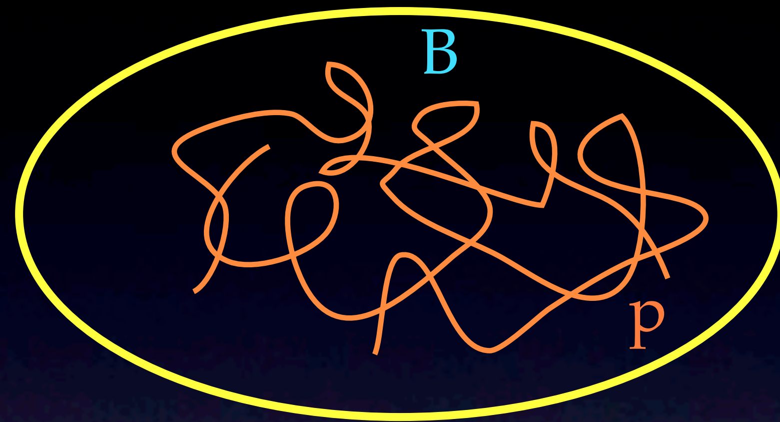
Baryogenesis

Matter vs Anti-matter

- Earth, Solar system

  made of baryons



galaxy

- Our Galaxy

  Anti-matter in cosmic rays

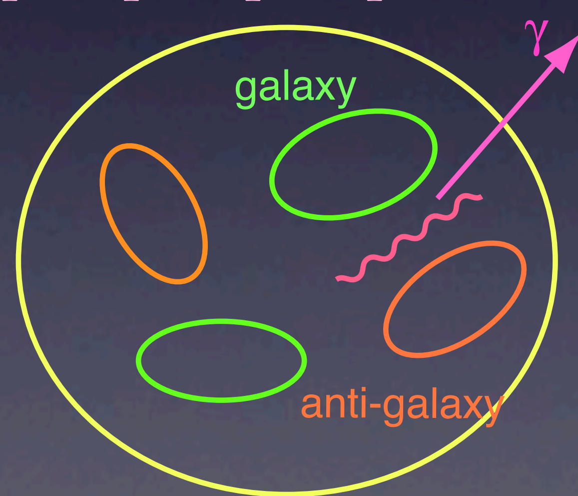
  $\bar{p}/p \sim O(10^{-4})$ secondary

$$p + p \to p + p + p + \bar{p}$$

➡ Our Galaxy is made of baryons

- Cluster of Galaxies

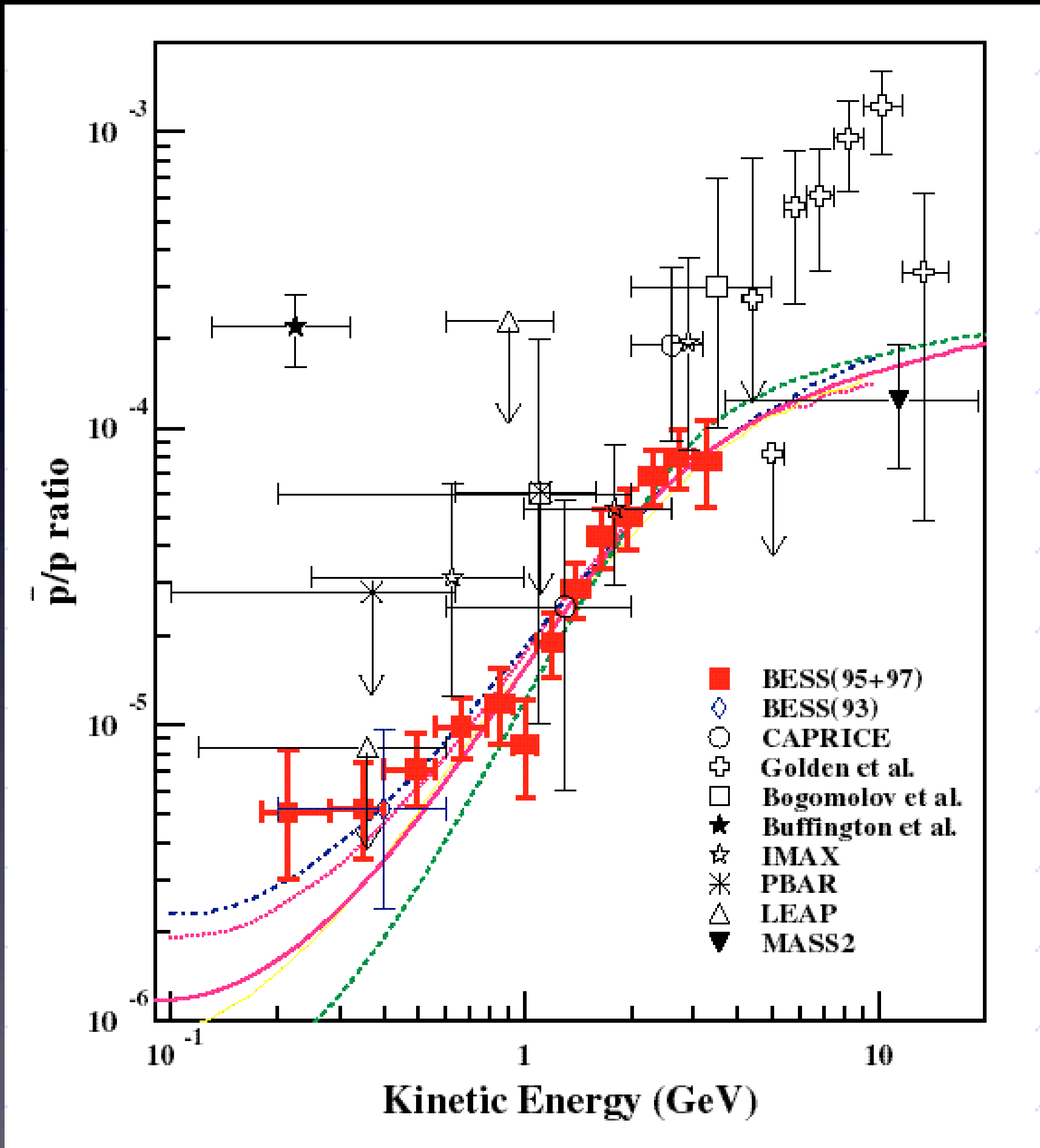
  No strong γ rays are observed



➡ Near clusters are made of baryons

BESS experiment

BESS97



Asymmetry between matter and anti-matter

How Large Asymmetry?

