10th Russbach School on Nuclear Astrophysics
Salzburg, Austria, March 10-16, 2013

Supernova Ncleosynthesis and Neutrino Oscillation

θ_{13} is known !
Mass hierarchy and CP-pahse come next ?

Taka KAJINO
National Astronomical Observatory
Department of Astronomy, University of Tokyo

Challenge of the Century

Universal expansion is most likely <u>accelerating</u> and <u>flat</u> !

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

- **What is the Cold Dark Matter, Ω_{CDM} = 0.23, and Dark Energy, Ω_Λ = 0.73 ?**

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

- **Is BARYON sector, Ω_B = 0.04, well understood ?**

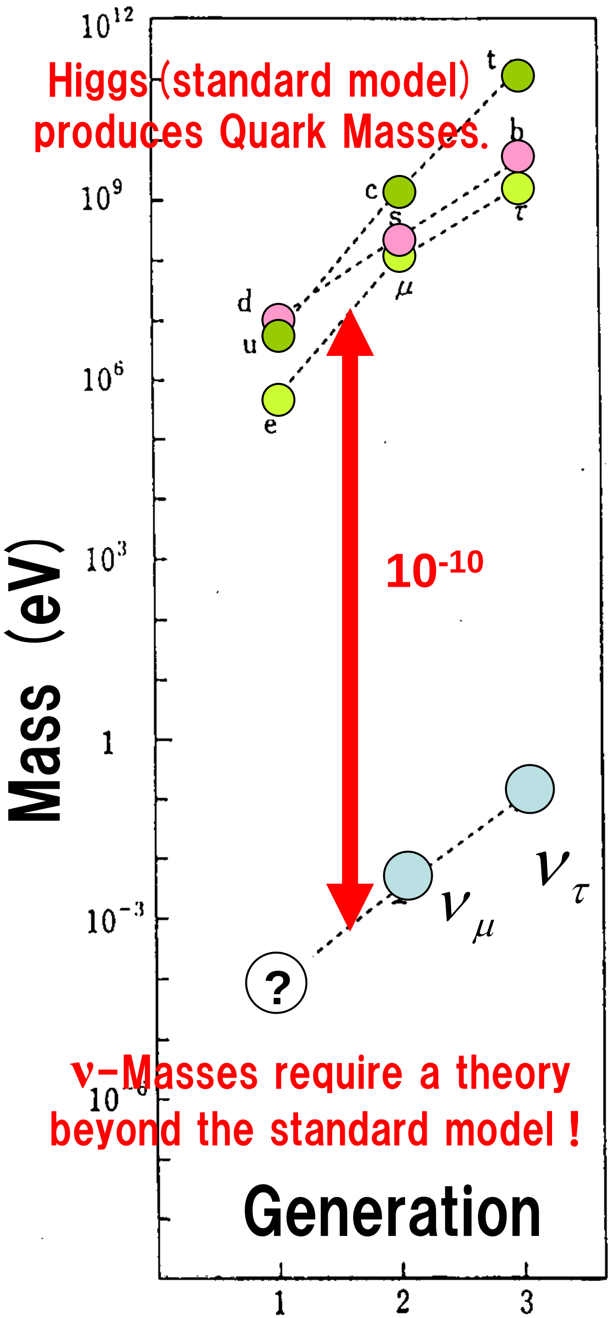
  BBN with **Axions + SUSY** to solve **Dark Matter Problem & Li Problem**:
  Kusakabe, Balantekin, Kajino & Pehlivan, Phys. Lett. B718 (2013) 704.

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

→ **ν mass and hierarchy ?**

Today's Talk

"Supernova ν-Process Nucleosynthesis" to determine the <u>ν-MASS HIERARCHY.</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 ?

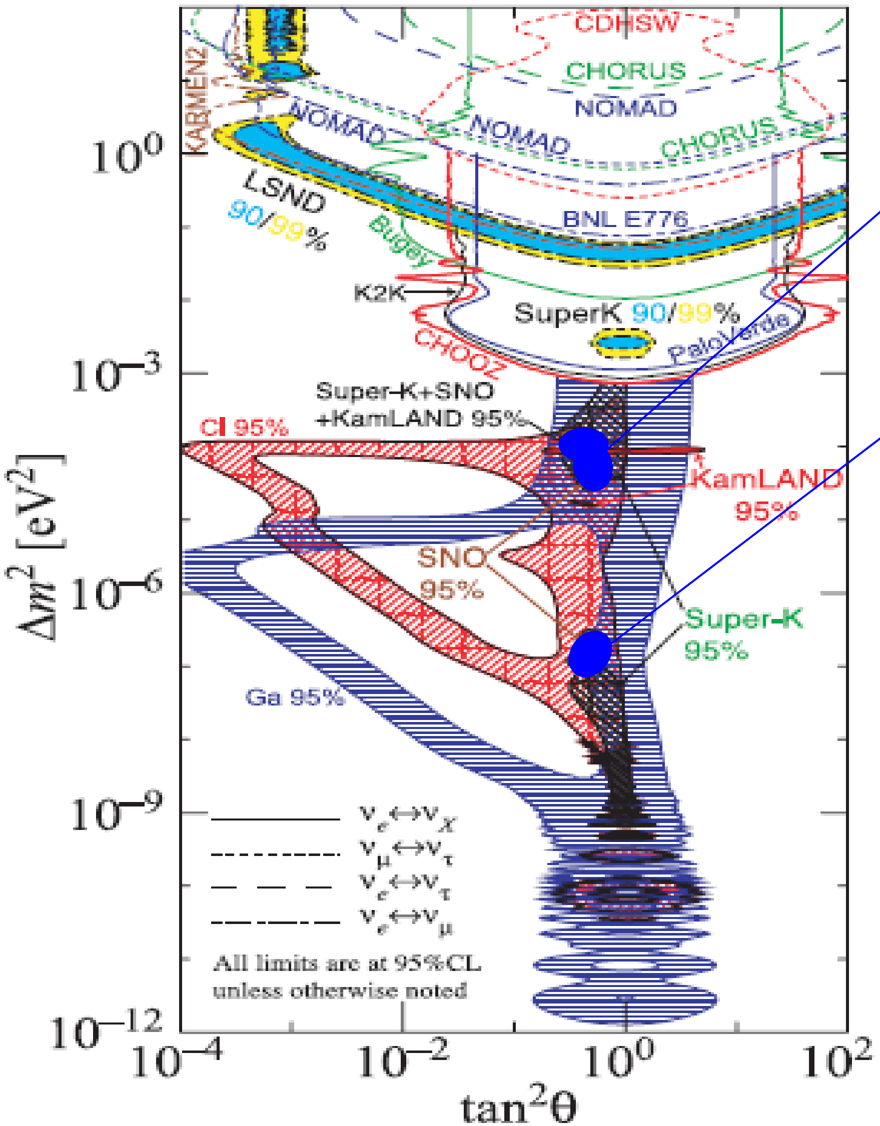
CP violation and Lepto- & Baryo-genesis ?

Why left-handed neutrinos, Majorana or Dirac ?

Explosion Mechanism of Supernovae ?

“KNOWN” of Neutrino Oscillations

KAMIOKANDE, SK, KamLand (reactor ν), SNO determined Δm_{12}^2 and θ_{12} uniquely, and also SK (atmospheric ν) determined Δm_{23}^2 and θ_{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

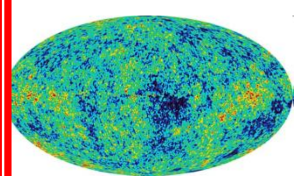
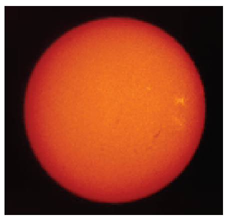
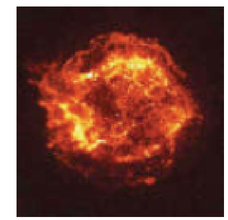
E(νμ)=E(ντ): Yokomakura et al., PL B544, 286.

Various Neutrino-Sources in Nature

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

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

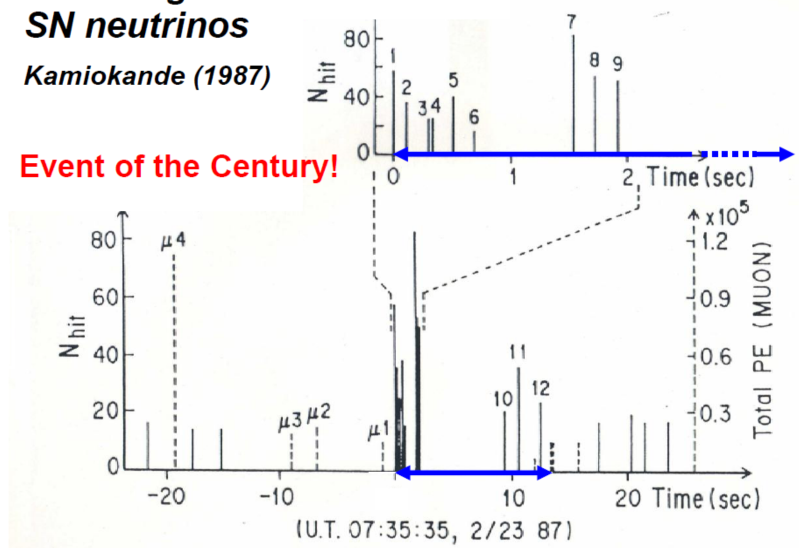
inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CMB Cosmic Background	^{7}Be solar neutrino	geo-neutrino	reactor neutrino	supernova relic neutrino etc.
				
Neutrino Cosmology	Neutrino Astrophysics	Neutrino Geophysics	Neutrino Physics	Neutrino Cosmology
verification of particle model	verification of SSM	verification of earth evolution model	Precision measurement of oscillation parameters	verification of universe evolution
ν_e, ν_μ, ν_τ				ν_e, ν_μ, ν_τ

Direct signal of SN neutrinos

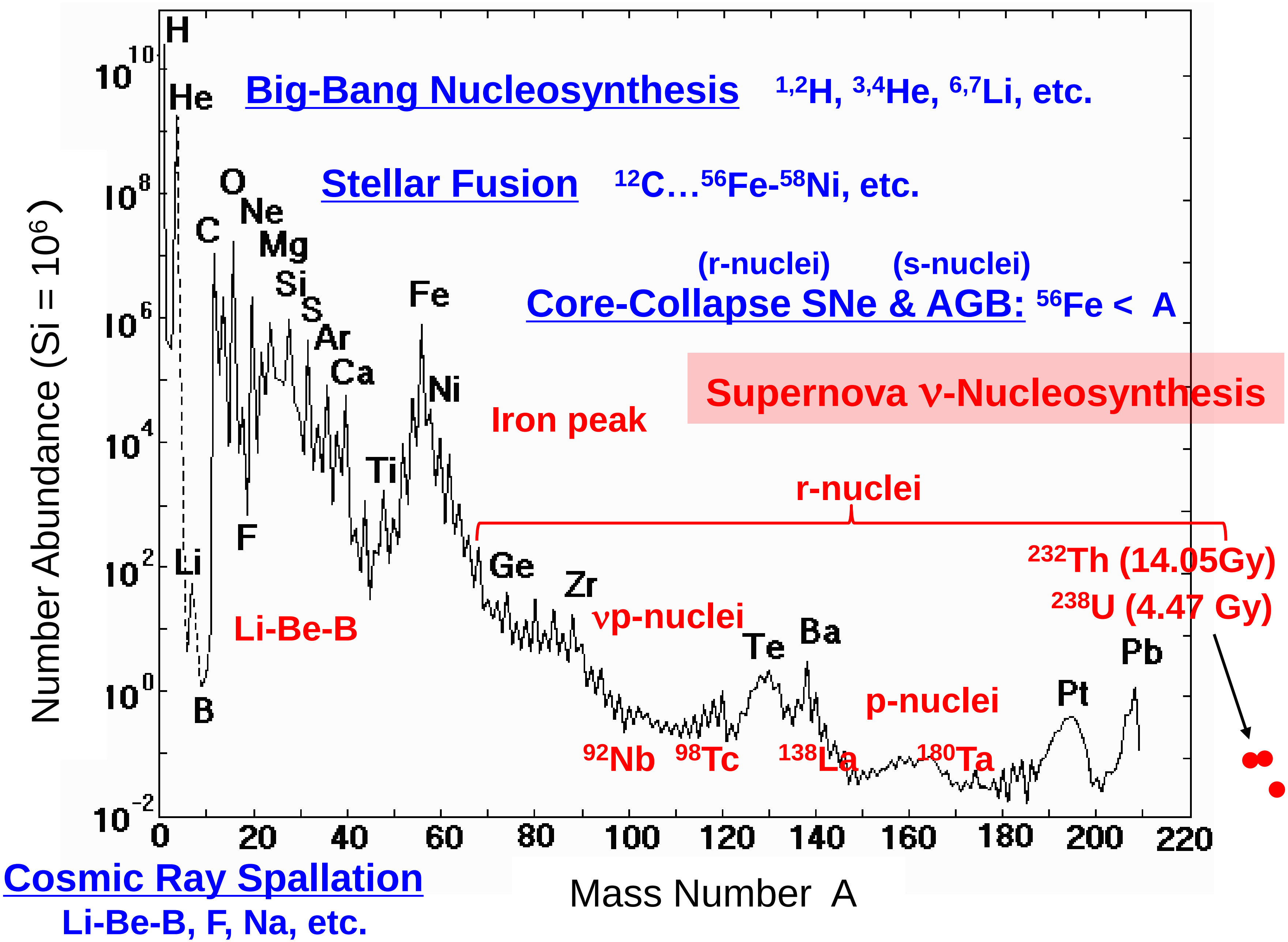
Kamiokande (1987)

Event of the Century!

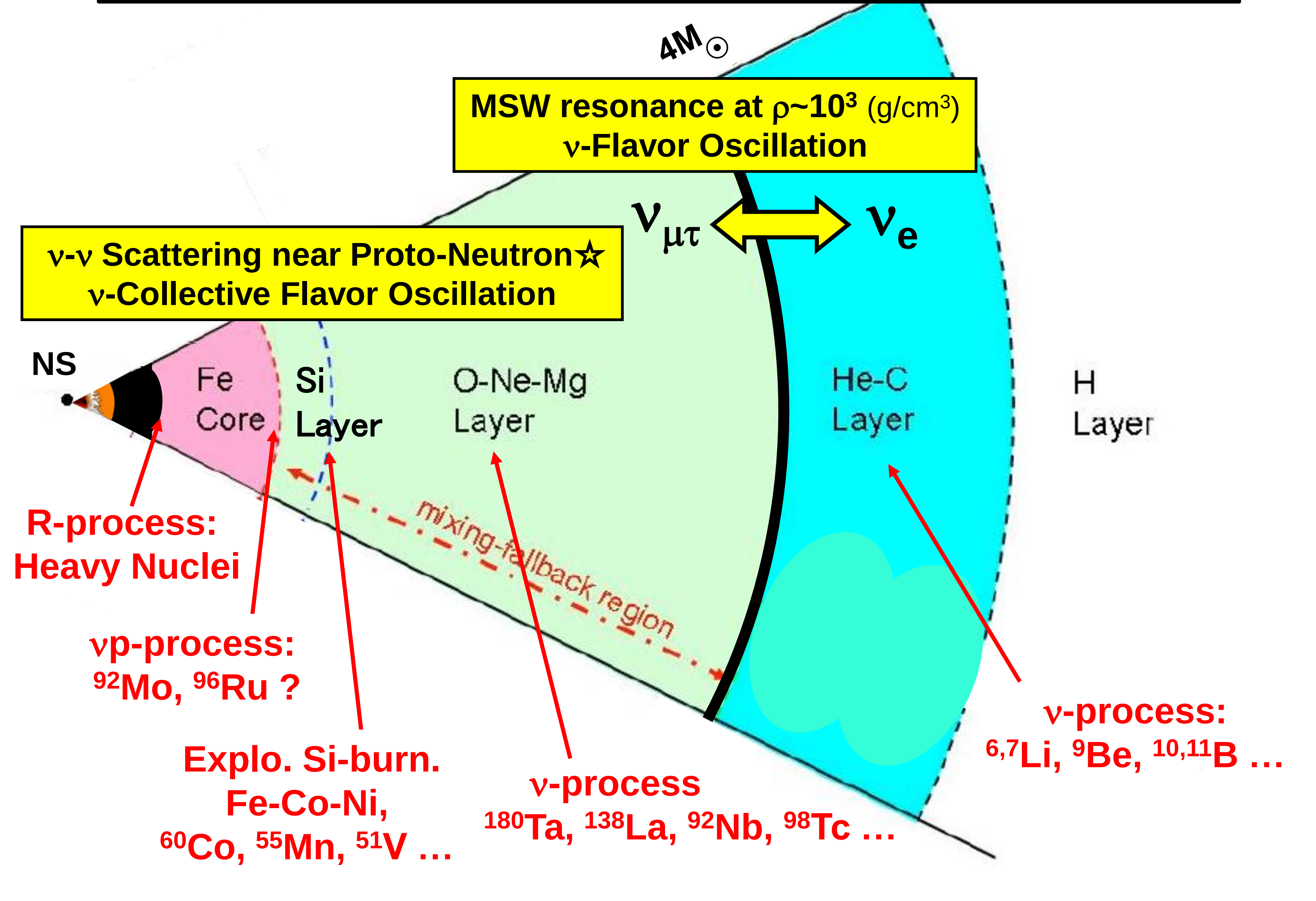


SN ν-spectra are still unknown !

