Toward new nuclear-astrophysics experiments for explosive nucleosynthesis in core-collapse supernovae

Nobuya Nishimura

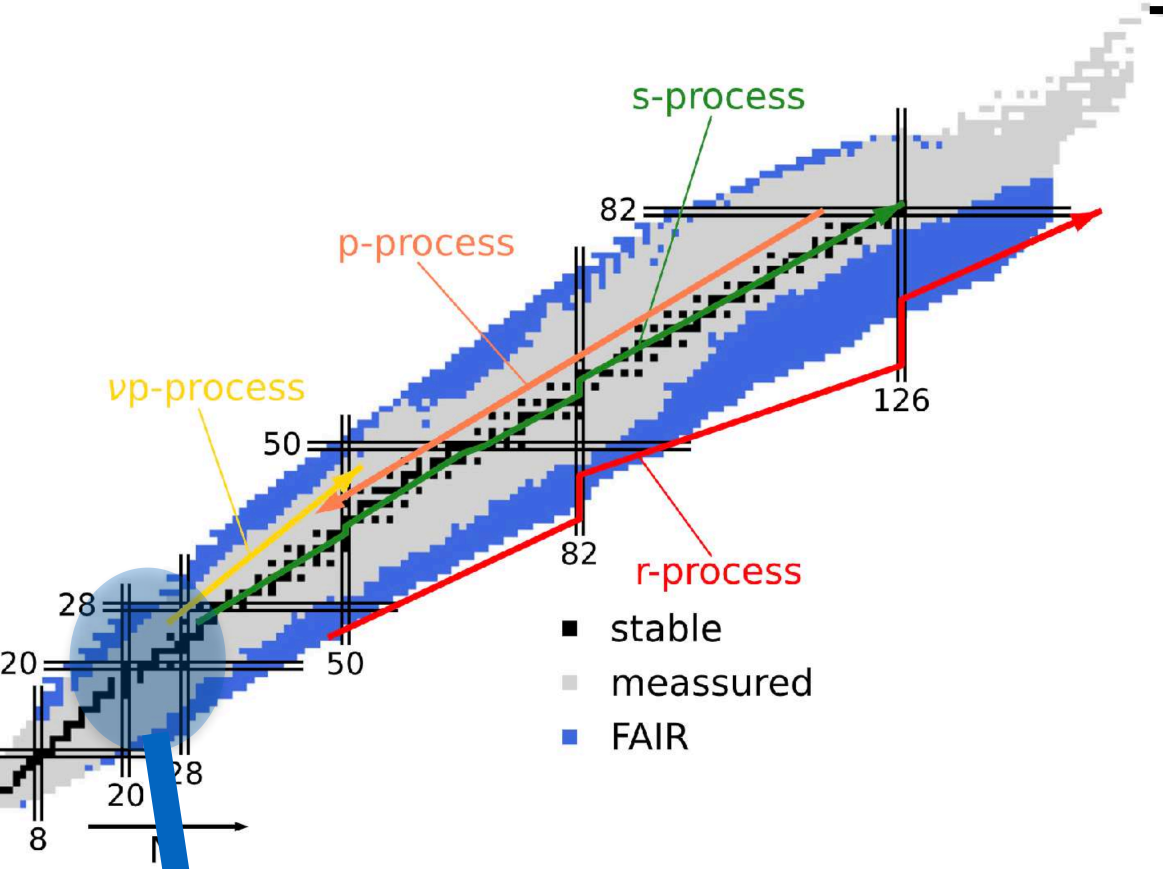
CNS (Center for Nuclear Study), U. of Tokyo / ABBL, RIKEN

Collaboration with

T. Rauscher (U Basel) & C. Fröhlich (NCSU)


Heavy nucle
e universe
solar abundances
(Anders & Grevesse
big-bang
stellar-evolution
explosive nucleosynthesis
n-nuclei
s-process
r-process
p-nuclei
Abundance, Y
s-process
p-process
νp-process
r-process
nuclear reactions
stable
Proton number, Z
Neutron number, N
neutron number
Flux, $\log_{10}(f)$
Z
N
Arcones & Thielemann (2023)

Key reactions in nucleosynthesis



"sensitivity" study

on nucleosynthesis?

our approach

reaction/decay uncertainty

Monte-Carlo + statistical analysis

astronomical observation

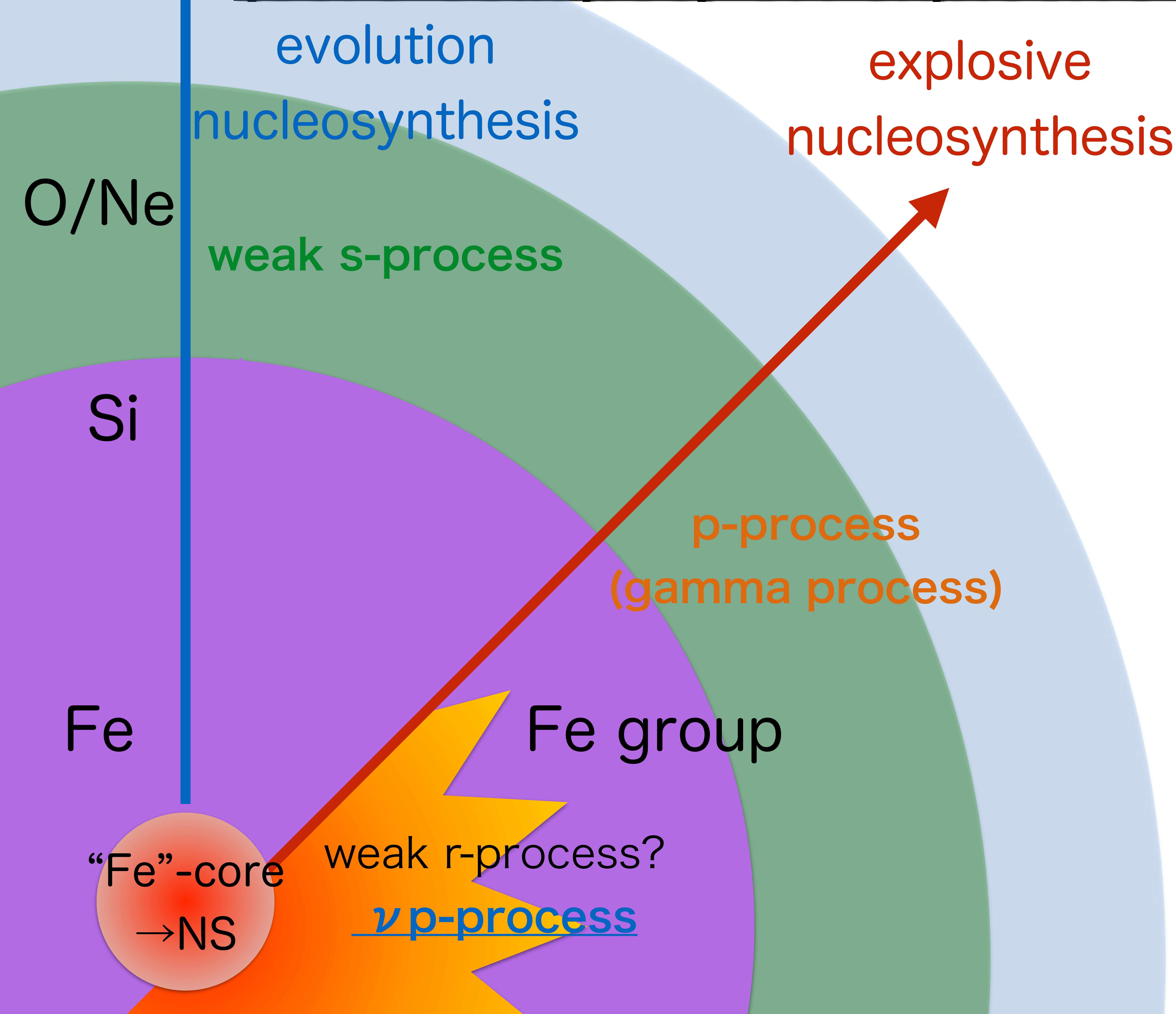
- s-process : (2) weak s (→ n_TOF (CERN) experiments), (4) main s
- p-process : (1) CC-SNe, (3)Type Ia SNe
- νp-process : (5) PNS wind → RIBF experiments and more?

(1) Rauscher, NN+(2016) MNRAS 463; (2) NN+(2017) MNRAS 469; (3) NN+(2018) MNRAS 474;
(4) Cescutti+NN+(2018) 478 MNRAS; (5) NN+(2019) MNRAS 489

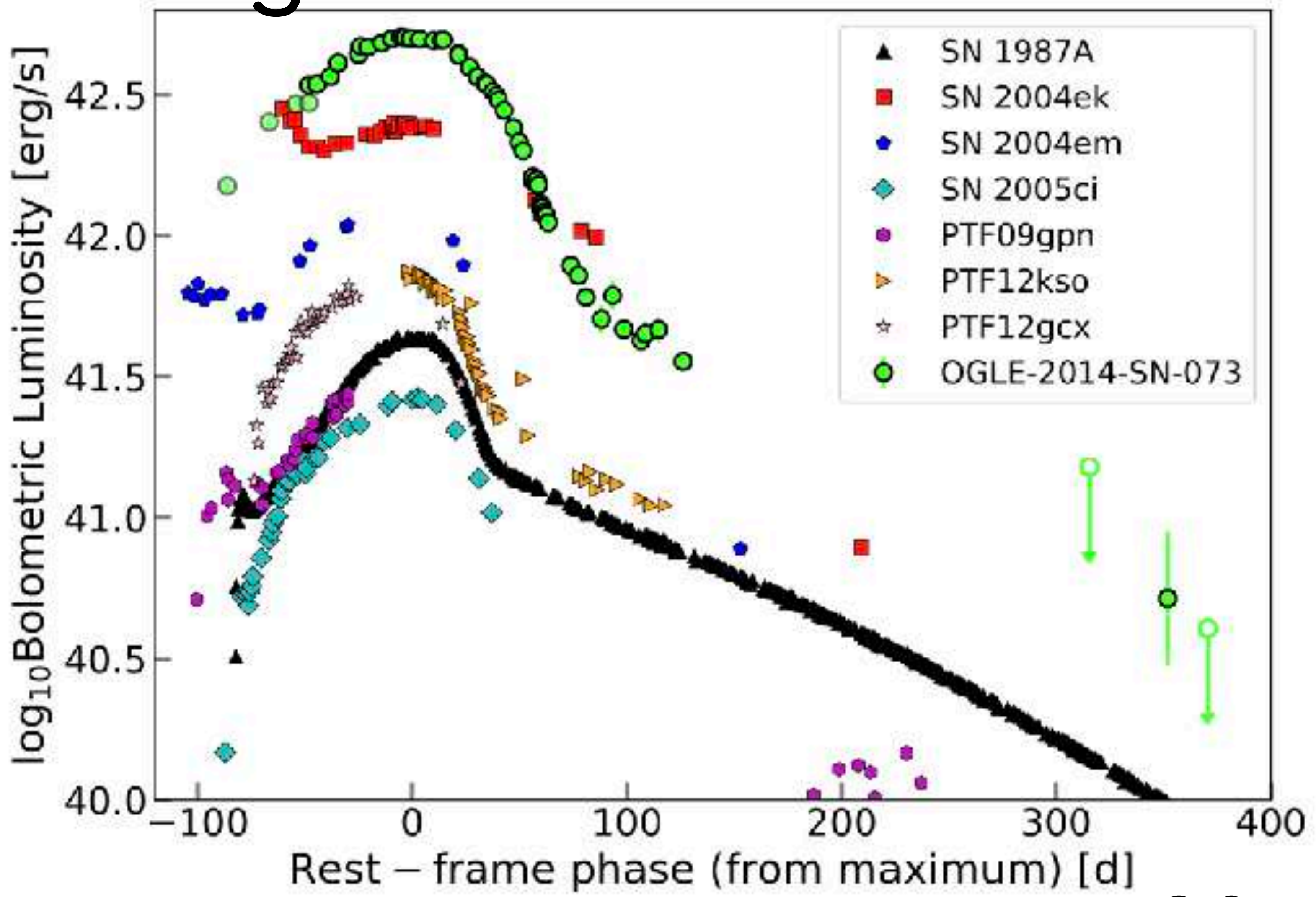
Collaborators: G. Cescutti, S. Cristallo, C. Fröhlich, J. den Hartogh,
A. Heger, R. Hirschi, A. Murphy, T. Rauscher, C. Travaglio

explosive nucleosynthesis in cc-SNe (e.g., ^{56}Ni, Fe-group, ^{44}Ti)

(core-collapse) SN explosive nucleosynthesis

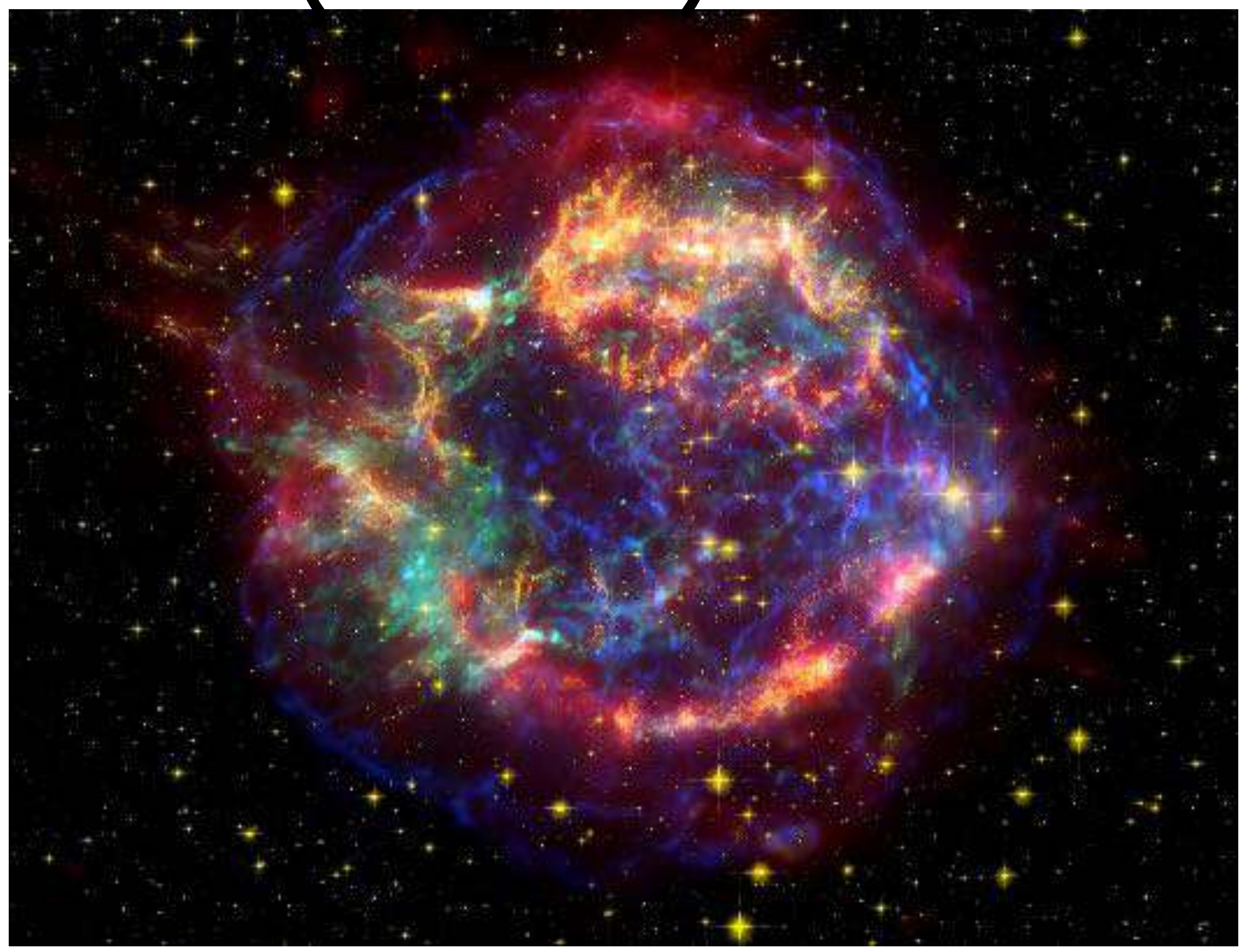


light curves cc-SNe



Terreran+2017

SNR (Cas A)



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2. **A new nuclear-astrophysics experiment for νp-process**
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3. **Explosive nucleosynthesis in supernovae**
    - overview: nucleosynthesis in core-collapse supernovae
    - method: SN models and nucleosynthesis
    - key reactions found by MC and statistical analysis

4. **Summary**

1. A new nulcear-physics experiment for the νp-process

(a brief progress report)

・NN+(2019), MNRAS

・NN & D. Suzuki

Experimental challenges

s-process

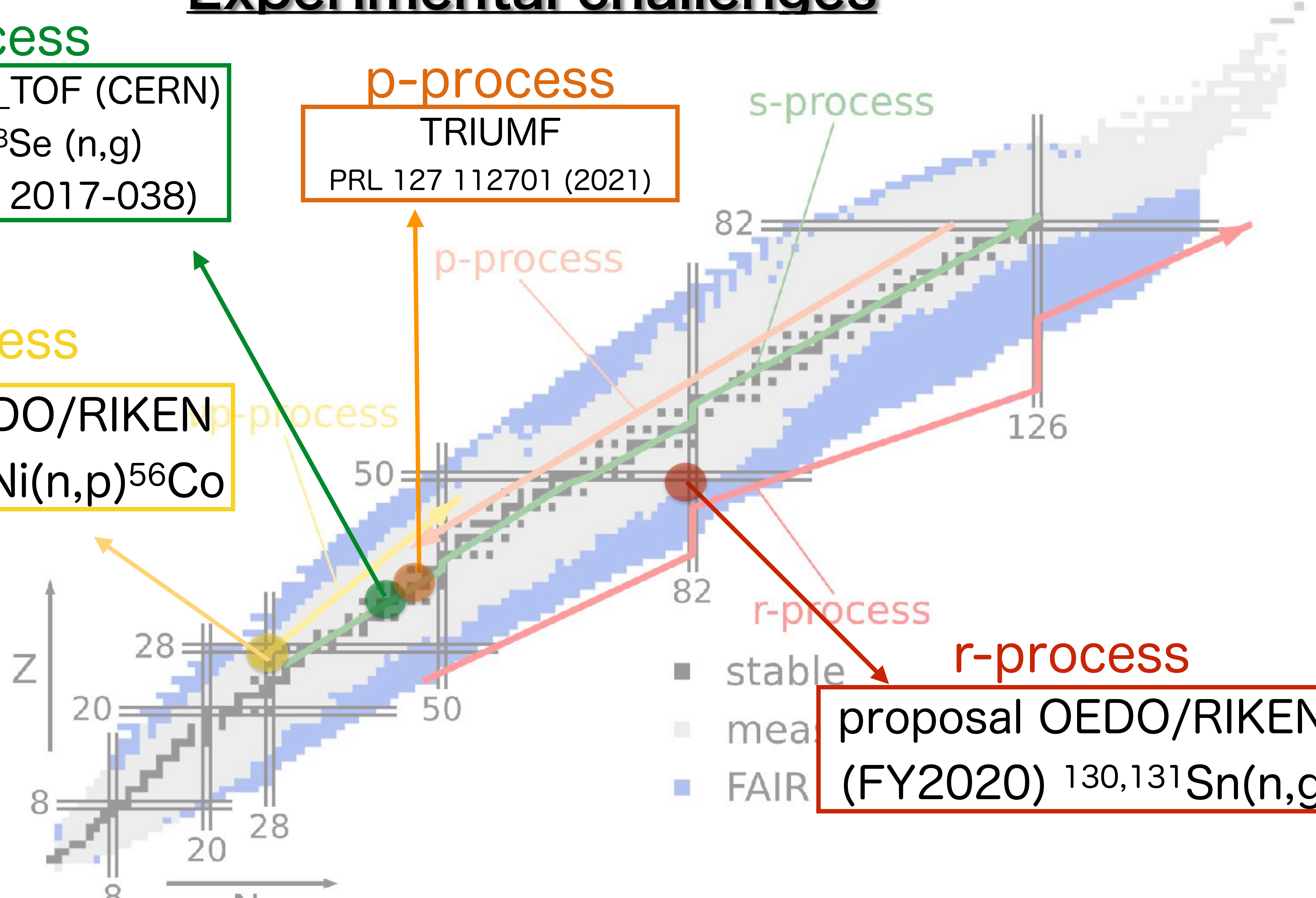
proposal to n_TOF (CERN)
^{68}Zn, $^{77,78}Se$ (n,g)
(CERN INTC 2017-038)

p-process

TRIUMF
PRL 127 112701 (2021)

