Uncertainty in nuclear reactions and decay in heavy-element nucleosynthesis beyond iron

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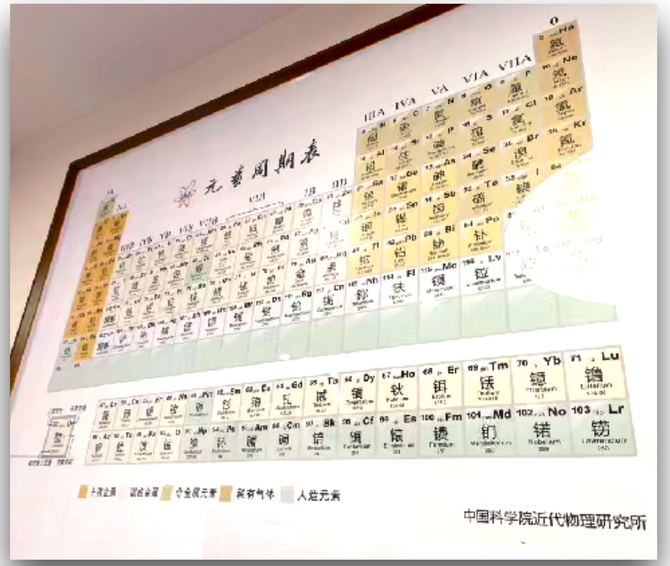
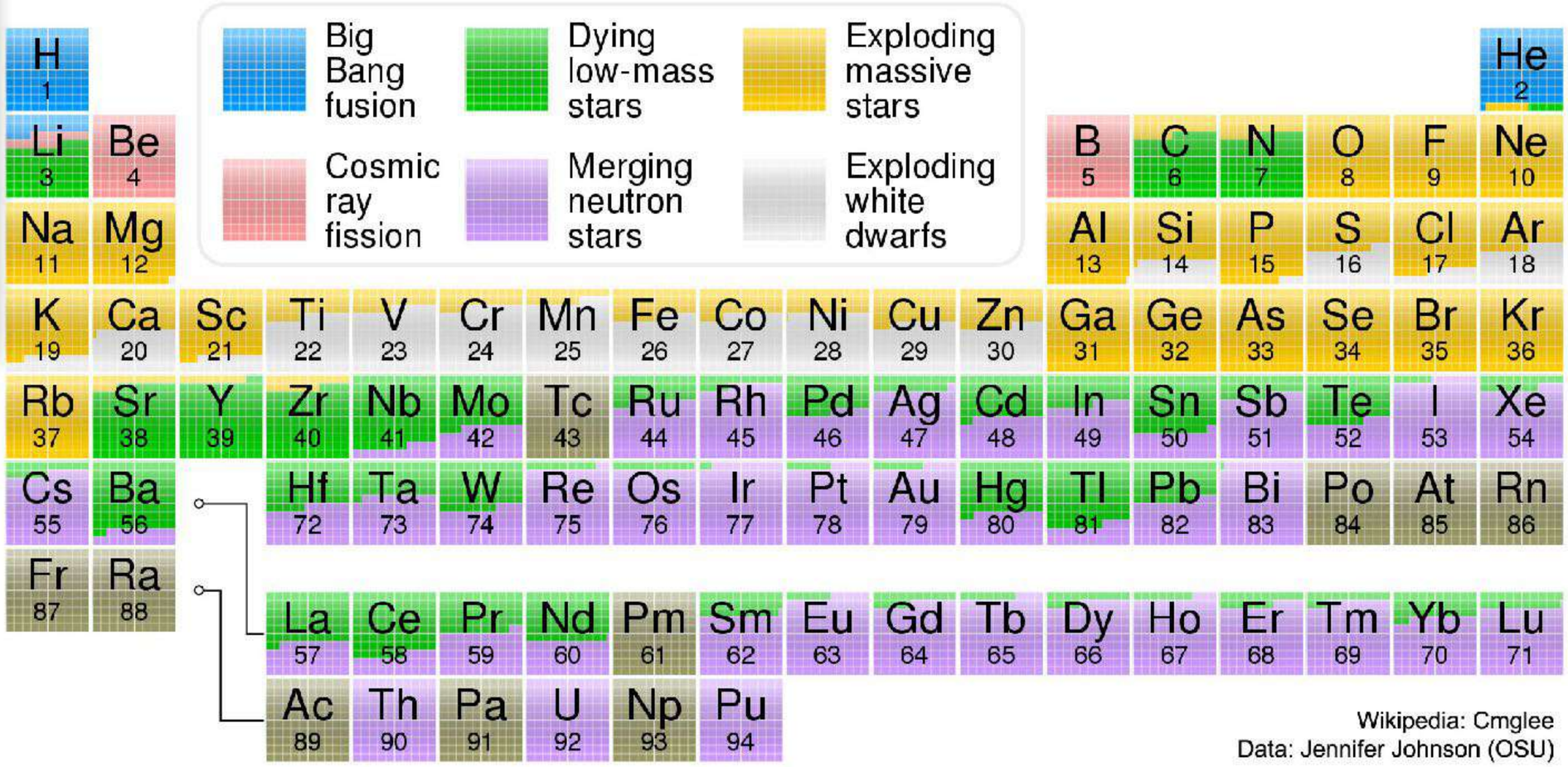
東京大学 THE UNIVERSITY OF TOKYO
科研費 KAKENHI

Origin of elements in the Universe

Chinese periodic table

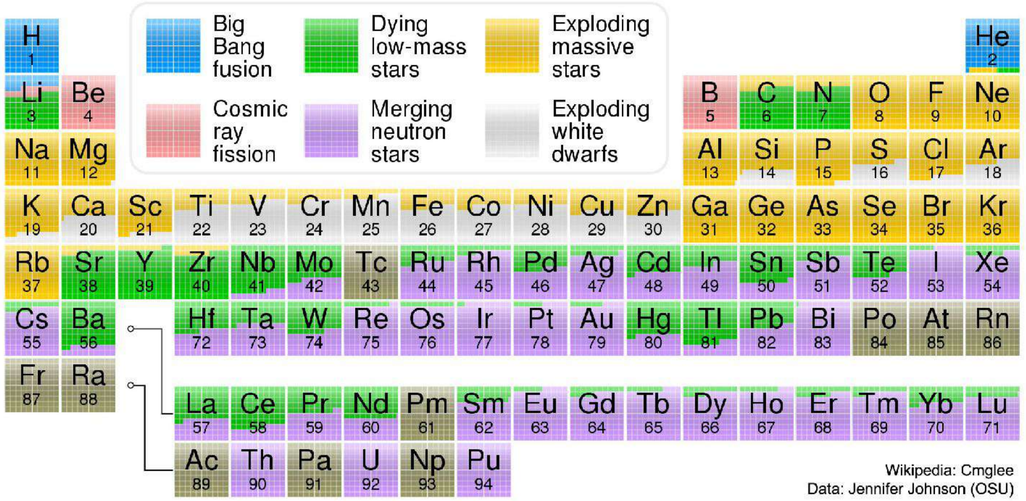


A periodic table with astrophysical origin

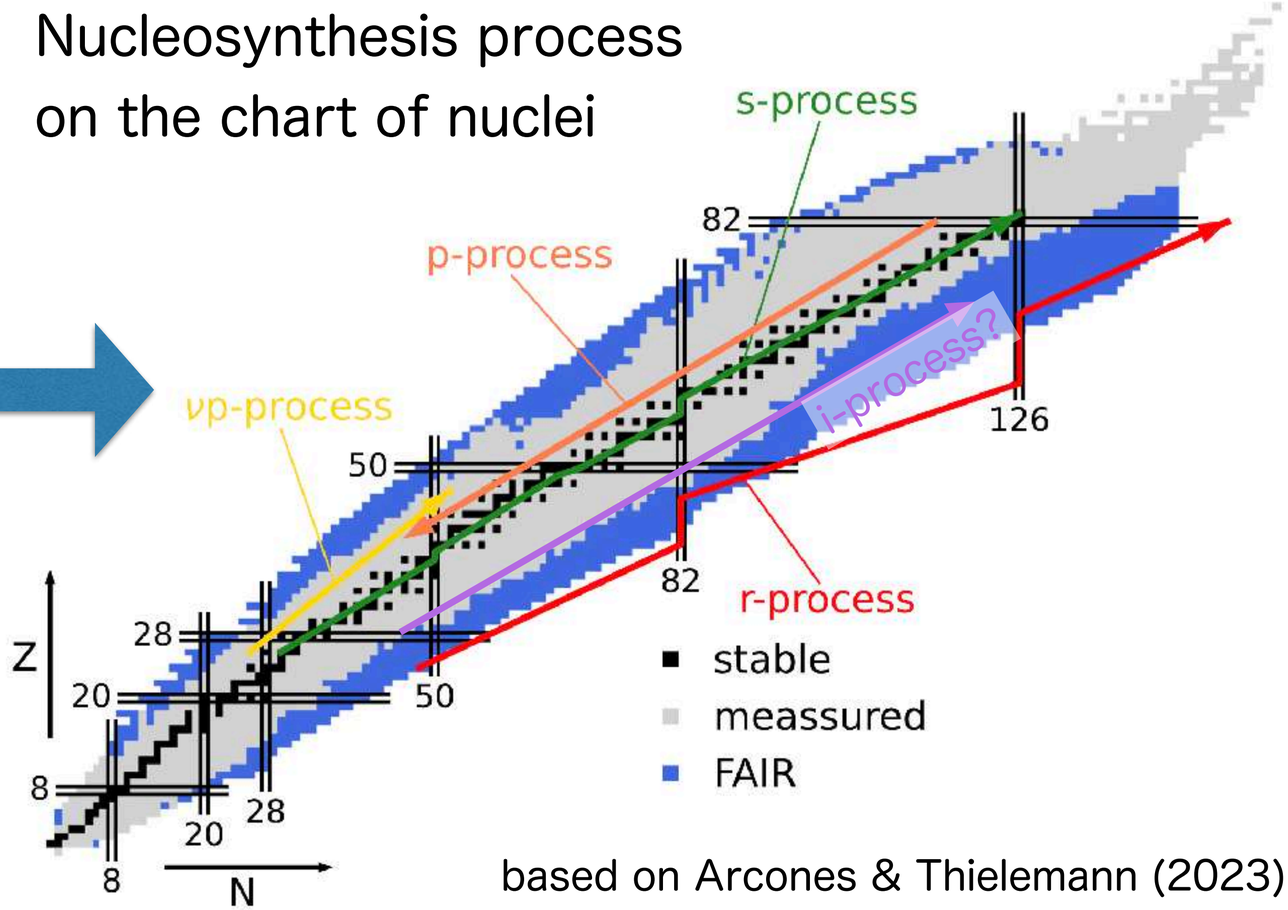


Origin of elements in the Universe

Astronomical origin of elements



Nucleosynthesis process on the chart of nuclei

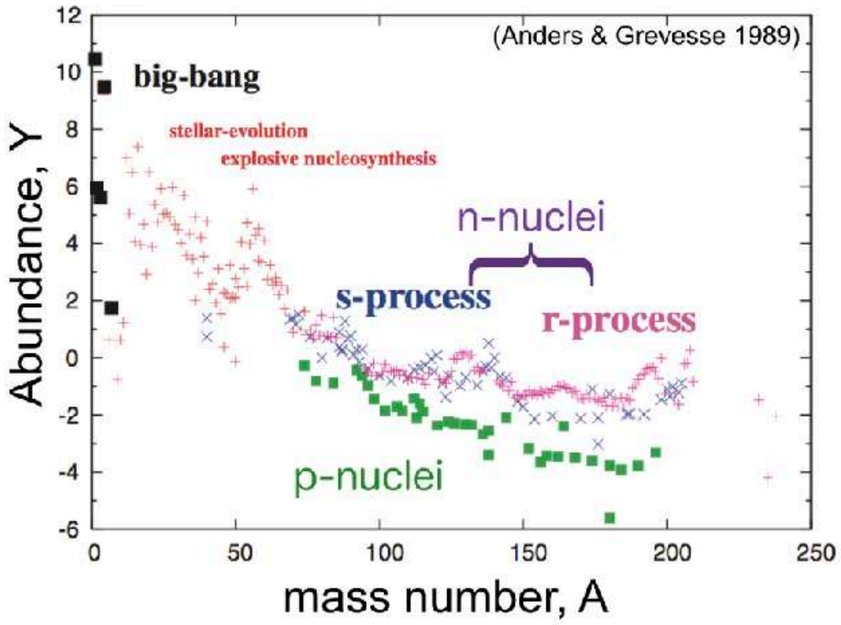


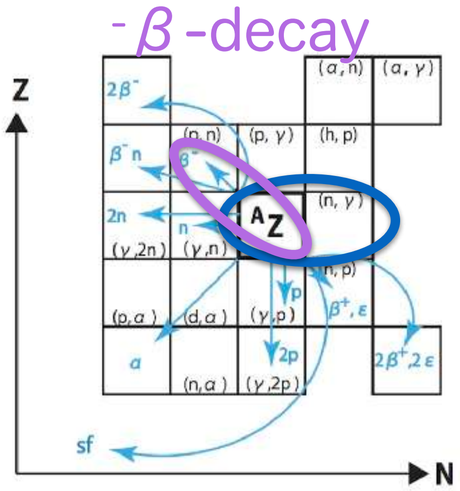
based on Arcones & Thielemann (2023)

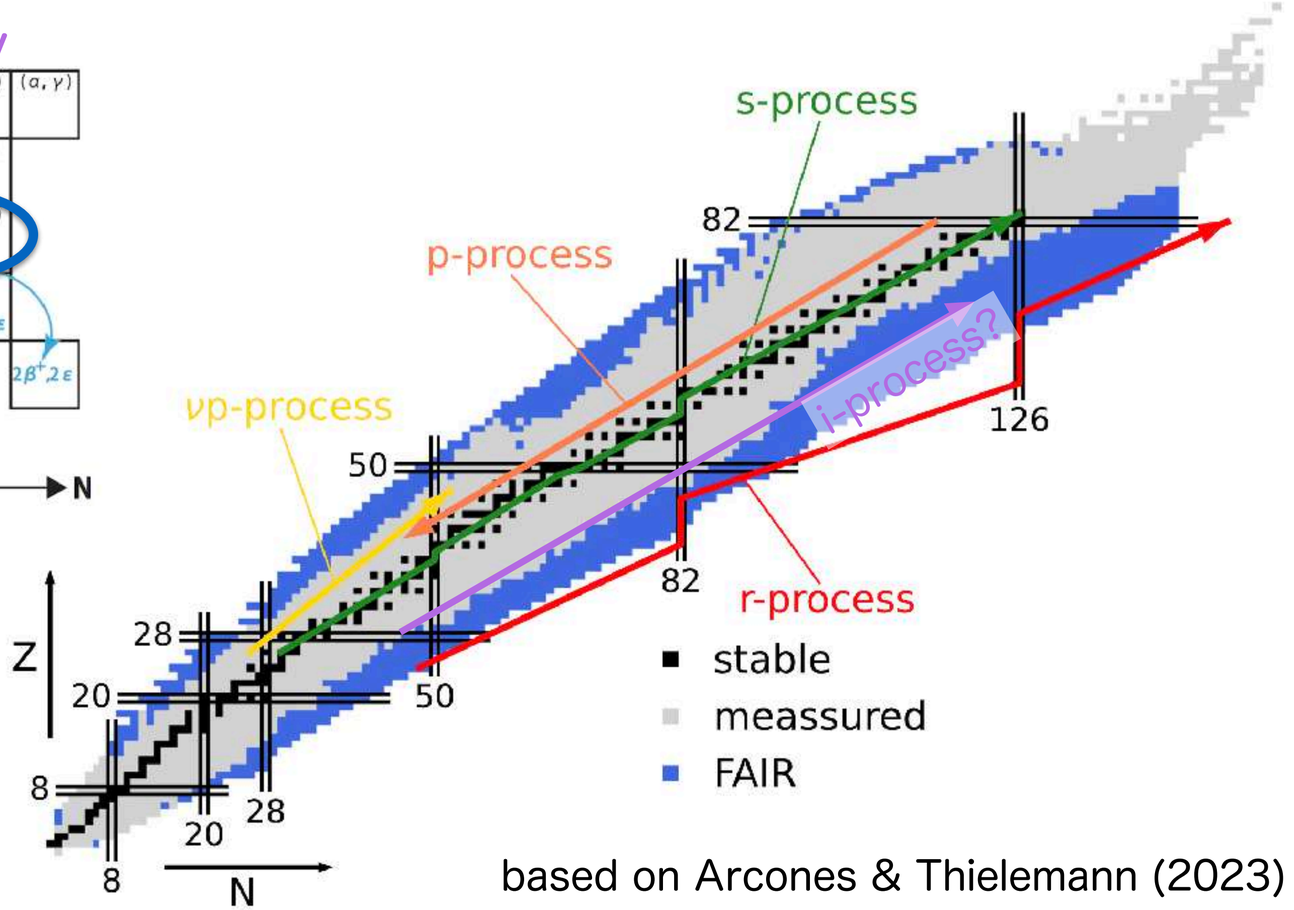
- Stellar nuclear fusion produces nuclei up to Fe
- trans-iron elements -> s-process, r-process, p-process etc.
- Nucleosynthesis process has been suggested for each element group (s/r-processes, i-process, p-process (rp/νp) + subclasses)

Origin of elements in the Universe

solar abundances







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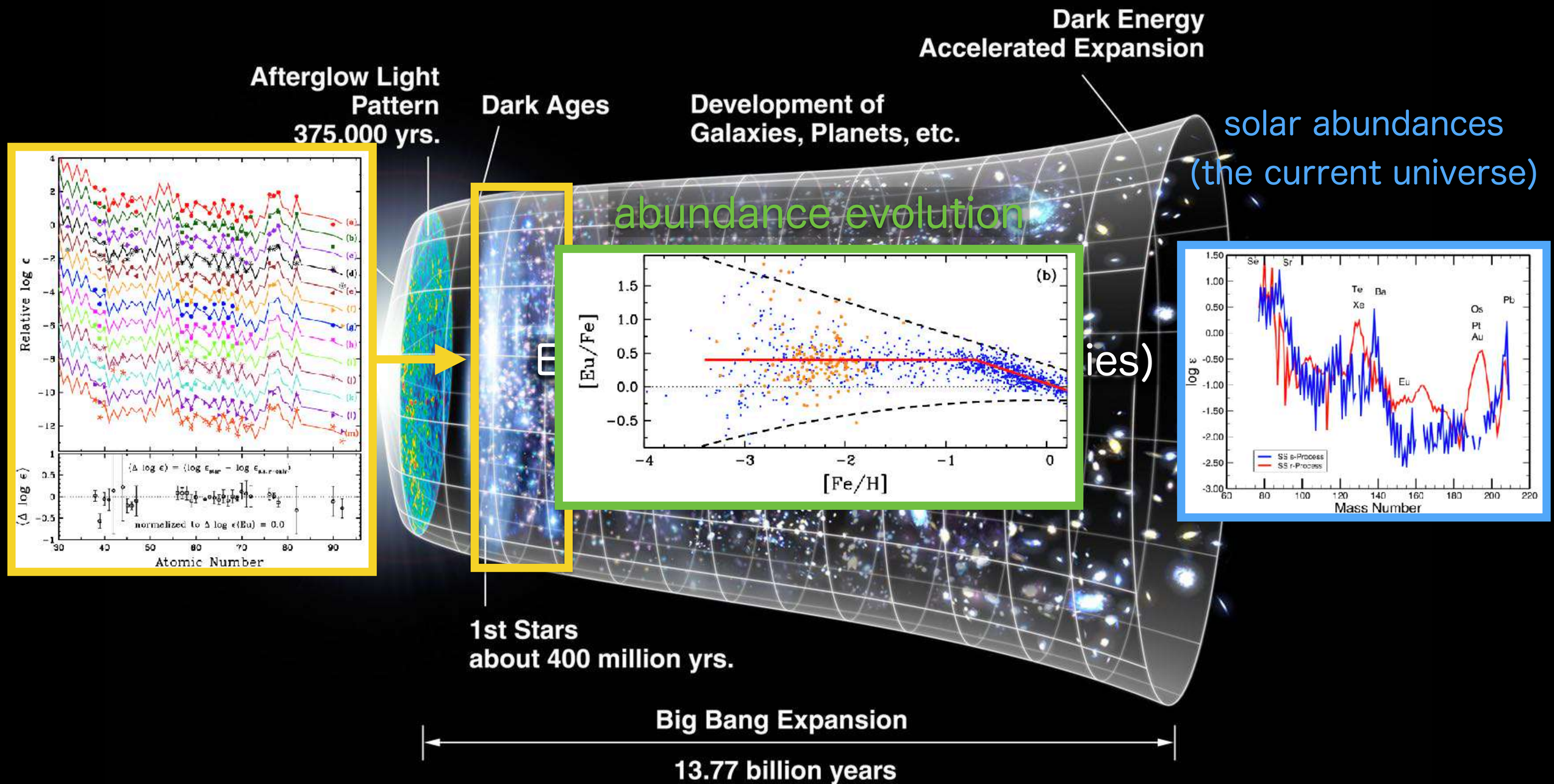
Galactic evolution of elements



Talk plan

1. Introduction

- Cosmic nucleosynthesis processes beyond

2. Comprehensive analysis of nuclear-reaction uncertainty

- MC-nucleosynthesis
- results on s-process, p-process, and νp-process
- ongoing studies: experiments and

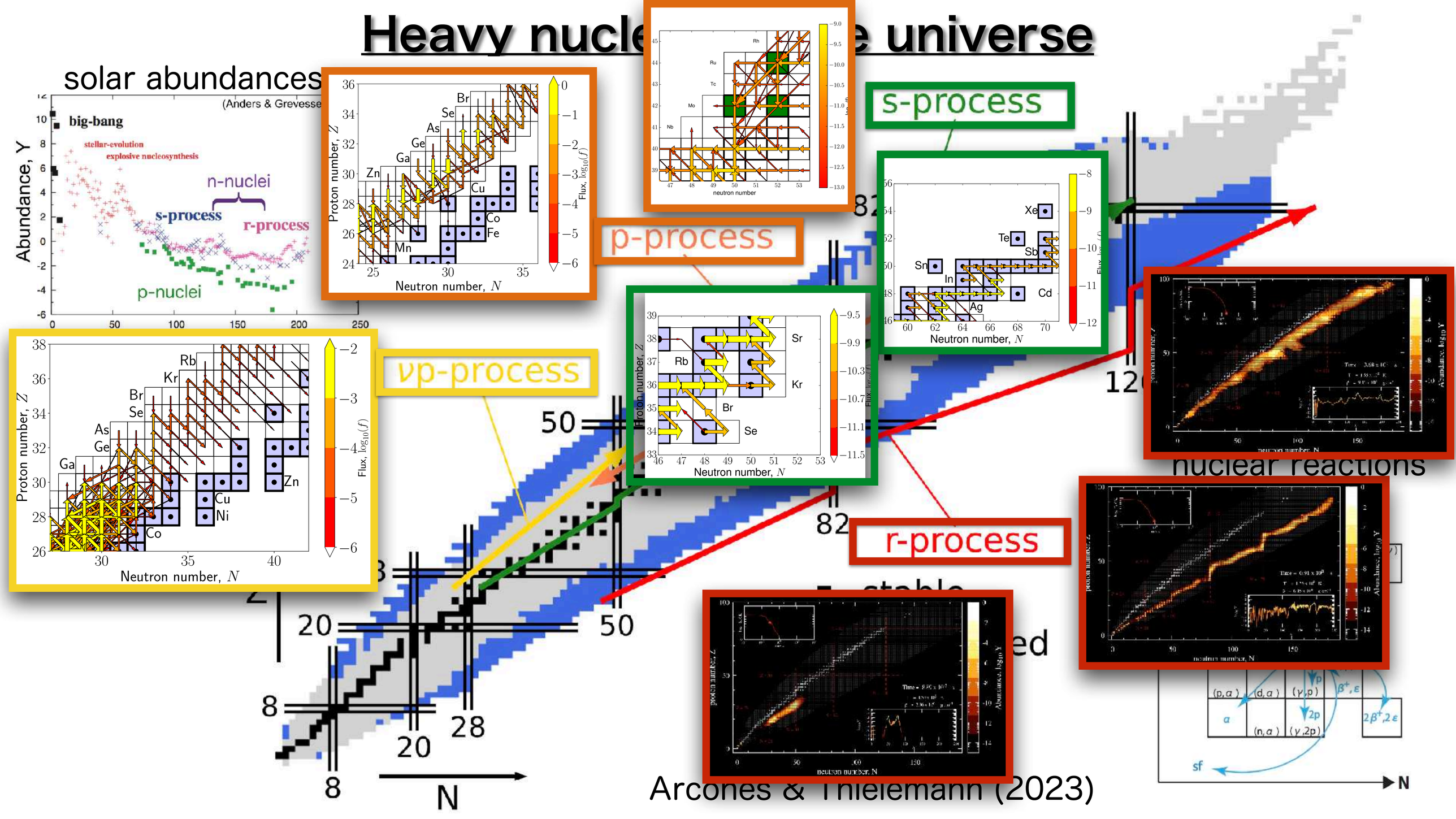
3. Uncertainties in r-process nucleosynthesis

- overview: r-process
- fission and beta-decay

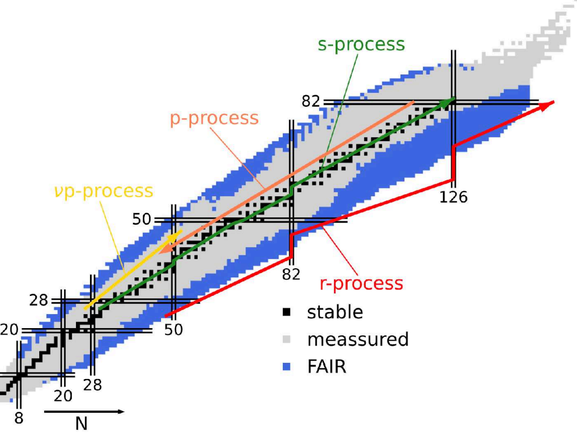
4. Summary

2. Comprehensive analysis of nuclear-reaction uncertainty

Heavy nucle e universe



Key reactions in nucleosynthesis



"sensitivity" study on nucleosynthesis?

our approach

reaction/decay uncertainty

↓ Monte-Carlo + statistical analysis ↑

astronomical observation

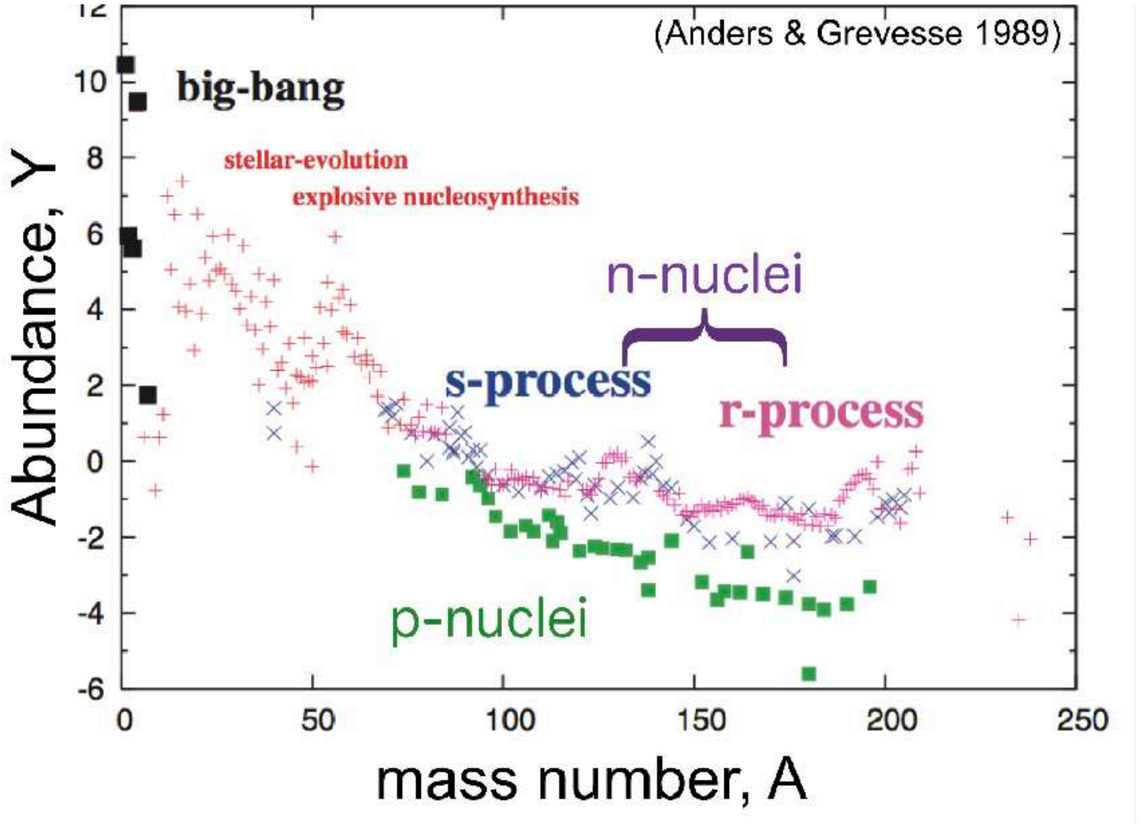
- s-process : (2) weak s (→ n_TOF (CERN) experiments), (4) main s
- p-process : (1) CC-SNe, (3)Type Ia SNe
- ν p-process : (5) PNS wind → RIBF experiments and more?

