Lorentz Violation and Generation of Baryon Asymmetry of the Universe

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Pavel A. Bolokhov

University of Victoria and St.Petersburg State University

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Part I
LV Interactions in the Standard Model

Introduction to LV

Study of Lorentz-violating theories provides probes of physics **far** beyond the Planck scale.
The most straightforward idea to test Lorentz invariance is the experiments of Michelson-Morley type. They have pushed New Physics beyond 10^{27} GeV scale.
Later came the idea of introducing *kinematic* Lorentz violation, i.e. modification of propagation of particles:

$$E^2 = m^2 + p^2 + \frac{\eta}{M} \cdot p^3 + \frac{\kappa}{M^2} \cdot p^4 + \ldots .$$

Here astrophysical observations have pushed M to 10^{33} GeV level.
The theories of this sort introduce LV in an *ad hoc* manner.

In the **Effective Field Theory** one introduces LV operators

$$\mathcal{L}_{\mathrm{LV}} = \mathcal{L}_{\mathrm{SM}} + \sum_n c_n^{\mu\nu\ldots} \frac{\mathcal{O}^n_{\mu\nu\ldots}}{\Lambda^n} \,.$$

This facilitates the study of observable effects caused by explicit violation of Lorentz symmetry.
The coefficients $c_n^{\mu\nu\ldots}$ are background tensors which break explicitly Lorentz invariance.
Such a theory may be viewed as a natural effective description of a *spontaneously* broken Lorentz invariance.
The latter assumption allows to alleviate most of the conceptual questions about Lorentz violation.

Common Sense Requirements

The operators should better be

- Gauge invariant
- Lorentz invariant, apart from coupling to the background tensor
- not reducible to lower dimension operators by the equations of motion
- not reducible to a total derivative
- coupled to an irreducible background tensor.

Lower-dimensional LV interactions

In QED, the generic expansion in terms of the gauge invariant operators starts at dimension three:

$$\mathcal{L}^{(3)}_{\rm QED} = -a_\mu\,\bar\Psi\gamma_\mu\Psi - b_\mu\,\bar\Psi\gamma^\mu\gamma_5\Psi - \frac{1}{2}H_{\mu\nu}\bar\Psi\sigma^{\mu\nu}\Psi - k_\mu\,\epsilon^{\mu\nu\kappa\lambda}A_\nu\partial_\kappa A$$

Dimension three operators create a problem: from dimensional counting one expects $a_\mu \sim M n_\mu$, where n_μ is a unit vector, and M is the scale of New Physics. That creates *disastrous* effects. Even if the LV coefficients are tuned small, they will be exploded by quantum corrections coming from quadratic divergencies of the higher-dimensional operators:

$$[LV]_{\rm dim\ 3} \;\sim\; ({\rm loop\ factor})\;\Lambda^2_{UV}\;\times\;[LV]_{\rm dim\ 5}\,.$$

Higher-dimensional LV interactions

Higher-dimensional operators start with dimension **five**.
Simple operators have been considered before, for instance

$$\mathcal{L}_{\rm QED}^{\rm dim\ 5} \;=\; C^{\mu\nu\rho}\cdot F_{\mu\lambda}\partial_\nu \widetilde{F}_\rho{}^\lambda \;+\; C_1^{\mu\nu\rho}\cdot \overline{\psi}\,\gamma_{(\mu}\mathcal{D}_\nu\mathcal{D}_{\rho)}\psi$$

These particular operators modify dispersion relations of the photon and electron.
Full classification of dimension five interactions has not been done.
In QED alone one finds 15 operators. Many more in the Standard Model.
However, the problem of quadratic divergencies plagues some portion of them:

$$\widetilde{c}^{\,\mu}_{Q,1}\cdot\overline{Q}\,\gamma^\lambda\widetilde{F}_{\mu\lambda}\,Q \;\longrightarrow\; \Lambda^2\,a^\mu\cdot\overline{Q}\,\gamma_\mu\,Q$$

Major grouping of operators

We group all operators in the Standard Model into 3 types:

- *Unprotected*

$$\tilde{c}_Q^{\mu} \cdot \overline{Q}\, \gamma^{\lambda} \widetilde{F}_{\mu\lambda}\, Q$$

