The impacts of nuclear-physics uncertainties on νp-process nucleosynthesis in cc-SNe

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→ RIKEN (from Apr. 2020)

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  - p-nuclei
  - several nucleosynthesis processes
- **Impacts of uncertainties and key reactions**
  - methodology
  - heavy trans-iron isotopes
  - seed production (vs SN conditions)
- **Summary**

based on NN+(2029), MNRAS 489 1379

Collaboration with

T. Rauscher (Basel), R. Hirschi (Keele), G. Cescutti (INAF),
A. St. J. Murphy (Edinburgh), C. Fröhlich (NCSU)

Nucleosynthesis of trans-iron elements

pre-SN

O/Ne

Si

Fe

Fe group

explosive
nucleosynthesis

weak s-process
(evolution)

p-process

weak r-process?

νp-process

"Fe"-core
→NS

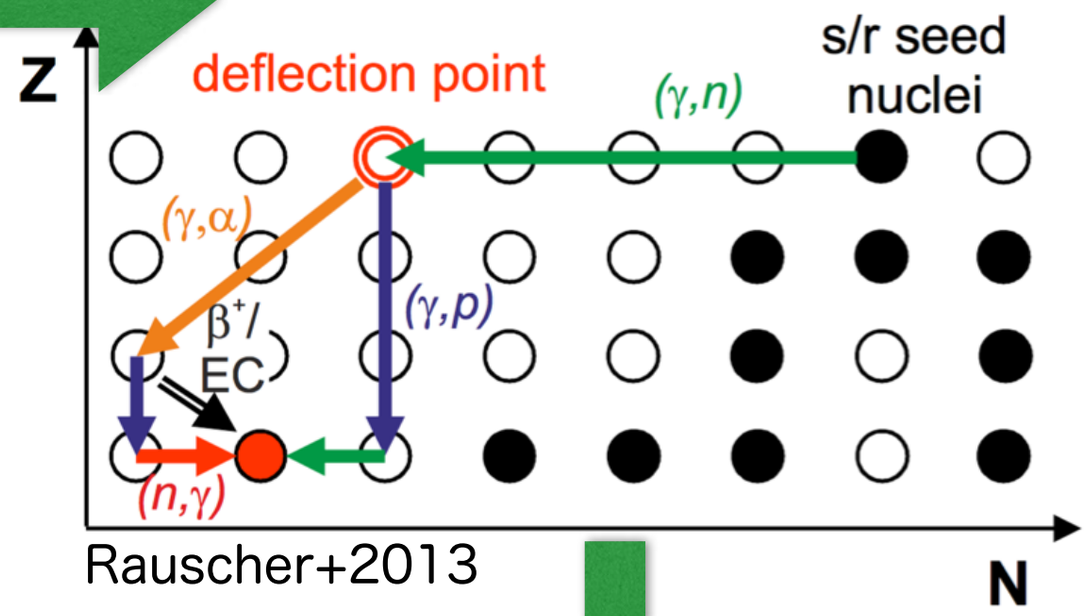
p-nuclei

35 neutron-deficient isotope

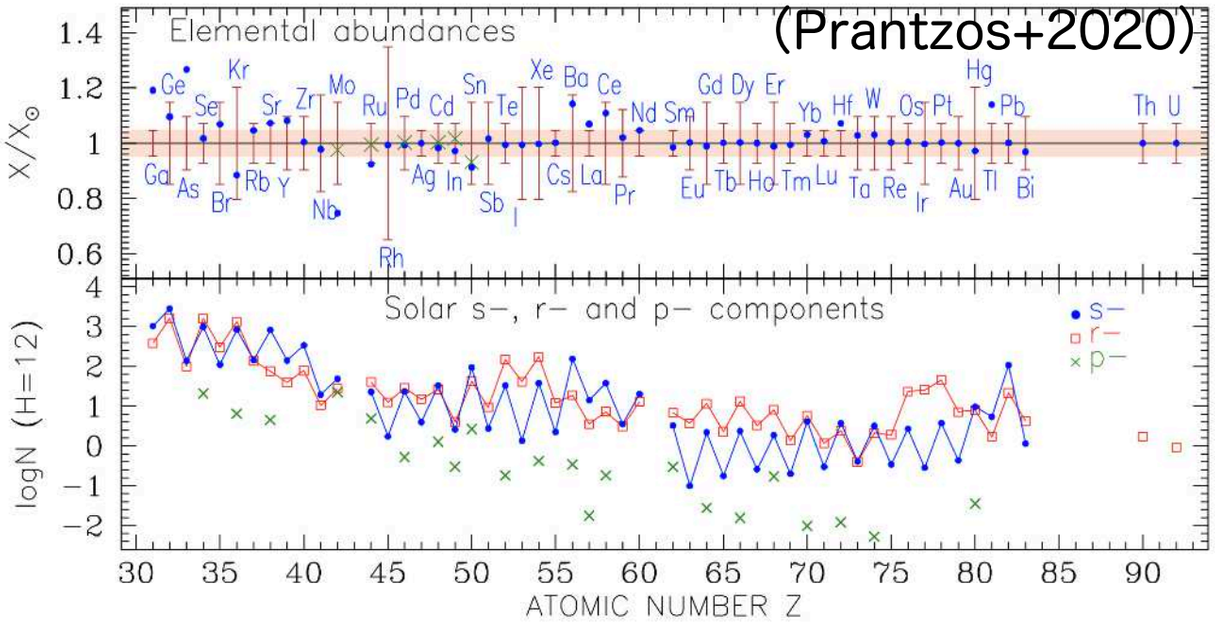
origin?

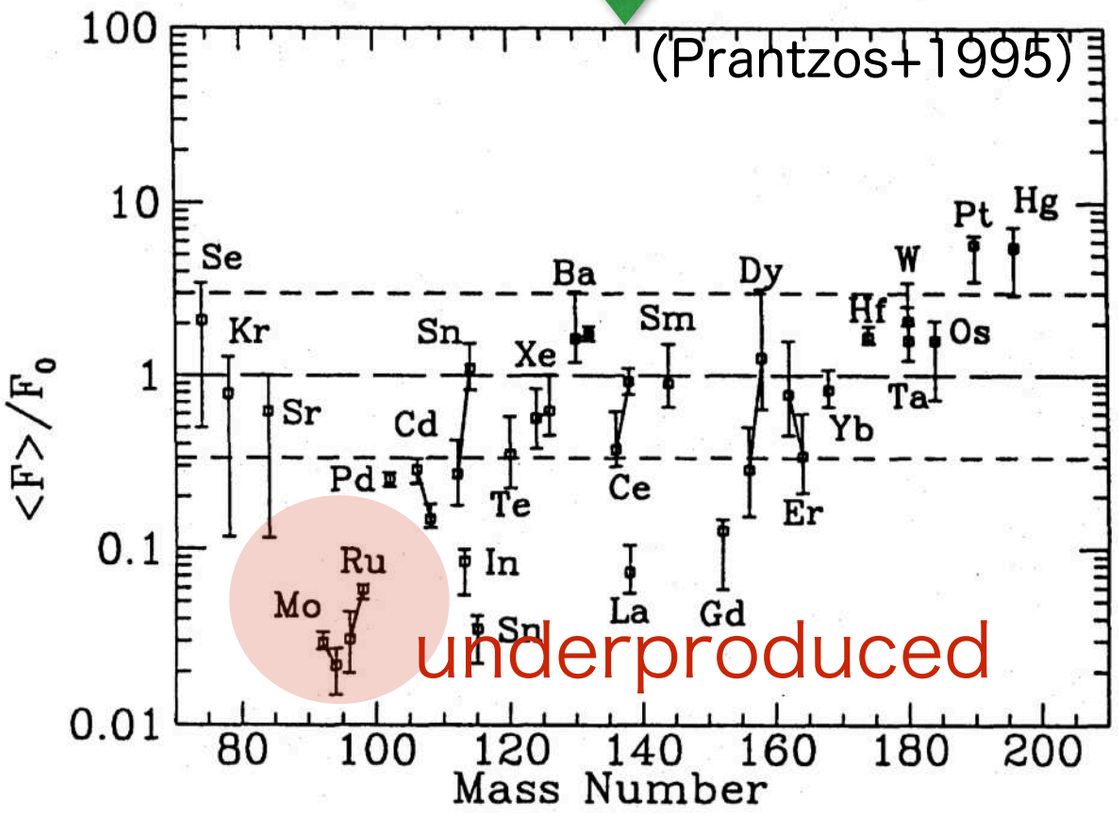
p-process
(gamma-process)





solar abundances





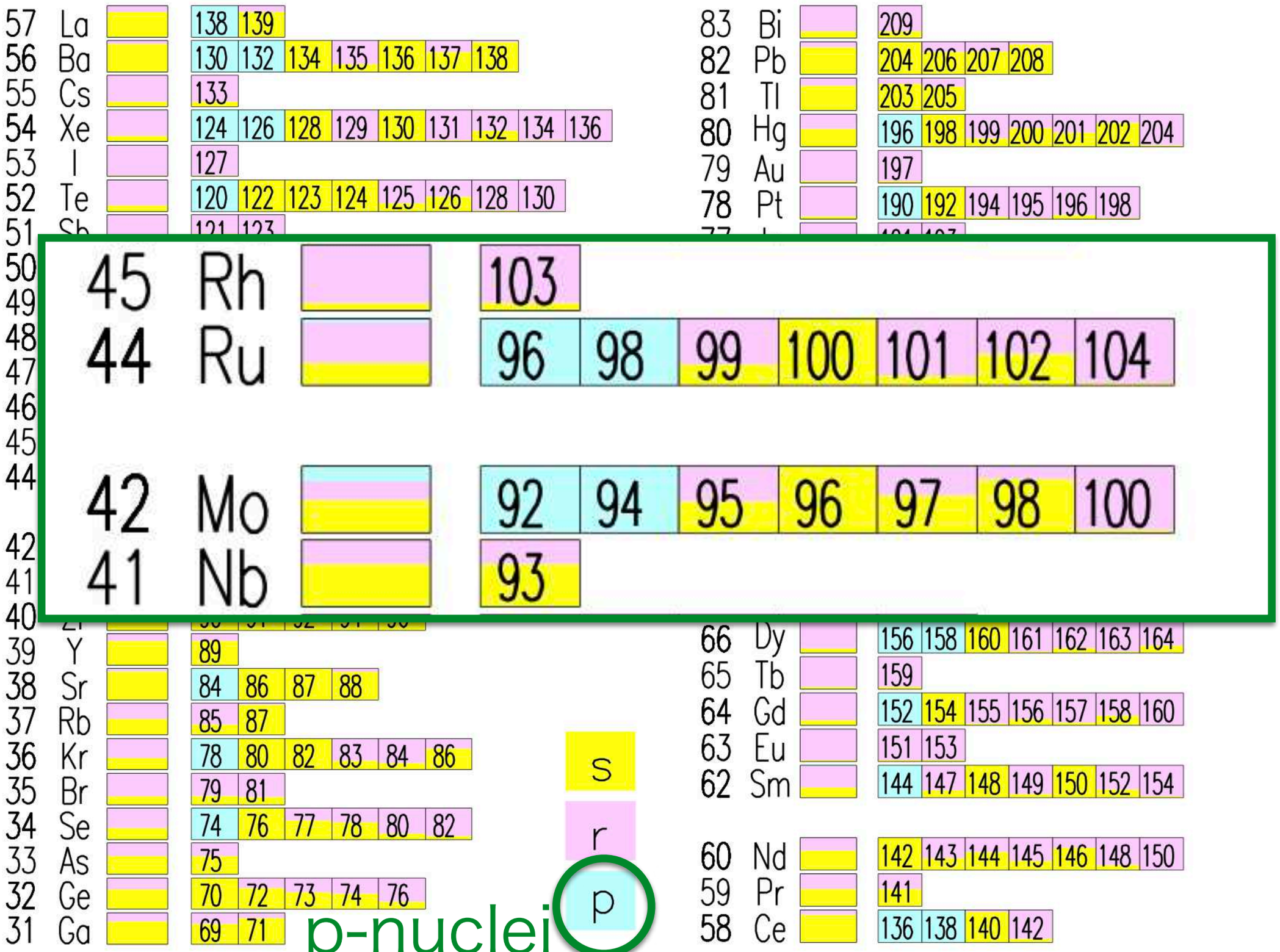
p-nuclei in the solar abundances

Prantzos+2020

p-nuc

7.4%

27%



The impacts of nuclear-physics uncertainties on νp-process nucleosynthesis in cc-SNe

