Physics of the neutrino masses

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Neutrino properties

- Mixing angles and mass squared differences are measured very precisely
  
  \[ \sin^2 \theta_{12} = 0.308^{+0.013}_{-0.012} \]  
  \[ \Delta m_{21}^2 = (7.49^{+0.19}_{-0.17}) \times 10^{-5} \text{ eV}^2 \]  
  \[ \sin^2 \theta_{23} = 0.440^{+0.023}_{-0.019} \]  
  \[ \Delta m_{31}^2 = (2.526^{+0.029}_{-0.037}) \times 10^{-3} \text{ eV}^2 \]  
  \[ \sin^2 \theta_{13} = 0.02163^{+0.00074}_{-0.00074} \]  
  
- Unknown properties
  
  - Absolute masses of neutrinos \( (m_{\nu_{\text{lightest}}} ? \text{ Mass ordering ?}) \)
  
  - CP violations \( \text{(Dirac phase ? Majorana phase(s) ?)} \)
  
  - Dirac or Majorana fermions

Gonzalez-Garcia, Maltoni and Schwetz \( (\nu\text{-fit, August '16}) \)
Physics of neutrino masses

- These unknown properties are important

- To identify new physics beyond the Standard Model
  - Models of neutrino masses
    - New particles? New interactions?

- To understand other questions in the Standard Model
  - Origin of matter of our universe
    - Baryon asymmetry of the Universe
    - Cosmic dark matter
    - ...
In this talk

- We discuss physics of right-handed neutrino ($\nu_R$)
  - $\nu_R$ and neutrino masses – seesaw mechanism –
  - $\nu_R$ and baryon asymmetry of the universe (BAU)
  - $\nu_R$ and experimental test of model
  - $\nu_R$ and neutrinoless double beta decay
$\nu_R$ and neutrino masses -- seesaw mechanism --
Extension by right-handed neutrinos $\nu_R$

\[ \delta L = i \bar{\nu}_R \gamma^\mu \partial_\mu \nu_R - \left( F \bar{L}_R \Phi + \frac{M_M}{2} \bar{\nu}_R \nu_R^c + h.c. \right) \]

- Seesaw mechanism $(M_D = F \langle \Phi \rangle \ll M_M)$

\[ -L = \frac{1}{2} (\nu_L, \nu_R^c) \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c. = \frac{1}{2} (\nu, N^c) \begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix} \begin{pmatrix} \nu^c \\ N \end{pmatrix} + h.c. \]

- Light active neutrinos $\nu$

\[ M_\nu = - \frac{M_D^T}{M_M} \times M_D \quad \Leftarrow \text{tiny neutrino masses!} \]

\[ \Rightarrow \text{explain neutrino oscillations} \]

- Heavy neutral leptons $N$ $(N \simeq \nu_R)$

- Mass $M_M$
- Mixing $\Theta = M_D / M_M$

\[ \nu_L = U \nu + \Theta N^c \]

Minkowski '77, Yanagida '79
Gell-Mann, Ramond, Slansky '79
Glashow '79,
Mohapatra, Senjanovic '79

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Yukawa coupling and Majorana mass

\[ m_\nu = \frac{M_D}{M_M} \times M_D = \frac{F^2 \langle \Phi \rangle^2}{M_N} \]

\[ F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle} \]

\[ m_\nu = 5 \times 10^{-11} \text{ GeV} \]
\[ |\theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N} \quad m_\nu = 5 \times 10^{-11} \text{ GeV} \]
Range of parameter space

$|\theta_1^2|$ vs $M_1$ [GeV]

Seesaw

$M_2 = M_1$
Bound from seesaw mechanism

- Mixings of HNL must be sufficiently large to explain masses of active neutrinos!

