Baryogenesis via Sterile Neutrino Oscillation and Neutrino Parameters

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In collaboration with H. Ishida (Niigata University)

Motivation

Origin of ν masses

Origin of BAU

Motivation

Heavy RH neutrinos

Seesaw

Tiny ν masses

$M_M > O(10^9)\mathrm{GeV}$

Leptogenesis

[Fukugita, Yanagida ’86]

Origin of ν masses

Origin of BAU

Motivation

Heavy RH neutrinos

$M_M > O(10^9)\text{GeV}$

Seesaw

Tiny ν masses

Leptogenesis

[Fukugita, Yanagida '86]

Origin of ν masses

Origin of BAU

Seesaw

Very small
Yukawa couplings

$M_M < O(10^2)\text{GeV}$

Baryogenesis via sterile ν osc.

[Akhmedov, Rubakov, Smirnov '98]

Light RH neutrinos

The νMSM

[TA, Shaposhnikov '05]

- The MSM + Three RH neutrinos (N_1, N_2, N_3)

$$L = i\bar{N}_I \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha \Phi N_I - \frac{M_I}{2} \bar{N}_I^c N_I + h.c.$$

  - Dirac and Majorana masses of neutrinos

$$[M_D]_{\alpha I} = F_{\alpha I} \langle \Phi \rangle \quad \text{and} \quad [M_M]_{II} = M_I \qquad (\alpha = e, \mu, \tau; \quad I = 1, 2, 3)$$

- Key Assumption

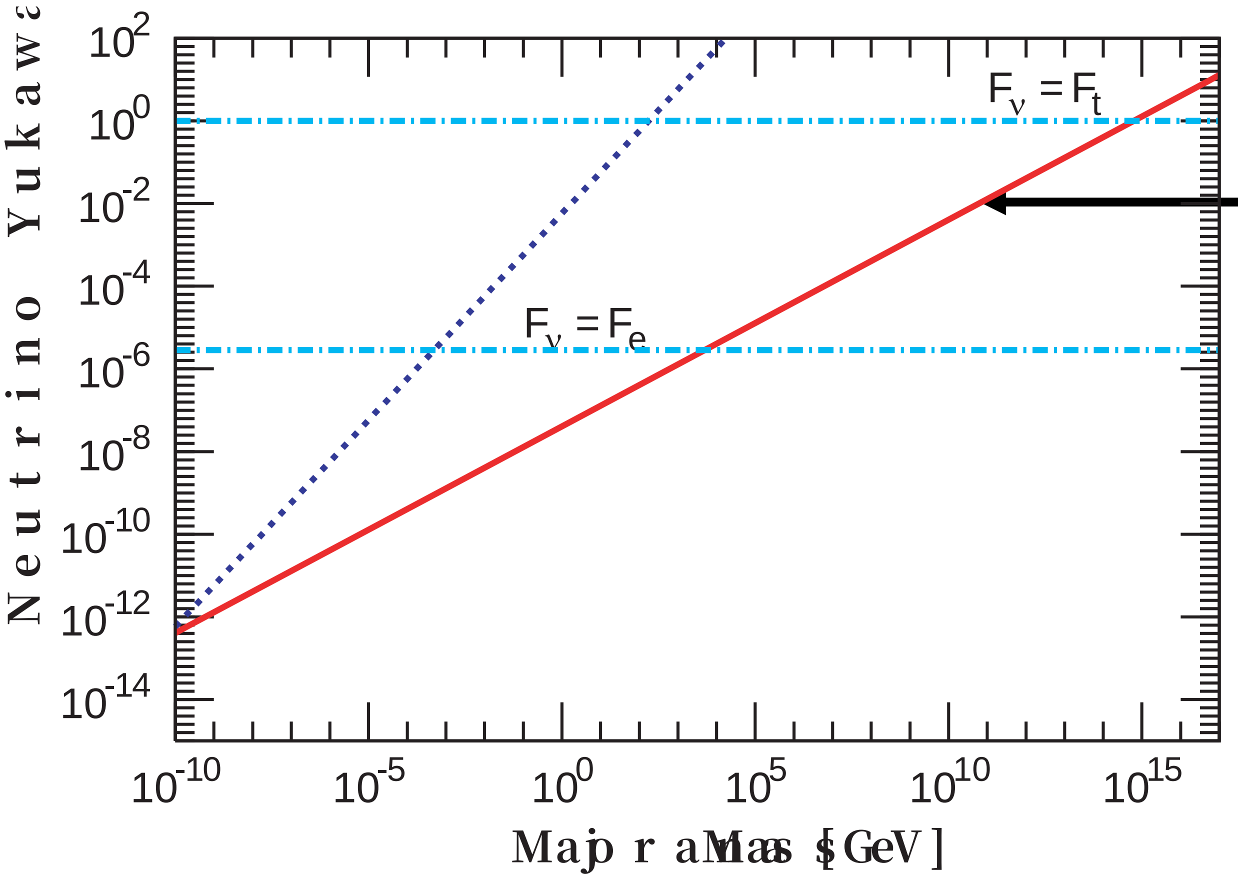
$$\boxed{|M_D|_{\alpha I} \ll M_I < O(10^2)\mathrm{GeV}}$$