- Methods
  - reactions in trans-iron nuclei
  - key reactions on seed/source production

“rp-process” by neutrino

large half-life ～ 1 min

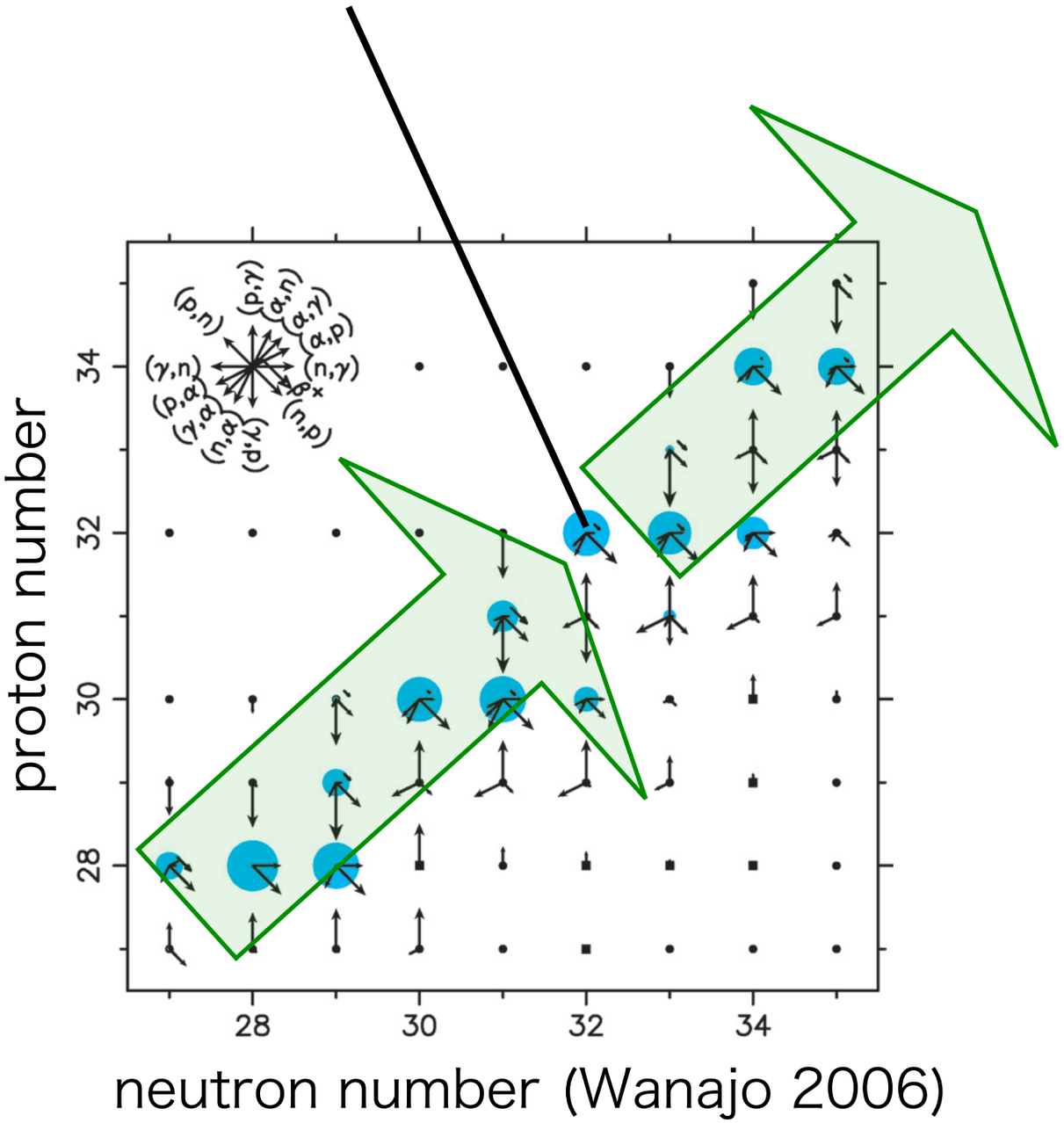
compare with τ_{dyn}

bypassed by neutron reactions

$$\nu_e + n \rightarrow p + e^-$$

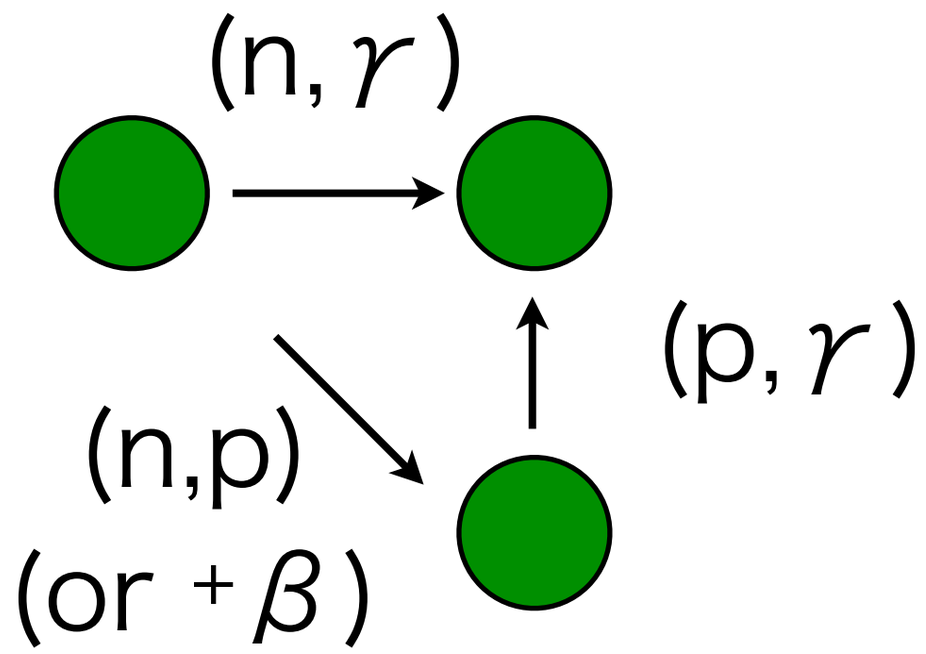
$$\bar{\nu}_e + p \rightarrow n + e^+$$

neutron source



$$(Z, N) + n \rightarrow (Z-1, N+1) + p$$

$$(Z, N) + n \rightarrow (Z, N+1) + \gamma$$

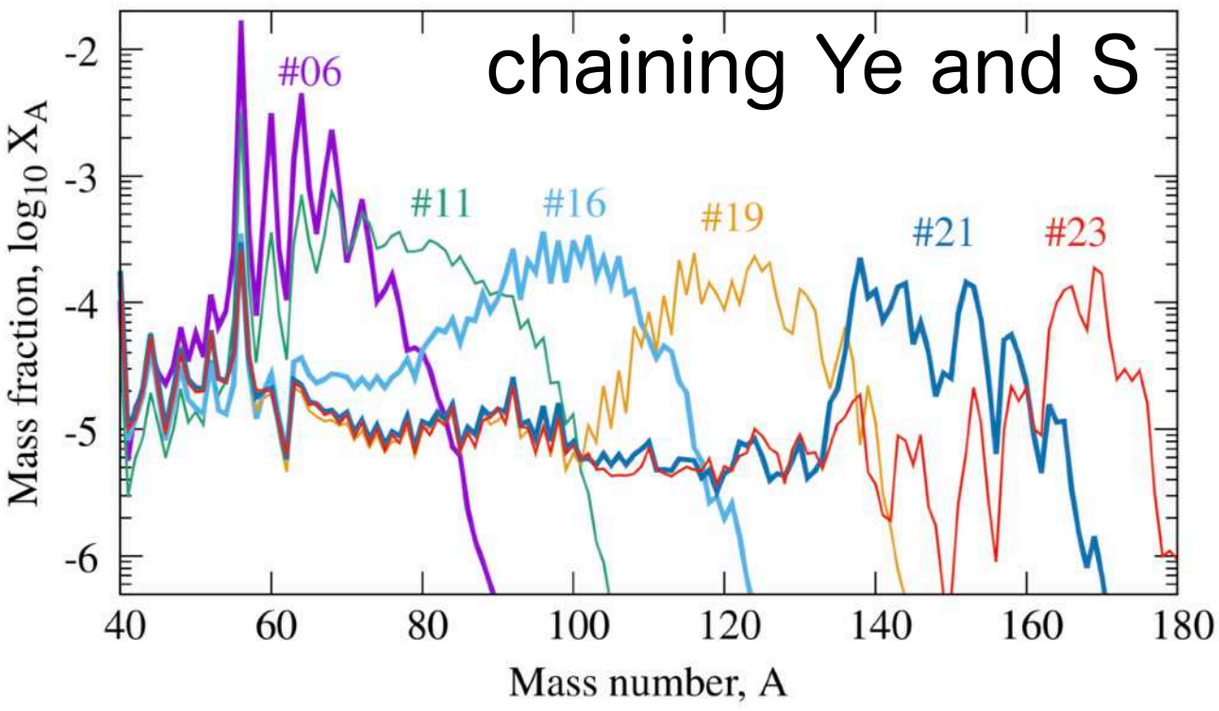


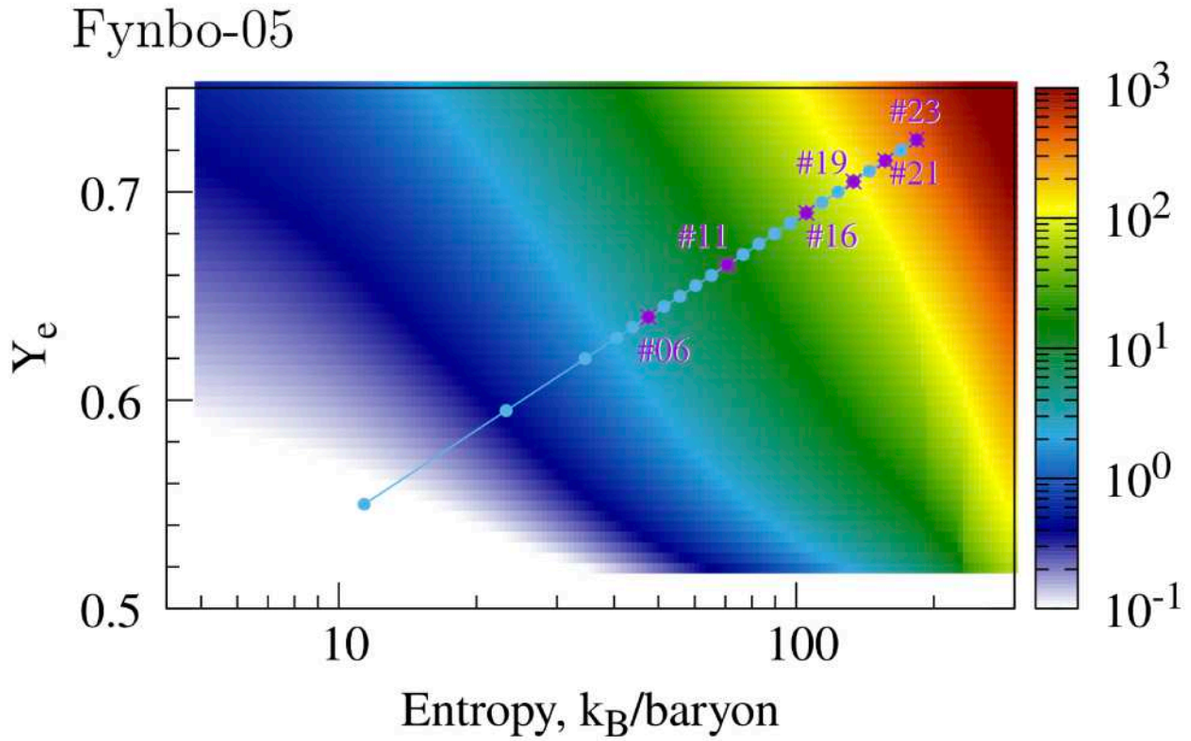
astrophysical models

1D neutrino-driven wind model (used in NN+2012)

