# Supernova Neutrino Nucleosynthesis

**Takashi YOSHIDA**

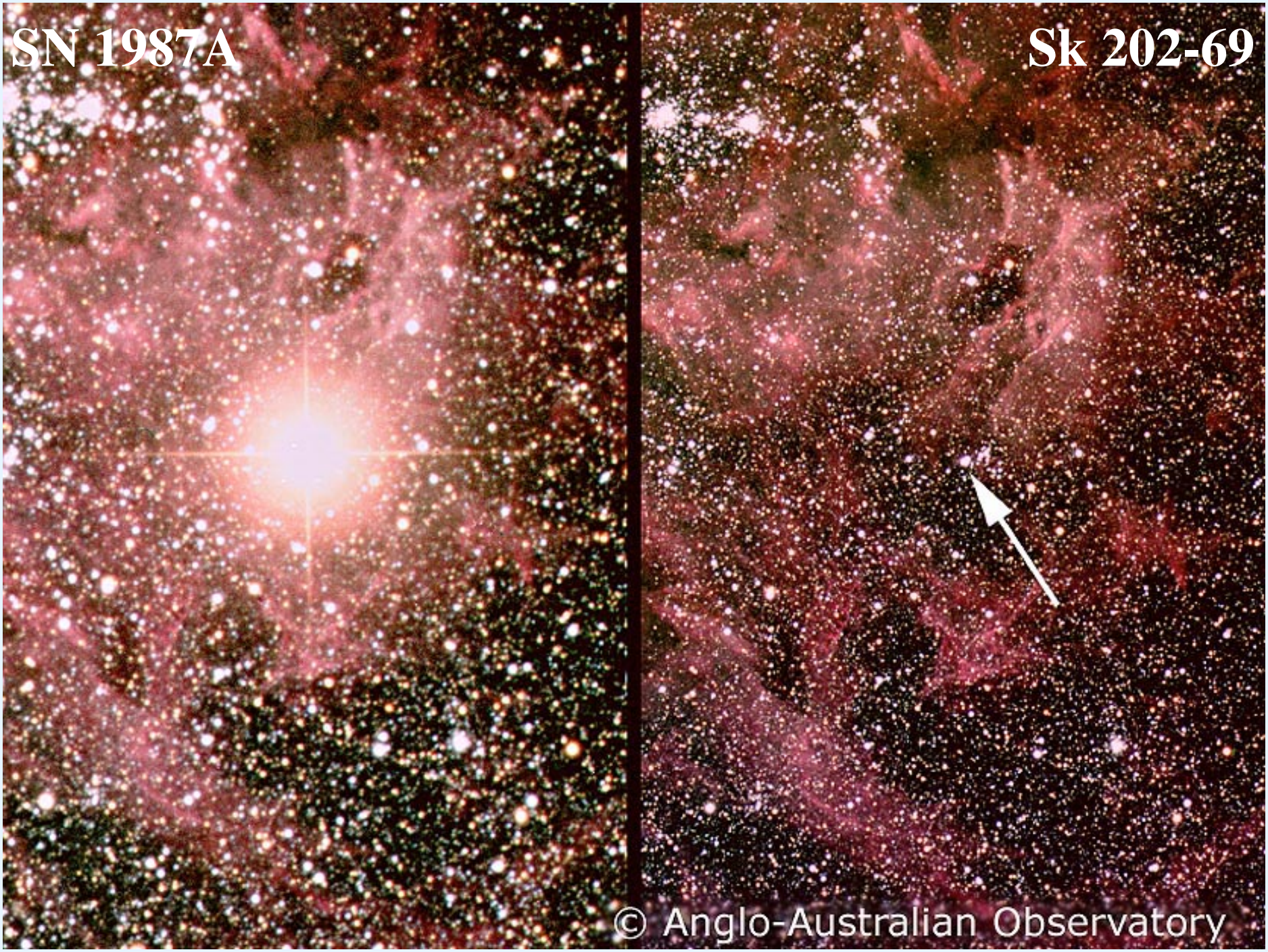
*National Astronomical Observatory of Japan*
*Institute de Physique Nucleaire d'Orsay*

**Collaborators**

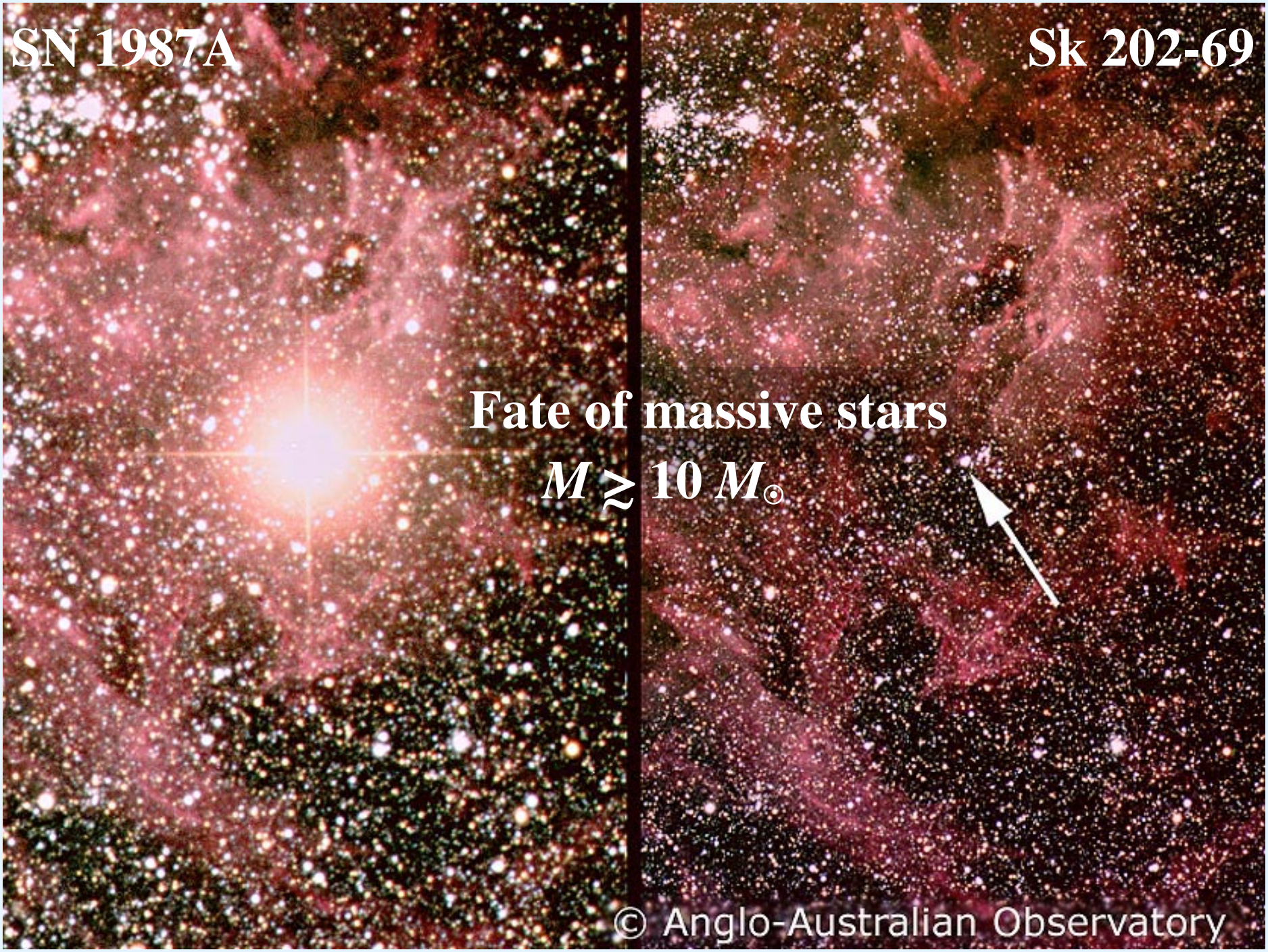
**Toshitaka Kajino (NAOJ)**
**Toshio Suzuki (Nihon Univ.), Satoshi Chiba (JAEA)**
**Hidekazu Yokomakura, Keiichi Kimura (Nagoya Univ.)**
**Akira Takamura (Toyota National College of Tech.)**
**Dieter H. Hartmann (Clemson Univ.)**

