Baryogenesis from symmetry principle

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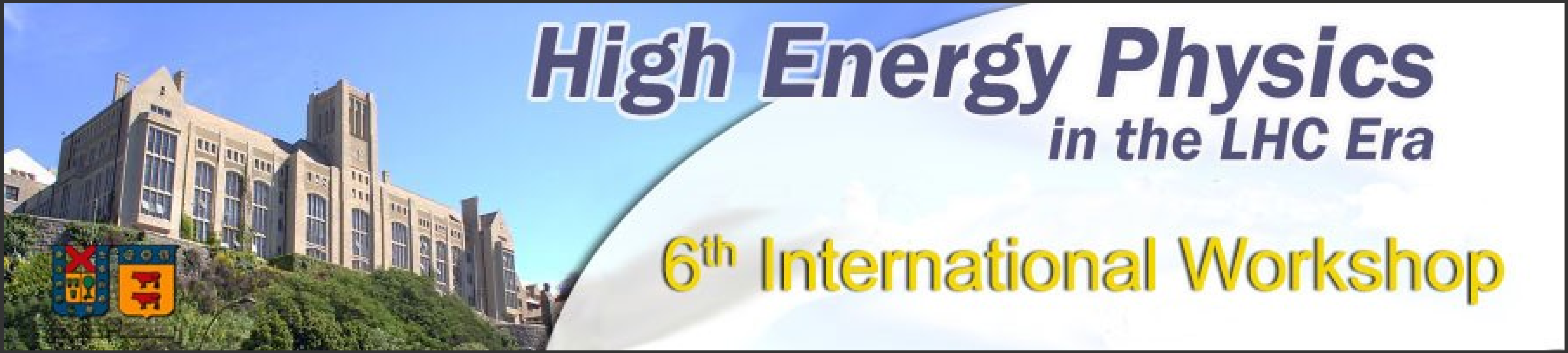

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Outline

- Motivations (review)
- Early Universe effective theories
- U(1) symmetries and Noether's charges
- Example: the Standard Model (SM)

Baryonic content of the Universe

- BBN: t ~ 1 seconds (T ~ MeV)
- CMB: t ~ 380000 years (T ~ eV)
- Both give $n_B/s \sim 10^{-10}$ to within 10% precision
- Impressive agreements between the two instill confidence in the *Standard Model of Cosmology* (SMC)
- *No evidence* of *primordial antimatter* on various scales:
  - Galaxy (antiproton flux consistent with secondary production)
  - Clusters of galaxies (no gamma ray from matter-antimatter annihilations)
  - Observable Universe (no distortion on CMB background) [Cohen, De Rujula & Glashow (1997)]

Is baryogenesis necessary?

- Starting with baryon-antibaryon symmetric Universe, their annihilations freeze out at t ~ 10^{-2} s (T ~ 20 MeV) with tiny $n_B/s = n_{\bar{B}}/s \sim 10^{-19}$ (but today $n_B/s \sim 10^{-10}$, $n_{\bar{B}}/s \sim 0$)
- Statistical fluctuation: at T > 1 GeV $\frac{1}{\sqrt{N_B}} \sim \frac{1}{\sqrt{N_{\bar{B}}}} \sim 10^{-40}$ [Riotto (1998)]
- Initial condition: **inflation** makes this very unlikely
- To explain this small $(n_B - n_{\bar{B}})/s \sim 10^{-10}$, a dynamical generation mechanism involving the interplay between *particle physics* and *cosmology* is called for

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T_{BBN} < Baryogenesis < T_{RH}

(MeV) ???

Ingredients for baryogenesis

- a.k.a. Sakharov's conditions (1967)
- 1) **Baryon number violation** (starting from B = 0)
- 2) Both **C and CP violation**

$$\Gamma(X \to B_L B_L) + \Gamma(X \to B_R B_R) \neq \Gamma(X \to B_R^c B_R^c) + \Gamma(X \to B_L^c B_L^c)$$

- 3) **Out-of-equilibrium condition** $n_B^{\mathrm{eq}}(\mu_B = 0) = n_{\bar{B}}^{\mathrm{eq}}(\mu_{\bar{B}} = 0)$
  - 1st order phase transition $CPT : m_B = m_{\bar{B}}$
  - Cosmic expansion $\Gamma(T) \lesssim H(T)$
- <u>All part of the SM and SMC</u>

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  - 1^{st} order phase transition $CPT : m_B = m_{\bar{B}}$
  - Cosmic expansion $\Gamma(T) \lesssim H(T)$
- All part of the SM and SMC but
  - Insufficient CP violation [Huet & Sather (1995)]

$$\frac{1}{T_c^{12}} J(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2) \sim 10^{-20}$$

