

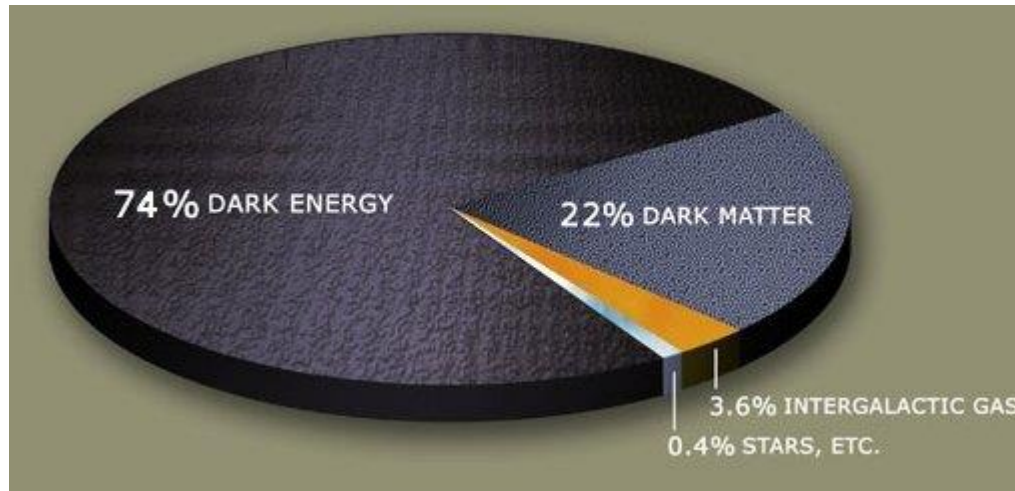
# The Origin of Matter

Tsutomu T. Yanagida  
(IPMU , Tokyo)

