What Do I Believe Now ?

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The Nanjing TeV physics 2019

Five Questions of Our Universe

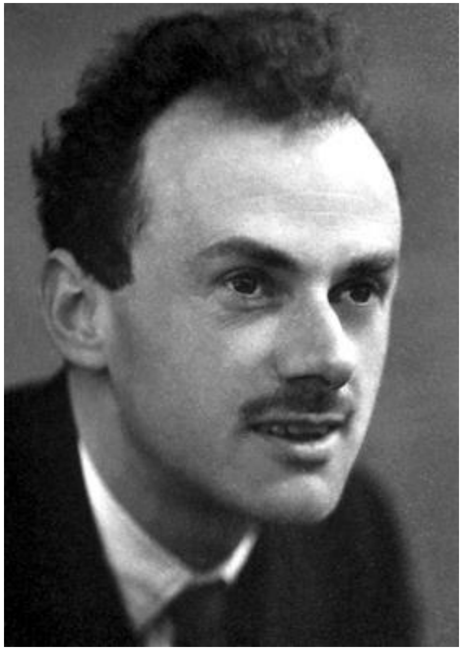
(2019)

- (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 ?

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

Why is our universe asymmetric ?



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.

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

we do not exist now !!!

Nothing → ***Nothing***

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

No convincing mechanism for baryogenesis was found till 1986

A big hint came from particle physics

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

SuperKamiokande (1998)

masses =O(0.1-0.001) eV !!!

The simplest way to give masses for neutrinos is to introduce right-handed neutrinos ν_R

The standard theory

ν_R^i →

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

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

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

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 :

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

$m_\nu \simeq 0.05\text{eV}$ $\longrightarrow$ $M \simeq 10^{15}\text{GeV}$ 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

Discovery of the Seesaw Mechanism in 1979

I will talk about my history
in Shanghai Jiao Tong University on 2?th in April

This is the first talk in my life !!!

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

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

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

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 !!!

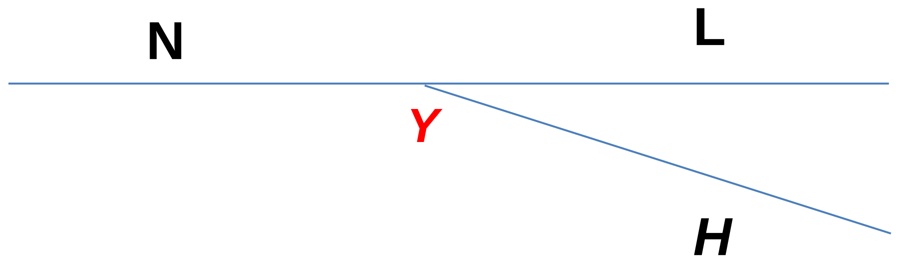
I strongly believe the leptogenesis is correct

BUT

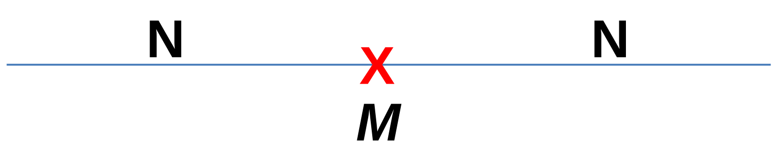
We have a problem

The leptogenesis is based on two important assumptions

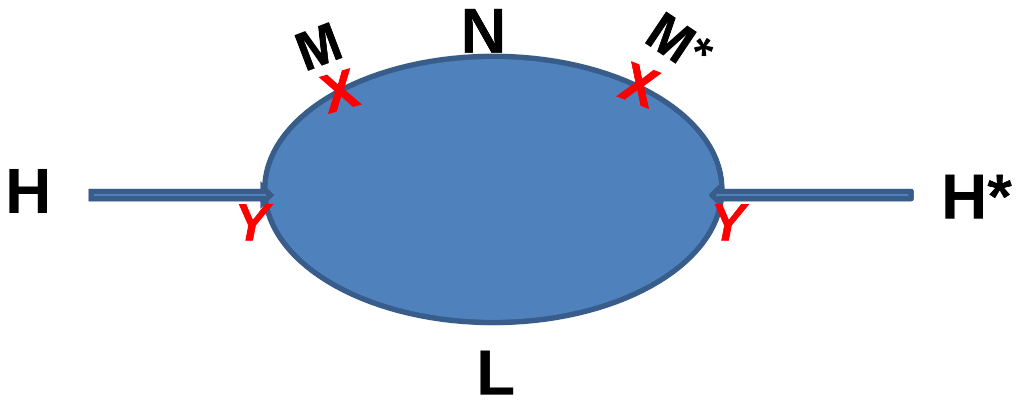
One is Yukawa couplings:



The other is Majorana masses :



Higgs Mass ?



m(Higgs) ~ *Y*M ~ 10^{10} GeV ???

m(Higgs) = 125 GeV LHC (2013)

Supersymmetry (SUSY)

is the unique solution to the problem !!!

