Baryon Asymmetry of the Universe

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content

§1. Evidence of the BAU

Baryon Asymmetry of the Universe

$$\frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{s} = (0.48 - 0.98) \times 10^{-10}$$

$s = \frac{\pi^2}{45} g_* T^3 \simeq 7.04 n_\gamma$: entropy density

g_* = massless degrees of freedom

— constant during the expansion of the universe, *once $\Delta B \neq 0$ is turrned off*

$n_b, n_{\bar{b}} \propto a(t)^{-3} \propto T^3$ [entropy $a^3 s \propto a^3 T^3$ = const., where a =scale factor]

This value is determined by the data of

⋆ WMAP — observation of fluctuation in the Cosmic Microwave Background Radiation

The evolution of the fluctuation is determined by the components of the universe (baryon, CDM, electron, photon) at the decoupling.

$\longrightarrow T_0,\ H_0\ (\rightarrow\ \rho_C = 3H_0^2/(8\pi G)),\ \Omega_B = \rho_B/\rho_C$ (ρ = energy density)

⋆ Big Bang Nucleosynthesis

- $T \gg 1\text{MeV}$

  $n + \nu_e \rightleftharpoons p + e^-$ $\therefore\ n_n \simeq n_p$

- $T = T_F \simeq 1\text{MeV}$ $(\Gamma_{n\leftrightarrow p} \simeq H)$

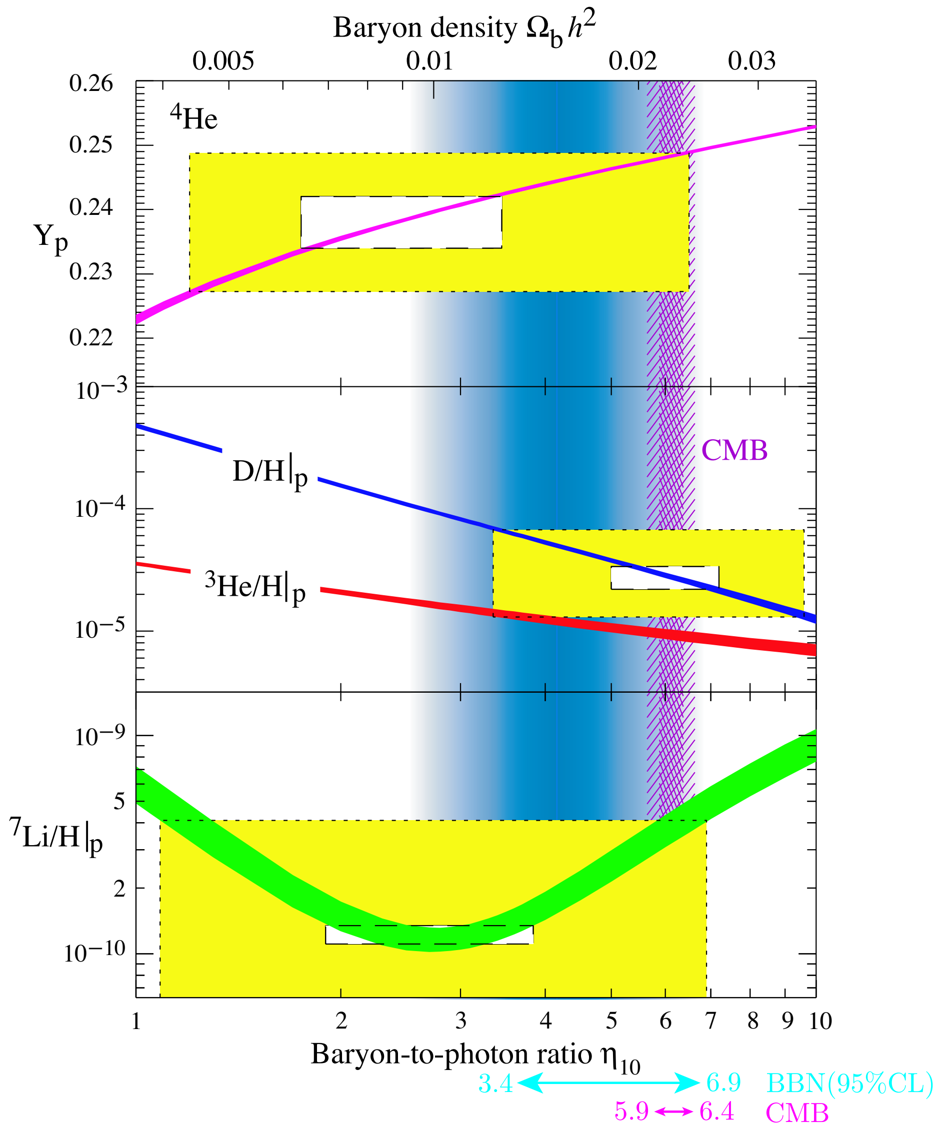
$$\frac{n_n}{n_p} \simeq e^{-(m_n - m_p)/T_F} \simeq \frac{1}{6}$$

- $T = 0.3 - 0.1\text{MeV}$

  depending on $\eta = \frac{n_B}{n_\gamma}$, $\frac{n_n}{n_p} = \frac{1}{7} - \frac{1}{6}$

^{4}He mass fraction

$$Y \equiv \frac{2n_n}{n_n + n_p} \quad \left(= 0.25 \leftrightarrow \frac{n_n}{n_p} = \frac{1}{7}\right)$$



Missing antimatter

[Steigman, Ann. Rev. Astron. Astrophys. 14 ('76)]

1. **observed antiparticles in cosmic rays = secondary antiparticles**
2. **clusters of galaxies are stable**

   mass of a cluster: $M_{\rm cluster} \simeq 10^{12-14} M_\odot$ ($M_\odot$ =solar mass)

In the universe, is there net baryon number?

Starting from a Baryon-symmetric universe, can we extract finite n_B?

