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# **Probing Neutrino Masses and Baryon Asymmetry in Kaon decays**

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## Model

# SM extended by two Right-handed (RH) neutrinos $\nu_R$

$$L = L_{\text{SM}} + i \bar{\nu}_{RI} \partial_\mu \gamma^\mu \nu_{RI} - F_{\alpha I} \bar{L}_\alpha \Phi \nu_{RI} - \frac{M_M}{2} \bar{\nu}_{RI}^c \nu_{RI} + h.c. \quad \begin{matrix} \alpha = e, \mu, \tau \\ I = 1, 2 \end{matrix}$$

Assumption :  $|\langle \Phi \rangle F| \equiv |M_D| \ll M_M < \Lambda_{EW} \sim O(100)\text{GeV}$

- Seesaw mechanism can explain two neutrino mass scales suggested by oscillation experiments  
⇒  $F_{\alpha I} \sim O(10^{-7})$
  - Baryogenesis via right-handed neutrino oscillation can produce the baryon asymmetry of the universe (BAU)  
⇒  $M_2 - M_1 = \Delta M \ll 2M_N = M_2 + M_1$  [Akhemedov, Rubakov, Smirnov ('98)  
[Asaka, Shaposhnikov ('01)]
  - Testable by direct search experiments due to  $M_M < \Lambda_{EW}$

# Motivation

## Probing the Origins of Neutrino Masses and Baryon Asymmetry of the Universe

Especially, we focus on  $\nu_R$ 's with  $M_{1,2} < m_K = 493\text{MeV}$

### (i) Search for $\nu_R$ 's by using K decays

⇒ Estimation of allowed parameter space from experimental and cosmological constraints

### (ii) Verification of this model

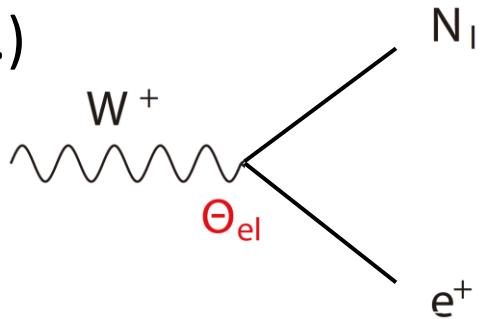
⇒ Determination of all unknown parameters in this model by using various observations

We will take the case of Majorana phase  $\eta$  in this talk

# Constraints of $\nu_R$

## Weak interaction of $\nu_R$

Ex.)



Production:  $\pi^+ \rightarrow e^+ N$  ,  $K^+ \rightarrow \mu^+ N$  , ...

Decay:  $N \rightarrow \nu \bar{\nu}$  ,  $N \rightarrow \nu e^+ e^-$  ,  $N \rightarrow e^+ \pi^-$  , ...

From seesaw mechanism,

$$\nu_{L\alpha} = (U_{PMNS})_{\alpha i} \nu_i + \Theta_{\alpha I} N_I^c \quad \text{and} \quad \nu_R \simeq N$$

**Mixing elements of heavy neutrinos**

$$\Theta_{\alpha I} \equiv \frac{(M_D)_{\alpha I}}{M_I} = \frac{\langle \Phi \rangle F_{\alpha I}}{M_I} \ll 1$$

