8th Int. WS on Neutrino-Nucleus Interactions in the Few-GeV Region
Rio de Janaeiro, Brazil, Oct. 22-27, 2012

Neutrino nucleosynthesis process in core-collapse supernovae and neutrino oscillation

θ_{13} is known now, but not the mass hierarchy!

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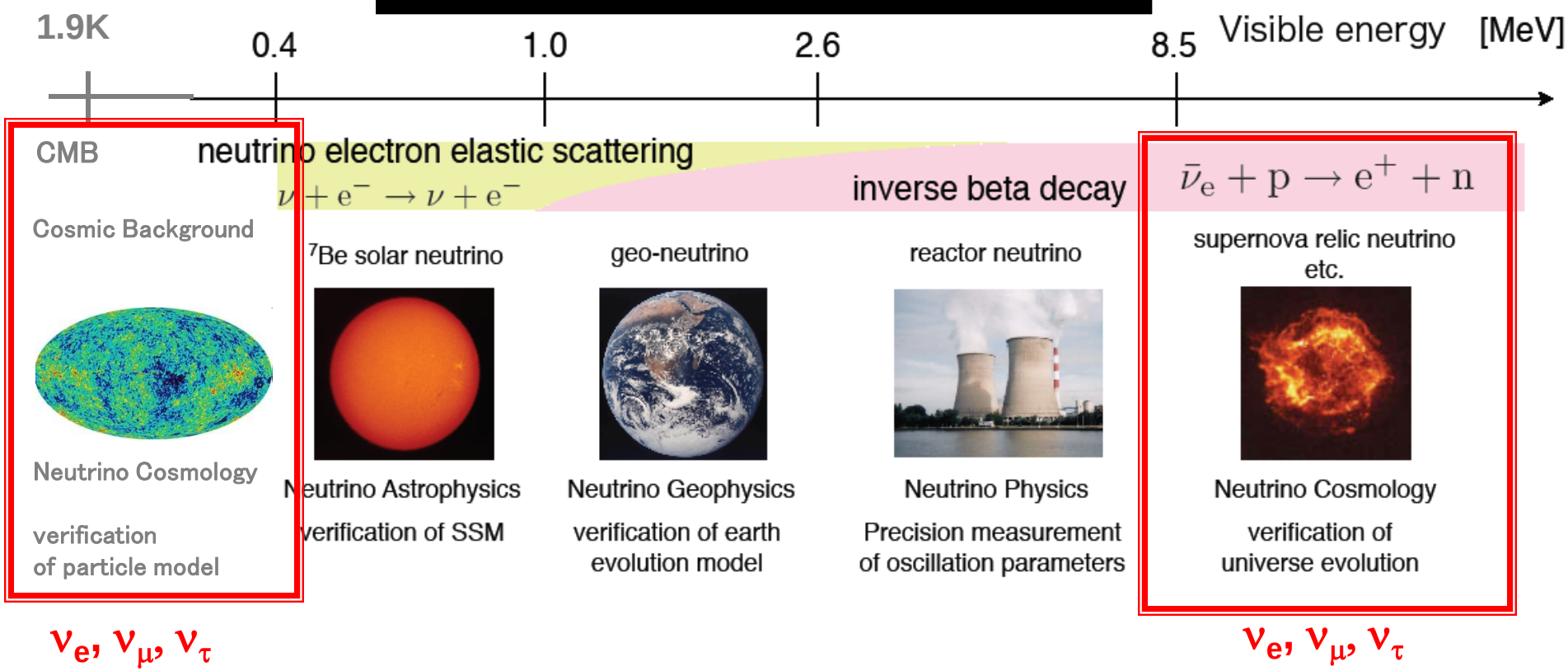
Various Neutrino-Sources in Nature



PURPOSE

: is to study supernova ν-process nucleosynthesis and cosmic neutrinos in order to constrain ν–mass hierarchy (for finite θ_{13}) and total mass.

Challenge of the Century

Universal expansion is most likely flat & accelerating !

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

- **What is the CDM, 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, Ω_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 ?

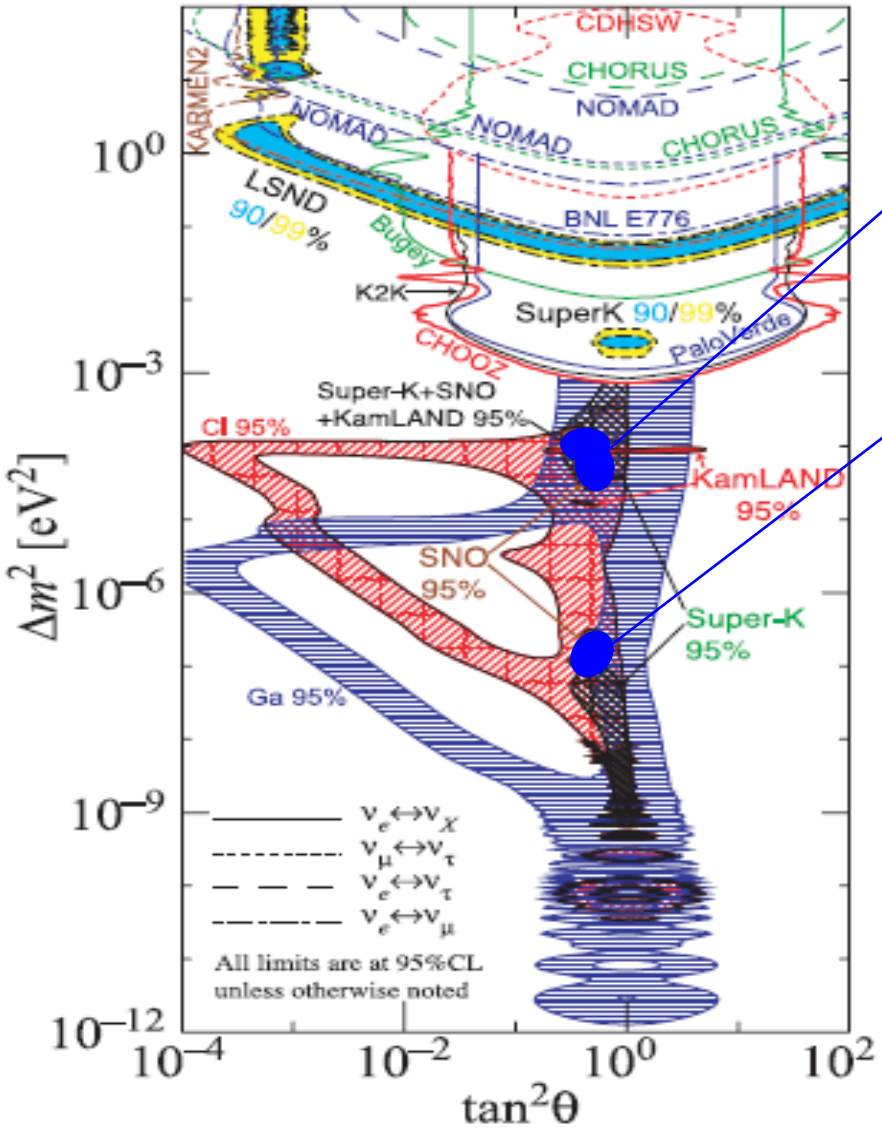
Plan of this Talk

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

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

"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

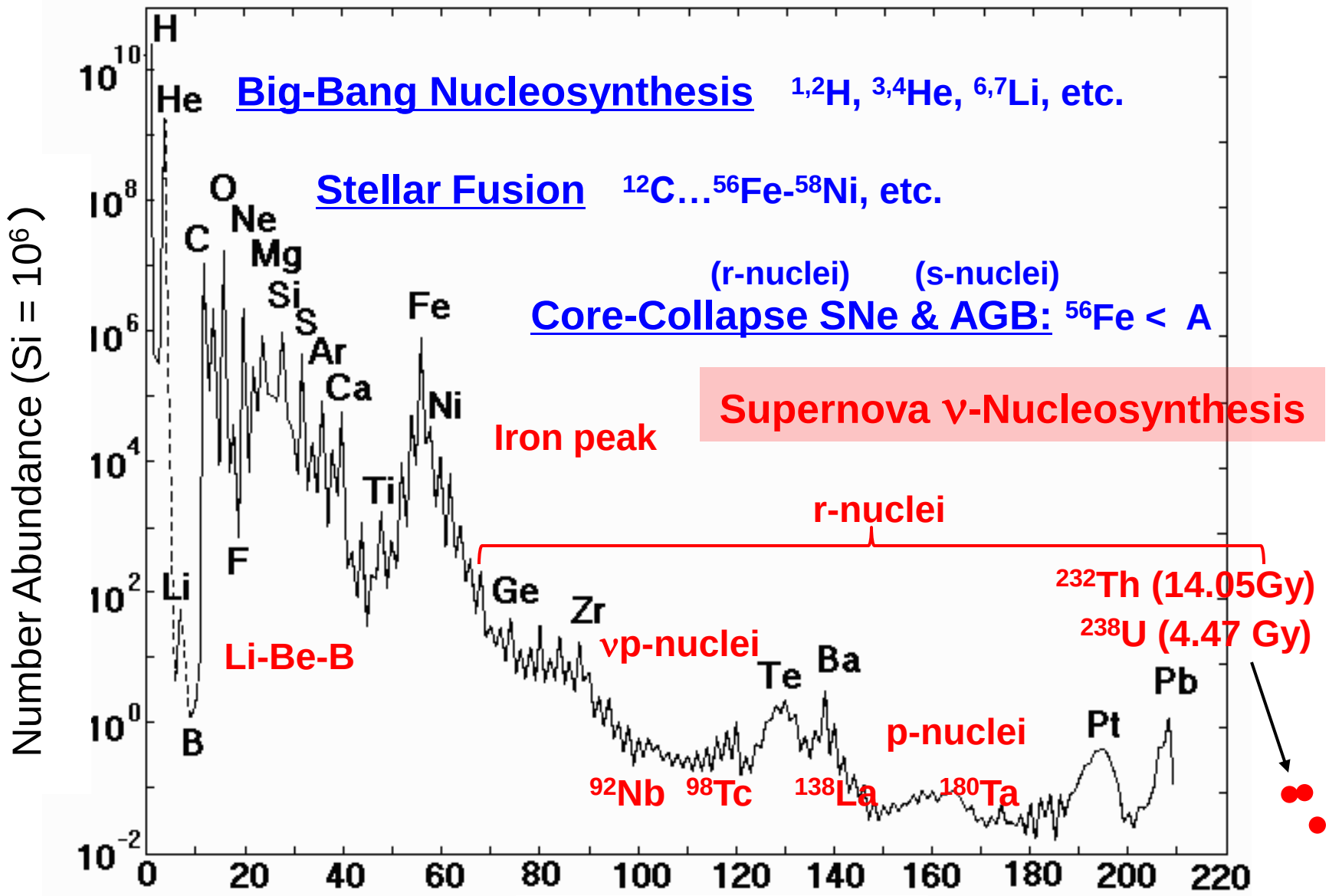
"UNKNOWN"

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.

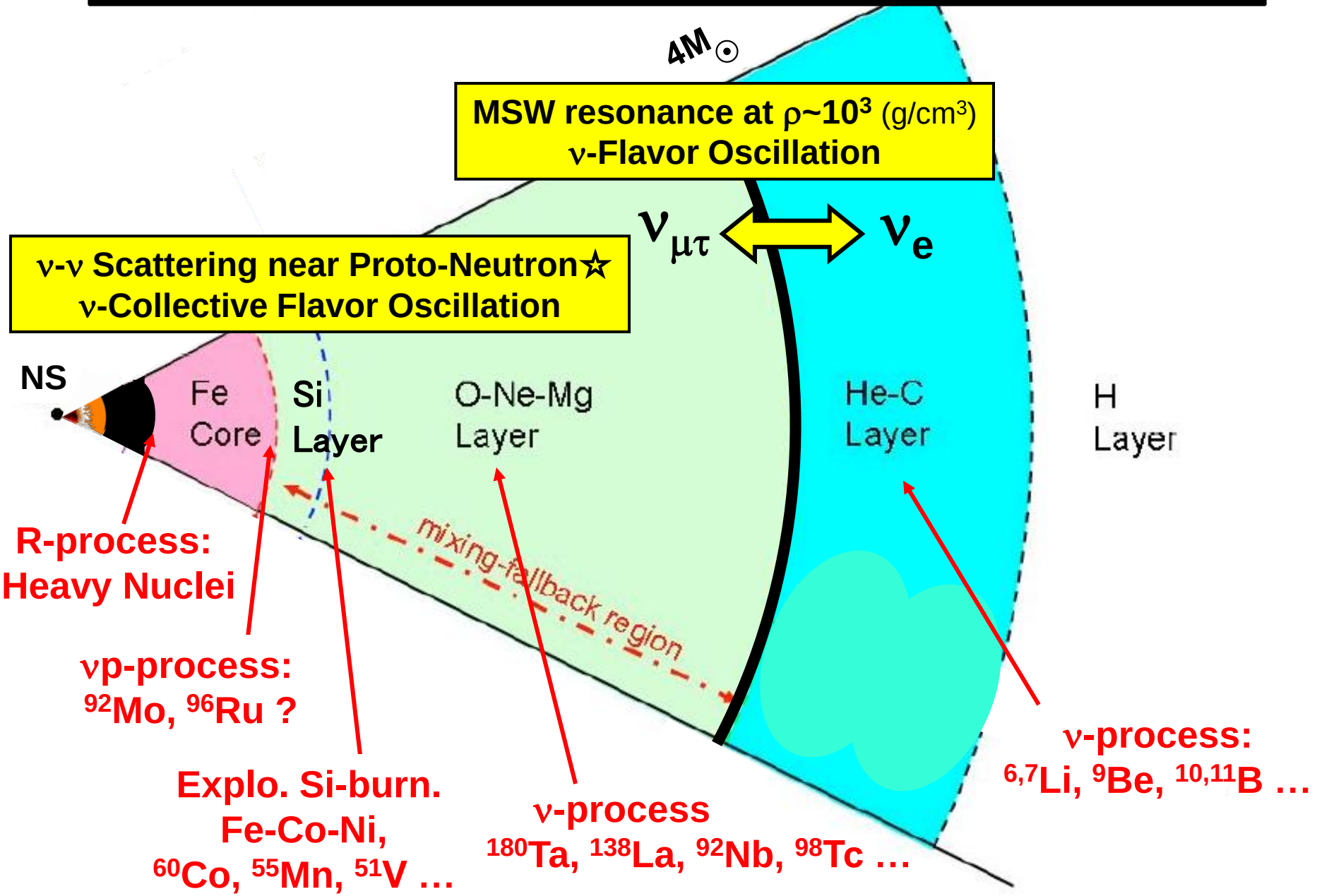
Solar System Abundance



Cosmic Ray Spallation

Li-Be-B, F, Na, etc.

