Nuclear Physics in Astrophysics XI @Dresden 15-20 Sep. 2024

The impacts of nuclear reaction uncertainties on explosive nucleosynthesis in core-collapse supernovae

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Collaboration with

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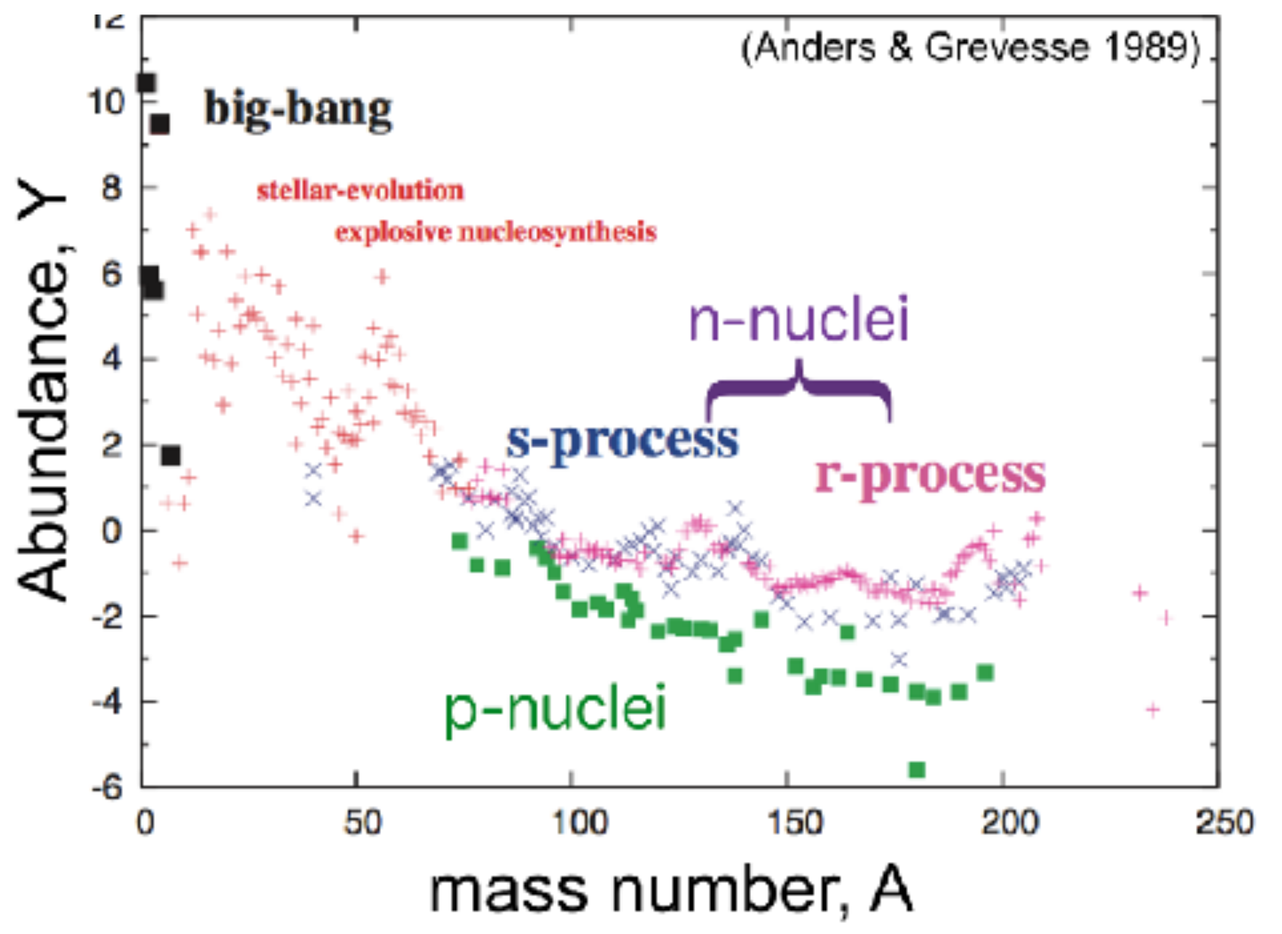
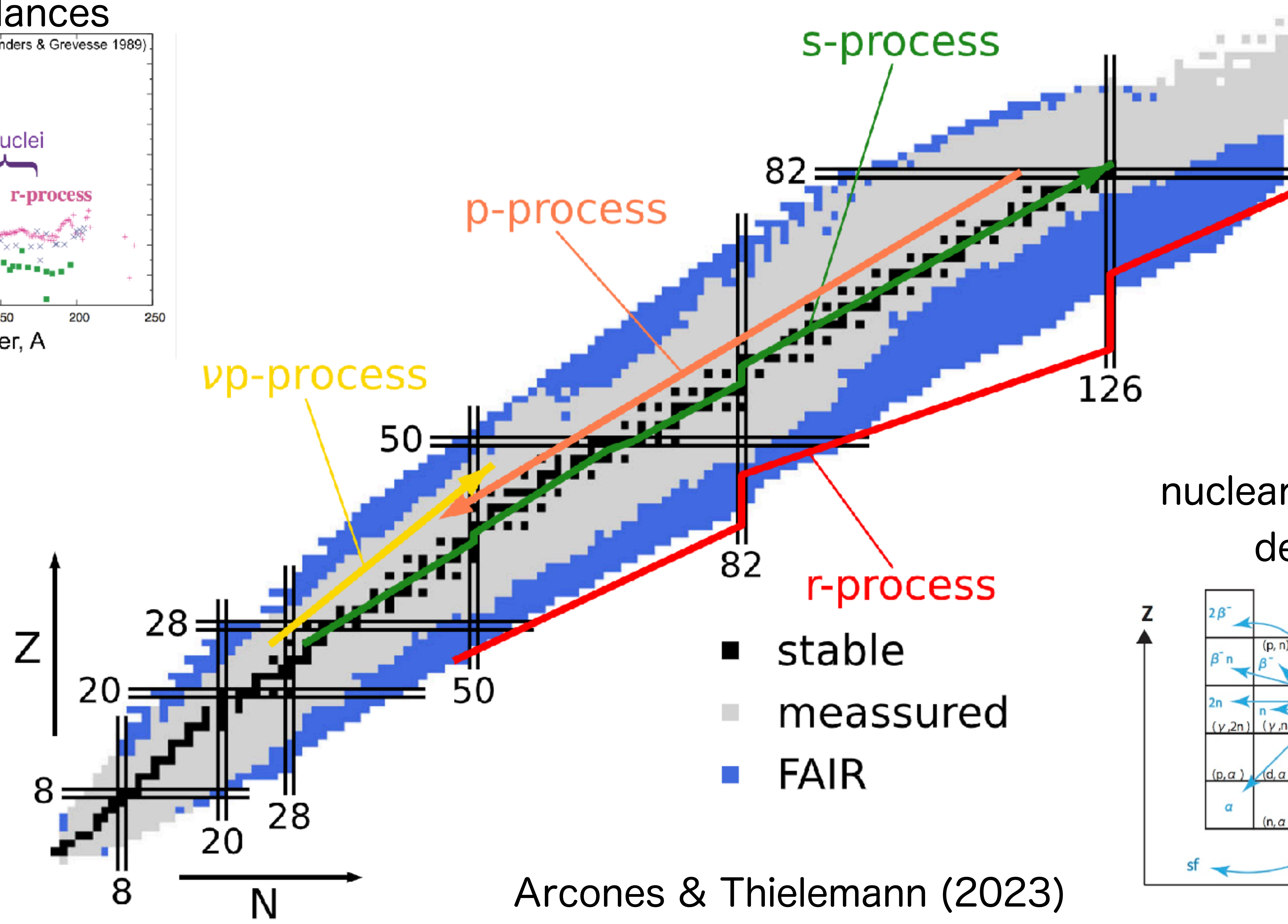
Heavy nucleus in the universe

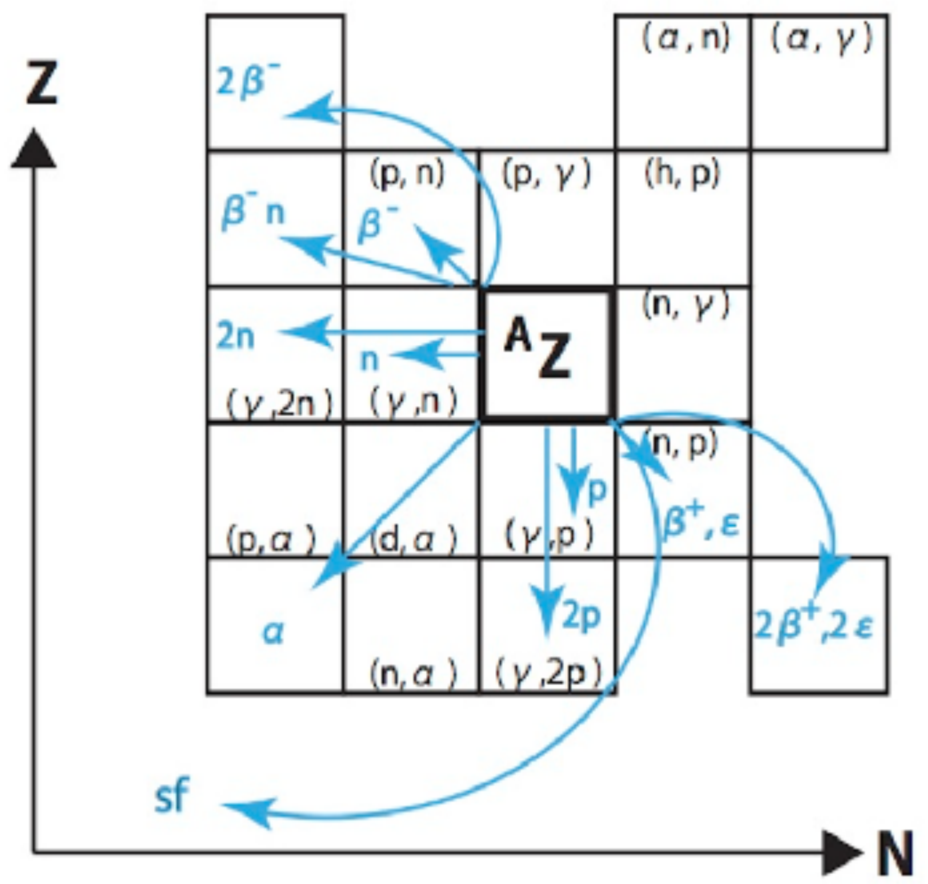
solar abundances





Arcones & Thielemann (2023)

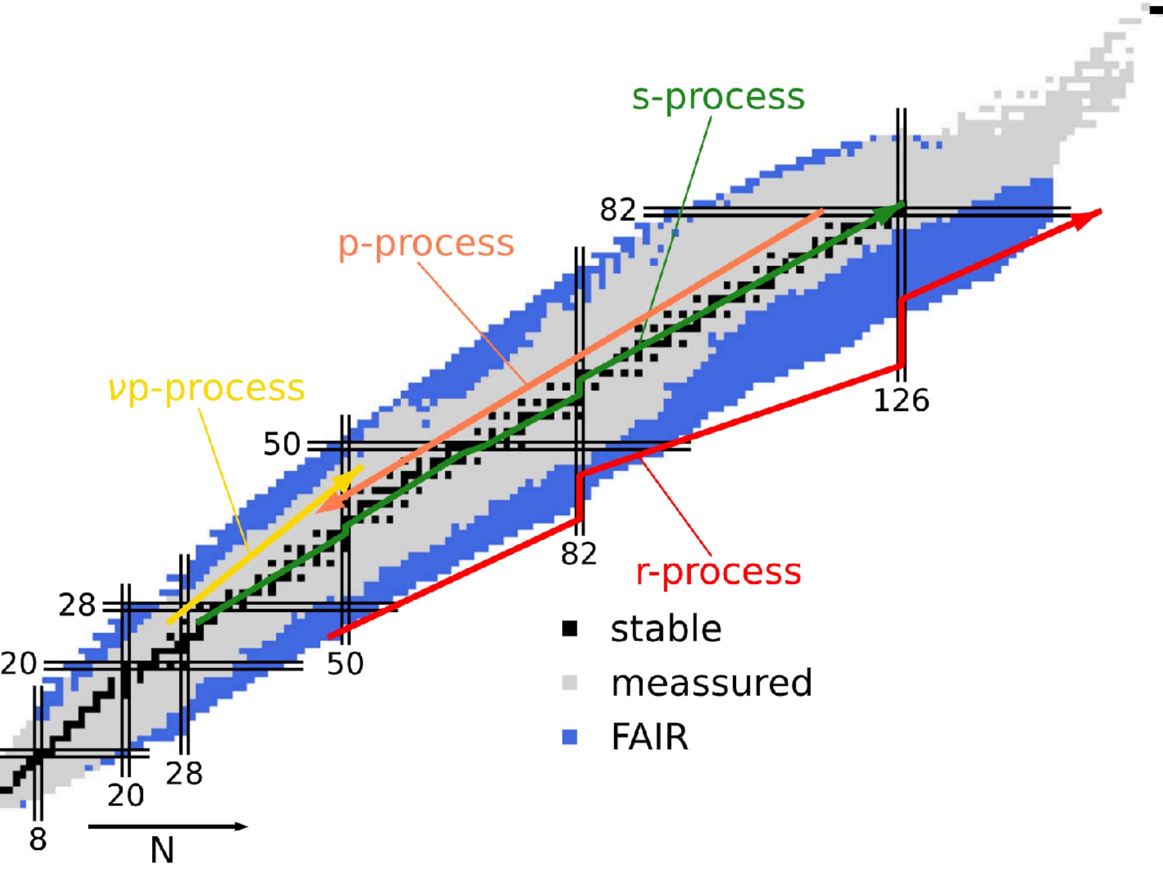
nuclear reactions
decays



Heavy nuclei in the universe

Arcones & Thielemann (2023)

Key reactions in nucleosynthesis



"sensitivity" study on nucleosynthesis?

