Imprints of recombination history of the Universe on 21 cm signal from neutral hydrogen during the Dark Ages

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in
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- First Law of Thermodynamics

$$dQ = \frac{3}{2} k_B dT_g - k_B T_g d\log \rho_b$$

- Heating rate per particle due to Compton scattering between CMB photons and residual electrons [1]

$$\frac{dQ}{dt} = \frac{4\sigma_T \rho_\gamma n_e}{3 m_e c \; n_{tot}} (T_\gamma - T_g)$$

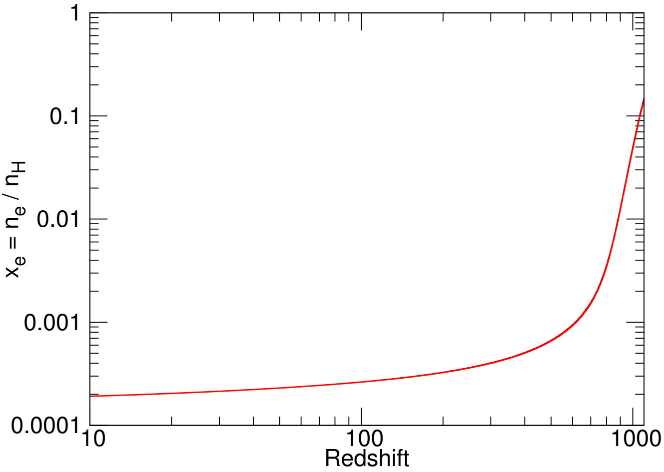
- Gas Temperature Evolution Equation[2]

$$\frac{\partial T_g}{\partial z} = \frac{2 T_g}{3\rho_b} \frac{\partial \rho_b}{\partial z} - \left(\frac{x_e}{1 + f_{He} + x_e} \right) \frac{8\sigma_T \rho_\gamma^0}{3 m_e c H_0 \Omega_m^{1/2}} (1+z)^{3/2} (T_\gamma - T_g)$$

[1] e.g., Pebbles (1993)
[2] Seager et al. (1999)

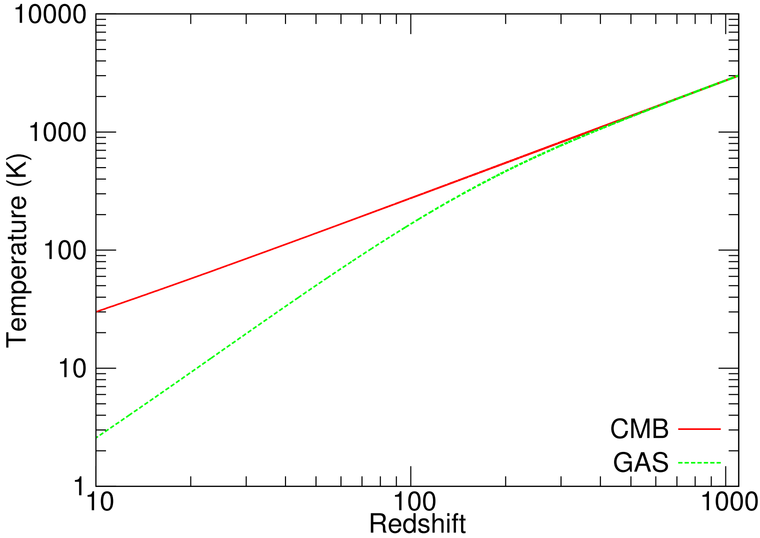
Variation of Ionization fraction with Redshift

From RECFAST code (Seager et al. 1999, 2000)



Multilevel calculations to compute ionization fraction of Hydrogen and Helium I

Mean Gas Temperature from RECFAST



Fixed x_e models

- Model 1: Bharadwaj & Ali (2004)

$$\frac{\partial T_g}{\partial z} = \frac{2T_g}{3\rho_b}\frac{\partial \rho_b}{\partial z} - \frac{9.88 \ x \ 10^{-8}}{\Omega_b h^2}(1+z)^{3/2}(T_\gamma - T_g)$$

