Polarized CMB Boltzmann hierarchy from neutrino non-standard interactions

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Abstract

The work focuses on the possibility to characterize and constrain the parameter space of the so-called Majoron models of neutrino mass generation through new cosmological observables not explored so far, like polarization and cosmic birefringence [1].
We investigated the evolution of the cosmic microwave background (CMB) photons density matrix induced by the energy transfer between neutrino and photon mediated by a pseudoscalar particle, through the use of the Quantum Boltzmann Equation (QBE) formalism [2, 3]. The resulting Botlzmann hierarchy shows a clear dependence on the parameters of the model, appearing as a modification of the optical depth of the cosmic fluid and a rotation of the polarization angle of the CMB photons.

Outline of the work

1 Phenomenological model

Keypoints in the cosmological hunt for neutrino Non-Standard Interactions (NSIs):

- Well grounded in particle physics models, and might be related to **neutrino mass generation**
- They could provide interesting signatures helping **indirect detection**
- They might help in explaining **ΛCDM tensions**

New searches for models with a pseudoscalar particle playing the role of an ALP and the Majoron simultaneously:

$$\mathcal{L}_{\rm int} = -i g_{\phi\nu\nu}\left(\bar{\psi}_\nu \gamma_5 \psi_\nu\right)\phi + \frac{1}{4} g_{\phi\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}\phi$$

2 The Quantum Boltzmann Equation (QBE)

Ensamble averaged Heinsenberg's time evolution equations

$$(2\pi)^3\,\delta^{(3)}(0)\,2E_{\mathbf{p}}\frac{\mathrm{d}}{\mathrm{d}t_{\rm mes}}\rho_{ij}(\mathbf{x},\mathbf{p},0) =$$

$$i\left\langle\left[\hat{H}^I_{\rm int}(0),\hat{\mathcal{N}}^I_{ij}(\mathbf{p},0)\right]\right\rangle - \frac{1}{2}\int_{-\infty}^{\infty} dt_{\rm mic}\left\langle\left[\hat{H}^I_{\rm int}(0),\left[\hat{H}^I_{\rm int}(t_{\rm mic}),\hat{\mathcal{N}}^I_{ij}(\mathbf{p},0)\right]\right]\right\rangle$$

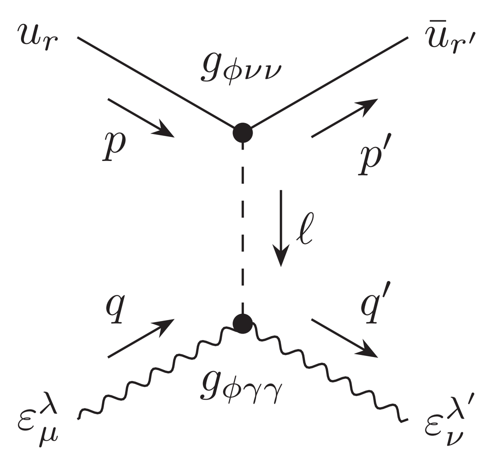
Collision term: reproduces results of standard Botlzmann equation approach

Forward scattering term: gives rise to decoherence effects like Faraday rotation (or conversion) and flavour oscillations

NB: assuming the **Markov hypothesis** the QBE is valid at any time

3 The physical case: neutrino-photon scattering

We can apply neutrino flavour oscillation technology to a photon population, making a parallelism between two **discrete quantum numbers**: the flavour and the helicity.



$$\hat{I} \equiv |\varepsilon_1\rangle\langle\varepsilon_1| + |\varepsilon_2\rangle\langle\varepsilon_2|$$
$$\hat{Q} \equiv |\varepsilon_1\rangle\langle\varepsilon_1| - |\varepsilon_2\rangle\langle\varepsilon_2|$$
$$\hat{U} \equiv |\varepsilon_1\rangle\langle\varepsilon_2| + |\varepsilon_2\rangle\langle\varepsilon_1|$$
$$\hat{V} \equiv i\left(|\varepsilon_2\rangle\langle\varepsilon_1| - |\varepsilon_1\rangle\langle\varepsilon_2|\right)$$

$$S^{(n)}_{\nu\gamma} \equiv -i\int_{-\infty}^{+\infty} dt\; H_{\nu\gamma}(t)$$

Debated situation about contribution from 1-loop diagrams in the Standard Model. Our revised calculations indicates no optical effects due to standard neutrino-photon scattering up to order $\mathcal{O}(\alpha_{\rm em} G_{\rm F})$.