台灣大學 3月8日、2016年

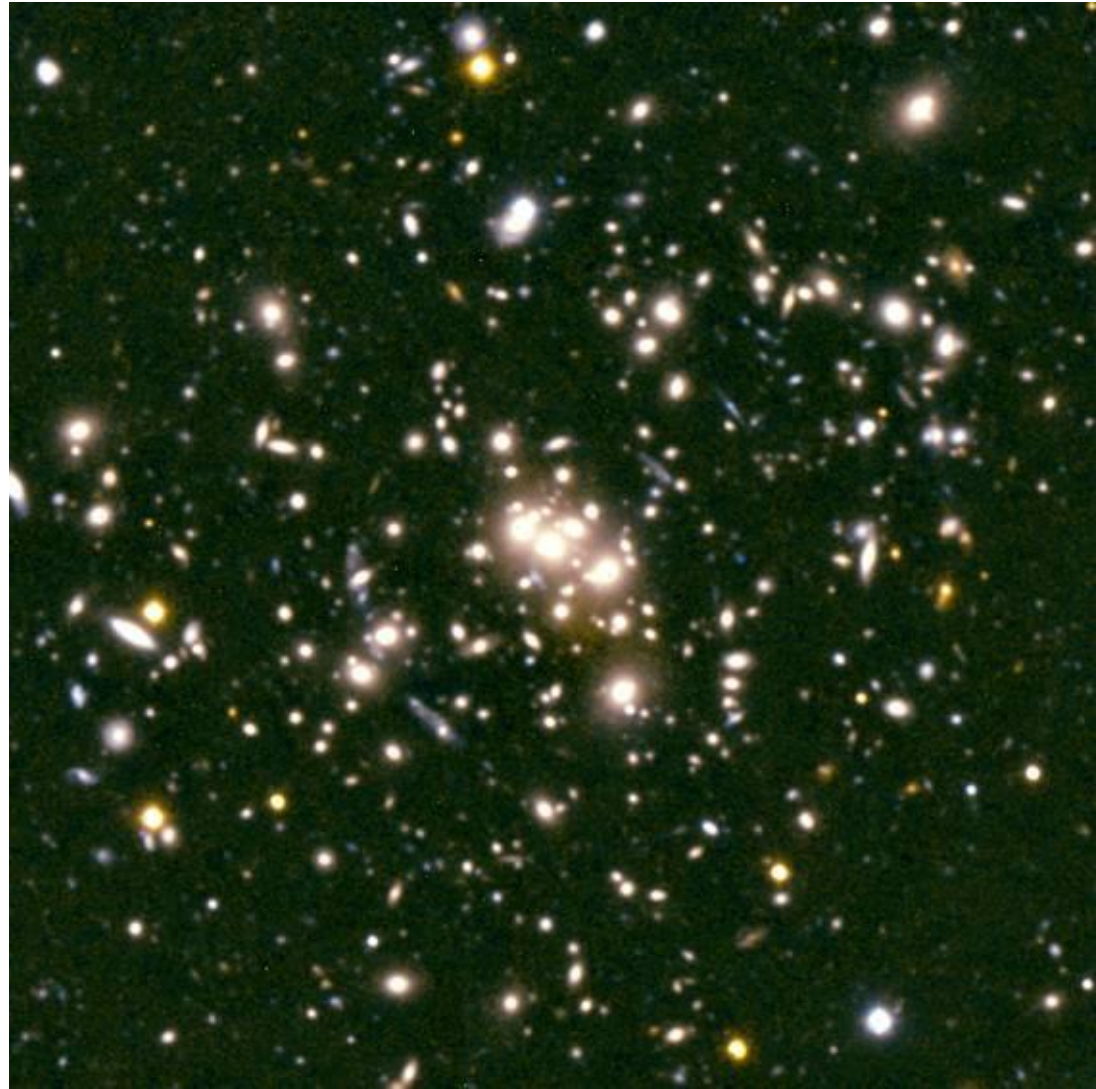


# Energy Content of the Universe



From Wikipedia

# Galaxy and Cluster of galaxies



# No antimatter is present

Observations have ruled out the presence of antimatter in the Universe up to the scale of clusters of galaxies ( $\sim Mpc$ ). Most significant upper limits are given by annihilation gamma rays:

$$N + \bar{N} \rightarrow \pi^0, \pi^\pm$$
$$\quad \quad \quad \downarrow$$
$$\quad \quad \quad \rightarrow \gamma + \gamma, \quad \langle E_\gamma \rangle > 100 MeV$$

## Upper bounds of antimatter fraction

$$\frac{\text{antimatter}}{\text{matter}} < 10^{-10} - 10^{-15} \quad (\text{galaxies})$$

$$< 10^{-7} - 10^{-12} \quad (\text{intergalactic gas})$$

$$< 10^{-6} - 10^{-9} \quad (\text{clusters of galaxies})$$

G. Steigman (2008)

The universe is composed of only matter and not antimatter

However, antimatter could have been equally present in our universe, since there is no difference between particles and antiparticles except for their charges.

In fact, Paul A.M. Dirac proposed a matter-antimatter symmetric universe in his Nobel Lecture in 1933.



## The symmetric Universe was proposed by Paul Dirac In 1933.

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

# I. Why is the present universe NOT symmetric?

How much asymmetric ?

Matter = Atoms → Matter Abundance = Numbers of Protons and Neutrons

The baryon asymmetry

$$\eta_B = \frac{n_B}{n_\gamma} \simeq \frac{n_B - n_{\bar{B}}}{n_\gamma}$$



# The baryon asymmetry

$$\Omega_b h^2 = 0.023 \pm 0.001 \quad \text{from CMBR anisotropy}$$

Spergel et al (WMAP)

Tegmark et al

$$\Omega_b h^2 = 0.0214 \pm 0.0020 \quad \text{from Primordial Nucleosynthesis}$$

Kirkman et al

$$\Rightarrow \eta_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.5) \times 10^{-10}$$

Very small !!!

Our universe may have begun symmetric

If our universe began baryon symmetric, those tiny imbalances in numbers of baryons and antibaryons must be generated by some physical processes in the early universe.

(If the universe had been symmetric, baryons and antibaryons started to annihilate each others when the temperature became well below the nucleon mass. The number of post-annihilation nucleons would be a billion times less abundant than observed today.)

## What are the processes ?

The present particle physics may answer to this fundamental question

# Generation of the baryon asymmetry

A.D.Sakharov (1966)



The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry)..... We wish to point out a possible explanation of C asymmetry in the hot model of the expanding universe by making use of effects of CP invariance violation (see [2]).....

