EFFECT OF NEUTRINO ON CMB

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OUTLINE

- PROBES FOR NEUTRINO IN COSMOLOGY
- MASSIVE NEUTRINO IN COSMOLOGY
- MASSLESS NEUTRINO IN COSMOLOGY
- EFFECT ON CMB
- CONCLUSION

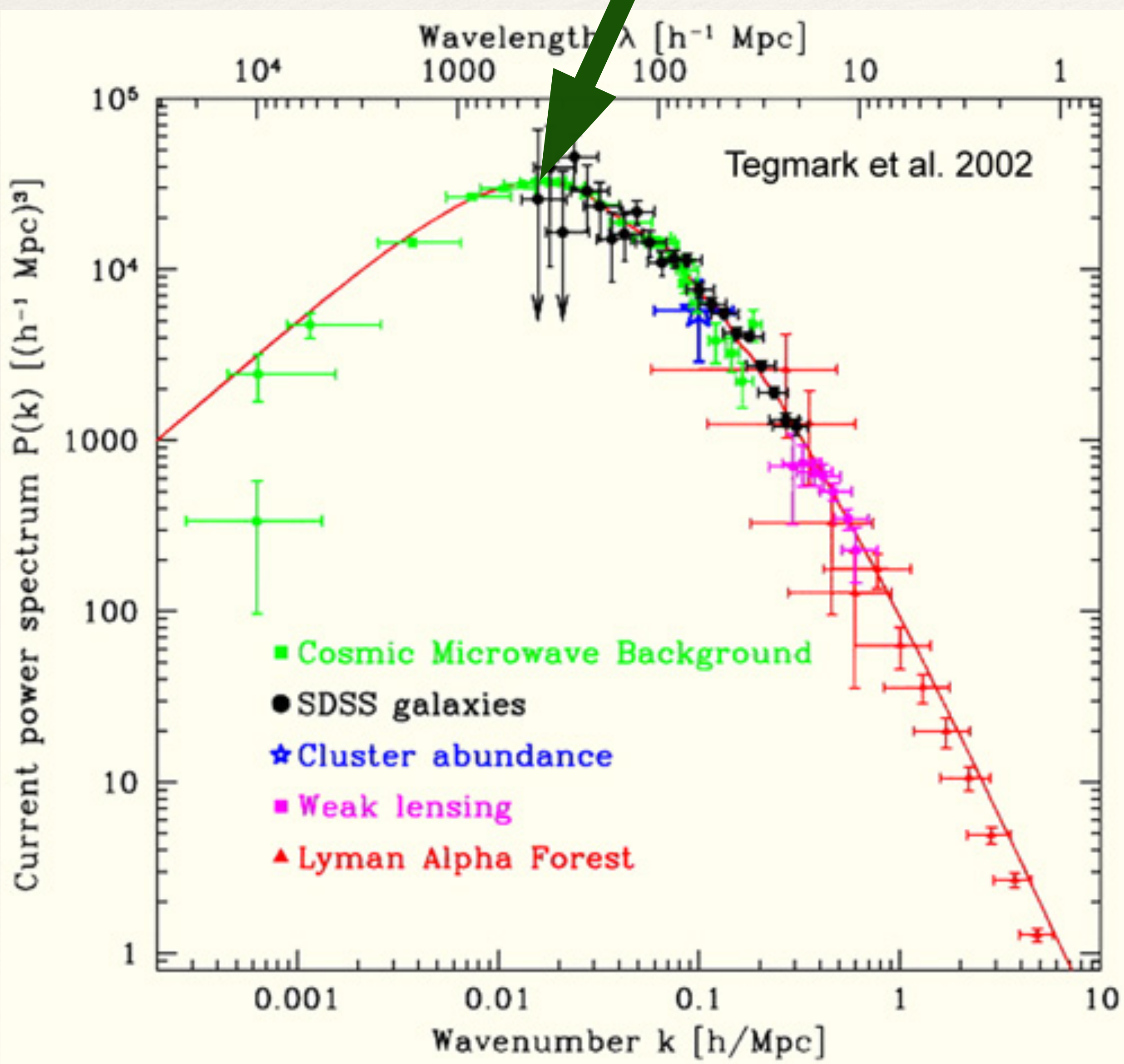
Probes for Neutrinos in Cosmology

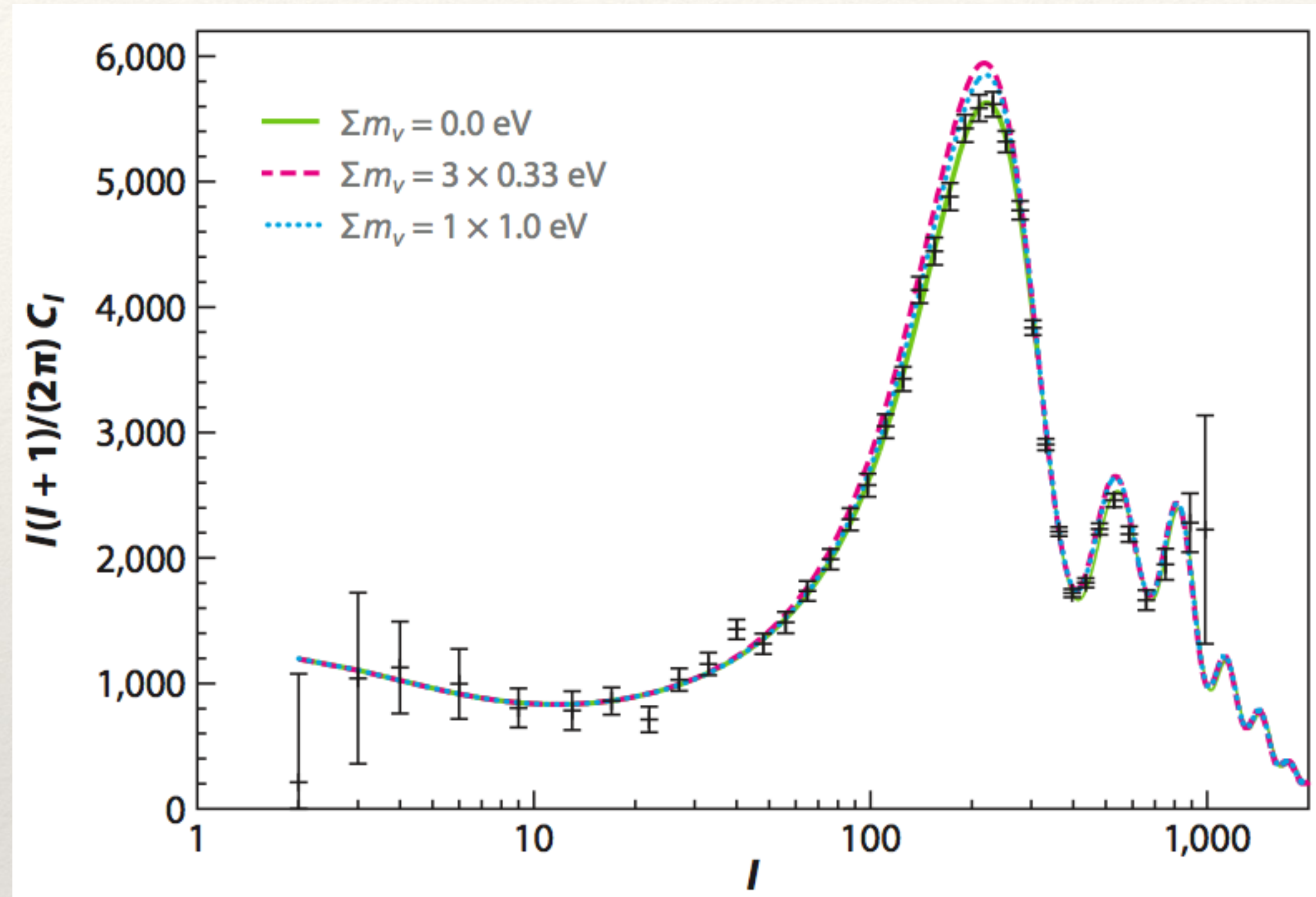
- Radiation and Matter equality epoch ($z_{eq} > z$: no matter perturbation can grow) : LSS (both massive and massless νs)
- Amplitude of matter power spectrum : LSS (massive neutrino)
- Acoustic angular size at the last scattering surface (z_{ls}) : CMB T and P anisotropies
- Amplitude of primordial gravitational waves : CMB P anisotropies + GWs

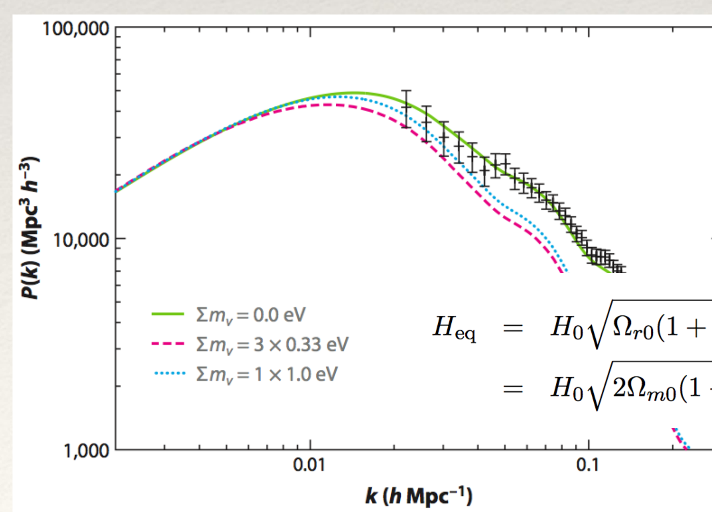
COSMOLOGICAL PROBES

- LSS vs CMB

$$ck_{\rm eq} = a_{\rm eq} H_{\rm eq}$$