  - Light RH neutrinos could be tested!!
  - Seesaw mechanism still works!! $M_\nu = -M_D M_M^{-1} M_D^T$

$$F \sim 4 \times 10^{-8} \left(\frac{M_I}{\mathrm{GeV}} \right)^{1/2} \left(\frac{m_\nu^2}{2.5 \times 10^{-3}\,\mathrm{eV}^2} \right)^{1/4}$$

Scale of Majorana mass

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



$$M_\nu = \sqrt{\Delta m^2_{atm}}$$

Roles of three sterile (RH) neutrinos

$\boxed{N_1}$ ("Dark" sterile neutrino)

- **Dark Matter Candidate** (Here, we do not specify its detail.)
- To avoid constraints, Yukawa's should be suppressed essentially, $\boxed{F_{\alpha 1} \approx 0}$

$\boxed{N_2 \text{ and } N_3}$ ("Bright" and "Clear" sterile neutrinos)

- **Neutrino Oscillation data**
  - Masses and mixings

LINK

- **Baryon Asymmetry of the Universe (BAU)**
  - Mechanism via sterile neutrino oscillation

In this talk

- We will show

How CPV in neutrino sector relates with BAU?

- Outline
  - Baryogenesis via sterile neutrino oscillation
  - BAU and low-energy CPV in neutrino sector
  - Summary

Baryogenesis via Sterile Neutrino Osillation

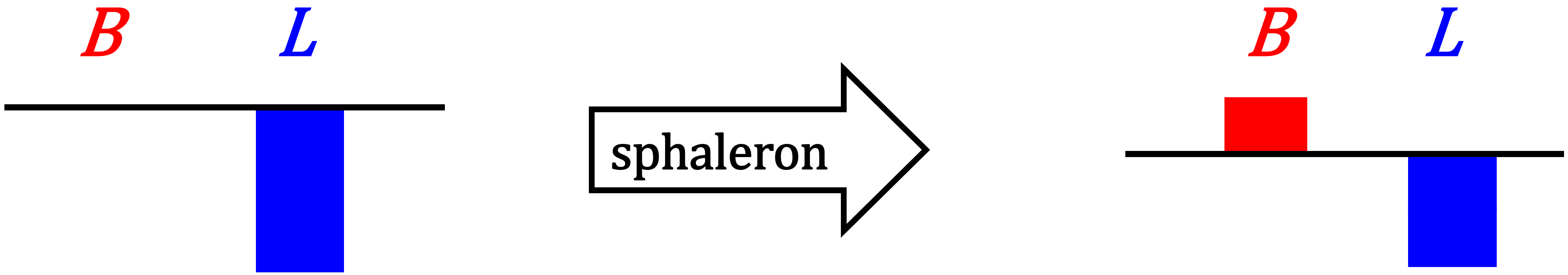
[Akhmedov, Rubakov, Smirnov '98]
[TA, Shaposhnikov '05]

Baryogenesis scenario
by sterile neutrinos
with $M_M < O(100)$ GeV

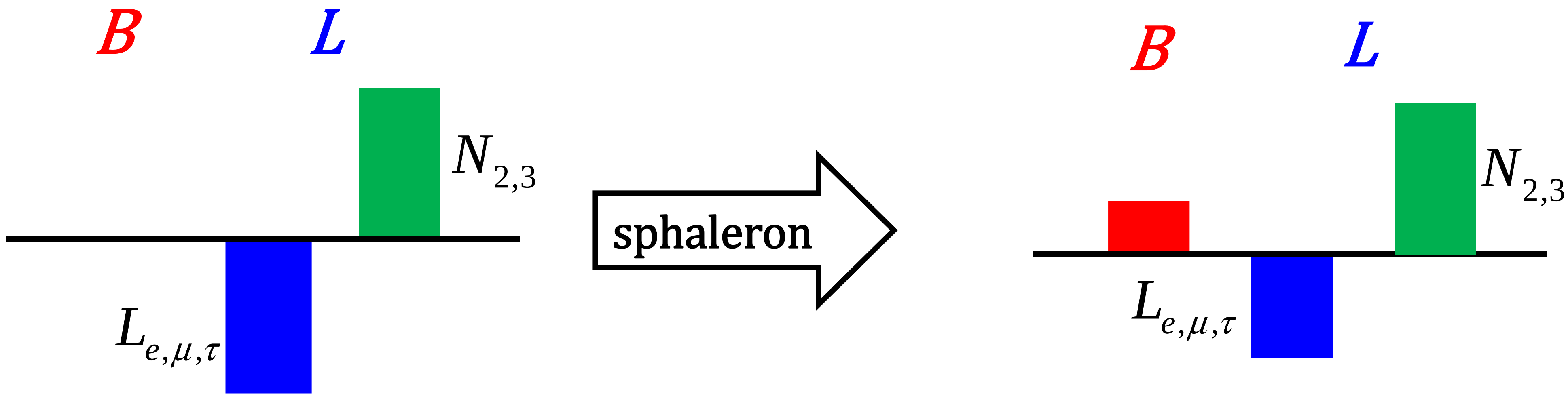
- The Sakharov's Conditions
  - **CPV**
    - CPV phases in neutrino sector
  - **Out of equilibrium**
    - No 1^{st} order phase transition as in the SM
    - N2,3 can be out of equilibrium due to small Yukawa couplings
  - **B (L) violation**
    - (B+L) violation due to sphaleron for T>100GeV
    - Total lepton number violation is ineffective for T>100GeV since $M_M < 100$ GeV

