

新学術領域「素・核・宇宙の融合」第2回研究会  
「クオーク力学・原子核構造に基づく爆発的天体现象と元素合成」  
2010年5月31日～6月1日 東京大学理学部天文教室

# 長寿命アイソマーと 核構造、超新星ニュートリノ過程

梶野敏貴(NAO／UT)

吉田 敬, 中村 航, 茂山和俊, 野本憲一, 梅田秀之, 岩本信之 +

H.横枕、K.木村、A.高村 +

早川岳人、鈴木俊夫、大塚孝治 +

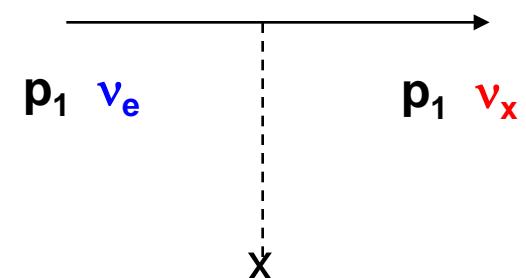
D.H. Hartmann, G.J. Mathews, M.K. Cheoun +

# Neutrino Hamiltonian

$$H_{tot} = H_\nu + H_{\nu\nu}$$

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

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



MSW (Matter) Effect

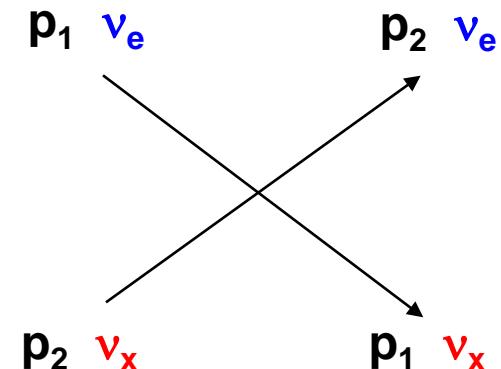
Mikeheev-Smirnov-Wolfeinstein (1978, 1985)

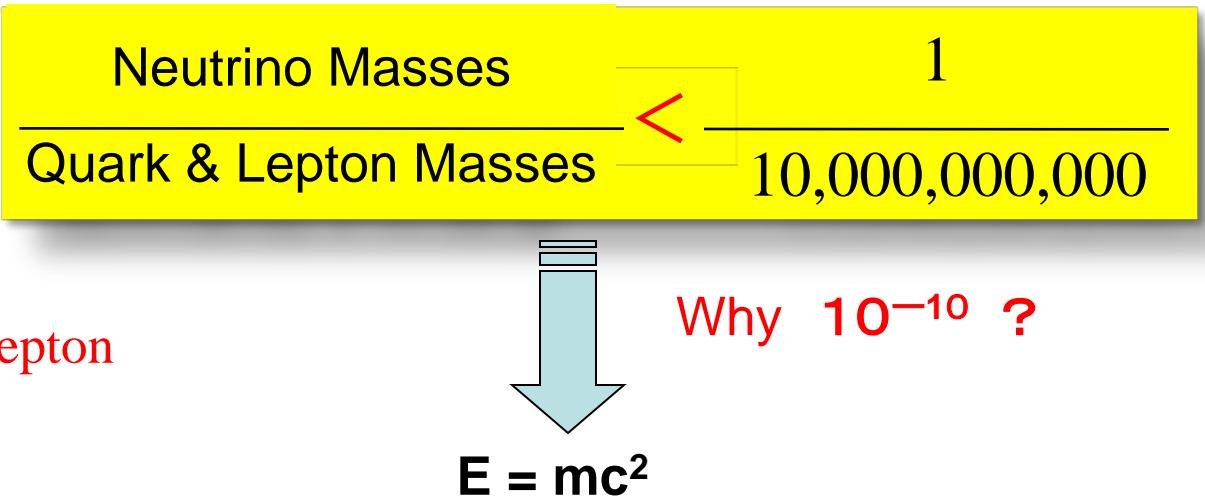
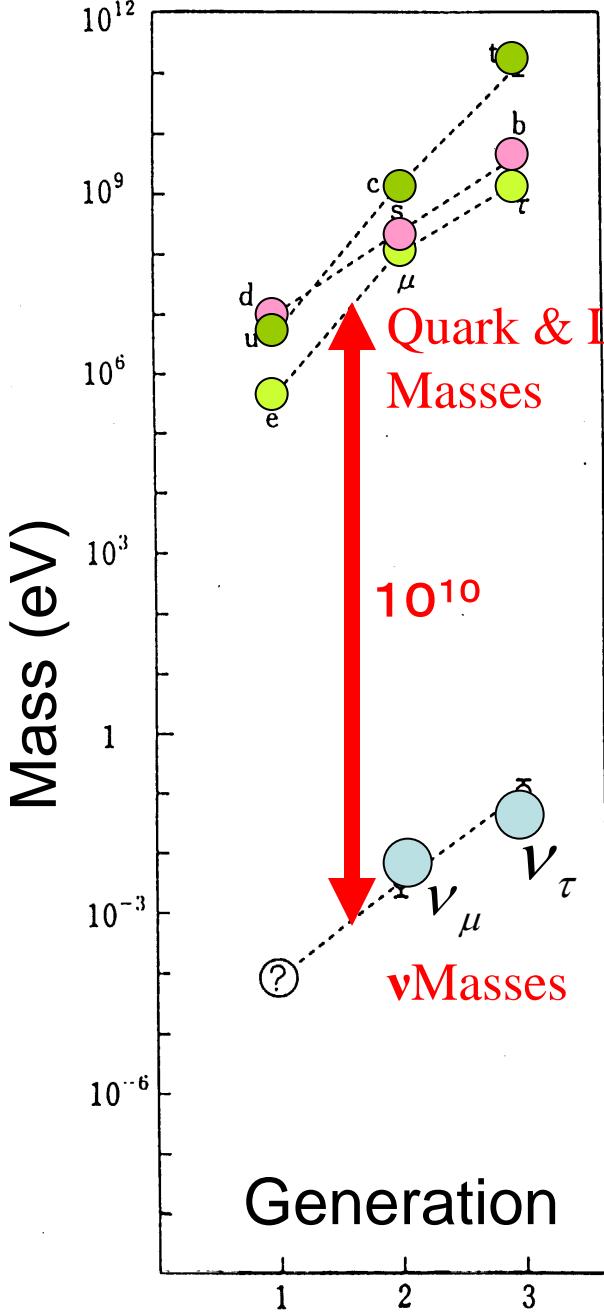
$N_e$  = electron density

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

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

Exact solution, still UNKNOWN !





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



Key Physics suggested by FINITE mass neutrinos

Unification of forces in the early Universe ?

CP violation and Lepto-baryogenesis ?

Majorana or Dirac ?

Difference of mixing angles between q's and v's ?

# Neutrino, Majorana or Dirac?

★ Oscillation → “Mass Hierarchy” !

★ We have only  $\nu_L$  &  $\bar{\nu}_R$  without  $\nu_R$  &  $\bar{\nu}_L$  !

Dirac mass term:

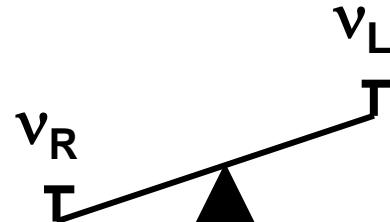
$$\mathcal{L}_D = -m_D \overline{\nu}_R^0 \nu_L^0 + \text{h. c.}$$

Majorana mass term:

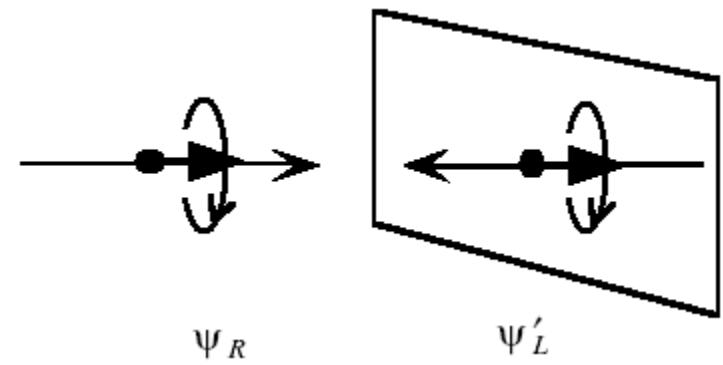
$$\mathcal{L}_{m_L} = -\frac{m_L}{2} (\overline{\nu}_L^0)^c \nu_L^0 + \text{h. c.}$$

- Neutral particle
- $m(\nu_L) \neq m(\nu_R)$
- Only light  $\nu_L$  exists,  $\nu_R$  be massive

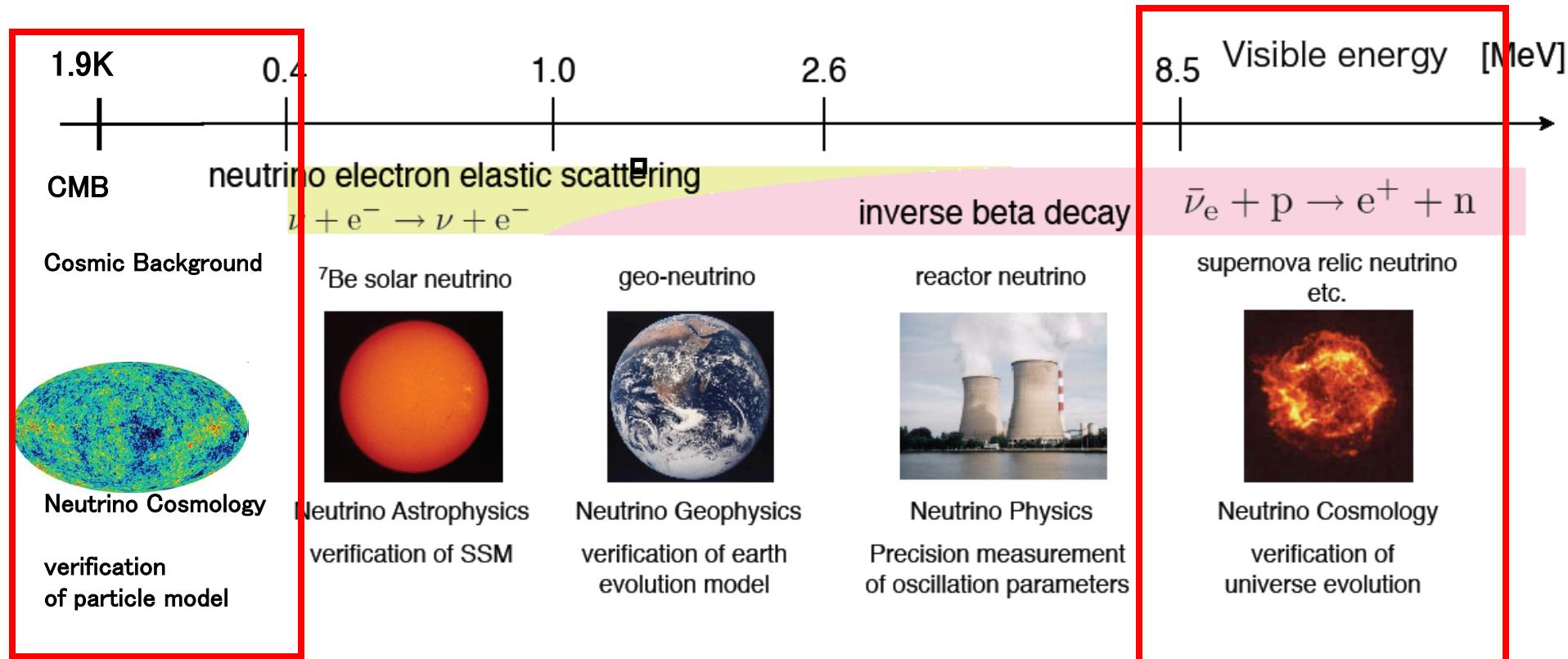
See-saw (Yanagida 1979)



Special Relativity  
Helicity flip  $\Leftrightarrow$  mass



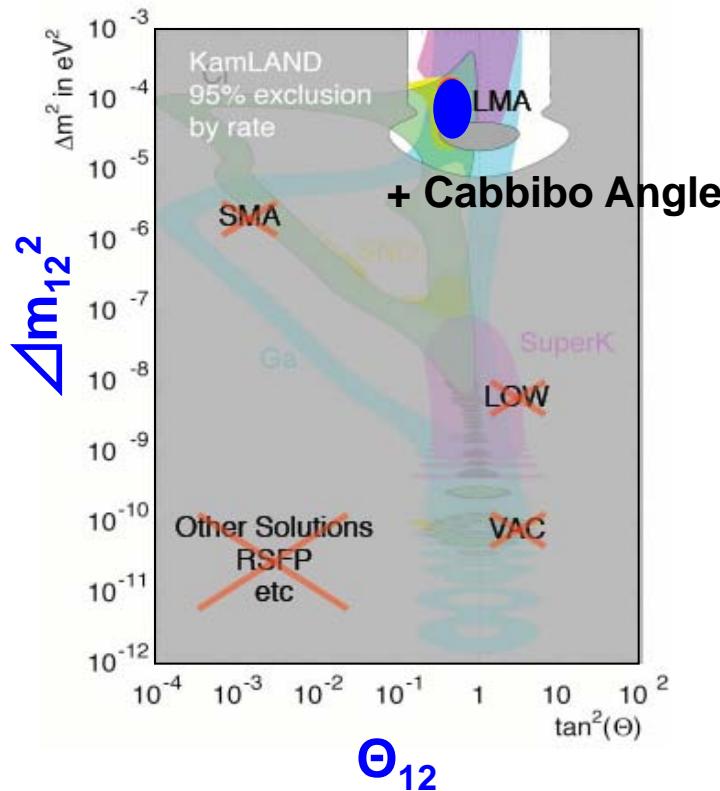
# Various Physics Targets with wide energy range



**How to know/determine, in astro-particle physics method,  
unknown  $\nu$ -oscillation parameters  $\Sigma m_\nu$ ,  $\theta_{13}$ , and  $\Delta m_{13}^2$   
using "SN  $\nu$ -process nucleosynthesis" !**

