21cm fluctuations from the dark ages including baryon-cdm relative velocities

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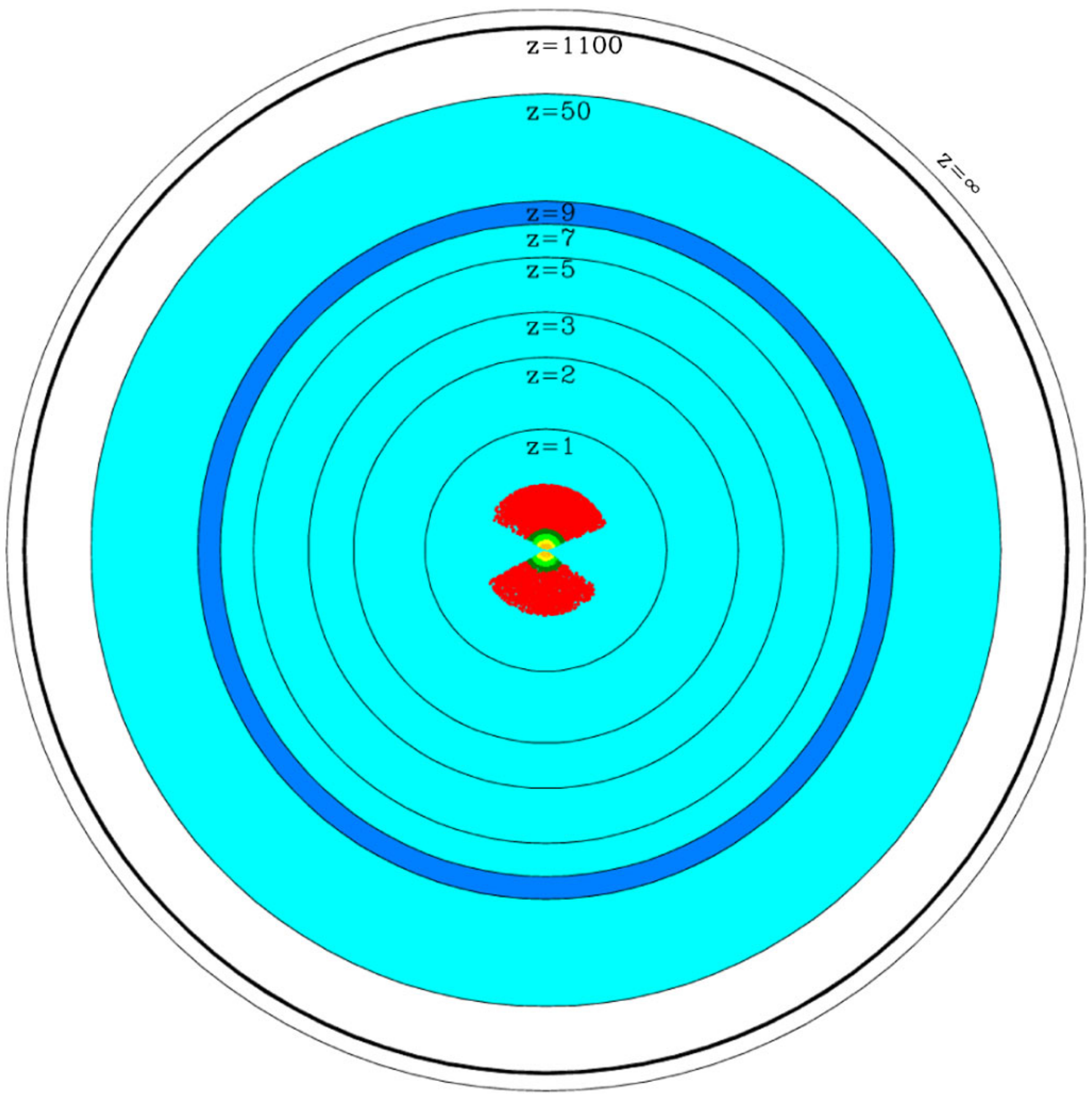
New frontiers with 21cm cosmology



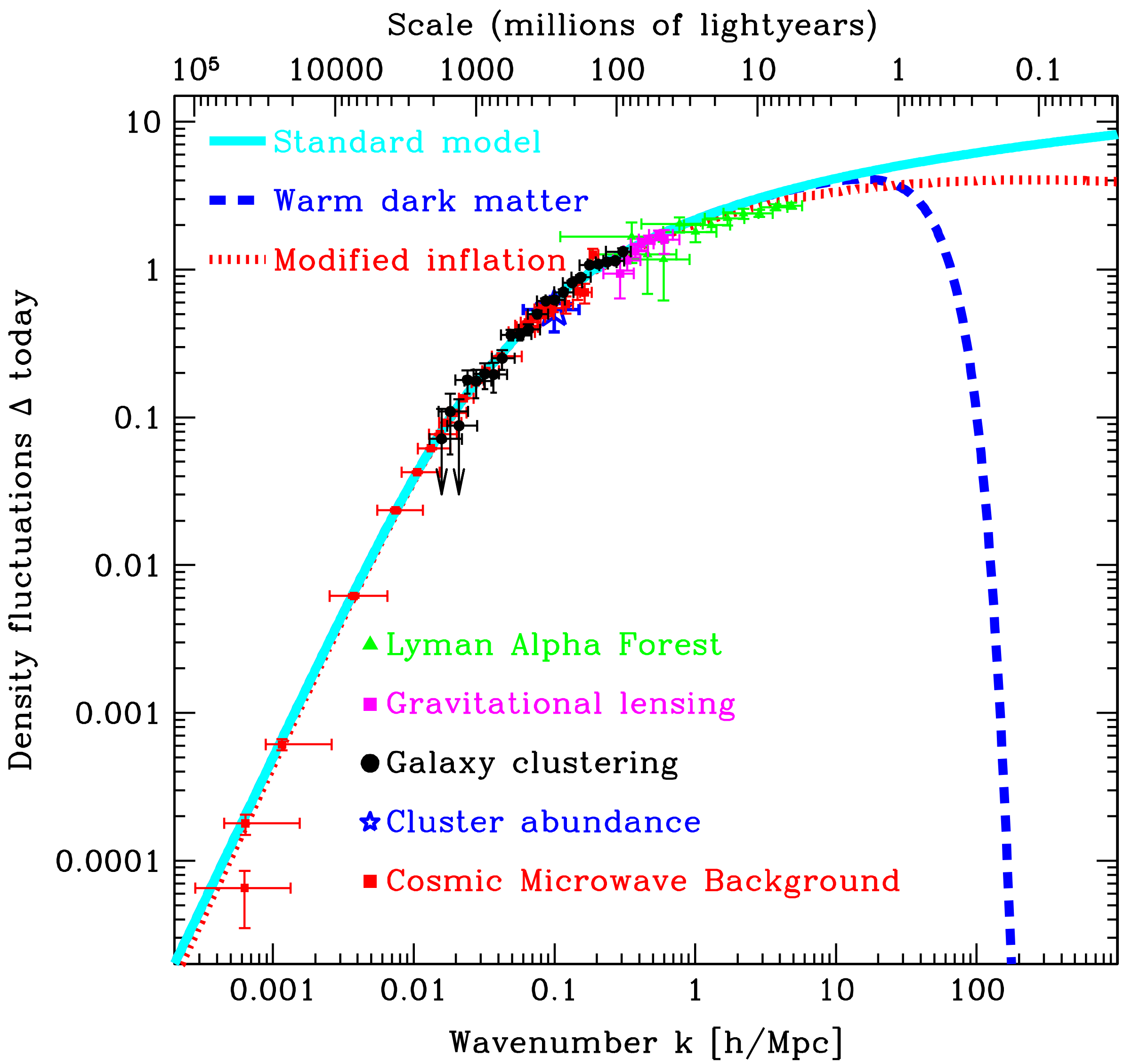
Tegmark & Zaldarriaga 2009

The time frontier:

CMB: thin shell around z=1100
LSS: $z \lesssim 1$
dark ages 21cm: $30 \lesssim z \lesssim 200$

- Expansion history H(z)
- Thermal history T(z)
- Dark matter annihilation/decay
- Change of fundamental constants

New frontiers with 21cm cosmology



Tegmark & Zaldarriaga 2009

<u>The scale frontier:</u>

CMB: $k \lesssim k_{Silk} \sim 0.15\ \mathrm{Mpc}^{-1}$

LSS: $k \lesssim k_{NL} \sim 0.1\ \mathrm{Mpc}^{-1}$ at $z = 0$

21cm: $k \lesssim k_{Jeans} \sim 300\ \mathrm{Mpc}^{-1}$

- Tests of inflation with n_s, running
- Warm dark matter
- Non-gaussianities

The cosmic dark ages ($30 \lesssim z \lesssim 1000$)

- No stars or other luminous sources have formed yet
- Growth of density perturbations can be accurately described by (linear) perturbation theory.
- Physics is still very simple!
- For effect at $z \lesssim 30$, see Fialkov et al. (2011-2013)

21cm line basics

F = 1 ———————

F = 0 ———————

E_{10} = 6 μeV = 68 mK

ν_{10} = 1420 MHz

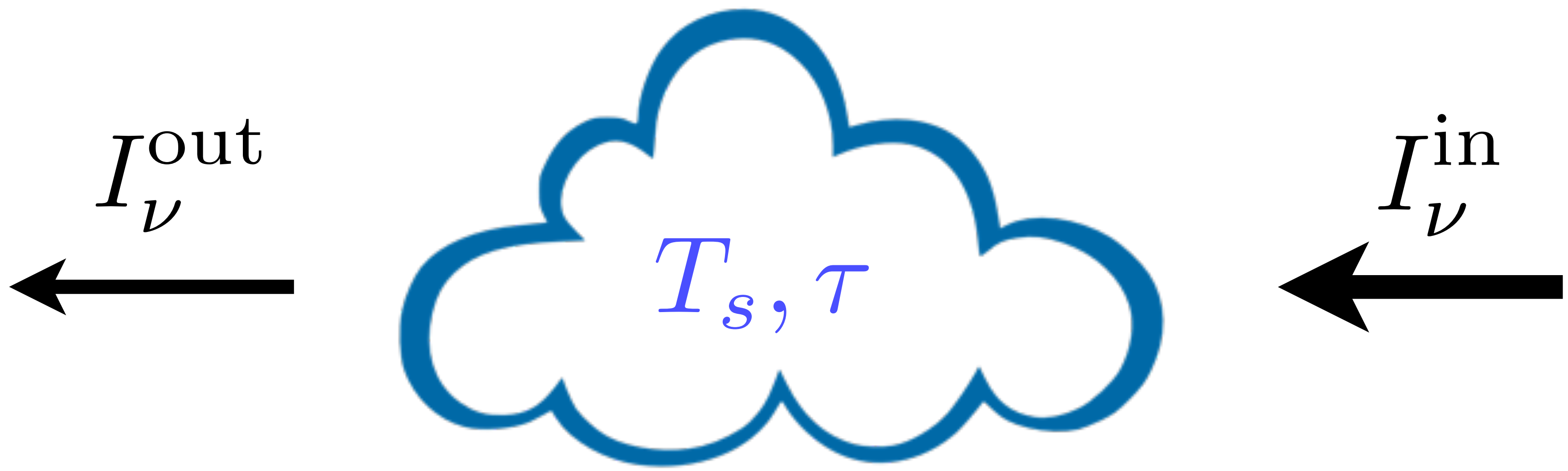
λ_{10} = 21.1cm

A_{10} = 2.85e^{-15} s^{-1} = (11 Myr)$^{-1}$

Spin temperature:

$$\frac{n_1}{3n_0} \equiv e^{-E_{10}/T_s} \approx 1 - \frac{E_{10}}{T_s}$$

21cm brightness temperature



$$I_\nu^{\rm out} = I_\nu^{\rm in} + (1 - e^{-\tau})(B_\nu(T_s) - I_\nu^{\rm in})$$

$$I_\nu^{\rm in,out} \equiv B_\nu(T_{\rm in,out})$$

$$h\nu \ll kT \qquad \tau \ll 1 \qquad T_{\rm in} = T_{\rm cmb}$$

$$T_b \equiv T_{\rm out} - T_{\rm cmb} = \tau(T_s - T_{\rm cmb})$$

21cm optical depth

$$\text{Usually}: \tau = \int n_{\rm abs}\sigma(\nu)dl$$

$$\text{Here}: dl = cdt = -c\frac{d\nu}{H\nu}, \quad \tau = n_{\rm abs}\int \sigma(\nu)\frac{cd\nu}{H\nu}$$

