Precise Capture Rates of Cosmic Neutrinos and Their Implications on Cosmology

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Introduction

- Precise CMB observations constrain many cosmological parameters.

- However, it is not enough to understand the early universe and particle physics.

→What are future observations to understand them?

The Cosmic Neutrino Background(C ν B)

The C ν B would be produced at 1 second of the universe.

(CMB: 400,000 years)

$$\underbrace{\nu_i}_{\text{The C}\,\nu\,\text{B}} + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$$

We formulate the C ν B and the future direct observation,
including sub-leading cosmological contributions in the Standard Model.

Outline

- Introduction
- Neutrino number density in the current universe
- Implication on the PTOLEMY experiment

$$\nu_i + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$$

- Summary

Neutrino number density

- **Capture rates will depend on the neutrino number density.**

In the current universe, momentum of cosmic neutrinos is

$$\langle|\boldsymbol{p}|\rangle \sim 0.53 \text{ meV} \ll \sqrt{\Delta m^2_{\text{sol}}} \simeq 8.6 \text{ meV}, \ \sqrt{|\Delta m^2_{\text{atm}}|} \simeq 50 \text{ meV}$$

At least, two neutrino species are non-relativistic.

Sub-leading cosmological contributions to number density:

○Spectral distortion from FD distribution by $e^- e^+$-annihilation in neutrino decoupling

$T_{e^- e^+} \sim m_e \simeq 0.5$ MeV $T_{\text{dec}} \sim 2$ MeV ➡ $e^- e^+$-pairs slightly annihilate into only high energy neutrinos

○ Gravitational clustering by our Galaxy and nearby galaxies

Non-relativistic neutrinos are attracted by their gravitational potential.

Neutrino number density

Number density including sub-leading cosmological contributions:

$$n_{\nu_i} \simeq n_0 \left(1 + \delta n^d_{\nu_i} + \delta n^c_{\nu_i}\right)$$

$\delta n^d_{\nu_1}$ (%)	$\delta n^d_{\nu_2}$ (%)	$\delta n^d_{\nu_3}$ (%)
1.13	1.01	0.91

Spectral distortion by e^-e^+-annihilation in the mass-diagonal basis, estimated by solving the Boltzmann equations in the mass basis

KA and M. Yamaguchi 2005.07047.

m (meV)	δn^c (%)
10	0.53
50	12

Gravitational clustering estimated by Mertsch's group.

P. Mertsch et al 1910.13388.

n_0 : number density if all e^-e^+ annihilate into photons.

$$n_0 = \frac{1}{(2\pi)^3} \int d^3p \frac{1}{e^{p/T_\nu} + 1} \simeq 56.01 \text{ cm}^3$$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.9454 \ K$$

$$T_\gamma = 2.72548 \pm 0.00057\text{K}$$

D. J. Fixsen 0911.1955.

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PTOLEMY experiment

P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
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The most discussed method of direct observation of the C ν B

$$\nu_i + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$$

100g of Tritium (${}^3\mathrm{H}$)　　We observe this electron (e^-).

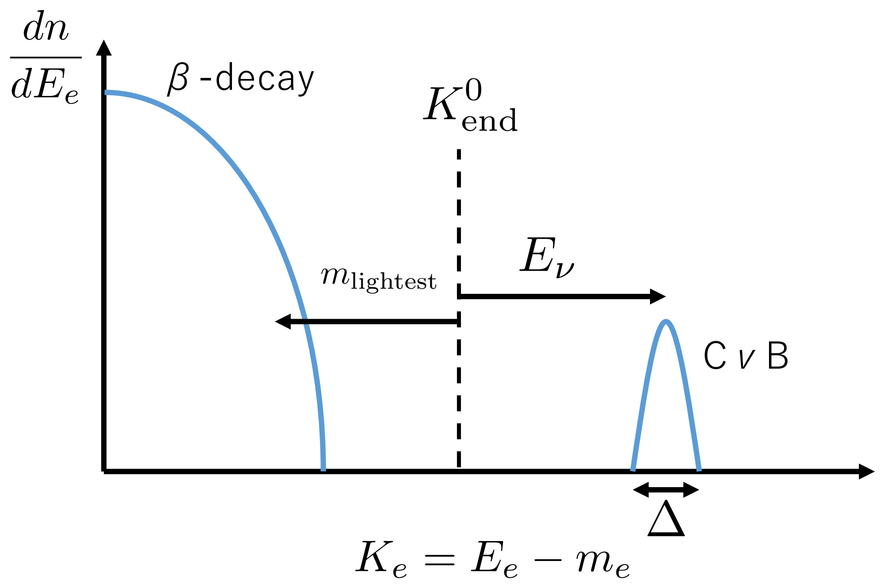
- No threshold energy E_{ν_i} because of $m_{^3\mathrm{H}} > m_{^3\mathrm{He}} + m_e$
- Long lifetime $t_{1/2} = 12.32\ \mathrm{years}$
- Relatively high cross section with the C ν B

PTOLEMY experiment

The most discussed method of direct observation of the CνB

$$\nu_i + \underline{{}^3\mathrm{H}} \to {}^3\mathrm{He} + \underline{e^-}$$

100g of Tritium — We observe this electron.