★ The discovery of CMB in 1964      A. A. Penzias and R. W. Wilson

★ The discovery of CP Violation in 1964  
in the decays of neutral kaons      J. Cronin, V. Fitch

Three conditions must be satisfied to produce an imbalance of baryons and antibaryons

- I. Violation of baryon number conservation
- II. Violation of C and CP invariance
- III. Out-of-thermal equilibrium process

## II. Baryogenesis in the standard theory

C violation was discovered in 1957 C.-S. Wu

CP violation was discovered in 1964 J. Cronin, V. Fitch

The second condition is satisfied

Is the first condition of baryon number violation also satisfied ?

# Baryon number violation in the standard theory

The baryon number is not conserved at quantum level

G. 't Hooft (1976)

$$\partial_\mu J^\mu(B) = \frac{g^2}{32\pi^2} F_{\mu,\nu} \bar{F}^{\mu,\nu}$$

The weak instanton induces baryon number violation, but the amplitude is suppressed by

$$A \simeq e^{-S_{\text{instanton}}}, \quad S_{\text{instanton}} = \frac{8\pi^2}{g^2}$$

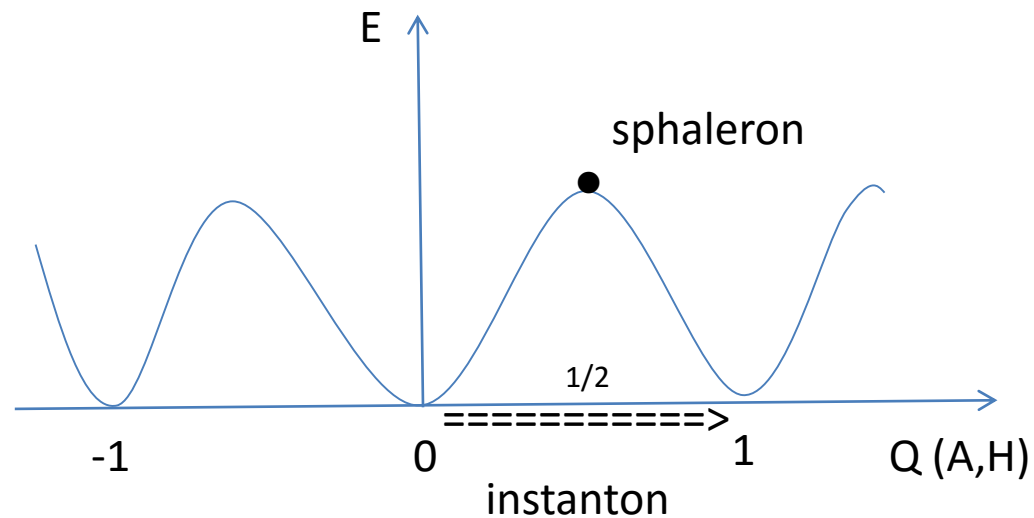
The proton decay is suppressed as

$$\Gamma_{\text{proton}} \simeq c e^{\frac{-16\pi^2}{g^2}} \simeq c 10^{-165}$$

# Saddle-point solution in the standard theory (Weinberg-Salam Model)

N.S. Manton (1983)

F.R. Klinkhamer, N.S. Manton (1984)



$$\Gamma_{\text{tunneling}} \simeq e^{-2V_{\text{barrier}}} \simeq e^{-2S_{\text{instanton}}}$$

(WKB)

# Unsuppressed baryon number violation in the early universe

V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov (1985)

$$\text{The height of the barrier} = M_{\text{sphaleron}} \simeq \frac{8\pi M_W}{g^2} \simeq 10\text{TeV}$$

The rate baryon number violation :

$$\frac{dN_B}{N_B dt} \simeq C(\alpha_2 T)^3 \exp\left(-\frac{M_{\text{sphaleron}}(T)}{T}\right)$$

P. Arnold, L. McLerran

It exceeds the expansion rate of the universe  
above  $T \simeq O(100)\text{GeV}$

The first condition is satisfied



The third condition may be satisfied if the electro-weak phase transition is the first order

This requires the Higgs boson mass,  $m_h < 60 - 80 \text{ GeV}$

But, it is excluded by LEP experiments

$$m_h > 114 \text{ GeV}$$

The condition III is not satisfied !!!