Key points of this baryogenesis

- Baryogenesis via leptogenesis

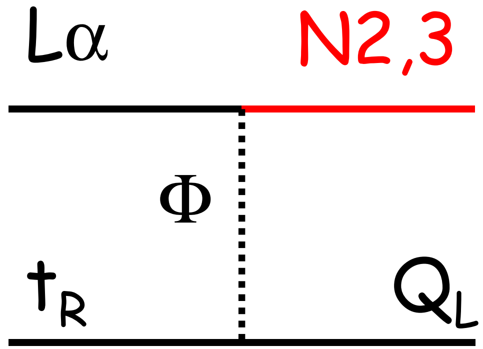


- Baryogenesis via sterile neutrino oscillation

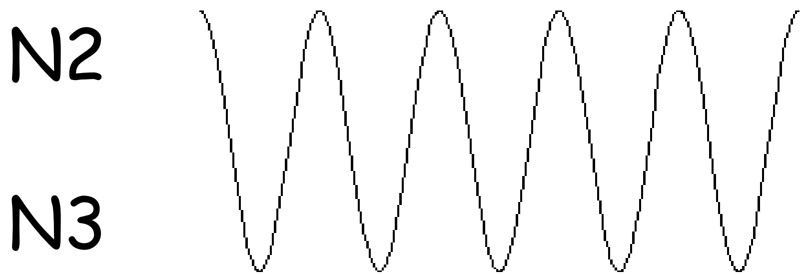


First step: at F^2 order

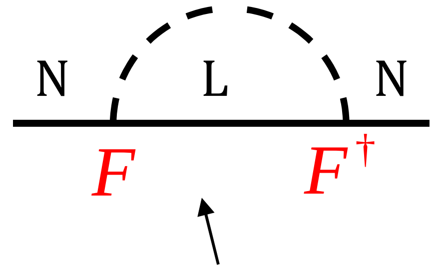
- N2 and N3 are produced via scatterings



- N2 and N3 oscillate at $T = T_L \sim (M_{pl} \Delta M_{32}^2)^{1/3}$



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

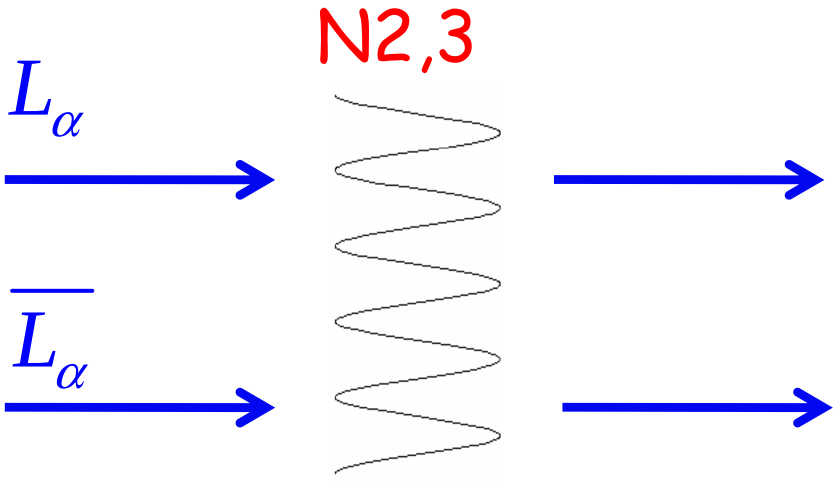


Medium effects

Second step: at F^4 order

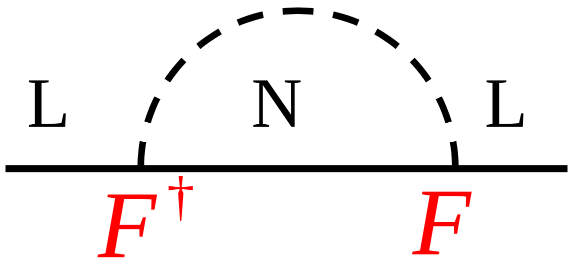
[TA, Shaposhnikov '05]

- Active flavor asymmetries are generated



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

- Evolution rates of L_α and $\overline{L_\alpha}$ are different due to CVP in



Final step: at F⁶ order

- Total asymmetries in active and sterile sectors are generated.