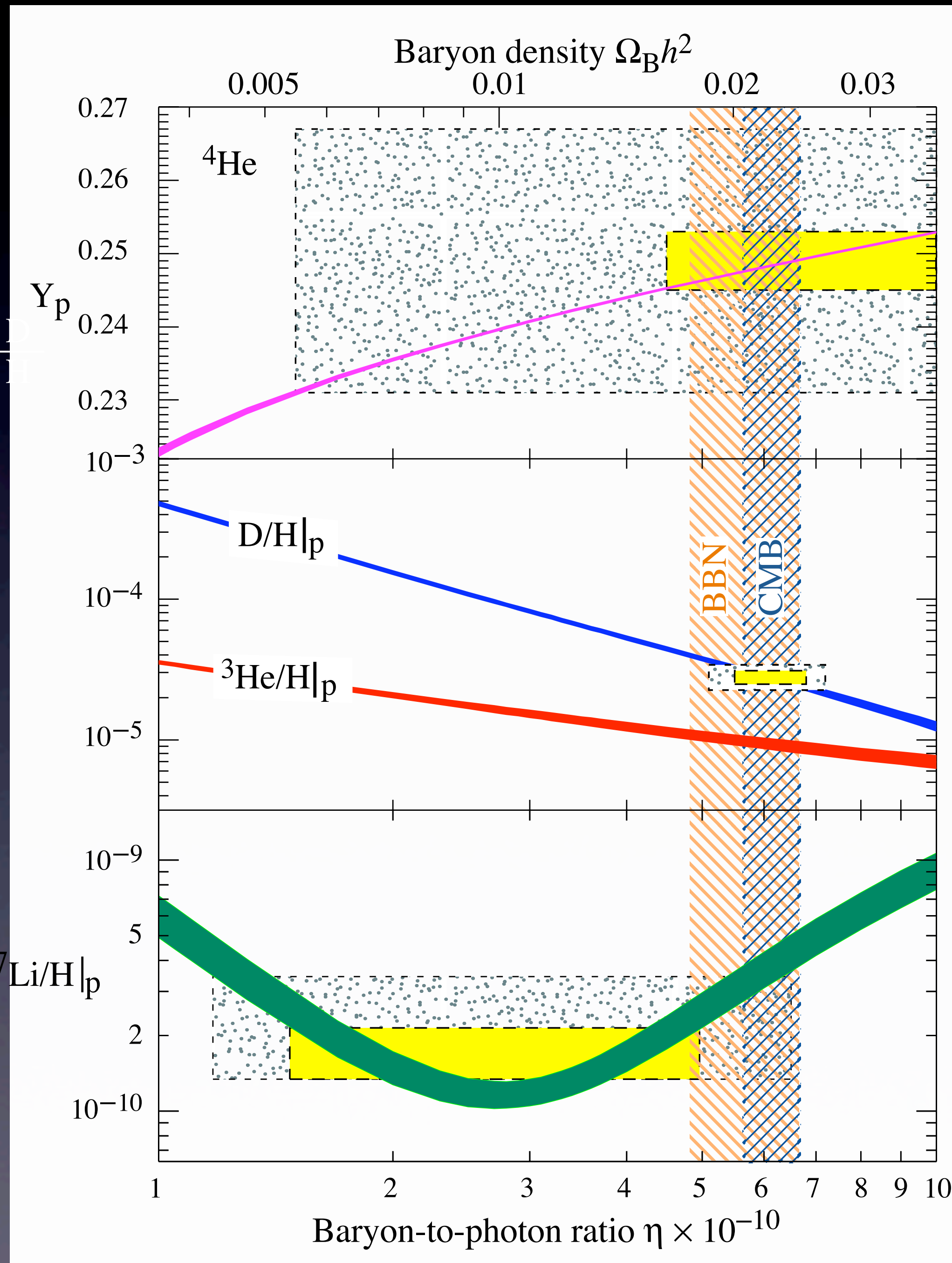
Big Bang Nucleosynthesis

$$\boxed{\frac{n_B}{s} = (6-8)\times 10^{-11}}$$

s: entropy density

Baryogenesis

before BBN after inflation



Baryogenesis

Sakharov's Condition

(1) B Violation

(2) C, CP Violation

(3)Out of Equilibrium

1. Necessary Obviously

2. e.g. $A + B \rightarrow C + D \Rightarrow A^c + B^c \rightarrow C^c + D^c$

C trans.

If C inv. $\Gamma(A^c + B^c \rightarrow C^c + D^c) = \Gamma(A + B \rightarrow C + D)$

$\Rightarrow$ B = 0

3. Thermal Equilibrium $\Rightarrow$ T invariance

+ CPT invariance $\Rightarrow$ CP invariance

$\Rightarrow$ B = 0

$$
\begin{aligned}
\langle B \rangle &= Tr(e^{-H/T}B) = Tr((CPT)(CPT)^{-1}e^{-H/T}B) \\
&= Tr((CPT)^{-1}e^{-H/T}B(CPT)) \\
&= -Tr(e^{-H/T}B) = 0
\end{aligned}
$$

Baryogenesis Mechanism

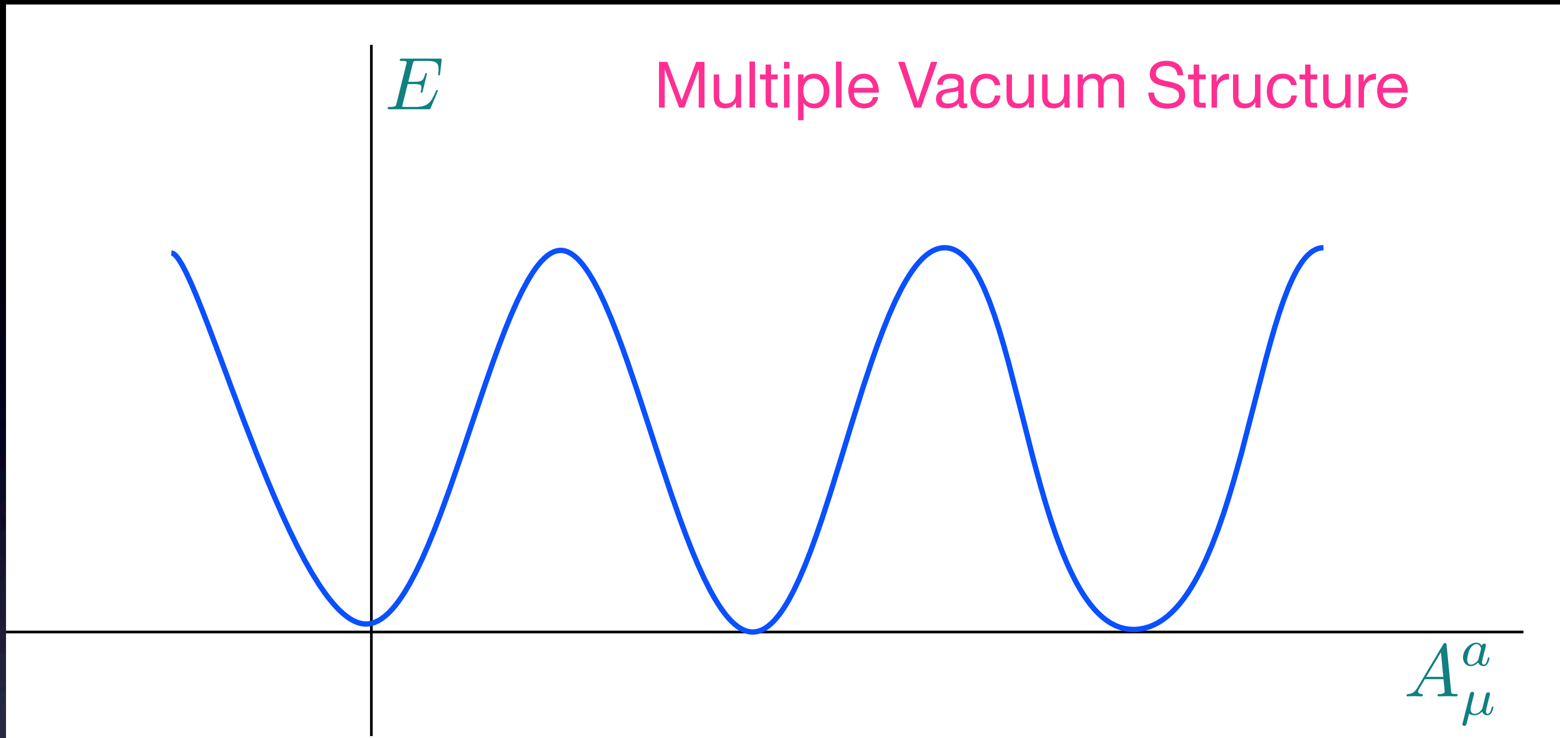
- Electroweak Baryogenesis
- Leptogenesis via Heavy Majorana Neutrino
- Affleck-Dine Mechanism
- ……

Electroweak Baryogenesis

- B violation ← Sphaleron Process
- C, CP violation ← Kobayashi-Maskawa
- Out of Equilibrium ← 1st order EW phase transition

→ Electroweak Baryogenesis

Vacuum Structure of SU(2) gauge Field



Chern-Simons Number

$$N_{CS} = \frac{g^2}{32\pi^2}\int d^3x \epsilon^{ijk} Tr\left[A_j \partial_j A_k - \frac{ig}{3} A_i A_j A_k\right]$$

$A_0 = 0$ gauge

Baryon Number Current

$$j_B^\mu \sim \bar{Q}\gamma^\mu Q = \frac{1}{2}[\bar{Q}\gamma^\mu(1-\gamma_5)Q + \bar{Q}\gamma^\mu(1+\gamma_5)Q]$$

EW ➡ Fermions couple chirally to W, B

Anomaly

n_f : number of generation

$$\tilde{W}_{a\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}W_{\alpha\beta}$$

$$\boxed{\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = n_f\left(\frac{g^2}{32\pi^2}W^a_{\mu\nu}\tilde{W}_{a\mu\nu} - \frac{g'^2}{32\pi^2}F_{\mu\nu}\tilde{F}_{\mu\nu}\right)}$$

$$\boxed{\partial_\mu j^\mu_B = \partial_\mu j^\mu_L = n_f \left(\frac{g^2}{32\pi^2}\partial_\mu K^\mu - \frac{g'^2}{32\pi^2}\partial_\mu k^\mu \right)}$$

$$K^\mu = \epsilon^{\mu\nu\alpha\beta}\left(W^a_{\nu\alpha}A^a_\beta - \frac{g}{3}\epsilon_{abc}A^a_\nu A^b_\alpha A^c_\beta \right)$$

$$k^\mu = \epsilon^{\mu\nu\alpha\beta}F_{\nu\alpha}B_\beta$$

$$\int d^4x\partial_\mu j_B = \int_{t=t_f} d^3x j^0_B - \int_{t=0} d^3x j^0_B = \Delta B$$

$$= \frac{n_f g^2}{32\pi^2}\left(\int_{t=t_f} d^3x K^0 - \int_{t=0} d^3x K^0 \right)$$

$$K^0 = \epsilon^{ijk}\left(W^a_{ij}A^a_k - \tfrac{g}{3}\epsilon_{abc}A^a_i A^b_j A^c_k \right)$$

