Neutrino oscillations breaking isotropy in the early Universe

based on Hansen, Shalgar and Tamborra, arxiv: 2012.03948

WIν 2021

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Collective neutrino oscillations are known to amplify anisotropies and inhomogeneities for supernova neutrinos. The same phenomenon is here demonstrated the early Universe, which is assumed to be almost perfectly isotropic and homogeneous. Despite the tiny initial seed, the anisotropy has an $\mathcal{O}(1)$ effect on neutrino oscillations for NO in a simple model with two bins.

The early Universe

The Universe starts in a hot and dense state and continues to expand even today.

Its overall evolution is described by the Friedmann equation:

$$H \equiv \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G \varrho}{3}}$$

and the continuity equation:

$$\dot{\rho} = -3H(\varrho + P).$$

At a temperature of ~ 10 MeV, the plasma consists of photons, neutrinos, antineutrinos, electrons and positrons (and a very small number of protons and neutrons). As the temperature approaches the electron mass $m_e = 511$ keV, electrons and positrons become Boltzmann suppressed, and the photon temperature T_γ increases compared to the comoving temperature $T_{\rm cm}$ (see Fig. 1).

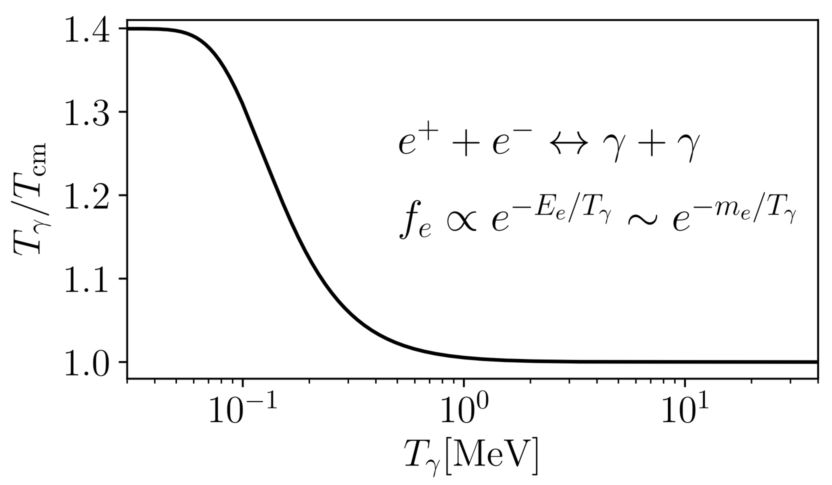


Fig. 1: *Evolution of photon and comoving temperatures.*

Neutrinos are tightly coupled until a temperature of ~ 1 MeV, but are still heated slightly by electrons and positrons. Electron neutrinos and antineutrinos have stronger interactions with electrons and positrons than the other neutrino flavors, and are hence produced in slightly larger numbers. **This difference in flavors can induce neutrino oscillations.**

Neutrino oscillations

The neutrino flavor state is described by density matrices ρ. The diagonal of ρ gives the occupation numbers and the off-diagonal quantify the coherence between different flavors.

The considered toy-model breaks isotropy by considering left (L) and right (R) moving neutrinos. Right moving neutrinos evolve according to:

$$\frac{\partial \rho_R(p)}{\partial t} - Hp\frac{\partial \rho_R(p)}{\partial p} = -i[\mathcal{H}_R(\rho_R, \rho_L, p), \rho_R(p)] + \mathcal{C}_R(\rho_R, \rho_L, p)\ ,$$

where $\mathcal{C}_R(\rho_R, \rho_L, p)$ is an approximation of the collision term and the Hamiltonian is given by

$$\mathcal{H}_R = \frac{\mathcal{U}\mathcal{M}^2\mathcal{U}^\dagger}{2p} + \sqrt{2}G_{\rm F}\int \frac{dp'}{2\pi^2}(\rho_L(p') - \bar{\rho}_L^*(p')) - \frac{8\sqrt{2}G_{\rm F}p}{3}\frac{\mathcal{E}_l}{m_W^2}\ .$$

The first term describes vacuum oscillations, the second is the neutrino-neutrino term, and the third is the matter term. Similar equations apply to ρ_L. The equations for $\bar{\rho}_R$ and $\bar{\rho}_L$ are obtained by substituting $\rho \leftrightarrow \bar{\rho}$.

Linear stability analysis

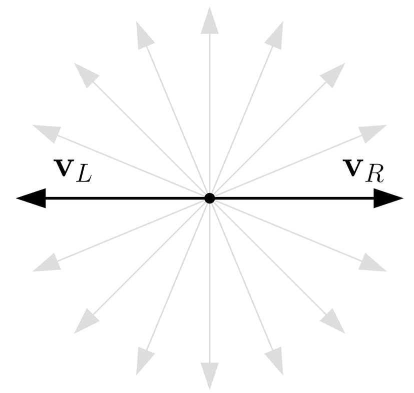
Collective oscillations occur when all momentum states oscillate with the same frequency.

