Baryogenesis Notes

6.1 Overview

- $G_{\Delta B} \sim M^{-2} \lesssim 10^{-30}\,GeV^{-2}$ M: energy scale of grand unification
- Proton lifetime: $\gtrsim 10^{33}\,yr$ (Super Kamiokande $p \to \mu^+ + \pi^0$, $p \to e^+ + \pi^0$)
  $\gtrsim 2.1 \times 10^{29}\,yr$ (Sudbury neutrino experiment, $p \to$ anything)

SU(5) predicts $10^{29 \pm 1}\,yr$, new limits set positron decay at $\gtrsim 10^{34}\,yr$

6.2 Evidence for a Baryon Asymmetry

- Cosmic rays from the Sun indicate it's made from matter.
- From other galaxies (and ours), $\frac{n_{\bar{p}}}{n_p} \sim 10^{-4}$ in cosmic rays, consistent with collisions in the ISM.

  $\frac{n_{^4\overline{He}}}{n_{^4He}} \sim 10^{-5}$, no detection of antinucleus
- Matter and antimatter galaxies in the same cluster would produce strong γ-ray emissions, which are not observed.
- No info on scales larger than clusters (check this). ← CMB thanks to WMAP
- Baryon Asymmetry of the Universe (BAU) parameter:

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

Current values: $\eta_{CMB} = (6.23 \pm 0.17) \times 10^{-10}$

Better parameter: $\frac{n_B - n_{\bar{B}}}{s}$, $s = 7.04\,n_\gamma \to \eta_s =$

$\frac{n_q - n_{\bar{q}}}{n_q} = 3 \times 10^{-8}$, $t \lesssim 10^{-6}\,s$

6.3 The Basic Picture

- Sakharov Conditions (1967)

  1) Baryon number violation
     - Generic feature of GUTs
     - Unifying strong and electroweak interactions places quarks and leptons in a common irreducible representation of the gauge group. Then there are gauge bosons which transform $q \to \ell$ or $\bar{q}$
     - Mass of those gauge bosons determined by τ_p:

       $$\tau_p \sim (G_{\Delta B}^2 m_p^5)^{-1} \sim \alpha_{GUT}^{-2} M^4 m_p^{-5} \longrightarrow M \gtrsim 10^{14}\,\text{GeV}$$
     - There may also be B-violating Higgs bosons with mass $\sim 10^{10}$ GeV due to the weaker coupling typical of a Higgs.

  2) C and CP violation
     - C is maximally violated by the weak interaction.
     - CP violation observed in neutral kaon system.
     - Necessary because decays which favor baryons would be balanced by those which favor antibaryons.

  3) Non-equilibrium conditions
     - In thermal equilibrium, baryons and antibaryons have the same phase space density: $\left(1 + e^{(p^2+m^2)^{1/2}/T}\right)^{-1}$
       This implies $n_b = n_{\bar{b}}$.
     - Provided by the expansion of the universe, which must be faster than key particle interaction rates.

• Simple Example

- Consider an X boson with 2 decay channels

$$X \to qq \quad (B = \tfrac{2}{3},\ B-L = \tfrac{2}{3})$$

$$X \to \bar{q}\bar{l} \quad (B = -\tfrac{1}{3},\ B-L = \tfrac{2}{3})$$

- CPT invariance implies $m_X = m_{\bar{X}}$ and that the decay rate of X and $\bar{X}$ are identical. It does not require, however, that the branching ratios be mirrored.

