（5）ニュートリノ振動と超新星元素合成

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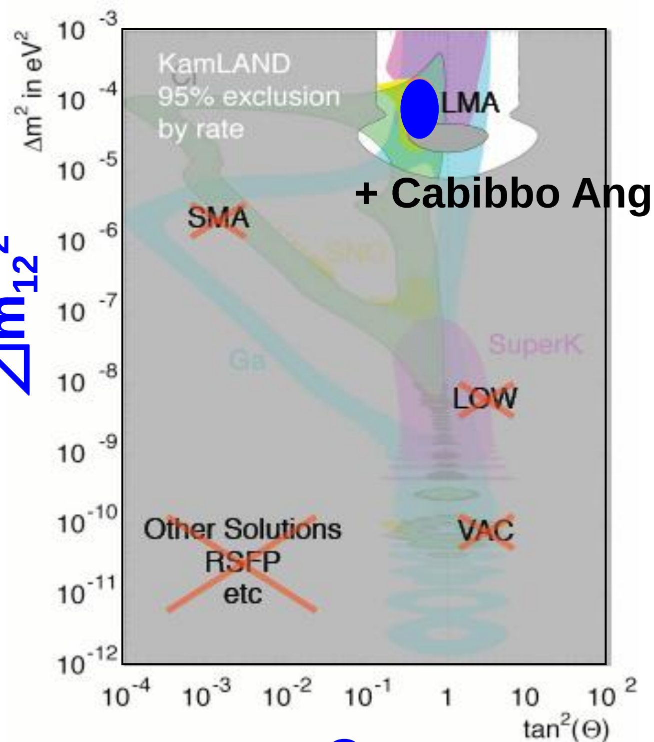
"KNOWN" Neutrino Oscillation Parameters

Super-K, SNO, KamLand (reactor ν) determined Δm_{12}^2 and θ_{12} uniquely.

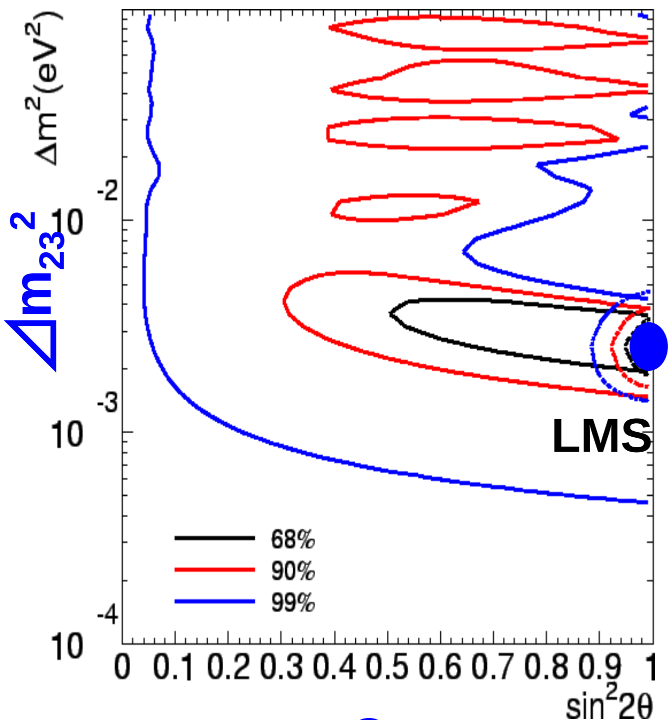
Super Kamiokande (atmospheric ν) determined Δm_{23}^2 and θ_{23} uniquely.



+ Cabibbo Angle

Δm_{12}^2

Θ_{12}



Δm_{23}^2

Θ_{23}

SN-neutrinos:
Yokomakura et al.
PL B544, 286

"Several UNKNOWNs"

Cosmology
ν-less double β-decay

(1) $\sin^2 2\theta_{13} < 0.1$, **(2) $|\Delta m_{13}^2| = 2.4 \times 10^{-3}\ eV^2$**

~~(3) δ = CP-phase,~~ ~~(4) Absolute Mass~~

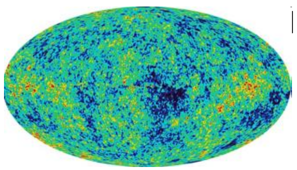
Various Physics Targets with wide Neutrino-Energy Range

1.9K — 0.4 — 1.0 — 2.6 — 8.5 Visible energy [MeV]

CMB

neutrino electron elastic scattering $\nu + e^- \rightarrow \nu + e^-$

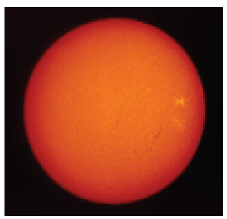
inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$



Neutrino Cosmology

verification of particle model

^{7}Be solar neutrino



Neutrino Astrophysics

verification of SSM

geo-neutrino

Neutrino Geophysics

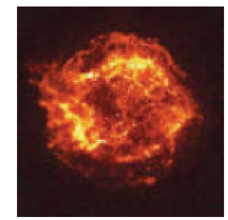
verification of earth evolution model

reactor neutrino

Neutrino Physics

Precision measurement of oscillation parameters

supernova relic neutrino etc.



Neutrino Cosmology

verification of universe evolution

ν_e, ν_μ, ν_τ

★ 観測に有利な($\sigma = G_F E_\nu^2$)高エネルギーニュートリノ

★ 三世代のニュートリノ(荷電カレント＋中性カレント)が同時に出現

SN1987Aニュートリノを KAMIOKANDE & IMB で検出！

小柴昌俊ら（東大, 1987）

消えた太陽（半電子型）ニュートリノの謎　Davisら

消えた大気（ミュー粒子型）ニュートリノの謎　梶田ら（東大）

解決案：３世代のニュートリノ（$\nu_e\ \nu_\mu\ \nu_\tau$）は振動して互いに入れ替わる！

Pontecorvo (1957)、牧・中川・坂田（1962）

振動の仕方が完全に解明されていない！ θ_{13}, Δm_{13}, δ_{CP}?

目的

超新星ニュートリノ物質振動（MSW）効果と元素合成を使って決定する方法の提案！

Wolfenstein (1978), Mikheyev & Smirnov (1986)
吉田・梶野ら（天文台/東大）

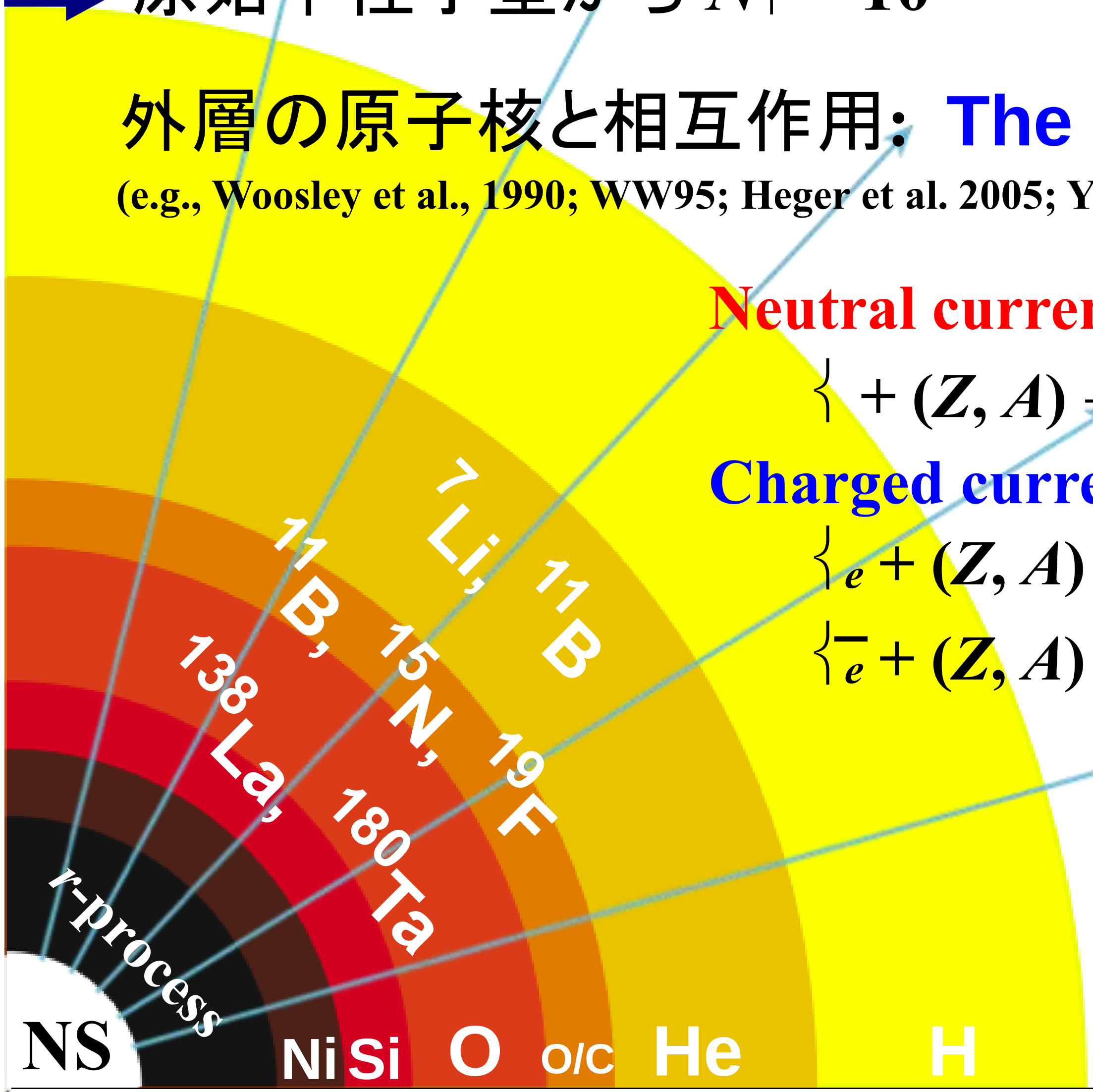
Neutrino元素合成 (ν-Process)