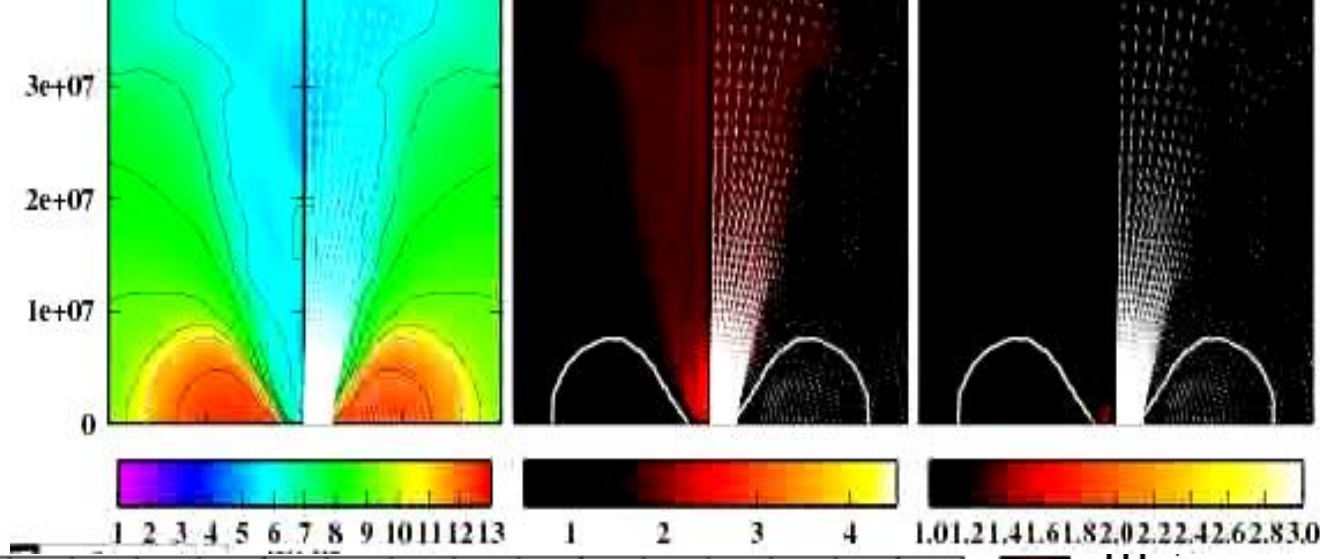
Various roles of ν's in SN-nucleosynthesis

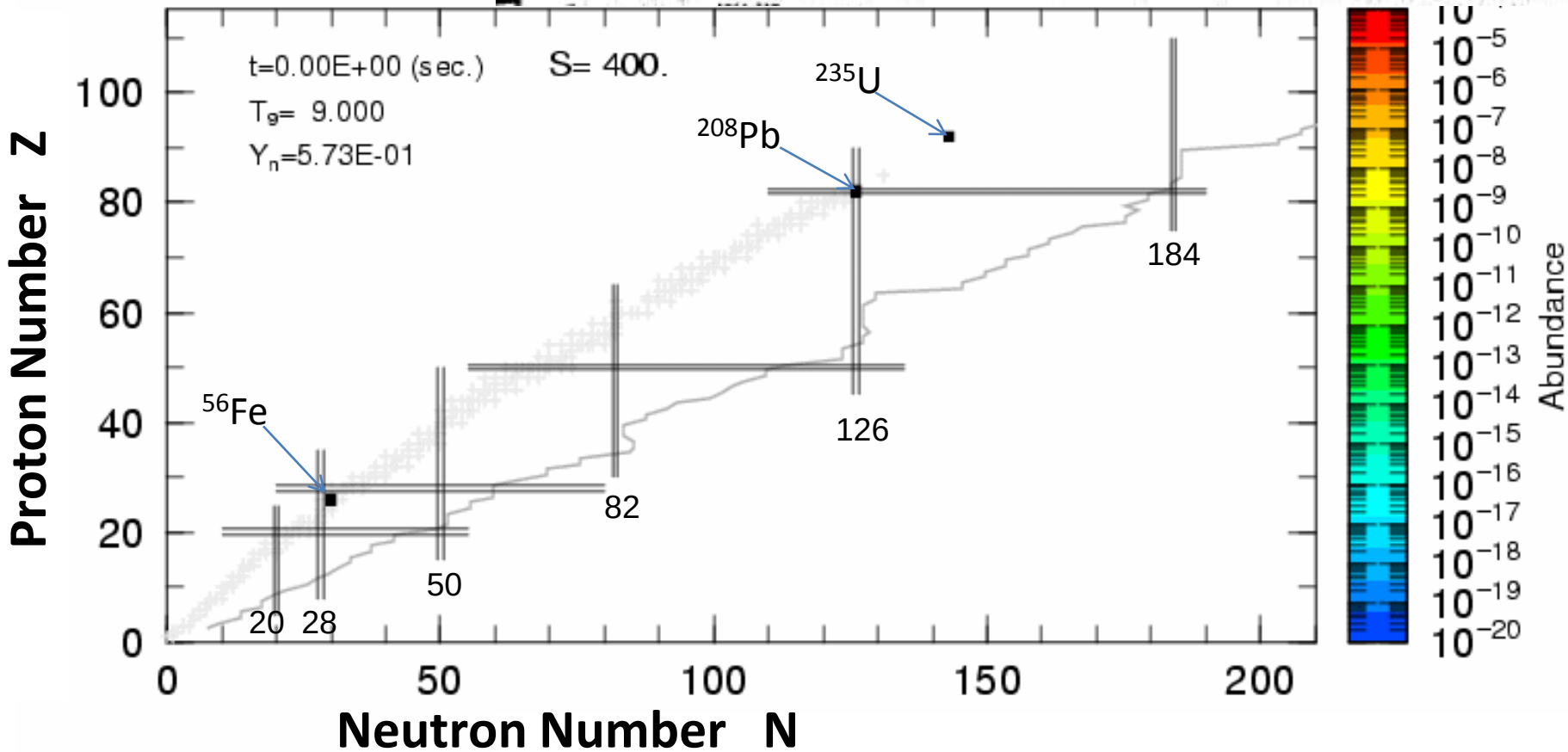


Supernova Nucleosynthesis Simulation

T. Kajino & S. Chiba

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





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

Challenge to identify astrophysical sites of the r-process:

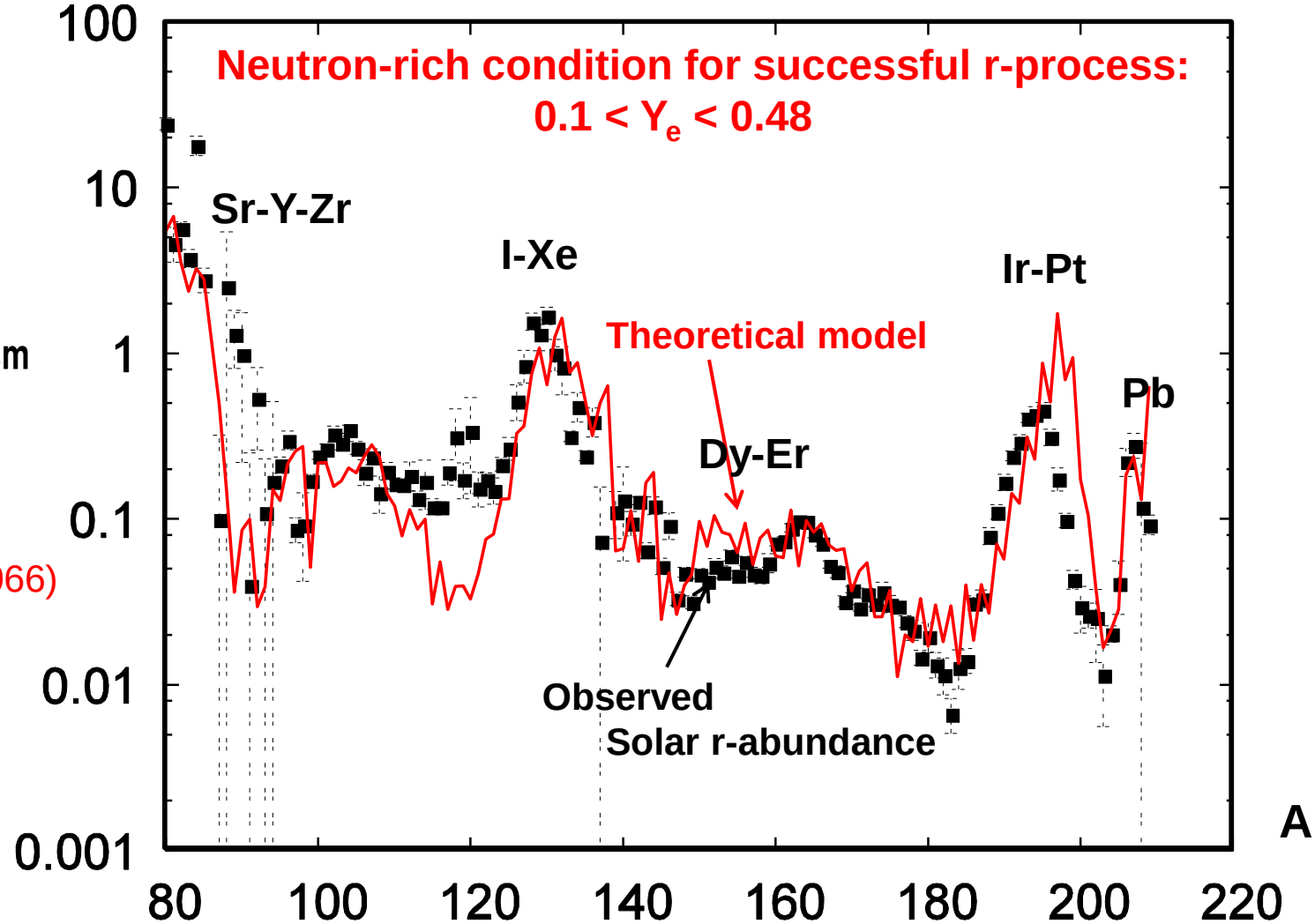
- ν-wind SNe
- MHD jet SNe
- NS mergers
- GRBs

\+

Explosion mechanism

$Y_e > 0.5$?

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



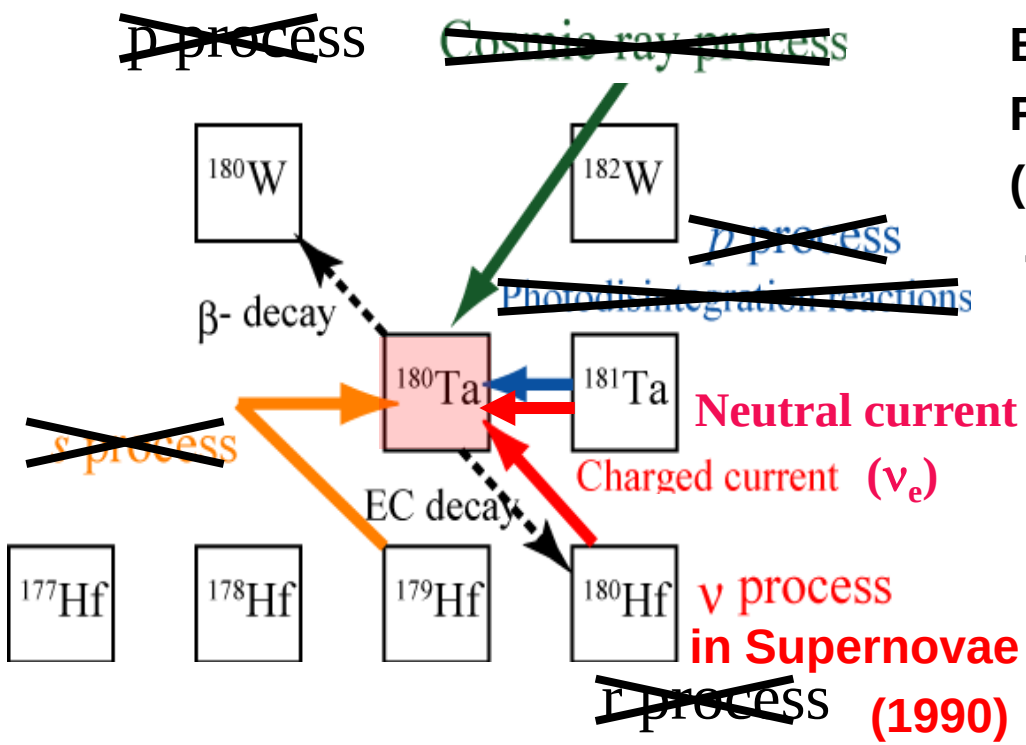
Tantalum (^{180,181}Ta)

$^{181}Ta_g$ (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!

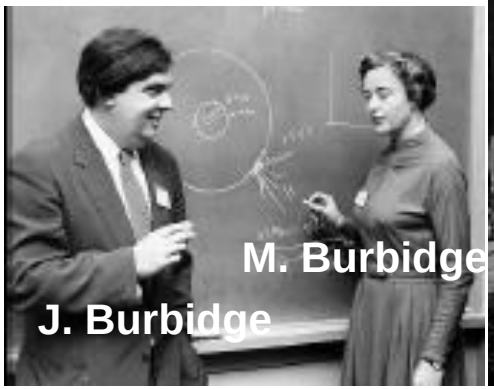
Origin of ^{180}Ta was unknown.

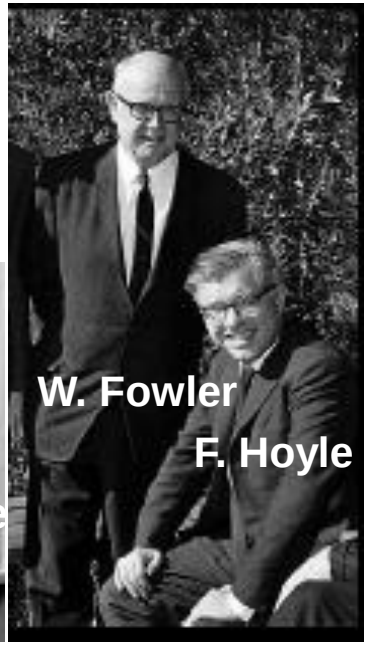
"SN ν-process", overproduces ^{180}Ta !