We have cancellations

The most important discovery in particle physics in the last 30 years is the standard-model like Higgs boson which was observed at the CMS and ATLAS experiments

Its mass is about 125 GeV !!!

The Higgs boson in the Standard Model

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$< \Phi >= \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \quad ; \quad v = \sqrt{\mu^2/\lambda}$$

$$m_H = \sqrt{2\lambda}v \quad ; \quad v \simeq 246\text{GeV}$$

The Higgs boson mass is **a free parameter** in the Standard Model

Are there any theories which predict
the Higgs boson mass ?

⟹ YES !!!!

Supersymmetry (SUSY)

The *coupling* is given by $\lambda = \frac{g_2^2 + g_1^2}{4}$ ← SUSY

Then, we predict

$$m_{\mathrm{H}} \simeq m_Z \cos(2\beta) \leq m_Z \leq 91\mathrm{GeV}$$

$$\tan(\beta) = \frac{< H_u >}{< H_d >}$$

Is the SUSY Standard Model excluded ?

No!

125 GeV Higgs boson mass is
what we predicted about 28 years ago !!!

One –loop corrections at the quantum level are non negligible

Okada, Yamaguchi, Yanagida (1991)
J. Ellis et al (1991)
H. Haber et al (1991)

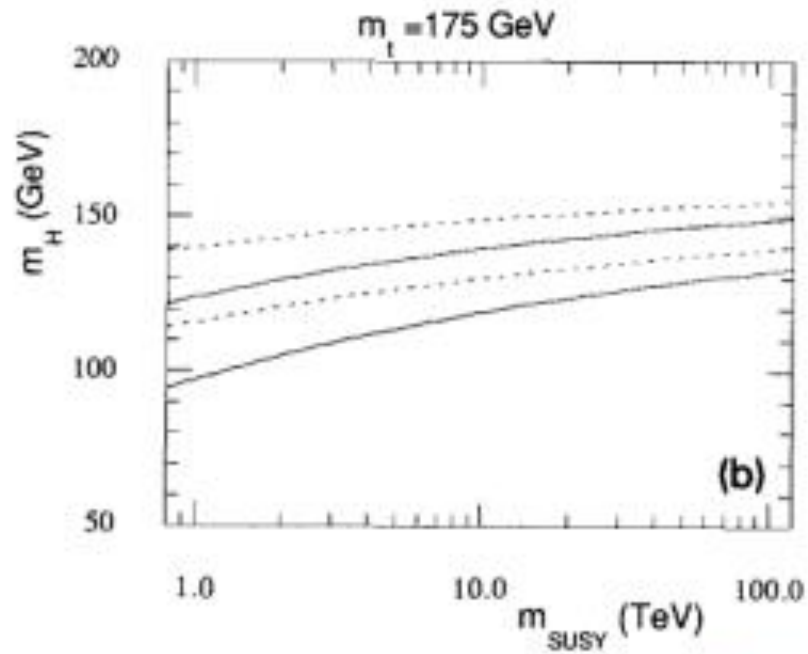
$$m_{\rm H}^2 \simeq m_{\rm Z}^2 \cos^2(2\beta) + \Delta m_{\rm H}^2$$

The quantum corrections are given by one-loop top quark and scalar top quark diagrams

$$m_{\rm light} \leq \sqrt{m_{Z^0}^2 \cos^2 2\theta + \frac{6}{(2\pi)^2}\left(\log \frac{m^2 + m_t{}^2}{m_t{}^2}\right)\frac{m_t{}^4}{v^2}}$$

mass of scalar top quark

The Higgs mass predicted



Okada, Yamaguchi, Yanagida (1991)

