The Origin of Matter

---- Leptogenesis ----

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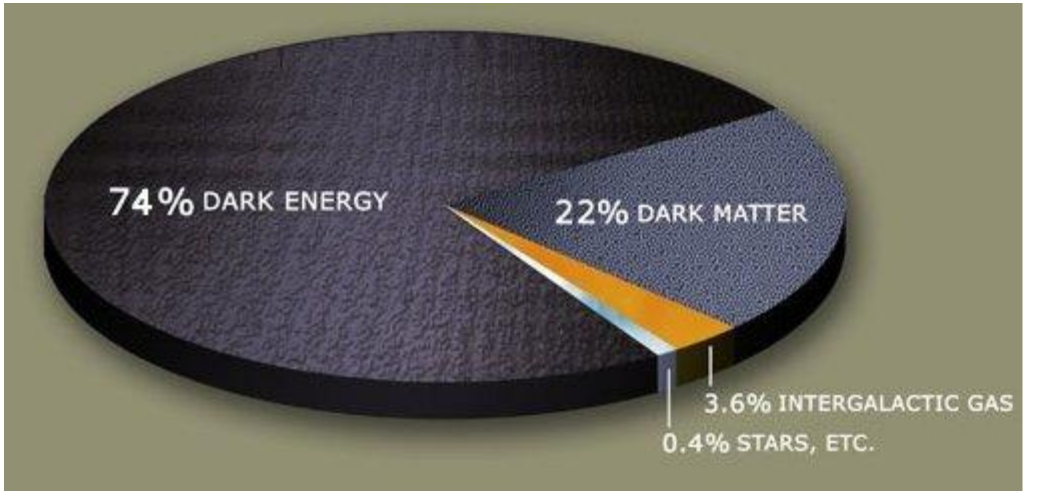
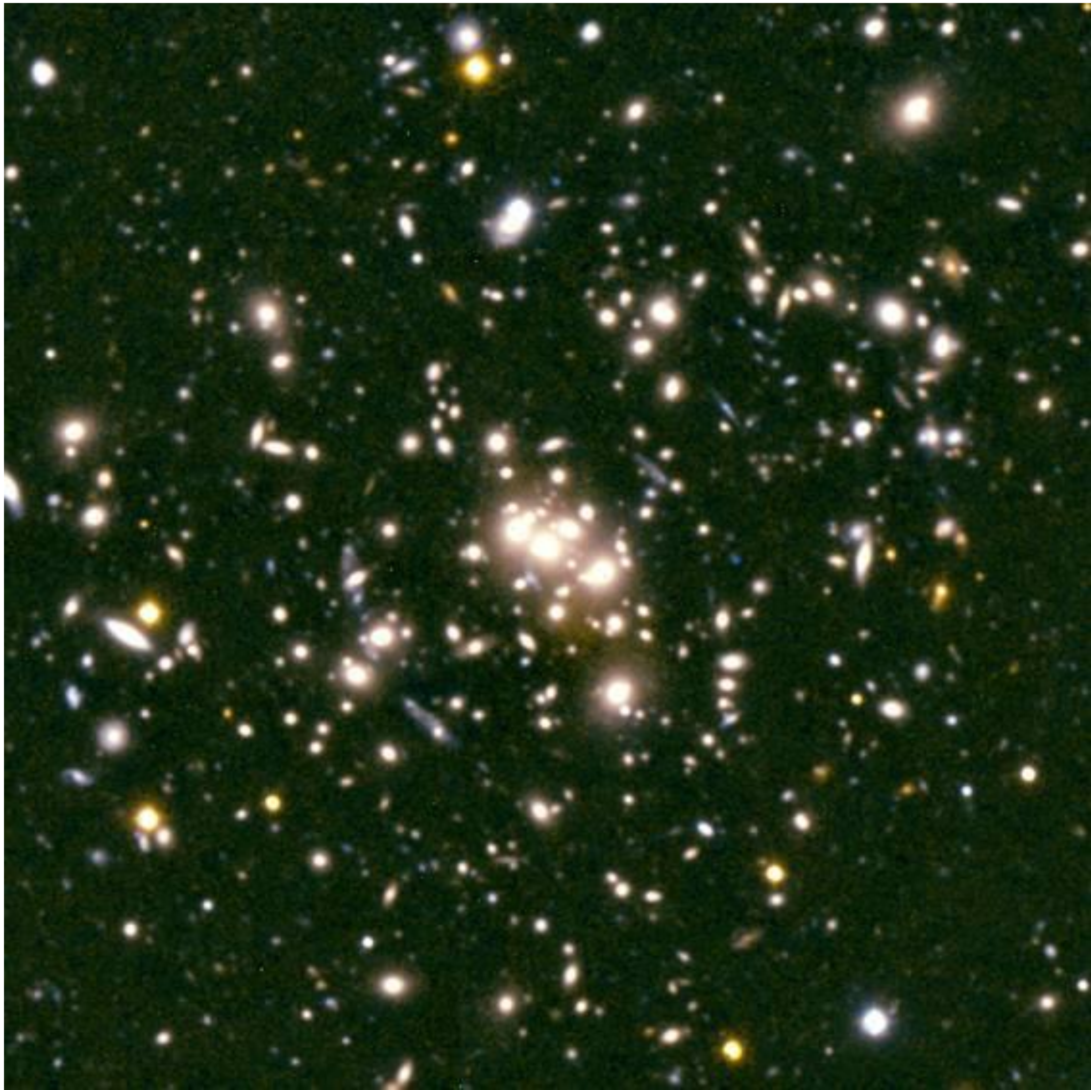
Shoichi Sakata Centennial Symposium

