Electroweak baryogenesis

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Plan

Motivation

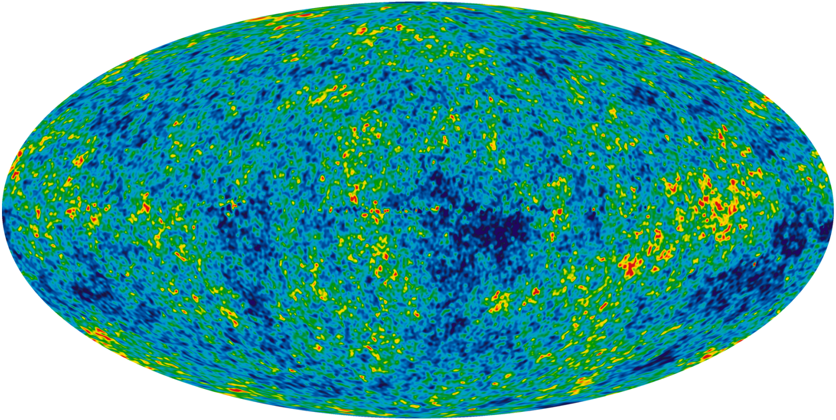
Motivation

The problem:

- the Standard Model (SM) predict that physics for matter and for anti-matter is the same (almost),
- if SM have been ultimate theory the Universe would be consist of photon predominately, because all matter have been annihilated yet.

Motivation

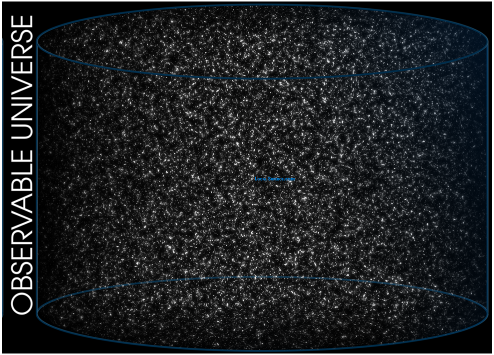
- Universe consist of matter but not of anti-matter.



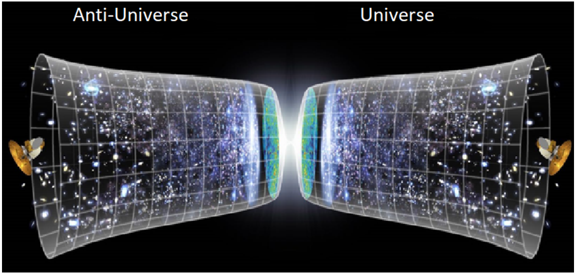
Motivation

Reasons why we believe that there is no antimatter:

- we don't observe annihilation processes,
- it is not enough antimatter in cosmic rays,
- there is no electric dipole moment of the Universe.



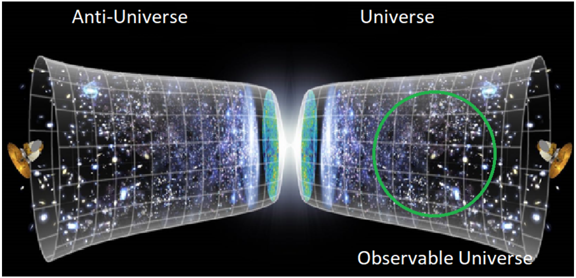
Motivation



- It is possible that there was Big Separation after big bang

Motivation

... and we observe only Universe which is consist of matter and doesn't observe anti-matter Universe



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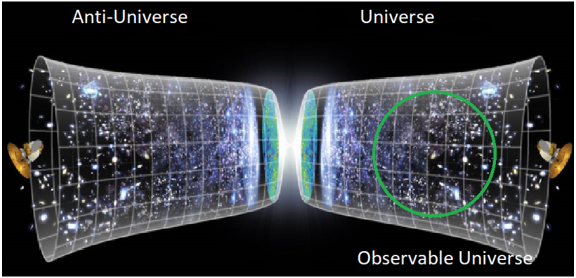

But:

- cosmic microwave background suggest that matter and anti-matter were created in almost equal amount, homogeneously and very actively have annihilated in the firsts seconds of Universe creation,

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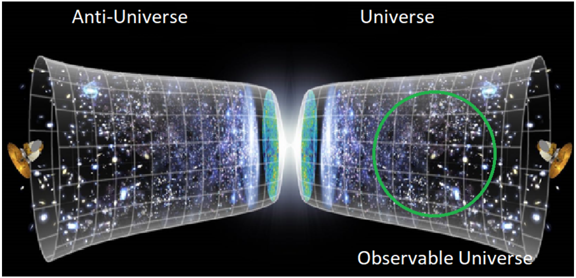

But:

- cosmic microwave background suggest that matter and anti-matter were created in almost equal amount, homogeneously and very actively have annihilated in the firsts seconds of Universe creation,
- known physics law don't explain Big Separation.