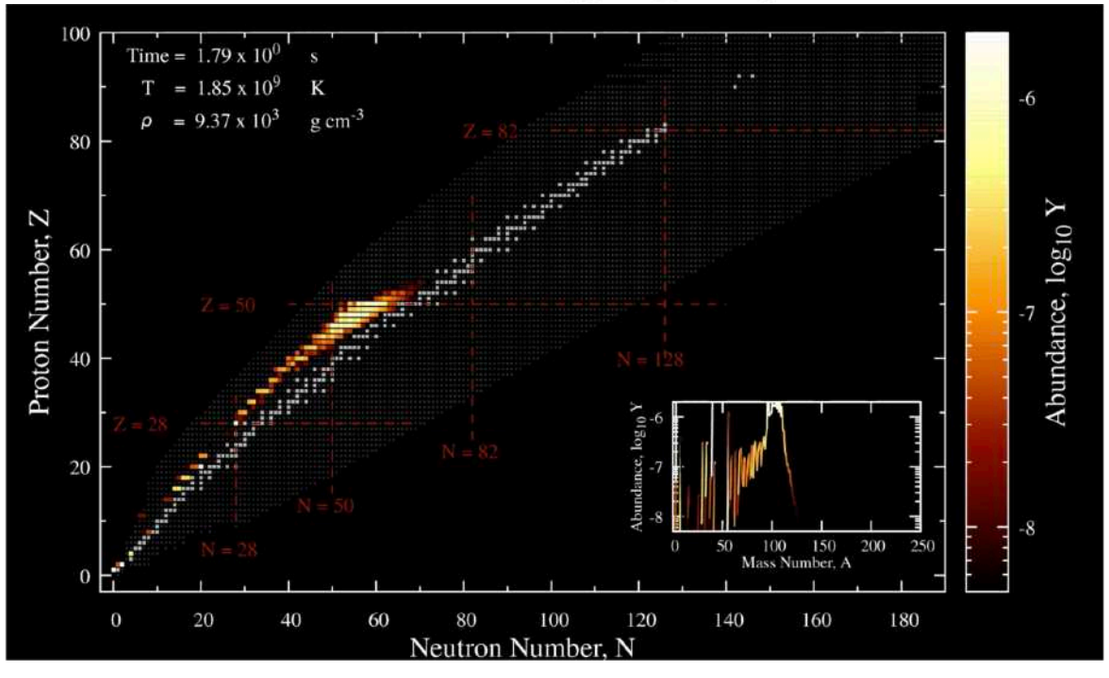
$$\Delta_{\rm n} \equiv \frac{Y_{\rm p}}{Y_{\rm h}} n_{\bar{\nu}_{\rm e}} = \frac{Y_{\rm p}}{Y_{\rm h}} \int_{T_9 \le 3} \lambda_{\bar{\nu}_{\rm e}} dt$$

Y_p: proton
Y_h: heavy nuclei
$n_{\nu e}$: neutron by ν-absorption





reaction network calculation



MC-based Nucleosynthesis



Reaction network

- Nucleosynthesis
  - reaction rates
  - decay rates

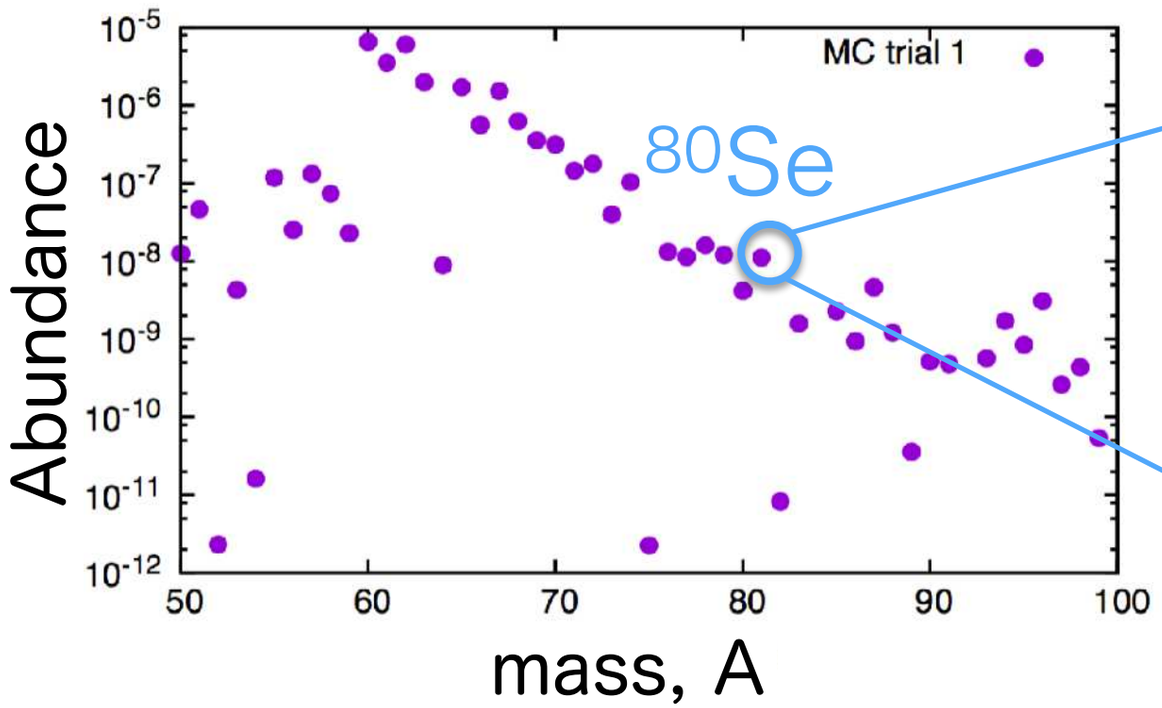
+ astrophysical model

Monte-Carlo

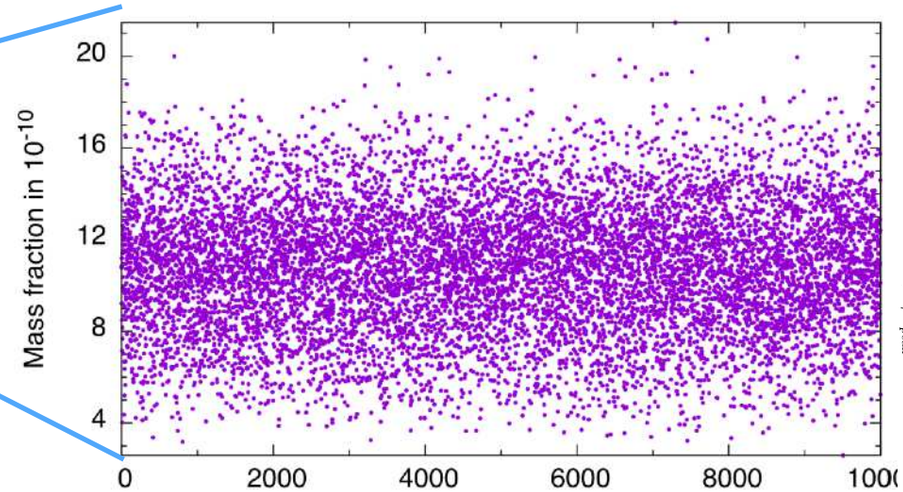
nucleosynthesis yields

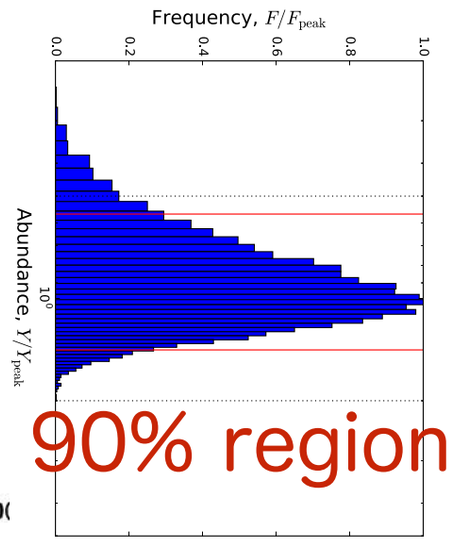
feedback (which are important reactions)

