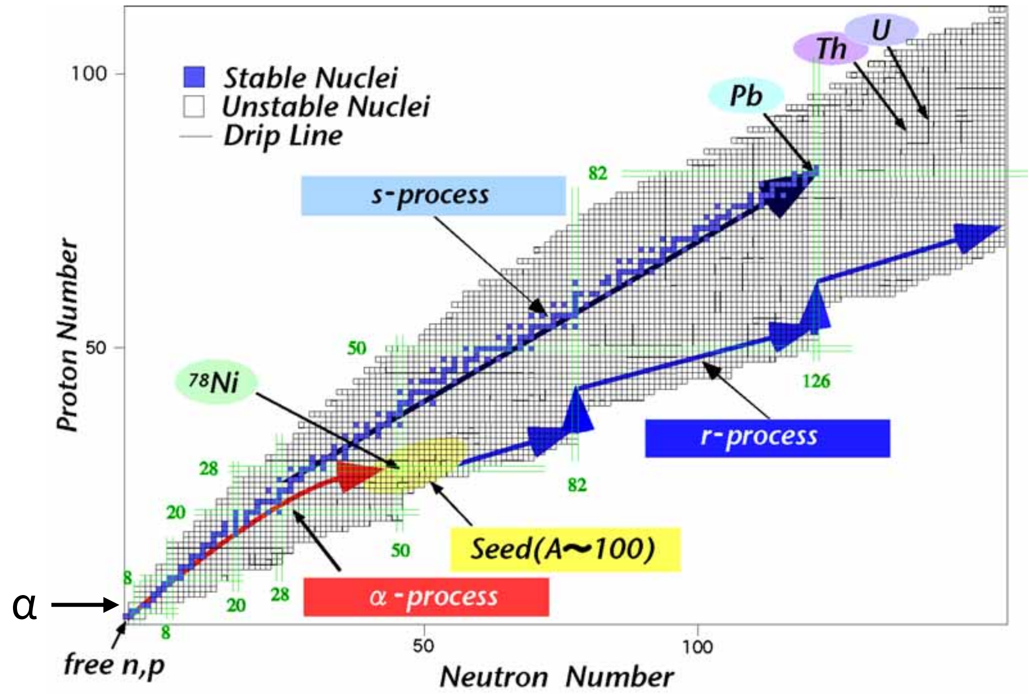
Neutrino Effects before, during, and after the Freezeout of the r-Process

