Baryogenesis through Leptogenesis

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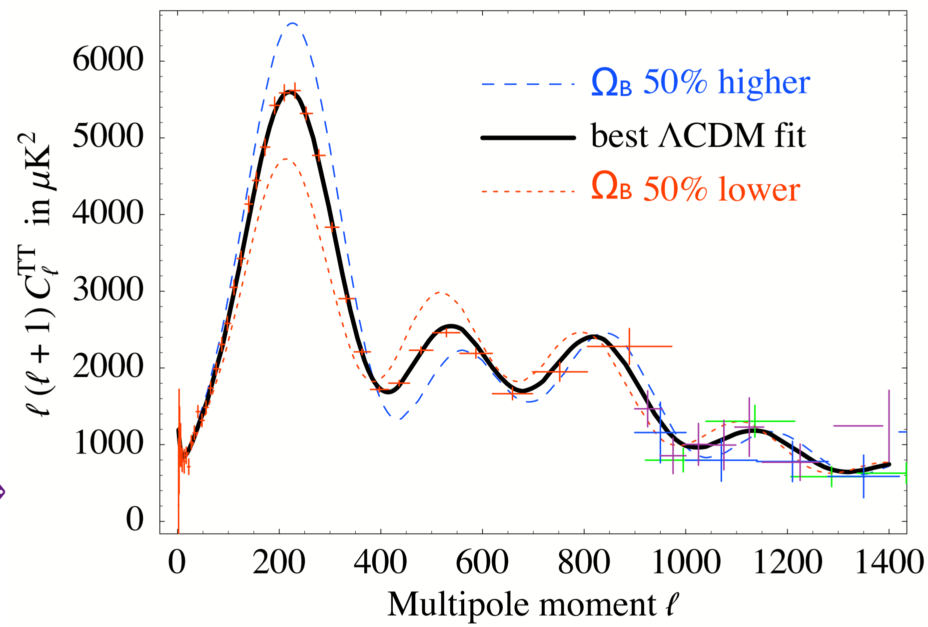
Evidence of Matter-Antimatter Asymmetry

- CMB anisotropy

$$\frac{\Delta T}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi) \qquad C_l = \langle |a_{lm}|^2 \rangle$$

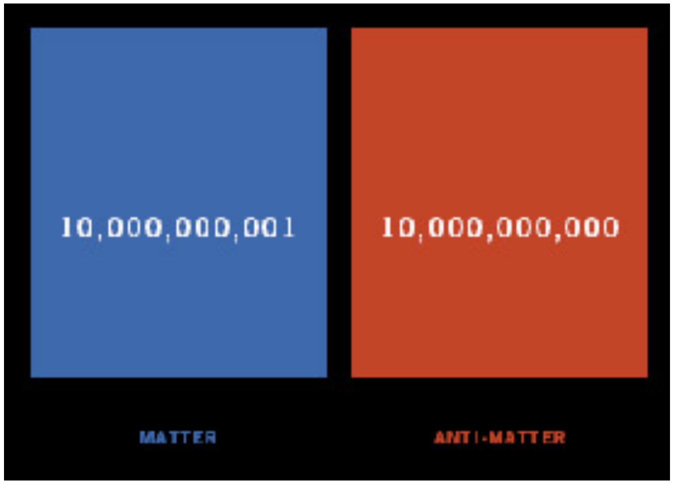


- Big Bang Nucleosynthesis
  - primordial deuterium abundance agree with WMAP $\Longleftrightarrow$
  - ^{4}He & ^{7}Li $\Longleftrightarrow$ discrepancies

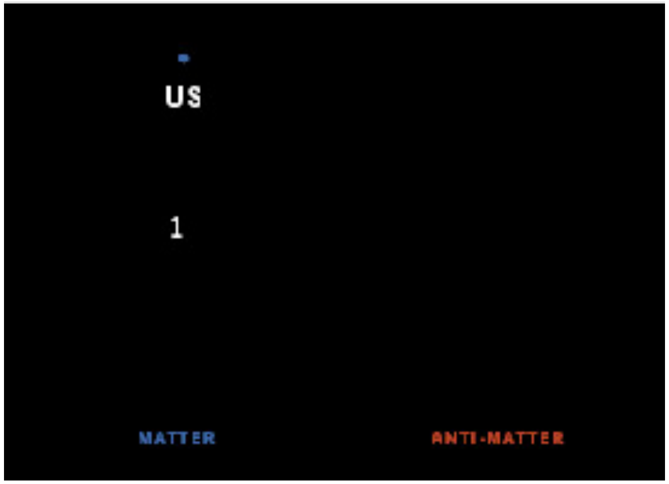
- WMAP + Deuterium Abundance

$$\frac{n_B}{n_\gamma} \equiv \eta_B = (6.1 \pm 0.3) \times 10^{-10}$$

Three Sakharov Conditions



Early Universe



Universe Now

[Picture credit: H. Murayama]

