Unstable Cosmic Neutrino Capture on Tritium

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Motivation

Why neutrino decay? Why cosmic neutrino decay?

See also P. Denton’s talk.

Motivation

- Neutrino oscillation experiments revealed

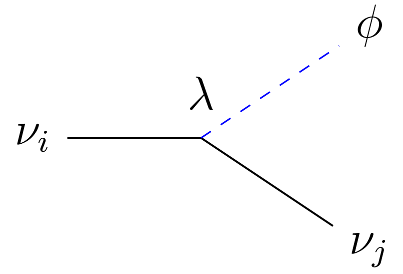
$$\Delta m^2_{21} \simeq (8.6\ \mathrm{meV})^2 \qquad |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq (50\ \mathrm{meV})^2$$

But, the neutrino-mass-generation mechanism remains mystery...

→ This implies neutrinos have non-standard interactions.

- If neutrinos are massive, what could happen?

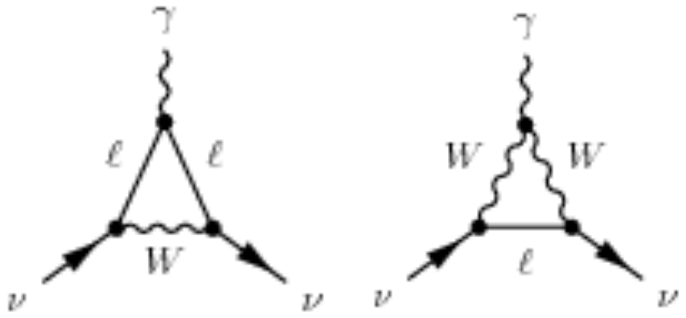
Neutrino Decay!



- Non-standard interactions may induce fast neutrino decay.

$$\nu_i \to \nu_j \phi$$

Neutrino Decay



- Neutrino Radiative Decay

Even the SM interactions induce radiative decays.

$$\nu_i \to \nu_j \gamma$$

(current age of the universe)

Its lifetime is extremely long: $\tau_{\nu_i} \gtrsim 10^{36} (m_{\nu_i}/\mathrm{eV})^{-5}\ \mathrm{yr} \gg t_0 \simeq 1.4 \times 10^{10}\ \mathrm{yr}$

There is already stringent constraint: $\tau_{\nu_i} \gtrsim 10^{18}\ \mathrm{yr} \gg t_0$

(neutrino-electron scattering)

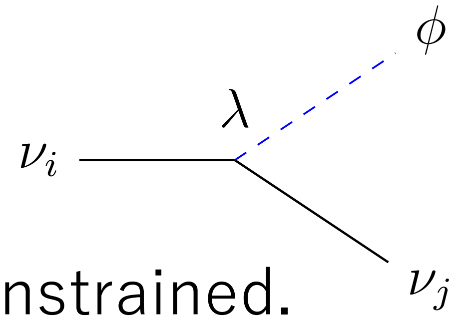
Borexino 2017

We focus on it.

- Neutrino Invisible Decay

$$\nu_i \to \nu_j \phi$$

Invisible particle like majoron etc



The lifetime (i.e. $\lambda,\ m$) of Invisible decay is much less constrained.