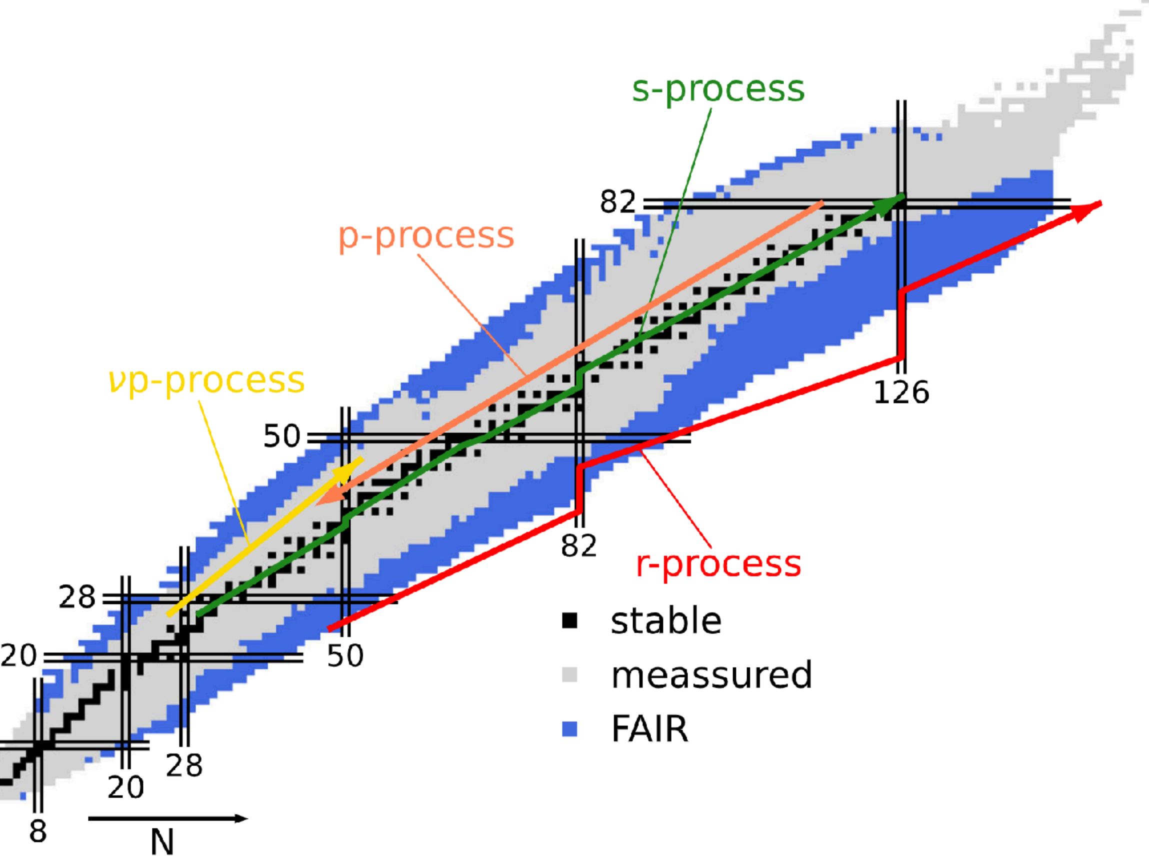
our approach

reaction/decay uncertainty

Monte-Carlo + statistical analysis

observation

Key reactions in nucleosynthesis



"sensitivity" study on nucleosynthesis?

our approach

reaction/decay uncertainty

↓ Monte-Carlo + statistical analysis ↑

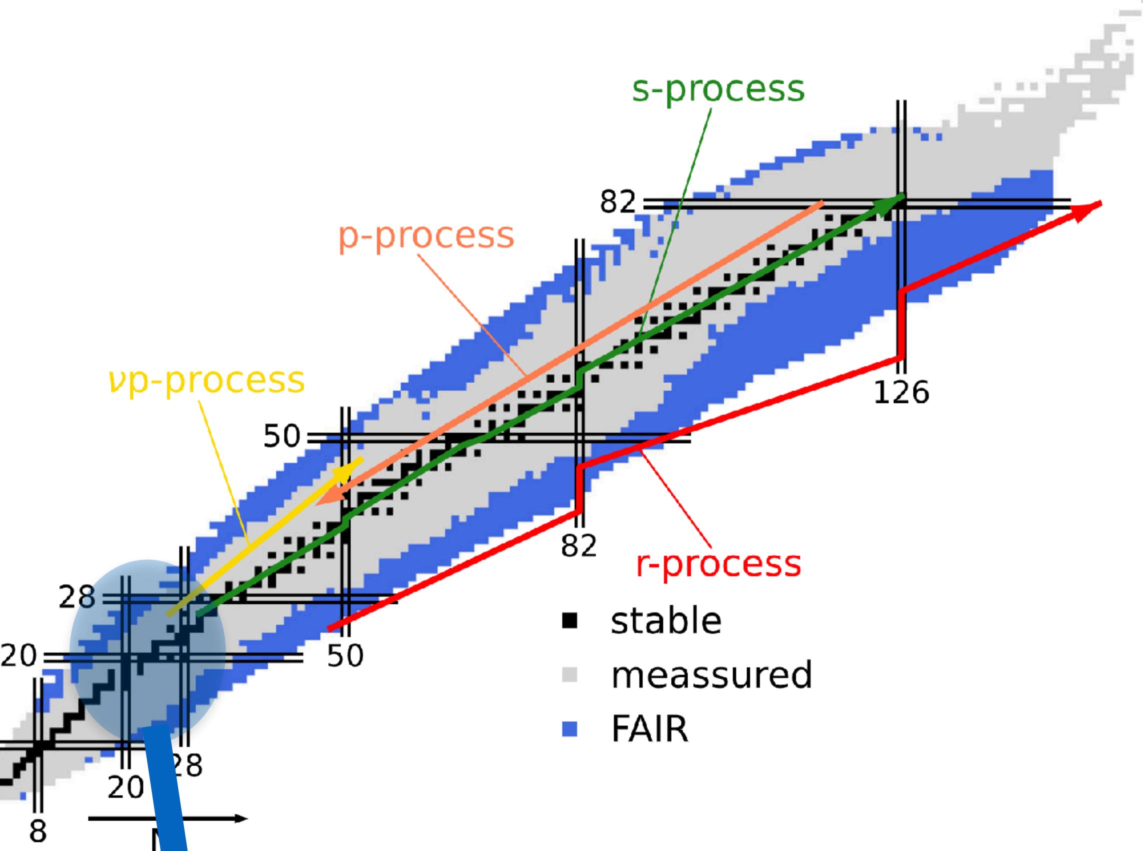
observation

- s-process : (2) weak s (→ n_TOF (CERN) experiments), (4) main s
- p-process : (1) CC-SNe, (2)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

Key reactions in nucleosynthesis



"sensitivity" study

or nucleosynthesis?

our approach

reaction/decay uncertainty

Monte-Carlo + statistical analysis

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

Contents

1. Introduction

・nucleosynthesis processes on the chart of nuclei

・reaction networks in nucleosynthesis

2. Explosive nucleosynthesis in supernovae

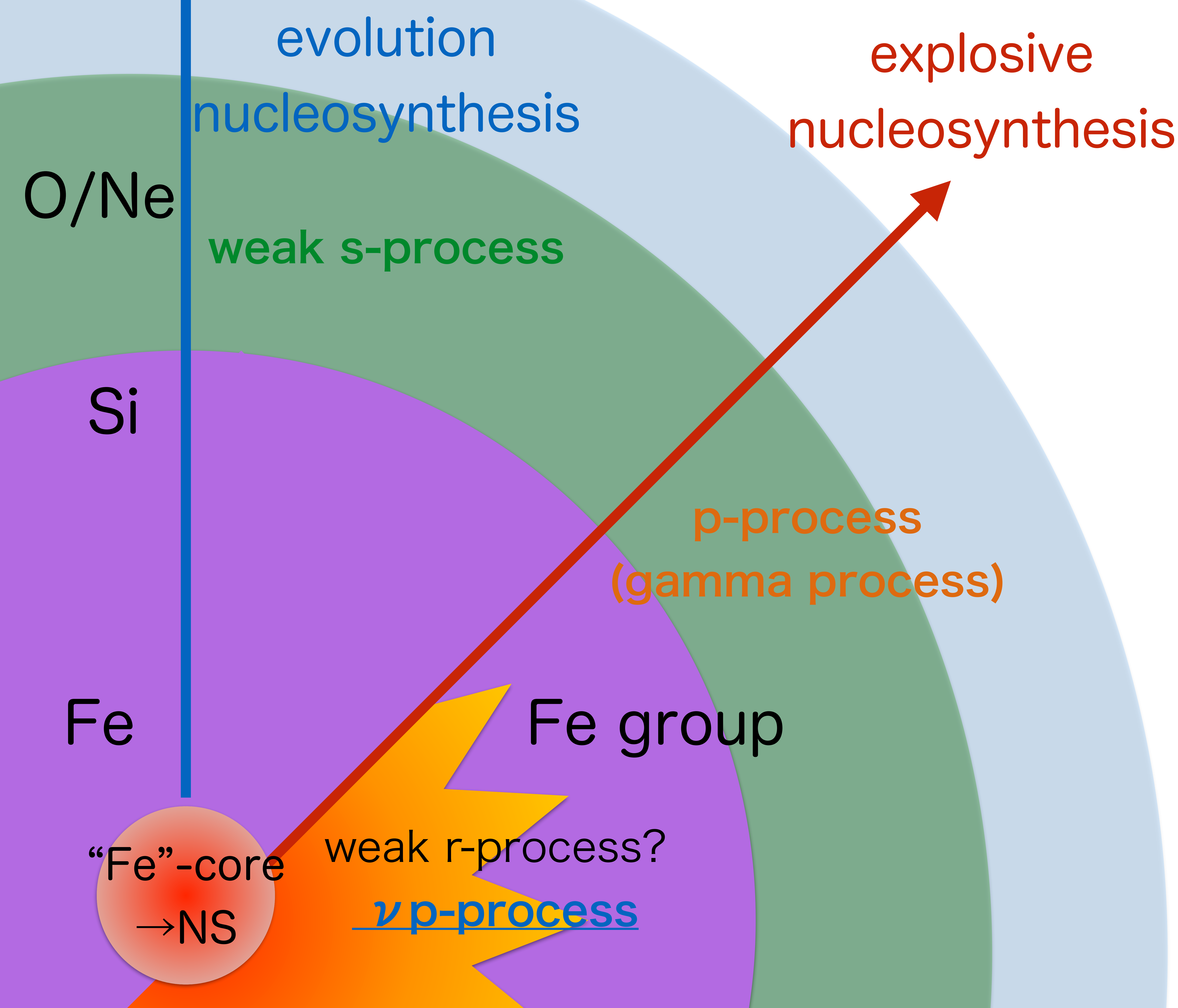
・overview: nucleosynthesis in core-collapse supernovae

・method: SN models and nucleosynthesis

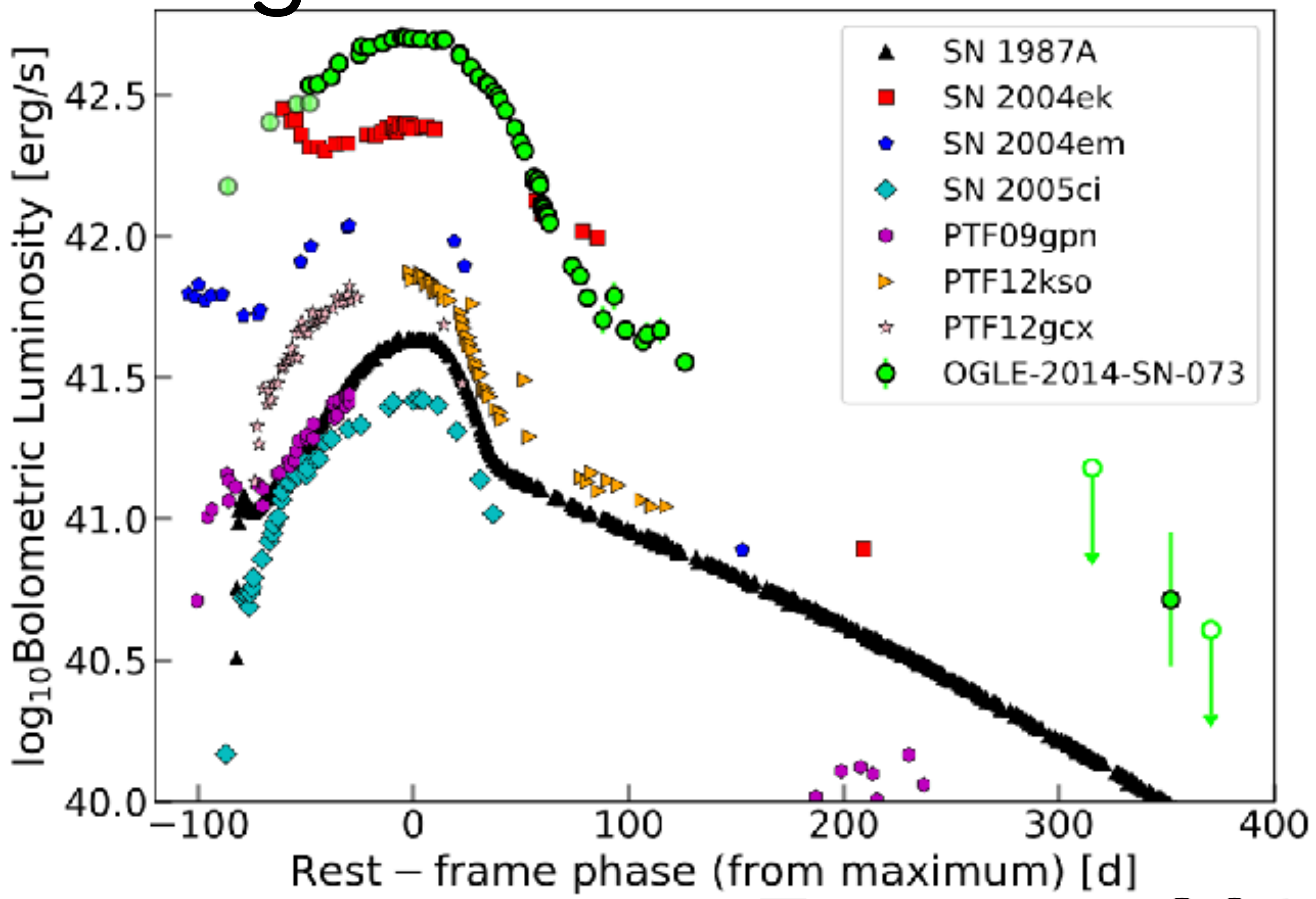
・key reactions found by MC and statistical analysis