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:

$$N + \bar{N} \to \pi^0, \pi^\pm$$

$$\hookrightarrow \gamma + \gamma, \qquad \langle E_\gamma \rangle > 100 MeV$$

Upper bounds of antimatter fraction

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

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

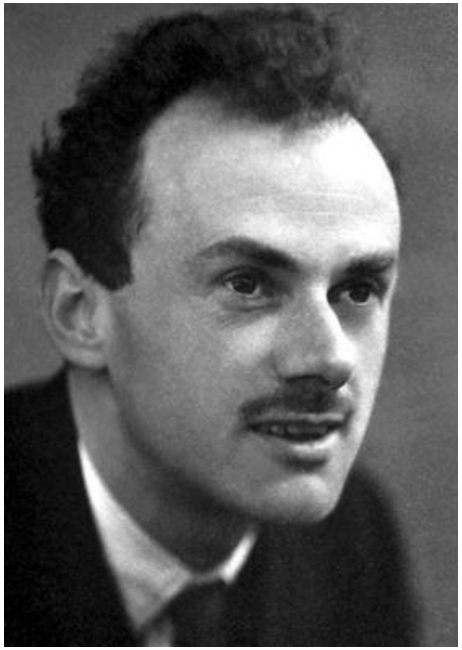
$$< 10^{-6} - 10^{-9} \qquad \text{(clusters of galaxies)}$$

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

$\Omega_b h^2 = 0.023 \pm 0.001$ from CMBR anisotropy

Spergel et al (WMAP)

Tegmark et al

$\Omega_b h^2 = 0.0214 \pm 0.0020$ from Primordial Nucleosynthesis

Kirkman et al

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

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

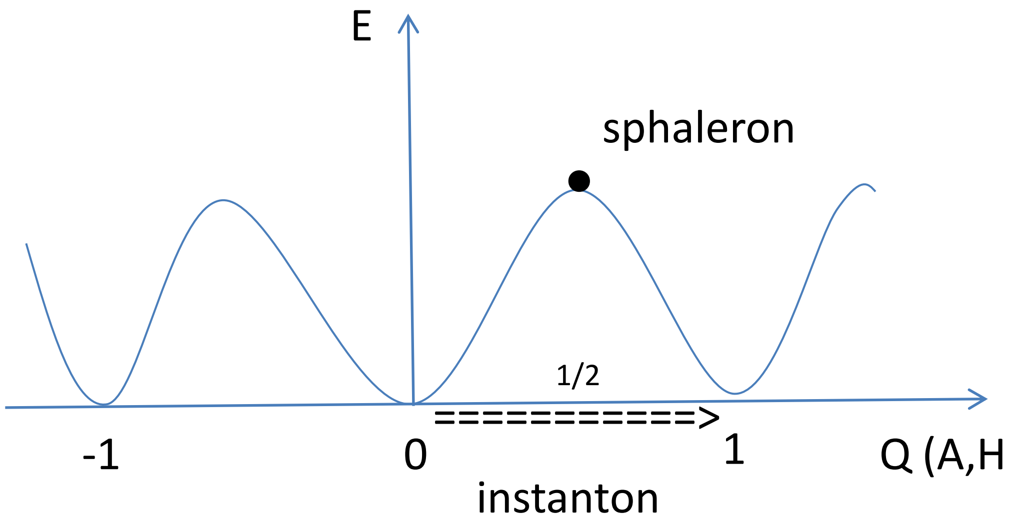
$$A \simeq e^{-S_{\text{instanton}}}, \qquad S_{\text{instanton}} = \frac{8\pi^2}{g^2}$$