- *UV-enhanced*

$$E^2 \;=\; m^2 \;+\; p^2 \;+\; \frac{\eta}{M} \cdot p^3$$

- *Soft LV interactions*

$$c_Q^{\mu} \cdot \overline{Q}\, \gamma^{\lambda} F_{\mu\lambda}\, Q$$

Protecting" the operators@

Some symmetry-based properties of dir
forbid their transmutation into lower-dir

- *Tensor Structure*. In the Standard M
CPT-odd dimension three operators

$$D_Q^{\mu\nu\rho} \cdot \overline{Q}\,\gamma_{(\mu} F$$

- *T-invariance*. In the Standard Mode
loops to flip T-parity of an operator

$$c_Q^{\mu} \cdot \overline{Q}\,\gamma^{\lambda} F_{\mu\lambda}\, Q \quad \not\rightarrow \quad \Lambda$$

Protecting” the operators@

- *Supersymmetry*. In the MSSM, din
operators do not exist at all.

$$\widetilde{c}^{\mu}_{\mathrm{SUSY,Q}} \cdot \left(Y_Q g' \, \overline{Q} \gamma^{\lambda} \widetilde{F}_{\mu\lambda} Q \ + \right.$$

$$\left. g_3 \, \overline{Q} \gamma^{\lambda} \widetilde{G}_{\mu\lambda} Q \right) \ +$$

As usual, supersymmetry turns qua
logarithmic.

- *Lepton number violation*. There is a
operator of dimension five which vi
by $\Delta L = 2$

$$\varsigma^{\mu\nu} \cdot \left(H^{\dagger} L \right)^{T} \sigma_{\mu\nu}$$

Sources of Constraints

- *Unprotected Operators*. Constraints on dimension 3 operators transfer into a limit $\ll 10^{-31}\ \mathrm{GeV}^{-1}$ for unprotected operators.
- *Ultra-high Energy Cosmic Rays*. The fact of observation of high-energy cosmic rays sets typical constraints on *UV-enhanced* LV of the order of $10^{-33-34}\ \mathrm{GeV}^{-1}$.
- *Precision Experiments*. Constraints from Cosmic Rays are not applicable. *Soft LV interactions* inducing coupling of nuclear spin to the preferred direction put constraints of order of $10^{-30-31}\ \mathrm{GeV}^{-1}$.

Sources of Constraints

- *Electric Dipole Moments*. The operators of the type $D_q^{\mu\nu\rho} \cdot \overline{q}\,\gamma_{(\mu} F_{\rho)\nu} \gamma^5\, q$ written in terms of effective Hamiltonian possess the signature of Electric Dipole Moment interactions. The existing limits on EDMs translate into the bound of 10^{-12} GeV^{-1}.
- *Neutrino Phenomenology*. At low energies

$$\varsigma^{\mu\nu} \cdot \left(H^\dagger L\right)^T \sigma_{\mu\nu} \left(H^\dagger L\right) \quad \rightarrow \quad \upsilon^2 \cdot \varsigma^{\mu\nu}_{(\nu)} \cdot \nu^T \sigma_{\mu\nu} \nu$$

  It can change the patterns of neutrino oscillations. Constraints from reactor and atmospheric neutrino oscillation data can be used to limit various components of $\varsigma^{\mu\nu}$ at 10^{-23-24} GeV^{-1} level.

Part II
CPT-odd Leptogenesis

The idea of LV-driven generation of Baryonic Asymmetry of the Universe (BAU) resides on the fact that dimension five LV operators are odd under CPT

$$E^2 \;=\; m^2 \;+\; p^2 \;\pm\; \frac{\eta}{M} \cdot p^3$$

This creates an effective chemical potential of opposite sign for quarks and antiquarks

$$f_{q,\overline{q}} \;\;=\;\; \left(1 \;+\; e^{(E \,\pm\, \mu_{\rm eff})}/T\right)^{-1} \;\; .$$

Therefore, non-zero BAU is created already in *equilibrium*.
The amount of final asymmetry is bound to the temperature of freeze-out of sphalerons $T \sim M_W$:

$$Y_b = \frac{\Delta b}{s} \sim \frac{M_W}{\Lambda_{CPT}}$$

In such scenarios, however, Λ_{CPT} has to be less than 10^{12} GeV.
However, experimental data require Λ_{CPT} to be greater than the **Planck scale**.

