Particle physics in the early universe

MASAHIDE YAMAGUCHI

(Tokyo Institute of Technology)

January 3-12, 2022@Physics of the Early Universe

- An online School -

$$c = \hbar = 1, \quad M_G = 1/\sqrt{8\pi G} \sim 2.4 \times 10^{18}\mathrm{GeV}.$$

Contents

Key topic : Non-topological solitons (Q-balls, Oscillons)

- **Motivation to Q-balls : Baryogenesis (and dark matter)**

By Prof. Katelin Schutz

A non-topological soliton made of a (charged) complex scalar field

- **Motivation to Oscillons : α-attractor inflation models**

A non-topological soliton made of a real scalar field

What are the conditions to form these objects ?
What are the similarity and the difference between them ?
…

Plan

Day 1 (Jan 6th) : Review of Baryogenesis (by slide)
(including Affleck-Dine baryogenesis as a motivation to Q-balls)

Day 2 (Jan 7th) : Basics of Q-balls (by whiteboard)

Day 3 (Jan 10th) : Continued.

Introduction to α-attractor inflation models
as a motivation to Oscillons (by slide)

Day 4 (Jan 11th) : Basics of Oscillons (by whiteboard)

Baryogenesis :
Motivation to Q-balls

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Contents

1. Introduction
2. GUT baryogenesis
3. Sphaleron
4. Models
    i. Electroweak baryogenesis
    ii. Leptogenesis
    iii. Affleck-Dine baryogenesis
5. Motivation to Q-balls

Introduction

Is there anti-matter in the Universe ?

- **Earth and solar system**

  We know that they consist of only matter.

- **Our galaxy**

  We found anti-protons in cosmic rays.
  But, their amount coincides with that produced at the collision of cosmic rays.

- **Cluster of galaxies**

  If there would be regions in which anti-matter is main component, large amount of gamma rays would be emitted from boundary of the regions of matter and anti-matter. But, we have not yet observed them.

How much is matter (baryon) asymmetry ?

- **Big-Bang nucleosynthesis (BBN)**

$$\Rightarrow \frac{n_B}{n_\gamma} = (6.143 \pm 0.190) \times 10^{-10}$$

- **Anisotropies of CMB**

$$\Rightarrow \frac{n_B}{n_\gamma} = (6.104 \pm 0.058) \times 10^{-10}$$

$$\left(n_B \equiv n_{\mathrm{baryon}} - n_{\mathrm{anti-baryon}} \right)$$

Particle data group

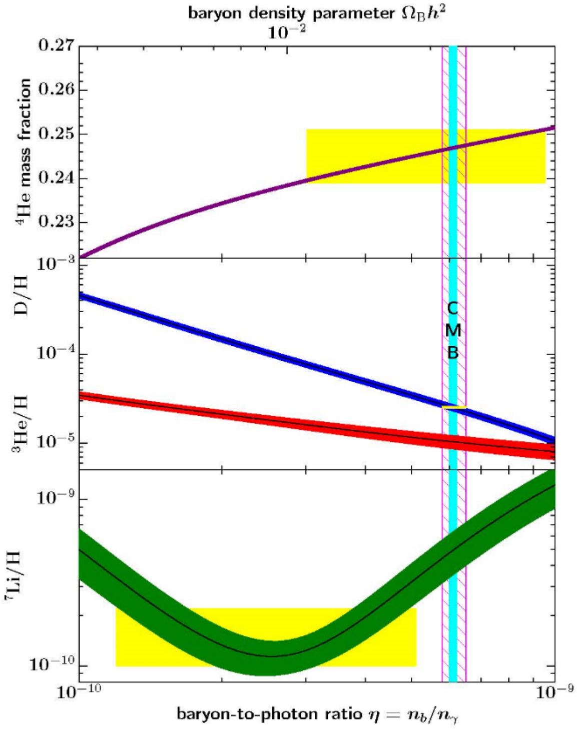


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [50]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).

Strictly speaking, these quantities represent baryon asymmetries at different epoch. Then, they do not necessarily coincide.

Big Bang Nucleosynthesis (BBN)

- **Light elements were synthesized in the early Universe (t = 1 - 100 sec).**
  (Heavy elements are synthesized in a star, SN, merger of neutron stars …)
- **Almost all neutrons are incorporated into ^{4}He.**

How to estimate the abundance of ^{4}He ?

(i) β equilibrium between p & n :

$$n \leftrightarrow p + e^- + \overline{\nu}_e, \quad n + \nu_e \leftrightarrow p + e^-, \quad n + e^+ \leftrightarrow p + \overline{\nu}_e.$$

$$(n/p) = \exp\left(-Q_{np}/T\right), \quad Q_{np} \equiv (m_n - m_p)c^2 = 1.29 \ \mathrm{MeV}.$$

(ii) β equilibrium freezes out when the expansion rate dominates.

$$\Gamma_\beta \simeq G_F^2 T^5 = H \simeq T^2/M_G^2 \implies T_f \simeq 1/\left(G_F^2 M_G\right)^{1/3} \simeq 1 \ \mathrm{MeV} \implies (n/p) \simeq 1/6\,.$$

(iii) Nucleosynthesis starts from D : p+n ➔ D+γ, B$_D$ =2.22 MeV.

$$(D/n) \simeq 7.2\eta\left(T/m_n\right)^{3/2}\exp\left(B_D/T\right) \implies T_D \sim 0.07 \ \mathrm{Mev} \implies (n/p) \simeq 1/7\,.$$

$$\left(\ \eta = n_b/n_\gamma \simeq 6 \times 10^{-10}\right)$$

(Decay of n with τn = 890 s)

$$Y \equiv \frac{\text{total mass of } {}^4\text{He}}{\text{total masses of p \& n}} = \frac{\frac{n_n}{2} \times 4m_p}{n_p m_p + n_n m_n} \simeq \frac{2\frac{n_n}{n_p}}{1 + \frac{n_n}{n_p}} \simeq 0.25.$$

Generation of baryon asymmetry

You may wonder if the Universe started from a baryon asymmetric state. That's it.

