Neutrino Oscillations and Nucleosynthesis in Supernovae

Takashi YOSHIDA
吉田　敬

Deparment of Astronomy, Graduate School of Science
University of Tokyo

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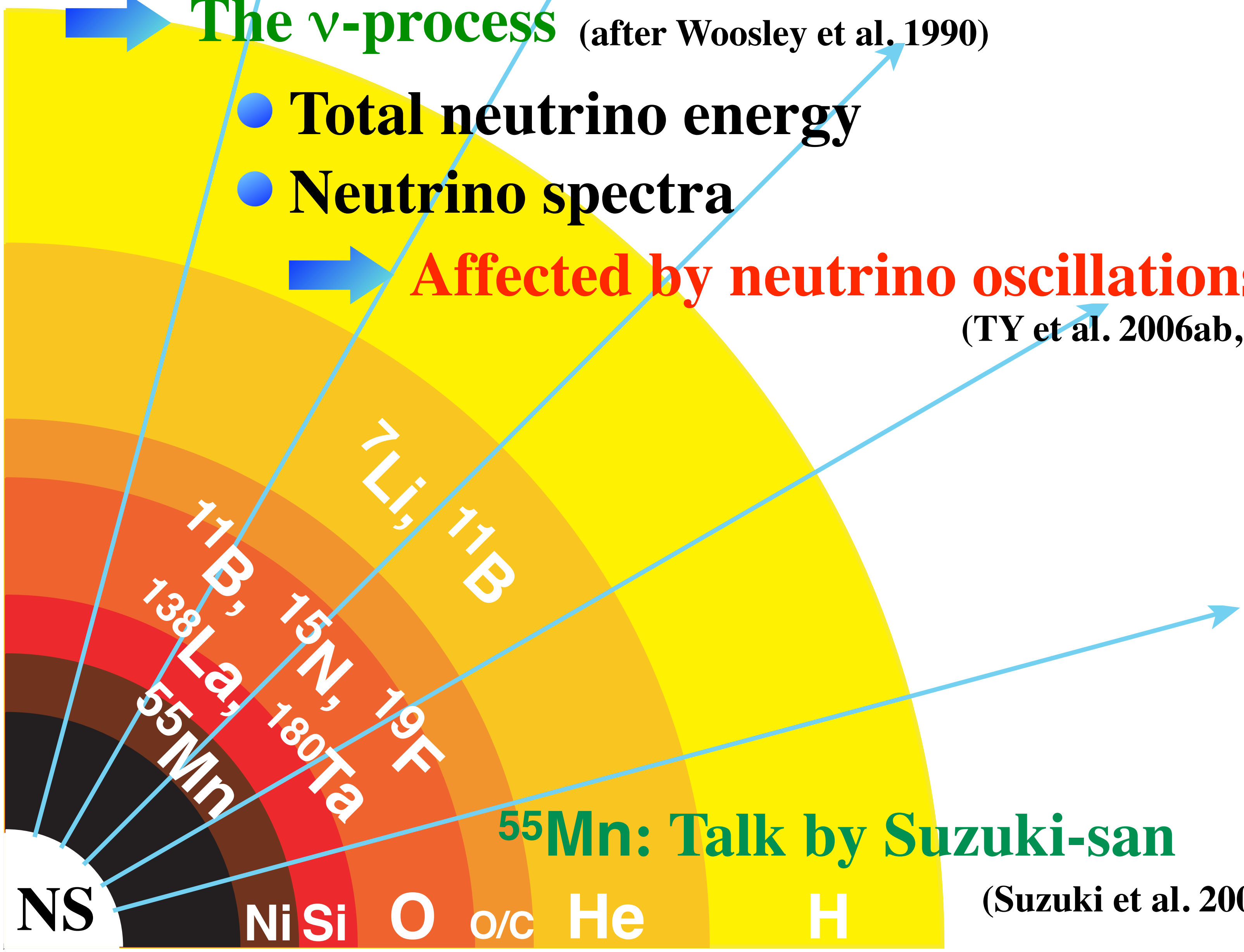
ν-Process and Neutrino Oscillations

- **Nucleosynthesis through neutrino-nucleus reactions**
  - ➡ **The ν-process** (after Woosley et al. 1990)
    - **Total neutrino energy**
    - **Neutrino spectra**
      - ➡ **Affected by neutrino oscillations** (TY et al. 2006ab, 2008)



^{55}Mn: Talk by Suzuki-san (Suzuki et al. 2009)

r-Process and Neutrino Self-Interactions

- **Neutrino driven winds**

  ➡ **One of promising sites for *r*-process**

  (e.g. Qian & Woosley 1996; Otsuki et al. 2000; Wanajo et al. 2001)

- **Neutrino reactions**

  ➡ **Increase in electron fraction (α-effect)**

  (McLaughlin et al., 1996; Meyer et al. 1998)

  Suppress of *r*-process

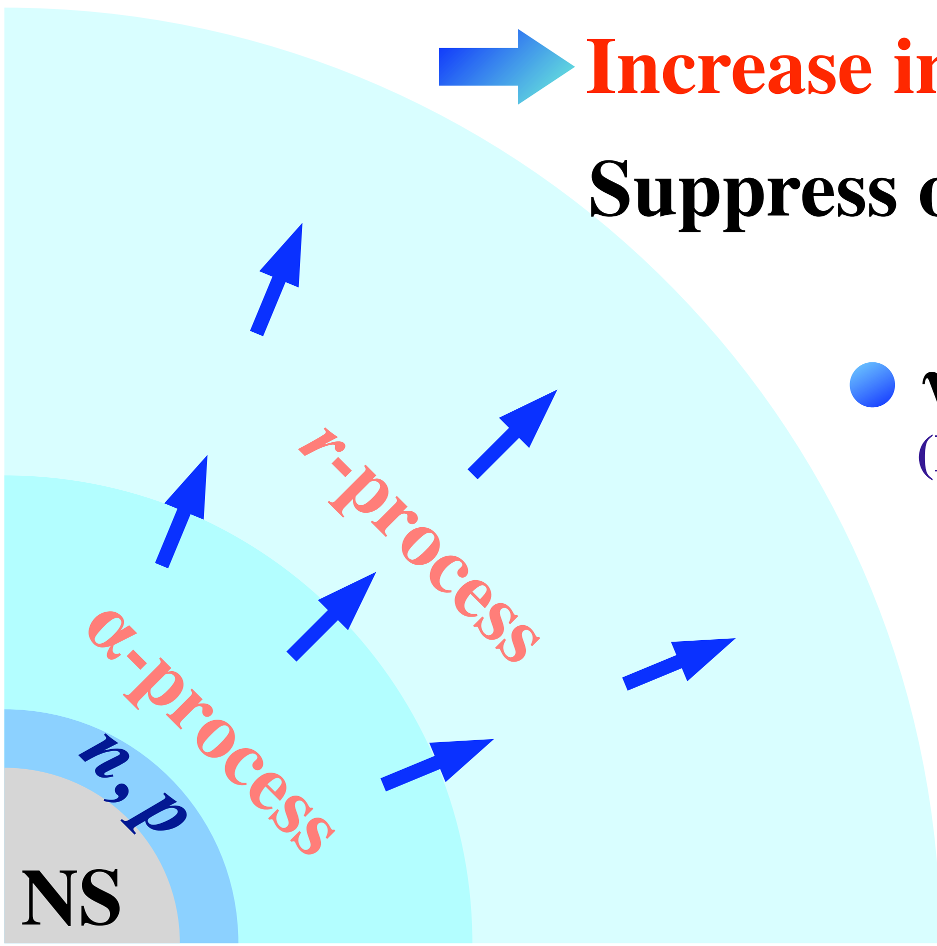
- **ν self-interactions**

  (Fuller, Qian, Kneller in the morning session)

  ➡ **Flavor change at ~100km**

  Effect to *r*-process?

