Cosmological & Supernova ν’s and Nucleosynthesis

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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 $\nu$-mass
- Is BARYON sector ($\Omega_B = 0.05$) well understood?
  - BBN with DM candidates (Axions, SUSY ...)
  - SUSY-DM \( \Rightarrow \) beyond the Standard Model

Key Physics with $m_\nu \neq 0$ beyond the Standard Model:
- Unification of elementary forces?
- CP violation and Lepto- & Baryo-genesis?
- Explosion Mechanism of Supernovae?

Purpose

is to constrain the total $\nu$-Mass, Mass Hierarchy, and Nuclear EOS from $\nu$-interactions in CMB, Supernova Nucleosynthetic and Relic SN $\nu$’s.
Total $\nu$-Mass constrained from Nuclear Physics and Cosmology

- $0\nu\beta\beta$ in COUORE, NEMO3, EXO, KamLAND Zen
  $|\sum U_{e\beta}^2 m_\beta| < 0.3$ eV: COUORE, NEMO3, EXO, KamLAND Zen (2012)

- CMB Anisotropies + LSS ($\rightarrow 0.05$ eV in the future)
  $\sum m_\nu < 0.36$ eV (95% C.L.): WMAP-7yr + HST + CMASS (Putter et al. arXiv:1201.1909)

★ $\nu$ free-streaming effects
★ Integrated Sachs-Wolfe Effect!

★ CMB anisotropies is generated even by:
  compensation mode of $\nu$-anisotropic stress ($\pi_\nu$)
  to primordial extra anisotropic stress ($\pi_{ext}$)
  arising from cosmic magnetic field, dark radiation,
  Ekpyrotic universe, etc.

Standard cosmology needs tuning primordial initial condition of the inflation-driven perturbation!

Roles of $\nu$-Anisotropic Stress with $m_\nu \gg 0$!
Curvature perturbation is generated by extra anisotropic stress $\pi_{\text{ext}}$ and regulated later by $\nu$-compensation mode $\pi_{\nu}$ after decoupling.

It is desirable to know the cosmological origin of extra anisotropic stress $\pi_{\text{ext}}$ and its generation epoch in the early universe.

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

$\nu$-compensation mode $(\pi_{\nu})$ plays a critical role in CMB with $\nu$ of finite mass!

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

$$|\pi_{\text{ext}}| \sim 8.4 \times 10^{-6}$$
Extra Anisotropic Stress of Primordial Magnetic Field: $B=3nG$, $n_B=-2.9$


Compensated tensor

Compensated vector

EE mode

$\ell_m^{(1)} \sim 27 \times \frac{m_\nu}{\text{eV}}^2$

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

$m_\nu = 1\text{eV}$
CMB Fit
Likelihoodness and Probability

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

$\Sigma m_\nu < 0.2 \text{ eV}$


Cosmological: \( \nu \rightarrow \nu' + \gamma_{NT} \)

Parent \( \nu \) could be massive!

 steriles (\( m_\nu = 0 \), \( \mu_\nu = 0 \)) sterile/active

\( \gamma_{NT} \) affects BBN: \( D(\gamma,p)n \), \( ^6Li(\gamma,d)\alpha \), \( ^7Li(\gamma,t)\alpha \)

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 \( X \)

\[
|\mu_{\text{eff}}|^2 = |\mu_{ij}|^2 + |\epsilon_{ij}|^2.
\]

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

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

Decoupling Temp. is \( \text{Max}[1\text{MeV}, m_X/20] \)

\[
\frac{n_X}{n_\gamma} = \frac{4}{11} \frac{n_dX(m_X)}{n_\gamma(T_d)} = \frac{2\pi^2}{11\xi(3)} \frac{n_dX(m_X)}{T_d^3}.
\]

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

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

longer \( \tau_X \)

BBN constraint

CBR constraint
Various Neutrino-Sources in Nature/Culture

1.9K  0.4  1.0  2.6  8.5  Visible energy [MeV]

CMB
Cosmic Background

Neutrino Cosmology
verification of particle model

Neutrino electron elastic scattering
\( \nu + e^- \rightarrow \nu + e^- \)

\( \tilde{\nu}_e + p \rightarrow e^+ + n \)
supernova relic neutrino etc.