Solar System Abundance



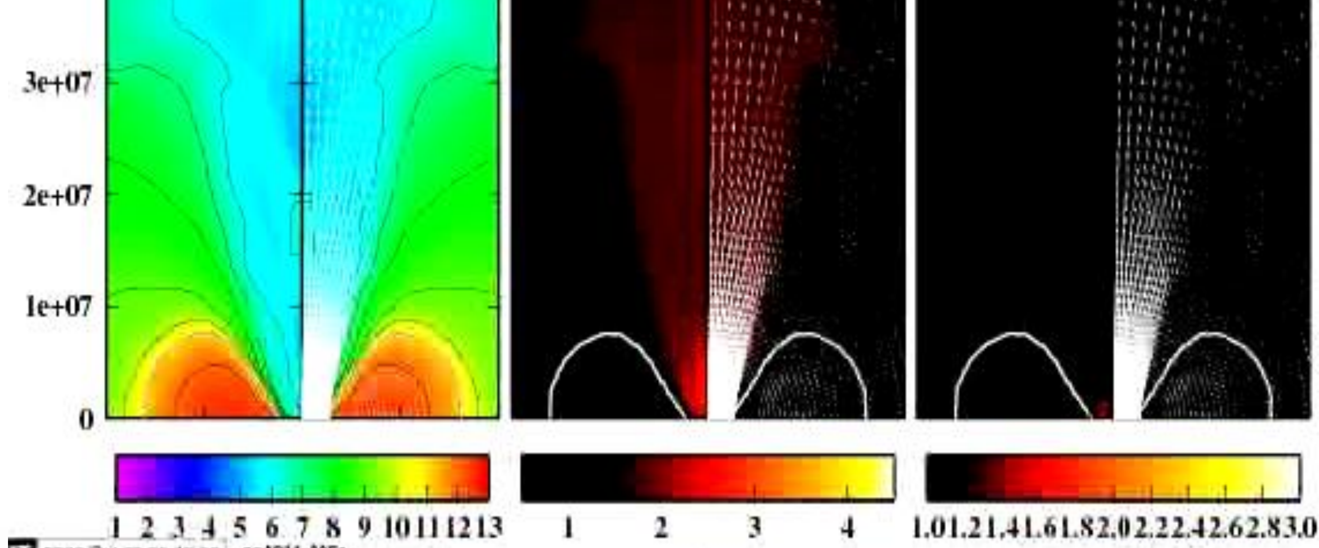
Various roles of ν's in SN-nucleosynthesis

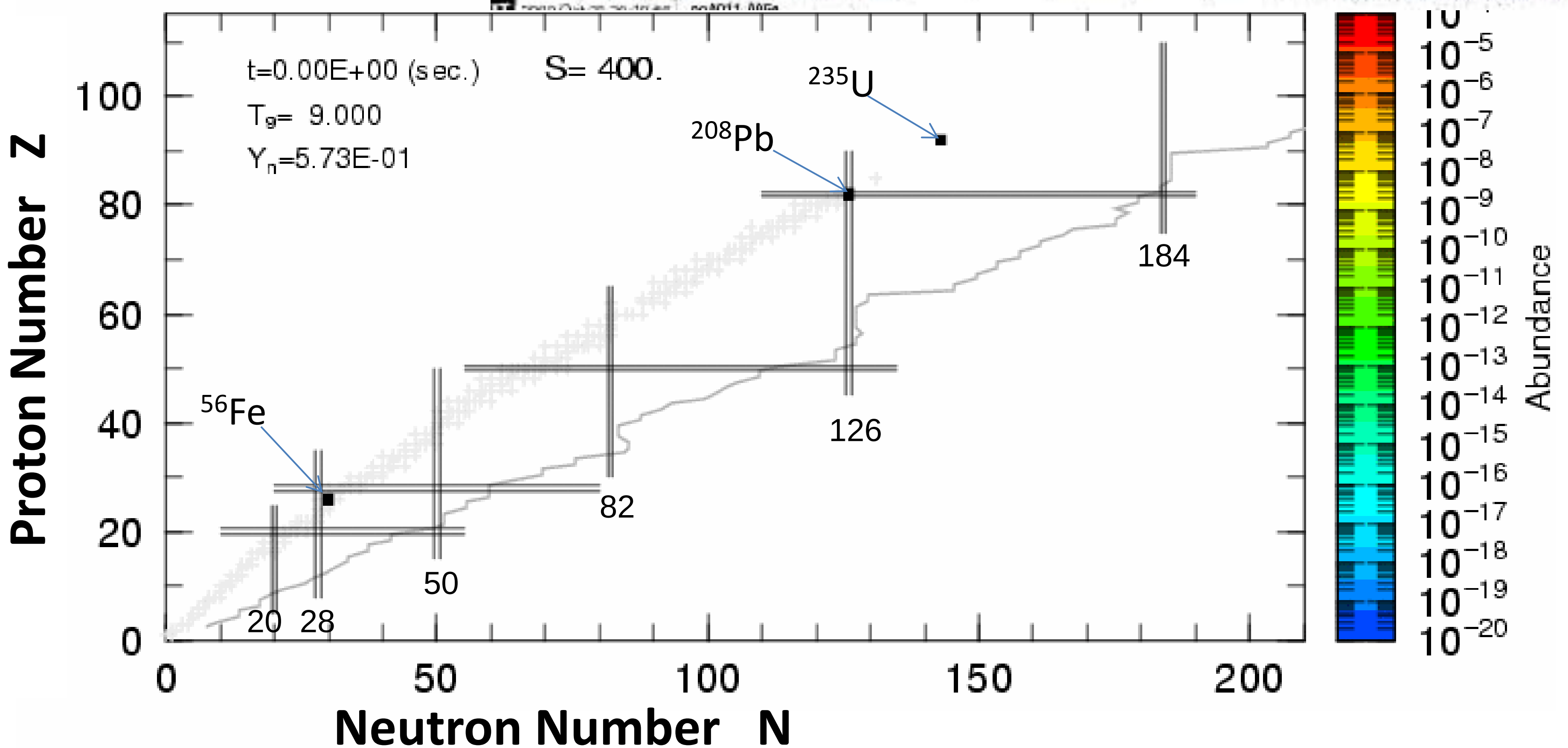


Supernova Nucleosynthesis Simulation

Chiba, Koura, Kajino

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





R–process Nucleosynthesis

Otsuki, Tagoshi, Kajino and Wanajo, ApJ 533 (2000), 424; Wanajo, Kajino, Mathews and Otsuki, ApJ J. 554 (2001), 578.

Neutron-rich condition for successful r-process: $0.1 < Y_e < 0.48$

$\nu_e + n \rightarrow p + e^-$

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

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

$\varepsilon_\nu = 3.15\, T_\nu$

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

Theoretical Challenge:

1) Astrophysical Sites ?

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

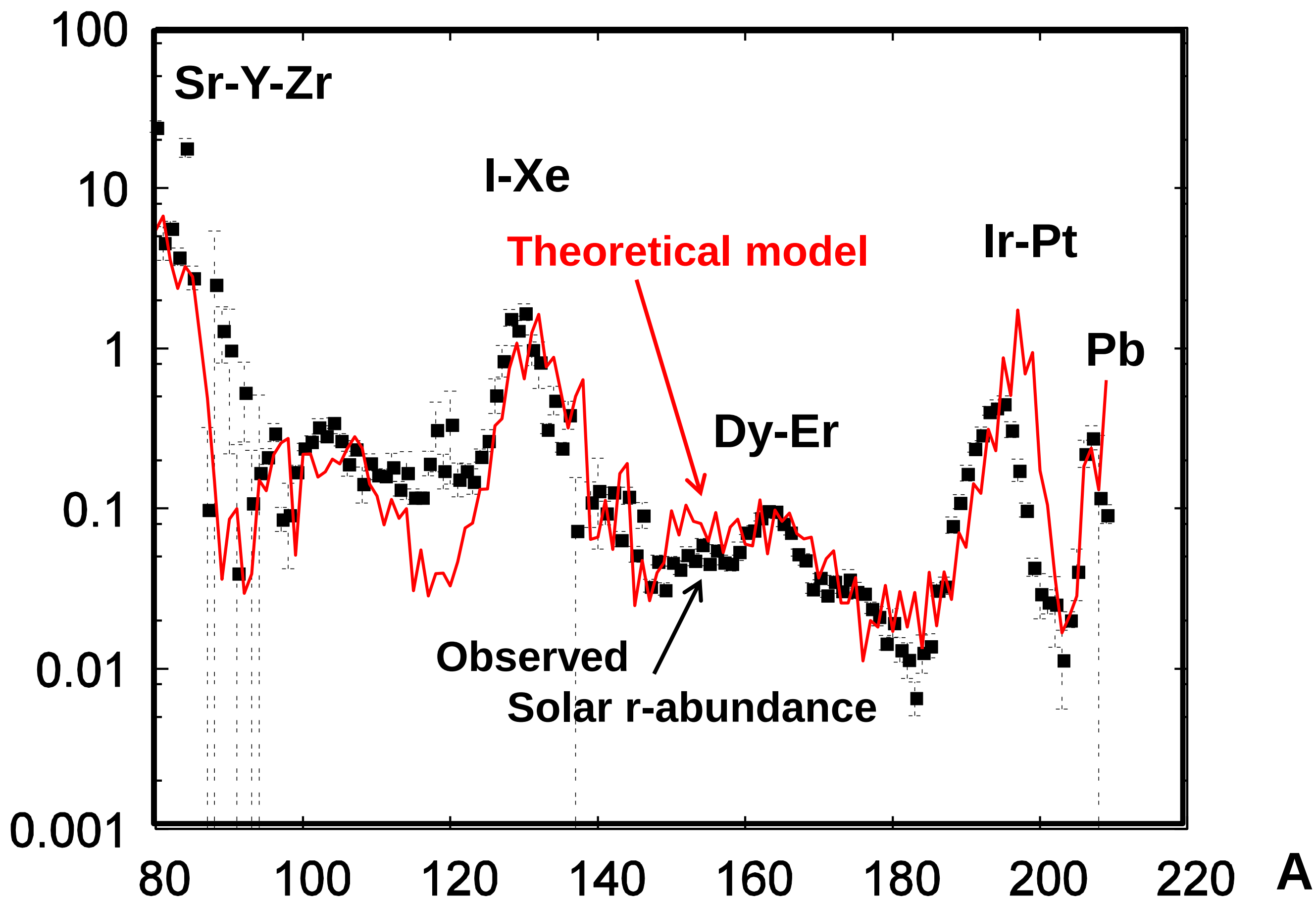
2) Neutrino effects ?

$Y_e > 0.5$?

Roberts, Reddy and Shen (PR C86, 065803, 2012) pointed out

$Y_e < 0.5$!

for nucleon potential and Pauli blocking effects.



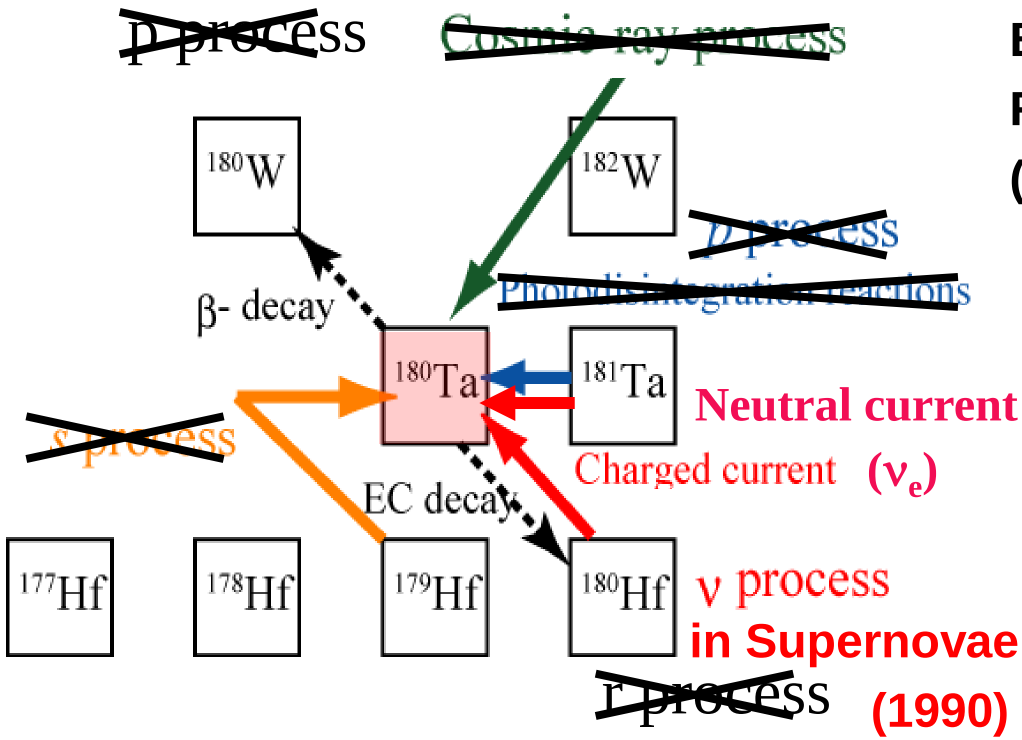
Tantalum (^{180,181}Ta)

$^{181}Ta_g$ (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!

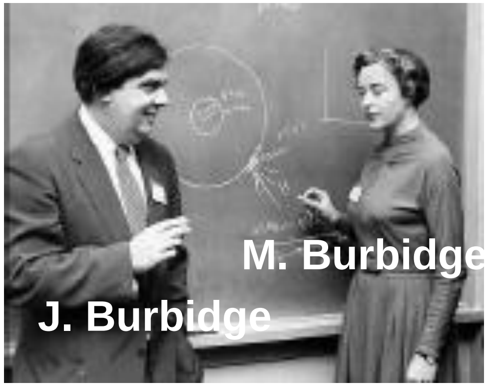
Origin of ^{180}Ta was unknown.

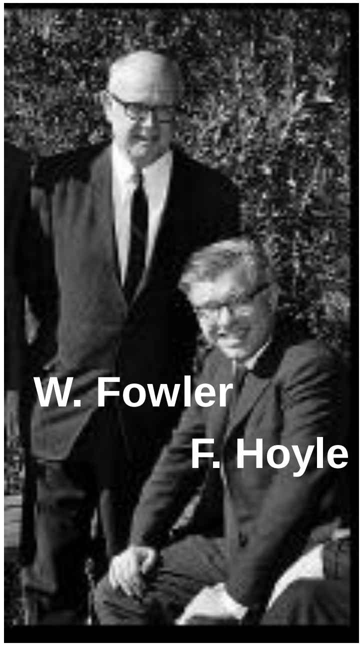
"SN ν-process" overproduces ^{180}Ta !



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

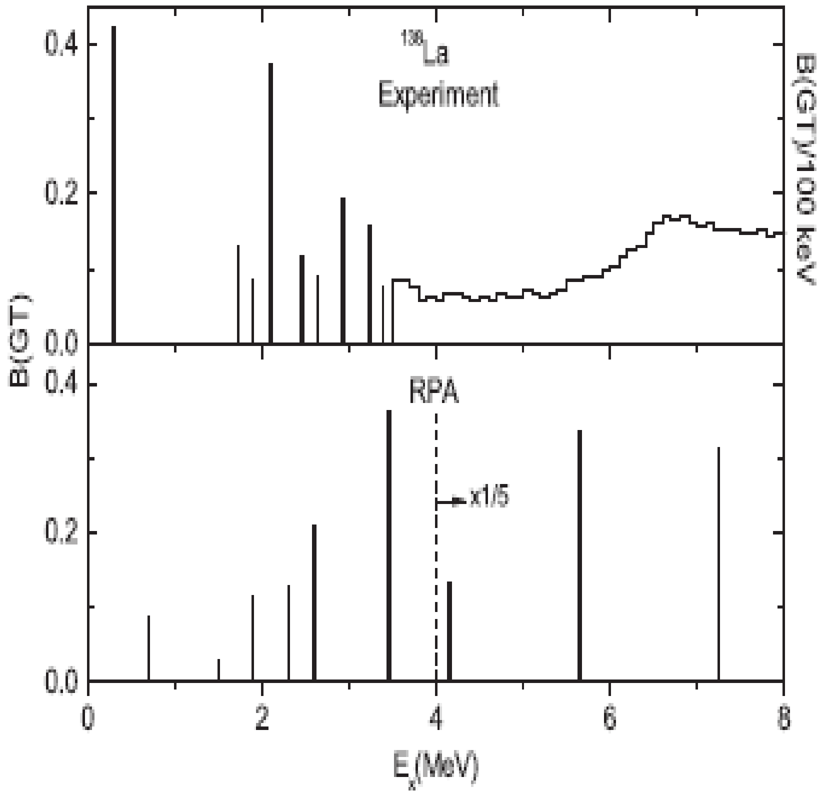
"Element Genesis"