At $T < 1$GeV, *a bit of* nucleons and anti-nucleons exist with the same number because of thermal fluctuation: $n_N = n_{\bar{N}} = (m_N T)^{3/2} e^{-m_N/T}$

$$\frac{n_b}{s} = \frac{n_{\bar{b}}}{s} \simeq 8 \times 10^{-11} \quad \text{at } T = 38\text{MeV}$$

At this T, total energy within a causal volume ($\sim H^{-3}$) is $10^{-7} M_\odot \ll 10^{12} M_\odot$

At a higher T, there are more n_b/s and $n_{\bar{b}}/s$, but

$$E_{\rm causal} \sim \rho(T) H^{-3}(T) \sim T^4 (T^2/m_{\rm Pl})^{-3} = m_{\rm Pl}^3 T^{-2} < 10^{-7} M_\odot,$$

where

$$H = \frac{\dot{a}(t)}{a(t)} = \sqrt{\frac{8\pi G}{3}\rho(T)} \qquad \text{with} \qquad \rho(T) = g_* \frac{\pi^2}{30} T^4$$

Even the *Maxwell's demon* could not separate matter and antimatter to create the present universe, without violating causality.

Before the era of nucleosynthesis, we must have

$$\frac{n_B}{s} = (0.48 - 0.98) \times 10^{-10}$$

over a region broader than a causal region at $T = 1$MeV.

§2. Requirements for the baryogenesis

= generating B starting from B-symmetric universe

Sakharov's 3 conditions

(1) **Baryon number violating process**

(2) **Violation of C *and* CP symmetries**

(3) **Out of equilibrium**

(1) is obvious.

(3) In equilibrium, $\Delta B \neq 0$-process and its inverse occur with the same probability. Then no B is generated.

Let us consider the case in which (2) is not satsified.

Suppose that a local state of the spatially uniform universe is described by

density operator

$$\rho(t) = \sum_n p_n |n(t)\rangle\langle n(t)| \qquad (p_n = \text{prob. to find the universe in the state } |n(t)\rangle)$$

Expectation value of some observable $\mathcal{O}$:

$$\langle\mathcal{O}\rangle(t) = \mathrm{Tr}\left[\rho(t)\mathcal{O}\right] = \sum_n p_n \langle n(t)|\mathcal{O}|n(t)\rangle$$

time evolution of $\rho(t)$ is governed by the Liouville equation:

$$i\hbar\frac{\partial\rho(t)}{\partial t} + [\rho(t), H] = 0$$

($\Leftarrow$ Schrödinger eq. $i\hbar\frac{\partial}{\partial t}|n(t)\rangle = H|n(t)\rangle$)

ρ_0: density operator of an initial state with $n_B = 0$ $\langle n_B \rangle_0 \equiv \mathrm{Tr}\,[\rho_0\, n_B] = 0$

density operator $\rho(t)$ at a later time is given by the solution to

$$i\hbar \frac{\partial \rho(t)}{\partial t} + [\rho(t), H] = 0$$

with the initial condition $\rho(t_0) = \rho_0$

The solution is formally written in terms of H and ρ_0

$\Rightarrow$ If H is invariant under C- *or* CP-trf. $\Longrightarrow$ $[\rho, \mathcal{C}] = 0$ *or* $[\rho, \mathcal{CP}] = 0$

$\mathcal{C} B \mathcal{C}^{-1} = -B$, $\mathcal{CP} B (\mathcal{CP})^{-1} = -B$ ($i.e.$, B is vectorlike and odd under C)

$$\Rightarrow \begin{cases} \langle n_B \rangle = \mathrm{Tr}[\rho n_B] = \mathrm{Tr}[\rho\, \mathcal{C} n_B \mathcal{C}^{-1}] = -\mathrm{Tr}[\rho n_B] = 0 \\ \quad \text{or} \\ \langle n_B \rangle = \mathrm{Tr}[\rho\, \mathcal{CP} n_B (\mathcal{CP})^{-1}] = -\mathrm{Tr}[\rho n_B] = 0 \end{cases}$$

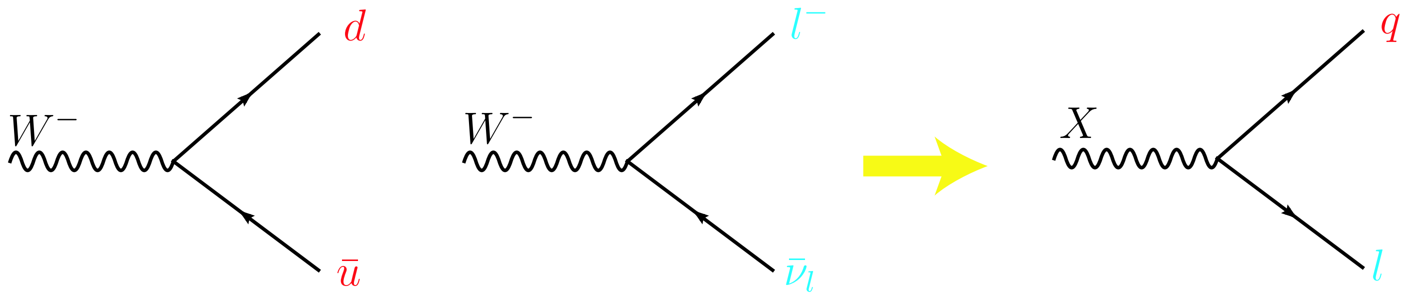
$\therefore$ **Both C and CP must be violated** to have $\langle n_B \rangle \neq 0$

§3. Scenarios of baryogenesis

— models of particle physics realizing baryogenesis

(1) $\Delta B \neq 0$ process

- quark-lepton mixing — in Grand Unified Theories (GUTs)



- in Supersymmetric theories,

$$\left.\begin{array}{lcl} \text{quark: } q & \leftrightarrow & \tilde{q} \text{ :scalar quark (squark)} \\ \text{lepton: } l & \leftrightarrow & \tilde{l} \text{ :scalar lepton (slepton)} \end{array}\right\} \Longrightarrow \langle \tilde{q} \rangle \neq 0, \ \langle \tilde{l} \rangle \neq 0$$

- axial $U(1)$ anomaly in the $(B+L)$-current

  — exists in the Standard Model

$$\partial_\mu j^\mu_{B+L} = \frac{N_f}{16\pi^2}[g_2^2 \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu}] \neq 0$$

for *some specific configuration* of the $SU(2)$-gauge field

We shall discuss this process later.

All these processes must be suppressed at $T = 0$, in order for a proton not to decay

$\Longrightarrow$

- in GUTs, m_X must be heavier than some value $\sim 10^{16}$GeV
- The potential for the squark fields must have such a form that $\langle \tilde{q} \rangle \neq 0$ is realized in the early universe, while $\langle \tilde{q} \rangle = 0$ at $T = 0$
- at $T = 0$, $\Delta(B + L) \neq 0$ process occurs by quantum tunneling

  As shown later, the probability is negligible

(2) C and CP violation

⋆ C violation ⟵ **chiral** gauge interactions in EW theory and GUTs

$SU(2)_L$ gauge int., different $U(1)_Y$ charges for L- and R-fermions

⋆ CP violation ⟵ complex parameters with irreducible phases

In renormalizable field theories, only some types of interactions can violate CP.

