Neutrino mass and baryon asymmetry in two right-handed neutrino model

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Introduction : Two Right-handed Neutrinos

SM extended by **two Right-handed (RH) neutrinos**

$$L = L_{\rm SM} + i\bar{\nu}_{RI}\partial_\mu\gamma^\mu\nu_{RI} - F_{\alpha I}\bar{L}_\alpha\Phi\nu_{RI} - \frac{M_I}{2}\bar{\nu}^c_{RI}\nu_{RI} + h.c. \qquad \alpha = e,\mu,\tau \quad I = 2,3$$

Neutrino masses $\Delta m^2_{\rm atm},\ \Delta m^2_{\rm sol}$ $\qquad M_I \gg M_D \equiv \langle\Phi\rangle F$

Seesaw mechanism →
- Light (active) neutrinos $\nu_1 \quad \nu_2 \quad \nu_3$
- Heavy neutrinos $N_2 \quad N_3$

Baryon Asymmetry of the Universe (BAU)

ex) Leptogenesis [Fukugita, Yanagida('86)]

Resonant Leptogenesis [Pilaftsis, Underwood('04)]

Baryogenesis via neutrino oscillation [Akhemedov, Rubakov, Smirnov('98)]

To probe the origins of neutrino masses and BAU the experimental test of RH neutrinos is crucial

Parameters in 2RHν model

Physics of heavy neutrinos is described by M_N and $F_{\alpha I}$

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

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

$I = 2, 3$

[Casas,Ibarra('01)]

Light neutrino sector

(in IH)

Dirac phase δ

Majorana phase η

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

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

Heavy neutrino sector

Complex parameter ω

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

$$\Omega = \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} \cos(\mathrm{Re}\,\omega) & -\sin(\mathrm{Re}\,\omega) \\ \xi\sin(\mathrm{Re}\,\omega) & \xi\cos(\mathrm{Re}\,\omega) \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cosh(\mathrm{Im}\,\omega) & -i\sinh(\mathrm{Im}\,\omega) \\ i\sinh(\mathrm{Im}\,\omega) & \cosh(\mathrm{Im}\,\omega) \end{pmatrix}$$

Sign parameter $\xi = \pm 1$

Parameters in 2RHν model

Physics of heavy neutrinos is described by M_N and $F_{\alpha I}$

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

[Casas,Ibarra('01)]

$$= F\Big(\underbrace{m_1,\ m_2,\ m_3,\ \theta_{12},\ \theta_{23},\ \theta_{13},\ \delta,\ \eta,}_{\text{Light } \nu \text{ sector}}\ \underbrace{M_N,\ \Delta M,\ \mathrm{Re}\,\omega,\ \mathrm{Im}\,\omega,\ \xi}_{\text{Heavy } \nu \text{ sector}}\Big)$$

This model introduces *12 real parameters* in addition to sign parameter

From oscillation experiments

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

Unknown parameters

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

M_N $\quad$ $\Delta M\ (\ll M_N)$ $\quad$ $\xi = \pm 1$

$\mathrm{Re}\,\omega = [-\pi/2, \pi/2]$ $\quad$ $X_\omega = \exp(\mathrm{Im}\,\omega) \geq 1$

Can these unknown parameters be determined experimentally?

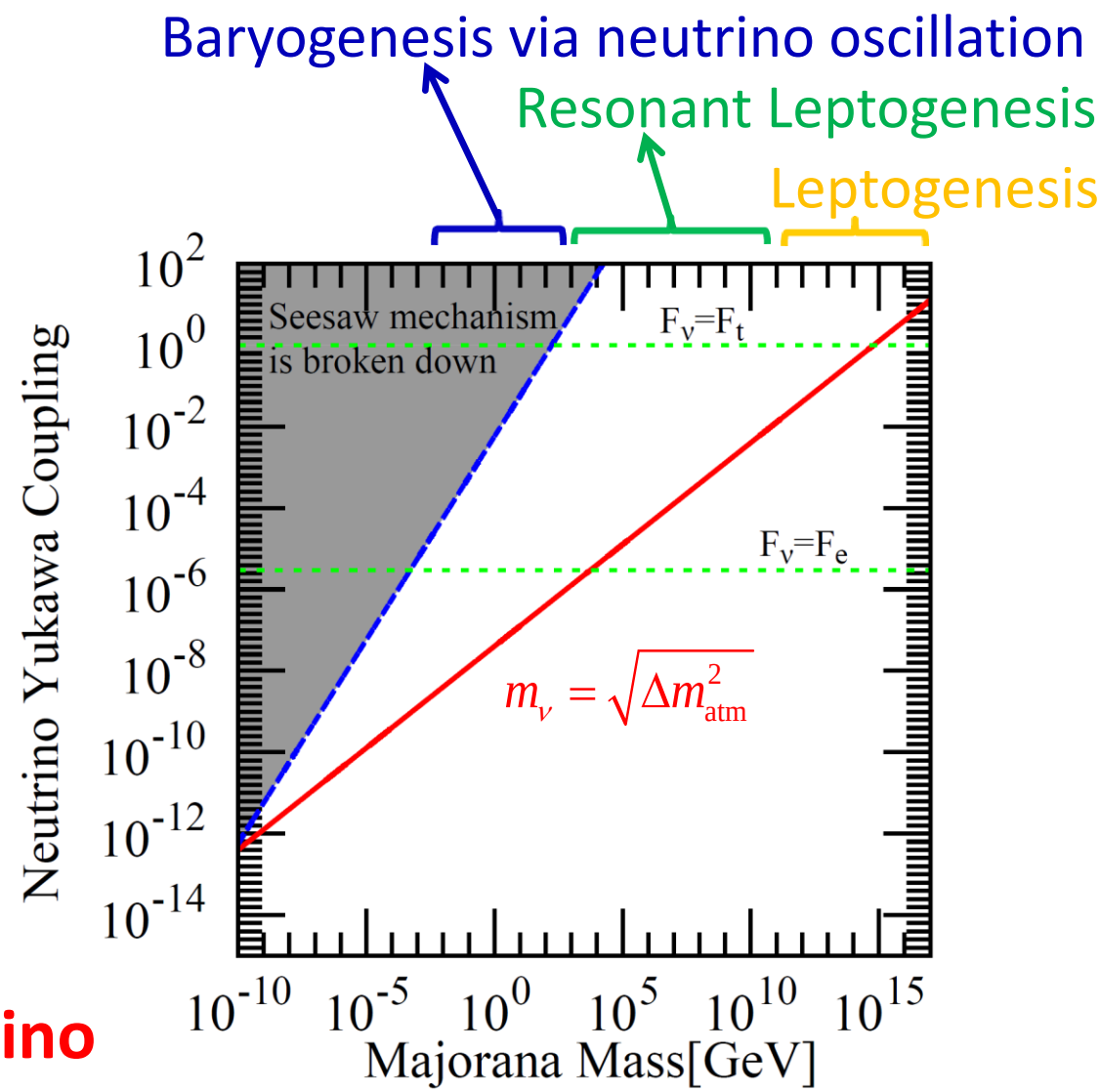
“Testable” Right-handed Neutrinos

Seesaw mechanism

Toy model with 1LHν + 1RHν

$$\begin{cases} m_\nu = -M_D \dfrac{1}{M_M} M_D \\ M_D = F\langle\Phi\rangle \end{cases}$$

$$\rightarrow \quad F^2 = m_\nu M_M \big/ \langle\Phi\rangle^2$$



When Majorana mass is small enough, RH neutrino is testable by experiments.

Framework in this talk

Target heavy neutrinos N_2 , N_3

- Lighter than charged Kaon mass $M_{2,3} < m_K = 493\text{MeV}$

$\Longrightarrow$ Direct test by Kaon decays is possible $K^+ \to l^+ N_I$

- Quasi-degenerate $M_3 - M_2 = \Delta M \ll 2M_N = M_3 + M_2$

$\Longrightarrow$ Baryogenesis via neutrino oscillation is possible

[Akhemedov, Rubakov, Smirnov('98)]

In this framework, we show

1. ***Parameters are restricted from current experiments and Big-Bang Nucleosynthesis (BBN)***

2. ***All unknown parameters might be determined by future experiments and BAU***

Constraints of heavy neutrinos N_2, N_3

Direct search (PS191 experiment)

[Bernardi et al.('88)]

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

Detection : $N \to l^+ l^- \nu,\ l^+ \pi^-$

Mixing elements

$$\nu_{L\alpha} = (U_{\mathrm{PMNS}})_{\alpha i} \nu_i + \Theta_{\alpha I} N_I^C$$

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

Upper bounds of mixing elements

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

(a,b,c:depend on M_N and channel)

Big-Bang Nucleosynthesis (BBN)

To keep the success of BBN

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

$\Longrightarrow$ Upper limit of lifetime $\tau_N < 0.1\mathrm{sec}$

$\Longrightarrow$ Lower bounds of mixing elements $\left(\tau_N^{-1} = \Gamma_N \propto |\Theta|^2 \right)$