3. Summary

(core-collapse) SN explosive nucleosynthesis

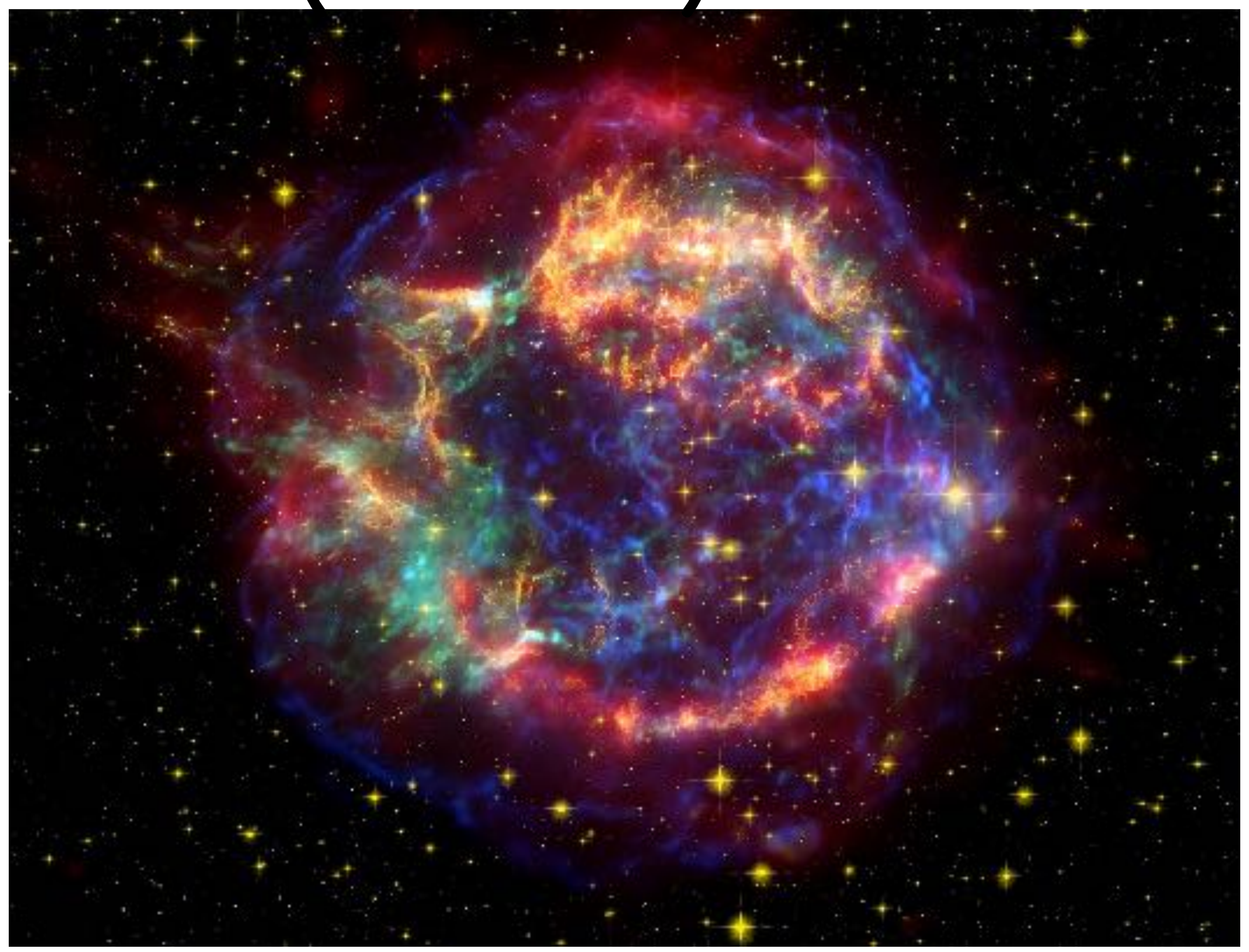


light curves cc-SNe

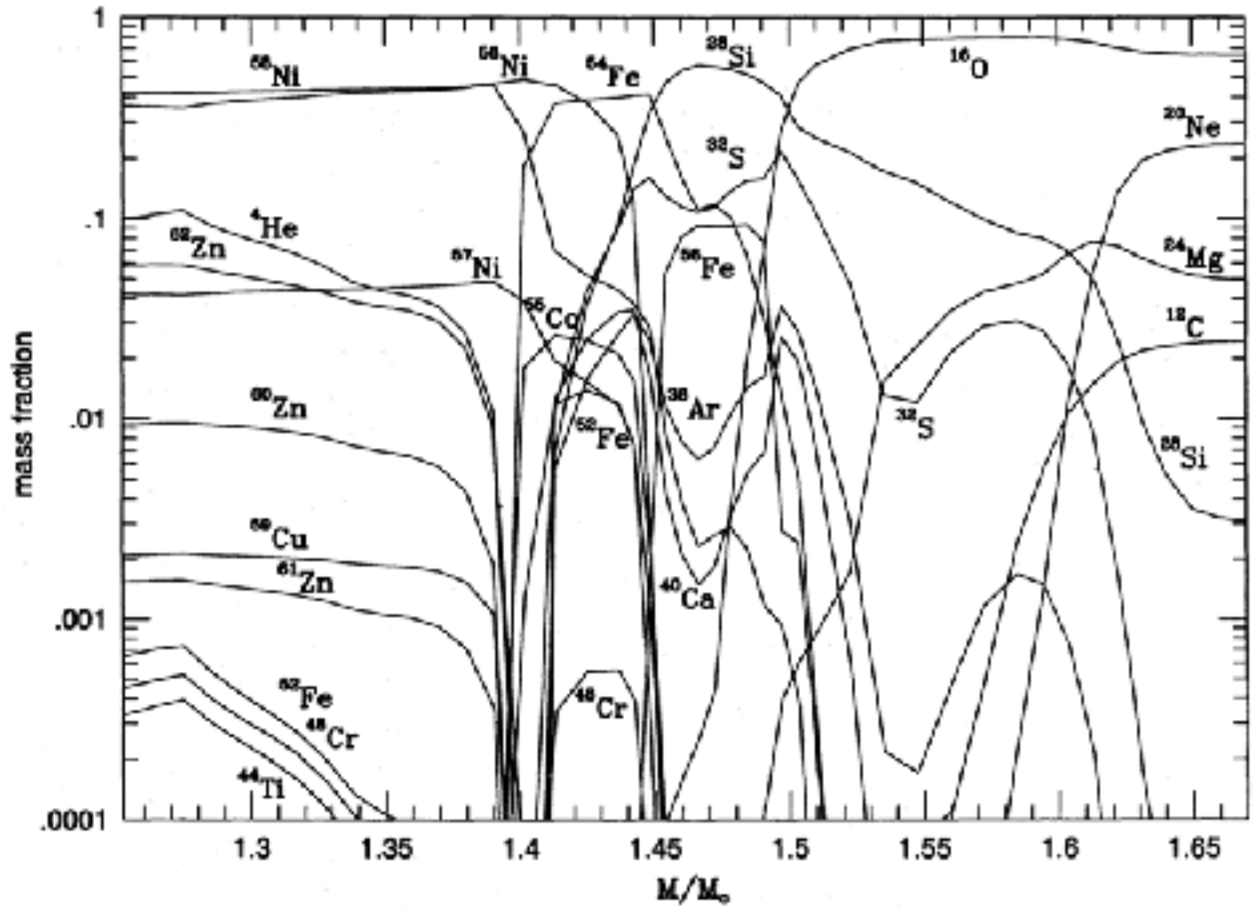


Terreran+2017

SNR (Cas A)



"1D" explosion models of cc-SN



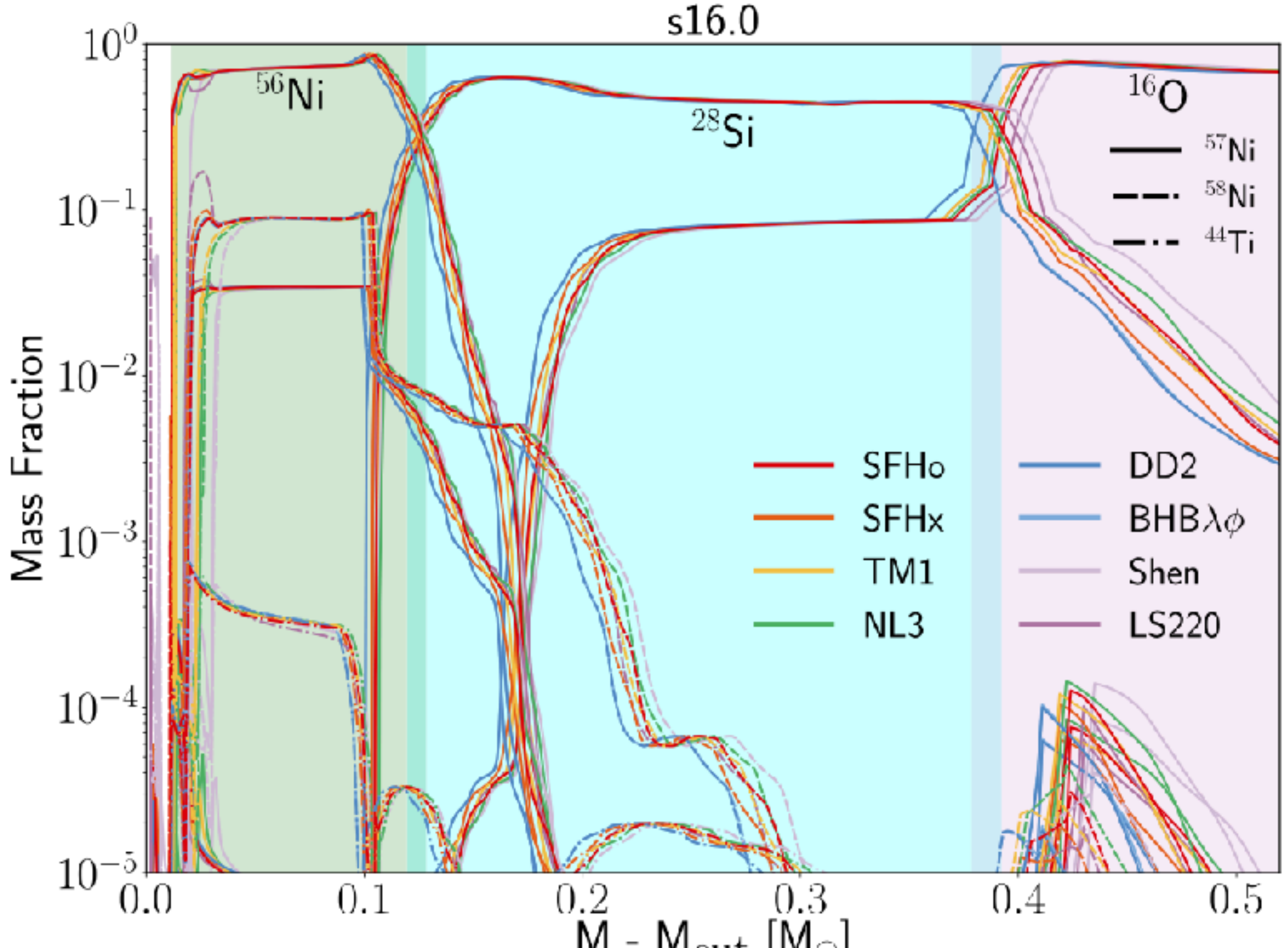
Thielemann+(1996)

- 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)

- $T_{9,p} > 5$: explosive Si & O burning (NSE)

  → ^{56}Ni, ^{57}Ni, ^{44}Ti, Fe peak
- $5 > T_{9,p} > 4$: incomplete Si & explosive O burning

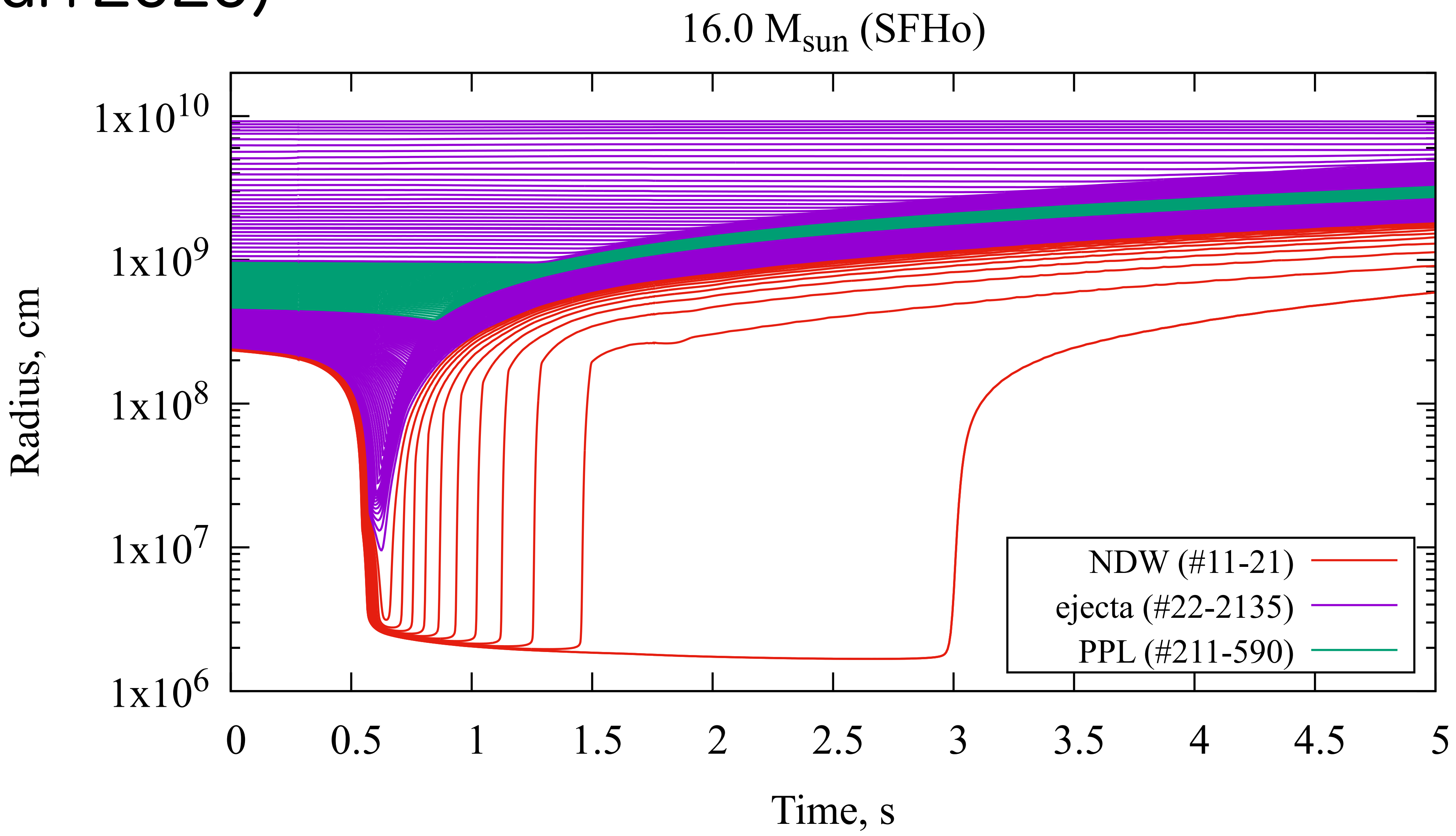
  → ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca (+ ^{56}Ni, ^{44}Ti)
- $4 > T_{9,p} > 3.3$: explosive Ne burning → ^{16}O, ^{28}Si, ^{32}S
- $3.3 > T_{9,p} > 2$: explosive C burning → ^{20}Ne, ^{24}Mg