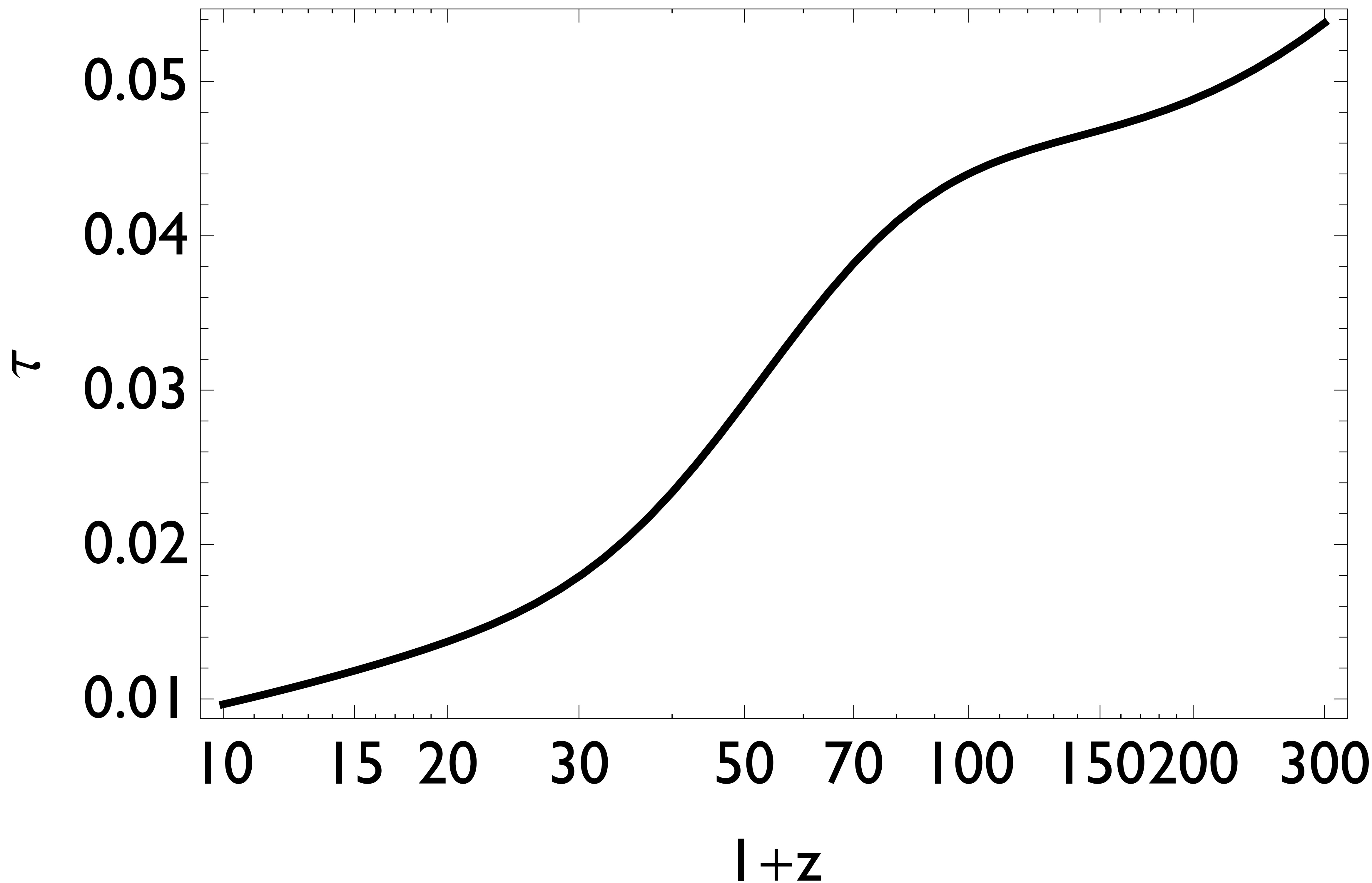
$$H \rightarrow H + \partial_{||}v_{||}$$

$$\sigma(\nu) \propto \lambda^2 A_{10}\phi(\nu) \approx \lambda^2 A_{10}\delta(\nu - \nu_{10})$$

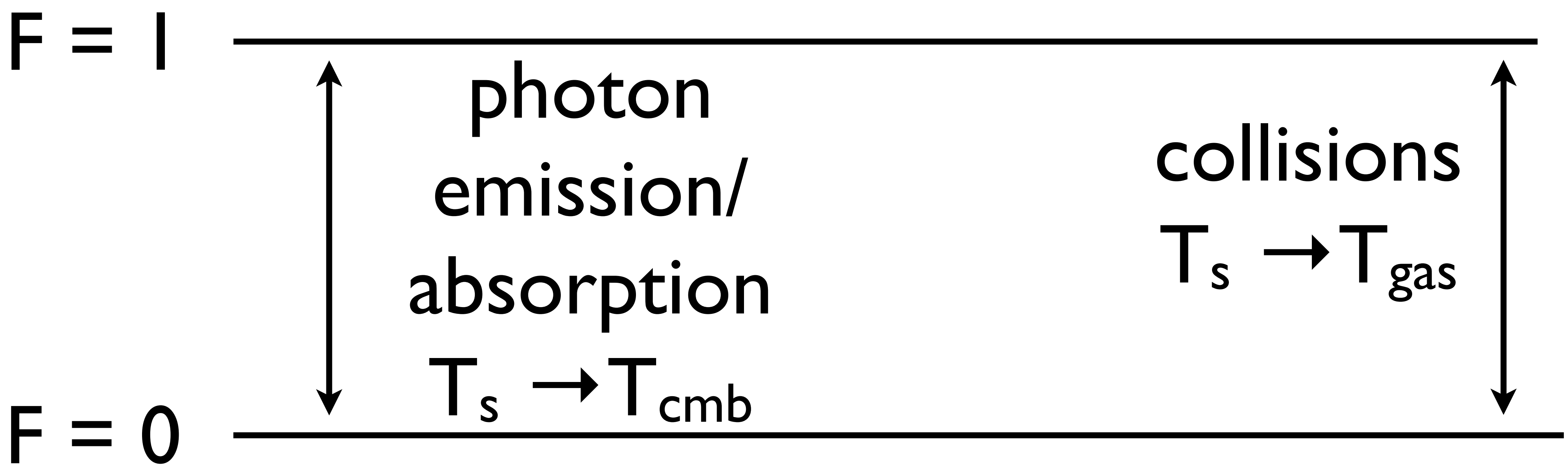
$$n_{\rm abs} = n_0 - \frac{n_1}{3} = n_0\left(1 - e^{-E_{10}/T_s}\right) \approx \frac{n_{\rm H}}{4}\frac{E_{10}}{T_s}$$

$$\tau = \frac{3E_{10}}{32\pi T_s}\frac{A_{10}}{H + \partial_{||}v_{||}}\lambda_{10}^3 n_{\rm H}$$

Average optical depth

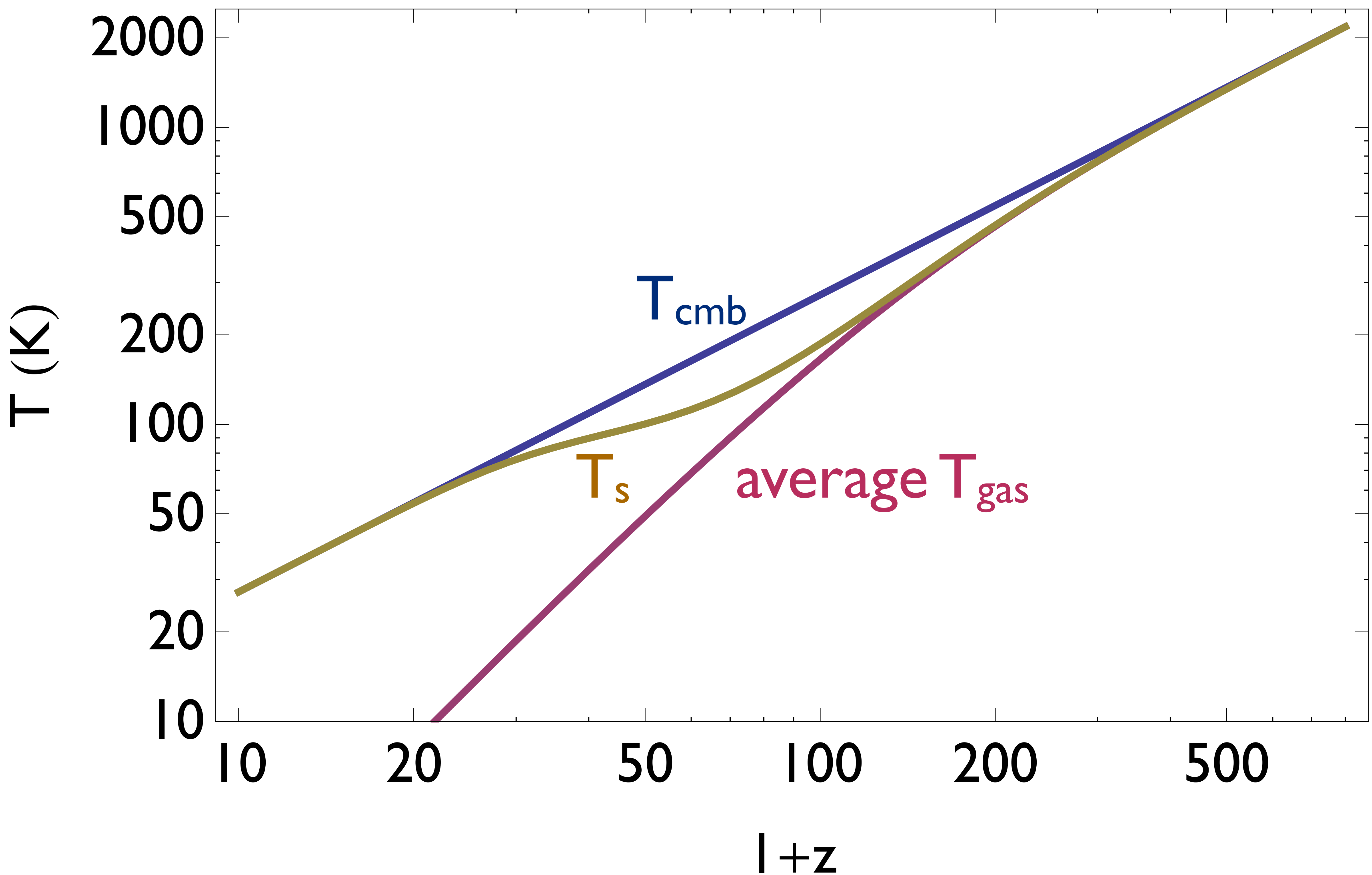


Spin temperature



$$\frac{n_1}{3n_0} = e^{-E_{10}/T_s} = \frac{n_{\rm H}\kappa_{01}(T_{\rm gas}) + R_{01}(T_{\rm cmb})}{3n_{\rm H}\kappa_{10}(T_{\rm gas}) + 3R_{10}(T_{\rm cmb})}$$

Average spin temperature



Brief recap

What is measured: $T_b = \tau(T_s - T_{\rm cmb})$

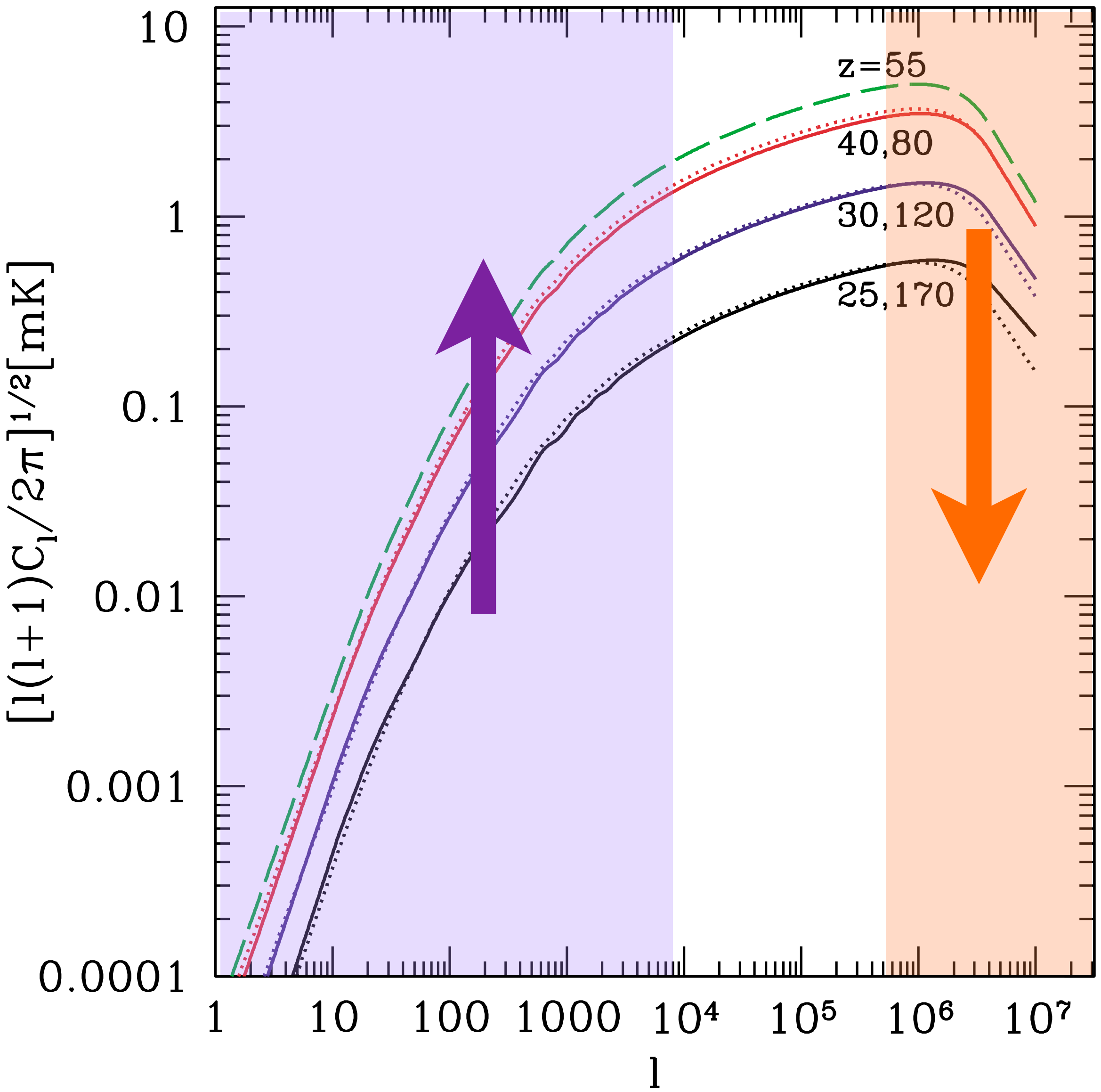
$$\tau \propto \frac{n_{\rm H}}{T_s(H + \partial_{||} v_{||})} \qquad\qquad T_s(n_{\rm H}, T_{\rm gas})$$