NO!!

Any asymmetry existed before inflation can be diluted.

↓

We have to generate baryon asymmetry after inflation.

Subtlety of baryon asymmetry

In the very early Universe, both matter(baryon) and anti-matter(anti-baryon) exist.

Their amounts are comparable to that of photons.

matter

10,000,000,001

anti-matter

10,000,000,000

⇨ $$\frac{n_B}{n_\gamma} = \mathcal{O}\left(10^{-10}\right)$$

matter

10,000,000,000

anti-matter

10,000,000,000

Imperfect cancellation

⇨ $$\frac{n_b}{n_\gamma} = \frac{n_{anti-b}}{n_\gamma} = \mathcal{O}\left(10^{-18}\right)$$

Sakharov's three conditions

Sakharov

1. **An interaction which violates baryon number.**
2. **C and CP violations.**

Let's consider a baryon violating interaction i → f $(B_i \neq B_f)$

If C(CP) is conserved, $\Gamma(i \to f) = \Gamma(i^{C(CP)} \to f^{C(CP)})$

⇒ $\Delta B = 0$ $\left(B^{C(CP)} = -B\right)$

3. **Deviation from thermal equilibrium.**

In thermal equilibrium (under CPT invariance)

$$\begin{aligned} \langle B \rangle &= \mathrm{Tr}(e^{-\beta H} B) = \mathrm{Tr}\left[(CPT)(CPT)^{-1} e^{-\beta H} B\right] \\ &= \mathrm{Tr}\left[e^{-\beta H}(CPT)^{-1} B (CPT)\right] = -\mathrm{Tr}(e^{-\beta H} B) = 0 \end{aligned}$$

(H is CPT invariant, B changes its sign under C and CPT.)

N.B. : These conditions are sufficient ones but not necessary ones. (CPT violation)

In fact, in an expanding universe, CPT symmetry can be violated !!

GUT (Grand Unified Theory) baryogenesis

SU(5) GUT

Yoshimura

Fermion :

$$\overline{5}_f = (d^c_L, L_L)$$

$$10_f = (Q_L, u^c_L, e^c_L)$$

Quarks and leptons belong to a same multiplet. No difference.

Gauge boson : $24_V =$

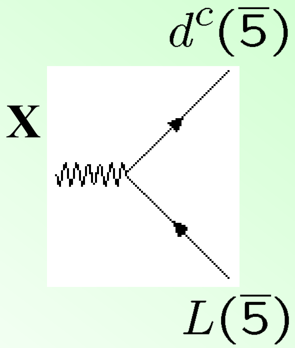
SU(3) gauge fields (8)
SU(2) gauge fields (3)
U(1) gauge field (1)
X, Y gauge fields (12)

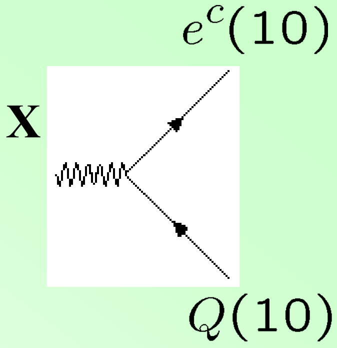
Decay of X and Y bosons create baryon asymmetry.

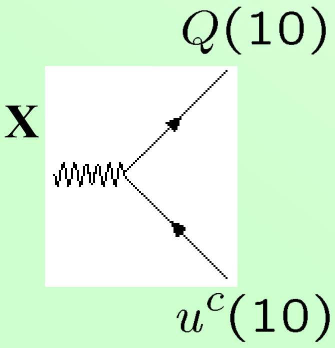
Decay of X (and Y) bosons

X (and Y) boson decay into quarks and leptons through the following interactions

Interactions: $$\frac{g}{\sqrt{2}} 24_V \left[(\overline{5}_f)^\dagger (\overline{5}_f) + (10_f)^\dagger 10_f \right]$$







$\Delta B = -1/3$ $\Delta B = -1/3$ $\Delta B = 2/3$

$$X \to \overline{q}\,\overline{l}$$ $$X \to q\,q$$

Decay rates

- **From CPT invariance:**

$$\Gamma(X \to qq) + \Gamma(X \to \overline{q}\overline{l}) = \Gamma(\overline{X} \to \overline{q}\overline{q}) + \Gamma(\overline{X} \to ql)$$

(Branching ratio: r + 1 - r = s + 1 – s)

- **If C and CP are violated,**

$$\begin{cases} \Gamma(X \to qq) \neq \Gamma(\overline{X} \to \overline{q}\overline{q}) \\ \Gamma(X \to \overline{q}\overline{l}) \neq \Gamma(\overline{X} \to ql) \end{cases} \quad (\Leftrightarrow\ r \neq s)$$

➡ $\Delta B = \frac{2}{3}r - \frac{1}{3}(1-r) - \frac{2}{3}s + \frac{1}{3}(1-s) = r - s \neq 0$

- **Then, out-of-equilibrium decay of $X, \overline{X}$ generates baryon asymmetry.**

1. For $T \gg m_X$, $n_X = n_{\overline{X}} \simeq n_\gamma$.

2. For $H > \Gamma$ $(T \lesssim m_X)$,
X is decoupled from thermal bath.

3. $X, \overline{X}$ decay non-thermally.

Difficulties

1．Can the reheating temperature be higher than X boson masses ? $m_X \sim 10^{16}\text{GeV}$

2．Monopole problem

3．Since B-L is conserved, sphaleron effects wash out the produced B asymmetry.

4．Is there sufficient CP violation ?

5．…

Sphaleron

Baryon number non-conservation in the standard model of particle physics

Baryon and lepton numbers are conserved at classical level in the standard model of particle physics

⇓

But, they are violated through chiral anomaly at quantum level.

