CPT-violating leptogenesis induced by gravitational backgrounds

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Abstract. We explore leptogenesis induced by the propagation of neutrinos in non-trivial gravitational backgrounds that may characterise the Early Universe epochs of various theories, including string theory. The key point in all these models is that the background induces different populations of fermions as compared to antifermions, and hence CPT Violation (CPTV), already in thermal equilibrium. Depending on the model, then, such populations may freeze out at various conditions leading to leptogenesis and baryogenesis. Among the considered scenarios, is a stringy one, in which the CPTV is associated with a cosmological background with torsion provided by the Kalb-Ramond antisymmetric tensor field (axion) of the string gravitational multiplet. We also discuss CPTV models that go beyond the *local* effective lagrangian framework, such as a stochastic (Lorentz Violating) Finsler metric and D-particle foam, where the CPTV is due to populations of stochastically fluctuating point-like space-time defects that can be encountered in string/brane theory (D0 branes).

1. Introduction

One of the most important issues of fundamental physics, relates to an understanding of the magnitude of the observed baryon asymmetry $n_B - n_{\overline{B}}$ (where B denotes baryon, $\overline{B}$ denotes antibaryon, n_B is the number density of baryons and $n_{\overline{B}}$ the number density of antibaryons in the universe). The universe is overwhelmingly made up of matter rather than anti-matter. According to the standard Big Bang theory, matter and antimatter have been created in equal amounts in the early universe. However, the observed charge-parity (CP) violation in particle physics [1], prompted A. Sakharov [2] to conjecture that for Baryon Asymmetry in the universe (BAU) we need:

- Baryon number violation to allow for states with $\Delta B \neq 0$ starting from states with $\Delta B = 0$ where ΔB is the change in baryon number.
- If C or CP conjugate processes to a scattering process were allowed with the same amplitude then baryon asymmetry would disappear. Hence C and CP need to be broken.
- Chemical equilibrium does not permit asymmetries. Hence Sakharov required that chemical equilibrium does not hold during an epoch in the early universe.

Hence non-equilibrium physics in the early universe together with baryon number (B), charge (C) and charge-parity (CP) violating interactions/decays of anti-particles in the early universe,

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may result in the observed BAU. In fact there are two types of non-equilibrium processes in the early universe that can produce this asymmetry: the first type concerns processes generating asymmetries between leptons and antileptons (*leptogenesis*), while the second produces asymmetries between baryons and antibaryons (*baryogenesis*). The near complete observed asymmetry today, is estimated in the Big-Bang theory [3] to imply:

$$\Delta n(T \sim 1 \text{ GeV}) = \frac{n_B - n_{\overline{B}}}{n_B + n_{\overline{B}}} \sim \frac{n_B - n_{\overline{B}}}{s} = (8.4 - 8.9) \times 10^{-11} \tag{1}$$

at the early stages of the expansion, e.g. for times $t < 10^{-6}$ s and temperatures $T > 1$ GeV. In the above formula s denotes the entropy density. Unfortunately, the observed CP violation within the Standard Model (SM) of particle physics (found to be of order $\epsilon = O(10^{-3})$ in the neutral Kaon experiments [1]) induces an asymmetry much less than that in (1) [4]. There are several ideas that go beyond the SM (*e.g.* grand unified theories, supersymmetry, extra dimensional models *etc.*) which involve the decays of right handed sterile neutrinos. For relevant important works on this see [5, 6, 7, 8, 9, 10, 11]. These ideas lead to extra sources for CP violation that could generate the observed BAU. Some degree of fine tuning and somewhat *ad hoc* assumptions are involved in such scenarios and the quest for an understanding of the observed BAU still needs further investigation. An example of fine tuning is provided by the choice of the hierarchy of the right-handed Majorana neutrino masses. For instance, enhanced CP violation, necessary for BAU, can be achieved in models with three Majorana neutrinos, by assuming two of these neutrinos are nearly degenerate in mass.

The requirement of non-equilibrium is on less firm ground [12] than the other two requirements of Sakharov, *e.g.* if the non-equilibrium epoch occurred prior to inflation then its effects would be hugely diluted by inflation. A basic assumption in the scenario of Sakharov is that *CPT symmetry* [13] (where T denotes time reversal operation) holds in the very early universe which leads to the production of matter and antimatter in equal amounts. Such *CPT invariance* is a cornerstone of all known *local* effective *relativistic* field theories without gravity, which current particle-physics phenomenology is based upon. It should be noted that the necessity of non-equilibrium processes in CPT invariant theories can be dropped if the requirement of CPT is relaxed [14]. This violation of CPT (denoted by CPTV) is the result of a breakdown of Lorentz symmetry (which might happen at ultrahigh energies [15]). For many models with CPTV, in the time line of the expanding universe, CPTV generates first lepton asymmetries (*leptogenesis*); subsequently through sphaleron processes [16] or Baryon-Lepton (B-L) number conserving processes in Grand Unified Theories (GUT), the lepton asymmetry can be communicated to the baryon sector to produce the observed BAU.

Thus, CPTV in the early universe may also obviate the need for including extra sources of CP violation, such as sterile neutrinos and/or supersymmetry, in order to obtain the observed BAU. In this talk, which is based on joint work appeared in [17], we will consider CPTV leptogenesis from a non-Riemannian point of view, inspired by a stringy model of gravitational defects and backgrounds interacting with neutral fermions. The explicit non-Riemannian structure that we investigate is Finsler geometry [18] where momentum as well as position are explicitly involved in its metric. The defects that we will consider are point-like solitonic structures in some string theories; they are known as D0-branes (or *D-particles*) [19]. Our generic model involves effectively three-space-dimensional brane universes, obtained from compactification of higher-dimensional branes, which are embedded in a bulk space punctured by D-particles (see e.g. [20]). One of these brane universes constitutes our observable world, which moves in the bulk. As a consequence of this motion, D-particles cross the brane. Open strings for electrically neutral particles on the brane can attach an end to the D-particle; subsequently this string can detach [21, 22]. Scattering off a *population* of D-particles (D-foam) affects the kinematics of the stringy matter and leaves an imprint on the background geometry [23] on the brane world. This geometry is similar to Finsler metrics but with stochastic parameters [24, 25, 26]. We first investigate the consequences for gravitational leptogenesis of this metric structure in the general setting of Finsler geometry without reference explicitly to D-foam. For the underlying stringy model however, since it is microscopic, we can consider in addition the kinematics of D particle scattering. This kinematical aspect leads naturally to the asymmetry between the particle and anti-particle abundances having the right sign. The kinematical argument, which involves recoil kinetic energy, does not fit into an effective local field theory approach and represents a new approach that is relevant to leptogenesis.

