31.08.2011@Odessa

New Supernova Scenarios for r-process Nucleosynthesis:
Heavy element Nucleosynthesis in a Supernova by Quark-Hadron Phase Transition

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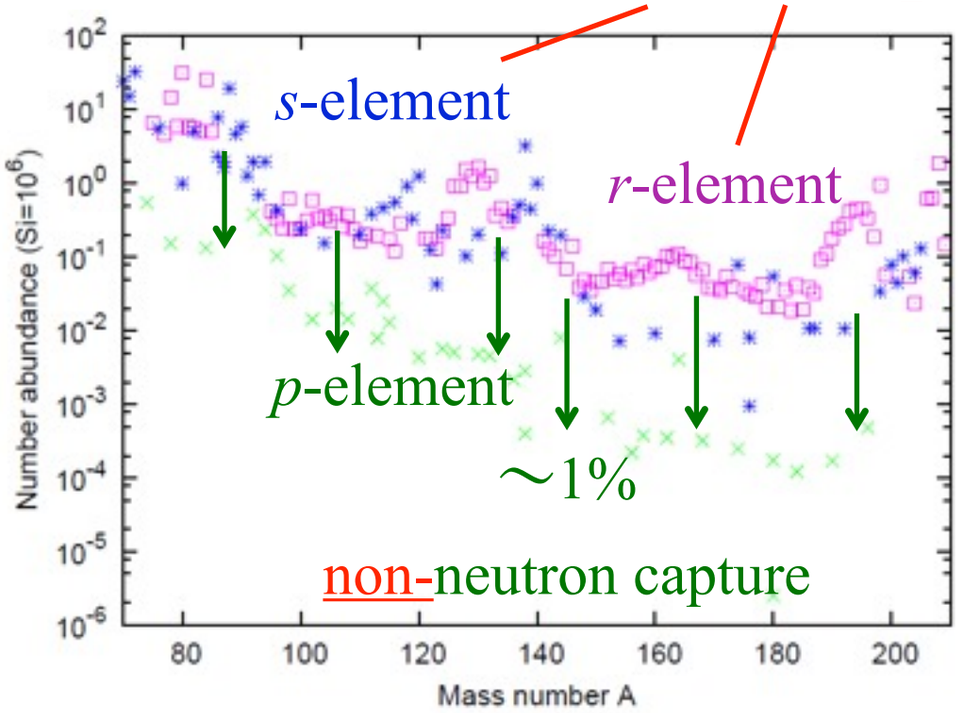
Introduction

- r-process and astronomical sites
- Supernova scenario
  by a quark-hadron phase transition

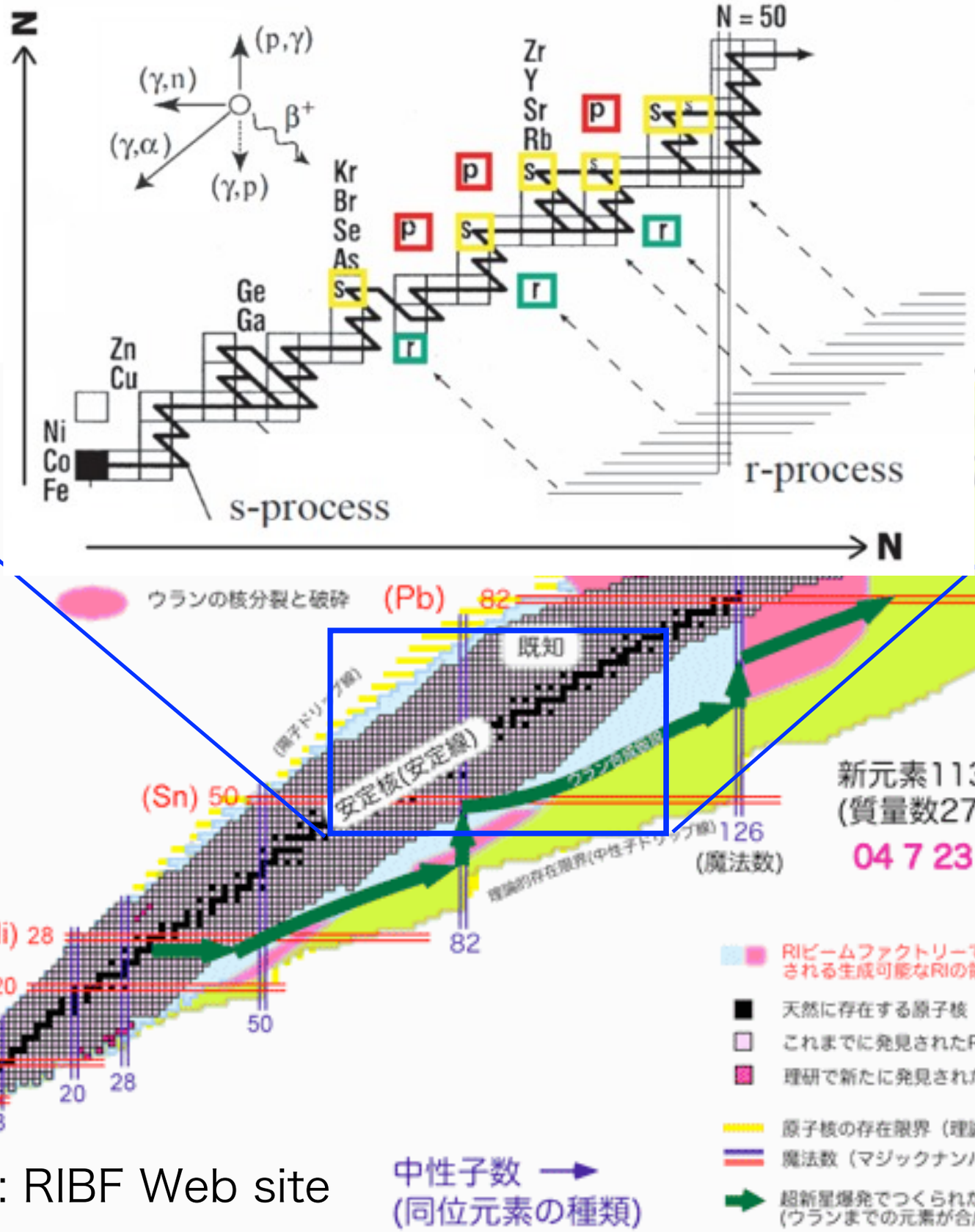
CC-SNe as the origin of r-process

Solar System heavy elements

neutron capture



Anders & Grevesse (1989)
(normalized by Si = 10^6)



RIKEN: RIBF Web site

Physical conditions for r-process

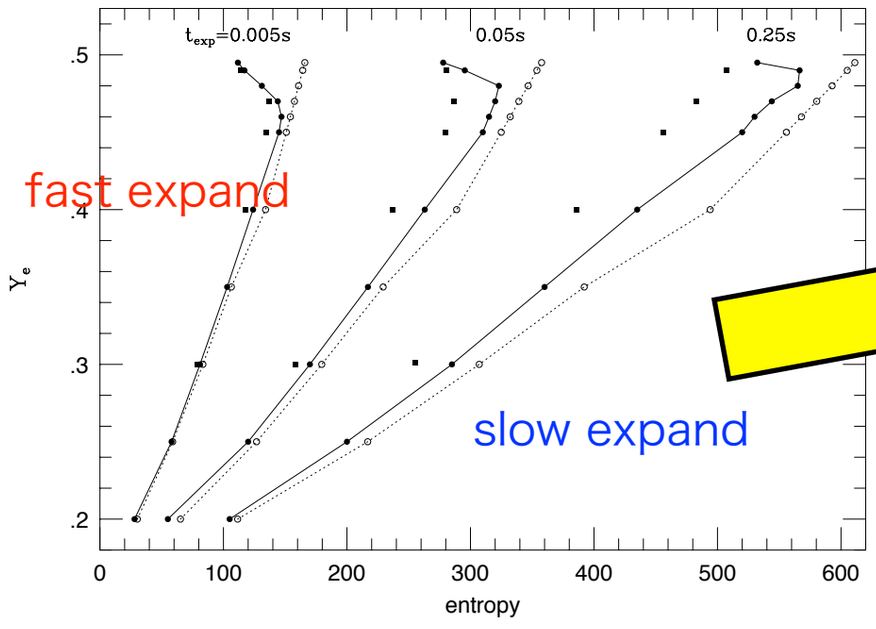
High entropy

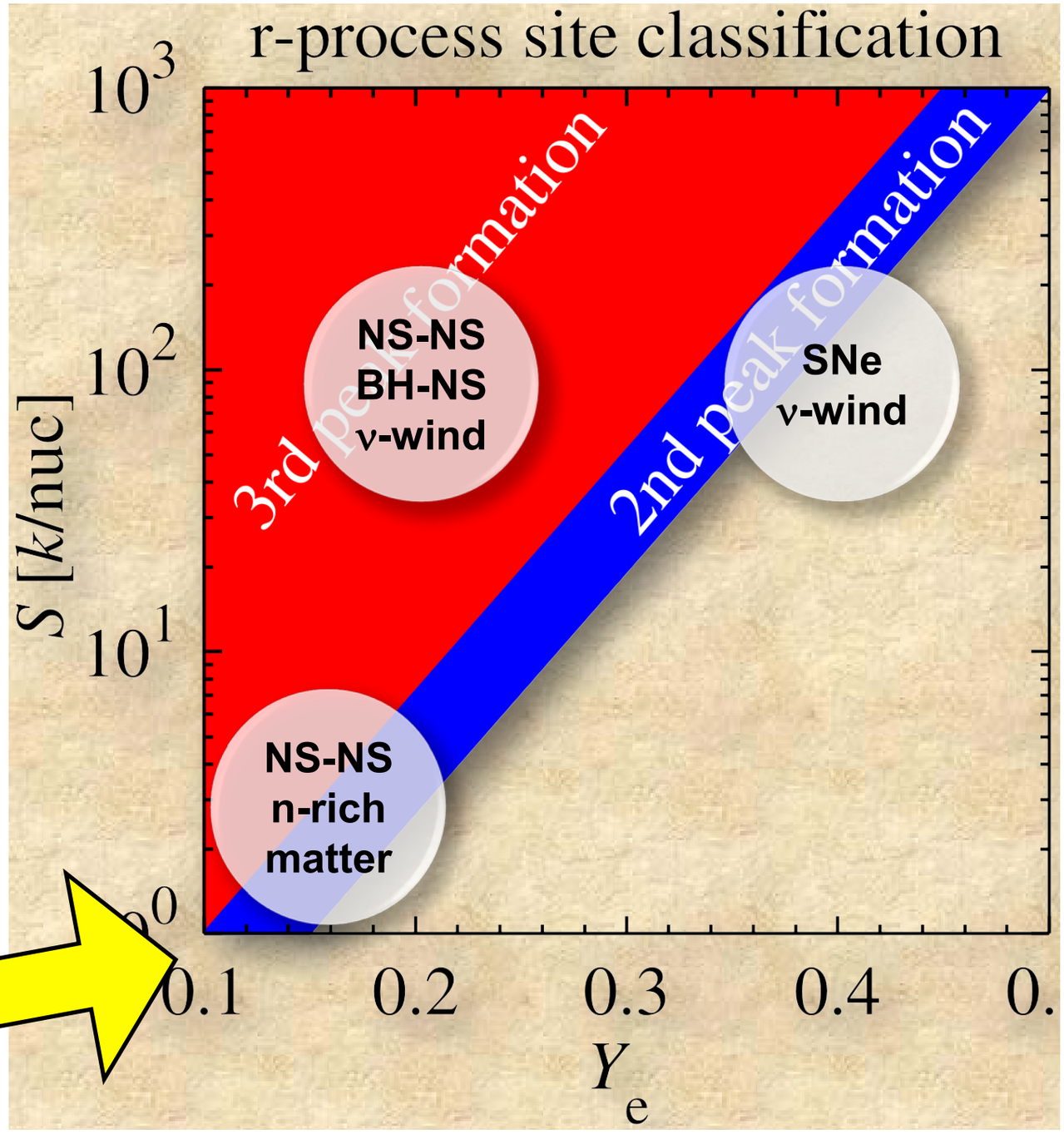
$Y_e = 0.3$ for $S \sim 100$

low entropy

$Y_e = 0.2$ for $S \sim 10$

Hoffman, Woosley, Qian (1997)