# “KNOWN” Neutrinos

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



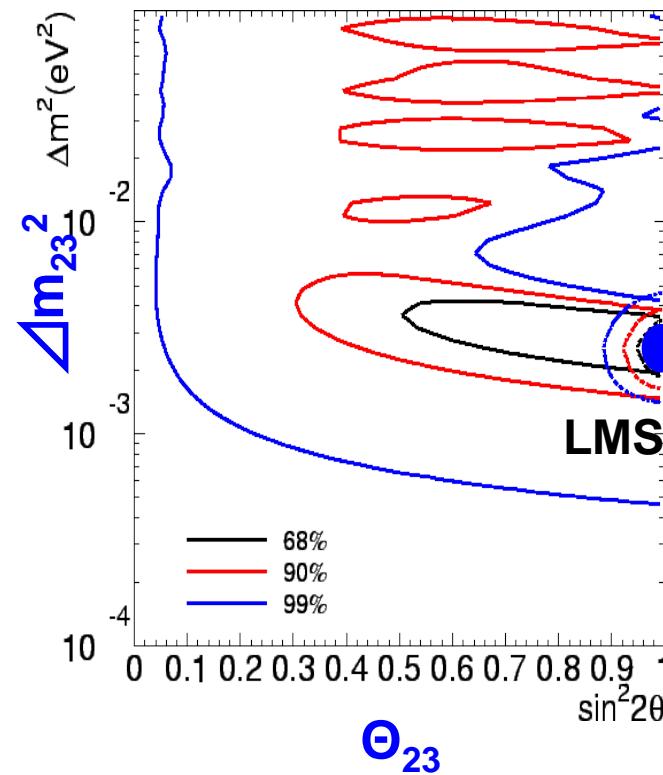
SN-neutrinos:  
Yokomakura et al.  
PL B544, 286

**“Several UNKNOWNs”**

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

~~(3) δ = CP phase,~~

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

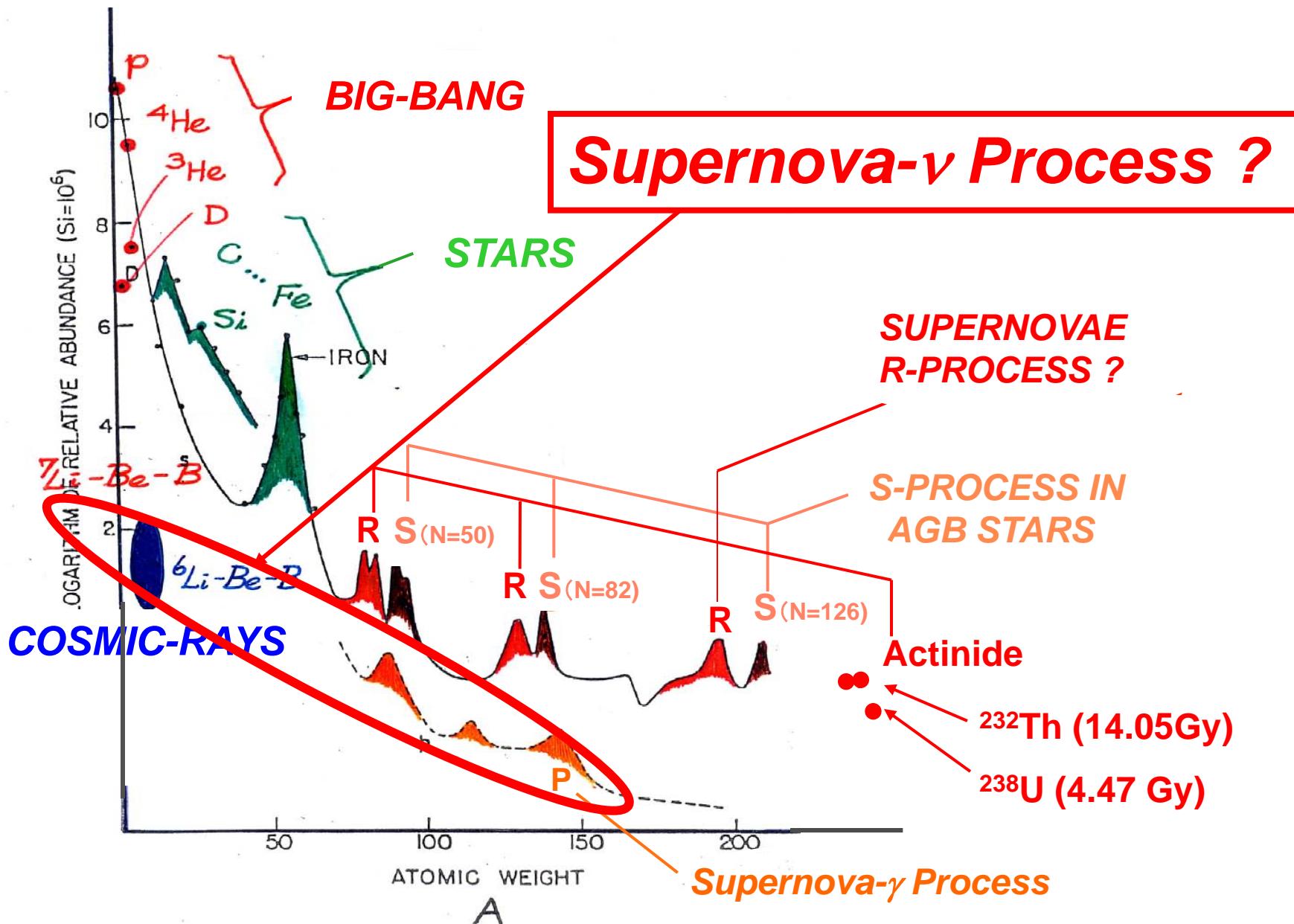


Yamazaki, Ichiki, Kajino,  
Mathews (2009,2010)

$$(2) |\Delta m_{13}^2| = 2.4 \times 10^{-3} \text{ eV}^2$$

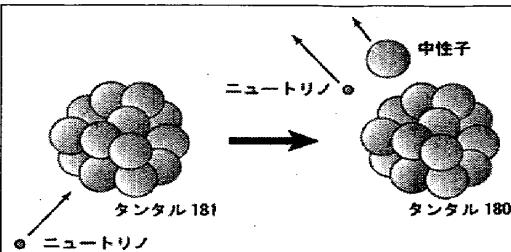
~~(4) Absolute Mass~~

# Solar System Abundance



太陽系で最も  
希少な同位体

# タンタル180



太陽系には約290種類の同位体がある。そのうち「タンタル180」の起源は、残された中性子による核反応によって生成したことを見出された。世界最大規模の三重県立天文台の研究グループによる観測の予想や、ニュートリノによる核反応によって生成したことを示す。この結果は、先行する世界各の研究者による計算と一致する。

原子力機構  
国立天文台  
記

超新星爆発の

科学新聞

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電話 03-3434-3741

FAX 03-3434-3745

mail:edit@sci-news.co.jp

振替 00170-8-33592

購読料 1ヶ月  
2,100円(消費税込)

## New estimate for the time-dependent thermal nucleosynthesis of Ta180<sup>m</sup>,

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

され、タンタル180が生成する。

「今後、より精密な計算」  
超新星爆発における電子型ニュートリノエネルギーは、これまでの反粒子のエネルギーをもとに、太陽系における推定で計算されたTa-180の推定量基底状態+核変異体によって得られる。

宇宙物理と原子核物理専門家の密接な協力によって問題が解決しました。計算の結果、超新星爆発度が十分に下がった時、核変異体が0・39生(全量を1として)するが分かった。このこと、既存の超新星爆発での

「テリ」元素生成理論は、理論研究を進め、「スーパーピーム応用研究部門」の櫻野台理論研究部の櫻野豊貴・准教授らの研究グループによる核反応で生成したことを見出された。世界最大規模の三重県立天文台の研究グループによる観測の予想や、ニュートリ

論的に解明

ンで生成

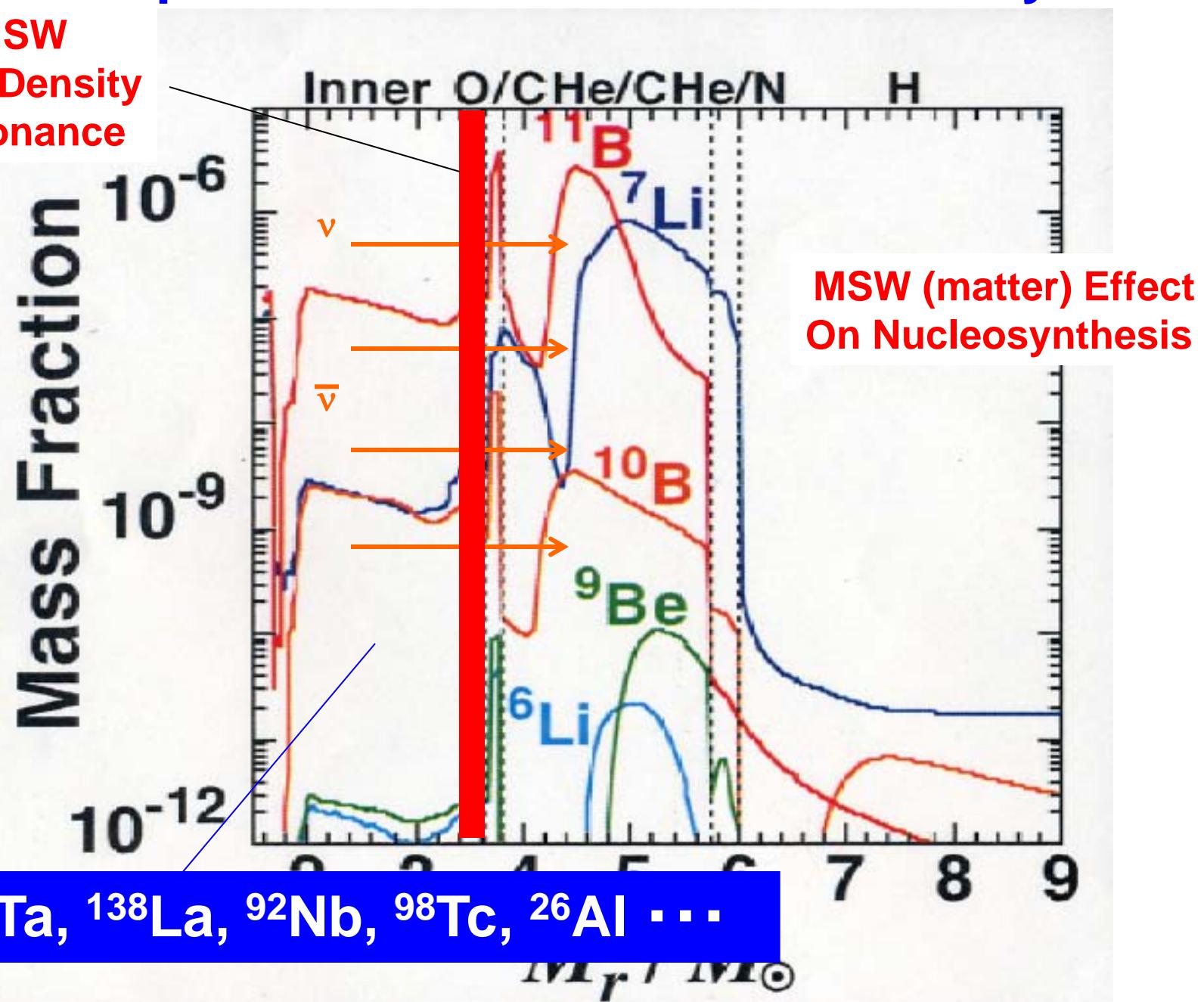
電波の日・情報  
通信月間特集 5面

科学新聞  
2010年5月28日(金)

# Type II Supernova $\nu$ -Process & Several Key Nuclei

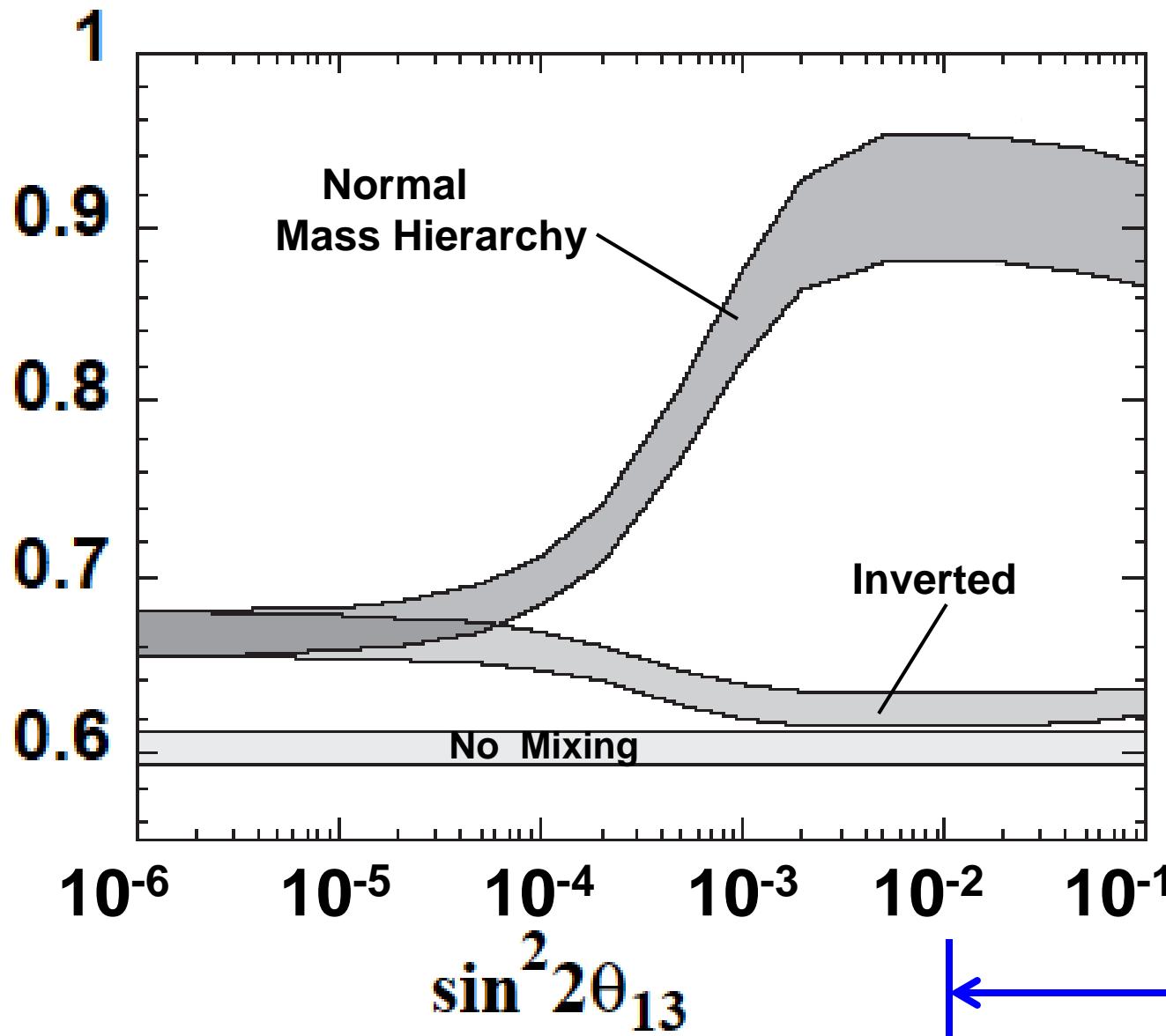
MSW

High-Density  
Resonance



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

# Hamiltonian Dependence of $\nu$ -A cross section?

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



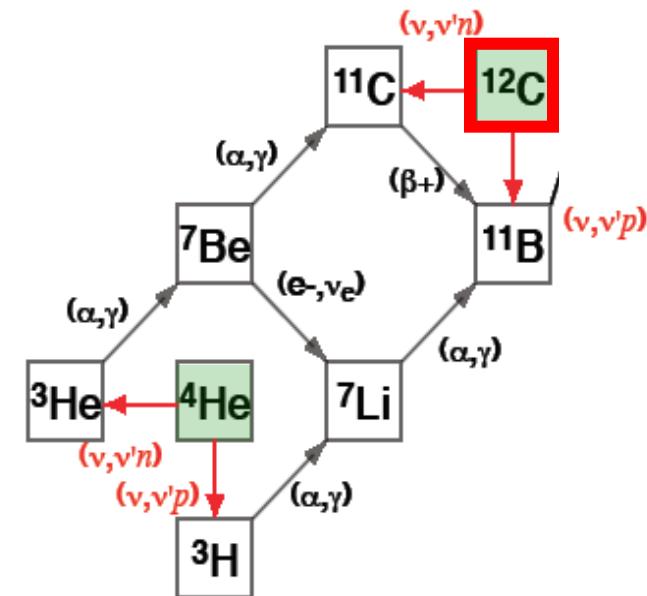
Suzuki's new SM cal. with NEW Hamiltonian