The structure of the talk will be as follows: in the next section 2 we shall briefly review some relevant existing models for fermionic asymmetry, which entail CPTV-induced differences in the dispersion relations between particles and antiparticles propagating in curved gravitational backgrounds in the early universe. In section 3, we review a new model for gravitational leptogenesis, proposed in [17], which follows broadly an earlier framework [27, 28], but differs crucially in that the full gravitational multiplet [29] that arises in string theory is used. The leptogenesis in this model is due to CPTV dispersion relations between fermions/antifermions, induced by the (constant) *torsion* associated with the antisymmetric Kalb-Ramond tensor field in the gravitational multiplet of the string. In section 4, we consider another scenario for gravitational leptogenesis that involves a non-Riemannian Finsler metric, with stochastically fluctuating parameters, a variant of which appears in our string/brane ("*D-foam*") model in section 5. In section 5 we present our D-foam model for the stringy universe and the induced CPTV and leptogenesis/baryogenesis. The model is characterised by CPTV and matter dominance over antimatter *naturally*, without the need for an adjustment of the sign of the lepton/antilepton asymmetry. This is an interesting feature of our model which differentiates it from earlier proposals on gravitational leptogenesis/baryogenesis [30, 31, 32, 33, 28, 27, 34, 35, 36], where the sign of the asymmetry is implicitly chosen. In common with earlier discussions of CPTV in baryogenesis [37], this class of models involves violation of Lorentz symmetry, but only because of a non-zero *variance* of the stochastic parameter.

2. Models of CPT violation (CPTV) in the early universe

In this section we shall review some existing models of CPTV induced asymmetry between matter and antimatter in the early universe, which can be contrasted with our approach in this article. We shall be brief in our exposition, referring the interested reader to the relevant literature for more details.

2.1. CPTV models with particle-antiparticle mass difference

The simplest possibility [38] for inducing CPTV in the early universe is through particle-antiparticle mass differences $m \neq \overline{m}$. These would affect the particle phase-space distribution function $f(E,\mu)$, $f(E,\mu) = [\exp(E-\mu)/T) \pm 1]^{-1}$, $E^2 = \vec{p}^2 + m^2$, and antiparticle phase-space distribution function $f(\overline{E},\bar{\mu}) = [\exp(\bar{E}-\bar{\mu})/T) \pm 1]^{-1}$, $\bar{E}^2 = \vec{p}^2 + \bar{m}^2$, with $\vec{p}$ being the $3-$momentum. (Our convention will be that an overline over a quantity will refer to an antiparticle, $+$ will denote a fermionic (anti-)particle and $-$ will denote a bosonic (anti-)particle). (Anti)particles will have, by definition, (negative) positive energies. Mass differences between particles and antiparticles, $\overline{m} - m \neq 0$, generate a matter-antimatter asymmetry in the relevant number densities n and $\overline{n}$ $n - \overline{n} = g_{d.o.f.} \int \frac{d^3p}{(2\pi)^3}[f(E,\mu) - f(\overline{E},\bar{\mu})]$, where $g_{d.o.f.}$ denotes the number of degrees of freedom of the particle species under study. In the case of spontaneous Lorentz violation [37] there is a vector field A_μ with a non-zero time-like expectation value which couples to a global current J^μ such as baryon number through an interaction lagrangian density

$$\mathcal{L} = \lambda A_\mu J^\mu. \tag{2}$$

This leads to $m \neq \bar{m}$ and $\mu \neq \bar{\mu}$. Alternatively, following [38] we can make the assumption that the dominant contributions to baryon asymmetry come from quark-antiquark mass differences, and that their masses "run" with the temperature i.e. $m \sim gT$ (with g the QCD coupling constant). One can provide estimates for the induced baryon asymmetry on noting that the maximum quark-antiquark mass difference is bounded by the current experimental bound on the proton-antiproton mass difference, $\delta m_p (= |m_p - \overline{m}_p|)$, known to be less than $2 \cdot 10^{-9}$ GeV. Taking $n_\gamma \sim 0.24\, T^3$ (the photon equilibrium density at temperature T) we have [38]:

$$\beta_T = \frac{n_B}{n_\gamma} = 8.4 \times 10^{-3} \, \frac{m_u \, \delta m_u + 15 m_d \, \delta m_d}{T^2} \ , \quad \delta m_q = |m_q - \overline{m}_q| \ . \tag{3}$$

β_T is too small compared to the observed one. To reproduce the observed $\beta_{T=0} \sim 6 \cdot 10^{-10}$ one would need $\delta m_q (T = 100 \text{ GeV}) \sim 10^{-5} - 10^{-6}$ GeV $\gg \delta m_p$, which is somewhat unnatural.

However, active (*light*) neutrino-antineutrino mass differences alone may reproduce BAU; some phenomenological models in this direction have been discussed in [39], considering, for instance, particle-antiparticle mass differences for active neutrinos compatible with current oscillation data. This leads to the result

$$n_B = n_\nu - n_{\overline{\nu}} \simeq \frac{\mu_\nu \, T^2}{6} \tag{4}$$

yielding $n_B/s \sim \frac{\mu_\nu}{T} \sim 10^{-11}$ at $T \sim 100$ GeV, in agreement with the observed BAU. (Here s, n_ν, and μ_ν are the entropy density, neutrino density and chemical potential respectively.)

2.2. CPTV decoherence models

Particle-antiparticle mass differences however may not be the only way by which CPT is violated. As discussed in [40, 41], quantum gravity fluctuations in the structure of space-time, may be strong in the early universe; the fluctuations may act as an *environment* inducing decoherence for the (anti-)neutrinos. However the couplings between the particles and the environment are different for the neutrino and antineutrino sectors. Once there is decoherence for an observer with a low energy (compared to the Planck scale $M_P \sim 10^{19}$ GeV), the effective CPT symmetry generator may be *ill-defined* as a quantum mechanical operator, according to a theorem by R. Wald [42], leading to an intrinsic violation of CPT symmetry. This type of violation may characterise models of quantum gravity with stochastic space-time fluctuations due, for instance, to gravitational space-time defects, as is the case of certain brane models [22, 20, 25]. In such a case, a slight mismatch in the strength of the stochastic space-time fluctuations between particle and antiparticle sectors, can lead to different decoherence parameters to describe the interaction of the gravitational environment with matter.

