Neutrino-Driven Nucleosynthesis in Metal-poor Stars

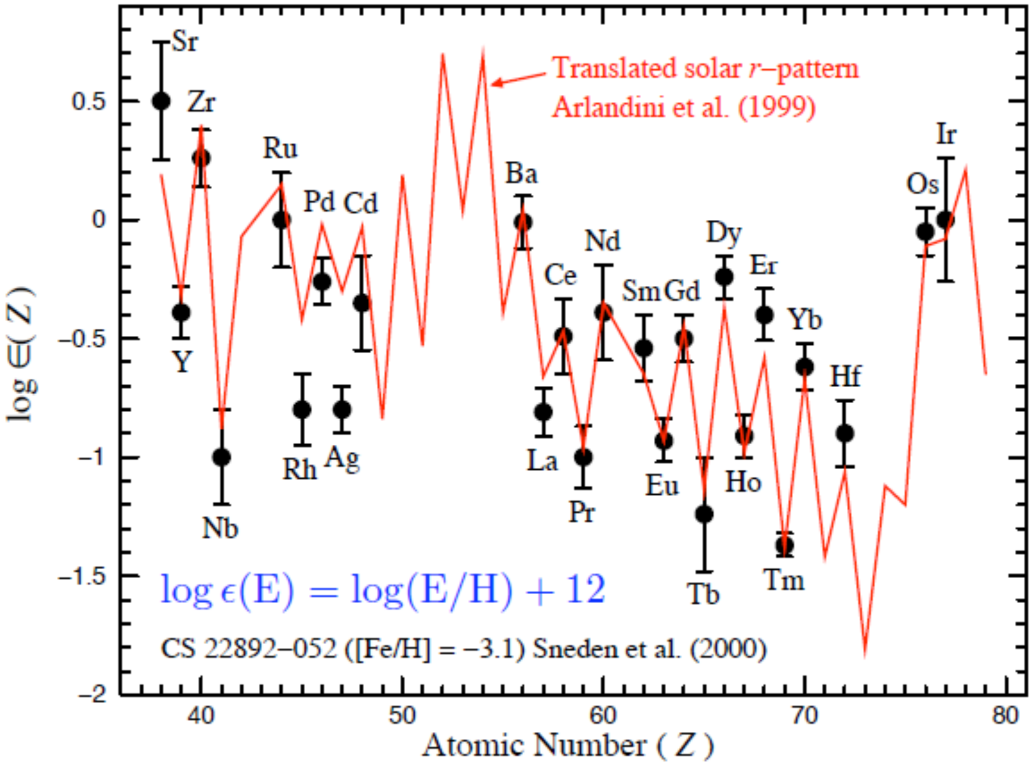
Projjwal Banerjee (UCB)
with
Wick Haxton, Yong-Zhong Qian & Alexander Heger

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

Neutrons formed by NC ν reaction

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

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

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

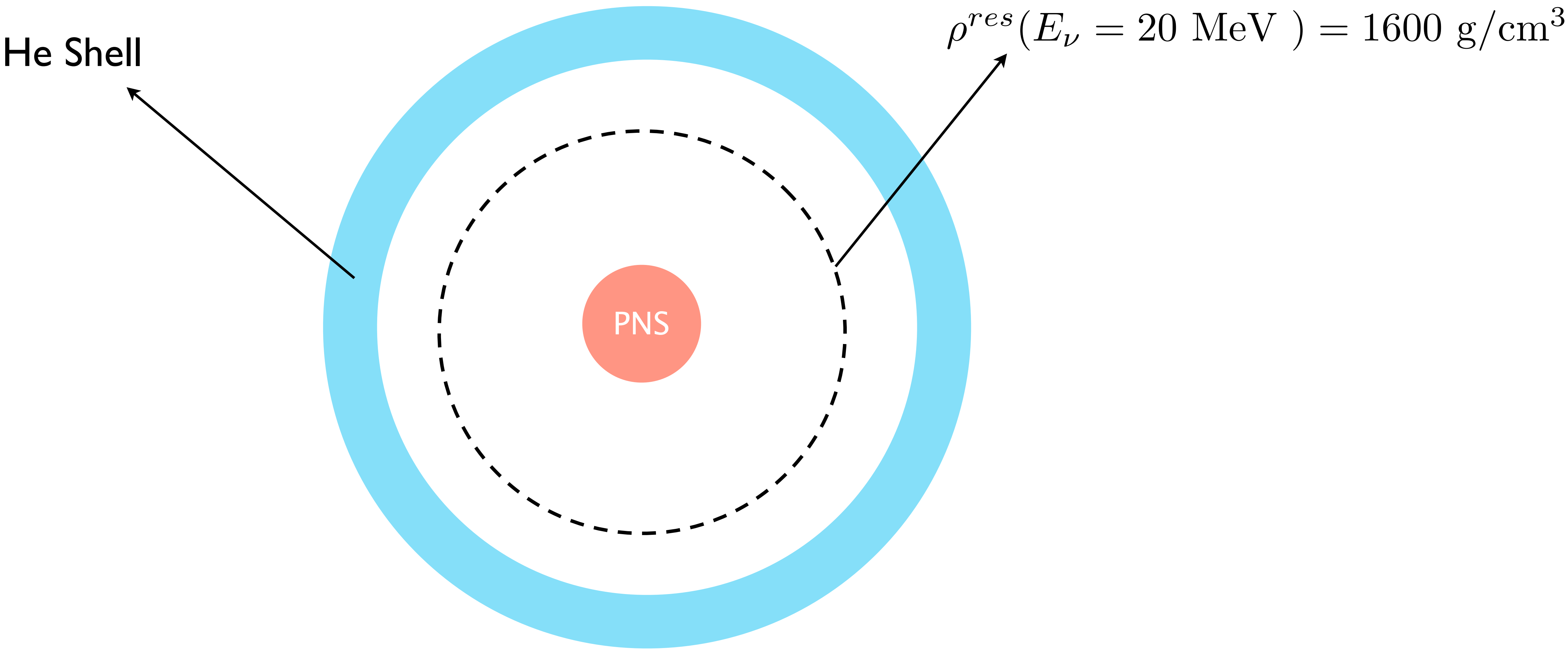
Neutron Poison: ${}^{14}\mathrm{N}$

${}^{12}\mathrm{C}$ 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) $(T_{\nu_e} = 4\ \mathrm{MeV} \to 8\ \mathrm{MeV})$

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

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

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

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

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

Only IH can work!

He Shell r-process

Revised Scenario (2011)

Requirements:

- Low abundance of poison
- low shock temperature
- high n/s ratio
- Beyond MSW resonance

$11\text{-}15\ M_\odot,\ Z = 10^{-4} Z_\odot$ **(Woosley, Heger, and Weaver 2002)**

