京都大学物理学第二教室談話会、2010年10月15日

# 原子核の弱電相互作用と超新星ニュートリノ

## ニュートリノ温度および振動パラメータの決定方法の提案

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# Neutrino Physics and Cosmology Today

## Neutrino Mass

**Cosmology**

**CMB and LSS constraint from cosmological parameter-fit:**

**$\Sigma m_\nu < 1.3$ eV ($2\sigma$ C.L.)** ⇒ **$\Omega_\nu h^2 < 0.013$**

WMAP-5yr, 7yr: Komatsu et al. (2008, 2010)

**New constraint: CMB + Magnetic Field + "ν+Prim." Anisotropic Stress:**

**$\Sigma m_\nu < 0.8$ eV ($1\sigma$ C.L.)** ⇒ **$\Omega_\nu h^2 < 0.008$ ($1\sigma$)**

Yamazaki, Ichiki, Kajino & Mathews, PRD (2010), in press.
Kojima, Kajino & Mathews, JCAP 02 (2010), 018.

**Nuclear Physics**

**$0\nu$-$\beta\beta$ :** **$|\sum U^2_{e\beta} m_\beta| < 1\sim6$ eV** ⇒ **0.1~0.05 eV !? (future)**

Lesgourgues and Pastor (2006)

## Neutrino Mass Difference and Hierarchy

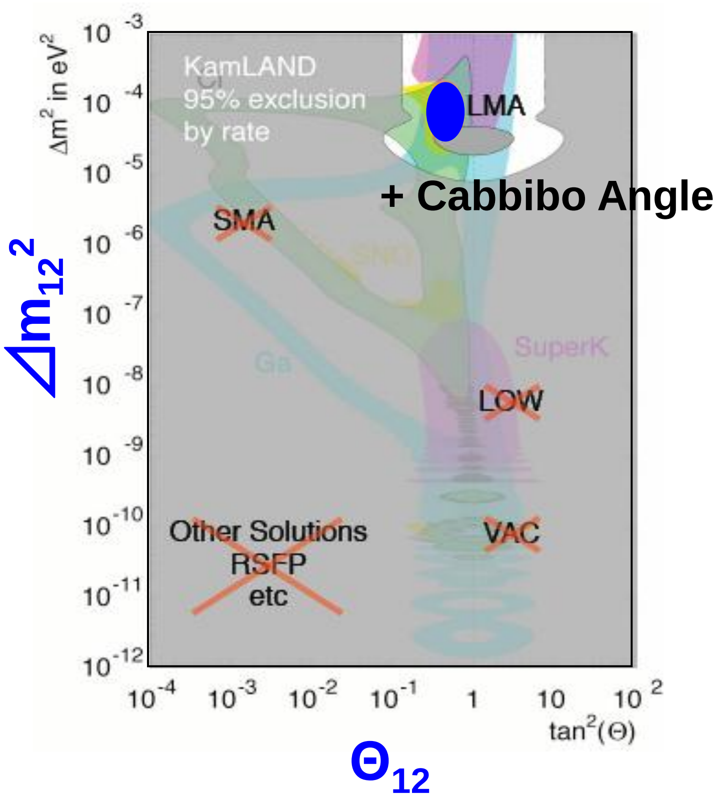
**Particle & Nuclear Physics:** **Underground Lab. + Long-Baseline Exp.**

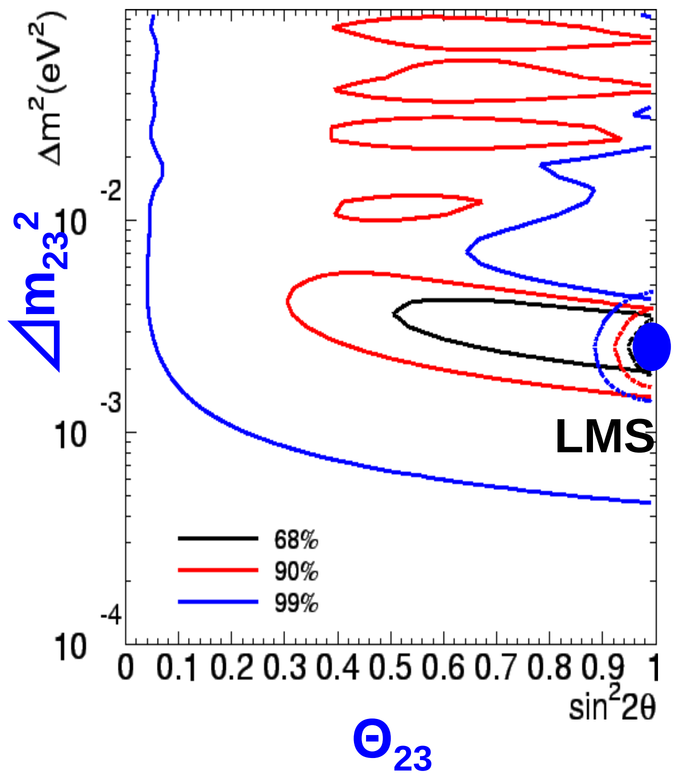
**Nuclear Astrophysics:** **SN Neutrino Nucleosynthesis**

# "KNOWN" Neutrinos

Super-K, SNO, KamLand (reactor ν) determined $\Delta m_{12}^2$ and $\theta_{12}$ uniquely.

Super Kamiokande (atmospheric ν) determined $\Delta m_{23}^2$ and $\theta_{23}$ uniquely.




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

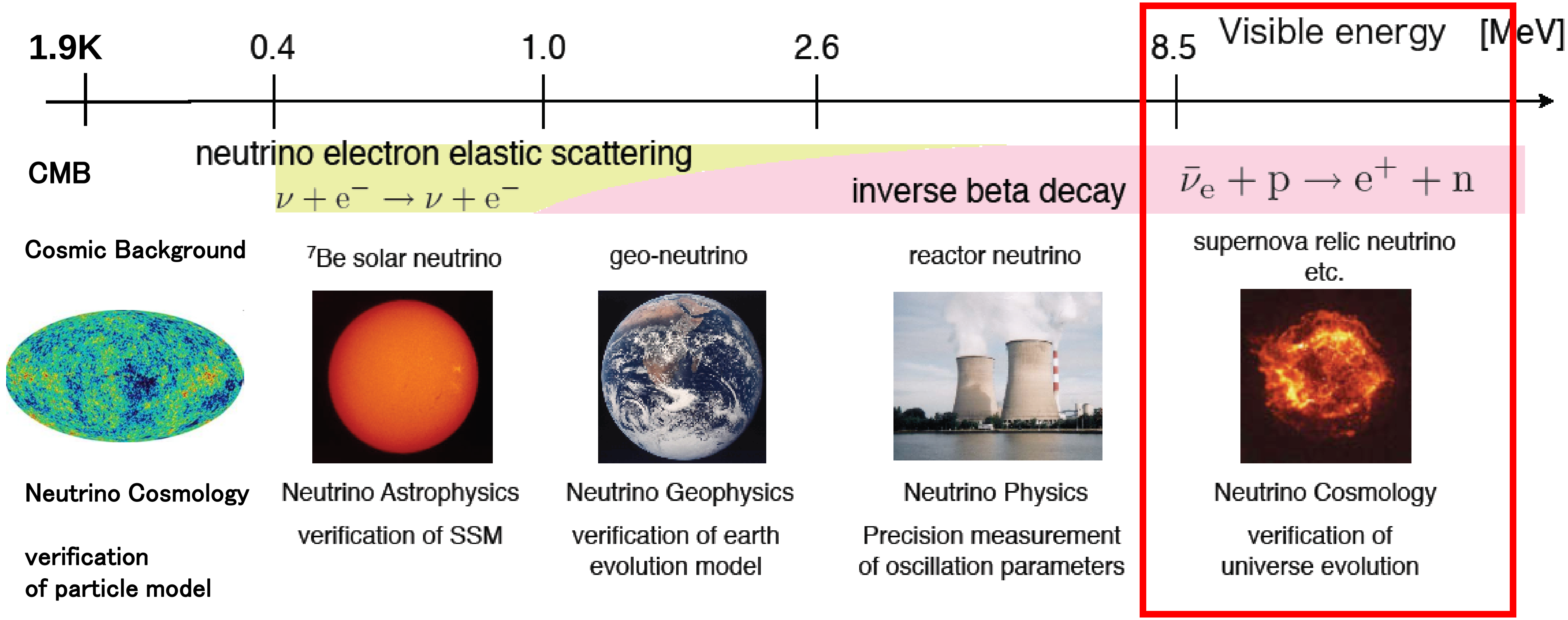
# "Several UNKNOWNs"

**Yamazaki, Ichiki, Kajino, Mathews (2009,2010)**

**(1) $\sin^2 2\theta_{13} < 0.1$,** **(2) $|\Delta m_{13}^2| = 2.4\times10^{-3}\ eV^2$**

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

# Various Physics Targets with wide Neutrino-Energy Range




$\nu_e, \nu_\mu, \nu_\tau$

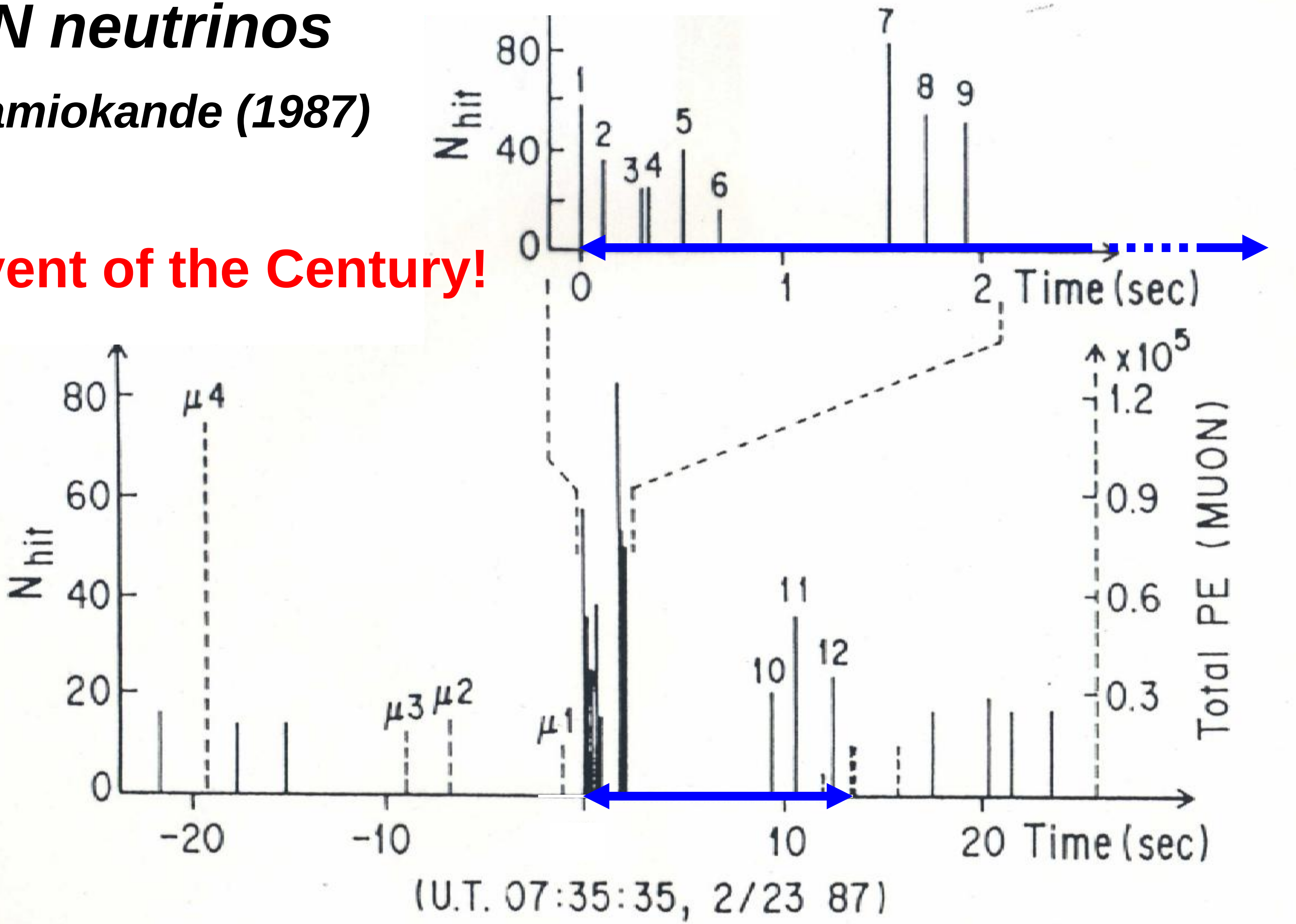
## PURPOSE

1. To determine SN-$\nu$ spectra, i.e. $\nu$-temperatures ?
2. To determine unknown $\nu$-oscillation parameters from SN-nucleosynthesis ?

