Dark Matter and Entropy Production in the νMSM

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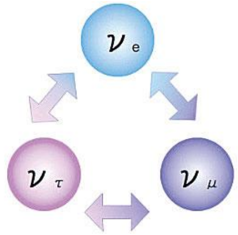
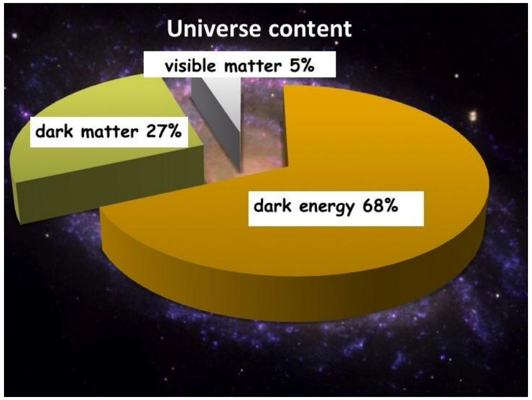
Introduction

■Problem of the Standard Model

- Neutrino mass
- Dark Matter
- BAU





■νMSM (Neutrino minimal standard model)

[T.Asaka, S.Blanchet, M.Shaposhnikov ('05), T.Asaka, M.Shaposhnikov ('05)]

νMSM: SM + 3 right-handed neutrinos (ν_R)

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM}} + \overline{\nu}_R i\partial_\mu \gamma^\mu \nu_R - F_{\alpha I}\overline{L}_\alpha \tilde{\Phi}\nu_{RI} - \frac{1}{2}(M_M)_{IJ}\overline{\nu}^c_{RI}\nu_{RJ} + h.c.$$

■Seesaw mechanism $|M_D| = |F\langle\Phi\rangle| \ll M_M < \Lambda_{\mathrm{EW}} \sim \mathcal{O}(100\mathrm{GeV})$

3 heavy neutrino

N_1 is DM candidate

N_2, N_3 explain neutrino mass and BAU

Purpose of study : Impact of entropy production by $N_{2,3}$ decay on DM physics in the νMSM

Motivation 1 – Constraint on DM candidate

The DM candidate N_1

Mass : O(1keV)
N1 behaves as WDM.

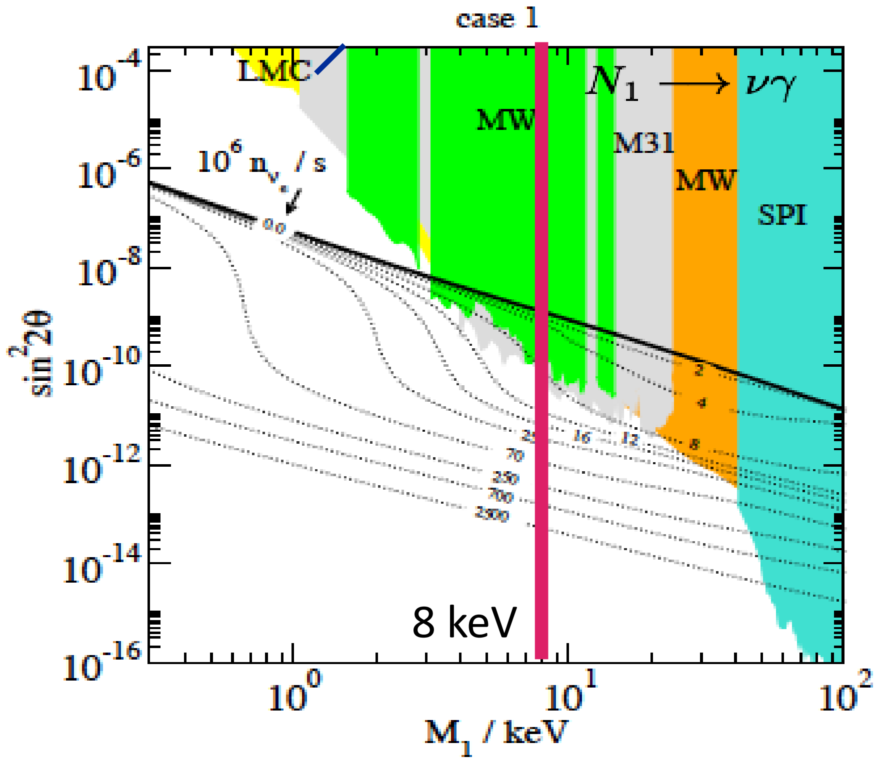
■Free-streaming length

$$\lambda_{FS} = 0.2\text{Mpc}\left(\frac{1\text{keV}}{M_{DM}}\right)\left(\frac{T_{DM}}{T_\nu}\right)\left[\ln\left(\frac{t_{EQ}}{t_{NR}}\right)+2\right]$$

$$(t_{EQ} \sim 10^{11}\text{sec},\ t_{NR} \sim 10^{7}\text{sec})$$

■ The lower limit of the DM mass (Lyman-α)

$$M_1 > 8\text{keV}$$ [A. Boyarsky, et al ,arXiv.0812.0010]



[M. Laine, M. Shaposhnikov, ('08)]

Considering the X-ray and Lyman-α constraints, the allowed region of DM is very limited.