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

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

Neutrons from CC ν reactions

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

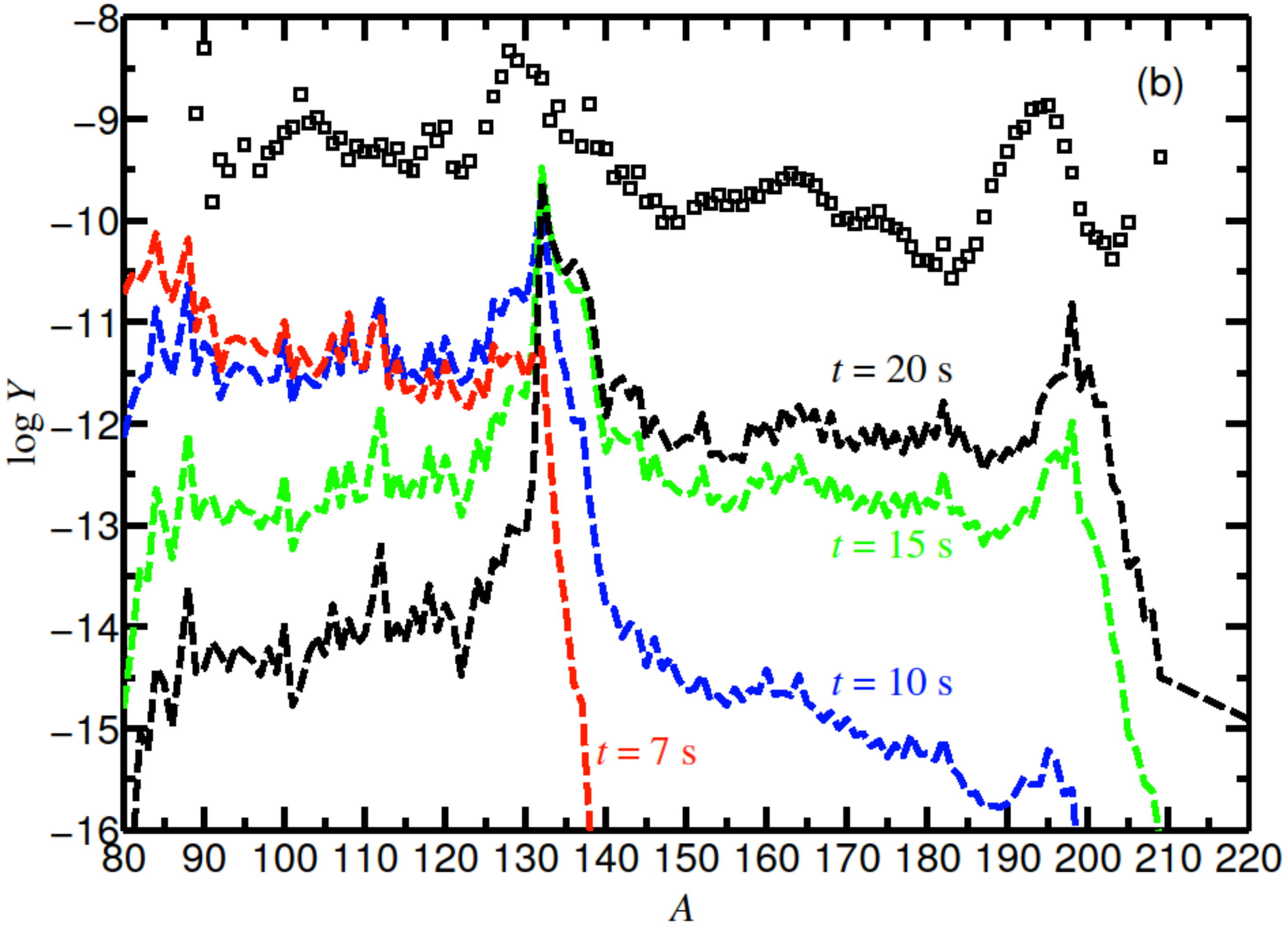
$\tau_{\mathrm{coll}} \gg \tau_{\mathrm{sh}} \rightarrow$ Pre-shock is hydrostatic

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

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

KEPLER code is used to calculate the nucleosynthesis

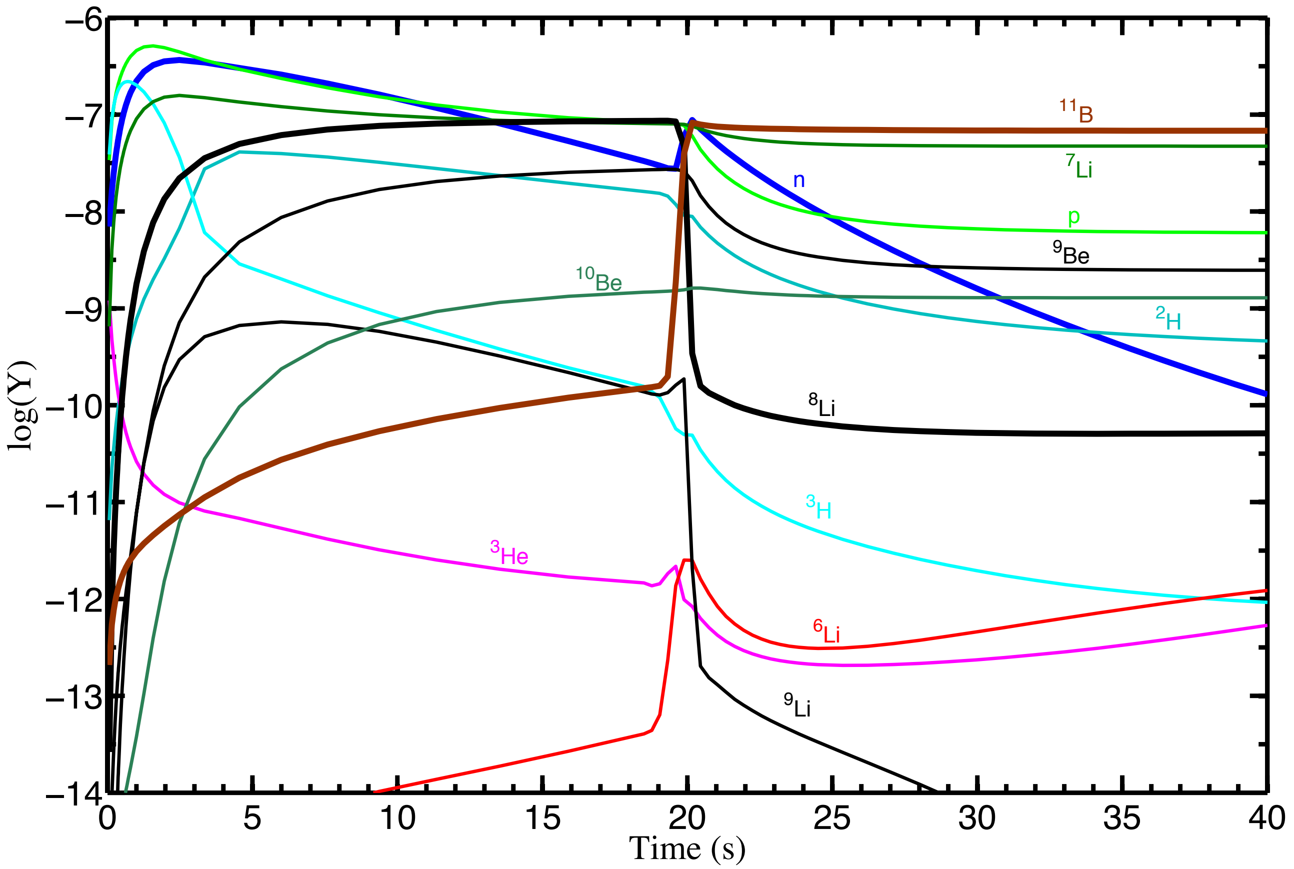
Pre-shock Hydrostatic Result



Model u11: zone 597

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

Effect of Shock



^{7}Li and ^{8}Li are the main poisons

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.

^{9}Be is produced via neutron capture on ^{7}Li

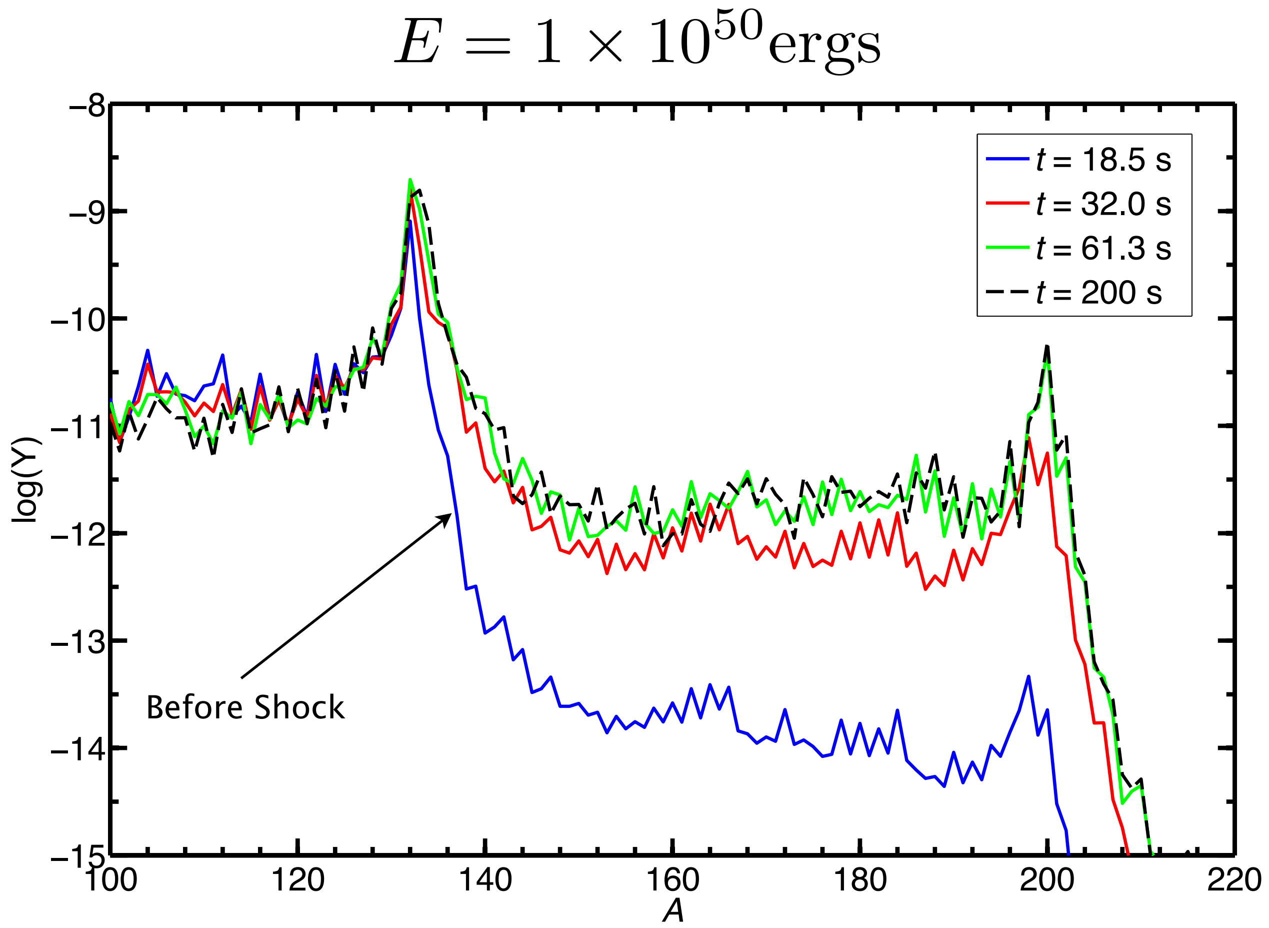
to produce ^{9}Li followed by β-decay.