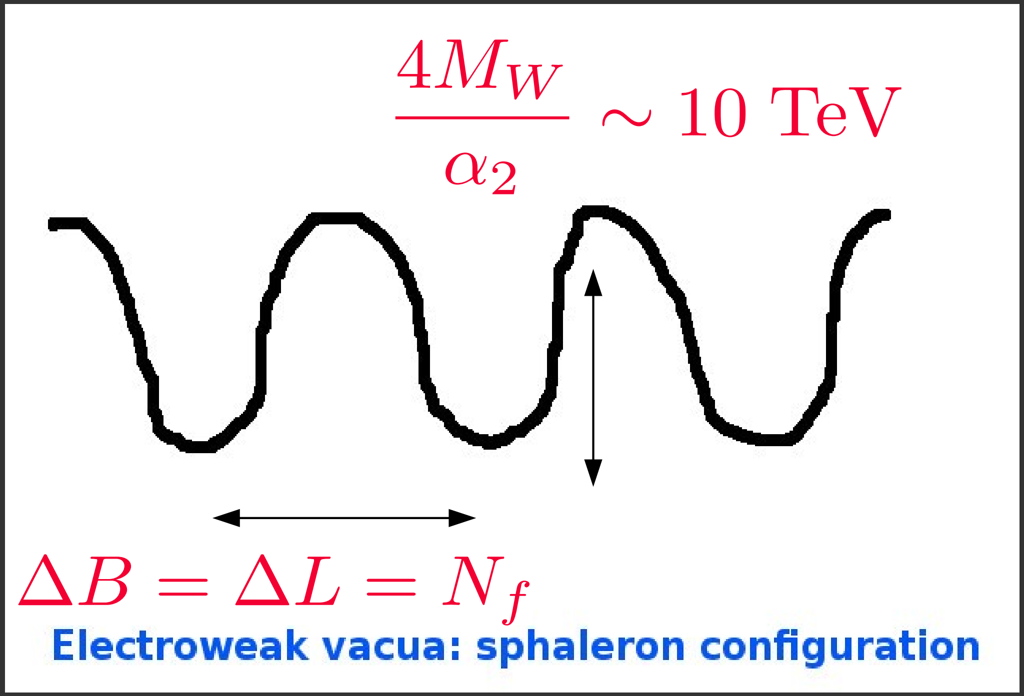
  - 1^{st} order SM EW phase transition requires $m_H < 70$ GeV

[Jansen (1995)]

Baryon number violation

Sk1: B violation

- Part of SM: Nontrivial vacua for non-abelian gauge theory



Electroweak vacua: sphaleron configuration

Anomalous symmetries

$$U(1)_B - SU(2)_L - SU(2)_L$$

$$U(1)_{L_\alpha} - SU(2)_L - SU(2)_L$$

T=0, quantum tunneling

$$\sim \exp\left(-\frac{4\pi}{\alpha_2}\right)$$ [t'Hooft (1976)]

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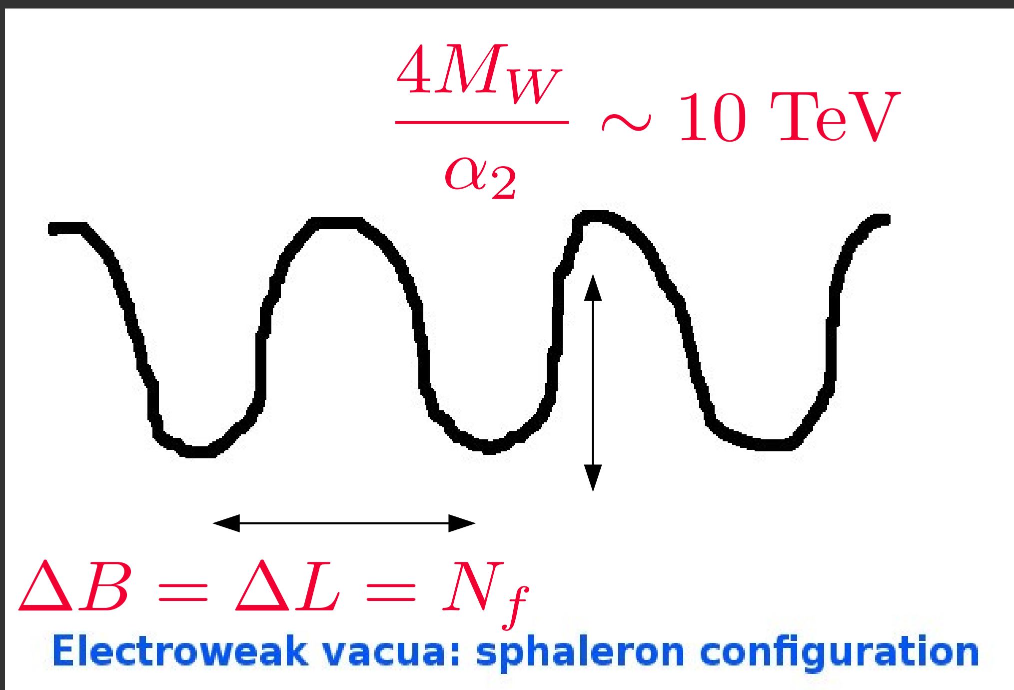