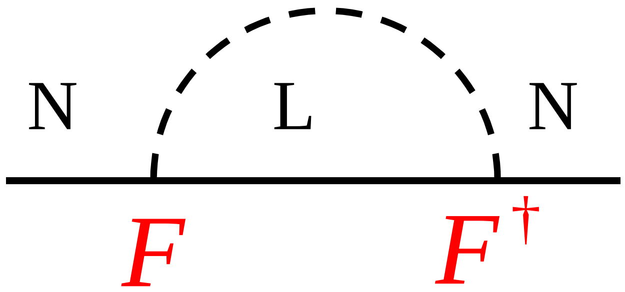
$$N_I \longrightarrow \quad \Delta L_e,\ \Delta L_\mu,\ \Delta L_\tau \quad \longrightarrow$$

$$\overline{N_I} \longrightarrow \quad \Delta L_e,\ \Delta L_\mu,\ \Delta L_\tau \quad \longrightarrow$$

$$\Delta N_{\text{tot}} = \Delta N_2 + \Delta N_3 \neq 0$$

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

- Evolution rates of N_I and $\overline{N_I}$ are different due to ΔL_α and CPV in



Evolution of each asymmetries

Active sector

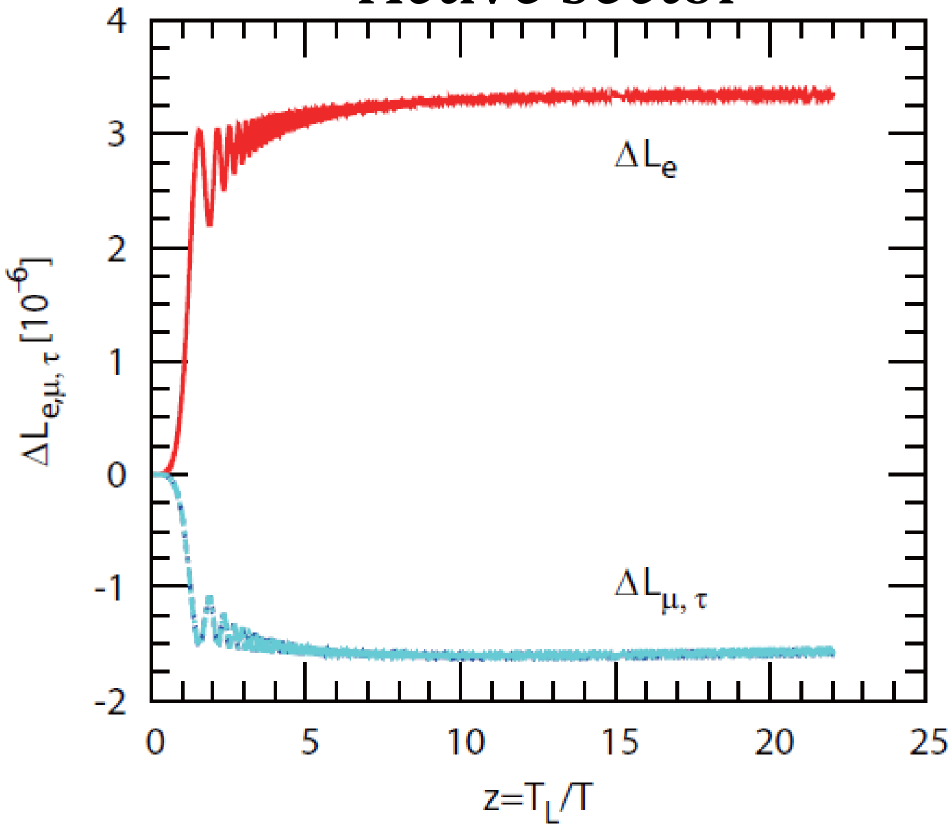


Figure 5: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Sterile sector

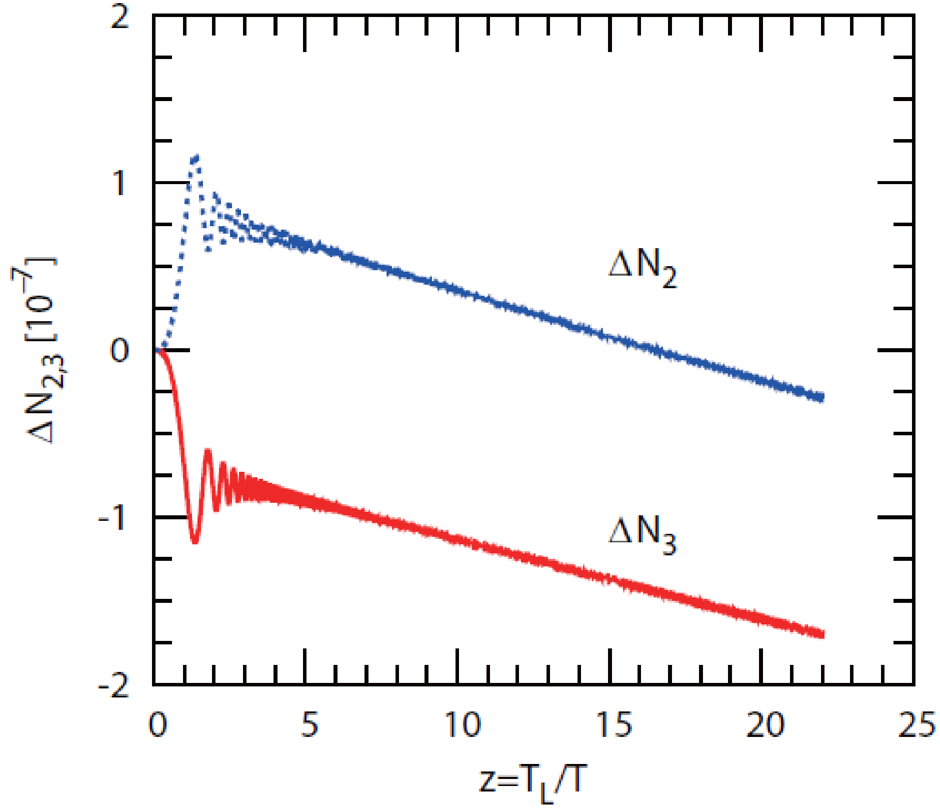
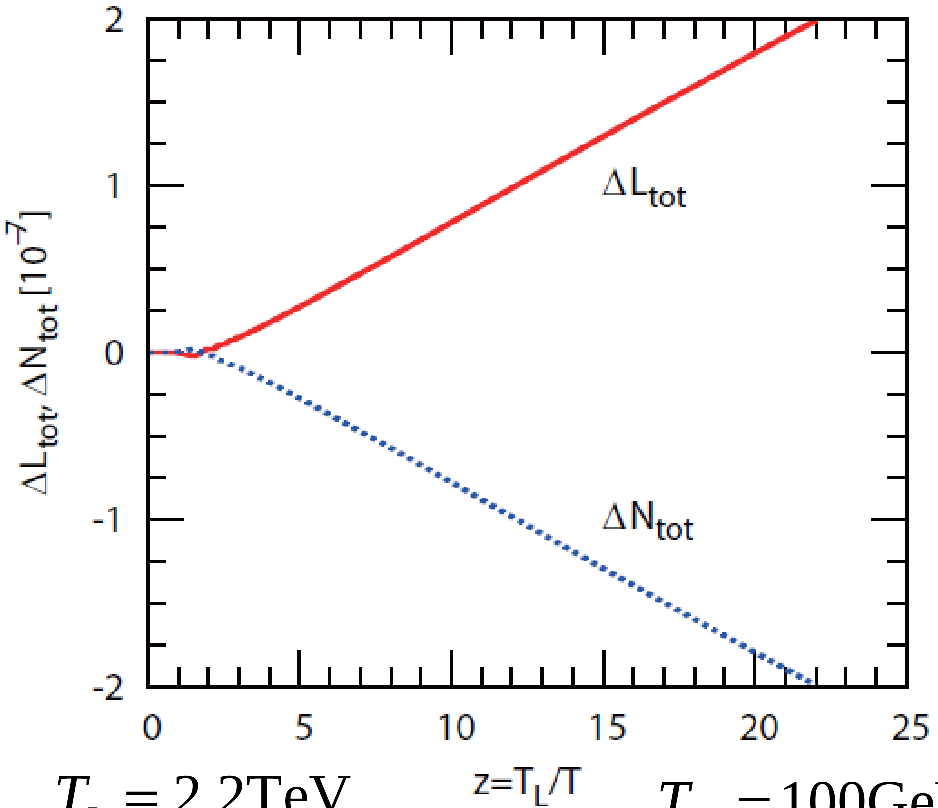


Figure 6: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

$$T_L \sim (M_{pl}\Delta M_{32}^2)^{1/3} = 2.2\text{TeV}$$

Evolution of asymmetries



$T_L = 2.2\text{TeV}$ $\quad$ $T_W = 100\text{GeV}$

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 $\delta = 3\pi/2$.

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

Degenerate masses are needed!

Sphaleron converts ΔL_{tot} partially into baryon asymmetry

[Kuzmin, Rubakov, Shaposhnikov '85]

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

BAU

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

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

Baryon Asymmetry of Univ. and Low-energy CPV in neutrino sector

[TA, Ishida in preparation]

Sterile Neutrinos: N_2 and N_3

Seesaw

$$[M_\nu]_{\alpha\beta} = -\sum_{I=2,3} \frac{[M_D]_{\alpha I}[M_D]_{\beta I}}{M_I}$$

BAU

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

Neutrino Yukawa couplings for N2,3

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

[Casas, Ibarra '01]
(in NH)

■ Low energy parameters

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

Dirac phase δ

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

Majorana phase ϕ

■ High energy parameters

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

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

ω : complex number

$\xi = \pm 1$

High energy phase ω

Kinetic equations in ARS [Akhmedov, Rubakov, Smirnov '98]

- Sterile neutrinos: ρ_{NN} : density matrix for $N_{2,3}$

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

Effective potential

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

Destruction rate

$$\Gamma^d_N \simeq 0.04\ V_N$$

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

Independent on neutrino mixing matrix U_{PMNS} !

→ insensitive to low-energy neutrino parameters !

Baryogenesis via sterile neutrino osc.