By expanding the equations to linear order in the off-diagonal part of the density matrix, **the criterion for collective oscillations to take place is:**

$$2\mu(\rho_{ee} - \rho_{xx}) > \omega + \lambda, \qquad (1)$$

where μ represents the neutrino-neutrino term, ω the vacuum term, and λ the matter term.

Isotropic



For the isotropic case, we assume that $\rho_R = \rho_L$ initially, and the numerical code preserves this symmetry throughout the calculation.

The linear stability analysis predicts normal mass ordering (NO) to be stable towards oscillations, and this is confirmed by the left panels in Fig. 2. Although Eq. (1) is satisfied for a range of temperatures below $T_\gamma \sim 14$ MeV, no collective oscillations appear due to the symmetry of the system.

The inverted mass ordering (IO) is predicted to be linearly unstable below $T_\gamma \sim 5$ MeV, which the numerical solution also shows. Collective oscillations lead to smaller difference between ν_e and ν_x. At low temperatures $T_\gamma < 1$ MeV vacuum oscillations dominate.

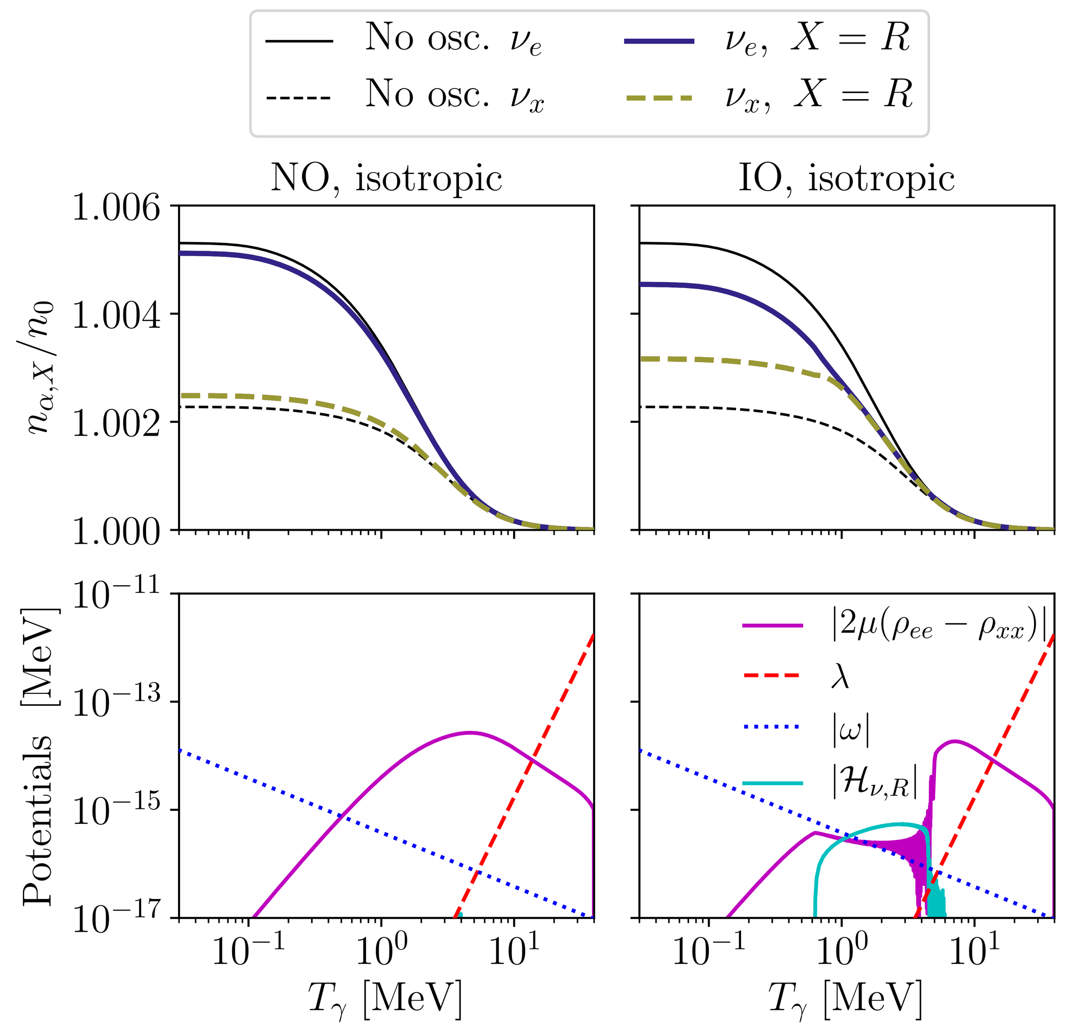
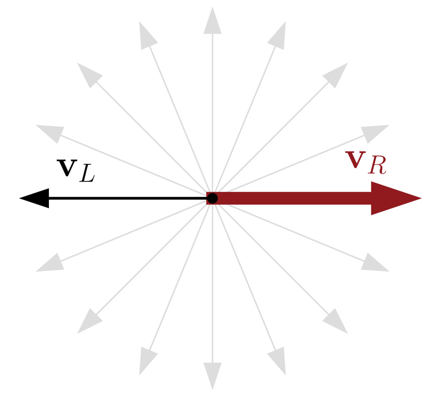