Constraints on neutrino lifetime

$$\tau'_\nu = \gamma(E_\nu)\tau_\nu \qquad \gamma(E_\nu) = \frac{E_\nu}{m_\nu}$$

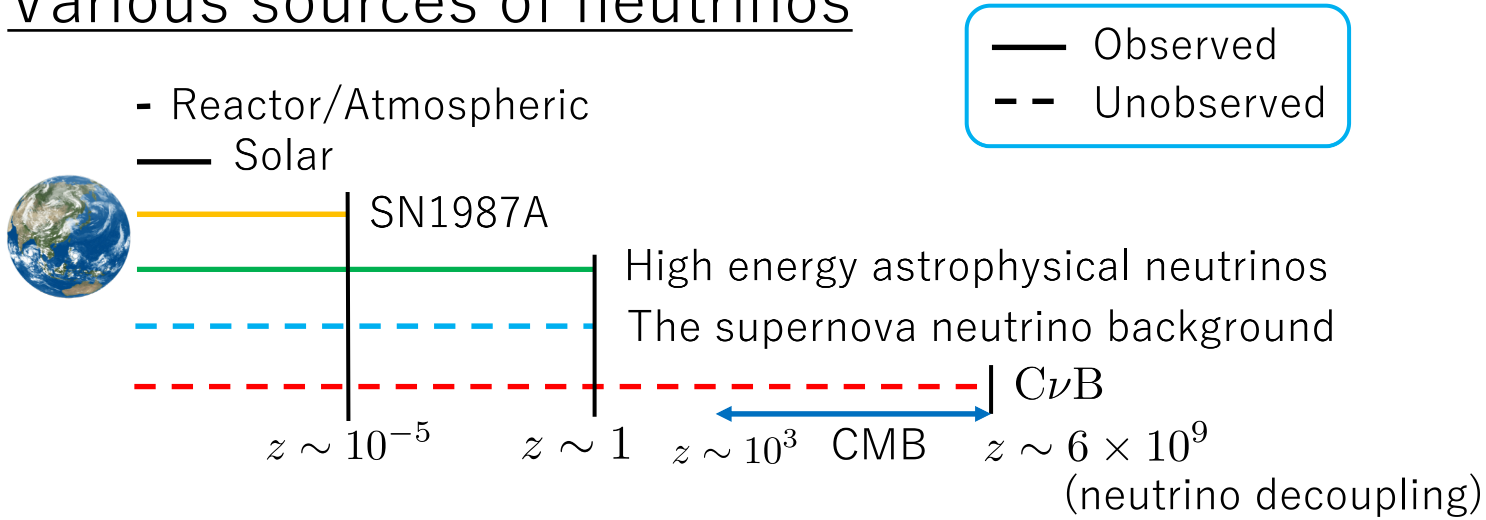
The Lorentz factor

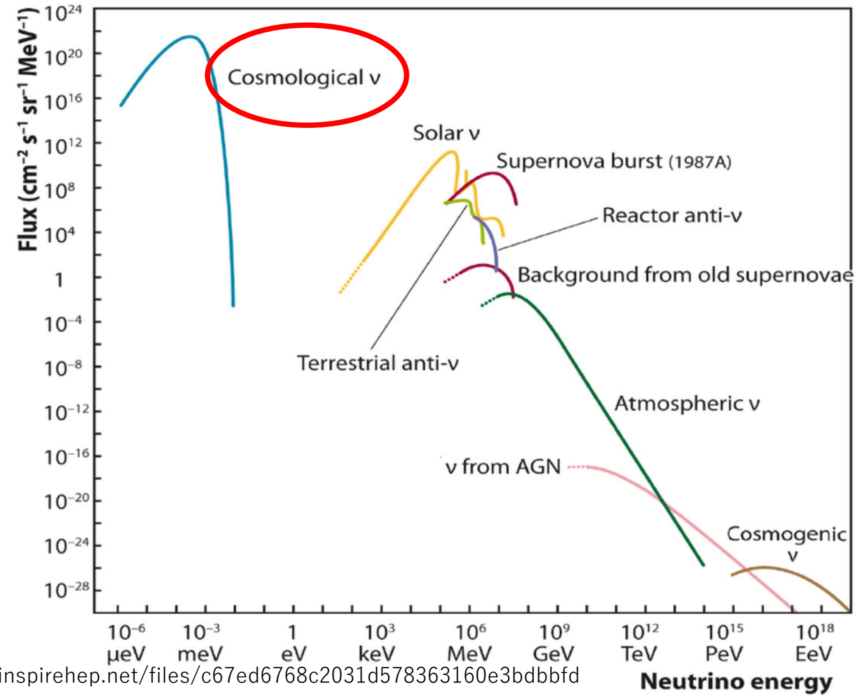
Observer frame

Rest frame for decaying neutrinos

Constraints on τ_ν are longer for long travel time/low energy.

