Key reaction rates of s-process nucleosynthesis and the impact of nuclear physics uncertainty

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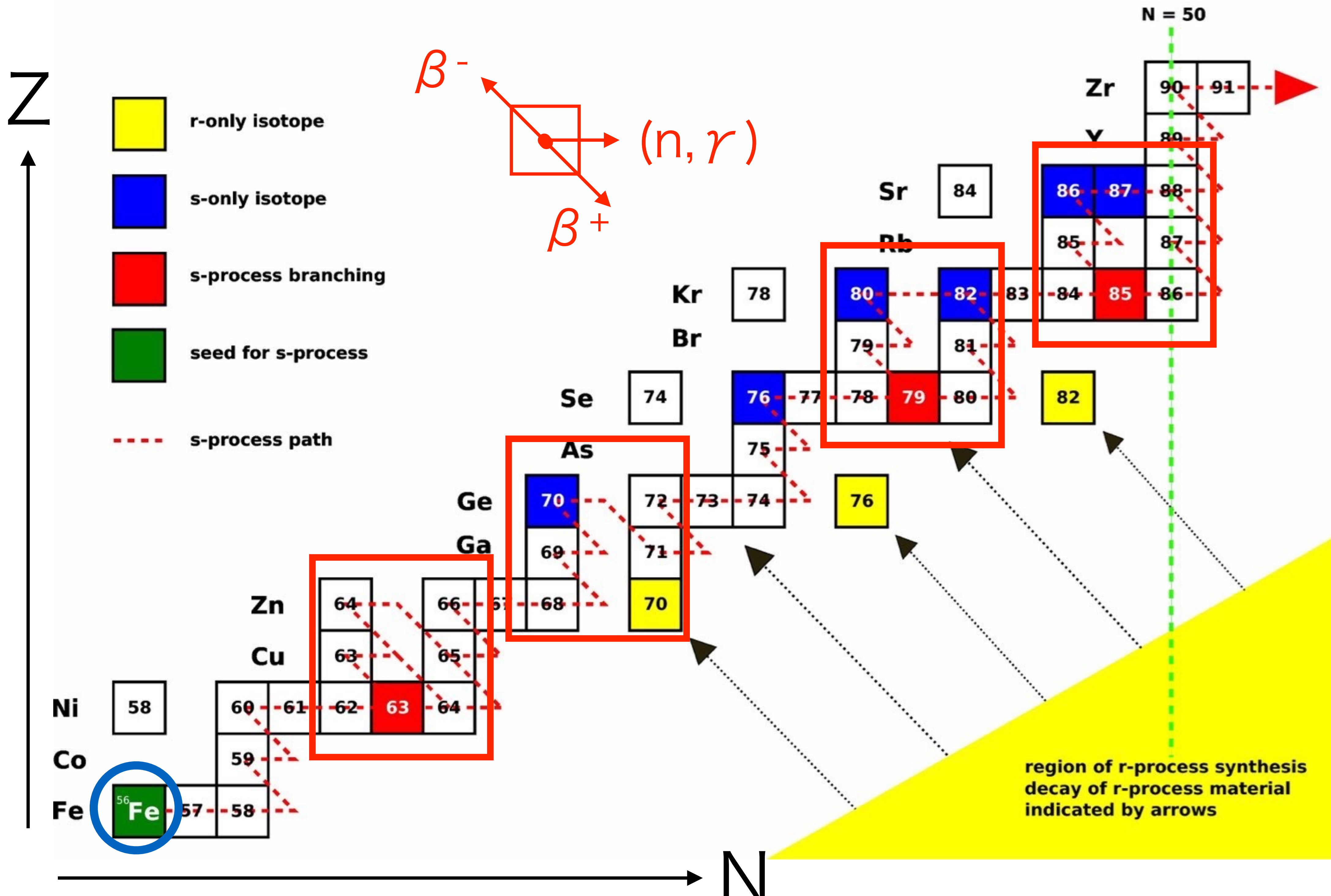
The s-process

- 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



Two sites of the s-process

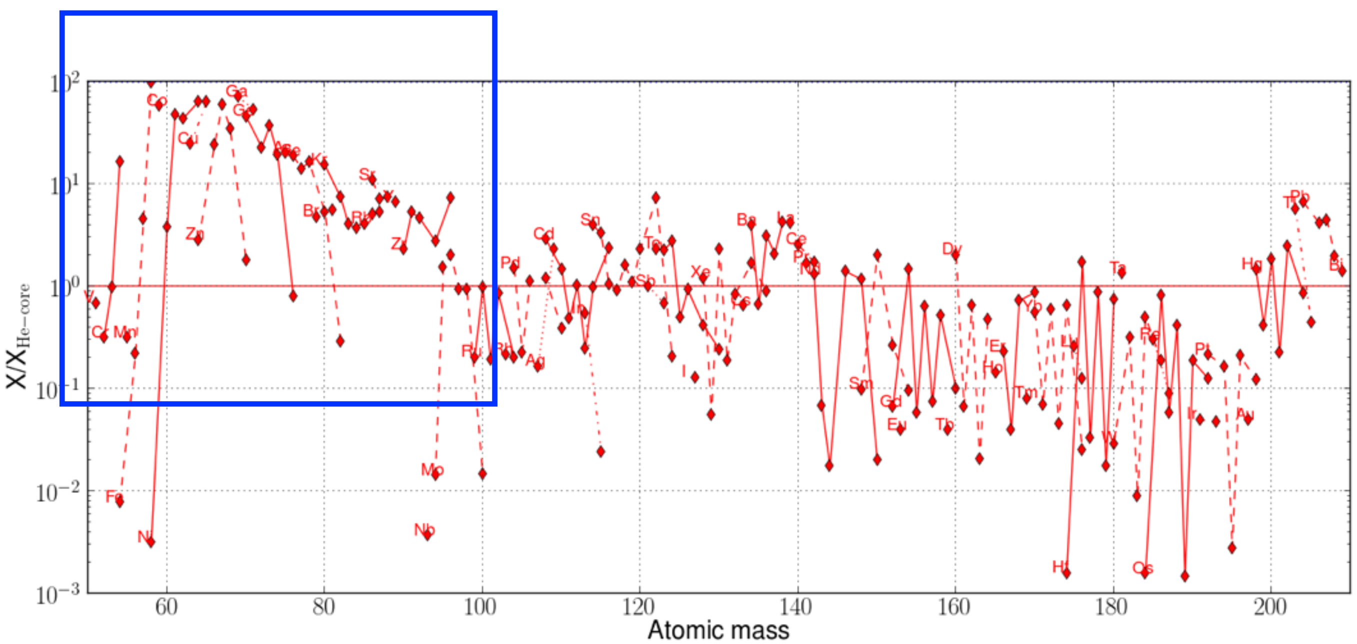
weak s-process

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

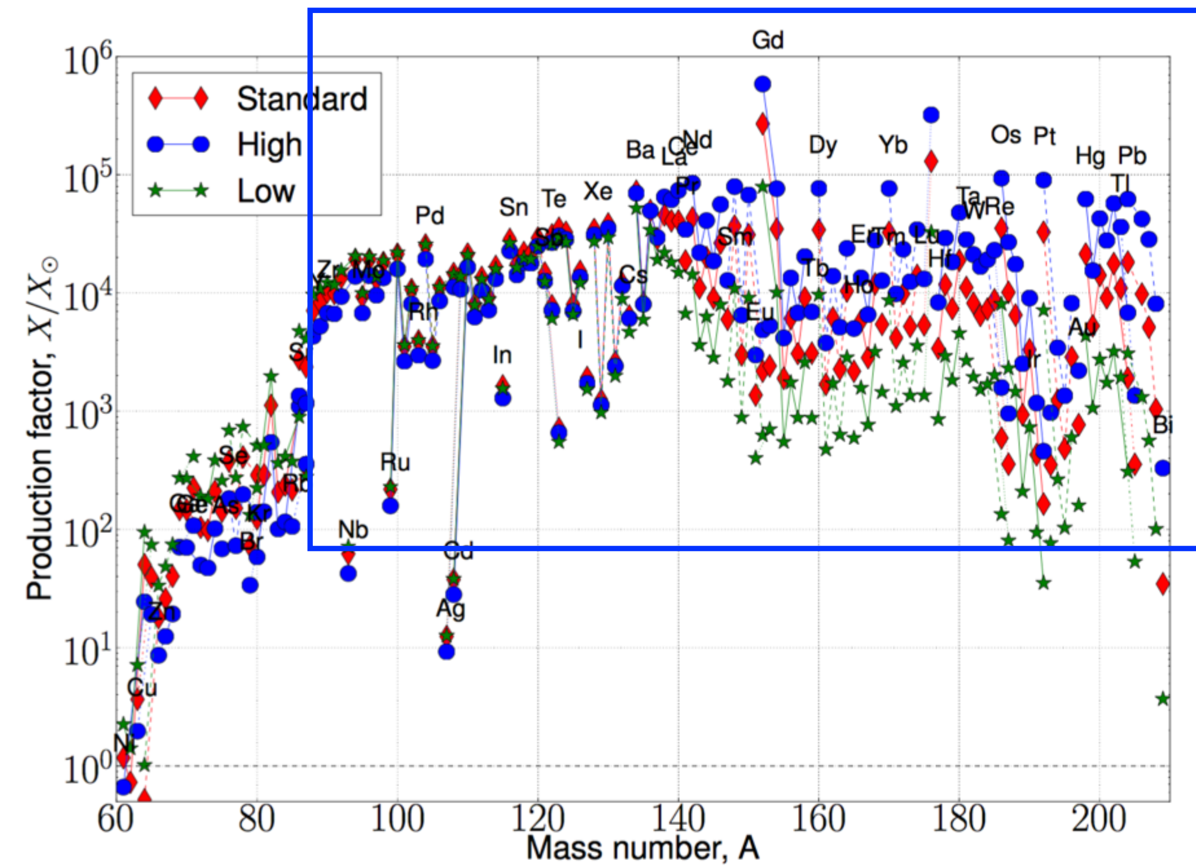
main s-process

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

weak s component



main s component



The s-process in massive stars: uncertainties

Nuclear property → Reaction model → Cross section, Rate → Astrophysical model → Reaction network → Abundances

by Rauscher (arXiV:1412.6990)

Stellar environment

- **Stellar (structure) evolution models**
  - mass, metallicity, dynamics: convection, rotation and magnetic fields, single/binary stars etc.
- **Nuclear burnings in the stellar interior**
  - main fusion reactions: triple-α, $^{12}C(a,g)^{16}O$, ⋯
  - n-source and n-poison reactions: $^{22}Ne(a,n)^{25}Mg$, ⋯

  (see e.g., Nishimura et al., AIPC 1594 p 146, 2014)

Network calculation

Monte-Carlo simulation

- Nucleosynthesis
  - (n,g) reaction
  - beta-decay

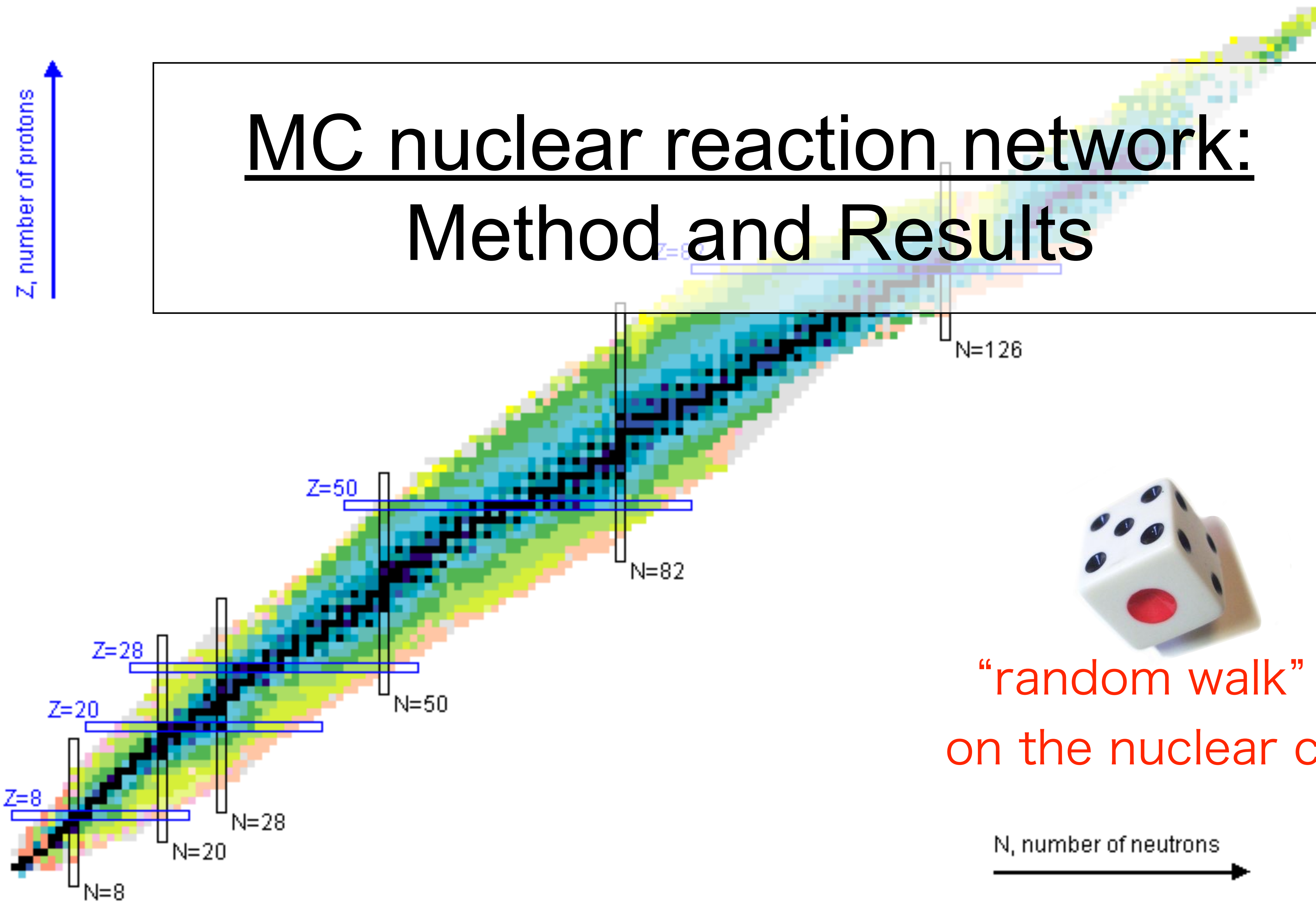
uncertainty in the final abundances

feedback (find key reaction/decay)

Contents

- Rauscher, NN+ (2016), MNRAS in press; arXiv1606.05671
- NN+ 2016, MNRAS, in prep.
- Cescutti, NN+ 2017(?), in prep.

MC nuclear reaction network: Method and Results



“random walk” (?)
on the nuclear chart

Nuclear chart : http://www.nndc.bnl.gov/nudat2/

Monte-Carlo network code

- Monte-Carlo framework
  - PizBuin MC-driver
    (developed by Rauscher, NN, Hirschi)
  - a simple "Brute-force" approach
  - parallelized by OpenMP for shared memory architectures
    (paralleled easily, but harder debugging. . .)

