第27回宇宙ニュートリノ研究会
「宇宙と実験室から測定するニュートリノの絶対質量」
ICRR-UT, Jan. 20, 2014

CMB, BBN, 超新星爆発による ニュートリノ質量および 振動への制限

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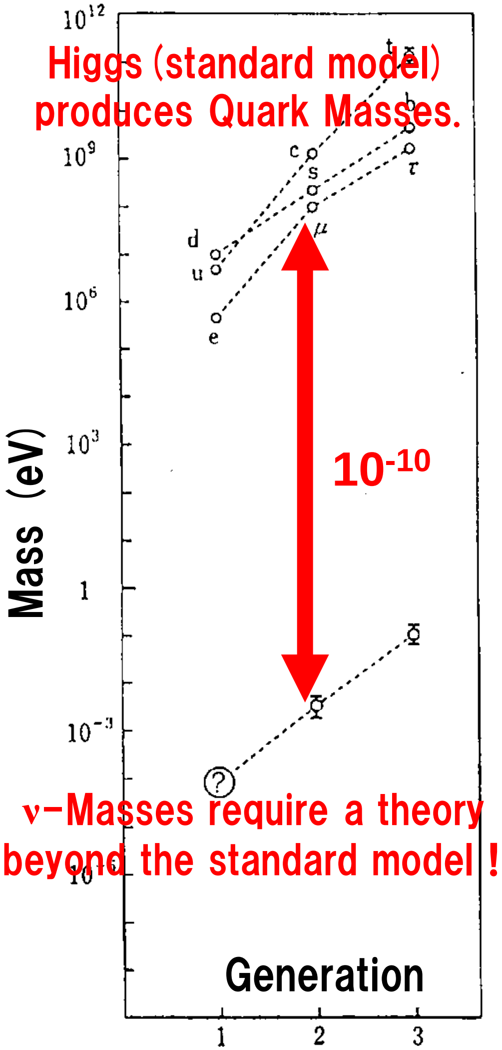
Challenge of the Century



Universe is flat and expanded acceleratingly.
$\Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1$

- **What is CDM ($\Omega_{CDM} = 0.27$) and DE ($\Omega_\Lambda = 0.68$) ?**
  CMB & LSS including absolute ν-mass
- **Is BARYON sector ($\Omega_B = 0.05$) well understood ?**
  BBN ^{7}Li-Problem with DMs (Axion, SUSY …)
  SUSY-DM ⇒ beyond the Standard Model ⇒ $m_\nu \neq 0$, unique signal

Key Physics with $m_\nu \neq 0$ beyond the Standard Model :

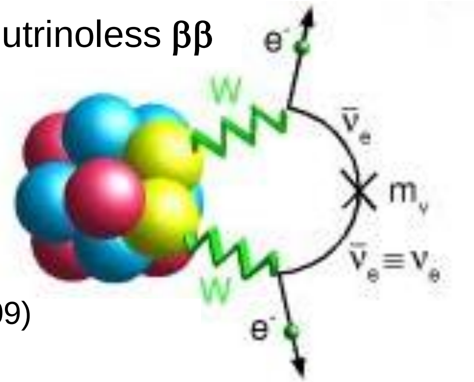
- Unification, CP & L- & B-genesis, Dirac or Majorana ?
- Dark Matter & Big Bang Nucleosynthesis ?
- Explosion Mechanism of CC-SNe & Nucleosynthesis ?

Purpose

is to constrain the total absolute ν-Mass, Hierarchy, and Nuclear EOS from ν-nucleus interactions in CMB, BBN, SNe and Relic SN ν's.

Original by courtesy of T. Kajita

Total ν-Mass constraint from Nuclear Physics and Cosmology



- **0νββ 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**

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

  $\sum m_\nu = 0.36 \pm 0.13$ eV: WMAP-9yr + BOSS (Beauler, Saito & Seo: Jan. 20, 2014)

  $\sum m_\nu < 0.2$ eV (2σ, B_λ<2nG): Incl. Magnetic Field; Ymazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141; Phys. Rev. D81 (2010), 103519.

★ **ν free-streaming effects**

★ **Integrated Sachs-Wolfe Effect !**

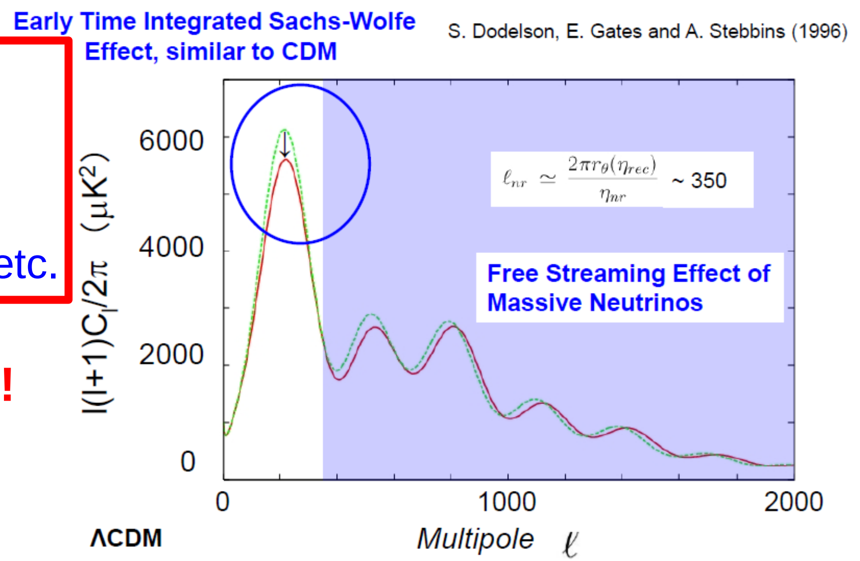
★ **CMB anisoteopies** is generated even by:
compensation mode of ν-anisotropic stress (π_ν)
to **primordial** extra anisotropic stress (π_{ext}).

Magnetic field, dark radiation, Ekpyrotic universe, etc.

Roles of ν-Anisotropic Stress with $m_\nu \fallingdotseq 0$!

Standard inflationary cosmology needs tuning primordial initial fluctuation !

Effects of Neutrino Mass m_ν (m_ν = 2eV)



Equations for CMB Calculations including Massive-ν, and Primordial Magnetic Field

Ma & Bertschinger, 1995, ApJ, 455, 7

Linearlized:
- Energy-momentum conservation $T_{\mu\ ;\nu}^{\ \nu} = 0$
- Boltzmann equation $P^\mu \frac{\partial f}{\partial x^\mu} - \Gamma^\mu_{\nu\lambda} P^{\nu\lambda} \frac{\partial f}{\partial P^\mu} = C[F]$

CDM

$$\dot{\delta}_c = -\frac{1}{2}\dot{h} \quad (1)$$

Massless neutrino

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu - \frac{2}{3}\dot{h} \quad (2)$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) \quad (3)$$

$$\dot{F}_{\nu 2} = 2\dot{\sigma}_\nu = \frac{8}{15}\theta_\nu - \frac{3}{5}kF_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta} \quad (4)$$

$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left(lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right), l \geq 3 \quad (5)$$

Massive neutrino

$$\dot{\Psi}_0 = -\frac{qk}{\epsilon}\Psi_1 + \frac{1}{6}\dot{h}\frac{d\ln f_0}{d\ln q} \quad (6)$$

$$\dot{\Psi}_1 = \frac{qk}{3\epsilon}(\Psi_0 - 2\Psi_2) \quad (7)$$

$$\dot{\Psi}_2 = \frac{qk}{5\epsilon}(2\Psi_1 - 3\Psi_3) - \left(\frac{1}{15}\dot{h} + \frac{2}{5}\dot{\eta}\right)\frac{d\ln f_0}{d\ln q} \quad (8)$$

$$\dot{\Psi}_l = \frac{qk}{(2l+1)\epsilon}\left(l\Psi_{l-1} - (l+1)\Psi_{l+1}\right), l \geq 3 \quad (9)$$

photon

$$\dot{\delta}_\gamma = -\frac{4}{3}\theta_\gamma - \frac{2}{3}\dot{h} \quad (10)$$

$$\dot{\theta}_\gamma = k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + an_e\sigma_T(\theta_b - \theta_\gamma) \quad (11)$$

$$\dot{F}_{\gamma 2} = 2\dot{\sigma}_\gamma = \frac{8}{15}\theta_\gamma - \frac{3}{5}kF_{\gamma 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta} - \frac{9}{5}an_e\sigma_T\sigma_\gamma + \frac{1}{10}an_e\sigma_T(G_{\gamma 0} + G_{\gamma 2}) \quad (12)$$

$$\dot{F}_{\gamma l} = \frac{k}{2l+1}\left(lF_{\gamma(l-1)} - (l+1)F_{\gamma(l+1)}\right) - an_e\sigma_T F_{\gamma l}, l \geq 3 \quad (13)$$

$$\dot{G}_{\gamma l} = \frac{k}{2l+1}\left(lG_{\gamma(l-1)} - (l+1)G_{\gamma(l+1)}\right) + an_e\sigma_T\left[-G_{\gamma l} + \frac{1}{2}(F_{\gamma 2} + G_{\gamma 0} + G_{\gamma 2})\left(\delta_{l0} + \frac{\delta_{l2}}{5}\right)\right], l \geq 3 \quad (14)$$

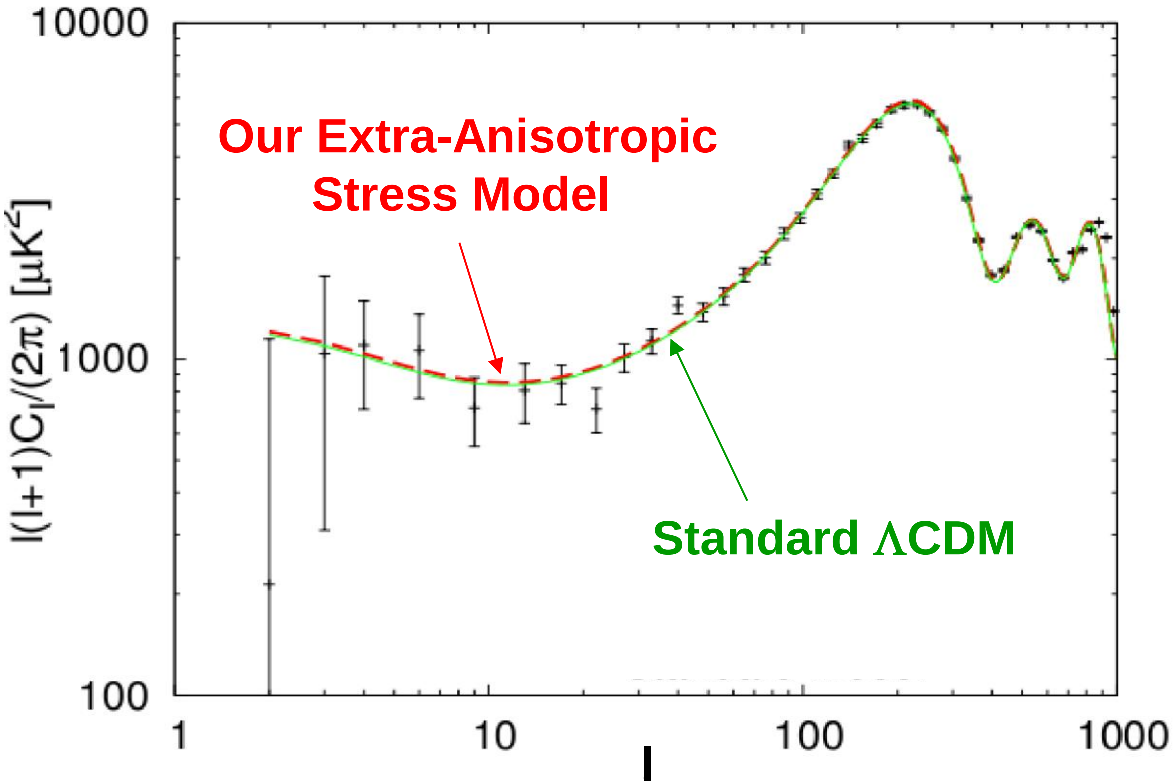
baryon

$$\dot{\delta}_b = -\theta_b - \frac{1}{2}\dot{h} \quad (15)$$

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_s^2k^2\delta_b + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_b}an_e\sigma_T(\theta_\gamma - \theta_b) \quad (16)$$

CMB from Neutrino & Extra Anisotropic Stress

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



Spectral index & strength of primordial extra-anisotropic stress are set equal to be the CMB-best fit value.

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

Our Extra-Primordial Aniso-tropic Stress Model is NOT an alternative to INFLATION !

ν–compensation mode (π_ν) plays a critical role in CMB with ν of finite mass !

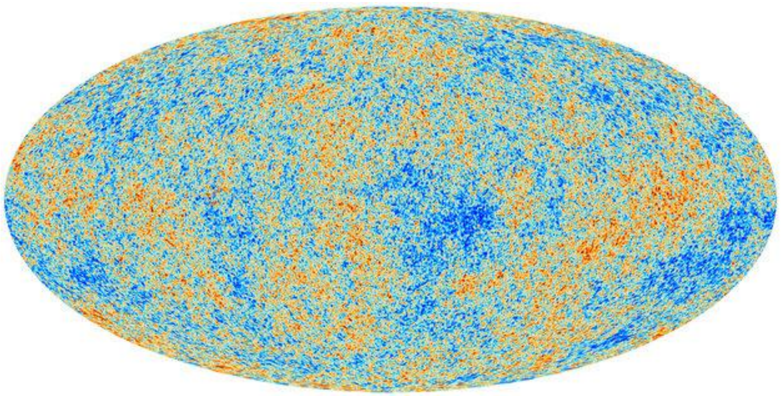
– Curvature perturbation is generated by extra anisotropic stress π_{ext} and regulated later by ν –compensation mode π_ν after decoupling.

– It is desirable to know the cosmological origin of extra anisotropic stress π_{ext} and its generation epoch in the early universe.