超新星ニュートリノ

➡ 原始中性子星から $N_\nu \sim 10^{58}$

外層の原子核と相互作用: **The ν-process**

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



Neutral current反応

$$\nu + (Z, A) \rightarrow (Z\text{-}z, A\text{-}a) + {}^{a}z + \nu'$$

Charged current反応

$$\nu_e + (Z, A) \rightarrow (Z\text{-}z\text{+}1, A\text{-}a) + {}^{a}z + e^-$$

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

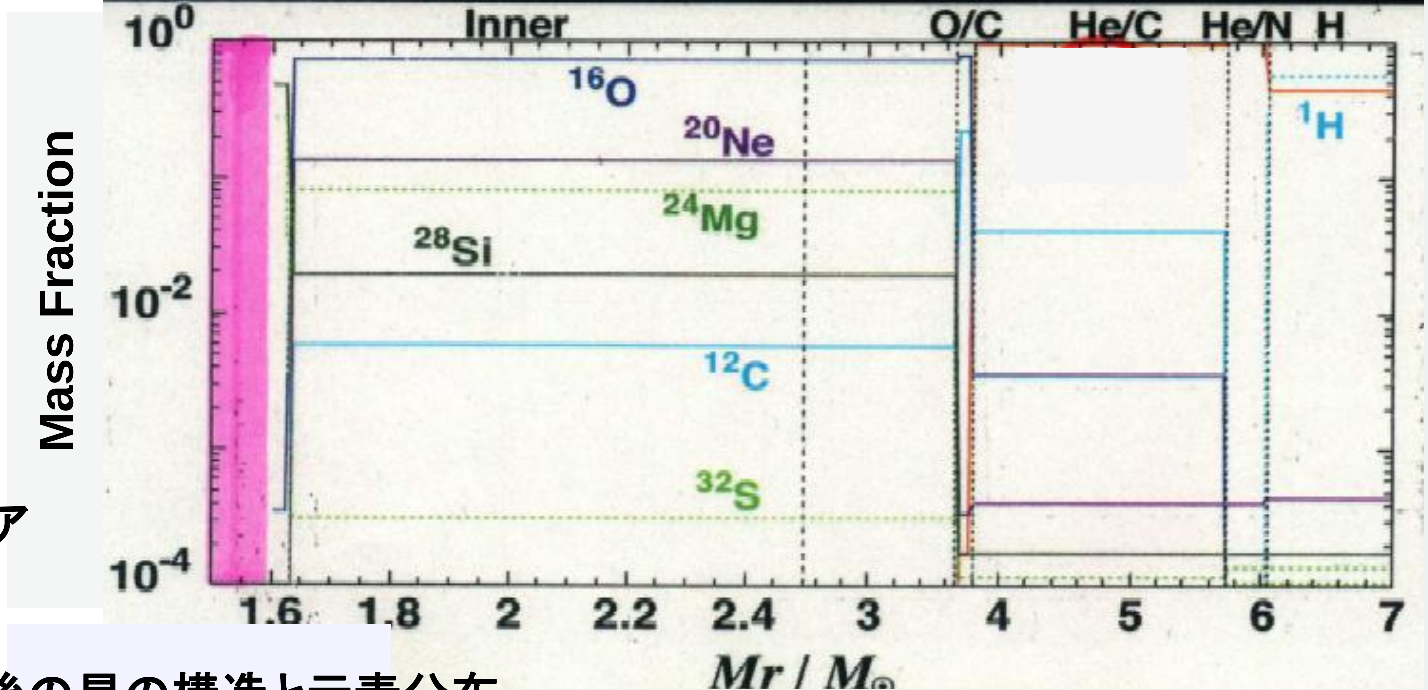
$T_{\nu e}$ = 3.2 MeV

$T_{\bar{\nu e}}$ = 4.0 MeV

$T_{\nu\mu\tau}$ = 6.0 MeV

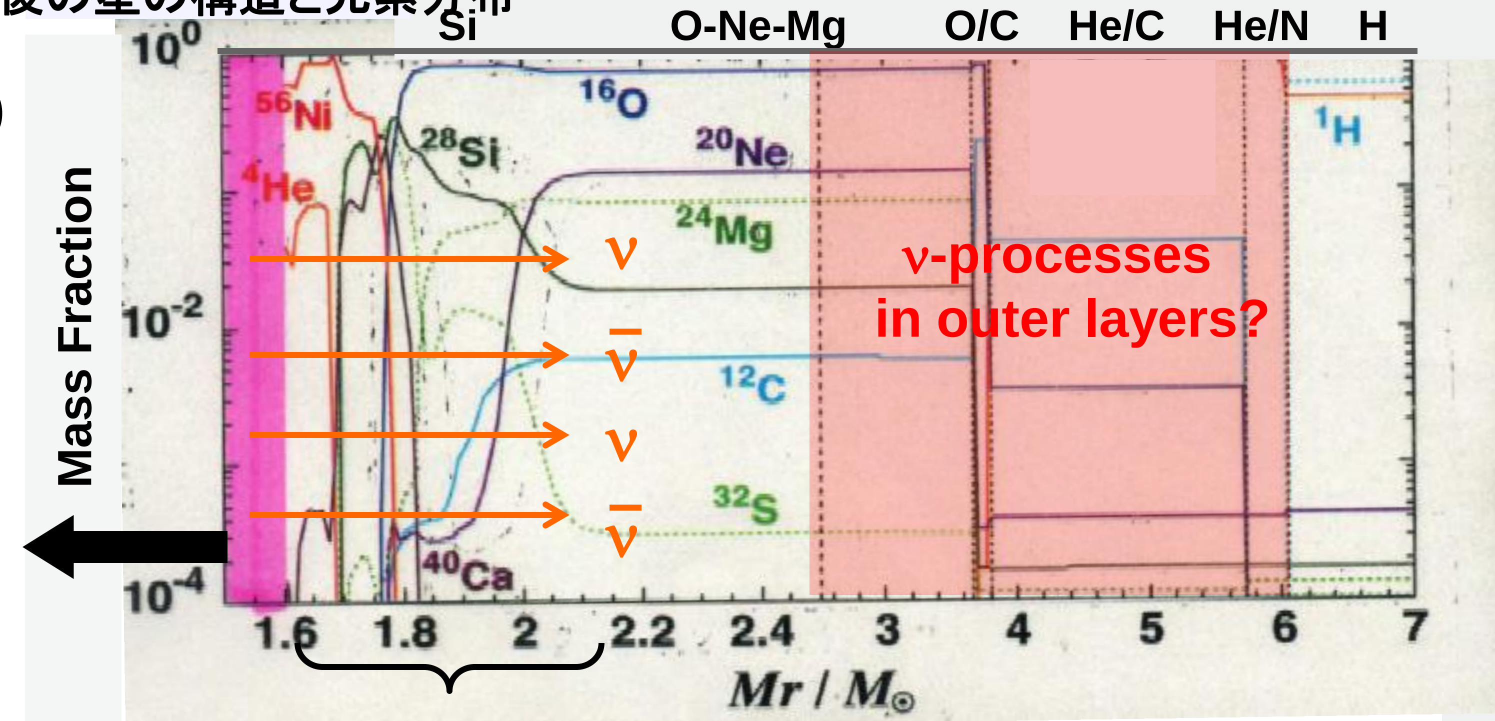
爆発直前

鉄・コバルト・ニッケルのコア



超新星爆発前後の星の構造と元素分布

Yoshida and Kajino (2005)

