PROCEEDINGS OF SCIENCE

Dark neutrino interactions make gravitational waves blue

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In ΛCDM cosmology neutrinos start free-streaming after weak decoupling epoch and contribute to the damping of Primordial gravitational waves entering the horizon. New interactions can stop neutrinos from free-streaming, therefore, enhance the primordial gravitational waves at small scale. This leads to enhancement of CMB - B mode compared to ΛCDM at higher multipoles (ℓ). This enhancement mimics blue initial spectrum of primordial gravitational waves. Therefore departure from the scale invariance, if observed in future observations of CMB - B modes, can be a signature of non-standard neutrino interactions. High precision detection of primordial gravitational waves or CMB - B modes will be able to distinguish between blue initial spectrum and new neutrino interactions.

Neutrino Oscillation Workshop (NOW2018)
9 - 16 September, 2018
Rosa Marina (Ostuni, Brindisi, Italy)

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PoS(NOW2018)086

1. Introduction

Primordial gravitational waves (PGW) are messengers of physics at exceptionally high energies (UV physics). These are tensor perturbations produced in the early universe which source polarization anisotropies in the Cosmic microwave background (CMB) as B modes. In the linear theory scalar perturbations do not create B modes, therefore, CMB-B modes provide a cleaner way to detect PGW.

In recent times, with the onset of gravitational wave experiments, lots of research are being carried out towards finding new sources of gravitational waves. Here we considered the inverse problem - disentangling UV physics (nature of PGW initial spectrum) in the case of detection of B - mode [1]. The propagation of gravitational waves depends crucially on the anisotropic stress of the medium which is sourced by free streaming relics such as neutrinos. Non-standard interactions of the neutrinos modify the anisotropic stress, thereby, leave imprints on the observed B-mode spectrum. These modifications can mimic features of the initial spectrum of the gravitational waves, therefore, can make extraction of UV physics very challenging.

2. Model for Dark matter - Neutrino Interaction.

New neutrino interactions are severely constrained within the Standard Model (SM). Therefore to get sizeable non-standard interactions of neutrinos, we need to couple them with new degrees of freedom beyond the SM. There is overwhelming evidence for the existence of one such candidate - Dark matter (DM). Dark-matter neutrino (DM-ν) interaction has been studied in the literature in the context of *small scale problem* of ΛCDM[2].

The lowest order gauge invariant Lagrangian involving dark matter and neutrino can be written as,

$$\mathscr{L} \supset Y \frac{1}{\Lambda} \left(H^\dagger l\right)(\psi\chi) \quad \Rightarrow \quad \eta\,\delta_{ij}\, \nu_i \psi_j \chi \quad \text{where } \eta = Y\frac{v}{\sqrt{2}\Lambda}\,, \tag{2.1}$$

which generates DM-ν interaction after higges gets a vev (v). In this Lagrangian, H and l are the SM Higges and lepton doublet. χ is the DM and ψ is the mediator having masses m_χ and m_ψ respectively ($m_\psi > m_\chi$). We introduce the mediator to preserve an additional $U(1)_D$ under which mediator and DM are oppositely charged to make the DM stable. We preserve lepton flavor symmetry by choosing ψ to be fundamental under $SU(3)_l$.

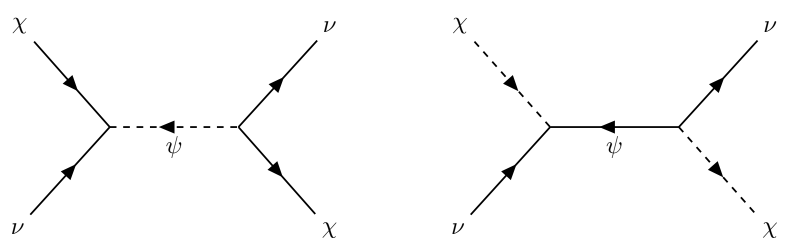


Figure 1: Feynman diagram for DM-ν scattering. Left one is for fermionic DM whereas the right one is for complex scalar DM.

