Neutrino-induced Nucleosynthesis in the Early Galaxy

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with
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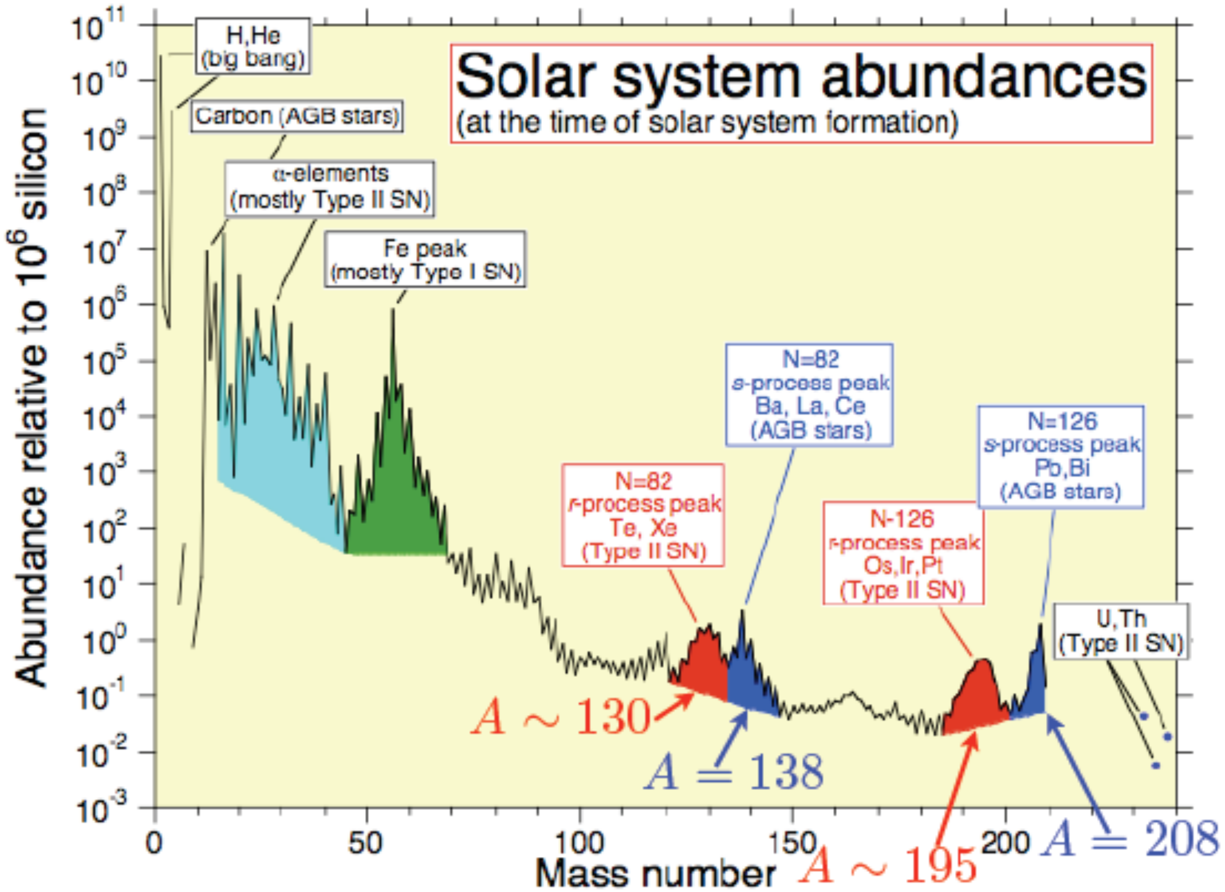
Origin of Elements



Nuclei beyond iron peak are mainly produced by neutron capture

r-process site: uncertain
Candidates: CCSNe, NSM

s-process site: 1-3 Solar Mass AGB Stars

Motivation: r-process in Metal-poor Stars ([Fe/H] <- 2.5)