Piz Buin (mountain)

- 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

T-dependent uncertainty: (n,γ) & β-decay

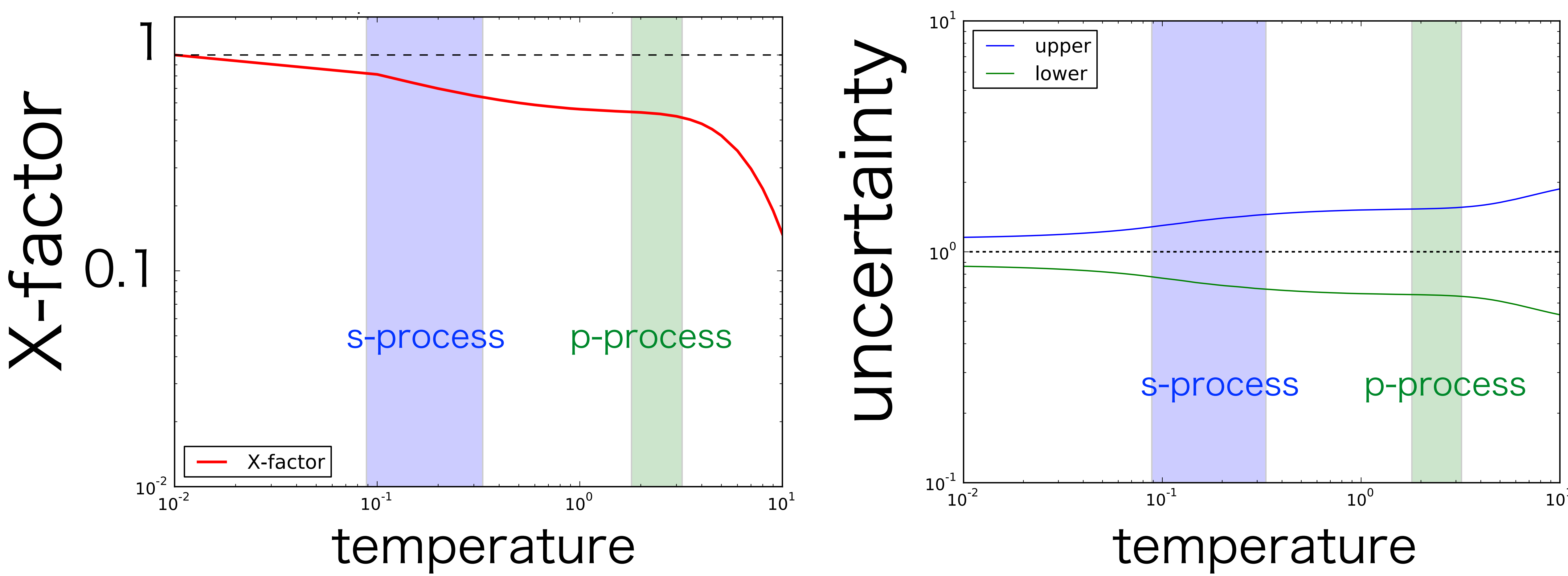
(n,g) reactions

- Experimental rates
  - base rates: KADoNiS v0.3 (Dillmann+, 2009)
  - consider both g.s. and e.s. (Rauscher, ApJ, 775, 2011

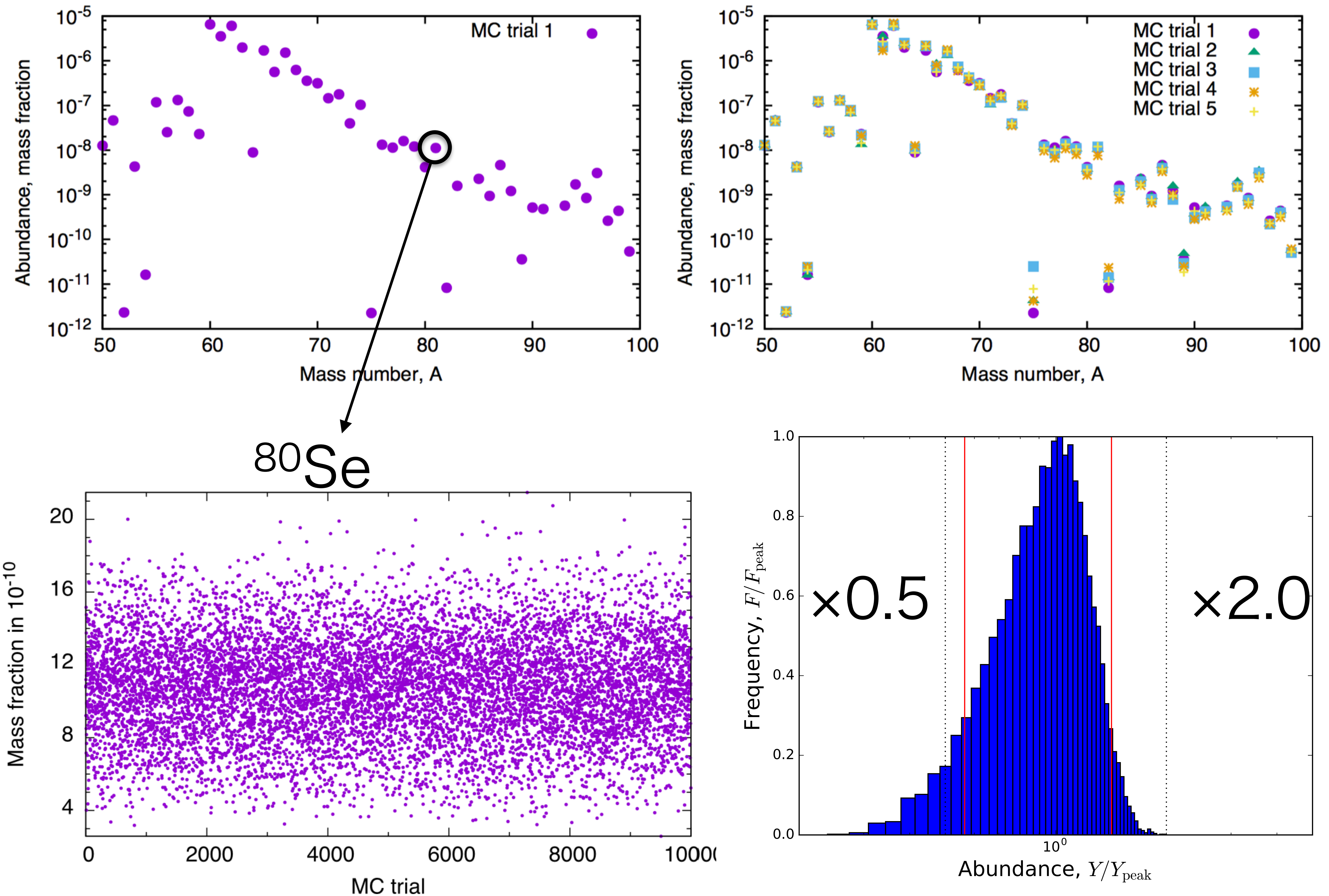
$$\boxed{U(T) = U_{\mathrm{g.s.}} X + U_{\mathrm{e.s.}} (1 - X)}$$

β-decay: a similar method using partition functions (See, NN+2016)

