Neutrino masses, dark matter and baryon asymmetry of the universe

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TA, S. Blanchet, M. Shaposhnikov, Phys.Lett.B631 (2005) 151
TA, M. Shaposhnikov, Phys.Lett.B620 (2005) 17
TA, A. Kusenko and M. Shaposhnikov, hep-ph/0602150
TA, M. Laine, M. Shaposhnikov, hep-ph/0606209

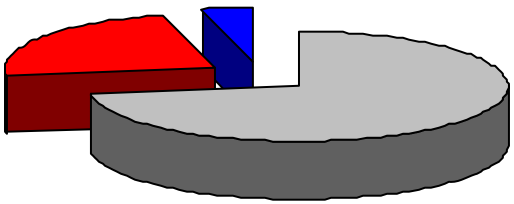
Cosmology

Galaxy NGC 4603 **HST** • WFPC2
PRC99-19 • STScI OPO
J. Newman (University of California, Berkeley) and NASA

We would like to understand the nature of the universe !

Origin of matter in the universe

- Content of the universe
  - Dark energy $\Omega_{DE} \sim 74\%$
  - Dark matter $\Omega_{DM} \sim 22\%$
  - Baryonic matter $\Omega_{B} \sim 4\%$



- Questions:
  - What is the dark matter (DM) ?
  - How generate the baryon asymmetry of the universe (BAU)?

- The minimal standard model (MSM) of particle physics cannot answer to these questions !

Neutrino oscillations

- Solar, atmospheric, reactor and accelerator experiments provide

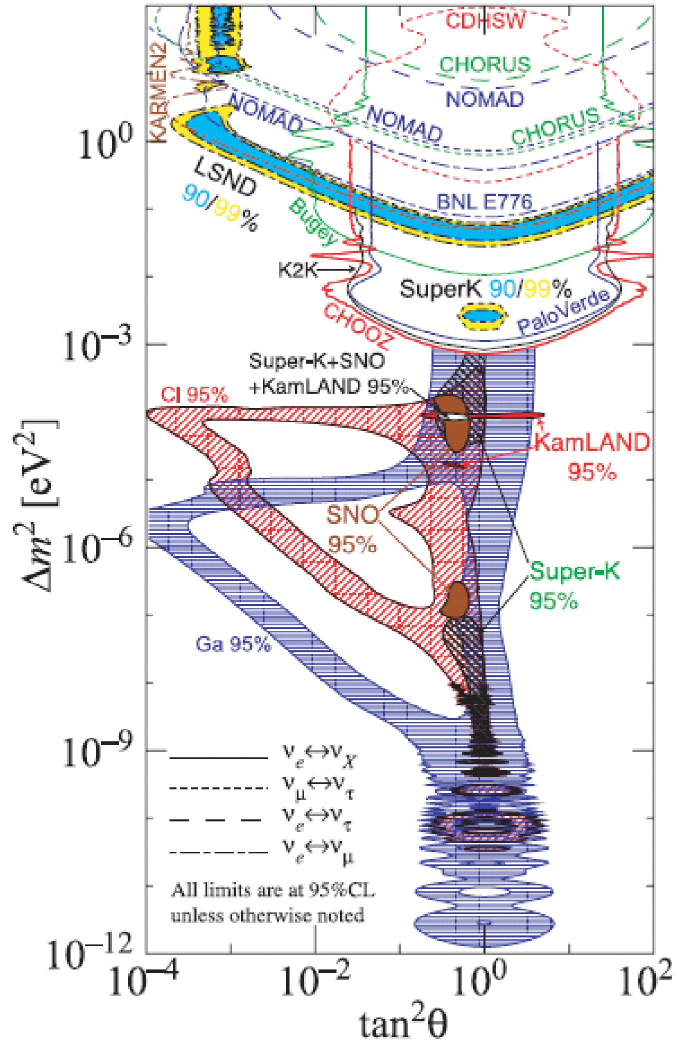
$$\Delta m^2_{atm} \simeq 2\times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{sol} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$$

We must go beyond the MSM !!!

- A simplest extension including neutrino masses is

the νMSM



TA, Blanchet, Shaposhnikov ’05
TA, Shaposhnikov ‘05

II. What is the νMSM?

What is the νMSM ?