The standard theory is unable to explain the baryon number asymmetry

I. No out-of-thermal equilibrium process

II. Too small CP violation

Jarlskog determinant

$$\begin{aligned}\Delta_{CP} &= v^{-12} \text{Im det}[m_u m_u^\dagger m_d m_d^\dagger] \\ &\simeq J v^{-12} m_t^4 m_c^2 m_b^4 m_s^2 \simeq 10^{-19}\end{aligned}$$

cf. cold electroweak baryogenesis

The Nobel Prize in Physics 2015 was awarded for the discovery of neutrino oscillations, which show that neutrinos have small masses

*The presence of small neutrino masses may give us a natural mechanism for creating the observed baryon asymmetry in the Universe!!!*

# III. Discovery of neutrino oscillation



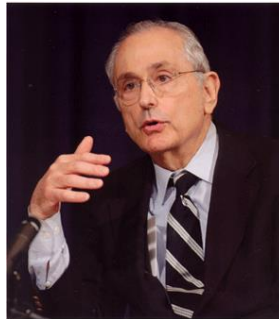
Бруно Понтекорво

## The solar neutrino problem

Davis found only one-third of the neutrinos predicted by the standard solar theories



Raymond Davis



John Bahcall

Superkamiokande confirmed the result of Davis in 1998

Superkamiokande discovered the oscillation of the atmospheric neutrinos in 1998



Yoji Totsuka

# Masses and mixing angles for neutrinos

The recent global analysis gives

T. Schwetz, M. Tortola, J.W.F. Valle (2011)

$$\Delta m_{21}^2 = 7.59_{-0.18}^{+0.20} \times 10^{-5} \text{eV}^2$$

$$\Delta m_{31}^2 = 2.50_{-0.16}^{+0.09} \times 10^{-3} \text{eV}^2$$

$$\sin^2 \theta_{12} = 0.312_{-0.015}^{+0.017}$$

$$\sin^2 \theta_{23} = 0.52_{-0.07}^{+0.06}$$

$$\sin^2 \theta_{13} = 0.013_{-0.005}^{+0.007}$$

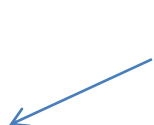
$$\delta_{CP} = (-0.61_{-0.65}^{+0.75})\pi$$

$$m_3 > m_2 > m_1 \quad \longrightarrow \quad \begin{array}{l} m_3 \simeq 0.05 \text{eV} \\ m_2 \simeq 0.009 \text{eV} \end{array} \quad \text{cf.} \quad \begin{array}{l} m_{\text{top}} \simeq 173 \text{GeV} \\ m_{\tau} \simeq 1.7 \text{GeV} \end{array}$$

Why are neutrino masses so small ?

# Introduction of right-handed neutrinos $\nu_R$

## The standard theory

$$q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \quad u_R^i \quad d_R^i \quad ; \quad l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \quad e_R^i \quad \nu_R^i \quad (i = 1 - 3)$$


neutrino mass term :  $y_\nu \bar{\nu}_R l_L \langle H \rangle$       cf. top-quark mass term :  $y_t \bar{t}_R q_L \langle H \rangle$

$$y_\nu \simeq 3 \times 10^{-13} \quad \text{for } m_\nu \simeq 0.05 \text{eV} \quad \longleftrightarrow \quad y_t \simeq 1$$



So small !!!

# Seesaw mechanism

T. Yanagida (1979)  
Gell-Mann, Ramond, Slansky (1979)  
P. Minkowski (1977)

$\nu_R$  is singlet and has no charge. Thus it may have a large Majorana mass

$$\frac{1}{2} M \bar{\nu}_R^C \nu_R$$

Pauli-Gursey transformation: Weyl fermion  $\rightarrow$  Majorana fermion

$$\nu = \nu_L + \nu_L^C \quad ; \quad N = \nu_R + \nu_R^C$$

neutrino mass matrix :

$$(\bar{\nu} \quad \bar{N}) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} \quad m = y_\nu \langle H \rangle$$