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

"Element Genesis"



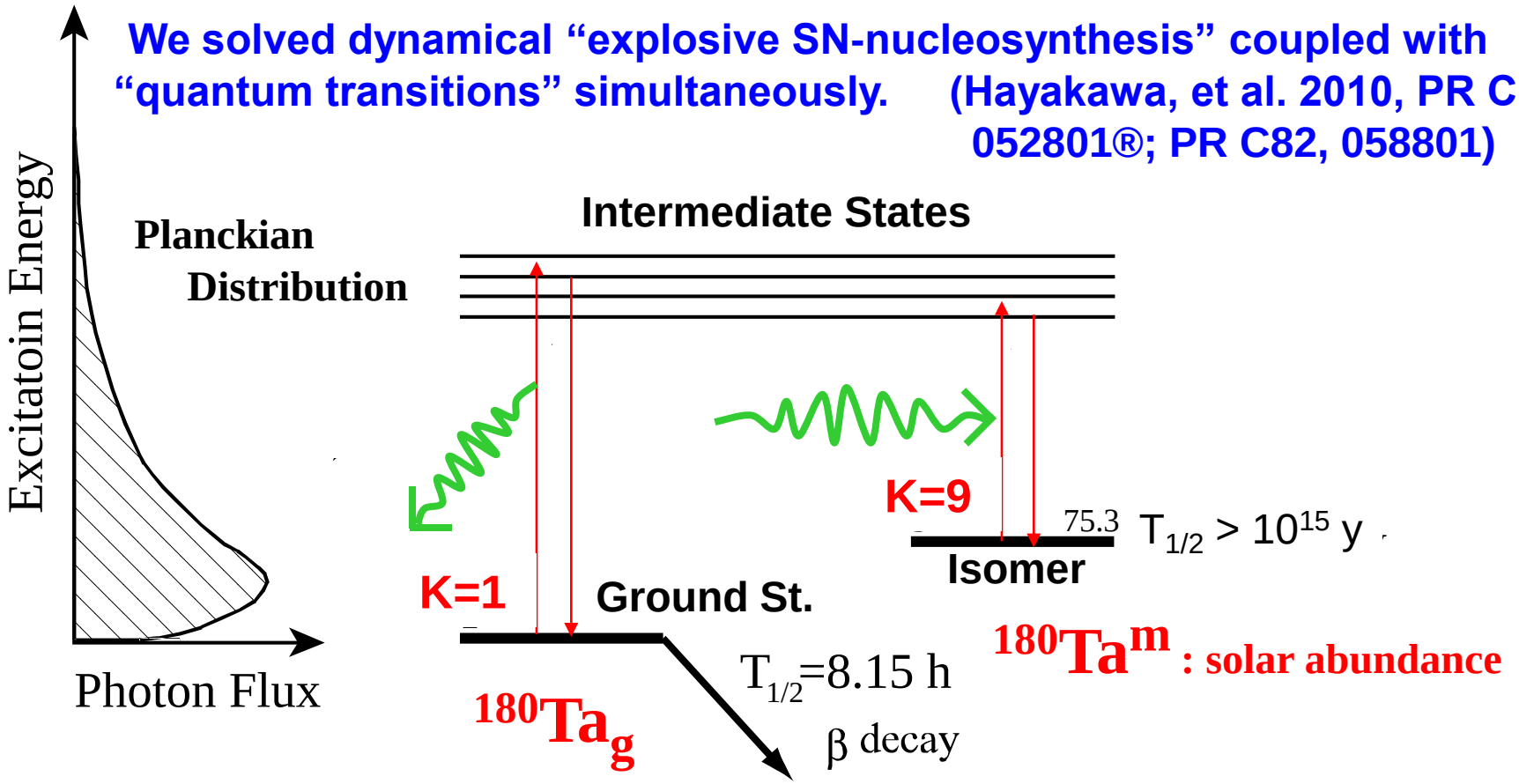


^{180}Ta-genesis needs Quantum Phys. + SN Hydro-dyn.

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

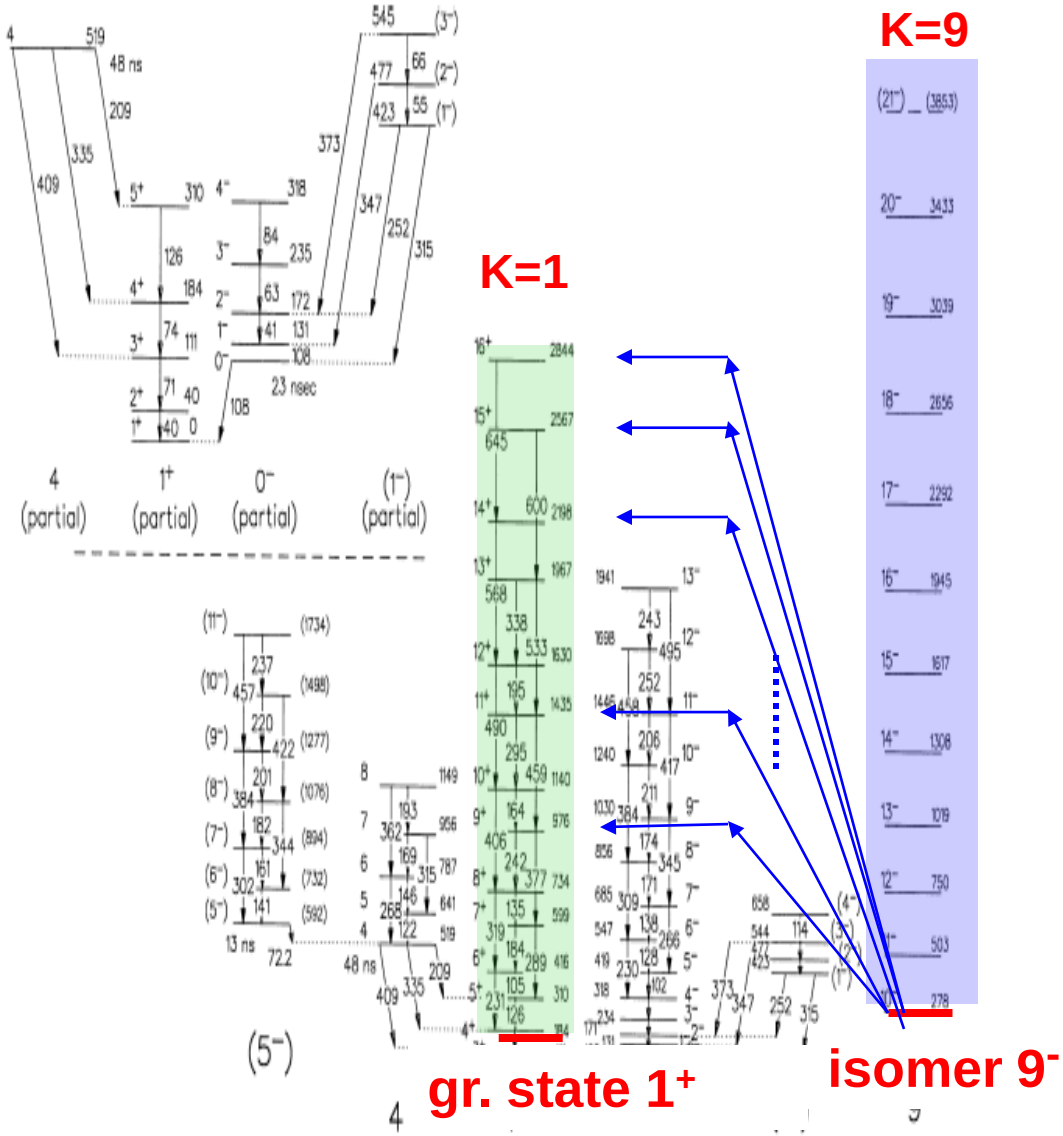
- **Long lived $^{180}Ta^{m}$ is excited in hot SN-photon bath.**
- **Intermediate states are depopulated to the ground state, which decays in 8 hours.**

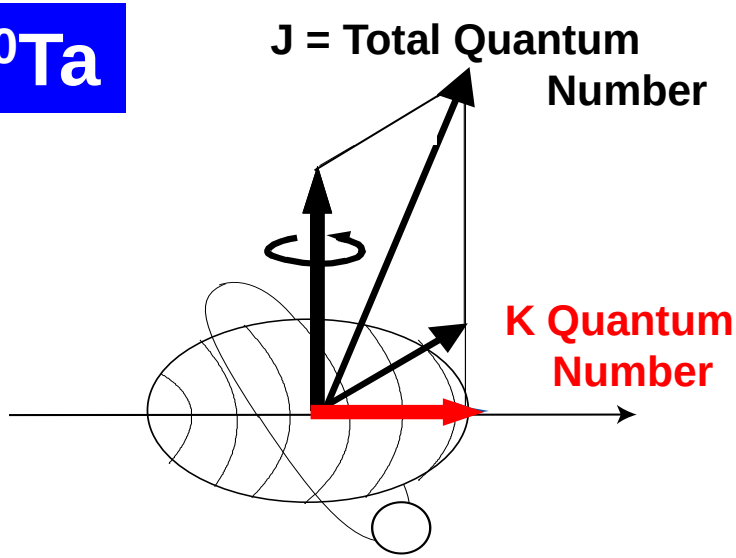
We solved dynamical "explosive SN-nucleosynthesis" coupled with "quantum transitions" simultaneously. (Hayakawa, et al. 2010, PR C81, 052801®; PR C82, 058801)