To linear order: $n_{\rm H} = \overline{n}_{\rm H}(1 + \delta_b)$

$$\delta T_b(z, \vec{k}) = \frac{\partial T_b}{\partial \log n_{\rm H}} \delta_b - \frac{\partial T_b}{\partial \log H} \frac{\partial_{||} v_{||}}{H} + \frac{\partial T_b}{\partial \log T_{\rm gas}} \frac{\delta T_{\rm gas}}{T_{\rm gas}}$$

Angular fluctuations of T_b probe the underlying density power spectrum

Previous studies



Loeb & Zaldarriaga 2004
(Only included the δ_b term)

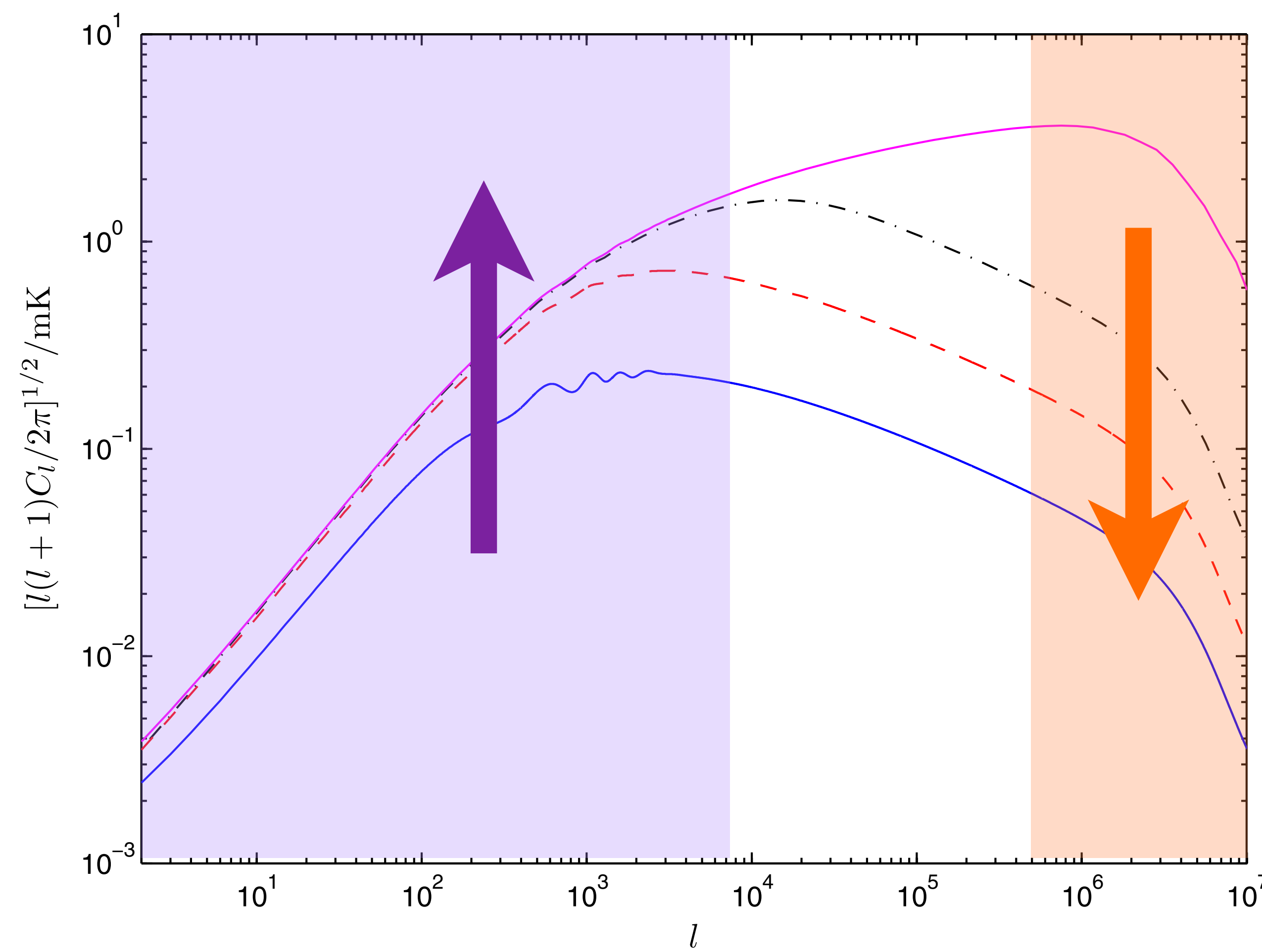


FIG. 8 (color online). The 21 cm power spectrum at $z = 50$ for $\Delta\nu = \{1, 0.1, 0.01, 0\}$ MHz (bottom to top). Large widths sup-

Lewis & Challinor 2007
Include all linear terms +
relativistic and velocity corrections

The relative velocity effect

(Tseliakhovich & Hirata 2010)

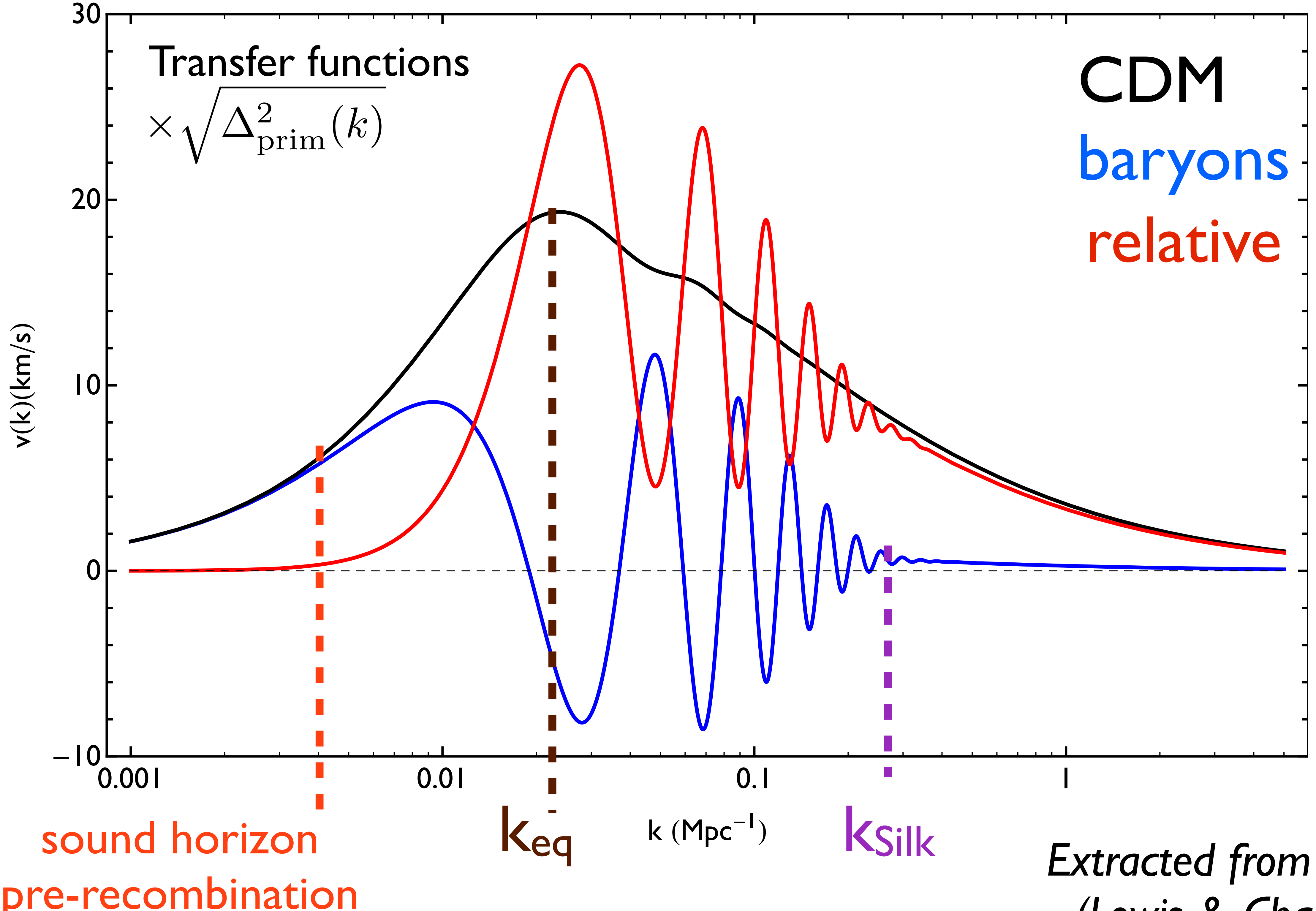
- Prior to recombination, baryons tightly coupled to photon ⇒ acoustic oscillations.

- Meanwhile, the CDM perturbations grow under their own gravity.

- After recombination, for $k < k_{Jeans}$, baryons and CDM perturbations grow together, BUT

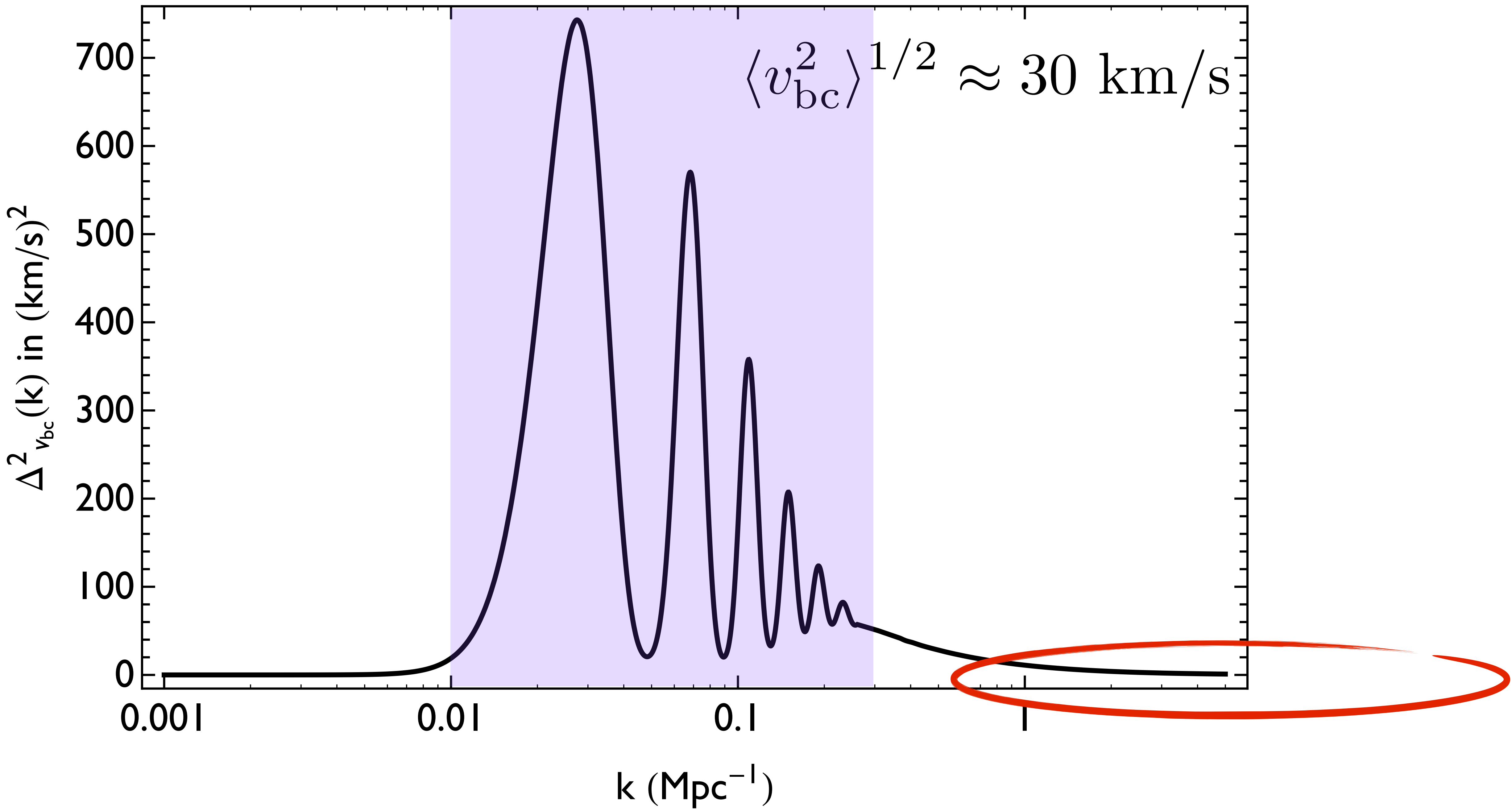
At $z = z_{rec} \approx 1000$, very different "initial conditions" for baryons and CDM.

