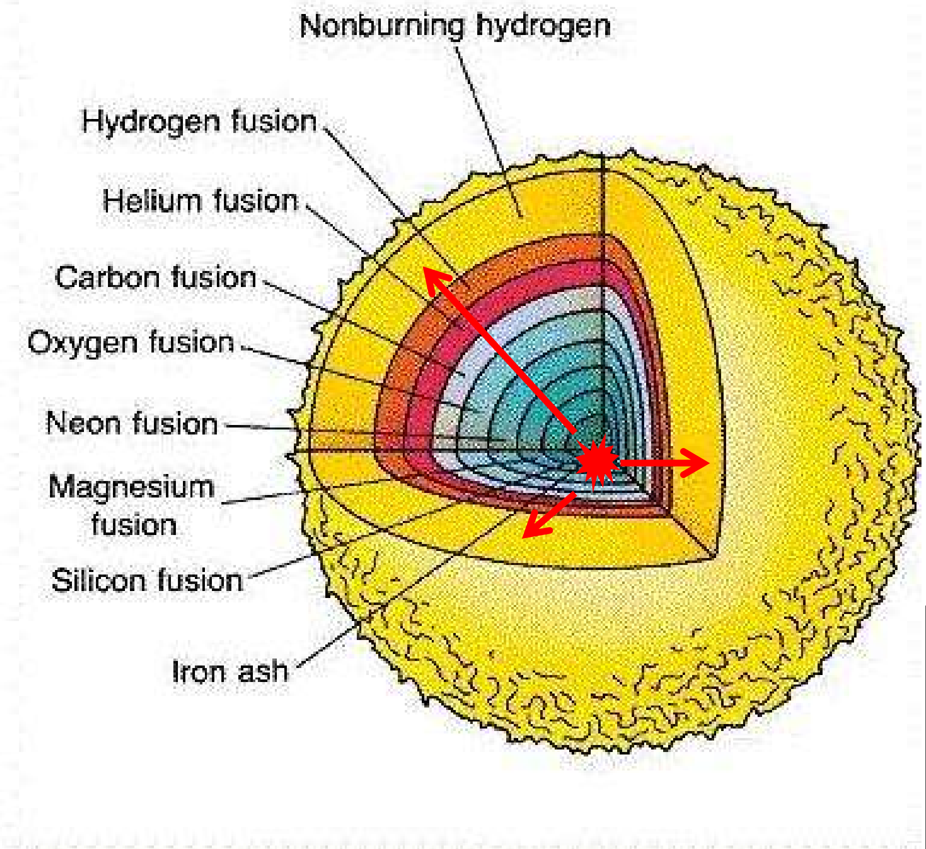
Explosive Nucleosynthesis in the Outer Shells of Massive Stars

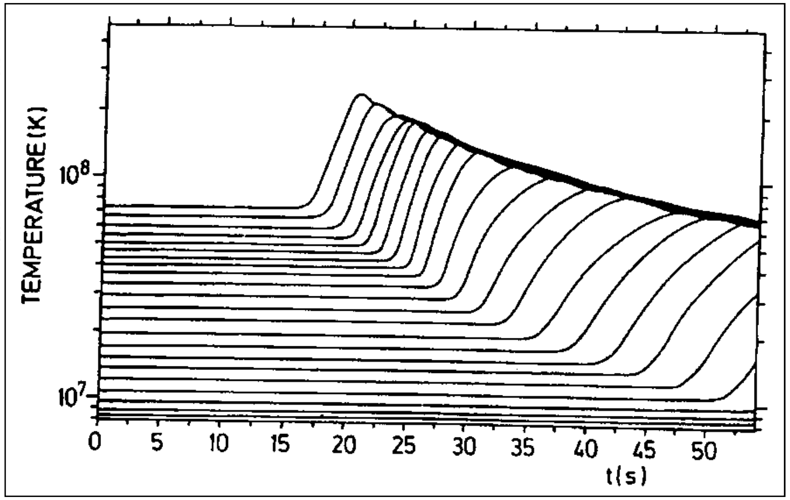
Thomas Rauscher

University of Basel, CH & University of Hertfordshire, UK

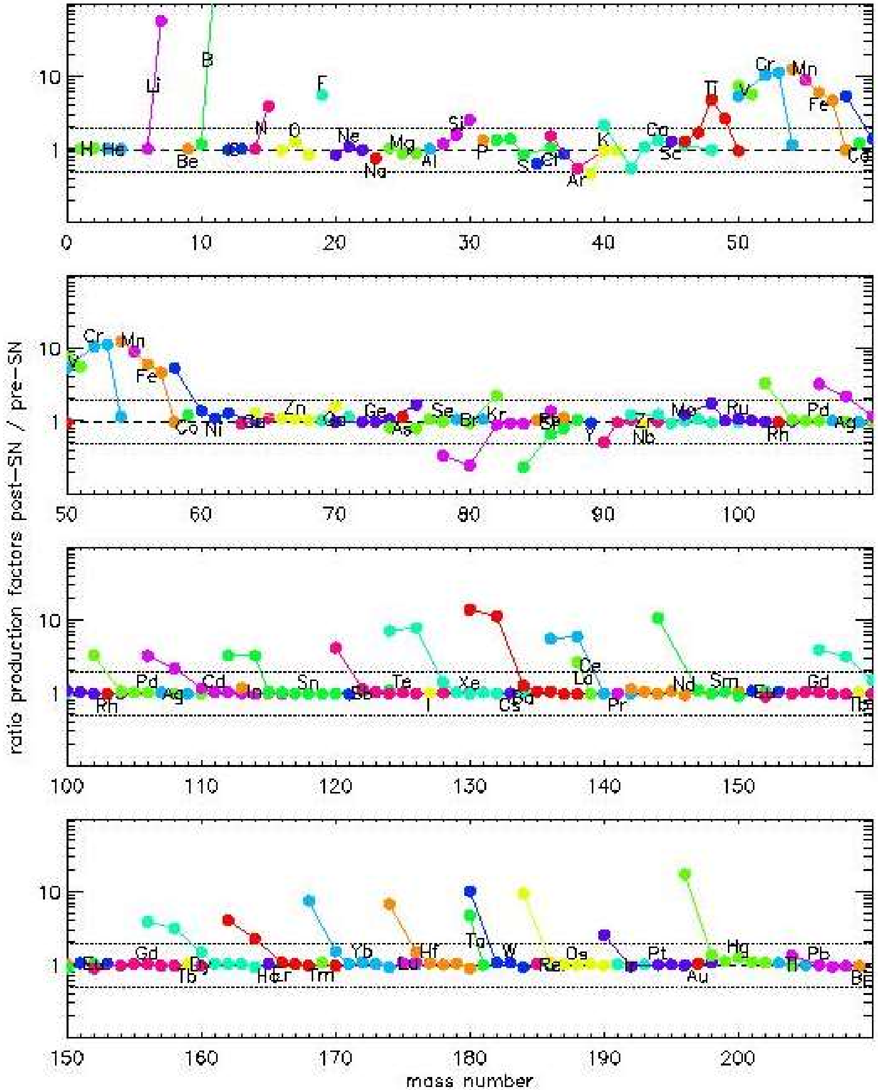


Nucleosynthesis depends on:

- Structure of star
- Energy and propagation of shockwave
- Nuclear reactions during shock passage