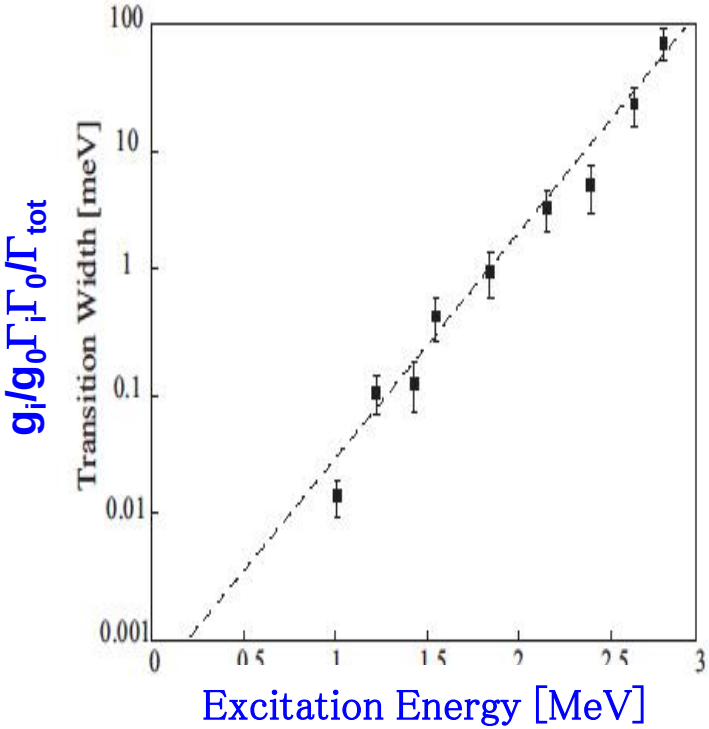
ν-Process and Structure of ^{180}Ta

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



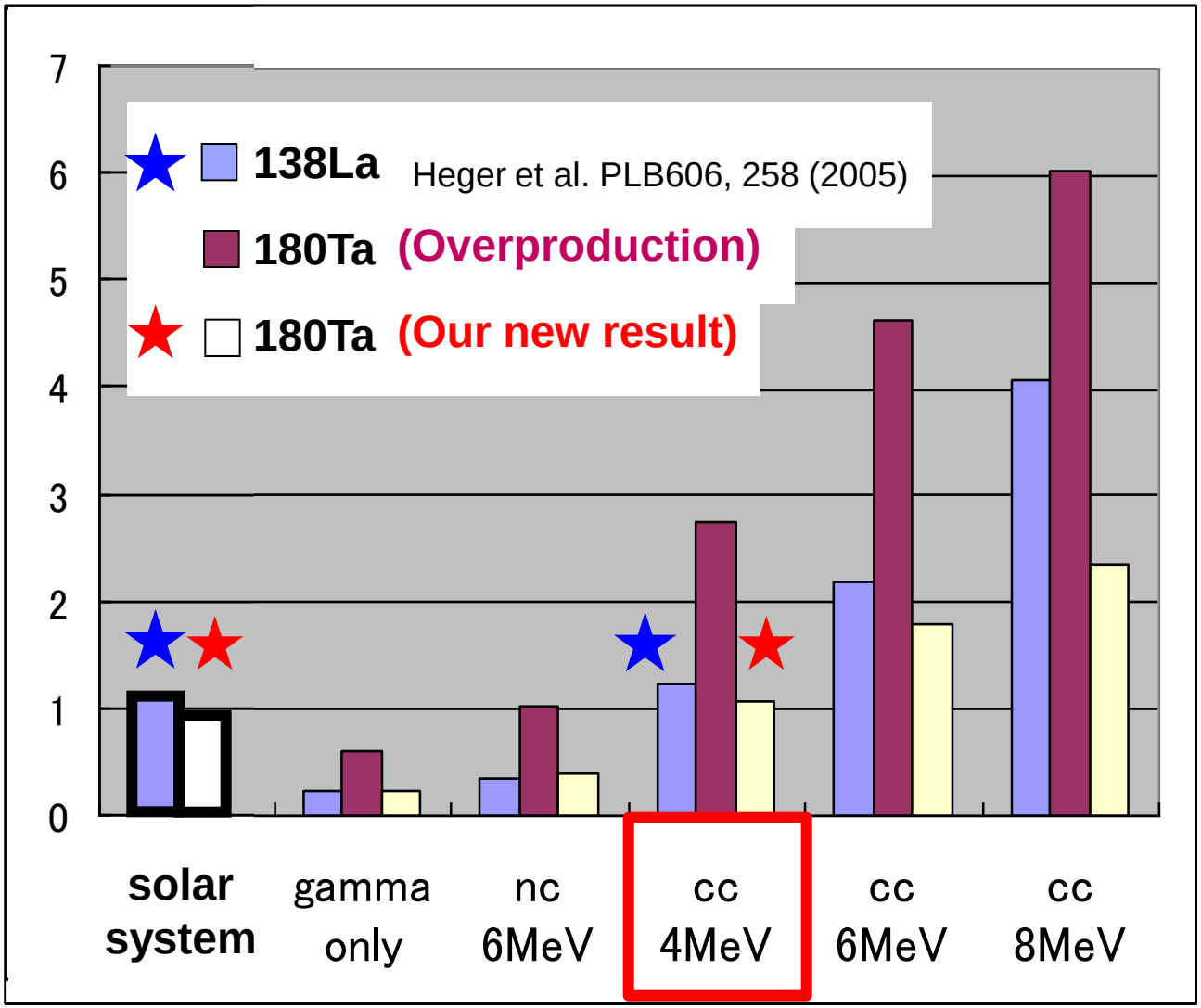


D. Belic et al., PR C65 (2002), 035801.



Result from ν-Nucleosynthesis

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



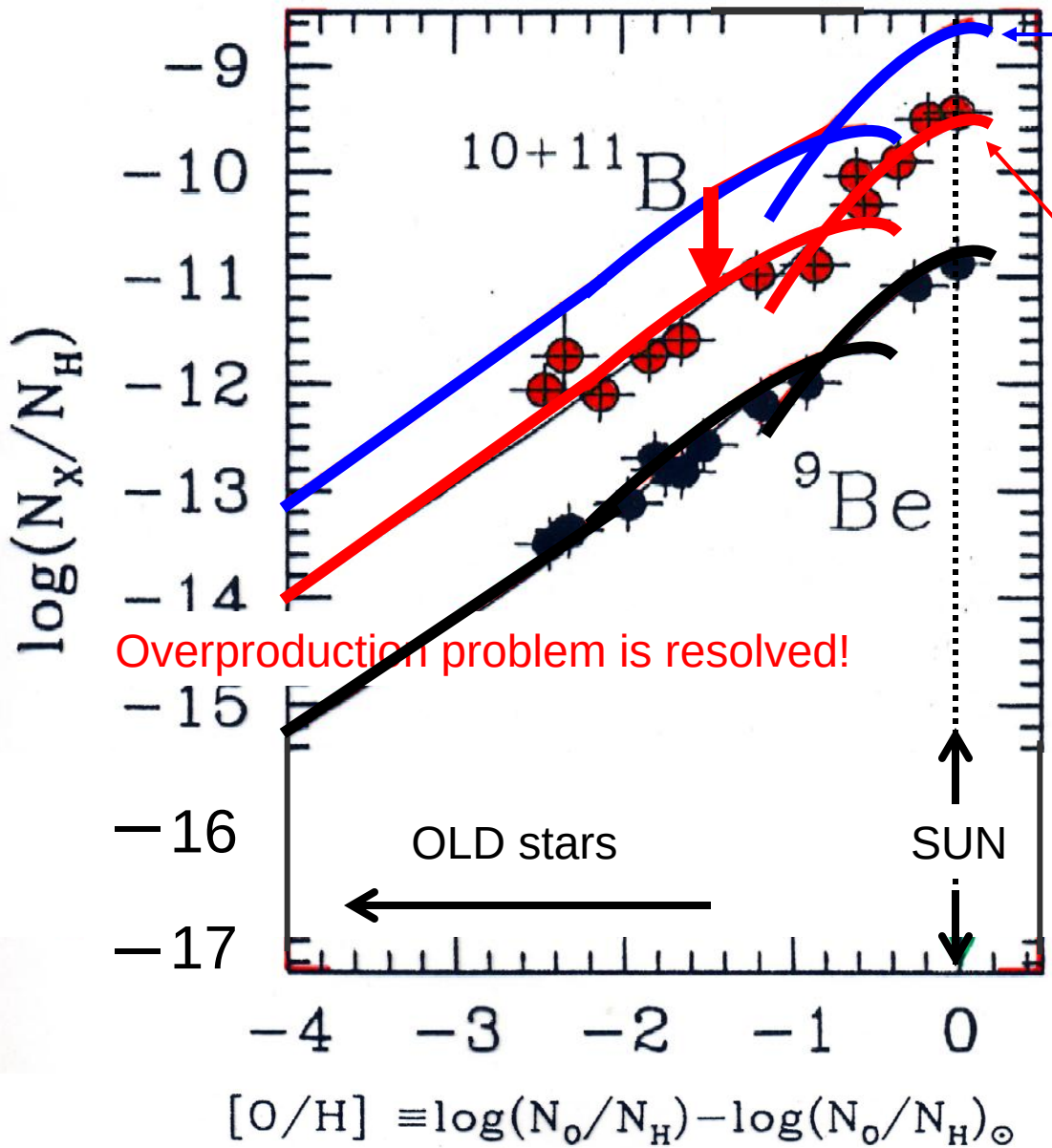
About 40% $^{180}Ta^{m}$ survives in supernova explosion.

Then, both ^{138}La and ^{180}Ta abundances can be consistently reproduced by the CC-int. of ν_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 !

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:

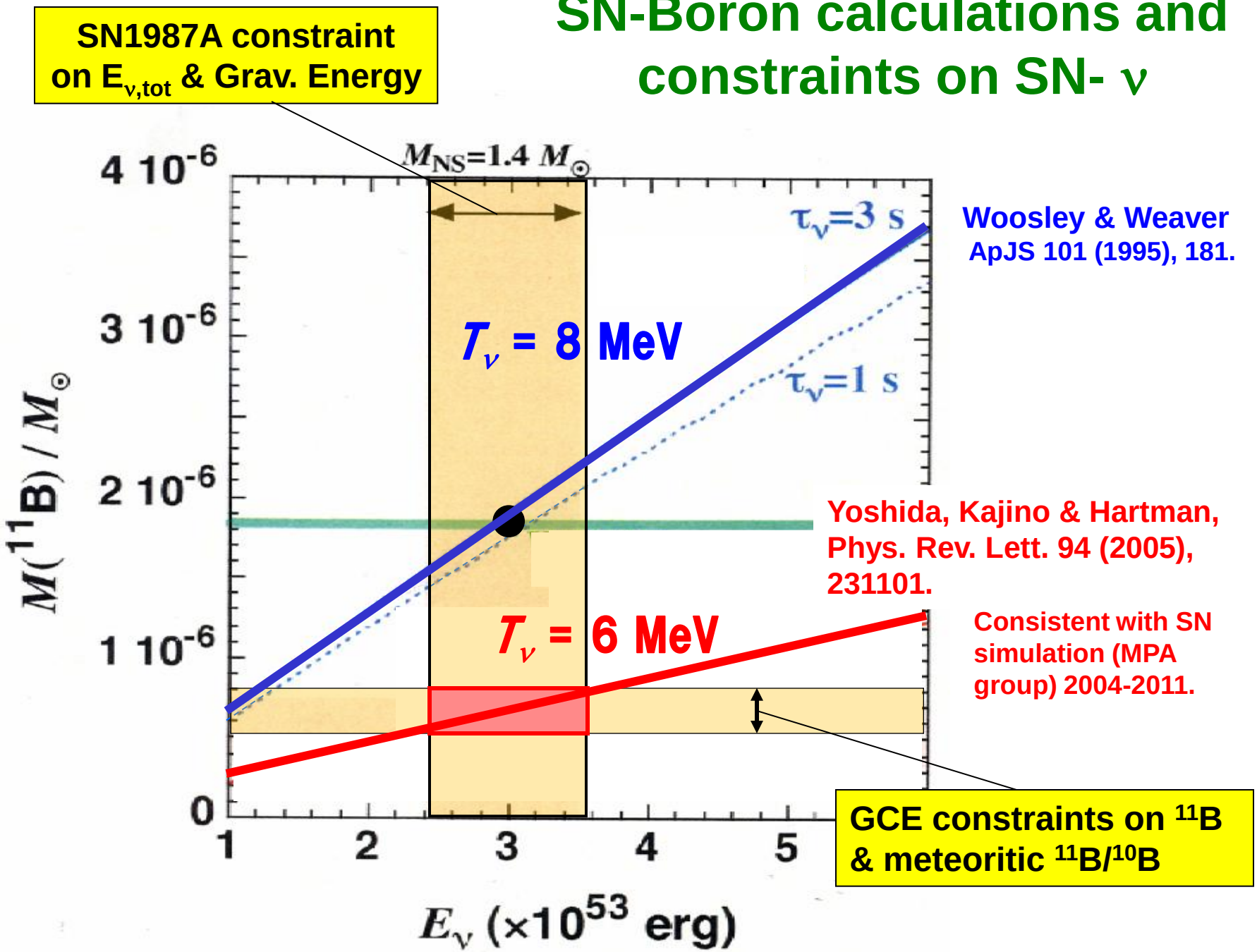
- Galactic Cosmic Rays

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

- Galactic Cosmic Rays
- Supernova ν–process

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

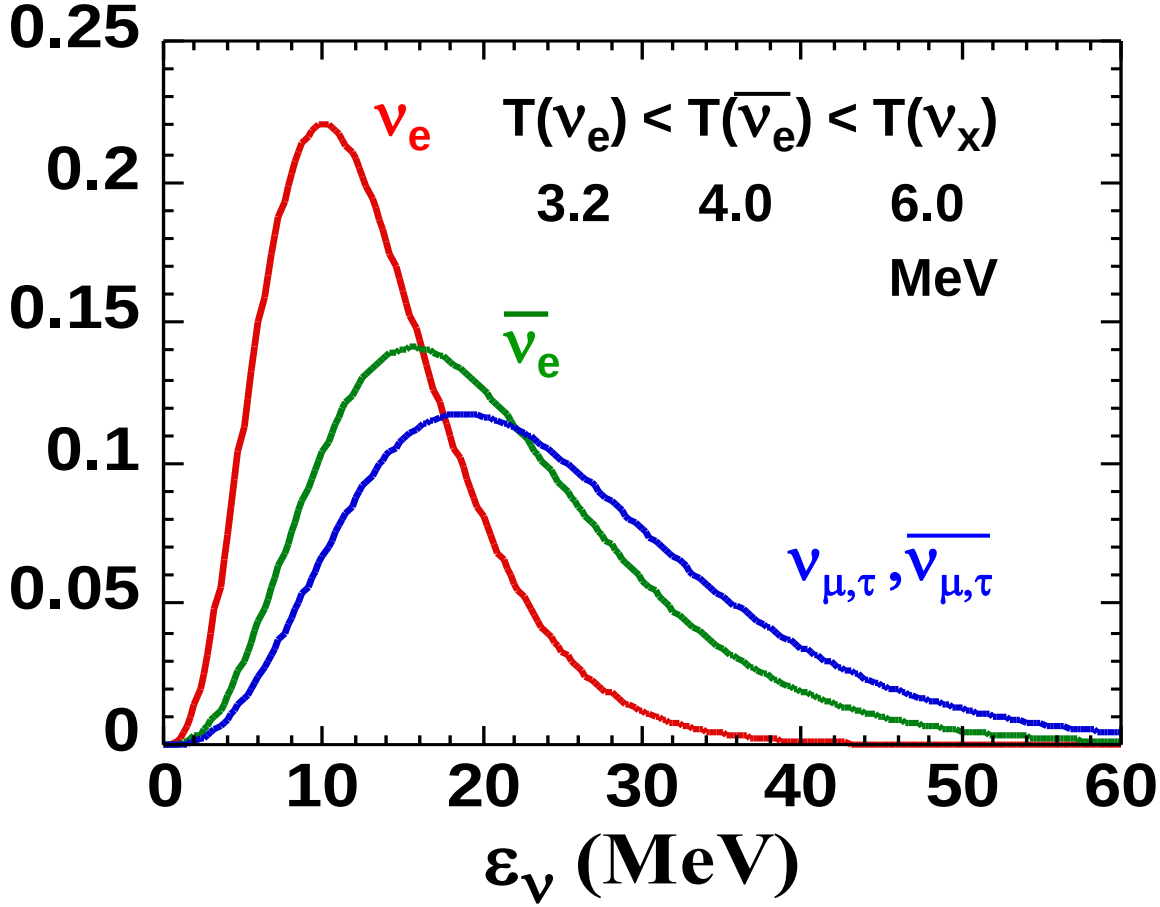
SN-Boron calculations and constraints on SN- ν

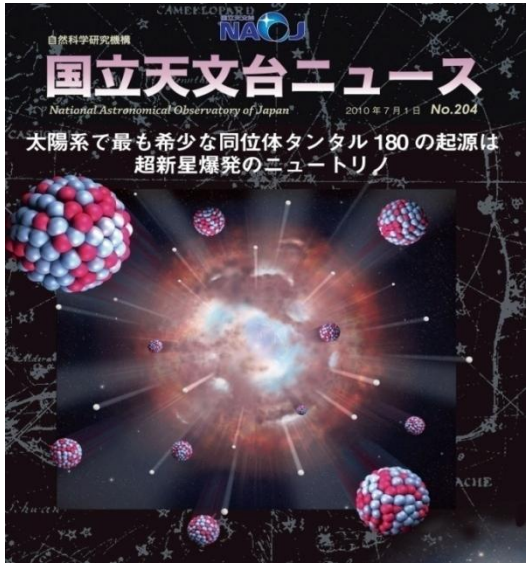


Average ν-temperatures are now known!

- 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

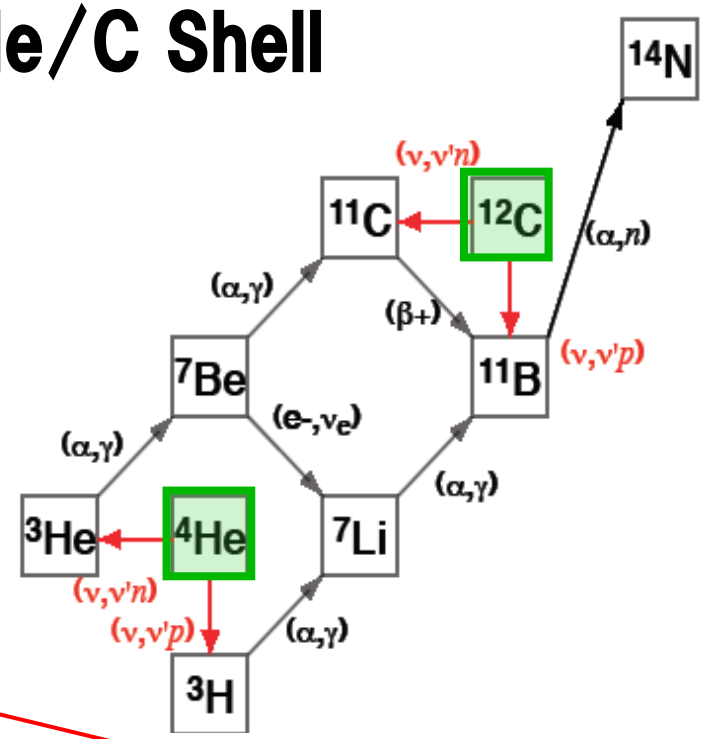
Neutrino Oscillation !