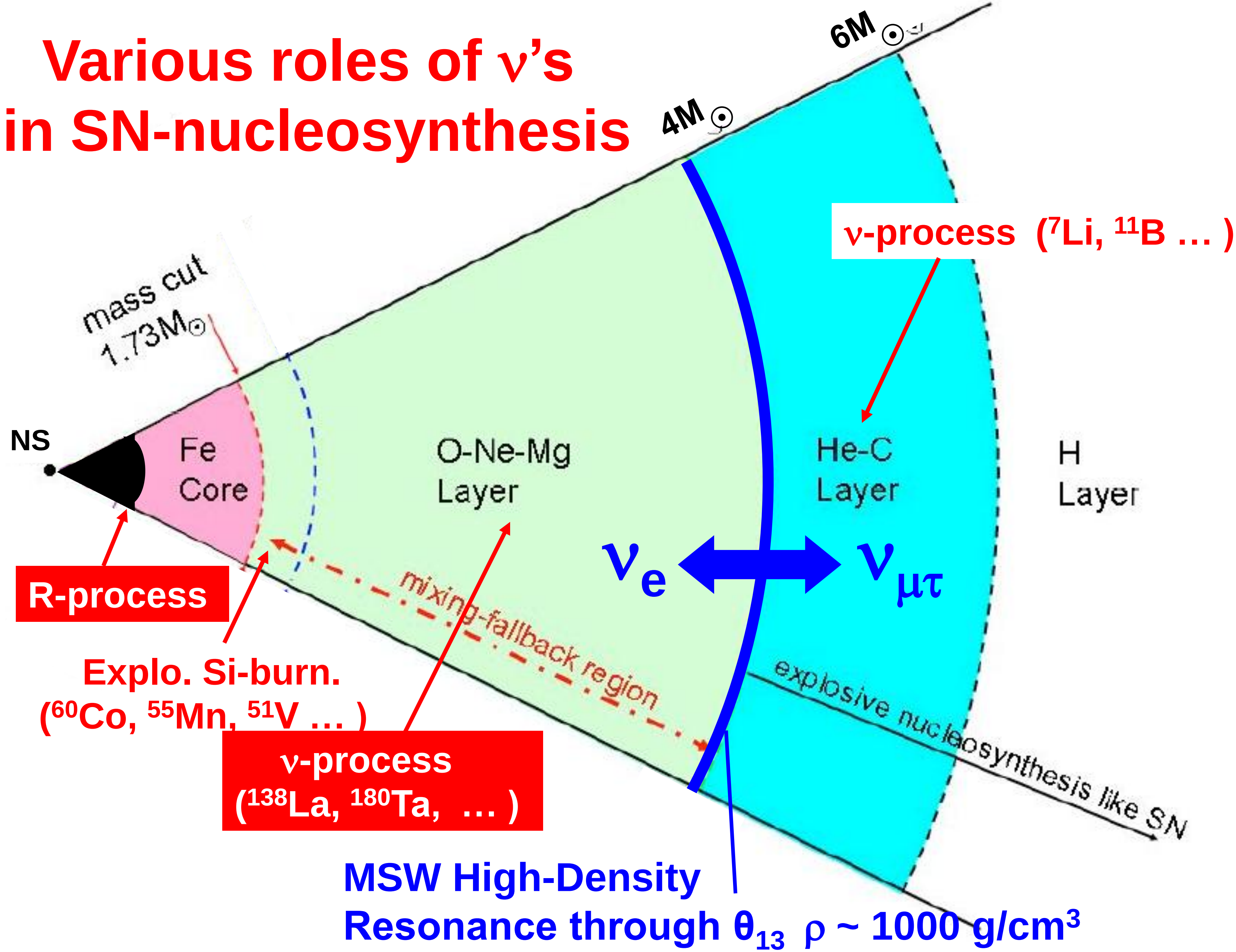
# *Direct sinal of SN neutrinos*

***Kamiokande (1987)***

**Event of the Century!**

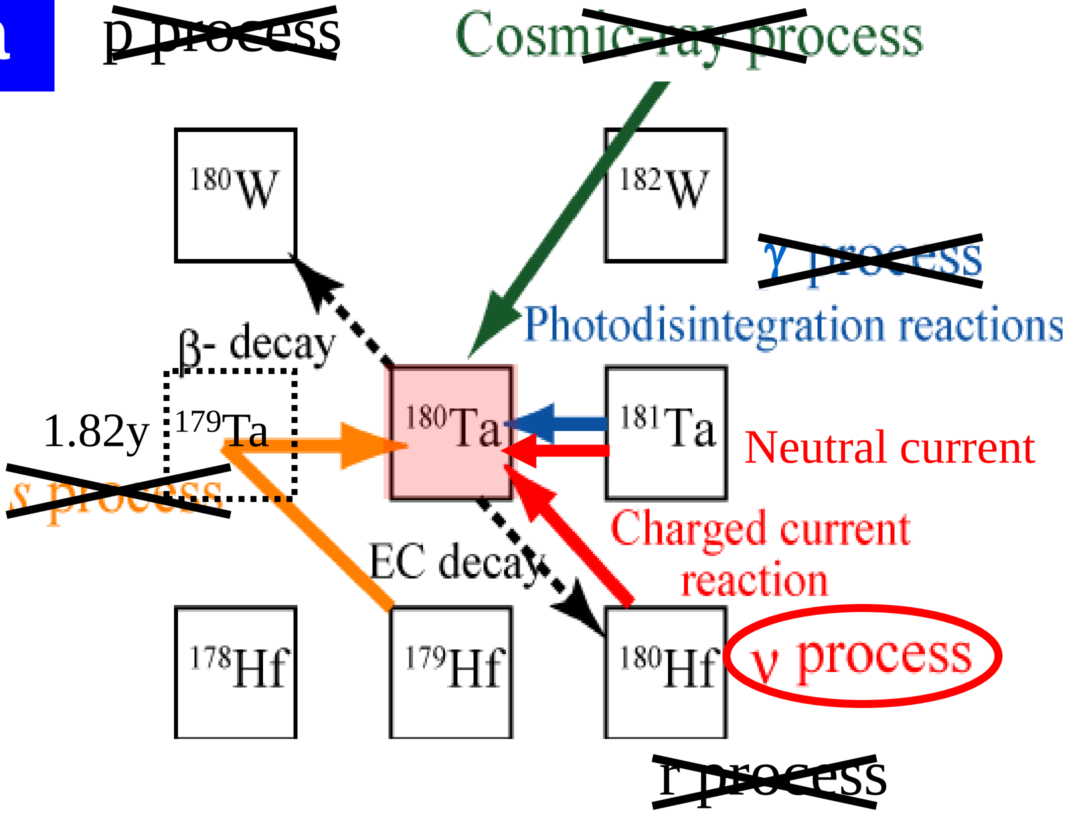


# Various roles of ν's in SN-nucleosynthesis



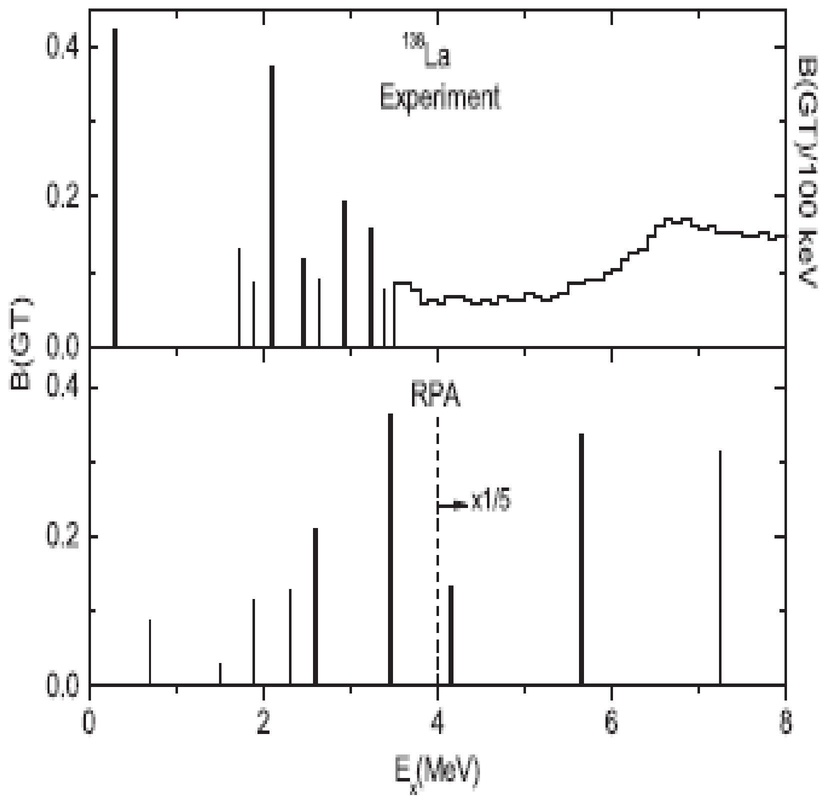
# Origin of $^{180}$Ta & $^{138}$La

**$^{138}$La ~ spherical nucleus**
**$^{180}$Ta ~ deformed nucleus**

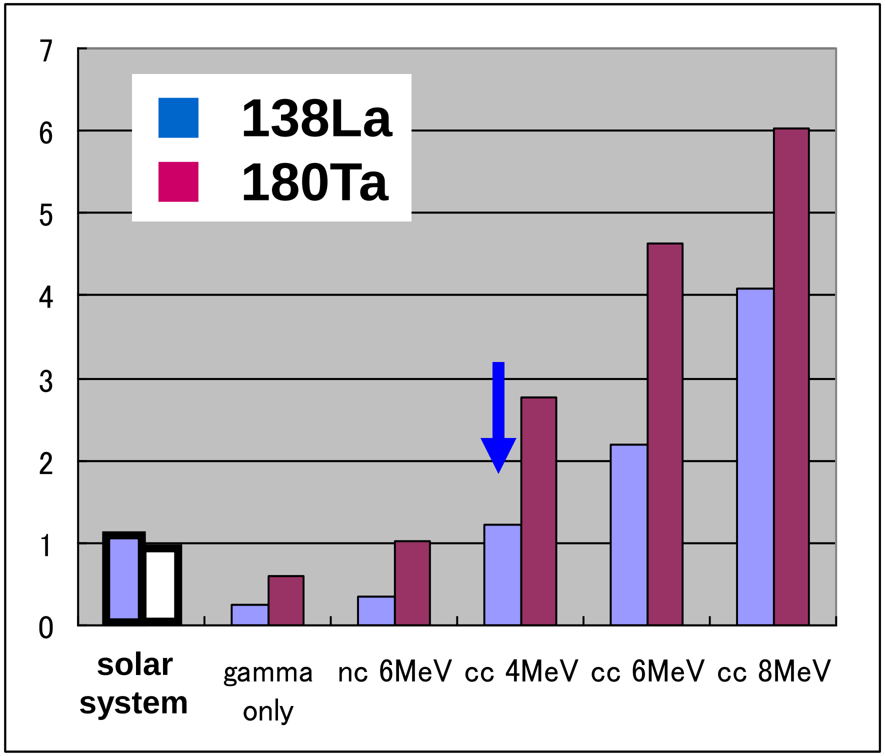


# Impact of CEX Reaction on ν-Process

**Byelikov + Fujita et al., PRL (2007) measurement of GT strength.**




**A. Heger, Phys. Lett. B 606, 258 (2005)**




**Overproduction problem of $^{180}$Ta relative to $^{138}$La!**

**Spin-dipole + multipole forbidden transitions + GT contribute!**

**Eν = 0 ~ 80 MeV**

★ **No ν-beam experiment yet for ν-A X-section !**
**We can use Electro-Magnetic PROBE !**

## Similarity between Electro-Magnetic & Weak Interactions

***EM-current = $\vec{V}$, Weak-current = $\vec{V}$ - $\vec{A}$***

$$\vec{V} \approx g_V^{IV} \frac{i}{2m} \vec{\sigma} \times \vec{q} + \frac{g_V}{2m} (\vec{p} + \vec{p}\,')$$

$$\vec{A} \approx g_A \vec{\sigma}$$

***Weak operator in non-relativistic limit***

*Gamow-Tellar operator =* $\vec{\sigma}\tau_{\pm}$

*Spin-Multipole operator =* $[\vec{\sigma} \times Y^{(L)}]^J \tau_{\pm}$

**Big-Bang nucleosynthesis with SUSY particle**

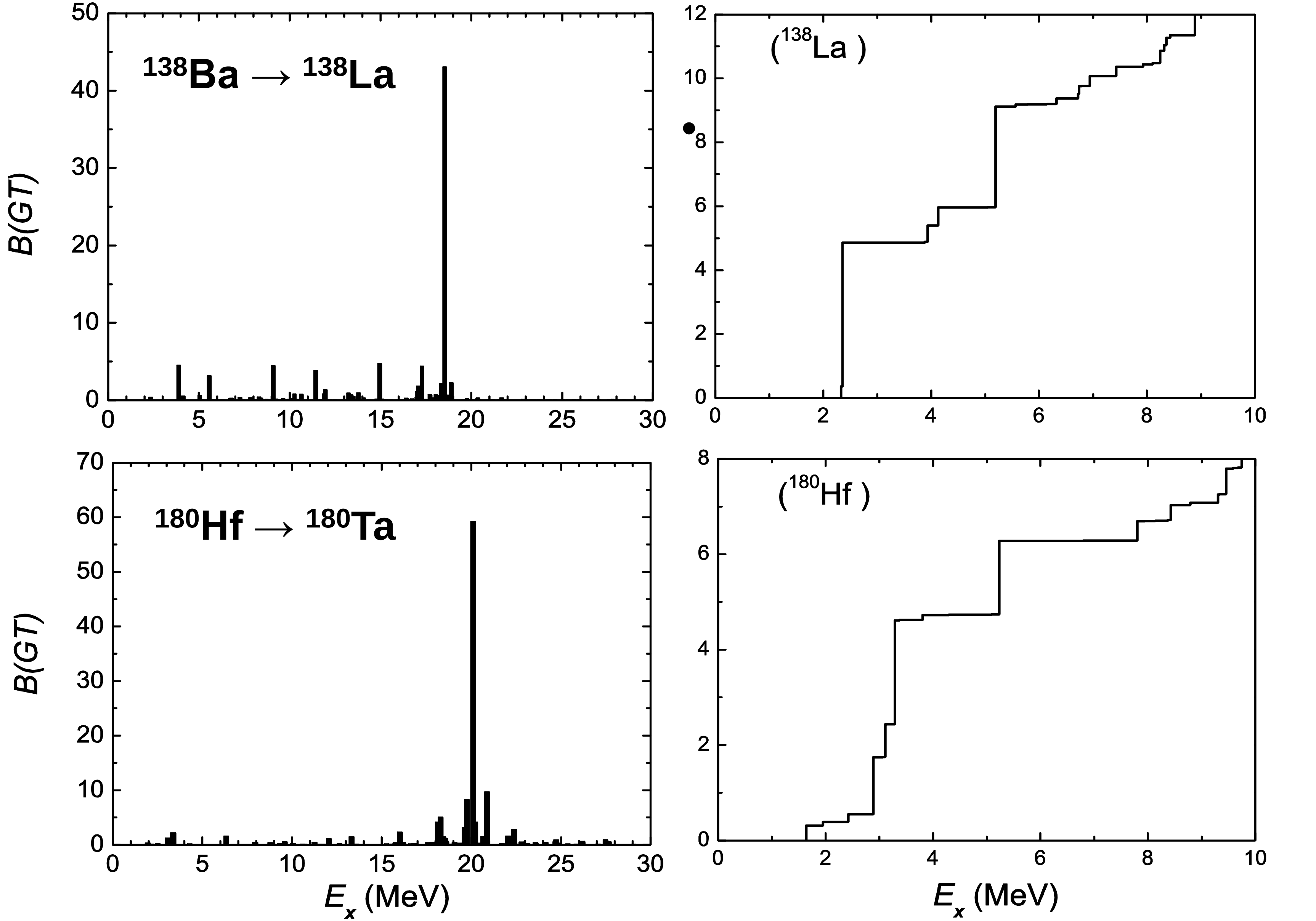
**$^4He(\gamma, n)^3He$ and $^4He(\gamma, p)^3H$**

⟷ **$^4He(\nu, \nu')$, $^4He(\nu_e, e^-)$, $^4He(\bar{\nu}_e, e^+)$**

**SN-ν nucleosynthesis for determining ν-oscillation param**

**Neutrino reactions on $^{138}$La and $^{180}$Ta via charged and neutral currents by the Quasi-particle Random Phase Approximation (QRPA),**

Cheoun, Ha, Hayakawa, Kajino & Chiba, PR C82 (2010), 035504.