Various Neutrino Sources in Nature/Culture

- \( ^7 \text{Be} \) solar neutrino
- \( \text{geo-neutrino} \)
- \( \text{atmospheric neutrino} \)
- \( \text{reactor neutrino} \)
- \( \text{supernova relic neutrino} \)

Direct signal of SN neutrinos in SN1987A
Kamiokande, IMB, Gdand Sasso

Event of the Century!

\( \nu_e, \nu_\mu, \nu_\tau \)
\( \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \)

\( T(\nu_e), T(\bar{\nu}_e), T(\nu_x) \) ?

By courtesy of K. Inoue
Solar System Abundance

Big-Bang Nucleosynthesis \( ^{1,2}H, ^{3,4}He, ^{6,7}Li, \text{etc.} \)

Stellar Fusion \( ^{12}C \ldots ^{56}Fe-^{58}Ni, \text{etc.} \)

Core-Collapse SNe & AGB: \( ^{56}Fe < A \)

Supernova \( v \)-processes

Iron peak

r-nuclei

\( ^{7}Li, ^{11}B \)

Cosmic Ray Spallation \( ^{6}Li, ^{9}Be-B, ^{12}F, ^{14}Na, \text{etc.} \)

p-nuclei

\( ^{92}Nb, ^{98}Tc, ^{138}La, ^{180}Ta \)

\( ^{232}Th (14.05\text{Gy}), ^{238}U (4.47\text{ Gy}) \)
Neutron-rich condition for successful r-process: $0.1 < Y_e < 0.5$

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

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

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

$$\epsilon_{\nu} = 3.15 \ T_{\nu}$$

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

Theoretical Challenge:

1) Astrophysical Sites?
   - $\nu$-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.

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**R-process Nucleosynthesis**


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**Observed Solar r-abundance**

I-Xe

Sr-Y-Zr

Dy-Er

Ir-Pt

Pb

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**Theoretical model**
$^{92}$Nb also has SN-$\nu$ Origin!


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

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

$^{92}$Nb ($\tau_{1/2}=3.47 \times 10^7$ y): Unique Chronometer of SN $\nu$-Process

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

$\Delta = 1 \times 10^6$—$3 \times 10^7$ y

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

$T_{\nu e} = 3.2$ MeV, $T_{\bar{\nu} e} = 4$ MeV
Overproduction problem is resolved!

**Livermore Model**

\[ T_{\mu,\tau} = 8 \text{ MeV} \]


\[ \sigma \propto E_{\nu}^{2} \]

**\[ T_{\mu,\tau} = 6 \text{ MeV} \]**

Consistent with SN1987A


\[ \frac{\log(N/H)}{[O/H]} = \log\left(\frac{N_0}{N_H}\right) - \log\left(\frac{N_0}{N_H}\right)_{\odot} \]

\[ [O/H] = \log\left(\frac{N_0}{N_H}\right) - \log\left(\frac{N_0}{N_H}\right)_{\odot} \]

**\[ {^{9}}\text{Be} \]:**

- Galactic Cosmic Rays

**\[ {^{10+11}}\text{B} + {^{11}}\text{B} \]:**

- Galactic Cosmic Rays
- Supernova \( \nu \)-process

Nucleosynthetic Constraints on $\nu$-Temperatures!

- **R-process (neutron-richness)** \( \Rightarrow T_{\nu_e} = 3.2 \text{ MeV}, \ T_{\bar{\nu}_e} = 4 \text{ MeV} \)
  

- **P-process; \(^{180}\text{Ta}/^{138}\text{La}, \ 92\text{Nb} (\text{CC-}\nu) \)** \( \Rightarrow T_{\nu_e} = T_{\bar{\nu}_e} = 4 \text{ MeV} \)
  

- **GCE; \(^{6,7}\text{Li}/^{9}\text{Be} -^{10,11}\text{B} \ & \text{Meteoritic} \ 11\text{B}/10\text{B} (\text{NC-}\nu) \)** \( \Rightarrow T_{\nu_{\chi=\mu,\tau}} = 6 \text{ MeV} \)
  

Variation of T’s for different Supernova Models is taken into account!