$$\begin{aligned} H_{\rm eq} &= H_0\sqrt{\Omega_{r0}(1+z_{\rm eq})^4 + \Omega_{m0}(1+z_{\rm eq})^3 + \Omega_{w0}(1+z_{\rm eq})^{3(1+w)}} \\ &= H_0\sqrt{2\Omega_{m0}(1+z_{\rm eq})^3 + \Omega_{w0}(1+z_{\rm eq})^{3(1+w)}} \simeq H_0\sqrt{2\Omega_{m0}(1+z_{\rm eq})^3} \end{aligned}$$

Y. Wong et.al 11

Massive Neutrino in Cosmology I

- For cold dark matter (CDM), perturbations of sub-horizon scales ($aH << k < k_{nl}$), δ_{cdm} grow uniformly (D(a) no k dependence)
- Eq for δ_{cdm} $\ddot{\delta}_{\rm cdm} + \frac{\dot{a}}{a}\dot{\delta}_{\rm cdm} - 4\pi G a^2 \delta\rho = 0$ where $\dot{\delta} \equiv \frac{d\delta}{d\eta}$ $\delta\rho \equiv \delta\rho_{\rm cdm} + \delta\rho_{\rm b}$
- Growing mode solution for δ_{cdm} $\delta_{\rm cdm} \propto a$ (in MD) , or $D(a)$ (with DE)
- Matter power spectrum of CDM

$$P_{\rm cdm}(k,a) \equiv \left\langle \left|\delta_{\rm cdm}(k,a)\right|^2 \right\rangle = AT^2(k)\left(\frac{k}{k_0}\right)^{n_s-1}\left(\frac{D_{\rm cdm}(a)}{D_{\rm cdm0}}\right)^2$$

However this is not an observed quantity (galaxy PS)