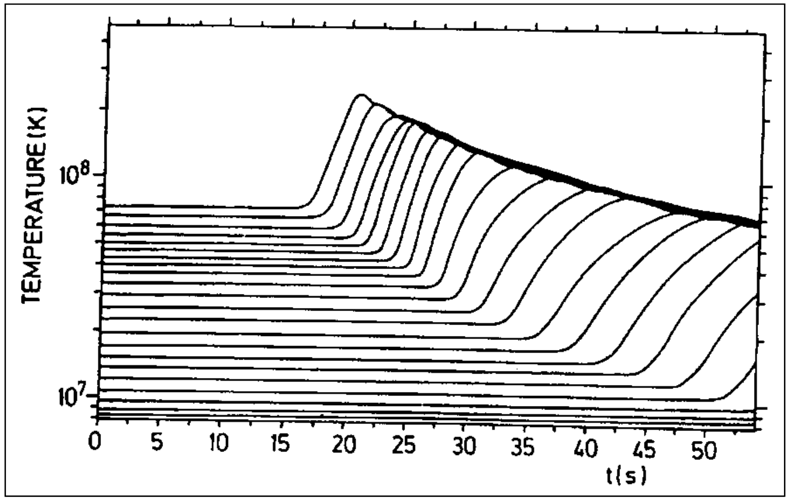


Explosive Nucleosynthesis

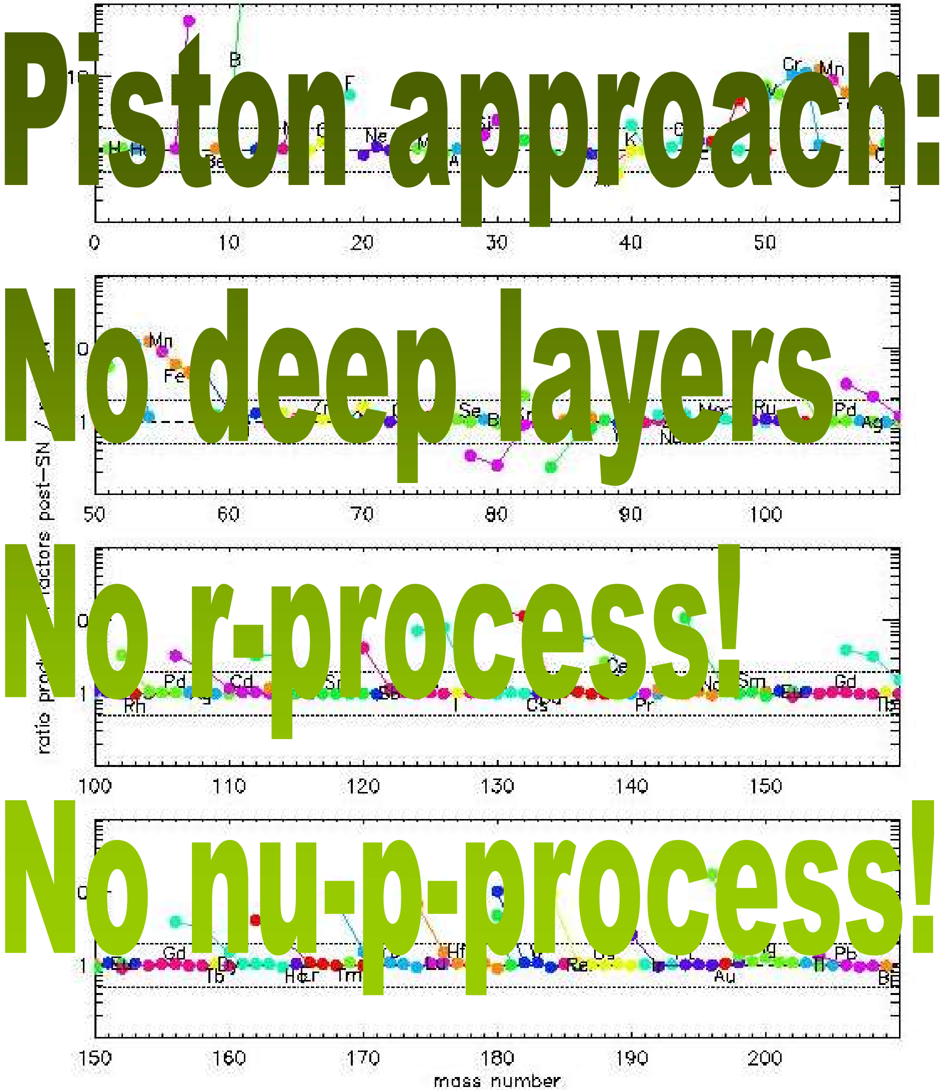


Rauscher et al. 2002 (with UCSC and LLNL)

- Li, B, F from ν-burst
- Ti-Fe-Ni: depends on expl. mech., mass cut, (n-flux)
- [γ-Process]() (depending on mass/stellar structure)



Explosive Nucleosynthesis



Piston approach:

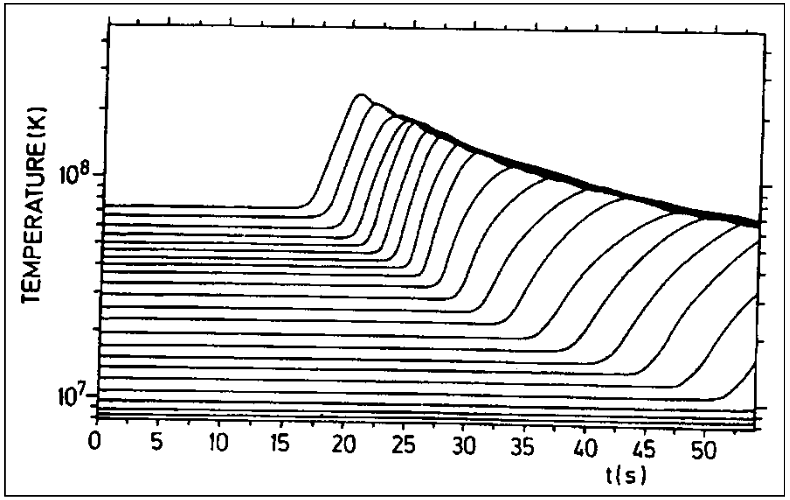
No deep layers

No r-process!

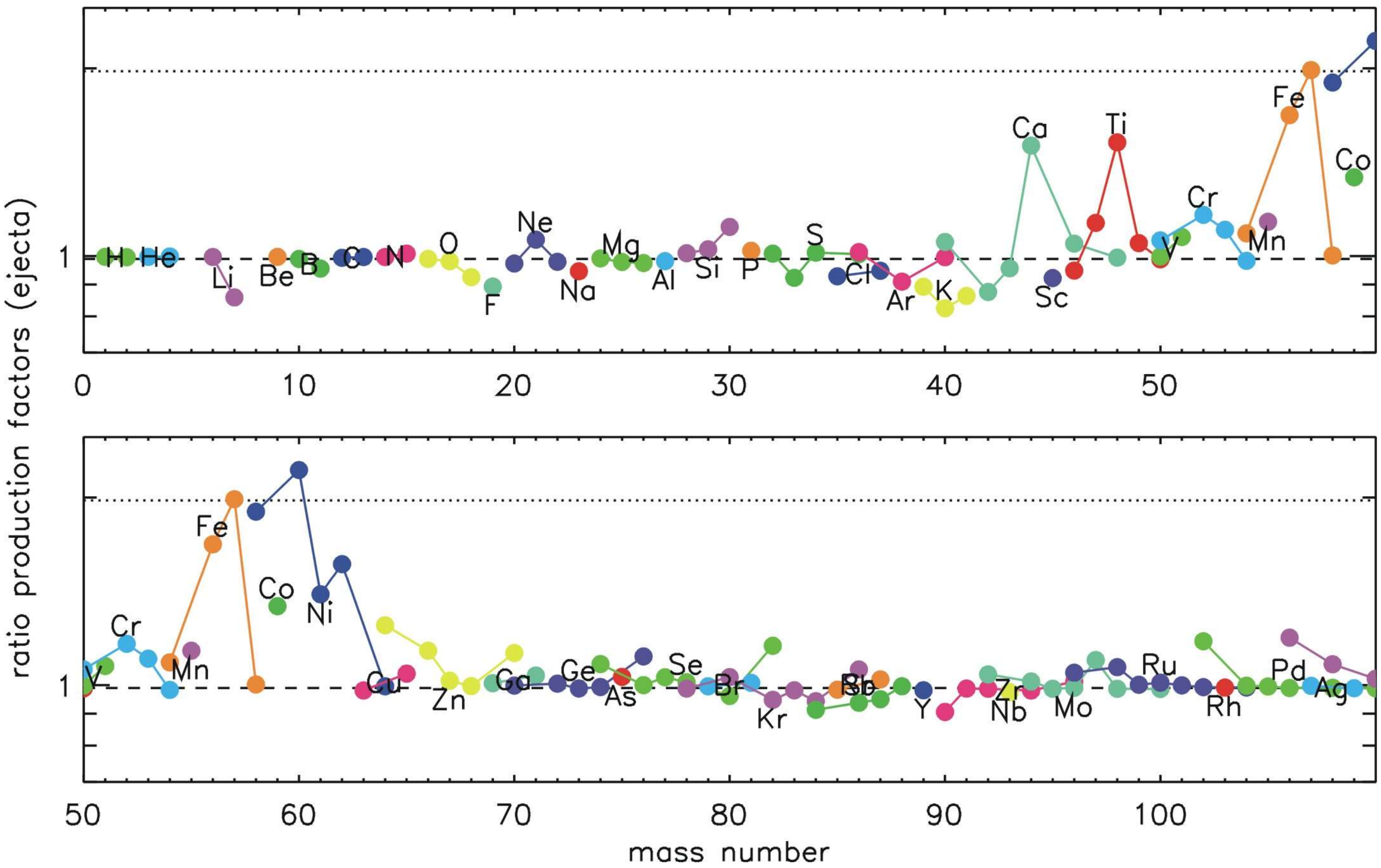
No nu-p-process!

Rauscher et al. 2002 (with UCSC and LLNL)

- Li, B, F from ν-burst
- Ti-Fe-Ni: depends on expl. mech., mass cut, (n-flux)
- γ-Process (depending on mass/stellar structure)



Dependence On Explosion Energy (25 M_{sol})



