Spontaneous CPT Violation and Quantum Anomalies in a model for Matter-Antimatter Asymmetry in the Cosmos

Sarben Sarkar

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

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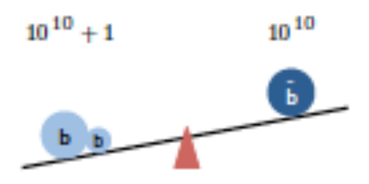
Baryogenesis (BAU)



Small difference between number of baryons and anti baryons

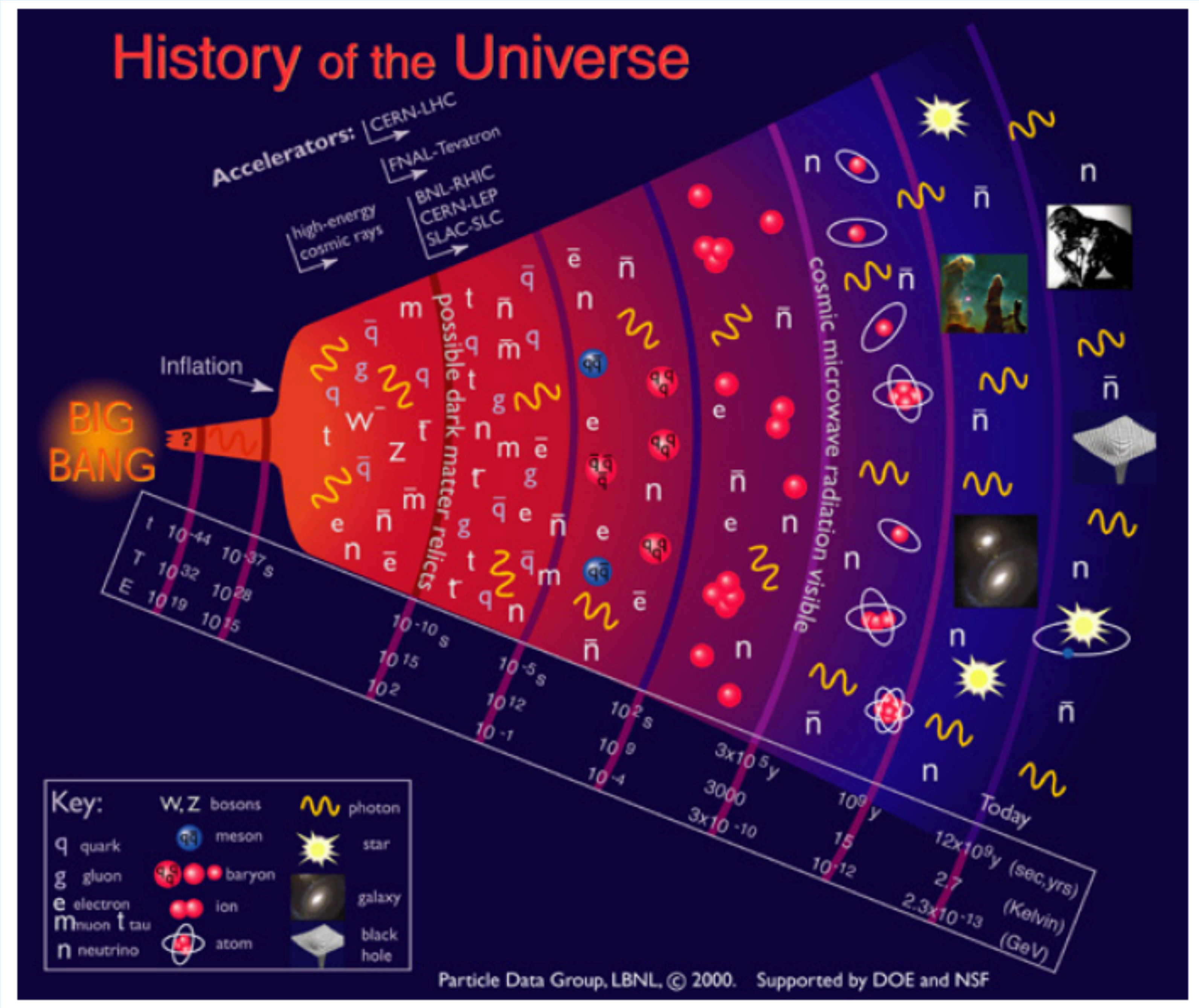
$$\beta \equiv \frac{n_B}{s} = \left(8.59 \pm 0.11\right) \times 10^{-11} \qquad n_B = n_b - n_{\bar{b}}$$