In the red-shift range of interest ($z \gtrsim 1000$) we assume the neutrinos to be massless and compute the *intensity averaged* scattering cross-section between the DM and the neutrinos. Depending on the mass difference of the mediator and the DM we get two kinds of temperature dependences of the cross-section. In the parameter space, where the mass difference is small compared to the momentum of neutrino, the cross-section is constant at leading order and given as,

$$\sigma_{\chi\nu} \approx \sigma^{(0)} \simeq 10^{-13} \times \sigma_{\rm Th} \times \left(\frac{\eta}{0.1}\right)^4 \left(\frac{m_\chi}{100\ \rm GeV}\right)^{-2} \tag{2.2}$$

where $\sigma_{\rm Th} = 6.65 \times 10^{-25}\ \rm cm^2$ is the Thomson scattering cross-section. In other regions of the parameter space the cross-section is dependent on square of neutrino temperature,

$$\sigma_{\chi\nu} \approx \sigma^{(2)} \left(\frac{T_\nu}{1.95\ \rm K}\right)^2 \simeq 10^{-39}\, \sigma_{\rm Th}\, a^{-2} \left(\frac{\eta}{0.1}\right)^4 \left(\frac{\Delta}{0.1}\right)^{-2} \left(\frac{m_\chi}{100\ \rm GeV}\right)^{-4} \tag{2.3}$$

where $\Delta \equiv \left(m_\psi^2 - m_\chi^2\right)/m_\chi^2$ and in the last line we have used the scaling of temperature with the scale factor ($T_\nu \propto 1/a$). We computed the modifications of neutrino tensor Boltzmann equations with the new interaction. As DM is non relativistic, it does not contribute to anisotropic stress. The comoving scattering rate is given by,

$$\dot{\mu} \equiv \begin{cases} a\rho_\chi \sigma^{(0)} \left(\frac{1}{m_\chi}\right) = u^{(0)} \left(\frac{\rho_\chi^{(0)}}{a^2}\right) \left(\frac{\sigma_{\rm th}}{100\rm GeV}\right) & : T_\nu \text{ independent} \\ a\rho_\chi \frac{\sigma^{(2)}}{a^2} \left(\frac{1}{m_\chi}\right) = u^{(2)} \left(\frac{\rho_\chi^{(0)}}{a^4}\right) \left(\frac{\sigma_{\rm th}}{100\rm GeV}\right) & : T_\nu^2 \text{ dependent} \end{cases} \tag{2.4}$$

where ρ_χ is the DM energy density which is related to present DM energy density by $\rho_\chi = \rho_\chi^{(0)}/a^3$. The scattering rate in each case is parametrized by $u^{(0)}$ and $u^{(2)}$ which are defined as,

$$u^{(0)} \equiv \left(\frac{\sigma^{(0)}}{\sigma_{\rm Th}}\right) \left(\frac{100\rm GeV}{m_\chi}\right), \qquad u^{(2)} \equiv \left(\frac{\sigma^{(2)}}{\sigma_{\rm Th}}\right) \left(\frac{100\rm GeV}{m_\chi}\right). \tag{2.5}$$

These modification are implemented in Boltzmann equation solver Cosmic Linear Anisotropy Solving System (CLASS)[3].

3. Results & Conclusion

Primordial Gravitational waves are frozen outside the horizon, and after horizon entry, they undergo damped oscillation. Anisotropic stress of the medium enhances the damping by removing energy from PGW to the free-streaming relics[4]. In SM, neutrinos start free streaming after decoupling from the plasma at redshift $z \sim 10^9$. Additional interaction, in this case, DM-ν interaction stops neutrinos from free streaming, thereby, suppress the growth of anisotropic stress. Therefore the amplitude of gravitational waves gets enhanced compared to the case of no new interaction which is ΛCDM.

The scattering rate is higher at earlier times, therefore, the enhancement is more prominent for modes with smaller wavelength (larger wave-number) which make horizon entry at an earlier