^{9}Be survives shock for low explosion energies

Be is destroyed via $^{9}\mathrm{Be}(p, {}^{4}\mathrm{He})^{6}\mathrm{Li}$

β-decay of ^{8}Li hinders ^{9}Be production

Hydrodynamic Evolution (KEPLER)


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

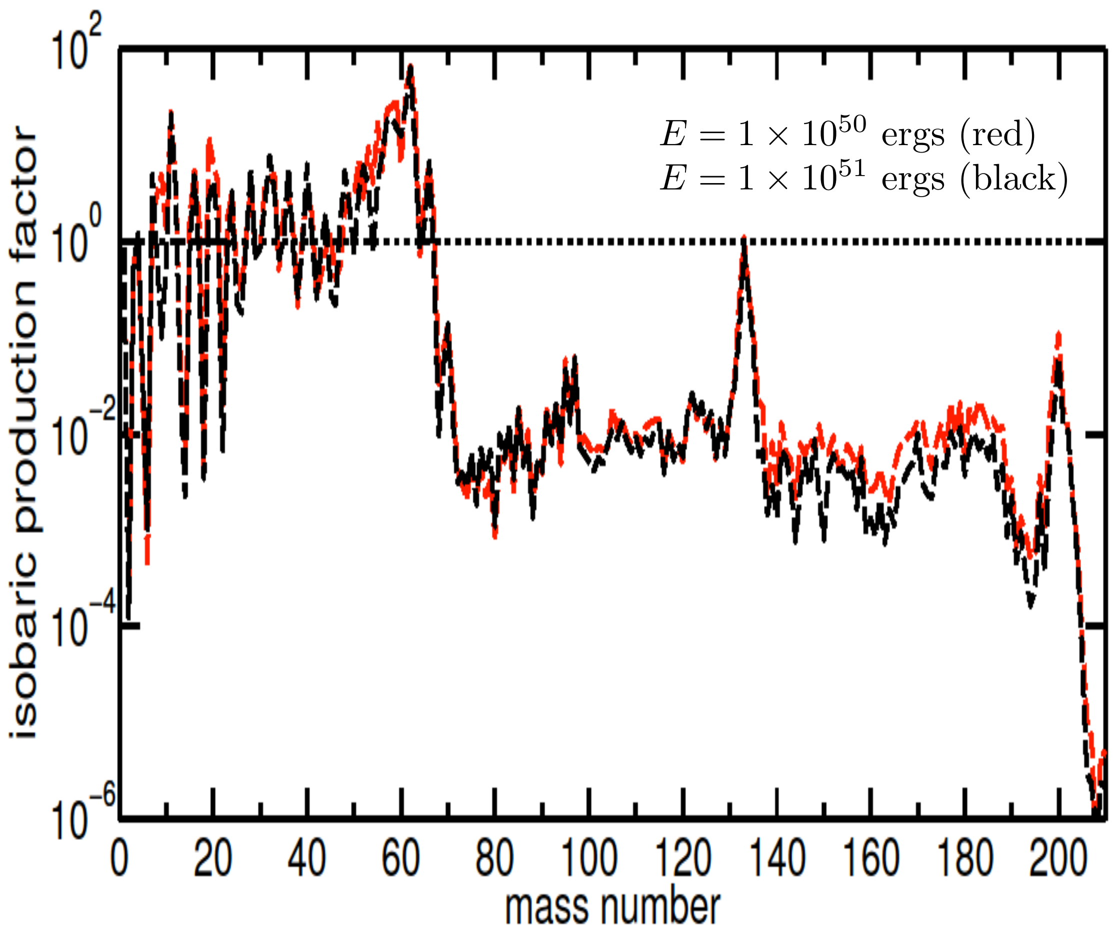
$(n, \gamma) - \beta$-decay equillibrium

r-process takes longer than estimated before!

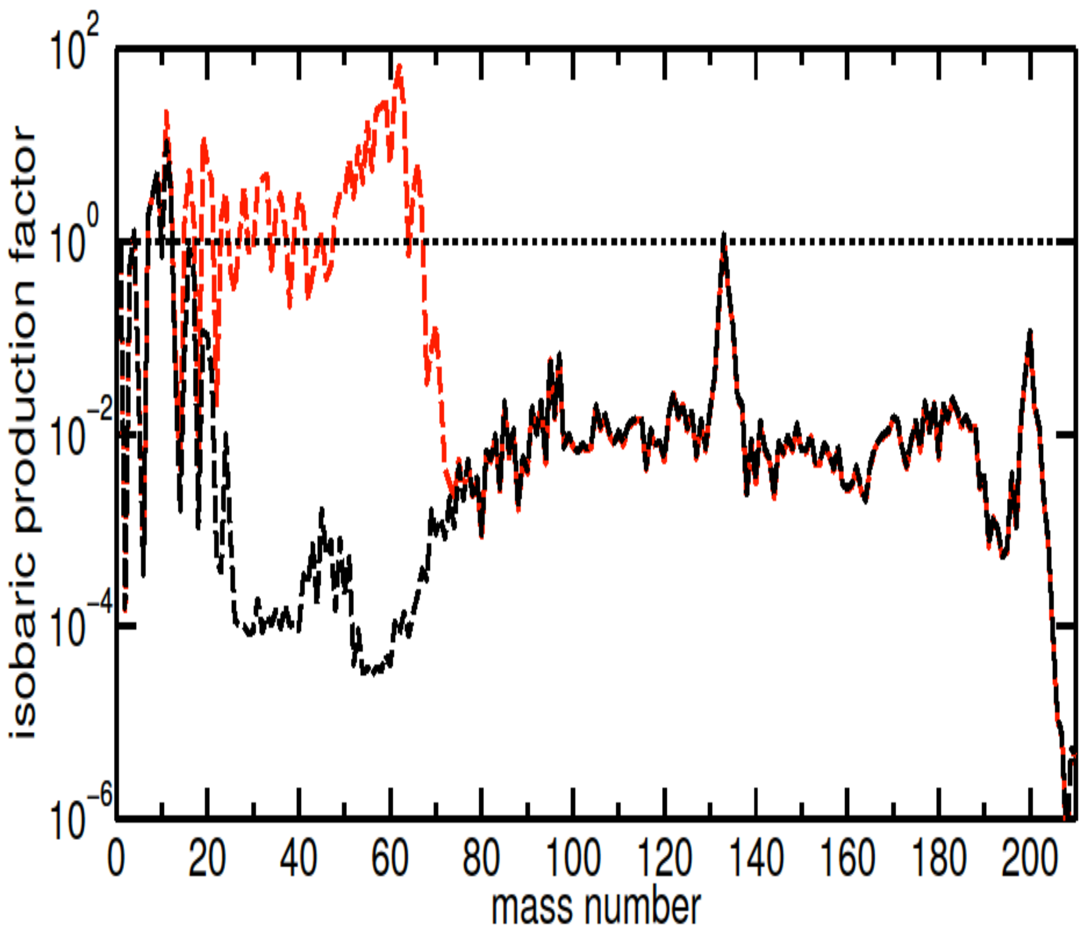
this is due to $^{8}\text{Li}(n, \gamma)^{9}\text{Li}$ reaction not included before

3rd r-process peak is still reached but takes ~60 s. Hard spectra needed.