Long Baseline $\nu$ — T2K & MINOS (2011)

\[
\sin^2 2\theta_{13} = 0.1
\]

Daya Bay 2012 \hspace{1cm} \sin^2 2\theta_{13} = 0.092 \pm 0.016\text{(stat)} \pm 0.005\text{(syst)}

Rino (2012) \hspace{1cm} \sin^2 2\theta_{13} = 0.113 \pm 0.013\text{(stat.)} \pm 0.019\text{(syst.)}

Double Chooz (2012) \hspace{1cm} 3\text{ reactor events}

Minos (2011) \hspace{1cm} 0.03(0.4) < \sin^2 2\theta_{13} < 0.28(0.34)

T2K (2012) \hspace{1cm} \sin^2 2\theta_{23} = 1

Mass hierarchy is still unknown!

Reactor $\nu$ — RENO, Daya Bay & Double Chooz (2012)

\[
P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_\nu} \right)
\]
Supernova $\nu$-Process; $^7\text{Li}$, $^{11}\text{B}$, $^{92}\text{Nb}$, $^{138}\text{La}$, $^{180}\text{Ta}$

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

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

$^{12}\text{C}(\nu_e,e^+n)^{11}\text{B}$

Shell Model:
QRPA:
Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504;

MSW high-density resonance is located at the bottom of He/C shell.
NO 13-mixing

\[ \sin^2 2\theta_{13} \]

\[ T_{ve} < T_{\bar{v}e} < T_{\nu\mu, \bar{\nu}\mu} \]

Normal Mass Hierarchy

Inverted

\[ \nu_3 \sim \nu_e \]

H-Resonance

\[ \nu_3 \sim \bar{\nu}_e \]

\[ \nu_1 \sim \nu_2 \]

\[ m_{\nu} \sim \nu_e \]

\[ L \]

\[ \bar{\nu}_1 \sim \bar{\nu}_2 \sim \bar{\nu}_3 \]

\[ \bar{\nu}_3 \sim \bar{\nu}_e \]

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

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

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

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

<table>
<thead>
<tr>
<th>Parameter $a_k$</th>
<th>prior</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>$e^{-(x-x_0)/2\sigma_x^2}$</td>
<td>$x_0 = 0.92$, $\sigma_x = 0.017$ [7]</td>
</tr>
<tr>
<td>$R_{3\alpha}$</td>
<td>$e^{-(x-x_0)/2\sigma_x^2}$</td>
<td>$x_0 = 1.0$, $\sigma_x = 0.12$ [35]</td>
</tr>
<tr>
<td>$R_{12C\alpha}$</td>
<td>$e^{-(x-x_0)/2\sigma_x^2}$</td>
<td>$x_0 = 1.2$, $\sigma_x = 0.25$ [36]</td>
</tr>
<tr>
<td>$M_{prog}(M_\odot)$</td>
<td>$m^{-2.65}$</td>
<td>$m_{min} = 10$, $m_{max} = 25$ [37]</td>
</tr>
<tr>
<td>$T_{\nu}(\text{MeV})$</td>
<td>Top hat</td>
<td>$T_{\nu} = 3.2 - 6.5$ (see text) [15]</td>
</tr>
</tbody>
</table>
MSW Effect & $\nu$ Mass Hierarchy

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

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

Normal Mass Hierarchy

Inverted Mass Hierarchy

"Inverted Mass Hierarchy" is statistically more preferred!

74% — Inverted
24% — Normal


Long Baseline Exp. in 2011:
- T2K (Kamioka)
- MINOS

Reactor Exp. in 2012:
- Double CHOOZ
- Daya Bay
- RENO (KOREA)

"Inverted Mass Hierarchy" is statistically more preferred!