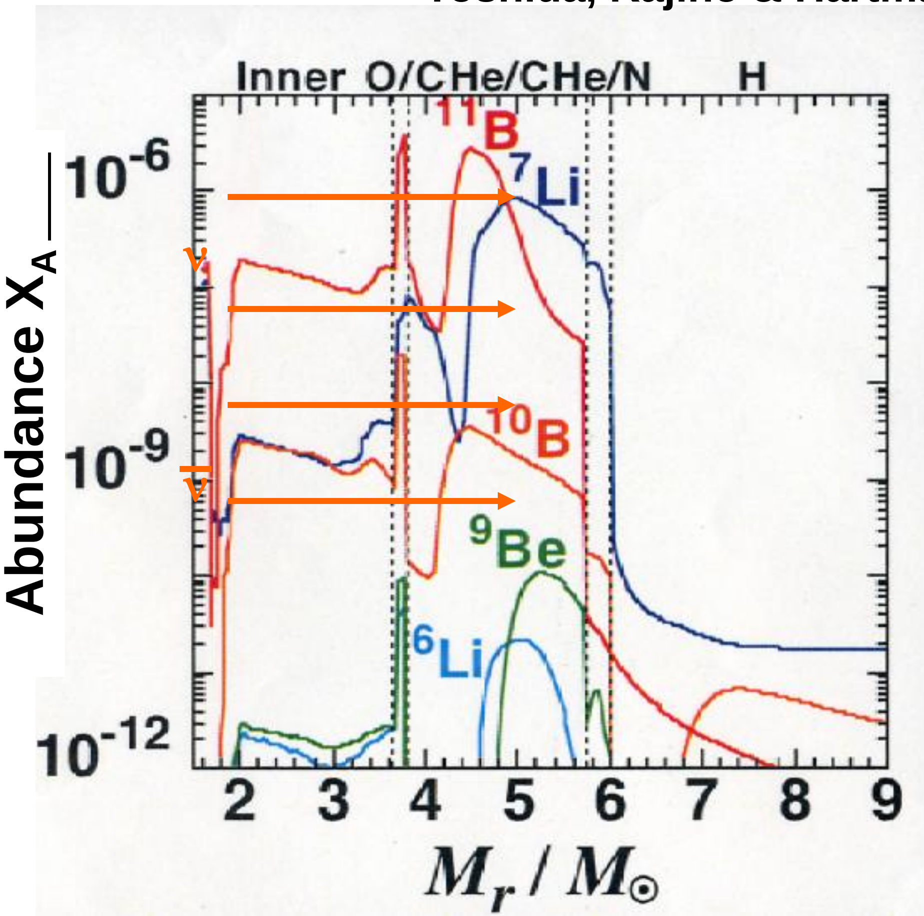


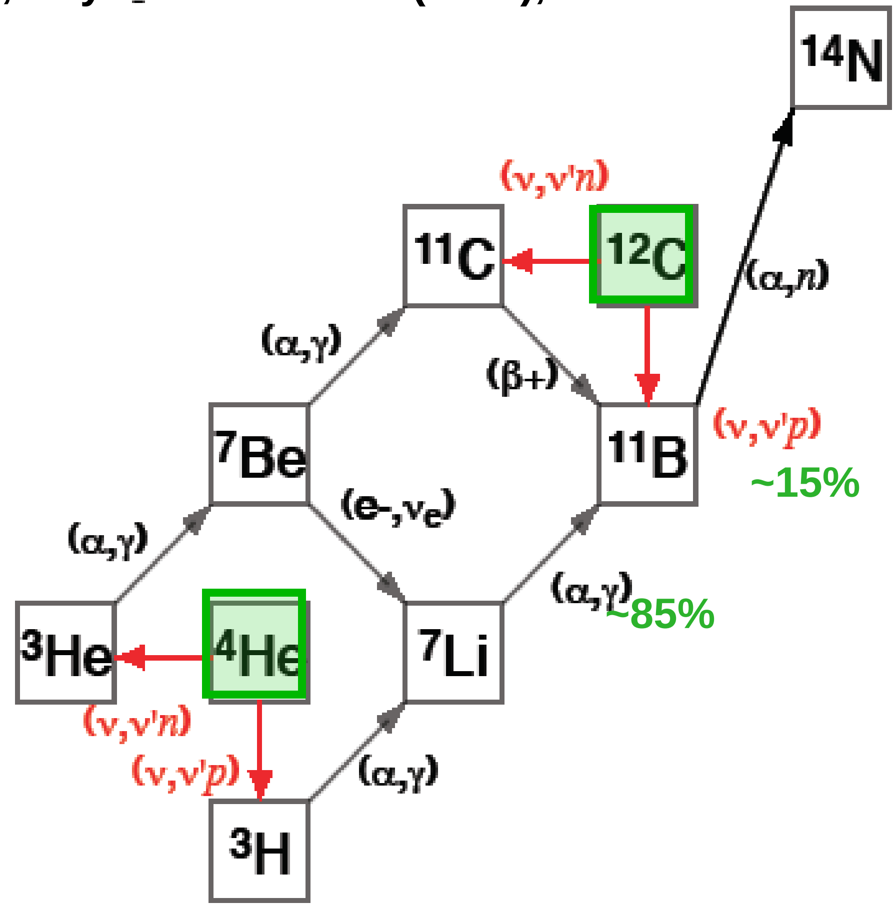
爆発直後
(約10秒)

中性子星に
重力崩壊
1.4

Supernova ν-Process & Key Reactions

Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101





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

(^{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

超新星元素合成モデル

Presupernova structure

SN 1987Aに対応した16.2 $M_{\odot}$恒星モデル

(Shigeyama & Nomoto 1990)

超新星爆発モデル

球対称爆発流体計算

爆発のエネルギー : $\mathbf{1 \times 10^{51}}$ **ergs**

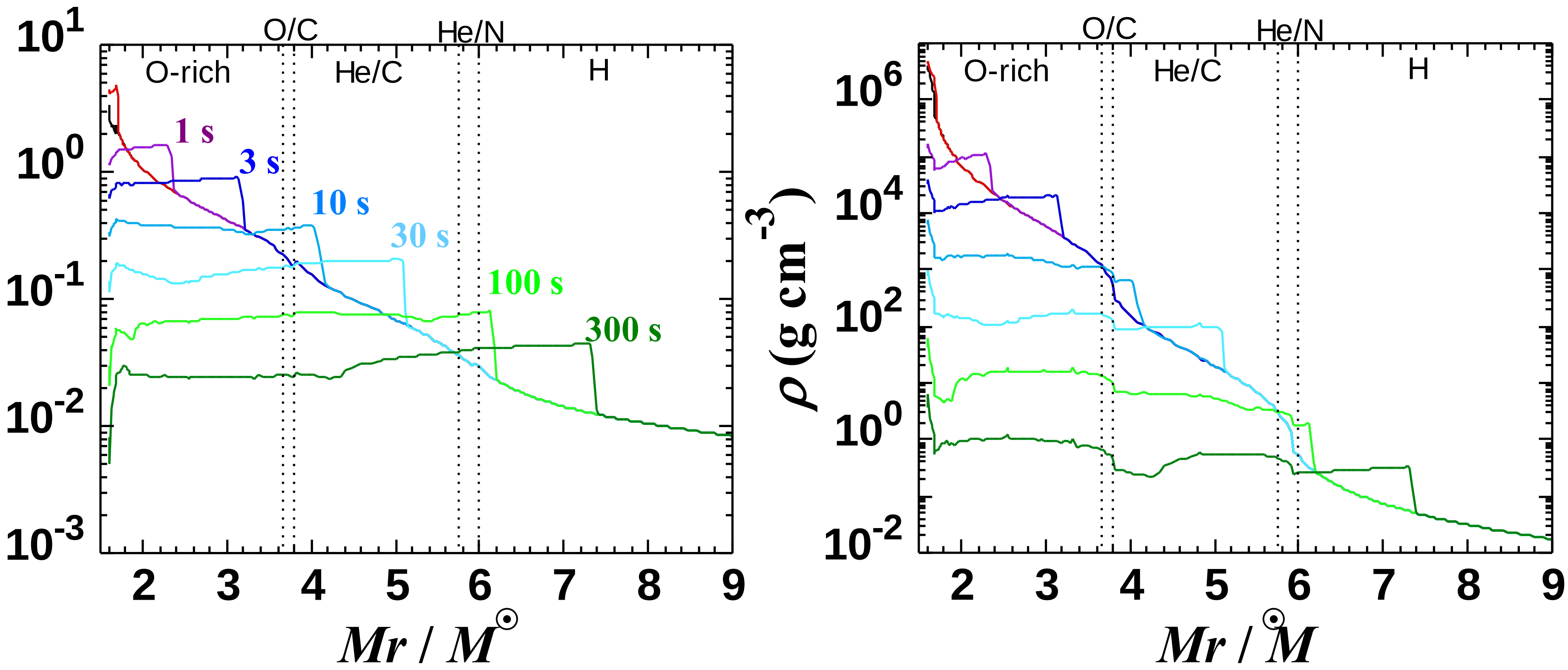
(Shigeyama et al. 1992)

元素合成計算

291核種からなる核反応ネットワーク

(Yoshida et al. 2004)

超新星爆発後の温度, 密度変化



超新星neutrinoモデルセッティング

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 (SN1987A)

$\tau_\nu = 3$ s

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

(After Woosley et al. 1990)

Neutrinosphereにおけるneutrino energy spectra

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

$(kT_{\nu e}, kT_{\bar{\nu} e}, kT_{\nu \mu\tau}) = (3.2\ \mathrm{MeV},\ 4\ \mathrm{MeV},\ 6\ \mathrm{MeV})$

(Yoshida et al. 2004—2010, Hayakawa et al. 2010)

Neutrino振動パラメータ

Large Mixing Angle solution

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

+: 順質量階層, -: 逆質量階層

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

$\sin^2 2\theta 12 = 0.816$, $\sin^2 2\theta 23 = 1$

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

SN ν-spectra are now KNOWN !