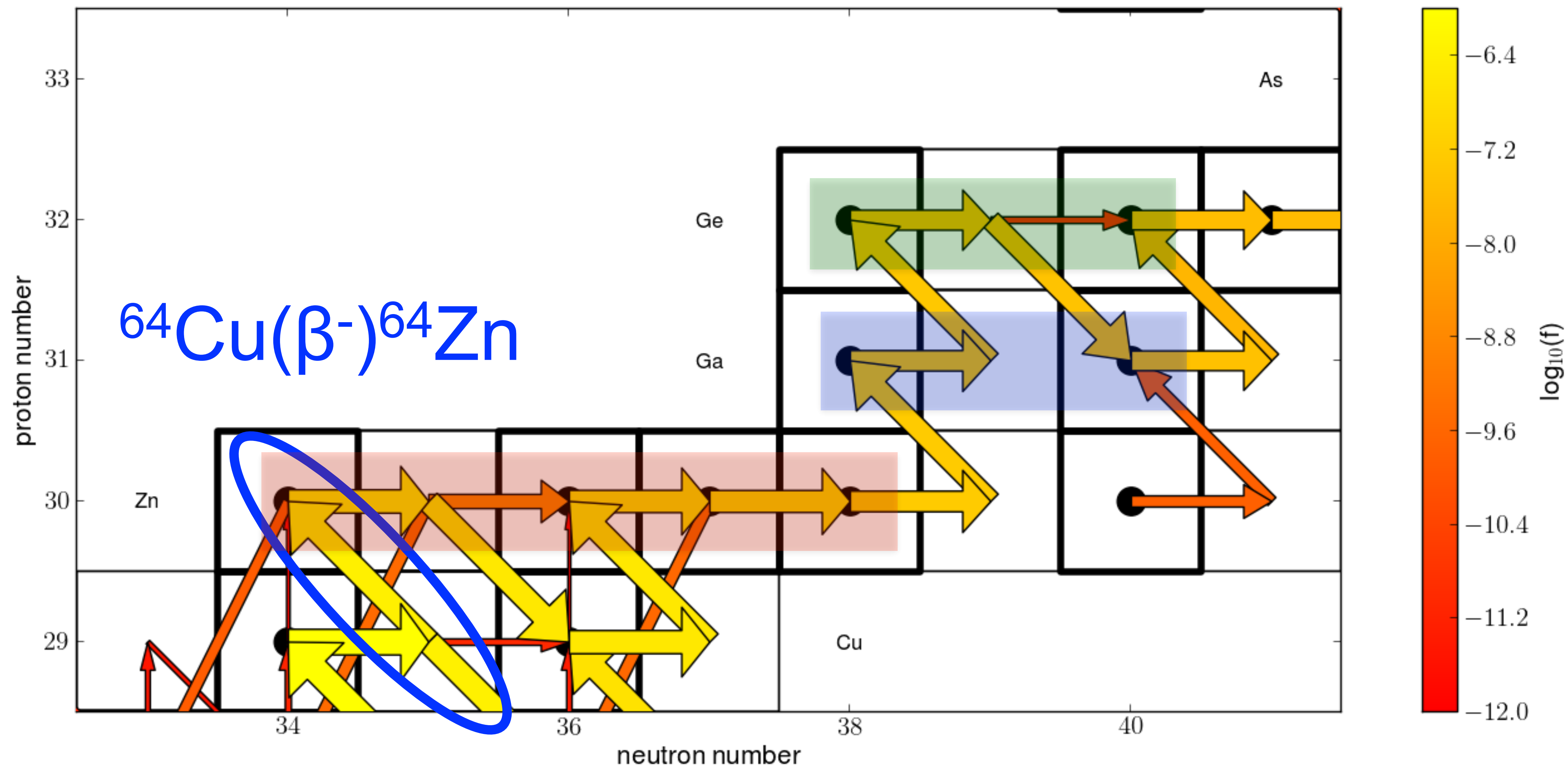
^{83}Kr(n,g)^{84}Kr

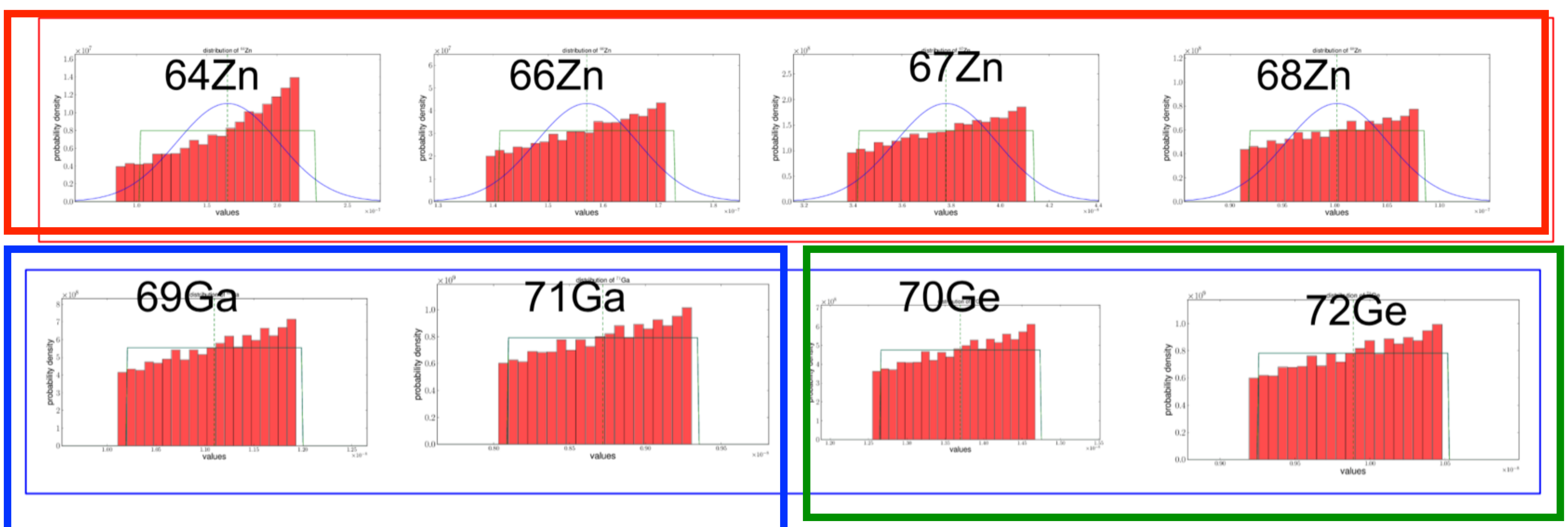


MC calculation with reaction network

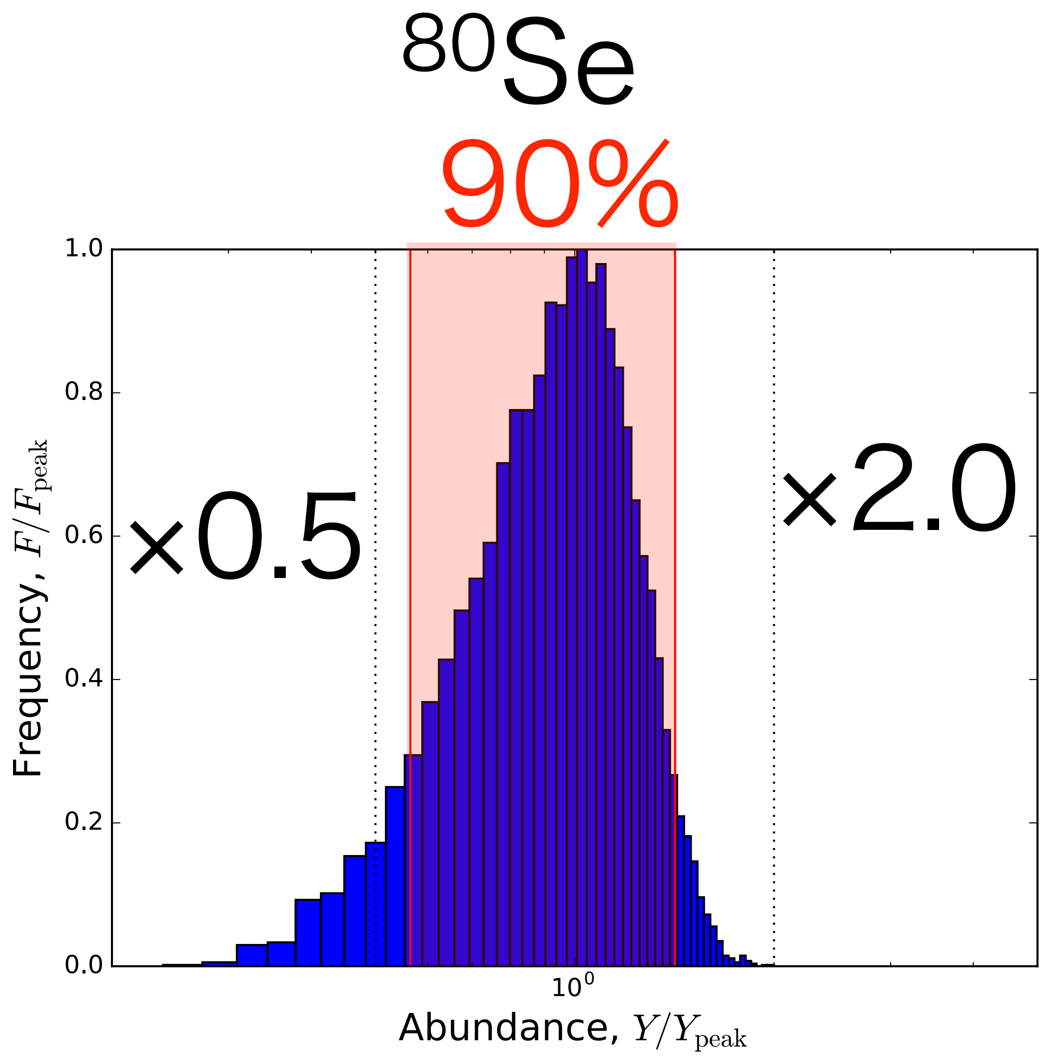


Propagation of uncertainty: $^{64}Cu(\beta-)^{64}Zn$

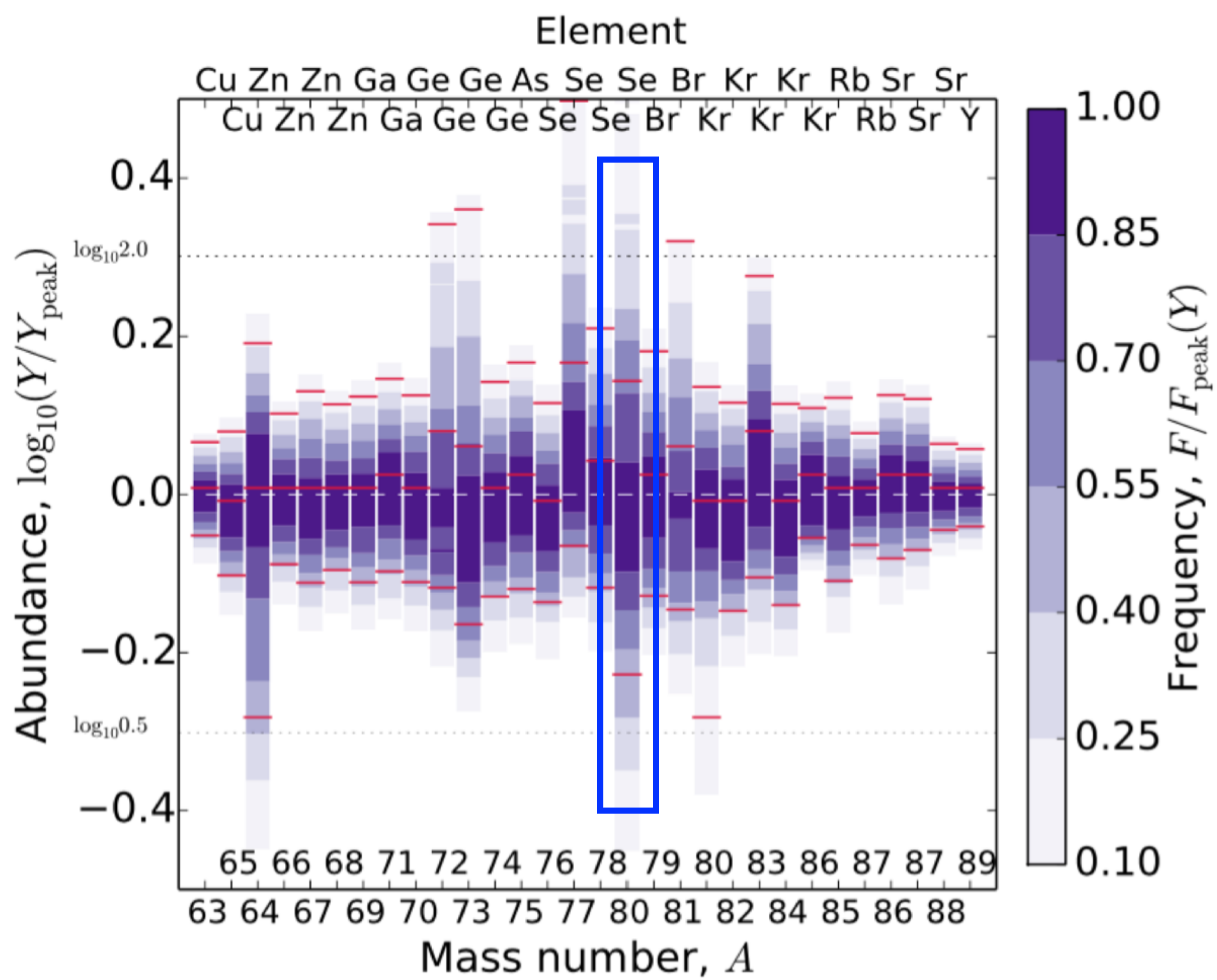




Uncertainty by MC: (n,g) and β-decay

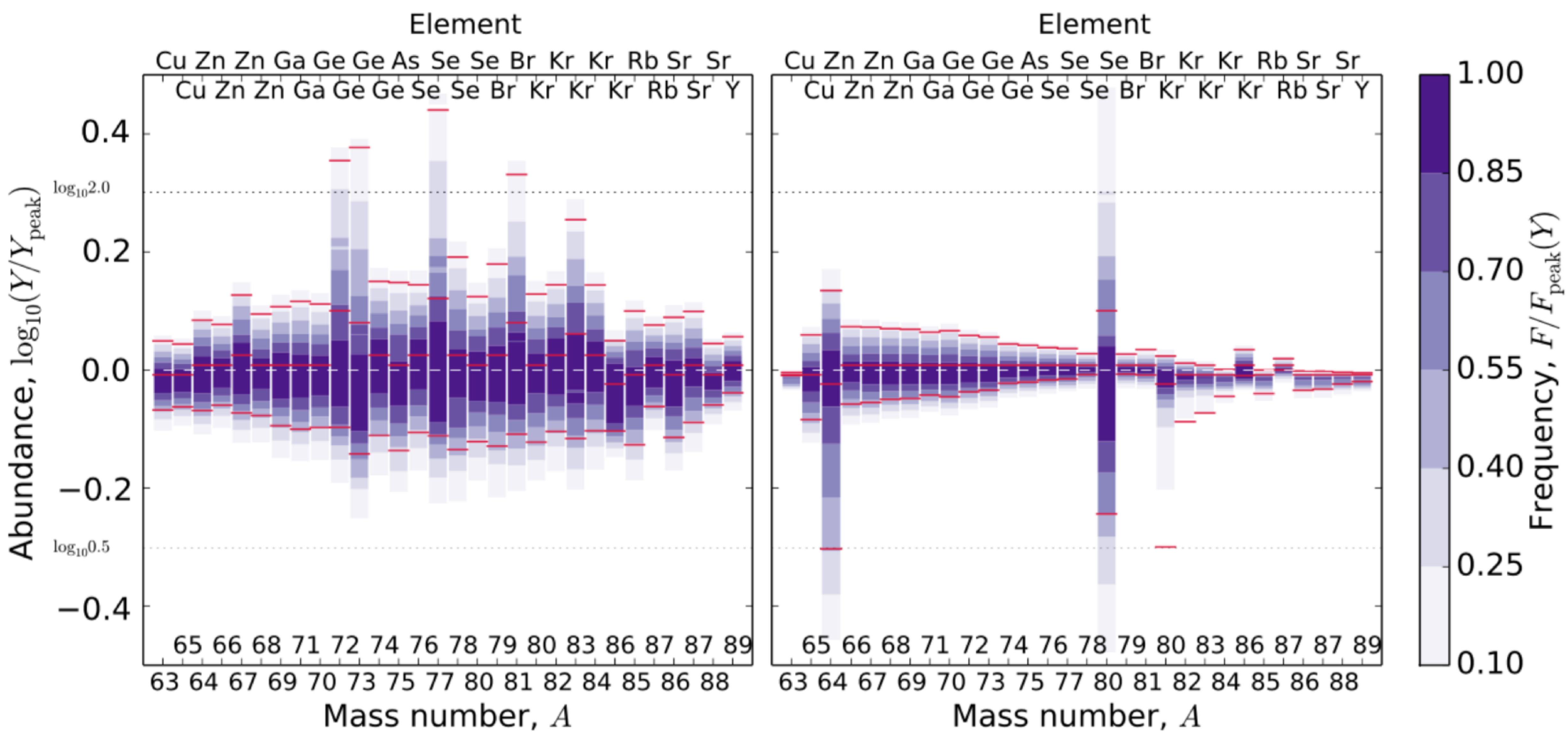


(n,g) & $\beta^{\pm}$



Uncertainty by MC: (n,g) and β-decay

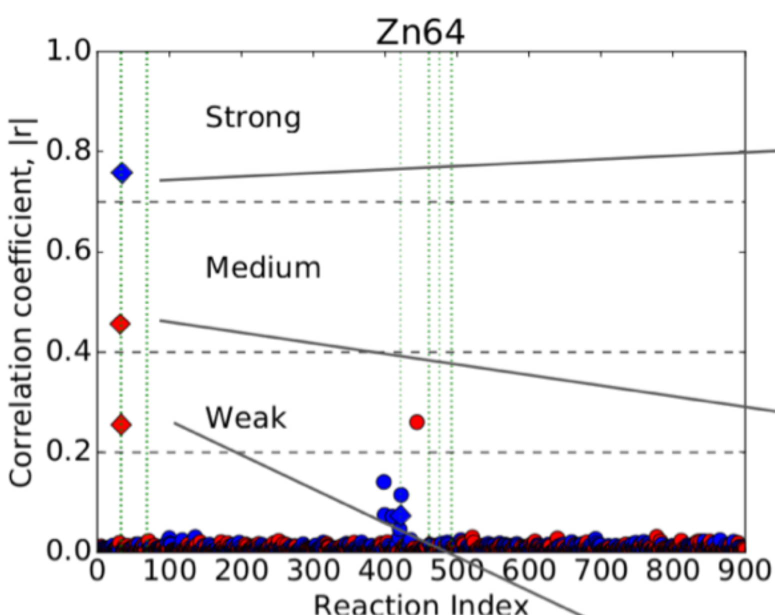
only (n,g) only $\beta^{\pm}$



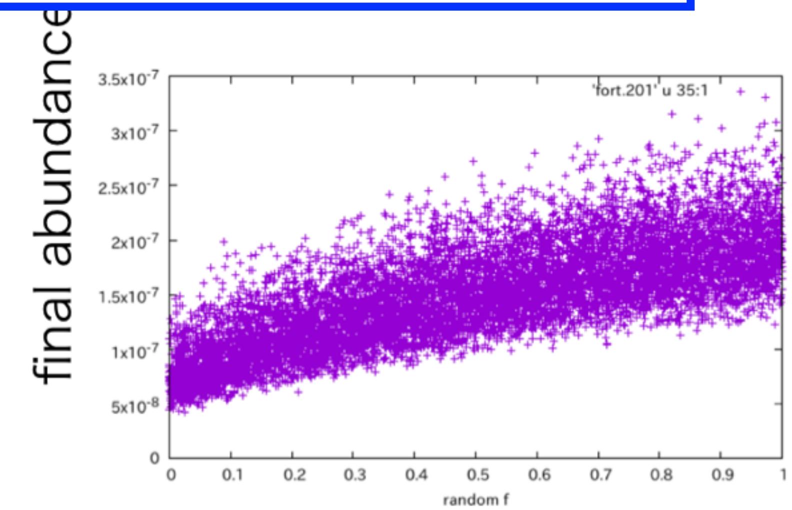
Correlation factors

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

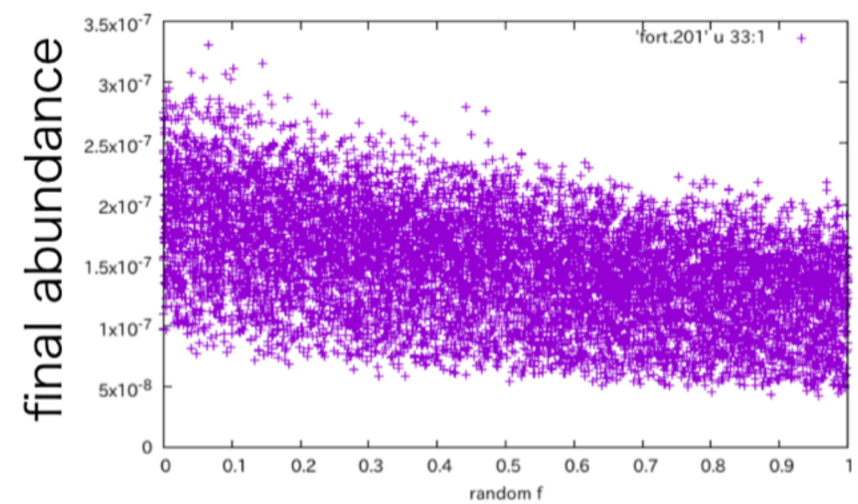
Blue: positive; red: negative

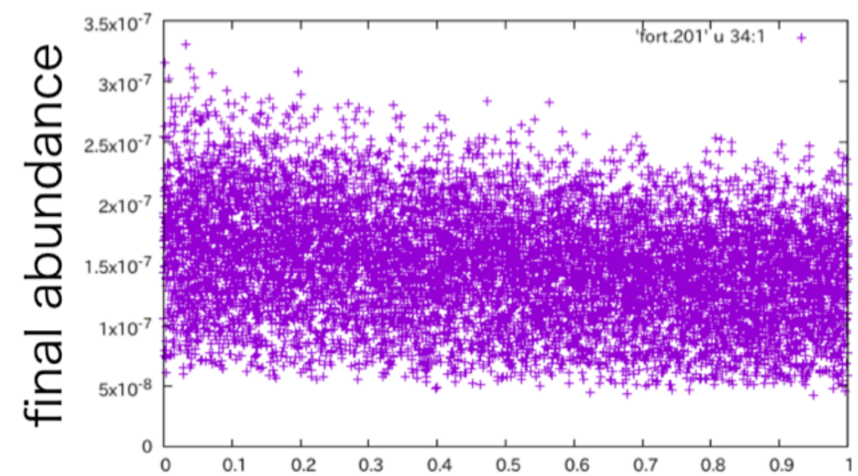


$^{64}\mathrm{Cu}\,(\beta^-)\,^{64}\mathrm{Zn}$



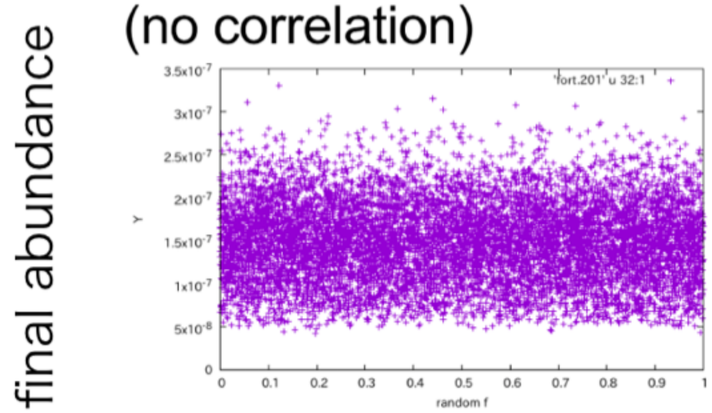
$^{64}\mathrm{Cu}\,(\beta^+)\,^{64}\mathrm{Ni}$