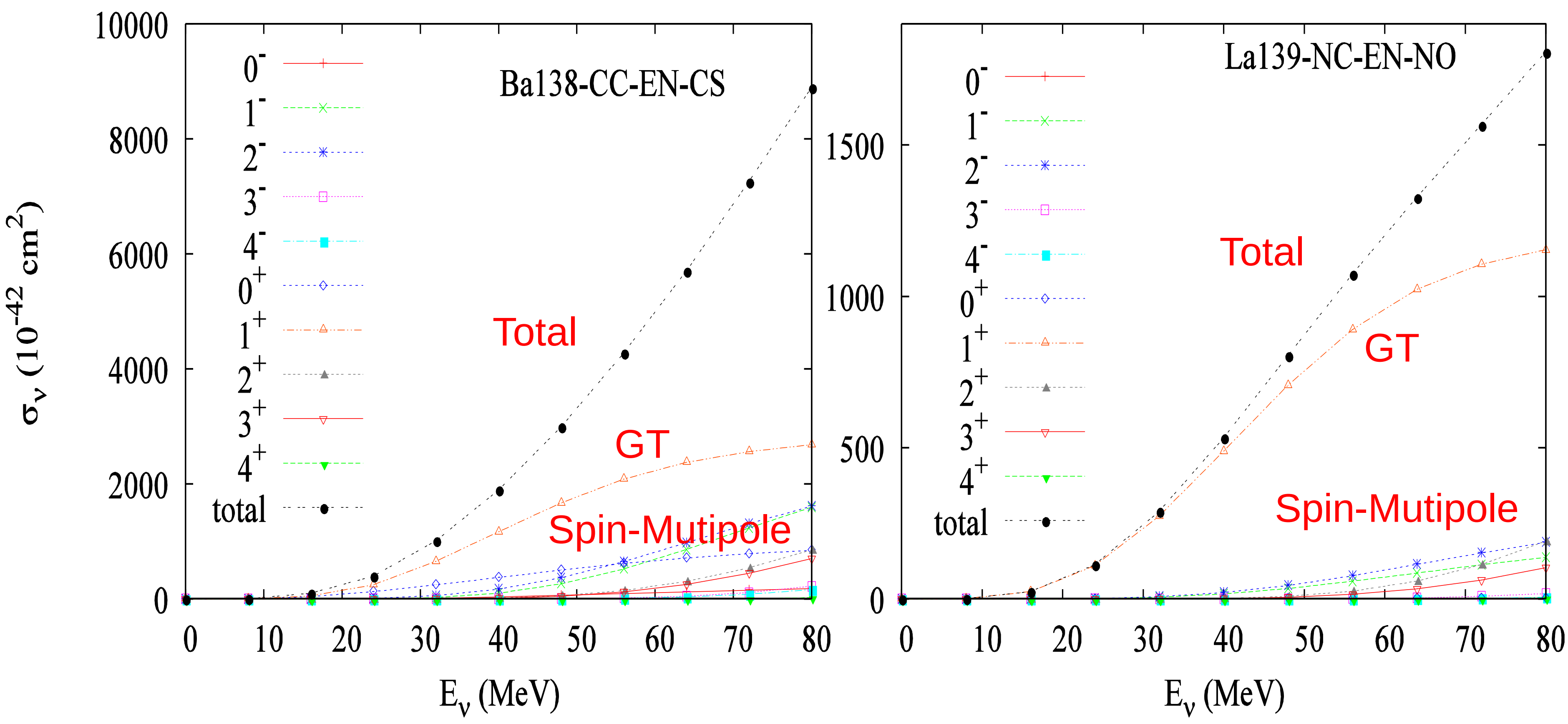
Cheoun, Ha, Hayakawa, Kajino & Chiba, PR C82 (2010), 035504.

## Larger Spin-Multipole Contribution

## GT Dominance

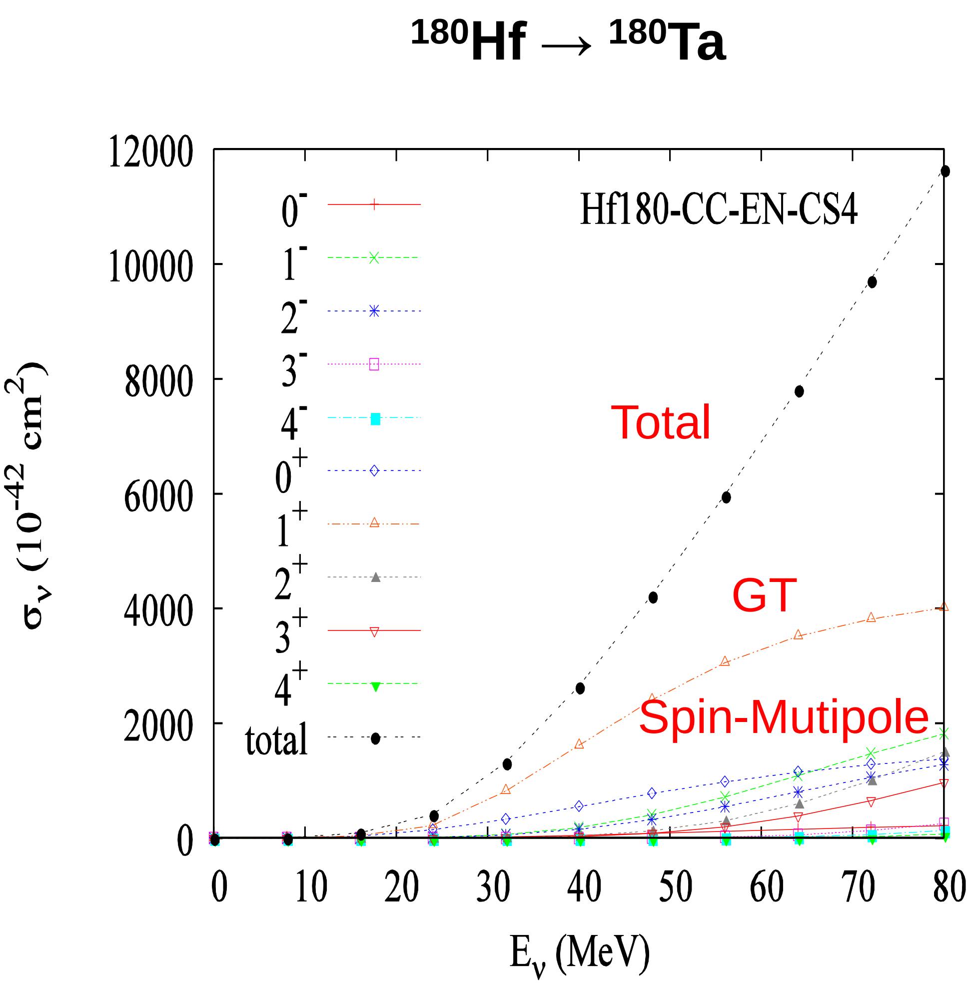
$^{138}Ba \rightarrow ^{138}La$

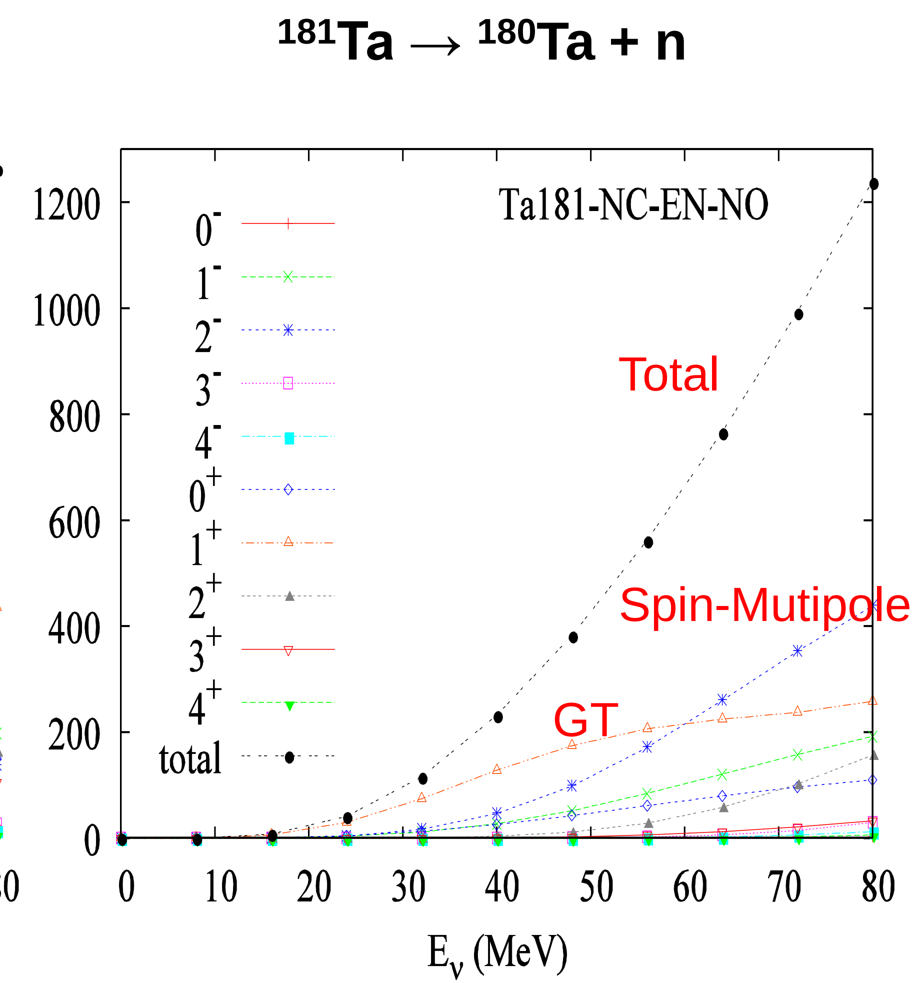
$^{139}La \rightarrow ^{138}La + n$



Cheoun, Ha, Hayakawa, Kajino & Chiba, PR C82 (2010), 035504.

# Larger Spin-Multipole Contribution



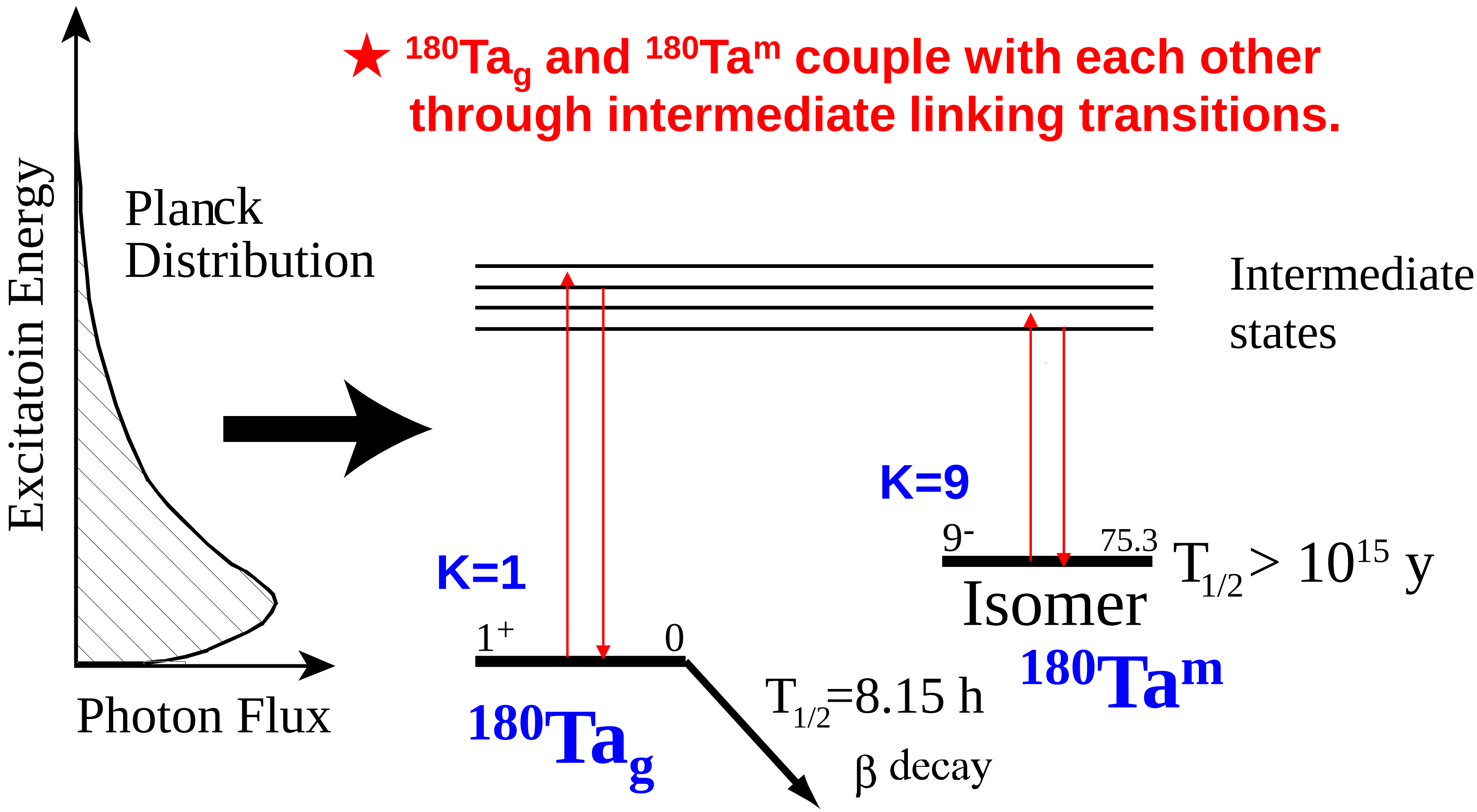



# Problem of Isomer Ratio of $^{180}$Ta

**Isomer Residual Ratio, isomer / (gs+isomer), is a critical factor for the calculation of 180Ta nucleosynthesis.**

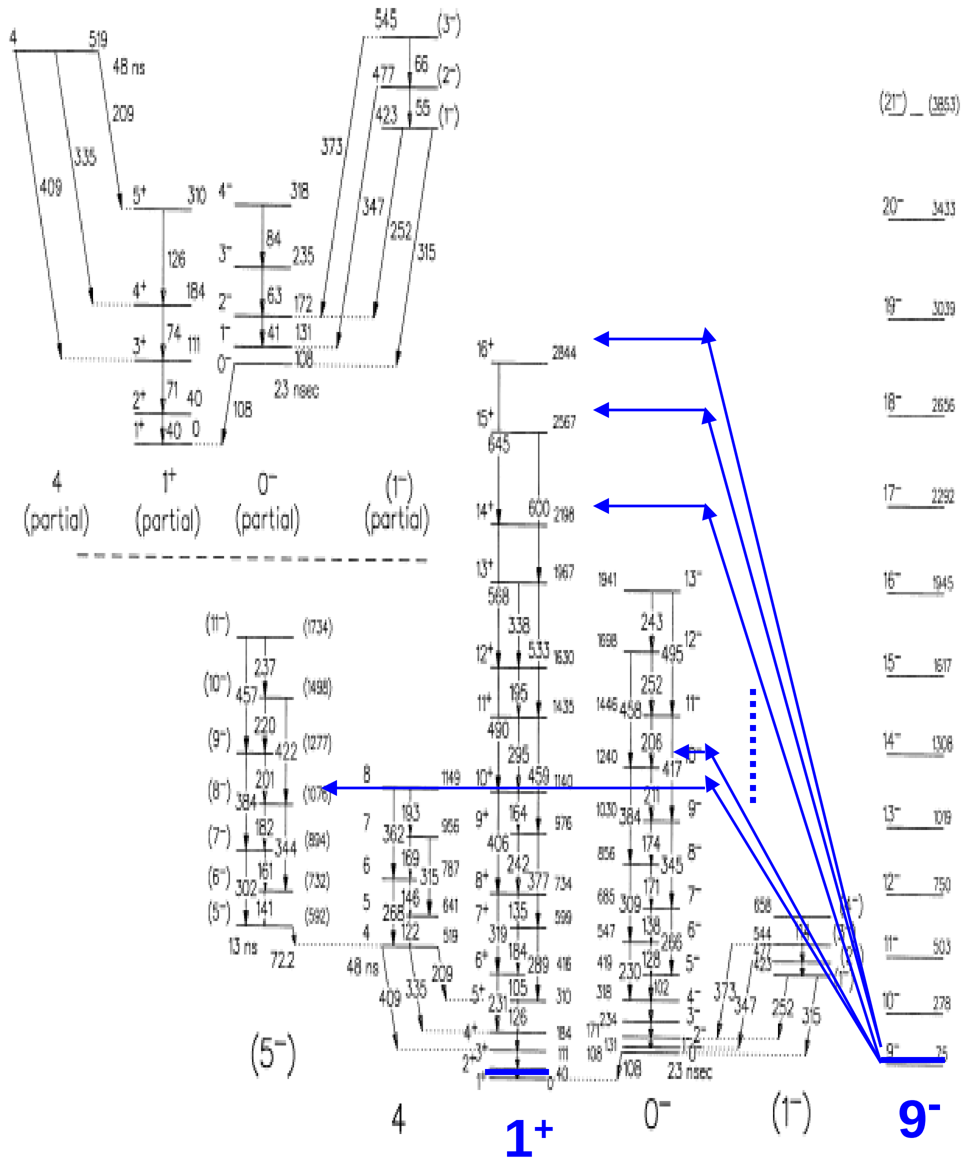
★ **Linking transitions between K = 1 and 9 bands are extremely weak.**