- Include the new effects [TA, Shaposhnikov ’05]
  - 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:

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

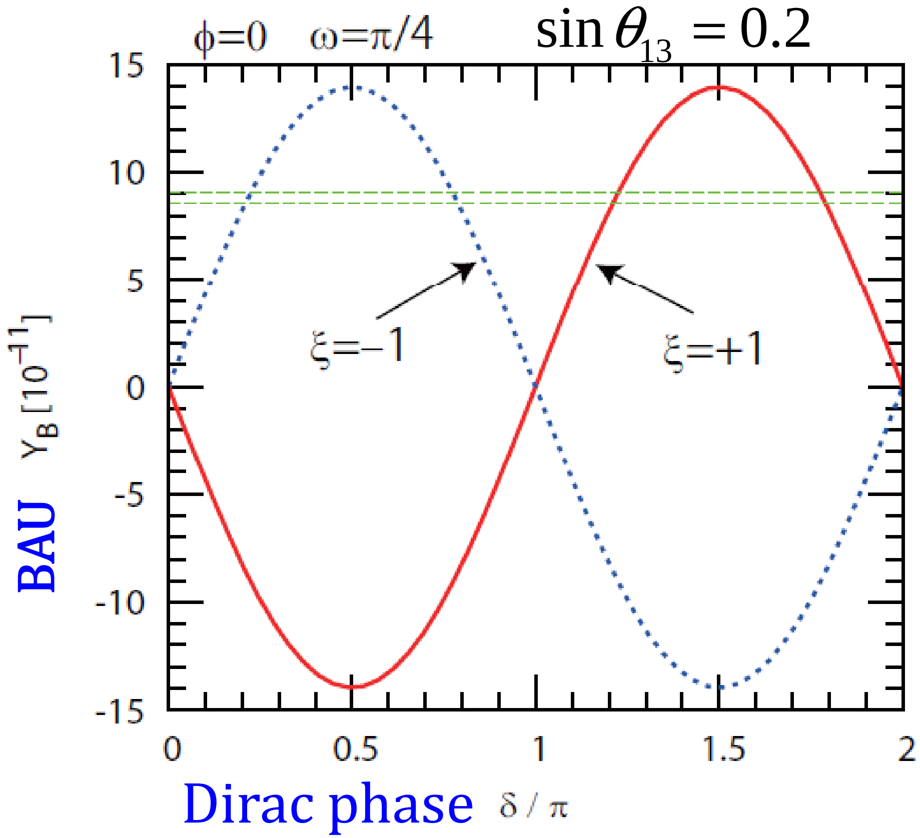
Does depend on neutrino mixing matrix U_{PMNS} !
→ sensitive to low-energy neutrino parameters !

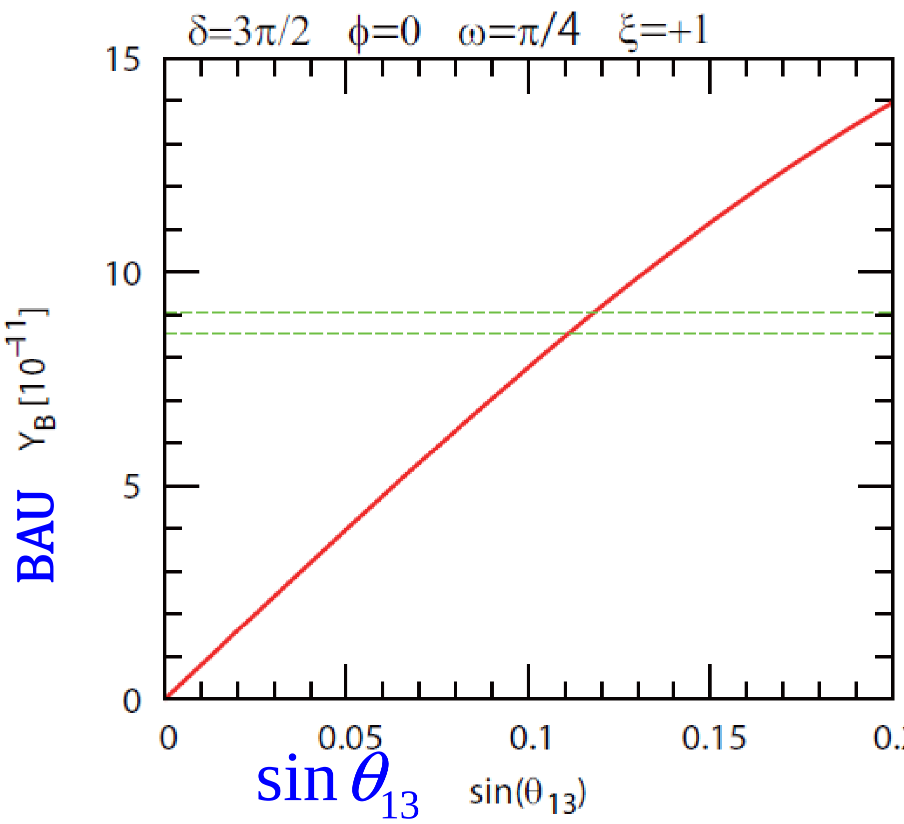
Let us see how BAU depends on

Dirac phase δ and Majorana phase ϕ !