uncertainty factor

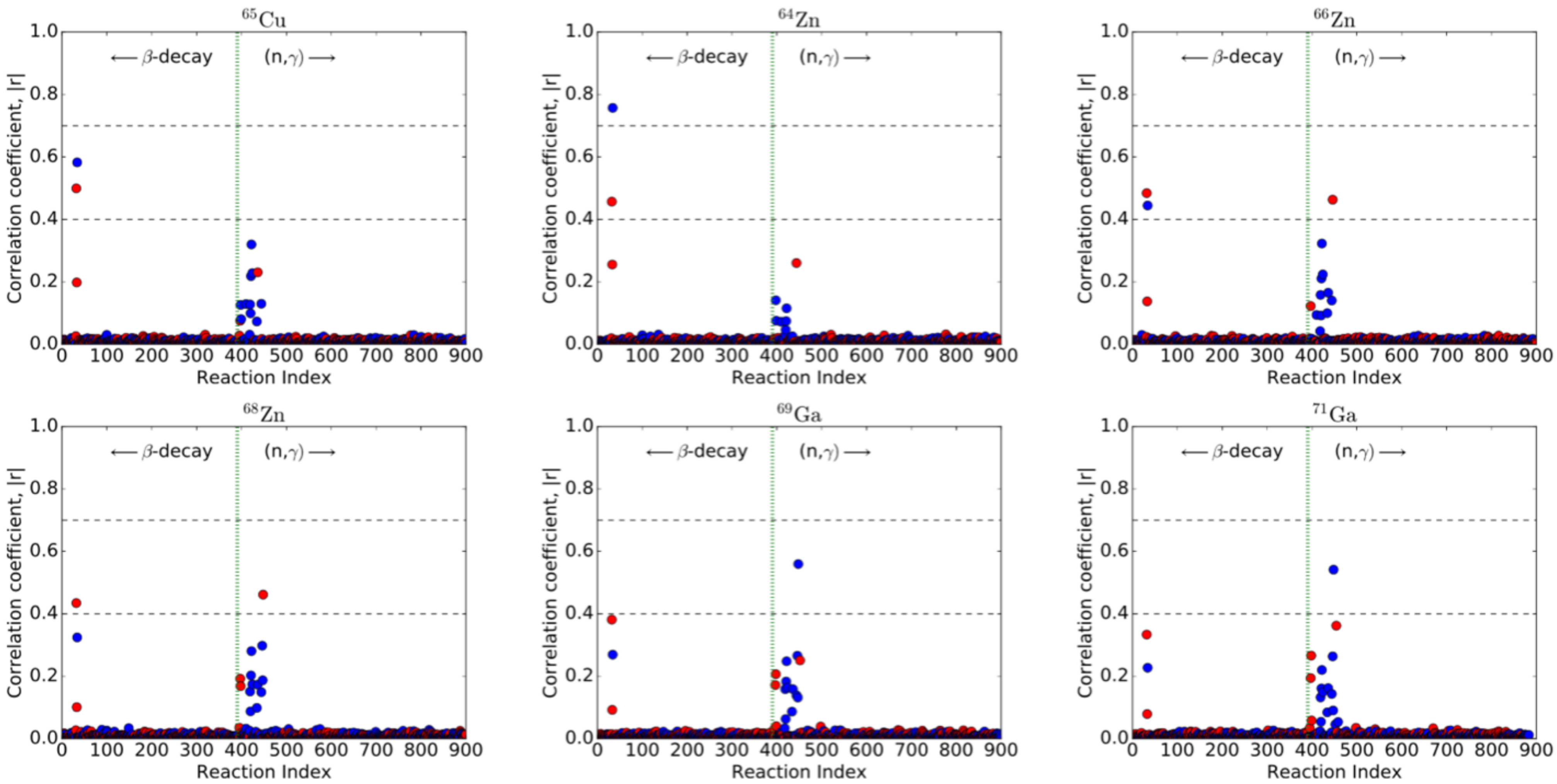
other rates
(no correlation)



uncertainty factor

no correlation

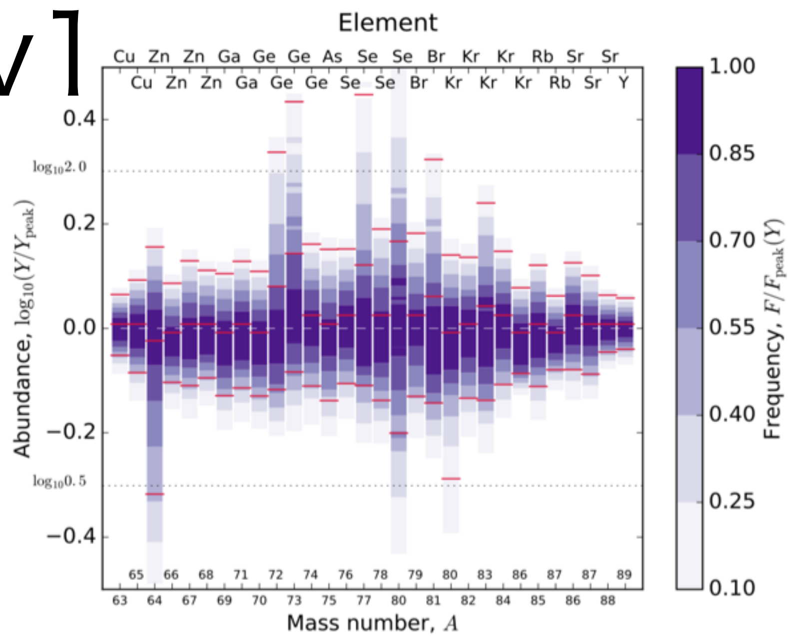
Correlation factors



We can derive key reaction rates from the MC results

Screening of the reaction rates

Lv1



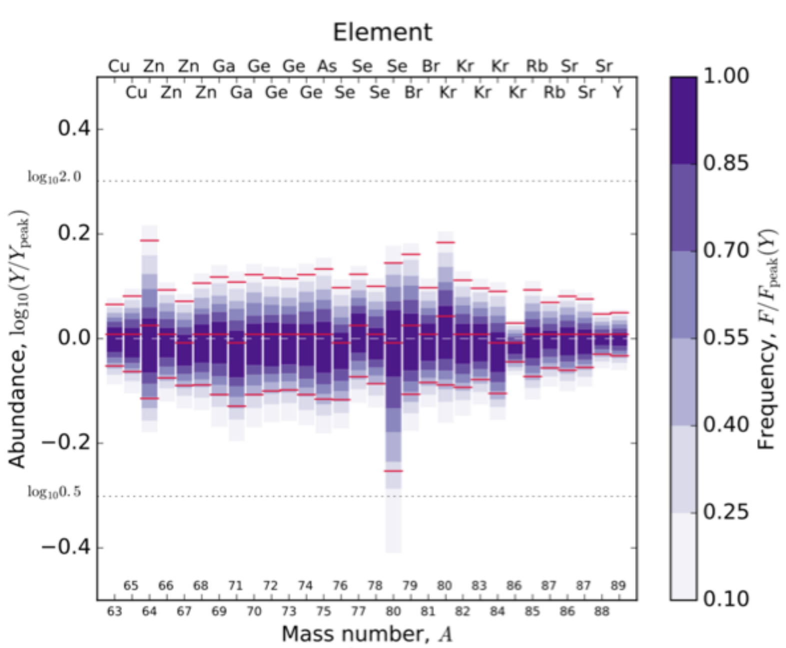
reactions

$|r| > 0.65$

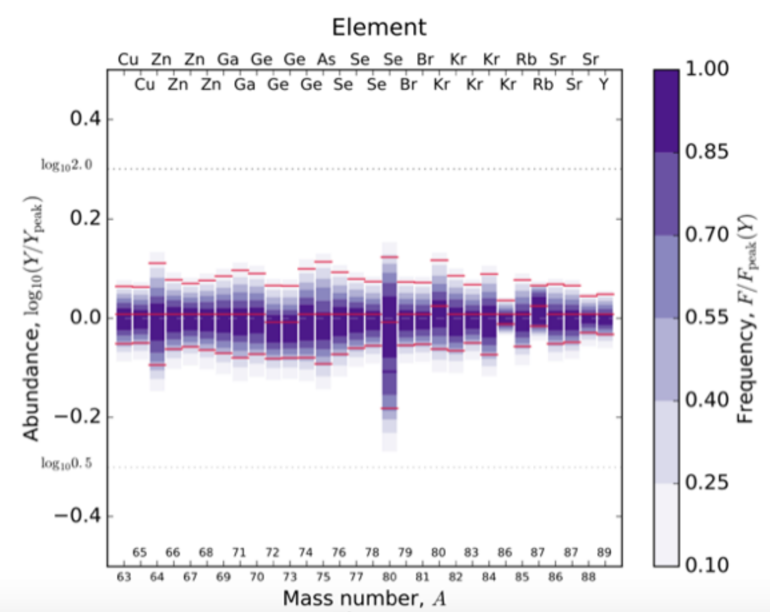
Key rate Level 1
$^{64}\mathrm{Cu}(+\beta)^{64}\mathrm{Zn}$
$^{67}\mathrm{Zn} + \mathrm{n} \leftrightarrow \gamma + {}^{68}\mathrm{Zn}$
$^{72}\mathrm{Ge} + \mathrm{n} \leftrightarrow \gamma + {}^{73}\mathrm{Ge}$
$^{73}\mathrm{Ge} + \mathrm{n} \leftrightarrow \gamma + {}^{74}\mathrm{Ge}$
$^{77}\mathrm{Se} + \mathrm{n} \leftrightarrow \gamma + {}^{78}\mathrm{Se}$
$^{78}\mathrm{Se} + \mathrm{n} \leftrightarrow \gamma + {}^{79}\mathrm{Se}$
$^{80}\mathrm{Br}(+\beta)^{80}\mathrm{Kr}$
$^{81}\mathrm{Kr} + \mathrm{n} \leftrightarrow \gamma + {}^{82}\mathrm{Kr}$
$^{83}\mathrm{Kr} + \mathrm{n} \leftrightarrow \gamma + {}^{84}\mathrm{Kr}$
$^{85}\mathrm{Kr} + \mathrm{n} \leftrightarrow \gamma + {}^{86}\mathrm{Kr}$