S. Wanajo @NIC-XI

r-process Astronomical Sites

astronomical site	r-element mass ($M_\odot$)	event rate (1/year/galaxy)	type*
Neutrino Driven Wind α	?10^{-5}	10^{-2}	high s
prompt-SN β	10^{-2}	?10^{-5}	low S
Neutron Star Merger γ	?10^{-2}	?10^{-5}	low S
Collapsar Model δ	10^{-2}	?$10^{-4,-5}$	high s/low s
Magneto-driven SN ε	10^{-2}	?10^{-5}	low s
Acoustic Wave SN ζ	10^{-2}	?10^{-5}	high s

process*: Wanajo (2007)

"high s" process (high entropy and not low Y_e)

"low s" process (low entropy and lowY_e)

α : Woosley et al. (1994), Otsuki et al.(2000) etc.

β : Wanajo(1994), Sumiyoshi(2000) etc.

γ : Freiburghaus et al. (1999), Wanajo et al. (2010) etc.

δ : disk wind: McLaughlin and Surman etc.
MHD Jet: Fujimoto(2007) etc.

ε : Nishimura et al. (2006), Nishimura(2011 prep.) etc.

ζ : Otsuki et al. (2011 prep.)

SN Senario: Quark-Hadron phase transition

collapse

Neutrino heating/
MHD driven

Neutron Star
(Magnetar)

Phase-transition

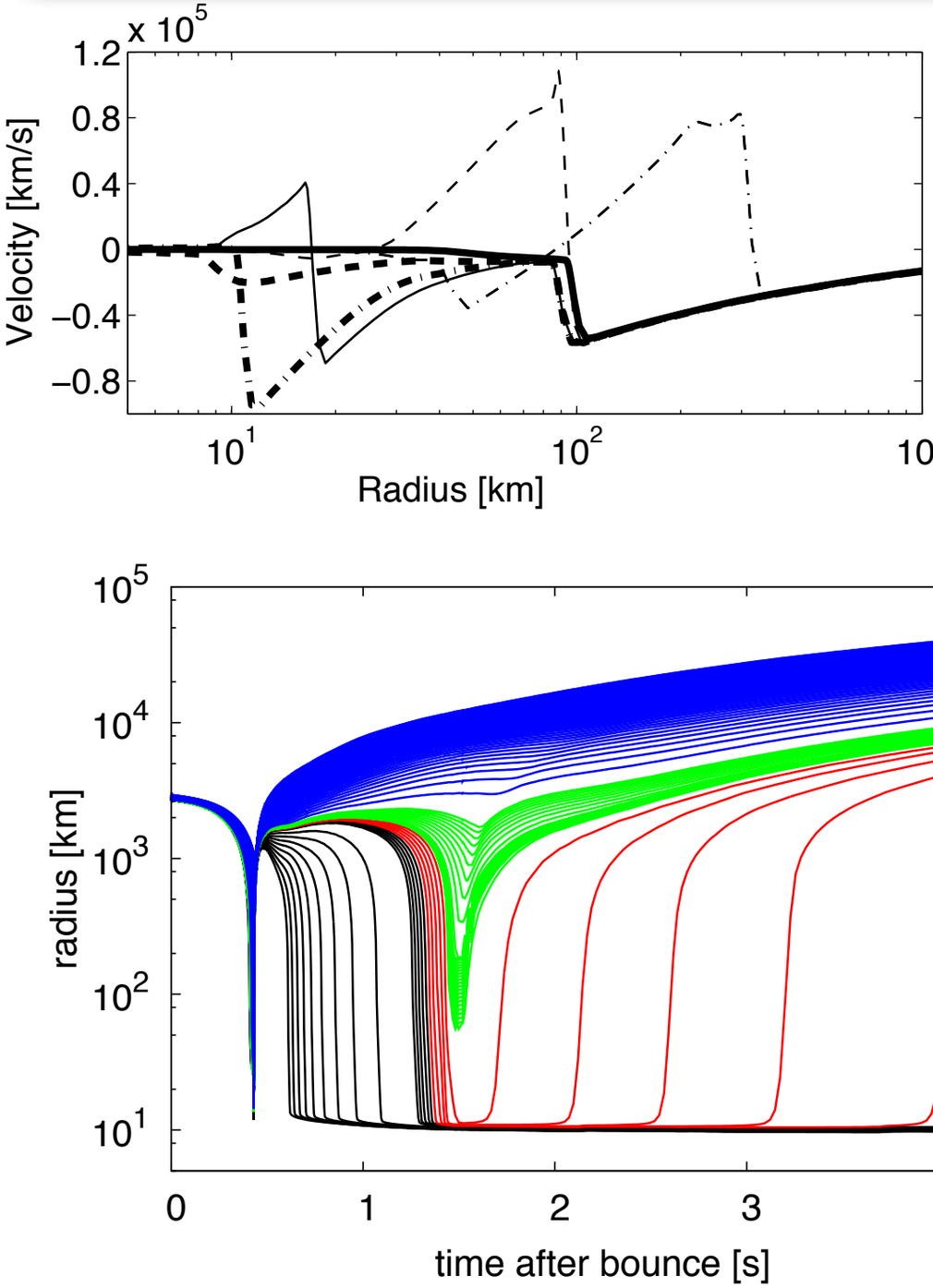
release additional
energy

Quark star

Q-H phase transition Supernova

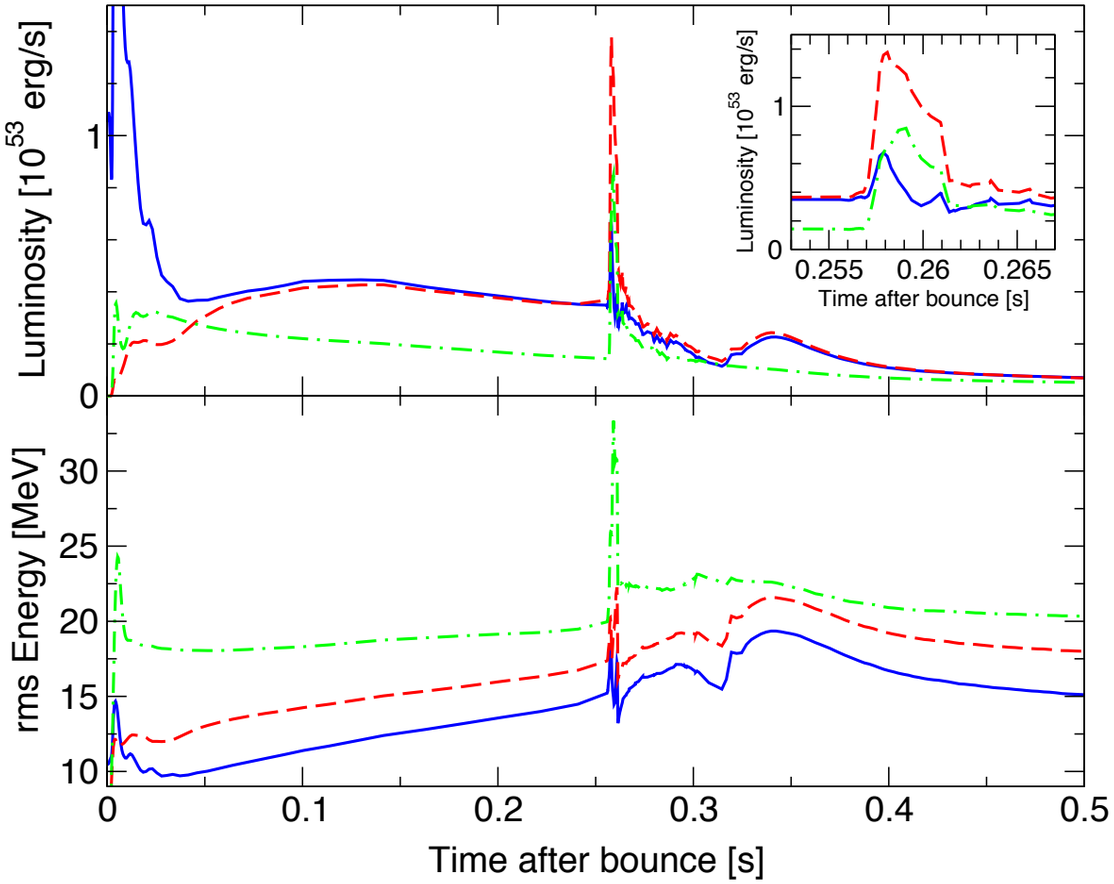
Stalled shock wave revived by Q-H phase transition

：Sagert et al. (2009), Tobias et al(2011)



- 1D General hydrodynamics with neutrino radiative transport
- EOS：Shen EOS + MIT bag model

