International Conference on Particle Physics and Cosmology
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Session: CMB / Inflation

Neutrino Physics Phenomenology:

Cosmological (CMB) and Astrophysical (Supernova) Constraints on ν-Mass and Mass Hierarchy

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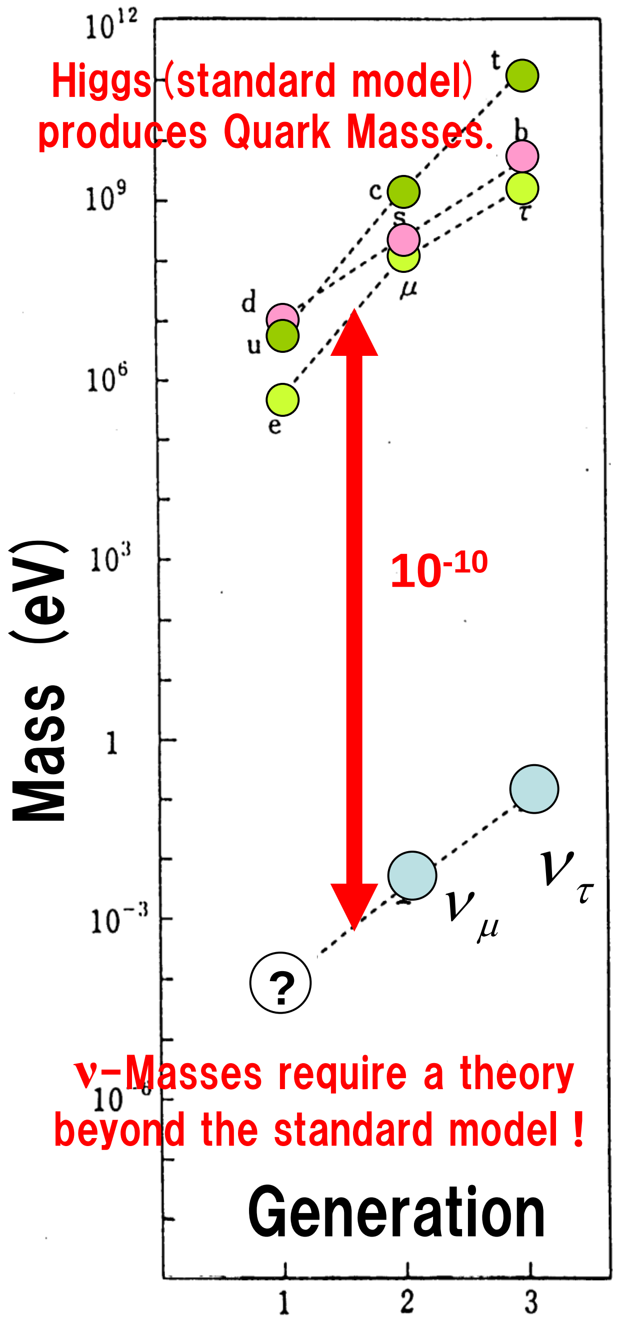


$$\frac{\text{Neutrino Masses}}{\text{Quark \& Lepton Masses}} = \frac{1}{10{,}000{,}000{,}000}$$

$E = mc^2$

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 ?

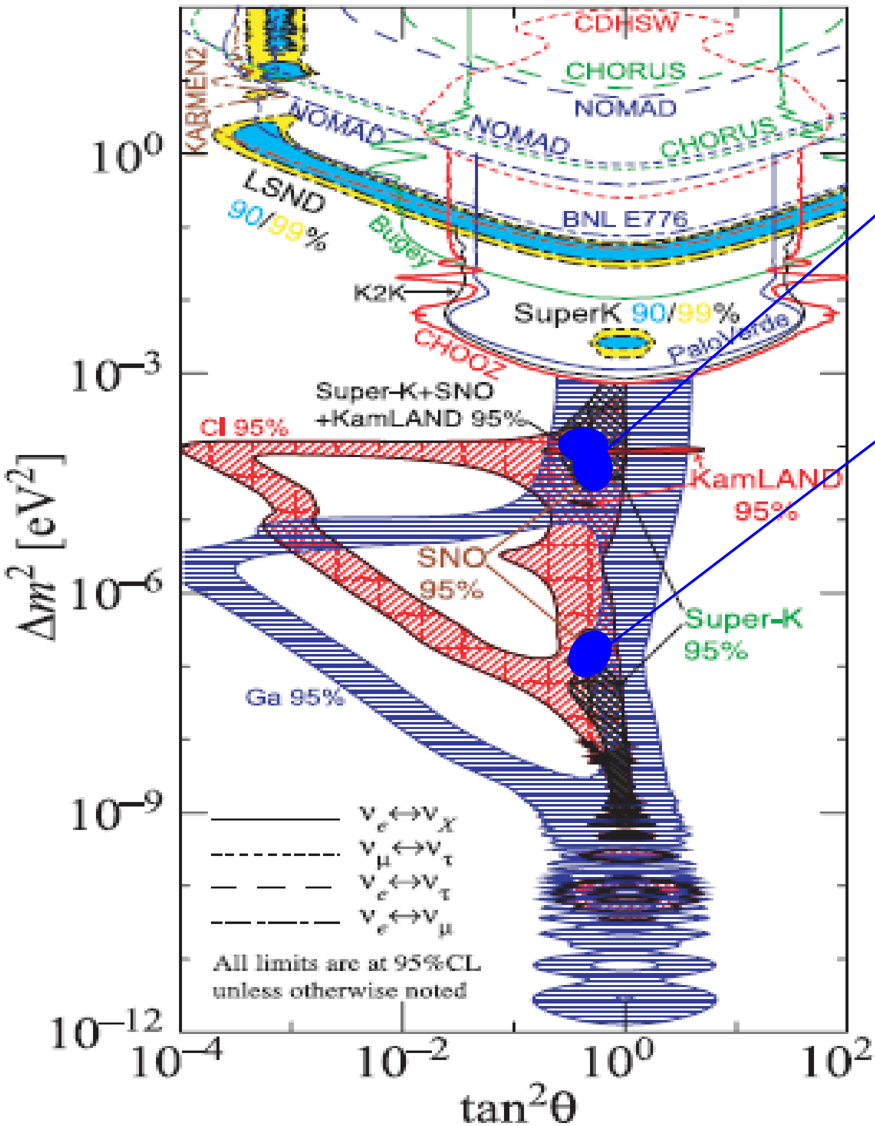
Purpose

(1) Supernova ν-Process Nucleosynthesis for <u>ν-Mass Hierarchy.</u>

(2) CMB Anisotropies in Inflation & <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

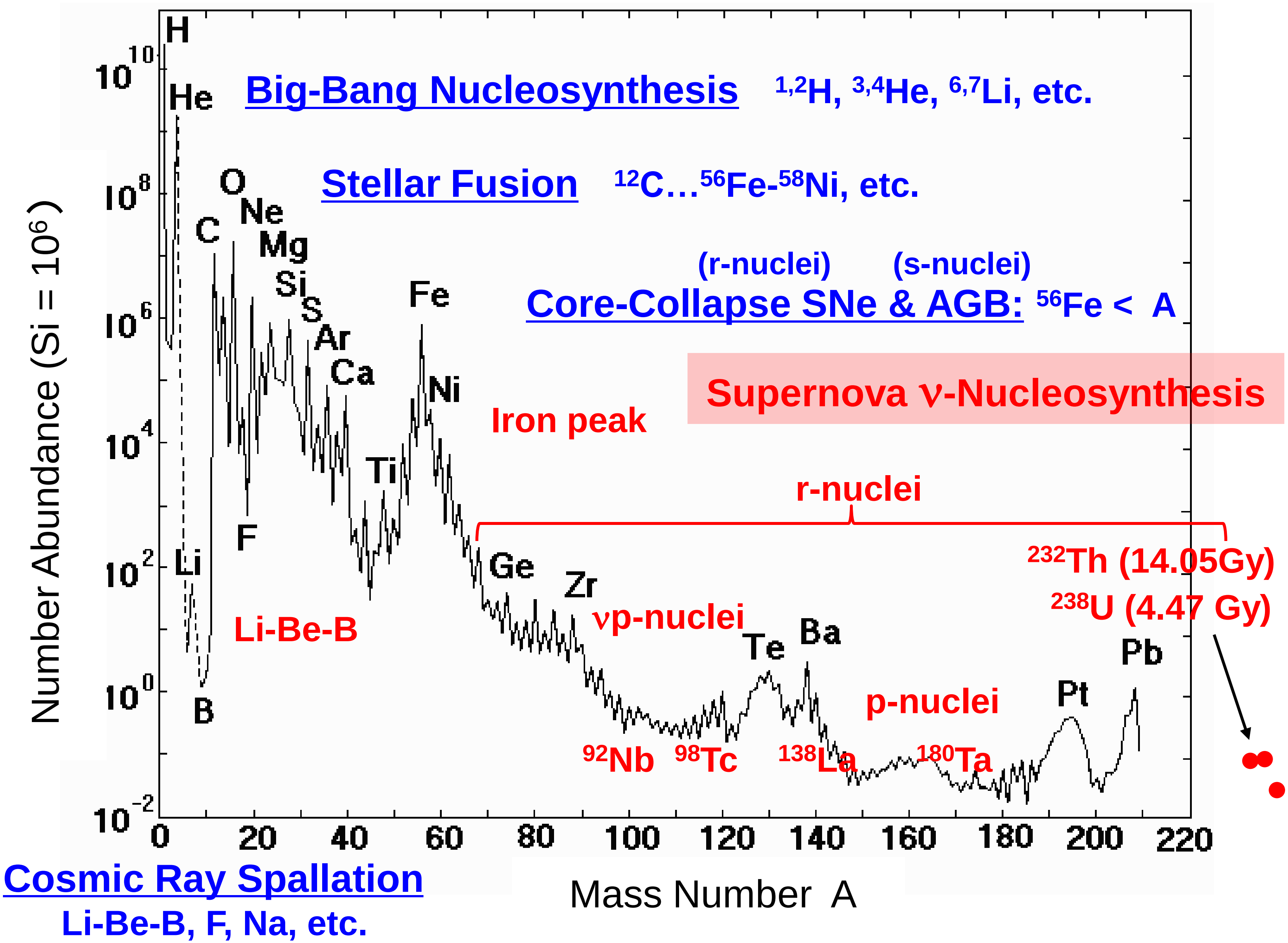
- $\sin^2 2\theta_{13}$ (< 0.1)

  T2K, MINOS, RENO, Daya Bay, Double Chooz

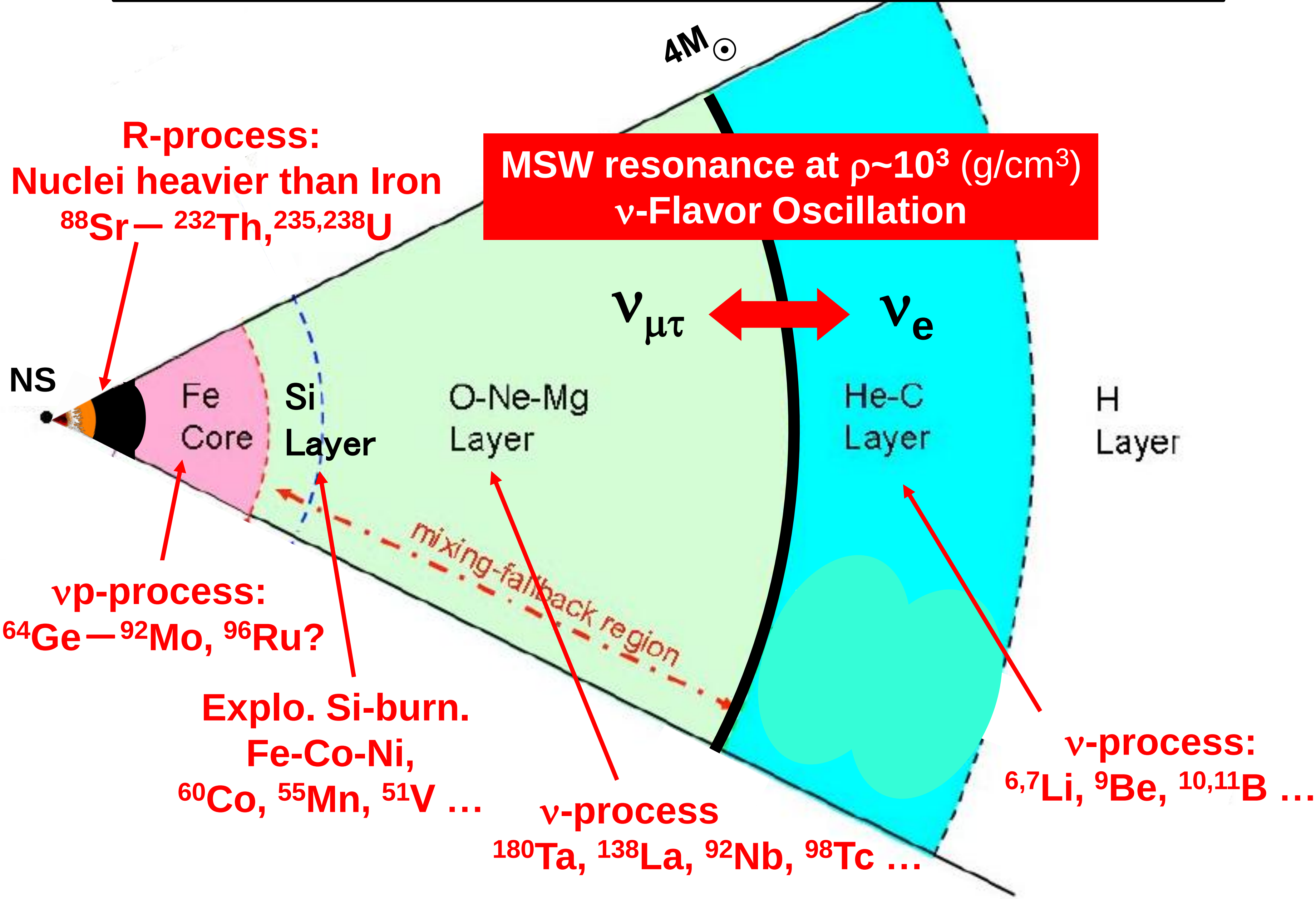
- $\Delta m_{13}^2 = \pm 2.4\times10^{-3}$ eV^2
- ~~δ=CP violation phase~~
- ~~Absolute Mass~~ 0νββ, cosmology

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

Solar System Abundance



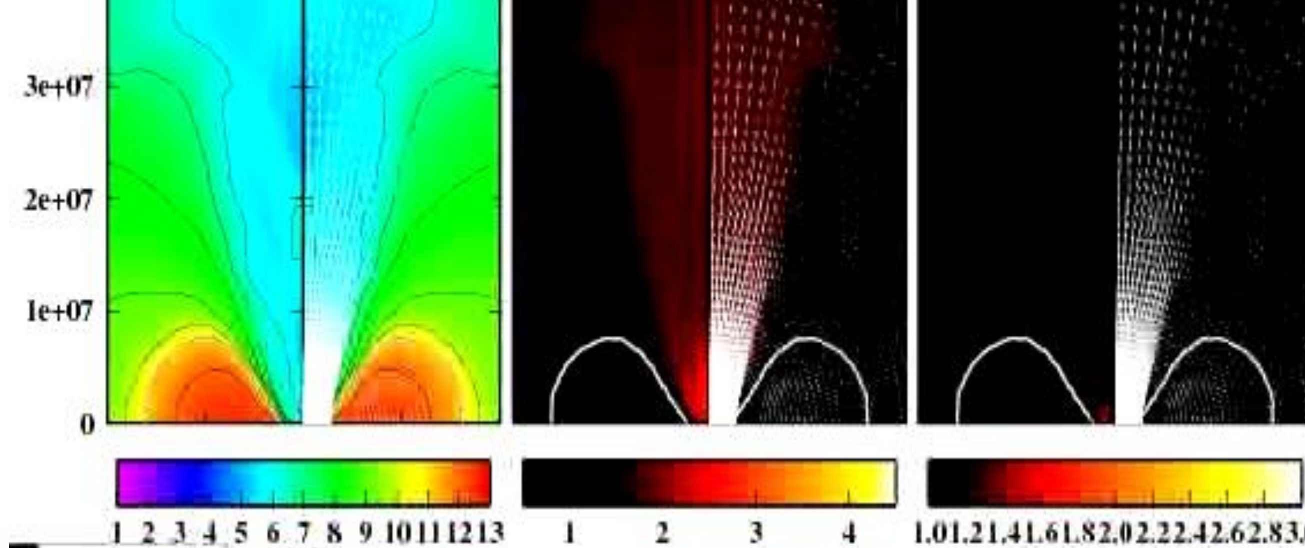
Various roles of ν's in SN-nucleosynthesis