CMB Temp. & Polar. *including* Cosmological Magnetic Field

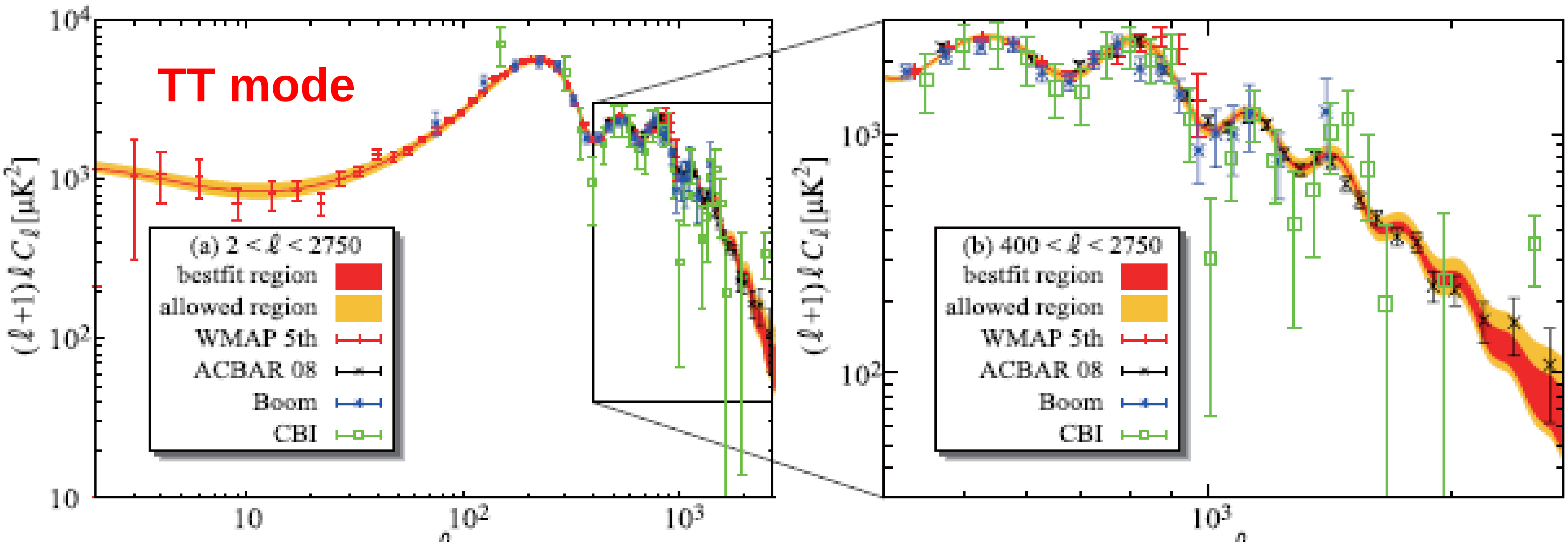
➡ Neutrino Mass Constraint

↑ An example Primordial Anisotropic Stress



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

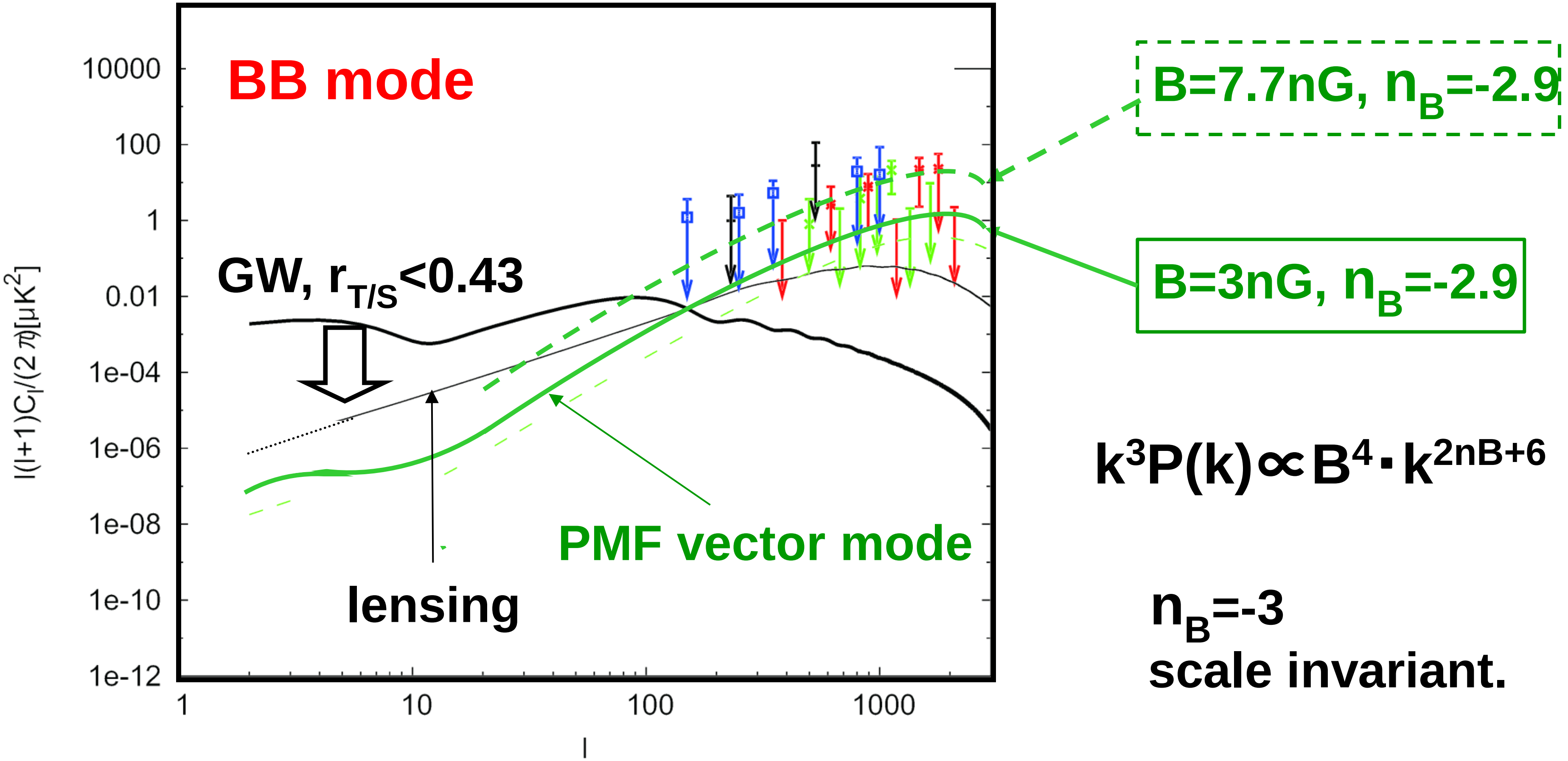
MCMC fit to CMB anisotropies D. Yamazaki, K. Ichiki, T. Kajino, G. J. Mathews, PR D81 (2010), 023008; PR D81 (2010), 103519; Phys. Rep. 517 (2012), 141.



Expected Presence of Primordial Magnetic Field (PMF)

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

Upper limit: B = 3nG, $m_\nu = 0$



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

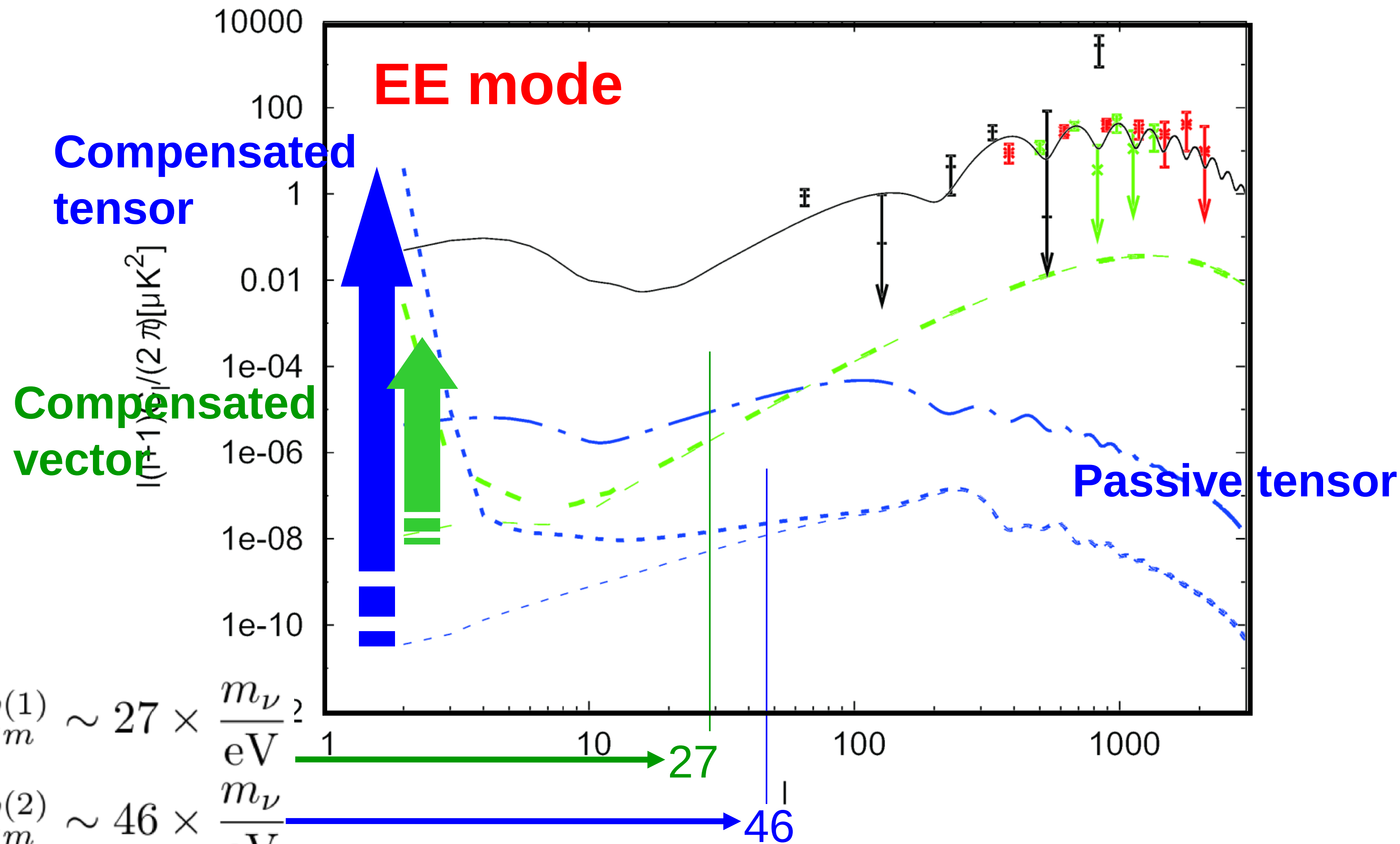
n_B=-3
scale invariant.

EE Polarization Mode with massive ν

$m_\nu = 1eV$

Kojima, Ichiki, Yamazaki,k Kajino & Mathews,
PR **D78** (2008), 045010;
Yamazaki, Kajino, Mathews & Ichiki, Phys. Rep.
517 (2012) 141.

Extra Anisotropic-Stress of Primordial Magnetic Field; B=3nG, n_B=-2.9



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

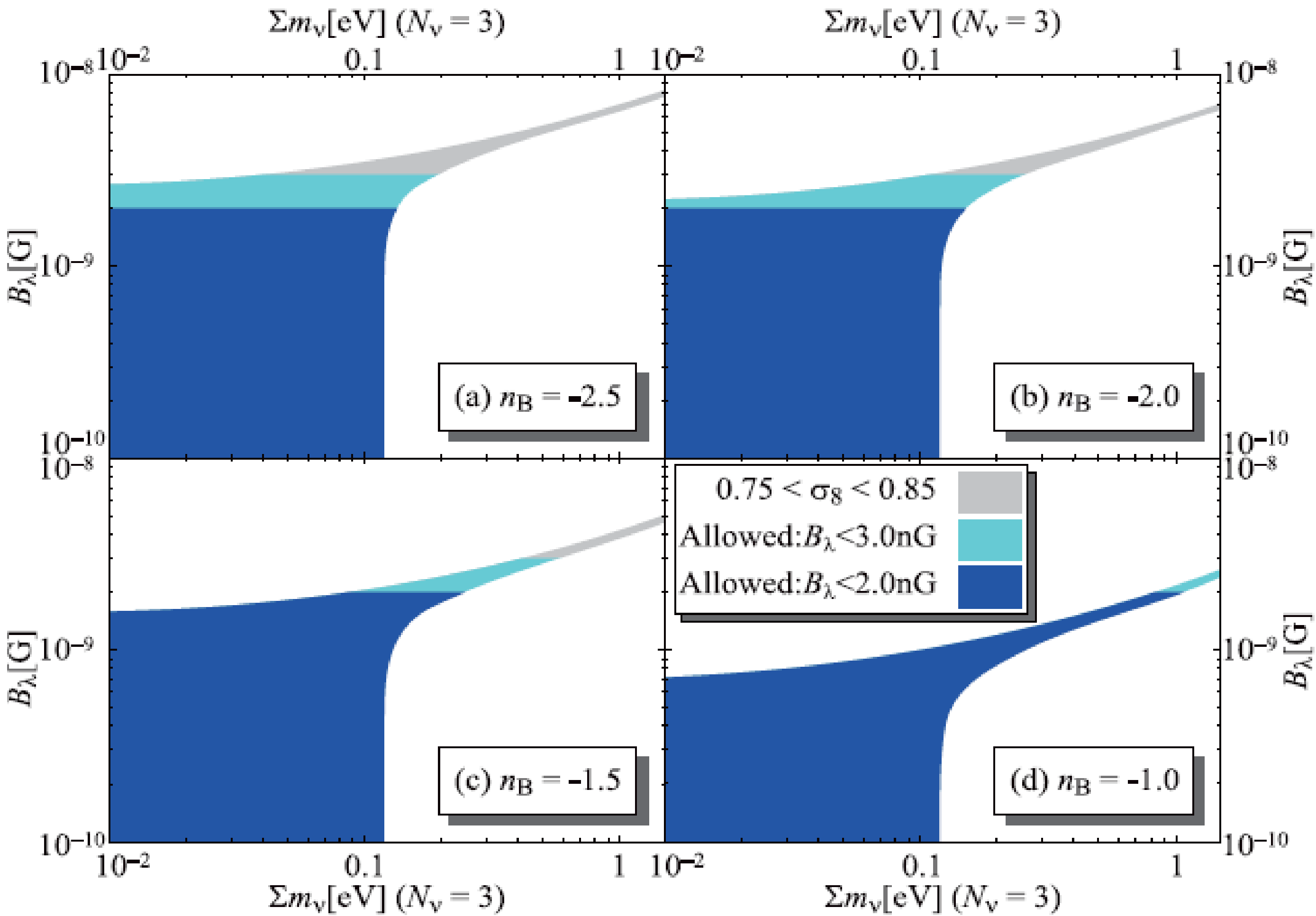
$$\ell_m^{(2)} \sim 46 \times \frac{m_\nu}{\mathrm{eV}}$$