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Decay channel	Branching Ratio	B	B − L
$X \to qq$	r	$\frac{2}{3}$	$\frac{2}{3}$
$X \to \bar{q}\bar{l}$	$1-r$	$-\frac{1}{3}$	$\frac{2}{3}$
$\bar{X} \to \bar{q}\bar{q}$	$\bar{r}$	$-\frac{2}{3}$	$-\frac{2}{3}$
$\bar{X} \to ql$	$1-\bar{r}$	$\frac{1}{3}$	$-\frac{2}{3}$

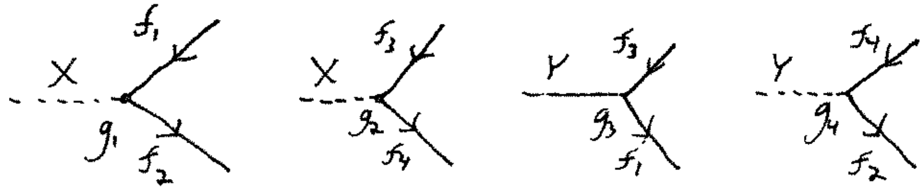
- $B_X = \frac{2}{3}r - \frac{1}{3}(1-r)$, $B_{\bar{X}} = -\frac{2}{3}\bar{r} + \frac{1}{3}(1-\bar{r})$

- $\varepsilon \equiv B_X + B_{\bar{X}} = r - \bar{r}$

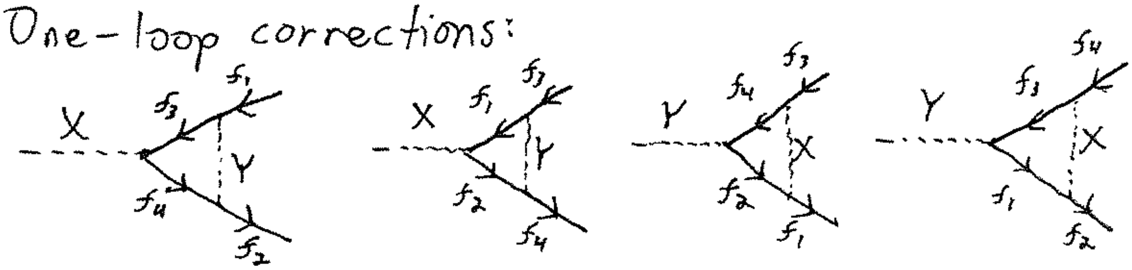
- C and CP invariance would imply $r = \bar{r}$.

- When $T \ll m_X$, X and $\bar{X}$ may decay freely without "back" reactions – inverse decays and other B-violating reactions.

- C, CP-violation example
  - Two superheavy bosons, X and Y
  - $$\varepsilon_X = \sum_f B_f \frac{\Gamma(X \to f) - \Gamma(\bar{X} \to \bar{f})}{\Gamma_X}$$
    $$\varepsilon_Y = \sum_f B_f \frac{\Gamma(Y \to f) - \Gamma(\bar{Y} \to \bar{f})}{\Gamma_Y}$$
  - Assume just 2 decays for X and Y, and that $\mathcal{L}_{int}$ is
    $$\mathcal{L}_{int} = g_1 X f_2^\dagger f_1 + g_2 X f_4^\dagger f_2 + g_3 Y f_1^\dagger f_3 + g_4 Y f_2^\dagger f_4 + h.c.$$



  - LO diagrams do not contribute to ε since
    $$\Gamma(\bar{X} \to f_1 \bar{f}_2) = |g_1^*|^2 I_{\bar{X}} = |g_1|^2 I_X = \Gamma(X \to \bar{f}_1 f_2)$$
    and $I_X = I_{\bar{X}}$ (phase space factors).
  - One-loop corrections:



$$\Gamma(X \to \bar{f}_1 f_2) = g_1 g_2^* g_3 g_4^* I_{XY} + (g_1 g_2^* g_3 g_4^* I_{XY})^* + \cdots$$
$$\Gamma(\bar{X} \to f_1 \bar{f}_2) = g_1^* g_2 g_3^* g_4 I_{XY} + (g_1^* g_2 g_3^* g_4 I_{XY})^* + \cdots$$

  - If f_{1-4} propagators are allowed to be on-shell (likely for heavy X and Y bosons) and f_{1-4} are relatively light, I_{XY} will be complex.

