

# 超新星ニュートリノに関する現状と課題

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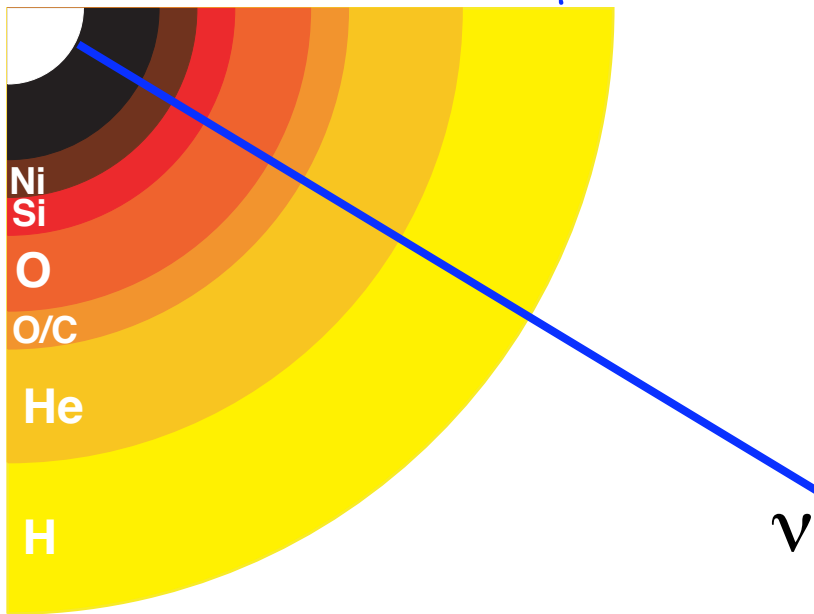
国立天文台理論研究部

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# 超新星ニュートリノ

$$\langle \epsilon_{\nu e} \rangle < \langle \epsilon_{\bar{\nu} e} \rangle < \langle \epsilon_{\nu \mu\tau} \rangle$$



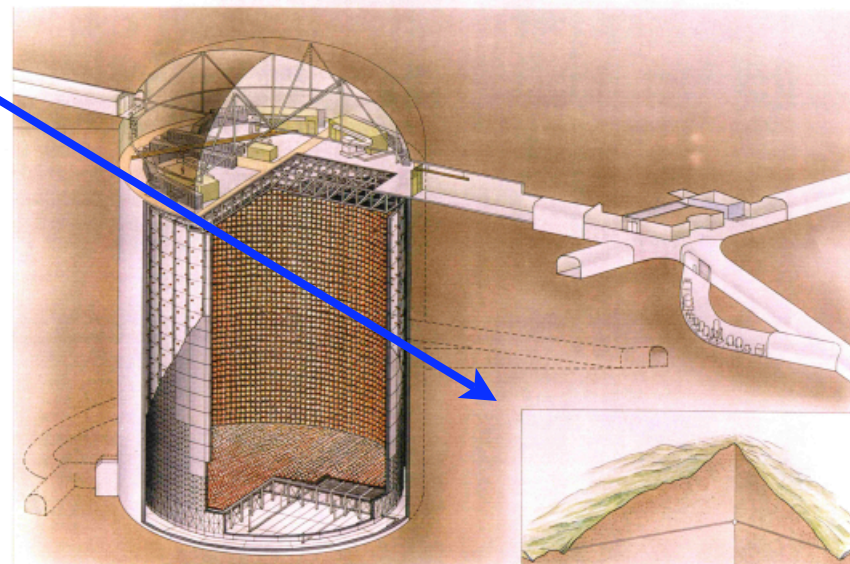
## ニュートリノ元素合成

- The  $\nu$ -process
- $\nu p$ -process
- $r$ -process

## 超新星ニュートリノの検出

- 直接検出
- 超新星 relic neutrinos

➡ 超新星ニュートリノ  
Collapsing stellar core  
ニュートリノ振動



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# 超新星ニュートリノ元素合成

## $\nu$ -processの反応率

Neutral current reactions e.g.,  $(Z,A) + \nu \rightarrow (Z-1,A-1) + \nu' + p$

$$\lambda_\nu = \sum_{\alpha=e,\mu,\tau} \frac{L_{\nu\alpha}}{4\pi r^2} \frac{1}{F_3(\eta_{\nu\alpha})(kT_{\nu\alpha})^4} \int_0^\infty \frac{\varepsilon^2 \sigma_\nu(\varepsilon) d\varepsilon}{\exp(\varepsilon/kT_{\nu\alpha} - \eta_{\nu\alpha}) + 1}$$

Charged current reactions e.g.,  $(Z,A) + \nu_e \rightarrow (Z+1,A) + e^-$

$$\lambda_{\nu e} = \sum_{\alpha=e,\mu,\tau} \frac{L_{\nu\alpha}}{4\pi r^2} \frac{1}{F_3(\eta_{\nu\alpha})(kT_{\nu\alpha})^4} \int_0^\infty \frac{\varepsilon^2 P_{\alpha e}(r;\varepsilon) \sigma_{\nu e}(\varepsilon) d\varepsilon}{\exp(\varepsilon/kT_{\nu\alpha} - \eta_{\nu\alpha}) + 1}$$

Neutrino luminosity

$$L_{\nu\alpha}(t) = \frac{1}{6} \frac{E_\nu}{\tau_\nu} \exp\left(-\frac{t-r/c}{\tau_\nu}\right) \Theta(t-r/c)$$

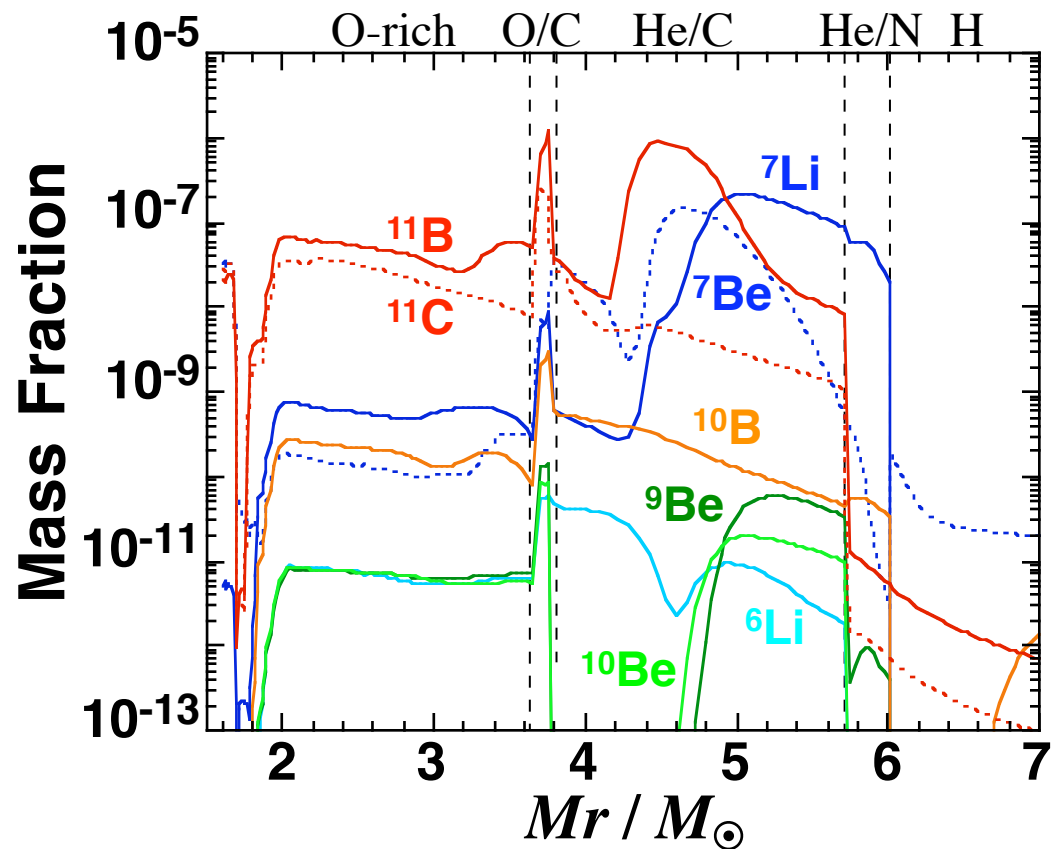
- $E_\nu$ : ニュートリノが運び去る全エネルギー
- $\tau_\nu$ : neutrino luminosityが減少するタイムスケール
- $T_{\nu\alpha}$ :  $\nu_\alpha$  の温度
- $P_{\nu\alpha e}(r;\varepsilon)$ :  $\nu_\alpha$  から  $\nu_e$  へのニュートリノ振動遷移確率

# $\nu$ -Processによる軽元素合成

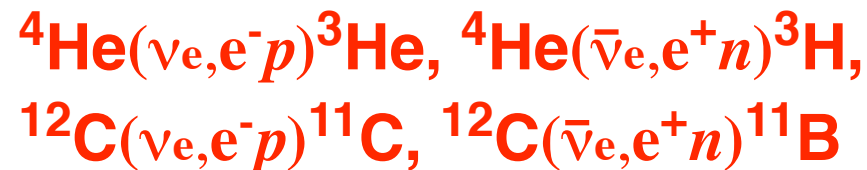
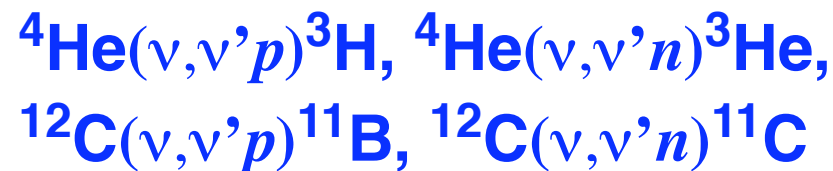
## ● 軽元素質量比分布

16.2  $M_{\odot}$  超新星 (SN 1987A)  $E_{\nu}=3\times 10^{53}$  ergs,  $T_{\nu,\mu,\tau}=6$  MeV

(Yoshida et al. 2008, ApJ 686, 448)