  (e.g. Balantekin & Yuksel 2005)



Outline

- **Light element (^{7}Li, ^{11}B) synthesis through the ν-process in supernovae**

- **Influence of neutrino oscillations (MSW effect) on light element synthesis in supernovae**

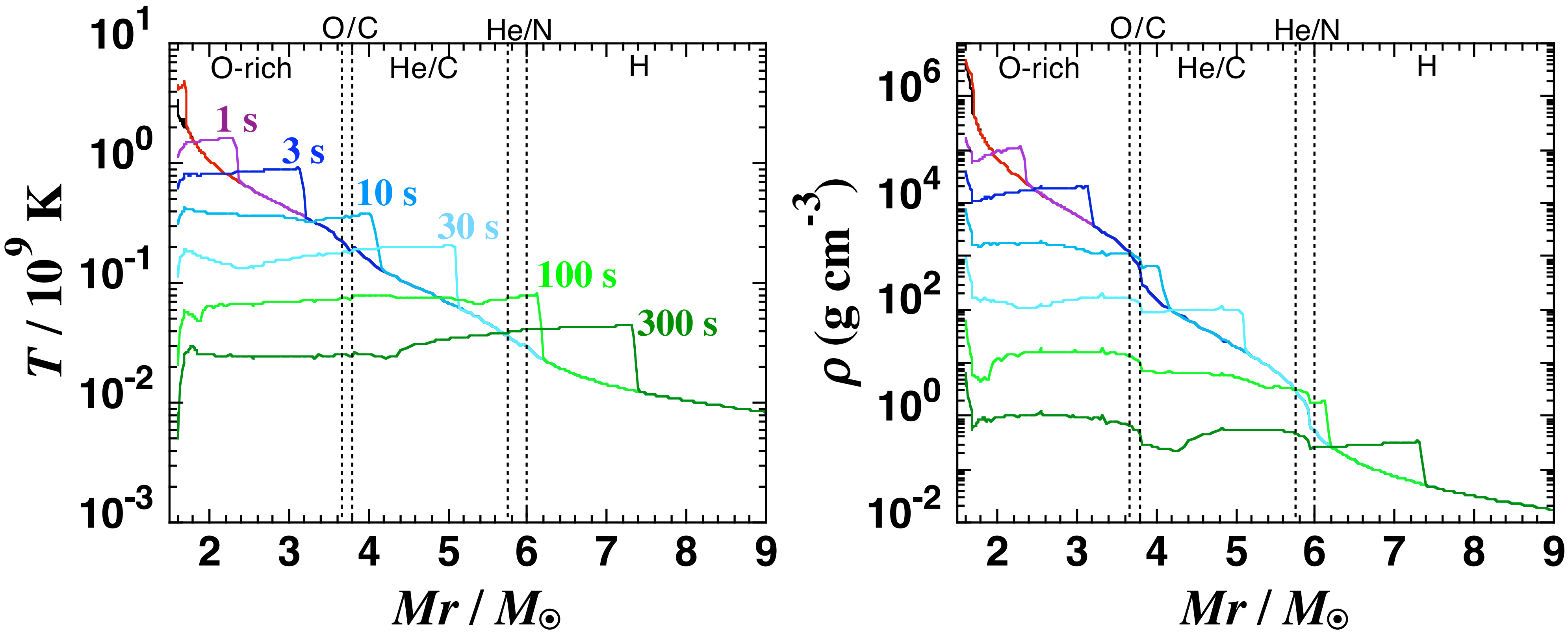
- ***r*-process nucleosynthesis with neutrino self-interactions in a simple wind model**

Supernova Explosion Model

- **16.2 $M_\odot$ supernova model** (Shigeyama & Nomoto 1990, ApJ 360, 242)

  E_{exp} = 1×10^{51} ergs

  Temperature and density evolution



- **Nucleosynthesis calculations**

  ➡ **Nuclear reaction network of 291 species of nuclei**

Supernova Neutrino Model

Neutrino luminosity

$$L_{\nu i}(t) = \frac{1}{6}\frac{E_\nu}{\tau_\nu}\exp\left(-\frac{t-r/c}{\tau_\nu}\right)\Theta(t-r/c) \qquad \nu i : \nu_{e\mu\tau}, \bar{\nu}_{e\mu\tau}$$

(after Woosley et al. 1990, ApJ 356, 272)

- $\tau_\nu = 3$ s
- $E_\nu = 3\times10^{53}$ ergs

Neutrino energy spectra at the neutrino sphere

- Fermi distribution $\eta_\nu = \mu_\nu/kT_\nu = 0$

$(kT_{\nu e}, kT_{\bar{\nu} e}, kT_{\nu\mu\tau}) = (3.2\ \text{MeV}, 5\ \text{MeV}, 6\ \text{MeV})$

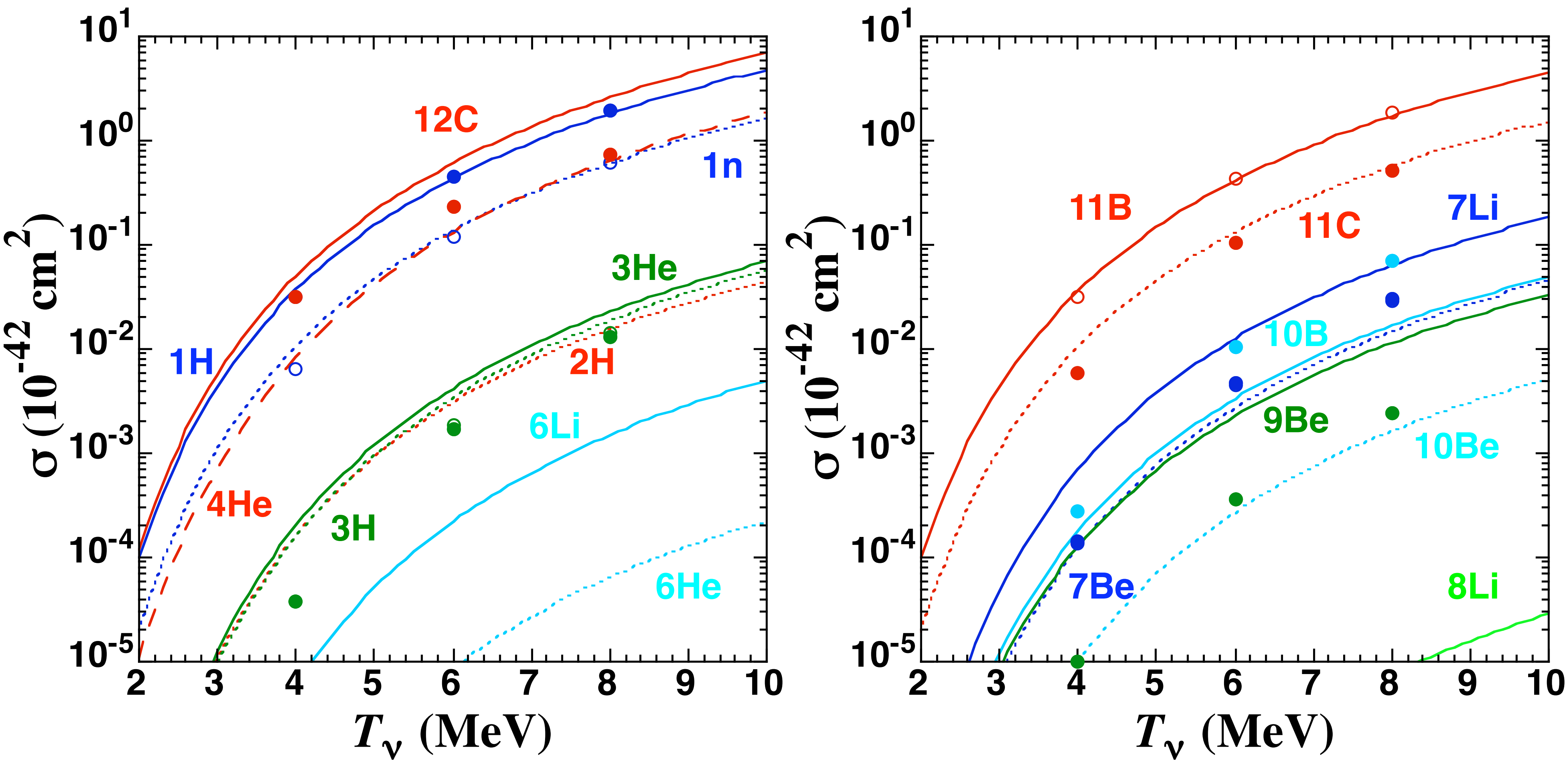
(e.g. TY et al. 2006ab; TY, Suzuki et al. 2008)