- $\Gamma(X \to \bar{f}_1 f_2) - \Gamma(\bar{X} \to f_1 \bar{f}_2) = 2i I_{XY} \mathrm{Im}(g_1 g_2^* g_3 g_4^*)$
$+2i I_{XY}^* \mathrm{Im}(g_1^* g_2 g_3^* g_4)$
$= 4 \mathrm{Im} I_{XY} \mathrm{Im}(g_1^* g_2 g_3^* g_4)$

- Similarly,

$$\Gamma(X \to \bar{f}_3 f_4) = g_1^* g_2 g_3^* g_4 I_{XY} + (g_1^* g_2 g_3^* g_4 I_{XY})^*$$

$$\Gamma(\bar{X} \to f_3 \bar{f}_4) = g_1 g_2^* g_3 g_4^* I_{XY} + (g_1 g_2^* g_3 g_4^* I_{XY})^*$$

$$\Gamma(X \to \bar{f}_3 f_4) - \Gamma(\bar{X} \to f_3 \bar{f}_4)$$
$$= 2i I_{XY} \mathrm{Im}(g_1^* g_2 g_3^* g_4) + 2i I_{XY}^* \mathrm{Im}(g_1 g_2^* g_3 g_4^*)$$
$$= 4 \mathrm{Im}(I_{XY}) \mathrm{Im}(g_1 g_2^* g_3 g_4^*)$$

- $$\varepsilon_X = \frac{1}{\Gamma_X}\Big[(B_2 - B_1)\big(\Gamma(X \to \bar{f}_1 f_2) - \Gamma(\bar{X} \to f_1 \bar{f}_2)\big) + (B_4 - B_3)\big(\Gamma(X \to \bar{f}_3 f_4) - \Gamma(\bar{X} \to f_3 \bar{f}_4)\big)\Big]$$

$$= \frac{1}{\Gamma_X}\Big[(B_2 - B_1) 4 \mathrm{Im}(I_{XY}) \mathrm{Im}(g_1^* g_2 g_3^* g_4) + (B_4 - B_3) 4 \mathrm{Im}(I_{XY}) \mathrm{Im}(g_1 g_2^* g_3 g_4^*)\Big]$$

$$= \frac{4}{\Gamma_X} \mathrm{Im}(I_{XY}) \mathrm{Im}(g_1 g_2^* g_3 g_4^*) \big[(B_4 - B_3) - (B_2 - B_1)\big]$$ (error in book)

- Repeating for Y decays, we find ~~$\varepsilon_X = -\varepsilon_Y$~~. $\Gamma_X \varepsilon_X = -\Gamma_Y \varepsilon_Y$ (error in book)
- 3 things are required for $\varepsilon \neq 0$
  $(\varepsilon \equiv \varepsilon_X + \varepsilon_Y) = \varepsilon_X\left(1 - \frac{\Gamma_X}{\Gamma_Y}\right)$
  1) There must be 2 baryon number violating bosons, each with $M > m_i + m_j$; $i, j = 1, \ldots, 4$ in the fermion loops. Otherwise, $\mathrm{Im}(I_{XY}) = 0$.

2) C and CP violation come from the interference between tree-and loop-level diagrams, which give rise to complex coupling constants.

- ε should be of the order α^N (which is small)
  - * α: "characterizes" the coupling constant of the loop particle(s)
  - * N: # of loops in lowest-order diagram whose interference with tree-level yields $\varepsilon \neq 0$

3) $m_X \neq m_Y$

- Otherwise, $\Gamma_X = \Gamma_Y$.