Massive Neutrino in Cosmology II

- For cold dark matter (CDM) with ν, perturbations of sub-horizon scales smaller than free-streaming scale ($k > k_{fs}$), δ_{cdm} is suppressed (P > g)
- Eq for δ_{cdm} with massive ν, $\ddot{\delta}_{\rm cdm} + \frac{\dot{a}}{a}\dot{\delta}_{\rm cdm} - 4\pi G a^2(\rho_{\rm m} - \rho_\nu)\delta_{\rm cdm} = 0$
- Growing mode solution for δ_{cdm}

$$\delta_{\rm cdm} \propto a^{1-\frac{3}{5}f_\nu} \ (\text{in MD}) \ \ \text{, or} \ (aD_{\rm cdm})^{1-\frac{3}{5}f_\nu} \ (\text{with DE})$$

$$f_\nu = \frac{\Omega_\nu}{\Omega_{\rm m}}$$

$$\Omega_{\nu 0} = \frac{8\pi G \rho_{\nu 0}^{\rm nr}}{3H_0^2} = \frac{8\pi G n_{\nu 0}}{3H_0^2}\sum_{i=1}^{N_\nu^{\rm nr}} m_{\nu,i} \simeq \frac{\sum_i m_{\nu,i}}{94.1 h^2 {\rm eV}}$$

can constrain sum of ν masses

Massive Neutrino in Cosmology III

- Suppression factor, $(1-f_\nu)^2$ in the matter power spectrum (for $k > k_{nr}$), give the limit on the sum of masses of νs
- Overall suppression factor in CDM PS is

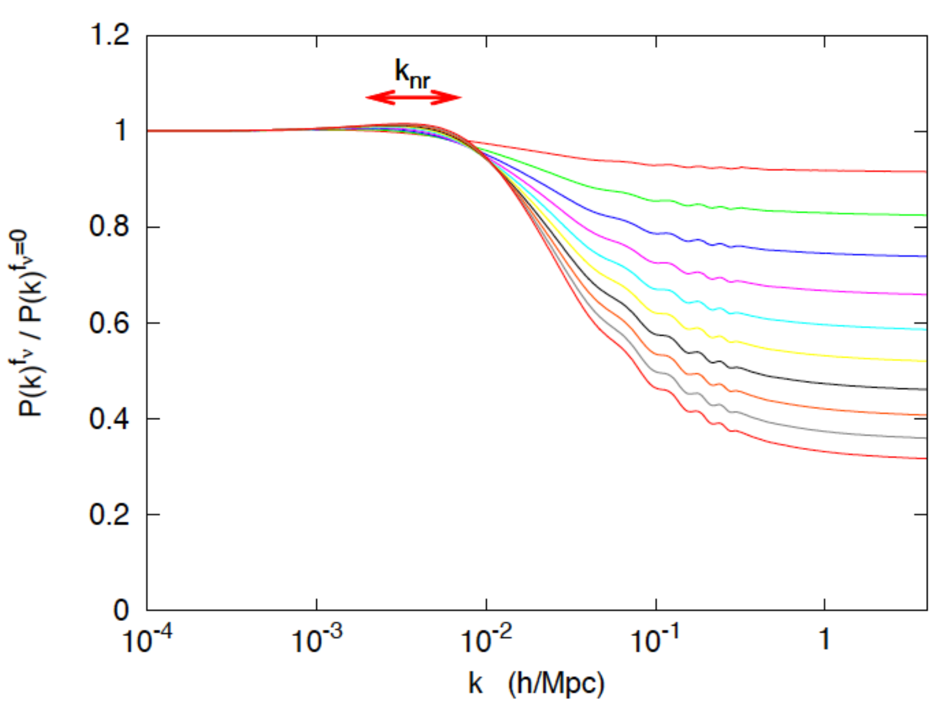


Fig. 13. Ratio of the matter power spectrum including three degenerate massive neutrinos with density fraction f_ν to that with three massless neutrinos. The parameters $(\omega_m, \Omega_\Lambda) = (0.147, 0.70)$ are kept fixed, and from top to bottom the curves correspond to $f_\nu = 0.01, 0.02, 0.03, \ldots, 0.10$. The individual masses m_ν range from 0.046 eV to 0.46 eV, and the scale k_{nr} from $2.1 \times 10^{-3} h\,\mathrm{Mpc}^{-1}$ to $6.7 \times 10^{-3} h\,\mathrm{Mpc}^{-1}$ as shown on the top of the figure. k_{eq} is approximately equal to $1.5 \times 10^{-2} h\,\mathrm{Mpc}^{-1}$.

Lesgourgues & Pastor 06

$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$

at z = 0

$$P(k,z) = \begin{cases} \left(\dfrac{g(z)}{(1+z)g(0)}\right)^2 P(k,0) & \text{for} \quad aH < k < k_{\mathrm{nr}} \\ \left(\dfrac{g(z)}{(1+z)g(0)}\right)^{2-6/5\,f_\nu} P(k,0) & \text{for} \quad k \gg k_{\mathrm{nr}} \end{cases}$$

Massive Neutrino in Cosmology IV

Jimenez et.al 10

- Massive neutrino with mass hierarchy
- Perturbation of massive neutrinos can grow only for scale bigger than free-streaming scale ($k < k_{fs}$)
- If we consider two degenerated neutrinos with normal and inverted hierarchy, then PS

$$\frac{k^3 P(k;z)}{2\pi^2} = \Delta_R^2 \frac{2k^2}{5H_0^2\Omega_m^2} D_\nu^2(k,z) T^2(k) \left(\frac{k}{k_0}\right)^{(n_s-1)}$$

$$f_{\nu,i} = \frac{\Omega_{\nu,i}}{\Omega_m} = 0.05 \left(\frac{m_{\nu_i}}{0.658\mathrm{eV}}\right)\left(\frac{0.14}{\Omega_m h^2}\right)$$