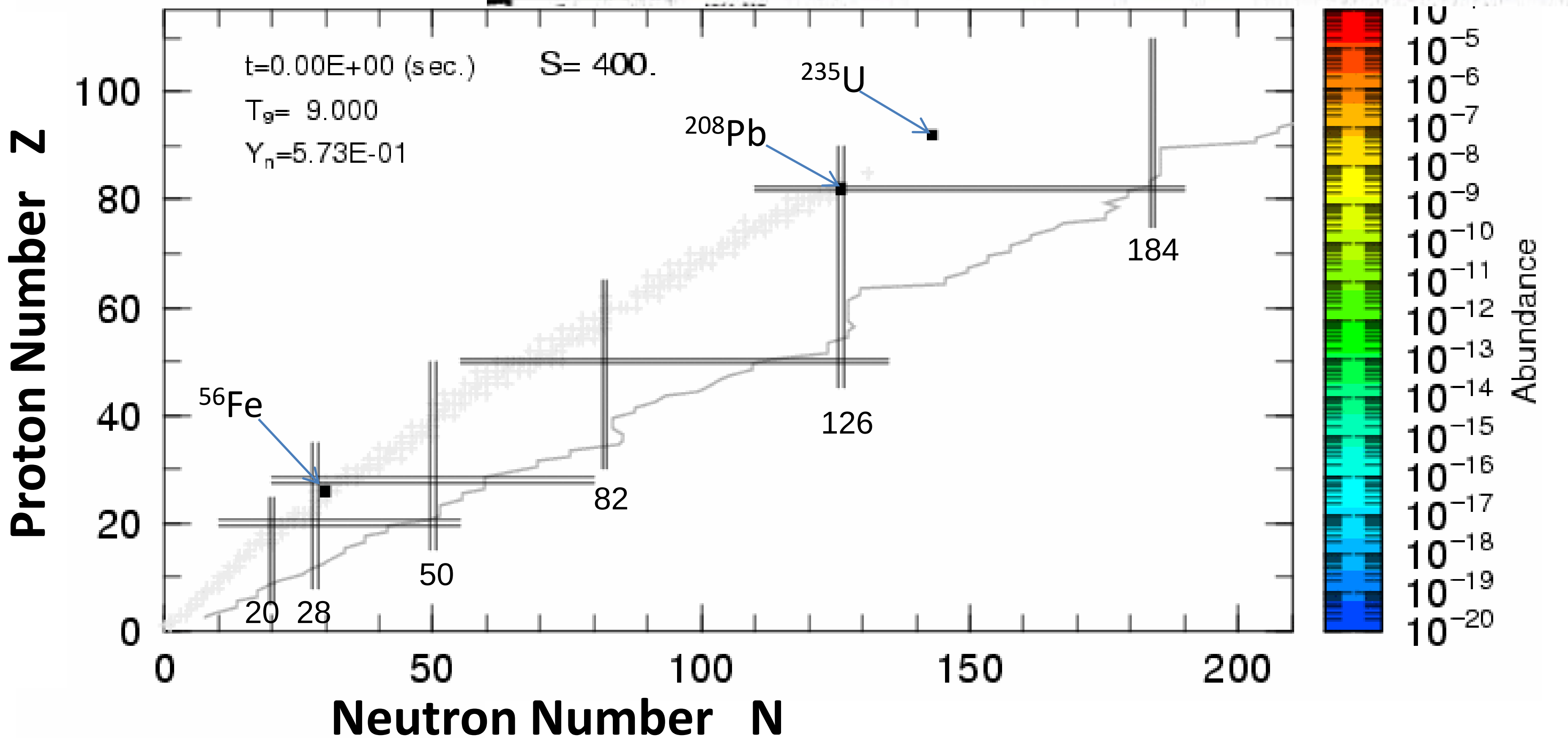


Supernova Nucleosynthesis Simulation

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.

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

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

Astrophysical Sites:

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

\+

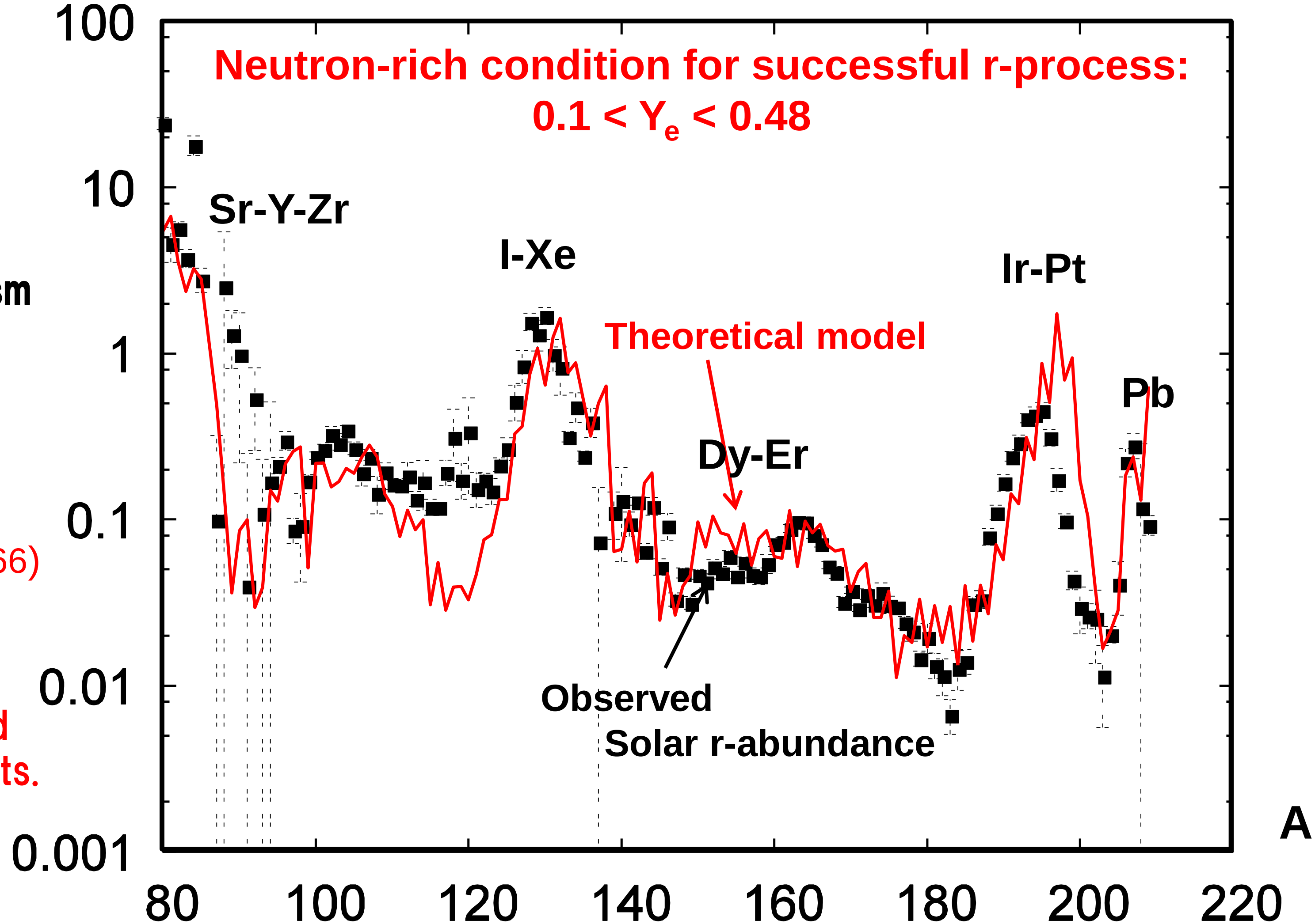
Explosion mechanism

$Y_e > 0.5$?

Roberts, Reddy and Shen (arXiv1205.4066) Confirmed

$Y_e < 0.5$!

for nucleon pot. and Pauli blocking effects.



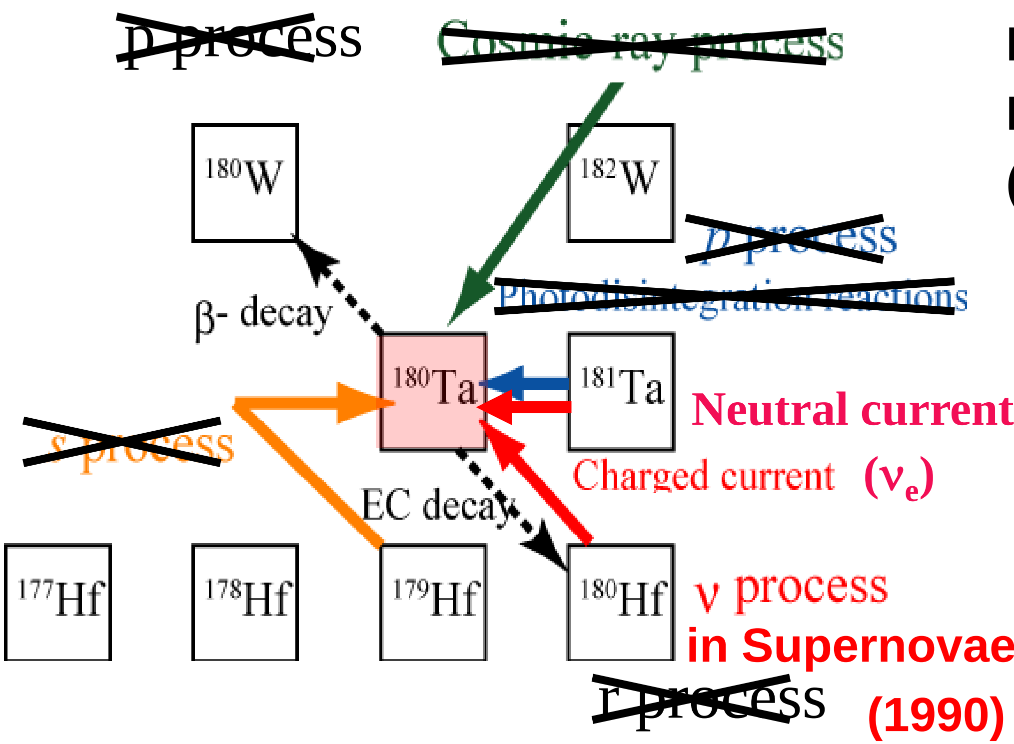
Tantalum (^{180,181}Ta)

$^{181}Ta_g$ (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!

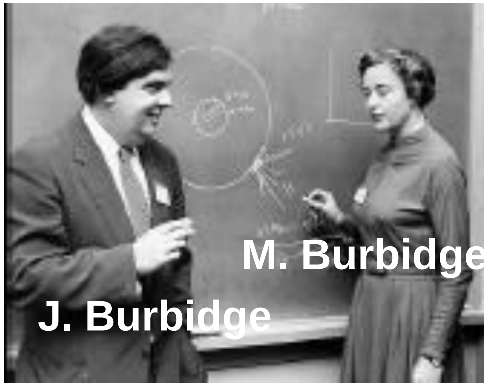
Origin of ^{180}Ta was unknown.

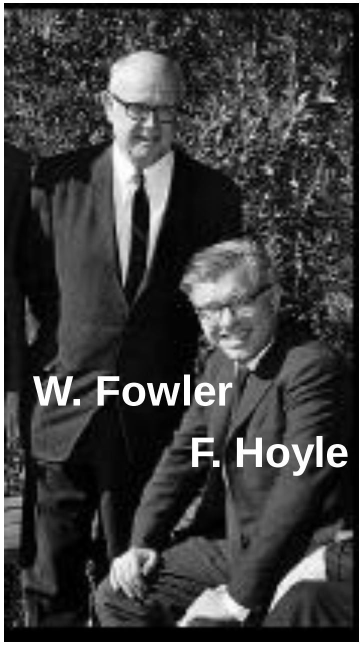
"SN ν-process", overproduces ^{180}Ta !



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

"Element Genesis"



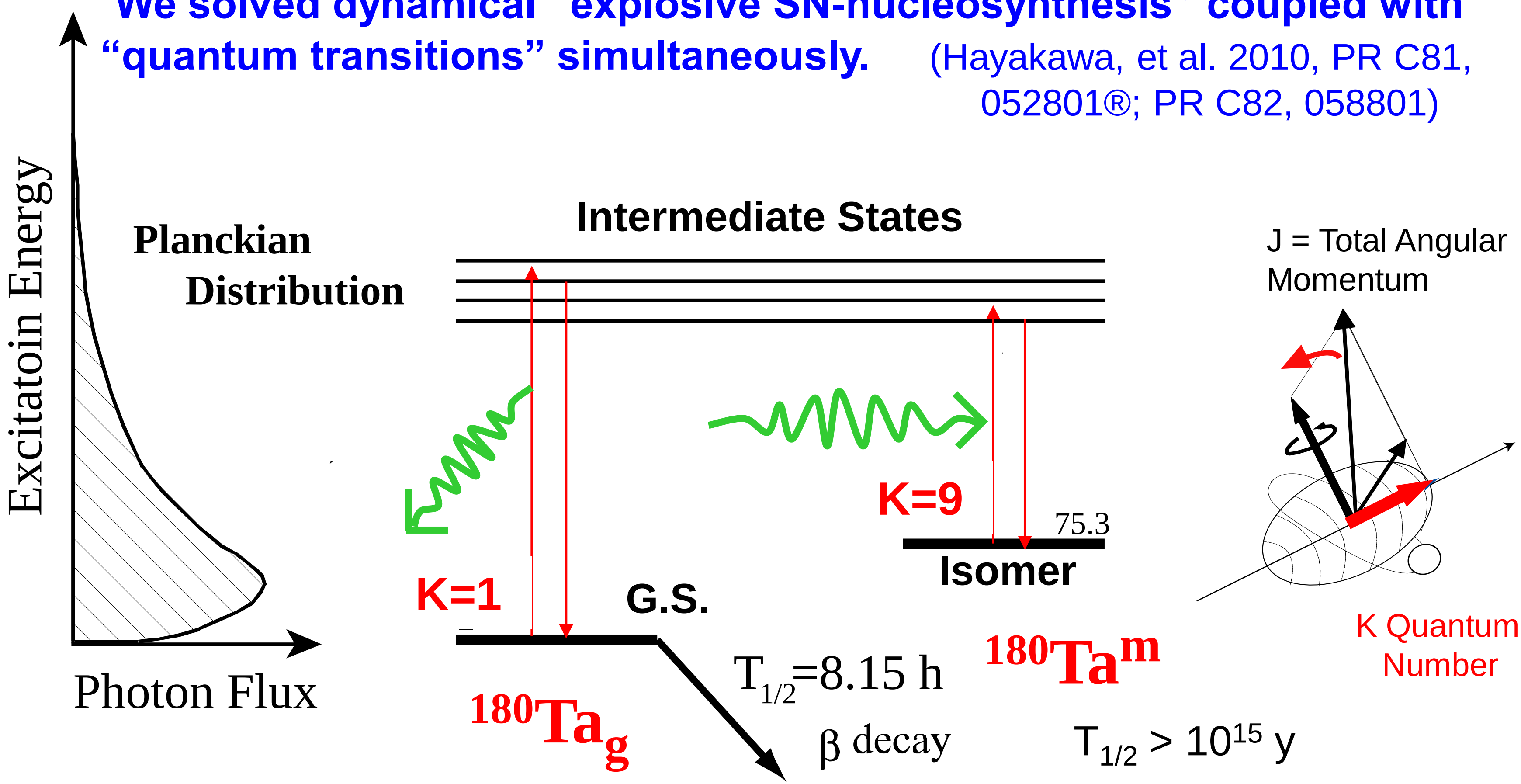


^{180}Ta-genesis needs Quantum Phys. + SN Hydro-dyn.