- Various sources of neutrinos





https://inspirehep.net/files/c67ed6768c2031d578363160e3bdbbfd

The Cosmic Neutrino Background (CνB)!

Constraints on neutrino invisible decay

- Current constraints:

$$\frac{\tau_{\nu_{1,2}}}{m_{\nu_{1,2}}} \gtrsim 10^5 \text{ s/eV}$$

(SN1987A)
Kamiokande-II 1987

$$\tau_{\nu_i} \gtrsim 4 \times 10^5 \left(\frac{m_{\nu_i}}{50 \text{ meV}}\right)^3 \text{s}$$

(CMB)
Barenboim et al. 2021

$$\frac{\tau_{\nu_i}}{m_{\nu_i}} \gtrsim 10^1 \text{ s/eV}$$ etc.

(High energy astrophysical neutrinos, see P. Denton's talk)
Pagliaroli et al. 2015

- Future sensitivity:

$$\frac{\tau_\nu}{m_\nu} \sim 10^{10} \text{ s/eV}$$

(supernova neutrino background)
DeGouvea et al. 2020

$$\tau_\nu \sim t_0 = 4.35 \times 10^{17} \text{ s}$$

($C\nu B$)
Long et al. 2014

The most discussed, but still difficult, method

We forecast constraints on neutrino decay via capture of the $C\nu B$ on tritium, and support the construction of a setup for such an experiment.

Outline

- Motivation
- Decay of cosmic neutrinos and their spectrum
- Implications on cosmic neutrino capture on tritium
- Conclusions

Decay of heavier neutrinos: $\nu_i \to \nu_j + \ldots$

- Number density today (t_0) : $n_{\nu_i}(t_0) = e^{-\lambda_\nu} f_c n_\nu^0$

$$\lambda_\nu = \int_{t_d}^{t_0} \frac{dt}{\gamma(E_\nu)\tau_\nu} \simeq \frac{t_0}{\tau_\nu} \qquad \gamma(E_\nu) = \frac{E_\nu}{m_\nu} \simeq 1 \qquad (T_\nu \sim T_{\rm CMB} \ll \Delta m_{21}^2,\ |\Delta m_{31}^2|)$$

$n_\nu^0 \equiv n_\nu(t_d)[a(t_d)/a(t_0)]^3 \simeq 56\ {\rm cm}^{-3}$: number density without decays

t_d: Neutrino decoupling time

f_c : the enhancement factor of gravitational clustering by nearby galaxies

m (meV)	f_c
10	1.053
50	1.12
100	1.5
200	3

P. Mertsch et al 1910.13388.

Produced lighter neutrinos: $\nu_i \to \nu_j + \ldots$

- Number density today (t_0) : $\tilde{n}_{\nu_j}(t_0) \simeq N_{\nu_j} n^0_{\nu_i}(1 - e^{-t_0/\tau_{\nu_i}})$

N_{ν_j} : the number of ν_j produced by one decay of ν_i

$\nu_i \to \nu_j \phi$: $N_{\nu_j} = 1$

$\nu_i \to \nu_j \nu_j \bar{\nu}_k$: $N_{\nu_j} = 2$

- Current energy spectrum:

$$\frac{d\tilde{n}_{\nu_j}(t_0)}{dE_{\nu_j}} = \int_0^\infty dz \frac{1}{H(z)} \frac{n^0_{\nu_i}}{\tau_{\nu_i}} e^{-t(z)/\tau_{\nu_i}} \frac{E_{\nu_j}}{p_{\nu_j}} \frac{p_{\nu_j}(z)}{E_{\nu_j}(z)} \frac{dN}{dE_{\nu_j}(z)}(E_{\nu_j}(z))$$

$\frac{dE_{\nu_j}(z)}{dE_{\nu_j}}$

Superposition of the decays

- Main contribution is $z \sim 1$ $(H(z) \gg 1$ for $z \gg 1)$
- Energy injection by the decay occur.