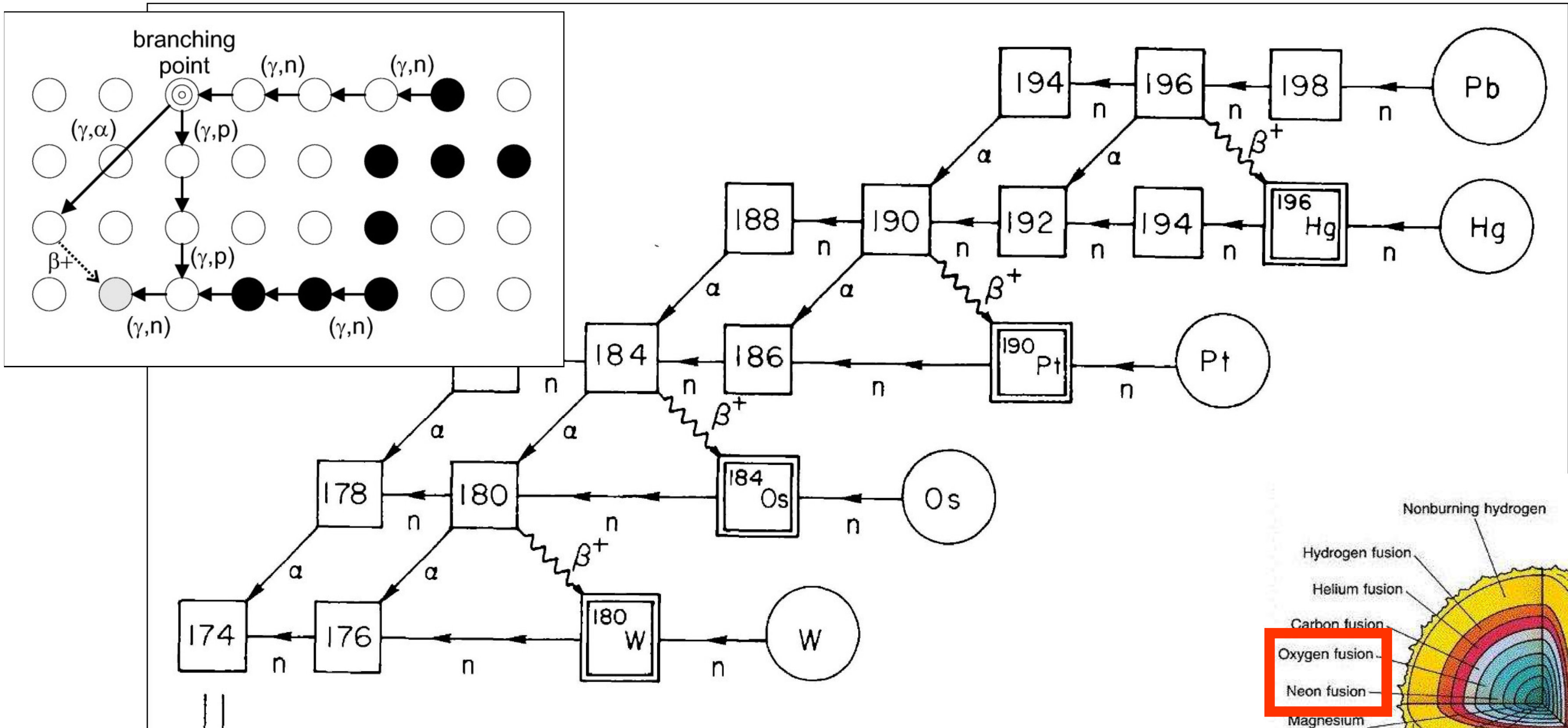
Ratio: H/L

L: 0.1 M_{sol} ^{56}Ni (1.735 x10^{51} ergs)

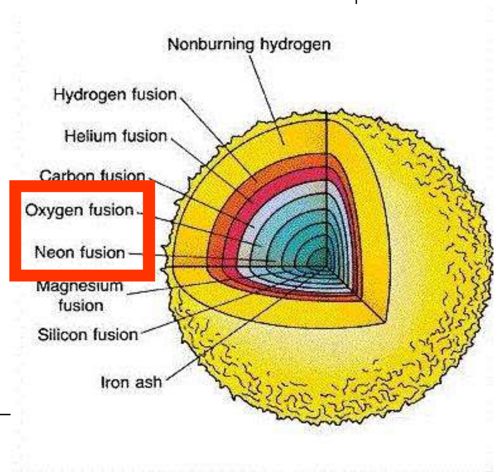
KEPLER code (piston)

H: 0.2 M_{sol} ^{56}Ni (2.293 x10^{51} ergs)

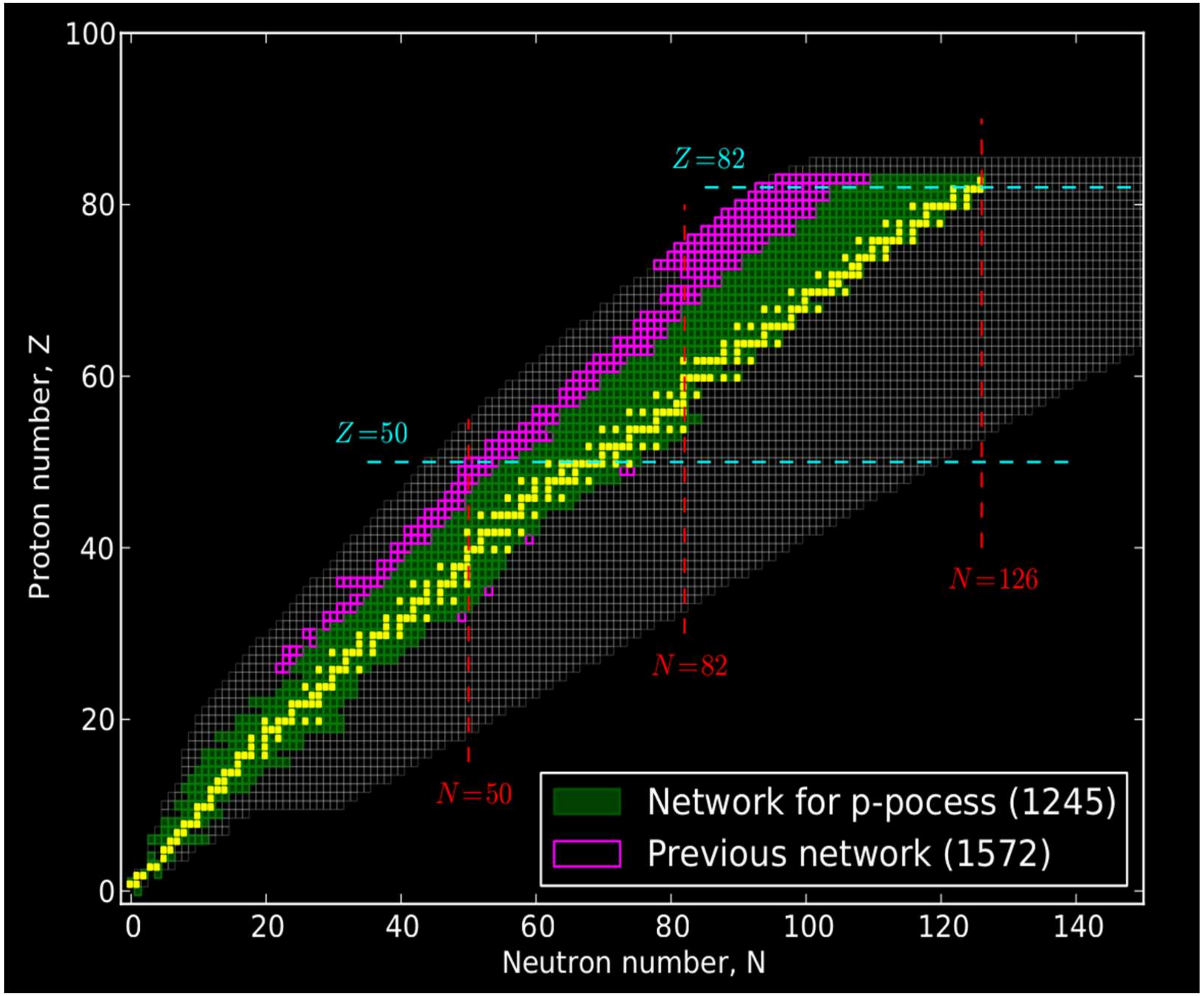
The γ-Process



Also possible in SN Ia (Travaglio et al 2011)