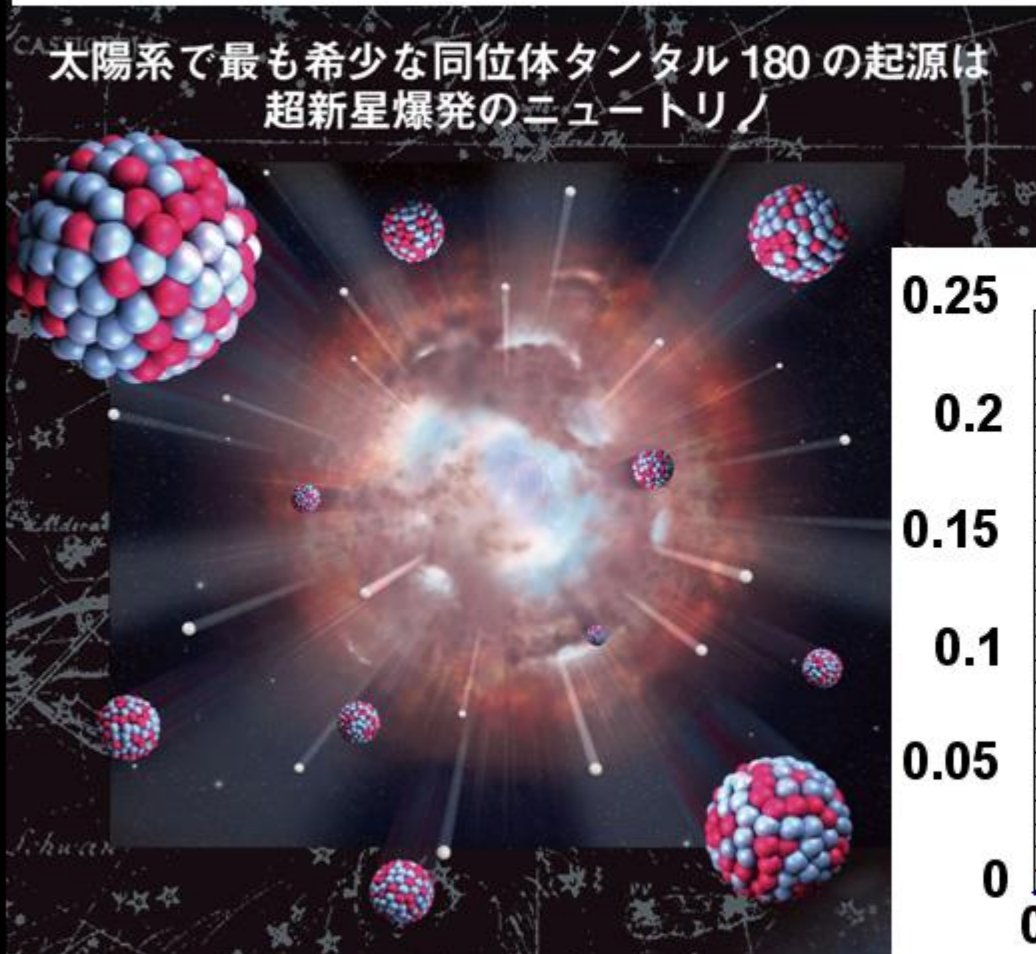
明日の談話会で議論

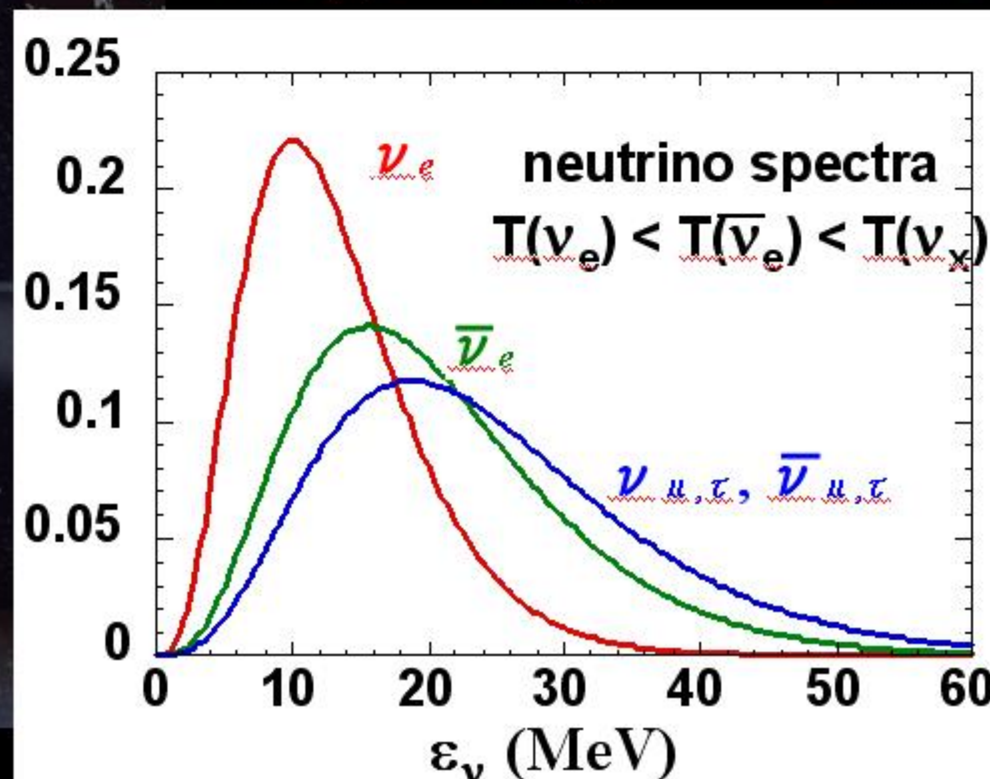
$T(\nu_e) < T(\bar{\nu}_e) < T(\nu_x)$

ν_e) = 3.2 MeV

$T(\bar{\nu}_e)$ = 4.0 MeV

$T(\nu_{\mu,\tau}) = T(\bar{\nu}_{\mu,\tau})$ = 6.0 MeV

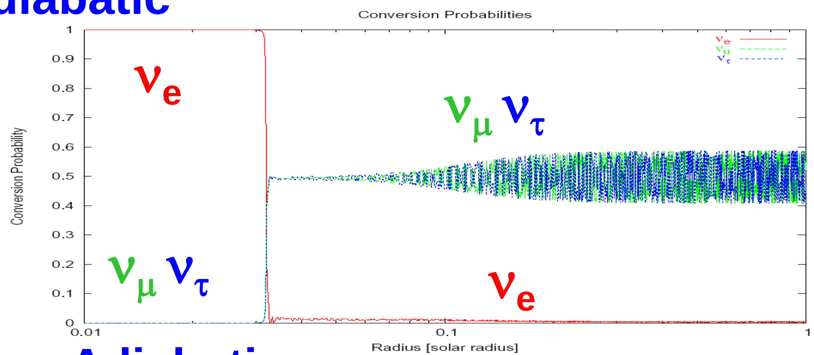




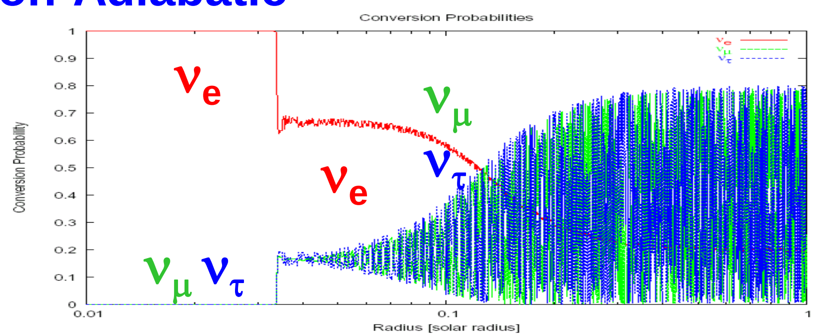
SN-Neutrino Oscillation (MSW) Effect on ν-Process

Conversion Probability

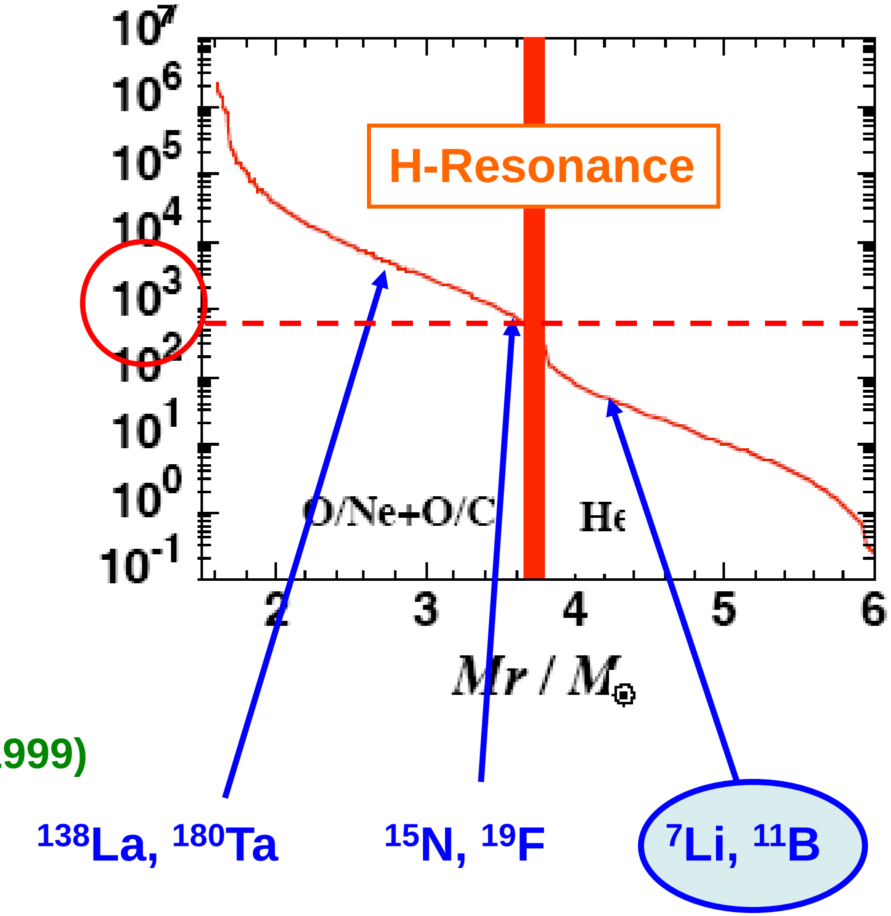
Adiabatic



Non-Adiabatic



Supernova Density Profile & Resonance



Parameters:

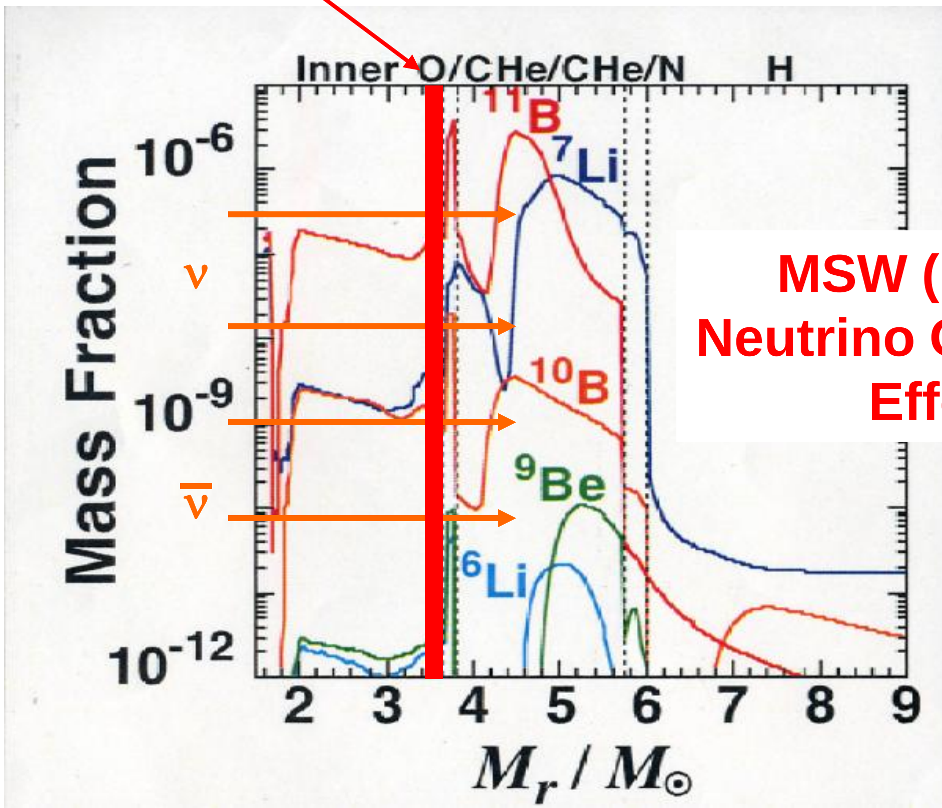
$25M_{solar}$ SN model (Hashimoto & Nomoto 1999)

- $\sin^2 2\theta_{13} = 0.04$
- $\Delta m_{13}^2 = 2.4 \times 10^{-3}$ eV^2
- $L_\nu = 3 \times 10^{53}$ erg, $\tau_\nu = 3$ sec
- $E_{\nu e}$=12MeV, $E_{\bar{\nu}e}$=20MeV, $E_{\nu\mu\tau}$=24MeV

Fermi-Dirac distr. of ν-spectrum, so that the observed ^{11}B abundance in Supernova Nucleosynthesis is reproduced.

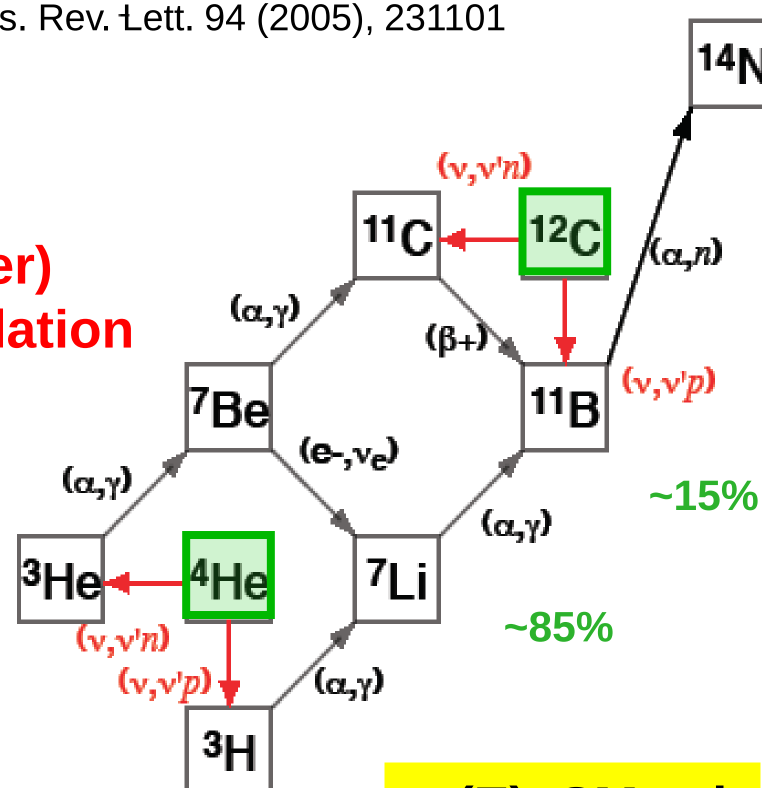
Supernova ν-Process & Key Reactions

H-Resonance



Yoshida, Kajino & Hartman,
Phys. Rev. Lett. 94 (2005), 231101

MSW (matter) Neutrino Oscillation Effect



σ_ν(E): SM cal.

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

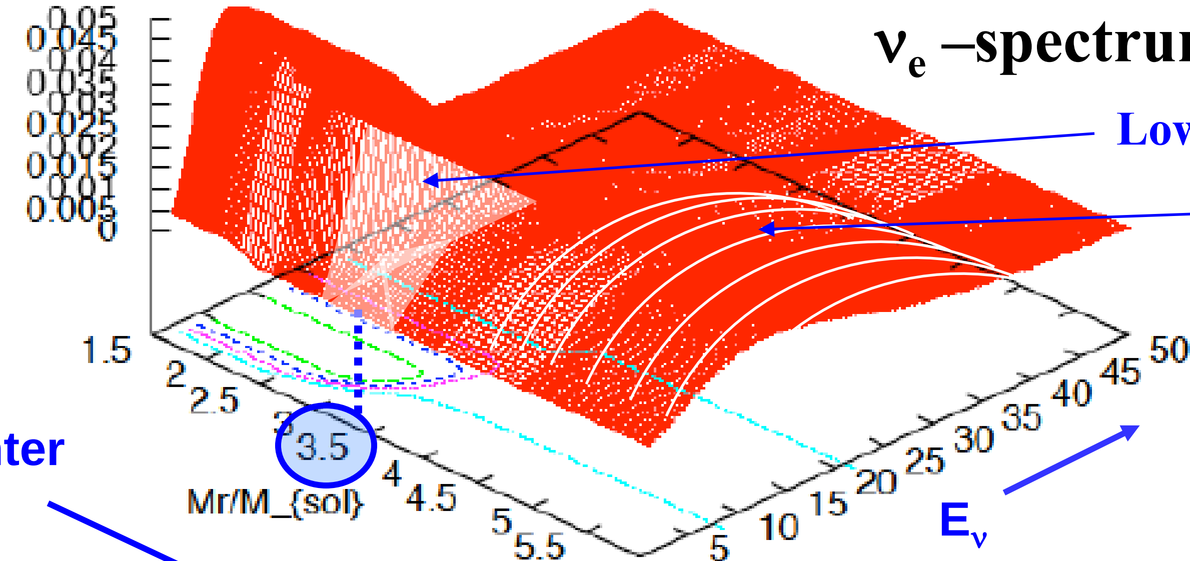
^{4}He(ν_e,e$^-$*p*)^{3}He, ^{4}He($\bar{\nu}_e$,e$^+$*n*)^{3}H, ^{12}C(ν_e,e$^-$*p*)^{11}C, ^{12}C($\bar{\nu}_e$,e$^+$*n*)^{11}B

Additional Charged Current Int.

$\nu_{\mu\tau}(\bar{\nu}_{\mu\tau}) \longrightarrow \nu_e\ (\bar{\nu}_e)$

^{4}He(ν_e,e$^-$*p*)^{3}He	&	^{4}He($\bar{\nu}_e$,e$^+$*n*)^{3}H
energetic		energetic

Neutrino Oscillation (MSW Effect) through propagation



Low-E comp. disappears !

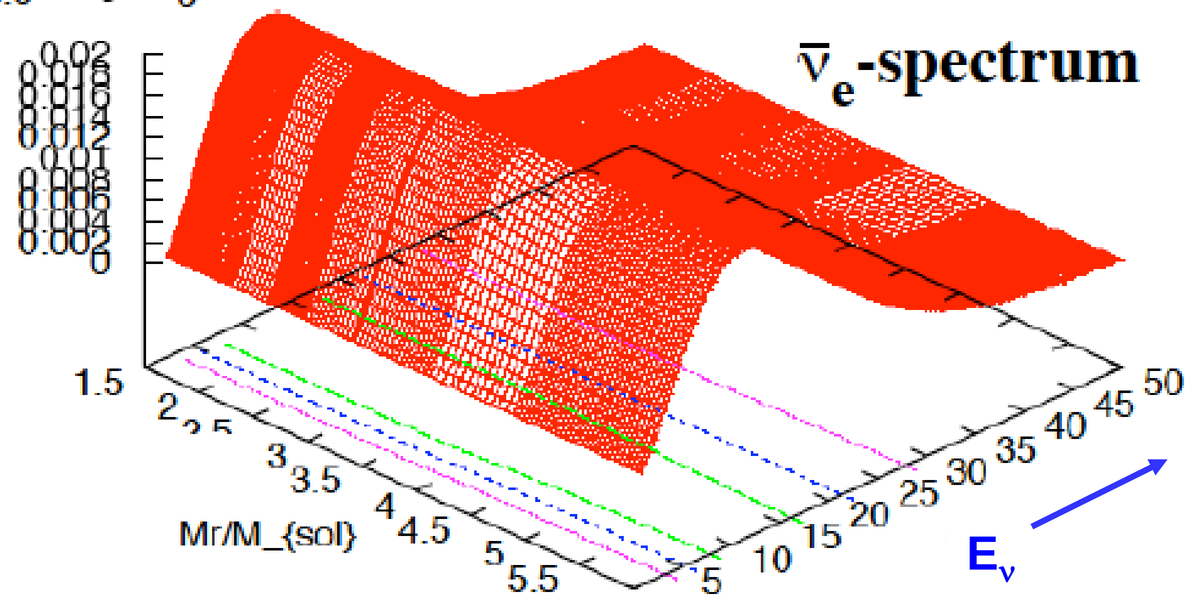
High-E comp. appears !