Blue：ν_e Red：$\bar{\nu}_e$ Green：$\nu_{\mu/\tau}$



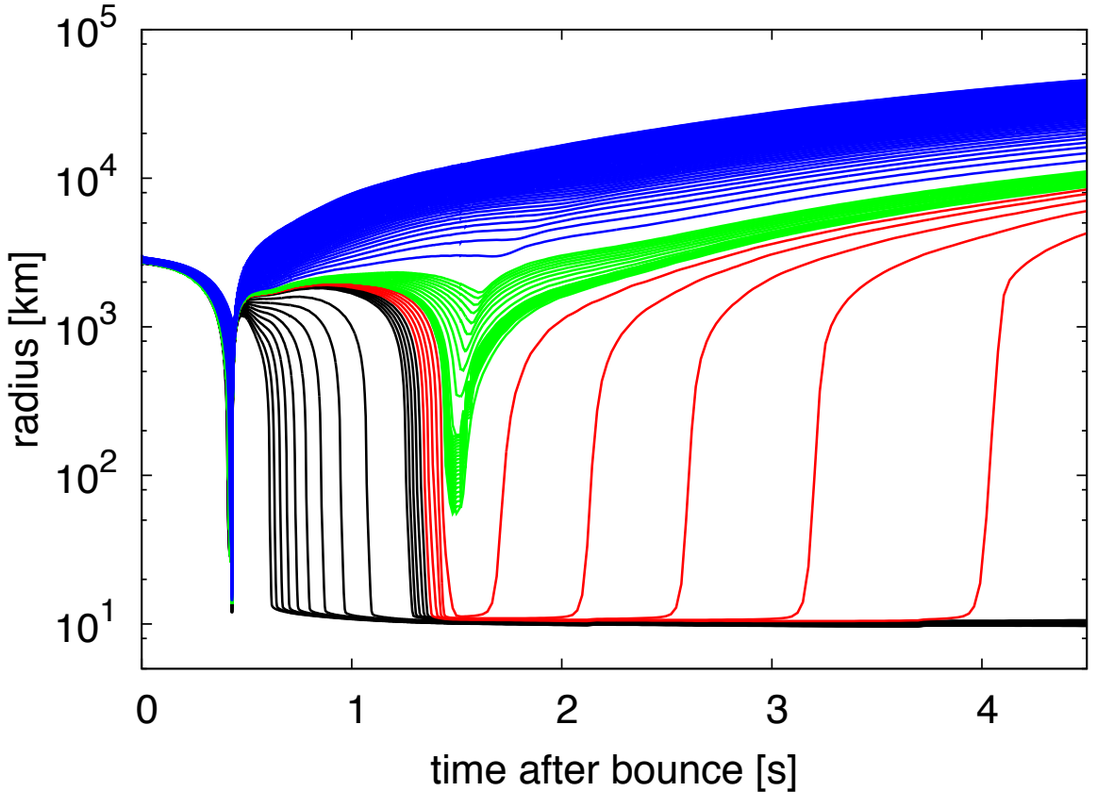
Dasgupta et al. PRD 81 (2010)

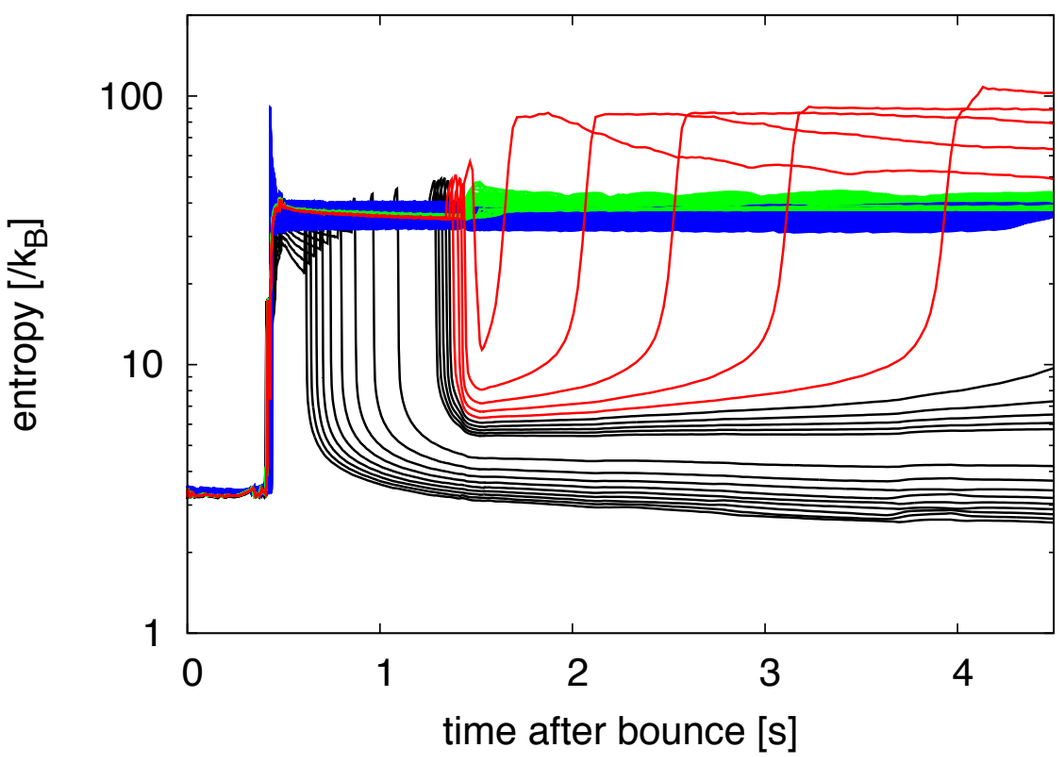
Methods and Results

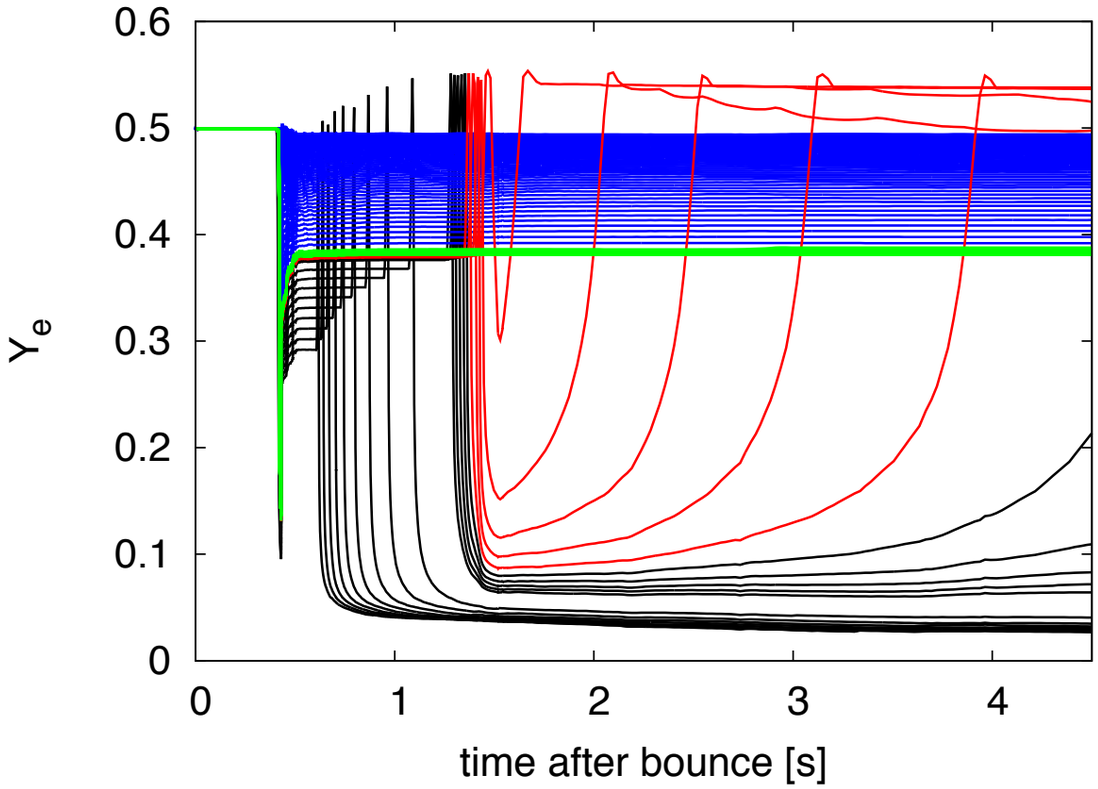
- tracers and nucleosynthesis
- r-process
- ν p-process

physical quantities: motion

tracer #	mass range [$M_\odot$]	Y_e at 0.5 [s]	t_{ej}[s]
001 - 014	$1.48000 - 1.48208$	$Y_{\rm e,f} < 0.10$	—
015 - 019	$1.48210 - 1.48216$	$0.50 < Y_{\rm e,f} < 0.55$	$1.5 \sim$
020 - 050	$1.48217 - 1.48232$	$0.35 < Y_{\rm e,f} < 0.40$	~ 0.5
051 - 120	$1.48250 - 1.49482$	$0.40 < Y_{\rm e,f} < 0.50$	~ 0.5



