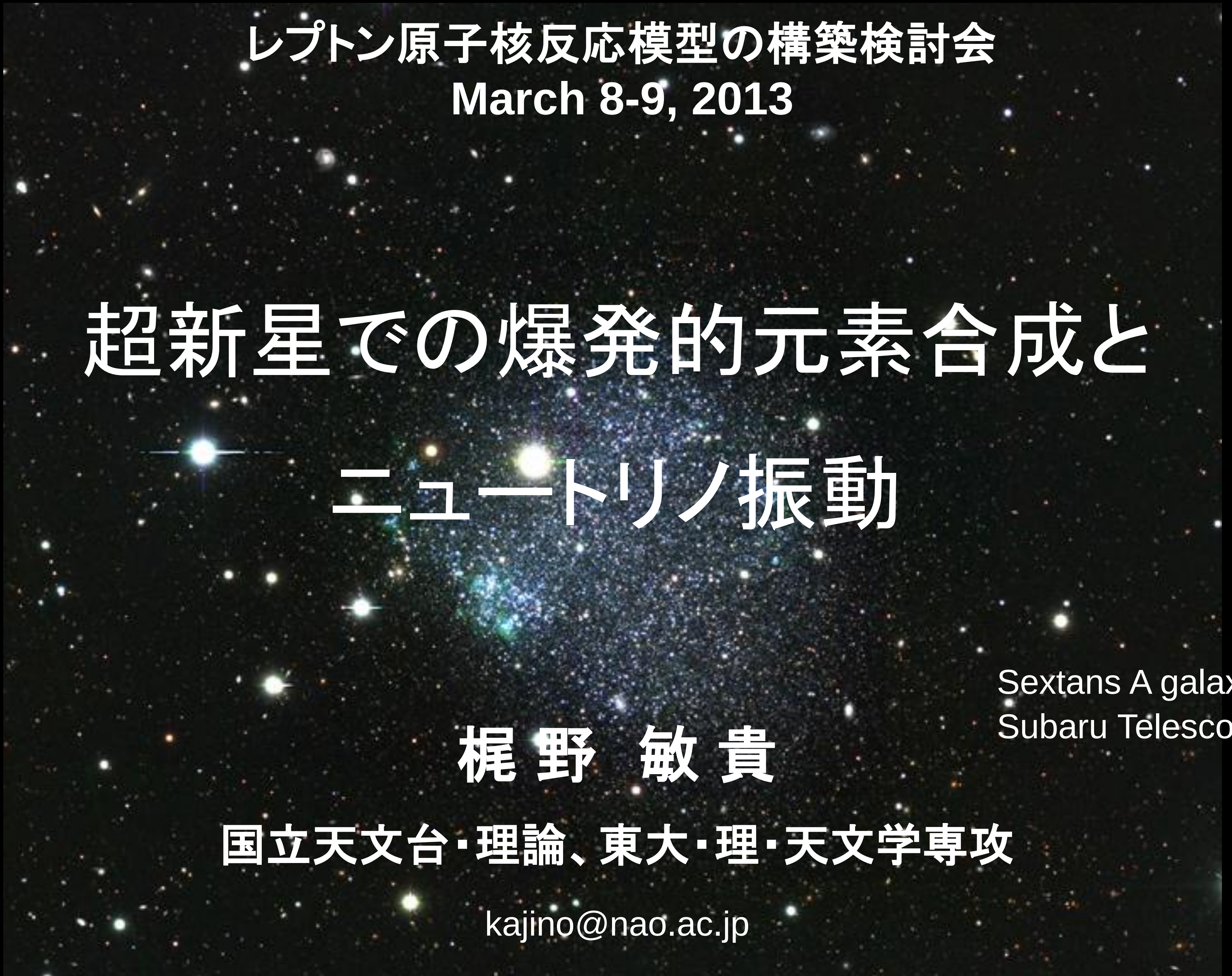
レプトン原子核反応模型の構築検討会
March 8-9, 2013

# 超新星での爆発的元素合成とニュートリノ振動



Sextans A galaxy
Subaru Telescope

**梶 野　敏 貴**

**国立天文台・理論、東大・理・天文学専攻**

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# Challenge of the Century

**Universal expansion is most likely flat & accelerating !**

$$\Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1$$

- **What is the CDM, $\Omega_{CDM}$ = 0.23, and Dark Energy, $\Omega_\Lambda$ = 0.73 ?**

  **CMB including ν-mass:** Yamazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012),141-167.

- **Is BARYON, $\Omega_B$ = 0.04, well understood ?**

  BBN with **Axions + SUSY** to solve **Dark Matter Problem & Li Problem**:
  Kusakabe, Balantekin, Kajino & Pehlivan, (2012) arXiv:1202.560.

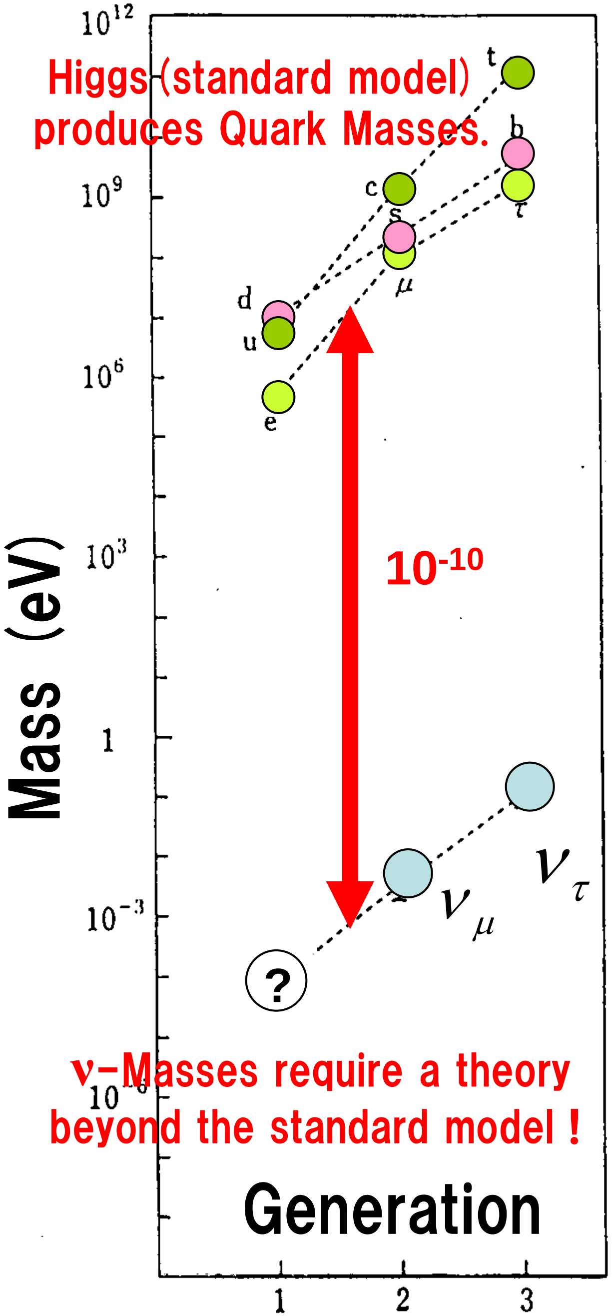
  **SUSY-DM ⇒ "beyond the Standard Model" ⇒ $m_\nu \neq 0$ is the unique signal !**

➡ **Total ν mass, and hierarchy ?**

## Plan of this Talk

**(1) "Supernova ν-Process Nucleosynthesis" to determine the <u>ν-MASS HIERARCHY.</u>**

**(2) "CMB Anisotropies" to determine the <u>TOTAL ν-MASS</u>.**




$$\frac{\text{Neutrino Masses}}{\text{Quark \& Lepton Masses}} = \frac{1}{10{,}000{,}000{,}000}$$

$E = mc^2$

**Why $10^{-10}$ ?**

This could be a signature of new physics at $10^{10}$ times higher energy scale than the ordinary scale.

$$\nu_i + \overline{\nu_i} \rightleftarrows e^+ + e^- \rightleftarrows 2\gamma\ (T)$$

**Key Physics suggested by FINITE mass neutrinos:**

Unification of elementary forces beyond the standard model ?

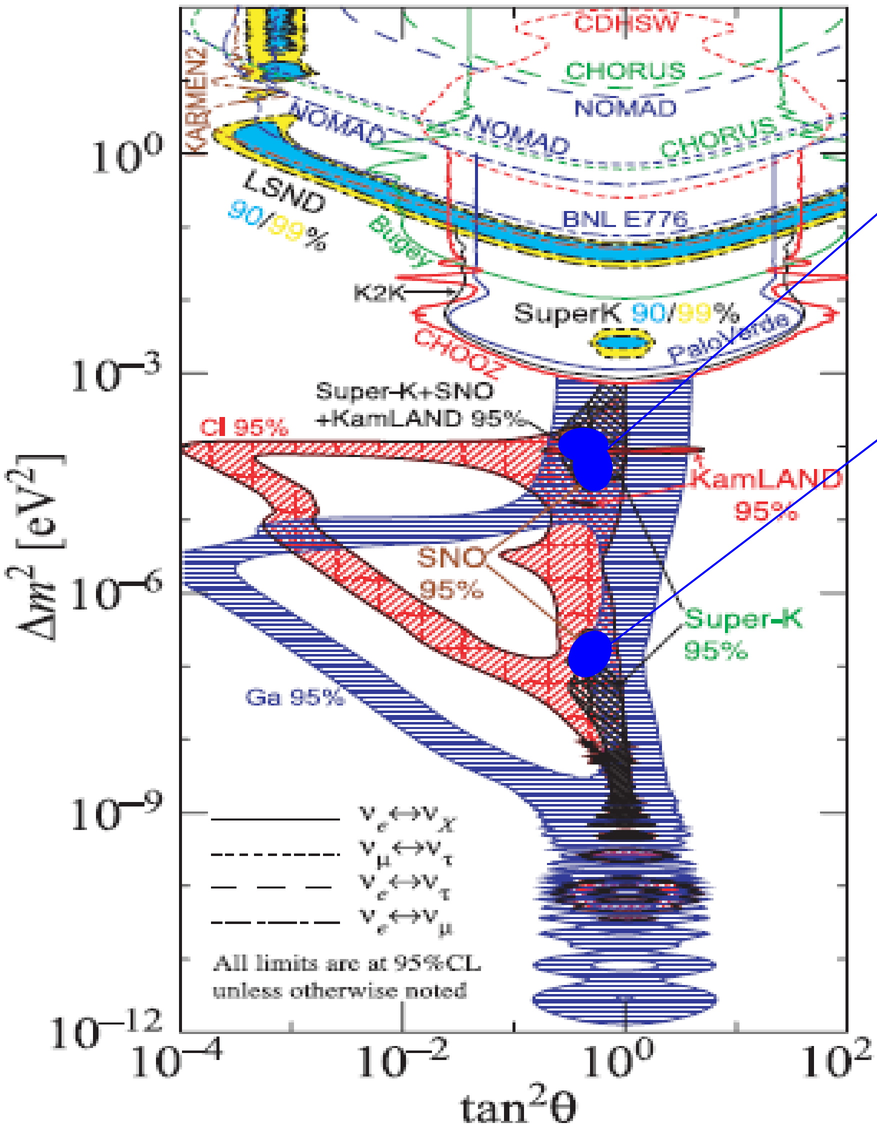
CP violation and Lepto- & Baryo-genesis ?

Why left-handed neutrinos, Majorana or Dirac ?

Explosion Mechanism of Supernovae ?

# “KNOWN” of Neutrino Oscillations

**KAMIOKANDE, SK, KamLand (reactor ν), SNO determined $\Delta m_{12}^2$ and $\theta_{12}$ uniquely, and also SK (atmospheric ν) determined $\Delta m_{23}^2$ and $\theta_{23}$ uniquely.**




**23－mixing**

$\sin^2 2\theta_{23} = 1.0$

$|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV$^2$

**12－mixing** Cabibbo angle

$\sin^2 2\theta_{12} = 0.816$ ($\theta_{12}+\theta_C=\pi/2$)

$\Delta m^2_{12} = 7.9 \times 10^{-5}$ eV$^2$

## “UNKNOWN”

**13-mixing, hierarchy, CP, mass**

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

  T2K, MINOS, RENO, Daya Bay, Double Chooz

- $\Delta m_{13}^2 = \pm 2.4 \times 10^{-3}$ eV$^2$
- ~~δ＝CP violation phase~~
- ~~Absolute Mass~~ 0νββ, cosmology

E(νμ)=E(ντ): Yokomakura et al., PL B544, 286.

# Various Neutrino-Sources in Nature

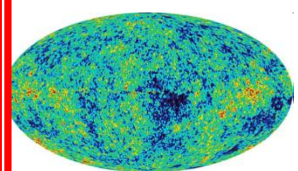
1.9K — 0.4 — 1.0 — 2.6 — 8.5 — Visible energy [MeV]

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

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

**CMB**

**Cosmic Background**

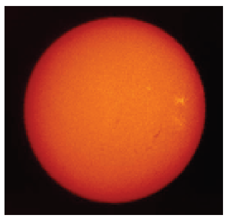


**Neutrino Cosmology**

**verification of particle model**

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

$^7$Be solar neutrino



Neutrino Astrophysics

verification of SSM

geo-neutrino

Neutrino Geophysics

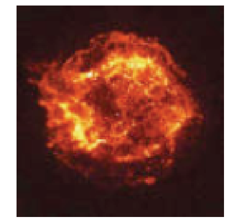
verification of earth evolution model

reactor neutrino

Neutrino Physics

Precision measurement of oscillation parameters

supernova relic neutrino etc.