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 :

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

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, $m_h < 60 - 80\mathrm{GeV}$

But, it is excluded by LEP experiments

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

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

$$\Delta_{CP} = v^{-12} \mathrm{Imdet}[m_u m_u^\dagger m_d m_d^\dagger]$$

$$\simeq J v^{-12} m_t^4 m_c^2 m_b^4 m_s^2 \simeq 10^{-19}$$

cf. cold electroweak baryogenesis

III. Discovery of neutrino oscillation

The solar neutrino problem

Davis found only one-third of the neutrinos predicted by the standard solar theories （John Bahcall）

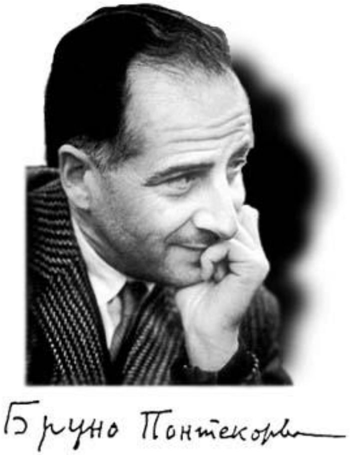
$^{37}\mathrm{Cl}+\nu_e \to {}^{37}\mathrm{Ar}+e^-$ Raymond Davis (1964-1996 at Homestake)

Superkamiokande confirmed the result of Davis in 1998

Superkamiokand dicovered the oscillation of the atmospheric neutrinos in 1998

Koshiba, Totsuka,……. (1998)

Neutrino Oscillation



Burno Pontecorvo proposed neutrino-antineutrino oscillation in analogy with $K^0 - \bar{K}^0$ oscillation in 1957

$$\nu_L \longleftrightarrow (\nu_R)^C$$

If neutrinos are Majorana fermions, the oscillation could take place

The flavor neutrino oscillation was first proposed by Maki, Nakagawa and Sakata in 1962

$$\nu_{eL} \longleftrightarrow \nu_{\mu L}$$

$$P_{\nu_e \to \nu_\mu} = \sin^2(2\theta_{12})\sin^2(\frac{\Delta m^2 L}{4E_\nu})$$

Before the Cabibbo angle !!! (in 1963)

Masses and mixing angles for neutrinos

The recent global analysis gives

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

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

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

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

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

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

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

$$m_3 > m_2 > m_1 \Longrightarrow \begin{array}{l} m_3 \simeq 0.05\mathrm{eV} \\ m_2 \simeq 0.009\mathrm{eV} \end{array}$$

cf. $m_{\mathrm{top}} \simeq 173\mathrm{GeV}$, $m_\tau \simeq 1.7\mathrm{GeV}$

Why are neutrino masses so small ?

Introduction of right-handed neutrinos ν_R

The standard theory

ν_R^i

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

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)

ν_R is singlet and has no charge. Thus it may have a large Majorana mass

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

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

neutrino mass matrix :

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

Pauli-Gursey transformation (1957)

Two mass eighen values :

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

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

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_ν 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

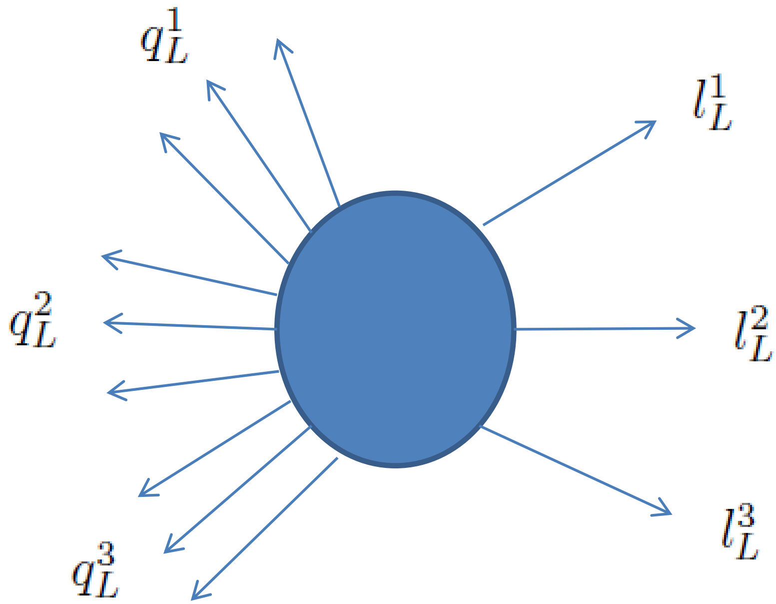
S. Weinberg (1979)