- **Baryon number can be generated dynamically, if**
    - violation of baryon number
    - violation of Charge (C) and Charge Parity (CP)
    - departure from thermal equilibrium

Group Work

In the Standard Model, what are the accidental symmetries?

Baryon Number Asymmetry beyond SM

- Within the SM:
  - CP violation in quark sector not sufficient to explain the observed matter-antimatter asymmetry of the Universe
  - accidental symmetries L_e, L_μ, L_τ, total L
  - massless neutrinos, no cLFV

- **neutrino oscillation ⇒ non-zero neutrino masses**
  - physics beyond the Standard Model
  - new CP phases in the neutrino sector

- neutrino masses open up a new possibility for baryogenesis   Fukugita, Yanagida, 1986

Leptogenesis

Plans

- Theoretical Foundation of Baryogenesis:
    - Sakharav's Three Conditions
    - Mechanisms for Baryogenesis & Their Problems
    - Sources of CP violation
- Standard Leptogenesis ("Majorana" Leptogenesis)
- Dirac Leptogenesis
- Gravitino Problem
- Non-standard Scenarios
    - Resonant Leptogenesis
    - Soft Leptogenesis
    - Non-thermal Leptogenesis
- Connection between leptogenesis & low energy CP violation

References

- A. Riotto, hep-ph/9901362
- M. Trodden, hep-ph/0411301
- W. Büchmuller, hep-ph/0502169
- "TASI 2006 Lectures on Leptogenesis," M.-C. Chen, hep-ph/0703087

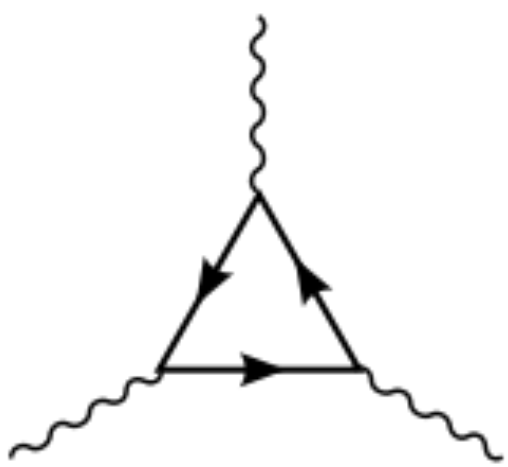
Three Sakharov Conditions (1)

Baryon Number Violation

- necessary for baryon symmetric Universe (B=0) → Universe with B ≠ 0
- GUT theories:
  - quarks and leptons in same representations → B-violation naturally through interactions with gauge or scalar fields
- SM:
  - B & L accidental symmetries
  - preserved at tree level

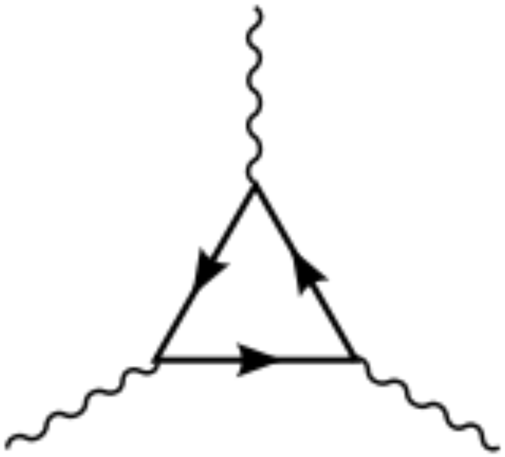
Three Sakharov Conditions

- Standard Model:
  - B & L accidental symmetries
  - Classically: B & L conserved
  - At quantum level: non-vanishing ABJ triangular anomaly through interactions with EW gauge fields