fix Lv1 key rates

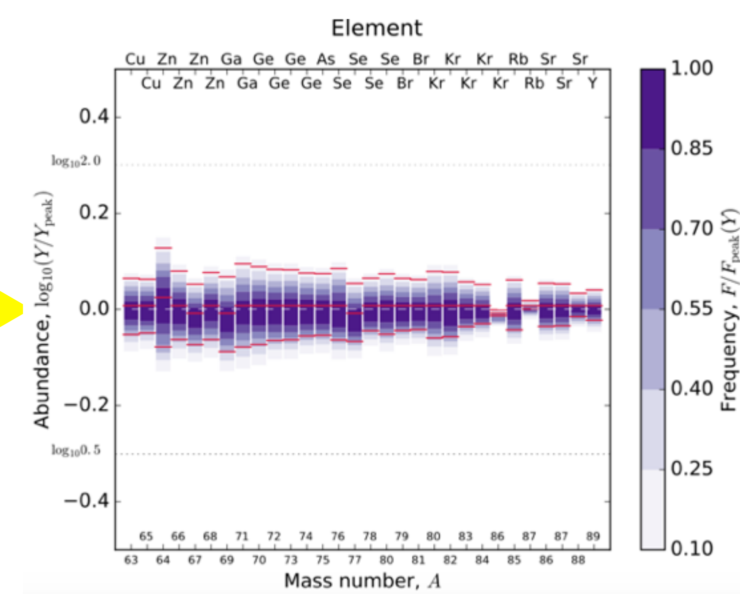
Lv2



Lv3



Lv4



Key reaction list

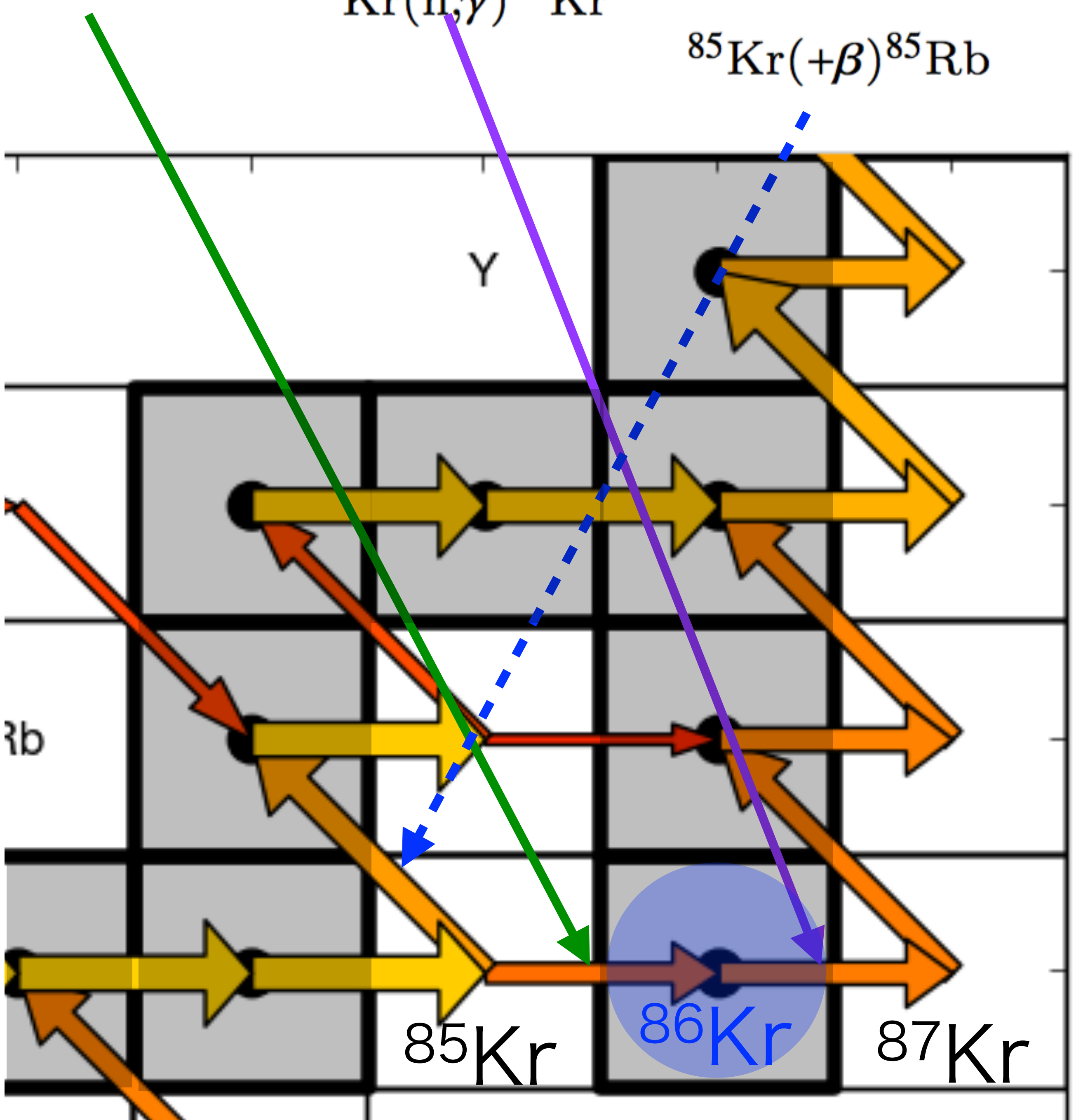
all Lv1 reaction are fixed

all Lv1+Lv2 reaction are fixed

Nuclide	$r_{cor,0}$	$r_{cor,1}$	$r_{cor,2}$	Key rate Level 1	Key rate Level 2	Key rate level 3	X_0 (30 keV)	X_0 (80 keV)
^{64}Zn	0.76			^{64}Cu$(+\beta)^{64}$Zn				
	-0.47	-0.73			^{64}Cu $+ e^- \leftrightarrow \nu_e +$ ^{64}Ni			
^{67}Zn	-0.67			^{67}Zn $+ n \leftrightarrow \gamma +$ ^{68}Zn			1.00	1.00
^{72}Ge	-0.85			^{72}Ge $+ n \leftrightarrow \gamma +$ ^{73}Ge			1.00	1.00
^{73}Ge	-0.84			^{73}Ge $+ n \leftrightarrow \gamma +$ ^{74}Ge			0.88	0.81
^{74}Ge	-0.44	-0.53	-0.67			^{74}Ge $+ n \leftrightarrow \gamma +$ ^{75}Ge	1.00	1.00
^{75}As	-0.50	-0.58	-0.70			^{75}As $+ n \leftrightarrow \gamma +$ ^{76}As	1.00	1.00
^{77}Se	-0.86			^{77}Se $+ n \leftrightarrow \gamma +$ ^{78}Se			1.00	1.00
^{78}Se	-0.71			^{78}Se $+ n \leftrightarrow \gamma +$ ^{79}Se			1.00	1.00
	0.37	0.68			^{68}Zn $+ n \leftrightarrow \gamma +$ ^{69}Zn		1.00	1.00
^{80}Se	-0.76			^{80}Br$(+\beta)^{80}$Kr				
	0.27	0.73			^{80}Br$(-\beta)^{80}$Se			
	0.16	0.44	0.88			^{80}Br $+ e^- \leftrightarrow \nu_e +$ ^{80}Se		
^{79}Br	-0.63	-0.73			^{79}Br $+ n \leftrightarrow \gamma +$ ^{80}Br		1.00	1.00
^{81}Br	-0.80			^{81}Kr $+ n \leftrightarrow \gamma +$ ^{82}Kr			1.00	1.00
^{83}Kr	-0.76			^{83}Kr $+ n \leftrightarrow \gamma +$ ^{84}Kr			0.81	0.74
^{84}Kr	-0.49	-0.64	-0.76			^{84}Kr $+ n \leftrightarrow \gamma +$ ^{85}Kr	1.00	1.00
^{86}Kr	0.84			^{85}Kr $+ n \leftrightarrow \gamma +$ ^{86}Kr			1.00	1.00
	-0.31	-0.71			^{86}Kr $+ n \leftrightarrow \gamma +$ ^{87}Kr		1.00	1.00
	-0.33	-0.62	-0.90			^{85}Kr$(+\beta)^{85}$Rb		
^{87}Rb	-0.57	-0.64	-0.95			^{87}Rb $+ n \leftrightarrow \gamma +$ ^{88}Rb	1.00	1.00

Key reaction list: ^{86}Kr

Key reaction Level 1	Key reaction Level 2	Key reaction level 3
^{85}Kr(n,γ)^{86}Kr	^{86}Kr(n,γ)^{87}Kr	^{85}Kr(+β)^{85}Rb

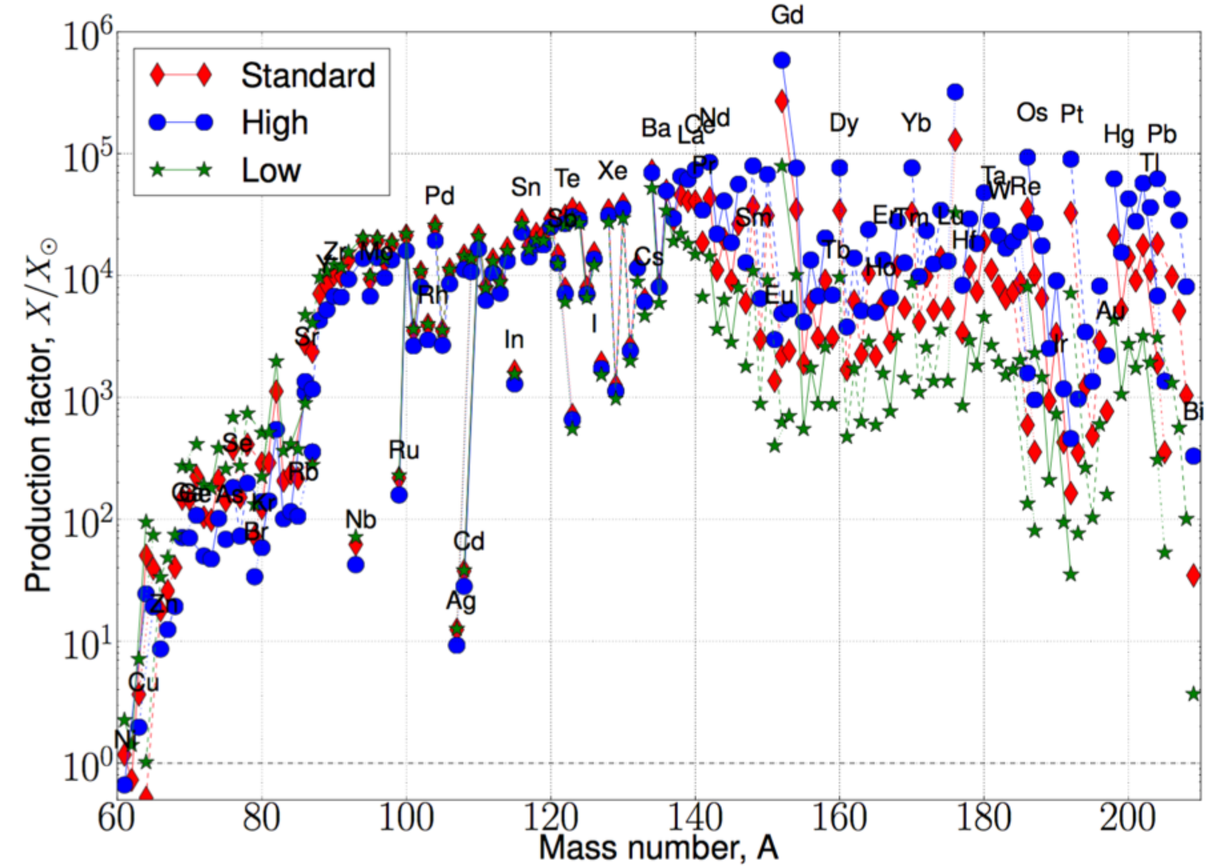


vs ^{85}Kr(n,g)^{86}Kr

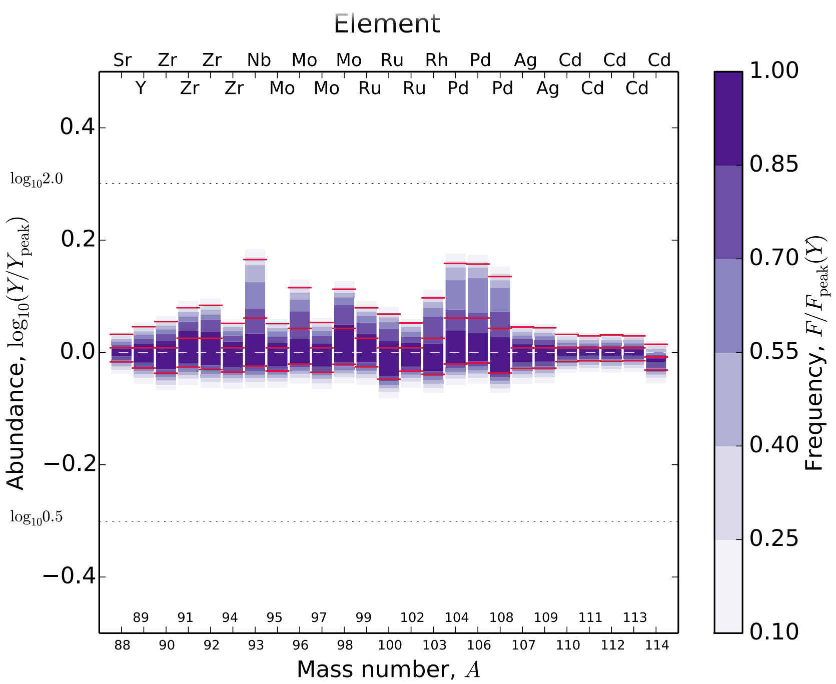
	^{86}Kr(n,g)	^{85}Kr(b+)
upper	-0.42	**-0.68**
standard	**-0.71**	-0.62
lower	**-0.84**	-0.42

main s-process

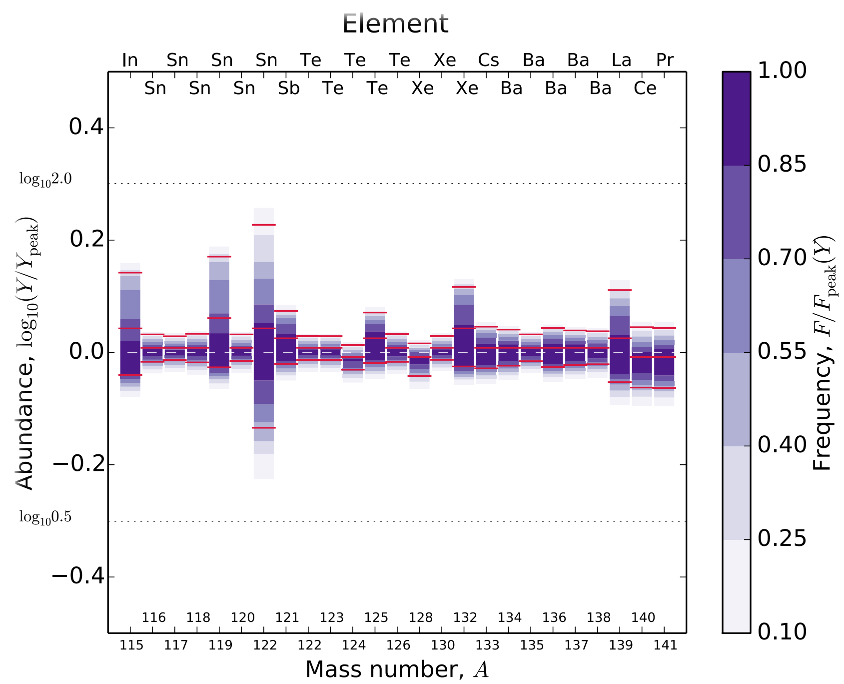
- ‘one zone’ a low mass AGB star
- 2Msun model by MESA code
- the initial ^{13}C is adjusted
- a typical s-process pattern



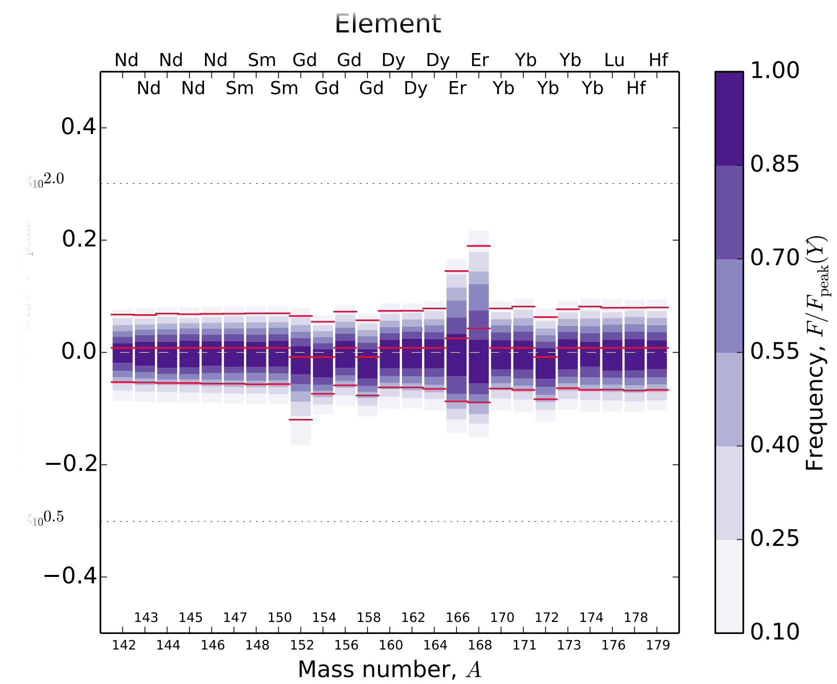
lighter



medium



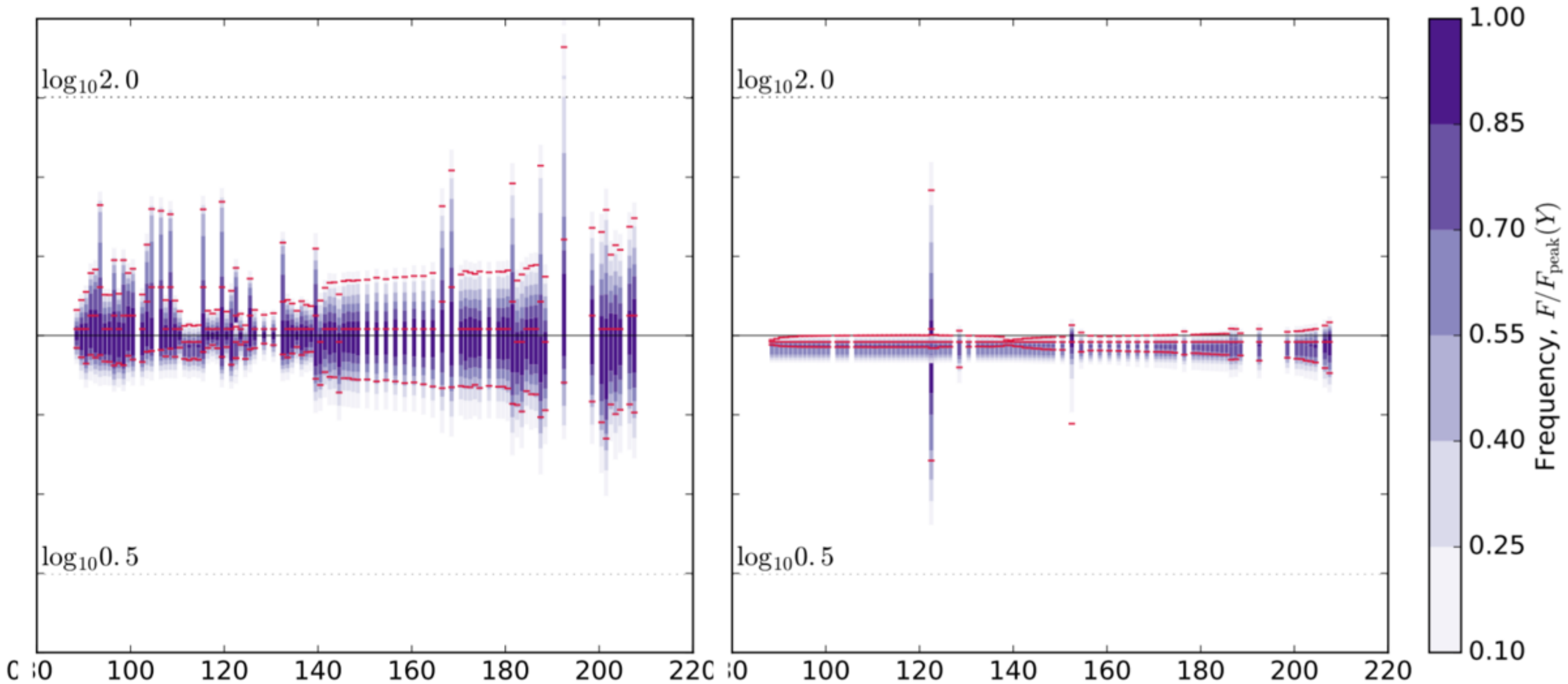
heavier



Cescutti+NN+, in prep.