We ignore clustering for ν_j .

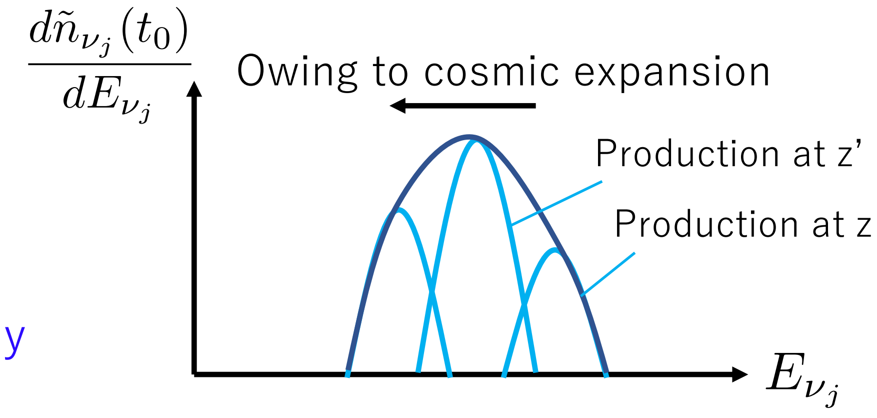
Decay rate per volume and time

$$\frac{1}{N_{\nu_j}} \frac{d\tilde{n}_{\nu_j}(t)}{dt}$$

Spectrum by one decay

$$\frac{dN}{dE_{\nu_j}} = \frac{N_{\nu_j}}{\Gamma_\nu} \frac{d\Gamma_\nu}{dE_{\nu_j}}$$

Decay rate



$$p_{\nu_j}(z) = p_{\nu_j}(1+z),$$

$$E_{\nu_j}(z) = \sqrt{p^2_{\nu_j}(1+z)^2 + m^2_{\nu_j}}.$$

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Neutrino capture on tritium

- The most discussed method proposed by Weinberg in 1962:

$$\nu_i + n \to p + e^-$$

No threshold energy E_{ν_i} because of $m_{^3\mathrm{H}} > m_{^3\mathrm{He}} + m_e$

- Tritium (PTOLEMY-type experiment)

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

Long lifetime: $t_{1/2} = 12.32\ \mathrm{years}$

High capture cross section

P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

Properties and Challenges

- Capture rate

Number of tritium: $N_T = \frac{\mathrm{M_T}}{m_{^3\mathrm{H}}}$ Total tritium mass

$$\Gamma^i_{\mathrm{C}\nu\mathrm{B}} \simeq 2|U_{ej}|^2 \bar{\sigma} n_{\nu_i} N_T \simeq 8\ \mathrm{yr}\ |U_{ej}|^2 \left(\frac{n_{\nu_i}}{56\ \mathrm{cm}^{-3}}\right)\left(\frac{M_T}{100\ \mathrm{g}}\right)$$

PMNS matrix

$$\bar{\sigma} = 3.76 \times 10^{-45}\ \mathrm{cm}^2$$

A large amount of tritium is required.