Anomalous symmetries

$$U(1)_B - SU(2)_L - SU(2)_L$$

$$U(1)_{L_\alpha} - SU(2)_L - SU(2)_L$$

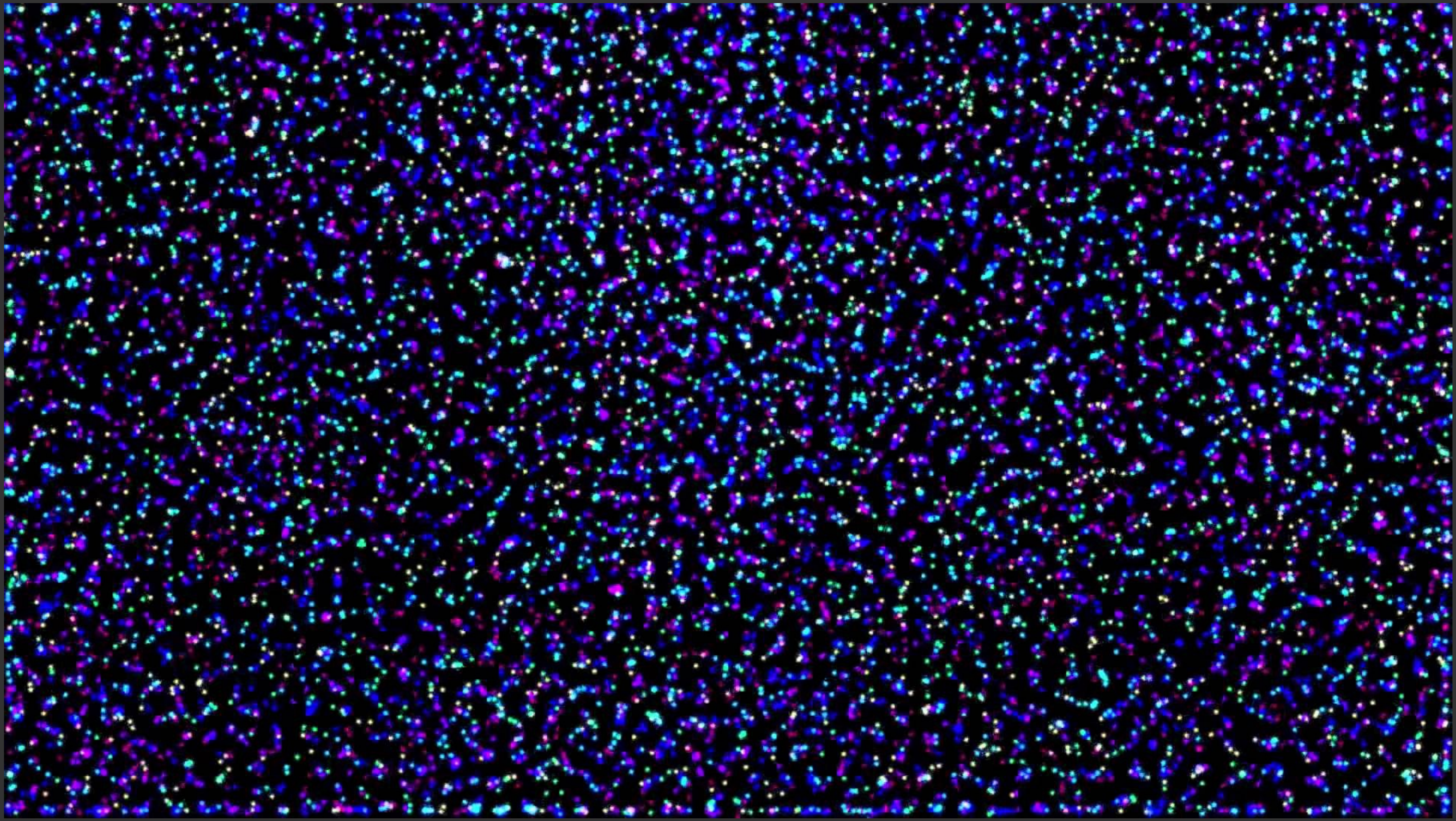
$T > T_{EWPT}$, no suppression

$\Gamma_{\mathrm{EWsp}} \sim \alpha_2^4 T$ [Kuzmin, Rubakov & Shaposhnikov (1985)]

$\Gamma_{\mathrm{EWsp}}(T) \gtrsim H(T)$: $T_{EWsp-} \sim 100$ GeV $< T < T_{EWsp+} \sim 10^{12}$ GeV

- For $T > T_{EWsp-}$, we have perfect source of B violation
- For $T < T_{EWsp-}$, new source of B violation is required!

The early Universe is ...