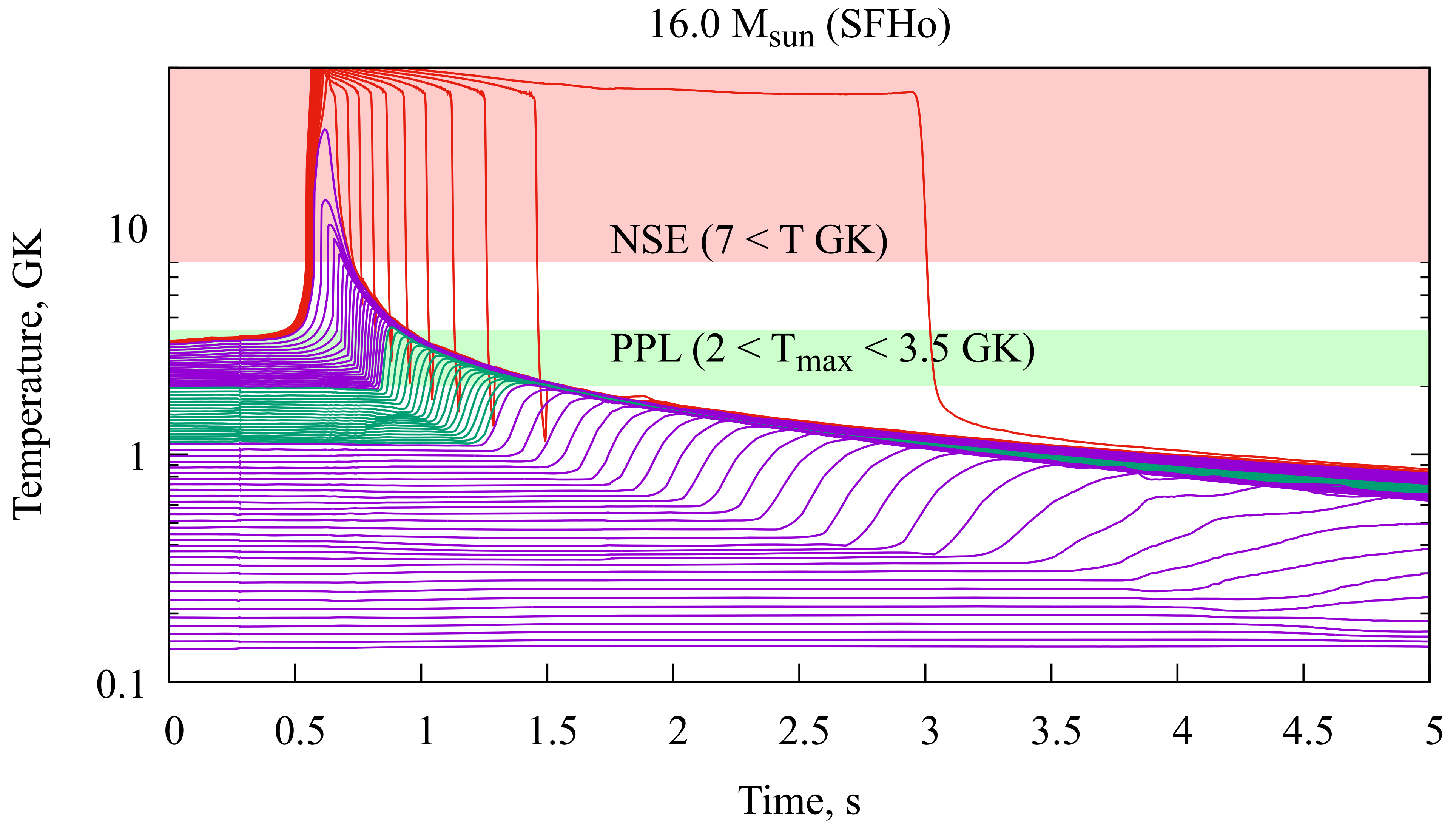
  \+ photodissociation of heavy seeds → p-process
- $2 > T_{9,p}$: no explosive burning

adopted model

$16\ M_\odot$

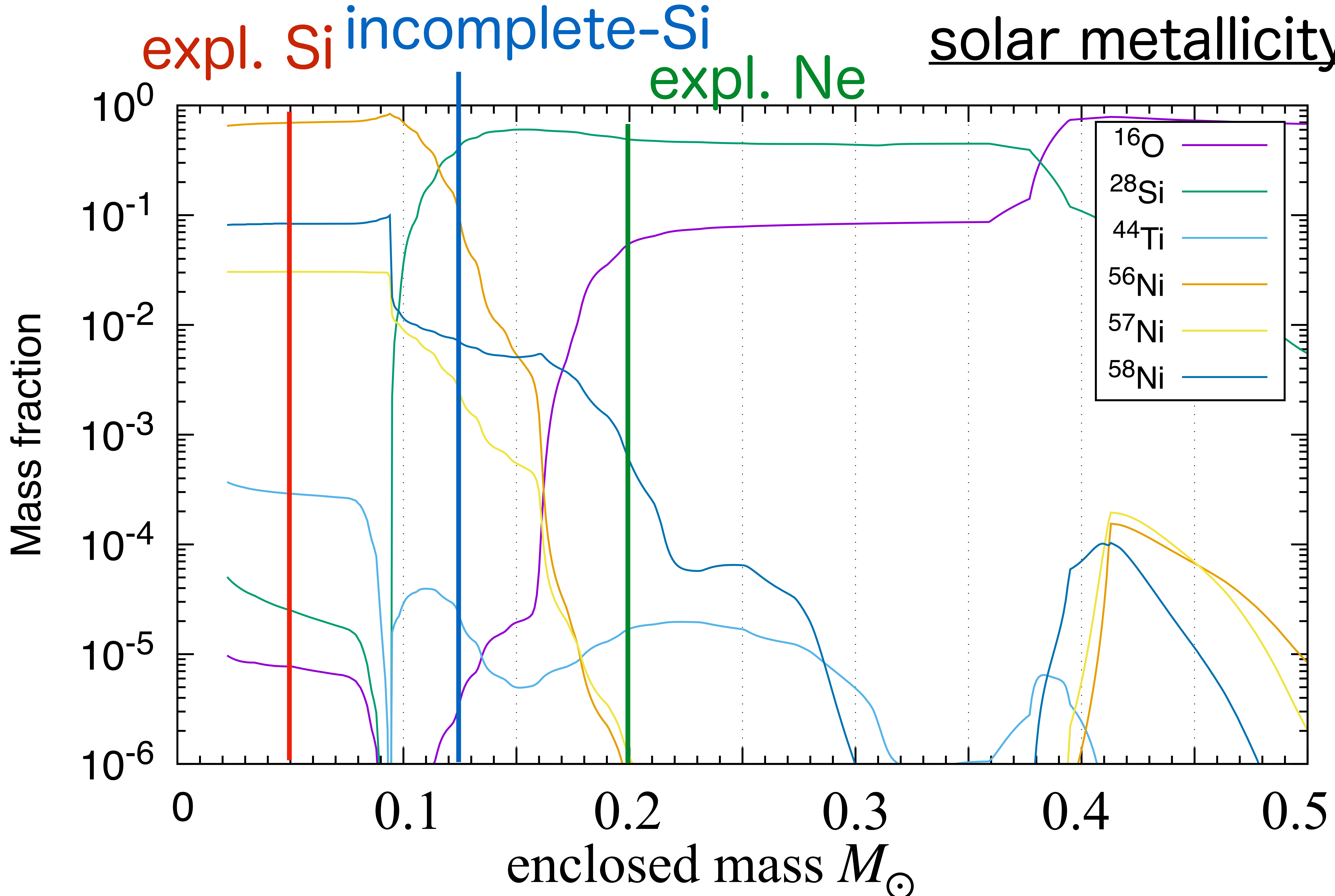
solar metallicity





MC nucleosynthesis: a PUSH model

solar metallicity $16M_{\odot}$ model



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

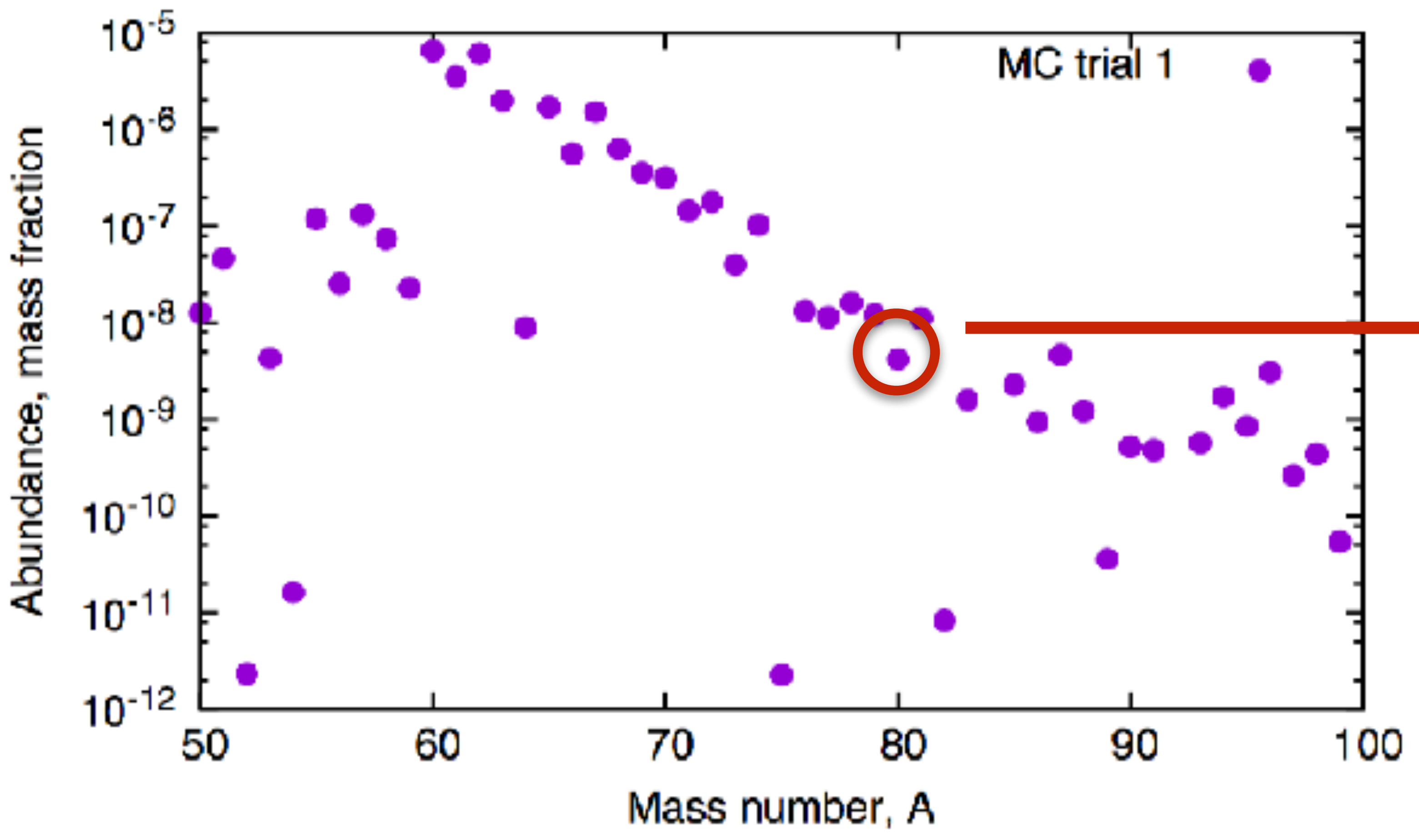
MC-variation reaction network code

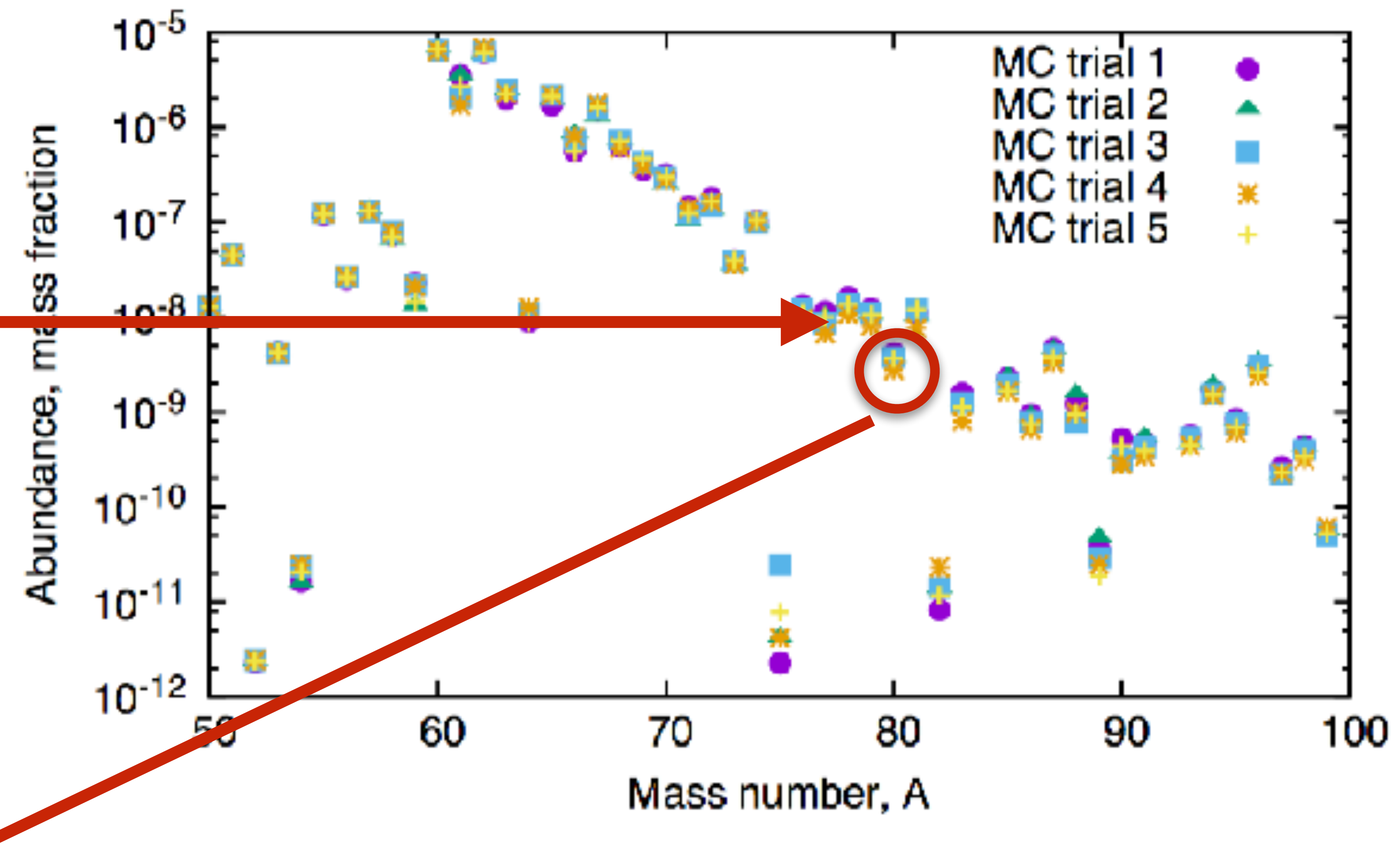
- Monte-Carlo framework
  - PizBuin MC-driver (developed by Rauscher, NN)
  - **parallelized by OpenMP** (shared memory)
- Nuclear Reaction network
  - Network solver:
    - WinNet: the latest Basel network, (Winteler+, 2012)
  - Reaction rates:
    - Reaclib: (Rauscher & Thielemann 2000)
    - T-dependent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