**October 25, 2007 GDR neutrino**

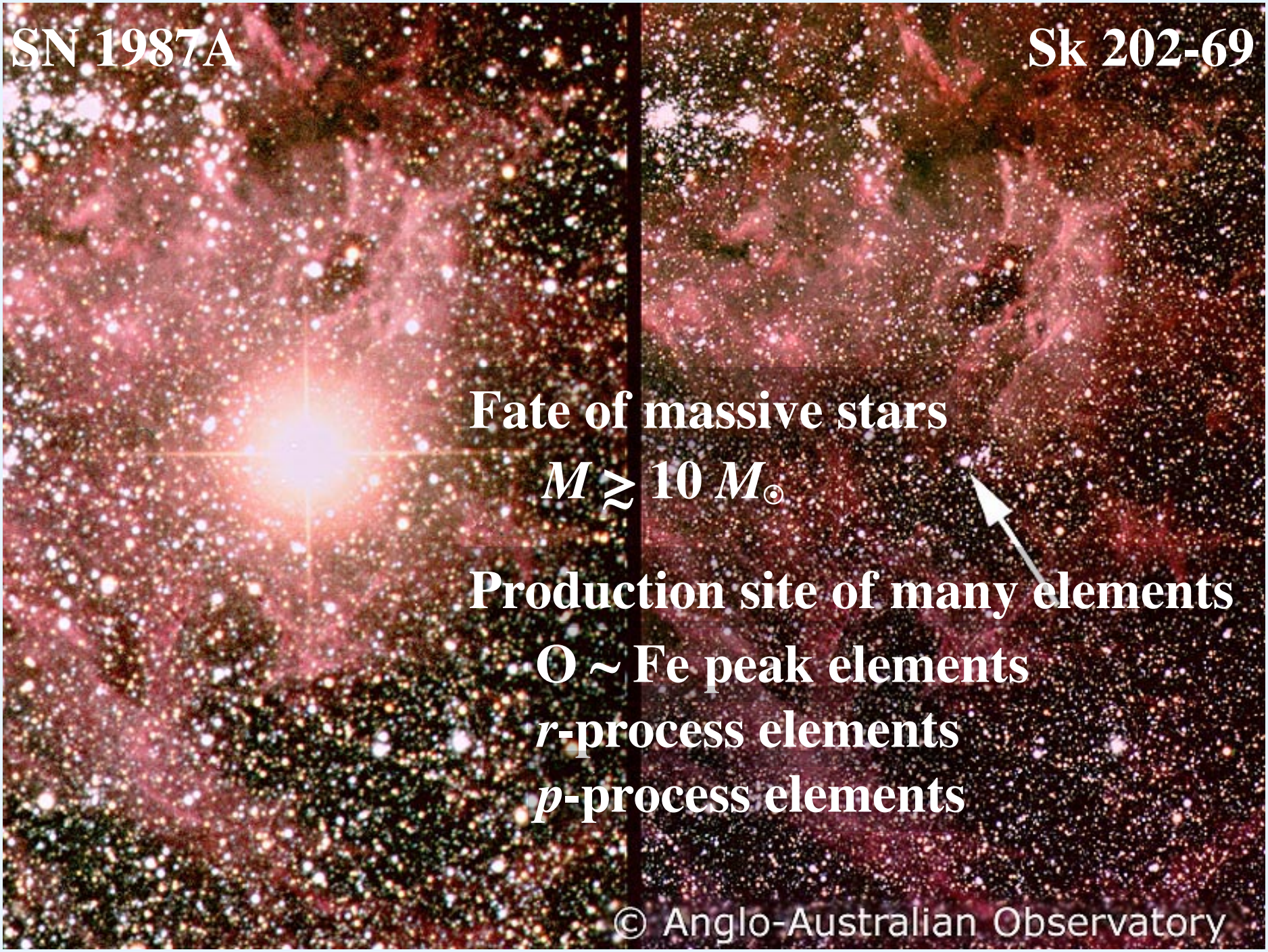
# Supernova Explosion



# Supernova Explosion



# Supernova Explosion




**Fate of massive stars**

$M \gtrsim 10\ M_\odot$

**Production site of many elements**

**O ~ Fe peak elements**

***r*-process elements**

***p*-process elements**

# Supernova Nucleosynthesis

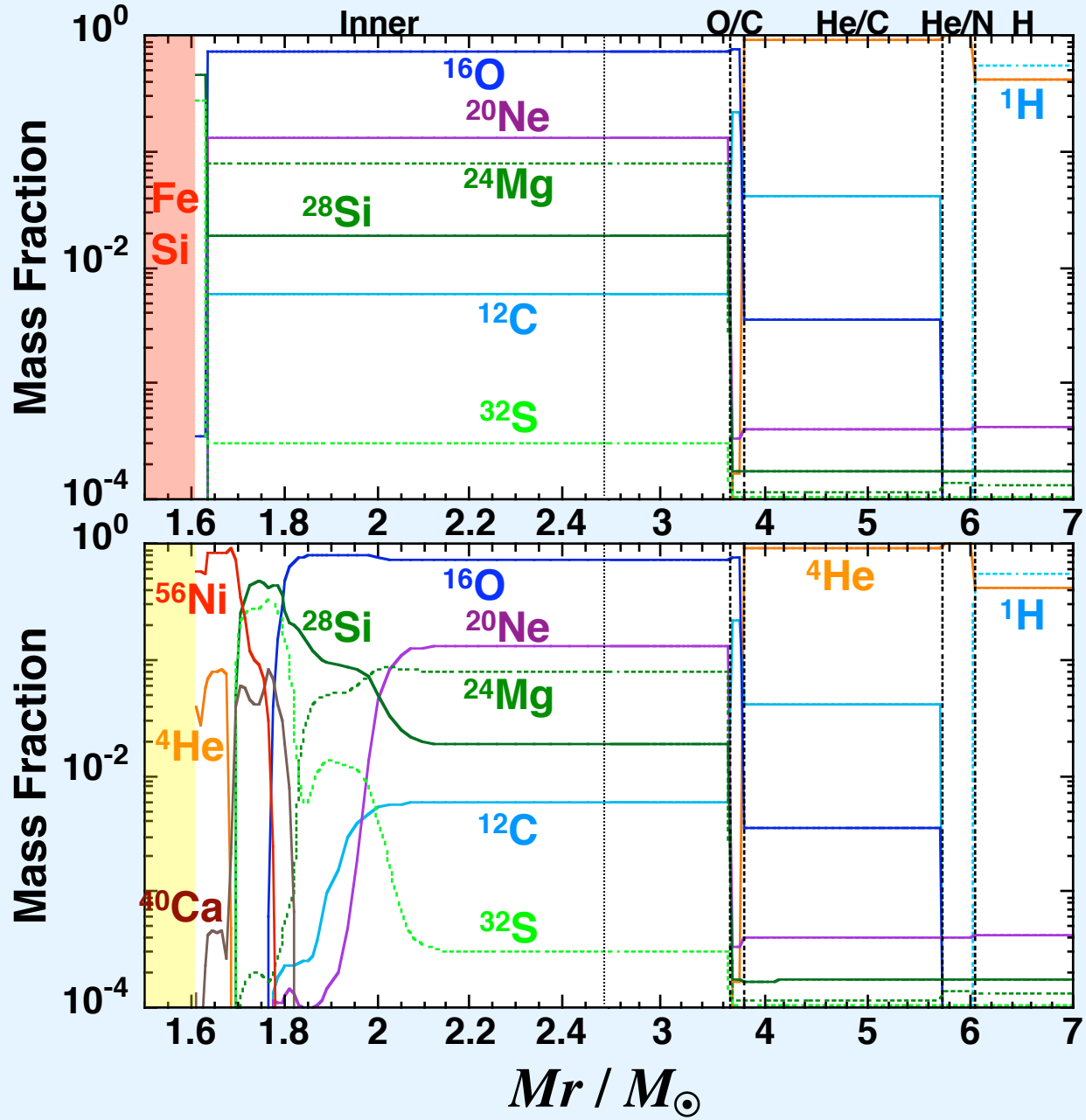
## Abundance distribution of major elements

**16.2 $M_\odot$ SN model corresponding to SN 1987A** (Result of our study)

**Presupernova**

**After explosion**

**(~1000 s)**



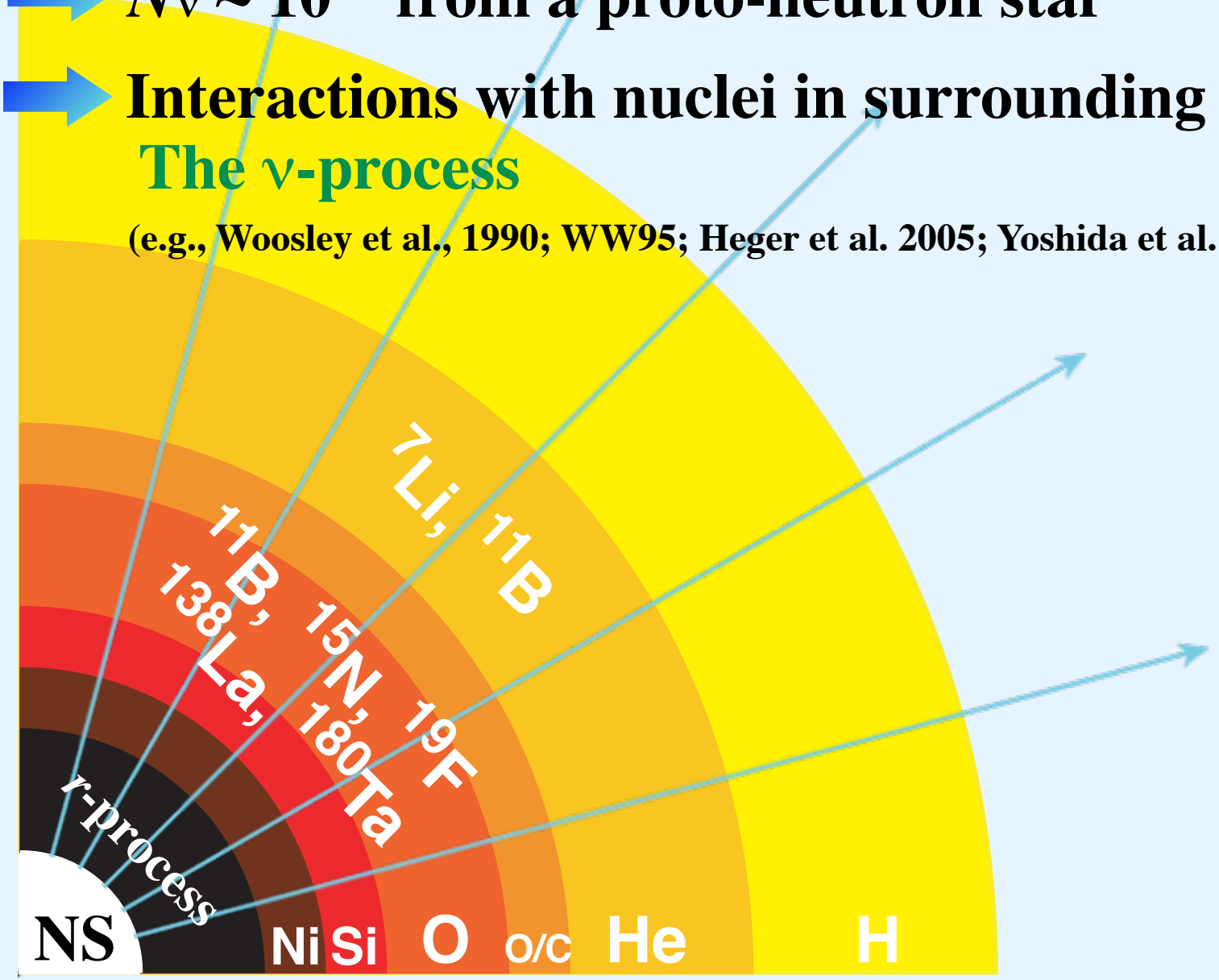
# Supernova Neutrino Nucleosynthesis

**Supernova (SN) neutrinos**

- $N\nu \sim 10^{58}$ from a proto-neutron star
- **Interactions with nuclei in surrounding materials**