Erza Anderson, Particle Soup

Early Universe effective theories

e.g. [CSF, Gonzalez-Garcia & Nardi (2011)]

For the range of temperatures of interest T, reactions can be categorized into three types according to timescale:

(i) $\Gamma(T) \gg H(T)$

- Very fast, achieve chemical equilibrium

$$\sum_I \mu_I = \sum_F \mu_F$$

Important assumption: fast gauge reactions $i + \bar{i} \rightarrow g$

$$\mu_g = 0 \implies \mu_i = \mu_{\bar{i}}$$

$$\sum_I \mu_I - \sum_F \mu_F = \sum_I \mu_I + \sum_F \mu_{\overline{F}} = 0 \implies \sum_i \mu_i = 0$$

- Can be "resummed" easily by identifying the *symmetries* of the system

Early Universe effective theories

e.g. [CSF, Gonzalez-Garcia & Nardi (2011)]

For the range of temperatures of interest T, reactions can be categorized into three types according to timescale:

(ii) Γ(T) << H(T)

- Very slow due to small couplings, suppressions by temperature/mass scale (results in *effective symmetry*)
e.g. electron Yukawa interactions

$$\Gamma_e(T) \sim 5 \times 10^{-3} y_e^2 T$$

$$T \gg 10^4 GeV \implies U(1)_e$$ [Cline, Kainulainen & Olive (1993)]

- Does no occur due to gauge symmetry (*exact symmetry*)
e.g. hypercharge, electric charge

Early Universe effective theories

e.g. [CSF, Gonzalez-Garcia & Nardi (2011)]

For the range of temperatures of interest T, reactions can be categorized into three types according to <u>timescale</u>:

(iii) $\Gamma(T) \sim H(T)$ <u>Sk3: Out-of-equilibrium condition</u>

- *Quasi/approximate symmetry*
- The evolution of the corresponding *Noether's charge* needs to be described by non-equilibrium dynamics like Boltzmann equation
- Essentially these are <u>all we need</u> to identify to obtain quantitative result

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Once we identity all the *U(1) symmetries* (effective/exact/approximate), the system can be described fully by the corresponding *Noether's charges*

U(1) symmetries and charges

Formalism first introduced in [Antaramian, Hall & Rasin (1994)]

- By symmetry, refer to U(1) symmetry which characterizes the *charge asymmetry* between particle & antiparticle (the diagonal generators of nonabelian group do not contribute)
- For each *complex* particle i (not real scalar or Majorana fermion), they can be assigned a *chemical potential* μ_i with charge q_i^x under $U(1)_x$
- For reactions of type (i), we have sets of linear equations

$$\sum_i \mu_i = 0$$

- By construction, if $U(1)_x$ is a symmetry of the system

$$\sum_i q_i^x = 0$$

- Hence the *most general solution* is $\mu_i = \sum_x C_x q_i^x$

Constants to be solved later

Some thermodynamics ...

- Particle i in *kinetic equilibrium* follows FD/BE distribution

$$f_i = \frac{1}{\exp(E_i - \mu_i)/T \pm 1}$$

Assumption: $i \to \bar{i}, \quad \mu_i \to -\mu_i$

- The number density is

$$n_i = g_i \int \frac{d^3p}{(2\pi)^3} f_i$$

- The number density *asymmetry* is

$$n_{\Delta i} \equiv n_i - n_{\bar{i}} = \frac{T^2}{6} g_i \zeta_i \mu_i$$

Assumption: $\mu_i/T \ll 1$

$$\zeta_i \to 1(2) \quad \text{for} \quad m_i \ll T; \quad \zeta_i \to 0 \quad \text{for} \quad m_i \gg T$$

- For each $U(1)_x$, the corresponding *Noether's charge*

$$n_{\Delta x} = \sum_i q_i^x n_{\Delta i}$$

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$$n_{\Delta x} = \sum_i q_i^x n_{\Delta i} \longrightarrow \frac{T^2}{6} \sum_i q_i^x g_i \zeta_i \mu_i \longrightarrow \frac{T^2}{6} \sum_y C_y \sum_i q_i^x g_i \zeta_i q_i^y$$

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J_{xy}

- For each U(1)$_x$, the corresponding *Noether's charge*

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Constants can be solved in terms of the *Noether's charge* and J_{xy}

Solutions

- The type (i) reactions are "resummed" in $J_{xy} \equiv \sum_i q_i^x g_i \zeta_i q_i^y$

$$C_y = \frac{6}{T^2} \sum_x J_{yx}^{-1} n_{\Delta x}$$

- The solutions in terms of only *Noether's charge*

$$n_{\Delta i} = g_i \zeta_i \sum_{x,y} q_i^y J_{yx}^{-1} n_{\Delta x}$$

- We can easily write down the *baryon asymmetry*

$$n_{\Delta B} = \sum_i q_i^B n_{\Delta i} = \sum_{x,y} J_{By} J_{yx}^{-1} n_{\Delta x}$$

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Detection of ("fast") B violation does not invalidate baryogensis (due to fast washout) but is a source of B violation

