Anomalies, CPT and Leptogenesis

Sarben Sarkar

Dept. of Physics, King's College London, UK

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Matter Antimatter Asymmetry

Baryon number asymmetry

Baryogenesis

Lepton Number asymmetry

Leptogenesis

DATA

- $\boldsymbol{\rho_0}$ component energy density
- $\boldsymbol{\rho_c}$ critical energy density
- $\boldsymbol{\Omega_{matter} = 0.27 \pm 0.04}$
- $\boldsymbol{\Omega_B = 0.044 \pm 0.004}$

DATA

- $\boldsymbol{n_B}$ baryon number density
- $\boldsymbol{n_\gamma}$ photon number density
- $\frac{n_B}{n_\gamma} = 6.1 \pm 0.3 \times 10^{-10}$ at $T \sim 1GeV$
- matter-antimatter symmetry

$$\Rightarrow \quad \frac{n_B}{n_\gamma} = \frac{n_{\overline{B}}}{n_\gamma} \approx 10^{-18}$$

How to get Baryogenesis in the Standard Model ?

- Since CPT invariance is assumed need non equilibrium physics
- Amount of CP violation not sufficient
- Beyond-the-Standard-Model physics is required

C(harge conjugation)P(arity)T(ime reversal)Theorem

Let $\boldsymbol{\Theta = CPT}$

Lagrangian density = $\mathcal{L}(x)$

For any Lorentz invariant Hermitian local Lagrangian

$$\Theta\mathcal{L}(x)\Theta^{-1}=\mathcal{L}^{\dagger}(-x)$$

Our BSM model for Leptogenesis

Spontaneously Broken Lorentz invariance

Spontaneously Broken CPT invariance

Sterile neutrino

String inspired gravitational degrees of freedom

Leptogenesis effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + i\,\overline{N}\gamma^{\mu}\partial_{\mu}N - \frac{m_N}{2}\left(\overline{N^c}N + \overline{N}N^c\right) - \overline{N}\gamma^{\mu}B_{\mu}\gamma^5 N - \sum_k y_k \overline{L}_k \tilde{\phi} N + h.c.$$