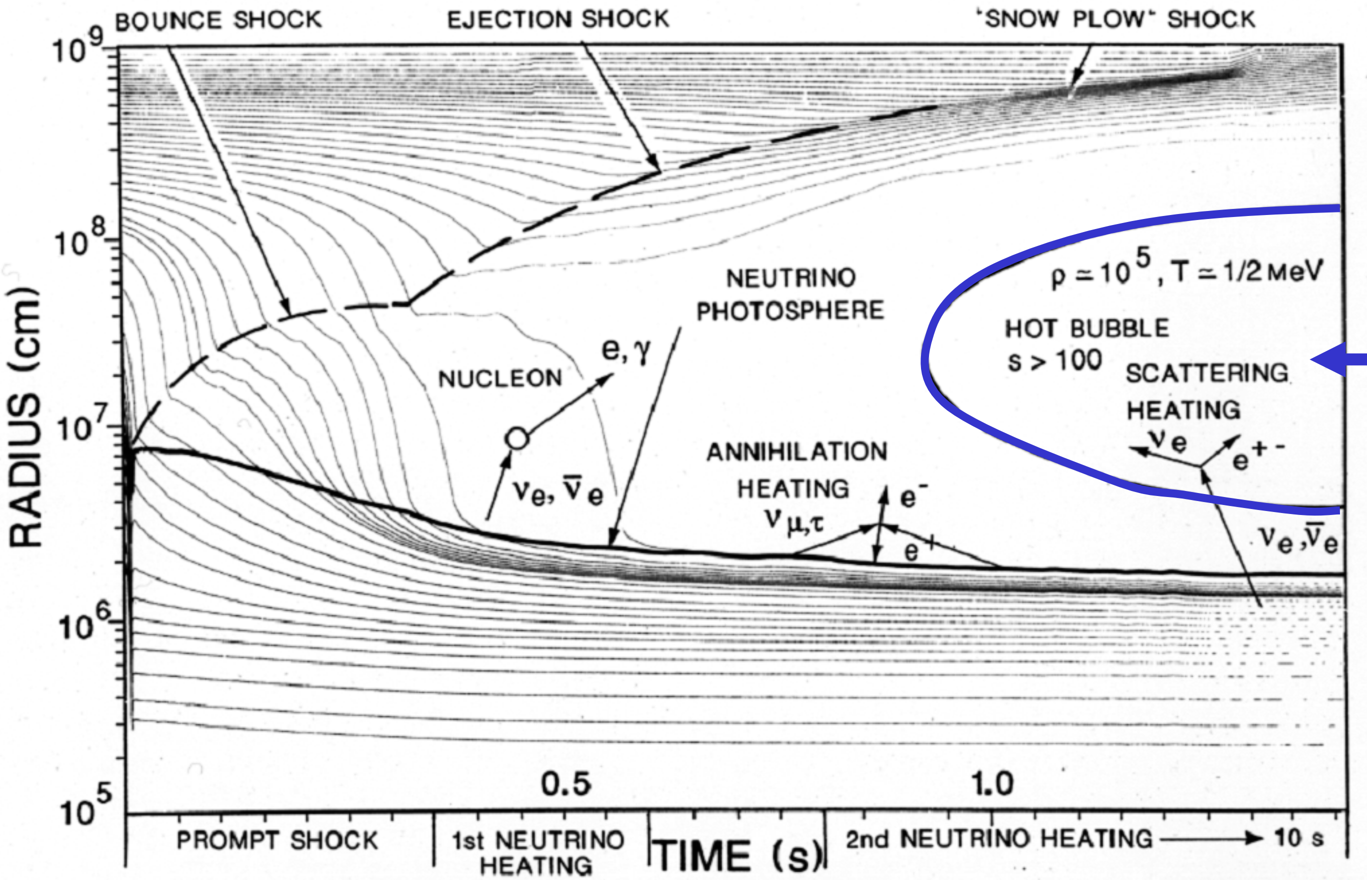


Mariko Terasawa (CNS),

K. Langanke, T. Kajino, G. J. Mathews

Neutrino-Driven Wind Model

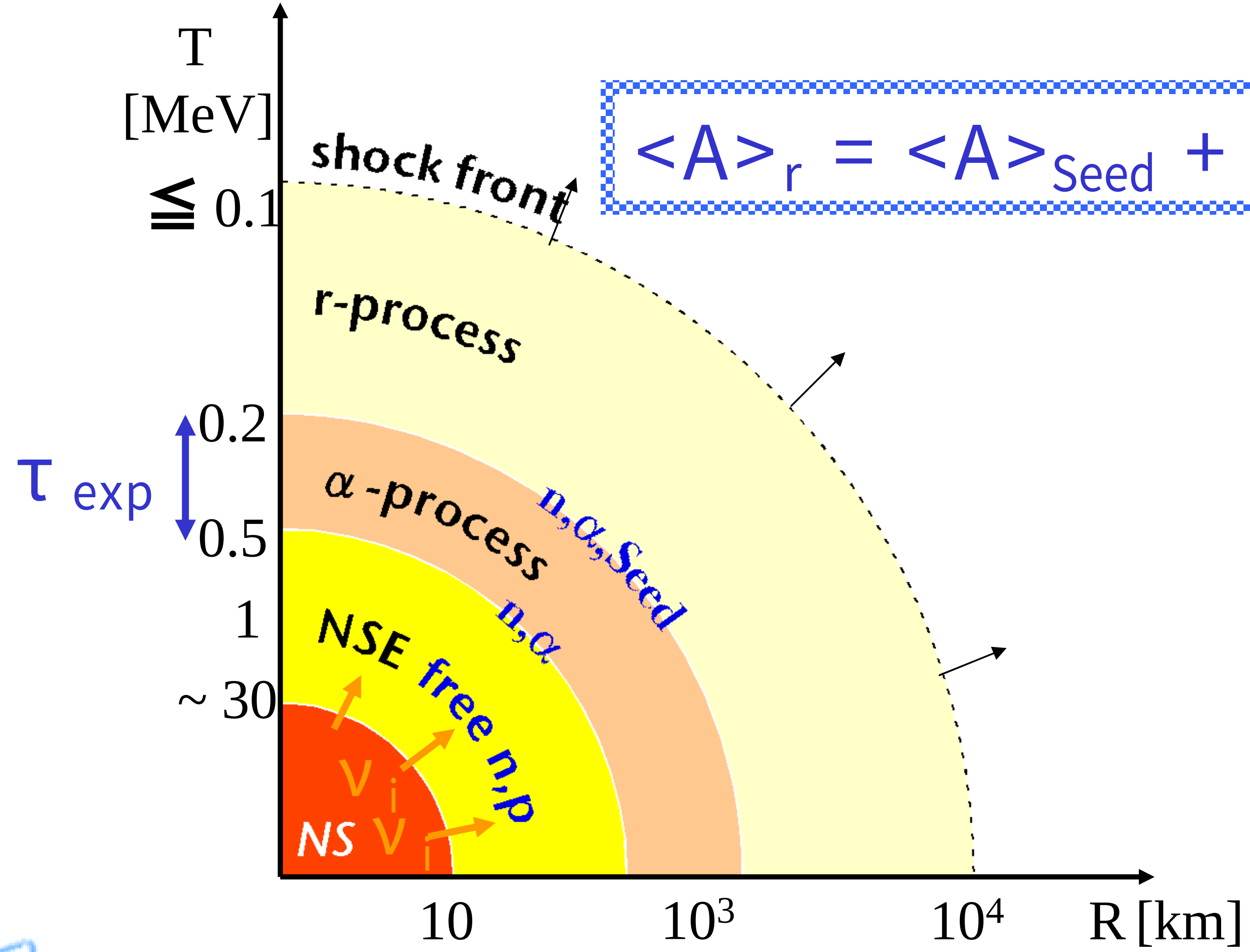
The r-process is considered to occur in the hot bubble region.



Hot Bubble Region
- low density
- high temperature
- high entropy

(Colgate 1989)

$$\langle A \rangle_r = \langle A \rangle_{Seed} + n/Seed$$



$$\tau_{exp} \equiv t(0.5/e) - t(0.5)\ [sec]$$

ν -Process

Charged current interactions

$$\nu_e + (A,Z) \rightarrow (A,Z+1)^* + e^-$$

$$\bar{\nu}_e + (A,Z) \rightarrow (A,Z-1)^* + e^+$$

➡ change the value of Y_e

Neutral current interactions

$\nu_i + (A,Z) \rightarrow (A,Z) + \nu_i'$

($\nu_i = \nu_e, \nu_\mu, \nu_\tau$, and their anti- ν_i)

Previous Studies

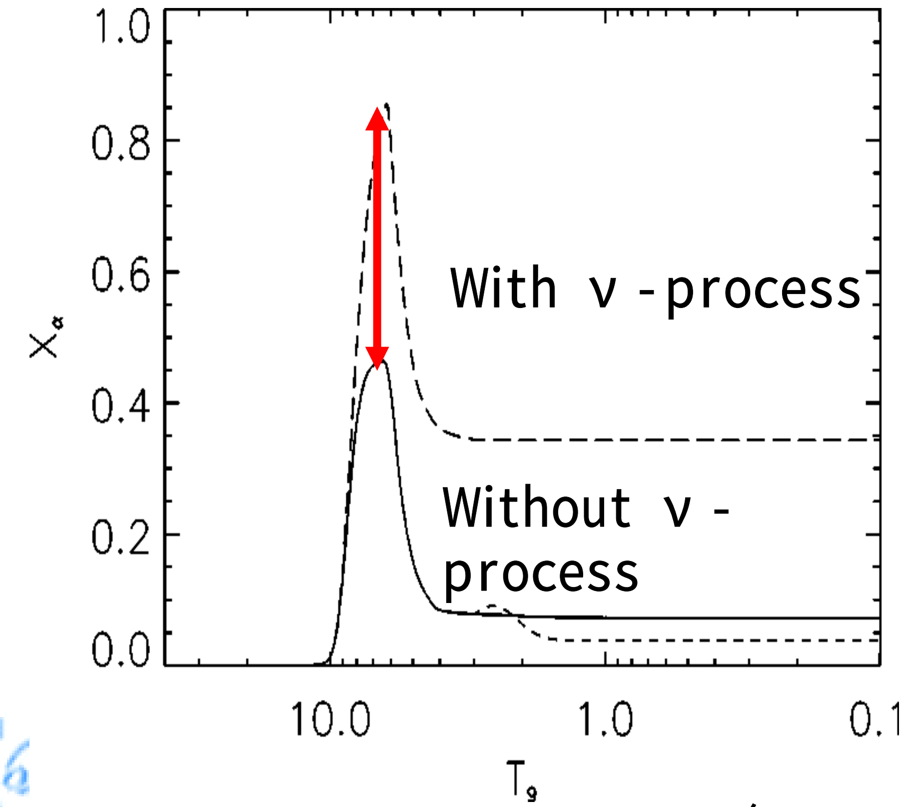
- Neutral current interactions (Meyer et al. 1992)

→ This effect is small.