main s-process

(n,g)-contribution β-decay contribution



Nuclide	$r_{cor,0}$	$r_{cor,1}$	$r_{cor,2}$	Key reaction Level 1	Key reaction Level 2	Key reaction level 3
Sr88	-0.65			^{88}Sr(n,γ)^{89}Sr		
Y89	-0.83			^{89}Y(n,γ)^{90}Y		
Zr90	-0.89			^{90}Zr(n,γ)^{91}Zr		
Zr91	-0.91			^{91}Zr(n,γ)^{92}Zr		
Zr92	-0.92			^{92}Zr(n,γ)^{93}Zr		
Zr94	-0.86			^{94}Zr(n,γ)^{95}Zr		
Nb93	-0.97			^{93}Zr(n,γ)^{94}Zr		
Mo95	-0.85			^{95}Mo(n,γ)^{96}Mo		
Mo96	-0.94			^{96}Mo(n,γ)^{97}Mo		
Mo97	-0.87			^{97}Mo(n,γ)^{98}Mo		
Mo98	-0.94			^{98}Mo(n,γ)^{99}Mo		
Ru99	-0.91			^{99}Tc(n,γ)^{100}Tc		
Ru100	-0.93			^{100}Ru(n,γ)^{101}Ru		
Ru102	-0.86			^{102}Ru(n,γ)^{103}Ru		
Rh103	-0.95			^{103}Rh(n,γ)^{104}Rh		
Pd104	-0.97			^{104}Pd(n,γ)^{105}Pd		
Pd106	-0.97			^{106}Pd(n,γ)^{107}Pd		
Pd108	-0.96			^{108}Pd(n,γ)^{109}Pd		
Ag107	-0.81			^{107}Pd(n,γ)^{108}Pd		
Ag109	-0.80			^{109}Ag(n,γ)^{110}Ag		
In115	-0.97			^{115}In(n,γ)^{116}In		
Sn119	-0.97			^{119}Sn(n,γ)^{120}Sn		
Sn122	-0.73			^{122}Sb(+β)^{122}Te		
	0.57	0.86			^{122}Sb($-\beta$)^{122}Sn	
	-0.33	-0.49	-0.96			^{122}Sn(n,γ)^{123}Sn
Sb121	-0.92			^{121}Sb(n,γ)^{122}Sb		
Te125	-0.92			^{125}Te(n,γ)^{126}Te		
Te126	-0.69			^{126}Te(n,γ)^{127}Te		
Xe128	0.66			^{128}I(+β)^{128}Xe		
Xe132	-0.97			^{132}Xe(n,γ)^{133}Xe		
Cs133	-0.89			^{133}Cs(n,γ)^{134}Cs		
Ba134	-0.85			^{134}Ba(n,γ)^{135}Ba		
Ba135	-0.70			^{135}Ba(n,γ)^{136}Ba		
Ba136	-0.88			^{136}Ba(n,γ)^{137}Ba		
Ba137	-0.84			^{137}Ba(n,γ)^{138}Ba		
Ba138	-0.65	-0.71			^{138}Ba(n,γ)^{139}Ba	
La139	-0.87			^{139}La(n,γ)^{140}La		
Gd152	0.59	0.60	0.66			^{151}Sm(+β)^{151}Eu
Er166	-0.81			^{166}Er(n,γ)^{167}Er		
Er168	-0.86			^{168}Er(n,γ)^{169}Er		
Ta181	-0.84			^{181}Ta(n,γ)^{182}Ta		
Os187	-0.86			^{187}Os(n,γ)^{188}Os		
Pt192	-0.89			^{192}Pt(n,γ)^{193}Pt		
Hg198	-0.63	-0.65	-0.68			^{198}Hg(n,γ)^{199}Hg
Hg200	-0.67			^{200}Hg(n,γ)^{201}Hg		
Hg201	-0.77			^{201}Hg(n,γ)^{202}Hg		

Ru100	-0.93			^{100}Ru(n,γ)^{101}Ru		
Ru102	-0.86			^{102}Ru(n,γ)^{103}Ru		
Rh103	-0.95			^{103}Rh(n,γ)^{104}Rh		
Pd104	-0.97			^{104}Pd(n,γ)^{105}Pd		
Pd106	-0.97			^{106}Pd(n,γ)^{107}Pd		
Pd108	-0.96			^{108}Pd(n,γ)^{109}Pd		
Ag107	-0.81			^{107}Pd(n,γ)^{108}Pd		
Ag109	-0.80			^{109}Ag(n,γ)^{110}Ag		
In115	-0.97			^{115}In(n,γ)^{116}In		
Sn119	-0.97			^{119}Sn(n,γ)^{120}Sn		
Sn122	-0.73			^{122}Sb(+β)^{122}Te		
	0.57	0.86			^{122}Sb($-\beta$)^{122}Sn	
	-0.33	-0.49	-0.96			^{122}Sn(n,γ)^{123}Sn

Cescutti+NN+, in prep.

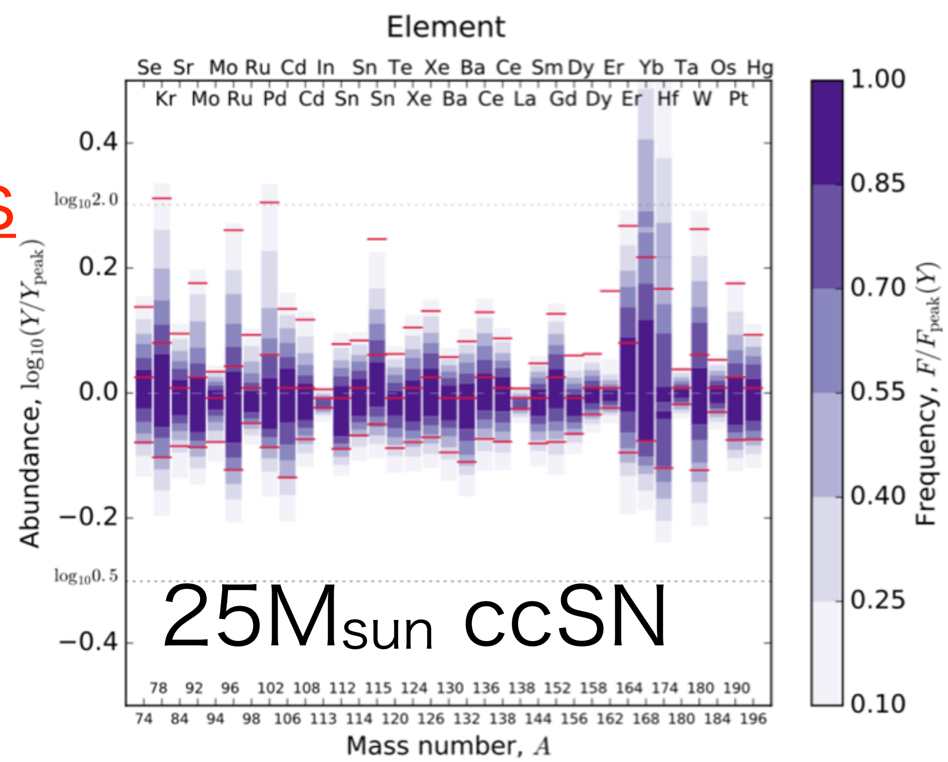
One more example: gamma-process

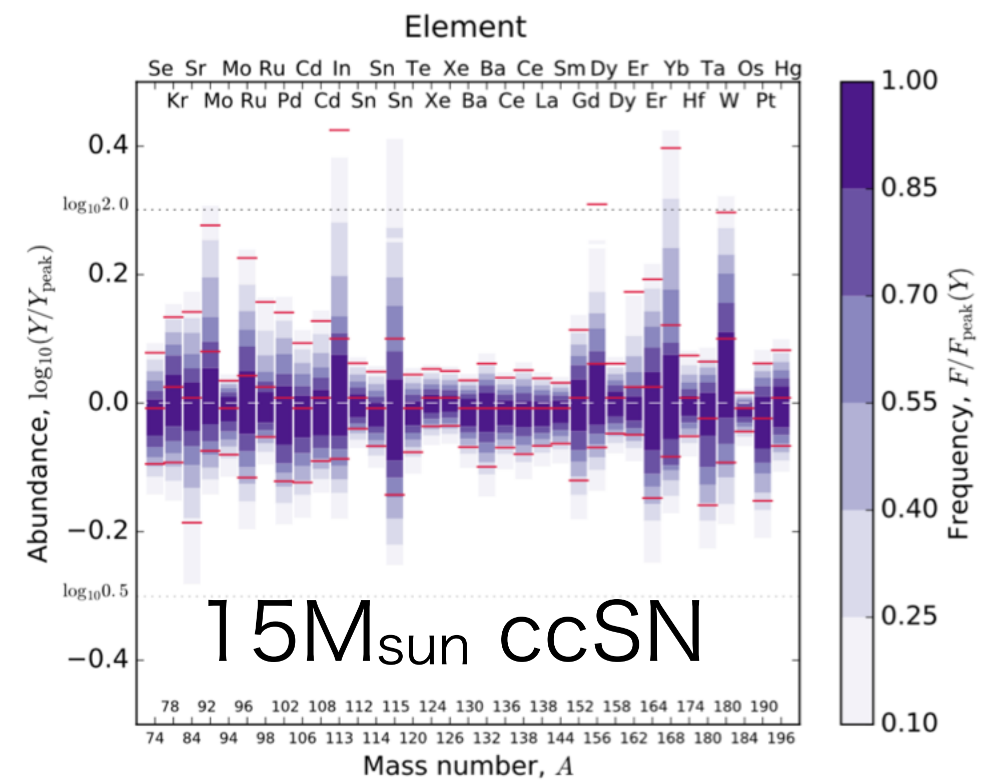
Rauscher, NN+ (2016), MNRAS (in press) arXiv:1606.05671