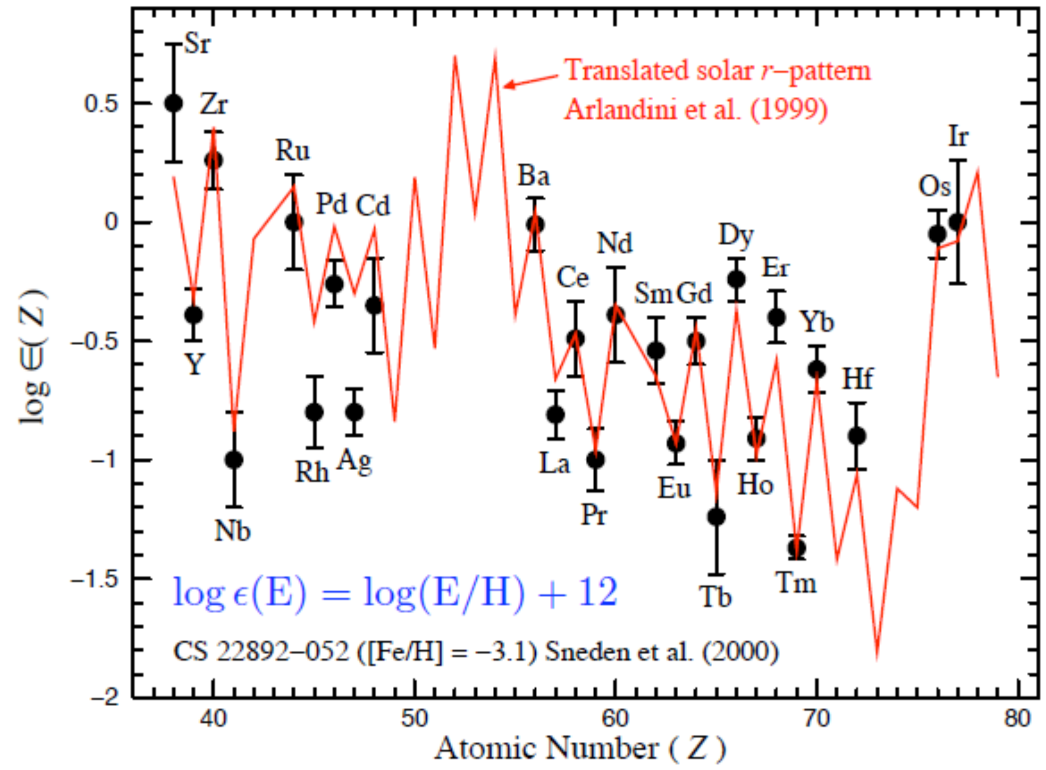
s-process does not contribute below
[Fe/H] <-2.5

Only high mass star (CCSNe) can contribute at early times.

Standard "hot" bubble r-process CCSNe runs into problems with seed overgrowth. Requires high entropies not observed in simulations.

Neutron Star Mergers are attractive sites
But not efficient below [Fe/H]<-2.5

Need a r-process site at early times to account for MP Stars if "hot" bubble does not work.



He Shell r-process

Proposed in Epstein, Colgate and Haxton in 1988

Idea: $\nu + {}^4\mathrm{He} \to$ free neutrons captured by Fe $\to$ r-process

Neutrons formed by NC ν reaction

$${}^4\mathrm{He}(\nu, \nu n)^3\mathrm{He}(n, p)^3\mathrm{H}(^3\mathrm{H}, 2n)^4\mathrm{He}$$

$${}^4\mathrm{He}(\nu, \nu p)^3\mathrm{H}(^3\mathrm{H}, 2n)^4\mathrm{He}$$

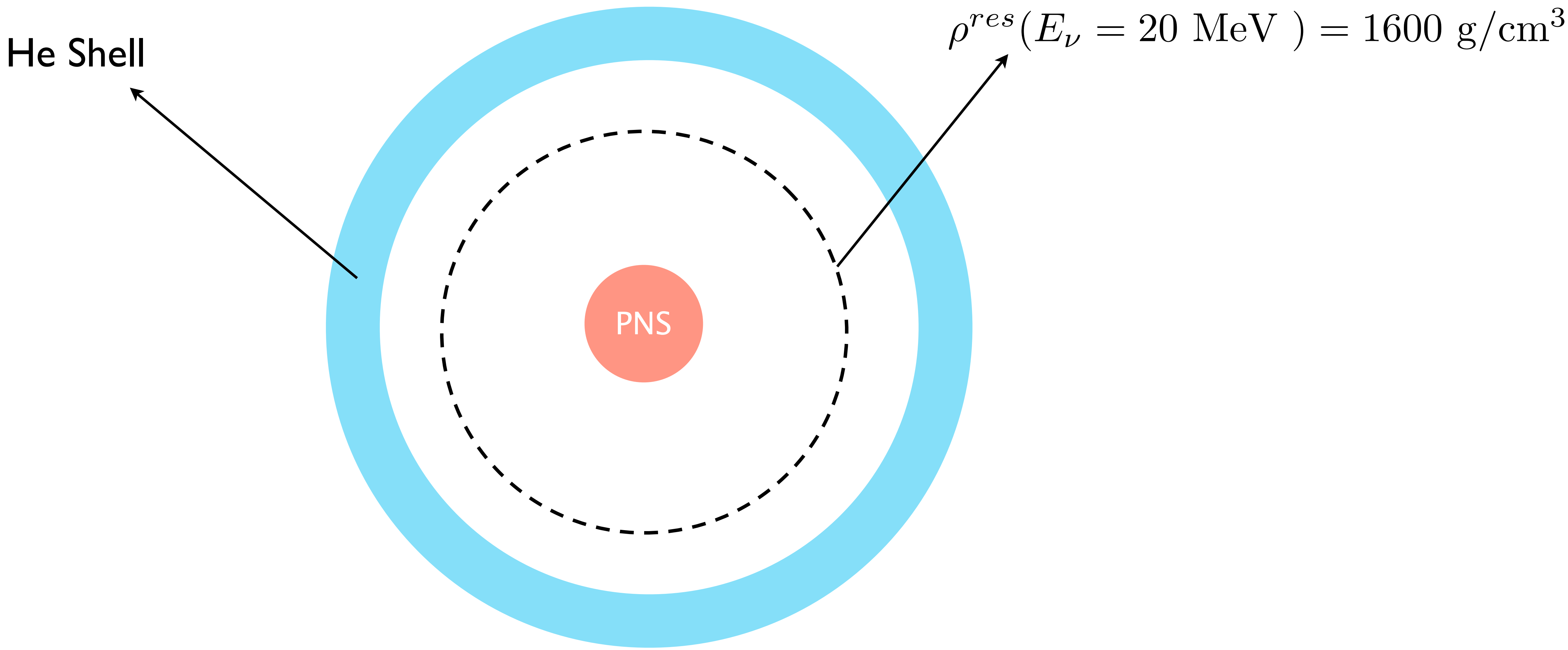
$$r = 10^9\mathrm{cm}, \rho = 3 \times 10^3\mathrm{g/cm}^3, T = 2 \times 10^8 \mathrm{~K}$$