Example (s-process): NN+2017



uncertainty of reactions

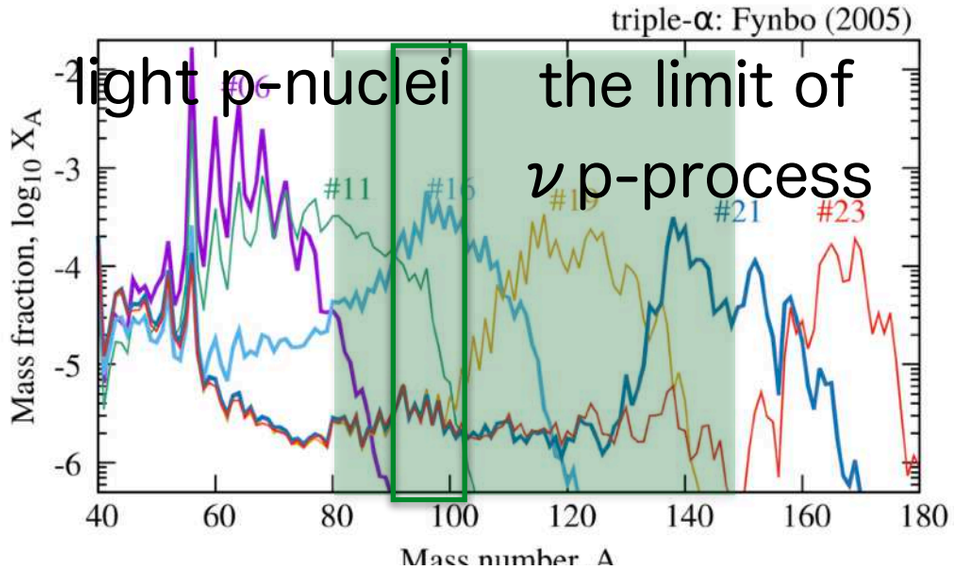




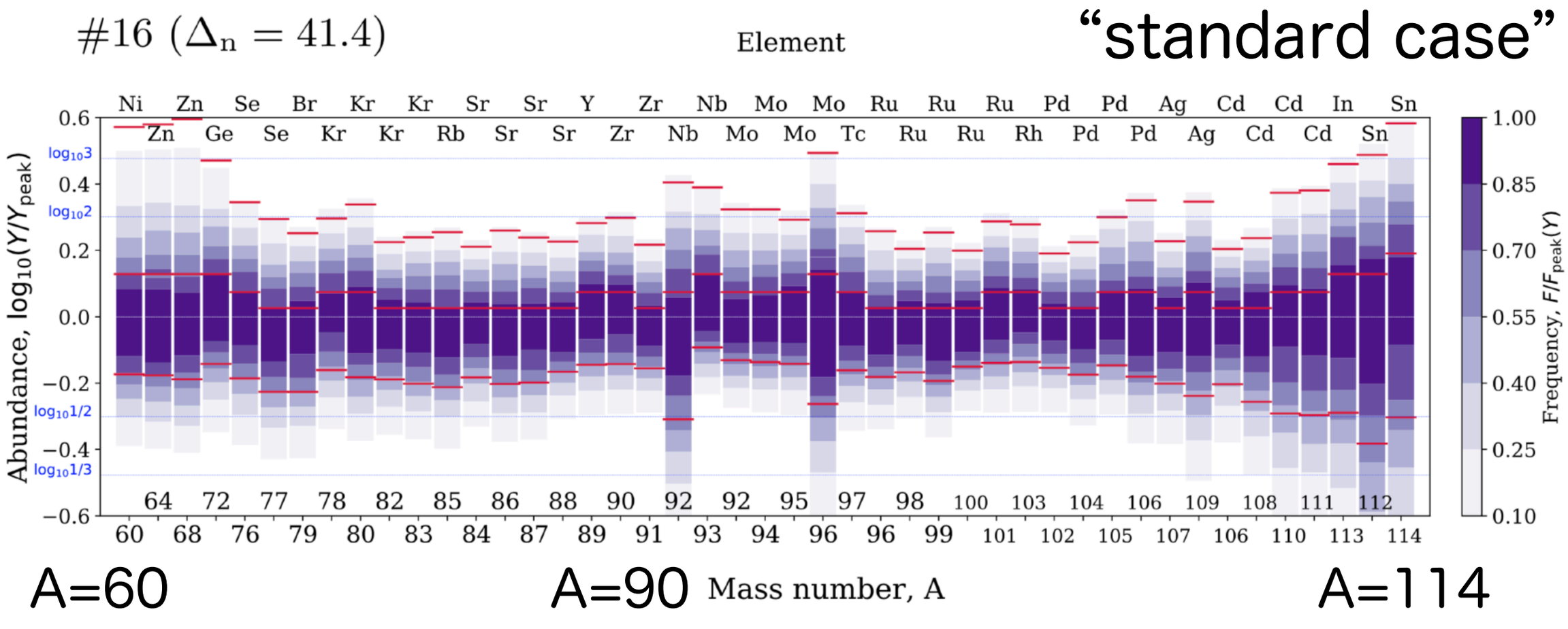
The impacts of nuclear-physics uncertainties on νp-process nucleosynthesis in cc-SNe

- Methods
- reactions in trans-iron nuclei
- key reactions on seed/source production

Uncertainty of the ν p-process

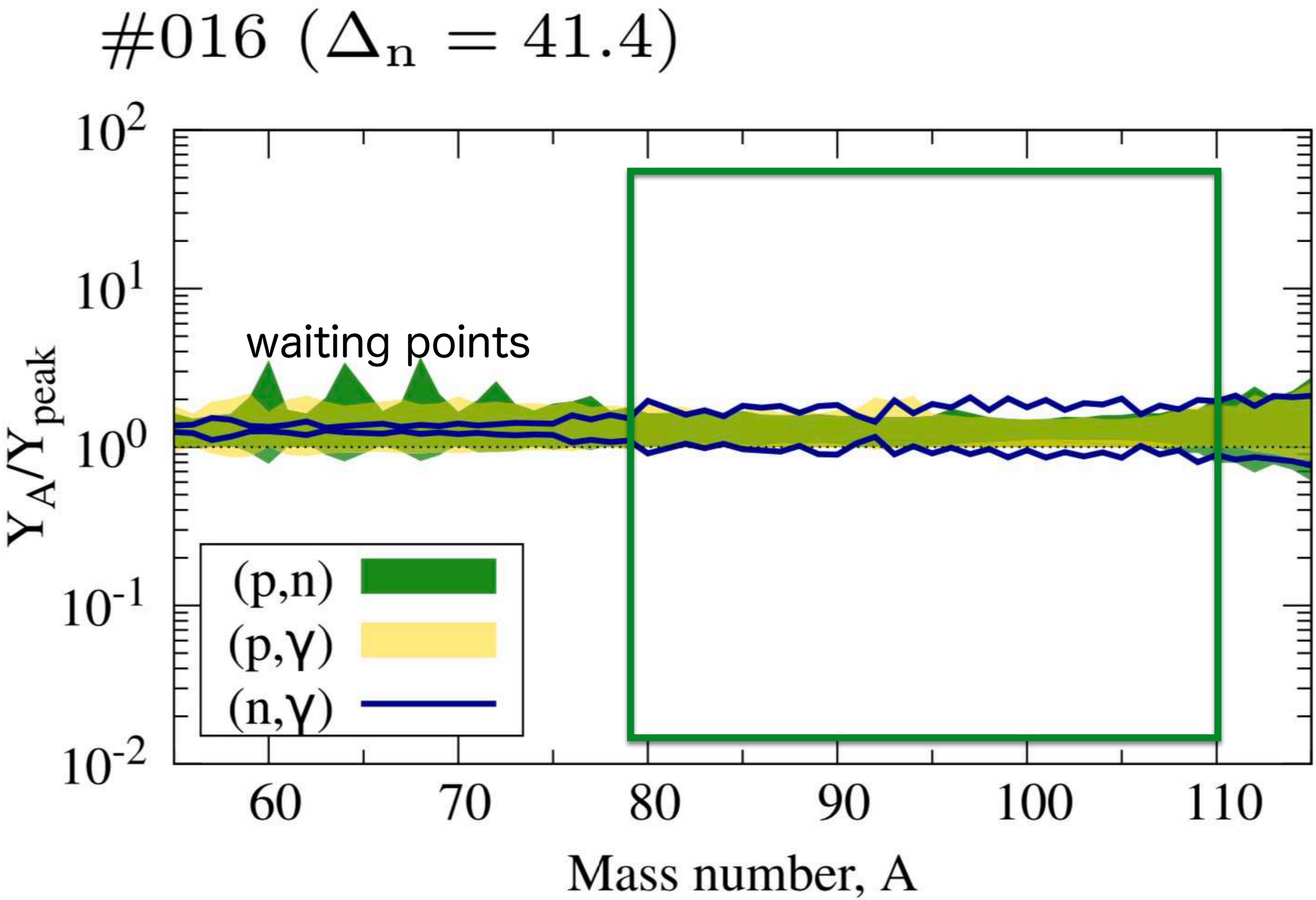


“standard case”



uncertainty is in the range of factor 2-3

Uncertainties by reaction channels



Key reactions

NN+2019

Nucleus	Reaction	#13	#14	#15	#16	#17	#18
^{56}Fe	^{59}Cu + p↔γ + ^{60}Zn	− 0.65 (Lv3)					
^{56}Fe	^{56}Ni + α↔p + ^{59}Cu	0.67 (Lv2)	0.65 (Lv2)				
^{57}Fe	^{57}Ni + p↔γ + ^{58}Cu	− 0.66 (Lv3)					
^{60}Ni	^{59}Cu + p↔n + ^{59}Zn	− 0.66 (Lv3)					
^{60}Ni	^{60}Cu + p↔n + ^{60}Zn	− 0.82 (Lv1)	− 0.81 (Lv1)	− 0.78 (Lv1)	− 0.75 (Lv1)	− 0.69 (Lv1)	
^{64}Zn	^{64}Ga + p↔n + ^{64}Ge	− 0.83 (Lv1)	− 0.80 (Lv1)	− 0.75 (Lv1)	− 0.70 (Lv1)		
^{68}Zn	^{68}As + p↔n + ^{68}Se	− 0.84 (Lv1)	− 0.81 (Lv1)	− 0.75 (Lv1)	− 0.68 (Lv1)		
^{70}Ge	^{70}Se + p↔γ + ^{71}Br	− 0.70 (Lv1)	− 0.68 (Lv1)	− 0.65 (Lv2)			
^{72}Ge	^{72}Br + p↔n + ^{72}Kr	− 0.78 (Lv1)	− 0.75 (Lv1)	− 0.66 (Lv1)			
^{76}Se	^{76}Rb + p↔n + ^{76}Sr	− 0.68 (Lv1)					
^{77}Se	^{77}Rb + p↔n + ^{77}Sr	− 0.69 (Lv1)	− 0.65 (Lv1)				
^{80}Kr	^{80}Sr + n↔γ + ^{81}Sr			− 0.65 (Lv2)			
^{93}Nb	^{93}Tc + n↔γ + ^{94}Tc				− 0.67 (Lv2)		
^{93}Nb	^{93}Tc + p↔γ + ^{94}Ru				− 0.70 (Lv3)		
^{92}Mo	^{92}Mo + p↔γ + ^{93}Tc				− 0.73 (Lv1)	− 0.71 (Lv1)	
^{94}Mo	^{94}Ru + p↔γ + ^{95}Rh		− 0.65 (Lv2)	− 0.65 (Lv3)	− 0.66 (Lv1)		
^{97}Tc	^{97}Rh + n↔γ + ^{98}Rh			− 0.70 (Lv1)	− 0.66 (Lv1)		
^{99}Ru	^{99}Rh + n↔γ + ^{100}Rh				− 0.65 (Lv3)		
^{100}Ru	^{100}Pd + n↔γ + ^{101}Pd				− 0.66 (Lv2)	− 0.68 (Lv1)	
^{113}In	^{113}In + n↔γ + ^{114}In					− 0.67 (Lv1)	
^{117}Sn	^{117}In + n↔γ + ^{118}In						− 0.74 (Lv1)