Two mass eigen values :

$$m_\nu \simeq \frac{m^2}{M} \quad ; \quad M_N \simeq M$$

$$m_\nu \simeq 0.05\text{eV} \quad \longrightarrow \quad M \simeq 10^{15}\text{GeV} \quad \text{for } m \simeq m_t \simeq 173\text{GeV}$$

The observed small neutrino masses strongly suggest the presence of super heavy Majorana neutrinos N

Out-of-thermal equilibrium processes may be easily realized around the threshold of the super heavy neutrinos N

The Yukawa coupling constants  $y_\nu$  can be a new source of CP violation



# GUT Baryogenesis

M. Yoshimura (1978)

Ignatiev, Krosnikov, Kuzmin, Tvkhelidze (1978)

Delayed decay of heavy colored Higgs boson

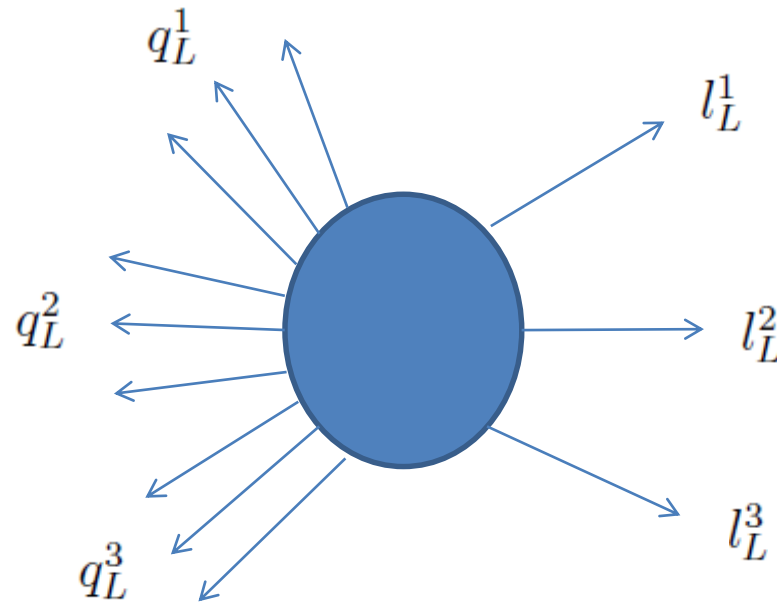
S. Weinberg (1979)

$$H_C \rightarrow q + l, \quad \bar{q} + \bar{q}$$

Baryon asymmetry can be produced in the decay processes

But, we have two serious problems:

- I. It predicts proton decay, but the decay was NOT observed
- II. The produced B asymmetry is washed out by the sphaleron processes



Sphaleron

B-L is conserved !!!

If  $\Delta(B - L) = 0$ , the B asymmetry is washed out by the sphaleron processes. The generation of B-L asymmetry is necessary

However, the GUT preserves the B-L and hence the B-L asymmetry is not generated

# IV. Leptogenesis

M. Fukugita, T. Yanagida (DESY 1986)

Decay of the super heavy Majorana neutrino  $N$  :

$$N_i \rightarrow l_j + H^\dagger, \quad \bar{l}_j + H$$

Two decay channels

If CP is broken, the lepton asymmetry is generated in the delayed decay of  $N$  in the early universe