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

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 (1986)

Decay of the super heavy Majorana neutrino N :

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

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

$$\Delta L_0 \to \Delta B$$

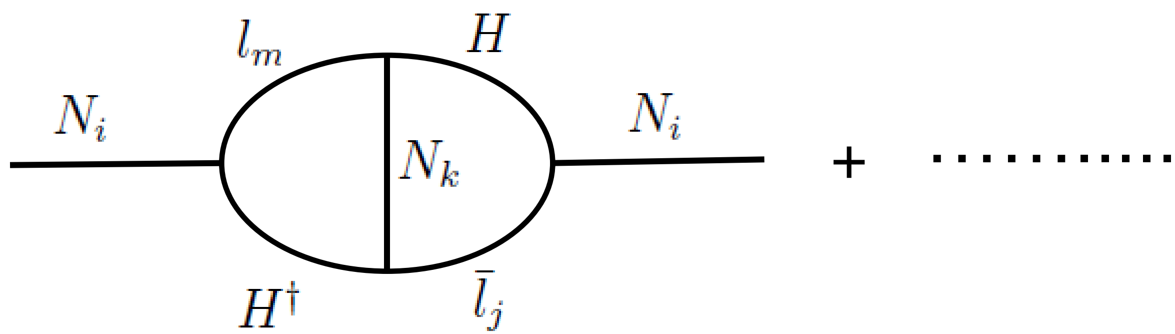
$$\Delta B\text{present} \simeq \frac{8N+4m}{22N+13m}\Delta(B-L)_0 = \frac{28}{79}(-\Delta L)_0 \quad \text{for } N=3,\ m=1$$

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

The first detailed calculation for the baryon asymmetry

M. Plumacher (1997)

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



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

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

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 $l + H^\dagger \to N_1$ 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.

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

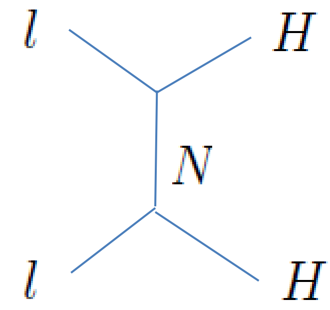
The out-of equilibrium decay condition (delayed decay)

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

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

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

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



We have the upper bound

$$m_3 < 0.14\mathrm{eV} \Longleftarrow m_3 \simeq 5 \times 10^{-2}\mathrm{eV}$$

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 $m_3 \simeq 5 \times 10^{-2}\mathrm{eV}$ and $M_1 \simeq 10^{10}\mathrm{GeV}$