- α-effects (Meyer 1995, Fuller and Meyer 1995, McLaughlin et al. 1996, Meyer et al. 1998 etc.)
  - $\nu_e + n \rightarrow p + e^-$, this proton is immediately incorporated into α with other neutrons.

α-effect 1

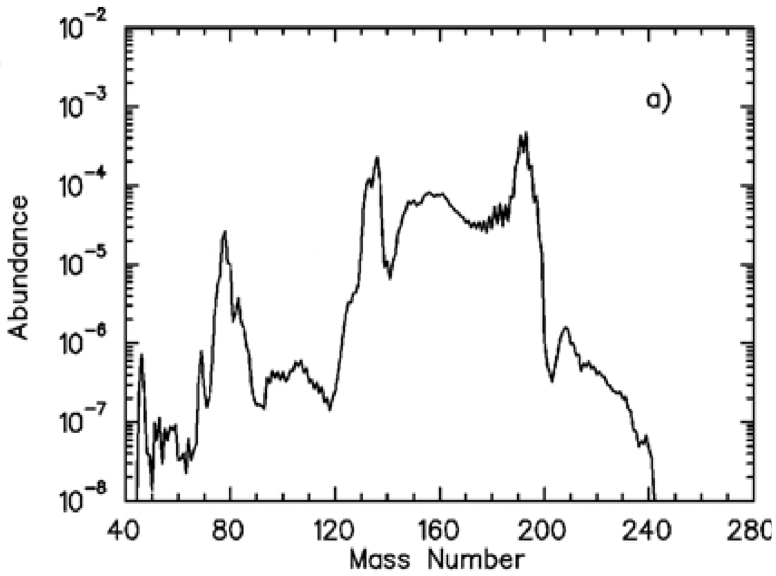
– ν_e+n → p + e^-, this proton is immediately incorporated into α with other neutrons. This effect occurs, when neutrons and protons assemble into α.



$Y_{e,i}$ = 0.23 (= $Y_{p,i}$)
$L\nu$ = 10^{51} erg/s

When there is no ν-process, $X_{\alpha,max} = Y_{p,i} \times 2 = 0.46$.
This increase of α is caused by the α-effect.

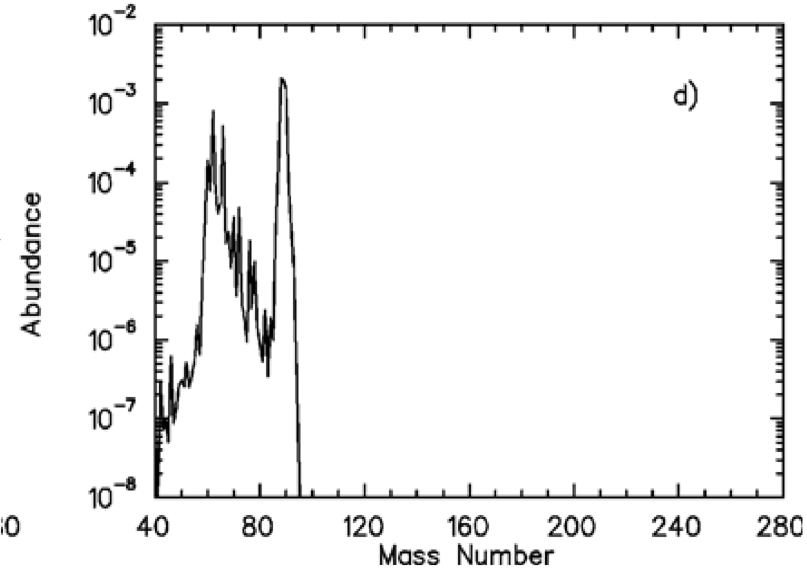
(Meyer et al. 1998)



Without ν-process

With ν-process

$Y_{e,i} = 0.23\ (= Y_{p,i})$
$L\nu = 10^{51}$ erg/s



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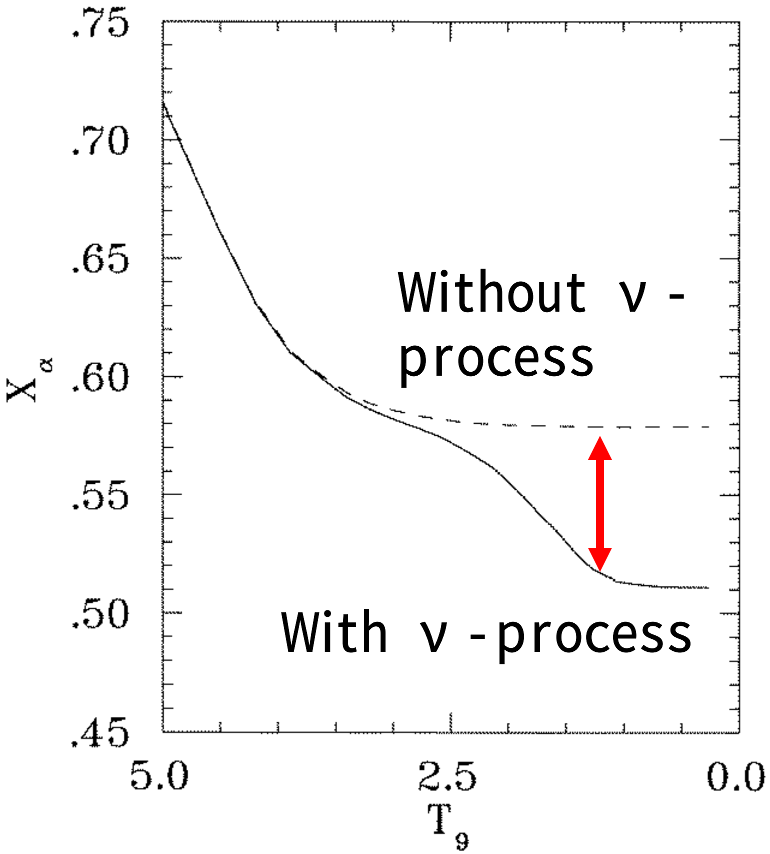
  - $\nu_e + n \to p + e^-$, this proton is immediately incorporated into α with other neutrons.
  - $\nu + \alpha \to {}^3H + p$ at low temperature.
    this proton makes α。
    $^3H(\alpha,\gamma)^7Li(\alpha,\gamma)^{11}B(\alpha,\gamma)$・・・Seed nuclei increase by α-captures.

α-effect 2

– $\nu + \alpha \rightarrow {}^3H + p$ at low temperature.