Neutron Poison: ${}^{14}\mathrm{N}$

${}^{12}\mathrm{C}$ not considered, burning by shock

Can Neutrino oscillations help?
If yes, then CC reactions will make the difference

MSW Effect



$\nu_e \rightleftharpoons \nu_x$ (NH) ($T_{\nu_e} = 4$ MeV $\to 8$ MeV)

$\nu_e + {}^4\mathrm{He} \to {}^3\mathrm{He} + p + e^-$

$\lambda^{CC}_{\nu_e \alpha} \propto T^6_{\nu_e}$

$\bar{\nu}_e \rightleftharpoons \bar{\nu}_x$ (IH) ($T_{\bar{\nu}_e} = 5.33$ MeV $\to 8$ MeV)

$\bar{\nu}_e + {}^4\mathrm{He} \to {}^3\mathrm{H} + n + e^+$

$\lambda^{CC}_{\bar{\nu}_e \alpha} \propto T^6_{\bar{\nu}_e}$

Only IH can work!

He Shell r-process

Revised Scenario (2011)

Requirements:
- Low abundance of poison
- low shock temperature
- high n/s ratio

$11\text{-}75\ M_\odot,\ Z = 10^{-4} Z_\odot$ **(Woosley, Heger, and Weaver 2002)**

$r = 10^{10}$ cm, $\rho = 50\text{g/cm}^3, T = 9 \times 10^7$ K

$T_{\rm sh}^{\rm peak} = 2 - 4 \times 10^8$ K (no burning)

Neutrons from CC ν reactions

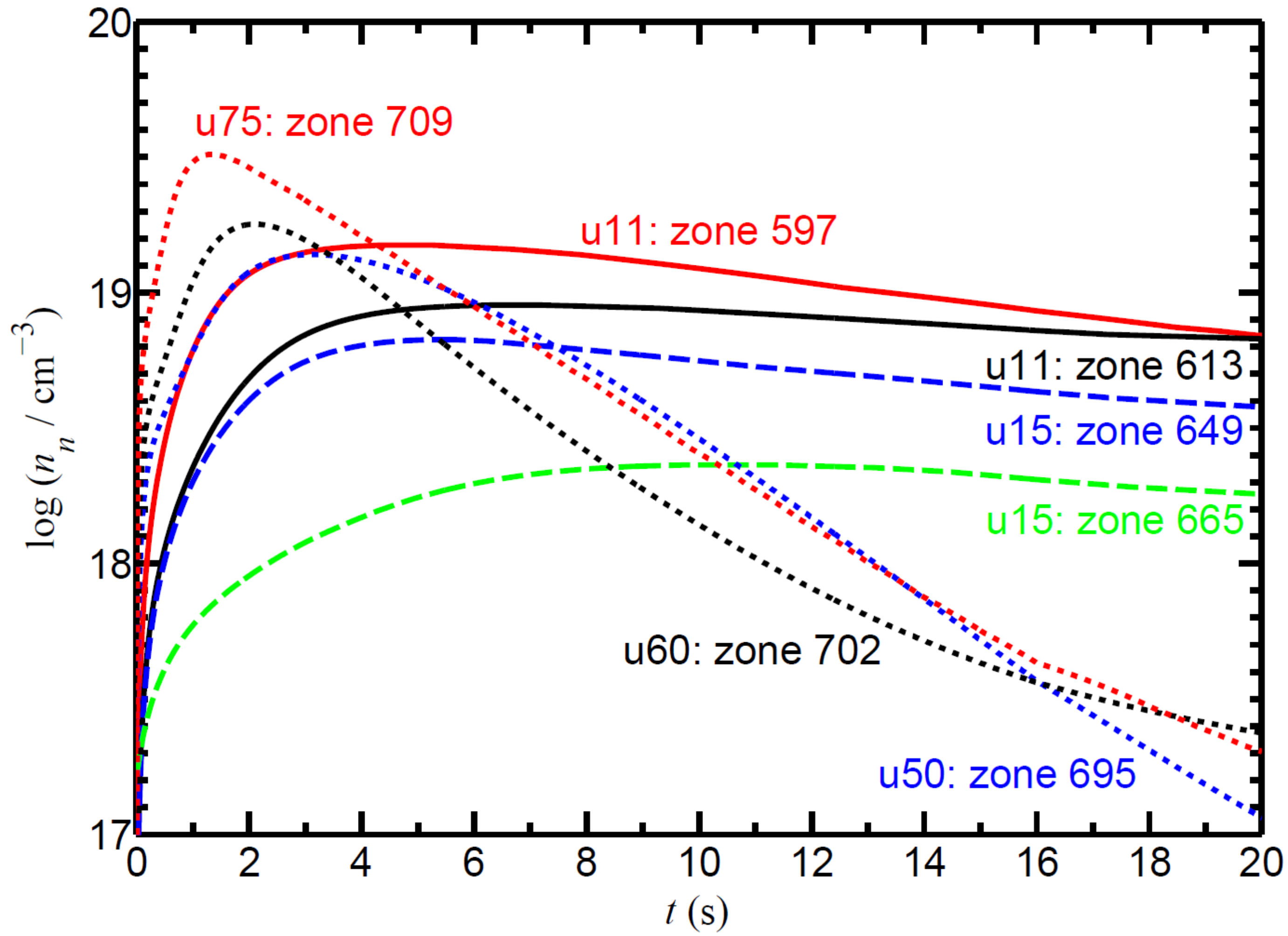
NC is inefficient as ^{3}H(^{3}H,2n)^{4}He does not work