**The ν-process**

**(e.g., Woosley et al., 1990; WW95; Heger et al. 2005; Yoshida et al. 2004, 2005)**



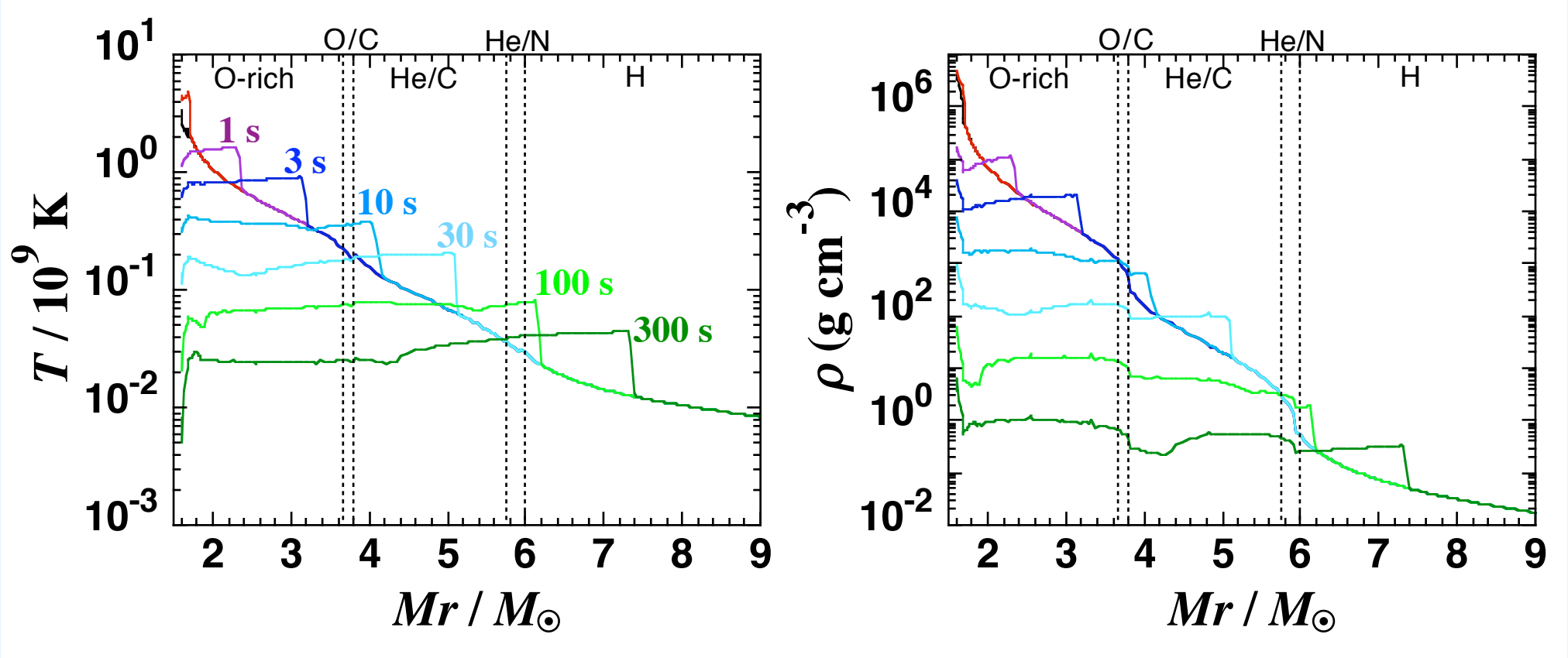
# Outline

**We investigate the nucleosynthesis of light elements through the ν-process in supernovae.**

- **Supernova explosion and neutrino models for nucleosythesis.**
- **The abundance distributions, production process, and yields of light elements, especially $^{7}$Li & $^{11}$B.**
- **Supernova light element nucleosynthesis with neutrino oscillations; the dependence of the $^{7}$Li & $^{11}$B yields on *mass hierarchies* and the mixing angle $\theta_{13}$.**

# Supernova Explosion Model

- **Supernova explosion model** (Shigeyama & Nomoto 1990)
  - ➡ **16.2 $M_\odot$ star corresponding to SN 1987A**
    **Explosion energy : $1 \times 10^{51}$ ergs  Mass cut : 1.61 $M_\odot$**




- **Nucleosynthesis calculations**
  - ➡ **Nuclear reaction network of 291 species of nuclei**
    (Yoshida et al. 2004)

# Supernova Neutrino Model

- **Neutrino luminosity**

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

$E_\nu = 3 \times 10^{53}$ ergs

$\tau_\nu = 3$ s

$\nu i$ : $\nu_{e\mu\tau}$, $\bar{\nu}_{e\mu\tau}$

(After Woosley et al. 1990)

- **Neutrino energy spectra at the neutrinosphere**

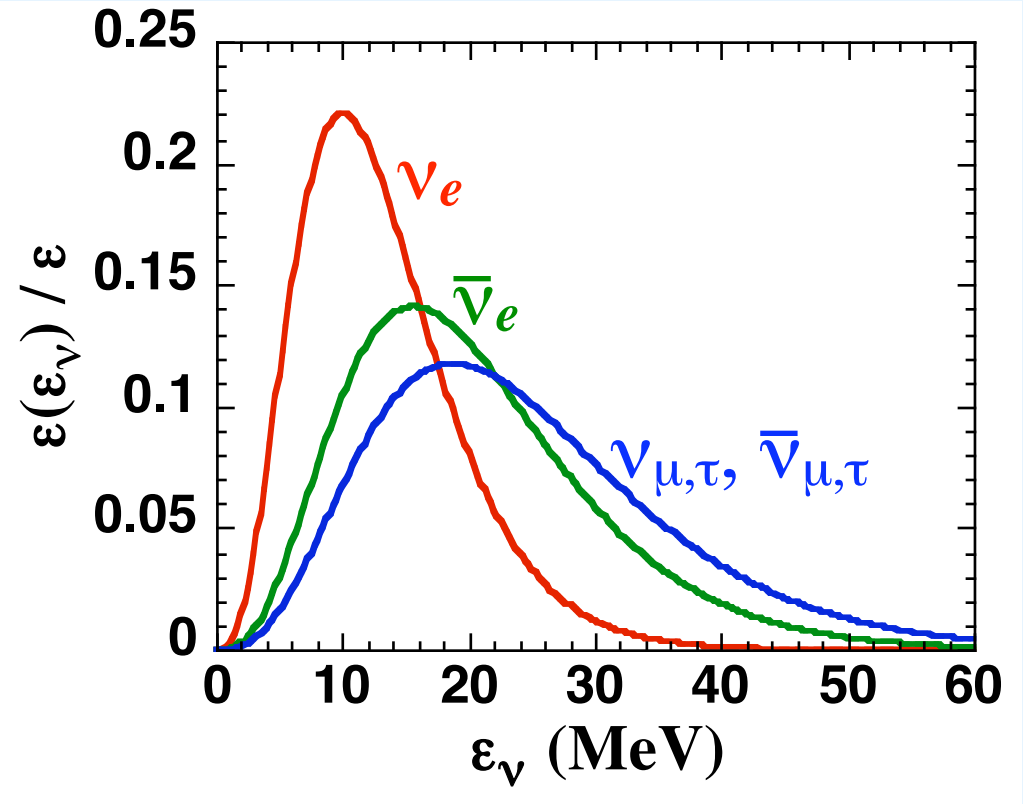
➡ **Fermi distributions**

$\eta_\nu = \mu_\nu / kT_\nu = 0$

$(kT_{\nu e}, kT_{\bar{\nu} e}, kT_{\nu\mu\tau}) =$

(3.2 MeV, 5 MeV, 6 MeV)