Characteristic velocities at z = 1000



Extracted from CAMB (Lewis & Challinor)

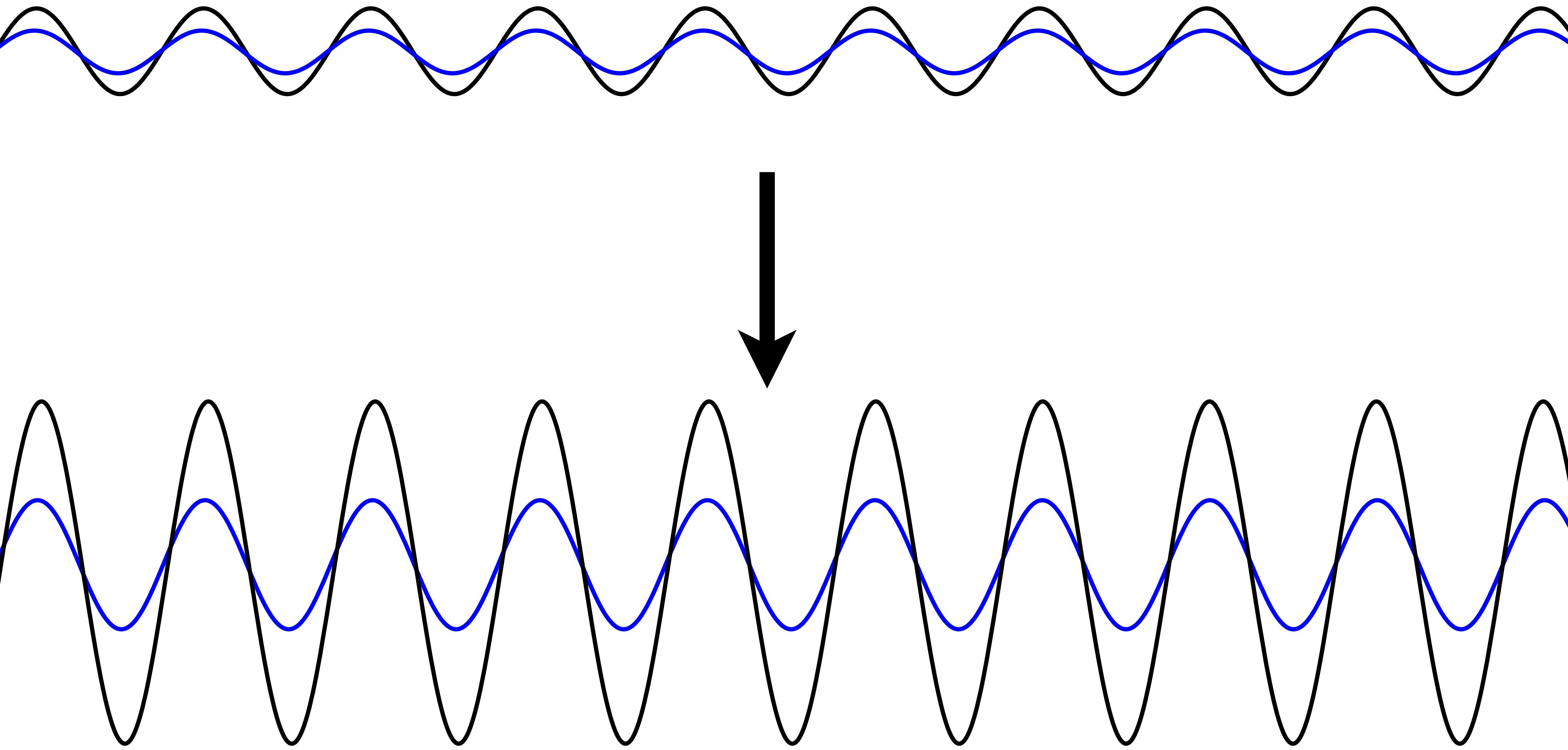
Relative velocity power spectrum



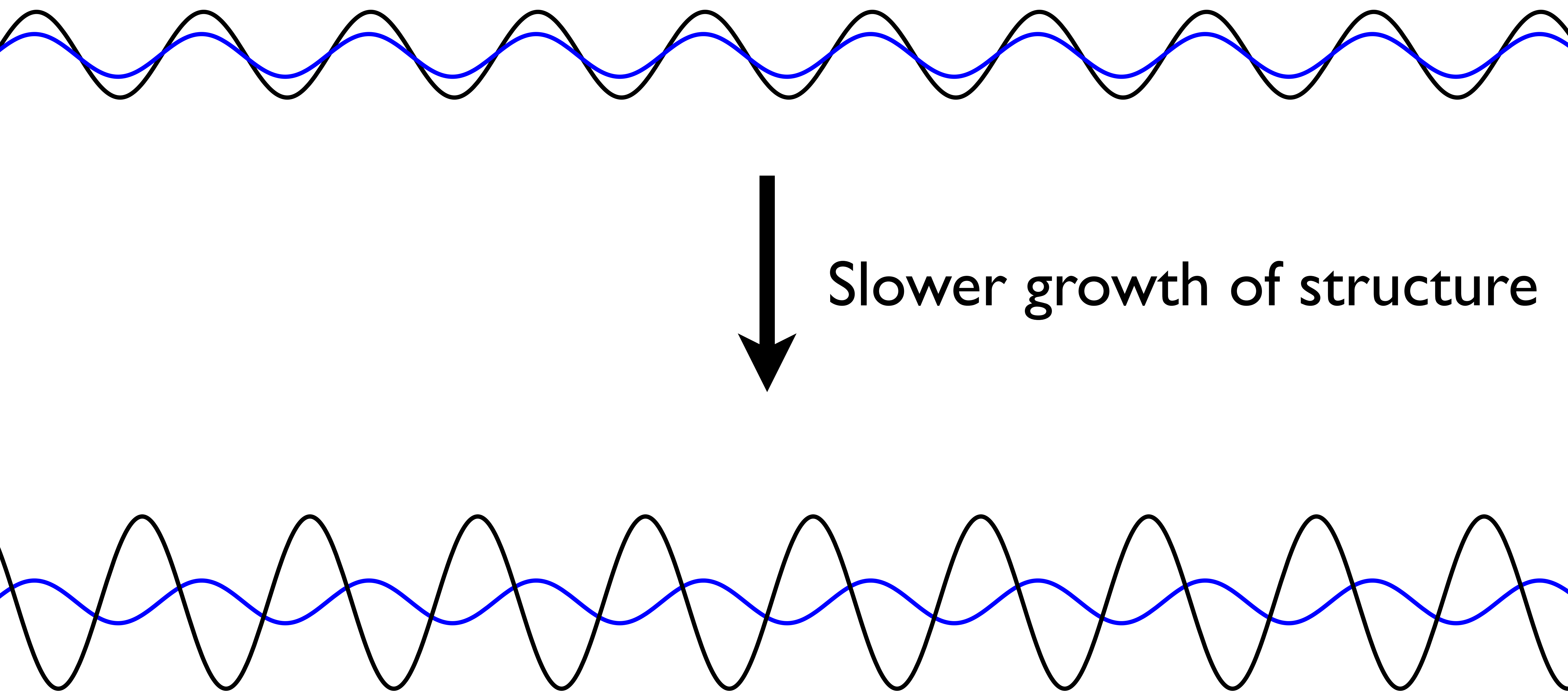
v_{bc} nearly uniform on a few Mpc scale: k_{coh} ~ 0.3 Mpc^{-1}

Maximum fluctuations for k ~ 0.01 - 0.3

Without relative velocity



With relative velocity, if $\lambda \lesssim v_{bc}/H$



- Characteristic scale of suppression:

$$k_{v_{\rm bc}} \sim \frac{aH}{v_{\rm bc}} \approx 40~{\rm Mpc}^{-1} \gg k_{\rm coh} \sim 0.3~{\rm Mpc}^{-1}$$

- Larger that the Jeans scale:

$$k_{\rm Jeans} \sim \frac{aH}{c_s} \sim 200~{\rm Mpc}^{-1}~~\text{with}~c_s \approx 6~{\rm km/s}$$

- The effect is fundamentally non-linear:

$$0 = \dot{\delta} + \vec{\nabla} \cdot \vec{v} + \vec{v} \cdot \nabla \delta$$

- Thanks to large separation of scales, one may still use perturbation theory around a given background relative velocity (Tseliakhovich & Hirata 2010)

Method of computation

- Fluid equations in the local baryon rest frame

$$\dot{\delta}_c - ia^{-1}(\boldsymbol{v}_{\rm bc}\cdot\boldsymbol{k})\delta_c + \theta_c = 0,$$
$$\dot{\theta}_c - ia^{-1}(\boldsymbol{v}_{\rm bc}\cdot\boldsymbol{k})\theta_c + 2H\theta_c - k^2\phi = 0,$$
$$\dot{\delta}_b + \theta_b = 0,$$
$$\dot{\theta}_b + 2H\theta_b - \frac{k^2}{a^2}\phi + \frac{\bar{c}_s^2}{a^2}k^2\left(\delta_b + \delta_{T_{\rm gas}}\right) = 0,$$
$$\frac{k^2}{a^2}\phi = -\frac{3}{2}\frac{H_0^2}{a^3}\left(\Omega_b^0\delta_b + \Omega_c^0\delta_c\right),$$

pressure term

$P = n_b T_{\rm gas}$

- **Gas temperature evolution:** $(dU + PdV = \delta Q)$

$$\dot{T}_{\rm gas} - \frac{2}{3}\frac{\dot{n}_{\rm H}}{n_{\rm H}} T_{\rm gas} = \frac{2}{3}\dot{q}_{\rm C}, \quad \left(+\frac{2}{3}\dot{q}_{\rm extra}\right)$$

where $\dot{q}_{\rm C}$ is the Compton heating rate per particle:

$$\dot{q}_{\rm C} = \frac{4\sigma_{\rm T} a_r T_{\rm cmb}^4}{(1 + x_{\rm He} + x_e) m_e} x_e (T_{\rm cmb} - T_{\rm gas})$$

Perturbed:

$$\dot{\delta}_{T_{\rm gas}} - \frac{2}{3}\dot{\delta}_b = \gamma_{\rm C}\overline{x}_e \left[\frac{\overline{T}_{\rm cmb} - \overline{T}_{\rm gas}}{\overline{T}_{\rm gas}}\delta_{x_e} - \frac{\overline{T}_{\rm cmb}}{\overline{T}_{\rm gas}}\delta_{T_{\rm gas}}\right]$$

- Free-electron fraction evolution

$$\dot{x}_e \approx -C\mathcal{A}_{\rm B} n_{\rm H} x_e^2.$$

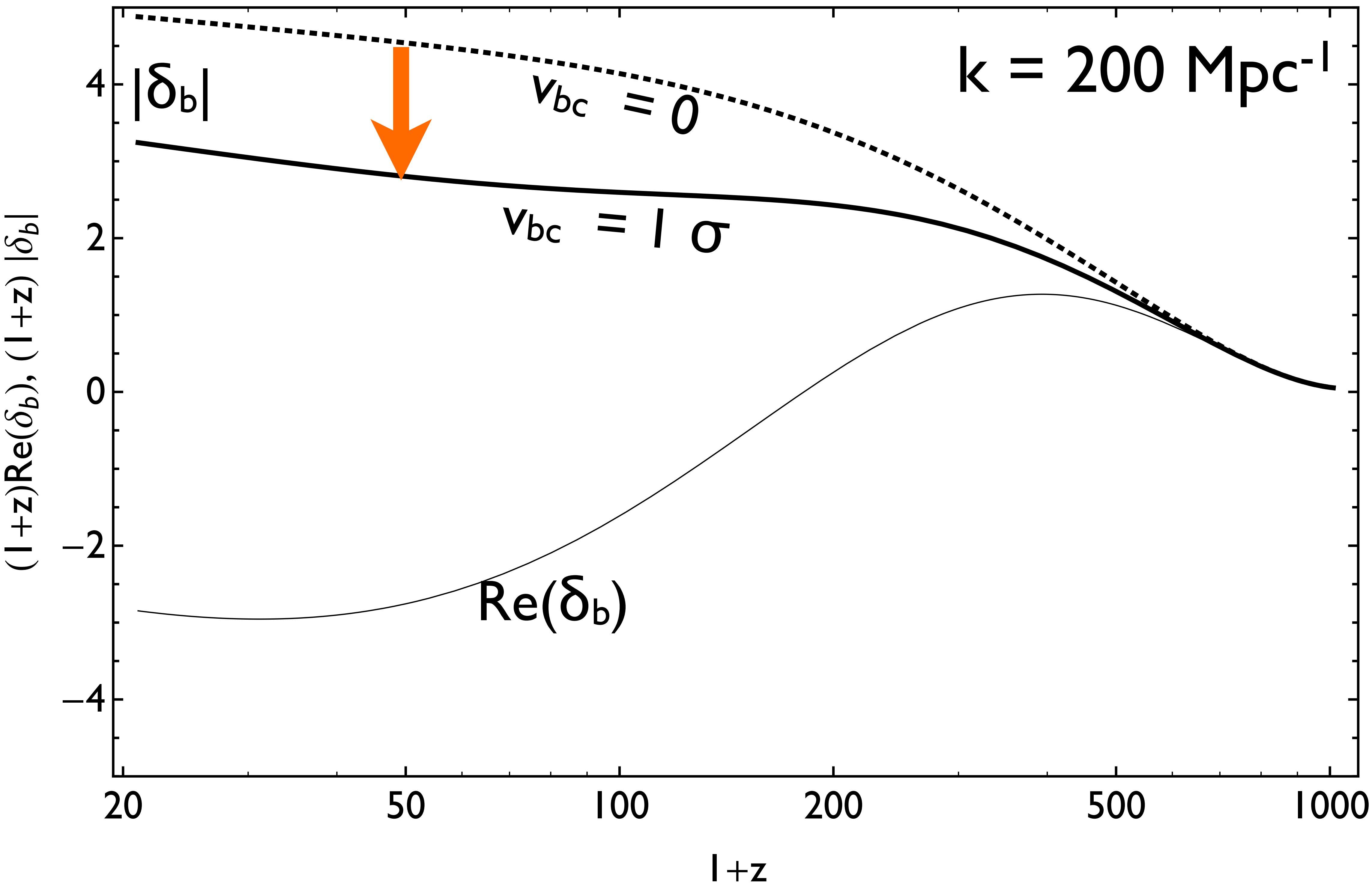
Peebles C-factor

Exact effective case-B recombination coefficient *(Ali-Haïmoud & Hirata 2010)*

Perturbed: $$\dot{\delta}_{x_e} = \ldots \delta_{x_e} + \ldots \delta_b + \ldots \theta_b + \ldots \delta_{T_{\rm gas}}$$