Piz Buin (mountain)

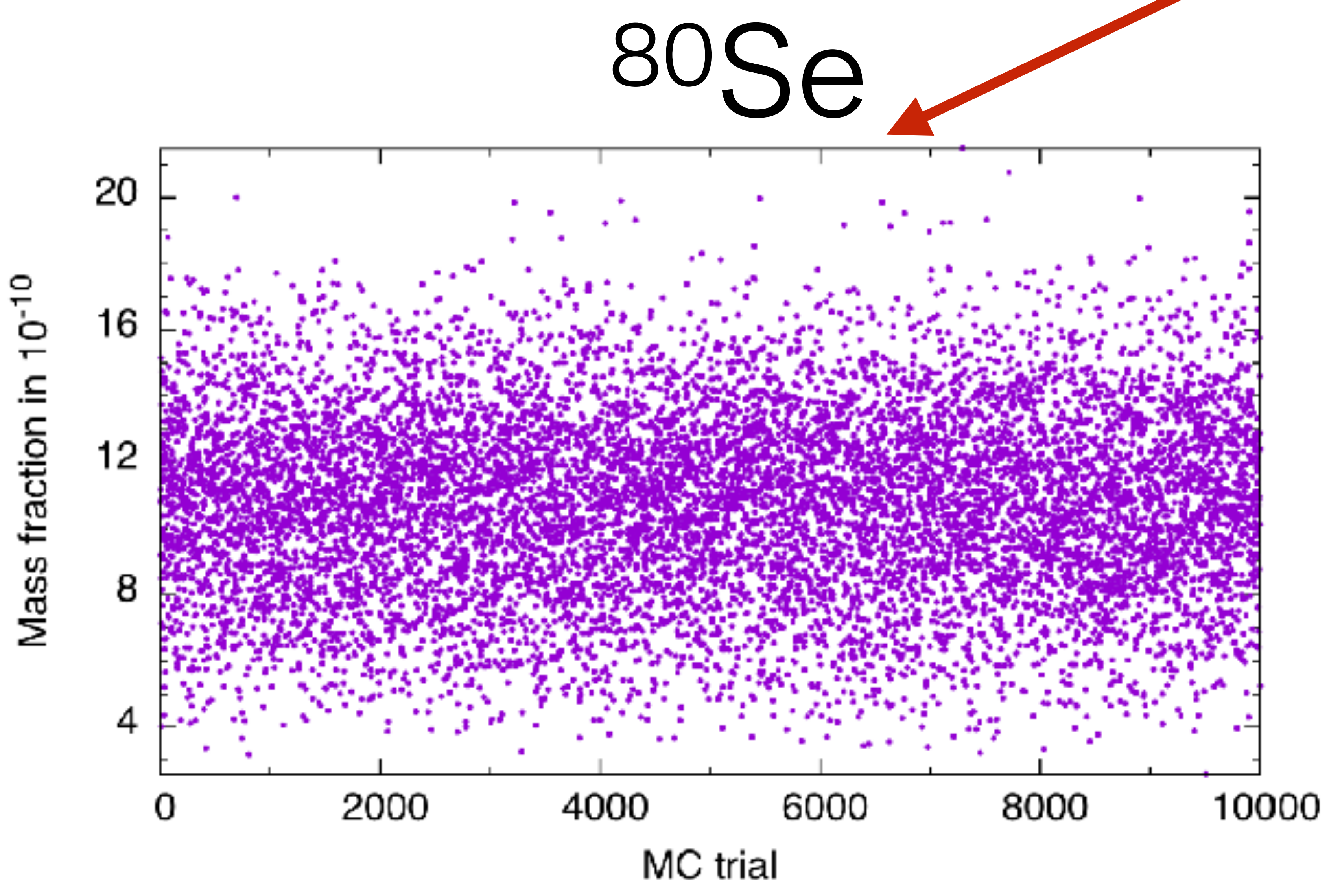
Monte-Carlo nucleosynthesis

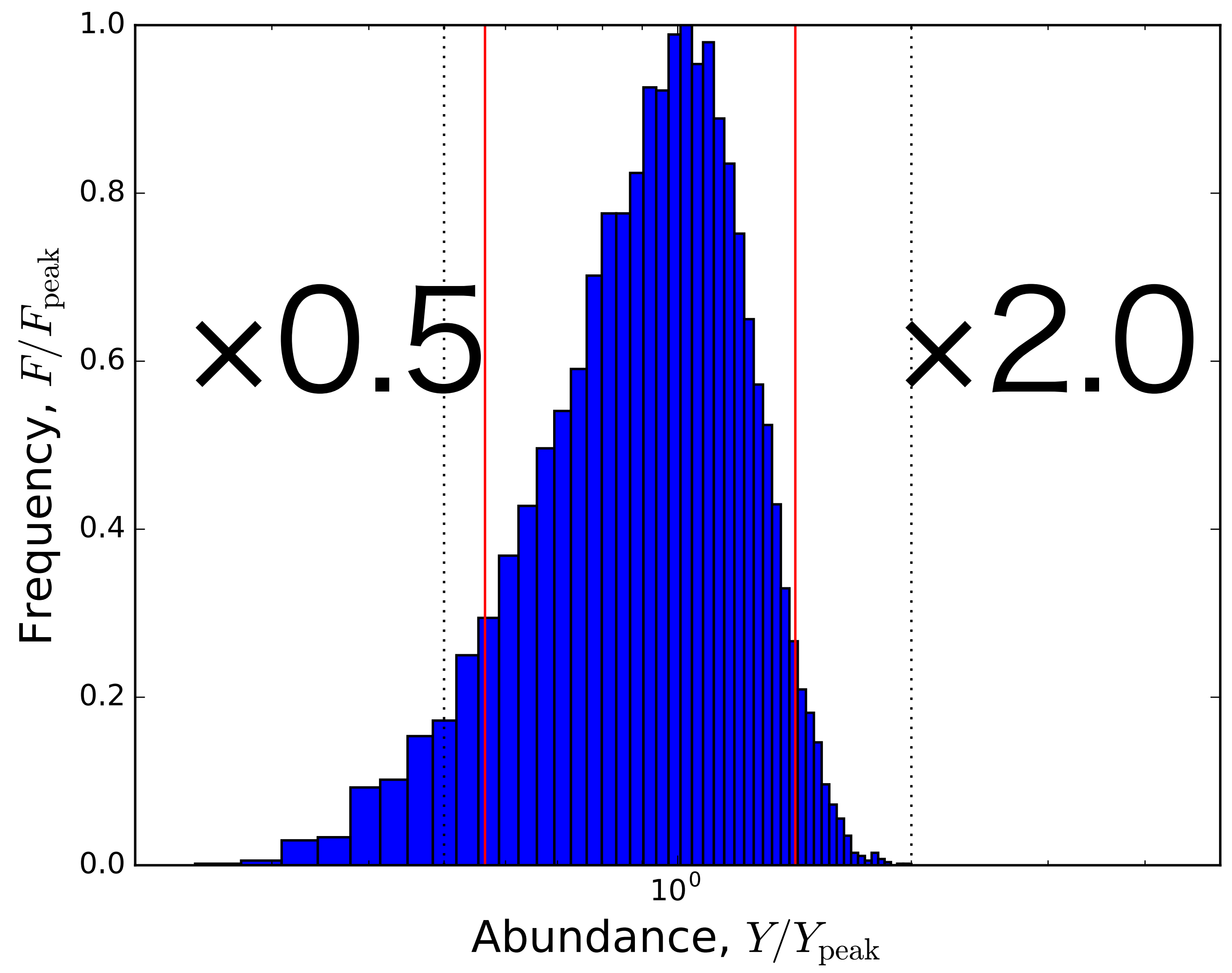
example: weak s-process





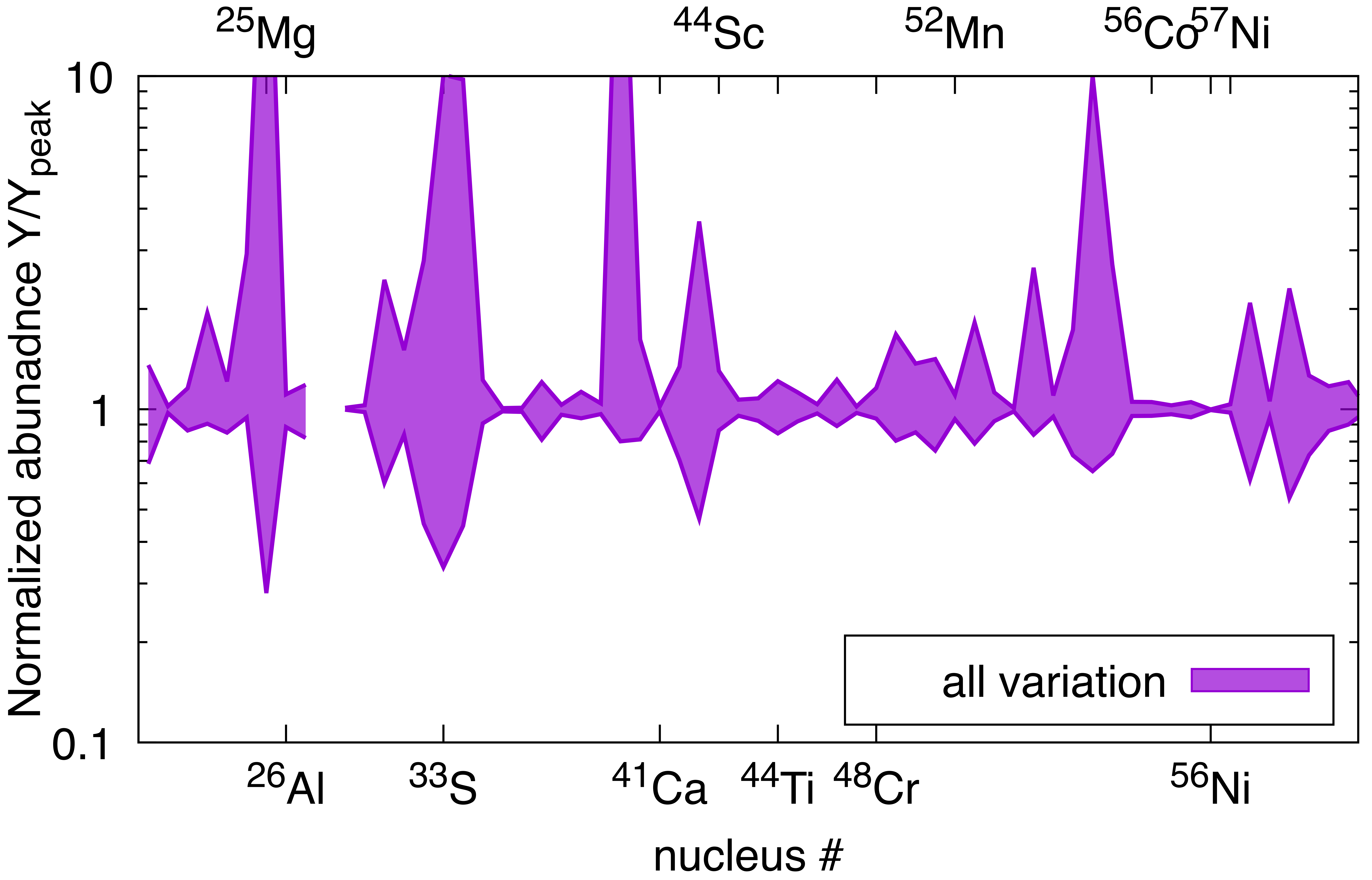
- 10,000 times iteration
- random variation (no correlation)
- uncertainty range