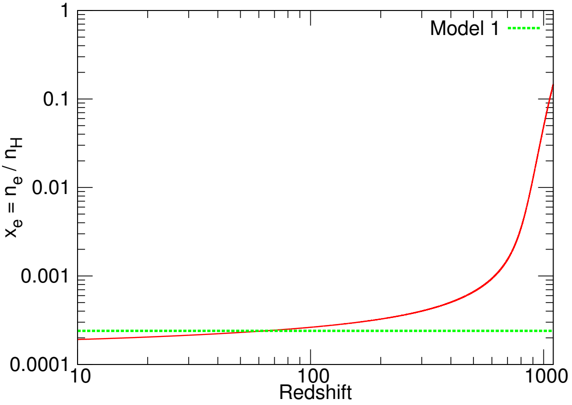
Fixed x_e models

- Model 1: Bharadwaj & Ali (2004)

$$\frac{\partial T_g}{\partial z} = \frac{2T_g}{3\rho_b}\frac{\partial \rho_b}{\partial z} - \frac{9.88 \ x \ 10^{-8}}{\Omega_b h^2}(1+z)^{3/2}(T_\gamma - T_g)$$

$$x_e = 2.40 \ x \ 10^{-4}$$

Fixed x_e models

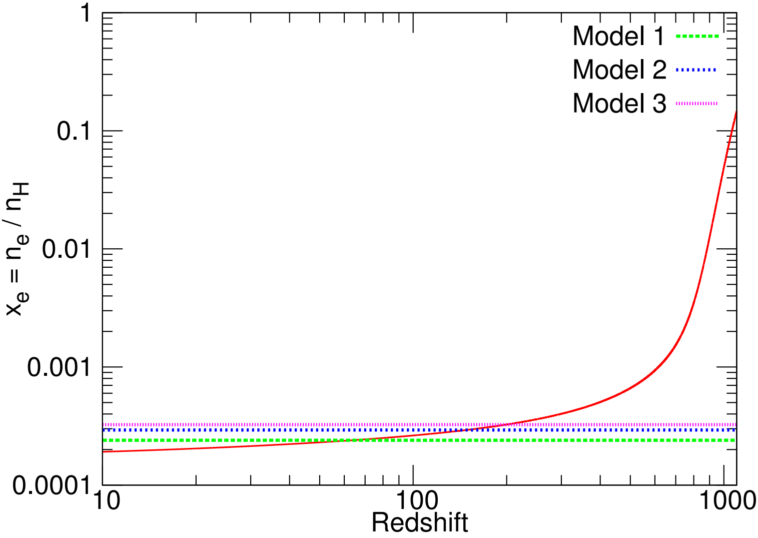


The ionization fraction at $z \sim 70$ is fixed throughout in Bharadwaj & Ali (2004)

Fixed x_e models

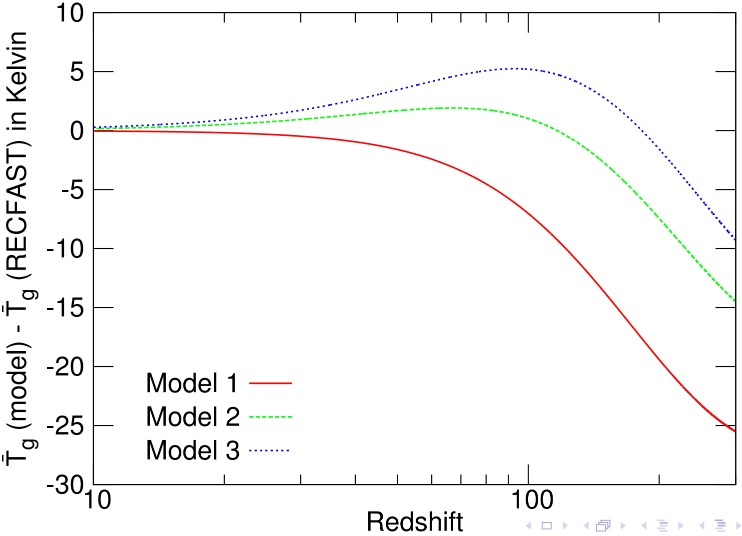
- Model 1: x_e fixed at 2.40 x 10^{-4} corresponding to $z \sim 70$ in RECFAST (Bharadwaj & Ali 2004)
- Model 2: x_e fixed at 2.93 x 10^{-4} corresponding to $z = 150$ in RECFAST
- Model 3: x_e fixed at 3.25 x 10^{-4} corrresponding to $z = 200$ in RECFAST (suggested in Furlanetto et al. 2006)