Effect of Explosion Energy



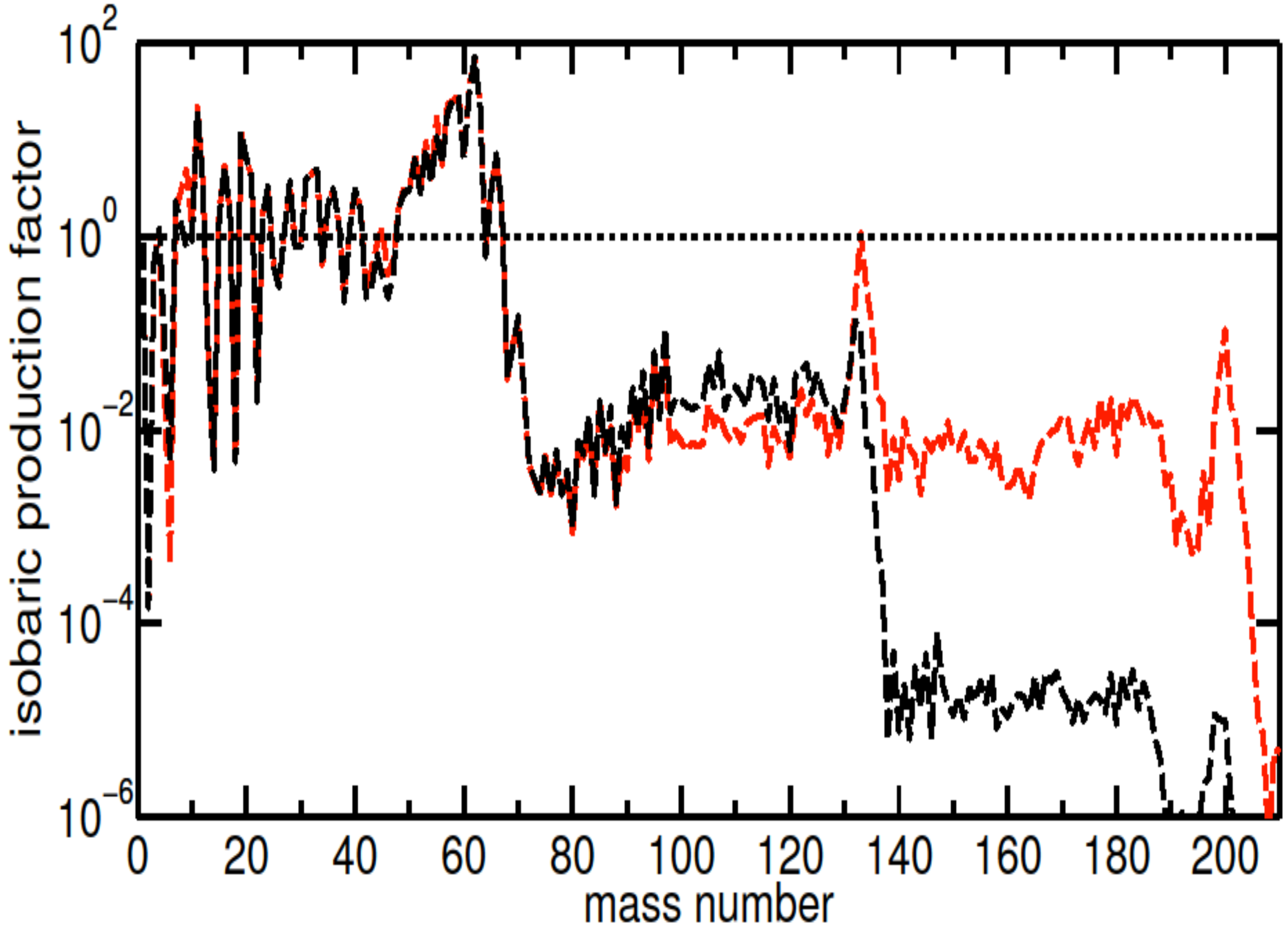
Abundance pattern not very sensitive to Explosion energy



Fallback for low explosion energy

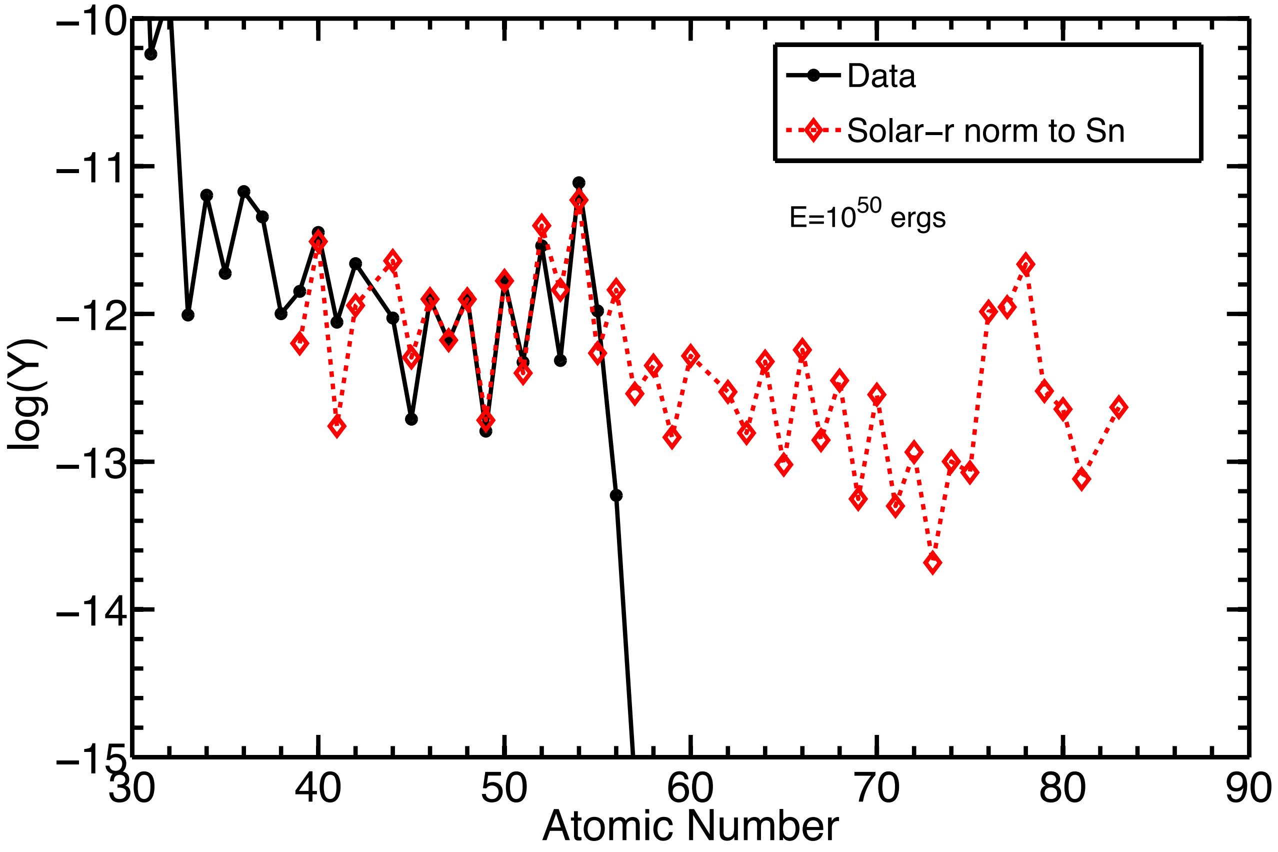
He and H shell is ejected for low energy