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

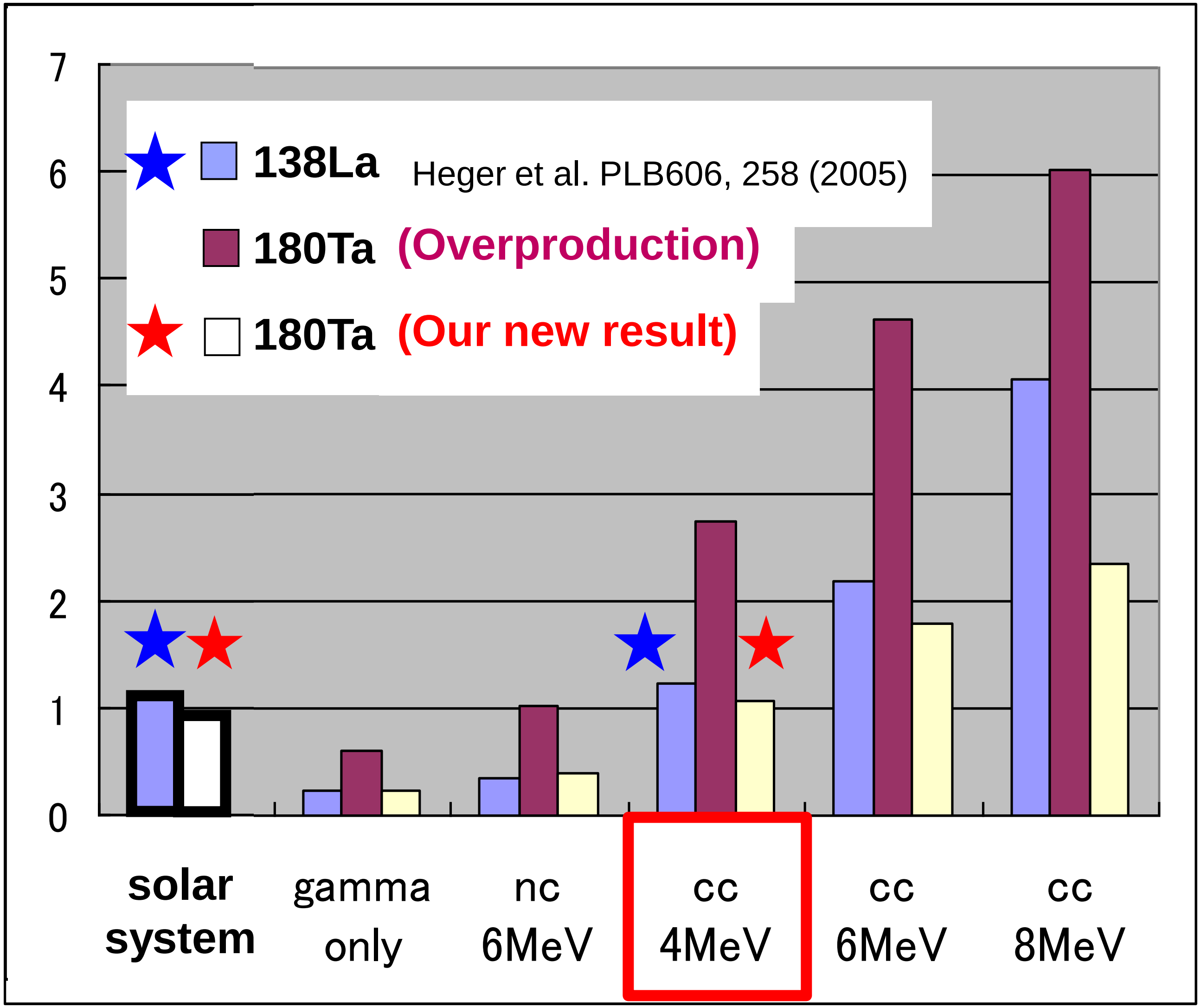
Long lived $^{180}Ta^{m}$ is excited to intermediate states in hot SN-photon bath, and decay to the ground state in 8 hours.

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



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.

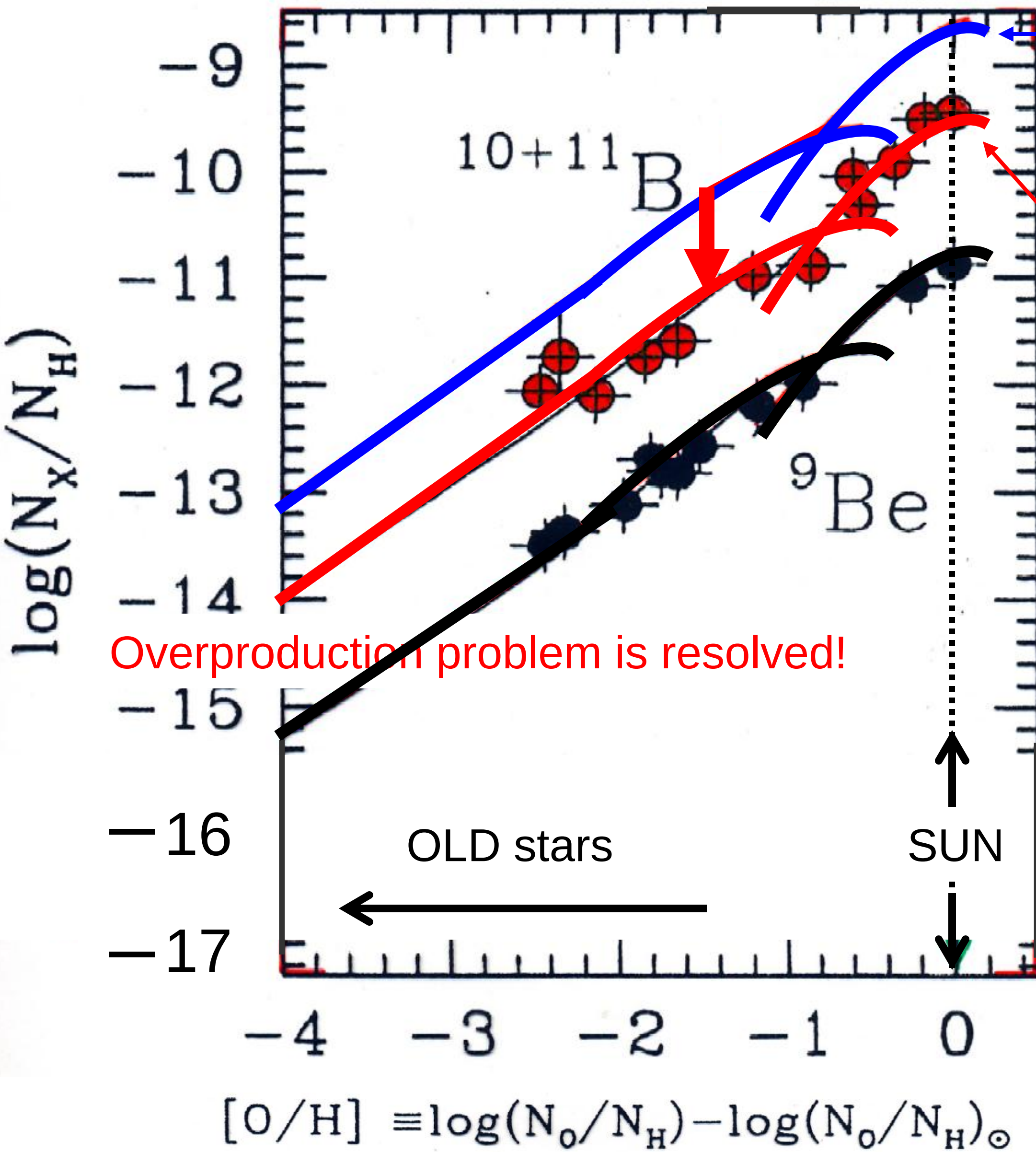
Then, both ^{138}La and ^{180}Ta abundances can be consistently reproduced by the CC-int. of ν_e and $\overline{\nu_e}$ of

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

Consistent with r-process !

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

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:

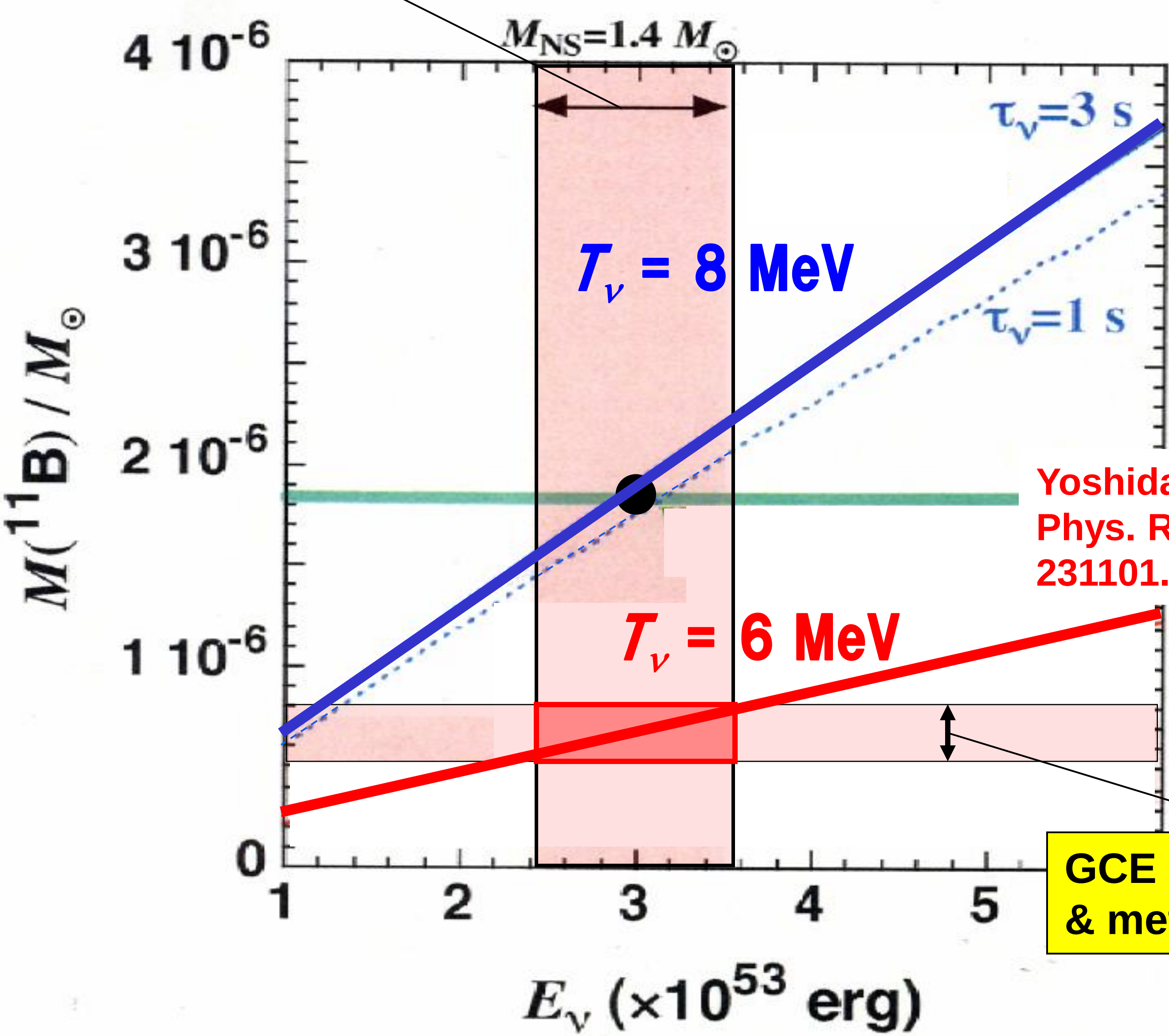
— Galactic Cosmic Rays

— Supernova ν−process

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

SN-Boron calculations and constraints on SN- ν

SN1987A constraint on $E_{\nu,tot}$ & Grav. Energy



Woosley & Weaver
ApJS 101 (1995), 181.

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

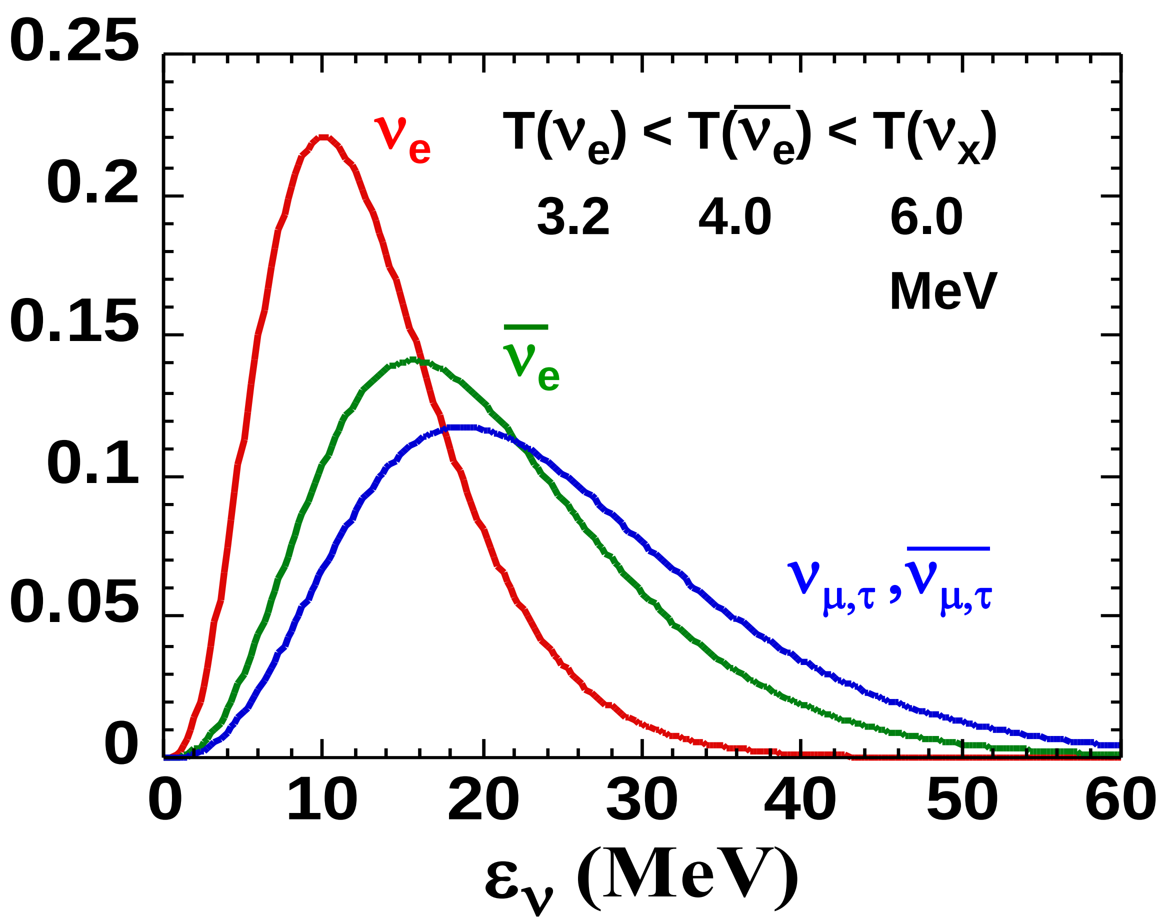
Consistent with SN simulation (MPA group) 2004-2011.

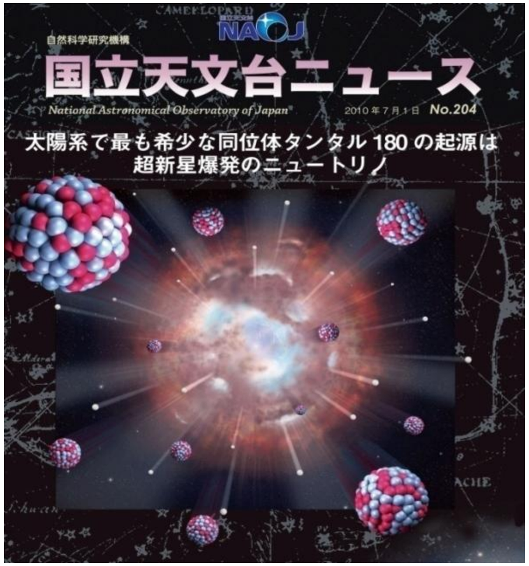
GCE constraints on ^{11}B & meteoritic $^{11}B/^{10}B$

Average ν-temperatures are now known!