- The νMSM = the MSM

  + three right-handed neutrinos $N_{1,2,3}$

- Most general renomalizable Lagrangian

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

- Neutrino masses $M_{Dirac} = F \langle \Phi \rangle$ $M_{Majorana} = M$

- 18 new parameters
  - 3 Majorana masses
  - 15 parameters in the neutrino Yukawa matrix
    - (3 Dirac masses, 6 mixing angles, 6 CP phases)

In this talk

- This simple extension can address
  - Neutrino oscillations
  - Dark matter
  - Baryon asymmetry

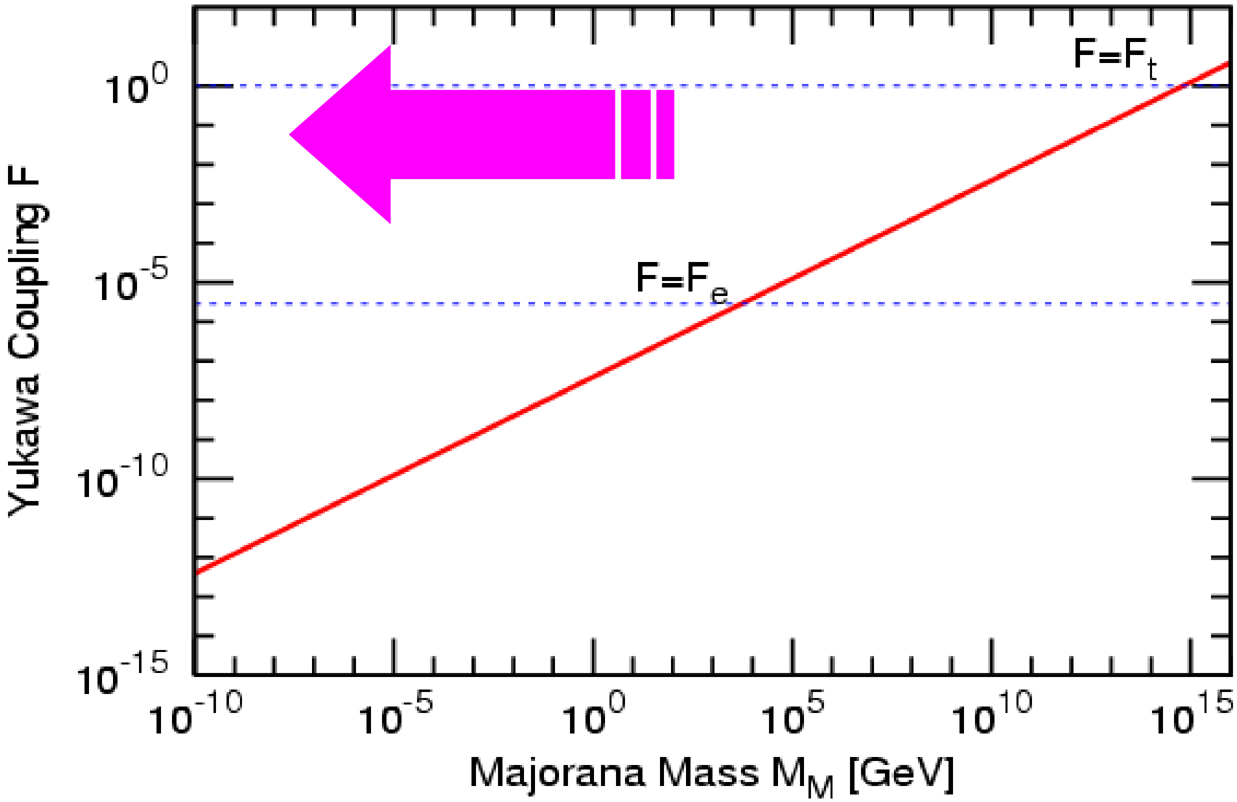
- The key point:

  Majorana masses are smaller than about 100GeV
  - No new energy scale is introduced
  - Seesaw mechanism still works

    if Dirac masses $\ll$ Majorana masses

Scale of the νMSM

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



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

$$\sim 5 \cdot 10^{-2} \mathrm{eV}$$

Very small Yukawa couplings!