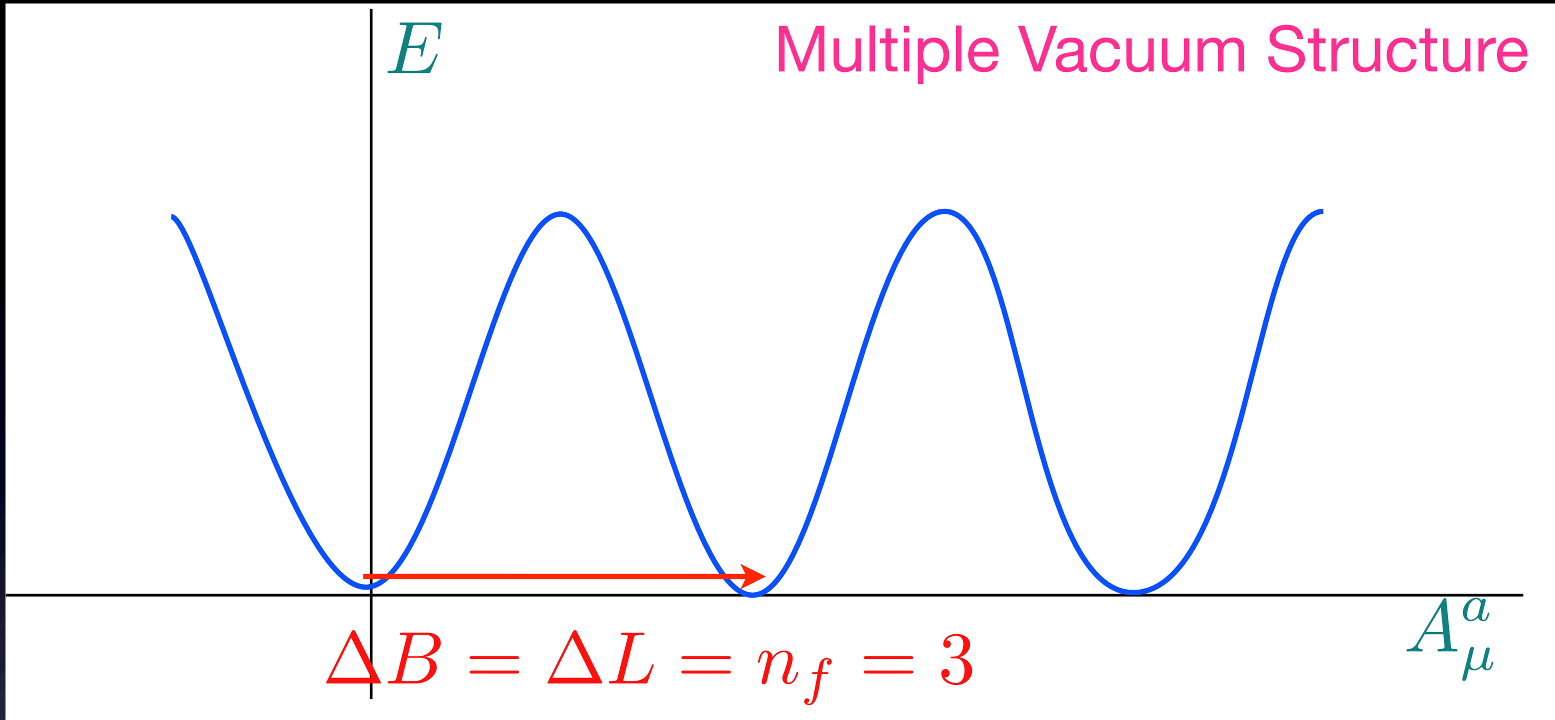
$$= \epsilon^{ijk}\left((\partial_i A^a_j - \partial_j A^a_i + g\epsilon_{abc}A^b_i A^c_j)A^a_k - \tfrac{g}{3}\epsilon_{abc}A^a_i A^b_j A^c_k \right)$$

$$= \epsilon^{ijk}\left(2\partial_i A^a_j A^a_k + \tfrac{2g}{3}\epsilon_{abc}A^1_i A^b_j A^c_k \right)$$

$$= \epsilon^{ijk} Tr\left(A_i\partial_j A_k - \tfrac{ig}{3}A_i A_j A_k \right)$$

$$\boxed{\Delta B = \int d^4x\partial_\mu j^\mu_B = \int_{t=t_f} d^3x j^0_B - \int_{t=0} d^3x j^0_B = n_f[N_{CS}(t_f) - N_{CS}(0)]}$$

Sphaleron



Tunneling by instanton

$$\int dx^4 (W^a_{\mu\nu} - \tilde{W}^a_{\mu\nu})^2 \geq 0$$

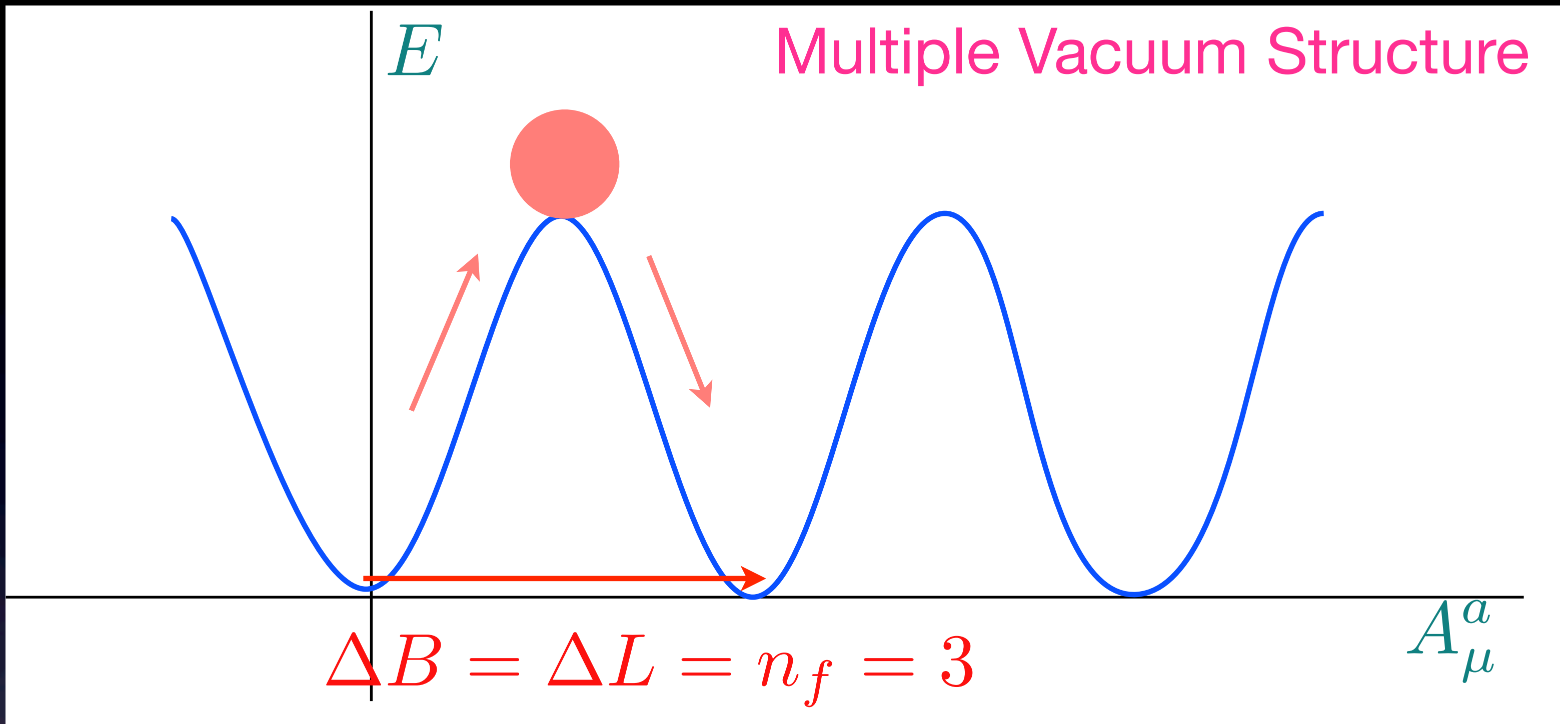
$$\Rightarrow \int dx^4 \left[\mathrm{Tr}(W_{\mu\nu} W^{\mu\nu}) + \mathrm{Tr}(\tilde{W}_{\mu\nu} \tilde{W}^{\mu\nu}) - 2\mathrm{Tr}(W_{\mu\nu} \tilde{W}^{\mu\nu}) \right] \geq 0$$

$$4S_E - 2\left(\frac{16\pi^2}{g^2}\right) N_{CS} \geq 0 \;\Rightarrow\; S_E \geq \frac{8\pi^2}{g^2} N_{CS}$$

$$\Gamma \sim \exp\left(-\frac{4\pi}{\alpha_W}\right) \sim 10^{-170}$$

too small !

Sphaleron



Tunneling by instanton

$$\Gamma \sim \exp\left(-\frac{4\pi}{\alpha_W}\right) \sim 10^{-170}$$

too small !