Sakharov's conditions

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- We believe that matter and anti-matter were created in the same amount and annihilation process required more anti-matter than matter, or
- ... a physical process initially created more matter than anti-matter.

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- ... a physical process initially created more matter than anti-matter.

In any case Sakharov conditions should be satisfied.

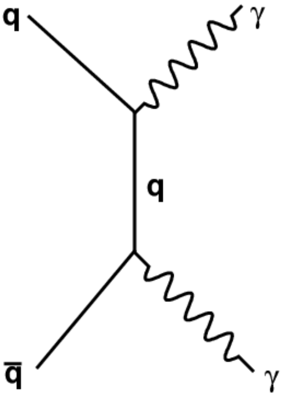
Sakharov's conditions

Sakharov's conditions necessary to obtain baryon asymmetry:

- baryon number violation,
- loss of thermal equilibrium,
- C and CP violation.

Baryon number violation

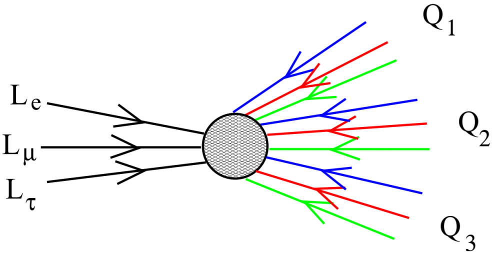
- Baryon number is a hypothetical quantum charge, which each quark has. Quarks have baryon number $1/3$ and anti-quarks have baryon number $-1/3$.
- Baryon number violation processes we need to remove all anti-baryons without removing all baryons.



Baryon number violation

- Within the SM the baryon number can be violated by triangle anomaly, where left handed quarks annihilated with leptons.

$$\partial_\mu J^\mu_{B_L+L_L} = \frac{3g}{32\pi}\epsilon_{\mu\nu\rho\sigma} W_a^{\mu\nu} W_a^{\rho\sigma} \quad (1)$$



Baryon number violation

- In 1976 t'Hooft [Phys. Rev. Lett. **37** (1976) 8] showed that within SM baryon number can be violated because of non-perturbative effects.
- To explain this we need to introduce concept of Chern-Simons numbers

$$N_{SC} = \int d^3x \, K^0, \tag{2}$$

where the current is given as

$$K^\mu = \frac{g^2}{32\pi}\epsilon_{\mu\nu\rho\sigma}(F_a^{\nu\rho}A_a^\sigma - \frac{g}{3}\epsilon^{abc}A_a^\nu A_b^\rho A_c^\sigma). \tag{3}$$

- This current is not conserved

$$\partial_\mu K^\mu = \frac{g^2}{32\pi}\epsilon_{\mu\nu\rho\sigma}F_a^{\mu\nu}F_a^{\rho\sigma}. \tag{4}$$

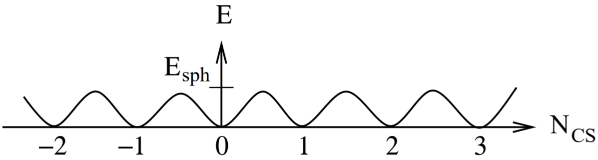
Baryon number violation

- Chern-Simons numbers has a topological nature

$$N_{CS}(t_1) - N_{CS}(t_1) = \int_{t_0}^{t_1} dt \int d^3x\, \partial_\mu K^\mu = \nu. \quad (5)$$

  where ν is a integer number.

- Energy of gauge field configurations as a function of Chern-Simons number



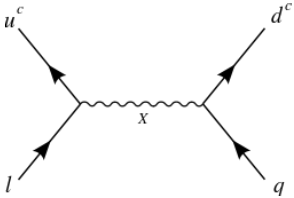
- Tunnelling amplitude is proportional to

$$\mathcal{A} \sim \exp(-8\pi/g^2) \sim 10^{-173}. \quad (6)$$

- The SM B violation is definitely not enough to produce baryons asymmetry which we observe.

Baryon number violation

- From others possible processes which provide B-violation one of most popular are natural in Grand Unification Theory (GUT) models.



- Quarks and leptons in GUT are in the same multiplet and vertices like Xlq are not avoidable.

The problem:

- GUT models are not satisfy phenomenology: this process predict proton decay, which is not observed.