Neutrino-^{12}C Reaction Cross Sections

- **Neutral-current cross sections with SFO Hamiltonian**

Branching ratios → Hauser-Feshbach theory

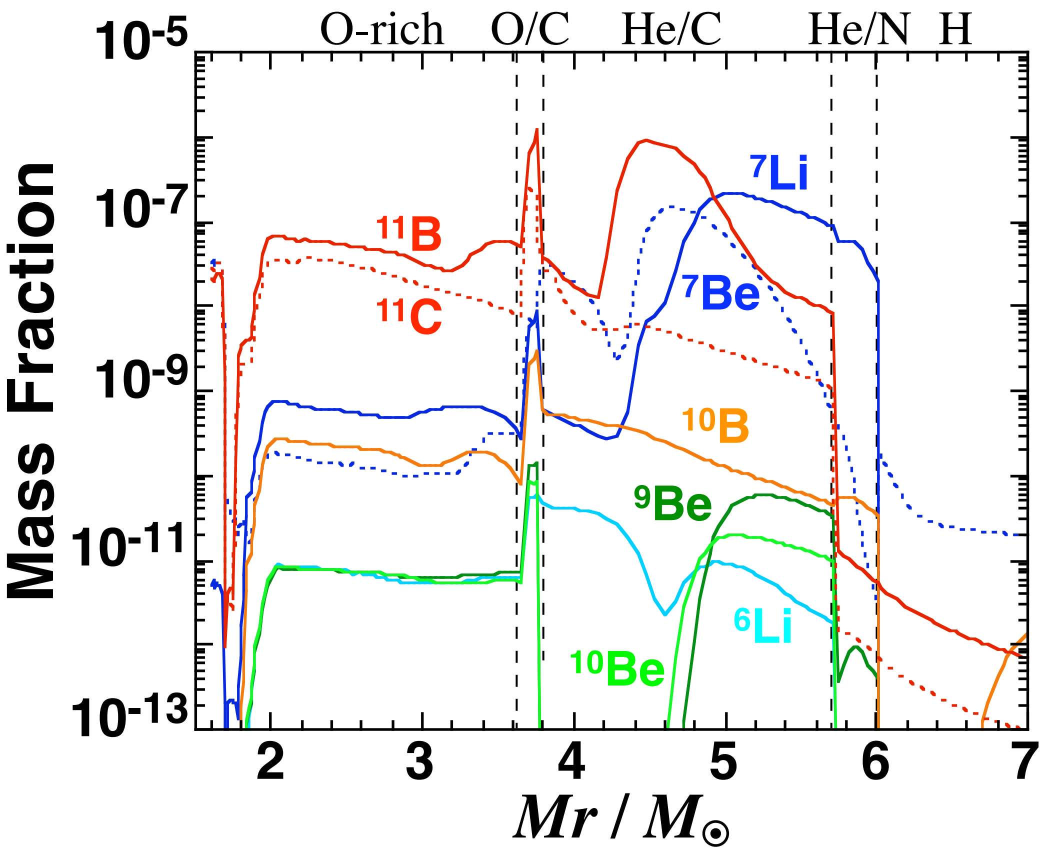
(TY, Suzuki et al. 2008, ApJ 686, 448)

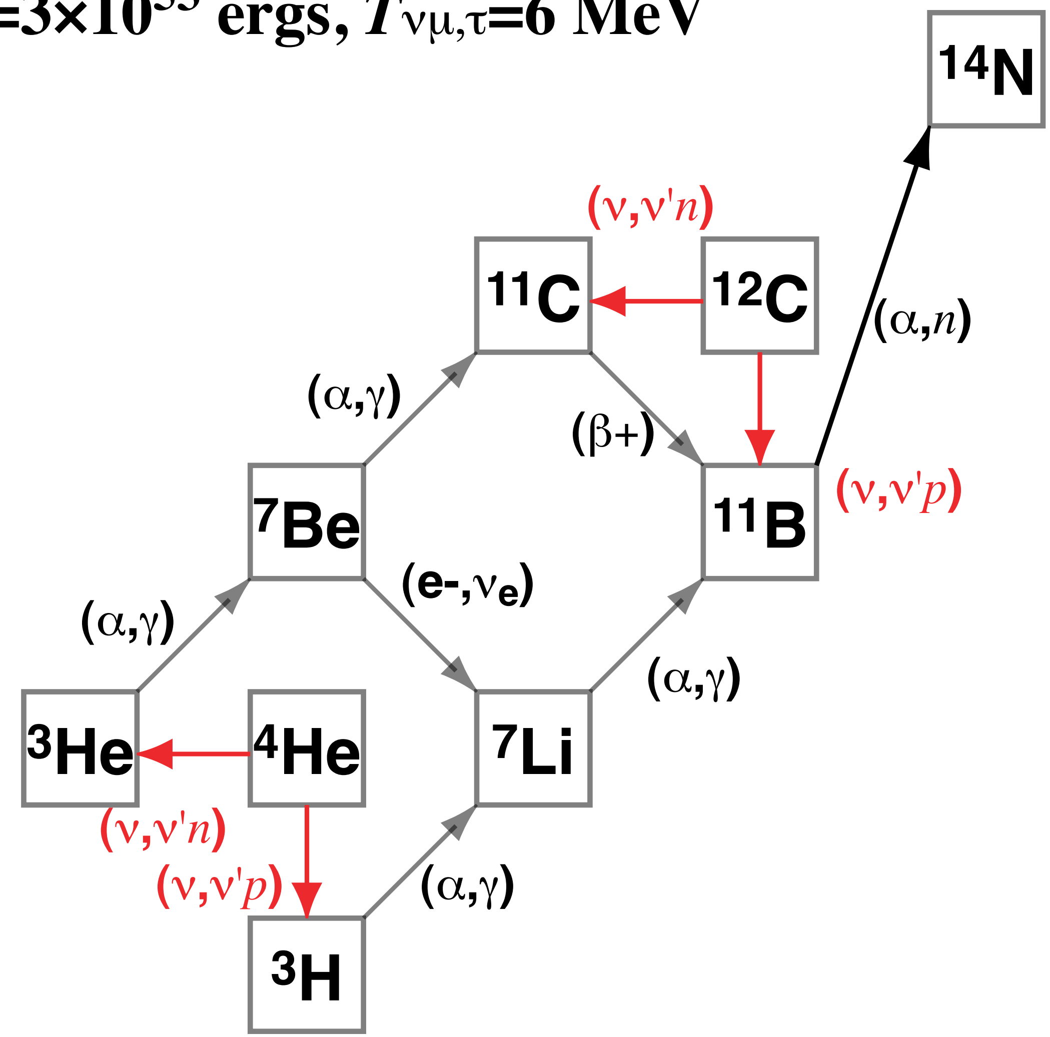


SN Light Element Synthesis

- **Mass fraction distribution of light elements**

16.2 $M_\odot$ Supernova (SN 1987A) $E_\nu = 3\times10^{53}$ ergs, $T_{\nu\mu,\tau} = 6$ MeV





- **ν-process reactions**

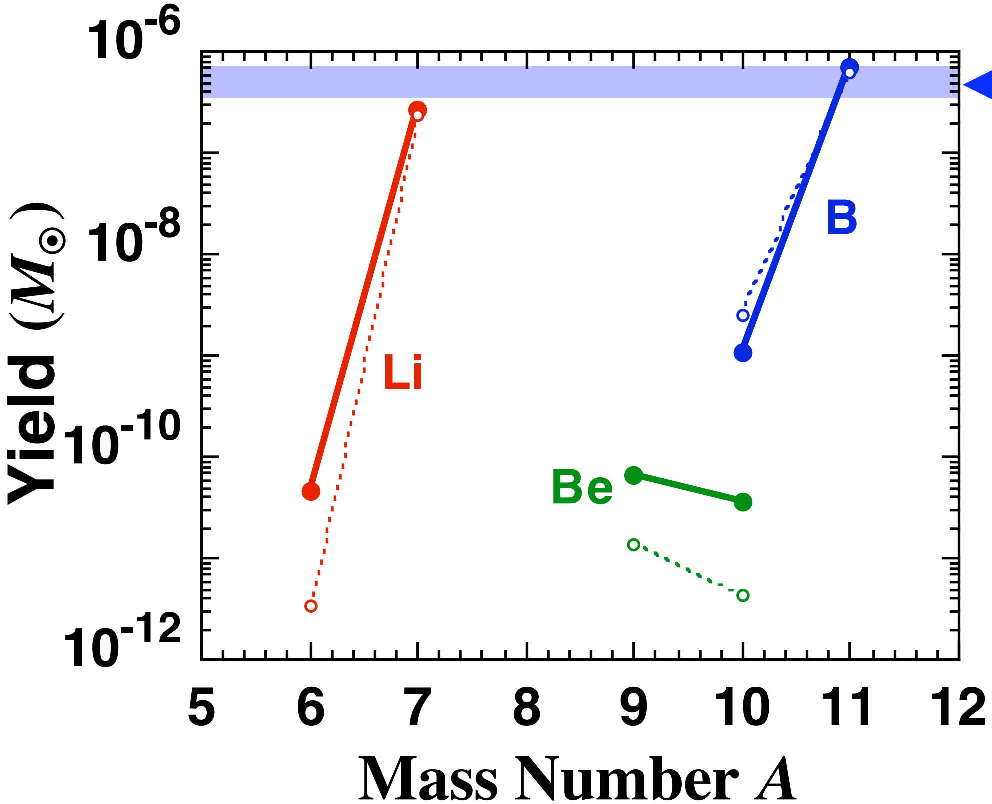
➡ ^{4}He(ν,ν'*p*)^{3}H, ^{4}He(ν,ν'*n*)^{3}He, ^{12}C(ν,ν'*p*)^{11}B, ^{12}C(ν,ν'*n*)^{11}C

