The Origin of Matter in The Universe

- Why do we exist ? -

Tsutomu Yanagida

(TDLI, Shanghai Jiao Tong University)

NORDITA 2020

Five Questions of Our Universe

(2019)

- (1) **Where did our universe come from ?**
- (2) **What is our universe made of ?**
- (3) **What are its fundamental laws ?**
- (4) **Why do we exist ?**
- (5) **Where is our universe going ?**

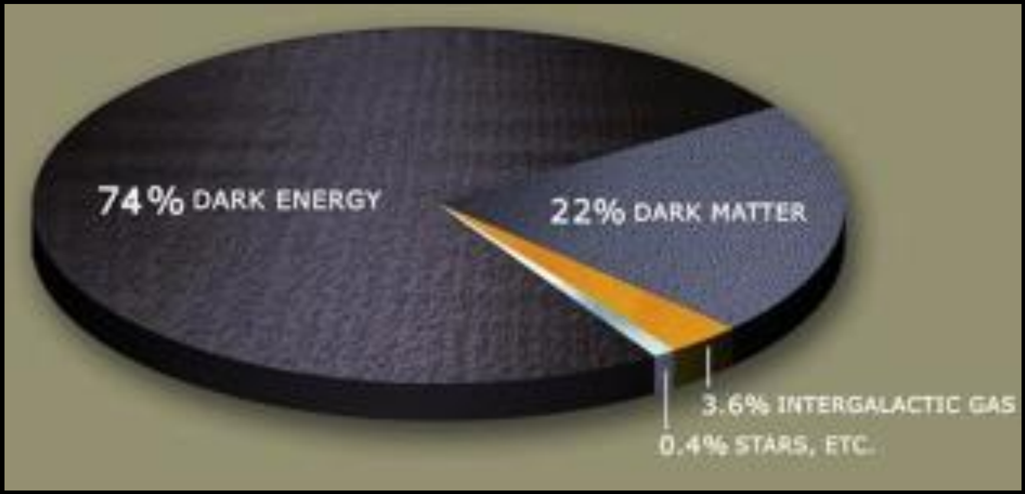
(4) Why do we exist ?

I think, therefore I am

Rene Descartes (1596~1650)

We → Scientific answer !

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:

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

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

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

(4) Why do we exist ?

The universe is composed of only matter and there is no antimatter ,

Why did antimatter disappear ?

The symmetric Universe
was proposed by Paul Dirac
In 1933.

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

There is no difference between particles and antiparticles except for their charges.

There are two reasons to believe that Dirac was correct

One is Theoretical

The other is observational

Inflation in the early universe

A. Guth (1981), A. Linde (1982), ...

It solves the flatness problem and the horizon problem

It provides the origin of density fluctuations

Now this Inflation of the universe is very consistent with all cosmological observations !!!

This Inflation universe strongly supports the Dirac idea of symmetric universe

Because our universe expanded exponentially at the early stage of the universe
and all preexisting asymmetries are diluted completely

⟹ **Symmetric Universe**

How much asymmetric ?

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

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

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

Very small !!!

Our universe is almost symmetric

Our universe may have begun symmetric !!!

Dirac may be correct
Our universe was created from nothing

But, if it is exactly symmetric, all matter and antimatter annihilated together and any matter does not exist today

Nothing → ***Nothing***

But, we do not exist now !!!

Tiny imbalances in numbers of baryons and antibaryons must be generated by some physical processes in the early universe

Steven Weinberg

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

The standard theory of particle physics does not satisfy the condition II. and III. !!!

We need
Beyond the Standard Theory

No convincing mechanism for baryogenesis was found till 1986

BUT

A big hint came from particle physics !!!

Discovery of neutrino oscillation

The solar neutrino problem

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

$37_{Cl} + v_e \longrightarrow 37_{Ar} + e^-$ (1964-1996 at Homestake)

Raymond Davis

John Bahcall

Superkamiokande confirmed the result of Davis in 1998

Superkamiokand dicovered 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)

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

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

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

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

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

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

$m_3 > m_2 > m_1$ ⇒ $m_3 \simeq 0.05 \mathrm{eV}$, $m_2 \simeq 0.009 \mathrm{eV}$

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

Why are neutrino masses so small ?

