Dynamical CP violation in the Early Universe

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Introduction

- ⋆ The observed baryon asymmetry (BA) requires CP violation as one of the three Sakharov conditions
- ⋆ The standard model of electroweak physics generates a CP asymmetry in the quark sector via the CKM phase
- ⋆ The conventional CKM phase generated CP asymmetry is far too small to explain the observed baryon asymmetry in the Universe $\sim 10^{-19}$ (Shaposhnikovs talk)
- ⋆ A CP asymmetric phase generated in the scalar fields in the early Universe could lead to large enough asymmetry to explain the BA
- ⋆ The CP phase can be generated when the scalars are excited and inflation provides a large coherent effect
- ⋆ The CP asymmetry is dynamical and is determined by the scalar field dynamics

CP asymmetry in the scalar sector

- ⋆ In the simplest scenario consider two scalar fields, $\phi_\pm$
- ⋆ The Lagrangian which describes the interaction can is given as

$$L = -m_i^2 \phi_i^\dagger \phi_i + g\phi_-^\dagger \phi_- \phi_+ + h.c.$$

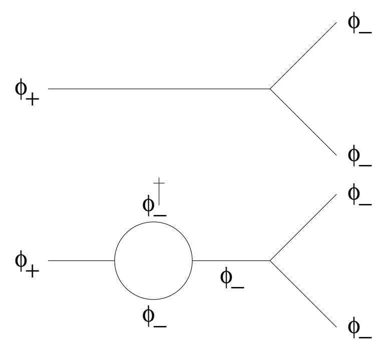
- ⋆ We take the coupling g to be real $\rightarrow$ the interaction is CP conserving
- ⋆ The fields $\phi_\pm$ can excite complex phase difference, say α
- ⋆ It is very natural for $\alpha \neq 0$ when the fields are in a hot early Universe
- ⋆ The induced phase difference can give rise to large CP asymmetry (DOLGOV)

Asymmetric initial conditions

- ⋆ In the hot early Universe, the excited fields can create a quanta of field via fluctuations
- ⋆ In general the field fluctuations $\phi'_- = \phi_- - c_- \; ; \; \phi'_+ = \phi_+ - c_+ e^{i\alpha}$ (Kalopers talk)
- ⋆ Generically, the initial conditions are asymmetric since $\alpha \neq 0$ and $c_+ \neq c_-$
- ⋆ A new cubic interaction is induced $V_3 = g(c_+ e^{i\alpha} \phi_- \dagger \phi_-^\dagger \phi_- + c_- \phi_-^\dagger \phi_-^\dagger \phi_+ + 2c_- \phi_-^\dagger \phi_- \phi_+)$
- ⋆ V_3 can contribute to a two-body CP violating decay
- ⋆ The CP asymmetry in the scalar sector can lead to an asymmetry in the number density of the ϕ_i particles
- ⋆ The dynamical nature is determined by the dynamics of the field values $c_\pm$

CP asymmetry in the number density

- ⋆ The CP violating two-body decay is via the process



- ⋆ The tree level graph $\sim gc_+ e^{i\alpha}$ while the loop level graph $\sim (2gc_-)^2 e^{-i\alpha}$
- ⋆ The net CP phase difference due to tree and loop interference is $\sin 2\alpha$
- ⋆ The decay $\phi_+ \to 2\phi_-$ leads to an asymmetry in the number density $\delta N = N(\phi_-) \neq N(\phi_-^\dagger) \sim \sin 2\alpha$
- ⋆ We require $m_+ \geq 2m_-$ for (i) kinematics and (ii) absorptive contributions

Some additional remarks

- ⋆ The background field values $[c_-,\ c_+]$ in general are non-zero and hence support a CP asymmetry
- ⋆ The asymmetry is expected to occur after inflation to avoid any dilution
- ⋆ The requirement $\sin 2\alpha \neq 0$ is extended coherently over a large Hubble patch due to inflation and hence is not washed out due any conceivable averaging of the CP phase
- ⋆ The time dependence of the asymmetry is determined by the time evolution of the backround values $c_\pm$
- ⋆ In the slow-roll approximation

$$\dot{c}_\pm \approx -\frac{1}{3H}\frac{dV}{d\phi_\pm}\Big|_{\phi_\pm = c_\pm}$$

Transfer of the asymmetry to fermions

- $\star$ The scalar asymmetry δN can be transferred to fermions
- $\star$ A fermion asymmetry can be achieved via the Yukawa interaction
  $Y = \bar{\psi}_L \phi_- \psi_R$ + h.c.
- $\star$ The interaction leads to the decays:
  $\phi_- \to \bar{\psi}_R \psi_L$ and $\phi_-^\dagger \to \bar{\psi}_L \psi_R$
- $\star$ The decay leads to an asymmetry in the left-handed fermion number density
- $\star$ The asymmetry: $\delta N_f = N(\bar{\psi}_L) - N(\psi_L) \sim \delta N \cdot \Gamma$
- $\star$ The asymmetry is possible only if fermions are Dirac!

Application: Baryon/lepton asymmetry

- ⋆ The left-handed fermion asymmetry can be transferred to a Dirac leptogenesis (Lindner *et al.*,)
- ⋆ The decay of ϕ_- to fermions leads to a lepton asymmetry
  $Y_l \sim \sin 2\alpha\Gamma = y_l \sin 2\alpha \frac{y_l^2 c_-}{8\pi}$
- ⋆ The chances that the fermion asymmetry does not equilibrate are only if $y_l \ll 1$
- ⋆ The condition is easily satisfied if we choose ϕ_- to decay in to Dirac neutrinos
- ⋆ The Dirac neutrino asymmetry is then converted to a baryon number asymmetry via sphaleron processes giving rise to:
  $Y_B \propto Y_l$ where the proportionality is determined by the particle spectrum in a given model

Conclusions

- ⋆ Early Universe can induce a large enough CP violation via initial conditions which are generic
- ⋆ Inflation redshifts this asymmetric initial conditions starting from a tiny region to a large Hubble patch
- ⋆ To generate a lepton asymmetry, it is preferable to have Dirac neutrinos since their small Yukawa couplings will ensure no wash-out of the generated asymmetry
- ⋆ The baryon asymmetry is generated via Dirac leptogenesis $\leftrightarrow$ asymmetric scalar density
- ⋆ Other alternatives are viable for generating a baryon asymmetry using asymmetric initial conditions
- ⋆ The dynamical nature of the asymmetry depends on the background evolution of the fields and hence on the values $c_{\pm}$