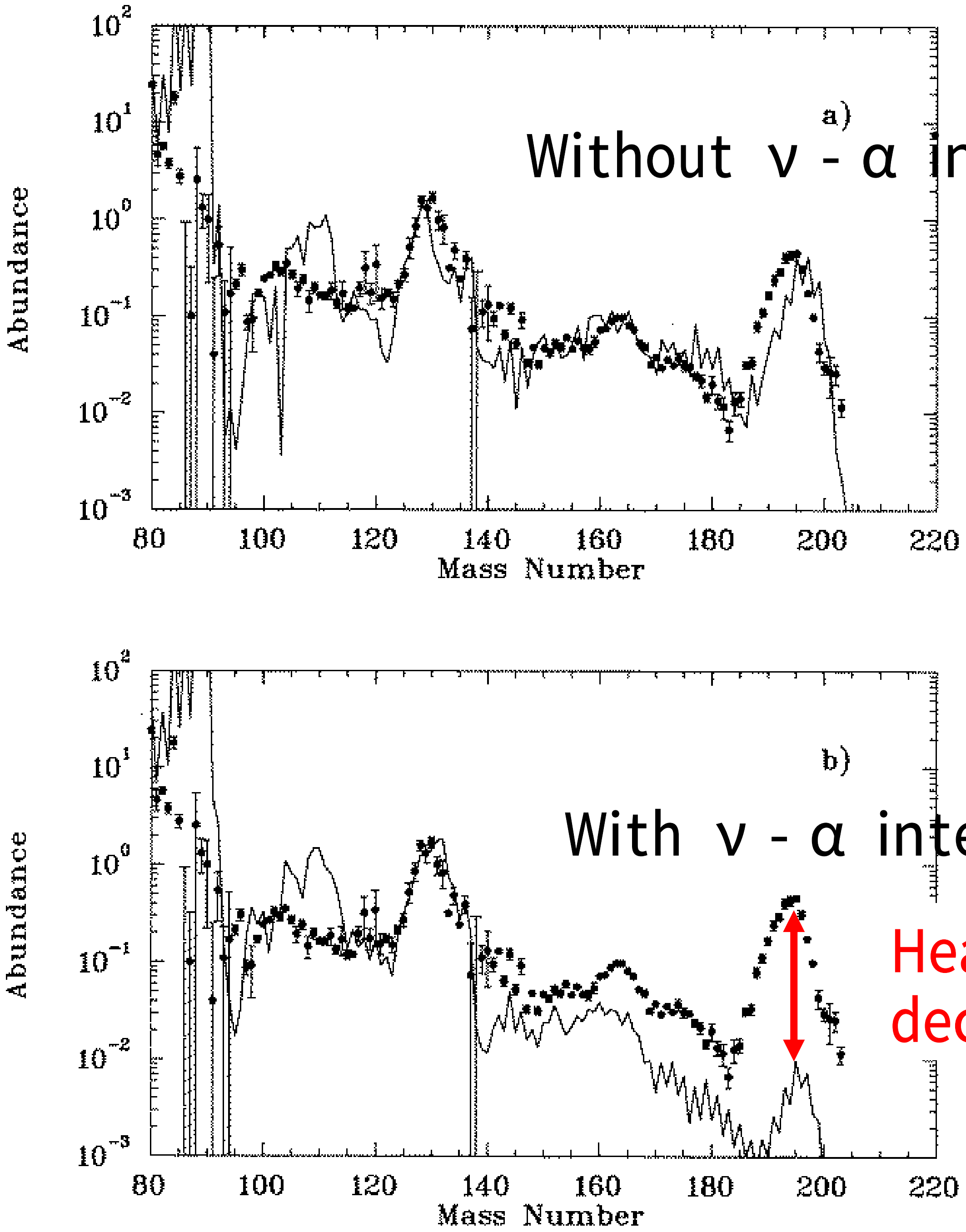
this proton makes α。

${}^3H(\alpha,\gamma){}^7Li(\alpha,\gamma){}^{11}B(\alpha,\gamma)$・・・Seed nuclei increase by α-captures.



This decrease of α caused by the α-effect. Because of this, seed nuclei increase.

(Meyer 1995)



a)
Without ν - α interactions
Abundance
Mass Number
b)
With ν - α interactions
Heavy elements decrease.

(Meyer 1995)

Previous Studies

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    ${}^3H(\alpha,\gamma){}^7Li(\alpha,\gamma){}^{11}B(\alpha,\gamma)$・・・Seed nuclei increase by α-captures.

  → The abundance of α increases and the r-process is hindered. This effect is large.

- Charged current interactions (Meyer et al. 1998)

→ This effect hinders the r-process.