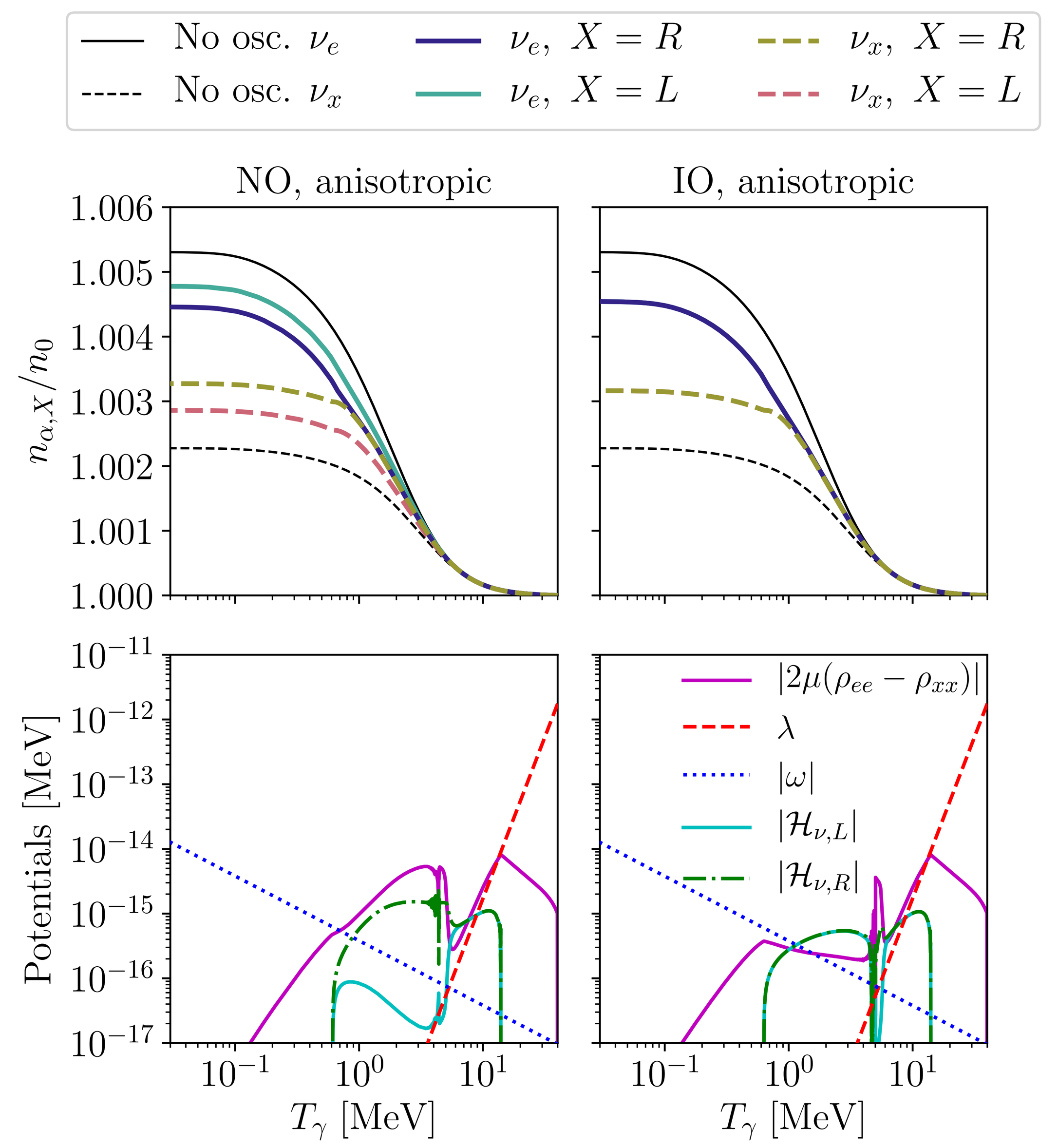
Fig. 2: *Neutrino number densities and potentials for isotropic initial conditions.*

Anisotropic



For the anisotropic case, we assume a tiny initial asymmetry between ρ_R and ρ_L of $\mathcal{O}(10^{-15})$. This asymmetry is amplified dynamically by the evolution. At $T_\gamma \sim 14$ MeV, collective oscillations start as predicted by linear stability analysis in Eq. (1). For IO, the evolution is approximately isotropic for $T < 5$ MeV, and the final number density is indistinguishable from the isotropic case. **In NO, a substantial anisotropy persists even at low temperatures.**

The lower abundance of ν_e and higher abundance of ν_x result in a shift in the effective number of neutrinos, $N_{\rm eff}$, of 5×10^{-4}, comparable to higher order QED effects.



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Co-financed by the Connecting Europe Facility of the European Union

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