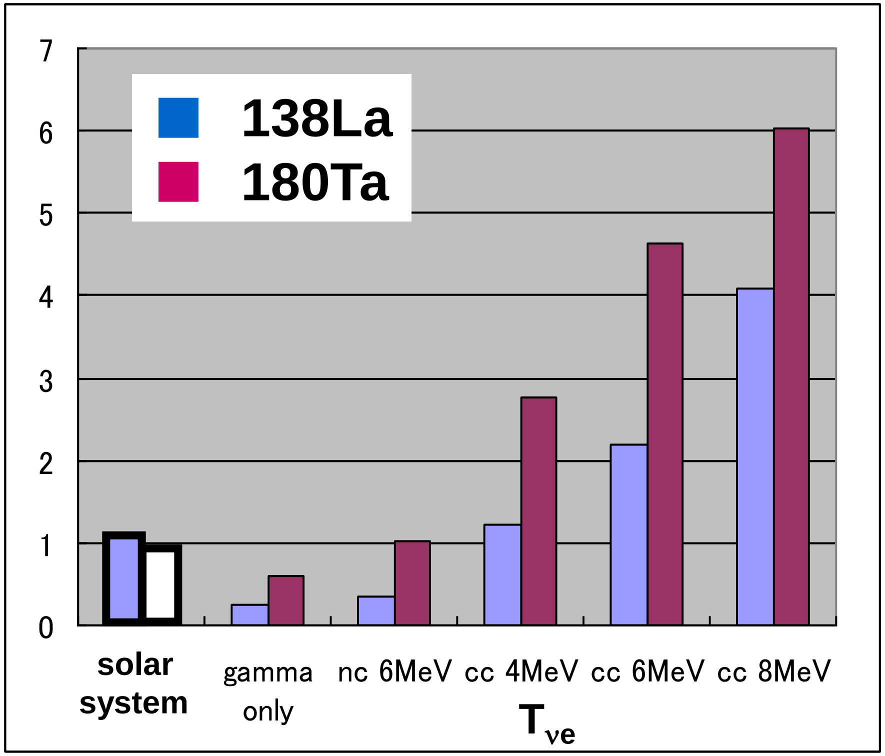




Supernova ν-Process Nucleosynthesis

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





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

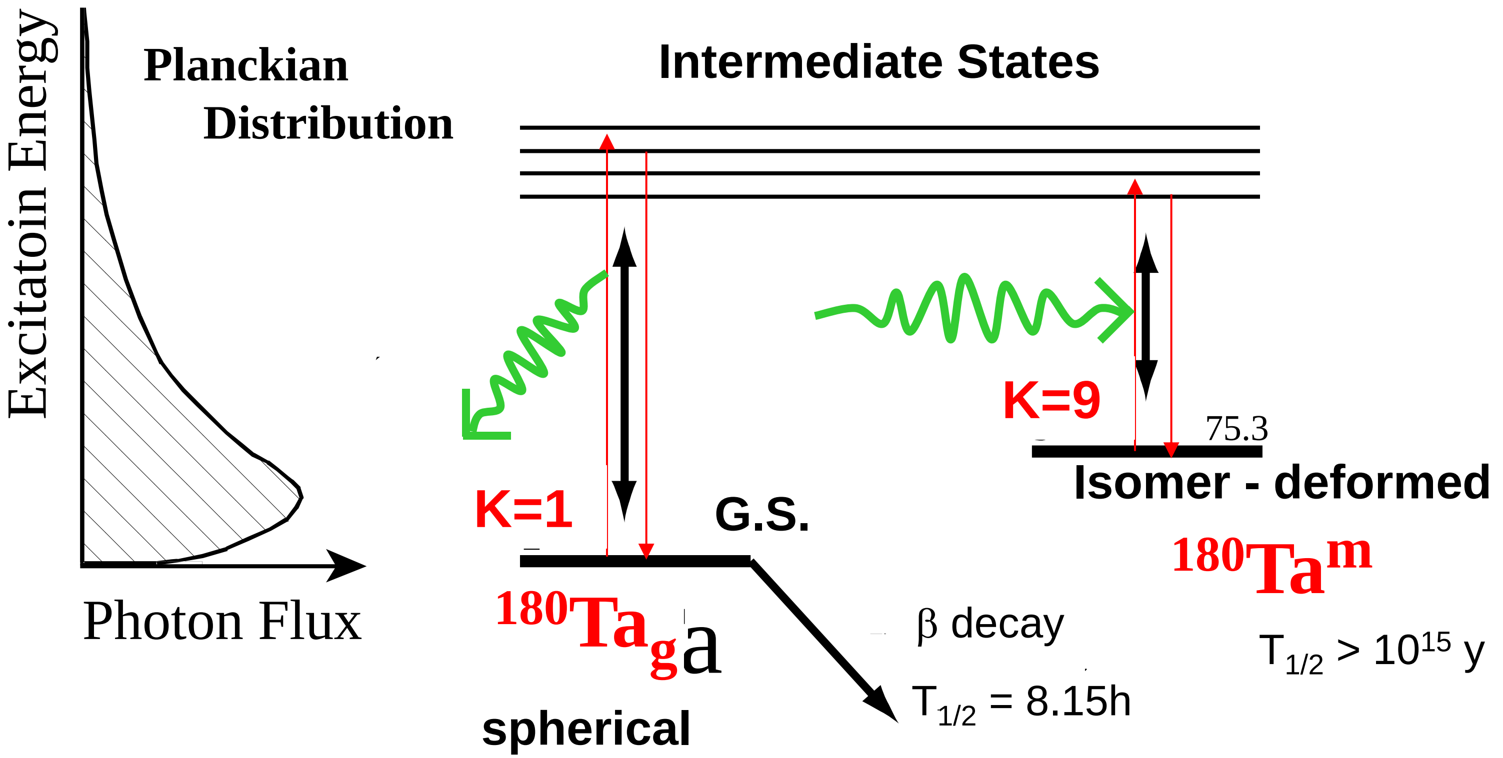
Overproduction of ^{180}Ta relative to ^{138}La!

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

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

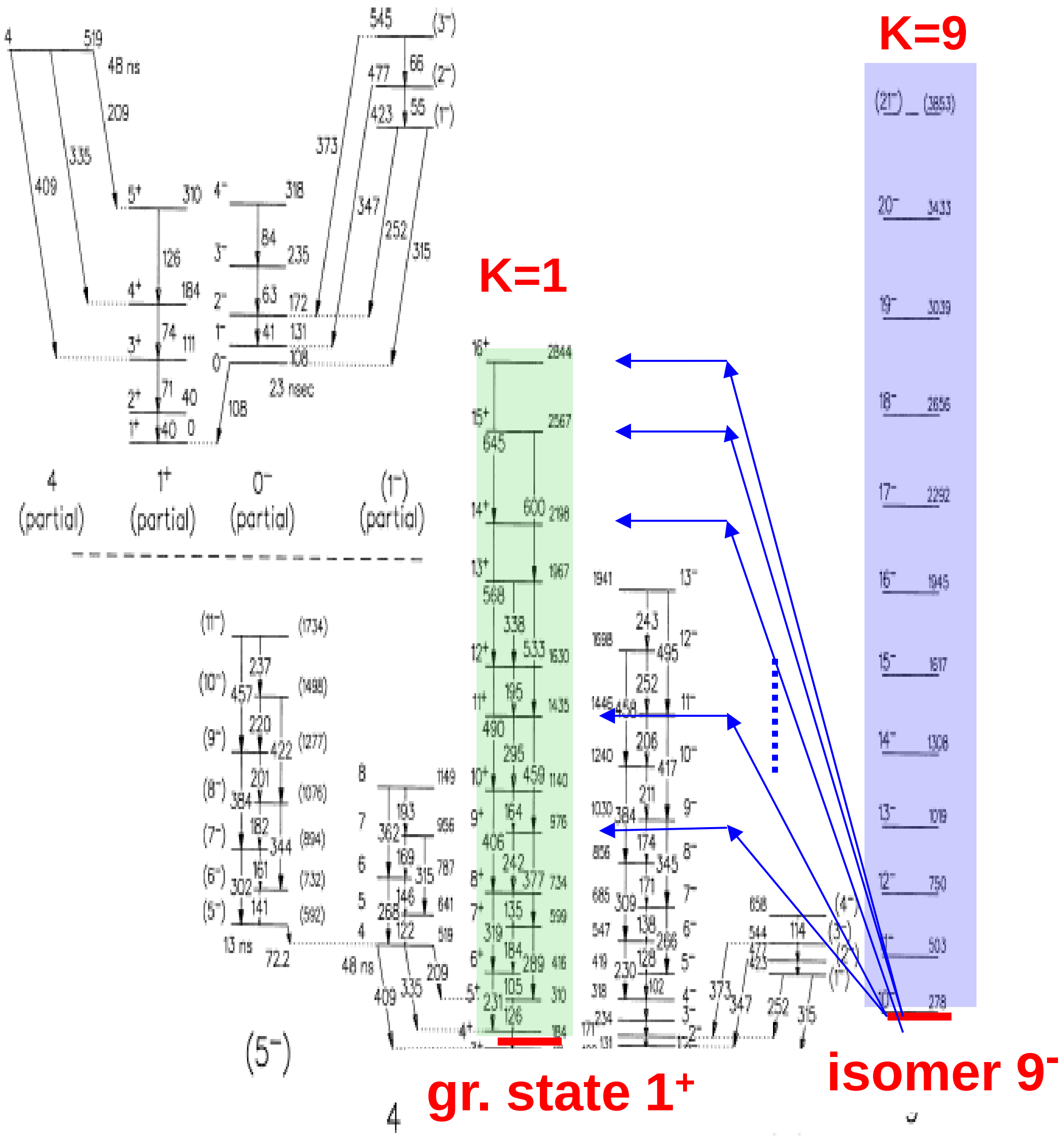
Long lived ^{180}Ta^{m} is excited to intermediate states in the photon bath in SNe, and decay with the ground state in 8 hours.

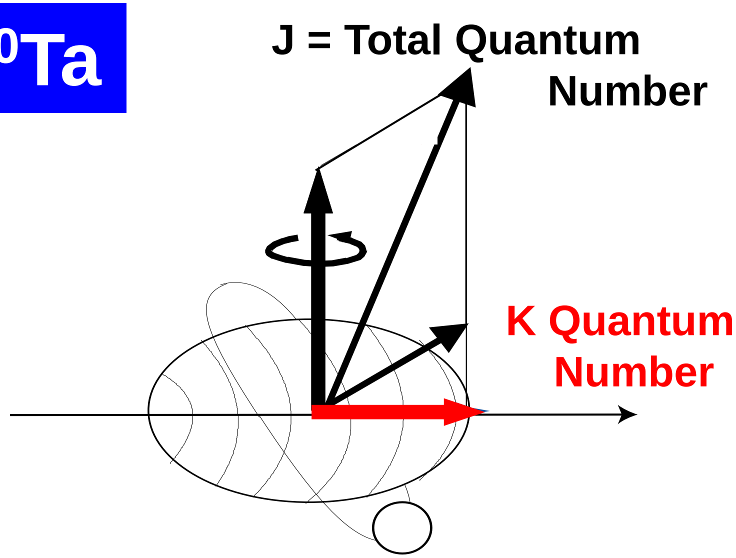
We solved dynamical "explosive SN-nucleosynthesis" coupled with "quantum transitions" simultaneously. (Hayakawa, et al. 2010, PR C81, 052801®; PR C82, 058801)



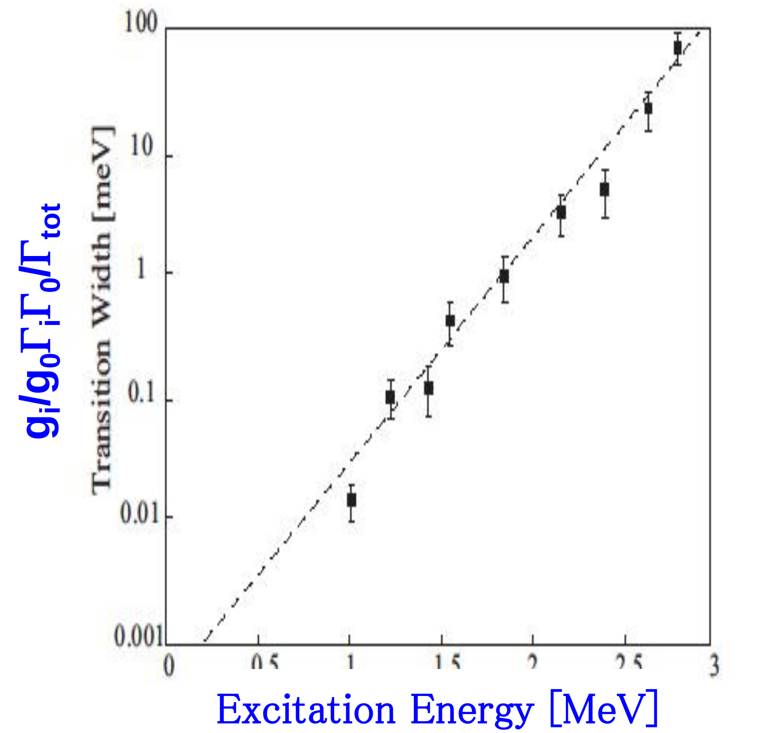
ν-Process and Structure of ^{180}Ta

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





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



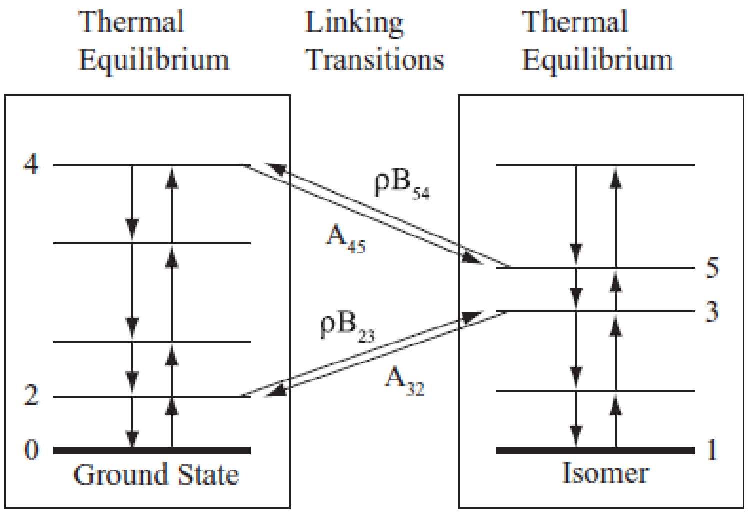
Formula to calculate time-dept linking transitions

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

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

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

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



1^+ 9^-

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

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

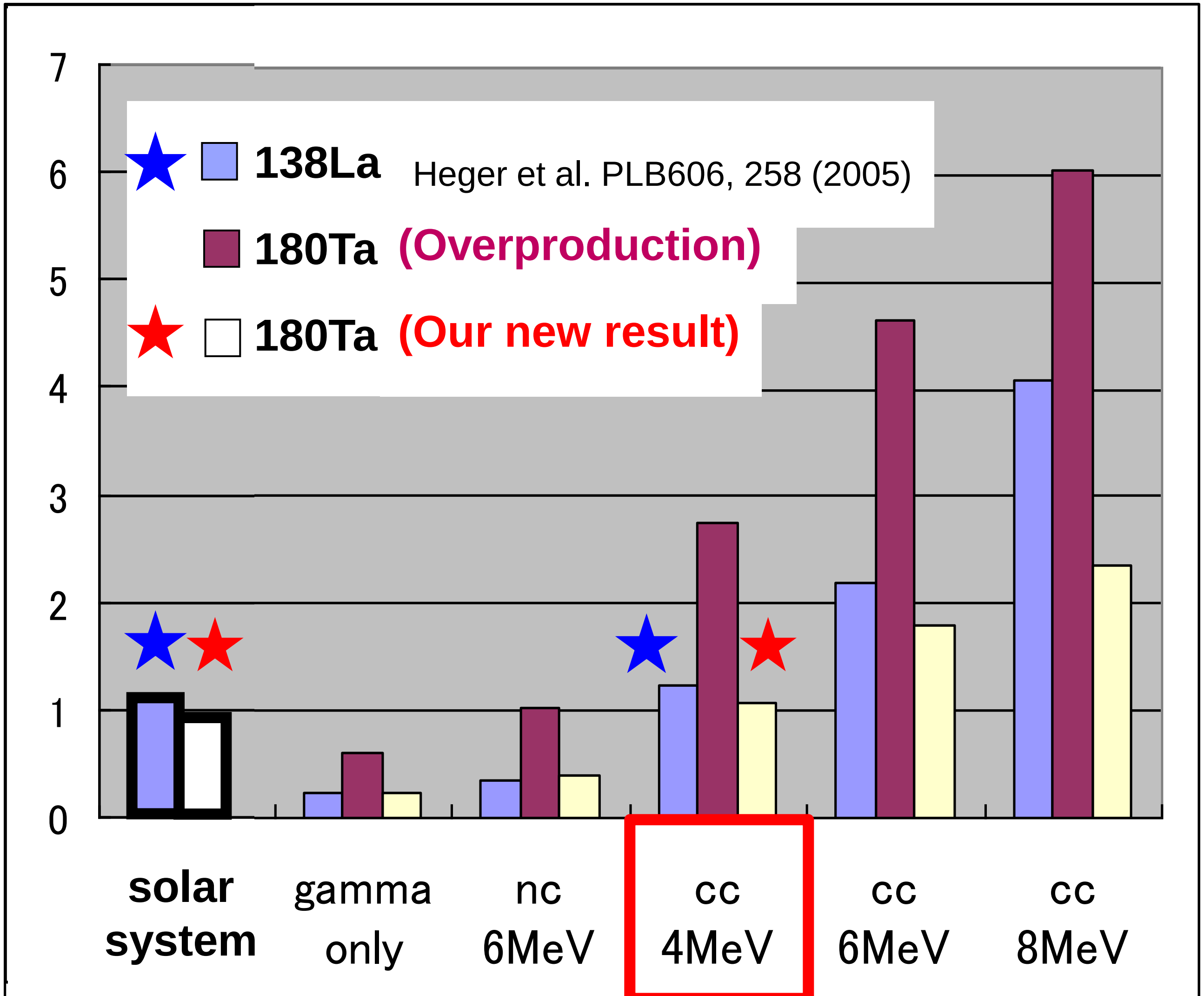
★ In the SPECIFIC case of ^{180}Ta:

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

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

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 ν_e and $\overline{\nu_e}$ of

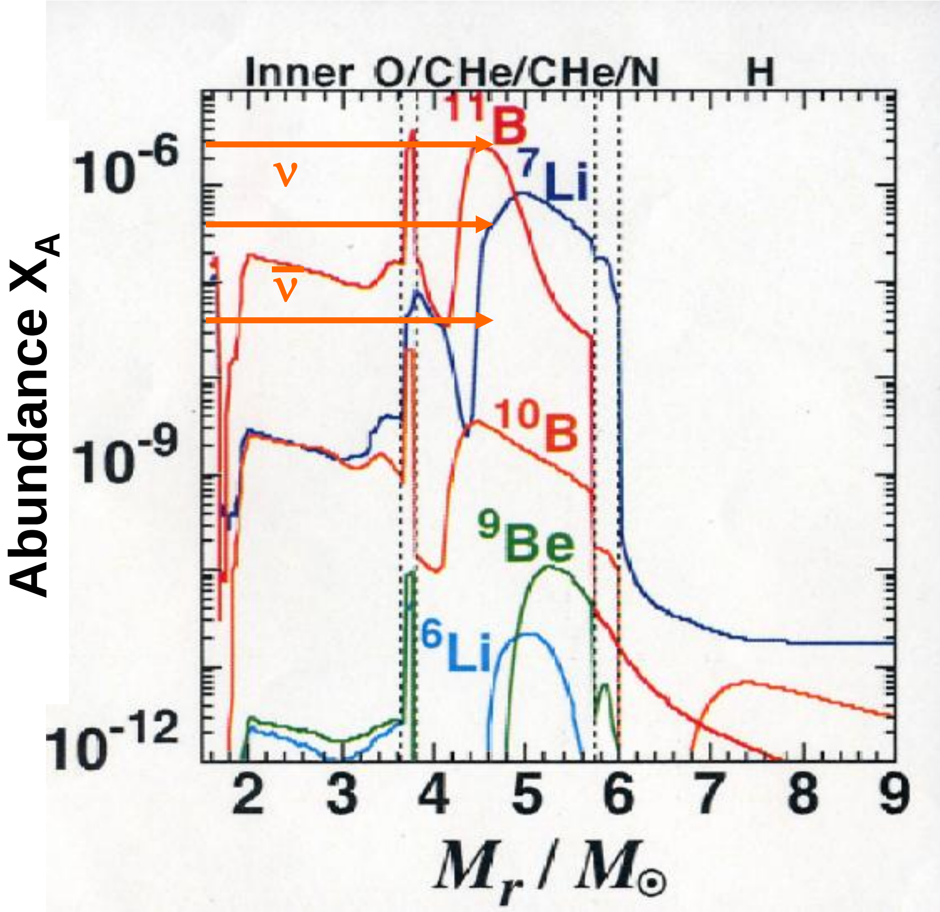
$$T_{\nu e} = T_{\overline{\nu e}} = 4 \text{ MeV.}$$