Network size

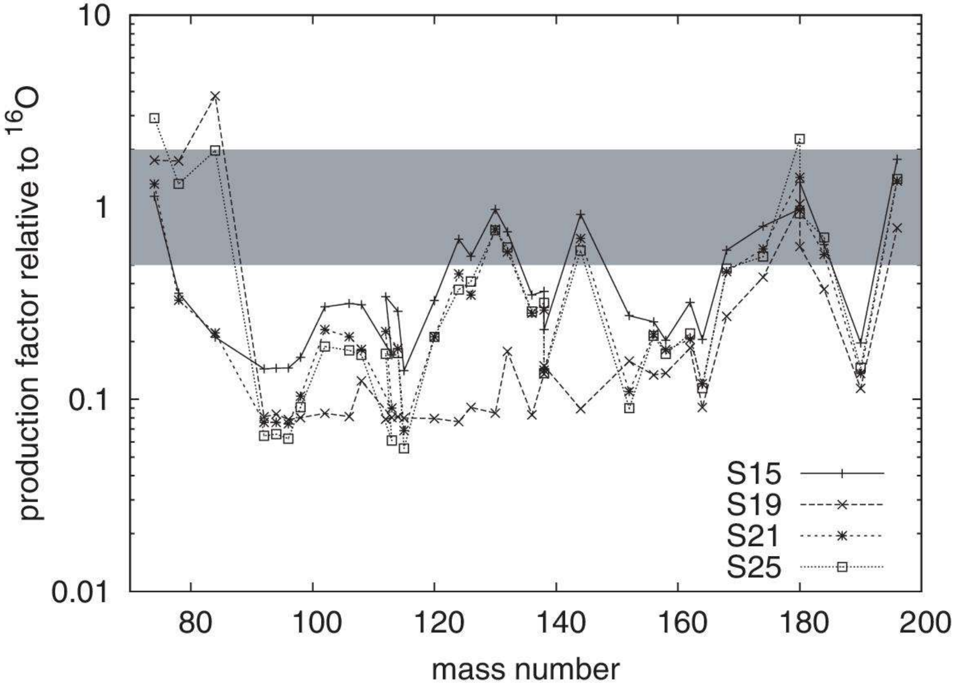


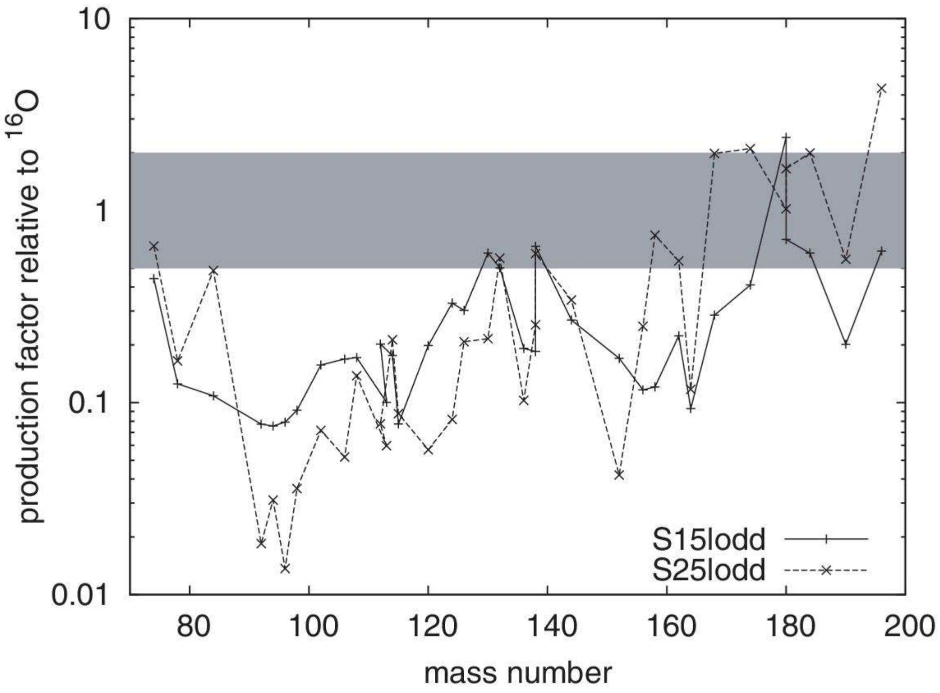
p-Production in various stellar models

- Depends on progenitor mass
- Depends on initial metallicity
  - Already new Lodders abundances lead to some differences
    - due to big ^{16}O differences
    - and different pre-SN evolution (mostly in He-burning)

T. Rauscher, N. Dauphas, I. Dillmann, C. Fröhlich, Zs. Fülöp, Gy. Gyürky, Rep. Prog. Phys. 76 (2013) 066201

T. Rauscher, A. Heger, R. D. Hoffman, S. E. Woosley, Ap. J. 576 (2002) 323



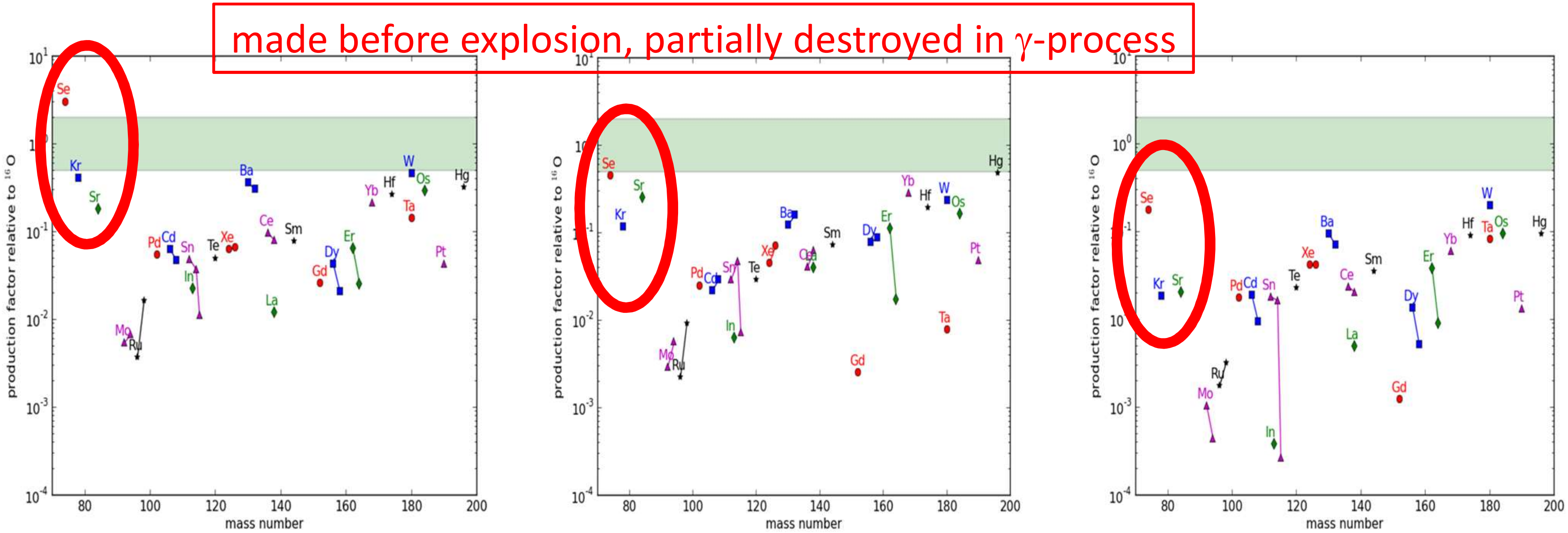


Production factors:

Hashimoto (1990)
(also used in Rayet et al 1995,
Rapp et al)
25 Msun

KEPLER 25Msun

KEPLER 15Msun



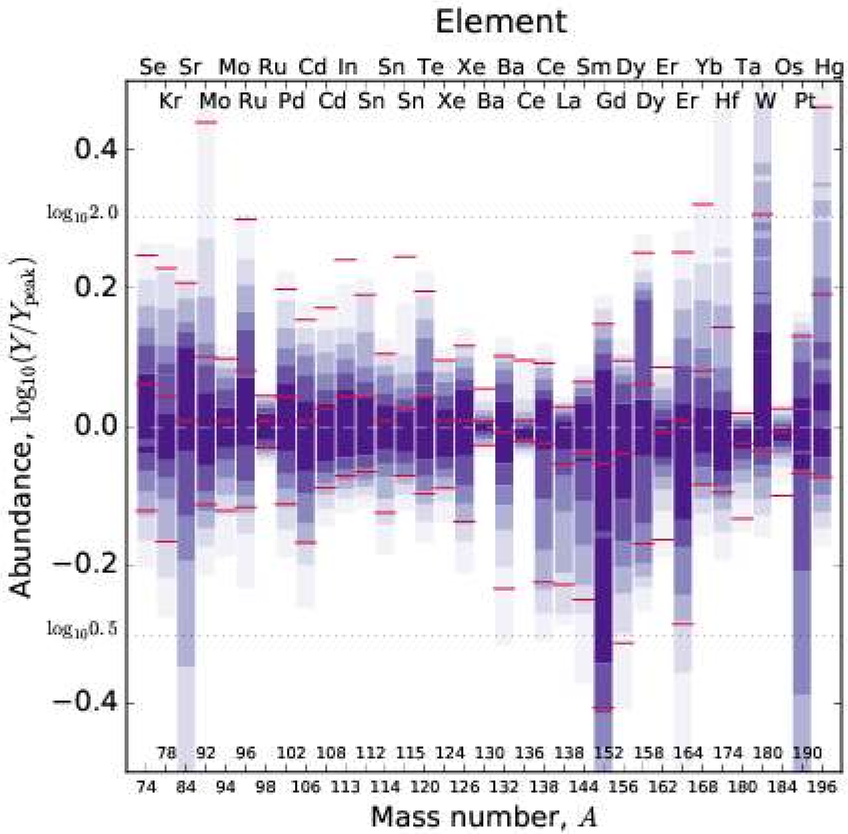
initial solar metallicity:
Anders & Grevesse (1989)

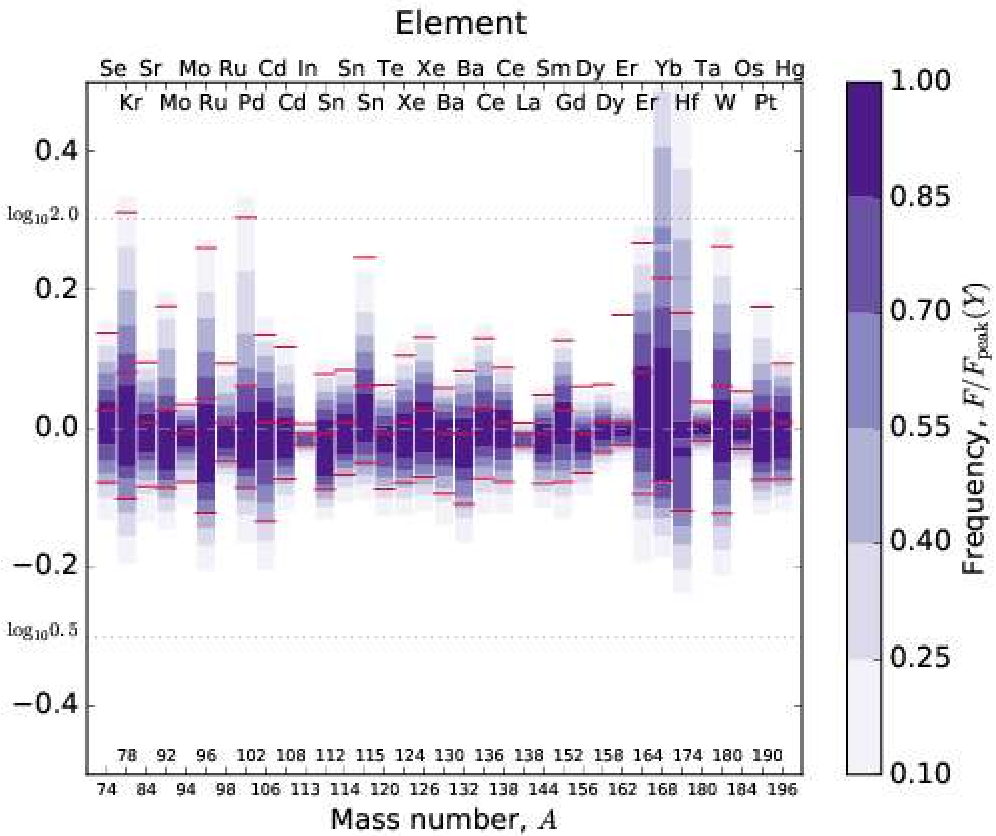
Lodders (2009)

Lodders (2009)

Note: ^{16}O considered only in PPL to calculate production factors.