$$k_{\mathrm{fs},i} = 0.113 \left(\frac{m_{\nu_i}}{1\mathrm{eV}}\right)^{1/2} \left(\frac{\Omega_m h^2}{0.14}\frac{5}{1+z}\right)^{1/2} \mathrm{Mpc}^{-1}$$

$$D_{\nu_i}(k,z) \propto (1 - f_{\nu_i}) D(z)^{1-p_i}$$

$$\begin{aligned} D_\nu(k,z) &= D(k,z) & k &< k_{\mathrm{fs},m} \\ D_\nu(k,z) &= (1-f_{\nu,m}) D(z)^{(1-p_m)} & k_{\mathrm{fs},m} &< k < k_{\mathrm{fs},\Sigma} \\ D_\nu(k,z) &= (1-f_{\nu,\Sigma}) D(z)^{(1-p_\Sigma)} & k &> k_{\mathrm{fs},\Sigma}\,, \end{aligned}$$

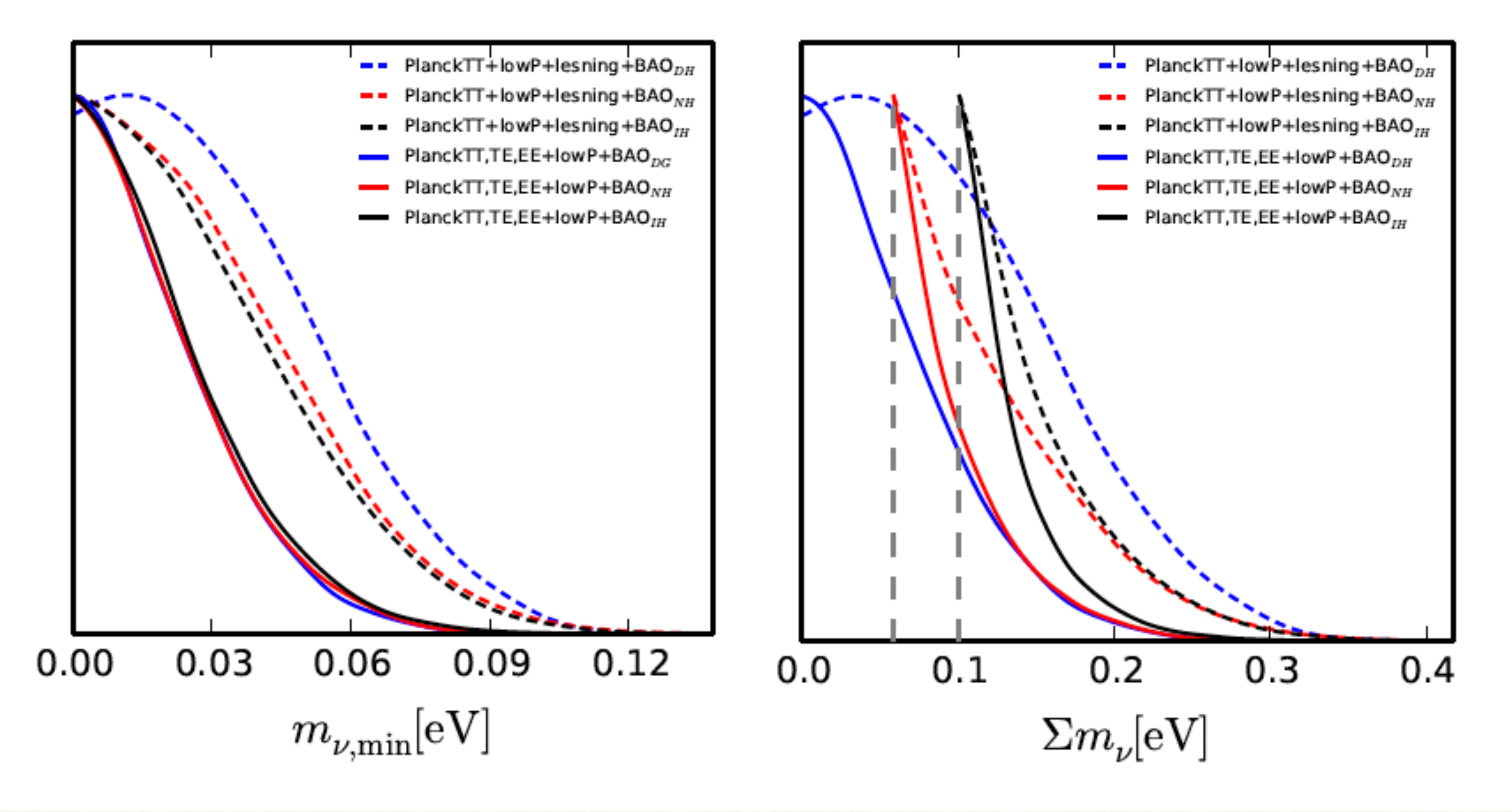
where $k \gg k_{\mathrm{fs},i}(z)$ and $p_i = (5 - \sqrt{25 - 24 f_{\nu_i}})/4$.

$$\begin{aligned} \mathrm{NH}: \quad & \Sigma = 2m + M \quad & \Delta = (M-m)/\Sigma \\ \mathrm{IH}: \quad & \Sigma = m + 2M \quad & \Delta = (m-M)/\Sigma \end{aligned}$$

Massive Neutrino in Cosmology V

- Current constraints

Huang 15



Massless Neutrino in Cosmology I

SL 14

- Acoustic angular scale (for location of first few peaks)
- Diffusion angular scale (for location of higher peaks)

$$\frac{\theta_{\rm s}[z, N_{\rm eff}, {\rm w}, {\rm h}]}{\theta_{\rm d}(z_*)[z, N_{\rm eff}, {\rm w}, {\rm h}, {\rm Y_P}]} = \frac{r_{\rm s}(z_*)[z, N_{\rm eff}, {\rm w}, {\rm h}]}{r_{\rm d}(z_*)[z, N_{\rm eff}, {\rm w}, {\rm h}, {\rm Y_P}]}$$