Neutrino Mass Constraints from CMB + LSS

$\Sigma m_\nu < 0.2$ eV

Yamazaki, Ichiki, Kajino, and Mathews, PR D81 (2010), 103519:

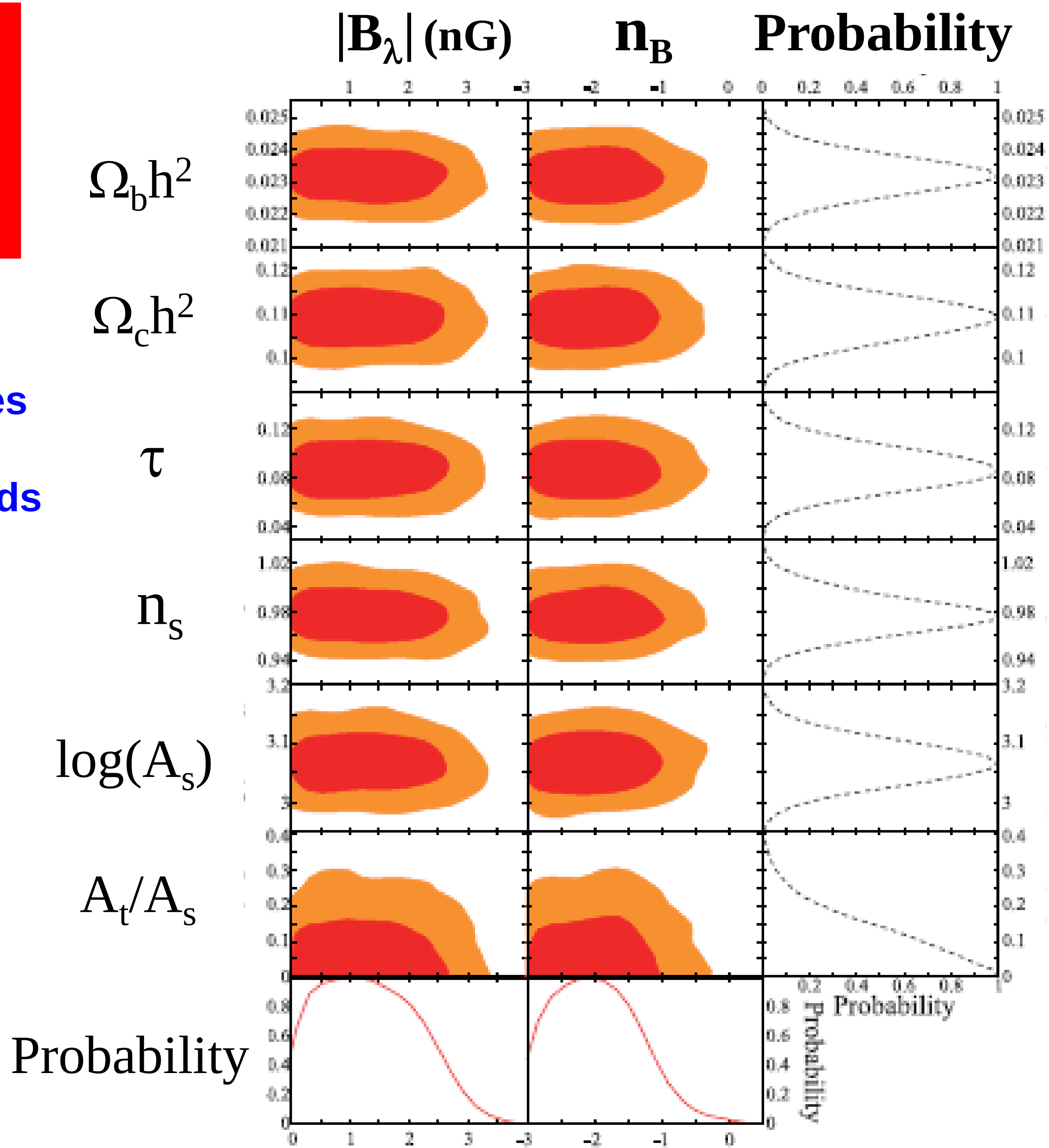
D. Yamazaki, T. Kajino, G. J. Mathews, and K. Ichiki, Phys. Rep. 517 (2012) 141.



Likelihoodness and Probability

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

$\Sigma m_\nu < 0.2$ eV



D. Yamazaki, K. Ichiki, T. Kajino & G.J. Mathews,
PR **D81** (2010),103519.

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

BBN Constraint on Magnetic Moment of Massive Neutrinos

M. Kusakabe, A. B. Balantekin, T. Kajino & Y. Pehlivan, PR D87 (2013), 085045.

Cosmological: $\nu \longrightarrow \nu' + \gamma_{NT}$ *Parent* ν *could be massive!*

sterile ($m_\nu \neq 0$, $\mu_\nu \neq 0$) sterile/active

γ_{NT} & BBN: D(γ,p)n, ^{6}Li(γ,d)α, ^{7}Li(γ,t)α

Current Constraints

Laboratory: $\mu_\nu < 2.9 \times 10^{-11} \mu_B$

Astrophysical: $\mu_\nu < 3 \times 10^{-12} \mu_B$

Magnetic Moment of massive neutrino X

$$|\mu_{\rm eff}|^2 = |\mu_{ij}|^2 + |\epsilon_{ij}|^2.$$

μ_ν

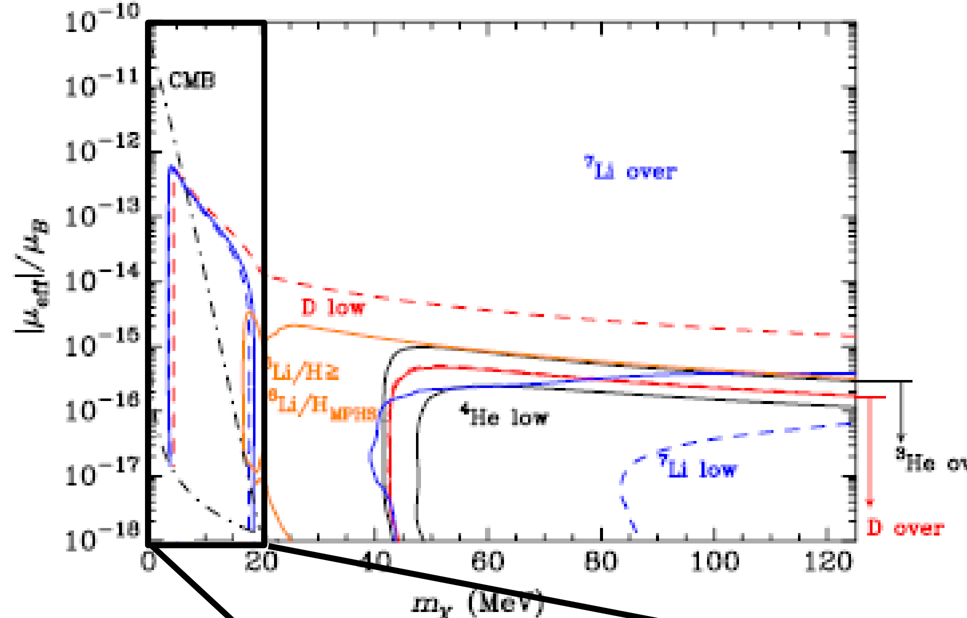
$$\tau_X^{-1} = \frac{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3$$

$$= 5.308\ {\rm s}^{-1}\left(\frac{\mu_{\rm eff}}{\mu_B}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{\rm eV}\right)^3$$

Decoupling Temp. is Max[1MeV, m_X/20]

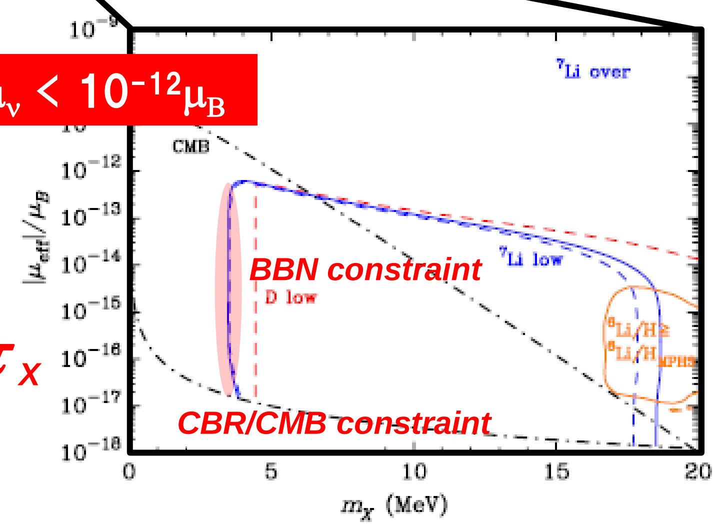
$$\frac{n_X}{n_\gamma} = \frac{4}{11}\frac{n_{dX}(m_X)}{n_\gamma(T_d)} = \frac{2\pi^2}{11\zeta(3)}\frac{n_{dX}(m_X)}{T_d^3}.$$

$$n_{dX}(m_X) = \frac{g_X}{2\pi^2}\int_0^\infty dp \frac{p^2}{\exp\left[\sqrt{p^2 + m_X^2}/T_d(m_X)\right] + 1}$$

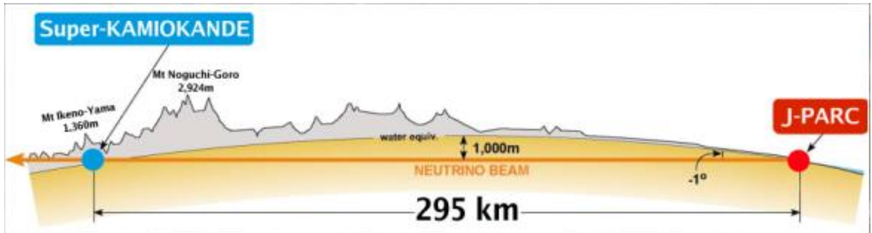


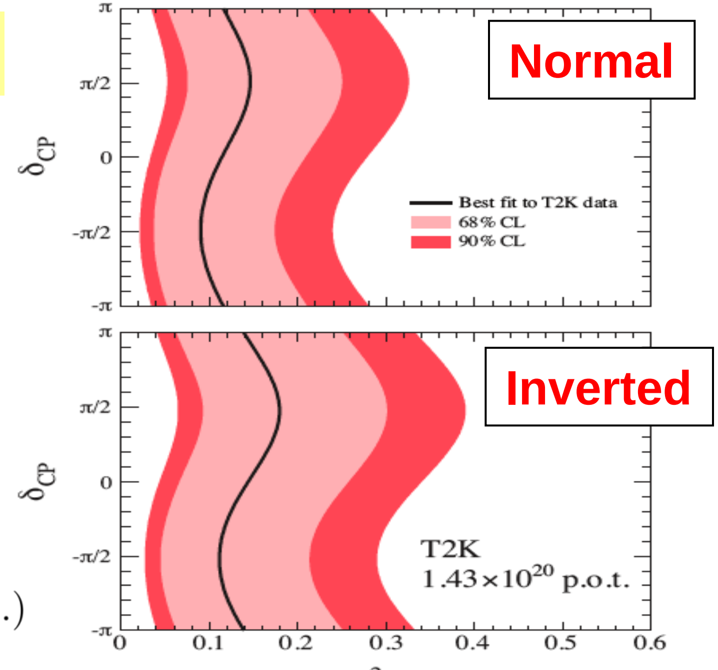
$10^{-17}\mu_B < \mu_\nu < 10^{-12}\mu_B$

longer τ_X



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) $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$

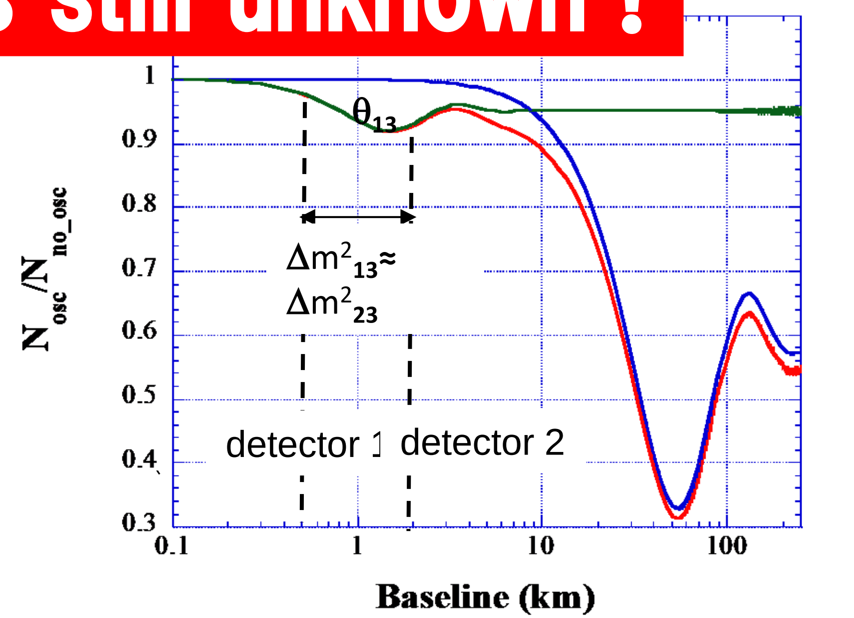
Double Chooz (2012)

Minos (2

T2K (2012) $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$

Mass hierarchy is still unknown !