## Experimental constraints

$\nu_R$ 's have not been discovered

⇒ Upper bounds on the interaction

⇒ Lower bound on the lifetime

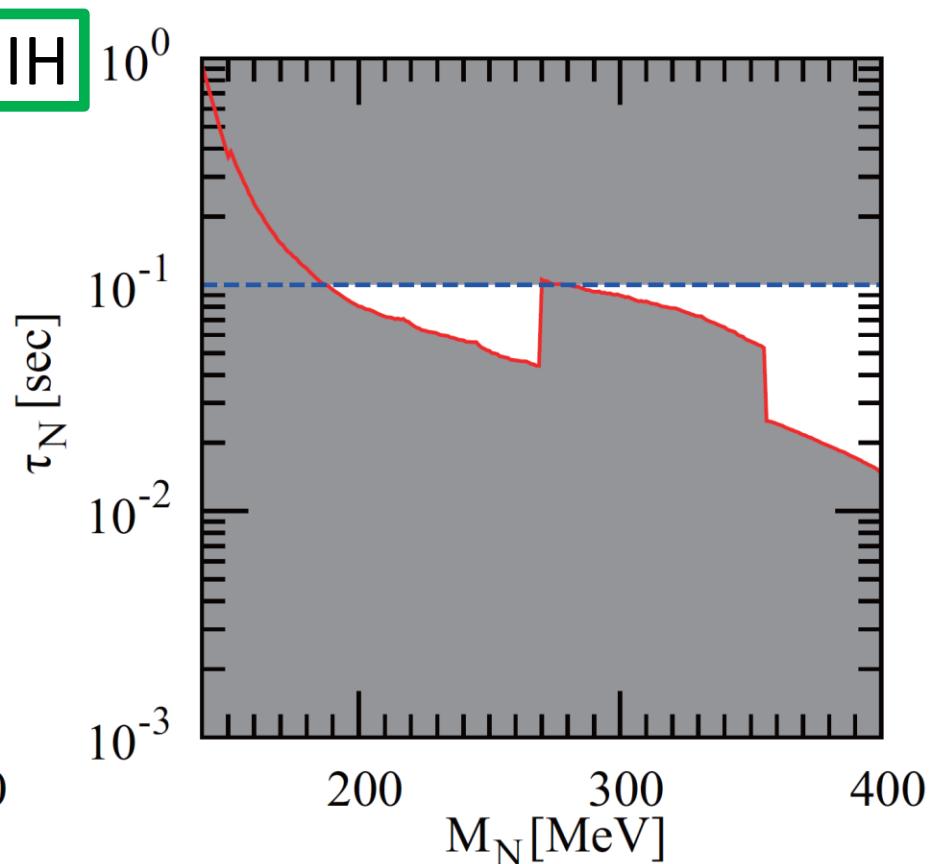
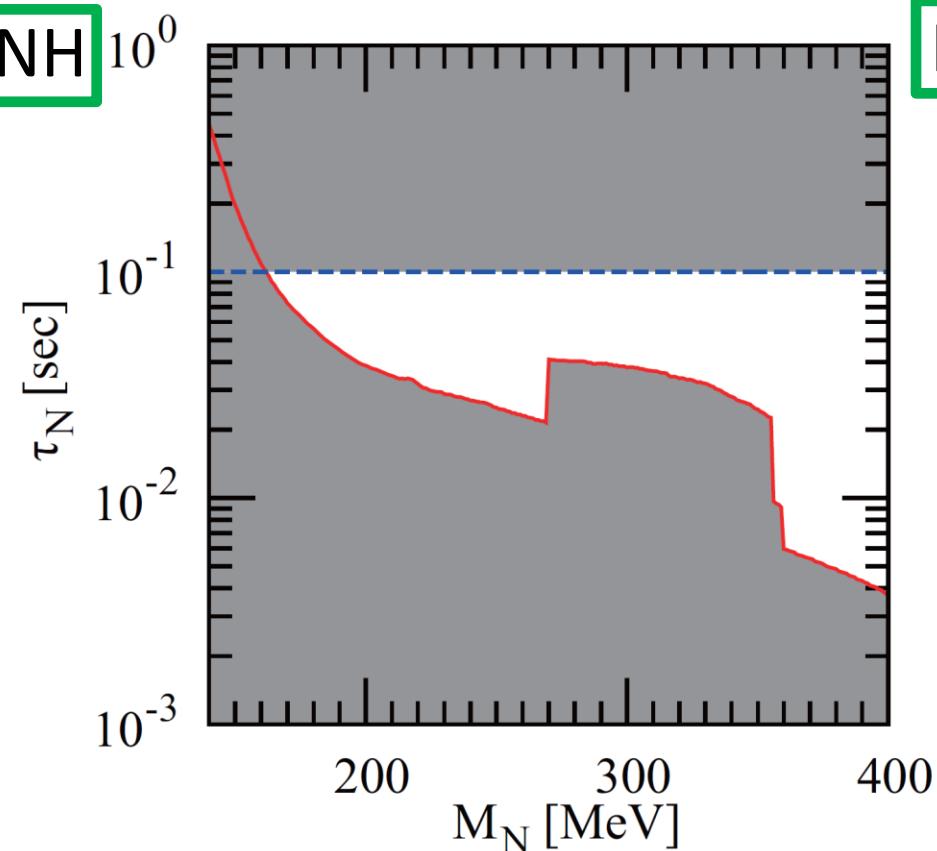
## Cosmological constraints