- In the SM, KM phase and $F_{\mu\nu}\tilde{F}^{\mu\nu}$ (θ-term)

  $|\theta_{\rm QCD}| \simeq 0$ by neutron EDM experiment

- Extended models:
  - ▷ SUSY models: relative phases of μ, gaugino mass, A, B (soft-SUSY-br.)
  - ▷ extended Higgs sector: complex Higgs self-couplings

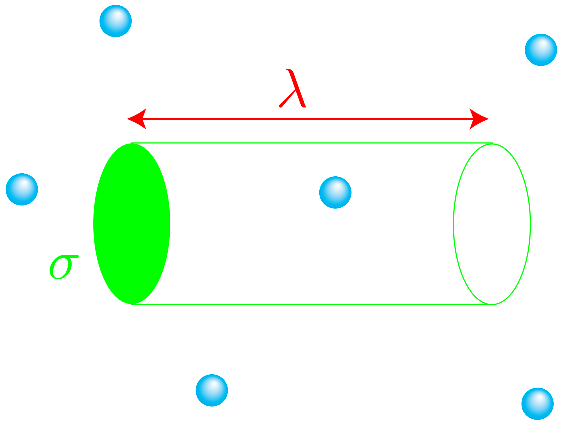
magnitude of CP violation is limited by experiments

— e.g., B-factory, EDM of neutron and lepton, K-rare processes

(3) Out of equilibrium

"equilibrium in the expanding universe" $\Leftrightarrow$ time scale of process: $\tau < H(T)^{-1}$

for relativistic particles, $\tau \simeq \lambda$: mean free path



σ : total cross section

$n(T)$: particle number density

$$\sigma \cdot \lambda = \frac{1}{n(T)}$$

$$H(T) = \sqrt{\frac{8\pi G}{3}\rho(T)} \simeq 1.66\sqrt{g_*}\frac{T^2}{m_{\rm Pl}}$$

$$\rho(T) = \frac{\pi^2}{30} g_* T^4$$

relativistic degrees of freedom for SM with N_f generation, N_H Higgs doublets

$$g_* = 24 + 4N_H + \frac{7}{8}\cdot 30 N_f \stackrel{\rm MSM}{=} 106.75$$

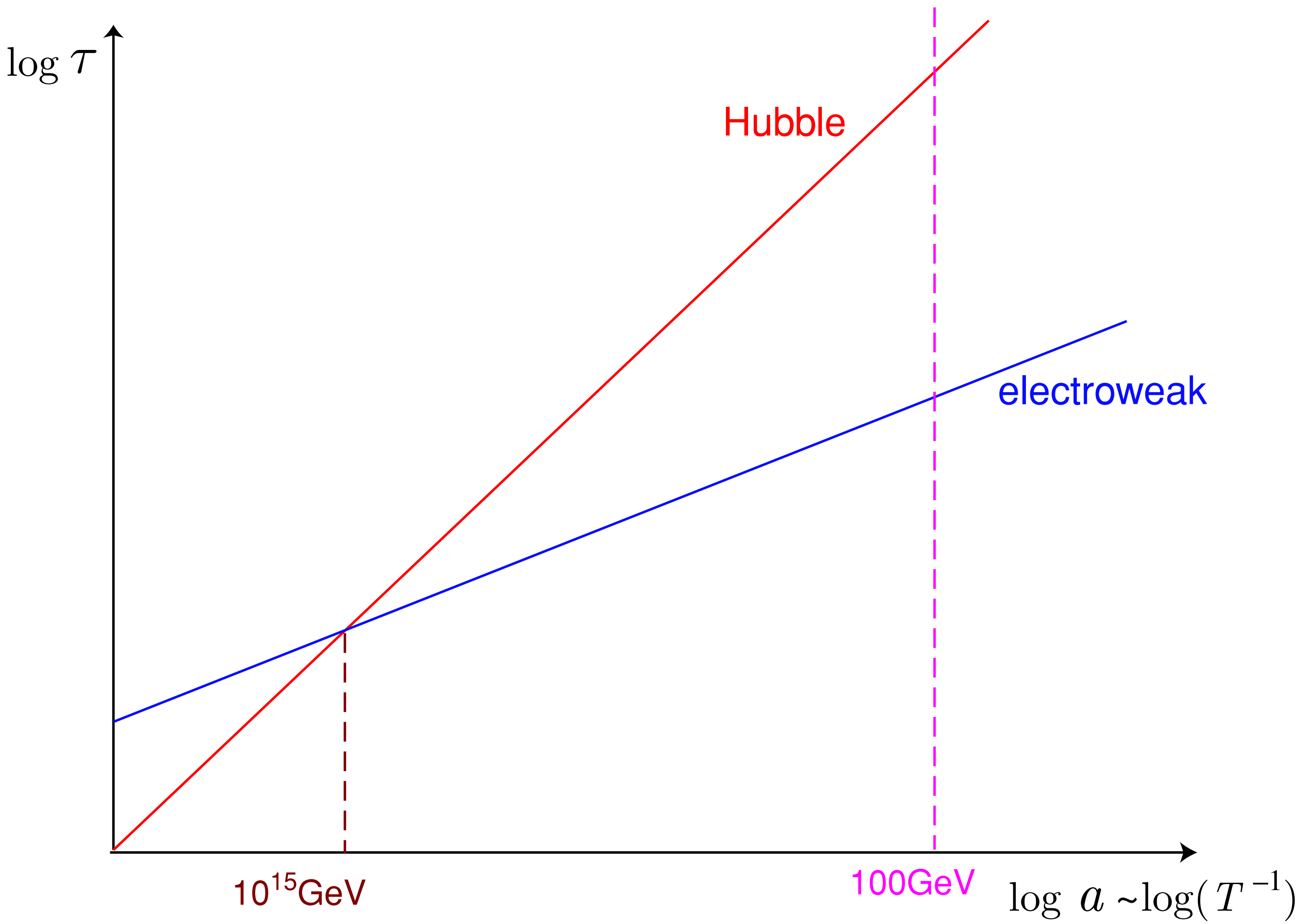
number density: $n(T) = g \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \frac{1}{e^{\sqrt{k^2+m^2}/T} \mp 1} \overset{m \ll T}{\simeq} g \begin{cases} \frac{\zeta(3)}{\pi^2} T^3 \\ \frac{3}{4} \frac{\zeta(3)}{\pi^2} T^3 \end{cases}$