- Bound on the mixing of the lightest HNL $N_1$

\[ |\Theta_1|^2 \geq \frac{m_l}{M_1} \]

\[ |\Theta_1|^2 \equiv \sum_{\alpha=e,\mu,\tau} |\Theta_{\alpha 1}|^2 \]

\[ m_l = \begin{cases} 
  m_1 \ (m_3) \text{ in the NH (IH) for 3RHN ($\mathcal{N} = 3$)} \\
  m_2 \ (m_1) \text{ in the NH (IH) for 2RHN ($\mathcal{N} = 2$)} 
\end{cases} \]

NOTE: $|\Theta_1|^2$ can be zero for $\mathcal{N} = 3$

(No lower bound for $\mathcal{N} > 3$)
Range of parameter space

\[ \Theta \]

Too small neutrino masses

Too large neutrino Yukawa couplings

\[ F^2 > 4\pi \]

\[ N = 2 \]

Seesaw

\[ M_2 = M_1 \]

Cosmology (BBN)

Direct search

TA, Tsuyuki ‘15

\[ M_1 \text{ [GeV]} \]

\[ |\Theta_1|^2 \]

2017/07/17
Baryogenesis regions

Baryogenesis via neutrino oscillation
(Akhmedov, Rubakov, Smirnov ’98, TA, Shaposhnikov ’05)

Resonant Leptogenesis
(Pilaftsis ’97, Pilaftsis, Underwood ’05)

Leptogenesis
(Fukugita, Yanagida ’86)

Baryogenesis regions
ν_{R} and baryon asymmetry of the universe (BAU)
Baryon asymmetry of the universe (BAU)

Baryon Number $B = (\# \text{ of baryons}) - (\# \text{ of antibaryons})$

$$\frac{n_B}{s} = (8.676 \pm 0.054) \times 10^{-11}$$

$n_B$: Baryon number density
$s$: Entropy density

Planck 2015
[arXiv:1502.01589]
Conditions for baryogenesis

- Sakharov (1967)

(1) Baryon number $B$ is violated
(2) $C$ and CP symmetries are violated
(3) Out of thermal equilibrium

“According to our hypothesis, the occurrence of $C$ asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot Universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions.”
Baryogenesis Conditions in the SM

- B+L violations
  - Sphaleron for T > 100 GeV

- C and CP violations
  - 1 CP phase in the quark-mixing (CKM) matrix
    \[ CPV \propto J_{CP}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) / T_{EW}^{12} : 10^{-19} \]
  - too small

- Out of equilibrium
  - Strong 1st order phase transition if \( m_H < 72 \) GeV, but \( m_H = 125 \) GeV
  - not satisfied

[New physics is needed!]

[Kajantie, Laine, Rummukainen, Shaposhnikov]
Baryogenesis conditions and $\nu_R$

- By introducing $\nu_R$, three conditions can be satisfied.

- The way to generate BAU is different depending on the scale of Majorana mass:
  - Leptogenesis
  - Resonant leptogenesis
  - Baryogenesis via neutrino oscillations
Leptogenesis

\[ \nu_R (N) \text{ can into LH leptons and also their anti-particles} \]

\[ \begin{align*}
N_1 & \rightarrow L_L + \Phi \\
& \rightarrow \overline{L}_L + \Phi
\end{align*} \]

- When CP is violated in neutrino sector,

\[ \epsilon_1 = \frac{\Gamma(N_1 \rightarrow L_L + \Phi) - \Gamma(N_1 \rightarrow \overline{L}_L + \Phi)}{\Gamma(N_1 \rightarrow L_L + \Phi) + \Gamma(N_1 \rightarrow \overline{L}_L + \Phi)} \neq 0 ! \]

⇒ generate asymmetry \( \Delta L_L \) between \#\( L_L \) and \#\( \overline{L}_L \)

- Asymmetry in \( L_L \) is partially converted into baryon asymmetry by EW sphaleron process \( (T \gtrsim 10^2 \text{ GeV}) \)

\[ \Delta L_L \Rightarrow B \]
Leptogenesis

- Yield of BAU

\[ \frac{n_B}{s} \propto \varepsilon_1 \propto M_1 \]

\[ M_1 \ll M_{2,3,...} \]

Lower bound on Majorana mass in order to explain the observed BAU

\[ M_1 > \mathcal{O}(10^9) \text{ GeV} \]