$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_f}{32\pi^2}\left(g^2 W_{\mu\nu}^p \widetilde{W}^{p\mu\nu} - g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)$$

Group Work



$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_f}{32\pi^2}\left(g^2 W^p_{\mu\nu}\widetilde{W}^{p\mu\nu} - g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)$$

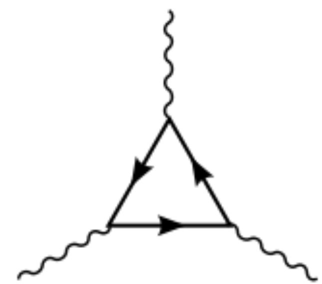
What are the broken symmetries?

Are there any unbroken symmetries?

Three Sakharov Conditions (1)

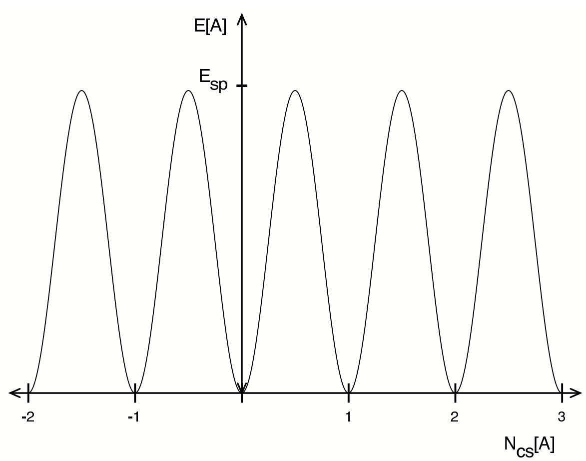
- Classically: B & L conserved
- At quantum level, non-vanishing ABJ triangular anomaly through interactions with EW gauge fields

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_f}{32\pi^2}\left(g^2 W_{\mu\nu}^p \widetilde{W}^{p\mu\nu} - g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)$$



$\Rightarrow$ (B+L) violated, (B-L) preserved

- vacuum structure of non-abelian gauge theories:
  - changes in B & L $\leftrightarrow$ changes in topological charges



$$\Delta B = \Delta L = N_f \Delta N_{cs} = \pm 3n,$$

$$\mathcal{O}_{B+L} = \prod_{i=1,2,3} (q_{L_i} q_{L_i} q_{L_i} \ell_{L_i})$$

Three Sakharov Conditions (1)

- 12 fermion Processes, e.g.

$$\overline{u} + \overline{d} + \overline{c} \rightarrow d + 2s + 2b + t + \nu_e + \nu_\mu + \nu_\tau$$

- T=0: transition rate negligible

Kuzmin, Rubakov, Shaposhnikov

$$\Gamma \sim e^{-S_{int}} = e^{-4\pi/\alpha} = \mathcal{O}(10^{-165})$$

- In thermal bath: transition by thermal fluctuations
  - at T > height of barrier: no Boltzmann suppression
    - $T < T_{ew}$: $\frac{\Gamma_{B+L}}{V} = k\frac{M_W^7}{(\alpha T)^3} e^{-\beta E_{ph}(T)} \sim e^{\frac{-M_W}{\alpha k T}}$ $\quad E_{sp}(T) \simeq \frac{8\pi}{g} \langle H(T) \rangle$
    - $T > T_{ew}$: $\frac{\Gamma_{B+L}}{V} \sim \alpha^5 \ln \alpha^{-1} T^4$
  - Sphelaron processes in thermal equilibrium

$\Rightarrow$ B-violating process unsuppressed

$$T_{EW} \sim 100 \text{ GeV} < T < T_{sph} \sim 10^{12} \text{ GeV}$$

Group Work

process	branching fraction	ΔB
$X \to qq$	α	$2/3$
$X \to \overline{q}\overline{\ell}$	$1-\alpha$	-1/3
$\overline{X} \to \overline{qq}$	$\overline{\alpha}$	-2/3
$\overline{X} \to q\ell$	$1-\overline{\alpha}$	$1/3$

What is the net Baryon number produced due to X, $\overline{X}$ decay?

What is the condition such that the net Baryon number is non-zero?