- More on thermal non-equilibrium
  - Assume that around the Planck time, when $T \gg m_X$, $n_X = n_{\bar{X}} \approx n_\gamma$
  - Thermal non-eq. occurs when there is an overabundance of $X, \bar{X}$ bosons.
  - For $T \lesssim m_X$, $n_X = n_{\bar{X}} \sim (m_X T)^{3/2} e^{-m_X/T} \ll n_\gamma$
  - For eq. to occur, processes which create and destroy $X, \bar{X}$ must satisfy $\Gamma > H$, H: expansion rate of universe
  - $\Gamma_{ANN} \propto n_X$, and decay is most important for maintaining eq. numbers of $X, \bar{X}$
  - Ignore annihilation

- Define the following rates:

Decay: $$\Gamma_D \approx \alpha m_X \begin{cases} m_X/T & T \gtrsim m_X \\ 1 & T \lesssim m_X \end{cases}$$

Creation: $$\Gamma_C \approx \Gamma_D \begin{cases} 1 & T \gtrsim m_X \\ \left(\frac{m_X}{T}\right)^{3/2} e^{-m_X/T} & T \lesssim m_X \end{cases}$$

2-2 B-violating scattering ($\bar{f}_1 f_2 \to \bar{f}_3 f_4$): $$\Gamma_S \approx n\sigma \approx T^3 \alpha^2 \frac{T^2}{(T^2+m_X^2)^2}$$

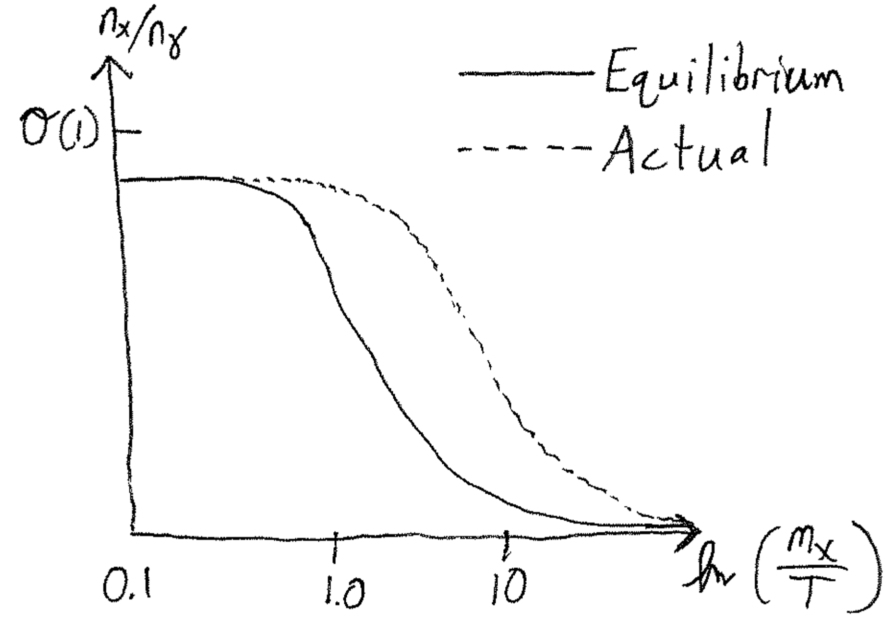
Expansion of Universe: $$H \approx \sqrt{g_*}\,\frac{T^2}{m_{Pl}}$$