→ impossible to test directly such a heavy particle by experiments

[Giudice et al '03]
Resonant leptogenesis

- Resonant production of lepton asymmetry occurs if right-handed neutrinos are quasi-degenerate

\[ \varepsilon_1 = \frac{\Gamma(N_1 \rightarrow L_L + \Phi) - \Gamma(N_1 \rightarrow \bar{L}_L + \Phi)}{\Gamma(N_1 \rightarrow L_L + \Phi) + \Gamma(N_1 \rightarrow \bar{L}_L + \Phi)} \]

\( \Delta M \ll M_N \)

\[ \Delta M = M_2 - M_1 \]

\[ M_N = (M_2 + M_1)/2 \]

\[ \varepsilon_1 \propto \frac{M_N^2}{\Delta M^2} \quad \text{(for } \Delta M^2 > O(M_N \Gamma_N)\text{)} \]

huge enhancement

\[ \Rightarrow \text{ Leptogenesis is possible even for } M_1 \ll 10^9 \text{ GeV} \]

Note that \( M_1 \approx 10^2 \text{ GeV} \) in this case in order to convert lepton asymmetry into baryon asymmetry by EW sphaleron process (\( T \approx 10^2 \text{ GeV} \))
Baryogenesis via Neutrino Oscillation

- Oscillation starts at $T_{osc} \sim (M_0 M_N \Delta M)^{1/3}$

- Asymmetries are generated since evolution rates of $L_\alpha$ and $\bar{L}_\alpha$ are different due to CPV

Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)
Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)
...
Baryogenesis Region

Region accounting for $\frac{n_B}{s} = (8.55-9.00) \times 10^{-11}$

Canetti, Shaposhnikov ‘10

$M_N > 2.1$ MeV (NH)  $M_N > 0.7$ MeV (IH)

TA, Eijima ‘13

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Constraints on HNL

$M_M > 122 \text{ MeV (NH)} \quad M_M > 136 \text{ MeV (IH)}$

$\tau_N < 1 \text{ sec}$
Baryogenesis regions

Baryogenesis via neutrino oscillation
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Resonant Leptogenesis
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Leptogenesis
(Fukugita, Yanagida ‘86)

TA, Tsuyuki ‘15
BAU and CPV in neutrino sector

- Neutrino Yukawa couplings

\[ M_\nu = -M_D^T M_{N,\text{diag}}^{-1} M_D \]

Casas, Ibarra (’01)

\[ F = \frac{i}{\langle \Phi \rangle} U M_{\nu,\text{diag}}^{1/2} \Omega M_{N,\text{diag}}^{1/2} \]

In mixing matrix \( U \)
- of active neutrinos
  - Dirac phase \( \delta \)
  - Majorana phase(s) \( \eta \) (\( \eta' \))

In mixing matrix \( U \)
- of RH neutrinos
  - Phase(s) for \( \nu_R \)

These phases are essential for BAU!
BAU and CPV in neutrino sector

- T2K and NOvA indicate CPV in neutrino sector

**T2K, PRL 118, 151801 ('17)**

Important step to understand baryogenesis by RH neutrinos!
Dirac phase $\delta$ and baryogenesis via oscillation

\[ U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \]

\[ \Omega = \begin{pmatrix} 0 & 0 \\ \cos \omega & -\sin \omega \\ \xi \sin \omega & \xi \cos \omega \end{pmatrix} \]
$\nu_R$ and experimental test of model
Baryogenesis region

**Normal Hierarchy**

- **Bound from BAU** to avoid strong washout
  - Canetti, Shaposhnikov ‘10 [arXiv:1006.0133]
  - Drewes, Garbrecht, Gueter, Klaric ‘16 [arXiv:1609.09069]
  - TA, Eijima, Ishida, Minogawa, Yoshii ‘17 [to appear]

- **Bound from Seesaw** to explain neutrino masses
  - $|\Theta|^2 > \frac{\sum m_i}{2 M_N}$

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Sensitivities by future searches

Normal Hierarchy

From experimental study of $\nu_R$ together with BAU, we may know parameters of the model!
Model with two right-handed neutrinos

