4th Int. Symp. on Neutrinos and Dark Matter in Nuclear Physics
Todaiji Kinsho Hall, Nara, June 11-15, 2012

# Neutrino Oscillation and Mass Hierarchy from Supernova Nucleosynthesis

## ($\theta_{13}$ is well known now.)

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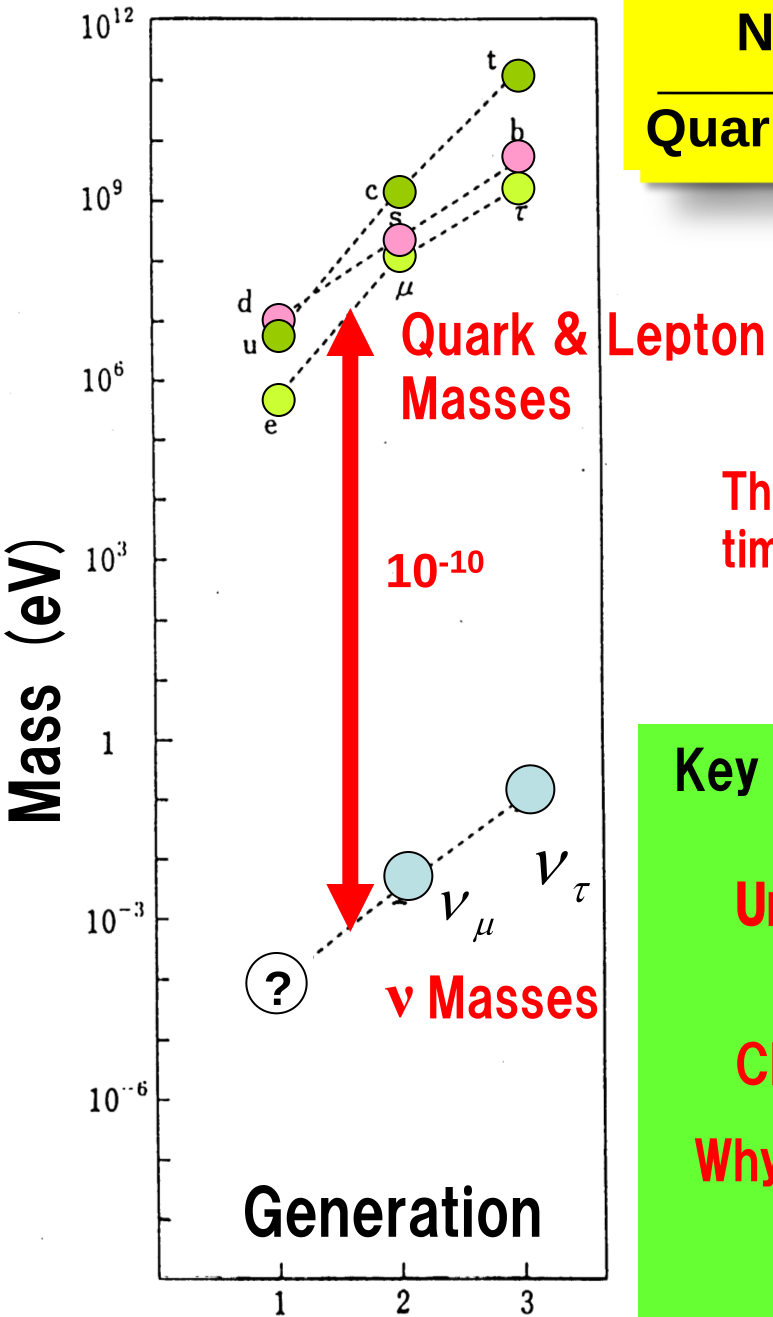
Department of Astronomy, University of Tokyo




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

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

$$E = mc^2$$

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 ?**

# Challenge of the Century

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

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

- **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. (2012), in press.

- **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, Hierarchy, details of mixing nature ?**

# Purpose

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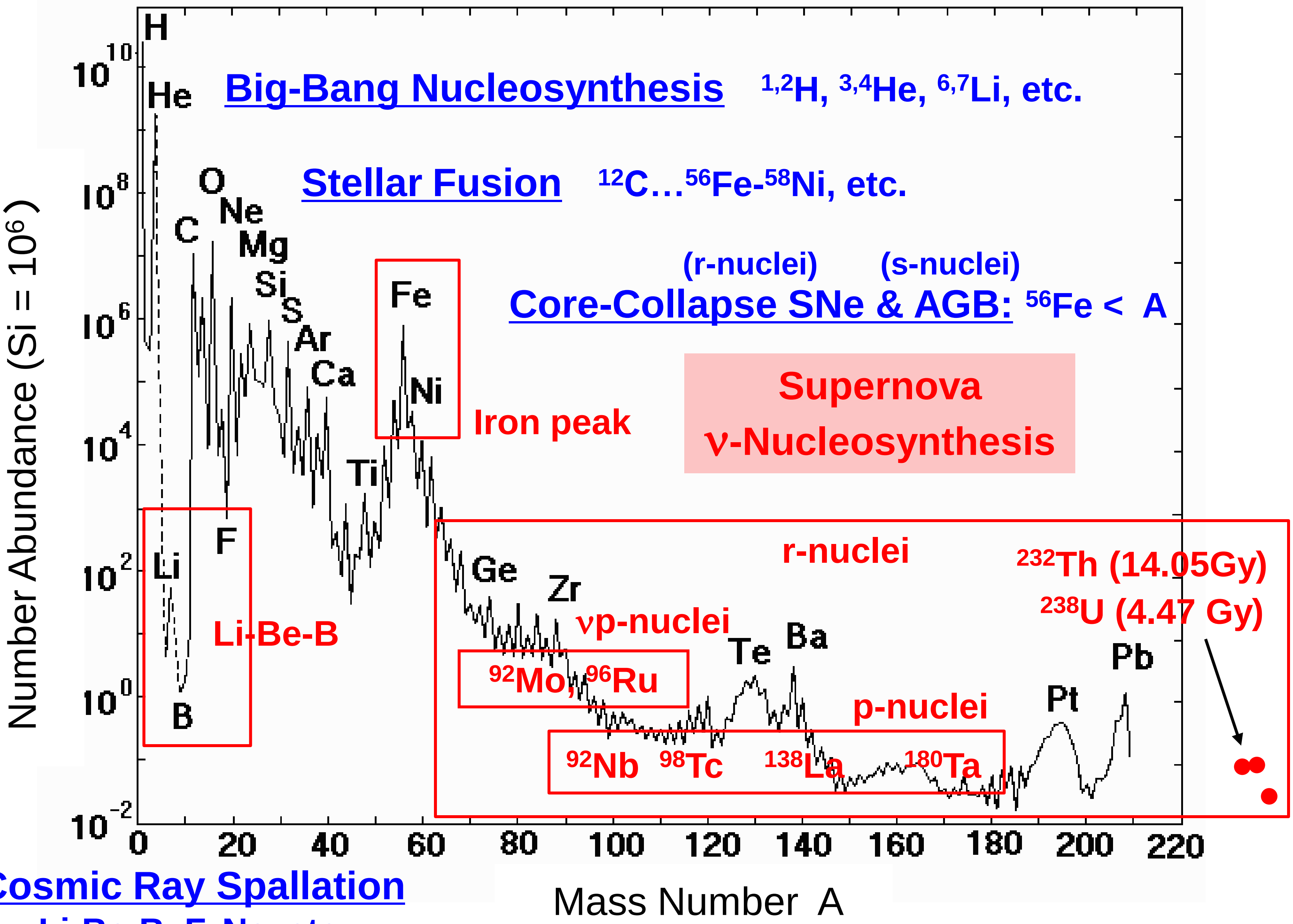
**"Supernova ν-Process Nucleosynthesis"**
**to determine the MASS HIERARCHY of Active Neurinos.**

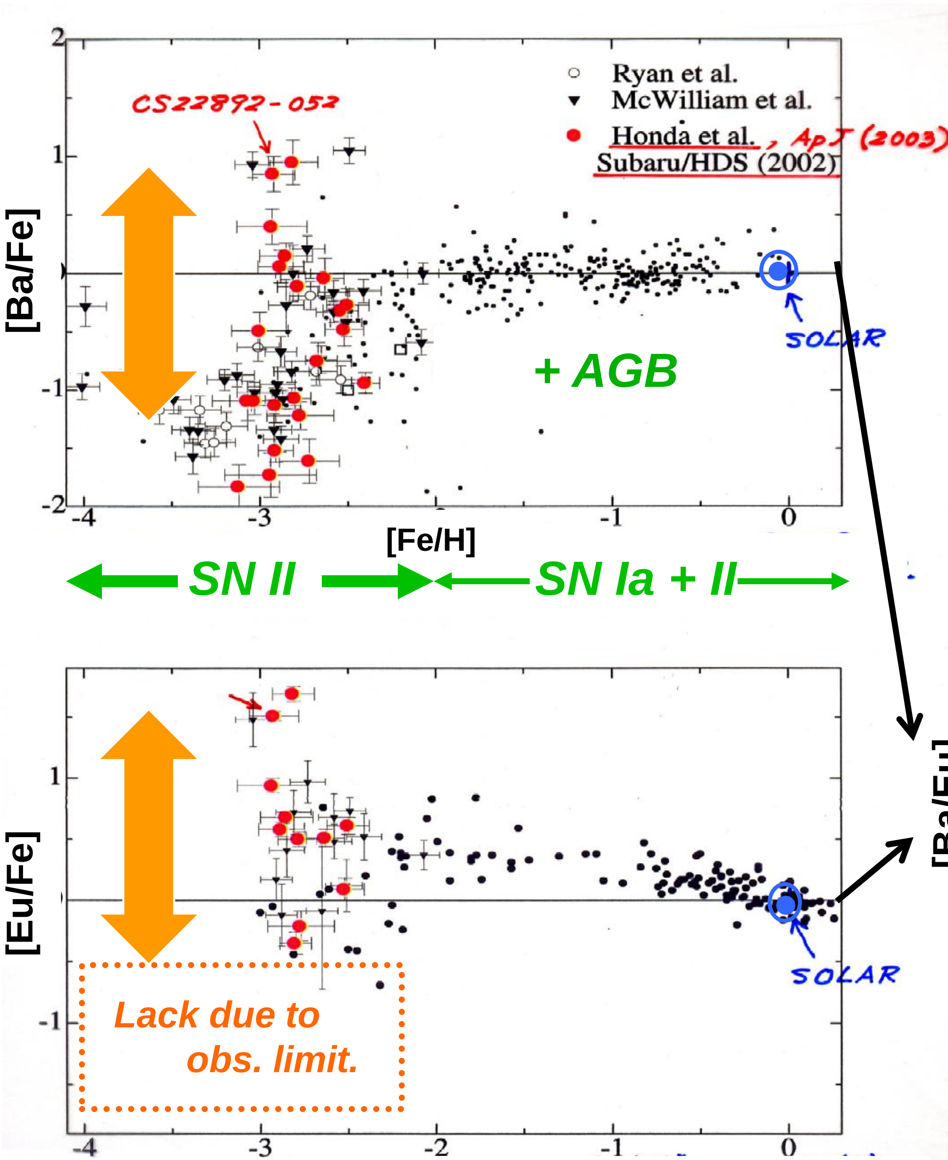
# Solar System Abundance




Cosmic Ray Spallation
Li-Be-B, F, Na, etc.

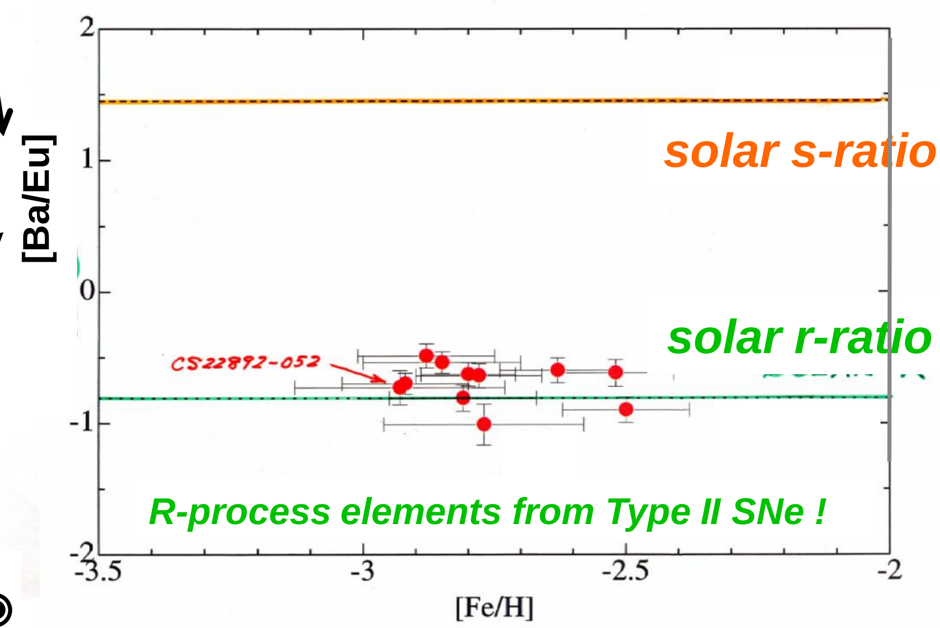
# SUBARU Telescope HDS

Honda, Aoki, Kajino et al.
(SUBARU/HDS Collaboration),
2004, ApJS 152, 113; 2004, ApJ 607, 474




★ Large scatter for metal-poor stars with [Fe/H]<-2 is an evidence for INDIVIDUAL supernova episode.