Motivation 1 – Impact of Entropy Production

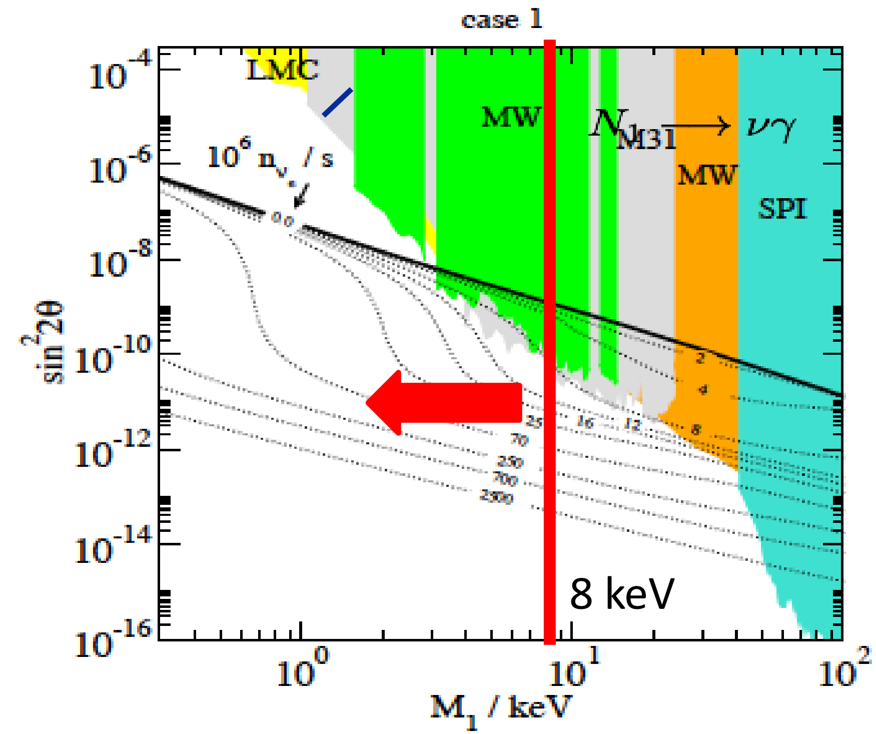
There is a possibility that the entropy production is induced by the $N_{2,3}$ decay before BBN.

If $N_{2,3}$ decay increase the entropy by ΔS the λ_{FS} becomes suppressed as,

$$\lambda_{\rm FS}^{\rm wEP} = \frac{\lambda_{\rm FS}^{\rm woEP}}{\Delta S^{\frac{1}{3}}}$$

The lower limit of DM mass from structure formation is relaxed.

$$M_N > 8\text{keV}\frac{1}{\Delta S^{1/3}}$$



[M. Laine, M. Shaposhnikov, ('08)]

We would like to know how large ΔS is obtained in the νMSM.

Motivation 2 – Evaluation of the previous work

Evaluation of the entropy production rate ΔS in the νMSM have been carried out.

[T.Asaka, M. Shaposhnikov, A. Kusenko ('06) }

■The maximal value of ΔS in the previous work

- $\Delta S = 29 \left(T_R > 0.7\text{MeV} \right)$
- $\Delta S = 10 \left(T_R > 4\text{MeV} \right)$

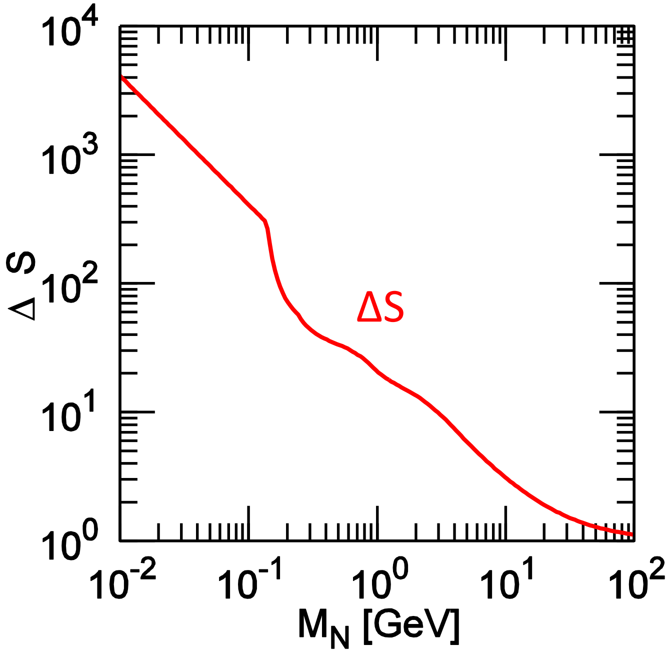
However, there were the unsatisfactory points .

