DνCLASS Documentation

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This code is built on existing CLASS: Cosmic Linear Anisotropy Solving System code developed by Julien Lesgourgues and Thomas Tram. This code computes CMB power spectrum and matter power spectrum for Dark Neutrino interaction (DNI) cosmology in a *flat* universe.
In DNI cosmology the Standard model neutrinos interact with a fraction of total dark matter of the universe (NIDM - Neutrino interacting DM) with temperature independent scattering cross-section. This cosmology predicts a higher value of Hubble constant owing to the modification of neutrino induced phase shift in the CMB [arXiv:1908.09843]. It also predicts enhancement of primordial gravitational waves and CMB B modes [arXiv:1711.09929].

****You can use DνCLASS freely, provided that in your publications, you cite at least these papers: Dark Neutrino interactions phase out the Hubble tension, Dark neutrino interactions make gravitational waves blue and CLASS II: Approximation schemes. Feel free to cite more CLASS papers!**

**To get support, please open a new issue on
`https://github.com/subhajitghosh-phy/CLASS_DNI/` or email at subhajit.tifr@gmail.com.

Given below are the modifications made in the CLASS code to incorporate DNI cosmology.

1 Getting started with the code

The installation is exactly same with that of the CLASS code. Please refer to `https://github.com/lesgourg/class_public` for details. The standard procedure of running CLASS is:
$ ./class [.ini file] [.pre file]
The ".pre" file is mandatory as explained below.

1.1 New parameters:

This code introduces two new parameters:

- f_{dni} - the fraction (f) of the total DM interacting with neutrinos.
- u_{dni} - the interaction strength (u) of DM-ν interaction. Please refer to [arXiv:1908.09843] for the exact definition.

The input parameter $\omega_{\rm cdm}(\Omega_{\rm cdm})$ is replaced with $\omega_{\rm dm}(\Omega_{\rm dm})$, the enrgy density of total DM. For a given f_{dni} and $\omega_{\rm dm}$ the code internally sets $\omega_{\rm cdm} = (1 - f_{dni})\ \omega_{\rm dm}$ and $\omega_{\rm nidm} = f_{dni}\ \omega_{\rm dm}$.
**The 'gauge' parameter must be set to Newtonian gauge because the modifications of the Boltzmann equations for neutrino and NIDM are coded only for Newtonian gauge. Also this code is valid only for flat cosmology (curvature $K = 0$).

**The code uses the 'dcdm' species already included in CLASS to implement NIDM. Sample .ini files with these new parameters is distributed with the code.

1.2 Precision parameters:

To successfully run the code the .pre (precision) file *must* have the following arguments.

- ur_fluid_approximation = 3
- radiation_streaming_approximation = 3
- start_small_k_at_tau_c_over_tau_h : should be set to a small number – 10^{-6} for reference.

  Since in DNI scenario neutrinos are tightly coupled to the DM, their initial anisotropic stress is set to 0 as a initial condition. The initial conditions should be set at a fairly high redshift where the DM-ν system becomes more tightly coupled due to the increase of interaction strength. This parameter ensures that the evolution of the small scale modes starts at a significantly higher redshift where this initial condition is valid.
- start_large_k_at_tau_h_over_tau_k = 0.03

Since the code is evaluating quantities from very high redshift we used some higher precision flags to avoid numerical error:

- tol_perturb_integration=1.e-7
- perturb_integration_stepsize = 0.01

A .pre file ("dni.pre") is distributed with the code.

2 Initial conditions (Newtonian gauge)

As mentioned before, in the DNI cosmology neutrinos are coupled with NIDM. We start evolving the modes from a fairly high redshift. The initial conditions are given below (following the notation of Ma & Bertschinger):