where $\alpha \sim \frac{g^2}{4\pi}$ is the coupling strength of the X

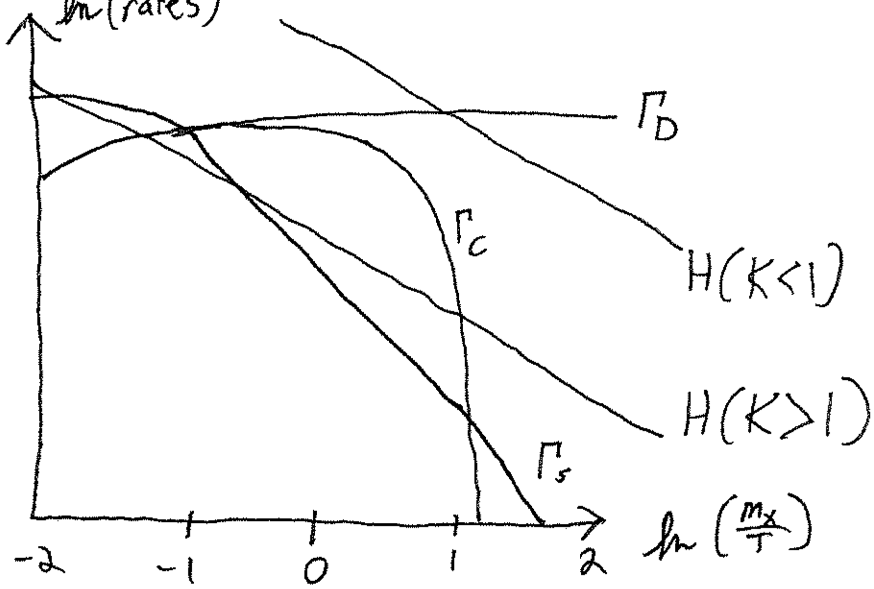
g_* is the degrees of freedom of relativistic ("massless") particles in the plasma.

m_{Pl} is the Planck mass, $m_P \approx 1.2 \times 10^{19}$ GeV

- Graph of # of $X, \bar{X}$ bosons per comoving volume



- Graph of rates vs. $\frac{m_X}{T}$



- Define $K \equiv \left(\frac{\Gamma_D}{2H}\right)_{T=m_X} = \frac{\alpha m_{Pl}}{3.3 g_*^{1/2} m_X}$

  * It measures strength of Γ_D at the "crucial epoch" $(T \sim m_X)$

  * For $T \lesssim m_X$, it measures the strength of Γ_C and Γ_S:

$$\frac{\Gamma_C}{H} \sim \left(\frac{m_X}{T}\right)^{3/2} e^{-\frac{m_X}{T}} K$$

$$\frac{\Gamma_S}{H} \sim \alpha \left(\frac{T}{m_X}\right)^5 K$$

  * If $K \ll 1$ (implying m_X is large), then at $T \sim m_X$, $\Gamma_D < H$, and the X's become overabundant. When they do decay at $t \sim \frac{1}{\Gamma_D}$ (or $T \sim \sqrt{K}\, m_X$), $n_X = n_{\bar{X}} \approx n_\gamma$, and they decay without exponential suppression.

* As an approximation, $n_B \sim \varepsilon n_X \sim \varepsilon n_\gamma$, and the entropy density is $s \sim g_* n_\gamma$. The produced baryon asymmetry is

$$B \equiv \frac{n_B}{s} \sim \frac{\varepsilon n_\gamma}{g_* n_\gamma} \sim \frac{\varepsilon}{g_*}$$

- Take $g_* = 10^2$ (or 10^3). Then $\varepsilon \sim 10^{-8}$ to 10^{-7} can account for $B \sim 10^{-10}$.
- $K \ll 1$ implies $m_X \gg \frac{\alpha}{\sqrt{g_*}} m_{Pl} \sim \frac{\alpha}{10^{-2}} 10^{16}\,\mathrm{GeV} = \alpha 10^{18}\,\mathrm{GeV}$

  For a gauge boson, $\alpha = \frac{g_{gauge}^2}{4\pi} \equiv \alpha_{GUT} \approx \frac{1}{45}$.

  This can be much smaller for a Higgs.
- $K \gg 1$ will not produce a baryon asymmetry.
- $K \approx 1$ can produce the asymmetry, but it requires more formalism.

