Exerices - CLASS
Dark Matter seminar

1. Background Cosmology

For this task use the predefined standard ΛCDM cosmology, so first create the model, and compute the Background using `.compute()` function. Then do the following tasks,

1.1. Density Parameters

Retrieve the density parameters and verify that $\Omega_{\rm cdm} + \Omega_b + \Omega_\gamma + \Omega_\Lambda \approx 1$. To retrieve the density parameters use tab button in the jupyter notebook environment as shown in the slides to find the corresponding function that will return the value of density parameters.

1.2. Age and Size of the universe *

a) Find the age of the universe using the `.age()` method. [Value returned in units Gyr]

b) Get the value of z_{rec} using `.get_current_derived_parameters(['z_rec'])`

c) Find the size of observable universe, i.e. the proper distance to the surface of last scattering, which is at the redshift z_{rec} [Remember that : Proper distance = Comoving Distance $\times$ a_0, and that $a_0 = 1$]

1.3. Age of the universe at Photon decoupling

From literature, we know that decoupling took place when the universe was $\sim$ 380000 years old. Let us verify the claim. To this end use the function `.get_background()` to get the background dictionary of ΛCDM model and store in the variable say for example `bg`

a) After retrieving the background dictionary using the `.keys()` method, find the quantities that are available.

b) Now, you will see two keys named `'z'`, `'propertime [Gyr]'`. Using an interpolator of choice, interpolate the values of z, t, and find the age of the universe at a redshift $\sim$ 1080

[Suggestion : For interpolation you can use the scipy package, i.e. do the following import : `from scipy.interpolate import interp1d`]

2. C_ℓ spectrum with lensing correction

Using the slides, and the notebook `slides.ipynb` as reference,

a) For the standard ΛCDM cosmology, plot the C_ℓ^{TT} with lensing correction. To include the lensing correction, you will have to use `.set({'lensing':'yes'})`, and include `'lCl'` in the output, i.e. `.set( {'output': 'tCl,lCl'} )`.
To plot polarization and temperature-polarization correlation spectrum, i.e. $C_\ell^{TT}, C_\ell^{TE}, C_\ell^{EE}$ for the ΛCDM cosmology with lensing correction additionally include the following in output, `'pCl'` i.e. you have `.set( {'output': 'tCl,lCl,pCl'} )`

b) Create a plot for varying $\Omega_b, \Omega_{\rm cdm}$ with lensing corrections, such that $\Omega_m = 0.3$, since any Boltzmann solver will throw an error if $\Omega_b = 0$, let us choose the values of Ω_b as {`1e-3, 5e-2`}

Note: Set Helium fraction using `.set({'YHe': 0.24})`. It is because CLASS does not solve the equations of BBN to find YHe, rather it uses a standard interpolation table to find the value of YHe for a given Ω_b. Therefore rather than using the table which is only available for a specific range of Ω_b, we manually set the value.

3. Parameter $p_{\rm ann}$ and C_ℓ spectrum

From the first presentation on 'Cosmological constraints on DM', we know that the effect of the DM annihilation parameter $p_{\rm ann} := f_{\rm eff}\frac{\langle\sigma v\rangle}{m_{\rm DM}}$ on the $C_\ell^{\rm TT}$ spectrum is degenerate with the parameters n_s, A_s.
For simplicity, we will not worry about the parameter f_{eff}, and let us try to produce the similar curves as δC_l^{tot} up-to a factor with units of temperature in the below given plot.

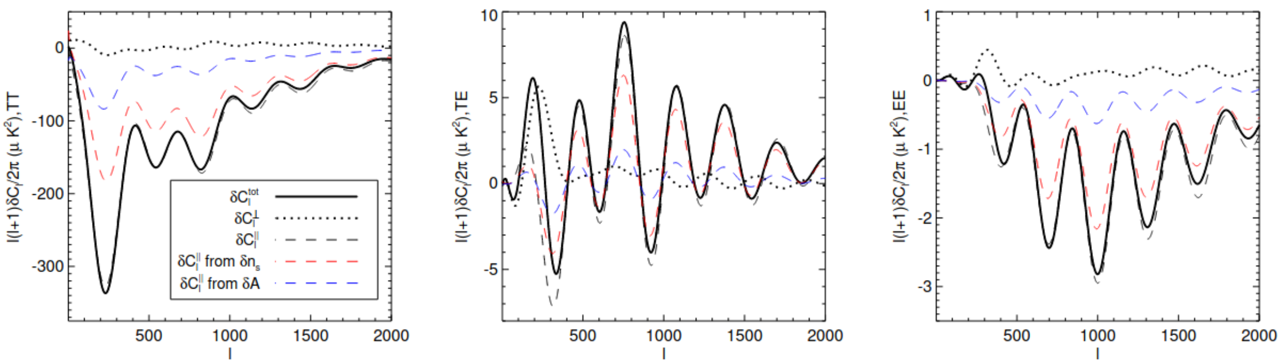

Figure 1: Fig taken from [1] pg. 12

a) For this you will have to create a new model, let us call it `DM`. To set the p_{ann} parameter use `.set({'DM_annihilation_efficiency': 1.248e-23})`. Then, compute the $C_\ell^{TT}, C_\ell^{TE}, C_\ell^{EE}$ spectrum.

The parameter 'DM_annihilation_efficiency' corresponds to $\frac{\langle\sigma v\rangle}{m_{\rm DM}}$ in the units $cm^3 s^{-1} J^{-1}$, for simple illustration purposes we will not worry about f_{eff}, and set the above-mentioned value of $1.248 \cdot 10^{-23}$ (the value is taken from the paper[1] and rescaled by the unknown factor f_{eff})

b) Now create the ΛCDM model and compute the C_ℓ^{TT}, C_ℓ^{TE}

c) Find the difference between C_ℓ^{XY} of ΛCDM and DM for these two models and plot $\ell(\ell+1)\delta C_\ell^{XY}$

References

[1] D.P.Finkbeiner et al., *Searching for Dark Matter in the CMB: A Compact Parameterization of Energy Injection from New Physics*, arXiv:1109.6322v1