Main difficulties

- Handling with large amounts of tritium
- Distinguishing from β-decay, ${}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_i$

Electron energy from the CνB : $E_e^{\mathrm{C}\nu\mathrm{B},i} \simeq K^0_{\mathrm{end}} + m_e + E_{\nu_i}$

Maximal energy from β-decay: $E_{\mathrm{end}} \simeq K^0_{\mathrm{end}} + m_e - m_{\mathrm{lightest}}$

The lightest neutrino mass

$$K^0_{\mathrm{end}} = \frac{(m_{^3\mathrm{H}} - m_e)^2 - m^2_{^3\mathrm{He}}}{2m_{^3\mathrm{H}}}$$

➡ $E_e^{\mathrm{C}\nu\mathrm{B},i} - E_{\mathrm{end}} \simeq m_{\mathrm{lightest}} + E_{\nu_i}$

A tiny detector energy resolution is required to be $\Delta \lesssim m_{\mathrm{lightest}} + E_{\nu_i}$.

Precise Capture Rates

$$\Gamma_i = N_T \sum_{s_\nu=\pm\frac{1}{2}} \int \frac{d^3p_\nu}{(2\pi)^3} \sigma_i(p_\nu, s_\nu) v_{\nu_i} f_{\nu_i}(p_\nu, s_\nu)$$

Number of tritium (N_T) Cross section (σ_i) Distribution (f_{ν_i})

- Capture Rates for non-relativistic neutrinos with 1% precision:

$$\Gamma_i \simeq N_T \frac{G_F^2}{2\pi} |V_{ud}|^2 |U_{ei}|^2 \frac{m_{^3\mathrm{He}}}{m_{^3\mathrm{H}}} \left(\langle f_F \rangle^2 + \frac{g_A^2}{g_V^2} \langle g_{GT} \rangle^2 \right)$$
$$\times F(2, \tilde{E}_e) \tilde{E}_e |\tilde{p}_e| \sum_{s_\nu=\pm\frac{1}{2}} \left(n_{\nu_i} - 2s_\nu \langle v_{\nu_i}^0 \rangle \right)$$

Nuclear coupling constants: $\left(\langle f_F \rangle^2 + \frac{g_A^2}{g_V^2} \langle g_{GT} \rangle^2 \right)$

Neglect neutrino momentum: $F(2, \tilde{E}_e)$

$$\langle v_{\nu_i}^0 \rangle = \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{p_\nu/T_\nu} + 1} v_{\nu_i} \quad (< n_{\nu_i})$$

Only the number density contains sub-leading cosmological contributions.

Values of Capture Rates

Normal hierarchy case for Majorana neutrinos on 100g of tritium

$$\Gamma_1^M \simeq 5.48 \text{ yr}^{-1}, \quad \Gamma_2^M \simeq 2.40 \text{ yr}^{-1}, \quad \Gamma_3^M \simeq 0.200 \text{ yr}^{-1}$$

- Contributions from $e^- e^+$-annihilation in neutrino decoupling

$$\delta\Gamma_1^{Md} \simeq 0.061 \text{ yr}^{-1}, \quad \delta\Gamma_2^{Md} \simeq 0.024 \text{ yr}^{-1}, \quad \delta\Gamma_3^{Md} \simeq 1.6 \times 10^{-3} \text{ yr}^{-1}$$

- Contributions from neutrino clustering $(m_{\nu_1} = 0 \text{ meV})$

$$\delta\Gamma_1^{Mc} \simeq 0 \text{ yr}^{-1}, \quad \delta\Gamma_2^{Mc} \simeq 0.013 \text{ yr}^{-1}, \quad \delta\Gamma_3^{Mc} \simeq 0.021 \text{ yr}^{-1}$$

We need about 10 kg of tritium to observe $\delta\Gamma_i^M$.

<u>Uncertainties of parameters</u>

$|U_{ei}|$ (PMNS matrix) : About 10% errors at 3 σ confidence

We need to reduce these uncertainties to observe $\delta\Gamma_i^M$.

Summary

- We estimated the C ν B number density including sub-leading contributions, in particular, contributions from e^-e^+-annihilation in neutrino decoupling for the first time.
- We also formulated the capture rates on tritium with 1% precision, including the above effects.
- The precise capture rates will also be useful to compare the SM and physics beyond the SM properly.

Outlook

- Methods to distinguish effects between gravitational clustering and e^-e^+-annihilation.
- Forecasts for constraints on physic beyond the SM in the PTOLEMY experiment

(ex: The C ν B decay,⋯) KA, M. Yamaguchi and G. Lambiase in preparation