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



Reactor ν — RENO, Daya Bay & Double Chooz（2012—）

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

Various Neutrino-Sources in Nature/Culture

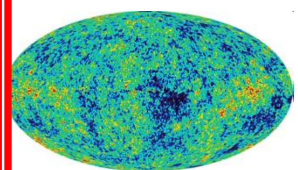
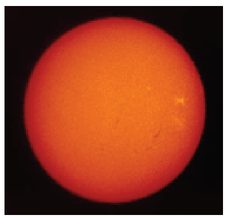
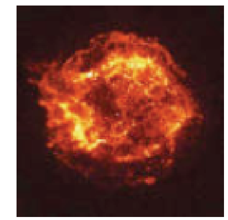
1.9K — 0.4 — 1.0 — 2.6 — 8.5 — Visible energy [MeV]

neutrino electron elastic scattering

$\nu + e^- \rightarrow \nu + e^-$

inverse beta decay

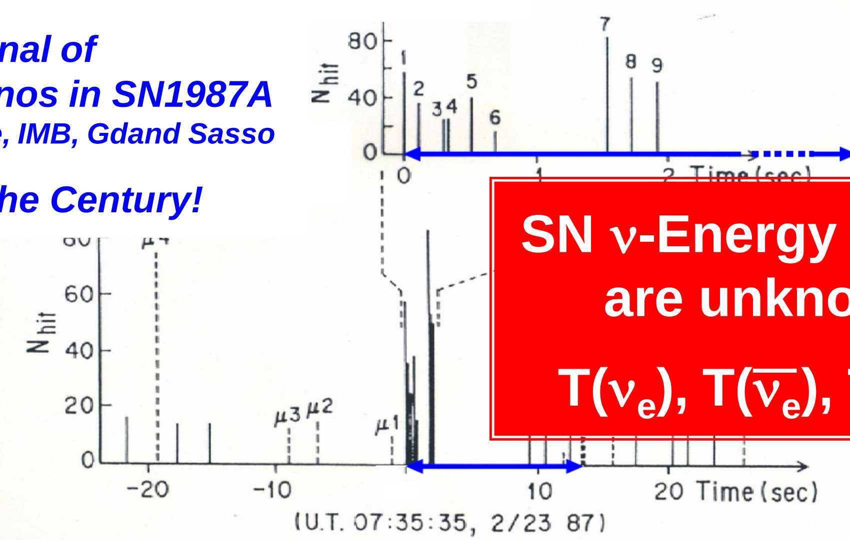
$\bar{\nu}_e + p \rightarrow e^+ + n$

CMB				
Cosmic Background	^{7}Be solar neutrino	atmospheric 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 $\overline{\nu_e}, \overline{\nu_\mu}, \overline{\nu_\tau}$	ν_e	$\overline{\nu_e}$ or $\nu_e\ \nu_\mu\ \overline{\nu_e}\ \overline{\nu_\mu}$	$\overline{\nu_e}$	ν_e, ν_μ, ν_τ $\overline{\nu_e}, \overline{\nu_\mu}, \overline{\nu_\tau}$

Direct signal of SN neutrinos in SN1987A

Kamiokande, IMB, Gdand Sasso

Event of the Century!

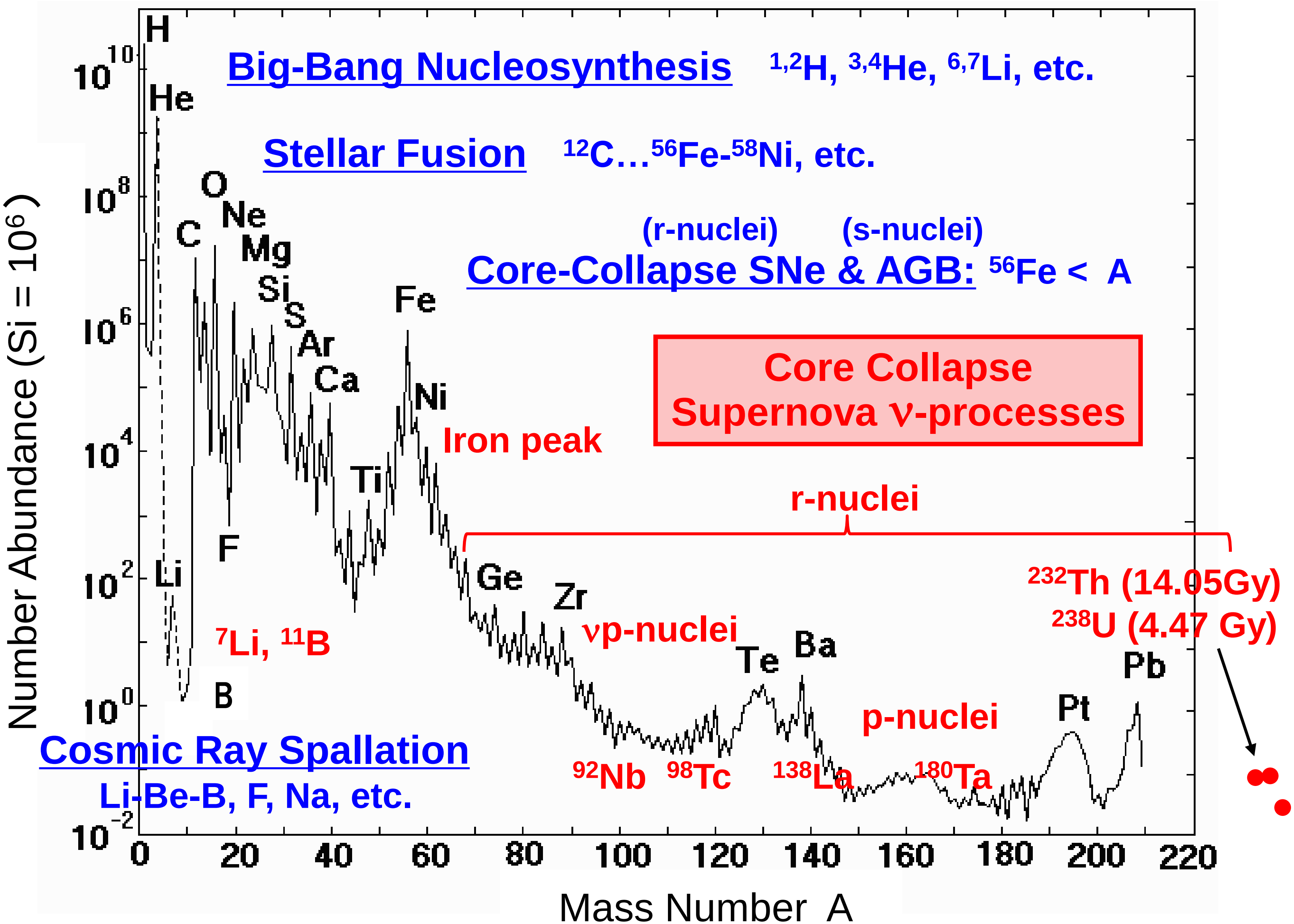


SN ν-Energy Spectra are unknown !

$T(\nu_e)$, $T(\overline{\nu_e})$, $T(\nu_x)$?

Original by courtesy of K. Inoue

Solar System Abundance



R-process Nucleosynthesis

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

Neutron-rich condition for successful r-process: $0.1 < Y_e < 0.5$

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

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

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

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

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

Theoretical Challenge:

1) Astrophysical Sites ?

- ν-wind SNe
- MHD jet SNe
- NS mergers (short GRB)
- long GRBs

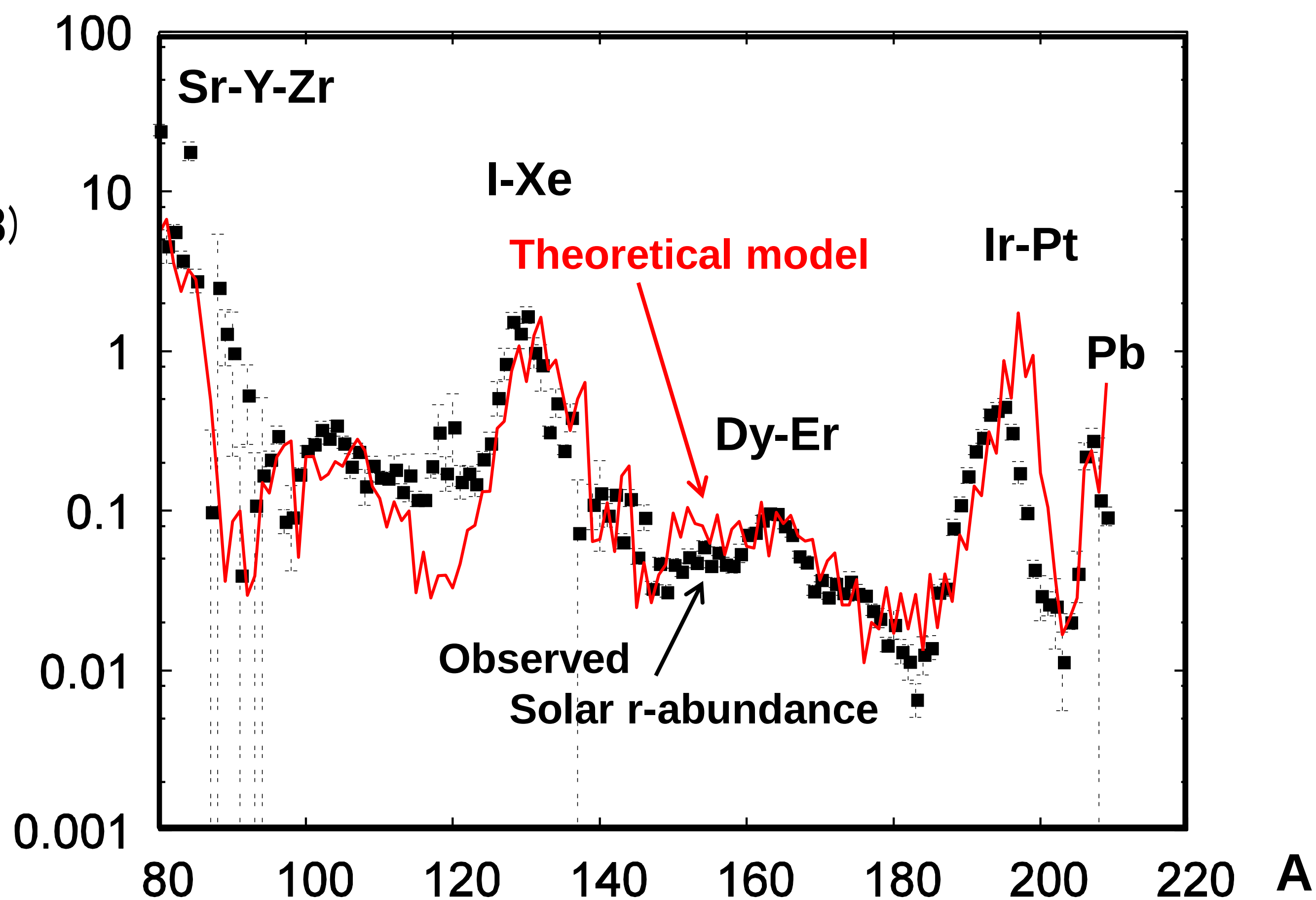
2) Neutrino effects ?

$Y_e > 0.5$?

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

$Y_e < 0.5$!

for nucleon potential and Pauli blocking effects.



^{92}Nb also has SN-ν Origin !

^{138}La, ^{180}Ta, too !

Hayakawa et al., ApJ 778 (2013) L1.

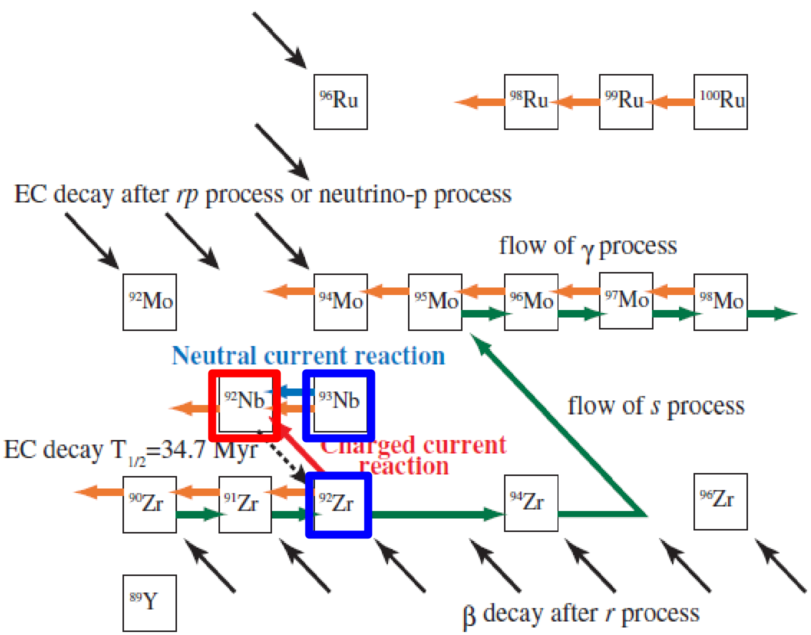
Hayakawa, et al., PR C81 (2010) 052801®,
Hayakawa et al., PR C82 (2010) 058801.

^{92}Nb ($\tau_{1/2}$=3.47x10^{7} y) : Unique Chronometer of SN ν-Process

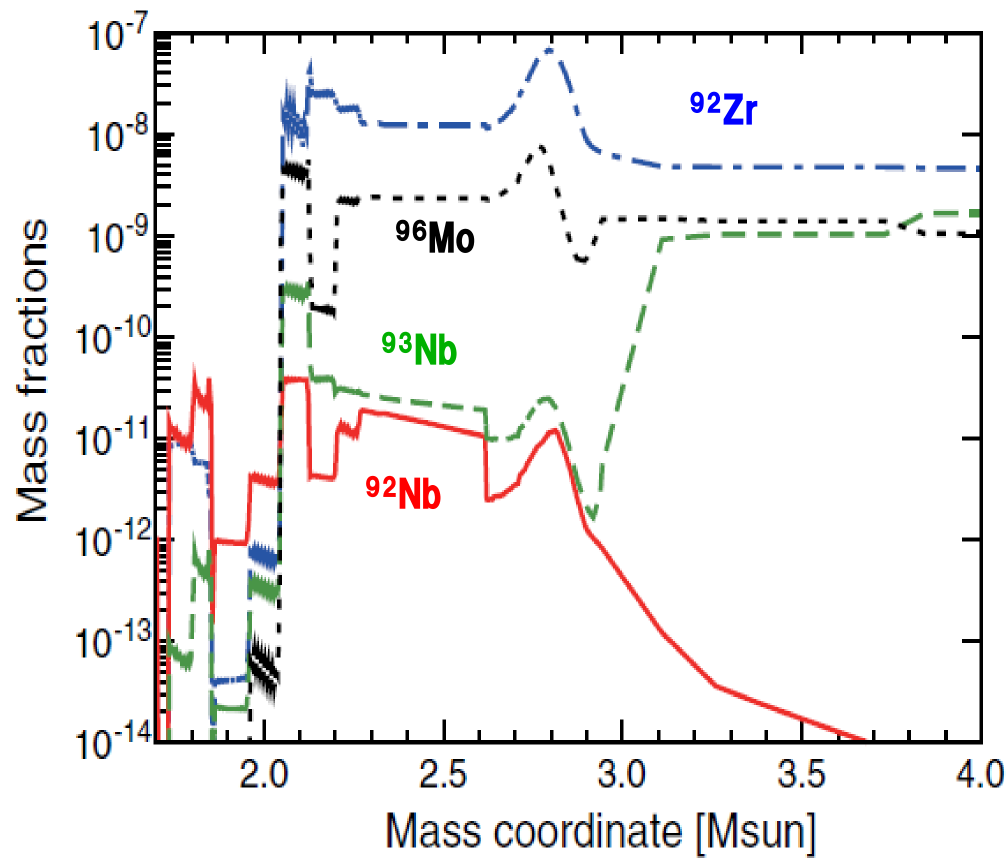
Isotopic anomaly in meteoritic ^{92}Zr/^{93}Nb:

Δ = 1x10^{6}—3x10^{7} y

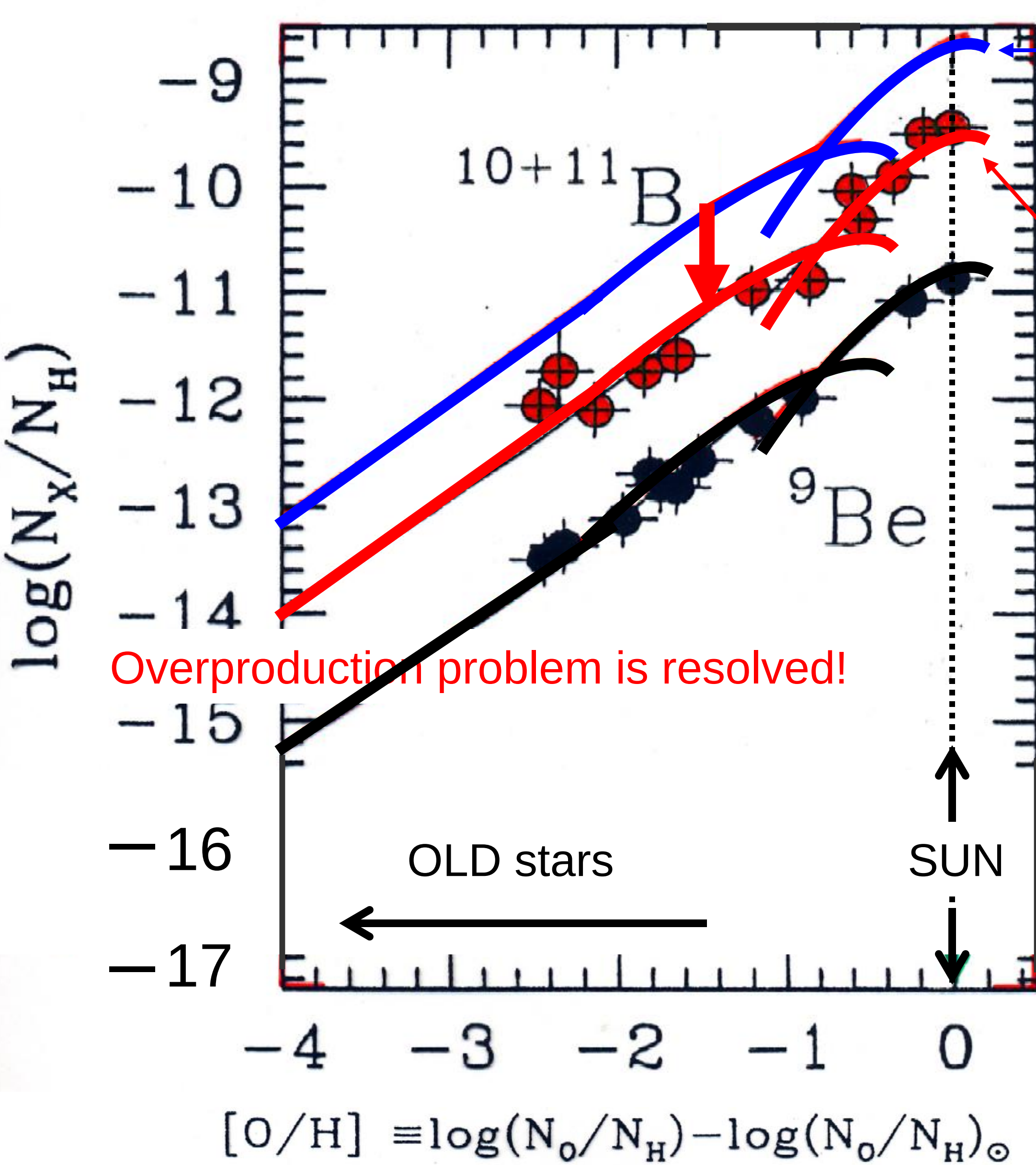
Time duration after the last nearby Supernova to the Solar-System (protosolar cloud) formation



$T_{\nu e}$ = 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.

Consistent with SN1987A

^{9}Be:

– Galactic Cosmic Rays

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

– Galactic Cosmic Rays

– Supernova ν–process

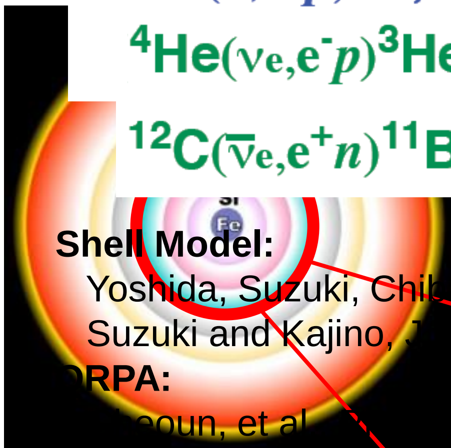
Yoshii, Kajino, Ryan, 1997, ApJ 486, 605.
Ryan, Kajino, Suzuki, 2001, ApJ549, 55.

Supernova ν-Process: ^{7}Li, ^{11}B, ^{92}Nb, ^{138}La, ^{180}Ta

^{4}He(ν,ν'*p*)^{3}H, ^{4}He(ν,ν'*n*)^{3}He, ^{12}C(ν,ν'*p*)^{11}B

^{4}He(νe,e^{-}*p*)^{3}He, ^{4}He($\overline{\nu}$e,e^{+}*n*)^{3}H, ^{12}C(νe,e^{-}*p*)^{11}C,

^{12}C($\overline{\nu}$e,e^{+}*n*)^{11}B



$$= 6.55 \times 10^{6} \left(\frac{\Delta m_{ji}^{2}}{1\ \mathrm{eV}^{2}}\right)\left(\frac{1\ \mathrm{MeV}}{\varepsilon_{\nu}}\right) \cos 2\theta_{ij}$$

Shell Model:

Yoshida, Suzuki, Chiba, Kajino, et al., ApJ 686 (2008), 448:

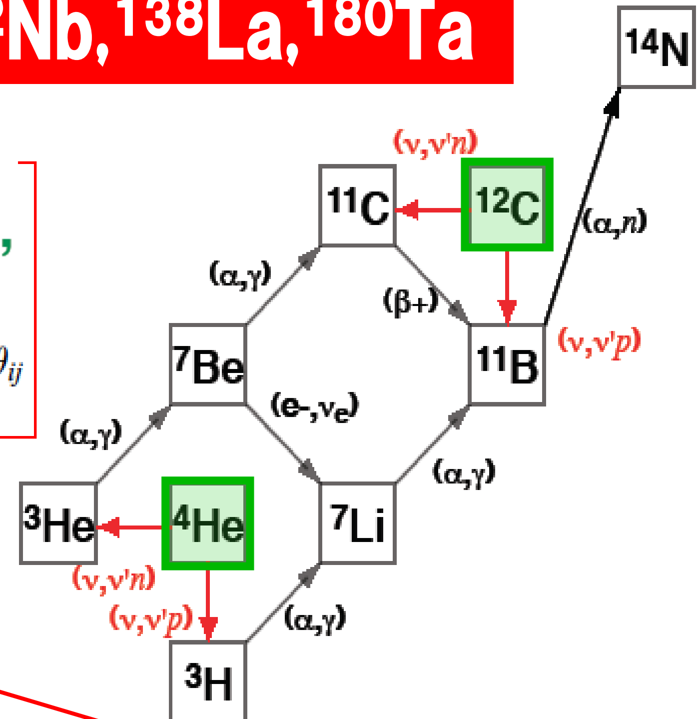
Suzuki and Kajino, J. Phys. G40 (2013), 083101:

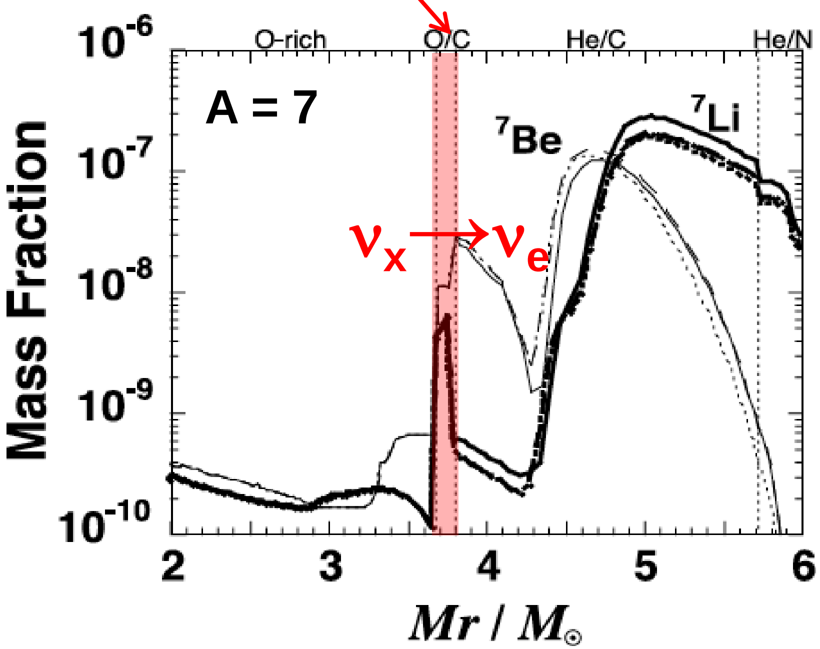
RPA:

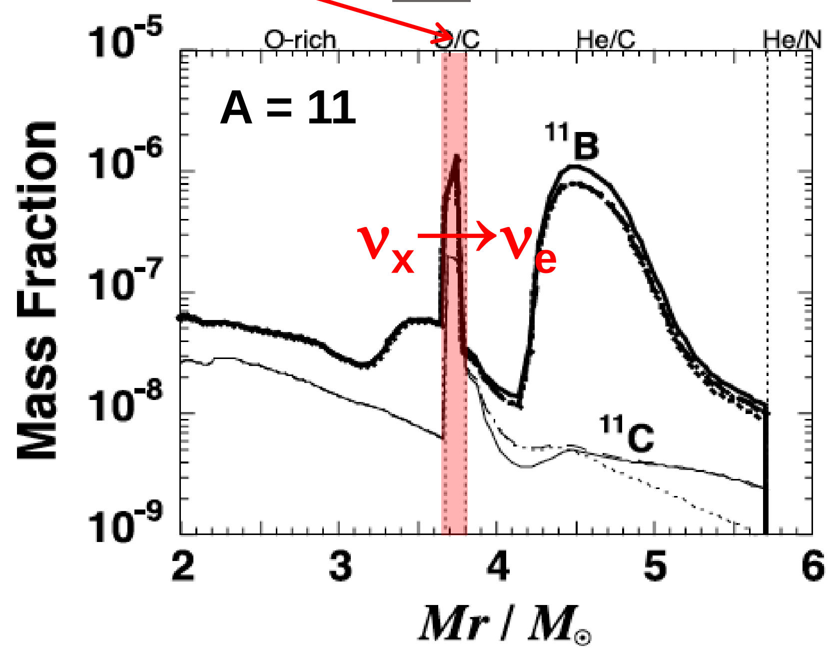
…eoun, et al. …1 (2010), 028501; PRC82 (2010), 035504;

J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801

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







Nucleosynthetic Constraints on ν-Temperatures!

- **R-process (neutron-richness)** ➡ $T\nu_e = 3.2$ MeV, $T\overline{\nu_e} = 4$ MeV

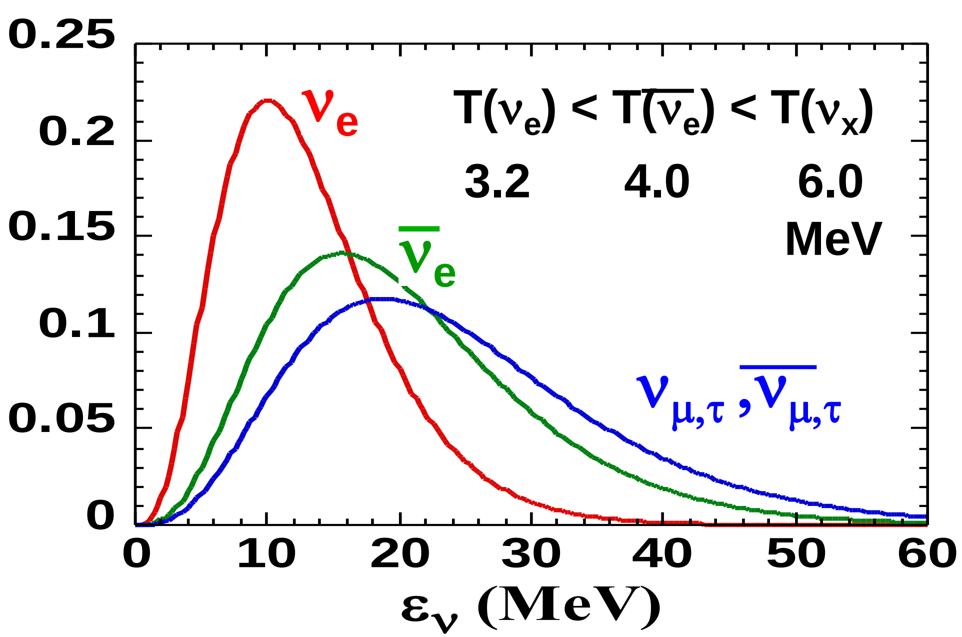
  Otsuki, Tagoshi, Kajino and Wanajo, Astrophys. J. 533 (2000) 424.
  Wanajo, Kajino, Mathews and Otsuki, Astrophys. J. 554 (2001) 578.
  Roberts, Reddy and Shen, Phys. Rev. C86 (2012) 065803.

- **P-process; ^{180}Ta/^{138}La, ^{92}Nb (CC-ν)** ➡ $T\nu_e = T\overline{\nu_e} = 4$ MeV

  Hayakawa, et al., Phys. Rev. C81 (2010) 052801®; Phys. Rev. C82 (2010) 058801.
  Hayakawa et al., Astrophys. J. Lett. 778 (2013) L1.