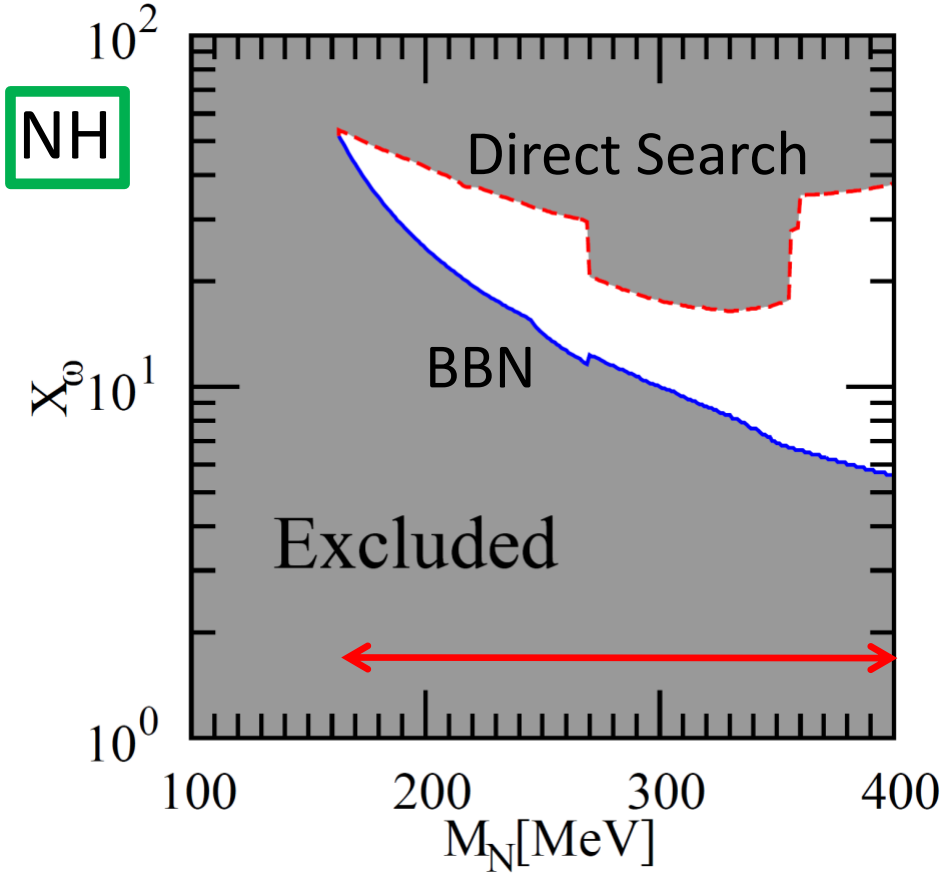
From above two types of constraint
we evaluate the allowed region of heavy neutrinos N_2, N_3

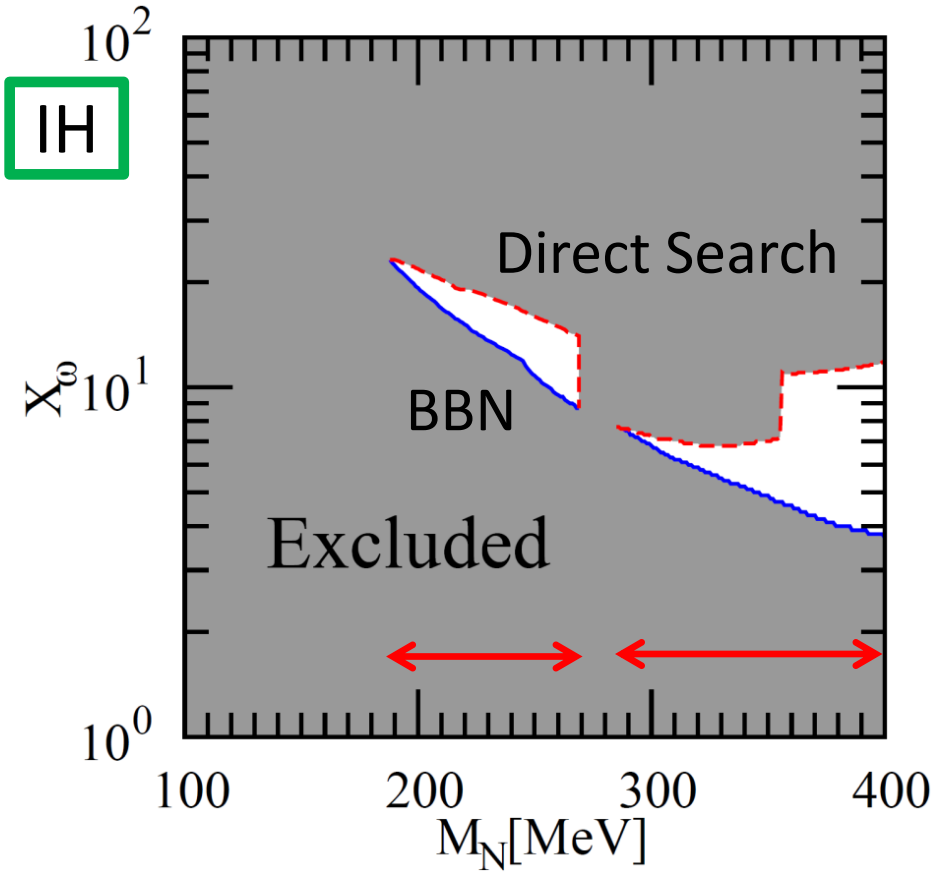
[Gorbunov, Shaposhnikov ('07)] [Ruchayski, Ivashko ('12)]

Allowed region of N_2, N_3

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

$$\begin{cases} |\Theta|^2 \propto |F|^2 \propto X_\omega^2 \text{ (large } \mathrm{Im}\,\omega\text{)} \\ \tau_N^{-1} = \Gamma_N \propto |\Theta|^2 \end{cases} \Longrightarrow \text{Bounds of } |\Theta|^2 \longrightarrow \text{Bounds of } X_\omega$$