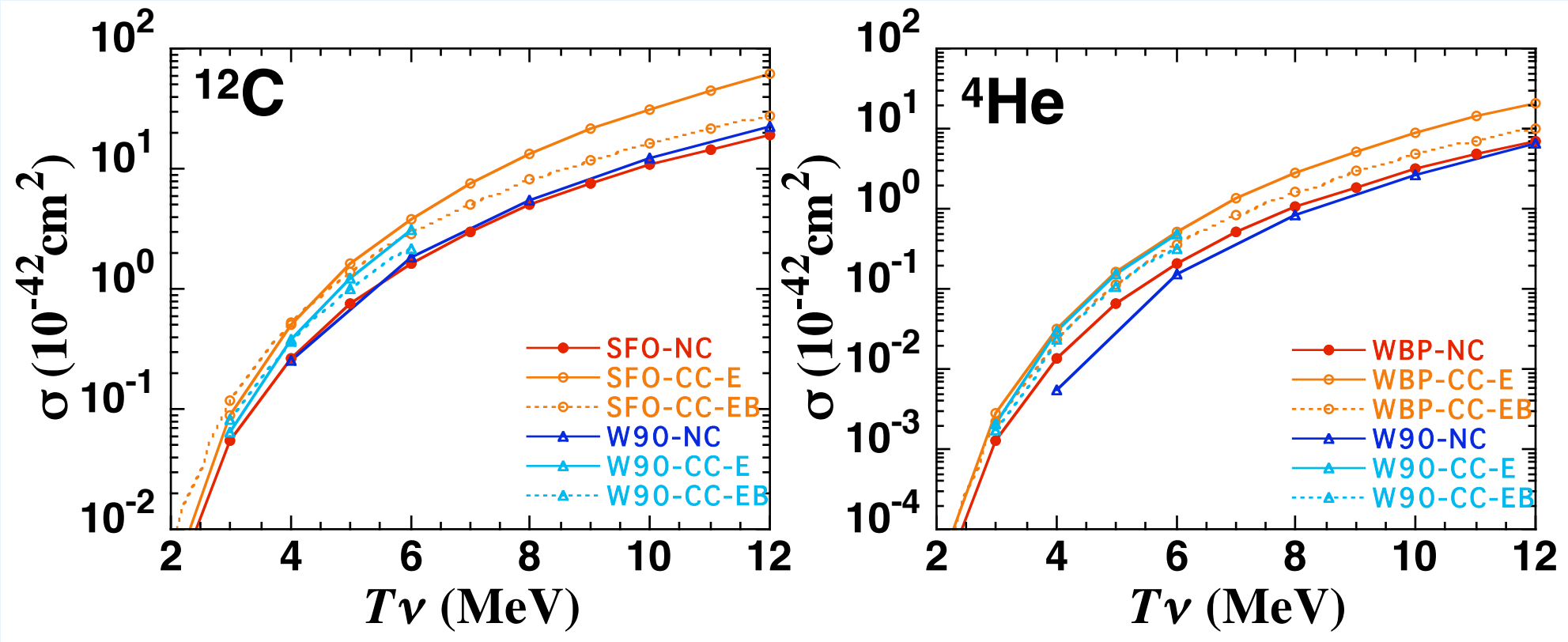
(Yoshida et al. 2004, 2005, 2006)



# Neutrino-Nucleus Cross Sections

- $^{12}$C ➡ New shell model for *p*-shell nuclei
  SFO (Suzuki-Fujimoto-Otsuka) Hamiltonian
- $^{4}$He ➡ WBP (Warburton-Brown) Hamiltonian

(Suzuki et al. 2006; RPC 74, 034307)

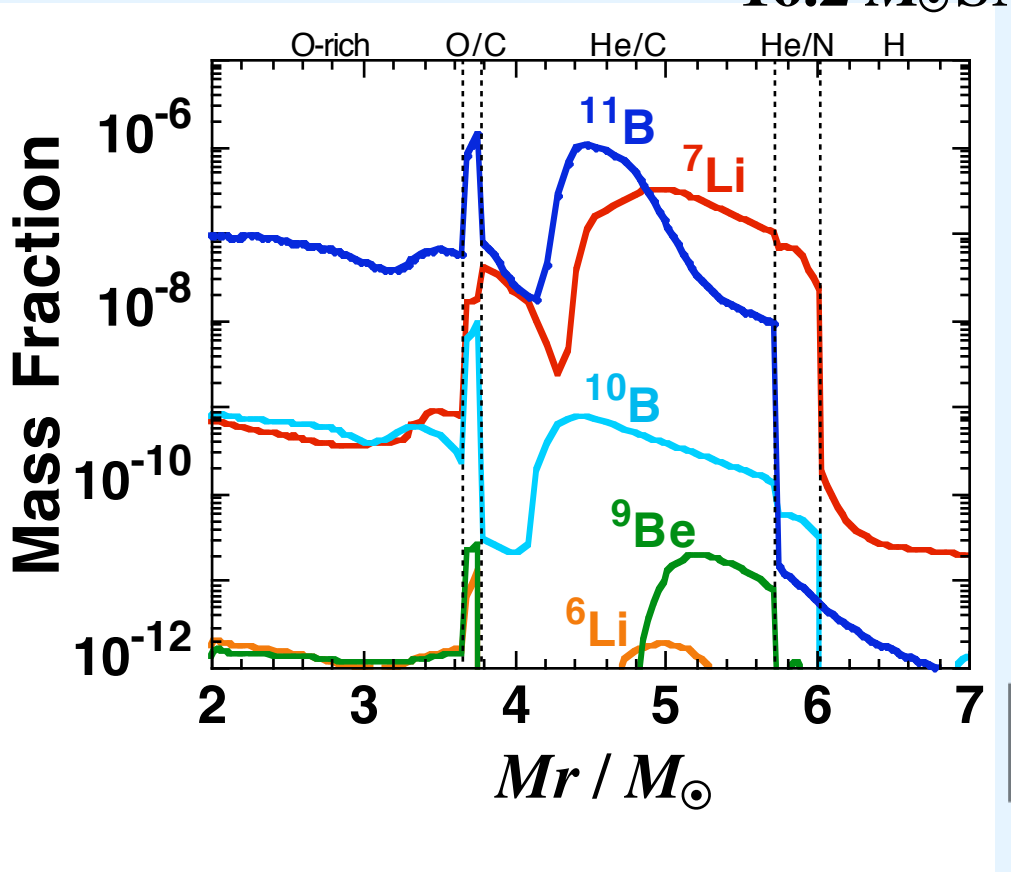


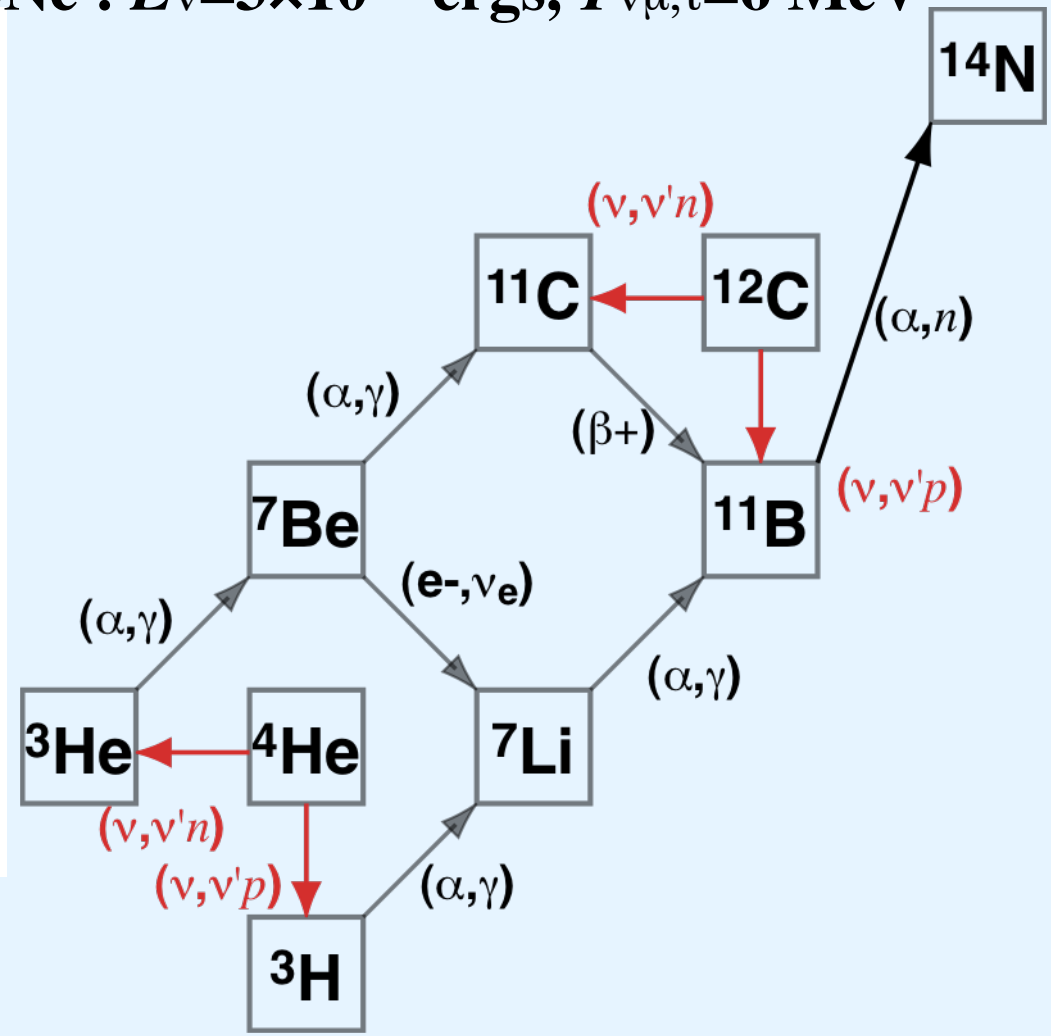

- Other neutrino-nucleus reaction rates
  ➡ Tables in Hoffman & Woosley (1992)