The lepton asymmetry is converted to baryon asymmetry by the sphaleron processes

$$\Delta L_0 \rightarrow \Delta B$$

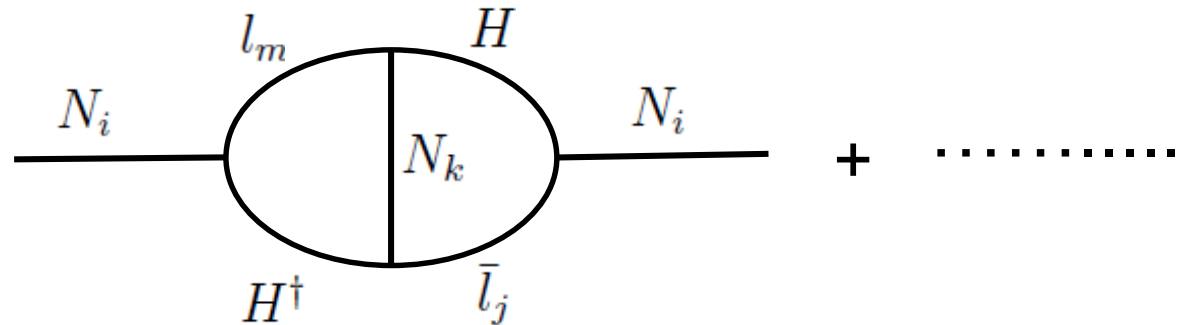
$$\Delta B_{\text{present}} \simeq \frac{8N + 4m}{22N + 13m} \Delta(B - L)_0 = \frac{28}{79} (-\Delta L)_0 \quad \text{for } N = 3, m = 1$$

J.A. Harvey, M.S. Turner (1990)

# The first detailed calculation for the baryon asymmetry

M. Plumacher (1997)

Asymmetry parameter: 
$$\epsilon_i = \frac{\Gamma(N_i \rightarrow l_j + H^\dagger) - \Gamma(N_i \rightarrow \bar{l}_j + H)}{\Gamma(N_i \rightarrow l_j + H^\dagger) + \Gamma(N_i \rightarrow \bar{l}_j + H)}$$



Assume  $M_1 \ll M_2 \ll M_3$ ,  $N_1$  decay is most important

$$\epsilon_1 \simeq \frac{3}{8\pi} \frac{1}{(y_\nu y_\nu^\dagger)_{11}} \text{Im}[(y_\nu y_\nu^\dagger)_{1k}^2] \frac{M_1}{M_k} \simeq 10^{-6} \frac{M_1}{10^{10} \text{GeV}} \frac{m_3}{0.05 \text{eV}}$$

for the maximal CP violation (neglecting the flavor effects)

In the early universe  $T > M_1$ , the heavy Majorana  $N_1$  were produced by the scattering processes  $l + H^\dagger \rightarrow N_1$  in the thermal bath. As the temperature went down  $T < M_1$ , the  $N_1$  started to decay and produced the lepton asymmetry. This lepton asymmetry was converted to the baryon asymmetry.

$$\eta_B \simeq D \times \epsilon_1 \times \kappa \times W \simeq 10^{-2} \epsilon_1 \times \kappa \times W$$

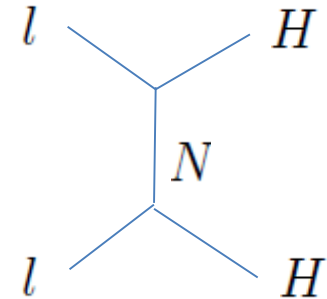
The out-of equilibrium decay condition (delayed decay)

$$\Gamma_{decay} \simeq \frac{1}{8\pi} (y_\nu y_\nu^\dagger)_{11} M_1 < O(1) \times H_{\text{exp.}}(T = M_1) \simeq O(1) \times \sqrt{g_*} \frac{M_1^2}{M_{PL}}$$

$$(y_\nu y_\nu^\dagger)_{11} \frac{v^2}{M_1} < O(1) \times (8\pi) \sqrt{g_*} \frac{v^2}{M_{PL}} \quad \longrightarrow \quad \bar{m}_\nu < O(1) \times 10^{-3} \text{eV} \quad !!!$$

$$m_2 \simeq 9 \times 10^{-3} \text{eV}, \quad m_3 \simeq 5 \times 10^{-2} \text{eV}$$

The washing out effects ;  $W = e^{-cM_1 m_\nu^2}$



We have the upper bound

$$m_3 < 0.14 \text{eV} \quad \longleftarrow \quad m_3 \simeq 5 \times 10^{-2} \text{eV}$$

W. Buchmuller, P. Di Bari, M. Plumacher (2004)

G.F. Giudice et al (2004)

Very consistent with the observed neutrino masses !!!