- Spectrum of the emitted electrons

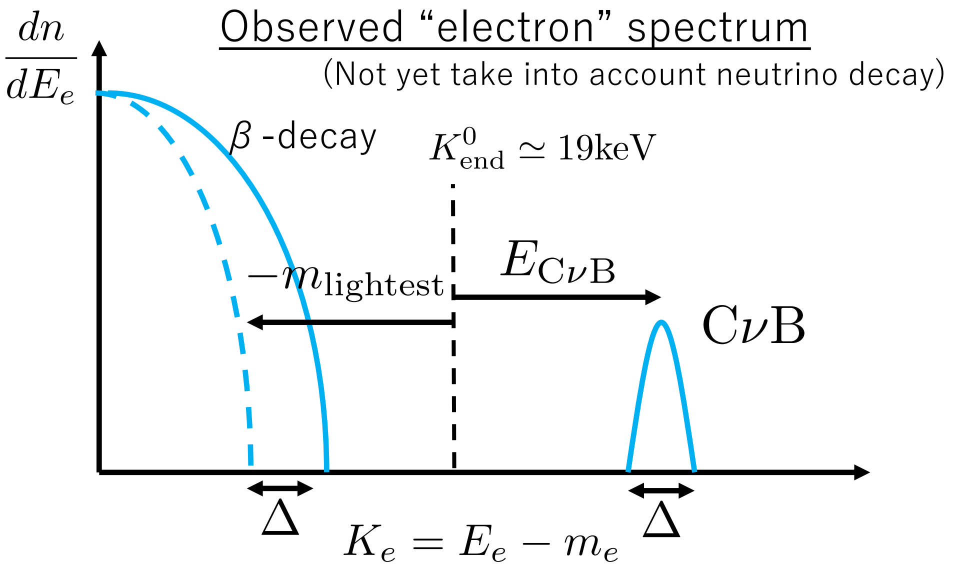
$$\frac{d\Gamma^i_{\mathrm{C}\nu\mathrm{B}}}{dE_e} \simeq 2|U_{ej}|^2 \bar{\sigma} N_T \frac{dn_{\nu_i}}{dE_{\nu_i}}(E_e) \qquad E_e \simeq K^0_{\mathrm{end}} + m_e + E_{\nu_i}$$

- Main background: $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_i$ (β-decay)

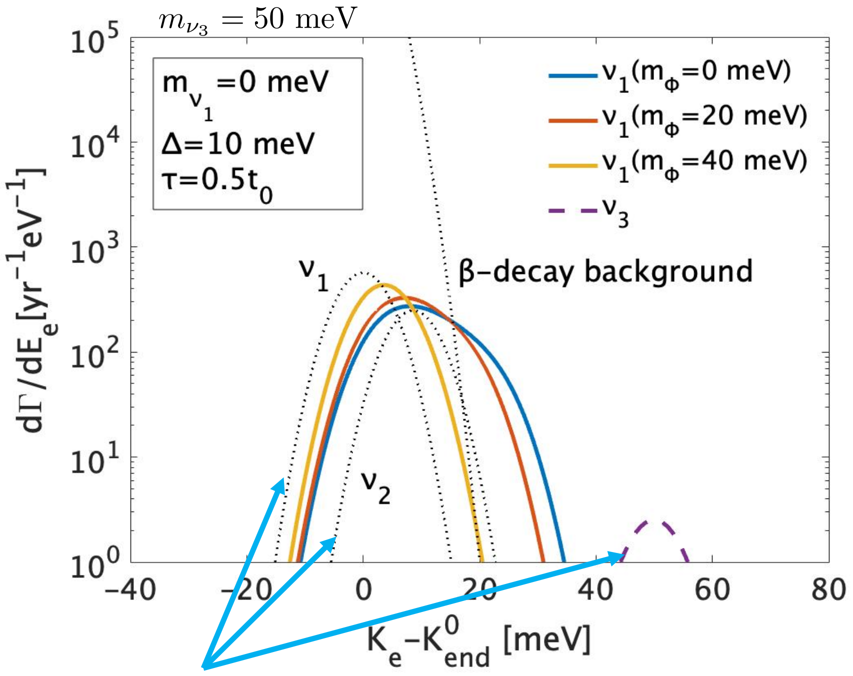
A tiny energy resolution is required.