- Degeneracy between # of massless neutrino and other parameters (w, h, Yp)

Massless Neutrino in Cosmology II

- Observationally indistinguishable CMB

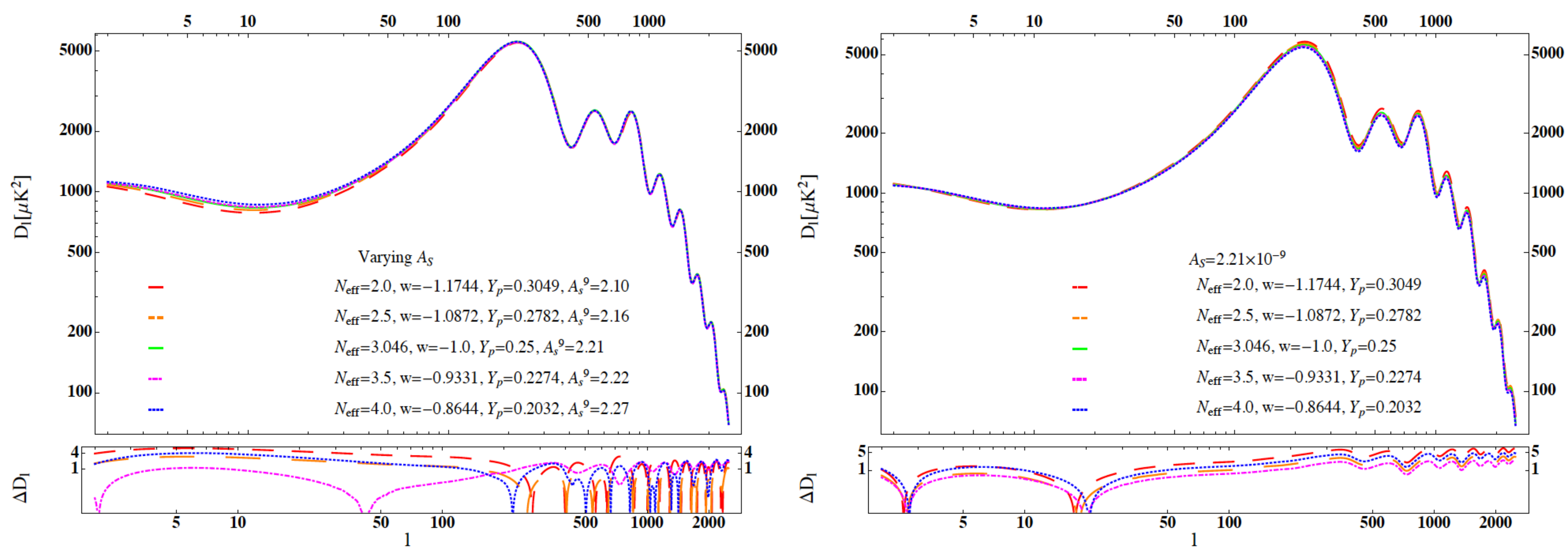


FIG. 1: CMB angular power spectra for different models and their differences from the fiducial model with different normalization. *Top left*) CMB angular power spectra for $N_{\rm eff} = 2$ (dashed), 2.5 (long-dashed), 3.046 (solid), 3.5 (dot-dashed), and 4 (dotted), respectively. *Bottom left*) The differences of CMB power spectra between $N_{\rm eff} = 2$ (2.5, 3.5, 4.0) model and the fiducial one depicted by dashed (long-dashed, dot-dashed, dotted) line. *Top right*) CMB angular power spectra using the same $A_S(10^9)$. *Bottom right*) The differences of CMB power spectra between models with the same notation as the left panel.