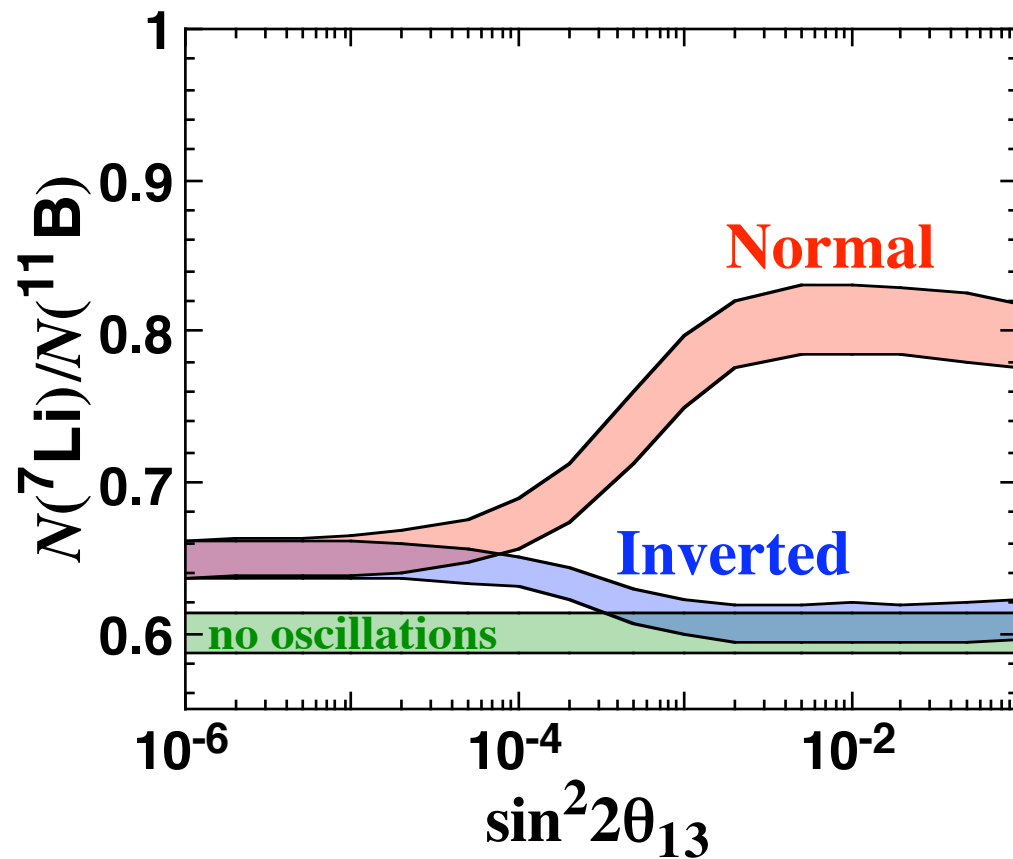
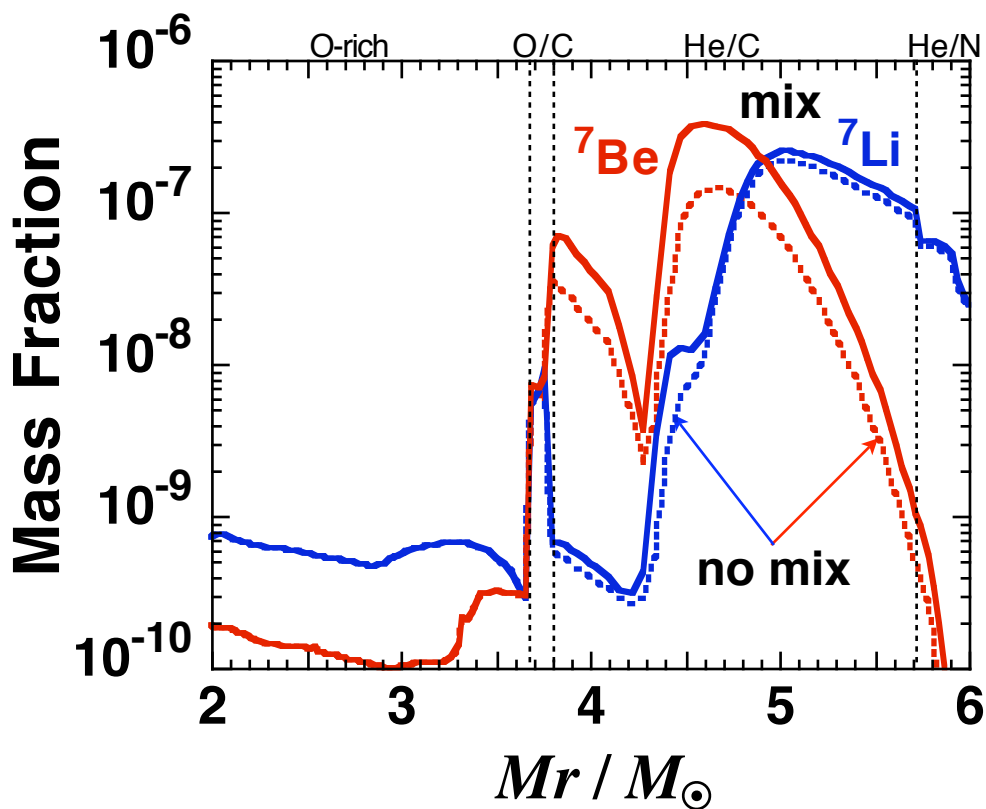
## ● 重要な $\nu$ -process反応



# ニュートリノ振動を考慮した $\nu$ -Process

- ${}^7\text{Li}$ ,  ${}^{11}\text{B}$ 生成量  $\rightarrow$  ニュートリノ振動によって増加

(Yoshida et al. 2006, PRL 96, 091101; Yoshida et al. 2008, ApJ 686, 448)



## Charged-current reactions

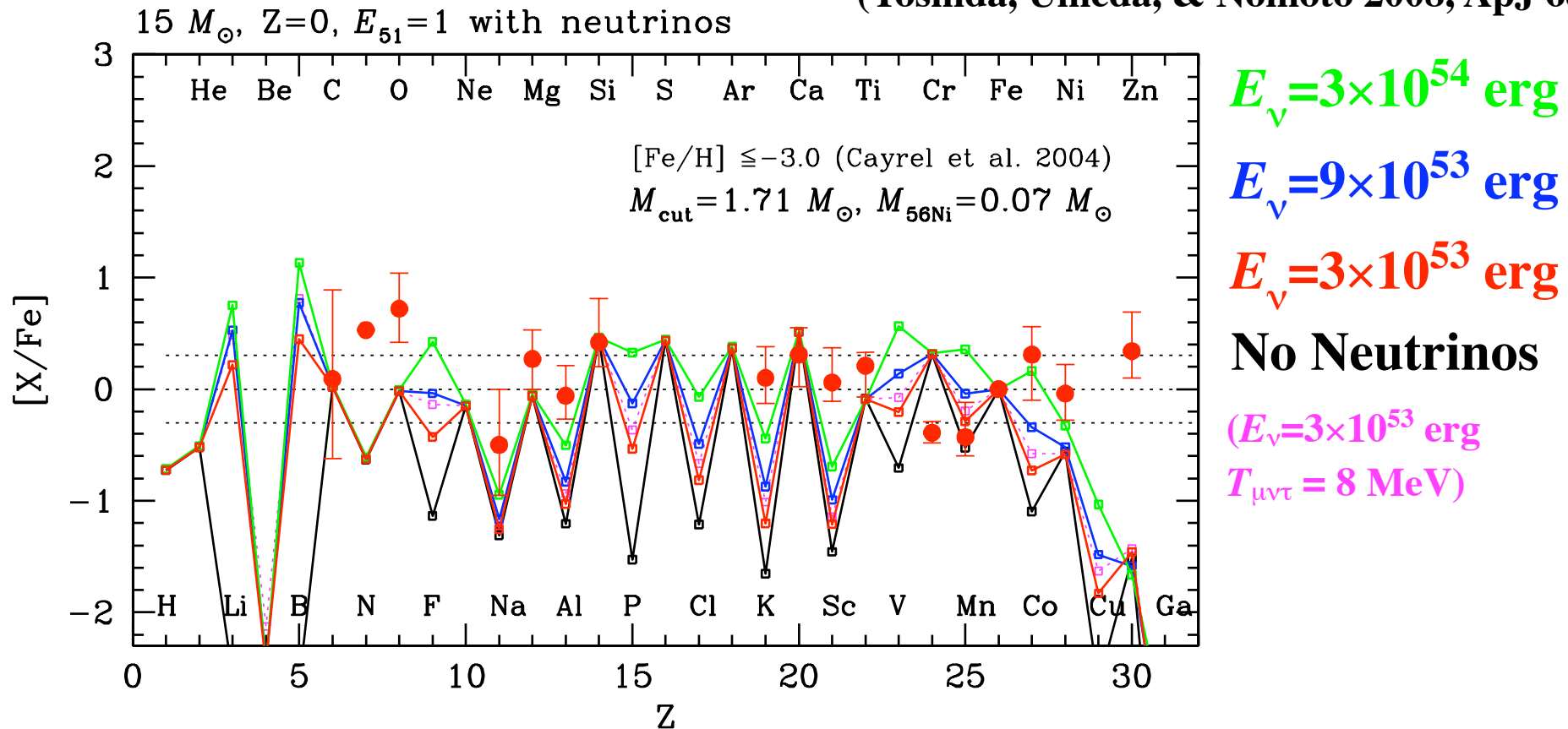


- $N({}^7\text{Li})/N({}^{11}\text{B})$ が振動パラメータへの制限となる可能性

# 鉄族元素におけるν-Process

## ● 15 M<sub>⊙</sub> Pop III 超新星における ν-process

(Yoshida, Umeda, & Nomoto 2008, ApJ 686, 448)



● Mn → <sup>56</sup>Ni(ν, ν'p) <sup>55</sup>Co(β<sup>+</sup>) <sup>55</sup>Fe(β<sup>+</sup>) <sup>55</sup>Mn

●  $E_{\nu} < 9 \times 10^{53}$

→ EMP starでのMn存在度を改善

# $\nu p$ -Process

超新星ejecta最深部 ( $Y_e > 0.5$ )