^{4}He(ν_e,e$^-$*p*)^{3}He, ^{4}He($\bar{\nu}_e$,e$^+$*n*)^{3}H, ^{12}C(ν_e,e$^-$*p*)^{11}C, ^{12}C($\bar{\nu}_e$,e$^+$*n*)^{11}B

SN Light Element Synthesis

- **Light element Yields**

16.2 $M_\odot$ Supernova (SN 1987A) $E_\nu = 3\times10^{53}$ ergs, $T_{\nu\mu,\tau} = 6$ MeV



Contribution of ^{11}B from SNe suggested from Galactic chemical evolution models

(e.g., Fields et al., 2000; Ramaty et al. 2000)

- **Yields of 10^{-7} $M_\odot$ for ^{7}Li and ^{11}B**
- **New ν-process cross sections for ^{12}C**

➡ **Enhancement of ^{6}Li, ^{9}Be, ^{10}Be yields**

Neutrino Oscillation Parameters

Neutrino oscillation parameters

- **Squared mass differences**

  $\Rightarrow$ $\Delta m^2{}_{31} = \pm 2.4\times10^{-3}\ \mathrm{eV}^2,\ \Delta m^2{}_{21} = 7.9\times10^{-5}\ \mathrm{eV}^2$

  (Based on SK 2004; SNO 2004; KamLAND 2005)

- **Mixing angles**

  $\Rightarrow$ $\sin^2 2\theta_{12} = 0.816,\ \sin^2 2\theta_{23} = 1$

  $10^{-6} \leq \sin^2 2\theta_{13} \leq 0.1$

  (Based on CHOOZ 2003; SK 2004; SNO 2004; KamLAND 2005)

Spectrum Change by Neutrino Oscillations

Supernova neutrinos ➡ $\langle \varepsilon_{\nu e} \rangle < \langle \varepsilon_{\bar{\nu} e} \rangle < \langle \varepsilon_{\nu \mu \tau} \rangle$

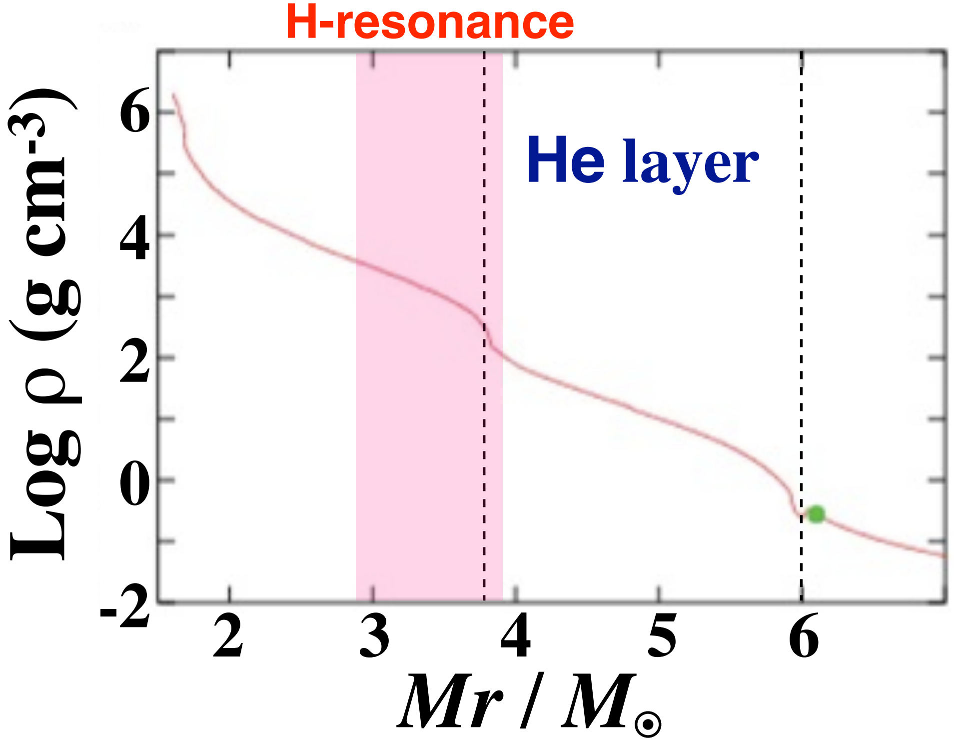
10 MeV, 16 MeV, 19 MeV

- **Neutrino oscillations change neutrino flavor**

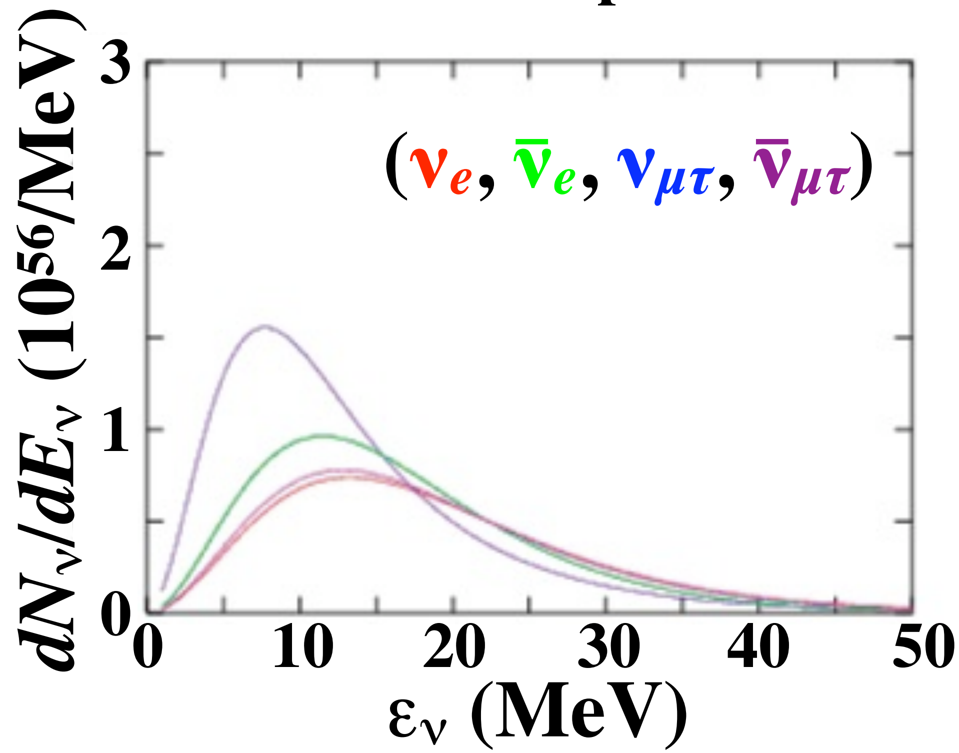
  ➡ *Mass hierarchy, the mixing angle* θ_{13}

