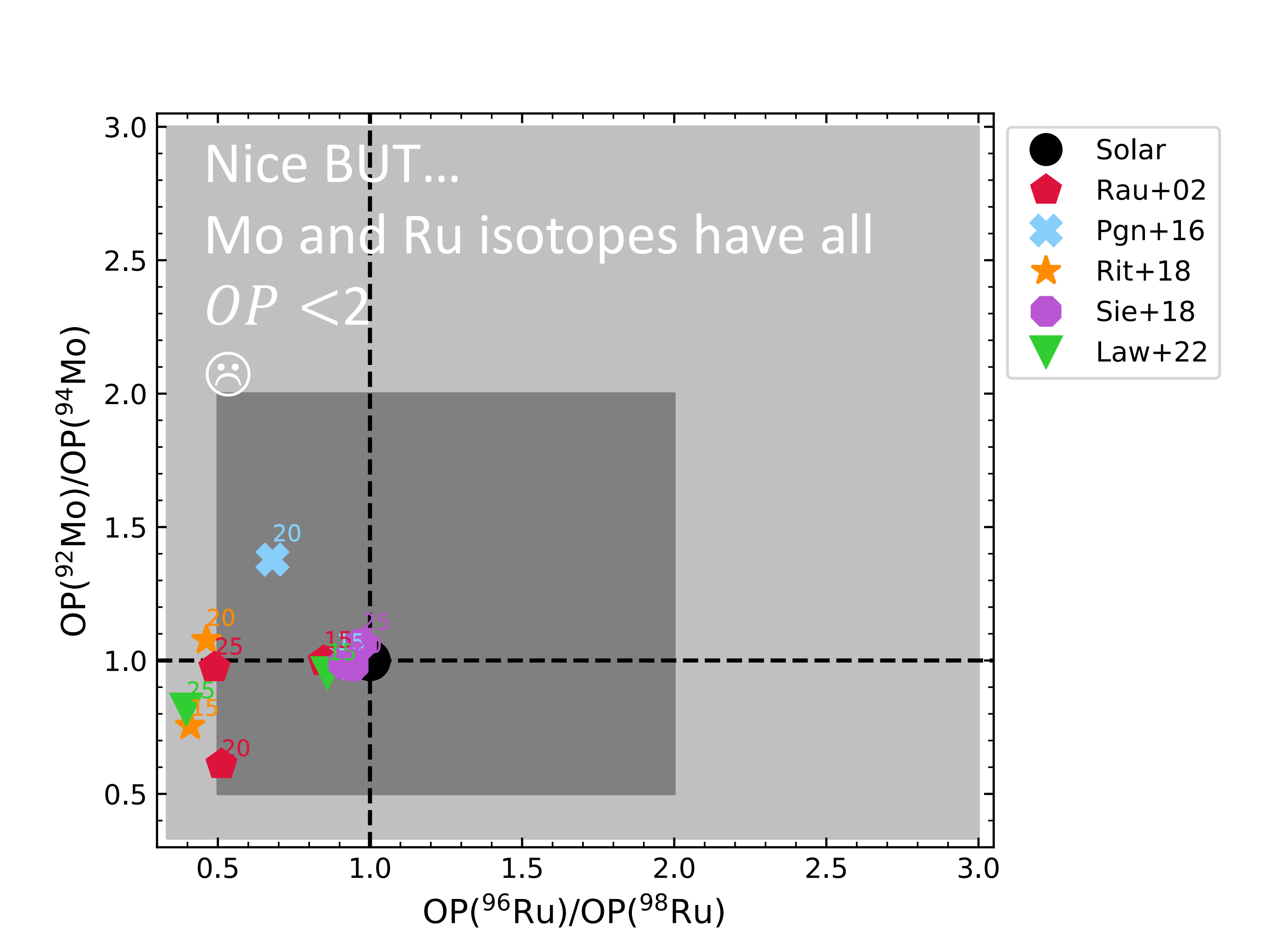