Electroweak Baryogenesis (EWB)

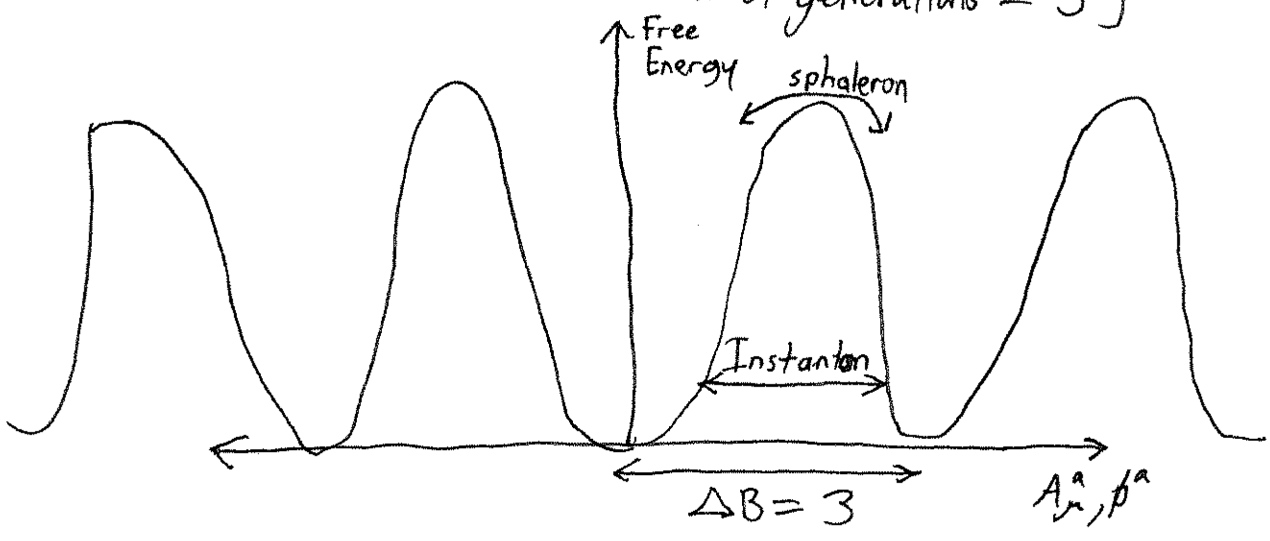
- Predicts the baryon asymmetry occurs at the EWSB phase transition (EWPT)

- Experimentally testable in the near-future since it predicts new particles only somewhat above the EW scale

- Assumes a hot, radiation-dominated early universe with zero net baryon charge

- The phase transition occurs around $T \lesssim 100\,\text{GeV}$ when the Higgs assumes a VEV and $SU(2)_L \times U(1)_Y$ breaks to $U(1)_{EM}$.
- The phase transition must be strong first-order.
    - First order PTs occur more rapidly than higher-order PTs.
    - The PT exists within the SM, but in order for it to be first order, $m_h \lesssim 70\,\text{GeV}$. Thus, EWB requires BSM physics and predicts particles on the order of the EW scale.

- Sphalerons (and Instantons)
  - A sphaleron is a static solution to the EW field equations of the SM. Its name is Greek for "ready to fall," which is appropiate since it corresponds to a saddle point in configuration space: the lowest point between two Θ-vacua.
  - The Θ-vacuum config of EW theory is such that different vacua correspond to different baryon numbers
    - * Anomalous non-conservation of baryon number
    - * Adjacent Θ-vacua differ in $B+L$ by $2N_G$ and in B by N_G (N_G = # of generations = 3)



  - Sphalerons are inherently non-perturbative.

via instantons (or tunneling)

- The rate of B-violation is proportional to $e^{-4\pi/\alpha_w}$, which is quite small. Thus, instantons were and are unimportant.
- $\mathcal{O}(100)$ GeV temperatures can trigger sphalerons. Thus, spholerons are effective in the unbroken phase ($\langle\Phi\rangle=0$), but are highly supressed in the broken phase.

- There are 3 main steps in EWB
  1) At the EWPT, the cosmological plasma, in which $\langle\Phi\rangle=0$, will begin to form "bubbles" of broken symmetry ($\langle\Phi\rangle\neq0$). Assuming the underlying theory contains C and CP violation (as required by the Sakharov conditions), particles in the plasma which scatter with the bubble walls will create C and CP asymmetries in front of the bubble wall.