$\tau_{\rm coll} \gg \tau_{\rm sh} \rightarrow$ Pre-shock is hydrostatic

$$T_{\nu_x} = 8 \text{ MeV},\ T_{\bar{\nu}_e} = 5.33 \text{ MeV},\ T_{\nu_e} = 4 \text{ MeV}$$

$$L_{\nu_x} = L_{\bar{\nu}_e} = L_{\nu_e} = \frac{E_B}{6\tau} e^{-t/\tau}, \tau = 3 \text{ s}$$

Pre-shock Hydrostatic Evolution



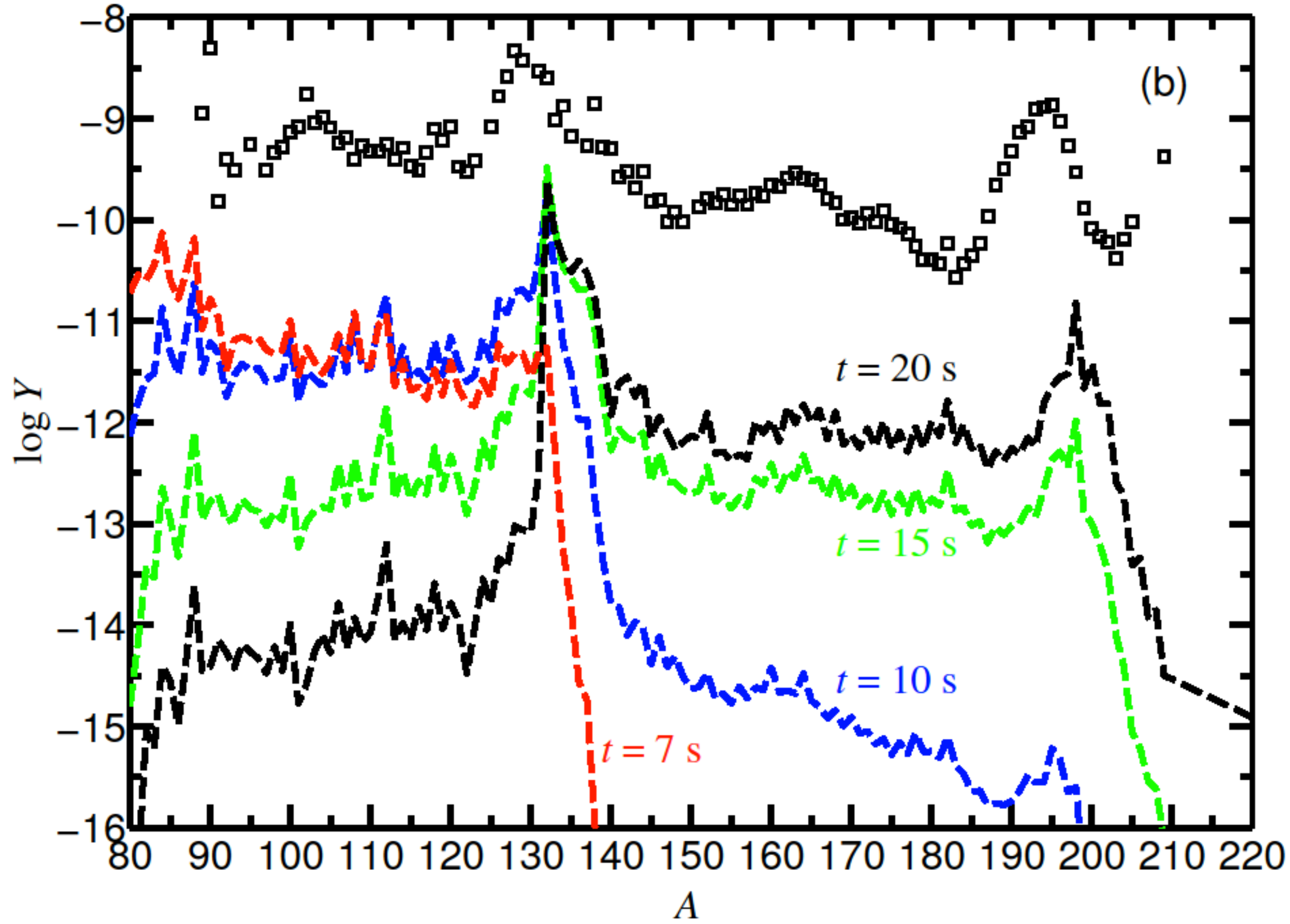
Outer He shell is hydrostatic before the arrival of shock