different key rates

compared to

e.g. Rapp+2006





25Msun

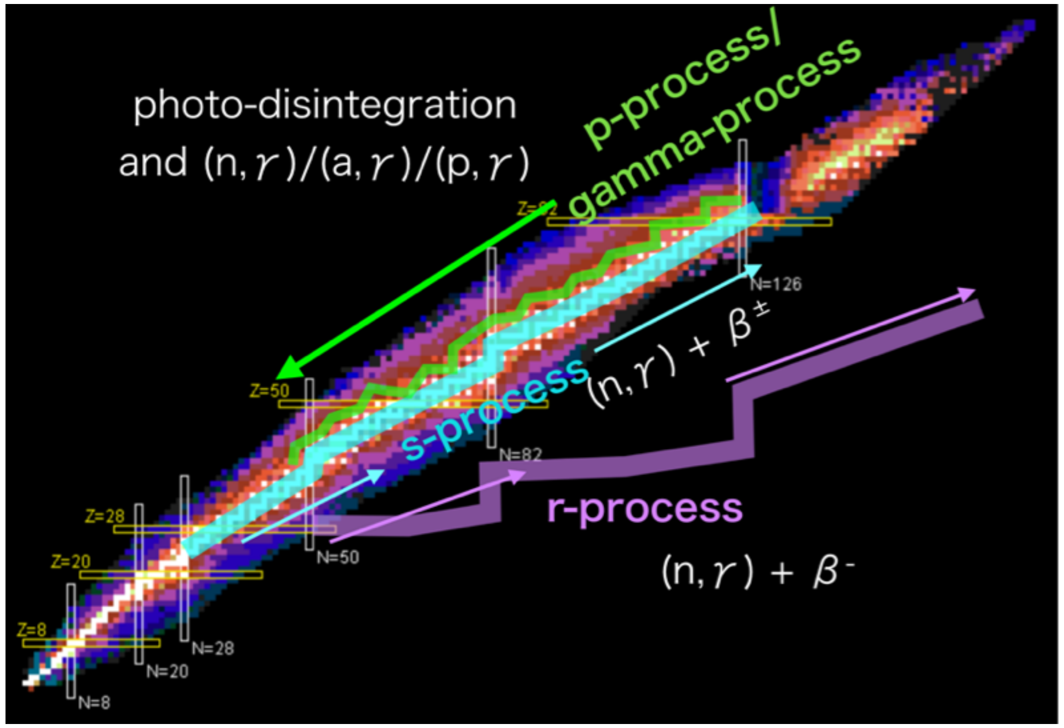
Nuclide	$r_{\mathrm{corr},0}$	$r_{\mathrm{corr},1}$	$r_{\mathrm{corr},2}$	Key rate Level 1	Key rate Level 2	Key rate Level 3	X_0 (2 GK) capture	X_0 (3 GK) capture
^{78}Kr	−0.84			$^{77}\mathrm{Br} + p \leftrightarrow \gamma + {}^{78}\mathrm{Kr}$			9.63×10^{-2}	4.44×10^{-2}
	0.34	0.87			$^{79}\mathrm{Kr} + n \leftrightarrow \gamma + {}^{80}\mathrm{Kr}$		1.28×10^{-1}	7.94×10^{-2}
^{92}Mo	−0.74			$^{91}\mathrm{Nb} + p \leftrightarrow \gamma + {}^{92}\mathrm{Mo}$			8.88×10^{-1}	8.24×10^{-1}
^{96}Ru	−0.73			$^{92}\mathrm{Mo} + \alpha \leftrightarrow \gamma + {}^{96}\mathrm{Ru}$			1.00	9.86×10^{-1}
	−0.43	−0.69			$^{95}\mathrm{Tc} + p \leftrightarrow \gamma + {}^{96}\mathrm{Ru}$		7.64×10^{-1}	6.60×10^{-1}
^{102}Pd	−0.87			$^{101}\mathrm{Pd} + n \leftrightarrow \gamma + {}^{102}\mathrm{Pd}$			5.62×10^{-1}	3.97×10^{-1}
^{112}Sn	−0.88			$^{111}\mathrm{Sn} + n \leftrightarrow \gamma + {}^{112}\mathrm{Sn}$			7.79×10^{-1}	6.73×10^{-1}
^{114}Sn	−0.77			$^{113}\mathrm{Sn} + n \leftrightarrow \gamma + {}^{114}\mathrm{Sn}$			1.82×10^{-1}	1.28×10^{-1}
^{120}Te	−0.64	−0.66			$^{119}\mathrm{Te} + n \leftrightarrow \gamma + {}^{120}\mathrm{Te}$		2.43×10^{-1}	1.77×10^{-1}
^{124}Xe	−0.74			$^{123}\mathrm{Xe} + n \leftrightarrow \gamma + {}^{124}\mathrm{Xe}$			8.25×10^{-2}	4.38×10^{-2}
^{126}Xe	−0.75			$^{125}\mathrm{Cs} + p \leftrightarrow \gamma + {}^{126}\mathrm{Ba}$			1.17×10^{-1}	7.41×10^{-2}
	0.30	0.64	0.65			$^{127}\mathrm{Ba} + n \leftrightarrow \gamma + {}^{128}\mathrm{Ba}$	5.78×10^{-2}	3.59×10^{-2}
^{130}Ba	−0.66			$^{129}\mathrm{Ba} + n \leftrightarrow \gamma + {}^{130}\mathrm{Ba}$			5.77×10^{-2}	3.55×10^{-2}
^{132}Ba	−0.77			$^{131}\mathrm{Ba} + n \leftrightarrow \gamma + {}^{132}\mathrm{Ba}$			1.07×10^{-1}	5.85×10^{-2}
^{136}Ce	−0.69			$^{135}\mathrm{Ce} + n \leftrightarrow \gamma + {}^{136}\mathrm{Ce}$			1.86×10^{-1}	8.94×10^{-2}
	0.31	0.72			$^{139}\mathrm{Ce} + n \leftrightarrow \gamma + {}^{140}\mathrm{Ce}$		8.56×10^{-1}	6.09×10^{-1}
^{138}Ce	−0.66			$^{137}\mathrm{Ce} + n \leftrightarrow \gamma + {}^{138}\mathrm{Ce}$			4.16×10^{-1}	2.54×10^{-1}
	−0.16	−0.19	−0.66			$^{136}\mathrm{Ce} + n \leftrightarrow \gamma + {}^{137}\mathrm{Ce}$	7.57×10^{-1}	4.70×10^{-1}
^{144}Sm	0.70			$^{145}\mathrm{Eu} + p \leftrightarrow \gamma + {}^{146}\mathrm{Gd}$			8.06×10^{-1}	6.02×10^{-1}
^{152}Gd	−0.74			$^{151}\mathrm{Gd} + n \leftrightarrow \gamma + {}^{152}\mathrm{Gd}$			6.18×10^{-1}	3.87×10^{-1}
	0.43	0.76			$^{153}\mathrm{Gd} + n \leftrightarrow \gamma + {}^{154}\mathrm{Gd}$		5.38×10^{-2}	2.78×10^{-2}
	-0.14	-0.26	-0.73			$^{148}\mathrm{Sm} + \alpha \leftrightarrow \gamma + {}^{152}\mathrm{Gd}$	8.14×10^{-1}	5.22×10^{-1}
^{164}Er	−0.78			$^{160}\mathrm{Er} + \alpha \leftrightarrow \gamma + {}^{164}\mathrm{Yb}$			2.13×10^{-1}	1.24×10^{-1}
^{180}W	−0.83			$^{176}\mathrm{W} + \alpha \leftrightarrow \gamma + {}^{180}\mathrm{Os}$			1.83×10^{-1}	1.04×10^{-1}
	-0.19	-0.60	-0.68			$^{179}\mathrm{Os} + n \leftrightarrow \gamma + {}^{180}\mathrm{Os}$	4.89×10^{-2}	2.49×10^{-2}
^{196}Hg	−0.83			$^{195}\mathrm{Pb} + n \leftrightarrow \gamma + {}^{196}\mathrm{Pb}$			2.97×10^{-1}	1.89×10^{-1}
	0.31	0.70			$^{197}\mathrm{Pb} + n \leftrightarrow \gamma + {}^{198}\mathrm{Pb}$		3.28×10^{-1}	2.39×10^{-1}
	0.17	0.35	0.67			$^{199}\mathrm{Pb} + n \leftrightarrow \gamma + {}^{200}\mathrm{Pb}$	6.37×10^{-1}	3.47×10^{-1}
^{92}Nb	0.76			$^{90}\mathrm{Zr} + p \leftrightarrow \gamma + {}^{91}\mathrm{Nb}$			1.00	9.95×10^{-1}
^{146}Sm	-0.57	-0.75			$^{144}\mathrm{Sm} + \alpha \leftrightarrow \gamma + {}^{148}\mathrm{Gd}$		9.99×10^{-1}	9.65×10^{-1}
	0.34	0.44	0.79			$^{147}\mathrm{Gd} + n \leftrightarrow \gamma + {}^{148}\mathrm{Gd}$	9.92×10^{-1}	9.28×10^{-1}

15Msun

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

Future

- Other nucleosynthesis



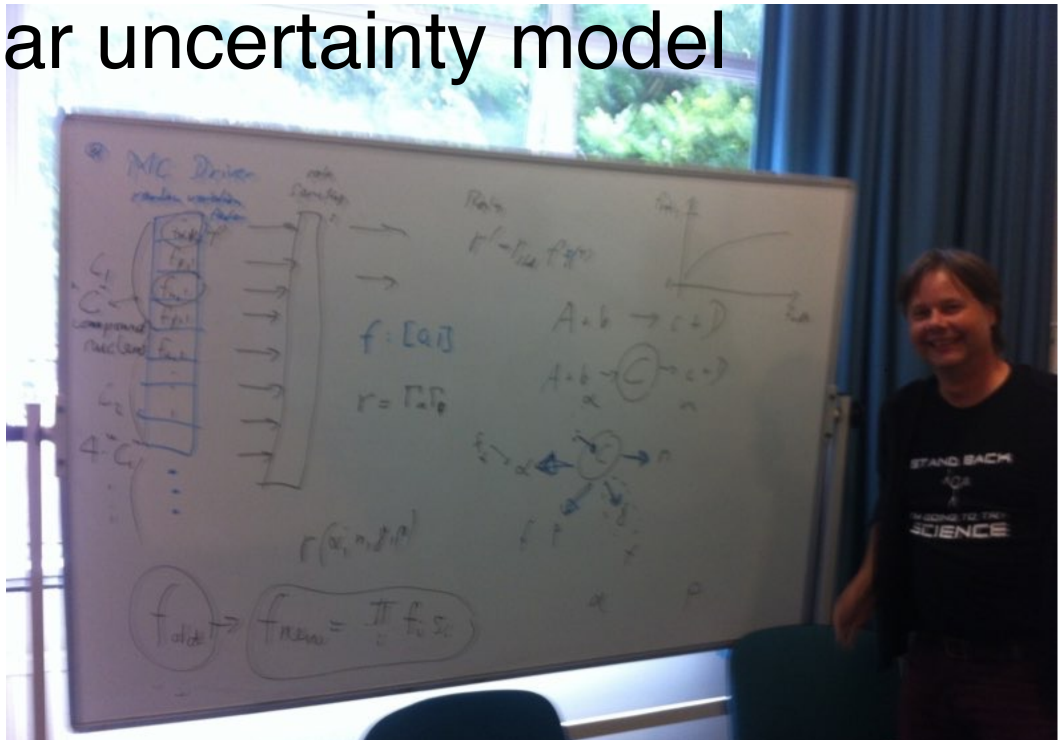
p-process, vp-process,
rp-process, r-process etc.

- UK Supercomputer facility

DiRAC

COSMOS at Cambridge

- Improved nuclear uncertainty model



w/ T. Rauscher
@UK BRIDGCE
meeting
(Keele U)

Summary:

- MC nuclear reaction network code
  - applicable to **general** nucleosynthesis
  - statistical analysis to find important reactions
  - parallelized by OpenMP for shared memory systems
- s-process
  - T-dependent uncertainty enhanced by exited state contribution
  - (n, γ) contributes global uncertainty, while few beta-decay affects uncertainty around branchings
  - key reactions (n,g) and β-decay are identified
    - weak s: 10+ reactions/decay
    - main s: ~50 mostly (n, γ) reactions

Backup slides

- T-dependent uncertainty
  - (n,g)
  - beta
- the main s-process key rate full list
- performance tests

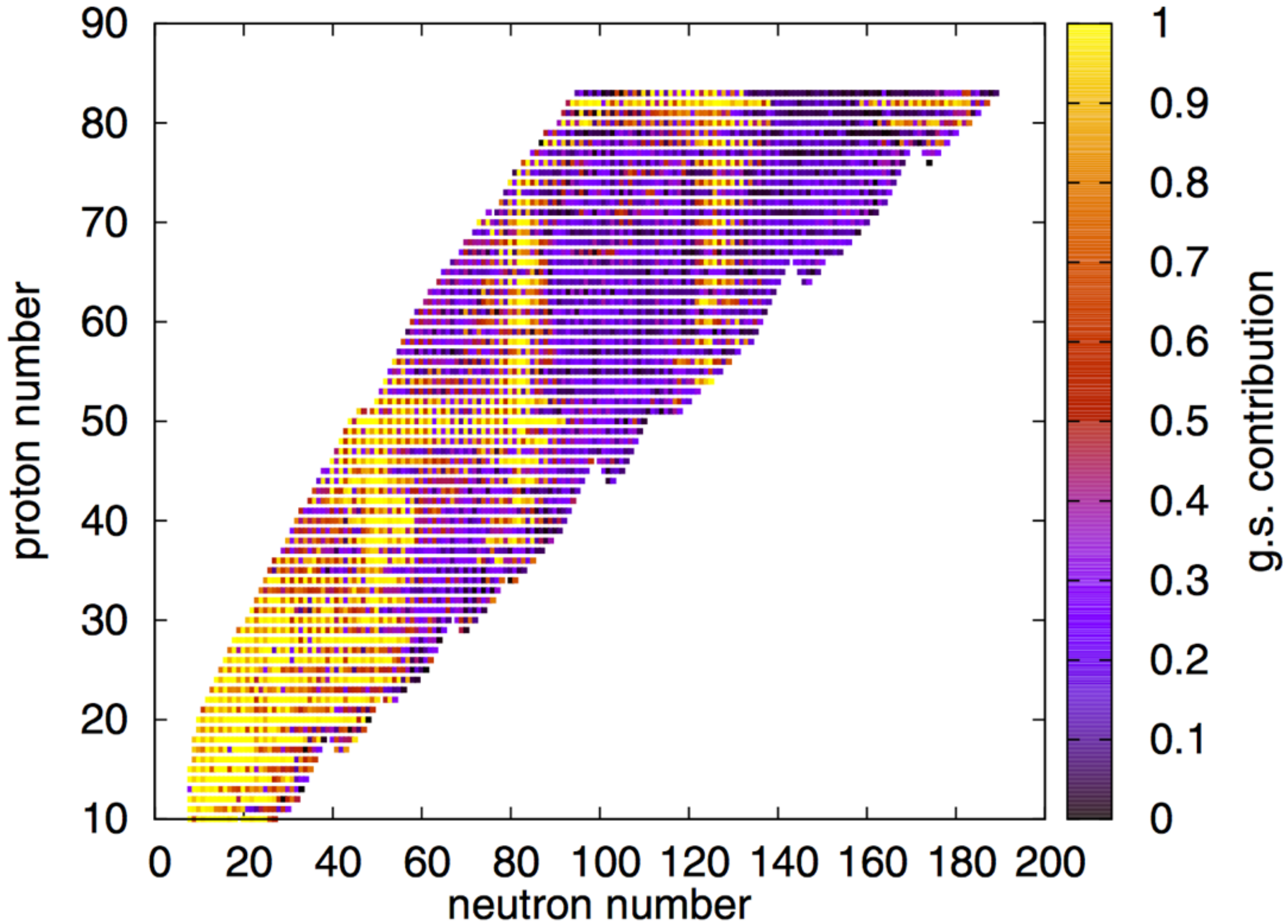
Importance of T-dependent uncertainty:

ground state contribution: X, by Rauscher, ApJS, 201, 2012

$$X(T) = \frac{r^{\mathrm{lab}}}{r^* G_0(T)} = \frac{\int_0^\infty \sigma^{\mathrm{lab}}(E)\,\Phi_{\mathrm{MB}}(E,T)\,dE}{\int_0^\infty \boxed{\sigma^{\mathrm{eff}}(E)}\,\Phi_{\mathrm{MB}}(E,T)\,dE}$$

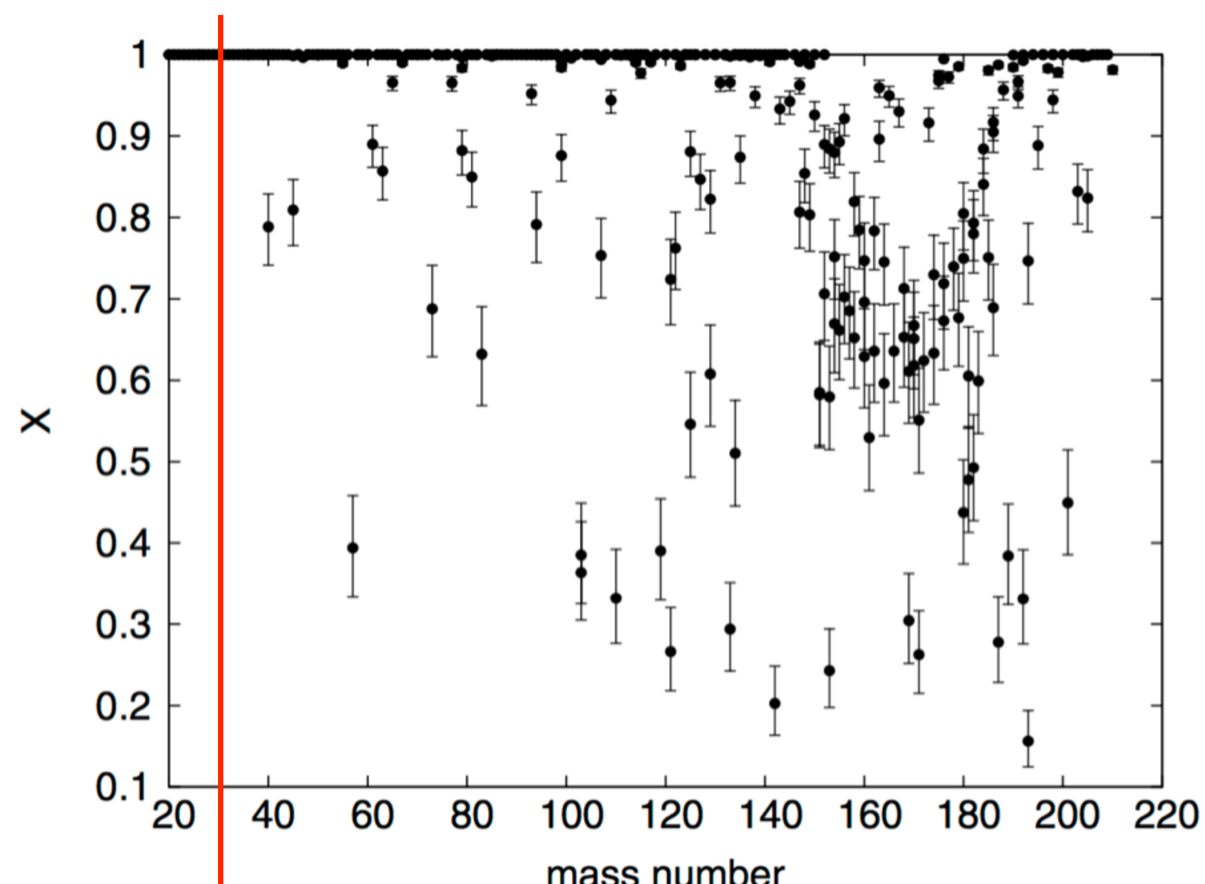
$$\boxed{\sigma^{\mathrm{eff}} = \sum_\mu \sum_\nu \frac{2J_\mu + 1}{2J_0 + 1} \frac{E - E_\mu}{E} \sigma^{\mu\to\nu}(E - E_\mu)}$$

factor X(T) (n,g) at 1.5 GK



(n,g) at 30 keV (0.384GK)

only g.s. Rauscher+ ApJL 2011



high e.s. contribution

T-dependent uncertainty: (n,g)