III. Dark matter in the νMSM

Dark matter in the νMSM

- Unique candidate:

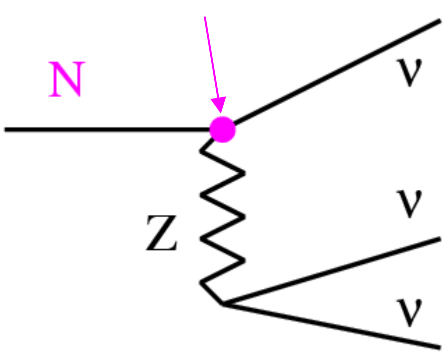
  the lightest right-handed sterile neutrino

  - Sterile neutrino is not stable particle
    - Main decay: $N \to 3\nu$

$$\tau \simeq 5\times 10^{23}\,\mathrm{sec}\left(\frac{10\mathrm{keV}}{M_I}\right)^5\left(\frac{10^{-10}}{|\Theta|^2}\right)$$

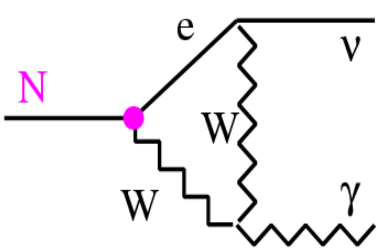
Barger, Phillips, Sarkar '95

$\Theta = M_D / M_I$



- Lifetime can exceed the age of the univ. $t_U \sim 10^{17}\,\mathrm{sec}$

Constraints on DM sterile neutrino



- X-ray observations:
  - Radiative decays of DM sterile neutrinos emit the line X-rays
  - Upper bound on mixing !

Dolgov Hansen (02)/Abazajian et al (01)
Mapelli Ferrara (05)/Abazajian (06)
Boyarsky et al (06)/Riemer-Sorensen et (06)

- Structure formation:
  - Free-streaming effects erase fluctuations on $\lambda \lesssim \lambda_{FS}$

$$\lambda_{FS} \sim \mathrm{Mpc}\left(\frac{\mathrm{keV}}{M_1}\right)\frac{T_{N_1}}{T_\nu}$$