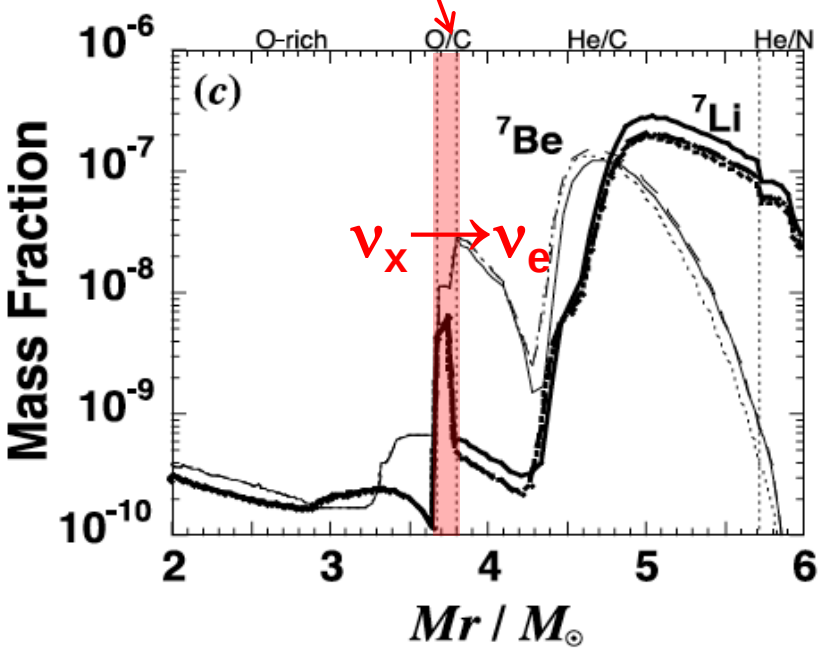


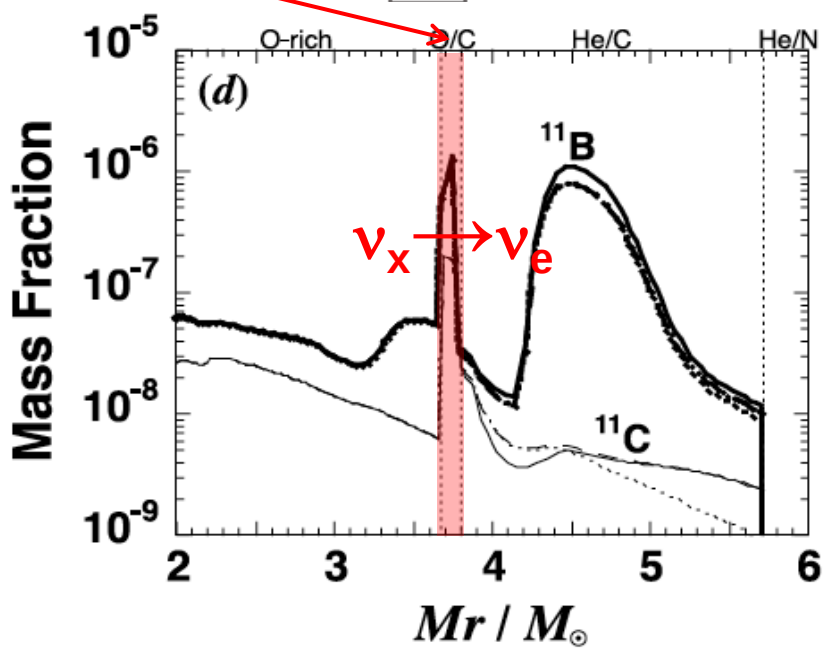
^{7}Li and ^{11}B are produced in the He/C Shell

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



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





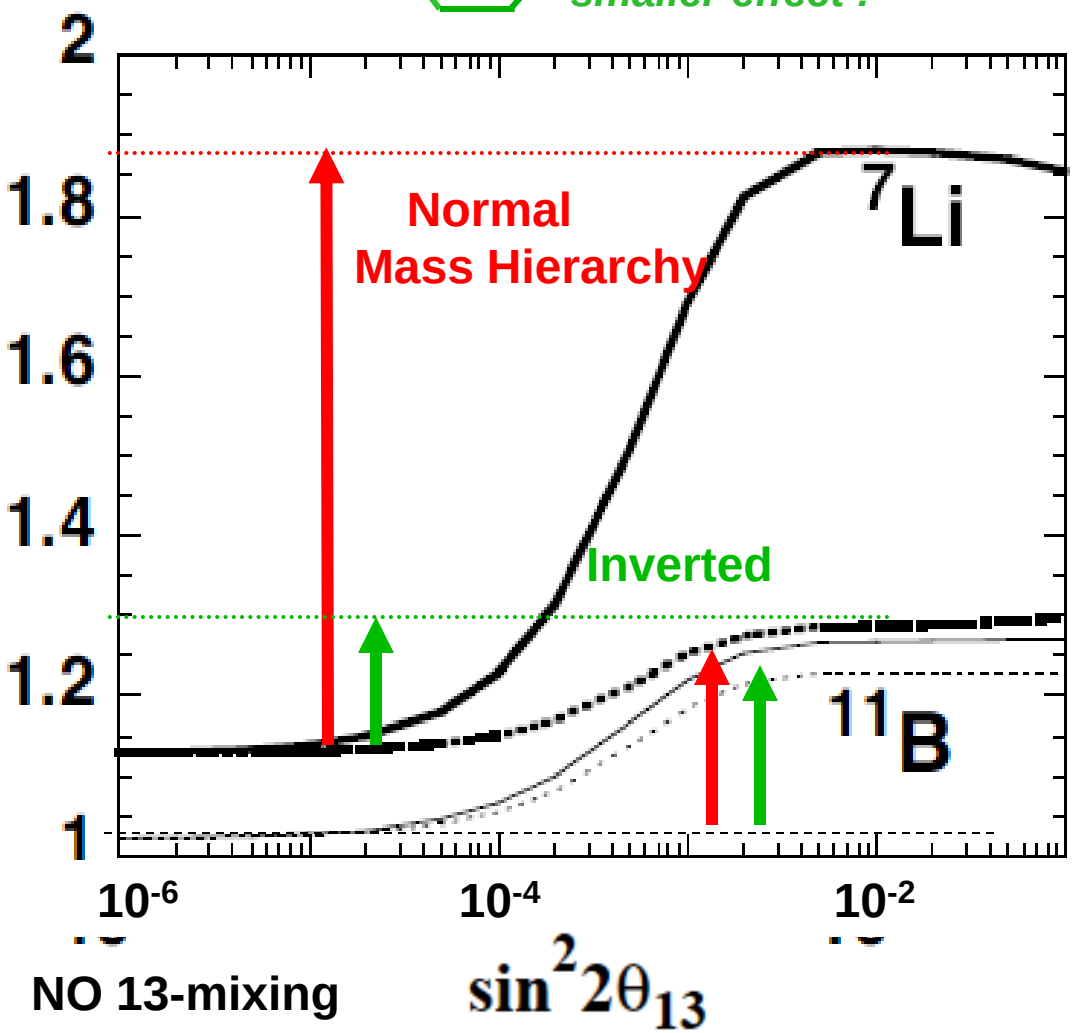
Yoshida, Kajino, Yokomakura, Kimura,Takamura & Hartmann, PRL 96 (2006) 09110; ApJ 649 (2006), 349.

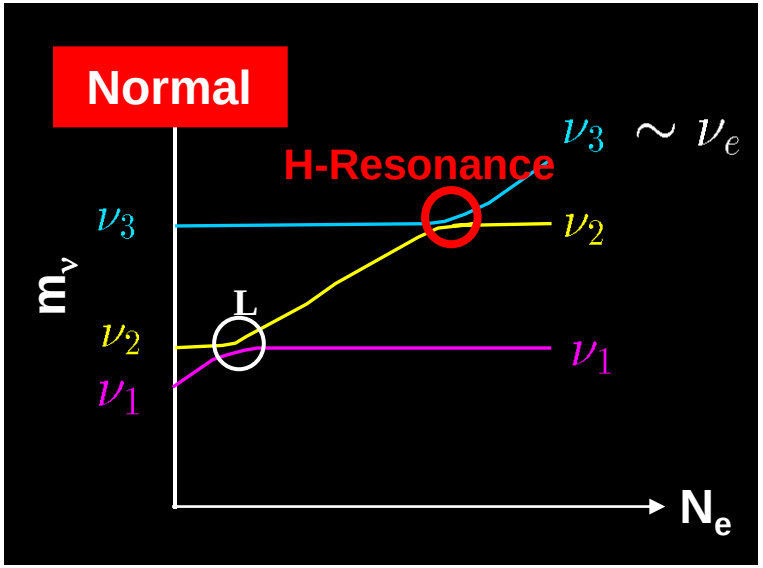
larger effect !

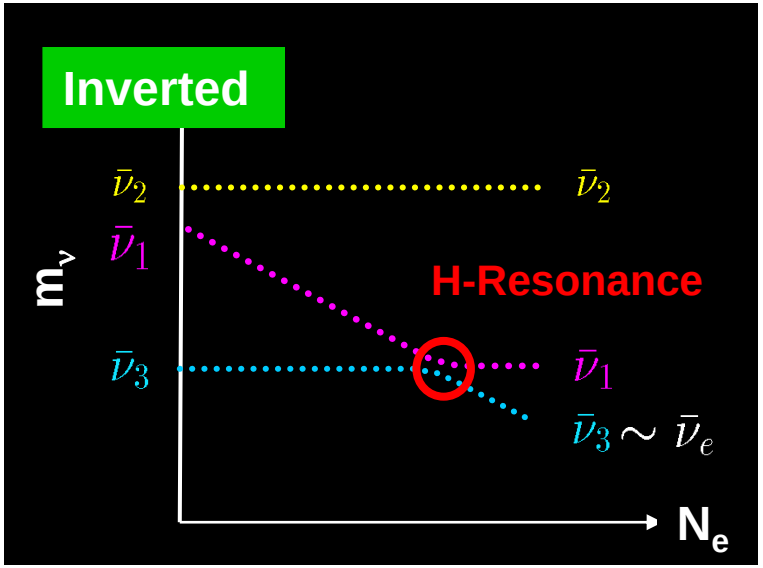
$T_{\nu e} < T_{\bar{\nu} e} < T_{\nu\mu\tau,\ \bar{\nu}\mu\tau}$

3.2MeV 4.0MeV 6.0MeV

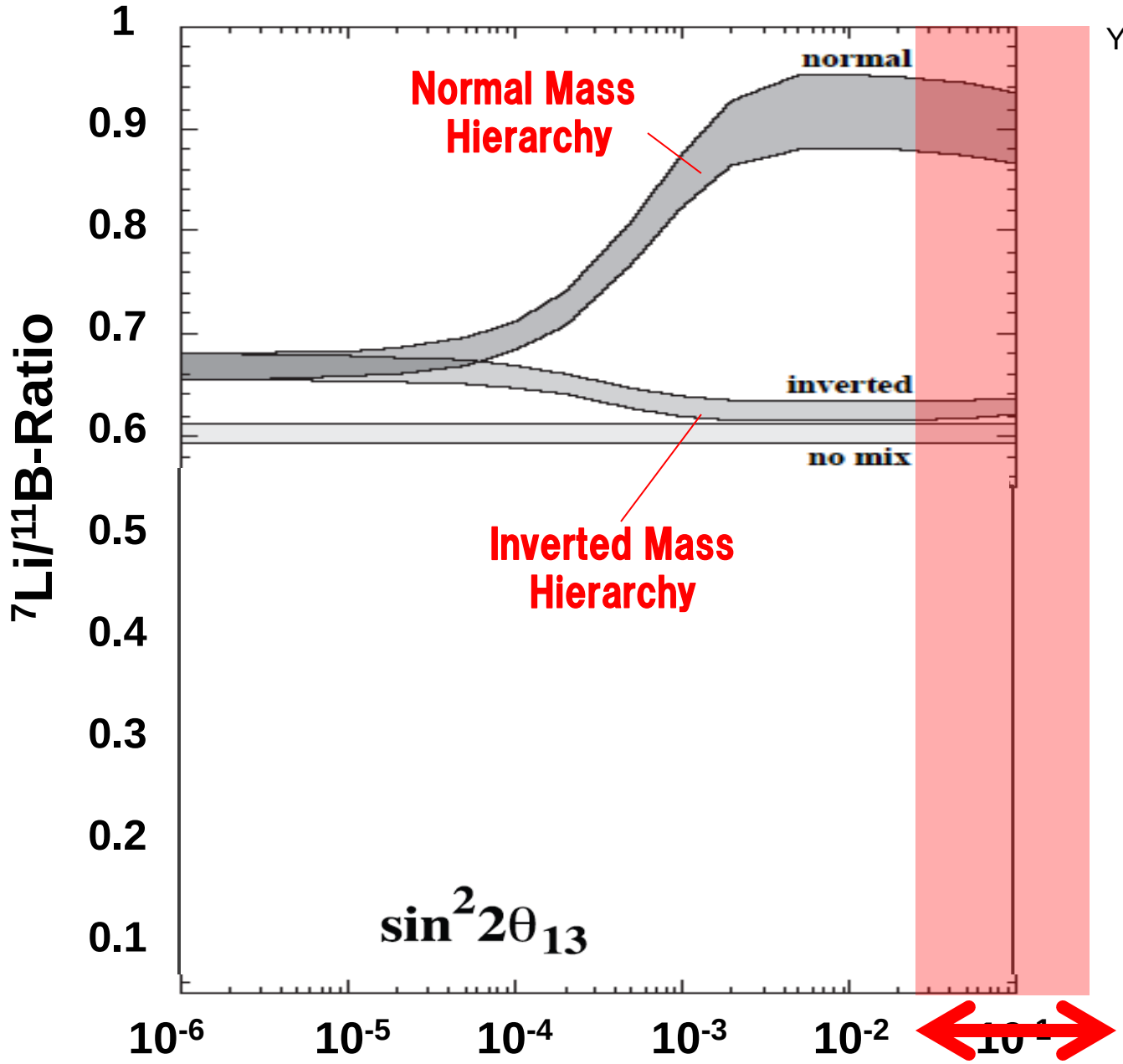
smaller effect !