(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

Neutron-capture nucleosynthesis

the solar abundances
(w/ nucleosynthesis processes)



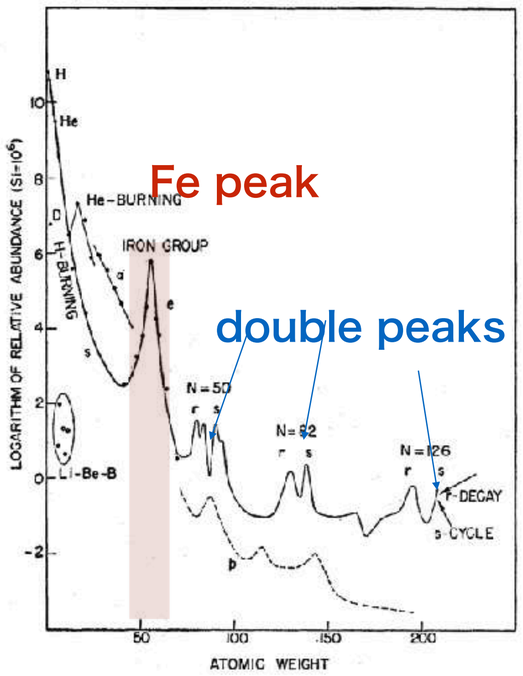
- B²FH paper (1957)
- also A. Cameron (1957)

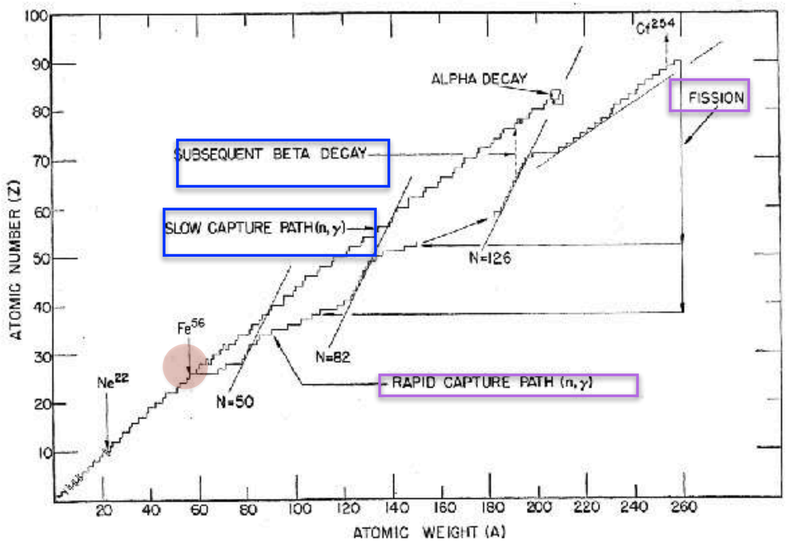
VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

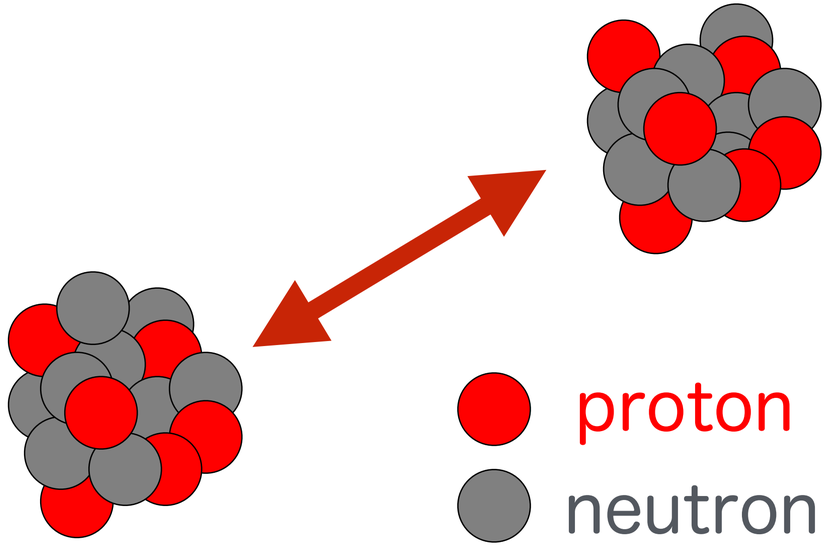




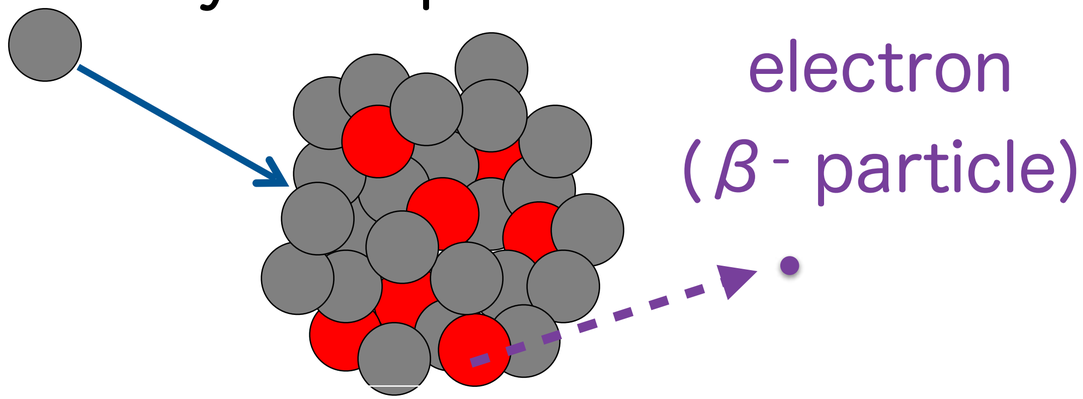
Neutron-capture nucleosynthesis

Strong Coulomb repulsion in heavy nuclei (higher Z)

(n,g): neutron capture (neutral) & β^- decay



① (n,g) → a heavy isotope: A+1



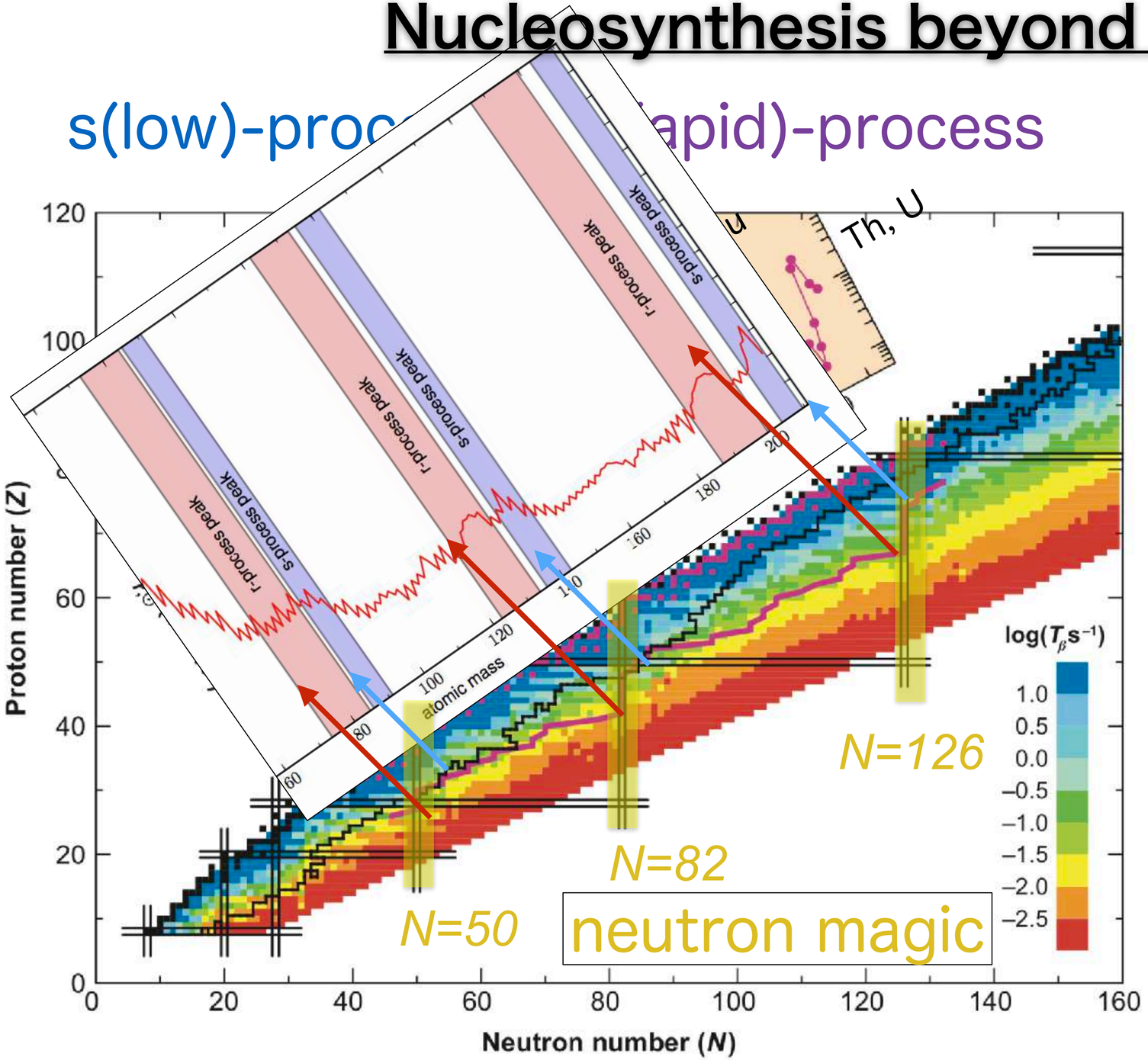
② β^- decay → increase atomic number: Z+1

- the slow process (s-process)
  - (n,g) is slower than β-decay
  - path is along to the stability line

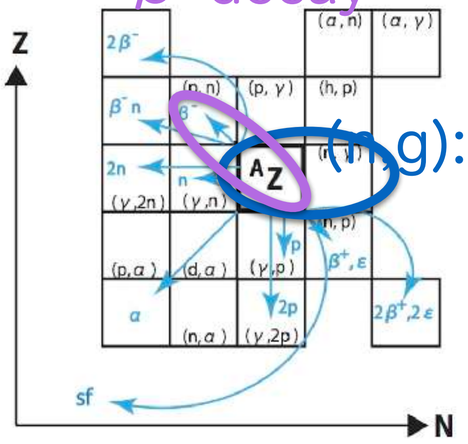
- the rapid process (r-process)
  - (n,g) is faster than β-decay
  - path goes very neutron-rich region (far from the stability)

Nucleosynthesis beyond Fe: n-capture

s(low)-proc apid)-process



- β -decay



(n, g): neutron capture

元素楽章

GENSOGAKUSHO × GENSOGOSEI

元素合成

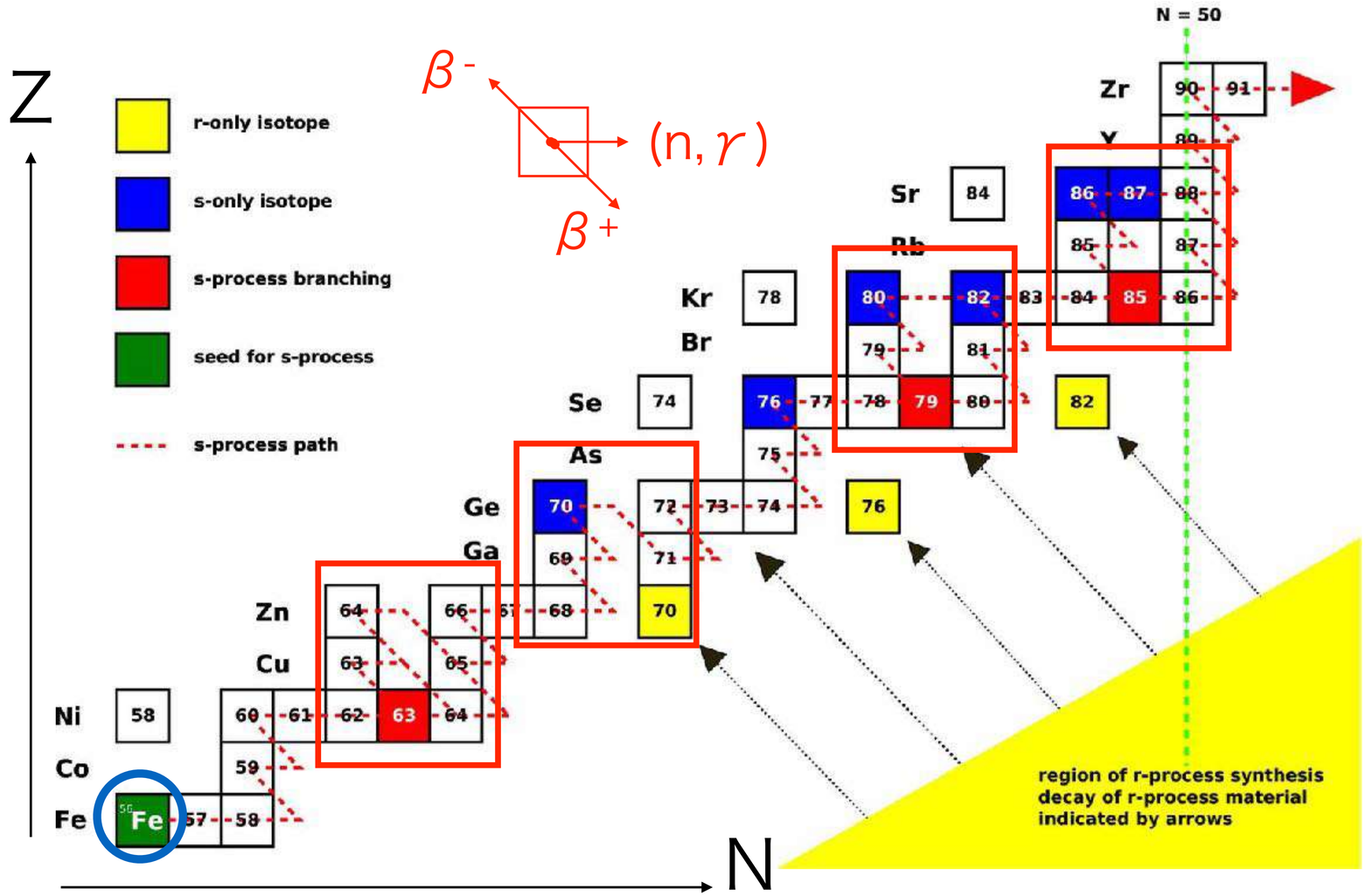
©agedoridori & NN

The s-process (slow process)

-produces a half amount of heavy isotopes beyond iron

(a recent review, Kaeppeler et al., 2011, RvMP, 83, 157)

-(n, γ) and β-decay from Fe seeds along the stable nuclei



Classical s-process (steady flow)

basic equation

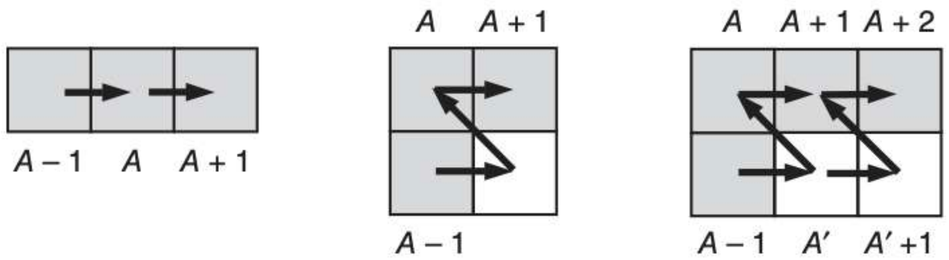
Iliadis 2007

$$\frac{dN_s(A)}{dt} = -N_n N_s(A)\langle\sigma v\rangle_A + N_n N_s(A-1)\langle\sigma v\rangle_{A-1}$$

→ equilibrium conditions (abundance flow)

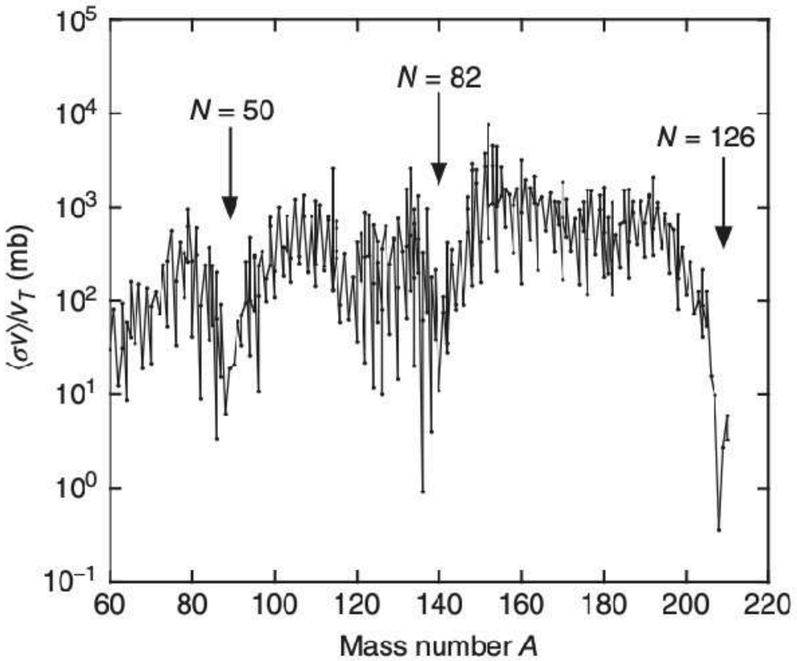
$$N_s(A,\tau)\langle\sigma\rangle_A \approx N_s(A-1,\tau)\langle\sigma\rangle_{A-1} \quad \text{or} \quad N_s(A,\tau)\langle\sigma\rangle_A \approx \text{const}$$

building blocks of the s-process

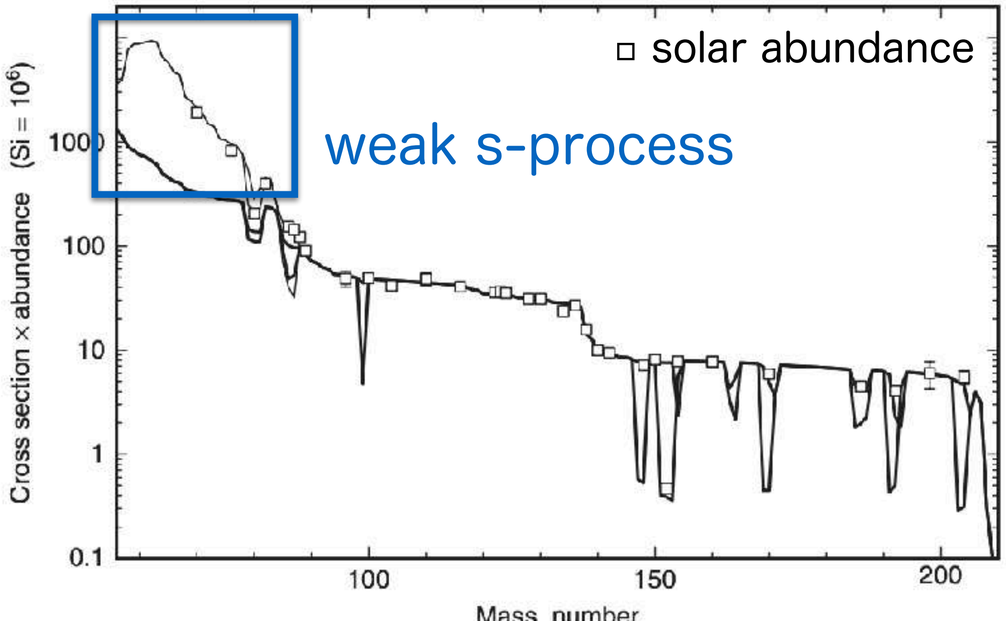


Cowan&Thieleman(2004)

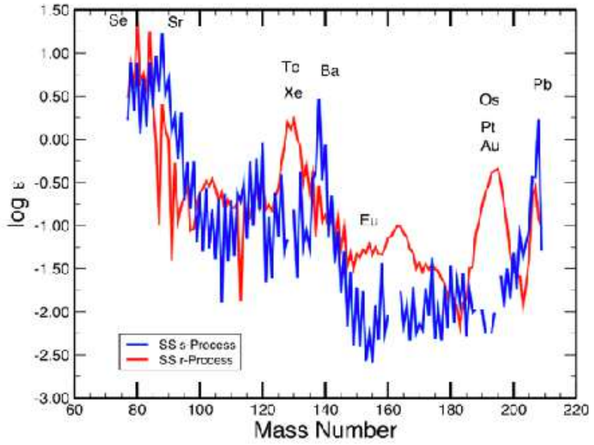
neutron capture (cross section)



s-process analytic solution
(cross-section x abundance)



solar s-process



Two astrophysical sites of the s-process

weak s-process

- massive stars (> 10 M⊙)
- core He and shell C-burnings
- neutron source: $^{22}Ne(a,n)^{25}Mg$
- weak component (A < 100)

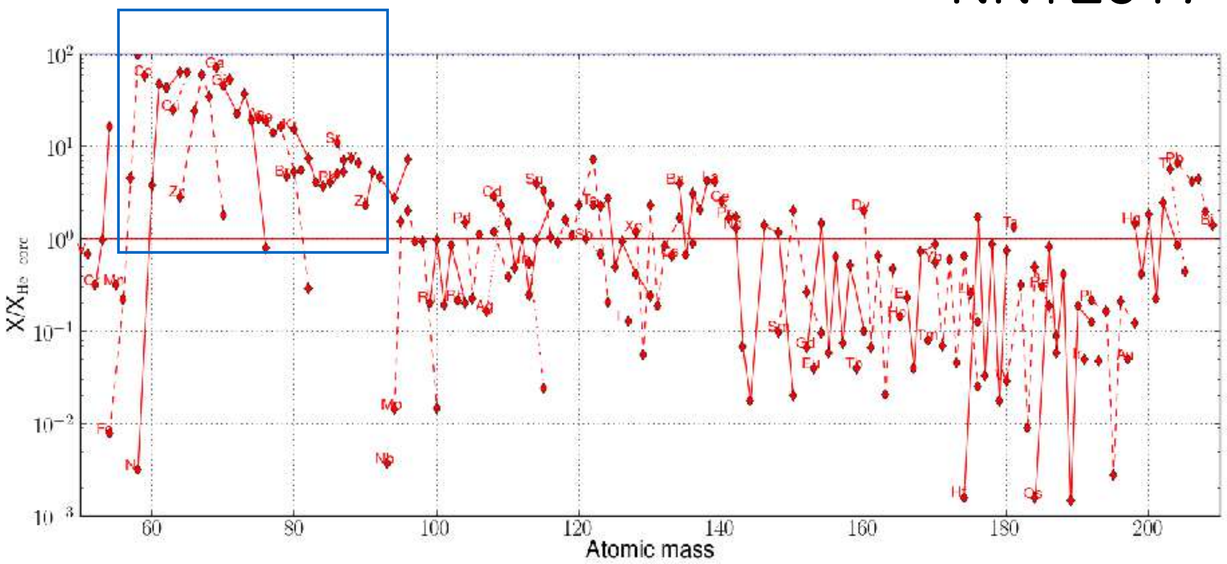
main s-process

- low mass AGB stars
- thermal pulses
- neutron source: $^{13}C(a,n)^{16}O$
- main component (up to Pb, Bi)

weak s component

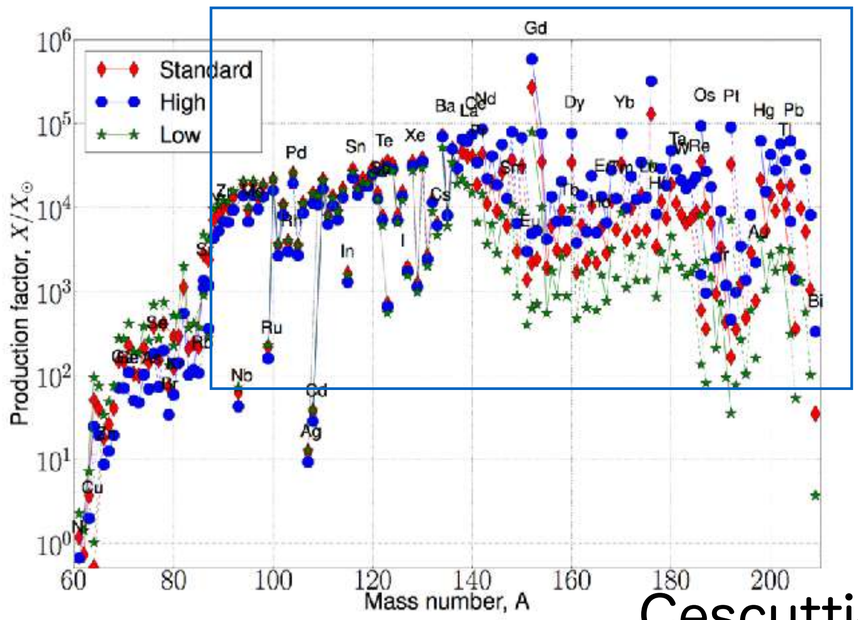
A∼60—90

NN+2017



main s component

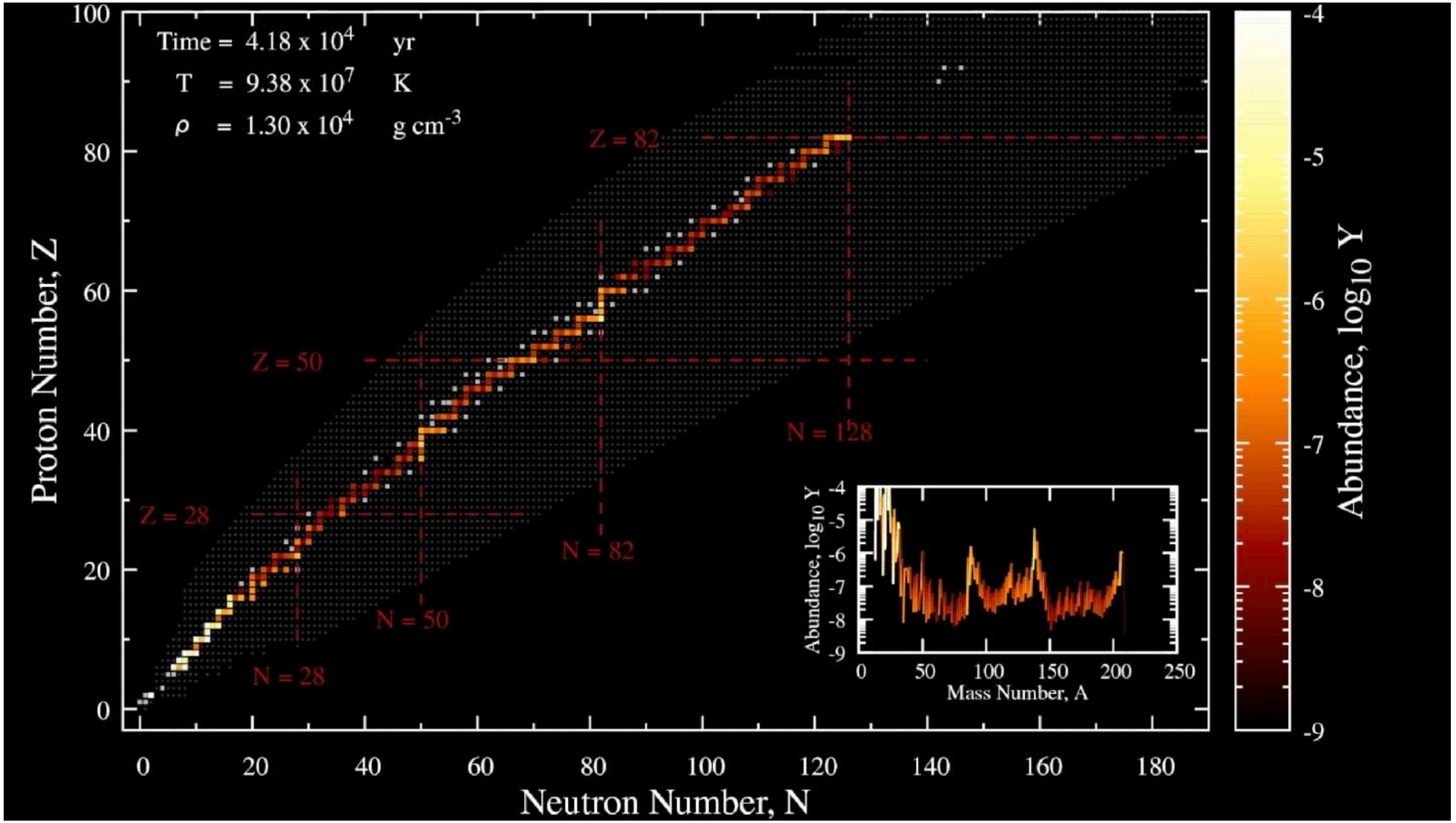
A∼90—210



Cescutti+NN+2018

s-process: nucleosynthesis flow

main s-process in low mass AGB star



Cescussti+NN+2018

Nuclear reaction network

(nuclear) abundance evolution: basic equations

thermonuclear reaction rate & astrophysics (temperature and density)

$$\dot{y}_i = \frac{dy_i}{dt} = \sum_j N_{ij} \boxed{\lambda_j} y_j + \sum_{j,k} N_{ijk} \boxed{\rho N_{\mathrm{Av}} \langle j,k \rangle} y_j + \sum_{j,k,l} N_{ijkl} \boxed{\rho^2 N_{\mathrm{Av}}{}^2 \langle j,k,l \rangle} y_j + \cdots$$

1 body (decay)

β-decay, e^+/e^- capture
(and fission)

2-body reaction
(incl. $2 \to 2$)

main nuclear reactions
n-induced decay

3-body reaction
($3 \to 1$, $3 \to 2$)

triple-α, (α, α, n)

- Ordinary differential eqs. for the change of $y_i(t)$ (the number fraction i th nucleus)
- The time variation $\dot{y}_i \sim \Delta y / \Delta t$ (finite difference) causes thermonuclear reaction (decay) rates
- In the astrophysical environments (fluids), the abundances are also changed by advection. But, the timescale of nuclear reactions can be small. (Lagrangian description is convenient.)

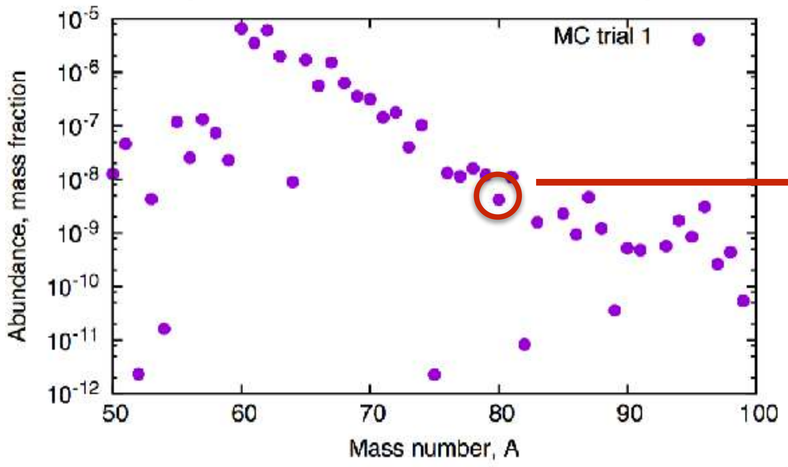
MC-variation reaction network code

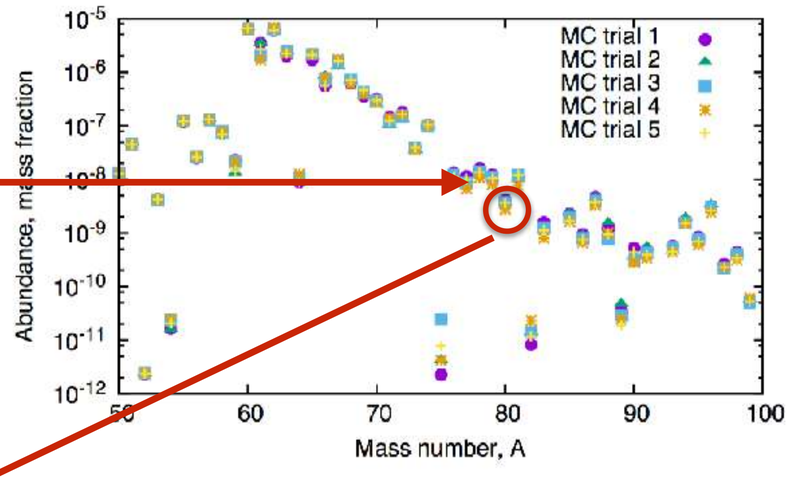
Piz Buin (mountain)

- 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

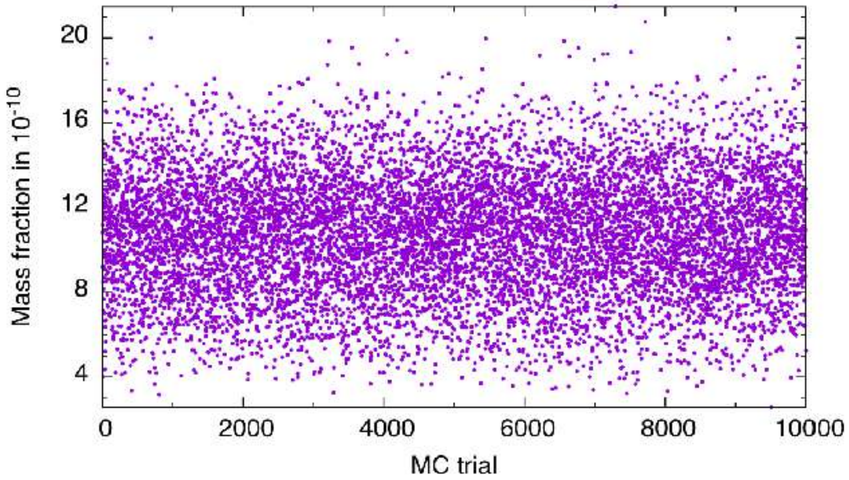
example: weak s-process

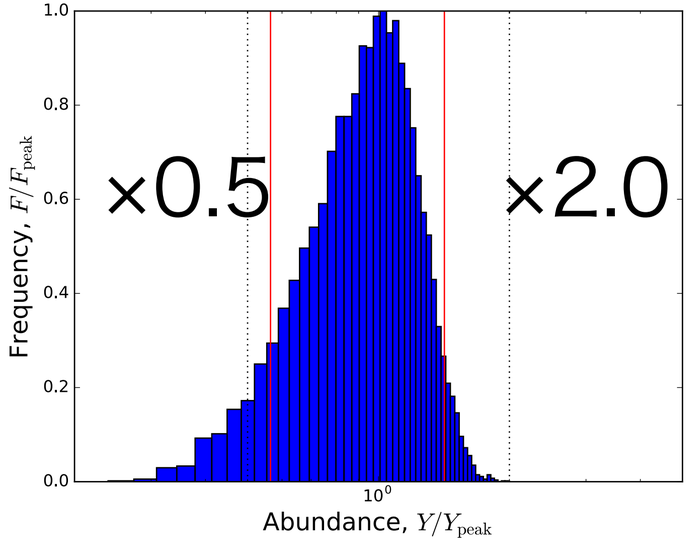




- 10,000 times iteration
- random variation (no correlation)
- uncertainty range

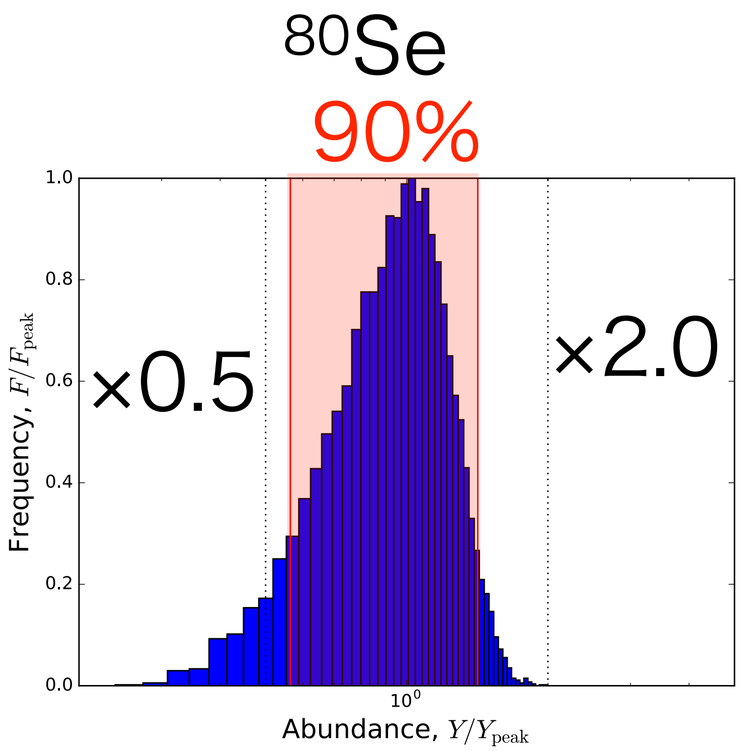
^{80}Se

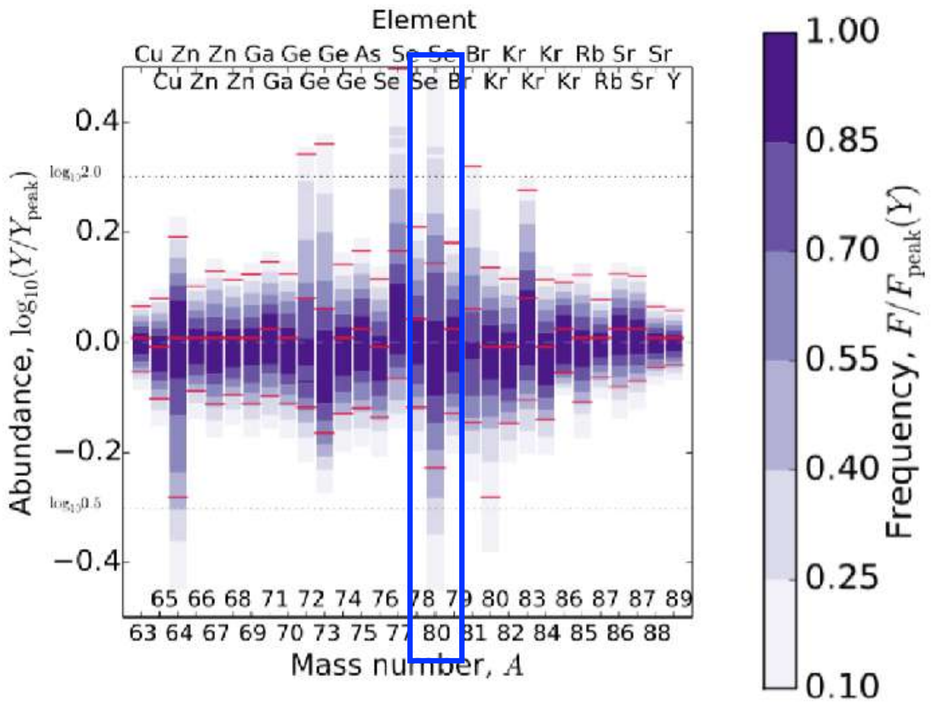


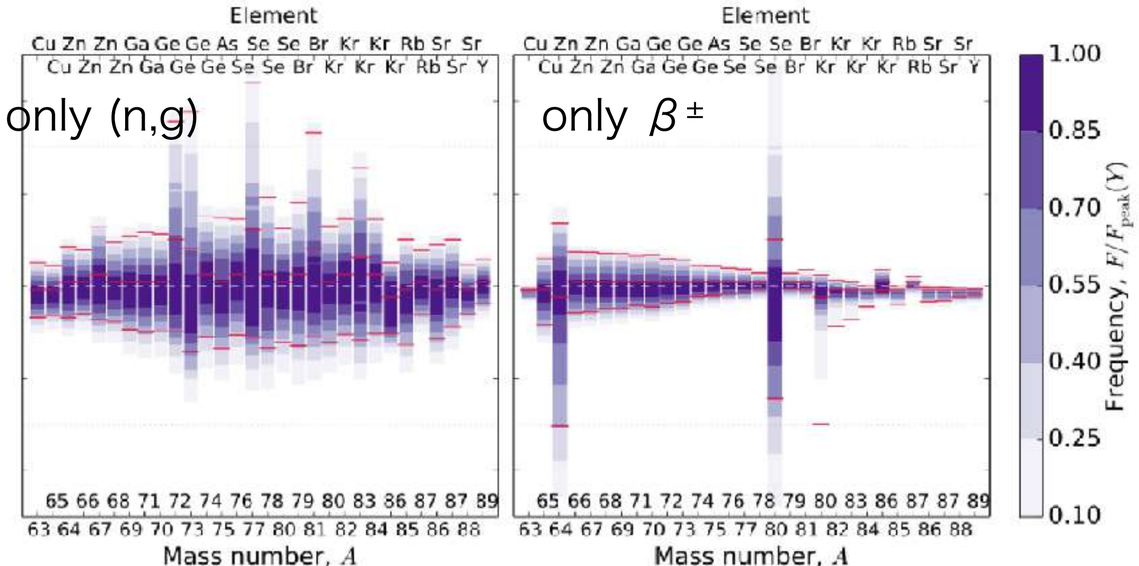


Reaction	upper	lower
(n,γ)	2.0	2.0
(p,γ)	2.0	3.0
(p,n)	2.0	3.0
(α,γ)	2.0	10.0
(α,n)	2.0	10.0
(α,p)	2.0	10.0