$\zeta(3) = 1.2020569 \cdots$

for relativistic particles, $\sigma \simeq \frac{\alpha^2}{s} \simeq \frac{\alpha^2}{T^2}$ $\therefore$ $\lambda \simeq \frac{10}{gT^3} \left(\frac{\alpha^2}{T^2} \right)^{-1} = \frac{10}{g\alpha^2 T}$

$T = 100$GeV: $\begin{cases} H(T)^{-1} \simeq 10^{14}\,\text{GeV}^{-1} & \text{expansion} \\ \lambda_s \simeq \frac{1}{\alpha_s{}^2 T} \sim 1\,\text{GeV}^{-1} & \text{strong interactions} \\ \lambda_{EW} \simeq \frac{1}{\alpha_W{}^2 T} \sim 10\,\text{GeV}^{-1} & \text{EW interactions} \\ \lambda_Y \simeq \left(\frac{m_W}{m_f} \right)^4 \lambda_{EW} & \text{Yukawa interactions} \end{cases}$

time scale of EW interaction vs that of the expansion



Possible out-of-equilibrium processes $\tau_{\rm process} < H(T)$?

- Expansion of the universe

  EW or GUTs interaction in the radiation dominated universe at $T > 10^{15}$GeV

  Heavy particle (e.g., heavy Majorana neutrino) at $T > 10^{10}$GeV

- First-order phase transition

  some *rare process* runs out of equil. even at $T = 100$GeV

  — $(B + L)$-violating process in EW theory

- Reheating or preheating after inflation

  accompanying production of a large amount of entropy

  $\longrightarrow$ dilution of baryon number density

An example — GUTs

[Yoshimura, Phys. Rev. Lett. 41 ('78)]

minimal $SU(5)$ model:

matter: $\begin{cases} \mathbf{5}^* : \psi^i_L & \ni \quad d^c_R, l_L \\ \mathbf{10} : \chi_{[ij]L} & \ni \quad q_L, u^c_R, e^c_R \end{cases}$ gauge: $A_\mu = \begin{pmatrix} G_\mu, B_\mu & X^{a\alpha}_\mu \\ X^{a\alpha}_\mu & W_\mu, B_\mu \end{pmatrix}$

$i = 1-5 \;\longrightarrow (\alpha = 1-3, a = 1, 2)$

$$\mathcal{L}_{\rm int} \ni g\bar\psi\gamma^\mu A_\mu\psi + g{\rm Tr}\left[\bar\chi\gamma^\mu\{A_\mu, \chi\}\right]$$

$$\ni gX^a_{\alpha\mu}\left[\varepsilon^{\alpha\beta\gamma}\bar u^c_{R\gamma}\gamma^\mu q_{L\beta a} + \epsilon_{ab}\left(\bar q^\alpha_{Lb}\gamma^\mu e^c_R + \bar l_{Lb}\gamma^\mu d^{c\alpha}_R\right)\right]$$

Expectation value of ΔB in decays of X-$\bar X$ pairs generated from the plasma

process	BR	ΔB
$X \longrightarrow qq$	r	$2/3$
$X \longrightarrow \bar q\bar l$	$1-r$	$-1/3$
$\bar X \longrightarrow \bar q\bar q$	$\bar r$	$-2/3$
$\bar X \longrightarrow q, l$	$1-\bar r$	$1/3$

$$\langle\Delta B\rangle = \frac{2}{3}r - \frac{1}{3}(1-r) - \frac{2}{3}\bar r + \frac{1}{3}(1-\bar r) = r - \bar r$$

$\therefore$ C *or* CP is conserved($r = \bar r$)

$\Longrightarrow \Delta B = 0$

If the inverse process is suppressed, $B \propto r - \bar{r}$ is generated.

Indeed, at $T \simeq m_X$, the decay rate of X: $\Gamma_D \simeq \alpha m_X$ $(\alpha \sim 1/40)$

$\Rightarrow \Gamma_D \simeq H(T = m_X)$ $\therefore$ annihilation and production of $X\bar{X}$ out of equil.

$$H(T) \simeq 1.66\sqrt{g_*}\frac{T^2}{m_{\rm Pl}}$$

SU(5) GUT conserves $B - L$ — $(B + L)$-genesis

EW $\Delta(B + L) \neq 0$ process in equilibrium $\rightarrow B + L \rightarrow 0$

$\Downarrow$

new possibility of baryogenesis

$B - L \neq 0$ before EW $\Delta(B + L) \neq 0$ process in equil.

Leptogenesis: $\Delta L \neq 0 \rightarrow B = -L$

EW $\Delta(B+L) \neq 0$ process

$\Leftarrow$ chiral $U(1)$ anomaly in $(B+L)$-current

$$\partial_\mu j^\mu_{B+L} = \frac{N_f}{16\pi^2}[g_2^2 \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu}]$$

$$\partial_\mu j^\mu_{B-L} = 0$$

$N_f = \#$ of genenrations

$$\tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$$

integrating the sum of these eqs.

$$B(t_f) - B(t_i) = \frac{N_f}{32\pi^2}\int_{t_i}^{t_f} d^4x \left[g_2^2 \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$