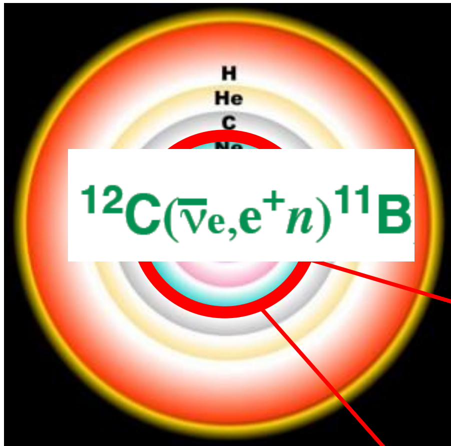
- R-process Elements & ^{180}Ta/^{138}La ➡ $T\nu_e = 3.2$ MeV, $T\bar{\nu}_e = 4$ MeV
- Astron. GCE of Light Elements & ^{11}B ➡ $T\nu_{\mu} = T\nu_{\tau} = 6$ MeV

➡ **Study Neutrino Oscillation !**



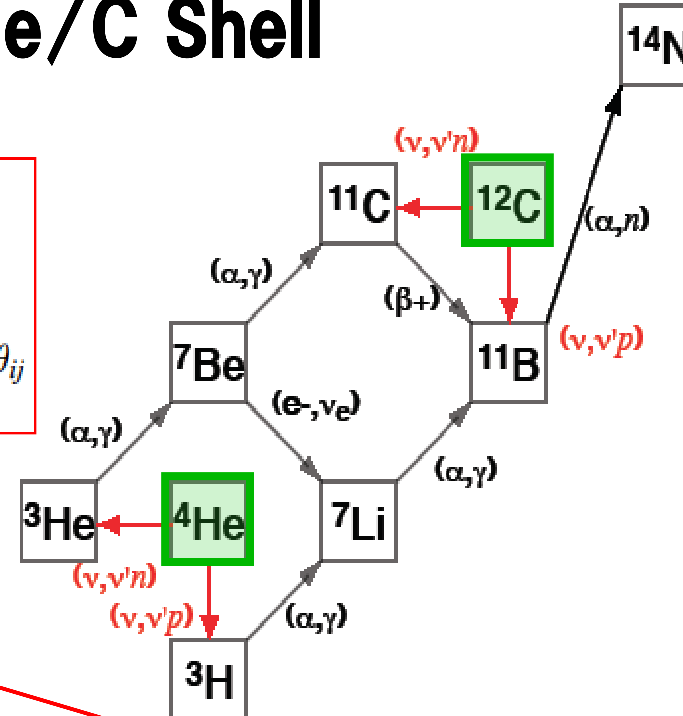


^{7}Li and ^{11}B are produced in the He/C Shell

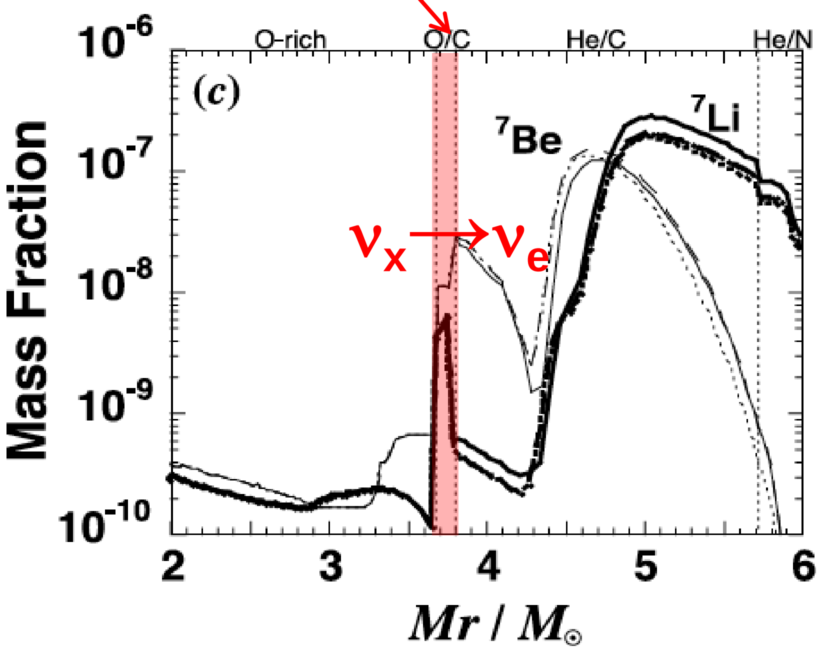


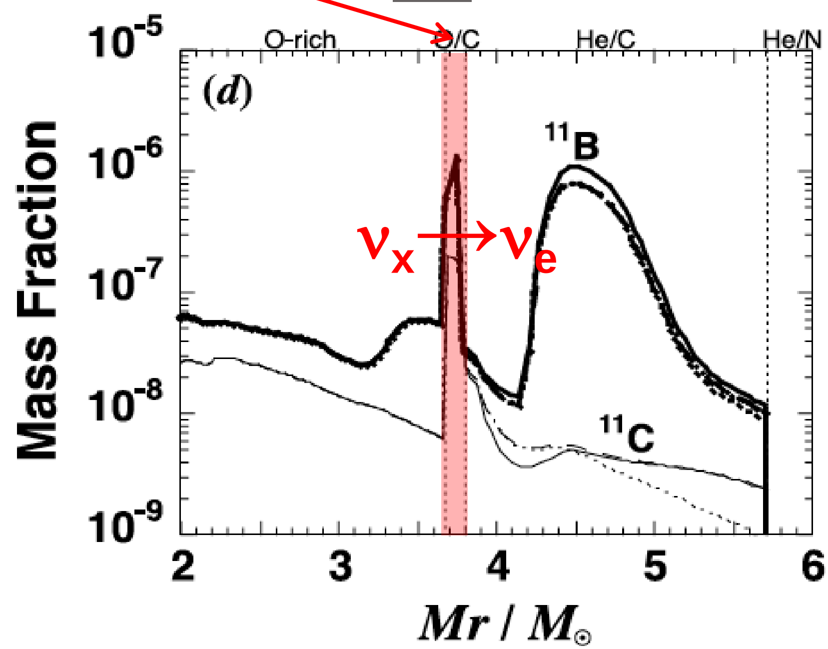
$$\rho_{\rm res} Y_e = \frac{m_u \Delta m_{ji}^2 c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_{\rm F} (\hbar c)^3 \varepsilon_\nu} \qquad [\ \text{g cm}^{-3}\ ]$$

$$= 6.55\times10^6 \left(\frac{\Delta m_{ji}^2}{1\ \text{eV}^2}\right)\left(\frac{1\ \text{MeV}}{\varepsilon_\nu}\right)\cos 2\theta_{ij}$$



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.

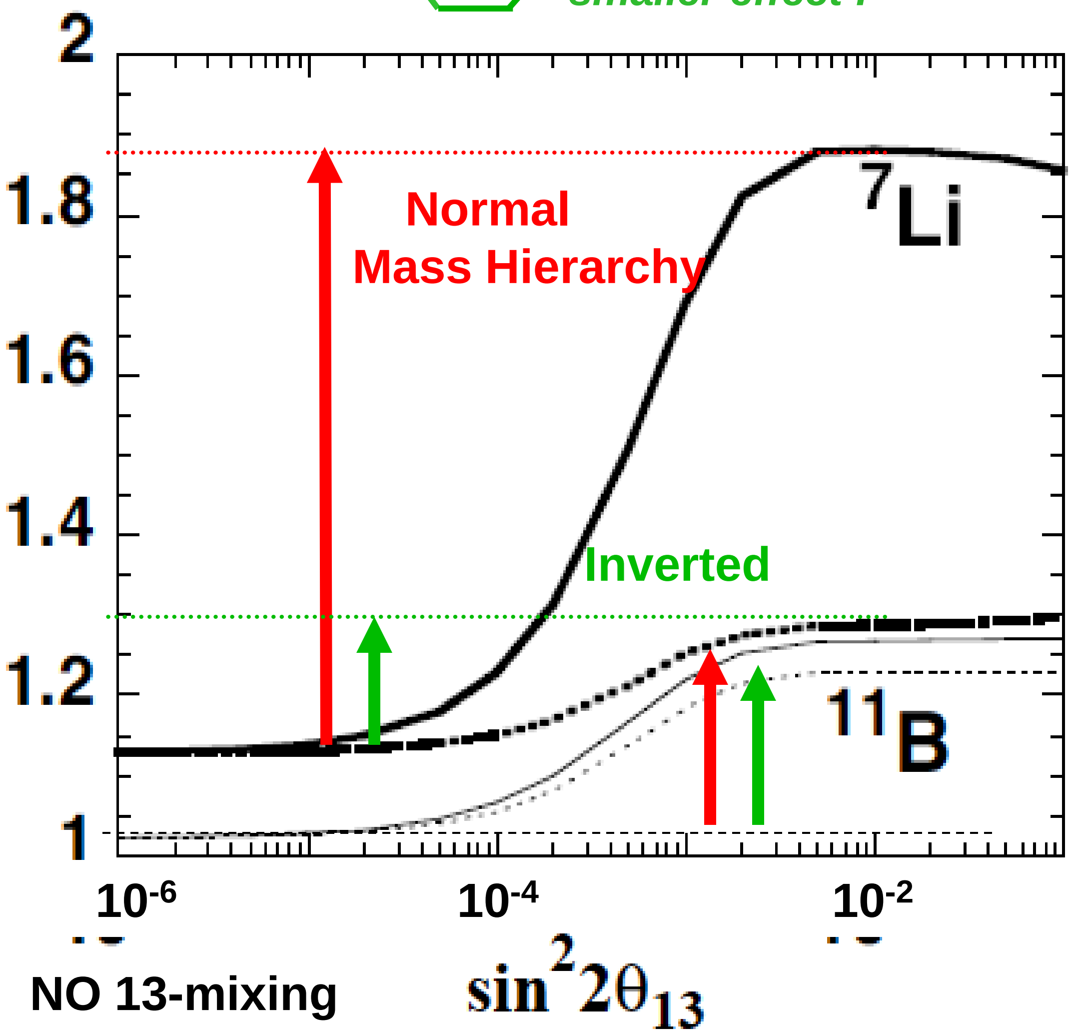
larger effect !

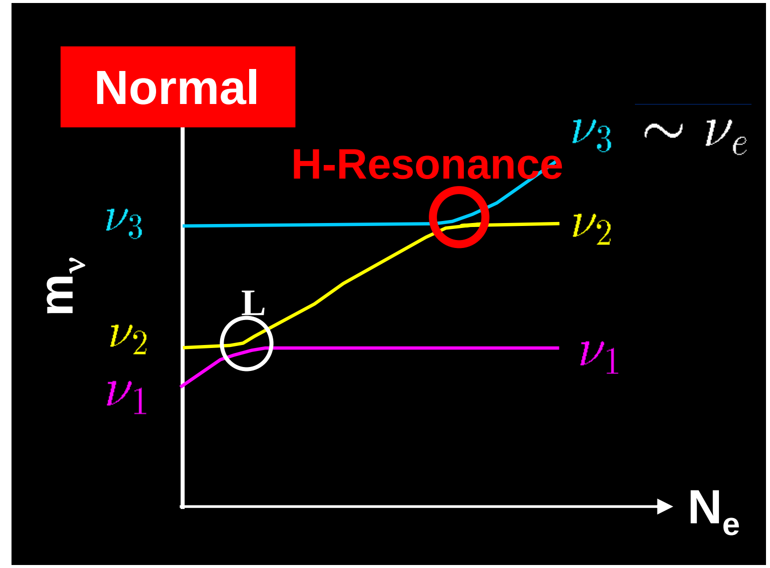
$$T_{\nu e} < T_{\overline{\nu e}} < T_{\nu\mu\tau,\ \overline{\nu\mu\tau}}$$

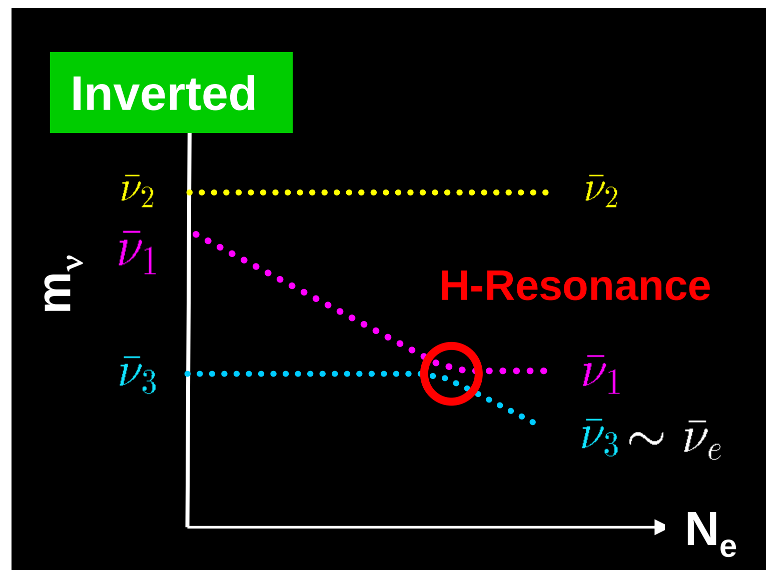
$$= \qquad = \qquad =$$

3.2MeV 4.0MeV 6.0MeV

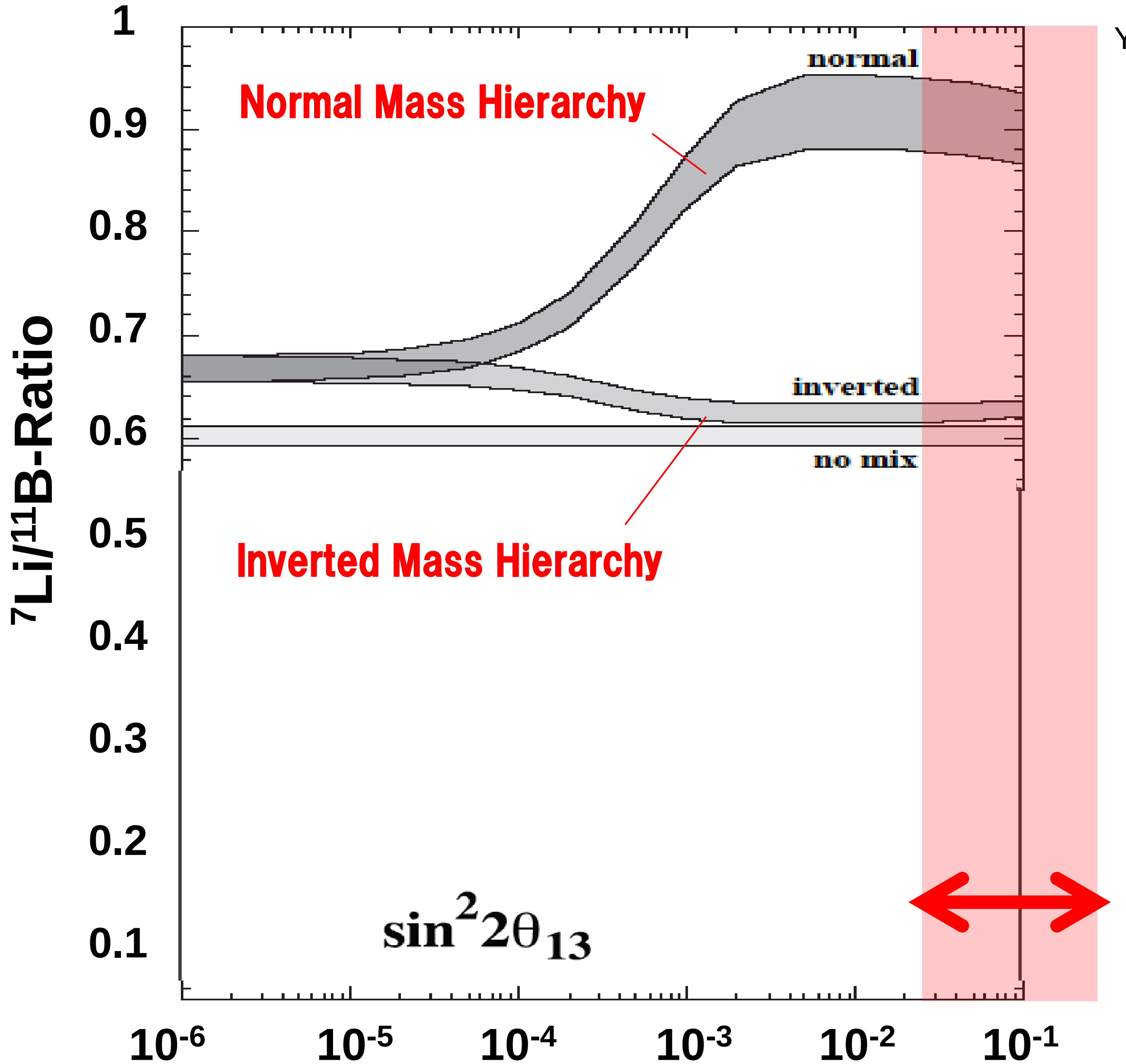
smaller effect !