Loss of thermal equilibrium

- In thermal equilibrium processes which are violate baryon number can go backward:

$$\Gamma(X \to Y + B) = \Gamma(Y + B \to X), \tag{7}$$

  where X and Y particles which have not a baryon number, B has a baryon number.
- This process possible when masses Y and B are much smaller than mass of X

C and CP violation

- C is an operator which transforms an electric charge into opposite one
$$C: \; Q \; \longrightarrow \; -Q. \tag{8}$$
- P is an operator which transforms a coordinate into opposite one
$$P: \; X \; \longrightarrow \; -X. \tag{9}$$
- We need C asymmetry because the rate of baryons production is proportional to the difference for rate of the process with particle and the same with anti-particle
$$\frac{dB}{dt} \propto \Gamma(X \to Y + B) - \Gamma(\overline{X} \to \overline{Y} + \overline{B}). \tag{10}$$

C and CP violation

But C is not enough!!!

But C is not enough!!!

- Weyl spinors under C transformation change charge to opposite, and under CP transformation with charge change change also chirality from left to right and vice versa

$$C: \; q_L \to \overline{q}_L, \qquad CP: \; q_L \to \overline{q}_R. \tag{11}$$

- Let us consider the process where C is broken,

$$\Gamma(X \to q_L q_L) \neq \Gamma(\overline{X} \to \overline{q}_L \overline{q}_L), \tag{12}$$

but CP is conserve

$$\begin{aligned} \Gamma(X \to q_L q_L) &= \Gamma(\overline{X} \to \overline{q}_R \overline{q}_R), \\ \Gamma(X \to q_R q_R) &= \Gamma(\overline{X} \to \overline{q}_L \overline{q}_L). \end{aligned} \tag{13}$$

C and CP violation

- This imply that total decay rate into left- and right- quarks would be the same as total decay rate into left- and right- anti-quarks

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\overline{X} \to \overline{q}_L \overline{q}_L) + \Gamma(\overline{X} \to \overline{q}_R \overline{q}_R). \tag{14}$$

To provide examples of CP violation I would like to remind transformation property of scalar, spinor and vector fields under C,P and CP symmetries

$$\begin{aligned} C &: \phi(\mathbf{x},t) \to \phi^\star(\mathbf{x},t), \\ P &: \phi(\mathbf{x},t) \to \pm\phi(-\mathbf{x},t), \\ CP &: \phi(\mathbf{x},t) \to \pm\phi^\star(-\mathbf{x},t), \end{aligned} \tag{15}$$

for vector fields

$$\begin{aligned} C &: A^\mu(\mathbf{x},t) \to -A^\mu(\mathbf{x},t), \\ P &: A^\mu(\mathbf{x},t) \to A_\mu(-\mathbf{x},t), \\ CP &: A^\mu(\mathbf{x},t) \to -A_\mu(-\mathbf{x},t), \end{aligned} \tag{16}$$

... and for fermions

$$C : \psi_L(\mathbf{x}, t) \to i\sigma_2 \psi_R^\star(\mathbf{x}, t), \qquad P : \psi_L(\mathbf{x}, t) \to \psi_R(-\mathbf{x}, t),$$
$$C : \psi_R(\mathbf{x}, t) \to -i\sigma_2 \psi_L^\star(\mathbf{x}, t), \qquad P : \psi_R(\mathbf{x}, t) \to \psi_L(-\mathbf{x}, t),$$
$$C : \psi(\mathbf{x}, t) \to i\gamma^0\gamma^2 \psi^\star(\mathbf{x}, t), \qquad P : \psi(\mathbf{x}, t) \to \gamma^0 \psi(-\mathbf{x}, t),$$

and

$$CP : \psi_L(\mathbf{x}, t) \to i\sigma_2 \psi_R^\star(-\mathbf{x}, t),$$
$$CP : \psi_R(\mathbf{x}, t) \to -i\sigma_2 \psi_L^\star(-\mathbf{x}, t),$$
$$CP : \psi(\mathbf{x}, t) \to i\gamma^2 \psi^\star(-\mathbf{x}, t).$$

C and CP violation examples

- 1. *CP* violation appears when couplings has complex phase which cannot be removed with field redefinition. As example let us consider the Lagrangian

$$\mathcal{L} = (\partial\phi)^2 - \mu^2\phi^2 - \lambda\phi^4. \tag{17}$$

If we apply *CP* transformation we obtain

$$\mathcal{L} = (\partial\phi^\star)^2 - \mu^2\phi^{\star 2} - \lambda\phi^{\star 4}. \tag{18}$$

Here we can see if m and λ are not real and can be written as

$$\mu^2 = |\mu|^2 e^{i\phi_\mu}, \qquad \lambda = \lambda e^{i\phi_\lambda}. \tag{19}$$

the Lagrangian is not invariant.