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

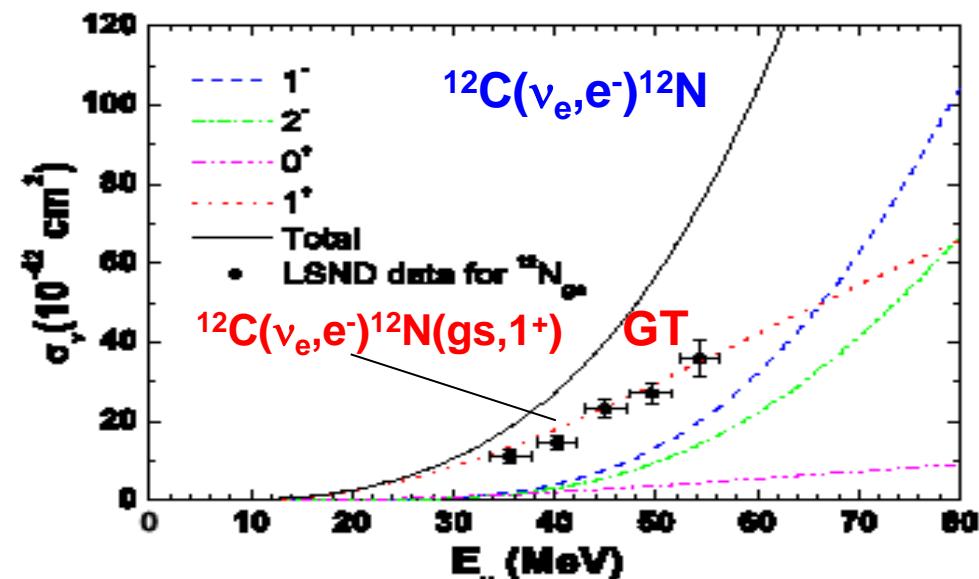
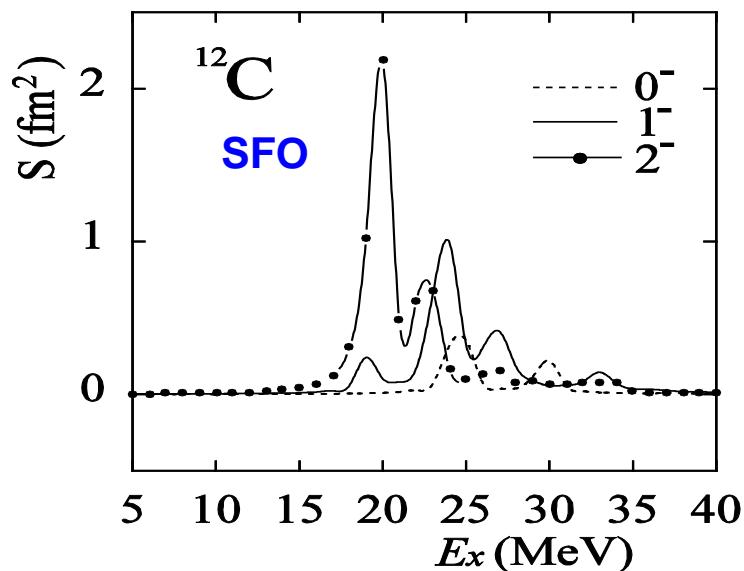
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003) → SFO

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

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



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



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



Suzuki's new SM cal. with NEW Hamiltonian

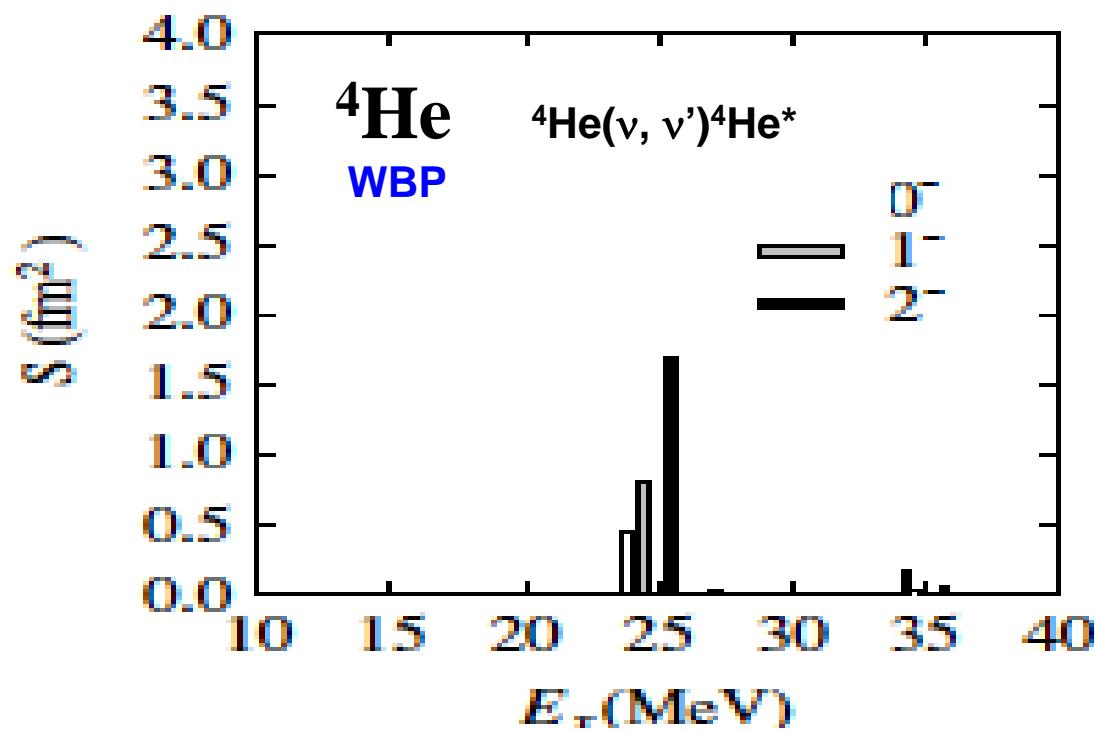
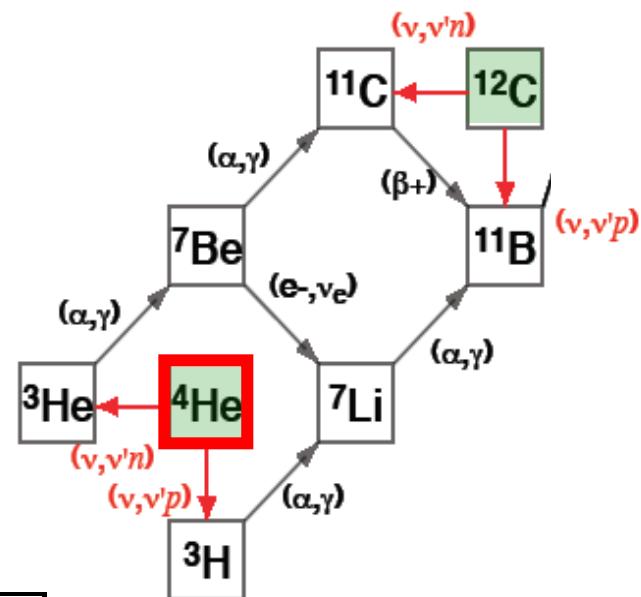
Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307.

Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005).

$^4\text{He}$ : WBP Hamiltonian

= Warburton & Brown, PRC 46 (1992), 923.

= Similar result to microscopic ab initio calculation of  
Gazit et al. PRC70 (2004) 048801.



★ No  $\nu$ -beam experiment yet for  $\nu$ -A X-section !  
 We can use Electro-Magnetic PROBE !

## Similarity between Electro-Magnetic & Weak Interactions

$$\begin{aligned} \text{EM-current} &= \vec{V}, \quad \text{Weak-current} = \vec{V} - \vec{A} \\ \vec{V} &\approx g_V^{IV} \frac{i}{2m} \vec{\sigma} \times \vec{q} + \frac{g_V}{2m} (\vec{p} + \vec{p}') \\ \vec{A} &\approx g_A \vec{\sigma} \end{aligned}$$

**Weak operator in non-relativistic limit**

$$\text{Gamow-Teller operator} = \vec{\sigma} \tau_{\pm}$$

$$\text{Spin-Dipole operator} = [\vec{\sigma} \times \vec{r}]^J \tau_{\pm}$$

Big-Bang nucleosynthesis with SUSY particle

${}^4\text{He}(\gamma, n){}^3\text{He}$  and  ${}^4\text{He}(\gamma, p){}^3\text{H}$

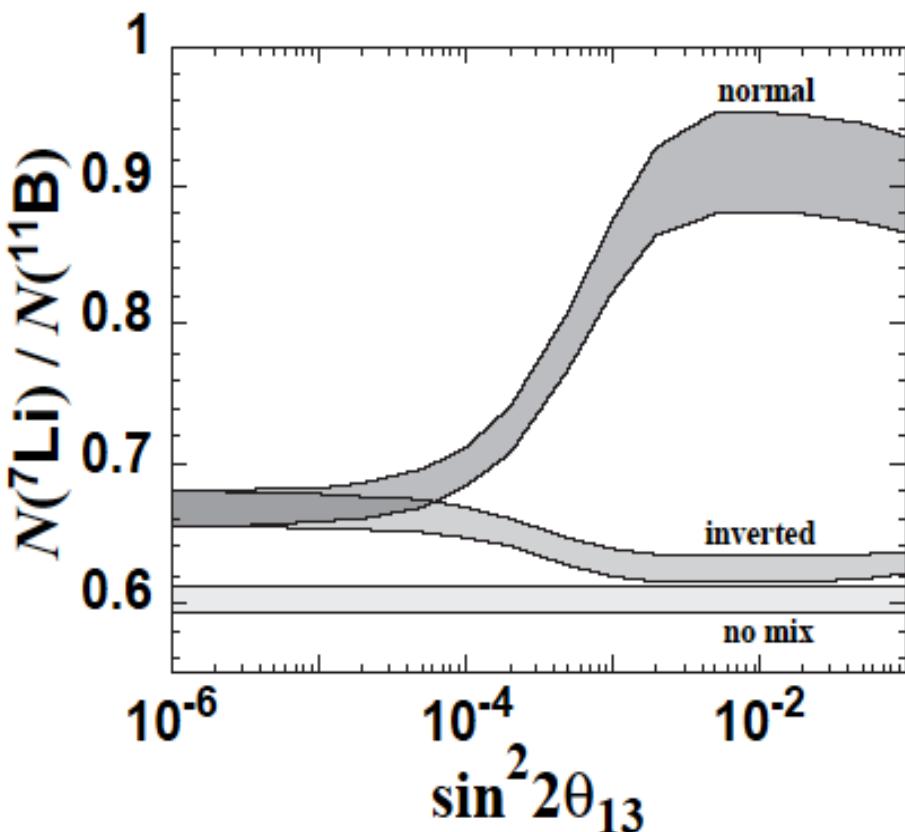
$\longleftrightarrow {}^4\text{He}(\nu, \nu'), {}^4\text{He}(\nu_e, e^-), {}^4\text{He}(\bar{\nu}_e, e^+)$

SN- $\nu$  nucleosynthesis for determining  $\nu$ -oscillation param

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

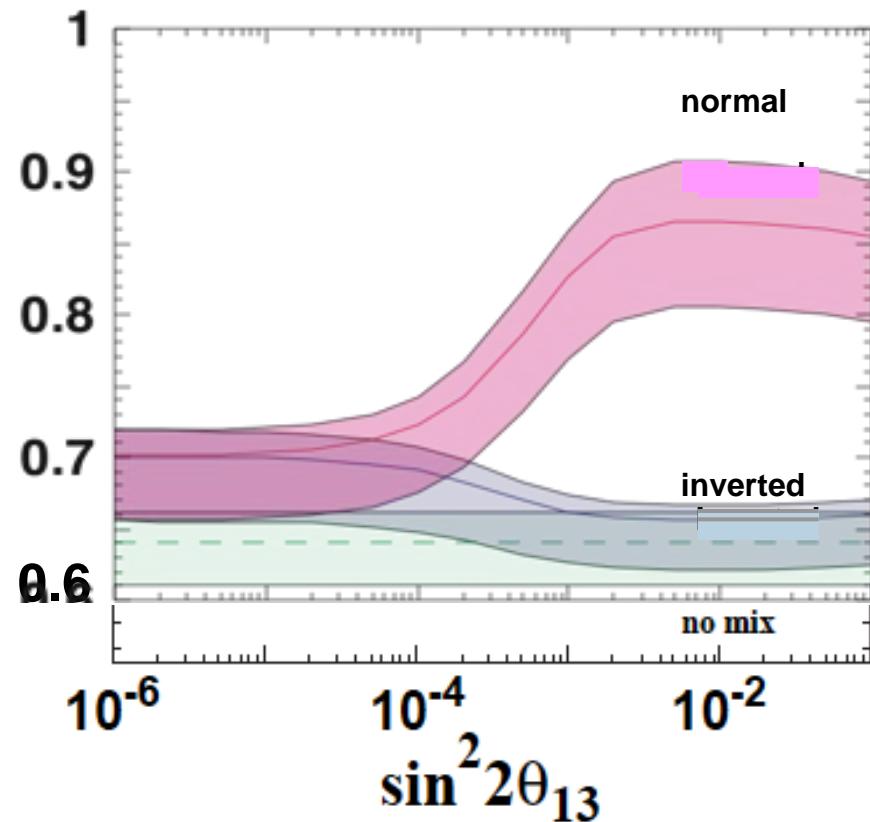
## Previous SM- $\sigma_\nu(E)$ of Haxton