- **Normal mass hierarchy**, $\sin^2 2\theta_{13}=0.01$

Presupernova density profile

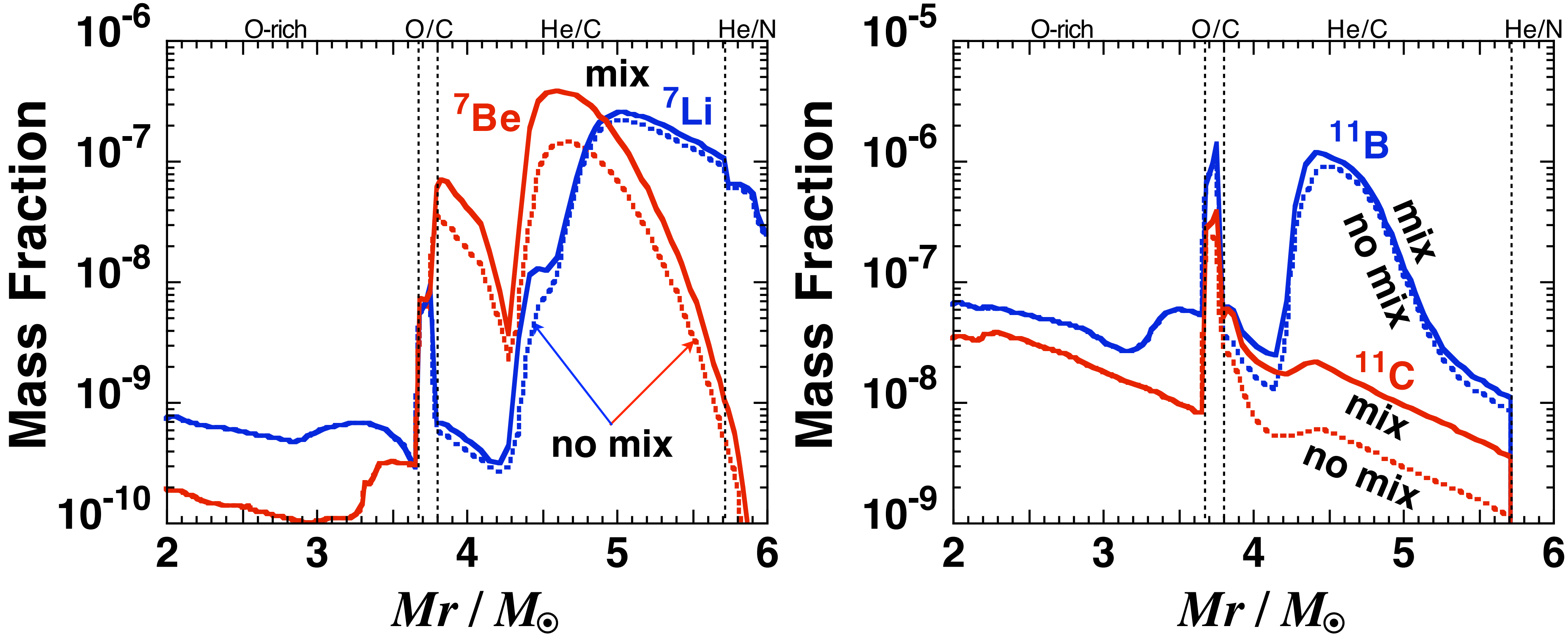


Neutrino Spectra



Mass Fraction Distribution of ^{7}Li and ^{11}B

- **Normal** mass hierarchy; $\sin^2 2\theta_{13}=0.01$



$E_\nu = 3\times10^{53}$ ergs, $T_{\nu\mu,\tau}=6$ MeV

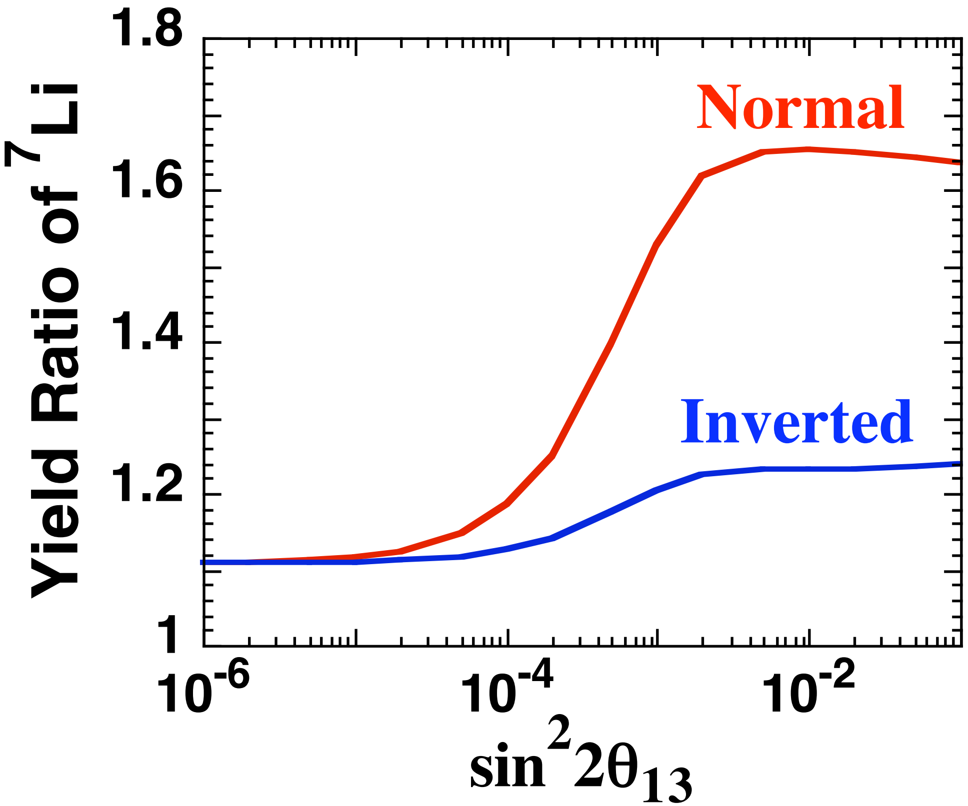
Increase in the mass fractions of ^{7}Be & ^{11}C in the He layer

⬅ Increase in the rates of $^{4}\mathrm{He}(\nu_e,e^-p)^{3}\mathrm{He}$, $^{12}\mathrm{C}(\nu_e,e^-p)^{11}\mathrm{C}$

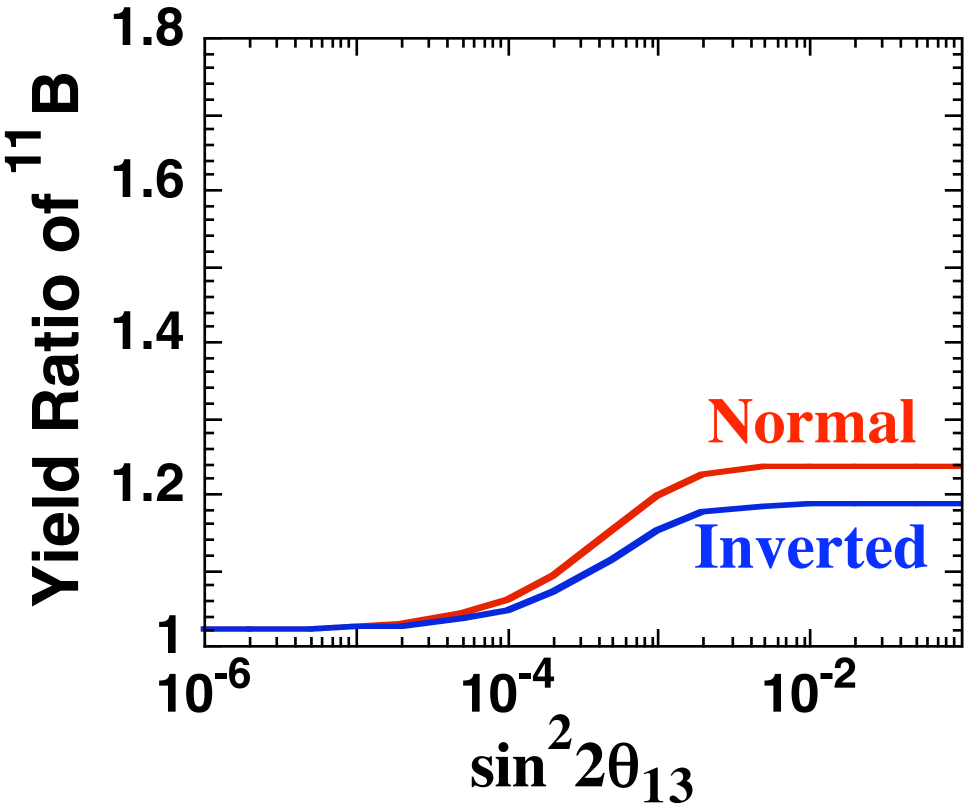
- ^{7}Be & ^{11}C yields ➡ Increase by factors of 2.5 & 1.4