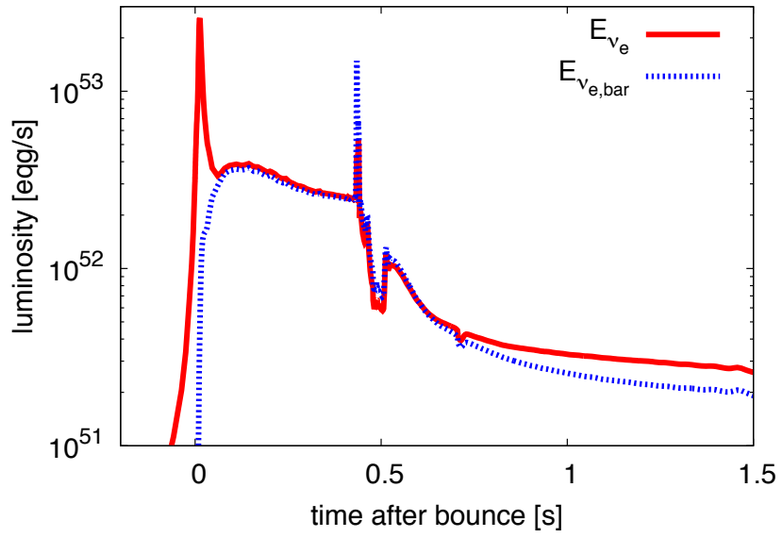


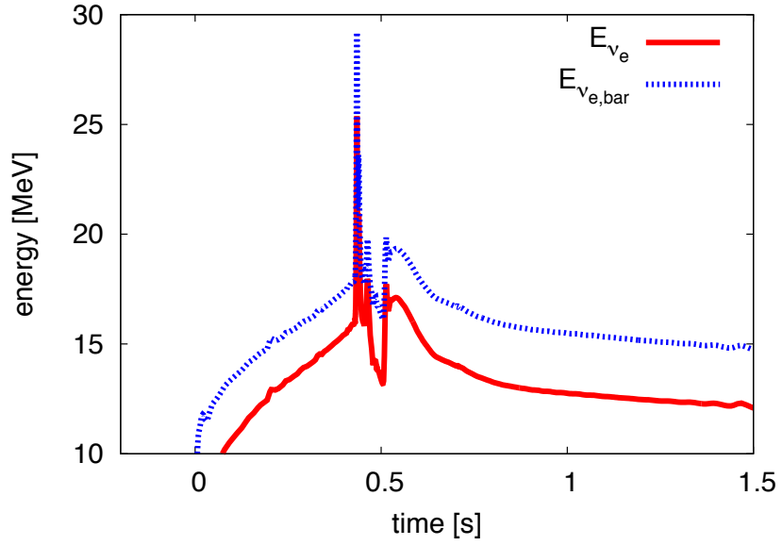


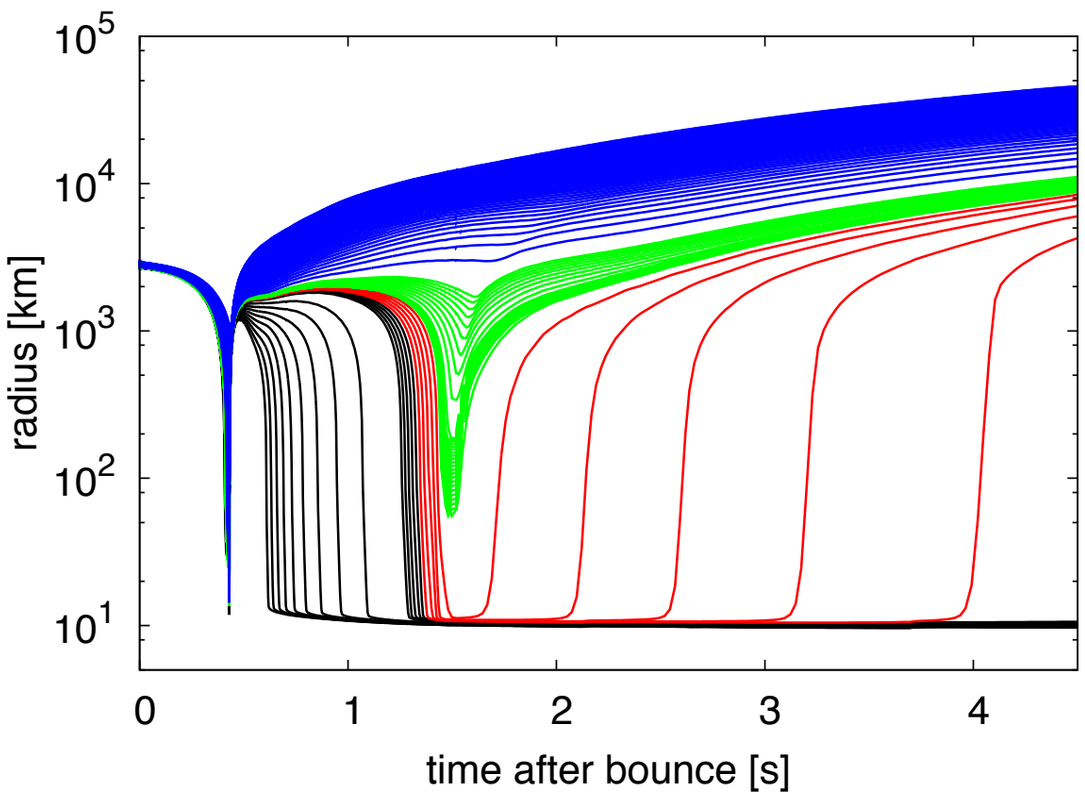
physical quantities (thermodynamics)

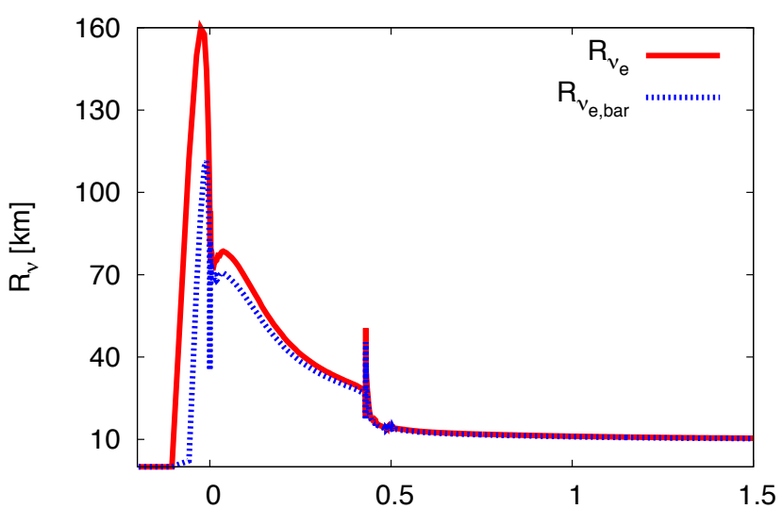
neutrino quantities

- Luminosity
- Energy
- Radius

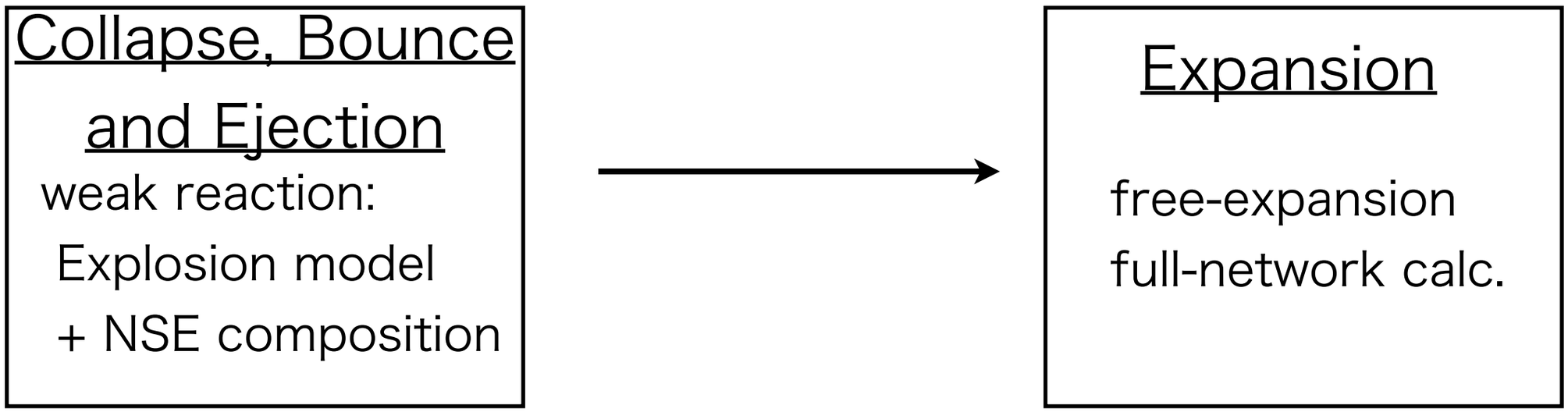








Post-process Nucleosynthesis



- weak interaction (Collapase and bounce)
  - evolutions of Y_e from hydrodynamic explosion model
  - NSE abundance (Temperature > 9 [GK])
- Nucleosynthesis （α-process, r-process ... ）
  - Post processing based on T, ρ and neutrino by SN model
  - full Nuclear Reaction Network （Nishimura et al. 2006 etc.)
  - 4071 isotopes、related reactions （REACLIB)
  - weak interaction (FFN + LMP reaction rates)

high temperature and density

abundances (NSE)

NSE condition

T9 > 5-9 [GK]

reactions (weak reaction)

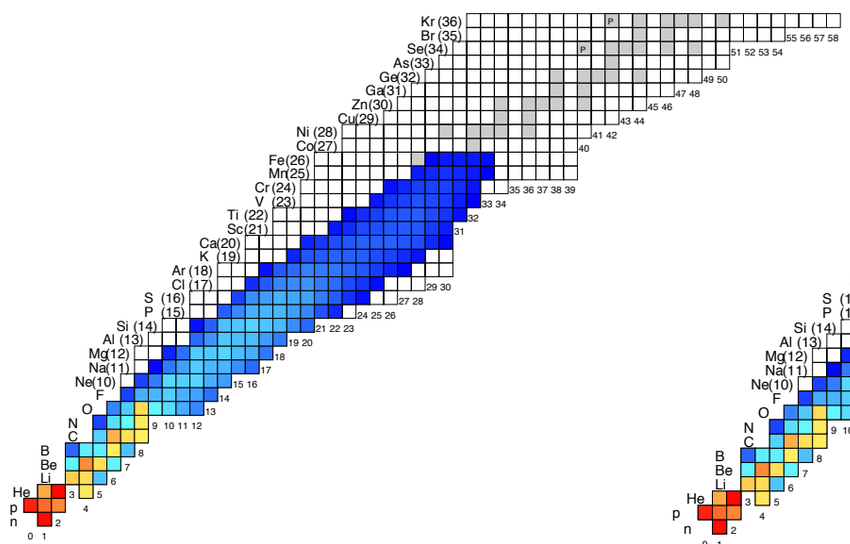
non-degenerate ideal gas

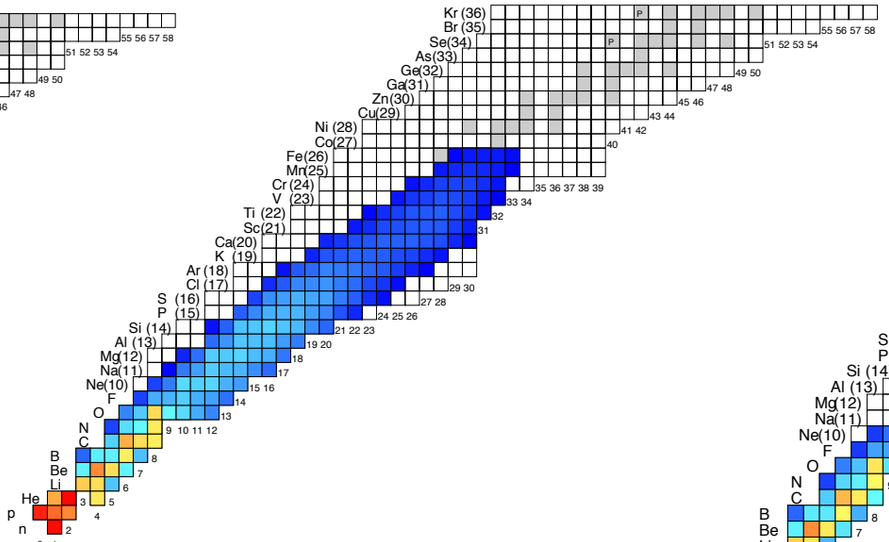
$$\rho \leq 2.4 \times 10^{-8}\ T^{3/2} \quad [\mathrm{g/cc}]$$

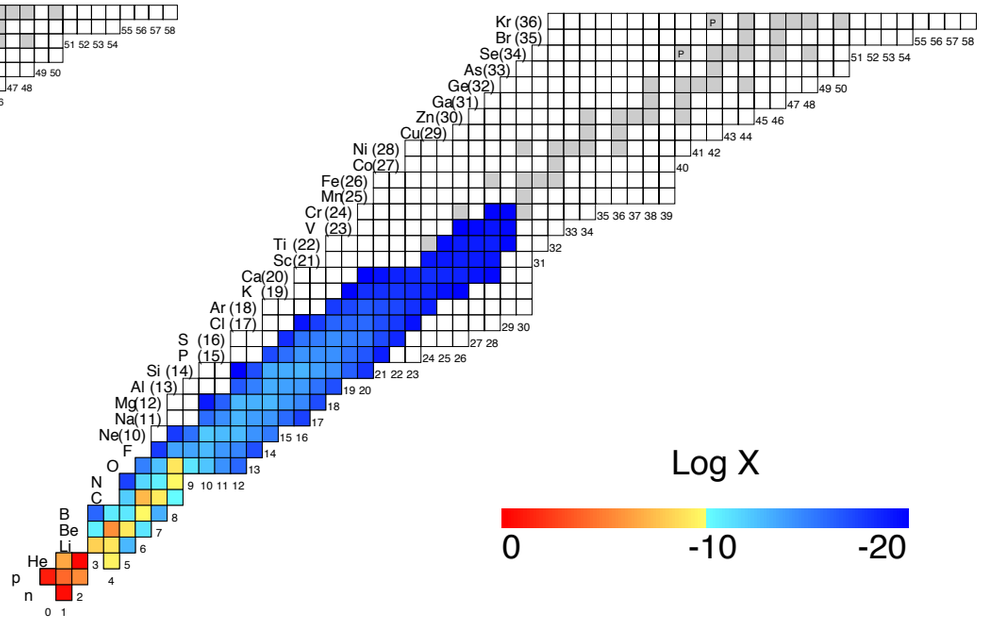
$$T = 1.0 \times 10^{10}\ [\mathrm{K}] \quad \rho \leq 2.4 \times 10^{7} \quad [\mathrm{g/cc}]$$

$$T = 5.0 \times 10^{9}\ [\mathrm{K}] \quad \rho \leq 8.5 \times 10^{6} \quad [\mathrm{g/cc}]$$