The baryon asymmetry in the present universe

$$\eta_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.5) \times 10^{-10}$$

can be explained for  $m_3 \simeq 5 \times 10^{-2} \text{eV}$  and  $M_1 \simeq 10^{10} \text{GeV}$

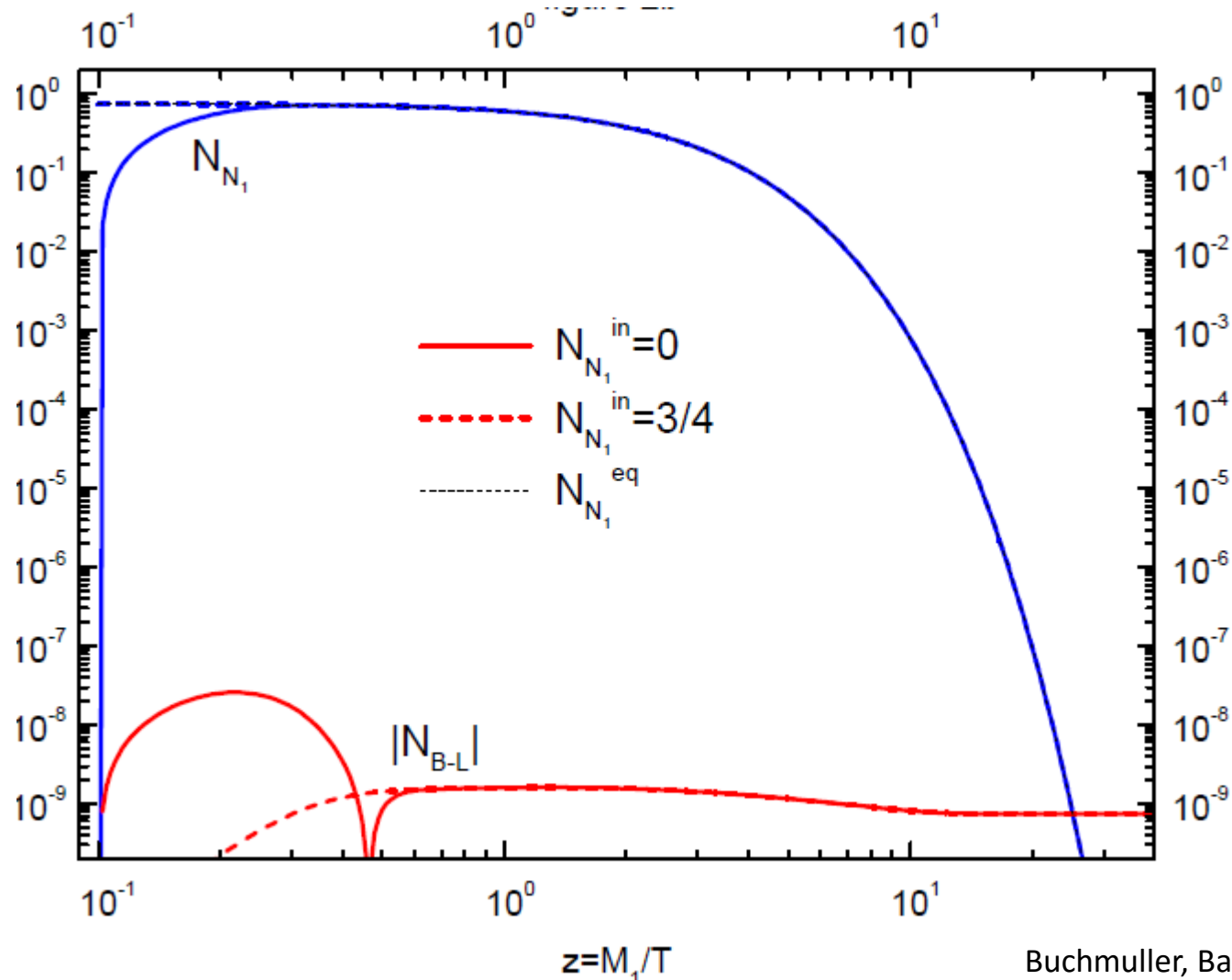
The produced B-L asymmetry is calculated by solving the Boltzmann equations;

$$\begin{aligned}\frac{dN_{N_1}}{dz} &= -(D + S) (N_{N_1} - N_{N_1}^{\text{eq}}) , \\ \frac{dN_{B-L}}{dz} &= -\varepsilon_1 D (N_{N_1} - N_{N_1}^{\text{eq}}) - W N_{B-L} \\ z &= M_1/T\end{aligned}$$