Massless Neutrino in Cosmology III

- Degeneracies between Neff , w, and Yp

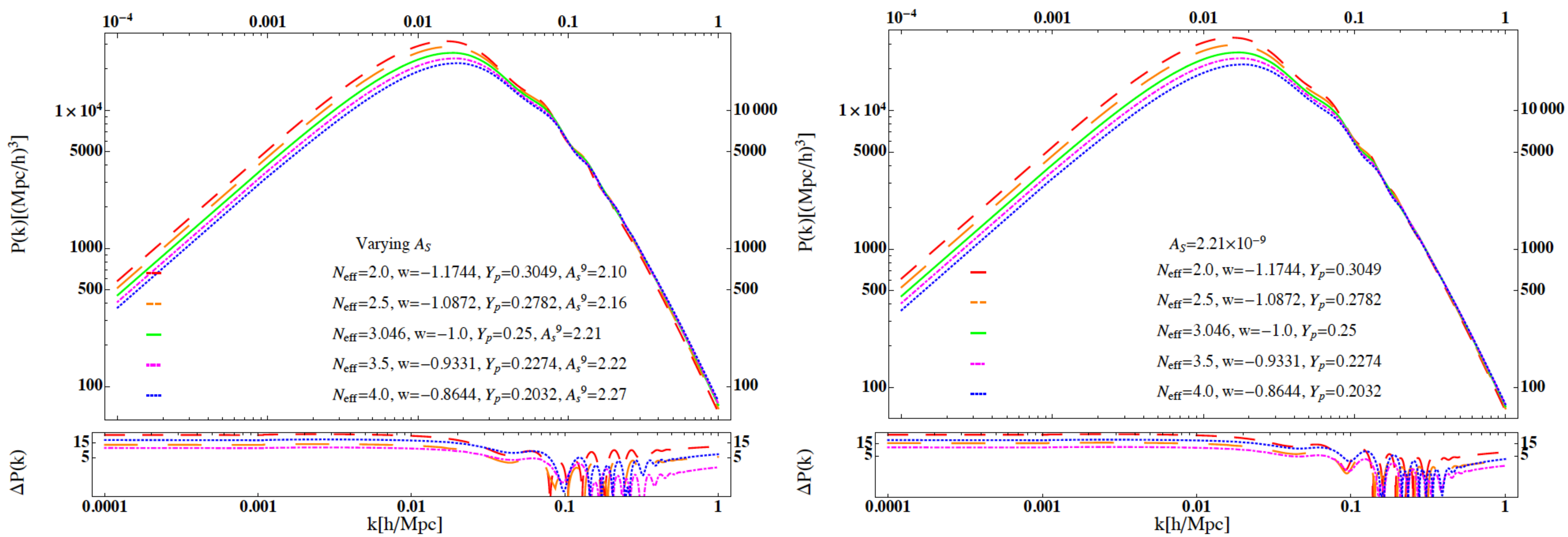


FIG. 2: Linear matter power spectra for different models and their differences from the fiducial model with different normalization. *Top left*) CMB angular power spectra for $N_{\rm eff} = 2$ (dashed), 2.5 (long-dashed), 3.046 (solid), 3.5 (dot-dashed), and 4 (dotted), respectively. *Bottom left*) The differences of CMB power spectra between $N_{\rm eff} = 2$ (2.5, 3.5, 4.0) model and the fiducial one depicted by dashed (long-dashed, dot-dashed, dotted) line. *Top right*) CMB angular power spectra using the same $A_S(10^9)$. *Bottom right*) The differences of CMB power spectra between models with the same notation as the left panel.

Massless Neutrino in Cosmology IV

- Degeneracies between Neff , w, and Yp

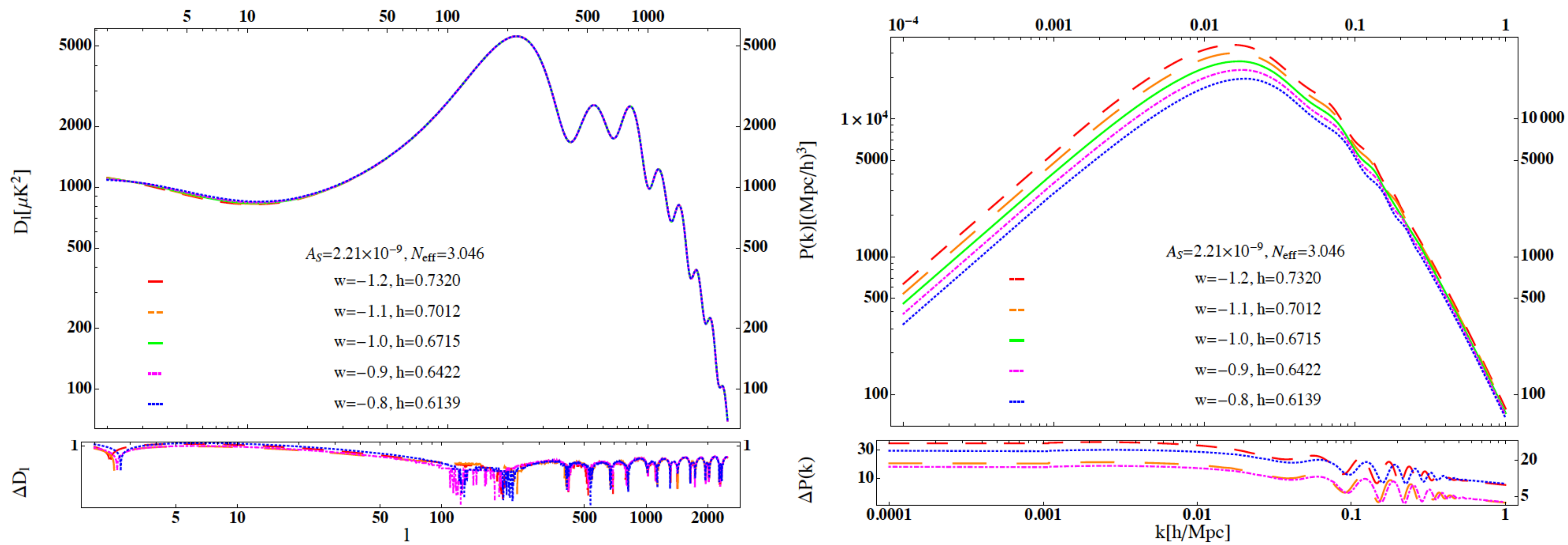


FIG. 3: CMB angular power spectra for different models and their differences from the fiducial model with different normalization. *Top left*) CMB angular power spectra for $N_{\rm eff} = 2$ (dashed), 2.5 (long-dashed), 3.046 (solid), 3.5 (dot-dashed), and 4 (dotted), respectively. *Bottom left*) The differences of CMB power spectra between $N_{\rm eff} = 2$ (2.5, 3.5, 4.0) model and the fiducial one depicted by dashed (long-dashed, dot-dashed, dotted) line. *Top right*) CMB angular power spectra using the same $A_S(10^9)$. *Bottom right*) The differences of CMB power spectra between models with the same notation as the left panel.