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The roles of U(1) symmetries

- To clarify the roles of U(1) symmetries, let us single out the *exact symmetries* $U_0=\{U(1)_a, U(1)_b, \ldots\}$ and denote the rest of them as $\overline{U}=U-U_0=\{U(1)_m, U(1)_n, \ldots\}$. We can eliminate the U_0 charges using the following relation

$$n_{\Delta a}=0 \implies \sum_b J_{ab}C_b+\sum_m J_{am}C_m=0 \implies C_a=-\sum_{b,m} J^{-1}_{ab}J_{bm}C_m$$

- The number density asymmetry is

$$n_{\Delta i}=g_i\zeta_i\sum_{m,n}\bar{q}^m_i\bar{J}^{-1}_{mn}n_{\Delta n}$$

$$\bar{q}^m_i \equiv q^m_i-\sum_{a,b}q^a_i J^{-1}_{ab}J_{bm}$$

$$\bar{J}_{mn}\equiv J_{mn}-\sum_{a,b}J_{ma}J^{-1}_{ab}J_{bn}$$

Matrix with reduced dimension

Only nonexact symmetries

The roles of U(1) symmetries

- The baryon asymmetry is

$$n_{\Delta B} = \sum_{m,n} \left[J_{Bm} - \sum_{a,b} J_{Ba} J^{-1}_{ab} J_{bm} \right] \bar{J}^{-1}_{mn} n_{\Delta n} = \sum_{m,n} \bar{J}_{Bm} \bar{J}^{-1}_{mn} n_{\Delta n}$$

Matrix with reduced dimension

Only nonexact symmetries

Direct contributions

particles charged under $\overline{U}$ and carry B

Indirect contributions

particles charged under U_0 and $\overline{U}$ but do not carry B

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particles charged under U_0 and $\bar{U}$ but do not carry B

Generalization of the result of [Antaramian, Hall & Rasin (1994)] which states that a nonzero asymmetry in a preserved sector $\bar{U}$ that has nonzero hypercharge U_0 implies nonzero baryon asymmetry (a=b=Y).

The roles of U(1) symmetries

Creator/destroyer: type (iii) reactions;

dynamical violation $n_{\Delta m} = 0 \rightarrow n_{\Delta m} \neq 0$

$\bar{U}$

Preserver: type (ii) reactions with $n_{\Delta m} \neq 0$

The lightest electrically neutral particle (if stable) can be *dark matter*

Nonbaryons

Messenger: type (ii) reactions with conservation law e.g. $n_{\Delta a} = 0$

U_0

Baryons

Example: The SM

Identity all the U(1)'s

- Let us define the U(1)$_x$-SU(N)-SU(N) mixed anomaly coefficient as $A_{xNN} \equiv \sum_i c_2(R) g_i q_i^x$

$c_2(R) = \frac{1}{2}$ fundamental $\qquad$ $c_2(R) = N$ adjoint

$$-\mathcal{L}_Y = (y_u)_{\alpha\beta} \overline{Q_\alpha} \epsilon H^* U_\beta + (y_d)_{\alpha\beta} \overline{Q_\alpha} H D_\beta + (y_e)_{\alpha\beta} \overline{\ell_\alpha} H E_\beta + \text{H.c.}$$

- We identify five U(1)'s: U(1)$_Y$, U(1)$_B$, U(1)$_{L\alpha}$

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- We identify five U(1)'s: $U(1)_Y$, ~~$U(1)_B$, $U(1)_{L\alpha}$~~
- The last four are anomalous: $A_{B22}=A_{L\alpha 22} = N_f/2$

$$\mathcal{O}_{\mathrm{EWsp}} = \sum_\alpha (QQQ\ell)_\alpha \longleftarrow$$ Type (i) reactions for T>100 GeV

Sk1: B violation

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- We identify ~~five~~ four U(1)'s: $U(1)_Y$, ~~$U(1)_B$, $U(1)_{L\alpha}$~~, $U(1)_{(B-L)\alpha}$
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Anomaly free