4 New cosmological observables?

Targets of next-generation CMB experiments:

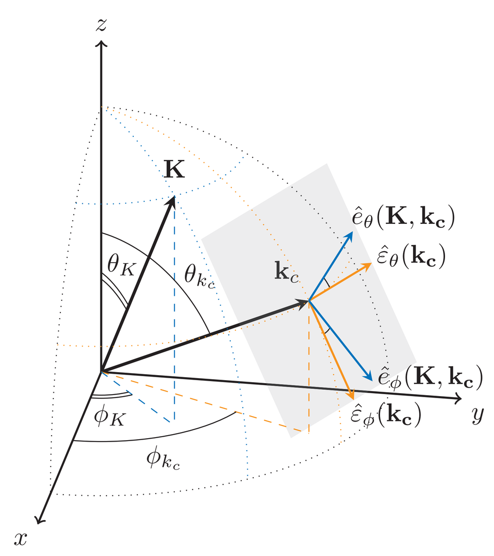
$$\alpha \equiv \frac{1}{2}\tan^{-1}\frac{U}{Q}$$ **Cosmic birefringence:** rotation of CMB linear polarization angle

B-modes polarization: hints for inflation and non-standard cosmology $$\langle a^*_{B,\ell'm'} a_{B,\ell m}\rangle \equiv C^{BB}_\ell \delta_{\ell\ell'}\delta_{mm'}$$

$$f = \frac{1}{e^{(E-\mu(E))/kT} - 1}$$ **Spectral distortions** in CMB photons distribution function

Full polarization equations

Written in terms of brightness perturbations, they follow the propagation of independent polarazation modes from the last scattering surface (LSS) to the present days.



Liouville operator: free streaming in the expanding Universe

$$\frac{d}{d\eta}\Delta_Q(\mathbf{K},\mathbf{k}_c) + iK\mu\Delta_Q(\mathbf{K},\mathbf{k}_c) =$$

Standard electromagnetism: linear polarization from Compton scattering

$$= -\tau'\left[-\Delta_Q(\mathbf{K},k_c) + \frac{1}{2}(1-P_2(\mu))(\cos(2\phi_{\mathbf{K}})\Delta_{I2}(\mathbf{K}) + \Delta_{Q0}(\mathbf{K},k_c) + \Delta_{Q2}(\mathbf{K},k_c))\right]$$

$$+\frac{1}{8a^2}\left(\frac{g_{\phi\nu\nu}g_{\phi\gamma\gamma}}{2\pi}\right)^2\left\{\frac{1}{32}\left[3\zeta(3)T^3_{\nu0} - \frac{\pi^2}{3k_c}a^2M^2T^2_{\nu0}\right]\Delta_Q(\mathbf{K},\mathbf{k}_c)\right.$$
$$\left.+\frac{1}{2\pi k_c}\left[\frac{\partial I_0}{\partial k_c}\right]^{-1}\int_0^\infty dq_c q_c^3\frac{\partial I_0}{\partial q_c}\int_{-1}^{1} d\cos\theta\;\mathcal{K}_2(k_c,q_c,\theta,\eta)\Big|_{\substack{T_\nu=T_{\nu0}\\ M=aM}}\Delta_Q(\mathbf{K},\mathbf{q}_2)\right\}$$

BSM physics: modification to the visibility function, rotation of polarization angle and coupling between different Fourier modes

Analogous for Δ_U, with differences in projection of CMB terms (i.e. non-trivial initial linear polarization) and relative sign between BSM terms (i.e. independent polarization directions propagate differently through the Universe).

Results

Order of magnitude estimates of the effects predicted by our equations (the two contributions were studied separately)

Correction to the visilibity function of the photons $$g_{\nu\gamma}(\eta) \simeq g(\eta)e^{A_{\nu\gamma}(\eta_0)-A_{\nu\gamma}(\eta)}$$

$$A'_{\nu\gamma} = \frac{1}{256a^2}\left(\frac{g_{\phi\nu\nu}g_{\phi\gamma\gamma}}{2\pi}\right)^2\begin{cases}3\zeta(3)T^3_{\nu0} - \dfrac{\pi^2}{3k_c}a^2M^2T^2_{\nu0}\\[2mm] 225\zeta(5)\dfrac{k_c^2T^5_{\nu0}}{a^4M^4}\end{cases}$$

$$\Delta C^{EE}_\ell/C^{EE}_\ell \simeq 0.05\ \text{(Planck 2018)} \quad\Rightarrow\quad g_{\phi\nu\nu}g_{\phi\gamma\gamma} \lesssim 10^{-4}\ \text{GeV}^{-1}$$

Cosmic birefringence $$\tan[2\alpha(\mathbf{K},\eta_0)] \simeq e^{-2[B_{\nu\gamma}(\eta_0)-B_{\nu\gamma}(\eta_{\rm rec})]}\tan(2\phi_{\mathbf{K}})$$

$$B_{\nu\gamma} = \frac{1}{8a^2}\left(\frac{g_{\phi\nu\nu}g_{\phi\gamma\gamma}}{2\pi}\right)^2\frac{k_c^2}{2\pi}f_\theta(-1)$$

$$\Delta\alpha/\alpha \simeq 0.3\ \text{(Planck 2018)} \quad\Rightarrow\quad g_{\phi\nu\nu}g_{\phi\gamma\gamma} \lesssim 10^{-11}\ \text{GeV}^{-1}$$

All these limits are inside a well explored region of the parameter space. Even with the sensitivity of next-generation experiement this scenario provides **non-competitive bounds with respect to other searches**.

Essential bibliography:

[1] Bartolo et al., *Phys. Rev. D* **100** (2019) 043516
[2] A. Kosowsky, *Annals. Phys.* **246** (1996) 49
[3] G. Sigl and G. Raffelt, *Nucl. Phys. B* **406** (1993) 423

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