→ 爆発時におけるニュートリノ照射  
 $p(\bar{\nu}_e, e^+)n$ による中性子の生成

●  $p(\bar{\nu}_e, e^+)n$ なし →  $^{64}\text{Ge}$ で反応凍結

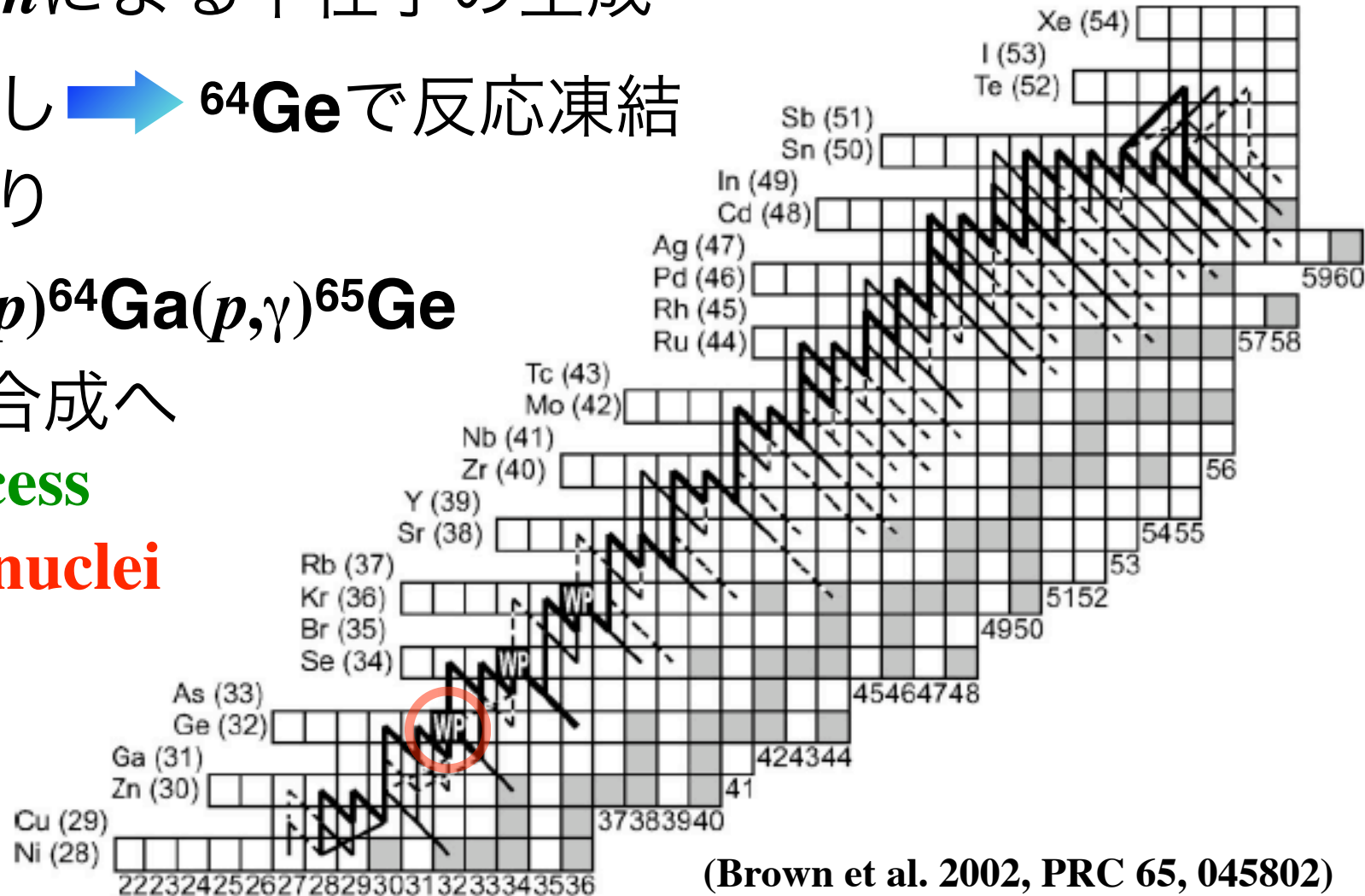
●  $p(\bar{\nu}_e, e^+)n$ あり

→  $^{64}\text{Ge}(n, p)^{64}\text{Ga}(p, \gamma)^{65}\text{Ge}$

重元素合成へ

$\nu p$ -process

$A > 64$  nuclei



(Brown et al. 2002, PRC 65, 045802)



# vp-Process

超新星ejecta最深部 ( $Y_e > 0.5$ )

→ 爆発時におけるニュートリノ照射  
 $p(\bar{\nu}_e, e^+)n$ による中性子の生成

●  $p(\bar{\nu}_e, e^+)n$ なし →  $^{64}\text{Ge}$ で反応凍結

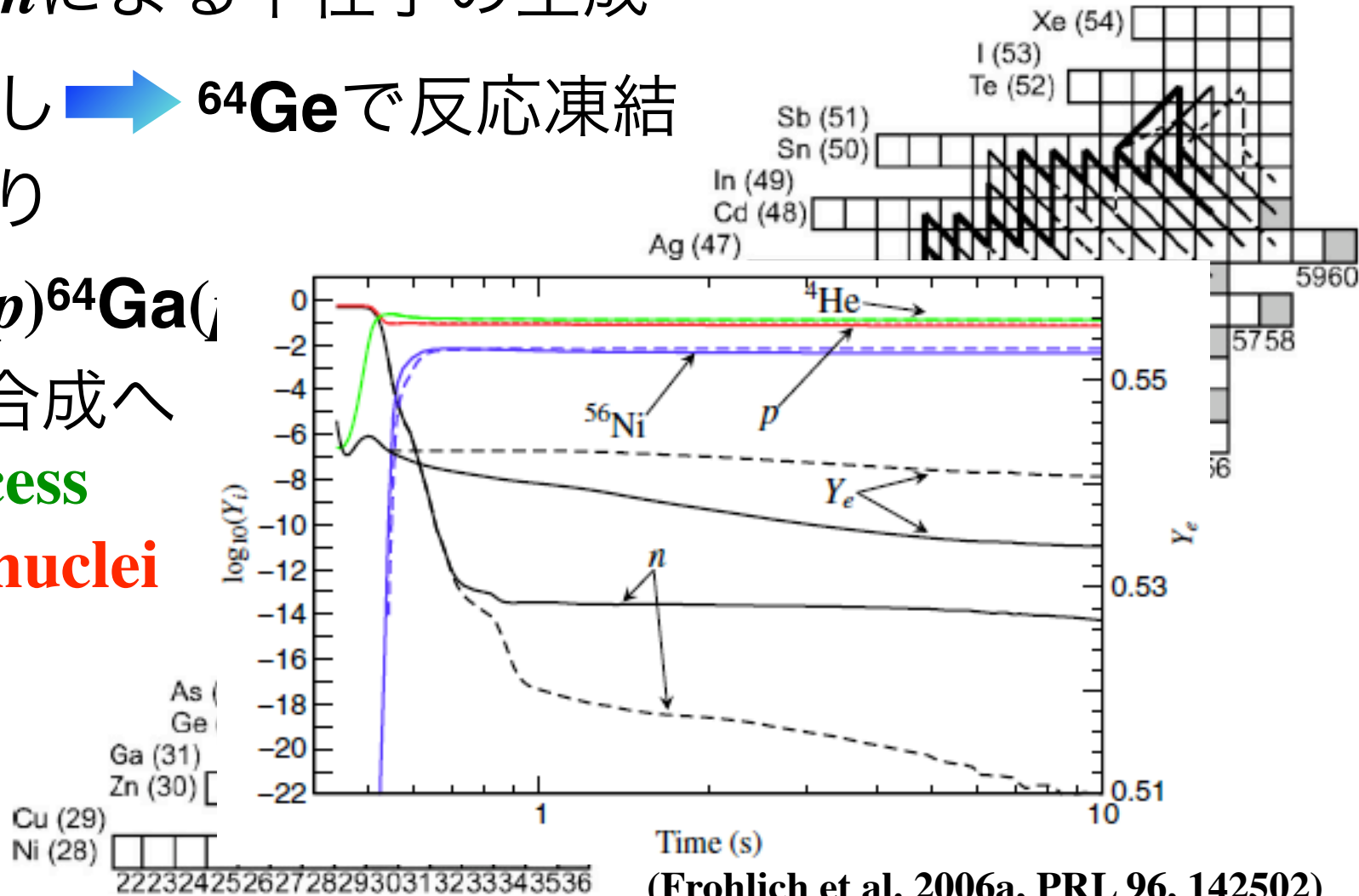
●  $p(\bar{\nu}_e, e^+)n$ あり

→  $^{64}\text{Ge}(n, p)^{64}\text{Ga}$

重元素合成へ

vp-process

$A > 64$  nuclei



(Frohlich et al. 2006a, PRL 96, 142502)



# $\nu p$ -Process

超新星ejecta最深部 ( $Y_e > 0.5$ )