Finite Temperature

Sphaleron

$$\Gamma \sim \begin{cases} M_W^4 \exp\left(-\frac{2M_W}{\alpha_W T}\right) & T \lesssim M_W \\ (\alpha_W T)^4 & T \gg M_W \end{cases}$$

Sphaleron

Saddle-point solution in Weinberg-Salam theory

$A^0 = 0$ gauge, static configuration

$$E = \int d^3x \left[\frac{1}{4} W^a_{ij} W^a_{ij} + \frac{1}{4} F_{ij} F_{ij} + (D_i \phi)^\dagger (D_i \phi) + V(\phi) \right]$$

$F_{ij} = 0$

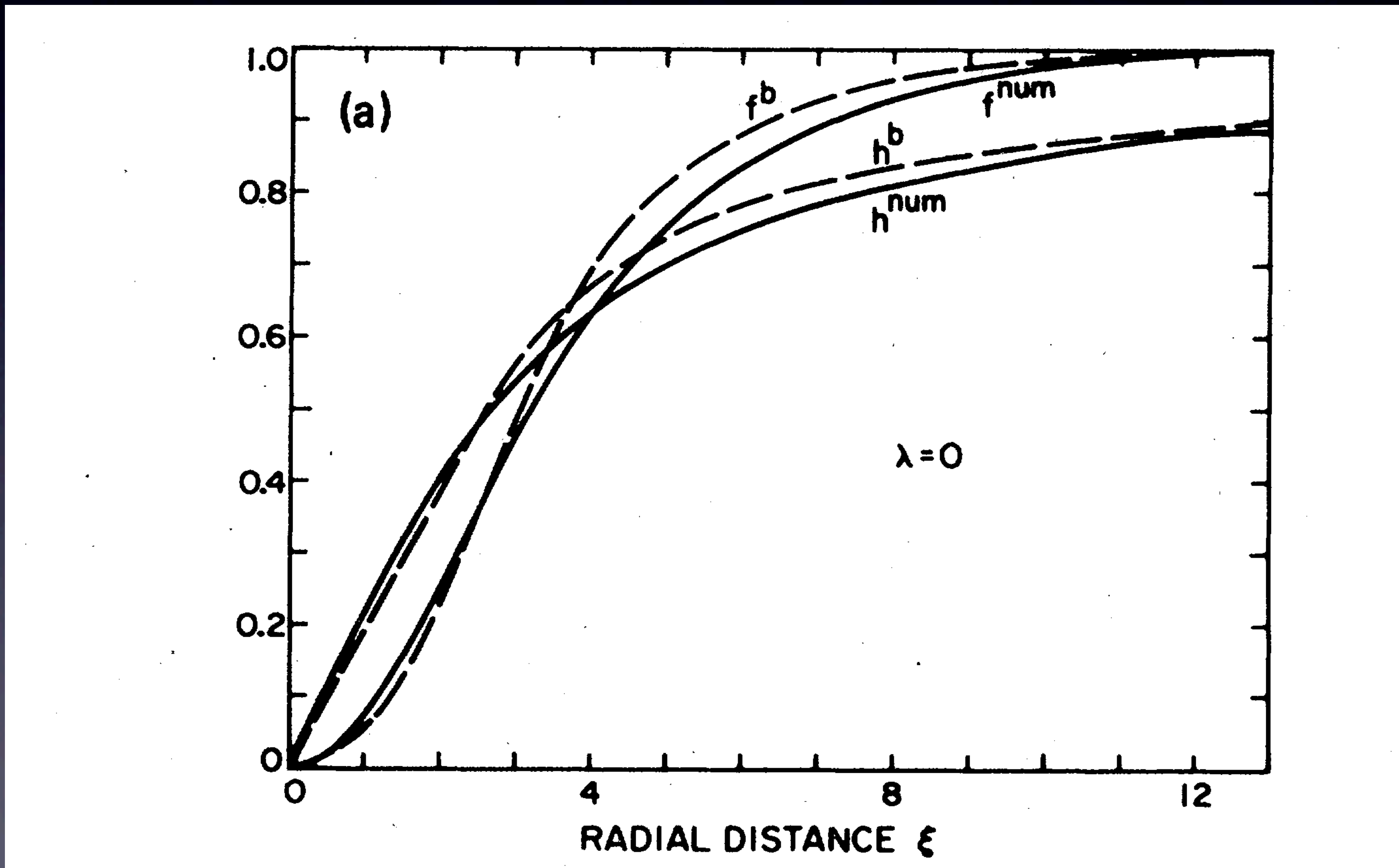
Ansatz $A^a_i = \frac{2}{g} \frac{\epsilon_{ija} x_j}{r^2} f(\xi) \qquad \phi = i \frac{v}{\sqrt{2}} \frac{\vec{\tau} \cdot \vec{x}}{r} h(\xi) \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

$\xi = rgv$

$f(0) = h(0) = 0 \qquad f(\infty) = h(\infty) = 1$

$$E = \frac{4\pi v}{g} \int_0^\infty d\xi \left[4 \left(\frac{df}{d\xi} \right)^2 \frac{8}{\xi^2} (f(1-f))^2 \right.$$
$$\left. + \frac{1}{2} \xi^2 \left(\frac{dh}{d\xi} \right)^2 + (h(1-f))^2 + \frac{1}{4} \left(\frac{\lambda}{g^2} \right) \xi^2 (h^2 - 1)^2 \right]$$

$$E = \frac{4\pi v}{g}\int_0^\infty d\xi \left[4\left(\frac{df}{d\xi}\right)^2 \frac{8}{\xi^2}(f(1-f))^2 + \frac{1}{2}\xi^2\left(\frac{dh}{d\xi}\right)^2 + (h(1-f))^2 + \frac{1}{4}\left(\frac{\lambda}{g^2}\right)\xi^2(h^2-1)^2\right]$$



$$E = \frac{4\pi v}{g} \int_0^\infty d\xi [\cdots] = 2\frac{4\pi}{g^2}\frac{1}{2} g v \int_0^\infty d\xi [\cdots]$$
$$= \frac{2M_W}{\alpha_W} \int_0^\infty d\xi [\cdots]$$

Sphaleron rate

$$\Gamma(T) \sim M_W^4 \exp\left(-\frac{E_{\mathrm{sph}}(T)}{T}\right)$$

$$E_{\mathrm{sph}}(T) \equiv \frac{M_W(T)}{\alpha_W}\varepsilon \qquad (3.2 < \varepsilon < 5.4)$$

High temperature

no Boltzmann suppression

magnetic screening length $= (\alpha_W T)^{-1}$

$$\Gamma(T) = \kappa(\alpha_W T)^4$$

CP Violation in Standard Model

Quark $\psi_{jL} = \begin{pmatrix} U_j \\ D_j \end{pmatrix}_L \quad U_{jR} \quad D_{jR} \quad (j = 1, \cdots, n_f)$

Mass Term

$$-M^D_{jk}\bar{D}_{jR}D_{kL} - M^U_{jk}\bar{U}_{jR}U_{kL}$$

Redefine $U_R, \ \psi_L$

$$\rightarrow \boxed{-\tilde{M}^U_{jk}\bar{U}_{jR}U_{kL}} \qquad \tilde{M}^U = diag(m_u, m_c, m_t)$$

Redefine D_R

$$\rightarrow \boxed{-\tilde{M}^D_{j\ell}U^\dagger_{\ell k}\bar{D}_{jR}D_{kL}} \qquad \tilde{M}^D = diag(m_d, m_s, m_b)$$

$U^\dagger$ unitary matrix = CKM matrix

$$\begin{bmatrix} d \\ s \\ b \end{bmatrix}_L = U^\dagger D_L \Longleftrightarrow D_L = U \begin{bmatrix} d \\ s \\ b \end{bmatrix}_L$$

mass eigenstate

still can define phase of mass eigenstate

$$U \;\Rightarrow\; V_1 U V_2 \qquad V_1, V_2 \;:\; \text{diagonal unitary}$$

$$2n_f - 1 \text{ relevant phase}$$

number of independent phases

$$n_f^2 - (2n_f - 1) - \frac{1}{2} n_f (n_f - 1) = \frac{1}{2}(n_f - 1)(n_f - 2)$$