1. Evaluation of the lifetime of the $N_{2,3}$ was incomplete.
   (In particular the decay modes into meson were not included.)
2. Only specific Yukawa coupling constant is considered.

We would like to solve these points.

1. All decay modes Including the decay into meson.
   (example : N →πν, Kl, Bl)
2. All parameter region in the Yukawa coupling constant .

Results



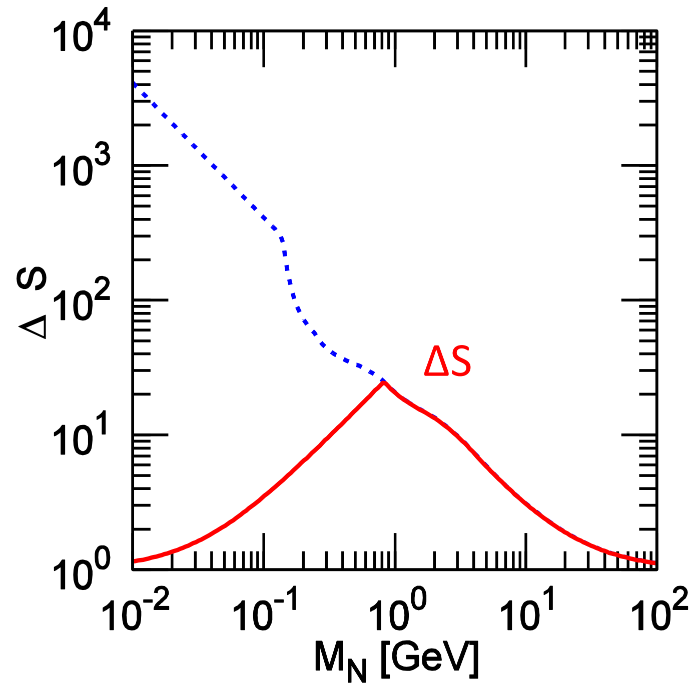
To evaluate the maximal of ΔS

- mass : M_2 = M_3 = M_N
- All parameter region in Yukawa coupling constant

■The constraint on the reheating temperature by the $N_{2,3}$ decay

$$T_R > 2\text{MeV}$$ (WMAP5)

[F. De. Bernardis et al. ('08)]



When M is lighter than 800MeV, the maximum of ΔS becomes suppressed.

■The maximal value of ΔS in this work

$\Delta S = 24$ at $M_N = 800\text{MeV}$

[T. Asaka, T.K. in preparation]