We have calculated the mass of the lightest Higgs boson in the minimal SUSY standard model postulating the SUSY breaking scale is much larger than the Fermi scale. Our results can be used to probe the SUSY breaking scale, with the situation where both m_t and m_{H^0} are given. For example, when $m_t = 150$ GeV, the existence of the Higgs boson below 70 GeV strongly suggests the presence of the SUSY below 1 TeV (see the lower solid line in fig. 1a). On the other hand, if the Higgs boson turns out to be heavier than 125 GeV, the SUSY breaking scale must be larger than

$$m_{\rm SUSY} = m_{stop} \geq O(10)\text{TeV}$$

The supersymmetry has many attractive points,

1. Gauge coupling unification
2. Stability of the Higgs potential
3. The observed light Higgs boson of mass about 125 GeV !!!

But, it has serious problems

We need to solve the problems

There were various motivations to consider the large SUSY breaking scale,

$$m_{\mathrm{SUSY}} = m_{stop} \geq O(10)\mathrm{TeV}$$

I. Gravitino over-production problem
II. Polonyi (Moduli) problem
III. Flavor-changing neutral current problem
IV. CP-violation problem

Solutions to each problems suggest the large SUSY breaking

$$m_{3/2} \simeq m_{\mathrm{SUSY}} \geq O(10)\mathrm{TeV}$$

gravitino mass

(1) The cosmological gravitino problem;

Buchmuller et al (1997)

The leptogenesis predicts $T \geq 2 \times 10^9 \mathrm{GeV}$, but
we have too many primordial gravitinos if $T \geq 2 \times 10^9 \mathrm{GeV}$

The gravitino of mass O(1) TeV is excluded, since the decay of the gravitino destroys the light elements created in the big-bang nucleosynthesis (BBN)

(2) The cosmological moduli problem;

Gravity mediation requires a singlet field called modulus field
The late decay of the modulus field produces too much entropy to dilute the baryon asymmetry

Both problems were solved in the Pure Gravity Mediation model proposed by

Ibe , Yanagida (2011)

The pure gravity mediation was proposed just after the LHC announcement of the evidence of Higgs boson in December 2011

The Higgs boson mass is about 125 GeV !

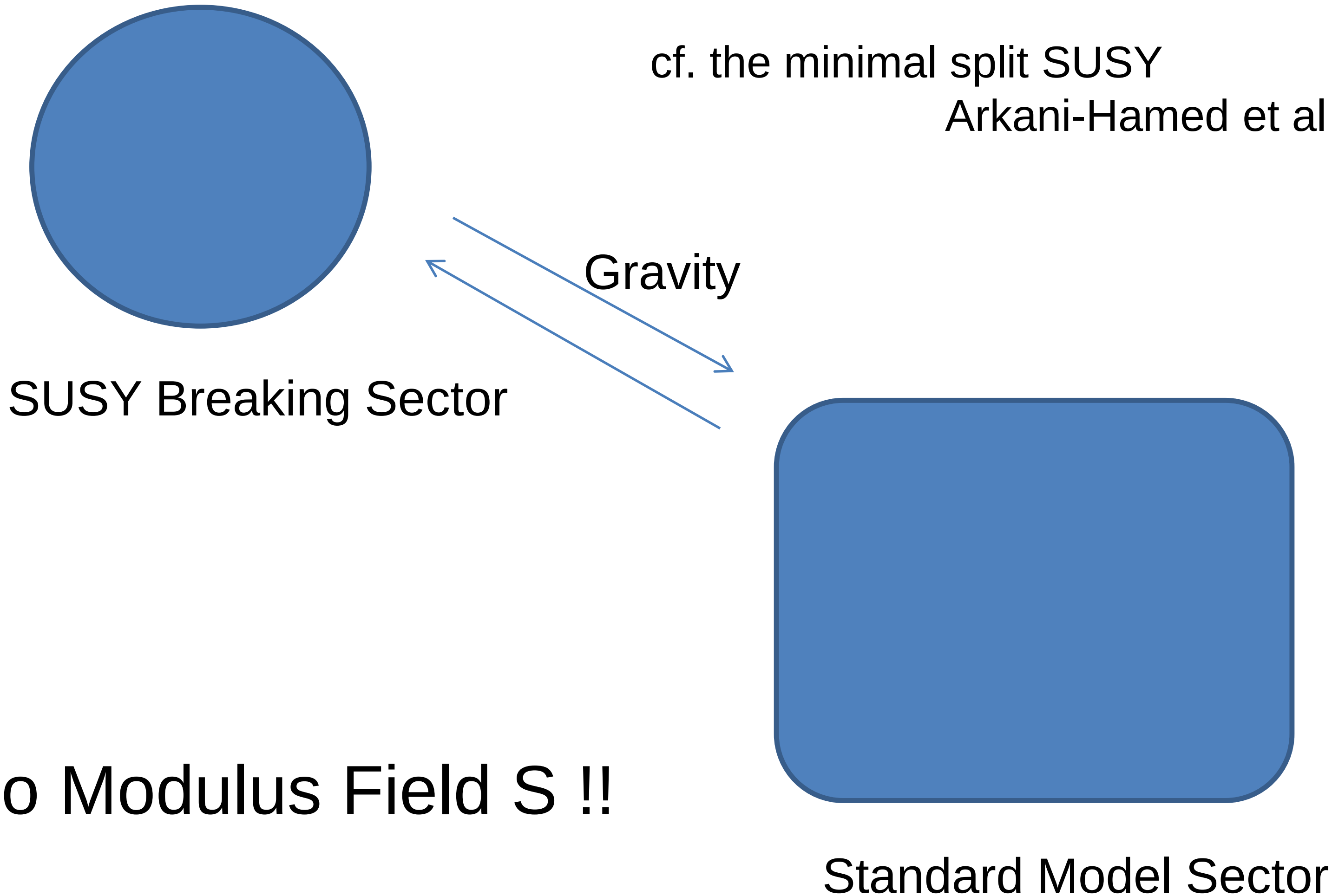
The Higgs boson mass of 125 GeV suggests large squark masses about 10-100 TeV !!!

