Probing baryon asymmetry by light right-handed neutrinos

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SM with TWO RH neutrinos

Introduce two RH neutrinos ν_{R2}, ν_{R3}

$$\delta L = i\overline{\nu_{RI}}\partial_\mu\gamma^\mu\nu_{RI} - F_{\alpha I}\overline{L_\alpha}\nu_{RI}\Phi - \frac{M_I}{2}\overline{\nu_{RI}}\nu_{RI}^c + \text{h.c.}$$

$I = 2,3$

$\alpha = e, \mu, \tau$

- Explain neutrino masses by seesaw mechanism
  - Light (active) neutrinos ν_1, ν_2, ν_3
  - **Heavy neutrinos** N_2, N_3
- Explain baryon asymmetry by RH neutrinos
  - Mechanism depends on masses of heavy neutrinos
    ex) Leptogenesis, Baryogenesis via Neutrino Oscillation
    Fukugita, Yanagida (86) Akhmedov, Rubakov, Smirnov (98)
- Heavy neutrinos can be tested directly by experiments, if their masses are small enough

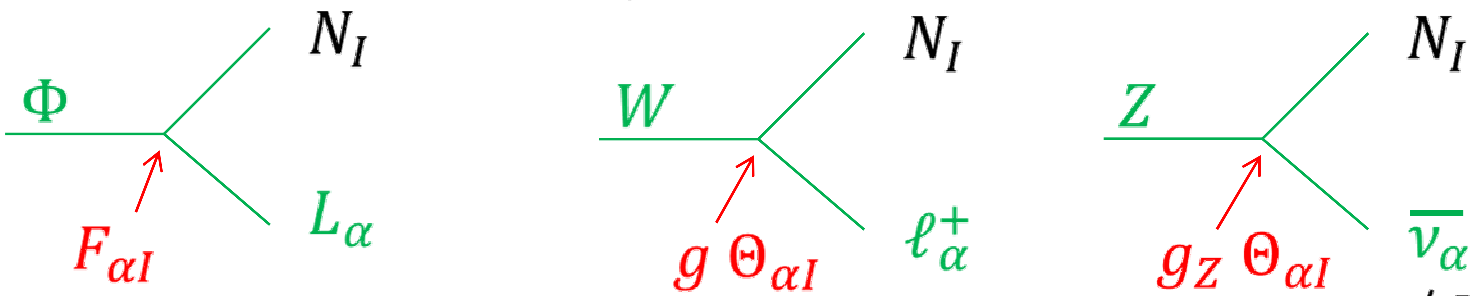
In this talk

Consider two quasi-degenerate (RH) heavy neutrinos N_2, N_3

- Lighter than charged kaon mass $M_{2,3} < m_K$
  $\longrightarrow$ Test by Kaon decays ($K^+ \to \ell^+ N_I$) is possible
- Quasi-degenerate $M_3 - M_2 = \Delta M \ll 2M_N = M_3 + M_2$
  $\longrightarrow$ Baryogenesis via neutrino oscillation is possible

Can we determine all the parameters of the model by experiments and cosmological observations ?

- Interactions of heavy neutrinos



$$\nu_{L\alpha} = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c \qquad \Theta_{\alpha I} = \frac{\langle\Phi\rangle F_{\alpha I}}{M_I}$$

$F_{\alpha I}$ determine the interactions

Yukawa couplings for $N_{2,3}$

$$F = U_{\mathrm{PMNS}}\, D_\nu^{1/2}\, \Omega\, D_N^{1/2} / \langle \Phi \rangle$$ (in IH)

Casas, Ibarra (01)

- Parameters of light (active) neutrinos

$D_\nu^{1/2} = \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3} = 0)$: ν masses

Dirac phase δ

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\eta} & \\ & & 1 \end{pmatrix}$$

Majorana phase η

- Parameters of heavy neutrinos

$D_N^{1/2} = \mathrm{diag}(\sqrt{M_2}, \sqrt{M_3})$: N masses

$$\Omega = \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$$

Complex number ω

Sign parameter $\xi = \pm 1$

Parameters of 2RHν model (IH)

- Global analysis   Fogli et al (12)

$\sin^2\theta_{12} = 0.307$ $\sin^2\theta_{23} = 0.392$ $\sin^2\theta_{13} = 0.0244$