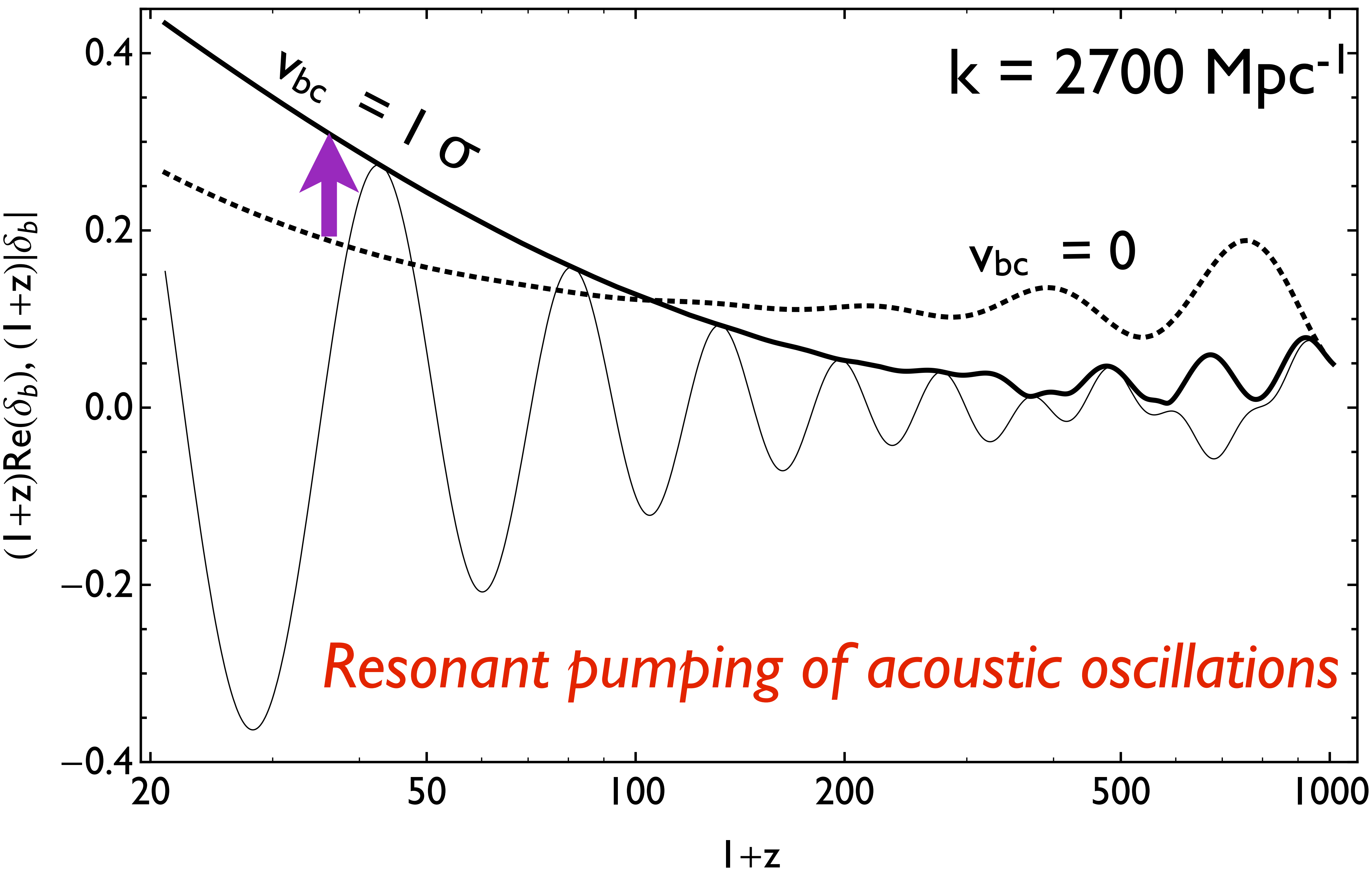
- Bottom line: for given k and v_{bc}, solve coupled ODEs for $\delta_b, \theta_b, \delta_c, \theta_c, \delta_{T_{\rm gas}}, \delta_{x_e}$

Results



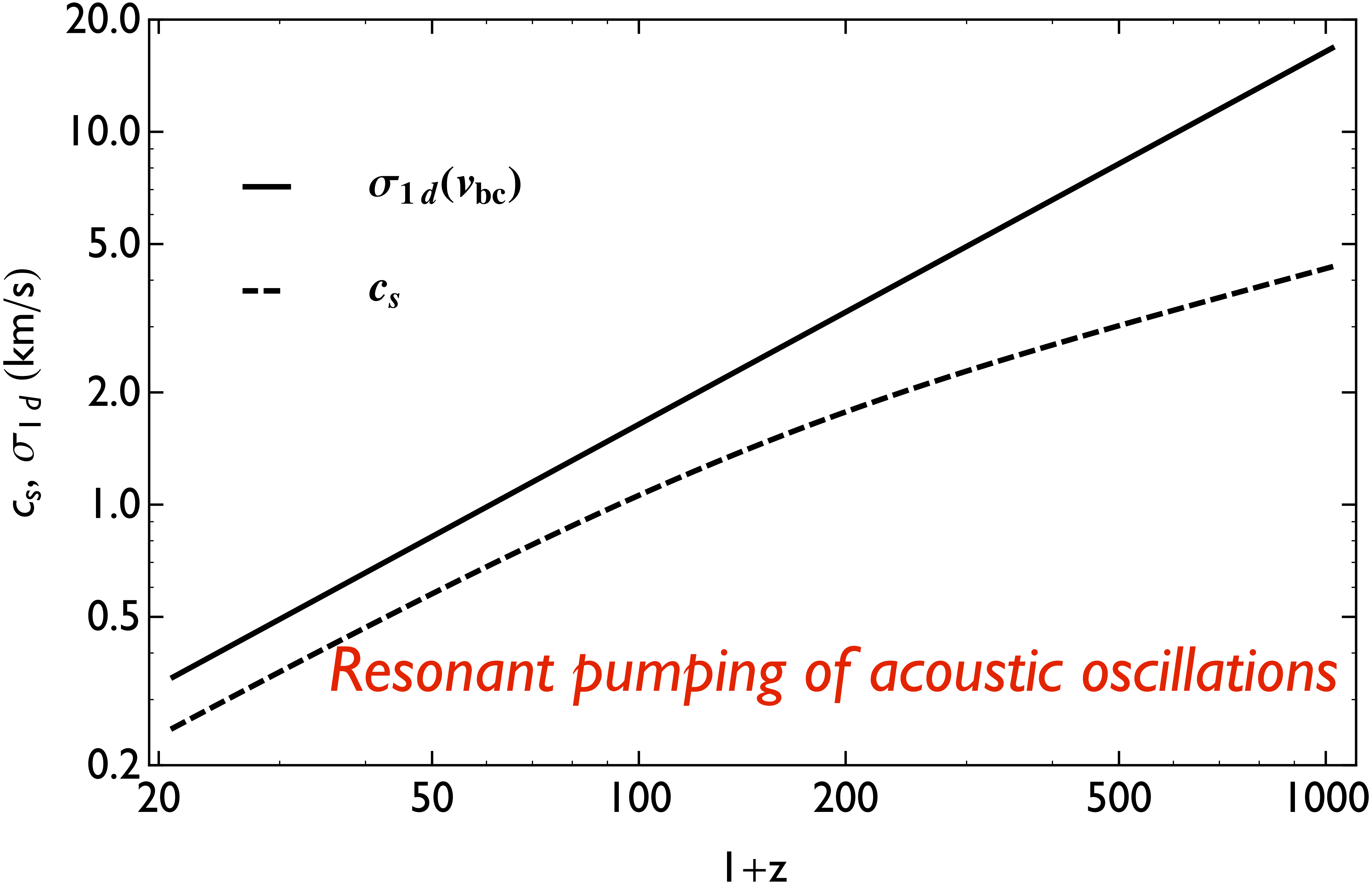
k = 200 Mpc-1
|δb|
vbc = 0
vbc = 1 σ
Re(δb)
(1+z)Re(δb), (1+z) |δb|
1+z
4
2
0
−2
−4
20
50
100
200
500
1000

Results

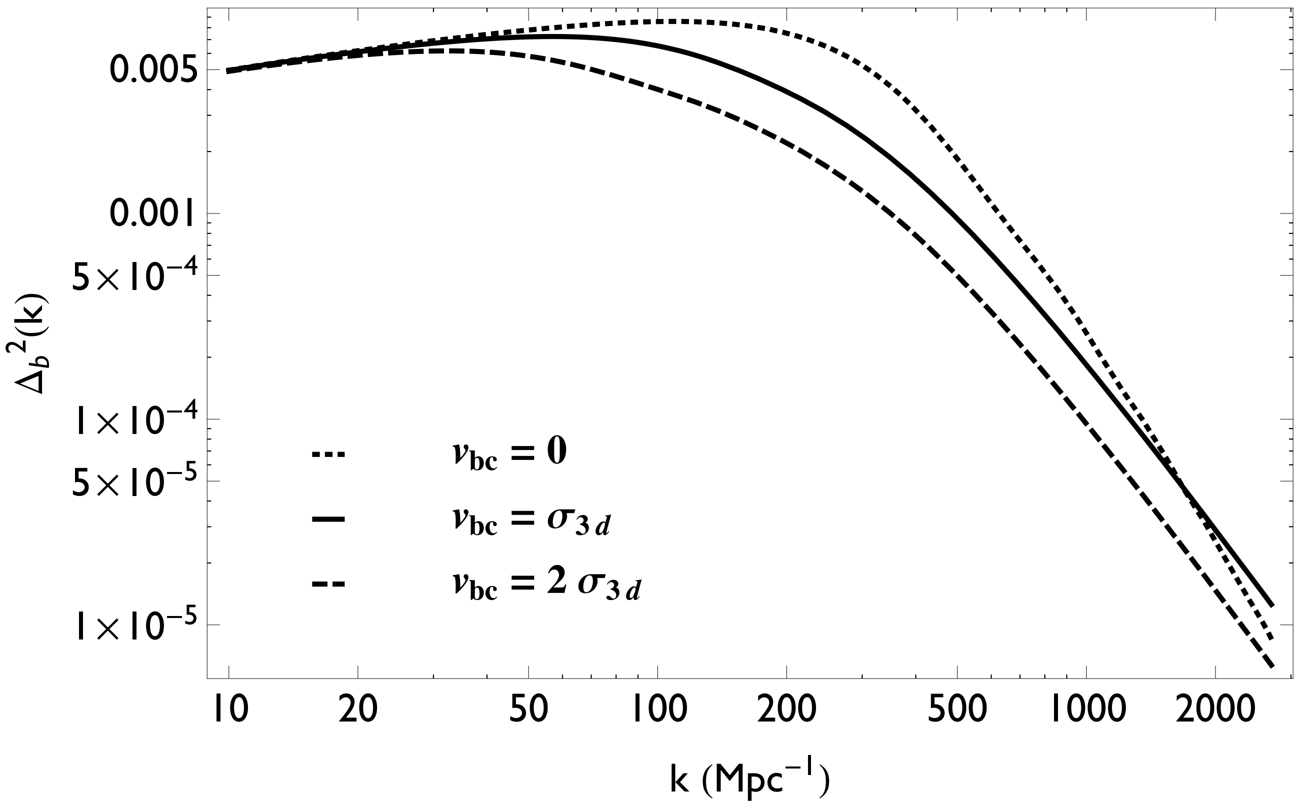


k = 2700 Mpc-1
vbc = 1 σ
vbc = 0
Resonant pumping of acoustic oscillations
(1+z)Re(δb), (1+z)|δb|
1+z
0.4
0.2
0.0
−0.2
−0.4
20
50
100
200
500
1000

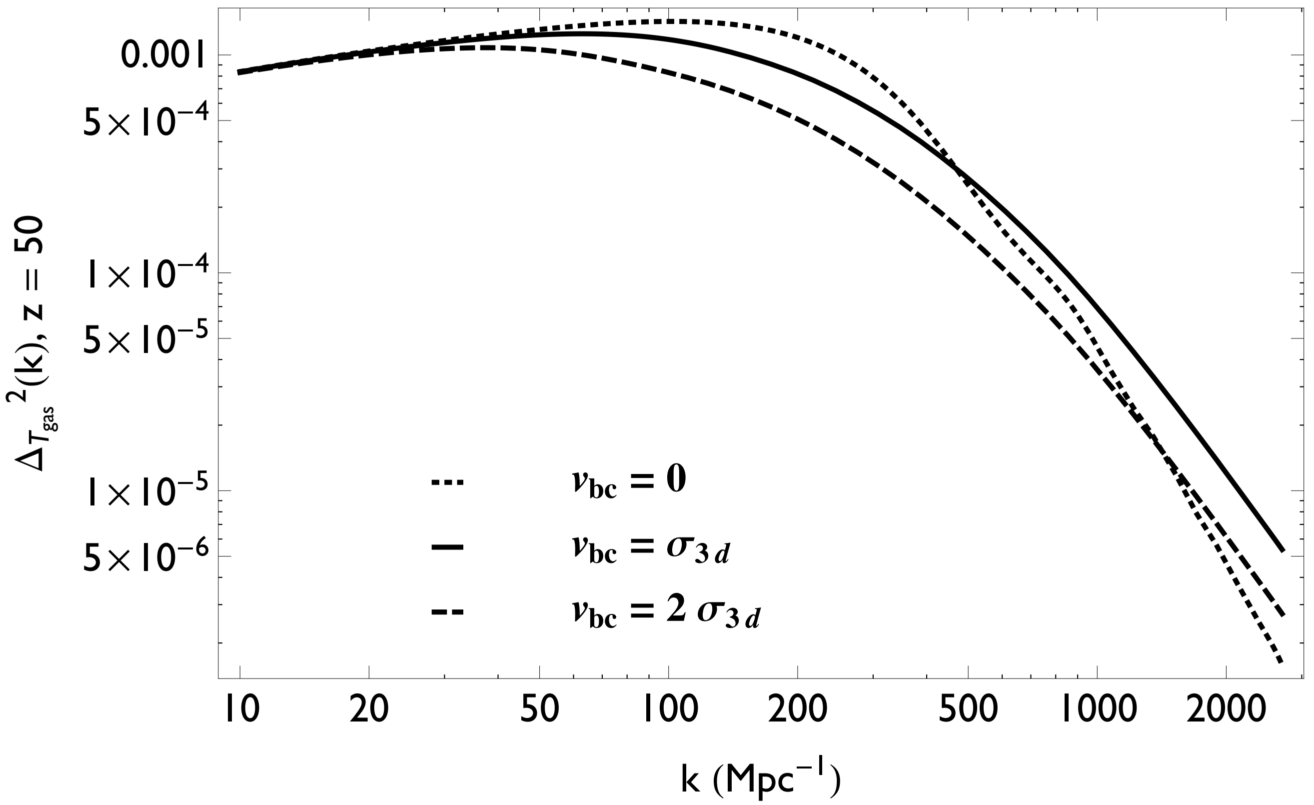
Results


20.0
10.0
5.0
2.0
1.0
0.5
0.2
20
50
100
200
500
1000
1+z
c_s, σ_{1d} (km/s)
$\sigma_{1d}(v_{bc})$
c_s
Resonant pumping of acoustic oscillations