- Physics is not depend on field definition, we can get rid of one of phase with phase redefinition

$$\phi \rightarrow e^{-i\phi_\mu}\phi, \tag{20}$$

and the Lagrangian obtain the form

$$\mathcal{L} = (\partial\phi)^2 - |\mu^2|e^{i(\phi_\lambda - 2\phi_\mu)}\phi^2 - |\lambda|\phi^4. \tag{21}$$

The combination of phases $\phi_\lambda - 2\phi_\mu$ is independent of field redefinition and brake the CP invariance.

- 2. There is no fermion quartic coupling in fundamental theories, because of this reason for fermion example if we want to see the same effect we need to consider quite more complicated theory

$$\mathcal{L} = \sum_{i=1}^{2} \overline{\psi}_i (i\gamma_\mu \partial^\mu - m_i e^{i\theta_i \gamma^5})\psi_i + \mu(\overline{\psi}_1 e^{i\alpha\gamma^5} \psi_2 + h.c.). \tag{22}$$

Here we redefine fields as

$$\psi_i \to \psi_i e^{-i(\theta_i/2)}, \tag{23}$$

after field redefinition we have

$$\mathcal{L} = \sum_{i=1}^{2} \overline{\psi}_i (i\gamma_\mu \partial^\mu - m_i)\psi_i + \mu(\overline{\psi}_1 e^{i(\alpha - \theta_1/2 - \theta_2/2)\gamma^5} \psi_2 + h.c.). \tag{24}$$

C and CP violation examples

- 3. As third example we consider strong CP problem.

Symmetries do not forbid us to introduce the term with dual strength tensor

$$\mathcal{L} = \frac{\theta_{QCD}}{2}\epsilon^{\mu\nu\rho\sigma}F^a_{\mu\nu}F^a_{\rho\sigma}, \quad (25)$$

which in terms of magnetic and electric fields

$$\mathcal{L} = 2\theta_{QCD}\mathbf{B}^a\mathbf{E}^a, \quad (26)$$

E is odd under C and P transformation and **B** is odd under C transformation and even under P transformation, so full combination is add under the CP transformation.

C and CP violation examples

- If this term have been exist it would provide anomalous electric dipole momentum for neutron. EDM operator is

$$
\begin{aligned}
K &= -\frac{i}{2} d_n \overline{n} \sigma_{\mu\nu} \gamma^5 F^{\mu\nu} n \\
&= d_n(n_L^\dagger \vec{\sigma} \vec{E} n_R + n_R^\dagger \vec{\sigma} \vec{E} n_L + i(n_L^\dagger \vec{\sigma} \vec{B} n_R + n_R^\dagger \vec{\sigma} \vec{B} n_L)).
\end{aligned} \tag{27}
$$

  Experimental limit on the neutron EDM

$$
|d_n| < 3 \times 10^{-26} e \cdot mc. \tag{28}
$$

- In SM the source of CP violation is Cabibbo-Kobayashi-Maskawa matrix. This matrix appears as a consequence of mass matrix diagonalization and characterize vertices of the weak interaction

$$q_{Wqq} \sim V_{ij}\overline{u}_i\gamma^{\mu}P_L u_j\varepsilon_{\mu}. \tag{29}$$

- The most general form of CKM matrix is

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 - s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_2 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

- We can quantify the invariant phase using Jarlskog invariant

$$\begin{aligned} J &= (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \\ &\times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) K, \end{aligned} \tag{30}$$

where

$$K = \mathrm{Im}\, V_{ii} V_{jj} V_{ij}^{\star} V_{ji}^{\star} = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta. \tag{31}$$

C and CP violation in the Standard Model

- Baryon asymmetry characterize by η parameter

$$\frac{1}{7.04}\eta = \frac{n_B - n_{\overline{B}}}{s}, \tag{32}$$

  where n_B, $n_{\overline{B}}$ and s are density of baryons, density of antibaryons and entropy density respectively.
- This value has been fixed by Wilkinson Microwave Anisotropy Probe experiment as

$$\eta = (6.14 \pm 0.25) \times 10^{-10}. \tag{33}$$

- From studying Jarlskog invariant we can conclude that CP asymmetry in SM correspond for $\eta \sim 10^{-20}$ what is definitely not enough.

