NEUTRINO MASSES, DARK MATTER AND BARYON ASYMMETRY OF THE UNIVERSE

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INTRODUCTION

NEUTRINO MASSES
AND
RIGHT-HANDED (RH) NEUTRINOS

Neutrino oscillation experiments

- Neutrino mass scales
  - Atmospheric: $\Delta m^2_{\rm atm} \simeq 2.5 \times 10^{-3}\,{\rm eV}^2$
    - Atmospheric neutrino exps. (…, SuperK)
    - Long-baseline accelerator exps. (K2K, MINOS)
  - Solar: $\Delta m^2_{\rm sol} \simeq 8.0 \times 10^{-5}\,{\rm eV}^2$
    - Solar neutrino exps. (…, SuperK, SNO)
    - Reactor exp. (KamLand)
- *Need for physics beyond the Minimal Standard Model*

Right-handed (RH) neutrinos

Three RH neutrinos N_1, N_2, N_3

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

$I = 1, 2, 3$

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

- **Neutrino masses**
  - Dirac: $M_D = F\langle \Phi \rangle$ and Majorana: $M_M = diag(M_1, M_2, M_3)$
  - We assume $|[M_D]_{\alpha I}| \ll M_I$

    ⇨ Seesaw mechanism $M_\nu = -M_D^T \frac{1}{M_M} M_D$

- **Key question:**

  " Where is the scale of Majorana mass?"

Conventstional seesaw scenario:

Neutrino Yukawa couplings are comparable to those of quarks and charged leptons

- M_M >> 100GeV

$$M_M \simeq 6\times10^{14}\,\mathrm{GeV}\,F^2\left(\frac{2.5\times10^{-3}\,\mathrm{eV}^2}{m_\nu^2}\right)^2 \qquad m_\nu \simeq \frac{M_D^2}{M_M}$$

  - Explain naturally smallness of neutrino masses via seesaw [Minkowski, Yanagida; Gell-Mann, Ramond, Slansky]
  - Decays of RH neutrinos can account for baryon asymmetry through leptogenesis [Fukugita, Yanagida]
  - Realize in GUT models
  - Physics of RH neutrinos cannot be tested by direct exp.

The νMSM:

TA, Blanchet, Shaposhnikov
TA, Shposhnikov

No new mass scale is introduced

- M_M <100GeV

$$F = 4\times10^{-7}\left(\frac{M_M}{100\mathrm{GeV}}\right)^{1/2}\left(\frac{m_\nu^2}{2.5\times10^{-32}}\mathrm{eV}\right)^{1/4}$$

$$m_\nu \simeq \frac{M_D^2}{M_M}$$

- Provide a dark-matter candidate
- Oscillations of RH neutrinos can account for baryon asymmetry of the universe [Akhmedov, Rubakov, Smirnov]
- *Potentially*, physics of RH neutrinos can be tested by experiments

Roles of three RH neutrinos

One RH neutrino N_1

- Candidate of Dark Matter

Other two RH neutrinos N_2, N_3

- Explain neutrino oscillation data via seesaw mechanism
- Explain BAU via sterile neutrino oscillation

- In this talk,
  we show the connection between BAU
  and low energy CPV in neutrino oscillation

BARYOGENESIS VIA STERILE NEUTRINO OSCILLATION

Akhmedov, Rubakov, Smirnov ’98
TA, Shaposhnikov ‘05

Baryon asymmetry of the universe (BAU)

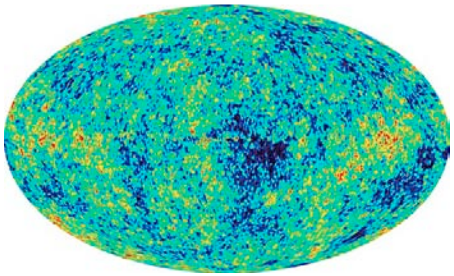
$$\left.\frac{n_B}{s}\right|_{obs} = (8.81 \pm 0.23) \times 10^{-11}$$

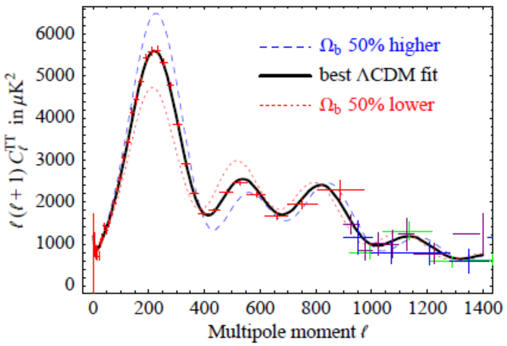
Baryon Number B = (# of baryons)
− (# of anti-baryons)

n_B : baryon number density

s : entropy density

[WMAP 5years]





Strumia 06

Sakharov's conditions (1967)

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

Baryogenesis in the MSM

- **B and L violations**
  - (B+L) violation due to sphaleron for T>100GeV
- **CP violation**
  - 1 CP phase in the quark-mixing (CKM) matrix

$$\mathrm{CPV} \propto J_{CP}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) / T_{EW}^{12} \sim 10^{-20}$$

→ **too small**

[Kajantie, Laine, Rummukainen, Shaposhnikov]

- **Out of equilibrium**
  - Strong 1st order phase transition if M_H <72GeV but M_H >114.4GeV (exp.)

→ **not satisfied**

We have to go beyond the MSM !!

Baryogenesis in the νMSM

- **B and L violations**
  - (B+L) violation due to sphaleron
  - L violation due to Majorana masses
    Majorana masses < 100 GeV
    → negligible for T>100 GeV

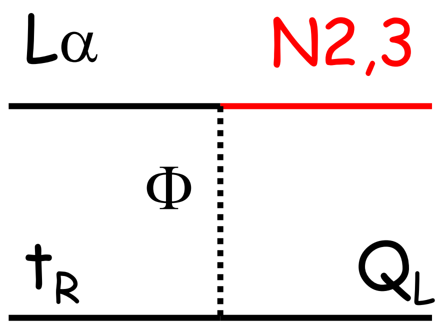
$$L = -\frac{M_I}{2}\overline{N_I} N_I^c + \text{h.c.}$$

- **C and CP violations**
  - 1 CP phase in quark sector
  - 6 CP phases in lepton sector,
    which can induce large CPV effects

Baryogenesis conditions

- **Out of equilibrium**
  - No 1st order EW phase transition as in the MSM
  - But, sterile neutrinos can be out of equilibrium if Yukawa couplings are small enough
    - To ensure this condition up to T～100GeV

➡ $F < 2 \times 10^{-7}$



Conclusion:
The νMSM can potentially realize all three conditions for baryogenesis

Baryogenesis via sterile neutrino osc.