^{7}Li and ^{11}B Yields with Neutrino Oscillations

- Dependence on mass hierarchies and $\sin^2 2\theta_{13}$



$M(^7\text{Li}) = 2.67\times10^{-7}\ M_\odot$



$M(^{11}\text{B}) = 7.14\times10^{-7}\ M_\odot$

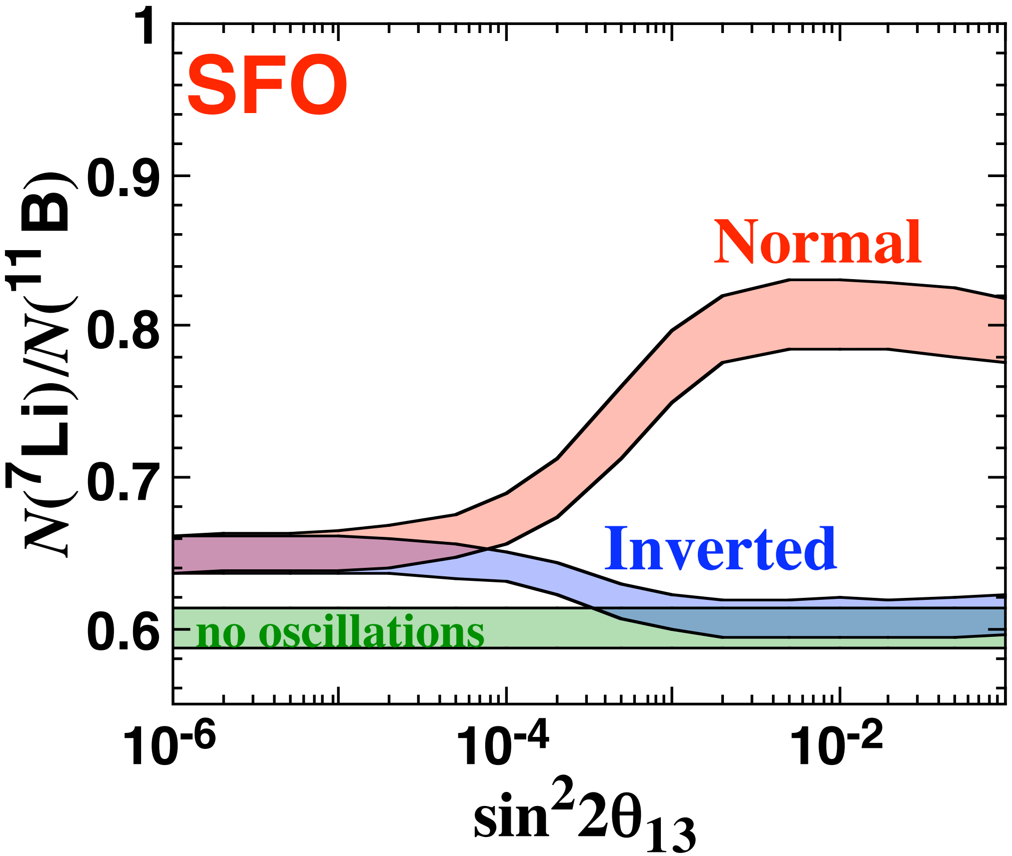
- **Normal** mass hierarchy and $\sin^2 2\theta_{13} > 0.001$

→ Enhancement of ^{7}Li and ^{11}B yields

$^4\text{He}(\nu_e,e^- p)^3\text{He}$, $^{12}\text{C}(\nu_e,e^- p)^{11}\text{C}$ rates become large.

^{7}Li/^{11}B Abundance Ratios

- ^{7}Li and ^{11}B yields ➡ Increase by neutrino oscillations



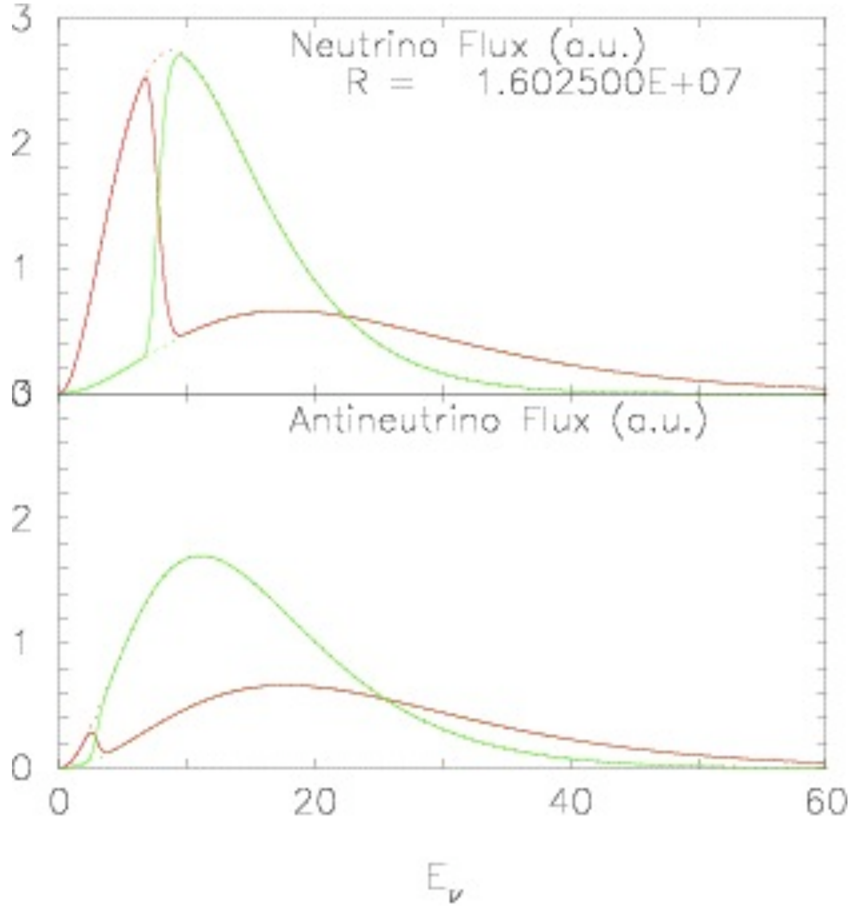
- ^{7}Li/^{11}B ratio

  ➡ Set off of uncertainties in yields by SN neutrino uncertainties

- $N(^7\mathrm{Li})/N(^{11}\mathrm{B})$ as *a constraint for oscillation parameters*

Neutrino Self-Interactions

- **Neutrino spectrum change by ν self-interactions**



2 flavor model
Single angle approximation

Inverted mass hierarchy
$\Delta m^2 = -2\times10^{-3}\ \mathrm{eV}^2,\ \sin^2 2\theta = 10^{-5}$

$L_{\nu\alpha} = 5\times10^{50}$ **ergs** s^{-1}
$(T_{\nu e}, T_{\bar{\nu} e}, T_{\nu x})$
= (4 MeV, 5MeV, 8MeV)

Spectrum split for ν_e
Spectrum conversion for $\bar{\nu}_e$

- **Change of ν_e and $\bar{\nu}_e$ spectra**

→ **Increase in *Ye* in neutrino driven winds**
Do ν self-interactions affect r-process nucleosynthesis?