★ **$^{180}Ta_g$ and $^{180}Ta^m$ couple with each other through intermediate linking transitions.**



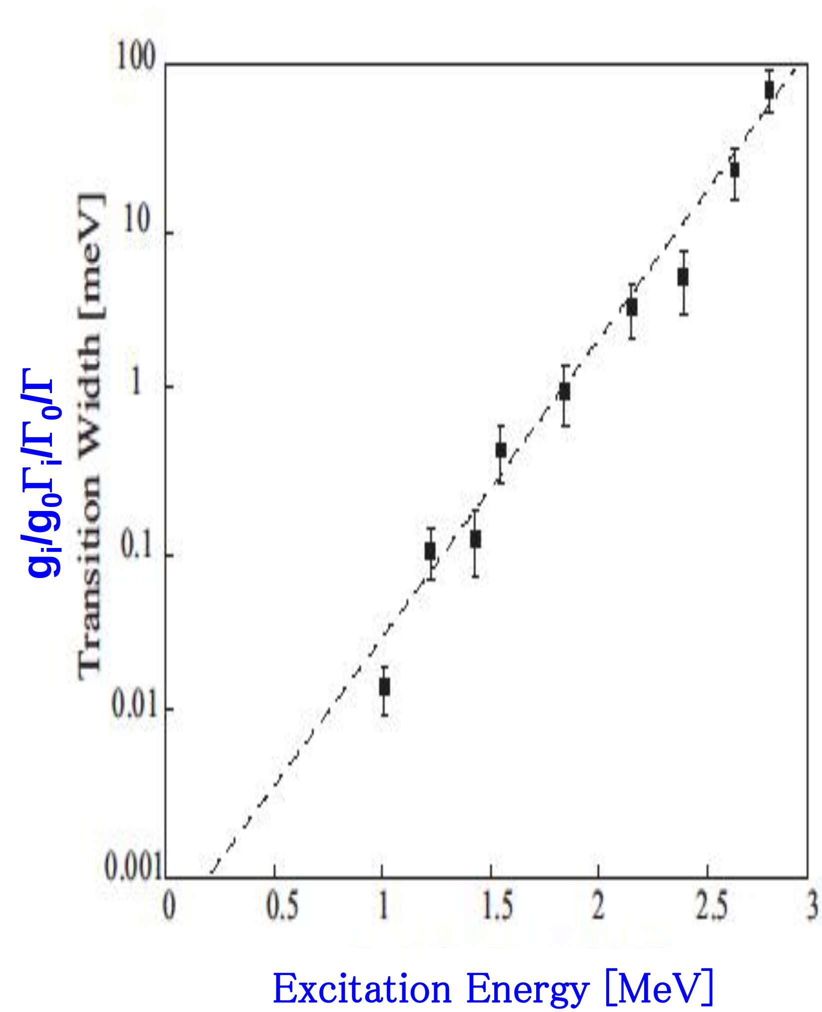
# Gamma-Decay Widths of Excited States

Saitoh et al. (NBI group), NPA 1999, ++
Dracoulis et al. (ANU group), PRC 1998, ++




# Total Gamma-Decay Width of $^{180}Ta_m$

D. Belic et al., PR C65 (2002), 035801.



# Formula to calculate time-dependent linking transitions

Hayakawa, Kajino, Chiba & Mathews, PR C81 (2010) 052801®.

**In general cases:**

$$\frac{dN_0}{dt} = -\sum_i P_i^g A_{ip} N_0 + \sum_i P_i^m \rho B_{pi}(1-N_0), -\sum_j P_j^g \rho B_{qj} N_0 + \sum_j P_j^m A_{jq}(1-N_0)$$

$$= -\sum_i P_0^g \frac{g_i}{g_0} exp(-(E_i - E_0)/kT) A_{ip} N_0 + \sum_i P_1^m \frac{g_i}{g_1} exp(-(E_i - E_1)/kT) A_{ip}(1-N_0), \quad (6)$$

$$P_i \equiv m_i/m_{total} = \frac{m_i/m_0}{\sum(m_i/m_0)}.$$

$$m_i/m_j = (2J_i+1)/(2J_j+1) exp(-(E_i - E_j)/kT),$$

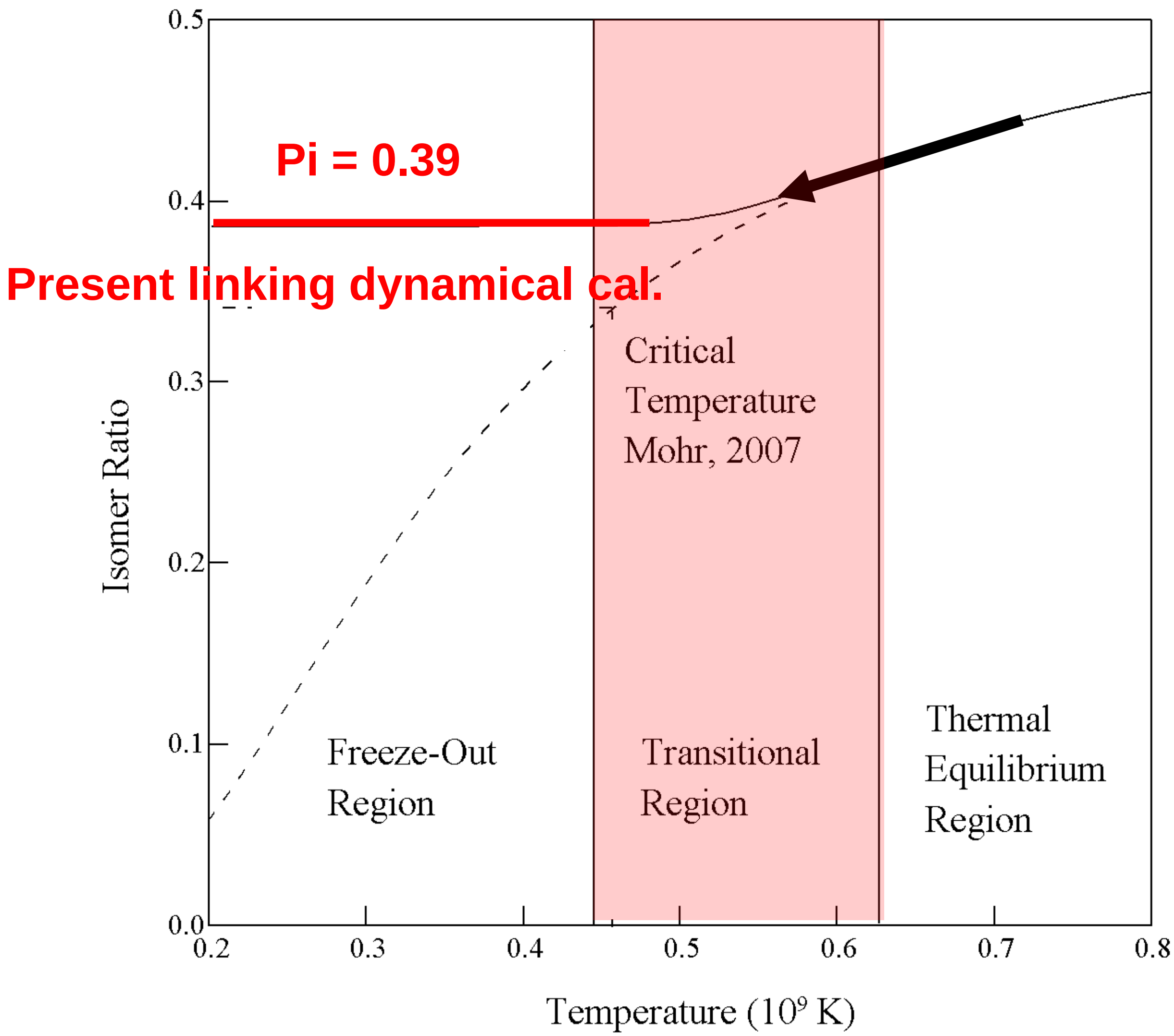
**In the case of $^{180}$Ta:**

$$\frac{dN_0}{dt} = -\sum_i P_0^g \frac{g_1}{g_0} exp(-(E_i - E_0)/kT) \frac{g_i}{g_1}\frac{\Gamma_i}{\hbar} N_0 + \sum_i P_1^m exp(-(E_i - E_1)/kT) \frac{g_i}{g_1}\frac{\Gamma_i}{\hbar}(1-N_0). \quad (7)$$

**Transition probabilities ⟵ Experimental Data**

# Calculated Result

Hayakawa, Kajino, Chiba & Mathews, PR C81 (2010), 052801®.



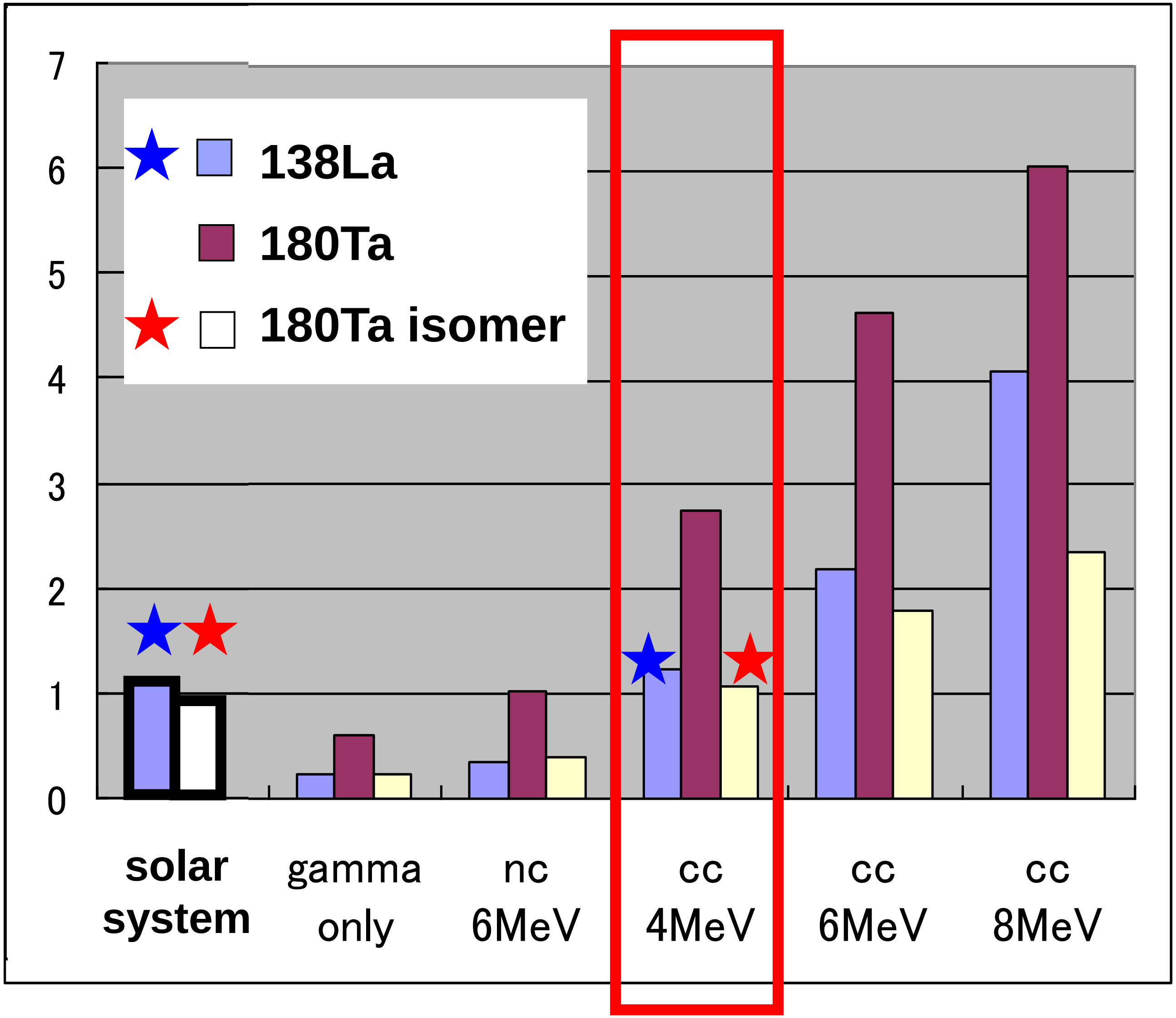

**We carried out time-dependent dynamical calculations to obtain**

**Pi ~ 0.39.**

**This result is almost independent of SN models, i.e.**
- **total explosion E,**
- **progenitor mass,**
- **ν-luminosity and**
- **its decay time scale.**

# Our New Result

T. Hayakawa, T. Kajino, S. Chiba, and
G.J. Mathews, Phys. Rev. C81 (2010), 052801®




(1) We should reduce $180Ta^{m}$ abundance by a factor Pi = 0.39.