Dirac phase δ

No Majorana phase ϕ

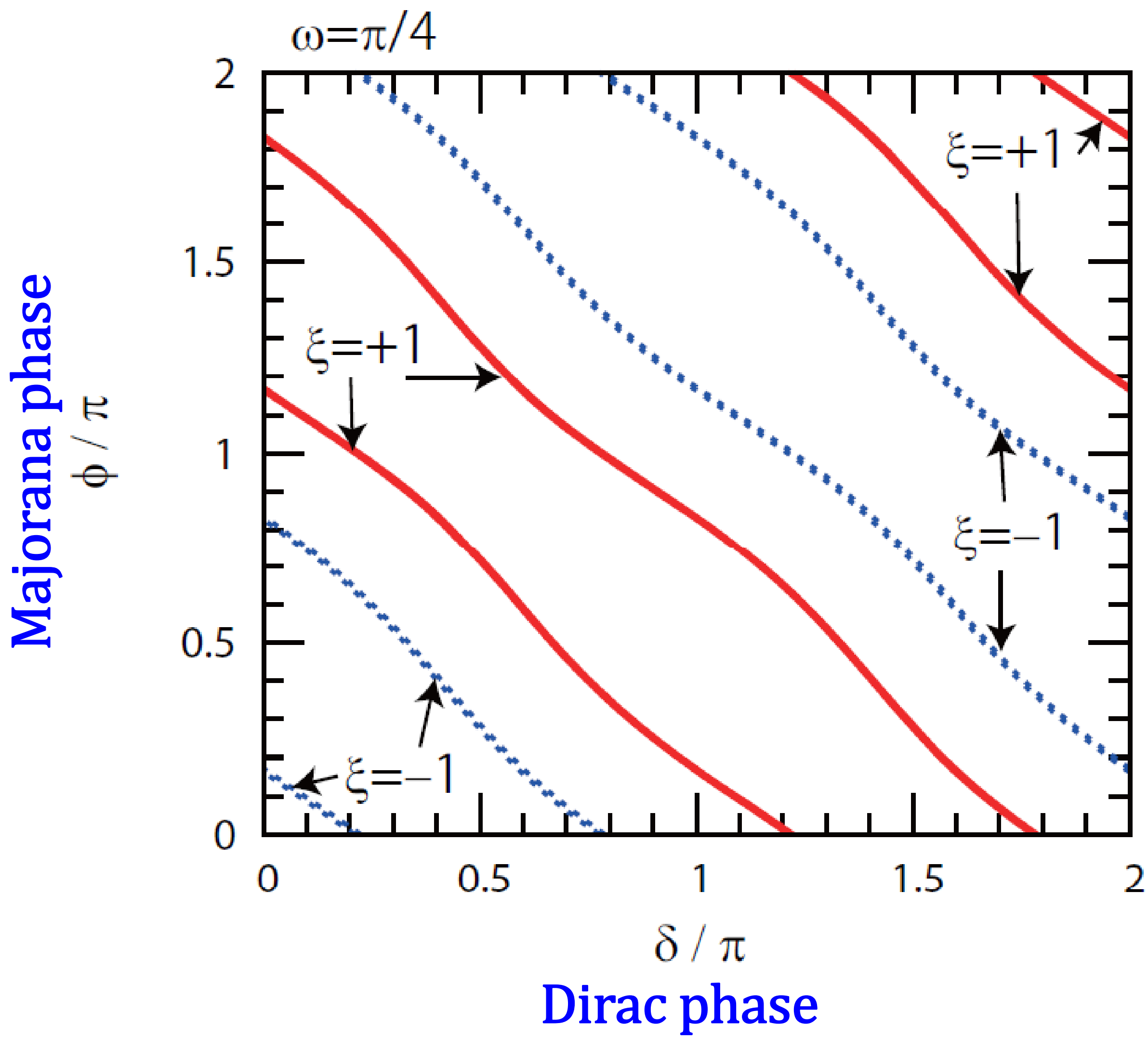




$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13}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

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

Regions accounting for BAU



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

Inputs:

$$M_3 = 3\text{GeV}$$

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

$$\sin\theta_{13} = 0.2$$

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

Summary

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

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

- Connection can be obtained even with $M_M < 10^2$GeV
  [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