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:

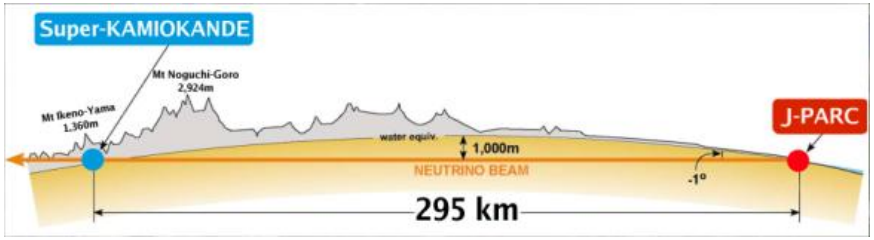
- T2K (Kamioka)
- MINOS

Reactor Exp. in2012:

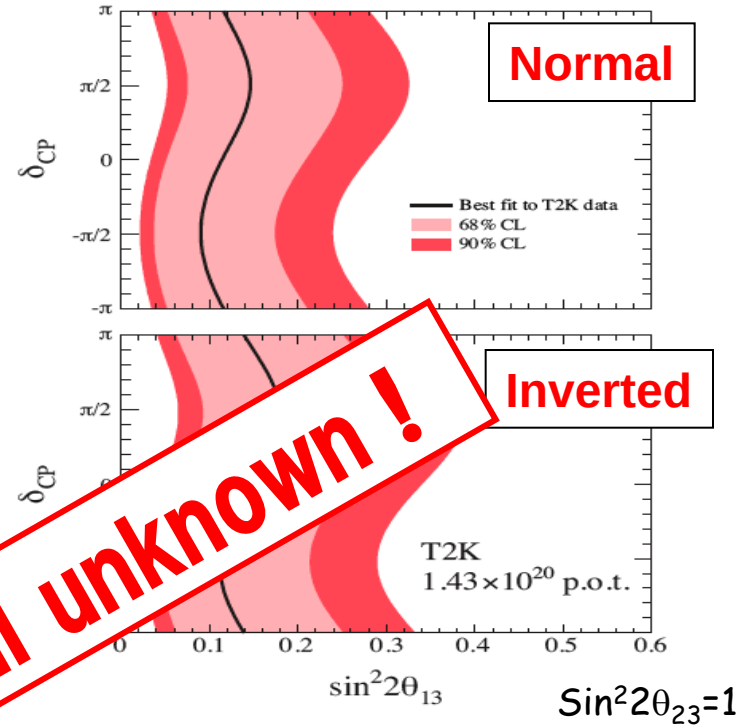
- Double CHOOZ
- Daya Bay
- RENO (KOREA)

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

Long Baseline ν — T2K & MINOS (2011)



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



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

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

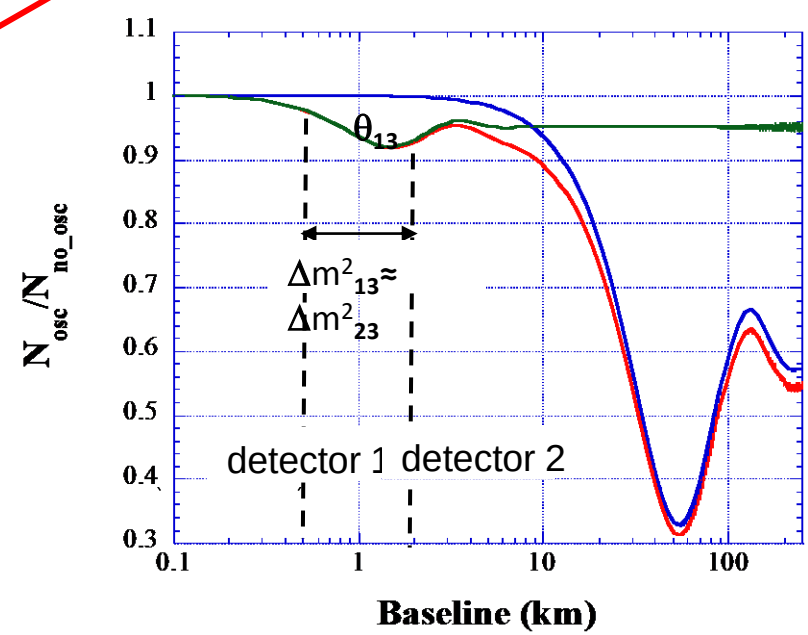
Minos (2011) $\sin^2 2\theta_{13} < 0.12(0.20$

T2K (2012) $0.03(0.04) <$ (0.34)

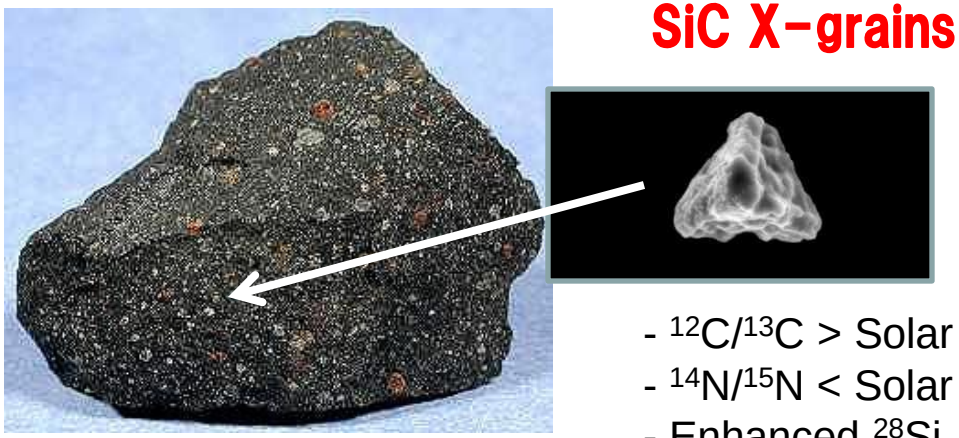
Mass hierarchy is still unknown !

Reactor ν — Daya Bay & Double Chooz (2012)

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

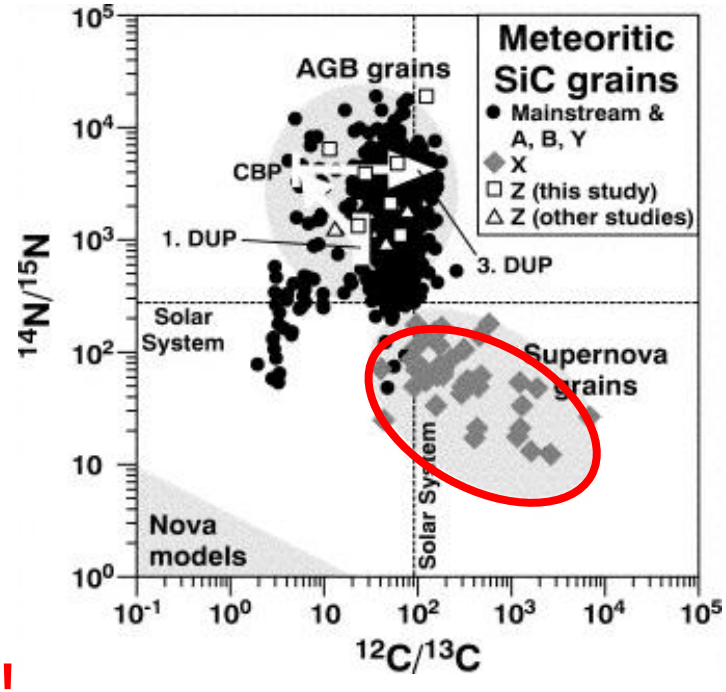


Murchison Meteorite



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)



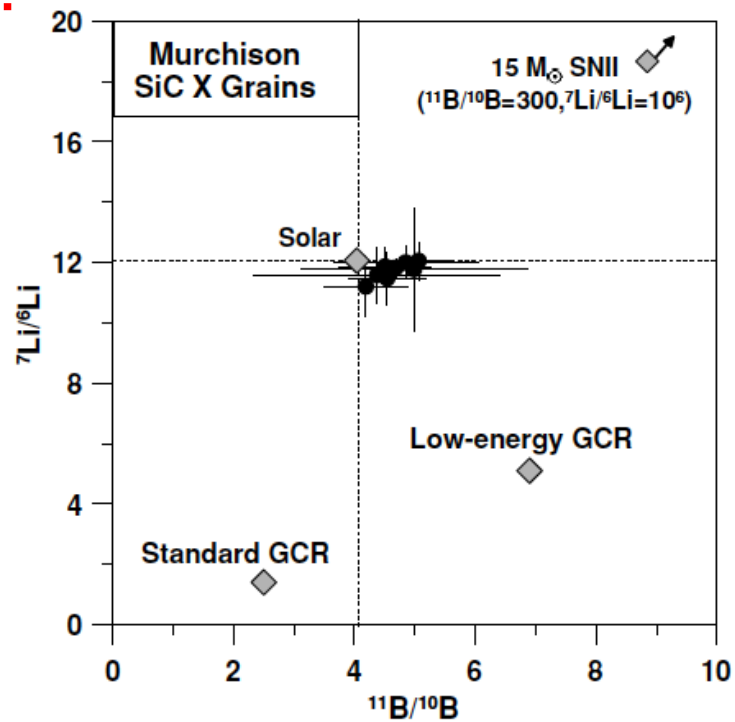
SiC X-grains are made of Supernova Dust !

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



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 — Astrophysical model dependence

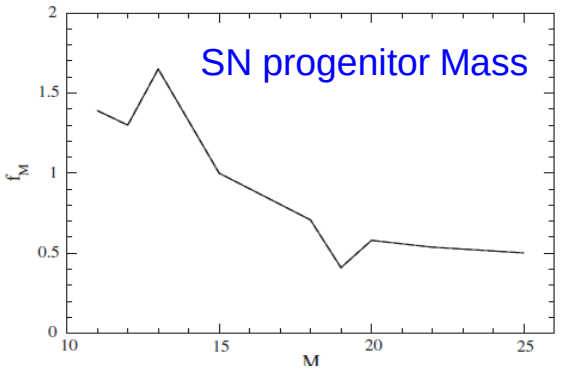
$$P(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_j P(D|M_j)P(M_j)}$$

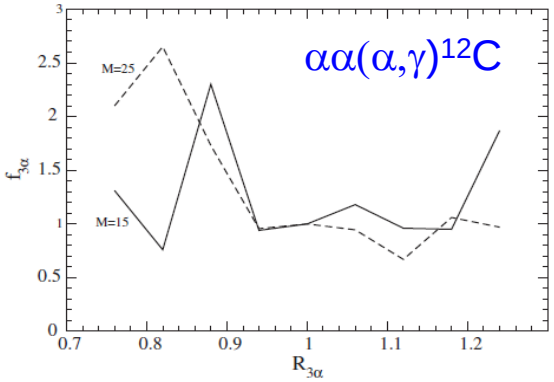
$$P(D|M_i) = \int dEdZda_k P(E,Z,D|M_i,a_k)P(a_k|M_i)$$

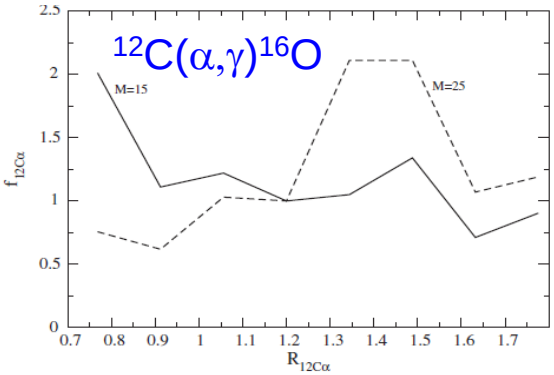
$$= \int dEdZda_k P(D|M_i,a_k,E,Z)P(Z,E|M_i,a_k)P(a|M_i)$$

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

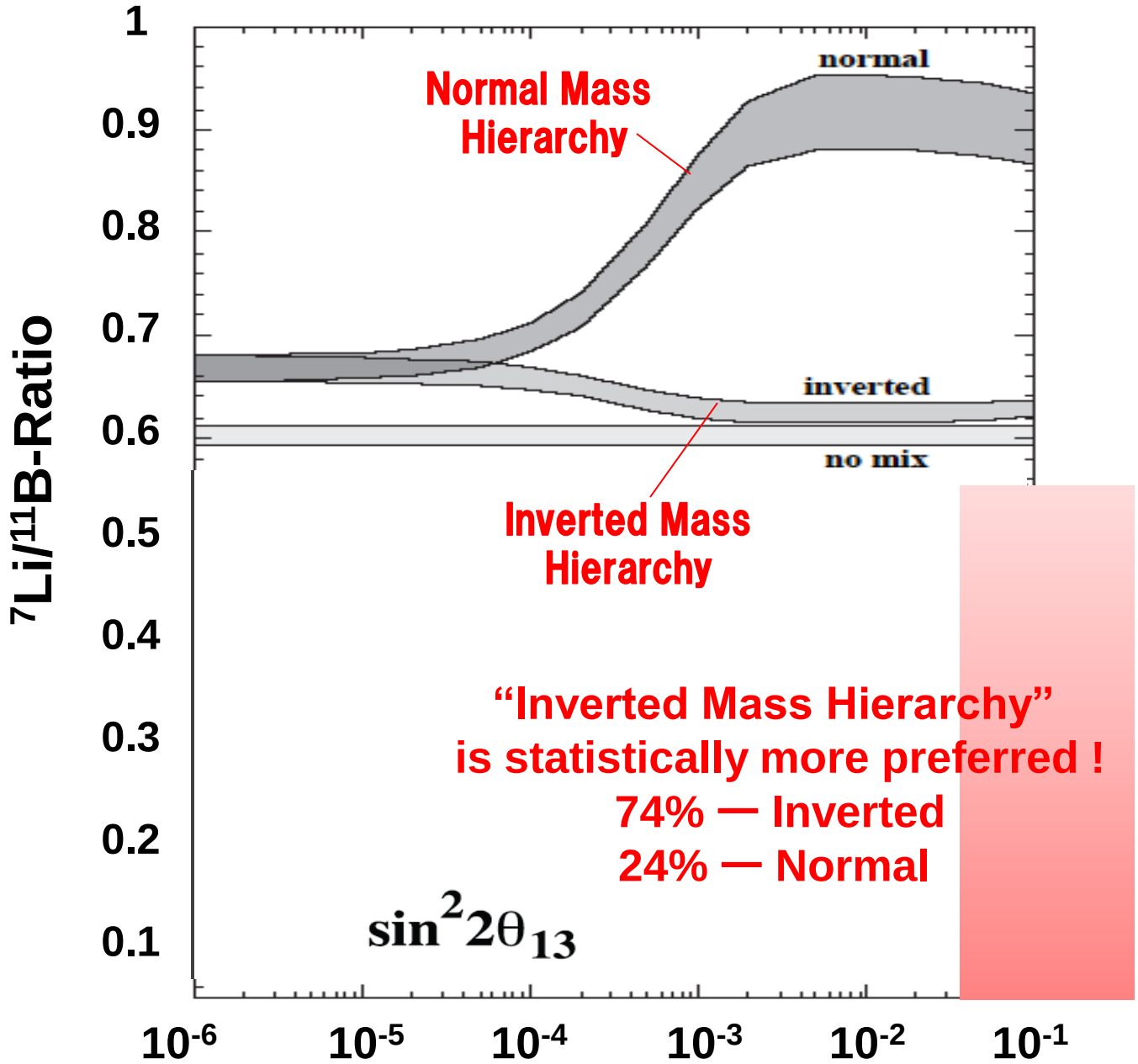
Parameter a_k	prior			reference
$\sin^2 2\theta_{13}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 0.92$	$\sigma_x = 0.017$	[7]
$R_{3\alpha}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 1.0$	$\sigma_x = 0.12$	[35]
$R_{12C\alpha}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 1.2$	$\sigma_x = 0.25$	[36]
$M_{prog}(\mathrm{M}_\odot)$	$m^{-2.65}$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







Supernova X-Grain Coinstraint

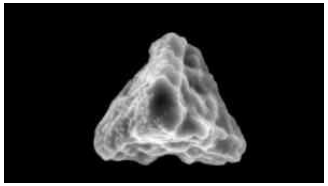


Mathews, Kajino, Aoki And Fujiya, Phys. Rev. D85,105023 (2012).

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

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

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



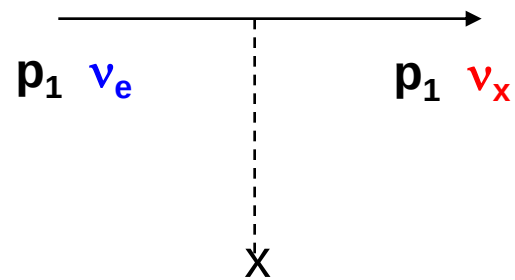
W. Fujiya, P. Hoppe, & U. Ott, ApJ 730, L7 (2011).