Uncertainty of weak s-process: (n,g) and β-decay







see NN+2017
more details,
e.g., tables

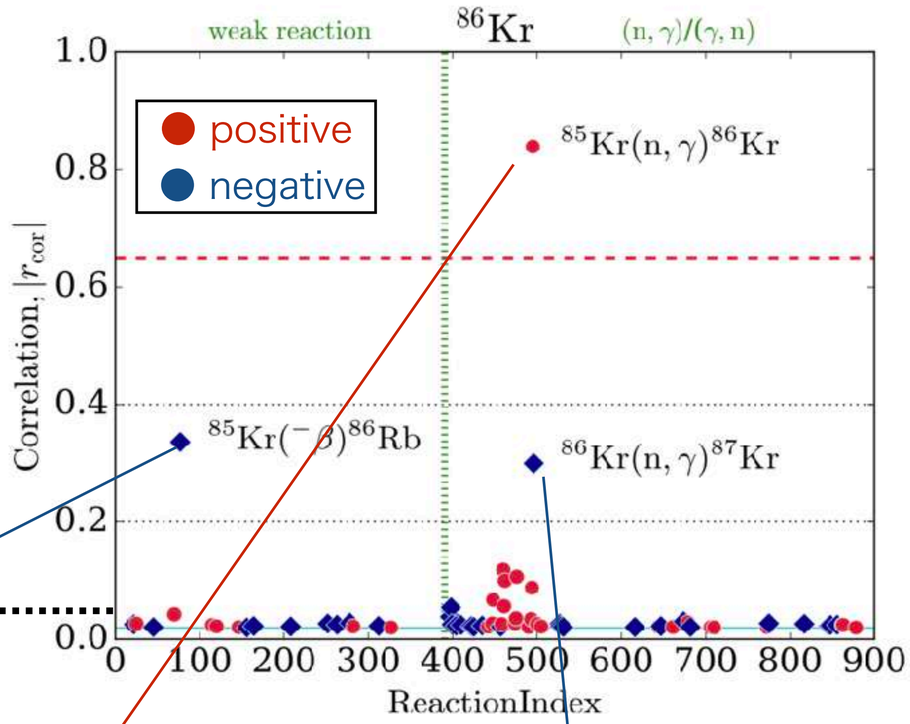
Selection by statistical analysis

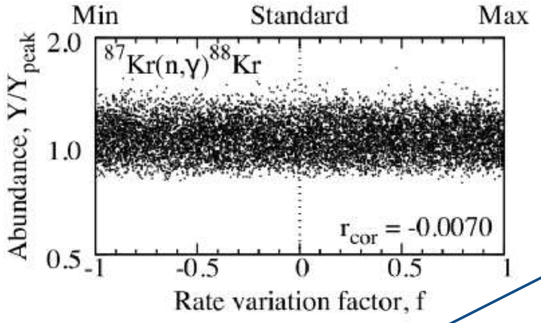
weak s-process

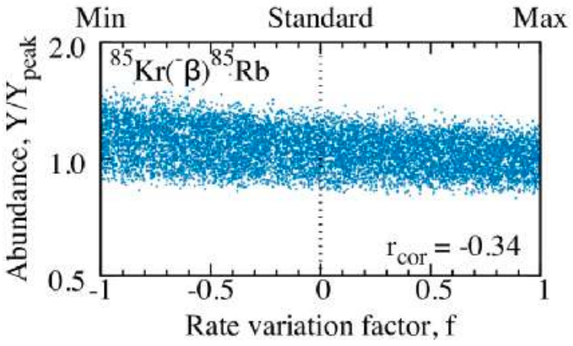
Pearson's coefficient

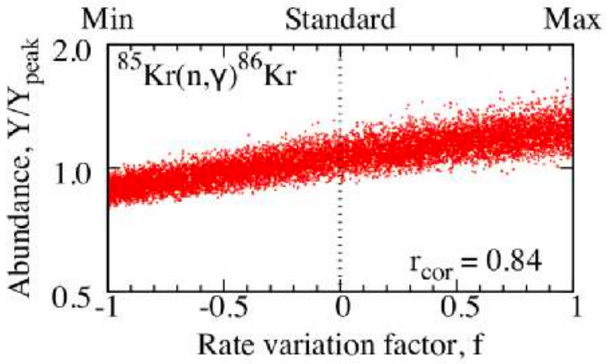
$$r_{\text{Pearson}} = \frac{\sum_{i=1}^{k} (\tilde{x}_i - \overline{x})(\tilde{y}_i - \overline{y})}{\sqrt{\sum_{i=1}^{k} (\tilde{x}_i - \overline{x})^2}\sqrt{\sum_{i=1}^{k} (\tilde{y}_i - \overline{y})^2}}$$

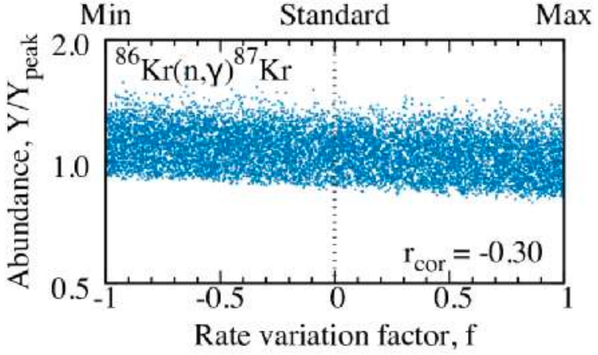
|r| > 0.65 → "strong"











Key reaction list: weak s-process

w/o Lv1 rates variation

w/o Lv1 & Lv2 rates variation

Nuclide	$r_{cor,0}$	$r_{cor,1}$	$r_{cor,2}$	Key rate Level 1	Key rate Level 2	Key rate Level 3	X_0 (8, 30 keV)	Weak rate (8, 30 keV)
^{64}Zn	0.76			^{64}Cu(β^-)^{64}Zn				1.30, 1.36
	−0.46	−0.73			^{64}Cu(e$^-$, ν_e)^{64}Ni			e$^-$ capture
^{67}Zn	−0.67			^{67}Zn(n, γ)^{68}Zn			1.00, 1.00	
^{72}Ge	−0.85			^{72}Ge(n, γ)^{73}Ge			1.00, 1.00	
^{73}Ge	−0.84			^{73}Ge(n, γ)^{74}Ge			0.88, 0.81	
^{74}Ge	−0.44	−0.54	−0.67			^{74}Ge(n, γ)^{75}Ge	1.00, 1.00	
^{75}As	−0.50	−0.59	−0.70			^{75}As(n, γ)^{76}As	1.00, 1.00	
^{77}Se	−0.86			^{77}Se(n, γ)^{78}Se			1.00, 1.00	
^{78}Se	−0.71			^{78}Se(n, γ)^{79}Se			1.00, 1.00	
	0.38	0.68			^{68}Zn(n, γ)^{69}Zn		1.00, 1.00	
^{80}Se	−0.76			^{80}Br(β^-)^{80}Kr				1.31, 4.70
	0.27	0.73			^{80}Br(β^+)^{80}Se			1.31, 4.70
	0.16	0.44	0.88			^{80}Br(e$^-$, ν_e)^{80}Se		e$^-$ capture
^{79}Br	−0.64	−0.73			^{79}Br(n, γ)^{80}Br		1.00, 1.00	
^{81}Br	−0.80			^{81}Kr(n, γ)^{82}Kr			1.00, 0.98	
^{83}Kr	−0.76			^{83}Kr(n, γ)^{84}Kr			0.81, 0.74	
^{84}Kr	−0.49	−0.65	−0.76			^{84}Kr(n, γ)^{85}Kr	1.00, 1.00	
^{86}Kr	0.84			^{85}Kr(n, γ)^{86}Kr			1.00, 1.00	
	−0.30	−0.70			^{86}Kr(n, γ)^{87}Kr		1.00, 1.00	
	−0.34	−0.62	−0.90			^{85}Kr(β^-)^{85}Rb		1.30, 1.30
^{87}Rb	−0.56	−0.65	−0.95			^{87}Rb(n, γ)^{88}Rb	1.00, 1.00	

MC results: main s-process

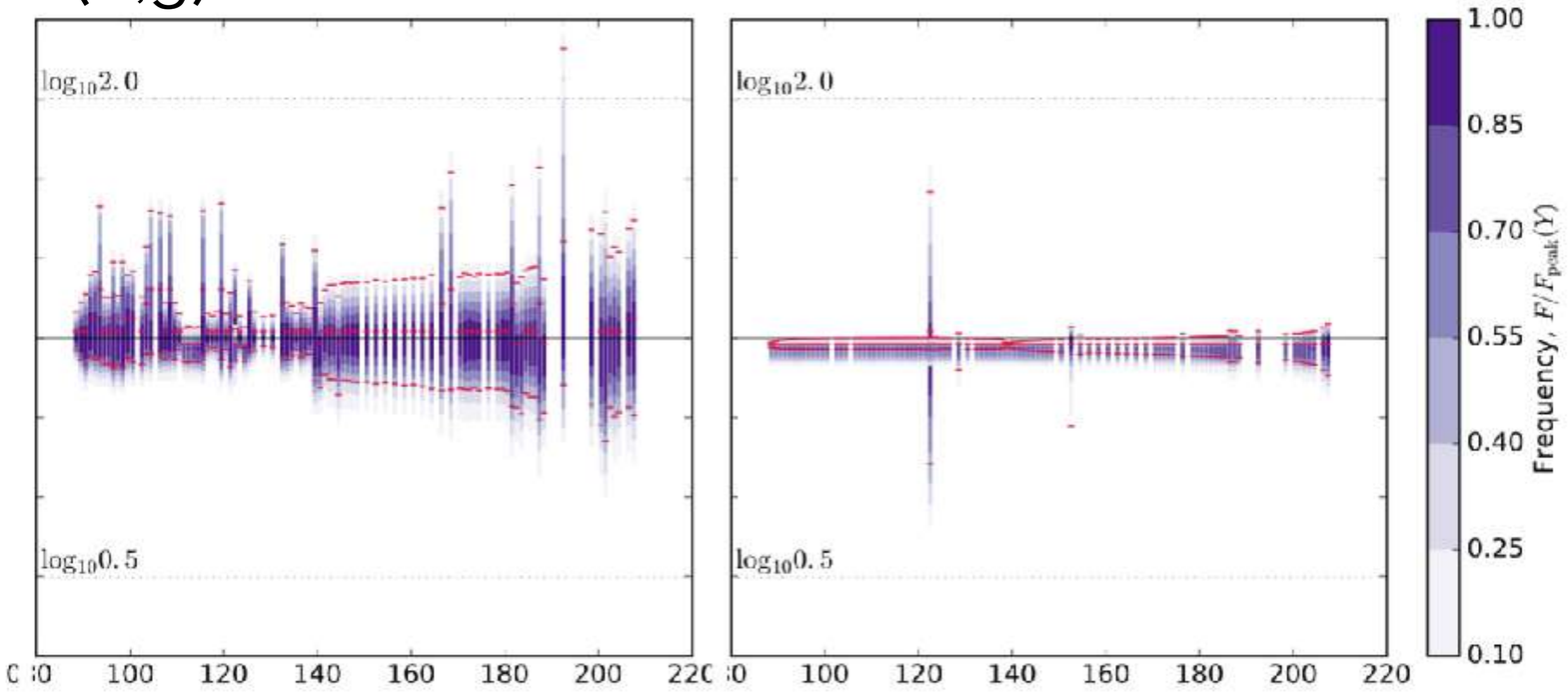
Key reactions

Cescutti+NN+(2018)

Nuclide	$r_{ca,0}$	$r_{ca,1}$	$r_{ca,2}$	Key rate Level 1	Key rate Level 2	Key rate level 3	X_0 (8, 30 keV)	β-decay
^{69}Ga	-0.77			^{69}Ga(n, γ)^{70}Ga			1.00, 1.00	
	-0.34	-0.67			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
^{71}Ga	-0.89			^{71}Ga(n, γ)^{72}Ga			1.00, 1.00	
^{70}Ge	-0.87			^{70}Ge(n, γ)^{71}Ge			1.00, 1.00	
	-0.27	-0.66			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
^{72}Ge	-0.93			^{72}Ge(n, γ)^{73}Ge			1.00, 1.00	
^{74}Ge	-0.97			^{74}Ge(n, γ)^{75}Ge			1.00, 1.00	
^{75}As	-0.86			^{75}As(n, γ)^{76}As			1.00, 1.00	
^{76}Se	-0.89			^{76}Se(n, γ)^{77}Se			1.00, 1.00	
^{78}Se	-0.97			^{78}Se(n, γ)^{79}Se			1.00, 1.00	
^{80}Se	-0.06			^{80}Se(n, γ)^{81}Se			1.00, 1.00	
^{79}Br	-0.94			^{79}Se(n, γ)^{80}Se			1.00, 1.00	
^{81}Br	-0.74			^{81}Br(n, γ)^{82}Br			1.00, 1.00	
^{80}Kr	-0.90			^{79}Se(n, γ)^{80}Se			1.00, 1.00	
	0.24	0.85			^{75}Br(β^+)^{79}Se			
^{82}Kr	-0.97			^{82}Kr(n, γ)^{83}Kr			1.00, 1.00	
^{84}Kr	-0.98			^{84}Kr(n, γ)^{85}Kr			1.00, 1.00	
^{86}Kr	0.88			^{85}Kr(n, γ)^{86}Kr			1.00, 1.00	
	-0.43	-0.95			^{85}Rb(β^+)^{85}Kr			
	-0.12	-0.28	-1.00			^{86}Kr(n, γ)^{87}Kr	1.00, 1.00	
^{85}Rb	-0.86			^{85}Rb(n, γ)^{86}Rb			1.00, 1.00	
^{87}Rb	0.86			^{85}Kr(n, γ)^{86}Kr			1.00, 1.00	
	-0.41	-0.85			^{85}Rb(β^+)^{85}Kr			
	0.20	0.39	0.77			^{86}Kr(n, γ)^{87}Kr	1.00, 1.00	
^{86}Sr	-0.94			^{86}Sr(n, γ)^{87}Sr			1.00, 1.00	
^{87}Sr	-0.92			^{87}Sr(n, γ)^{88}Sr			1.00, 1.00	
^{88}Sr	-0.65			^{88}Sr(n, γ)^{89}Sr			1.00, 1.00	
	0.47	0.69			^{56}Fe(n, γ)^{57}Fe		1.00, 1.00	
	0.47	0.68			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
	0.06	0.11	0.65			^{58}Fe(n, γ)^{59}Fe	1.00, 1.00	
^{89}Y	-0.83			^{89}Y(n, γ)^{90}Y			1.00, 1.00	
	0.33	0.67			^{56}Fe(n, γ)^{57}Fe		1.00, 1.00	
	0.34	0.68			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
	0.07	0.15	0.67			^{58}Fe(n, γ)^{59}Fe	1.00, 1.00	
^{90}Zr	-0.89			^{90}Zr(n, γ)^{91}Zr			1.00, 1.00	
	0.28	0.68			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
^{92}Zr	-0.92			^{92}Zr(n, γ)^{93}Zr			1.00, 1.00	
	0.22	0.67			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
^{94}Zr	-0.86			^{94}Zr(n, γ)^{95}Zr			1.00, 1.00	
	0.30	0.65			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
^{93}Nb	-0.97			^{93}Zr(n, γ)^{94}Zr			1.00, 1.00	
	0.14	0.67			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
^{95}Mo	-0.85			^{95}Mo(n, γ)^{96}Mo			1.00, 1.00	
	0.29	0.65			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
^{96}Mo	-0.94			^{96}Mo(n, γ)^{97}Mo			1.00, 1.00	
^{97}Mo	-0.87			^{97}Mo(n, γ)^{98}Mo			1.00, 1.00	
^{98}Mo	-0.94			^{98}Mo(n, γ)^{99}Mo			1.00, 1.00	
^{99}Ru	-0.91			^{99}Tc(n, γ)^{100}Tc			1.00, 1.00	
^{100}Ru	-0.93			^{100}Ru(n, γ)^{101}Ru			1.00, 1.00	
^{102}Ru	-0.86			^{102}Ru(n, γ)^{103}Ru			1.00, 1.00	
^{103}Rh	-0.95			^{103}Rh(n, γ)^{104}Rh			0.95, 0.80	
^{104}Pd	-0.97			^{104}Pd(n, γ)^{105}Pd			1.00, 1.00	
^{106}Pd	-0.97			^{105}Pd(n, γ)^{107}Pd			1.00, 1.00	
^{108}Pd	-0.96			^{108}Pd(n, γ)^{109}Pd			1.00, 1.00	
^{107}Ag	-0.81			^{107}Pd(n, γ)^{108}Pd			1.00, 1.00	
^{109}Ag	-0.80			^{109}Ag(n, γ)^{110}Ag			1.00, 1.00	
^{110}Cd	-0.41	-0.48	-0.71			^{110}Cd(n, γ)^{111}Cd	1.00, 1.00	
^{112}Cd	-0.40	-0.45	-0.69			^{112}Cd(n, γ)^{113}Cd	1.00, 1.00	
^{114}Cd	-0.30	-0.43	-0.65			^{114}Cd(n, γ)^{115}Cd	1.00, 1.00	
^{115}In	-0.97			^{115}In(n, γ)^{116}In			1.00, 1.00	

(n,g)-contribution

β-decay contribution



- (n,g) reactions along to the s-process path
- and weak rates (beta-decay) In the branchings

Proposal of experiments at CERN

Report Number: CERN-INTC-2017-038; INTC-P-509

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Neutron capture measurements on ^{77,78}Se and ^{68}Zn, and the origin of selenium in massive stars

April 13, 2017

C. Lederer-Woods[1,10], A. St. J. Murphy[1,10], G. Cescutti[2,10], M. Dietz[1], C. Domingo-Pardo[3], A. Gawlik[4], K. Göbel [5], R. Hirschi[6,10] , F. Käppeler[7], , D. Kurtulgil[5], S.J. Lonsdale[1], N. Nishimura[8,10], J. Perkowski[4], T. Rauscher[9,10], R. Reifarth[5], P.J. Woods[1,10], and the n_TOF Collaboration.

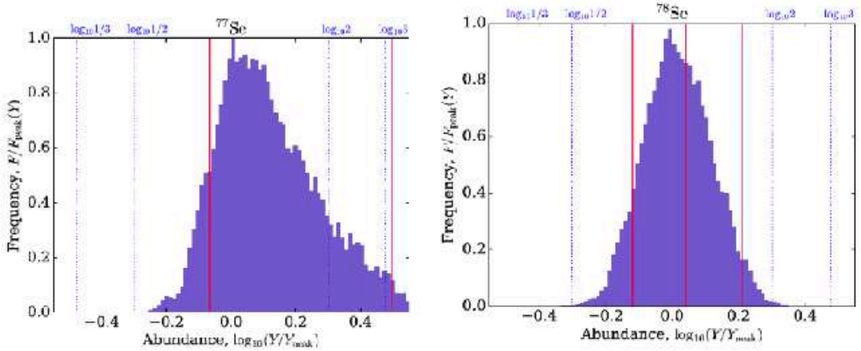


Figure 1: The final abundance distributions of ^{77}Se (left) and ^{78}Se (right) in the weak s-process, based on the result of 10,000 MC iterations. The plot shows the histogram of the frequency F for the final abundance Y normalized to the peak value, F_{peak}. Red lines correspond to the values of 5%, 50% and 95% in the cumulative frequency. Note that the histogram is plotted for logarithmic value of abundances, i.e., $\log_{10}(Y/Y_{peak})$, not for Y/Y_{peak}.

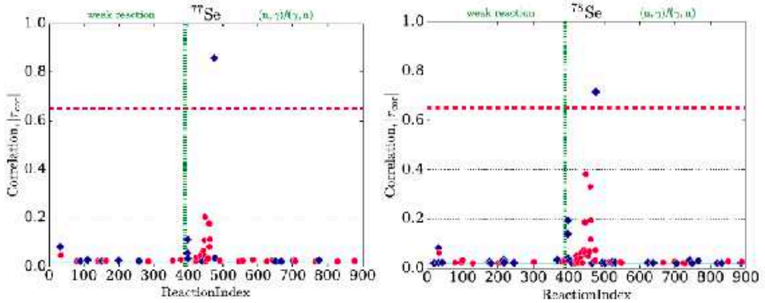
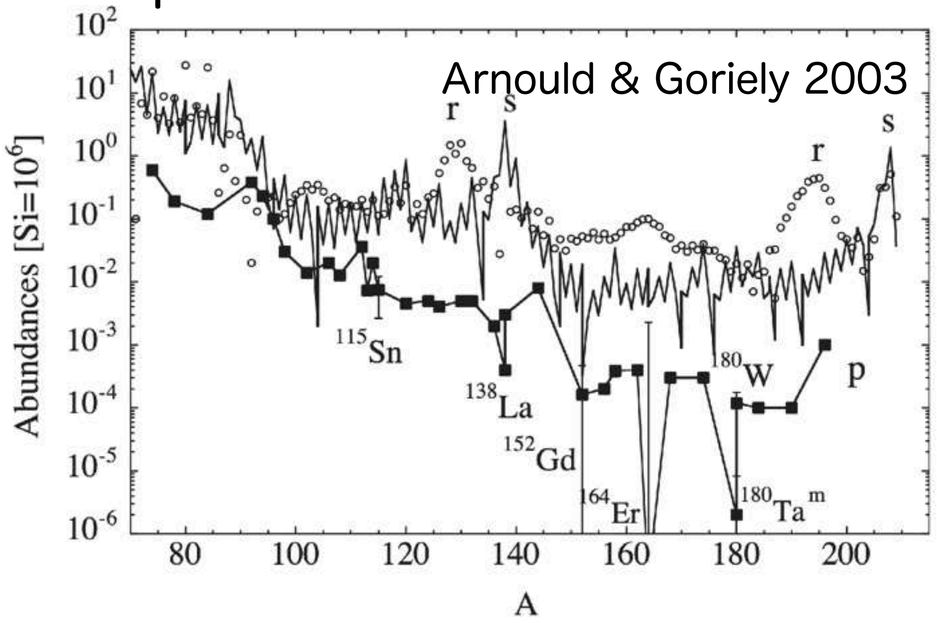


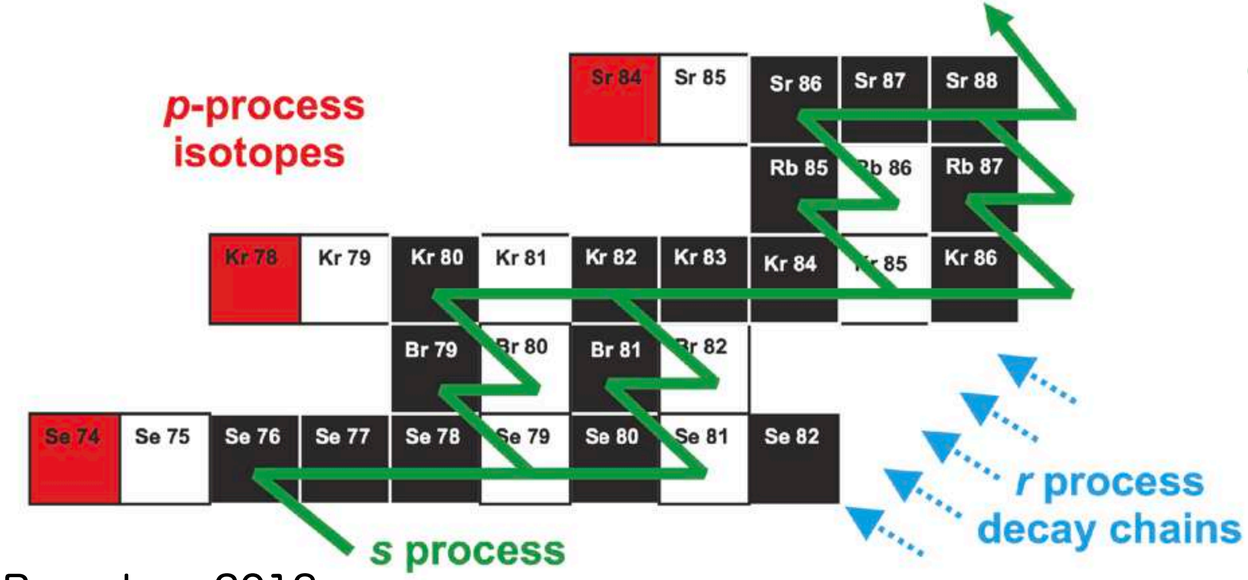
Figure 2: The correlation coefficients of reactions with respect to an abundance change of ^{77}Se (left) and ^{78}Se (right) in the weak s-process. The absolute values of the coefficients are plotted against a reaction index number. Red circles stand for positive and blue squares for negative correlation, respectively. Reaction indices in the range of 1-390 denote weak reactions and those in the range 391 – 900 identify neutron captures. Note that, for better readability, reactions with correlation factors $|r_{cor}| < 0.02$ are omitted from this plot.

Origin of p-nuclei

"p-nuclei" in the solar abundances



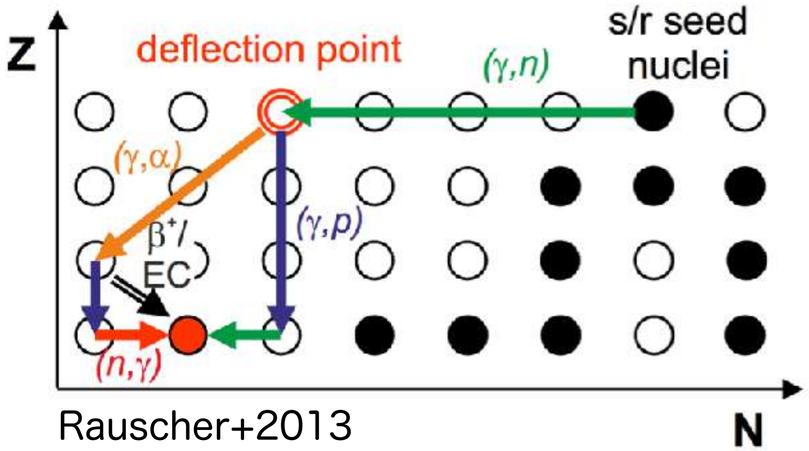
35 neutron-deficient isotope



Rauscher+2013

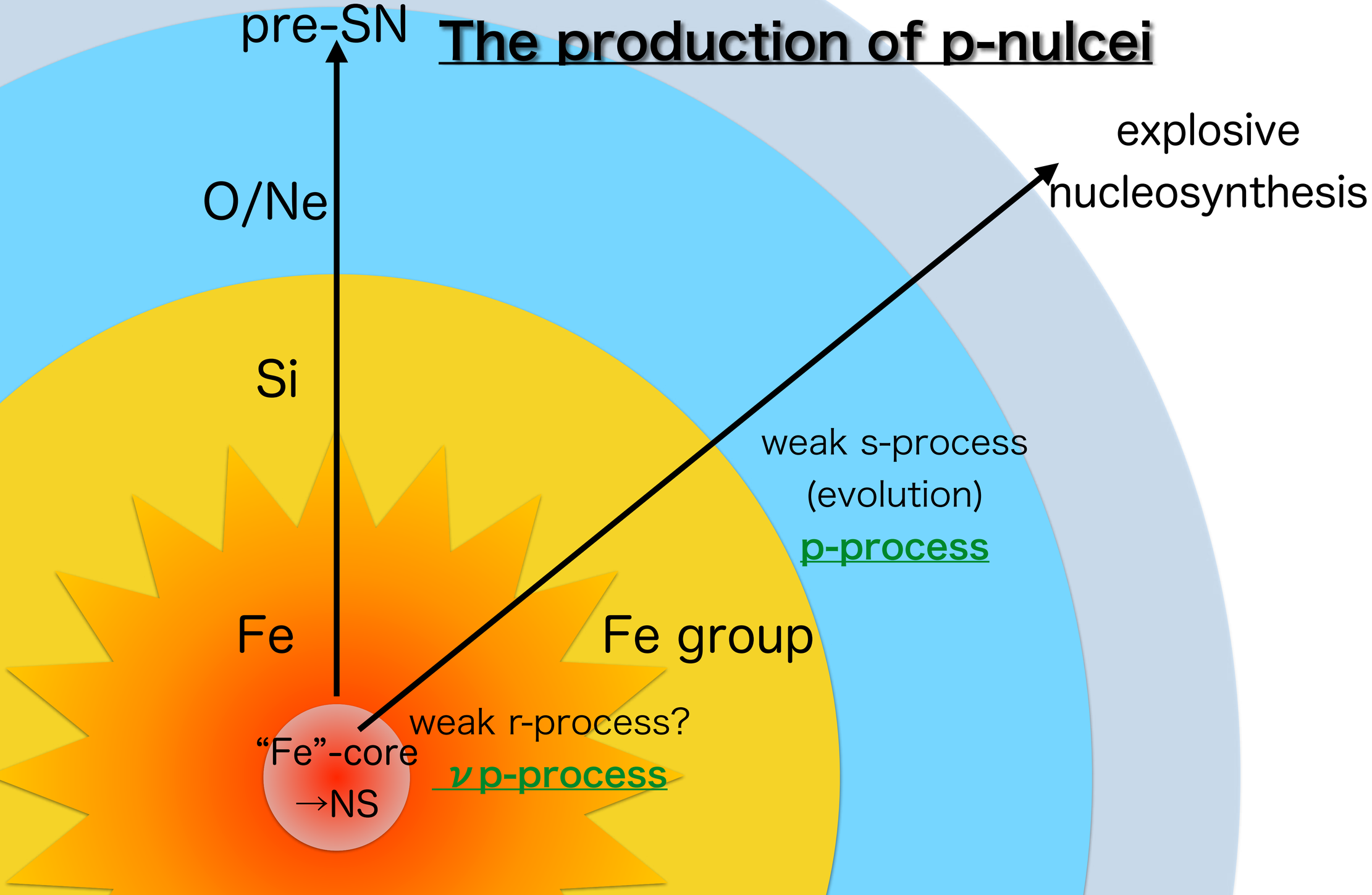
origin?

p-process
(gamma-process)