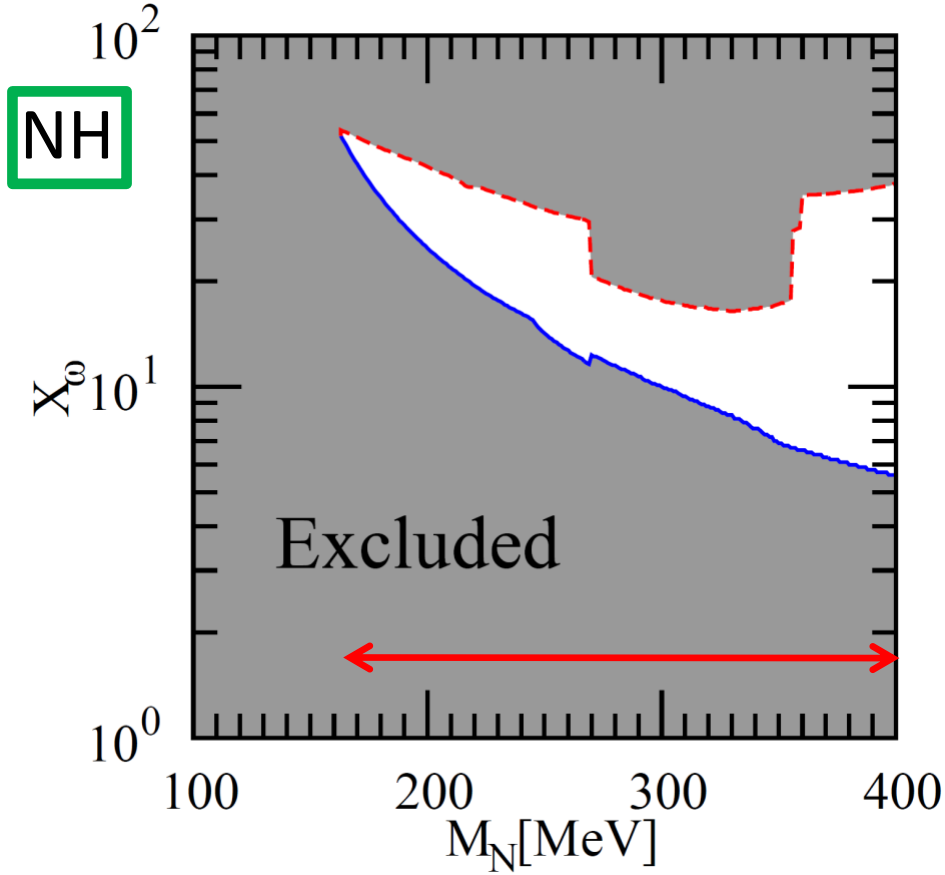


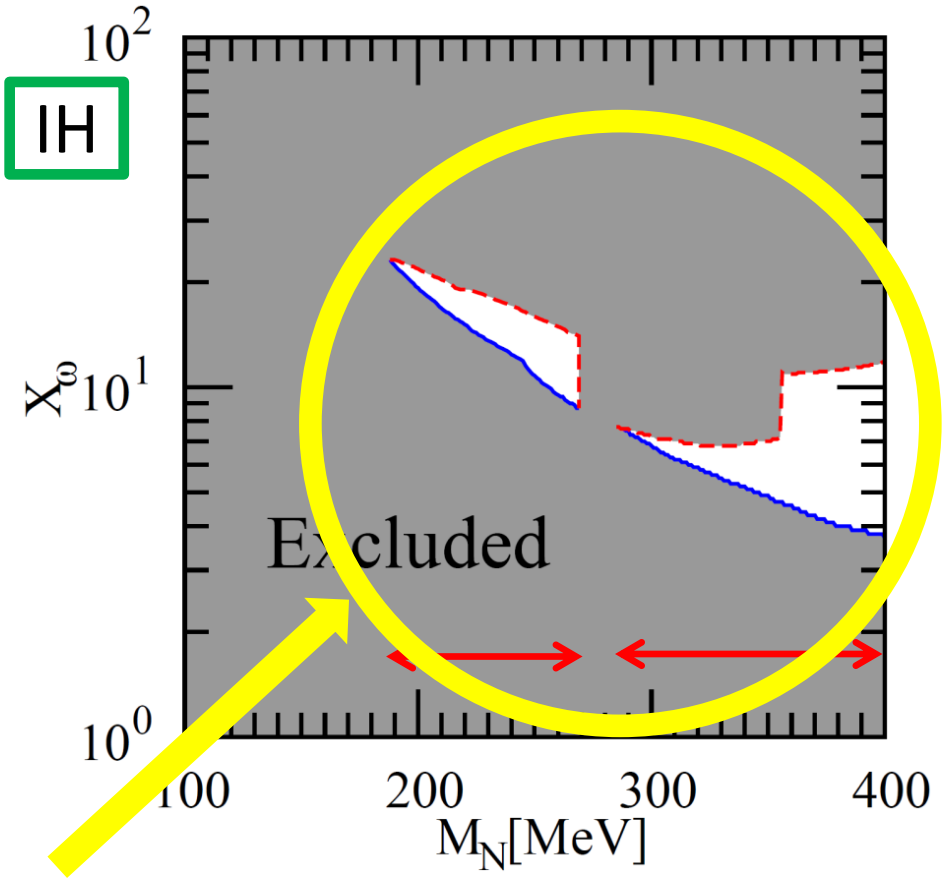
We find the allowed range of M_N and $X_\omega = O(10)$

Allowed region of N_2, N_3

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

$$\begin{cases} |\Theta|^2 \propto |F|^2 \propto X_\omega^2 \text{ (large } \mathrm{Im}\,\omega\text{)} \\ \tau_N^{-1} = \Gamma_N \propto |\Theta|^2 \end{cases} \Longrightarrow \text{Bounds of } |\Theta|^2 \longrightarrow \text{Bounds of } X_\omega^2$$





We find another interesting result in IH case!

Mixing elements of heavy neutrinos

When $\Delta M \ll M_N$ and $X_\omega \gg 1$,

mixing elements of N_2 and N_3 are same, $\Theta_{\alpha 2} = \Theta_{\alpha 3}$ [Asaka,SE,Ishida('11)]

Mixing elements in IH

$$\begin{cases} |\Theta_e|^2 \simeq 1.20\times 10^{-8}\left(\dfrac{\mathrm{MeV}}{M_N}\right)\left(1.000 - 0.925\xi\sin\eta\right)X_\omega^2 \\ |\Theta_\mu|^2 \simeq 0.76\times 10^{-8}\left(\dfrac{\mathrm{MeV}}{M_N}\right)\left(1.000 + 0.895\xi\sin\eta - 0.250\xi\cos\eta\sin\delta + 0.092\xi\sin\eta\cos\delta\right)X_\omega^2 \\ |\Theta_\tau|^2 \simeq 0.50\times 10^{-8}\left(\dfrac{\mathrm{MeV}}{M_N}\right)\left(1.000 + 0.860\xi\sin\eta + 0.380\xi\cos\eta\sin\delta - 0.140\xi\sin\eta\cos\delta\right)X_\omega^2 \end{cases}$$

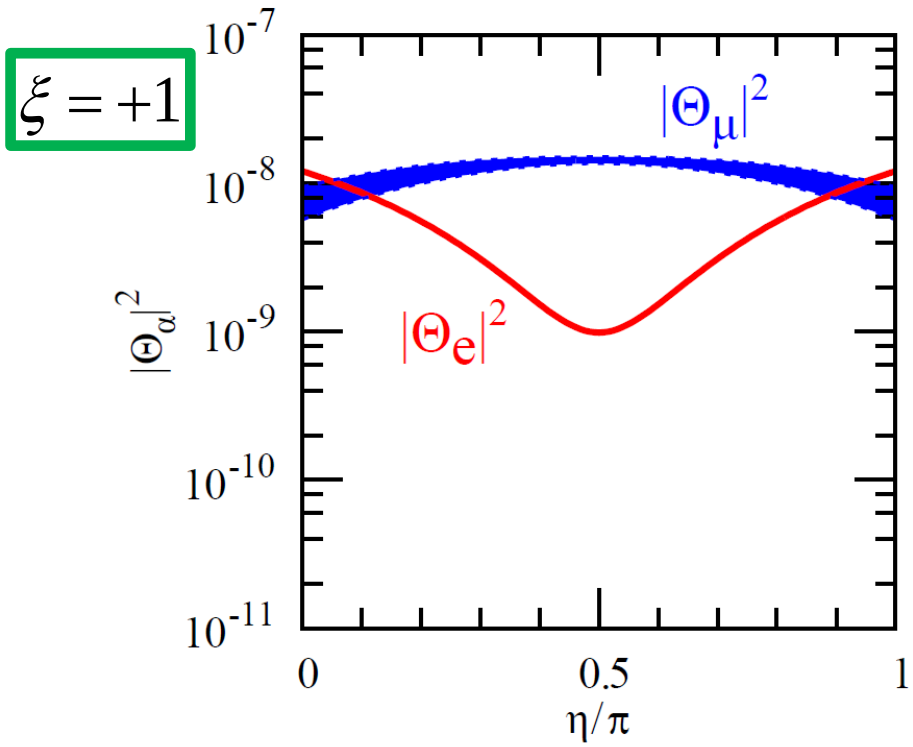
Mixing elements strongly depend on "$\xi\sin\eta$"

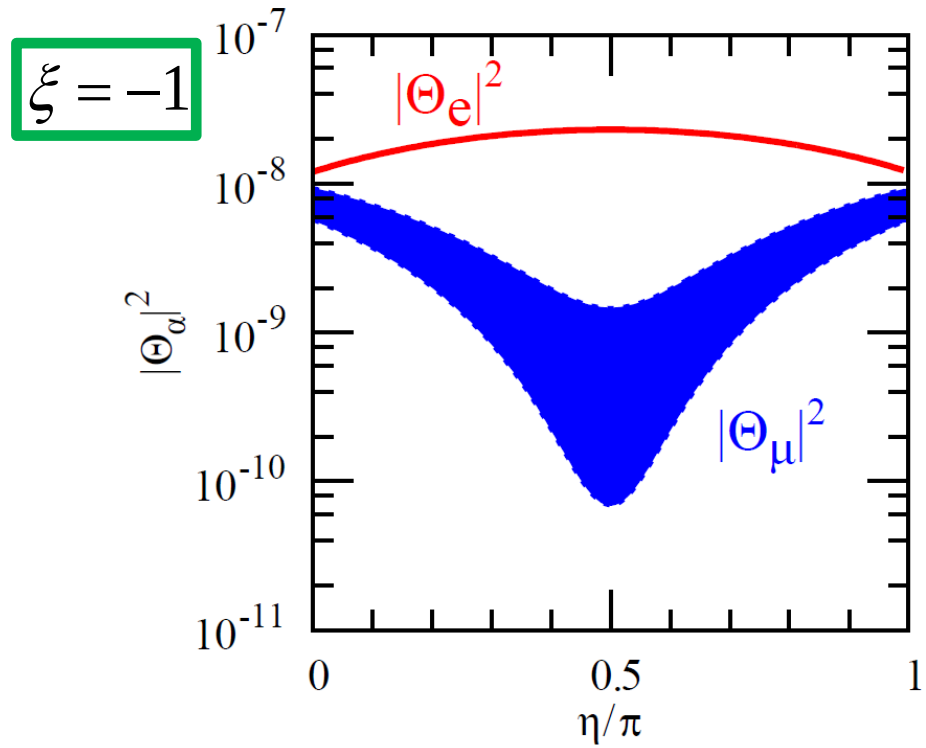
$\Longrightarrow$ Flavor dependence of mixing elements