Three Sakharov Conditions (2)

process	branching fraction	ΔB
$X \to qq$	α	2/3
$X \to \overline{q}\overline{\ell}$	$1-\alpha$	-1/3
$\overline{X} \to \overline{q}\overline{q}$	$\overline{\alpha}$	-2/3
$\overline{X} \to q\ell$	$1-\overline{\alpha}$	1/3

C and CP Violations

- superheavy X boson decay
  - Baryon number produced

$$B_X = \alpha\left(\frac{2}{3}\right) + (1-\alpha)\left(-\frac{1}{3}\right) = \alpha - \frac{1}{3} \,,$$

$$B_{\overline{X}} = \overline{\alpha}\left(-\frac{2}{3}\right) + (1-\overline{\alpha})\left(\frac{1}{3}\right) = -\left(\overline{\alpha} - \frac{1}{3}\right) \,,$$

  - net Baryon number $\epsilon \equiv B_X + B_{\overline{X}} = (\alpha - \overline{\alpha})$
  - if CP is conserved: $\alpha = \overline{\alpha}, \quad \epsilon = 0.$

- Toy Model: two heavy scalar fields: X, Y; 4 fermions f_i

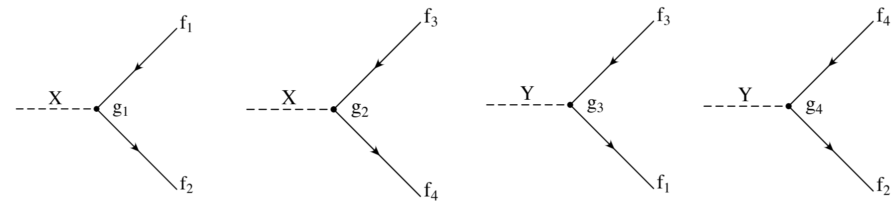
$$\mathcal{L} = g_1 X f_2^\dagger f_1 + g_2 X f_4^\dagger f_3 + g_3 Y f_1^\dagger f_3 + g_4 Y f_2^\dagger f_4 + h.c.$$

  - possible decays

$$X \to \overline{f}_1 + f_2,\ \overline{f}_3 + f_4 \,,$$
$$Y \to \overline{f}_3 + f_1,\ \overline{f}_4 + f_2 \,,$$

Three Sakharov Conditions (2)

- at tree level:



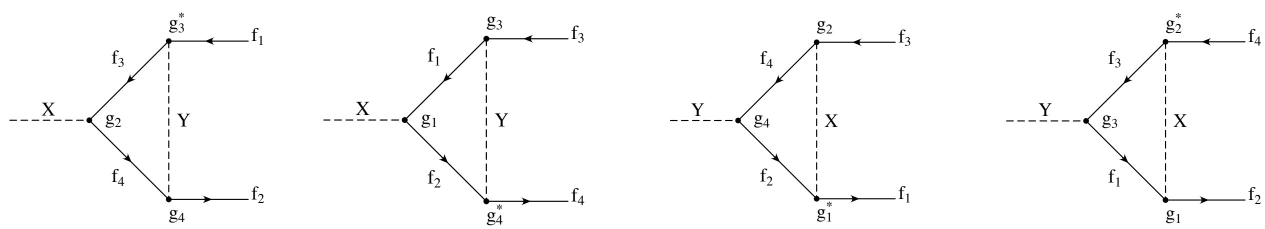
$$\Gamma(X \to \overline{f}_1 + f_2) = |g_1|^2 I_X$$

$$\Gamma(\overline{X} \to f_1 + \overline{f}_2) = |g_1^*|^2 I_{\overline{X}}$$

phase space factor I_X and $I_{\overline{X}}$ equal

$\Rightarrow$ no asymmetry

- at one-loop



$$\Gamma(X \to \overline{f}_1 + f_2) = g_1 g_2^* g_3 g_4^* I_{XY} + c.c.$$

$$\Gamma(\overline{X} \to f_1 + \overline{f}_2) = g_1^* g_2 g_3^* g_4 I_{XY} + c.c.$$

I_{XY}: phase space + kinematics

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

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

Three Sakharov Conditions (2)

- total asymmetry

$$\epsilon_X = \frac{(B_1 - B_2)\Delta\Gamma(X \to \overline{f}_1 + f_2) + (B_4 - B_3)\Delta\Gamma(X \to \overline{f}_3 + f_4)}{\Gamma_X}$$

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

$$\epsilon_Y = \frac{4}{\Gamma_Y} Im(I'_{XY}) Im(g_1^* g_2 g_3^* g_4)[(B_2 - B_4) - (B_1 - B_3)]$$

Group Work

Is it necessary that the total asymmetry $\epsilon = \epsilon_X + \epsilon_Y$ is non-zero?