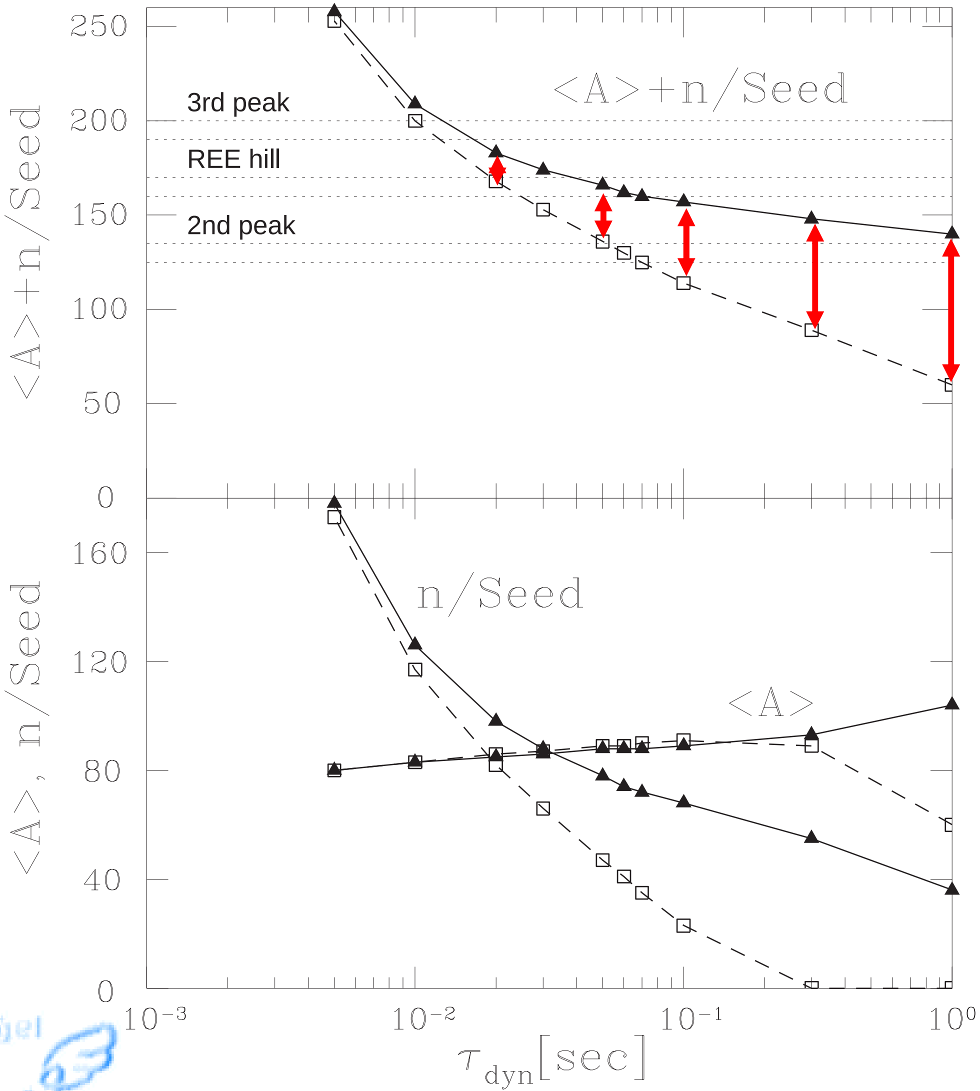
Anyway,

all neutrino-processes decrease neutron to seed ratio and hinder the r-process.

In order to increase the value of n/Seed, wind models should have the small value of τ_{exp}.

(Qian and Woosley 1996, Cardall and Fuller 1997, Ostuki et al. 2000, Sumiyoshi et al. 2000, Thompson et al. 2001, Terasawa et al. 2002 etc.)

Dependence of ν -process on τ_{exp}

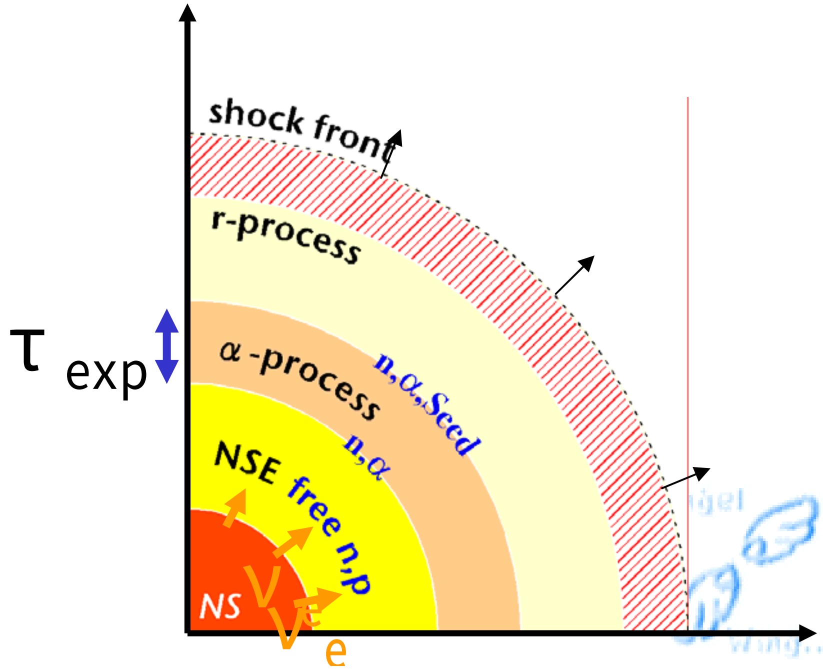


(Terasawa 1999)

▲ without ν -Process

□ with ν -Process

$\tau_{exp} \ll \tau_{\nu} \rightarrow$ ν -process does not work because of little interactions.



ν -Process

Charged current interactions

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Neutral current interactions

ν_i+(A,Z) → (A,Z)+ ν_i'

(ν_i= ν_e, ν_μ, ν_τ, and their anti- ν_i)

Due to high energy neutrinos, neutron emissions occur.

PURPOSE

We study effects of neutrino-induced neutron emissions on the r-process.

Calculations

Explosion Model

- Neutrino-Driven Wind Model (Terasawa et al. 2002)
  - Implicit Lagrangian code for general relativistic and spherically symmetric hydrodynamics (Yamada 1997, Sumiyoshi et al. 2000)

  NS mass : $1.4M_{\odot}$, NS radius : 10 km

The result:

$\tau_{exp} \sim 23$ msec, entropy $\sim 200k_B$

Because of the low temperature at the outer-boundary, less seed nuclei are synthesized by α-process and the r-process successfully occurs.

Reaction Network

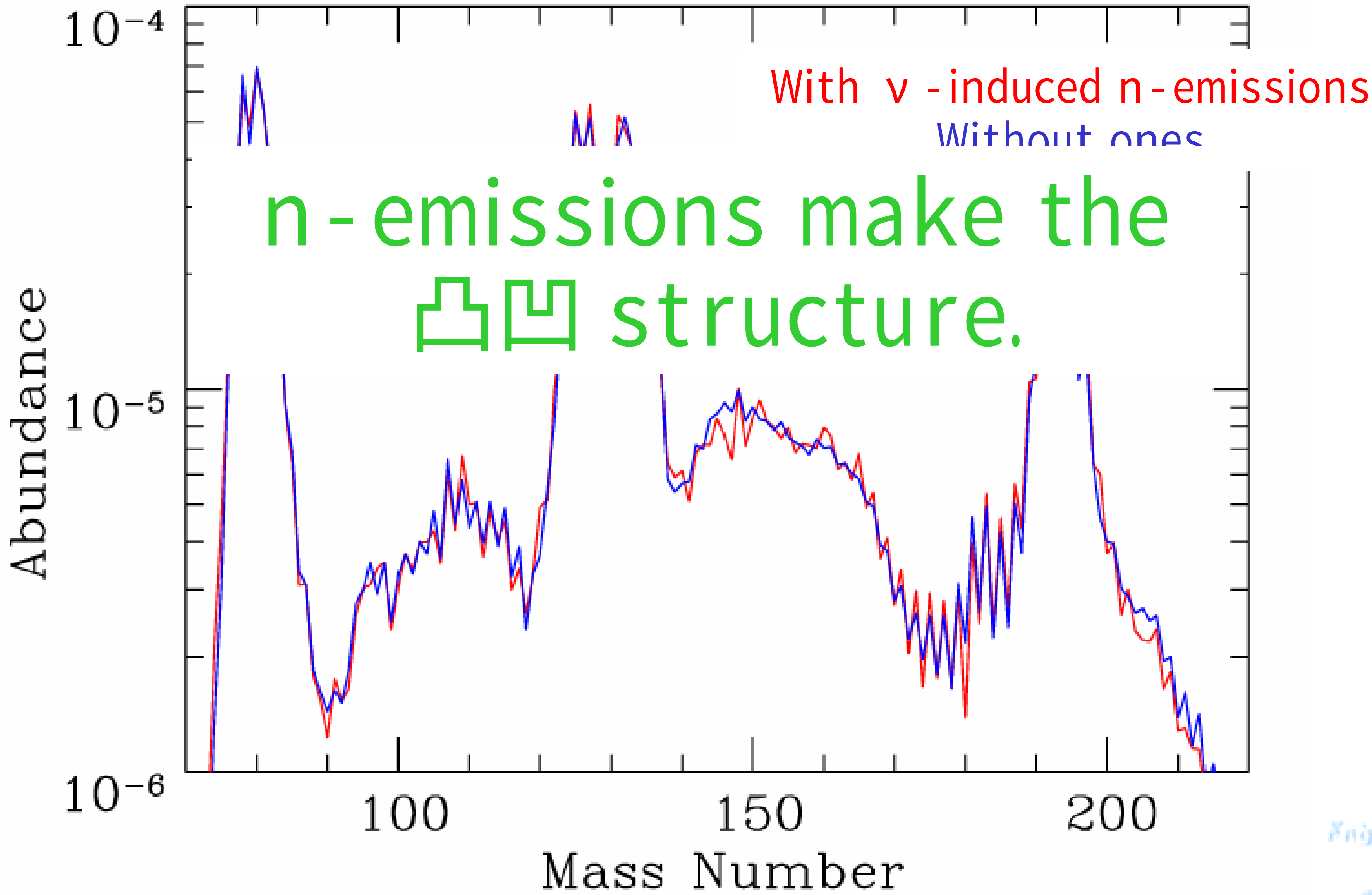
- Over 3000 species from the stability line to the neutron drip line (Terasawa et al. 2001)