In CPT-odd Leptogenesis, we introduce

$$\eta^{\mu\nu\rho}_{\text{lepton}} \cdot \overline{\psi}\gamma_\mu \mathcal{D}_\nu \mathcal{D}_\rho \psi \ ,$$

in the lepton sector.
Heavy majorana neutrinos induce

$$\mathcal{L}_{\text{eff}} \ = \ \frac{Y^\nu_{ij}}{2\,M_R} H^\dagger L^\alpha_i H^\dagger L_{j\alpha} \ + \text{h.c.},$$

An initial $B - L$ is generated through majorana neutrinos at high energies and is preserved by sphalerons from 10^{12} to 10^2 GeV
Heavy neutrinos keep the lepton number in equilibrium (which is non-zero) *until* the neutrino-mediated processes (*L-processes*) become slower than the Hubble rate.

Therefore, the final asymmetry is determined by the freeze-out temperature of L-violating processes

$$\Gamma_L \;\propto\; \frac{T^3}{M_R^2} \;\sim\; \Gamma_H \;\propto\; \frac{T^2}{M_{\rm Pl}},$$

which results in

$$T_R \;\propto\; \frac{M_R^2}{M_{\rm Pl}} \;\Rrightarrow\; T_R/M_W \;\sim\; 10^9 \qquad \text{for} \quad M_R \sim 10^{15}\ \text{GeV}$$

Another feature of CPT-odd leptogenesis is that one only needs **one generation** of heavy neutrinos.

The prediction on the BAU we have made was based on dimensional counting.

A more sophisticated prediction should involve the dynamics of the number density of leptons and baryons.

In particular, one has to account for the sphaleron processes which change the baryon and lepton densities, leaving intact their difference $n_b - n_l$:

$$\partial_t \left(n_b + n_l\right) \quad = \quad - \, \Gamma_{\rm sph} \left(n_b - n_b^{\rm eq} \; + \; n_l - n_l^{\rm eq} \right)$$

This is a reasonable approximation for dynamics of $B + L$.

$$\Gamma_{\rm sph} \;\simeq\; \omega T \,, \qquad\qquad \text{with}\, \omega \;\simeq\; 10^{-5} \,.$$

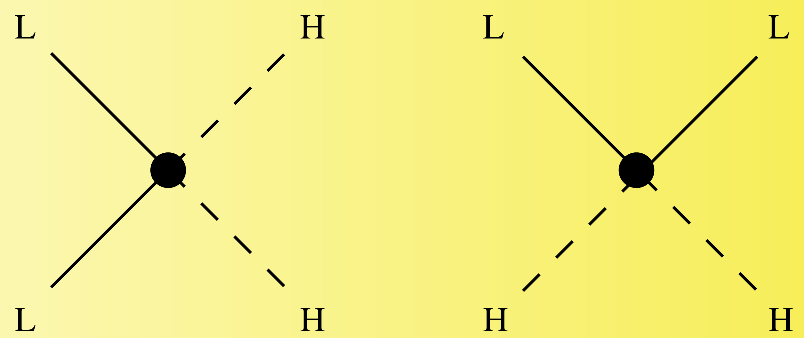
L-processes

The kinetic equations are based on the rate of heavy neutrino-mediated processes.

$$\mathcal{L}_m = -\frac{1}{2}M_R\left(NN + \overline{NN}\right) + h_a \cdot \overline{L}_a \overline{N} H + h_a^\dagger \cdot H^\dagger N L_a$$

Neutrinos can be integrated out to produce an effective vertex

$$\mathcal{L}_{\rm eff} = \frac{Y^\nu_{ij}}{2\,M_R} H^\dagger L_i^\alpha H^\dagger L_{j\alpha} + \text{h.c.}$$