ν p-process

proposal OEDO/RIKEN
(FY2020) $^{56}Ni(n,p)^{56}Co$



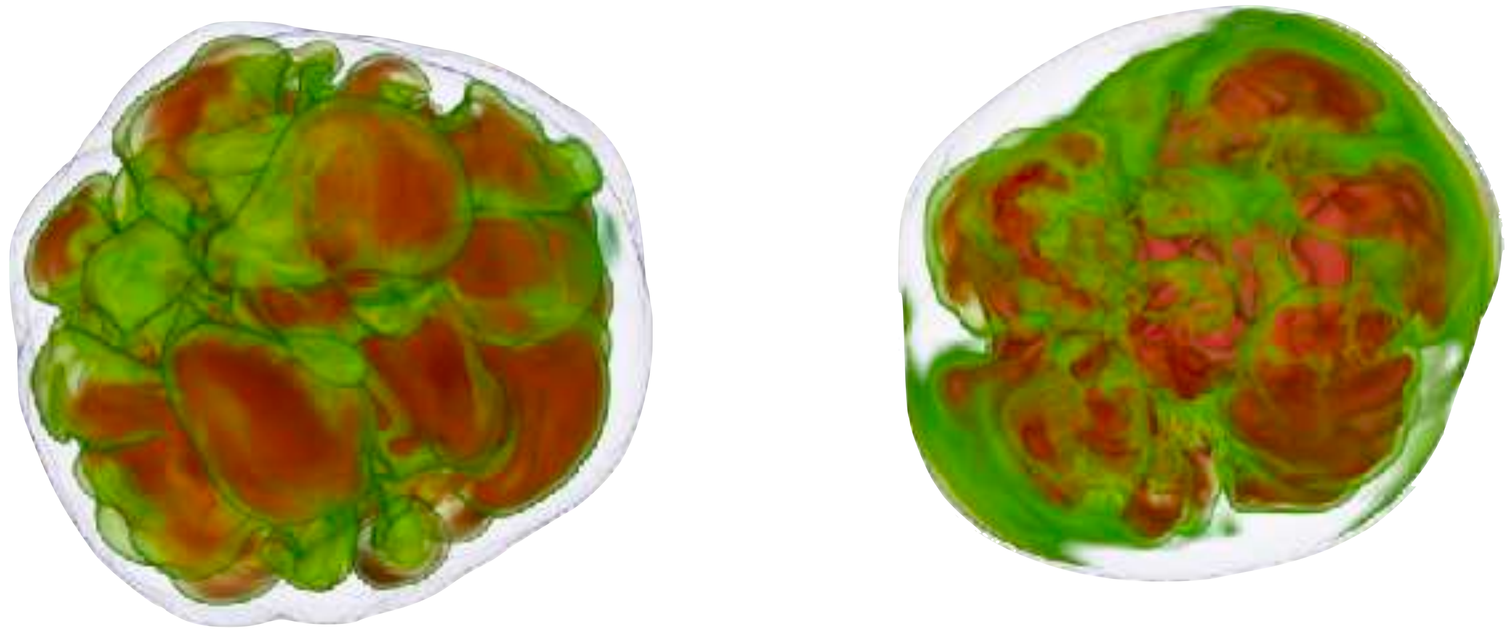
r-process

proposal OEDO/RIKEN
(FY2020) $^{130,131}Sn(n,g)$

νp-process in core-collapse supernovae

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

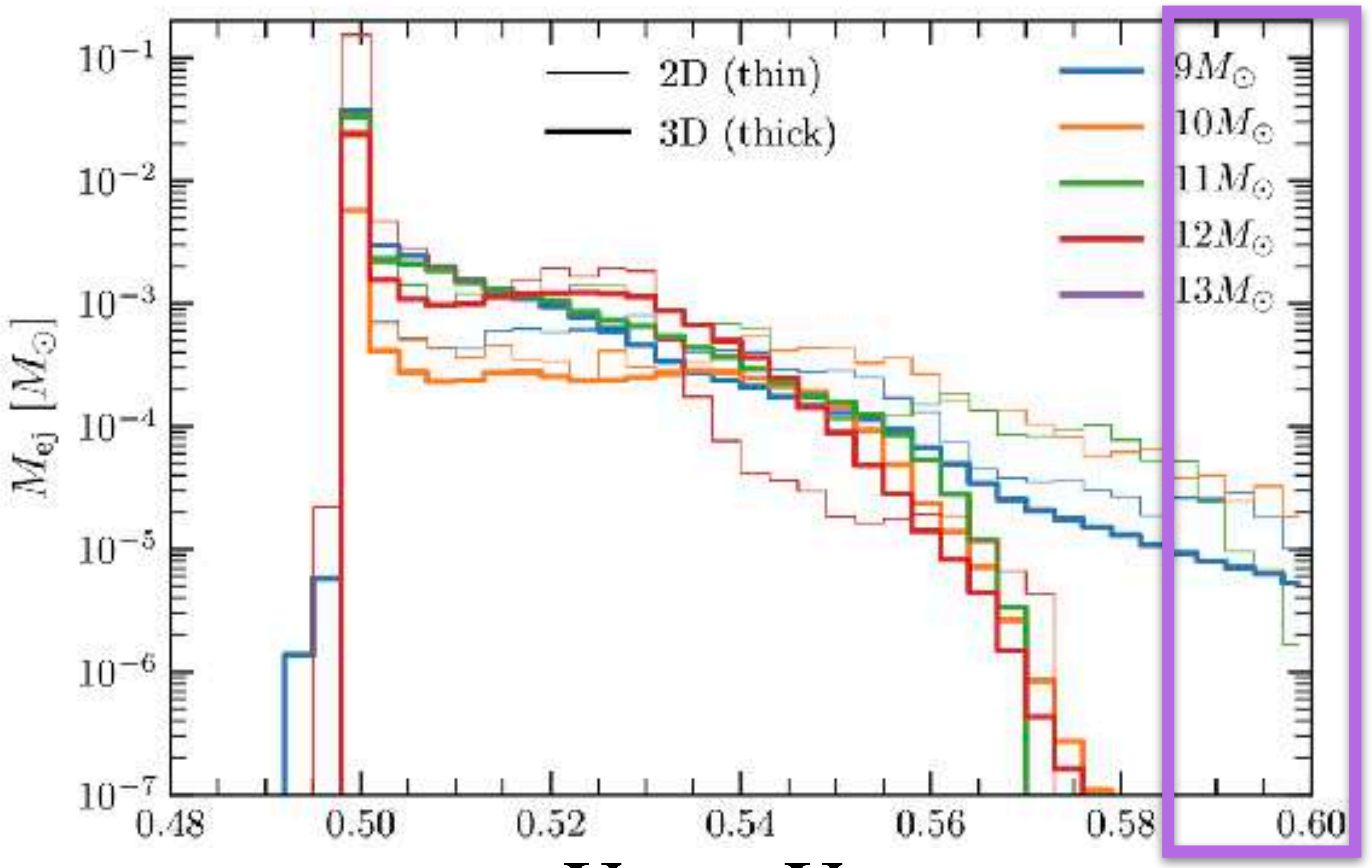
explosion by ν heating (entropy)



400 km　　6000 km

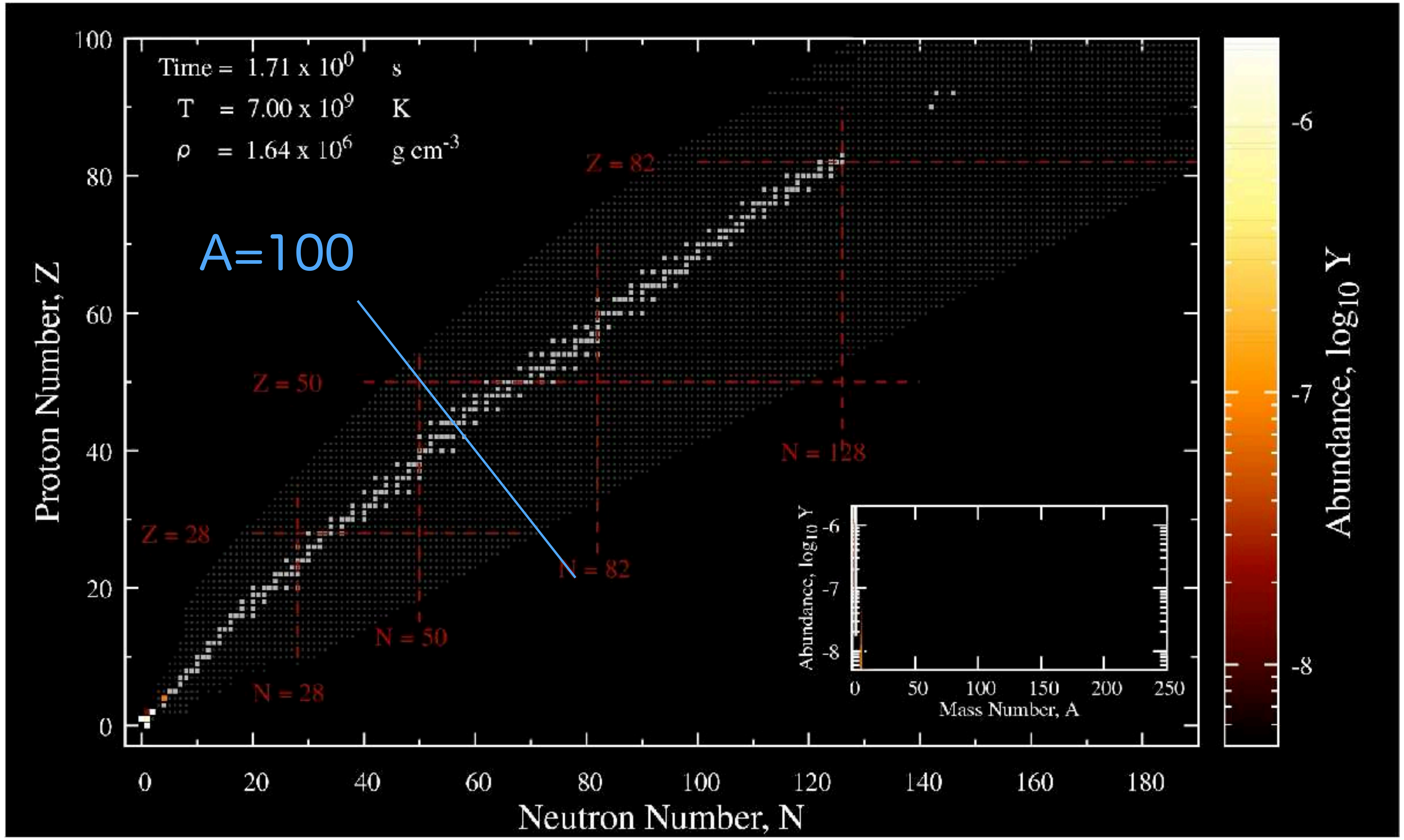
ejecta becomes proton-rich?

can exceed $Y_e = 0.6$



$Y_e \sim Y_p$

νp-process ($Y_e \sim 0.6$ model)



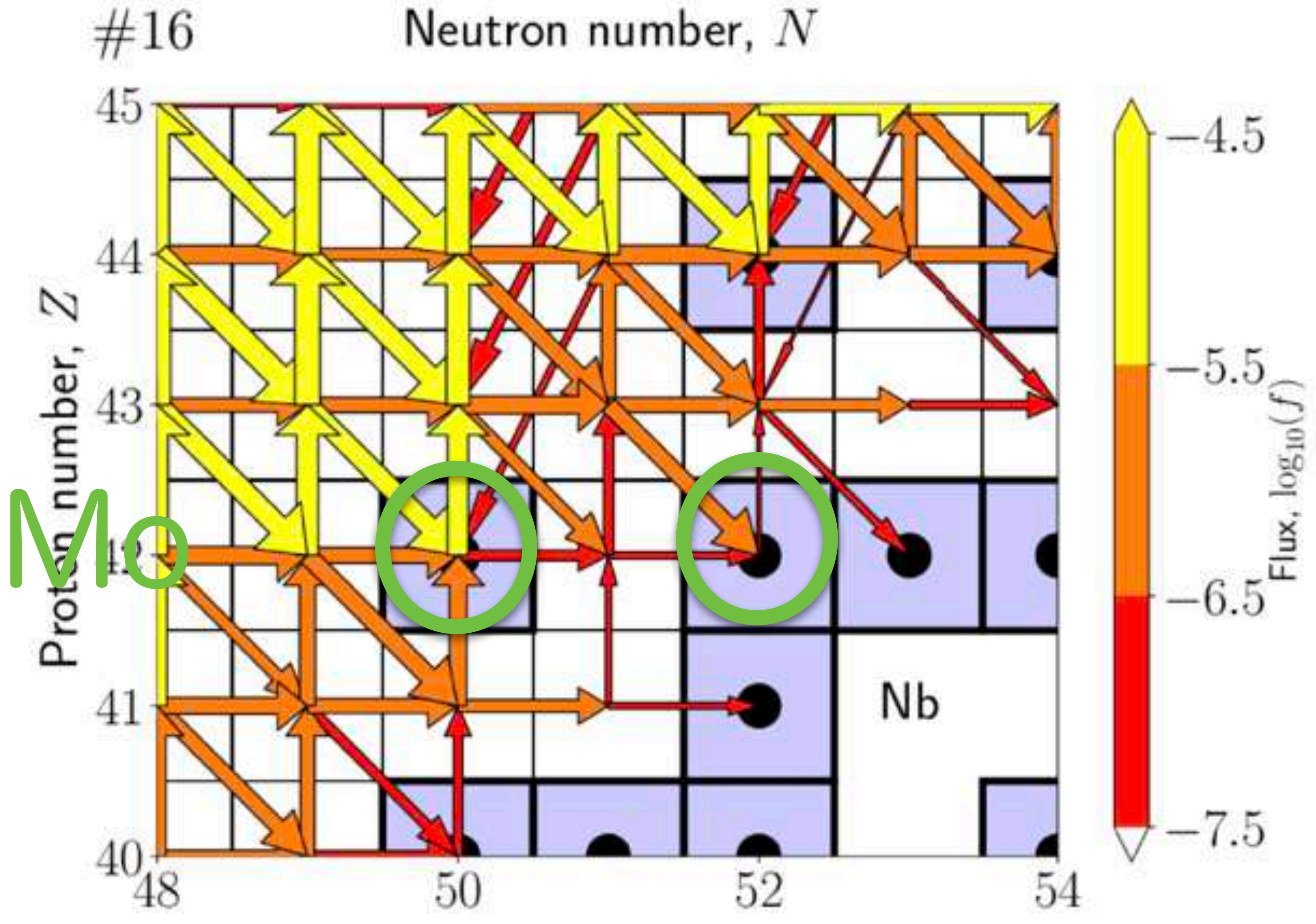
NN+2019

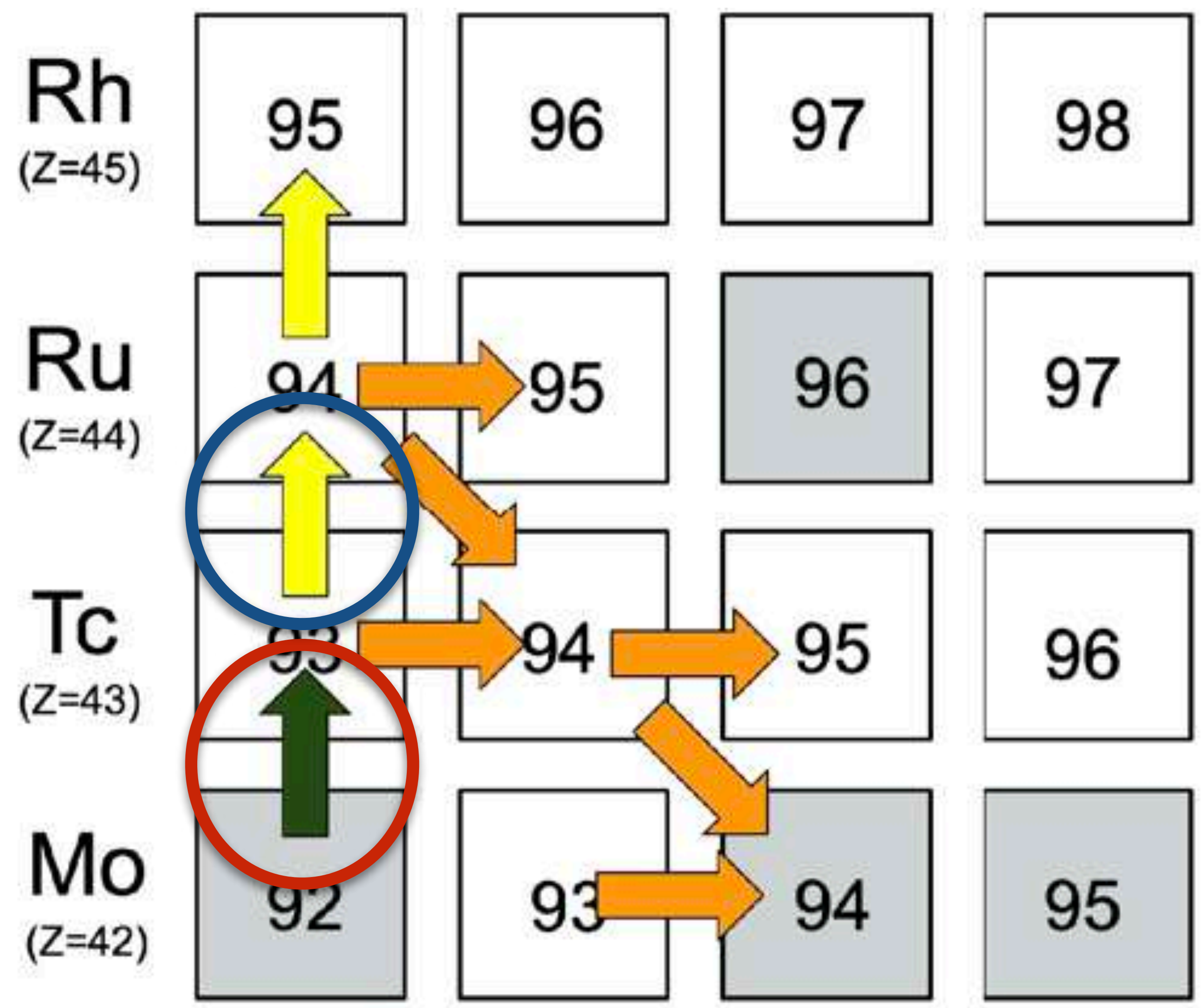
Solar isotopic ratios

the solar isotopic ratio (Lodders 2003): /^{94}Mo
^{92}Mo/^{94}Mo = 1.6, ^{84}Sr/^{94}Mo = 0.54, ^{78}Kr/^{94}Mo = 0.82