MASSLESS NEUTRINO IN COSMOLOGY V

- Degeneracies between Neff , h, and As

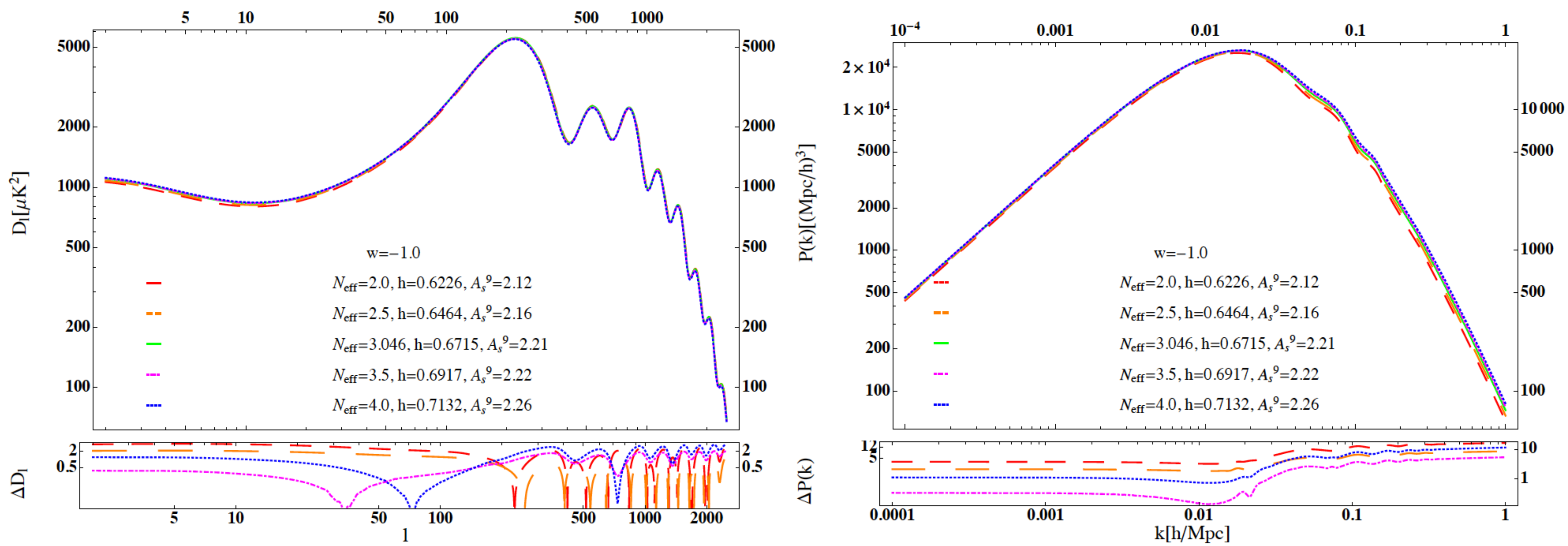
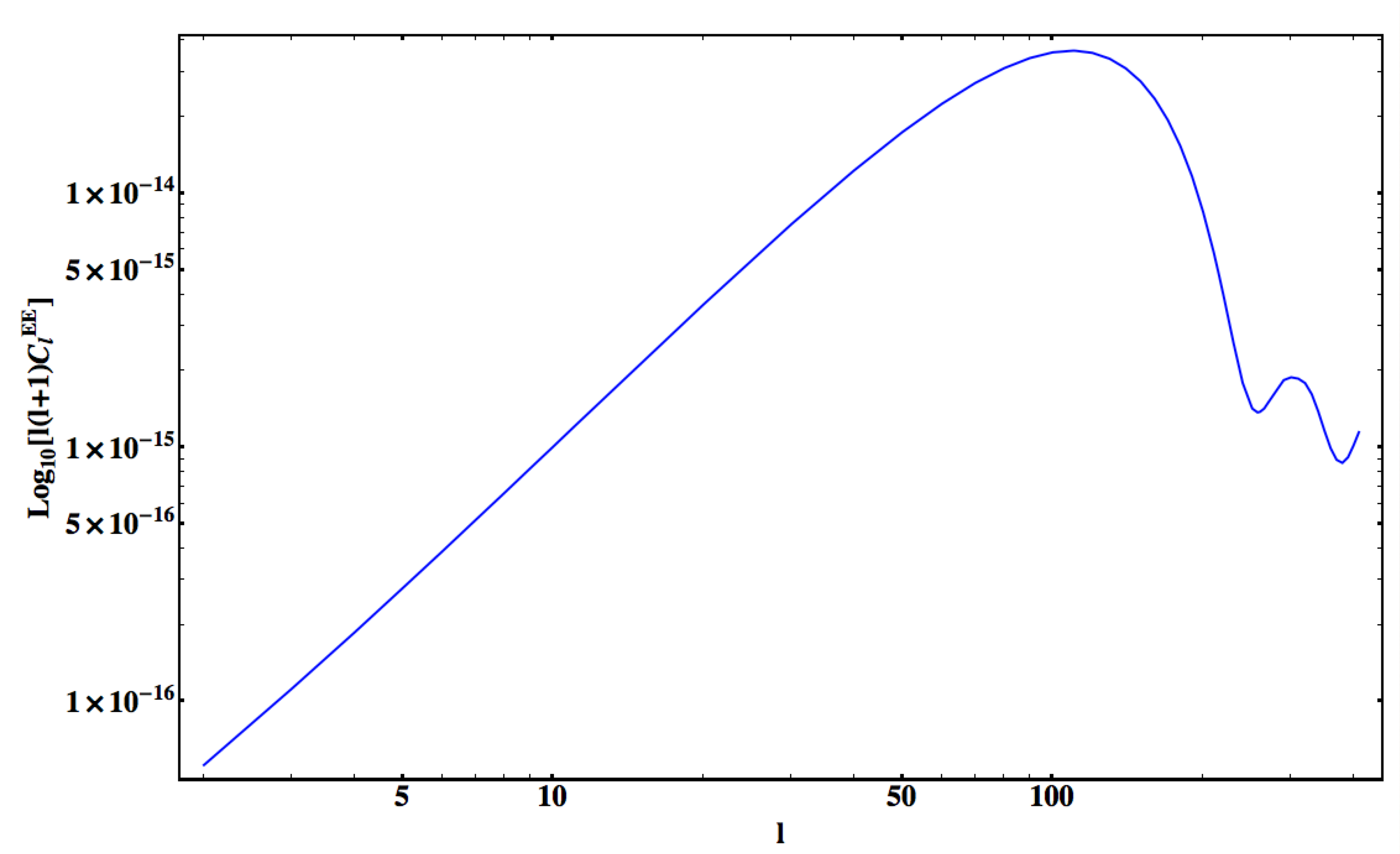


FIG. 4: CMB angular power spectra for different models and their differences from the fiducial model with different normalization. *Top left*) CMB angular power spectra for $N_{\rm eff} = 2$ (dashed), 2.5 (long-dashed), 3.046 (solid), 3.5 (dot-dashed), and 4 (dotted), respectively. *Bottom left*) The differences of CMB power spectra between $N_{\rm eff} = 2$ (2.5, 3.5, 4.0) model and the fiducial one depicted by dashed (long-dashed, dot-dashed, dotted) line. *Top right*) CMB angular power spectra using the same $A_S(10^9)$. *Bottom right*) The differences of CMB power spectra between models with the same notation as the left panel.