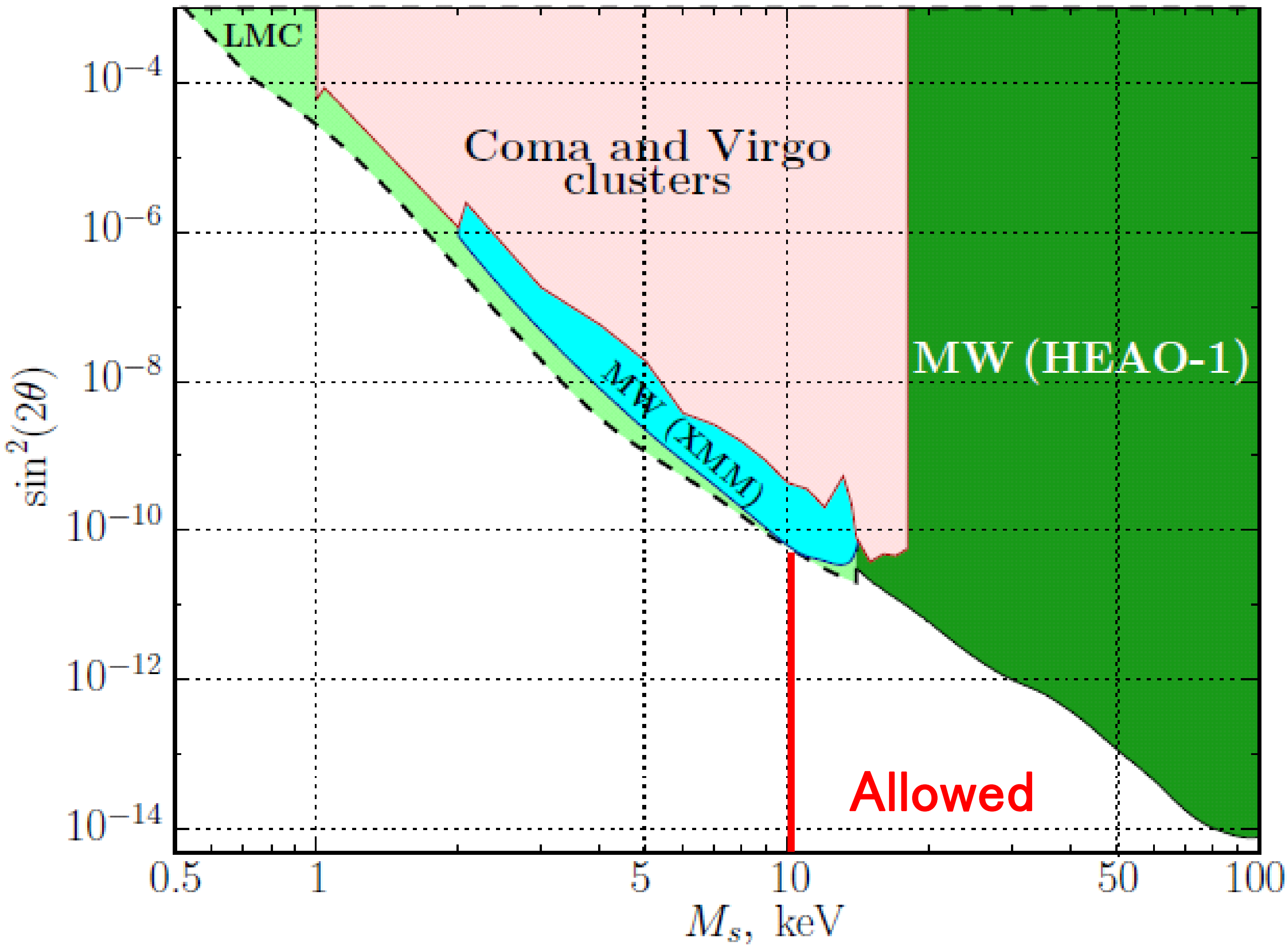
  - Lower bound on mass !

$$M_1 > 14(10)\ \mathrm{keV}$$

Seljak et al (06)/Viel et al (06)

WMAP + Ly-α

Allowed region for DM sterile neutrino



Boyarsky et al (astro-ph/0603660)

Implications of DM sterile neutrino

TA, M.Blanchet, M.Shaposhnikov (05)/Boyarsky et al (06)