To keep the success of Big Bang Nucleosynthesis (BBN)

⇒ Upper bound on the lifetime

# Allowed region of $\mathcal{V}_R$

$\theta_{ij}$  and  $\Delta m_{ij}$  are fixed on the central values  
[Fogli et al.('12)]



In the white region,

[Asaka, SE ('13)]

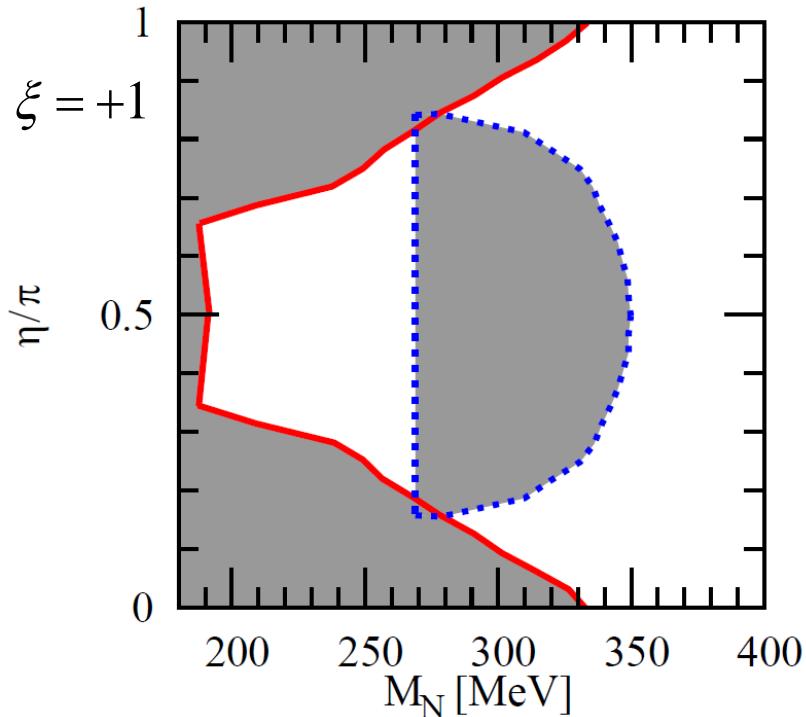
$\mathcal{V}_R$ 's are allowed from the experimental and cosmological constraints

Enough baryon asymmetry is generated  $Y_B^{Max} \geq Y_B^{Obs}$

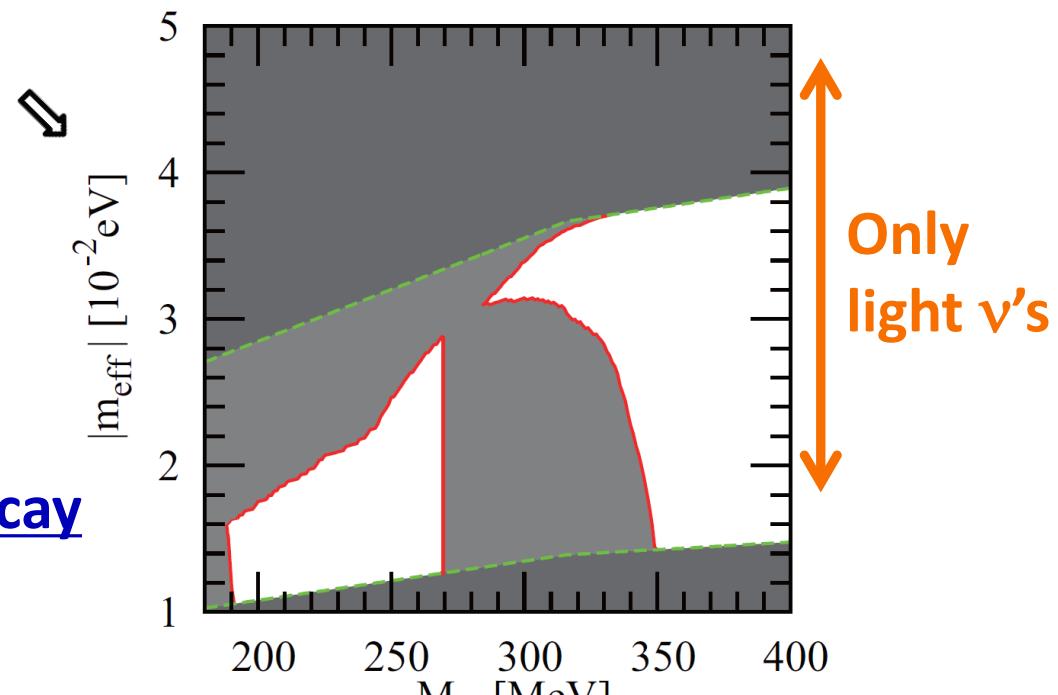
⇒ Neutrino masses and BAU can be explained at the same time