Motivated by this high scale SUSY breaking, we proposed “Pure Gravity Mediation” .

Pure Gravity Mediation

Ibe, Yanagida (2011)
Ibe, Matsumoto, Yanagida (2012)

cf. the minimal split SUSY
Arkani-Hamed et al (2012)



No Modulus Field S !!

I. The gaugino masses can be generated by quantum corrections without the Modulus field in supergravity

H. Murayama et al (1998)
Randall, Sundrum (1999)

Anomaly mediation:

$$\begin{aligned} m_{\rm bino} &\simeq 10^{-2} m_{3/2} , \\ m_{\rm wino} &\simeq 3 \times 10^{-3} m_{3/2} , \\ m_{\rm gluino} &\simeq (2-3) \times 10^{-2} m_{3/2} . \end{aligned}$$

$$m_{\rm gluino} > 1.5 \text{ TeV} \rightarrow m_{3/2} > 50 \text{ TeV}$$

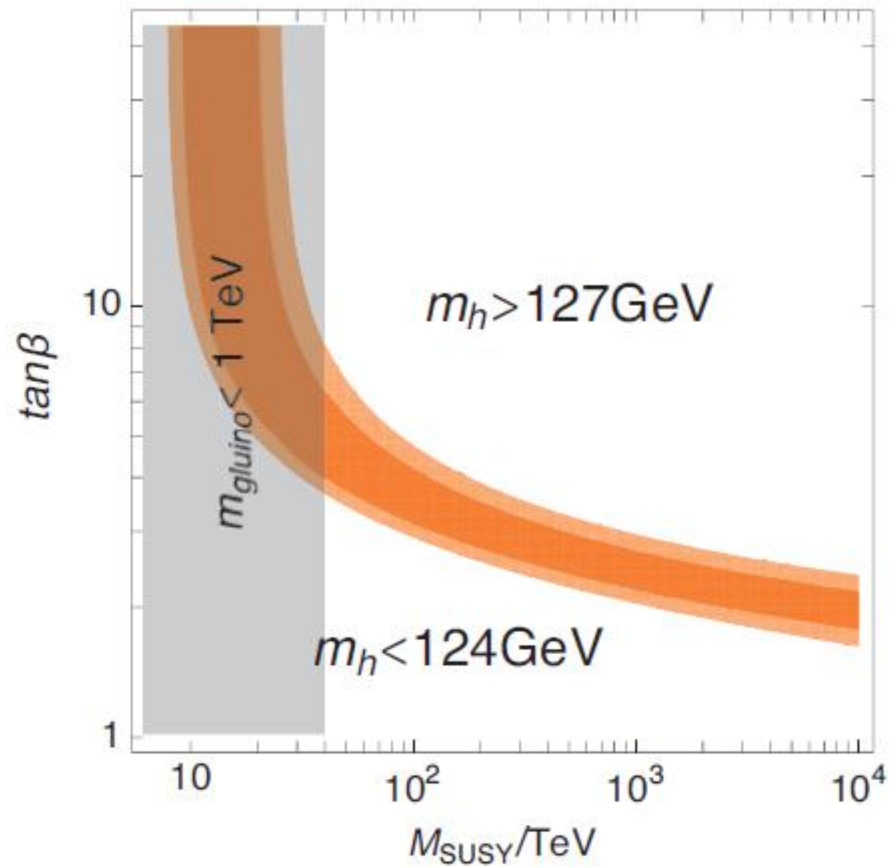
II. The Higgsino mass can be generated by the supergravity effects without the Modulus field at the classical level