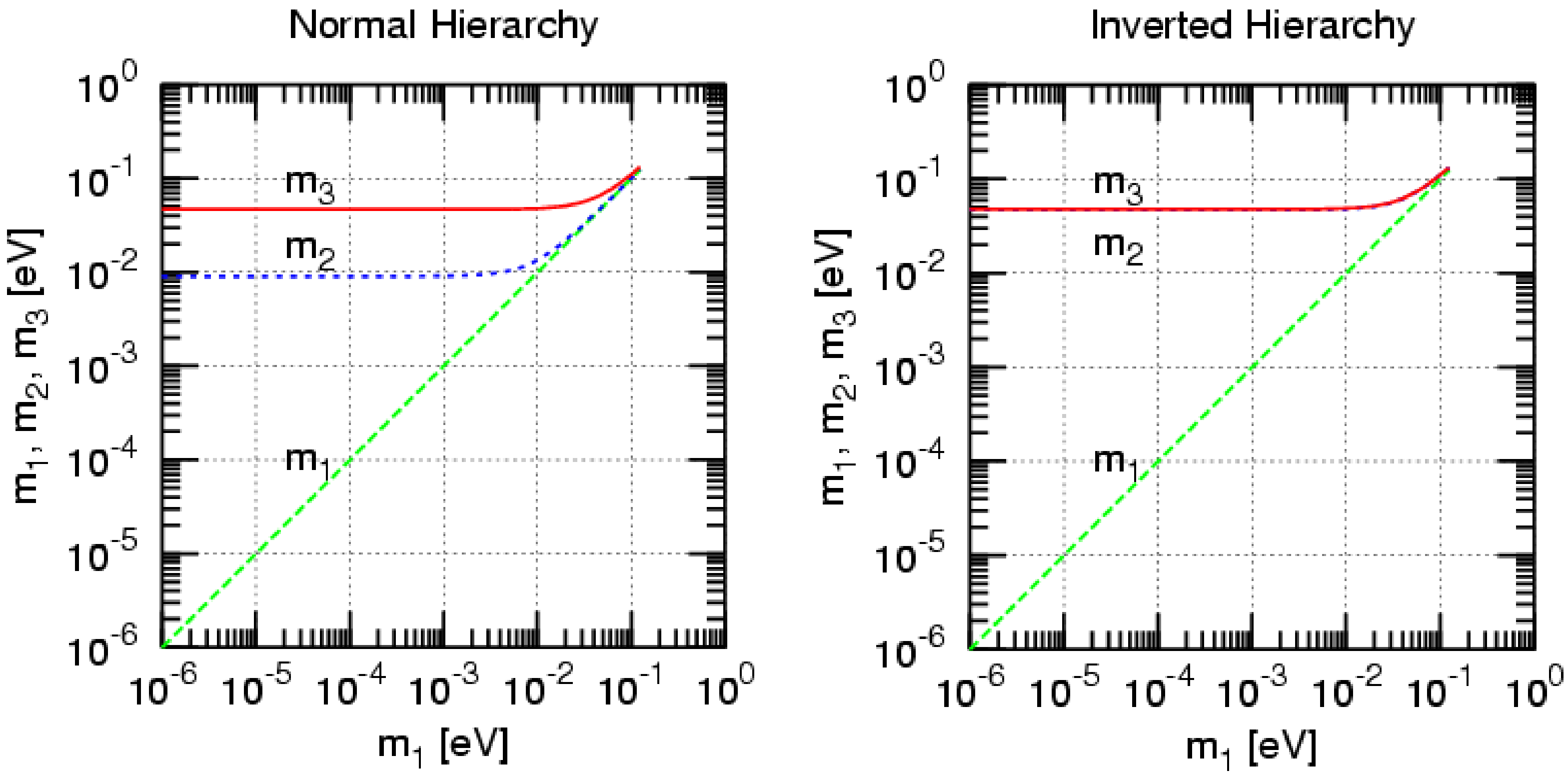
- The minimal number of sterile (RH) neutrinos for explaining dark matter and ν oscillations is "three"
  - Only one sterile neutrino can be dark matter

- The lightest active neutrino mass should be smaller than $O(10^{-6})\mathrm{eV}$
  - We can determine the absolute masses of $\nu_{2,3}$
    - In normal hierarchy
      $$m_3 \simeq \sqrt{\Delta m^2_{atm}} = (4-6)\cdot 10^{-2}\,\mathrm{eV}$$
      $$m_2 \simeq \sqrt{\Delta m^2_{sol}} = (8.5-9.5)\cdot 10^{-3}\,\mathrm{eV}$$
    - In inverted hierarchy
      $$m_{3,2} \simeq \sqrt{\Delta m^2_{atm}} = (4-6)\cdot 10^{-2}\,\mathrm{eV}$$

Masses of active neutrinos

- The absolute values of active ν masses

$$m_1 \leq O(10^{-6})\ \mathrm{eV} \ \Rightarrow \ m_2, m_3$$



IV. Baryogenesis in the νMSM

Baryogenesis

- **Baryon asymmetry of the universe**

$$\frac{n_B}{s} = (8.4 - 8.9) \times 10^{-11}$$

$n_B : (\mathrm{B} - \overline{\mathrm{B}})$ number density

s: entropy density

  – Primordial inflation sets $\Delta B = \# B - \# \overline{B} = 0$

- **Baryogenesis**

$$\Delta B = \# B - \# \overline{B} = 0 \;\Rightarrow\; \Delta B \neq 0$$

  – Three conditions: Sakharov '67
    - Baryon number violation
    - C and CP violation
    - Out of equilibrium

Baryogenesis conditions in the νMSM

- B and L violations
  - B and L are violated at quantum level
  - EW sphaleron is active for $T > T_{EW} \sim 100$GeV
    - L violation in Majorana masses is negligible for $T > T_{EW}$,
- C and CP violations
  - 1 CKM phase in quark sector and