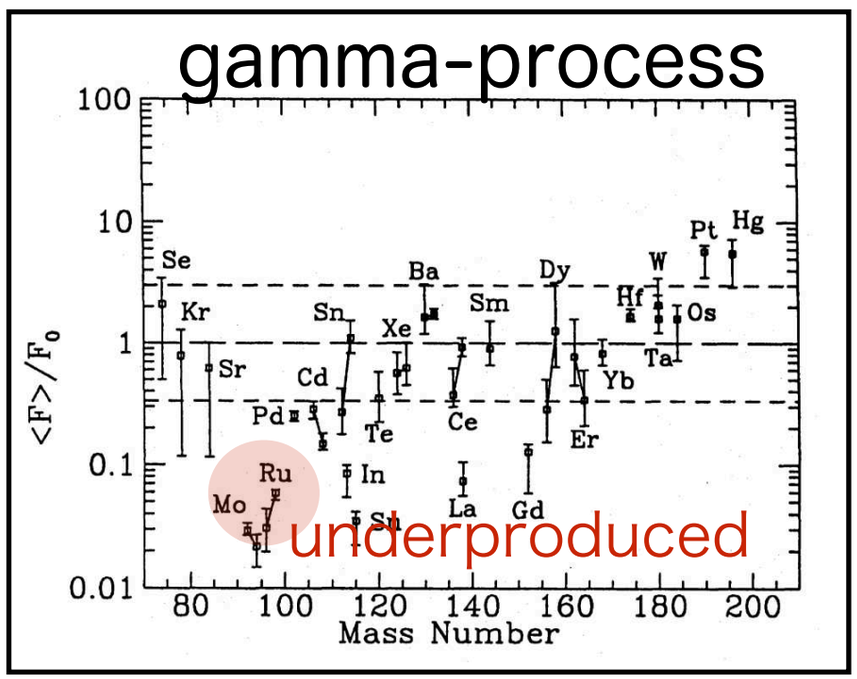
“standard”

^{92}Mo ^{92}Mo + p↔γ + ^{93}Tc

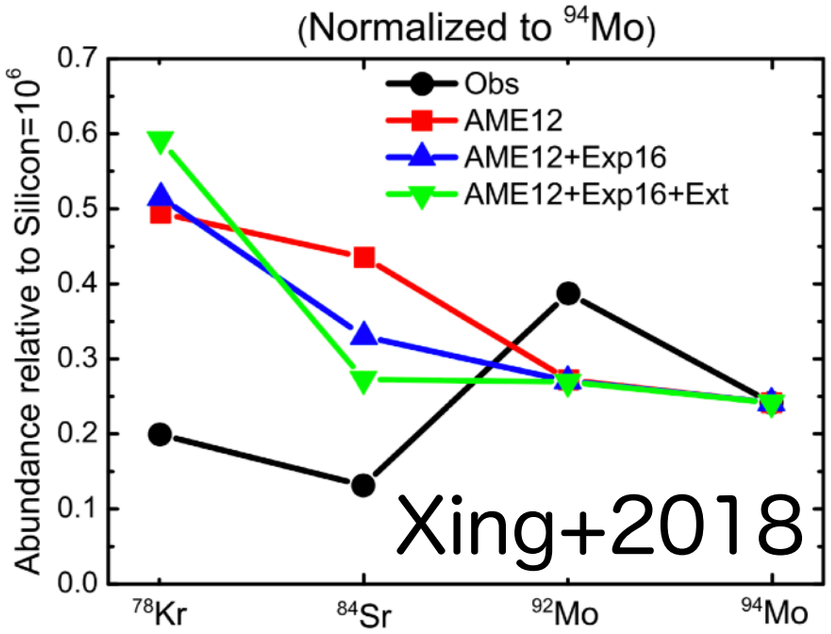
^{94}Mo ^{94}Ru + p↔γ + ^{95}Rh

^{97}Tc ^{97}Rh + n↔γ + ^{98}Rh

isotopic ratios



ν p-process w/ new mass measurement



nuclear masses?

→ still low ^{92}Mo/^{94}Mo

NN+2019

Trajectory	^{92}Mo/^{94}Mo				^{84}Sr/^{94}Mo				^{78}Kr/^{94}Mo			
	$\frac{Y(92)}{Y(94)}\Big\|_{peak}$	$\frac{Y(92)}{Y(94)}\Big\|_{50}$	Up	Down	$\frac{Y(84)}{Y(94)}\Big\|_{peak}$	$\frac{Y(84)}{Y(94)}\Big\|_{50}$	Up	Down	$\frac{Y(78)}{Y(94)}\Big\|_{peak}$	$\frac{Y(78)}{Y(94)}\Big\|_{50}$	Up	Down
#06	2.00	2.60	2.24	0.770	76.5	99.4	5.49	0.336	194	718	24.8	0.608
#11	0.923	1.20	2.14	0.793	1.86	2.41	3.03	0.627	2.18	2.83	3.64	0.547
#16	0.631	0.820	2.79	0.666	0.213	0.277	2.50	0.618	0.0837	0.109	2.76	0.573
#19	0.876	1.14	2.98	0.627	0.530	0.689	2.37	0.611	0.311	0.404	2.47	0.618
#21	0.980	1.27	2.87	0.675	0.664	0.862	2.25	0.744	0.390	0.507	2.32	0.733
#23	0.983	1.28	2.85	0.651	0.693	0.900	2.23	0.766	0.393	0.511	2.32	0.749

solar abundances (Lodders 2003): /^{94}Mo

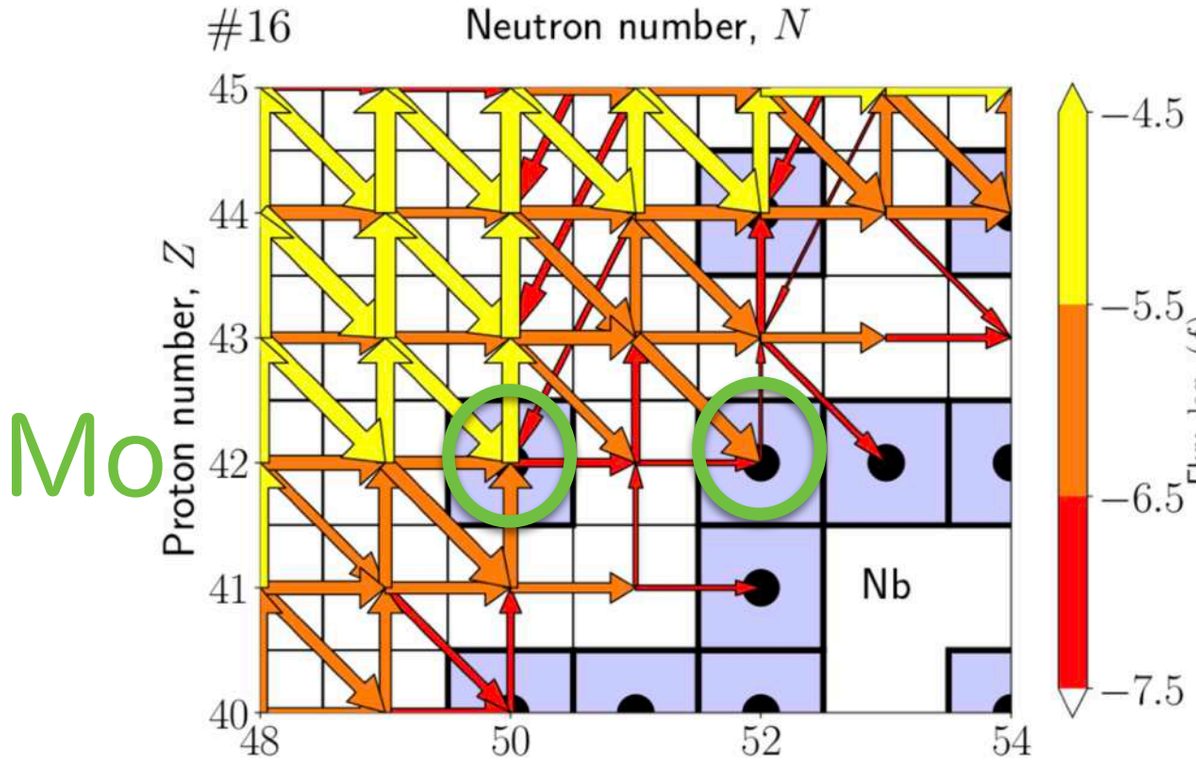
^{92}Mo/^{94}Mo = 1.6, ^{84}Sr/^{94}Mo = 0.54, ^{78}Kr/^{94}Mo = 0.82

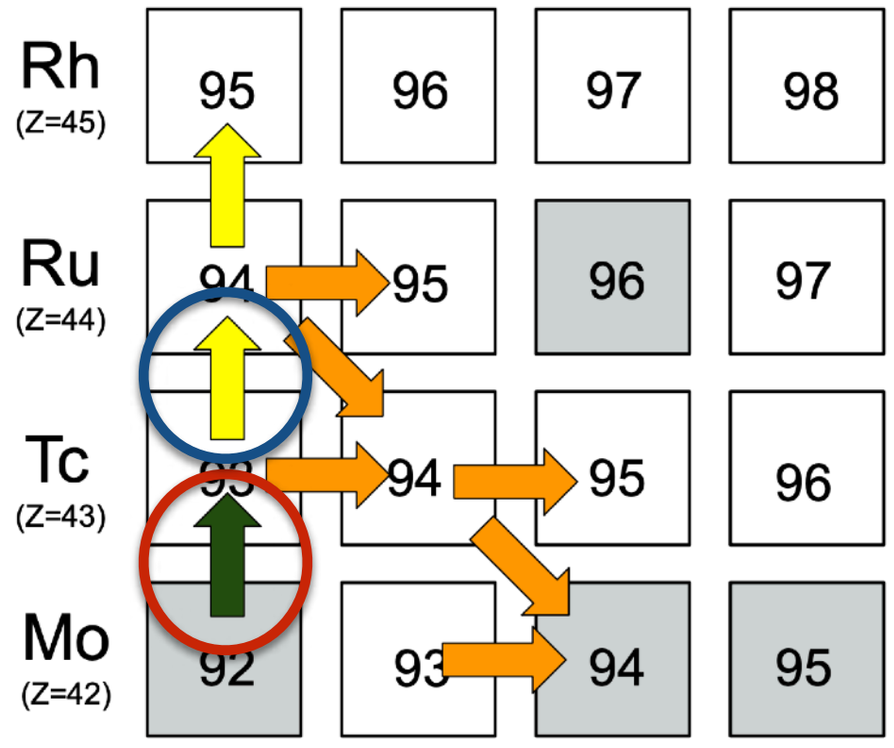
#16 :