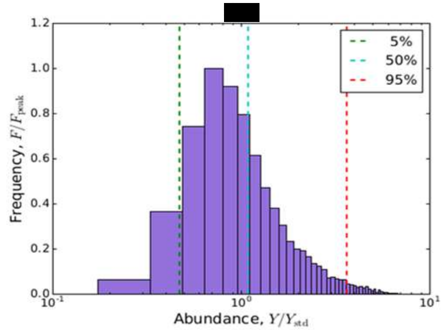
Monte Carlo uncertainties of p-production





Hashimoto (1990)

KEPLER 25Msun

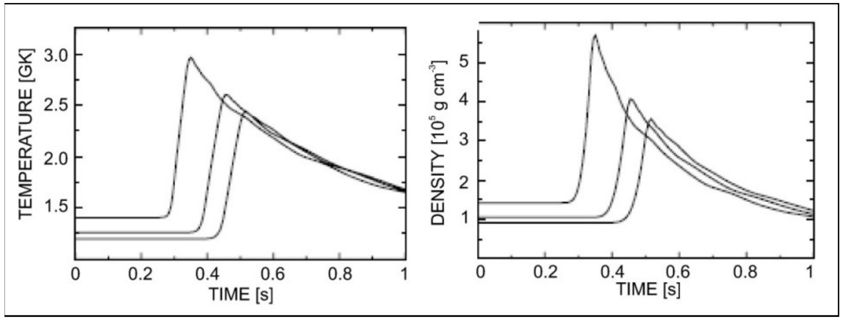


$\log_{10}(2)\approx0.3$
$\log_{10}(1.6)\approx0.2$

post-processing with simultaneous MC variation of all rates, using T-dependent nuclear uncertainties

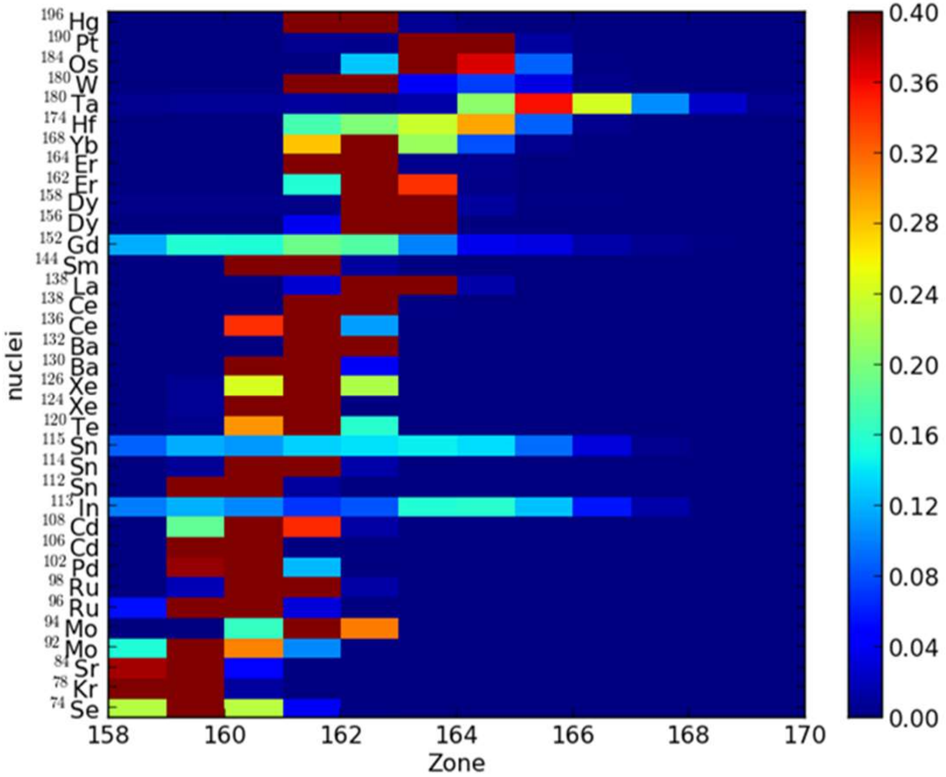
(Rauscher et al, MNRAS, in press arXiv:1606.05671)

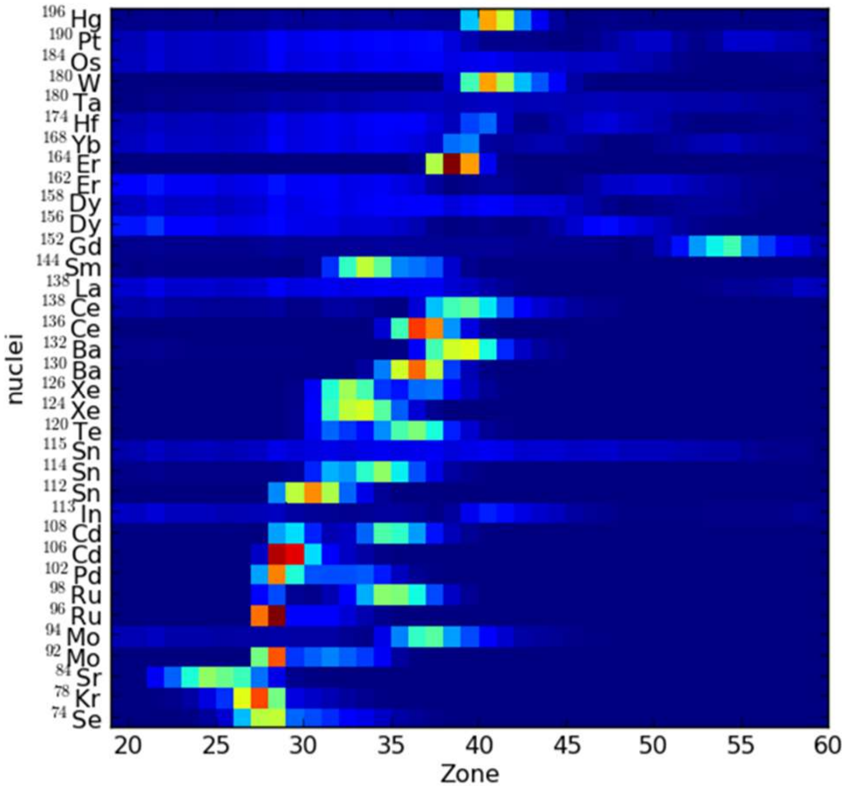
p-Nucleus Production/Destruction per Zone



Resolution of Hashimoto (1990) zones too crude, especially for light nuclei and some heavy species

Cannot follow detailed temperature evolution, overemphasizes certain temperatures/reactions





Previous variation study using Hashimoto model and manually varying individual rates and rate groups

The Astrophysical Journal, 653:474–489, 2006 December 10

SENSITIVITY OF p-PROCESS NUCLEOSYNTHESIS TO NUCLEAR REACTION RATES IN A 25 $M_\odot$ SUPERNOVA MODEL

W. Rapp, J. Görres, and M. Wiescher
Department of Physics and Joint Institute of Nuclear Astrophysics, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556

H. Schatz
Department of Physics and Astronomy, National Superconducting Cyclotron Laboratory and Joint Institute of Nuclear Astrophysics, Michigan State University, 1 Cyclotron Laboratory, East Lansing, MI 48824

and

F. Käppeler
Forschungszentrum Karlsruhe, Institut für Kernphysik, P.O. Box 3640, 76021 Karlsruhe, Germany
Received 2005 August 5; accepted 2006 August 14

ABSTRACT

The astrophysical p-process, which is responsible for the origin of the proton-rich stable nuclei heavier than iron, was investigated using a full nuclear reaction network for a Type II supernova explosion when the shock front passes through the O/Ne layer. Calculations were performed with a multilayer model adopting the seed of a preexplosion evolution of a 25 $M_\odot$ **star. The reaction flux was calculated to determine the main reaction path and branching points** responsible for synthesizing the proton-rich nuclei. In order to investigate the impact of nuclear reaction rates on the predicted p**-process abundances, extensive simulations with different sets of collectively and individually modified** neutron-, proton-, and α-capture and photodisintegration rates have been performed. These results are not only relevant to explore the nuclear-physics-related uncertainties in p-process calculations but are also important for identifying the strategy and planning of future experiments.