Mixing elements of heavy neutrinos

Mixing elements in IH

$M_N = 100\text{MeV},\ X_\omega = 10,\ \text{Re}\,\omega = 0$





$$\begin{cases} |\Theta_e|^2_{UB} \gg |\Theta_\mu|^2_{UB} \ : \ \eta \sim \dfrac{\pi}{2},\ \xi = +1 \\ |\Theta_e|^2_{UB} \ll |\Theta_\mu|^2_{UB} \ : \ \eta \sim \dfrac{\pi}{2},\ \xi = -1 \end{cases}$$

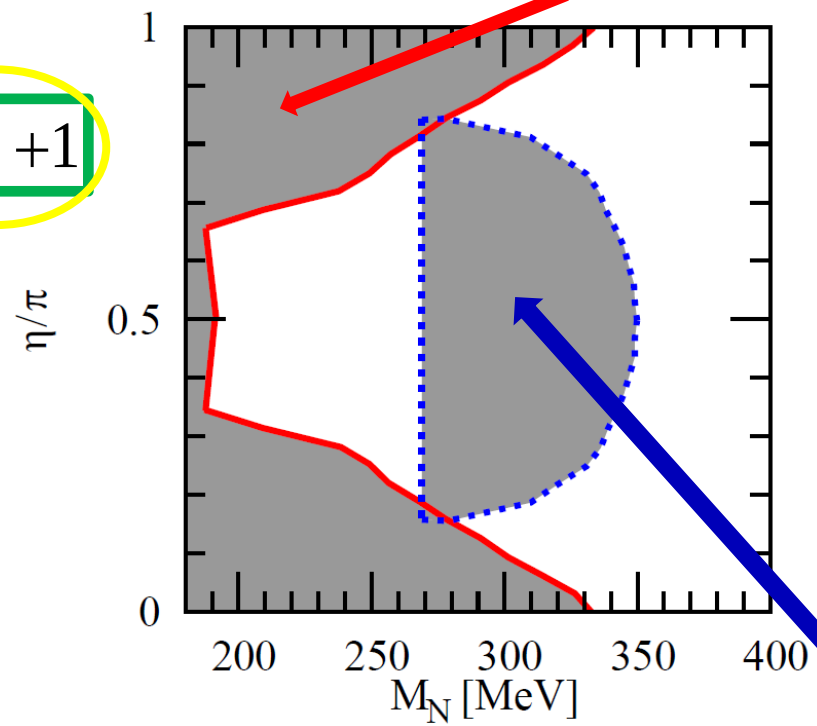
favored

Allowed range of Majorana phase in IH

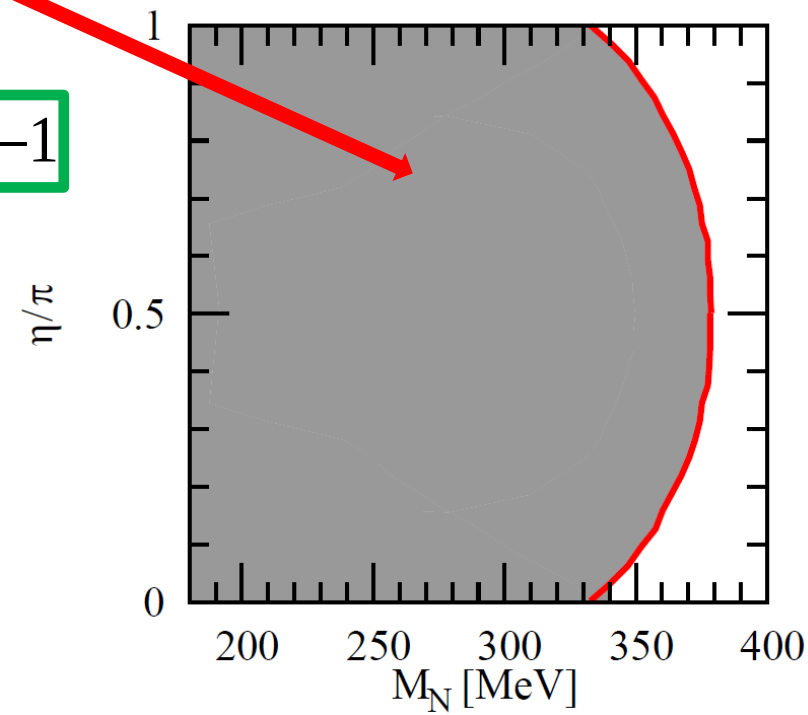
Majorana phase is restricted by direct search experiment and BBN

Excluded by PS191 + BBN : $K^+ \to e^+ N$, $N \to e^- \pi^+ + cc$

$\xi = +1$



$\xi = -1$



Excluded by PS191 + BBN : $K^+ \to \mu^+ N$, $N \to \mu^- \pi^+ + cc$

Majorana phase is restricted for $M_N \lesssim 350\text{MeV}$

$\Longrightarrow$ Impact on neutrinoless double beta decay

0νββ decay in IH

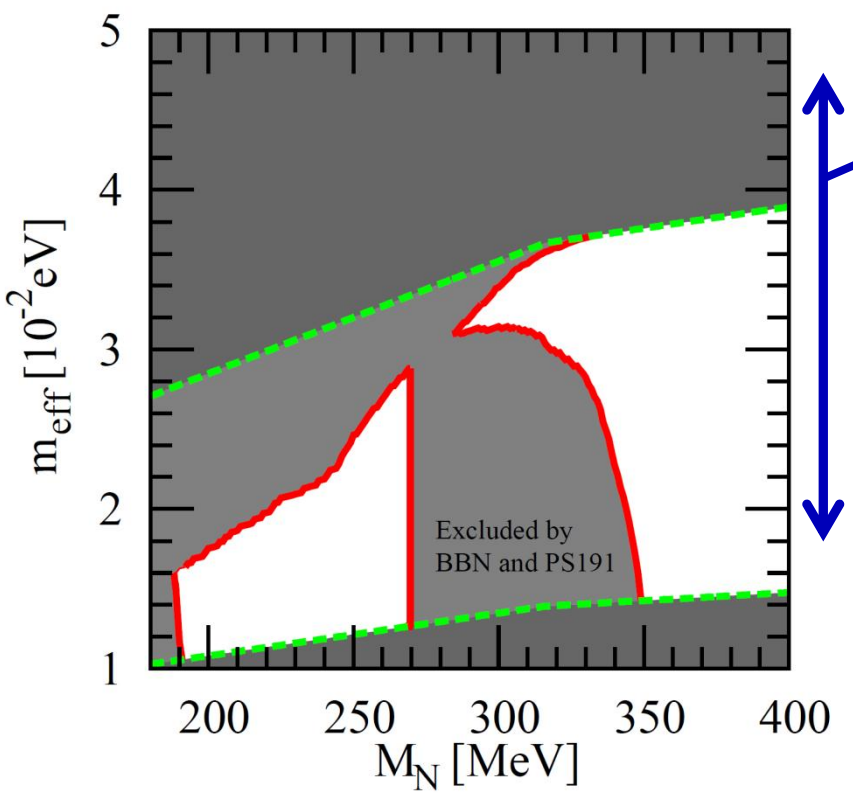
Impact on 0νββ decay by restricted Majorana phase

Effective neutrino mass m_{eff}

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

[Asaka,SE,Ishida('11)]

$$m_{\mathrm{eff}}^\nu = \cos^2\theta_{13}\left(m_1^2\cos^4\theta_{12} + m_2^2\sin^4\theta_{12} + 2m_1m_2\cos^2\theta_{12}\sin^2\theta_{12}\cos 2\eta\right)^{1/2}$$