We include all neutrino-nucleus interactions and neutrino-induced neutron emissions.

Neutrino-Nucleus Interaction Cross Section

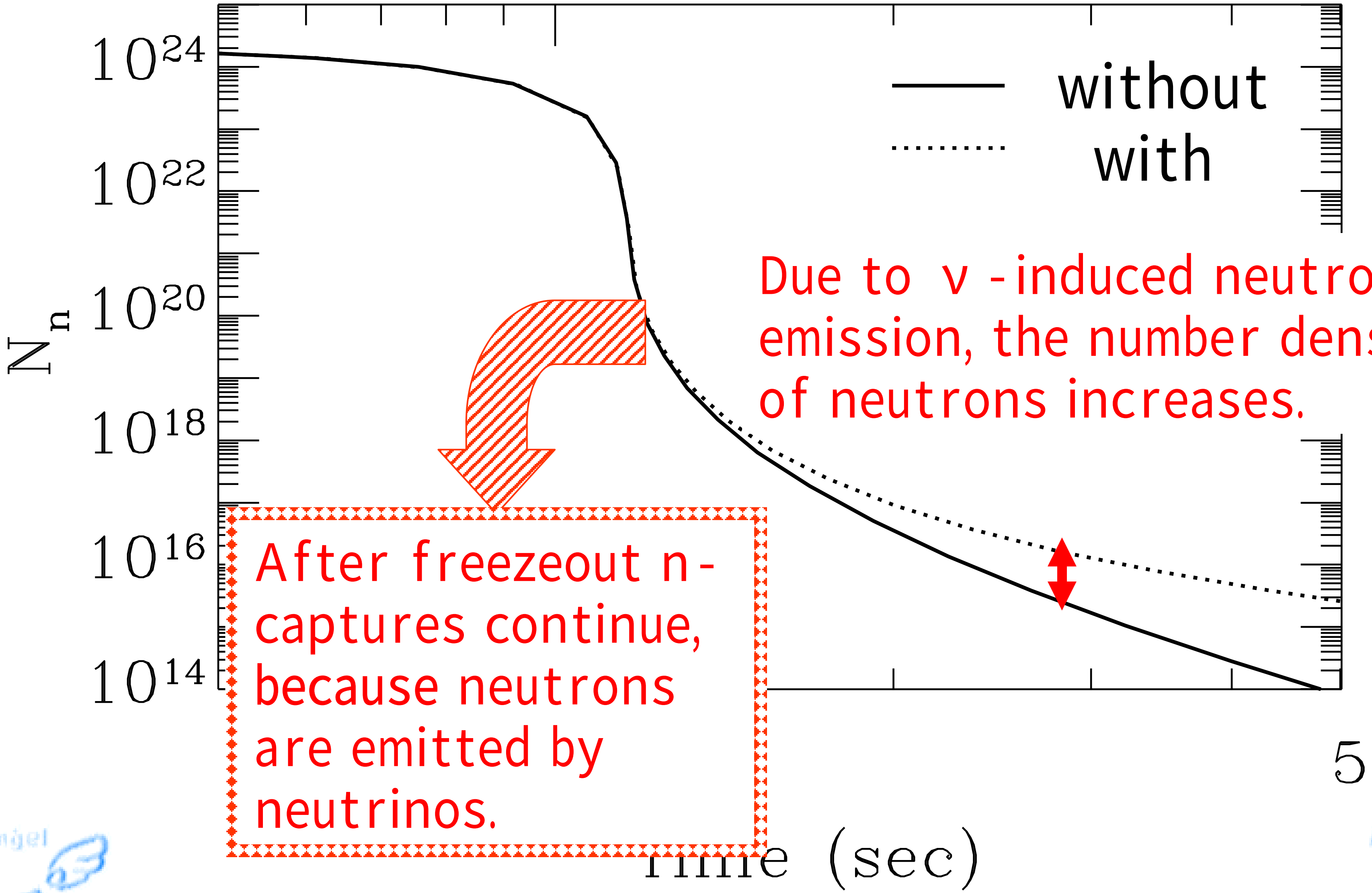
- Charged and neutral current interactions (Kolbe and Langanke 2002).
 They calculated the averaged number of emitted neutrons hit by a high-energy neutrino.

Result(L_ν = 10^{51} erg/s)



n-emissions make the 凸凹 structure.