In [40, 41], simple models of Lindblad decoherence [43], conjectured to characterise quantum-gravity-induced CPTV decoherent situations [44, 45], have been considered for neutrinos [46]. It was assumed on phenomenological grounds, that non-trivial decoherence parameters were *only* present in the antiparticle sector: this is consistent with the lack of any experimental evidence to date [47, 48, 49] for vacuum decoherence in the particle sector. The antineutrino decoherence parameters (with dimension of energy) had a mixed energy dependence. The model of [40, 41] assumes a diagonal $\mathcal{L}_{\mu\nu}$. A diagonal Lindblad decoherence matrix for three-generation neutrinos requires eight coefficients $\overline{\gamma}_i$. Some of the eight coefficients were assumed for simplicity in [40, 41] to be proportional to the antineutrino energy $\overline{\gamma}_i = \frac{T}{M_P} E$, $i = 1, 2, 4, 5$, while the remaining (subdominant) ones were inversely proportional to it $\overline{\gamma}_j = \frac{10^{-24}\,(\text{GeV})^2}{E}$, $j = 3, 6, 7, 8$. The model was proposed without any microscopic justification; its choice was originally motivated by fitting the LSND "anomalous data" in the antineutrino sector [50] with the rest of the neutrino data.

and this required T to be $T/M_P \sim 10^{-18}$,i.e. in the temperature range of electroweak symmetry breaking. One can derive [40, 41] an active (light) $\nu - \overline{\nu}$ asymmetry of order

$$\mathcal{A} = \frac{|n_\nu - n_{\overline{\nu}}|}{n_\nu + n_{\overline{\nu}}} = \frac{\overline{\gamma}_1}{\sqrt{\Delta m^2}} = \frac{T}{M_P} \cdot \frac{E}{\sqrt{\Delta m^2}} \ , \tag{5}$$

where Δm^2 denotes the (atmospheric) neutrino mass squared difference, which plays the role of a characteristic low mass scale in the problem. This lepton number violation is communicated to the baryon sector by means of baryon number (B) plus lepton number (L) conserving sphaleron processes (in fact, in this case one needs an antilepton excess in order to produce a baryon excess). These processes lead to an estimate [40] for the current value of B to be

$$B = \frac{n_\nu - n_{\overline{\nu}}}{s} \sim \mathcal{A}\,\frac{n_\nu}{g^\star\, n_\gamma} \tag{6}$$

with n_γ the photon number density, $g^\star$ the effective number of degrees of freedom (at the temperature where the asymmetry developed, i.e. the electroweak symmetry breaking temperature in the model of [40]). $g^\star$ depends on the matter content of the model (with a typical range $g^\star \in [10^2 - 10^3]$). For such parameter values $\mathcal{A} \sim 10^{-6}$ and so the observed BAU may be reproduced in this case without the need for extra sources of CP violation e.g. sterile neutrinos. Such models, however, do not provide an underlying microscopic understanding. In particular there is missing an understanding of the preferential role of the neutrino compared to other particles of the Standard Model in the CPT violating decoherence process. Within some microscopic models of space-time foam, involving populations of point-like brane defects (D-particles) puncturing three(or higher)-spatial dimension brane worlds [22, 20, 25], such a preferred role may be justified as we shall discuss in section 5.

2.3. CPTV-induced by curvature effects in background geometry
Although the role of gravity was alluded to in the last subsection, associated features of space-time were not discussed. In the literature the role of gravity has been explicitly considered within a local effective action framework which is essentially that of (2) A coupling to scalar curvature R [31, 27, 34, 32] through a CP violating interaction Lagrangian $\mathcal{L}$:

$$\mathcal{L} = \frac{1}{M_*^2}\int d^4x\sqrt{-g}\,(\partial_\mu R)\,J^\mu \tag{7}$$

where M_* is a cut-off in the effective field theory and J^μ could be the current associated with baryon (B) number. There is an implicit choice of sign in front of the interaction (7), which has been fixed so as to ensure matter dominance.

It has been shown that [31]

$$\frac{n_{B-L}}{s} = \frac{\dot{R}}{M_*^2 T_d}, \tag{8}$$

T_d being the freeze-out temperature for $B-L$ interactions. The idea then is that this asymmetry can be converted to baryon number asymmetry provided the $B+L$ electroweak sphaleron interaction has not frozen out. To leading order in M_*^{-2} we have $R = 8\pi G(1-3w)\rho$ where ρ is the energy density of matter and the equation of state is $p = w\rho$ where p is pressure. For radiation $w = 1/3$ and so in the radiation dominated era of the Friedmann-Robertson-Walker cosmology $R = 0$. However w is precisely 1/3 when $T_\mu^\mu = 0$. In general $T_\mu^\mu \propto \beta(g)F^{\mu\nu}F_{\mu\nu}$ where $\beta(g)$ is the beta function of the running gauge coupling g in a $SU(N_c$ gauge theory with N_c colours. This allows $w \neq 1/3$. Further issues in this approach can be found in [31, 27, 34, 32].

Another approach involves an axial vector current [28, 33, 35, 36] instead of J_μ. The scenario is based on the well known fact that fermions in curved space-times exhibit a coupling of their spin to the curvature of the background space-time.The Dirac Lagrangian density of a fermion can be re-written as:

$$\mathcal{L} = \sqrt{-g}\,\overline{\psi}\left(i\gamma^a\partial_a - m + \gamma^a\gamma^5 B_a\right)\psi\ , \quad B^d = \epsilon^{abcd}e_{b\lambda}\left(\partial_a e^{\lambda}_{\ c} + \Gamma^{\lambda}_{\nu\mu}\,e^{\nu}_{\ c}\,e^{\mu}_{\ a}\right)\ , \tag{9}$$

in a standard notation, where $e^{\mu}_{\ a}$ are the vielbeins, $\Gamma^{\mu}_{\alpha\beta}$ is the Christoffel connection and Latin (Greek) letters denote tangent space (curved space-time) indices. The space-time curvature background has, therefore, the effect of inducing an "axial" background field B_a which can be non-trivial in certain anisotropic space-time geometries, such as Bianchi-type cosmologies [28, 33, 35, 36]. For an application to particle-antiparticle asymmetry it is necessary for this axial field B_a to be a constant in some local frame. The existence of such a frame has not been demonstrated. As before if it can be arranged that $B_a \neq 0$ for $a = 0$ then for constant B_0 CPT is broken: the dispersion relation of neutrinos in such backgrounds differs from that of antineutrinos. Explicitly we have

$$E = \sqrt{(\vec{p}-\vec{B})^2 + m^2} + B_0\ , \quad \overline{E} = \sqrt{(\vec{p}+\vec{B})^2 + m^2} - B_0\ . \tag{10}$$

The relevant neutrino asymmetry emerges on following the same steps used when there was an explicit particle-antiparticle mass difference, As a consequence the following neutrino-antineutrino density difference is found in Bianchi II Cosmologies [28, 33, 35, 36]:

$$\Delta n_\nu \equiv n_\nu - n_{\overline{\nu}} \sim g^\star T^3 \left(\frac{B_0}{T}\right) \tag{11}$$

with $g^\star$ the number of degrees of freedom for the (relativistic) neutrino. An excess of particles over antiparticles is predicted only when $B_0 > 0$, which had to be assumed in the analysis of [28, 33, 35, 36]; we should note, however, that the sign of B_0 and its constancy have not been justified in this phenomenological approach [2].

At temperatures $T < T_d$, with T_d the decoupling temperature of the lepton-number violating processes, the ratio of the net Lepton number ΔL (neutrino asymmetry) to entropy density (which scales as T^3) remains constant,

$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} \sim \frac{B_0}{T_d} \tag{12}$$

which, for $T_d \sim 10^{15}$ GeV and $B_0 \sim 10^5$ GeV, implies a lepton asymmetry (leptogenesis) of order $\Delta L \sim 10^{-10}$, in agreement with observations. The latter can then be communicated to the baryon sector to produce the observed BAU (baryogenesis) by a B-L conserving symmetry in the context of either Grand Unified Theories (GUT) [28], or sphaleron processes in the standard model. (Note that in the scenario of decoherence-induced CPT Violating case of [40, 41], mentioned previously, $B + L$ was assumed to be conserved in the corresponding sphaleron processes; in such a case one needs an antilepton excess to produce baryogenesis.)