0.55 < ^{92}Mo <2.29, 0.17< ^{84}Sr < 0.69, 0.062 < ^{78}Kr < 0.30

key reactions for ^{92}Mo/^{94}Mo

Trajectory	^{92}Mo/^{94}Mo $\frac{Y(92)}{Y(94)}\Big\|_{peak}$	$\frac{Y(92)}{Y(94)}\Big\|_{50}$	Up	Down	^{84}Sr/^{94}Mo $\frac{Y(84)}{Y(94)}\Big\|_{peak}$	$\frac{Y(84)}{Y(94)}\Big\|_{50}$	Up	Down	^{78}Kr/^{94}Mo $\frac{Y(78)}{Y(94)}\Big\|_{peak}$	$\frac{Y(78)}{Y(94)}\Big\|_{50}$	Up	Down
#06	2.00	2.60	2.24	0.770	76.5	99.4	5.49	0.336	194	718	24.8	0.608
#11	0.923	1.20	2.14	0.793	1.86	2.41	3.03	0.627	2.18	2.83	3.64	0.547
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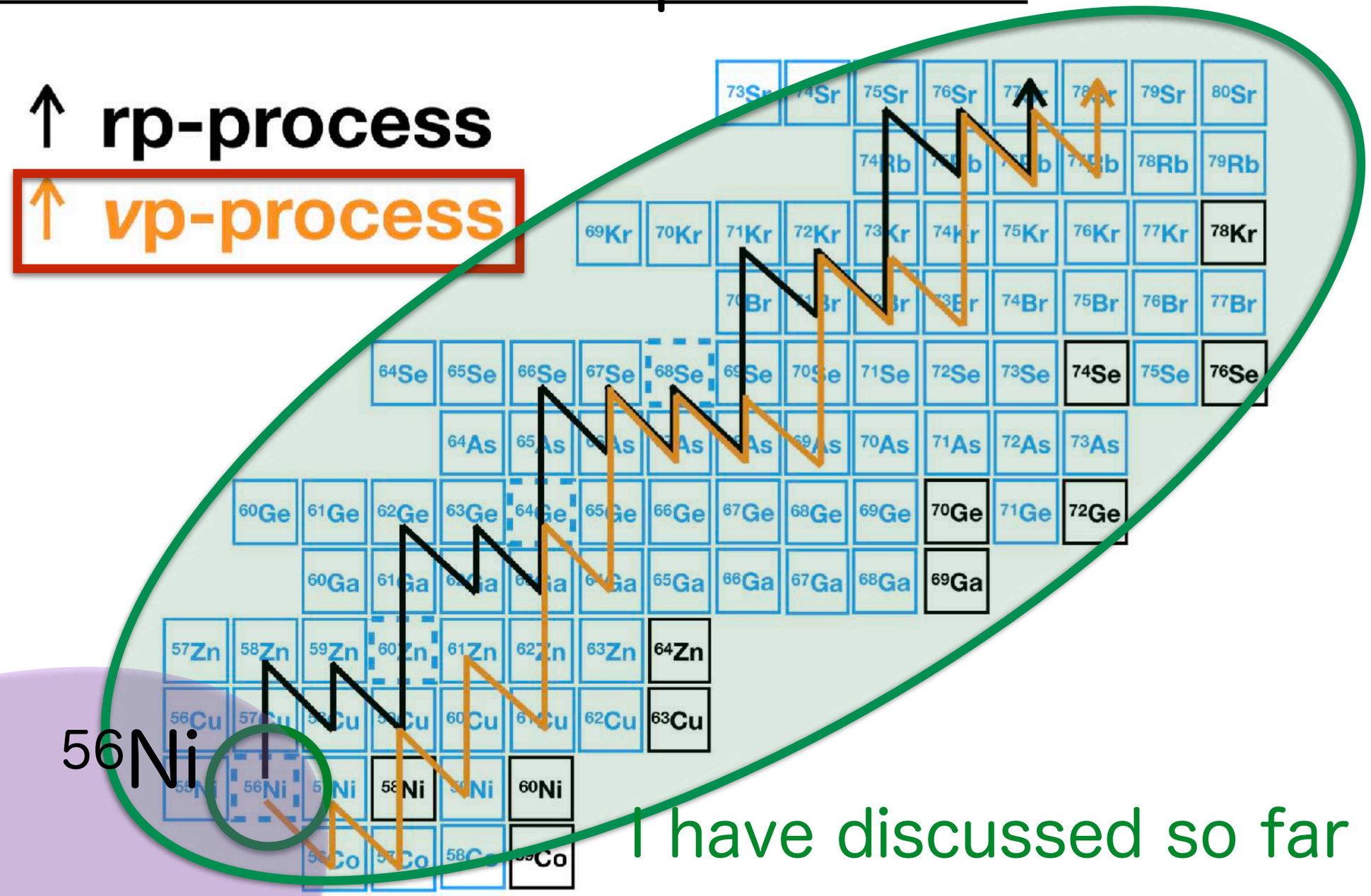
key reaction : ^{92}Mo(p,g)^{93}Tc

(next priority: ^{93}Mo(p,g)^{94}Ru)

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Reactions for seed production



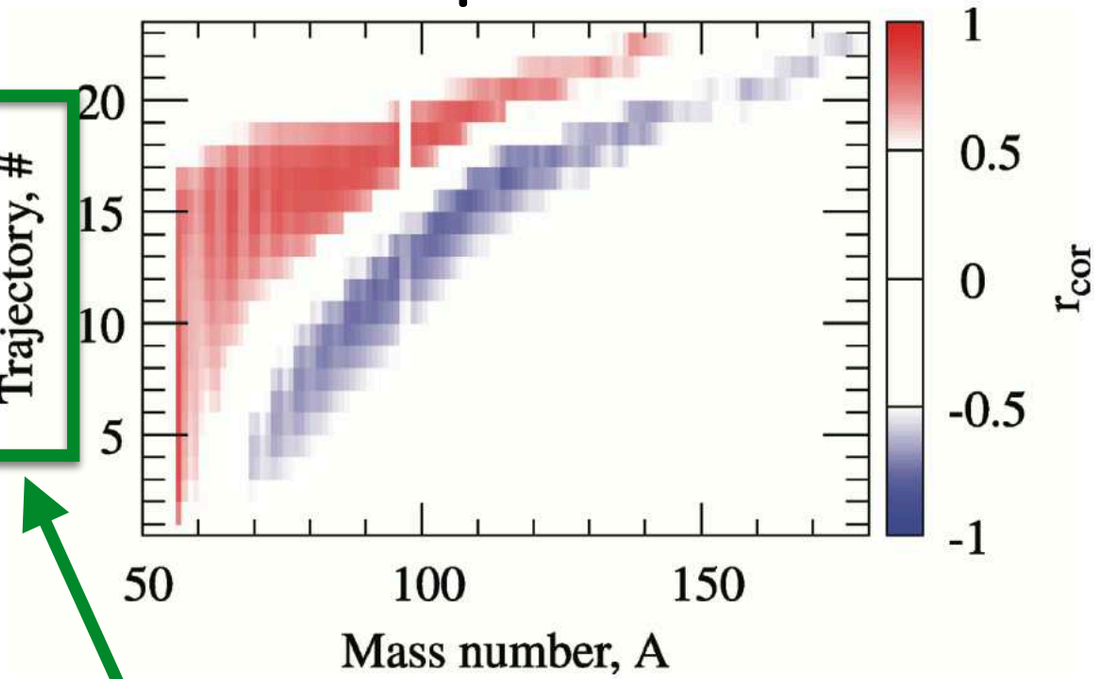
I have discussed so far

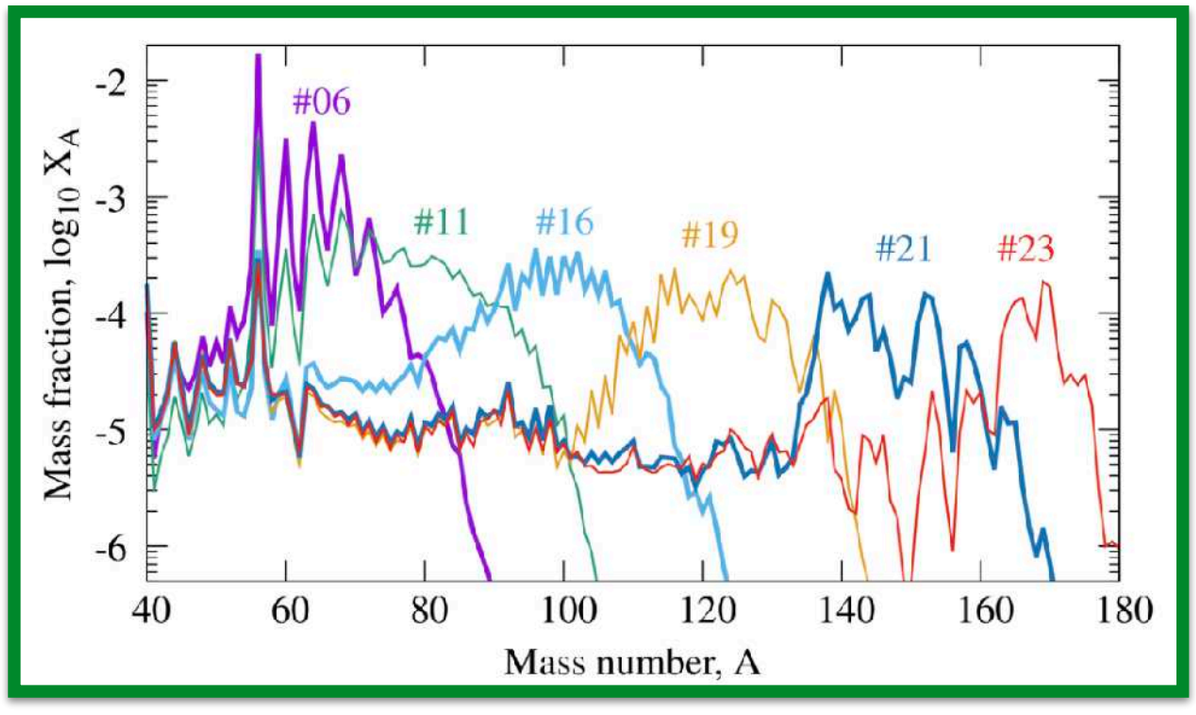
breaks through ^{56}Ni-peak

seed production
(from the triple-α)