Fixed x_e models



Mean Gas Temperature in fixed x_e models

Comparison with respect with RECFAST



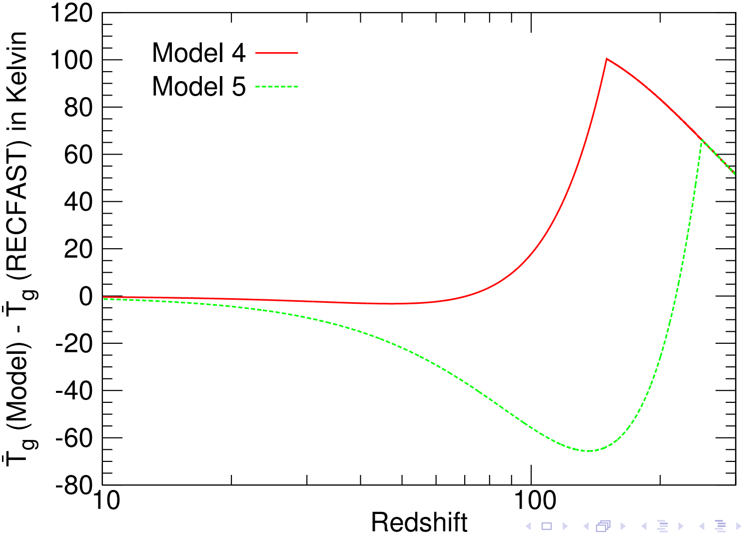
Other Simple Models

- Gas fully coupled with CMB upto $z = z_{dec}$ and falls adiabatically below z_{dec}.
- $x_e = 0.0$ for $z \leq z_{dec}$

$$\overline{T}_g = \overline{T}_{cmb} \qquad z > z_{dec}$$
$$\overline{T}_g = \frac{2.73(1+z)^2}{(1+z_{dec})} \qquad z \leq z_{dec}$$

- Model 4: $z_{dec} = 150$ (Ghara et al. 2015)
- Model 5: $z_{dec} = 250$ (Thomas et al. 2008)

Comparison with respect to RECFAST



First Order Perturbation in Gas Temperature

- Basic Framework

$$\Delta_b(x,z) = \frac{\rho_b(x,z) - \overline{\rho}_b(z)}{\overline{\rho}_b(z)}$$

$$\Delta_g(x,z) = \frac{T_g(x,z) - \overline{T}_g(z)}{\overline{T}_g(z)}$$

$$\Delta_b \propto a(t)$$

$$\Delta_g = g(z)\Delta_b$$

First Order Perturbation in Gas Temperature

- Gas Temperature Perturbation equation[3]