For details, see T. Rauscher, ApJL, 775, 2011

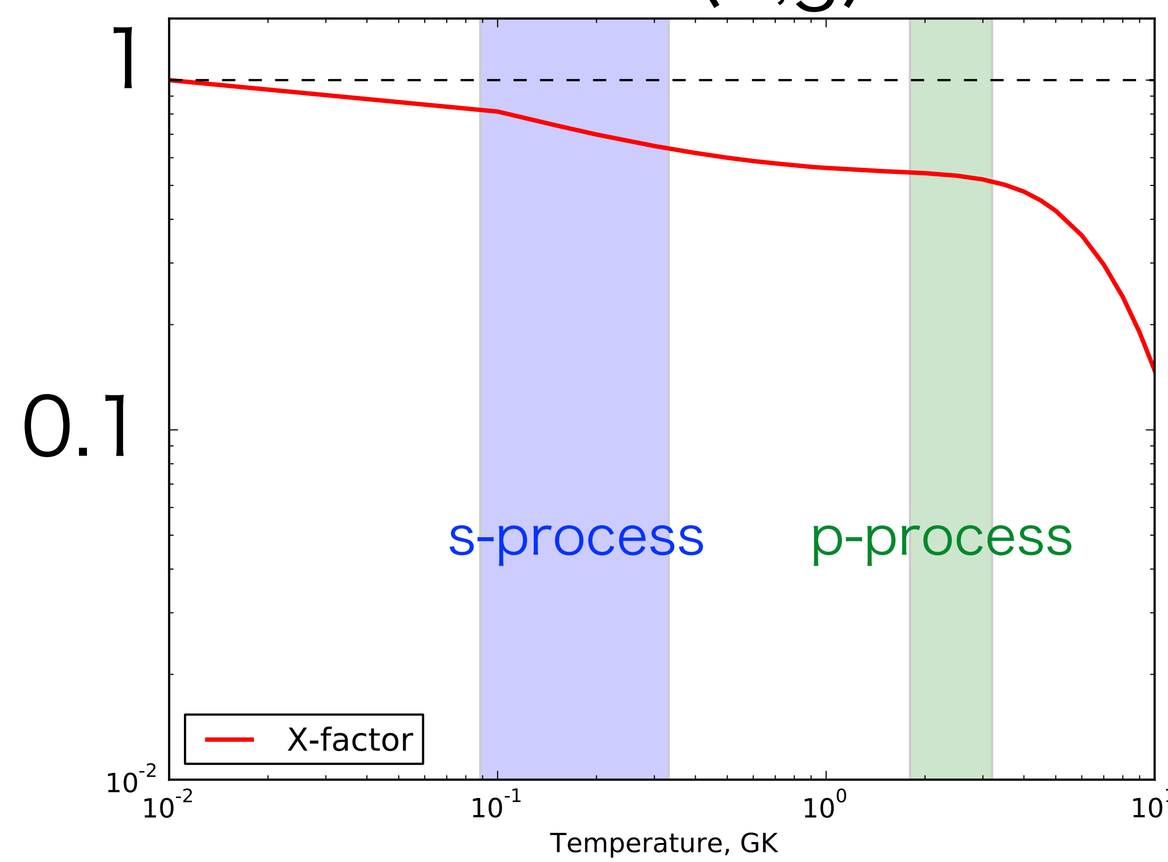
- Theoretical rates (incl. some experimental ones)
  - basic rates: Reaclib (Rauscher & Thielemann 2000)
  - a constant factor 2
- Experimental rates
  - base rates: KADoNiS v0.3 (Dillemann el al., 2009)
  - the formula: Rauscher, ApJ, 775, 2011

$$U(T) = U_{\mathrm{g.s.}} X + U_{\mathrm{e.s.}} (1 - X)$$

- ground state (experimental based): $u_{\mathrm{g.s.}} \sim 1.0 - 1.3$
- excited states (theory based): $u_{\mathrm{e.s.}} = 5$ (given constant)

$X(T)$: the fraction of particles in the ground state

X: ^{83}Kr(n,g)^{84}Kr



T-dependent uncertainty: beta-decay

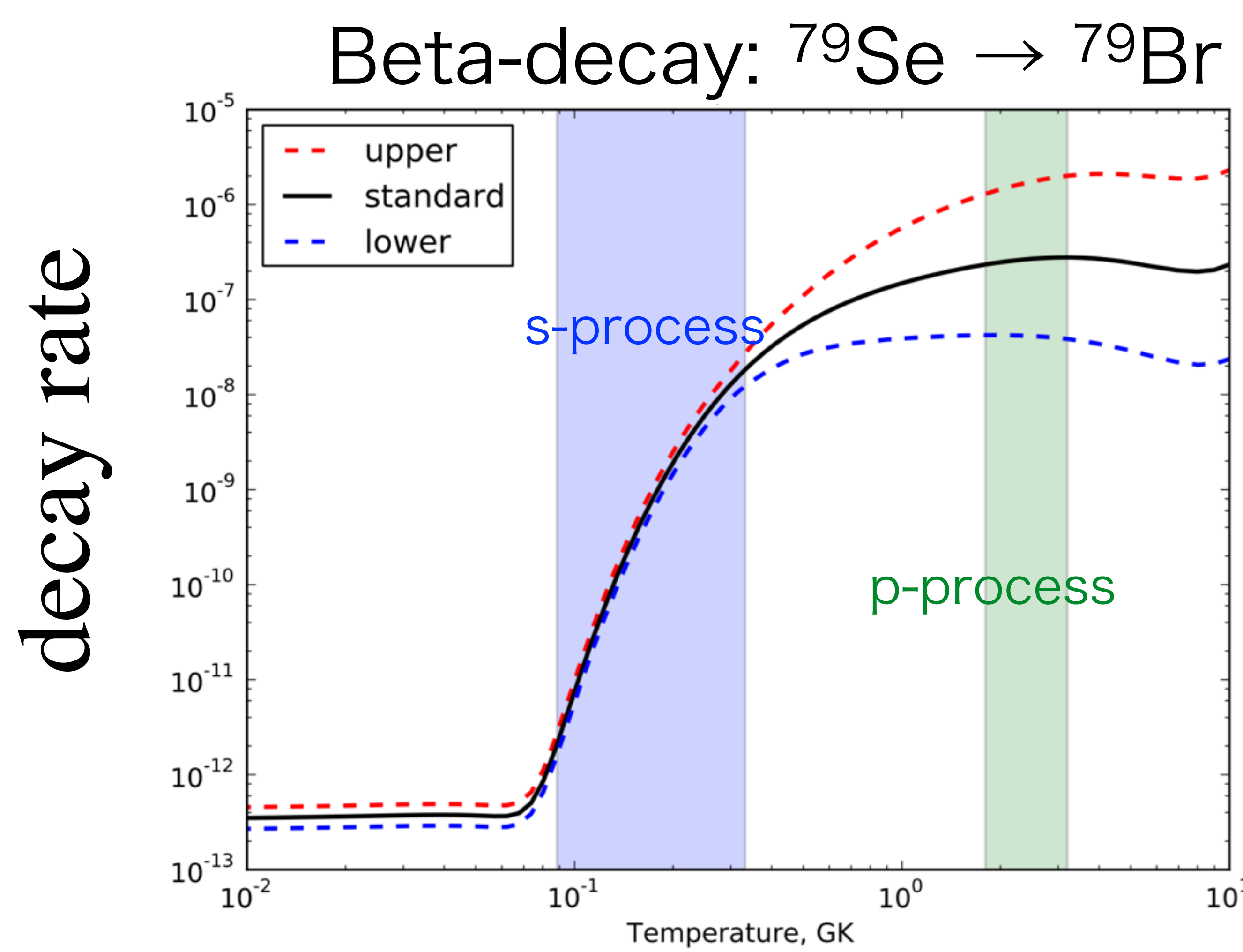
- beta-decay: only the ground state 1.3 (30%)
- beta-decay: T-dependent

  (Bruslib: Takahashi & Yokoi 1987, Goriely 1999)

$$U(T) = \frac{u_{\text{g.s.}}}{g_0(T)} + u_{\text{e.s.}} \left(1 - \frac{1}{g_0(T)}\right)$$

- ground state: $u_{\text{g.s.}} = 1.3$ (30 %)
- excited states: $u_{\text{e.s.}} = 10$

g_0: partition function of the ground state



main s-process: full list

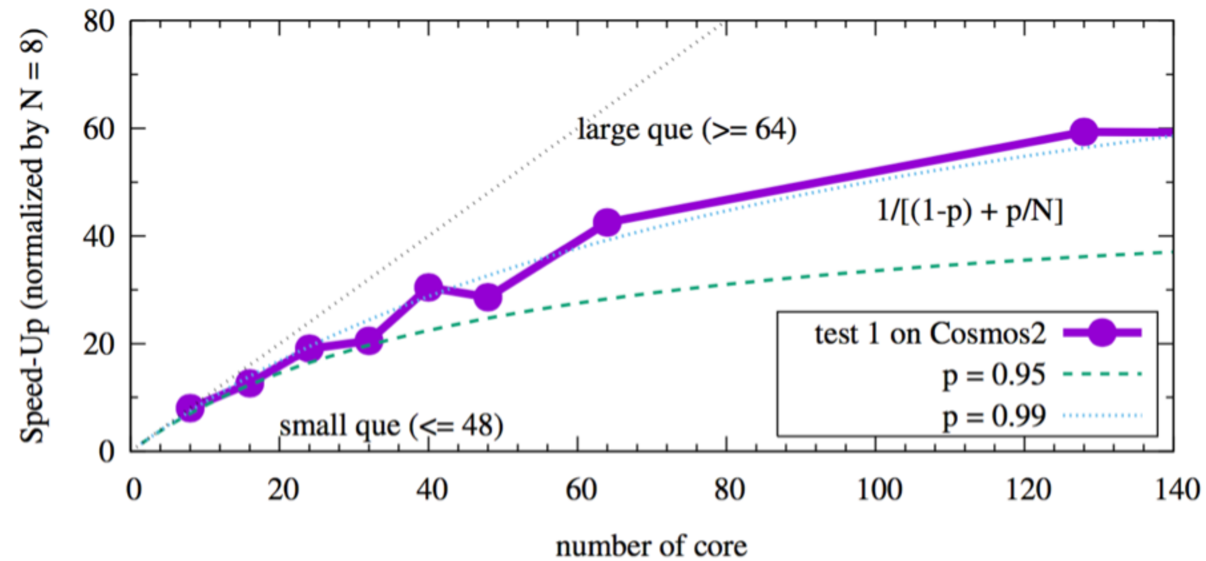
Nuclide	$r_{\mathrm{cor},0}$	$r_{\mathrm{cor},1}$	$r_{\mathrm{cor},2}$	Key reaction Level 1
Sr88	-0.65			^{88}Sr(n,γ)^{89}Sr
Y89	-0.83			^{89}Y(n,γ)^{90}Y
Zr90	-0.89			^{90}Zr(n,γ)^{91}Zr
Zr91	-0.91			^{91}Zr(n,γ)^{92}Zr
Zr92	-0.92			^{92}Zr(n,γ)^{93}Zr
Zr94	-0.86			^{94}Zr(n,γ)^{95}Zr
Nb93	-0.97			^{93}Zr(n,γ)^{94}Zr
Mo95	-0.85			^{95}Mo(n,γ)^{96}Mo
Mo96	-0.94			^{96}Mo(n,γ)^{97}Mo
Mo97	-0.87			^{97}Mo(n,γ)^{98}Mo
Mo98	-0.94			^{98}Mo(n,γ)^{99}Mo
Ru99	-0.91			^{99}Tc(n,γ)^{100}Tc
Ru100	-0.93			^{100}Ru(n,γ)^{101}Ru
Ru102	-0.86			^{102}Ru(n,γ)^{103}Ru
Rh103	-0.95			^{103}Rh(n,γ)^{104}Rh
Pd104	-0.97			^{104}Pd(n,γ)^{105}Pd
Pd106	-0.97			^{106}Pd(n,γ)^{107}Pd
Pd108	-0.96			^{108}Pd(n,γ)^{109}Pd
Ag107	-0.81			^{107}Pd(n,γ)^{108}Pd
Ag109	-0.80			^{109}Ag(n,γ)^{110}Ag
In115	-0.97			^{115}In(n,γ)^{116}In
Sn119	-0.97			^{119}Sn(n,γ)^{120}Sn
Sn122	-0.73			^{122}Sb(+β)^{122}Te
	0.57	0.86		
	-0.33	-0.49	-0.96	
Sb121	-0.92			^{121}Sb(n,γ)^{122}Sb
Te125	-0.92			^{125}Te(n,γ)^{126}Te
Te126	-0.69			^{126}Te(n,γ)^{127}Te
Xe128	0.66			^{128}I(+β)^{128}Xe
Xe132	-0.97			^{132}Xe(n,γ)^{133}Xe
Cs133	-0.89			^{133}Cs(n,γ)^{134}Cs
Ba134	-0.85			^{134}Ba(n,γ)^{135}Ba
Ba135	-0.70			^{135}Ba(n,γ)^{136}Ba
Ba136	-0.88			^{136}Ba(n,γ)^{137}Ba
Ba137	-0.84			^{137}Ba(n,γ)^{138}Ba
Ba138	-0.65	-0.71		
La139	-0.87			^{139}La(n,γ)^{140}La
Gd152	0.59	0.60	0.66	
Er166	-0.81			^{166}Er(n,γ)^{167}Er
Er168	-0.86			^{168}Er(n,γ)^{169}Er
Ta181	-0.84			^{181}Ta(n,γ)^{182}Ta
Os187	-0.86			^{187}Os(n,γ)^{188}Os
Pt192	-0.89			^{192}Pt(n,γ)^{193}Pt
Hg198	-0.63	-0.65	-0.68	
Hg200	-0.67			^{200}Hg(n,γ)^{201}Hg
Hg201	-0.77			^{201}Hg(n,γ)^{202}Hg

Large-scale MC calculations

for shared memory systems

- Fortran + OpenMP
- parallelized well
- optimized code/matrix library for large scared memory computers (multi threads)

performance tests of matrix solvers on shared memory system



- Computer resources

numascale

Shyne cluster @Keele (ERC)

Cosmos2 @Cambridge (UK DiRAC facility, STFC)