    6 CP violating phases in lepton sector
- Out of equilibrium
  - No strong 1st order EW phase transition
  - Sterile neutrinos are not equilibrated for $T > T_{EW}$

    ➡ $f_I \le 2\times 10^{-7}$ ➡ $M_I \le 17\,\mathrm{GeV}$ (atm)

Baryogenesis via neutrino oscillations

Akhmedov, Rubakov, Smirnov ’98

Idea: Sterile neutrino oscillation is a source of BAU

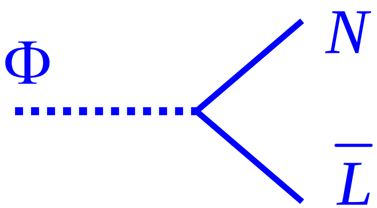
- Sterile neutrinos are created and oscillate with CPV
- The total lepton number is zero but is distributed between active and sterile neutrinos
- The asymmetry in active (left-handed) neutrinos is transferred partially into baryon asymmetry by sphaleron

Point: Not lepton-number generation,
but lepton-number separation !!

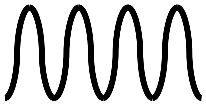
Generation of asymmetries

TA, M.Shaposhnikov (05)

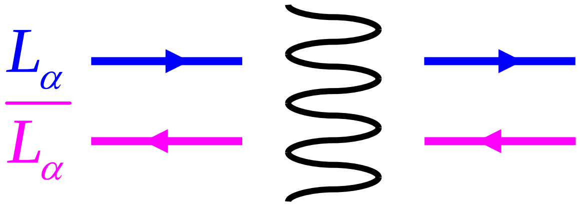
- At F^2, production of sterile neutrinos



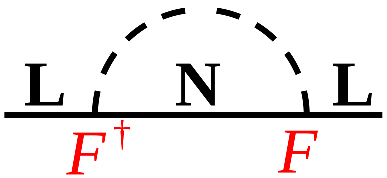
Oscillation between N_2 and N_3



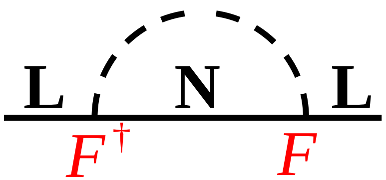
- At F^4, generation of $\Delta L_{e,\mu,\tau}$ but $\Delta L = \Delta L_e + \Delta L_\mu + \Delta L_\tau = 0$



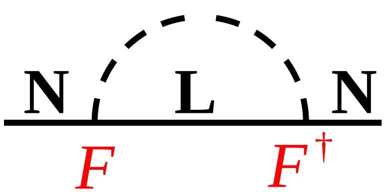
$\# L_\alpha \neq \# \overline{L_\alpha}$