- νp-process w/ updated masses?
  → still low ^{92}Mo/^{94}Mo (Xing+2018)
- nuclear reactions?
  - → 0.67 < ^{92}Mo/^{94}Mo < 2.79 for a specific model (NN+2019)

NN+2019

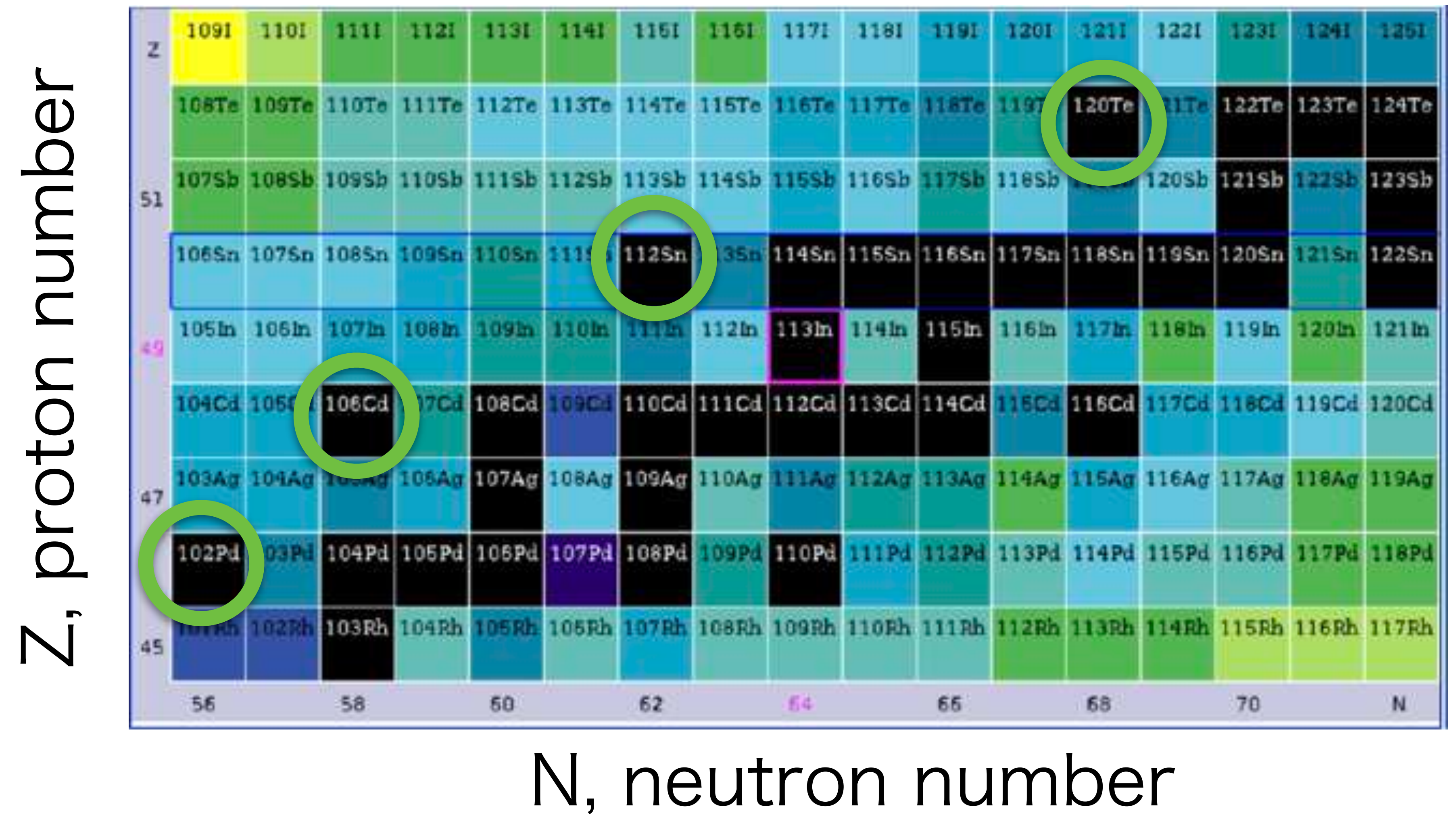


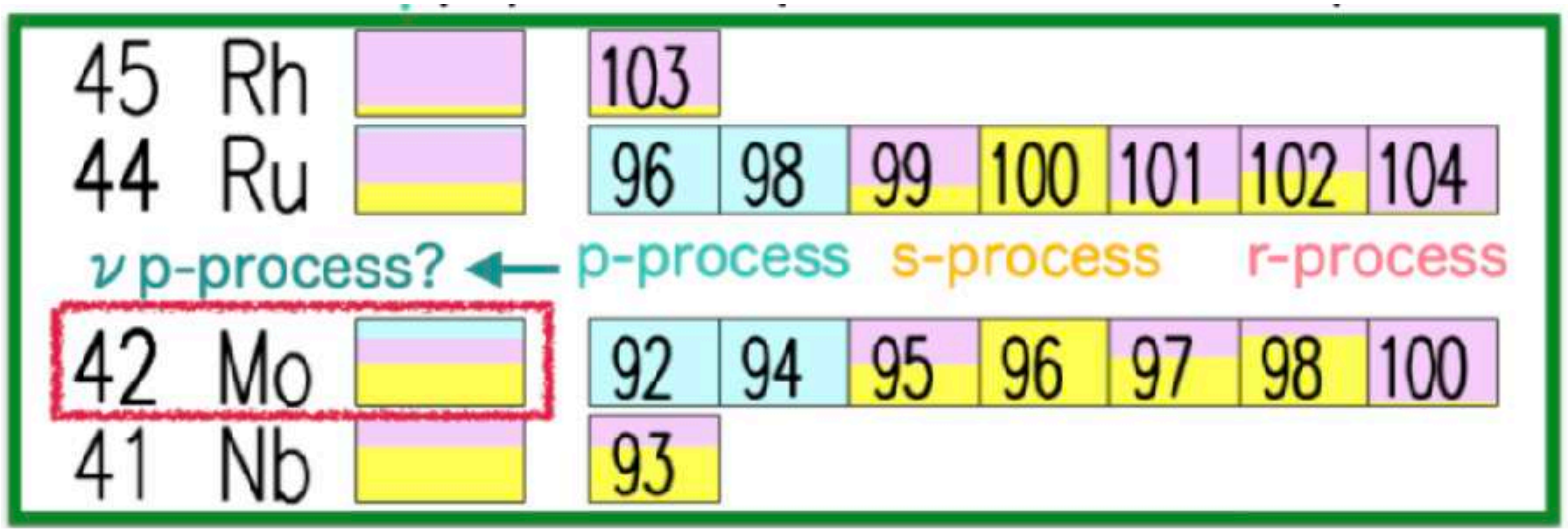


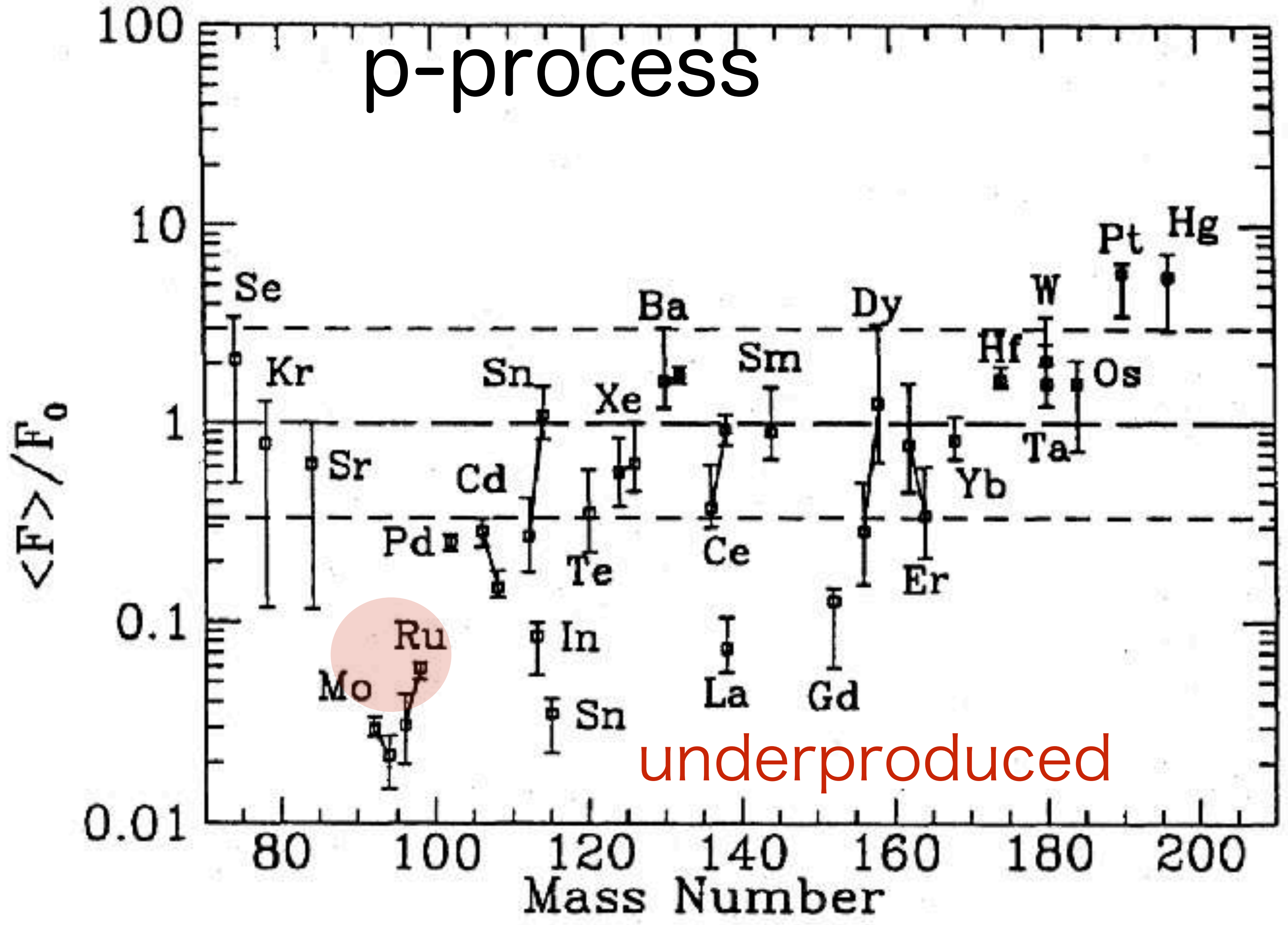
key reaction : ^{92}Mo(p,g)^{93}Tc
(next priority: ^{93}Tc(p,g)^{94}Ru)

"Molybdenum (Mo) problem" (lighter p-nuclei)

35 neutron-deficient isotope



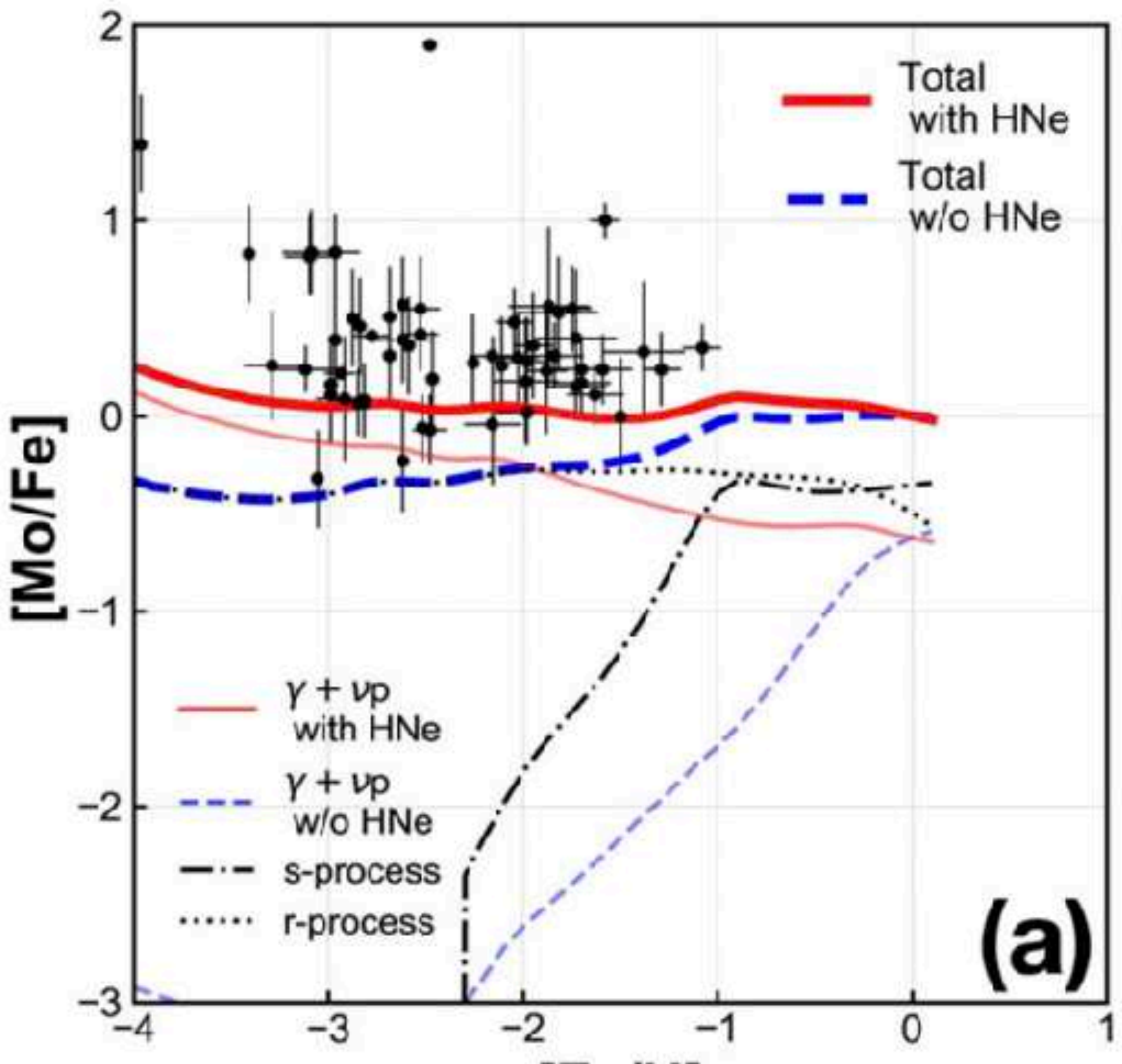




ν p-process in GCE

(see, Travaglio+2018 for the entire p-nuclei)

Sasaki+(2022)

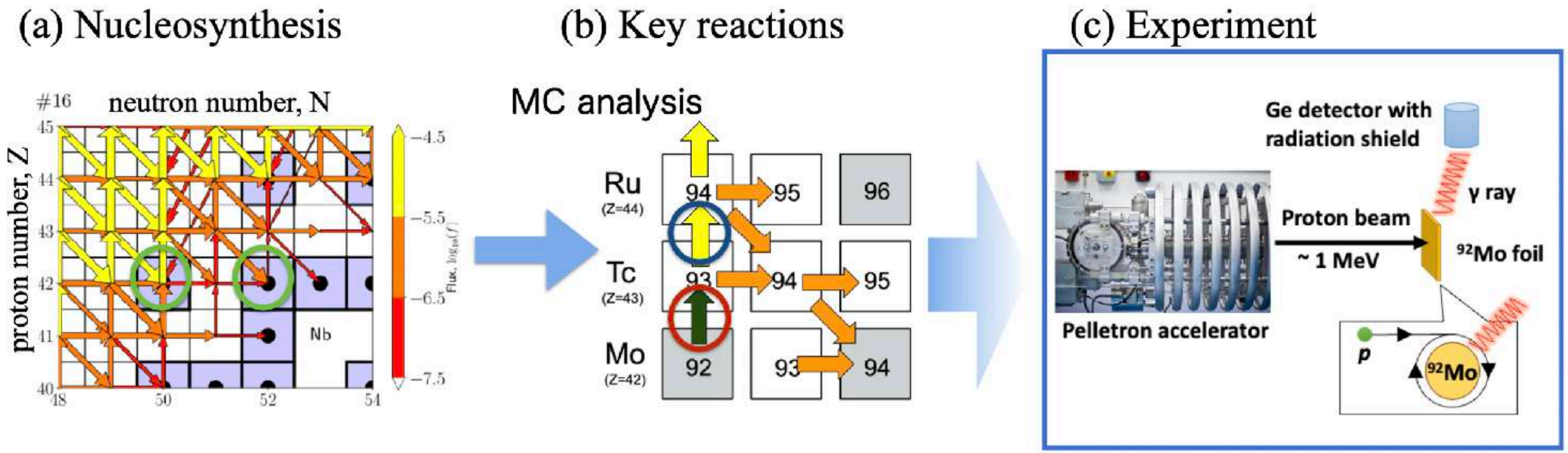


key reactions: νp-process

- **production of Mo: ^{92}Mo(p,g)^{93}Tc**
  - key reaction for determination of ^{92}Mo/^{94}Mo; theoretical descrepancy to solar isotopic ratio: critical to solve “Mo origin probelem” by νp-process
  - FY2021: N.N. initiated the plan of experiment w/ D. Suzuki (RIKEN → U Tokyo)
  - FY2022—2023:
    - applied RIKEN’s funding: Intensive Reserch project (300 MJPY. 2yr for non-PI)
      → approved (FY2024–2025)

We assumed to use Peletron accelerator at Science Tokyo.