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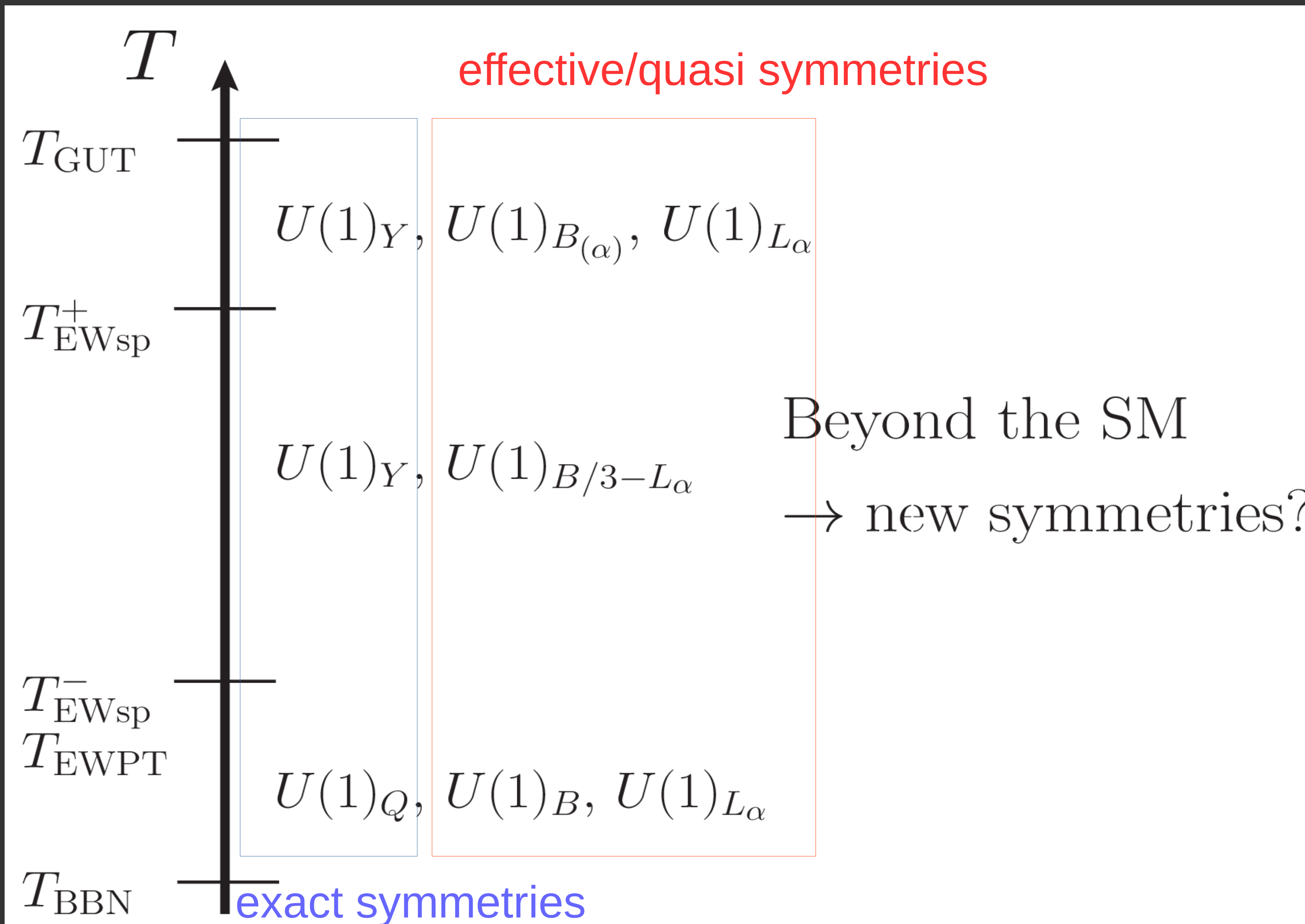
Type (i) reactions for T>100 GeV

Sk1: B violation

Due to quark mixing, $U(1)_{(B-L)\alpha} \rightarrow U(1)_{B/3-L\alpha}$

Example: The SM



Example: The SM

Solve the system: Calculate J

What we need … a Table (& perhaps mathematica)

Table 1

The list of SM fields, their $U(1)$ charges q_i^x and gauge degrees of freedom g_i with fermion family index α. Here $N_H - 1$ is number of extra pairs of Higgses H' with the assumption that they maintain chemical equilibrium with the SM Higgs H.

$i =$	Q_α	U_α	D_α	ℓ_α	E_α	H	H'
$q_i^{\Delta\alpha}$	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$	-1	-1	0	0
q_i^Y	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\frac{1}{2}$	$\frac{1}{2}$
q_i^B	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
$q_i^{L\alpha}$	0	0	0	1	1	0	0
g_i	3×2	3	3	2	1	2	$2(N_H - 1)$

Example: The SM

Solve the system: Calculate J

Define the vectors: $q_i^T \equiv \left(q_i^{\Delta_\alpha}, q_i^Y\right), \quad n^T \equiv (n_{\Delta_\alpha}, n_{\Delta_Y})$

$$\Delta_\alpha \equiv B/3 - L_\alpha$$

At T ~ 10^4 GeV where all Yukawa interactions are in chemical eq.