Key reaction comparison to the 25 M_{sol} model of Rapp et al. (2006)

N.B.: Comparison of our key rates found by MC variation of KEPLER trajectories

SELECTED (γ, p) OR (n, p) REACTIONS

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

Lv 2 rate only important after ^{92}Mo + α ↔ γ + ^{96}Ru has been constrained

Lv 1 key rate

SELECTED (γ, α) REACTION CHAINS

Reaction Chains	
~~$^{196}Pb(\gamma,\alpha)^{192}Hg^*$~~	~~$^{166}Hf(5\gamma,5\alpha)^{146}Sm^*$~~
$^{195}Pb(3\gamma,3\alpha)^{183}Os$	~~$^{156}Er(3\gamma,3\alpha)^{144}Sm^*$~~
$^{190}Hg(3\gamma,3\alpha)^{178}W^*$	~~$^{128}Ba(\gamma,\alpha)^{124}Xe$~~
$^{189}Hg(3\gamma,3\alpha)^{177}W$	~~$^{122}Xe(\gamma,\alpha)^{118}Te$~~
$^{188}Hg(5\gamma,5\alpha)^{168}Yb^*$	~~$^{120}Te(\gamma,\alpha)^{116}Sn^*$~~
$^{183}Pt(3\gamma,3\alpha)^{171}Hf$	~~$^{110}Sn(\gamma,\alpha)^{106}Cd^*$~~
$^{178}Os(4\gamma,4\alpha)^{162}Er^*$	~~$^{106}Cd(\gamma,\alpha)^{102}Pd$~~
$^{177}Os(3\gamma,3\alpha)^{165}Yb$	$^{96}Ru(\gamma,\alpha)^{92}Mo^*$
$^{176}Os(5\gamma,5\alpha)^{156}Dy^*$	~~$^{74}Se(\gamma,\alpha)^{70}Ge^*$~~
~~$^{167}Hf(\gamma,\alpha)^{163}Yb$~~	

Our Lv 1 key rates ^{160}Er + α ↔ γ + ^{164}Yb, ^{176}W + α ↔ γ + ^{180}Os appear in two of the chains

We find additional key rates not listed in these tables (see list of key rates on previous slide)

Key reaction comparison to the 25 M_{sol} model of Rapp et al. (2006)

N.B.: Comparion of our key rates found by MC variation of Hashimoto (1990) trajectories

Selected (γ, p) or (n, p) Reactions

Reactions		
^{126}Ba$(\gamma,p)^{125}$Cs*	^{92}Mo$(\gamma,p)^{91}$Nb*	^{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*	^{73}As$(\gamma,p)^{72}$Ge
^{96}Ru$(\gamma,p)^{95}$Tc*	^{77}Se$(n,p)^{77}$As	^{71}Ge$(n,p)^{71}$Ga

Lv 2 rate only important after a number of others have been constrained

Lv 1 key rate

Selected (γ, α) Reaction Chains

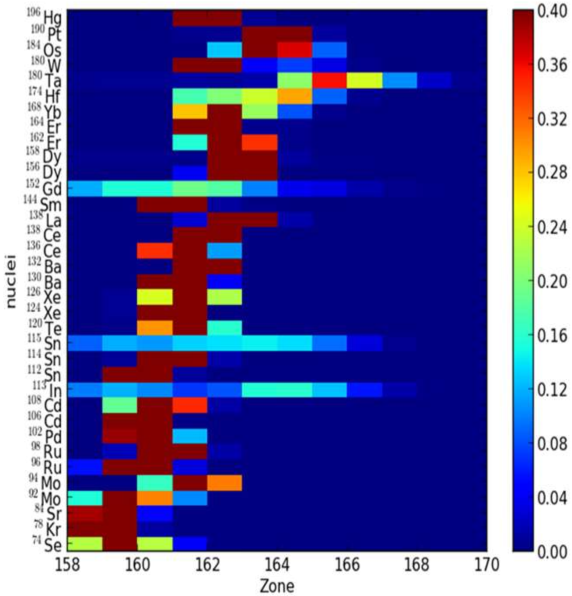
Reaction Chains	
^{196}Pb$(\gamma,\alpha)^{192}$Hg*	^{166}Hf$(5\gamma,5\alpha)^{146}$Sm*
^{195}Pb$(3\gamma,3\alpha)^{183}$Os	^{156}Er$(3\gamma,3\alpha)^{144}$Sm*
^{190}Hg$(3\gamma,3\alpha)^{178}$W*	^{128}Ba$(\gamma,\alpha)^{124}$Xe
^{189}Hg$(3\gamma,3\alpha)^{177}$W	^{122}Xe$(\gamma,\alpha)^{118}$Te
^{188}Hg$(5\gamma,5\alpha)^{168}$Yb*	^{120}Te$(\gamma,\alpha)^{116}$Sn* Lv 2
^{183}Pt$(3\gamma,3\alpha)^{171}$Hf	^{110}Sn$(\gamma,\alpha)^{106}$Cd*
^{178}Os$(4\gamma,4\alpha)^{162}$Er*	^{106}Cd$(\gamma,\alpha)^{102}$Pd
^{177}Os$(3\gamma,3\alpha)^{165}$Yb	^{96}Ru$(\gamma,\alpha)^{92}$Mo*
^{176}Os$(5\gamma,5\alpha)^{156}$Dy*	^{74}Se$(\gamma,\alpha)^{70}$Ge*
^{167}Hf$(\gamma,\alpha)^{163}$Yb	

Our Lv 1 key rates
^{164}Yb + α ↔ γ + ^{168}Hf,
^{176}W + α ↔ γ + ^{180}Os
appear in two of the chains

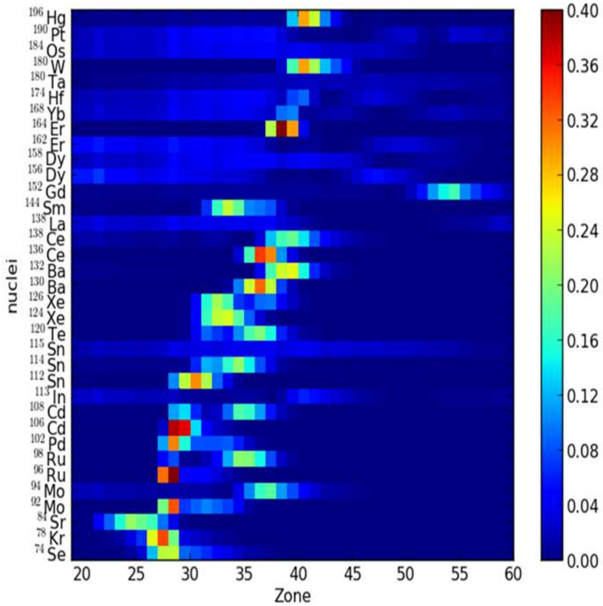
We find additional key rates (Lv 1-3) not listed in these tables.

Abundance change in mass zone:

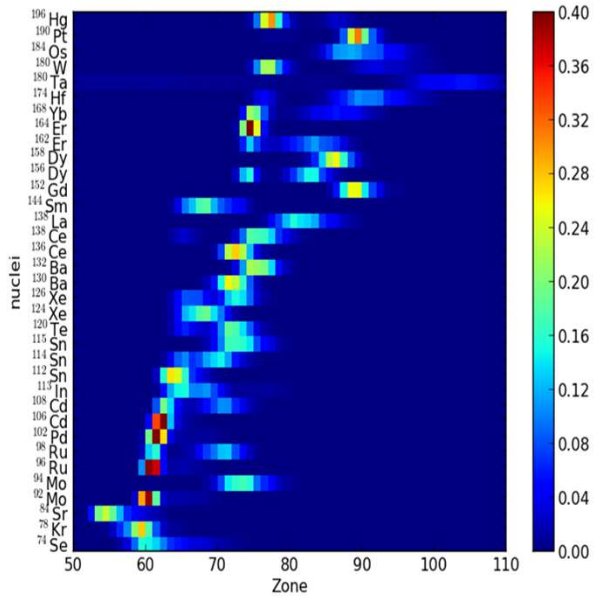
Hashimoto (1990)