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:

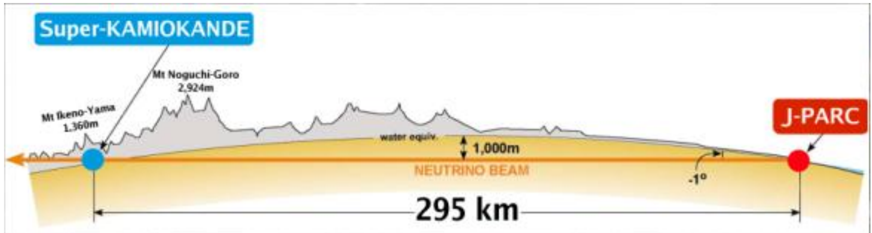
- T2K (Kamioka)
- MINOS

Reactor Exp. in2012:

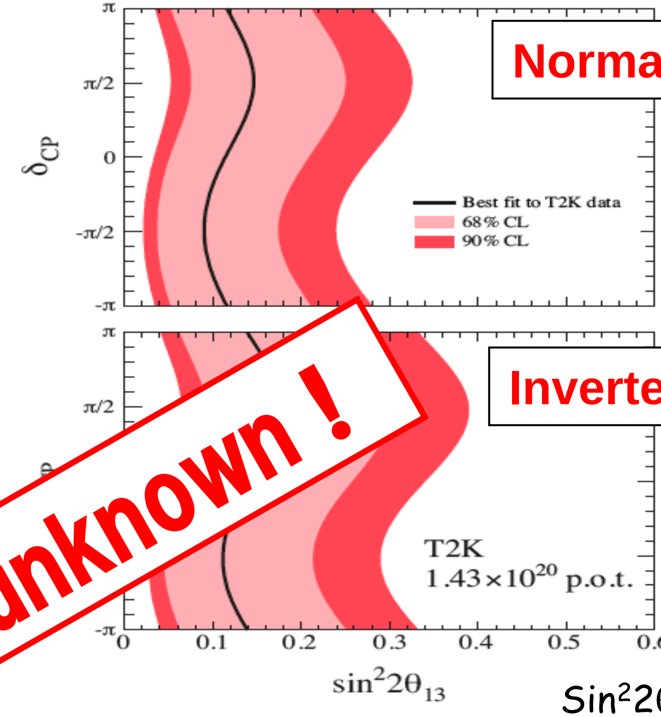
- Double CHOOZ
- Daya Bay
- RENO (KOREA)

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

Long Baseline ν — T2K & MINOS (2011)



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



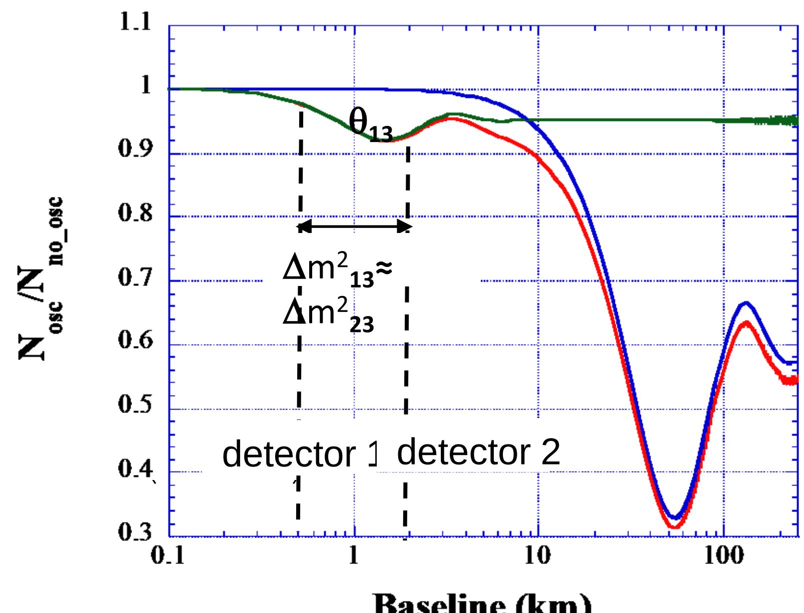
$\mathrm{Sin}^2 2\theta_{23}=1$

Daya Bay 2012	$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$
Rino (2012)	$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\mathrm{stat.}) \pm 0.0$
Double Chooz (2012)	$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\mathrm{stat}$
Minos (2011)	$\sin^2 2\theta_{13} < 0.12(0.20$
T2K (2012)	$0.03(0.04) <$ ... $0.34)$

Mass hierarchy is still unknown !

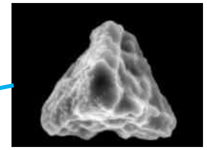
Reactor ν — Daya Bay & Double Chooz (2012)

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

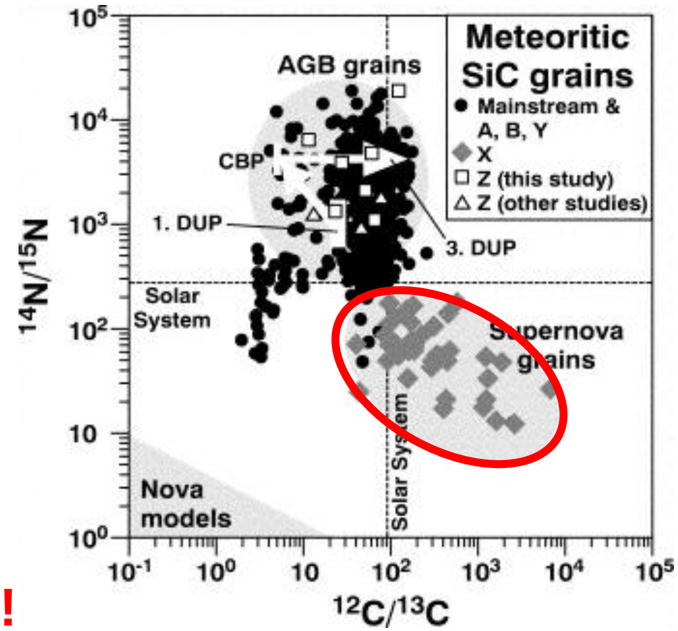


Murchison Meteorite

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) and ^{44}Ti ($t_{1/2}$=60yr)



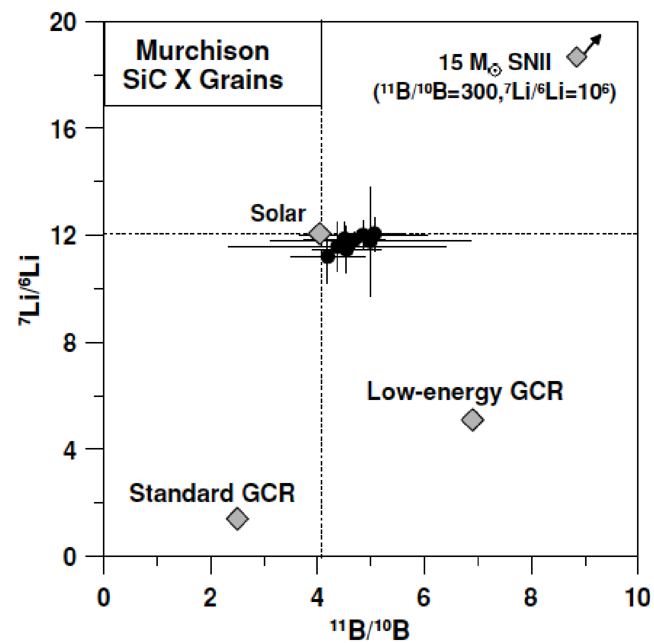
SiC X-grains are made of Supernova Dust !

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



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

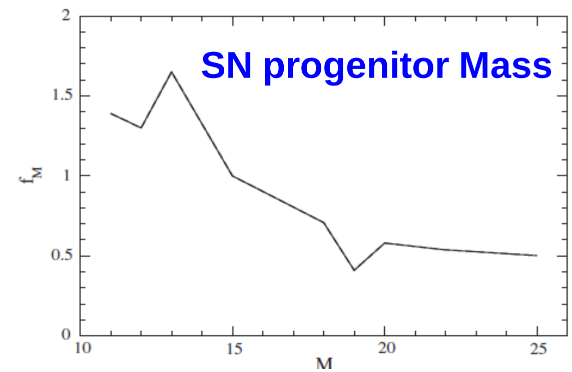
$$P(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_j P(D|M_j)P(M_j)}$$

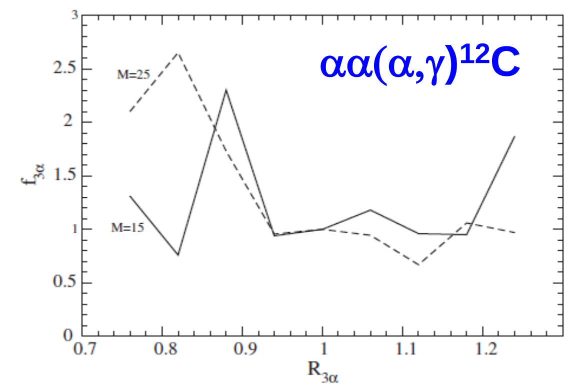
$$P(D|M_i) = \int dE dZ da_k P(E,Z,D|M_i,a_k)P(a_k|M_i)$$

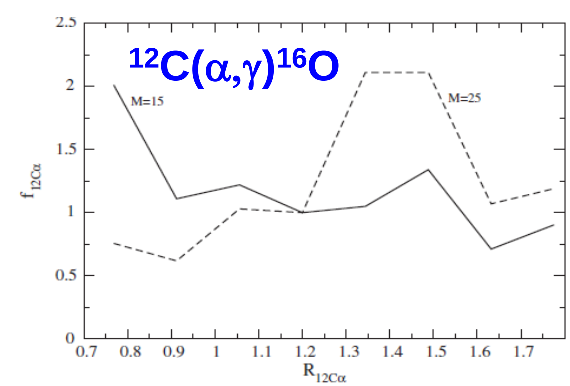
$$= \int dE dZ da_k P(D|M_i,a_k,E,Z)P(Z,E|M_i,a_k)P(a|M_i)$$

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

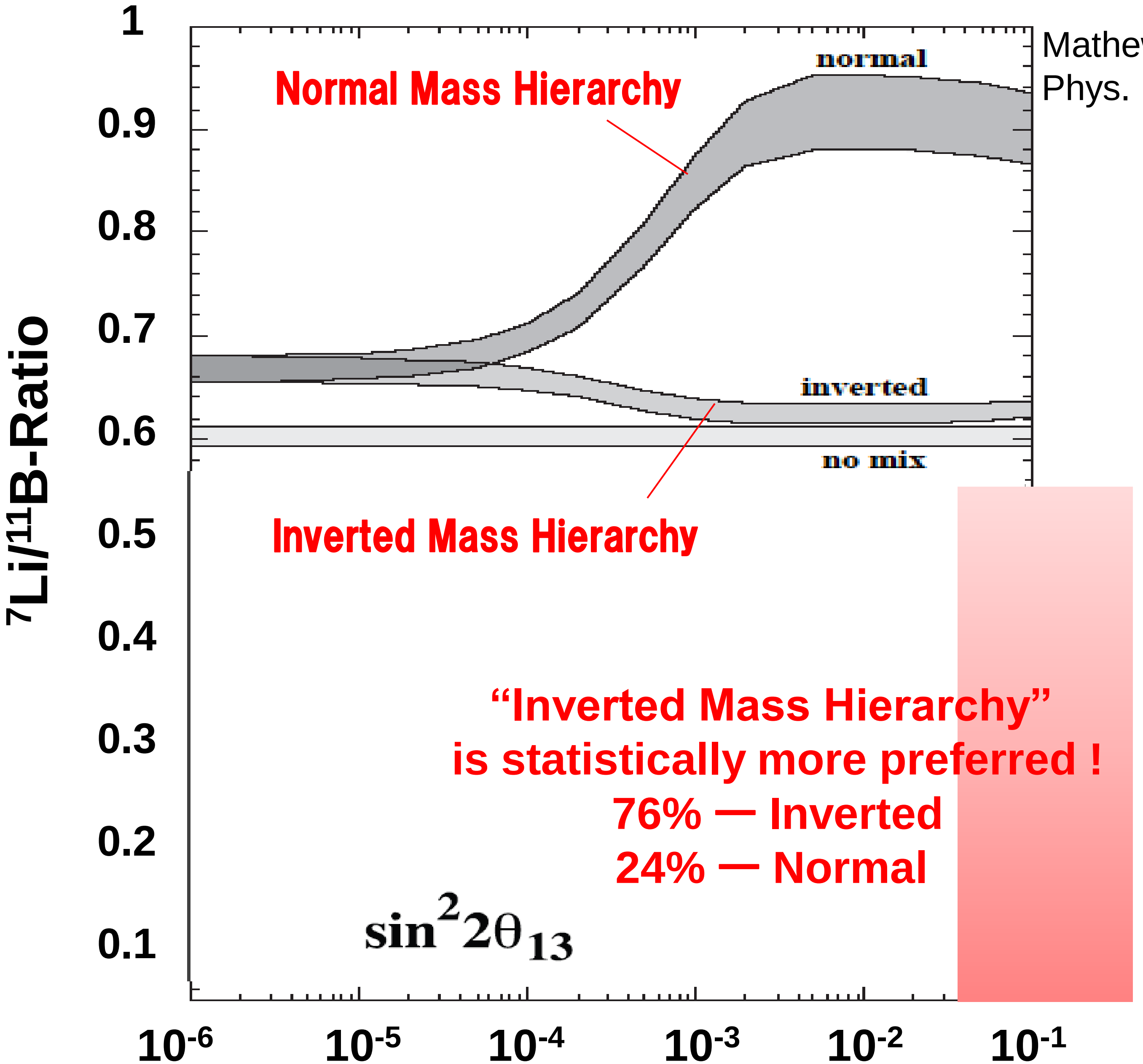
Parameter a_k	prior			reference
$\sin^2 2\theta_{13}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 0.92$	$\sigma_x = 0.017$	[7]
$R_{3\alpha}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 1.0$	$\sigma_x = 0.12$	[35]
$R_{12C\alpha}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 1.2$	$\sigma_x = 0.25$	[36]
$M_{prog}(\mathrm{M}_\odot)$	$m^{-2.65}$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







Supernova X-Grain Coinstraint



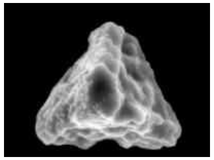
Mathews, Kajino, Aoki & Fujiya, Phys. Rev. D85,105023 (2012).

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).

Neutrino Physics in Cosmology

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

  $|\sum U^2_{e\beta} m_\beta| < 0.3$ eV: COUORE, NEMO3, EXO, KamLAND Zen (2012)

- **CMB Anisotropies + LSS**

  $\sum m_\nu < 0.28$ 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)

  $\sum m_\nu < 0.2$ eV (2σ, B_λ<2nG): Yamazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141; PR D81 (2010), 103519; D77, (2009) 043005.