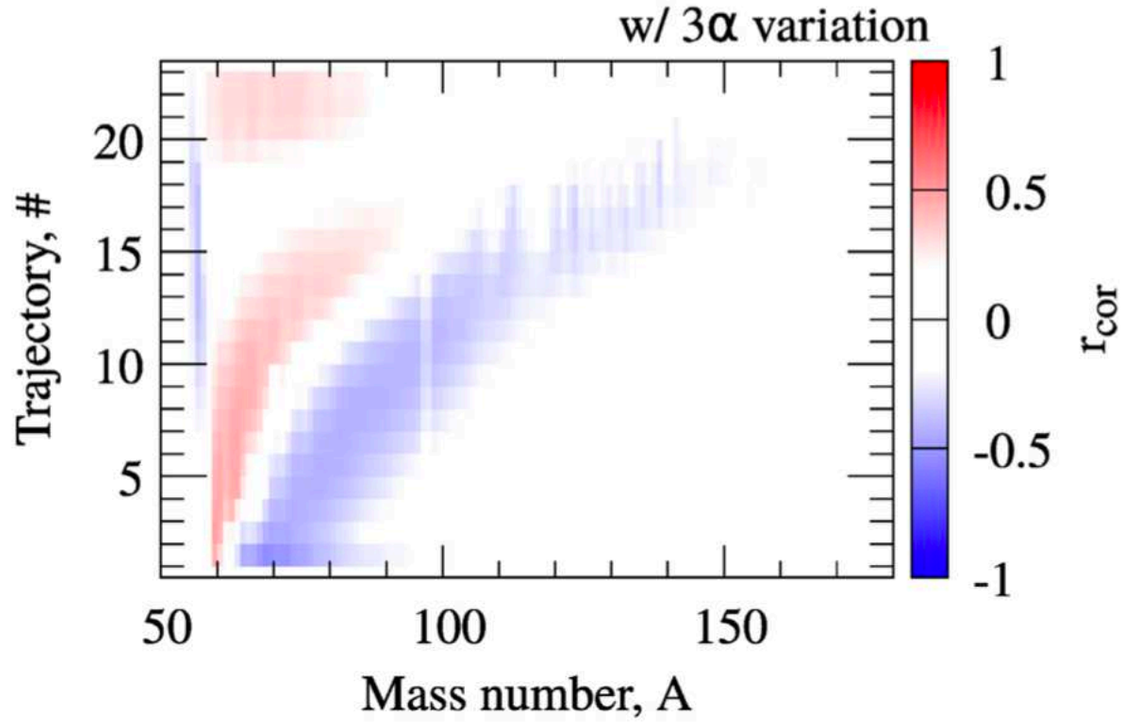
key reactions in lighter than Fe-group

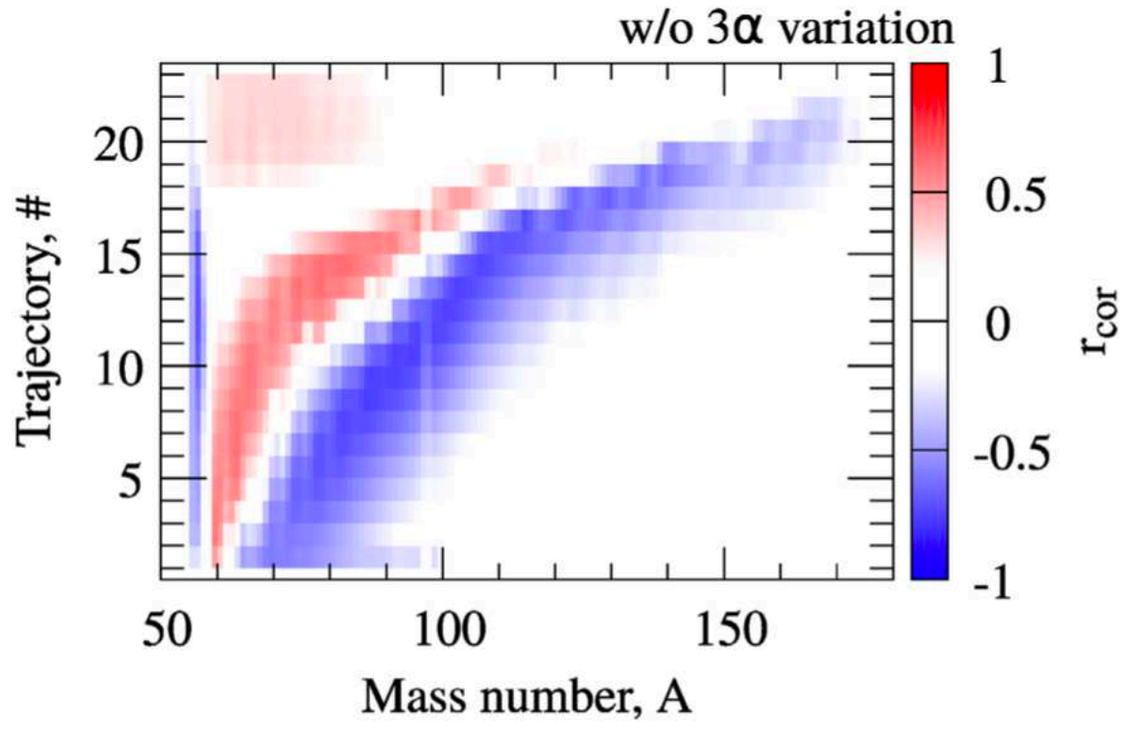
triple-α





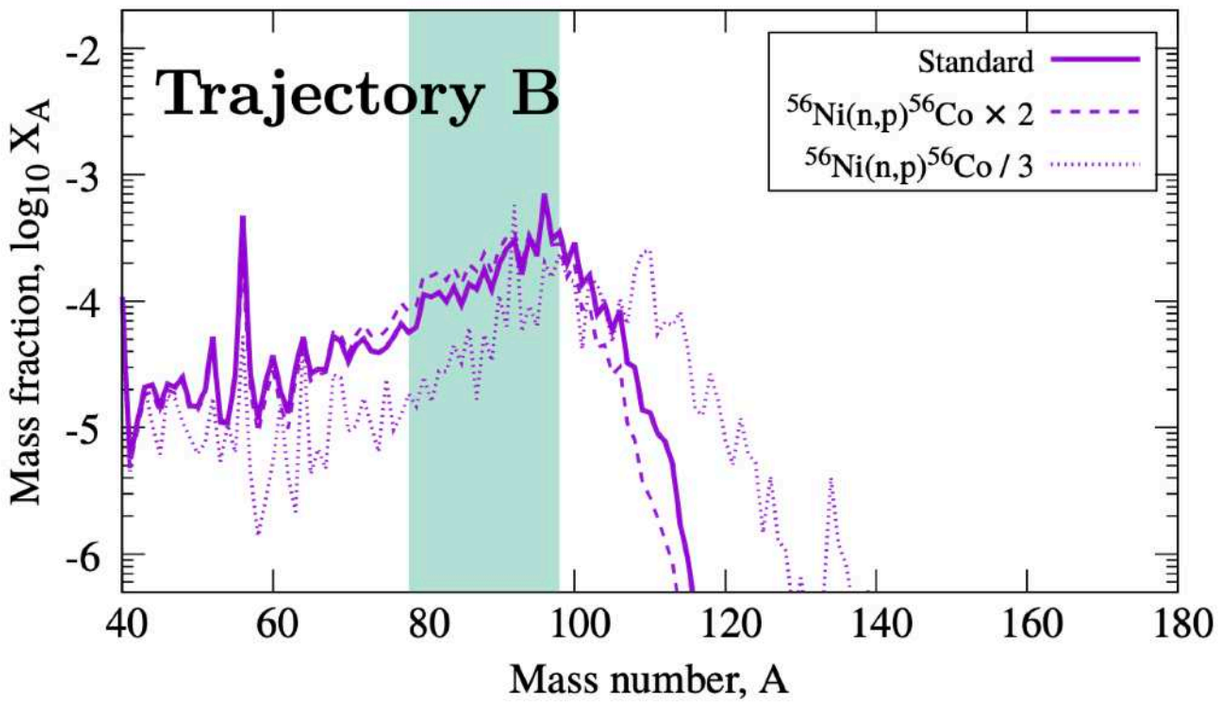
$^{56}Ni(n,p)^{56}Co$

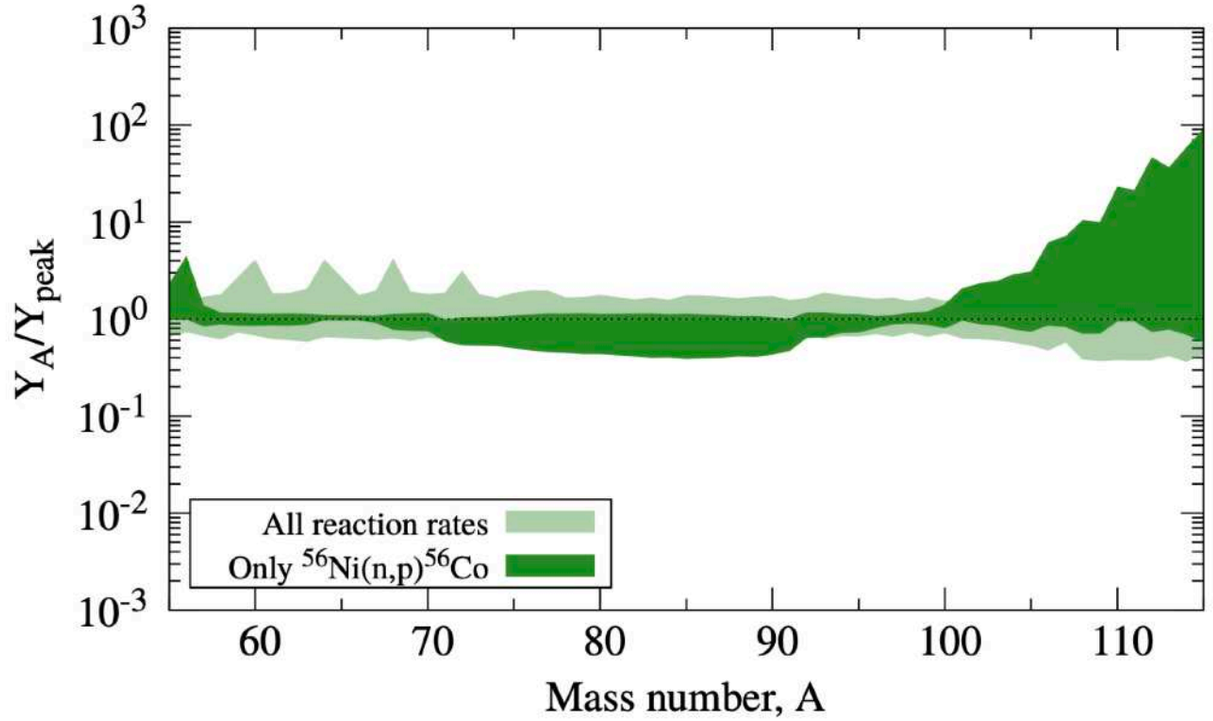




^{56}Ni(n,p)^{56}Co reaction

Impact of ^{56}Ni(n,p)^{56}Co on the ν p-process

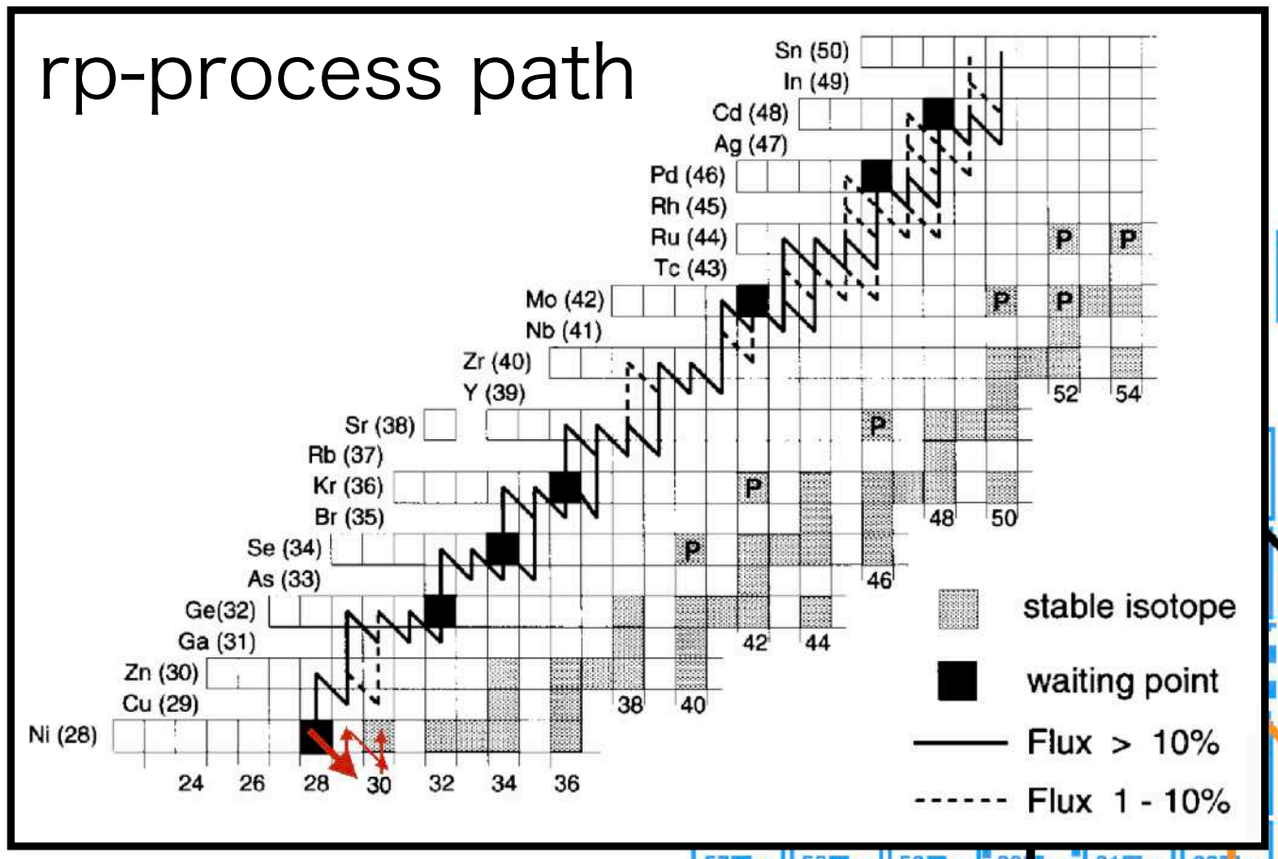


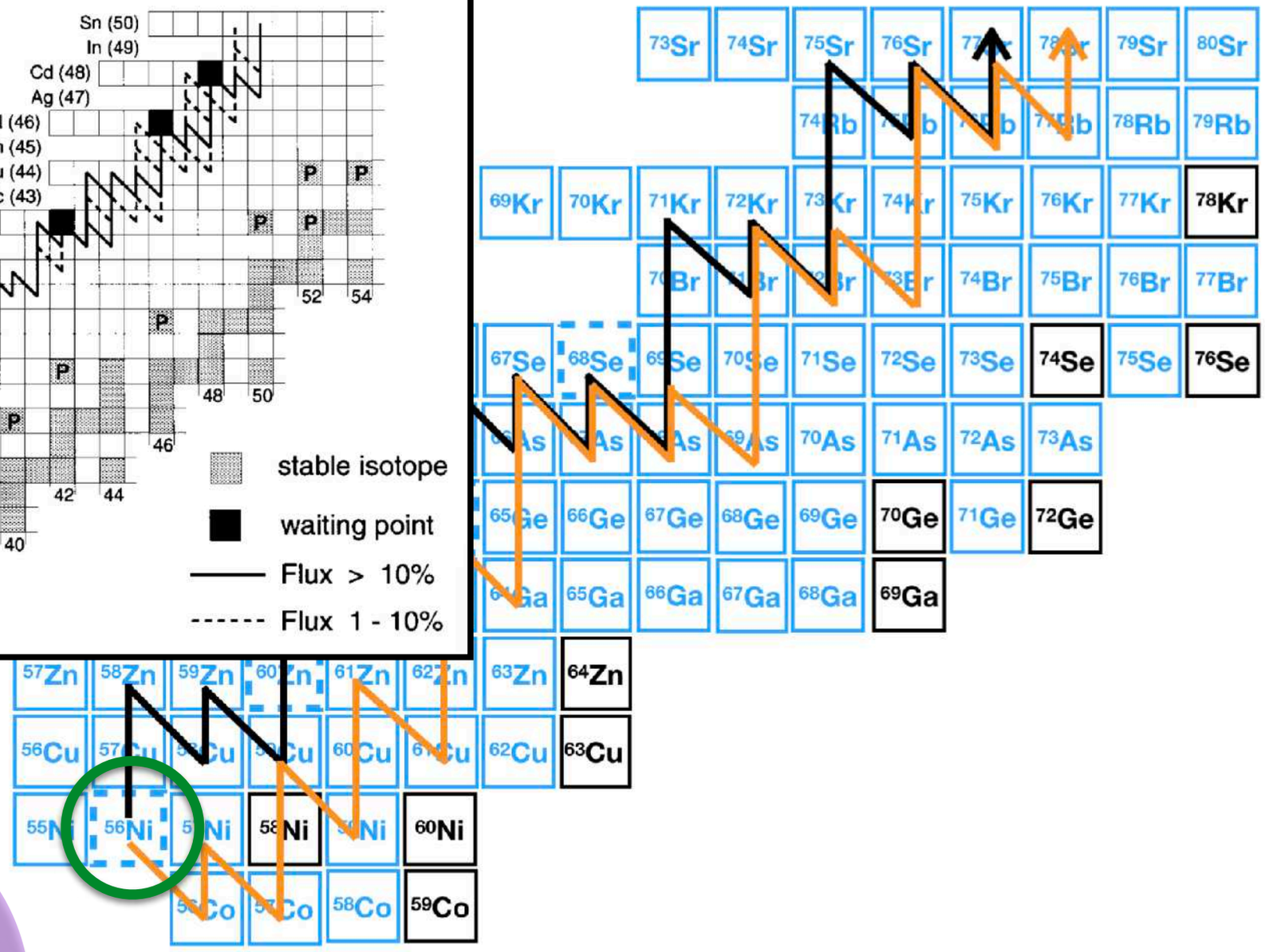


experiment at RIBF+OEDO (in 2020)

- PI: B. Mauss & D. Suzuki (Riken)
- determined by a surrogate reaction (^{56}Ni(d,p)^{57}Ni)
- “it is important in astrophysics” and “experimentally possible” (NN+2019, Rauscher2013)

Whey previous studies miss this rate?





seed production
begins with triple-α

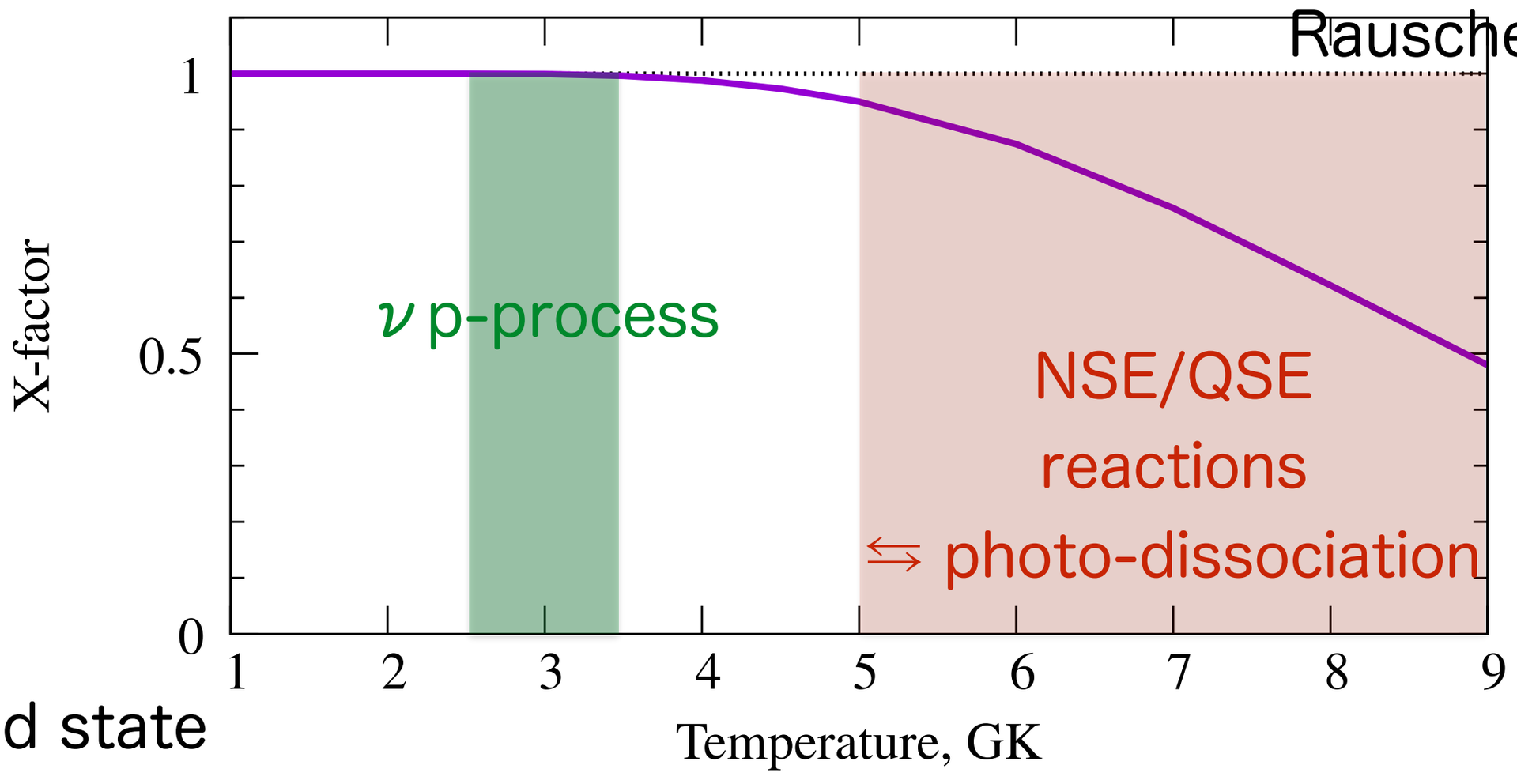
breaks through ^{56}Ni-peak

limited experiment can have impacts?

- reactions in astrophysical environments
  - Maxwell-averaged reaction rates (in a wide range of energy)
  - experiments can performed in limited energy (ground state)

ground state contribution (low T/low E)

excited state $^{56}Ni(n,p)^{56}Co$ based on



ground state

Summary

- ν p-process astrophysical models
  - developed a grid of ν p-process "trajectories" varying Ye-S, based on 1D porto-neutron star wind models
  - a strong correlation between the strength of ν p-process and "bulk n-capture" (Δ_n)
- Uncertainty and key reactions
  - overall large uncertainty: factor 2-3
  - key reactions for trans-iron elements including p-nuclei
  - ν p-process can be the origin of ligh p-nuclei
    (reproduce the solar ^{92}Mo/^{94}Mo ratio within uncerainty)
  - re-evaluate key reactions for the seed production
    - highest priority: triple-α, ^{56}Ni(n,p)^{56}Co