Rauscher+2013

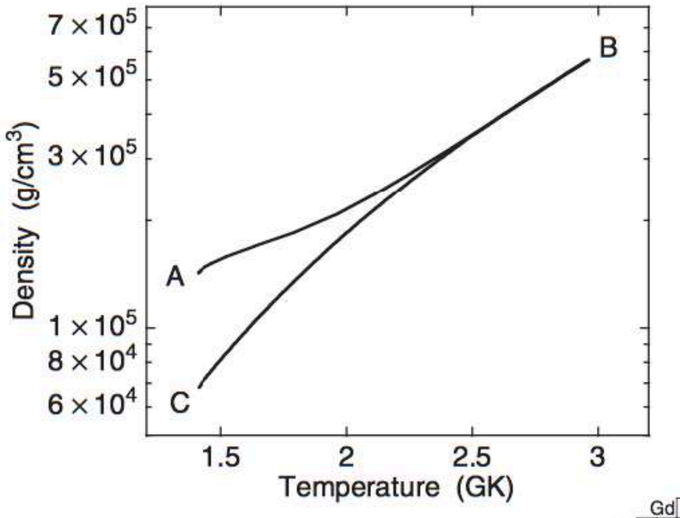
The production of p-nulcei

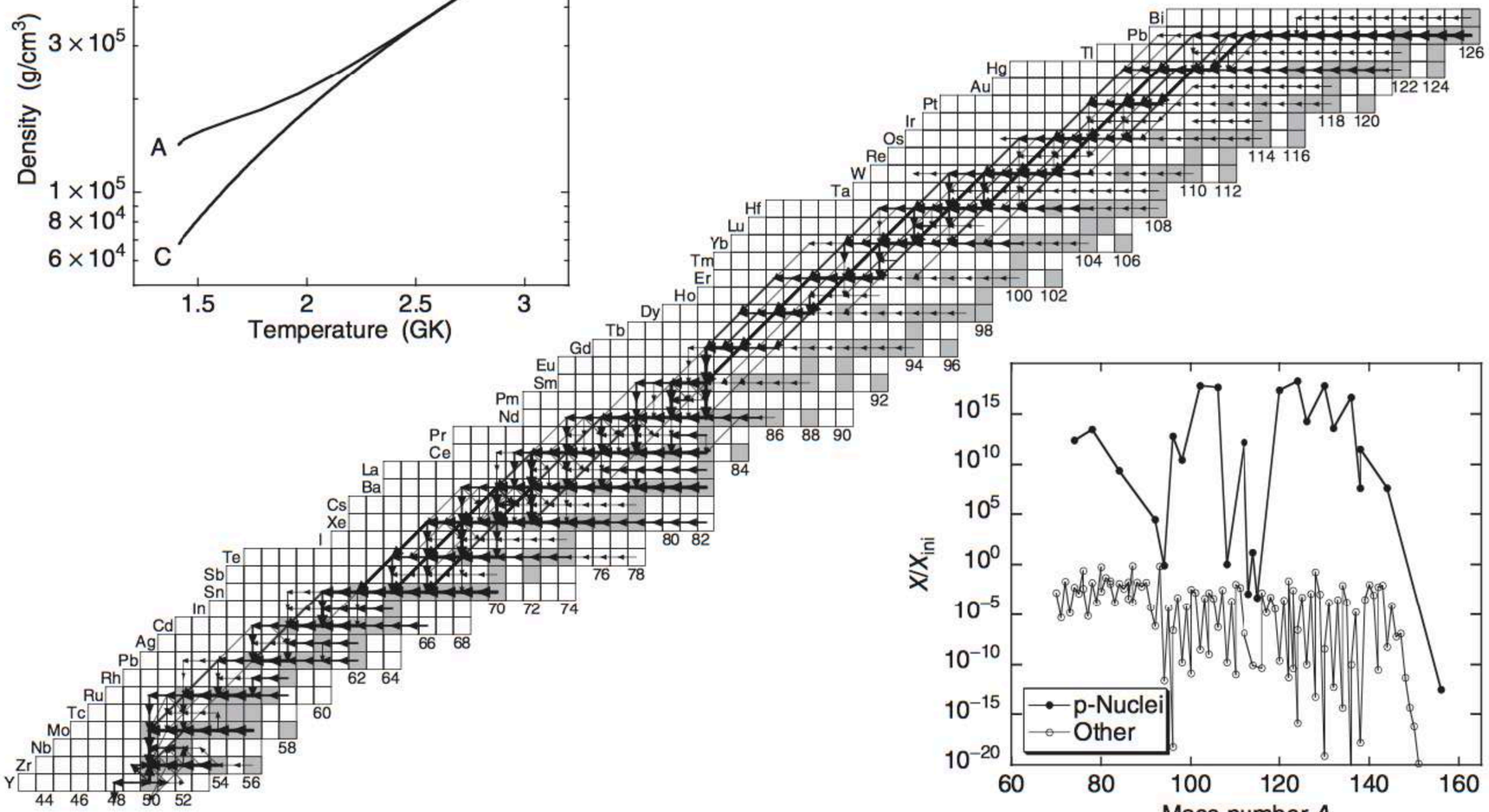


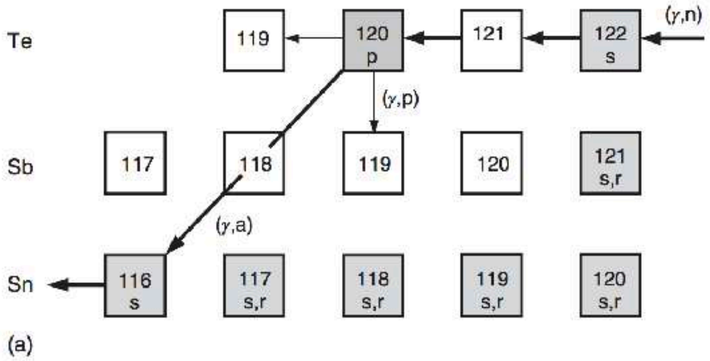
p-process (gamma-process)

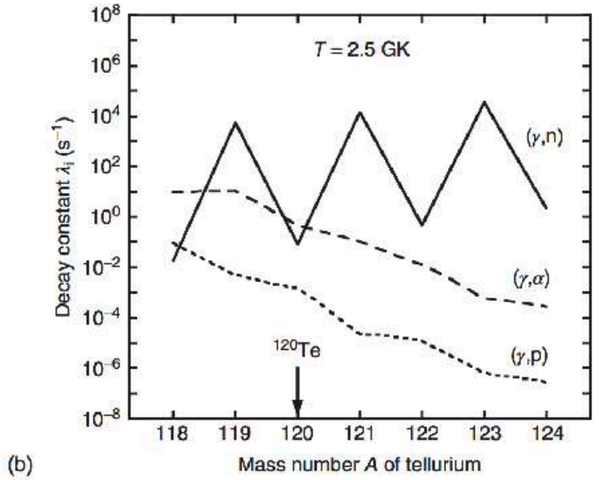
Iliadis 2015

p-Process for core-collapse supernova



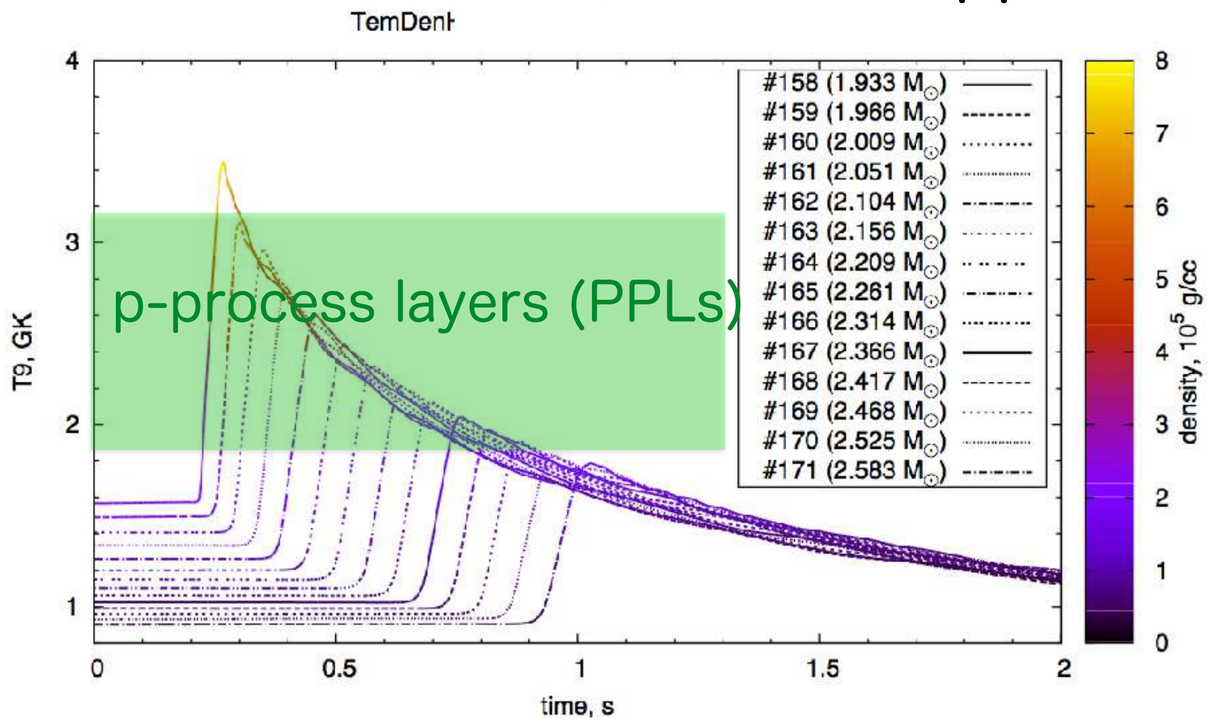






Setup: explosion model and reaction uncertainty

"Hashimoto model" (used in Rapp+ 2006; equivalent to Rayet+ 1990)



- 25 Msun model
- a simple explosion method
  - input thermal energy
- seeds used in Rayet et al. 1990

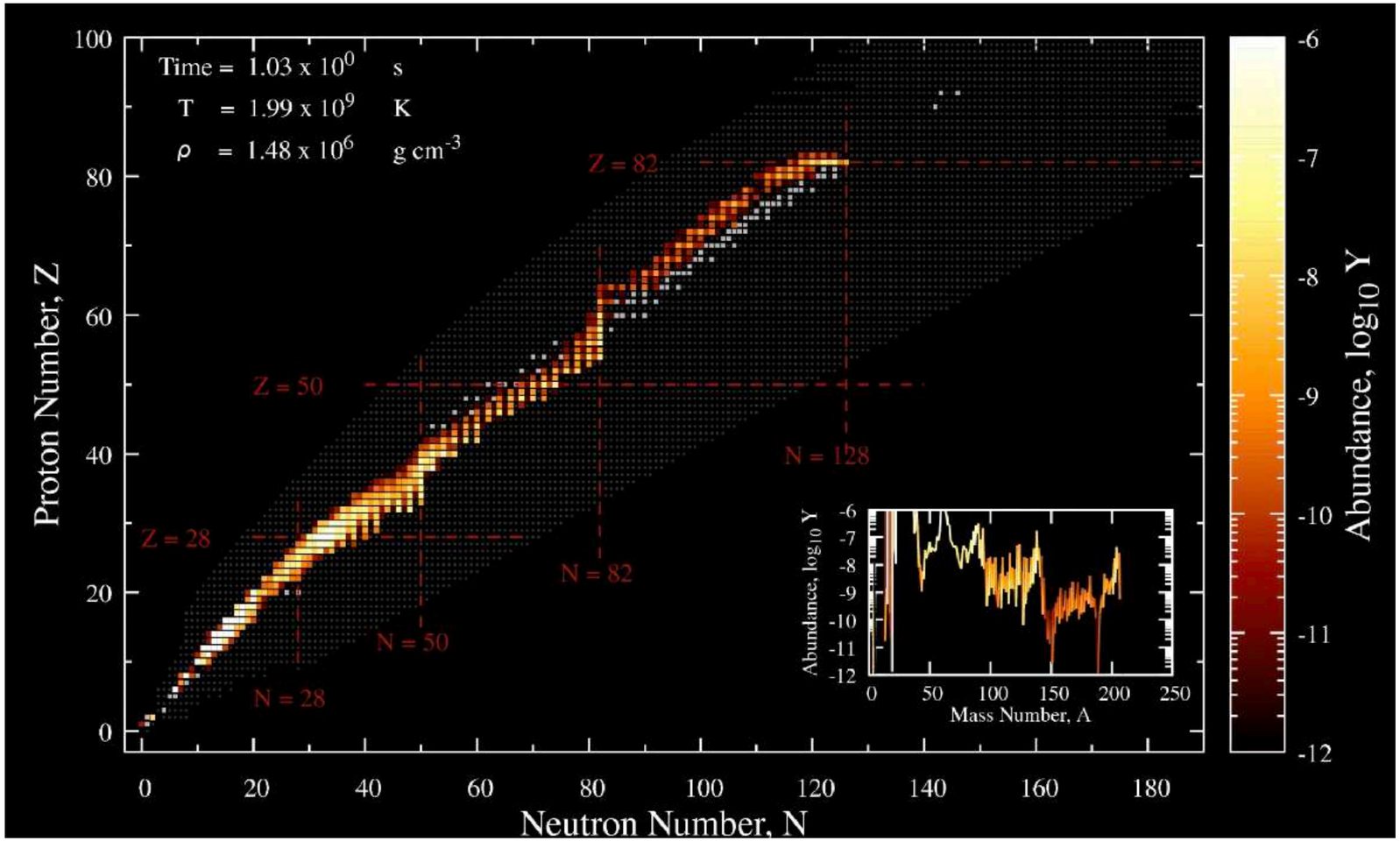
Kepler model (Rauscher 2003)

reaction types and uncertainties

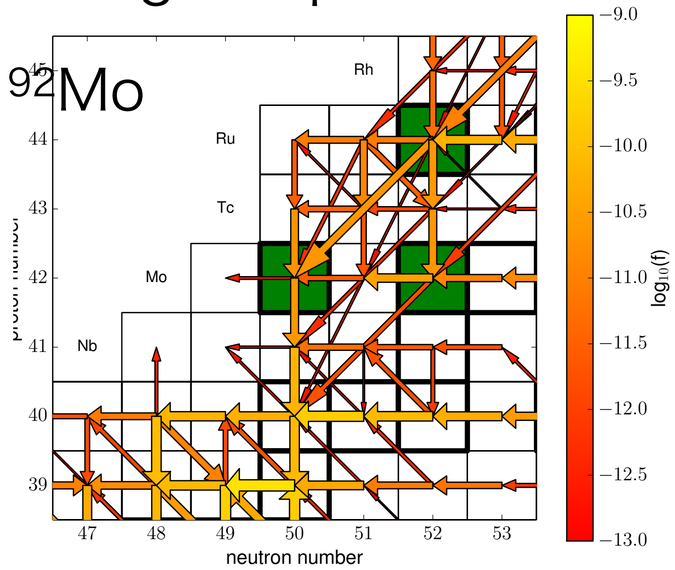
Reaction	upper	lower
(n,γ)	2.0	2.0
(p,γ)	2.0	3.0
(p,n)	2.0	3.0
(α,γ)	2.0	10.0
(α,n)	2.0	10.0
(α,p)	2.0	10.0

The p-process nucleosynthesis flow

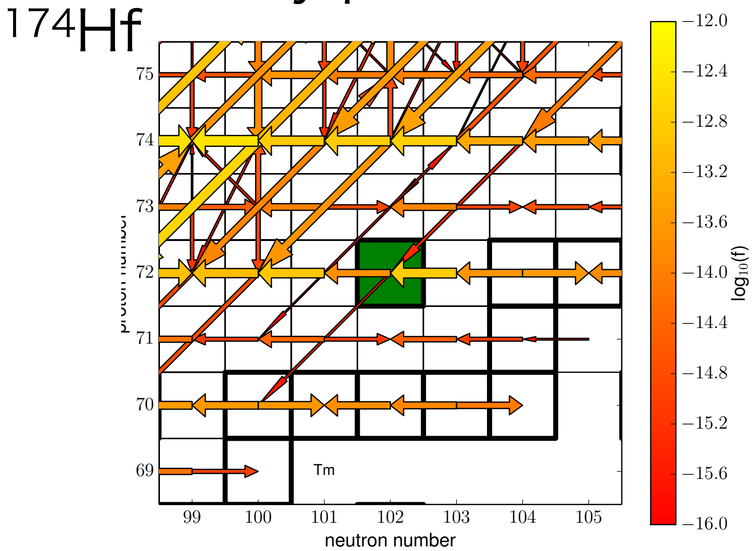
reaction network calculation
(a case of heavy p-nuclei)



lighter p-nuclei



heavy p-nuclei



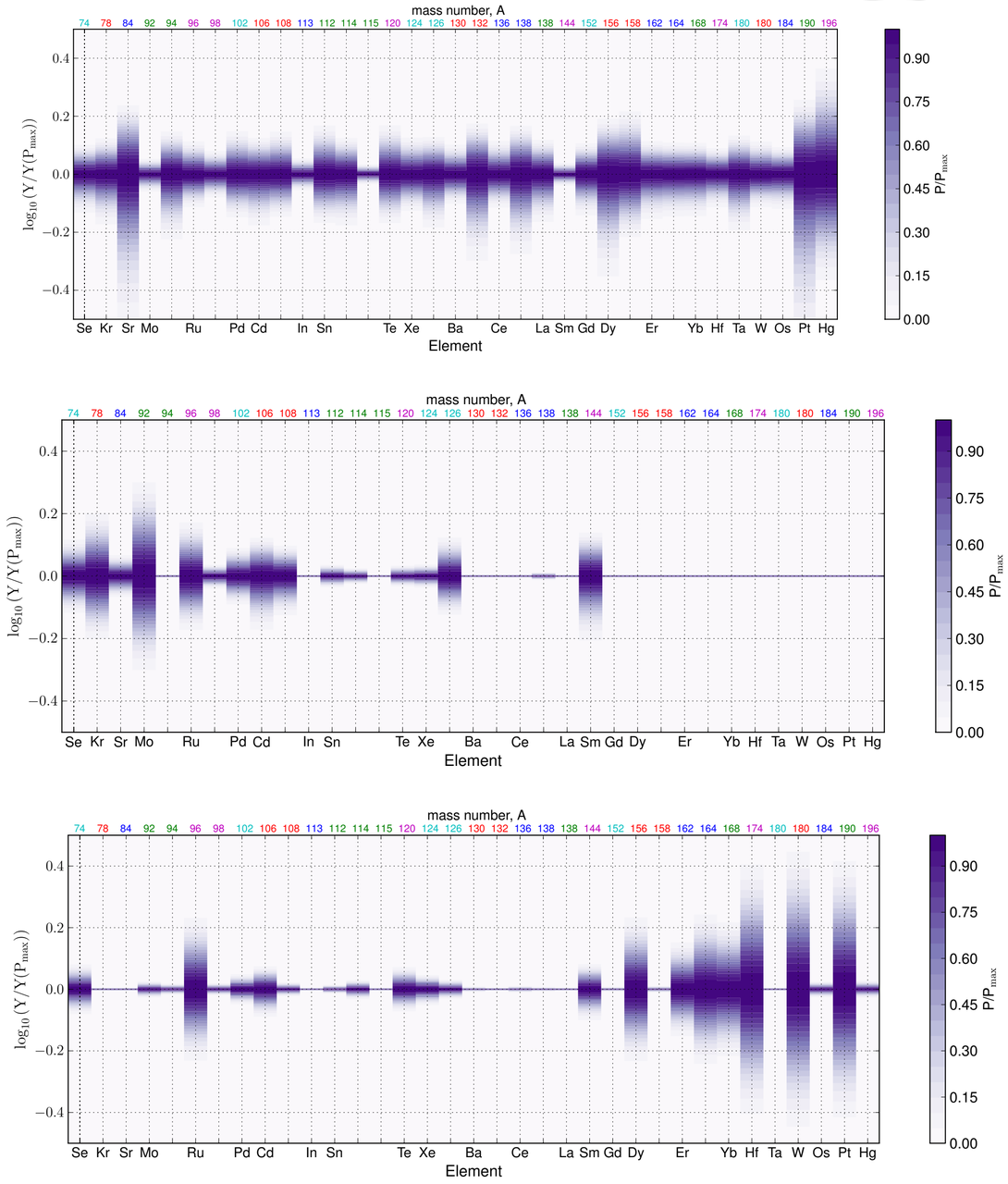
Uncertainty with individual reaction types

(n,g)/(g,n)

(p,g)/(g,p)

(a,g)/(g,a)

Light p-nuclei



Heavy p-nuclei

“key” reactions on ccNS (15 Msun)

g.s. contirbution

Nuclide	$r_{corr,0}$	$r_{corr,1}$	$r_{corr,2}$	Key rate Level 1	Key rate Level 2	Key rate Level 3	X_0 (2 GK) capture	X_0 (3 GK) capture
^{78}Kr	−0.77			^{77}Br + p ↔ γ + ^{78}Kr			9.63×10^{-2}	4.44×10^{-2}
	0.38	0.66			^{79}Kr + n ↔ γ + ^{80}Kr		1.28×10^{-1}	7.94×10^{-2}
^{92}Mo	−0.87			^{91}Nb + p ↔ γ + ^{92}Mo			8.88×10^{-1}	8.24×10^{-1}
^{94}Mo	0.78			^{95}Mo + n ↔ γ + ^{96}Mo			9.14×10^{-1}	7.69×10^{-1}
^{96}Ru	−0.67			^{92}Mo + α ↔ γ + ^{96}Ru			1.00	9.86×10^{-1}
^{102}Pd	−0.71			^{101}Pd + n ↔ γ + ^{102}Pd			5.62×10^{-1}	3.97×10^{-1}
^{112}Sn	−0.74			^{111}Sn + n ↔ γ + ^{112}Sn			7.79×10^{-1}	6.73×10^{-1}
^{136}Ce	0.53	0.66			^{137}Ce + n ↔ γ + ^{138}Ce		4.16×10^{-1}	2.54×10^{-1}
^{138}Ce	0.71			^{139}Ce + n ↔ γ + ^{140}Ce			8.71×10^{-1}	6.43×10^{-1}
^{138}La	0.94			^{138}La + n ↔ γ + ^{139}La			6.18×10^{-1}	4.92×10^{-1}
^{144}Sm	0.79			^{145}Eu + p ↔ γ + ^{146}Gd			8.06×10^{-1}	6.02×10^{-1}
^{164}Er	−0.76			^{160}Er + α ↔ γ + ^{164}Yb			2.13×10^{-1}	1.24×10^{-1}
^{168}Yb	−0.80			^{164}Yb + α ↔ γ + ^{168}Hf			2.12×10^{-1}	1.26×10^{-1}
	−0.14	−0.67			^{166}Yb + α ↔ γ + ^{170}Hf		1.80×10^{-1}	1.10×10^{-1}
^{180}Ta	−0.88			^{180}Ta + n ↔ γ + ^{181}Ta			7.09×10^{-2}	3.96×10^{-2}
	0.09	0.90			^{179}Ta + n ↔ γ + ^{180}Ta		2.37×10^{-1}	1.46×10^{-1}
^{180}W	−0.82			^{176}W + α ↔ γ + ^{180}Os			1.83×10^{-1}	1.04×10^{-1}
^{190}Pt	−0.79			^{190}Pt + n ↔ γ + ^{191}Pt			3.58×10^{-1}	1.58×10^{-1}
^{196}Hg	−0.86			^{195}Pb + n ↔ γ + ^{196}Pb			2.97×10^{-1}	1.89×10^{-1}
	0.17	0.64	0.65			^{197}Pb + n ↔ γ + ^{198}Pb	3.28×10^{-1}	2.39×10^{-1}
^{92}Nb	0.75			^{92}Zr + p ↔ γ + ^{93}Nb			9.91×10^{-1}	9.76×10^{-1}
^{98}Tc	0.89			^{96}Mo + p ↔ γ + ^{97}Tc			9.50×10^{-1}	8.56×10^{-1}
^{146}Sm	−0.65			^{144}Sm + α ↔ γ + ^{148}Gd			9.99×10^{-1}	9.65×10^{-1}
	0.33	0.79			^{147}Gd + n ↔ γ + ^{148}Gd		9.92×10^{-1}	9.28×10^{-1}

Comparison to previous works

compared with Rapp+ 2006

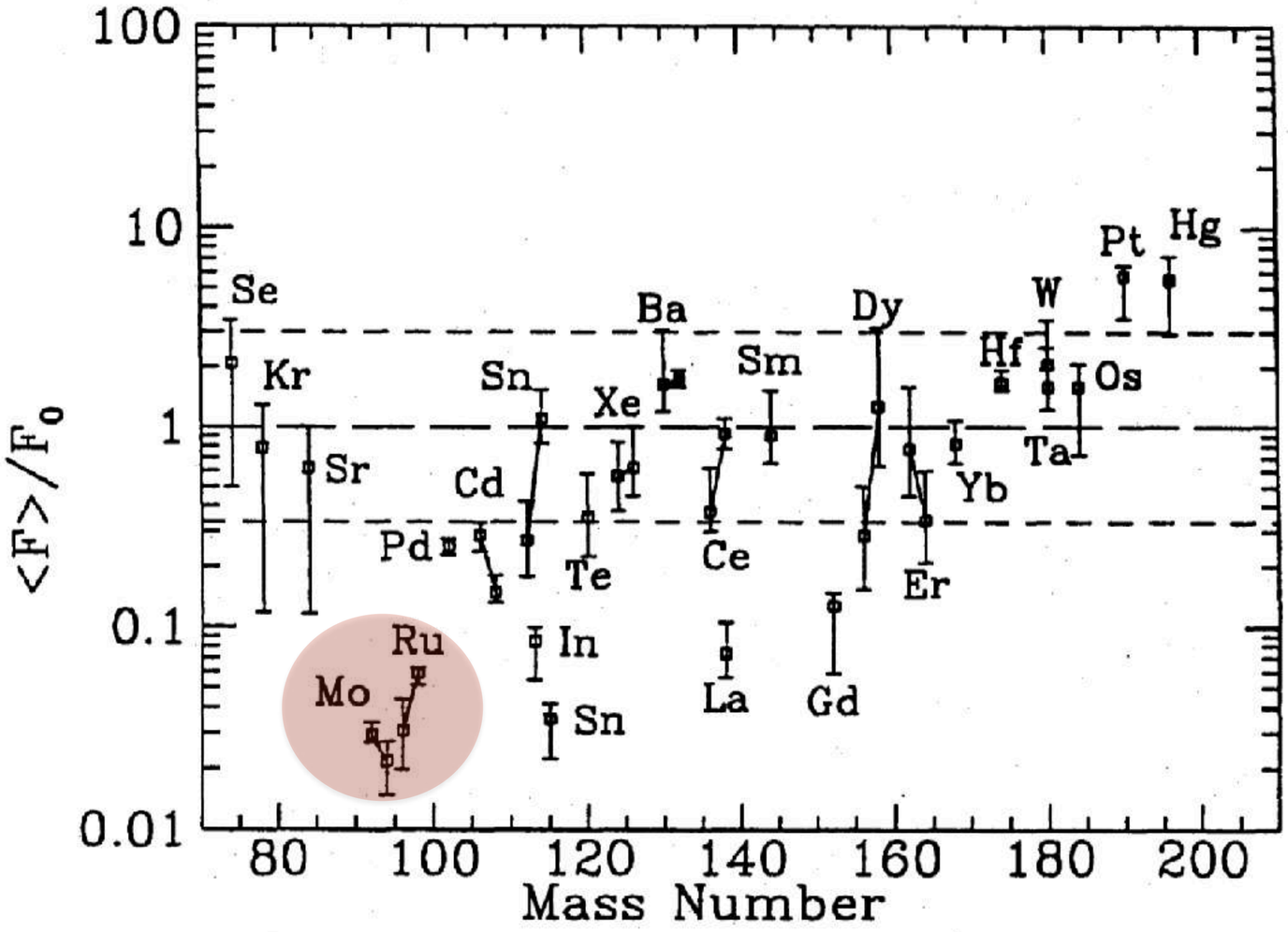
SELECTED (γ,p) OR (n,p) REACTIONS

Reactions					
$^{126}Ba(\gamma,p)^{125}Cs^*$	Lv1	$^{92}Mo(\gamma,p)^{91}Nb^*$	Lv1	~~$^{75}Se(n,p)^{75}As^*$~~	
~~$^{110}Sn(\gamma,p)^{109}In^*$~~		~~$^{86}Rb(n,p)^{86}Kr^*$~~		~~$^{74}Se(\gamma,p)^{73}As^*$~~	
$^{106}Cd(\gamma,p)^{105}Ag$		~~$^{85}Sr(n,p)^{85}Rb^*$~~		~~$^{76}As(n,p)^{76}Ge^*$~~	
$^{104}Cd(\gamma,p)^{103}Ag$		~~$^{84}Sr(\gamma,p)^{83}Rb^*$~~		~~$^{75}As(\gamma,p)^{74}Ge^*$~~	
$^{100}Pd(\gamma,p)^{99}Rh$		$^{78}Kr(\gamma,p)^{77}Br^*$	Lv1	$^{73}As(\gamma,p)^{72}Ge$	
$^{96}Ru(\gamma,p)^{95}Tc^*$	Lv2	$^{77}Se(n,p)^{77}As$		$^{71}Ge(n,p)^{71}Ga$	

* especially important

Lighter p-nuclei?

Prantzos+1995

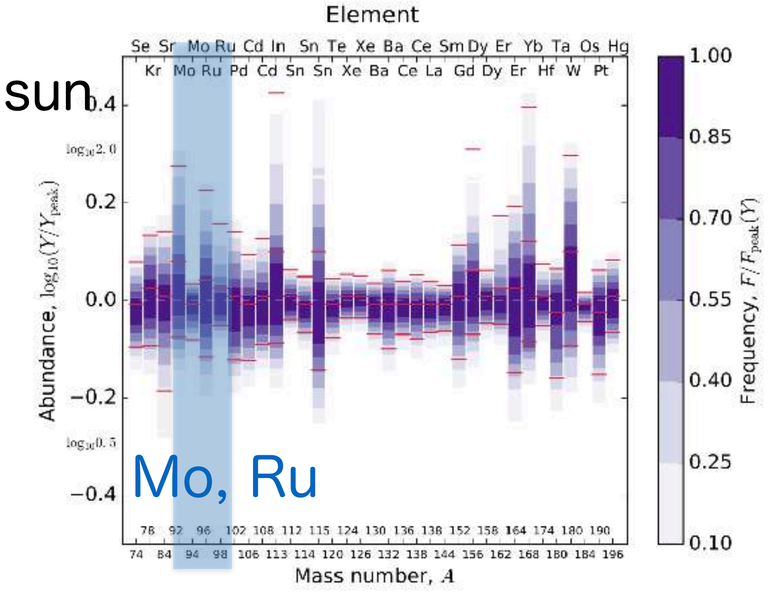


error bars:

different SN (progenitor) models

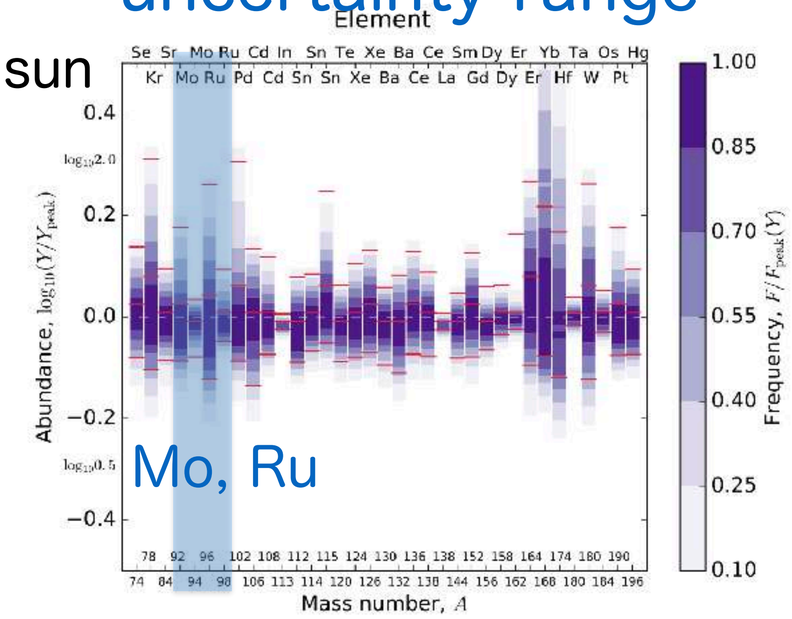
Rascher, NN+2016

15Msun



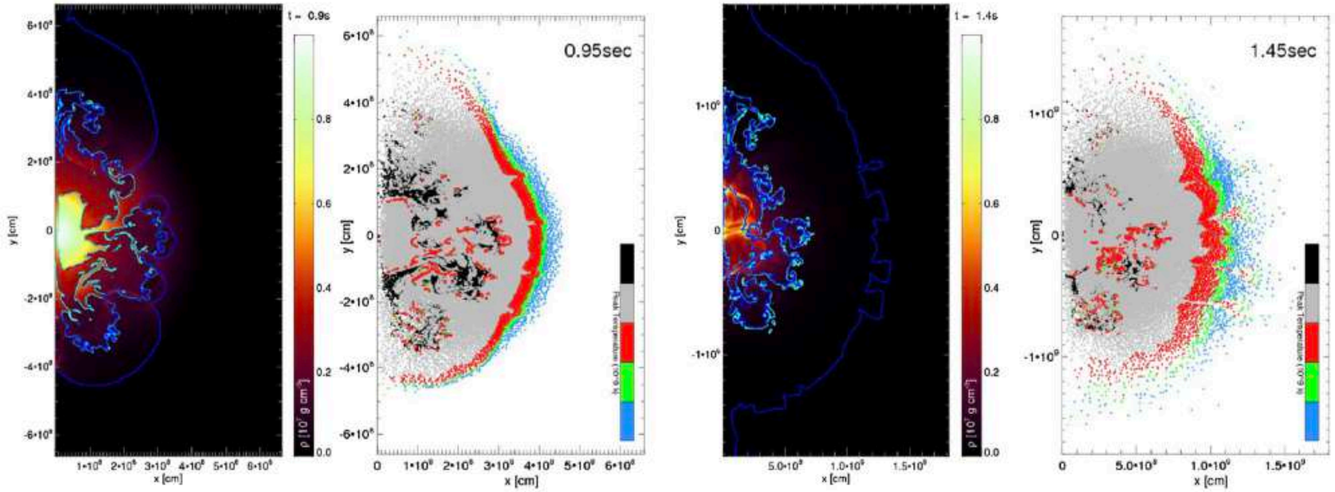
uncertainty range

25Msun



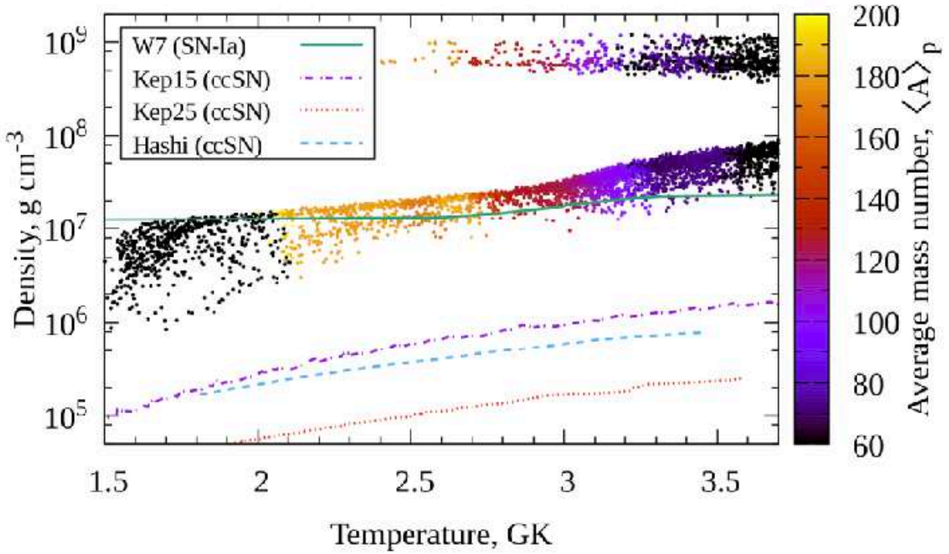
the p-process in type Ia SNe

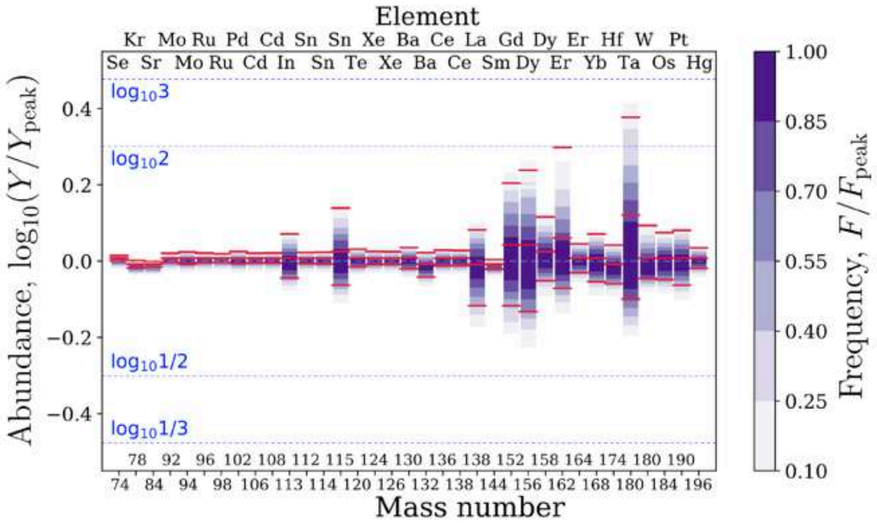
p-process in a type Ia SN (Travaglio+2011)