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = N_g \left(\frac{g_2^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} W_{\mu\nu}^a W_{\rho\sigma}^a - \frac{g_1^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} \right)$$

N_g : **number of generations**
$W_{\mu\nu}^a$: **SU(2) field strength**
$F_{\mu\nu}$: **U(1) field strength**

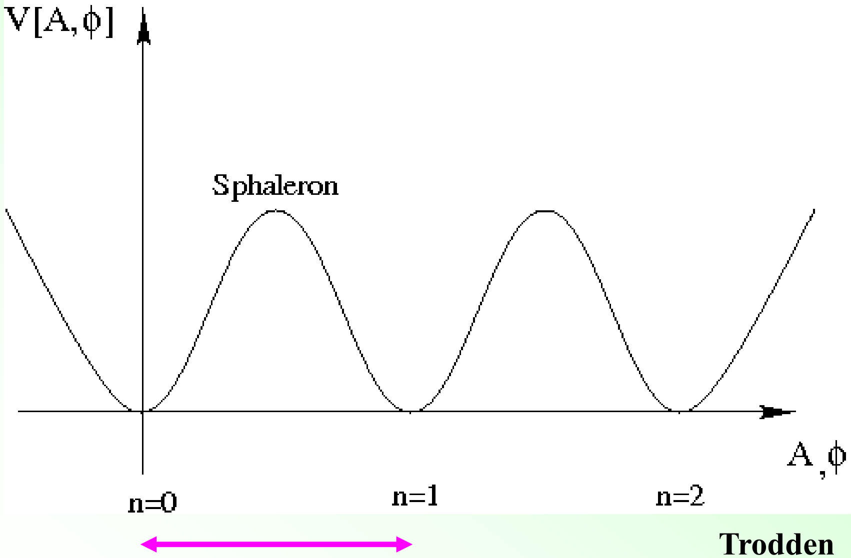
g1, g2 : gauge couplings

N.B. B – L is conserved : $\partial_\mu (j_B^\mu - j_L^\mu) = 0$

B+L

$$\begin{aligned}\Delta(B+L) &= \int d^4x\partial_\mu(j_B^\mu + j_L^\mu) \\ &= 2N_g\frac{g_2^2}{64\pi^2}\int d^4x\epsilon^{\mu\nu\rho\sigma}W^a_{\mu\nu}W^a_{\rho\sigma} \\ &= 2N_g\, n\end{aligned}$$

n : integer called winding number



$\Delta B = \Delta L = N_g$

Trodden

B+L is changed once n is changed.

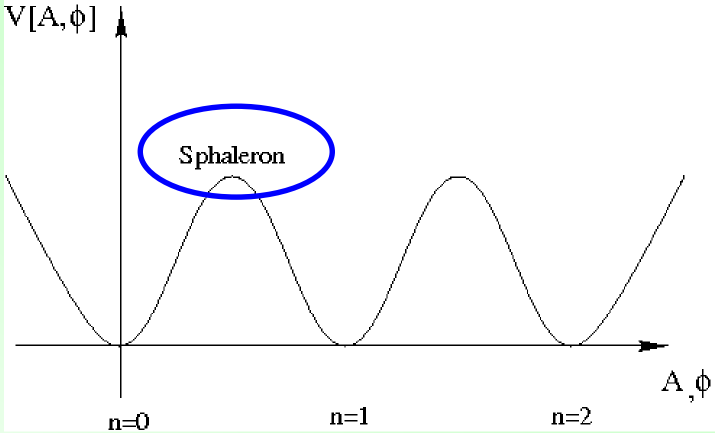
But, the tunneling rate at zero T is exponentially suppressed.

$$\begin{aligned}\Gamma &\sim |e^{-S_{\text{instanton}}}|^2 \\ &= e^{-16\pi^2/g_2^2} \sim 10^{-170}\end{aligned}$$

't Hooft

Sphaleron

Sphaleron : saddle-point solution connecting n=0 and n= 1



Trodden

Klinkhammer and Manton

$$\begin{cases} A_i^a = \frac{2i}{g_2} f(r) \left(i\epsilon_{iaj} x_j \frac{1}{r^2} \right) \\ \phi = \frac{v}{\sqrt{2}} h(r) \frac{i\tau^i x_i}{r} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \\ f(0) = h(0) = 0 \\ f(\infty) = h(\infty) = 1 \\ v \simeq 174\,\mathrm{GeV} \end{cases}$$

$$B_{\mathrm{sph}} = L_{\mathrm{sph}} = \frac{1}{2} N_g$$

$$\begin{aligned} E_{\mathrm{sph}} &= \mathcal{O}(4\pi v/g_2) = \mathcal{O}(8\pi M_W/g_2^2) \\ &= (8-14)\mathrm{TeV} \end{aligned}$$

Transition rate

Arnold and McLerran

Tunneling rate is enhanced thanks to thermal fluctuations at high temperature.

$T \gtrsim T_C$ **: symmetric phase**

$$\Gamma(T)^{\mathrm{sph}} \sim \kappa_2(\alpha_W) T^4$$

$$\kappa_1,\ \kappa_2,\ \mathcal{E} = \mathcal{O}(1)$$

$T \lesssim T_C$ **: broken phase**

$$\Gamma(T)^{\mathrm{sph}} \sim \kappa_1 \left(\frac{M_W}{\alpha_W T}\right)^3 M_W^4 \exp\left(-\frac{E_{\mathrm{sph}}(T)}{T}\right), \qquad E_{\mathrm{sph}}(T) = \frac{M_{\mathrm{W}}(T)}{\alpha_{\mathrm{W}}}\mathcal{E}, \quad \alpha_{\mathrm{W}} = \frac{g_2^2}{4\pi}$$

⇒ $\Gamma^{\mathrm{sph}} T^3 > H \;\leftrightarrow\; 100\mathrm{GeV} \lesssim T \lesssim 10^{12}\mathrm{GeV}$

Wash-out

Khlebnikov and Shaposhniko
Harvey and Turner

$$B_f = \frac{8N_g + 4N_h}{22N_g + 13N_h}(B-L)_i \simeq 0.35(B-L)_i$$

(for SM or MSSM)

- Even if B asymmetry was created, it would be eventually washed out as long as $(B-L)_i = 0$.