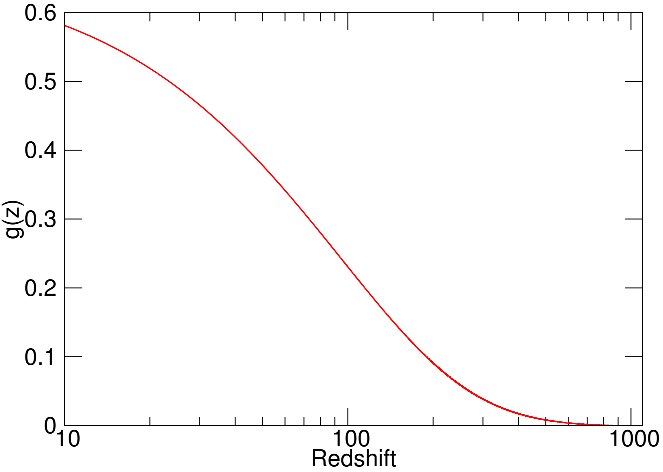
$$\frac{dg}{dz} = \left(\frac{x_e}{1 + f_{He} + x_e}\right) \frac{T_\gamma g}{t_\gamma H_0 \Omega_m^{1/2} T_g} (1+z)^{3/2} + \left(\frac{2}{3} - g\right) \frac{1}{\Delta_b} \frac{d\Delta_b}{dz}$$

- In the simple models
  $g = 0.0$ for $z > z_{\rm dec}$ and $g = \frac{2}{3}$ for $z \leq z_{\rm dec}$

[3] Barkana & Loeb 2005, Bharadwaj & Ali 2004

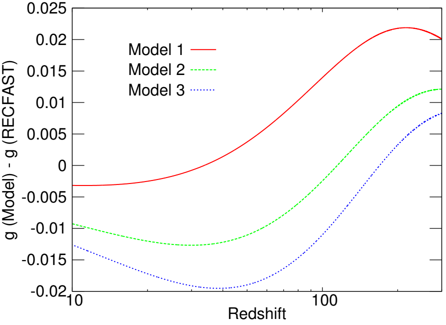
First Order Pertubation in Gas Temperature

From RECFAST

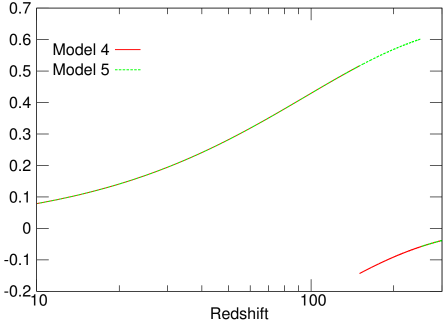


Evolution of g(z) from RECFAST

Comparison with respect to RECFAST



Fixed x_e models



Other simple models

- Definition of Spin Temperature, T_s

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{\frac{-h\nu_e}{k_B T_s}}$$

n_1, n_0 : number density of neutral hydrogen atoms in triplet and singlet states
$g_1 = 3$, $g_0 = 1$: Corresponding state degeneracy factors
$\nu_e = 1420 MHz$: rest frame frequency for transition between the two states

- Balancing excitation and de-excitation terms[4]

$$n_1(C_{10} + A_{10} + B_{10} I_{\nu_e}) = n_0(C_{01} + B_{01} I_{\nu_e})$$

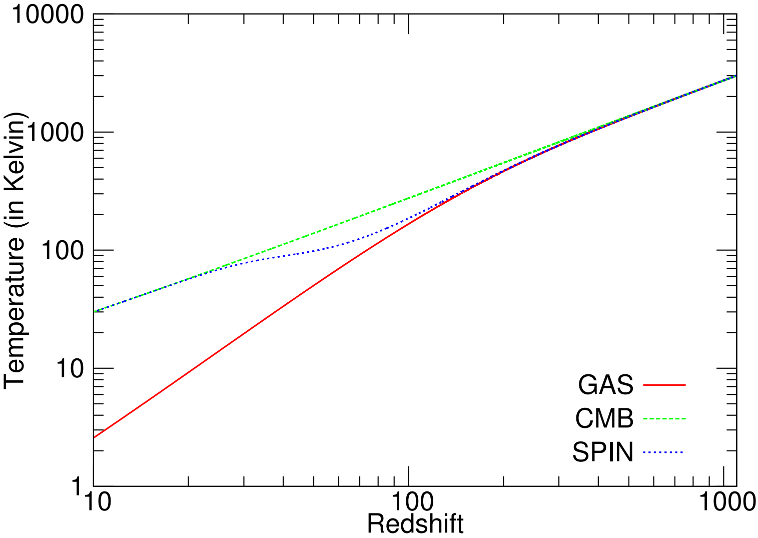
C_{01}, C_{10} : collisional excitation and de-excitation rates of the hyperfine levels
A_{10}, B_{01} and B_{10} : Einstein coefficients
I_{ν_e} : specific intensity of the CMB at ν_e