Modified a BBN Code to calculate neutron density

Constant neutron sink to account for poisons with A >16

Used neutron density in a bigger network (TORCH) for r-process

Pre-shock Hydrostatic Result

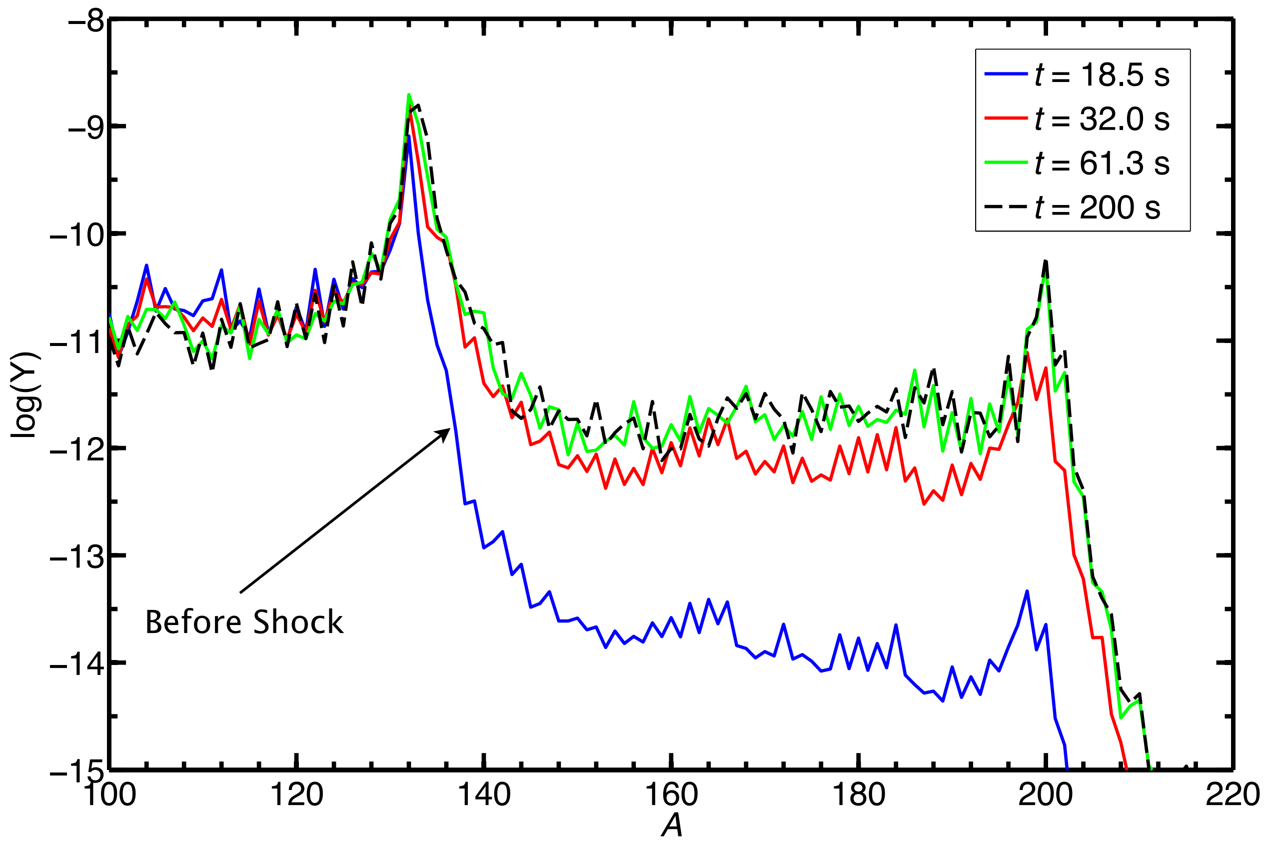


Model u11: zone 597

PB, W. Haxton & Y. -Z. Qian, PRL 106, 201104 (2011)

Hydrodynamic Evolution (KEPLER)