⇒ SU(5) GUT baryogenesis does not work.

- As long as L or B – L could be created at early epoch, B would be generated through sphaleron effects.

⇒ Leptogenesis

- Even in case that only B+L can be generated, B would survive if sphaleron effects do not work efficiently.

⇒ Electroweak baryogenesis

Electroweak baryogenesis

(e.g. Baryogenesis in the standard model)

Sakharov's three conditions

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$\Longrightarrow$ **B = 0**

3. **Deviation from thermal equilibrium.**

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In fact, in an expanding universe, CPT symmetry can be violated !!

Baryogenesis in the standard model

1. **An interaction which violates baryon number.**

   B (B+L) is violated through chiral anomaly.

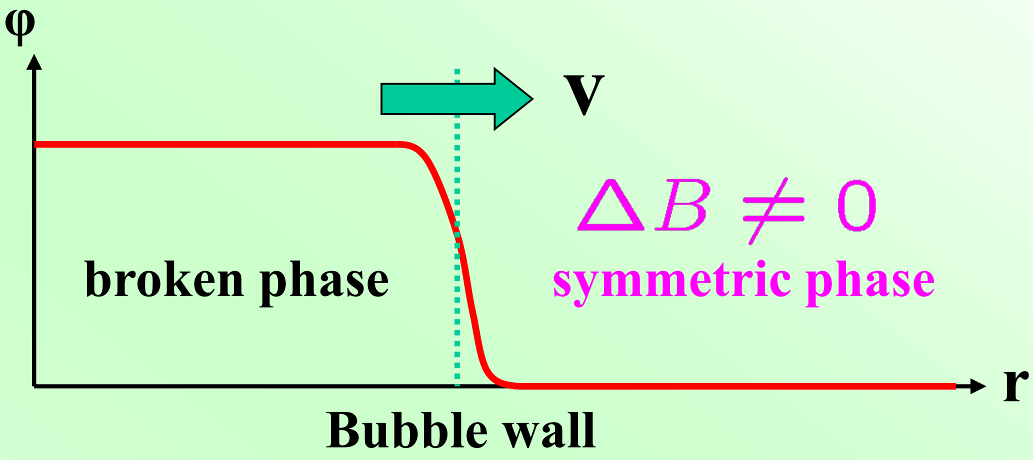
2. **C and CP violations.**

   C is violated in a chiral gauge theory.
   CP is violated through CKM matrix.

3. **Deviation from thermal equilibrium.**

   If the electroweak phase transition is (strong) first order, critical bubbles are formed and the phase transition proceeds through the expansions of such bubbles.
   These expansions cause deviation from equilibrium.

Scenario



Local baryogenesis

Ambjorn, Turok and Zadrozny, McLerran et al.

Both B violating and CP violating interactions happen very close to the bubble wall.

Non-local baryogenesis

Cohen et al., Joyce et al.

A net chiral charge flux is generated through CP violating interaction because particles with opposite chirality interact differently with the wall. Its asymmetry is converted to B number violation through B violating interaction in the symmetric phase. B number is conserved after the pass of the bubble wall.

$$n_B = \underline{n_b^L - n_{\bar{b}}^L} + n_b^R - n_{\bar{b}}^R = 0$$

(changed by sphaleron processes) ➡ $n_B \neq 0$

Difficulties

1. **Amount of CP violation in CKM matrix is too small.**

μ-term & soft SUSY breaking term can be other sources of CP violation e.g. in the minimal SUSY extension of SM(MSSM).

2. **The phase transition is not (strong) first order.**

   I. **The phase transition does not proceed through creation and expansion of critical bubbles.**

   II. **B violating interaction is not sufficiently suppresed in the broken phase.**

These conditions give stringent constraints on MSSM parameters.

Leptogenesis

Right handed neutrino and seesaw mechanism

Neutrino masses (squared) are very tiny. NuFIT 5.0(2020)

$$\begin{cases} \Delta m_{31}^2 = (2.517^{+0.026}_{-0.028}) \times 10^{-3}\mathrm{eV}^2 \\ \Delta m_{21}^2 = \left(7.42^{+0.21}_{-0.20}\right) \times 10^{-5}\mathrm{eV}^2 \end{cases}$$

(normal ordering)

⇦ **Seesaw mechanism** Minkowski, Yanagida, Gell-Mann et al.

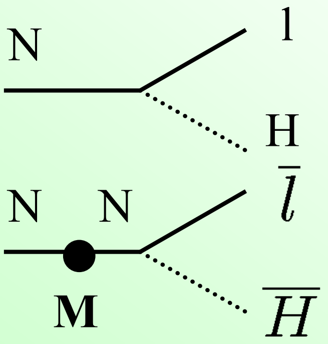
Right handed neutrino :

$$\mathcal{L} = y_{ij}^{(\nu)} N_i l_j H + \frac{1}{2} M_i N_i N_i + \mathrm{h.c.}$$

Mass matrix $\begin{pmatrix} o & m_D \\ m_D & M \end{pmatrix} \longrightarrow m \sim M,\, m_D^2/M \ll m_D$

Decay of right handed neutrino

$$N \begin{cases} \nearrow \; l + H \; (\Delta L = +1) \\ \searrow \; \bar{l} + \overline{H} \; (\Delta L = -1) \end{cases}$$



➡ N decay process violates L number.

➡ If the rates of there two processes are different, L asymmetry is produced.