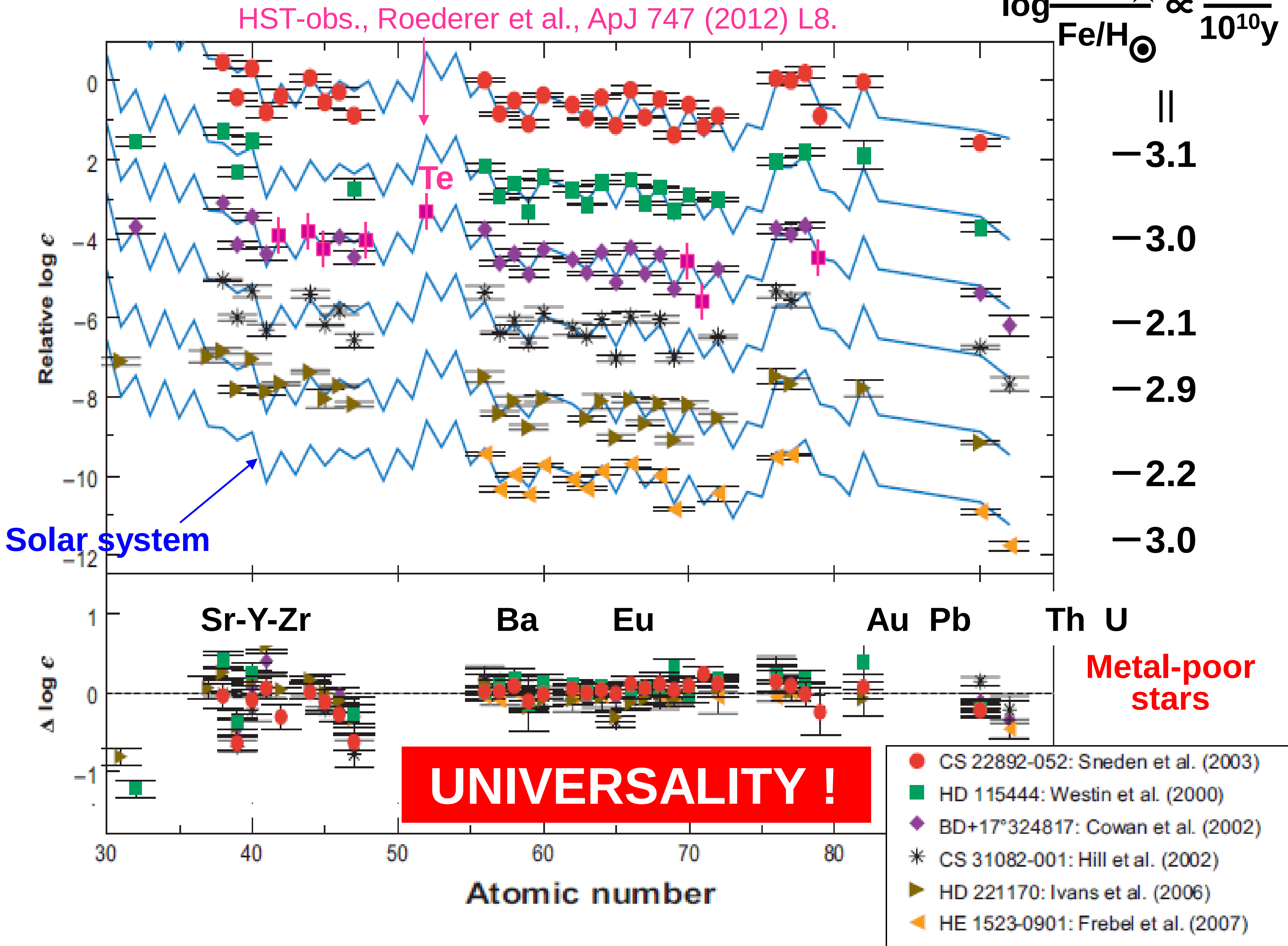
★ Only core-collapse supernova (Type II) can contribute to such 2nd generation metal-poor stars in the early Galaxy.




Early Universe

$$[Fe/H] = \log(N_{Fe}/N_H)_\star - \log(N_{Fe}/N_H)_\odot$$

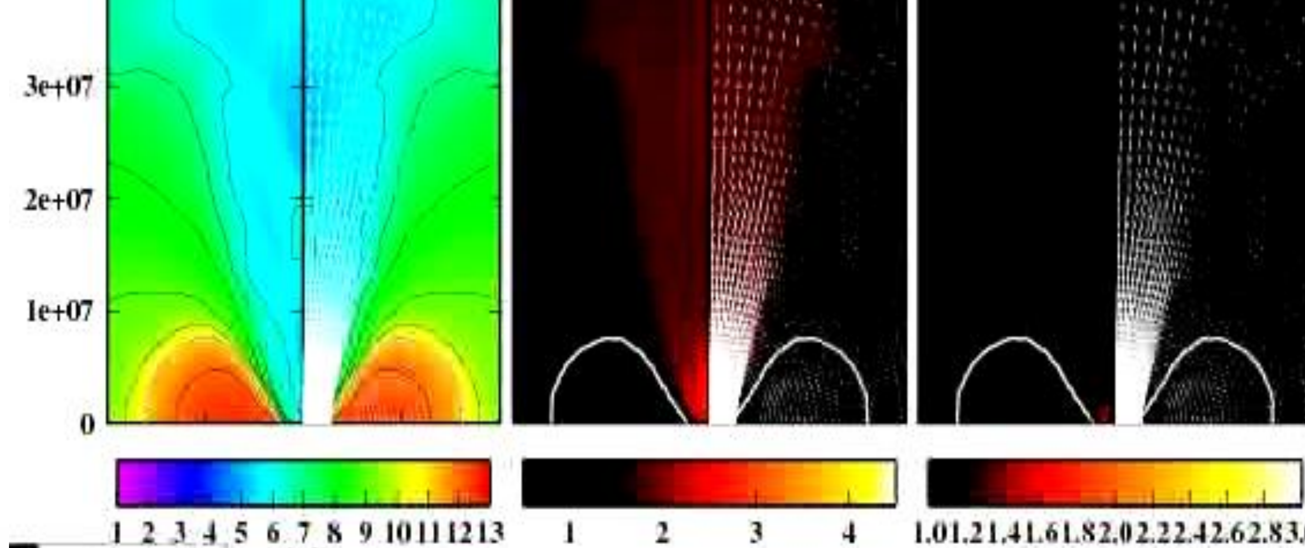
Sneden, Cowan, Gallino, ARAA 46 (2008) 241.

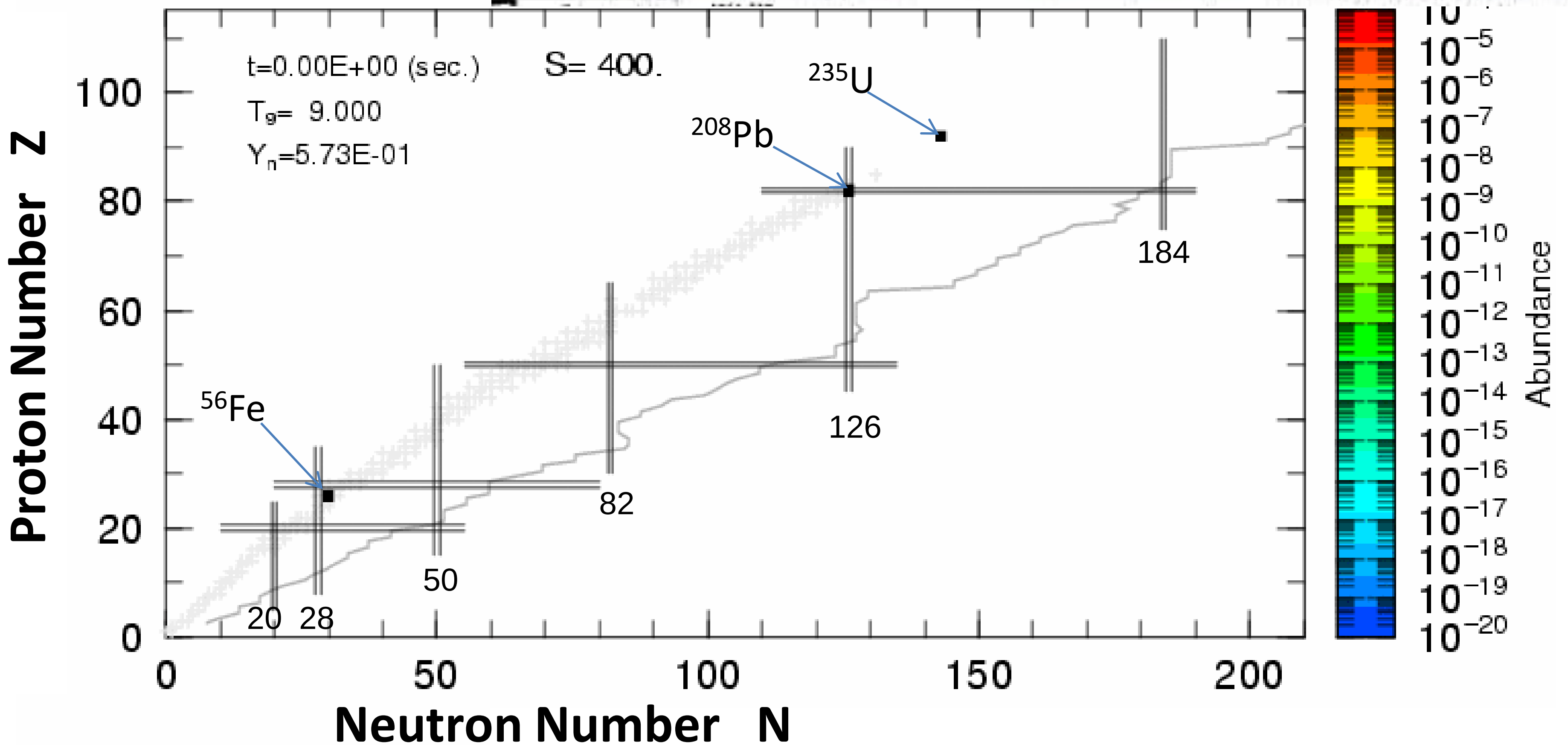


# Supernova Nucleosynthesis Simulation

T. Kajino & S. Chiba

ν-Pair Heated Collapsar Model
K. Nakamura, et al. ApJ (2012).