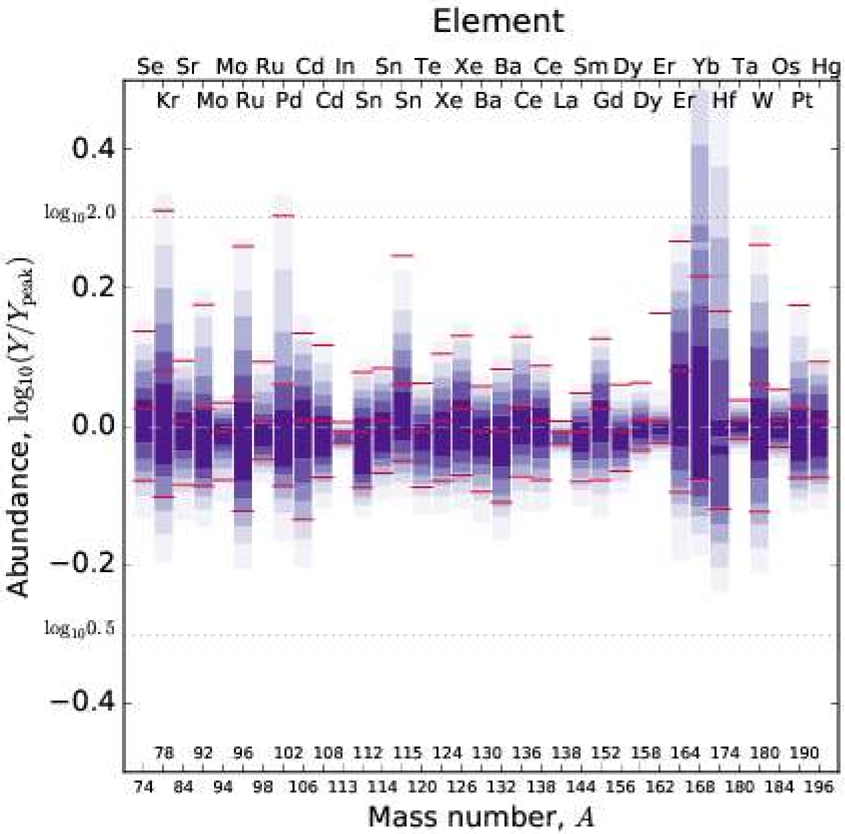
KEPLER 25Msun

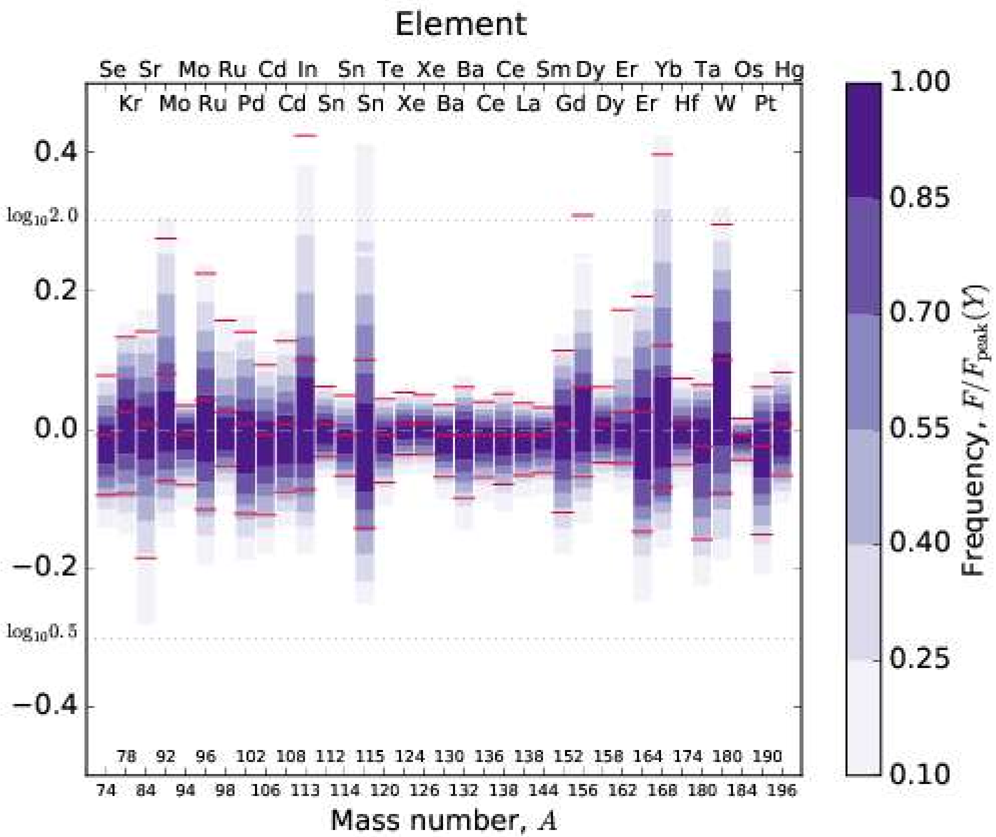


KEPLER 15Msun

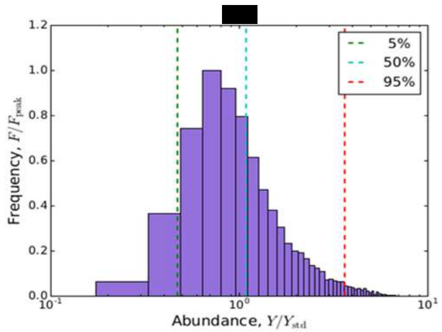


Uncertainty distribution functions for final p-production





KEPLER 25 Msun



KEPLER 15 Msun

$\log_{10}(2) \approx 0.3$
$\log_{10}(5) \approx 0.7$

- Level 1 key rate: strong correlation with abundance change
- Level 2: strong correlation with remaining abundance after level 1 key rates kept fixed (level 1 rates covered their contribution before)
- Level 3: strong corr. after level 1 and 2 kept fixed

Consider g.s. contribution to judge experimental possibility for improvement.

Independent of initial magnitude of uncertainty!

KEPLER 15 Msun

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}

Resulting from simultaneous variation of all rates within uncertainties!

Advantage over (manual) independent variations of individual rates:

1. Complex, changing flow patterns can be explored without previous identification of paths.
2. Rates with larger uncertainty (and even far away from p-nuclide) can dominate uncertainty even when p-abundance is not strongly sensitive to rate change.

KEPLER 25 Msun

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			$^{77}\mathrm{Br} + \mathrm{p} \leftrightarrow \gamma + {}^{78}\mathrm{Kr}$			9.63×10^{-2}	4.44×10^{-2}
	0.34	0.87			$^{79}\mathrm{Kr} + \mathrm{n} \leftrightarrow \gamma + {}^{80}\mathrm{Kr}$		1.28×10^{-1}	7.94×10^{-2}
^{92}Mo	−0.74			$^{91}\mathrm{Nb} + \mathrm{p} \leftrightarrow \gamma + {}^{92}\mathrm{Mo}$			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			$^{95}\mathrm{Tc} + \mathrm{p} \leftrightarrow \gamma + {}^{96}\mathrm{Ru}$		7.64×10^{-1}	6.60×10^{-1}
^{102}Pd	−0.87			$^{101}\mathrm{Pd} + \mathrm{n} \leftrightarrow \gamma + {}^{102}\mathrm{Pd}$			5.62×10^{-1}	3.97×10^{-1}
^{112}Sn	−0.88			$^{111}\mathrm{Sn} + \mathrm{n} \leftrightarrow \gamma + {}^{112}\mathrm{Sn}$			7.79×10^{-1}	6.73×10^{-1}
^{114}Sn	−0.77			$^{113}\mathrm{Sn} + \mathrm{n} \leftrightarrow \gamma + {}^{114}\mathrm{Sn}$			1.82×10^{-1}	1.28×10^{-1}
^{120}Te	−0.64	−0.66			$^{119}\mathrm{Te} + \mathrm{n} \leftrightarrow \gamma + {}^{120}\mathrm{Te}$		2.43×10^{-1}	1.77×10^{-1}
^{124}Xe	−0.74			$^{123}\mathrm{Xe} + \mathrm{n} \leftrightarrow \gamma + {}^{124}\mathrm{Xe}$			8.25×10^{-2}	4.38×10^{-2}
^{126}Xe	−0.75			$^{125}\mathrm{Cs} + \mathrm{p} \leftrightarrow \gamma + {}^{126}\mathrm{Ba}$			1.17×10^{-1}	7.41×10^{-2}
	0.30	0.64	0.65			$^{127}\mathrm{Ba} + \mathrm{n} \leftrightarrow \gamma + {}^{128}\mathrm{Ba}$	5.78×10^{-2}	3.59×10^{-2}
^{130}Ba	−0.66			$^{129}\mathrm{Ba} + \mathrm{n} \leftrightarrow \gamma + {}^{130}\mathrm{Ba}$			5.77×10^{-2}	3.55×10^{-2}
^{132}Ba	−0.77			$^{131}\mathrm{Ba} + \mathrm{n} \leftrightarrow \gamma + {}^{132}\mathrm{Ba}$			1.07×10^{-1}	5.85×10^{-2}
^{136}Ce	−0.69			$^{135}\mathrm{Ce} + \mathrm{n} \leftrightarrow \gamma + {}^{136}\mathrm{Ce}$			1.86×10^{-1}	8.94×10^{-2}
	0.31	0.72			$^{139}\mathrm{Ce} + \mathrm{n} \leftrightarrow \gamma + {}^{140}\mathrm{Ce}$		8.56×10^{-1}	6.09×10^{-1}
^{138}Ce	−0.66			$^{137}\mathrm{Ce} + \mathrm{n} \leftrightarrow \gamma + {}^{138}\mathrm{Ce}$			4.16×10^{-1}	2.54×10^{-1}
	−0.16	−0.19	−0.66			$^{136}\mathrm{Ce} + \mathrm{n} \leftrightarrow \gamma + {}^{137}\mathrm{Ce}$	7.57×10^{-1}	4.70×10^{-1}
^{144}Sm	0.70			$^{145}\mathrm{Eu} + \mathrm{p} \leftrightarrow \gamma + {}^{146}\mathrm{Gd}$			8.06×10^{-1}	6.02×10^{-1}
^{152}Gd	−0.74			$^{151}\mathrm{Gd} + \mathrm{n} \leftrightarrow \gamma + {}^{152}\mathrm{Gd}$			6.18×10^{-1}	3.87×10^{-1}
	0.43	0.76			$^{153}\mathrm{Gd} + \mathrm{n} \leftrightarrow \gamma + {}^{154}\mathrm{Gd}$		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			$^{179}\mathrm{Os} + \mathrm{n} \leftrightarrow \gamma + {}^{180}\mathrm{Os}$	4.89×10^{-2}	2.49×10^{-2}
^{196}Hg	−0.83			$^{195}\mathrm{Pb} + \mathrm{n} \leftrightarrow \gamma + {}^{196}\mathrm{Pb}$			2.97×10^{-1}	1.89×10^{-1}
	0.31	0.70			$^{197}\mathrm{Pb} + \mathrm{n} \leftrightarrow \gamma + {}^{198}\mathrm{Pb}$		3.28×10^{-1}	2.39×10^{-1}
	0.17	0.35	0.67			$^{199}\mathrm{Pb} + \mathrm{n} \leftrightarrow \gamma + {}^{200}\mathrm{Pb}$	6.37×10^{-1}	3.47×10^{-1}
^{92}Nb	0.76			$^{90}\mathrm{Zr} + \mathrm{p} \leftrightarrow \gamma + {}^{91}\mathrm{Nb}$			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			$^{147}\mathrm{Gd} + \mathrm{n} \leftrightarrow \gamma + {}^{148}\mathrm{Gd}$	9.92×10^{-1}	9.28×10^{-1}

Remaining rates with some correlation: Cannot account for the remaining uncertainty alone! Not "key rates" but of interest in combination with other rates after key rates have been determined.