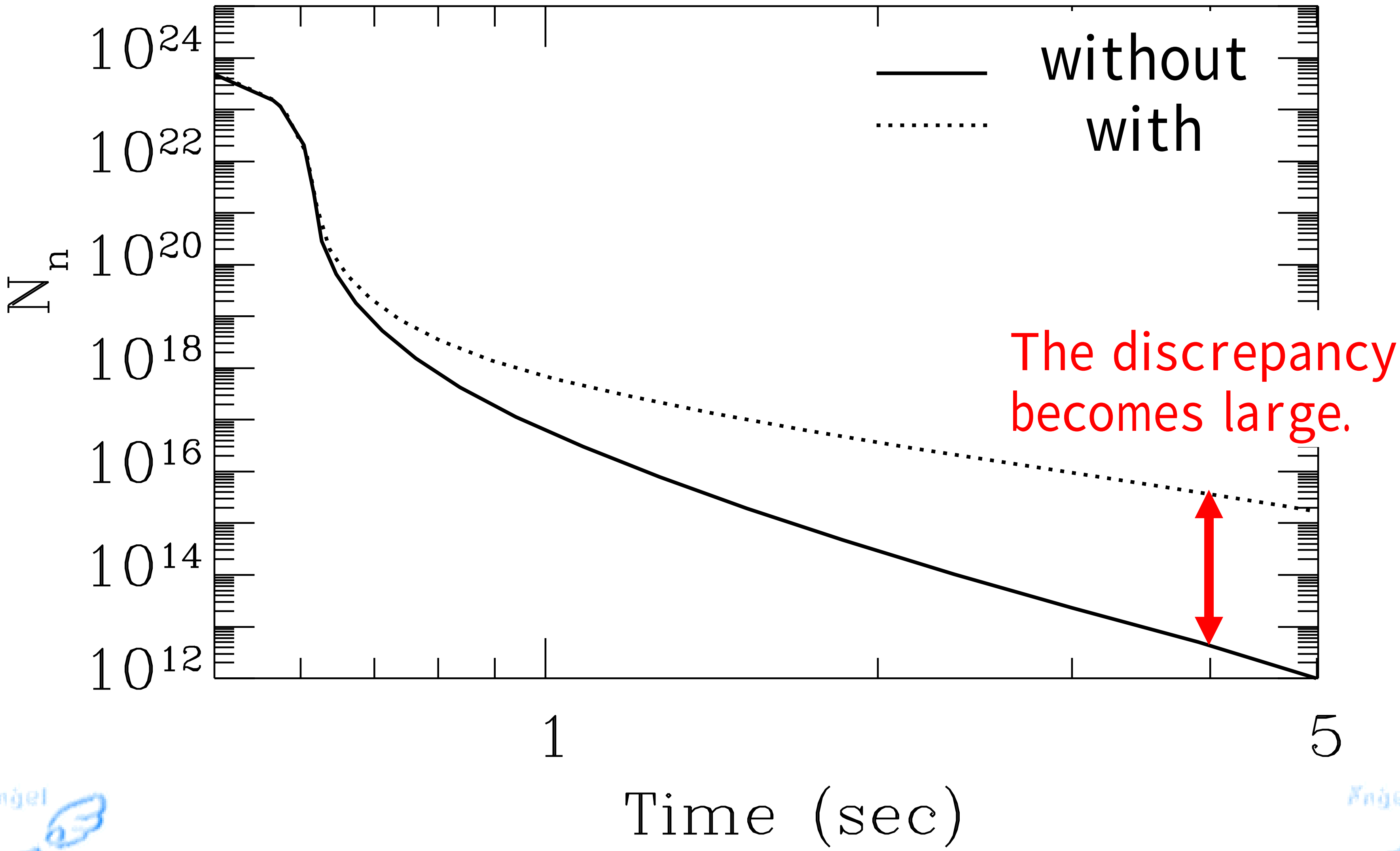
Number density of neutron, N_n



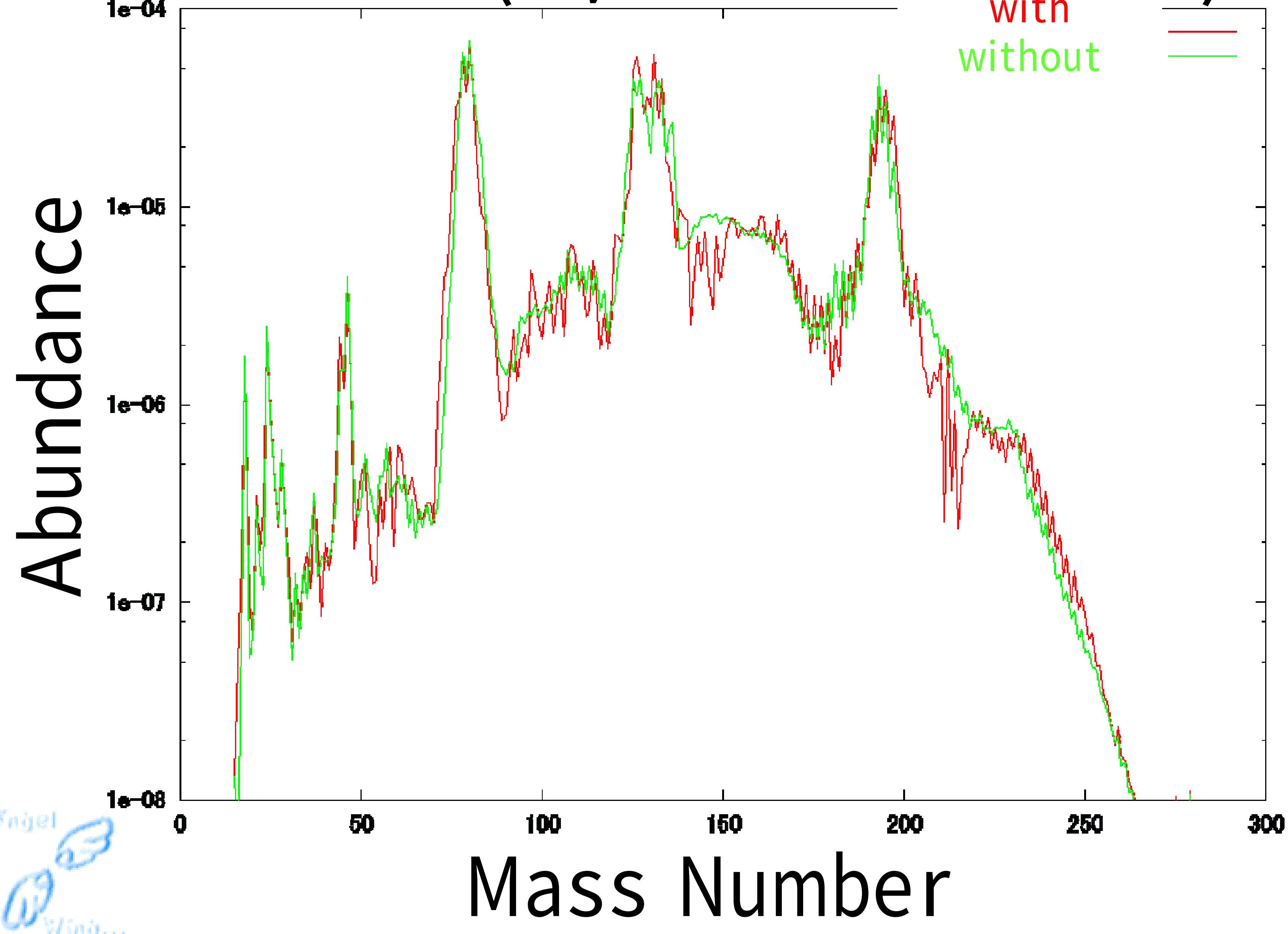
Due to ν -induced neutron emission, the number density of neutrons increases.