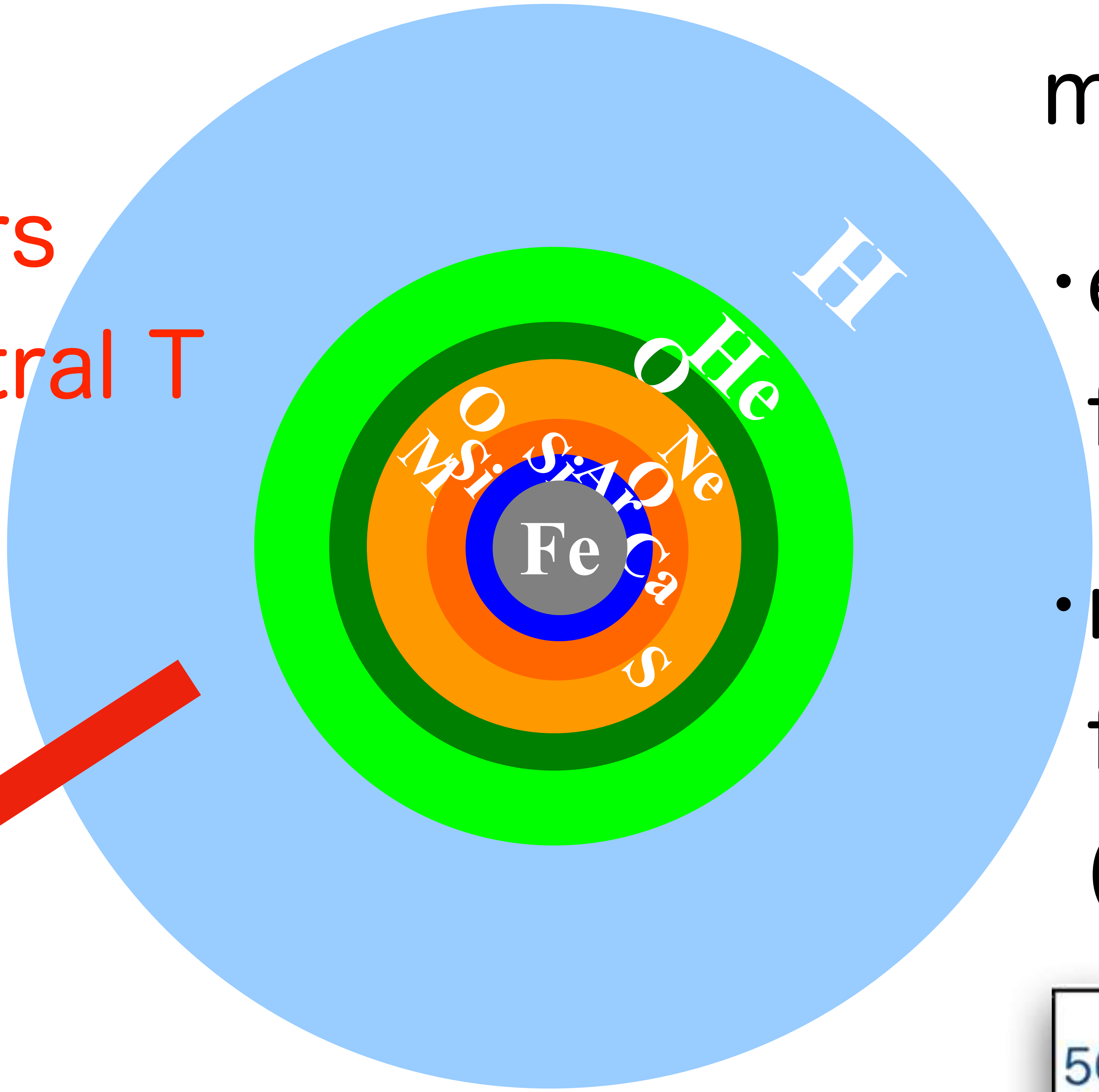
a figure in the proposal



2. Explosive nucleosynthesis in core-collapse supernovae

・NN, Fröhlich and Rauscher, in prep.

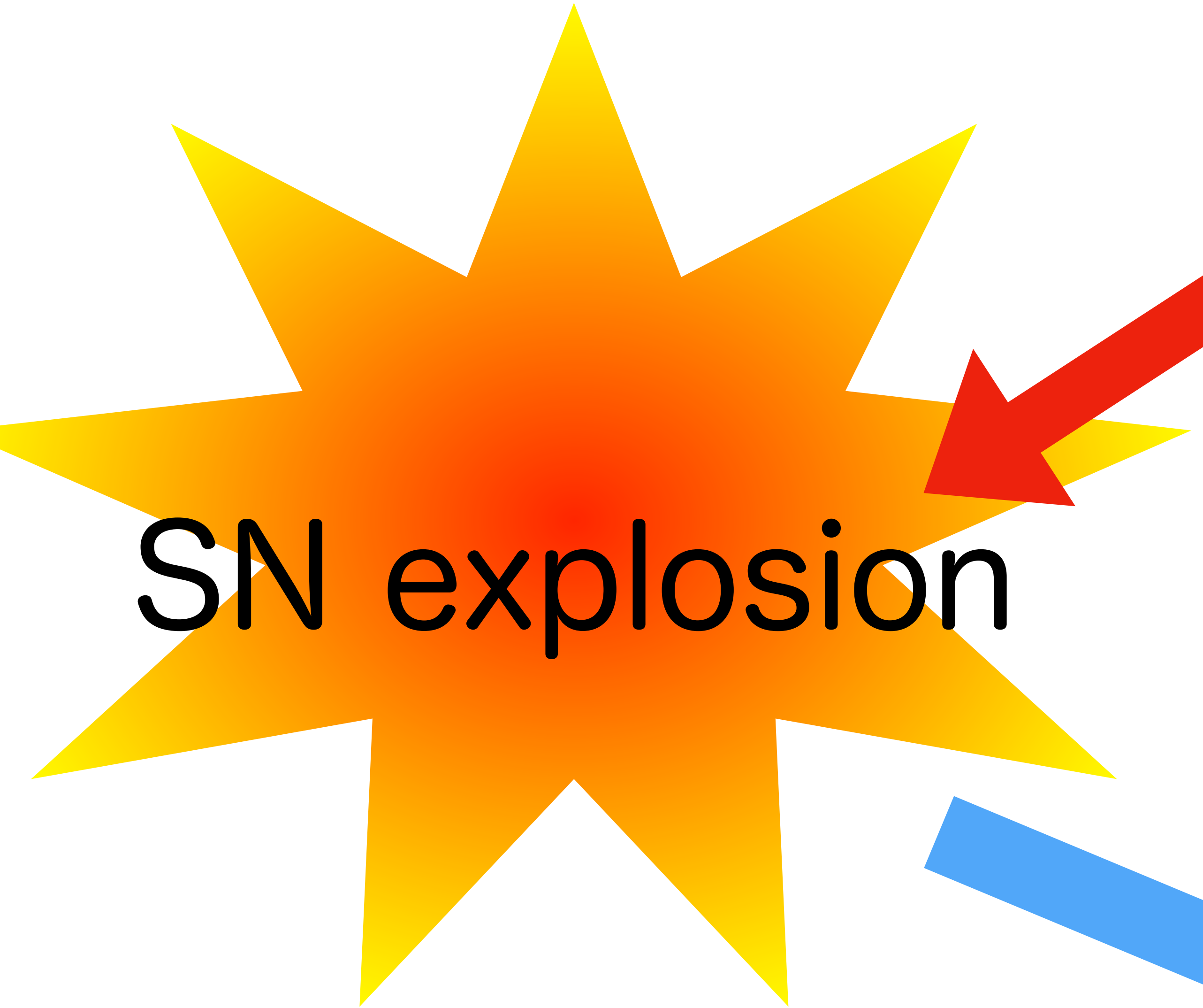
Core-collapse SN (Type Ib, Ic, II, not Ia)



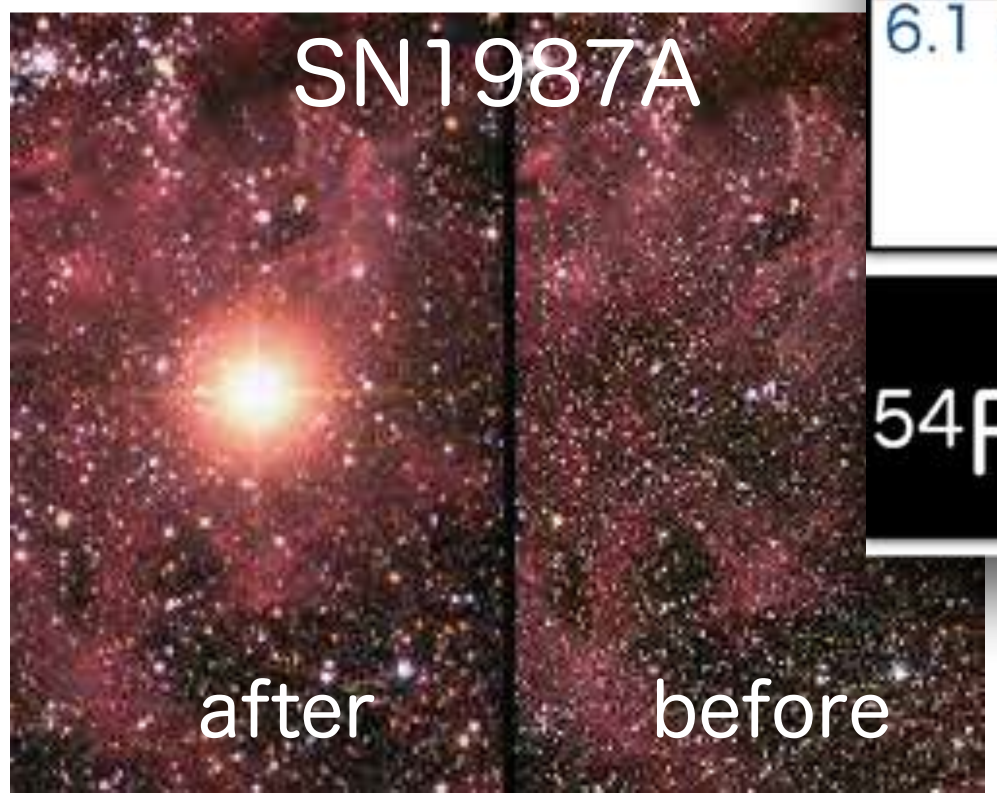
massive stars (>10 M_{sun})

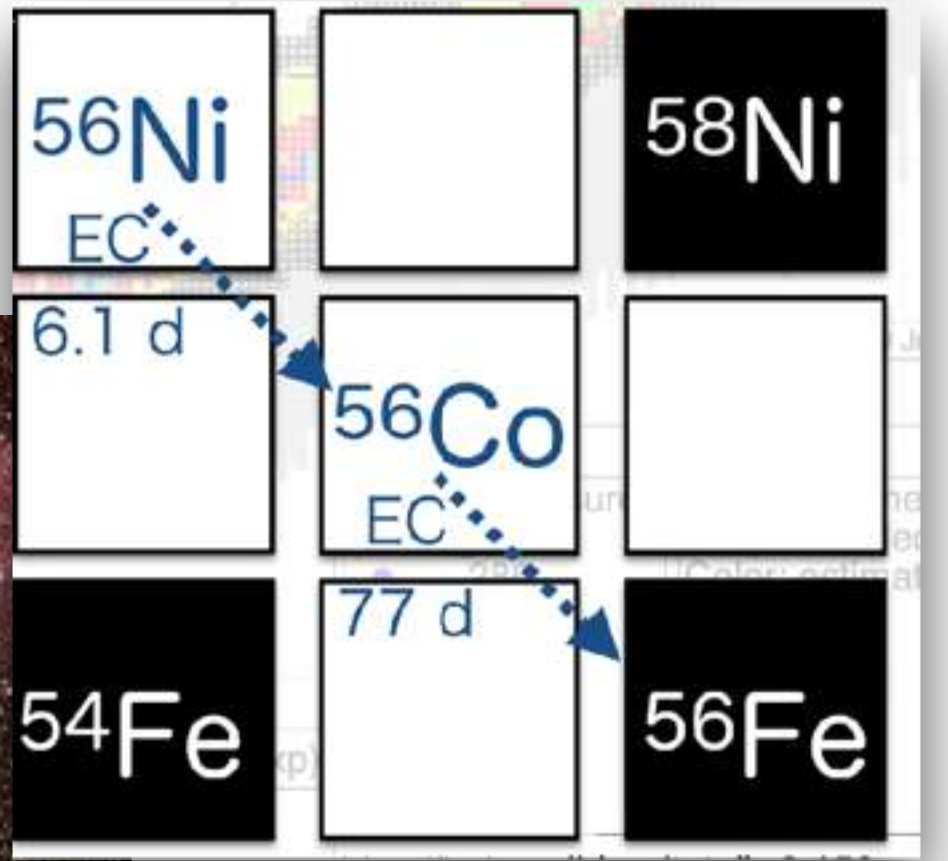
more massive stars makes higher central T

- energy generation by nuclear fusion (=bright stars)
- nulclear "ashes" becomes fuel for further burnings (H → He → C → O → ··· →Fe)



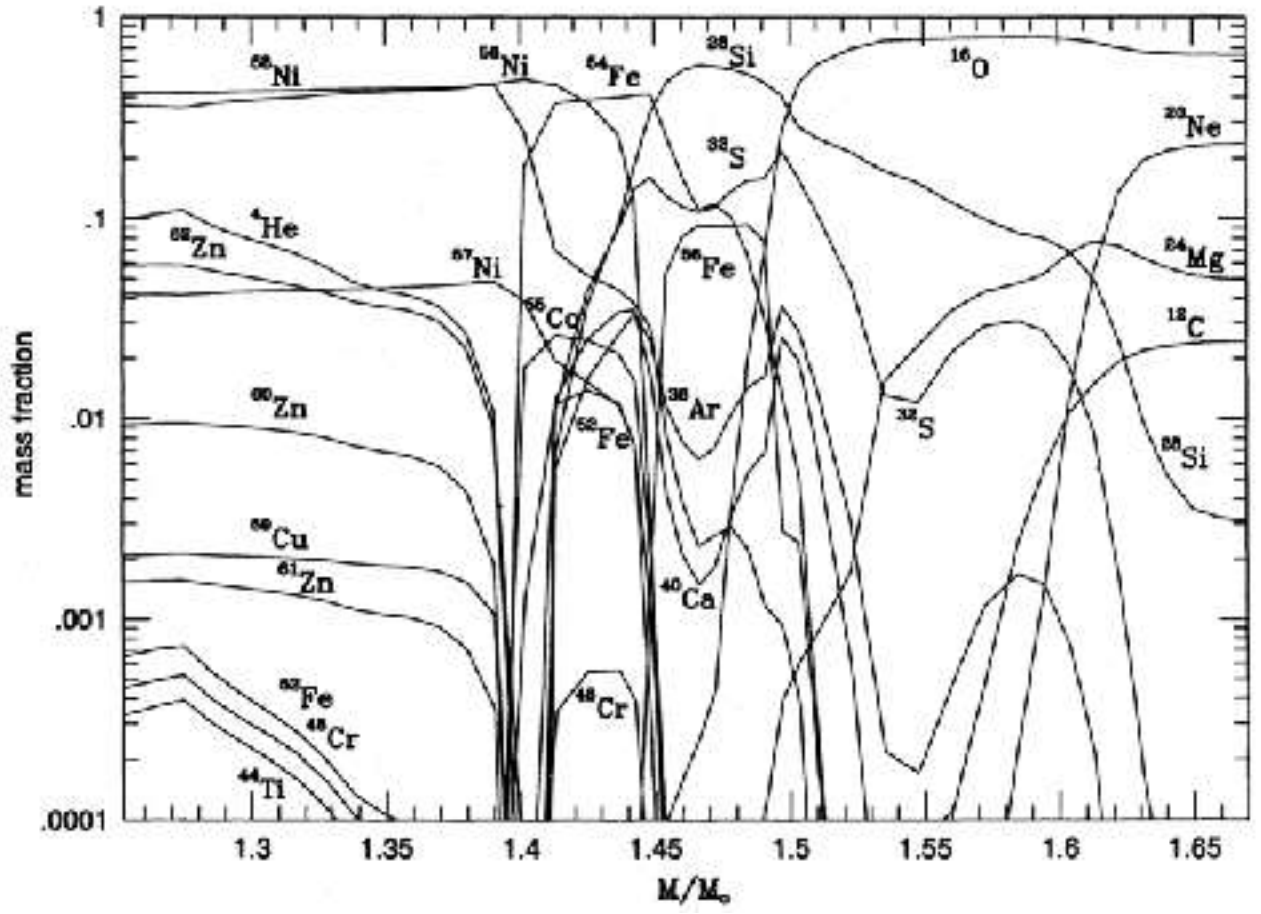
explosive nucleosynthesis
(Fe-group peak)





radioactive decay

“1D” explosion models of cc-SN



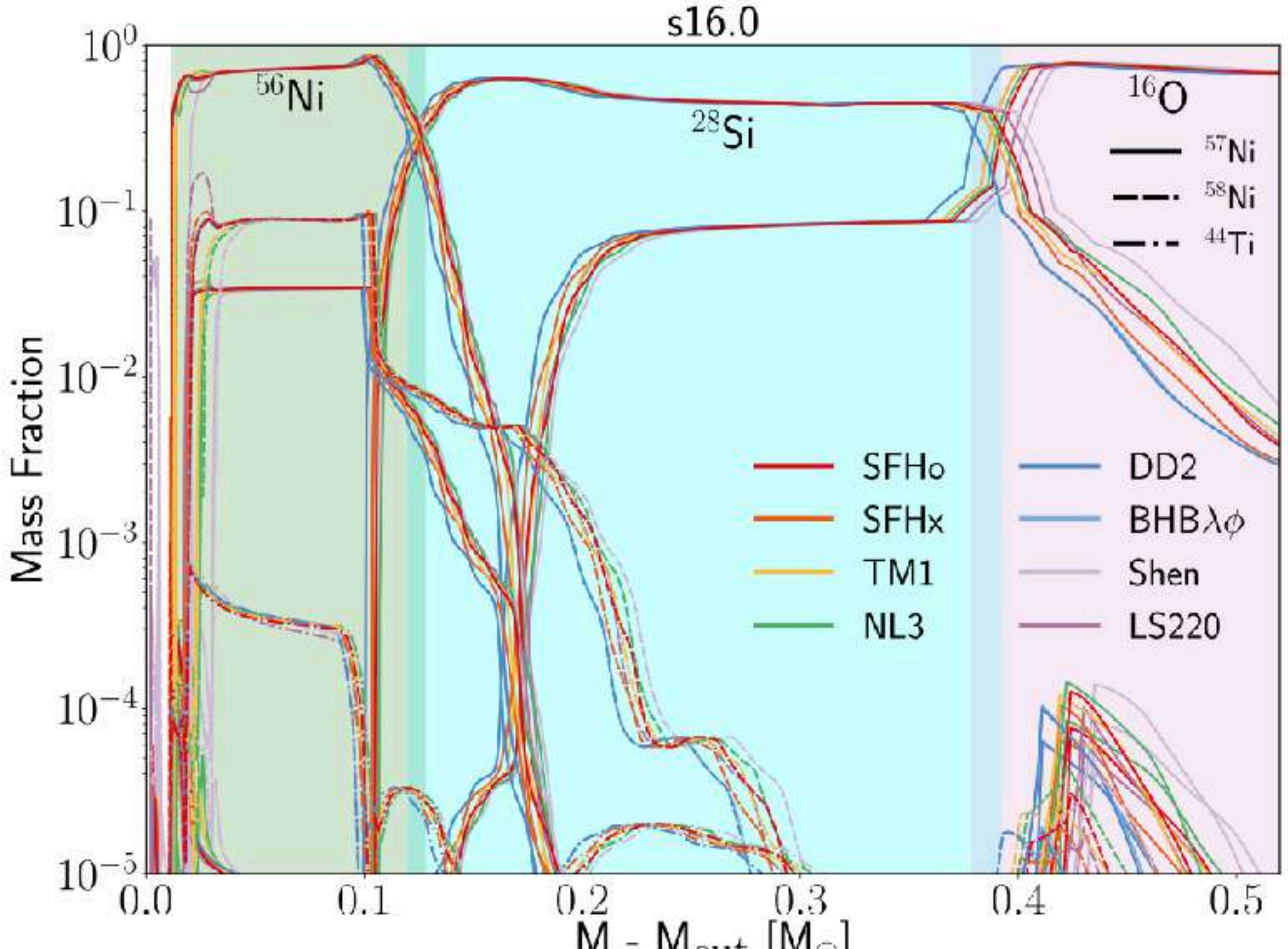
Thielemann+(1996)