[2] The above considerations concern the dispersion relations for any fermion, not only neutrinos. However, when one considers matter excitations from the vacuum, as relevant for leptogenesis, we need chiral fermions to get non trivial CPTV asymmetries in *populations* of particle and antiparticles, because $<\psi^\dagger\gamma^5\psi> = -<\psi_L^\dagger\gamma^5\psi_L> + <\psi_R^\dagger\gamma^5\psi_R>$.

3. CPTV-induced in (string-inspired) background geometry with torsion

In this section we will discuss the case of a constant B^0 "axial" field that appears due to the interaction of the fermion spin with a string-theory background geometry with *torsion*. This is a novel observation, which (as far as we are aware) was discussed for first time in [17]. In the presence of torsion the Christoffel symbol contains a part that is antisymmetric in its lower indices: $\Gamma^{\lambda}{}_{\mu\nu} \neq \Gamma^{\lambda}{}_{\nu\mu}$. Hence the last term of the right-hand side of the Eqn.(9) is *not* zero. Since the torsion term is of gravitational origin it couples universally to all fermion species. The effect of the coupling to neutrinos will be clarified below.

The massless gravitational multiplet in string theory contains the dilaton (spin 0, scalar), Φ, the graviton (spin 2, symmetric tensor), $g_{\mu\nu}$, and the spin 1 antisymmetric tensor $B_{\mu\nu}$. The (Kalb-Ramond) field B appears in the string effective action only through its totally antisymmetric field strength, $H_{\mu\nu\rho} = \partial_{[\mu} B_{\nu\rho]}$, where $[\ldots]$ denotes antisymmetrization of the indices within the brackets. The calculation of string amplitudes [51] shows that $H_{\mu\nu\rho}$ plays the role of *torsion* in a generalised connection $\overline{\Gamma}$:

$$\overline{\Gamma}^{\lambda}{}_{\mu\nu} = \Gamma^{\lambda}{}_{\mu\nu} + e^{-2\Phi} H^{\lambda}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} + T^{\lambda}{}_{\mu\nu} \; . \tag{13}$$

$\Gamma^{\lambda}{}_{\mu\nu} = \Gamma^{\lambda}{}_{\nu\mu}$ is the torsion-free Einstein-metric connection, and $T^{\lambda}_{\mu\nu} = -T^{\lambda}_{\nu\mu}$ is the *torsion*.

In ref. [52] exact solutions to the conformal invariance conditions (to all orders in α') of the low energy effective action of strings have been presented. In four "large" (uncompactified) dimensions of the string, the antisymmetric tensor field strength can be written uniquely as

$$H_{\mu\nu\rho} = e^{2\Phi} \epsilon_{\mu\nu\rho\sigma} \partial^{\sigma} b(x) \tag{14}$$

with $\epsilon_{0123} = \sqrt{g}$ and $\epsilon^{\mu\nu\rho\sigma} = |g|^{-1}\epsilon_{\mu\nu\rho\sigma}$, with g the metric determinant. The field $b(x)$ is a "pseudoscalar " *axion*-like field. The dilaton Φ and axion b fields are fields that appear as Goldstone bosons of spontaneously broken scale symmetries of the string vacua, and so are exactly massless classically. In the effective string action such fields appear only through their derivatives.The exact solution of [52] in the *string frame* requires that both dilaton and axion fields are linear in the target time X^0, $\Phi(X^0) \sim X^0$, $b(X^0) \sim X^0$. This solution will shift the minima of all fields in the effective action which couple to the dilaton and axion by a space-time independent amount.

In the "physical" *Einstein frame* , relevant for cosmological observations, the temporal component of the metric is normalised to $g_{00} = +1$ by an appropriate change of the time coordinate. In this setting, the solution of [52] leads to a Friedmann-Robertson-Walker (FRW) metric, with scale factor $a(t) \sim t$, where t is the FRW cosmic time. Moreover, the dilaton field Φ behaves as $-\ln t + \phi_0$, with ϕ_0 a constant, and the axion field $b(x)$ is linear in t. There is an underlying world-sheet conformal field theory with central charge $c = 4 - 12Q^2 - \frac{6}{n+2} + c_I$ where $Q^2 (> 0)$ is the central-charge deficit and c_I is the central charge associated with the world-sheet conformal field theory of the compact "internal" dimensions of the string model [52]. The condition of cancellation of the world-sheet ghosts that appear because of the fixing of reparametrisation invariance of world-sheet co-ordinates requires that $c = 26$. The solution for the axion field is

$$b(x) = \sqrt{2} e^{-\phi_0} \sqrt{Q^2} \frac{M_s}{\sqrt{n}} t \; , \tag{15}$$

where M_s is the string mass scale and n is a positive integer, associated with the level of the Kac-Moody algebra of the underlying world-sheet conformal field theory. For non-zero Q^2 there is an additional dark energy term in the effective target-space time action of the string [52] of the form $\int d^4x \sqrt{-g} e^{2\Phi}(-4Q^2)/\alpha'$. The linear axion field (15) *remains* a non-trivial solution *even* in the *static* space-time limit with a constant dilaton field [52]. In such a case space time is an Einstein universe with positive cosmological constant and constant positive curvature proportional to $6/(n+2)$.

For the solutions of [52], the covariant torsion tensor $e^{-2\Phi}H_{\mu\nu\rho}$ is *constant.* (This follows from (13) and (14) since the exponential dilaton factors cancel out in the relevant expressions.) Only the spatial components of the torsion are nonzero in this case,

$$T_{ijk} \sim \epsilon_{ijk}\dot{b} = \epsilon_{ijk}\sqrt{2Q^2}e^{-\phi_0}\,\frac{M_s}{\sqrt{n}}\ , \tag{16}$$

where the overdot denotes derivative with respect to t.

As discussed in [17], in the framework of the target-space effective theory, the relevant Lagrangian terms for fermions (to lowest order in α') will be of the form (9), with the vector B^0 being associated with the spatial components of the constant torsion part $B^0 \sim \epsilon^{ijk}T_{ijk}$, where From (13), (14) and (9), we also observe that only the temporal component B^0 of the B^d vector is nonzero. Note that the torsion-free gravitational part of the connection (for the FRW or flat case) yields a vanishing contribution to B^0. From (9) and (16) then we obtain a constant B^0 of order

$$B^0 \sim \sqrt{2Q^2}e^{-\phi_0}\,\frac{M_s}{\sqrt{n}}\ \text{GeV} > 0. \tag{17}$$

We follow the conventions of string theory for the sign of B^0 . From phenomenological considerations M_s and $g_s^2/4\pi$ are taken to be larger than $\mathrm{O}(10^4)$ GeV and about $1/20$ respectively. A stringent constraint on the Kac-Moody level is not imposed from the requirement of CPTV-induced leptogenesis. We observe from (17) that the central charge deficit Q^2 of the underlying conformal field theory determines the order of particle-antiparticle asymmetries in this model.