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)

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

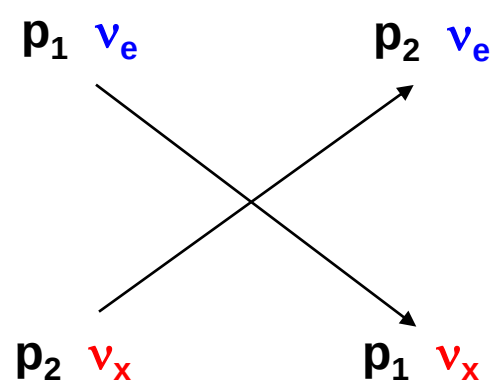


N_e = electron density

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

Self-Interaction

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

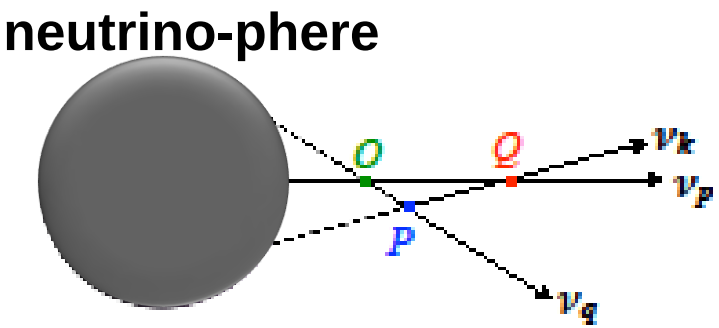


Quest for EXACT Many-Body SOLUTION !

"Invariants of collective neutrino oscillations"

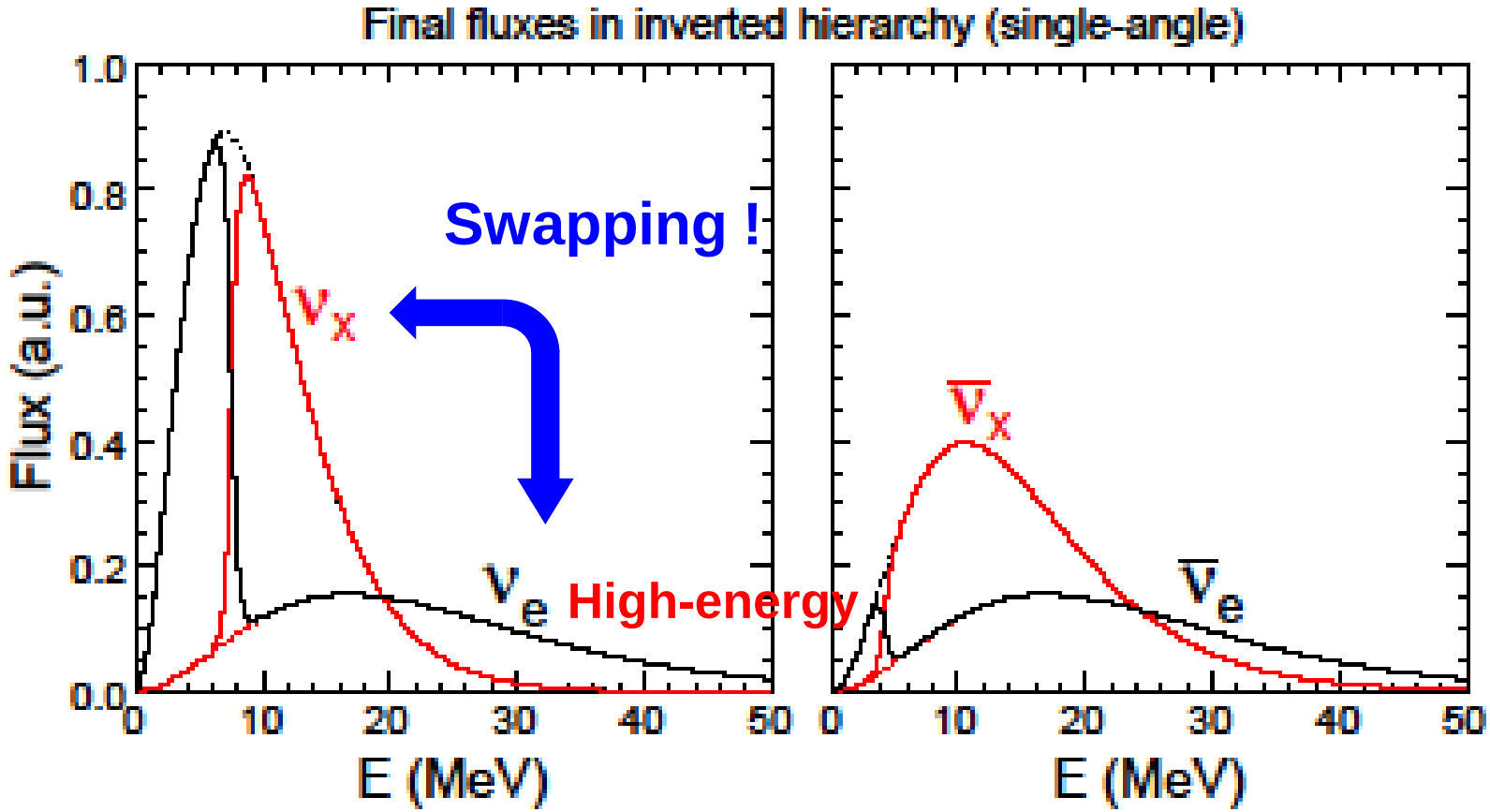
Y. Pehlivan, A.B. Balantekin, T. Kajino & T. Yoshida
Phys. Rev. D84, 065008 (2011)

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



Neutrino Mass in Cosmology

- **$0\nu\beta\beta$ COUORE, NEMO3, EXO, KamLAND Zen:**

  $|\sum U^2_{e\beta} m_\beta| < 0.3$ eV ⇒ **0.01 ~ 0.05 eV ! (future)**

- **CMB Anisotropies + LSS**

  $\Sigma m_\nu < 0.28$ eV (95% C.L.): WMAP-7yr +SPT (Benson et al. arXiv:1112.5435)

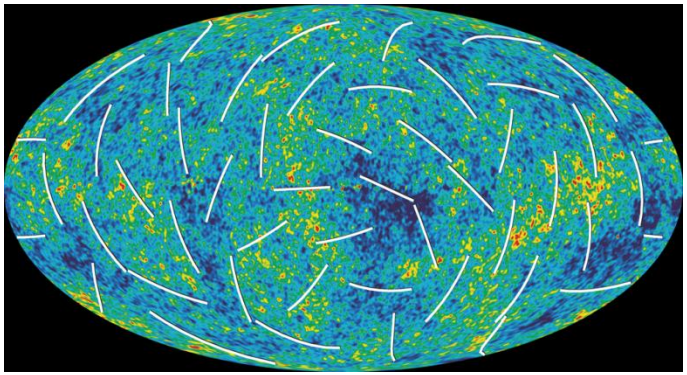
  < 0.36 eV (95%C.L.): WMAP-7yr + HST + CMASS (Putter et al. arXiv:1201.1909)

Recent more complete analysis:

Cosamic Magnetic Field + Neutrino Mass
(+ SZ effect + integrated SW effect
+ Neutrino free streaming)

$\sum m_\nu < 0.2$ eV (2σ, B<2nG)

Yamazaki, Kajino, Mathews & Ichiki,
Phys. Rep. 517 (2012), 141;
PR D81 (2010), 103519; D77, (2009) 043005.



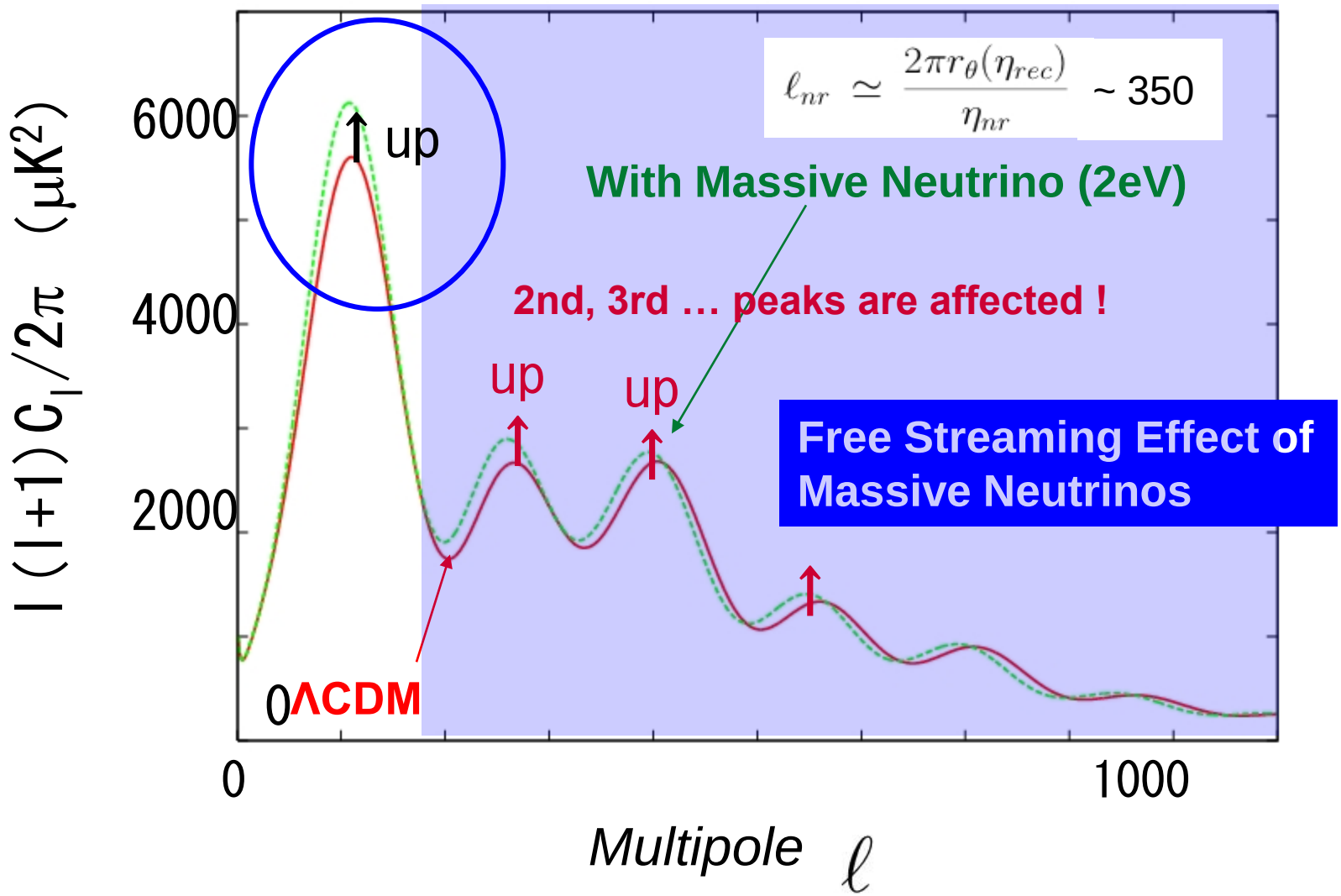
http://lambda/gsfc.nasa.gov/

Effects of Neutrino Mass m_ν

$\vec{B}_{PMF} = \vec{0}$

Integrated Sachs-Wolfe Effect, similarly to CDM

S. Dodelson, E. Gates and A. Stebbins (1996)



Effective k for FINITE Neutrino Mass

☆**Analytical solution of massless neutrino anisotropic stress:**

$$\pi_\nu = -\pi_{PMF}\frac{R_\gamma}{R_\nu}\left(1-\frac{c(k\tau)^2}{4R_\nu+15}\right)$$ (Super horizon scale)

☆**Anisotropic stress of massive neutrino:**

$$\pi_h^{(m)} \simeq \pi_x^{(m)}\left(1-\frac{1}{2}\frac{5}{7\pi^2}H_0^2\Omega_R m_\nu^2\tau^2\right)$$

$$\simeq -\pi_{PMF}\frac{R_\gamma}{R_\nu}\left(1-\frac{c(k_{\rm eff}\tau)^2}{4R_\nu+15}\right)$$

Effective wave number

$$k_{\rm eff}^2 = k^2 + k_{\rm m}^2$$

$$k_{\rm m} = \sqrt{\frac{1}{2}\frac{5}{7\pi^2}H_0^2\Omega_R\frac{4R_\nu+15}{c}m_\nu^2}$$

Neutrino Mass Effects on CMB Anisotropies

CMB anisotropies and polarization are influenced by

- **Integrated Sachs-Wolfe Effect**
- **Free Streaming Effect**
- **Compensation effect of anisotropic stress of magnetic field & neutrinos**

Massless or Massive is critical !

Cosmological constraints should be made carefully !

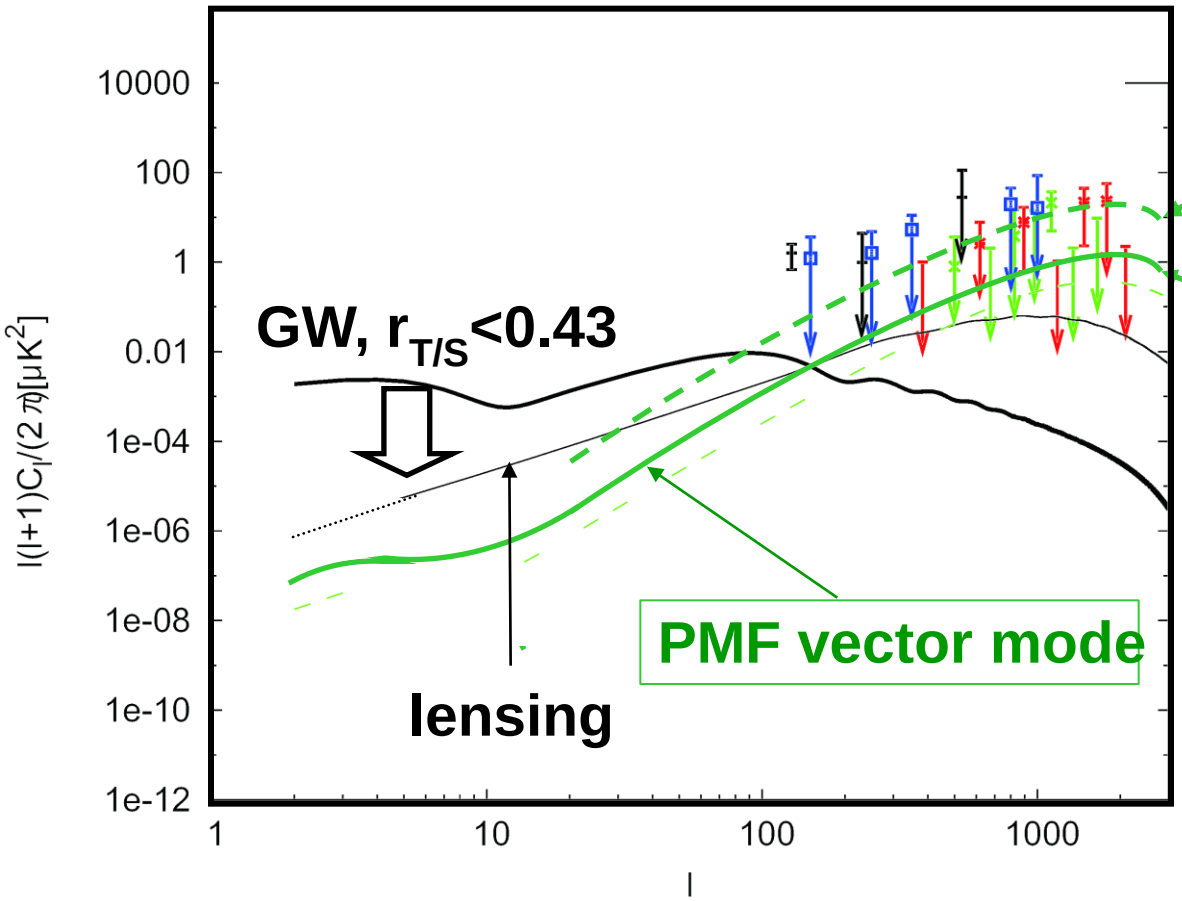
$$\underbrace{\Omega_b,\ \Omega_{CDM},\ \Omega_\Lambda,\ H_0,\ \tau,\ n_S,\ A_S,\ A_T/A_S}_{\text{Standard Cosmological Parameters}} \quad + \quad \underbrace{B,\ n_B}_{\text{Primordial Magnetic Field}} \quad + \quad \underbrace{m_\nu}_{\text{Neutrino Mass}}$$

Expected Presence of Primordial Magnetic Field (PMF)

Yamazaki, Ichiki & Kajino, ApJ 825 (2006), L1.