$D = \Gamma_D/(H z)$  accounts for decays and inversed decays

$S = \Gamma_S/(H z)$  represents the  $\Delta L = 1$  scattering

$W = \Gamma_W/(H z)$  is the total washout term of B-L asymmetry




Buchmuller, Bari, Plumacher (2002)

Produced lepton asymmetry for  $M_1 = 10^{10}\text{GeV}$ ,  $m_\nu = 0.1\text{eV}$



## V. Summary

$$q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \quad u_R^i \quad d_R^i \quad ; \quad l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \quad e_R^i \quad \nu_R^i \quad (i = 1 - 3)$$


$$\mathcal{L} = \mathcal{L}(\text{standard theory}) + y_\nu^{ij} \bar{\nu}_R^i l_L^j H + M_{ij} \nu_R^i \nu_R^j + h.c.$$

In particular,

$$\eta_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.5) \times 10^{-10} \quad \longrightarrow \quad 10^{-5} \text{eV} < m_\nu < 0.14 \text{eV}$$

Very consistent with observation :  $m_3 \simeq 0.05 \text{eV}$   $m_2 \simeq 0.009 \text{eV}$

(pre-existing B-L may be washed out)

# Test of the Leptogenesis

The standard theory + right-handed neutrinos  $\nu_R^i$

It explains two fundamental parameters simultaneously:

- I. Small neutrino masses
- II. Universe's baryon asymmetry

$$\begin{aligned} \Delta m_{21}^2 &= 7.59^{+0.20}_{-0.18} \times 10^{-5} \text{eV}^2 \\ \Delta m_{31}^2 &= 2.50^{+0.09}_{-0.16} \times 10^{-3} \text{eV}^2 \end{aligned} \quad \Longleftrightarrow \quad \eta_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.5) \times 10^{-10}$$

Very Consistent !!

Can we test the leptogenesis ?

A robust prediction is  $\Delta B = -\frac{28}{79}\Delta L_0$ ,  $\Delta L = \frac{51}{79}\Delta L_0$

$$\frac{\eta_L}{\eta_B} = -\frac{51}{28}, \quad \eta_L = \frac{n_e + n_\nu - n_{\bar{e}} - n_{\bar{\nu}}}{n_\gamma}$$

It may be impossible to test this prediction

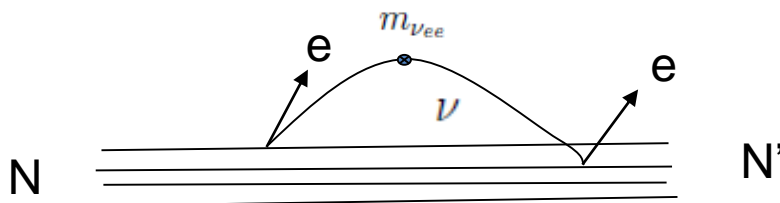
The leptogenesis has two testable predictions

### I. CP violation in neutrino oscillations

We will see it in future  $\longleftarrow 0.03 \leq \sin^2(2\theta_{13}) \leq 0.28$

T2K experiments (2011)

### II. Neutrinoless double beta decays



$$\langle m_{ee} \rangle \geq \text{meV}$$

W.H. Furry (1939)

## CP violation in neutrino oscillations

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) = 4J_{CP}^\nu (\sin D_{12} + \sin D_{23} + \sin D_{31})$$

$$D_{ij} = \Delta m_{ij}^2 \frac{L}{2E}$$

$$J_{CP}^\nu = \text{Im}(U_{\mu 3} U_{\tau 3}^* U_{\mu 2}^* U_{\tau 2}) = s_{12} s_{23} s_{13} c_{12} c_{23} c_{13}^2 \sin \phi$$

$$0.03 \leq \sin^2(2\theta_{13}) \leq 0.28 \quad \longrightarrow \quad -0.025 < J_{CP}^\nu < +0.025 \quad !!!$$

T2K experiments

The neutrino masses observed in neutrino oscillation experiments strongly support the leptogenesis

What is the Next ?

See my talk at NCU

“The Seesaw Mechanism --- 37 Years Later ---”