Results

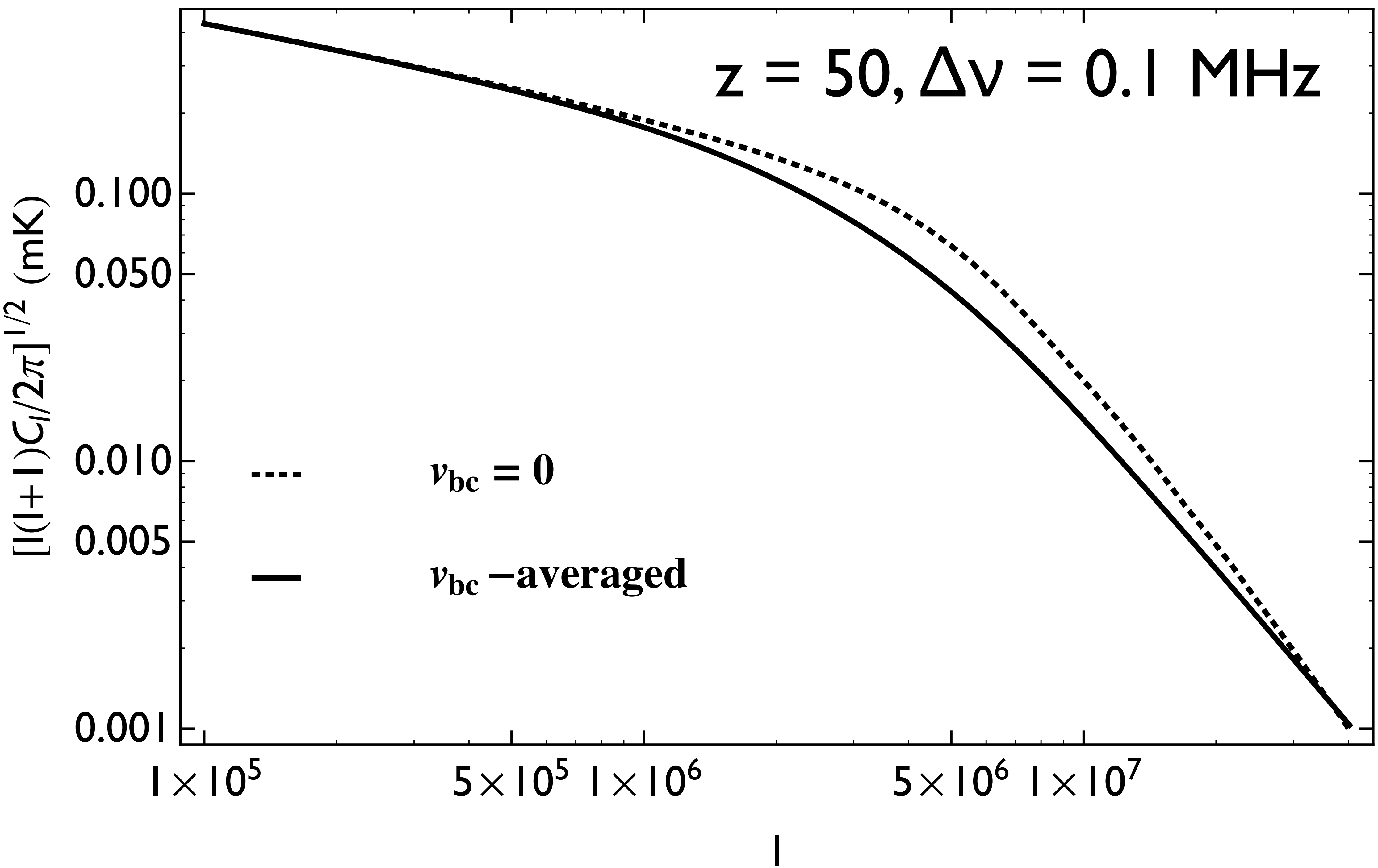


0.005
0.001
5×10⁻⁴
1×10⁻⁴
5×10⁻⁵
1×10⁻⁵
$\Delta_b{}^2(k)$
$v_{bc} = 0$
$v_{bc} = \sigma_{3d}$
$v_{bc} = 2\,\sigma_{3d}$
10 20 50 100 200 500 1000 2000
k (Mpc⁻¹)

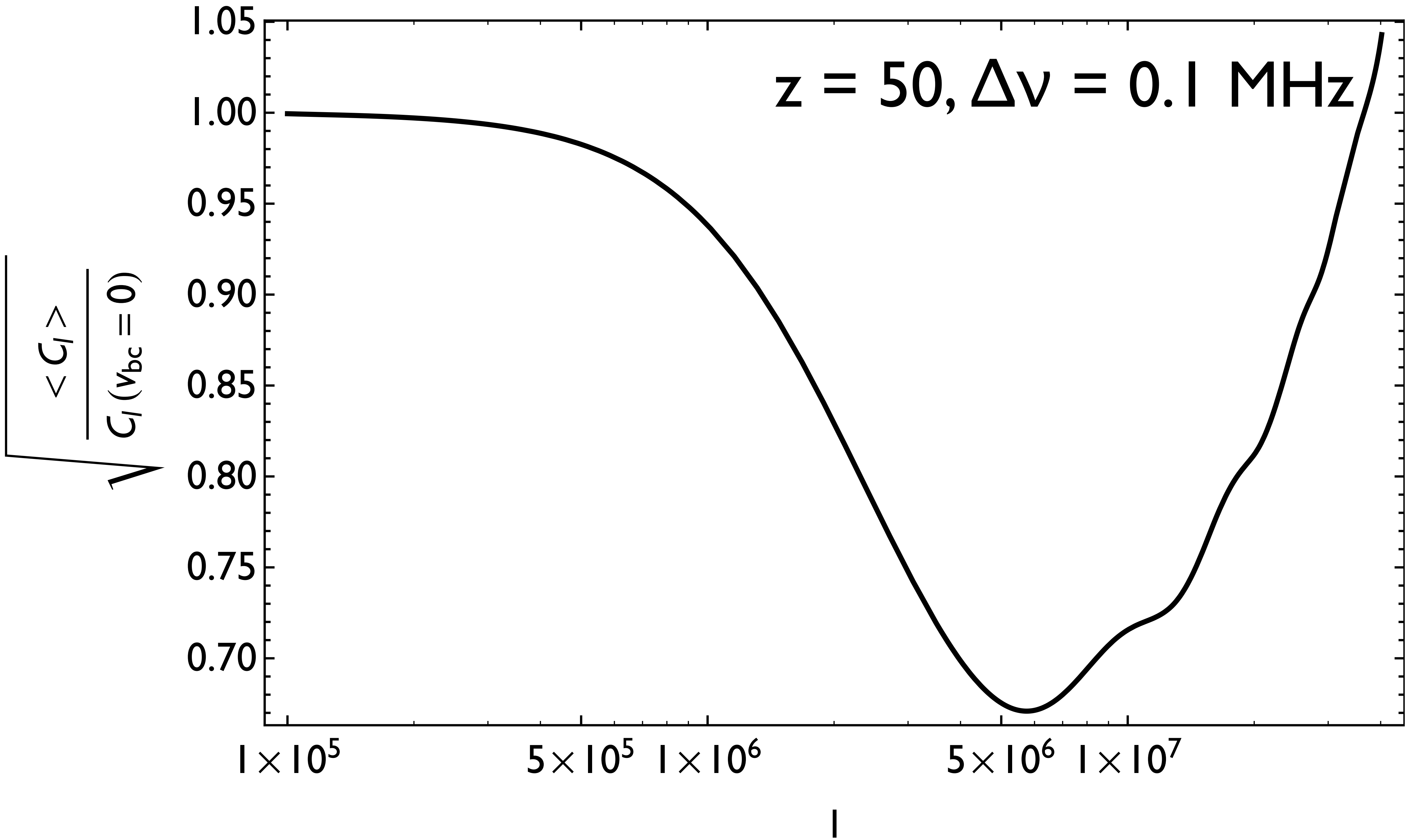


0.001
5×10⁻⁴
1×10⁻⁴
5×10⁻⁵
1×10⁻⁵
5×10⁻⁶
$\Delta_{T_{gas}}{}^2(k)$, z = 50
$v_{bc} = 0$
$v_{bc} = \sigma_{3d}$
$v_{bc} = 2\,\sigma_{3d}$
10 20 50 100 200 500 1000 2000
k (Mpc⁻¹)

Effect on small-scale 21cm angular power spectrum



Effect on small-scale 21cm angular power spectrum



Effect on the large scale signal

What is measured: $T_b = \tau(T_s - T_{\rm cmb})$

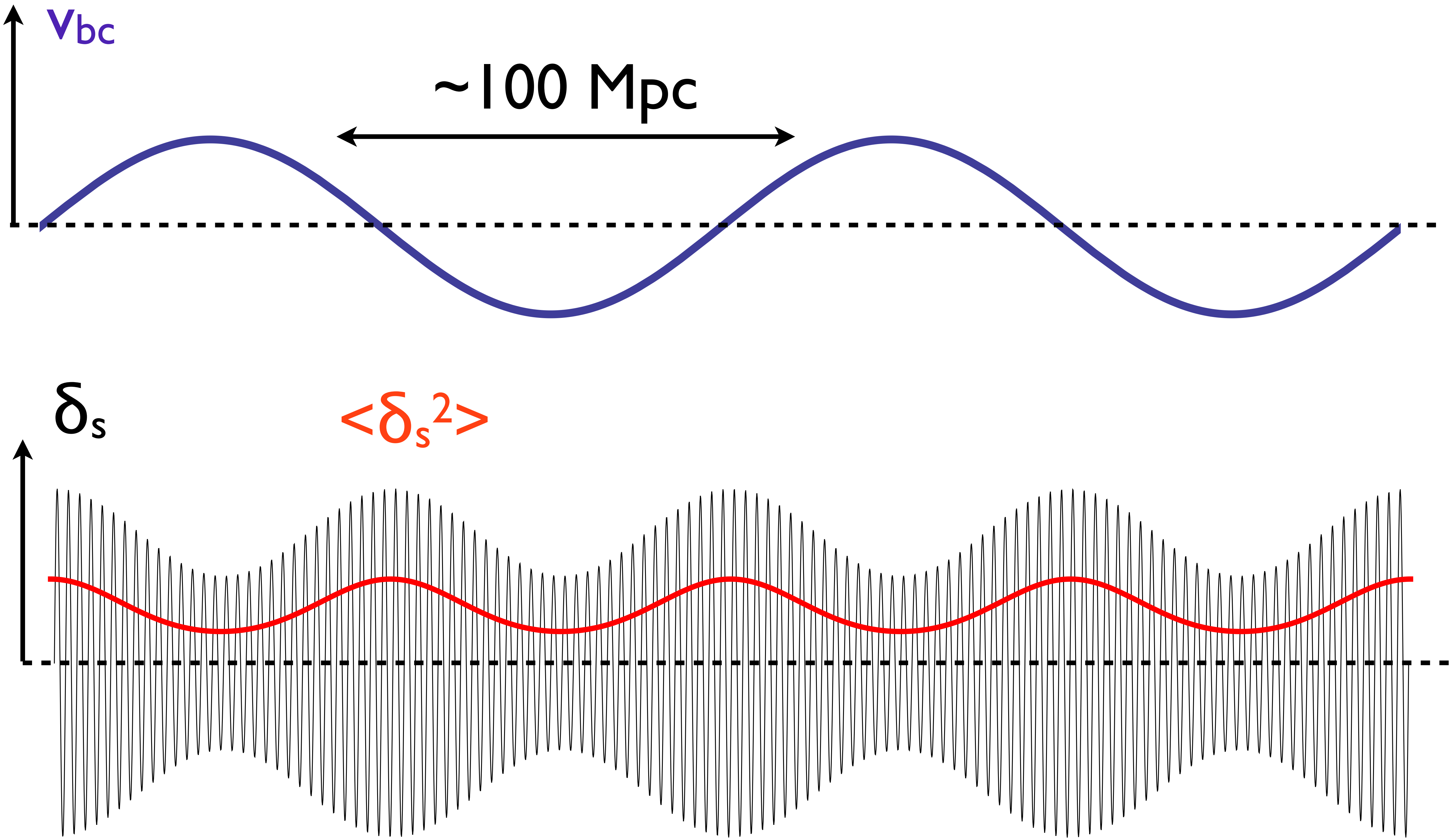
$$\tau \propto \frac{n_{\rm H}}{T_s(H + \partial_{||} v_{||})}$$