$$K = H_u H_d + ... \Longrightarrow m_{\rm Higgsino} = \mu \simeq m_{3/2} \quad ; \quad \tan\beta \simeq O(1)$$

Inoue, Kawasaki, Yamaguchi, Yanagida (1992)
Casas, Munoz (1993)

The Higgs mass about 125 GeV can be explained for small

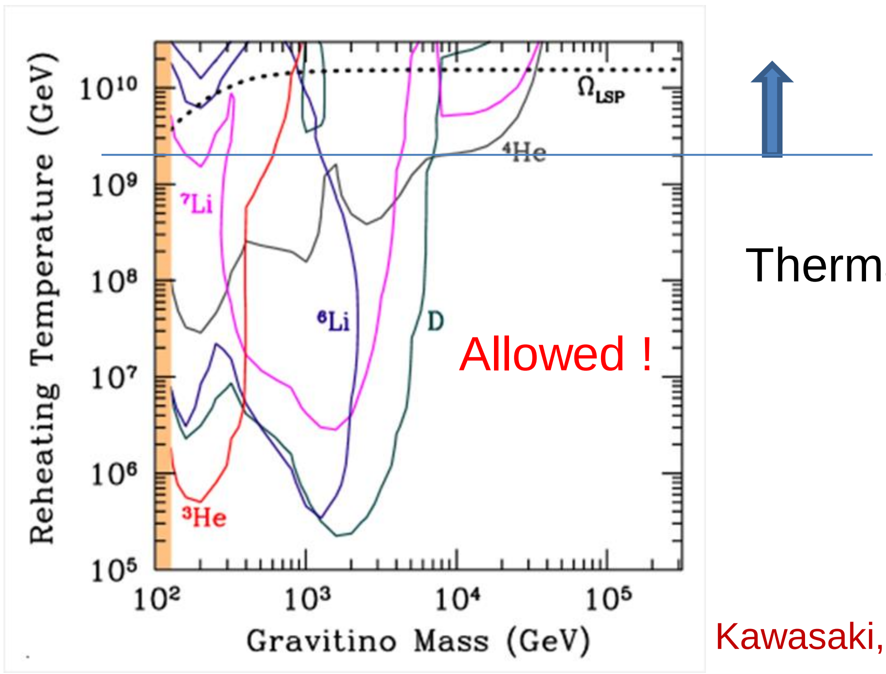
$\tan\beta \simeq O(1)$ and a large $m_{3/2} \simeq 50 - 1000$ TeV



Gravitino over-production problem

S. Weinberg (1982)

The gravitinos are produced by particle scattering in thermal bath in the early universe. They decay after the BBN and destroy the light elements produced by the BBN. We have constraints on T_R and m_3/2 not to disturb the BBN (big bang nucleosynthesis).



Thermal Leptogenesis

Fukugita, Yanagida (1986)

Kawasaki, Moroi, Yotsuyanagi

The thermal leptogenesis predicts $m_{3/2} \simeq m_{\rm SUSY} \geq O(10)\,{\rm TeV}$

The Pure Gravity Mediation is very successful

I. It easily explains 125 GeV Higgs mass
II. Successful gauge coupling unification
III. No Gravitino over-production problem
IV. No Polonyi (Moduli) problem
V. No Flavor-changing neutral current problem
VI. No CP-violation problem

It predicts the wino LSP of mass O(1) TeV which is a good candidate for the DM

The wino is the LSP and a candidate for the DM

Ibe, Matsumoto, Yanagida (2012)