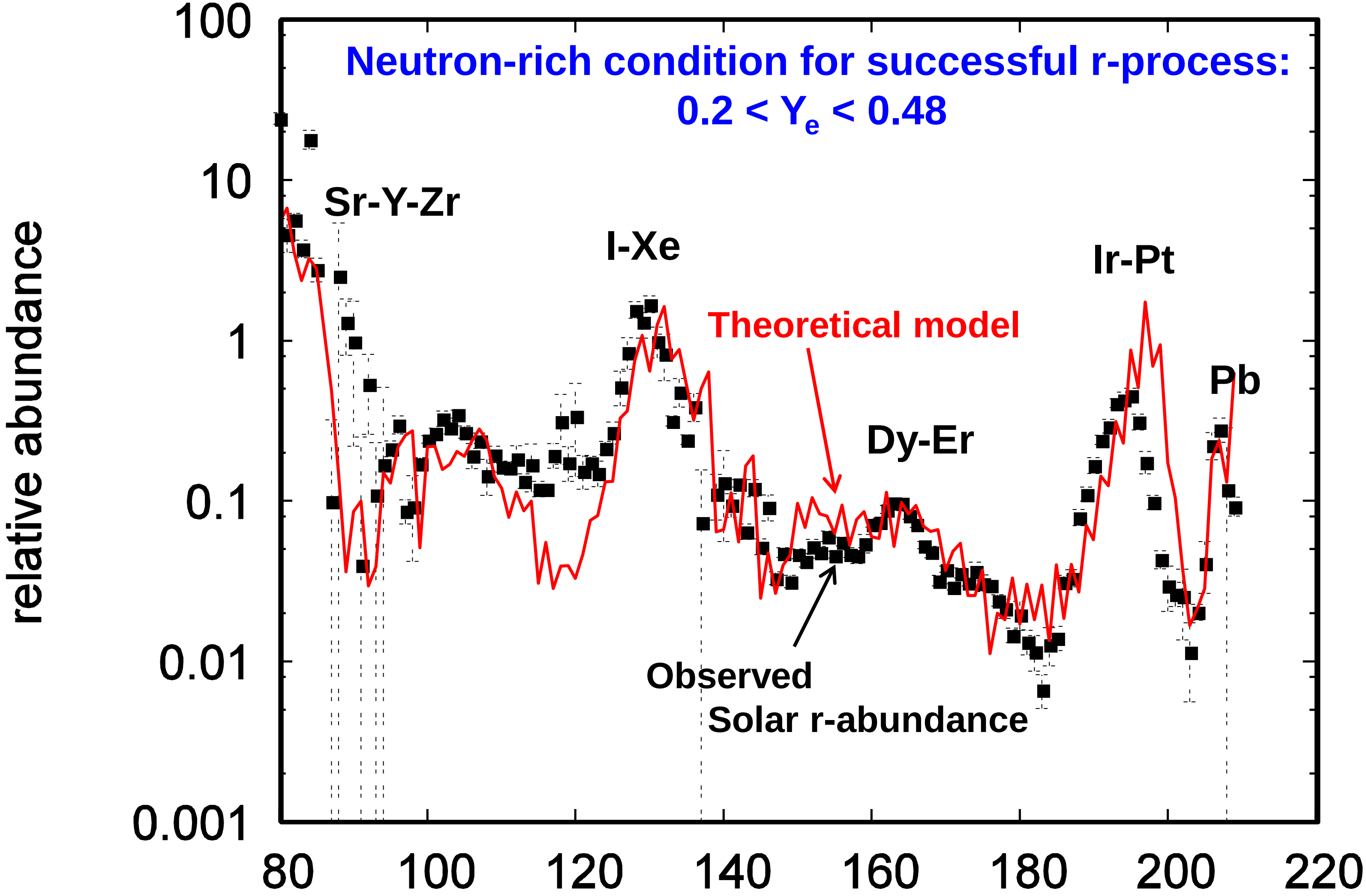



# R–process Nucleosynthesis

K. Nakamura. S. Sato. S. Harikae. T. Kajino and G.J. Mathews (2012), submitted to ApJ.

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

$T_{\nu e}$ = 3.2 MeV < $T_{\bar{\nu} e}$ = 4 MeV

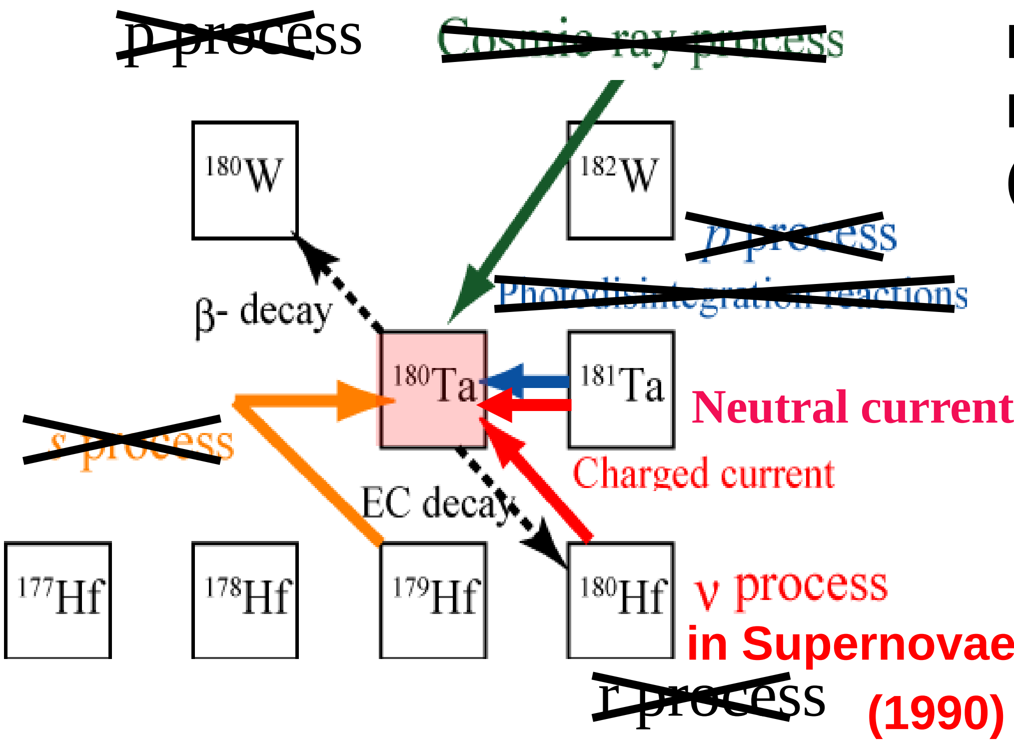


# Tantalum ($^{180,181}$Ta)

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

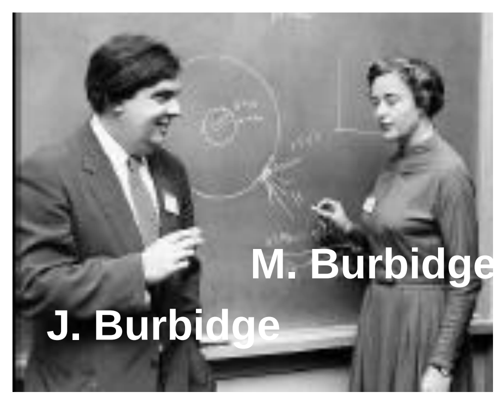
The rarest isotope in the Universe!

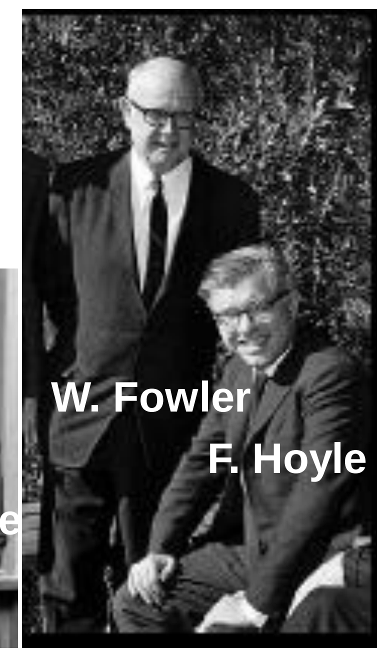
## Origin of $^{180}$Ta was unknown.




Burbidge[2]-Fowler-Hoyle,
Rev. Mod. Phys. 29
(1957), 547-650.

“Element Genesis”



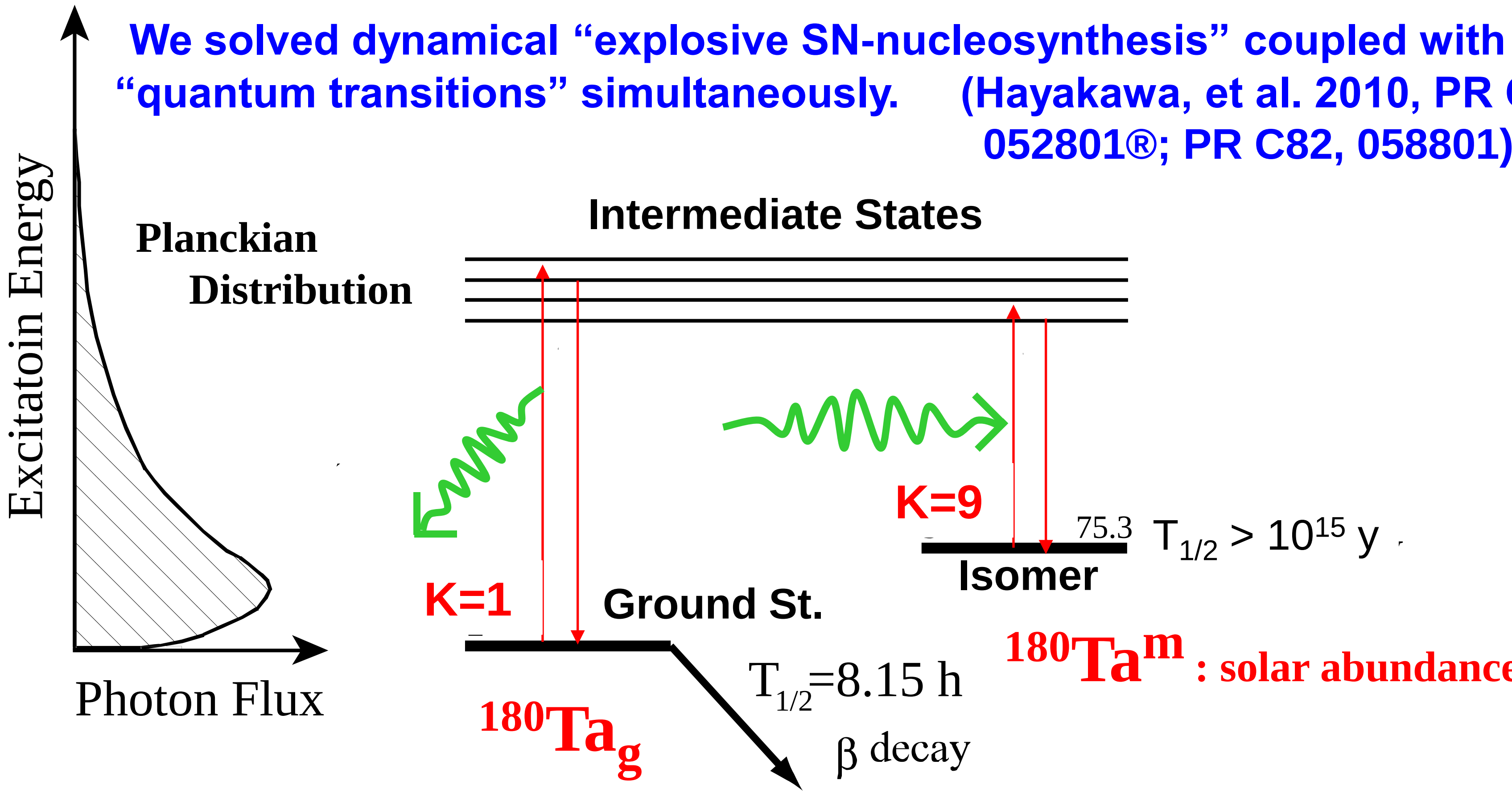



# $^{180}$Ta-genesis needs Quantum Phys. + SN Hydro-dyn.

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

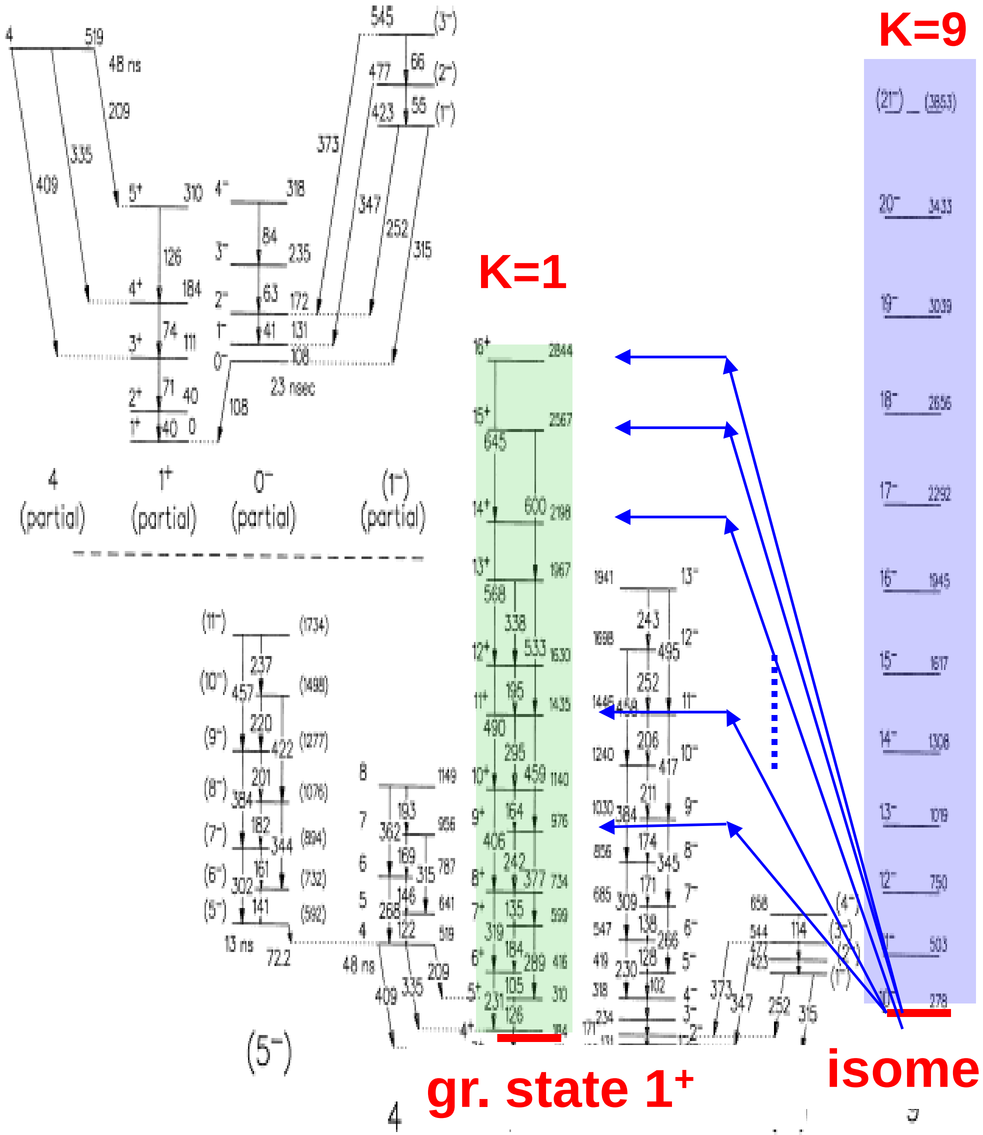
- **Long lived $^{180}$Ta$^m$ is excited in hot SN-photon bath.**
- **Intermediate states are depopulated to the ground state, which decays in 8 hours.**

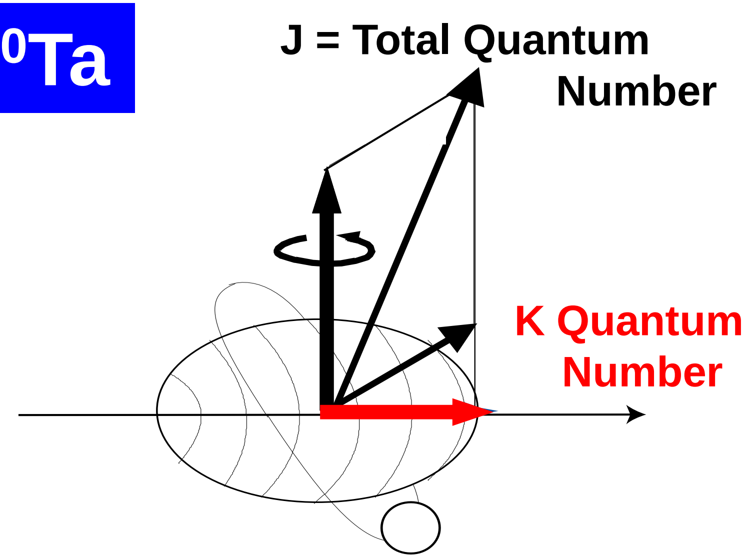
**We solved dynamical "explosive SN-nucleosynthesis" coupled with "quantum transitions" simultaneously. (Hayakawa, et al. 2010, PR C81, 052801®; PR C82, 058801)**