# Restricted Majorana phase and the impact (IH)

[Asaka, SE ('13)]



$\eta$  is restricted by search experiments  
and BBN for  $M_N \lesssim 350\text{MeV}$



## Neutrinoless double beta decay

$$\Gamma_{0\nu 2\beta} \propto m_{\text{eff}}$$

$$|m_{\text{eff}}| = [1 - f_\beta(M_N)] |m_{\text{eff}}^\nu|$$

$$|m_{\text{eff}}^\nu| = \cos^2 \theta_{13} (m_1^2 \cos^4 \theta_{12} + m_2^2 \sin^4 \theta_{12} + 2m_1 m_2 \cos^2 \theta_{12} \sin^2 \theta_{12} \cos 2\eta)^{1/2}$$

⇒ The prediction of  $|m_{\text{eff}}|$  is different from the conventional case

# Majorana phase and direct search for $\nu_R$ (IH)

If  $\nu_R$ 's are discovered by Peak search experiments,

Ex.)  $K^+ \rightarrow e^+ + N_I$   
measured

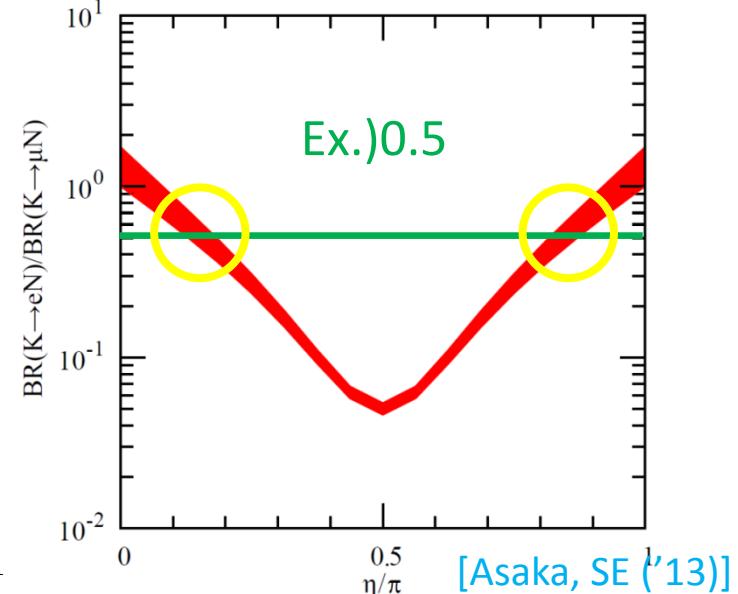
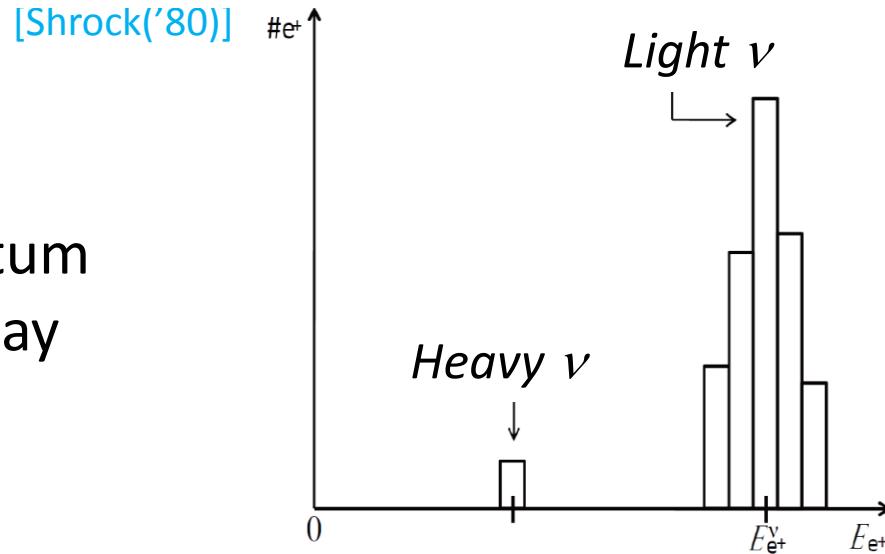
From conservation of momentum  
and energy, and two-body decay