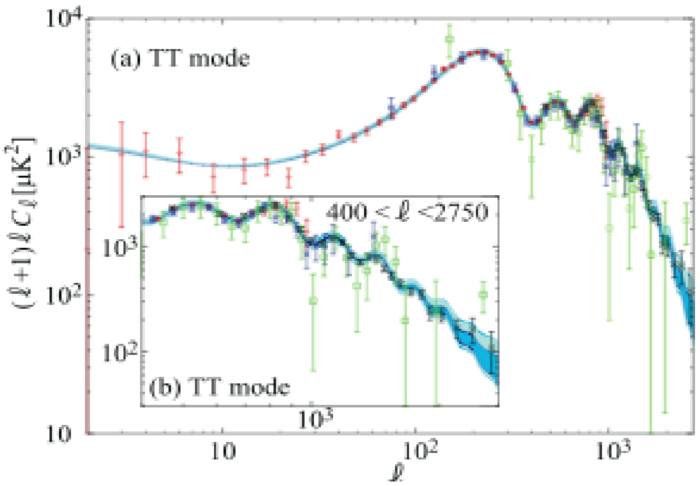
Roles of Neutrino Anisotropic Stress

CMB is affected by:

- integrated Sachs-Wolfe effect
- neutrino free streaming effect

CMB is generated even by :

- compensation mode of neutrino anisotropic stress (π_ν)
- another primordial source of extra anisotropic stress (π_{ext})



Standard cosmology needs tuning initial condition of the inflation-driven (pre-Big-Bang) perturbation !

Anisotropic Stress (e.g. Magnetic Field)

Energy density

$$T_{\mu\nu} = \begin{pmatrix} \frac{B^2}{2} & 0 & 0 & 0 \\ 0 & -B_x B_x + \frac{B^2}{2} & -B_y B_x & -B_z B_x \\ 0 & -B_y B_x & -B_y B_y + \frac{B^2}{2} & -B_z B_y \\ 0 & -B_z B_x & -B_z B_y & -B_z B_z + \frac{B^2}{2} \end{pmatrix} \propto a^{-4}$$

$\mathbf{B} \propto a^{-2}$

Stress part (space-space part)

Trace part $\frac{1}{3}\delta_{ij}\mathrm{Tr}(T_{ij})$ **Pressure**

Traceless part $\boxed{T_{ij} - \frac{1}{3}\delta_{ij}\mathrm{Tr}(T_{ij})}$ **Anisotropic Stress**

Candidates for Primordial Extra Anisotropic Stress π_{ext} :

- **Dark Radiation in Brane World Cosmology**

  String-theory motivated Ekpyrotic/Cyclic model

  Lehners & Steinhardt 2008; Khoury et al. 2001;
  Steinhardt & Turok 2002; Lehners et al. 2007)

- **Primordial Magnetic Field (PMF)**

→ **CMB power spectrum becomes too BLUE !**

ν-anisotropic stress π_ν helps this defect?

Basic Equations for Metric Perturbation with ANISOTROPIC STRESS π_ν and π_{ext}

Isotropic & Homogeneous BG

$$\frac{1}{a^2}\left(\frac{a'}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

Friedmann Eq.

$$k\frac{1}{a^2}\frac{a'}{a}\mathcal{Z} = 4\pi G\delta\rho + k^2\frac{H_T}{a^2}$$

Linear Metric Perturbation

Perturbed Einstein Equation of "Super-Horizon Scale (kτ<<1)"

$$\boxed{\ddot{H}_T} + 2\frac{\dot{a}}{a}\dot{H}_T = 8\pi G a^2 (p_\nu \boxed{\pi_\nu} + p_\gamma \boxed{\pi_{ext}})$$

Metric perturbation

ν-anisotropic stress

Extra anisotropic stress

Assumption

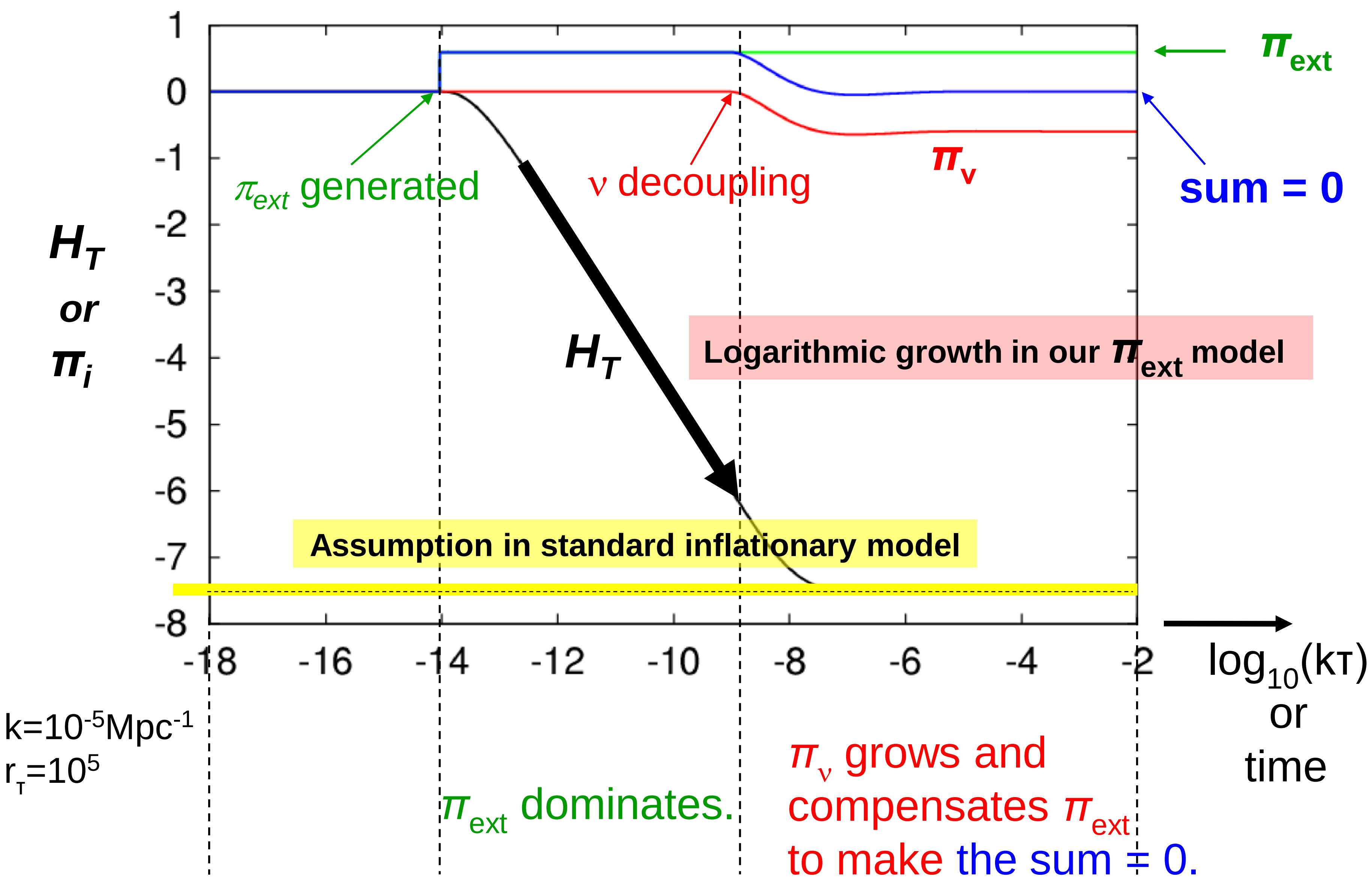
$\pi_{ext} \propto a^{-4}$

Roles of π_{ext} BEFORE the ν-decoupling was not discussed!

Only π_{PMF} after the ν-decoupling was discussed by Ma and Bertschinger (1995) and Giovannini et al. (2006, 2008).

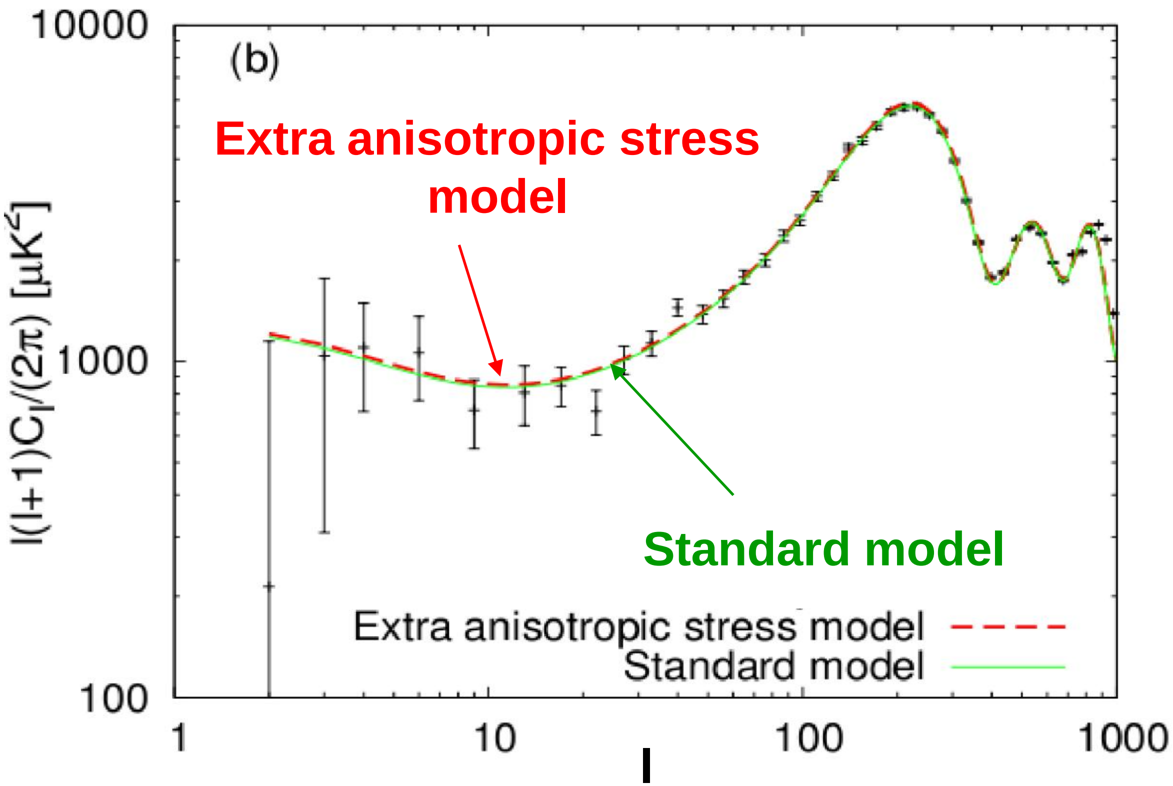
Evolution of metric perturbation H_T

Kojima, Kajino & Mathews, JCAP **02** (2010), 0182009).



CMB from Neutrino & Extra Anisotropic Stress

K. Kojima, T. Kajino & G. J. Mathews, JCAP **02** (2010), 0182009.



Spectral index is set equal to be the WMAP-best fit value.

$|\pi_{ext}| \sim 8.4 \times 10^{-6}$

$r_T = 10^{18}$

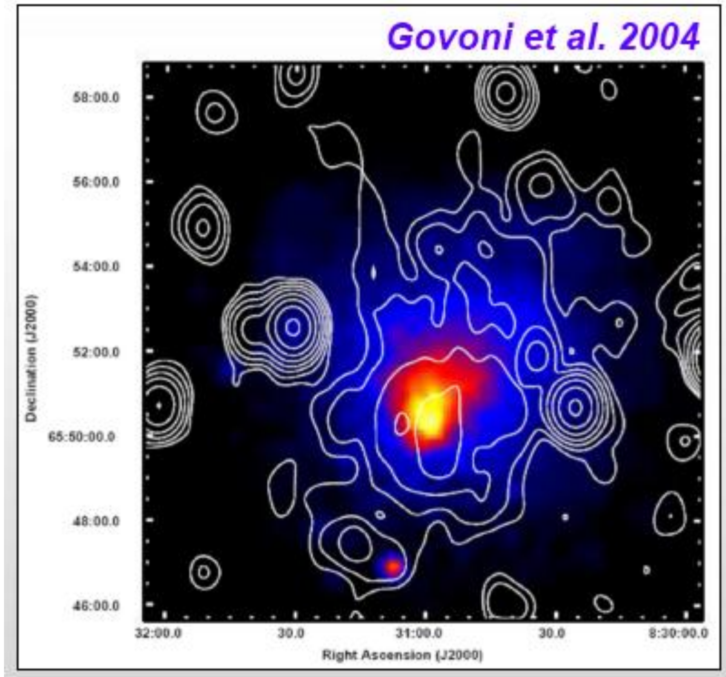
Extra Primordial Anisotropic Stress Model is NOT an alternative to INFLATION !

However, this mechanism of ν (π_ν) compensation makes a potential significance in ν mass !

– **Curvature perturbation is generated by Extra Anisotropic Stress π_{ext} without assuming inflation-driven (pre-Big-Bang) perturbation.**

– **It would make a great progress if we could know the nature of π_{ext} and its generation epoch before ν-decoupling.**

Primordial Magnetic Field (PMF): $\pi_{ext} = \pi_{PMF}$

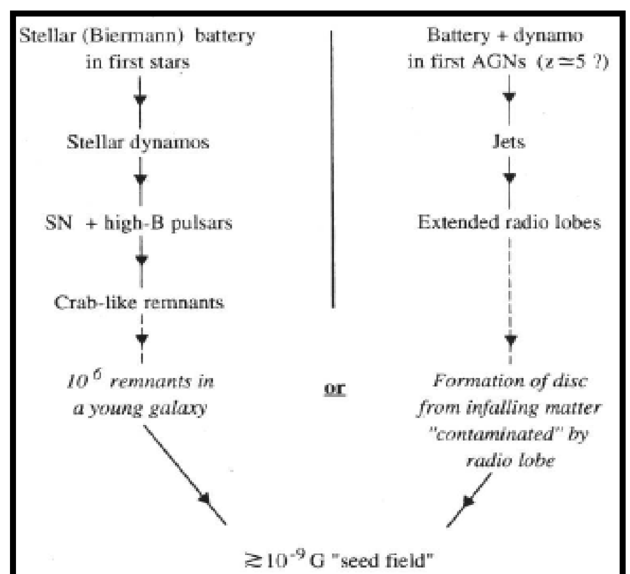


Cosmological Magnetic Field ?

- **Inflation** (Turner & Widraw 1988; Ratra 1992)
- **EW Baryogenesis via Sphaleron Transitions $\theta_W = 0$, then $\mu_M = 0$**
  (Nambu 1977, Hindmarsh & James 1994)
- **Dynamics of recombination**
  (Ichiki et al. 2005)

Galactic or Stellar Source + Dynamo in Post-Recombination Epoch?