→ 爆発時におけるニュートリノ照射  
 $p(\bar{\nu}_e, e^+)n$ による中性子の生成

●  $p(\bar{\nu}_e, e^+)n$ なし →  $^{64}\text{Ge}$ で反応凍結

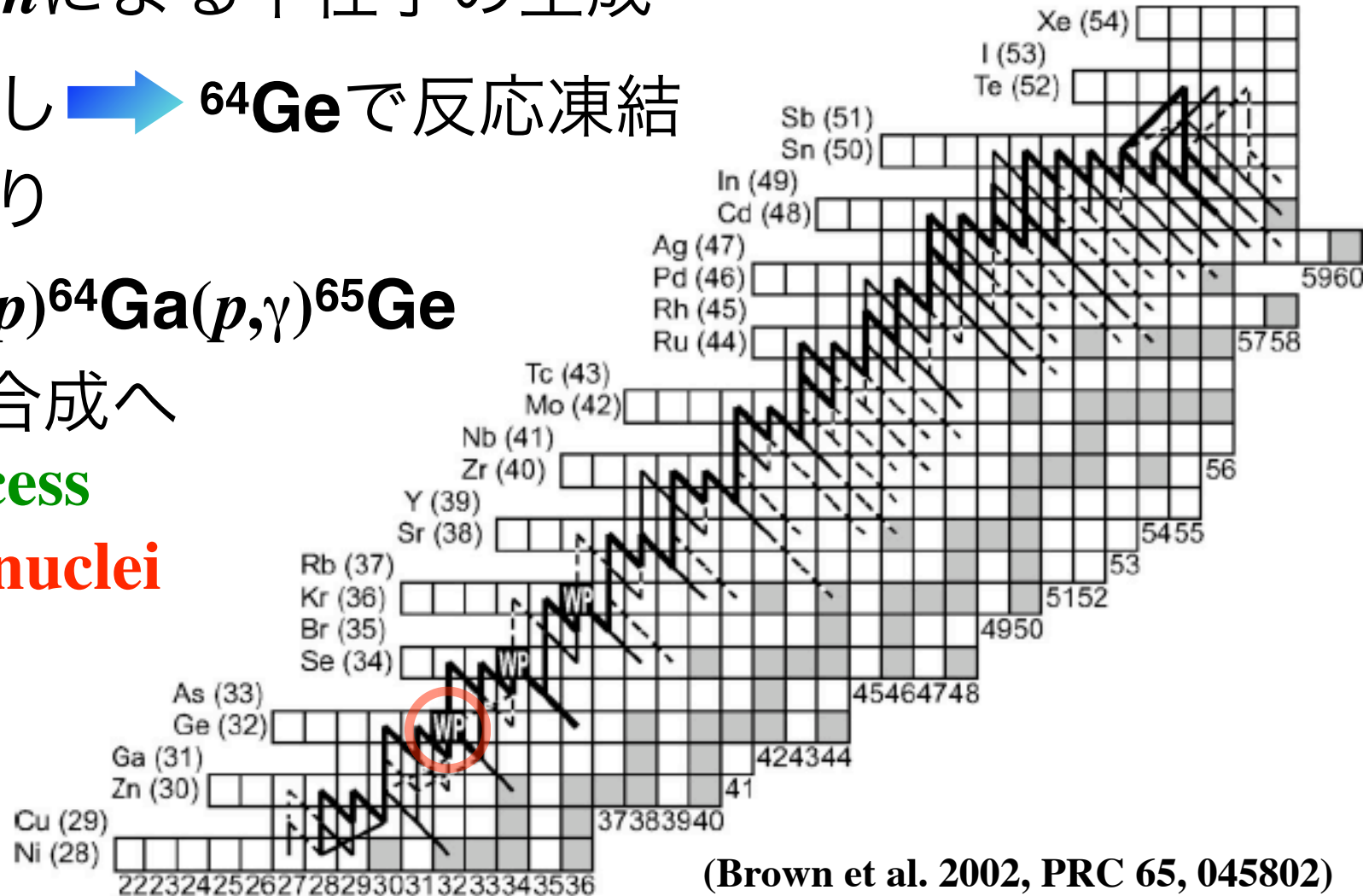
●  $p(\bar{\nu}_e, e^+)n$ あり

→  $^{64}\text{Ge}(n, p)^{64}\text{Ga}(p, \gamma)^{65}\text{Ge}$

重元素合成へ

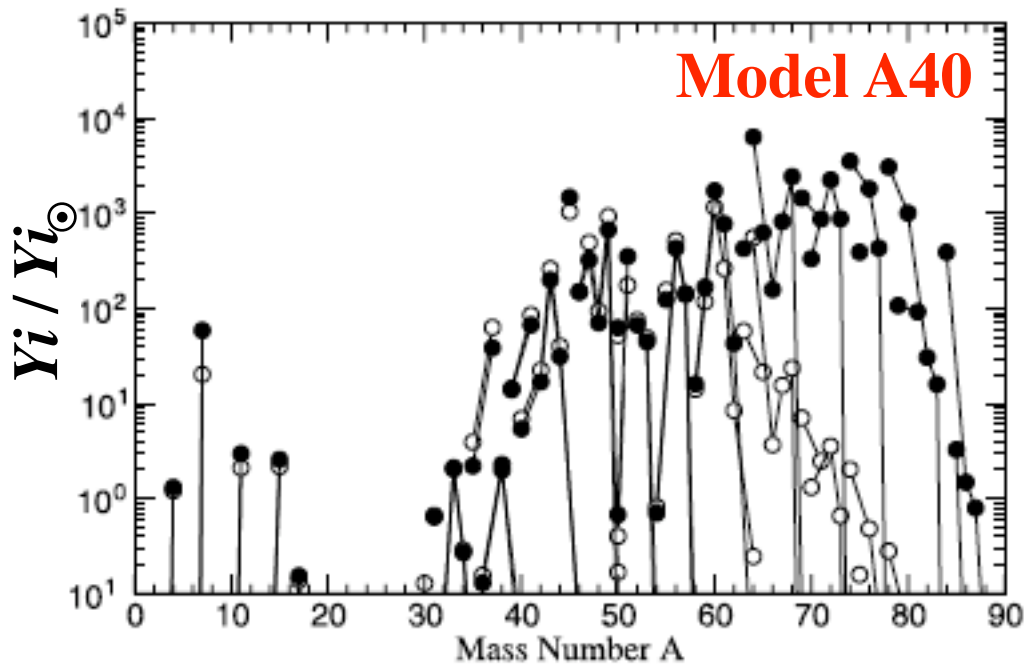
$\nu p$ -process

$A > 64$  nuclei



(Brown et al. 2002, PRC 65, 045802)

# vp-Process



(Frohlich et al. 2006a, PRL 96, 142502;  
 Frohlich et al. 2006b, ApJ 637, 415  
 Pruet et al. 2006, ApJ 644, 1028;  
 Wanajo 2006, ApJ 647, 1323)

From Frohlich et al. 2006a

○  $p(\bar{\nu}_e, e^+)n$  なし

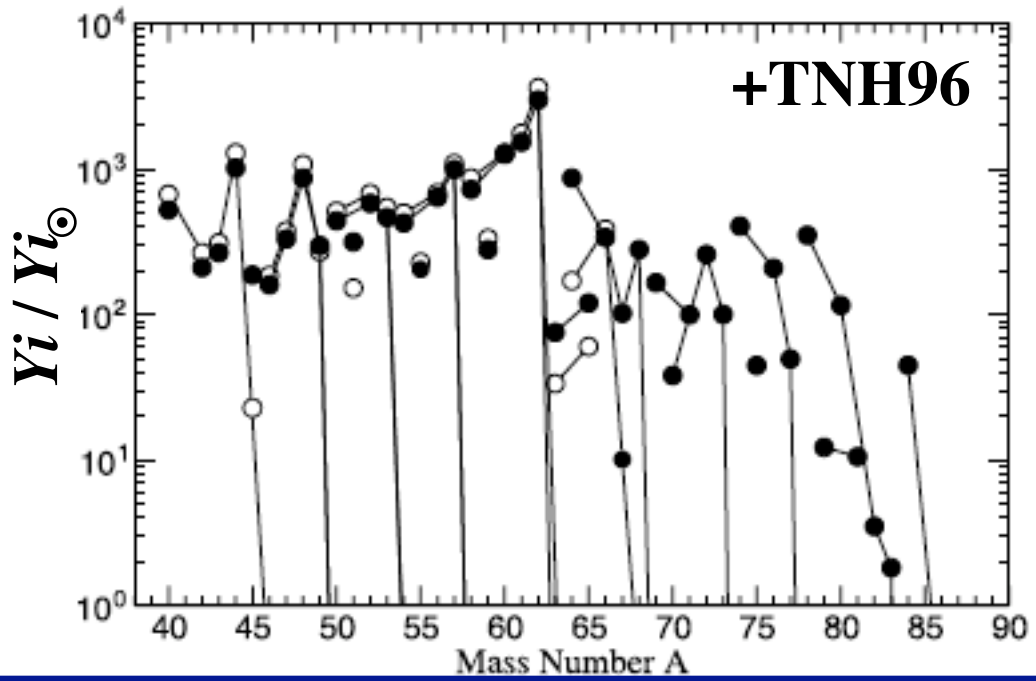
➡  $^{64}\text{Ge}$  で反応凍結

$^{45}\text{Sc}, ^{49}\text{Ti}, ^{64}\text{Zn}$

●  $p(\bar{\nu}_e, e^+)n$  あり

➡  $^{64}\text{Ge}(n, p)^{64}\text{Ga}(p, \gamma)^{65}\text{Ge}$

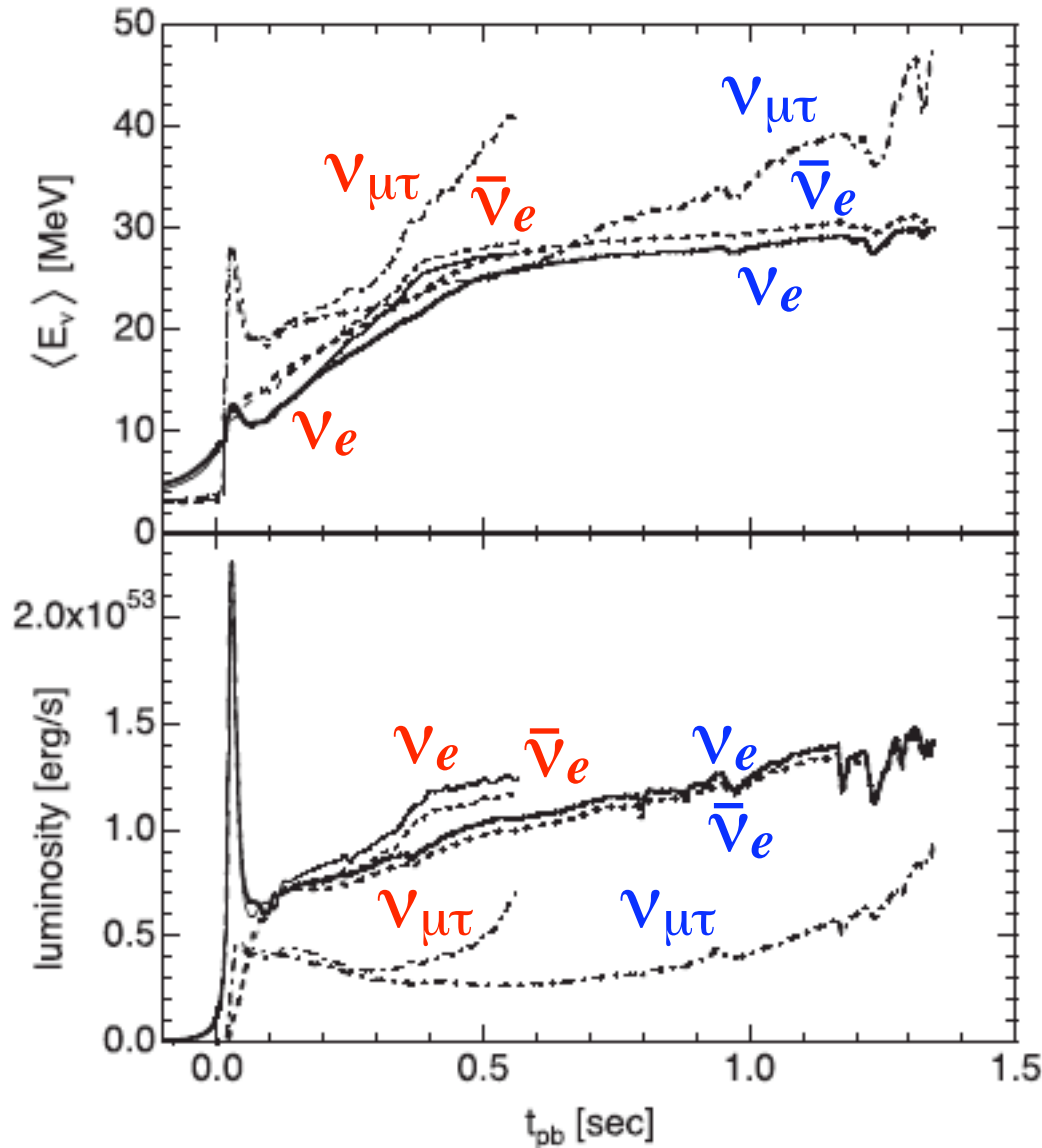
$A > 64$  nuclei



# Neutrinos from Collapsing Stars

## Neutrinos from a BH forming collapse

(Sumiyoshi et al. 2006, PRL 97, 091101; 2007, ApJ 667, 382; 2008, ApJ 688, 1176)