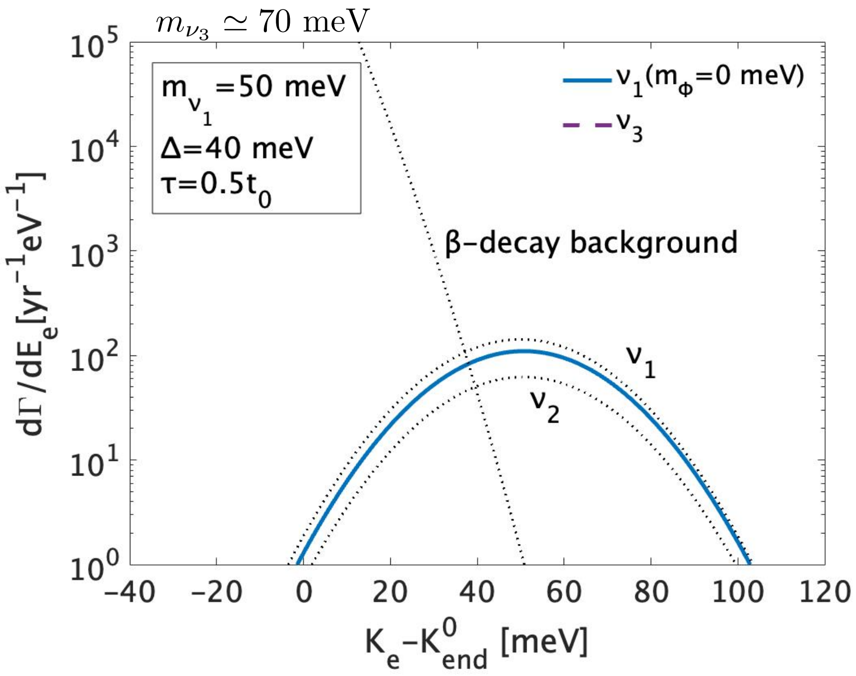
$$\Delta \lesssim m_{\mathrm{lightest}} + E_{\mathrm{C}\nu\mathrm{B}}$$

The lightest neutrino mass



Observed "electron" spectrum in normal ordering (NO): $\nu_3 \to \nu_1 \phi$





CνB produced in the early universe

- We model the Gaussian-smeared spectrum to take into account the energy resolution of the detector Δ .

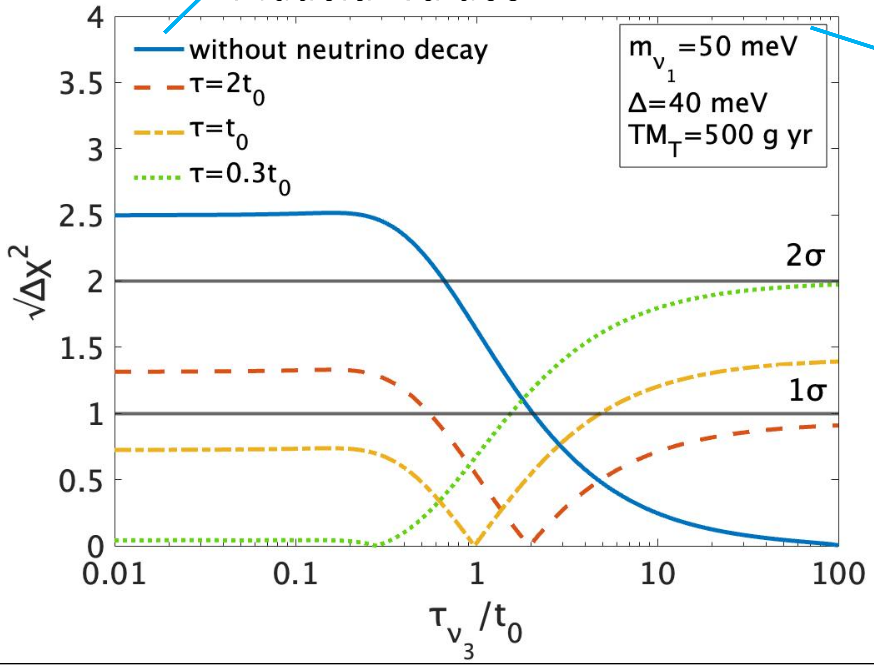
$$\frac{d\mathbf{\Gamma}^i_{\mathrm{C}\nu\mathrm{B}}}{dE_e} = \frac{1}{\sqrt{2\pi}\sigma} \int_{\infty}^{\infty} dE'_e \frac{d\Gamma^i_{\mathrm{C}\nu\mathrm{B}}}{dE_e}(E'_e) \exp\left[-\frac{(E'_e - E_e)}{2\sigma^2}\right] \qquad \sigma = \Delta/\sqrt{8 \ln 2}$$