$$E_{e^+} = \frac{1}{2m_K} (m_K^2 + m_e^2 - M_N^2)$$

$$\Rightarrow \frac{\text{BR}(K \rightarrow e + N)}{\text{BR}(K \rightarrow \mu + N)}$$

Once the ratio is measured,  
Majorana phase is limited only  
two points

$$M_N = 250\text{MeV}, \xi = +1$$



# Summary

- We focused on two RH neutrinos explaining neutrino masses and baryon asymmetry of the universe  
Especially, we considered the case for  $M_{1,2} < m_K$
- We estimated the allowed parameter space of  $\nu_R$ 's from experimental and cosmological constraints
  - ⇒ Majorana phase is restricted for  $M_N < 350\text{MeV}$  in IH case and the impact on neutrinoless double beta decay is evaluated
- We discussed determination of unknown parameters to verify this model
  - ⇒ For example, Majorana phase might be determined by direct search experiments of  $\nu_R$ 's and neutrinoless double beta decay experiments in future

*Backup slides*

# Backup slides

Parameters in Yukawa matrix of  $N_{1,2}$

$$F_{\alpha I} = i U_{\text{PMNS}} D_\nu^{1/2} \Omega D_N^{1/2} / \langle \Phi \rangle$$

$$= F \left( \underbrace{\mathbf{m}_1, \mathbf{m}_2, \mathbf{m}_3, \theta_{12}, \theta_{23}, \theta_{13}, \delta, \eta}_{\text{Light } \nu \text{ sector}}, \underbrace{M_N, \Delta M, \text{Re } \omega, \text{Im } \omega, \xi}_{\text{Heavy } \nu \text{ sector}} \right) \quad \begin{matrix} \alpha = e, \mu, \tau \\ [Casas, Ibarra ('01)] \end{matrix} \quad I = 1, 2$$

This sector introduces 12 real parameters in addition to a sign parameter

From oscillation experiments

Global analysis (IH) [Fogli et al. ('12)]	$m_1 = 0.0488 \text{eV}$	$m_2 = 0.0496 \text{eV}$	$m_3 = 0$
	$\sin^2 \theta_{12} = 0.307$	$\sin^2 \theta_{23} = 0.392$	$\sin^2 \theta_{13} = 0.0244$