unitary matrix

orthogonal matrix

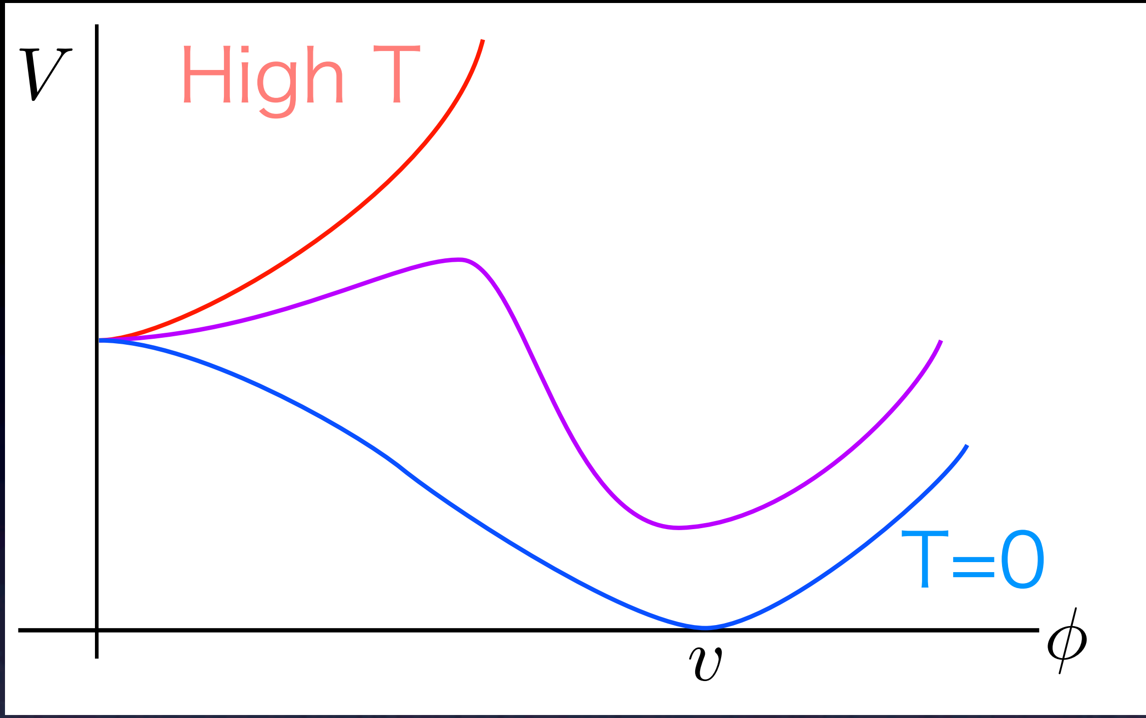
$n_f = 3$ ➡ only one phase δ_{CP}

$$\boxed{\delta_{CP} \neq 0 \;\Rightarrow\; \text{CP violation}}$$

EW Phase Transition

Higgs potential

$$\boxed{V(\phi, T=0) = \lambda(|\phi|^2 - v^2)}$$



- V takes min. at Φ = 0

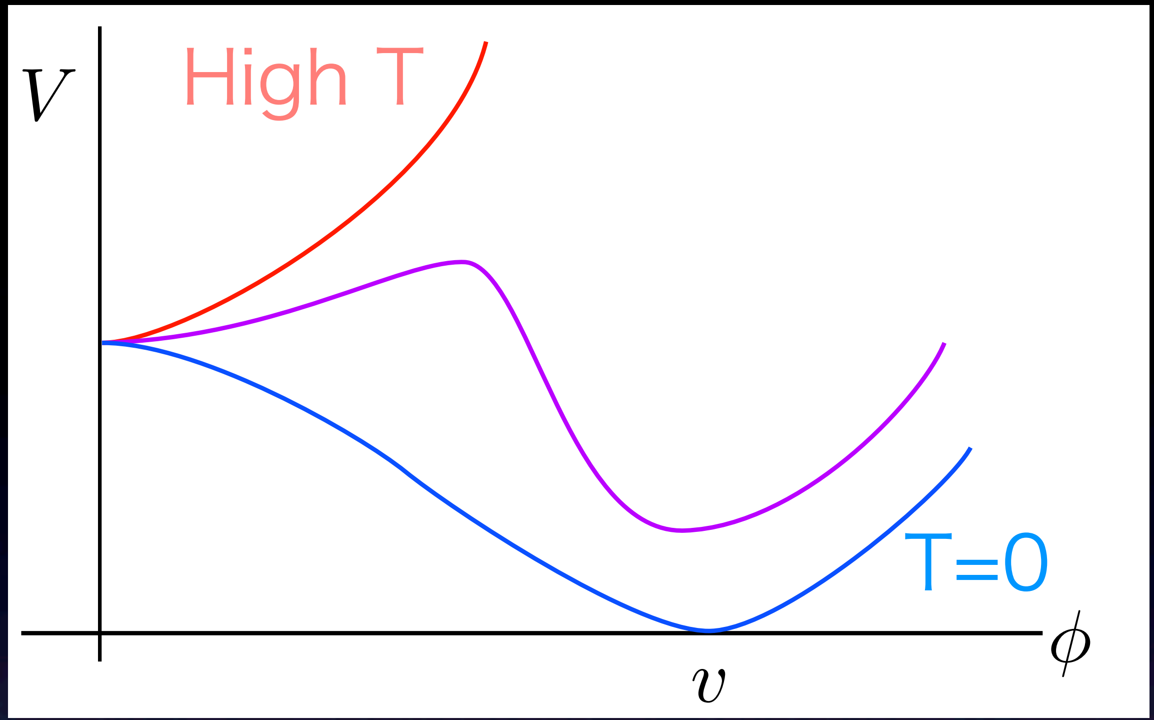
  W in thermal eq. $\Leftarrow \; M_W \sim 0$

$$g^2|W|^2|\phi|^2 \in V \;\rightarrow\; g^2\frac{T^2}{2}|\phi|^2$$

$$V_{\rm eff} \simeq \frac{g^2}{2}T^2|\phi|^2 - 2\lambda v^2|\phi|^2 \qquad \Rightarrow \boxed{T \gtrsim \frac{2\sqrt{\lambda}}{g}v}$$

- V takes min. at Φ = v

W not in thermal eq.



$$M_W \sim g\phi \gtrsim 3T$$

$$\Rightarrow \; V(\phi, T) = V(\phi, T=0) \quad \text{for} \quad \phi \gtrsim 3T/g$$

$$\rightarrow \; \boxed{v \gtrsim \frac{3T}{g}}$$

$$2\frac{\sqrt{\lambda}}{g}v \lesssim T \lesssim \frac{g}{3}v \quad \rightarrow \quad \sqrt{\lambda} \lesssim \frac{g^2}{6} \simeq \frac{2\pi\alpha_W}{3}$$

Higgs mass $m_H \sim 2\sqrt{\lambda}v \lesssim 40\text{GeV}$

small Higgs mass

However,

- Small CP Violation

$$\delta_{\mathrm{CP}} \simeq \frac{1}{T^{12}}(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2) \simeq 10^{-20}$$

- EW Phase Transition is 2nd Order

1st Order ➡ Higgs mass $m_H \leq 80\mathrm{GeV}$

experiment $m_H \geq 114\mathrm{GeV}$

➡ EW Baryogenesis may not work

Baryogenesis Mechanism

- Electroweak Baryogenesis
- Leptogenesis via Heavy Majorana Neutrino
- Affleck-Dine Mechanism
- ……

Leptogenesis

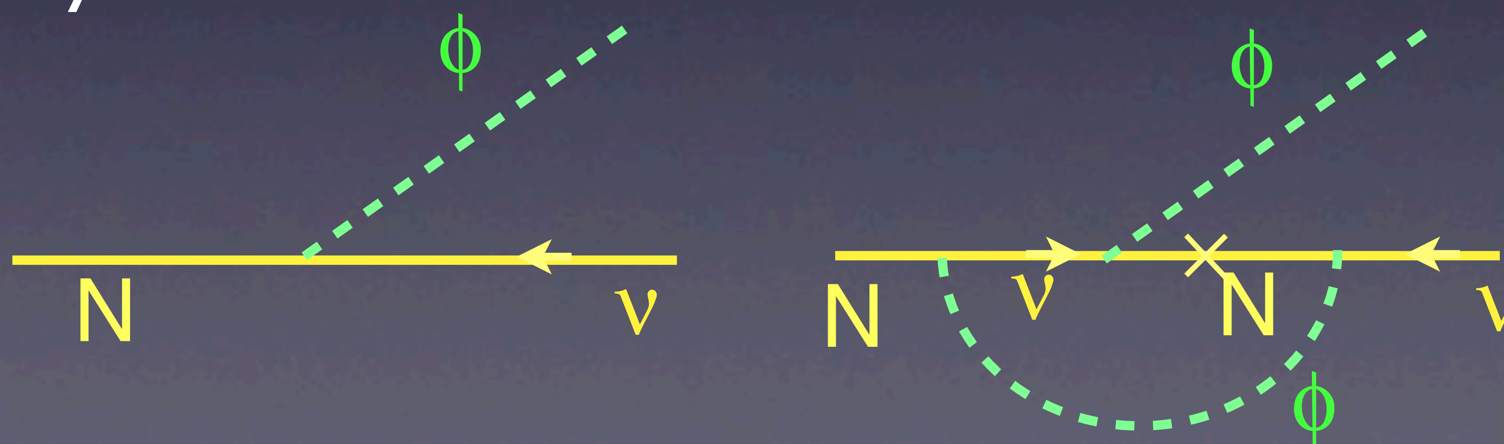
Heavy Majorana Neutrino

← small neutrino mass by see-saw mechanism

← Super-K discovery

$$N \to \begin{cases} \nu + \phi & (\Delta L = +1) \\ \bar{\nu} + \phi & (\Delta L = -1) \end{cases} \qquad \nu \text{ neutrino}, \quad \phi \text{ Higgs}$$

Deacy Process



- CP Violation
  CP phase in mass matrix of N

$$\Rightarrow \quad \Gamma(N \to \nu + \phi) \neq \Gamma(N \to \bar{\nu} + \phi)$$