- Model parameters

\[ F = \frac{i}{\langle \Phi \rangle} U M_{\nu,\text{diag}}^{1/2} \Omega M_{N,\text{diag}}^{1/2} \]

masses of \( \nu_i \)
\( m_1, m_2, m_3 \)

Mass ordering
mixings of \( \nu_i \)
\( \theta_{23}, \theta_{12}, \theta_{13} \)

Dirac phase
\( \delta \)

Majorana phase
\( \eta \)

masses of \( \nu_R \)
\( M_N, \Delta M \)

How do we determine these unknown parameters?
Consider $\nu_R$ would be discovered with large mixing $\Theta$

- Degenerate mass $M_N$ can be measured
  - NOTE: BAU requires $\Delta M \ll M_N$
- Mixing can be measured $\Rightarrow X_\omega \gg 1$ or $X_\omega \ll 1$ can be measured
  - $|\Theta|^2 = \sum_{\alpha=e,\mu,\tau} |\Theta_{\alpha l}|^2 = \frac{\Sigma m_i}{2 M_N} (X_\omega^2 + X_\omega^{-2})$

- $|\Theta|^2_{e}$, $|\Theta|^2_{\mu}$, and $|\Theta|^2_{\tau}$ depend on Majorana phase $\eta$ and $X_\omega$

The ratio $|\Theta_{\mu}|^2 / |\Theta_{e}|^2$ may determine $\eta$

We may also learn whether $X_\omega \gg 1$ or $X_\omega \ll 1$
Baryon asymmetry

- Re\(\omega\) and \(\Delta M\) are difficult to be probed by search experiments, since |\(\Theta_{\alpha l}\)| are insensitive in large mixing region
- BAU is crucial to determine them

Mixing angle Re\(\omega\) between two RH neutrinos

BAU (sign and magnitude) can indicate the region of

Re\(\omega\) and \(\Delta M\)
Model with two right-handed neutrinos

- **Model parameters**

  \[ F = U_{\text{PMNS}} M_v^{1/2} \Omega M_M^{1/2} \]

  - Masses of \( \nu_i \) \( m_1, m_2, m_3 \)
  - Mass ordering
  - Mixings of \( \nu_i \) \( \theta_{23}, \theta_{12}, \theta_{13} \)
  - Dirac phase \( \delta \)
  - Majorana phase \( \eta \)
  - Masses of \( \nu_R \) \( M_N, \Delta M \)

  \[ \Omega = \begin{pmatrix} 0 & 0 \\ \cos \omega & -\sin \omega \\ \sin \omega & \cos \omega \end{pmatrix} \]

  \[ \Re \omega, \quad X_\omega = e^{i m_\omega} \]

  - Oscillation experiments
  - Search experiments
  - Baryon asymmetry

Casas, Ibarra (01)
$\nu_R$ and neutrinoless double beta decay
Neutrinoless double beta ($0\nu\beta\beta$) decay

- Neutrinoless double beta ($0\nu\beta\beta$) decay
  
  $$(Z, A) \rightarrow (Z + 2, A) + 2e^-$$

- LNV ($\Delta L = +2$) process mediated by Majorana massive neutrinos

- Half-life of $0\nu\beta\beta$ decay
  
  $$T_{1/2}^{-1} = A \frac{m_p^2}{\langle p^2 \rangle^2} |m_{\text{eff}}|^2$$

  $$m_{\text{eff}} = \sum_{i=1,2,3} m_i U_{ei}^2 + ...$$

W.H. Furry 1939

Faessler, Gonzalez, Kovalenko, Simkovic ‘14
$0\nu\beta\beta$ decay in the seesaw

$$m_{\text{eff}} = \sum_{i=1,2,3} m_i U_{ei}^2 + \sum_I f_\beta(M_I) M_I \Theta_{ei}^2$$

active neutrinos

heavy neutral leptons

HNLs may give a significant contribution to $m_{\text{eff}}$!