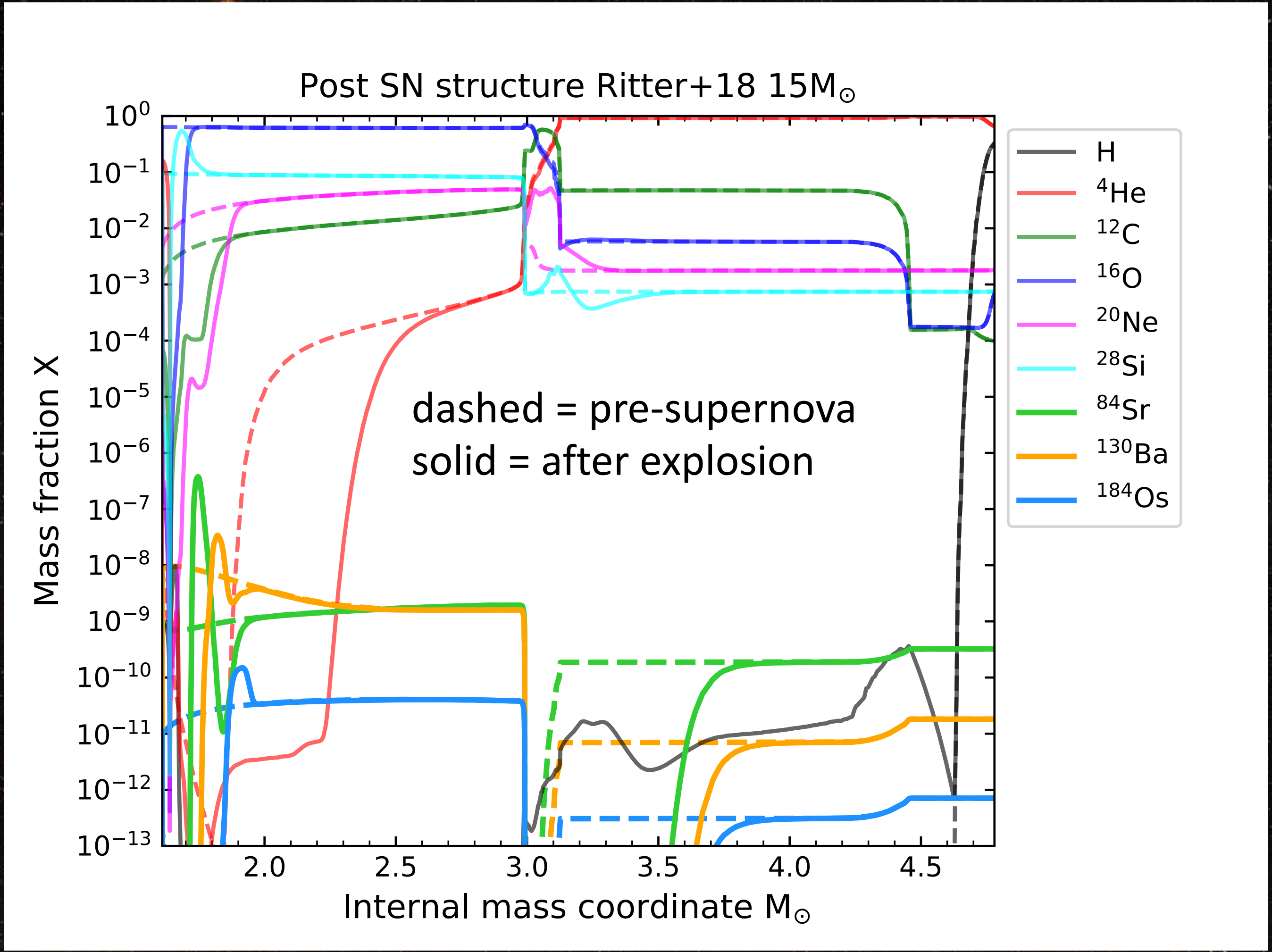