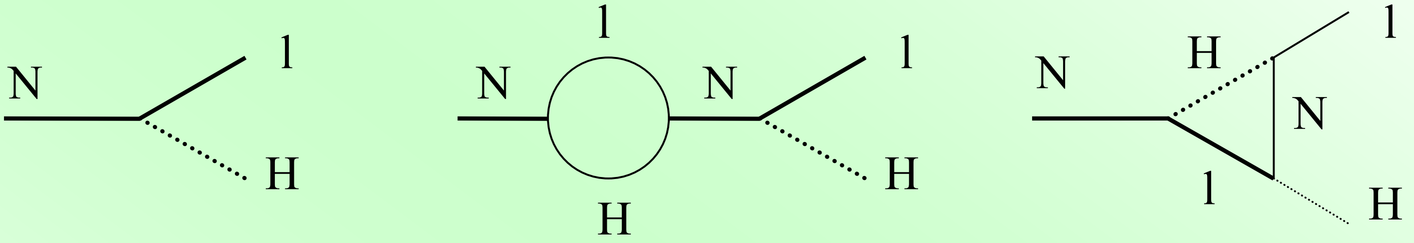
➡ **L asymmetry is converted to B asymmetry through sphaleron effects.**

Fukugita and Yanagida

Decay rates

Covi, Rouchet, and Vissani
Flanz, Paschos, and Sarkar
Buchmuller and Plumacher

Due to CP violation, $\Gamma(N \to l + H) \neq \Gamma(N \to \bar{l} + \overline{H})$



$$\begin{aligned}\epsilon_1 &\equiv \frac{\Gamma(N_1 \to l + H) - \Gamma(N_1 \to \bar{l} + \overline{H})}{\Gamma(N_1 \to l + H) + \Gamma(N_1 \to \bar{l} + \overline{H})} \\ &\simeq \frac{3}{16\pi \left(y^{(\nu)} y^{(\nu)\dagger}\right)_{11}} \left[\mathrm{Im} \left(y^{(\nu)} y^{(\nu)\dagger}\right)^2_{13} \frac{M_1}{M_3} + \mathrm{Im} \left(y^{(\nu)} y^{(\nu)\dagger}\right)^2_{12} \frac{M_1}{M_2} \right] \\ &\simeq \frac{3}{16\pi} \delta_{\mathrm{eff}} |y^{(\nu)}_{33}|^2 \frac{M_1}{M_3} \simeq \frac{3}{16\pi} \delta_{\mathrm{eff}} \frac{m_{\nu 3} M_1}{\langle H \rangle^2} \\ &\simeq 2 \times 10^{-6} \left(\frac{M_1}{10^{10}\mathrm{GeV}}\right) \left(\frac{m_{\nu 3}}{0.05\mathrm{eV}}\right) \delta_{\mathrm{eff}}\end{aligned}$$

$$\left(|\epsilon_1| \lesssim \frac{3 M_1}{8\pi \langle H \rangle^2} (m_{\nu 3} - m_{\nu 1}) \right)$$

Davidson-Ibarra bound

δ_{eff} **: effective CP violating phase,** $y^{(\nu)}_{33} \gg y^{(\nu)}_{22}, y^{(\nu)}_{11}$ and $M_1 \ll M_2, M_3$

Baryogenesis through leptogenesis

① **Right handed neutrinos are produced**

There are some scenarios depending how right handed neutrinos are created.

② **Decay of N generates L asymmetry**

③ **It is converted to B asymmetry through sphaleron effects.** $B_f = \frac{8N_g + 4N_h}{22N_g + 13N_h}(B-L)_i \simeq 0.35(B-L)_i$

$$\frac{n_B}{n_\gamma} = \frac{n_N}{n_\gamma} \times \epsilon_1 \times 0.35$$

① ② ③

Thermal leptogenesis

① For $T_R > M_1$, N is produced thermally.

$$\frac{n_N}{n_\gamma} \simeq 0.01 \, \frac{g_N^{\rm eff}}{g_*} \simeq 1.7 \times 10^{-4}$$

② For $\Gamma_N < H(T < M_1)$, the inverse process is sufficiently suppressed, N can decay non-thermally.

$$\epsilon_1 \simeq 2 \times 10^{-6} \left(\frac{M_1}{10^{10}{\rm GeV}}\right) \left(\frac{m_{\nu 3}}{0.05{\rm eV}}\right) \delta_{\rm eff}$$

$$\frac{n_B}{n_\gamma} \simeq 10^{-10} \left(\frac{M_1}{10^{10}{\rm GeV}}\right) \left(\frac{m_{\nu 3}}{0.05{\rm eV}}\right) \delta_{\rm eff}$$

$$T_R > (10^9 - 10^{10}){\rm GeV}$$

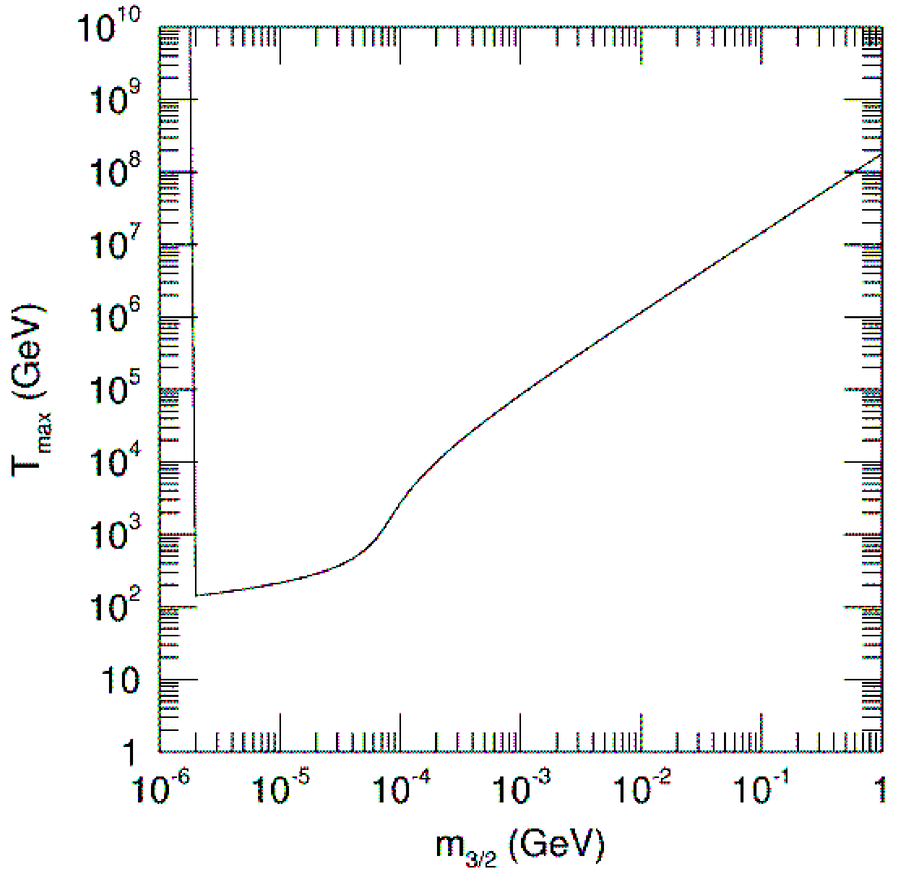
Gravitino problem ?