$m_2 = 0.0496$ eV $m_1 = 0.0488$ eV $m_3 = 0$

- **Unknown parameters**

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

$\eta = [0,\pi]$

$\xi = +1,-1$

M_N

$\Delta M \ (\ll M_N)$

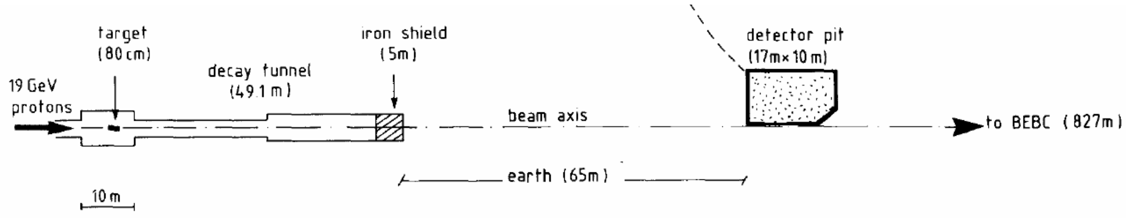
$\mathrm{Re}\omega = [-\frac{\pi}{2},\frac{\pi}{2}]$

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

What can we learn from present experiments and cosmological observations ?

Direct search experiments

- PS191 experiment   PLB203,332 (1988)
  - Production $\pi^+, K^+ \to e^+ N, \mu^+ N$
  - Detection $N \longrightarrow \ell^+ \ell^- \nu, \ell^+ \pi^-$



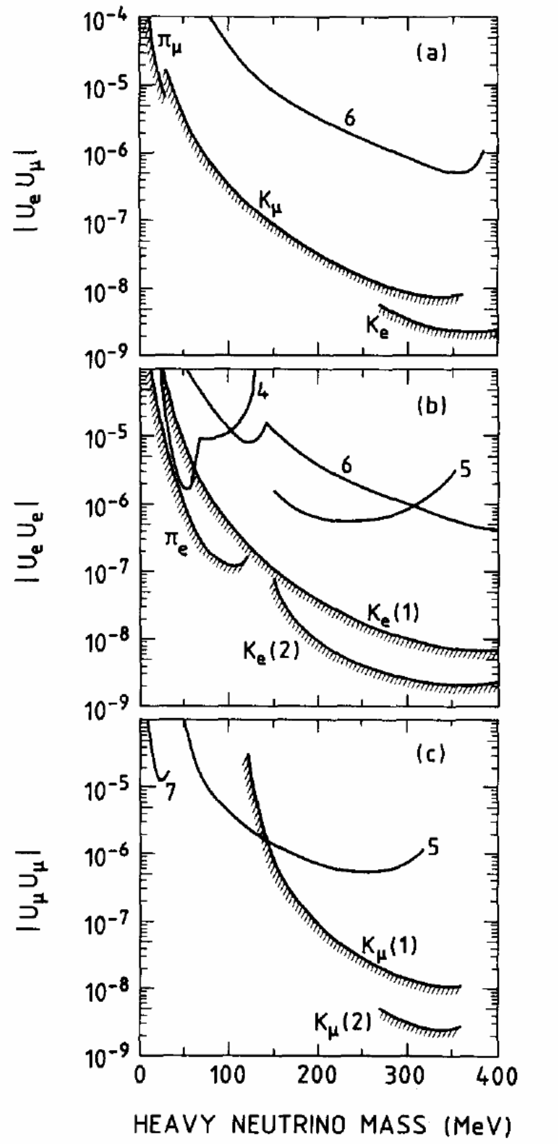
- Upper bounds

$$\boxed{|\Theta_{\alpha I}|^2 \left(a|\Theta_{eI}|^2 + b|\Theta_{\mu I}|^2 + c|\Theta_{\tau I}|^2\right)}$$

a, b, c: depends on M_N and search channel

Ruchayski, Ivashko '12

- Majorana (rather than Dirac)
- Not only CC but also NC contributions
- Two quasi-degenerate heavy neutrinos (N_2, N_3)