Boltzmann equations

Combining the Hubble expansion rate, and the rate of L-processes and sphaleron processes, one obtains

$$
\begin{aligned}
g_l \frac{d}{dT} Y_l &= \frac{0.6}{g_*^{1/2}} \frac{\omega\, M_{\rm Pl}}{T^2} \Big(g_l (Y_l + 12\, \eta_l\, T) \;+\; g_b (Y_b + 12\, \eta_b\, T) \Big) \\
&+ \frac{0.6\, \pi^2}{g_*^{1/2}} \frac{\gamma\, M_{\rm Pl}}{M_R^2} \cdot (Y_l + 12\, \eta_l\, T) \\
g_b \frac{d}{dT} Y_b &= \frac{0.6}{g_*^{1/2}} \frac{\omega\, M_{\rm Pl}}{T^2} \Big(g_l (Y_l + 12\, \eta_l\, T) \;+\; g_b (Y_b + 12\, \eta_b\, T) \Big)
\end{aligned}
$$

Here ω parametrizes the sphaleron rate, and γ the rate of L-processes.

Soluable limit

This system can be solved in the limit of small sphaleron rate, $\omega \to 0$:

$$\frac{d}{dT} Y_l \;=\; g_l \, \frac{0.6\,\pi^2}{g_*^{1/2}} \, \frac{\gamma\, M_{\mathrm{Pl}}}{M_R^2} \cdot \left(Y_l \,+\, 12\,\eta_l\, T \right)$$

yielding an estimate for the freeze-out temperature

$$T_R \;\sim\; \frac{M_R^2}{\lambda\, M_{\mathrm{Pl}}} \;=\; 10^{12-14}\,\mathrm{GeV}$$

Evolution

We obtain the amount of LV (in terms of η_l, η_b) required to produce the observed BAU, and confront them with the known experimental limits on LV.

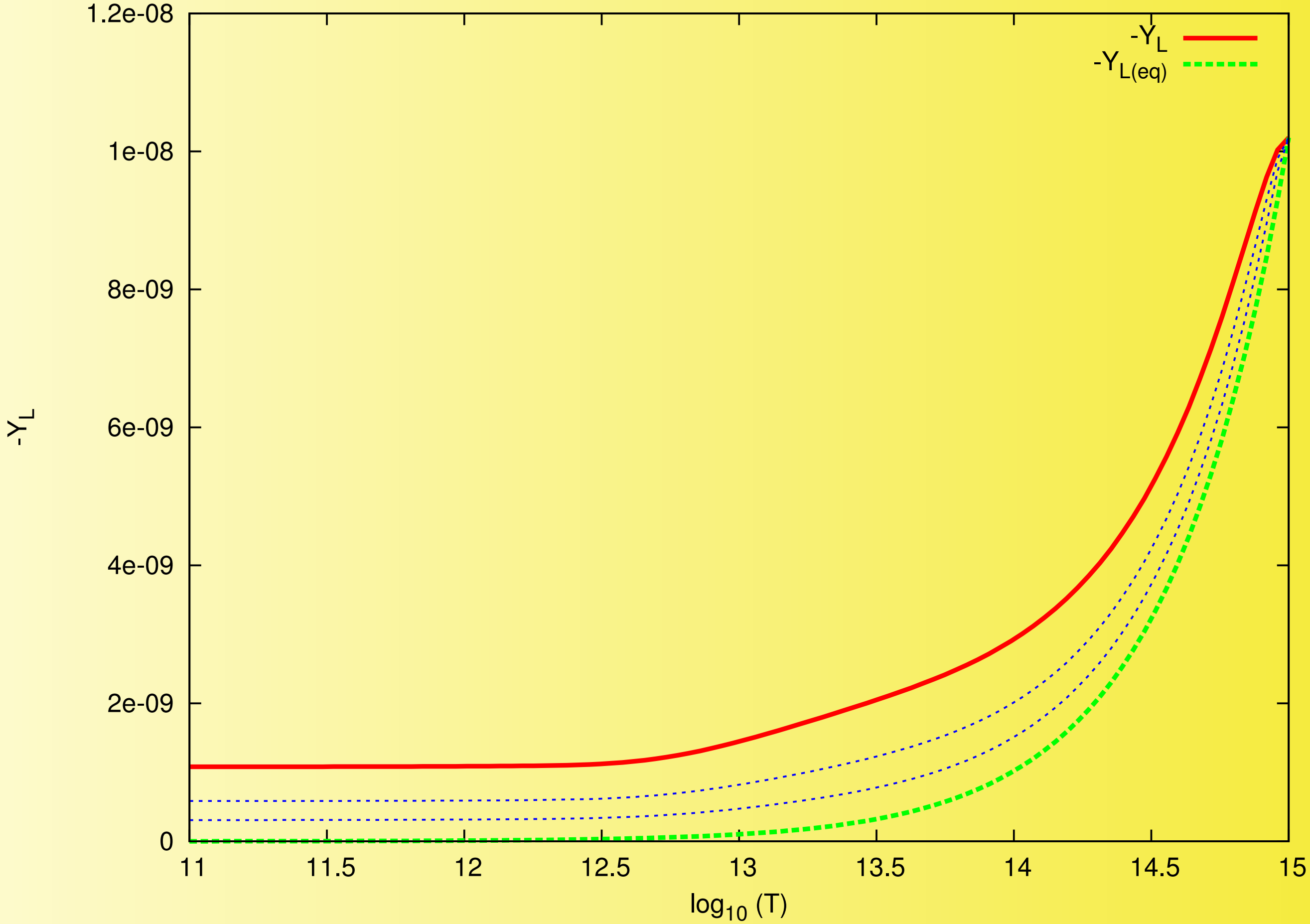
Since the kinetic equations are linear in the number densities, it can be done separately for η_l and η_b.