Setting $n_{\Delta Y} = 0$, we obtain

$$J^{-1} = \frac{1}{3\,(198+39N_H)} \times \begin{pmatrix} 222+35N_H & 4\,(6-N_H) & 4\,(6-N_H) & -72 \\ 4\,(6-N_H) & 222+35N_H & 4\,(6-N_H) & -72 \\ 4\,(6-N_H) & 4\,(6-N_H) & 222+35N_H & -72 \\ -72 & -72 & -72 & 117 \end{pmatrix}$$

SM: $N_H = 1$

Equivalently, we can use the second formalism by constructing reduced matrix of 3 x 3 $\bar{J}$

Example: The SM

Relate B to B-L

Define the vectors: $q_i^T \equiv \left(q_i^{B-L}, q_i^Y\right), \quad n^T \equiv \left(n_{B-L}, n_{\Delta_Y}\right)$

- Assuming EW sphalerons decouple before EW phase transition (EWPT) i.e. consider the degrees of freedom in unbroken EW
- Consider all particles relativistic $\xi_i = 1(2)$, N_f fermion generations and N_H pairs of Higgs.

$$J^{-1} = \frac{1}{N_f\left(N_f + 13N_H\right)}\begin{pmatrix} 10N_f + 3N_H & -8N_f \\ -8N_f & 13N_f \end{pmatrix}$$

$$n_{\Delta B} = \frac{4\left(2N_f + N_H\right)}{22N_f + 13N_H} n_{\Delta(B-L)}$$

Result of [Harvey & Turner (1990)] but simpler derivation and easy to extend or generalize i.e. to consider mass threshold effects with ξ_i [Inui et al. (1994), Chung et al. (2008)])

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Table 2

Similar to Table 1 but for field components after EWPT where we use subscript 'L' to denote the left-handed fields which participate in weak interaction.

$i =$	$U_{\alpha,L}$	$D_{\alpha,L}$	U_α	D_α	$\nu_{\alpha,L}$	$E_{\alpha,L}$	E_α	W^+	H'^+
$q_i^{\Delta_\alpha}$	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$	-1	-1	-1	0	0
q_i^Q	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	-1	-1	1	1
q_i^B	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0	0
q_i^L	0	0	0	0	1	1	1	0	0
g_i	3	3	3	3	1	1	1	3	$N_H - 1$

Example: The SM

Relate B to B-L

Define the vectors: $q_i^T \equiv \left(q_i^{B-L}, q_i^Y\right), \quad n^T \equiv \left(n_{B-L}, n_{\Delta_Y}\right)$

- Assuming EW sphalerons decouple after EW phase transition (EWPT) i.e. consider the degrees of freedom in broken EW
- Consider all particles relativistic ξ_i = 1(2), N_f fermion generations and N_H pairs of Higgs.

$$J^{-1} = \frac{1}{2N_f\left[24N_f + 13\left(2+N_H\right)\right]}\begin{pmatrix} 2\left(6+8N_f+3N_H\right) & -8N_f \\ -8N_f & 13N_f \end{pmatrix}$$

$$n_{\Delta B} = \frac{4\left(2+2N_f+N_H\right)}{24N_f+13\left(2+N_H\right)} n_{\Delta(B-L)}$$

Result of [Harvey & Turner (1990)] but simpler derivation and easy to extend or generalize i.e. to consider mass threshold effects with ξ_i [Inui et al. (1994), Chung et al. (2008)])

Some takeaways

- The use of *symmetry formalism* makes it clear from the outset that the asymmetries of all particles will depend only on the *Noether's charges*
- Type (i) reactions are implicitly taken into account without having to be referred to explicitly. Useful for more complicated models e.g. MSSM
- Type (ii) reactions → effective/exact symmetries: act as *preserver* or *messenger*
- Type (iii) reactons → quasi symmetries: the only ones that need to be solved *dynamically* for *quantitative* results
- Detection of (“fast”) B violation does not invalidate baryogensis but will be a source of B violation and points to new U(1)'s as *creator/preserver/messenger*

Thank you for your attention

Additional slides

Example: The SM

Solve the system: Calculate J

Define the vectors: $q_i^T \equiv \left(q_i^{\Delta_\alpha}, q_i^Y \right), \quad n^T \equiv (n_{\Delta_\alpha}, n_{\Delta_Y})$

$$\Delta_\alpha \equiv B/3 - L_\alpha$$

At T ~ 10^9 GeV where 1st gen. Yukawa interactions are out of chemical eq.

Setting $y_e, y_u, y_d \to 0$, we gain $U(1)_e$, $U(1)_u$, $U(1)_d$

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- u and d are indistiguisable under SU(3) (enter the same way in QCD sphalerons), set $Y_u = Y_d = 1/6$.

$$J^{-1} = \frac{1}{12\,(138 + 41 N_H)} \times \begin{pmatrix} 807 + 210 N_H & 12\,(5 - 2N_H) & 12\,(5 - 2N_H) & -222 \\ 12\,(5 - 2N_H) & 696 + 148 N_H & 4\,(15 - 2N_H) & -312 \\ 12\,(5 - 2N_H) & 16\,(9 - N_H) & 696 + 148 N_H & -312 \\ -222 & -312 & -312 & 492 \end{pmatrix}$$