BBN constraint

- Heavy neutrino decays

  $N_I \to 3\nu, \ell^+\ell^-\nu, \pi^0\nu, \pi^+\ell^-$

  $\longrightarrow N_I$ is long lived particle

- To keep the success of BBN

  $\longrightarrow \tau_N < 0.1$ sec

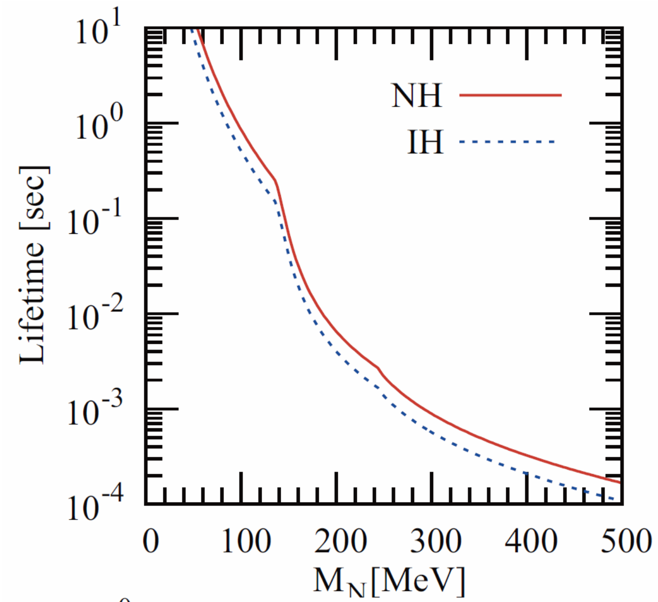
  Dolgov, Hansen, Rafflet, Semikoz ('00)

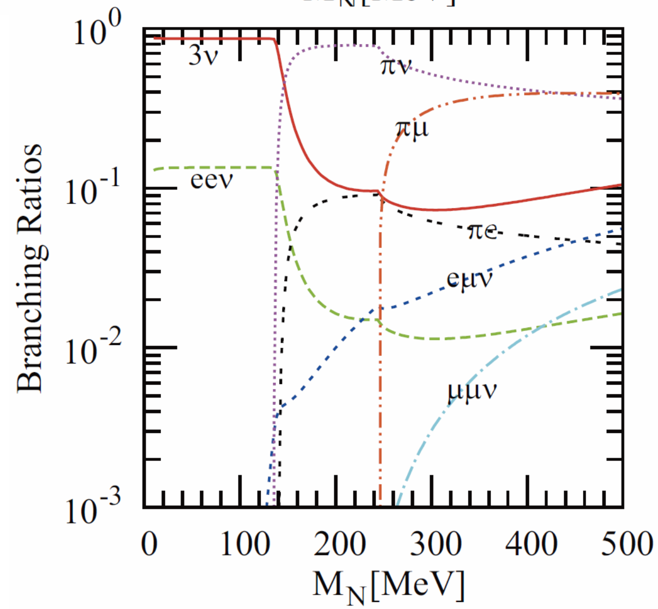
- **Lower bounds**

$$\boxed{a'|\Theta_{eI}|^2 + b'|\Theta_{\mu I}|^2 + c'|\Theta_{\tau I}|^2}$$

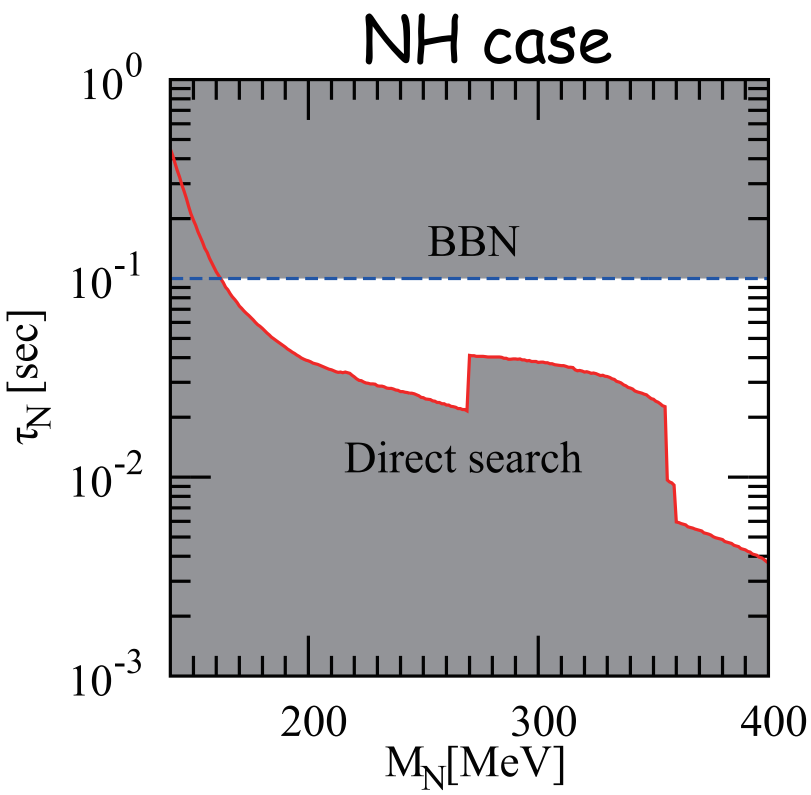
Together with search bounds, we obtain allowed range !