### 40 $M_\odot$ progenitor

(Woosley & Weaver 1995, ApJS 101, 181)

### Neutrino signal

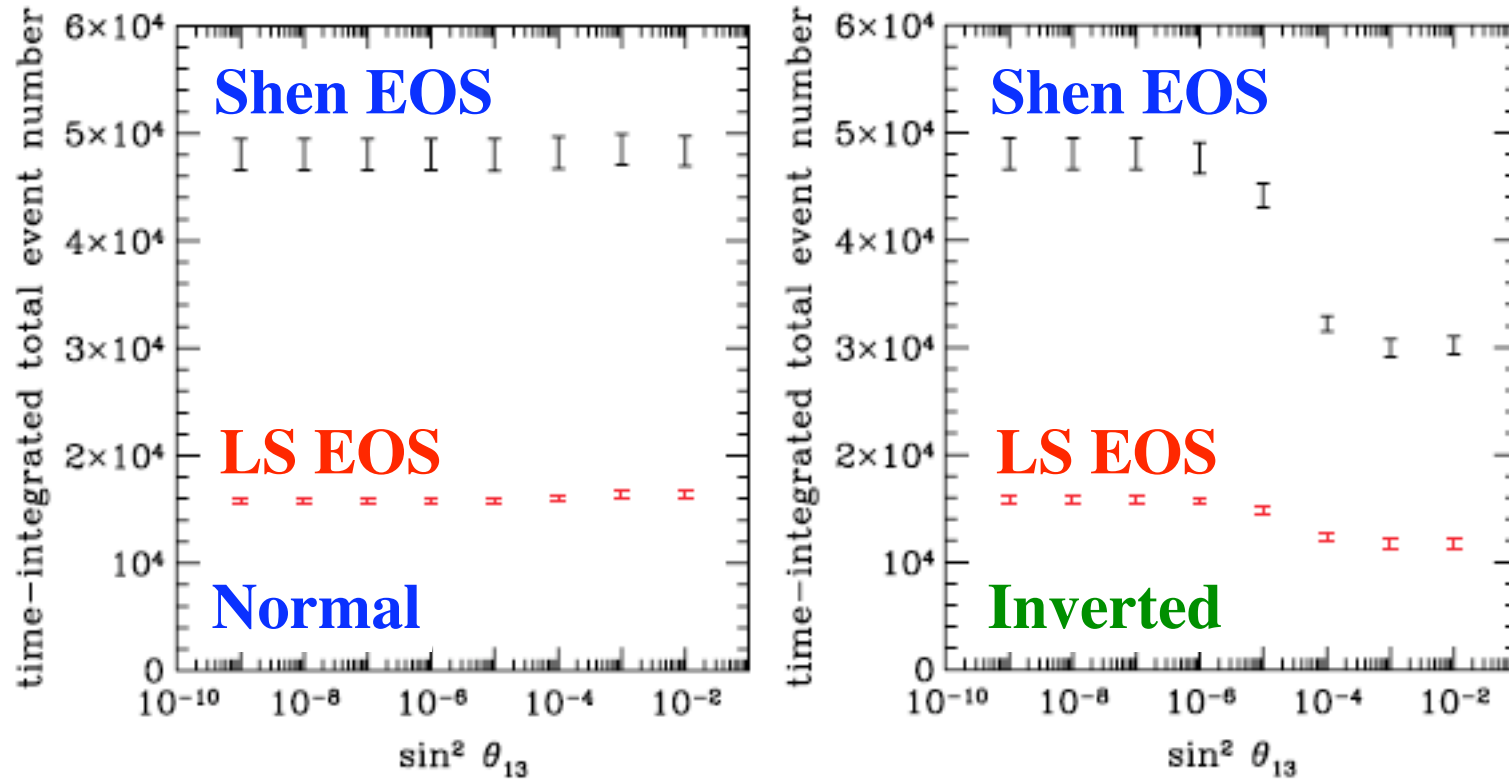
➡ collapsing coreの  
状態方程式に依存

Shen EOS

Lattimer & Swesty EOS

# Neutrinos from Collapsing Stars

SKによる $\bar{\nu}_e$ 検出予測 (Nakazato et al. 2008, PRD 78, 083014)



Shen EOS



$(2.9 - 4.9) \times 10^4$  events

Lattimer & Swesty EOS

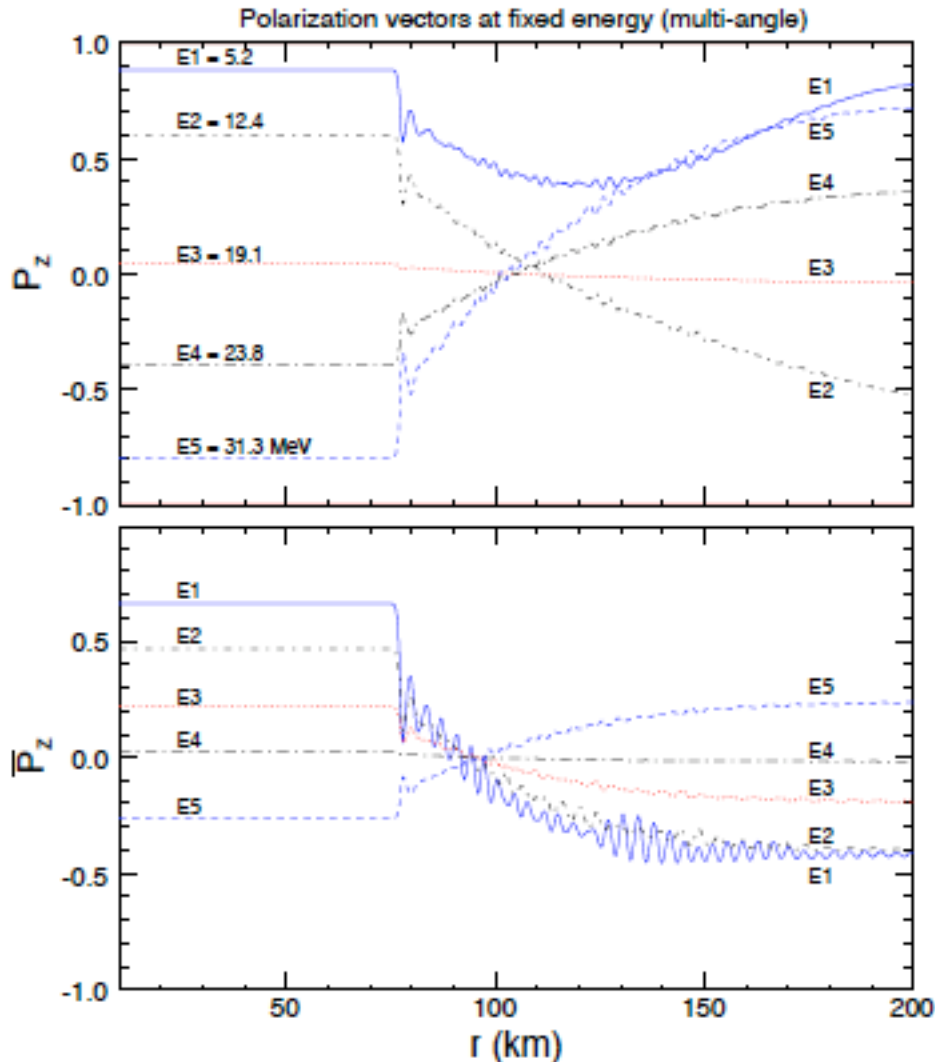


$(1.1 - 1.7) \times 10^4$  events

collapsing coreの状態方程式に制限

# Neutrino Oscillations with $\nu\nu$ -Interactions

$$i\hbar c \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = [UMU^\dagger + H_e + H_{\nu\nu}] \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$



$H_e$  : MSW effect

$H_{\nu\nu}$  :  $\nu\nu$  forward scattering

$$P_z = (n_{\nu e} - n_{\nu x}) / (n_{\nu e} + n_{\nu x})$$

$$\bar{P}_z = (n_{\bar{\nu} e} - n_{\bar{\nu} x}) / (n_{\bar{\nu} e} + n_{\bar{\nu} x})$$

Inverted mass hierarchy

$$L_\nu = 10^{51} \text{ ergs}; |\Delta m^2 c^4| = 2 \times 10^{-3} \text{ eV}^2; \sin^2 \theta_{13} = 10^{-4}$$

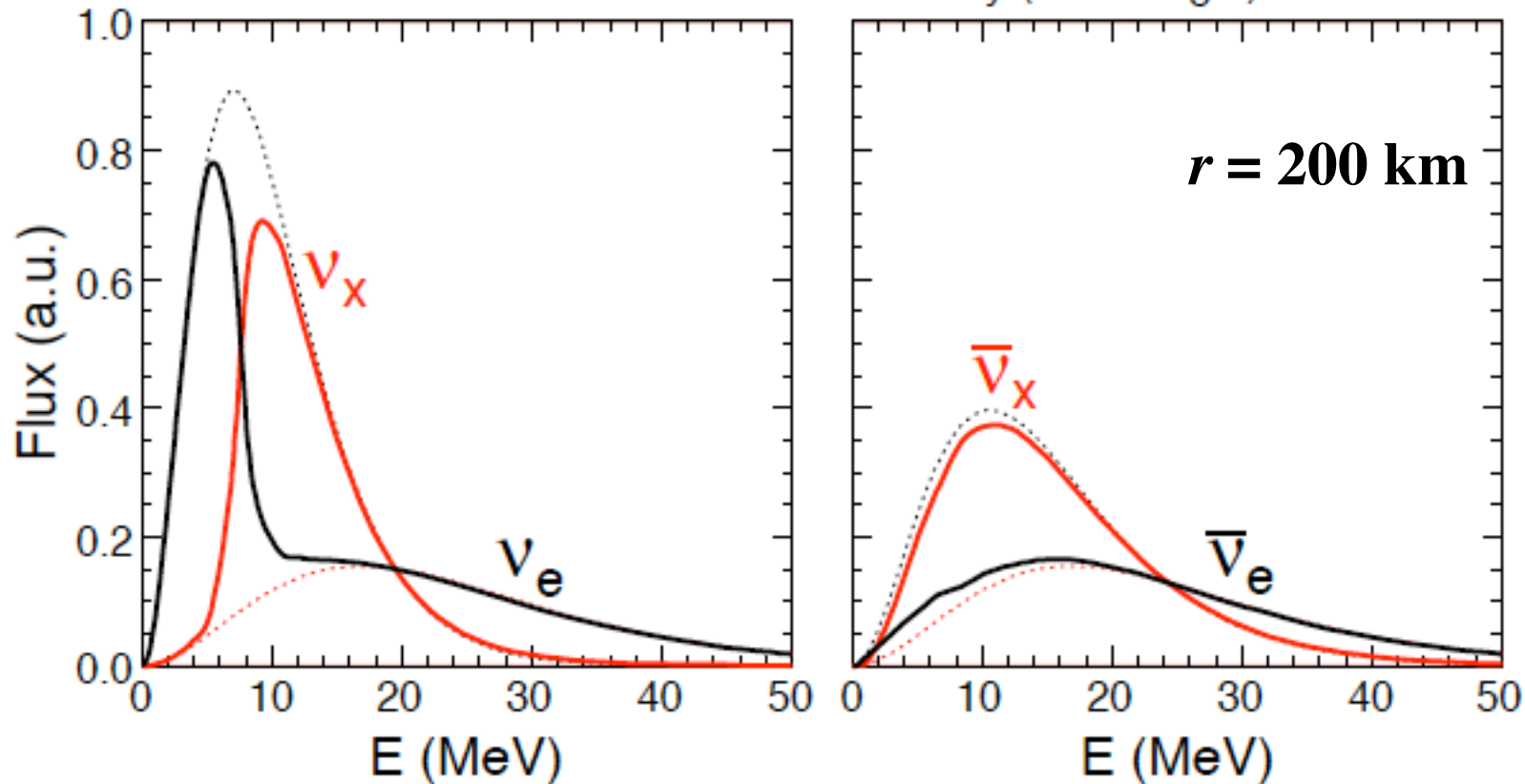
(Fogli et al. 2007, JCAP 12, 010)