Possible constraints in NO: $\nu_3 \to \nu_1 \phi$

- We employ a simple χ^2 test.

We use a Gaussian likelihood.
A Poisson likelihood reproduce almost the same results.

Fiducial values



Even marginalizing m_{ν_1}
with 10% or 50% uncertainties,
the result is the same.

Measuring β -decay background
determine m_{ν_1} .

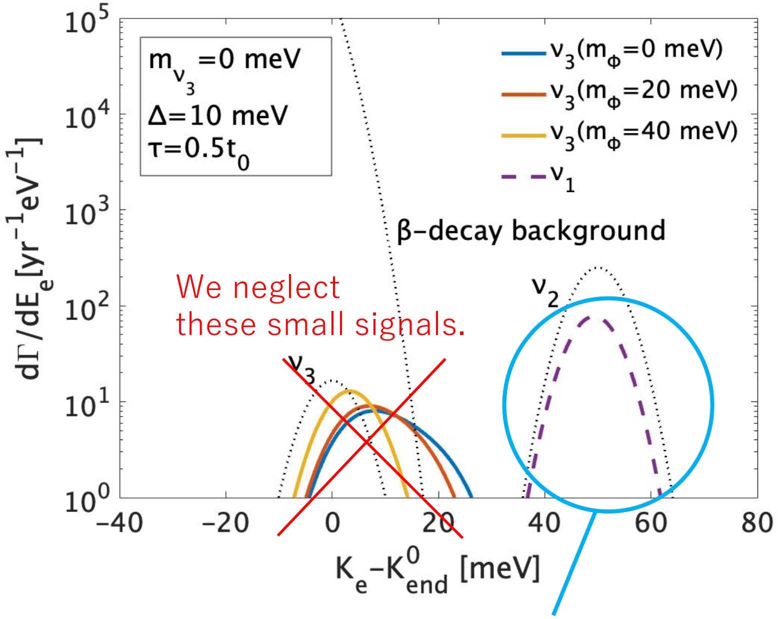
*We marginalized m_ϕ

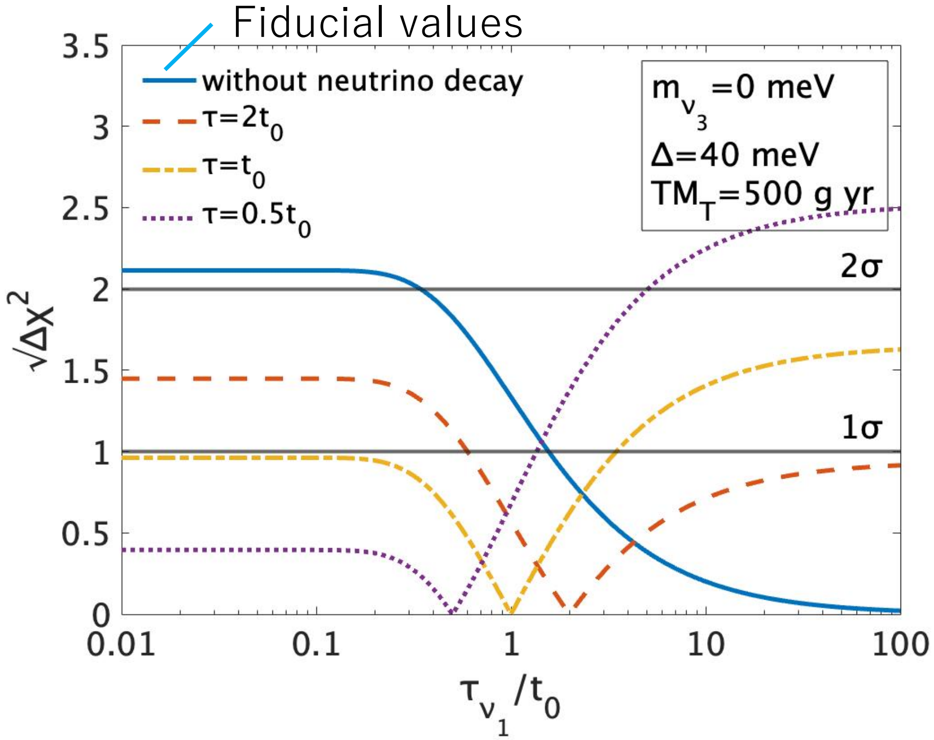
Ordering	m_{ν_1} (meV)	Δ (meV)	$\mathrm{TM_T}$ (g yr)	$\hat{\tau}_{\nu_3}$	$1\sigma(\hat{\tau}_{\nu_3} = t_0)$	$\hat{\tau}_{\nu_3}$	$1\sigma(\hat{\tau}_{\nu_3} = \infty)$
NO	0	10	500	t_0	$0.2t_0 \lesssim \tau_{\nu_3} \lesssim 3t_0$	∞	No bound
	50	40			$\tau_{\nu_3} \lesssim 5t_0$		$2t_0 \lesssim \tau_{\nu_3}$
	100	60			$\tau_{\nu_3} \lesssim 3t_0$		$4t_0 \lesssim \tau_{\nu_3}$
	200	120			$\tau_{\nu_3} \lesssim 7t_0$		$6t_0 \lesssim \tau_{\nu_3}$

Possible constraints in Inverted Ordering (IO):

$\nu_1 \to \dots$

The expected spectrum for $\nu_1 \to \nu_3 \phi$





We only consider the suppression of ν_1.
These constraints can apply any decay process for $\nu_1 \to \dots$.