The discovery of neutrino oscillation proved that neutrinos have very tiny masses !!!

(1998)

65 years after the Dirac proposal

neutrino mass ~ 0.1 eV = 10^{-10} GeV

cf. top quark mass = 173 GeV

Why do the neutrinos have so tiny masses ?

The simplest way to give masses for neutrinos is to introduce 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 : $y_t \bar{t}_R q_L \langle H \rangle$

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

So small !!!

I found a natural mechanism generating such a small mass for neutrino about 40 years ago

I called it

“The Seesaw Mechanism”

I will show you my history of the discovery of the seesaw mechanism

Discovery of The Seesaw Mechanism

40 years ago !

up quark	charm quark	top quark
down quark	strange quark	bottom quark
Electron neutrino	Muon neutrino	Tau neutrino
Electron	Muon	Tau lepton

← ***SU(3)*** →

Why does Nature repeat three times ?

I considered a Horizontal **SU(3)** gauge symmetry

A Big Problem !!!

Theory has a gauge anomaly and it is inconsistent with quantum mechanics

The anomaly is canceled out
by introducing three right-handed neutrinos

3x N_R

***What happens for the* right-handed neutrinos after**
the Horizontal SU(3) is spontaneously broken ?

We do not need the right-handed neutrinos at low energies

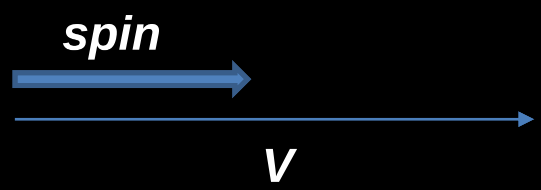
N_R may become superheavy !

But, How ???

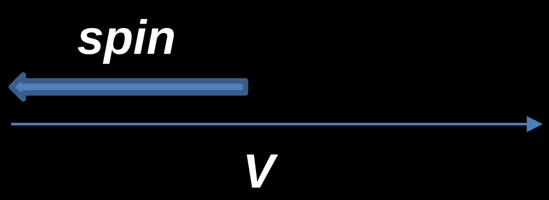
Mass of Fermion

Let us consider a massless electron which has spin 1/2

| left-handed electron > :



| right-handed electron > :

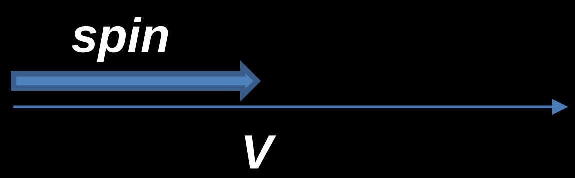


They are completely independent states !

However, if the electron is massive, the two states should not be independent

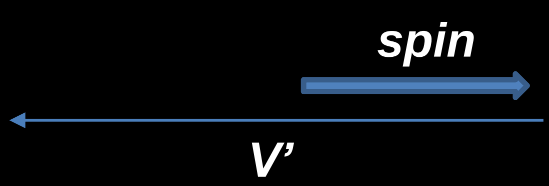
One state must mix with the other

Consider the left handed electron



If the electron is massive, its velocity is smaller than the light velocity c !

Now, ride on a rocket which runs faster than the electron



It is the right-handed electron !

We need both of left-handed and right-handed states to give a mass for a fermion

Now, we have only right-handed neutrinos N_R

But, the right handed neutrinos must be superheavy !!!

How to give masses to them ?

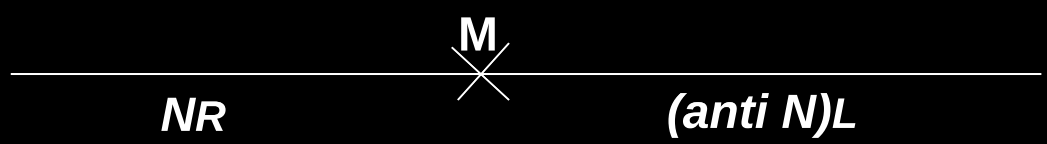
Pauli 's papers might have a hint !