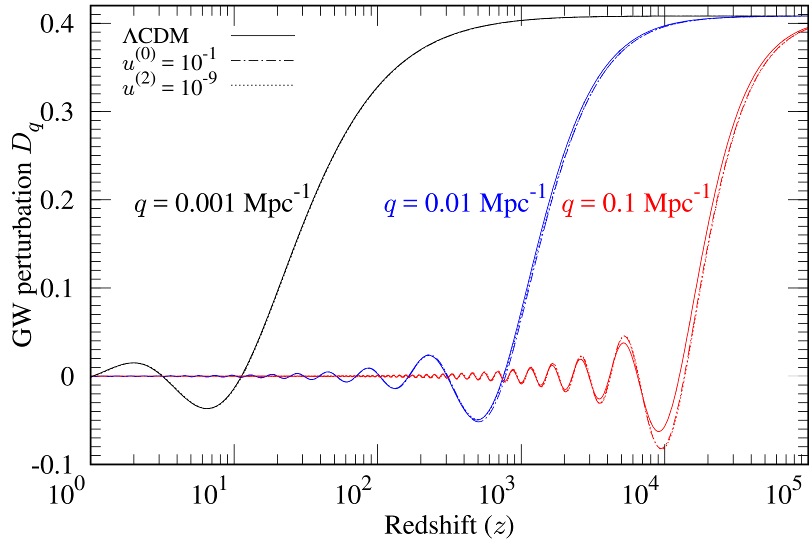
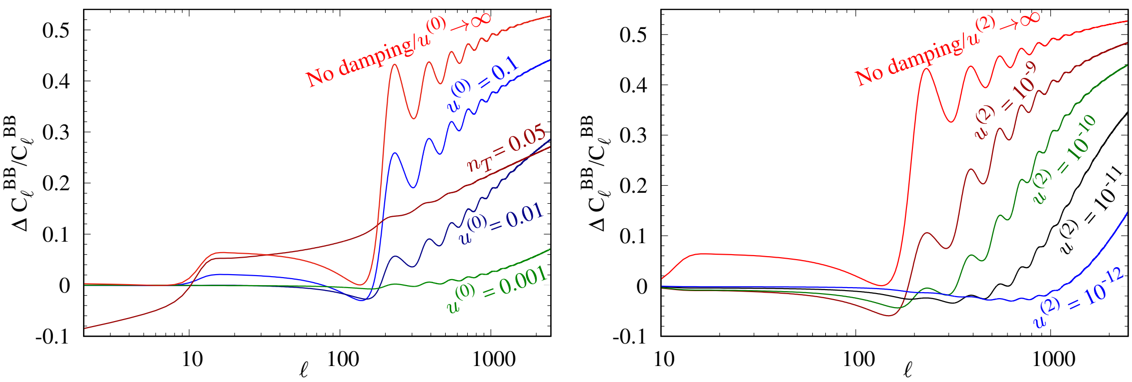


Figure 2: Evolution of the PGWs for three different wave-numbers for ΛCDM and after including additional neutrino interaction. This figure is adapted from [1].

time [Fig. 2]. The effects on unlensed CMB B mode are shown in Fig. 3a where we have plotted the fractional change of B-mode power spectrum from the ΛCDM case. Here we also see that small scale modes which correspond to large multi-poles (ℓ) get enhanced compared to ΛCDM and the enhancement increases as we go to larger ℓ. The curves labelled 'no damping' represent the maximum change in B mode in the extreme case when neutrinos never free streamed.



(a) T_ν independent

(b) T_ν^2 dependent

Figure 3: Fractional change of B-mode power spectrum compared to ΛCDM. $\Delta C_l^{BB}/C_l^{BB} \equiv (C_l'^{BB} - C_l^{BB})/C_l^{BB}$ where $C_l'^{BB}$ is the modified spectrum and C_l^{BB} is ΛCDM spectrum. These figures are adapted from [1].

The amplitude and shape of the initial tensor power spectrum are determined by tensor to scalar ratio r and tensor spectral index n_T. For ΛCDM, assuming single field slow roll inflation, $n_T \sim 0$. In fig 3a we show the effect of a *blue* primordial tensor spectrum ($n_T > 0$) with $n_T = 0.05$ which may occur in some complicated model of inflation. It also enhances the small scale modes compared to ΛCDM similar to the DM-ν case.

Therefore DM-ν interaction mimics blue primordial tensor spectrum which is a UV property of primordial gravitational waves. However the shapes of these two types of modifications are different, therefore, high precision CMB - B mode experiment should be able to differentiate between these two scenarios. However, if the first detection of the B modes is just above the noise threshold, then dark matter-neutrino interaction may be mistaken for a blue primordial tensor spectrum.

DM-ν interaction also modifies CMB scalar modes and matter power spectrum, therefore, gets constrained from CMB and Large scale structure (LSS) observations[5, 6, 7, 8]. These bounds which assume all the DM interacting with neutrinos can be weakened significantly in multicomponent DM scenario where only a fraction of the total DM interacts with neutrinos[9, 10]. Therefore in multicomponent model DM-ν interaction can have a larger effect on CMB - B modes.

Acknowledgments

The research presented in this talk is funded by the SERB grant no ECR/2015/000196 and ECR/2015/000078 of Science and Engineering Research board, Dept. of science and technology, Govt. of India and by Max-Planck-Gesellschaft through the partner group between MPI for Astrophysics, Garching and TIFR, Mumbai. I am very thankful to the organisers of Neutrino Oscillation Workshop and the conveners for the invitation to the workshop and their kind hospitality.

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