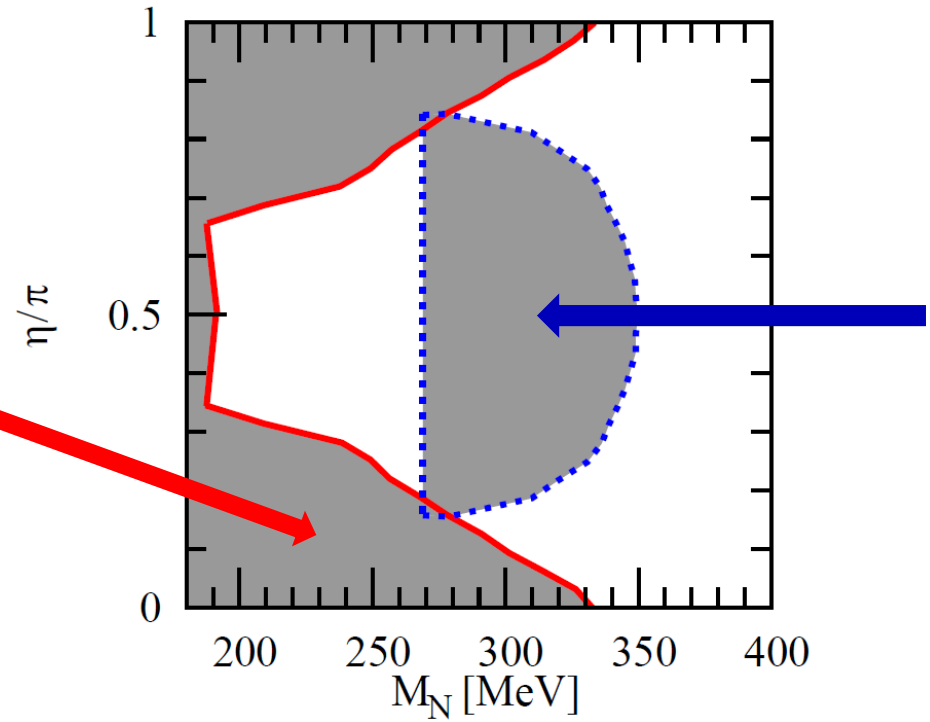
Only light neutrinos

$m_{\mathrm{eff}}^\nu \quad \eta = 0 - \pi$

- Heavy neutrinos give negative contribution of m_{eff}
- The restricted η predicts the limited $|m_{\mathrm{eff}}|$ for $M_N \lesssim 350\mathrm{MeV}$

Allowed range of Majorana phase in IH

Excluded by
PS191 + BBN
$K^+ \to e^+ N$
$N \to e^- \pi^+ + cc$



Excluded by
PS191 + BBN
$K^+ \to \mu^+ N$
$N \to \mu^- \pi^+ + cc$

- Future search experiments by Kaon decays can provide strong information on Majorana phase
- If M_N is determined by a experiment (Peak search), Majarana phase may be also determined

Heavy neutrino mass M_N from experiments

Direct search experiments of heavy neutrinos

Peak Search experiment [Shrock('80)]

ex) $\pi^+ \to e^+ + N_I$

mixing Θ_{eI} measured

Search for the peak corresponding to heavy neutrino in positron energy distribution

From { conservation of momentum and energy; two-body decay }

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

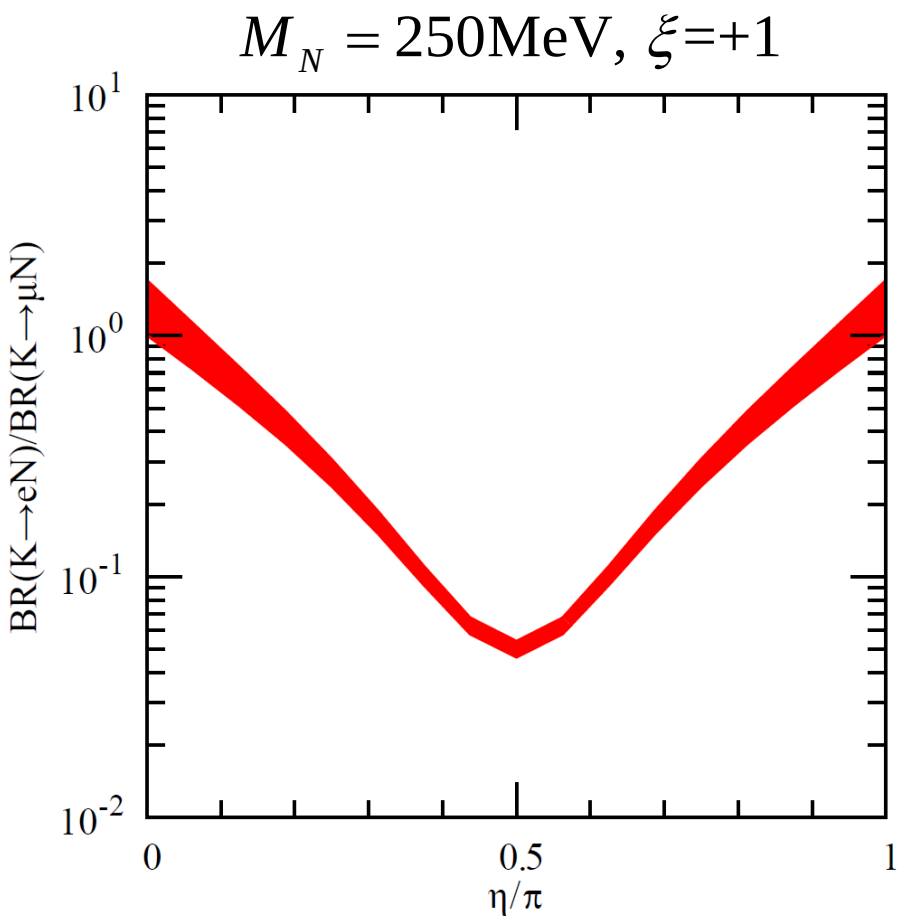
Unique for a heavy neutrino mass

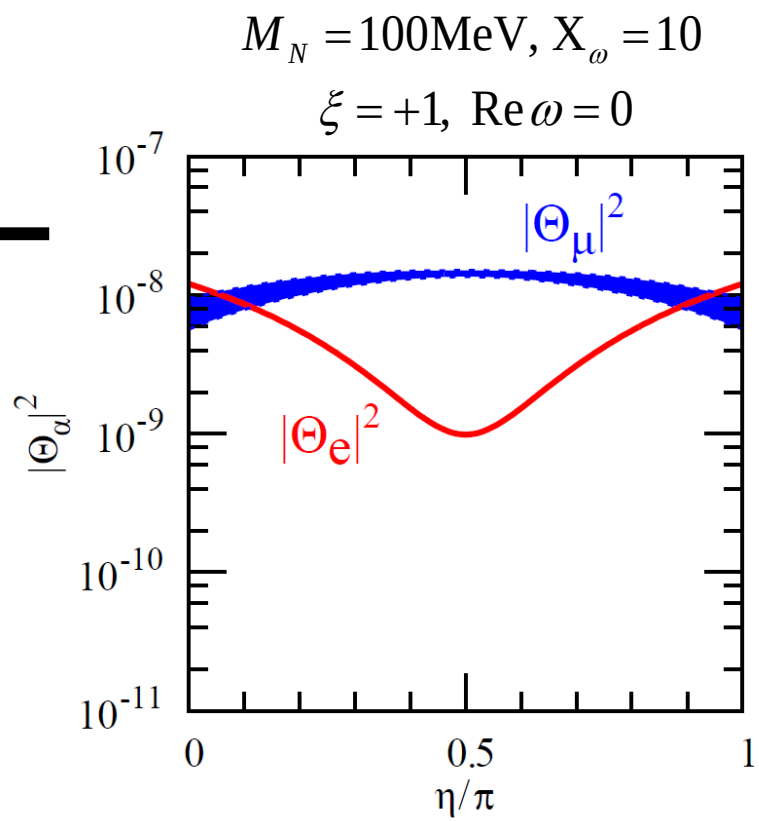
$\Longrightarrow M_N$ is determined by the Peak search experiments

Majorana phase η from experiments

Ratio: $\dfrac{\mathrm{BR}(K \to e + N)}{\mathrm{BR}(K \to \mu + N)} \propto \dfrac{|\Theta_e|^2}{|\Theta_\mu|^2}$ ⟶ X_ω^2 is cancelled