The particle-antiparticle asymmetry occurs already in thermal equilibrium, due to the background-induced [28] difference in the dispersion relations between particles and antiparticles. Since the coupling of fermions to torsion is *universal*, the axion background would also couple to quarks and charged leptons.For CPT-Violating leptogenesis at the GUT scales [28] $B^0 \sim 10^5$ GeV. Hence a constant torsion-induced B^0 could lead directly to *baryogenesis* at the quark decoupling temperature $T_q \sim 100$ MeV, provided B^0 is much lower than $B^0 \sim 10^5$ GeV.In such a scenario, the observed BAU could be realised directly through the quark-H-torsion interactions; unfortunately, the corresponding neutrino asymmetry would be too high, given that the neutrino decoupling temperatures are at 1 MeV scale. Note that standard model B-L conserving sphaleron processes freeze-out much earlier (at temperatures of order 100 GeV), but such interactions cannot produce sufficient baryon asymmetry in the universe without extra sources for CP violation [4].

A phenomenologically viable alternative scenario is one in which B^0 is not constant with time. In such a scenario the universe undergoes a phase transition at GUT scales ($\sim 10^{15}$ GeV). Above the GUT temperature heavy right-handed Majorana neutrinos could decouple or lepton number violating (but B-L conserving) processes could occur. At the phase transition the value of the H-torsion background could change from a large to a smaller value. This approach is based on the possibility that conformal field theories with different central charges characterise different epochs of the early universe [52]. Transitions between such conformal (fixed) points in moduli space correspond to non-conformal (Liouville) time evolution [53] and represent phase transitions in the early universe [3]. In this scenario, leptogenesis occurs at GUT scales (just after

[3] An enlightening example of such a scenario is provided by the quantum Hall system in condensed matter where, as the temperature varies, there are transitions between plateaux with fixed values of the conductivity. The plateaux correspond to underlying conformal field theories of a "stringy" nature [54, 55], with different values of the central charge. Transitions between the plateaux are not described by conformal field theories. In the approach of [53] the cosmic time evolution in the universe is associated with a world-sheet renormalization group flow, whose description lies beyond the scope of the talk

inflation). Following the idea of Ref.[28], this leptogenesis can be communicated to the baryon sector by means of B-L conserving sphaleron processes. The difference between the fermion and antifermion populations is due to the interaction with a CPTV background torsion and occurs already in thermal equilibrium. Provided the background torsion is constant in time over the appropriate epoch of the evolution of the universe (until the freeze out of the pertinent processes characterising the epoch), such differences cannot be eroded during the expansion of the universe. No enhanced CP violation in the lepton sector is essential for leptogenesis in this approach, in contrast to the case of conventional leptogenesis [56, 57, 58, 5, 59].(This observation does not completely remove the need for right-handed sterile neutrinos.The latter may be essential, for instance, for explaining the smallness of the active neutrino masses, through see-saw mechanisms, or may play the role of dark matter [5, 59].)

4. CPTV in stochastic Finsler geometries

Although all the models displaying CPTV that we have considered so far are based on local effective field theories, there is no compelling reason for a restriction to such a framework. In fact a microscopic model involving space-time defects based on string-brane theory suggests the use of a non-Riemannian metric background similar to that which occurs in Finsler geometry [18, 60].(This model will be discussed in a subsequent section.) Independently there has been much interest in Finsler geometry [61, 62, 63, 64, 65, 66, 67, 68, 69, 70] for characterising the Early universe [71, 72, 73, 74, 75] and for descriptions of modified dispersion relations for particle probes [76, 72, 60, 77]. Finsler geometry has a metric which, in addition to space-time coordinates, depends also on "*velocities*". Lorentz symmetry is broken through some fixed vectors in the metric. We explore the consequences of making such vectors having components which are stochastic with possibly zero mean. This is a feature that arises in the defect model of D-foam [76, 20, 22] that we will consider in the next section. The defects stochastically fluctuate, due to both statistical and quantum stringy effects in large populations of such D-particles that can populate eras of the early universe. As we shall discuss below, the result of the interaction of neutrinos with these defects, leads to stochastically fluctuating Finsler-like metrics. However we wish to consider the consequences for CPTV and matter-antimatter asymmetry of this stochasticity in a general context. This underlying model provides our main motivation to study this class of space-times in this section and to contrast our findings on the induced CPTV for such cases with the corresponding ones for the D-foam model.

Below we shall be brief in our description of the stochastic CPTV backgrounds, concentrating only on the main features leading to modified dispersion relations that are different between particles and antiparticles. For the interested reader details can be found in [17].

We focus on on-shell neutrinos (which are now known to have small masses). Again, this is motivated by our desire to discuss leptogenesis in such geometries. Moreover, for reasons that will become clear in section 5, it is neutrinos that play a preferential rôle in interacting non-trivially with the D-particle foam background, which induces stochastically fluctuating Finsler-like space times. As our main motivation is to compare the generic Finsler-like case with the D-foam model, as far as CPTV is concerned, we restrict our attention here on the effects of stochastically fluctuating Finsler geometries on dispersion relations of neutrinos and antineutrinos. We shall consider a particular type of Finsler metric on a manifold M which is known as the Randers metric [18] [4]. It was noted in [80] that the geodesics of this metric coincided with the minimum

[4] We mention, for completeness, that the other popular class of Finsler geometries, that appears in the General Relativistic version [63, 66, 64, 65] of the so-called Very Special Relativety Model [78], and cosmological extensions thereof [71, 73] are *not* characterised by CPTV in the dispersion relations, nor of the spin-curvature type discussed in section 2.3. In fact such VSR-related models have been prop[osed in the past as candidates for the generation of Lepton-number conserving neutrino masses [79], and hence our Lepton-number violating considerations in this work do not apply.

time trajectories of a particle moving on a Riemannian manifold in the presence of a time independent drift given by a vector field. This is similar to Fermat's principle for propagation in refractive media. We mention in passing that similarities of D-particle foam to a refracting medium have been discussed in the literature [76, 81, 82]. If we were to assume that the result on minimum time trajectories was true for a pseudo-Riemannian situation and the drift was given by collisions due to D-particle scattering, then at a heuristic level a stochastic drift could be a reasonable generic phenomenological model of the back-reaction of low dimensional recoiling branes on matter.