74% — Inverted
24% — Normal
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!
<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>detail</th>
<th>ONeMg SN</th>
<th>CC-SN</th>
<th>fSN (SH EOS)</th>
<th>fSN (LS EOS)</th>
<th>GRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass($M_\odot$) Remnant</td>
<td>mass</td>
<td>(8 ~ 10)</td>
<td>8 ~ 25(10~25)</td>
<td>25 ~ 125 (99.96%)</td>
<td>25 ~ 125 (99.96%)</td>
<td>25 ~ 125 (0.04%)</td>
</tr>
<tr>
<td>Neutron Star Supernova</td>
<td></td>
<td></td>
<td>Neutron Star Supernova</td>
<td>Black Hole</td>
<td>Black Hole</td>
<td>Black Hole</td>
</tr>
<tr>
<td>$T_{\nu_e}$(MeV)</td>
<td>$T_{\nu_e}$</td>
<td>3.0</td>
<td>3.2</td>
<td>5.5</td>
<td>7.9</td>
<td>3.2</td>
</tr>
<tr>
<td>$T_{\bar{\nu}_e}$(MeV)</td>
<td>$T_{\bar{\nu}_e}$</td>
<td>3.6</td>
<td>4.0</td>
<td>5.6</td>
<td>8.0</td>
<td>5.3</td>
</tr>
<tr>
<td>$T_{\nu_x}$(MeV)</td>
<td>$T_{\nu_x}$</td>
<td>3.6</td>
<td>6.0</td>
<td>6.5</td>
<td>11.3</td>
<td>4.4</td>
</tr>
<tr>
<td>$E_{total}$(erg)</td>
<td>$E_{total}$</td>
<td>3.3×10^{52}</td>
<td>5.0×10^{52}</td>
<td>5.5×10^{52}</td>
<td>8.4×10^{52}</td>
<td>1.7×10^{53}</td>
</tr>
<tr>
<td>$E_{\nu_e}$(erg)</td>
<td>$E_{\nu_e}$</td>
<td>2.7×10^{52}</td>
<td>5.0×10^{52}</td>
<td>4.7×10^{52}</td>
<td>7.5×10^{52}</td>
<td>3.2×10^{53}</td>
</tr>
<tr>
<td>$E_{\bar{\nu}_x}$(erg)</td>
<td>$E_{\bar{\nu}_x}$</td>
<td>1.1×10^{53}</td>
<td>5.0×10^{52}</td>
<td>2.3×10^{52}</td>
<td>2.7×10^{52}</td>
<td>1.9×10^{52}</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td></td>
<td>few s</td>
<td>few s</td>
<td>$\sim 0.5$s</td>
<td>$\sim 0.5$s</td>
<td>$\sim 10$s</td>
</tr>
</tbody>
</table>

**Recommended Temperatures from Nucleosyntheses!**

- **ONeMg SN** Hudepohl, et al., PRL 104 (2010)
- **Shen-EOS** Shen et al. (1998), Lattimer & Swesty (1991)

Collapsar Model
for Long Gamma-Ray Bursts

R-Process Nucleosynthesis in Gamma-Ray Bursts

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 \times Volume

\( \nu \)-spectrum at Various SNe & GRB

No \( \nu \)-oscillation

Star Formation Rate [M_{sun}/yr/Mpc^3]

\( z \)

Energy of neutrino [MeV]

Neutrino flux [MeV/cm^2/s/sr]
Non-Adiabatic Matter (MSW) Oscillation

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

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

Failed SNe (LS-EOS)

Failed SNe (Shen-EOS)

ONeMg SNe

Horiuchi, Beacom et al. (2011)

100%

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

Adiabatic Matter (MSW) Oscillation
**SUMMARY**

**Total $\nu$-mass:**

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

**$\nu$-Mass hierarchy:**

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

**Relic Supernova-$\nu$:**

Future observation of Relic Supernova $\nu$’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.