CMB Temperature Spectrum considering massive neutrinos.

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September 24, 2020

Outline

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Standard Cosmology

Fridman equations

This metric has to satisfy the Einstein equations, so we get

$$H^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2}, \tag{1}$$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho + 3P). \tag{2}$$

They can be written in function of density parameter

$$\Omega_M + \Omega_K = 1\,, \tag{3}$$

where

$$\Omega_M = \frac{8\pi G\rho}{3H^2}, \qquad \Omega_k = -\frac{k}{(aH)^2} \tag{4}$$

Outline

Boltzmann equation for photons

The interaction between photons and electrons induced a perturbation in the photons temperature Θ.

$$f = \left[\exp\left(\frac{p}{T[1+\Theta(t,\boldsymbol{x},\hat{p})]}\right) - 1\right]^{-1} , \tag{5}$$

where $\Theta = \frac{\delta T}{T}$. This interaction can be described by Boltzmann equations,

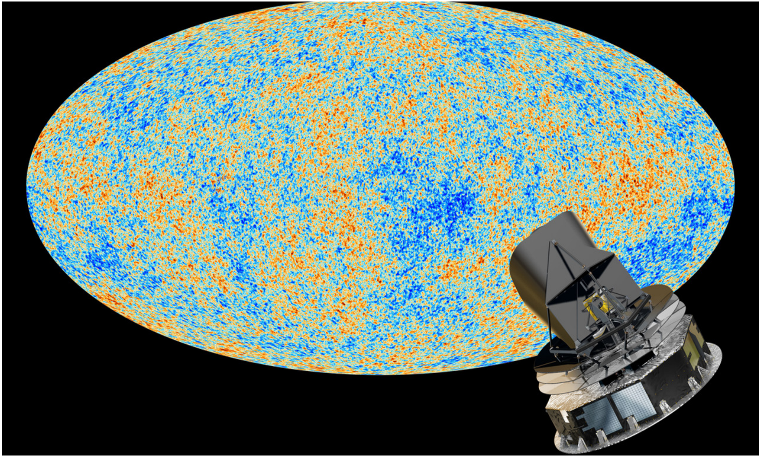
$$\frac{df}{dt} = C[f] \,. \tag{6}$$

so we get the Boltzmann equations for photons.

$$\dot{\Theta}_k + ik\mu\Theta_k + \dot{\Phi}_k - ik\mu\Phi_k = -\dot{\tau}[\Theta_{k0} - \Theta_k + \mu v_b] \,. \tag{7}$$

Outline

Planck Mission



Planck Collaboration

$$\Omega_k = 0.001 \pm 0.002, \;\; \Omega_b = 0.0492 \pm 0.0003, \;\; \Omega_r \propto 10^{-5}$$
$$\Omega_{cdm} = 0.264 \pm 0.002, \; , \sum m_\nu < 0.12eV, \; \Omega_\Lambda = 0.689 \pm 0.006 \; .$$

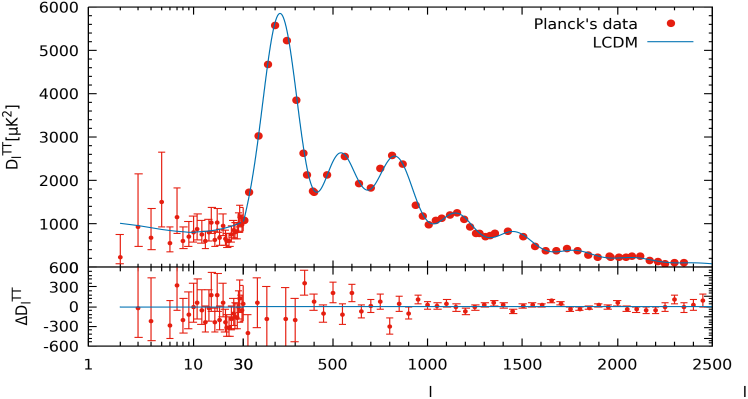


Figure 1: CMB Temperature Spectrum.

Outline

Neutrinos

Normal Hierarchy :

Small difference between lightest neutrinos.

$$\sum m_\nu \geq 0.06eV \; . \tag{8}$$

Inverted Hierarchy

Small difference between two most massive neutrinos.

$$\sum m_\nu \geq 0.1eV \; . \tag{9}$$

ΛCDM consider normal mass hierarchy, 1 massive and 2 massless neutrinos.

$$m_\nu = 0.06eV \; . \tag{10}$$

Neutrinos

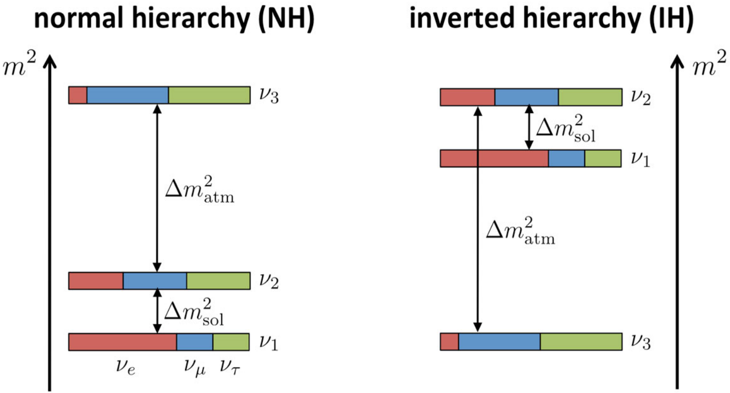


Figure 2: Hierarchy mass

Neutrinos

CMB Temperature Spectrum with normal and inverted hierarchy.

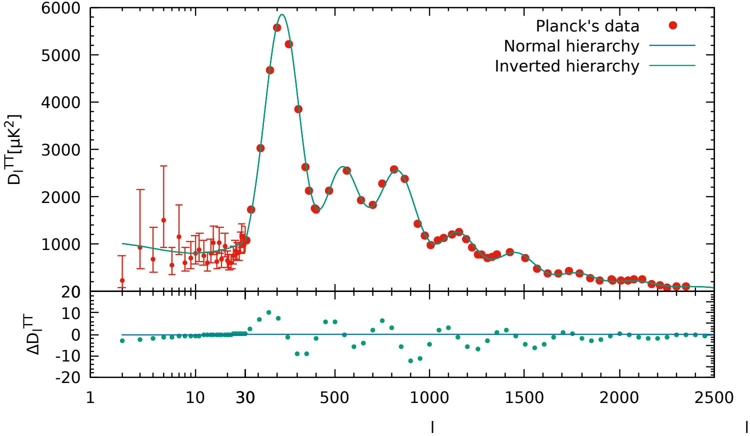


Figure 3: CMB TT with NH and IH.

Conclusions

1. Observations from CMB set and constrain the cosmological parameters.
2. CMB Temperature spectrum with normal and inverted hierarchy are similar.
3. Better observations could rule out inverted hierarchy (precision cosmology) since $0.10eV \leq \sum m_\nu \leq 0.12eV$.