# Supernova Nucleosynthesis

## Mass fraction distribution of Light elements

16.2 $M_\odot$SNe : $E_\nu$=3×10$^{53}$ ergs, $T_{\nu\mu,\tau}$=6 MeV




- ν-process reactions

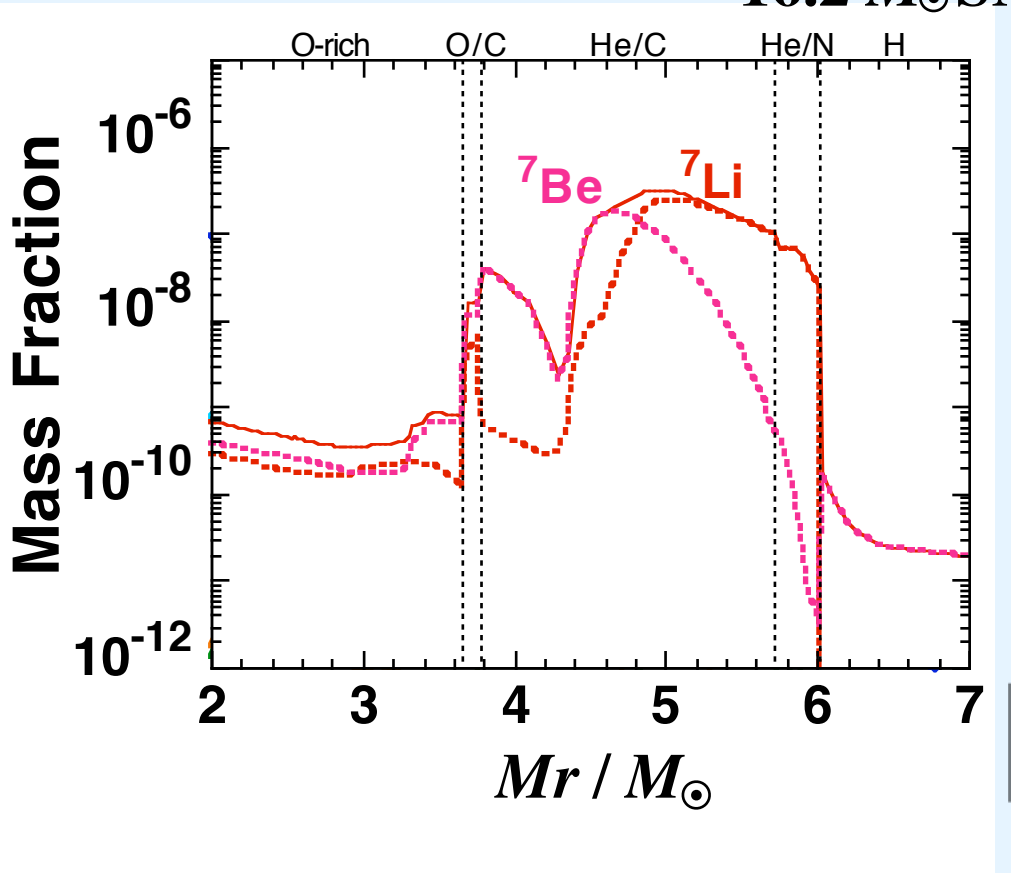
$^4$He(ν,ν'$p$)$^3$H, $^4$He(ν,ν'$n$)$^3$He, $^{12}$C(ν,ν'$p$)$^{11}$B, $^{12}$C(ν,ν'$n$)$^{11}$C

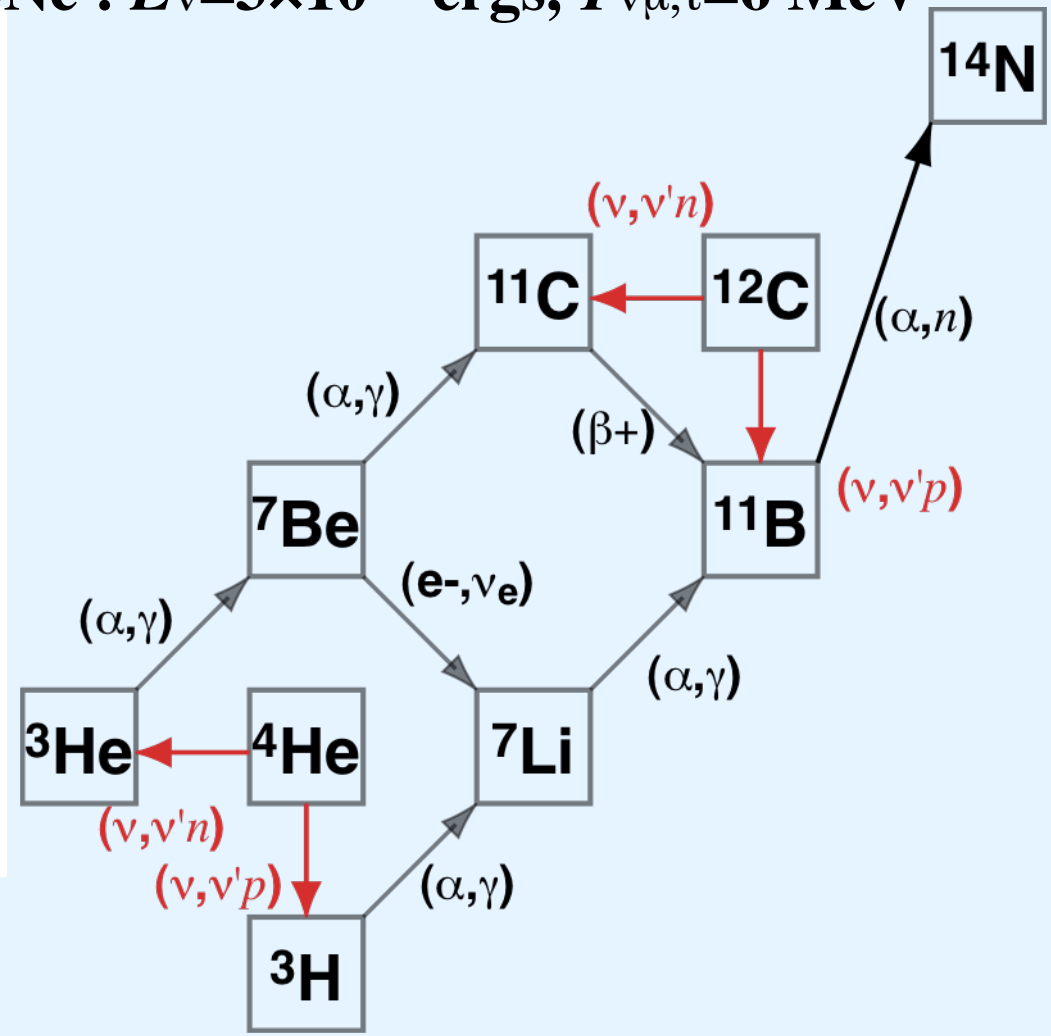
$^4$He($\nu_e$,e$^-p$)$^3$He, $^4$He($\bar{\nu}_e$,e$^+n$)$^3$H, $^{12}$C($\nu_e$,e$^-p$)$^{11}$C, $^{12}$C($\bar{\nu}_e$,e$^+n$)$^{11}$B

# Supernova Nucleosynthesis

## Mass fraction distribution of Light elements

**16.2 $M_\odot$SNe : $E_\nu$=3×10$^{53}$ ergs, $T_{\nu\mu,\tau}$=6 MeV**




- **ν-process reactions**

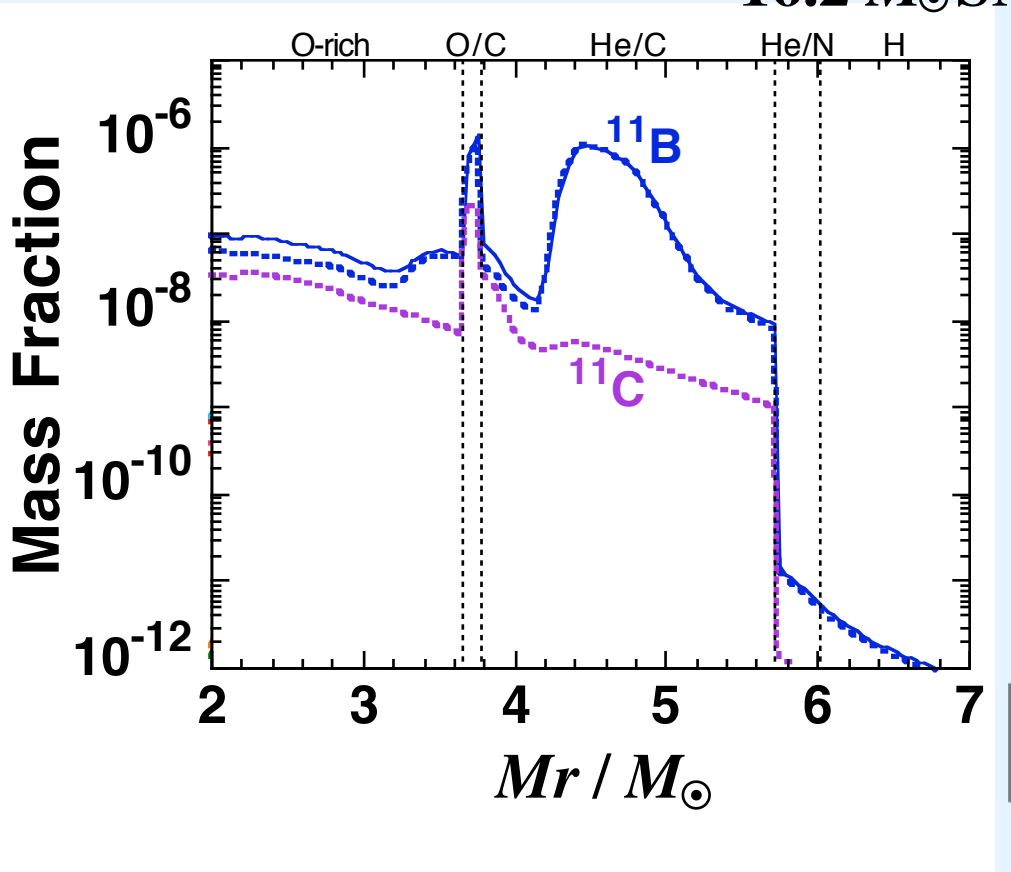
$^4$He(ν,ν'$p$)$^3$H, $^4$He(ν,ν'$n$)$^3$He, $^{12}$C(ν,ν'$p$)$^{11}$B, $^{12}$C(ν,ν'$n$)$^{11}$C