$$m_{\text{eff}}^N = \begin{cases} 
M_I \Theta_{ei}^2 & (M_I^2 \ll \langle p \rangle^2) \\
\frac{\langle p \rangle^2}{M_I} \Theta_{ei}^2 & (M_I^2 \gg \langle p \rangle^2) 
\end{cases}$$

$$f_\beta(M_I) = \frac{\langle p \rangle^2}{\langle p \rangle^2 + M_I^2}$$

$$\sqrt{\langle p \rangle^2} \sim 200 \text{ MeV}$$

Faessler, Gonzalez, Kovalenko, Simkovic ‘14
$0\nu\beta\beta$ decay in the seesaw

- When all HNLs are degenerate $M_I = M_N$,

$$m_{\text{eff}} = \sum_i m_i U_{ei}^2 + \sum_i f_\beta(M_I) M_I \Theta_{ei}^2 = m^v_{\text{eff}} \left[ 1 - f_\beta(M_N) \right]$$

- This shows $0\nu\beta\beta$ decay does not depend on the mixing of HNL
- In this case, there is no bound on the mixing from $0\nu\beta\beta$ decay
Recently, it has been pointed out that $\nu_R'$'s give a significant, additive contribution to effective mass for IH and $M_N \sim 500$ MeV when $\Delta M$ is relatively large.

Drewes, Eijima (‘16), TA, Eijima, Ishida (‘16), Hernandez, Kekic, Lopez-Pavon, Racker, Salvado (‘16)

It is an interesting signal of $\nu_R'$'s for the seesaw mechanism and baryogenesis via neutrino oscillation!
Summary

- Right-handed neutrinos are well-motivated physics beyond the Standard Model

- They can explain neutrino masses through the seesaw mechanism and baryon asymmetry of the universe (BAU) (via leptogenesis, neutrino oscillation, …) at the same time.

- Experimental tests of such right-handed neutrinos are important to understand the origin of neutrino masses and BAU
Backup
Evolution of Each Asymmetry

Active Sector

$\Delta L_{\mu, \tau}$

$\Delta L_{\mu, \tau}$

$\Delta N_{2,3}$

$\Delta N_{2,3}$

Sterile Sector

$T_{osc} = 2.2 \text{ TeV}$
Shaleron converts $\Delta L$ partially into baryon asymmetry

[Kuzmin, Rubakov, Shaposhnikov]

$$B = -\frac{28}{79} \Delta L_{\text{tot}} \neq 0$$

$$\frac{n_B}{s} = -2.5 \times 10^{-4} \Delta L_{\text{tot}}(T_W)$$

$$\frac{n_B}{s} = (8.579 \pm 0.109) \times 10^{-11}$$

[Planck 2013]
Key Point

Baryogenesis via Leptogenesis

B L

sphaleron

B L

Baryogenesis via Neutrino Oscillation

B L

sphaleron

B L

\( B_R \)

\( L_L \)
Regions accounting for BAU

\[
\frac{n_B}{s}_{\text{obs}} = (8.81 \pm 0.23) \times 10^{-11}
\]

Inputs:

- \( M_3 = 3\text{GeV} \)
- \( M_2^2 = M_3^2 (1 - 10^{-8}) \)
- \( \sin \theta_{13} = 0.2 \)

\[
\Omega = \begin{pmatrix}
0 & 0 \\
\cos \omega & -\sin \omega \\
\xi \sin \omega & \xi \cos \omega
\end{pmatrix}
\]
0νββ \textit{decay in the seesaw}

- Seesaw relation plays an important role!

\[
0 = \sum_i m_i U_{ei}^2 + \sum_l M_l \Theta_{ei}^2
\]

- When all HNLs are light \( M_l \ll \sqrt{\langle p^2 \rangle} \sim 0.1 \text{ GeV} \) (i.e. \( f_\beta = 1 \)),

\[
m_{\text{eff}} = \sum_i m_i U_{ei}^2 + \sum_l f_\beta(M_l) M_l \Theta_{ei}^2 = 0
\]

- This shows 0νββ decay does not occur even if neutrinos are Majorana fermions.
- In this case, there is no bound on the mixing from 0νββ decay
Upper bound on mixing from BAU

- Large mixing region
  - good for search of HNLs
  - bad for strong washout of BAU

- Large mixing means ...