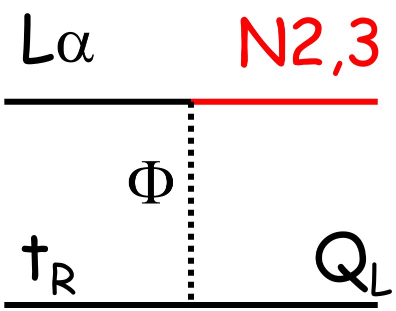
Akhmedov, Rubakov, Smirnov '98

Idea: Sterile neutrino oscillation is a source of BAU

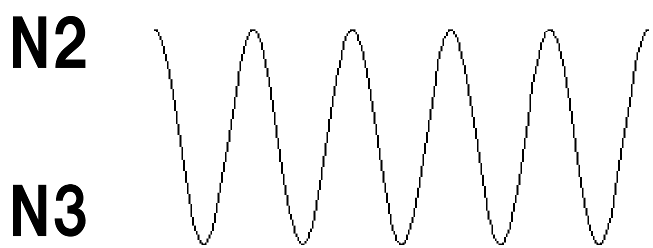
- Sterile neutrinos are created and oscillate with CPV
- The total lepton number is zero but is distributed between active and sterile neutrinos
- The asymmetry of active neutrinos is transferred into baryon asymmetry by sphaleron effects

First step: at F^2 order

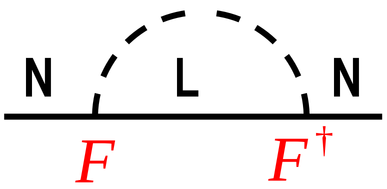
- Initially, N2 and N3 are absent
- N2 and N3 are produced via scatterings



- N2 and N3 oscillate



Medium effects

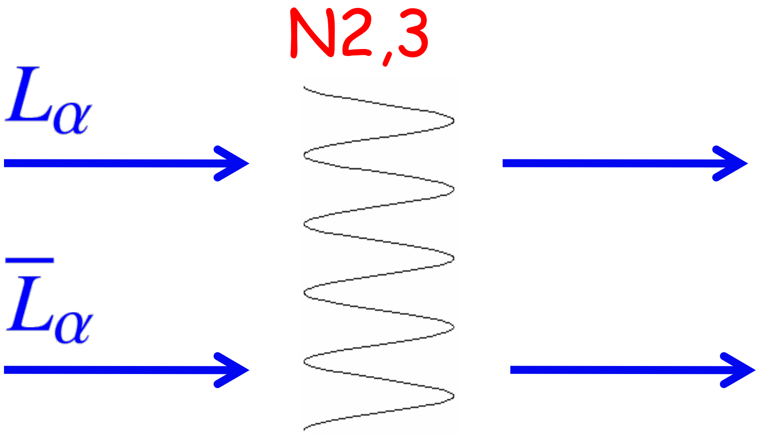


$$V_N = \frac{T^2}{8k} F^\dagger F$$

Osc. Starts at $T_L \approx (M_P \Delta M_{32}^2)^{1/3}$

Second step: at F^4 order [TA, Shaposhnikov]

- Active flavor asymmetries are generated

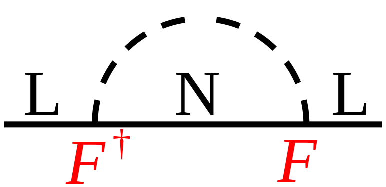


$$\Delta L_e \neq 0 \quad \Delta L_\mu \neq 0 \quad \Delta L_\tau \neq 0$$

$$\Delta L_{\rm tot} = \Delta L_e + \Delta L_\mu + \Delta L_\tau = 0$$

$$\Delta N_{\rm tot} = 0 \quad \Delta N_I = 0$$

Evolution rates of L_α and $\overline{L}_\alpha$ are different due to CPV in



Final step: at F^6 order

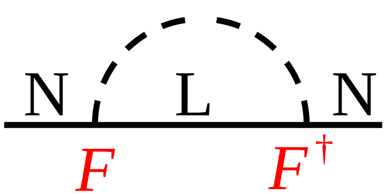
- Total asymmetries in active and sterile sectors are generated.

$N_I \longrightarrow$ ΔL_e $\longrightarrow$ $\Delta L_{\mathrm{tot}} \neq 0 \quad \Delta N_{\mathrm{tot}} \neq 0$

ΔL_μ

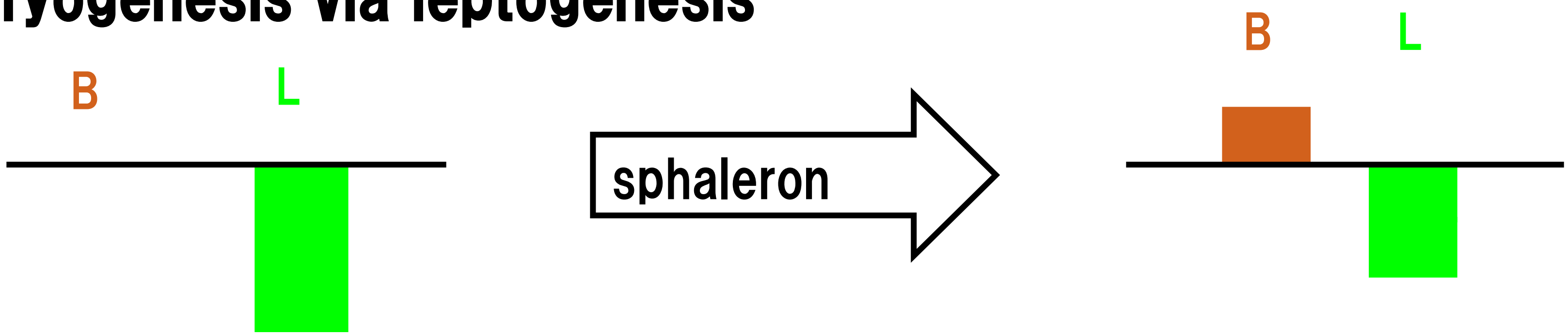
$\overline{N}_I \longrightarrow$ ΔL_τ $\longrightarrow$ $\Delta L_{\mathrm{tot}} + \Delta N_{\mathrm{tot}} = 0$