Effect of Initial Composition

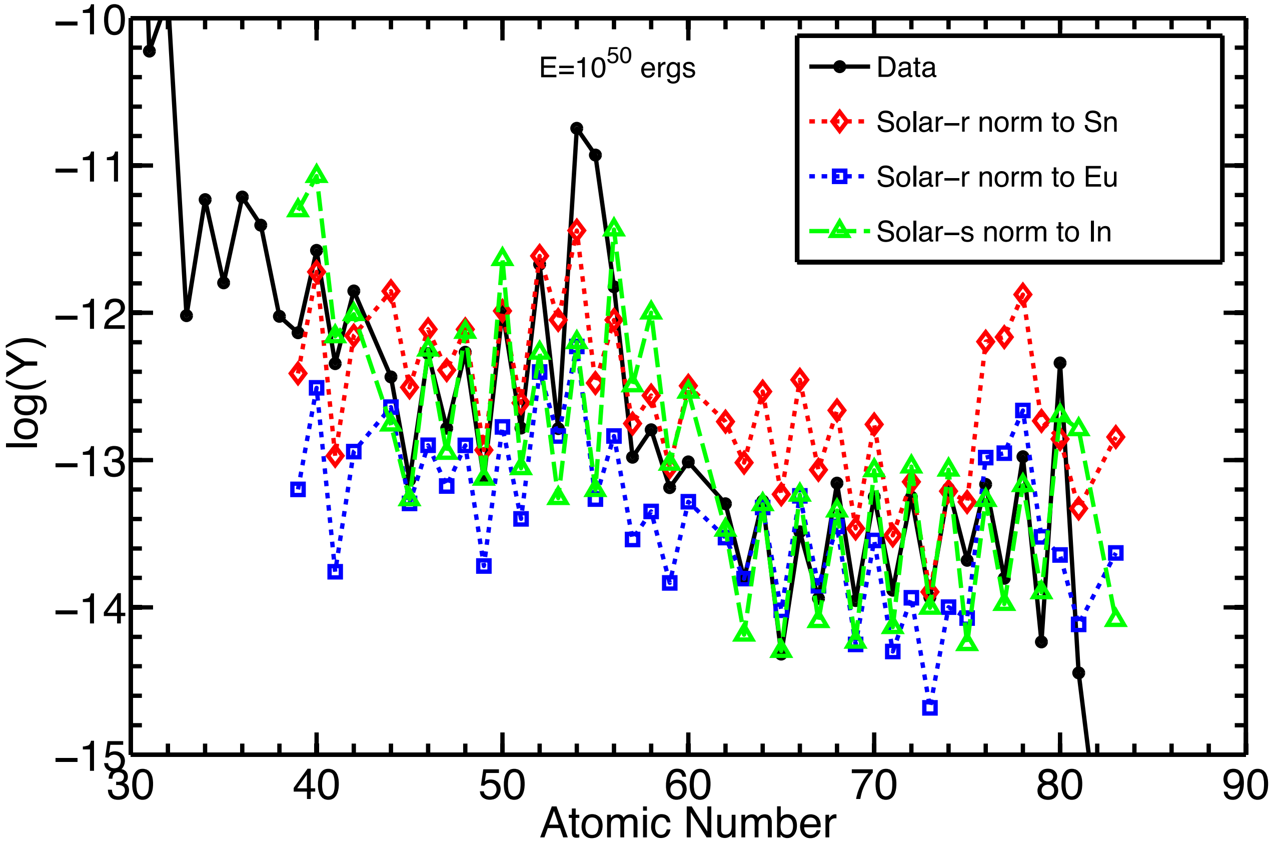


New u11 model with $E = 1 \times 10^{50}$ ergs. New Poisons: ^{28}Si, ^{32}S

Elemental Abundance



new u11 model: Fits reasonably well to Solar r-pattern



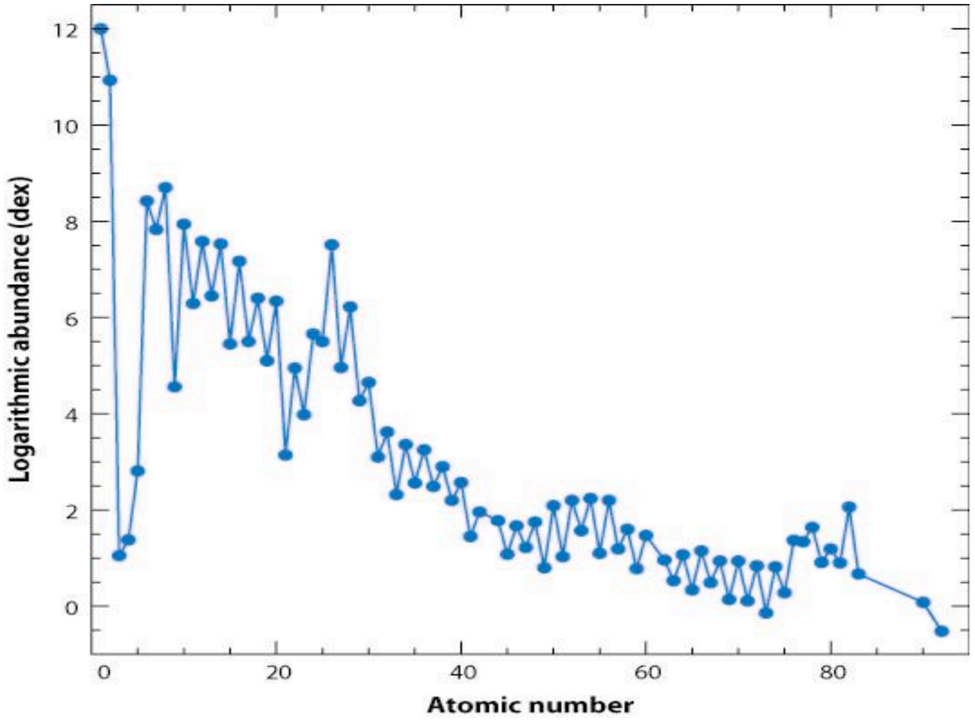
2002 u11 model: Pattern is somewhere in between Solar r and s-pattern

Cannot account for the robust r-process pattern at low metallicities for Z>56

Might still play an important role in MP star abundance (eg. “r+s” stars)

Origin of Light Elements Li-Be-B

- Not made efficiently in stars as they are fragile.
- Li- BBN, Galactic Cosmic Rays (GCR), AGB stars/ Novae
- Be- Only from GCR
- B- GCR, nu-process in SNe



Asplund M, et al. 2009.
Annu. Rev. Astron. Astrophys. 47:481–522

Light Elements from GCR

$$\frac{dY_L}{dt} = \phi^{GCR}_{p,\alpha}\sigma_{p\alpha+CNO}Y^{ISM}_{CNO} + \phi^{GCR}_{CNO}\sigma_{p\alpha+CNO}Y^{ISM}_{p,\alpha} + \phi^{GCR}_{\alpha}\sigma_{\alpha+\alpha}Y^{ISM}_{\alpha}$$

Always produces secondary LiBeB

produces secondary LiBeB if $Y^{GCR}_{CNO} \sim Y^{ISM}_{CNO}$

produces primary LiBeB if $Y^{CNO}_{GCR} \sim \text{const}$

Always produces primary Li

Standard GCR Scenario:

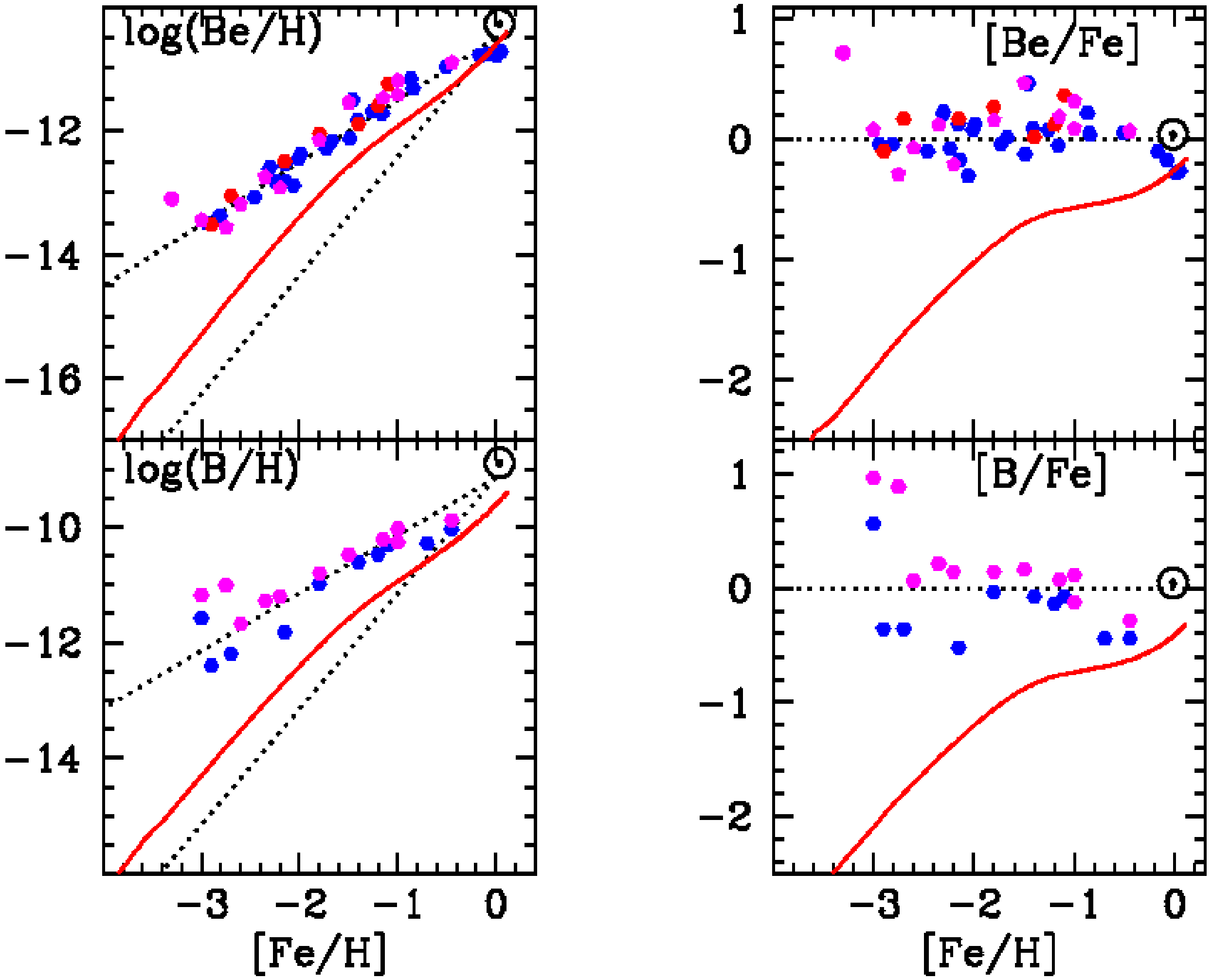
$$\phi^{GCR}(t) \propto Y^{GCR}(t)\frac{dN_{SN}}{dt}$$