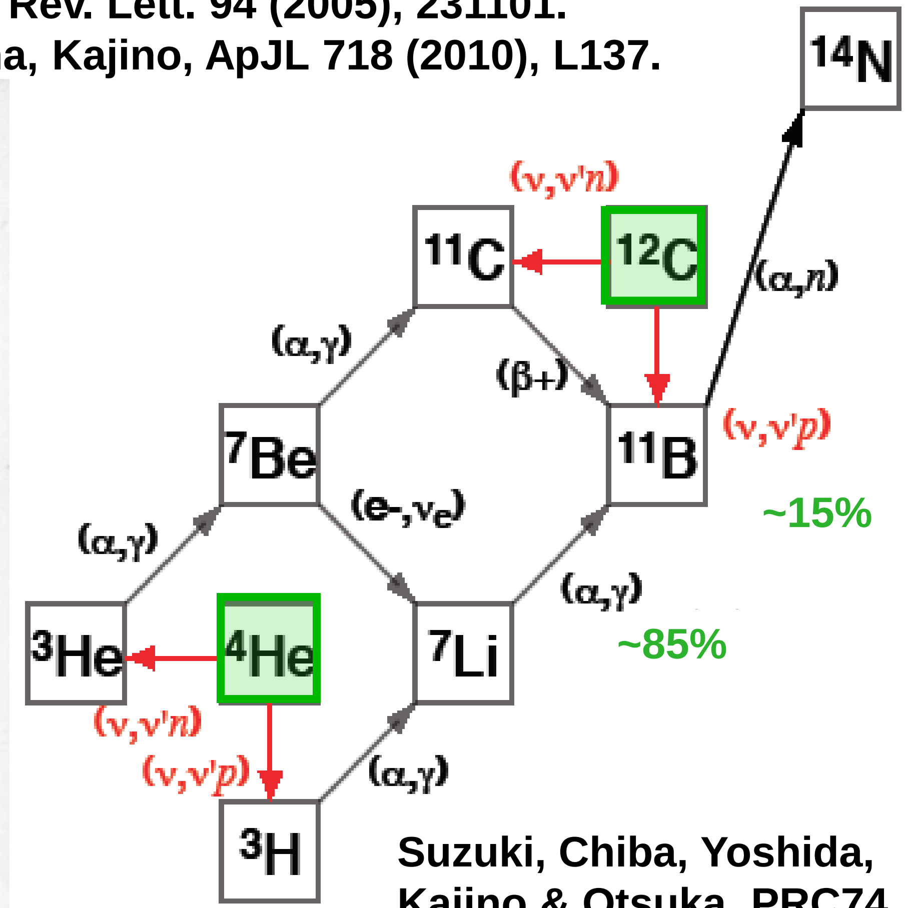
Consistent with r-process !

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

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

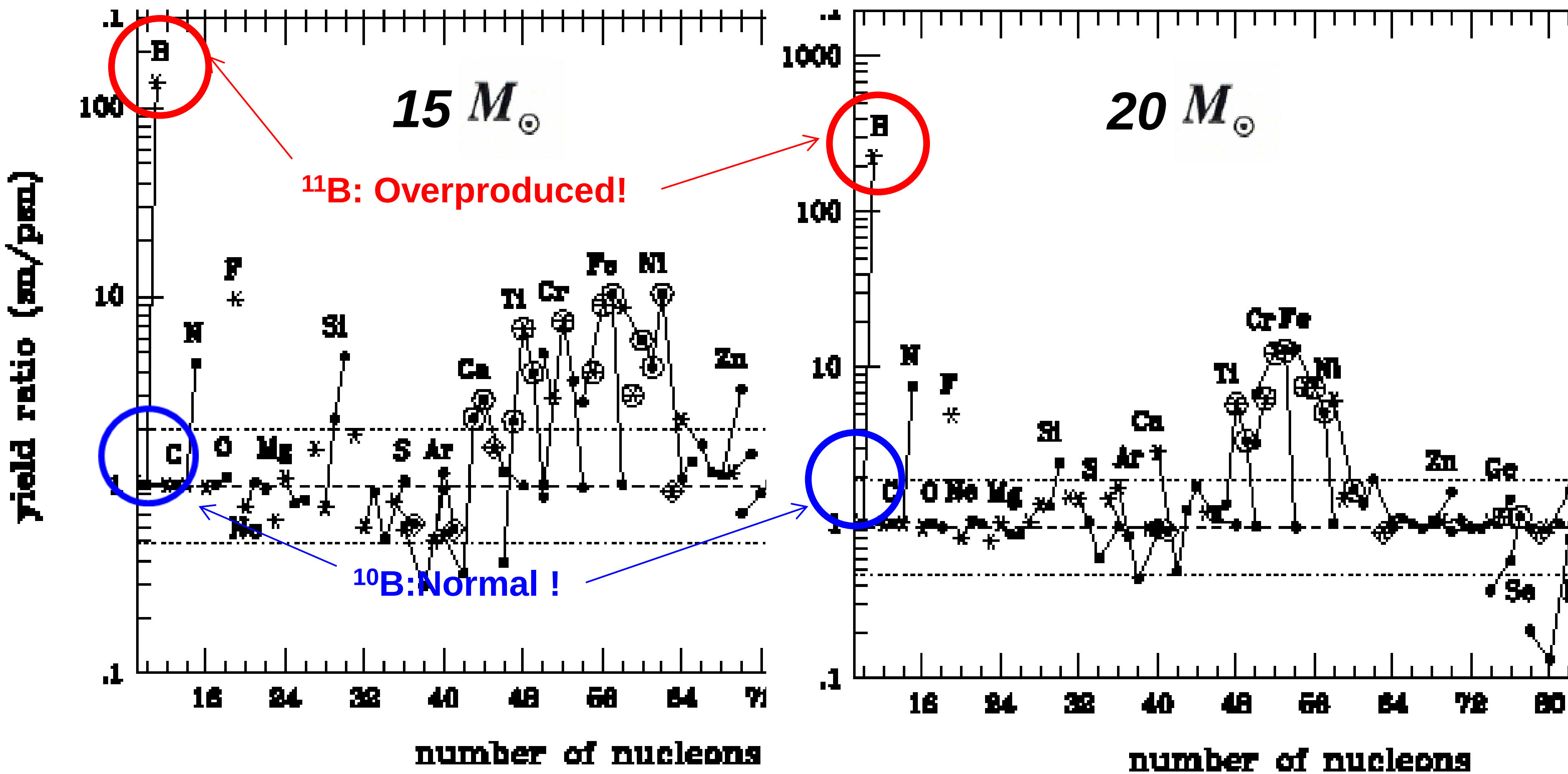
(^{4}He$(\nu_e,e^{-}p)^{3}$He, ^{4}He$(\bar{\nu}_e,e^{+}n)^{3}$H, ^{12}C$(\nu_e,e^{-}p)^{11}$C, ^{12}C$(\bar{\nu}_e,e^{+}n)^{11}$B

Overproduction Problem of Supernova-^{11}B

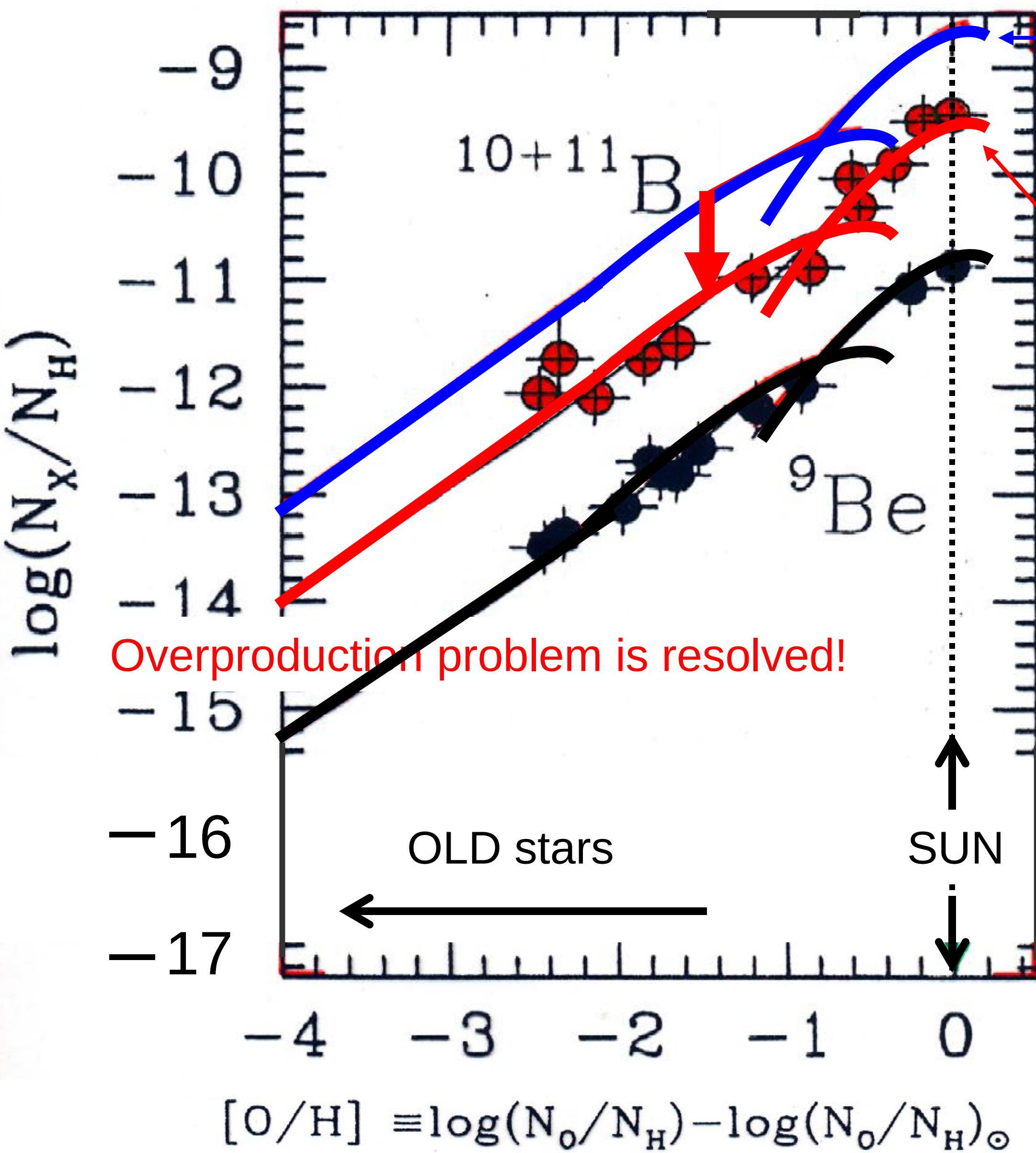
S. M. Austin, Prog. Part. Nucl. Phys. 7, 1 (1981)

- **Meteoritic Abundances:** $^{11}B/^{10}B = 4.05 \pm 0.10$ **(GCR + SNe)**
- **Galactic Cosmic-Ray:** $^{11}B/^{10}B = 2.0 \pm 0.2$ **(GCR)**

SUPERNOVA Nucleosynthesis: Hoffman, Woosley & Weaver 2001, ApJ 549, 1085.



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

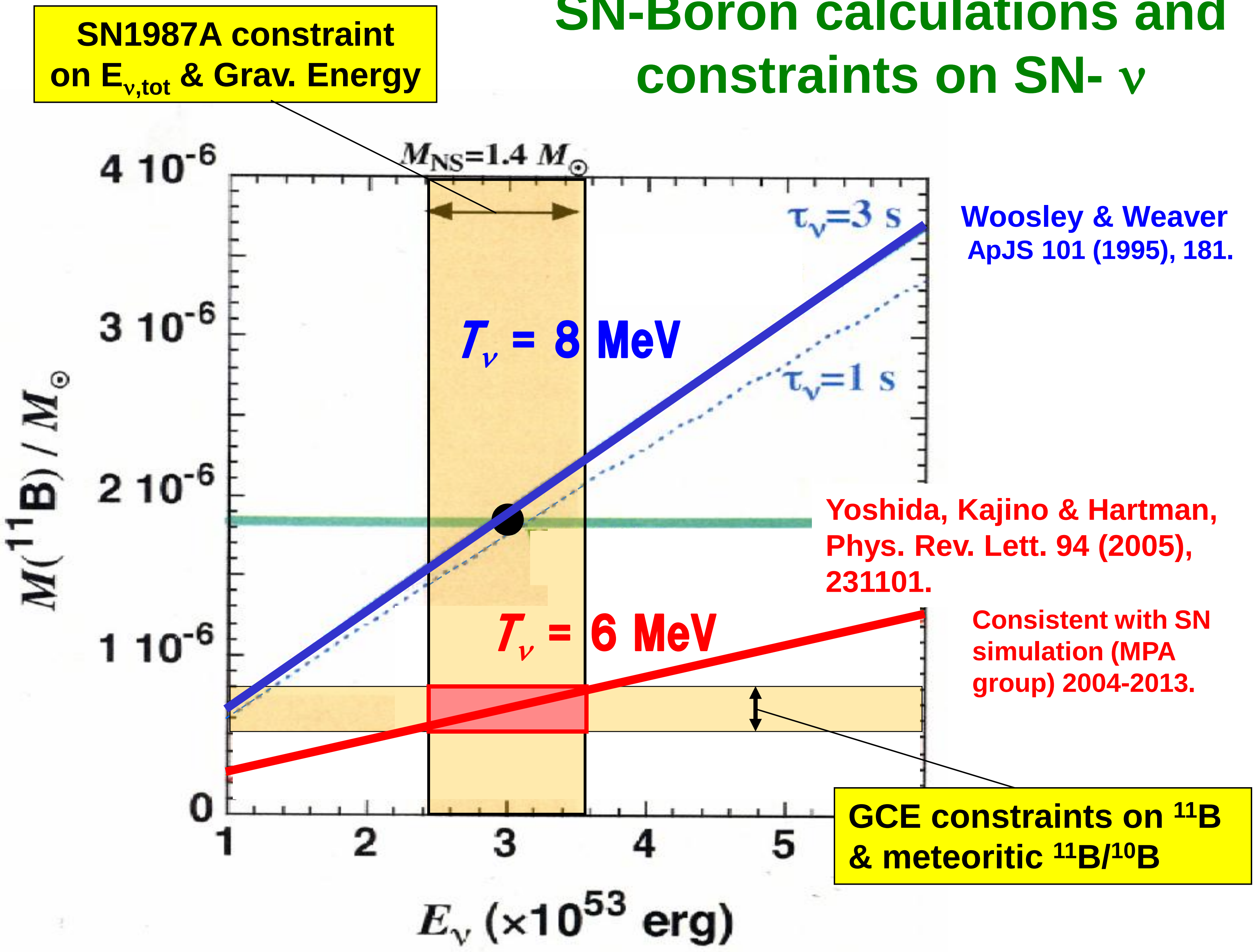
$^{10+11}$B + ^{11}B:

— Galactic Cosmic Rays

— Supernova ν–process

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

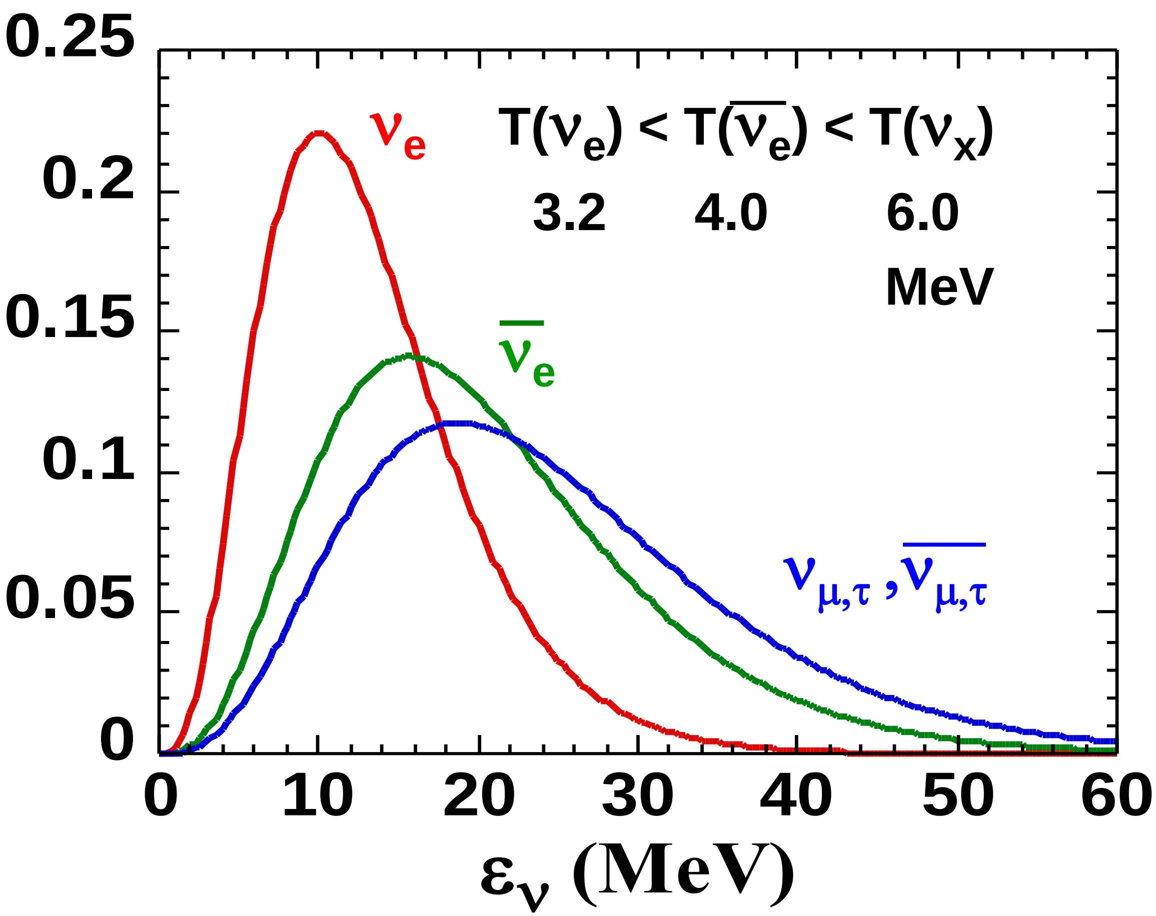
SN-Boron calculations and constraints on SN- ν

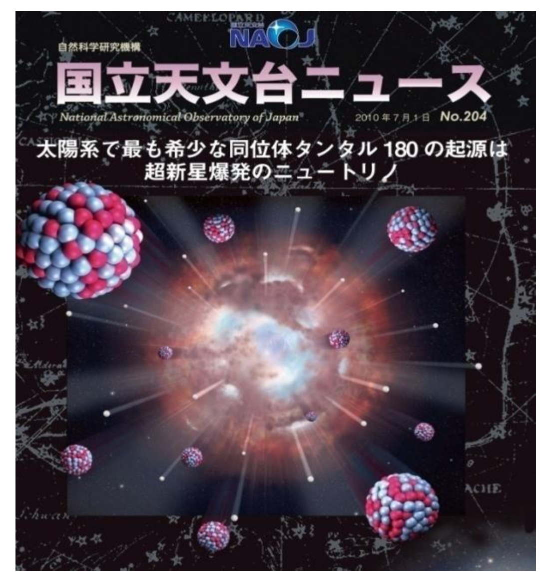


Average ν-temperatures are now known!