MASSLESS ν

- In CMB Polarization



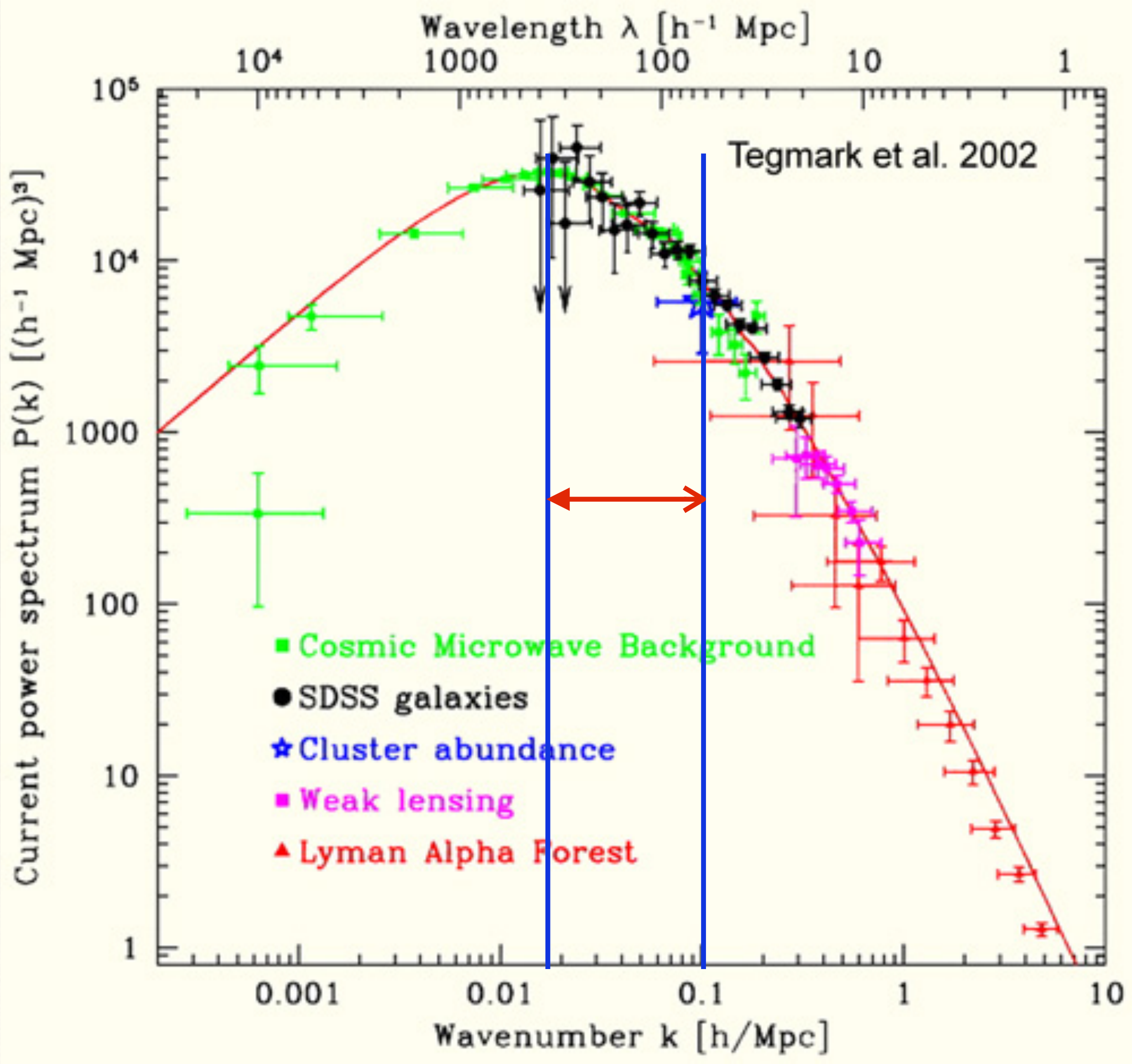
REALITY I

- Both massless and massive neutrinos is degenerated by CMB
- Theoretically, both massless and massive neutrino can be distinguished by LSS
- However, what we measure is the galaxy (baryon) matter power spectrum not the DM PS (bias factor)
- $k > 0.1$ h/Mpc is non-linear regime (difficulty in handle on perturbation)

REALITY II

- baryon vs DM perturbation

$$\delta_{\rm b}(k,a) = b(k,a)\delta_{\rm DM}(k,a)$$



What we calculate

$$P_{\rm b}(k,a) = b(k,a)^2 P_{\rm DM}(k,a)$$

What we measure

$b(k,a) \simeq b(a)$, in linear regime

Mode coupling in non-linear regime

$$\left\langle \delta(k_1,a)\delta(k_2,a) \right\rangle \neq P(k,a)\delta_{\rm D}(k_1 - k_2)$$

CONCLUSION

- Massive neutrino mainly affects on LSS
- Massless neutrino mainly affects on CMB
- However, effects of neutrino mass and number are degenerated with other cosmological parameters
- LSS with PS are unknown both in theory and in observation
- Better to use the standard ruler or candle methods (distance instead of amplitude) or bias free observation