$$T_s(n_{\rm H}, T_{\rm gas})$$

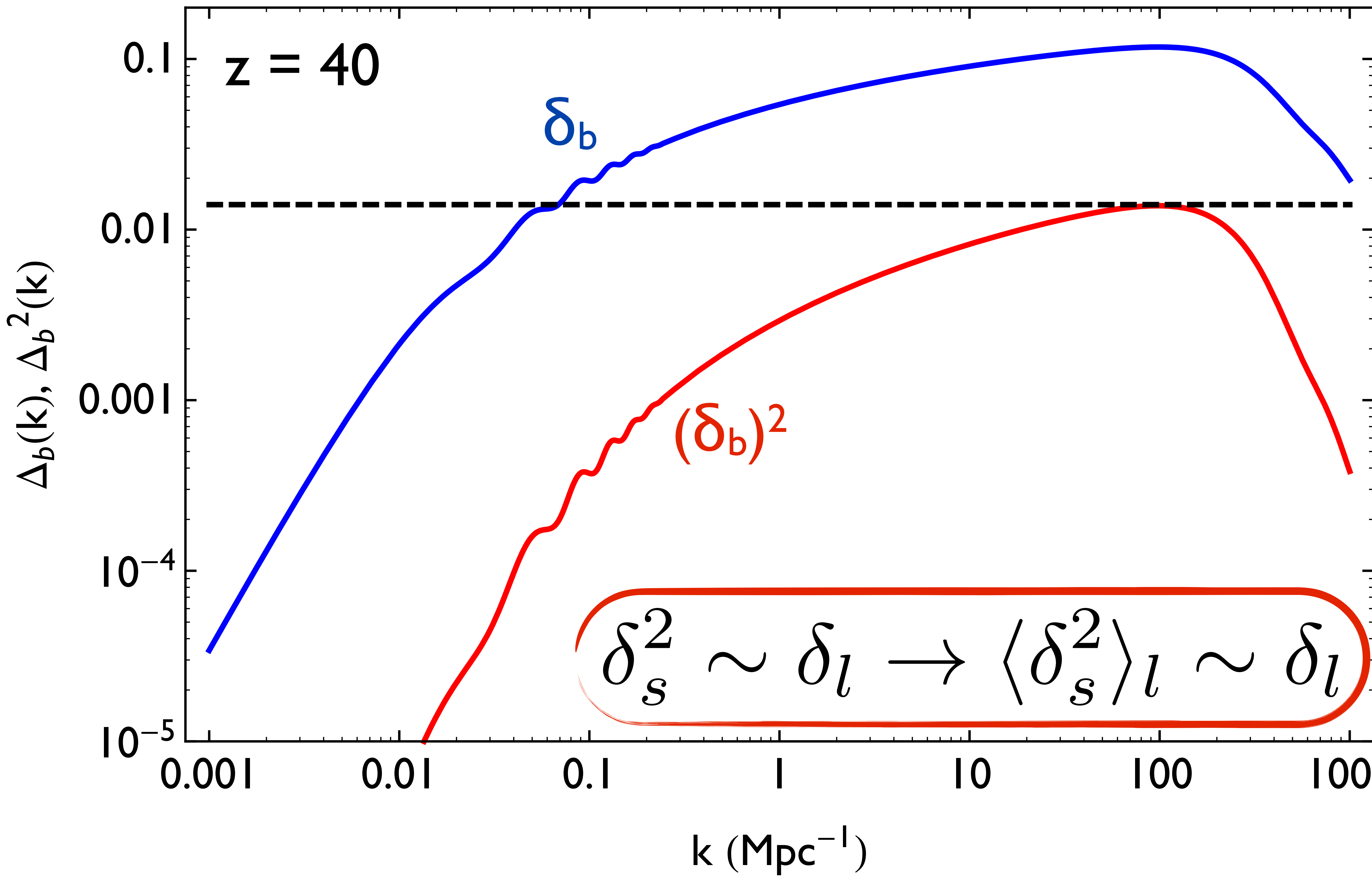
☞ T_b is a fully non-linear function of the δ's

$$\delta T_b = T_1\ \delta + T_2\ \delta^2 + \ldots$$

$$\delta_l \ll \delta_s \ll 1$$

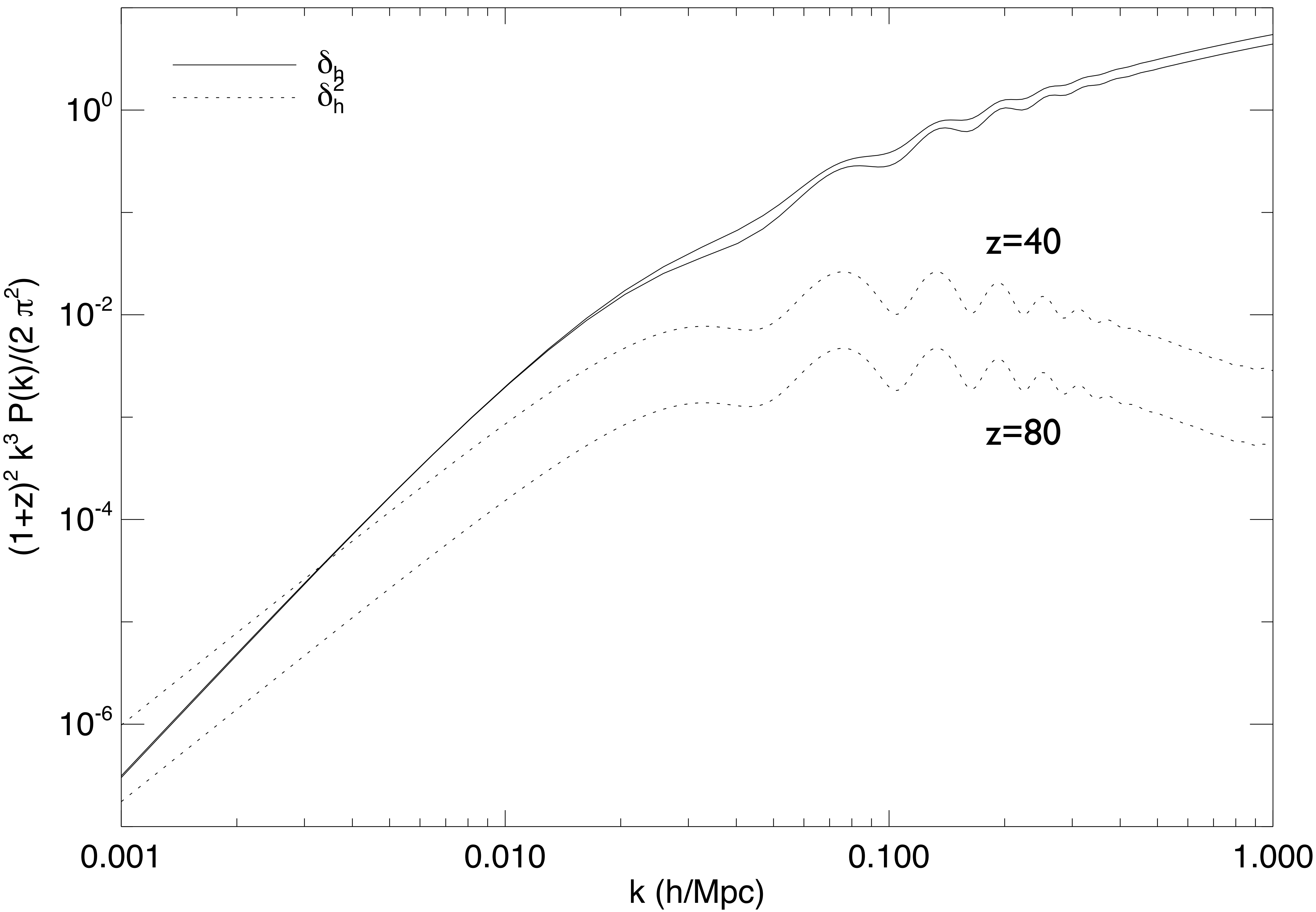


$$(\delta^2)_l = \langle \delta_s^2 \rangle_l \sim \delta_s^2$$



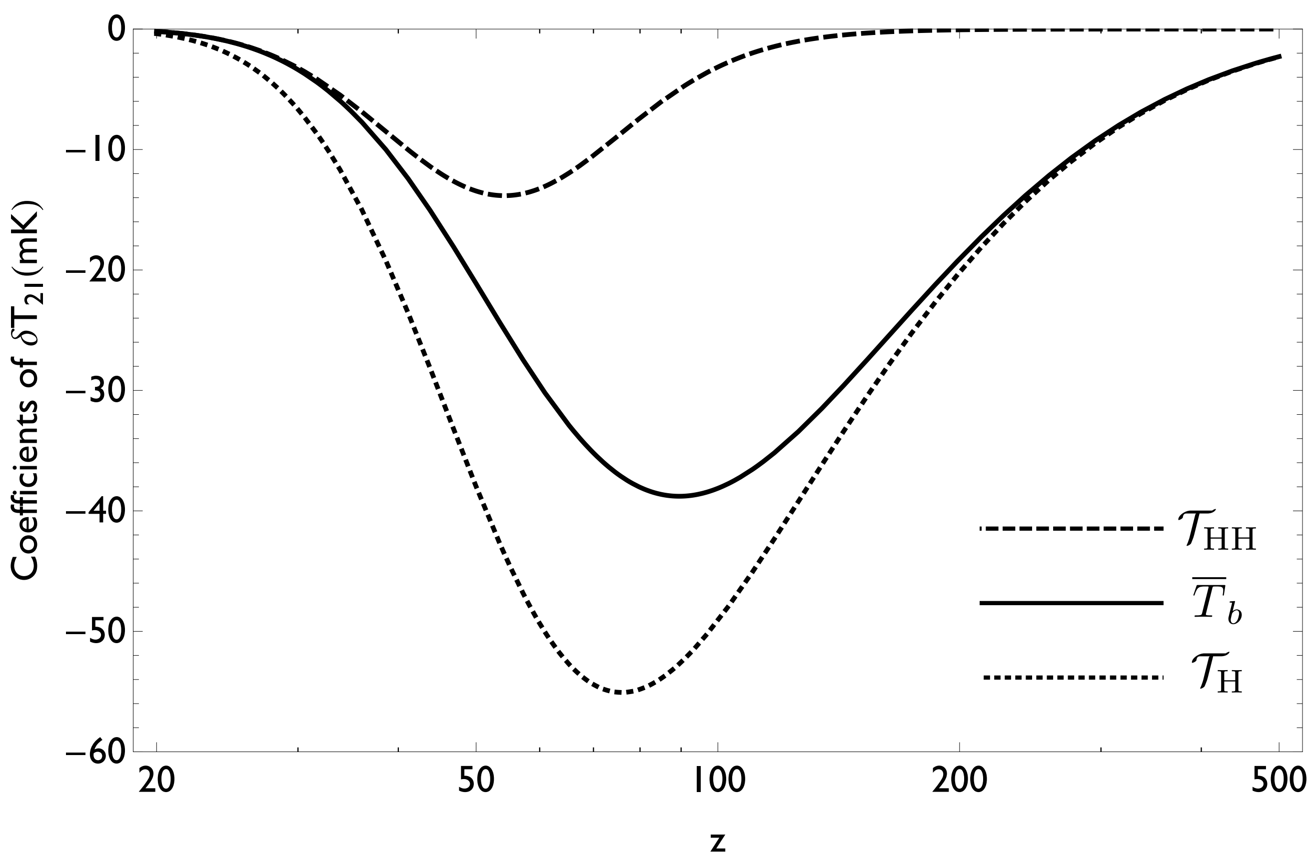
z = 40
δ_b
$(\delta_b)^2$
$\delta_s^2 \sim \delta_l \to \langle \delta_s^2 \rangle_l \sim \delta_l$
0.1
0.01
0.001
10^{-4}
10^{-5}
0.001
0.01
0.1
1
10
100
1000
$\Delta_b(k)$, $\Delta_b{}^2(k)$
k (Mpc^{-1})

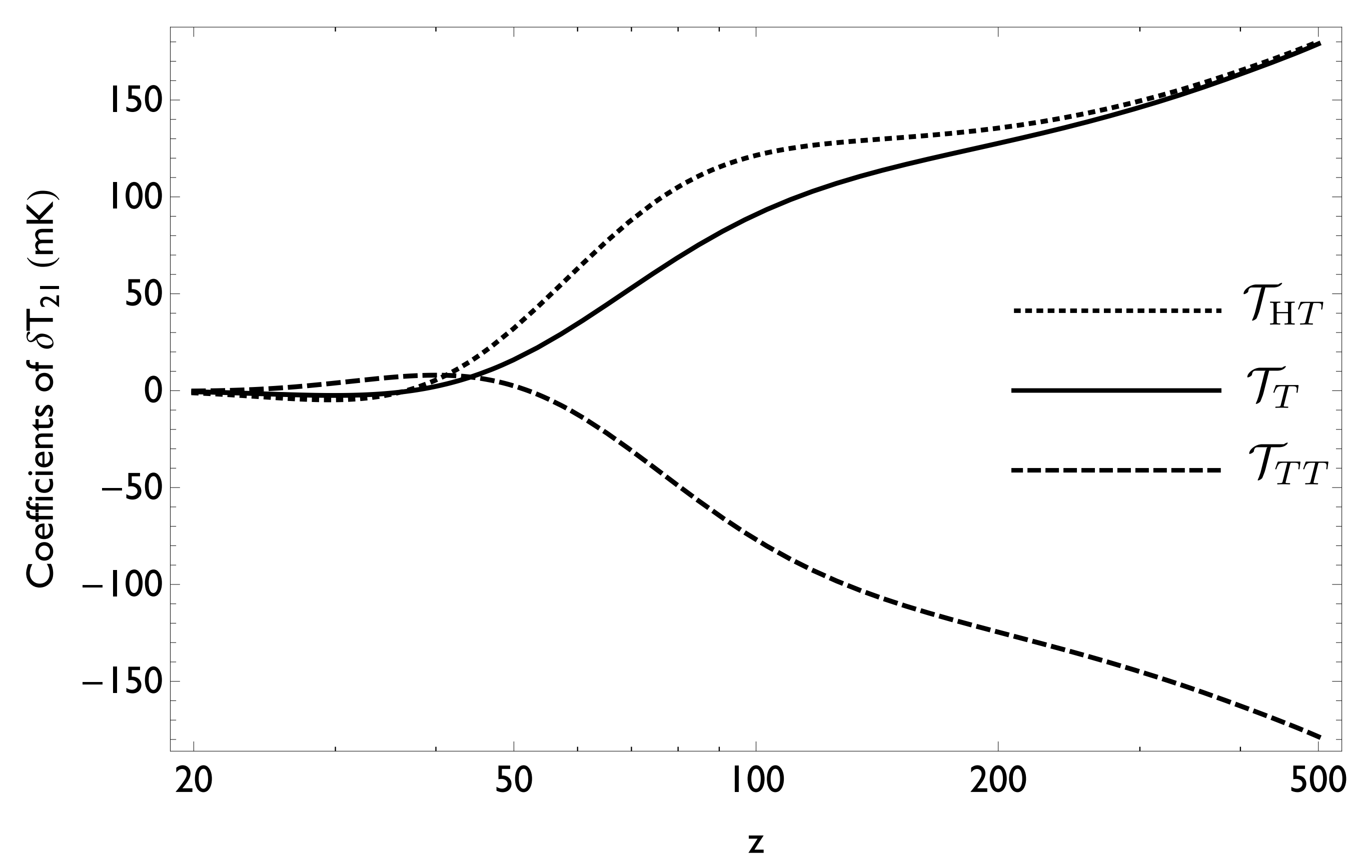
Large-scale fluctuations of δ_b and (δ_b^2)