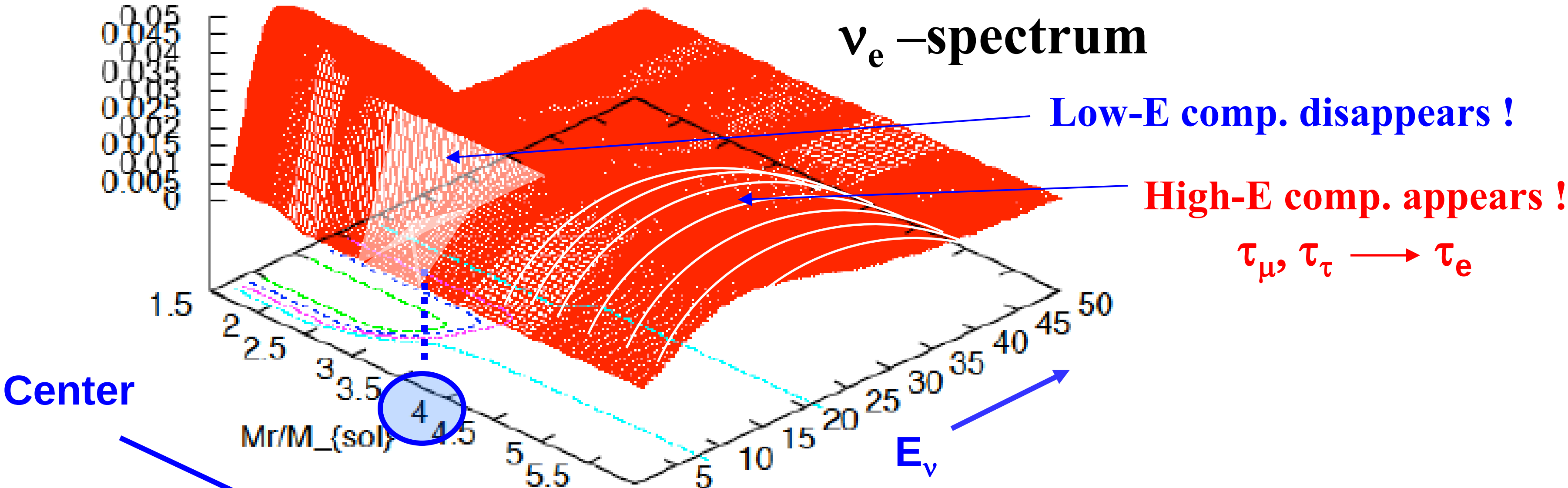
- R-process Elements & ^{180}Ta/^{138}La ➡ T_{ν_e} = 3.2 MeV, $T_{\bar{\nu}_e}$ = 4 MeV
- Astron. GCE of Light Elements & ^{11}B ➡ $T_{\nu_\mu,}$ = T_{ν_τ} = 6 MeV

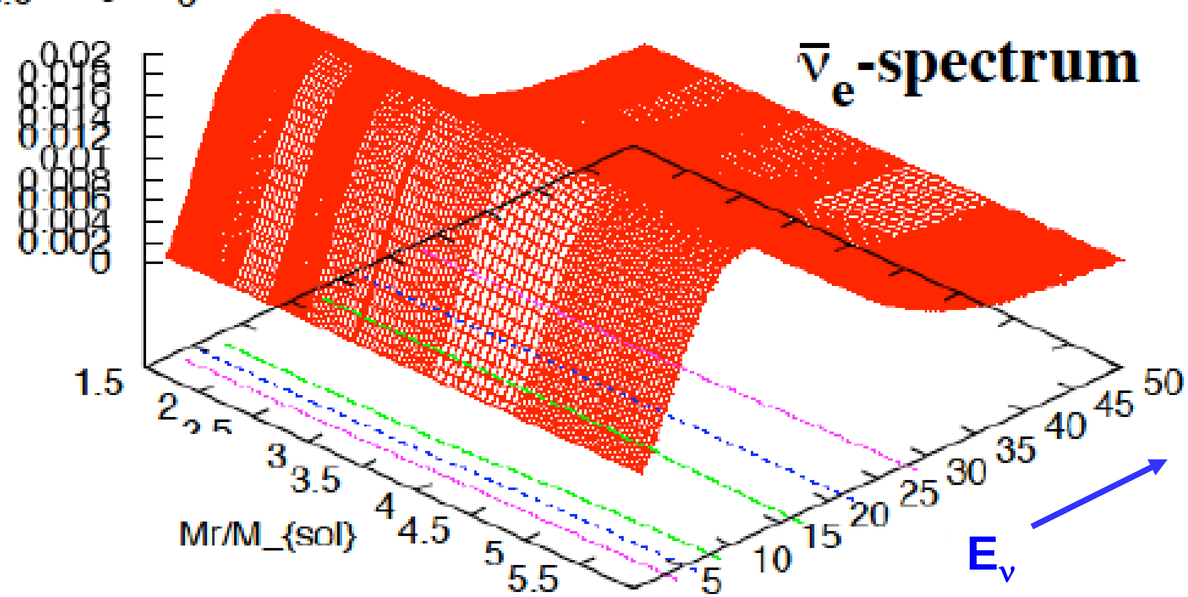
Neutrino Oscillation !





Neutrino Oscillation (MSW Effect) through propagation



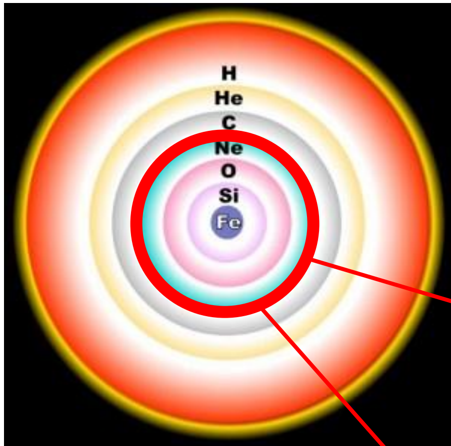


Parameters:

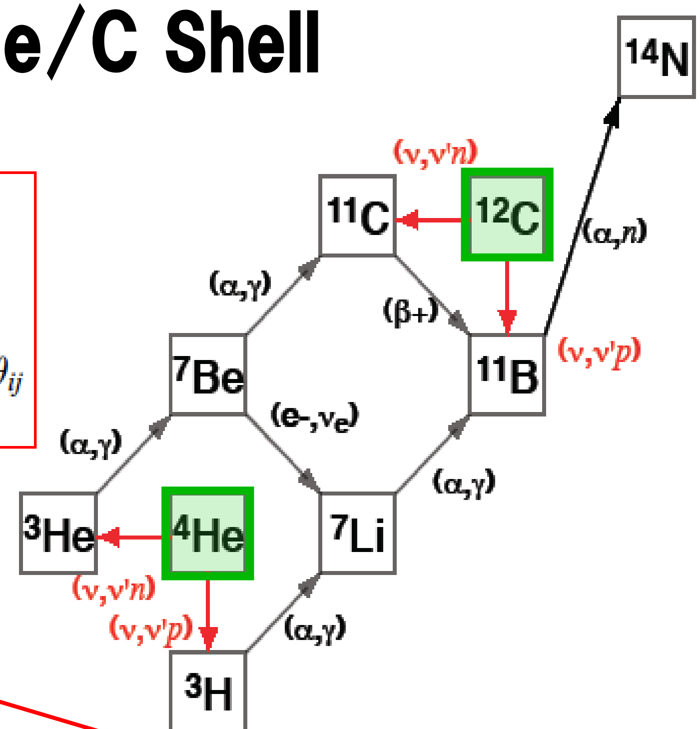
$25M_{solar}$ progenitor SN model (Hashimoto & Nomoto 1999)

- **$\sin^2 2\theta_{13} = 0.04$**
- **$\Delta m_{13}^2 = 2.4 \times 10^{-3}$ eV^2**
- **$L_\nu = 3 \times 10^{53}$ erg, $\tau_\nu = 3$ sec**
- **$T_{\nu e}$=3.2MeV, $T_{\nu e}$=5.0MeV, $T_{\nu\mu\tau}$=6.0MeV**

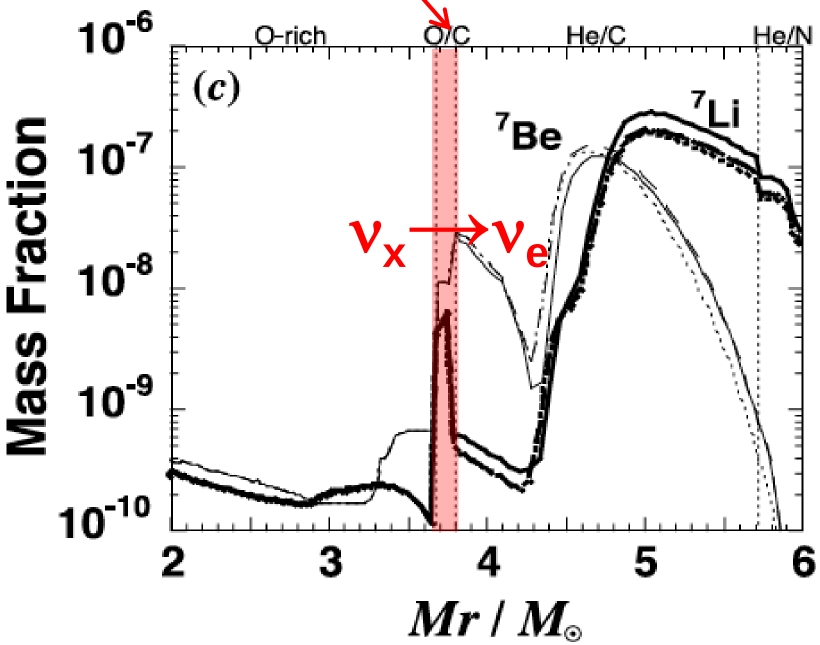
^{7}Li and ^{11}B are produced in the He/C Shell

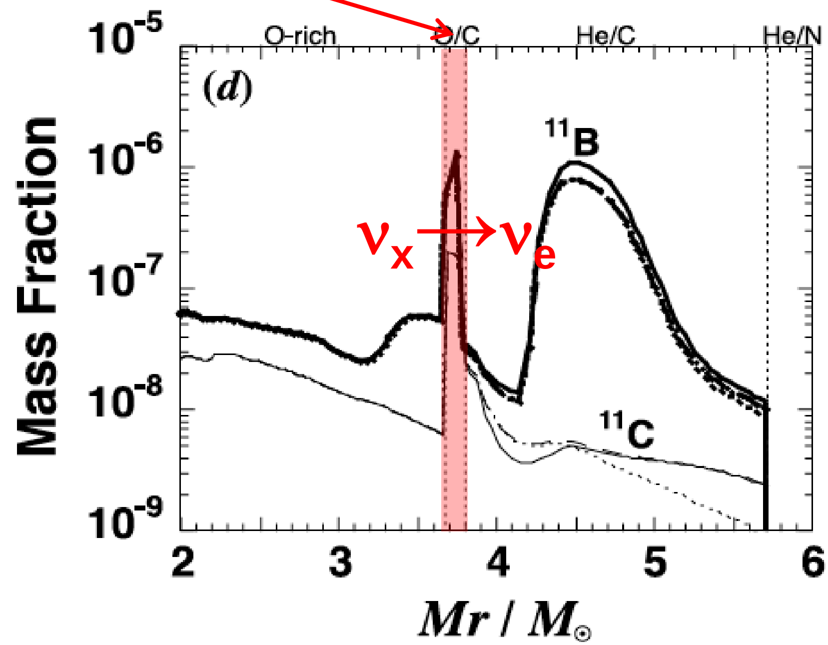


$$\rho_{\rm res} Y_e = \frac{m_u \Delta m_{ji}^2 c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_{\rm F} (\hbar c)^3 \varepsilon_\nu} \qquad [\ {\rm g\ cm^{-3}}\ ]$$
$$= 6.55 \times 10^6 \left(\frac{\Delta m_{ji}^2}{1\ {\rm eV}^2} \right) \left(\frac{1\ {\rm MeV}}{\varepsilon_\nu} \right) \cos 2\theta_{ij}$$

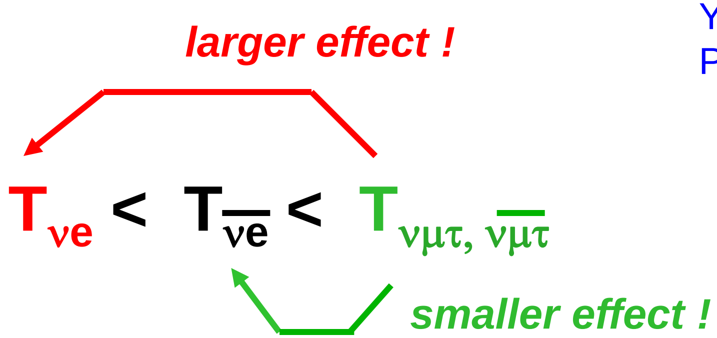


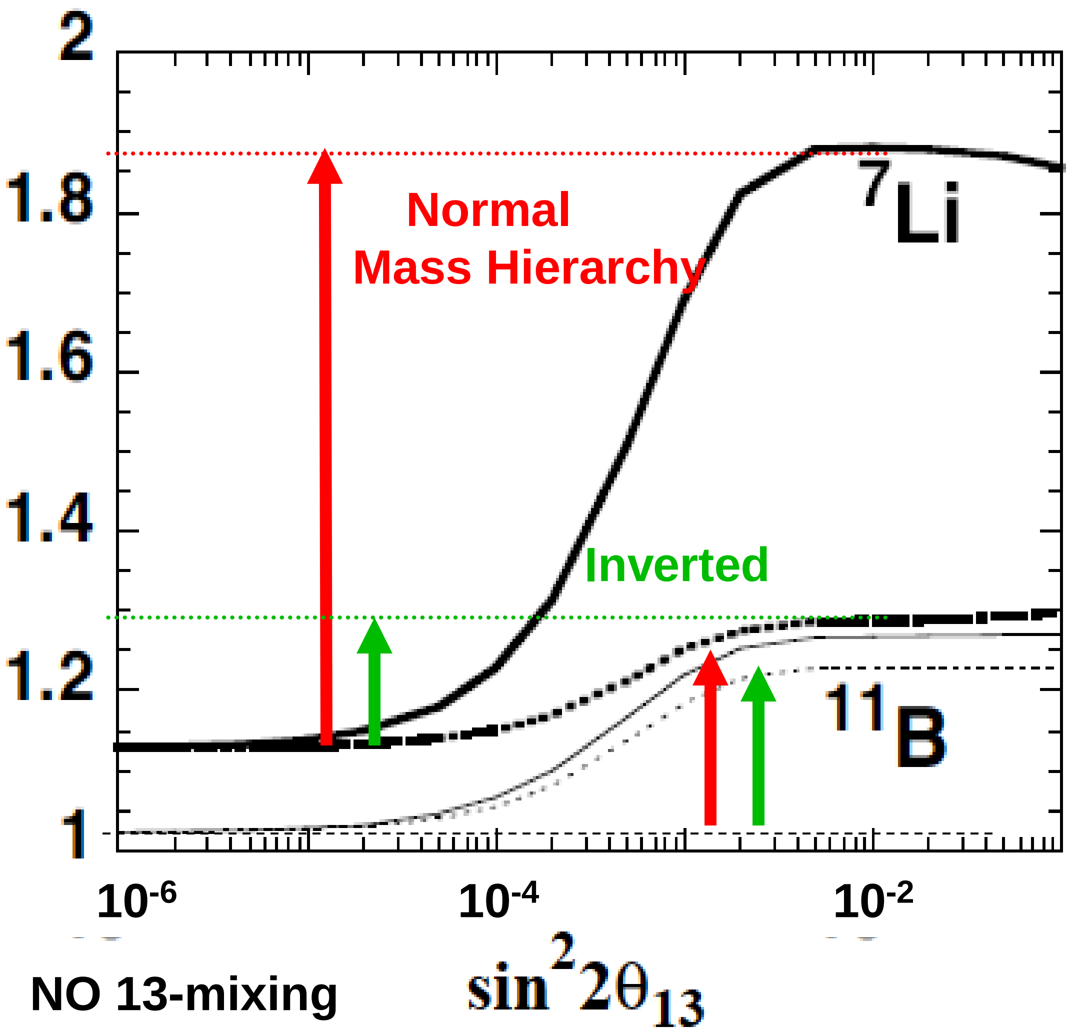
MSW high-density resonance is
located at the bottom of C shell.