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



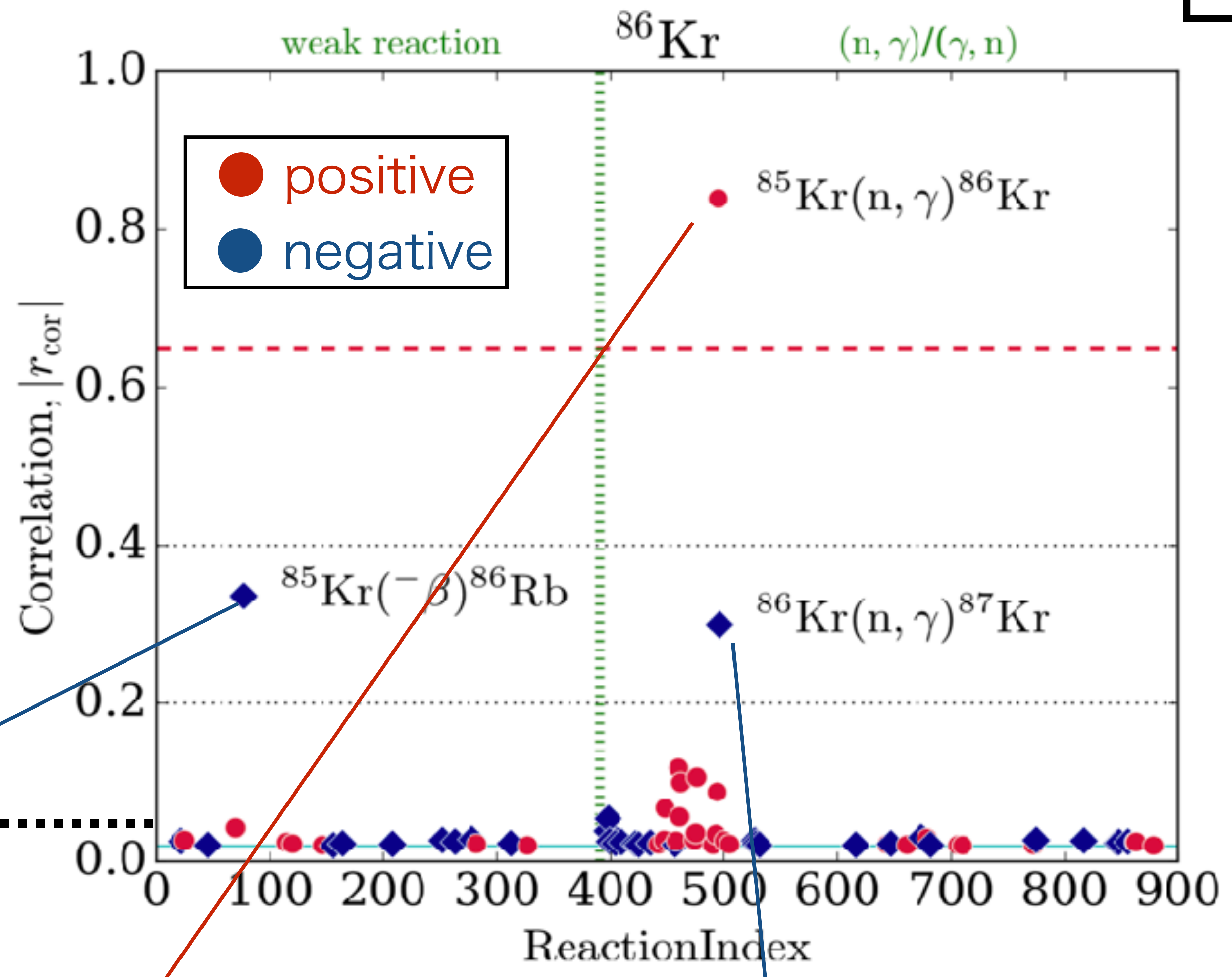
Selection by statistical analysis

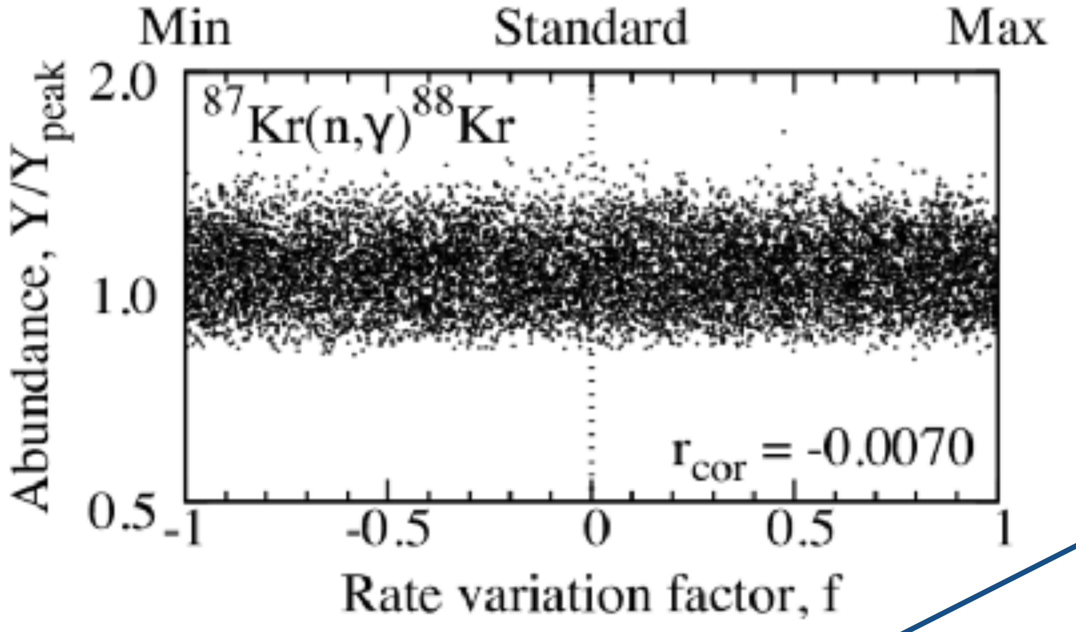
s-process

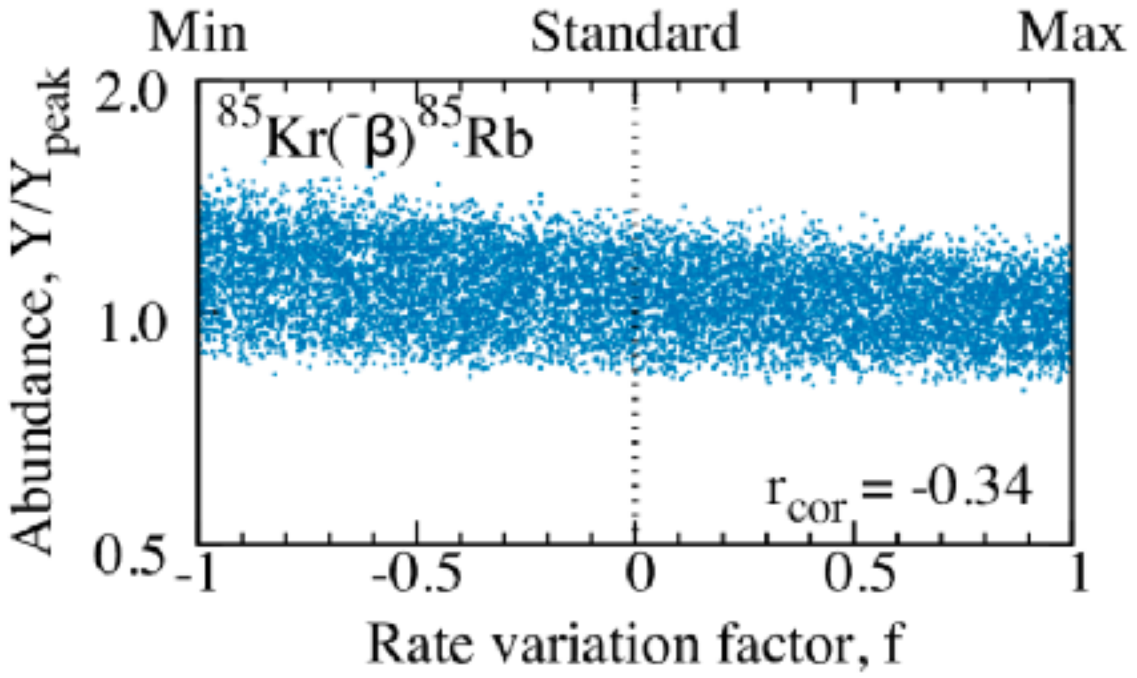
Pearson's coefficient

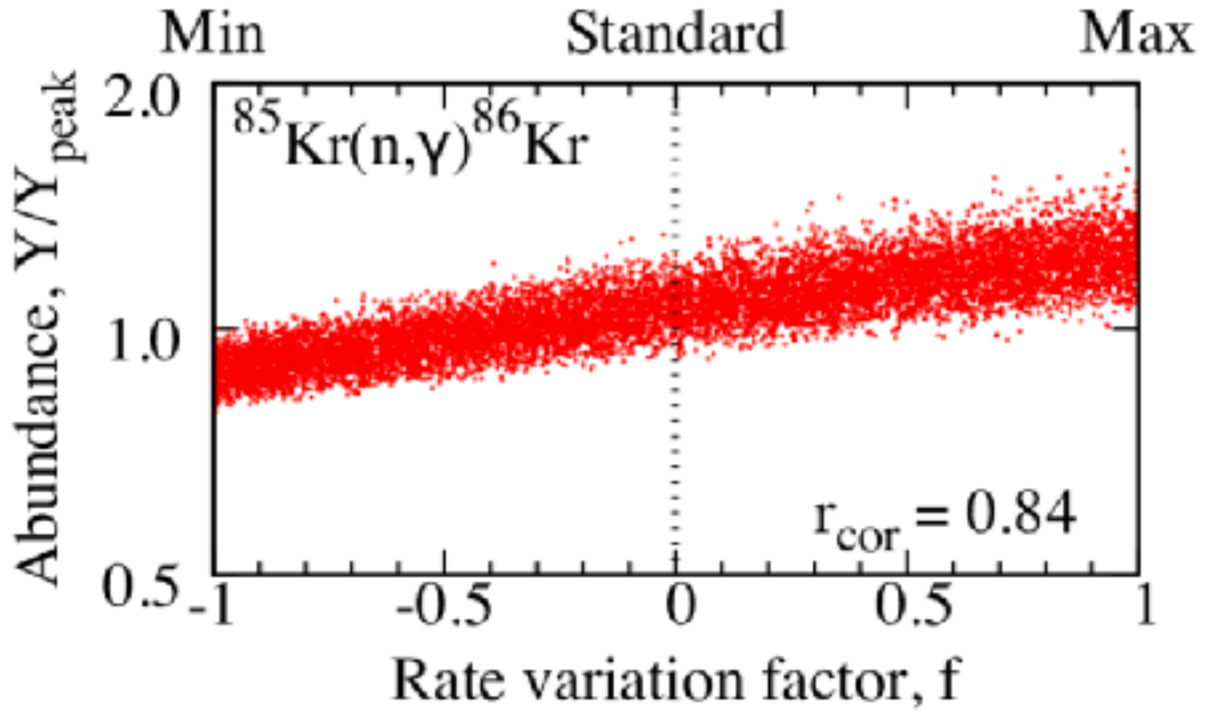
$$r_{\text{Pearson}} = \frac{\sum_{i=1}^{k} (\tilde{x}_i - \overline{x})(\tilde{y}_i - \overline{y})}{\sqrt{\sum_{i=1}^{k} (\tilde{x}_i - \overline{x})^2} \sqrt{\sum_{i=1}^{k} (\tilde{y}_i - \overline{y})^2}}$$

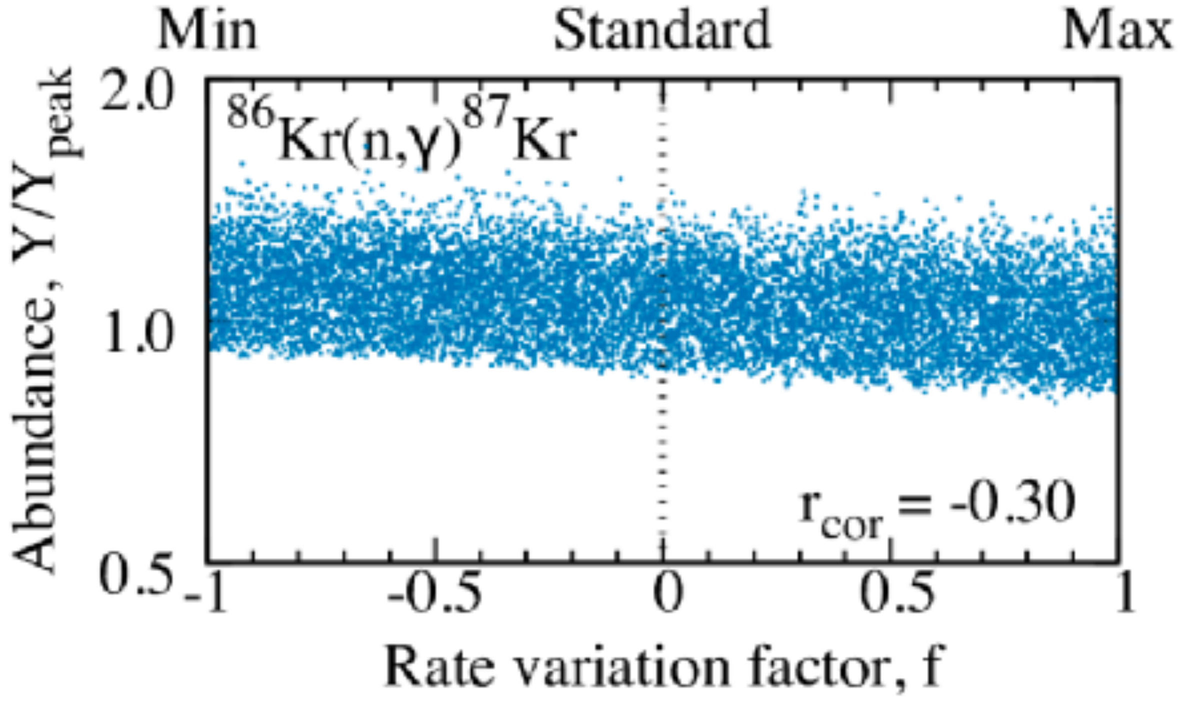
|r| > 0.65 → "strong"











Key reactions

7 decays/reaction rates

product — correlation — key reaction

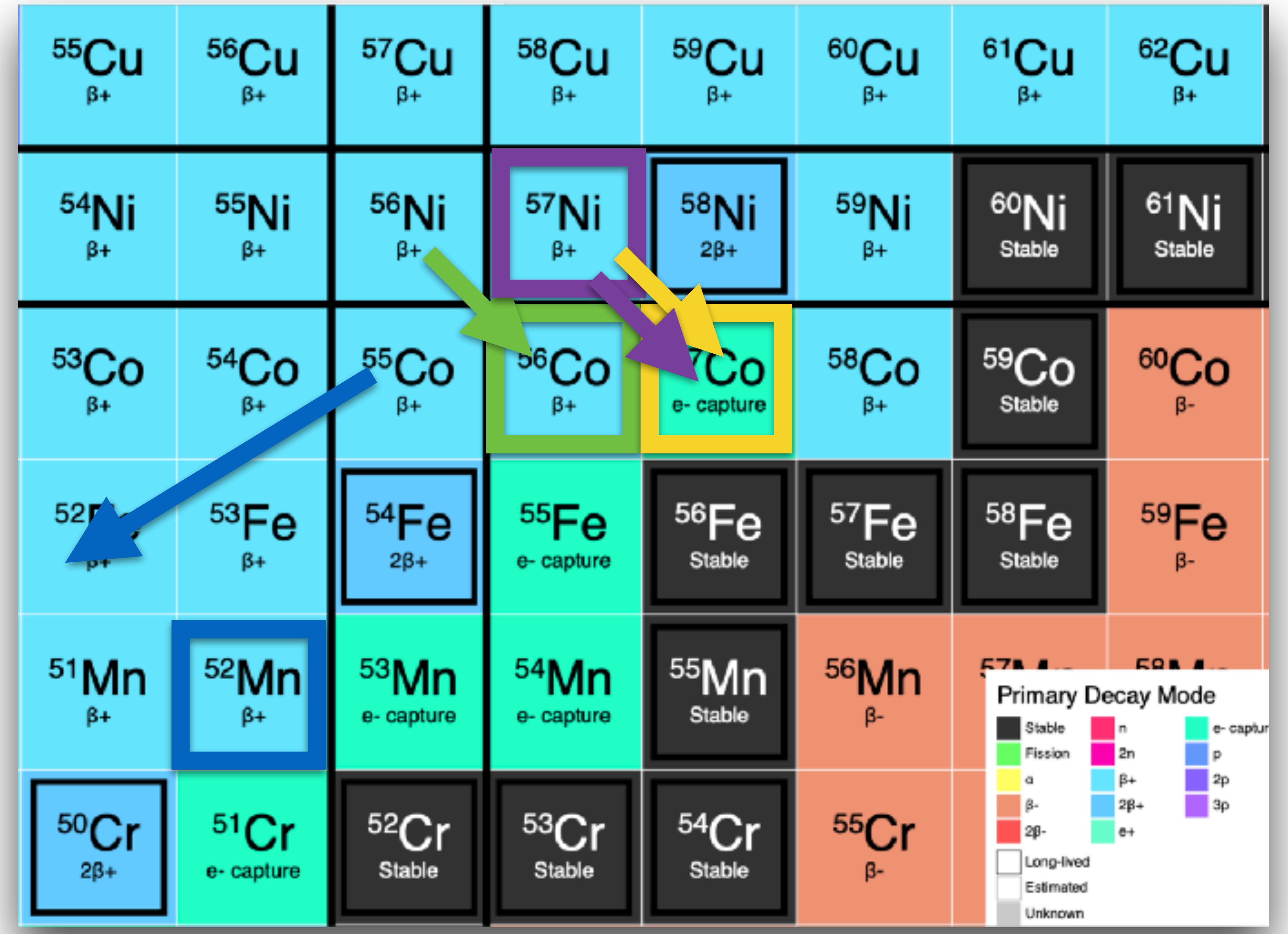
nuclide		r_{cor}	reaction
^{44}Sc	Radioactive	-0.77	^{44}Sc$(+\beta)^{44}$Ca
^{56}Co	Radioactive	1.00	^{56}Ni$(+\beta)^{56}$Co
^{57}Co	Radioactive	0.92	^{57}Ni$(+\beta)^{57}$Co
^{41}Ca	Radioactive	-0.67	^{38}Ar$(\alpha, n)^{41}$Ca
^{48}Cr	Radioactive	-0.82	^{48}Cr$(\alpha, p)^{51}$Mn
^{52}Mn	Radioactive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

preliminary

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

→ affects on SN lightcurve?