- **GCE; ^{6,7}Li-^{9}Be-^{10,11}B & Meteoritic ^{11}B/^{10}B (NC-ν)** ➡ $T\nu_{x=\mu,\tau)} = 6$ MeV

  Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005) 231101.
  Suzuki & Kajino, J. Phys. G37 (2010), 055101.



Variation of T's from different Supernova Models is taken into account !

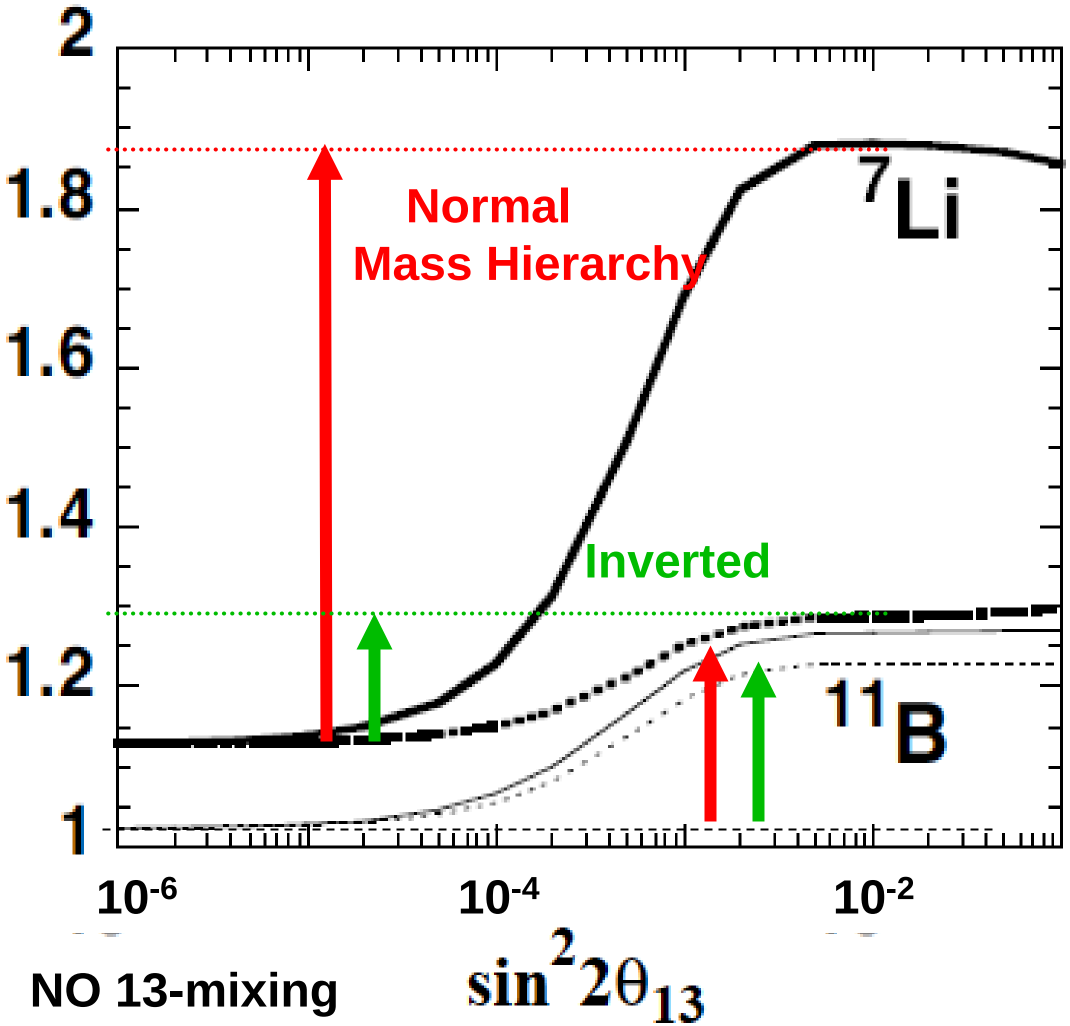
Mathews, Kajino, Aoki, Fujita & Pitts, Phys. Rev. D85 (2012) 105023.

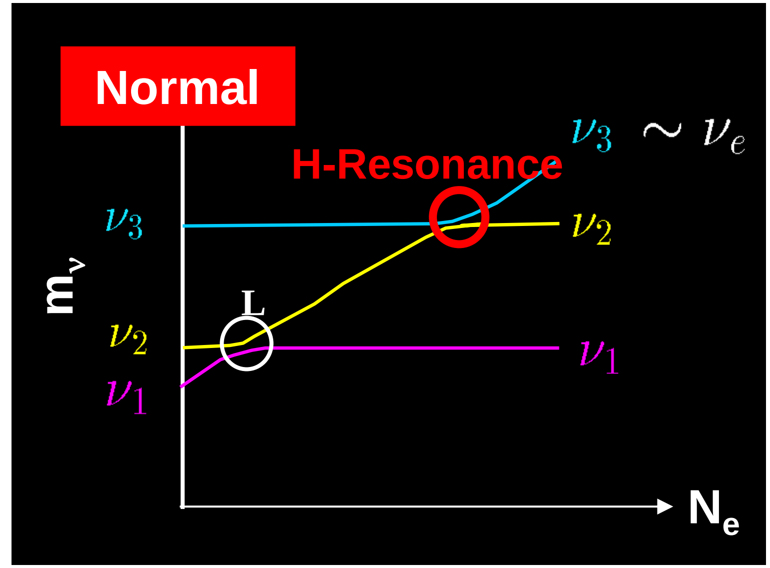
Yoshida, Kajino, Yokomakura, Kimura, Takamura & Hartmann, PRL 96 (2006) 09110; ApJ 649 (2006), 349.

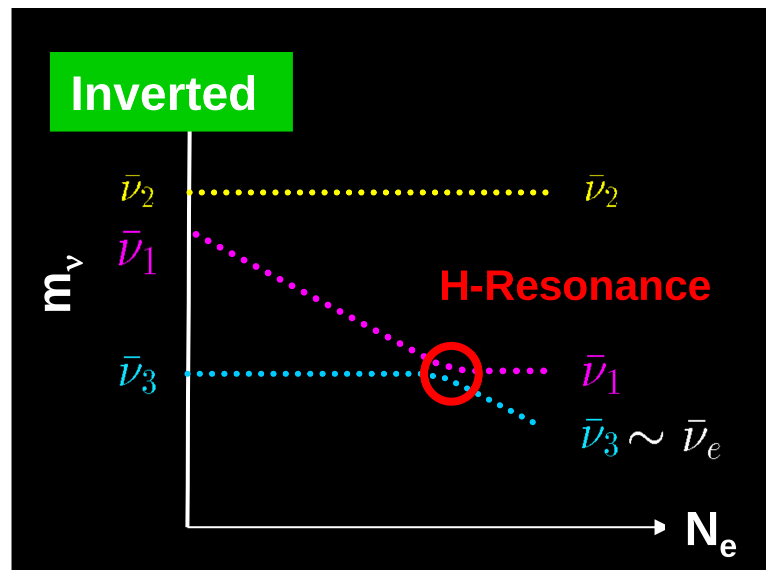
larger effect !

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

smaller effect !







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 masses, ν-temps. ($T_{\nu e}$,$T_{\nu e}$,$T_{\nu\mu\tau,\, \overline{\nu\mu\tau}}$) and nuclear input data.

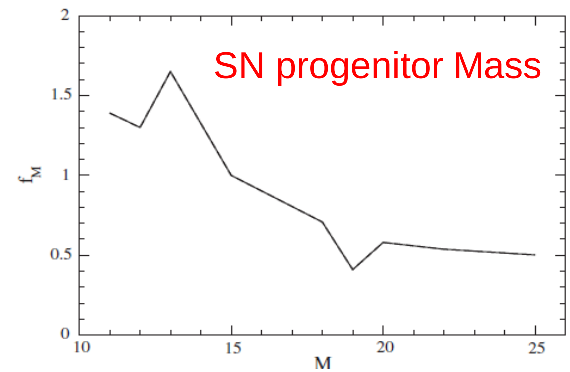
$$P(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_j P(D|M_j)P(M_j)}$$

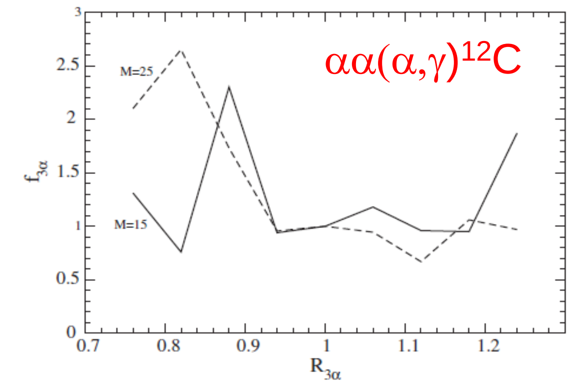
$$P(D|M_i) = \int dEdZda_k P(E,Z,D|M_i,a_k)P(a_k|M_i)$$

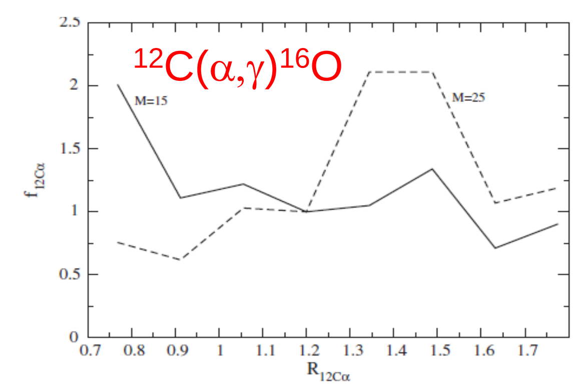
$$= \int dEdZda_k P(D|M_i,a_k,E,Z)P(Z,E|M_i,a_k)P(a|M_i)$$

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]



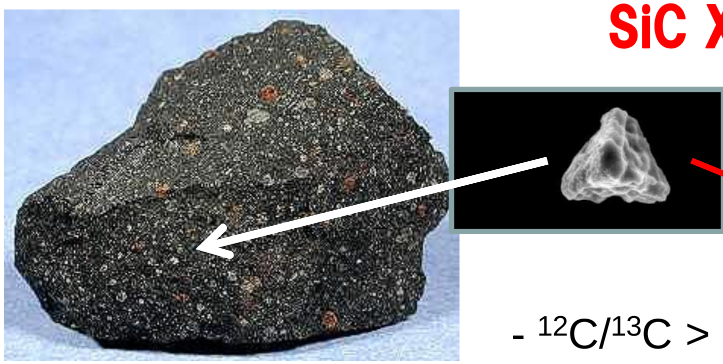


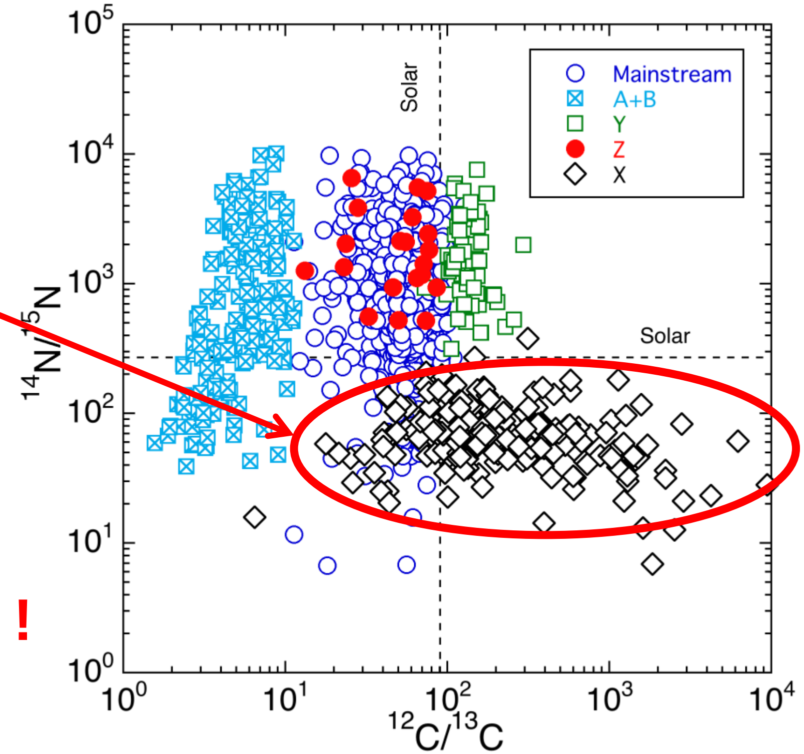


Murchison Meteorite

By courtesy of S. Amari

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)

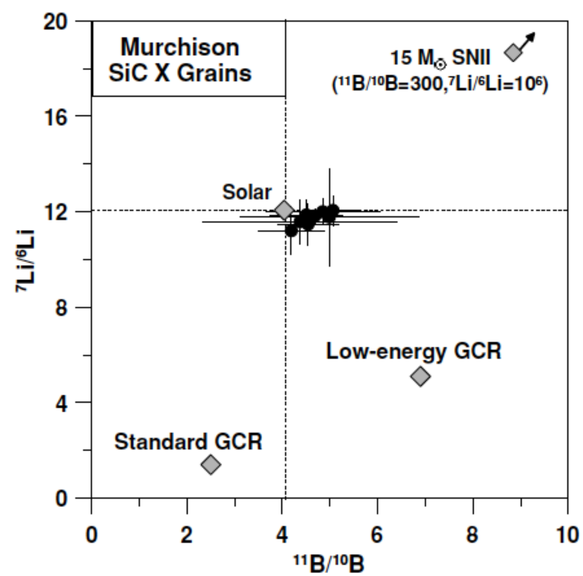
SiC X-grains are made of cc-SN Dust !