$$= N_f\,[N_{CS}(t_f) - N_{CS}(t_i)]$$

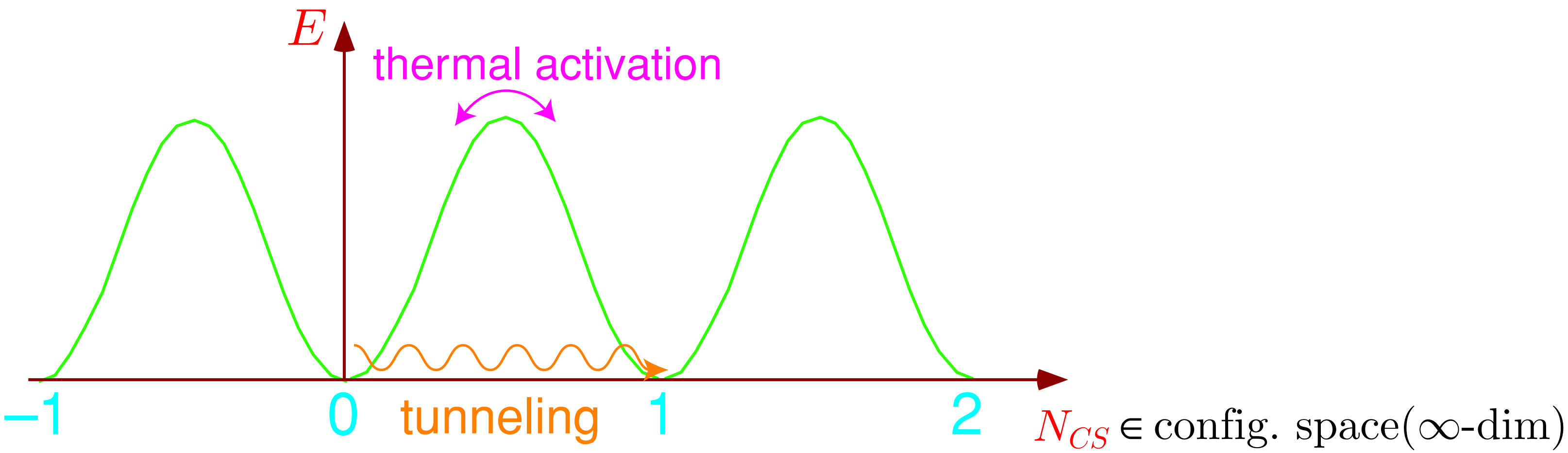
where N_{CS} is the Chern-Simons number: in the $A_0 = 0$-gauge

$$N_{CS}(t) = \frac{1}{32\pi^2}\int d^3x\,\epsilon_{ijk}\left[g_2^2 \mathrm{Tr}\left(F_{ij}A_k - \frac{2}{3}gA_iA_jA_k\right) - g_1^2 B_{ij}B_k\right]_t$$

classical vacuum of the gauge fields: $\mathcal{E} = \frac{1}{2}(\boldsymbol{E}^2 + \boldsymbol{B}^2) = 0 \Longleftrightarrow F_{\mu\nu} = B_{\mu\nu} = 0$

$\Longleftrightarrow A = iU^{-1}dU$, $B = dv$ with $U \in SU(2)$ $\quad U(\boldsymbol{x}) : S^3 \to U \in SU(2) \simeq S^3$

$\pi_3(S^3) \simeq \mathbf{Z} \Longrightarrow U(\boldsymbol{x})$ is classified by the integer N_{CS}



$\Delta(B+L) \neq 0$ process

- ▷ **Quantum Tunneling** low-T
- ▷ **Thermal Activation** high-T

tunnel. prob. $\sim e^{-2S_{\text{instanton}}} = e^{-8\pi^2/g_2^2} \simeq e^{-164} \ll 1$

$\therefore$ no proton-decay problem

⋆ $(B+L)$-transition (sphaleron transition) rate ⋆

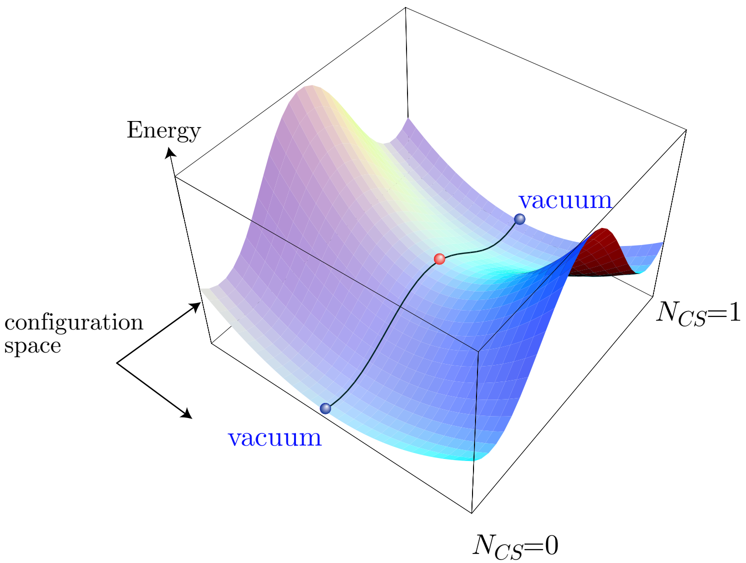
- $T < T_C$: EW phase transition temperature (broken phase)

$$\Gamma^{(b)}_{\rm sph} \simeq T\, e^{-E_{\rm sph}/T}$$

- $T > T_C$ (symmetric phase)

$$\Gamma^{(s)}_{\rm sph} \simeq \kappa \alpha_W^4 T \quad \text{with } \kappa \sim O(1)$$