Evolution rates of N_I and $\overline{N}_I$ are different and CPV in

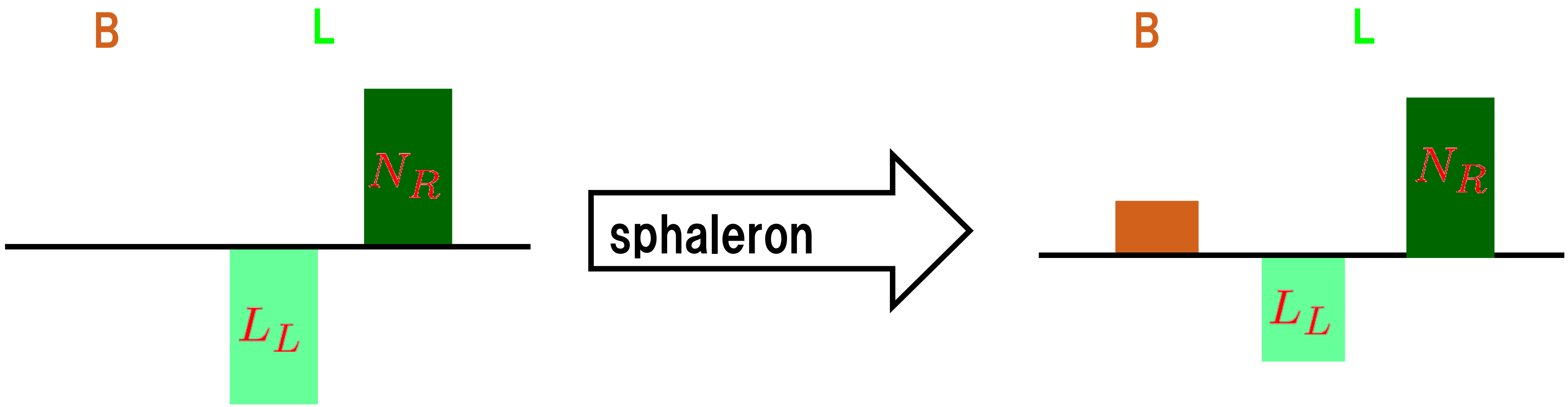


Key points

Baryogenesis via leptogenesis

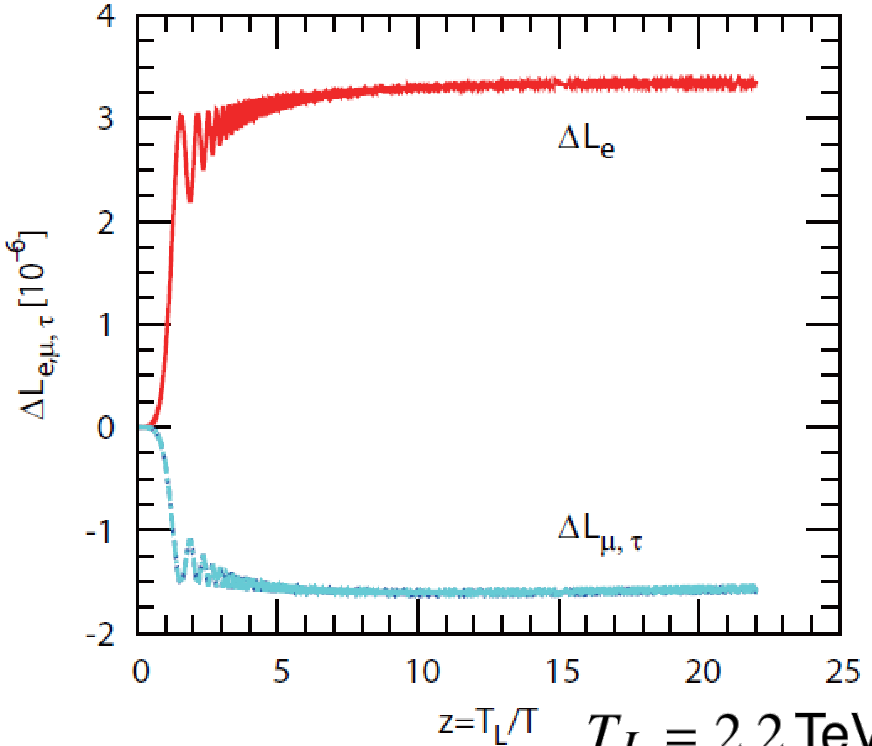


Baryogenesis via sterile neutrino osc.



Evolution of each asymmetries

Active sector



$T_L = 2.2$ TeV

Figure 5: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Sterile sector

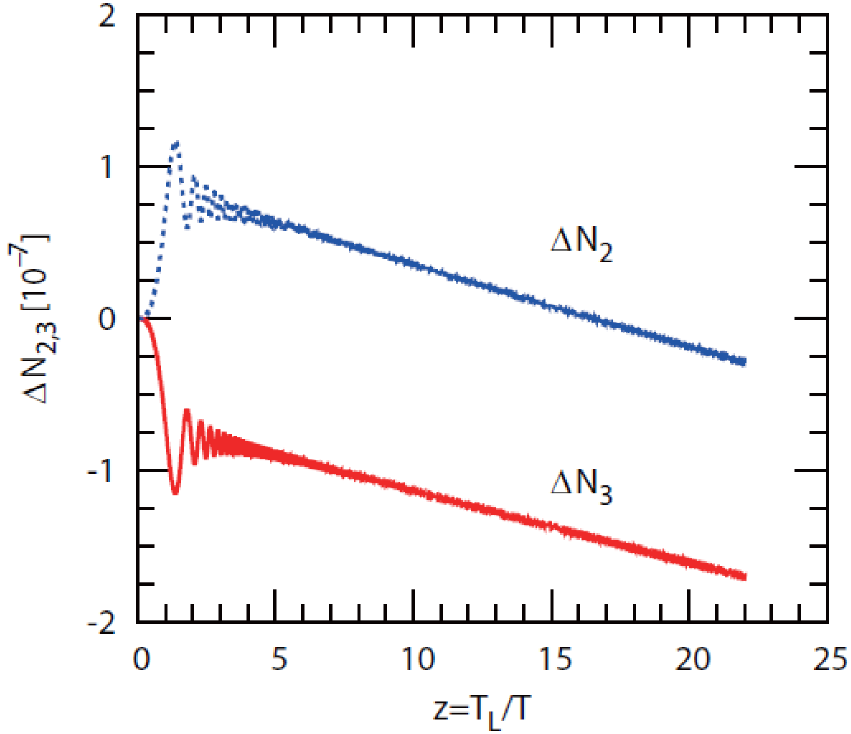
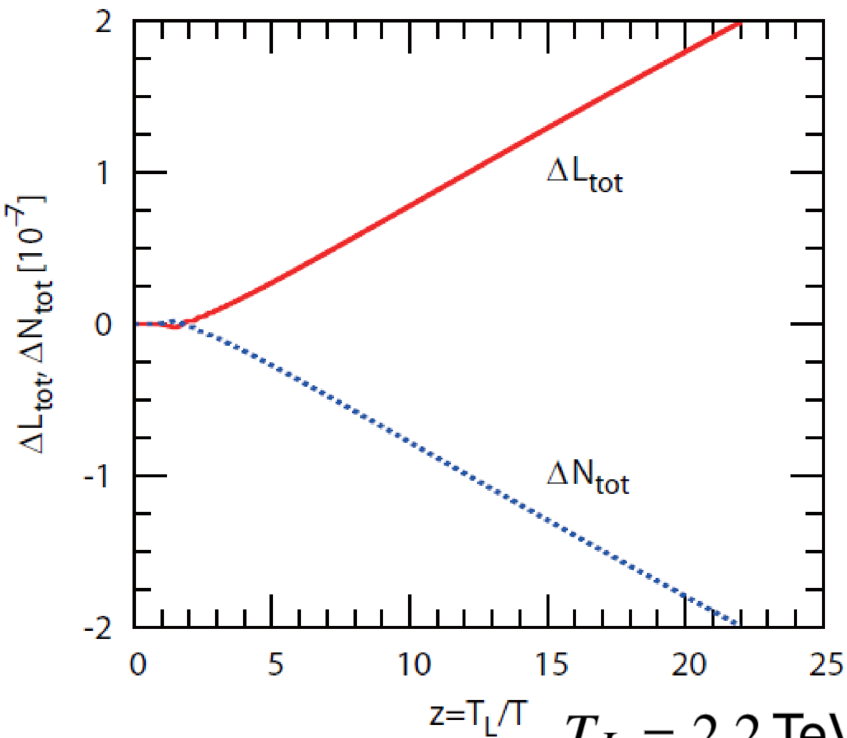