The metric in this models is given by [17] (below, x^μ denotes space-time coordinates, while the variables y^ν play the rôle of "velocities" in the Finsler framework)

$$g_{\mu\nu}(x,y) = r_{\mu\nu}(x) + \phi^2(x)\, l_\mu l_\nu + \left(\frac{r_{\mu\nu}(x)}{\alpha(x,y)} - \frac{r_{\mu\varrho}(x)\, r_{\nu\sigma}(x)\, y^\varrho y^\sigma}{\alpha(x,y)^3}\right)\phi(x)\, l_c y^c$$
$$+ \frac{1}{\alpha(x,y)}\left(r_{\mu\varrho}(x)\, y^\varrho \phi(x)\, l_\nu + r_{\nu\varrho}(x)\, y^\varrho \phi(x)\, l_\mu\right) \ ,\ \alpha(x,y) = \sqrt{r_{\mu\nu}(x)\, y^\mu\, y^\nu} \ ,$$

where l_μ is a constant vector. In our model $\phi(x)$ will be a gaussian stochastic variable. On average the metric will be like a Riemannian metric if the mean of $\langle\phi\rangle$ vanishes.

We shall consider a situation with $r_{\mu\nu}(x) = \eta_{\mu\nu}$ where $\eta_{\mu\nu}$ is the diagonal Minkowski matrix with entries $(1,-1,-1,-1)$. (The summation convention of repeated indices will be always understood unless explicitly stated otherwise.) Within the framework of a Robertson-Walker metric we shall ignore effects on the time-scale of the inverse expansion We have assumed a homogeneous ϕ with ϕ being x independent. The mass shell conditions of generalised plane-wave solutions for particles in this background $h^{\mu\nu}\omega_\mu\omega_\nu = m^2$, where $\omega_\mu = g_{\mu\nu}(x,y)y^\nu$ is a "phase-space" variable, dual to y^μ, and $h^{\mu\nu}(x,\omega)$ is the inverse of the Finsler metric in phase-space [17], lead to the generalised dispersion relations. In the model it is possible to choose l_μ. Not all choices will lead to asymmetric population distributions between particles and anti-particles.The space-like choice $l_0 = 0$ gives a degenerate spectrum for particle and anti-particle and hence no CPTV in dispersion relations. Therefore this case cannot be used for Leptogenesis in our framework.

More generally the dispersion relation is [17]

$$\omega_0 = \pm\frac{\phi}{m} l_0 \left(2\vec{\omega}^2 + m^2\right) + \mathfrak{K}(\phi,\omega,m) \tag{18}$$

where $\mathfrak{K}(\phi,\omega,m) = \left(\vec{\omega}^2 + m^2 + \frac{2\phi}{m}\left(2\vec{\omega}^2 + m^2\right)(l_1\omega_1 + l_2\omega_2 + l_3\omega_3)\right)^{1/2}$. The +sign is for the particle and the −sign is for the antiparticle. For the "time-like" case $l_0 = 1$, $l_1 = l_2 = l_3 = 0$ the dispersion relation reduces to e $\omega_0 = \sqrt{\vec{\omega}^2 + m^2} \pm \frac{\phi}{m}\left(2\vec{\omega}^2 + m^2\right)$. The sign of l_0 can be reabsorbed in ϕ.

For the "null" case $l_0 = l_1 = 1$ and $l_2 = l_3 = 0$ the dispersion relation reduces to $\omega_0 = \sqrt{\vec{\omega}^2 + m^2}\left(1 + \frac{\phi}{m}\left(2 - \frac{m^2}{\vec{\omega}^2 + m^2}\right)\omega_1\right) \pm \frac{\phi}{m}\left(2\vec{\omega}^2 + m^2\right)$. The parameters $\vec{\omega}$ play the rôle of momenta $\vec{p}$ in our case of neutrinos of mass $m = m_\nu$ propagating in these space-times, and the Finsler metric may be seen as sort of back reaction on the space-time of such a propagation (to better appreciate this, the reader is invited to the discussion in the next section 5, where a particular model of D(efect)-foam is considered as a medium for neutrino propagation in the early universe, leading to Finsler-like metric distortions as a consequence of medum/particle interactions).

Corresponding to such models involving D-foam, the parameter ϕ is modelled as a stochastic gaussian process with a mean $\mathfrak{a}$ and standard deviation σ. The fermion number distribution n from equilibrium statistical mechanics is given by $n = g_{d.o.f.} \int \frac{d^3p}{(2\pi)^3}\frac{1}{\exp(\beta(\omega_0-\mu))+1}$. where we have ignored degeneracy factors. First of all, it immediately follows from the corresponding dispersion relation that for the "time-like" case, when $\mathfrak{a} = 0$, there is no particle/antiparticle asymmetry. This is to be expected, given that $\mathfrak{a} \neq 0$ corresponds in a sense to an averaged Lorentz violation in this stochastic geometry, and hence one of the basic assumptions for CPT Invariance of the effective theory of neutrinos in this "medium" is relaxed.

For the "time-like" case, when $\mathfrak{a} \neq 0$ and β small, we obtain to leading order in $T/m \gg 1$ [17]:

$$\ll \triangle n \gg \sim -\frac{2}{\pi^2}\mathfrak{a}\, g_{d.o.f.} T^3 \left(\frac{T}{m}\right) \int_0^\infty \frac{dx\, x^4\, e^x}{(1+e^x)^2} = -\mathfrak{a}\, g_{d.o.f.} T^3 \frac{7\pi^2}{15}\left(\frac{T}{m}\right) \tag{19}$$

We require $\mathfrak{a} < 0$ in order to have a particle-antiparticle asymmetry where the particle distribution dominates the antiparticle distribution. This yields the following Lepton (neutrino) asymmetry, assumed to freeze at the neutrino decoupling temperature T_d

$$\triangle L(T \sim T_d) = \frac{\triangle n_\nu}{s} \sim -10\, \mathfrak{a}\, \frac{T_d}{m_\nu} \tag{20}$$

where, as usual, s denotes the entropy density, which for relativistic species is assumed to be $s \sim g_{d.o.f.} \frac{2\pi^2}{45} T^3$. Thus, from (20) we see that there is no CPTV asymmetry in the Lorentz invariant (on average) case $\mathfrak{a} = 0$.

To obtain the phenomenologically correct value of $\Delta L(T \sim T_d) \sim 10^{-10}$, which is then communicated to the baryon sector via B-L conserving sphaleron processes, or B-L conserving grand unified models (assumed appropriately embedded in such space-time geometries), one needs to fix appropriately the value of $\mathfrak{a}$, consider appropriate conditions for freeze-out, that depend on the underlying microscopic model, and take into account that, according to current data, the masses of the active neutrinos that are assumed to participate in (20) must be smaller than $m_\nu < 0.2$ eV. For example, in GUT-scale lepton-number violation models, as we discussed before, $T_d \sim 10^{15}$ GeV, which implies that one needs only an extremely small in magnitude violation of Lorentz symmetry on average in this stochastic Finsler space time, $\mathfrak{a} \sim -10^{-36}$, in order to reproduce the observed Baryon Asymmetry in the universe. The assumption of fixing the sign of $\mathfrak{a}$ is considered as fine tuning, and is a feature that is common in the models of gravitational leptogenesis/baryogenesis that exist in the current literature, as discussed briefly above [30, 31, 28, 33, 35, 36, 27, 34, 32]. One can calculate the asymmetry for the null case with results similar to the time-like case considered above [17].