The γ-process nucleosynthesis in C-O shell mergers



The γ-process nucleosynthesis in C-O shell mergers

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

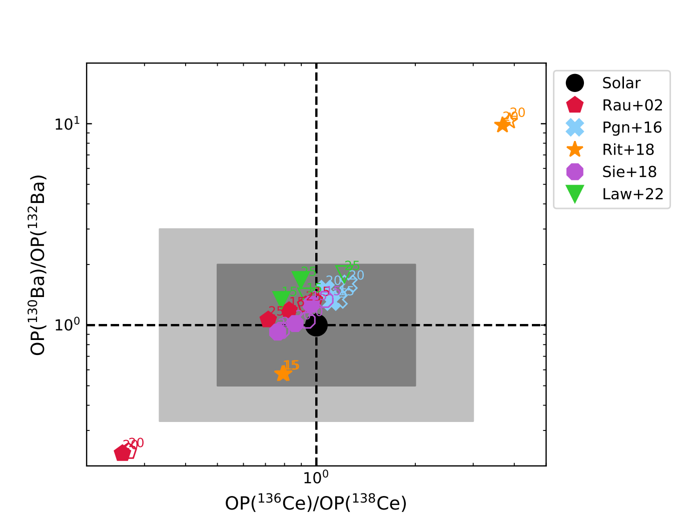
Models with C-O shell mergers:

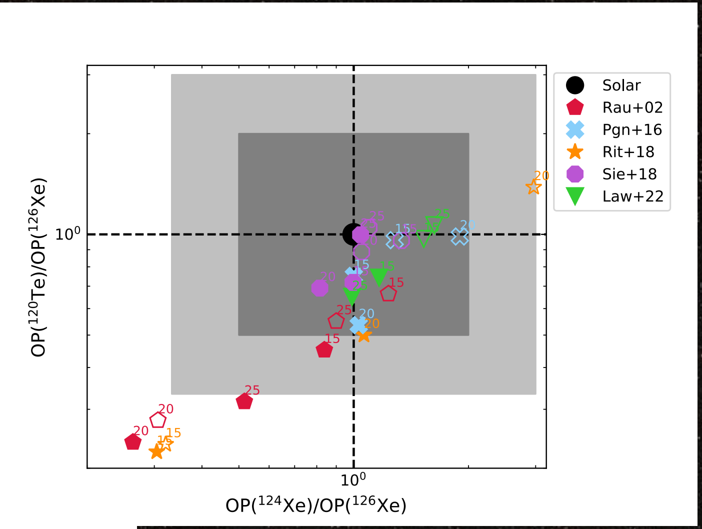
- 20 $M_\odot$ Rauscher+02
- 15 $M_\odot$ Ritter+18

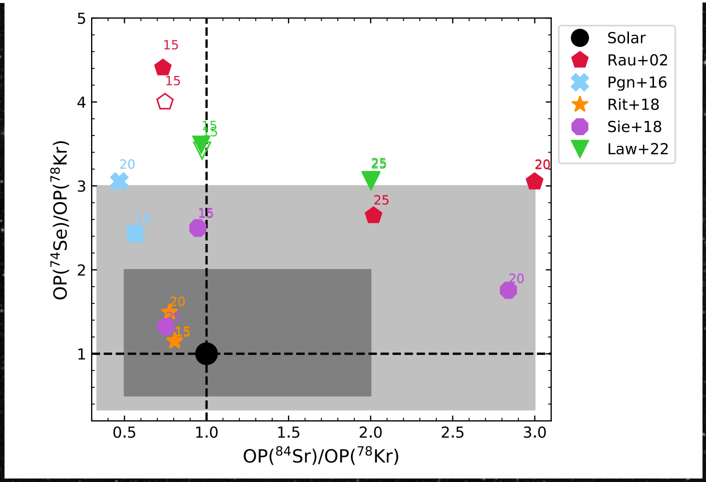
Dominant effect on yields of nuclei with A≥ 110.