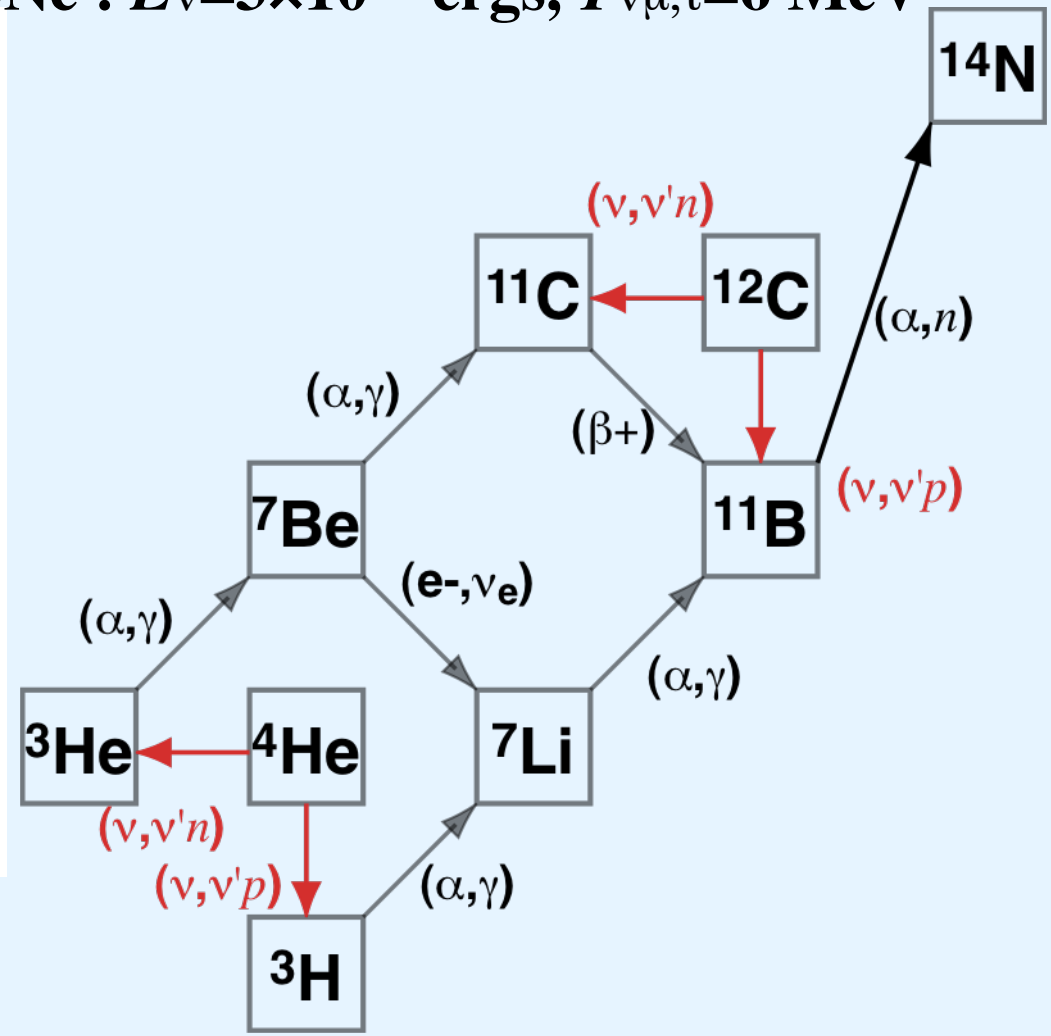
$^4$He($\nu_e$,e$^-p$)$^3$He, $^4$He($\bar{\nu}_e$,e$^+n$)$^3$H, $^{12}$C($\nu_e$,e$^-p$)$^{11}$C, $^{12}$C($\bar{\nu}_e$,e$^+n$)$^{11}$B

# Supernova Nucleosynthesis

## Mass fraction distribution of Light elements

16.2 $M_\odot$SNe : $E_\nu$=3×10$^{53}$ ergs, $T_{\nu\mu,\tau}$=6 MeV



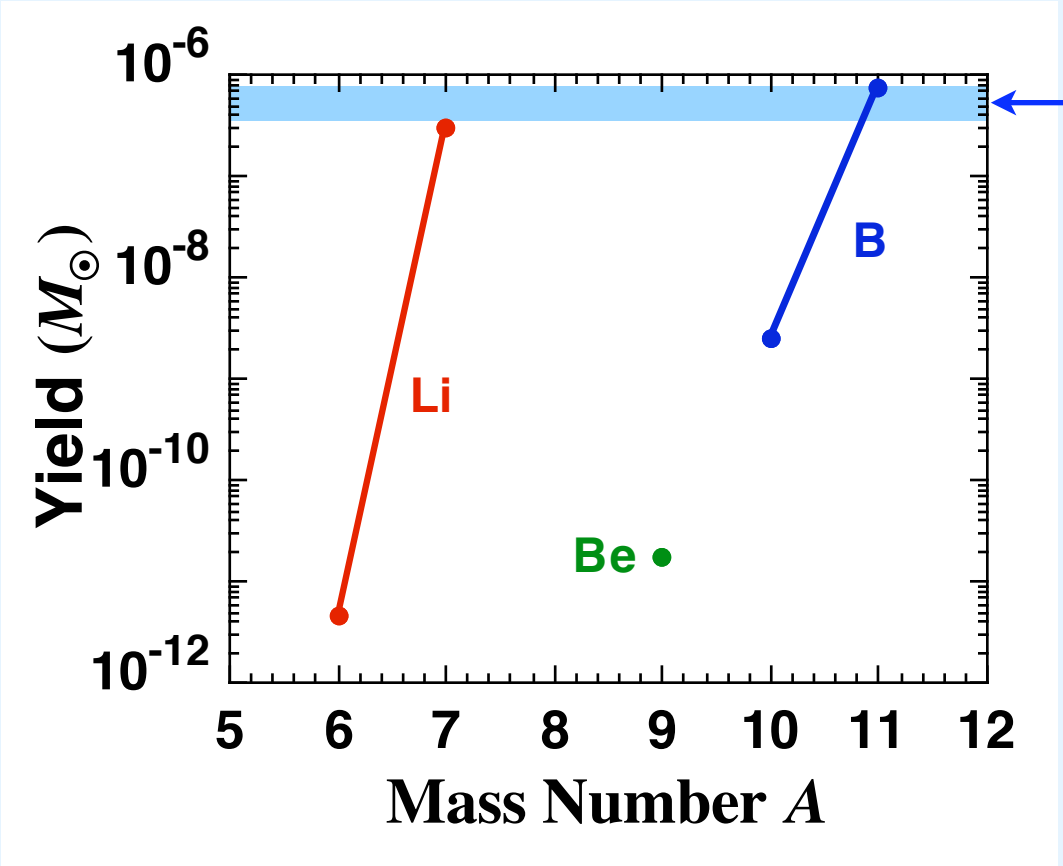

- ν-process reactions

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

# Light Element Yields

## Yields of Light elements in SN 1987A model



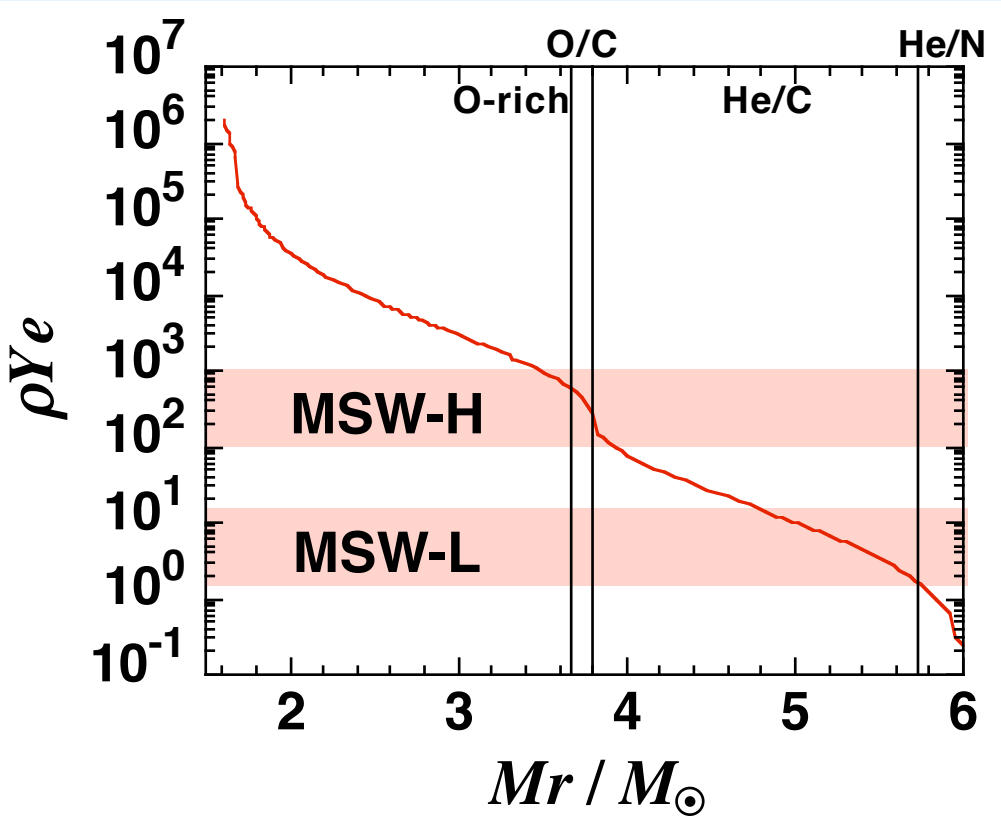

SN contribution of $^{11}$B from Galactic chemical evolution models

(Fields et al. 2000, Ramaty et al. 2000)

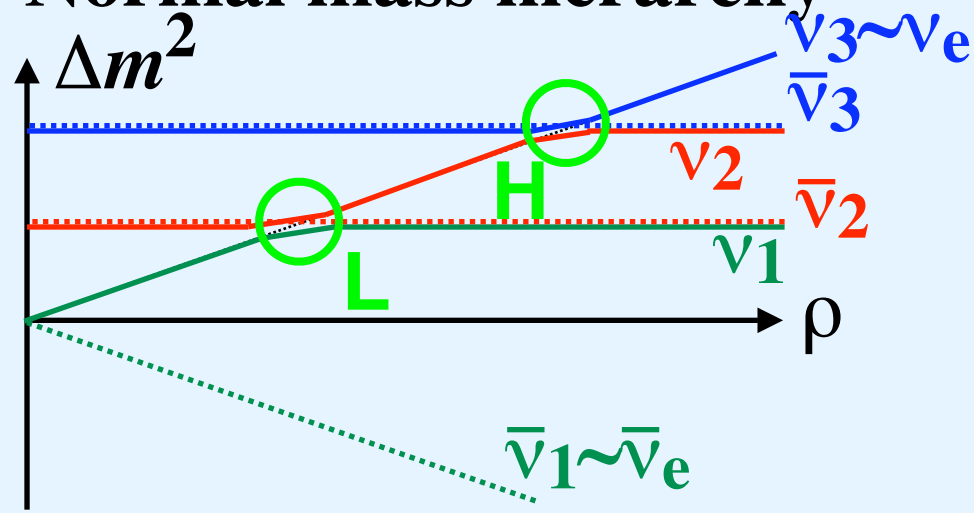
- Yields of $^{7}$Li & $^{11}$B are on the order of $10^{-7}$ $M_\odot$.
- Yields of $^{6}$Li, $^{9}$Be, & $^{10}$B are much smaller.