$$Y^{GCR}_{p,\alpha} \sim Y^{BBN}_{p,\alpha} \sim \text{const}$$

$$Y^{GCR}_{CNO} \sim Y^{ISM}_{CNO} \propto N_{SN}(t)$$

Standard scenario can only produce secondary Be, B

Evolution of Be and B



Prantzos

Evolution with Standard GCR Scenario

Need a primary source for Be (and B)

Primary Be and B

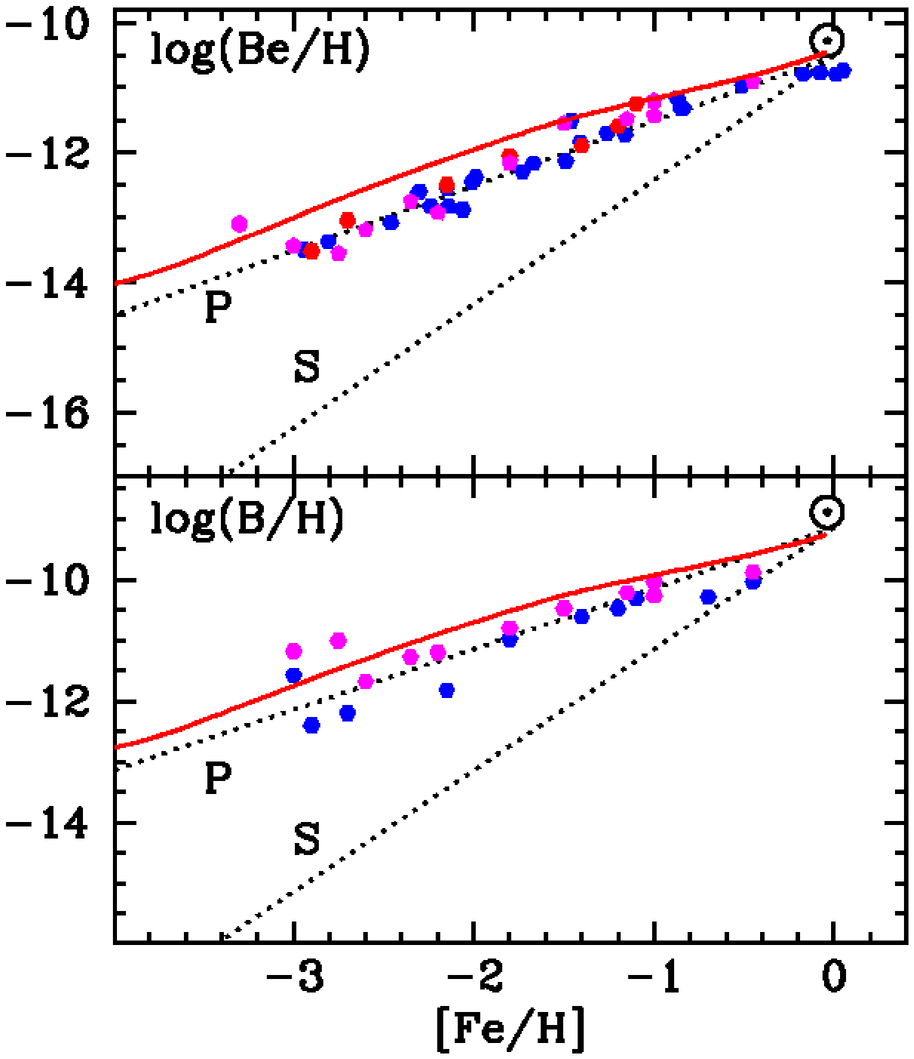
Solution for Primary Be and B by GCR: $Y^{GCR}_{CNO}(t) \sim \text{const}$

Problem: What kind of source can give $Y^{GCR}_{CNO} \sim \text{const?}$

Such a GCR source is a still a matter of debate

nu-process can account for primary B production

^{11}B produced via $\nu(^{12}\text{C}, \nu p)^{11}\text{B}$ and $\nu(^{12}\text{C}, \nu n)^{11}\text{C}$



Prantzos, 2007

Neutrino-induced Be in the Early Galaxy

We consider two different scenarios: $8.1 M_\odot, Z = 10^{-4} Z_\odot$ (Heger, 2011)

11-15 $M_\odot$, $Z = 10^{-4} Z_\odot$ (Already Discussed)

We use a FD neutrino spectra with a soft $(T_{\nu_e}, T_{\bar{\nu}_e}, T_{nu_x} = 3, 4, 6 \text{ MeV})$ and a hard $(T_{\nu_e}, T_{\bar{\nu}_e}, T_{nu_x} = 4, 5.33, 8 \text{ MeV})$ spectra

Oscillation scenarios: Complete $\bar{\nu}_e \rightleftharpoons \bar{\nu}_x$, and no oscillations.

Low Mass CCSN

Inner ejected zone: Initial Composition: X(^{16}O)$\approx$ 0.41, X(^{20}Ne)$\approx$ 0.48, X(^{24}Mg)$\approx$ 0.1

$T \approx 1.8 \times 10^9$ K, $\rho \approx 8 \times 10^5$ g/cc, $r \approx 1.7 \times 10^8$ cm

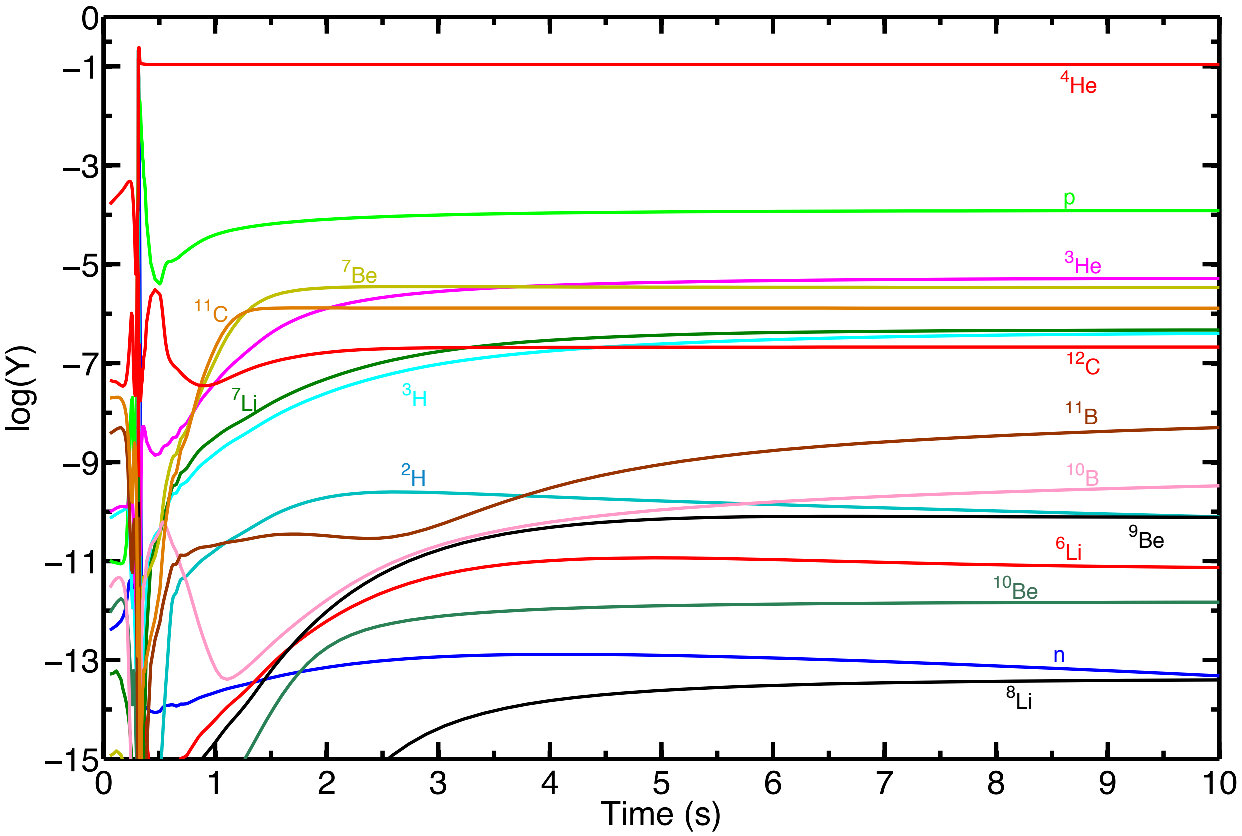
$T_{sh}^{peak} \approx 1.1 \times 10^{10}$ K, $\rho_{sh}^{peak} \approx 6 \times 10^7$ g/cc