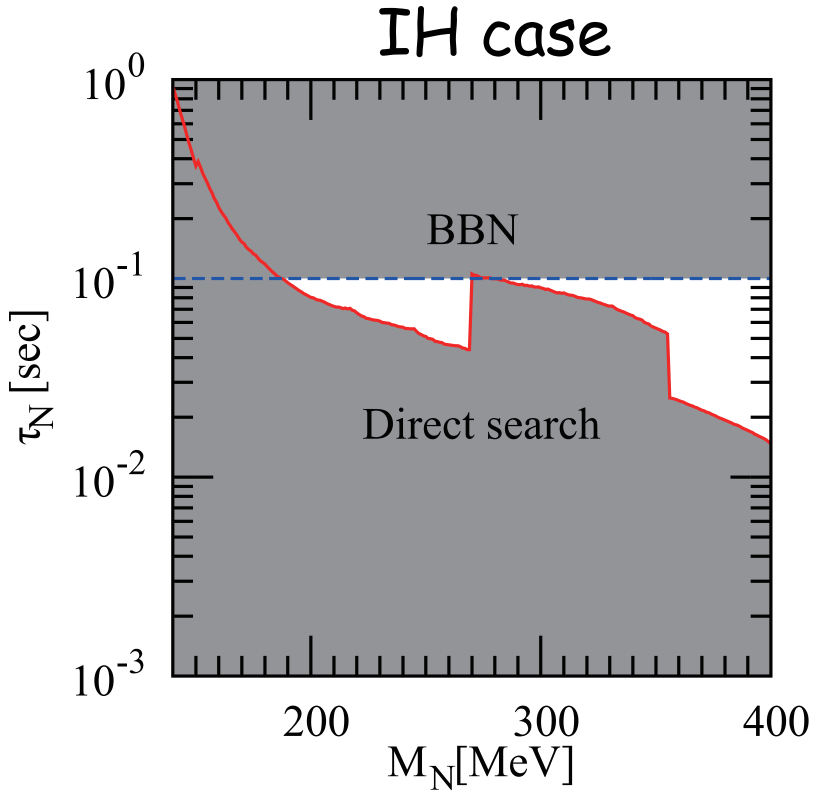
Gorbunov, Shaposhnikov (07), Ruchayski, Ivashko (12)