SM: $N_H = 1$

Example 2: The MSSM

- The superpotential

$$W = \mu_H H_u \epsilon H_d + (y_u)_{\alpha\beta} Q_\alpha \epsilon H_u U^c_\beta + (y_d)_{\alpha\beta} Q_\alpha \epsilon H_d D^c_\beta + (y_e)_{\alpha\beta} \ell_\alpha \epsilon H_d E^c_\beta$$

- Besides $U(1)_Y$, $U(1)_{(B-L)\alpha}$, we have an *R-symmetry* e.g.

$$q^R(H_d) = q^R(\ell_\alpha) = q^R(U^c_\alpha) = -q^R(E^c_\alpha) = 2$$

- This remains also with *R-parity violating* terms as well as *type-I seesaw* with $q^R(N_i^c) = 0$

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Contruct *<u>anomaly-free</u>* charge:

$$\bar{R} \equiv R + \frac{2}{3c_{BL}}(c_B B + c_L L), \quad c_{BL} \equiv c_B + c_L$$

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[Ibanez & Quevedo (1992)]

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- Similarly at this temperatures, we can also set $\mu_H \to 0$ and we gain a *PQ symmetry (anomalous)* [Ibanez & Quevedo (1992)]

e.g. $-q^{PQ}(Q_\alpha) = q^{PQ}(\ell_\alpha) = q^{PQ}(H_u) = q^{PQ}(H_d) = 1,\ q^R(E_\alpha^c) = -2$

- Anomalies: $A_{PQ22} = -N_f + N_H$, $A_{PQ33} = -N_f$

With $N_f=3$, $N_H=1$, contruct A_{PQ22} *anomaly-free* charge:

$$\bar{P} \equiv \frac{3}{4} c_{BL} PQ + c_B B + c_L L, \quad c_{BL} \equiv c_B + c_L$$

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With $N_f=3$, $N_H=1$, contruct A_{PQ22} *anomaly-free* charge:

We still have to cancel A_{PQ33}!

$$\bar{P} \equiv \frac{3}{4} c_{BL} PQ + c_B B + c_L L, \quad c_{BL} \equiv c_B + c_L$$

Example 2: The MSSM

- We can make use of quark chiral symmetry discussed earlier. E.g. at T >> 10^6 GeV, up quark Yukawa interactions are out-of-equilibrium: $y_u \rightarrow 0$, gain anomalous $U(1)_u$
- Anomaly-free charge

$$\bar{\chi}_{u^c} \equiv \bar{P} + \frac{9}{2} c_{BL} u^c / q^{u^c}$$

$i =$	Q_a	U_a^c	D_a^c	ℓ_α	E_α^c	H_u	H_d
$q_i^{\Delta_\alpha}$	$\frac{1}{9}$	$-\frac{1}{9}$	$-\frac{1}{9}$	-1	1	0	0
q_i^Y	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	$\frac{1}{2}$	$-\frac{1}{2}$
$q_i^{\overline{R}}$	$\frac{2c_B}{9c_{BL}}$	$2-\frac{2c_B}{9c_{BL}}$	$-\frac{2c_B}{9c_{BL}}$	$2+\frac{2c_L}{3c_{BL}}$	$-2-\frac{2c_L}{3c_{BL}}$	0	2
$q_i^{\overline{P}}$	$\frac{c_B}{3}-\frac{3c_{BL}}{4}$	$-\frac{c_B}{3}$	$-\frac{c_B}{3}$	$c_L+\frac{3c_{BL}}{4}$	$-c_L-\frac{3c_{BL}}{2}$	$\frac{3c_{BL}}{4}$	$\frac{3c_{BL}}{4}$
q_i^B	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	0	0	0
q_i^L	0	0	0	1	-1	0	0
q_i^{PQ}	-1	0	0	1	-2	1	1
q_i^R	0	2	0	2	-2	0	2
g_i	3×2	3	3	2	1	2	2

Table 3: The $U(1)$ charges of left-handed chiral superfields. All gauginos $\widetilde{G}$, $\widetilde{W}$ and $\widetilde{B}$ have both R and $\overline{R}$ charges equal 1. Since all fermions in chiral superfields have R charges one less than that of bosons i.e. $R\,(\text{fermion}) = R\,(\text{boson}) - 1$, the differences between number density asymmetries of bosons and fermions are equal to that of gauginos.

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- Several comments:
  - c_B and c_L can be chosen at will as is convenient e.g. consider a model with $\mathcal{O}_B = U^c_\alpha D^c_\beta D^c_\delta$, choose c_B=0, c_L≠0 such that $\bar{R}$ and $\bar{P}$ are conserved by $\mathcal{O}_B$
  - Choosing c_B=c_L, the results are in *disagreement* with [Ibanez & Quevedo (1992)] due to sign error of gaugino chem. potential (could be avoided)
  - Effects of R-symmetry in supersymmetric leptogenesis (O(1) effect) [CSF, Gonzalez-Garcia, Nardi & Racker (2010)] and soft leptogenesis (O(100) effect) [CSF, Gonzalez-Garcia & Nardi (2011)]