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

Results: C-O shell mergers







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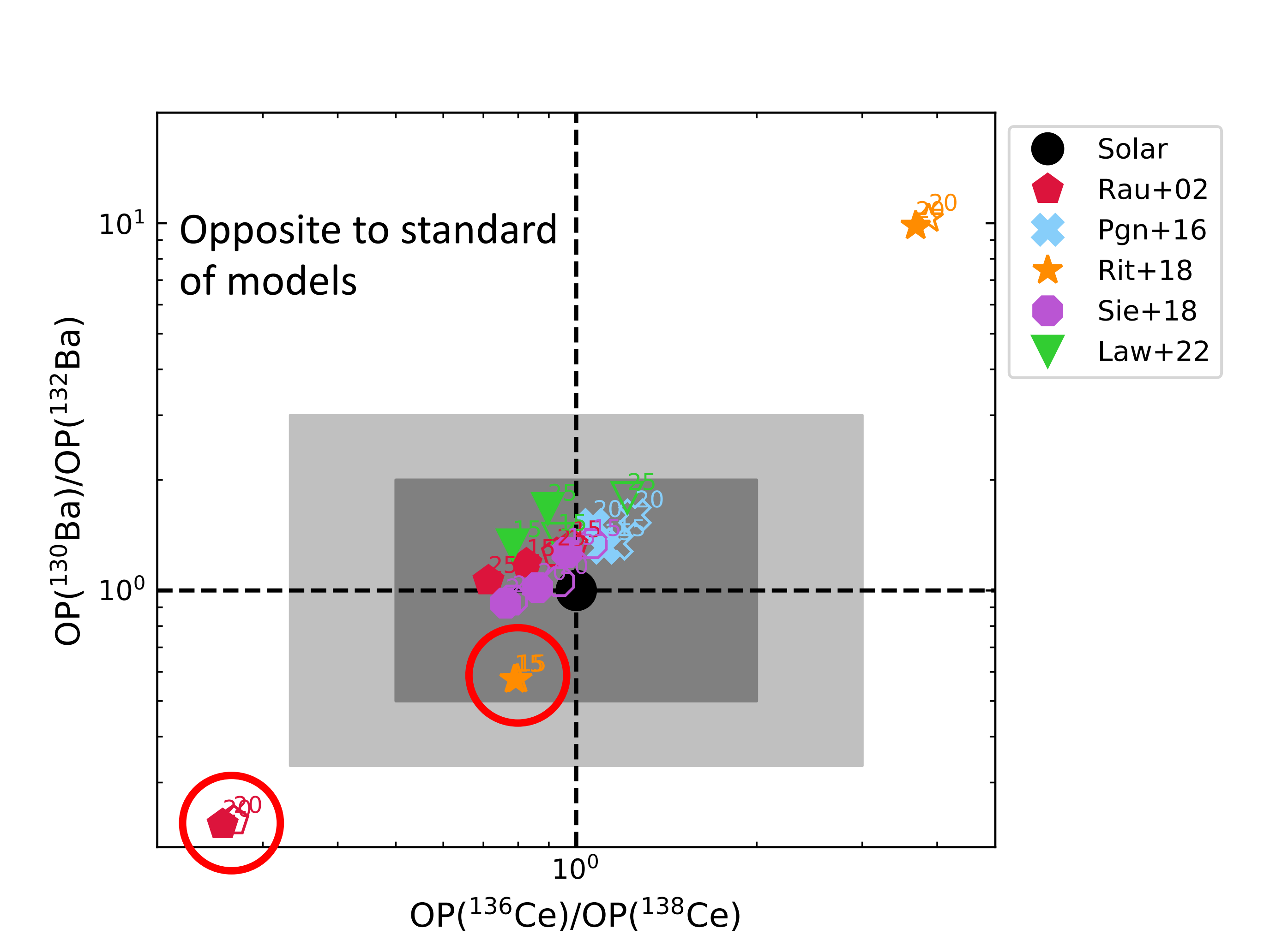