Allowed range of M_N

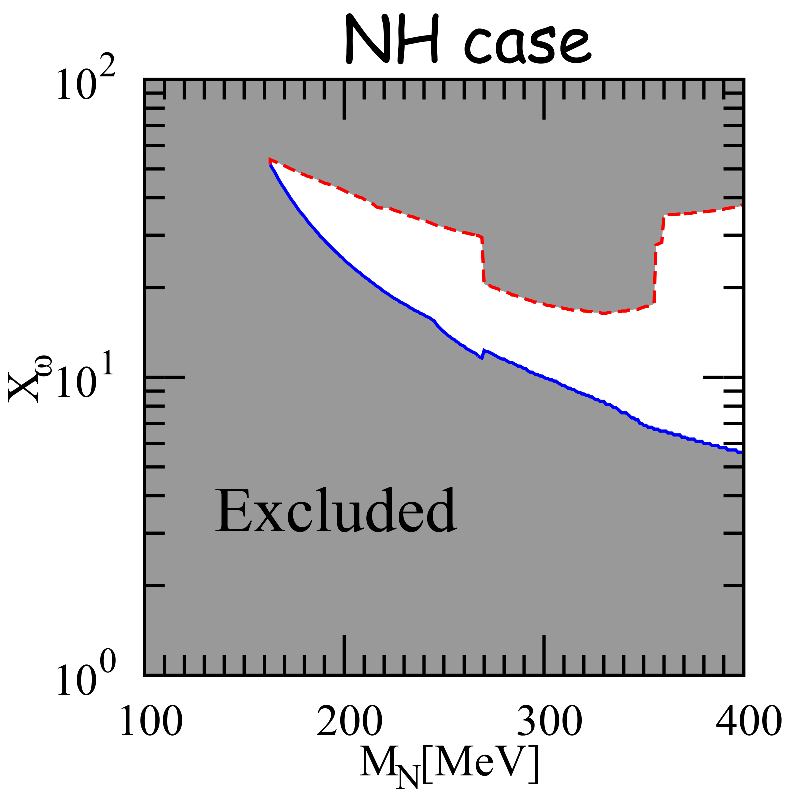


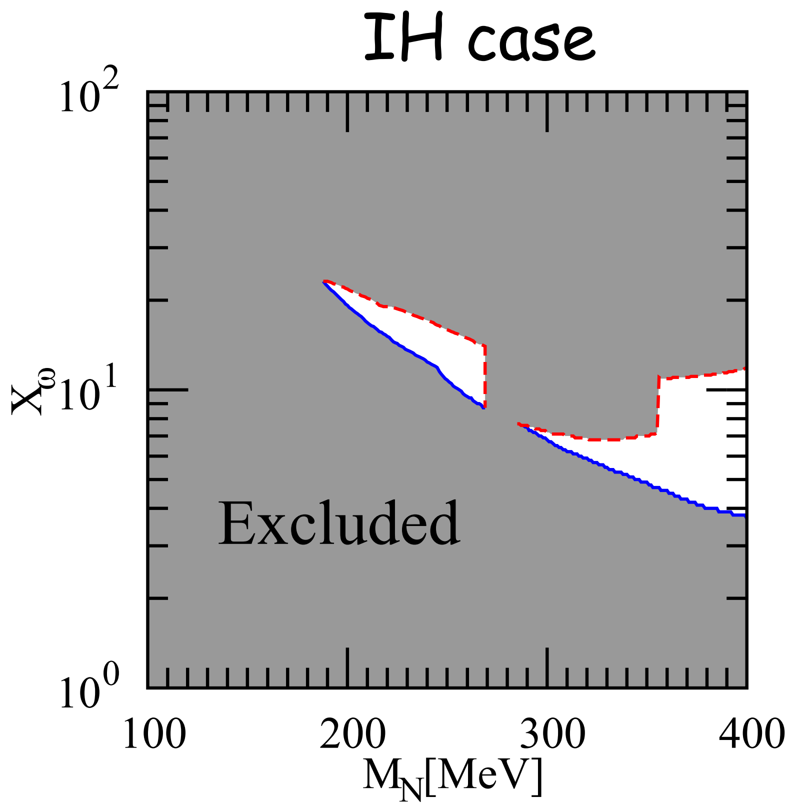


We can obtain allowed range of $X_\omega = \exp(\mathrm{Im}\omega)$

$\because\ \Gamma_N = \tau_N^{-1} \propto \Theta^2 \propto F^2$ and $F \propto X_\omega$ for large $\mathrm{Im}\omega$

Allowed range of X_ω





We find other interesting information in IH case !

Mixing elements in IH case

Mixing elements of heavy neutrinos

- Since $\Delta M \ll M_N$ and $X_\omega \gg 1$, mixing elements of N_2 and N_3 are the same

$$\Theta_{\alpha 2} = \Theta_{\alpha 3}$$

TA, Eijima, Ishida ('11)

- Mixing elements strongly depend on "$\xi \sin \eta$"