($\epsilon_1 \gtrsim 10^{-6}$ & Davidson-Ibarra bound)

Reheating temperature and gravitino

Stable gravitino

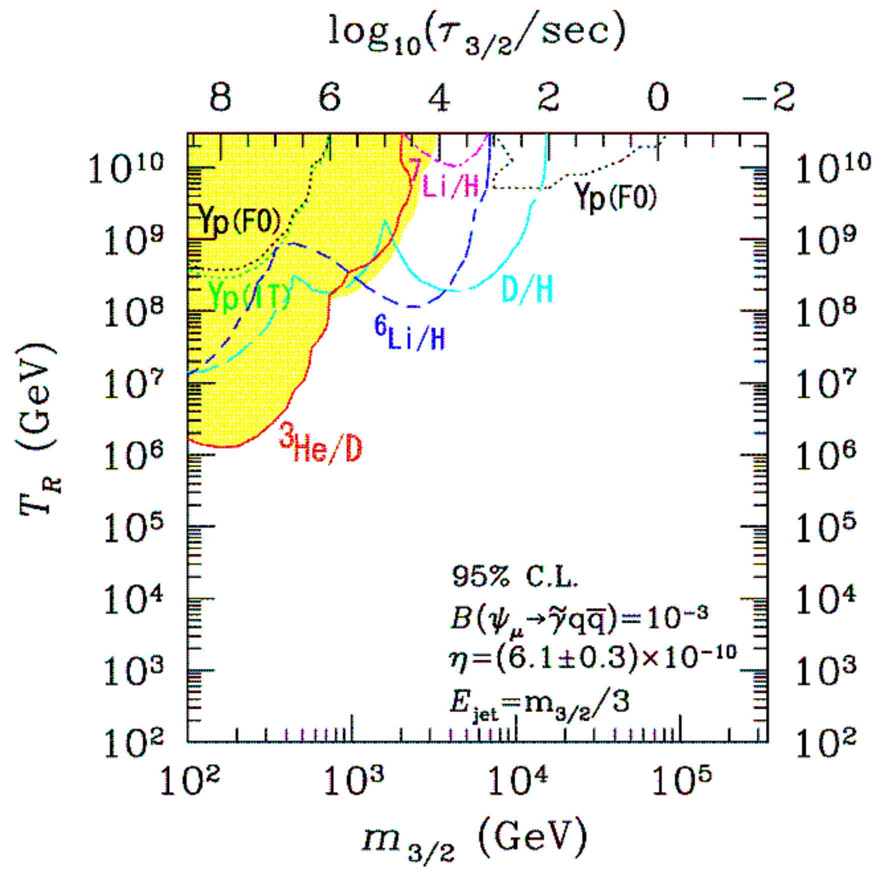
(Gauge mediated SUSY breaking)



Moroi et al.

Unstable gravitino

(Gravity or Anomaly mediated)



Kawasaki et al.

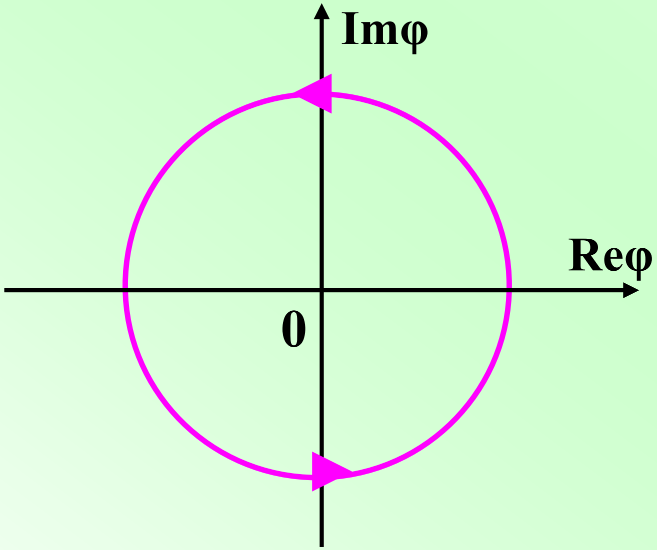
Affleck-Dine baryogenesis

Scalar field condensation

Affleck-Dine field φ:

A complex scalar field with baryon or lepton number q

$$\Rightarrow \quad \begin{aligned} n_B &= iq\left(\dot{\phi}^*\phi - \phi^*\dot{\phi}\right) \\ &= 2q\,\omega\phi_0^2 \quad \text{when} \quad \phi = \phi_0 e^{i\omega t} \end{aligned}$$



Affleck-Dine field gets angular momentum ⟷ **B or L number is generated.**

Candidate of AD field

Supersymmetry (SUSY)

Symmetry between fermions and bosons:

Standard particles and their partner particles have same masses and same coupling constants.