Neutrino Cosmology

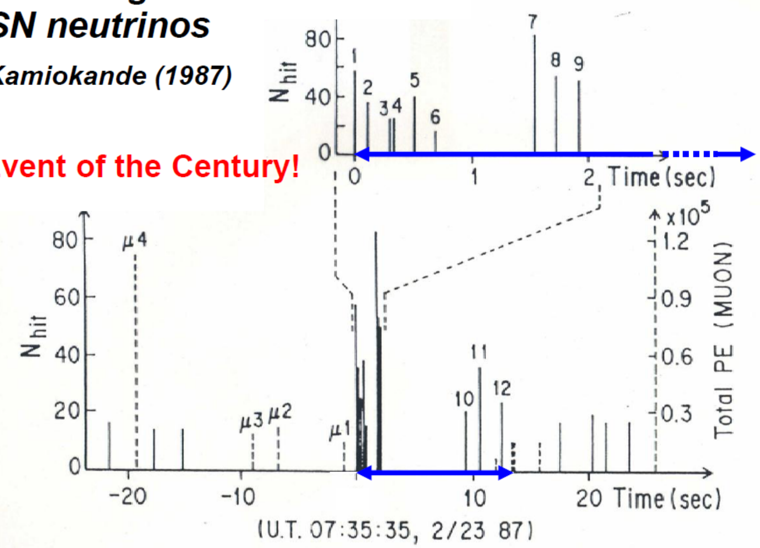
verification of universe evolution

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

***Direct signal of SN neutrinos***

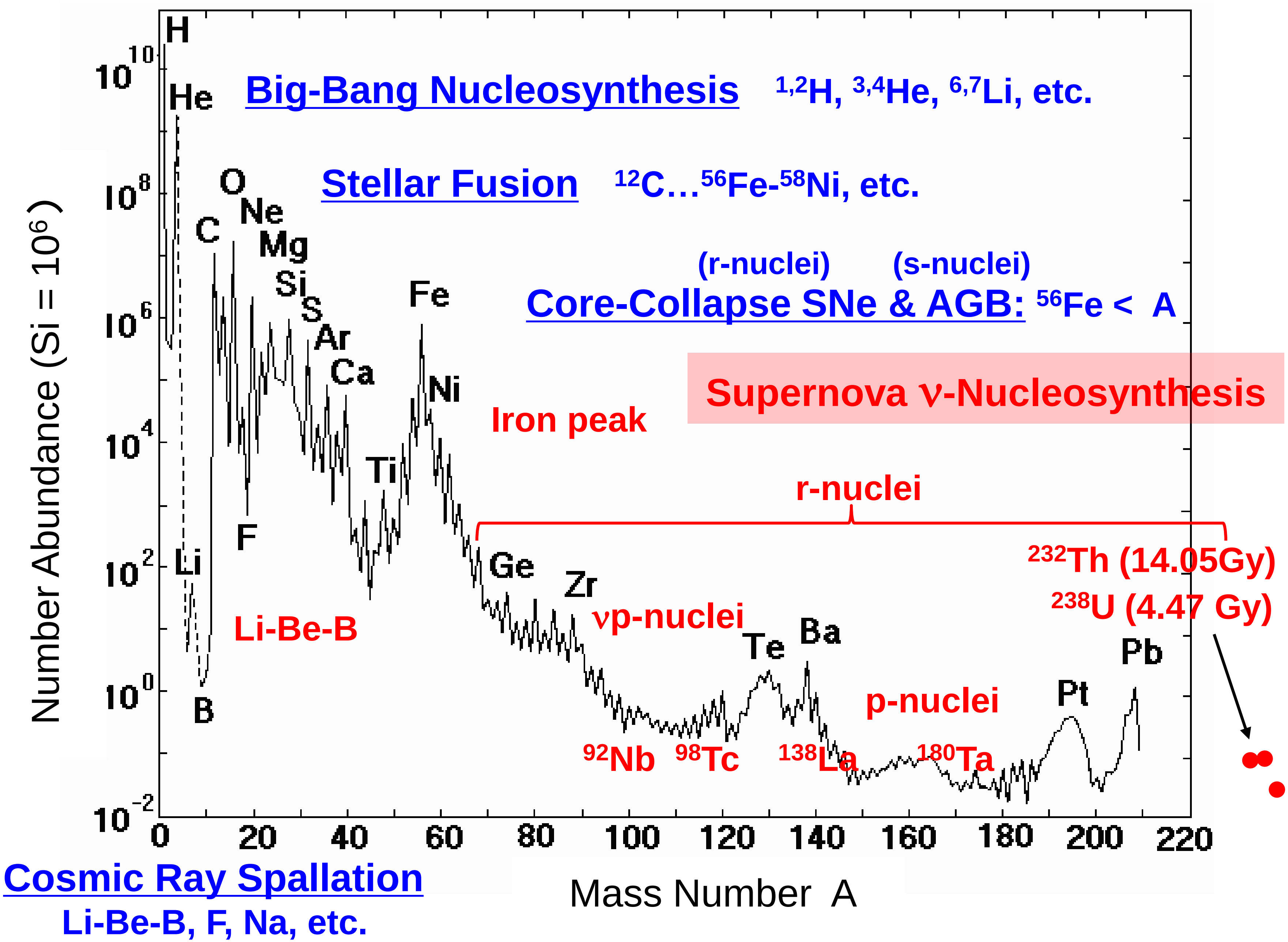
***Kamiokande (1987)***

**Event of the Century!**

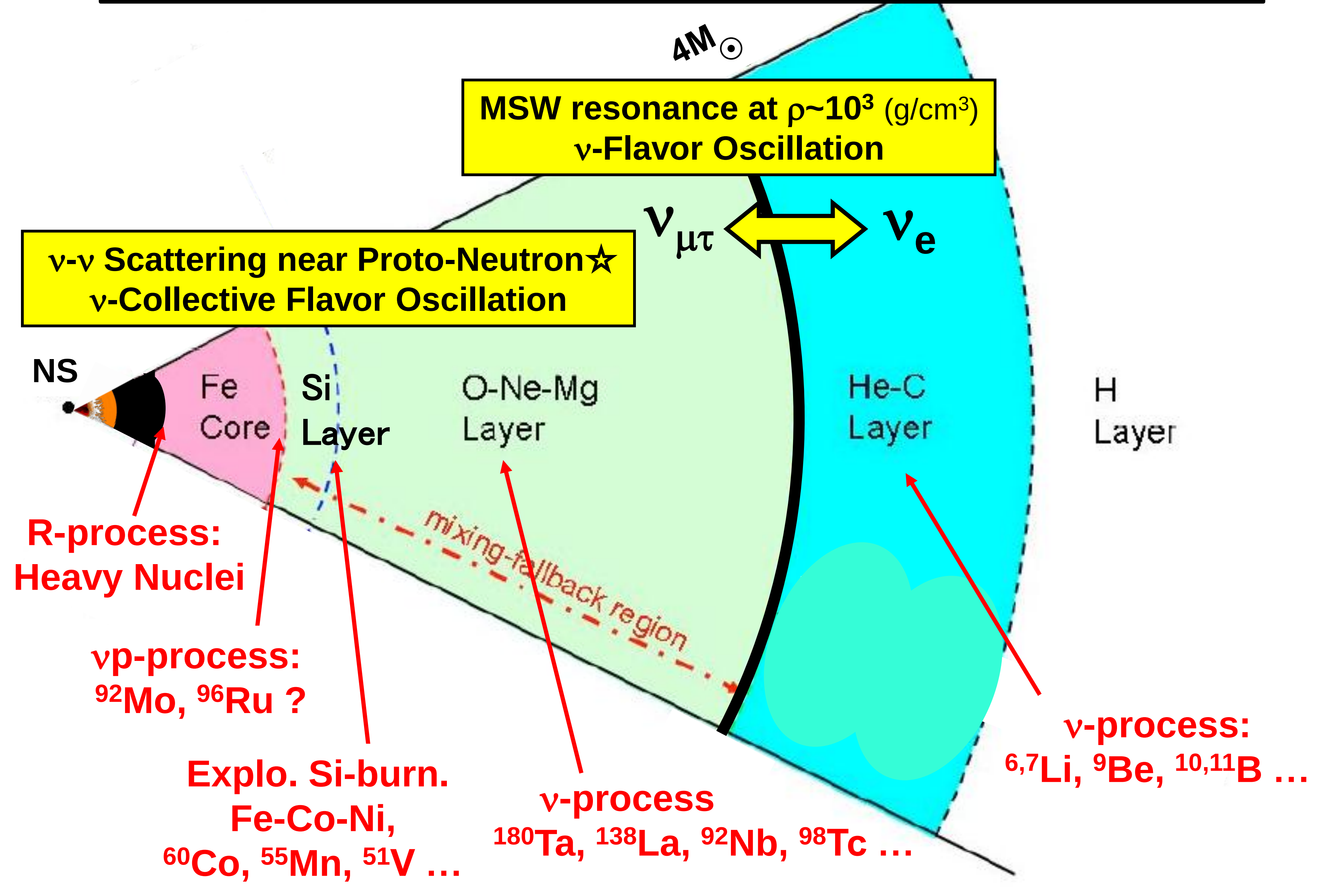



**SN ν-spectra are known INCOMPLETELY !**

# Solar System Abundance



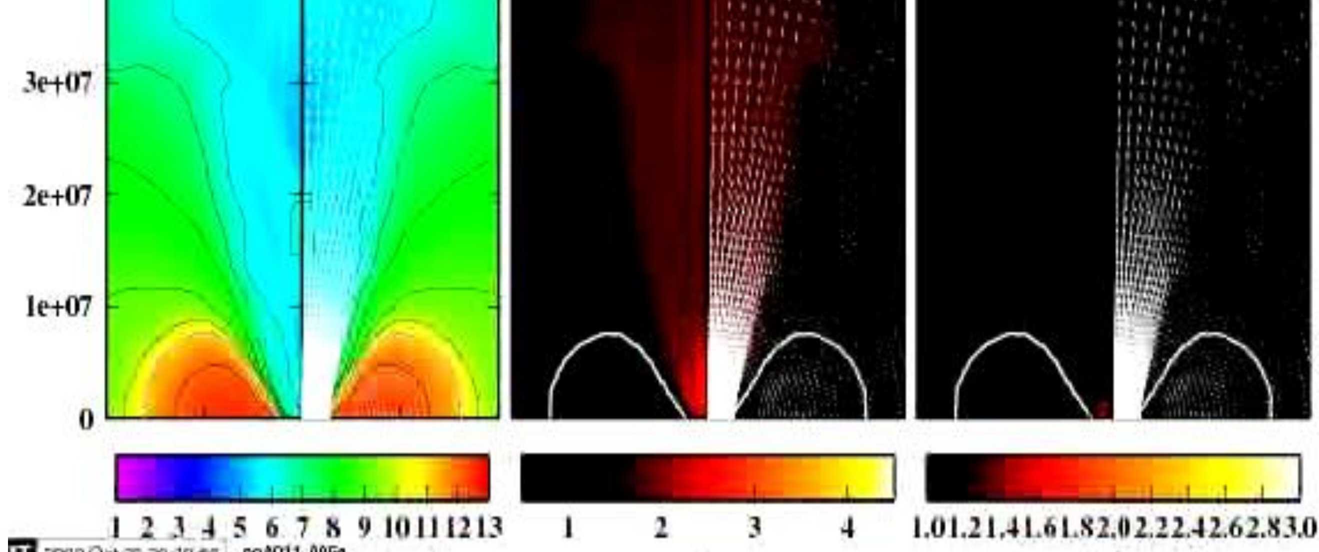
# Various roles of ν's in SN-nucleosynthesis

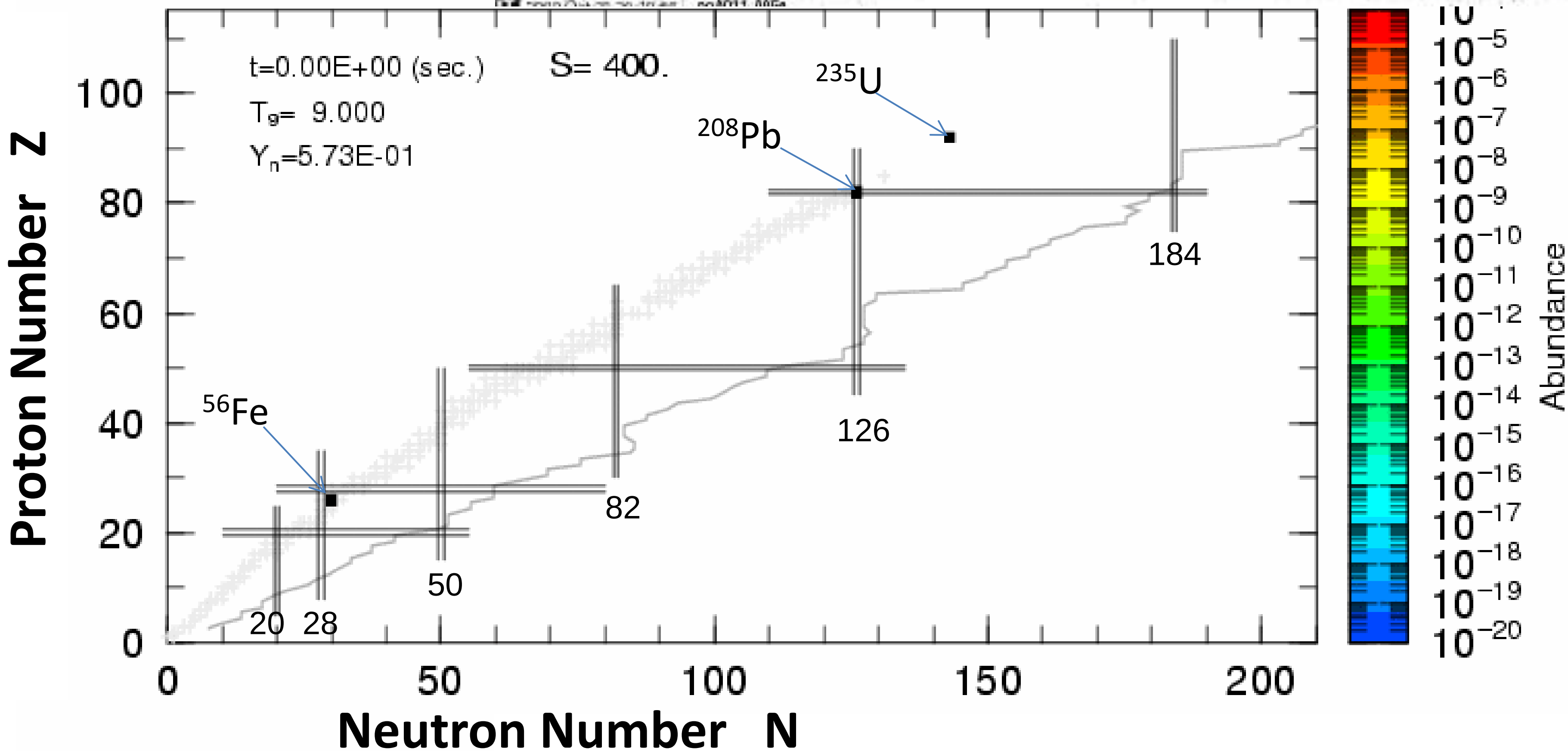


# Supernova Nucleosynthesis Simulation

Chiba, Koura, Kajino

ν-Pair Heated Collapsar Model
K. Nakamura, et al. ApJ (2013).



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

$$\nu_e + n \to p + e^-$$
$$\bar{\nu}_e + p \to n + e^+$$

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

$L_{\nu_e} = L_{\bar{\nu}_e}$ = equi-partition of thermal neutrinos

$\Delta$ = 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:

$0.42 < Y_e < 0.48$ ➡ $T_{\nu e}$ = 3.2 MeV, $T_{\overline{\nu e}}$ = 4 MeV

# *R-process Nucleosynthesis*

K. Otsuki, H. Tagoshi, T. Kajino and S. Wanajo, ApJ 533 (2000), 424;
S. Wanajo, T. Kajino, and G. J. Mathews, and K. Otsuki, ApJ J. 554 (2001), 578.

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

$T_{\nu e} = 3.2$ MeV, $T_{\overline{\nu e}} = 4$ MeV

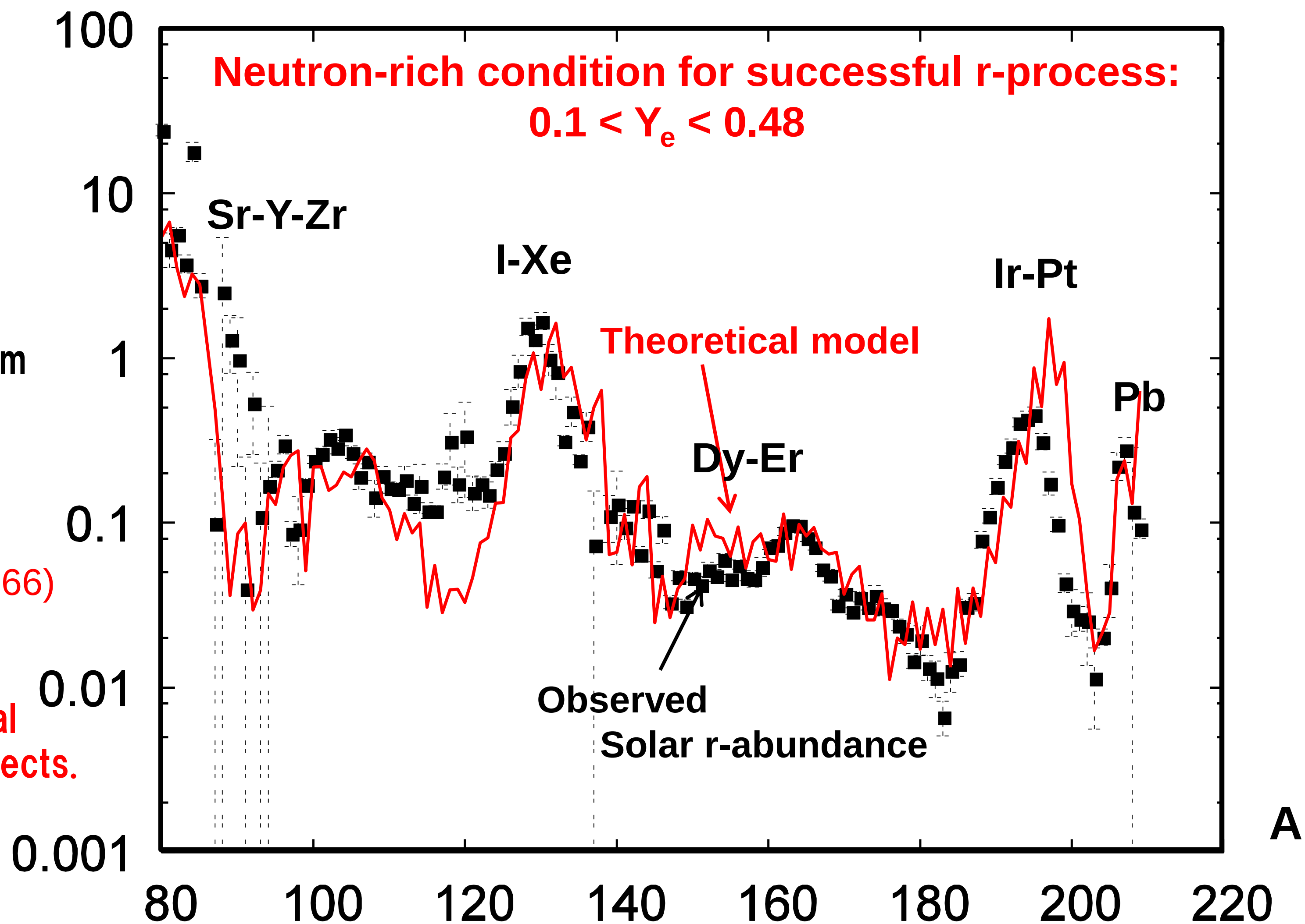
Challenge to identify astrophysical sites of the r-process:

- ν-wind SNe
- MHD jet SNe
- NS mergers
- GRBs

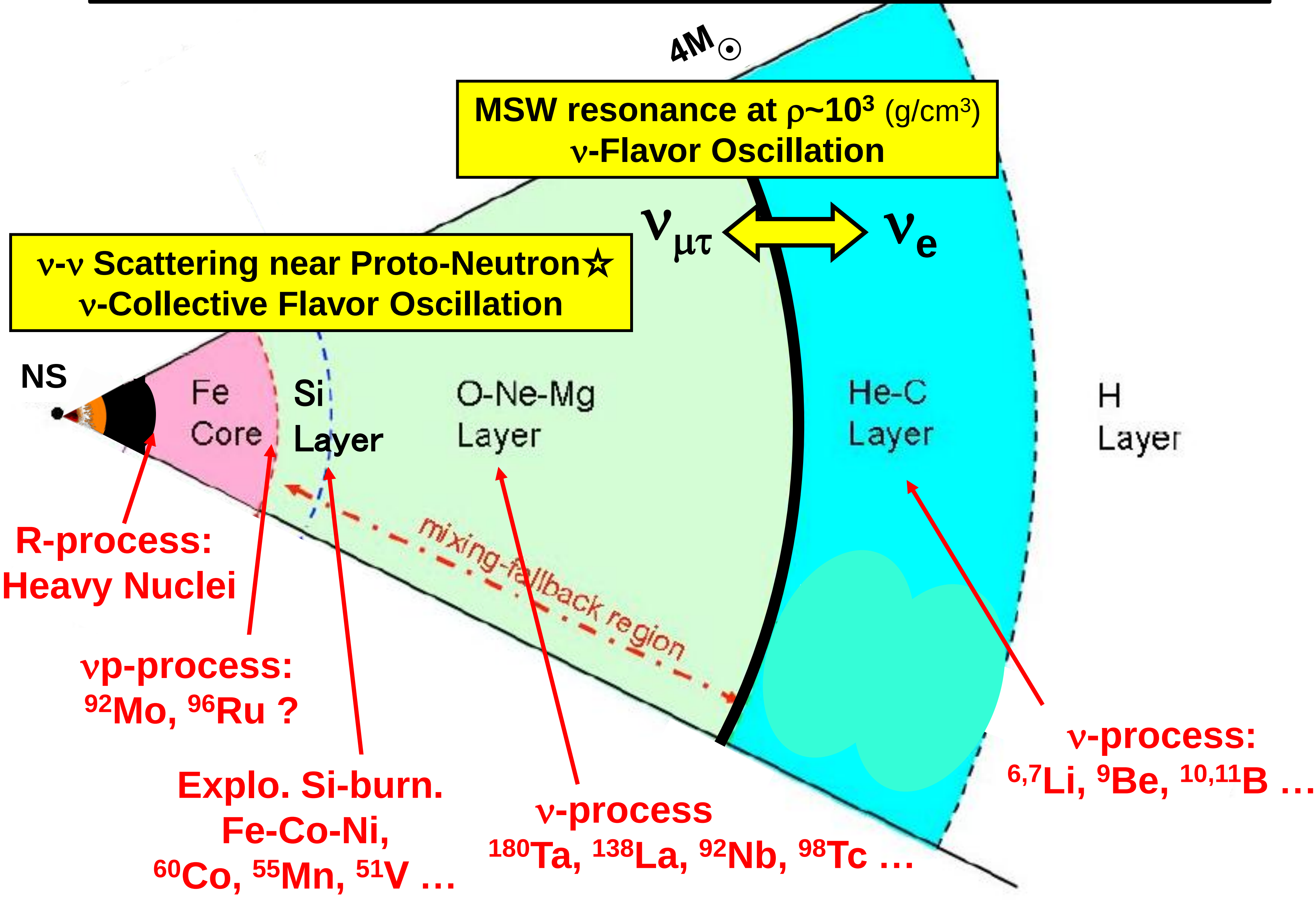
+
Explosion mechanism

$Y_e > 0.5$ ?

Roberts, Reddy and Shen (arXiv1205.4066) pointed out
$Y_e < 0.5$
for nucleon potential & Pauli blocking effects.



# Various roles of ν's in SN-nucleosynthesis



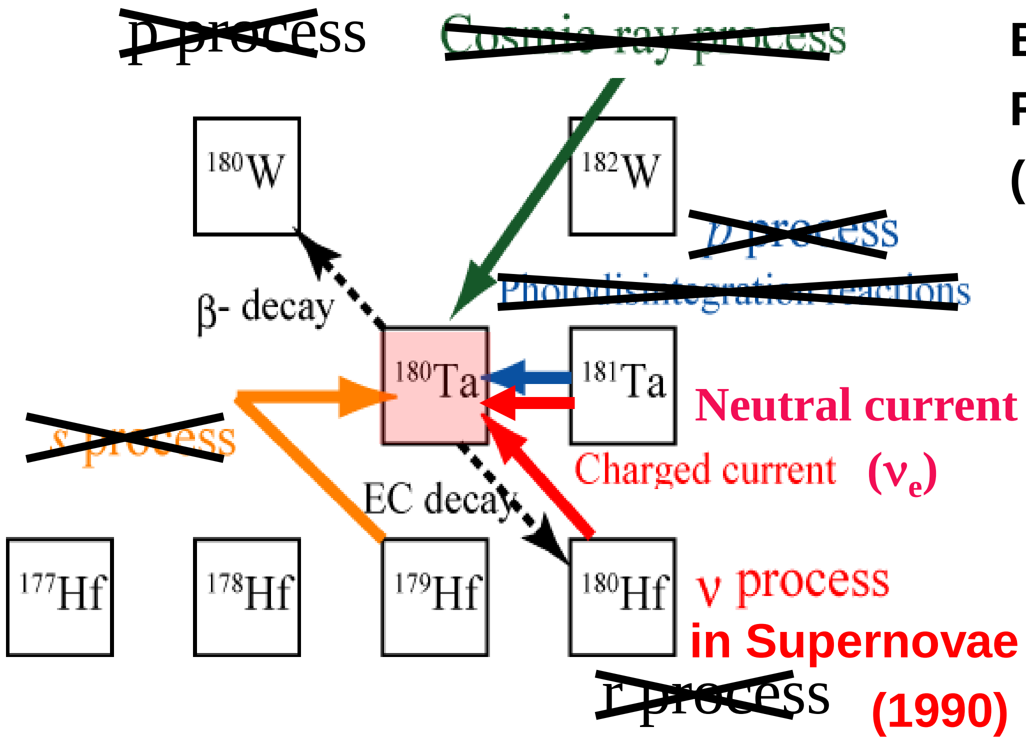
# Tantalum ($^{180,181}$Ta)

$^{181}$Ta$_g$ (stable), $^{180}$Ta$_g$(unstable, $\tau_{1/2}$ = 8h), $^{180}$Ta$^m$ (isomer, $\tau_{1/2} > 10^{15}$y)

The rarest isotope in the Universe!