Figure 6: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

$$T_L \approx (M_P \Delta M_{32}^2)^{1/3}$$

Evolution of asymmetries



$T_L = 2.2$ TeV

Figure 7: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M^2_{32}/M^2_3 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Shaleron converts ΔL partially into baryon asymmetry

Kuzmin, Rubakov, Shaposhnikov

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

$$\left.\frac{n_B}{s}\right|_0 = 7.0 \times 10^{-4}\,\Delta L_{\rm tot}(T_W)$$

⬍

$$\left.\frac{n_B}{s}\right|_{\rm obs} = (8.81 \pm 0.23) \times 10^{-11}$$

BAU AND LOW-ENERGY NEUTRINO PARAMETERS

TA, H. Ishida（in preparation）

The νMSM

- RH neutrinos N_1, N_2, N_3 with M_I < 100GeV

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

- Roles
  - One RH neutrino N1
    - Candidate of Dark Matter
    - Yukawa couplings are highly suppressed

$$F_{\alpha 1} = 0$$

  - Other two RH neutrinos N2, N3
    - Neutrino oscillation data
    - Baryogenesis via sterile neutrino oscillation

Relation between BAU and ν osc. data???

Neutrino Yukawa Matrix for N2,N3

$$F = \frac{1}{\langle \Phi \rangle} U_{\rm MNS}\, D_\nu^{1/2}\, \Omega\, D_N^{1/2}$$

3x2 matrix

Casas, Ibarra '01

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

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

$$U_{\rm MNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}\,e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}\,e^{+i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}\,e^{+i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}\,e^{+i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}\,e^{+i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{-i\phi} & \\ & & 1 \end{pmatrix}$$

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

ω: complex number

$\xi = \pm 1$

3 CP phases

- Dirac phase — δ ← will be tested by CPV in neutrino oscillations
- Majorana phase — ϕ
- Phase in Ω — $\mathrm{Im}\,\omega$

Kinetic equations in ARS

Akhmedov, Rubakov, Smirnov '98

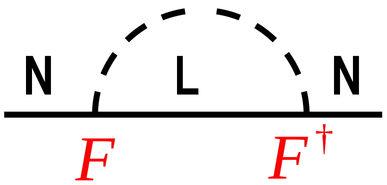
- Sterile neutrinos:

ρ_{NN} : density matrix (2 x 2 matrix) for N2 and N3
its diagonal elements are occupation numbers

$$i\frac{d\rho_{NN}}{dt} = \left[H^0_{NN} + V_N , \rho_{NN} \right] - \frac{i}{2}\left\{ \Gamma^d_{NN} , \rho_{NN} - \rho^{eq}_{NN} \right\}$$

- Effective potential and destruction rate

$$V_N = \frac{T}{8} F^\dagger F \qquad \Gamma^d_{NN} = 0.04\ V_N$$



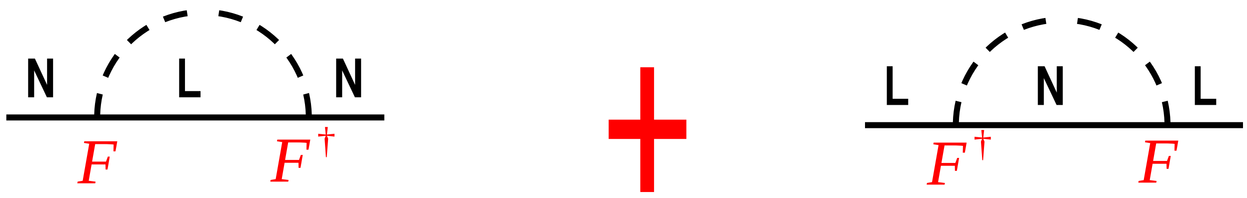
$$F^\dagger F = D_N^{1/2} \Omega^\dagger D_\nu \Omega D_N^{1/2} \Leftarrow \text{independent on } U_{MNS}$$

Produced BAU is insensitive to
low-energy neutrino parameters !

Baryogenesis via sterile neutrino osc.

TA, Shaposhnikov '05

- **Include the new effects**
  - Exchange of asymmetries between sterile neutrinos and active neutrinos (+ charged leptons)



Kinetic equations in AS

TA, Shaposhnikov '05

- Sterile neutrinos:

$$i\frac{d\rho_{NN}}{dt} = \left[H^0_{NN} + V_N, \rho_{NN}\right] - \frac{i}{2}\left\{\Gamma^d_{NN}, \rho_{NN} - \rho^{eq}_{NN}\right\} + \frac{i\sin\phi}{4} T \cdot F^\dagger(\rho_{LL} - \rho^{eq}_{LL})F$$

- Active neutrinos:

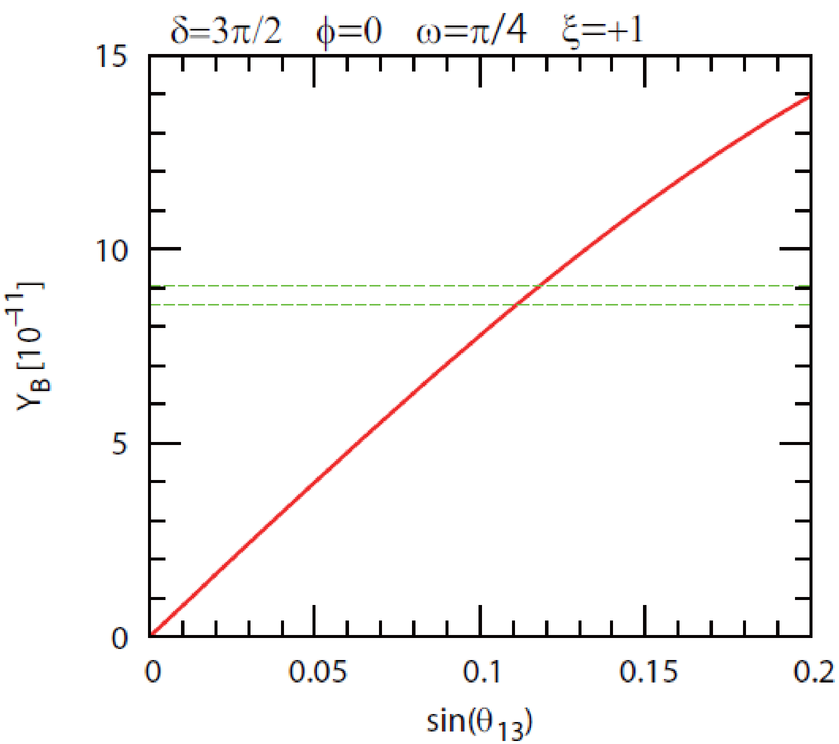
$$i\frac{d\rho^{diag}_{LL}}{dt} = [H^0_{LL} + V_L, \rho^{diag}_{LL}] - \frac{i}{2}\left\{\Gamma^d_{LL}, \rho^{diag}_{LL} - \rho^{eq}_{LL}\right\} + \frac{i\sin\phi}{4} T \cdot F(\rho_{NN} - \rho^{eq}_{NN})F^\dagger$$