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



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

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



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

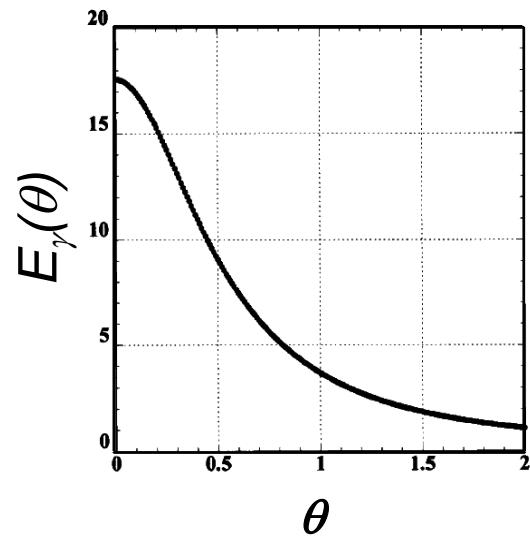
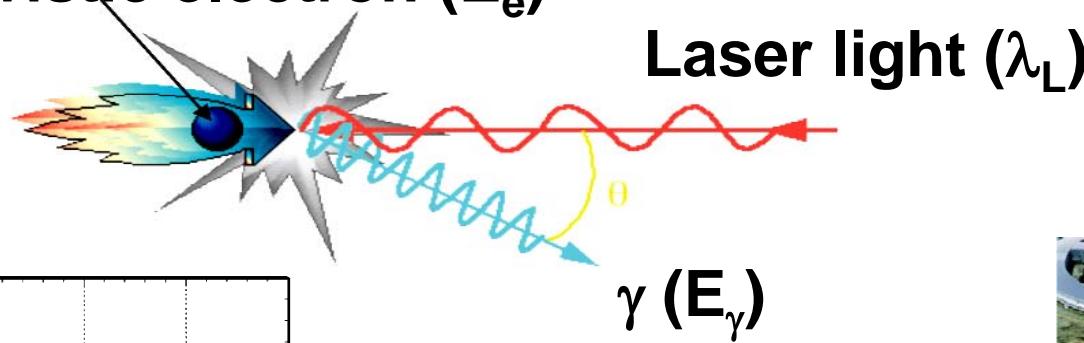
Mixing angle  $\theta_{13}$  dependence, almost the same !

# Laser Compton-scattered photon (LCS- $\gamma$ )

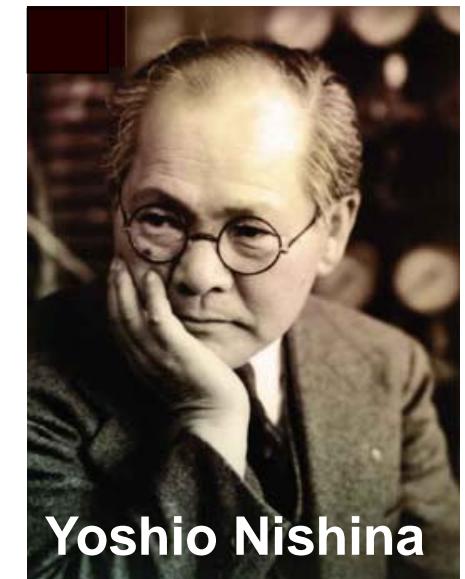
## Klein–Nishina formula

$$E_\gamma = \frac{4hc}{\lambda_L} \cdot \frac{\gamma^2}{1 + \gamma^2 \theta^2}, \quad \gamma = \frac{E_e}{m_e c^2}$$

## Relativistic electron ( $E_e$ )



$$\begin{aligned}\lambda_L &= 1.064 \mu\text{m}, E_e = 800 \text{ MeV} \\ &\Rightarrow E_\gamma = 11 \text{ MeV}\end{aligned}$$
$$\begin{aligned}\lambda_L &= 1.064 \mu\text{m}, E_e = 1.5 \text{ GeV} \\ &\Rightarrow E_\gamma = 39 \text{ MeV}\end{aligned}$$



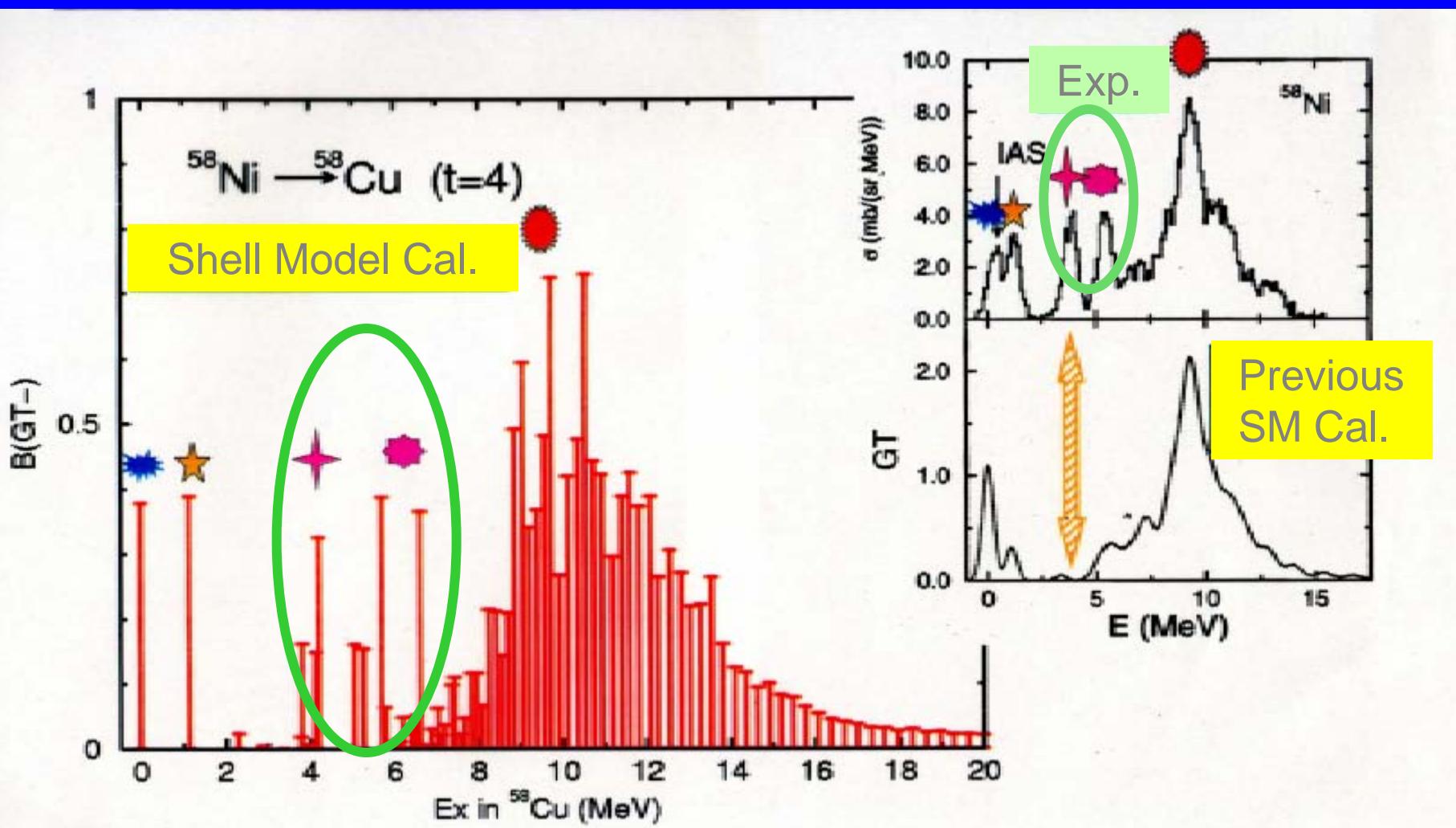
Yoshio Nishina



Prof. Miyamoto

# Gamow-Teller ( $\beta$ -decay) Strength Distribution in $^{55}\text{Mn}$ - $^{56}\text{Fe}$ - $^{56,58}\text{Ni}$ region

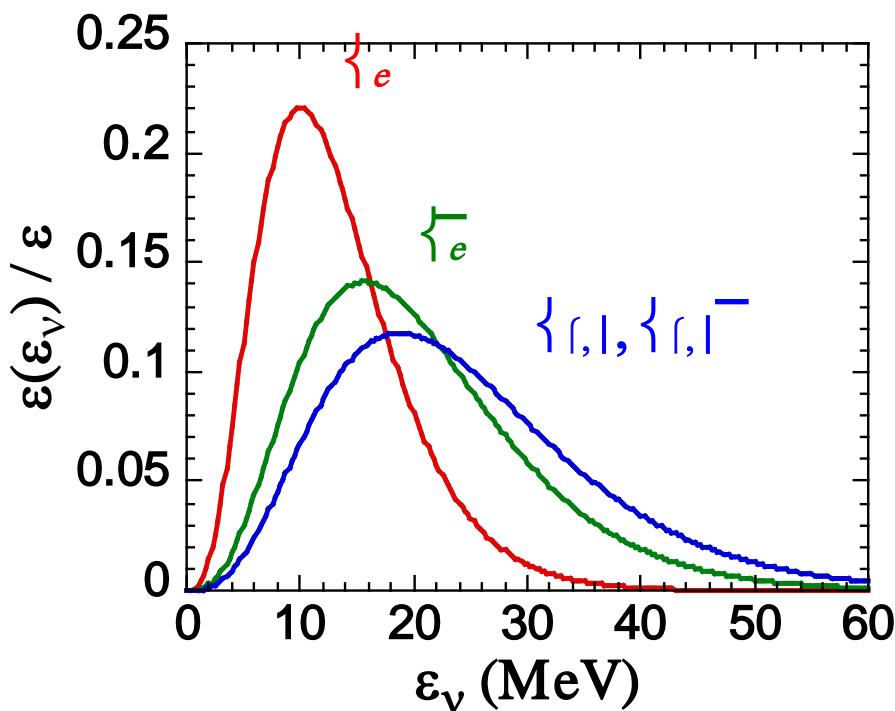
Suzuki, Honma, Higashiyama, Yoshida, Kajino, Otsuka, Umeda & Nomoto,  
PRC79 (2009), 061603 (R).  
Experiment: Rapaport (1983), NP A410, 371.



# Uncertainties in Neutrino-Spectrum ?

$$T(\nu_e) = 3.2 \text{ MeV} < T(\bar{\nu}_e) = 5.0 \text{ MeV} < T(\nu_{\mu,\tau}) = T(\bar{\nu}_{\mu,\tau}) = 6.0 \text{ MeV}$$

Neutrino energy distribution



- SN1987A Neutrinos?

Only 11  $\nu$ -events, too small,  
but total Energy is estimated !

- Nucleosynthetic  
Calibration

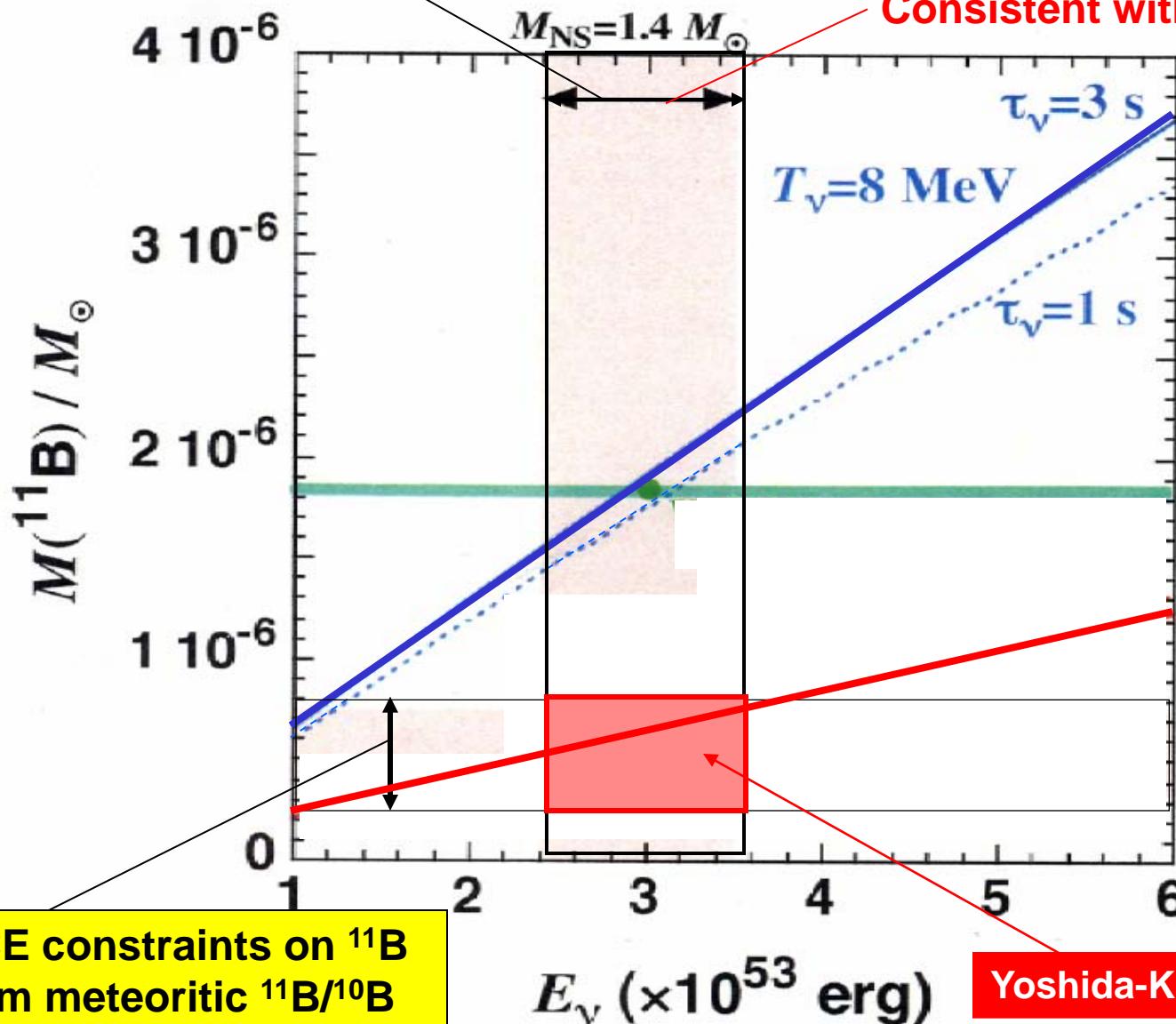
Galactic Chemical Evolution  
of the Light LiBeB Elements,

Meteoritic  $^{11}\text{B}/^{10}\text{B}$ -Ratio.