\[
\Theta_{\alpha l} = \frac{[M_D]_{\alpha l}}{M_I} = \frac{F_{\alpha l} \langle \Phi \rangle}{M_I}
\]

→ large Yukawa couplings

→ thermalization of $\nu_R$

→ strong washout of BAU

TA, Eijima, Ishida, Minogawa, Yoshii '17 [to appear]
Mass difference of $\nu_R$

- $\Delta M$ is important parameter for baryogenesis
  - CP asymmetry
  - Oscillation temperature

$$T_{osc} \approx (M_0 M_N \Delta M)^{1/3}$$

![Graph showing mass difference and yield](image)

$Y_B$ vs $\Delta M$ for $M_N = 3$ GeV, $X_\omega = 1$

$Y_B^{obs} = 8.6 \times 10^{-11}$

![Graph showing mass difference and CP asymmetry](image)

$\Delta M$ in GeV for $M_N = 3$ GeV

- NH, $X_\omega = 150$
- IH, $X_\omega = 150$
- IH, $X_\omega = 1/150$

Position is temporary.

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Limits on the mixing $\Theta_{\mu I}$
BBN Constraint on Lifetime

- Long-lived $N_{2,3}$ may spoil the success of BBN
  - Speed up the expansion of the universe
    - $\rho_{\text{tot}} = \rho_{\text{MSM}} + \rho_{N_{2,3}} \Rightarrow H^2 = \frac{\rho_{\text{tot}}}{3 M_p^2}$
    - p-n conv. decouples earlier $\Rightarrow$ overproduction of $^4\text{He}$
      - $n + \nu \leftrightarrow p + e^-, ...$
  - Distortion of spectrum of active neutrinos
    - $N_{2,3} \rightarrow \nu \bar{\nu}, e^+ e^- \nu, ...$
    - Additional neutrinos may not be thermalized
      - $\Rightarrow$ Upper bound on lifetime

- Dolgov, Hansen, Rafflet, Semikoz (’00)
  - One family case:
    - $\tau_N < 0.1 \text{ sec for } M_N > m_\pi$
$$\delta_\nu = \frac{1}{2} \sin \theta_{12} \sin 2\theta_{13} [\cos^2 \theta_{13} (3 + \cos 4\theta_{23}) - 4 \sin^2 \theta_{13}] \sin(\delta + \eta)$$

$$+ \cos \theta_{12} \sin 4\theta_{23} \cos^3 \theta_{13} \sin \eta + \mathcal{O}(r_m).$$

$$r_m = m_{\text{sol}} / m_{\text{atm}} = 0.18$$

- When $\theta_{23} = \pi/4$ (maximal)
  - $\text{BAU} \propto \sin(\delta + \eta)$
- When $\theta_{13} = 0$
  - $\text{BAU} \propto \sin \eta$

- When $\theta_{23} = \pi/4$ and $\theta_{13} = 0$
  - $\delta_\nu = 0$

No BAU is generated!
$0\nu\beta\beta$ decay

- Contribution from active neutrinos

$$m_{\text{eff}}^\nu = \sum_{i=1,2,3} m_i U_{ei}^2$$

Planck 2015

$$\Sigma m_i < 0.23 \text{ eV}$$

$$m_{\nu \text{lightest}} < 0.07 \ (0.06) \text{ eV}$$

$$m_{\text{eff}} \approx (0.185 - 0.276) \text{ eV}$$

KamLAND-Zen 1211.3863 $^{136}\text{Xe}$

$$m_{\text{eff}} \approx (0.213 - 0.308) \text{ eV}$$

GERDA 1307.4720 $^{76}\text{Ge}$

2017/07/17
LNV in the seesaw

- Other LNV processes induced by Majorana HNL in the seesaw mechanism

- $pp \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ j j \quad @LHC$
- $B^+ \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ \pi^- \quad @SuperKEKB$
- $K^+ \rightarrow \ell^+ N \rightarrow \ell^+ \ell^+ \pi^- \quad @J-PARC$
- $e^- e^- \rightarrow W^- W^- \quad @ILC, FCC-ee$
- ...

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