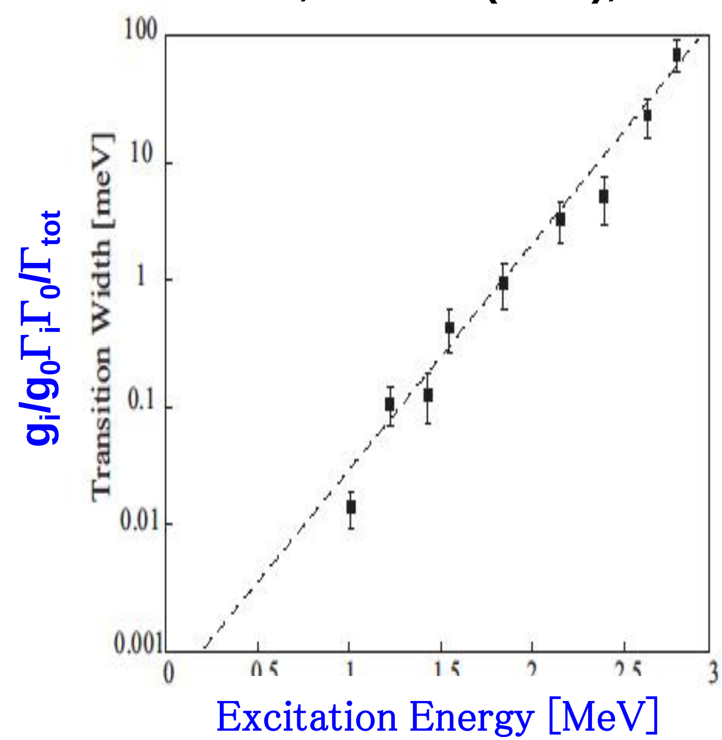
# ν-Process and Structure of $^{180}$Ta

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



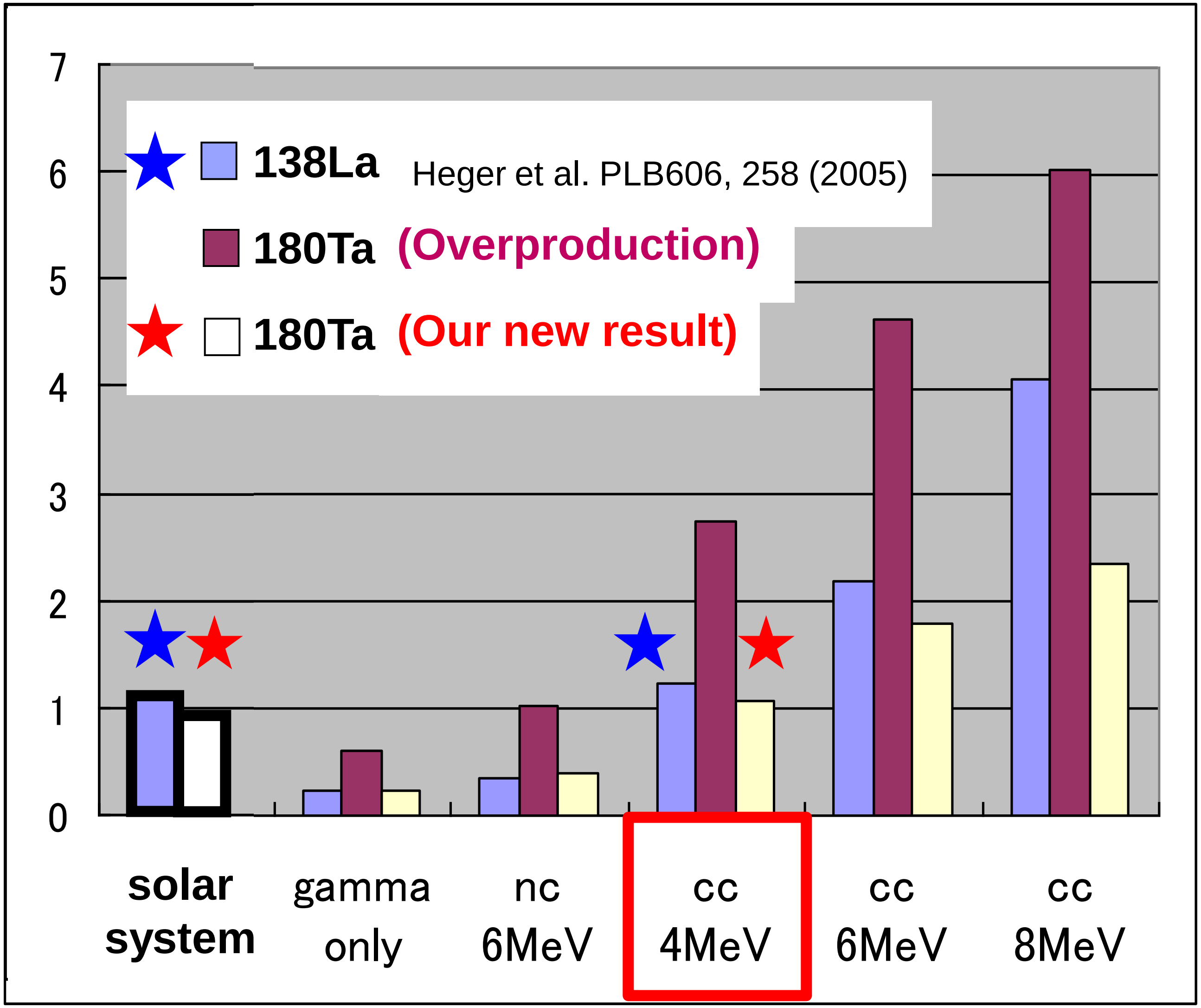




D. Belic et al., PR C65 (2002), 035801.



# 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 !**

# ν-A reaction cross sections?

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

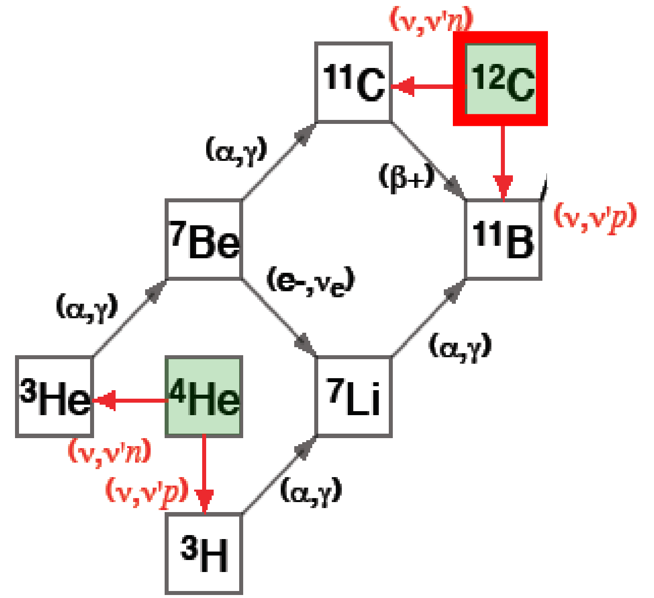
**Suzuki's new SM cal. with NEW Hamiltonian**

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

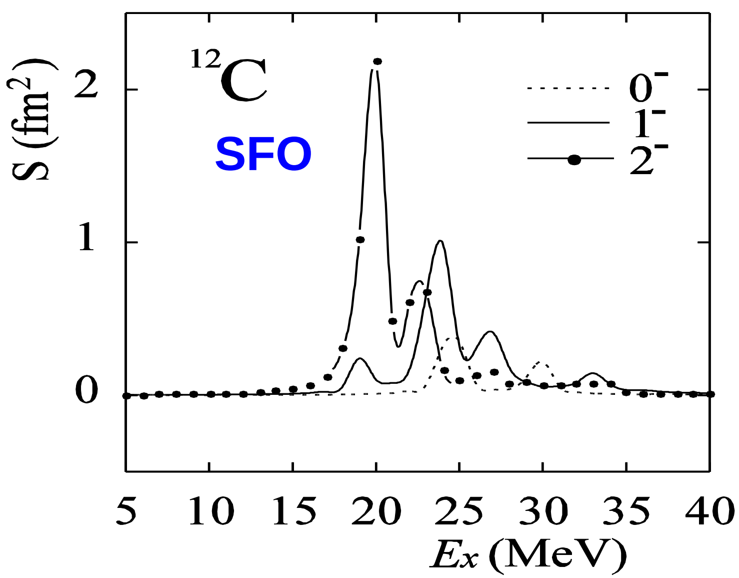
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003)

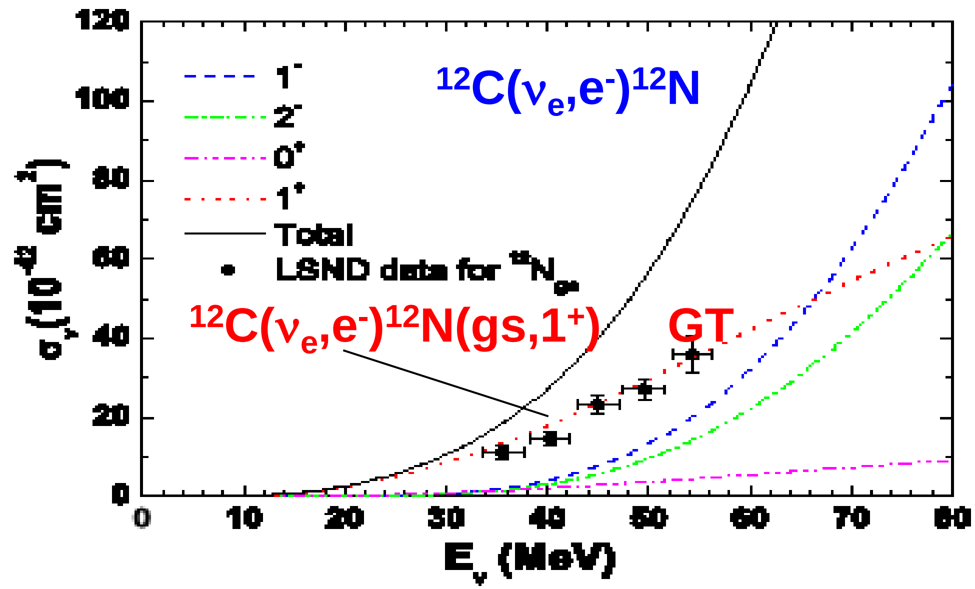
**$^{12}$C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.**

- **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**




**Cheoun et al., PRC81 (2010), 028501; J. Phys. G37 (2010) 055101: QRPA Cal.**



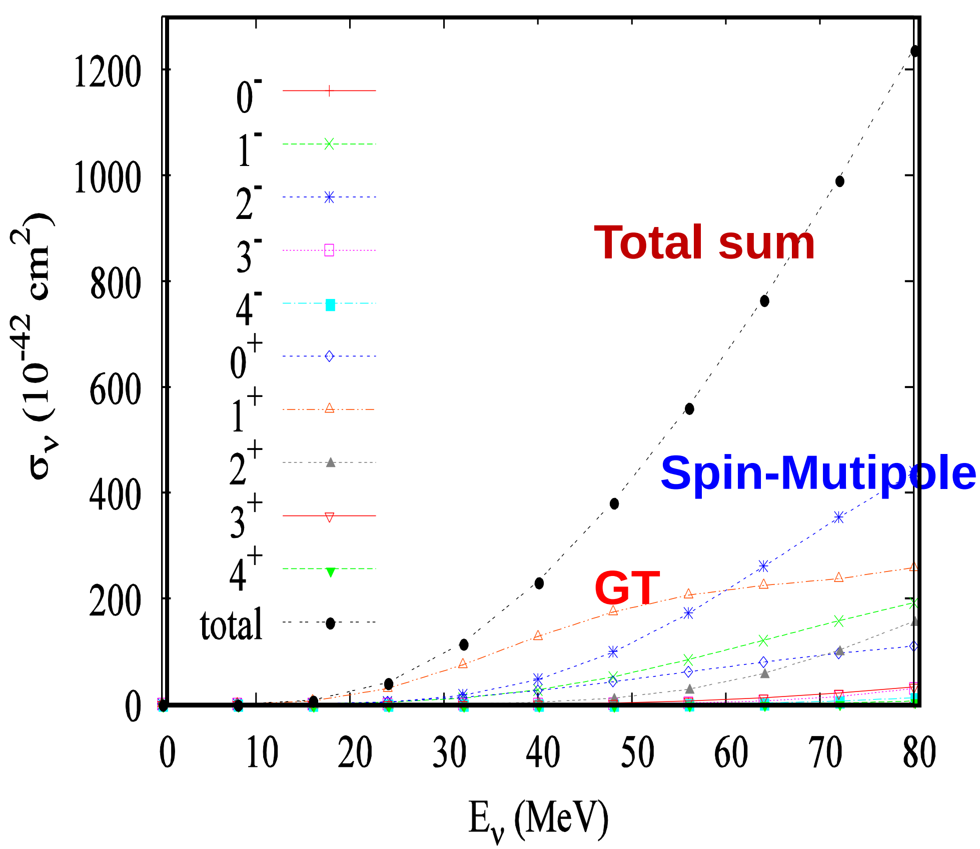



# $\nu$-$^{180}$Ta, $^{138}$La, $^{92}$Nb, $^{42}$Ca, $^{12}$C, $^{4}$He… X-sections in Quasi-particle Random Phase Approximation (QRPA)