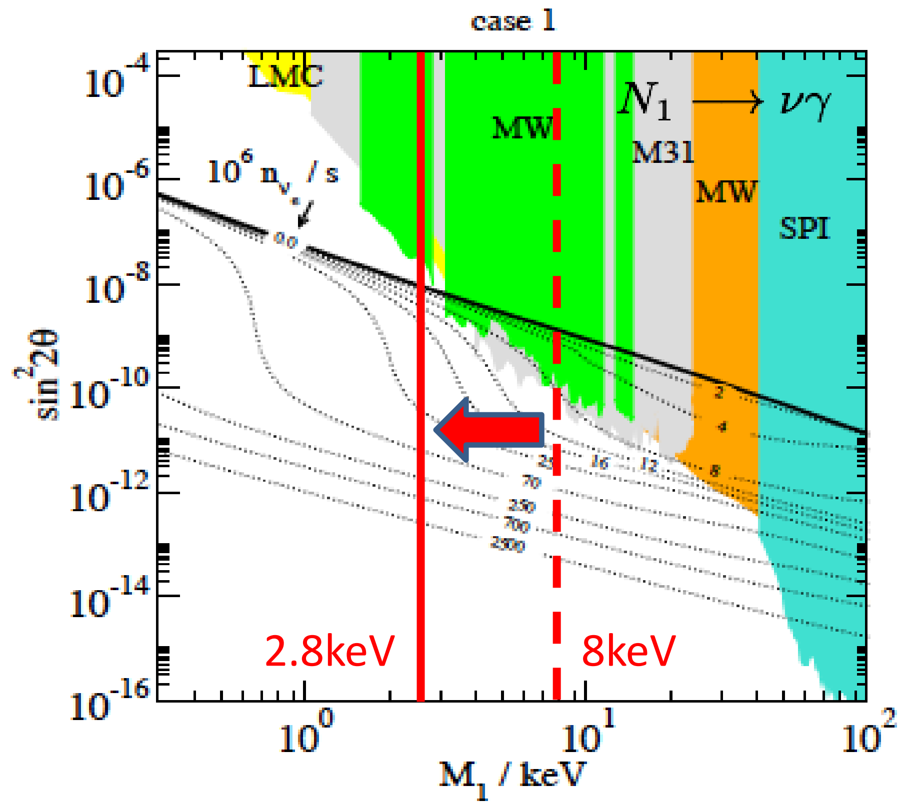
Results

■Impact to dark matter physics

$$M_1 > 8\text{keV}$$

[A. Boyarsky, et al ,arXiv.0812.0010]

$$M_1 > 2.8\text{keV}\left(\frac{24}{\Delta S}\right)^{\frac{1}{3}}$$



The lower limit of DM mass is relaxed and the allowed region of DM becomes wider.

Summary

In this talk, We discussed **the Entropy Production** by $N_{2,3}$ decay in the νMSM.

■In the Evaluation of the Entropy Production

- We calculated the decay width for the possible decay modes of $N_{2,3}$.
- We evaluated ΔS with all free parameter in the Yukawa coupling constant.