If not, what are the conditions that must be satisfied in order to have non-vanishing total asymmetry?

Three Sakharov Conditions (2)

- total asymmetry

$$\epsilon_X = \frac{(B_1 - B_2)\Delta\Gamma(X \to \overline{f}_1 + f_2) + (B_4 - B_3)\Delta\Gamma(X \to \overline{f}_3 + f_4)}{\Gamma_X}$$

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$$\epsilon_Y = \frac{4}{\Gamma_Y} Im(I'_{XY}) Im(g_1^* g_2 g_3^* g_4)[(B_2 - B_4) - (B_1 - B_3)]$$

- non-zero total asymmetry $\varepsilon = \varepsilon_X + \varepsilon_Y$
  - two B-violating bosons with masses > sum of loop fermion masses
  - complex coupling constants: CP violation from interference between tree and 1-loop diagrams
  - non-degenerate X and Y masses

Three Sakharov Conditions (3)

Departure from Thermal Equilibrium

- B: odd under C and CP
- in equilibrium: $$< B >_T = \mathrm{Tr}[e^{-\beta H} B] = \mathrm{Tr}[(CPT)(CPT)^{-1} e^{-\beta H} B)]$$ $$= \mathrm{Tr}[e^{-\beta H} (CPT)^{-1} B (CPT)] = -\mathrm{Tr}[e^{-\beta H} B]$$

  $\Rightarrow$ average $\langle B \rangle_T = 0$

- Possible ways to achieve departure from thermal equilibrium
  - out-of-equilibrium decay of heavy particles:
    - GUT baryogenesis, leptogenesis
  - EW phase transition: EW baryogenesis

Three Sakharov Conditions (3)

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Three Sakharov Conditions (3)

- Out-of-equilibrium decay of heavy particles in **expanding universe**
- superheavy particle X: decay rate Γ_X , Mass M_X
- at T ~ M_X : become non-relativistic
  - if $\Gamma_X < H$:
    - X cannot decay on the time scale of the expansion
    - remains initial thermal abundance $n_X = n_{\overline{X}} \sim n_\gamma \sim T^3, \text{ for } T \lesssim M_X$
- at T > M_X : interact so weakly, cannot catch up expansion
  - decouple from thermal bath while relativistic
  - populate at T ~ M_X with abundance >> than in equilibrium
- recall: in equilibrium

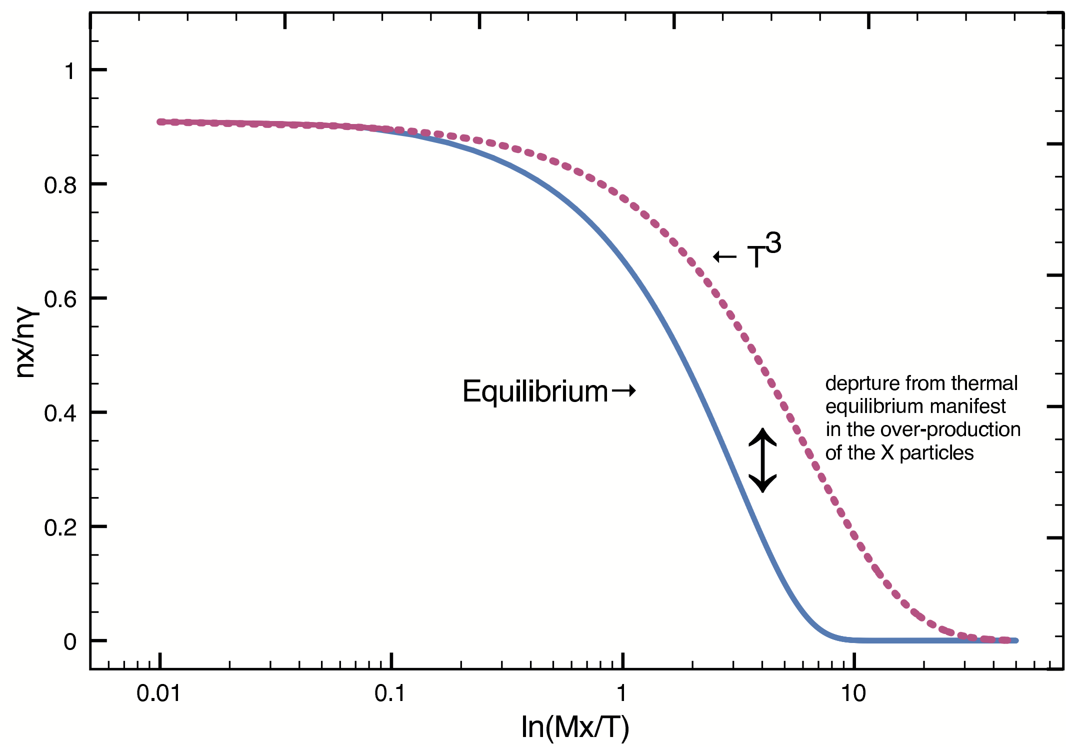
$$n_X = n_{\overline{X}} \simeq n_\gamma \quad \text{for} \quad T \gtrsim M_X \ ,$$