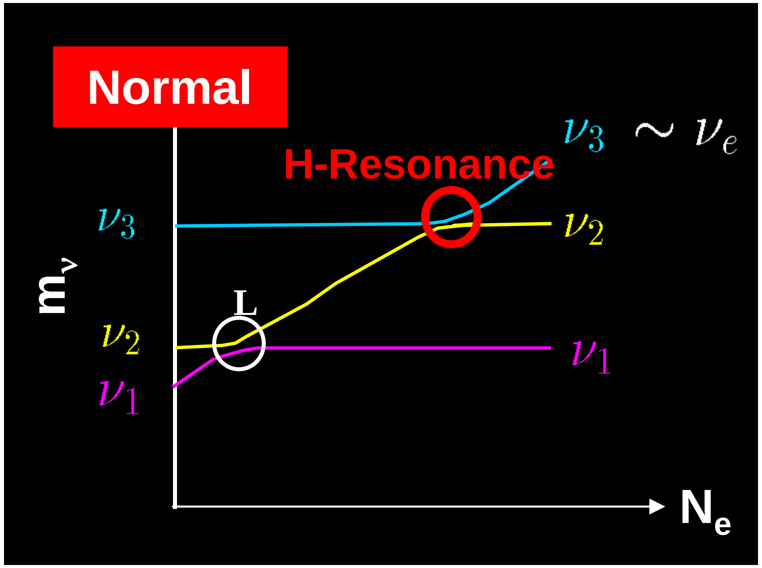


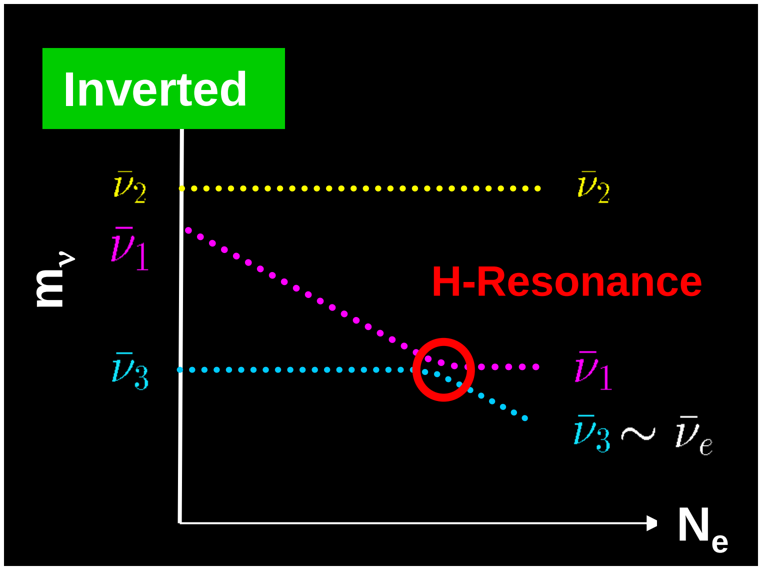


Yoshida, Kajino, Yokomakura, Kimura,Takamura & Hartmann,
PRL 96 (2006) 09110; ApJ 649 (2006), 349.







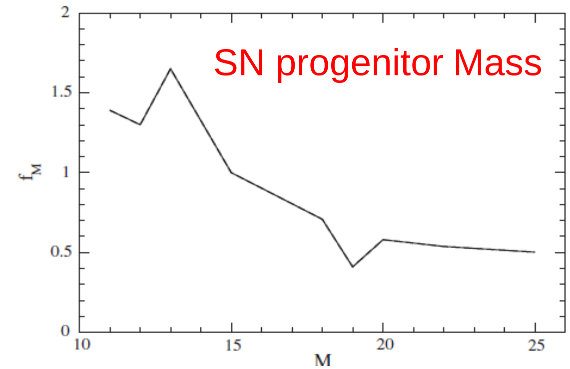


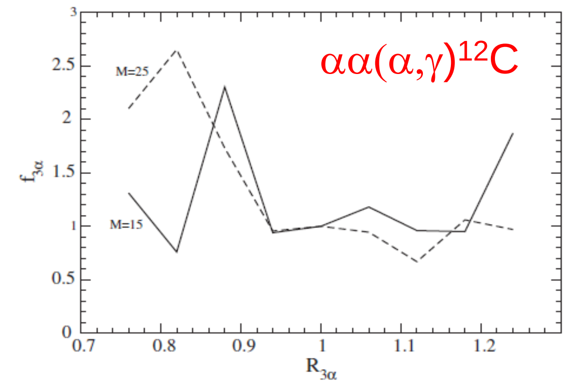
PHYSICAL REVIEW D **85**, 105023 (2012)

Exploring the neutrino mass hierarchy probability with meteoritic supernova material, ν-process nucleosynthesis, and θ_{13} mixing

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

Bayesian Analysis, including astrophysical model dependence on SN progenitor mass, ν-temp. ($T_{\nu e}$,$T_{\nu e}$,$T_{\nu\mu\tau,\ \overline{\nu\mu\tau}}$) and nuclear input data.





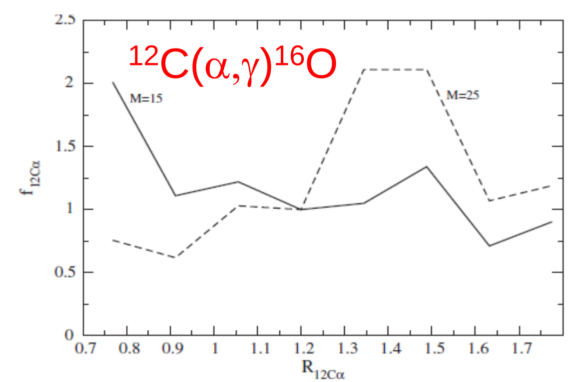
$$P(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_j P(D|M_j)P(M_j)}$$

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

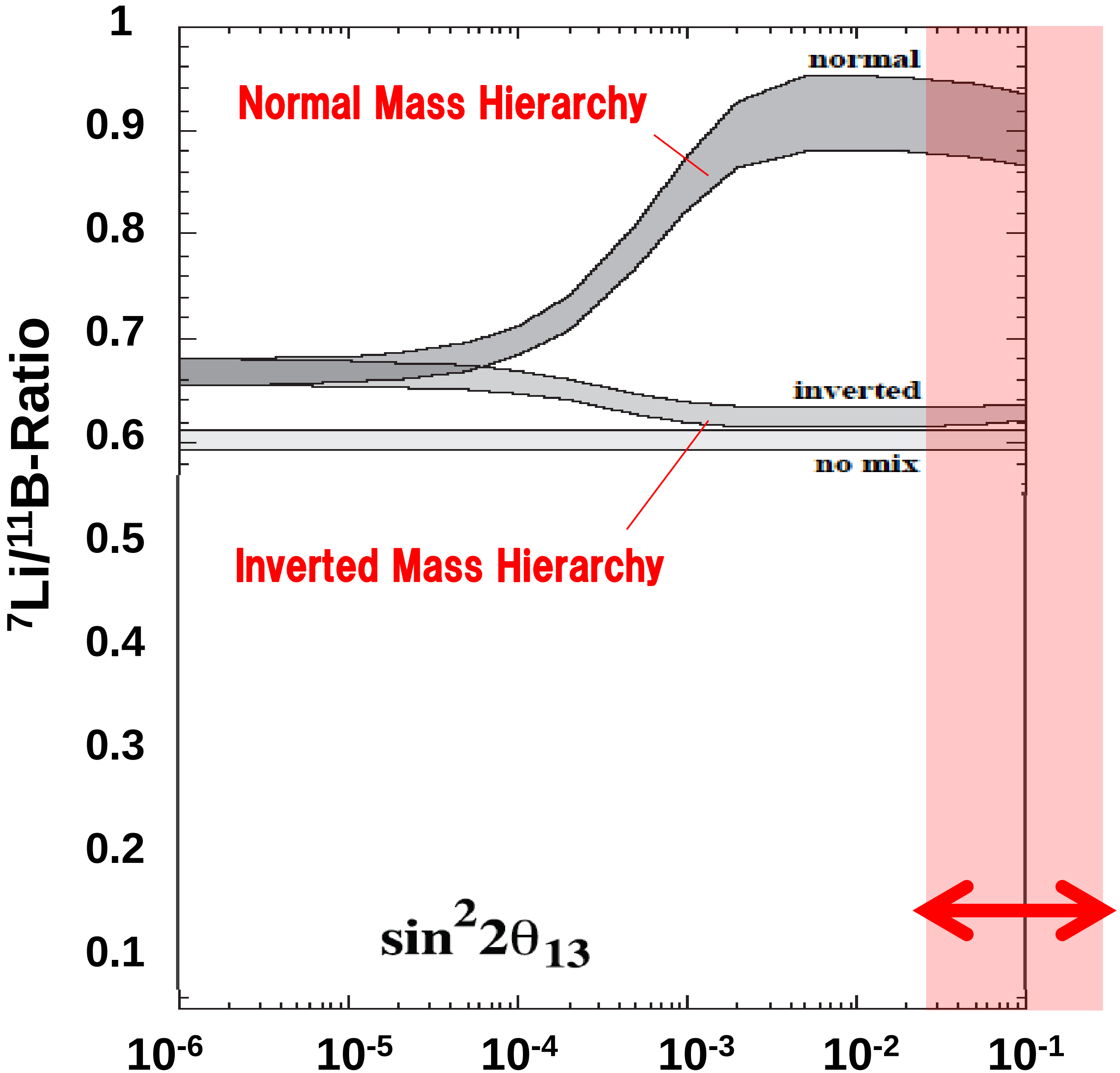
$$= \int dEdZda_k P(D|M_i,a_k,E,Z)P(Z,E|M_i,a_k)P(a|M_i)$$

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_ν(MeV)	Top hat	$T_\nu = 3.2 - 6.5$	(see text)	[15]



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:

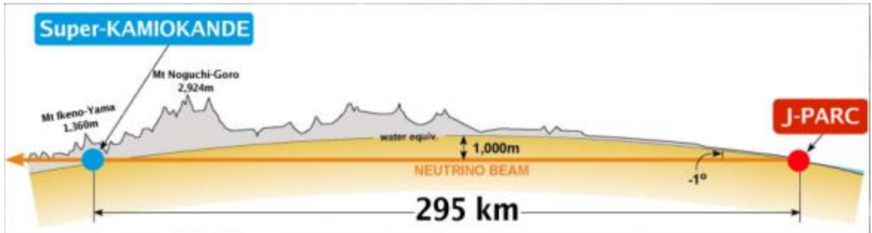
- T2K (Kamioka)
- MINOS

Reactor Exp. in2012:

- Double CHOOZ
- Daya Bay
- RENO (KOREA)

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

Long Baseline ν — T2K & MINOS (2011)



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

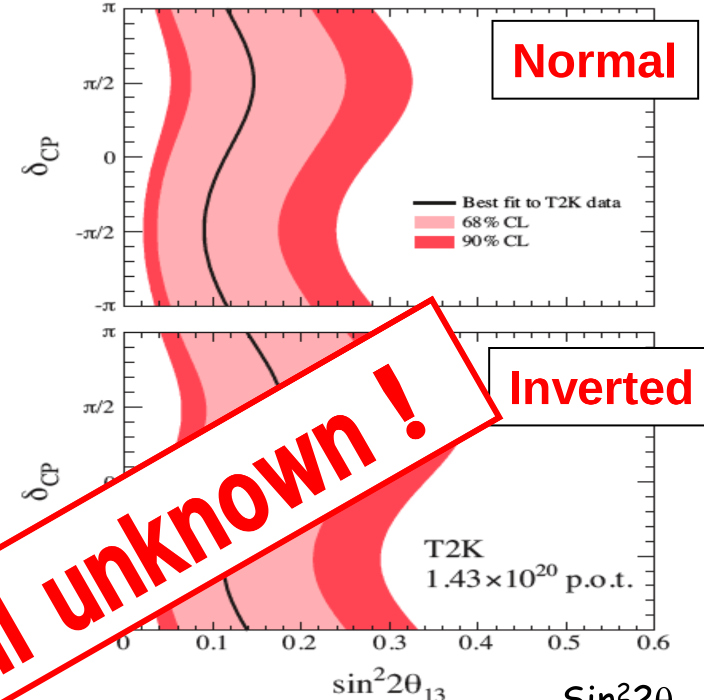
Daya Bay 2012 $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

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)

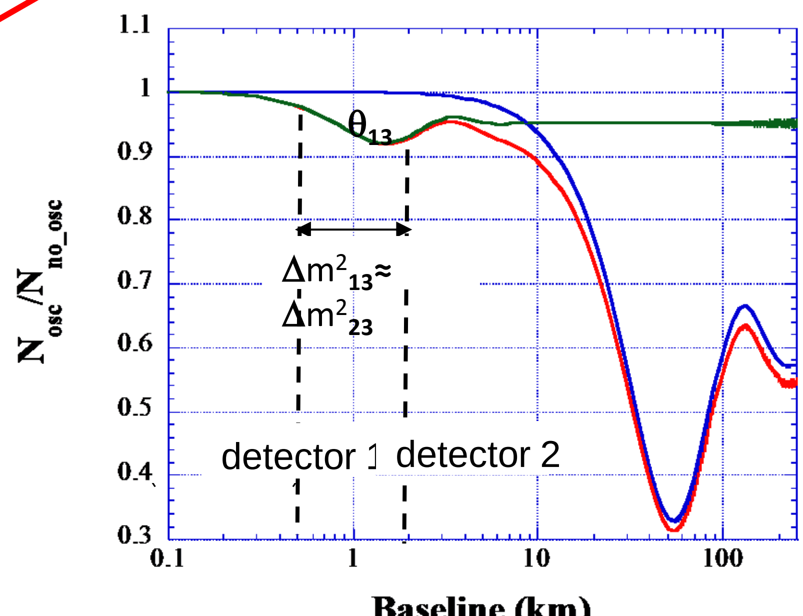


$\sin^2 2\theta_{23} = 1$

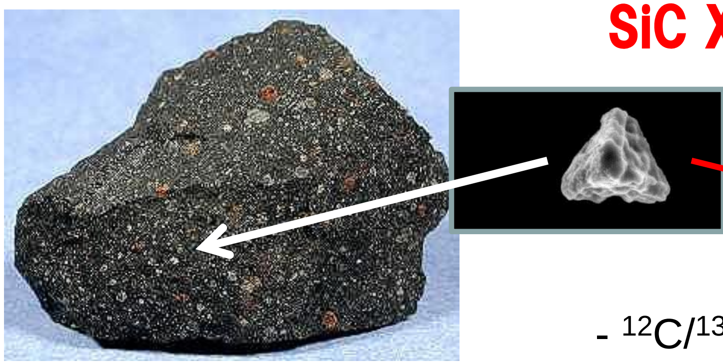
Mass hierarchy is still unknown !

Reactor ν — … a Bay & … le Chooz (2012)

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

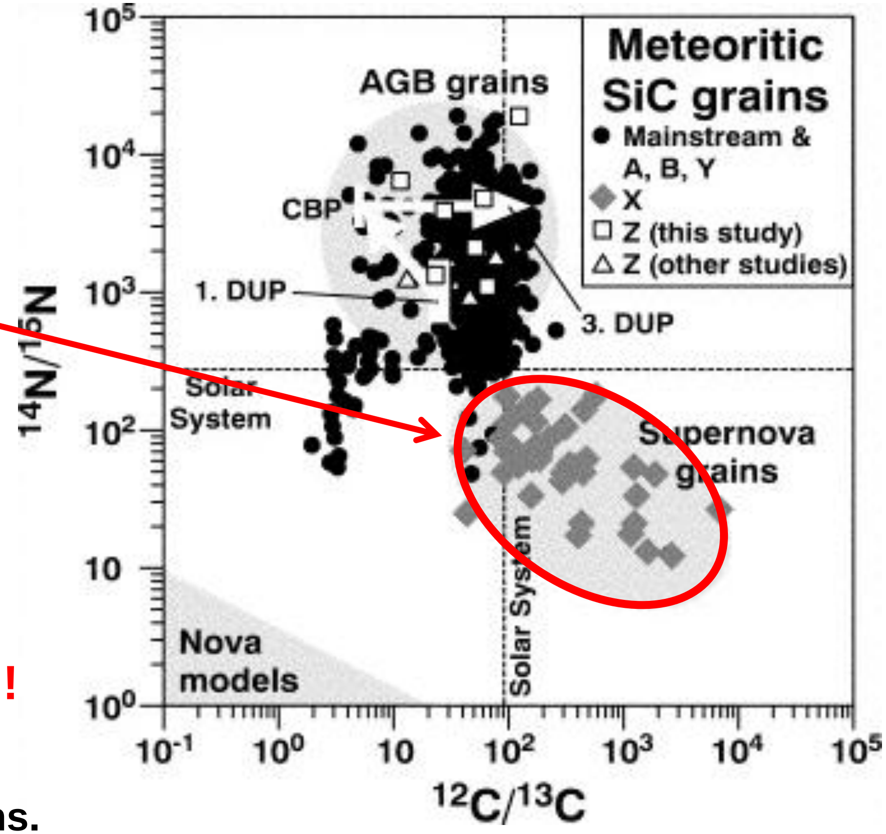


Murchison Meteorite



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 !