NN+2018, MNRAS

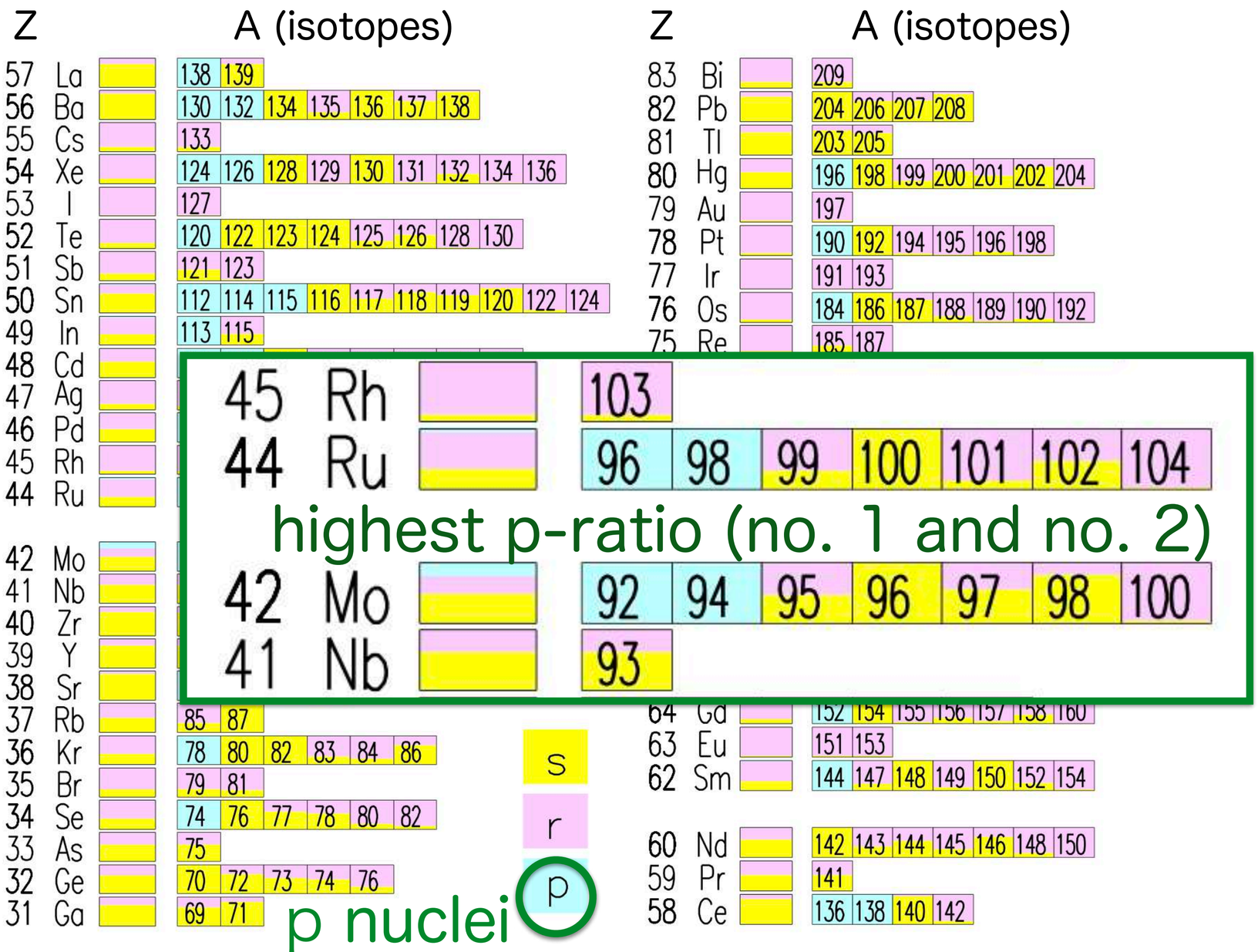
“key reaction” $^{145}\mathrm{Eu} + \mathrm{p} \leftrightarrow \gamma + {}^{146}\mathrm{Gd}$





The solar isotopic abundances

Prantzos+2020



Proton-rich matter in cc-SNe

around the SN core: neutron-rich? → NO, due to neutrino heating

(strong magnetic explosion?, if you want to see the r-process → next topic)

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

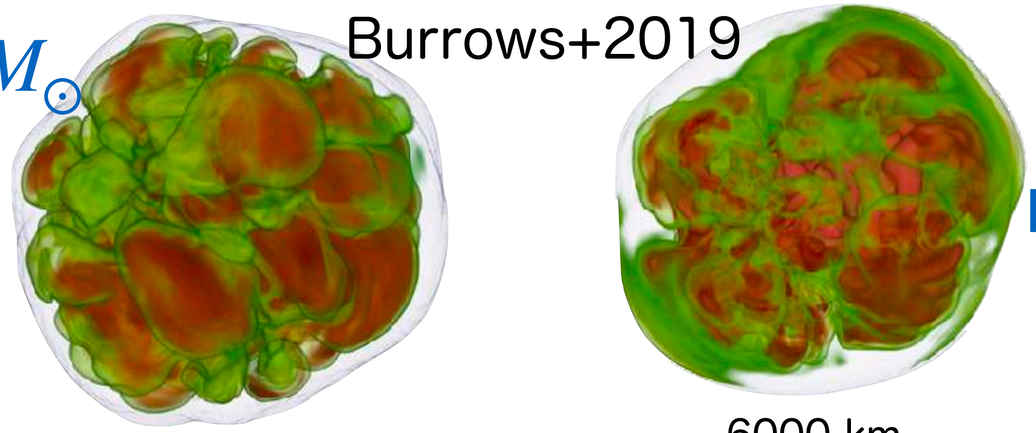
Y_e tail reaches proton-rich?

can exceed $Y_e = 0.6$

(also several other groups, e.g., K. Nakamura+)

Burrows+2019

$9M_\odot$

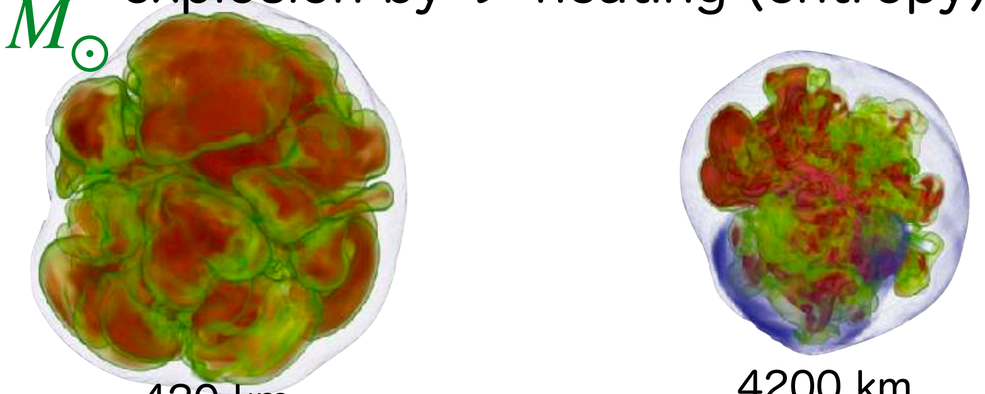


400 km

6000 km

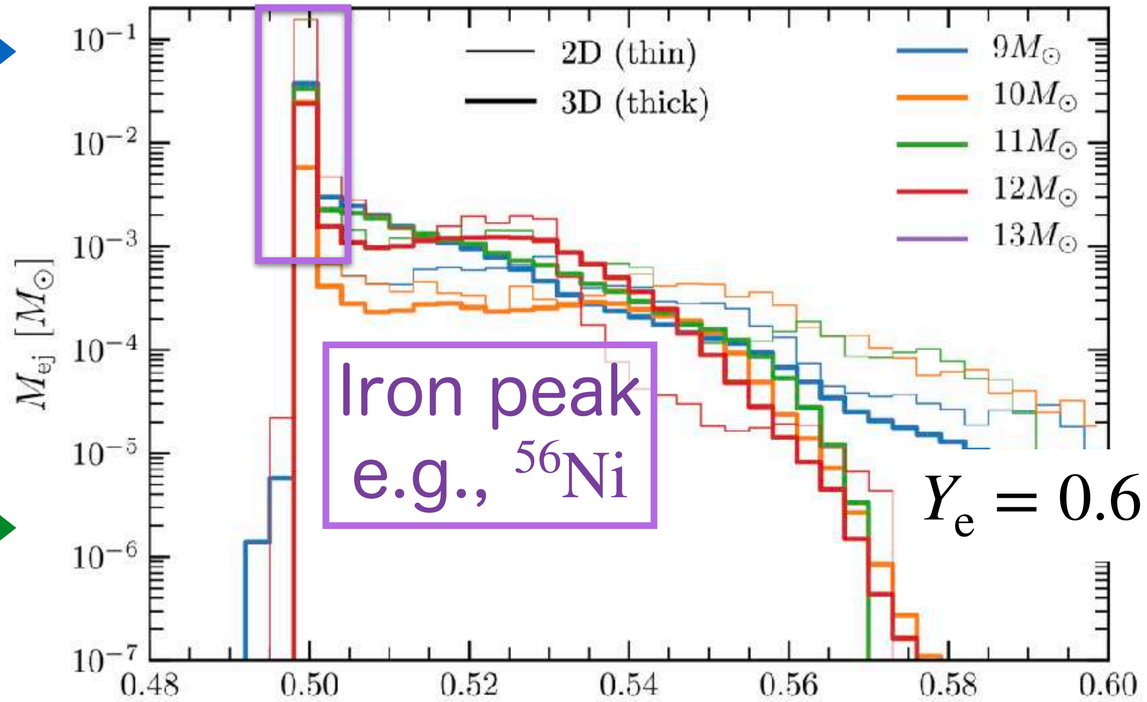
explosion by ν heating (entropy)

$11M_\odot$



420 km

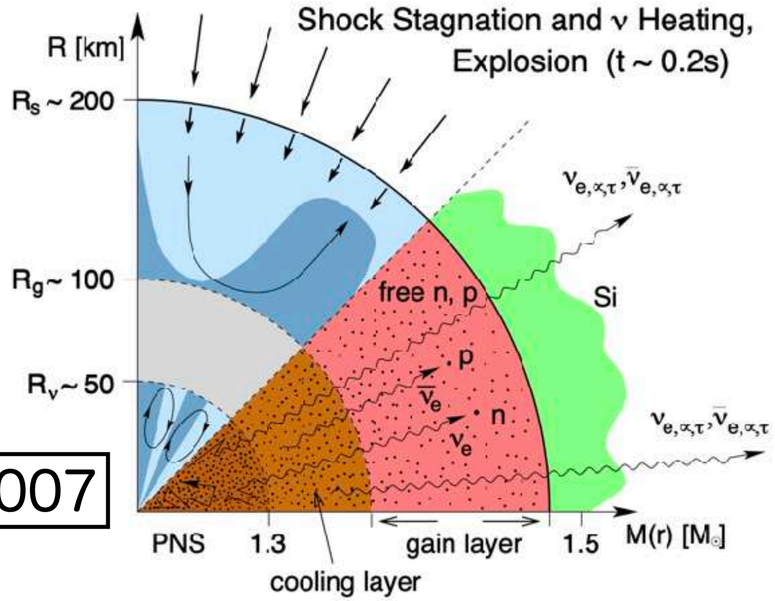
4200 km



$Y_e \sim Y_p$ Burrows+2019

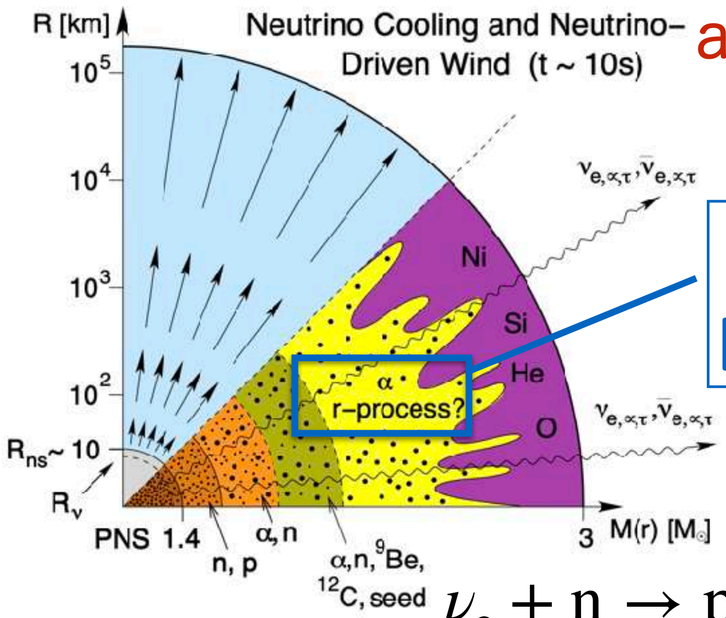
νp-process: p-capture accelerated by the ν-reaction

ν heating and explosion



Janka+2007

proto-NS cooling and ν-driven wind



r-process if n-rich but p-rich conditions?

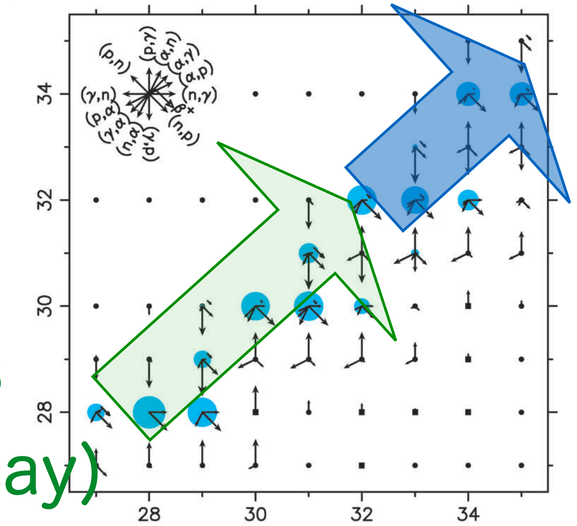
$\nu_e + n \rightarrow p + e^-$ & $\bar{\nu}_e + p \rightarrow n + e^+$

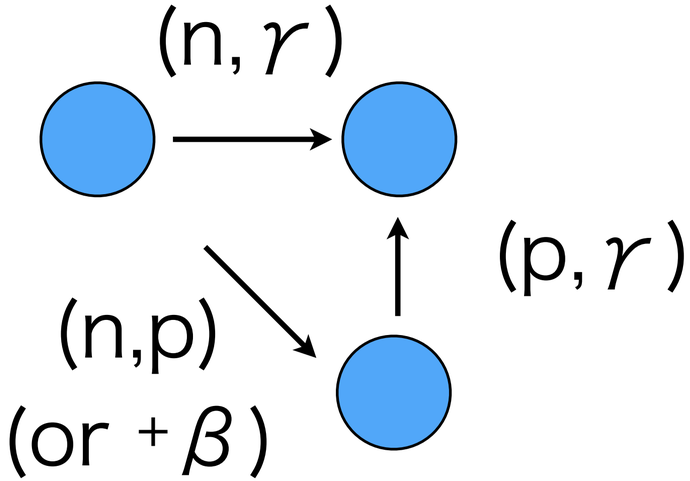
- α recombination: initiated by triple-α immediately reaches Fe peak (^{56}Ni)
- sequence of (p,g) and β^+ decay

^{64}Ge: half-life ~ 1 min.

explosion time scale ~ s

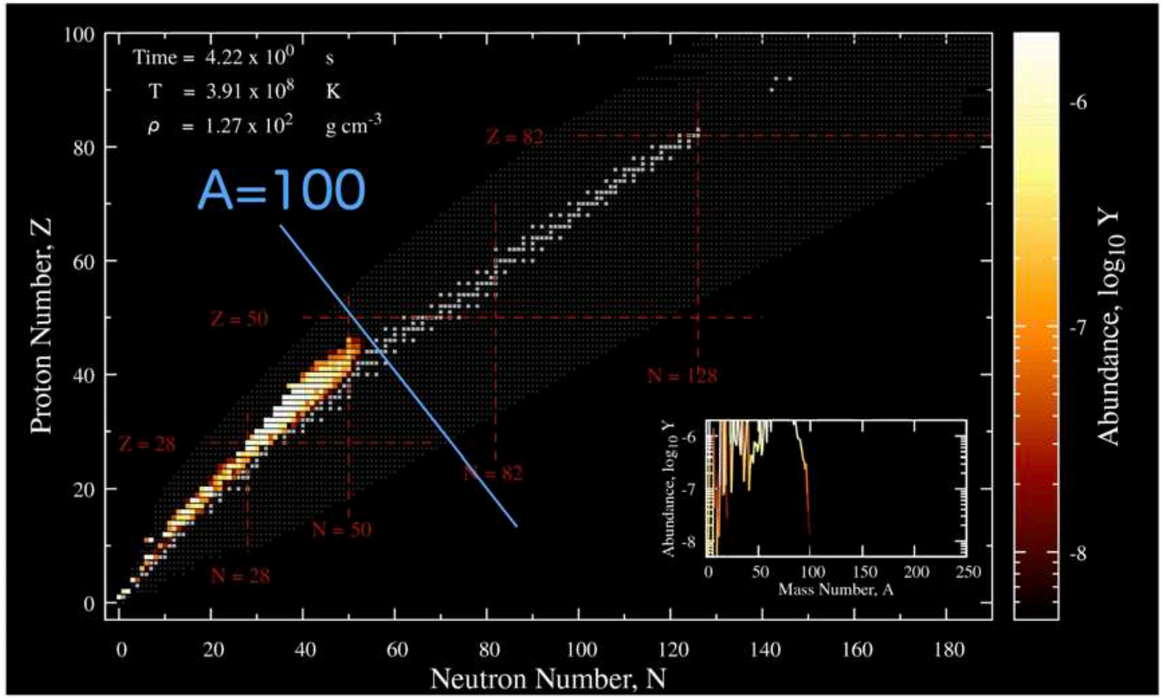
(stalls by waiting β decay)



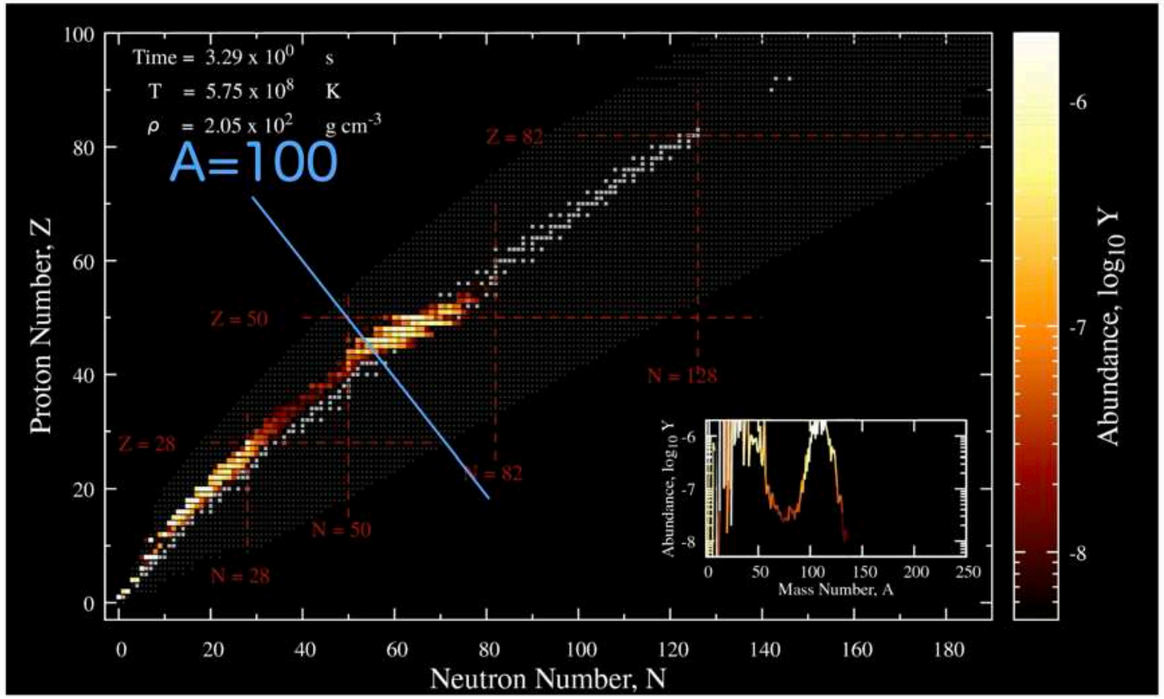


Nucleosynthesis simulations

ν p-process ("initial" $Y_e \sim 0.6$)



stronger ν p-process ("initial" $Y_e \sim 0.7$)



NN+2019

※1D wind model with parameters suggested by SN simulations

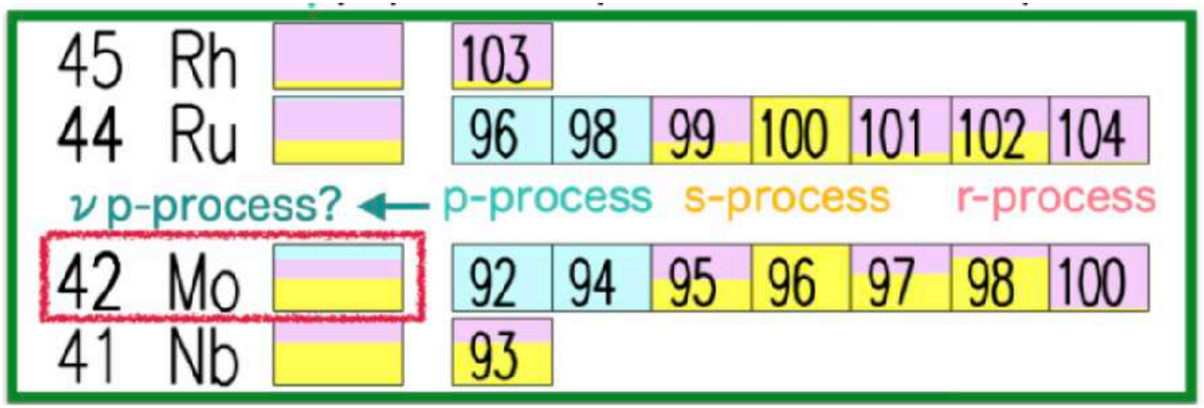
Can the ν p-process happen in realistic cc-SNe?

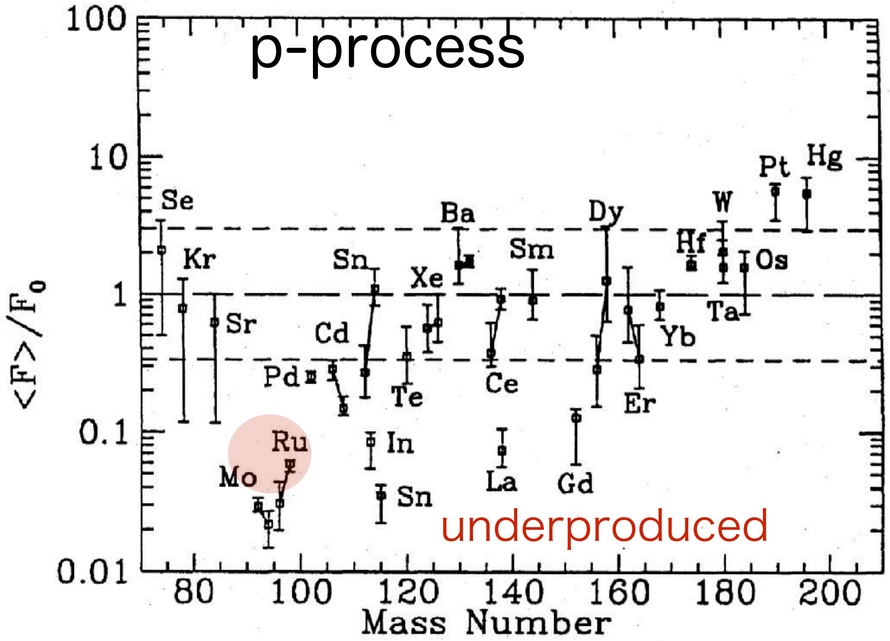
→ surely happen, but how far it reaches (heavy nuclei) remains unsolved

→ a major source of p-rich nuclei in cc-SNe

“Molybdenum (Mo) problem” (lighter p-nuclei)

35 neutron-deficient isotope

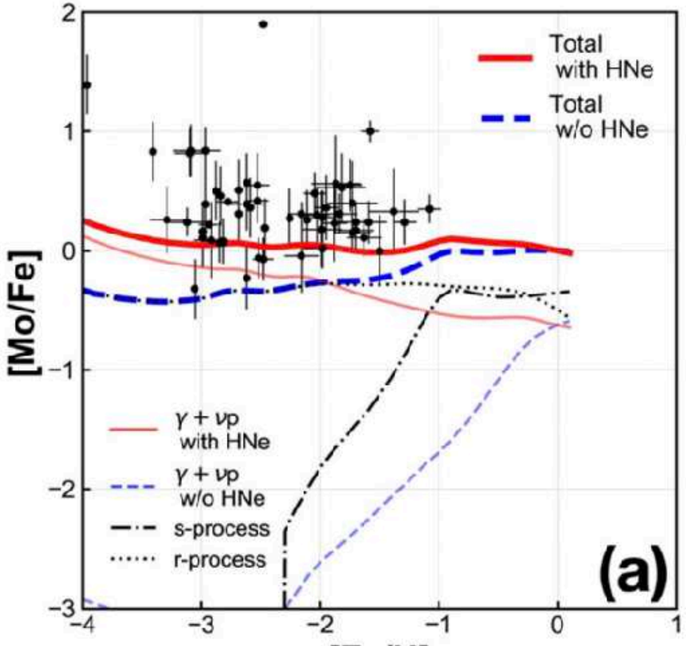




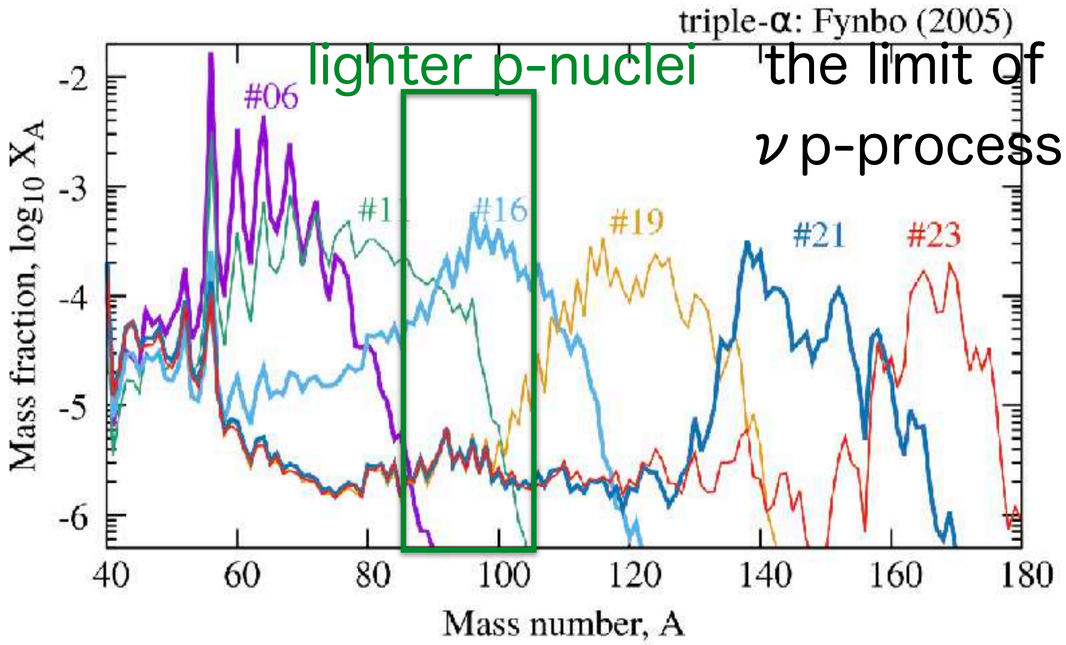
ν p-process
in GCE

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

Sasaki+(2022)



Uncertainty by individual reaction types

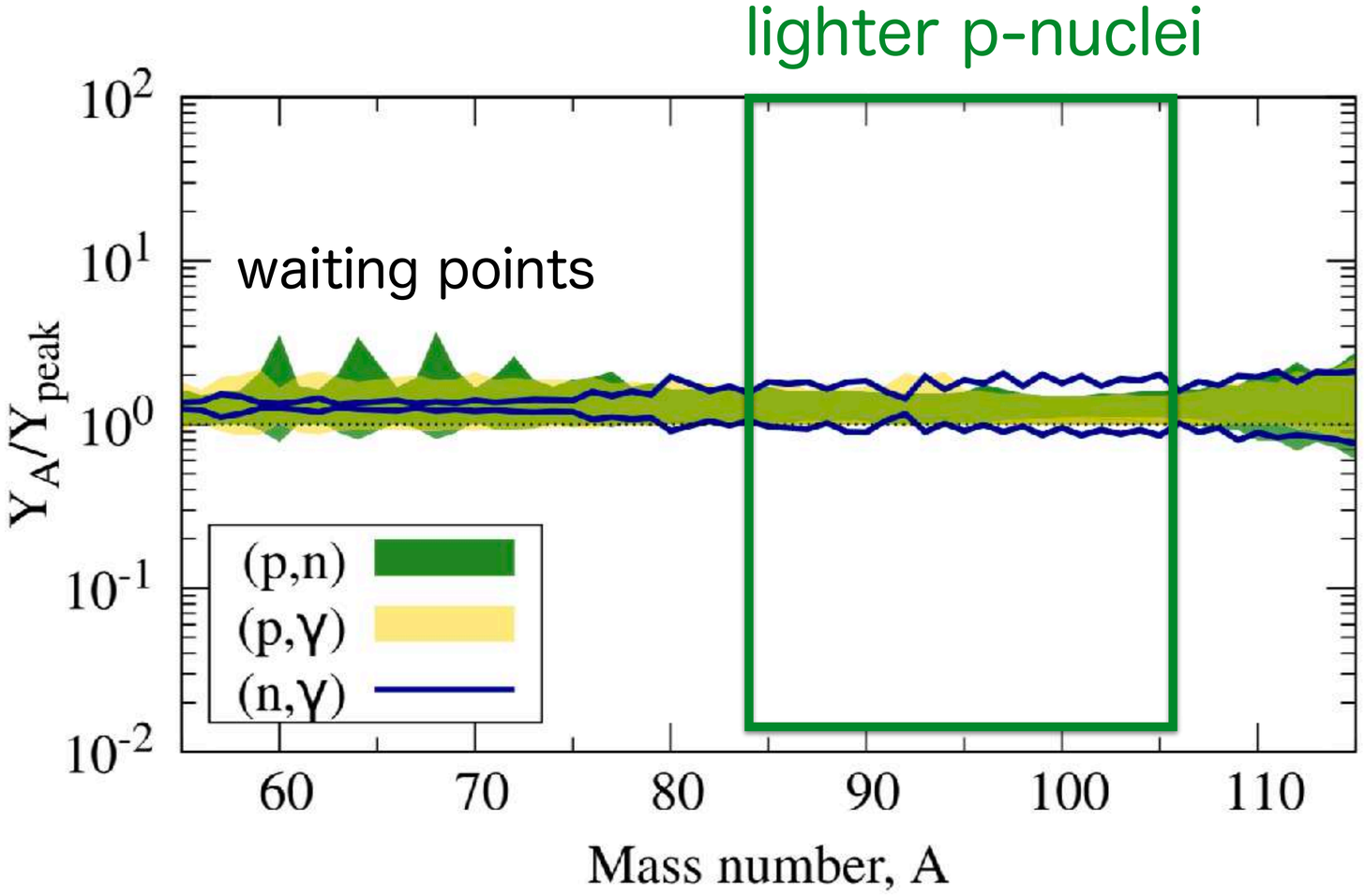


the limit of ν p-process

consider uncertainty of all reactions except for w/o triple-α and ^{56}Ni(n,p)