$E = 1 \times 10^{50}\text{ergs}$

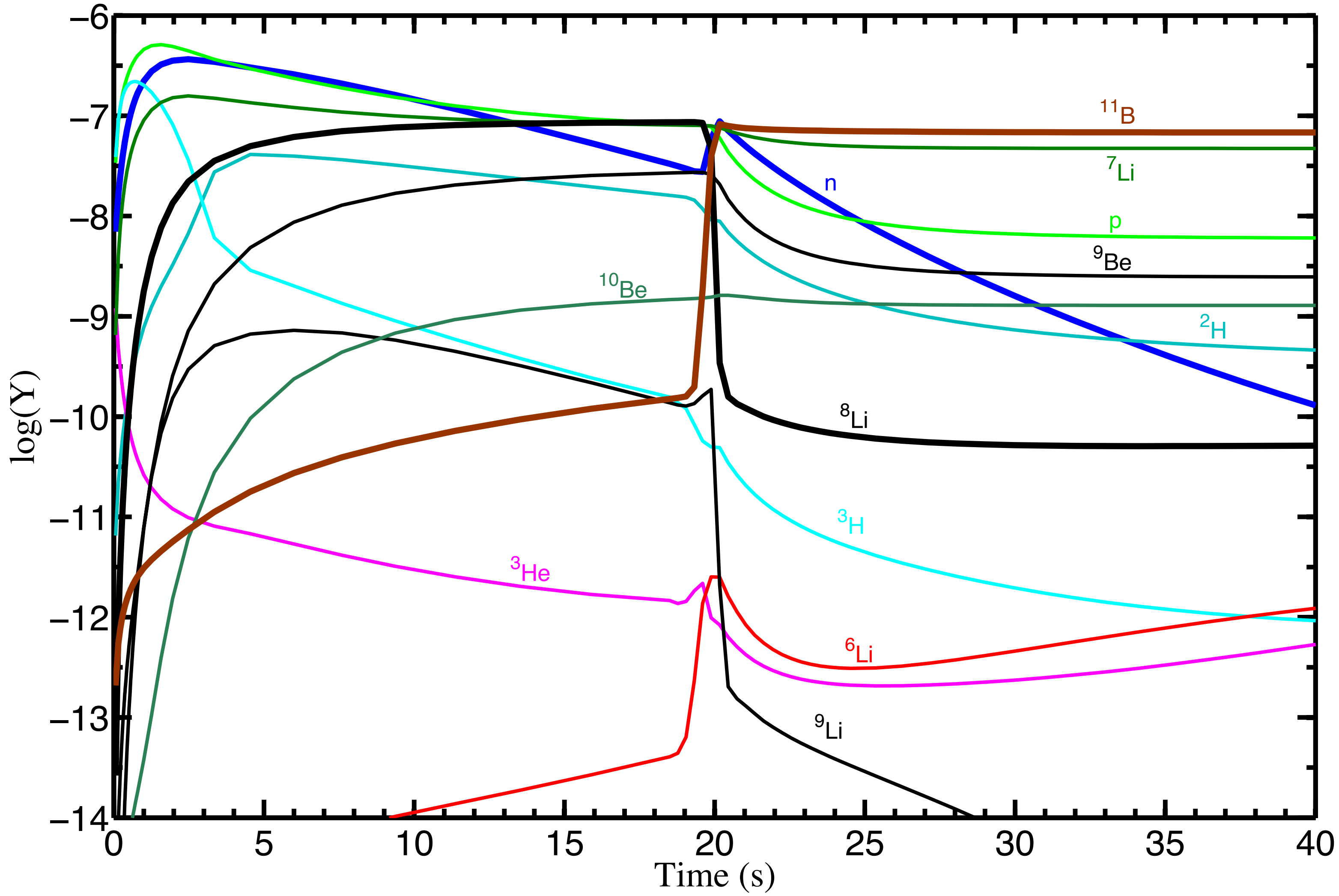


r-process takes longer than estimated before!

this is due to $^{8}\mathrm{Li}(n,\gamma)^{9}\mathrm{Li}$ reaction not included before

3rd r-process peak is still reached!