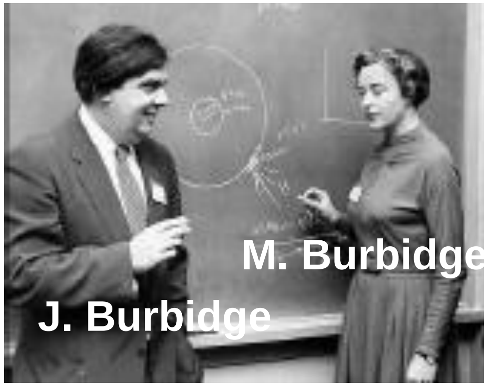
**Origin of $^{180}$Ta was unknown.**

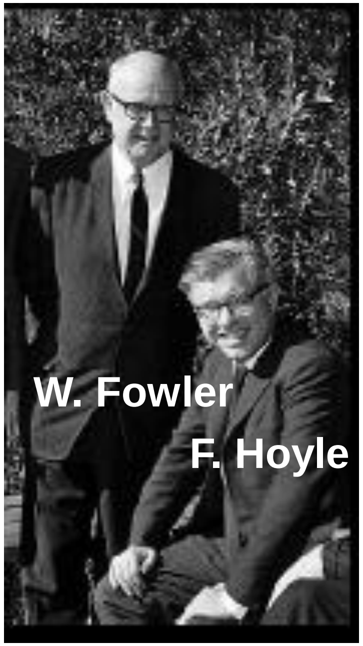
**"SN $\nu$-process" overproduces $^{180}$Ta !**




**Burbidge²-Fowler-Hoyle, Rev. Mod. Phys. 29 (1957), 547-650.**

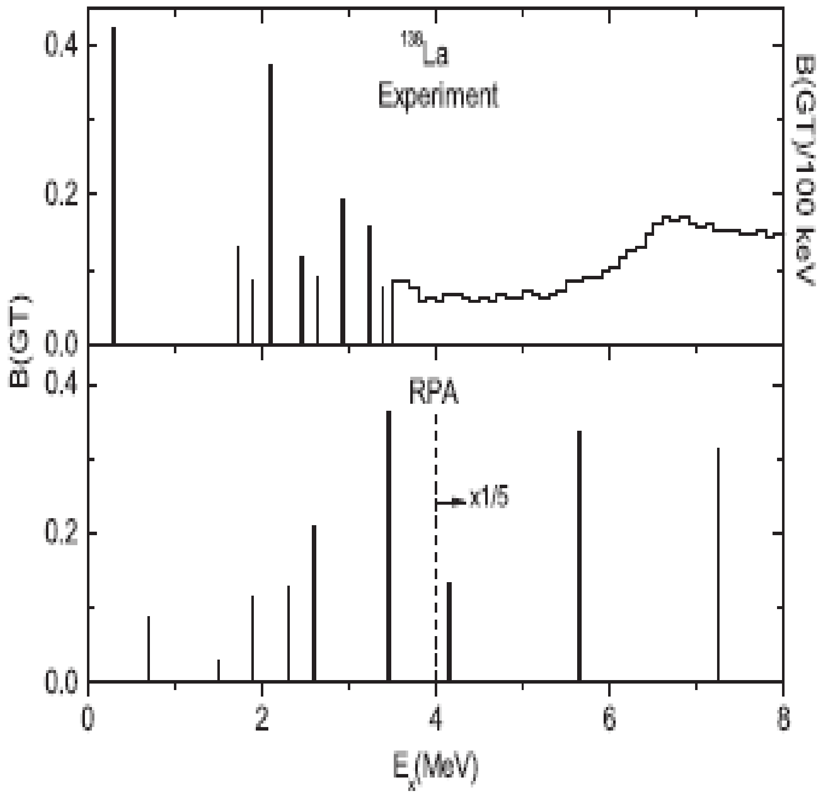
**"Element Genesis"**



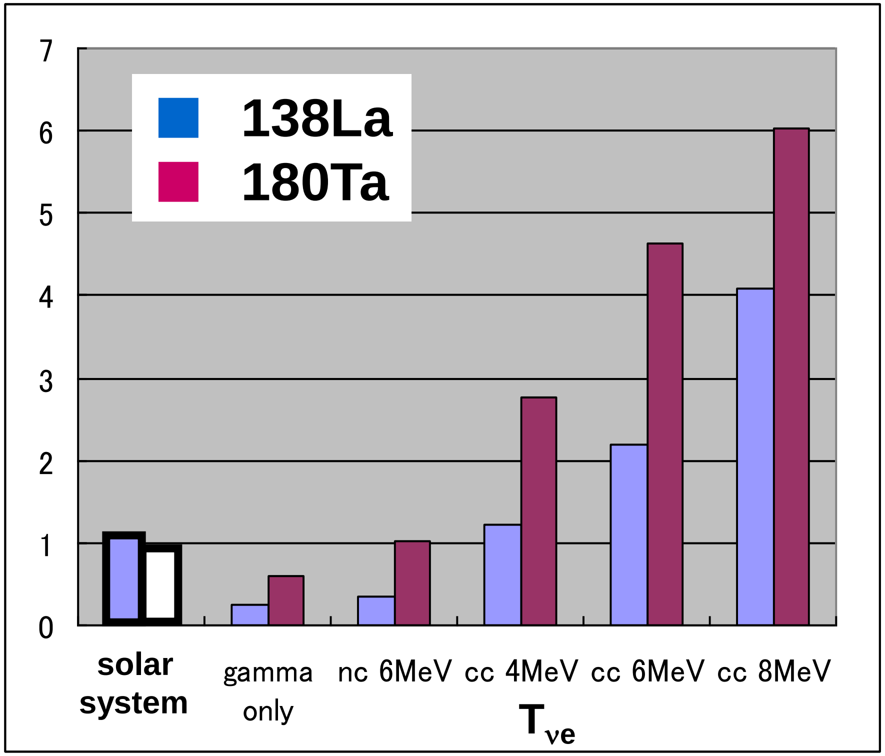



# Supernova ν-Process Nucleosynthesis

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




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




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

**Eν = 0 ~ 80 MeV → Prof. Suzuki's lecture**

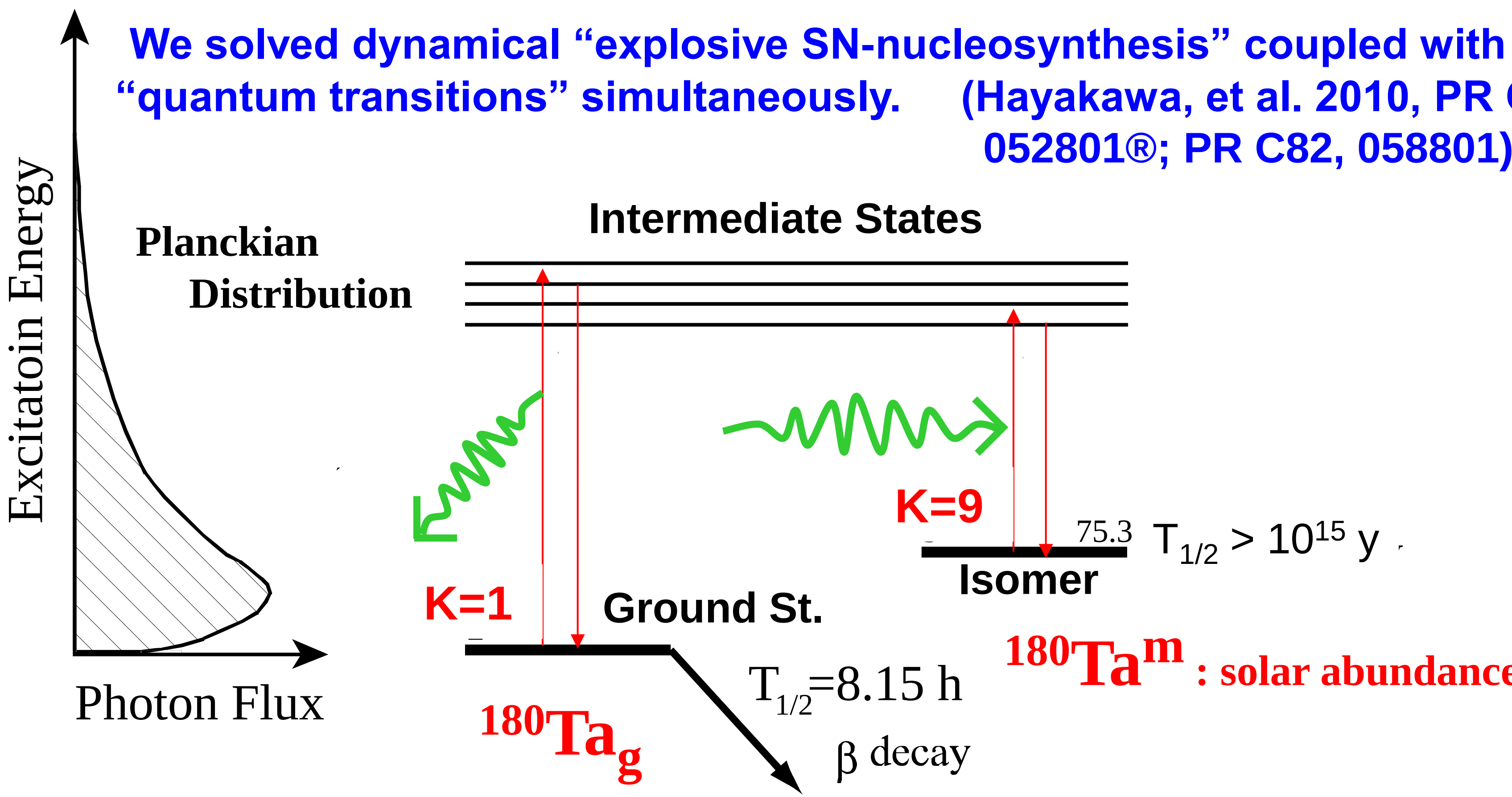
**Overproduction problem of $^{180}$Ta relative to $^{138}$La!**

# $^{180}$Ta-genesis needs Quantum Phys. + SN Hydro-dyn.

**Solar-$^{180}$Ta is all "ISOMER" with $T_{1/2} > 10^{15}$ y!**

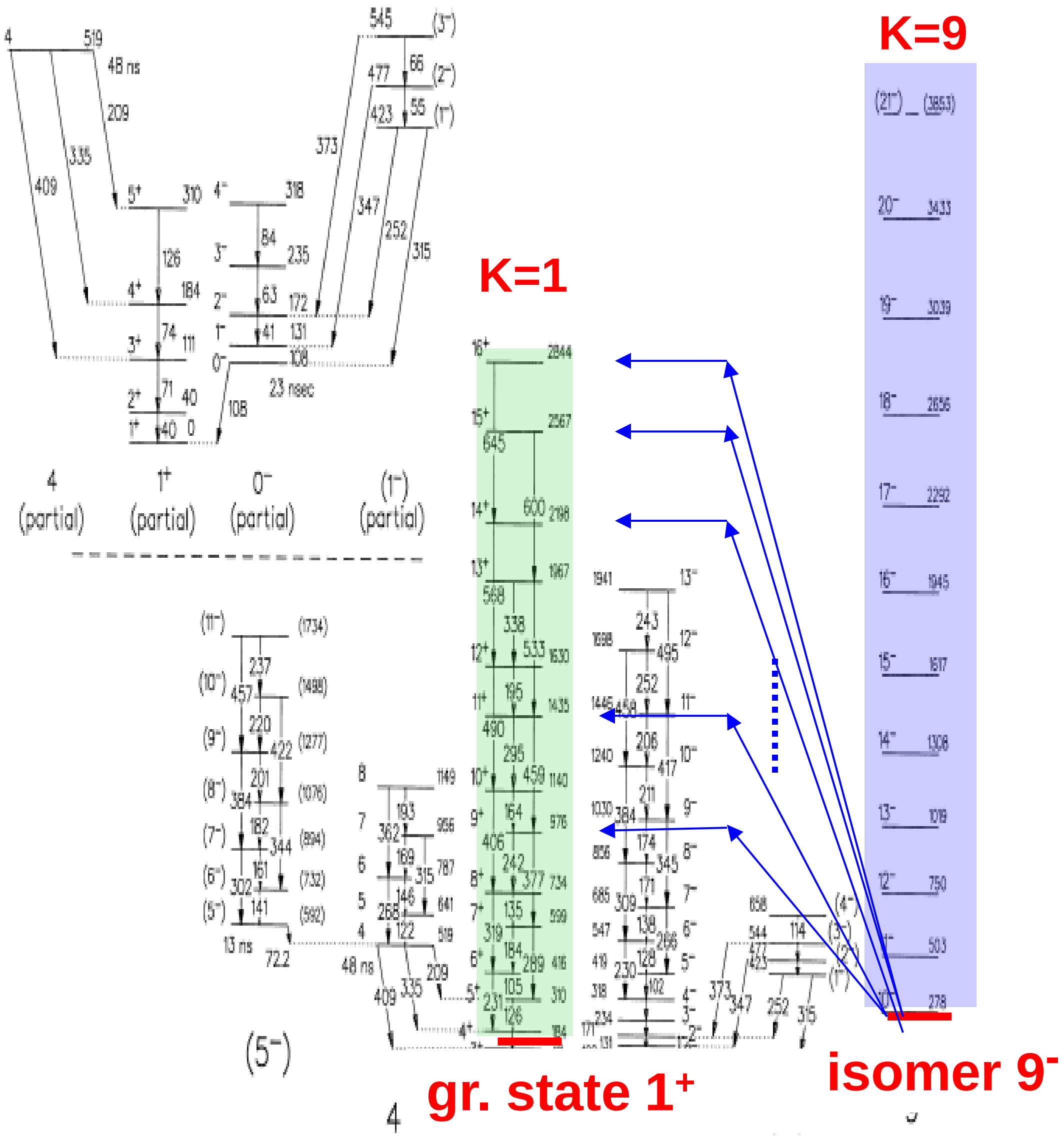
- **Long lived $^{180}Ta^m$ is excited in hot SN-photon bath.**
- **Intermediate states are depopulated to the ground state, which decays in 8 hours.**

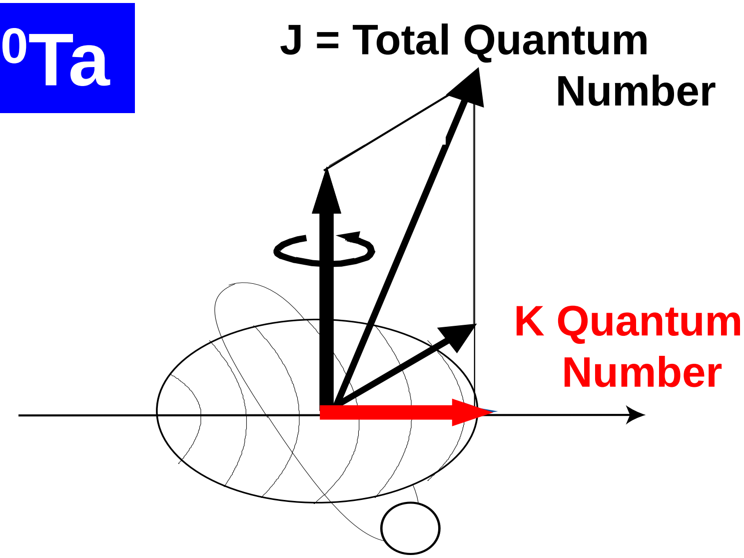
**We solved dynamical "explosive SN-nucleosynthesis" coupled with "quantum transitions" simultaneously. (Hayakawa, et al. 2010, PR C81, 052801®; PR C82, 058801)**



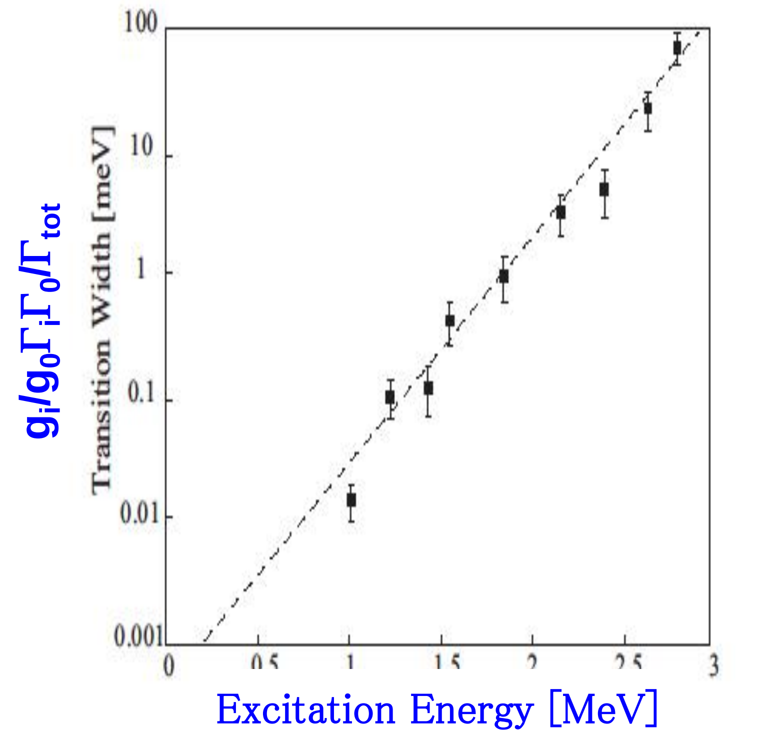
# ν-Process and Structure of $^{180}$Ta

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




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



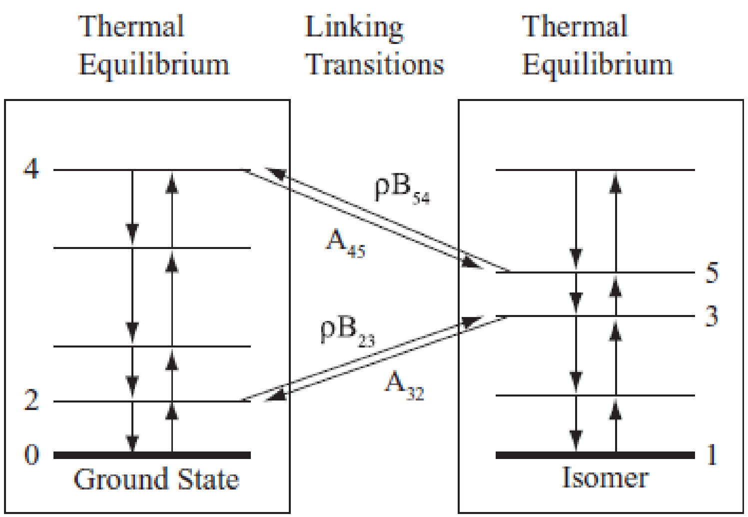
# Formula to calculate time-dept linking transitions

Hayakawa, Kajino, Chiba & Mathews, PR C81 (2010), 052801®; + Mohr, PR C82 (2010), 058801

## ★ General formula (Einstein AB theory) for $kT \ll \Delta E_{ij}$:

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

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




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

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

$1^+$ $9^-$

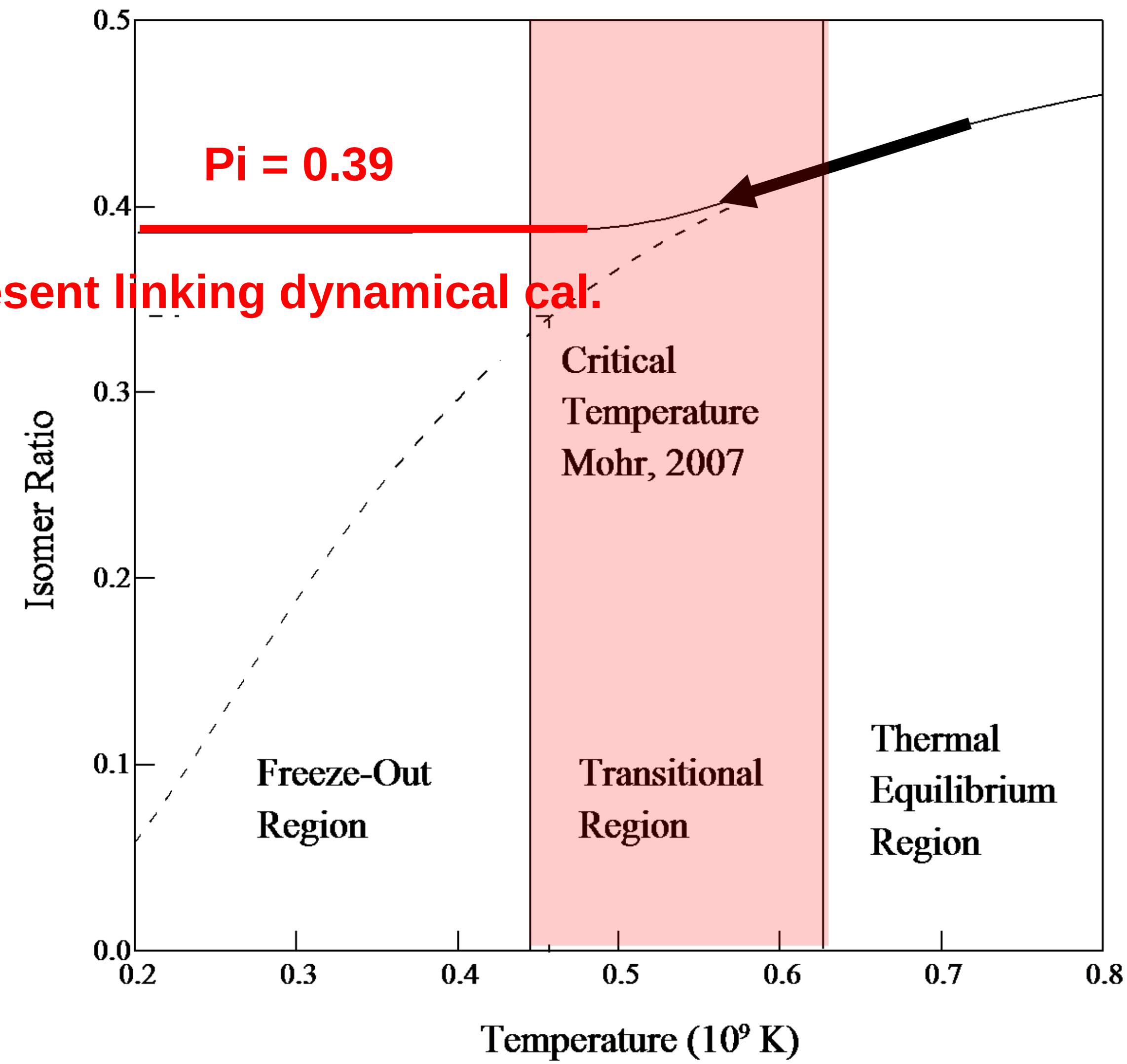
## ★ In the SPECIFIC case of $^{180}$Ta:

**Transition prob. $\Sigma_p A_{ip} = \Gamma_i / \hbar$ ⟵ Exp.**

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

# Calculated Result

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




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

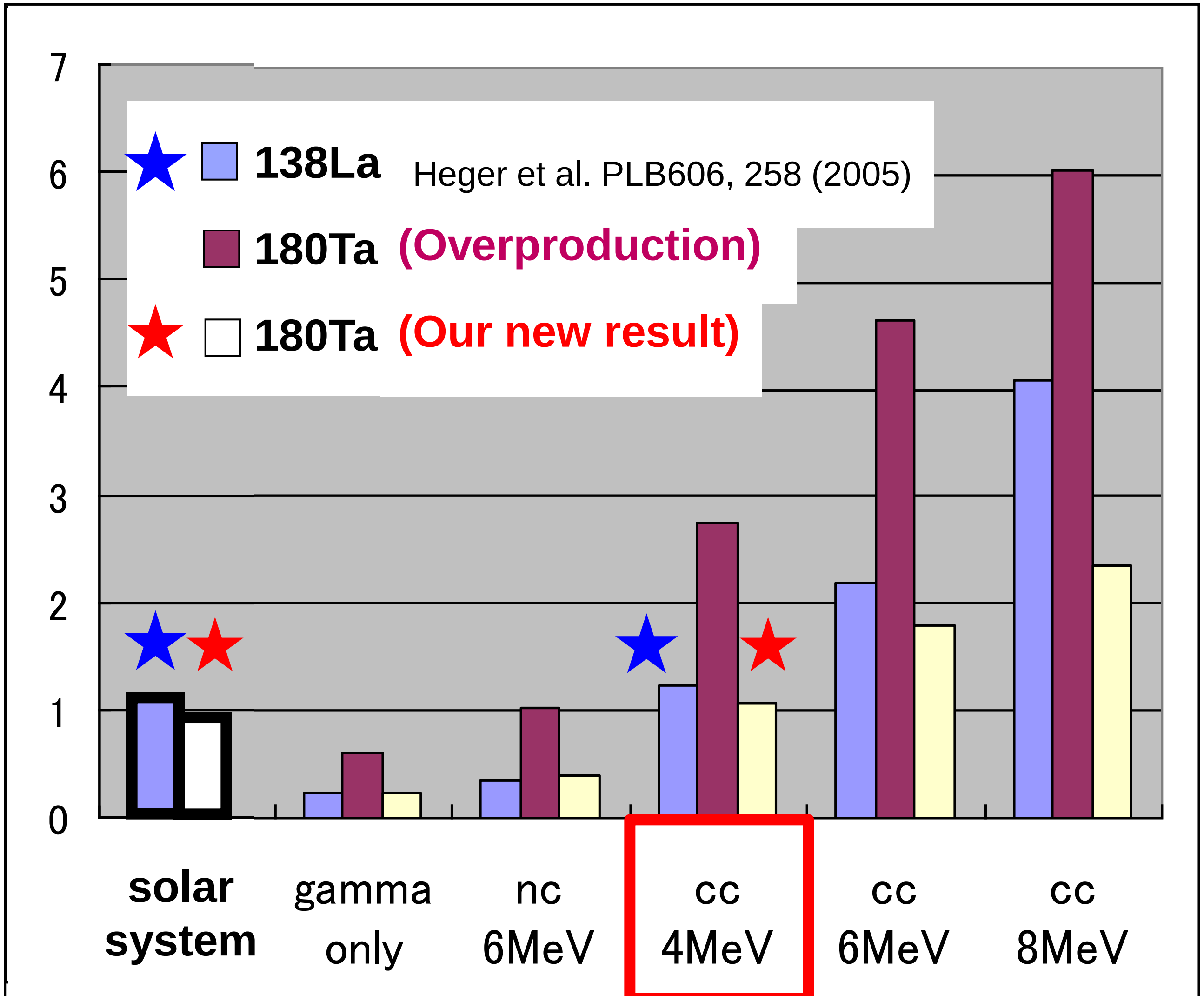
**Pi ~ 0.39 survives!**

**This result is almost independent of SN models, i.e.**

**total explosion E, progenitor mass, ν-luminosity and its decay time scale.**

# Result from ν-Nucleosynthesis

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




About 40% $^{180}Ta^{m}$ survives in supernova explosion.

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

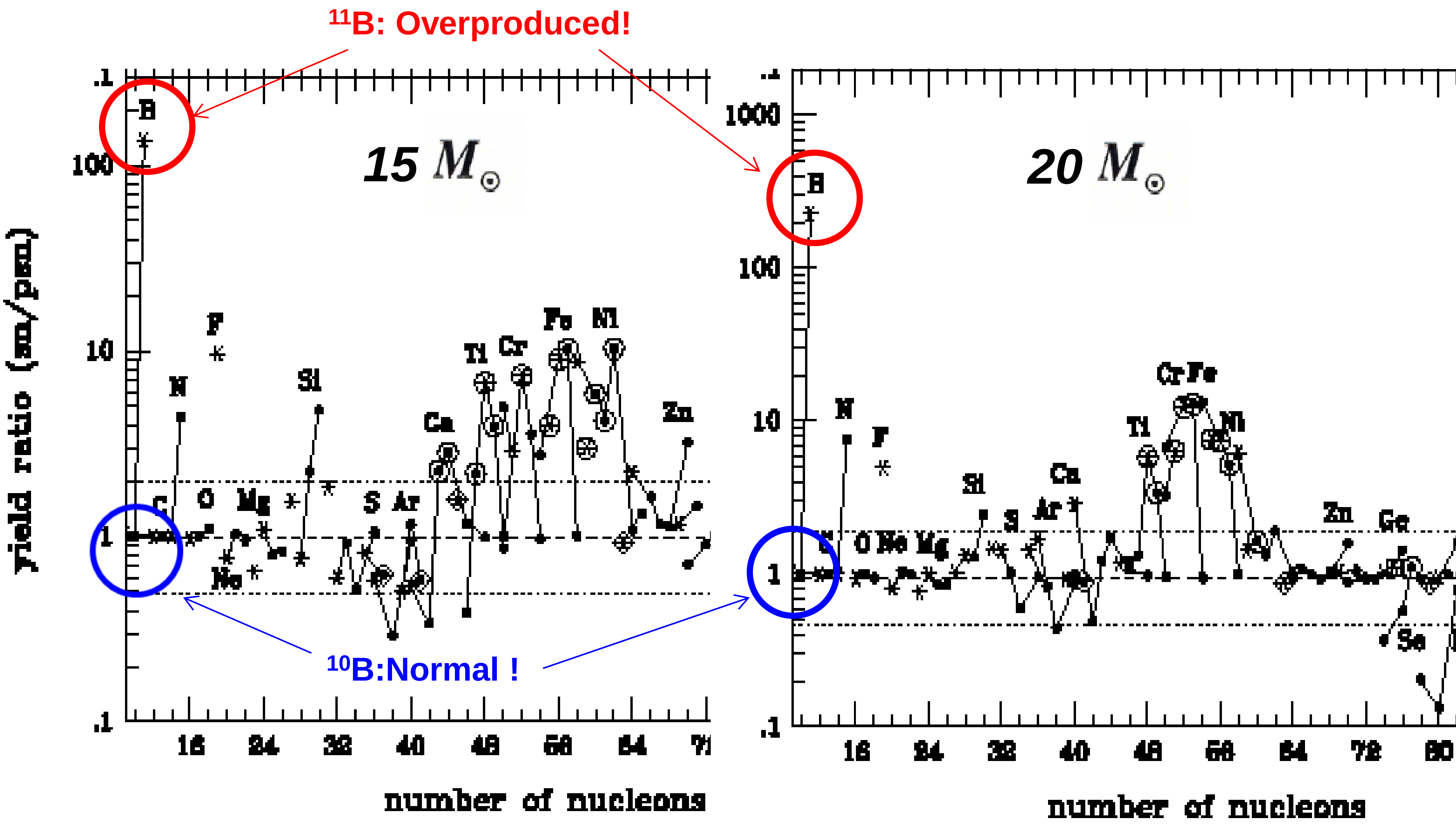
$$T_{\nu e} = 3.2 \text{ MeV},$$
$$T_{\overline{\nu e}} = 4 \text{ MeV}.$$

⇕

Consistent with the r-process !

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

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



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) |
| $^6Li$ | $70(2) \times 10^{-12}$ | $300(2) \times 10^{-12}$ |
| $^7Li$ | $900(2) \times 10^{-12}$ | $4600(2) \times 10^{-12}$ |
| $^9Be$ | $14(1.6) \times 10^{-12}$ | $90(1.6) \times 10^{-12}$ |
| $^{10}B$ | $30(2) \times 10^{-12}$ | $200(1.6) \times 10^{-12}$ |
| $^{11}B$ | $120(2) \times 10^{-12}$ | $900(2) \times 10^{-12}$ |

**Measured Meteoritic Ratio**

**GCR + SN-v**

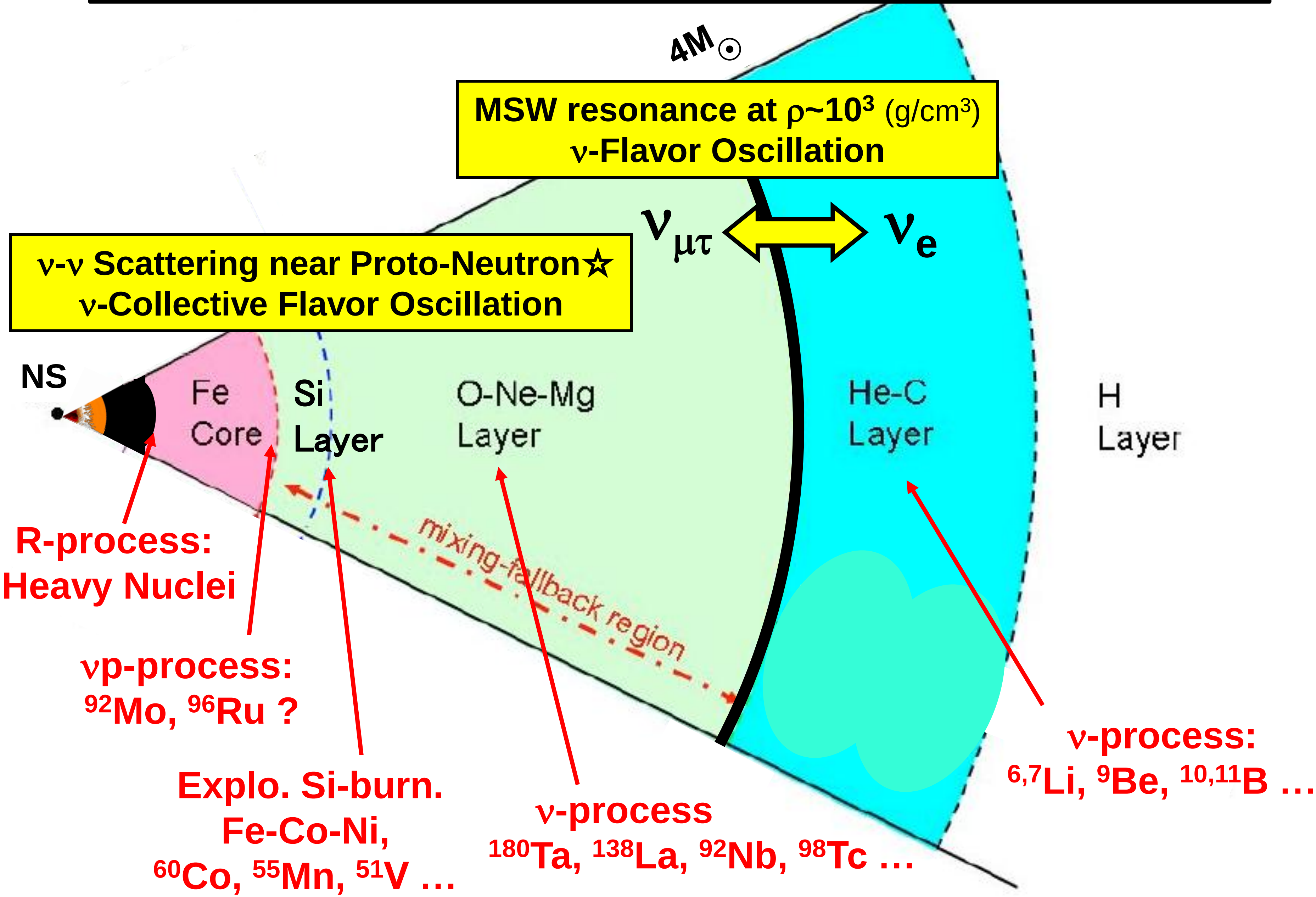
**$^{11}B/^{10}B$ = 4.05 +- 0.10**

**Measured GCR Ratio**

**GCR**

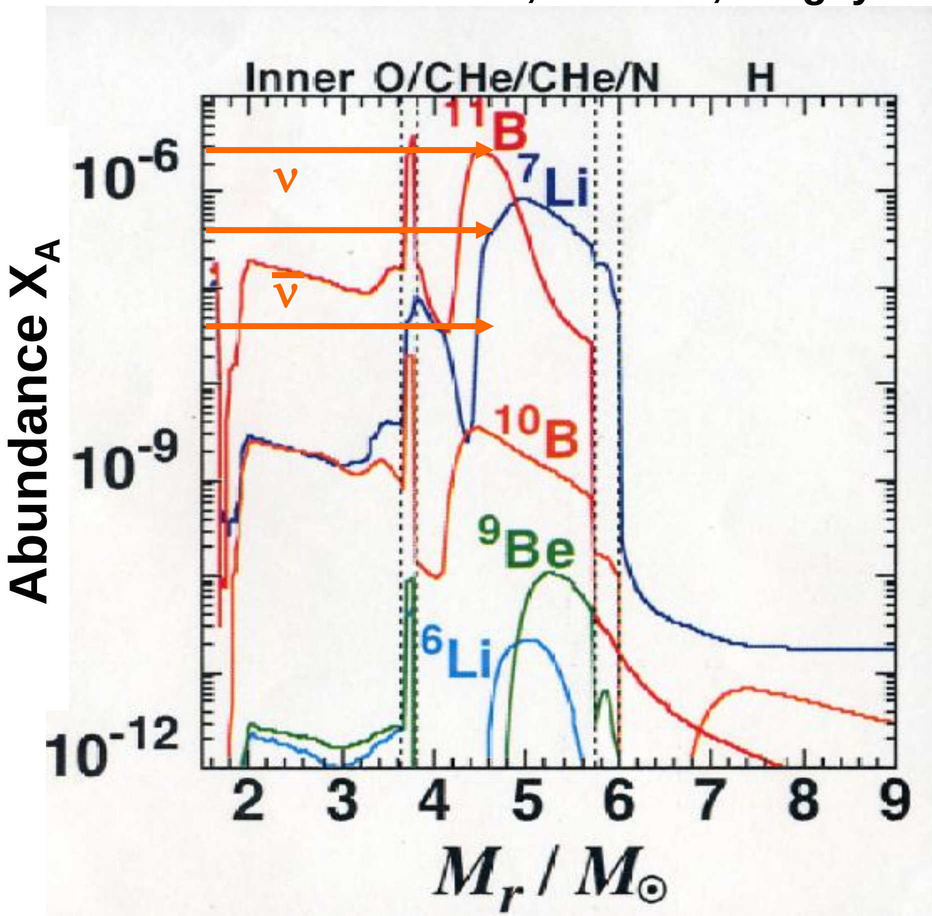
**$^{11}B/^{10}B$ = 2.0 +- 0.2**

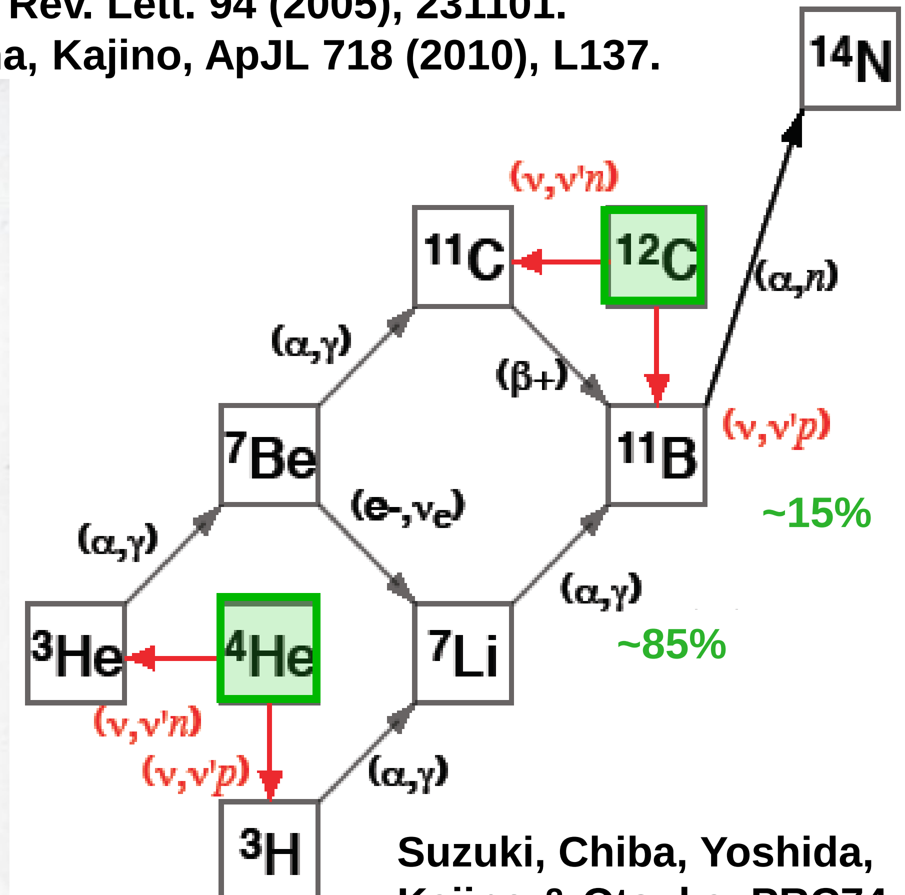
# Various roles of ν's in SN-nucleosynthesis



# Supernova ν-Process to estimate $T\nu_{\mu}$, and $T\nu_{\tau}$

**SN II: Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101.**
**SNIc + II: Nakamura, Yoshida, Shigeyama, Kajino, ApJL 718 (2010), L137.**



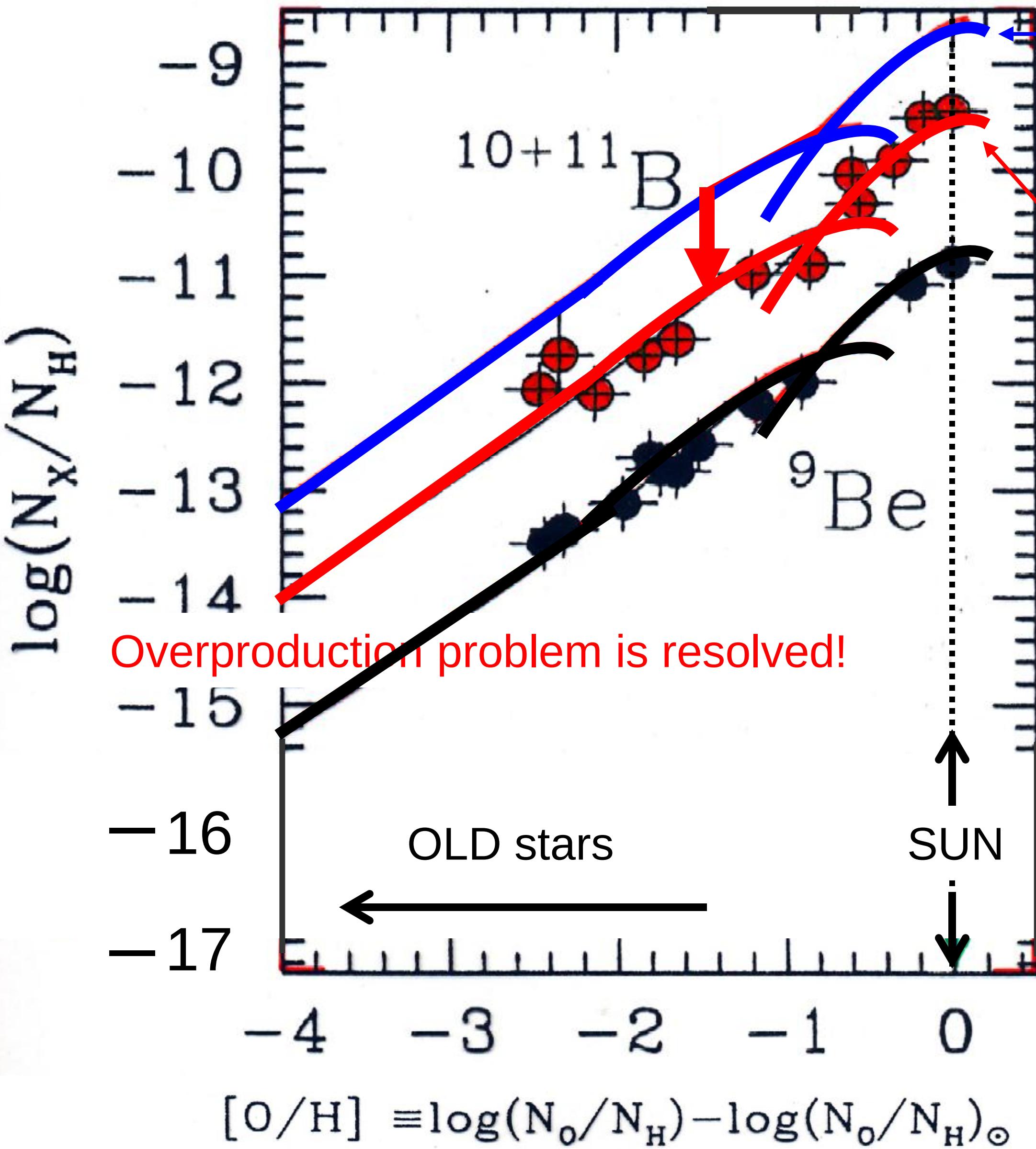




**Suzuki, Chiba, Yoshida, Kajino & Otsuka, PRC74 (2006), 034307**

$^{4}$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

# Galactic Chemical Evolution of $^9$Be & $^{10,11}$B




Livermore Model

$T_{\nu_{\mu,\tau}}$ = 8 MeV

Woosley -Weaver 1995, ApJS 101, 181.