sphaleron = static saddle-point solution of $SU(2)$-gauge-Higgs system



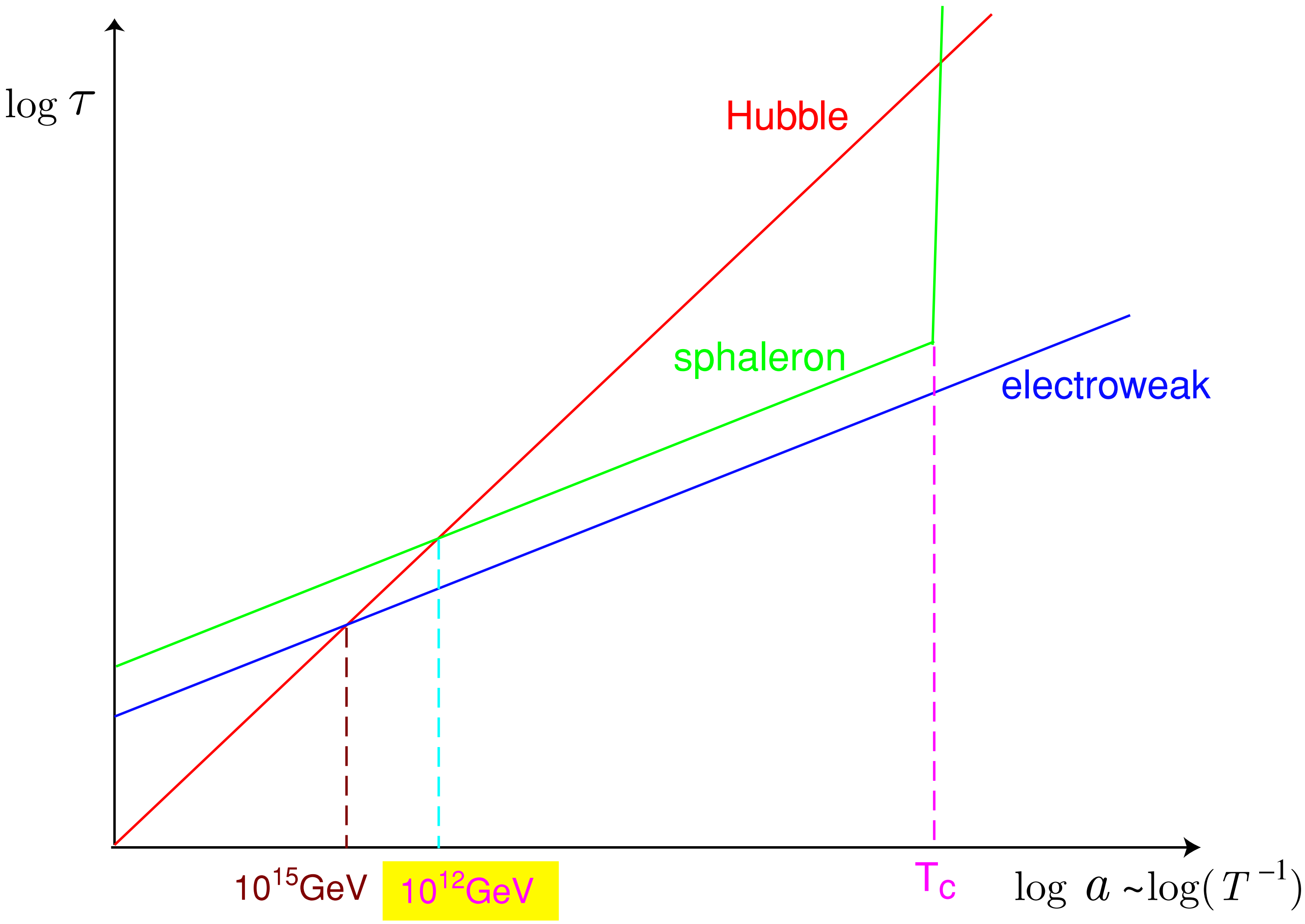
$E_{\rm sph} = O(1)$TeV

first found by Manton [Phys. Rev. D28 ('83)]

Now found in the MSSM (2HDM),

the Next-to-MSSM

time scale of the sphaleron transition vs that of the expansion



For $T_C < T < 10^{12}$GeV, $\Gamma^{(s)}_{\rm sph} > H(T)$

$\Longrightarrow$ $B \propto (B-L)_{\rm primoridal}$ at $T \le T_C$

$\therefore$ For the matter in the Universe to be left at present, either

(i) $B - L \neq 0$ must exist **before the sphaleron process decouples**, or

(ii) $B + L$ **must be generated at the EW phase transition** *and*
the sphaleron process becomes ineffective after that.

(i) $\Rightarrow$ $(B-L)$-violating GUTs, Leptogenesis

(ii) $\Rightarrow$ Electroweak baryogenesis

sphaleron decoupling condition: $\Gamma^{(b)}_{\rm sph}(T_C) < H(T_C)$

$\longrightarrow$ lower bound on $E_{\rm sph}(T_C) \propto v(T_C)$ ($v(T) = \langle \Phi \rangle$; $\Phi =$ Higgs doublet)

$\longrightarrow$ upper bound on the Higgs mass (see below)

§4. Electroweak baryogenesis

— closely related to the particle physics at the weak scale

(i) Baryon number violation $\longleftarrow$ sphaleron process in the symmetric phase

must decouple just after the EW phase transition

(ii) C and CP violation $\longleftarrow$ KM phase, or complex parameters in extended models

(iii) Out of equilibrium $\longleftarrow$ sphaleron process can be out of equilibrium at the EWPT

if $E_{\rm sph}(T_C)/T_C$ is sufficiently large

— strongly first-order PT

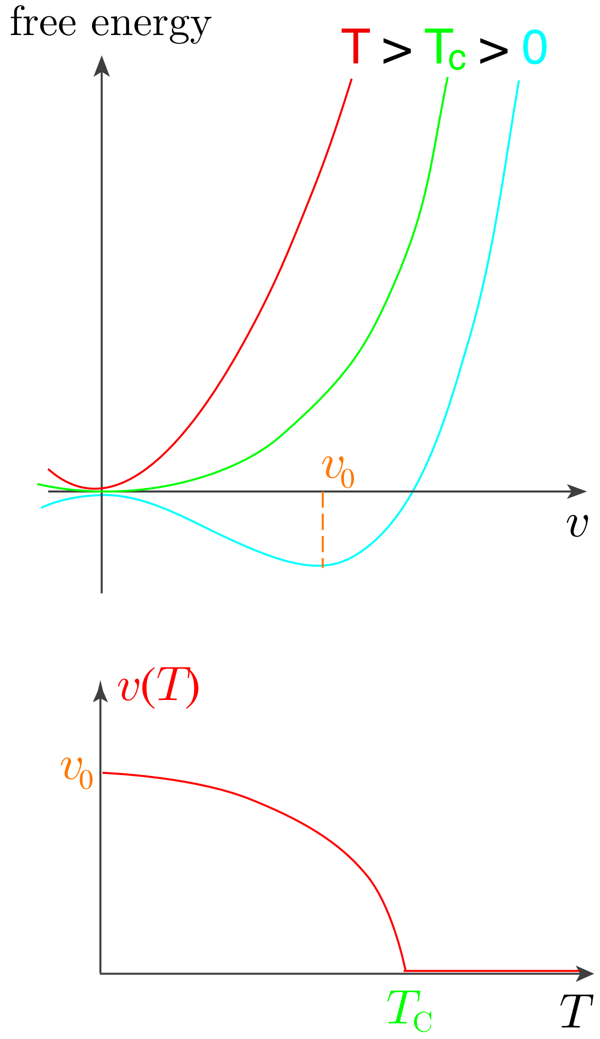
As we shall see, the conditions (ii) and (iii) require an extension of the standard model, because