Effect of Shock

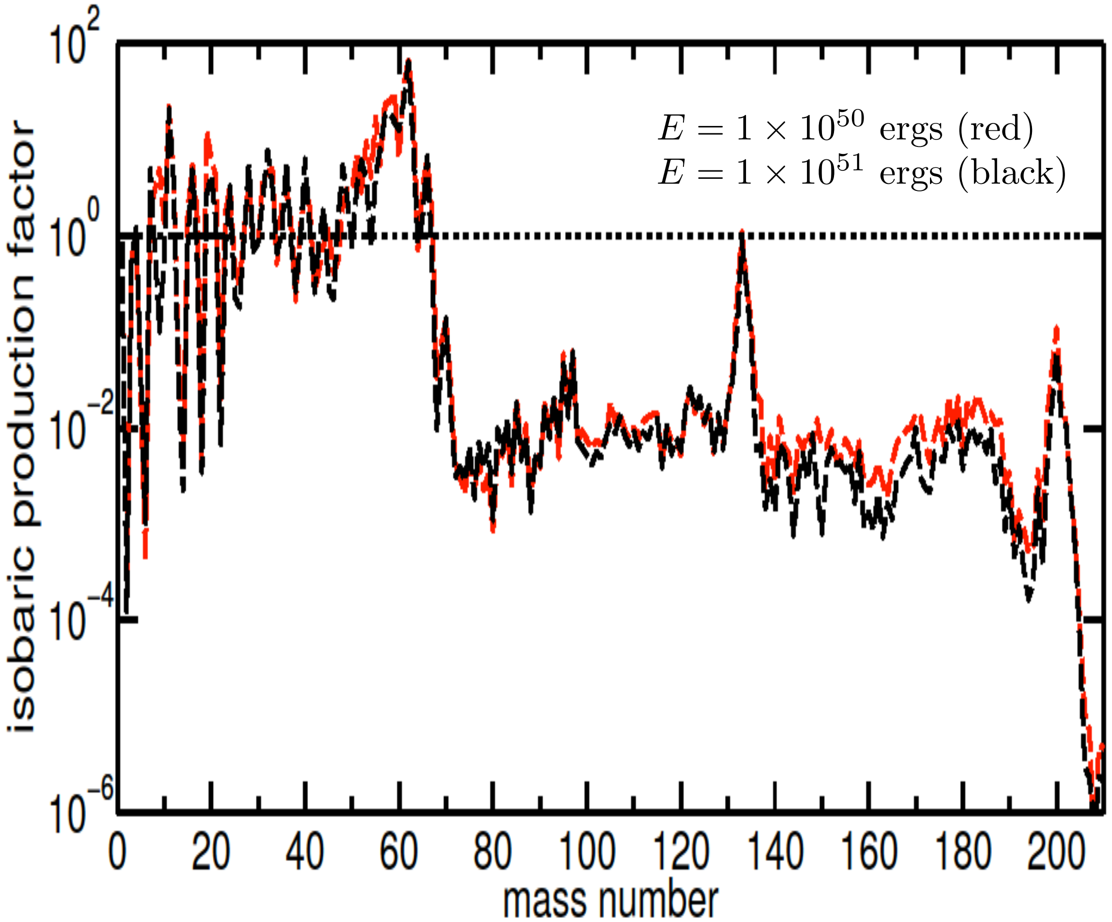


Some neutrons are recovered by $^{8}\mathrm{Li}(\alpha, \mathrm{n})^{11}\mathrm{B}$ due to shock heating

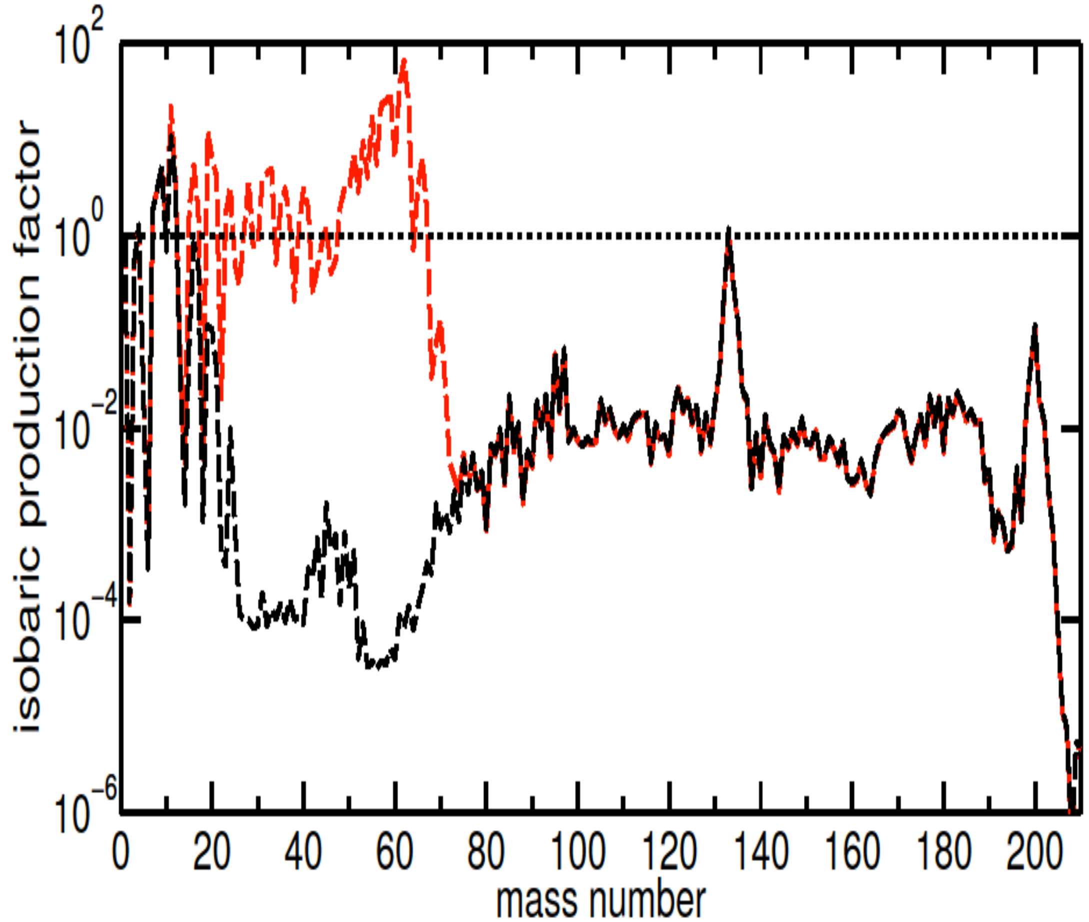
Allows r-process to reach the third peak.