- Spin Temperature Evolution Equation in Equilibrium

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_c T_g^{-1}}{1 + x_c}$$
$$x_c = \frac{C_{10} h \nu_e}{k_B A_{10} T_\gamma},$$

[4] Furlanetto et al. 2006

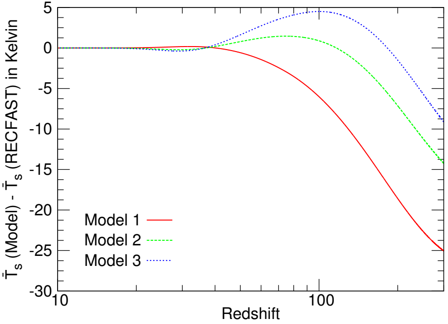
Mean Spin Temperature from RECFAST



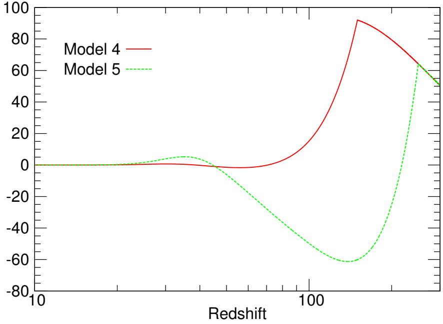
Evolution of Spin Temperature in RECFAST

Mean Spin Temperature in Other Models

Comparison with respect to RECFAST



Fixed x_e models



Other simple models

First Order Perturbation in HI Spin Temperature

- Basic Framework

$$\Delta_s(x,z) = \frac{T_s(x,z) - \overline{T}_s(z)}{\overline{T}_s(z)}$$

$$\Delta_s = s(z)\Delta_b$$

First Order Perturbation in HI Spin Temperature

- Spin Temperature Perturbation equation

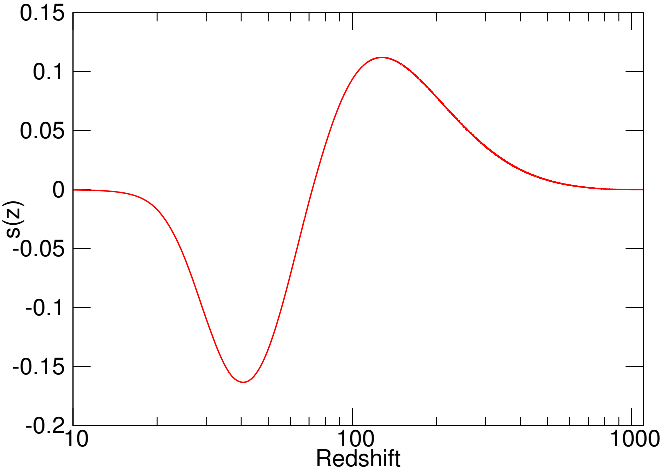
$$s = \left(\frac{x_c}{1+x_c}\right)\left[\left(\frac{dlnK}{dlnT_g}g+1\right)\left(1-\frac{T_s}{T_g}\right)+\frac{T_s}{T_g}g\right]$$

- In the simple models

  $s = 0.0 \text{ for } z > z_{\rm dec}$ and the above equation holds for $z \leq z_{dec}$

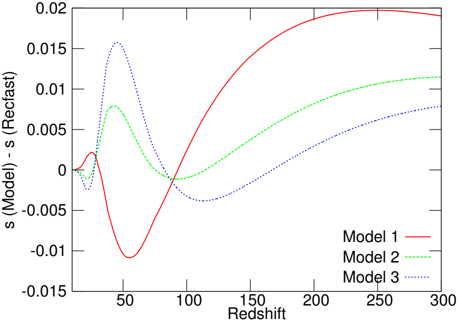
First Order Perturbation in HI Spin Temperature