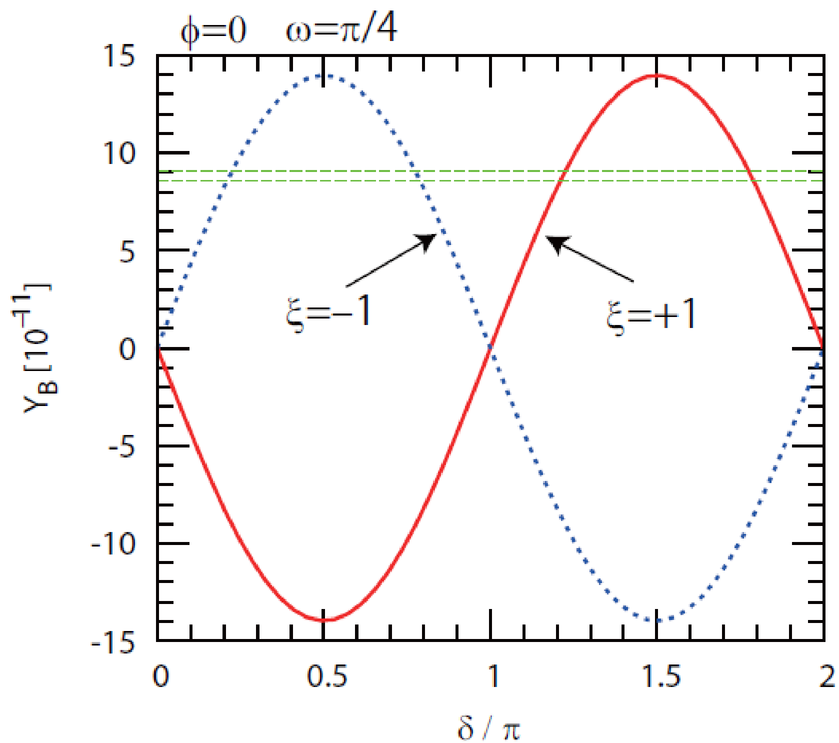
Does depend on MNS matrix !
→ sensitive to low-energy neutrino parameters !

Let us see how BAU depends on Dirac phase δ !

$\phi = 0, \quad \mathrm{Im}\,\omega = 0$

Dirac phase δ





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

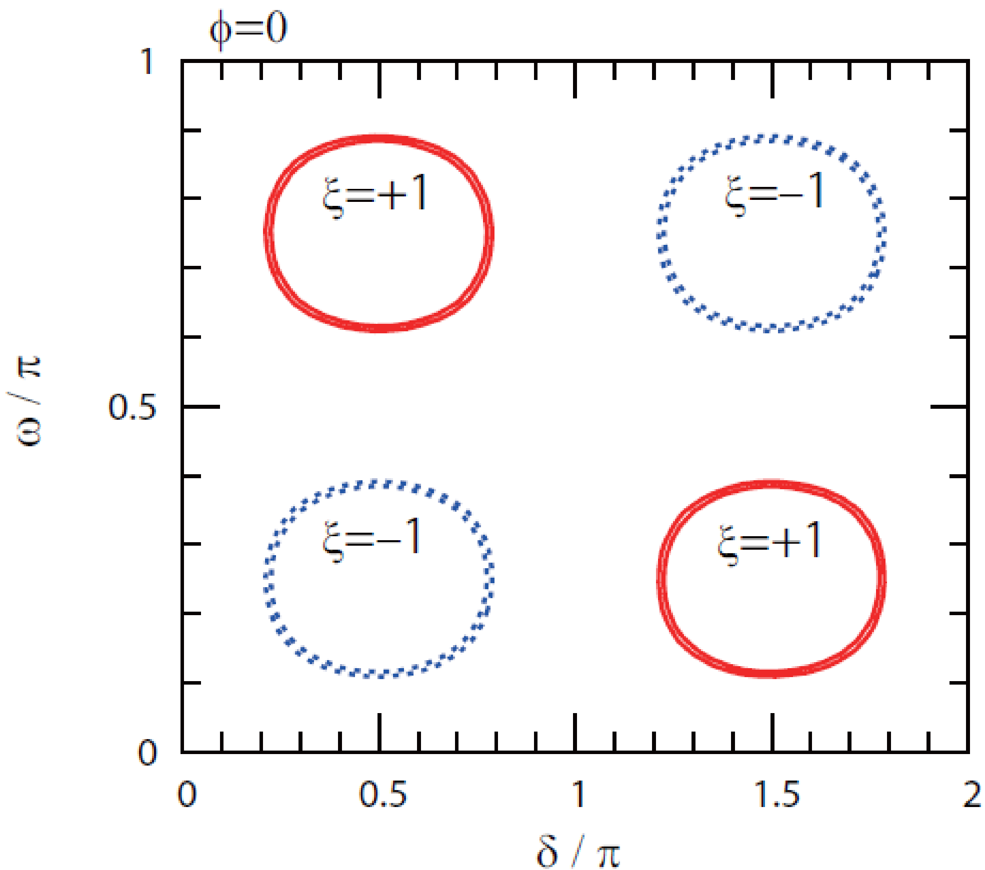
$$\xi = \pm 1$$

Figure 10: Baryon asymmetry in terms of the Dirac phase δ in the MNS matrix. The solid-red (dotted-blue) line corresponds to the case when $\xi = +1$ ($\xi = -1$), respectively. The horizontal dashed-green lines show the 3σ range of BAU. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\sin\theta_{13} = 0.2$, $\phi = 0$, and $\omega = \pi/4$.

$$U_{\rm MNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}\,e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}\,e^{+i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}\,e^{+i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}\,e^{+i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}\,e^{+i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{-i\phi} & \\ & & 1 \end{pmatrix}$$

Regions accounting for BAU

- $$\left.\frac{n_B}{s}\right|_{\rm obs} = (8.81 \pm 0.23) \times 10^{-11}$$



Normal hierarchy

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

Summary

- Connection between neutrino masses and BAU is attractive and important idea

- Conventional seesaw scenario（$M>10^9$GeV)
  [Seesaw + Leptogenesis]
  → Natural framework of SUSY GUT …
  → Exp. test for RH neutrinos is impossible

- Connection can be obtained even with $M<10^2$GeV（νMSM)
  [Seesaw + Baryogenesis via sterile neutrino osc.]
  → Such sterile neutrinos might be tested
  → Connection between BAU and CPV in neutrino oscillations