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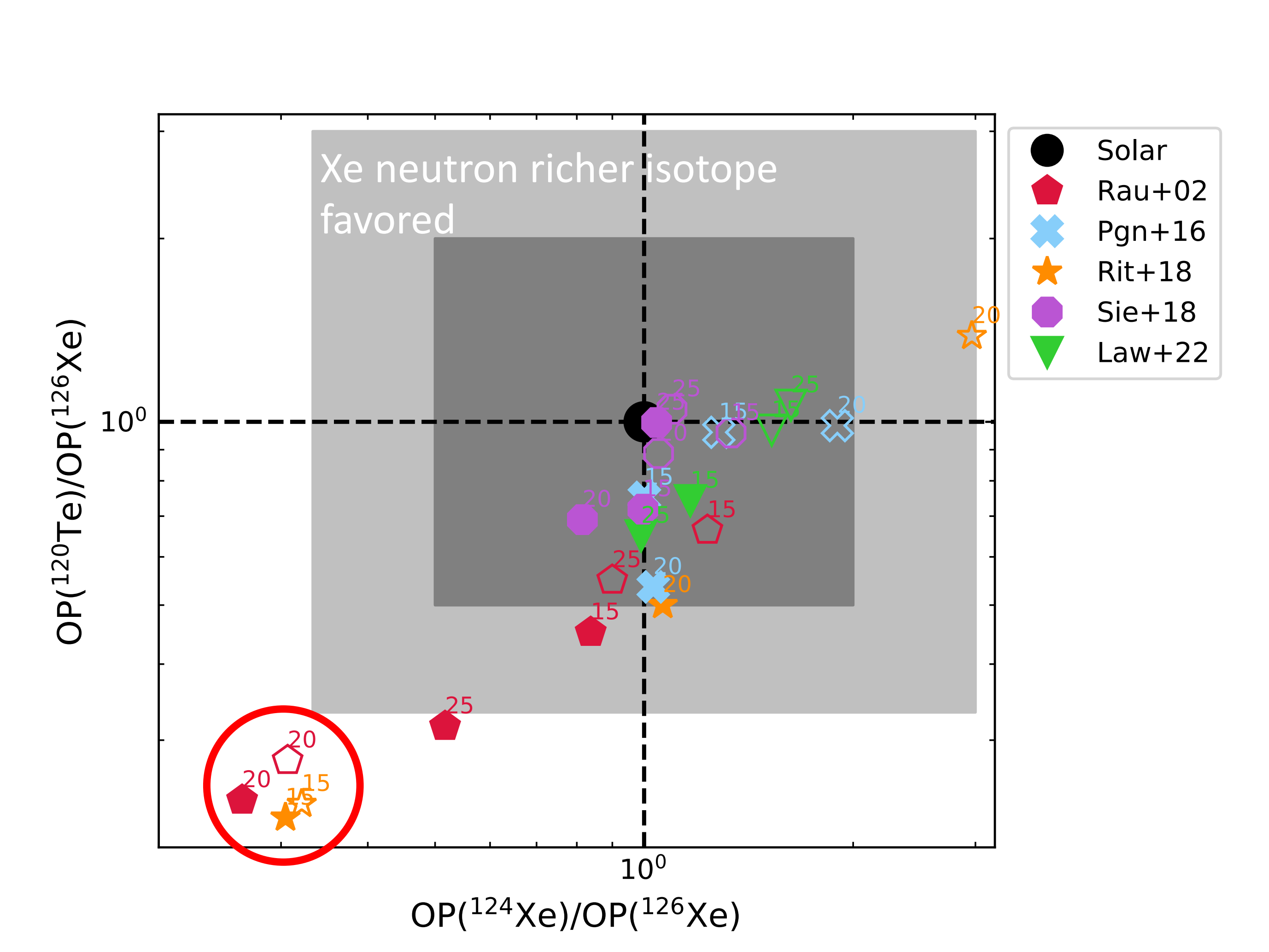