NSE abundances for tracers







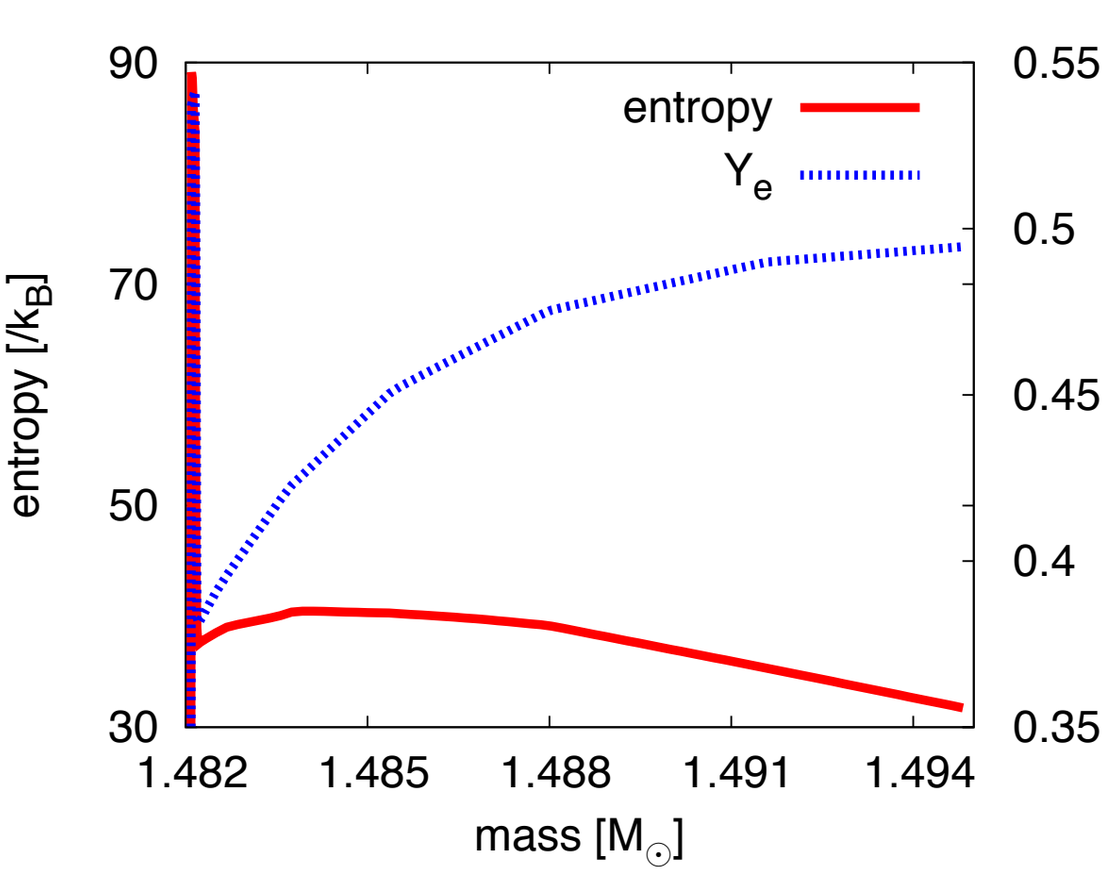
z	a		x
2	4	He4	5.7641774E-01
0	1	n	3.7803856E-01
1	1	p	4.5456105E-02
1	2	D	7.8632120E-05
1	3	T	4.8630673E-06
4	8	Be8	3.7365977E-06
2	3	He3	2.2252386E-07
6	12	C12	1.2162225E-07
3	6	Li6	9.2243331E-09
8	16	O16	2.5193770E-09

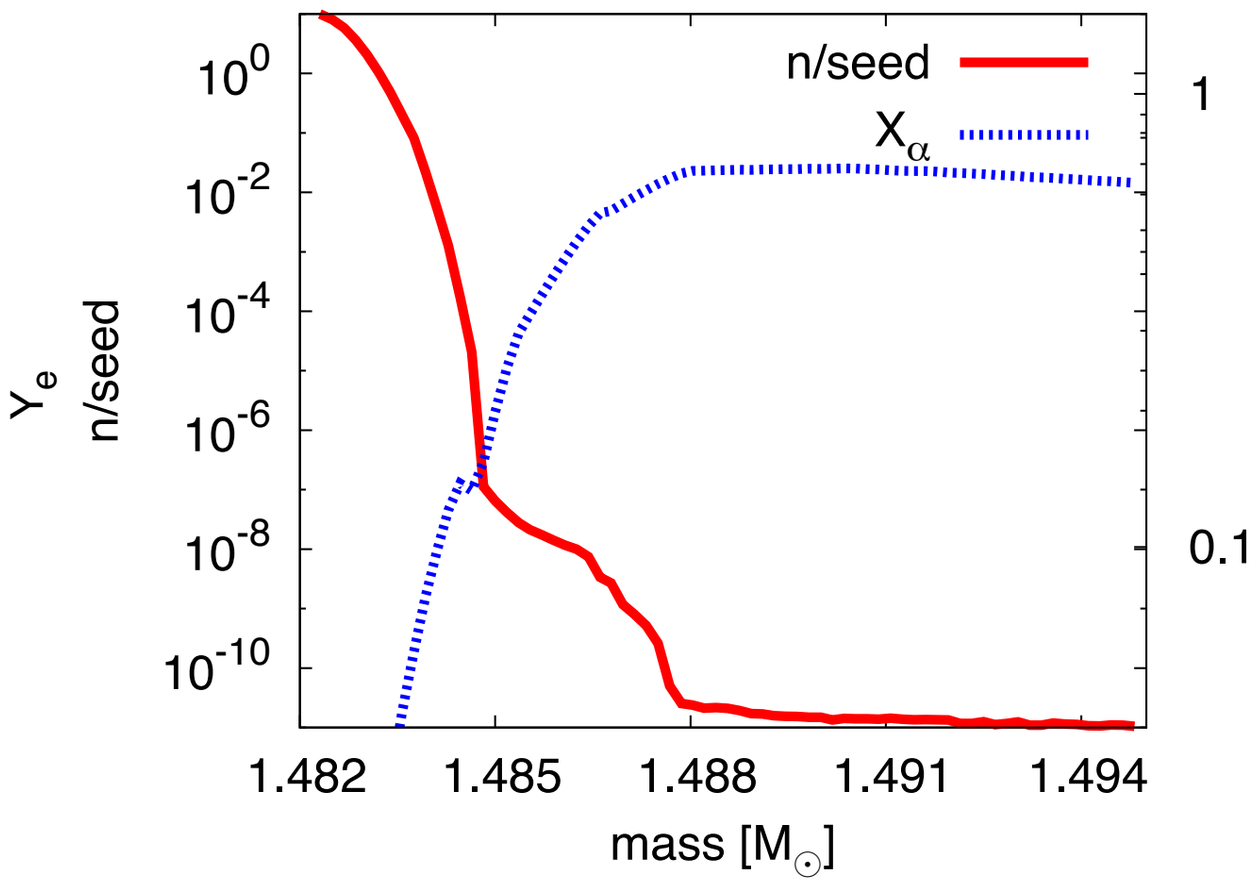
z	a		x
2	4	He4	5.7671943E-01
0	1	n	3.4329333E-01
1	1	p	7.9896356E-02
1	2	D	8.4705918E-05
1	3	T	3.3607706E-06
4	8	Be8	2.4508372E-06
2	3	He3	2.9509233E-07
6	12	C12	5.7292597E-08
3	6	Li6	6.6533730E-09
3	7	Li7	1.0003146E-09

z	a		x
2	4	He4	3.6785234E-01
0	1	n	3.6465686E-01
1	1	p	2.6734346E-01
1	2	D	1.4360240E-04
1	3	T	2.5027556E-06
2	3	He3	7.1119032E-07
4	8	Be8	5.2188898E-07
3	6	Li6	3.5236660E-09
6	12	C12	3.0602468E-09
3	7	Li7	2.2468669E-10