# 3-Flavor Neutrino Oscillations in SNe

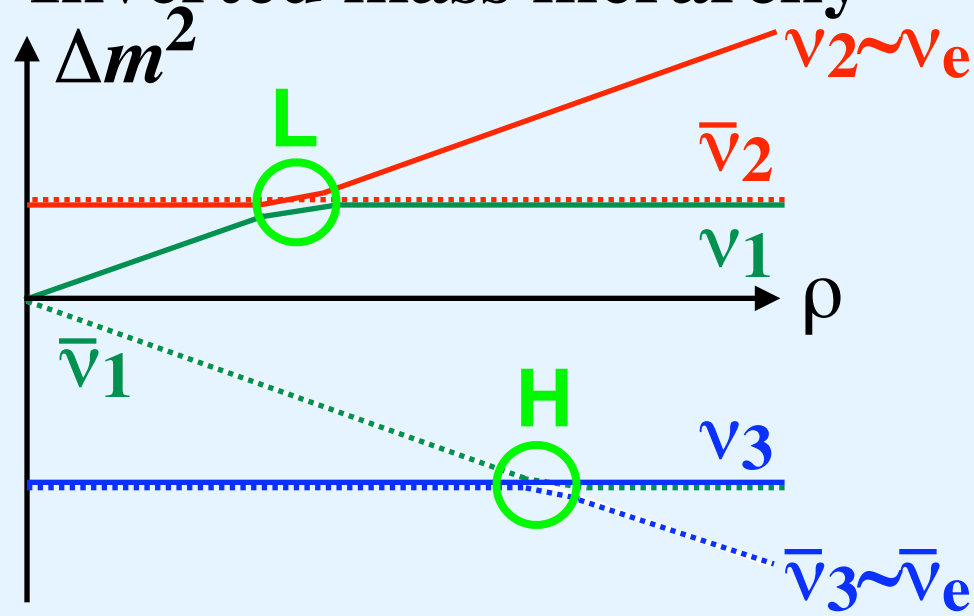
## SN 1987A presupernova




- **Normal mass hierarchy**




- **Inverted mass hierarchy**




## Oscillation parameters

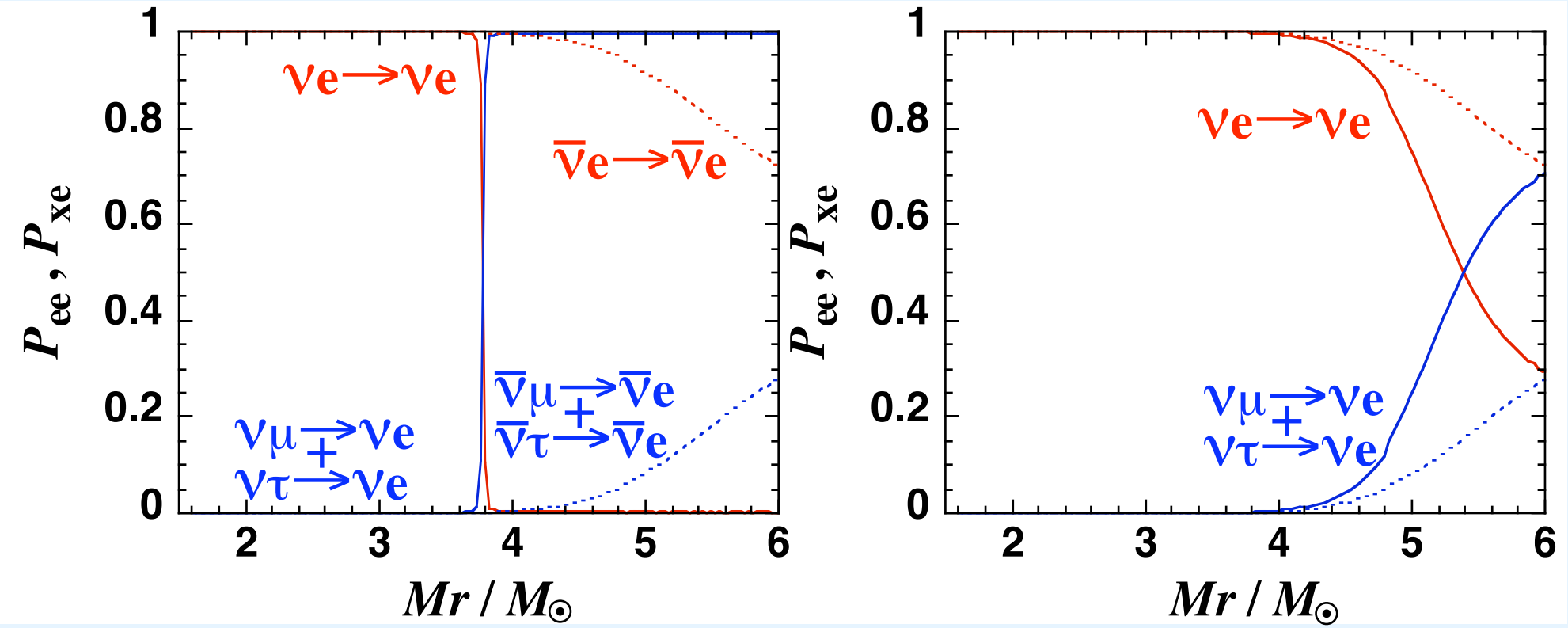
- **Large Mixing Angle solutions**
- ***Parameters*** ➡ **Mass hierarchies, $\sin^2 2\theta_{13} < 0.1$**

# Neutrino Oscillations in SNe

Yoshida et al. (2006; PRL 96, 091101; ApJ 649, 319)

- **Normal mass hierarchy**

*adiabatic* $\sin^2 2\theta_{13} = 0.01$ *nonadiabatic* $\sin^2 2\theta_{13} = 10^{-6}$




$\varepsilon_\nu = 50$ MeV

**MSW-H** *adiabatic*

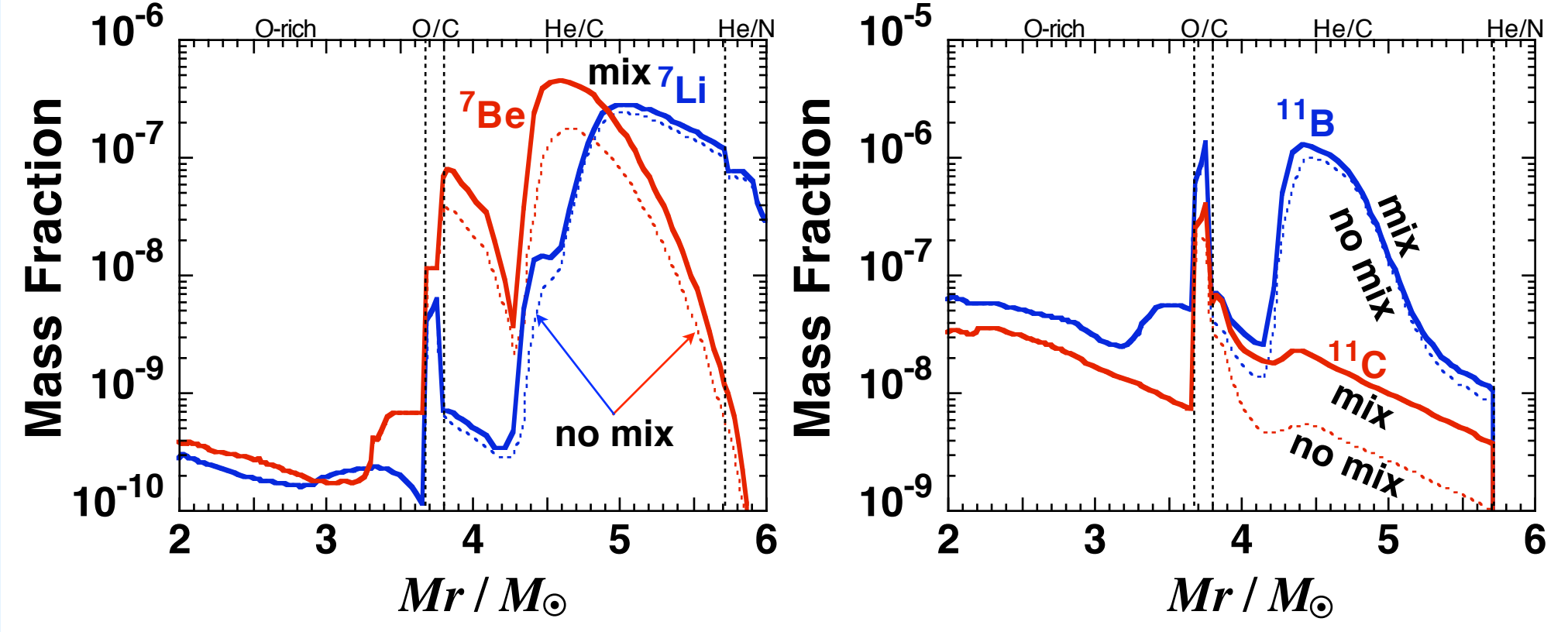
➡ All $\nu_e$ in the He layer have changed from $\nu_{\mu\tau}$.