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



“Key” reactions in individual models

NN+2019

“standard”

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						
^{93}Nb	^{93}Tc + p↔γ + ^{94}Ru						
^{92}Mo	^{92}Mo + p↔γ + ^{93}Tc						
^{94}Mo	^{94}Ru + p↔γ + ^{95}Rh						
^{97}Tc	^{97}Rh + n↔γ + ^{98}Rh						
^{99}Ru	^{99}Rh + n↔γ + ^{100}Rh						
^{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)

^{92}Mo	^{92}Mo + p↔γ + ^{93}Tc
^{94}Mo	^{94}Ru + p↔γ + ^{95}Rh
^{97}Tc	^{97}Rh + n↔γ + ^{98}Rh

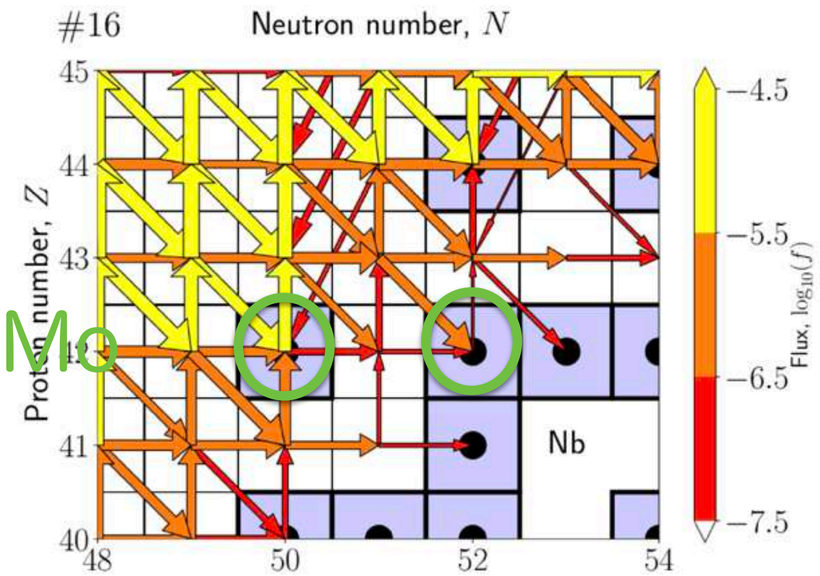
Solar isotopic ratios

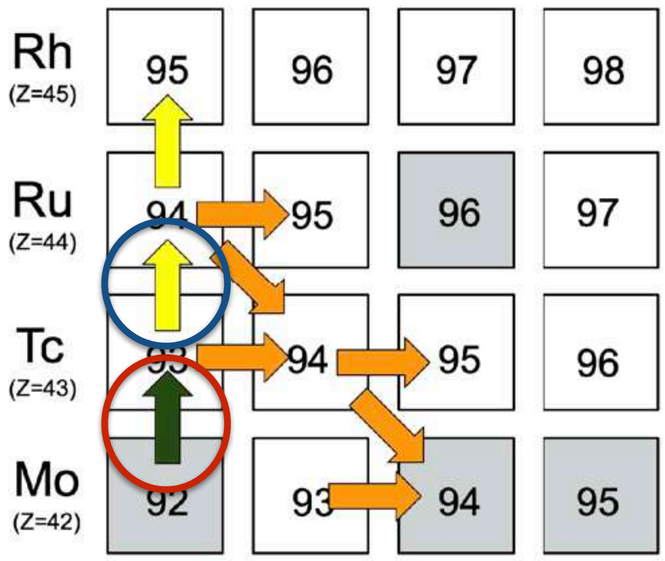
the solar isotopic ratio (Lodders 2003): /^{94}Mo

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

- ν p-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





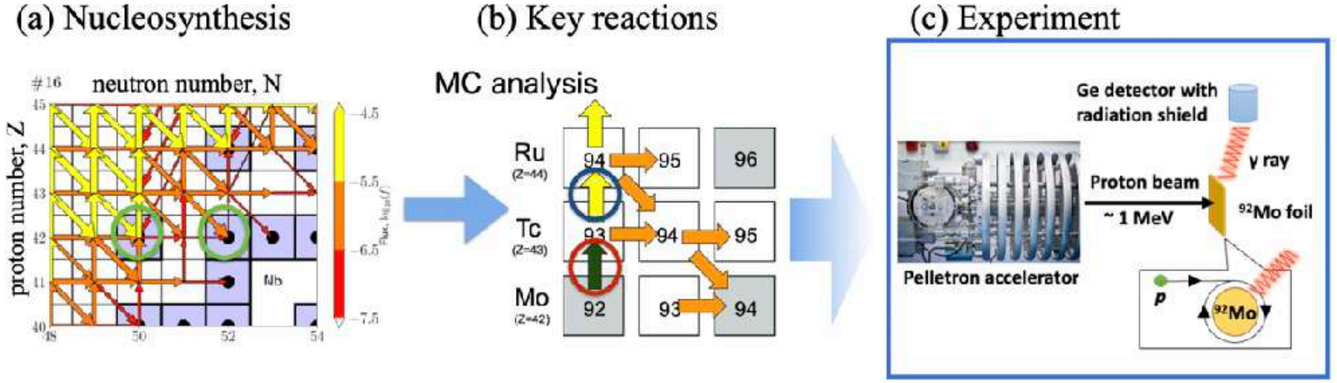
key reaction : ^{92}Mo(p,g)^{93}Tc

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

“New mesurements”? : ν p-process

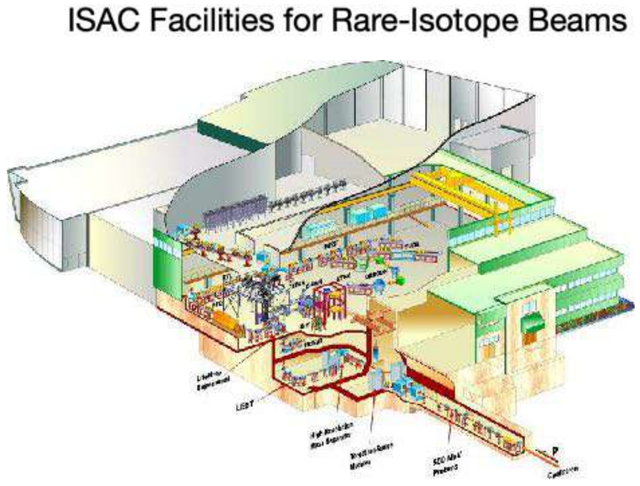
- **“waiting point” at ^{56}Ni: ^{56}Ni(n,g)^{56}Co (surrogate reaction (d,p))**
  - breakthrough reaction from seed region; important for producing heavy nuclei > Fe
  - RIBF + OEDO experiment at RIKEN (approved in FY2022)
  - N.N. supported experimat proposal at RIBF (RIKEN); impacts on nucleosynthesis
- **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 ν p-process
  - N.N. initiated the plan of experiment w/ D. Suzuki (RIKEN/U Tokyo)
    - applied RIKEN’s funding → approved (300 MJPY)
    - FY2024—2025: preparing ^{92}Mo target
    - FY2025— : experiment at Pelletron accelerator (Sci. Tokyo)
    …

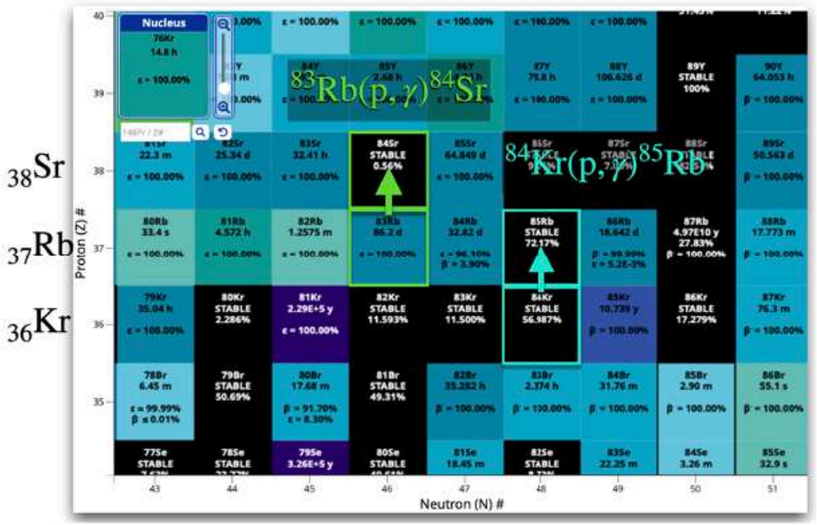
a figure
in proposal

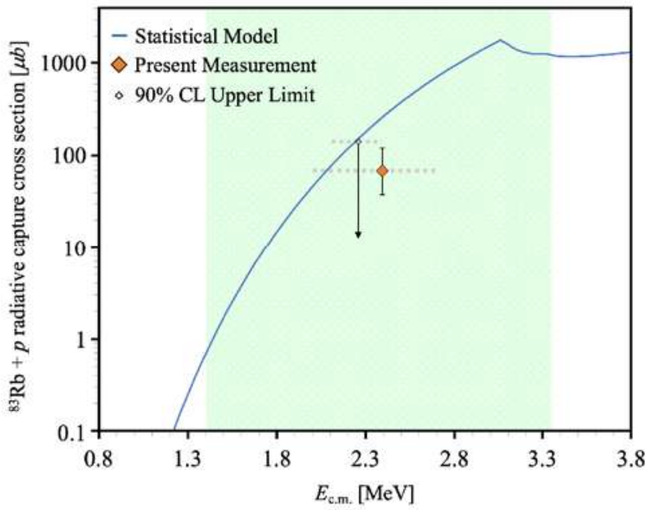


Evaluation of the impacts of measured reactions

new measurement of $^{83}Rb(p,g)^{84}Sr$ and $^{84}Kr(p,g)^{85}Rb$

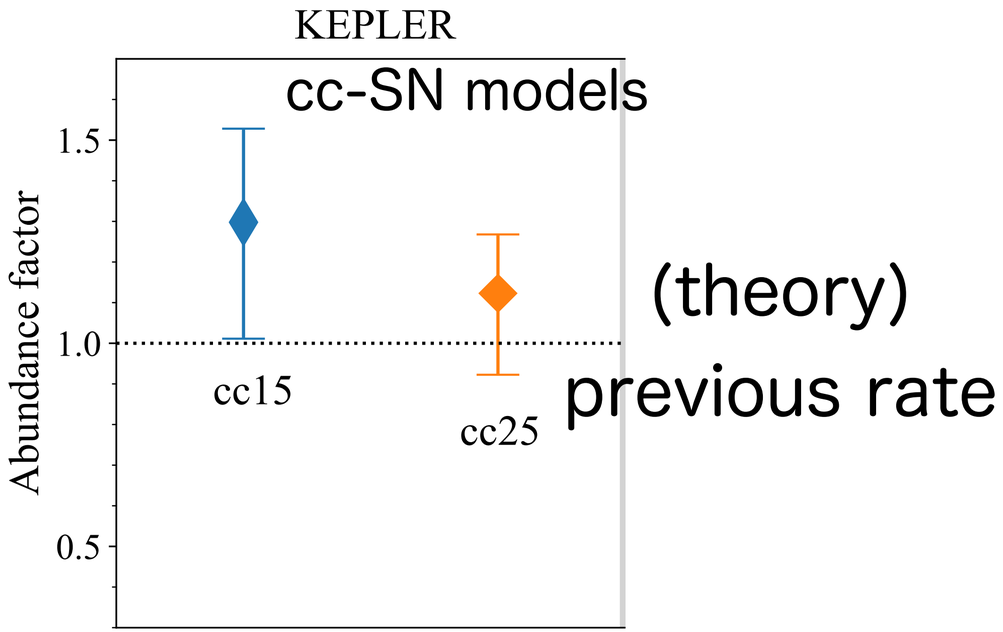






- Lotay+NN+(2021) PRL 127
- Williams+NN, Rauscher+(2023) PRC 2023

relative abundance of ^{84}Sr

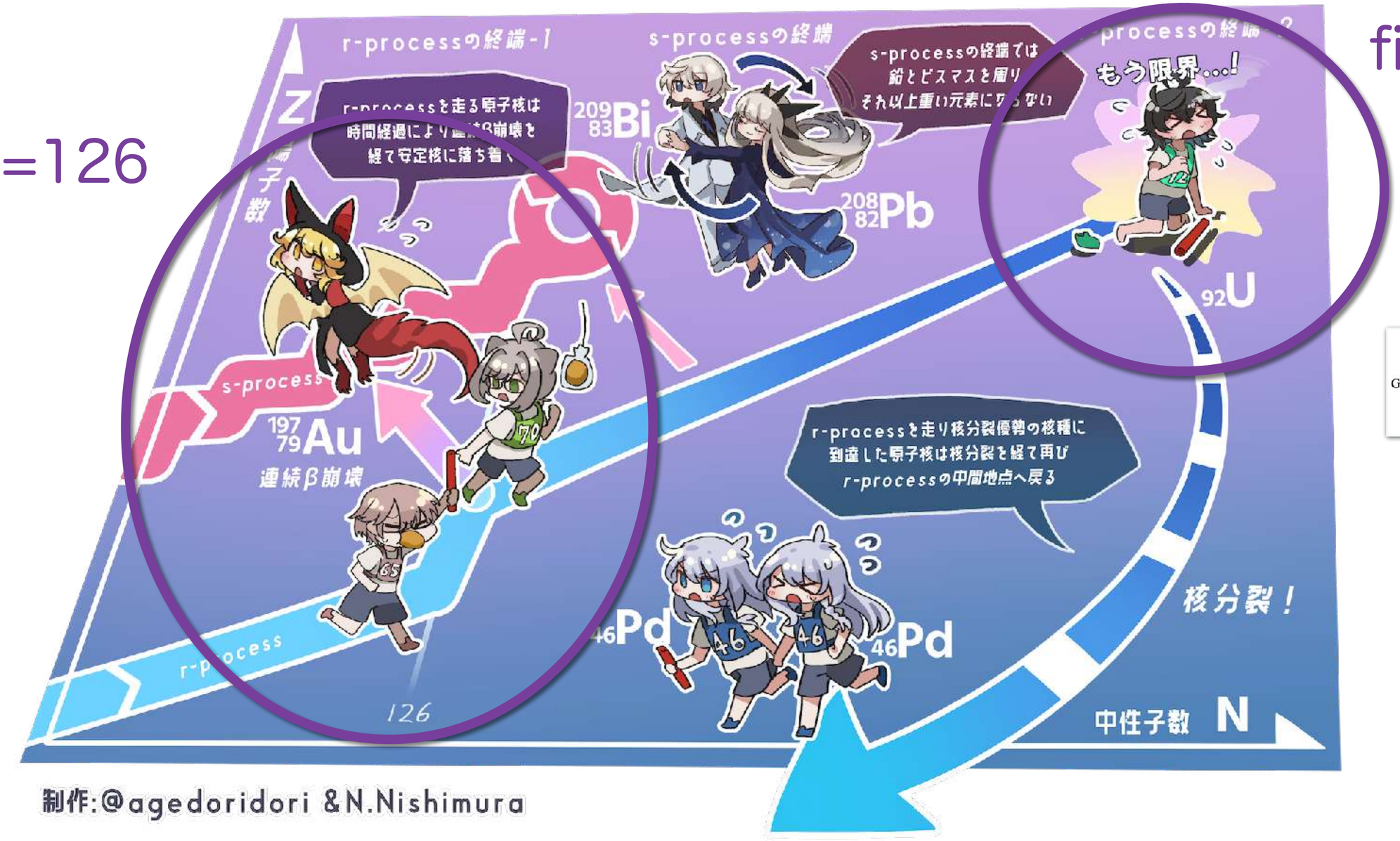


3. Uncertainties in r-process nucleosynthesis

N = 126 β-decay and fission

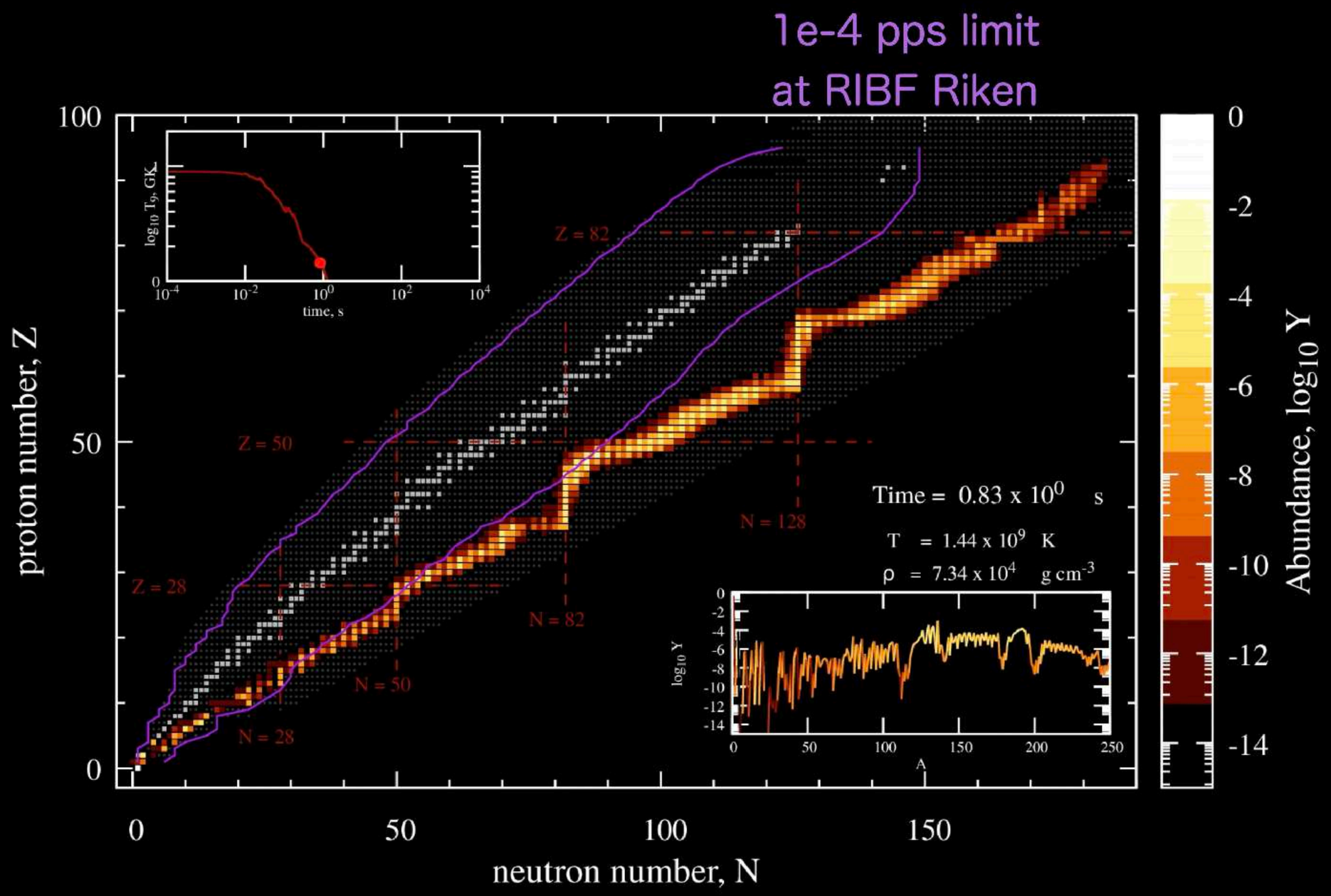
N=126

fission



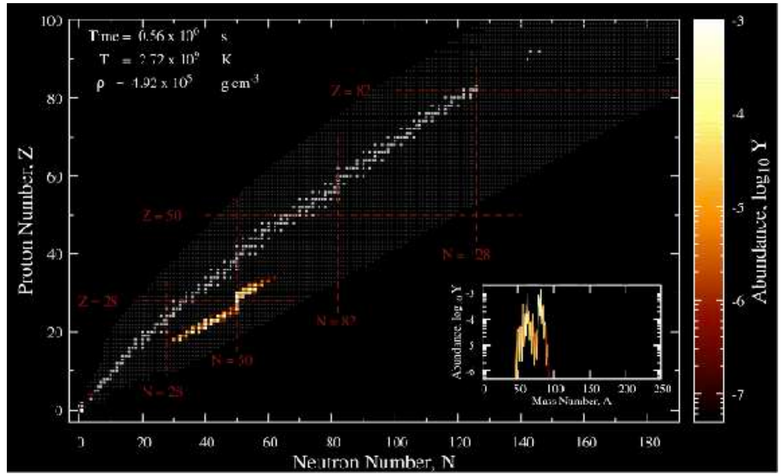
元素楽章
GENSOGAKUSHO × GENSOGOSEI
元素合成

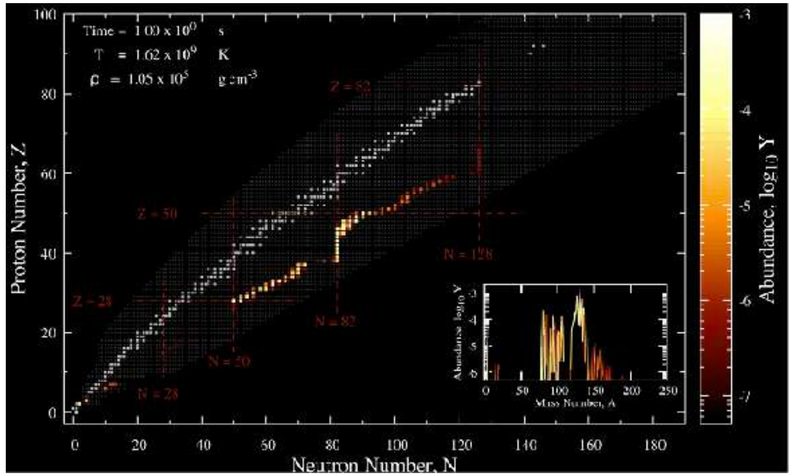
r-process nucleosynthesis “flow”

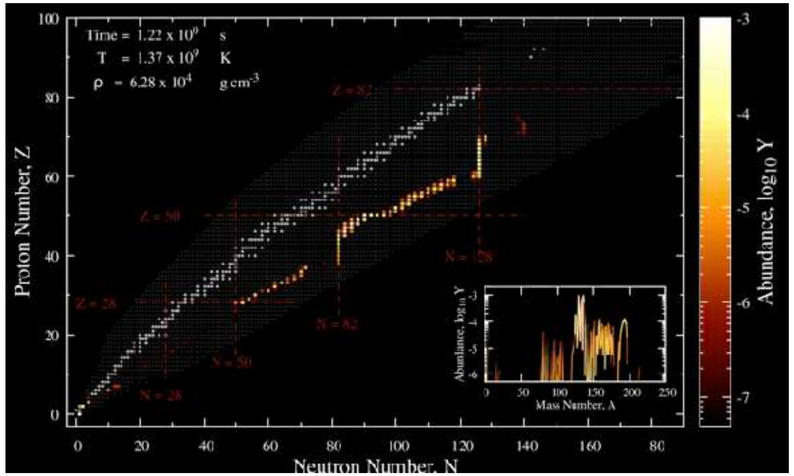


Modern nucleosynthesis simulations

- Nuclear physics
  - method : calculations by nuclear reaction network
    - consider all possible reactions and decays
    - (n,g)/(g,n) partially achieved or not realized (cold r-process)
    - β-decay, (n,g), fission for a wide range of n-rich nuclei

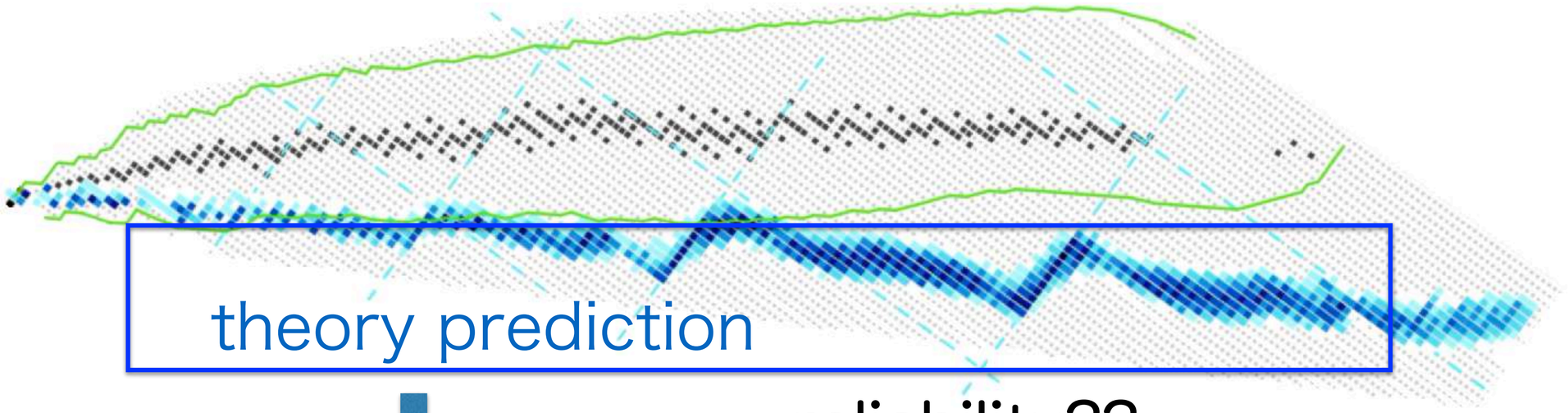






Theoretical Prediction

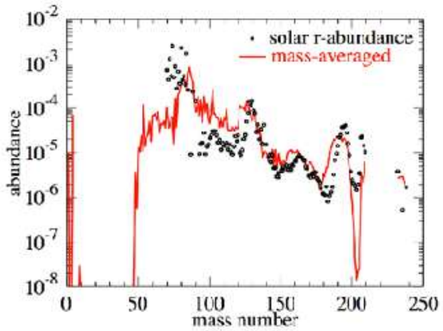
r-process path is beyond experimental accessible region

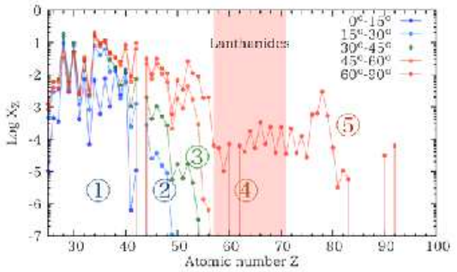


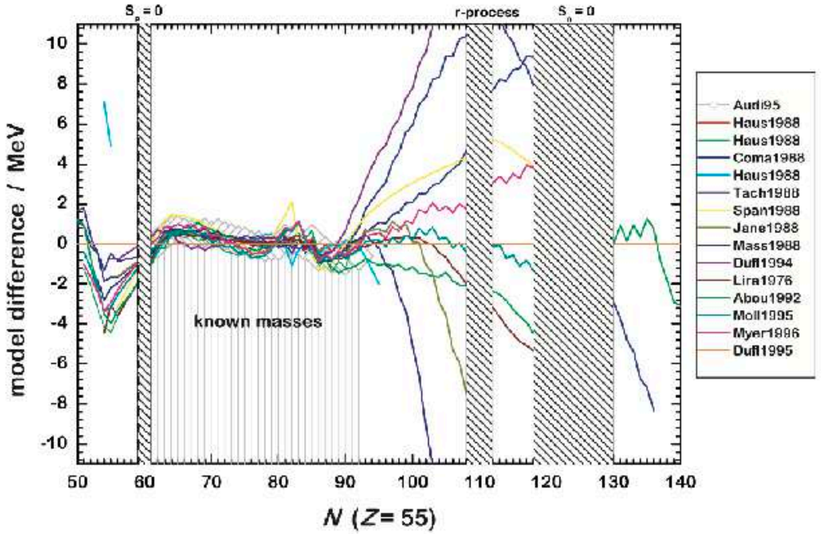
astrophysics

reliability??

large uncertainty in theory







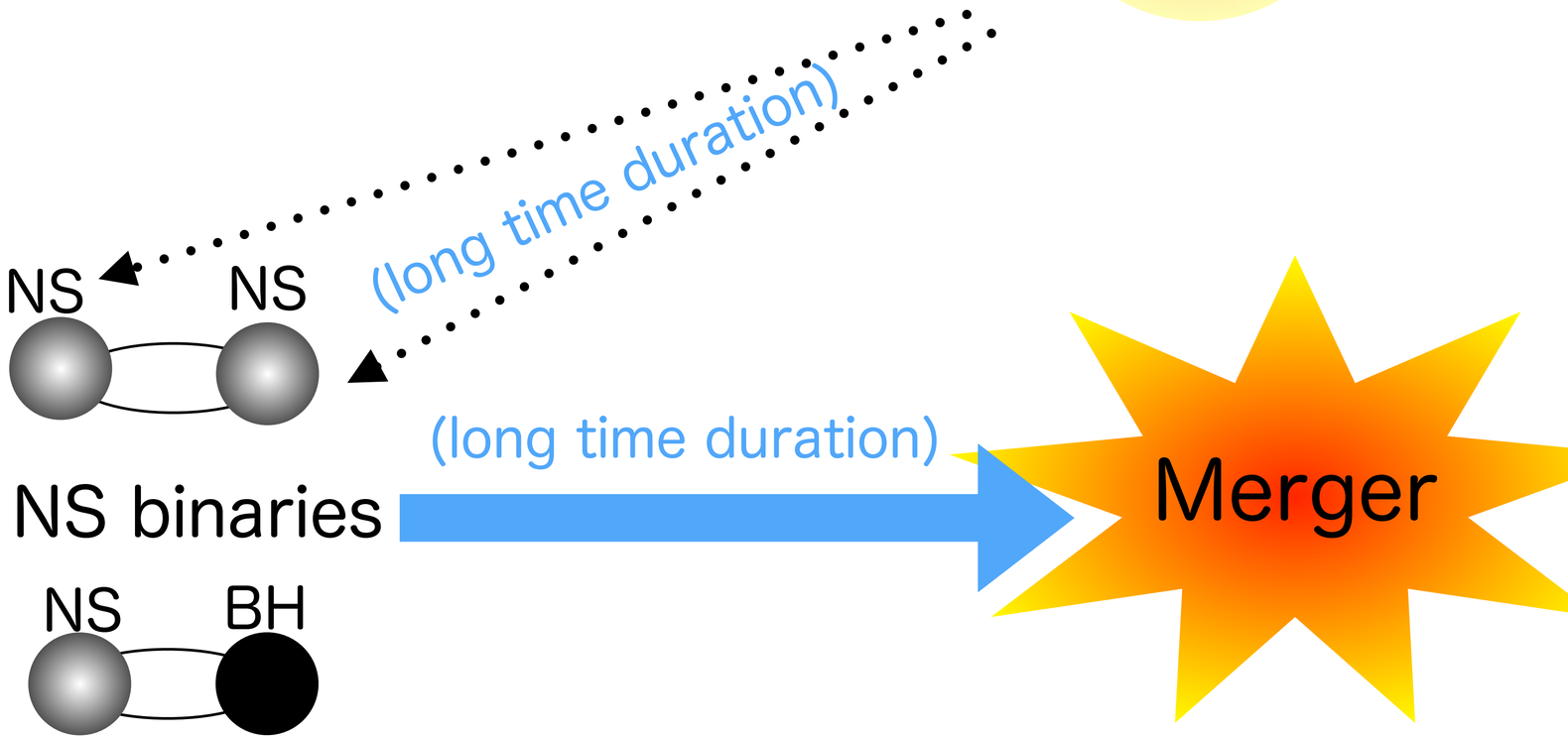
Astrophysical r-process sites

core-collapse SNe

- NO direct r-process observation
- Theoretically difficult
  - not very neutron-rich

NS (binary) mergers

The “observational” evidence with gravitational waves (GW170817)



Nuclear fission in r-process nucleosynthesis

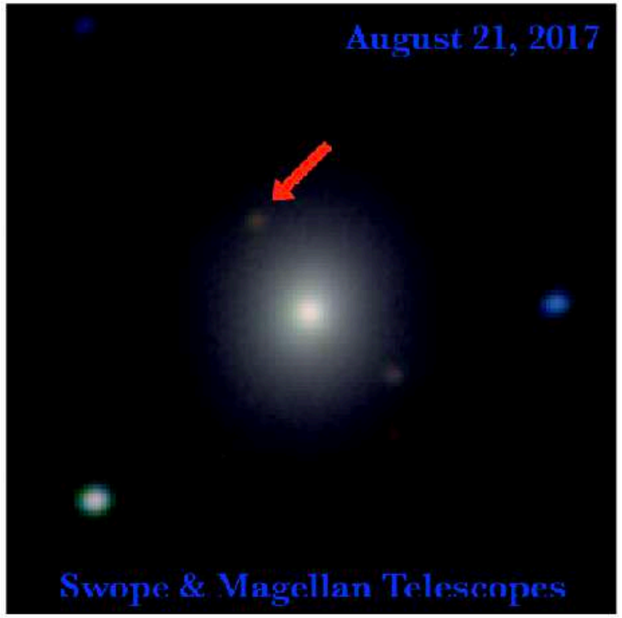
r-process → fission : termination, heating source of “kilonovae”

fission → r-process : unique natural source, beyond accelerator experiments

kilonova (AT2017gfo/SSS17a)

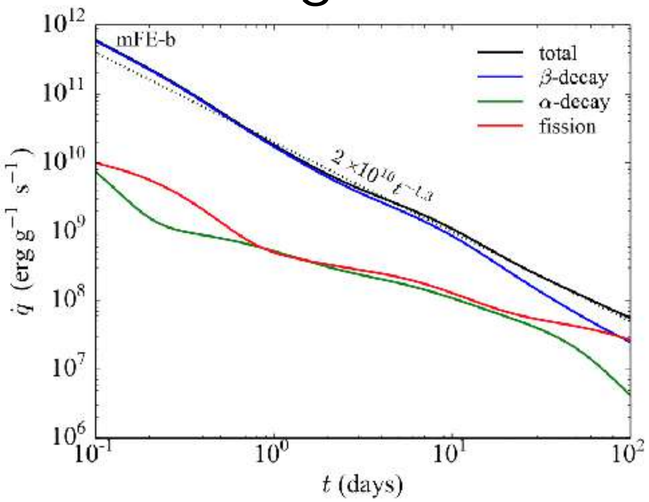
associated with NS merger (GW170817)