The kinetic equations depend on an "effective" mass of the light neutrinos (through the rate of L-processes)

$$\Gamma_L \;\sim\; (m_\nu^{\rm eff})^2\,, \quad m_\nu^{\rm eff} \equiv \left(\sum m_{\nu_i}^2\right)^{1/2} \;=\; 0.05\,{\rm eV} \;\;\ldots\;\; 0.65\,{\rm eV}$$

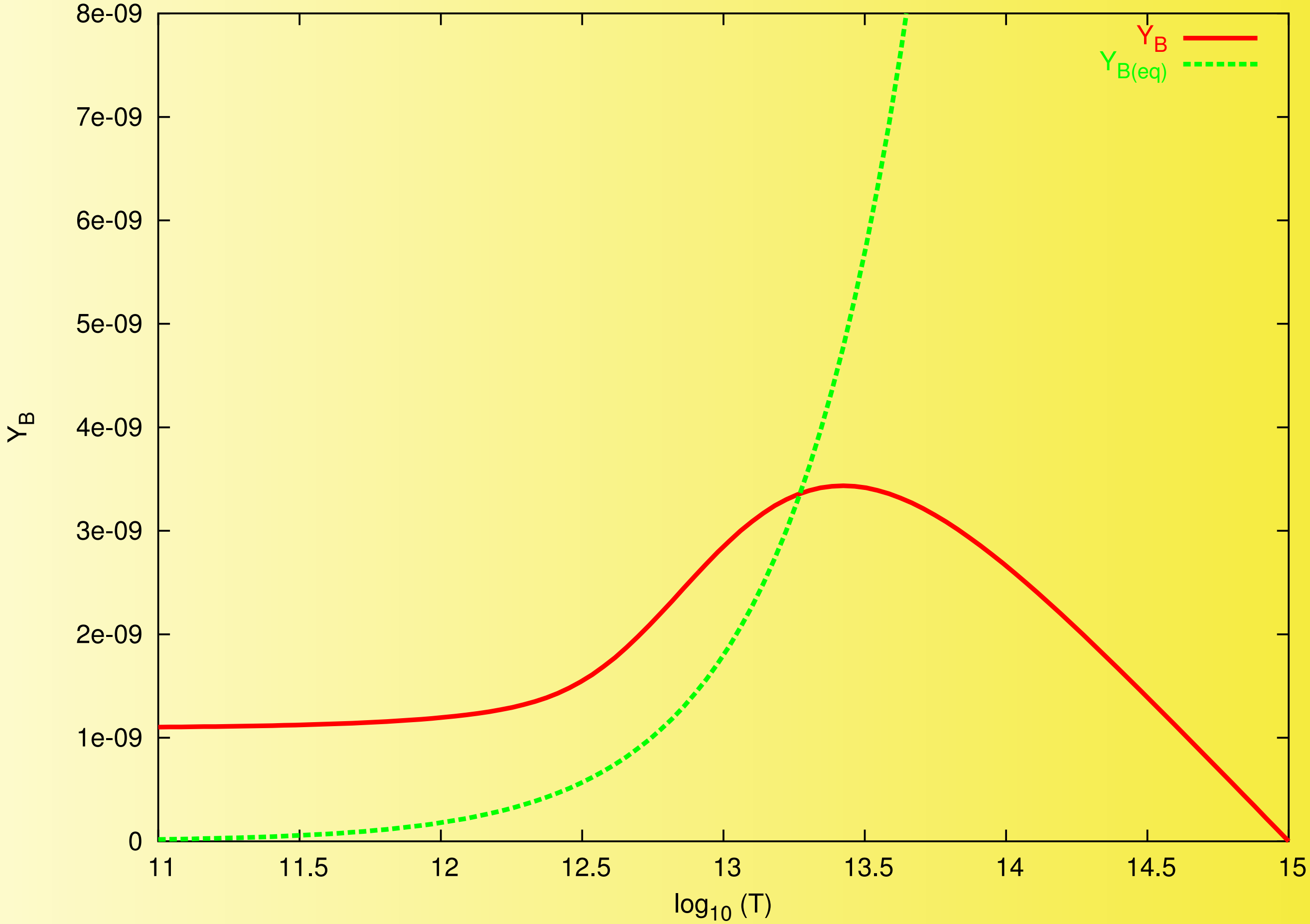
The lower bound for this parameter comes from the largest observed neutrino oscillations; the upper bound comes from the cosmological limit on the sum of neutrino masses $\sum m_{\nu_i}$