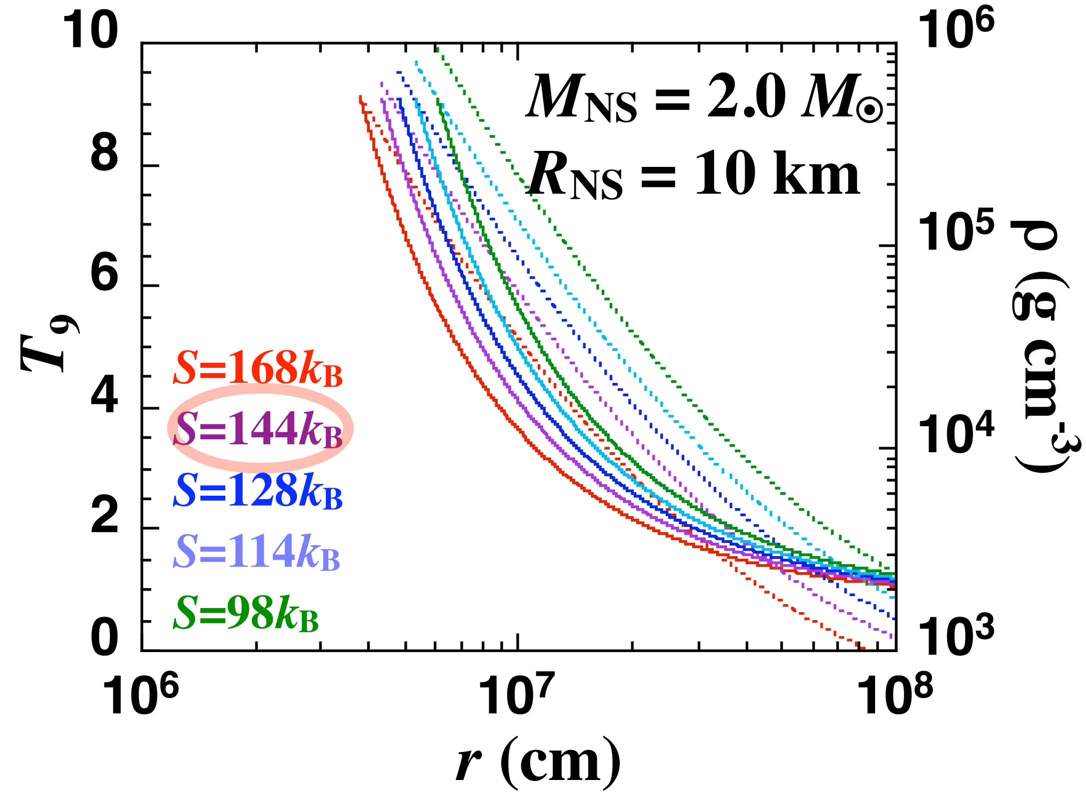
Constant Entropy Wind Model

$$v\frac{dv}{dr} = -\frac{c_s^2}{\rho}\frac{d\rho}{dr} - \frac{GM}{r^2}$$

$$\frac{dm}{dt} = 4\pi r^2 \rho v$$

$$S = \frac{4}{3} m_u a \frac{T^3}{\rho}$$

$$c_s^2 = \frac{4P}{3\rho}$$



- **Relation of S, $\dot{m}$, $L_{\nu\alpha}$, $\langle \varepsilon_{\bar{\nu}e} \rangle$ from Qian & Woosley (1996)**

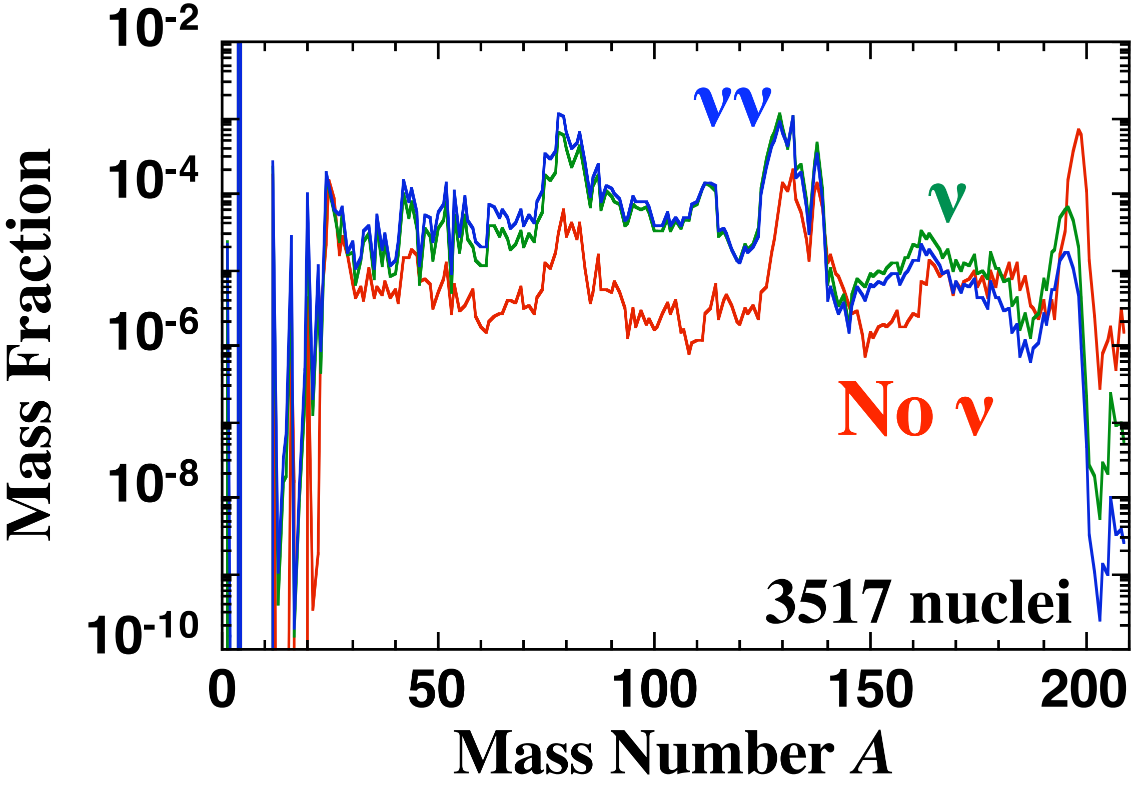
  $S/k_B \sim 235\ C^{-1/6} L_{\bar{\nu}e}^{-1/6} \langle \varepsilon_{\bar{\nu}e} \rangle^{-1/3} R_6^{-2/3} (M/1.4M_{\odot})$

  $dm/dt \sim 1.14\times10^{-10}\ C^{5/3} L_{\bar{\nu}e}^{5/3} \langle \varepsilon_{\bar{\nu}e} \rangle^{10/3} R_6^{5/3} (M/1.4M_{\odot})^2\ M_{\odot}\ s^{-1}$

- **Time scale of temperature decrease**

  ➡ ~ 0.01 - 0.1 s

r-Process Nucleosynthesis



TY09 in prep.

$M_{NS} = 2.0\ M_{\odot}$, $R_{NS} = 10$ km

$S = 144 k_B$

$dm/dt = 1.1\times10^{-6}\ M_{\odot}\ s^{-1}$

$L_{\nu\alpha} = 5\times10^{50}$ ergs s^{-1}

$(T_{\nu e}, T_{\bar{\nu}e}, T_{\nu x})$
$= (4\ \mathrm{MeV}, 5\mathrm{MeV}, 8\mathrm{MeV})$

$\tau_{(T9=5\rightarrow2)} = 5.3\times10^{-2}$ s

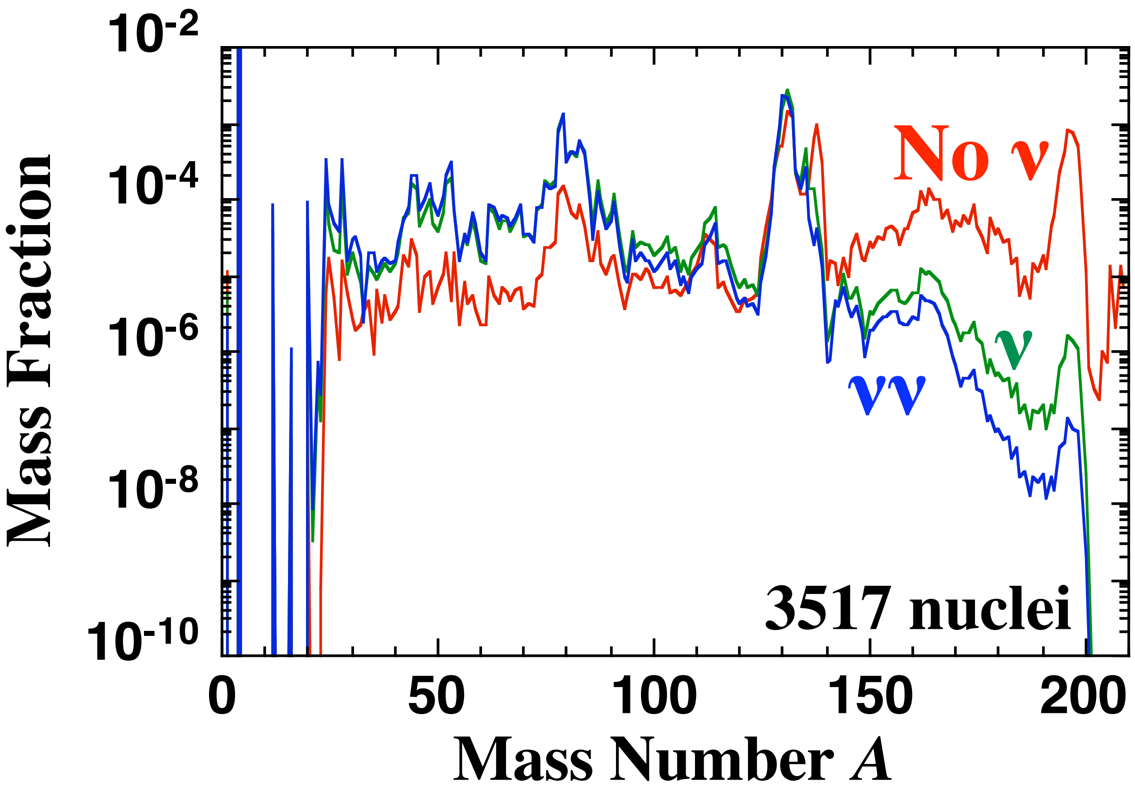
$Ye_{ini} = 0.40$

- r-process suppressed by ν-reactions (α-effect)
  (McLaughlin et al., 1996; Meyer et al. 1998)