n_b is the baryon number density
$n_{\bar{b}}$ is the anti-baryon number density
s is the entropy densitys$\approx 7.04 n_\gamma$

For $T \geq GeV \quad n_b \sim n_{\bar{b}} \sim n_\gamma$

- **BAU cannot be due to an initial condition**
- **Galaxy and anti-galaxy: large gamma ray emissions not observed**

- **BAU needs BSM physics: many proposals; many satisfy Sakharov criteria**


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Sakharov criteria (Sakarov JETP Lett 5 (1967) 24)

- **Baryon number violating process (BVP)**
- **C and CP violations**
- **Out of equilibrium (<u>assumes</u> CPT invariance)**

- **BVP not present at perturbative level in SM**
- **Second requirement**

Since $\Gamma\left(X \to Y + b\right) \neq \Gamma\left(\overline{X} \to \overline{Y} + \overline{b}\right)$ **and**

$X \to Y + b \quad \Delta B = 1$ $\qquad \overline{X} \to \overline{Y} + \overline{b} \quad \Delta B = -1$

- **The third condition avoids**

$$\Gamma\left(X \to Y + b\right) = \Gamma\left(Y + b \to X\right)$$

which otherwise would lead to $\Delta B = 0$

- **Expanding universe leads to non-equilibrium**

Standard model: electroweak BAU

- **Baryon number violating process: sphaleron process**
- **C and P violations: chiral gauge theory and CP phase**
- **Out of equilibrium: *first order* electroweak phase transition**

  (Kuzmin, Rubakov, Shaposhnikov, Cohen, Kaplan, Nelson …)

- **Attractive scenario but not viable since phase transition is second order for Higgs mass $M_H > 70 GeV\ in\ the\ SM$**

- **An alternative mechanism is baryogenesis through leptogenesis using a background induced *CPTV* and *anomalies***
- ***(see de Cesare,Mavromatos, Sarkar: Eur Phys J C75 (2015) 514, Bossingham,Mavromatos, Sarkar: Eur. Ohys. J C78 (2018) 113 Bossingham,Mavromatos,Sarkar: Eur. Phys. J C79 (2019) 50)***

CPT symmetry

- ***C*** **is charge conjugation**
- ***P*** **is parity (space reflection)**
- ***T*** **is time-reversal**
- ***CPT*** **theorem:** **For any *Lorentz invariant Lagrangian L(x)* in *flat* space times**

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

where $\Theta \equiv CPT$.

based on *unitarity* and *locality* of interactions (Schwinger, Pauli, Luders , Jost and Bell)

Assumptions of CPT theorem may not hold in the early universe, e.g. Lorentz invariance

- **An approach to CPTV :Standard Model Extension *effective* field theory with ψ_f a generic fermion**

$$L \supset \cdots + \bar{\psi}^f \left(i\gamma^\mu \nabla_\mu - m_f \right) \psi^f + a_\mu \bar{\psi}^f \gamma^\mu \psi^f + b_\mu \bar{\psi}^f \gamma^\mu \gamma^5 \psi^f + \cdots$$

Lorentz and CPT from spontaneous violation

(See: Collady,Kostelecky Phys Rev D55 (1997) 676,
Bluhm et al,Phys Rev Lett 84 (2000) 1098,
Kostelecky,Russell Rev. Mod. Phys. 83 (2011) 11)