where N is a right-handed Majorana neutrino with heavy mass m_N

$\overline{N}\gamma^{\mu}B_{\mu}\gamma^5 N$ is CPTV and LIV

Features of model

Majorana nature of N leads to acceptable leptogenesis

Very heavy N leads to freeze out at TeV scale

B-L conservation converts ΔL to ΔB

Leptogenesis occurs at tree level

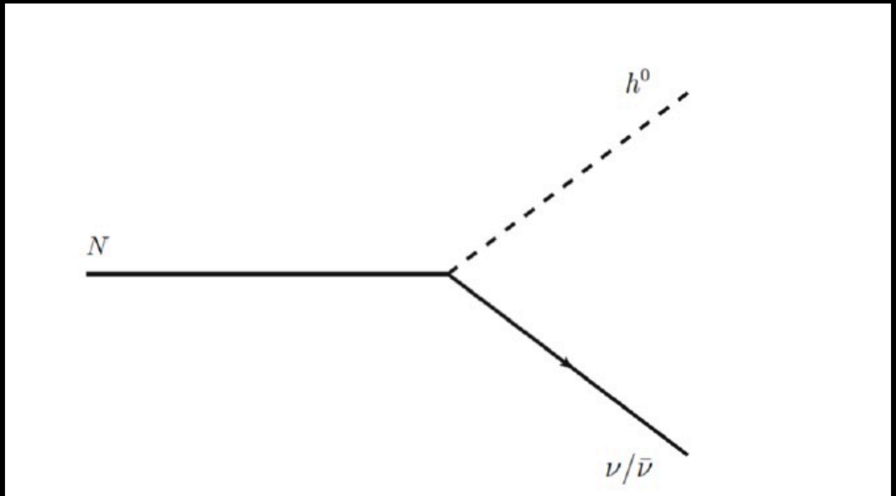
CP and CPT violating decays

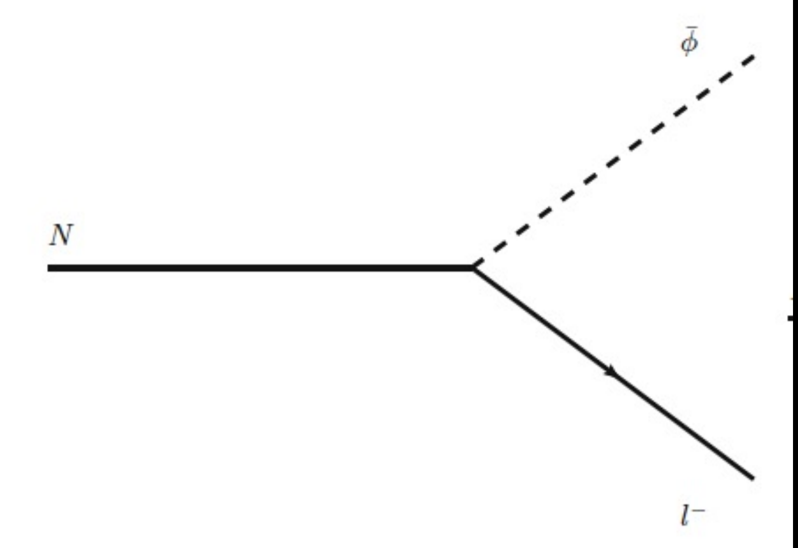
- Background

$$B_i = 0, \qquad i = 1, 2, 3$$
$$B_0(z) = \Phi f(z)$$

$z = \frac{m_N}{T}$, and $f(z) = 1$ or $f(z) = z^{-3}$

- Tree-level decays:
  - $N \to l^- h^+, \upsilon h^0$ channel 1
  - $N \to l^+ h^-, \bar{\upsilon} h^0$ channel 2


h^0
N
$\nu/\bar{\nu}$


$\bar{\phi}$
N
l^-

CP violation through CPTV: decay rates

Channel 1 $N \to l^- \bar{\phi}$

Channel 2 $N \to l^+ \phi$

$$\Gamma_1 = \sum_k \frac{|Y_k|^2}{32\pi^2} \frac{m^2}{\Omega} \frac{\Omega + B_0}{\Omega - B_0},$$

$$\Gamma_2 = \sum_k \frac{|Y_k|^2}{32\pi^2} \frac{m^2}{\Omega} \frac{\Omega - B_0}{\Omega + B_0}.$$

$$\Gamma_1 \neq \Gamma_2$$

$$\Omega = \sqrt{B_0^2 + m^2}.$$

Lepton asymmetry

$$\boxed{\frac{\Delta L}{n_\gamma} \simeq 10^{-10},} \Rightarrow \boxed{\frac{B_0}{m} \simeq 10^{-8}}$$

Boltzmann analysis

$$\frac{\Delta L^{tot}}{s} \simeq .017\,\frac{B_0}{m_N}$$

at freezeout temperature $T = T_D$

$$\frac{m_N}{T_D} \simeq 1.6$$

$m_N = O(100)TeV$

For $y{\sim}10^{-5}$

$B_0{\sim}0.1MeV$

$T_D{\sim}60TeV$

String inspired microscopic origin of B_μ

1. Gravitational multiplet in bosonic string theory: $g_{\mu\nu}, H_{\mu\nu\lambda}, \phi$
2. $S = \frac{1}{2\kappa^2}\int\sqrt{g}\,\left[R - e^{-4\phi}H_{\mu\nu\lambda}H^{\mu\nu\lambda}\right]$
3. $\bar{\Gamma}^\lambda_{\mu\nu} = \Gamma^\lambda_{\mu\nu} + \sqrt{\kappa^2/3}\,g^{\lambda\rho}H_{\mu\nu\rho}$ to $O(\alpha')$ $\Rightarrow$ $R(\bar{\Gamma})$
4. Contorsion $H_{\mu\nu\rho}$

$$H_{\mu\nu\rho} = \partial_{[\mu}B_{\nu\rho]}$$

$$e^{-2\Phi}\varepsilon_{bac}{}^{\mu}H^{abc} = 4\partial^\mu \underbrace{b(x)}_{\text{axion}} = 4B_\mu(x)$$