- ⋆ KM phase is insufficient to produce the present BAU
- ⋆ EWPT is not of first order for the Higgs mass $m_h > 114$GeV (LEP bound)

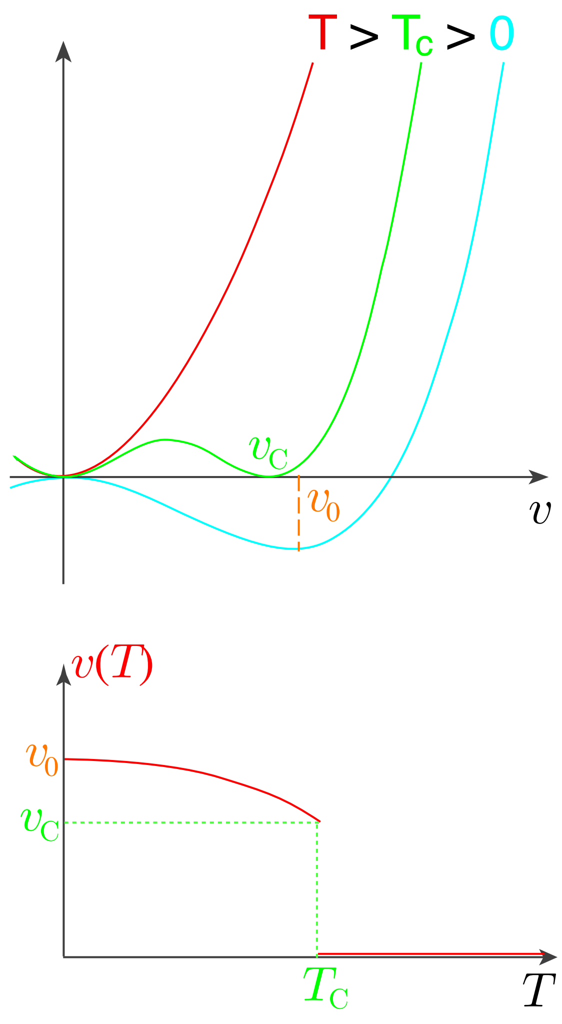
for reviews , see

- KF, Prog. Theor. Phys. 96 (1996) 475
- Riotto and Trodden, Ann. Rev. Nucl. Part. Sci. 49 (1999) [hep-ph/9901362]
- Bernreuther, Lec. Notes Phys. 591 (2002) 237 [hep-ph/0205279]

Electroweak phase transition (EWPT)



2nd order PT



1st order PT

Standard Model

order parameter:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \varphi \end{pmatrix}$$

$\therefore$ 1st order EWPT

$\Updownarrow$

$$v_C \equiv \lim_{T \uparrow T_C} \varphi(T) \neq 0$$

Minimal SM — perturbation at the 1-loop level (W, Z, top quark loop)

$$V_{\rm eff}(\varphi;T) = -\frac{1}{2}\mu^2\varphi^2 + \frac{\lambda}{4}\varphi^4 + 2Bv_0^2\varphi^2 + B\varphi^4\left[\log\left(\frac{\varphi^2}{v_0^2}\right) - \frac{3}{2}\right] + \bar{V}(\varphi;T)$$

where $$B = \frac{3}{64\pi^2 v_0^4}(2m_W^4 + m_Z^4 - 4m_t^4),$$

$$\bar{V}(\varphi;T) = \frac{T^4}{2\pi^2}\left[6I_B(a_W) + 3I_B(a_Z) - 6I_F(a_t)\right], \qquad (a_A = m_A(\varphi)/T)$$

$$I_{B,F}(a) \equiv \int_0^\infty dx\, x^2 \log\left(1 \mp e^{-\sqrt{x^2+a^2}}\right).$$

high-temperature expansion $[m/T \ll 1]$ $\qquad$ $\gamma_E = 0.5772\cdots$

$$I_B(a) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}a^2 - \frac{\pi}{6}(a^2)^{3/2} - \frac{a^4}{16}\log\frac{\sqrt{a^2}}{4\pi} - \frac{a^4}{16}\left(\gamma_E - \frac{3}{4}\right) + O(a^6)$$

$$I_F(a) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{16}\log\frac{\sqrt{a^2}}{\pi} - \frac{a^4}{16}\left(\gamma_E - \frac{3}{4}\right) + O(a^6)$$

Applying the high-T expansion assuming $T > m_W, m_Z, m_t$,

$$V_{\rm eff}(\varphi; T) \simeq D(T^2 - T_0^2)\varphi^2 - E\,T\varphi^3 + \frac{\lambda_T}{4}\varphi^4$$

where

$$D = \frac{1}{8v_0^2}(2m_W^2 + m_Z^2 + 2m_t^2), \qquad E = \frac{1}{4\pi v_0^3}(2m_W^3 + m_Z^3) \sim 10^{-2}$$

$$\lambda_T = \lambda - \frac{3}{16\pi^2 v_0^4}\left(2m_W^4 \log\frac{m_W^2}{\alpha_B T^2} + m_Z^4 \log\frac{m_Z^2}{\alpha_B T^2} - 4m_t^4 \log\frac{m_t^2}{\alpha_F T^2}\right)$$

$$T_0^2 = \frac{1}{2D}(\mu^2 - 4Bv_0^2), \qquad \log\alpha_{F(B)} = 2\log(4)\pi - 2\gamma_E$$

At T_C, $^{\exists}$degenerate minima: $\varphi_C = \dfrac{2E\,T_C}{\lambda_{T_C}}$

$$\Gamma_{\rm sph}^{(\rm br)} < H(T_C) \iff \frac{\varphi_C}{T_C} \gtrsim 1$$ $\Longrightarrow$ upper bound on λ $[m_H = \sqrt{2\lambda}v_0]$

$\longrightarrow$ $m_H \lesssim 46$GeV $\Longrightarrow$ Minimal SM is excluded!