Condition for nucleosynthesis

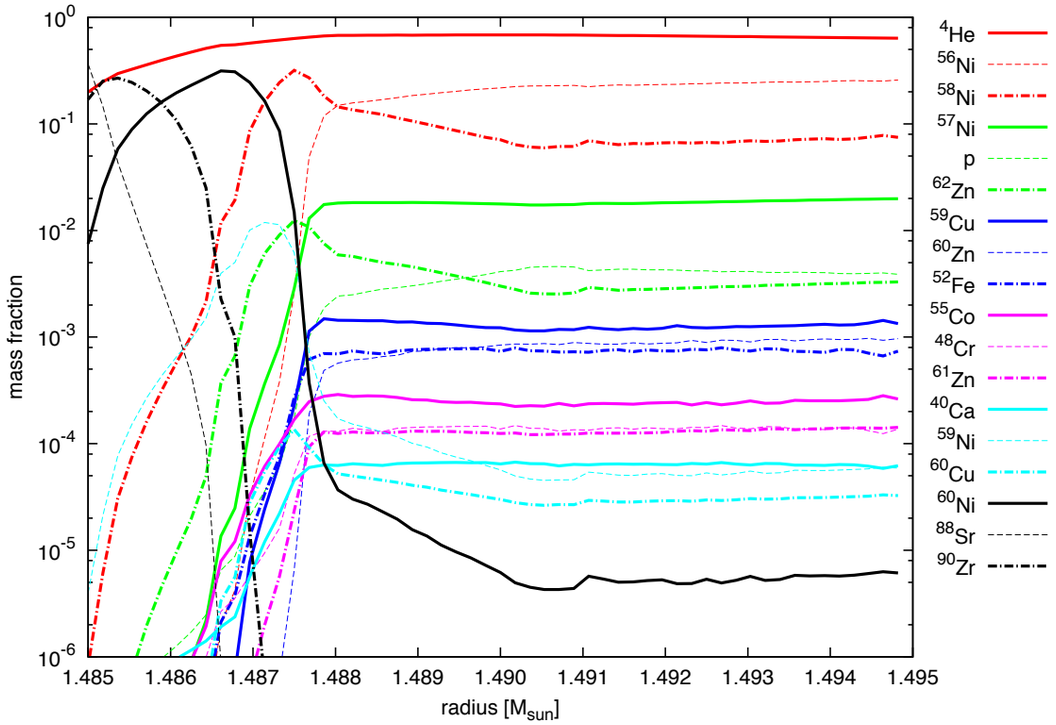
at the time of α-rich freez-eout



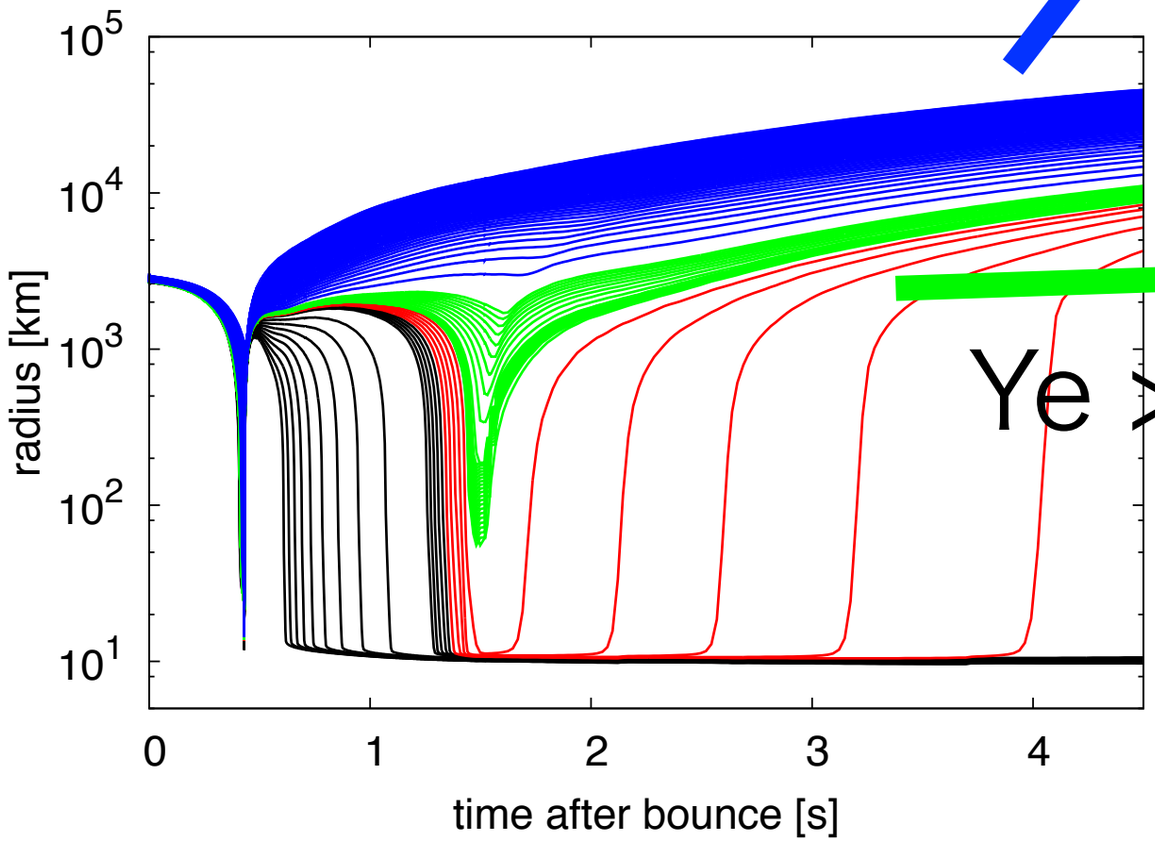


nucleosynthesis: neutron rich tracers

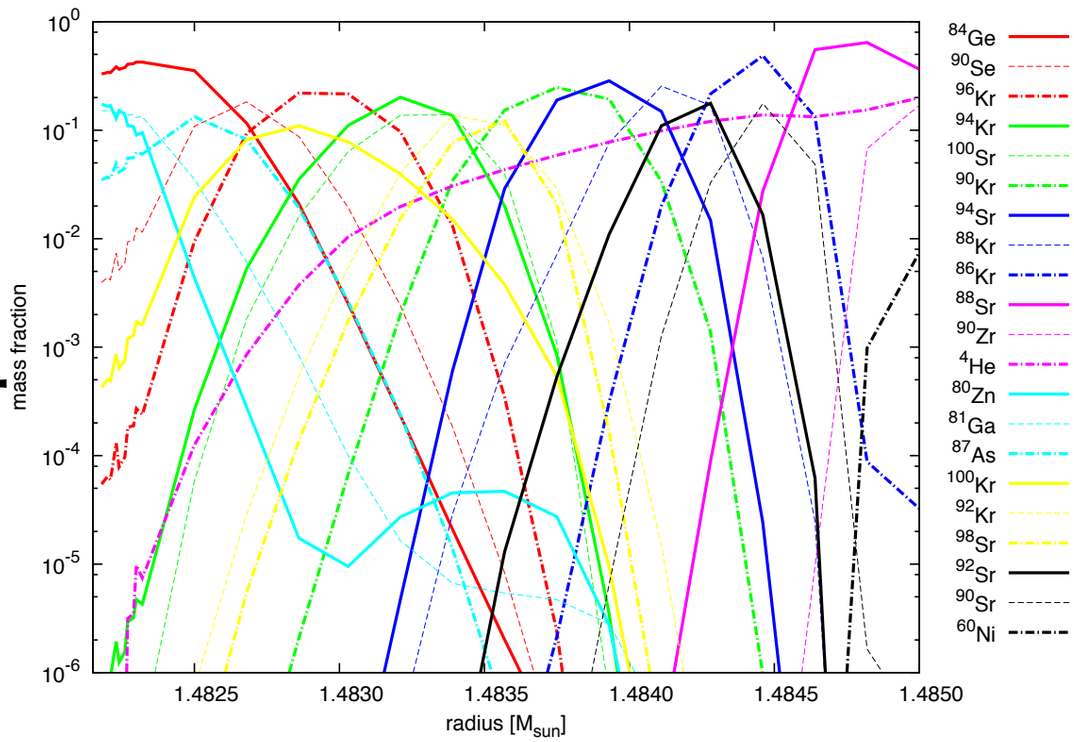
dominant abundances:
at the time of alpha freezeout
(the beginning of r-process)