## 7 Unknown parameters

Dirac phase:  $\delta = [0, 2\pi]$       Majorana phase:  $\eta = [0, \pi]$

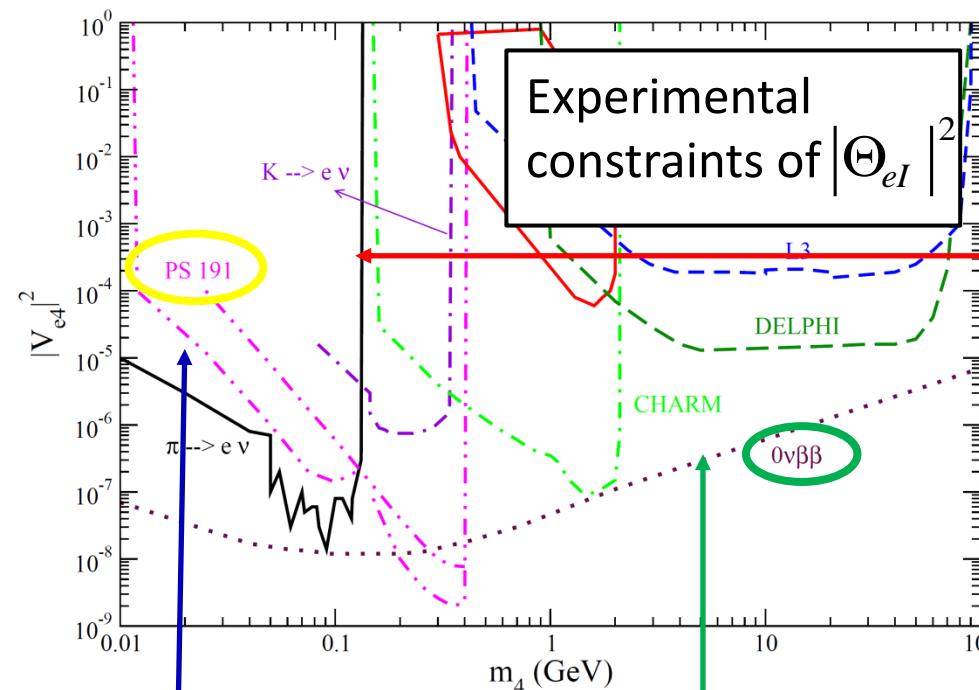
Averaged mass:  $M_N$    Mass difference:  $\Delta M$  ( $\ll M_N$ )   Sign parameter:  $\xi = \pm 1$

Complex parameter  $\rightarrow \text{Re } \omega = [-\pi/2, \pi/2]$        $X_\omega = \exp(\text{Im } \omega) \geq 1$

# Backup slides

## Constraints from search experiments

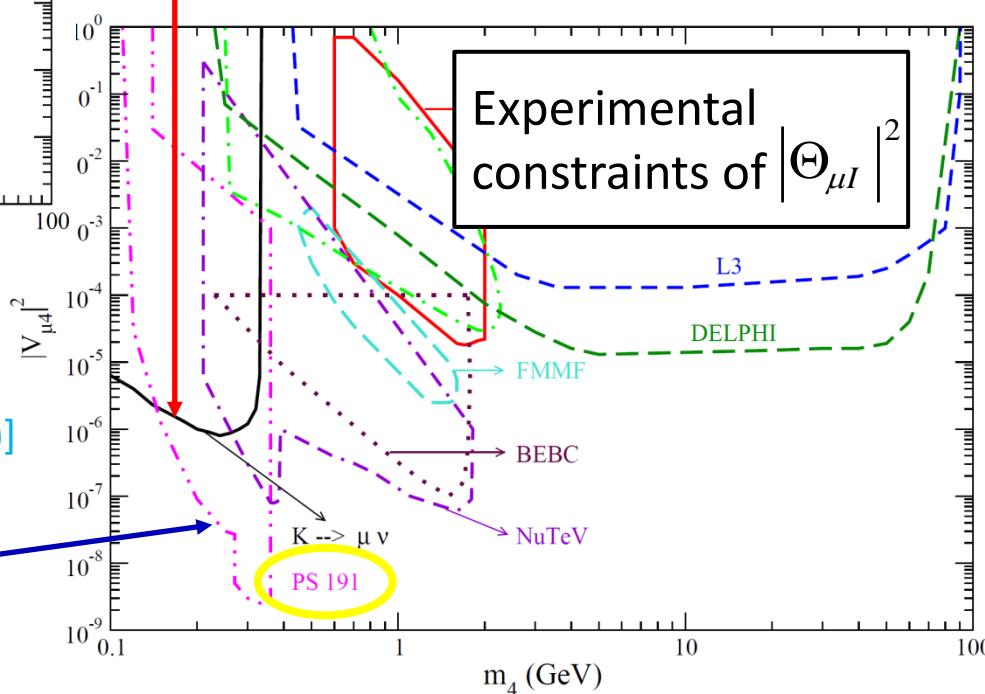
[Atre,Han,Pascoli,Zhang('09)]



This bound is not applied  
to the vMSM [Asaka, SE, Ishida('11)]