(M. Rees 1994)



Galaxy Cluster scales:

B ~ 1.0 μG

(Moffet & Birkinshaw 1989, Jones et al. 1996, Giovannini & Feretti 2000, Feretti et al. 2004)

B ~ 1.0 nG

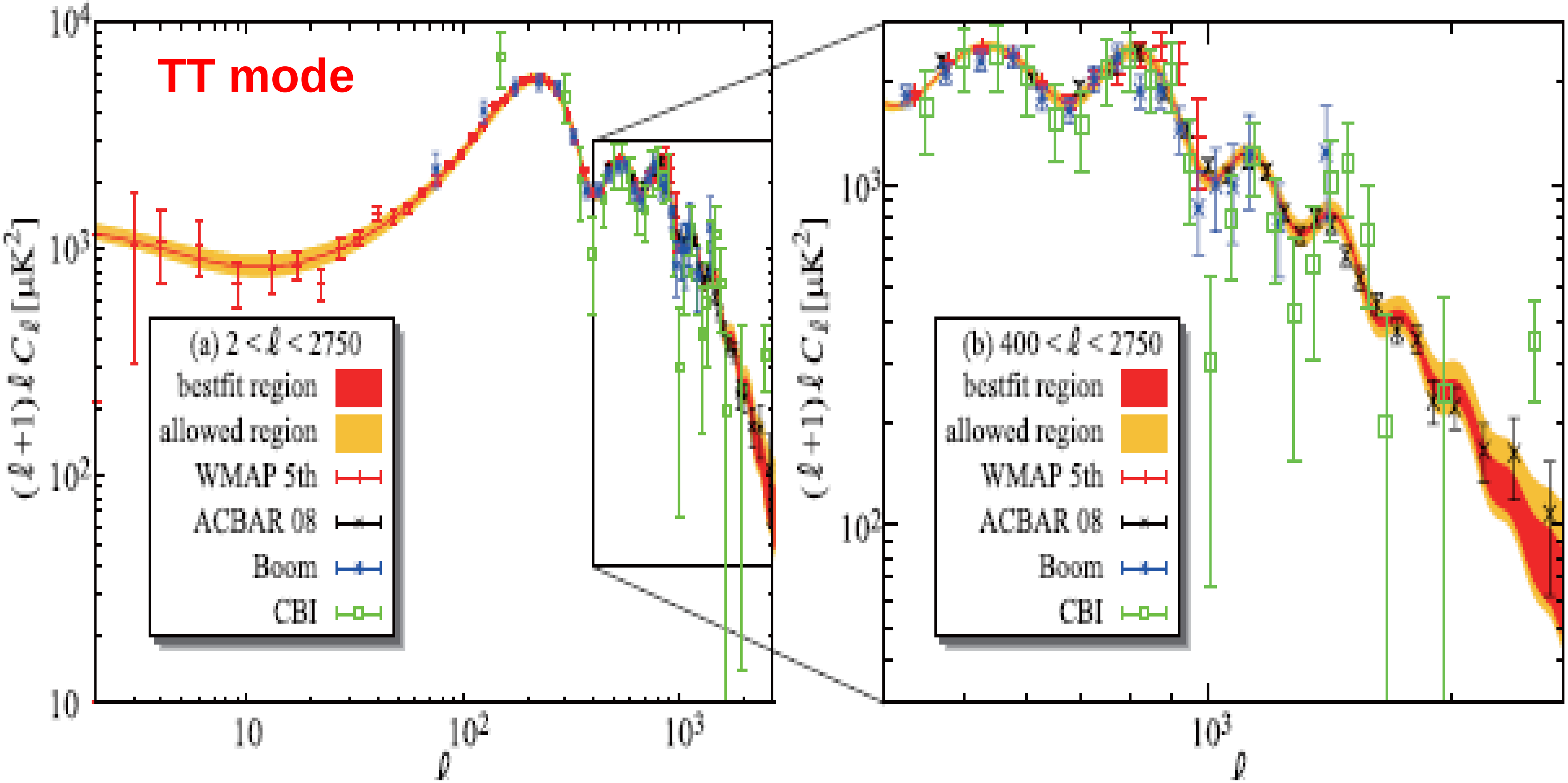
(Initial Seed) — Origin ?

Observed non-Gaussianity rules out large PMF !

PMF could be **only a part** of required full Extra Anisotropic Stress.

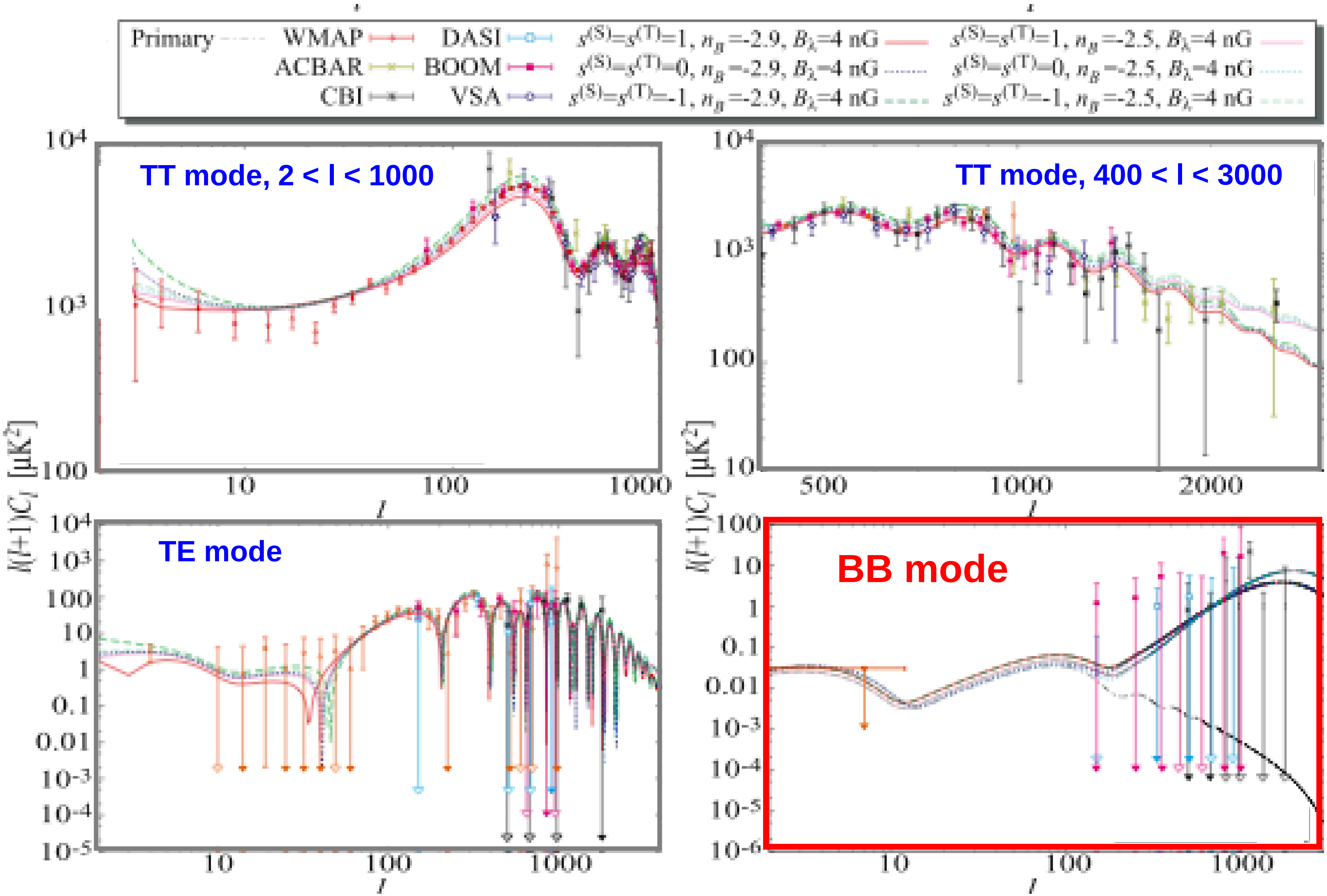
Lewis 2004; Mack 2002; Challinor 2004; Kahniashvili & B. Ratra 2005; Kosowsky et al. 2005; Yamazaki et al. 2005 - 2012; Kojima et al. 2009 – 2010.

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



Polarization - BB Mode exhibits a signal of PMF !

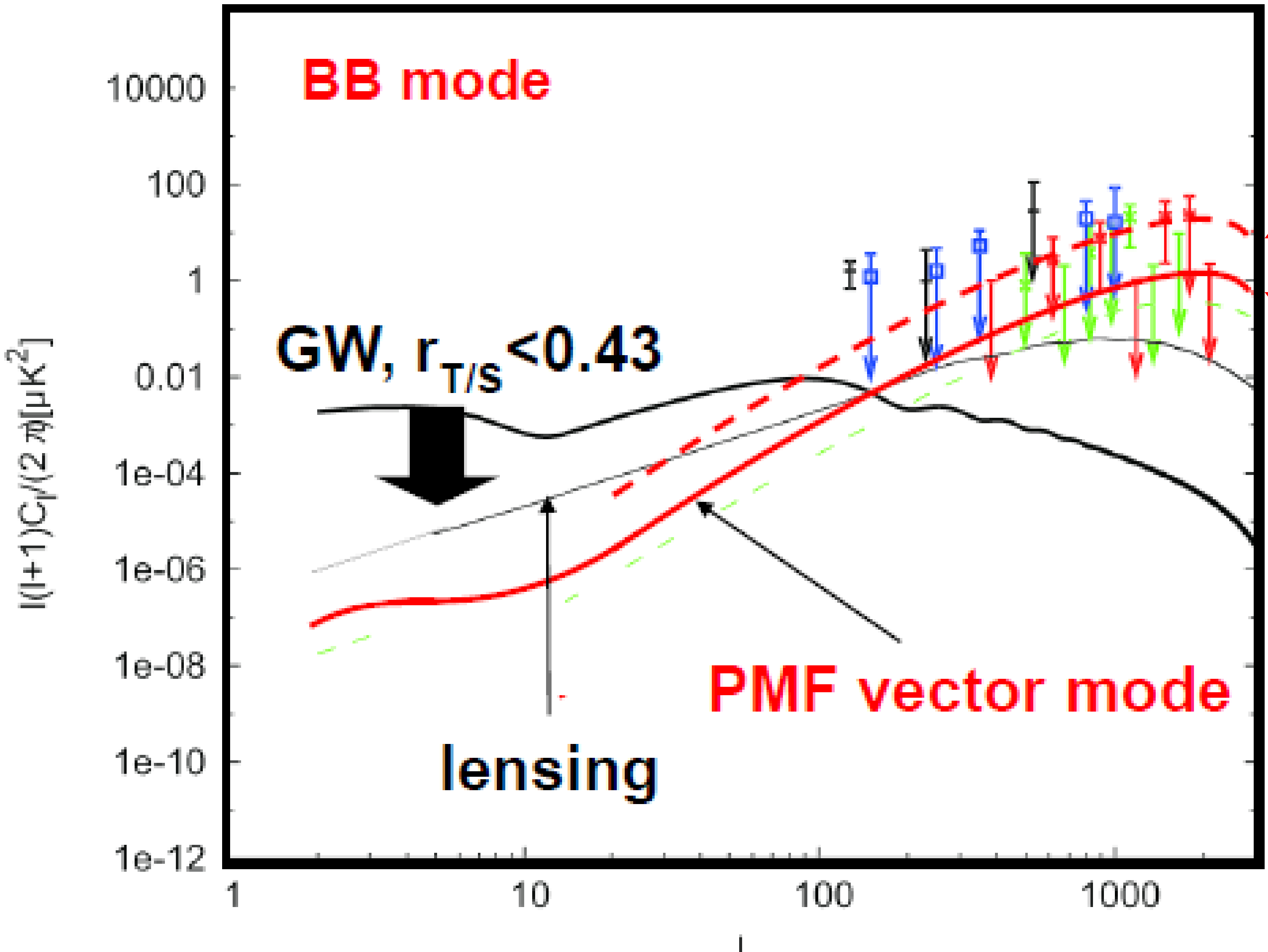
Yamazaki, Ichiki & Kajino, ApJ 825 (2006), L1; Yamazaki, Ichiki, Kajino, Mathews PRD, 77, 043005 (2008).



Yamazaki, Ichiki & Kajino, ApJ 825 (2006), L1
Yamazaki, Ichiki, Kajino, Mathews
PRD, 77, 043005 (2008)

$m_\nu = 0$ eV

PMF could manifest itself at smaller angular scales !



(for m_ν = 0)

Upper limit:
B = 7.7nG

n_B=-2.9

B=5nG

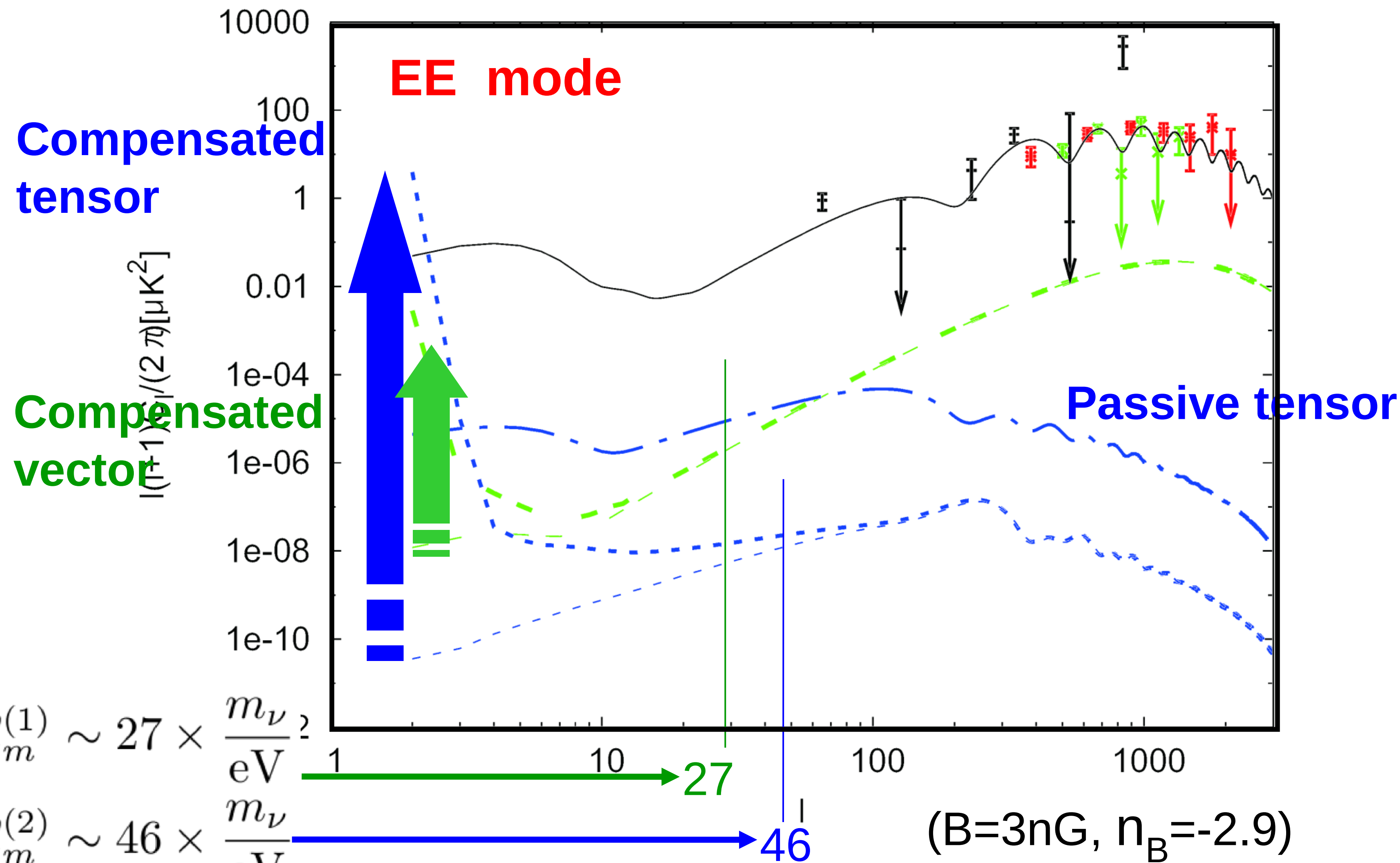
$k^3P(k) \propto B^4 \cdot k^{2n+6}$

$n = n_B = -3$
Scale invariant.