# Neutrino Oscillations with $\nu\nu$ -Interactions

$$i\hbar c \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = [UMU^\dagger + H_e + H_{\nu\nu}] \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$H_e$  : MSW effect       $H_{\nu\nu}$  :  $\nu\nu$  forward scattering

Final fluxes in inverted hierarchy (multi-angle)



**Inverted mass hierarchy**

$$L_\nu = 10^{51} \text{ ergs}; |\Delta m^2 c^4| = 2 \times 10^{-3} \text{ eV}^2; \sin^2 \theta_{13} = 10^{-4}$$

(Fogli et al. 2007, JCAP 12, 010)

# まとめと課題

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## ニュートリノ元素合成 The $\nu$ -process, $\nu p$ -process

- $\nu$ -process → 軽元素, 鉄族元素(奇数核)  
ニュートリノ振動の効果
- $\nu p$ -process → 重元素合成( $p$ 核)

→ 詳細な爆発モデルと合わせた元素合成  
(特にejectaの最深部)

→ Effects by  $\nu\nu$  interactions →  $r$ -process?



# まとめと課題

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## 超新星ニュートリノの検出

- **BH forming** コアからのニュートリノ

➡ **progenitor**や状態方程式の依存性

- **$\nu\nu$  interactions**

➡ 爆発モデル依存性

**Effects by  $\nu\nu$  interactions?**

**progenitor**の違いを他の方法で見られるか

➡ **relic neutrinos?**

# Neutrino Oscillations

$$i\hbar \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left\{ U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 c^4 / 2\varepsilon_\nu & \\ & & \Delta m_{31}^2 c^4 / 2\varepsilon_\nu \end{pmatrix} U^\dagger + A(n_e) \right\} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

*flavor eigenstate*

*MNS matrix*  
(Maki, Nakagawa, Sakata)

*mass eigenstate*

$$A(n_e) = \begin{pmatrix} \pm\sqrt{2}G_F(\hbar c)^3 n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad n_e : \text{electron number density}$$

- Squared mass differences
- Mixing angles

$$\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$$

$$s_{ij} \equiv \sin\theta_{ij}, \quad c_{ij} \equiv \cos\theta_{ij}$$

- *CP* phase  $\delta$   $\delta=0$  (This study)

# Neutrino Oscillation Parameters

- Squared mass differences

➔  $\Delta m^2_{31} = \pm 2.4 \times 10^{-3} \text{ eV}^2, \Delta m^2_{21} = 7.9 \times 10^{-5} \text{ eV}^2$

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

## Mass hierarchy

**Normal**

**Inverted**

$m_3$  —————

$m_3 < m_1 < m_2$

—————  $m_2$   
—————  $m_1$

—————  
—————

$m_1 < m_2 < m_3$

—————  $m_3$

$\Delta m^2_{13} + \Delta m^2_{32} + \Delta m^2_{21} = 0$

- Mixing angles

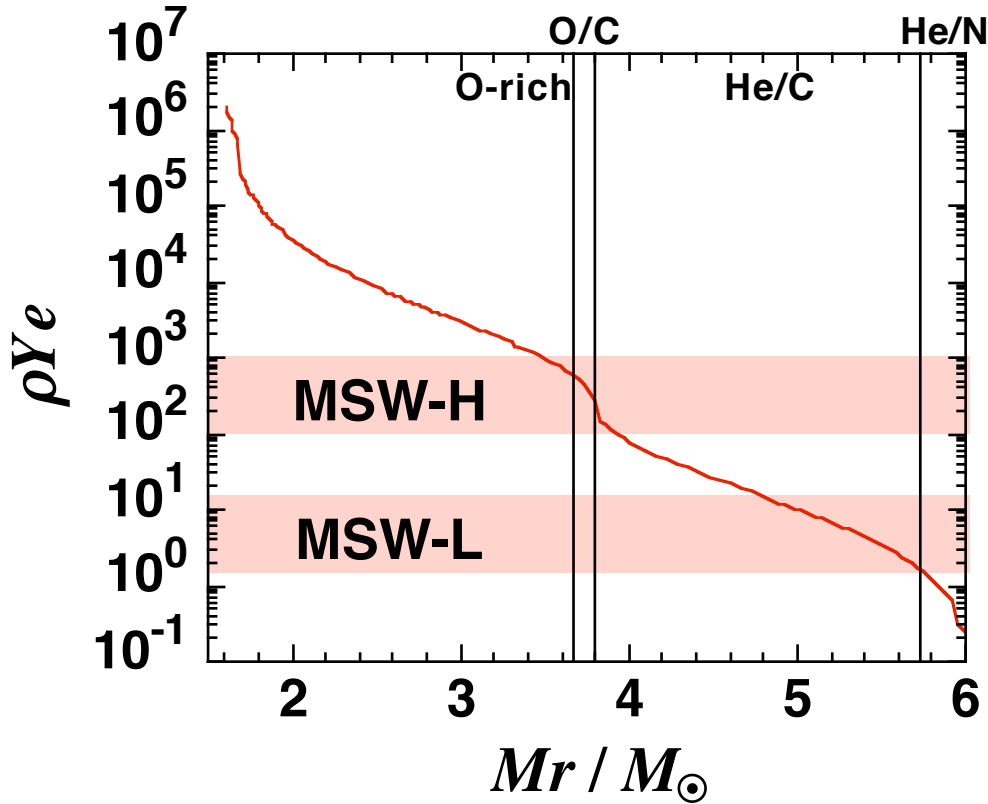
➔  $\sin^2 2\theta_{12} = 0.816, \sin^2 2\theta_{23} = 1$

$\sin^2 2\theta_{13} < 0.1$  (Based on CHOOZ 2003; SK 2004; SNO 2004; KamLAND 2005)

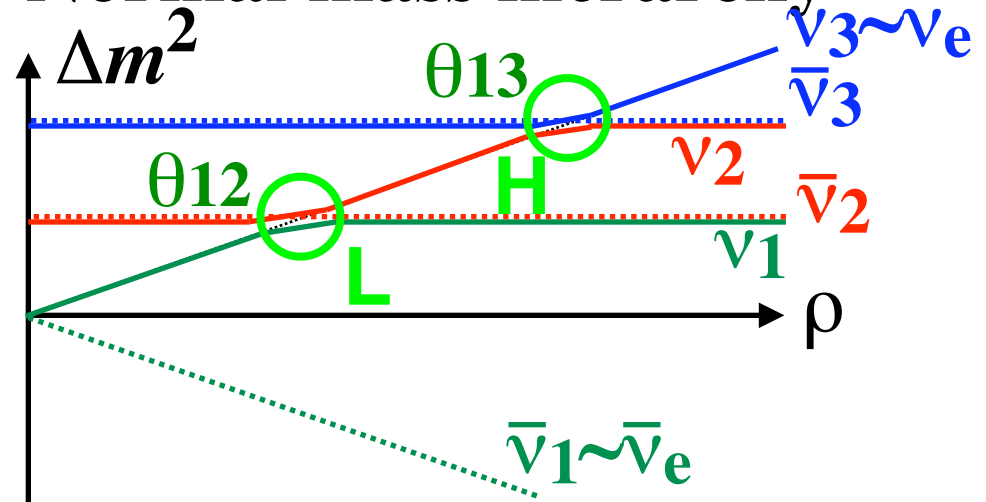
# Resonances of Neutrino Oscillations

- Flavor change occurs at resonances.