Considerable amount of Be survives shock heating for low explosion energy!

Effect of Explosion Energy



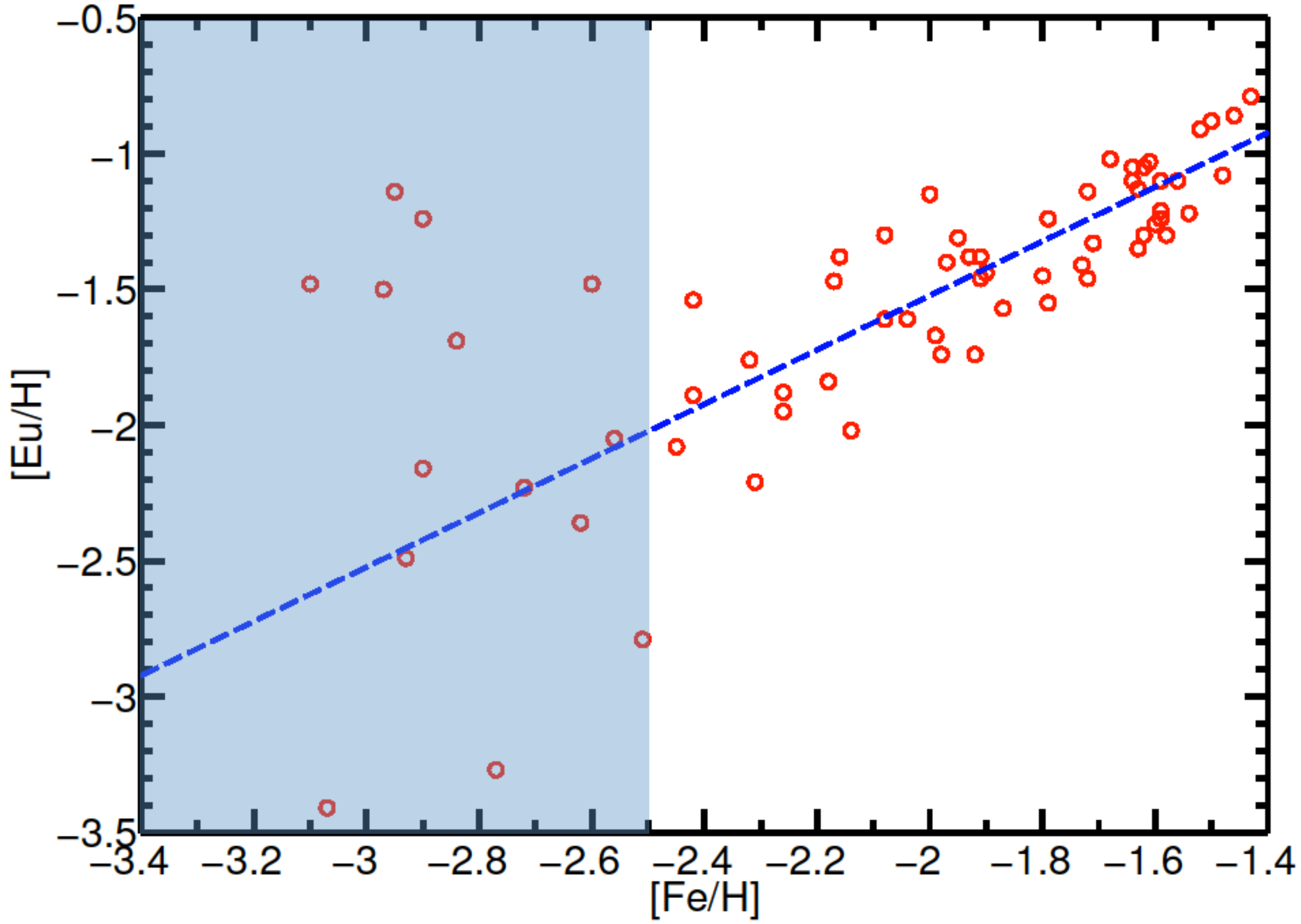
Abundance pattern not very sensitive to Explosion energy



Fallback for low explosion energy

Non-uniform Mixing?

- Large spread in Eu (r-element) in MP stars with [Fe/H]< -2.5
- r-process material can be mixed with different amount inner ejecta?



Roederer *et al.* ApJ 724, 975 (2010)

Summary

- Neutrino-induced r-process can occur in the He zones in metal-poor stars with [Fe/H] <~ -3.
- Neutrino oscillations, mass hierarchy, and the CC reaction on He play a critical role.
- Sensitive to neutrino parameters, shell but insensitive to explosion energy.
- The effect of shock is beneficial as it increases free neutron density.
- The r-process is long (about 60 s) and cold (about 10^8 K).
- This mechanism can be part of multiple-r-process explanation of Galactic chemistry.