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

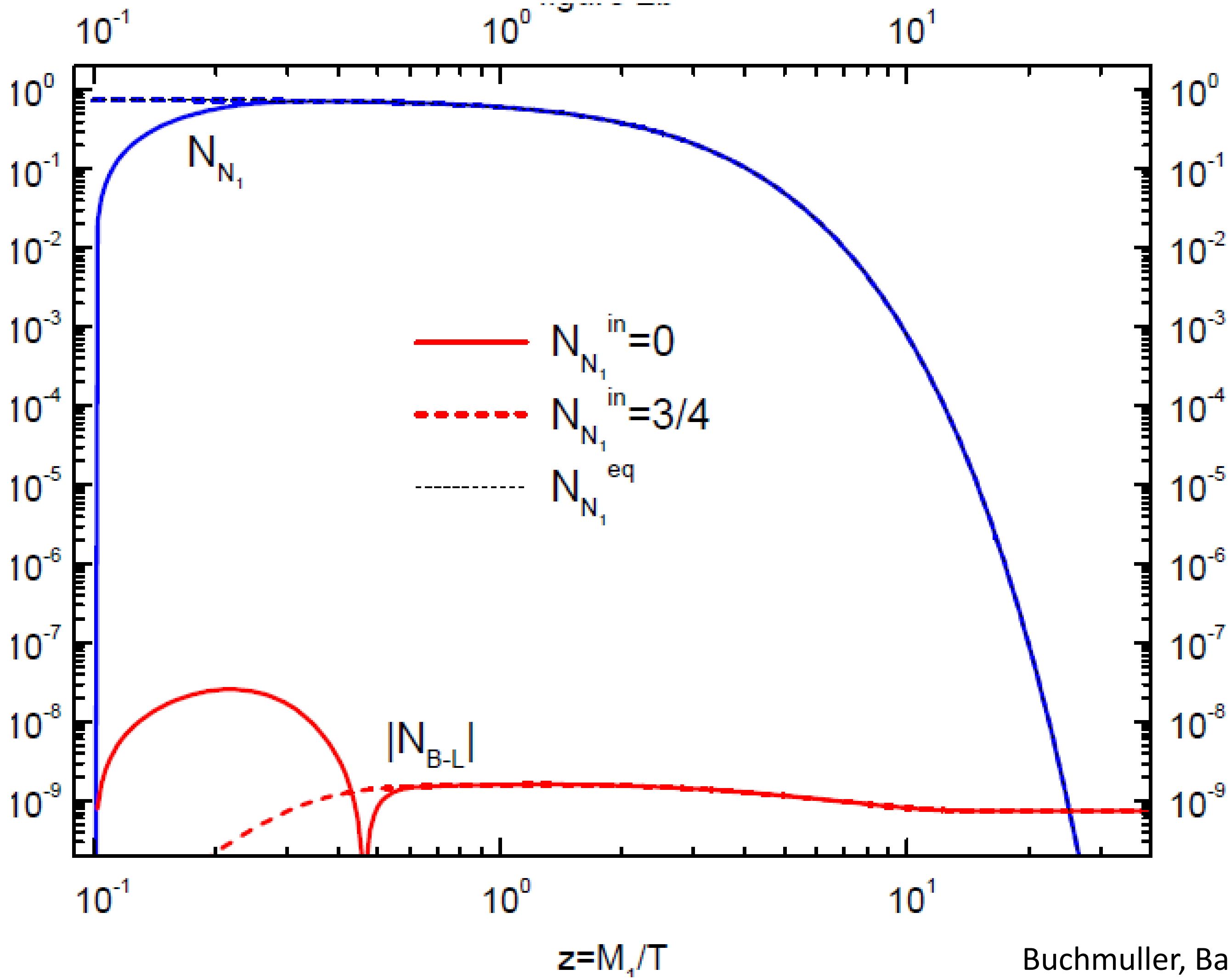
$$\frac{dN_{N_1}}{dz} = -(D+S)\,(N_{N_1} - N_{N_1}^{\rm eq})\ ,$$
$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\, D\,(N_{N_1} - N_{N_1}^{\rm eq}) - W\, N_{B-L}$$

$$z = M_1/T$$

$D = \Gamma_D/(H\,z)$ 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

$$\nu_R^i$$

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

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

In particular,

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

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 ν_R^i

It explains two fundamental parameters simultaneously:

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

$$\Delta m_{21}^2 = 7.59^{+0.20}_{-0.18} \times 10^{-5}\mathrm{eV}^2$$
$$\Delta m_{31}^2 = 2.50^{+0.09}_{-0.16} \times 10^{-3}\mathrm{eV}^2$$

$$\Longleftrightarrow$$

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

Very Consistent !!

Can we test the leptogenesis ?

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

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

It may be impossible to test this prediction

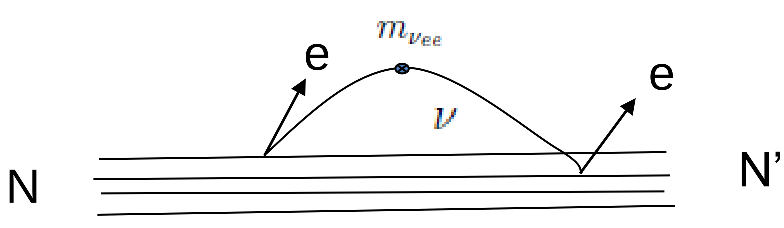
The leptogenesis has two testable predictions

I. CP violation in neutrino oscillations

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

T2K experiments (2011)

II. Neutrinoless double beta decays



$\langle m_{ee} \rangle \ge meV$

W.H. Furry (1939)

CP violation in neutrino oscillations

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) - P(\nu_\mu \to \nu_e) \;=\; 4J^\nu_{CP}(\sin D_{12} + \sin D_{23} + \sin D_{31})$$

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

$$J^\nu_{CP} = \mathrm{Im}(U_{\mu 3}U^*_{\tau 3}U^*_{\mu 2}U_{\tau 2}) = s_{12}s_{23}s_{13}c_{12}c_{23}c^2_{13}\sin\phi$$

$0.03 \leq \sin^2(2\theta_{13}) \leq 0.28$ $\Longrightarrow$ $-0.025 < J^\nu_{CP} < +0.025$!!!