Inputs

- Normal hierarchy of (active) neutrino masses

$$m_3 = \sqrt{\Delta m_{atm}^2 + \Delta m_{sol}^2}\,,\; m_2 = \sqrt{\Delta m_{sol}^2}\,,\; m_1 = 0$$

$$\Delta m_{atm}^2 = 2.5\times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m_{sol}^2 = 8.0\times 10^{-5}\,\mathrm{eV}^2$$

$$\theta_{23} = \pi/4,\; \theta_{12} = \pi/5 \qquad \sin\theta_{13} \le 0.2$$

$$\delta,\; \phi$$

$$M_3 = 3\mathrm{GeV},\; M_2^2 = M_3^2(1-10^{-8})$$

$$F = \mathrm{O}(10^{-8})$$

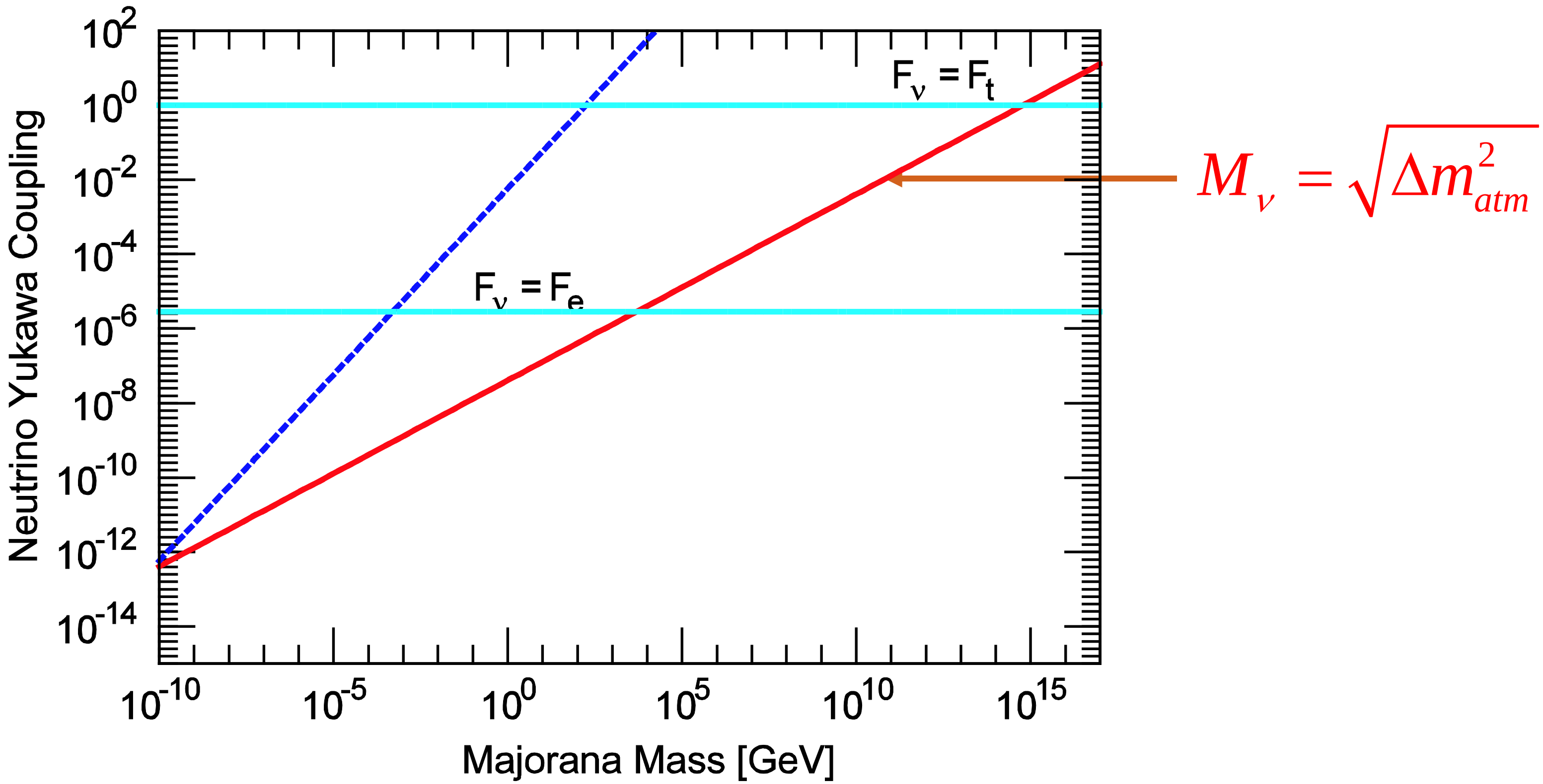
$$\Theta = \mathrm{O}(10^{-6})$$

$$\omega = \mathrm{Re}\,\omega + \mathrm{Im}\,\omega$$

$$\xi = \pm 1$$

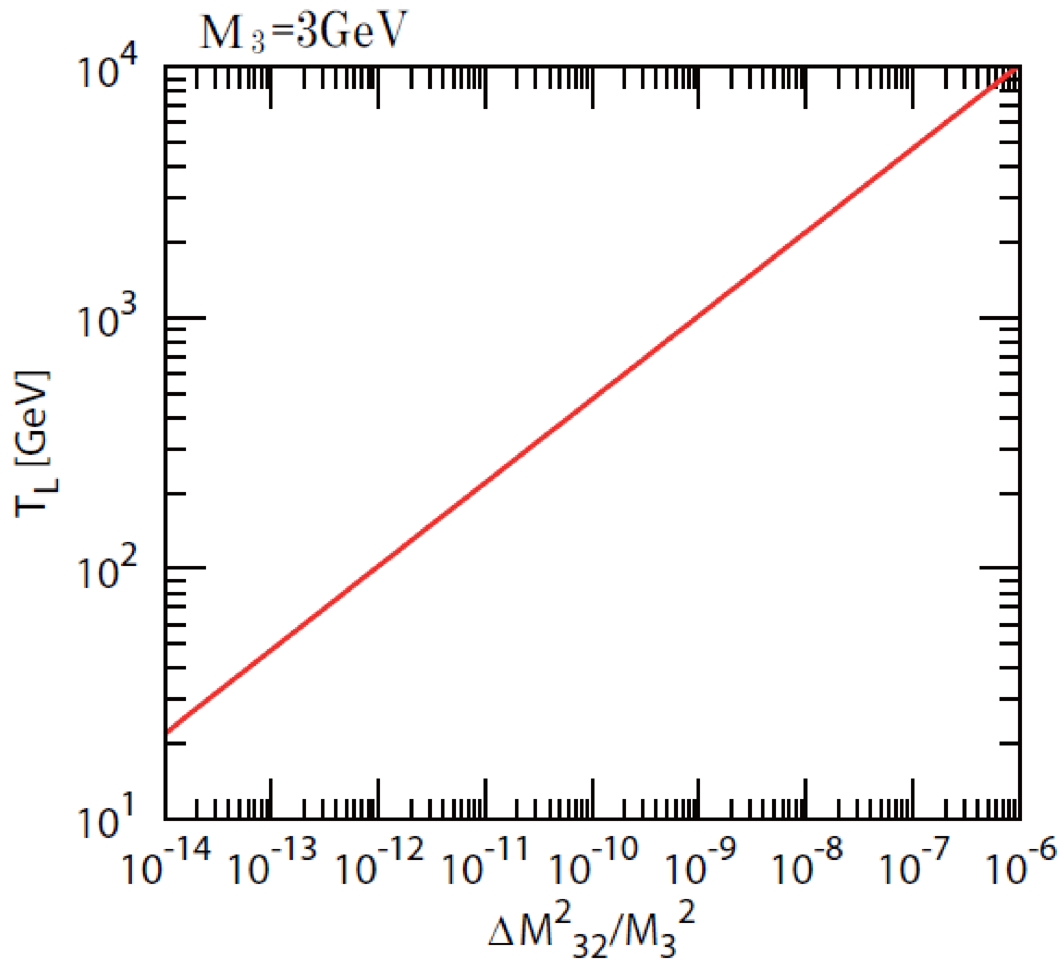
Scale of Majorana mass

$$M_\nu = -M_D^T \frac{1}{M_M} M_D \quad \Rightarrow F^2 = M_M M_\nu / \langle H \rangle^2$$