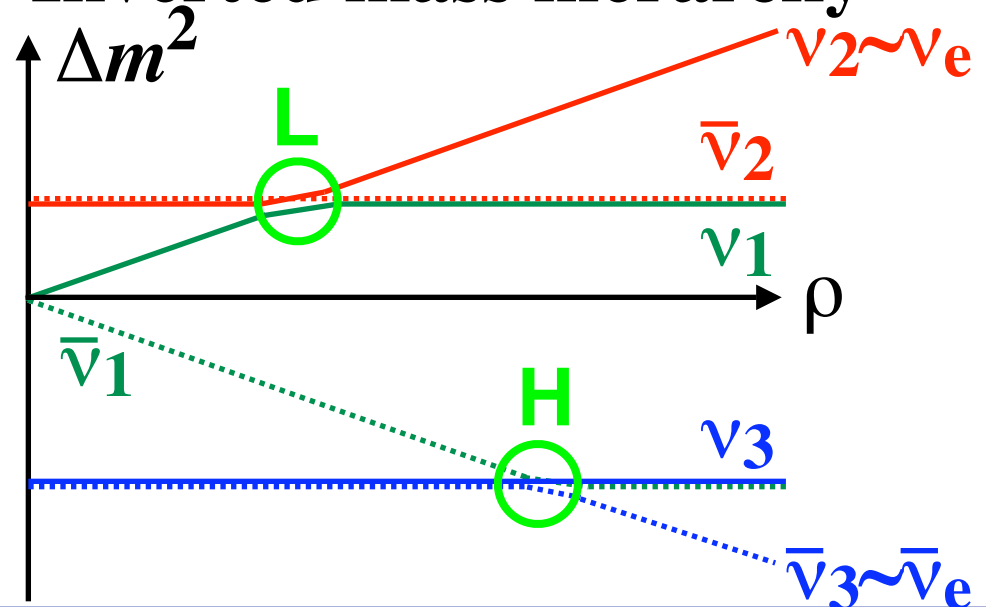
## SN 1987A presupernova



- Normal mass hierarchy



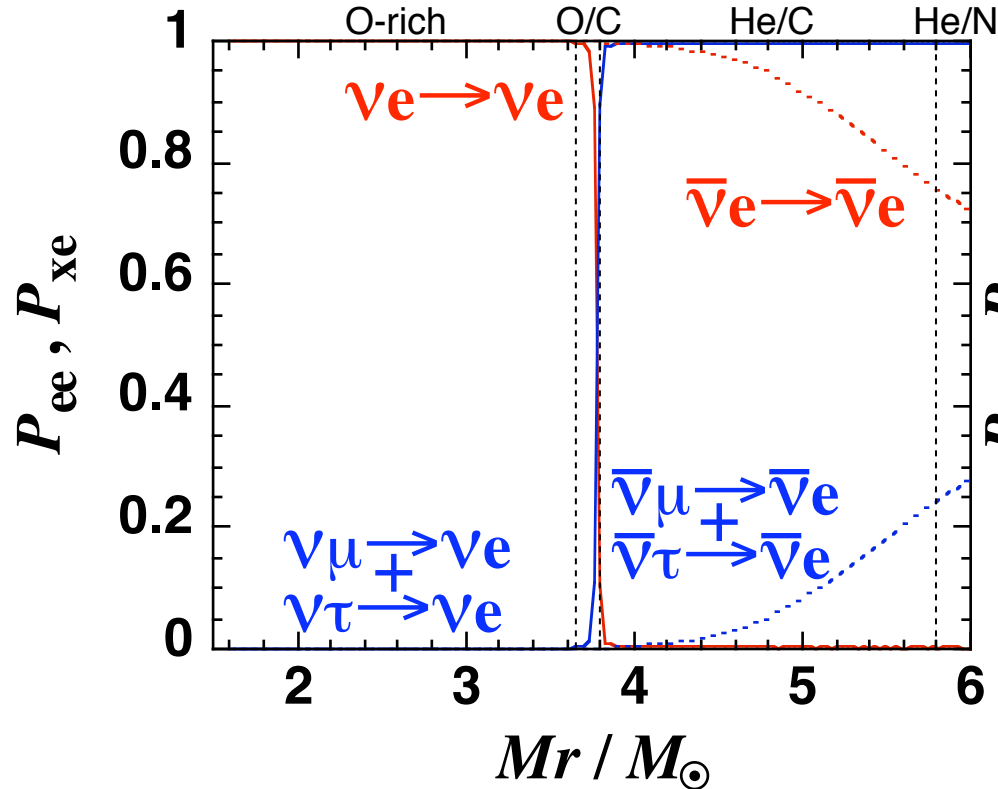
- Inverted mass hierarchy



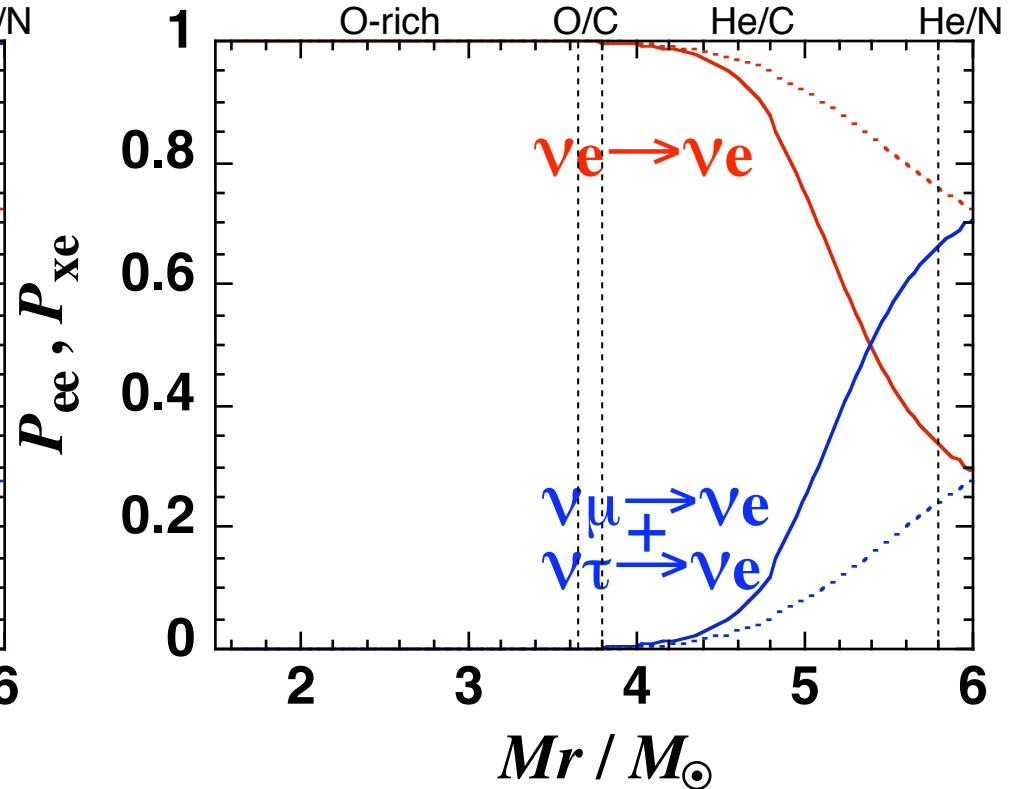
# Conversion Probabilities

## ● Normal mass hierarchy

*adiabatic*  $\sin^2 2\theta_{13} = 0.01$



*nonadiabatic*  $\sin^2 2\theta_{13} = 10^{-6}$



*adiabatic* H-resonance

➡ All  $\nu_e$  in He layer have changed from  $\nu_{\mu\tau}$ .

*nonadiabatic* H-resonance

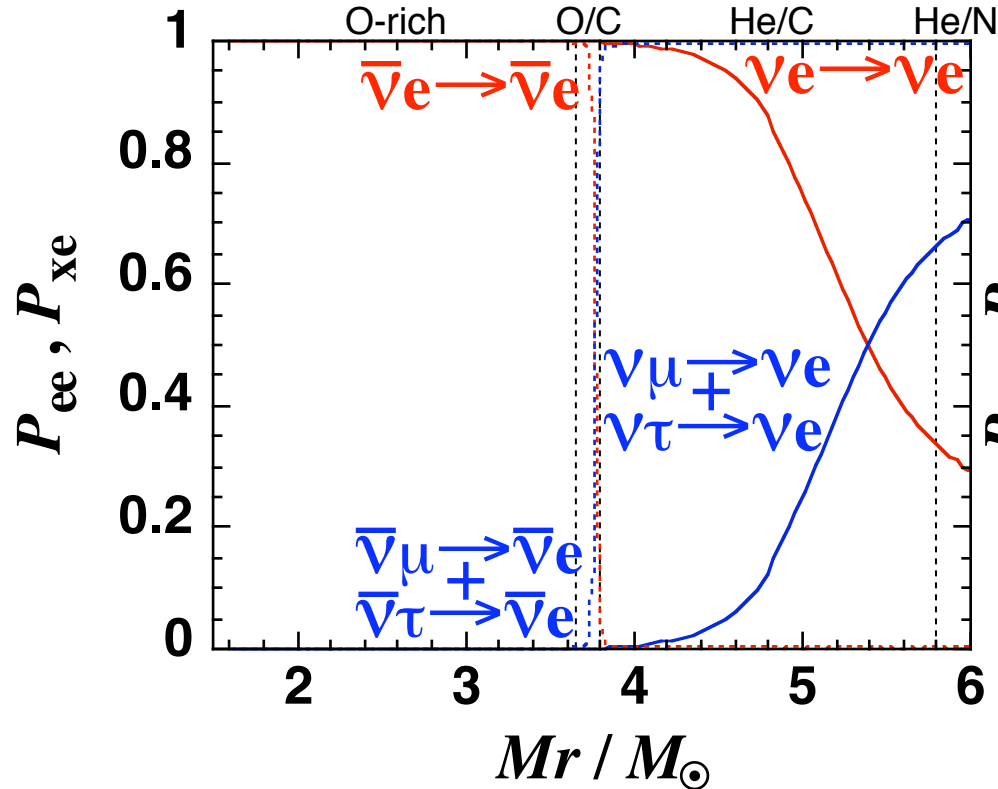
➡ Neutrino flavors gradually change in He layer.

$\epsilon_\nu = 50 \text{ MeV}$

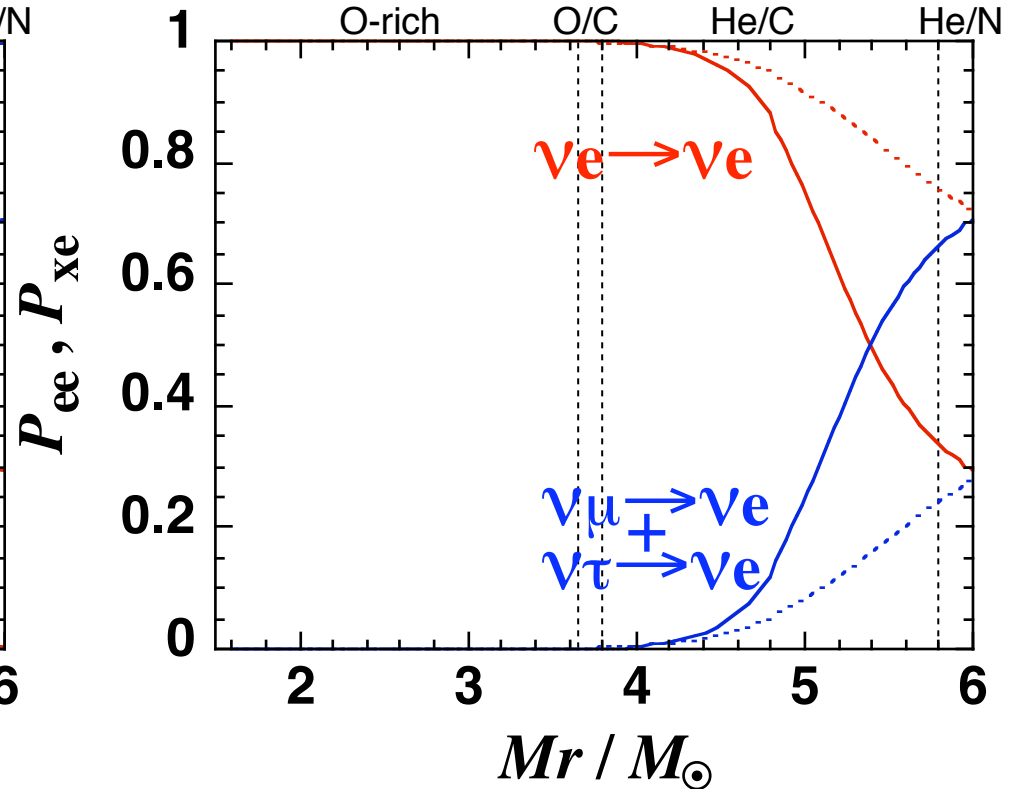
# Conversion Probabilities

## ● Inverted mass hierarchy

*adiabatic*  $\sin^2 2\theta_{13} = 0.01$



*nonadiabatic*  $\sin^2 2\theta_{13} = 10^{-6}$



*adiabatic* H-resonance

➡ All  $\bar{\nu}_e$  in He layer have changed from  $\bar{\nu}_{\mu\tau}$ .