  ➡ Reduction of the 3rd peak height
  Abundances of the 2nd peak elements enhance.
- *ν self-interactions enhance the supression.*

  ➡ Abundances beyond the 2nd peak are reduced.

r-Process Nucleosynthesis



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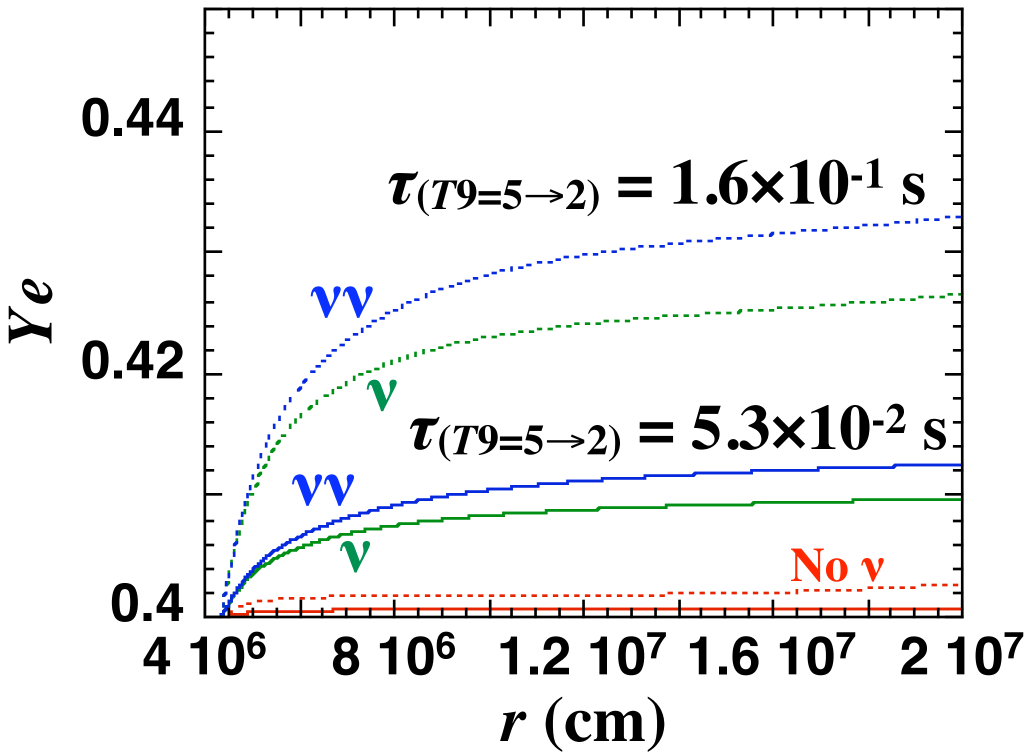
$(T_{\nu e}, T_{\bar{\nu}e}, T_{\nu x})$
$= (4$ MeV, 5MeV, 8MeV$)$

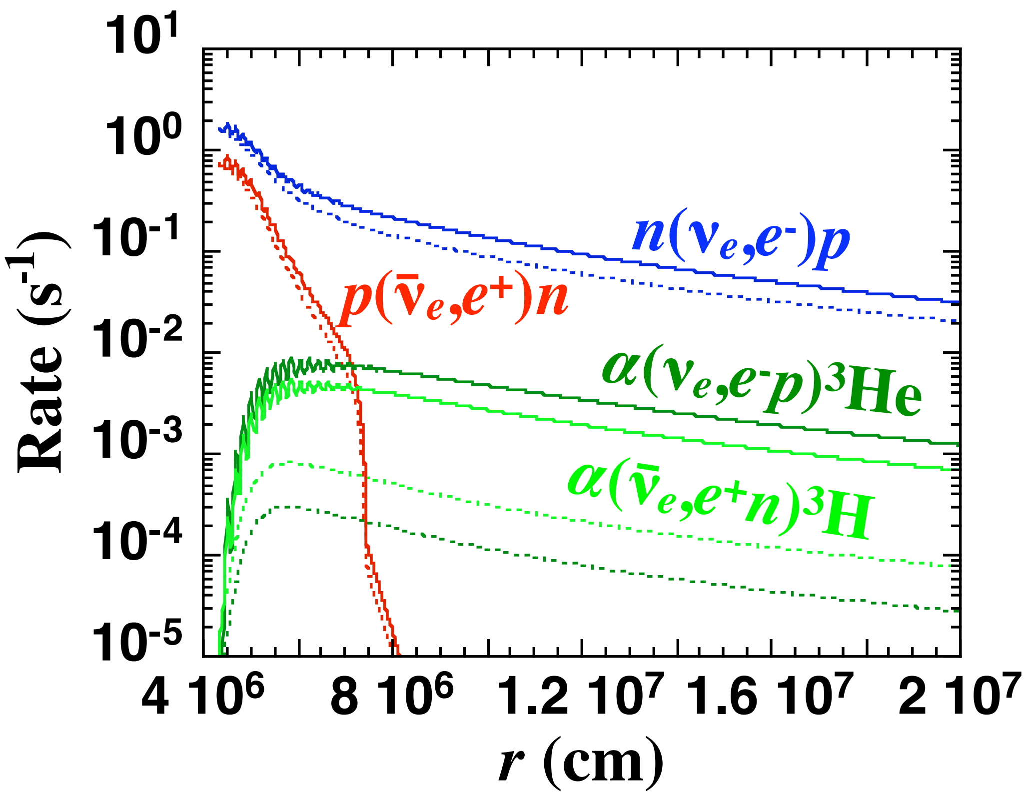
$\tau_{(T9=5\rightarrow2)} = 1.6\times10^{-1}$ s

$Ye_{ini} = 0.40$

- **Slower winds**
  - ➡ **Influence of ν-reactions (α-effect) becomes large.**
- ***ν self-interactions enhance the suppression.***
  - ➡ **More reduction of abundances beyond the 2nd peak**

Ye Change





- ***Ye*** **increases to 0.41 (fast) and ~0.43 (slow) by ν-reactions.**
  $n(\nu_e,e^-)p$
- **Spectrum split of ν_e and ν_x by ν self-interactions**

  ➡ **Enhancement of *Ye* increase by about 20%**

  The effect is seen but it is *not* drastic.

Effect to Other Elements

- Light elements (^{7}Li and ^{11}B)

  ➡ Affected by ν self-interactions and MSW effect

  Yields depend on mass hierarchy and θ_{13}

- ^{19}F, ^{55}Mn, ^{138}La, and ^{180}Ta

  ➡ Increase in their yields by ν self-interactions

Summary

- **Light element synthesis through the ν-process**
  - ➡ **^{7}Li and ^{11}B are main products**
    ^{4}He(ν,ν'*p*)^{3}H, ^{4}He(ν,ν'*n*)^{3}He, ^{12}C(ν,ν'*p*)^{11}B, ^{12}C(ν,ν'*n*)^{11}C

- **Light element synthesis with neutrino oscillations in SNe**
  - ➡ **Enhancement of the contribution from charged-current reactions**
  - ➡ ***N*(^{7}Li)/*N*(^{11}B) as a *constraint for oscillation parameters***

- ***r*-process with ν self-interactions in wind model**
  - ➡ ***r*-process suppressed by ν-reactions (α-effect)**
    ν self-interactions enhance *Ye* increase but *not* drastic.

Collaborators

Astrophysicists

- **Toshitaka Kajino (National Astronomical Observatory of Japan)**
- **Dieter H. Hartmann (Clemson University)**

Nuclear physicists

- **Toshio Suzuki (Nihon University)**
- **Satoshi Chiba (Japan Atomic Energy Agency)**

Particle physicists

- **Akira Takamura (Toyota National College of Technology)**
- **Keiichi Kimura (Nagoya University)**
- **Hidekazu Yokomakura (Nagoya University)**