(2) We should use more reliable ν-A cross sections, including GT and spin-mutipole transitions.

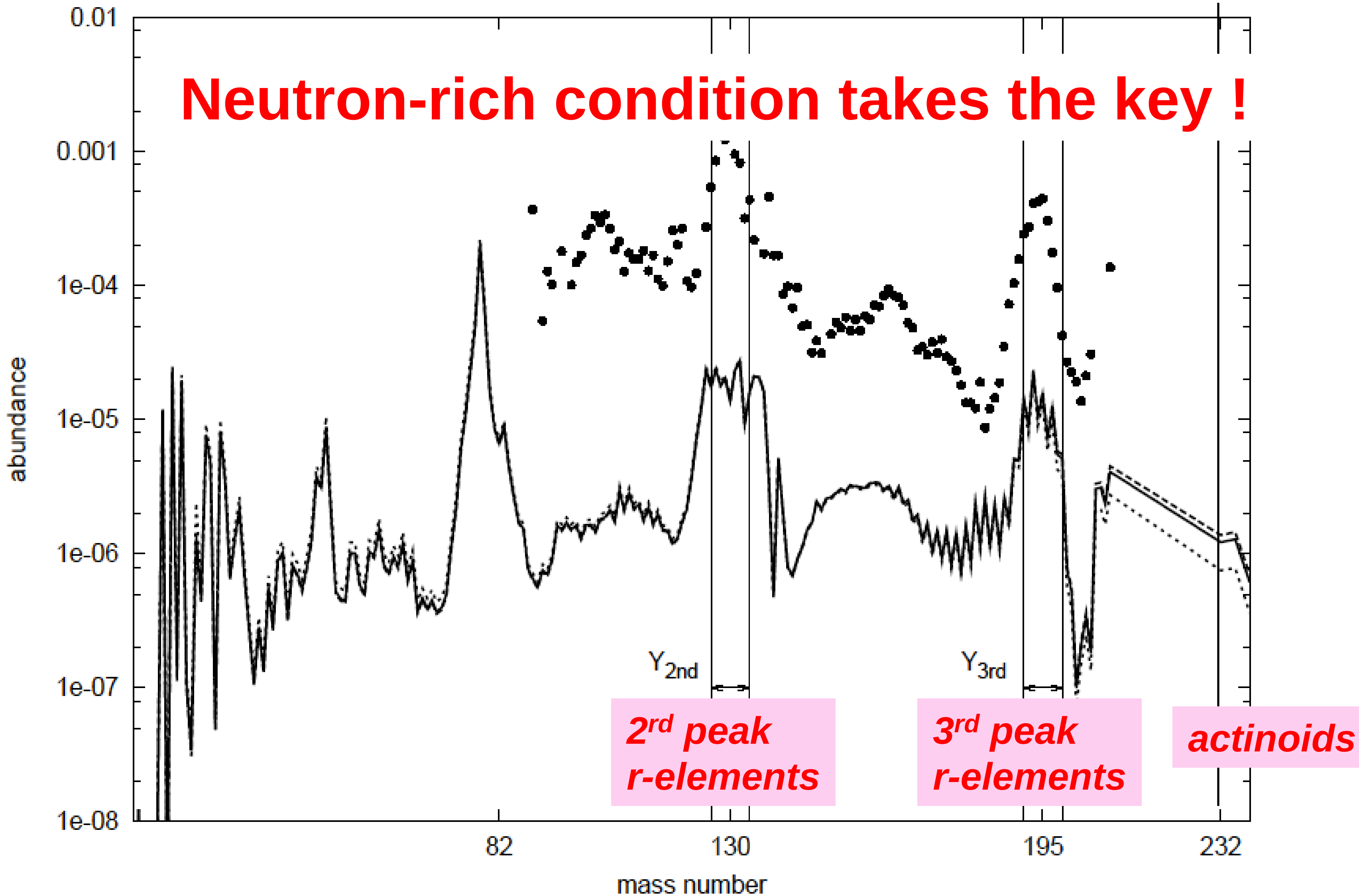
⇩

**Then, both 138La and 180Ta abundances can be consistently reproduced by the CC-int. of $\nu_e$ and $\overline{\nu}_e$ of**

$$T_{\nu e} \sim T_{\overline{\nu e}} = 4\text{MeV}.$$

# R-Process Yields in Type-II SN ν-Driven Wind Model

Yoshida, Terasawa, Kajino & Sumiyoshi, ApJ 600 (2004) 204
Sasaqui, Kajino, Otsuki, Mathews & Nakamura, ApJ 634 (2005) 1173



# Initial n/p ratio (& $Y_e$) vs. $\nu$-Temperatures

$$\nu_e + \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^-$$

$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+$$

$$Y_e = \frac{\mathrm{p}}{\mathrm{n}+\mathrm{p}} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \times \frac{\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e}}{\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right)^{-1}$$

$L_{\nu_e} = L_{\bar{\nu}_e}$

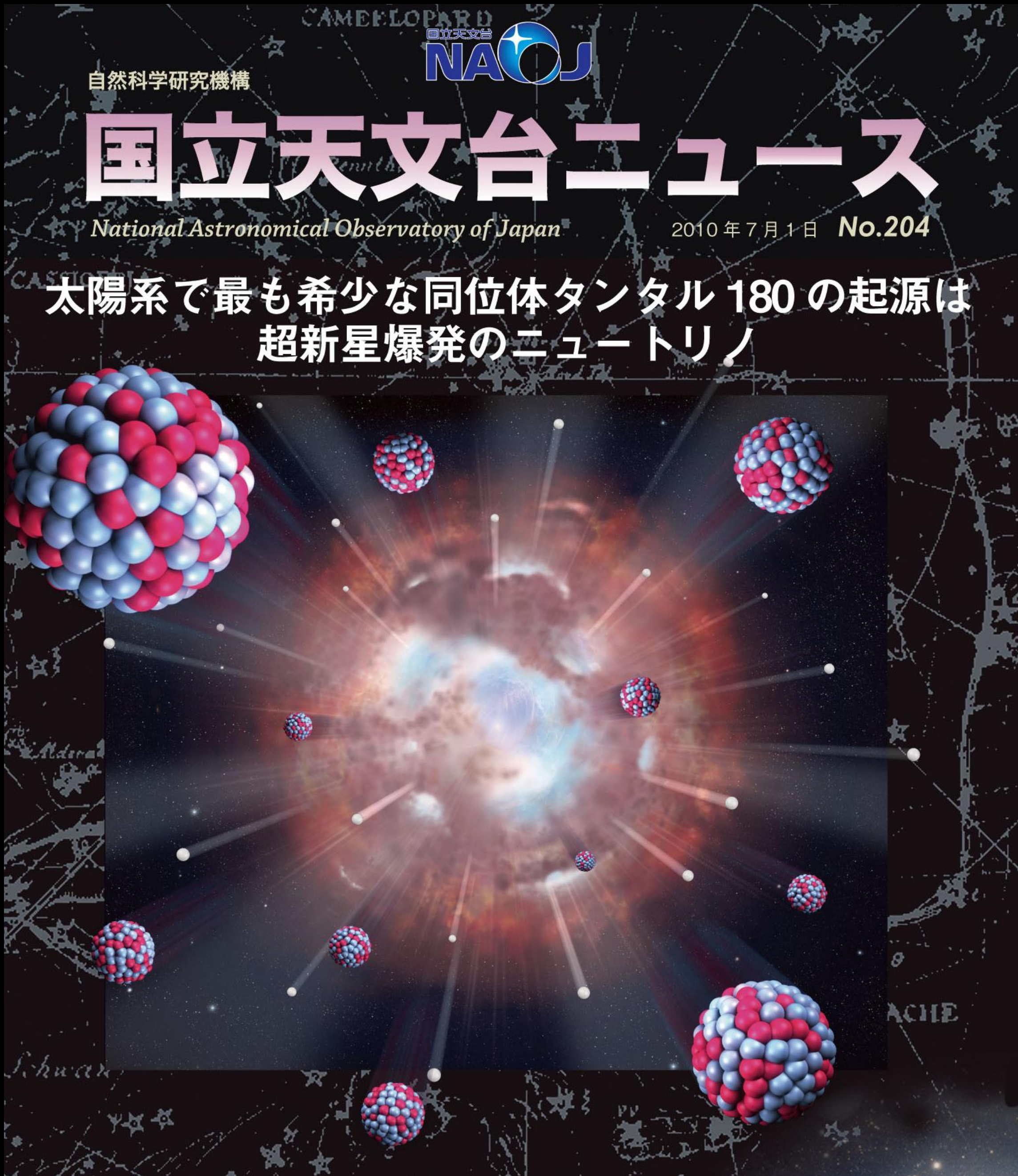
$\Delta$ = 1.29 MeV

$\epsilon_{\nu_e}$ = 3.15 x $T_{\nu e}$

$\epsilon_{\bar{\nu}_e}$ = 3.15 x $T_{\overline{\nu e}}$

Neutron-rich condition for successful r-process

0.4 < $Y_e$ < 0.5 ⇒ **$T_{\nu e}$ = 3.2 MeV, $T_{\overline{\nu e}}$ = 4 MeV**




T. Hayakawa, T. Kajino,
S. Chiba, and G.J. Mathews,
Phys. Rev. C81 (2010), 052801®

$$T(\nu_e) = 3.2 \text{ MeV}$$

$$T(\overline{\nu_e}) = 4 \text{ MeV}$$

$$T(\nu_{\mu,\tau}) = T(\overline{\nu}_{\mu,\tau})$$

$$= \ ?$$

S.M. Austin, Prog. Part. Nucl. Phys. 7, 1 (1981)

# The Creation of the Light Elements—Cosmic Rays and Cosmology

Table 4. Abundances of the light elements

| Nuclide | $N_i/^1H$ [a] | $X_i$ (fraction by mass) [a][b] |
|---|---|---|
| $^1H$ | 1.00 | 0.75 |
| $^2H$ | $(1.6 \pm 1.0) \times 10^{-5}$ | $(2.5 \pm 1.5) \times 10^{-5}$ |
| $^3He$ | $(1.8 \pm 1.2) \times 10^{-5}$ | $(4.2 \pm 2.8) \times 10^{-5}$ |
| $^4He$ | $0.075 \pm 0.009$ | $0.23 \pm 0.02$ (primordial) |
| | $0.095 \pm 0.013$ | $0.27 \pm 0.03$ (solar system) |
| $^6Li$ | $70(2) \times 10^{-12}$ | $300(2) \times 10^{-12}$ |
| $^7Li$ | $900(2) \times 10^{-12}$ | $4600(2) \times 10^{-12}$ |
| $^9Be$ | $14(1.6) \times 10^{-12}$ | $90(1.6) \times 10^{-12}$ |
| $^{10}B$ | $30(2) \times 10^{-12}$ | $200(1.6) \times 10^{-12}$ |
| $^{11}B$ | $120(2) \times 10^{-12}$ | $900(2) \times 10^{-12}$ |