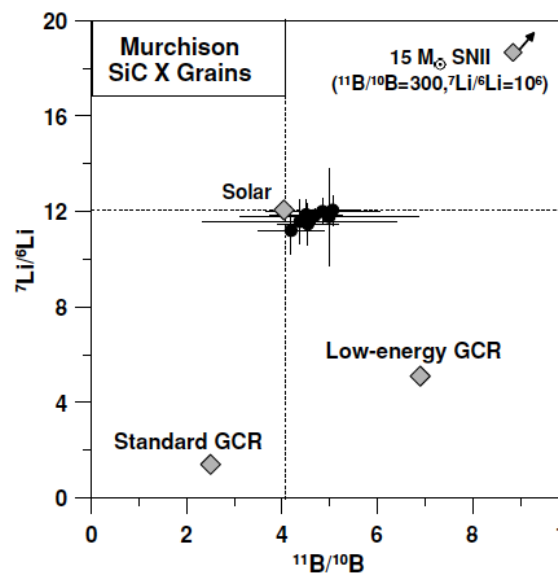
Fujiya, Hoppe and Ott (2011, ApJ 730, L7) discovered ^{11}B and ^{7}Li isotopes in 13 SiC X-grains.

Table 1

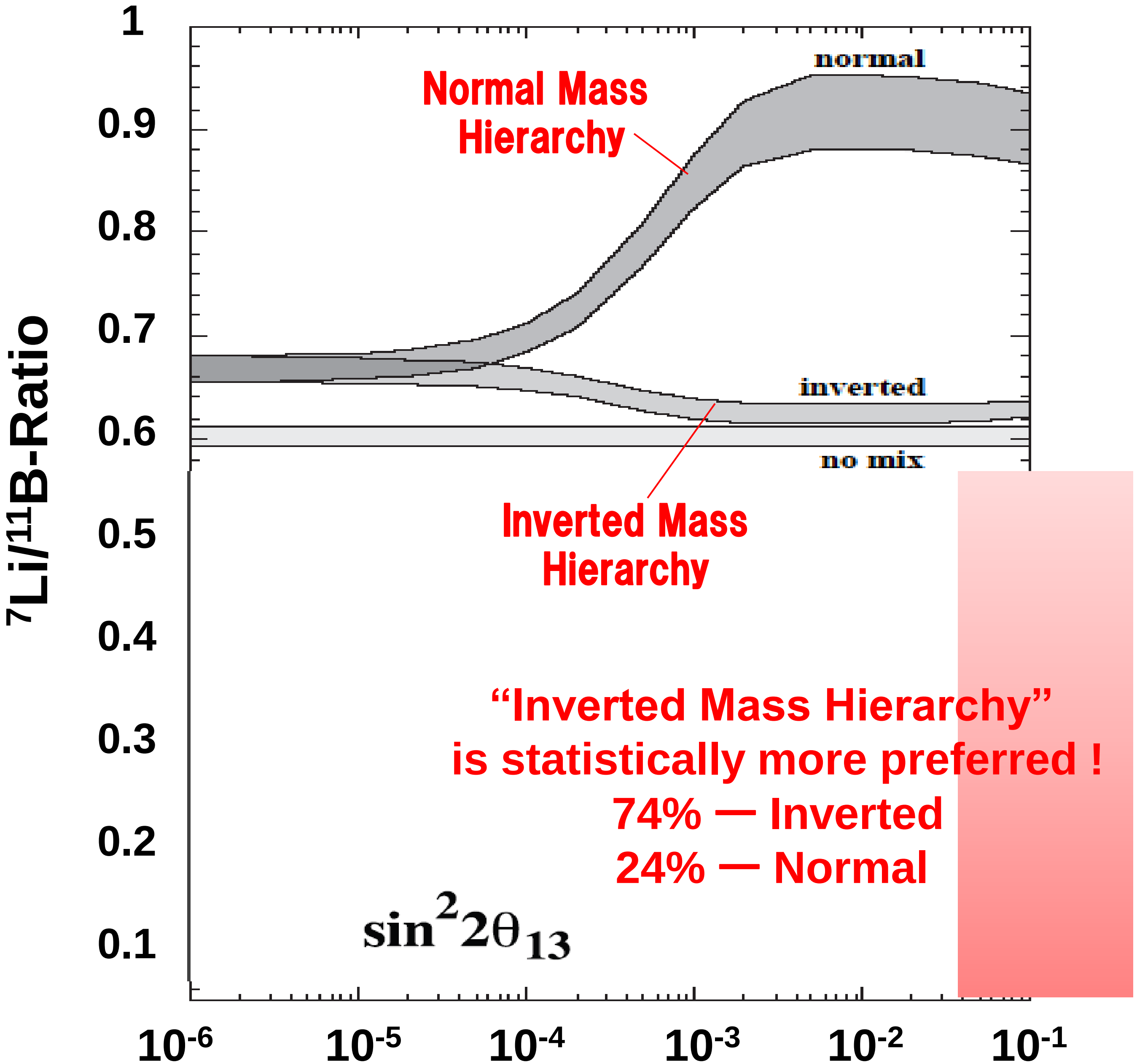
C-, Si-, Li-, and B-isotopic Compositions of SiC X Grains from the Murchison Meteorite

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



Supernova X-Grain Coinstraint

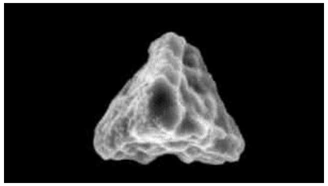


Mathews, Kajino, Aoki And Fujiya, Phys. Rev. D85,105023 (2012).

- 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).

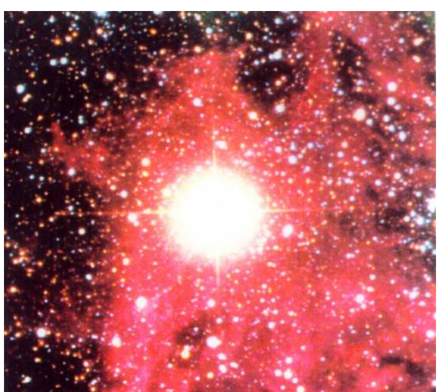
More Observational Effort is required !

Astron. Observations

SN-remnants & r-enhanced metal-poor stars are enriched by SN-products!

^{7}Li & ^{11}B, separately detected !
^{7}Li/ ^{6}Li isotopic ratio has recently detected in supernova remnant IC443.
(Ritchey et al. 2012)

Simultaneous detection is highly desirable!

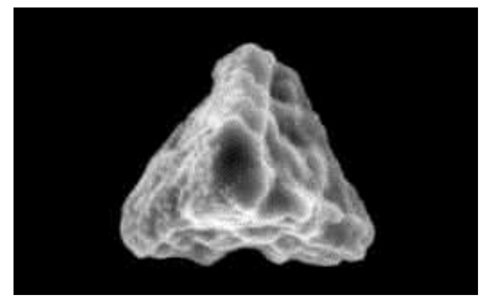


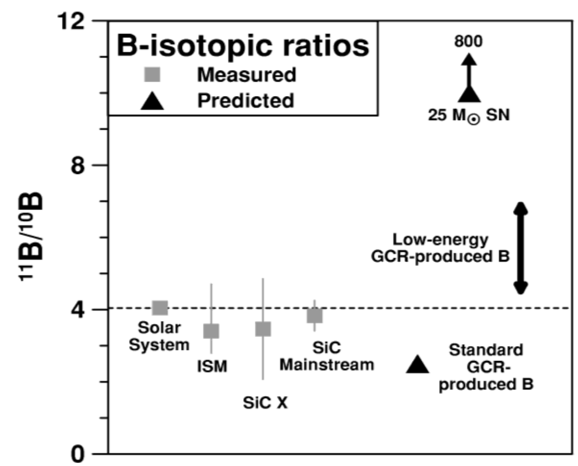
Presolar SiC grains

X-grains are made of SN-dusts!

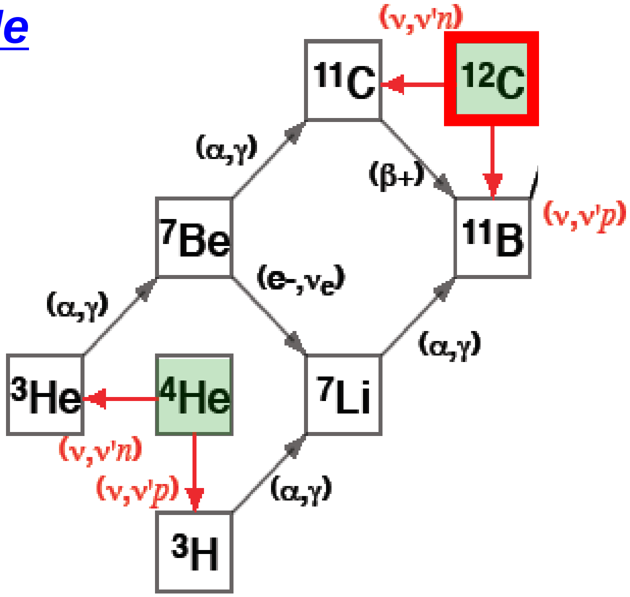
P. Hoppe et al. ApJ 551 (2001) 478,
W. Fujiya, P. Hoppe, and U. Ott, ApJ 730, L7 (2011).

^{7}Li/ ^{11}B; more data, required !





ν–Nucleus Cross-Sections



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

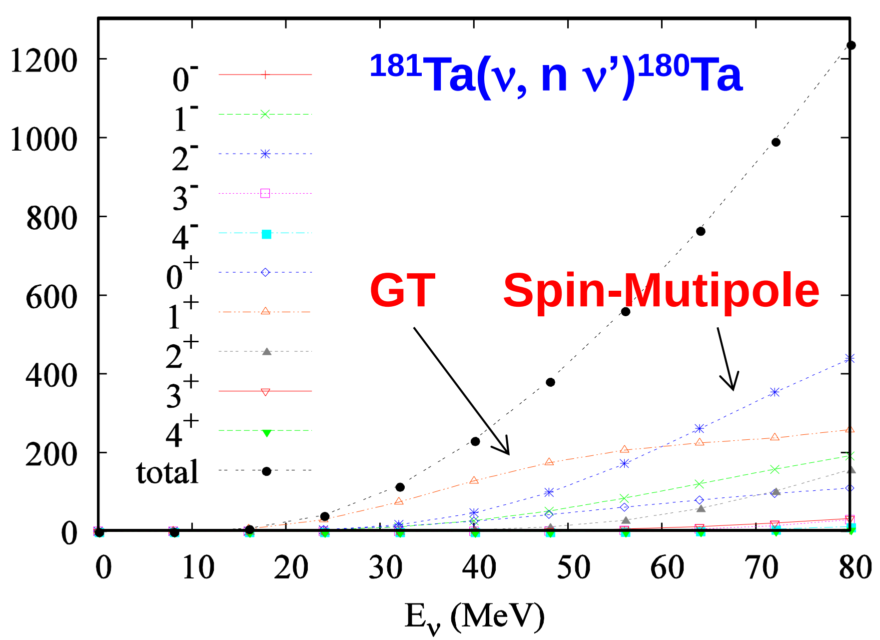
Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307.
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003)

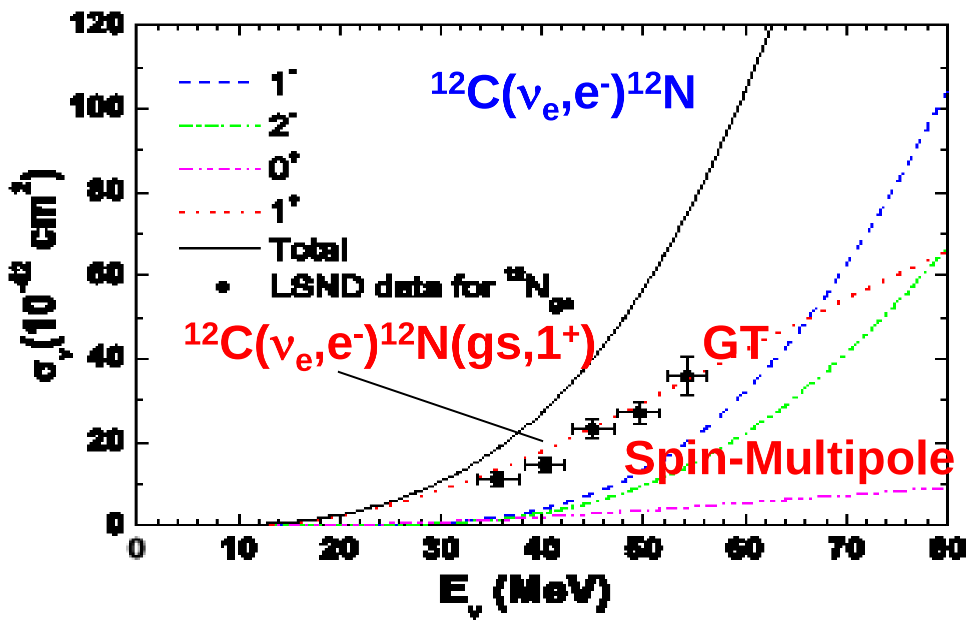
^{12}C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

- μ-moments of p-shell nuclei
- GT strength for ^{12}C→^{12}N, ^{14}C→^{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





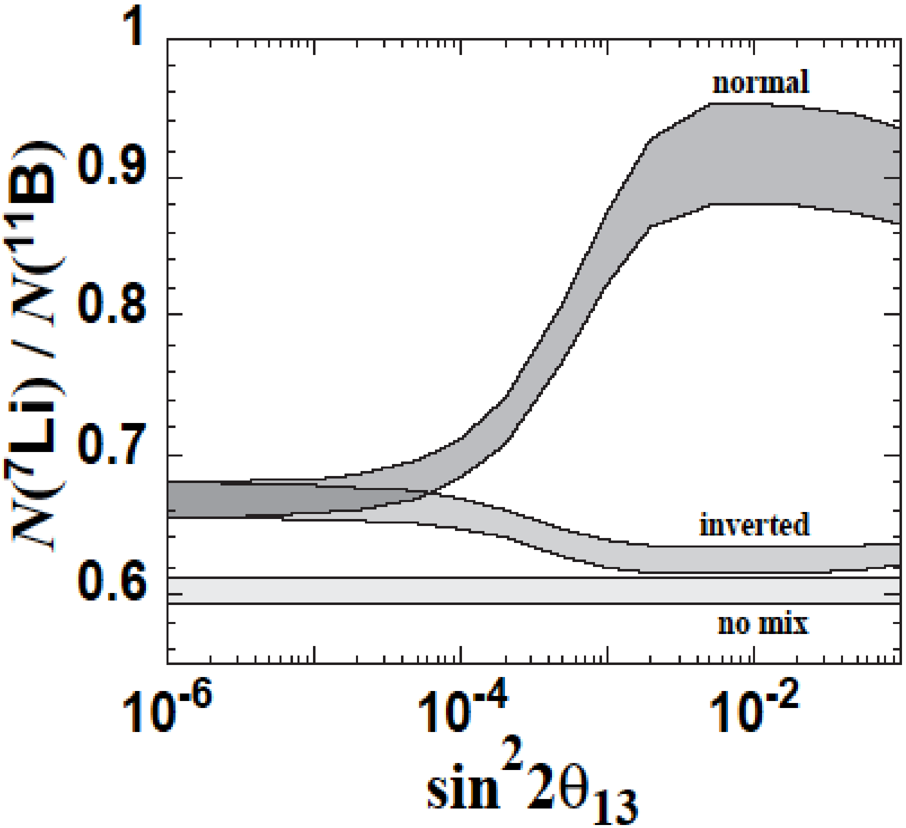
Hamiltonian Dependence on MSW-Effect

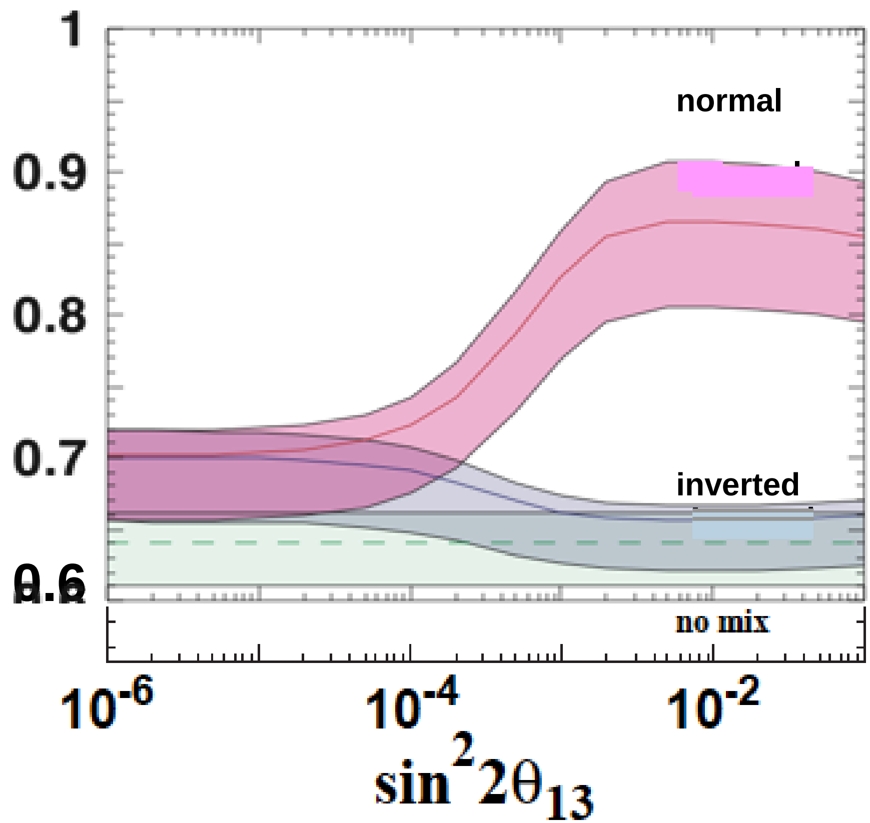
Previous SM-σ_ν(E) of Haxton

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

New SM-σ_ν(E) using WBP(^{4}He) & SFO(^{12}C) interactions

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307: Suzuki & Kajino, J. Phys. G (2013).





Normal / inverted, well separated ! → $^7Li/^{11}B$-ratio is SM independent !
Mixing angle θ_{13} dependence, almost the same !

★ ν-beam experiment is not available !