T2K experiments

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

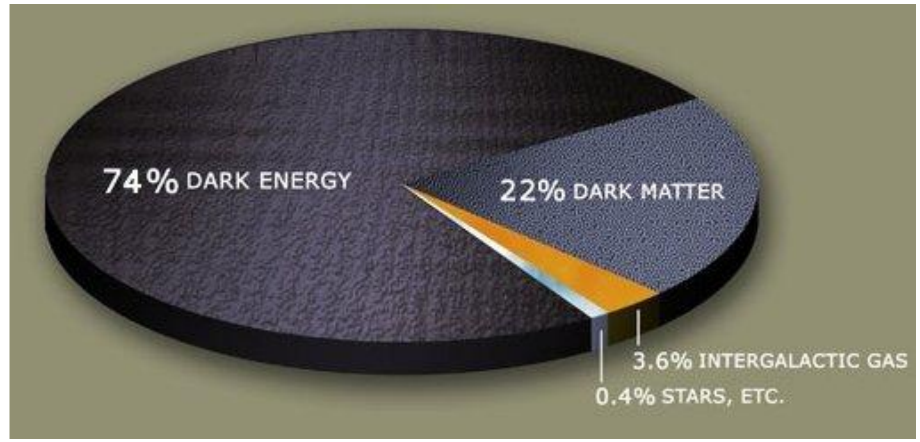
What is the Next ?

Test of the new “standard theory” via dark matter

M. Ibe, S. Matsumoto, T. T. Yanagida (2011)

Dark matter in the universe

Energy content of the universe



What is the DM and Why is it stable ?

The stability may be guaranteed by some discrete gauge symmetry. But, the standard theory does not have such a discrete symmetry.

The introduction of the right-handed neutrinos ν_R^i changes the situation. We can gauge the U(1) B-L, since the ν_R^i cancel out all gauge anomalies

The Majorana mass term of ν_R^i preserves the discrete subgroup $Z_2(B-L)$. Thus, the low-energy exact symmetry is now $SU(3)_{\rm QCD} \times U(1)_{\rm em} \times Z_2(B-L)$

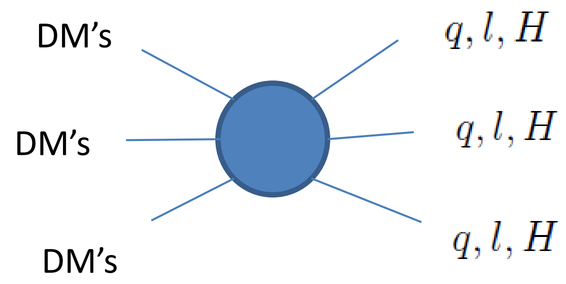
The DM stability can be guaranteed by the $Z_2(B-L)$

Fermions of even parity are absolutely stable and Bosons of odd parity are also absolutely stable

How to produce the DM in the early universe ?

We need interactions between DM's and ST particles

$$\mathcal{L} = \mathcal{O}_{DM}\mathcal{O}_{q,l,H}$$



D.E. Kaplan, M.A. Luty, K.M. Zurek (2009)

The interactions must conserve the B-L, otherwise all baryon number asymmetry is washed out

$$N_{\rm DM}Q_{\rm DM} + N_{q,l}Q_{q,l} = 0$$

$Q_{\rm DM}$: B-L charge for DM

$Q_{q,l}$: B-L charges for quarks and leptons

Assuming the new interactions are in chemical equilibrium in the early universe $T > T_{\rm sph.}$, we obtain the DM asymmetry

$$\frac{\Delta DM}{\Delta B} = \frac{407}{474} Q_{\rm DM} \quad \Longrightarrow \quad \frac{m_{\rm DM}}{\Omega_{\rm DM}} \frac{\Omega_B}{m_N} = \frac{474}{407} \frac{1}{Q_{\rm DM}}$$

(We assume that DM annihilation is sufficiently fast)

Using the observed values of energy densities for baryon and the dark matter, we obtain

$$m_{\rm DM} \simeq 5 - 7 {\rm GeV} \frac{1}{Q_{\rm DM}}$$

We may check the quantization of the DM mass in direct DM detection experiments

CoGeNT New Data

$$m_{DM} = 6 - 8 \text{ GeV}$$

may be consistent with the XENON 100