2.1 ΛCDM initial conditions:

$$\psi = \frac{20C}{15 + 4R_\nu} \tag{1}$$

$$\phi = \left(1 + \frac{2}{5}R_\nu\right)\psi \tag{2}$$

$$\sigma_\nu = \frac{k^2\tau^2}{15}\psi \tag{3}$$

$$\delta_\gamma = \delta_\nu = \frac{4}{3}\delta_c = \frac{4}{3}\delta_i = \frac{4}{3}\delta_b = \left(\frac{2}{3}\frac{k^2}{(a'/a)^2}\phi - 2\psi\right)\frac{1 + \frac{\rho_m}{\rho_r}}{1 + \frac{3\rho_m}{4\rho_r}} \tag{4}$$

$$\theta_\gamma = \theta_\nu = \theta_c = \theta_i = \theta_b = \frac{k^2\psi}{2(a'/a)}\frac{1 + \frac{\rho_m}{\rho_r}}{1 + \frac{3\rho_m}{4\rho_r}} \tag{5}$$

2.2 DNI initial conditions:

$$\psi = \phi = \frac{20C}{15} \tag{6}$$

$$\sigma_\nu = 0 \tag{7}$$

$$\delta_\gamma = \delta_\nu = \frac{4}{3}\delta_c = \frac{4}{3}\delta_i = \frac{4}{3}\delta_b = \left(\frac{2}{3}\frac{k^2}{(a'/a)^2} - 2\right)\psi\frac{1+\frac{\rho_m}{\rho_r}}{1+\frac{3\rho_m}{4\rho_r}} \tag{8}$$

$$\theta_\gamma = \theta_\nu = \theta_c = \theta_i = \theta_b = \frac{k^2\psi}{2(a'/a)}\frac{1+\frac{\rho_m}{\rho_r}}{1+\frac{3\rho_m}{4\rho_r}} \tag{9}$$

δ, θ, σ stand for over-density, divergence of fluid velocity and shear respectively for each spices individually. Here the subscript 'i' stands for NIDM. See Ma & Bertschinger) for the definition of these variables. Here dot denotes derivative with respect to the to conformal time, prime denotes derivative with respect to co-ordinate time and a denotes the scale factor.

2.3 Scalar Boltzmann equation for neutrino and NIDM

$$\dot{\delta}_i = -\theta_i + 3\dot{\phi} \tag{10}$$

$$\dot{\theta}_i = -\frac{\dot{a}}{a}\theta_i + k^2\psi - \left(\frac{4\rho_\nu}{3\rho_i}\right)\dot{\mu}(\theta_i - \theta_\nu) \tag{11}$$

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} \tag{12}$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi + \dot{\mu}(\theta_i - \theta_\nu) \tag{13}$$

$$\dot{\sigma}_\nu = \frac{1}{2}\left(\frac{8}{15}\theta_\nu + k^2\psi - \frac{3}{5}kF_{\nu 3}\right) - \dot{\mu}\sigma_\nu \tag{14}$$

$$\dot{F}_{\nu l} = \frac{k}{(2l+1)}\left[lF_{\nu\ l-1} - (l+1)F_{\nu\ l+1}\right] - \dot{\mu}F_{\nu l} \tag{15}$$

Here $\dot{\mu} = an_i\sigma_{\chi\nu}$ [arXiv:1908.09843], n_i is number-density of NIDM and $\sigma_{\chi\nu}$ interaction cross-section.

2.4 Tensor Boltzmann equation for neutrino (no tensor equation for NIDM)

$$\dot{\delta}^T_\nu = -\frac{4}{3}\theta^T_\nu - 2\frac{\partial\mathcal{D}_q}{\partial\eta} - \dot{\mu}\delta^T_\nu \tag{16}$$

$$\dot{\theta}^T_\nu = k^2\left[\frac{1}{4}\delta^T_\nu - \sigma^T_\nu\right] - \dot{\mu}\theta^T_\nu \tag{17}$$

$$\sigma^T_\nu = \frac{4}{15}\theta^T_\nu - \frac{3}{10}F^T_{\nu 3} - \dot{\mu}\sigma^T_\nu \tag{18}$$

$$\dot{F}^T_{\nu l} = \frac{k}{(2l+1)}\left[lF^T_{\nu,l-1} - (l+1)F^T_{\nu,l+1}\right] - \dot{\mu}F^T_{\nu,l} \tag{19}$$

For the definition of the tensor variables please refer to [arXiv:1711.09929]. $\dot{\mu}$ is defined in the same way as above.
**search for the flag 'DNI' in the source code to locate the modifications.