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

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

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

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

$$\delta,\ \phi$$

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

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

$$\xi = \pm 1$$

Sterile neutrino oscillation

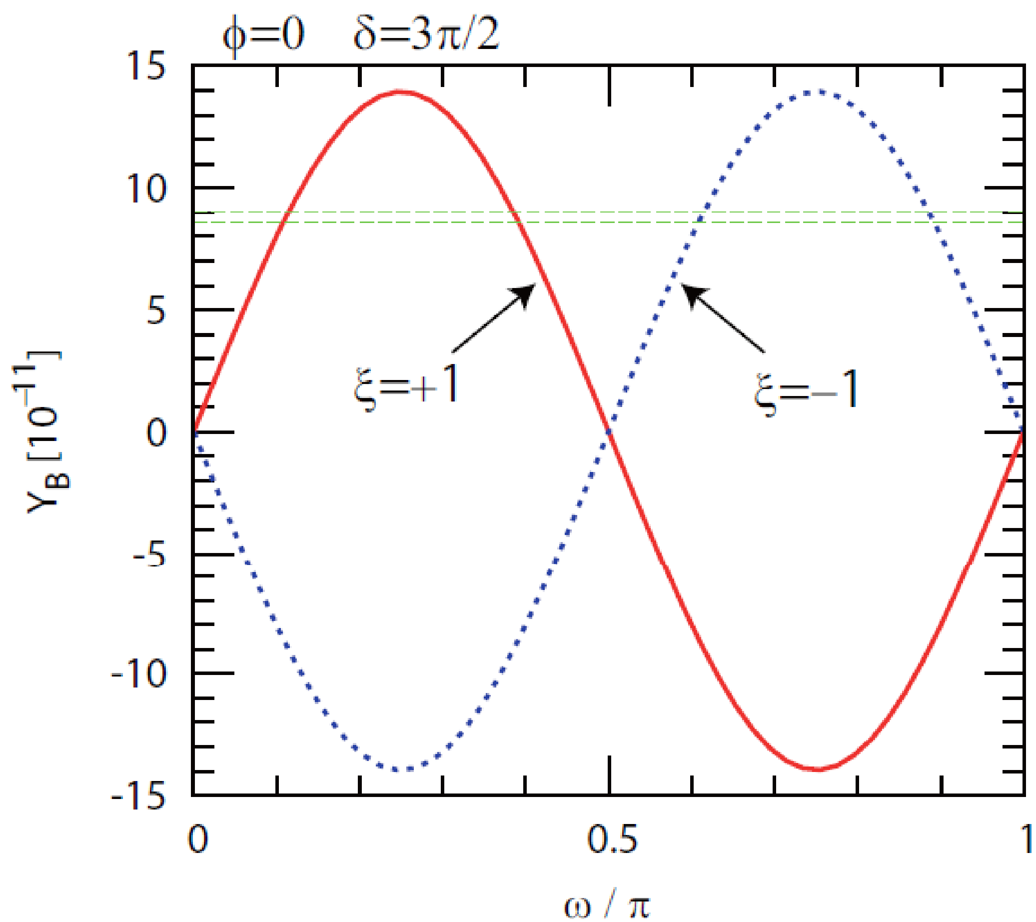
- Flavor mixing of sterile neutrinos is induced from thermal potential

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

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

ω: complex number

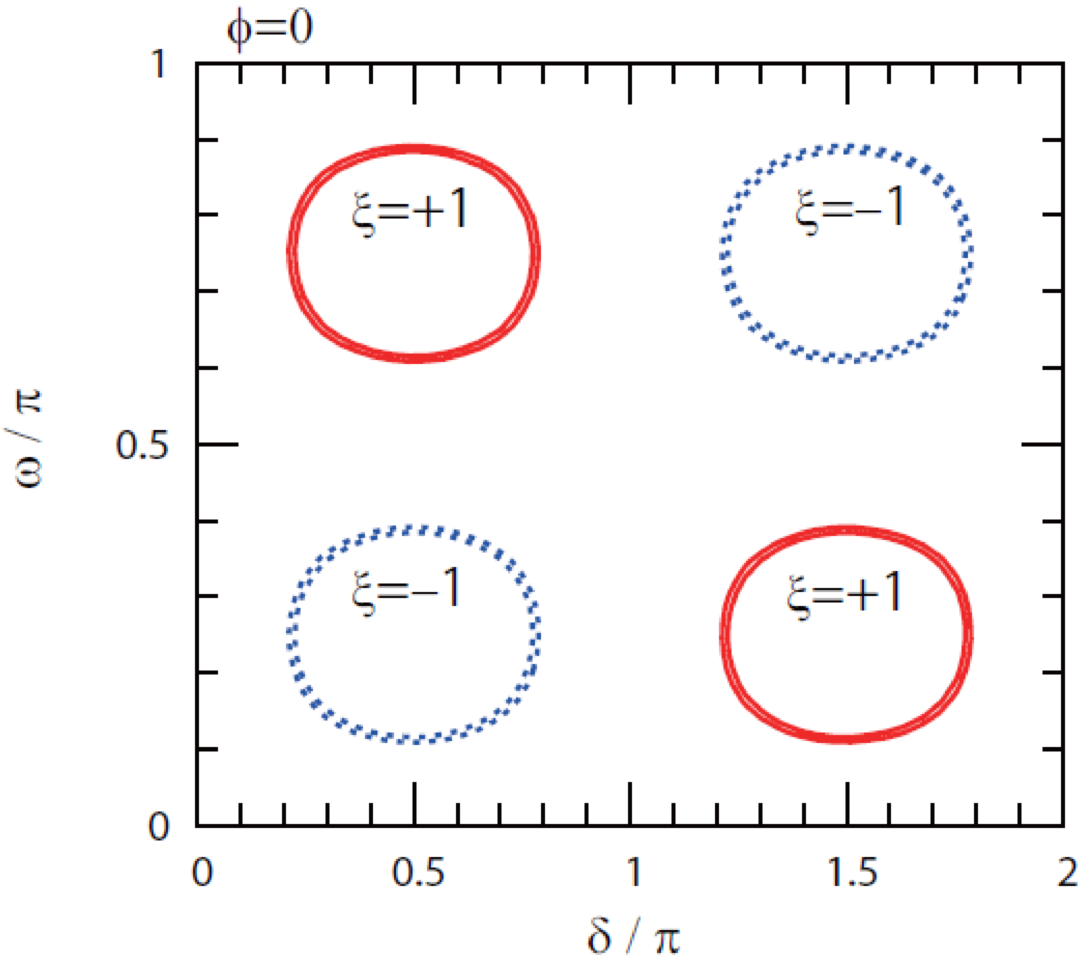
$\xi = \pm 1$



BAU vanishes when there is no sterile neutrino oscillation !

Regions accounting for BAU

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



Normal hierarchy

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