- $\Delta m = m - \overline{m}$ **for quarks and antiquarks because of CPTV but in equilibrium has to be too large for BAU (Dolgov 2009)**

CPT violation in a String Inspired Model

- CPT violation $\longrightarrow$ violation of Lorentz invariance (Greenberg 2002)
- A CPTV possibility:

1. Bosonic gravitational multiplet of strings consists of graviton $g_{\mu\nu}$, spin 0 scalar field the dilaton Φ, spin 1 antisymmetric gauge field $B_{\mu\nu}$ which has gauge symmetry $B_{\mu\nu} \rightarrow B_{\mu\nu} + \partial_\mu \theta_\nu - \partial_\nu \theta_\mu$

   in closed string sector
2. Gauge invariant field strength

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

3. Bosonic part of $(3+1)$ dimensional effective action

$$S_B = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(R - e^{-4\Phi}H_{\lambda\mu\nu}H^{\lambda\mu\nu} - \Omega\right) + \ldots$$

Role of H-field as Torsion

- **Effective gravitational action in string low energy limit**

$$S=\int d^4x\sqrt{-g}\left(\frac{1}{2\kappa^2}R-\frac{1}{6}H_{\mu\nu\rho}H^{\mu\nu\rho}\right)=\int d^4x\sqrt{-g}\left(\frac{1}{2\kappa^2}\bar{R}\right)$$

where

$$\bar{\Gamma}^{\mu}_{\nu\rho}=\Gamma^{\mu}_{\nu\rho}+\underbrace{\frac{\kappa}{\sqrt{3}}H^{\mu}_{\nu\rho}}_{\text{contorsion}}\neq\bar{\Gamma}^{\mu}_{\rho\nu}$$

- **Generalised curvature** $\bar{R}\left(\bar{\Gamma}\right)$

Dual pseudoscalar in 3 + 1 dimensions:

- $\boldsymbol{b(x)}$ **Kalb-Ramond axion**

$$B^{\mu} = \partial^{\mu} b = -\frac{1}{4} e^{-2\Phi} \varepsilon_{abc}{}^{\mu} H^{abc}$$

Split quantum field into a *background* and fluctuation:

$$b(x) = \bar{b}(x) + \tilde{b}(x)$$

Possible backgrounds:

$$\bar{b}(x) \propto t$$

such backgrounds exist in bosonic non-critical strings

(Antoniadis, Bachas, Ellis and Nanopoulos, Nucl. Phys B 328 (1989) 117)

Fermion coupling to H-torsion using vielbeins

$$g_{\mu\nu} = e^a_\mu \eta_{ab} e^b_\nu \qquad \omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu} e^\gamma_c e^\mu_a\right)$$

Spin connection

$$\bar{D}_a = \left(\partial_a - \frac{i}{4}\bar{\omega}_{bca}\sigma^{bc}\right)$$ **where** $$\bar{\omega}_{ab\mu} = \omega_{ab\mu} + K_{ab\mu}$$

and

$$K_{abc} = \frac{1}{2}\left(H_{cab} - H_{abc} - H_{bca}\right)$$

$$\boxed{S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\left(\bar{\psi}\gamma^\mu \bar{D}_\mu \psi - \bar{D}_\mu \bar{\psi}\gamma^\mu\psi\right)}$$

$$S_\psi \supset \int d^4x\, B_a \bar{\psi}\gamma^a\gamma^5\psi$$ **where** $$B^d \sim \varepsilon^{abcd} H_{bca}$$

Effective action for axions

- Let $S_{eff} = S + S_{\psi}$
- The axion terms in S_{eff} are

$$\sim \int d^4x \sqrt{-g}\left[\frac{4}{3\kappa^2}\partial_\mu b \partial^\mu b - \partial_\nu b J^{5\nu}\right]$$