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

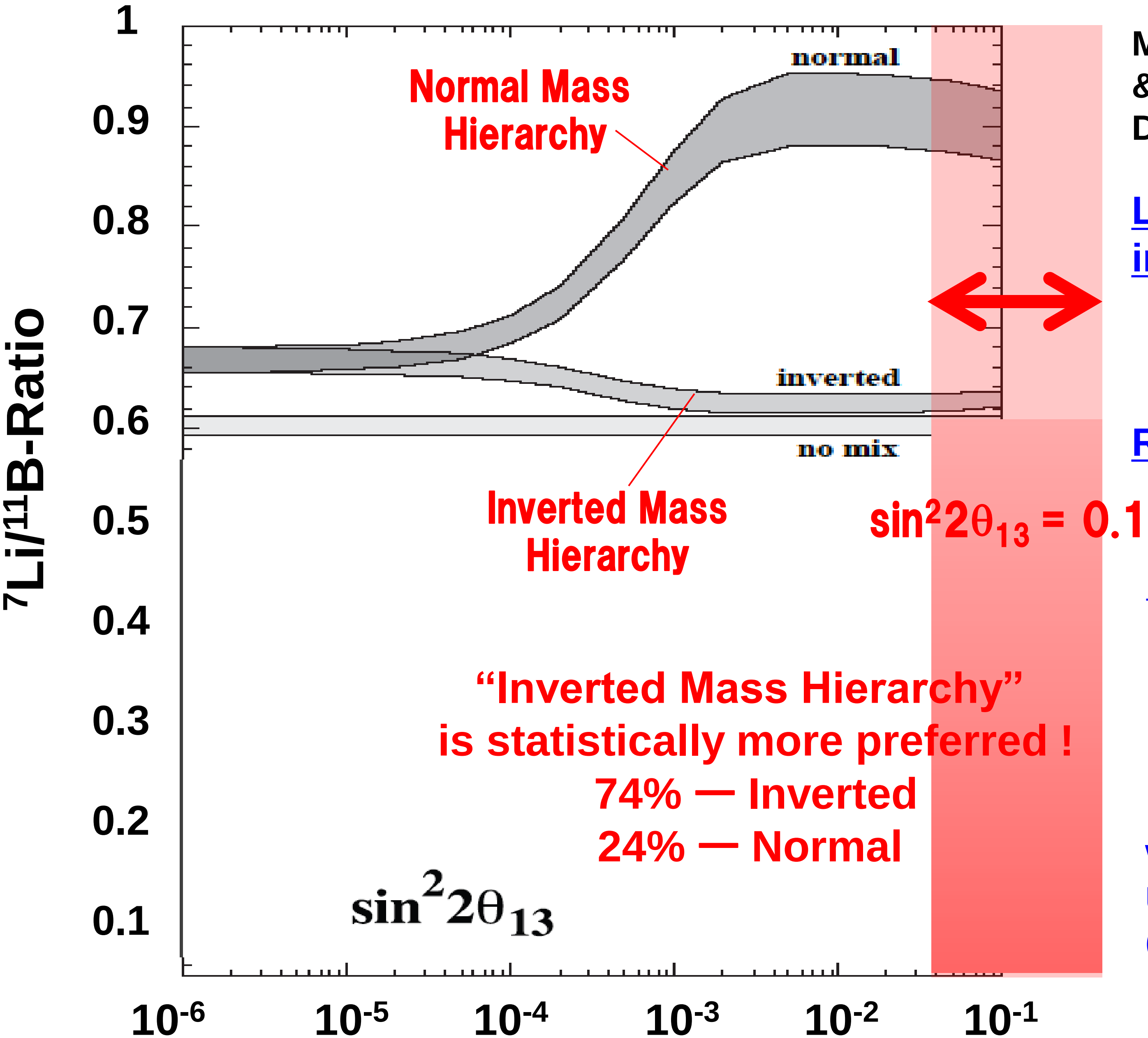
Table 1
C-, Si-, Li-, and B-isotopic Compositions of SiC X Grains from the Murchison Meteorite

Grain	Size (μm)	$^{12}C/^{13}C$	$\delta^{29}Si^a$ (‰)	$\delta^{30}Si^a$ (‰)	$^7Li/^6Li$	$^{11}B/^{10}B$	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. $^a\delta^iSi = [(^iSi/^{28}Si)/(^iSi/^{28}Si)_\odot - 1] \times 1000$.



MSW Effect & ν Mass Hierarchy



"Inverted Mass Hierarchy"
is statistically more preferred !
74% — Inverted
24% — Normal

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

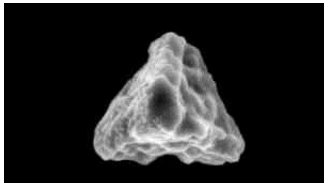
Long BaselineExp. in 2011:

- T2K (Kamioka)
- MINOS

Reactor Exp. in2012:

- Double CHOOZ
- Daya Bay
- RENO (KOREA)

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



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

A New Method to constrain EOS & ν-Osclation

G.J. Mathews, J. Hidaka, T. Kajino & J. Suzuki, ApJ (2014), submitted.

The Astrophysical Journal, 738:154 (16pp), 2011 September 10

THE COSMIC CORE-COLLAPSE SUPERNOVA RATE DOES NOT MATCH THE MASSIVE-STAR FORMATION RATE

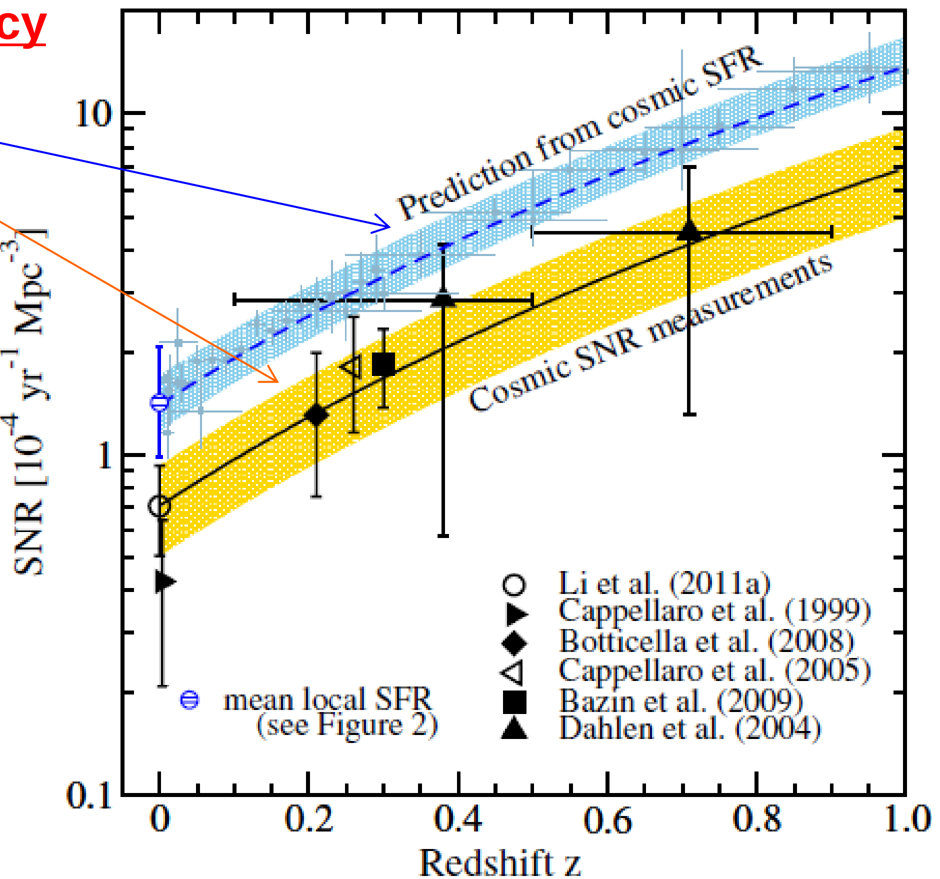
Shunsaku Horiuchi[1,2], John F. Beacom[1,2,3], Christopher S. Kochanek[2,3], Jose L. Prieto[4,5], K. Z. Stanek[2,3], and Todd A. Thompson[2,3,6]

Supernova Rate Problem/Discrepancy

SFR of Massive Stars at birth

SNR: Supernova Explosions at death !

50% Massive Stars, missing !



Expected Reasons:

Half was evolved into too dark SNe to detect!

1. Failed SNe (<25M⊙ BH formation)
2. Faint ONeMg-SNe (8-10 M⊙)

or the mass function changed!

Electron-capture SN (Faint SnNe) — **Normal SNe (Neutron Star fromation)** — **Failed Sne (Black Hole formation)**

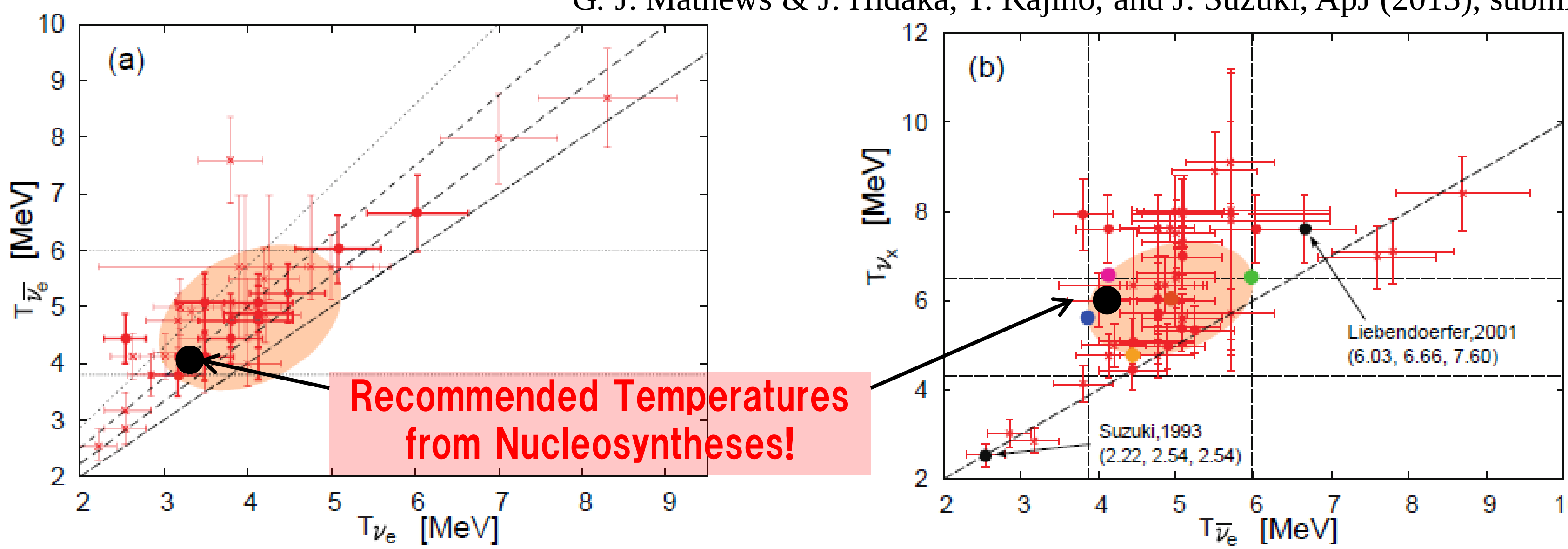
detail	ONeMg SN	CC-SN	fSN(SH EOS)	fSN(LS EOS)	GRB
mass($M_\odot$)	(8 ∼ 10)	8 ∼ 25(10∼25)	25 ∼ 125 (99.96%)	25 ∼ 125 (99.96%)	25 ∼ 125 (0.04%)
Remnant	Neutron Star	Neutron Star	Black Hole	Black Hole	Black Hole
Phenomenon	Supernova	Supernova	Failed Supernova	Failed Supernova	Gamma-Ray Burst
T_{ν_e} (MeV)	3.0	3.2	5.5	7.9	3.2
$T_{\bar{\nu}_e}$ (MeV)	3.6	4.0	5.6	8.0	5.3
T_{ν_x} (MeV)	3.6	6.0	6.5	11.3	4.4
$E_{\nu_e}^{total}$(erg)	3.3×10^{52}	5.0×10^{52}	5.5×10^{52}	8.4×10^{52}	1.7×10^{53}
$E_{\bar{\nu}_e}^{total}$(erg)	2.7×10^{52}	5.0×10^{52}	4.7×10^{52}	7.5×10^{52}	3.2×10^{53}
$E_{\nu_x}^{total}$(erg)	1.1×10^{53}	5.0×10^{52}	2.3×10^{52}	2.7×10^{52}	1.9×10^{52}
△ t	few s	few s	∼ 0.5s	∼ 0.5s	∼ 10s

■ ONeMg SN — Hudepohl, et al., PRL 104 (2010)

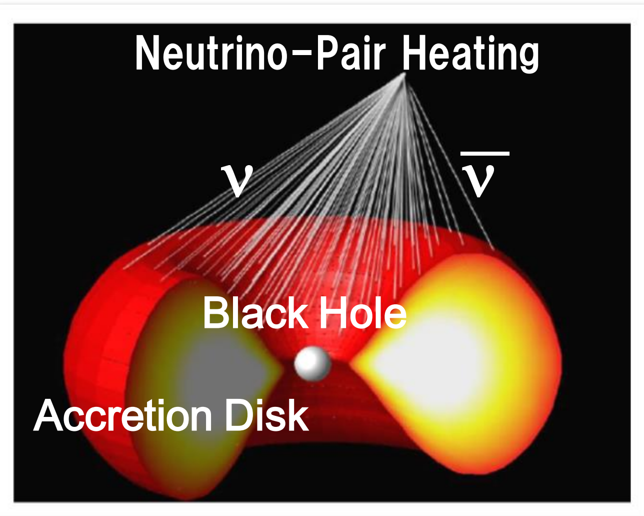
■ fSN (failed SN) — Sumiyoshi, et al., ApJ 688 (2008), 1176; Shen-EOS: Shen et al. (1998), LS-EOS: Lattimer & Swesty (1991)

■ CC-SN — Yoshida, et al., ApJ 686 (2008), 448; Suzuki & Kajino, J. Phys. G40 (2013) 83101 +

G. J. Mathews & J. Hidaka, T. Kajino, and J. Suzuki, ApJ (2013), submitted.



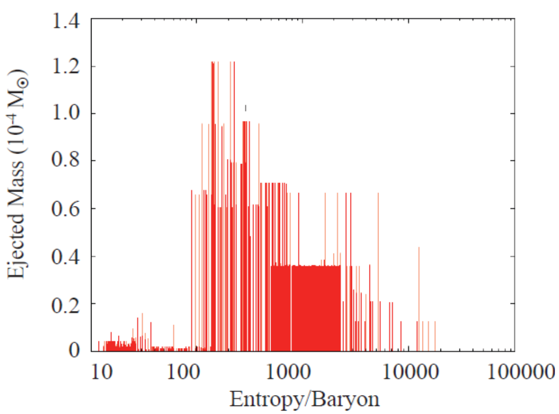
Recommended Temperatures from Nucleosyntheses!