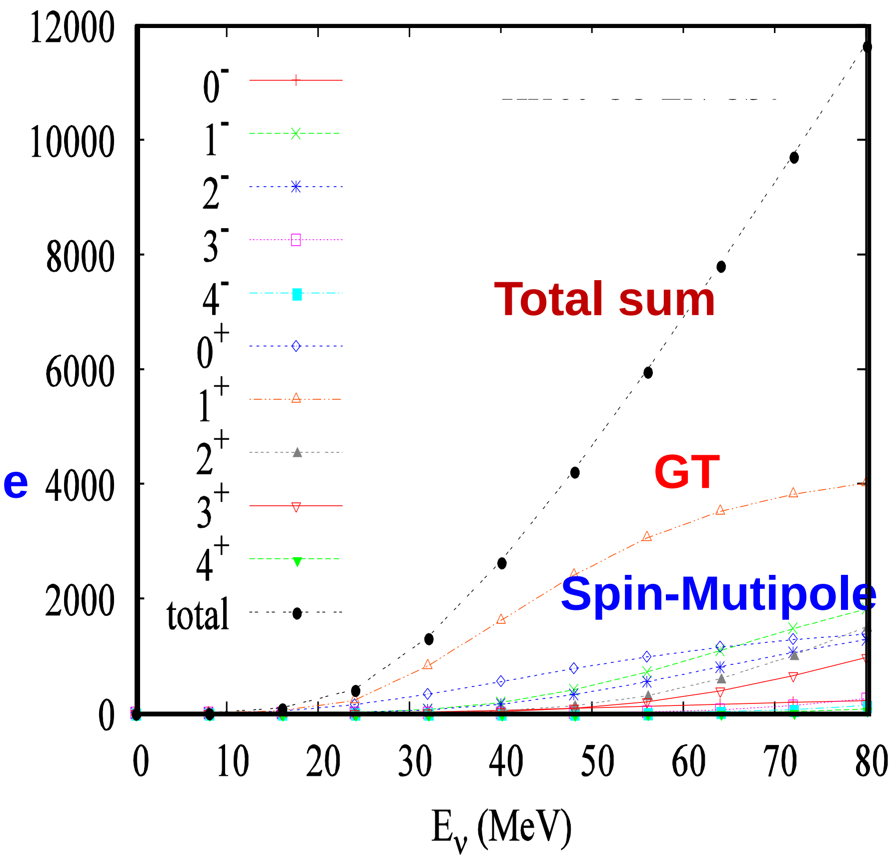
Cheoun, Ha, Hayakawa, Kajino & Chiba, PRC82 (2010), 035504;
Cheoun, Ha, Kim, & Kajino, J. Phys. G37 (2010) 055101; Cheoun, Ha & Kajino, PRC 83 (2011), 028801

## GT + Spin-Multipole transitions !

$^{181}$Ta + $\nu \rightarrow$ $^{180}$Ta + n + $\nu'$ (NC)




$^{180}$Hf + $\nu \rightarrow$ $^{180}$Ta + $e^-$ (CC)

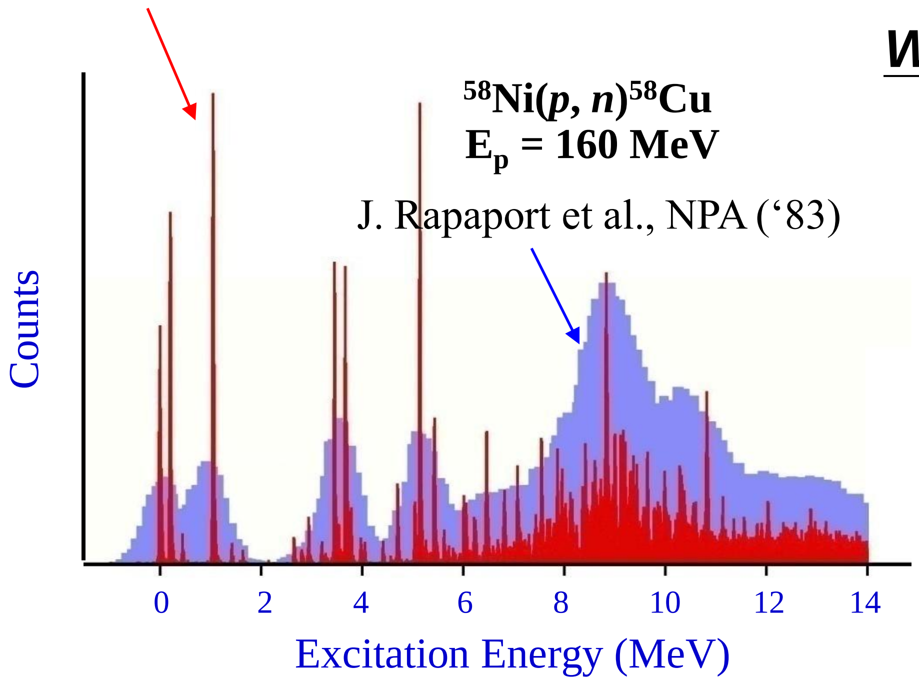


- ν-beam is not yet available !
- EM-PROBE (CEX hadrons, γ's) ! c.f. Harakeh, Shima

## 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***

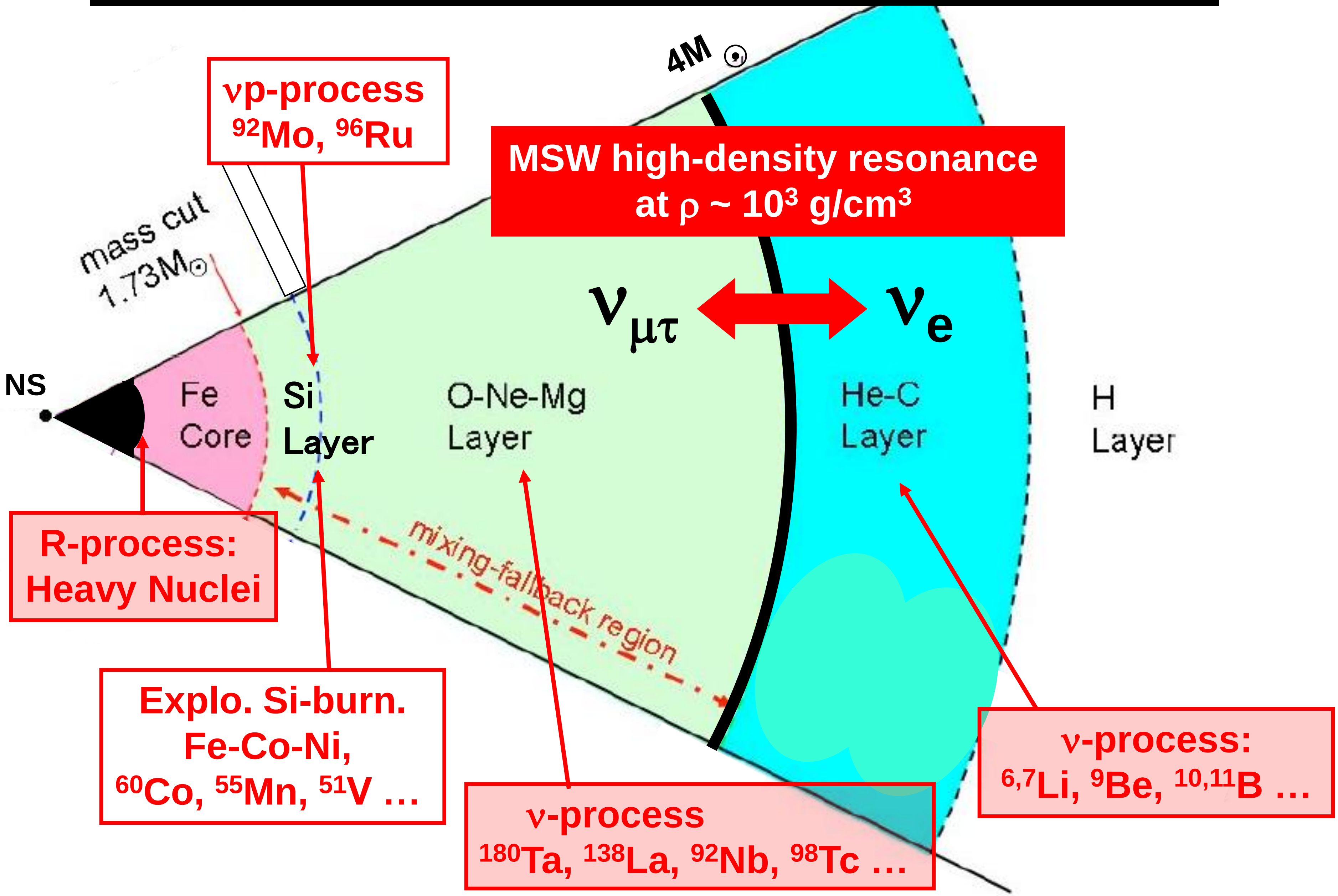
*Gamow-Tellar operator* = $\vec{\sigma}\tau_{\pm}$