- ・thermal “bomb” (e.g., Thielemann, Nomoto, Hashimoto 1996)
- ・“piston” (e.g., Woosley & Weaver 1995)
- ・recent debate on reasonable 1D explosion treatments (see, Sawada+2019, Imasheva, Janka+2023)

PUSH model (Perego et al. 2015): “energy deposition” by heavy flavor neutrino (not electron type) → “consistent” Y_e to explosion dynamics

adopted model $16\ M_\odot$ solar metallicity

PUSH results (EOS dependence)



Basics: explosive nucleosynthesis

- complex combination of reactions and photo-dissociation (partially in NSE)
- What happens at each layer of the star is relatively well known.

  several studies on the reaction rate sensitivity

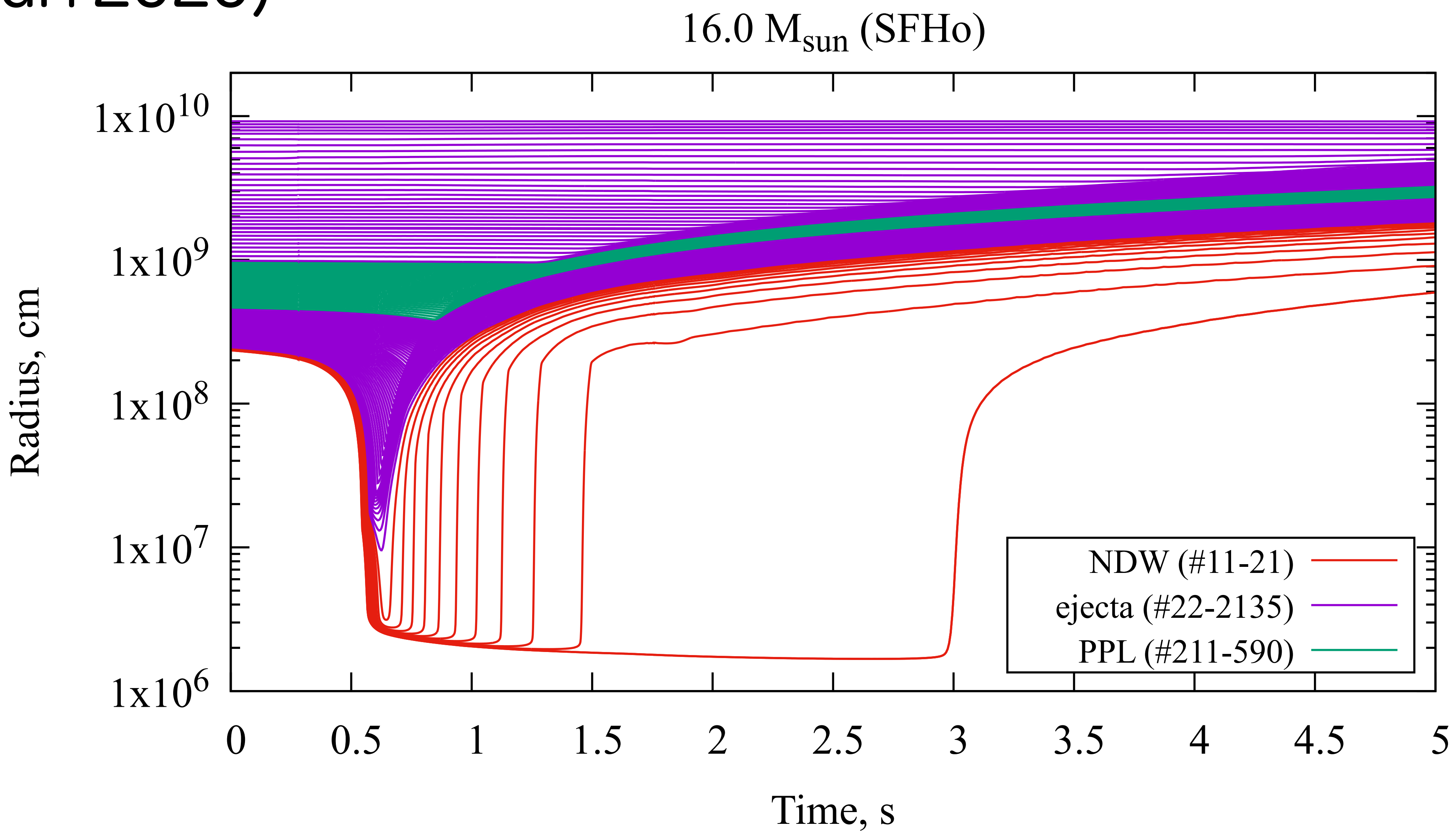
  (e.g., Magkotsios+2010, Subedi+2020)

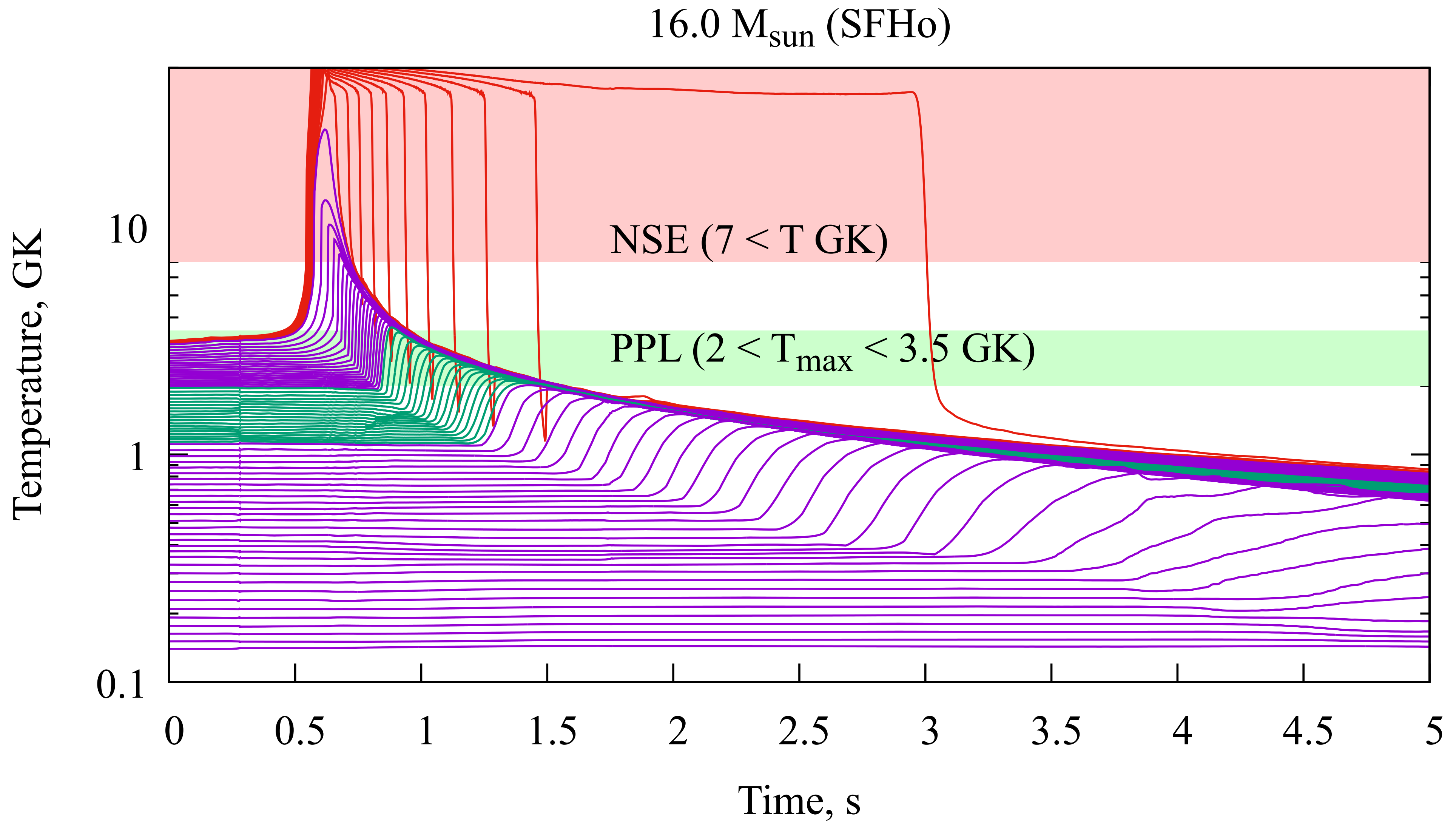
- $T_{9,p} > 5$: <u>explosive Si & O burning (NSE)</u>
  → ^{56}Ni, ^{57}Ni, ^{44}Ti, Fe peak
- $5 > T_{9,p} > 4$: <u>incomplete Si & explosive O burning</u>
  → ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca (+ ^{56}Ni, ^{44}Ti)
- $4 > T_{9,p} > 3.3$: <u>explosive Ne burning</u> → ^{16}O, ^{28}Si, ^{32}S
- $3.3 > T_{9,p} > 2$: <u>explosive C burning</u> → ^{20}Ne, ^{24}Mg
  + photodissociation of heavy seeds → p-process
- $2 > T_{9,p}$: no explosive burning