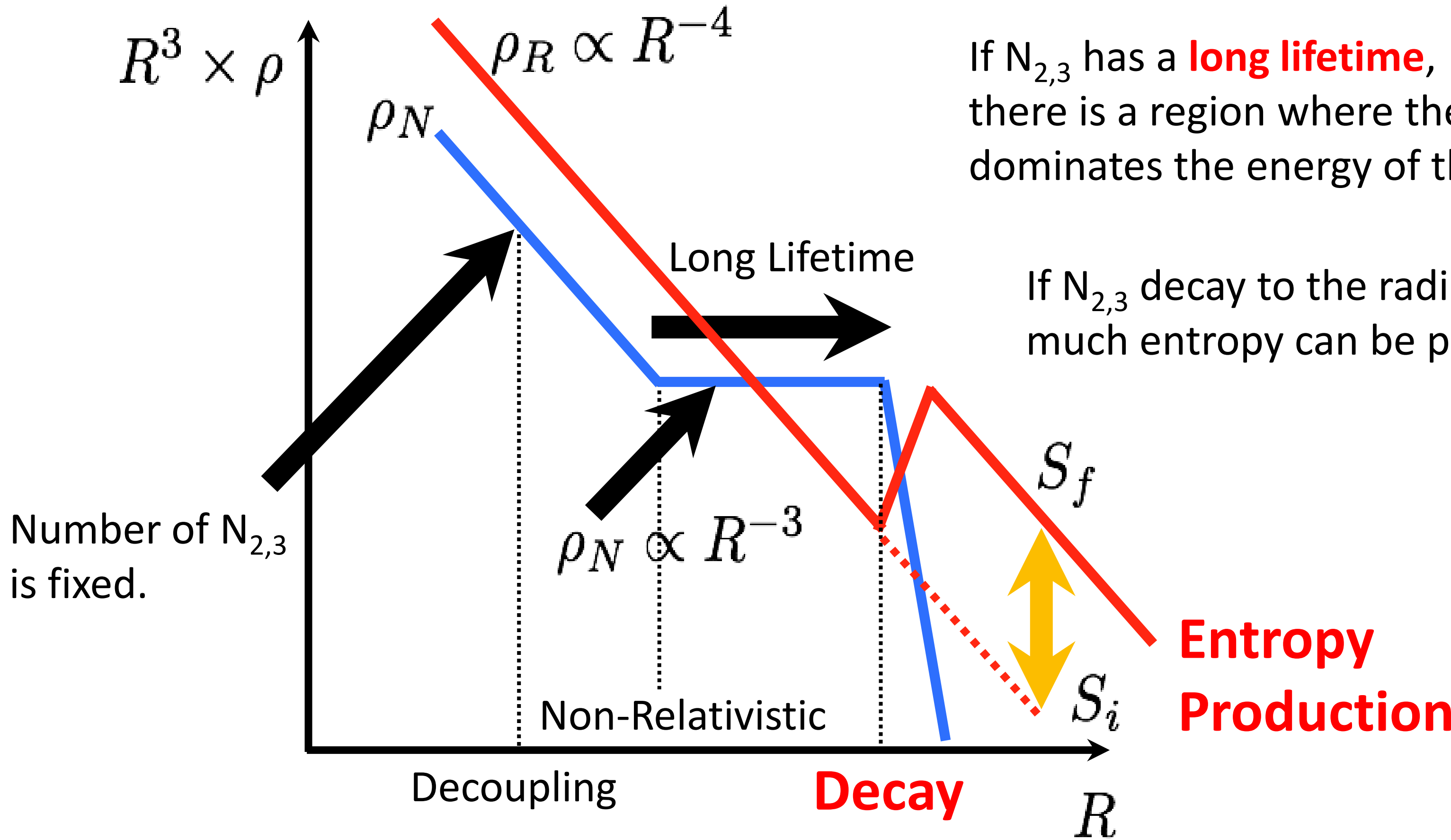
■Results

- By constraint from the cosmic background radiation, we got **$\Delta S < 24$**.
- The DM mass limit is relaxed by the influence to free-Streaming length.
- By the entropy production, the baryon number asymmetry and the dark matter abundance are diluted. These values have to be produced more larger by ΔS.

Back Up

The Entropy Production by $N_{2,3}$ Decay

Consider the case that $N_{2,3}$ decoupled from heat bath and behave Non-relativistic.



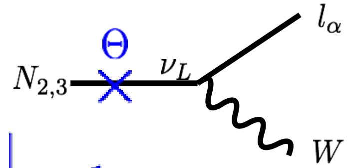
If $N_{2,3}$ has a **long lifetime**, there is a region where the energy of $N_{2,3}$ dominates the energy of the universe.

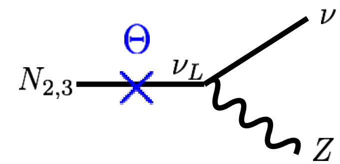
If $N_{2,3}$ decay to the radiation in this area, much entropy can be produced.

We had better check if $N_{2,3}$ lifetime is sufficiently long to evaluate the produced entropy of the universe.

Decay of $N_{2,3}$

■neutrino mixing : $\nu_{L\alpha} = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c$

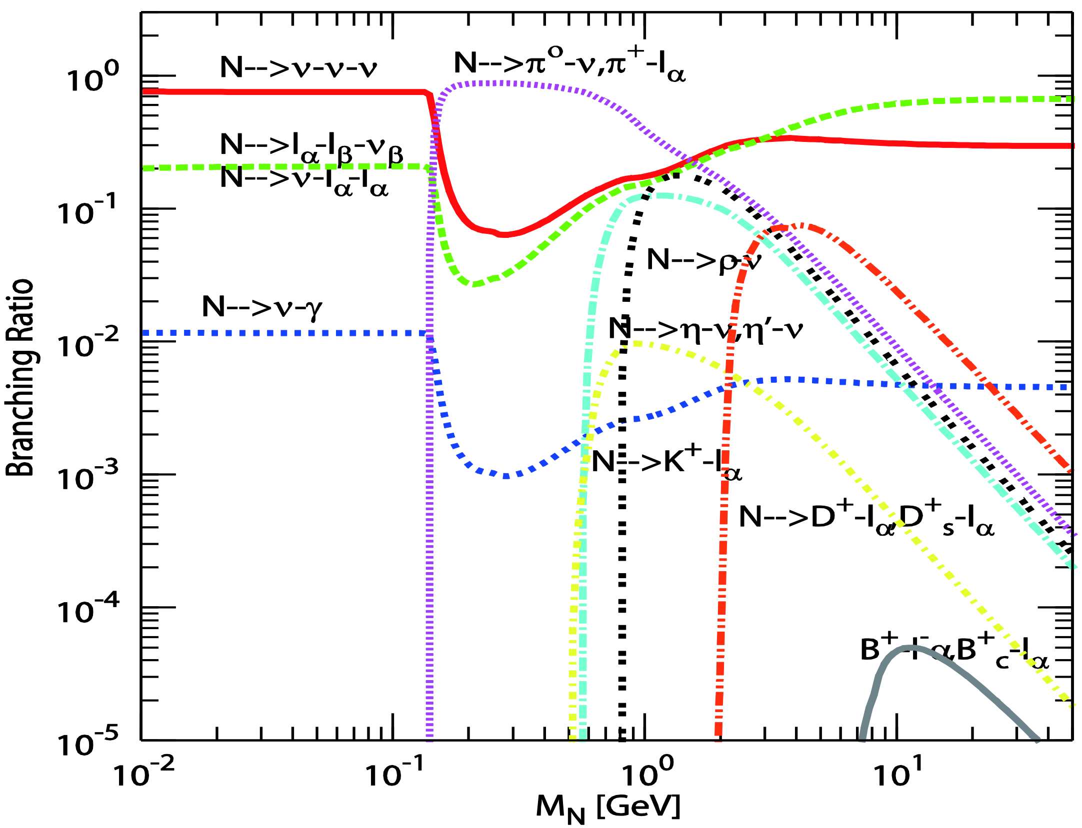




$$|F\langle\Phi\rangle| \ll M_M < \mathcal{O}(100\mathrm{GeV}) \qquad \Theta = \frac{|F\langle\Phi\rangle|}{M_M} \ll 1$$

In the νMSM, $N_{2,3}$ has a weak interaction that suppressed by mixing matrix Θ.