CMB Polarization Anisotropies
BB mode

Upper limit: B = 7.7nG, for $m_\nu = 0$



B=7.7nG, n_B=-2.9

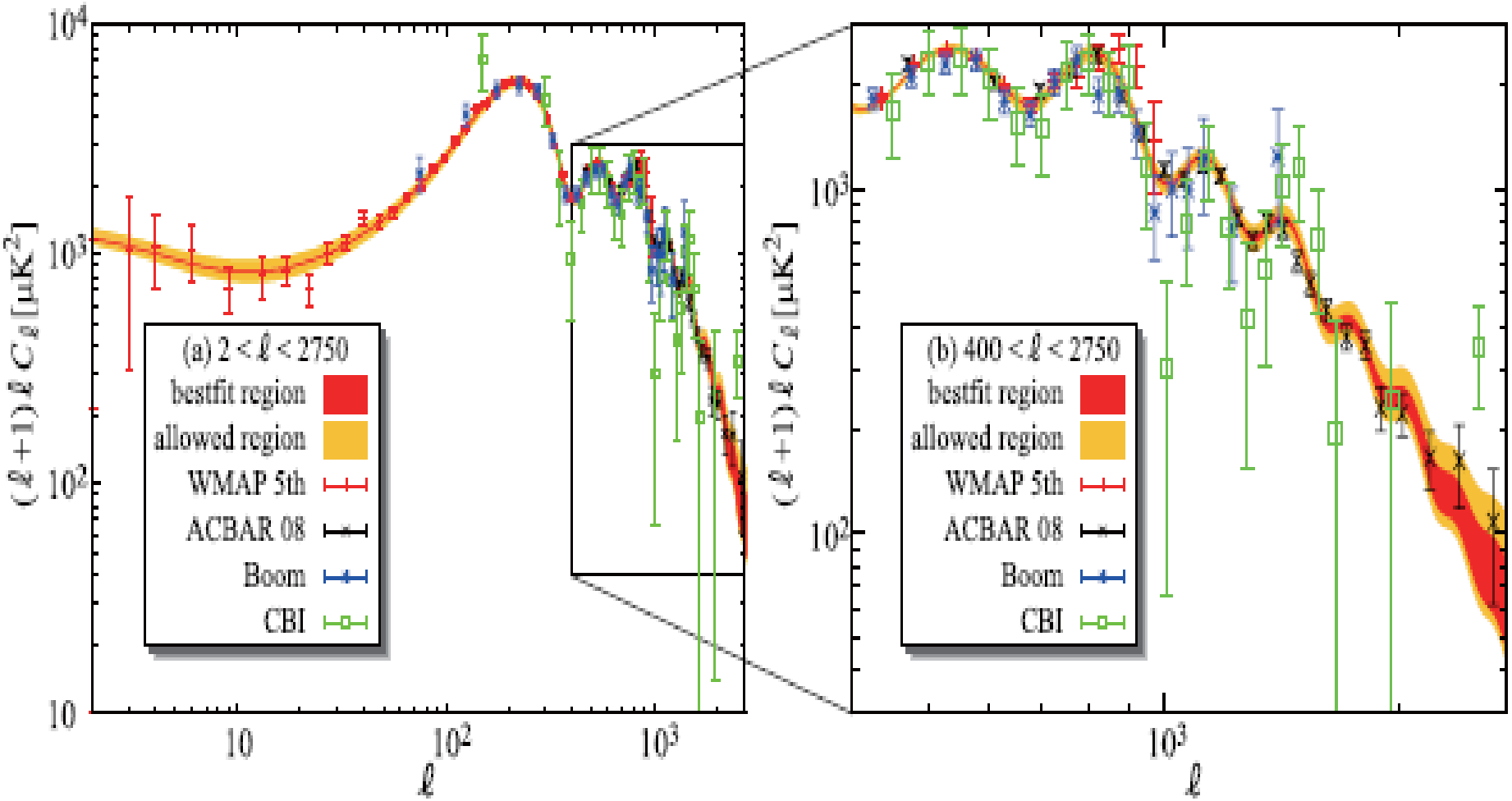
B=5nG, n_B=-2.9

$$k^3P(k) \propto B^4 \cdot k^{2n+6}$$

$n = n_B = -3$
scale invariant.

MCMC Fit to CMB-Temperature Anisotropies

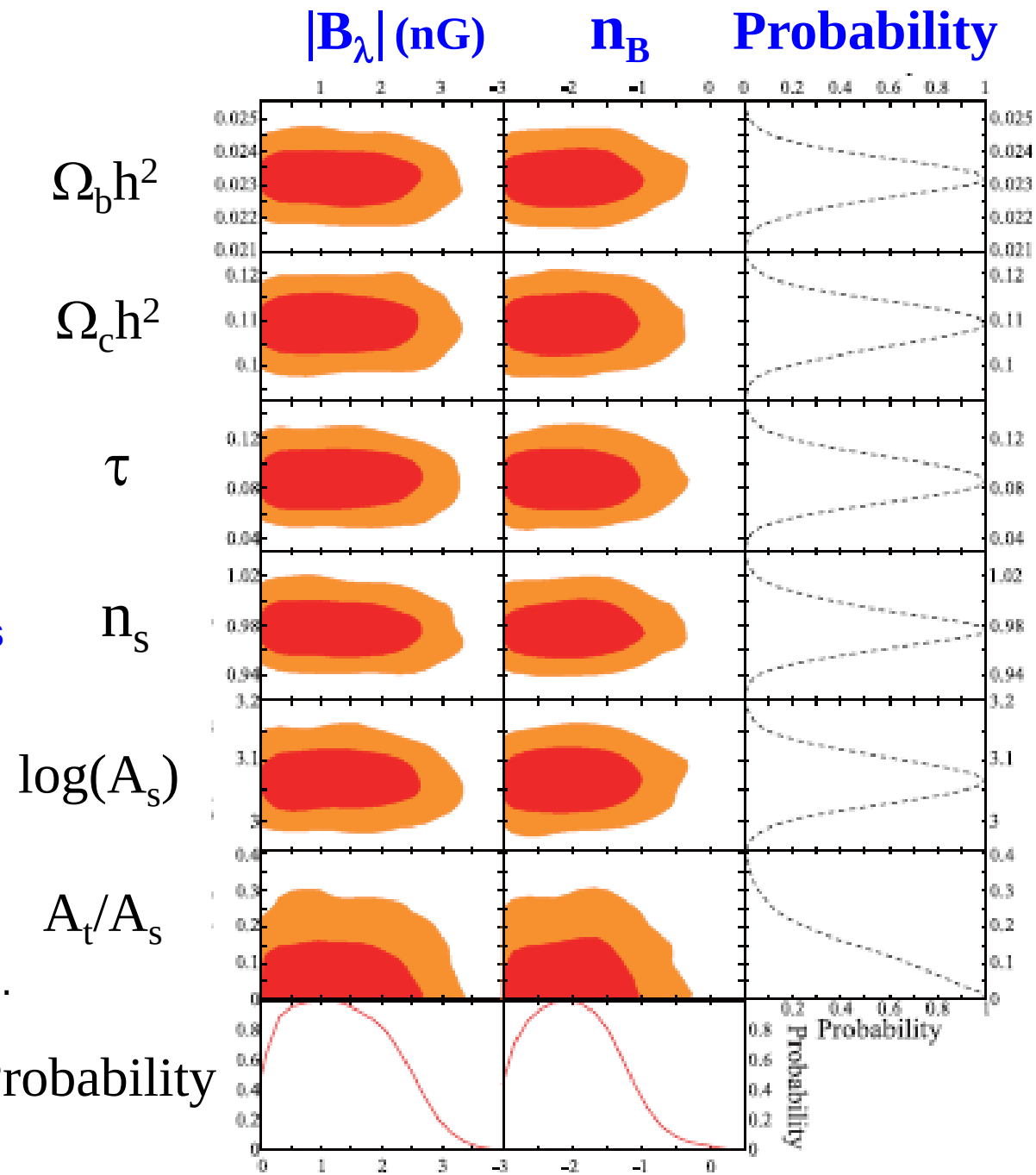
D. Yamazaki, K. Ichiki, T. Kajino, G. J. Mathews,
Phys. Rep. 517 (2012), 141; PR D81 (2010), 023008; PR D81 (2010), 103519.



Likelihoodness and Probability

CMB Temperature and Polarization Anisotropies including Primordial Magnetic Fields and Neutrino Mass

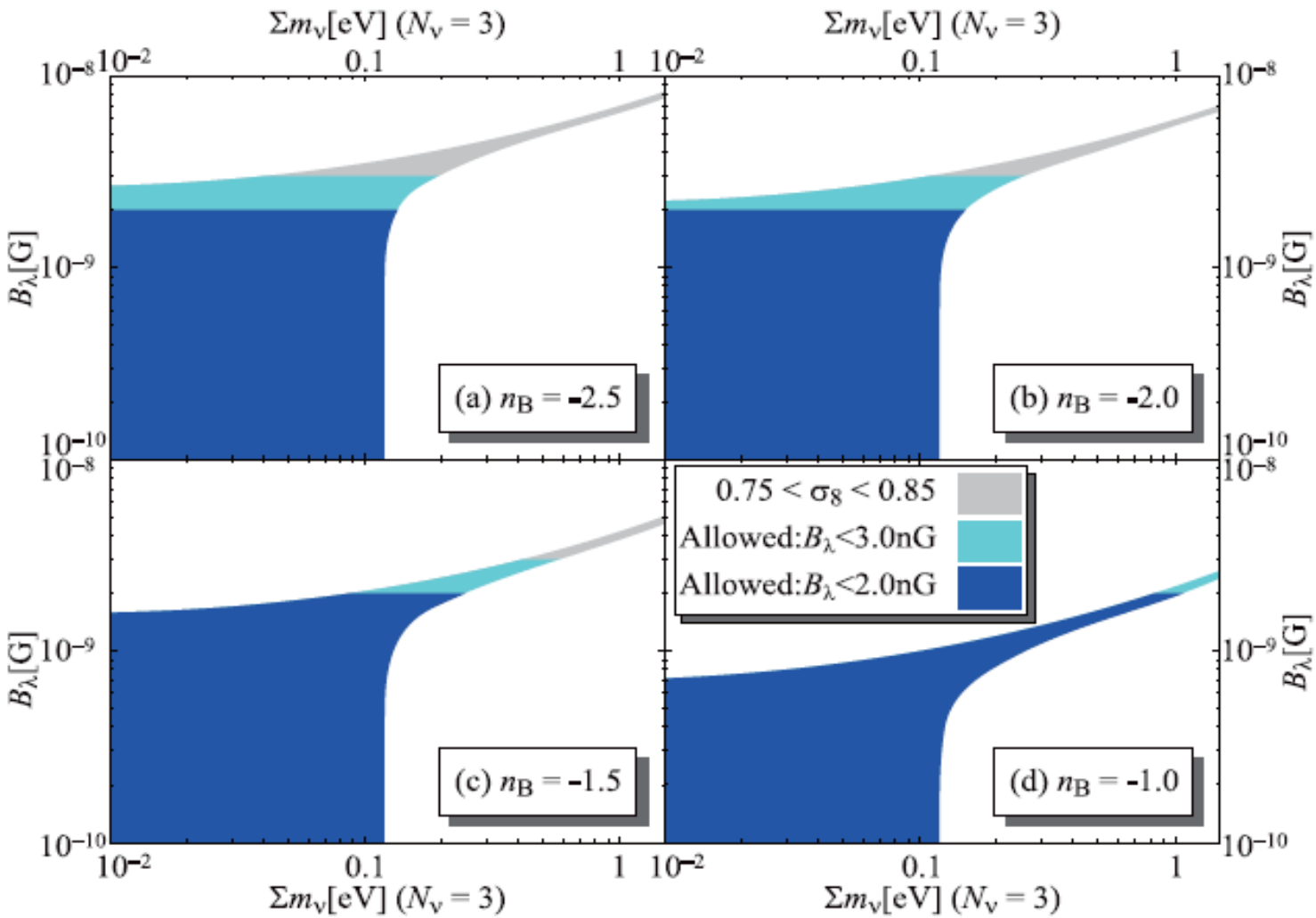
D. Yamazaki, T. Kajino, G. J. Mathews, & K. Ichiki, Phys. Rep. 517 (2012), 141.



Neutrino Mass Constraints

$\Sigma\, m_\nu < 0.8$ eV

Yamazaki, Ichiki, Kajino, and Mathews, PR D81 (2010), 103519:
D. Yamazaki, T. Kajino, G. J. Mathews, and K. Ichiki, Phys. Rep. 517 (2012) 141.



CONCLUSION

We propose a new astrophysical method, which is free from CP-violation phase and total mass to determine the unknown ν-mass hierarchy Δm_{13}^2 in terms of the MSW effects on the supernova ν-process nucleosynthesis.

$^7Li/^{11}B$ 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 statistically more preferred.

We constrain the total ν-mass to be $\Sigma m_\nu < 0.8$ eV from the MCMC analysis of CMB temperature and polarization anisotropies.