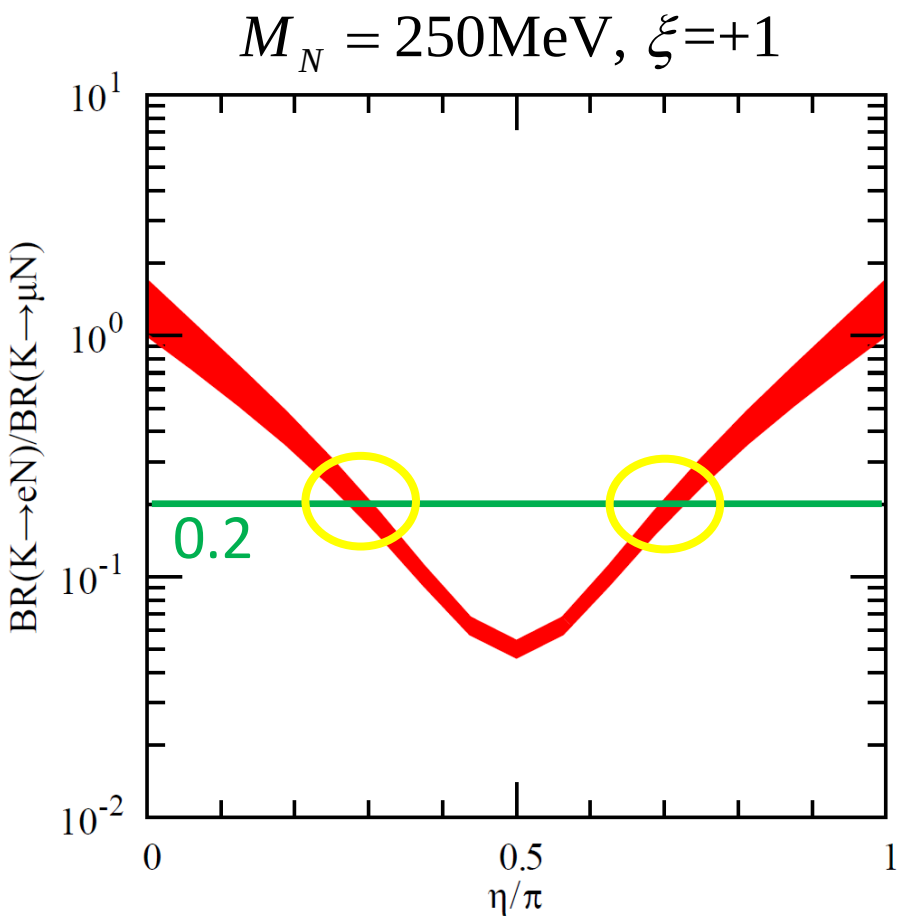
⟶ Information of CP phases





Majorana phase η from experiments

Ratio: $\dfrac{\mathrm{BR}(K \to e + N)}{\mathrm{BR}(K \to \mu + N)} \propto \dfrac{|\Theta_e|^2}{|\Theta_\mu|^2}$ ⟶ Information of CP phases



ex) $\dfrac{\mathrm{BR}(K \to e + N)}{\mathrm{BR}(K \to \mu + N)} = 0.2$

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

Heavy neutrino search

⟶ M_N, X_ω, ξ and η are determined

Relation between η and $\mathrm{Re}\,\omega$ from BAU

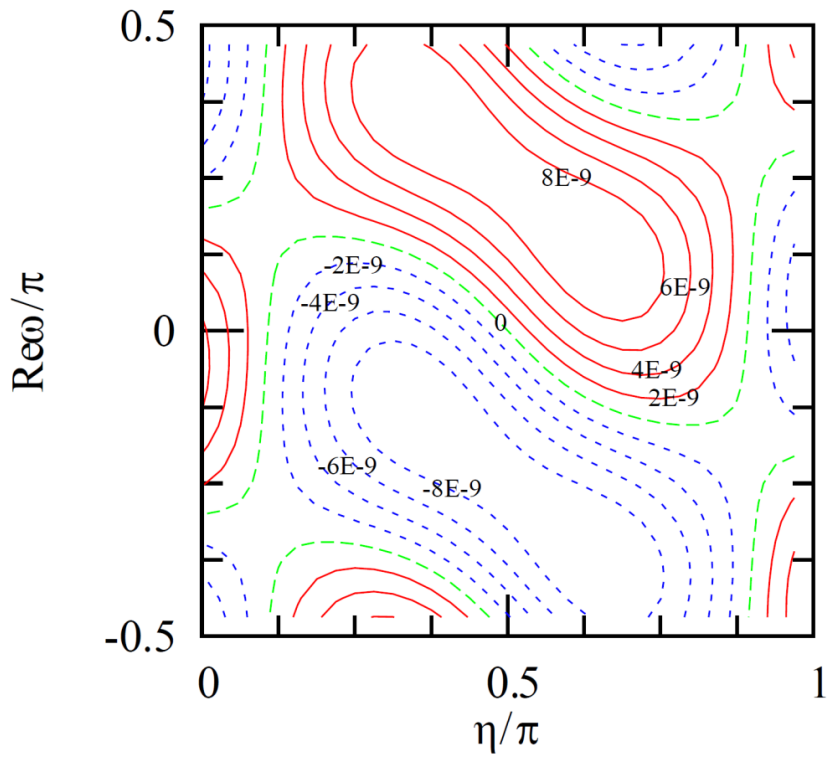
Baryogenesis via Neutrino Oscillation

Generation of asymmetry is controlled by $F_{\alpha I}$

- Dependence of δ is very small and doesn't change sign of BAU
- Relation between η and $\mathrm{Re}\,\omega$

Contour of baryon-to-entropy ratio Y_B

$M_N = 250\mathrm{MeV},\ \delta = \pi$



Correct sign of BAU restricts the region of $\mathrm{Re}\,\omega$ depending on η

Relation between $\mathrm{Re}\,\omega$ and ΔM from BAU

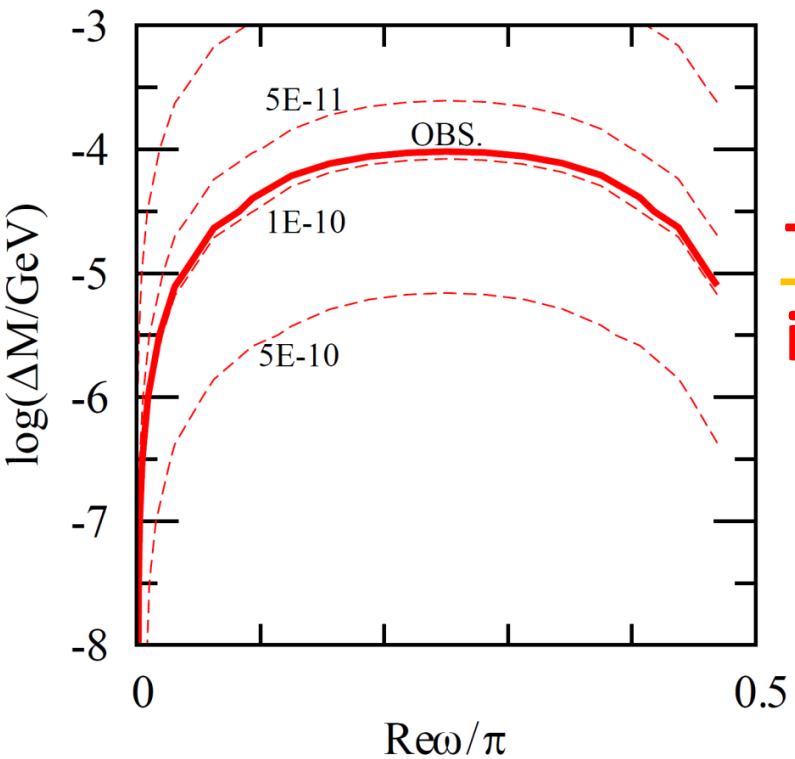
Baryogenesis via Neutrino Oscillation

Temperature of oscillation is crucial

$$T_{\mathrm{osc}} \sim \left(M_0 M_N \Delta M\right)^{1/3} \qquad \left(M_0 \simeq 7.1\times 10^{11}\,\mathrm{GeV}\right)$$

- If η is determined $\Longrightarrow$ Relation between $\mathrm{Re}\,\omega$ and ΔM

Contour of baryon-to-entropy ratio Y_B $\qquad M_N = 250\mathrm{MeV},\ \delta = \pi,\ \eta = \pi/2$



The order of ΔM is determined if $\mathrm{Re}\,\omega$ is not around 0 or $\pi/2$

Result : Parameters in 2RHν model (IH)

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

<u>Unknown parameters</u>

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

$$M_N \qquad \Delta M \ (\ll M_N) \qquad \xi = \pm 1$$

$$\mathrm{Re}\,\omega = [-\pi/2, \pi/2] \qquad X_\omega = \exp(\mathrm{Im}\,\omega) \geq 1$$

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Search experiments by K decays
+
BBN