17 Aug. 2017



21 Aug. 2017

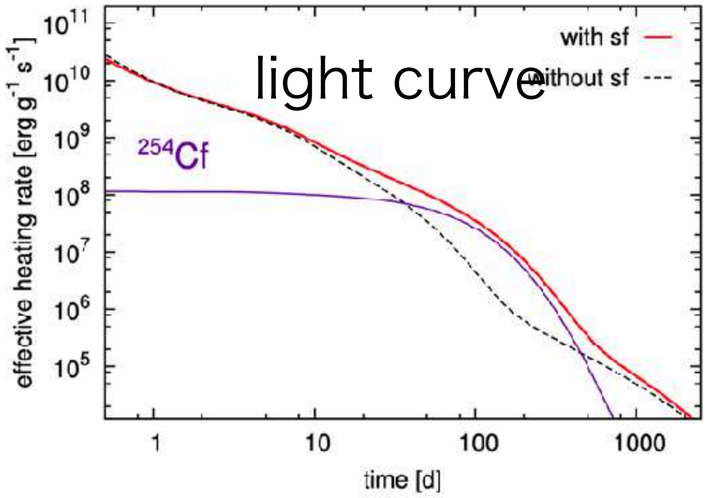
light curve



Wanajo+2018

mostly by β-decay

light curve

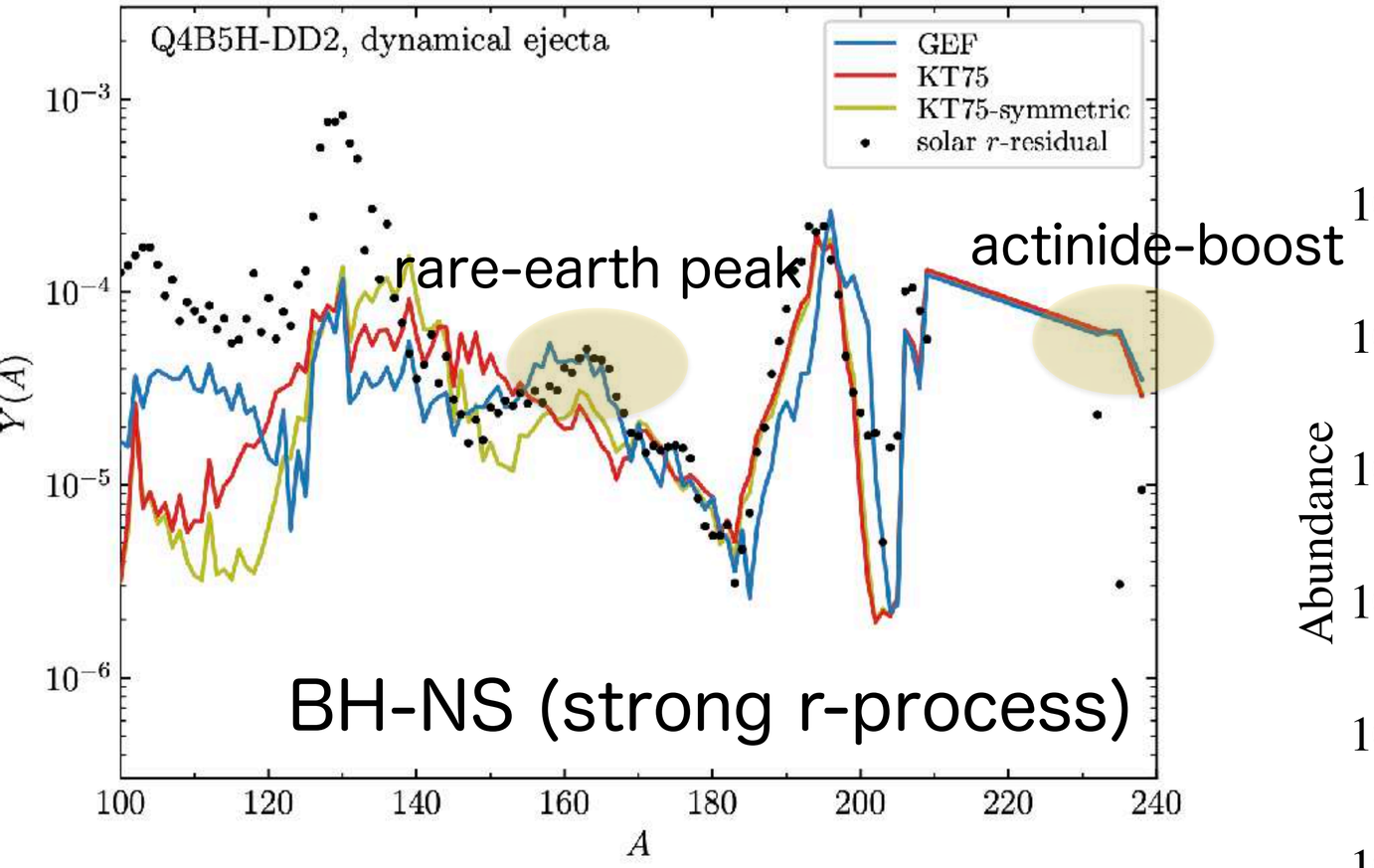


Zhu+2018

fission by specific nucleus affects?

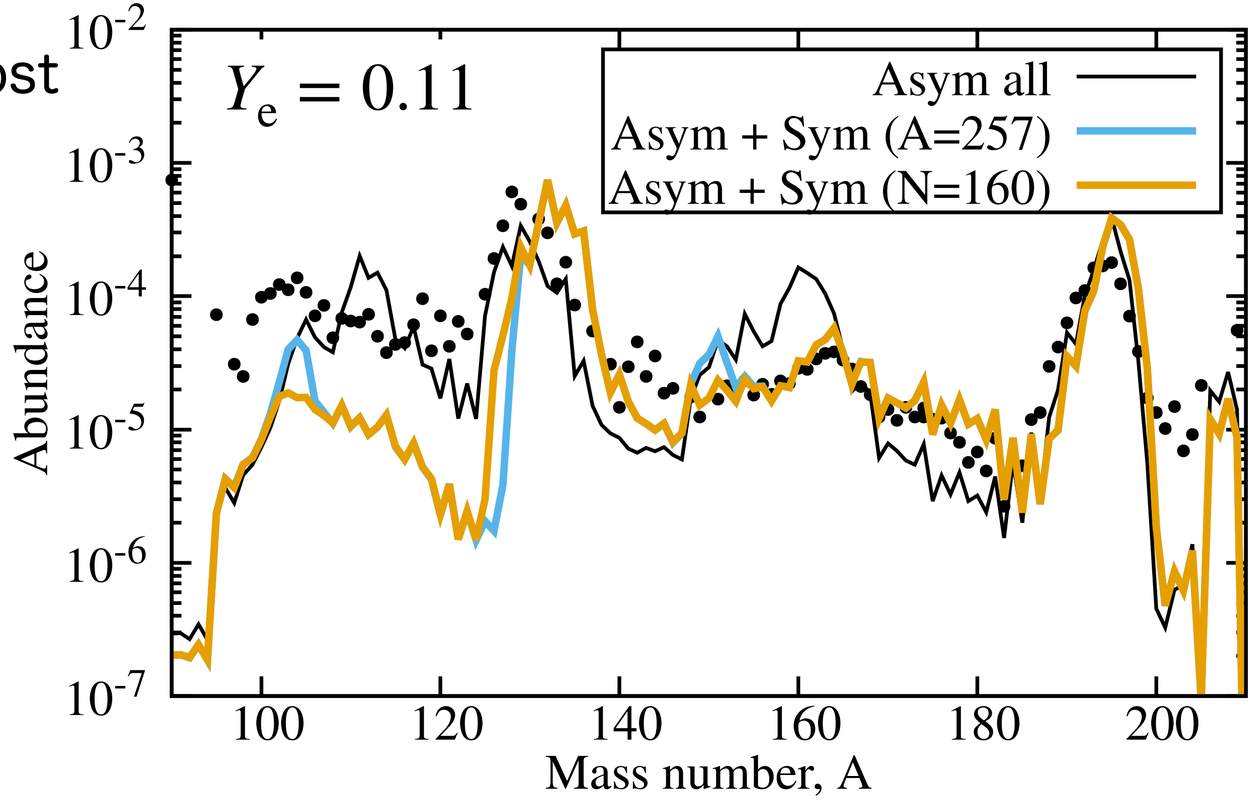
The impacts on the r-process

strong fission recycle
Wanajo+2013 (arXiv: 2212.04507)



・Comparison: all asymmetric, asymmetric
→ symmetric A = 257 & N = 160

neutron-rich condition (by NN)



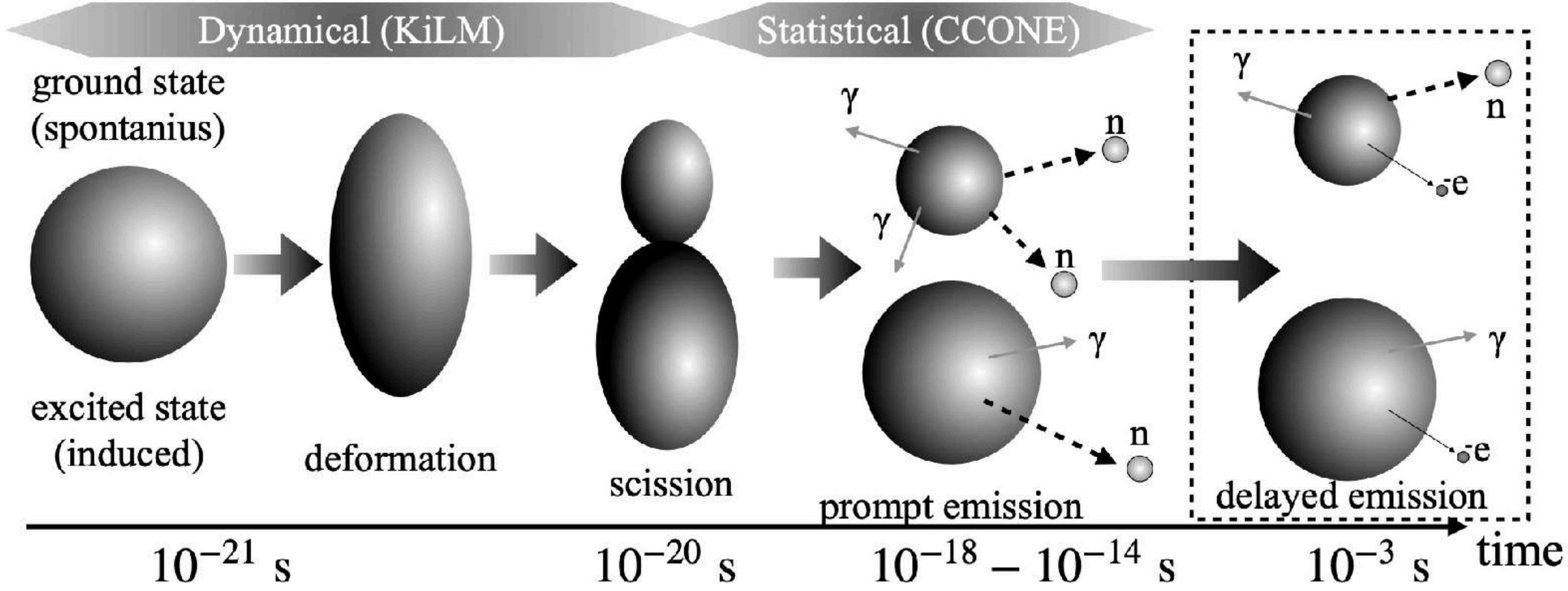
Comparison to several fission data

toward complete fission yields for r-process

theoretical data ↔ astrophysical nucleosynthesis

fission process has several experimental data → comparison

Tanaka, NN+2023



Dynamical fission model

$$V(q,\ell,T) = V_{LDM}(q) + \frac{\hbar^2 \ell(\ell+1)}{2I(q)} + V_{SH}(q,T)$$

$$V_{LDM}(q) = E_S(q) + E_C(q)$$

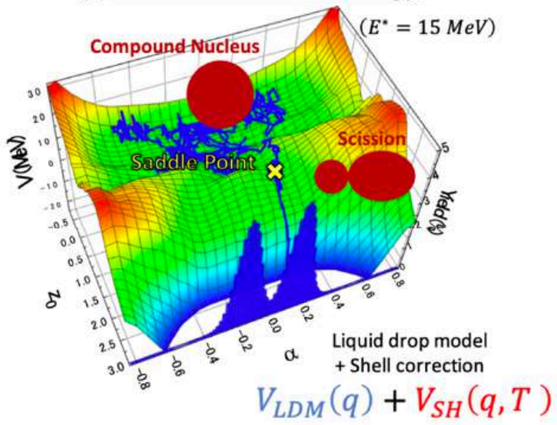
$$V_{SH}(q,T) = E^0_{shell}(q)\Phi(T)$$

Temperature dependent factor

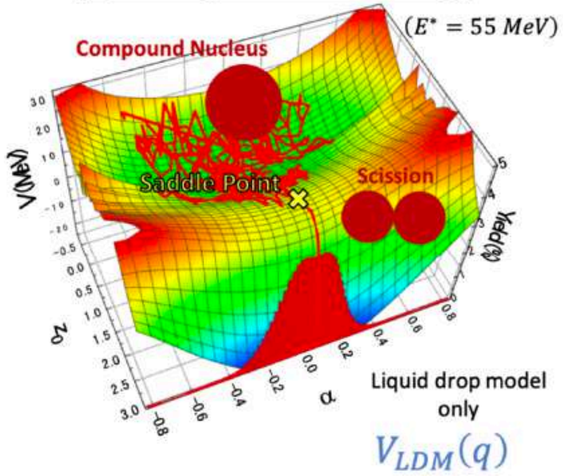
$$\Phi(T) = \exp(-\frac{aT^2}{E_d}) \quad E_d = 20[MeV]$$

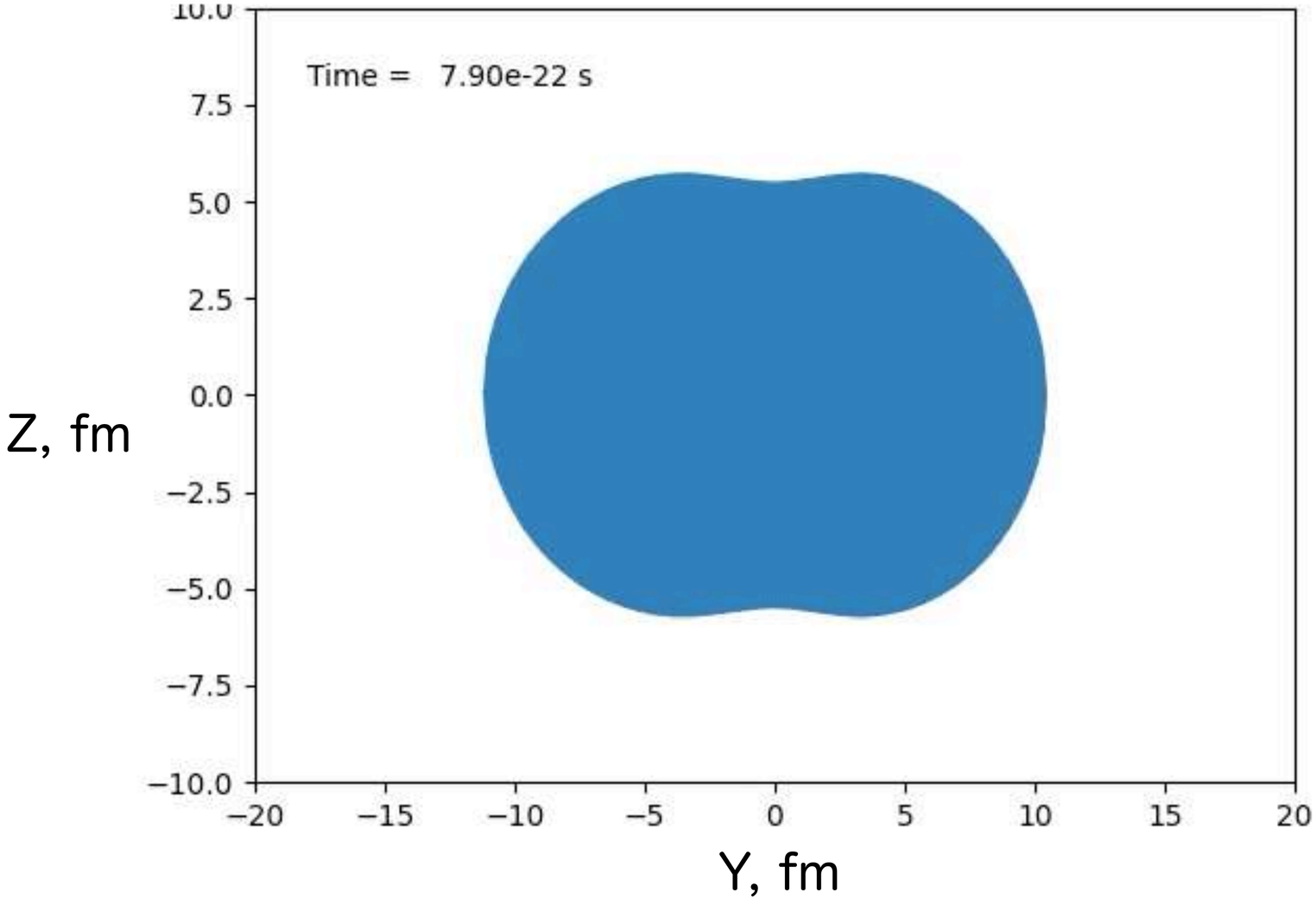
^{253}U : symmetric fission

(a) At low excitation energy



(b) At high excitation energy

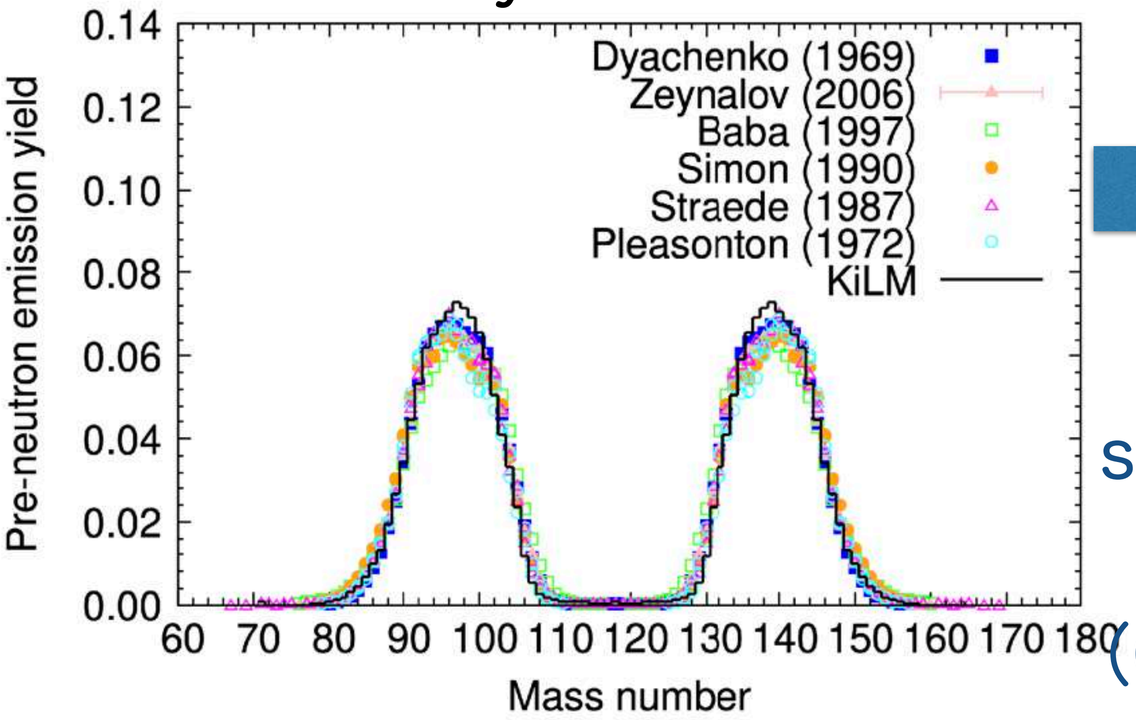




^{236}U : fission + n emission

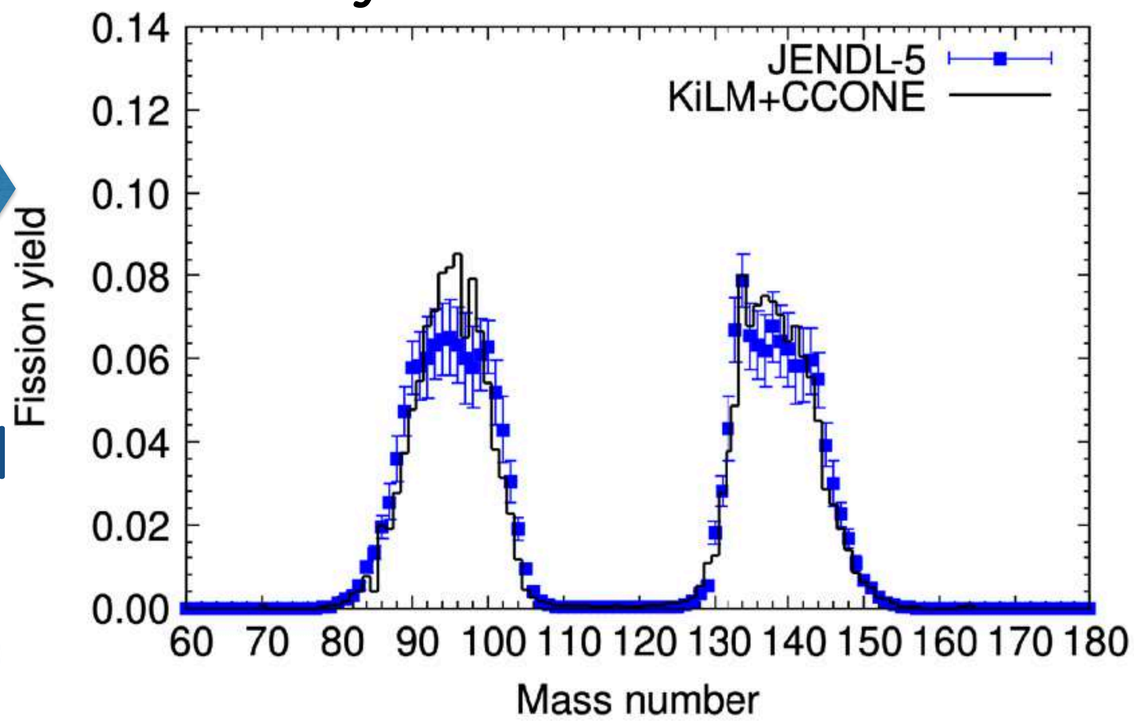
^{236}U (E^*=9 MeV)

primary fission yields
by KiLM



HF
statistical
model
(CCONE)
Iwamoto et al.

independent fission yields
by KiLM + CCONE



multiplicity $\langle n \rangle = 2.574$
(experiment : 2.413)

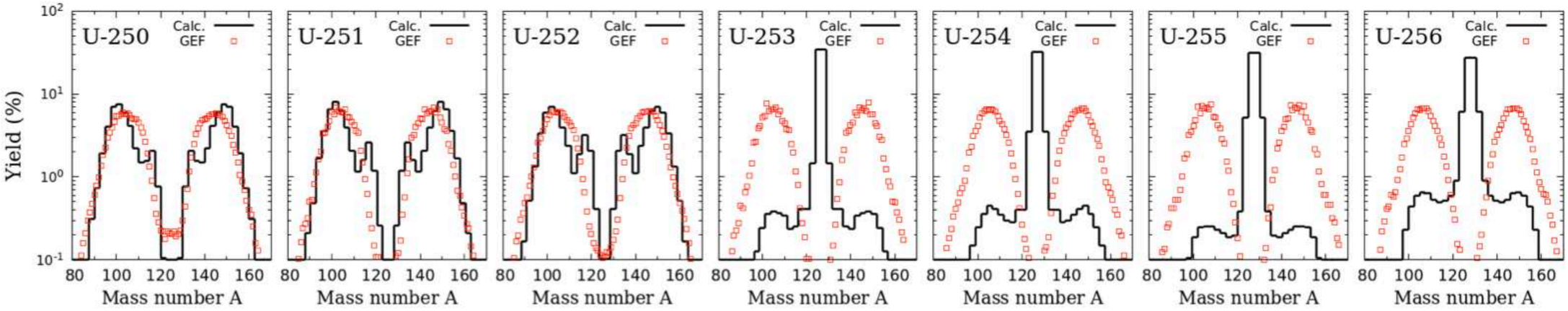
Tanaka, NN+2023

$^{250,\,255}$U : fission + prompt n emission

KiLM

GEF

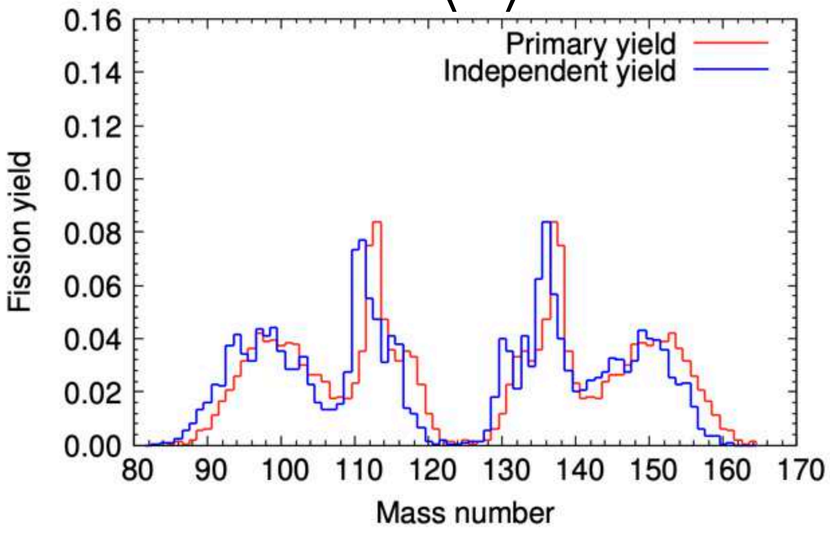
(Schmidt & Jurado)



$\langle n \rangle = 2.574$ for ^{236}U

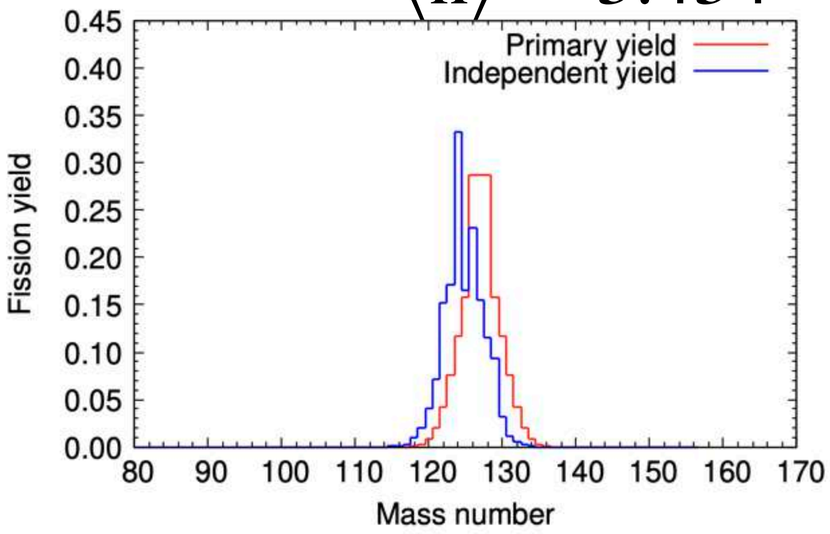
^{250}U (E* = 9 MeV)

$\langle n \rangle = 4.185$

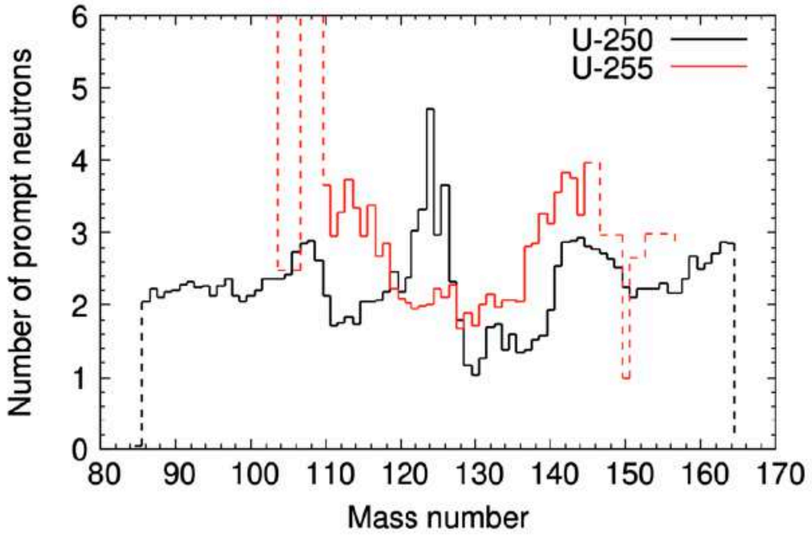


^{255}U (E* = 9 MeV)