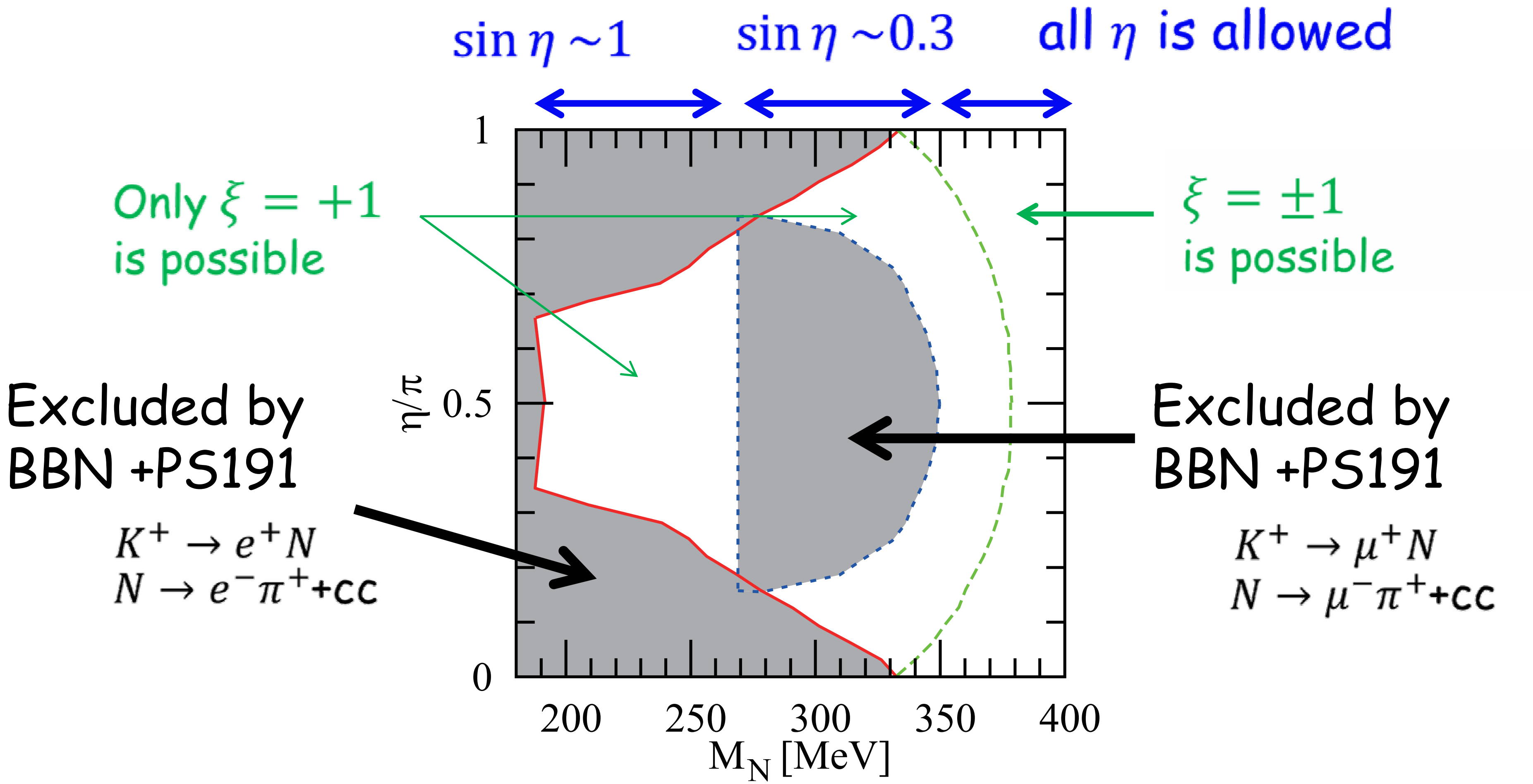
$$|\Theta_e|^2 \simeq 1.20 \times 10^{-8} \left(\frac{\mathrm{MeV}}{M_N}\right) (1.000 - 0.925 \xi \sin \eta) X_\omega^2,$$

$$|\Theta_\mu|^2 \simeq 0.76 \times 10^{-8} \left(\frac{\mathrm{MeV}}{M_N}\right) (1.000 + 0.895 \xi \sin \eta - 0.250 \xi \cos \eta \sin \delta + 0.092 \xi \sin \eta \cos \delta) X_\omega^2,$$

$$|\Theta_\tau|^2 \simeq 0.50 \times 10^{-8} \left(\frac{\mathrm{MeV}}{M_N}\right) (1.000 + 0.860 \xi \sin \eta + 0.380 \xi \cos \eta \sin \delta - 0.140 \xi \sin \eta \cos \delta) X_\omega^2.$$

We find allowed range of Majorana phase !

Majorana phase in IH case



Future search experiments by Kaon decays can provide strong information on Majorana phase