adopted model

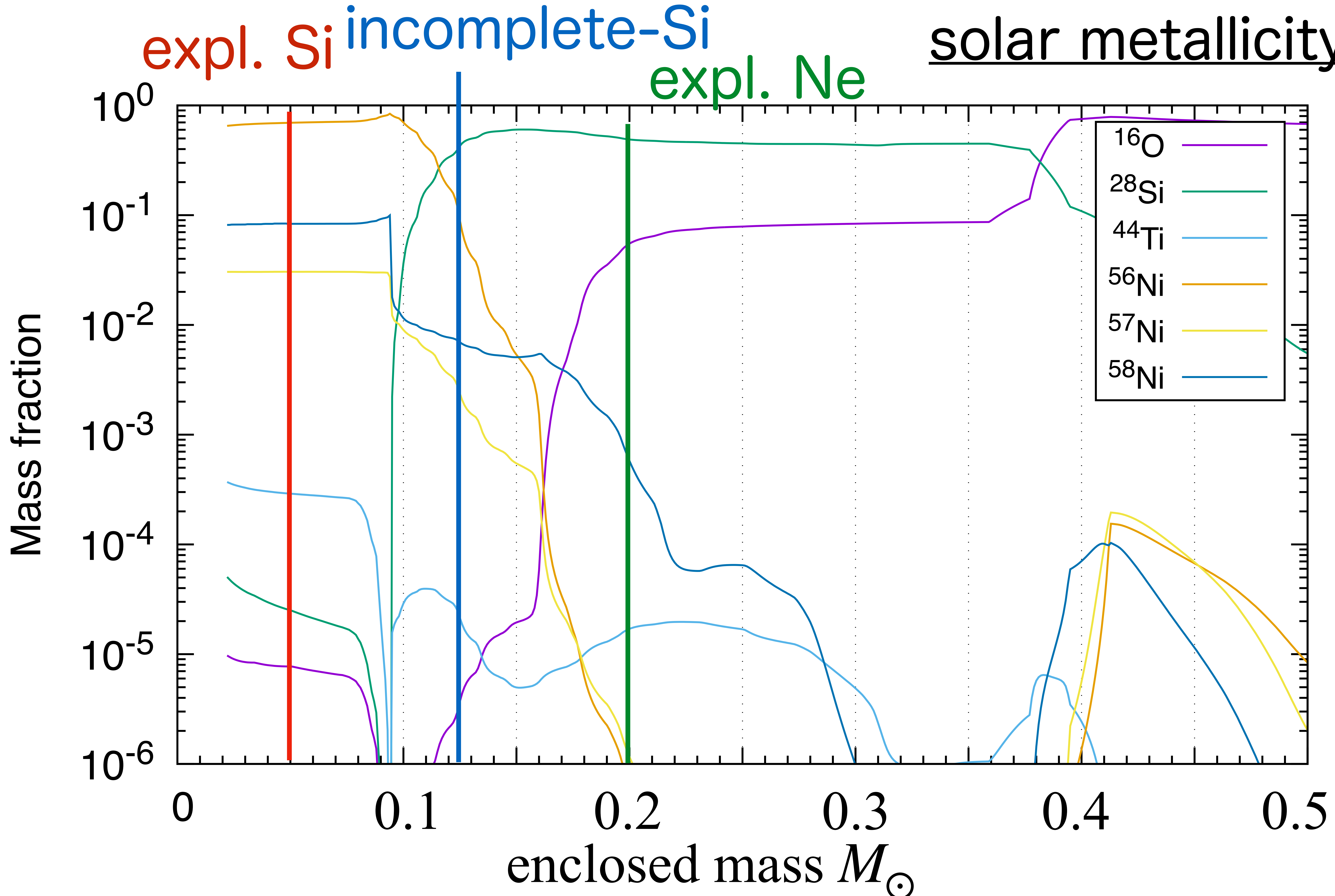
$16\ M_\odot$

solar metallicity





MC nucleosynthesis: a PUSH model



- expl. Si
- i-Si
- expl. Ne

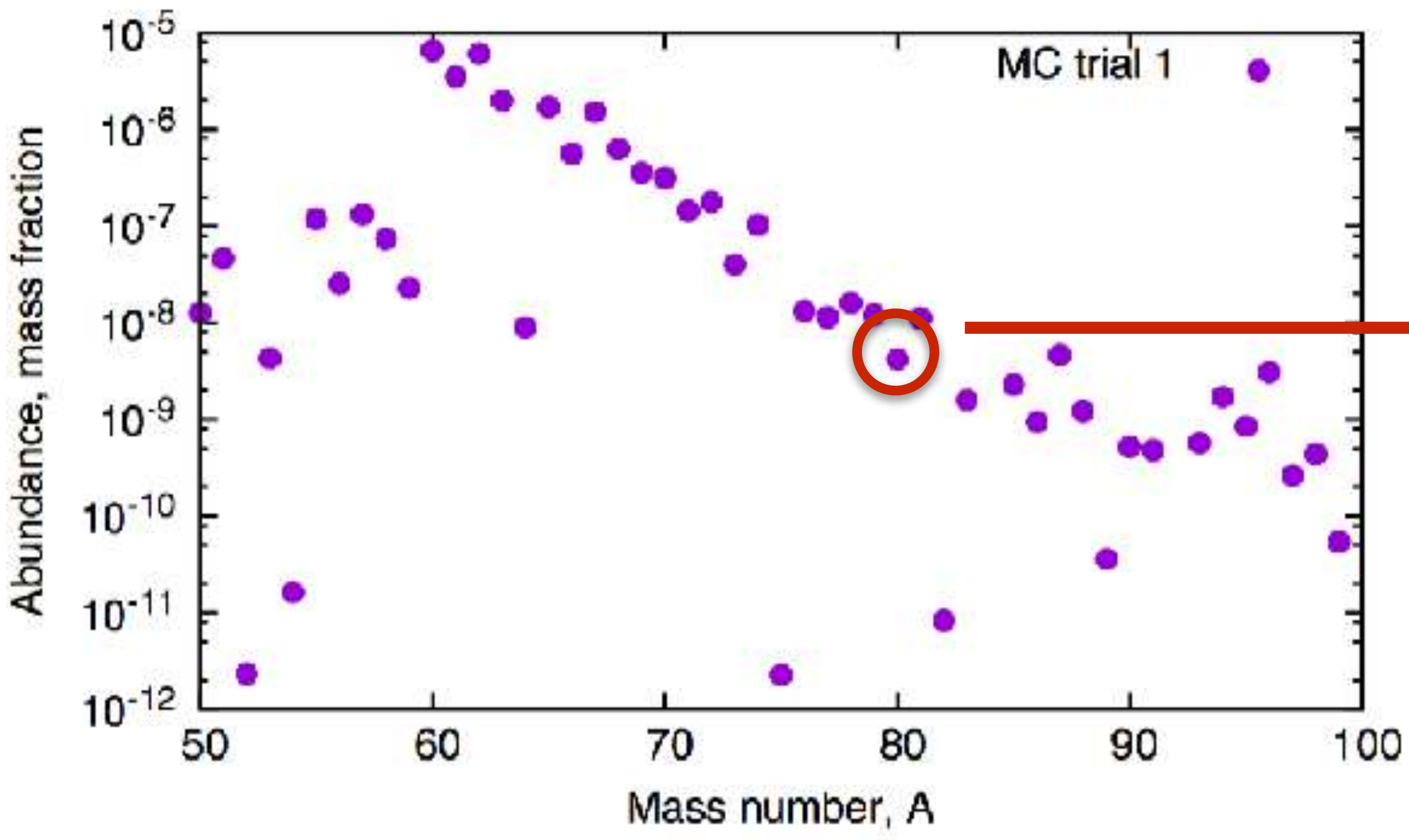
MC-variation reaction network code

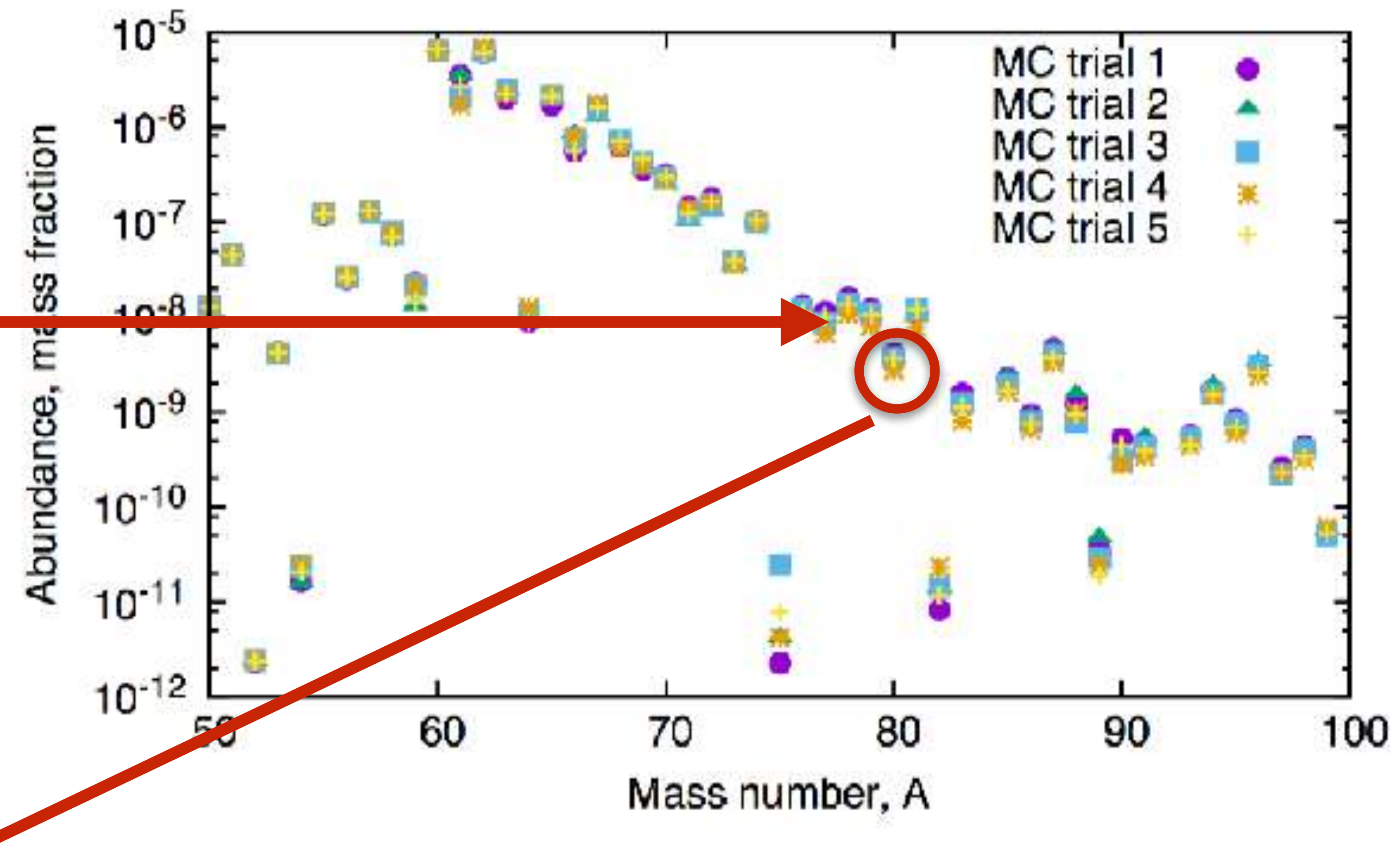
Piz Buin (mountain)

- Monte-Carlo framework
  - PizBuin MC-driver (developed by Rauscher, NN)
  - **parallelized by OpenMP** (shared memory)
- Nuclear Reaction network
  - Network solver:
    - WinNet: the latest Basel network, (Winteler+, 2012)
  - Reaction rates:
    - Reaclib: (Rauscher & Thielemann 2000)
    - T-dependent beta-decay (Takahashi & Yokoi 1987, Goriely 1999)
  - T-dependent uncertainty:
    - Provided by Reaclib format, based on Rauscher 2012

Monte-Carlo nucleosynthesis

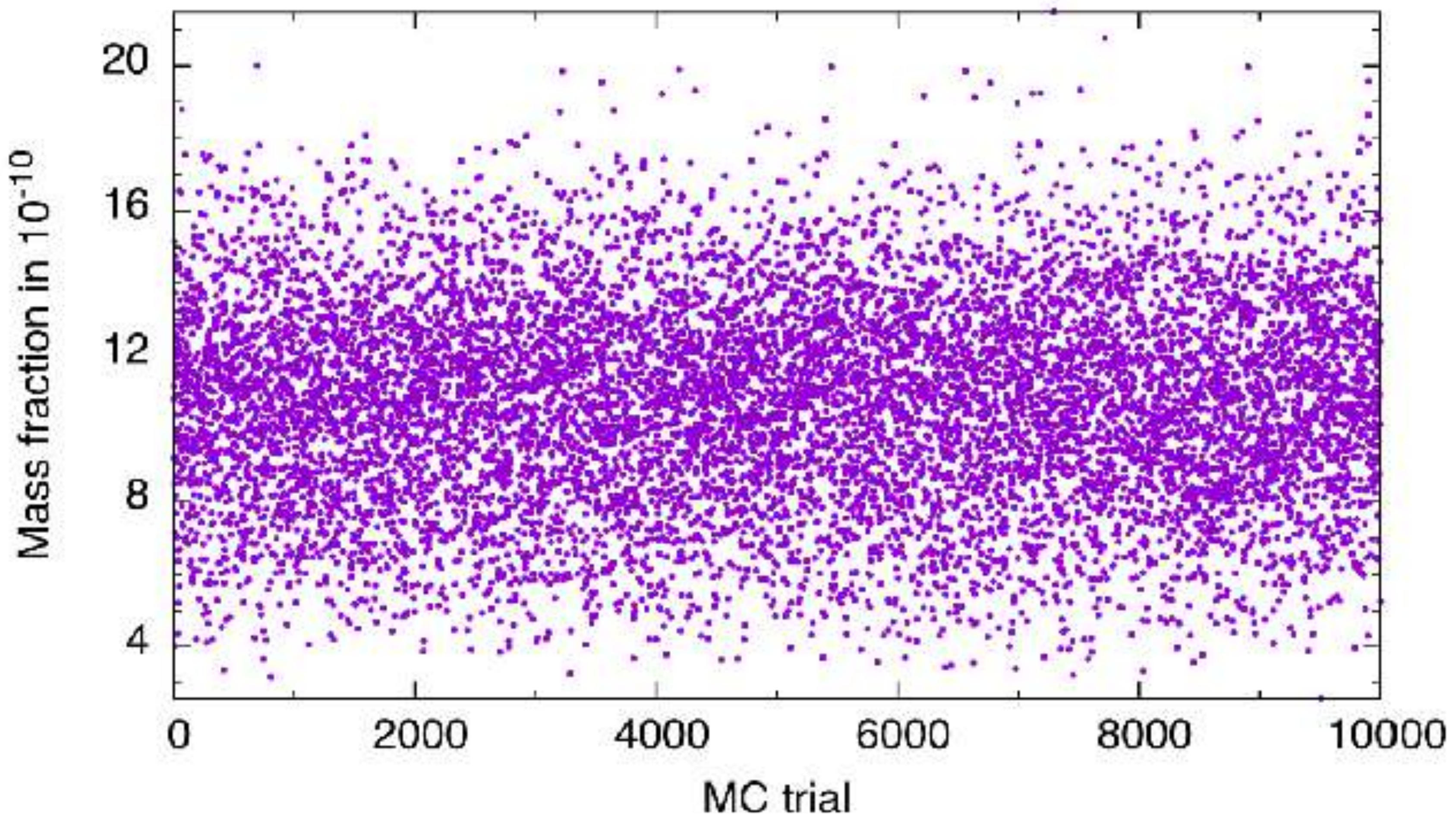
example: weak s-process

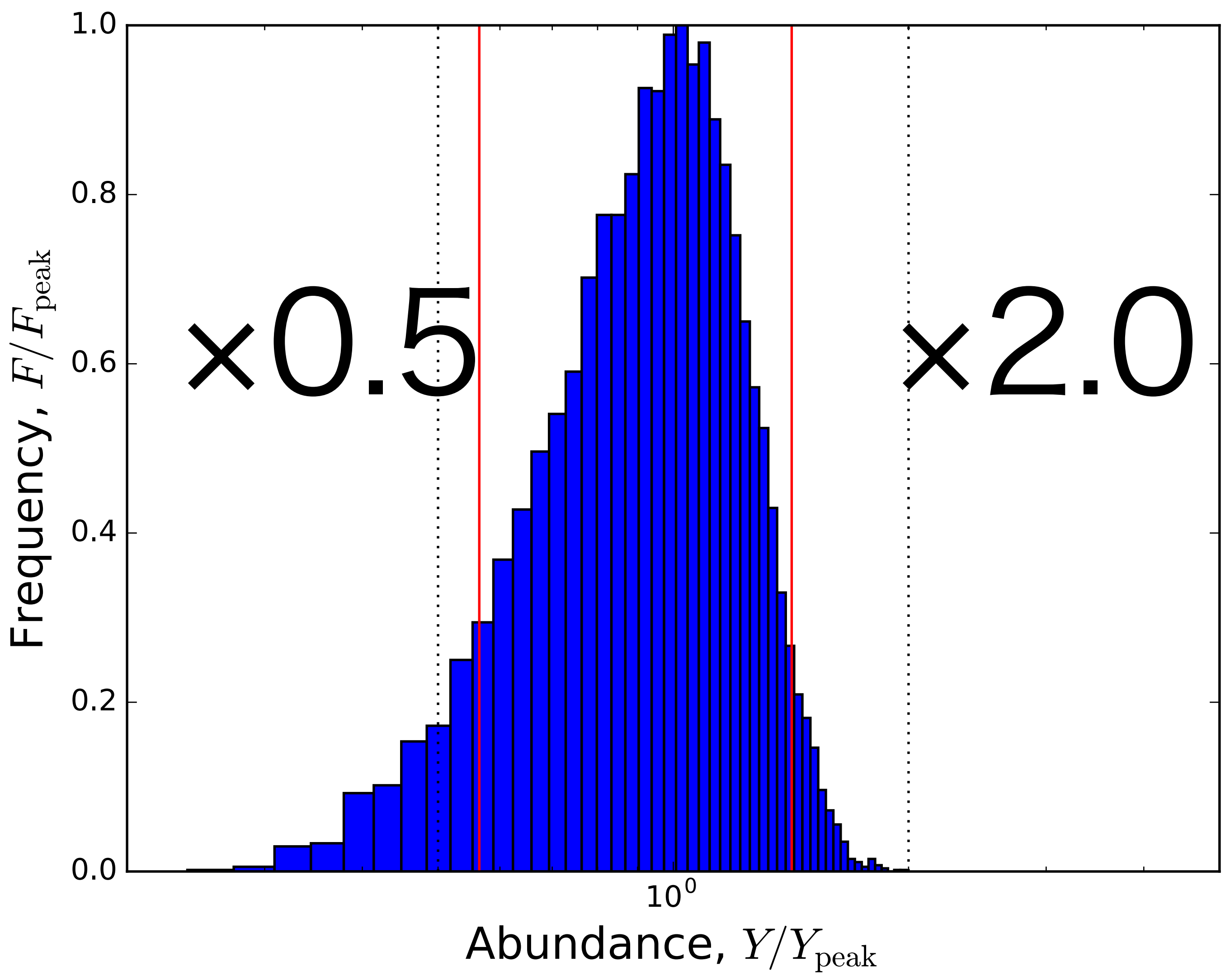




- 10,000 times iteration
- random variation (no correlation)
- uncertainty range

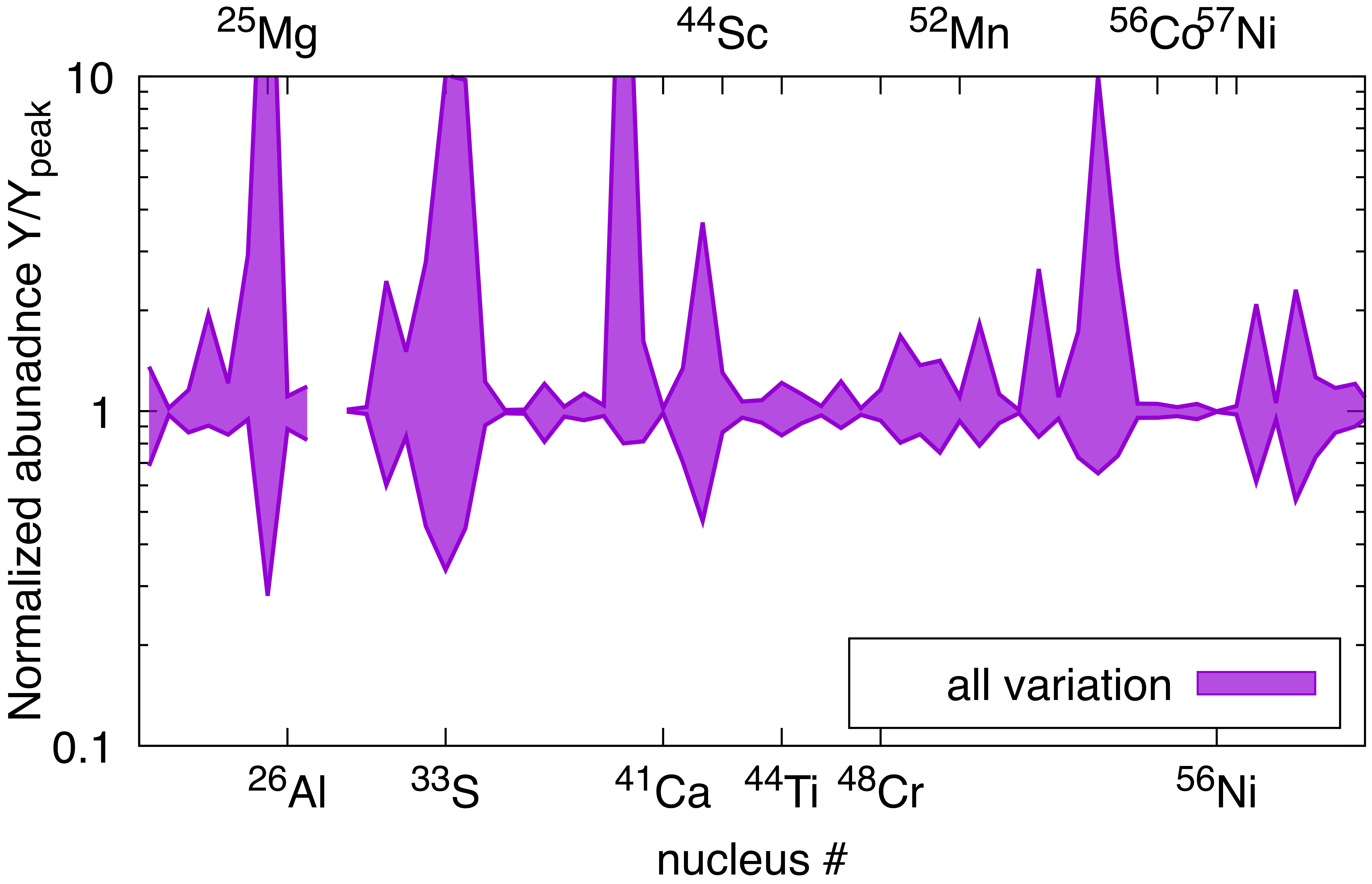
^{80}Se





Reaction	upper	lower
(n,γ)	2.0	2.0
(p,γ)	2.0	3.0
(p,n)	2.0	3.0
(α,γ)	2.0	10.0
(α,n)	2.0	10.0
(α,p)	2.0	10.0