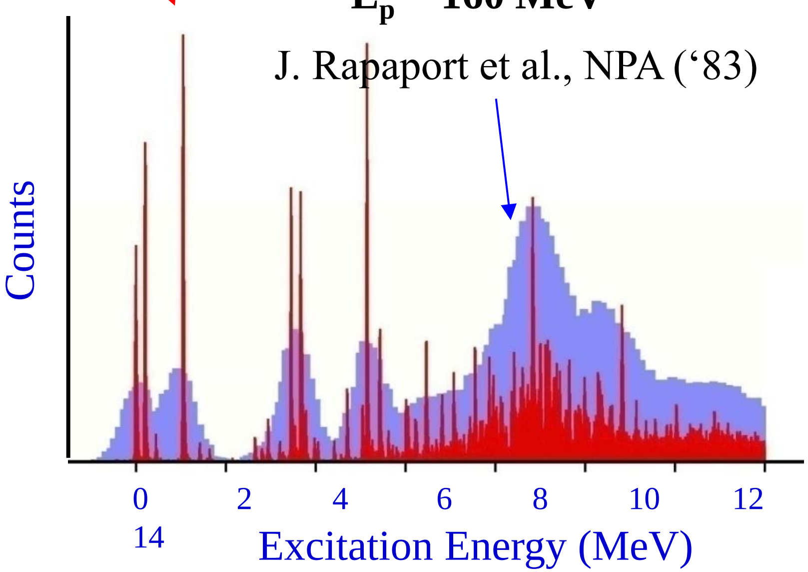
★ EM-PROBE (CEX hadrons, γ's) !

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)

^{58}Ni(*p*, *n*)^{58}Cu
E_p = 160 MeV



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

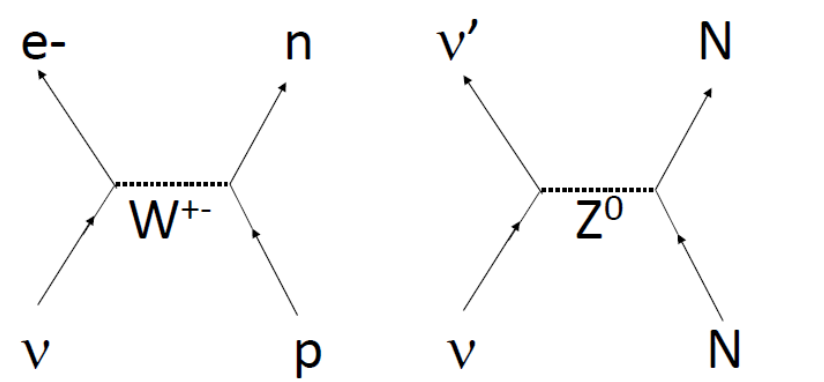
$$\vec{V} \approx g_V^{IV} \frac{i}{2m} \vec{\sigma} \times \vec{q} + \frac{g_V}{2m} (\vec{p} + \vec{p}\,')$$

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

Weak operator in non-relativistic limit

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

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



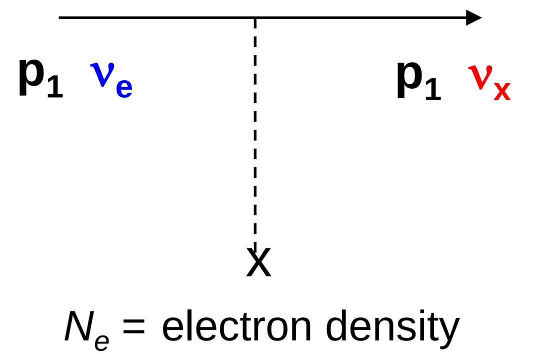
charged-current neutral-current

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

H_{ν} = Mixing and Interaction with Background Electrons

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

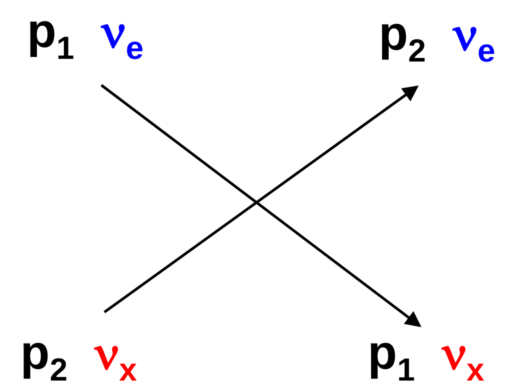
$$H_{\nu} = \frac{1}{2}\int d^3p \left(\frac{\delta m^2}{2p}\cos 2\theta - \sqrt{2}G_F N_e\right)\left(a_x^{\dagger}(p)a_x(p) - a_e^{\dagger}(p)a_e(p)\right) + \frac{1}{2}\int d^3p \frac{\delta m^2}{2p}\sin 2\theta\left(a_x^{\dagger}(p)a_e(p) + a_e^{\dagger}(p)a_x(p)\right).$$



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

Self-Interaction

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



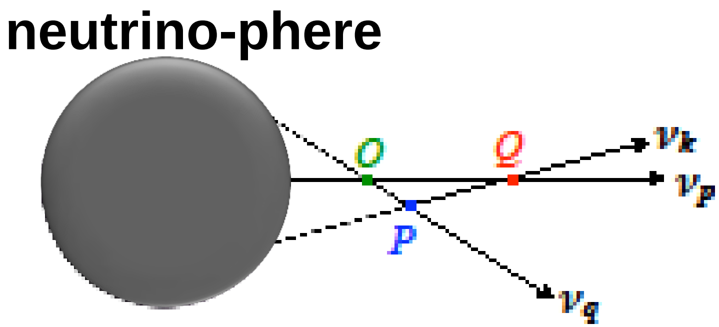
Quest for EXACT Many-Body SOLUTION !

"Invariants of collective neutrino oscillations"

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

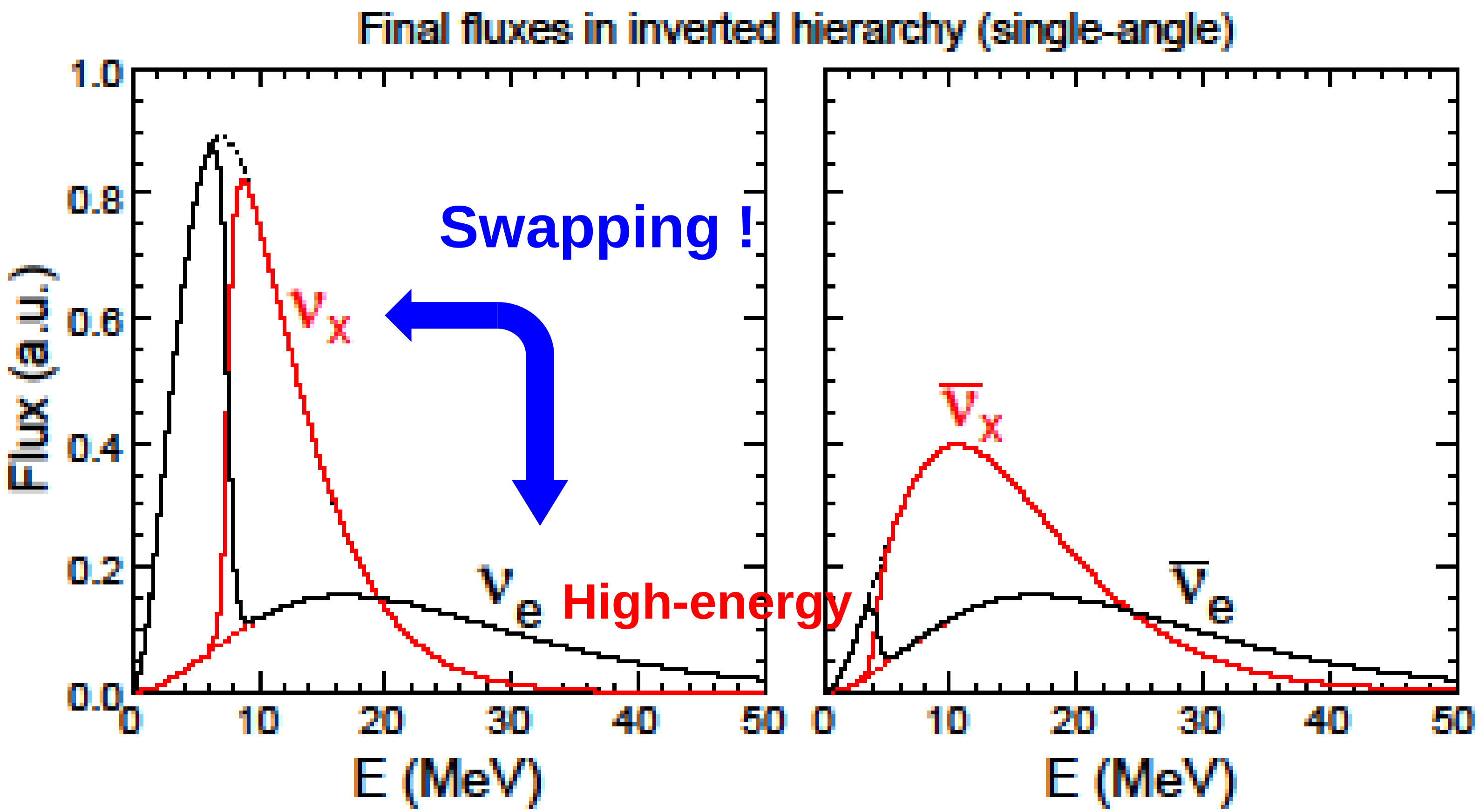
Phys. Rev. D84, 065008 (2011)

ν self-interaction (Quantum Effect)



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

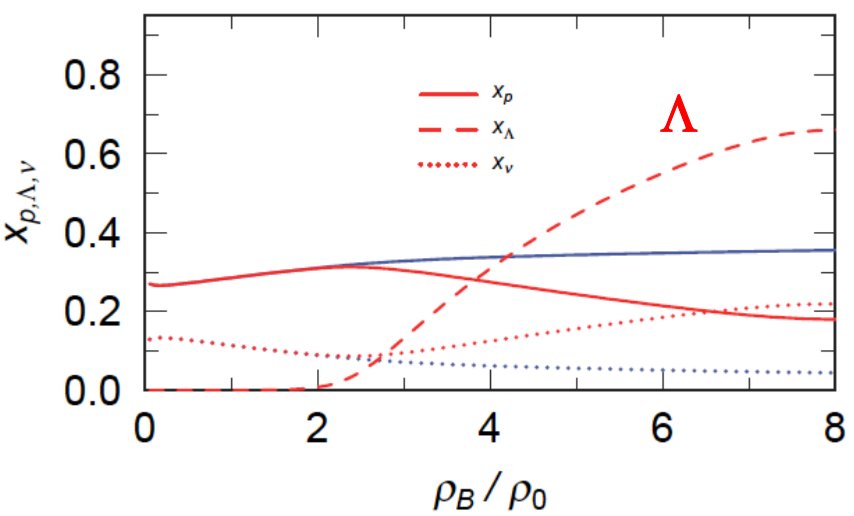


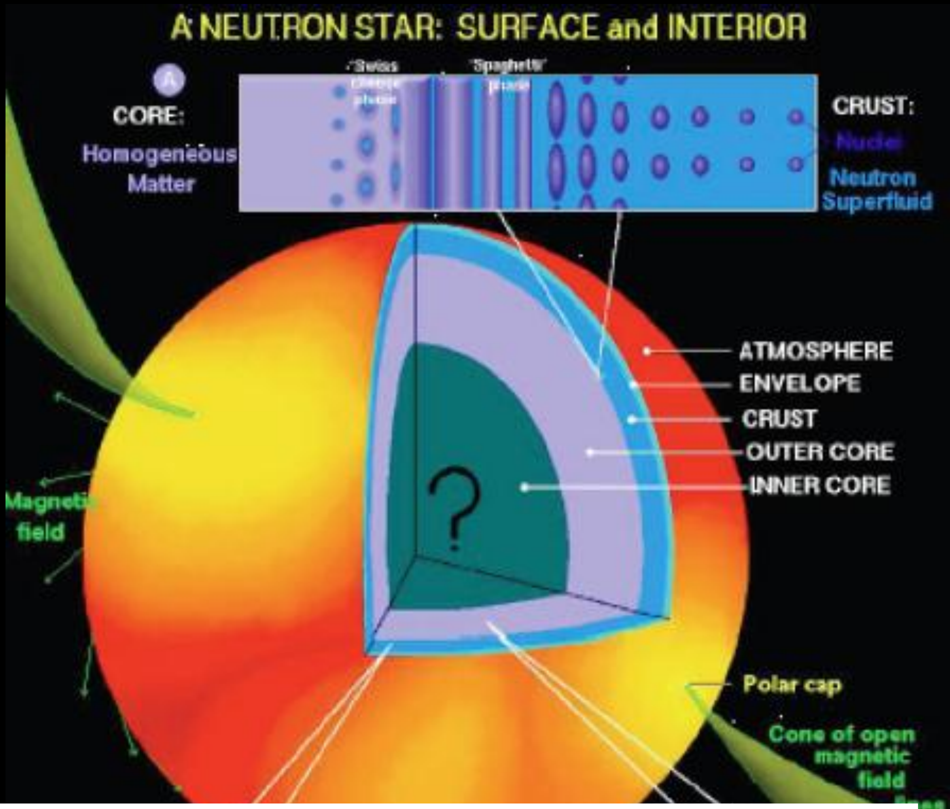
ν-Asymmetry under the Strong Dipole (Poroidal) Magnetic Field

Proto-neutron stars in c.c. Supernovae

Fundamental Interactions among Hadrons (p, n, Λ, Σ …) and Lepton (e,ν…) at High-ρ and High-T in Relativistic Field Theory and QCD

Maruyama, Kajino, Yasutake, Cheoun, & Ryu, PRD83 (2011), 081302 (R).





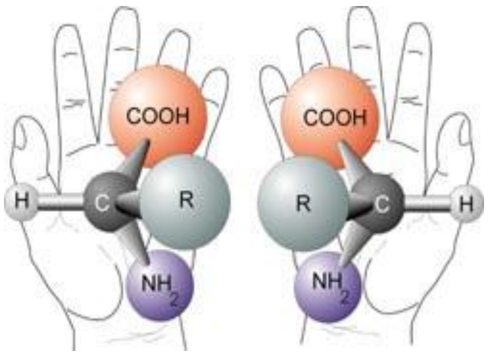
Neutrino scattering and absorption process inside the magnetized Neutron star (10^{15}G) is asymmetric.

⇒ ~ 2 % asymmetric ν-abs. (drift)

⇒ Enough for Pulsar-Kick ~500km/s !

Why Amino Acids on the Earth, All Left-Handed?

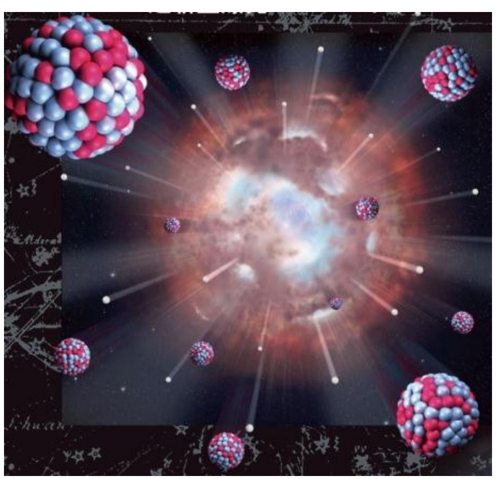
Chitrality, earth origin or universal ?

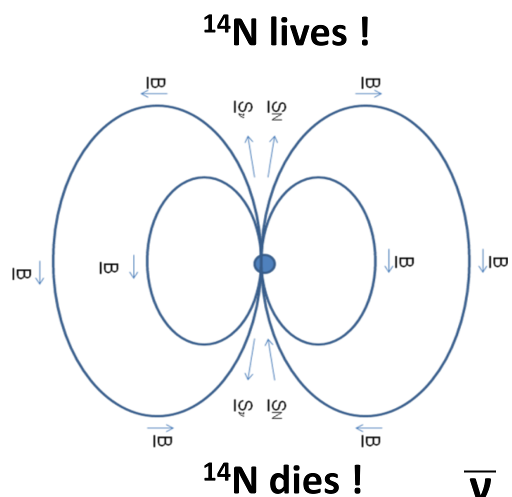


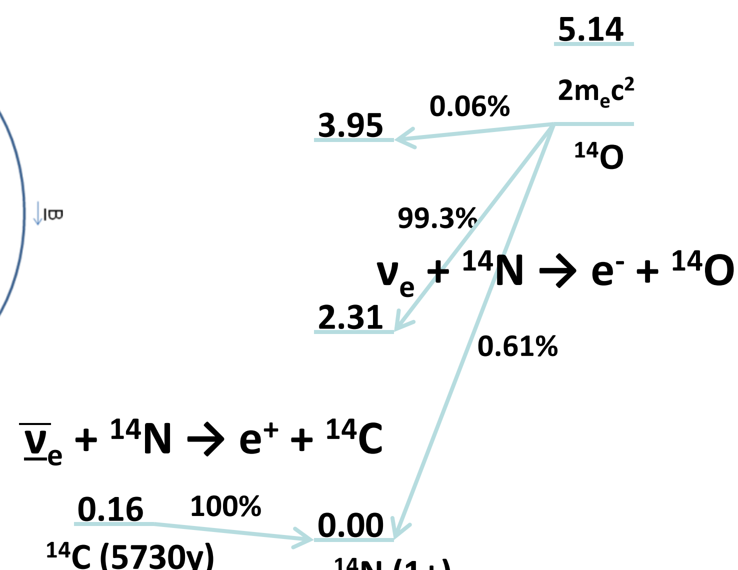
- ★ **Neutrinos are all left-handed!**
- ★ **Supernovae with strongly magnetized neutron star or BH emit intensive flux of neutrinos over 10^{10} yrs!**
- ★ **SN ejecta including ^{14}N interact with neutrino under strong magnetic field!**
- ★ **Neutrino-^{14}N coupling is asymmetric & chiral selective!**

Boyd, Kajino, & Onaka suggested that the L-handed chirality of amino acids is UNIVERSAL! (Astrobio. 10, 2010, 561-568; Int. J. Mol. Sci. 12, 2011, 3432)

Magnetized Supernovae







Mann and Primakoff (Origins of Life, 11 (1981), 255) suggested β-decay of 14C, but it's too SLOW!

SUMMARY

ν-Mass hierarchy:

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

Total ν-mass:

- Curvature perturbation is shown to be generated by the extra anisotropic stress π_{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) π_{ext}.
- Total ν-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.