I. The thermal wino DM; its mass is predicted as

Hisano, Matsumoto, Nojiri

$$m_{\rm wino} \simeq 2.7 \ {\rm TeV}$$

II. The non-thermal wino DM through the gravitino decay; its abundance depends on the reheating temperature

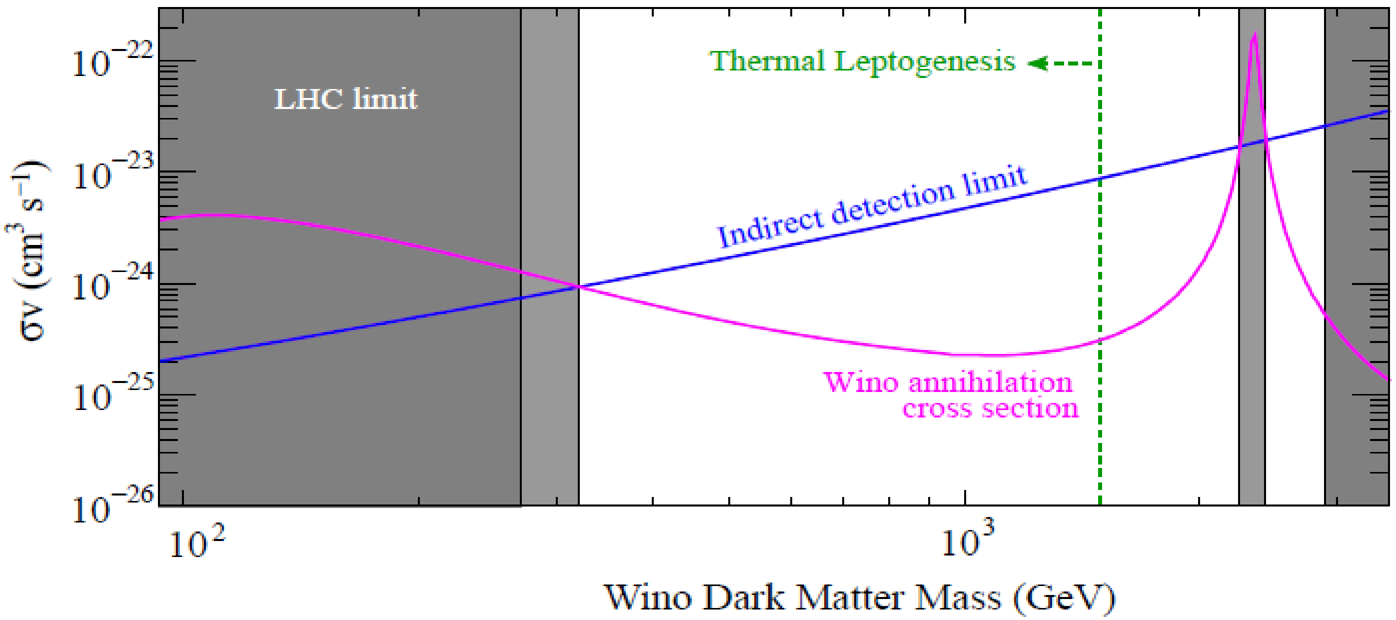
The thermal leptogenesis needs $T_R > 2 \times 10^9 \ {\rm GeV}$

which predicts $m_{\rm wino} < 1.5 \ {\rm TeV}$

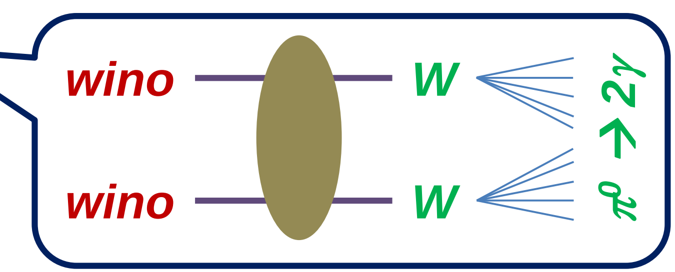
The wino mass O(1) TeV region is very interesting !!!

The disappearing charged track by the charged wino decay may be observed at the future LHC !!!