The classical homogeneous isotropic background can be

$$\partial_t\left[\sqrt{-g}\left(\frac{8}{3\kappa^2}\partial_0 \bar{b} - J_0^5\right)\right] = 0$$

$$J_\mu^5 = \sum_i \bar{\psi}_i \gamma_\mu \gamma^5 \psi_i$$

An approximate solution is plausibly obtained on using from thermal average $\left\langle J_0^5 \right\rangle = 0$

$$\frac{d}{dT}\left(a^3(T)B_0\right) \simeq 0 \Rightarrow B_0(T) = AT^3$$

Dispersion relations for (Dirac) fermions and anti-fermions in presence of background

$$E = \sqrt{\vec{p}^2 + m^2 + B_0^2 + 2\left|\vec{p}\right| B_0}$$

$$\overline{E} = \sqrt{\vec{p}^2 + m^2 + B_0^2 - 2\left|\vec{p}\right| B_0}$$

$$n - \overline{n} = \frac{g}{(2\pi)^3} \int d^3p \left(\frac{1}{1 + \exp\left(\frac{E}{T}\right)} - \frac{1}{1 + \exp\left(\frac{\overline{E}}{T}\right)} \right) \neq 0$$

Is direct baryogenesis possible?
BUT

Detailed mechanisms for freeze out?
Phenomenologically relevant baryogenesis need non-minimal higher derivative LV and CPTV fermionic interactions

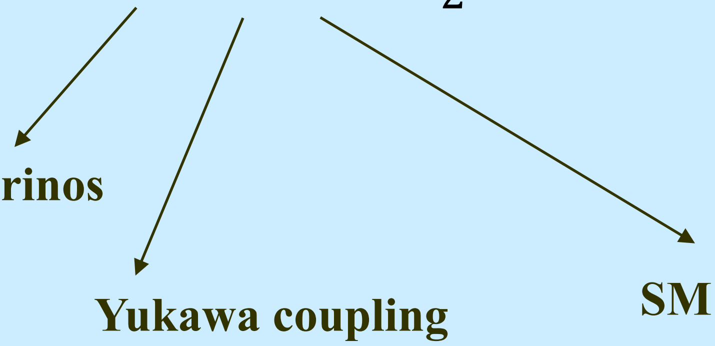
Leptogenesis model ⊃ Standard Model has baryogenesis

Existing such model (*seesaw mechanism*):

Produces light neutrino masses relevant for neutrino oscillations

SM extension with heavy N_I extra right-handed neutrinos $(N_f = 2, 3)$

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - f_{\alpha I}\bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\bar{N}_I^c N_I + h.c.$$



Sterile neutrinos

Yukawa coupling

SM lepton

(Minkowski, Yanagida, Mohapatra, Senjanovic, Sechter, Valle, …)

CPTV leptogenesis model motivated by seesaw model

$$B_0 = \text{const} \neq 0$$

$$\tilde{\varphi}_i = \varepsilon_{ij}\varphi_j$$

$$L = L_{SM} + i\bar{N}\not{\partial}N - \frac{m_N}{2}\left(\bar{N}^c N + \bar{N}N^c\right)$$
$$-\bar{N}\not{B}\gamma^5 N - \sum_k y_k \bar{L}_k \tilde{\varphi} N + h.c.$$

- **Kalb-Ramond background model for leptogenesis**
- **N is a Majorana spinor; is the adjoint of the Higgs field**
- **L_k is the lepton doublet of the kth generation of the standard model**
- **Restrict to generation $k = 1$**
-

  homogeneous and isotropic
- **The model breaks Lorentz invariance and CPT**
- **Gives microscopic justification of standard model extension**
- **Decay of heavy right-handed Majorana neutrino**

-411 De Cesare, NEM & Sarkar, Eur.Phys.J. C75 (2015) no.10, 514 Bossingham, NEM & Sarkar, Eur.Phys.J. C78 (2018) no.2, 113 & arXiv:1810.13384 [hep-ph].