5. Stringy-defect (D-)foam-induced CPTV and leptogenesis

In this section we shall consider a population of D0-branes (or lower dimensional compactified D-branes which are effectively point-like from from the point of view of a brane world observer [5]) interacting with neutral fermions such as the neutrino and anti-neutrino. This interaction leads to different dispersion relations for neutrinos and anti-neutrinos which in turn leads to an excess of the population of neutrinos over anti-neutrinos. The freeze-out of neutrinos at the decoupling temperature of neutrinos leads to leptogenesis given by the standard cosmological considerations. The latter results, through standard Baryon (B) and Lepton (L) number violating sphaleron processes or B-L conserving interactions in grand unified models describing matter excitations on the brane, to the observed Baryon Asymmetry in the Unverse, with complete dominance of matter over antimatter, in a rather natural way, as we shall discuss below. Moreover, as we shall explain below, in this model of D(efect)-foam, the prevalence of matter over antimatter, *i.e.* the *positive sign* of the asymmetry $\Delta n > 0$, follows naturally, as a consequence of loss of

[5] It should be remarked that for the effective compactified D-"particles" the interactions with the charged matter excitations are suppressed relative to the neutral ones [82]. Hence, even in this case, it is the electrically neutral excitations which interact primarily with the D-foam.

energy of neutrinos during their interactions with the space-time defects, due to recoil of the latter. Thus, the sign of the induced asymmetry need not be fixed by hand, unlike the cases of gravitational leptogenesis discussed in previous sections. For instructive purposes, we first discuss the properties of the foam model, in the next subsection, before moving onto issues of CPTV and leptogenesis.

D-foam models [22, 20, 25] are stringy models of space-time foamy geometries, which involve brane universes, propagating in higher-dimensional bulk geometries. The bulk contains point-like D-brane defects ("D-particles" or D0 branes) whose population density is constrained by the amount of CPTV that we observe. In many string theories (such as bosonic and type IIA string theories) they are stable zero-dimensional defects. However for our purposes we will consider them to be present in string theories of phenomenological interest [81] since, even when elementary D-particles cannot exist consistently, as is the case of type IIB string models, there can be effective D-particles formed by the compactification of higher dimensional D-branes [82] (*e.g.* three-branes wrapped around three-cycles, with relatively small radii).

The preferential rôle of neutrinos in feeling the full effects of D-foam, and hence the CPTV, is attributed to electric charge conservation: the representation of SM particles as open strings, with their ends attached to the brane worlds, prevents capture and splitting of open strings carrying electric fluxes by the D-particles. (We should recall that in string theory the electric charge is at the end point of an open string.) D-particles are electrically neutral and thus electric charge would not have been conserved if such processes had taken place. This is also consistent with the effective D-particles which may have formed as a result of nucleation [30]. Hence, the D-particle foam is transparent to charged excitations of the SM, leaving neutral particles, in particular neutrinos, susceptible to the foam effects. This different behaviour of neutrinos from charged leptons implies a background-induced breaking of the SU(2) gauge symmetry of the standard model. In type IIB string theories, effective D-particles [82] can interact, but in a suppressed manner, with the entire SU(2) lepton doublet, so the SU(2) symmetry is not broken. However, in such scenarios these interactions are suppressed compared to photons, as discussed in [82]. The D-foam interactions with sterile right-handed Majorana neutrinos, though, remain unsuppressed, since the sterile neutrinos do not have any standard model charges. Such heavy states can participate in lepton-number violating processes freezing out at GUT scales.

For our purposes in this work we may consider that statistically significant populations of D-particles existed in the early eras of the brane universe. As the time elapses, the brane universe, which propagates in the higher-dimensional bulk, enters regions characterised by D-particle depletion, in such as way that the late eras cosmology of the universe is not affected. Nevertheless, as we shall discuss below, the early D-particle populations may still have important effects in generating neutrino-antineutrino populations differences (asymmetries), which are then communicated to the baryon sector via the standard sphaleron processes [16] or B-L conserving GUT symmetries in unified particle physics models.

To this end, we need to consider the *effective dispersion relation* of a (anti)neutrino field in a brane space-time punctured with statistically significant populations of D-particles. The latter is a dynamical population, consisting of defects crossing the brane all the time, thereby appearing to a brane observer as flashing "on" and "off" space-time "foamy" structures. The (anti)neutrino excitations are represented as matter open strings with their ends attached on the brane.The number density of (anti) neutrinos on the brane world is limited by the requirement that they do not overclose the universe.

In [17] we estimated the *modification of the dispersion relations* of neutrinos in such a "media" of D-particles in the early universe. The interaction of a string with a D-particle implies that at least one of the ends of the string is attached to the D-particle defect. Furthermore, the simultaneous creation of virtual strings stretched between the defect and the brane, describes the recoil of the D-particle. During the interaction time, the D-particle undergoes motion characterized by non-trivial "recoil" velocities, $u_\| = \frac{g_s}{M_s}\Delta p_i = \frac{g_s}{M_s} r_i\, p_i$ along the brane longitudinal dimensions, where r_i denotes the proportion of the incident neutrino momentum that corresponds to the momentum transfer Δp_i during the scattering, and $v_\perp$ in directions transverse to the brane world [24] .

As discussed in [76, 25, 83] the non-trivial capture and splitting of the open string during its interaction with the D-particle, and the recoil of the latter, result in a *local* effective metric distortions, which acquire a Finsler-like form

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = (\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu \ , \qquad h_{0i} = (u^a_{i\,\|}\sigma_a) \ , \tag{21}$$

where $u_{i\,\|}$ is the recoil velocity of the D-particle *on* the D-brane world, with $i = 1, 2, 3$ a spatial space-time index, σ_a, with $a = 1, 2, 3$, are the 2×2 Pauli flavour matrices, whose presence is necessitated by the assumption that neutrinos can undergo flavour oscillations during their capture by D-particles (we assume here two-flavour oscillations for definiteness and simplicity).

However, the effects of D-foam go beyond those encoded in the induced Finsler like metric. The fine tuning that is required in stochastic Finsler metrics to get the correct sign for the particle-antiparticle asymmetry is a feature, although commonplace in other approaches, that is not entirely satisfactory. However because we have a microscopic model we can consider the kinematics of D-particle scattering. On considering string theory scattering amplitudes we find that the four momentum is conserved in the scattering of D-particles and strings. Indeed, upon averaging $\langle\langle \ldots \rangle\rangle$ over a statistically significant number of events, due to multiple scatterings in a D-foam background, we may use the following stochastic hypothesis [25]

$$\ll u_{i\,\|} \gg = 0 \ , \qquad \ll u_{i\,\|} u_{j\,\|} \gg = \sigma^2 \delta_{ij} \ . \tag{22}$$

implying that Lorentz invariance holds only as an average symmetry over large populations of D-particles in the foam. At a microscopic level, (22) translates to momentum conservation on average.