Fermions in torsion background

- Gravity …… gauge theory …… local Lorentz invariance

- Spin connection $\Longleftrightarrow$ gauge field

- Spin connection $\supset$ torsion

- Fermions $\longrightarrow$ torsion $\longrightarrow$ gauge D_μ

- Fermion-torsion coupling: $\int B_\mu \bar{\psi}\gamma^\mu\gamma^5\psi\sqrt{-g}\,d^4x$

$B_d = \frac{1}{3!}\varepsilon^{abc}{}_d T_{abc}$ T_{abc} torsion tensor.

Background for B_μ

- $B_\mu = \partial_\mu b \quad (4D)$
- $b(x) = \bar{b}(x) + \tilde{b}(x)$

background fluctuation

- (1) $\frac{d}{dt}\,\bar{b}$ = *constant*
- (2) $\partial_\mu\left[\sqrt{g}\left(\frac{8}{3\kappa^2}\partial^\mu \bar{b} - J^{5\mu}\right)\right] = 0$

Background solutions

$$1. B_0 = constant \quad B_i = 0$$

$$2. \langle J^{5\quad 0} \rangle \neq 0 \Longrightarrow B_0 = \frac{3\kappa^2}{8} \langle J^{5\quad 0} \rangle$$

Current constraints

$$|B_0| < .01\ eV$$

$$|B_i| < 10^{-31} GeV$$

What if ?

$\langle J^{5\quad 0}\rangle$=0 $\qquad T_D \sim 10^5 GeV$

$B_0 \sim T^3 \qquad T \leq T_D$

$$B_0(T_D \approx 10^5 GeV) = 0.1 MeV$$

$$\Longrightarrow B_0(T_0 \approx 0.23\ meV) = O(10^{-57}) GeV$$

Technical details

Classical torsionful spacetime manifold

$$d\underline{e}^a + \underline{\omega}^a{}_b \wedge \underline{e}^b = \mathfrak{I}^a$$

$$d\underline{\omega}^a{}_c + \underline{\omega}^a{}_b \wedge \underline{\omega}^b{}_c = \underline{R}^a{}_c$$

$\underline{e}^a$ is the vierbein

$\underline{\omega}^a{}_b$ is the spin-connection

fermions of SM on a torsionful manifold

$$S = S_{gravity} - \frac{1}{2}\Sigma_f \int \left(\overline{\Psi}_f \underline{\gamma} \wedge * \mathcal{D}\Psi_f - \mathcal{D}\overline{\Psi}_f \wedge * \underline{\gamma}\Psi_f\right) - \frac{1}{2}\int \mathcal{F} \wedge * \mathcal{F} - \int Tr[G \wedge * G]$$

$$\mathcal{D}\Psi = d\Psi + \frac{1}{4}\underline{\omega}^{ab}\gamma_{ab}\Psi + ie\underline{\mathcal{A}}\Psi + ig\underline{\mathcal{B}}\,\Psi$$

$$S_{gravity} = \frac{1}{4\kappa^2}\int \varepsilon_{abcd}\,\underline{\mathcal{R}}^{ab} \wedge \underline{e}^c \wedge \underline{e}^d$$

$\underline{\gamma} = \gamma_a \underline{e}^a$ and $\gamma_{ab} = \frac{1}{2}[\gamma_a, \gamma_b]$

$\underline{\mathcal{A}}$ and $\underline{\mathcal{B}}$ the gauge connection 1-forms

Equation of motion with respect to $\underline{\omega}^{ab}$

$$\mathcal{T}_{abc} = -\frac{\kappa^2}{2}\varepsilon_{abcd}\sum_f J_f^{5\,d}$$

$$J_f^{5\,d} = i\overline{\Psi}_f\gamma^d\gamma^5\Psi_f$$

Anomalies

axial anomaly

$$d * \underline{J}^5 = -\frac{\alpha_{em}\overline{Q}^2}{\pi}\mathcal{F} \wedge \mathcal{F} - \frac{\alpha_s N_q}{2\pi} Tr[G \wedge G] - \frac{N_f}{8\pi^2}\widetilde{R}^{ab} \wedge \widetilde{R}^{ab}$$

