Cold Electroweak Baryogenesis in the Two Higgs-Doublet Model

Bin Wu

University of Bielefeld

7. Kosmologietag, University of Bielefeld, Germany
May 3, 2012

Universität Bielefeld

This talk is based on:

Anders Tranberg and Bin Wu
"Cold Electroweak Baryogenesis in the Two Higgs-Doublet Model", [arXiv:1203.5012].

Outline

- **Strong evidence for BAU**
- **Useful quantity**

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 7.04\frac{n_B - n_{\bar{B}}}{s}$$

- **Big Bang Nucleosynthesis**

$$5.1 \leq \eta \times 10^{10} \leq 6.5(95\% \ \textbf{CL})$$

- **CMB**

$$\eta = 6.23 \pm 0.17 \times 10^{-10}$$

A recent review, see, PDG(http://pdg.lbl.gov/2011/reviews/rpp2011-rev-bbang-nucleosynthesis.pdf).

1.2 Baryogenesis

- **To understand BAU**

  From an initially baryon symmetric universe after, say, an inflationary stage

- **Sakharov's conditions**

  1. **Baryon number violation**
  2. **C and CP violation**
  3. **Departure from equilibrium**

1.3 Cold Electroweak Baryogenesis

- **Basic idea:**
  1. **Inflation with reheating below the electroweak scale**
  2. **Cold state with bosonic fields misplaced from equilibrium vacuum values**
  3. **Reheating:** $T_{rh} < T_c \sim 100$ **GeV**
  4. **Standard Big Bang: BBN etc...**

- **The baryon asymmetry is generated between steps 2 and 3**

  $H \sim 10^{-5}$ eV $\Rightarrow$ The expansion of the universe is negligible

L. M. Krauss and M. Trodden, Phys. Rev. Lett. **83** *(1999) 1502 [arXiv:hep-ph/9902420].*

J. Garcia-Bellido, D. Y. Grigoriev, A. Kusenko and M. E. Shaposhnikov, Phys. Rev. D **60** *(1999) 123504 [arXiv:hep-ph/9902449].*

- **The action:** **one more SU(2) doublet with hypercharge $+1$**

$$S = -\int d^4x \left[\frac{1}{2g^2}\mathrm{Tr}\, F^{\mu\nu}F_{\mu\nu} + (D^\mu\phi_1)^\dagger D_\mu\phi_1 + (D^\mu\phi_2)^\dagger D_\mu\phi_2 + V(\phi_1,\phi_2) + S_{C/P}\right],$$

where $V(\phi_1,\phi_2)$ is the Higgs potential and $S_{C/P}$ is a higher dimensional P violating term.

- **Gauge choice:** $A_0 = 0$
- **One vacuum**

$$A^\mu = 0, \qquad \phi_1 = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}}e^{i\theta} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

- **The topological vacuum structure**
  - **Define**

$$\hat{\Phi}_a = \frac{\Phi_a}{\sqrt{\det \Phi_a}}$$

where

$$\Phi_a = \begin{pmatrix} \phi_{a1} & -\phi_{a2}^* \\ \phi_{a2} & \phi_{a1}^* \end{pmatrix} = (\phi_a, -i\sigma^2\phi_a^*)$$

with $\phi_a = (\phi_{a1}, \phi_{i2})^T$ and $a = 1, 2$

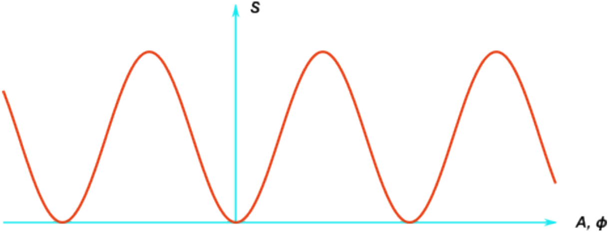
  - **The vacuum**

$$A^\mu = 0, \hat{\Phi}_1 = \hat{\Phi}_2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

  - **Gauge transformation**

$$A_\mu \to -\frac{1}{ig}\partial_\mu U U^\dagger \quad \text{and} \quad \hat{\Phi}_i \to U\hat{\Phi}_i$$

with $U(\vec{x}) \in SU(2)$.