Lepton number evolution, $\eta_l \neq 0$



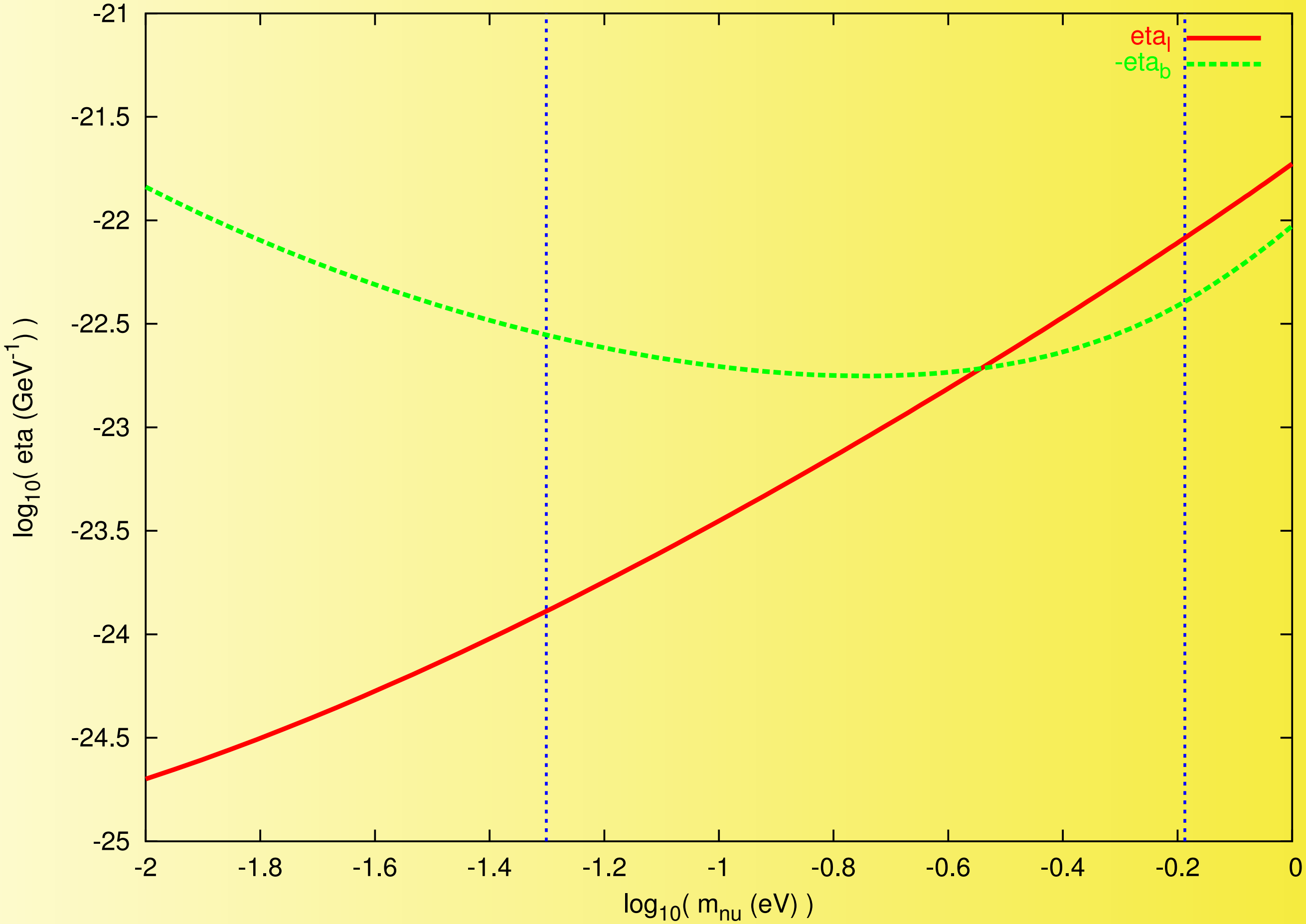
With the increase of the effective neutrino mass, the rate of L-processes increases, and the lepton number density follows closer to the equilibrium curve.