# Detection of Direct Supernova vs

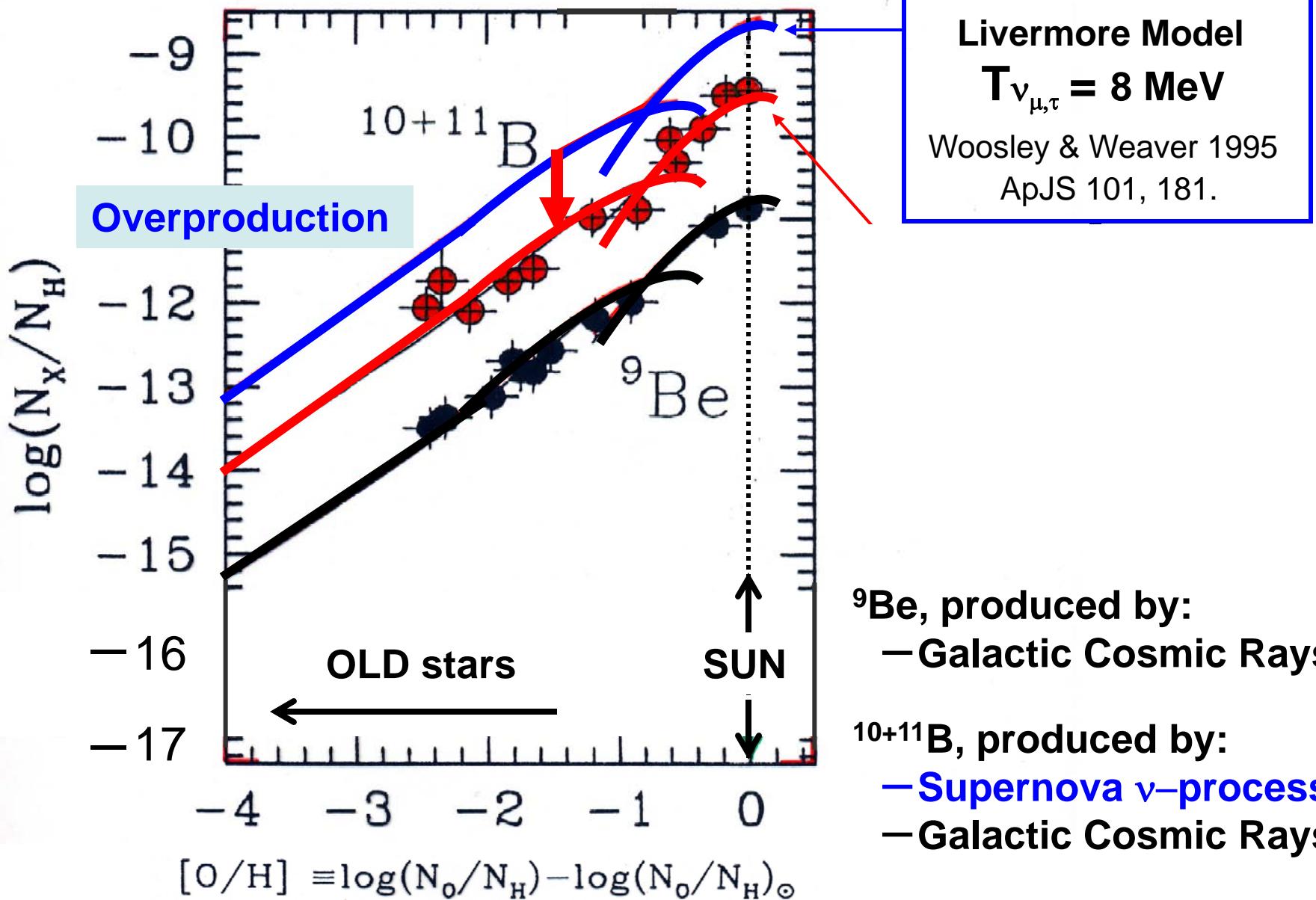
Grav. Potential constraint

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



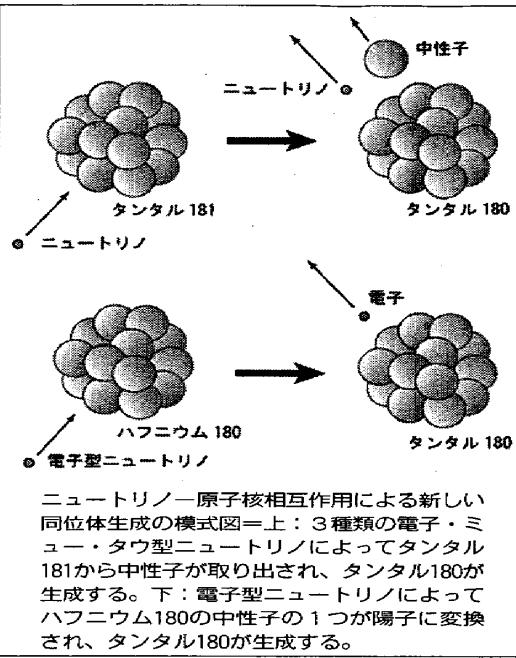
Woosley & Weaver  
ApJS 101 (1995), 181.  
**OVERPRODUCTION**

# Galactic Chemical Evolution of ${}^9\text{Be}$ &



## 太陽系で最も希少な同位体

# タンタル180



ニュートリノー原子核相互作用による新しい同位体生成の模式図=上：3種類の電子・ミュー・タウ型ニュートリノによってタンタル181から中性子が取り出され、タンタル180が生成する。下：電子型ニュートリノによってハフニウム180の中性子の1つが陽子に変換され、タンタル180が生成する。

「今後、より精密な研究が必要なことが判明した。」  
電子型ニュートリノ  
超新星爆発における基底状態+核変異体  
おもにその反粒子の平均エネルギーは約12 MeVでなければ

太陽系には約290種類の同位体が存在するが、なかでも最も希少な同位体、タンタル180 ( $Ta-180$ ) の起源は、残された大きな謎となっていた。日本原子力研究開発機構等、応用研究部門の早川岳人・研究主幹、同機構先端基礎研究センターの千葉敏・研究主幹、国立天文台理論研究部の梶野敏貴・准教授らの研究グループは、 $Ta-180$ が超新星爆発において発生する膨大な量のニュートリノによる核反応で生成したことを見理論的に明らかにすることに成功した。この成果は、岐阜県の神岡鉱山内に設置された世界最大規模のニュートリノ検出装置「スーパーカミオカンデ」で期待される超新星ニュートリノ観測の予想やニュートリノ振動の理解が進むものと期待される。

早川研究主幹によると、「超新星爆発において時刻と共に刻々と温度変化する環境(数十億度の温度から数十秒で冷却してしまう)における $Ta-180$ の基底状態と核変異体の存在する割合を計算する手法を新たに考案したところ、この手法が指摘したが、誰も成功していないその理由として、従来の理論では、基底状態と核変異体を別々の種類の同位体と見なした点に

原子力機構 国立天文台 起源の謎を理論的に解明

## 超新星爆発のニュートリノで生成

# 科学新聞

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電波の日・情報  
通信月間特集<sup>5</sup>面

科学新聞  
2010年5月28日(金)

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

$^{138}\text{La}$  ~ spherical nucleus

$^{180}\text{Ta}$  ~ deformed nucleus

K.Yokoi, Nature (1983)

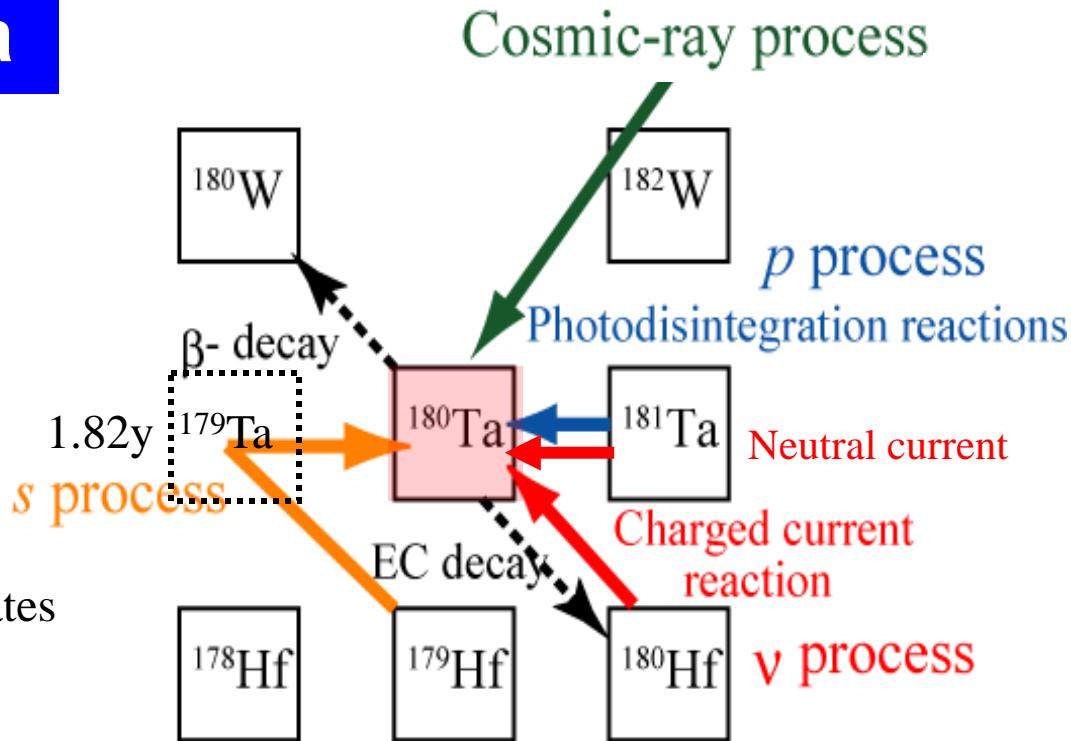
Proposal of s-process origin

D.Belic et al., Phys. Rev. Lett. (1999)

Measurement of transition probability  
between the isomer and the ground states

K.Wisshak, Phys. Rev. Lett. (2001)

Neutron capture cross section of  $^{180}\text{Ta}$



Goko, Phys. Rev. Lett. (2007)

Measurement of ( $\gamma$ ,n) reactions

D. Byelilov , Phys. Rev. Lett. (2007)

( $^3\text{He},\text{t}$ ) experiments for neutrino-process

GT, measured at RCNP:  $E_n < 50 \text{ MeV}$  !

M.-K.Cheoun et al., (2010), in preparation.

**Supernova neutrino-process:**

Woosley, Hartmann, Hoffman, & Haxton,  
ApJ 356 (1990), 272.

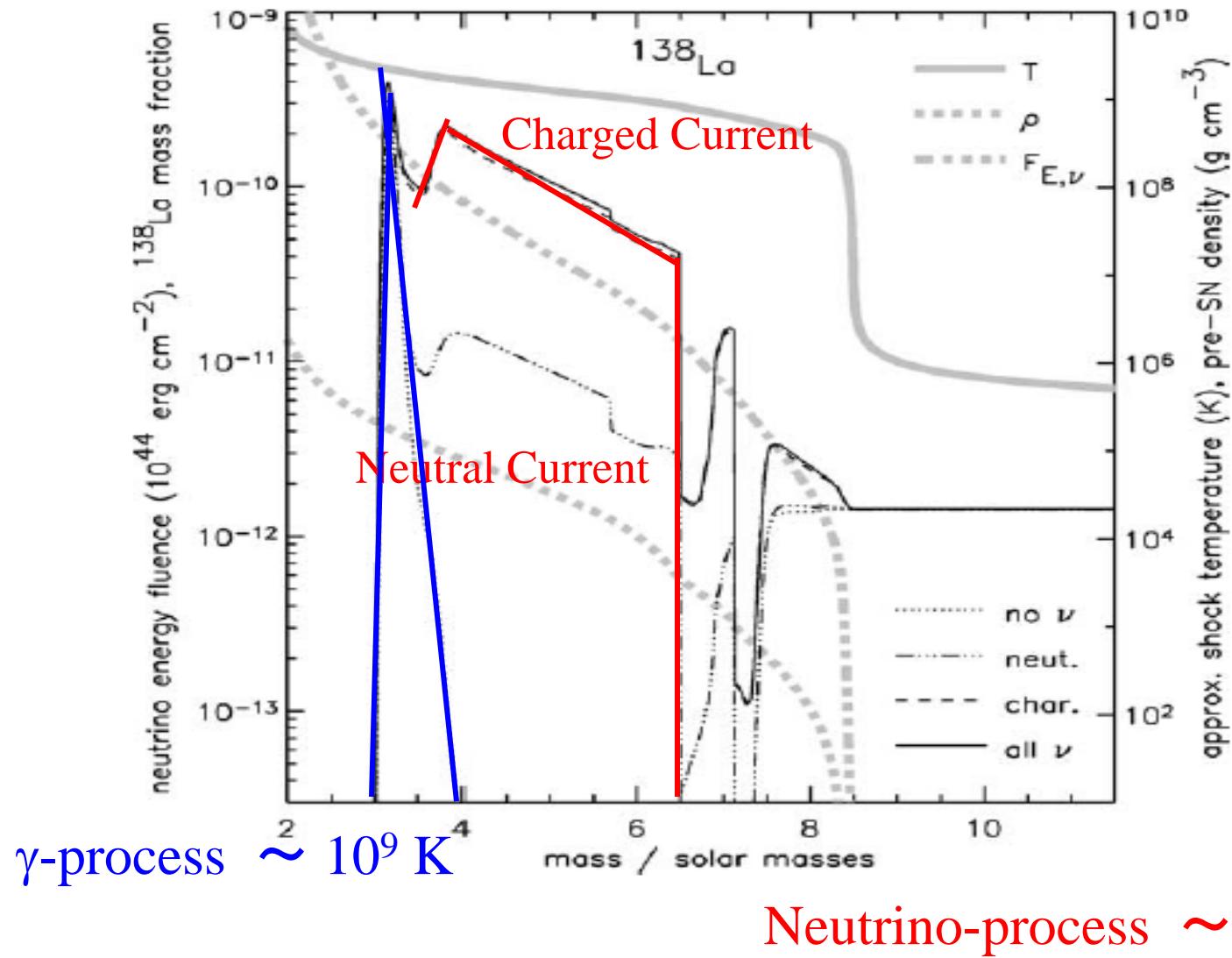
Heger et al., Phys. Lett. B 606, 258 (2005)

**Nucleo-Cosmochronology:**

Hayakawa, Shimizu, Kajino, Ogawa, & Nakada,  
PRC 77 (2008), 065802; 79 (2009) 059802.