$\tau_\mu, \tau_\tau \longrightarrow \tau_e$

E_ν

Center

outside



E_ν

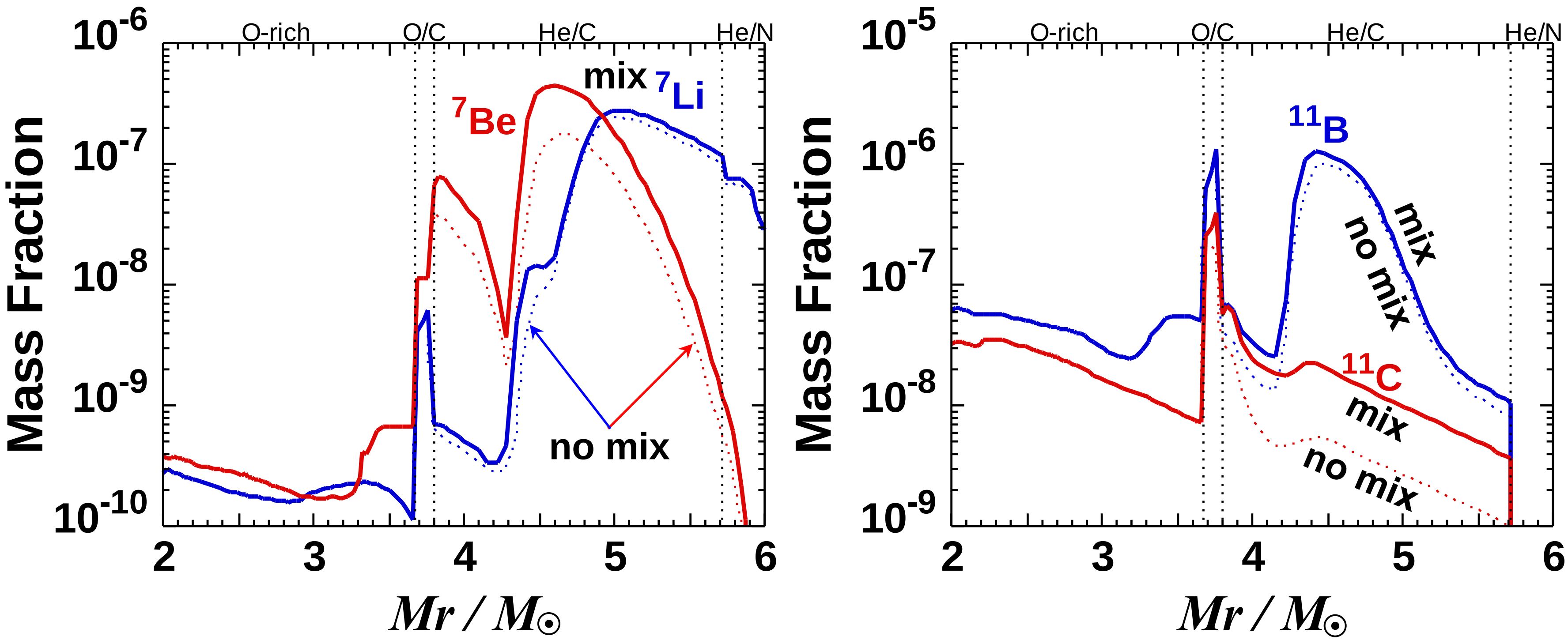
Parameters:

25M_{solar} progenitor SN model (Hashimoto & Nomoto 1999)

- $\sin^2 2\theta_{13} = 0.04$
- $\Delta m_{13}^2 = 2.4\times10^{-3}$ eV^2
- $L_\nu = 3\times10^{53}$ erg, $\tau_\nu = 3$ sec
- $T_{\nu e}$=3.2MeV, $T_{\nu e}$=5.0MeV, $T_{\nu\mu\tau}$=6.0MeV

SN Nucleosynthesis with Neutrino Oscillations

- Supernova nucleosynthesis (ν-process)
  16.2 $M_\odot$ star supernova model corresponding to SN 1987A
  Normal mass hierarchy, $\sin^2 2\theta_{13} = 0.01$



- **^{7}Be, ^{11}C** abundance ➡ Increase by a factor of 2.5 and 1.4
  ⬅ Increase in the rates of charged-current reactions
  ^{4}He$(\nu_e, e^- p)$**^{3}He** and **^{12}C**$(\nu_e, e^- p)$**^{11}C** in the He layer

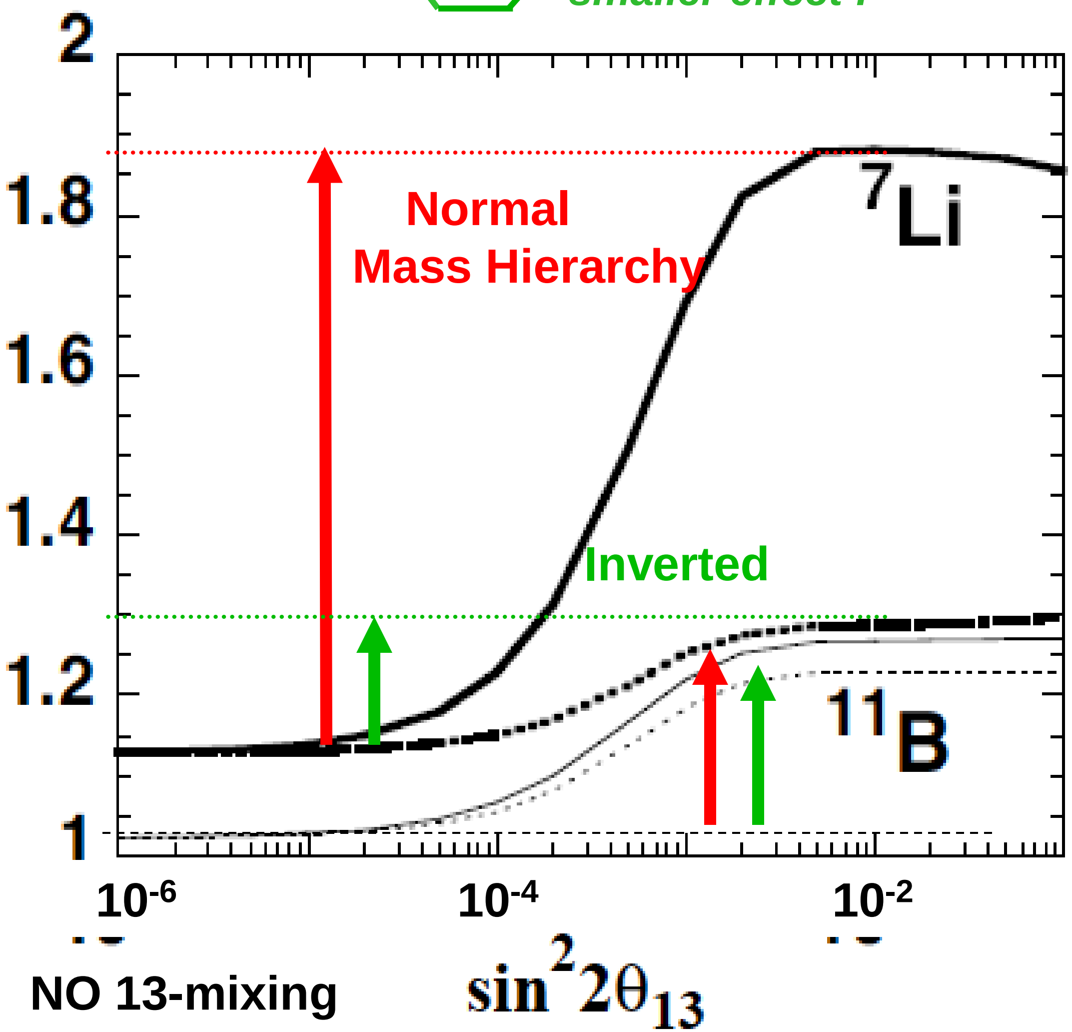
larger effect !