- At F^6, generation of ΔL and ΔN, but $\Delta L + \Delta N = 0$



$\Delta L = \Delta L_e + \Delta L_\mu + \Delta L_\tau \neq 0$

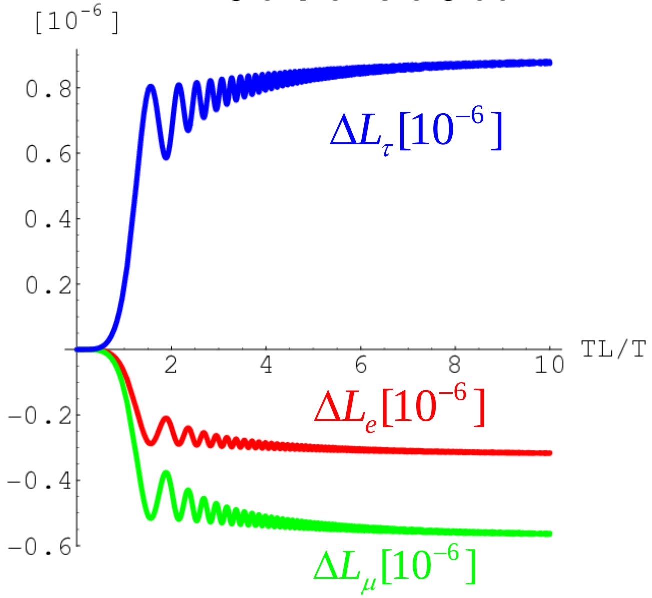


$\Delta N = \Delta N_1 + \Delta N_2 + \Delta N_3 \neq 0$

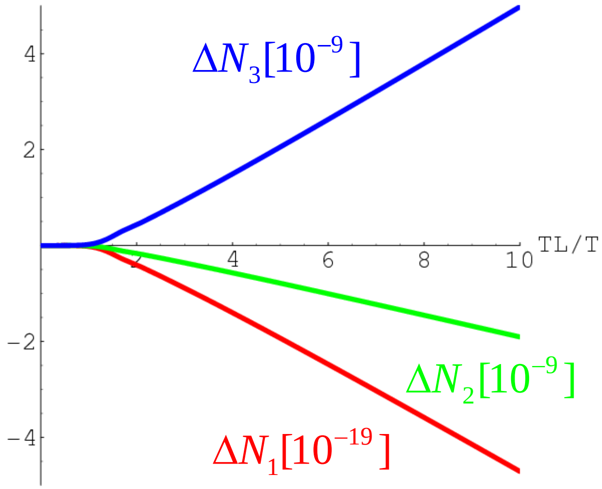
but $\Delta L + \Delta N = 0$

Evolution of asymmetries

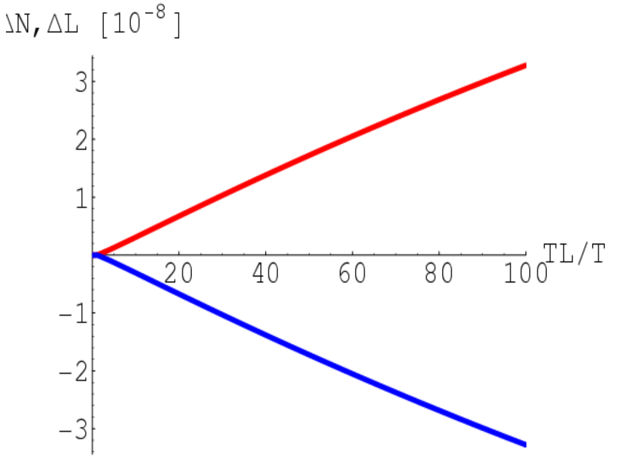
Active sector



Sterile sector



$\Delta N = \Delta N_1 + \Delta N_2 + \Delta N_3$



$\Delta L = \Delta L_e + \Delta L_\mu + \Delta L_\tau$

- Shaleron converts ΔL partially into baryon asymmetry

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

Kuzmin, Rubakov, Shaposhnikov

Baryon asymmetry of the universe

$$\frac{n_B}{s} \simeq 2\times 10^{-10}\ \delta_{CP}\left(\frac{10^{-5}}{\Delta M_{32}^2/M_3^2}\right)^{2/3}\left(\frac{M_3}{10\mathrm{GeV}}\right)^{5/3}$$

in NH $m_3 \approx \sqrt{\Delta m_{atm}^2},\ m_2 \approx \sqrt{\Delta m_{sol}^2}$

$$\left(\frac{n_B}{s}\right)_{\mathrm{OBS}} = (8.4-8.9)\times 10^{-11}$$

- The effective CP violation parameter

$$\delta_{CP} = 4 s_{R23} c_{R23}\Big[s_{L12} s_{L13} c_{L13}\left(\left(c_{L23}^4 + s_{L23}^4\right)c_{L13}^2 - s_{L13}^2\right)\cdot \sin\left(\delta_L + \alpha_2\right) + c_{L12} c_{L13}^3 s_{L23} c_{L23}\left(c_{L23}^2 - s_{L23}^2\right)\cdot \sin\alpha_2 \Big]$$

$\delta_{CP} \sim 1$ may be possible

- Heavier sterile neutrinos should be degenerate in mass

$M_2, M_3 \sim 10\mathrm{GeV}$

V. Summary

- We can solve experimental and observational problems
  ––ν oscillations, dark matter and baryon asymmetry––
  in the

MSM

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- We can solve experimental and observational problems
  ――ν oscillations, dark matter and baryon asymmetry――
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νMSM

= the MSM + 3 right-handed neutrinos