From RECFAST

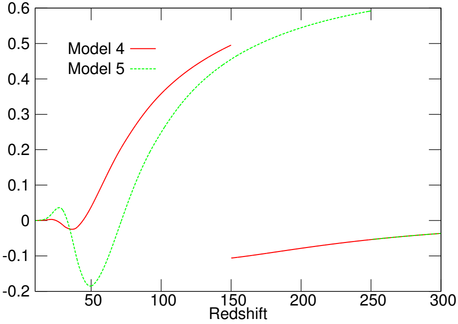


Evolution of s(z) from RECFAST

Comparison with respect to RECFAST



Fixed x_e models



Other simple models

Brightness Temperature of the HI 21 cm line

$$T_b(z) = \frac{(T_s - T_\gamma)}{1+z}\tau(z)$$

τ is the optical depth of the HI 21 cm absorption given as

$$\tau(z) = \frac{3\bar{n_{HI}} hc^3 A_{10}}{32\pi k_B T_s \nu_e^2 H(z)} \left(1 + \Delta_H + \frac{1}{H(z)a(z)}\frac{\partial v}{\partial r}\right)$$

taking into account both Hydrogen density perturbation Δ_H and peculiar velocity v. r is the comoving distance to HI.[5]

[5] Bharadwaj & Ali 2004

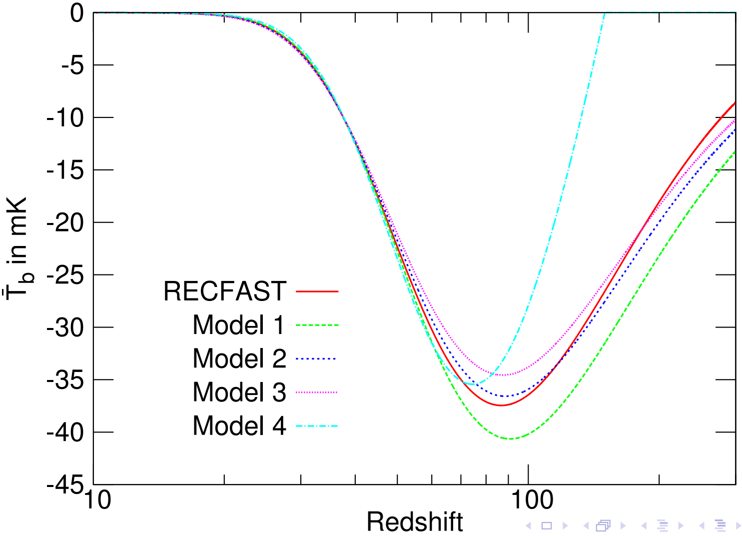
Average Brightness Temperature

$$\bar{T}_b(z) = \bar{T}\left(1 - \frac{T_\gamma}{\bar{T}_s}\right)$$

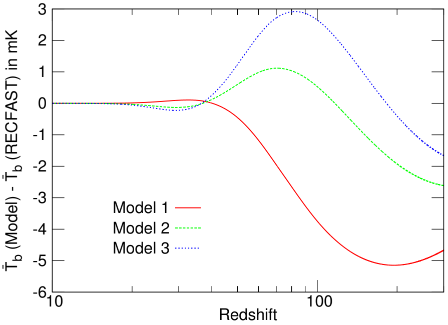
$$\bar{T} = \frac{3\bar{n_{HI}}hc^3A_{10}}{32\pi k_B \nu_e^2 H(z)}\frac{1}{1+z}$$

Average Brightness Temperature

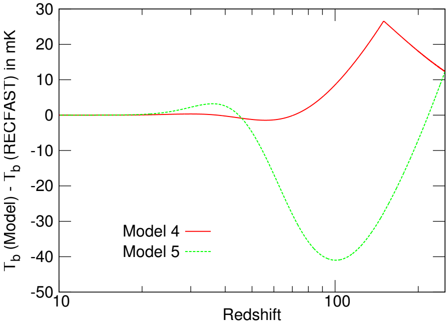
Comparison between RECFAST and all other Models