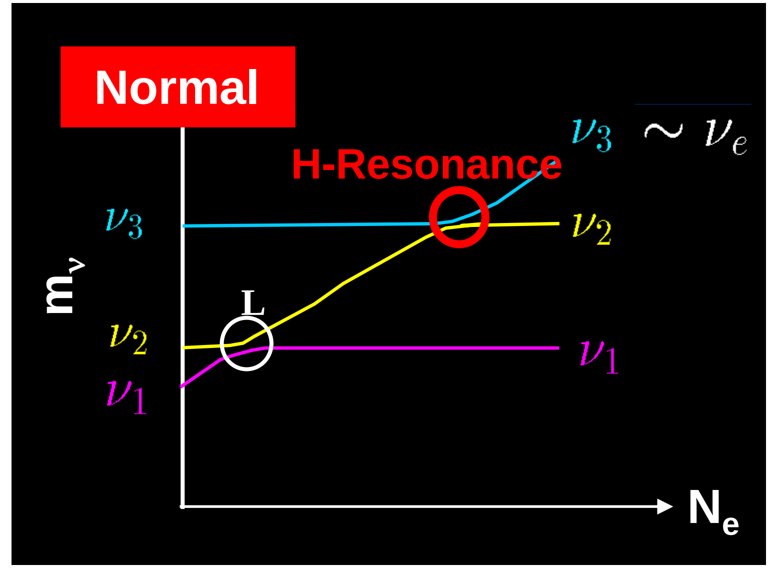
Yoshida, Kajino, Yokomakura, Kimura,Takamura & Hartmann, PRL 96 (2006) 09110; ApJ 649 (2006), 349.

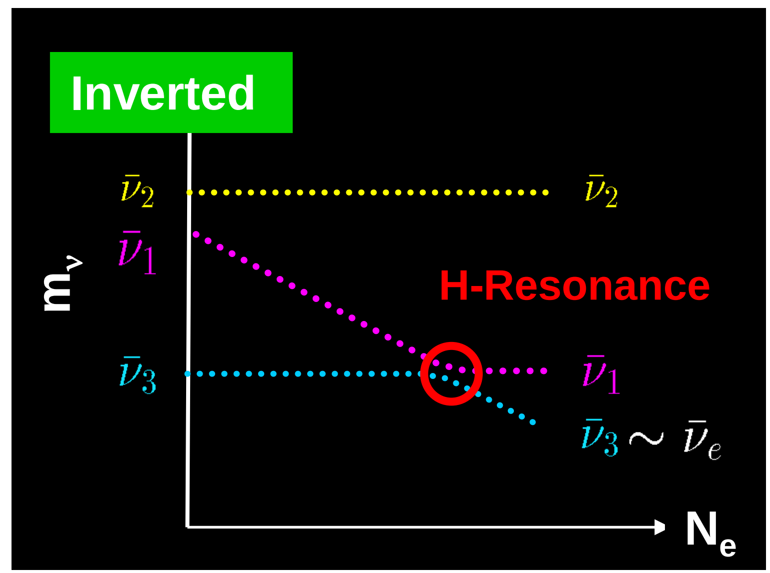
$T_{\nu e} < T_{\overline{\nu e}} < T_{\nu\mu\tau,\ \overline{\nu\mu\tau}}$

$T_{\nu e}$	$T_{\overline{\nu e}}$	$T_{\nu\mu\tau,\ \overline{\nu\mu\tau}}$
= 3.2MeV	= 5.0MeV	= 6.0MeV

smaller effect !

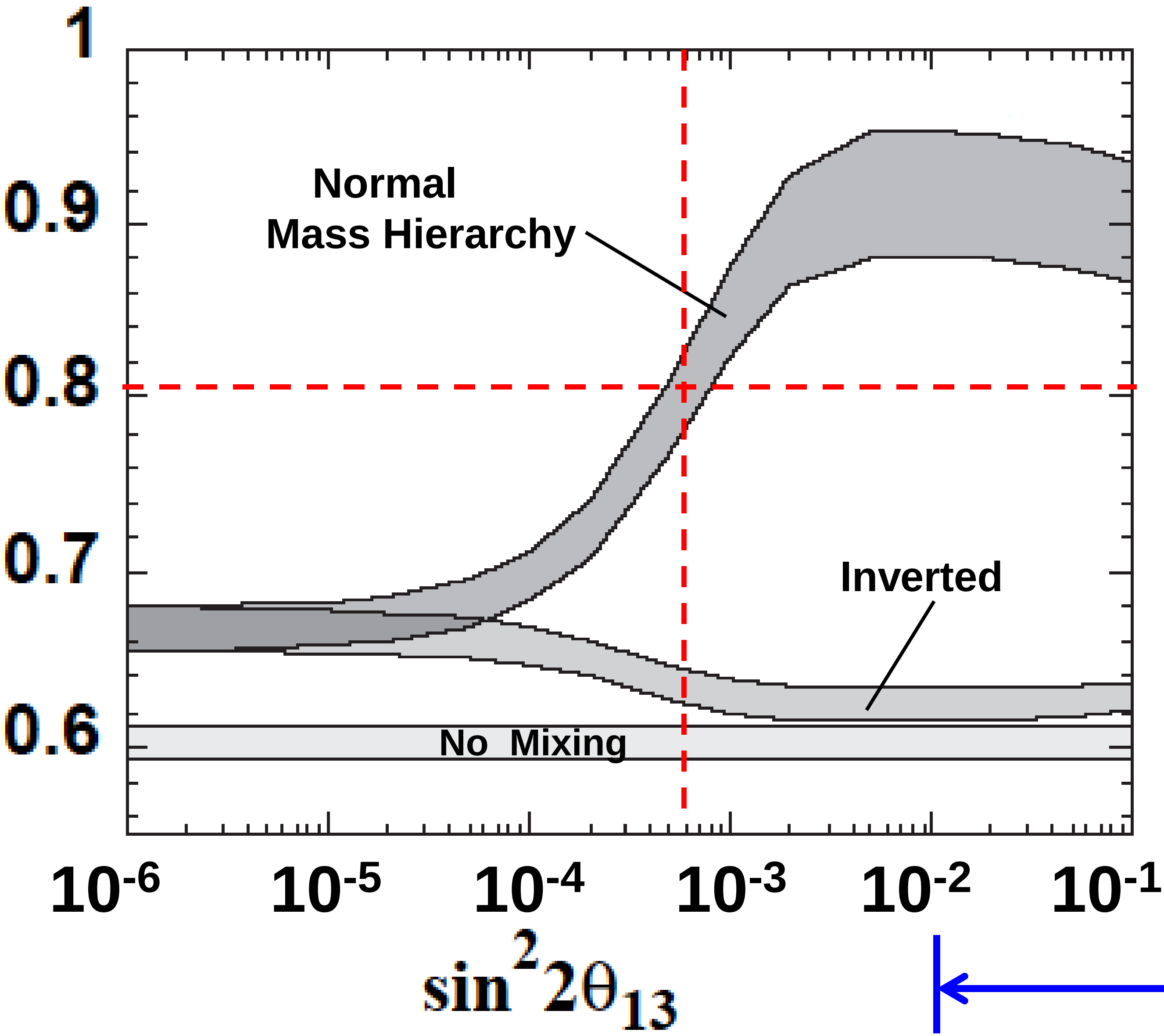






$^7Li/^{11}B$ - Ratio

MSW Effect: Wolfenstein 1978, PR D17, 2369; Mikheyev & Smirnov 1986, Sov. J. Nucl. Phys. 42, 913.
Yoshida, Kajino et al. ,2005, PRL94, 231101; 2006, PRL 96, 091101; 2006, ApJ 649, 319; 2008 ApJ 686, 448.



Astrophysics:

Mass Hierarchy

Δm_{13}^2

13-Mixing Angle

θ_{13}

↕

Long Baseline Exp:

T2K (Kamioka)

T2KK (KOREA)

Double CHOOZ

Daya Bay

$^{7}Li/^{11}B$-理論予測の検証観測の提案

(1) 大望遠鏡、宇宙望遠鏡による超新星の光学的観測

^{11}B 吸収線 ～ 2497 A （宇宙望遠鏡）

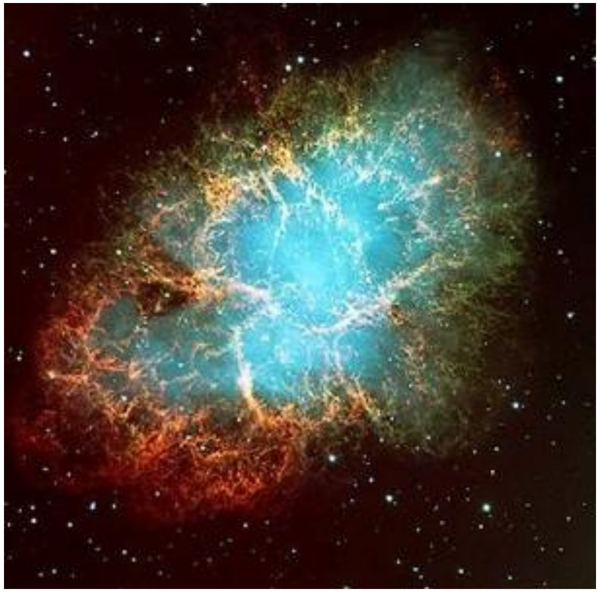
$^{11}B/^{10}B$, 金属欠乏星で観測に成功! Rebull et al. ApJ 507 (1998) 387; Proc. (2000)

^{7}Li 吸収線 ～ 6708 A (すばる望遠鏡)

^{7}Li & $^{7}Li/^{6}Li$,金属欠乏星で観測に成功! Many observations (1982 – present)