Baryon number evolution, $\eta_b \neq 0$



The baryon density curve starts from zero and jumps over the equilibrium curve.

Required amount of LV



η_l changes over the "physical" interval.

Experimental constraints

Required amount of Lorentz violation is

$$\eta_l \;\simeq\; 10^{-22-24}\,\mathrm{GeV}^{-1} \qquad \text{or} \qquad \eta_b \;\simeq\; -\,10^{-23}\,\mathrm{GeV}^{-1}$$

Low-energy precision experiments set the bounds

$$|\eta_d - \eta_Q - 0.5(\eta_u - \eta_Q)| \;<\; 10^{-27}\,\mathrm{GeV}^{-1}$$

The strongest constraints on the lepton sector come from the observation of high-energy cosmic rays, $E_{max} \sim 10^{12}$ GeV.
Non-zero η_l makes possible the decay of the proton $p \to p l \bar{l}$ and prevents acceleration of the rays.
Observation of these cosmic rays places a bound

$$|\eta_L|,\; |\eta_E| \;<\; 10^{-33}\,\mathrm{GeV}^{-1}$$

There is a loophole which the cosmic rays do not cover.

In the case that all LV is concentrated in the up-quark sector, protons will be favored to decay into $p \to \Delta^{++}\pi^{-}$.

This needs the negative sign of η_U.

Then the cosmic rays could exist in the form Δ^{++} and not constrain η_U.

However $10^{-22-23}\ \mathrm{GeV}^{-1}$ is not compatible with the low energy experiments.

Higher-dimensional operators

Asymmetry generated by dimension seven and so on operators can be estimated by the freeze-out temperature

$$\eta^{(7)} T_R^3 \,, \qquad \eta^{(9)} T_R^5 \,, \qquad \ldots$$

Astrophysical constraints are still strong, as their strength scales as E_{max}/Λ_{CPT}.
However, the same loophole with stable Δ^{++} exists, and the right-handed up-quark CPT-violation

$$\eta_U^{(7)} = -[(10^{17} - 10^{18})\ \mathrm{GeV}]^{-3}$$

results in the right magnitude of BAU while avoiding experimental constraints.

Conclusions

- CPT-odd Baryogenesis is an equilibrium alternative to the conventional baryogenesis
- CPT-odd Leptogenesis is advantageous in the **gain** of the final BAU — determined by high freeze-out temperature
- Study of dynamics of the number densities in this scenario yields the amount of Lorentz violation capable of producing the observed BAU, $\eta \sim 10^{-22-23}\ \mathrm{GeV}^{-1}$
- Strong experimental constraints on LV most certainly exclude this type of scenarios
- We have only considered the *UV-enhanced* operators; other interactions *e.g.* $\overline{Q}\,\gamma_\mu Q H^\dagger H$ could produce an effective chemical potential, although they have problems of their own.