The dispersion relation then of a neutrino of mass m propagating on such a deformed isotropic space-time, then, reads:

$$p^\mu p^\nu g_{\mu\nu} = p^\mu p^\nu(\eta_{\mu\nu} + h_{\mu\nu}) = -m^2 \ \Rightarrow\ E^2 - 2E\vec{p}\cdot u_\| - \vec{p}^2 - m^2 = 0 \ , \tag{23}$$

which upon averaging over D-particle populations, can be solved to yield the following dispersion relations for particles and antiparticles

$$\ll E_\nu \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) - \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2 \, , \ \ll E_{\overline{\nu}} \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) + \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2 \tag{24}$$

with $E_{\overline{\nu}} > 0$ representing the positive energy of a physical antiparticle. In our analysis above we have made the symmetric assumption that the recoil-velocities fluctuation strengths are the same between particle and antiparticle sectors. (Scenarios for which this symmetry was not asssumed have also been considered in an early work [25].) There can thus be *local* CPTV in the sense that the effective dispersion relation between neutrinos and antineutrinos are different. This is a consequence of the local violation of Lorentz symmetry (LV), as a result of the non-trivial recoil velocities of the D-particle, leading to the LV space-time distortions (21).

The discussion of CPTV in such foamy universes now follows the line of argument adopted by others: the difference in the dispersion relations between particles and antiparticles will imply differences in the relevant populations of neutrinos (n) and antineutrinos ($\overline{n}$), (*cf.* the dispersion (24)). This difference between neutrino and antineutrino phase-space distribution functions in D-foam backgrounds generates a matter-antimatter lepton asymmetry in the relevant densities

$$\ll n - \overline{n} \gg = g_{d.o.f.} \int \frac{d^3p}{(2\pi)^3} \ll [f(E) - f(\overline{E})] \gg \ , \tag{25}$$

where $g_{d.o.f.}$ denotes the number of degrees of freedom of relativistic neutrinos, and $\ll \cdots \gg$ denotes an average over suitable populations of stochastically fluctuating D-particles (22).

The result for the D-foam-induced lepton asymmetry can be estimated from (25), using (24). Ignoring neutrino mass terms and $(1+\frac{\sigma^2}{2})$ square-root prefactors in (24), as yielding subleading contributions for $\sigma^2 \ll 1$ we are considering here, setting the (anti)neutrino chemical potential to zero (which is a sufficient approximation for relativistic light neutrino matter) and performing a change of variables $|\vec{p}|/T \to \tilde{u}$ we obtain from (25) the result [17]:

$$\Delta n_\nu = \frac{g_{d.o.f.}}{2\pi^2}\, T^3 \int_0^\infty d\tilde{u}\, \tilde{u}^2 \,[\frac{1}{1+e^{\tilde{u}-\frac{M_s\sigma^2}{2g_s\,T}}} - \frac{1}{1+e^{\tilde{u}+\frac{M_s\sigma^2}{2\,g_s\,T}}}] \simeq \frac{g_{d.o.f.}}{\pi^2}\, T^3 \left(\frac{M_s\sigma^2}{g_s\,T}\right) \,>\, 0, \qquad (26)$$

to leading order in σ^2. We thus observe that the CPTV term $-\frac{1}{2}\frac{M_s}{g_s}\sigma^2$ in the dispersion relation (24) for the neutrino, which corresponds to the energy 'loss' due to the D-particle recoil kinetic energies, comes with the right sign ('loss') so as to guarantee an excess of particles over antiparticles. Unlike the model of [28, 33, 35, 36], then, where the sign of the B_0 parameter had to be assumed, in our D-foam case there is no such freedom, and the positive Δn_ν is derived from first principles. We consider this a nice feature of our model.

As in standard scenarios of Leptogenesis, the Lepton asymmetry (26) decreases with decreasing temperature up to a freeze-out point, which occurs at temperatures T_d at which the Lepton-number violating processes decouple. For reasons already stated in section 3 the phenomenologically realistic scenario in string theory frameworks, like the present one, seems to be the one in which one has GUT scale lepton-number violating processes, which freeze out the lepton-antilepton number at temperatures $T_d \sim 10^{15}$ GeV. In the context of D-particle brane Universe one may assume that at such early epochs one has a sufficiently dense D-particle gas in the bulk and on the brane, so that phenomenologically realistic Leptogenesis takes place. The latter then can be communicated via B-L conserving GUT processes to the baryon sector. After the GUT scale freeze out the bulk population of D-particles can be depleted, in the sense that the brane world representing our Universe passes through an area with scarce D-particle populations, so that late eras of the Universe are characterised by a more-or-less conventional Cosmology.

The above estimate ignores an important fact, namely the dependence of the stochastic variable σ^2 on the neutrino energy. Indeed, as discussed in detail in [24, 25], one may parameterise the momentum transfer by the fraction parameter of the incident momentum r, which is in turn assumed stochastic, that is

$$u_i = \frac{g_s}{M_s}\Delta p_i \to g_s\, r_i \frac{p_i}{M_s} \text{ ,no sum over i },\quad \ll r_i \gg = 0\ , \quad \ll\ r_i r_j \gg = \Delta^2 \delta_{ij}\ .$$

In this case, the dispersion relations (24) are modified by the replacement of $\sigma^2 \to \frac{g_s^2}{M_s^2}\,\Delta^2 p^2$, which is now momentum dependent: A detailed analysis in [17] leads in this case to the following result for the lepton asymmetry (assuming a freeze-out temperature T_d of the Lepton-Violating processes):

$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} = \frac{2\Delta^2 g_s T_d}{M_s}. \qquad (27)$$

From (27), we observe that for a freeze-out temperature $T_d \sim 10^{15}$ GeV, which characterises GUT scale Lepton-Violating processes (*e.g* involving heavy Majorana neutrinos $N_I \to H\,\nu,\, \overline{H}\,\overline{\nu}$), the phenomenological value $\Delta L \sim 10^{-10}$ is attained for $\frac{M_s}{g_s} \sim 10^{25}\,\Delta^2$ GeV . For $\Delta^2 \sim 10^{-6}$ a Planck size D-particle mass $M_s/g_s \sim 10^{19}$ GeV is required so that the D-foam provides the physically observed Lepton and, thus, Baryon Asymmetry. For the unnaturally small $\Delta^2 < 10^{-21}$ one arrives at $M_s/g_s \sim 10$ TeV. Unfortunately, for $\Delta^2 \sim \mathcal{O}(1)$ transplanckian D-particle masses are required.

Our approach to leptogenesis is distinguished from others in that a local effective field theoretical description is not adopted. Because of D-particle recoil when scattering off matter strings the background of D-particles can be modelled as a stochastic medium [24, 26, 25]. The underlying string theoretic description provides the rigorous description of the scattering of D-particles. The D-particles backreact (as seen from infra-red divergences in perturbation theory) and change the metric which influences the space in which matter is moving. Furthermore as discussed at length in [26], and mentioned briefly above, the D-particle foam model does *not* lead to overclosing the universe. Hence despite having statistically significant populations of D-particles in the early universe, which provide the CPTV background on which neutrinos propagate, the assumption of a subcritical energy density for the universe can still hold.

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