I searched for Pauli's papers and found a paper published in 1957

The anti-particle of a chiral fermion has its opposite chirality

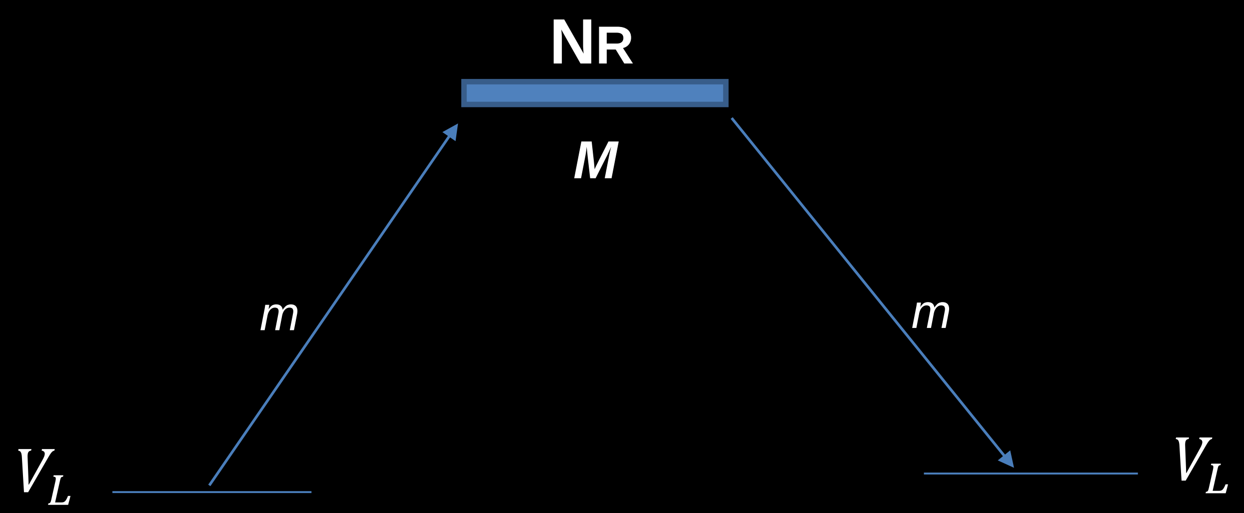
The anti-particle of N_R is left-handed !

They are neutral and mix with each other



M_R becomes superheavy !!!

What happens for the left handed neutrinos ?



Heisenberg Uncertainty Principle

dt x dE ~1 : (dE=M)

The left-handed neutrino transfers to NR for a very short time dt~1/M and gets a mass m (1/M) m

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

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

Pauli-Gursey transformation: Weyl fermion → Majorana fermion

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

neutrino mass matrix :

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

Two mass eighen values :

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

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

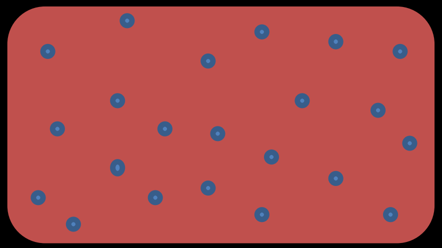
The small neutrino masses strongly suggest the presence of super heavy Majorana neutrinos N