- Out of Equilibrium Condition

- Sphalelon Process

$$\Rightarrow \quad (L + B) = 0$$

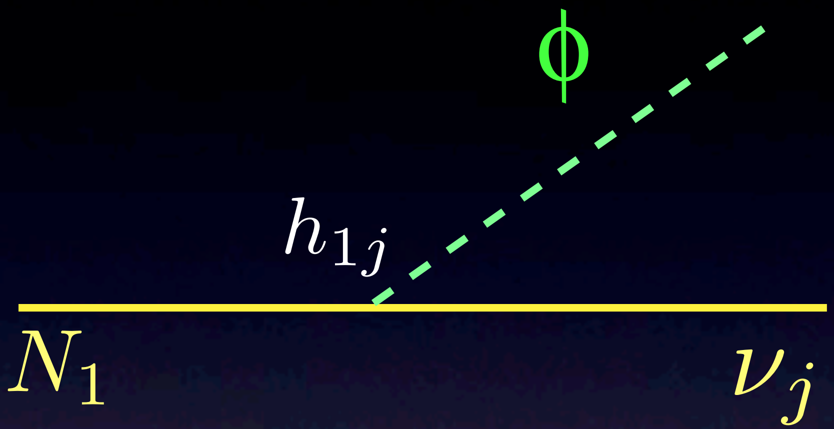
$$(L - B) \neq 0 \Rightarrow B \neq 0$$

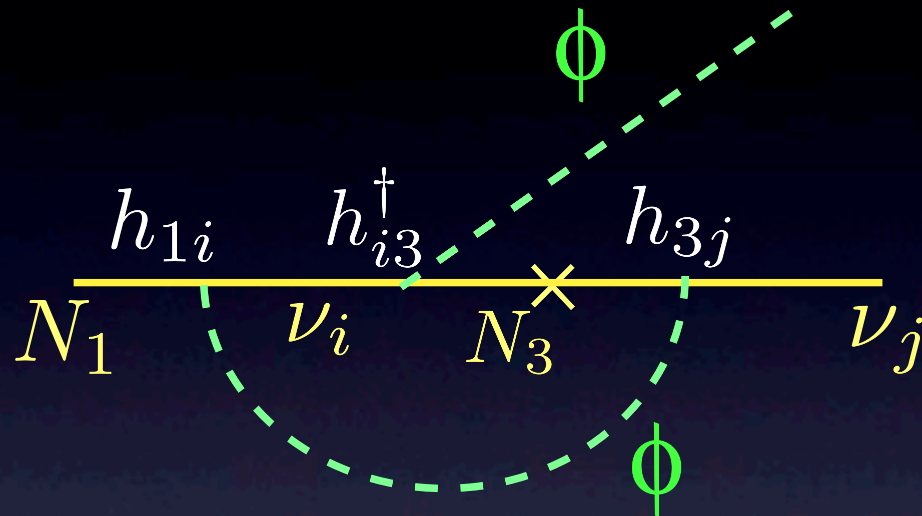
$$\boxed{B = \frac{8N_g + 4N_H}{22N_g + 13N_H}(B - L) \simeq 0.3(B - L)}$$

N_g : # of generations , N_H : # of Higgs doublets

⇒ Successful Baryogenesis [Fukugita-Yanagida (1986)]

Deacy Process





Interference term

$$\Gamma(N \to \ell + \phi) \neq \Gamma(N \to \bar{\ell} + \bar{\phi})$$

$$\epsilon_1 = \frac{\Gamma(N \to \ell + \phi) - \Gamma(N \to \bar{\ell} + \bar{\phi})}{\Gamma(N \to \ell + \phi) + \Gamma(N \to \bar{\ell} + \bar{\phi})}$$

$$|h_{i3}| > |h_{i2}| \gg |h_{i1}| \quad (i = 1, 3)$$

$$= \frac{3}{16\pi} \frac{1}{(hh^\dagger)_{11}} \left[\mathrm{Im}(hh^\dagger)^2_{13} \frac{M_1}{M_3} + \mathrm{Im}(hh^\dagger)^2_{12} \frac{M_1}{M_2} \right]$$

$$\simeq \frac{3}{16\pi} \delta_{\mathrm{eff}} \frac{|h_{33}|^2 M_1}{M_3}$$

$$M_1 \ll M_2, M_3$$

$$(hh^\dagger)^2_{13} = [(hh^\dagger)_{13}]^2$$

h_{33} Largest

$$\boxed{\epsilon_1 \simeq \frac{3}{16\pi} \delta_{\mathrm{eff}} \frac{m_{\nu 3} M_1}{\langle \phi \rangle^2}}$$

Decay Rate

$$\Gamma_{N_i} = \Gamma(N_i \to \ell + \phi) + \Gamma(N_i \to \bar{\ell} + \bar{\phi})$$