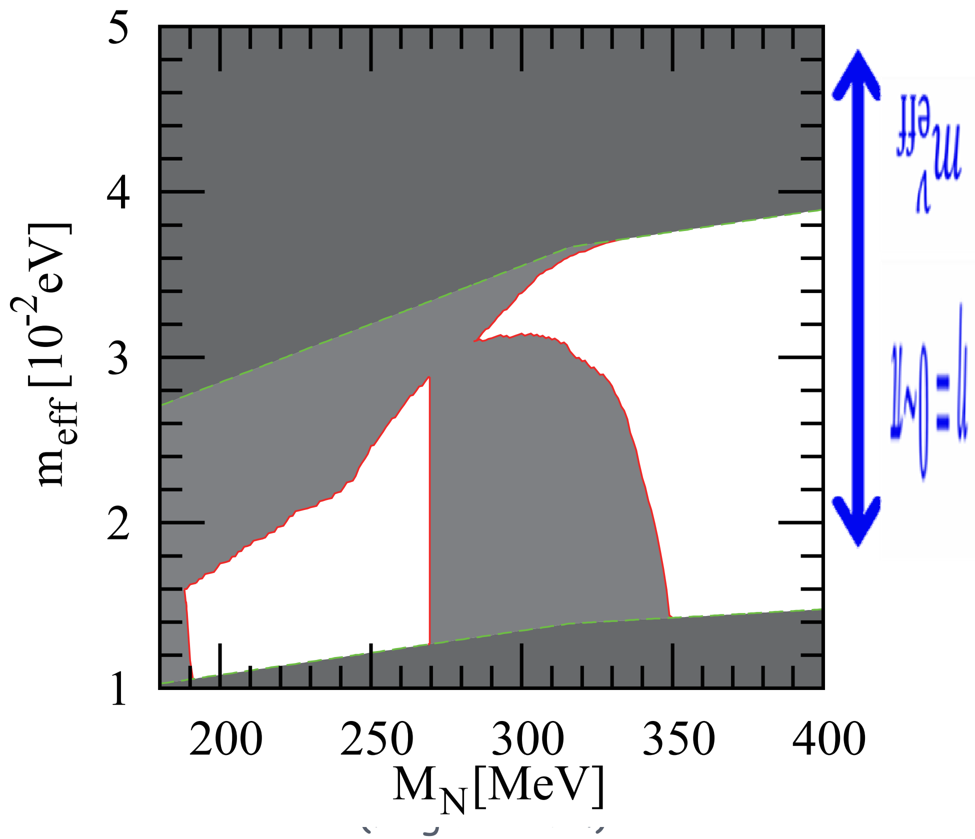
$0\nu\beta\beta$ decays in IH

Effective neutrino mass from light and heavy neutrinos

$$m_{\rm eff} = m_i U_{ei}^2 + f_\beta(M_I) M_I \Theta_{eI}^2 = \left[1 - f_\beta(M_N)\right] m_{\rm eff}^\nu$$

TA, Eijima, Ishida ('11)

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



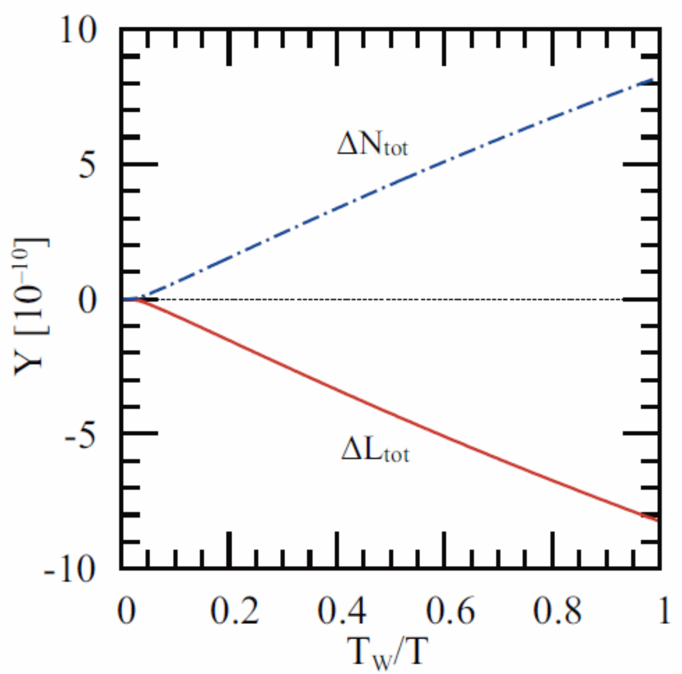
- Heavy neutrinos give negative contribution to m_{eff}
- Constraint on η restricts the predicted range of m_{eff}

Baryon asymmetry

Oscillation of heavy neutrinos can be a source of BAU

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)

- CPV in oscillation and production generates asymmetries
- Asymmetries are separated into LH and RH leptons
- Asymmetry in LH leptons is converted into BAU