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

Consider the very early universe, where the temperature T > the mass of N_R

We had many right-handed neutrinos in the hot thermal bath



T goes down

When T < the mass of N_R, they start to decay into leptons and Higgs bosons

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

Atiyah-Patodi-Singer index theorem

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

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

Baryon number violation in the standard theory

The baryon number is not conserved at quantum level

G. 't Hooft (1976)

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

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

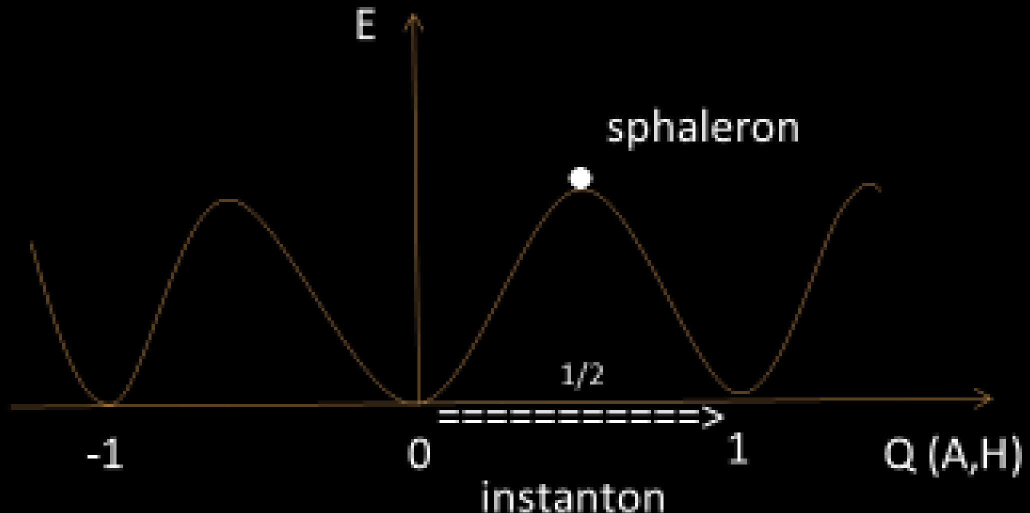
$$A \simeq e^{-S_{\text{instanton}}}, \qquad S_{\text{instanton}} = \frac{8\pi^2}{g^2}$$

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)

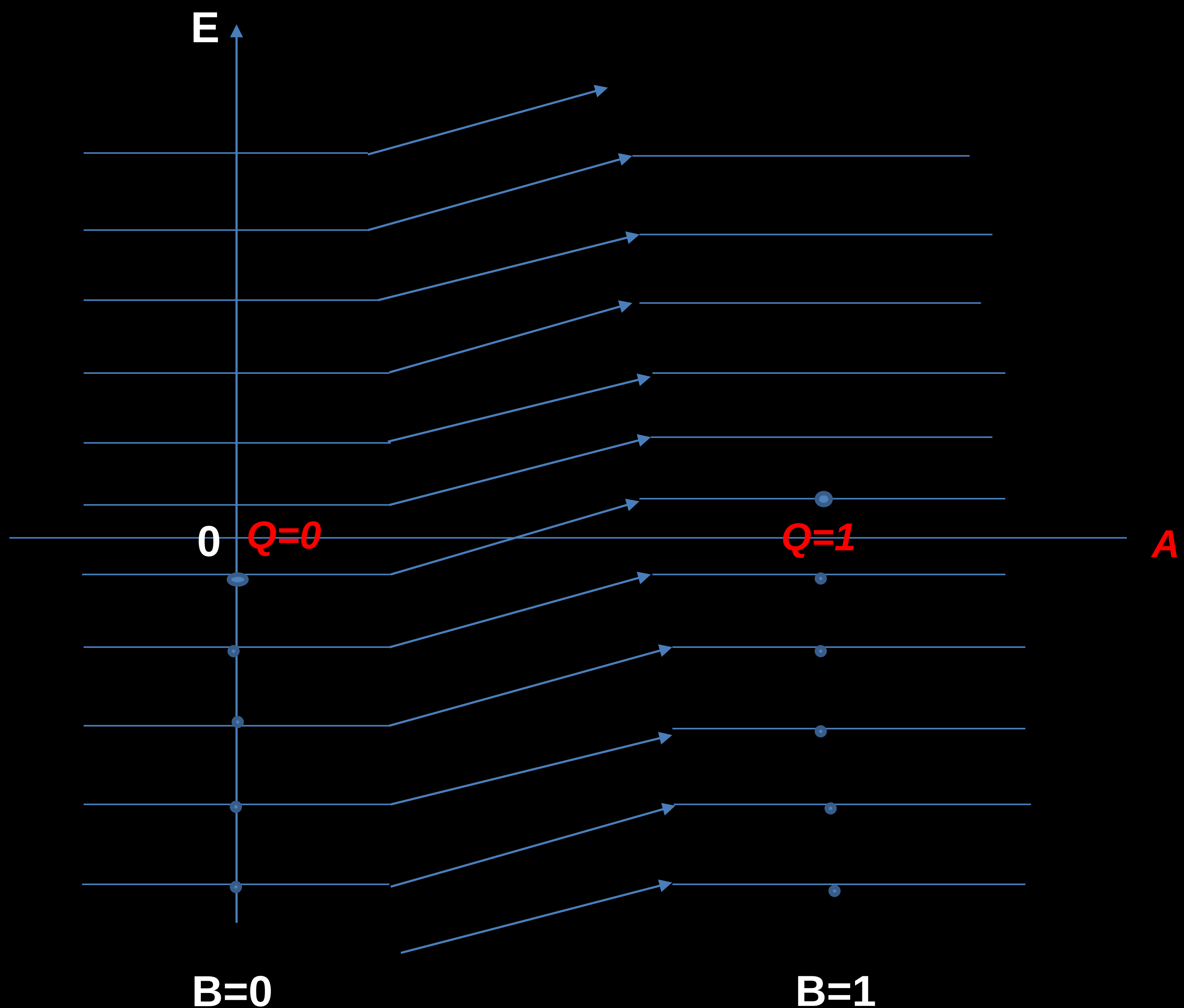
N.S. Manton (1983)
F.R. Klinkhamer , N.S. Manton (1984)