$$^{11}B/^{10}B = 4.05 \pm 0.10$$

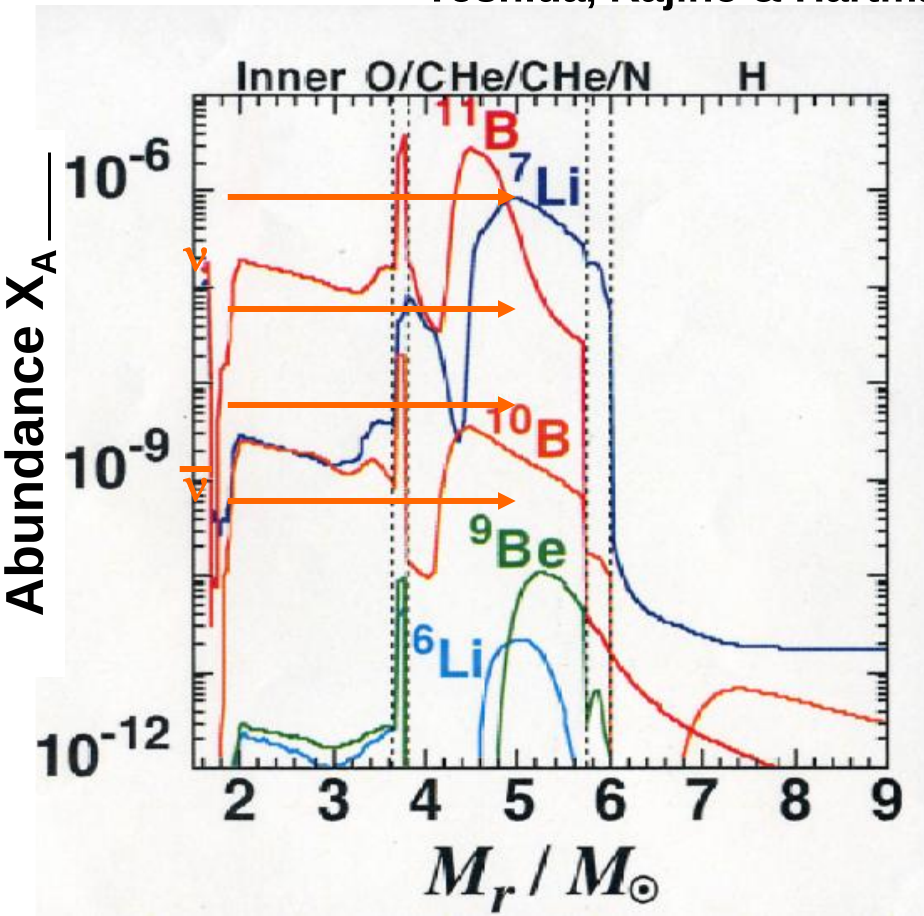
**Measured Meteoritic Ratio**

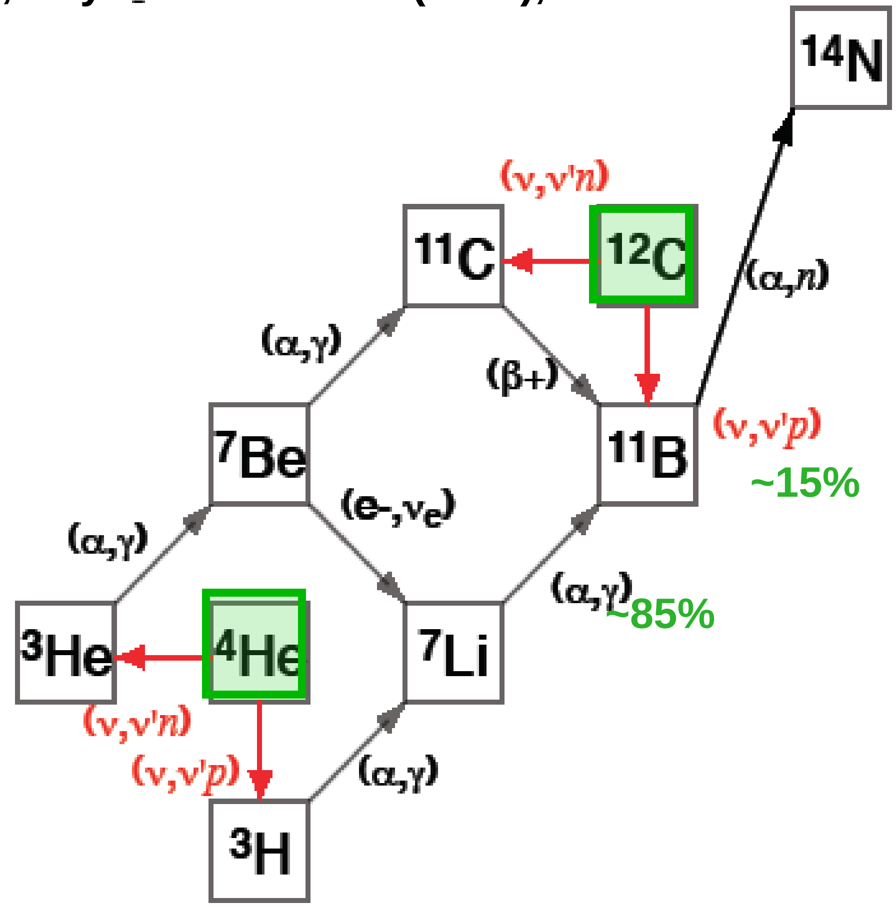
**GCR - $^{11}B/^{10}B$ = 2.0 +- 0.2**

**Measured GCR Ratio**

# Supernova ν-Process & Key Reactions

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



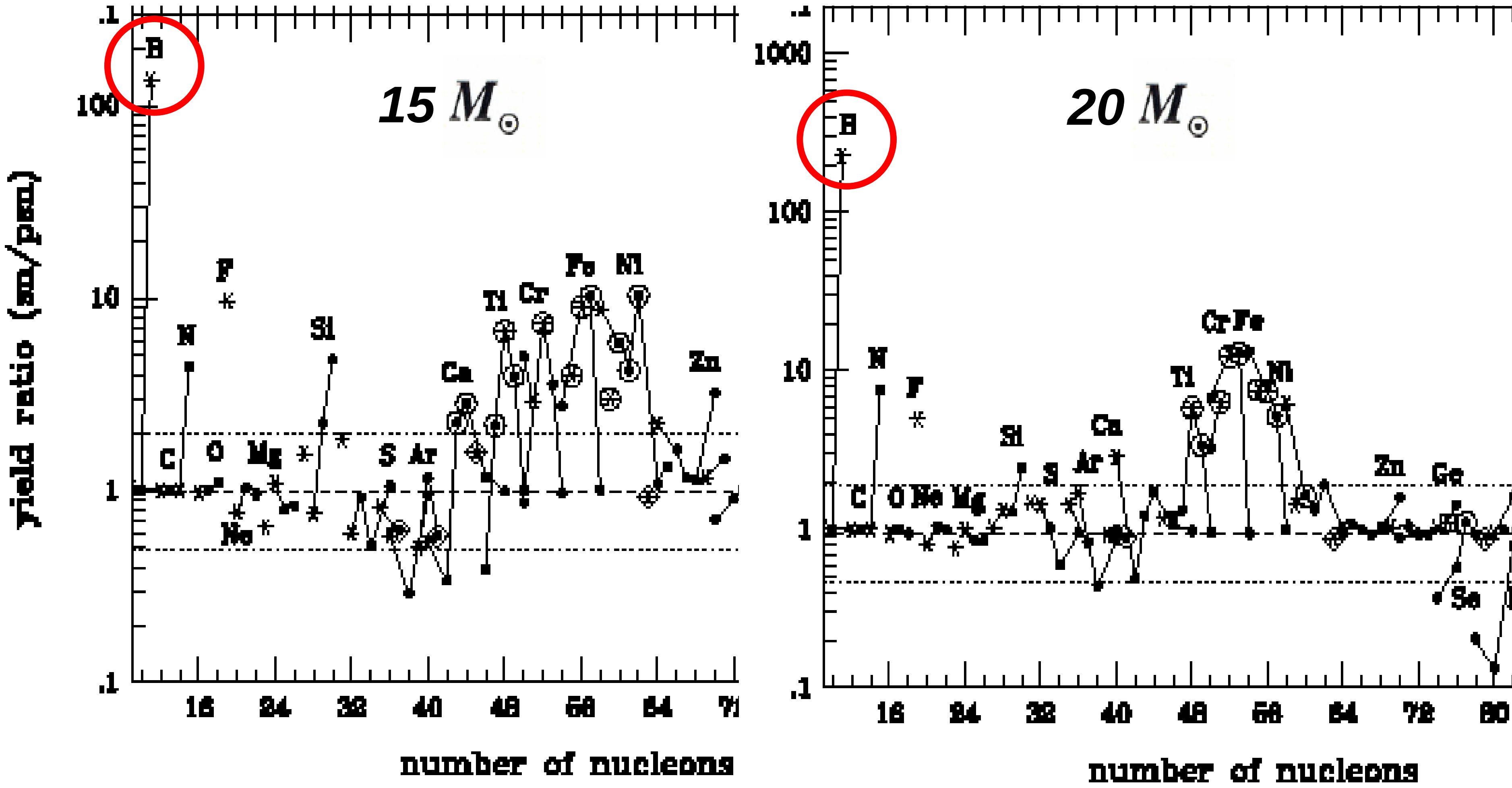




$^{4}$He$(\nu,\nu' p)^{3}$H, $^{4}$He$(\nu,\nu' n)^{3}$He, $^{12}$C$(\nu,\nu' p)^{11}$B

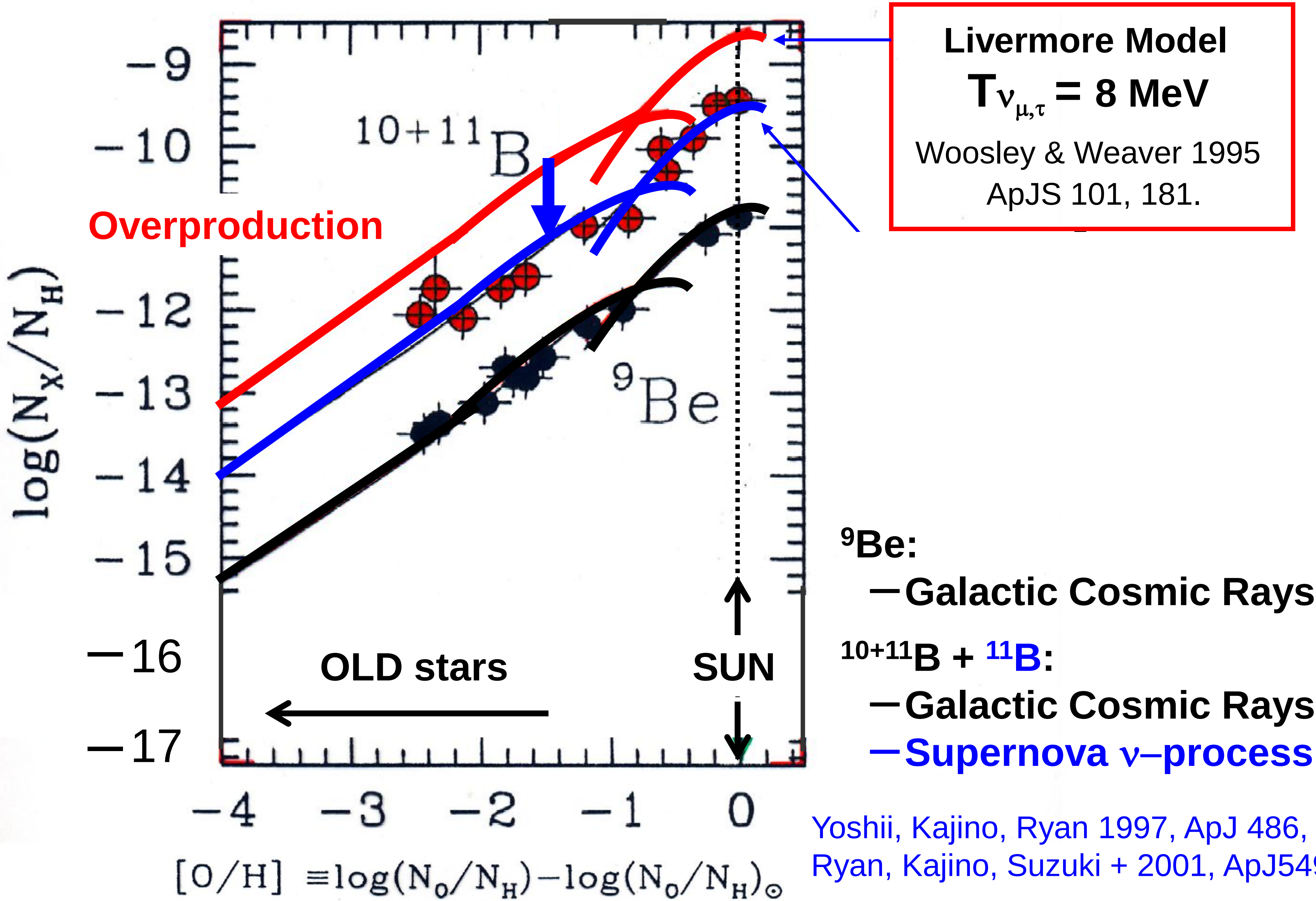
($^{4}$He$(\nu_e,e^- p)^{3}$He, $^{4}$He$(\bar{\nu}_e,e^+ n)^{3}$H, $^{12}$C$(\nu_e,e^- p)^{11}$C, $^{12}$C$(\bar{\nu}_e,e^+ n)^{11}$B

# Overproduction Problem of Supernova-$^{11}$B

**Hoffman, Woosley & Weaver 2001, ApJ 549, 1085.**



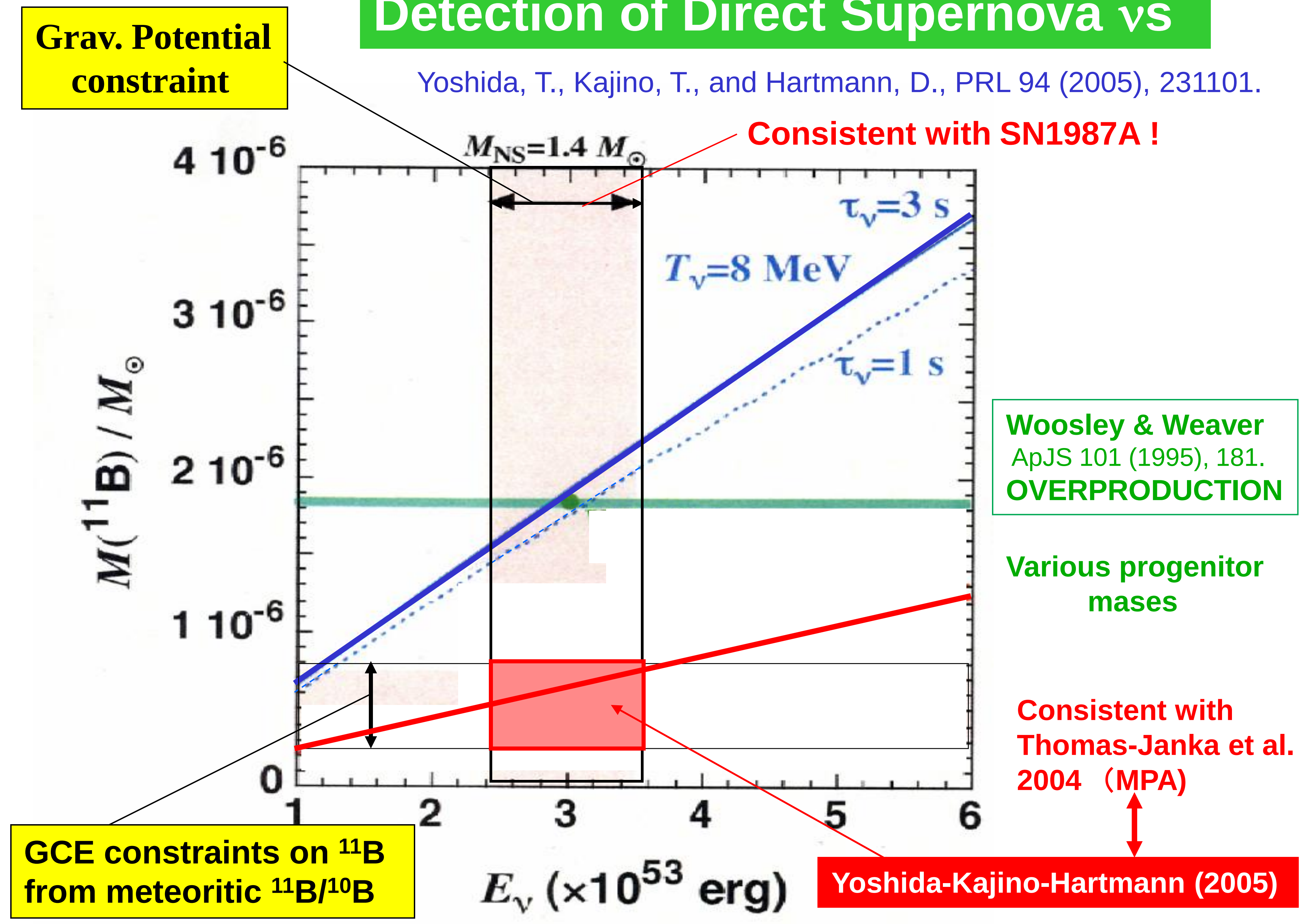
# Galactic Chemical Evolution of $^9$Be &




Yoshii, Kajino, Ryan 1997, ApJ 486, 605
Ryan, Kajino, Suzuki + 2001, ApJ549, 55

# Detection of Direct Supernova νs

Yoshida, T., Kajino, T., and Hartmann, D., PRL 94 (2005), 231101.



# SN ν-spectra are now KNOWN !


**ν-oscillation !**

(1) $\sin^2 2\theta_{13} < 0.1$ ?

(2) $\Delta m_{13}^2 = +/-2.4 \times 10^{-3}\ eV^2$ ?