Polarization - EE Mode for massive ν

m_ν= 1eV

Kojima, Ichiki, Yamazaki,k Kajino & Mathews, Phys. Rev. D78 (2008), 045010.



$$\ell_m^{(1)} \sim 27 \times \frac{m_\nu}{\mathrm{eV}}$$

$$\ell_m^{(2)} \sim 46 \times \frac{m_\nu}{\mathrm{eV}}$$

(B=3nG, n_B=-2.9)

Neutrino Mass Effect

☆**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)

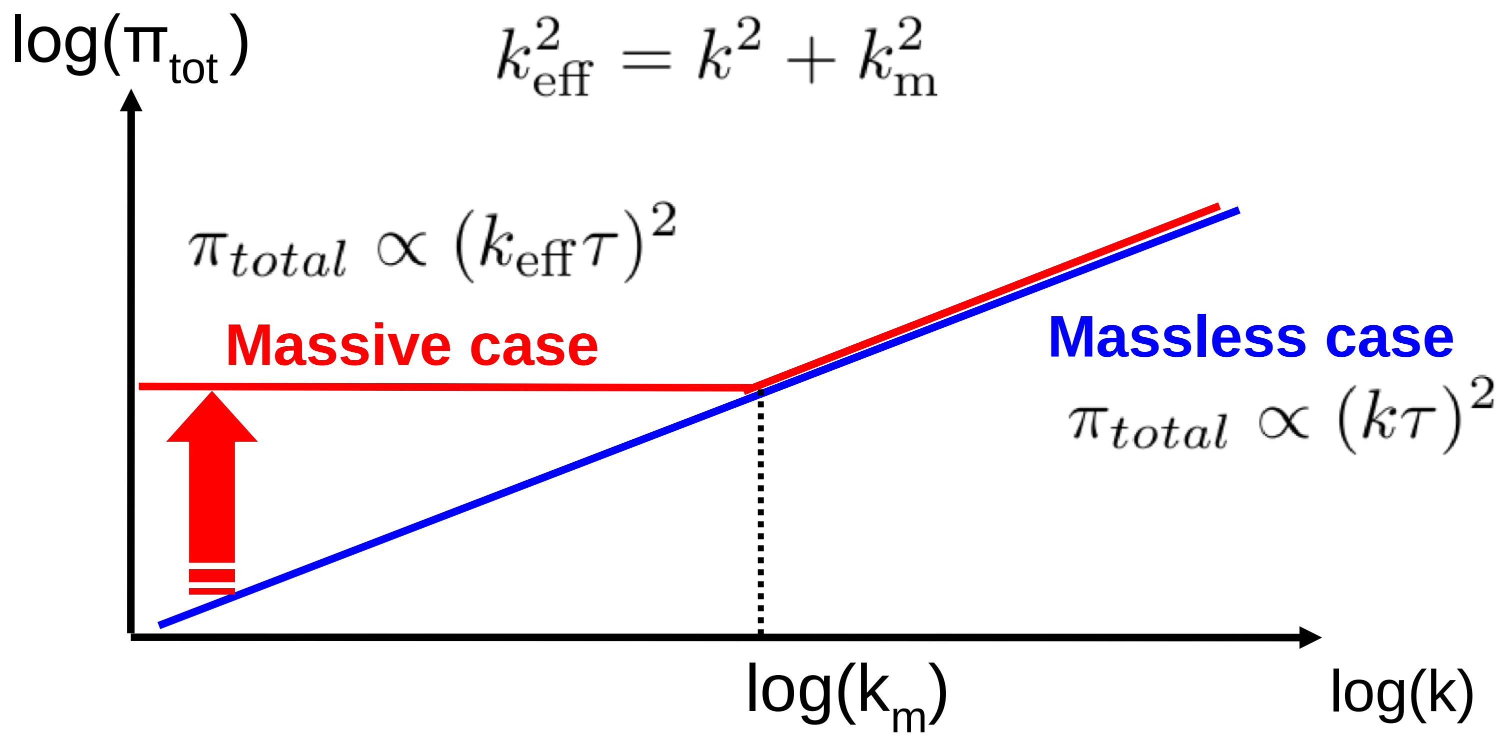
☆**Anisotropic stress of massive neutrino:**

$$\begin{aligned}\pi_h^{(m)} &\simeq \pi_\nu^{(m)}\left(1-\frac{1}{2}\frac{5}{7\pi^2}H_0^2\Omega_R m_\nu^2\tau^2\right)\\ &\simeq -\pi_{PMF}\frac{R_\gamma}{R_\nu}\left(1-\frac{c(k_{\mathrm{eff}}\tau)^2}{4R_\nu+15}\right)\end{aligned}$$

Effective wave number

$$\boxed{\begin{aligned}k_{\mathrm{eff}}^2 &= k^2+k_{\mathrm{m}}^2\\ k_{\mathrm{m}} &= \sqrt{\frac{1}{2}\frac{5}{7\pi^2}H_0^2\Omega_R\frac{4R_\nu+15}{c}m_\nu^2}\end{aligned}}$$

Total anisotropic stress



Vector mode $k_m^{(1)} = 1.9 \times 10^{-3} \times \frac{m_\nu}{\mathrm{eV}} \ \mathrm{Mpc}^{-1} \quad \ell_m^{(1)} \sim 27 \times \frac{m_\nu}{\mathrm{eV}}$

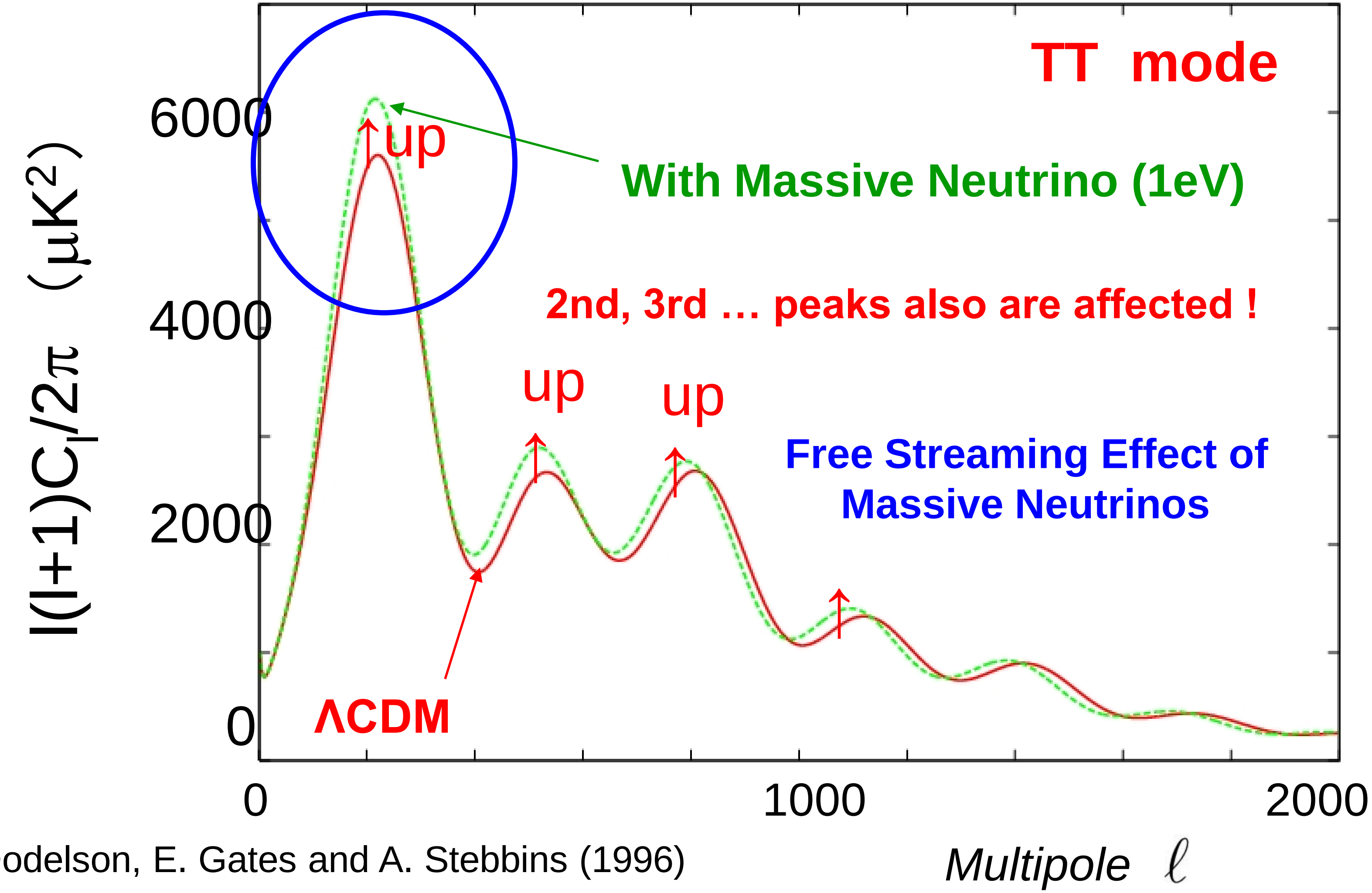
Tensor mode $k_m^{(2)} = 3.3 \times 10^{-3} \times \frac{m_\nu}{\mathrm{eV}} \ \mathrm{Mpc}^{-1} \quad \ell_m^{(2)} \sim 46 \times \frac{m_\nu}{\mathrm{eV}}$

Effects of Neutrino Mass m_ν

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

Integrated Sachs-Wolfe Effect, similarly to CDM

$$\ell_{nr} \simeq \frac{2\pi r_\theta(\eta_{rec})}{\eta_{nr}} \sim 350$$

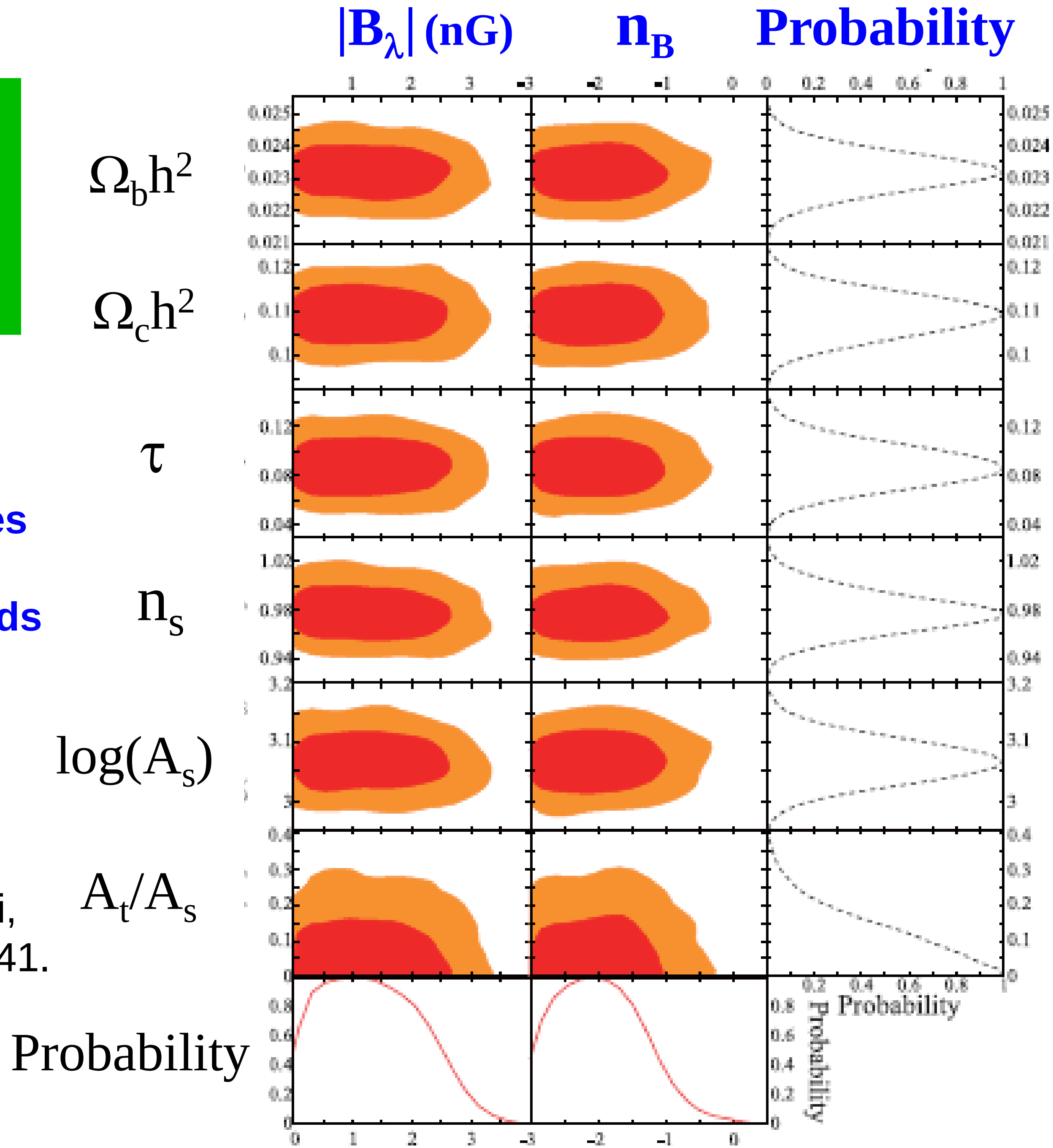


S. Dodelson, E. Gates and A. Stebbins (1996)

Likelihoodness and Probability

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

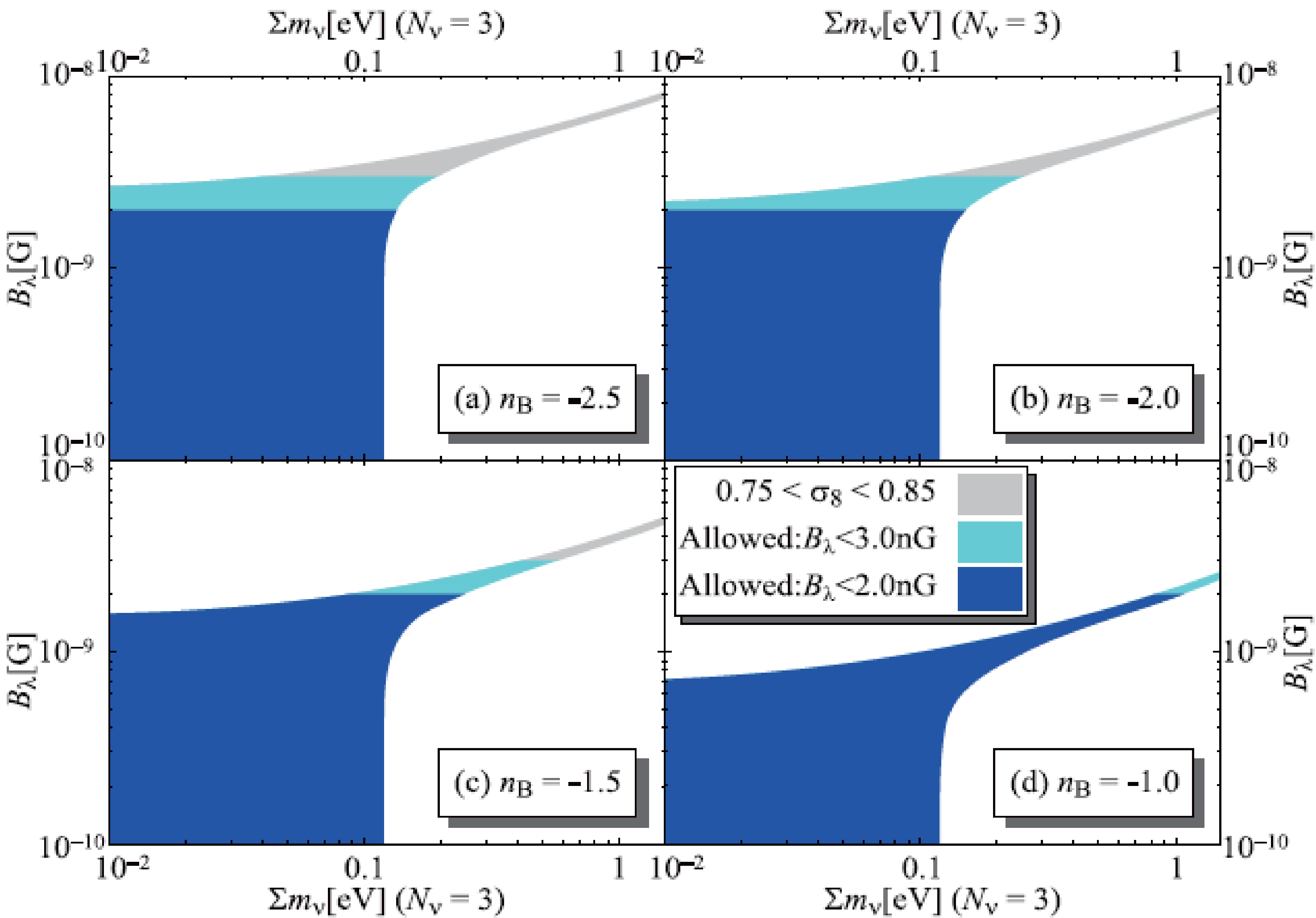
D. Yamazaki, T. Kajino, G. J. Mathews, & K. Ichiki, Phys. Rep. 517 (2012), 141.



Neutrino Mass Constraints

$\Sigma\, m_\nu < 0.2$ 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.



SUMMARY

ν-Mass hierarchy:

- We proposed a new nucleosynthetic method to estimate average ν-spectra from core-collapse supernovae: $T(\nu_e) = 3.2$MeV, $T(\overline{\nu_e}) = 4.0$MeV, $T(\nu_x) = 6.0$MeV.
- ^{7}Li/^{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.