- **Assuming** $U(\vec{x} \to \infty) = 1$
    - **Mapping**

$$U : \mathcal{R}^3 \to S^3 \to SU(2)$$

    - **Divided into inequivalent homotopic classes**

$$n = 0, \pm 1, \ldots$$

- **Higgs' winding numbers**

$$N_{Ha} = -\frac{1}{24\pi^2}\int d^3x\epsilon_{ijk}\mathbf{Tr}\left[\partial_i\hat{\Phi}_a\hat{\Phi}_a^\dagger\partial_j\hat{\Phi}_a\hat{\Phi}_a^\dagger\partial_k\hat{\Phi}_a\hat{\Phi}_a^\dagger\right]$$

- **The Chern-Simons number**

$$N_{CS} = \frac{g^2}{16\pi^2}\int d^3x\epsilon_{ijk}\mathbf{Tr}\left[A_iF_{jk} - \frac{2}{3}igA_iA_jA_k\right]$$

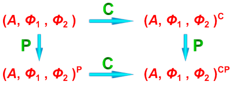
- **In vacuum**

$$\boxed{N_{H1} = N_{H2} = N_{CS}}$$

Note: under parity $\vec{x} \to -\vec{x}$, $N_{Ha} \to -N_{Ha}$ and $N_{CS} \to N_{CS}$.

2.1.1 A bosonic model in the 2HDM

- **Numerical setup**
  - **A pair of initial configurations at** $t = t_i$



$$\Phi_i\,(t_i,\vec{x}) \xrightarrow{P} \Phi_i\,(t_i,-\vec{x})\,, \vec{A}\,(t_i,\vec{x}) \xrightarrow{P} -\vec{A}\,(t_i,-\vec{x})$$
$$\Phi_i\,(t_i,\vec{x}) \xrightarrow{C} \Phi_i^*\,(t_i,\vec{x})\,, A_\mu\,(t_i,\vec{x}) \xrightarrow{C} -A_\mu^*\,(t_i,\vec{x})$$

  - **Ensemble average**

$$\bar{\mathcal{O}} = \frac{1}{N_{\rm init}} \sum_i \mathcal{O}(\{\phi_i\})$$

where

$$\mathcal{O}(\{\phi_i\}) = \frac{1}{4}\left[\mathcal{O}(\phi_i) + \mathcal{O}(\phi_i^C) + \mathcal{O}(\phi_i^P) + \mathcal{O}(\phi_i^{CP})\right].$$

  - **Example:** $\mathcal{O} = N_{CS}$

- **In the 2HDM as well as in the Standard Model**

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{3}{32\pi^2}\left(g^2 F^a \cdot \tilde{F}^a\right)$$

where

$$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta},$$
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + ig[A_\mu, A_\nu],$$

and A_μ is the gauge fields of $SU(2)$.

- **The baryon number generated at time** t

$$\Delta B(t) = \frac{3g^2}{32\pi^2}\int d^4x F^a \cdot \tilde{F}^a = 3\left[N_{CS}(t) - N_{CS}(0)\right],$$

where N_{CS} is the Chern-Simons number in the $SU(2)$ gauge fields.

2.2.3 C and CP violation

- **The Higgs potential**

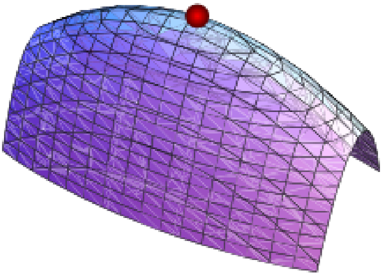
$$
\begin{aligned}
V(\phi_1,\phi_2) \quad = \quad & -\frac{1}{2}\mu_1^2\phi_1^\dagger\phi_1 - \frac{1}{2}\mu_2^2\phi_2^\dagger\phi_2 + \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 \\
& +\lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\
& +\frac{1}{2}\left(\lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_5^*(\phi_2^\dagger\phi_1)^2\right) - \frac{1}{2}\left(\mu_{12}^2\phi_1^\dagger\phi_2 + \mu_{12}^{2*}\phi_2^\dagger\phi_1\right).
\end{aligned}
$$

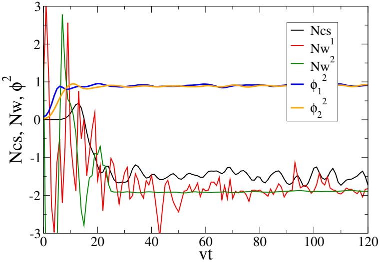
The parameters $\lambda_{1,2,3,4}$ and $\mu_{11,22}^2$ are real and in general λ_5 and μ_{12}^2 are complex.

- **One CP violating phase**

$$\textbf{Im}\ \mu_{12}^2 = v_1 v_2 \textbf{Im}\ \lambda_5$$

2.2.4 Departure from thermal equilibrium: spinodal transition





- **Initial field configuration($t = t_i$)**
  1. **Initially the potential is** $V(\phi_1, \phi_2)$
  2. $A^\mu = 0$
  3. $\phi_1 \simeq 0, \phi_2 \simeq 0$: **Monte Carlo**
  4. **Keep only spinodally unstable momentum modes: classical**

$$\phi_{a\vec{k}} \sim e^{\sqrt{\mu_a^2 - \vec{k}^2}}$$

  5. **Quantum fluctuations neglected**

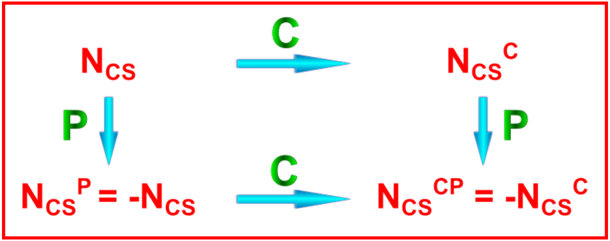
- **EOM $\Rightarrow$ latetime field configurations**