**MSW-H** *nonadiabatic*

➡ Neutrino flavors gradually changes in the He layer.

# Mass Fraction Distribution of Light Elements in SNe

- **Normal mass hierarchy & MSW-H *adiabatic***




$E_\nu = 3\times10^{53}$ ergs, $T_{\nu\mu,\tau}$=6 MeV, $\sin^2 2\theta_{13} = 0.01$

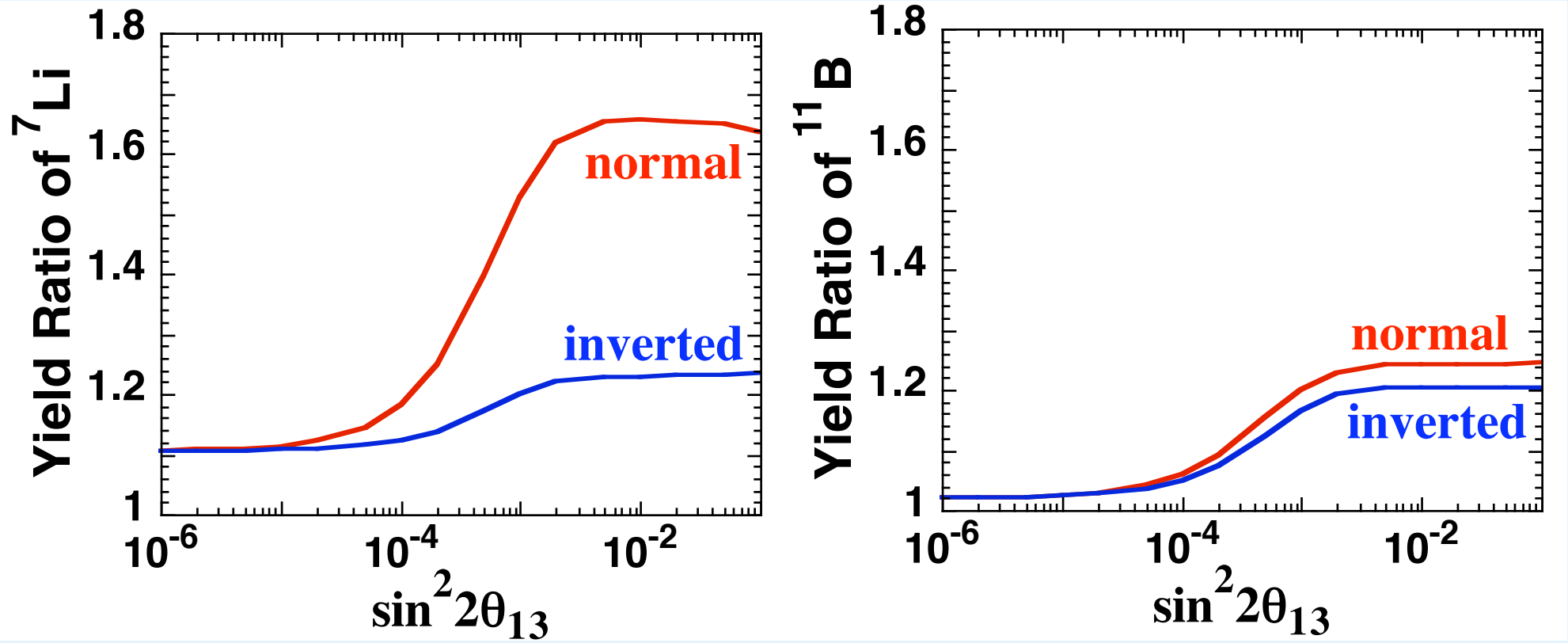
**Increase in the mass fractions of $^7$Be & $^{11}$C in the He layer**

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

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

# Yield Ratios of $^7$Li, $^{11}$B

## $\sin^2 2\theta_{13}$ dependence




$M(^7\text{Li}) = 3.06\times10^{-7}\ M_\odot$ $M(^{11}\text{B}) = 7.51\times10^{-7}\ M_\odot$

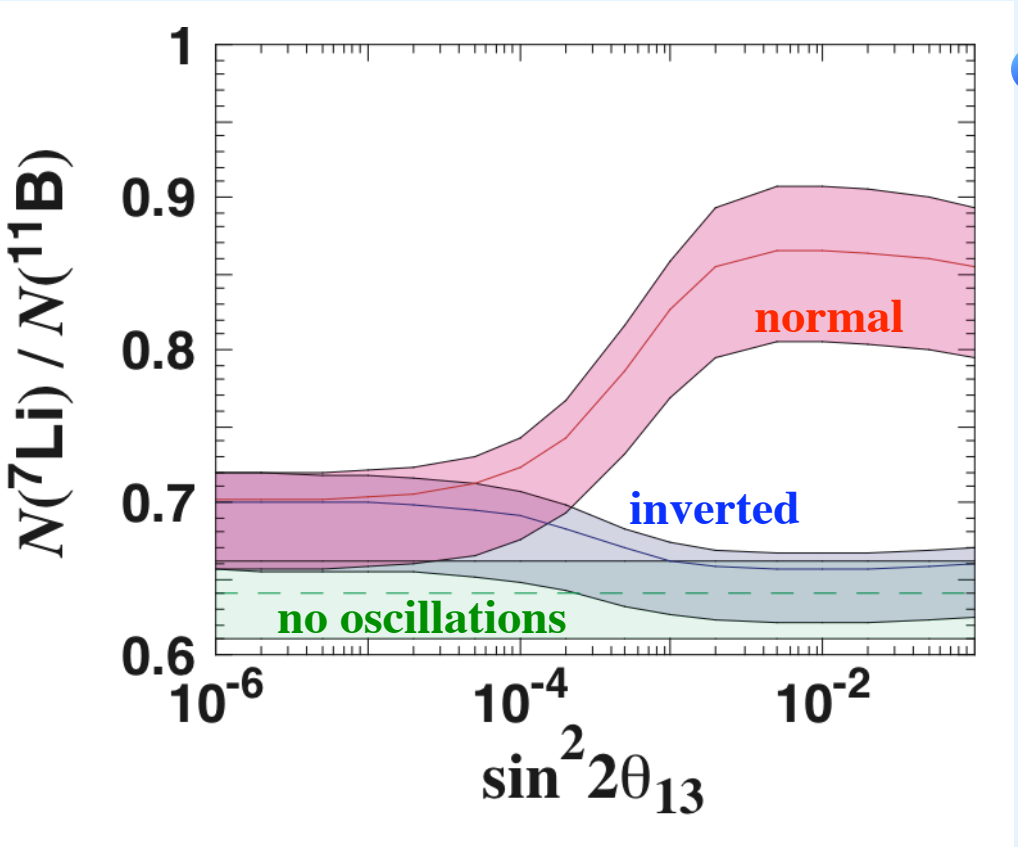
**$^7$Li & $^{11}$B yields depend on *mass hierarchy* and $\theta_{13}$.**

- **Normal mass hierarchy & MSW-H *adiabatic***

  ➡ **$^7$Li & $^{11}$B yields increase by factors of 1.7 and 1.2.**

# $^7$Li/$^{11}$B abundance ratio

$^7$Li/$^{11}$B ratio ➡ Including uncertainties of neutrino temperatures




- $(T_{\nu e}, T_{\bar{\nu} e}, T_{\nu \mu,\tau}, E_\nu)$ = (3.2, 5.0, 6.0, 3.0)
  , (3.2, 4.8, 5.8, 3.0)
  , (3.2, 5.0, 6.4, 2.4)
  , (3.2, 4.1, 5.0, 3.5)
  , (4.0, 4.0, 6.0, 3.0)
  , (4.0, 5.0, 6.0, 3.0)

  (MeV, MeV, MeV, $\times 10^{53}$ ergs)

- Normal mass hierarchy & MSW-H *adiabatic*

  ➡ $N(^7\mathrm{Li})/N(^{11}\mathrm{B}) > 0.8$

# Can Oscillation parameters be constrained?

- **Normal mass hierarchy & MSW-H *adiabatic***

  ➡ $N(^7\mathrm{Li})/N(^{11}\mathrm{B}) > 0.8$

  **Including the uncertainties of neutrino temperatures**

## Problems

- **Stellar mass dependences**
- **Dependence on stellar evolution model**

## Attempt of observations

- **Observations of $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio** (Rebull et al. 1998, 2000)

  ➡ **Large $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio may indicate traces of SNe.**

  **It has not been observed.**

# Summary

**We investigate the nucleosynthesis of light elements through the ν-process in supernovae.**

- **$^{7}$Li & $^{11}$B are mainly produced among light elements.**

  ➡ **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

  **Production during Galactic chemical evolution**

- **$^{7}$Li & $^{11}$B yields depend on neutrino oscillations.**

  **Normal mass hierarchy & $\sin^2 2\theta_{13} > 0.002$**

  ➡ **$^{7}$Li & $^{11}$B yields increase by factors 1.7 and 1.2.**

  ➡ $N(^{7}\mathrm{Li})/N(^{11}\mathrm{B}) > 0.8$

  **Possibility for constraining *mass hierarchy* and the mixing angle $\theta_{13}$.**