$\sigma \propto E_\nu^2$

$T_{\nu_{\mu,\tau}}$ = 6 MeV

Consistent with SN1987A

Yoshida, Kajino & Hartmann 2005, PRL 94 (2005), 231101.

**$^9$Be:**

– Galactic Cosmic Rays

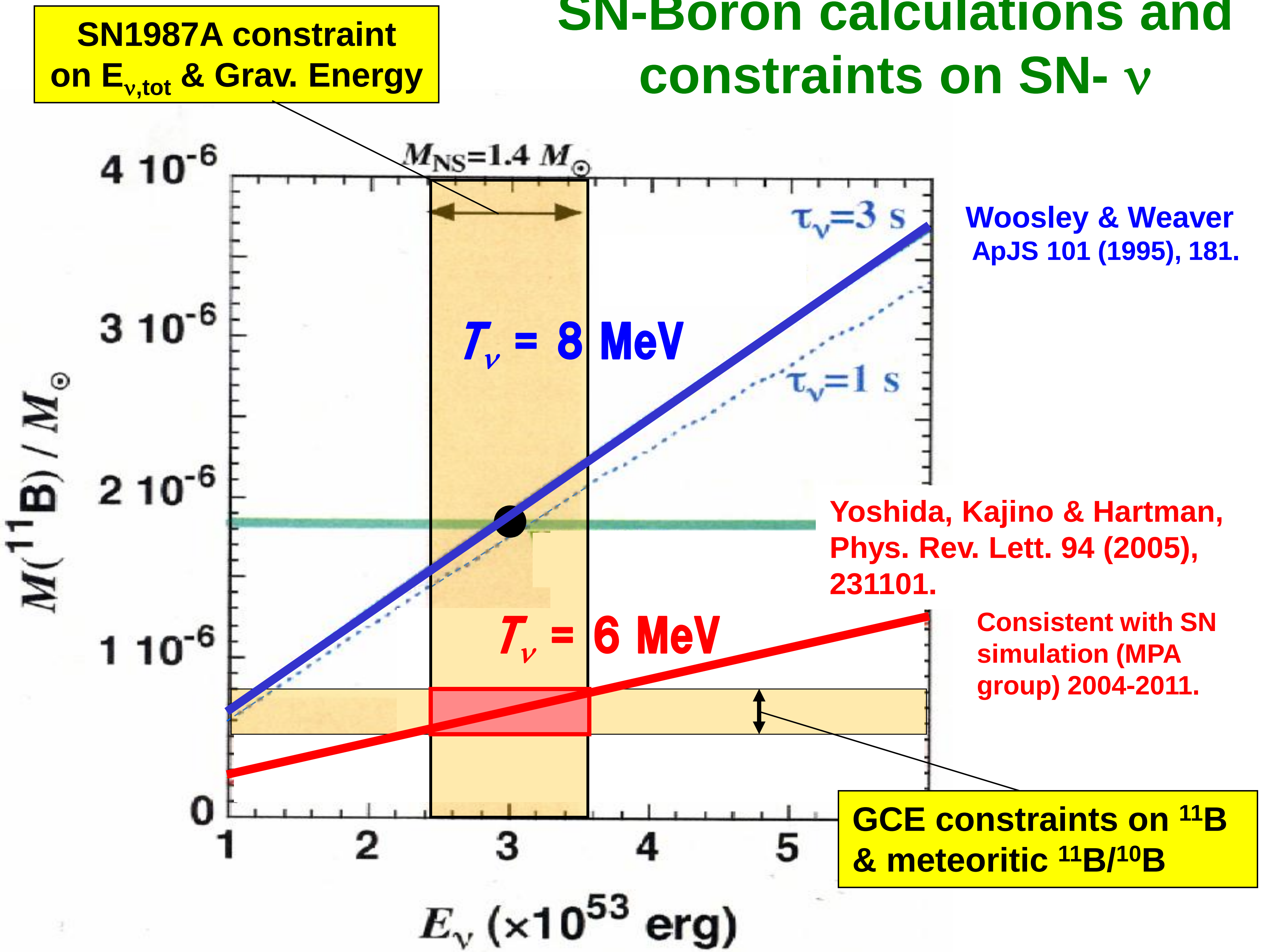
**$^{10+11}$B + $^{11}$B:**

– Galactic Cosmic Rays

– Supernova ν–process

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

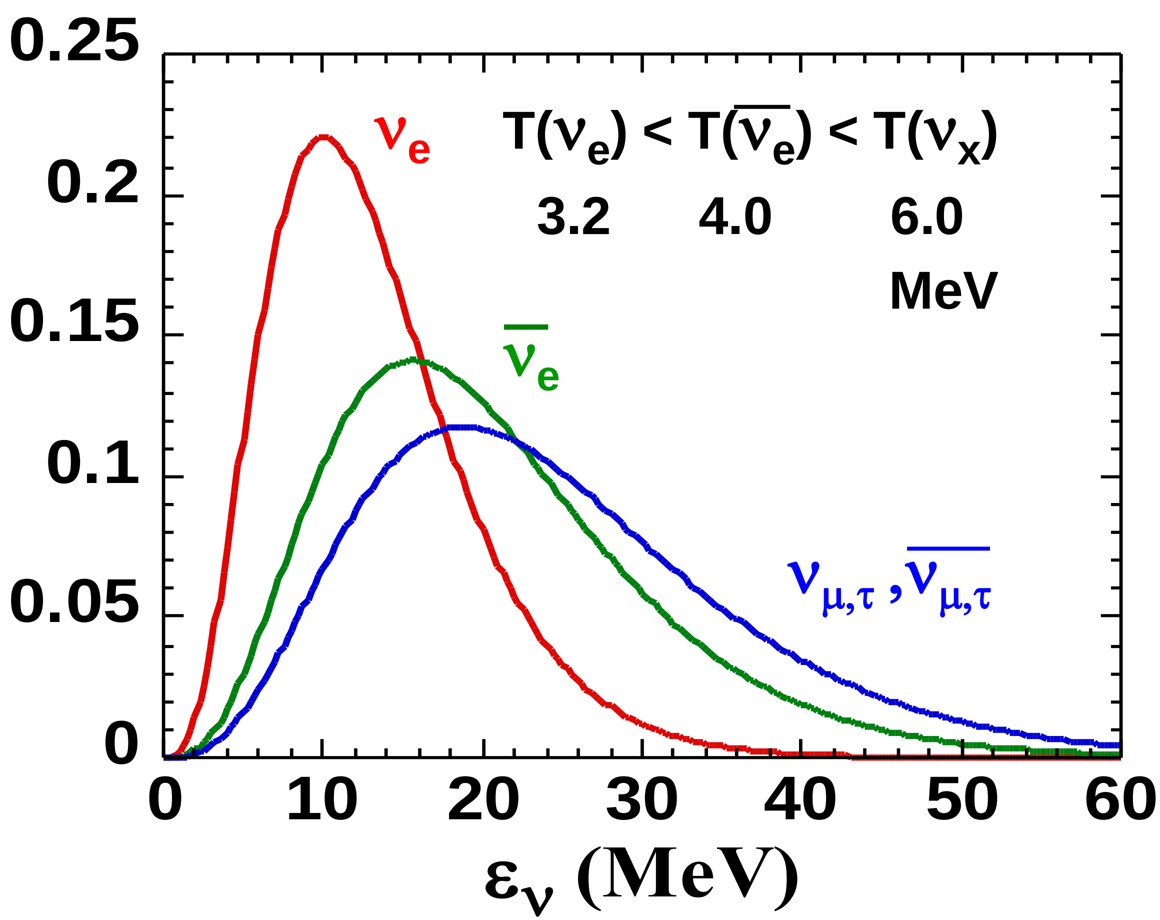
# SN-Boron calculations and constraints on SN- ν



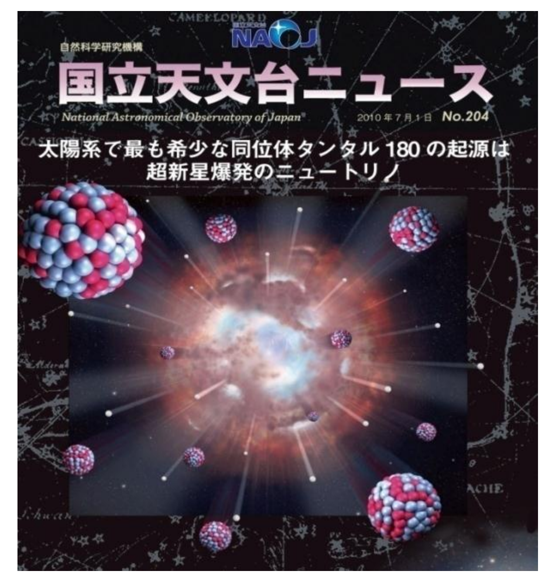
# Average ν-temperatures are now known!

- R-process Elements & $^{180}$Ta/$^{138}$La ➡ $T\nu_e$ = 3.2 MeV, $T\overline{\nu_e}$ = 4 MeV
- Astron. GCE of Light Elements & $^{11}$B ➡ $T\nu_{\mu}$, = $T\nu_{\tau}$ = 6 MeV

**Neutrino Oscillation !**







## ディラック方程式（Dirac-Pauli 表示）

$$(i\gamma^\mu \partial_\mu - m)\psi(x) = 0$$

$$\boldsymbol{\alpha} = \begin{pmatrix} 0 & \boldsymbol{\sigma} \\ \boldsymbol{\sigma} & 0 \end{pmatrix}, \quad \gamma_0 = \beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

$$\boldsymbol{\gamma} = \beta\boldsymbol{\alpha} = \begin{pmatrix} 0 & \boldsymbol{\sigma} \\ -\boldsymbol{\sigma} & 0 \end{pmatrix}, \quad \gamma_5 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

## エネルギーE, 運動量 p のニュートリノの固有状態（m = 0）

$$\psi = u \exp\frac{i}{\hbar}(\boldsymbol{p}\boldsymbol{r} - Et).$$

Dirac spinor

左巻きニュートリノ

$$u(p, 1) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}, \quad u(p, -1) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix}, \quad E > 0$$

右巻き反ニュートリノ

$$v(p, 1) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix}, \quad v(p, -1) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \\ 0 \\ 1 \end{pmatrix}, \quad E < 0$$

真空振動・物質（MSW）振動・自己相互作用振動は、スピノール構造を変えない。
フレーバー振動の物理で重要なのは、エネルギー質量の固有状態の時間発展。

# 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：$1 \times 10^{51}$ **ergs = 1 Bethe**

**(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; Kajino et al. 2000)**

PHYSICAL REVIEW D **85**, 105023 (2012)

# Exploring the neutrino mass hierarchy probability with meteoritic supernova material, $\nu$-process nucleosynthesis, and $\theta_{13}$ mixing

G. J. Mathews,[1,2] T. Kajino,[2,3] W. Aoki,[2] W. Fujiya,[4] and J. B. Pitts[5]

## Bayesian Analysis — Astrophysical model dependence

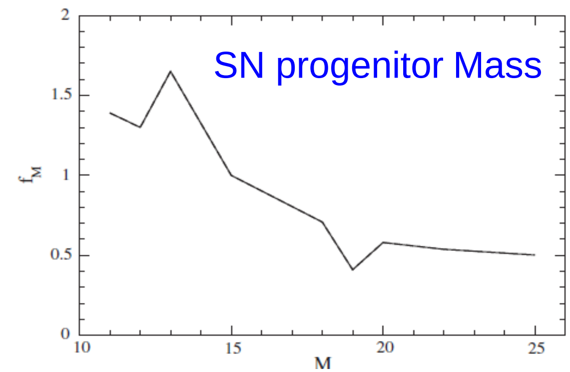
$$P(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_j P(D|M_j)P(M_j)}$$

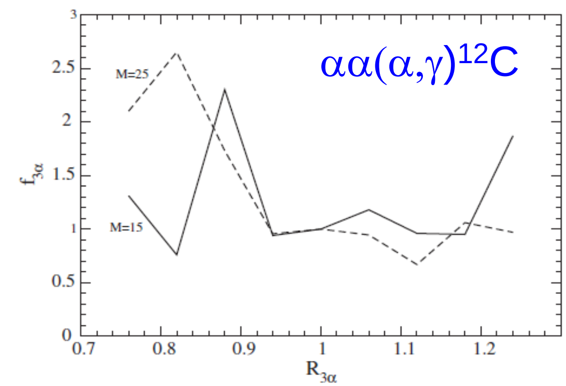
$$P(D|M_i) = \int dEdZda_k P(E,Z,D|M_i,a_k)P(a_k|M_i)$$

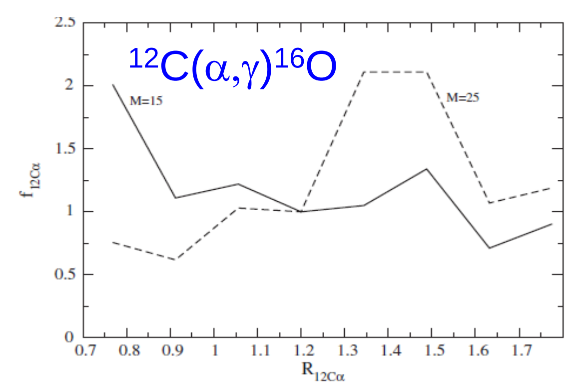
$$= \int dEdZda_k P(D|M_i,a_k,E,Z)P(Z,E|M_i,a_k)P(a|M_i)$$

TABLE I: Parameter likelihood functions $P(a_k|M_i)$.

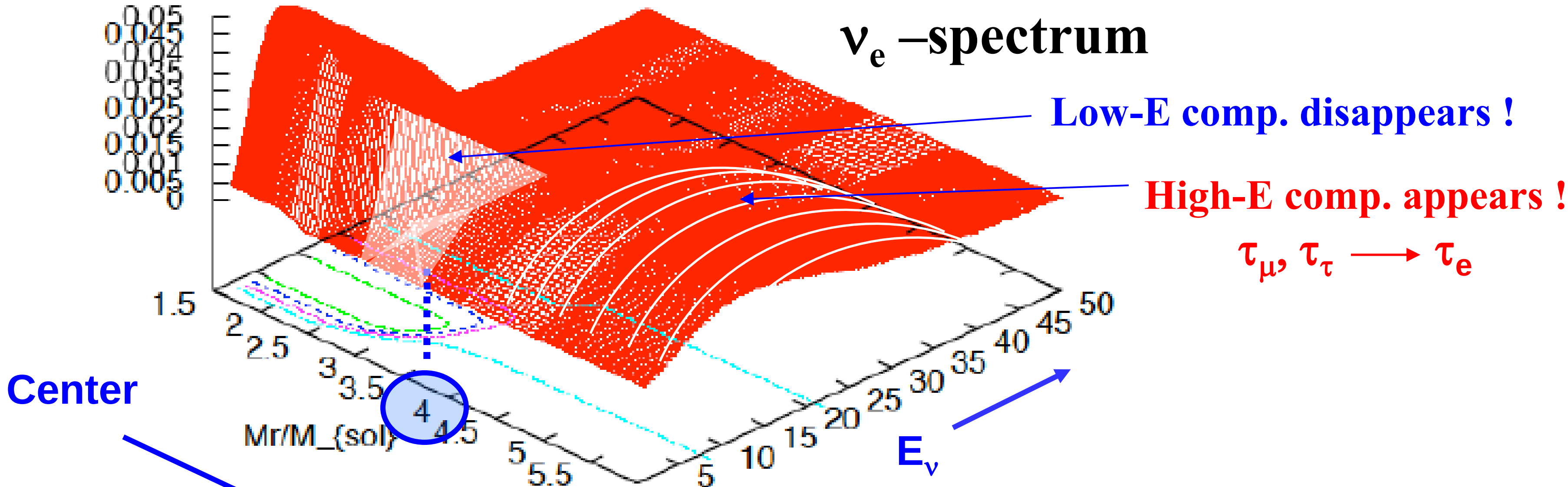
| Parameter $a_k$ | prior | | | reference |
|---|---|---|---|---|
| $\sin^2 2\theta_{13}$ | $e^{-(x-x_0)/2\sigma_x^2}$ | $x_0 = 0.92$ | $\sigma_x = 0.017$ | [7] |
| $R_{3\alpha}$ | $e^{-(x-x_0)/2\sigma_x^2}$ | $x_0 = 1.0$ | $\sigma_x = 0.12$ | [35] |
| $R_{12C\alpha}$ | $e^{-(x-x_0)/2\sigma_x^2}$ | $x_0 = 1.2$ | $\sigma_x = 0.25$ | [36] |
| $M_{prog}(M_\odot)$ | $m^{-2.65}$ | $m_{min} = 10$ | $m_{max} = 25$ | [37] |
| $T_\nu$(MeV) | Top hat | $T_\nu = 3.2 - 6.5$ | (see text) | [15] |