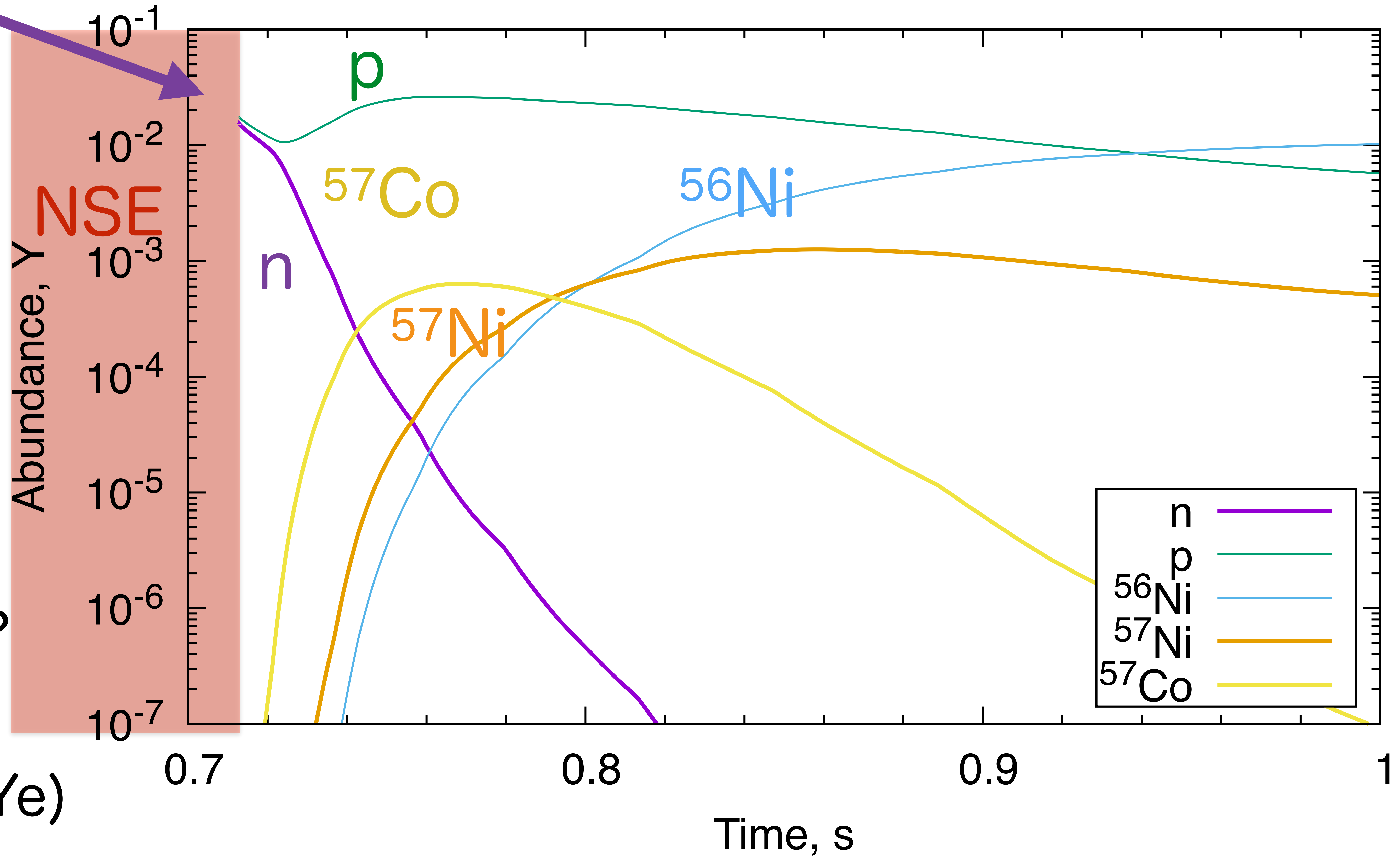
key reactions (selected)
on the N-Z plane



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)

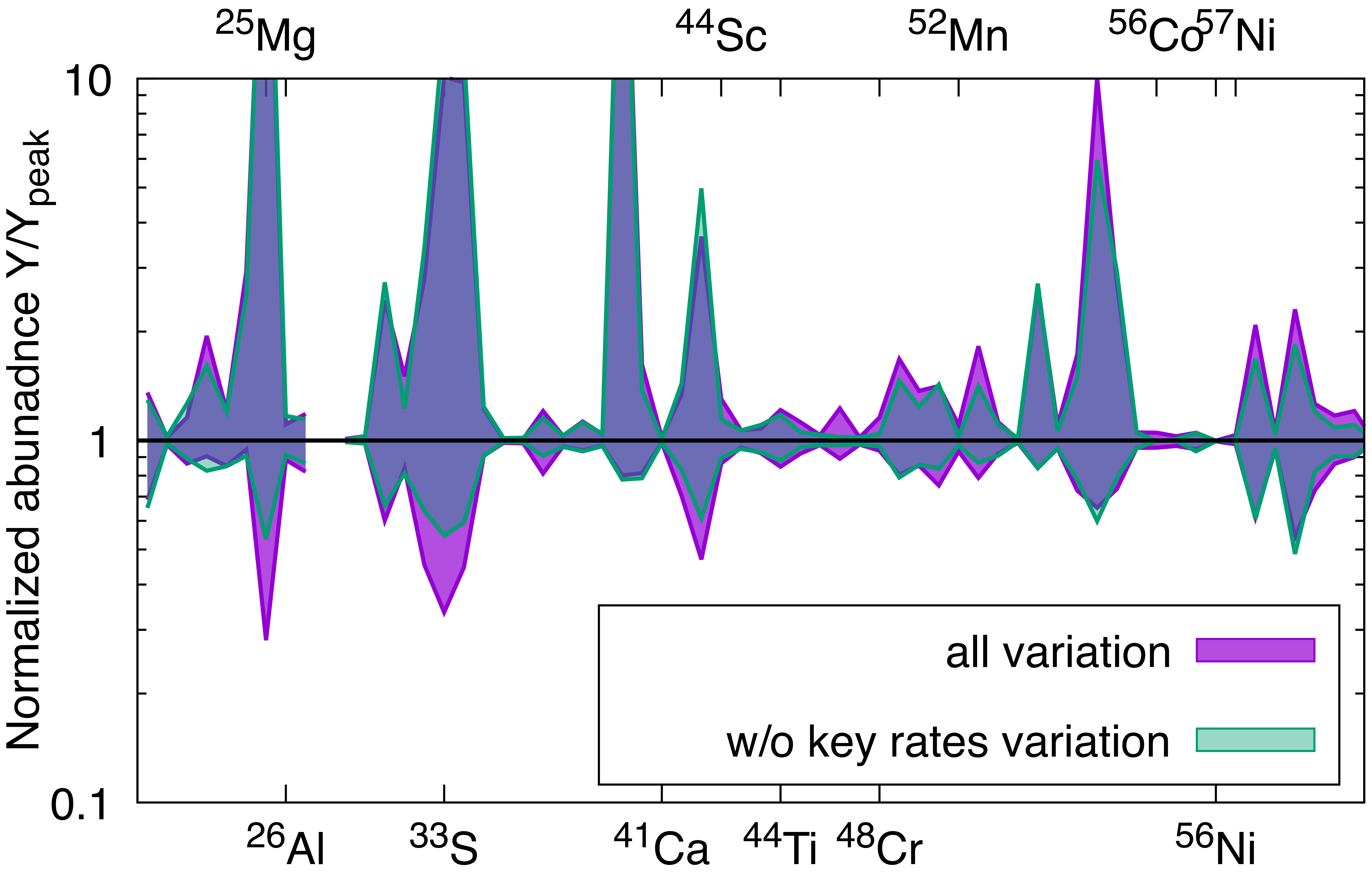


impacts of ν reaction?

→ may be minor

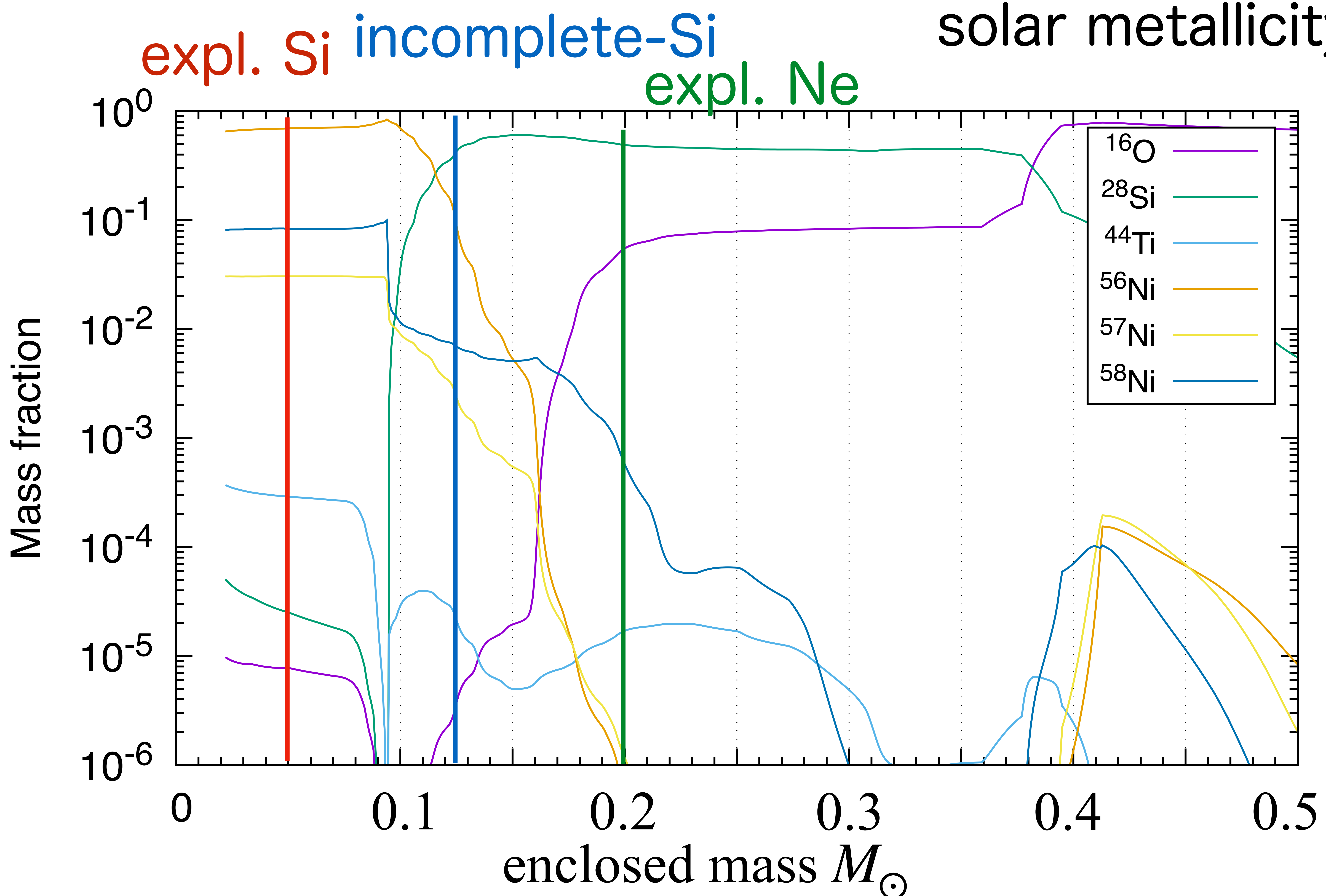
(changes a few % in Ye)