Beam dump experiment

Peak search experiment



# Backup slides

## Constraint from Big-Bang Nucleosynthesis (BBN)

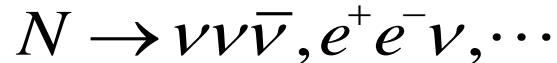
### ■ Speed up effect

$$\rho_{\text{tot}} = \rho_{\text{MSM}} + \rho_{N_2, N_3} \quad \rightarrow \quad H^2 = \rho_{\text{tot}} / 3M_P^2 \quad \uparrow$$

Freeze-out of p-n conversion occurs earlier  $n + \nu \leftrightarrow p + e^-$ , ...

$$n_n/n_p = \exp(-Q/T) \quad (Q = m_n - m_p) \quad \rightarrow \quad {}^4\text{He} \quad \uparrow$$

### ■ Influence of neutrinos out of thermal equilibrium



### ■ Photodissociation, Hadrodissociation, ...

To keep the success of BBN

Upper limit of lifetime

[Dolgov, Hansen, Rafflet, Semikoz ('00)]

$$\tau_N < \begin{cases} 128.7(M_N/\text{MeV})^{-1.828} + 0.04179 \text{ sec} & (M_N \leq m_\pi) \\ 0.1 \text{ sec} & (M_N > m_\pi) \end{cases}$$

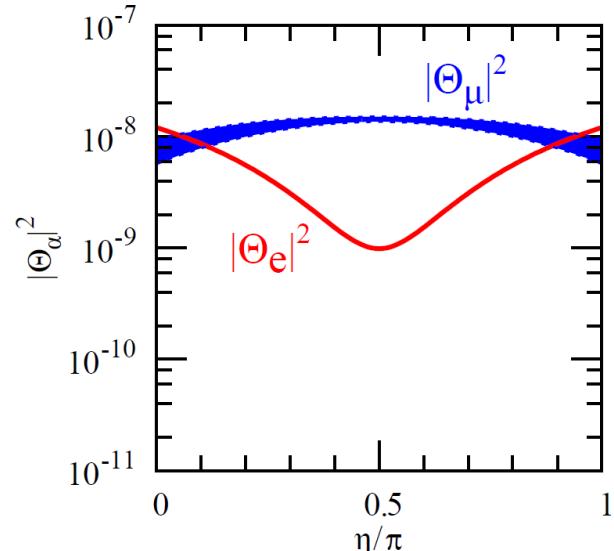
# Backup slides

## Electron and muon elements $(X_\omega \gg 1)$

$$\left[ \begin{array}{l} |\Theta_e|^2 \simeq 1.20 \times 10^{-8} \left( \frac{\text{MeV}}{M_N} \right) (1.000 - 0.925 \xi \sin \eta) X_\omega^2 \\ \\ |\Theta_\mu|^2 \simeq 0.76 \times 10^{-8} \left( \frac{\text{MeV}}{M_N} \right) (1.000 + 0.895 \xi \sin \eta - 0.250 \xi \cos \eta \sin \delta + 0.092 \xi \sin \eta \cos \delta) X_\omega^2 \end{array} \right]$$

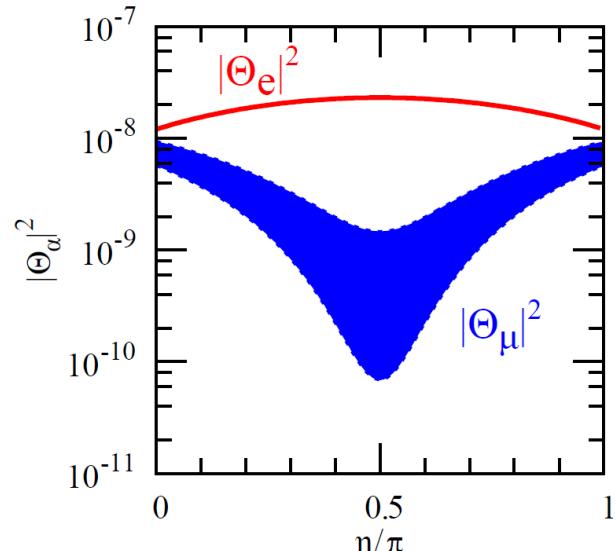
Mixing elements strongly depend on “ $\xi \sin \eta$ ”

$$\xi = +1$$



$$\xi = -1$$

$$\begin{aligned} M_N &= 100 \text{ MeV} \\ X_\omega &= 10 \\ \text{Re } \omega &= 0 \end{aligned}$$