Ordering	m_{ν_3} (meV)	Δ (meV)	TM_T (g yr)	$\hat{\tau}_{\nu_1}$	$1\sigma(\hat{\tau}_{\nu_1} = t_0)$	$\hat{\tau}_{\nu_1}$	$1\sigma(\hat{\tau}_{\nu_1} = \infty)$
IO	0	40	500	t_0	$\tau_{\nu_1} \lesssim 4t_0$	∞	$t_0 \lesssim \tau_{\nu_1}$
	50	60			$\tau_{\nu_1} \lesssim 3t_0$		$t_0 \lesssim \tau_{\nu_1}$
	100	100			$\tau_{\nu_1} \lesssim 3t_0$		$t_0 \lesssim \tau_{\nu_1}$
	200	200			$\tau_{\nu_1} \lesssim 3t_0$		$2t_0 \lesssim \tau_{\nu_1}$

Conclusions

- The $\mathrm{C}\nu\mathrm{B}$ capture on tritium have the potential to explore a neutrino lifetime, especially in the region of the age of the universe $t_0 = 4.35 \times 10^{17}$ s.

We will mainly observe it due to a large PMNS matrix U_{e1} .

- In normal ordering, we can constrain neutrino lifetime for $\nu_3 \to \nu_1 \phi$ when an exposure of $\gtrsim 500$ g yr and energy resolution $\Delta \lesssim 0.6 m_{\mathrm{lightest}}$ are obtained.

We will mainly observe it.

- In inverted ordering, we can constrain neutrino lifetime for $\nu_1 \to \ldots$ when an exposure of $\gtrsim 500$ g yr and $\Delta \lesssim m_{\mathrm{lightest}}$ are obtained.

- When the setup is determined more concretely, a more quantitative discussion will be possible.

Thank you!