0.35 < Ye < 0.4

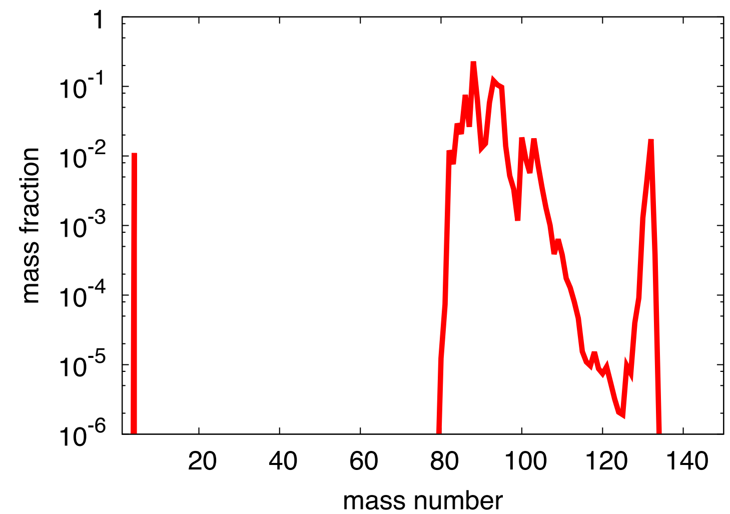


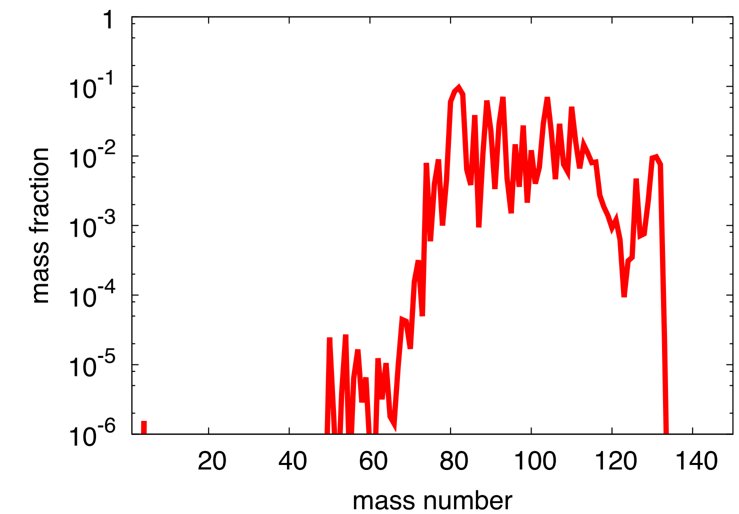
Ye > 0.4

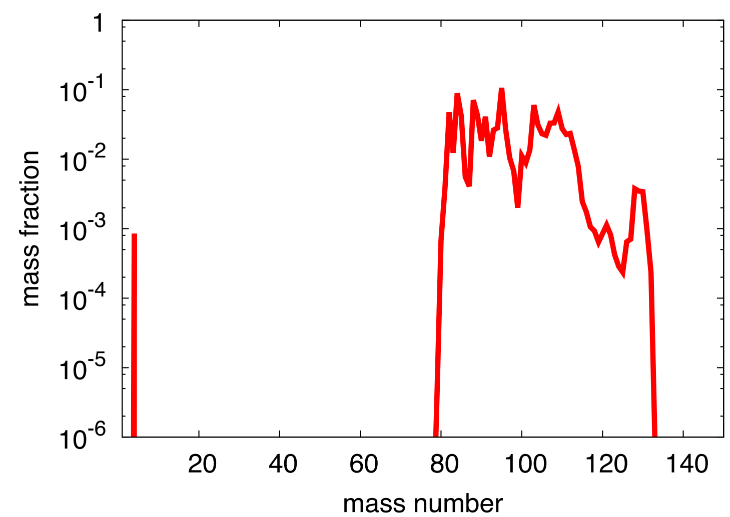


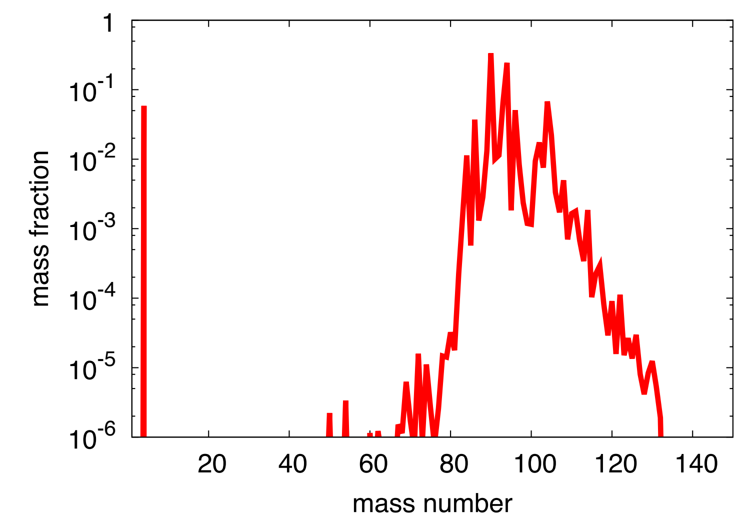
neutron rich: r-process

Ye ～ 0.35 - 0.4

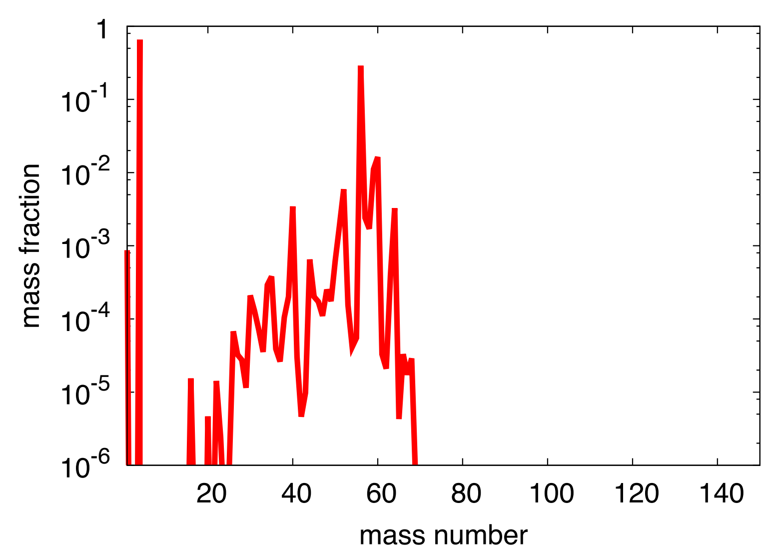


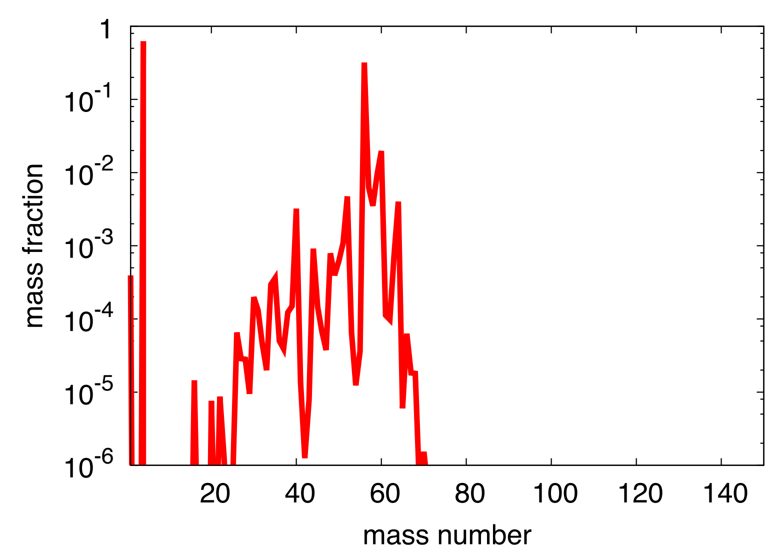






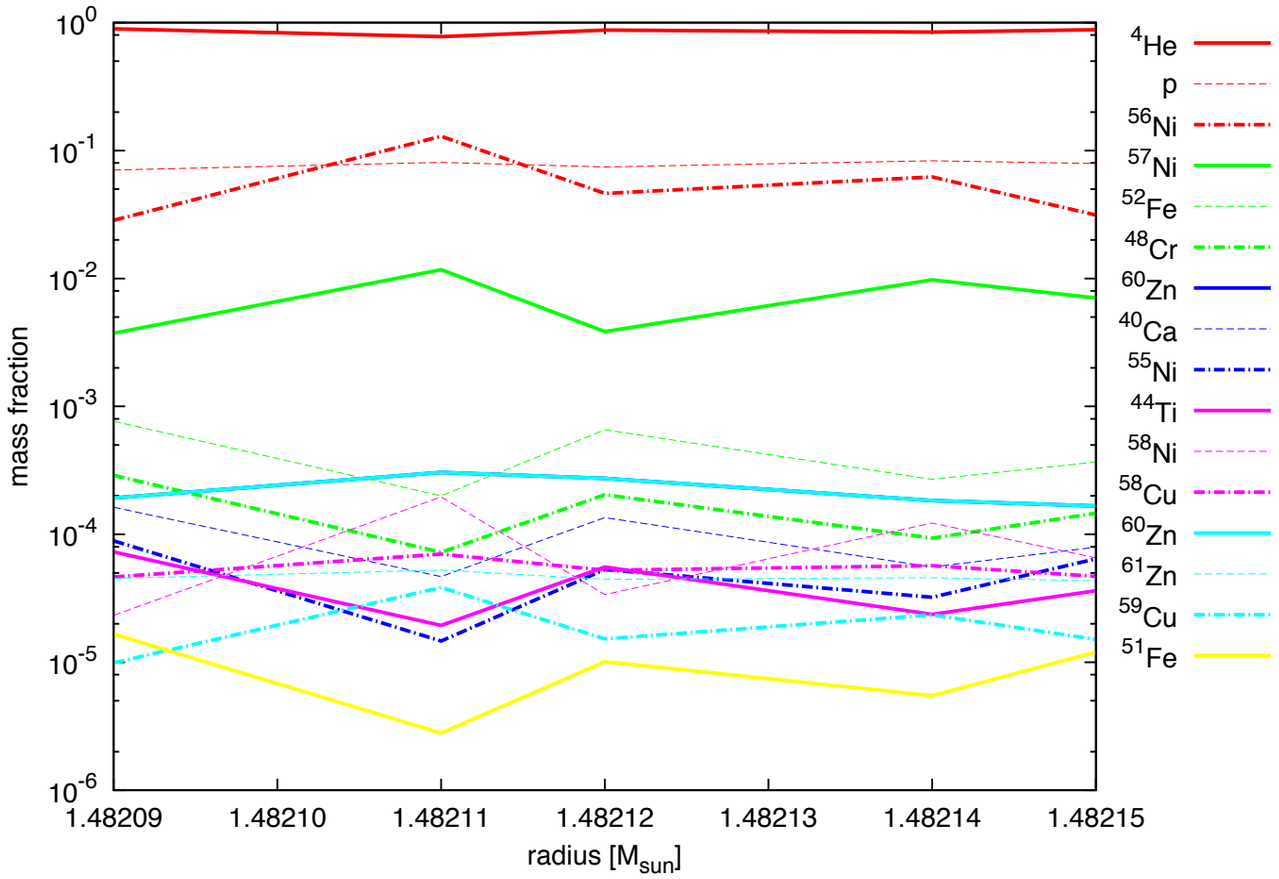
Ye ～ 0.4 -

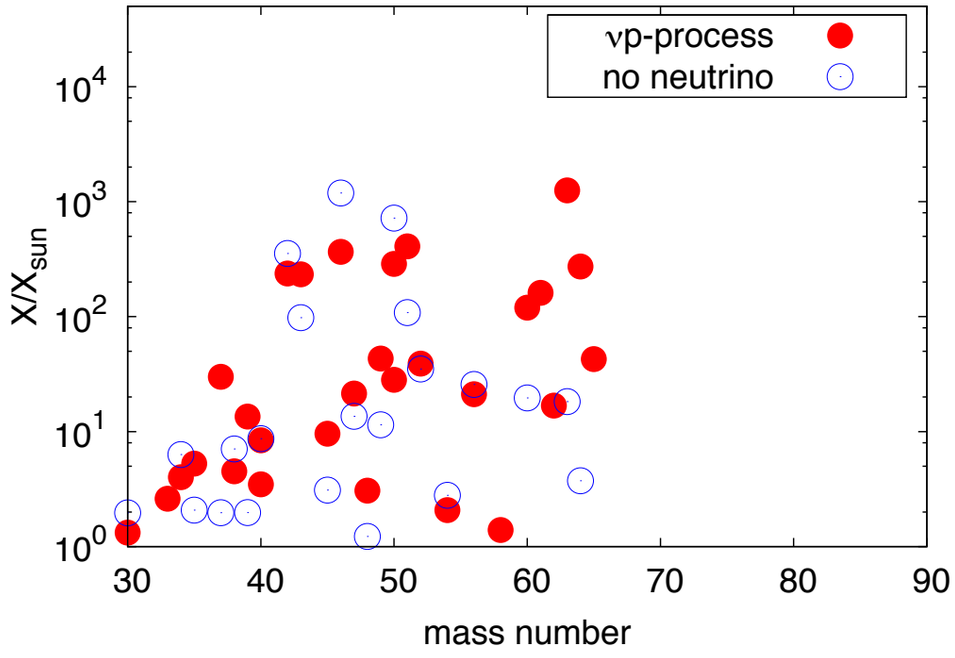


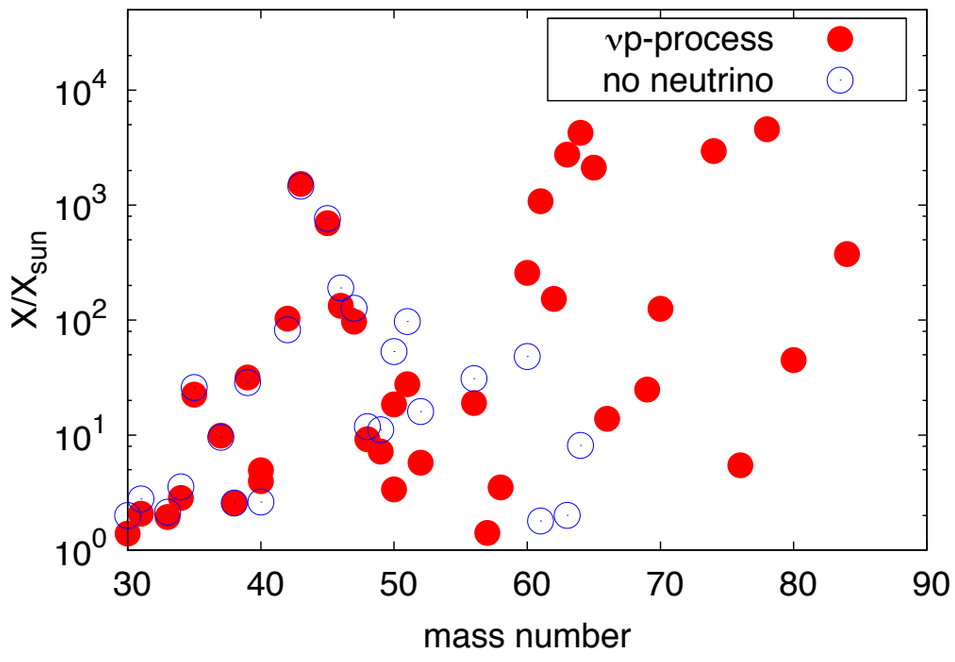


wind from PNS: ν p-process

on set of ν p-process



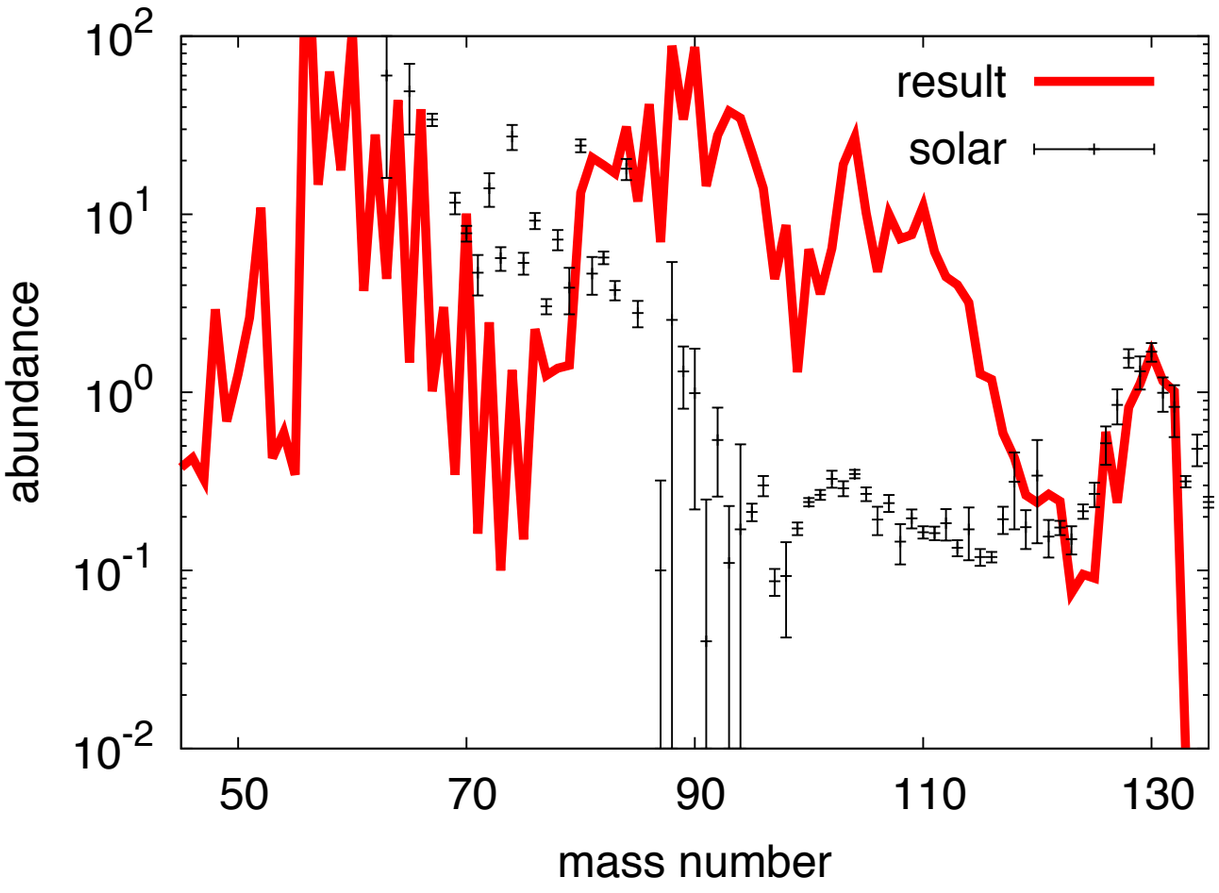


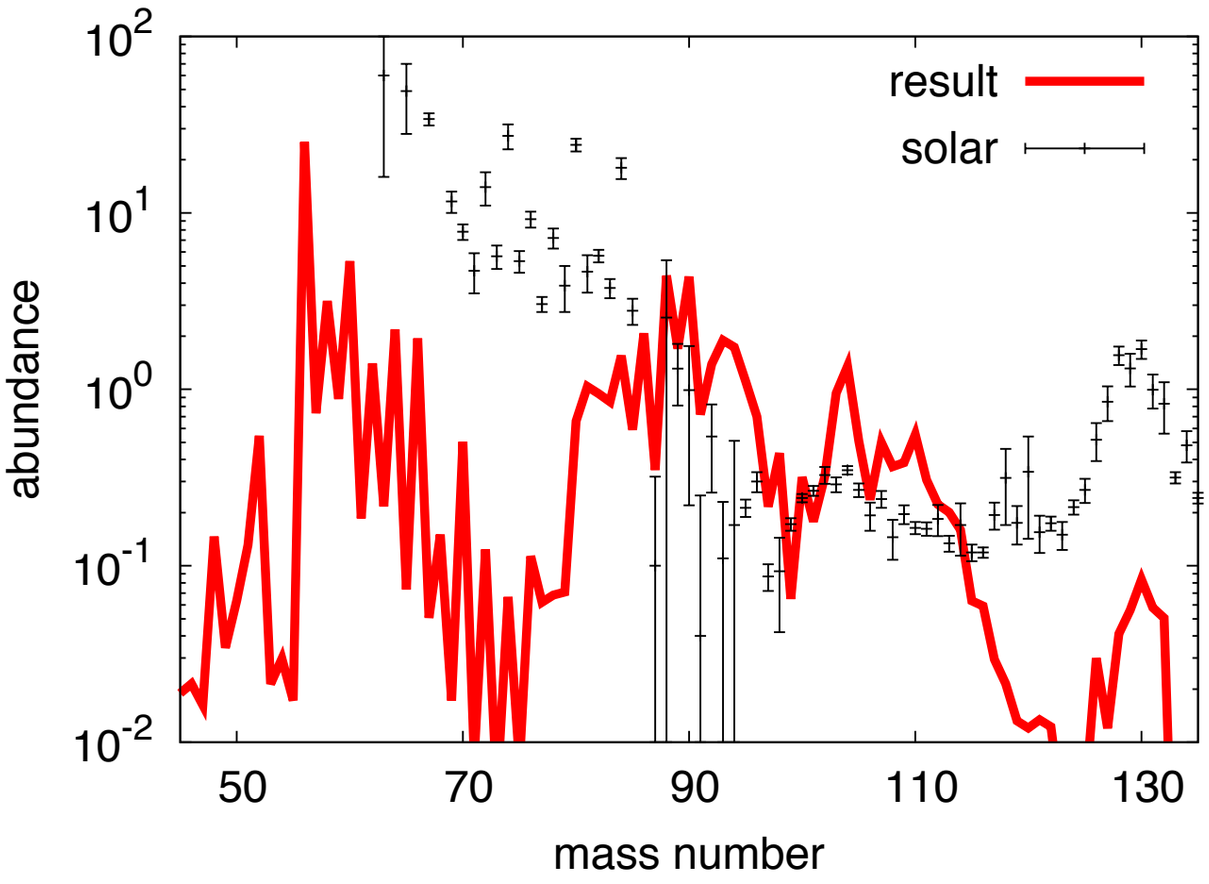