~~(3) δ = CP-phase~~

Yokomakura et al., PL B544, 286

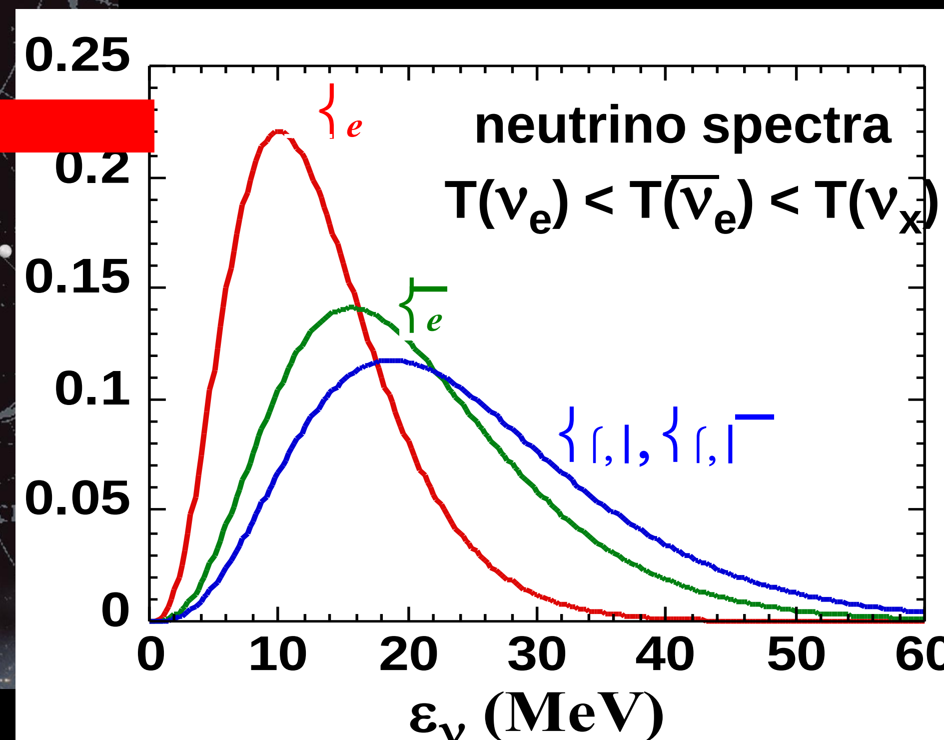
~~(4) Absolute Mass~~

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

$T(\nu_e) = 3.2$ MeV

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

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



# 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）

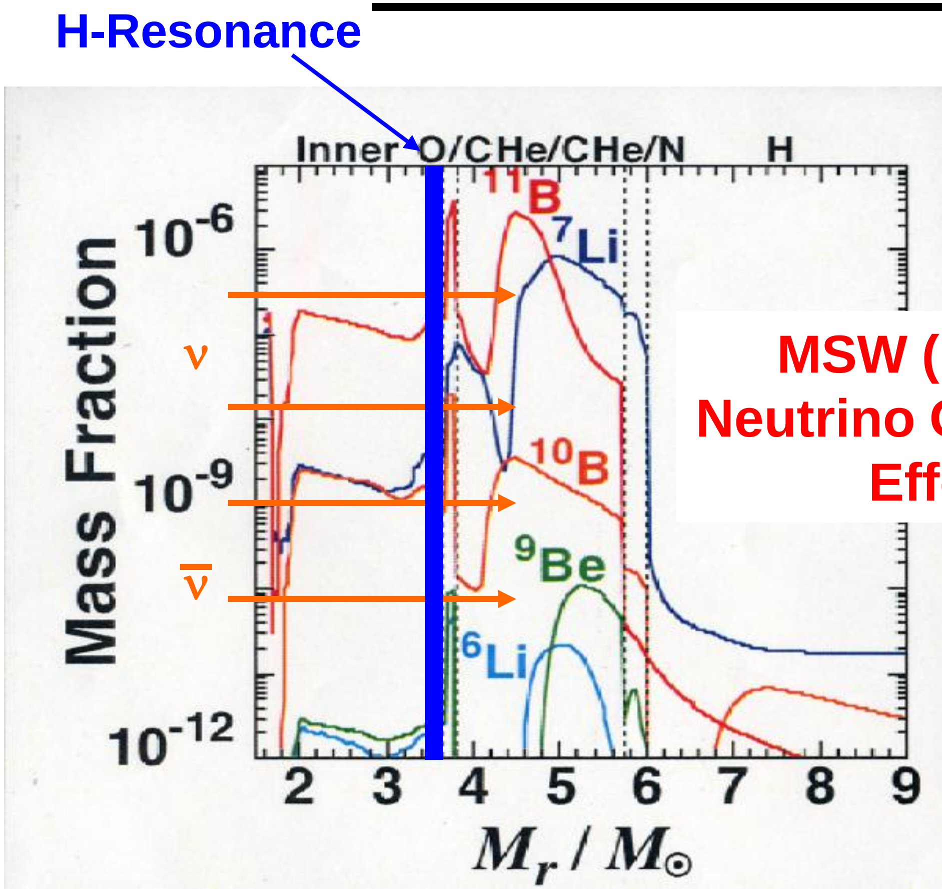
振動の仕方が完全に解明されていない！ $\theta_{13}$, $\Delta m_{13}$, $\delta_{CP}$?

## 目的

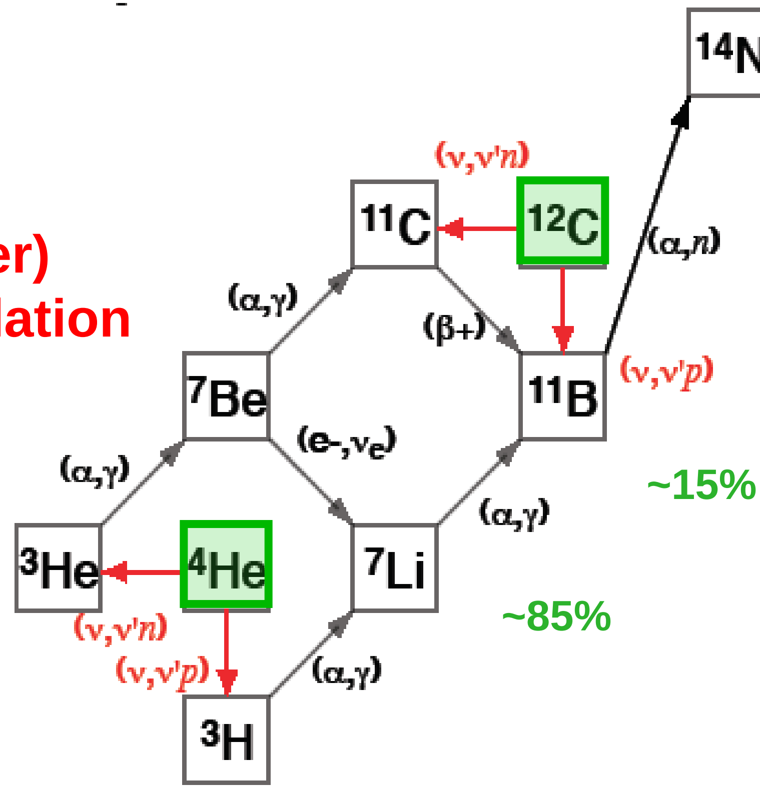
**超新星ニュートリノ物質振動（MSW）効果と
元素合成を使って決定する方法の提案！**

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

# Supernova ν-Process & Key Reactions




MSW (matter) Neutrino Oscillation Effect




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

$^{4}$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

**Additional Charged Current Int.**

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

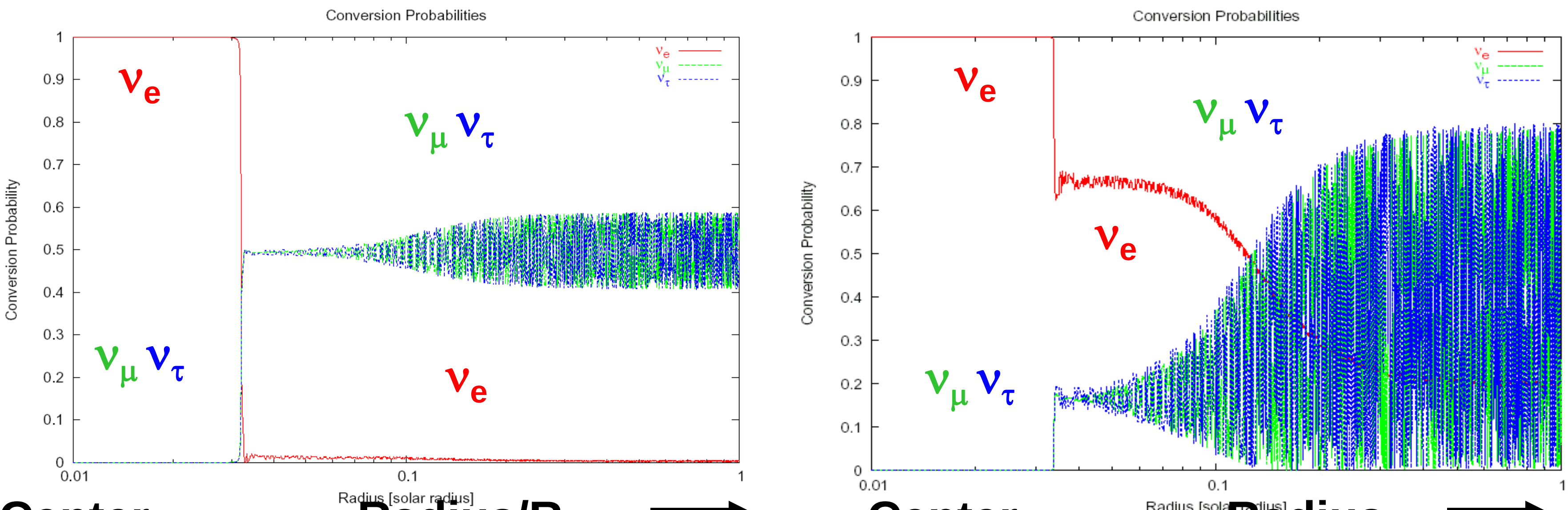
$^{4}$He$(\nu_e,e^- p)^{3}$He & $^{4}$He$(\bar{\nu}_e,e^+ n)^{3}$H

energetic energetic

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

## Conversion Probability

**Adiabatic** | **Non-Adiabatic**




**Center** **Radius/$R_{sun}$** → **Center** **$Radius_{sun}$** →

### Parameters:

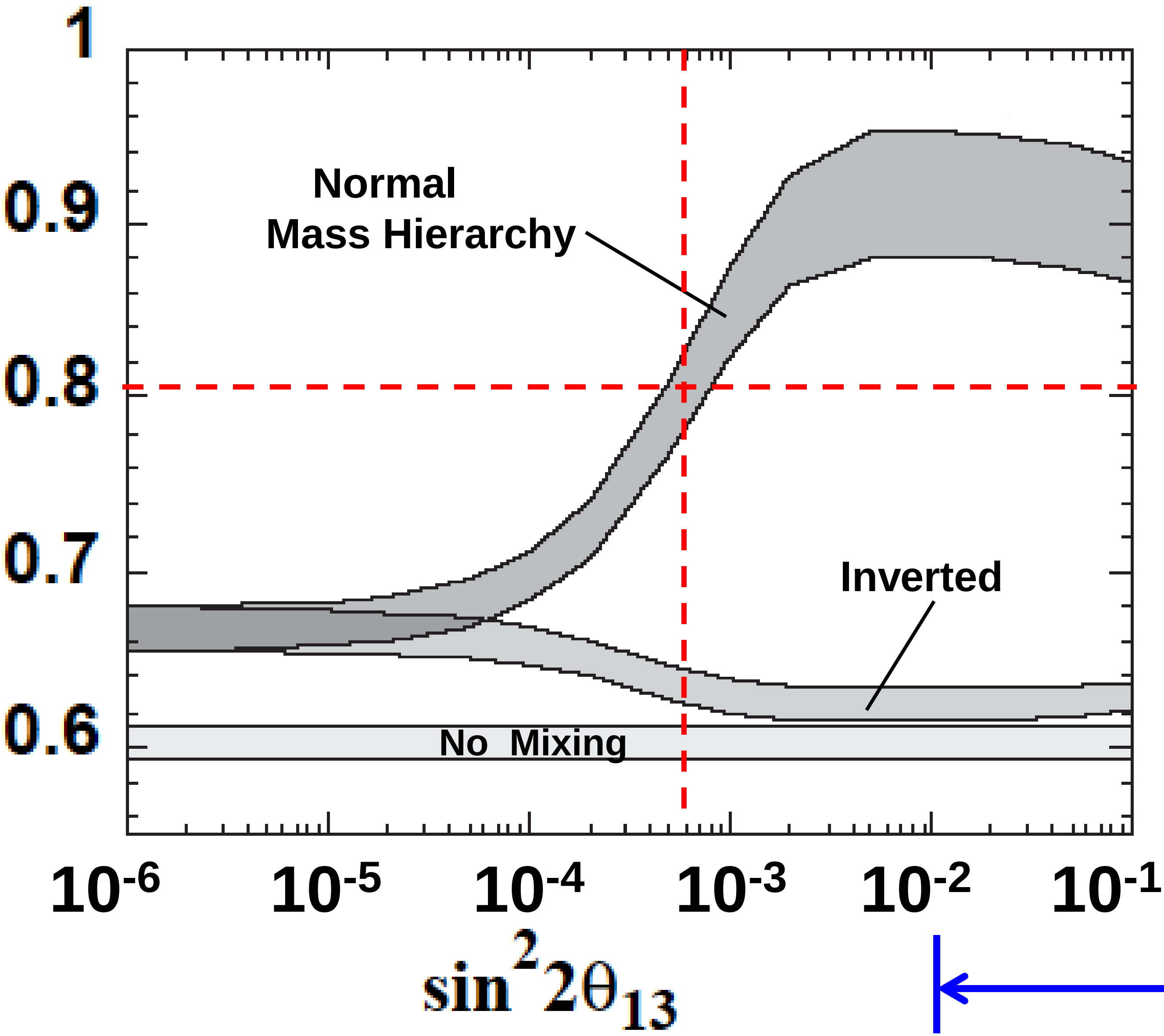
**$25M_{solar}$ SN model (Hashimoto & Nomoto 1999)**

- $\sin^2 2\theta_{13} = 0.04$
- $\Delta m_{13}^2 = 2.4\times10^{-3}$ eV$^2$
- $L_\nu = 3\times10^{53}$ erg, $\tau_\nu = 3$ sec
- $E_{\nu e}$=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.**