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

(WKB)

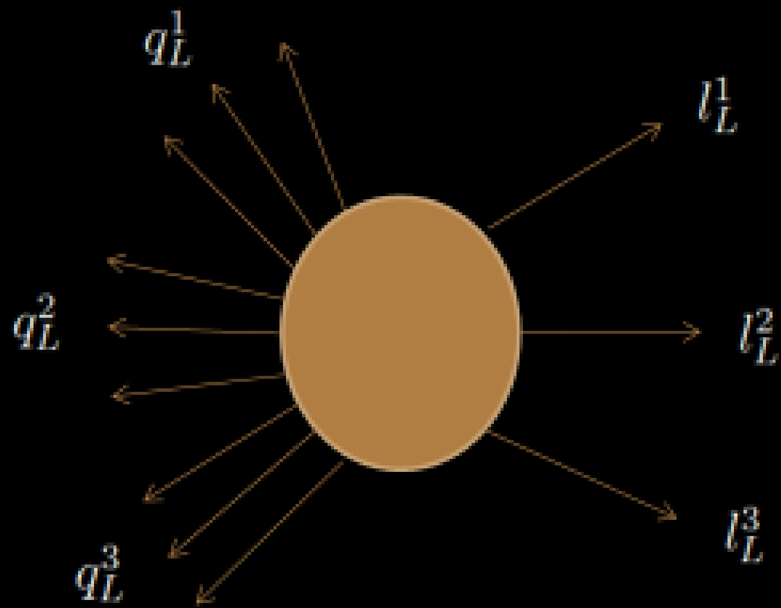
Fermion Energy Spectrum



Consider T > E(sphaleron)

Baryon and Lepton number are no longer conserved at T > O(100) GeV in the standard theory !!!

Kuzmin, Rubakov, Shaposhnikov (1985)



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

Leptons → *Baryons*

Leptogenesis

Fukugita, Yanagida (1986)

The leptogenesis predicted small neutrino masses

Fukugita, Yanagida (1986)

It was confirmed
by the discovery of neutrino oscillation !!!

SuperKamiokande (1998)

Now we have solved one of fundamental problems in the universe !!!

I strongly believe the leptogenesis is correct

BUT

We have a problem

It is very difficult to test directly the leptogenesis, since the right-handed neutrinos are extremely heavy

We need more indirect tests of the leptogenesis

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

It may be impossible to test this prediction

The Leptogenesis has two testable predictions

I. CP violation in neutrino oscillations

Positive Indications are reported

T2K experiments (2016)
NOVA experiments (2016)

II. Neutrinoless double beta decays

W.H. Furry (1939)

CP violation in neutrino oscillations will be confirmed soon

hyperKamiokande ….

I hope

Neutrinoless double beta decay will be confirmed in ……….. years

Kamland Zen
PandaX3 (SJTY) …..

If CP violation in neutrino oscillation and neutrinoless double beta decay are observed in future

We can understand why antimatter disappeared and why we do exist now !!!

The next will be a solution to the first question
(1) Where did our universe come from ?