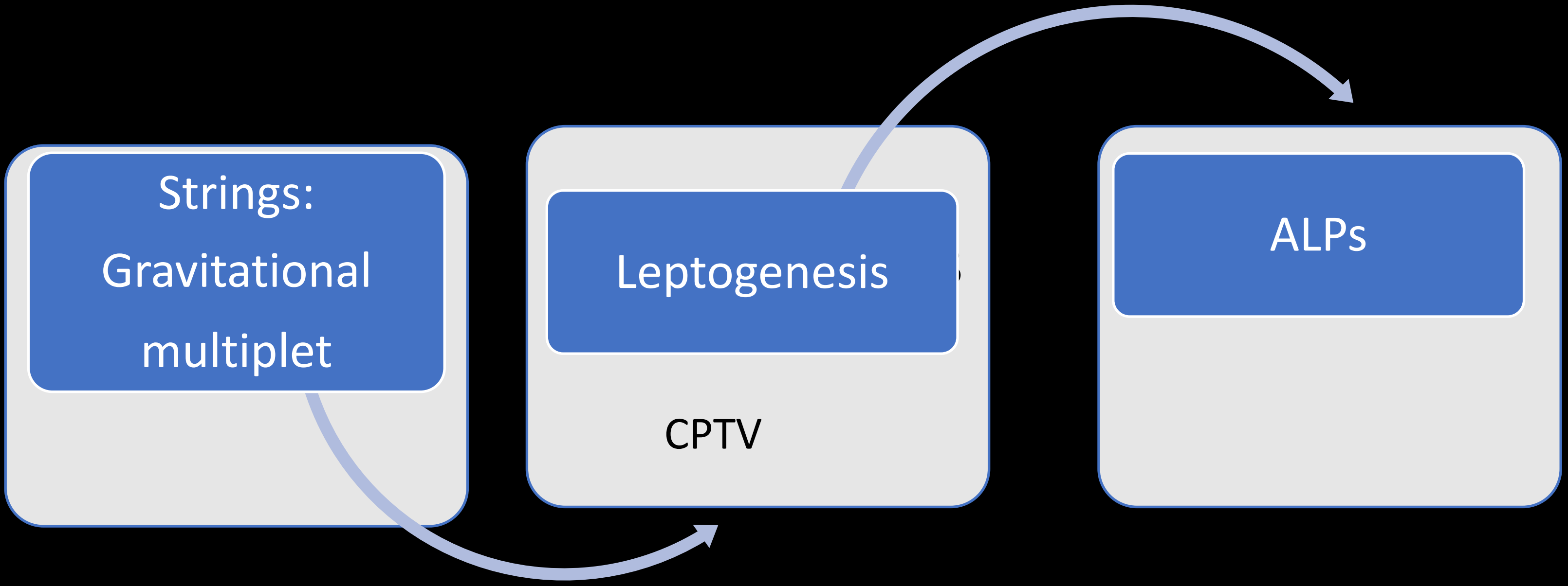
Dynamical torsion

Axial anomaly $\Rightarrow$

$$-\frac{\alpha_{em}\overline{Q}^2}{\pi f_b}\int b\,\mathcal{F}\wedge\mathcal{F} - \frac{1}{2}\int db\wedge{*}\,db - \frac{1}{8\pi^2}\int\left(\Theta+\frac{N_f}{f_b}b\right)\widetilde{R}^{ab}\wedge\widetilde{R}_{ab} - \frac{\alpha_s}{2\pi}\int\left(\theta+\frac{N_q}{f_b}b\right)Tr[G\wedge G]$$

$$f_b = \kappa^{-1}\sqrt{8/3} = 4\times10^{18}\ \text{GeV.}$$

CONCLUDING remarks



Viable scenario

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