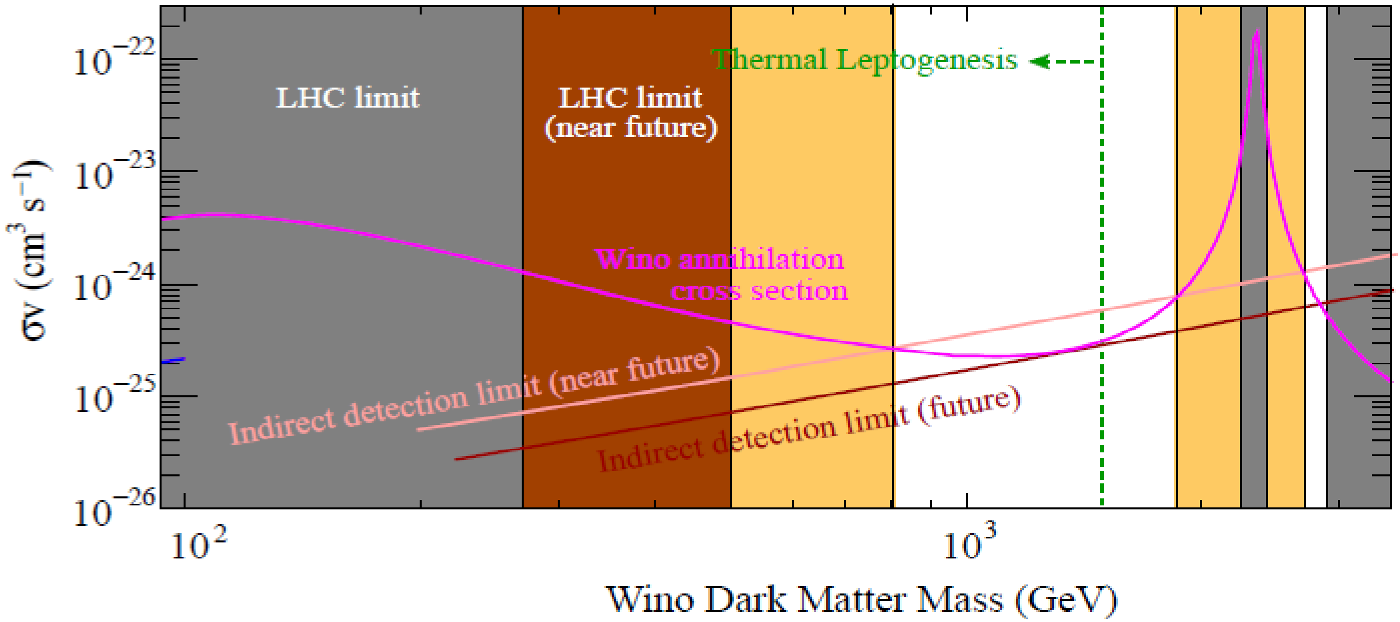
Present status of wino DM searches



- ***The wino DM must be lighter than 2.9TeV not to overclose the universe.***
- ***The LHC [8TeV & 20fb^{-1}] currently excludes the region m_{wino}< 270GeV by the disappearing charged track search.*** Ibe, Matsumoto, Sato (2013)
- ***Annihilation of the wino DM produces γ–rays by the boosted cross section.*** Hisano, Nojiri, Matsumoto
- ***Observation of γ–rays from dSphs at Fermi-LAT [4yrs] excludes the region m_{wino}< 320GeV, 2.3TeV < m_{wino}< 2.4TeV.***



Future prospects of wino DM searches



- ***The future LHC [14TeV & 100 fb^{-1}] will cover the region m_{wino}< 500GeV.***
- ***The γ–ray observation of dSphs will cover the region m_{wino}< 810GeV & 1.9TeV < m_{wino}< 2.7TeV [Fermi-LAT 10yrs] in near future and the entire region m_{wino}< 2.9TeV [Fermi-LAT 15yrs P GAMMA-400 10yrs] in future, when the DM distributions inside dSphs are accurately measured.***

⇓⇓⇓

Interdisciplinary studies inside the Kavli IPMU is now being developed for this purpose with the use of "Prime Focus Spectrograph (PFS)" in the SuMIRe project.

Ibe, Ichikawa, Ishigaki, Matsumoto, Sugai

Anomaly mediation

Murayama et al (1998)

Universe's baryon asymmetry
Leptogenesis

Fukugita, Yanagida (1986)

Mass for Higgs boson
LHC (2013)

Pure Gravity Mediation

Ibe, Yanagida (2011)

KamLAND Zen

Double beta decay

T2K
neutrino oscillation
CP violation

SuMIRe project

Neutrino mass
DM profile in dSph
Curvature

Discovery of SUSY particles !!!