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

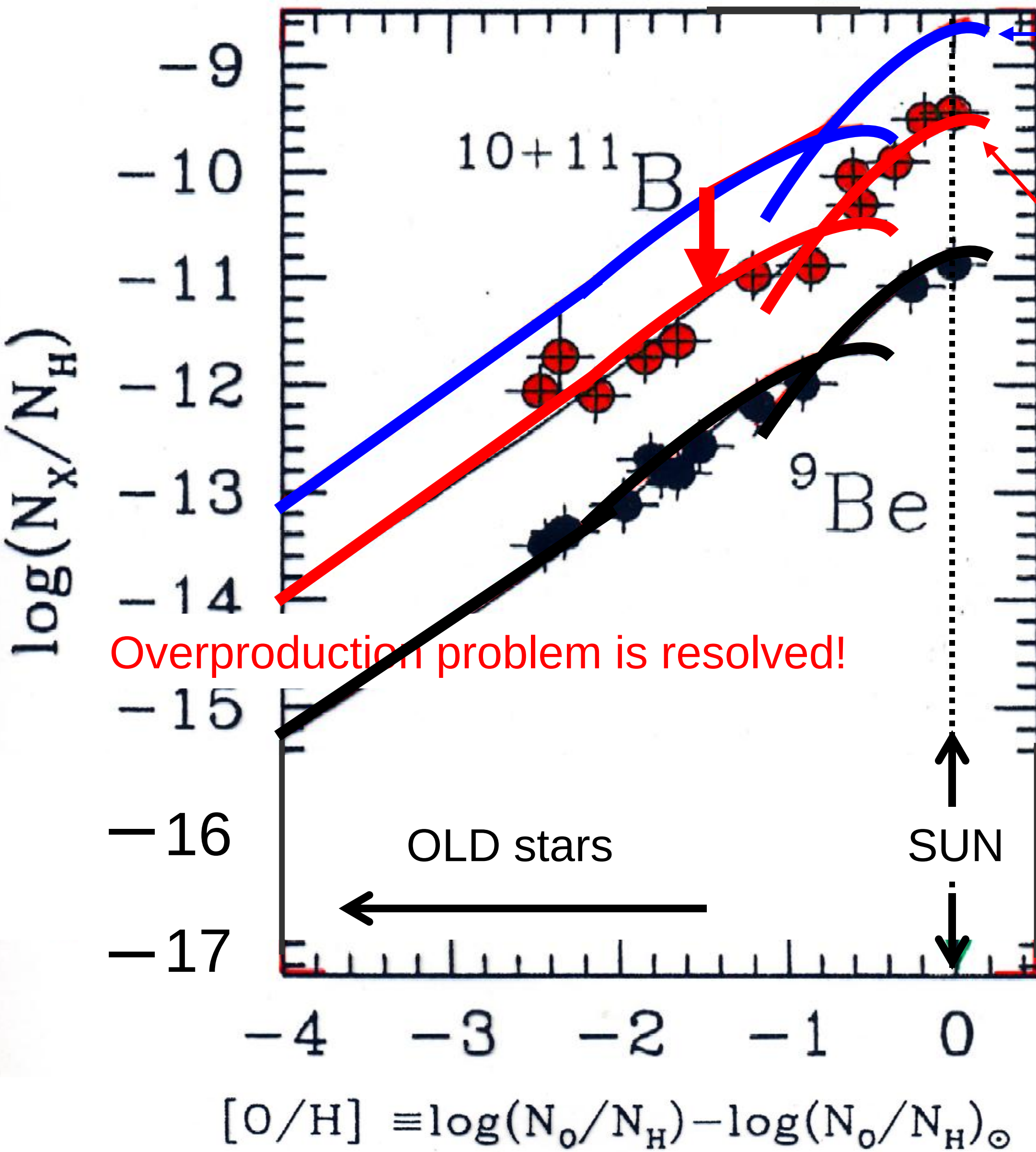
★ **Charge-Exchange Reaction**

★ **Photo-induced Reaction**

# Various roles of ν's in SN-nucleosynthesis



# 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

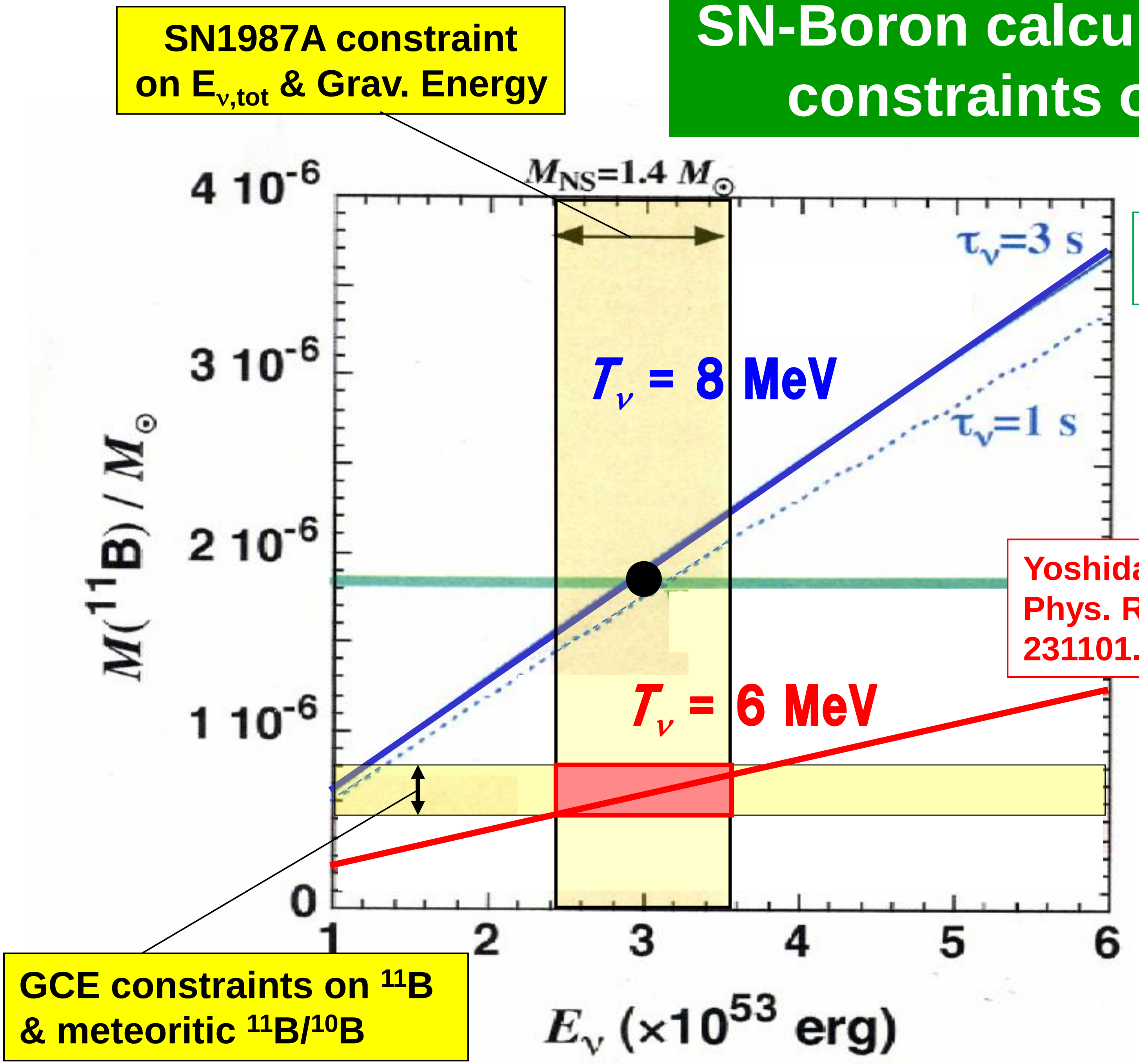
**$^{10+11}$B + $^{11}$B:**

— 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




Woosley & Weaver
ApJS 101 (1995), 181.

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

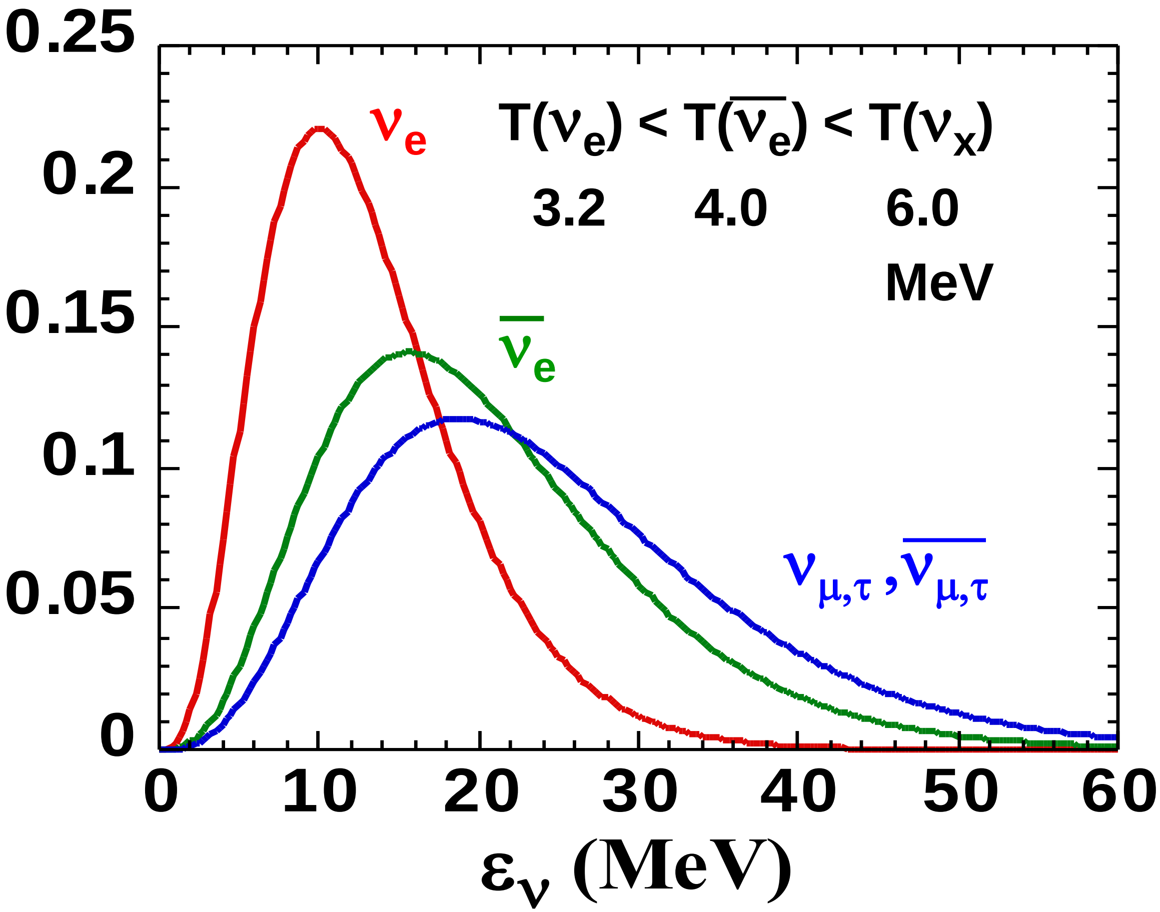
Consistent with recent numerical simulation by Thomas-Janka et al. (MPA group) 2004-2011.

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

R-process, $^{180}$Ta/$^{138}$La ⇨ $T\nu_e$ = 3.2 MeV, $T\bar{\nu}_e$ = 4 MeV

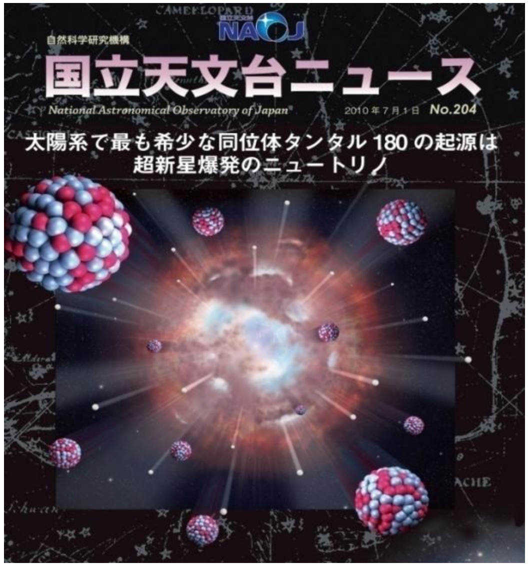
Astron. GCE of $^{11}$B & $^{11}$B/$^{10}$B ⇨ $T\nu_{\mu}$, = $T\nu_{\tau}$ = 6 MeV

ν-temperatures are known!





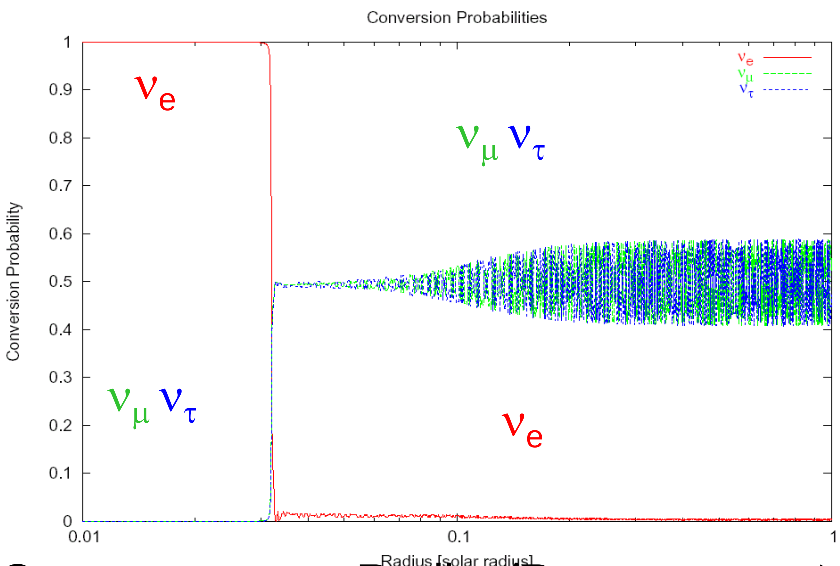
科学新聞
太陽系で最も希少な同位体
タンタル180
超新星爆発のニュートリノで生成
原子力機構 国立天文台
起源の謎を理論的に解明

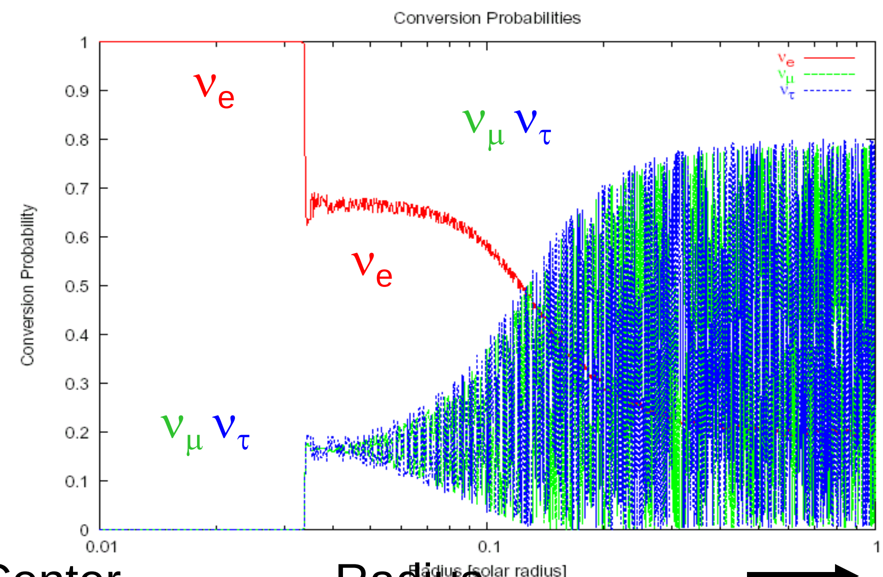


# SN-Neutrino Oscillation (MSW) Effect on ν-Process

Conversion Probability

Adiabatic | Non-Adiabatic




Center Radius/$R_{sun}$ → Center Radius$_{sun}$ →

## Parameters:

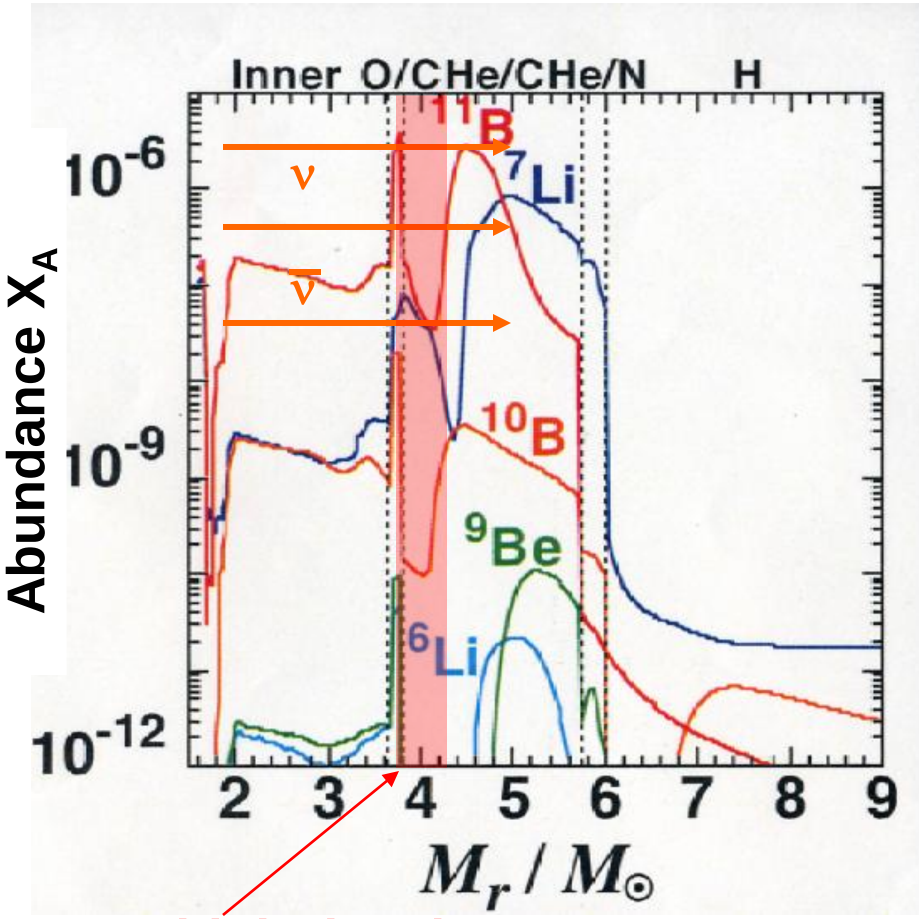
$25M_{solar}$ SN model (Hashimoto & Nomoto 1999)