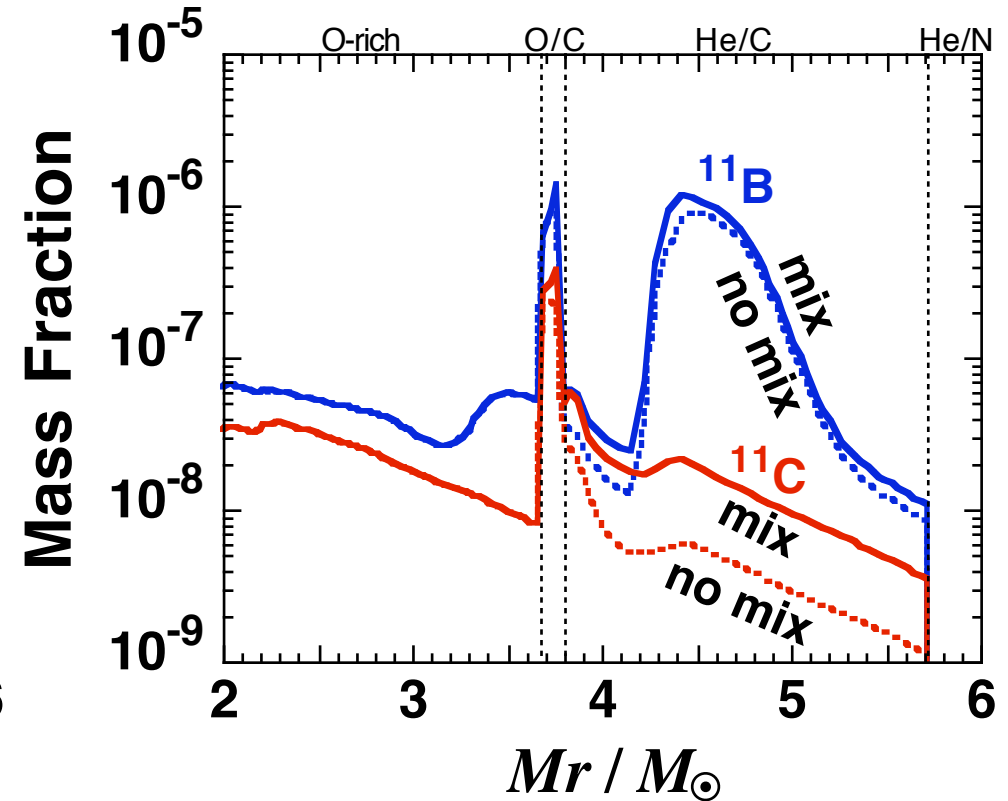
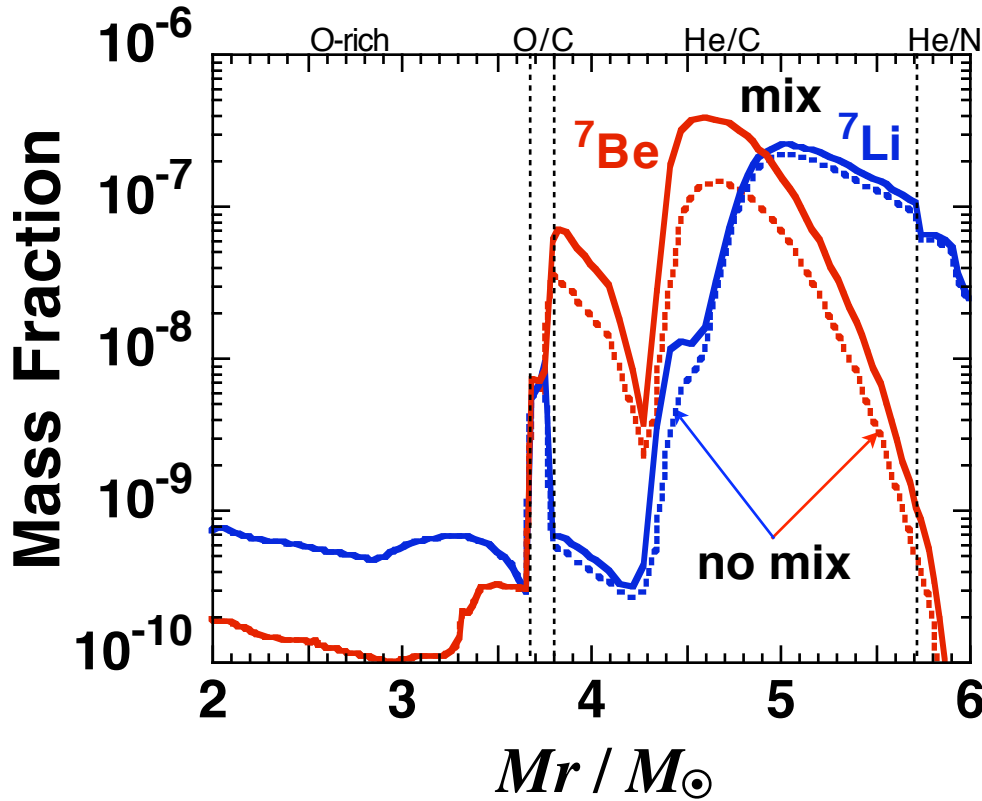
*nonadiabatic* H-resonance

➡ Neutrino flavors gradually change in He layer.

$\epsilon_{\nu} = 50 \text{ MeV}$

# Mass Fraction Distribution of ${}^7\text{Li}$ and ${}^{11}\text{B}$

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



$E_\nu = 3 \times 10^{53}$  ergs,  $T_{\nu\mu,\tau} = 6$  MeV,  $\sin^2 2\theta_{13} = 0.01$

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

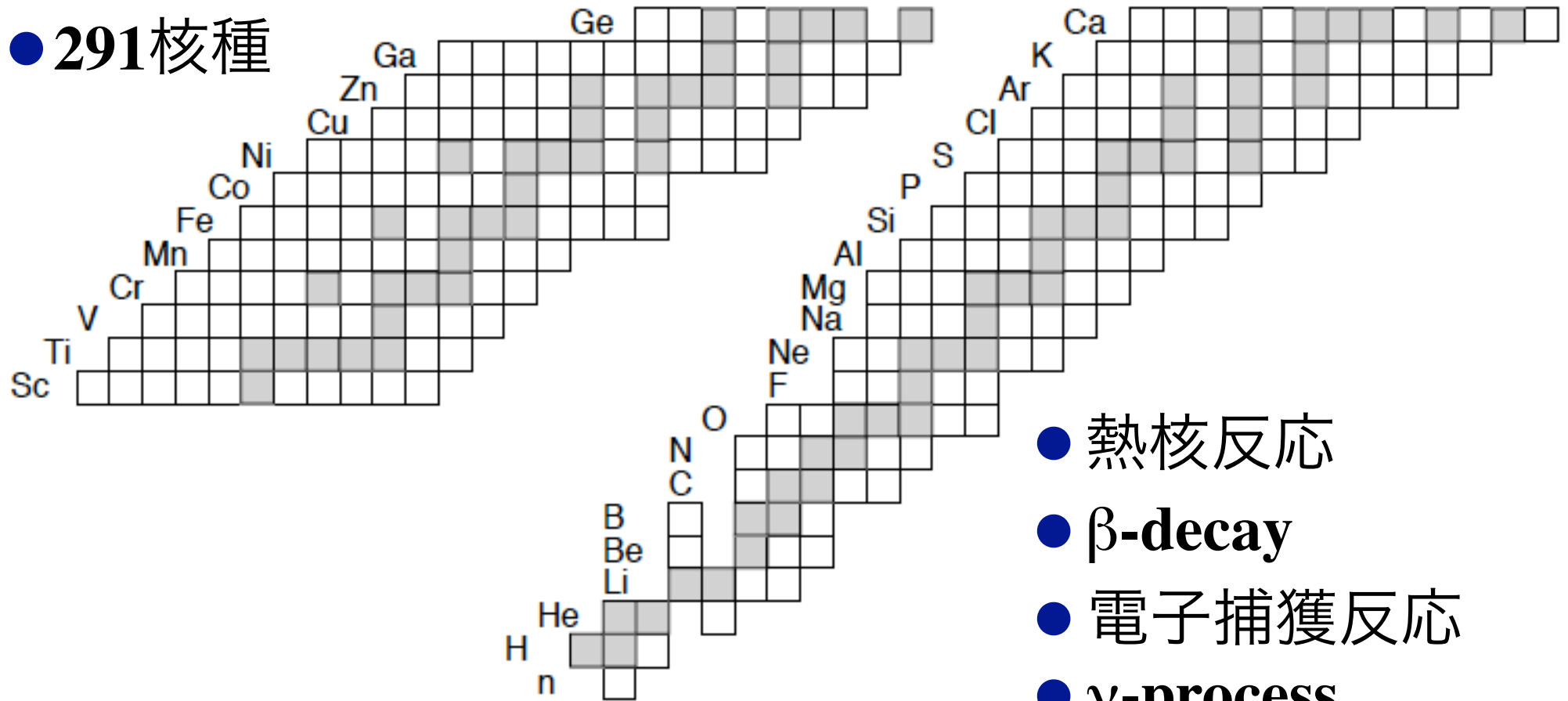
← Increase in the rates of  ${}^4\text{He}(\nu_e, e^-p){}^3\text{He}$ ,  ${}^{12}\text{C}(\nu_e, e^-p){}^{11}\text{C}$

●  ${}^7\text{Be}$  &  ${}^{11}\text{C}$  yields → Increase by factors of 2.5 & 1.4



# 核反応ネットワーク

## ● 291核種



$$\frac{dY_i}{dt} = -\lambda_i Y_i + \sum_k \lambda_k Y_k - \sum_j \rho N_A [ij]_{kl} Y_i Y_j + \sum_{k,l} \rho N_A [kl]_{ij} Y_k Y_l + \dots$$

温度, 密度進化に従い元素合成過程を計算する