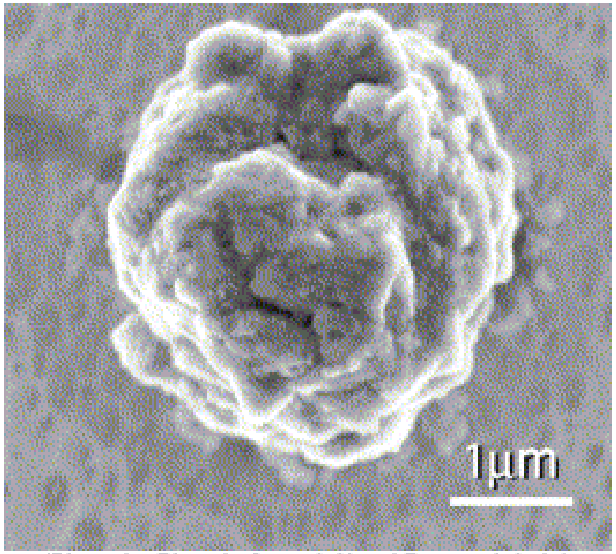
超新星1987A 残骸
未測定

かに星雲（超新星残骸）
未測定

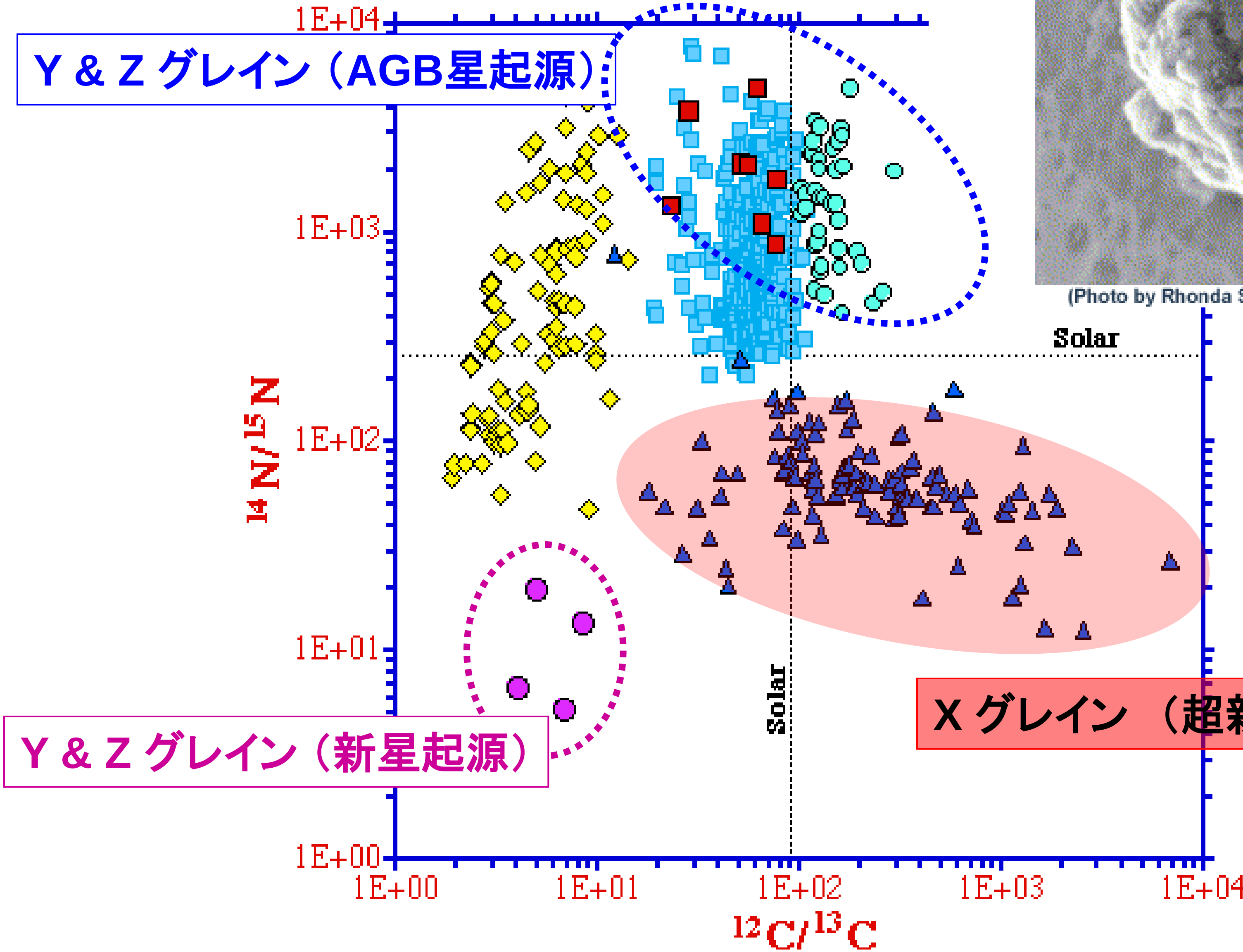


金属欠乏星の観測
測定成功

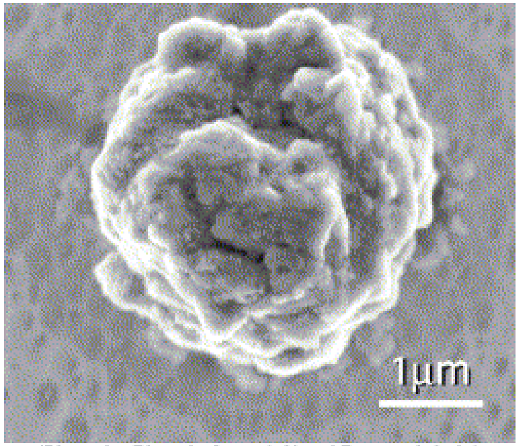
(2) プレソーラーグレイン（シリコンカーバイト）の分析



(Photo by Rhonda Stroud, Naval Research Lab.)

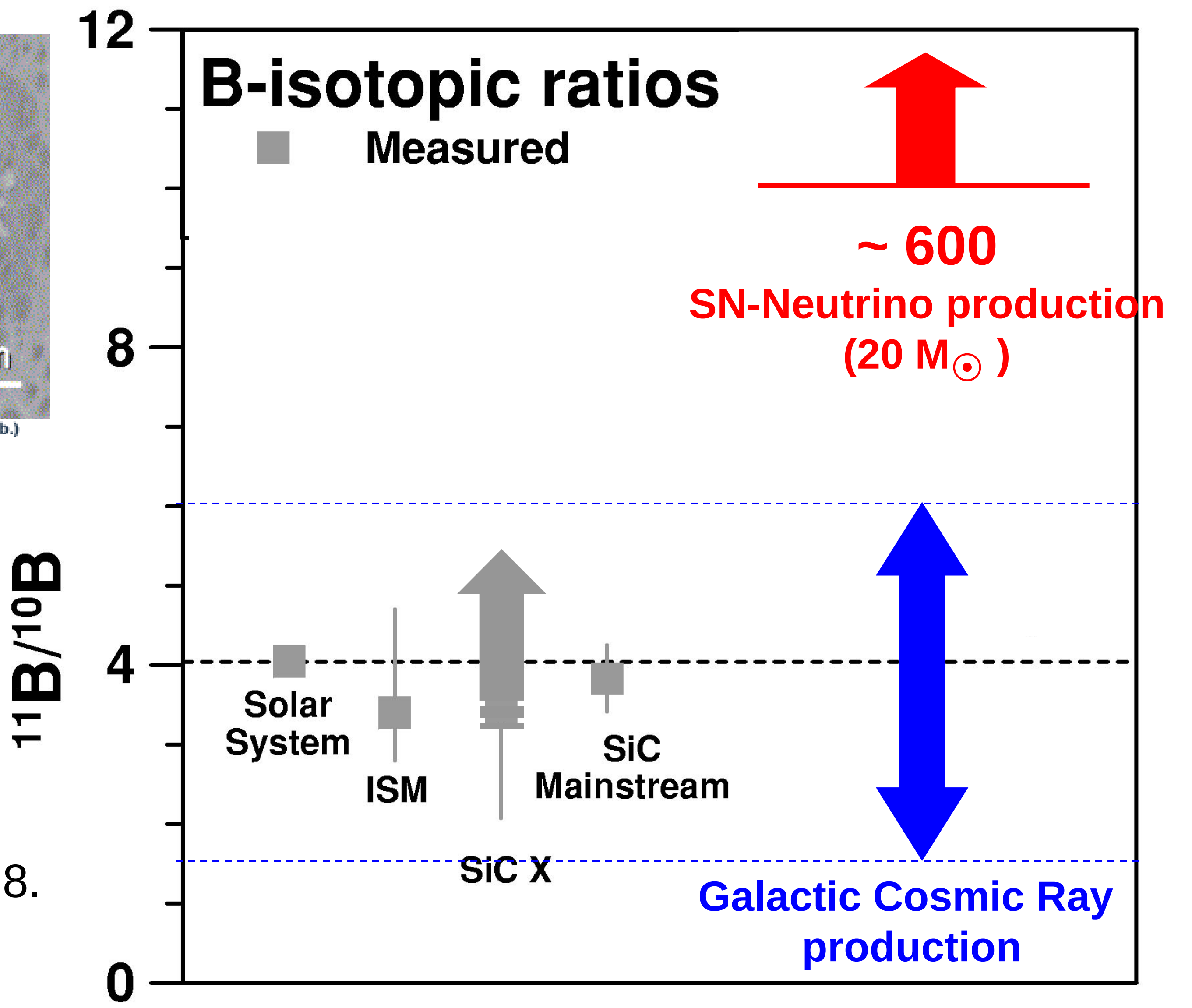


Presolar SiC X-grains from SNe



(Photo by Rhonda Stroud, Naval Research Lab.)

P. Hoppe et al.
ApJ 551 (2001) 478.



SUMMARY

2. SN ν-process on Li-Be-B isotopic ratios are sensitive measure of the MSW effect in order to determine the unknown ν-oscillation parameter θ_{13} and mass hierarchy of active ν_e , ν_μ, ν_τ.

X(SN)-grains search & SN-remnant spectr. obs.