Abundance uncertainty: impacts of key rates



Analysis on different stellar layers

solar metallicity 16$M_\odot$ model



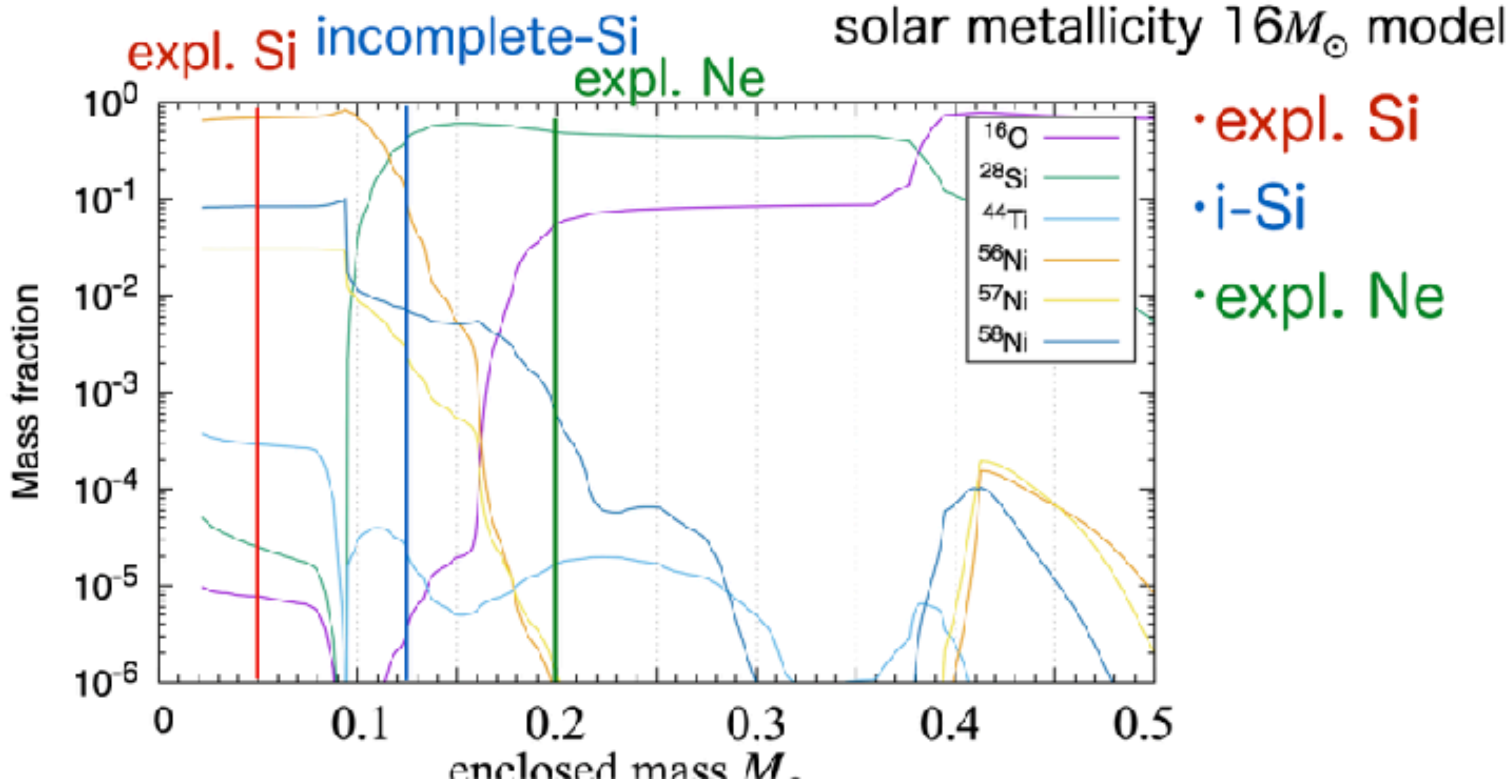
- expl. Si
- i-Si
- expl. Ne

Key reactions: ^{44}Ti different layers

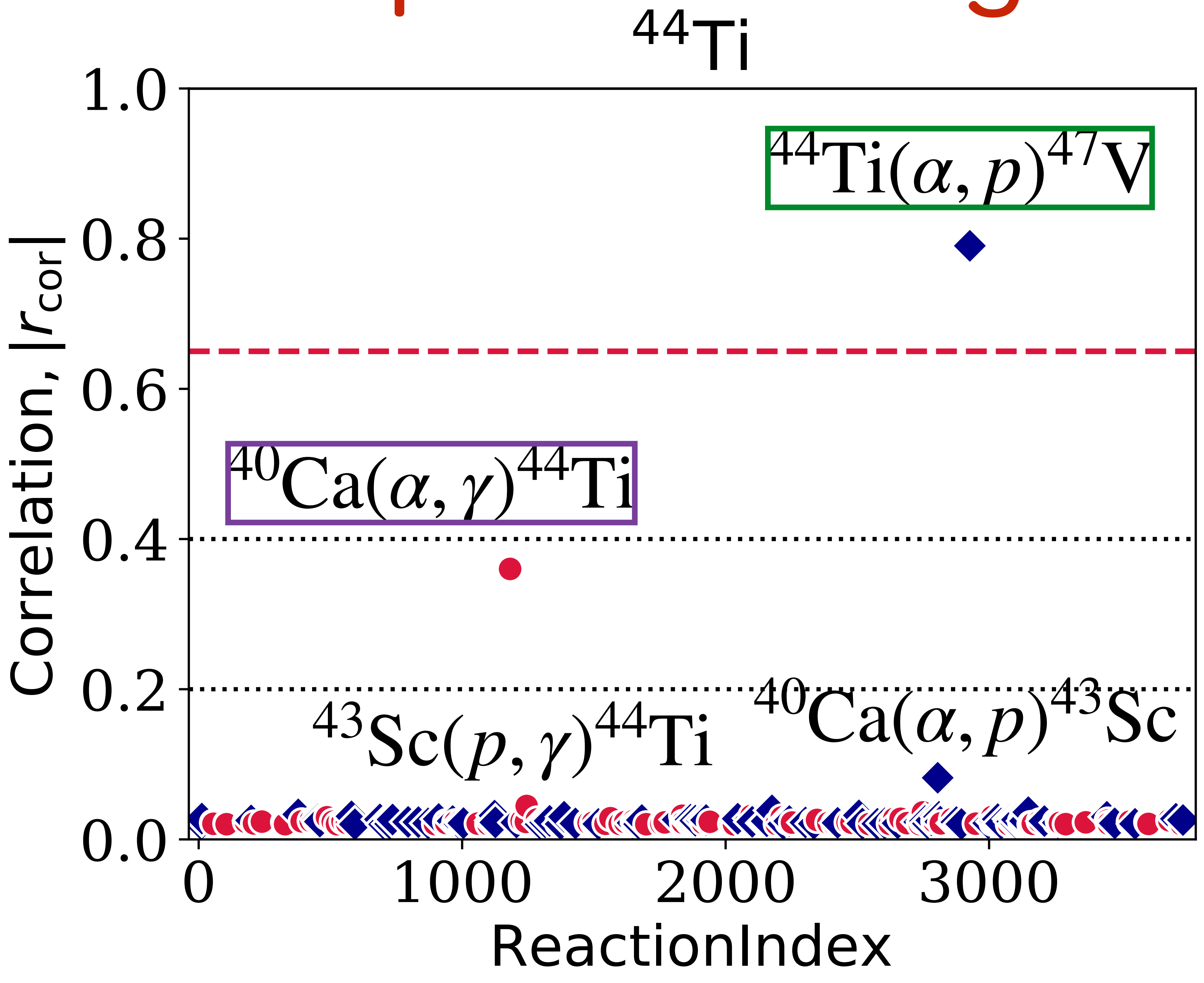
Pearson's coefficient

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

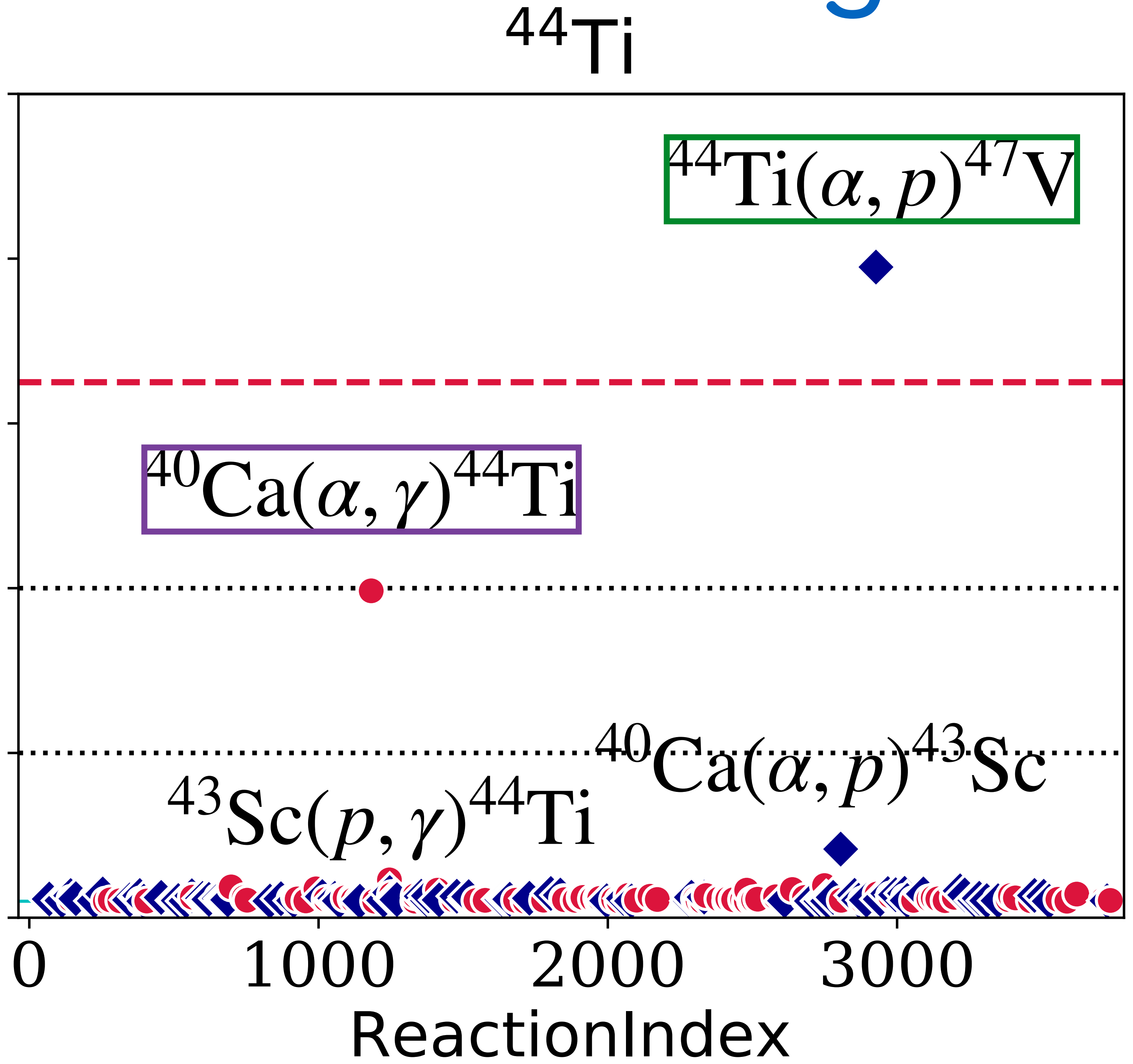
● positive
◆ negative



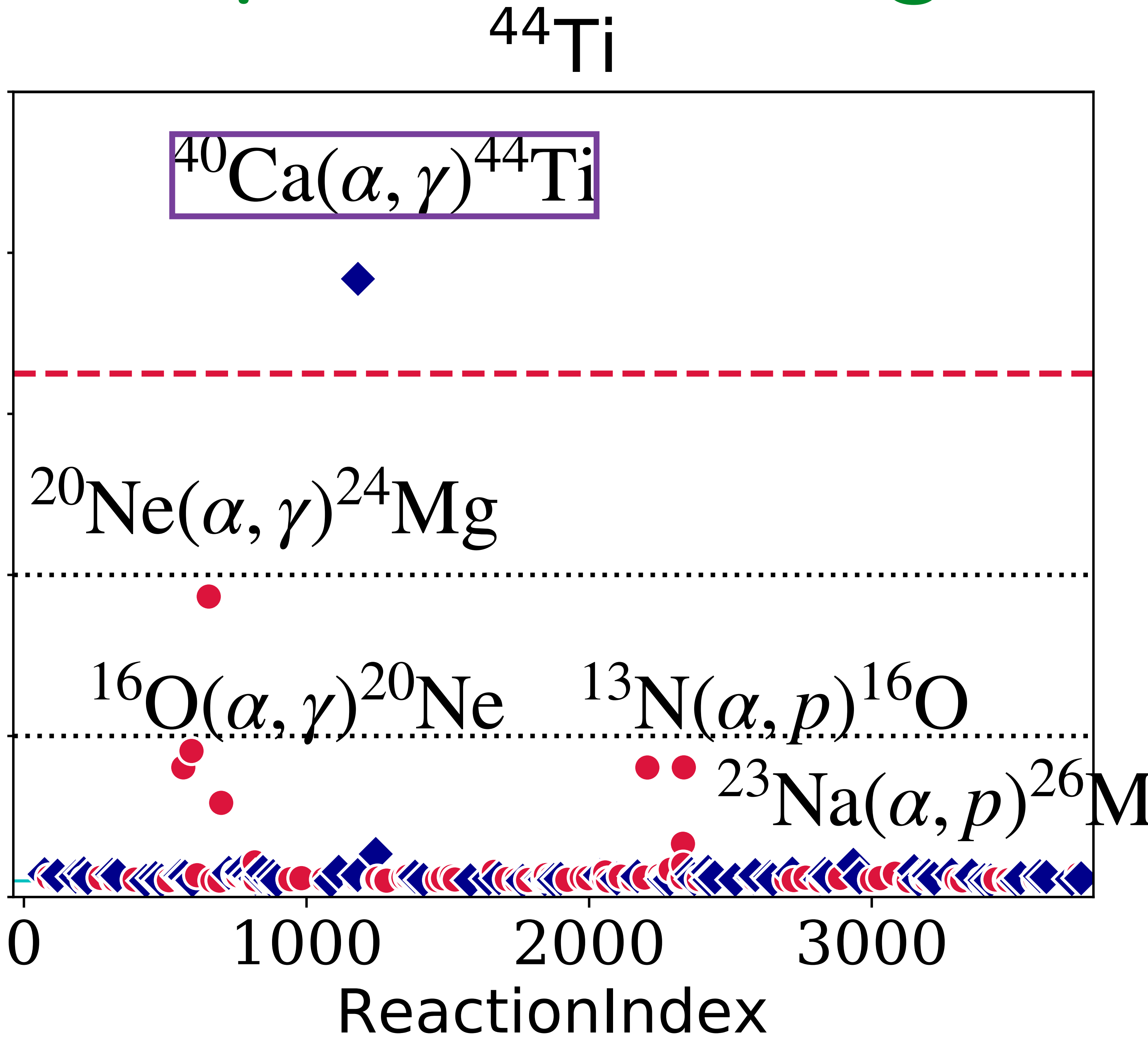
exp Si burning



i-Si burning



exp Ne burning



"Nucleosynthesis and Evolution of Neutron stars"

中性子星の進化と元素合成

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

京都大学 KYOTO UNIVERSITY

- **topic:** Supernovae, NSs, XRBs, Nucleosynthesis and related nuclear astrophysics
- **27-30 Jan. 2025** @YITP, Kyoto University
- regist. & abst. submission will open soon!

website

- LOC: A. Dohi, E. Kido, T. Naito (co-chair), M. Kitazawa, N. Nishimura (co-chair), T. Tamagawa, H. Yamaguchi

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

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

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