$$= \frac{1}{8\pi}(hh^\dagger)_{ii} M_i$$

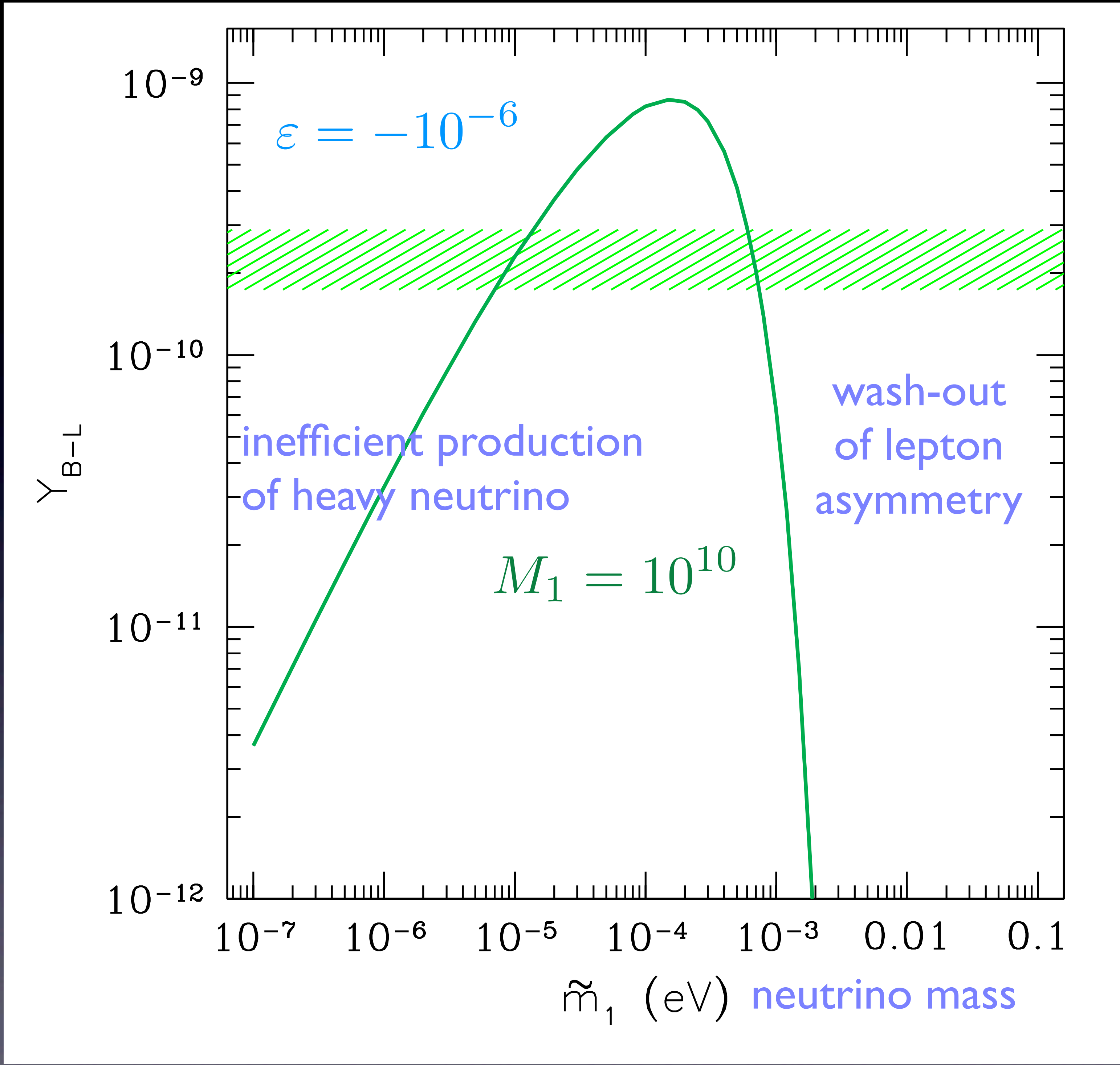
Out of EQ Decay

$$\Gamma_{N_i} < H(T = M_i) \simeq \frac{g^{1/2} M_i^2}{3 M_G}$$

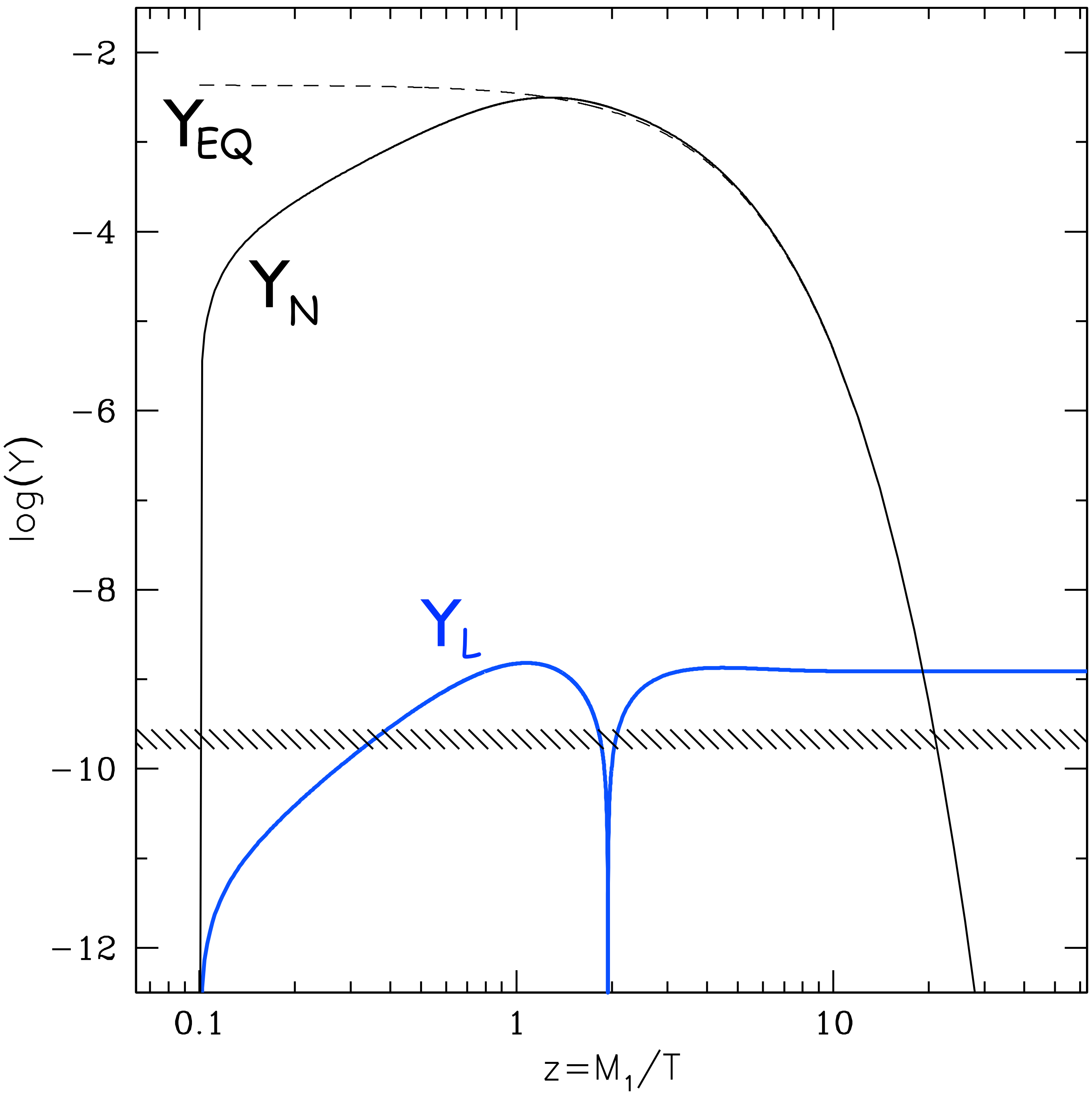
$$\boxed{m_{\nu_1} = (hh^\dagger)_{11} \frac{\langle\phi\rangle^2}{M_1} \simeq 4 g_*^{1/2} \frac{\langle\phi\rangle^2}{M_G} \left(\frac{\Gamma_{N_1}}{H}\right)_{T=M_1} \lesssim 10^{-3}\mathrm{eV}}$$

$$\langle\phi\rangle = 174\mathrm{GeV}$$

$$g_* \simeq 100$$



Plümacher (1998)



Buchmuller, Plümacher (2000)

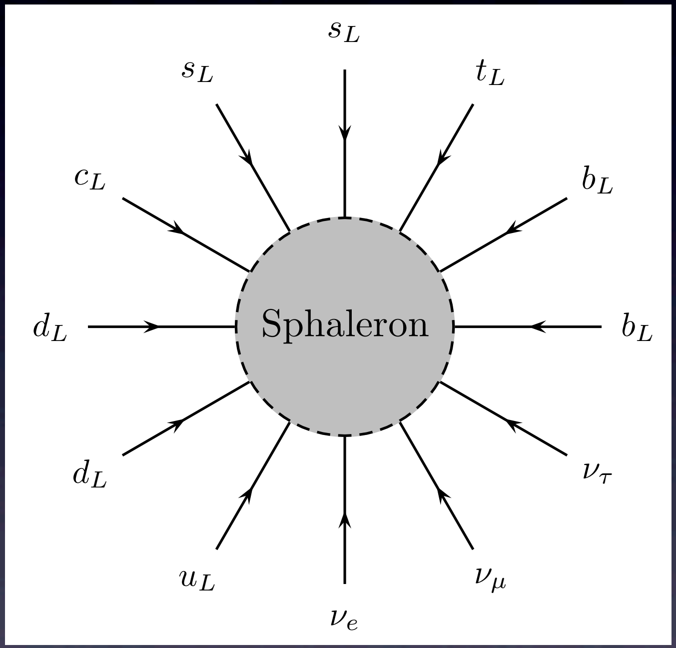
Chemical Equilibrium

chemical potential for massless particles

$$n_i - \bar{n}_i = \begin{cases} \frac{gT^2}{6}\mu_i & \text{(fermion)} \\ \frac{gT^2}{3}\mu_i & \text{(boson)} \end{cases}$$

- Sphaleron interaction

$$O_{B+L} = \prod_i (q_{Li} q_{Li} q_{Li} \ell_{Li})$$



$$\rightarrow \quad \boxed{\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0}$$

- total hypercharge = 0

$$\rightarrow \quad \boxed{\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + 2\mu_\phi / N_g) = 0}$$

- Yukawa interaction

$$\mathcal{L} = -h_{d_{ij}}\bar{d}_{Ri}q_{Lj}\phi - h_{u_{ij}}\bar{u}_{Ri}q_{Lj}\phi^c - h_{e_{ij}}\bar{e}_{Ri}q_{Lj}\phi$$

$$\rightarrow \boxed{\begin{aligned} \mu_{q_i} - \mu_\phi - \mu_{d_j} &= 0 \\ \mu_{q_i} + \mu_\phi - \mu_{u_j} &= 0 \\ \mu_{\ell_i} - \mu_\phi - \mu_{e_j} &= 0 \end{aligned}}$$

mixing in Yukawa couplings

$$\mu_{\ell_i} = \mu_\ell \quad \mu_{q_i} = \mu_q \quad \cdots$$

$$\rightarrow \boxed{\begin{aligned} \mu_e &= \frac{2N_g+3}{6N_g+3}\mu_\ell & \mu_d &= -\frac{6N_g+1}{6N_g+3}\mu_\ell \\ \mu_u &= \frac{2N_g-1}{6N_g+3}\mu_\ell & \mu_d &= \frac{4N_g}{6N_g+3}\mu_\ell \\ \mu_q &= -\frac{1}{3}\mu_\ell & & \end{aligned}}$$

$$n_B = \frac{B}{6}T^2 \qquad n_L = \frac{L}{6}T^2$$

$$\Rightarrow \quad B = N_g(2\mu_q + \mu_u + \mu_d) = -\frac{4}{3}N_g\mu_\ell$$

$$L = N_g(2\mu_\ell + \mu_e) = -\frac{10N_g + 11}{6N_g + 3}N_g\mu_\ell$$

$$\boxed{B = \frac{8N_g + 4}{22N_g + 13}(B - L) \simeq 0.3(B - L)}$$

Baryogenesis Mechanism

- Electroweak Baryogenesis
- Leptogenesis via Heavy Majorana Neutrino
- Affleck-Dine Mechanism
- ......