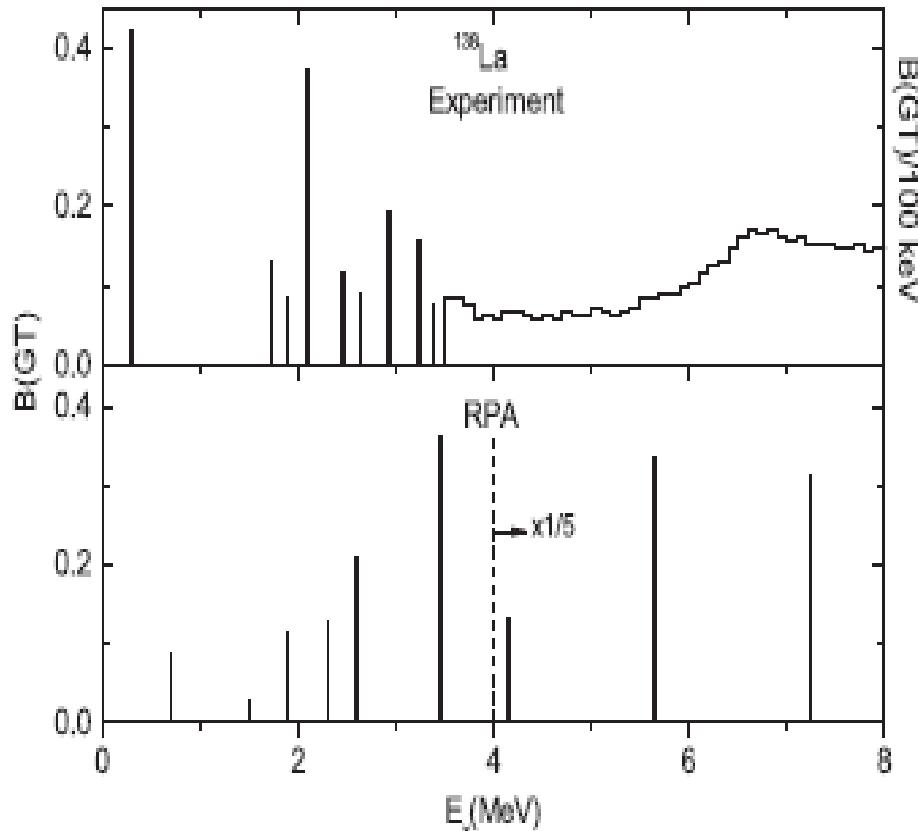
# Supernova $\nu$ -process of $^{138}\text{La}$

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

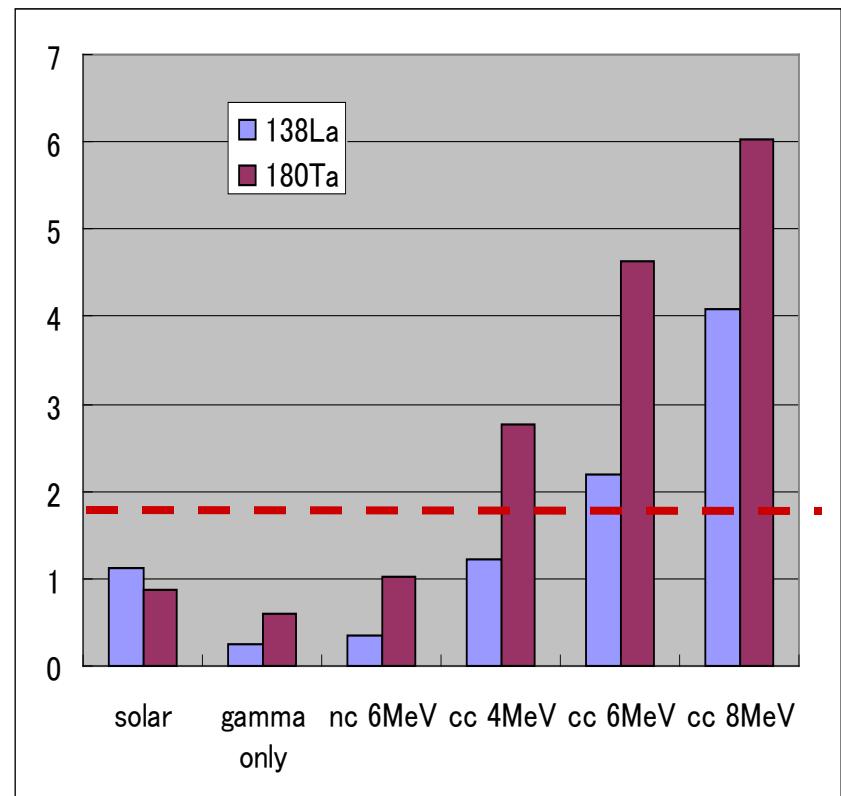


# Effect of Charged Current reaction

Byelikov + Fujita et al., PRL (2007)  
measured GT strength at RCNP, Osaka.



A. Heger, recalculated Supernova nucleosynthesis of  $^{138}\text{La}$  &  $^{180}\text{Ta}$ .



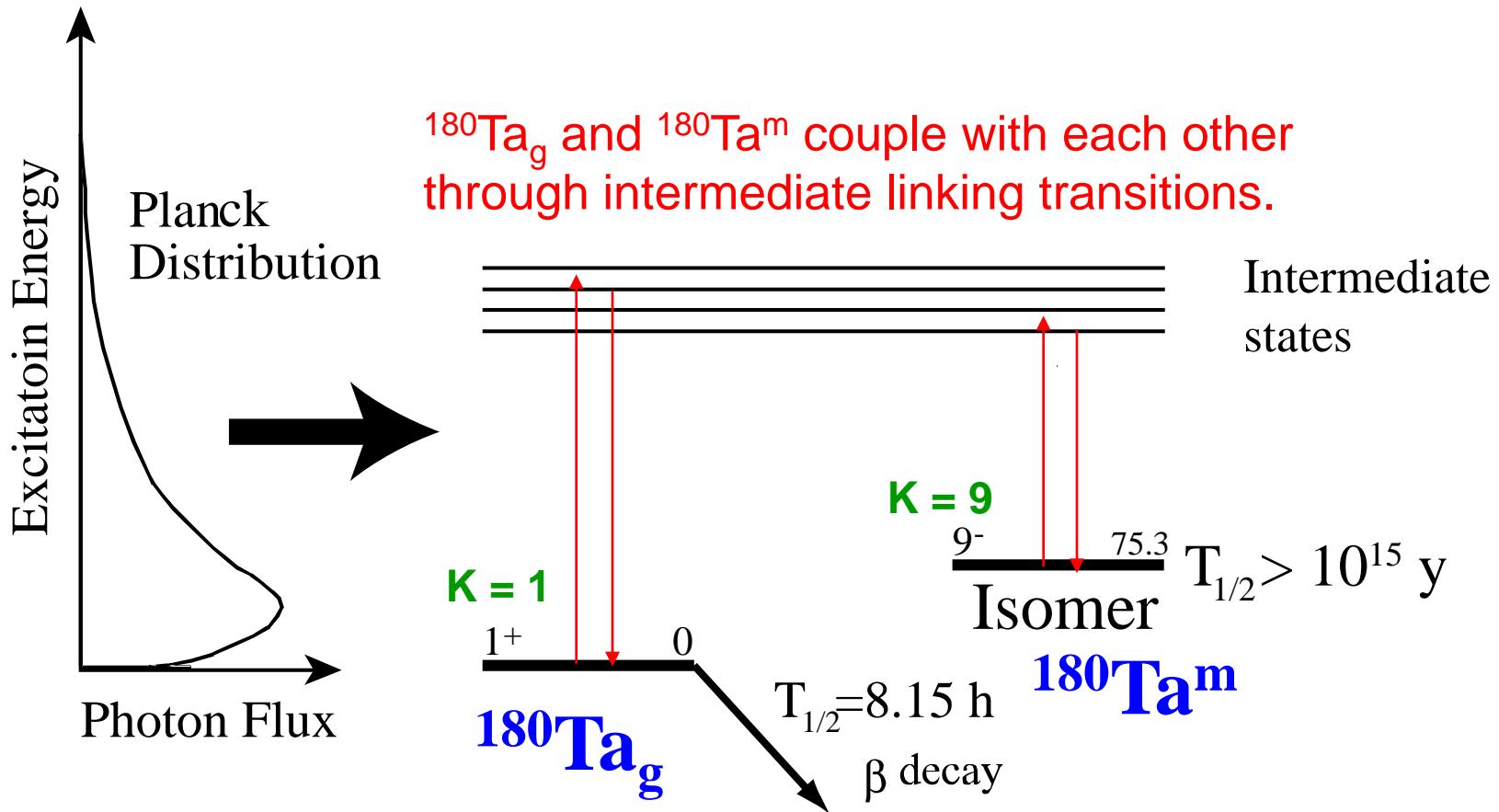
Overproduction Problem of  $^{180}\text{Ta}$  relative to  $^{138}\text{La}$ !

Spin-dipole and multipole forbidden transitions + GT does !

# Problem of Isomer Ratio

Isomer Residual Ratio, isomer / (gs+isomer), is a critical factor for calculation of  $^{180}\text{Ta}$  nucleosynthesis.

- ★ Linking transitions between  $K = 1$  and  $K = 9$  bands are extremely weak.
- ★ Theoretical formula for  $\text{Al}26$  with strong linking transitions does not apply!



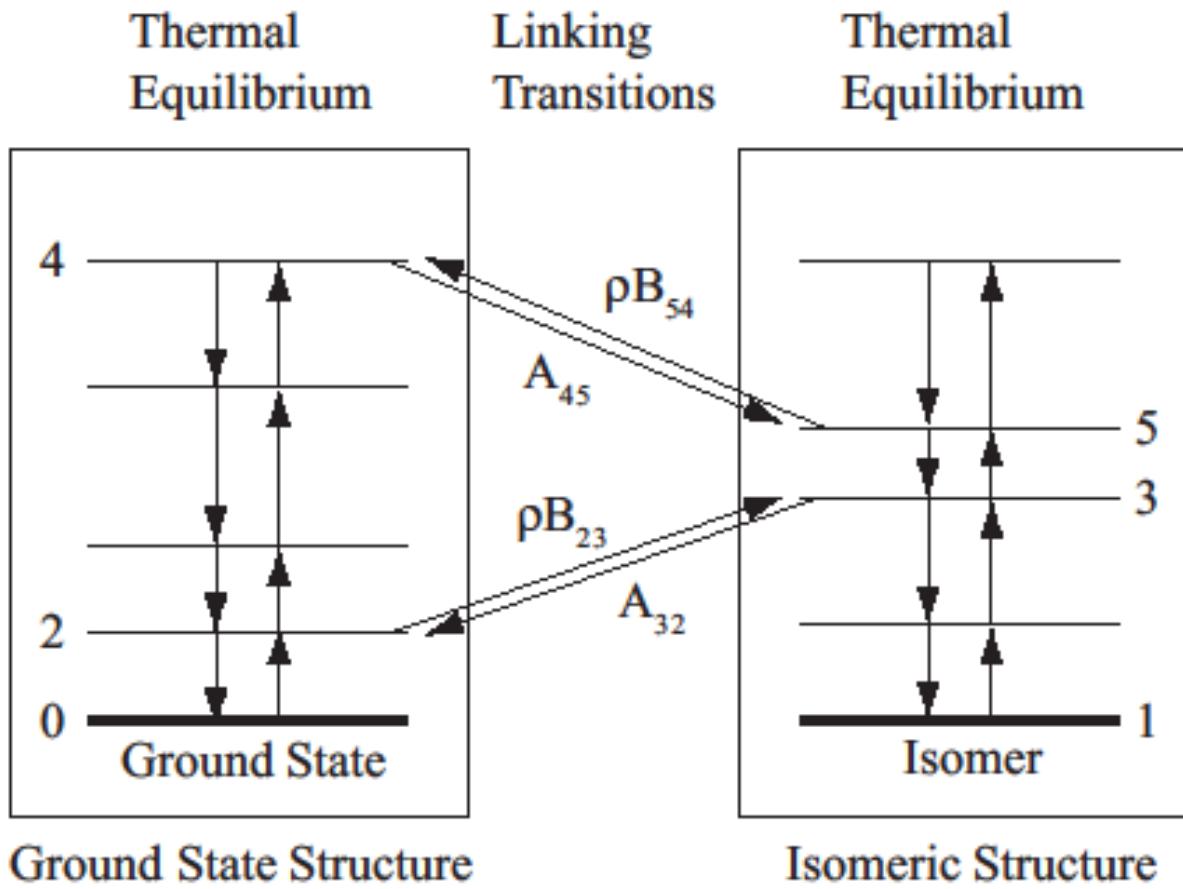


FIG. 2: Schematic illustration of the nuclear structure relevant during the transitional temperature region. The ground state structure (i.e. the ground state and excited states above the ground state) is in thermal equilibrium. The isomeric structure is also in thermal equilibrium. The ground state and isomeric structures are connected via the indicated linking transitions.