⇒ We can expect that $N_{2,3}$ lifetime is sufficiently long.



■ The decay modes

$$\begin{aligned} N_{2,3} &\longrightarrow \nu\nu\nu \\ &\longrightarrow \nu l^+ l^- \\ &\longrightarrow \nu\gamma \\ &\longrightarrow \pi^0\nu, \pi^+ l^- \\ &\longrightarrow K^+ l^- \\ &\longrightarrow \rho\nu \\ &\longrightarrow \eta\nu, \eta'\nu \\ &\longrightarrow D^+ l^-, D_s^+ l^- \\ &\longrightarrow B^+ l^-, B_c^+ l^- \end{aligned}$$

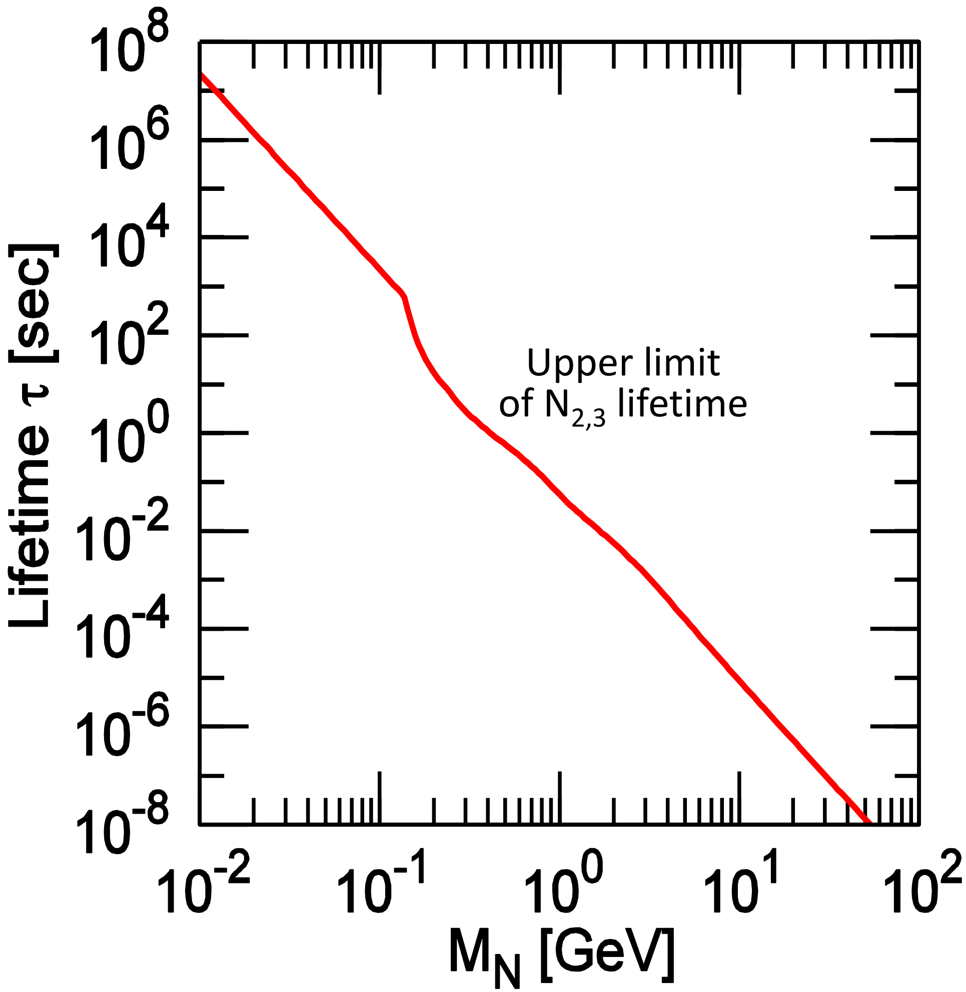
⇒The main decay modes change according to $N_{2,3}$ mass.

Upper limit of $N_{2,3}$ lifetime

We have to fix Yukawa coupling constant and $N_{2,3}$ mass to calculate their lifetime.