Outer ejected zone: Initial Composition: X(^{4}He)$\approx$ 0.95, X(^{12}C)$\approx$ 0.04

$T \approx 2.2 \times 10^8$ K, $\rho \approx 2.8 \times 10^2$ g/cc, $r \approx 1.6 \times 10^9$ cm

$T_{sh}^{peak} \approx 8 \times 10^8$ K, $\rho_{sh}^{peak} \approx 1 \times 10^3$ g/cc

Be Production in CCSN



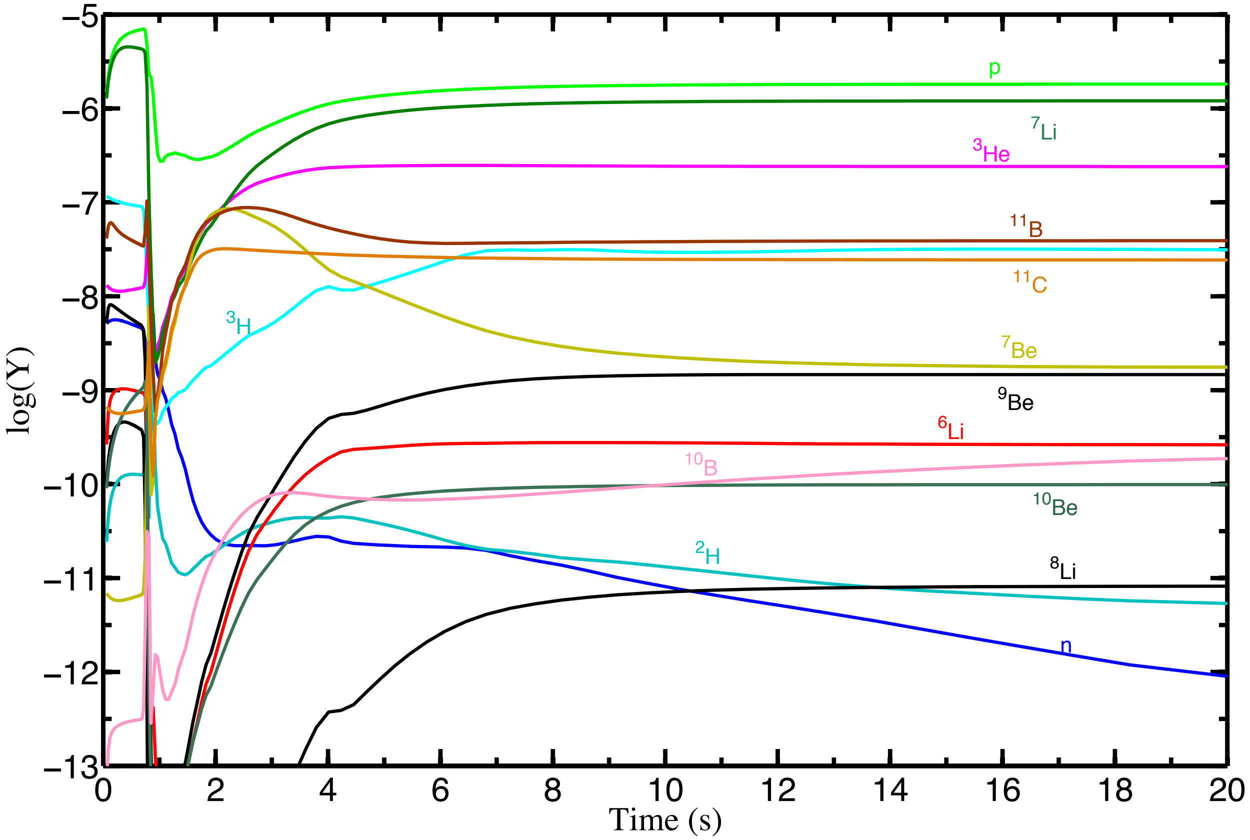
Material is dissociated into free nucleons due to shock.

Reassembles into He and Fe group elements.

Neutrino interaction on He gives Be.

Only contributes to about 1% of total Be production.

^{9}Be produced via ^{4}He(^{3}H$,\gamma)^{7}$Li(^{3}H$,n)^{9}$Be



Bulk material such as He remains unchanged as the shock temperature is low.

Other light elements are dissociated and re-assembled.

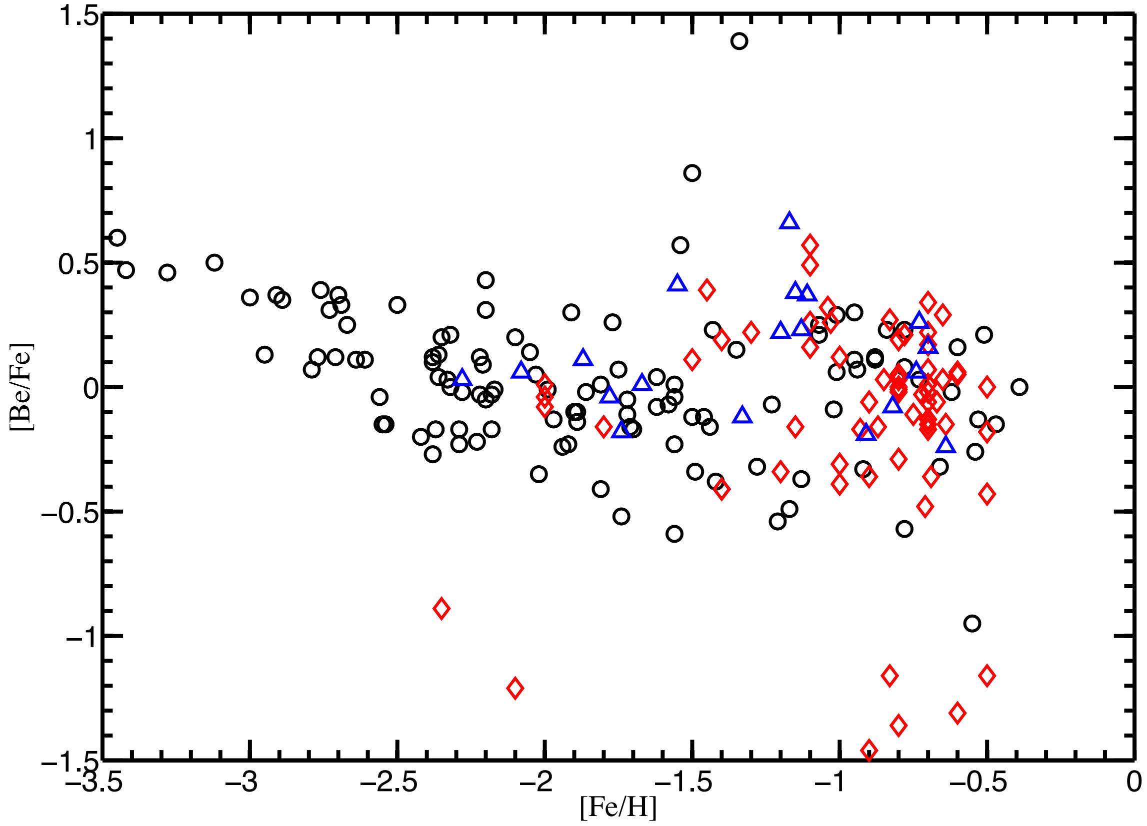
Neutrino interaction on He gives Be.