# Formula to calculate time-dependent linking transitions

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

In general cases:

$$\begin{aligned} \frac{dN_0}{dt} = & -\sum_i P_i^g A_{ip} N_0 + \sum_i P_i^m \rho B_{pi} (1 - N_0), -\sum_j P_j^g \rho B_{qj} N_0 + \sum_j P_j^m A_{jq} (1 - N_0) \\ = & -\sum_i P_0^g \frac{g_i}{g_0} \exp(-(E_i - E_0)/kT) A_{ip} N_0 + \sum_i P_1^m \frac{g_i}{g_1} \exp(-(E_i - E_1)/kT) A_{ip} (1 - N_0), \quad (6) \end{aligned}$$

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

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

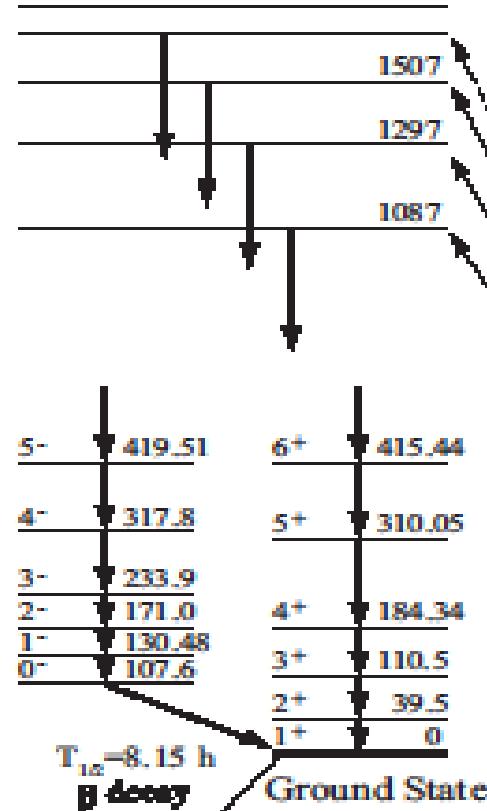
In the case of  $^{180}\text{Ta}$ :

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

Transition probabilities ← Experimental Data

$\nu$  process

$\gamma$  process

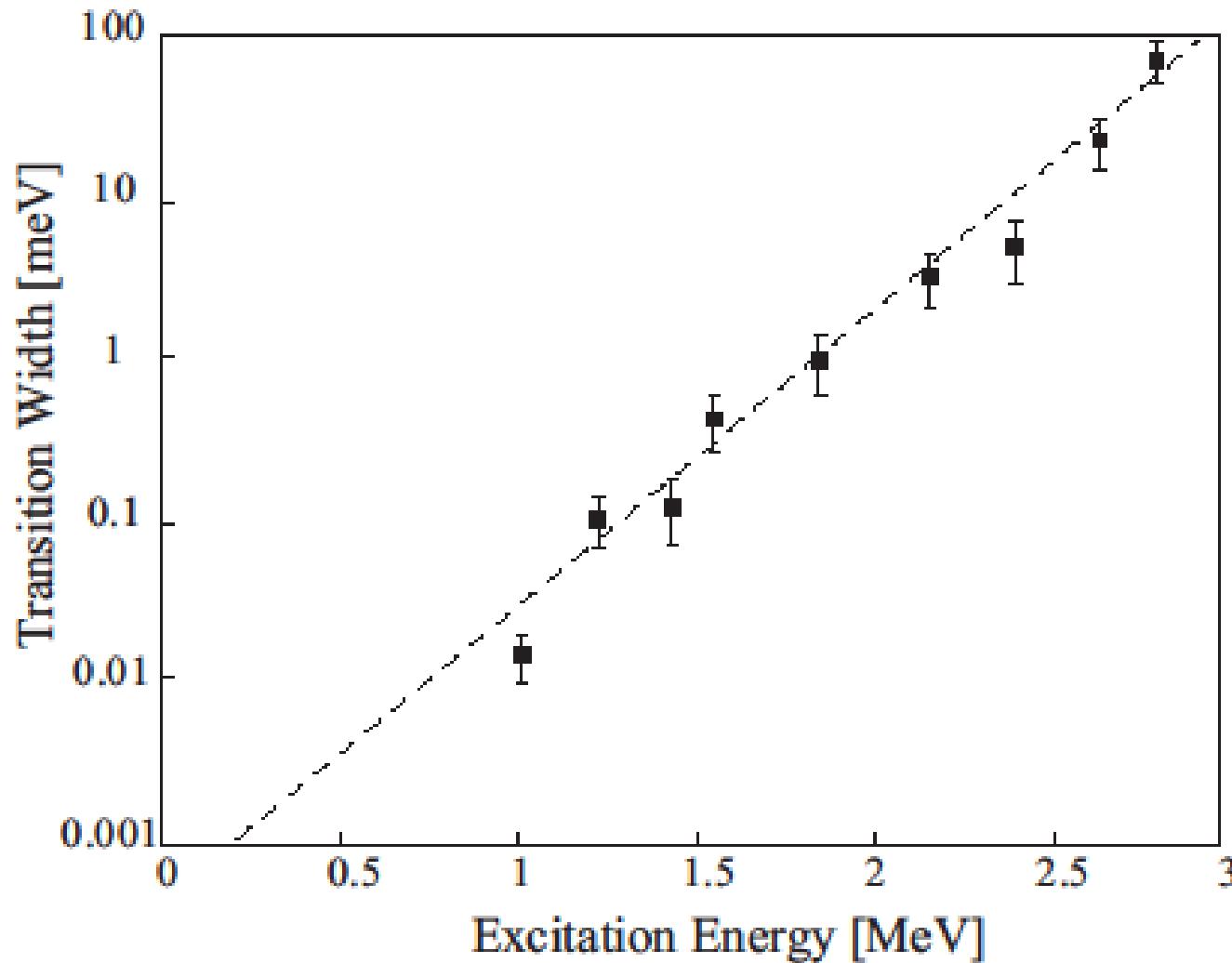


$^{180}\text{Ta}$

# Measured Widths

$g_1/g_1\Gamma_i\Gamma_0/\Gamma$  [meV]

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



# Nuclear Structure of $^{180}\text{Ta}$

Excited states in  $^{180}\text{Ta}$  have been studied well by using in-beam gamma-ray spectroscopy.

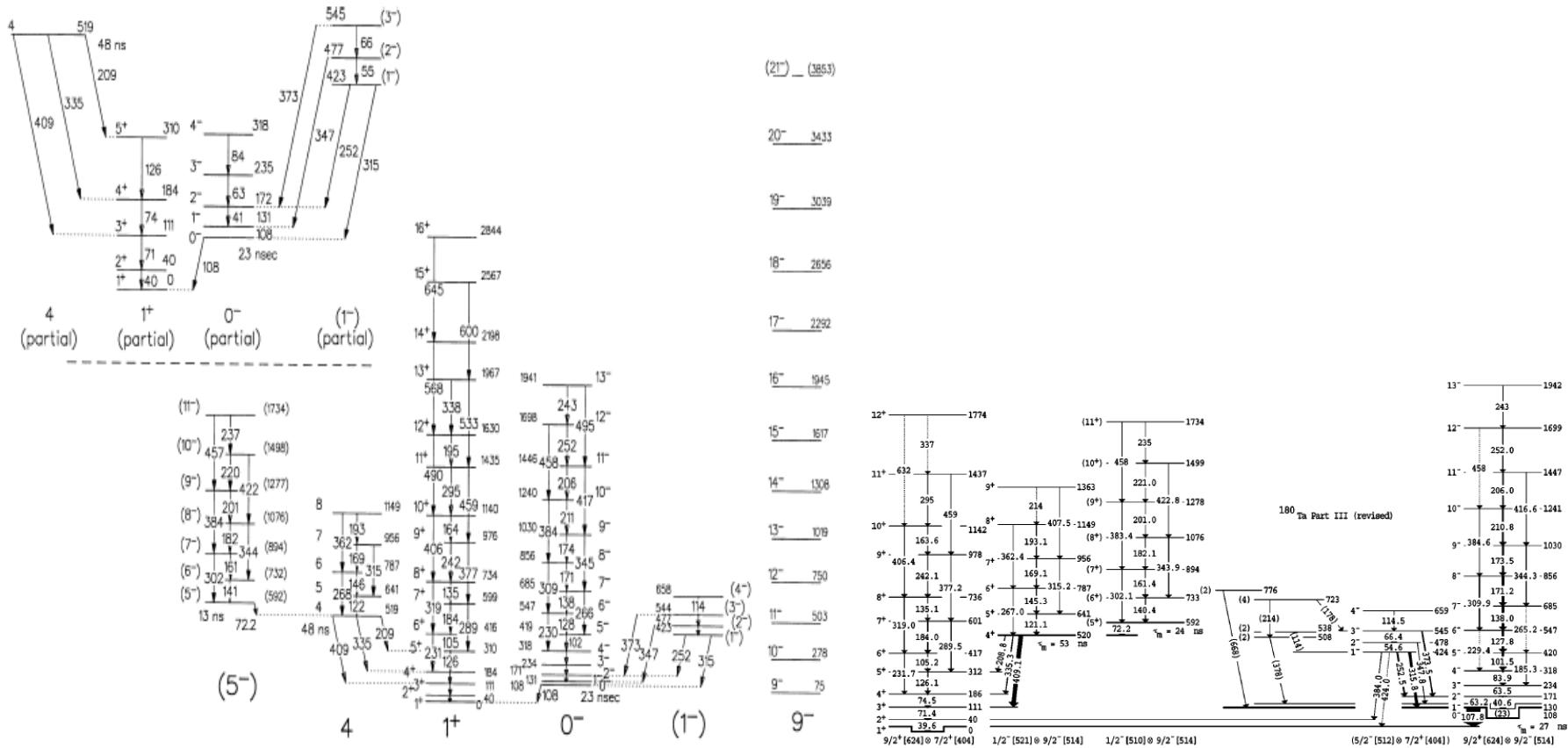


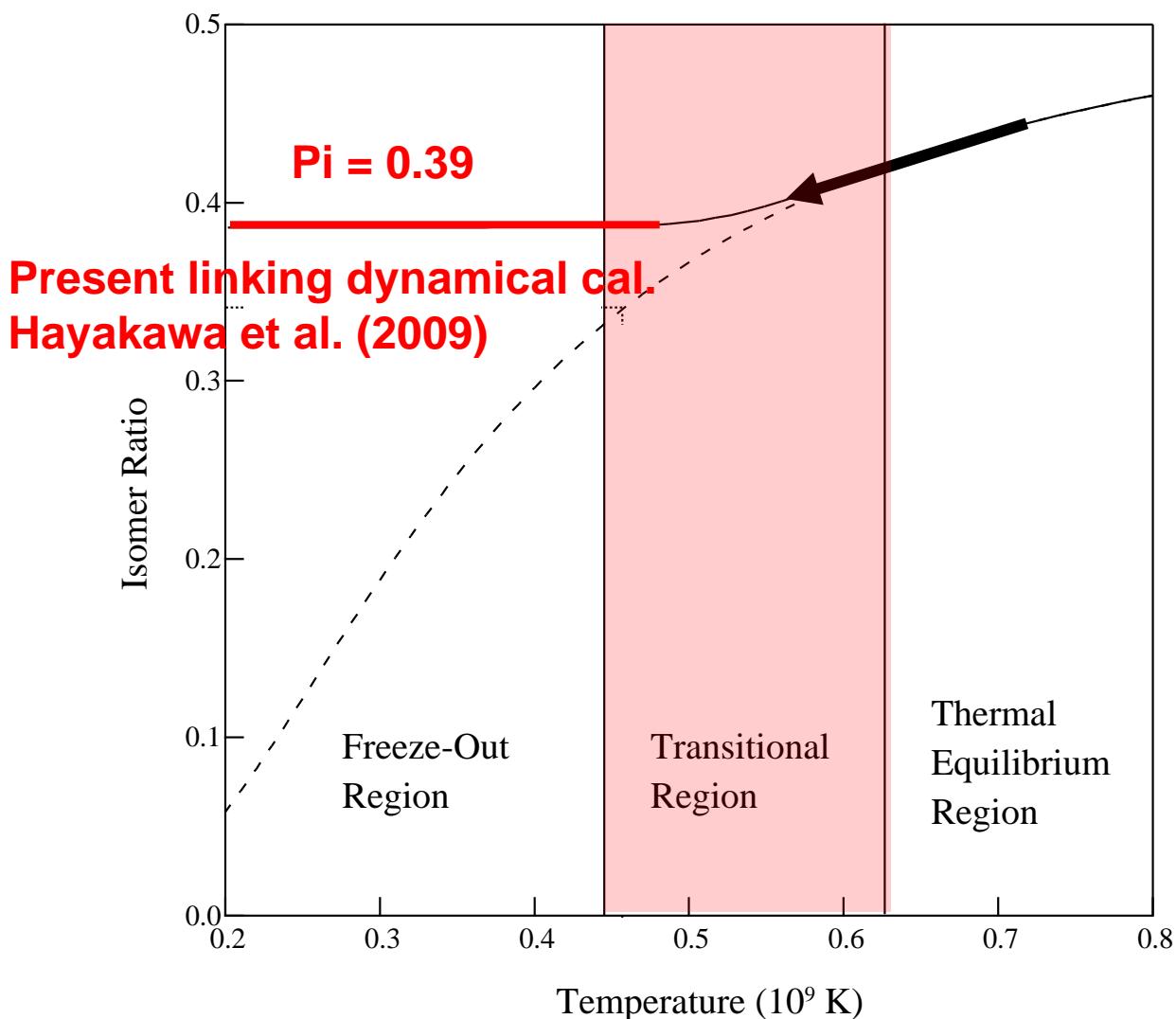
Fig. 4. Partial level scheme of  $^{180}\text{Ta}$ , Part 4.

T.R. Saitoh, NPA 1999,  
NBI group

G. D. Dracoulis, PRC 1998, ANU group

# Calculated Result

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



We carried out time-dependent dynamical calculations.

