Early Universe

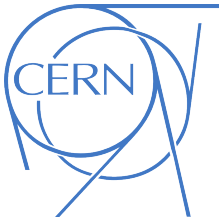
Lectures at Canary Islands Winter School 2022

Outline:

1) CMB & BBN
2) Baryogenesis
3) Inflation (background)
4) Inflation (perturbations)

Literature

- Bailin, Love : Cosmology in gauge field theory and string theory
- Baumann: TASI Lecture Notes Inflation arxiv: 0907.5424



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Lecture 2 – Baryogenesis

0) Recap

- CMB — T = 0.3 eV — $\rightarrow T_0, \Omega_m, \Omega_B, \Omega_r, \Omega_\Lambda, \Omega_{\rm tot}$
- radiation matter equality — T ~ 1 eV
- BBN — T ~ 0.07 MeV — $\rightarrow \eta \leftrightarrow \Omega_B/\Omega_r$

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1) Baryon asymmetry of the Universe

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1) Baryon asymmetry of the Universe

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nucleon freeze-out

in equilibrium: $n_N = n_{\bar{N}} = 2\left(\frac{m_N T}{2\pi}\right)^{3/2} e^{-m_N/T}$

freeze-out at $H = \Gamma = n_N \underbrace{\langle \sigma_{ann} v \rangle}_{\simeq m_\pi^{-2}}$, $H \sim \# \frac{T^2}{M_P}$

↳ $T_{f.o.} \simeq 20$ MeV

→ $\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} = \frac{2\pi^2}{\zeta(3)}\left(\frac{m_N}{2\pi T_{f.o.}}\right)^{3/2} e^{-m_N/T_{f.o.}} \simeq 10^{-18} \ll \eta$

→ we need $\frac{n_N - n_{\bar{N}}}{n_\gamma} \sim 10^{-10}$ "initially"

2) Conditions for baryogenesis (Sakherov 1967)

i) B violation

ii) C and CP violation

iii) departure from thermal equilibrium

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$i \xrightarrow{\Delta B} f$. $C: \bar{i} \xrightarrow{-\Delta B} \bar{f}$, $\Delta B - \Delta B = 0$

$CP \hat{=} T: f \xrightarrow{-\Delta B} i$, $\Delta B - \Delta B = 0$ assumes CPT

iii) departure from thermal equilibrium

$n_X^{eq} \simeq g_X (m_X T)^{3/2} e^{(-m_X + \mu_X)/T}$

$n_{\bar{X}}^{eq} = \quad " \quad e^{(-m_X + \mu_{\bar{X}})/T}$

$i): XX \leftrightarrow \bar{X}\bar{X} \Rightarrow 2\mu_X = 2\mu_{\bar{X}} \Rightarrow n_X^{eq} = n_{\bar{X}}^{eq} \Rightarrow \eta = 0$

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→ but quantitatively insufficient, baryogenesis requires BSM physics

3) Traditional baryogenesis models

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$X \xrightarrow{\not{C}, \not{B}} SM$

Heavy GUT particle

↳ i) & ii) ✓

out-of-equilibrium decay:

$T \gg m_X : n_X^{eq} = n_{\bar{X}}^{eq} \propto T^3 , \frac{n_X^{eq}}{n_\gamma} = \frac{g_X}{2}$

$T \ll m_X : n_X^{eq} = n_{\bar{X}}^{eq} \propto (m_X T)^{3/2} e^{-m_X/T}$

$n_\gamma \propto T^3$

$\rightarrow n_X \gg n_X^{eq}$ occurs for freeze-out (i.e $\Gamma_X = H$) at $T \gtrsim m_X$

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But:
- GUT decays typically violate B+L with B-L conserved
- B+L violation via sphalerons 'washes out' B+L asymmetry at T >> T_{EW}

$$\dot{n}_{B+L} \sim -(3H + \Gamma_{\rm sph}) n_{B+L} \quad \rightarrow \quad n_{B+L}^{\rm eq} = 0$$

B) Leptogenesis

neutrino masses → introduce N_R

$$\mathcal{L} \supset Y_N N_R L H + M_N N_R \bar{N}_R \quad \rightarrow \quad m_\nu \sim \frac{Y_N}{M_N} v_{\mathrm{EW}}^2$$

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‘standard’ high-scale
thermal leptogenesis

$M_N \sim 10^{10}\ \mathrm{GeV}\,, \quad Y_N \sim 10^{-3}$

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out-of-equilibrium N_R decay

low-scale leptogenesis via N_R oscillations

$M_N \sim \text{GeV}, \quad \Delta M_N \ll M_N$

$\not{L}$ from sphaleron coupling to ν only

$\not{eq}$ from N_R oscillations

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- Baryogenesis from helical magnetic fields

  CP violation from primordial helical hypermagnetic fields converted to B+L asymmetry at EW PT

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- Wash-in leptogenesis

  primordial B - L conserving asymmetries + washout of L by N_R → B – L asymmetry

- and many more….