Abundance uncertainty



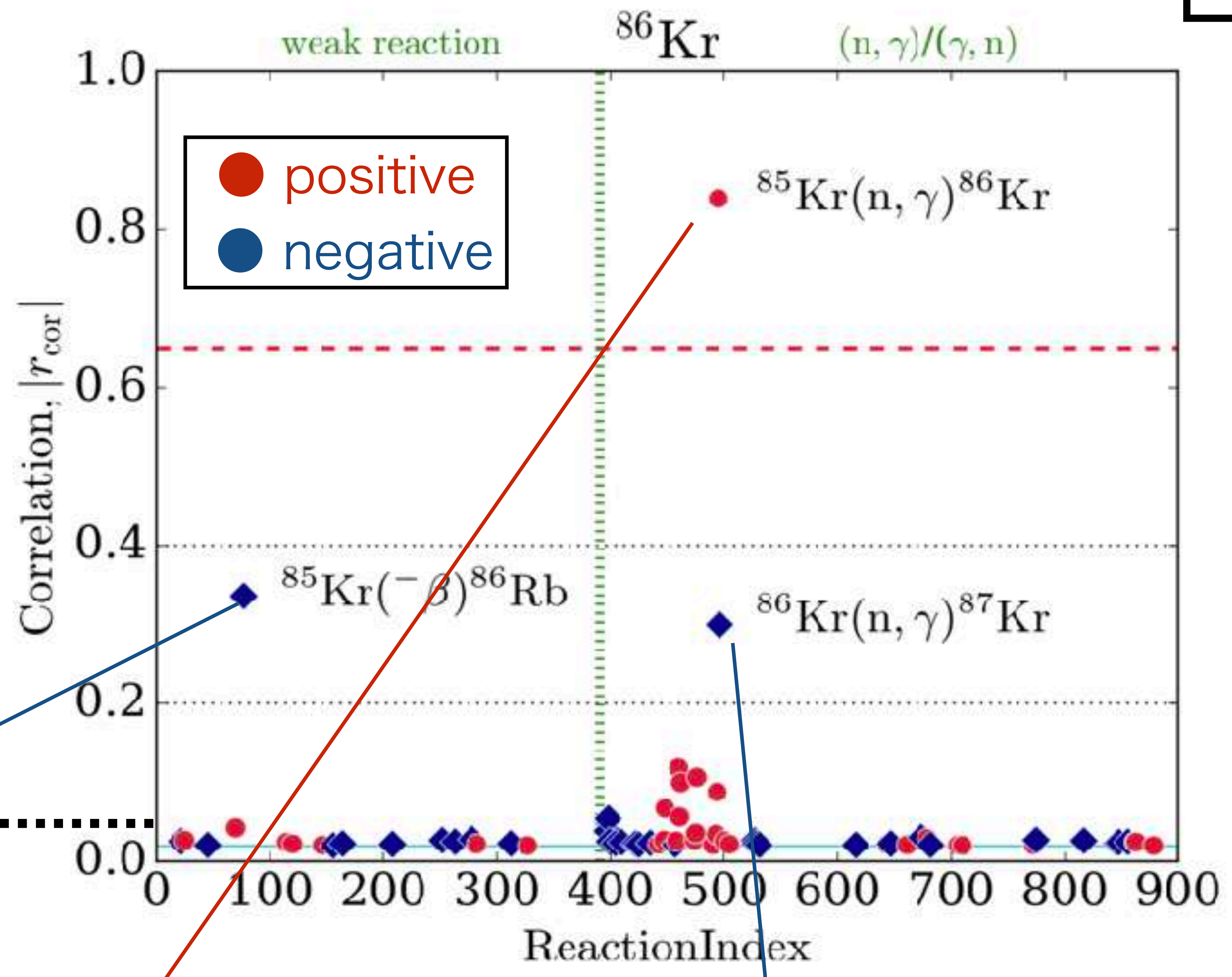
Selection by statistical analysis

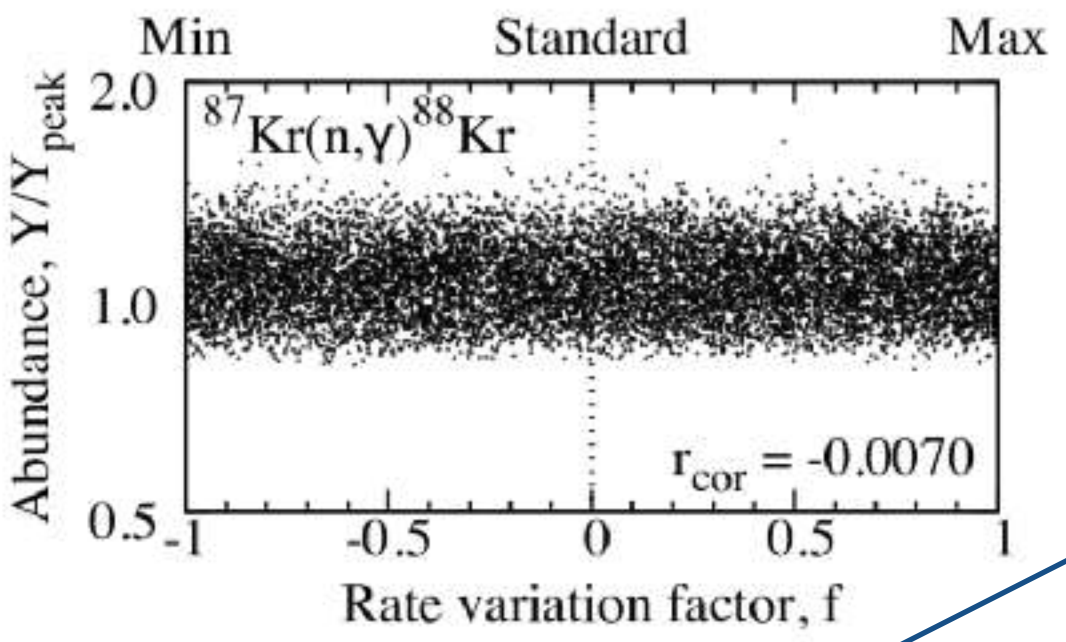
s-process

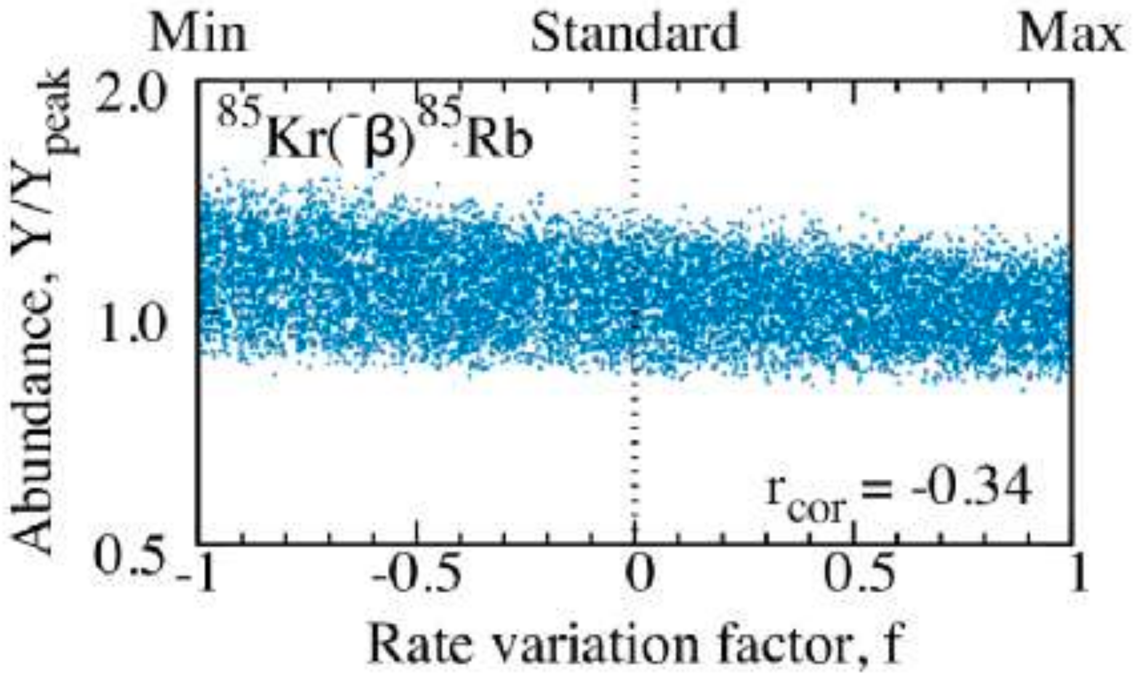
Pearson's coefficient

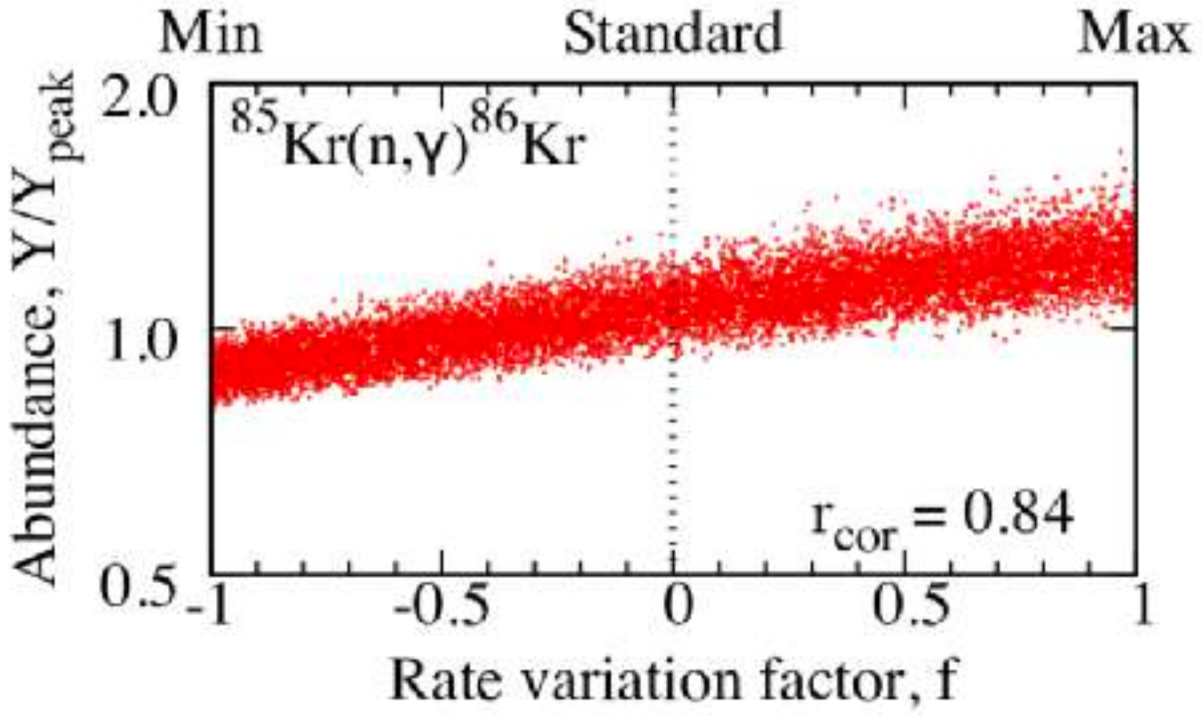
$$r_{\text{Pearson}} = \frac{\sum_{i=1}^{k} (\tilde{x}_i - \overline{x})(\tilde{y}_i - \overline{y})}{\sqrt{\sum_{i=1}^{k} (\tilde{x}_i - \overline{x})^2} \sqrt{\sum_{i=1}^{k} (\tilde{y}_i - \overline{y})^2}}$$

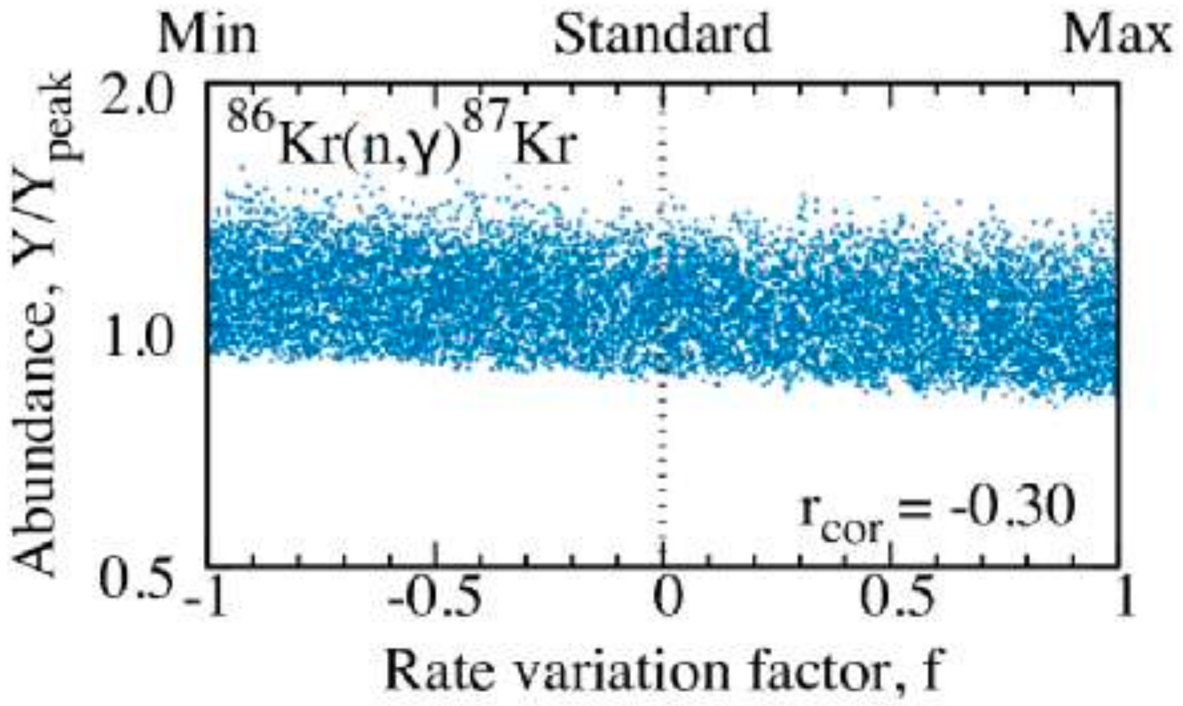
$|r| > 0.65 \rightarrow$ "strong"









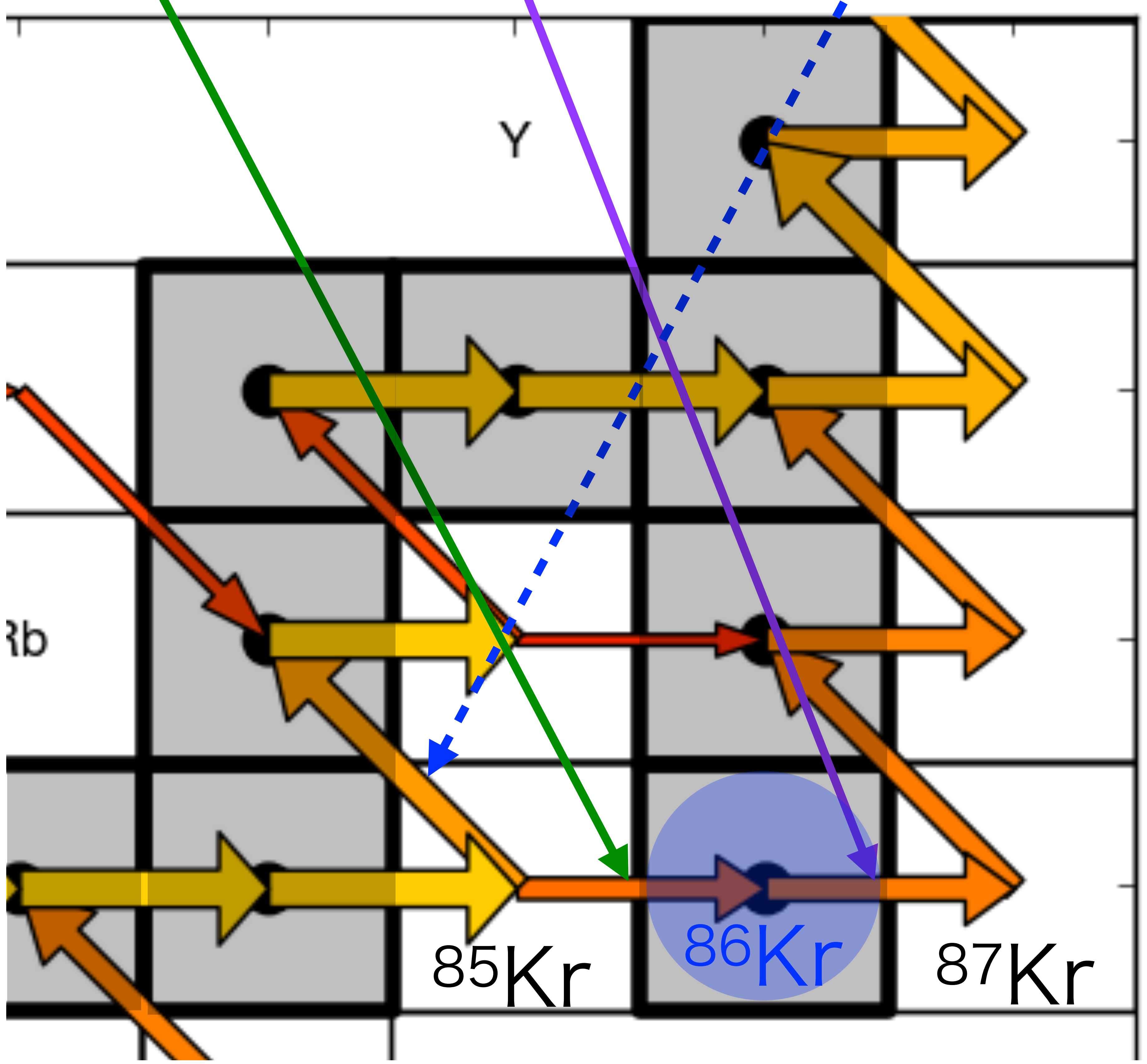


Selection by statistical analysis

NN+(2017)

$r_{cor,0}$	$r_{cor,1}$	$r_{cor,2}$	Key reaction Level 1	Key reaction Level 2	Key reaction level 3
0.84			^{85}Kr(n,γ)^{86}Kr		
-0.31	-0.71			^{86}Kr(n,γ)^{87}Kr	
-0.33	-0.62	-0.90			^{85}Kr(+β)^{85}Rb

key reactions for ^{86}Kr



s-process

- less uncertainty
  - nuclear reactions: (n,g) & weak
  - stellar environments

vs ^{85}Kr(n,g)^{86}Kr

	^{86}Kr(n,g)	^{85}Kr(b+)
upper	-0.42	**-0.68**
standard	**-0.71**	-0.62
lower	**-0.84**	-0.42