$$n_X = n_{\overline{X}} \simeq (M_X T)^{3/2} e^{-M_X/T} \ll n_\gamma \quad \text{for} \quad T \lesssim M_X$$

Three Sakharov Conditions (3)

- Over abundance at $T < M_X$
  $\Rightarrow$ departure from thermal equilibrium

  $\Rightarrow$ final non-vanishing B-asymmetry



$$\frac{\Gamma}{H} \propto \frac{1}{M_X}$$

To have $\Gamma < H$
$\Rightarrow$ heavy particle

decay thru renormalizable operators
$\Rightarrow$

Gauge boson: $M_X \geq 10^{(15\text{-}16)}$ GeV
Scalar fields: $M_X \geq 10^{(10\text{-}16)}$ GeV

Precise computation
$\Rightarrow$ Boltzmann equations

Relating ΔB to ΔL

- weakly couple plasma: chemical potential
- SM: N_f generations of fermions + 1 Higgs
  - $(5N_f + 1)$ chemical potential μ_i
  - **number density** of non-interacting, massless fermions

$$n_i - \overline{n}_i = \frac{1}{6} g T^3 \begin{cases} \beta\mu_i + \mathcal{O}((\beta\mu_i)^3), & \text{fermions} \\ 2\beta\mu_i + \mathcal{O}((\beta\mu_i)^3), & \text{bosons} . \end{cases}$$

- **thermal equilibrium → relations among μ_i**
  - sphaleron process O_{B+L} : $\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$
  - QCD instanton processes, $\prod_i (q_{L_i} q_{L_i} u^c_{R_i} d^c_{R_i})$: $\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0$
  - hypercharge charge: $\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + \frac{2}{N_f}\mu_H) = 0$

Relating ΔB to ΔL

- Yukawa coupling and gauge interactions:

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

  - T=100 - 10^{12} GeV: gauge interactions in equilibrium
  - Yukawa interactions: more restricted range of temperatures → flavor effects

- B and L in terms of chemical potentials:

$$n_B = \tfrac{1}{6} g B T^2 \qquad n_L = \tfrac{1}{6} g L_i T^2$$

$$B = \sum_i (2\mu_{q_i} + \mu_{u_i} + \mu_{d_i}) \qquad L = \sum_i L_i, \quad L_i = 2\mu_{\ell_i} + \mu_{e_i}$$

- equilibrium among generations:

$$\mu_e = \frac{2N_f+3}{6N_f+3}\mu_\ell, \quad \mu_d = -\frac{6N_f+1}{6N_f+3}\mu_\ell, \quad \mu_u = \frac{2N_f-1}{6N_f+3}\mu_\ell \quad \mu_q = -\frac{1}{3}\mu_\ell, \quad \mu_H = \frac{4N_f}{6N_f+3}\mu_\ell$$

Relating ΔB to ΔL

- Corresponding B & L asymmetries:

$$B = -\frac{4}{3} N_f \mu_\ell \qquad L = \frac{14N_f^2 + 9N_f}{6N_f + 3}\mu_\ell$$