# $^{7}Li/^{11}B$ - 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**

**$\Delta m_{13}^2$**

**13-Mixing Angle**

**$\theta_{13}$**

**Long Baseline Exp:**

**T2K (Kamioka)**

**T2KK (KOREA)**

**Double CHOOZ**

**Daya Bay**

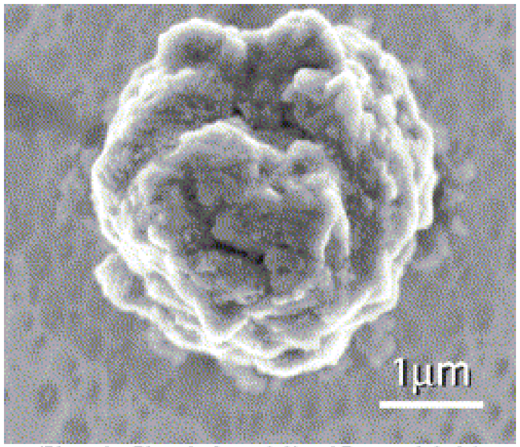
## Metal-poor Halo Stars


## Supernova Rem.

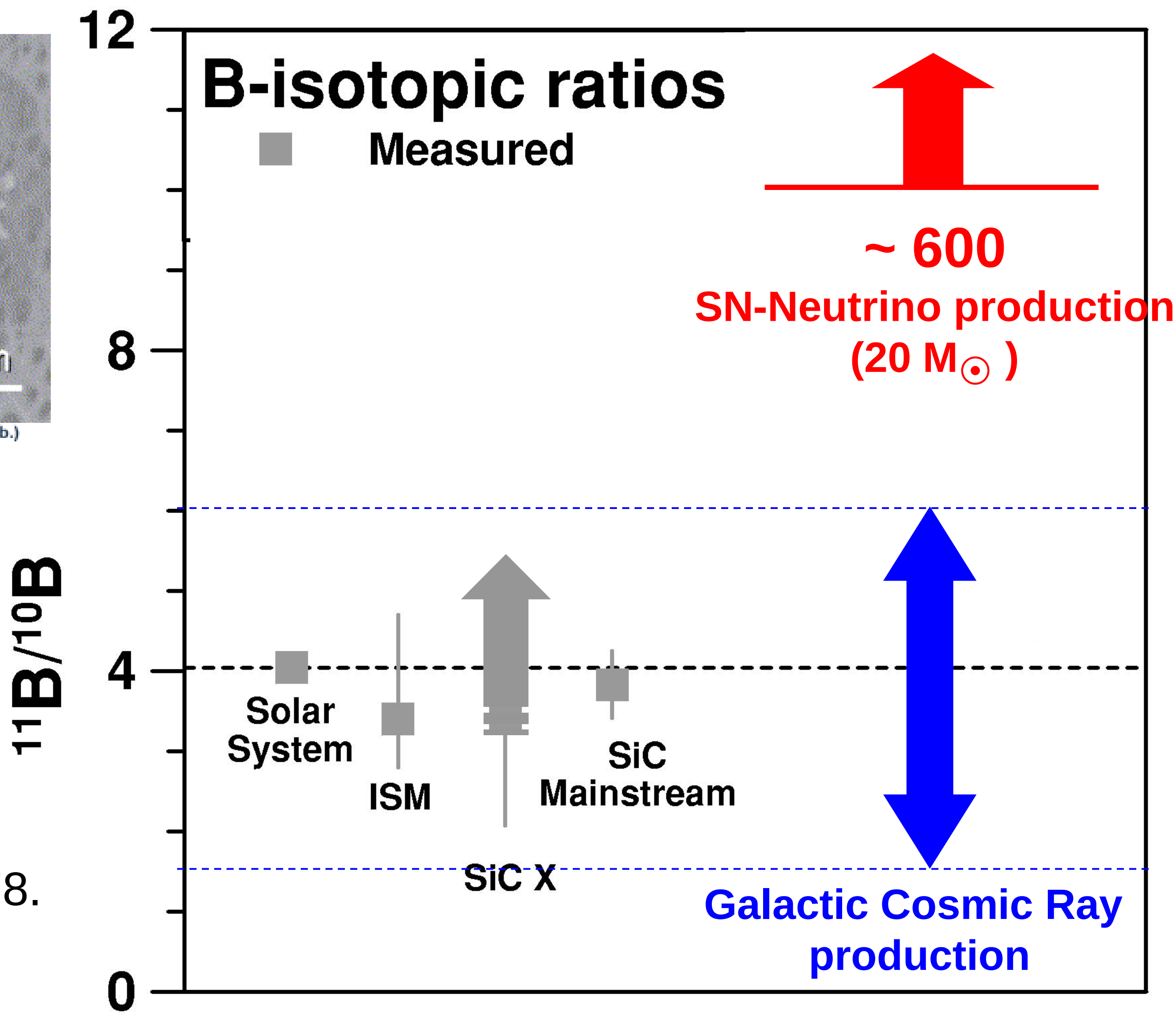
# Observational Signature ?

$^{7}$Li & $^{11}$B have already been separately detected and measured !

# Presolar SiC X-grains from SNe




(Photo by Rhonda Stroud, Naval Research Lab.)




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

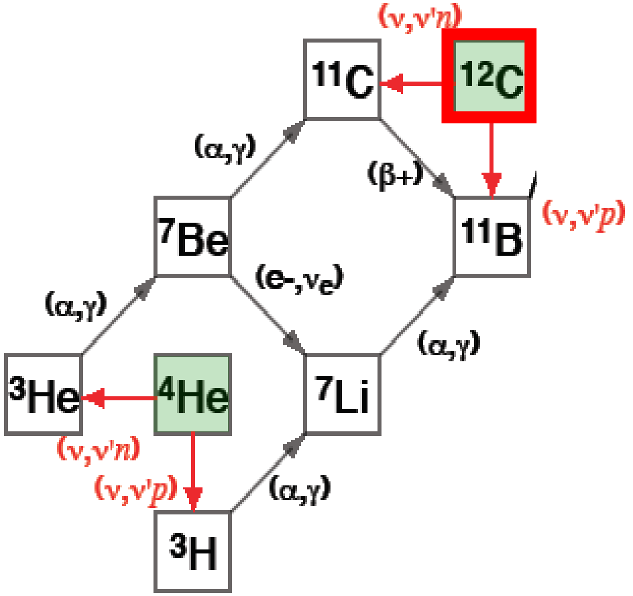
# Hamiltonian Dependence of ν-A cross section?

**Haxton's SM cal.** (Woosley et al. ApJ. 356 (1990), 272)

**Suzuki's new SM cal. with NEW Hamiltonian**

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307.

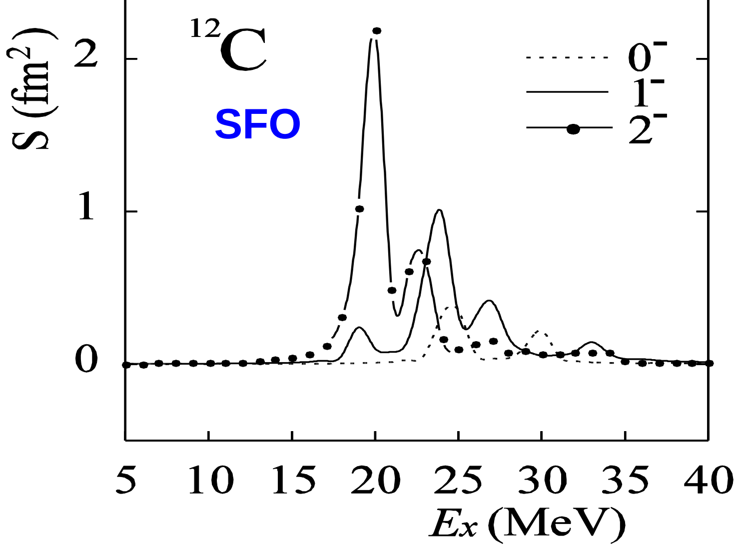
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003) → **SFO**

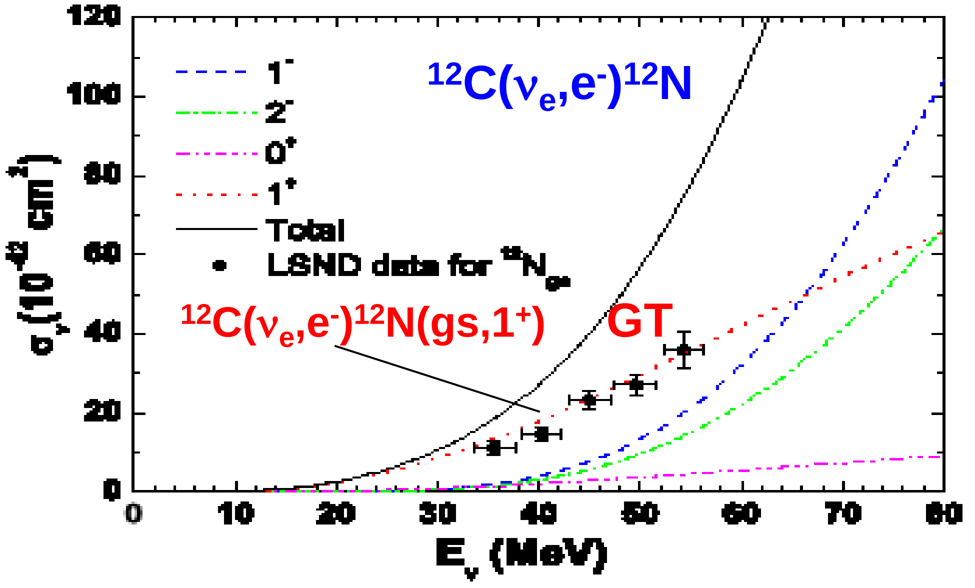



**$^{12}$C: SFO Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.**

- **μ-moments of p-shell nuclei**
- **GT strength for $^{12}C \rightarrow ^{12}N$, $^{14}C \rightarrow ^{14}N$, etc. (GT)**
- **DAR (ν,ν'), (ν,e-) cross sections**

**Cheoun et al., PRC81 (2010), 028501: QRPA**



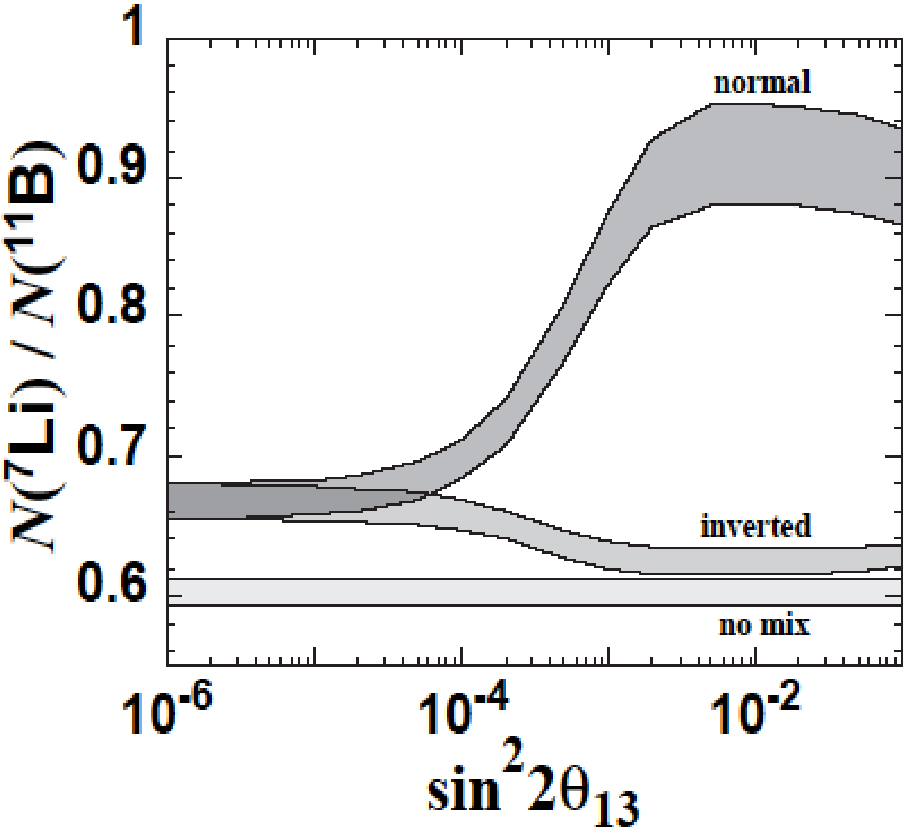
# Hamiltonian Dependence of MSW-Effect on $^7Li/^{11}B$

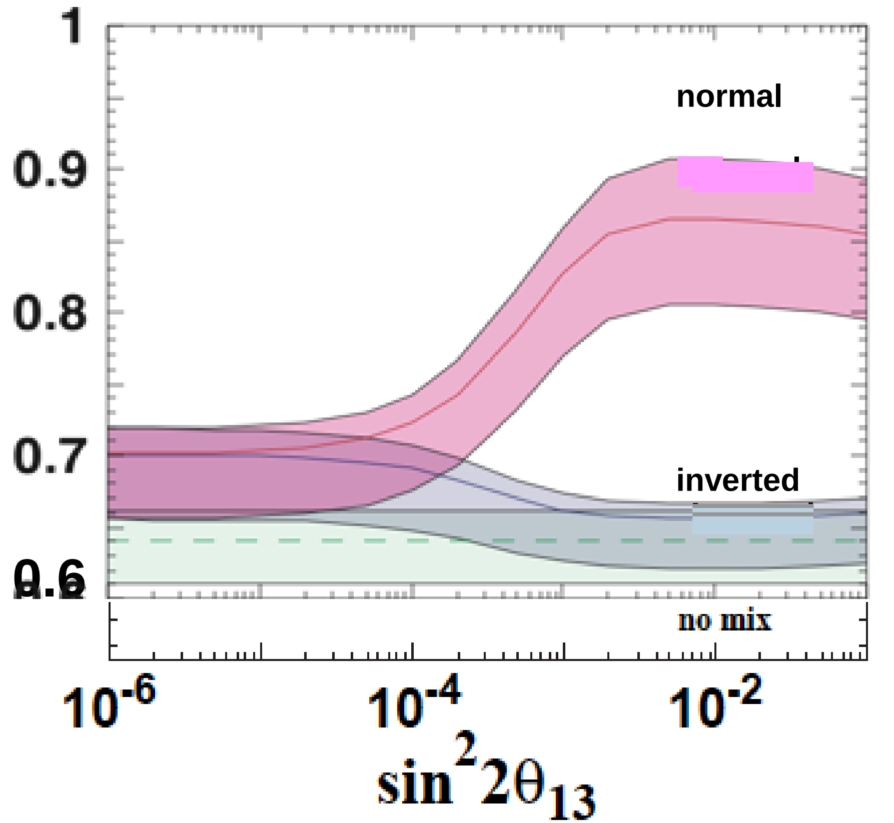
**Previous SM-$\sigma_\nu$(E) of Haxton**

Woosley, Haxton, Hoffmann, Wilson, ApJ. (1990).
Hoffmann & Woosley, ApJ. (1992).

**New SM-$\sigma_\nu$(E) using WBP($^4$He) & SFO($^{12}$C) interactions**

Suzuki, Chiba, Yoshida, Kajino & Otsuka, Phys. Review C74 (2006), 034307.




**Normal / inverted, well separated ! → $^7Li/^{11}B$-ratio is SM independent !**

**Mixing angle $\theta_{13}$ dependence, almost the same !**

# SUMMARY

1. $\nu$-process (especially on $^{180}$Ta) and r-process nucleo-syntheses in core-collapse SNe provide unique tool to determine the neutrino spectra. Neutron star properties are almost independent on progenitor mass and others.

   $T(\nu_e) = 3.2$ MeV, $T(\bar{\nu}_e) = 4.0$ MeV

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

2. SN $\nu$-process on Li-Be-B isotopic ratios are sensitive measure of the MSW effect in order to determine the unknown $\nu$-oscillation parameter $\theta_{13}$ and mass hierarchy of active $\nu_e$, $\nu_\mu$, $\nu_\tau$.

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

3. Precise theoretical studies of $\nu$-nucleus interactions and experimental studies of spin-isospin responses in nuclear structure & reactions are critically important.