  2) The asymmetries which occur outside the bubbles will bias sphalerons to produce more baryons than antibaryons.

3) As the bubble walls expand, baryons will be eaten by the bubbles, in which sphaleron transitions are greatly suppressed, preventing the asymmetry from being "washed-out."

- Creating CP asymmetries
  - A net CP asymmetry is required to bias the the sphalerons to produce a baryon asymmetry
  - What's important is n_L, the density of left-handed fermions over their antiparticles
  - An equal and opposite density n_R will also be created, but only n_L will matter since sphalerons correspond to transitions between $SU(2)_L$ vacua.
  - The baryon density n_B is

$$\partial_\mu j_B^\mu = -\frac{N_f}{2}\left[k_{ws}^{(1)}(T,x)n_B(x) + k_{ws}^{(2)}(T,x)n_L(x)\right]$$

j_B^μ: baryon number current density

x: coordinate orthogonal to bubble wall

$k_{ws}^{(j)}(T,x)$: weak sphaleron rate constants which account for ~~changes~~ the change in rate outside and inside the bubbles

$$k_{ws}^{(1)}(T,x)\Big|_{out} = R\cdot\frac{\Gamma_{ws}}{VT^3} \qquad k_{ws}^{(2)}(T,x) = \frac{\Gamma_{ws}}{VT^3}$$

$$R \simeq \frac{15}{4} \qquad \frac{\Gamma_{ws}}{VT^3}\Big|_{out} \cong 120\,\alpha_w^5\,T$$

(weak sphaleron rate per unit volume for N_f fermion families)

$$k_{ws}^{(1)}\Big|_{in} = \frac{13N_f}{2}\frac{\Gamma_{ws}}{VT^3}, \quad k_{ws}^{(2)}\Big|_{in} \simeq 0$$

- The interaction of particles with the bubble wall is much faster than k_{ws}, and so the formula for $\partial_\mu j^\mu_B$ may be decoupled from the evolution of n_L.
- The following contribute to the evolution of n_L:
  a) C- and CP- violating interactions with the bubble wall
  b) Interactions which change particle-number and drive the plasma to chemical equilibrium.
  c) flavor oscillations due to off-diagonal mass-matrix elements
  d) scattering and creation-annihilation reactions

Other Baryogenesis Hypotheses

- Baryogenesis through leptogenesis
  - Predicts that at temperatures around 10^{10} GeV a lepton asymmetry was generated through decays of heavy Majorana fermions
  - Sphalerons, which conserve $B-L$ but break $B+L$, generate a baryon asymmetry from the lepton asymmetry
- SUSY condensate (Affleck–Dine)
  - In SUSY, there are scalar superpartners of baryons or leptons, χ
  - If the potential $U(\chi)$ is not symmetric under $\chi \to e^{i\theta\chi}$ (B charge not conserved in χ self-interaction), then, as χ relaxes to 0, the field "rotates" about the origin, acquiring a large baryonic charge.
  - As temperatures decrease, χ decays through B (or L) conserving processes, transferring its baryonic charge to the quarks (or leptons)
  - A problem with this theory is that it predicts $\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 1$
  - Predicts astronomically large quantities of antimatter

- Evaporation of primordial black holes
  - Hawking radiation spectrum is emitted in thermal equilibrium, but the strong gravitational field of the black hole creates non-equilibrium conditions
  - Suppose the black hole emits a heavy X-boson which decays close to the event horizon into a light baryon and heavy antibaryon or vice-versa with different decay rates:

    $$\Gamma(X \to L + \bar{H}) \neq \Gamma(X \to \bar{L} + H)$$

  - Gravitational "back-capture" of the heavy particle is more likely than for the light one, thus creating the asymmetry

- Gravitational repulsion of matter and antimatter
  - This would separate regions of matter and antimatter.
  - Unlikely since it disagrees with general relativity, which predicts that antimatter is attracted to both matter and antimatter