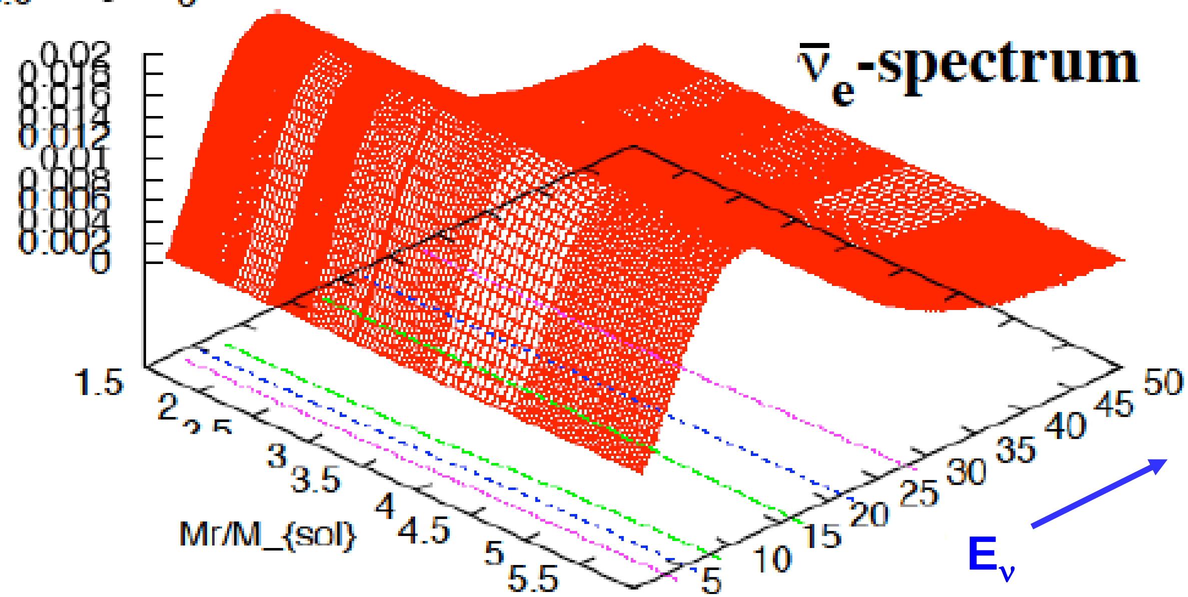


# Neutrino Oscillation (MSW Effect) through propagation



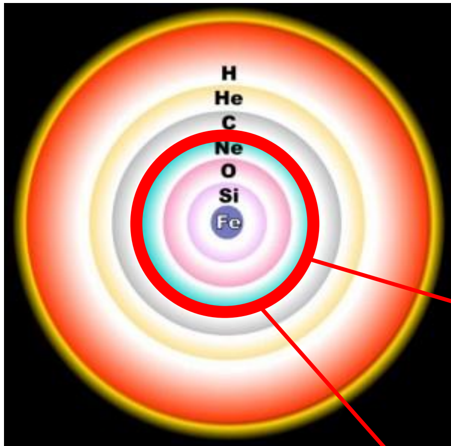




**Parameters:**

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

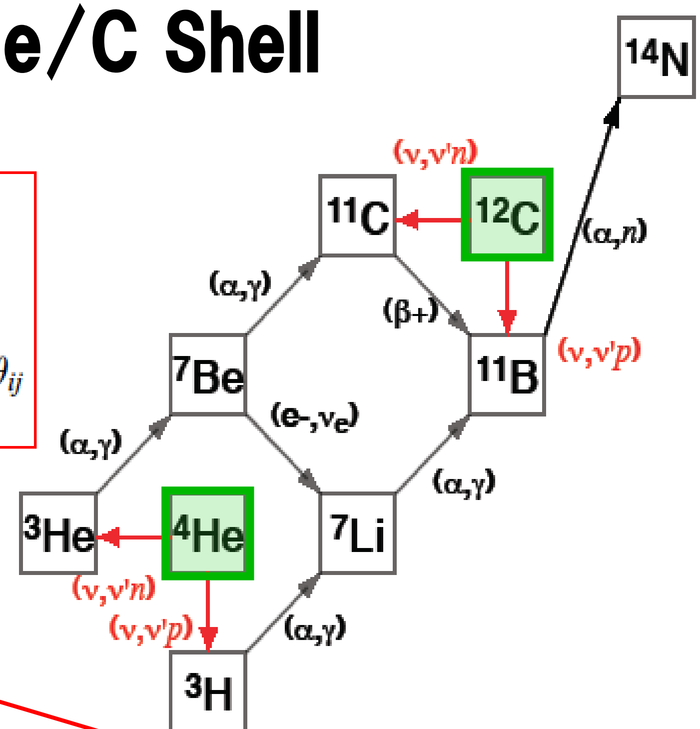
- $\sin^2 2\theta_{13} = 0.04$
- $\Delta m_{13}^2 = 2.4\times10^{-3}$ eV$^2$
- $L_\nu = 3\times10^{53}$ erg, $\tau_\nu = 3$ sec
- $T_{\nu e}$=3.2MeV, $T_{\nu e}$=5.0MeV, $T_{\nu\mu\tau}$=6.0MeV

# $^7$Li and $^{11}$B are produced in the He/C Shell

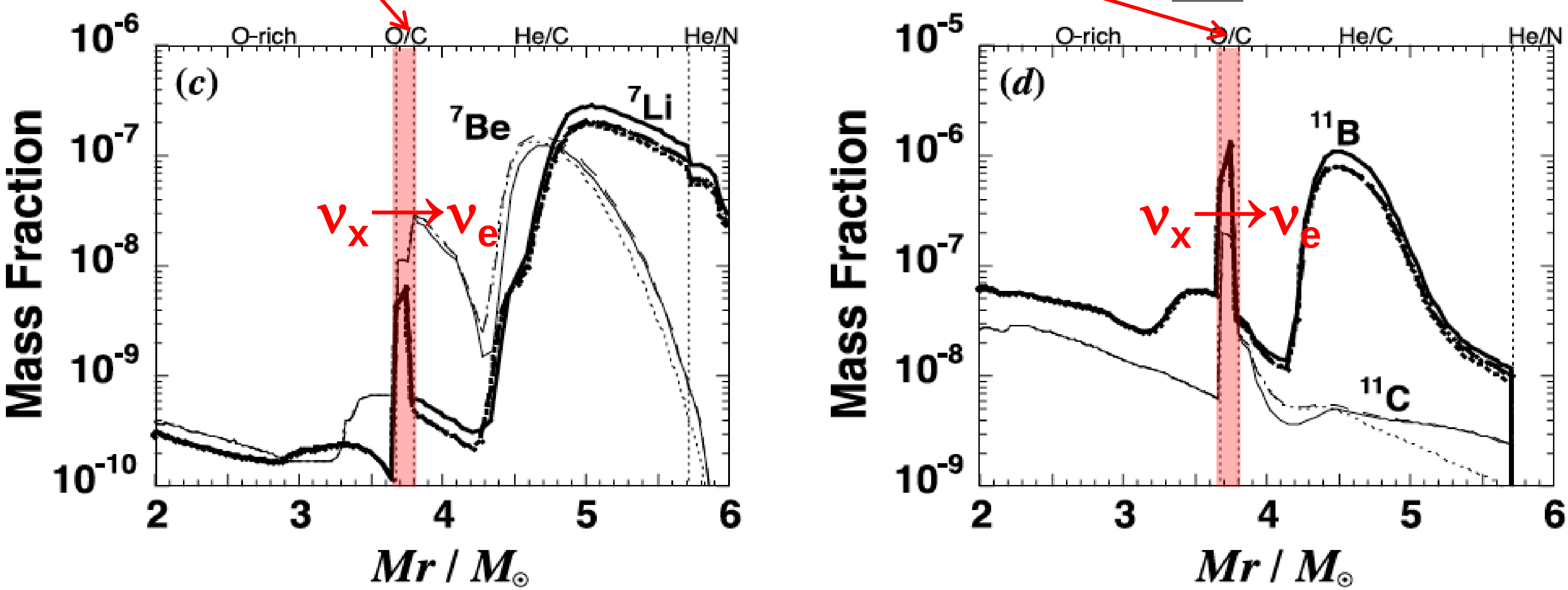



$$\rho_{\rm res} Y_e = \frac{m_u \Delta m_{ji}^2 c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_{\rm F} (\hbar c)^3 \varepsilon_\nu} \qquad [\,{\rm g\ cm^{-3}}\,]$$

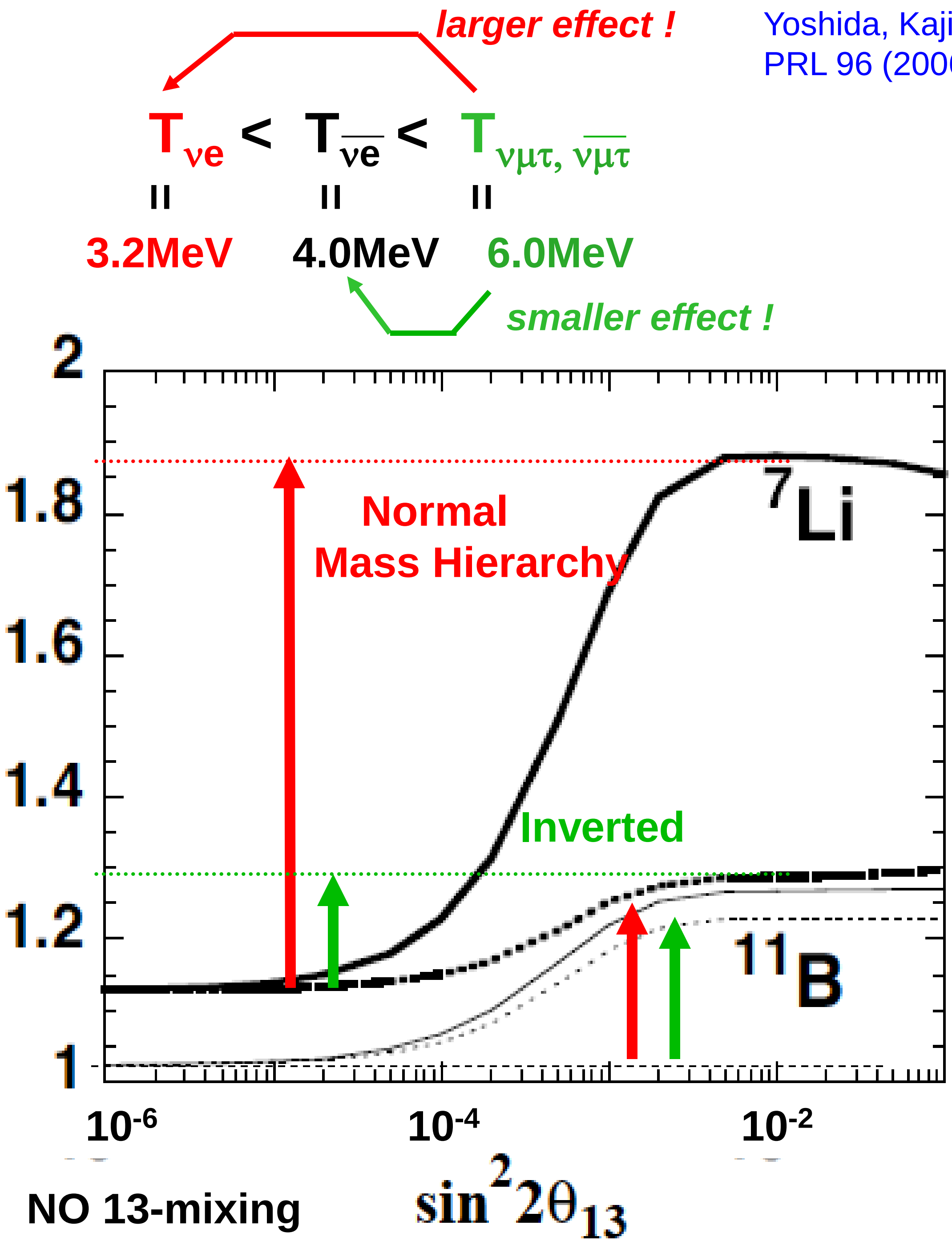
$$= 6.55 \times 10^6 \left(\frac{\Delta m_{ji}^2}{1\ {\rm eV}^2}\right)\left(\frac{1\ {\rm MeV}}{\varepsilon_\nu}\right) \cos 2\theta_{ij}$$

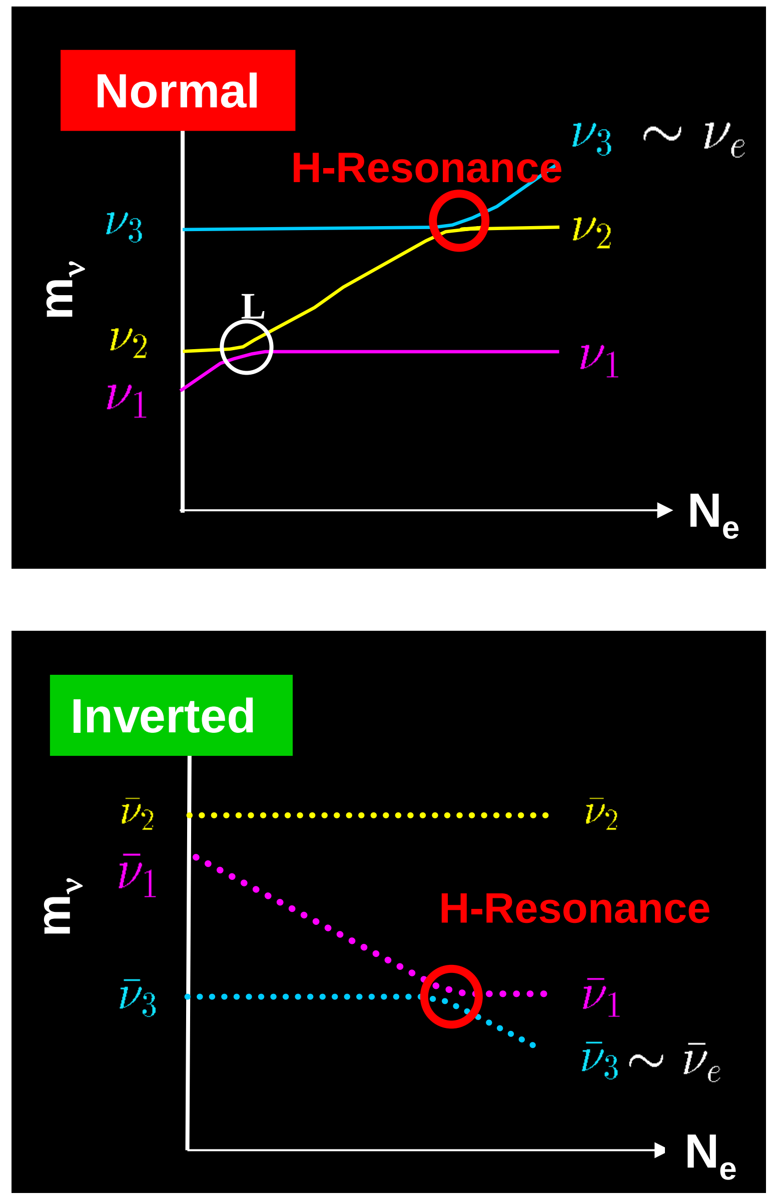



**MSW high-density resonance is located at the bottom of C shell.**

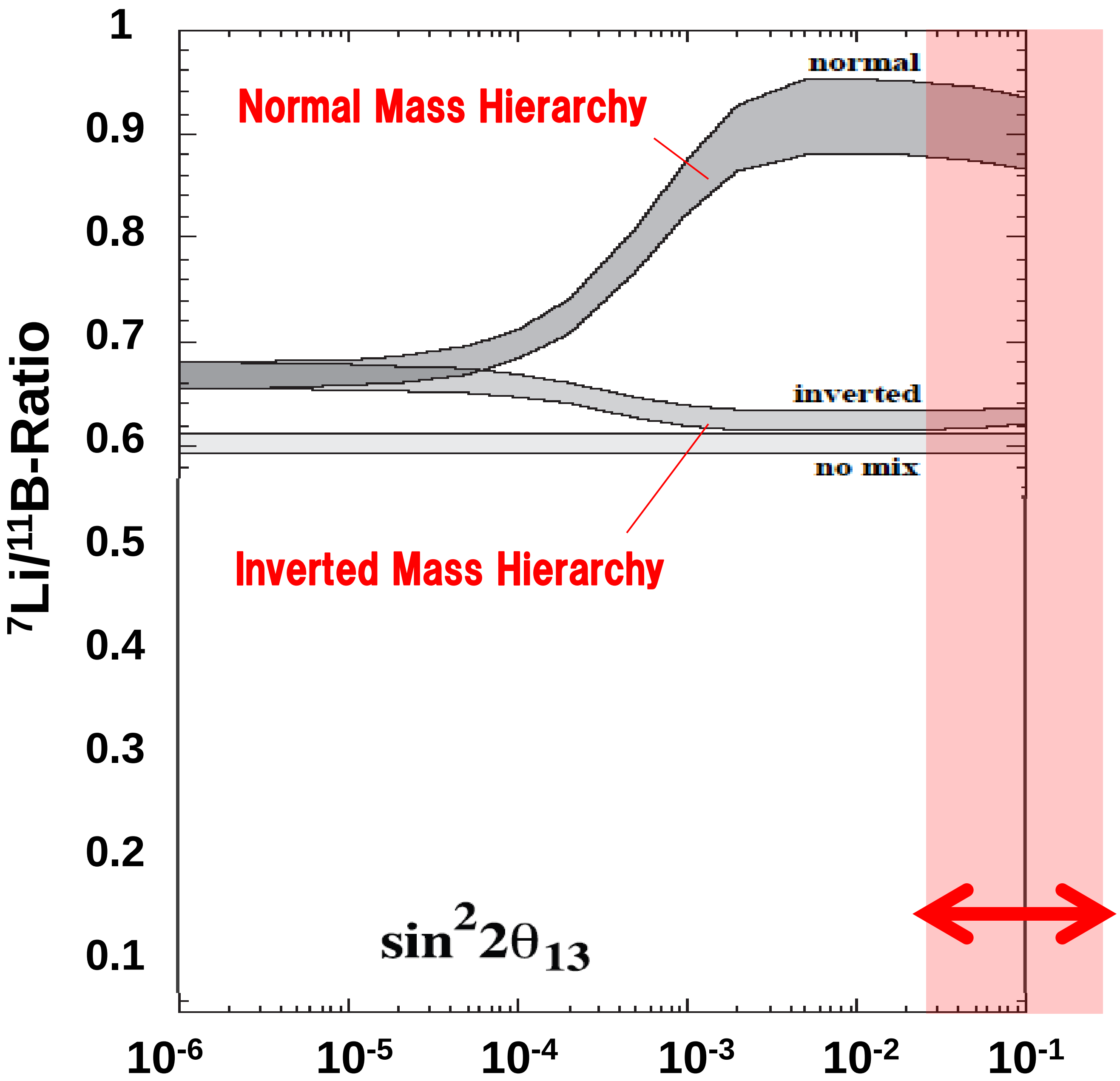


Yoshida, Kajino, Yokomakura, Kimura, Takamura & Hartmann,
PRL 96 (2006) 09110; ApJ 649 (2006), 349.



# MSW Effect & ν Mass Hierarchy




Yoshida, Kajino et al .
2005, PRL94, 231101;
2006,PRL 96, 091101;
2006, ApJ 649, 319;
2008, ApJ 686, 448.

**Long BaselineExp. in 2011:**

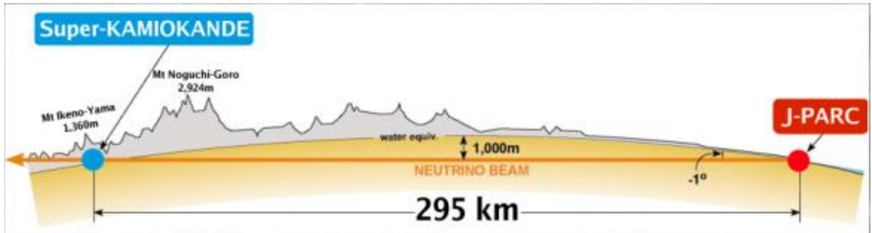
- T2K (Kamioka)
- MINOS

**Reactor Exp. in2012:**

- Double CHOOZ
- Daya Bay
- RENO (KOREA)

$\sin^2 2\theta_{13} = 0.1$

# Long Baseline ν — T2K & MINOS (2011)




**$\sin^2 2\theta_{13} = 0.1$**

Daya Bay 2012 $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

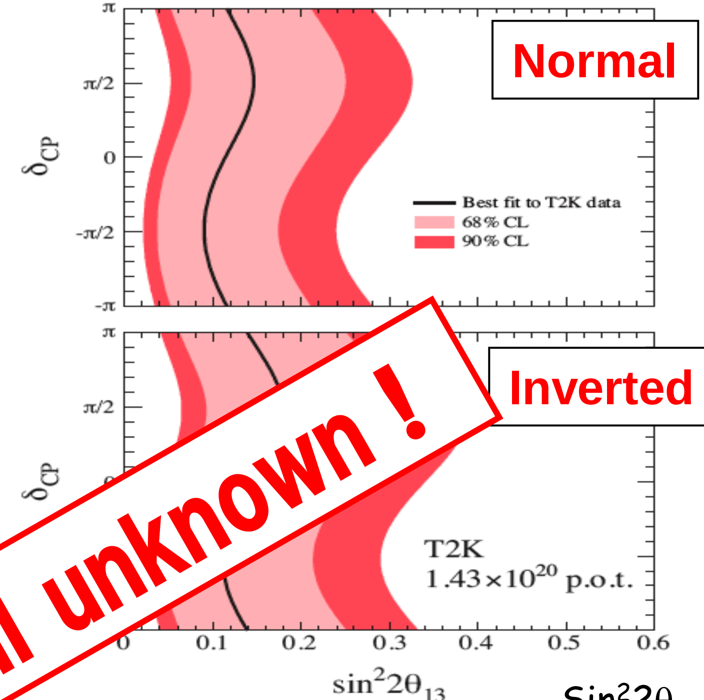
Rino (2012) $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.01$