$N_{2,3}$ mass : $M_{N2} = M_{N3} = M_N$

Yukawa coupling : Consider all free parameter region



■The rough behavior of lifetime τ

$$\tau \propto \begin{cases} |\Theta|^{-2} M_N^{-5} \text{ (3-body decay)} \\ |\Theta|^{-2} M_N^{-3} \text{ (2-body decay)} \end{cases}$$

If $N_{2,3}$ mass is light,
their lifetime is sufficiently long.

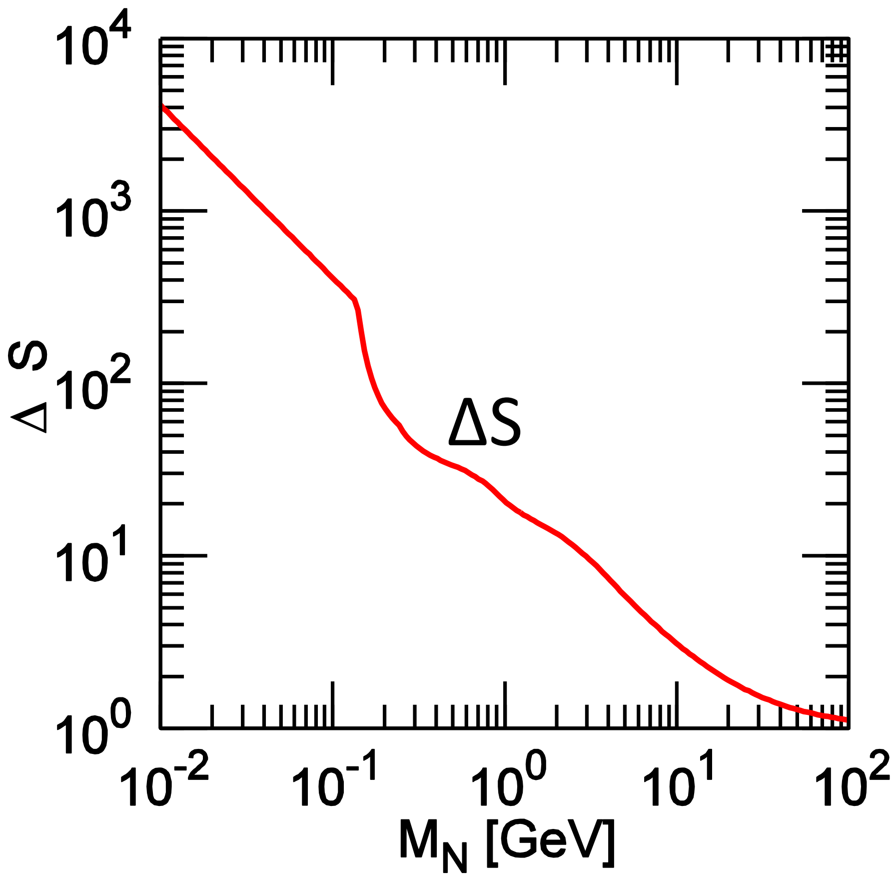
Evaluation of The entropy Production rate

■The Evaluation formula of entropy production rate in the νMSM

$$\Delta S = \frac{S_f}{S_i} = \left[1 + \left(\frac{1.37\,\tau}{M_{pl}\left(\frac{g_*(T_D)}{M_N}\right)^2}\right)^{\frac{2}{3}}\right]^{\frac{3}{4}} \propto (M_N^2\,\tau)^{\frac{1}{2}}$$

T_D : temperature of $N_{2,3}$ decoupling

[R.J. Scherrer, M.S. Turner, Phys. ReV. D31 (1985) 681]