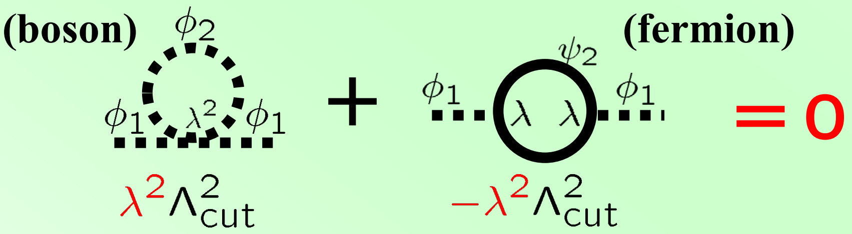
Quark ←−−→ Squark
(scalar field with baryon number)
Lepton ←−−→ Slepton
(scalar field with lepton number)
Gaugino ←−−→ Gauge boson
Higgsino ←−−→ Higgs boson
Gravitino ←−−→ Graviton

Why supersymmetry (supergravity) ?

Boson ⟷ Fermion

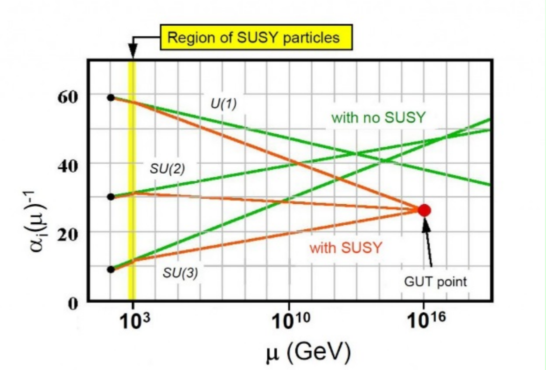
- **Protects the electroweak scale mass of the Higgs boson and an inflaton mass against quantum corrections.**

➡ **Stabilization of Higgs (inflaton) mass**



- **Unification of the gauge coupling constants**

➡ **Suggestion of GUT**



http://sites.uci.edu/energyobserver/2012/12/02/update-on-some-higgs-blog-entries/

LHC has not yet discovered SUSY.
But I expect that SUSY exists as fundamental symmetry
because it is still useful for controlling quantum corrections and
constructing string theory, and would be important in inflationary energy scale.

Flat directions

(Gherghetta et al. 96)

In SUSY, there are scalar fields with baryon or lepton numbers.
Some of them consist of flat directions,
along which the potential is (almost) flat.

$$V = V_F + V_D$$

From e.g. the Yukawa interactions (to V_F)　　**From the gauge interactions** (to V_D)

Example: $Q_1 = \frac{1}{\sqrt{3}}\begin{pmatrix}\phi \\ 0\end{pmatrix}, \quad L_1 = \frac{1}{\sqrt{3}}\begin{pmatrix}0 \\ \phi\end{pmatrix}, \quad \bar{d}_2 = \frac{1}{\sqrt{3}}\phi$

$$V_D \overset{U(1)_Y}{\supset} \frac{1}{6}\left(-\frac{1}{6}|\phi|^2 + \frac{1}{2}|\phi|^2 - \frac{1}{3}|\phi|^2\right)^2 = 0$$

We often parameterize this direction in a gauge invariant way as

$$X = Q_1 L_1 \bar{d}_2 \qquad \textbf{(B - L = -1)}$$

Flat directions in a SUSY standard model

Some combinations of squark and/or slepton fields :

- have no classical potential in the SUSY exact limit (called flat directions).
- often have baryon and/or lepton charge
- are lifted by SUSY breaking effects and the non-renormalizable terms
- can acquire a large amount of VEV during inflation

$$V(\phi) = m_\phi^2|\phi|^2 + \frac{|\phi|^{2n-2}}{M^{2n-6}} + \frac{m_{3/2}}{nM^{n-3}}\left(a_m\phi^n + a_m^*\phi^{*n}\right) \qquad (n > 3)$$

soft mass **non-renormalizable terms** **A-term**

B or L is conserved **violate**

⇨ **B or L is generated dynamically thanks to A-term when a flat direction has baryon and/or lepton charge.**

During inflation

Inflation is caused by positive potential energy.

$V \neq 0$ → **SUSY breaking**

(SUSY exact → $V = 0$, $m_S = m_F$)

↑

(boson & fermion contributions cancel)

(mediated by gravity)

soft breaking masses : $|\Delta m^2| \sim G_N V \sim H^2$

(In the current universe, Δm2 ≳ $(1\ \mathrm{TeV})^2$ to explain the naturalness.)

→ **If a flat direction receives $\Delta m^2 \sim - H^2$ during inflation, it rolls down and gets a large expectation value.**

Flat directions during inflation

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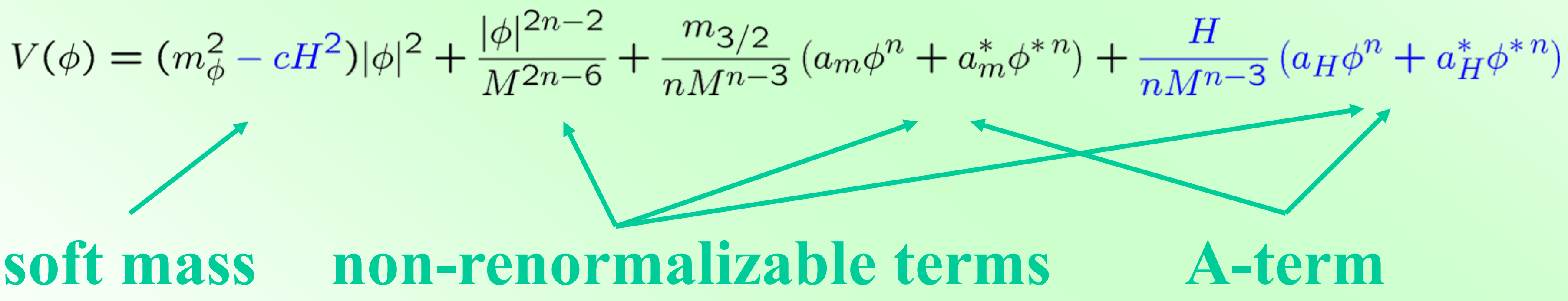
- **have no classical potential in the SUSY exact limit (called flat directions).**
- **often have baryon and/or lepton charge**
- **are lifted by SUSY breaking effects and the non-renormalizable terms**
- **can acquire a large amount of VEV during inflation**



$$V(\phi) = (m_\phi^2 - cH^2)|\phi|^2 + \frac{|\phi|^{2n-2}}{M^{2n-6}} + \frac{m_{3/2}}{nM^{n-3}}(a_m\phi^n + a_m^*\phi^{*\,n}) + \frac{H}{nM^{n-3}}(a_H\phi^n + a_H^*\phi^{*\,n})$$