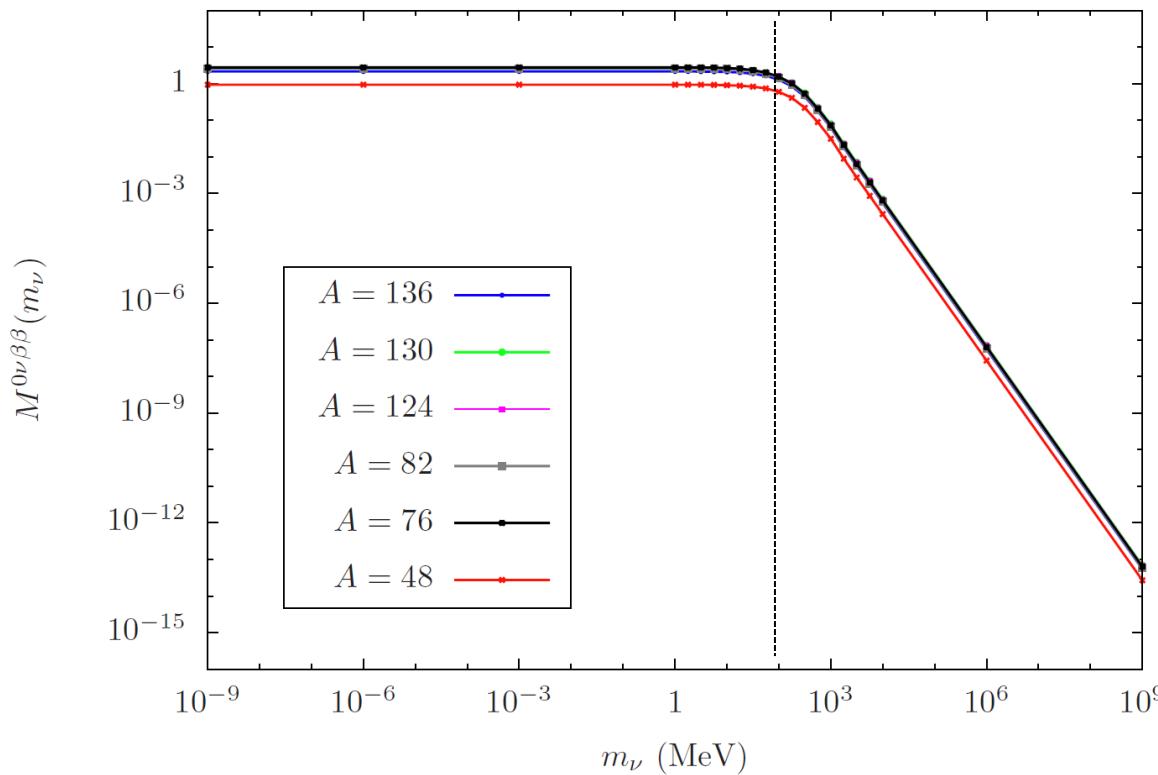


# Backup slides

## Negative contribution from heavy neutrinos for $0\nu 2\beta$ decay

$$f_\beta(M_N) = M^{0\nu\beta\beta}(M_N)/M^{0\nu\beta\beta}(0)$$

Introduced to represent the suppression of the nuclear matrix element depends on  $M_N$  and the atomic number of the decaying nucleus



$$M_N \lesssim 1 \text{ MeV}$$
$$f_\beta(M_N) = 1$$

# Backup slides

## Determination of unknown parameters

(IH) [Asaka, SE ('13)]

All unknown parameters have the potential to be determined from future experiments and cosmological observations.

$0\nu\beta\beta$  experiments

Search experiments by K decays

+  
BBN

7 unknown parameters

$$\delta = [0, 2\pi]$$

$$\eta = [0, \pi]$$

$$M_N$$

$$\Delta M \quad (\ll M_N)$$

$$\xi = \pm 1$$

$$\text{Re } \omega = [-\pi/2, \pi/2]$$

$$X_\omega = \exp(\text{Im } \omega) \geq 1$$

Baryon asymmetry

Oscillation experiments