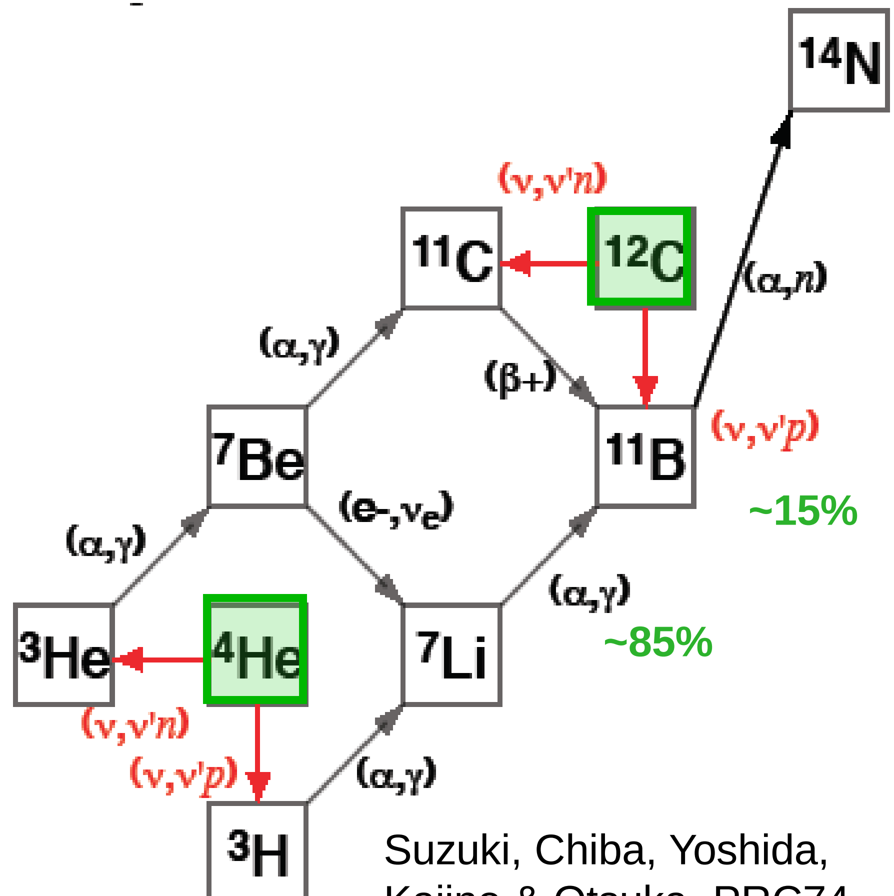
- $\sin^2 2\theta_{13}$ = 0.04
- $\Delta m_{13}^2 = 2.4 \times 10^{-3}$ eV$^2$
- $L_\nu = 3 \times 10^{53}$ erg, $\tau_\nu$ = 3 sec
- $E_{\nu e}$=12MeV, $E_{\bar{\nu}e}$=20MeV, $E_{\nu\mu\tau}$=24MeV

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

# Oscillation (MSW) Effect on Supernova ν-Process

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

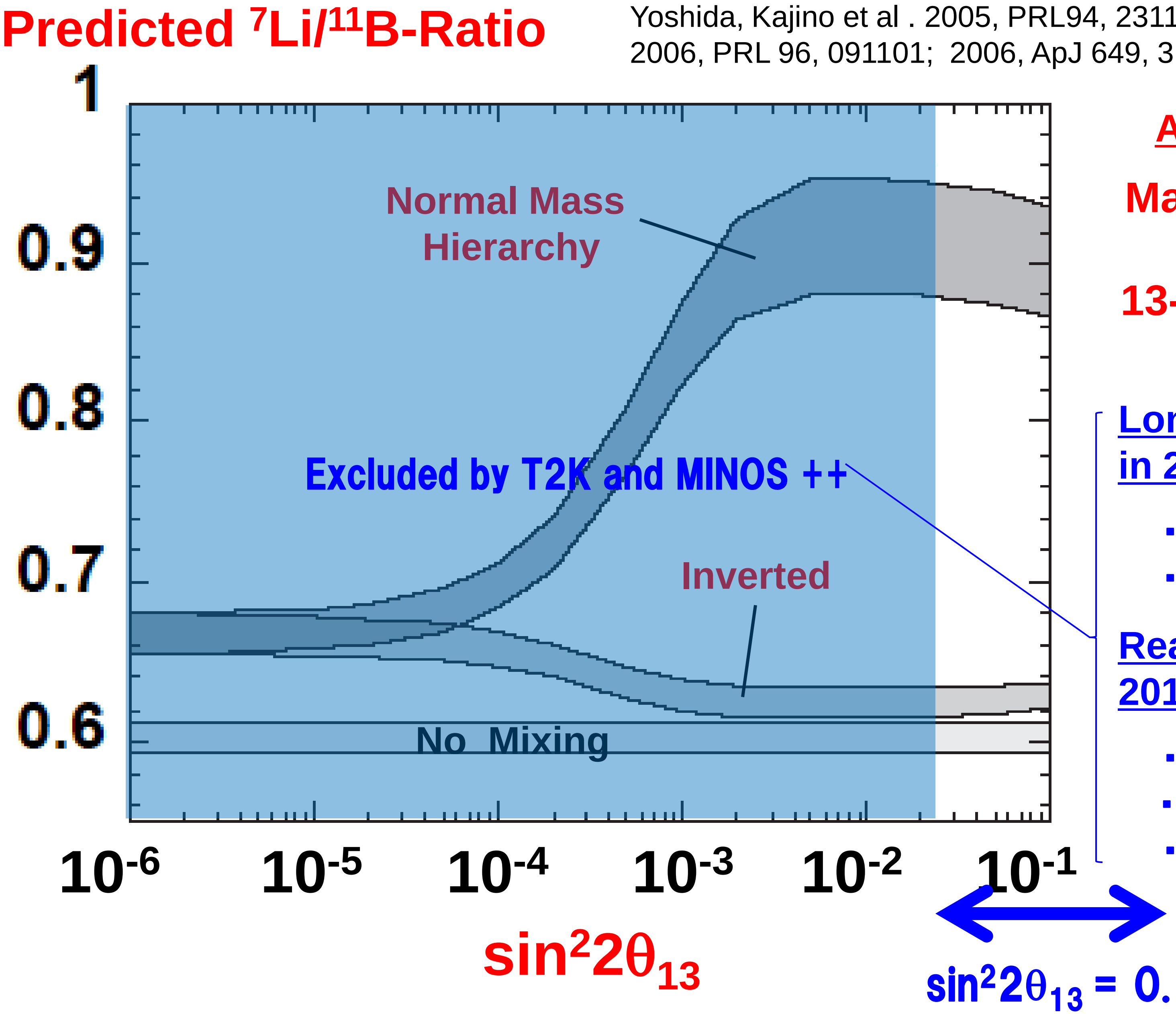
**MSW high-density resonance**

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

$\nu_x \rightarrow \nu_e$ $^4$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

# Our Theoretical Prediction

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 BaselineExp. in 2011:**

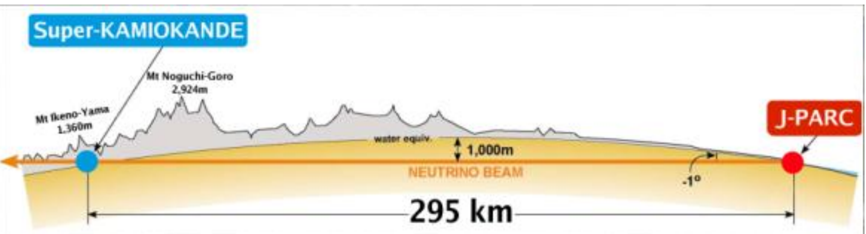
- T2K (Kamioka)
- MINOS

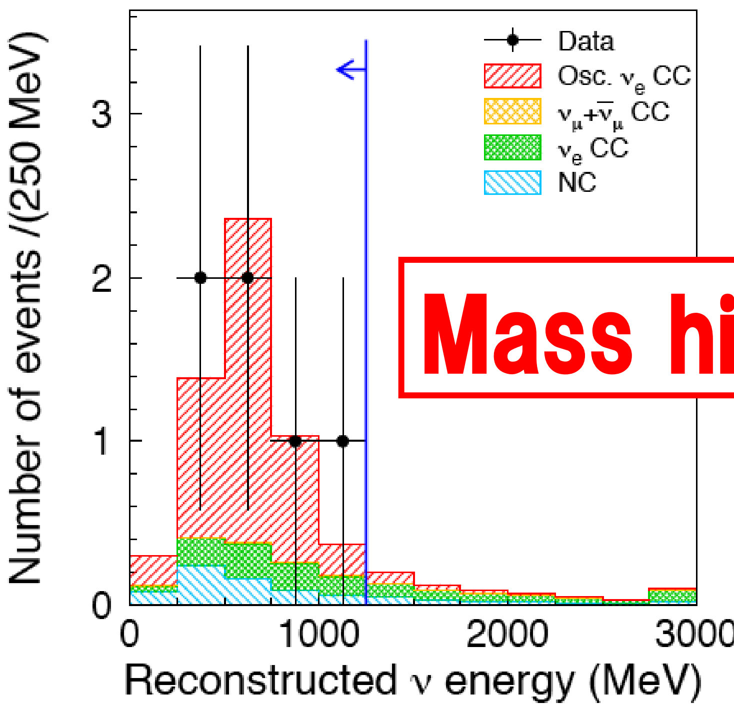
**Reactor Exp. in 2012:**

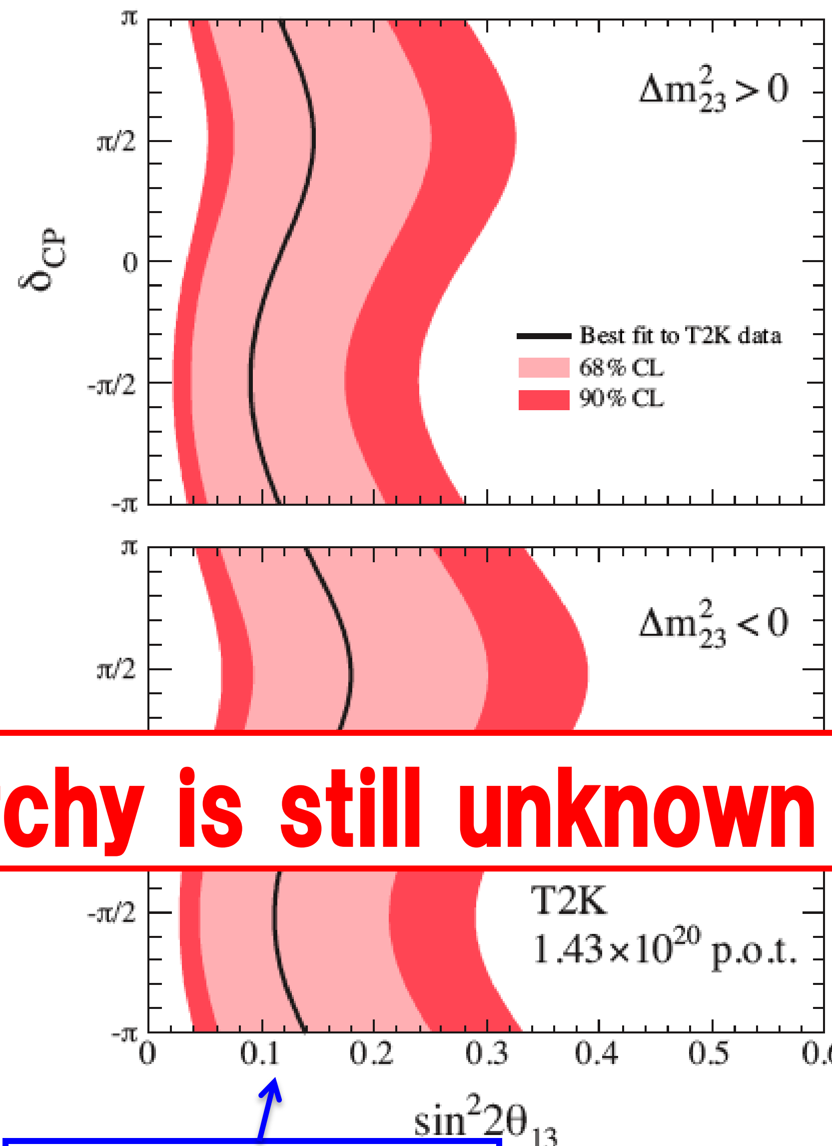
- Double CHOOZ
- Daya Bay
- RENO (KOREA)