- Relation between B and L:

$$B = c_s(B-L), \qquad L = (c_s - 1)(B-L)$$

  - where

$$c_s = \frac{8N_f + 4}{22N_f + 13}$$

  - For model with N_H Higgses

$$c_s = \frac{8N_f + 4N_H}{22N_f + 13N_H}$$

-

Mechanisms for Baryogenesis

- GUT Baryogenesis
  - single particle physics interaction at high T

$$G \rightarrow H \rightarrow ..... \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

  - B-violation natural
    - quarks & leptons in same representation
    - superheavy gauge boson mediating B-changing processes
  - C & CP violation: naturally built in
  - Out-of-equilibrium
    - GUT effects at very early times
    - cosmic expansion much faster (than gauge interactions)
    - decay inherently out-of-equilibrium $\Gamma < H$

Mechanisms for Baryogenesis

- GUT Baryogenesis
  - problems:
    - require high reheating temperature after inflation → dangerous production of relics -- gravitino problem
    - extremely hard to test GUT models experimentally at colliders
    - EW theory violates baryon number and can erase pre-existing asymmetry, unless GUT mechanism generates excess in (B-L) → SO(10) attractive

Mechanisms for Baryogenesis

- EW Baryogenesis
  - departure from thermal equilibrium provided by strong 1st order phase transition
  - can be tested at collider experiments
  - problems:
    - require more CP violation than provided in SM (may be found in SUSY)
    - need strong enough 1st order phase transition
    - MSSM: strong bound on Higgs mass < 120 GeV
      - stringent constraints on SUSY parameter space

Sources of CP Violation: SM

- SM: CP is not exact symmetry in weak interactions (Kaon & B-meson systems)
- charged current interactions in weak basis

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \overline{U}_L \gamma^\mu D_L W_\mu + h.c. \qquad \text{where } U_L = (u, c, t)_L \text{ and } D_L = (d, s, b)_L$$

- rotate to mass basis

$$\mathrm{diag}(m_u, m_c, m_t) = V_L^u M^u V_R^u \qquad U'_L \equiv V_L^u U_L \text{ and } D'_L \equiv V_L^d D_L$$

$$\mathrm{diag}(m_d, m_s, m_d) = V_L^d M^d V_R^d \,. \qquad U_{CKM} \equiv V_L^u (V_L^d)^\dagger$$

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \overline{U}'_L U_{CKM} \gamma^\mu D'_L W_\mu + h.c.$$

Sources of CP Violation: SM

- CKM: 3 families, unitary matrix
  - 3 angles
  - (6-5) = 1 phase
- CP phase in CKM matrix:

$$B \simeq \frac{\alpha_w^4 T^3}{s} \delta_{CP} \simeq 10^{-8} \delta_{CP} \qquad \delta_{CP} \simeq \frac{A_{CP}}{T_C^{12}} \simeq 10^{-20}$$

- effects of CP violation suppressed by small quark mixing

$$A_{CP} = (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2)\,(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2) \cdot J$$

$$\longrightarrow \quad B \sim 10^{-28}$$

  - too small to account for the observed value

$$B \sim 10^{-10}$$

Sources of CP Violation: MSSM

- soft SUSY breaking terms → new sources of CPV
- superpotential of MSSM

$$W = \mu \hat{H}_1 \hat{H}_2 + h^u \hat{H}_2 \hat{Q} \hat{u}^c + h^d \hat{H}_1 \hat{Q} \hat{d}^c + h^e \hat{H}_1 \hat{L} \hat{e}^c$$

- parameters in soft SUSY breaking sector
  - tri-linear couplings:

$$\Gamma^u H_2 \widetilde{Q} \widetilde{c}^c + \Gamma^d H_1 \widetilde{Q} \widetilde{d}^c + \Gamma^e H_1 \widetilde{L} \widetilde{e}^c + h.c. \qquad \Gamma^{(u,d,e)} \equiv A^{(u,d,e)} \cdot h^{(u,d,e)}$$

  - bi-linear coupling in Higgs sector: $\mu B H_1 H_2$
  - gaugino masses: M_i for $i = 1, 2, 3$
  - soft scalar masses: $\widetilde{m}_f$
- cMSSM w/ mSUGRA → 2 physical phases → soft leptogenesis

$$\phi_A = \mathrm{Arg}(AM), \quad \phi_\mu = -\mathrm{Arg}(B)$$