Accounts for 99% of the total Be production

Fast expansion is the key

^{9}Be produced when $T \lesssim 2 \times 10^{8}$ K

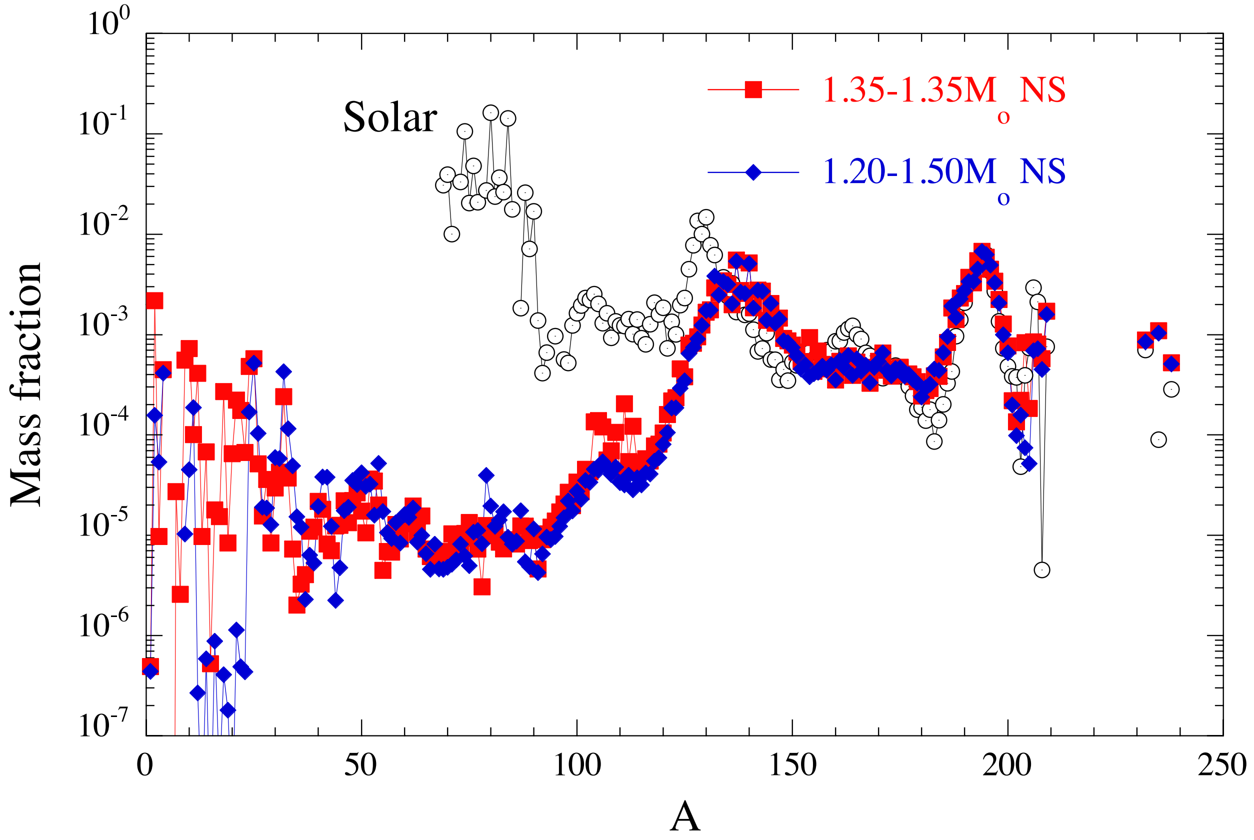
Results: Be Yields

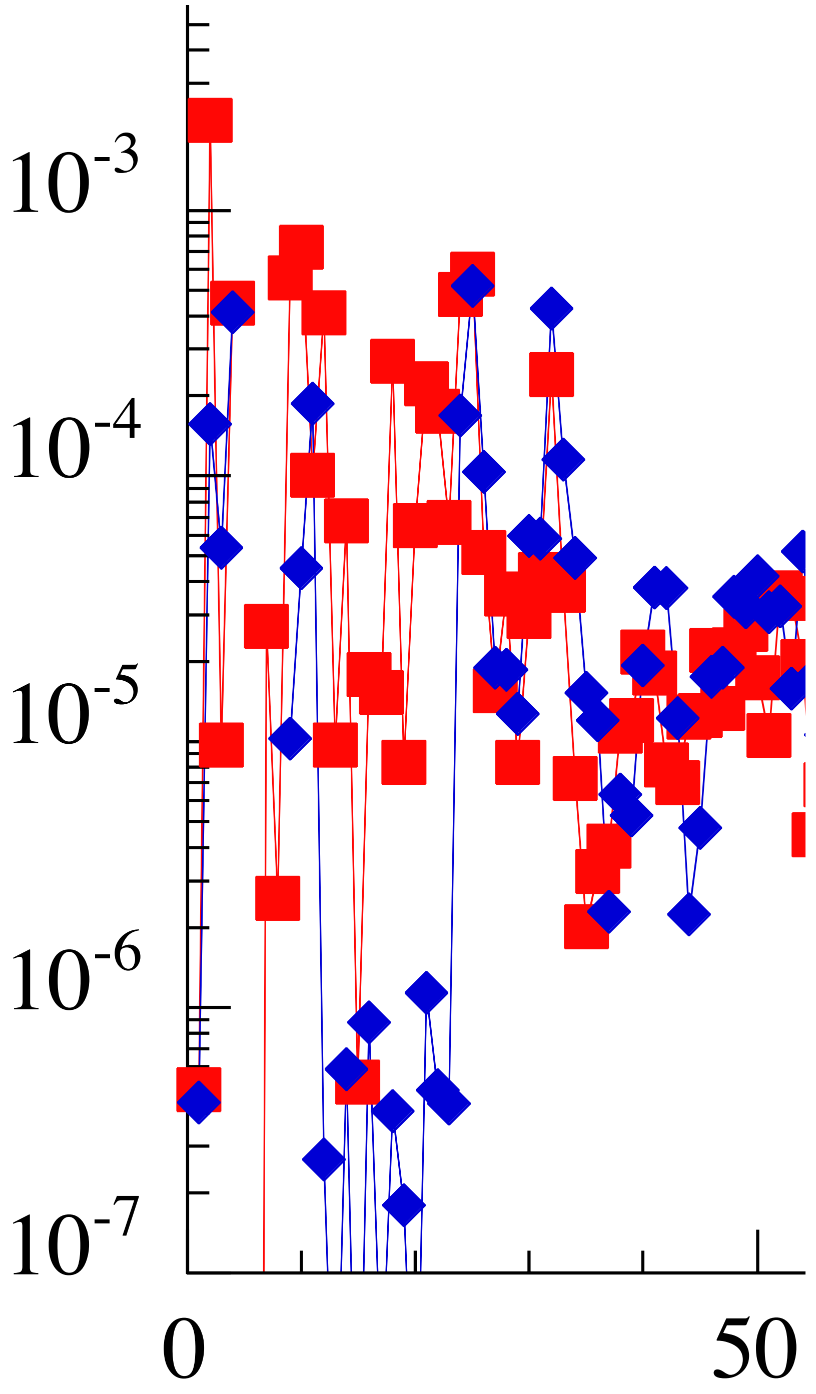


model	$M_{\rm Be}$ $(M_\odot)$	[Be/Fe]
u8.1$\overline{\rm H}$.1	2.0×10^{-10}	-0.01
u8.1$\overline{\rm H}$.3	2.6×10^{-10}	0.18
u8.1H.1	1.2×10^{-10}	-0.24
u8.1$\overline{\rm S}$.1	5.0×10^{-11}	-0.61
u8.1S.1	2.55×10^{-11}	-0.90
u11$\overline{\rm H}$.1	1.4×10^{-9}	-0.79
u11*$\overline{\rm H}$.1	9.1×10^{-9}	0.01
u11*$\overline{\rm H}$.3	9.8×10^{-10}	-1.0
u15$\overline{\rm H}$.1	5.2×10^{-10}	-0.99
u15*$\overline{\rm H}$.1	2.9×10^{-9}	-0.24
u15*$\overline{\rm H}$.3	7.2×10^{-10}	-0.87

Boesgaard 2011, Smiljanic 2009, Tan 2009

Other Non-GCR Sources of Be?





Goriely, Bauswein & Janka (2011)

$1.35 - 1.35 M_\odot$ NS merger

$X(^9\mathrm{Be}) \sim 5 \times 10^{-4}, X(^9\mathrm{Eu}) \sim 5 \times 10^{-4}, X(^9\mathrm{Be}) \sim 5 \times 10^{-4}$

Be/Eu ~ 8 comparable to $(\mathrm{Be/Eu})_\odot \sim 7.76$

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 and initial metallicity 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).

- Elemental abundance pattern is in between solar r and s pattern. Could possibly help in explaining abundance pattern of so called "r+s" stars?

- This mechanism can be part of multiple r-process explanation of Galactic chemistry.

Summary

- Two new mechanisms to produce Be was discussed.
- First mechanism works in low mass SN and is independent of metallicity. Less sensitive to neutrino parameters and explosion energy.
- The second mechanism is tied to the He shell r-process and works only at [Fe/H] <~ -3 with a hard spectra and low explosion energy.
- Other mechanisms such as NSM can contribute to primary Be production.