After freezeout n-captures continue, because neutrons are emitted by neutrinos.

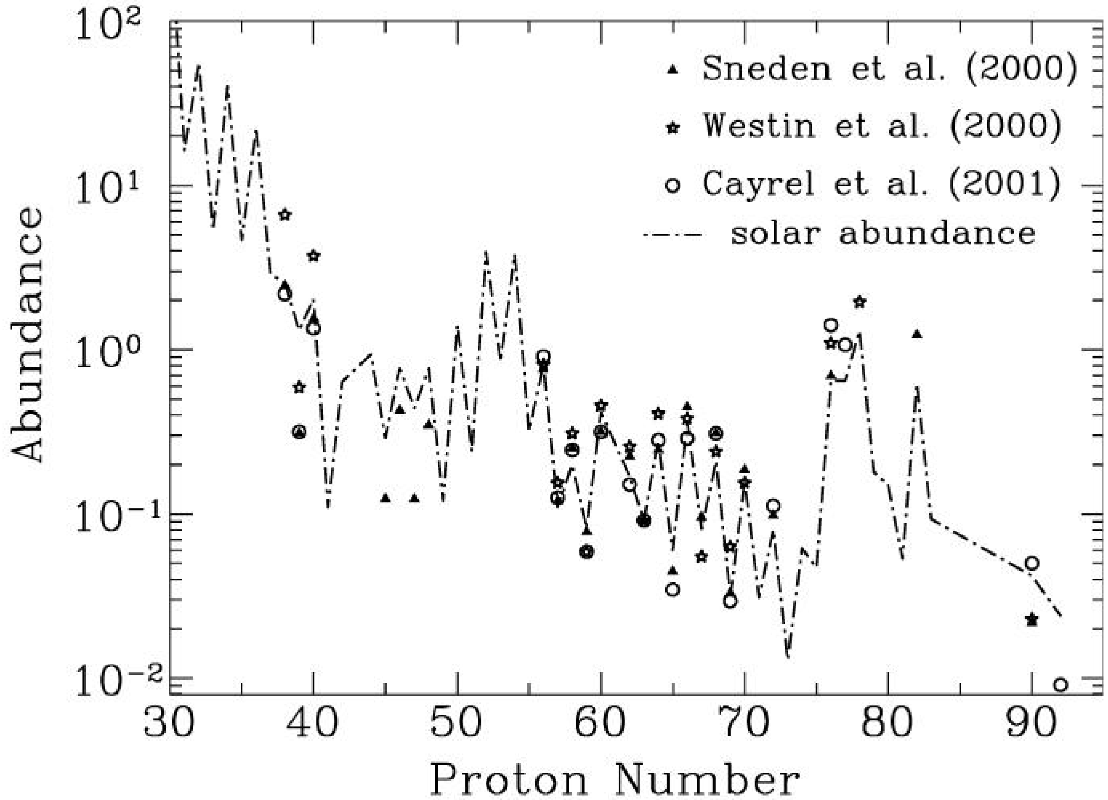
$L_\nu = 10^{52}$ erg/s



Result ($L_\nu = 10^{52}$ erg/s)



Observations of Heavy Elements

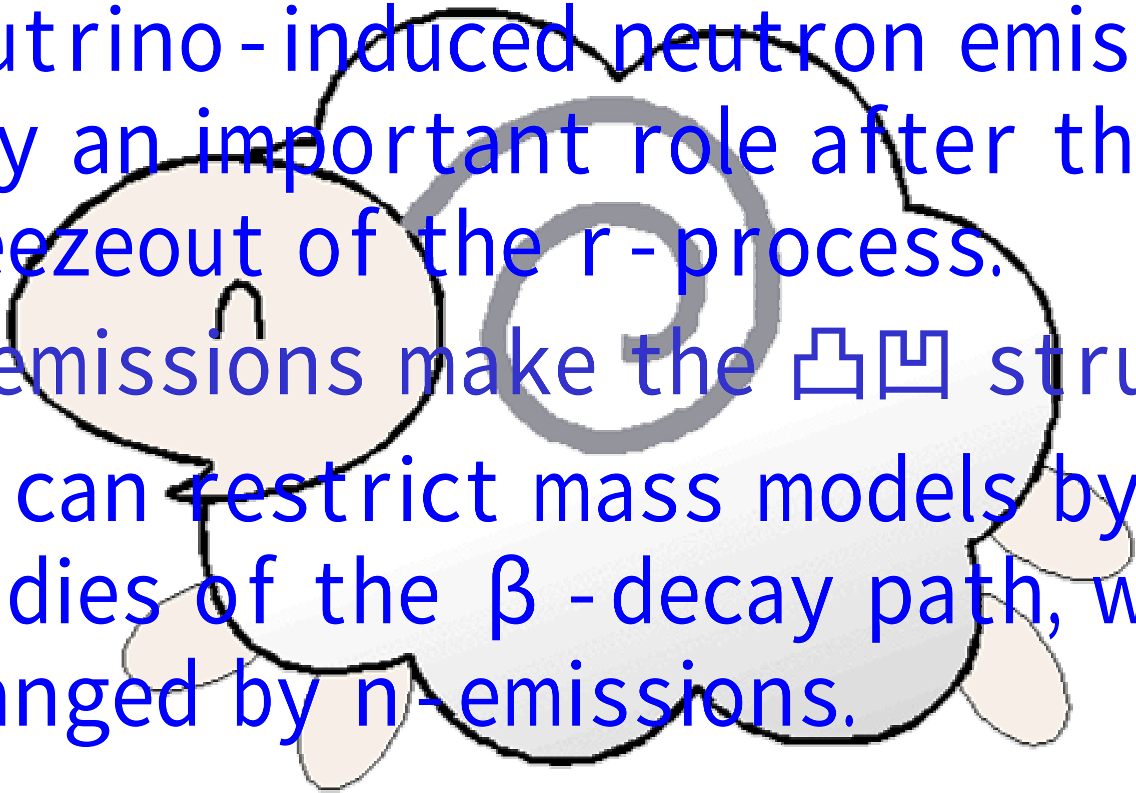


[Fe/H] ~ -3.1
[Fe/H] ~ -3.0
[Fe/H] ~ -3.0

Observations have good agreement with the solar pattern as a whole pattern.

However, the detailed structures have gaps!!

Summary



- Neutrino-induced neutron emissions play an important role after the freezeout of the r-process.
- n-emissions make the 凸凹 structure.
- We can restrict mass models by detailed studies of the β-decay path, which is changed by n-emissions.