Typical temperature TL

$$T_L \approx (M_P \Delta M_{32}^2)^{1/3}$$



Sterile neutrino oscillation

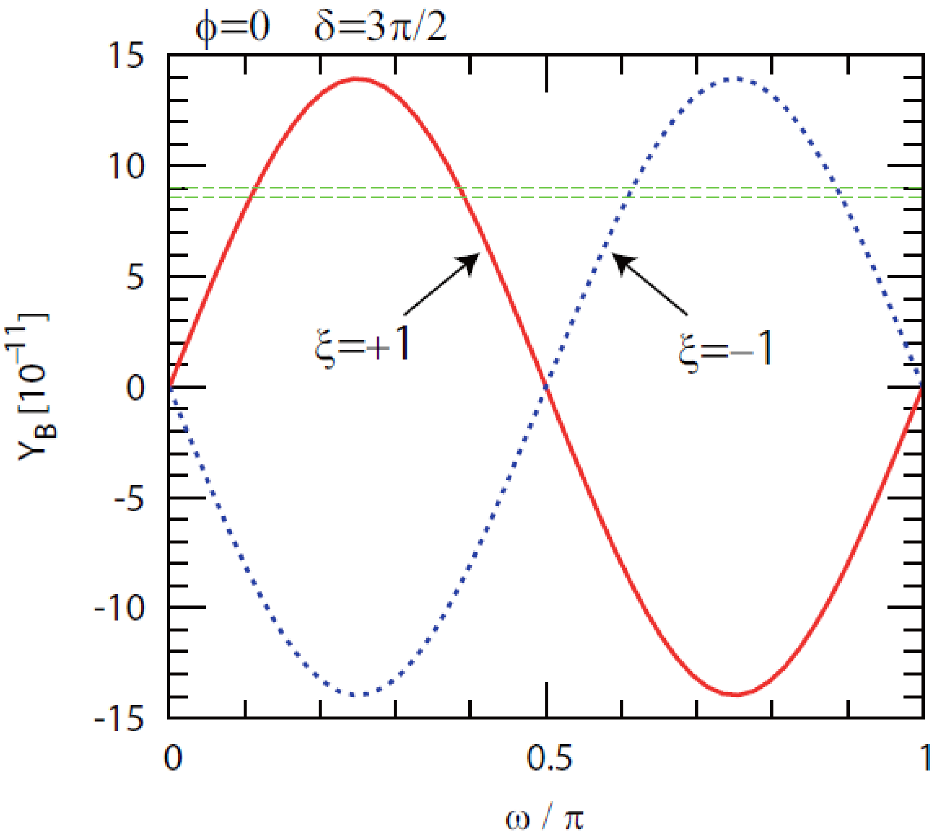
- Flavor mixing of sterile neutrinos is induced from thermal potential

$$V_N \propto F^\dagger F = D_N^{1/2} \Omega^\dagger D_\nu \Omega D_N^{1/2}$$

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

ω: complex number

$\xi = \pm 1$



BAU vanishes when there is no sterile neutrino oscillation !

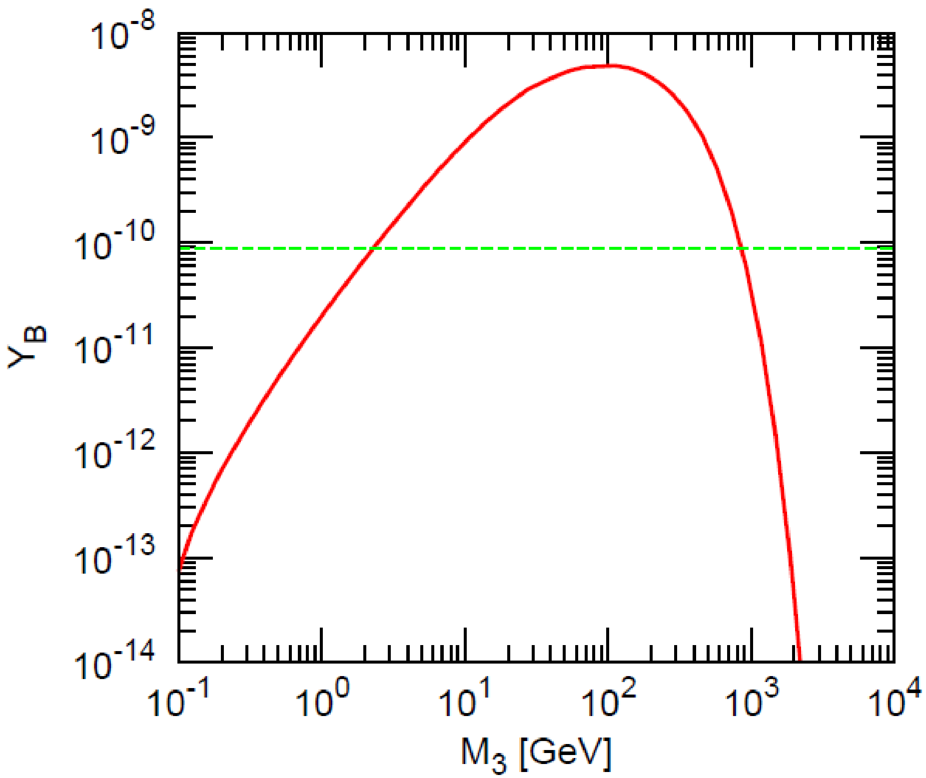


Figure 2: Baryon asymmetry in terms of the sterile neutrino mass M_3. (the solid-red line). The horizontal dashed-green lines show the 3σ range of BAU. Here we take $\Delta M^2_{32}/M^2_3 = 10^{-8}$, $\phi = 0$, $\delta = 3\pi/2$ and $\omega = \pi/4$.