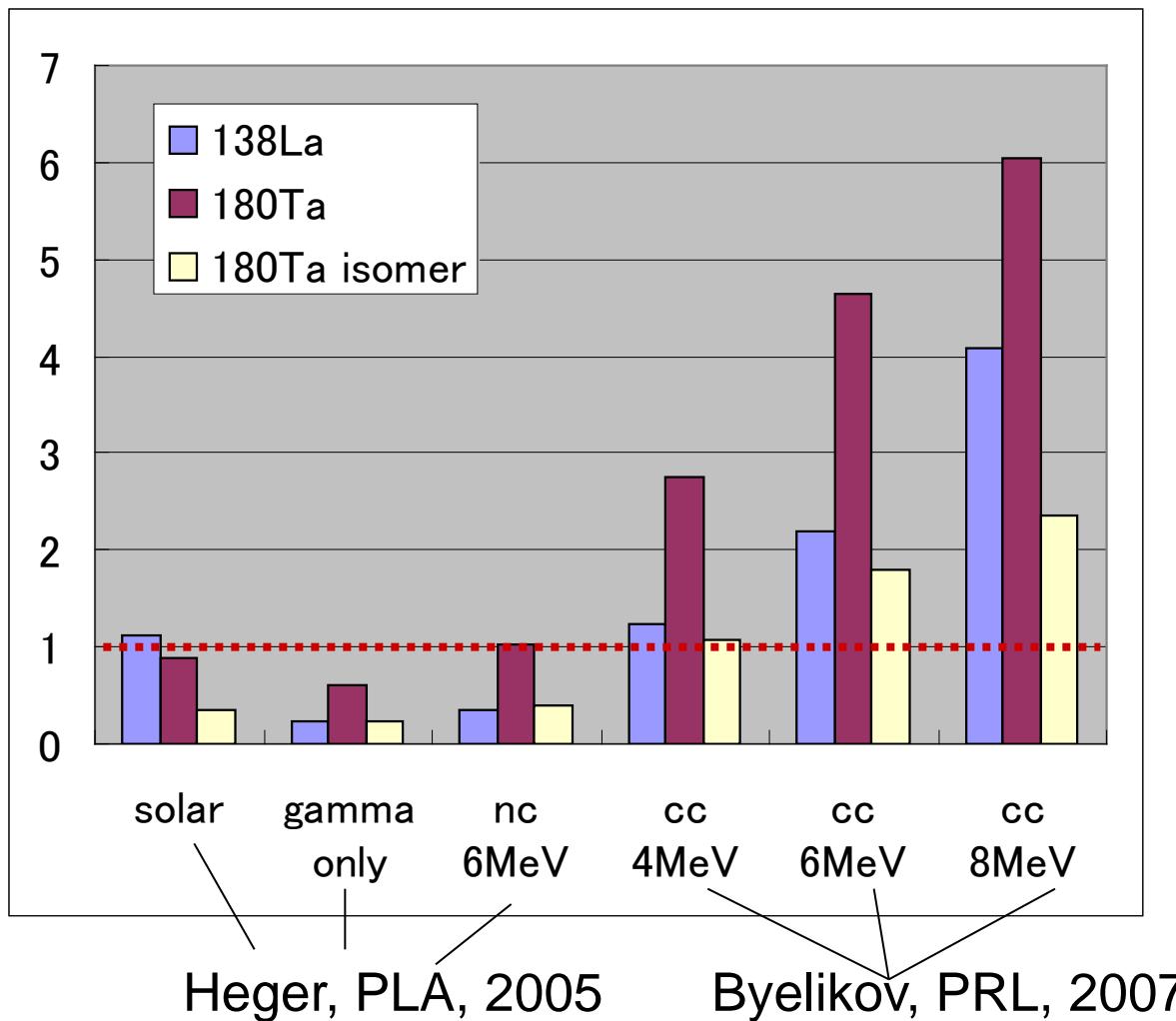
Model:

$$T = \exp(-t/\tau)$$

$$\tau = 0.3, 1, 3 \text{ s}$$

$$\text{Init : } T_0 = 1.0$$

# New Result



We multiply the calculated abundance by the factor of  $\text{Pi} = 0.39$

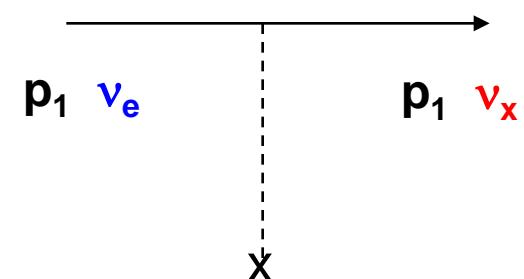
Both the nuclei can be reproduced consistently by +CC at 4MeV.

# Neutrino Hamiltonian

$$H_{tot} = H_\nu + H_{\nu\nu}$$

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

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



MSW (Matter) Effect

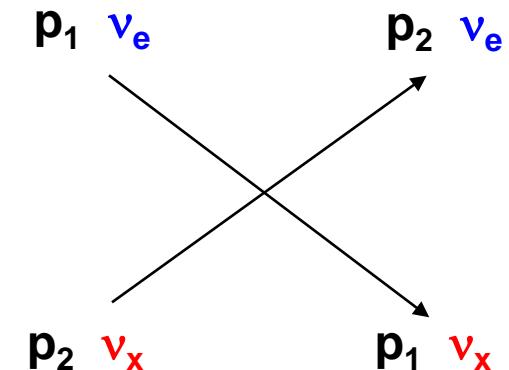
Mikeheev-Smirnov-Wolfeinstein (1978, 1985)

$N_e$  = electron density

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

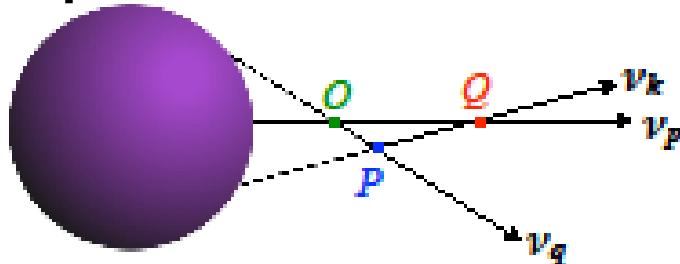
$$H_{\nu\nu} = \frac{G_F}{\sqrt{2}V} \int d^3 p d^3 q R_{pq} [a_e^\dagger(p) a_e(p) a_e^\dagger(q) a_e(q) + a_x^\dagger(p) a_x(p) a_x^\dagger(q) a_x(q) \\ + a_x^\dagger(p) a_e(p) a_e^\dagger(q) a_x(q) + a_e^\dagger(p) a_x(p) a_x^\dagger(q) a_e(q)].$$

Exact solution, still UNKNOWN !



# $\nu$ self-interaction (Quantum Effect)

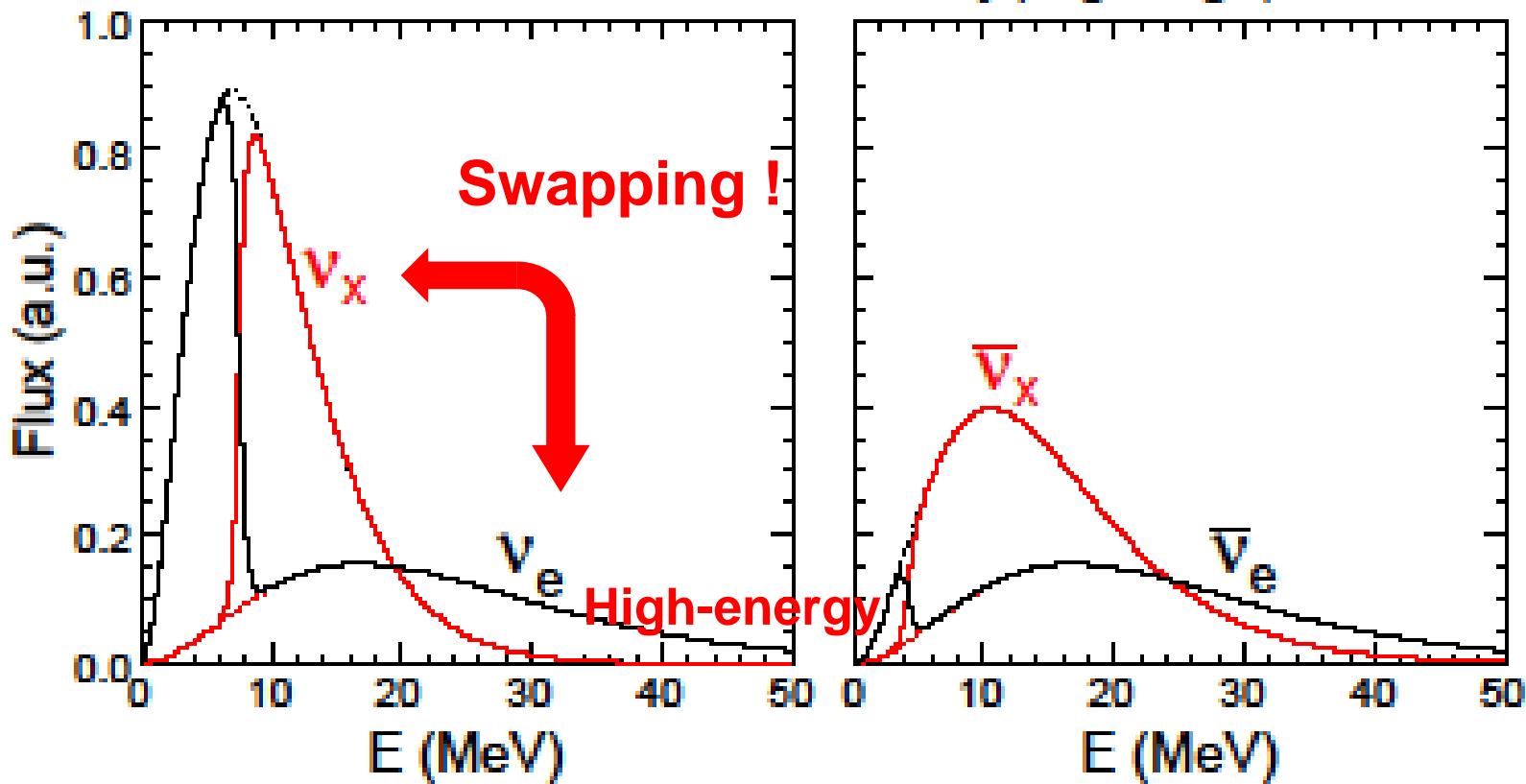
$\nu$ -sphere in SN core



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.

$r = 200\text{km}$

Final fluxes in inverted hierarchy (single-angle)



# **SUMMARY**

- The n-process in core-collapse SNe provides unique tool in terms of MSW effect to determine the unknown  $\nu$ -oscillation parameter  $\theta_{13}$  and mass hierarchy of active  $\nu$ 's.
- Neutrino—Nuclear Astrophysics takes the keys to elucidate Cosmic, Galactic and Stellar Evolution in terms of nucleosynthesis.
- Time is matured to promote US-Japan Collaboration in this field to:
  - provide fundamental knowledge of neutrino-nucleus interactions,
  - apply to nucleosynthesis & evolution of various stellar objects.

**US-Japan Nucl. Astro. THEORY:** Discussion has just launched.

Extension of JUSTIPEN; UT-IPMU; 10 peta flops Supercomputer in particle-nuclear-astrophysics unification in Japan ...

**Nucl. EXPERIMENT:** Promissing !?

ORNL—JPARC (in Neutrino Beam Physics)

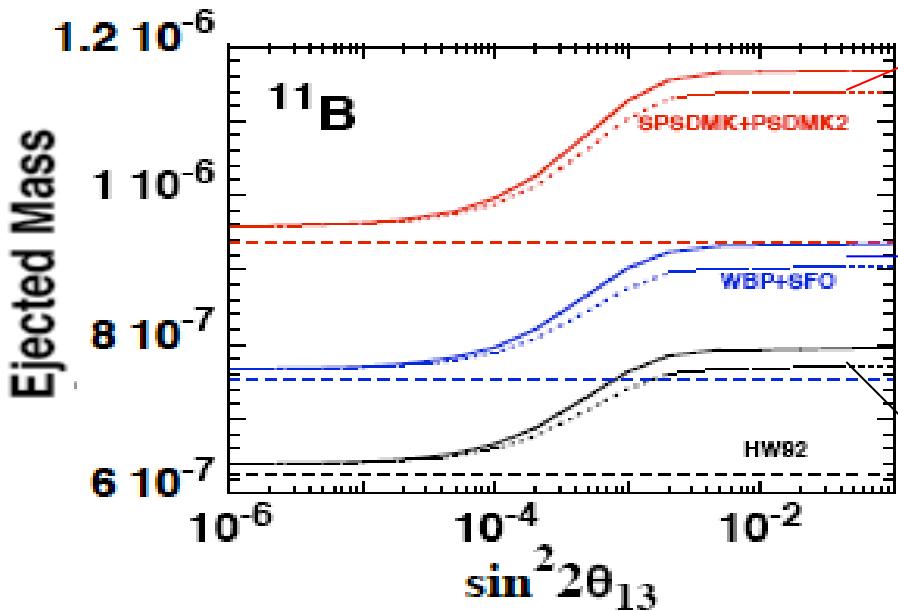
FRI<sup>B</sup> (MSU)—RIBF (RIKEN) (in Exotic Nuclear Physics)

**Astronomy & Particle Astrophys.: Will go !?**

30 Meter Telescope (TMT); Hyper-Kamiokande ...

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

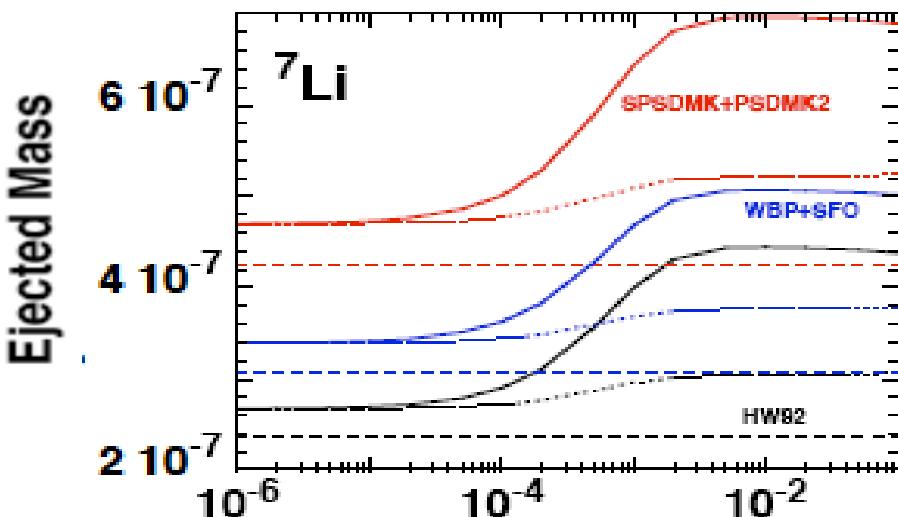
Yoshida, Suzuki, Chiba, Kajino, Yokomakura, Kimura, Takamura & Hartmann, ApJ 686 (2008), 448.



**PSDMK:** OXBASH: Brown, Etchegoyen & Rae, MSU-CL Report No. 524 (1986); Millener & Kurath, NPA 255 (1975), 315.

**WBP:** Warburton & Brown, PRC 46 (1992), 923,  
**SFO:** Suzuki, Fujimoto & Otsuka, PR C67, (2003), 044302.

**HW92:** Hoffman & Woosley, LLNL-HP (1992); Woosley, Hartmann, Hoffman & Haxton, ApJ 356 (1990), 272.



**Absolute  $^{7}\text{Li}$  &  $^{11}\text{B}$  yields depend strongly on different Hamiltonians !**

**But, MSW effect is quantitatively very similar to one another !**