B or L is conserved

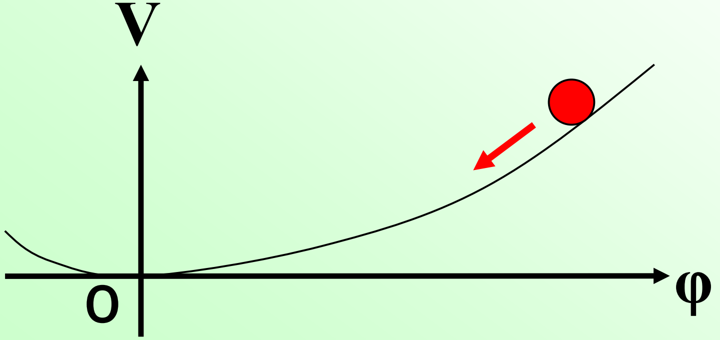
violate

➡ **B or L is generated dynamically thanks to A-term when a flat direction has baryon and/or lepton charge.**

Scenario

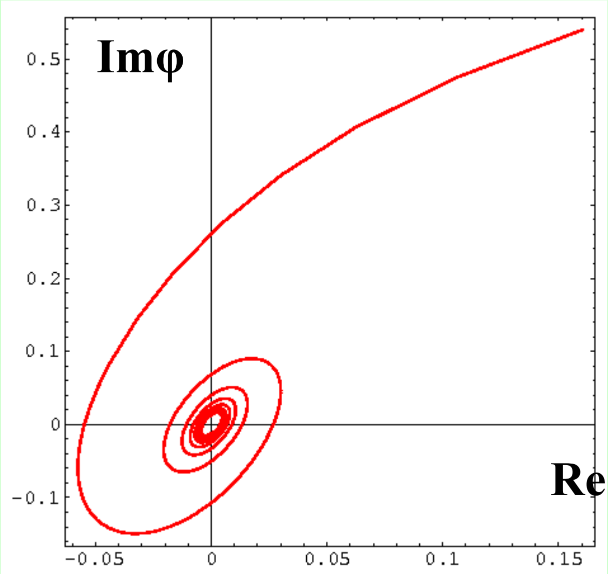
Dine, Randall, and Thomas

φ acquires a large VEV during inflation thanks to large negative mass squared $(- c H^2 |\varphi|^2)$.



After inflation, around $H \lesssim m_\phi$ it starts oscillation around the origin.

At the same time, it starts rotation due to A-term and B and/or L number is produced.



Fujii

φ decays into quarks and/or leptons, the stored B or L number is transferred to them.

Revisit scenario

Dine, Randall, and Thomas

φ acquires a large VEV during inflation thanks to large negative mass squared $(- c H^2 |\varphi|^2)$.

After inflation, around $H \lesssim m_\phi$ it starts oscillation around the origin.

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How does this process happen ??

φ decays into quarks and/or leptons, the stored B or L number is transferred to them.

In fact, non-topological solitons called Q-balls are formed.

Q-balls

Coleman

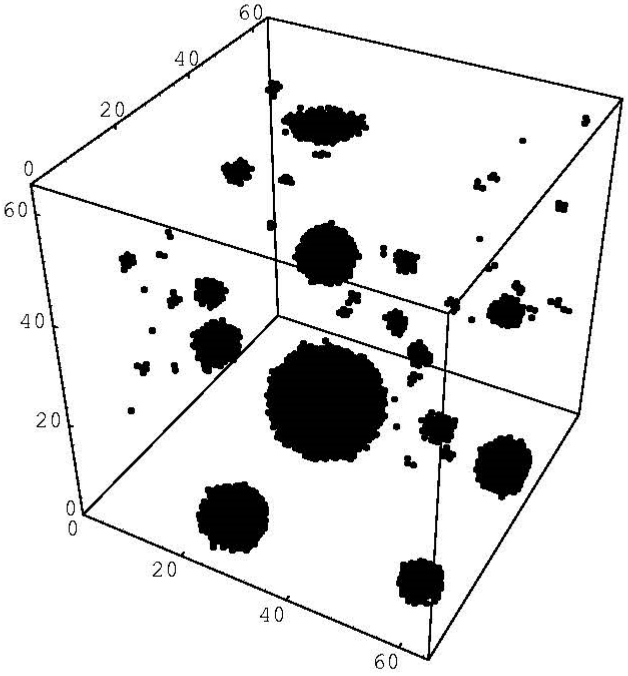

FIG. 1. Configuration of Q balls on three dimensional lattice. More than 30 Q balls are formed, and the largest one has the charge with $Q \simeq 1.96 \times 10^{16}$.

Figure taken from Kasuya & Kawasaki 2000

Q-balls are formed through the Affleck-Dine mechanism.

Summary

- BBN and CMB observations like PLANCK determine the amount of baryon asymmetry more precisely.
- A lot of baryogenesis scenarios have been proposed so far, none of them has yet been convinced though some of them have strong motivations.
- We expect that future experiments will give stringent constraints on (or rule out) some models and eventually would ping down the baryogenesis mechanism.
- In the Affleck-Dine scenario, non-topological solitons called Q-balls are formed in some cases.

⇨ Shall we discuss more detailed properties of Q-balls through whiteboard.