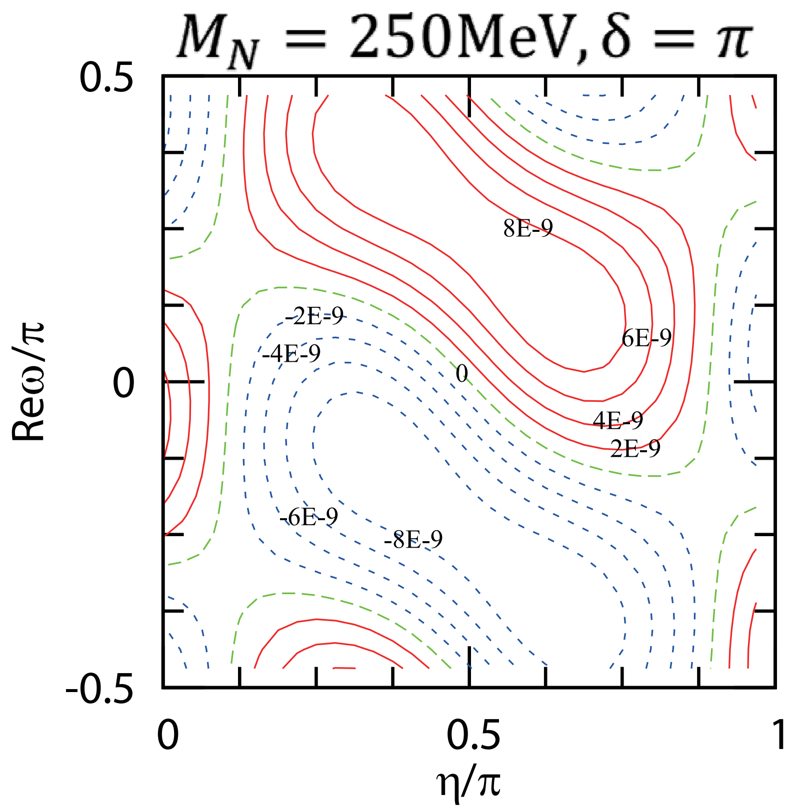


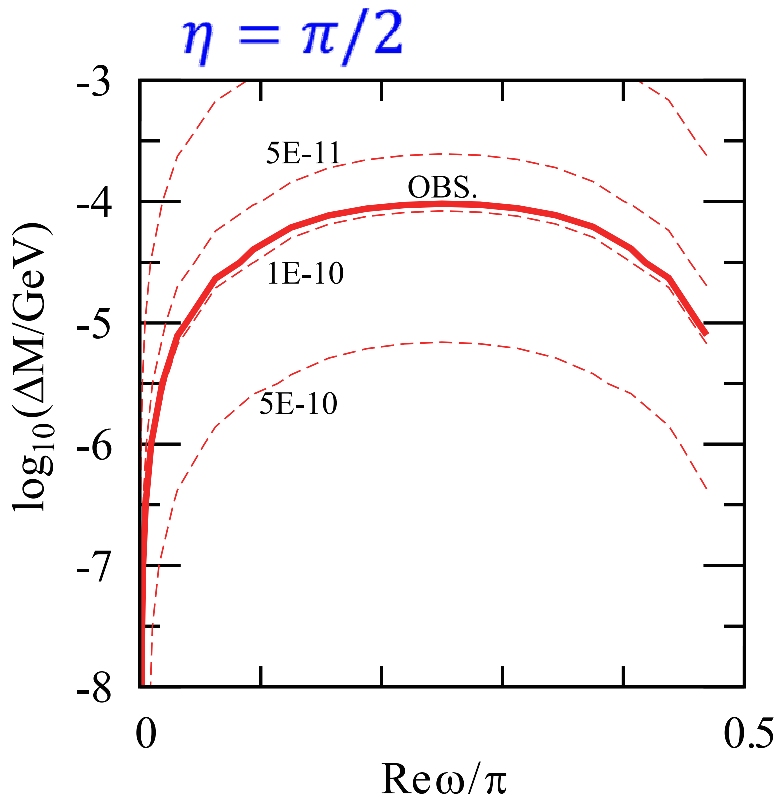
BAU can provide information on $F_{\alpha I}$ since generation of asymmetry is controlled by $F_{\alpha I}$

Especially, CP violating parameters and mass difference

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

Reω, ΔM and BAU (IH)





- η and Reω are important for the sign of BAU
- Correct sign of BAU restricts the region of Reω depending on η

- Once η is determined, we obtain the relation between Reω and ΔM
- Together with measurement of δ we may probe ΔM if Reω is away from 0 and $\pi/2$

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- Free parameters

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

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M_N

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$\mathrm{Re}\,\omega = [-\frac{\pi}{2}, \frac{\pi}{2}]$

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

Future

Oscillation experiments

Present and future

Search experiments in K decays (beam dump/ peak search) + BBN

Future

$0\nu\beta\beta$ experiments

Present

Baryon asymmetry

Summary

- Two right-handed neutrinos offer
  - Seesaw mechanism for neutrino masses
  - Baryogenesis for baryon asymmetry of the universe

- When heavy neutrinos are quasi-degenerate with M_N ~ 200-400MeV,

we may have a chance to test directly the origin of neutrino masses and baryon asymmetry by using kaon decays !