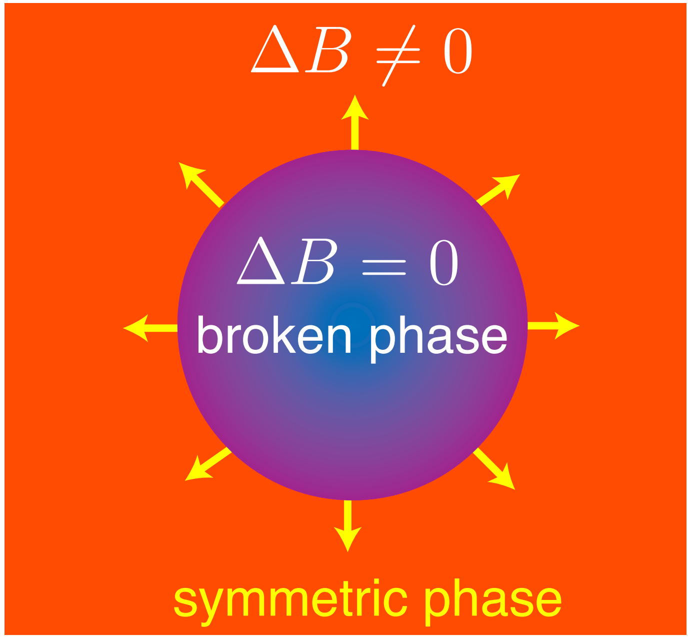
Nonperturbative study by Lattice Gauge Theory:

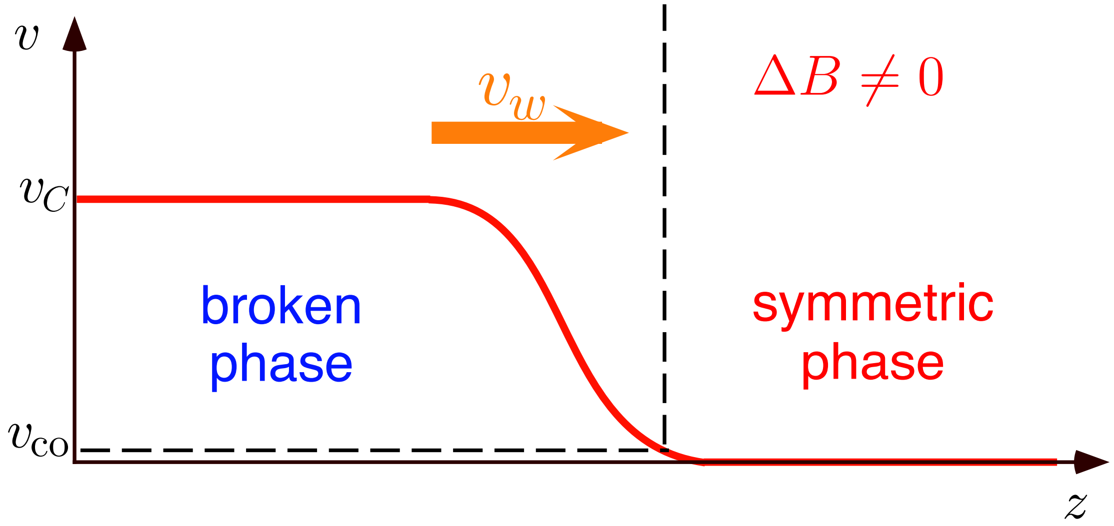
$m_h > 73\text{GeV} \Rightarrow$ PT disappears (crossover)

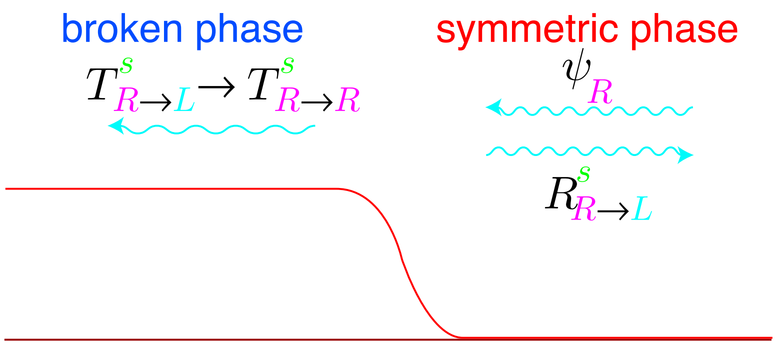
$\therefore$ The EWBG does not work in the Standard Model with $m_h \geq 114\text{GeV}$.

If the EWPT is of first order,
it proceeds accompanying nucleation and growth of the bubble walls:

$\longrightarrow$ sphaleron process becomes out of equilibrium







Difference in the reflection rate for ψ_L and ψ_R

$\Downarrow$

chiral charge flux into the sym. phase

$Q_L \neq Q_R$, conserved in sym. phase: Y, I_3

$\Downarrow$

bias on the sphaleron process

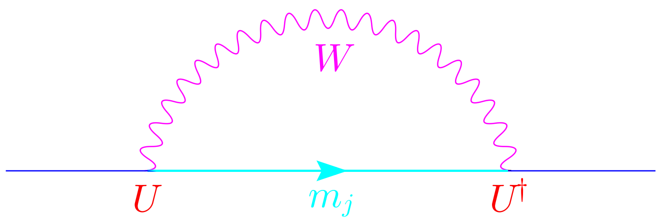
$\Downarrow$

$B + L \neq 0$ in the symmetric phase

$\Downarrow$

$B + L$ frozen in the broken phase

⋆ Minimal SM — CKM phase



$\longrightarrow$ $m_i \neq m_j$:

$O(\alpha_W)$ effect in the dispersion

[Farrar, Shaposhnikov, Phys. Rev. 50 ('94)]

▷ decoherence by QCD correction [Gavela, et al., Nulc. Phys. B430 ('94)]

$$\longrightarrow \left|\frac{n_B}{s}\right| < 10^{-26}$$

effective CP violation at the tree level

⋆ relative phase of Higgs doublets in the extended models

$$m_f(x) = y_f\,|\phi(x)|\,e^{i\theta(x)}$$ — spacetime-dependent phase

⋆ complex parameters in the mass matrices of SUSY particles

$e.g.$ chargino: $M_{\chi^\pm} = \begin{pmatrix} M_2 & -\frac{i}{\sqrt{2}}g_2 v_u e^{-i\theta} \\ -\frac{i}{\sqrt{2}}g_2 v_d & -\mu \end{pmatrix}$

x-dependent v_d and v_u $\longrightarrow$ effectively x-dependent phases

For the EWBG to work, we need an extension of the Standard Model.

▷ Higgs sector — MSSM: $m_{H_1} \leq 120\text{GeV}$ and a light stop $m_{\tilde{t}_1} \leq m_t$
2HDM, NMSSM: possible for $m_h > 130\text{GeV}$

▷ CP violation — Higgs doublets more than 2
complex parameters in the SUSY models