<u>Unknown parameters</u>

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

M_N $\Delta M \ (\ll M_N)$ $\xi = \pm 1$

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0νββ experiments

Search experiments by K decays
+
BBN

Unknown parameters

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

M_N $\Delta M \ (\ll M_N)$ $\xi = \pm 1$

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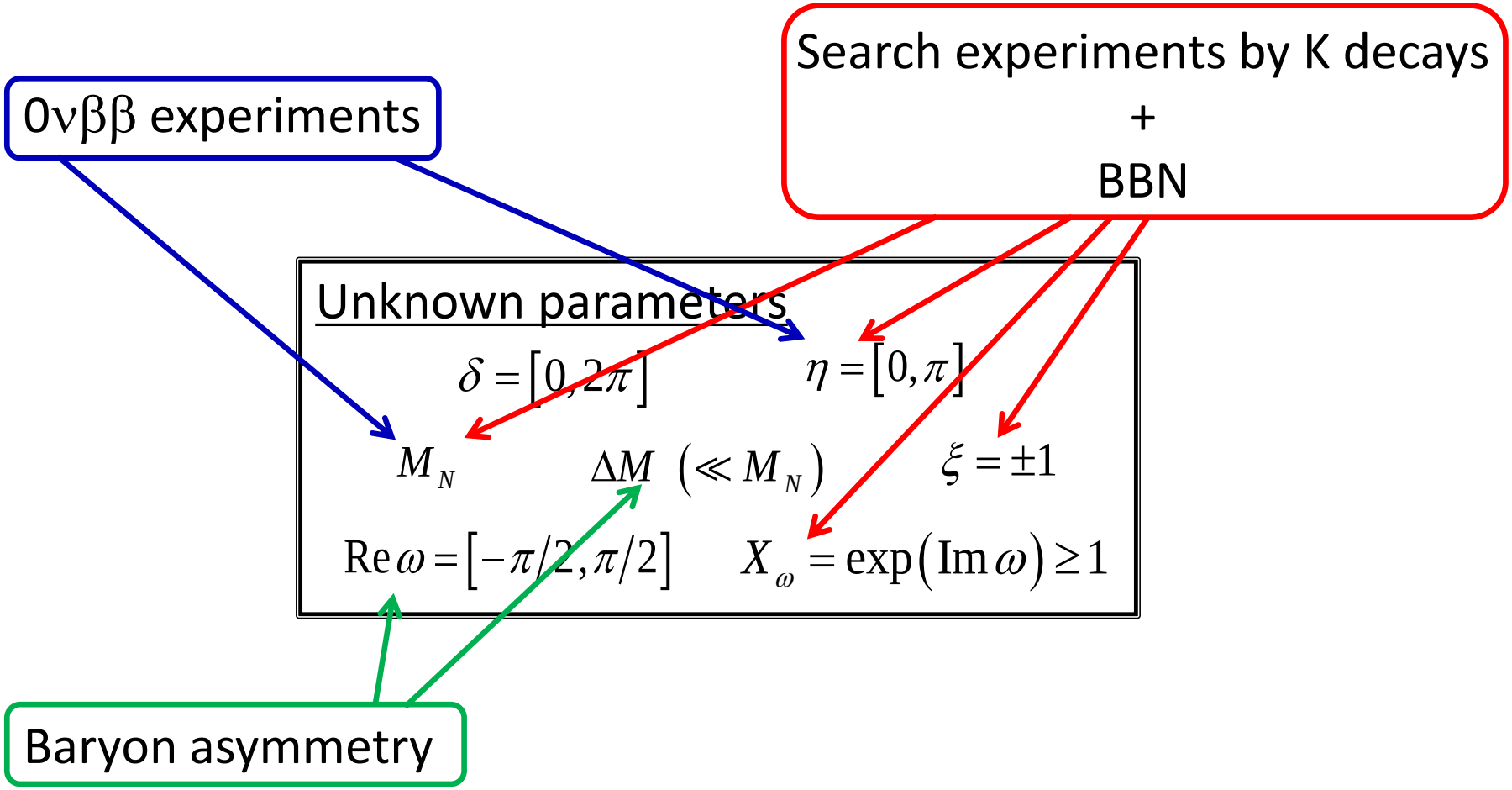

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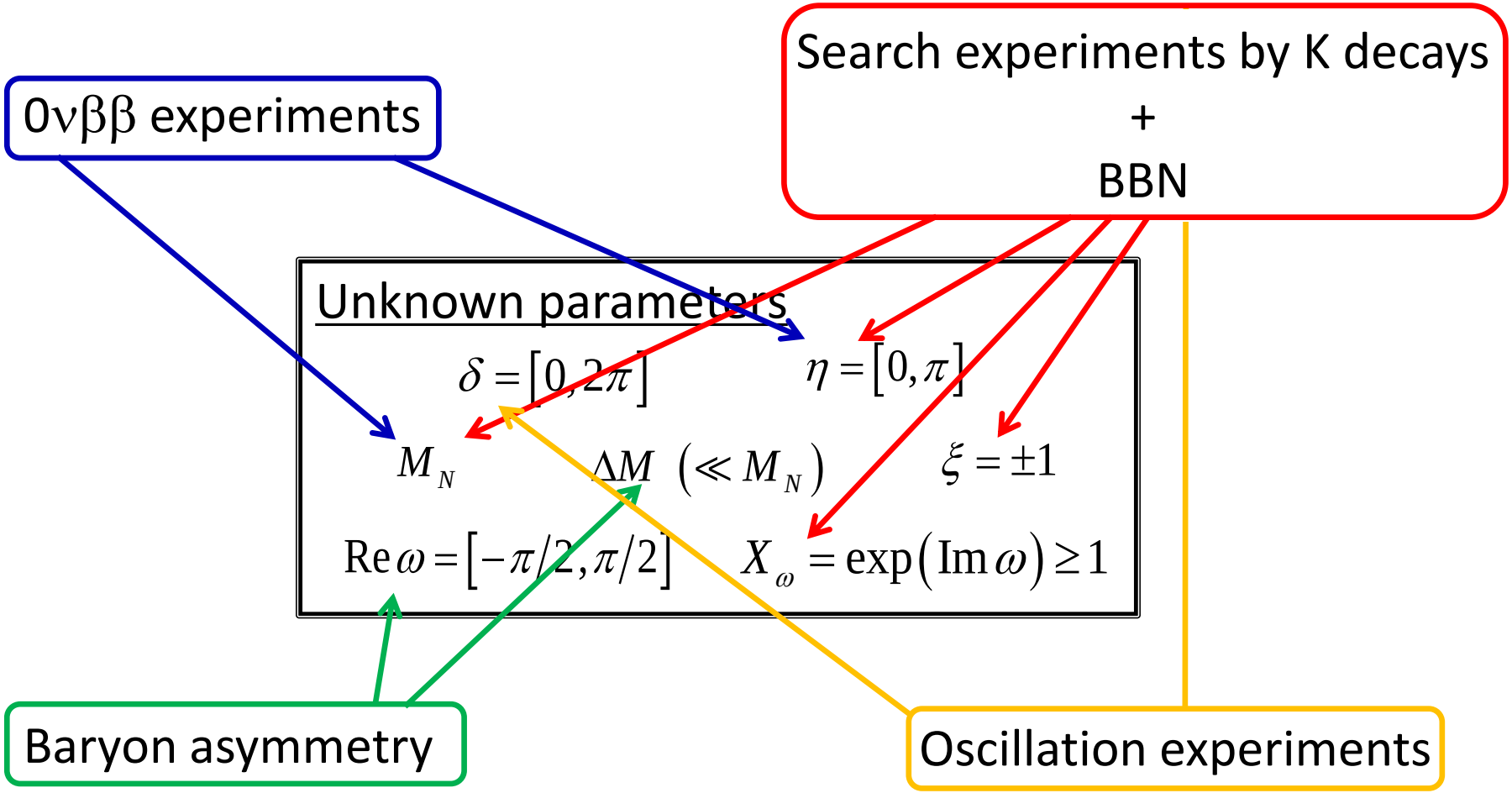


Summary

Two right-handed neutrinos are the minimal option for

- neutrino masses from seesaw mechanism
- baryon asymmetry of the universe from Baryogenesis

When heavy neutrinos are quasi-degenerate with $M_N \sim 200 - 400\mathrm{MeV}$

We may have a chance to probe directly the origins of neutrino masses and baryon asymmetry by using kaon decays!

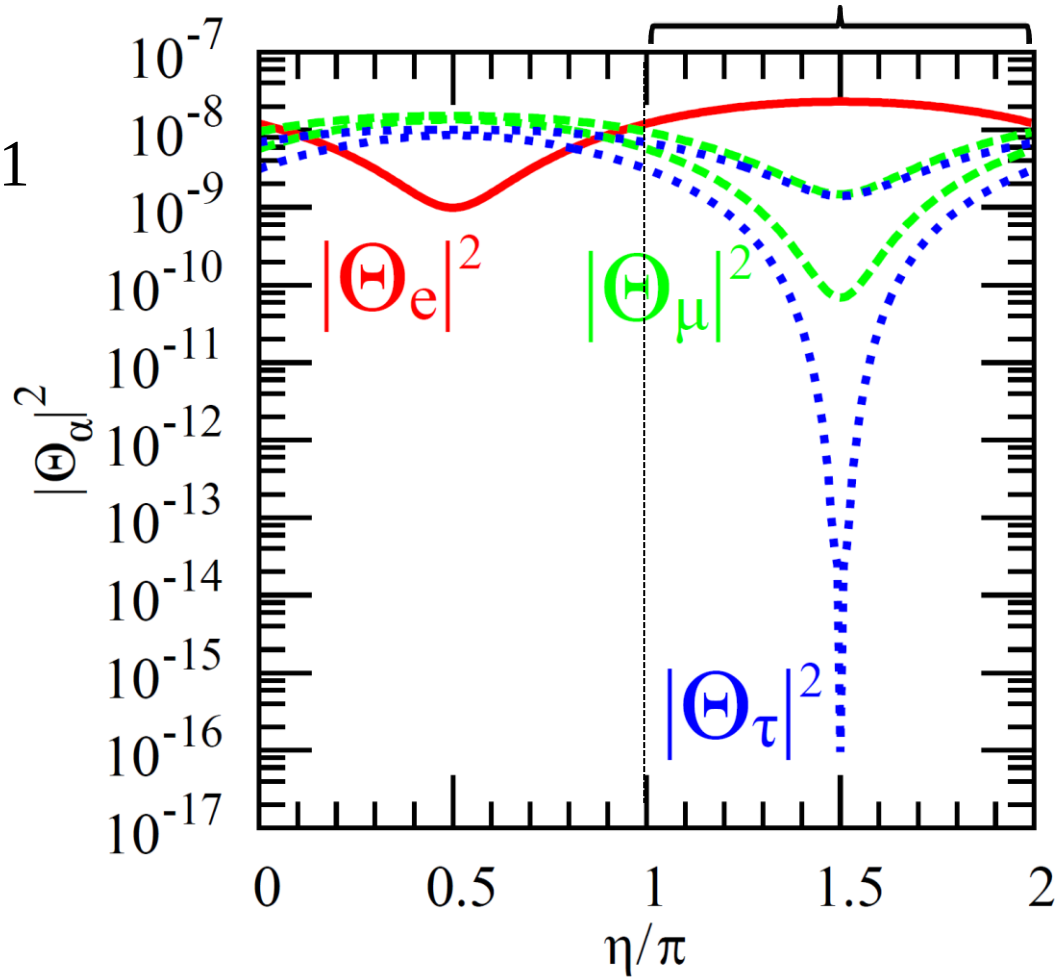
Thank you very much!