Differences with respect to RECFAST



In fixed x_e models



In other simple models

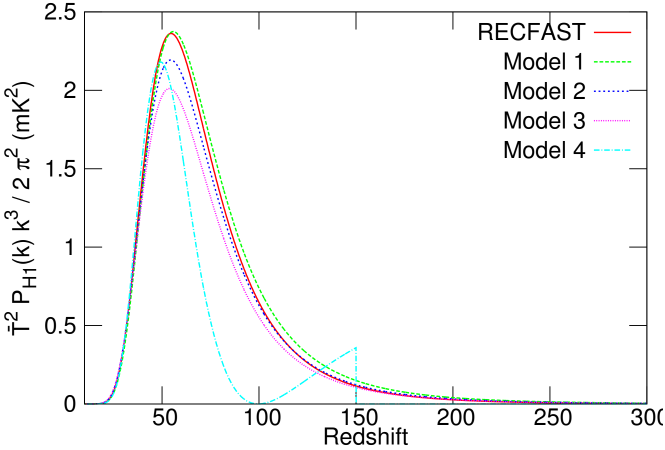
$$\delta T_b(z, \hat{n}) = \bar{T} \int \frac{d^3k}{2\pi^3} e^{-ikr\mu} \Delta(k, z) \left[\left(1 - \frac{T_\gamma}{T_s} \right) (1 + \mu^2) + \frac{T_\gamma}{T_s} s \right]$$

$\Delta(k, z)$ is the Fourier transform of $\Delta_H(x, z)$ and μ is the cosine of the angle between the comoving wave vector k and the line of sight $\hat{n}$.

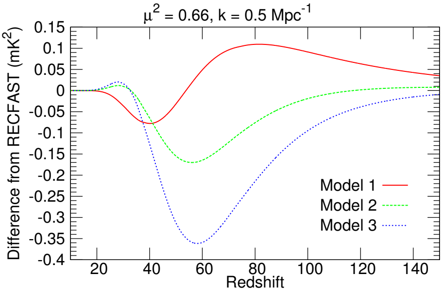
$$P_{HI}(k, z) = \left[\left(1 - \frac{T_\gamma}{T_s} \right) (1 + \mu^2) + \frac{T_\gamma}{T_s} s \right]^2 P(k, z)$$

$P(k, z)$ is the Dark Matter Power Spectrum

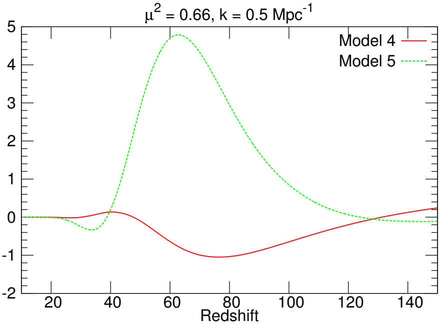
Comparison between RECFAST and all other Models



Differences with respect to RECFAST



In fixed x_e models



In other simple models

Conclusions

- The prediction for the 3D power spectrum in Bharadwaj & Ali (2004) is consistent with RECFAST to within $\pm 5\%$ upto $z = 70$. However, it sharply diverges thereafter and at $z = 100$ and $z = 150$ differs by 15% and 30% respectively.
- Fixing x_e at $z = 200$ leads to around -15% difference at $z = 50$ to 100 and -8% at $z = 150$
- Fixing x_e at $z = 150$ leads to a difference of -7% to 7% from $z = 50$ to $z = 150$
- In Ghara et al. (2015) model, the percentage change is below 5% upto $z = 50$ and steadily increases thereafter, being 30% at $z = 60$ and 100% at $z = 100$
- In Thomas et al. (2008) model, the percentage change is 130% at $z = 50$ going down to -100% at $z = 150$