integrated final abundances

compared to solar r-element

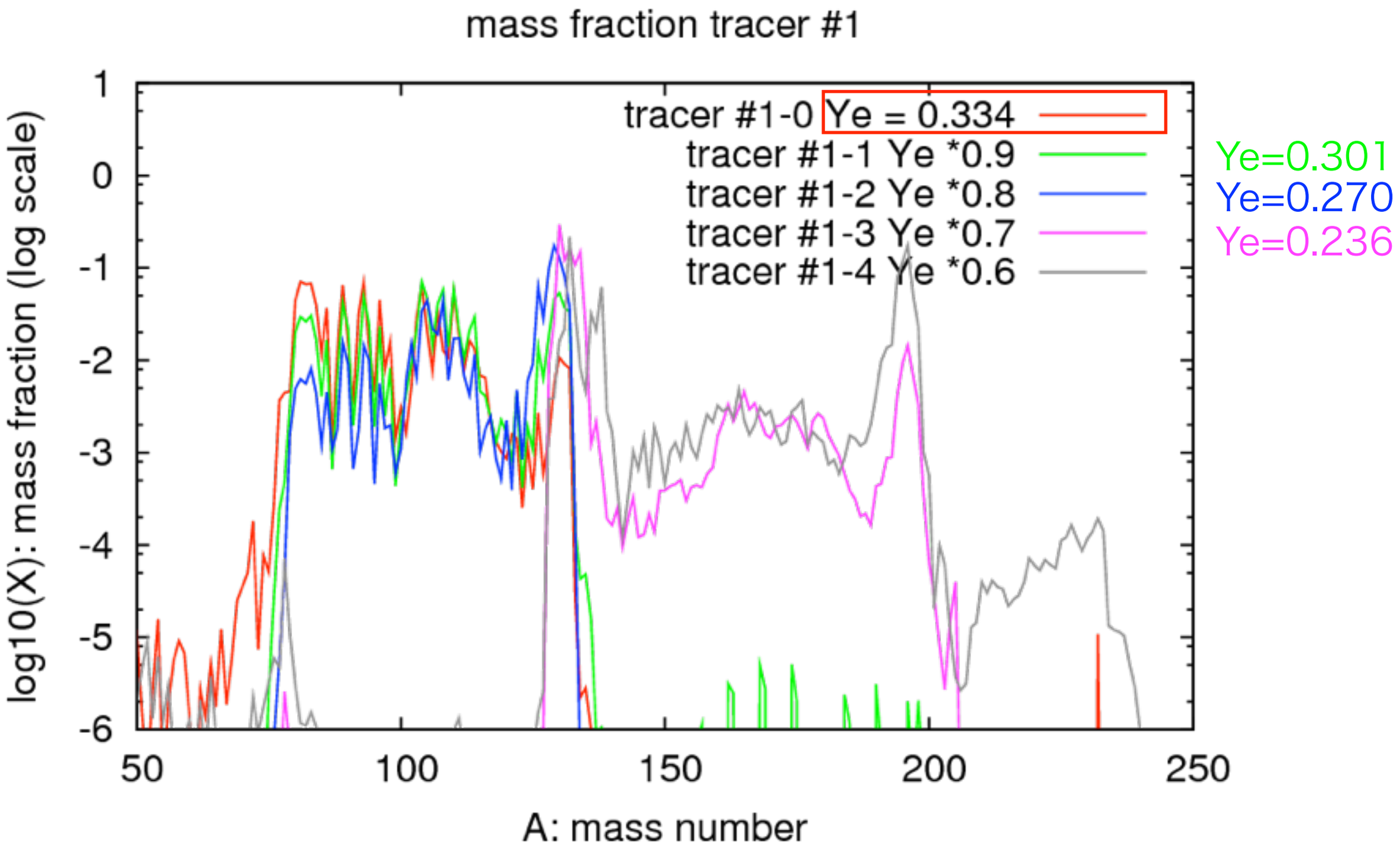
(in different vertical scales)





Ye uncertainty： r-process

fixed tracer: different initial Y_e （90～60 %)



Conclusions

Conclusions

- neutron rich component (main)
  - reproduce A～100 r-element (weak r-process)
  - (strong r-process does not occur)
- proton rich componet
  - up to A=90 isotopes by ν p-process
  - (distribution is minor)

Perspective

- Multi Dimensional Explosion Simulations

→ Y_e is sensitive to dynamics

→ Nucleosynthesis also quite sensitive to Y_e