$$B_i = 0, \quad i = 1,2,3$$

Leptogenesis implies baryogenesis in model $\supset$ SM

- **SM Lagrangian has global $U(1)$ chiral symmetry**
- **Classically: *B* and *L* conservation for *individual* generations**
- **Quantum mechanically: *B*+*L* is anomalous, $B-L$ is exact symmetry**
- **So non-conservation of *L* → non-conservation of *B***
- ***C* is explicitly broken in SM**
- **CP is broken by background Kalb-Ramond**
- **The expansion of the Universe is an out of equilibrium situation: freeze out**
- **Prediction of BAU from $B-L$ conservation**

Contrast with Fukugita-Yanagida leptogenesis

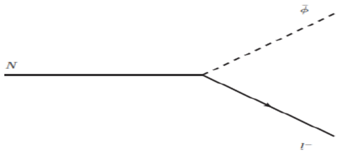
Channels

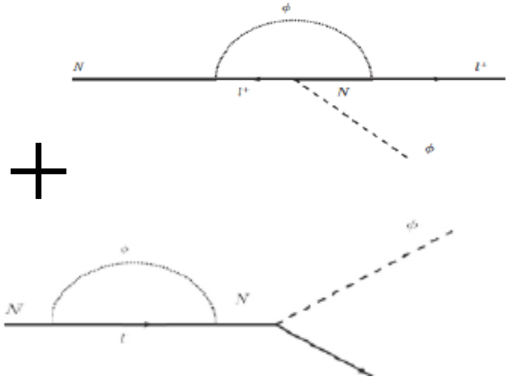
$N \to l^- \phi^+ , \nu\phi^0$

$N \to l^+ \phi^- , \bar{\nu}\phi^0$

Tree level

Lepton number and CP violation





$Early\ universe\ T > 10^5\ GeV$

Boltzmann equations

- **Boltzmann equations to find the out equilibrium abundances**

$$xHs\frac{dY_1}{dx} - \lambda I = -\sum\left[\gamma^{eq}(1,2... \to 3,4...)\frac{Y_1}{Y_1^{eq}}\frac{Y_2}{Y_2^{eq}}... - \gamma^{eq}(3,4... \to 1,2...)\frac{Y_3}{Y_3^{eq}}\frac{Y_4}{Y_4^{eq}}...\right]$$

RHS are all the different interactions that take place

Only need to consider the tree level decays of the heavy neutrinos into leptons/anti-leptons and the reverse processes

$$N \to l^{-}\phi^{+}, \nu\phi^{0} \qquad N \to l^{+}\phi^{-}, \overline{\nu}\phi^{0}$$

$$x \equiv \frac{m_N}{T}, \qquad Y_\chi \equiv \frac{n_\chi}{s}$$

Vacuum energy

$$\rho_{B_0}^{DE}\left(x\right)=\frac{4}{3\kappa^2}\partial_\mu\bar{b}\,\partial^\mu\bar{b}$$

$$=\frac{M_P^2}{6\pi}B_0^2=\frac{M_P^2\Phi^2}{6\pi}x^{-6}$$

$$\rho_{B_0}^{DE}\left(x_0\right)\simeq10^{-158}M_P^2$$

$$\frac{\Delta L^{total}}{s}=q\frac{\Phi}{m_N}\simeq8\times10^{-11}$$

$$B_i<10^{-31}\mathrm{GeV}$$

$$B_0<.01\mathrm{eV}$$

$$T_D=O\left(100\right)\mathrm{TeV}$$

$$B_0\left(x\right)\simeq\Phi x^{-3}$$

$$\Phi\simeq\left(0.36-0.74\right)\mathrm{keV}$$

Conclusions

B_0 **DOES NOT contribute to the CME in the presence of a magnetic field even though it looks like a chiral chemical potential**

(Hull, Mavromatos, Dvornikov)

gravitational anomaly

$$Tr\left(\bar{R}\left(\bar{\omega}\right)\wedge\bar{R}\left(\bar{\omega}\right)\right)=Tr\left(R\left(\omega\right)\wedge R\left(\omega\right)\right)$$
$$+d\left[Tr\left(H\wedge R+H\wedge DH+\frac{2}{3}H\wedge H\wedge H\right)\right]$$

Dark energy contribution less than cosmological constant