Nuclide	$r_{corr,3}$	Rate	X_0 (2 GK)	X_0 (3 GK)
^{74}Se	−0.5	$^{73}As + p \leftrightarrow \gamma + {}^{74}Se$	3.39×10^{-1}	2.41×10^{-1}
	−0.4	$^{70}Ge + \alpha \leftrightarrow \gamma + {}^{74}Se$	9.87×10^{-1}	9.15×10^{-1}
	−0.4	$^{75}Se + n \leftrightarrow \gamma + {}^{76}Se$	4.37×10^{-1}	3.22×10^{-1}
^{84}Sr	−0.6	$^{83}Rb + p \leftrightarrow \gamma + {}^{84}Sr$	2.83×10^{-1}	2.47×10^{-1}
^{94}Mo	0.6	$^{95}Mo + n \leftrightarrow \gamma + {}^{96}Mo$	8.93×10^{-1}	7.59×10^{-1}
	−0.4	$^{93}Mo + n \leftrightarrow \gamma + {}^{94}Mo$	9.98×10^{-1}	9.71×10^{-1}
^{96}Ru	−0.6	$^{95}Ru + n \leftrightarrow \gamma + {}^{96}Ru$	9.90×10^{-1}	9.23×10^{-1}
	−0.4	$^{105}Cd + n \leftrightarrow \gamma + {}^{106}Cd$	5.25×10^{-1}	3.71×10^{-1}
	−0.4	$^{109}In + p \leftrightarrow \gamma + {}^{110}Sn$	9.89×10^{-1}	9.28×10^{-1}
^{98}Ru	−0.6	$^{97}Ru + n \leftrightarrow \gamma + {}^{98}Ru$	8.07×10^{-1}	6.26×10^{-1}
^{106}Cd	−0.6	$^{105}Cd + n \leftrightarrow \gamma + {}^{106}Cd$	5.25×10^{-1}	3.71×10^{-1}
	0.4	$^{109}In + p \leftrightarrow \gamma + {}^{110}Sn$	9.89×10^{-1}	9.28×10^{-1}
^{108}Cd	−0.6	$^{107}Cd + n \leftrightarrow \gamma + {}^{108}Cd$	6.19×10^{-1}	4.22×10^{-1}
^{113}In	0.5	$^{114}In + n \leftrightarrow \gamma + {}^{115}In$	1.94×10^{-1}	9.60×10^{-2}
^{115}Sn	−0.4	$^{114}Sn + n \leftrightarrow \gamma + {}^{115}Sn$	9.93×10^{-1}	9.14×10^{-1}
^{168}Yb	−0.6	$^{164}Yb + \alpha \leftrightarrow \gamma + {}^{168}Hf$	2.14×10^{-1}	1.28×10^{-1}
^{174}Hf	−0.4	$^{170}Hf + \alpha \leftrightarrow \gamma + {}^{174}W$	1.78×10^{-1}	1.08×10^{-1}
^{97}Tc	0.5	$^{98}Tc + n \leftrightarrow \gamma + {}^{99}Tc$	2.83×10^{-1}	2.25×10^{-1}
	−0.5	$^{96}Tc + n \leftrightarrow \gamma + {}^{97}Tc$	3.00×10^{-1}	2.53×10^{-1}

25 Msun

Nuclide	$r_{corr,3}$	Rate	X_0 (2 GK)	X_0 (3 GK)
^{74}Se	0.4	$^{75}As + p \leftrightarrow n + {}^{75}Se$	3.53×10^{-1}	1.76×10^{-1}
	−0.4	$^{73}As + p \leftrightarrow \gamma + {}^{74}Se$	3.39×10^{-1}	2.41×10^{-1}
^{84}Sr	0.6	$^{84}Sr + n \leftrightarrow \gamma + {}^{85}Sr$	9.31×10^{-1}	7.27×10^{-1}
	−0.5	$^{83}Rb + p \leftrightarrow \gamma + {}^{84}Sr$	2.83×10^{-1}	2.47×10^{-1}
^{98}Ru	−0.6	$^{97}Ru + n \leftrightarrow \gamma + {}^{98}Ru$	8.07×10^{-1}	6.26×10^{-1}
^{106}Cd	−0.6	$^{105}Cd + n \leftrightarrow \gamma + {}^{106}Cd$	5.25×10^{-1}	3.71×10^{-1}
	0.6	$^{109}In + p \leftrightarrow \gamma + {}^{110}Sn$	9.89×10^{-1}	9.28×10^{-1}
^{108}Cd	−0.6	$^{107}Cd + n \leftrightarrow \gamma + {}^{108}Cd$	6.19×10^{-1}	4.22×10^{-1}
	0.4	$^{109}In + p \leftrightarrow \gamma + {}^{110}Sn$	9.89×10^{-1}	9.28×10^{-1}
^{113}In	0.6	$^{113}Sn + n \leftrightarrow \gamma + {}^{114}Sn$	1.89×10^{-1}	1.37×10^{-1}
^{114}Sn	−0.6	$^{113}Sn + n \leftrightarrow \gamma + {}^{114}Sn$	1.89×10^{-1}	1.37×10^{-1}
^{115}Sn	−0.6	$^{114}Sn + n \leftrightarrow \gamma + {}^{115}Sn$	9.93×10^{-1}	9.14×10^{-1}
^{120}Te	0.5	$^{121}Te + n \leftrightarrow \gamma + {}^{122}Te$	2.02×10^{-1}	9.50×10^{-2}
^{124}Xe	−0.5	$^{123}Xe + n \leftrightarrow \gamma + {}^{124}Xe$	8.19×10^{-2}	4.78×10^{-2}
^{130}Ba	−0.5	$^{130}Ba + n \leftrightarrow \gamma + {}^{131}Ba$	3.75×10^{-1}	1.65×10^{-1}
	0.5	$^{131}Ba + n \leftrightarrow \gamma + {}^{132}Ba$	1.07×10^{-1}	5.85×10^{-2}
^{132}Ba	0.4	$^{133}Ba + n \leftrightarrow \gamma + {}^{134}Ba$	1.17×10^{-1}	6.91×10^{-2}
^{152}Gd	−0.6	$^{152}Gd + n \leftrightarrow \gamma + {}^{153}Gd$	4.39×10^{-1}	1.97×10^{-1}
	0.4	$^{153}Gd + n \leftrightarrow \gamma + {}^{154}Gd$	5.38×10^{-2}	2.78×10^{-2}
^{158}Dy	−0.6	$^{157}Dy + n \leftrightarrow \gamma + {}^{158}Dy$	8.23×10^{-2}	4.12×10^{-2}
	0.5	$^{156}Dy + n \leftrightarrow \gamma + {}^{157}Dy$	1.49×10^{-1}	7.70×10^{-2}
^{162}Er	−0.5	$^{158}Er + \alpha \leftrightarrow \gamma + {}^{162}Yb$	3.10×10^{-1}	1.71×10^{-1}
^{174}Hf	−0.4	$^{174}Hf + n \leftrightarrow \gamma + {}^{175}Hf$	1.01×10^{-1}	5.56×10^{-2}
^{184}Os	−0.5	$^{184}Os + n \leftrightarrow \gamma + {}^{185}Os$	1.39×10^{-1}	7.78×10^{-2}
^{196}Hg	0.5	$^{199}Pb + n \leftrightarrow \gamma + {}^{200}Pb$	4.21×10^{-1}	2.03×10^{-1}
^{97}Tc	−0.4	$^{96}Ru + n \leftrightarrow \gamma + {}^{97}Ru$	1.00	9.91×10^{-1}

15 Msun

Possible Discussion Topics

- Stellar structure from stellar evolution models
  - differences from numerical modelling
  - effects of rotation
  - going beyond 1-D: how nucleosynthesis is affected by
    - differences in structure (shells, convection zones)
    - differences in convection
- Stellar explosions
  - Differences from numerical modelling
  - Explosion energy, mass cut (mostly affecting inner zones?)
  - Differences from "effective" explosion treatment (piston, thermal bomb, PUSH, etc)
  - Neutrino fluxes "far out", neutrino spectra
  - beyond 1-D:
    - asphericity in burning front?
    - aspherical explosion (ejecting chunks in different directions)
- *how do these really affect explosive nucleosynthesis in outer layers?!*

➢ Nuclear physics uncertainties
- involves nuclei at or close to stability
- high Coulomb barriers pose problem for experiments at relevant energies
- experiments cannot constrain most rates directly due to high *T* and high level densities
- most reactions are non-resonant compound (Hauser-Feshbach)
  - » low energy γ-widths (γ-strength function, NLD)
  - » low energy α-widths (α-optical potentials)
- comprehensive test of dependence of nucleosynthesis on nuclear input: Further MC studies planned!
- weak interactions for ν-process

➢ Observational constraints
- mostly indirect (ws-process, γ-process)
- e.g., no direct obs. possible for p-nuclei

➢ Feeding into GCE models
- contribution of stars with different masses and metallicities