Mixing elements of heavy neutrinos

Mixing elements in IH

Correspond to $\xi = -1$ and $\eta = 0 - \pi$

$\xi = +1$



Backup

Negative contribution from heavy neutrinos for 0νββ decay

From neutrino mass matrix

$$\begin{cases} \hat{M} = \begin{pmatrix} 0 & M_{\mathrm{D}} \\ M_{\mathrm{D}}^{T} & M_{\mathrm{M}} \end{pmatrix} \longrightarrow \left[\hat{M}\right]_{ee} = 0 \\ \sum_{i=1,2,3} m_i U_{ei}^2 + \sum_{I=1,2,3} M_I \Theta_{eI}^2 = \left[\hat{U}\hat{M}^{\mathrm{diag}}\hat{U}^T\right]_{ee} = \left[\hat{M}\right]_{ee} \end{cases}$$

$$\Longrightarrow \sum_{I=2,3} M_I \Theta_{eI}^2 = -\sum_{i=1,2,3} m_i U_{ei}^2 = -m_{\mathrm{eff}}^{\nu}$$

$$m_{\mathrm{eff}} = \sum_{i=1,2,3} m_i U_{ei}^2 + \sum_{I=2,3} f(M_I) M_I \Theta_{eI}^2 \simeq (1 - f_\beta(M_N)) \sum_{i=1,2,3} m_i U_{ei}^2$$

for ΔM is negligible

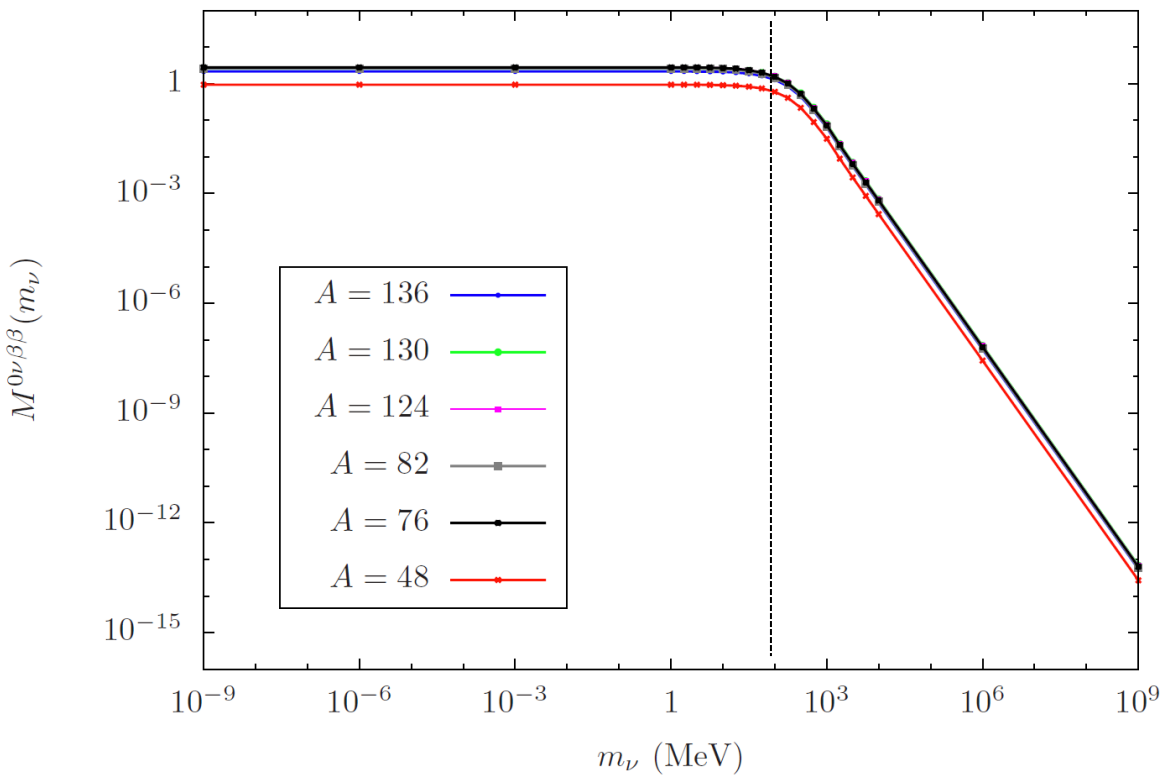
Backup

Negative contribution from heavy neutrinos for 0νββ 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



$$M_N \lesssim 100\text{MeV}$$

$$f_\beta(M_N) = 1$$

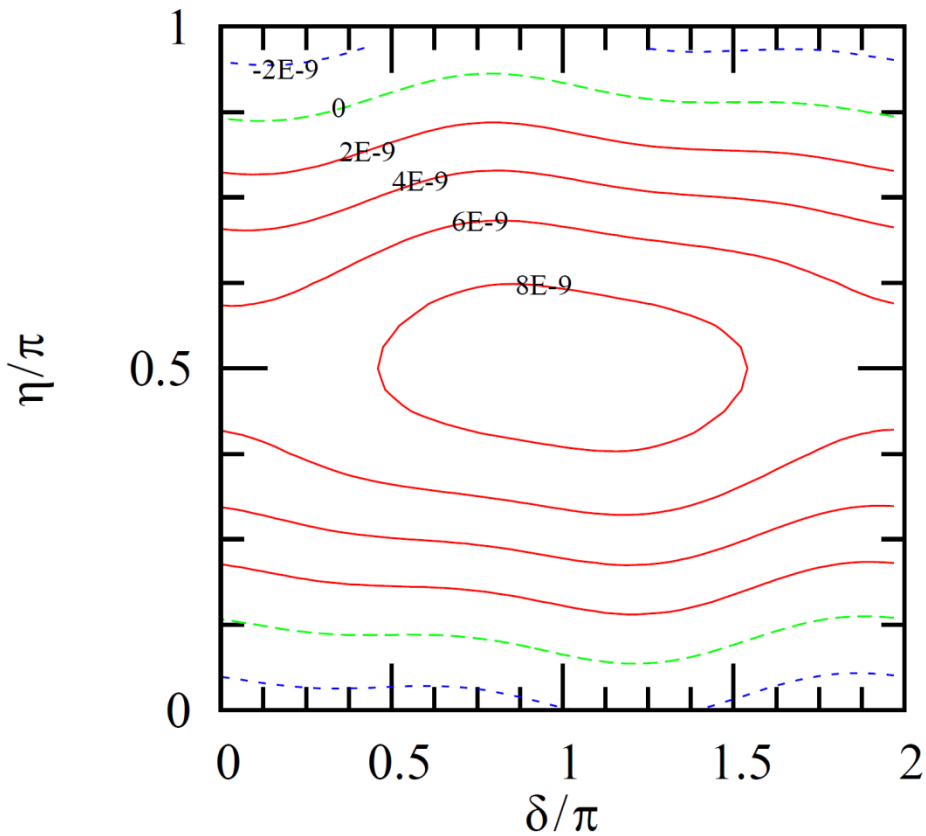
[Blennow,Frenandez-Martinez, Pavon,Mnendez('10)]

Backup

Dependence on Dirac phase of BAU

$M_N = 250\text{MeV}$ (IH)

$\delta - \eta$ plane $(\text{Re}\,\omega = \pi/4)$



$\delta - \text{Re}\,\omega$ plane $(\eta = \pi/2)$