EWBG

- SM satisfy two of three Sakharov conditions: baryon number violation and also source of CP violation.
- Baryon number violation within SM predict sphalerons amplitude order

$$\mathcal{A} \sim \exp(-8\pi/g^2) \sim 10^{-173}, \qquad (34)$$

what is definitely not enough to produce the Universe. But at higher temperature lattice calculations predicts higher amplitudes.
- The parameter which is responsible for *CP* violation is also too small for creation the Universe.

- If baryogenesis is possible within SM, than thermal instability will require the electro-weak phase transition.

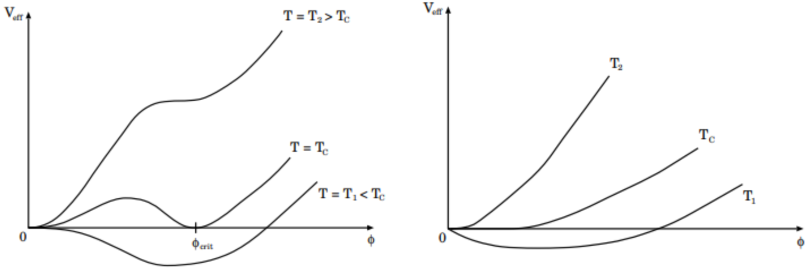
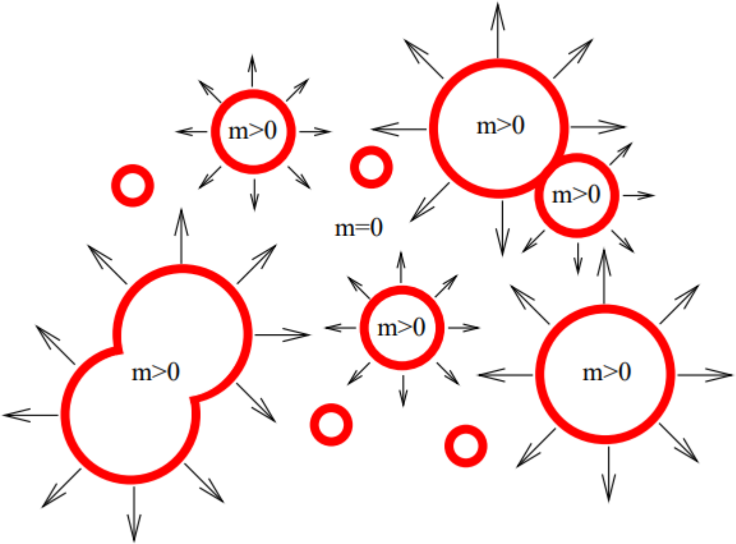


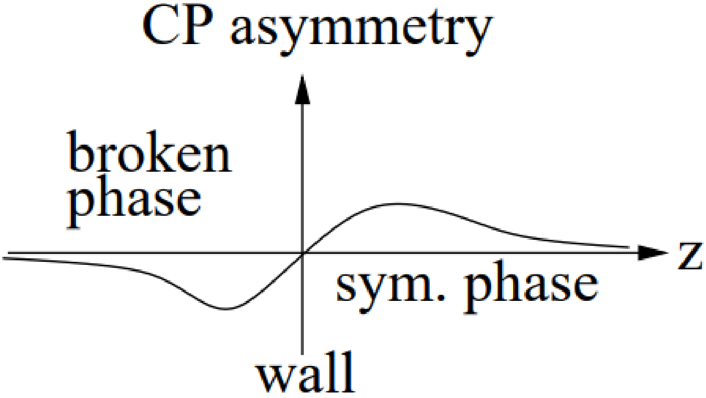
Figure: Evolution of Higgs potential for the first (left) and second (right) order phase transition

EWBG

- In the case of first order phase transition we have two minimum: one is corresponded to vev production, second local minimum is in zero.



- Sphalerons tunnelling through the wall brake CP and B symmetries.



EWBG

- Higgs potential depends on parameter λ and μ. Before mass of Higgs boson was discovered, the first order phase transition was the main candidate to explain loss of thermal equilibrium and explain baryogenesis within SM.
- With fixed λ and μ 1st order phase transition is not possible within SM.

Conclusion

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- Baryogenesis is very unlike to be achieved within SM.
- We need a New Physics!

This presentation based on texts and pictures from:

- J. M. Cline, hep-ph/0609145,
- W. Bernreuther, Lect. Notes Phys. **591** (2002) 237,
- P. Kooijman & N. Tuning, Lectures on CP violation,
- M. C. Chen, hep-ph/0703087 [HEP-PH].

Pictures has been taken also from

- https://curiosmos.com