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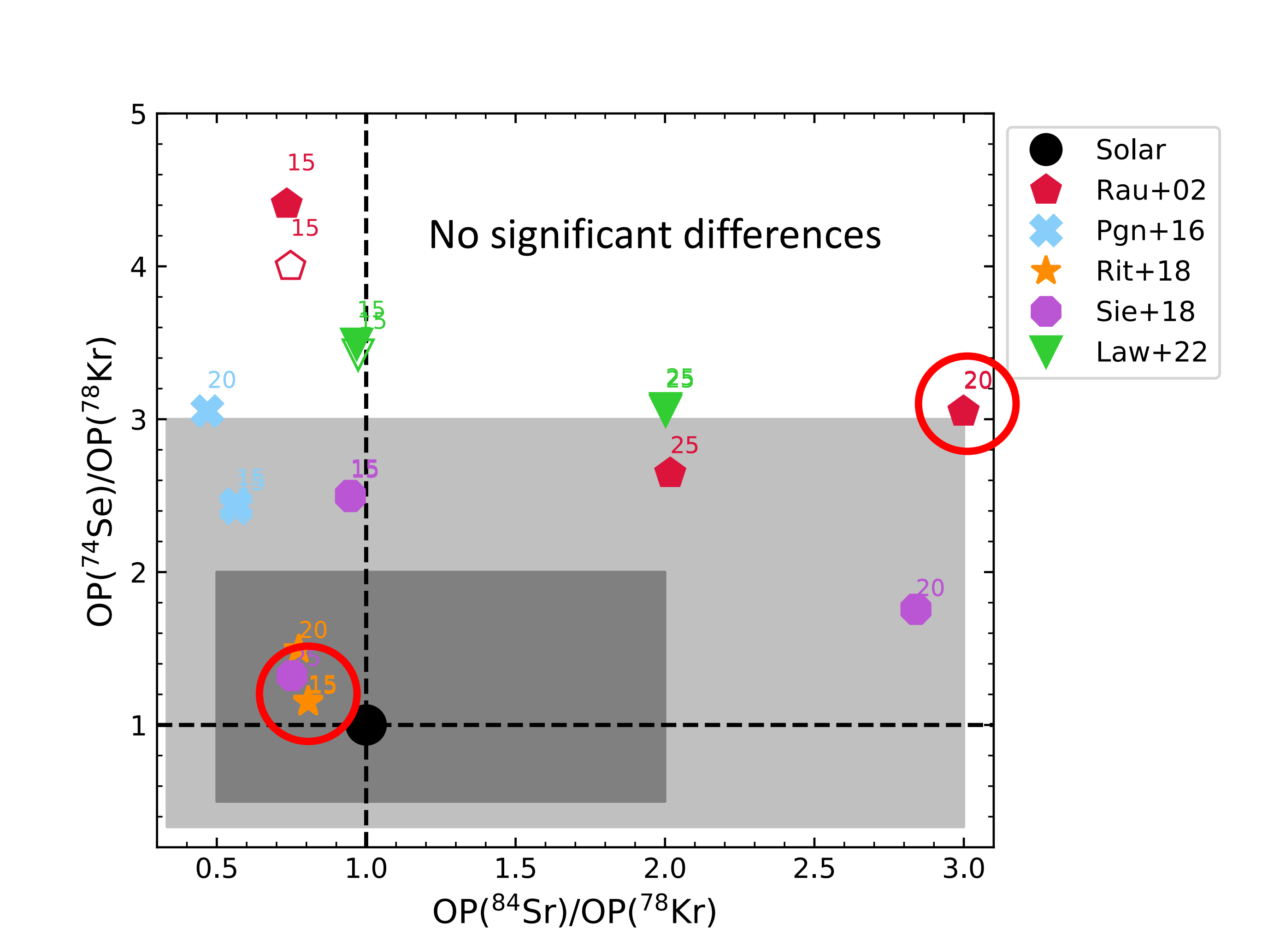

Summary

- The production of p-nuclei is still unclear, therefore we aim to explore in more detail the CCSN scenario;
- We analysed the γ-process nucleosynthesis in 5 existing different sets of CCSN models. We found large differences, mostly depending on the structure of the progenitor at the onset of the Fe core collapse;
- The contribution of C– O shell mergers is important 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, energy explosion dependence.