# T2K & MINOS results (2011)

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




**Mass hierarchy is still unknown !**

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

# RENO, Daya Bay and Double Chooz results (2012)

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

**Measuring $\theta_{13}$ with Reactor Anti-neutrinos**

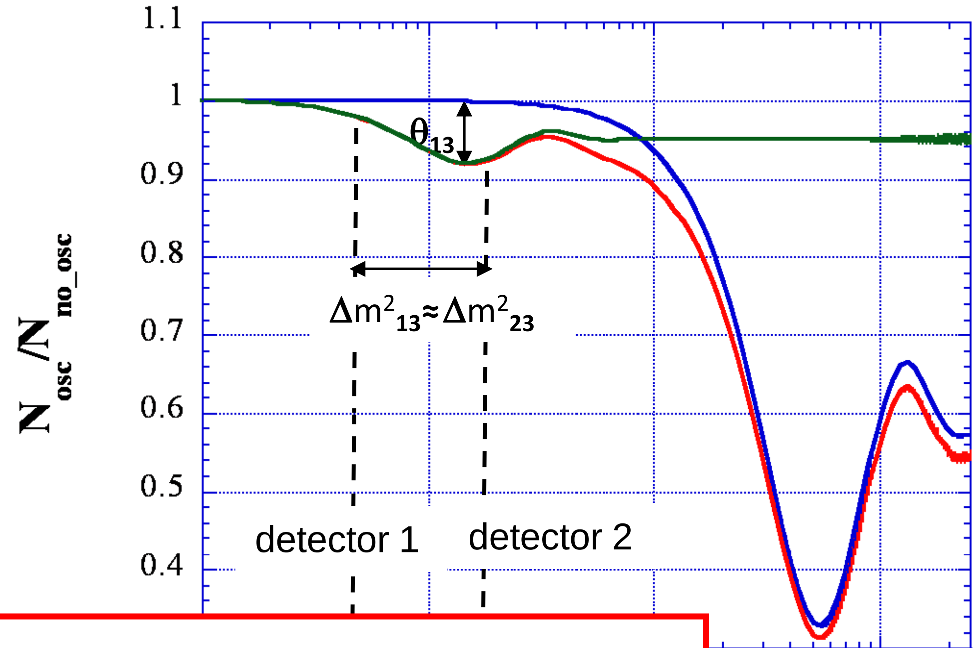
$\sin^2 2\theta_{13} = 0.103 \pm 0.013\,(\mathrm{st}) \pm 0.011\,(\mathrm{sys})$

$\rightarrow \theta_{13} = 8.88$ deg

**Reactor neutrino energies are too low to produce muons. Hence this is an antineutrino disappearance experiment (also no matter effects).**

Small-amplitude oscillation due to $\theta_{13}$ integrated over E

Large-amplitude oscillation due to $\theta_{12}$

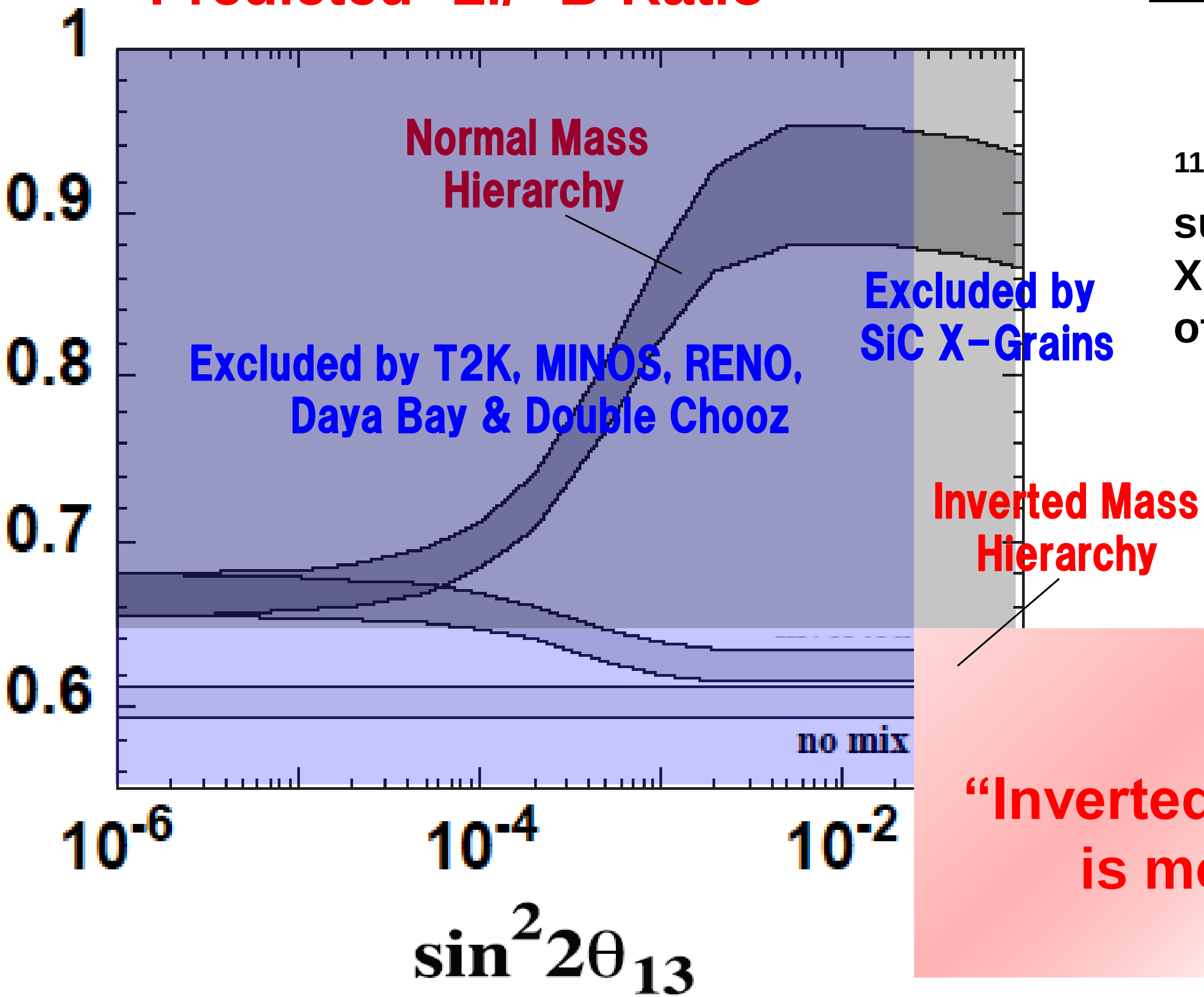



**Mass hierarchy is still unknown !**

# Mass Hierarchy, Normal or Inverted ?

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

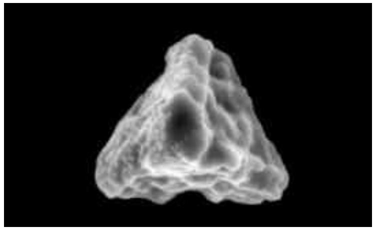
## Predicted $^{7}Li/^{11}B$-Ratio




## First Detection of $^{7}Li/^{11}B$

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

**$^{11}B$ and $^{7}Li$ were measured in SiC presolar X-grains which are made of Supernova dusts.**



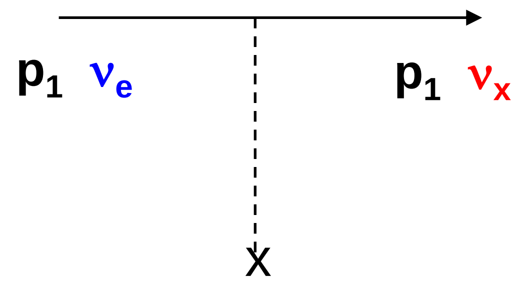
**"Inverted Mass Hierarchy" is more preferred !**

# 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)**

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

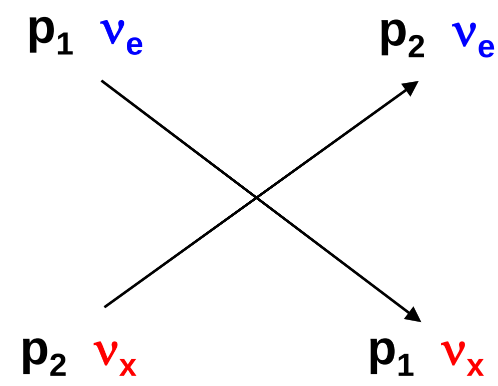



$N_e$ = electron density

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

**Self-Interaction**

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




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

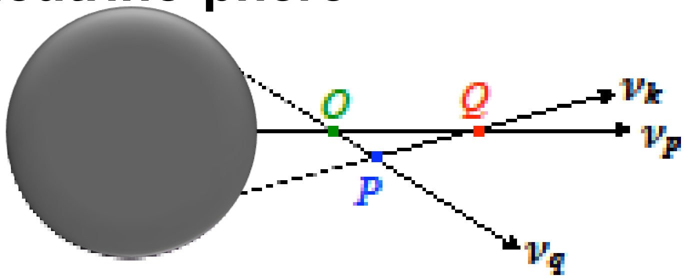
"Invariants of collective neutrino oscillations"

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

Phys. Rev. D84, 065008 (2011)

# ν self-interaction (Quantum Effect)

**neutrino-phere**




H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian,
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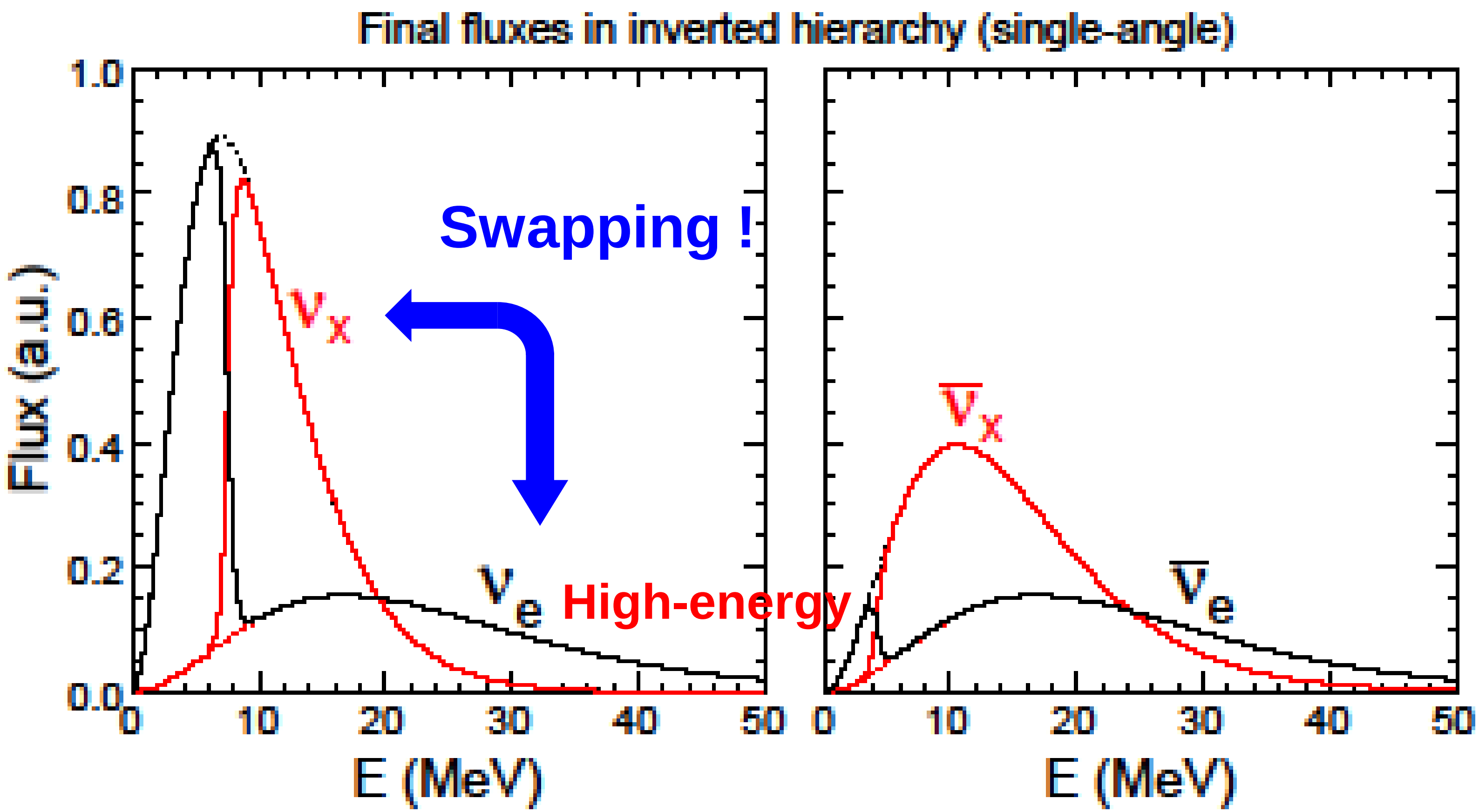
A. B. Balantekin, Y. Pehlivan, J. Phys.G34, (2007) 47.

**r = 200km**



# CONCLUSION

We propose a new astrophysical method to determine the unknown $\nu$-mass hierarchy $\Delta m_{13}{}^2$ in terms of the supernova $\nu$-nucleosynthesis by taking account of the MSW effects.

Combining the recent detection of $^7Li/^{11}B$ isotopic ratio measured in presolar Supernova X-grains and the $\theta_{13}$ value determined from the long-baseline and reactor neutrino-oscillation experiments,
we can conclude that the "inverted mass hierarchy" is statistically more preferred.

We need to study the nature of neutrino oscillation due to the MSW matter effects and the effects of self interactions.