Double Chooz (2012) $\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}$

Minos (2011) $\sin^2 2\theta_{13} < 0.12(0.20$

T2K (2012) $0.03(0.04) <$ … $(0.34)$

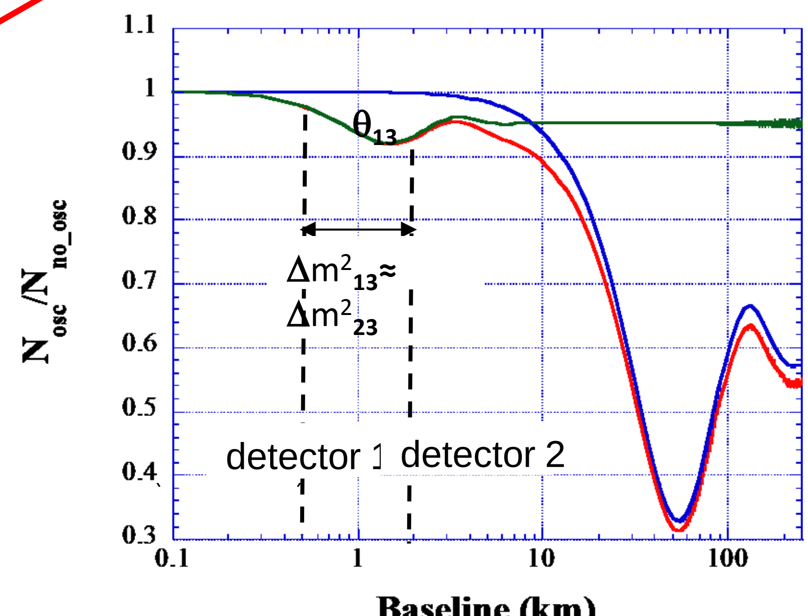
**Mass hierarchy is still unknown !**



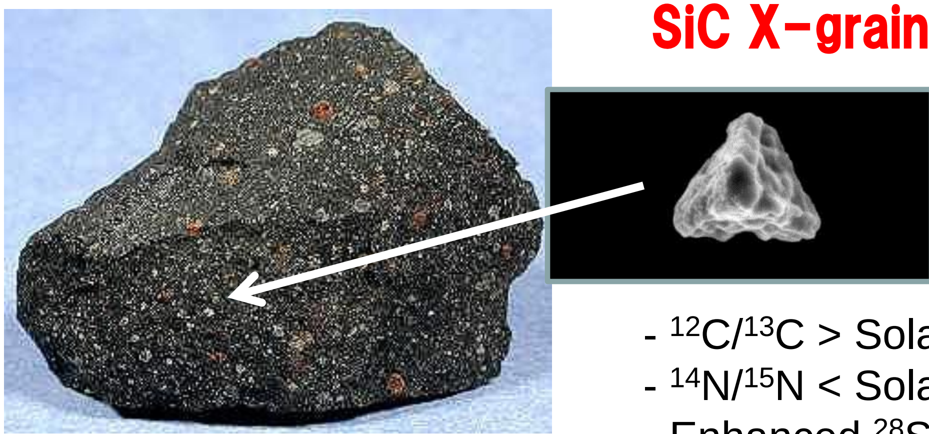

$\sin^2 2\theta_{23}=1$

# Reactor ν — … Bay & … Chooz (2012)

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

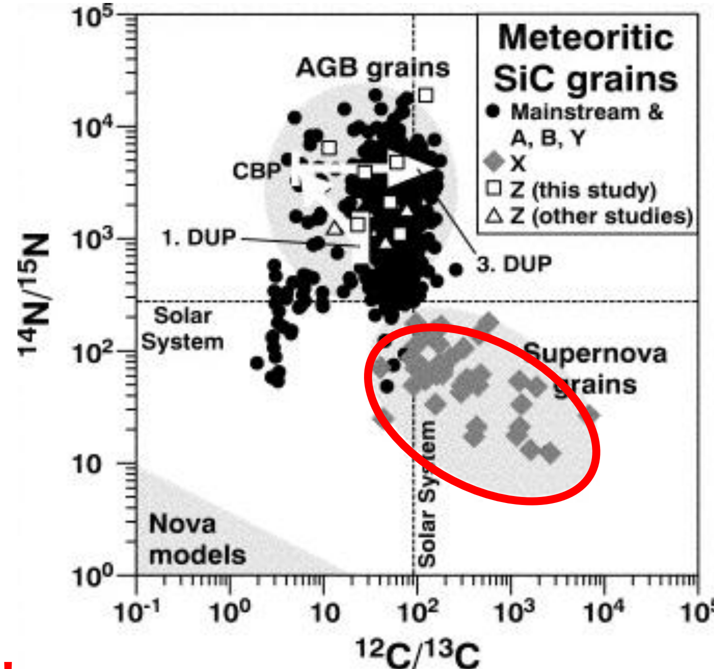


# Murchison Meteorite



## SiC X-grains

- $^{12}C/^{13}C$ > Solar
- $^{14}N/^{15}N$ < Solar
- Enhanced $^{28}Si$
- Decay of $^{26}Al$ ($t_{1/2}$=7x10$^5$yr), $^{44}Ti$ ($t_{1/2}$=60yr)



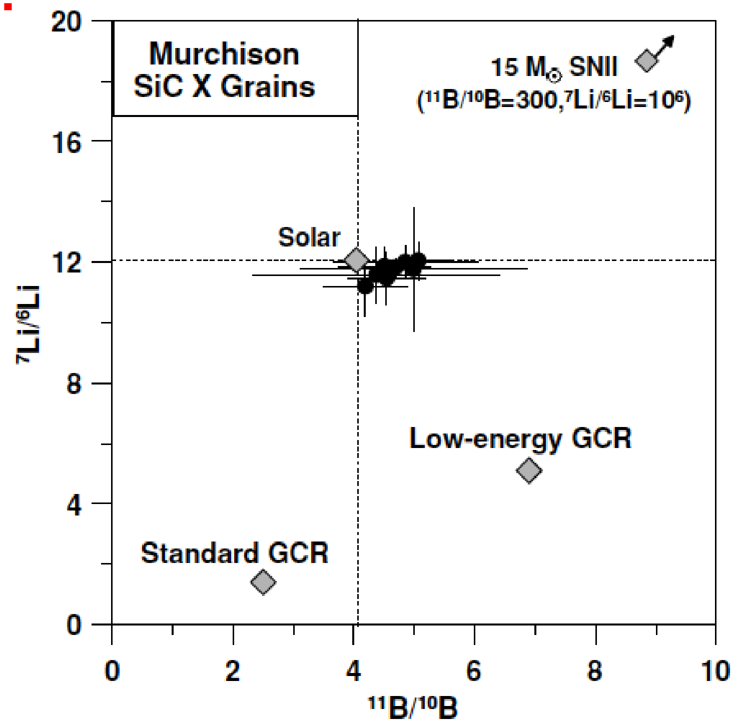

**SiC X-grains are made of Supernova Dust !**

**W. Fujiya, P. Hoppe, and U. Ott (2011, ApJ 730, L7) discovered $^{11}B$ and $^{7}Li$ isotopes in 13 SiC X-grains.**

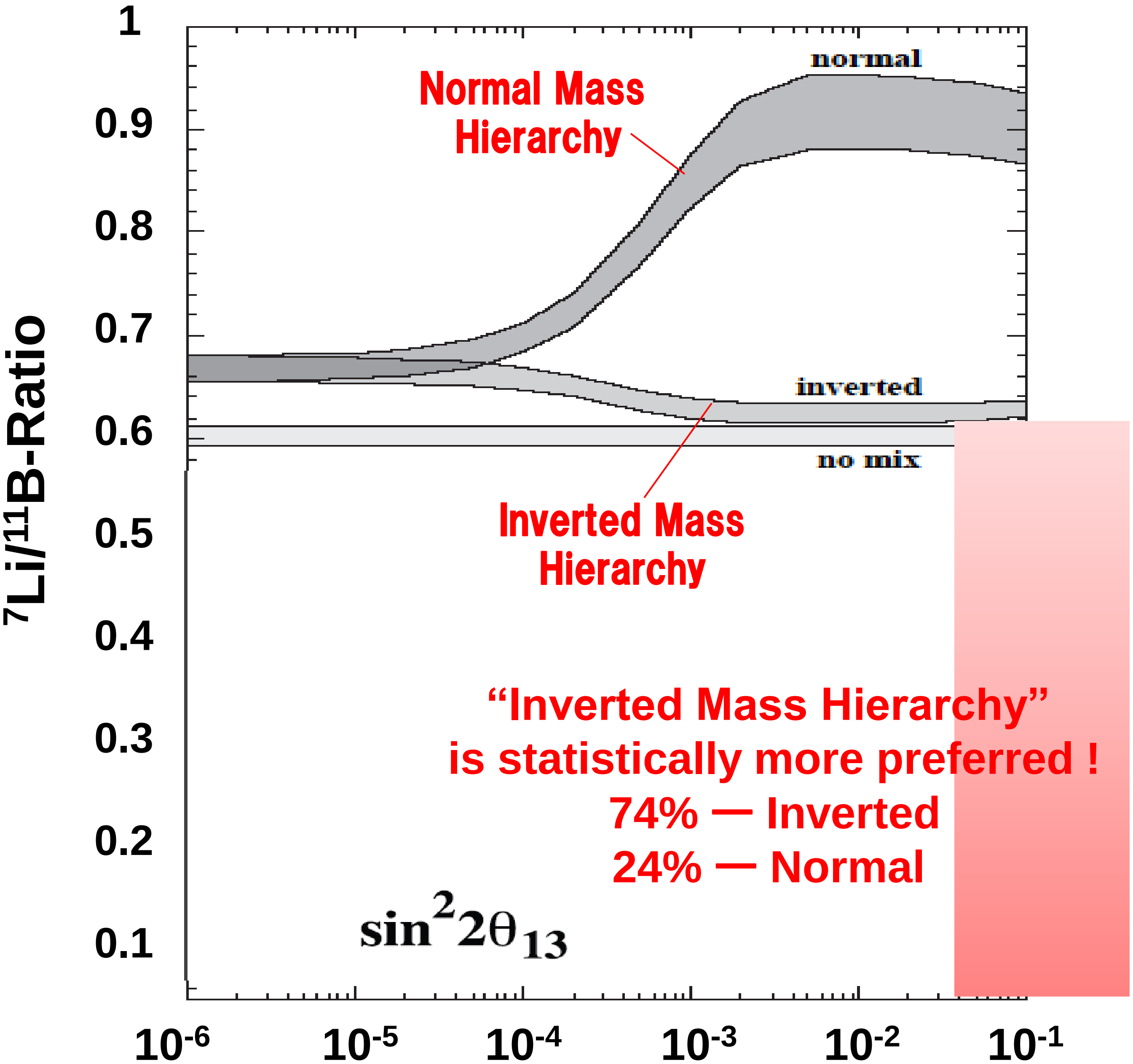
Table 1
C-, Si-, Li-, and B-isotopic Compositions of SiC X Grains from the Murchison Meteorite

| Grain | Size (μm) | $^{12}C/^{13}C$ | $\delta^{29}Si^a$ (‰) | $\delta^{30}Si^a$ (‰) | $^{7}Li/^{6}Li$ | $^{11}B/^{10}B$ | Li/Si ($10^{-5}$) | B/Si ($10^{-5}$) |
|---|---|---|---|---|---|---|---|---|
| Single X grains | | | | | | | | |
| X1 | 0.6 | 114 ± 2 | −178 ± 11 | −265 ± 9 | 11.87 ± 0.63 | 4.51 ± 0.77 | 9.69 | 3.33 |
| X2 | 1.2 | 128 ± 2 | −377 ± 11 | −261 ± 10 | 12.06 ± 0.62 | 5.06 ± 0.58 | 23.8 | 18.8 |
| X3 | 1.5 | 244 ± 5 | −205 ± 10 | −297 ± 7 | 11.48 ± 0.86 | 4.54 ± 0.63 | 1.76 | 1.92 |
| X4 | 1.0 | 241 ± 6 | −556 ± 10 | −245 ± 9 | 12.00 ± 0.56 | 4.85 ± 1.19 | 24.8 | 3.31 |
| X9 | 0.6 | 38 ± 1 | −361 ± 10 | −394 ± 8 | 11.20 ± 1.01 | 4.19 ± 0.70 | 10.8 | 11.4 |
| X11 | 0.8 | 326 ± 14 | −358 ± 12 | −432 ± 11 | 11.78 ± 2.03 | 4.99 ± 1.88 | 3.66 | 3.00 |
| X13 | 0.7 | 345 ± 6 | −261 ± 10 | −424 ± 7 | 11.59 ± 0.93 | 4.37 ± 2.04 | 10.7 | 1.14 |
| Average | | | | | 11.83 ± 0.29 | 4.68 ± 0.31 | | |
| X grains + other nearby/attached SiC grains | | | | | | | | |
| X5 | | 34 ± 1 | −226 ± 11 | −120 ± 10 | 12.21 ± 0.41 | 4.36 ± 0.40 | 40.2 | 18.8 |
| X6 | | 88 ± 1 | −236 ± 11 | −189 ± 9 | 13.06 ± 1.36 | 3.83 ± 0.27 | 2.15 | 14.2 |
| X7 | | 78 ± 1 | −281 ± 11 | −208 ± 10 | 11.20 ± 2.40 | 11.47 ± 6.36 | 8.28 | 9.48 |
| X8 | | 76 ± 1 | −223 ± 10 | −266 ± 8 | 11.29 ± 0.64 | 4.27 ± 0.29 | 4.80 | 12.4 |
| X12 | | 83 ± 1 | −271 ± 11 | −242 ± 10 | 11.54 ± 0.52 | 4.13 ± 0.46 | 24.3 | 14.2 |
| Average | | | | | 11.90 ± 0.28 | 4.16 ± 0.17 | | |
| Solar | | 89 | 0 | 0 | 12.06 | 4.03 | 5.6 | 1.9 |

**Note.** $^a\delta^iSi = [(^iSi/^{28}Si)/(^iSi/^{28}Si)_{\odot} - 1] \times 1000$.



# Supernova X-Grain Coinstraint

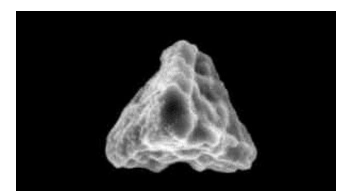



**Mathews, Kajino, Aoki And Fujiya, Phys. Rev. D85,105023 (2012).**

- T2K, MINOS (2011)
- Double CHOOZ, Daya Bay, RENO (2012)

**$\sin^2 2\theta_{13} = 0.1$**

First Detection of $^{7}Li/^{11}B$ in SN-grains



W. Fujiya, P. Hoppe, & U. Ott, ApJ 730, L7 (2011).

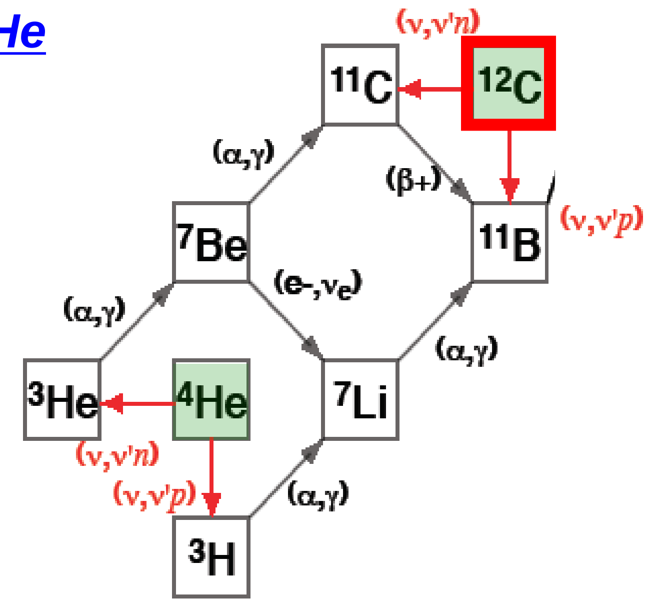
# 超新星元素合成に必要なν原子核反応率の理論計算

## New Shell Model cal. with NEW Hamiltonian: *ν-$^{12}$C, $^{4}$He*

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307.
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003)

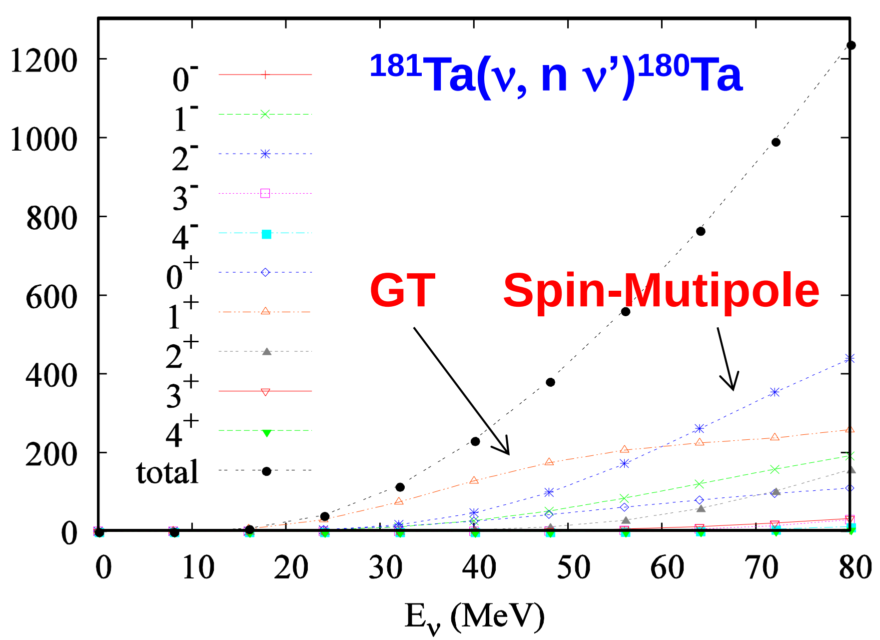
**$^{12}$C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.**

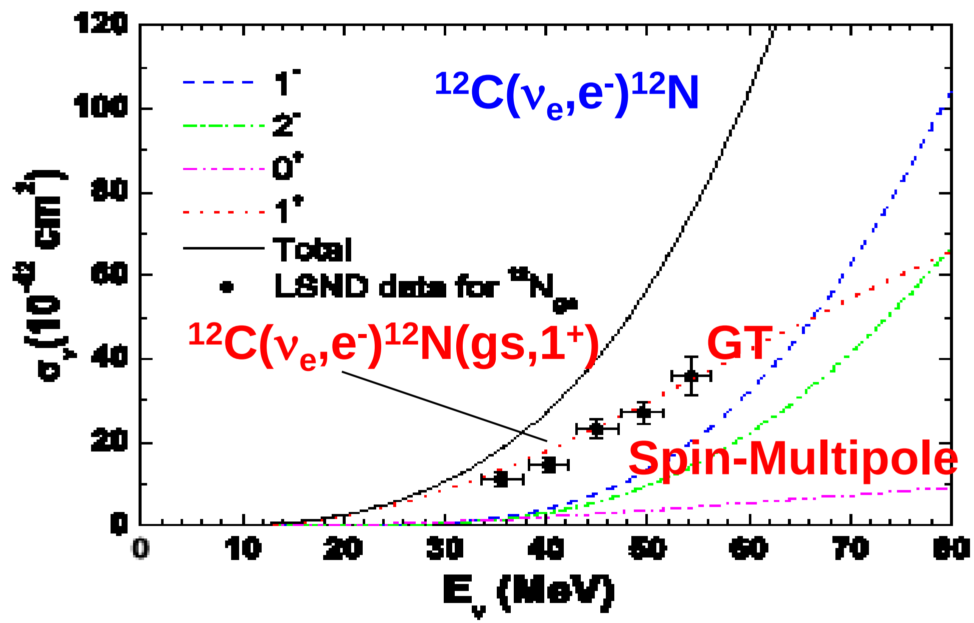
- μ-moments of p-shell nuclei
- GT strength for $^{12}C \rightarrow {}^{12}N$, $^{14}C \rightarrow {}^{14}N$, etc. (GT)
- DAR (ν,ν'), (ν,e-) cross sections




## QRPA cal.: *ν-$^{180}$Ta, $^{138}$La, $^{98}$Tc, $^{92}$Nb, $^{42}$Ca, $^{12}$C, $^{4}$He…*

Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504: J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801



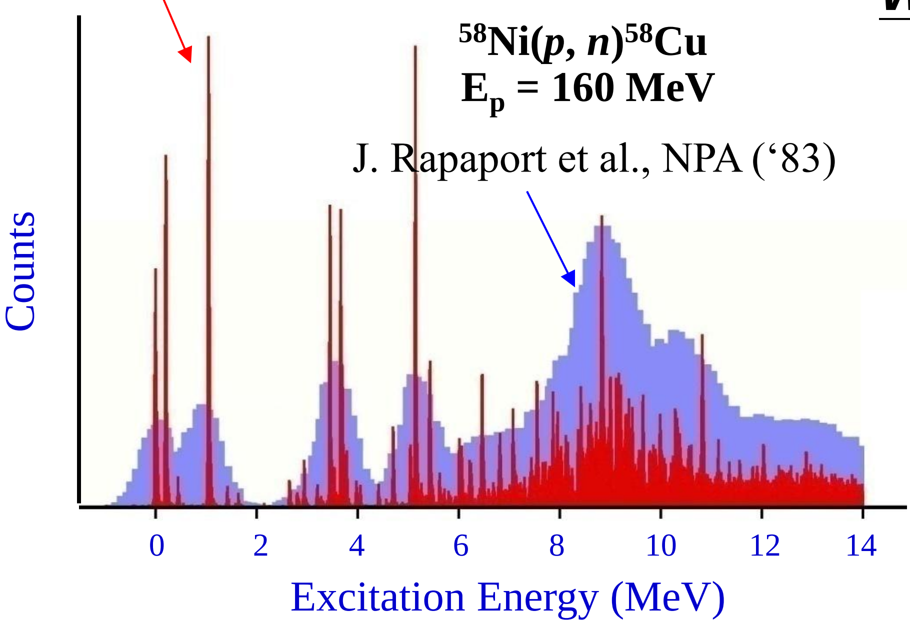



- **ν-beam is not yet available !**
- **EM-PROBE (CEX hadrons, γ's) !**

# Similarity between Electro-Magnetic & Weak Interactions

**$^{58}$Ni($^{3}$He, *t*)$^{58}$Cu**
**E = 140 MeV/u**

Y. Fujita et al., EPJ A 13 ('02) 411.
Y. Fujita et al., PRC 75 ('07)




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

**★ Charge-Exchange Reaction**

**★ Photo-induced Reaction**

# Double β decay – ν mass – Astro-Cosmology Connection

K. Yako et al., PRL 103 (2009) 012503.

## B(GT$^{+/-}$) distribution

Shell model …

with quenched operator

Spectra agree qualitatively up to …

(p,n) : $E_x$ = 15 MeV

(n,p) : 8 MeV

Strengths beyond … underestimated.