$\langle n \rangle = 3.434$



number of n emission



Tanaka, NN+2023

fission: symmetric vs asymmetric

元素楽章

GENSOGAKUSHO × GENSOGOSEI

元素合成

Fission yields of neutron-rich U

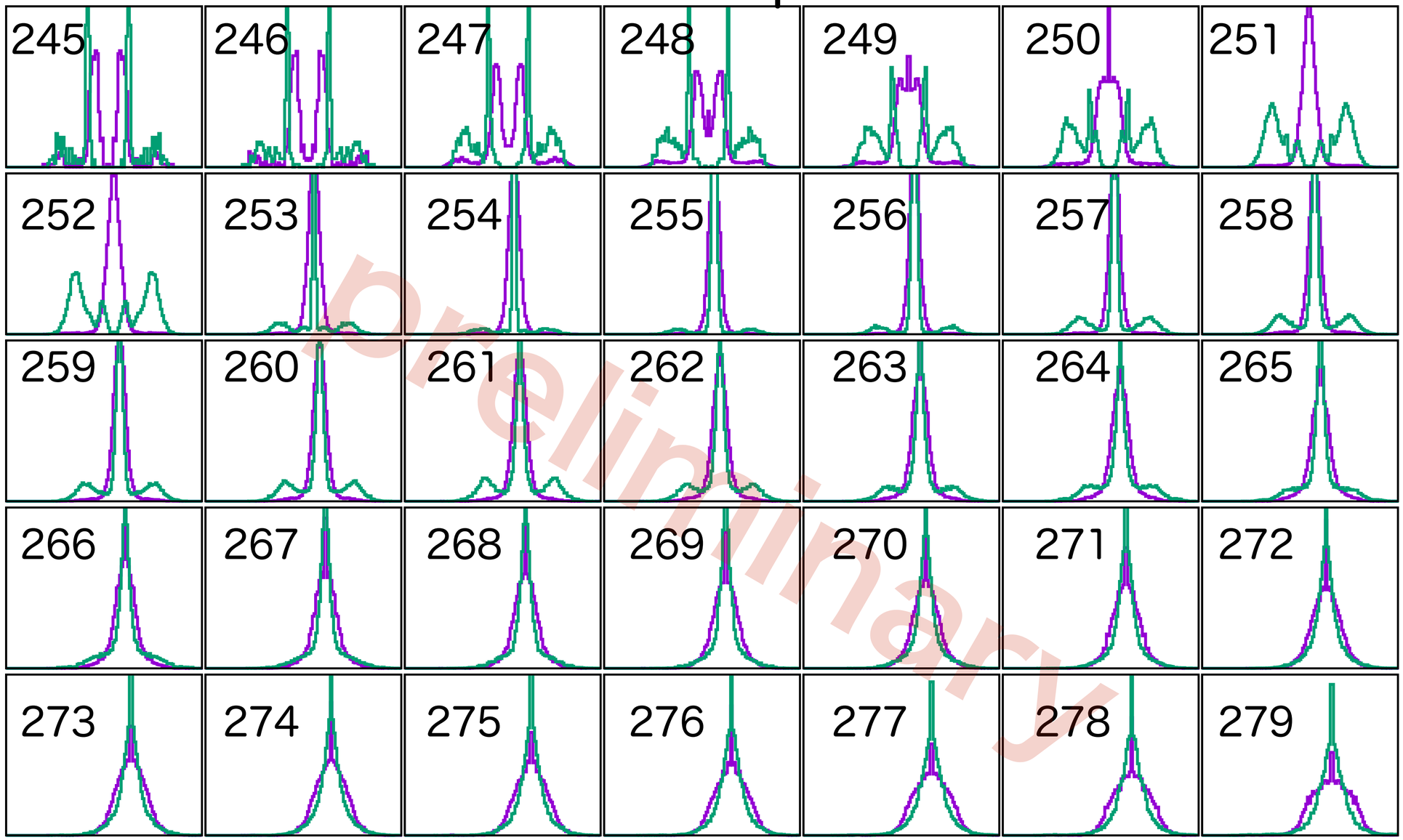
U isotopes

neck parameter

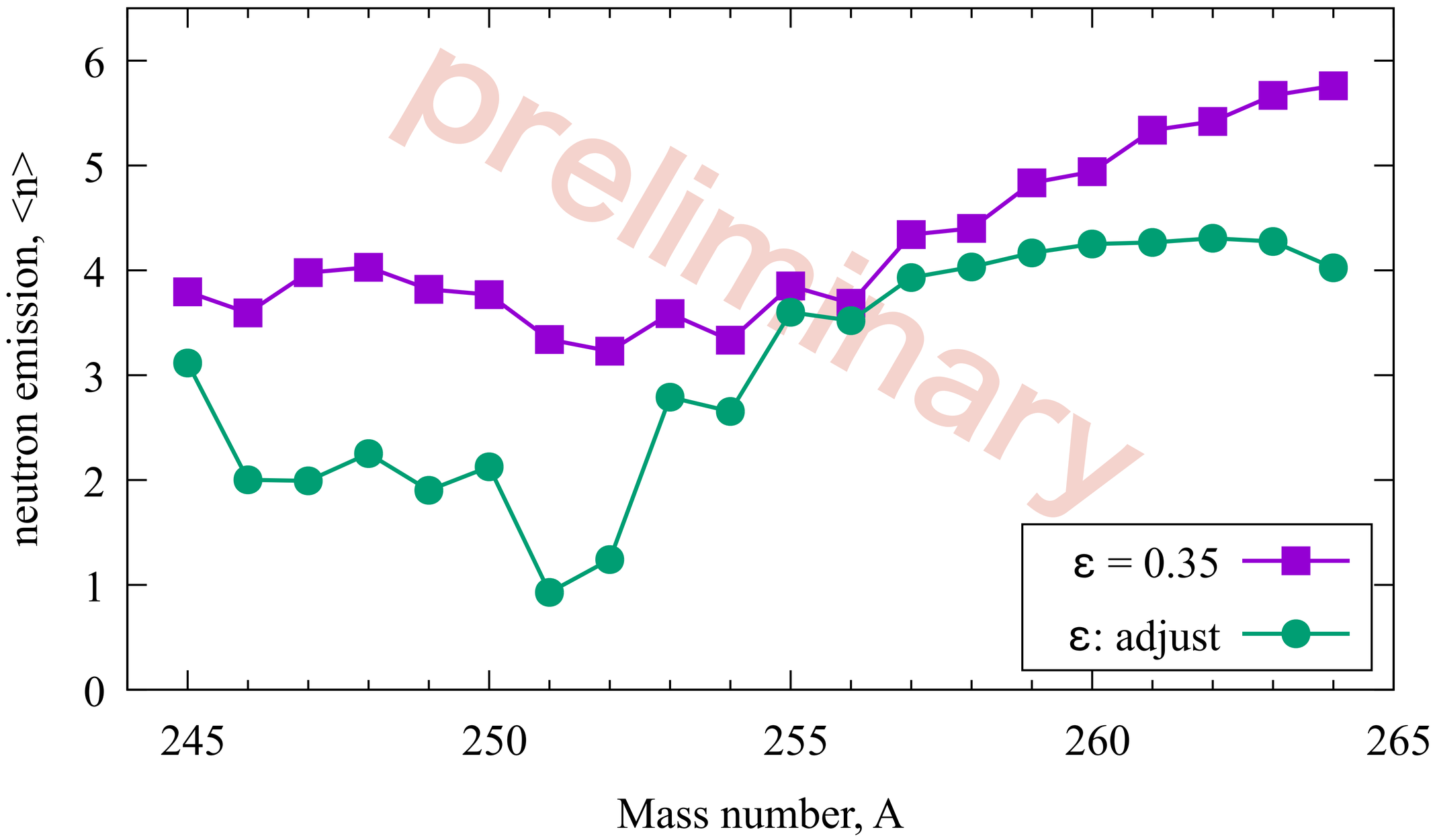
— $\varepsilon = 0.35$

— adjust ε

Miyamoto's systematics



n multiplicity for neutron-rich U



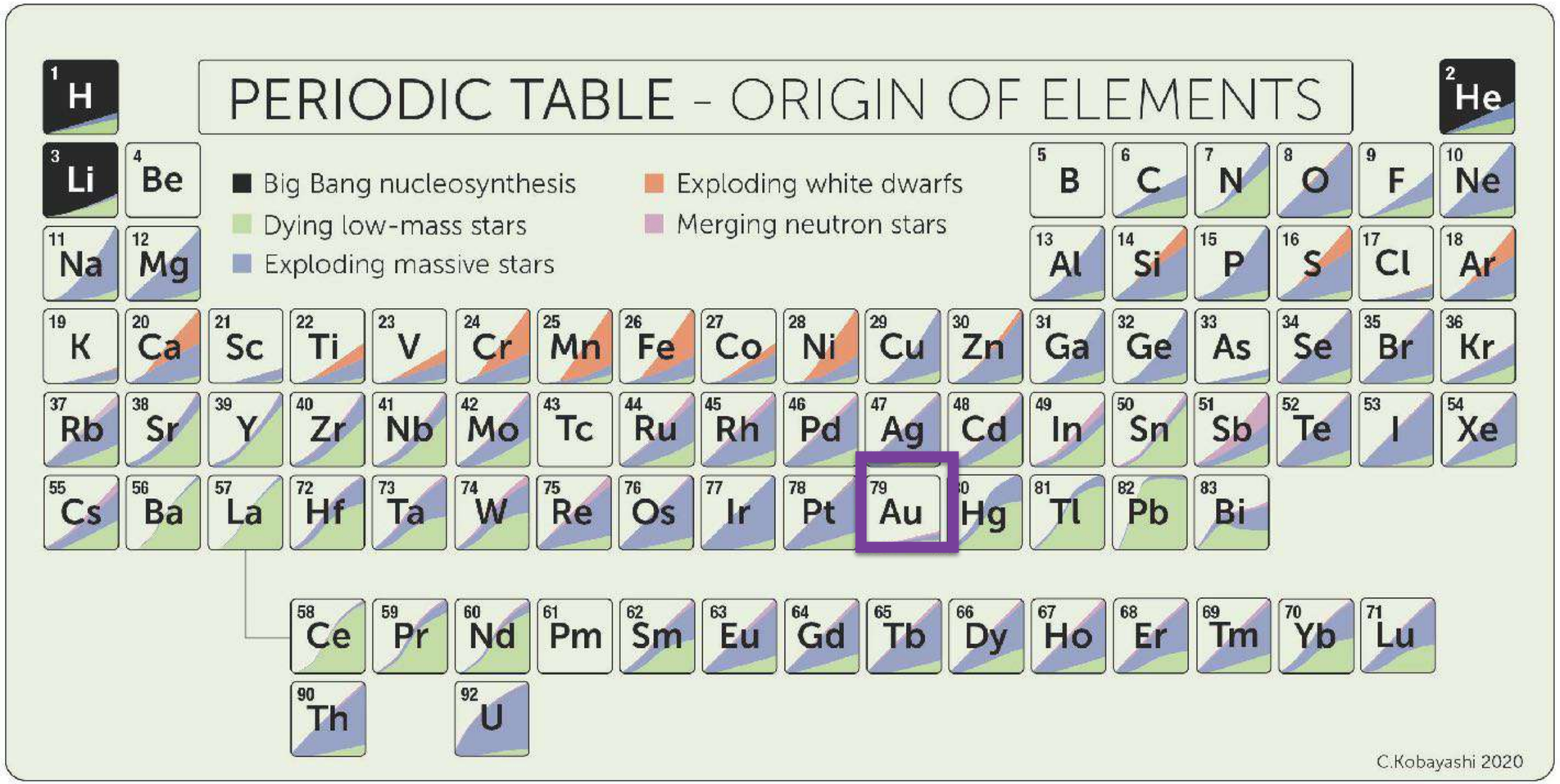
Cosmic (Galactic) evolution of elements

C. Kobayashi, A. Karakas, M. Lugaro, ApJ 2020

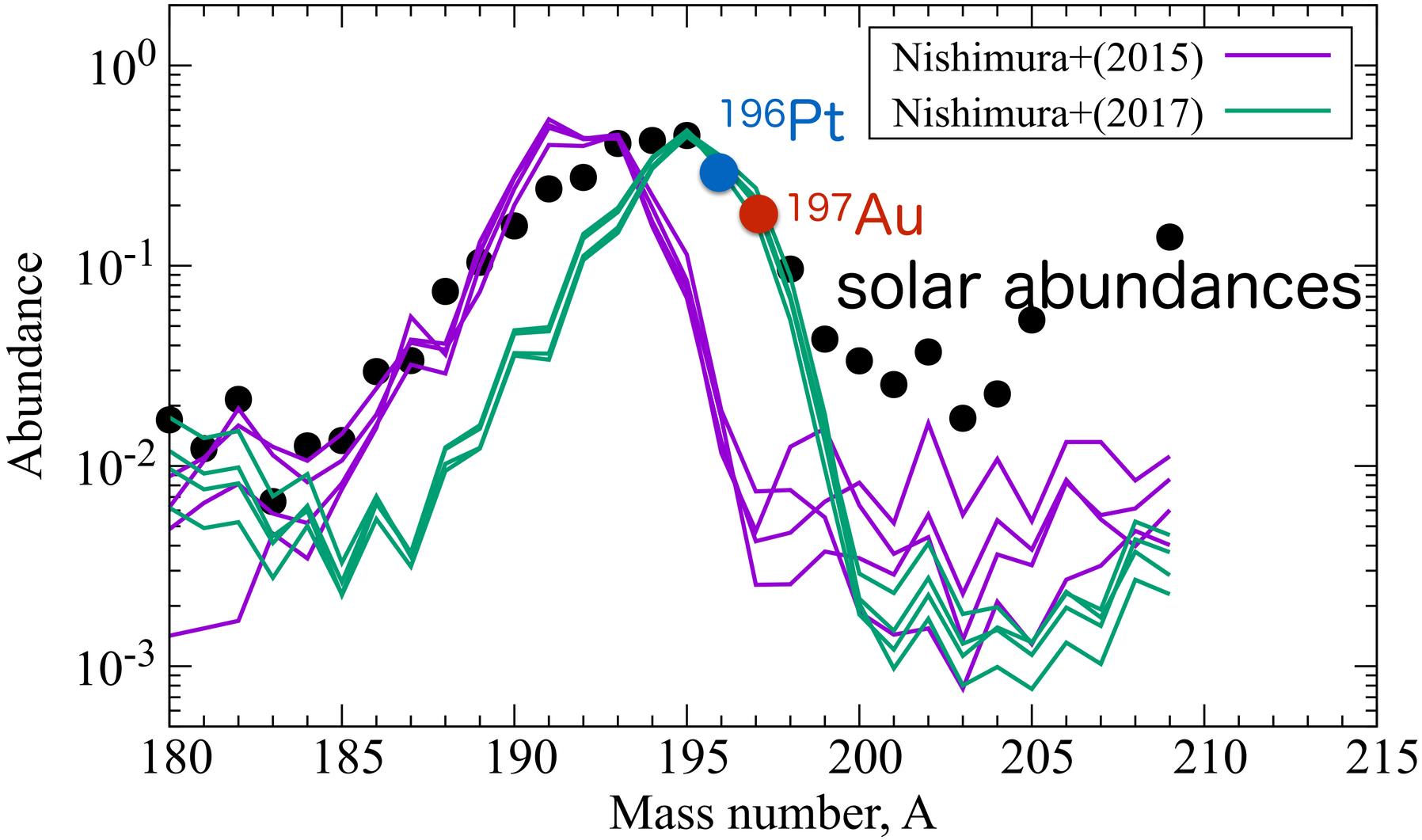
"The origin of Elements from Carbon to Uranium"

・challenge to explain all the isotopes in GCE (Galactic Chemical Evolution)

・they assume supernovae are the main source of r-process (than NS mergers)



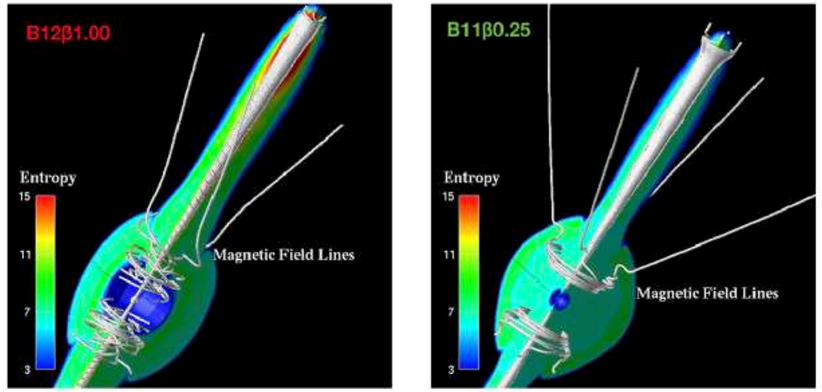
“missing gold”?: nuclear physics inputs

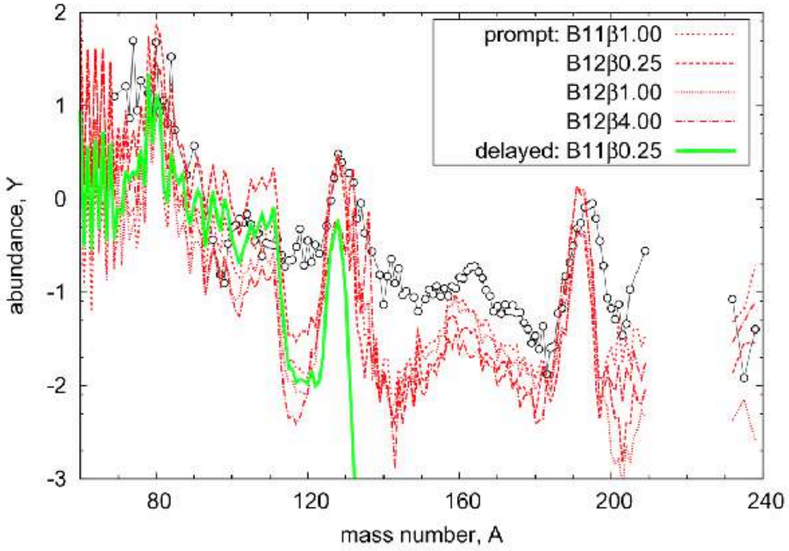


Kobayashi+(2020) adopted Nishimura+(2015) data

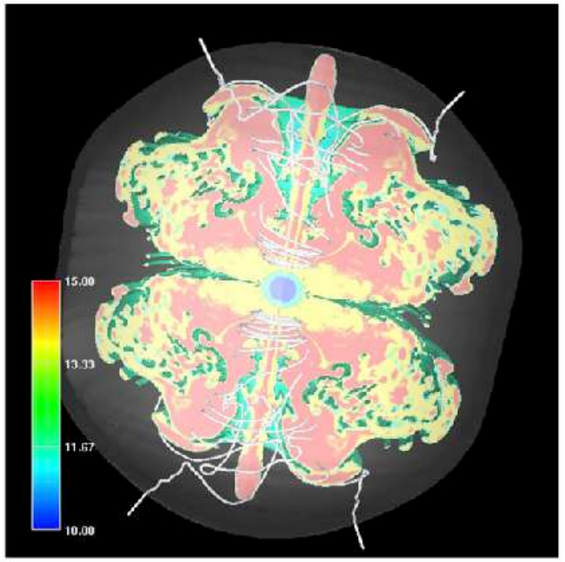
Difference in NN+2015 and NN+2017

Nishimura+(2015) ApJ

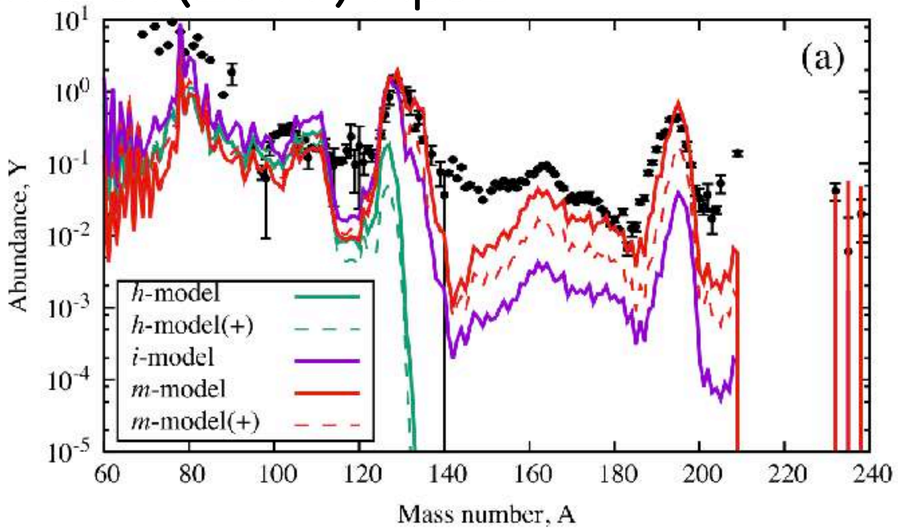




used by Kobayashi+2020

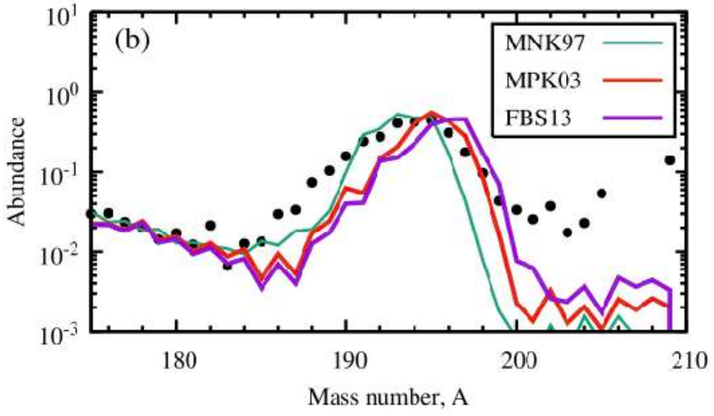


Nishimura+(2017) ApJL



update my r-process calculations (β-decay)

NN+2016, PLB (2016)

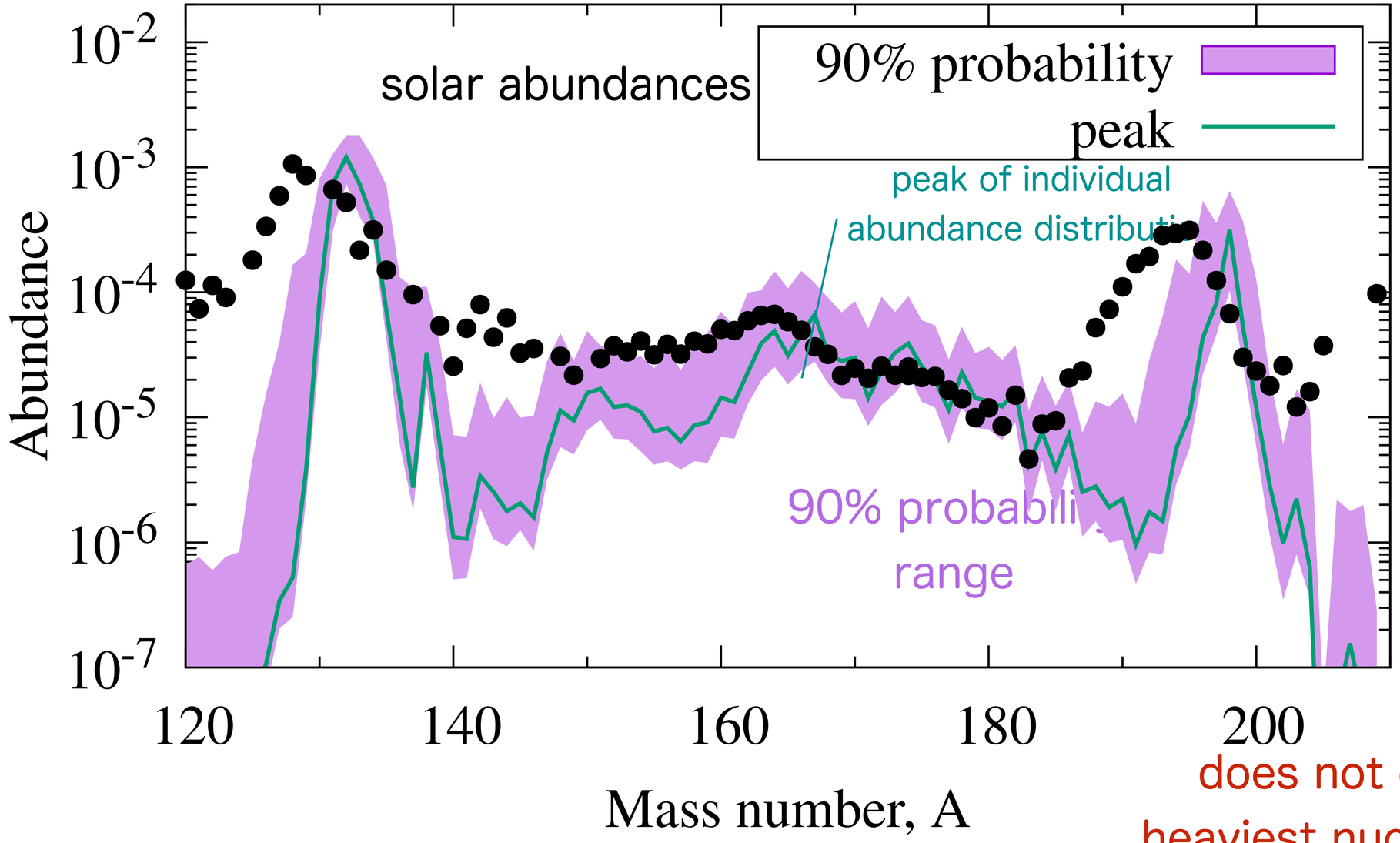


comparison of different beta-decay rates

Collective uncertainties on the r-process

impacts on reaction/decay rate variation with MC nucleosynthesis

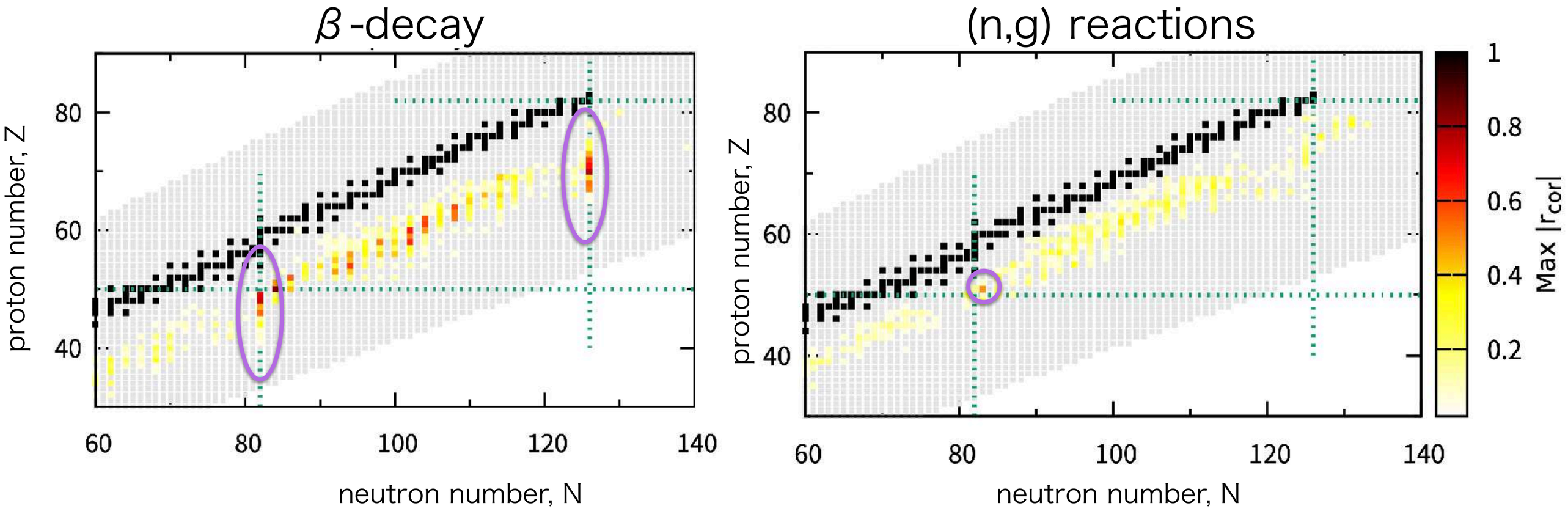
(n,g) x50, β x10



does not consider
heaviest nuclei (fission)

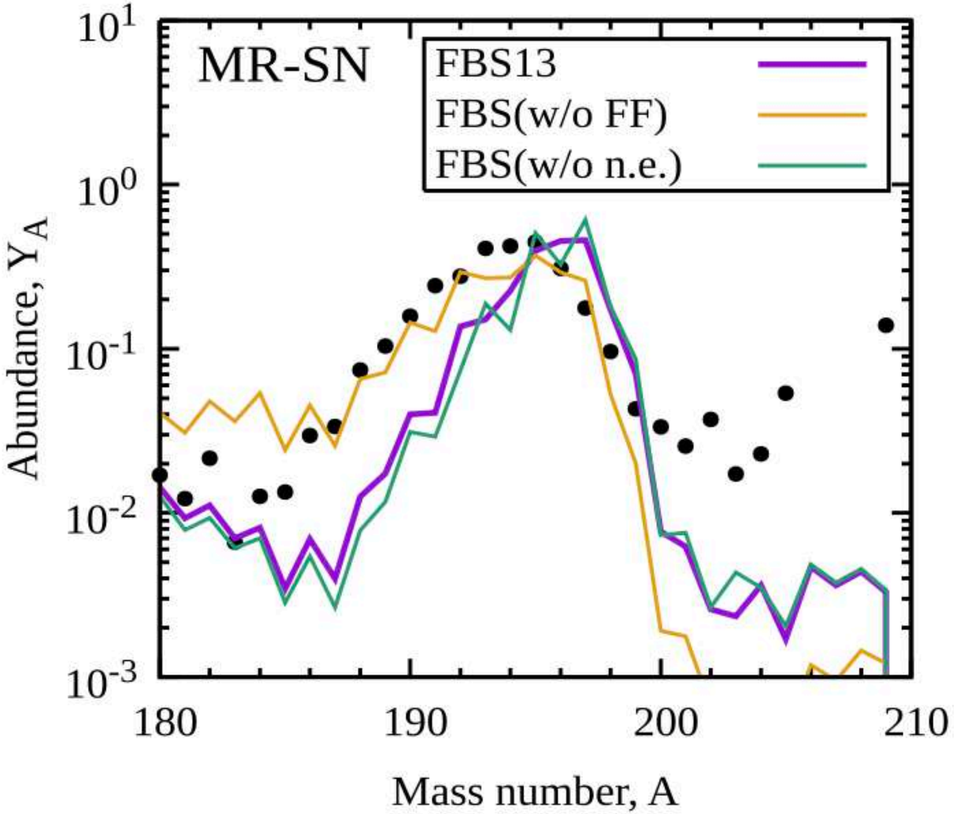
The impacts of β-decay vs (n,g)

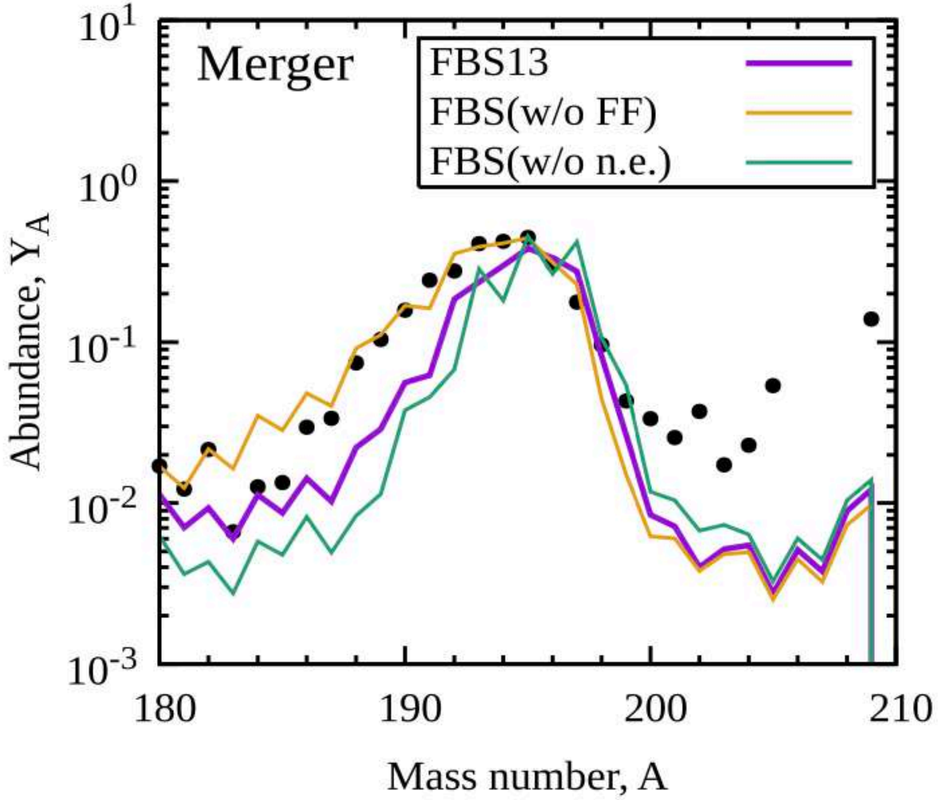
Impacts on the r-process of individual rates



β-decay impacts on the 3rd peak

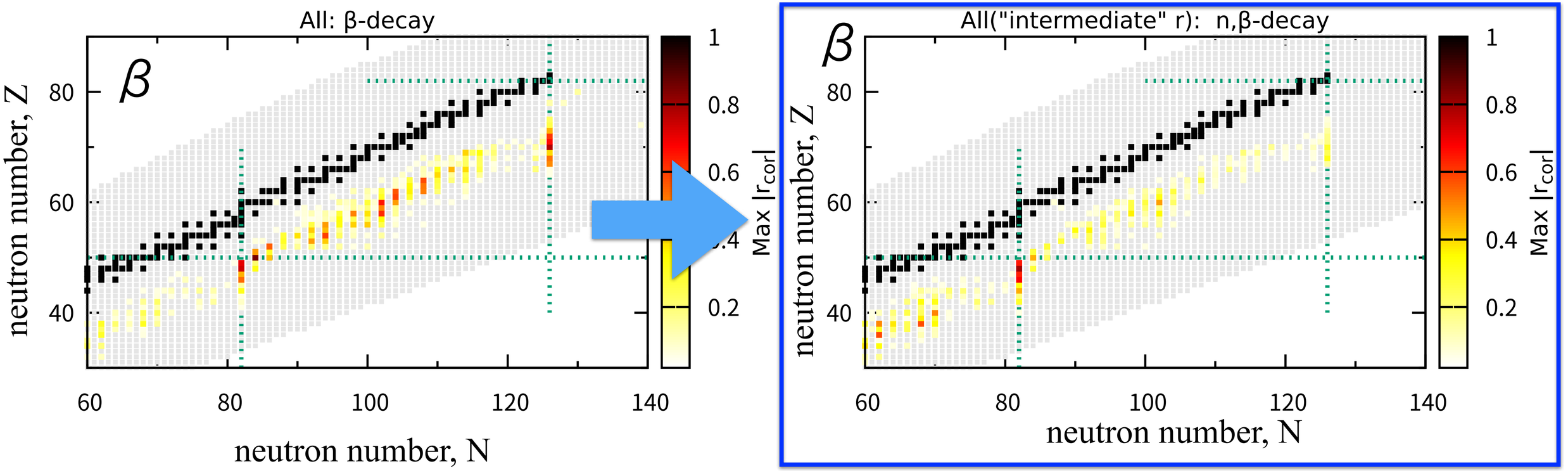
different astrophysics models NN+2016



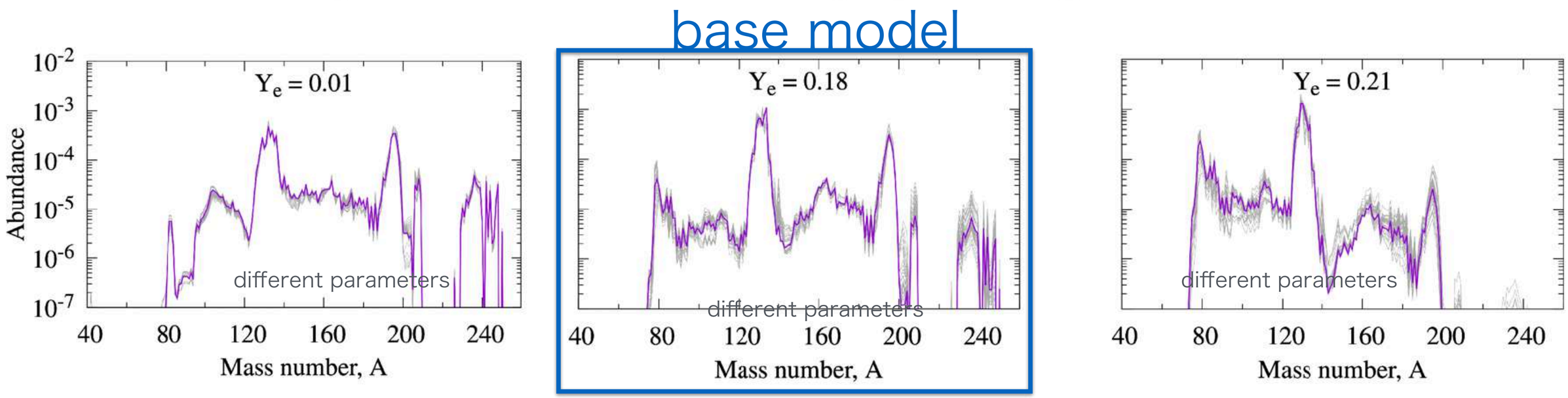


The impacts in different astrophysical

different scenario (NN+207: less n-rich)



Dependence on astrophysical parameters



- Here, we adopt a range of Y_e, velocity, and entropy based on the neutron-star merger simulations
- the final abundances are strongly depend on the initial Y_e (see the different Y_e = 0.18 —> 0.21)
- nuclear-physics uncertainty can show significant impacts if Y_e's are well determined against other astrophysical parameters

Summary

- **Comprehensive analysis of nuclear-reaction uncertainty**
  - key reactions of s-process, p-process, and νp-process
  - significant contribution to nuclear physics experiment studies
    → (future) nuclear theory and astrophysics

- **Uncertainties in r-process nucleosynthesis**
  - Nuclear fission
    - Nuclear fission is important for the termination of r-process in heaviest nuclei, production of intermediate mass nuclei, and kilonova light-curves
    - a new fission calculation with Langevin (dynamical) + CCONE (statistical)
    - (a)symmetricity is significant for neutron emissivity as well as neutron-richness
  - β decay of N = 126 isotopes
    - N=126 have significant impact for the production of 3rd peak
    - even only N = 126 isotones dominant (confirmed by MC calculations)
    - differences in astrophysical models