Affleck-Dine Mechanism

Affleck, Dine
(1985)

In Scalar Potential (= sauark, slepton, higgs)
of MSSM (minimal supersymmetric standard model)

There exist Flat Directions = Φ (AD-field)

(Flat if SUSY and no cutoff)

Dynamics of AD Field → Baryon Number Generation

Supersymmetry (SUSY)

Fermion ⟷ Boson

- Hierarchy Problem
  Keep electroweak scale against radiative correction
- Coupling Constant Unification in GUT

quark	⟷	squarks
lepton	⟷	slepton
photon	⟷	photino
graviton	⟷	gravitino

SUSY Breaking Scheme

Low Energy ~~SUSY~~ $(m_{\tilde{q}}, m_{\tilde{\ell}} \sim 1\mathrm{TeV} \gg m_q, m_\ell)$

(A) Gravity Mediated SUSY Breaking

~~SUSY~~ sector M_{SUSY} $\longleftrightarrow$ gravity $\longleftrightarrow$ Observable sector (s)quark,(s)lepton

- Squark, slepton masses

$$m_{\tilde{q}}, m_{\tilde{\ell}} \sim \frac{M_{\mathrm{SUSY}}^2}{M_p} \sim 10^{2-3}\ \mathrm{GeV}$$

$$M_{\mathrm{SUSY}} \sim 10^{11-13}\ \mathrm{GeV}$$

- Gravitino

$$\boxed{m_{3/2} \sim 10^{2-3}\ \mathrm{GeV}}$$

(B) Gauge Mediated SUSY Breaking

~~SUSY~~ sector M_{SUSY} $\xleftrightarrow{\text{gauge int.}}$ Messenger sector M_F $\xleftrightarrow{\text{gauge int.}}$ Observable sector (s)quark,(s)lepton

- Squark, slepton masses

$$m_{\tilde{q}}, m_{\tilde{\ell}} \sim \frac{g^2 M_{\mathrm{F}}}{16\pi^2} \sim 10^{2-3}\ \mathrm{GeV}$$

$$M_F \sim 10^{4-6}\ \mathrm{GeV}$$

- Gravitino

$$\boxed{m_{3/2} \sim \frac{M_{\mathrm{SUSY}}^2}{M_p} \sim \mathrm{keV} - \mathrm{GeV}}$$

Affleck-Dine Mechanism

Affleck, Dine (1985)

In Scalar Potential (= sauark, slepton, higgs) of MSSM(minimal supersymmetric standard model)

There exist Flat Directions = Φ (AD-field)

(Flat if SUSY and no cutoff)

$$\boxed{V(\Phi) = m_\Phi^2|\Phi|^2 + \frac{|\Phi|^{2n+4}}{M_*^{2n}} + A(\Phi^{n+3} + \Phi^{*n+3}) + \cdots}$$

SUSY breaking

Non-renormalizable term

A-term

$A \sim \frac{m_{3/2}}{M_*^n}$

U(1) symmetry

~~U(1)~~

Superpotential

$$W = \frac{\Phi^{n+3}}{M_*^n} + C$$

Scalar potential

$$V(\Phi) = \left|\frac{\partial W}{\partial \Phi}\right| - \frac{3}{M_G}|W|$$

$$= \frac{|\Phi|^{2n+4}}{M_*^{2n}} - \frac{3C}{M_G^2 M_*^n}(\Phi^{n+3} + \Phi^{*n+3}) - 3\frac{C^2}{M_G^2}$$

$$+F_{\rm susy}^2$$

SUSY breaking

Cosmological const. = 0

$$C \sim M_G F_{\rm susy} \sim m_{3/2} M_G^2$$

$$\uparrow$$

$$m_{3/2} \sim F_{\rm susy}/M_G$$

Dynamics of Affleck-Dine Field

$$V = (m_\Phi^2 - cH^2)|\Phi|^2 + \lambda \frac{|\Phi|^{2n+4}}{M_*^{2n}} + \tilde{a}\frac{m_{3/2}}{M_*^n}(\Phi^{n+3} + \Phi^{*n+3})$$

(i) During Inflation

$$H \sim O(10^{13})\ \mathrm{GeV} n \gg m_\Phi \sim O(100)\ \mathrm{GeV}$$

for simplicity $\lambda = c = 1, \quad n = 1$

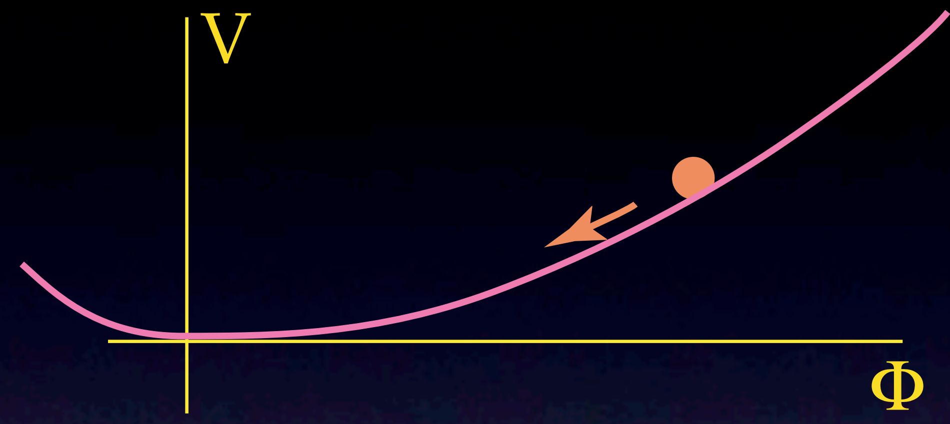
$$V = -cH^2|\Phi|^2 + \frac{|\Phi|^{2n+4}}{M_*^{2n}} \quad \Rightarrow \quad |\Phi| \sim (M_* H)^{1/2}$$

$$\left[\tilde{a}\frac{m_{3/2}}{M_*}|\Phi|^4 \sim \tilde{a} m_{3/2} H|\Phi|^2 \ll H^2 \Phi|^2\right]$$

(ii) After Inflation

$H > m_\Phi \quad H \propto a^{-3/2}$

$|\Phi| \sim (M_* H)^{1/2}$



$H \sim m_\Phi \;\; \Rightarrow \;\; \Phi$ oscillation

$\Phi_0 \simeq (m_\Phi M_*)^{1/2}$

$$V = m_\Phi^2 |\Phi|^2 + \tilde{a} \frac{m_{3/2}}{M_*^n} (\Phi^{n+3} + \Phi^{*n+3})$$

$\downarrow$

Kick in phase direction

$$\boxed{n_B = -i(\dot{\Phi}^* \Phi - \Phi^* \dot{\Phi})}$$

$$\sim \dot{\theta} |\Phi|^2$$

AD Baryogenesis

$$V = (m_\Phi^2 - cH^2)|\Phi|^2 + \lambda \frac{|\Phi|^{2n+4}}{M_*^{2n}} + \tilde{a}\frac{m_{3/2}}{M_*^n}(\Phi^{n+3} + \Phi^{*n+3})$$

$\Phi \ni \tilde{q},\ \tilde{\ell},\ H$ In geberal Φ has a baryon number

$$U_B(1):\ \Phi \ \rightarrow\ e^{i\alpha}\Phi$$

Noether current $j_{B,\mu} = \frac{1}{2i}(\Phi^*\partial_\mu\Phi - \partial_\mu\Phi^*\Phi)$

baryon density $n_B = j_{B,0}$

- Potential A-term violates $U_B(1)$
- during inflation $\langle|\Phi|e^{i\theta}\rangle \neq 0 \ \Rightarrow$ ~~CP~~, out of eq.

$$\dot{n}_B = \frac{d}{dt}\left(\frac{1}{2i}(\Phi^*\dot{\Phi} - \dot{\Phi}^*\Phi)\right) = \frac{1}{2i}(\Phi^*\ddot{\Phi} - \ddot{\Phi}^*\Phi)$$

Equation of Motion $\quad \ddot{\Phi} + 3H\dot{\Phi} + \frac{\partial}{\partial\Phi^*}V(\Phi) = 0$

$$\Rightarrow \quad \dot{n}_B + 3Hn_B = \frac{1}{2i}\left(\Phi^*\frac{\partial V}{\partial\Phi^*} - \Phi\frac{\partial V}{\partial\Phi}\right)$$

$$\begin{aligned} \dot{n}_B + 3Hn_B &= \frac{4\tilde{a}m_{3/2}}{M_*}|\Phi|^4 \sin 4\theta \\ a^3 n_B &= \int dt a^3 |\Phi|^4 \frac{4\tilde{a}m_{3/2}}{M_*} \sin 4\theta \end{aligned}$$

$$\left\{\begin{array}{lll} |\Phi| & \propto & a^{-3/2} \\ t & \propto & a^{3/2} \end{array}\right. \quad \Rightarrow \quad |\Phi|^4 \propto a^{-6} \propto t^{-4}$$

$$
\begin{aligned}
n_B &\simeq \tilde{a} H_{\rm osc}^{-1} \frac{m_{3/2}}{M_*} \sin(4\theta) |\Phi_0|^4 \\
\Rightarrow \qquad &\simeq \frac{\tilde{a}}{m_\Phi} \frac{m_{3/2}}{M_*} \sin(4\theta) (m_\Phi^2 M_*^2) \\
&\sim m_\Phi m_{3/2} M_* \sin(4\theta)
\end{aligned}
$$

$$
\frac{n_B}{\rho_{\rm inf}} \simeq \frac{m_\Phi m_{3/2} M_* \sin(4\theta)}{H_{\rm osc}^2 M_*^2} \simeq \frac{m_{3/2}}{m_\Phi M_*} \sin 4\theta
$$

Reheating $\rho_{\rm inf} \sim T_R^4 \sim s T_R$

$$
\Rightarrow \quad \frac{n_B}{s} = \frac{n_B}{\rho_{\rm inf}/T_R} \simeq \frac{m_{3/2} T_R}{m_\Phi M_*} \sin 4\theta
$$

Gravity mediation $m_{3/2} \sim m_\Phi$

$$
\boxed{\frac{n_B}{s} \simeq \frac{T_R}{M_*} \sin 4\theta \sim 10^{-10} \left(\frac{T_R}{10^{10} {\rm GeV}} \right) \sin 4\theta}
$$