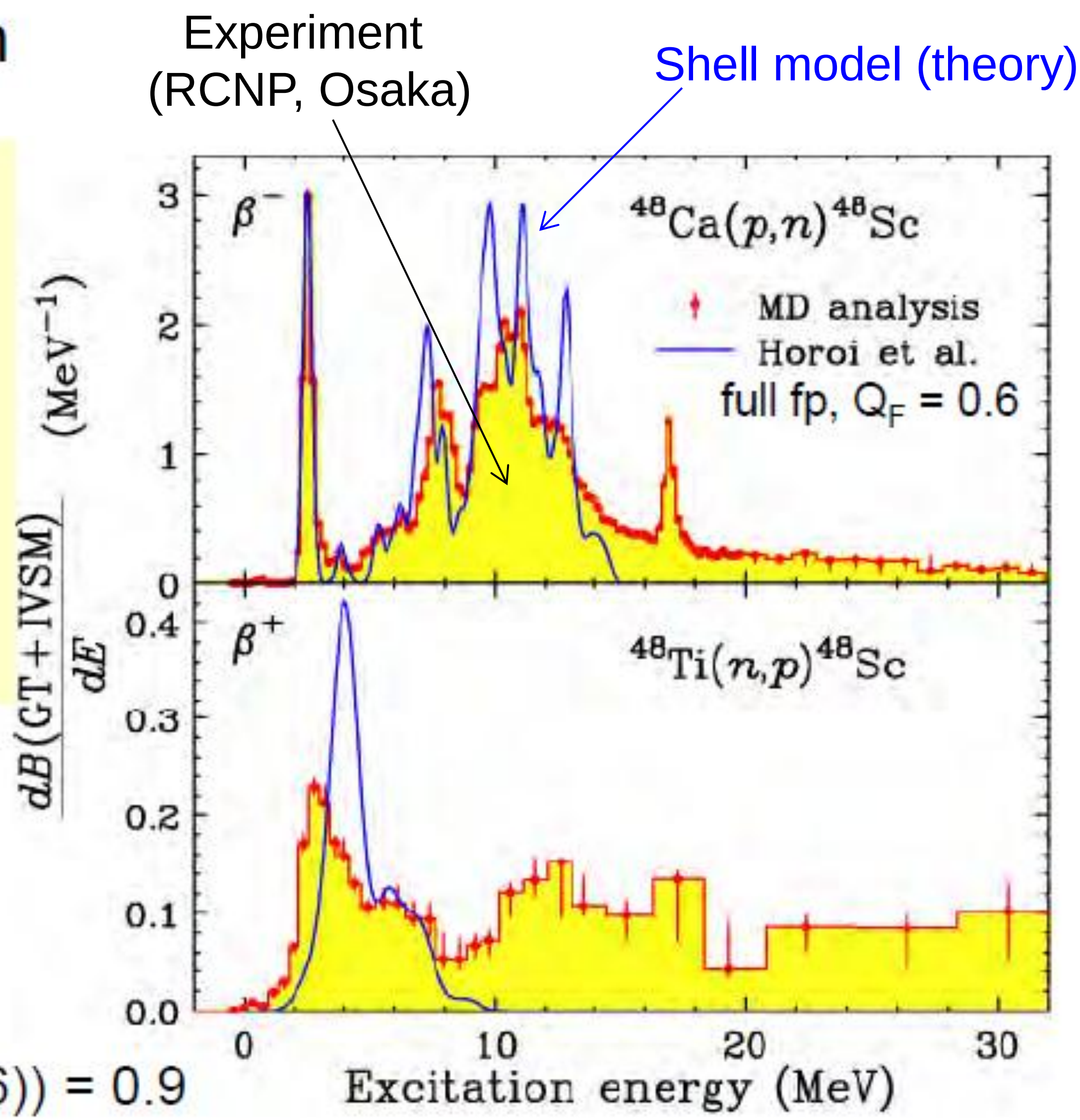
(n,p) channel :

ΣB(GT$^+$;exp) = 1.9±0.3…

(w subtraction of IVSM)

⬍

ΣB(GT$^+$;ShellModel($Q_F$=0.6)) = 0.9



# *Nuclear Astrophysics Programs of Photo-Induced and Charge-Exchange Reactions for the Studies of Element Genesis*

**The developed HI & RIB technique**
**+ Intense RI-Beam at RIKEN**
**+ High Precision Spectrometer at RCNP**

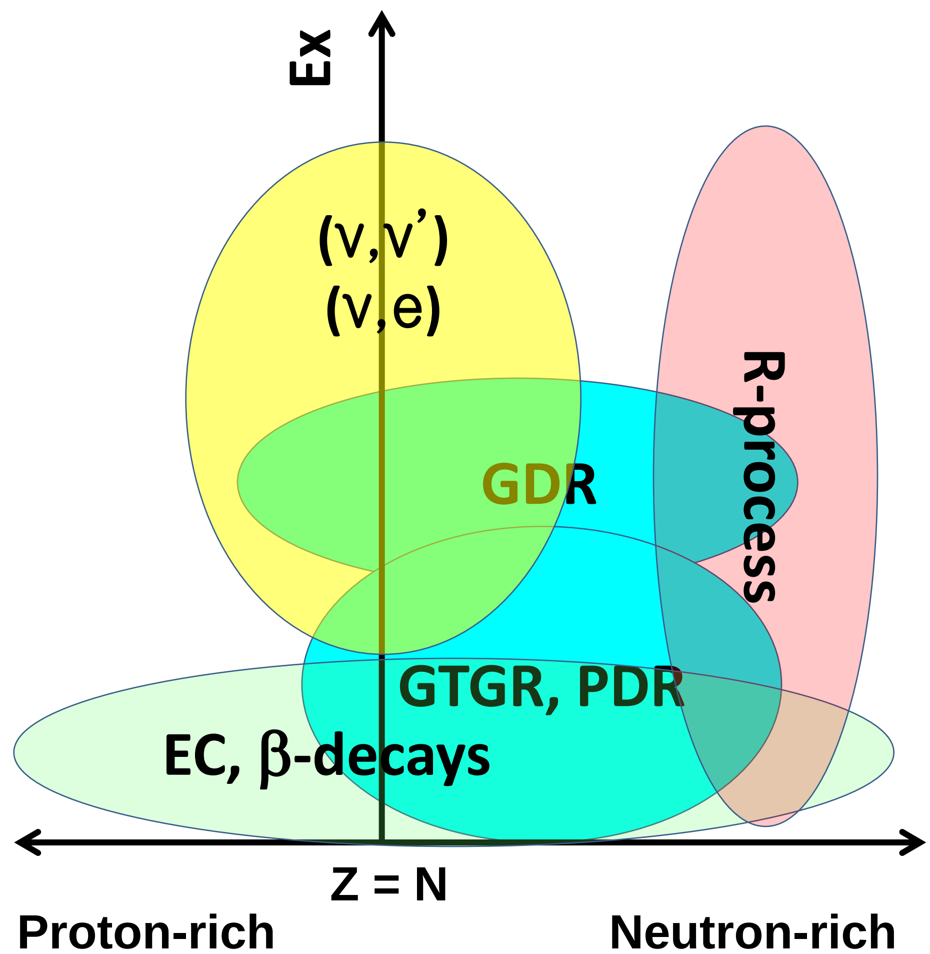
**Probe any Energy on wide N-Z (Isospin)**

**Understanding of nuclear weak response in astrophysical processes**

→ **R-process (GT + first forbidden)**
- SN explosion mechanism
- Th-U synthesis & cosmochronology

→ **Neutral & Charged currents**
- LiBeB synthesis & ν-oscillation
- Fe-Mn synthesis in 1st generations of star
- La, Ta, Nb synthesis & cosmic clock

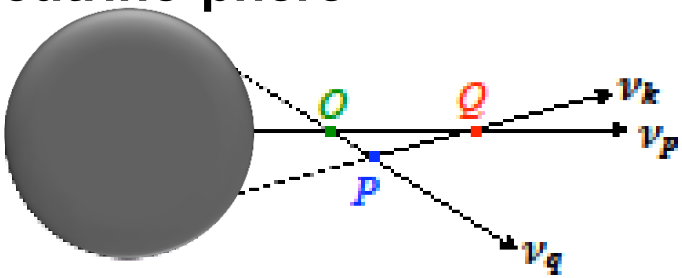
→ **EC/beta-decays**
- SN II, SN Ia, X-ray bursts




Sasano @ Uesaka Spin-Isospin Labo., RIKEN

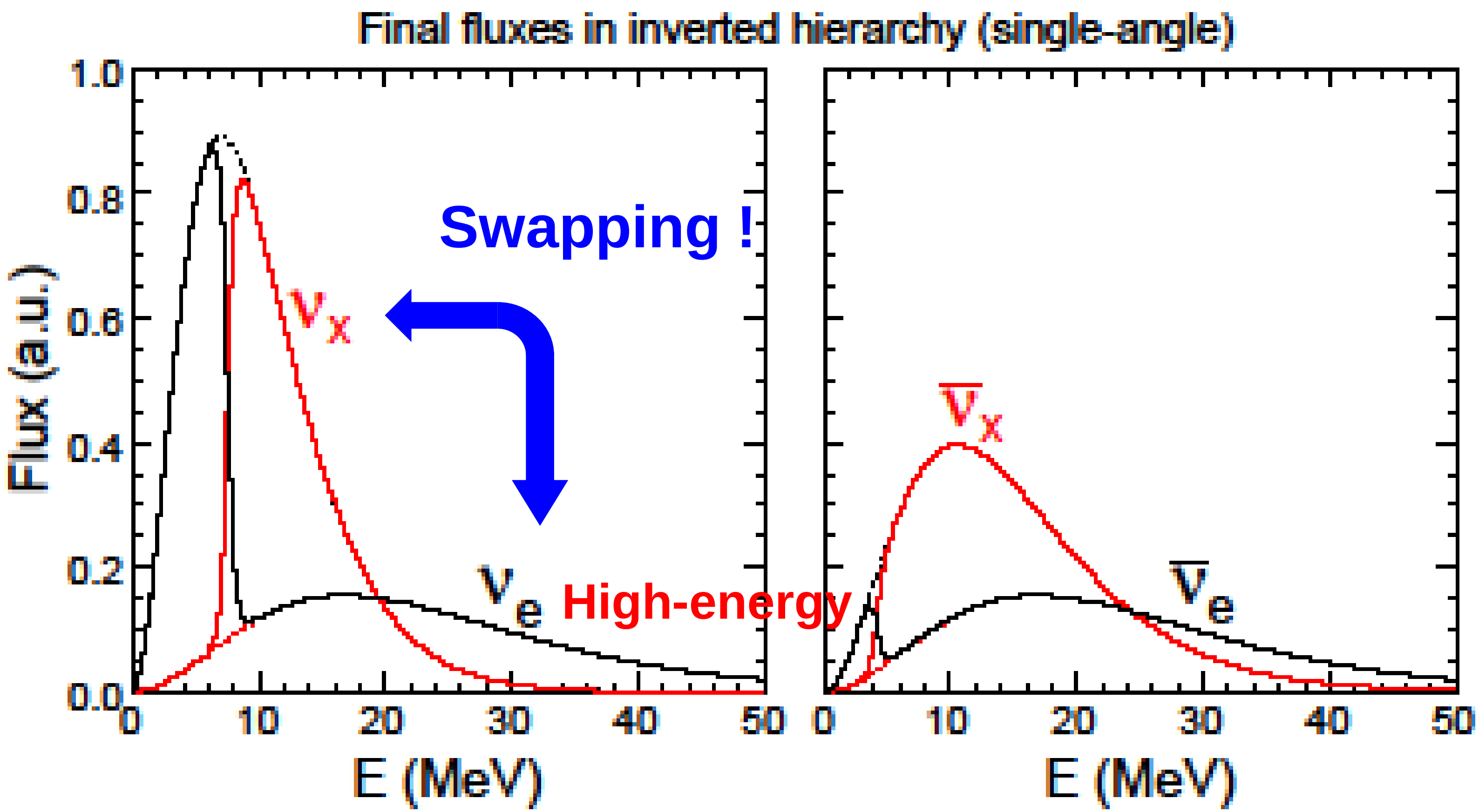
# ν self-interaction (Quantum Effect)

neutrino-phere




H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, PRL 97 (2006), 241101.
G. Fogli, E. Lisi, A. Marrone, & A. Mirizzi, JCAP 12, (2007) 010.
A. B. Balantekin, Y. Pehlivan, J. Phys.G34, (2007) 47.

r = 200km

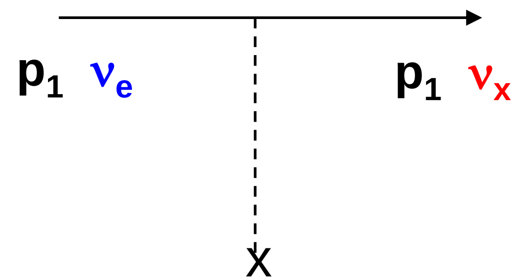


# Neutrino Hamiltonian: $H_{tot} = H_\nu + H_{\nu\nu}$

## $H_\nu$ = Mixing and Interaction with Background Electrons

**MSW (Matter) Effect: Mikeheev-Smirnov-Wolfebstein (1978, 1985)**

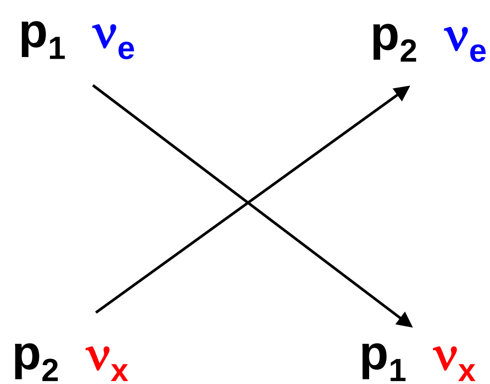
$$H_\nu = \frac{1}{2}\int d^3p \left(\frac{\delta m^2}{2p}\cos 2\theta - \sqrt{2}G_F N_e\right)\left(a_x^\dagger(p)a_x(p) - a_e^\dagger(p)a_e(p)\right)$$
$$+\frac{1}{2}\int d^3p \frac{\delta m^2}{2p}\sin 2\theta\left(a_x^\dagger(p)a_e(p) + a_e^\dagger(p)a_x(p)\right).$$




$N_e$ = electron density

## $H_{\nu\nu}$ = Self-Interaction

**Self-Interaction**




$$H_{\nu\nu} = \frac{G_F}{\sqrt{2}V}\int d^3p\, d^3q\, R_{pq}\left[a_e^\dagger(p)a_e(p)a_e^\dagger(q)a_e(q) + a_x^\dagger(p)a_x(p)a_x^\dagger(q)a_x(q)\right.$$
$$\left. + a_x^\dagger(p)a_e(p)a_e^\dagger(q)a_x(q) + a_e^\dagger(p)a_x(p)a_x^\dagger(q)a_e(q)\right],$$

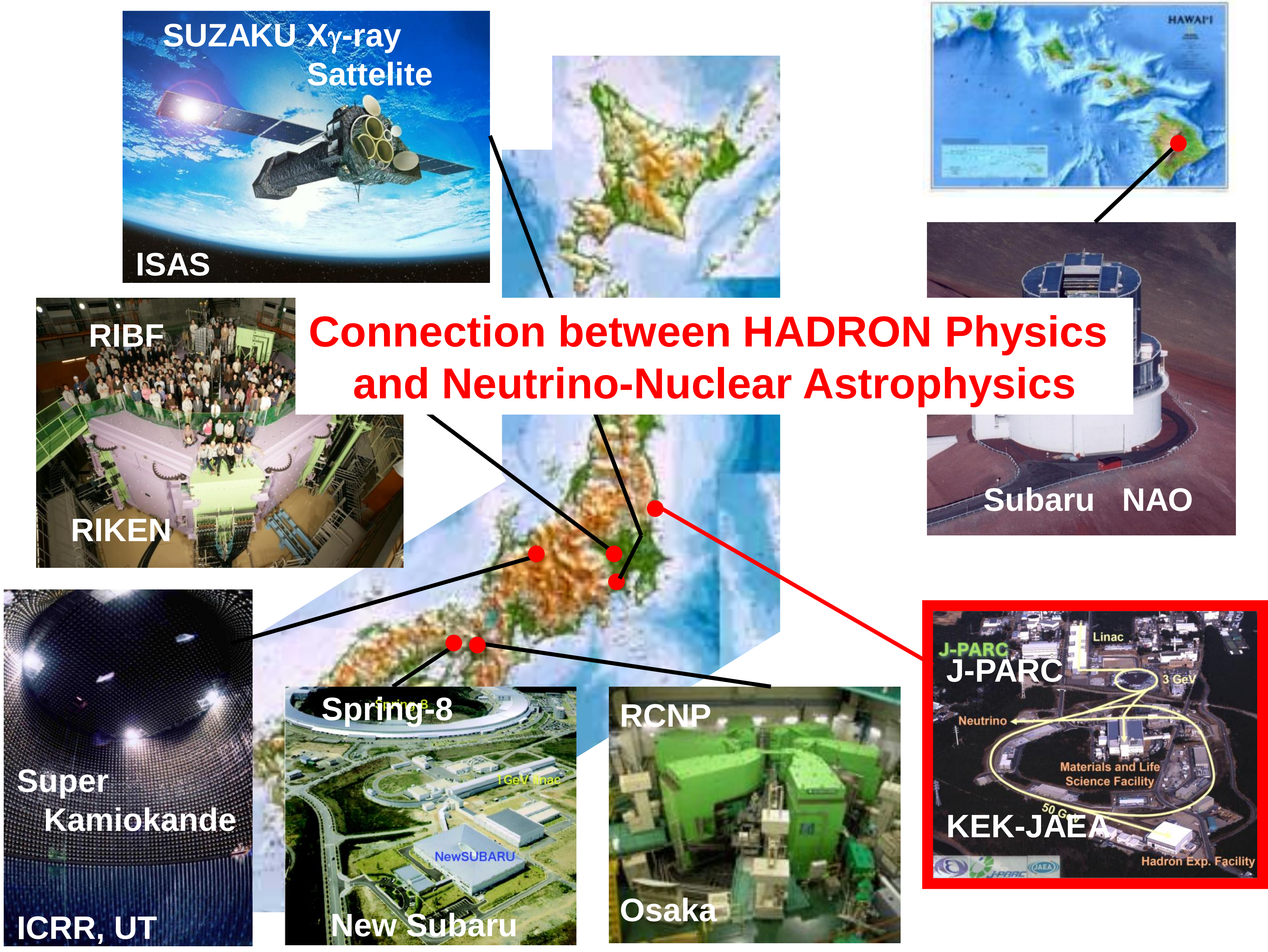
**Quest for EXACT Many-Body SOLUTION !**

"Invariants of collective neutrino oscillations"

Y. Pehlivan, A.B. Balantekin, T. Kajino & T. Yoshida

Phys. Rev. D84, 065008 (2011)

# Connection between HADRON Physics and Neutrino-Nuclear Astrophysics



# SUMMARY

## $\nu$-Mass hierarchy:

- We proposed a new nucleosynthetic method to estimate average $\nu$-spectra from core-collapse supernovae: $T(\nu_e)$ = 3.2MeV, $T(\overline{\nu_e})$ = 4.0MeV, $T(\nu_x)$ = 6.0MeV.
- $^7$Li/$^{11}$B isotopic ratios of SiC X-grains (SN-grains) enriched in $\nu$-process materials have the potential to solve the mass hierarchy for finite $\theta_{13}$. Inverted hierarchy is more preferred statistically.

## Total $\nu$-mass:

- Curvature perturbation is shown to be generated by the extra anisotropic stress $\pi_{ext}$ without tuning the initial condition of inflation-driven (pre-Big-Bang) perturbation. This would constrain the generation epoch and the nature of primordial (unknown) $\pi_{ext}$.
- Total $\nu$-mass is constrained to be $\Sigma\, m_\nu < 0.2$ eV from the MCMC analysis of CMB temperature and polarization anisotropies including the primordial magnetic field.