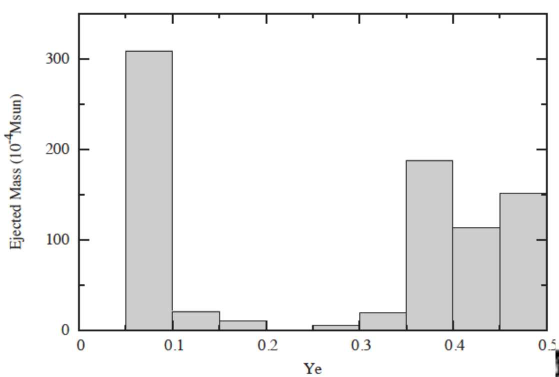


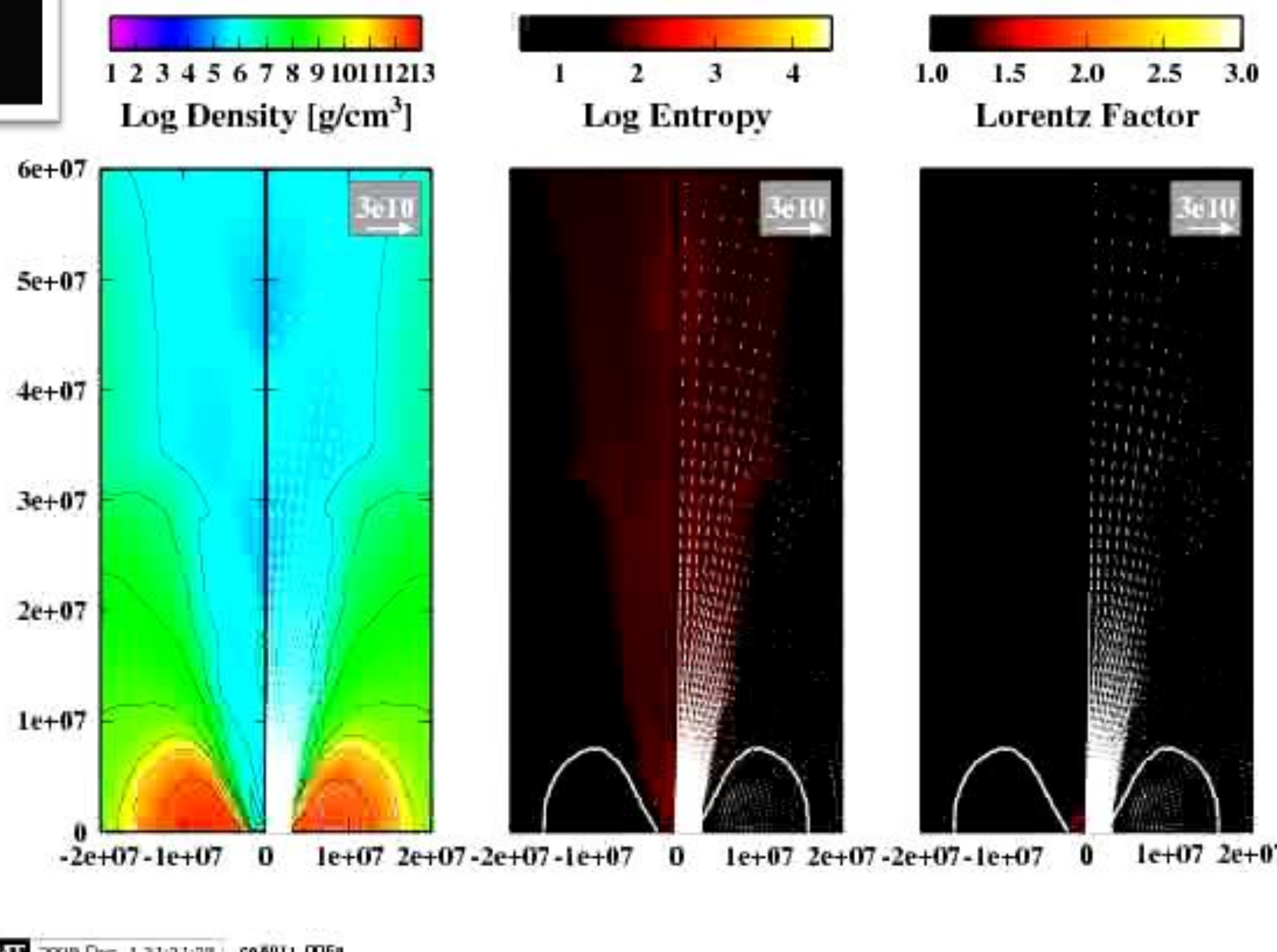
Collapsar Model for Long Gamma-Ray Bursts

Harikae et al., ApJ 704 (2009), 354; 713 (2010) 304.

Nakamura, Kajino, Mathews, Sato & Harikae, IJMP 22 (2013), 1330022.





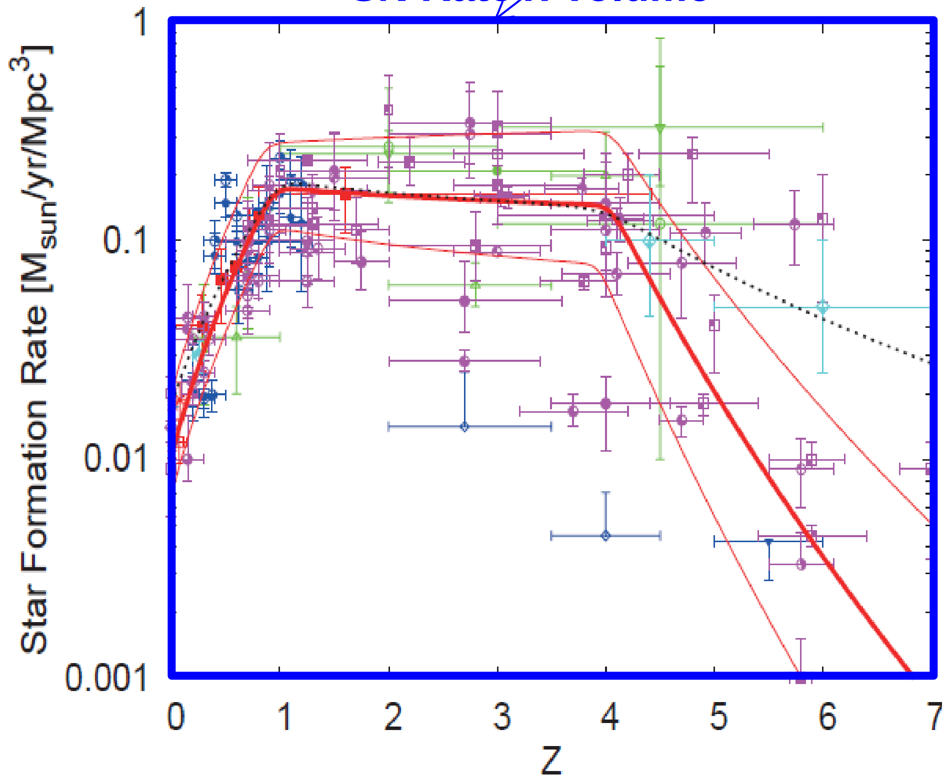


Spectrum of Relic Supernova Neutrinos (RSNs)

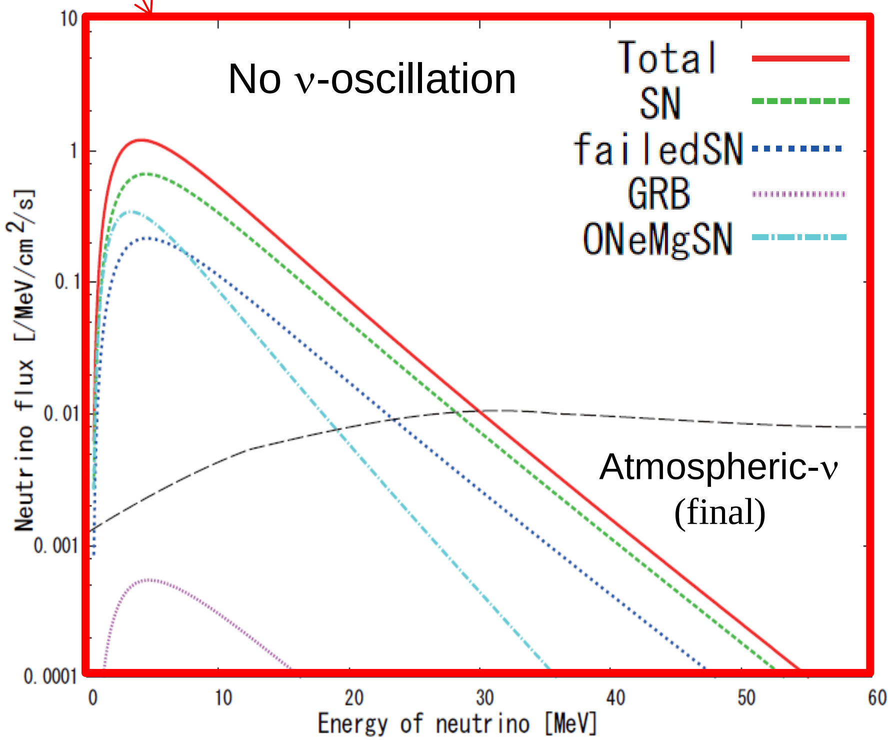
for Hyper-Kamiokande (Mega-ton): Water Cherenkov $\bar{\nu}_e + p \rightarrow e^+ + n$

$$\frac{dN_\nu}{dE_\nu} = \frac{c}{H_0} \int_0^{z_{max}} R_{SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} \times \frac{dz}{\sqrt{(\Omega_m)(1+z)^3 + \Omega_\Lambda}}$$

SN Rate x Volume



ν-spectrum at Various Sne & GRB



Relic Supernova Neutrinos (RSNs)

G. J. Mathews, J. Hidaka, T. Kajino, and J. Suzuki, ApJ (2014), submitted.

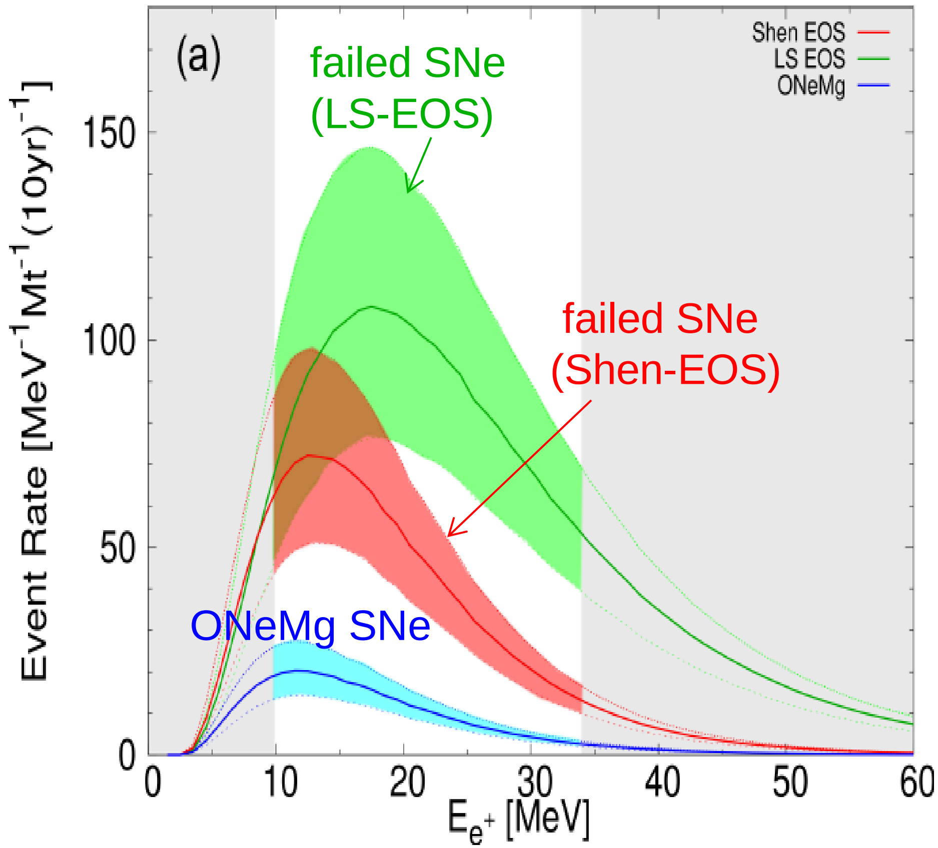
Hyper-Kamiokande (Mega-ton, 10y), Gd-loaded Water Cherenkov Detector

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

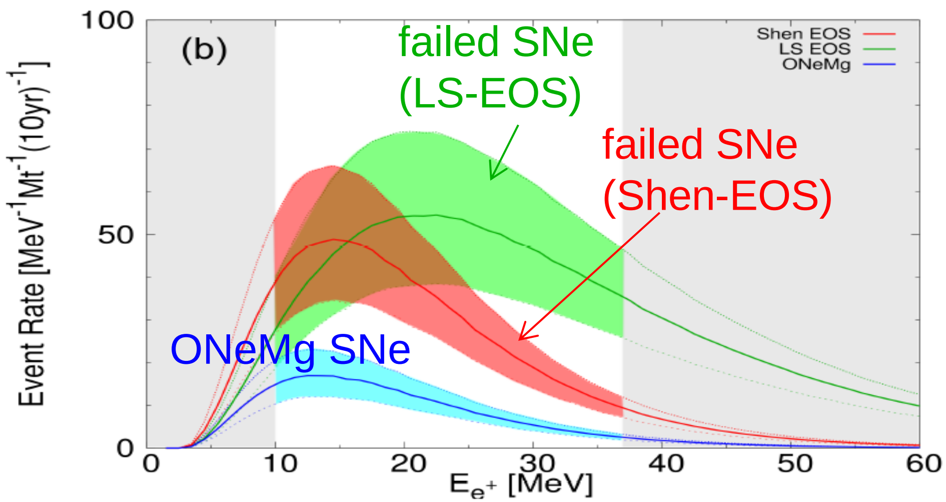
Assuming Horiuchi, Beacom et al. 2011
100% missing Sne:

Standard + MISSING SNe (ONeMg+CC+fSN) + GRB

Non-Adiabatic Matter (MSW) Oscillation



Adiabatic Matter (MSW) Oscillation



SUMMARY

Total ν-mass:

Total ν-mass is constrained to be $\Sigma\, m_\nu < 0.2$ eV for the primordial magnetic field B < 3nG.

ν-Mass hierarchy:

Supernova ν-process could determine the mass hierarchy Δm_{13}^2 and $\sin^2\theta_{13} \sim 0.1$ simultaneously. Inverted hierarchy is more preferred statistically.

Relic Supernova-ν:

Future observation of Relic Supernova ν's in megaton Hyper-Kamiokande (i.e. Gd-loaded Water Cherenkov detector in 10y run) could identify the missing SN component and discriminate EoS of proto-neutron star and neutrino oscillation pattern.