2.2.5 Additional requirement: P violation

- **A P-violating term given by**

$$S_{\mathrm{C/P}} = \frac{\delta_{\mathrm{C/P}}}{16\pi^2 m_W^2} i(\phi_1^\dagger \phi_2 - \phi_2^\dagger \phi_1) \,\mathrm{Tr}\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- **Why? Otherwise**



3 Results

- **Parameters**

$$\lambda_1 = 0.86175, \quad \lambda_2 = 2.36749, \quad \lambda_3 = 5.7886, \quad \lambda_4 = -3.5845,$$
$$\lambda_5 = 1.3774, \mu_{11}^2 = 34673, \quad \mu_{22}^2 = 120680, \quad \mu_{12}^2 = 13268 - i7763$$

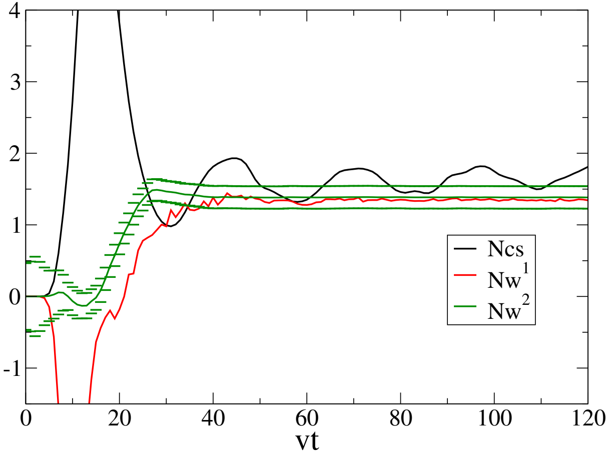
- **Correspond to**
  - Vacuum

    $\theta = \theta_1 - \theta_2 = -1.39, \ v_1 = 220 \text{ GeV}, \ v_2 = 110 \text{ GeV}$
  - Higgs' masses

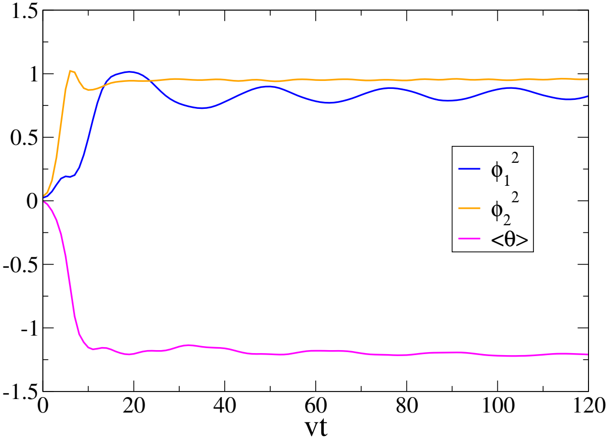
    $(m_\pm, m_1, m_2, m_3) = (400, 125, 300, 350)$ GeV

3 Results

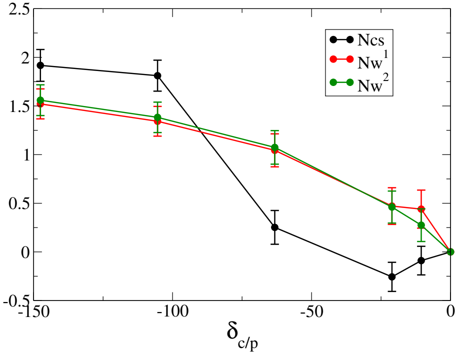
- **Chern-Simons number and Higgs winding numbers**



- **Spinodal transition**



- **Dependence of $\delta_{C/P}$**



The signs of $\delta_{C/P}$ and θ determine the sign of B.

- The value in confrontation with η

$$\delta_{C/P} = -(2 \text{ to } 3) \times 10^{-4}$$

4 Conclusions

- **In the 2HDM, $N_{H1} = N_{H2} = N_{CS}$ in the vacuum**

  This approximately holds in the spontaneously symmetry breaking phase.

- **In addition to Sakharov's conditions, P violation is also needed**
- **A very small P-violation ($\delta_{C/P} = -(2 \text{ to } 3) \times 10^{-4}$) is needed**
- **What's next?**

  1. Evaluate $\delta_{C/P}$ in effective field theory?
  2. Constrain parameters space together with LHC phenomena?
  3. ...