Key reactions

7 decays/reaction rates

product | correlation | key reaction

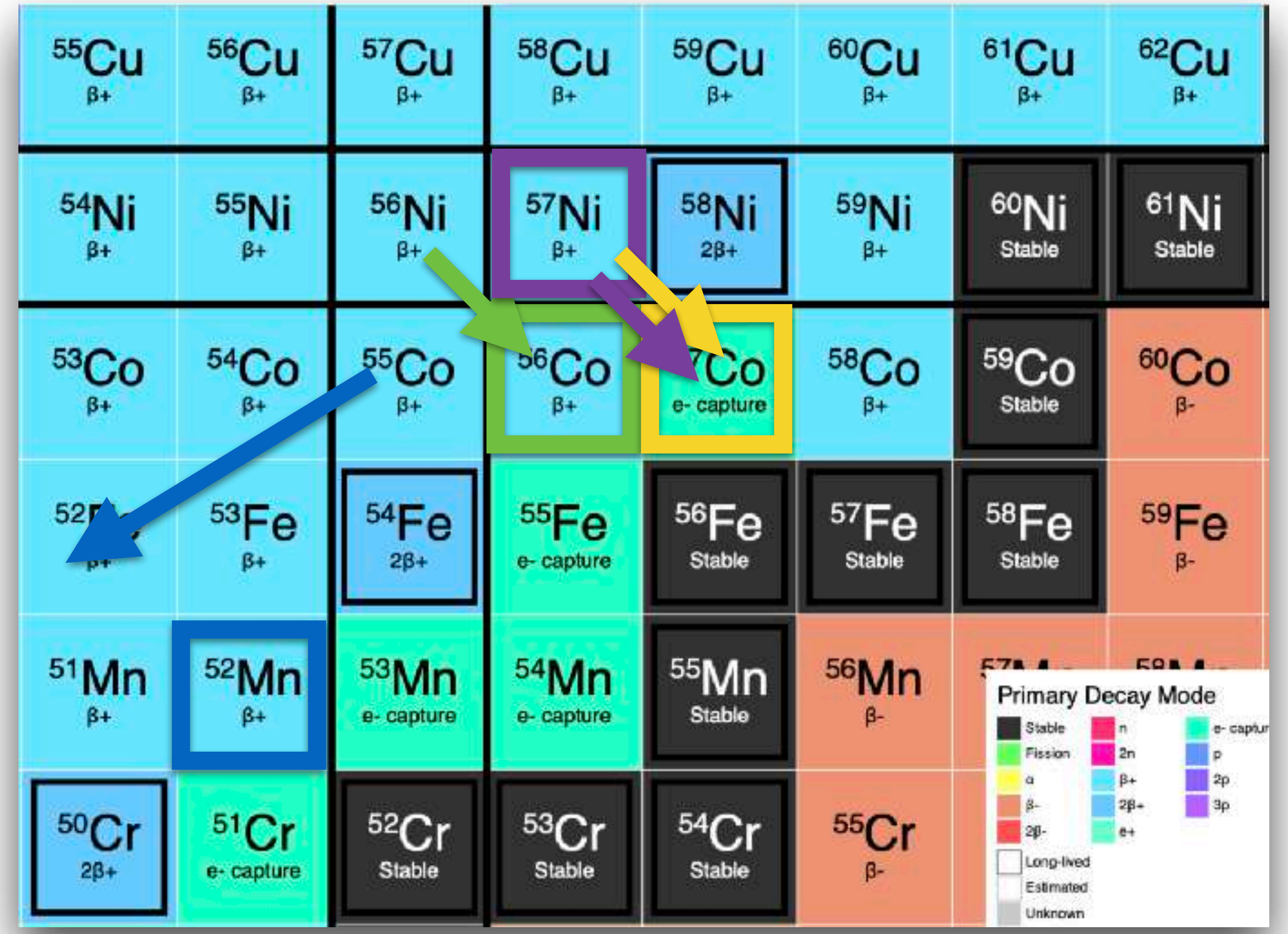
nuclide		r_{cor}	reaction
^{44}Sc	Radioactive	-0.77	^{44}Sc$(+\beta)^{44}$Ca
^{56}Co	Radioactive	1.00	^{56}Ni$(+\beta)^{56}$Co
^{57}Co	Radioactive	0.92	^{57}Ni$(+\beta)^{57}$Co
^{41}Ca	Radioactive	-0.67	^{38}Ar$(\alpha, n)^{41}$Ca
^{48}Cr	Radioactive	-0.82	^{48}Cr$(\alpha, p)^{51}$Mn
^{52}Mn	Radioactive	-0.69	^{52}Fe$(\alpha, p)^{55}$Co
^{57}Ni	Radioactive	-0.79	^{57}Co$(p, n)^{57}$Ni

^{57}Ni: half-life 36 h ^{57}Ni(n,p)^{57}Co

→ affects on SN lightcurve?

note: the compound nucleus of this reaction ^{58}Ni is stable

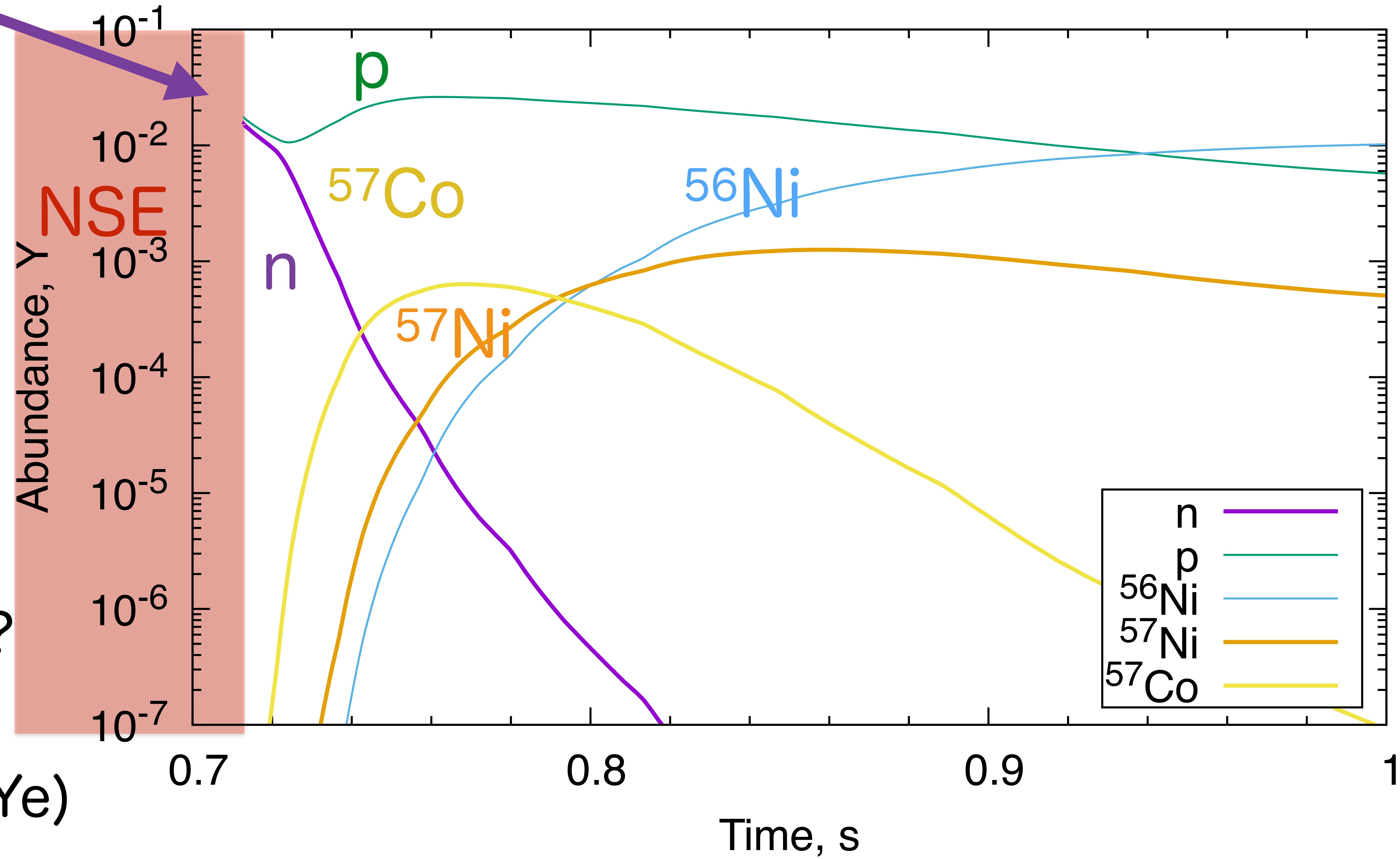
key reactions (selected) on the N-Z plane



Time evolution of ^{57}Co, ^{57}Ni

n: neutron in ^{57}Ni(n,p)^{57}Co is caused by the initial (NSE) free neutron

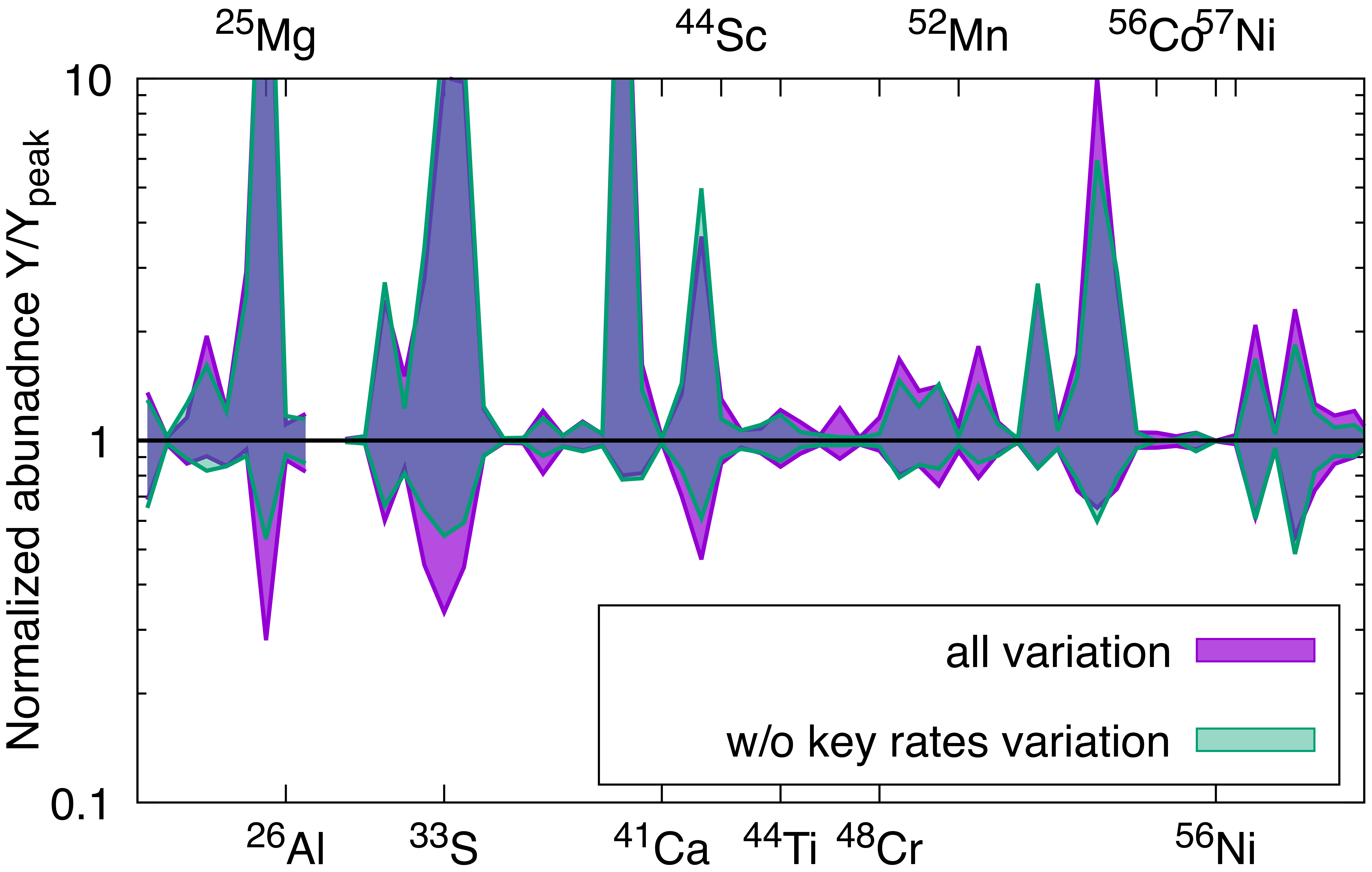
abundance evolution (innermost zone)



impacts of ν reaction?

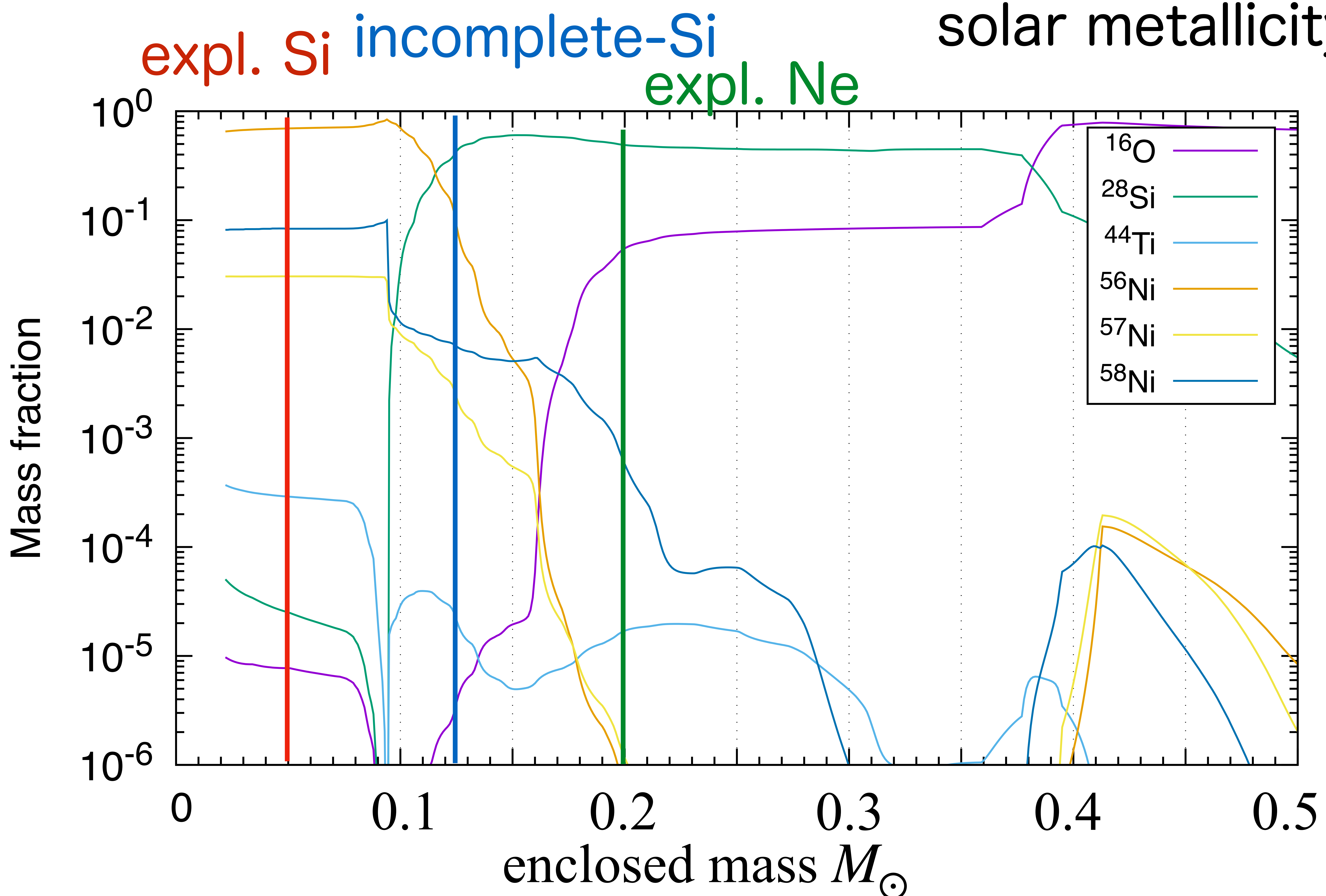
→ may be minor (changes a few % in Ye)

Abundance uncertainty: impacts of key rates



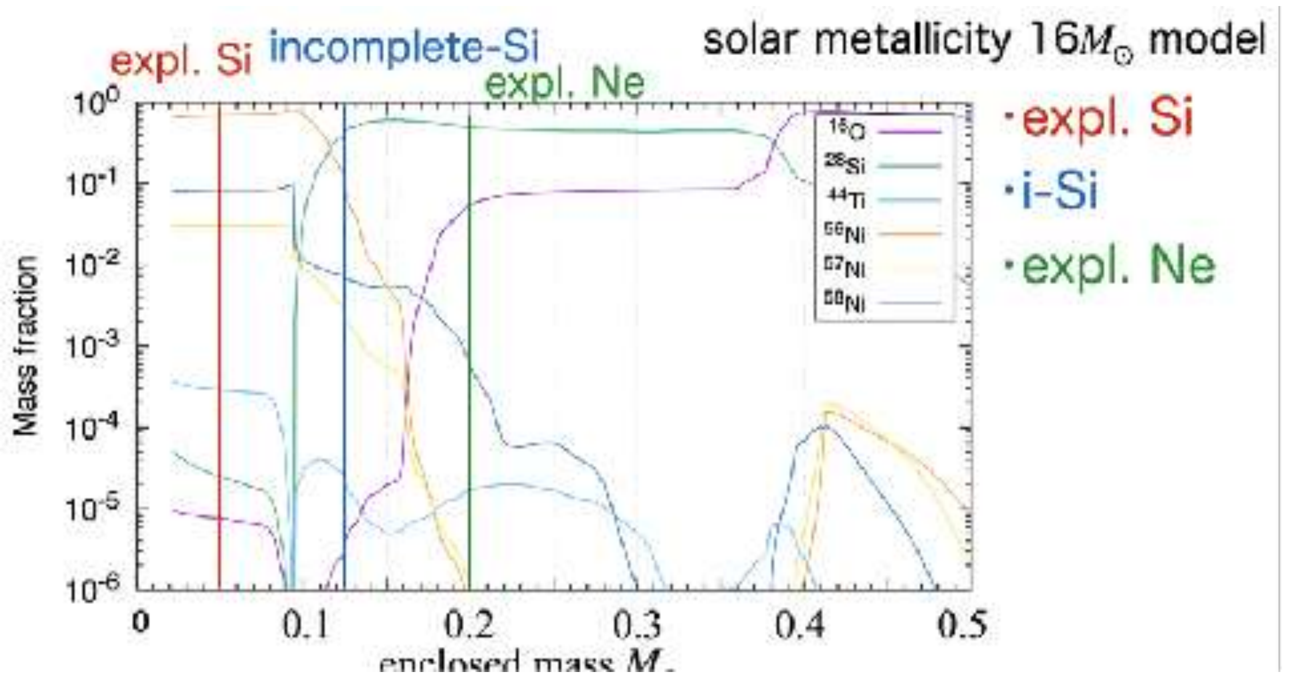
Analysis on different stellar layers

solar metallicity $16M_\odot$ model



- expl. Si
- i-Si
- expl. Ne

Key reactions: ^{44}Ti different layers



Pearson's coefficient

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● positive
◆ negative

- lower $|r_{\mathrm{cor}}|$ (lower priority) for multi-layers (the entire star)
- ^{44}Ti production explosion models (e.g., Magkotsios et al. 2010, Wang & Burrows 2024)

Summary

・ccSN explosive nucleosynthesis

・origin of iron peak and radioactive nuclei

→ astronomical observation: optical transients and chemical origin

・explosive nucleosynthesis: complex "network" of reactions

・Key reactions ?

・mostly in NSE, no significant key reaction for ^{56}Ni (only decay works); few key reactions for including ^{57}Ni → ^{57}Ni(n, p)^{57}Co

・Focusing on different layers (Si-burn/i-Si-burn/Ne-burning) additional key reactions are identified (but, not our recommenanded "key reaction")

・e.g., for ^{44}Ti → ^{44}Ti(α, p)^{47}V, ^{40}Ca(α, γ)^{44}Ti