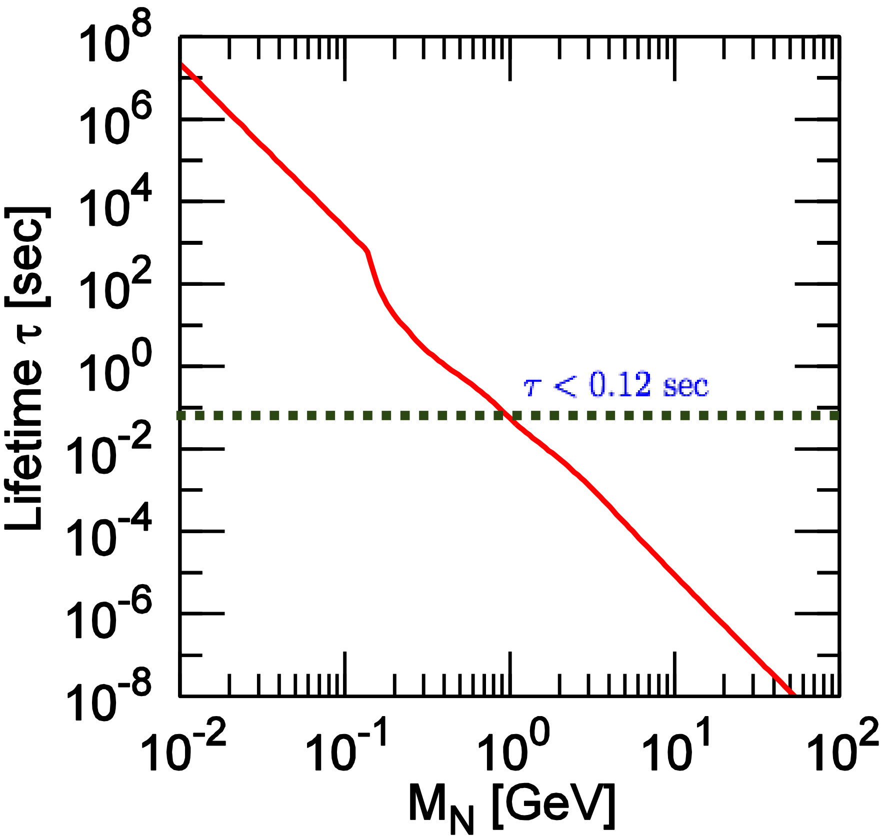
Assumption : $g_*(T_D) \approx 10.75$

In the region where $N_{2,3}$ mass is light, a lot of Entropy is produced.

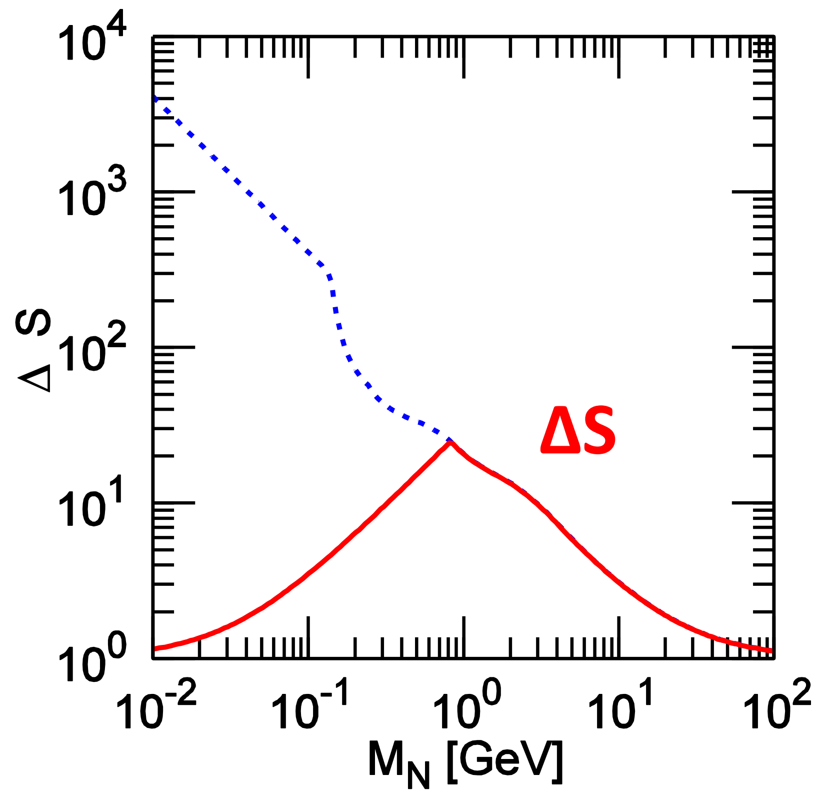
Constraint from the cosmic background radiation

■The upper limit of $N_{2,3}$ lifetime

$$\tau < 0.12 \text{ sec}$$



In the νMSM, the upper limit of $N_{2,3}$ lifetime is lower than 0.12s in the region **M_N > 800 MeV**.



In the region M_N < 800 MeV, we fixed τ =0.12 sec .

The upper limit of ΔS

$$\Delta S < 24$$

[T. Asaka, T.K. ('13)]

The Yukawa coupling constant

$$F = \frac{i}{v} U D_{\nu}^{1/2} \Omega D_{N}^{1/2}$$

U : PMNS matrix (3 mixing angles and 2 CP phases)

$$D_{\nu} = \mathrm{diag}(m_1, m_2, m_3)$$ (m is the mass of light neutrinos.)

$$D_{N} = \mathrm{diag}(M_2, M_3)$$ (M is the mass of heavy neutrinos.)

$$\Omega_{\mathrm{NH}} = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix}$$

$$\Omega_{\mathrm{IH}} = \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$$

Free parameter : M2, M3, Reω, Imω, ξ, Dirac phase, Majorana phase