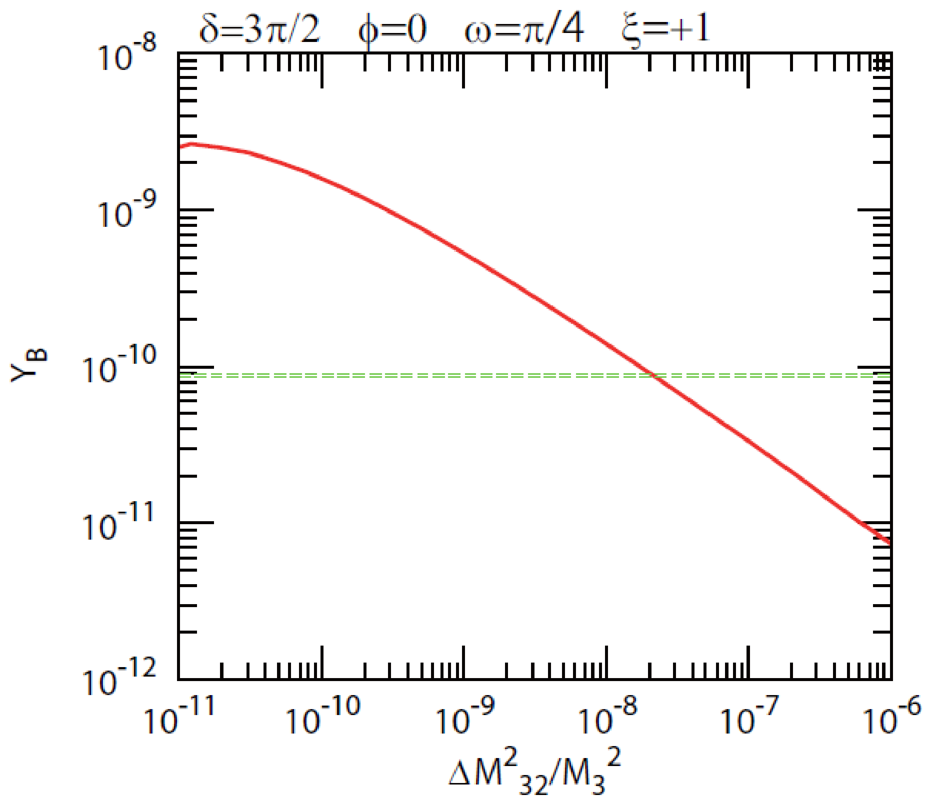
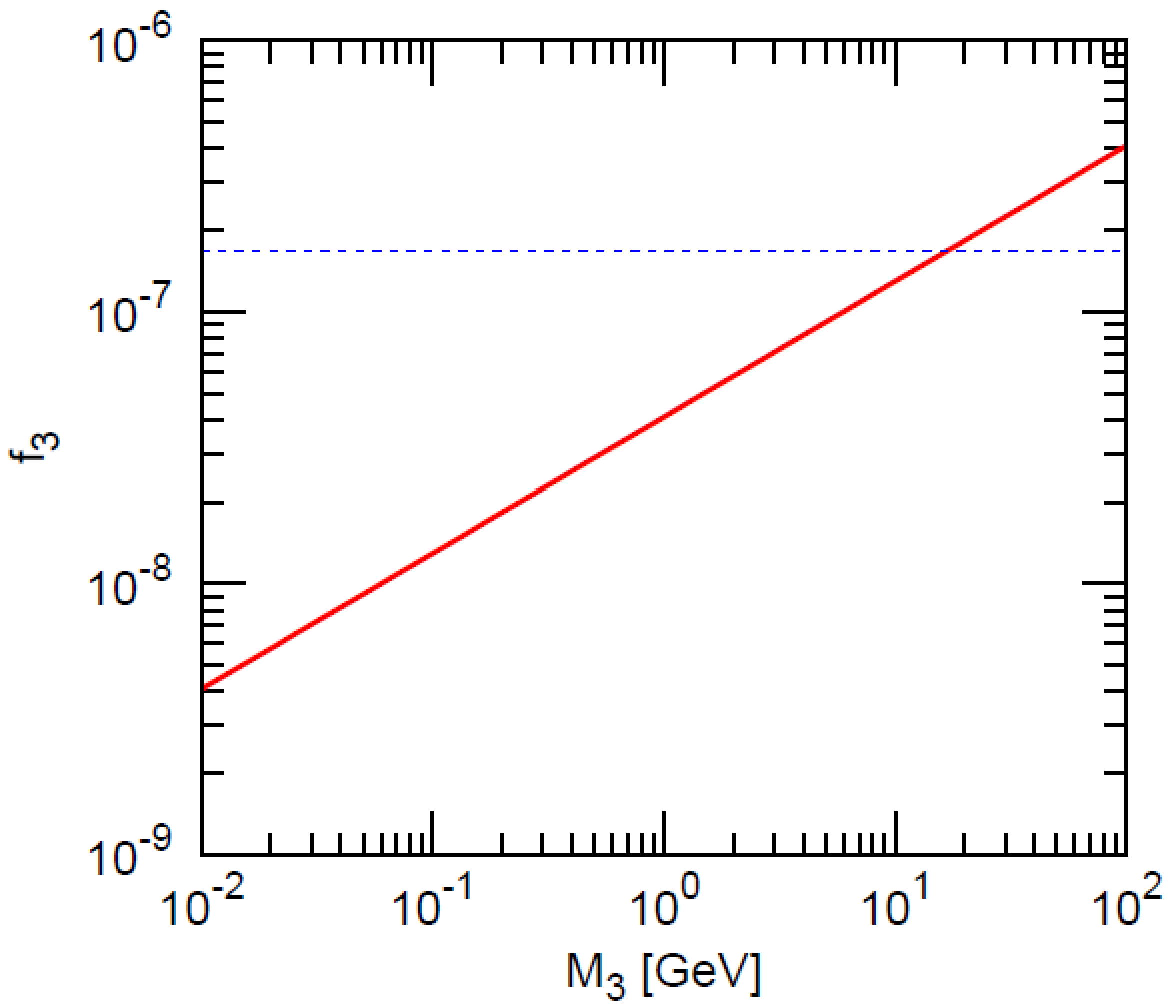


Figure 9: Baryon asymmetry in terms of the neutrino mixing angle $\sin\theta_{13}$ in the MNS matrix (the solid-red line). The horizontal dashed-green lines show the 3σ range of BAU. Here we take $M_3 = 3$ GeV, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\delta = 3\pi/2$ and $\omega = \pi/4$.

Eigenvalue of Yukawa matrix



$M_3 = 3\mathrm{GeV}$

$f_3 = 7\times10^{-8}$

$\Theta = \frac{f_3\langle\Phi\rangle}{M_3} = 4\times10^{-6}$

CPV in neutrino oscillation

$$P(\nu_\mu \to \nu_\tau) - P(\bar{\nu}_\mu \to \bar{\nu}_\tau) = 4 J_{CP}^{\nu} A$$

$$J_{CP}^{\nu} = s_{12} s_{13} s_{23} c_{12} c_{23} c_{13}^2 \cdot \sin\delta$$

$$A = \sin\left(\frac{\Delta m_{12}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right)$$

CPV in neutrino oscillations measure the Dirac phase δ !