Expansion of δT_b to second order in fluctuations:

$$\delta T_b^{\rm obs} = \mathcal{T}_{\rm H}\ \delta_{\rm H} + \mathcal{T}_T\ \delta_{T_{\rm gas}} - \overline{T}_b\ \delta_v$$
$$+ \mathcal{T}_{\rm HH}\Delta(\delta_{\rm H}^2) + \mathcal{T}_{TT}\Delta(\delta_{T_{\rm gas}}^2) + \mathcal{T}_{{\rm H}T}\Delta(\delta_{\rm H}\delta_{T_{\rm gas}})$$





In the adiabatic limit ($\gamma_C \rightarrow 0$):

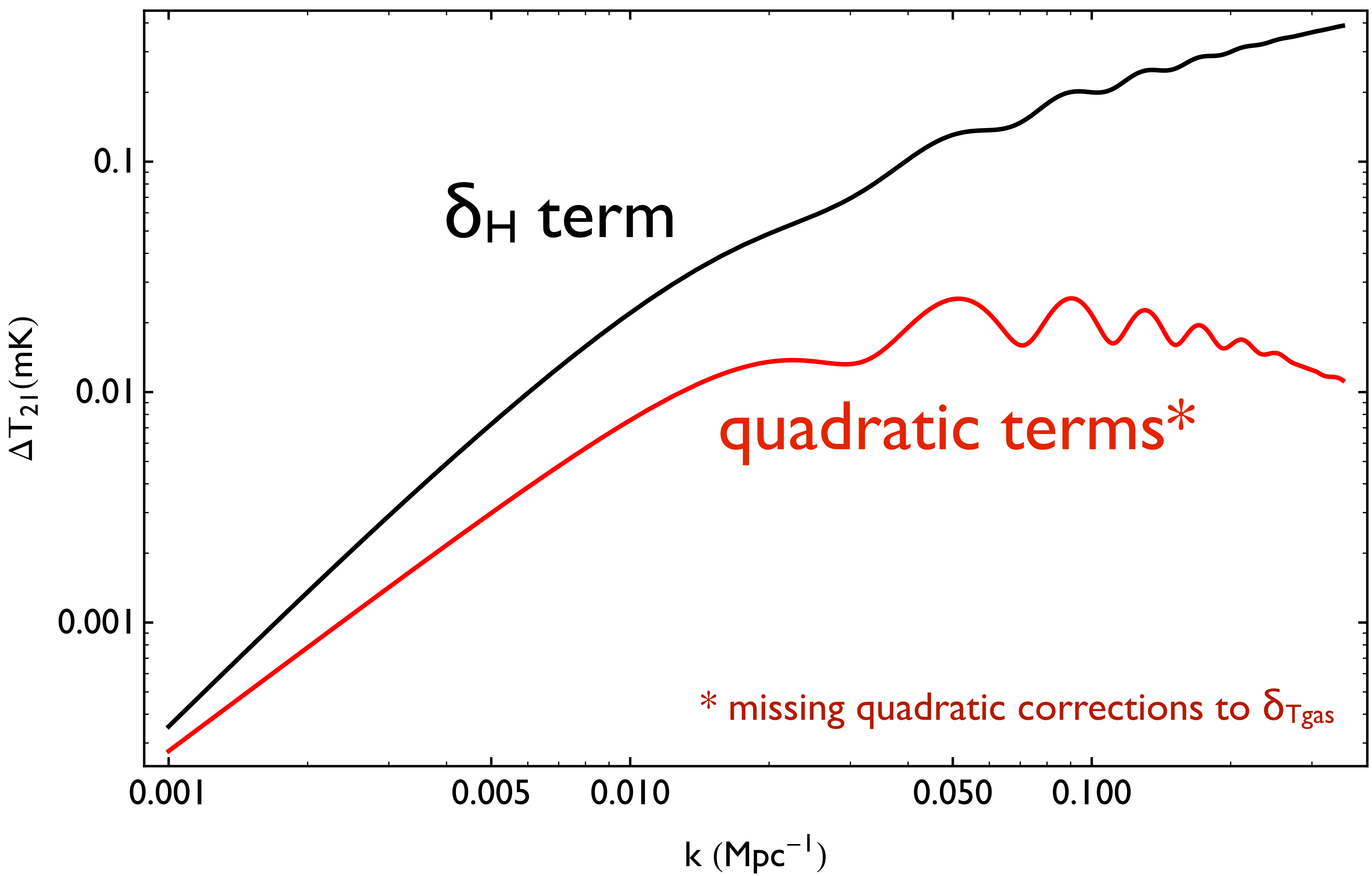
$$T_{\rm gas} \propto n_{\rm H}^{2/3}$$

$$\delta_{T_{\rm gas}} = \frac{2}{3}\delta_b - \frac{1}{9}\delta_b^2$$

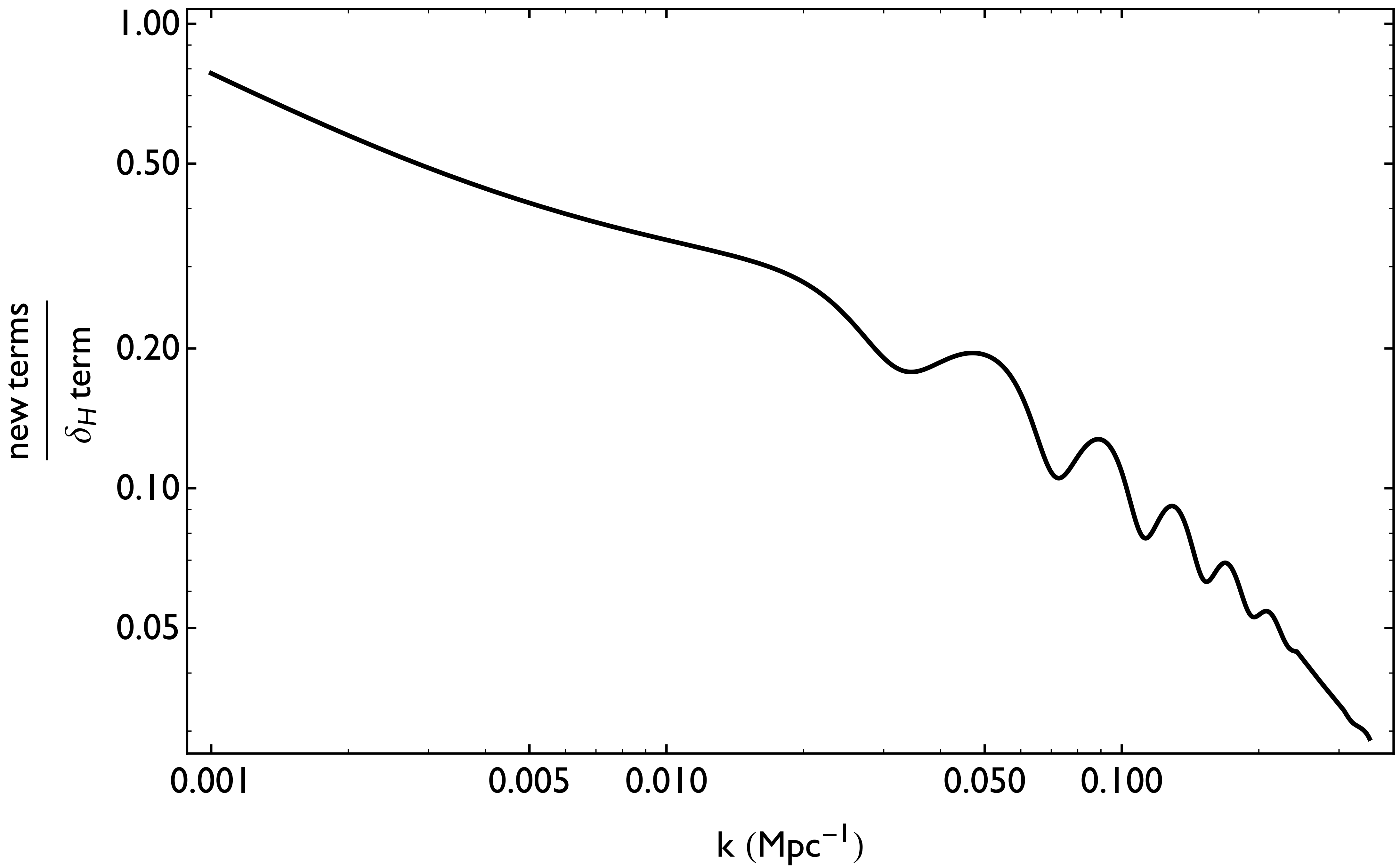
Expansion of $\delta T_{\rm gas}$ to second order in fluctuations:

$$\dot{T}_{\rm gas} - \frac{2}{3}\frac{\dot{n}_{\rm H}}{n_{\rm H}} T_{\rm gas} = \frac{3}{2}\gamma_{\rm C}\ x_e (T_{\rm cmb} - T_{\rm gas})$$

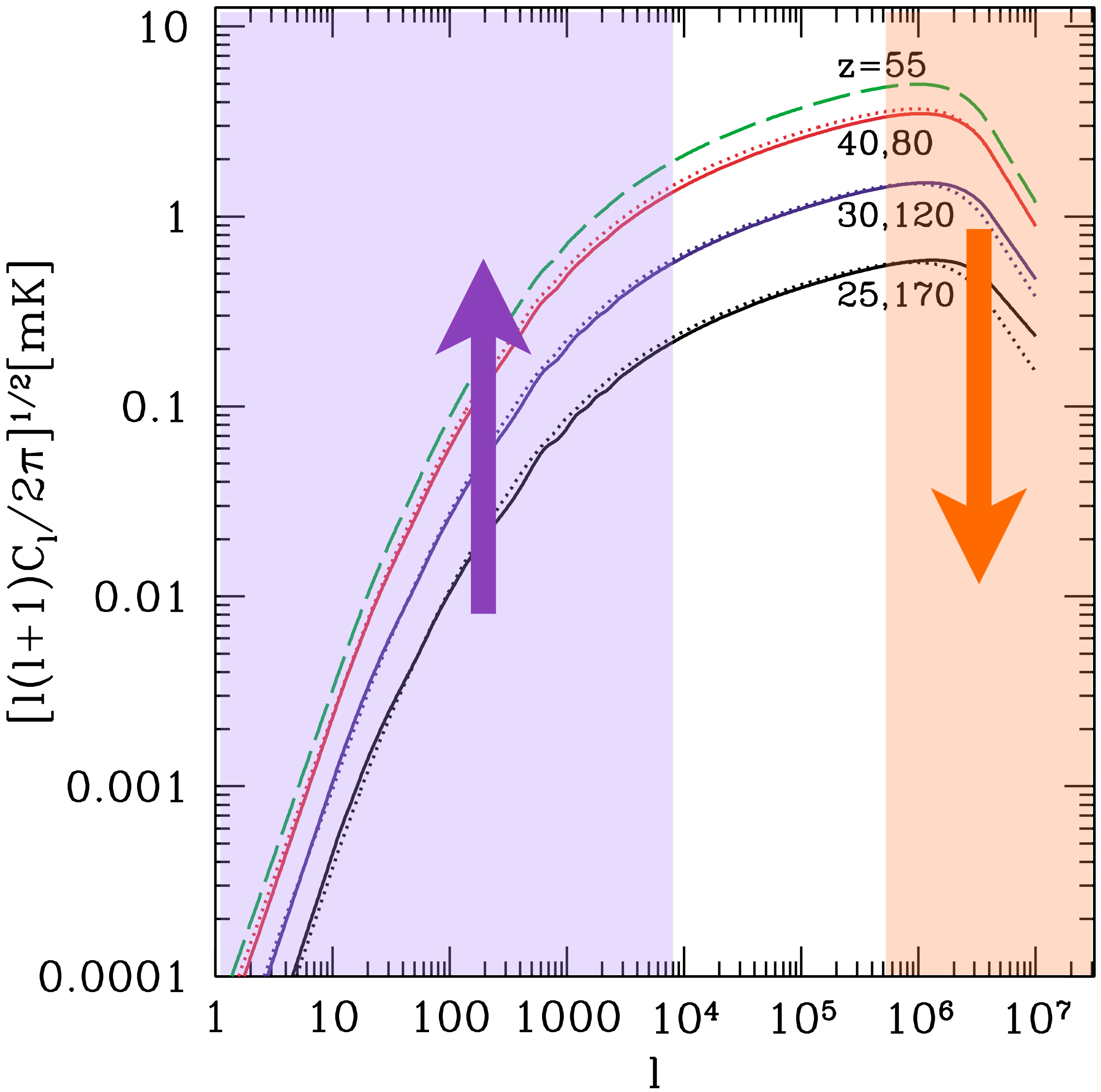
Characteristic 21cm fluctuations on large scales at z = 30 *(preliminary)*



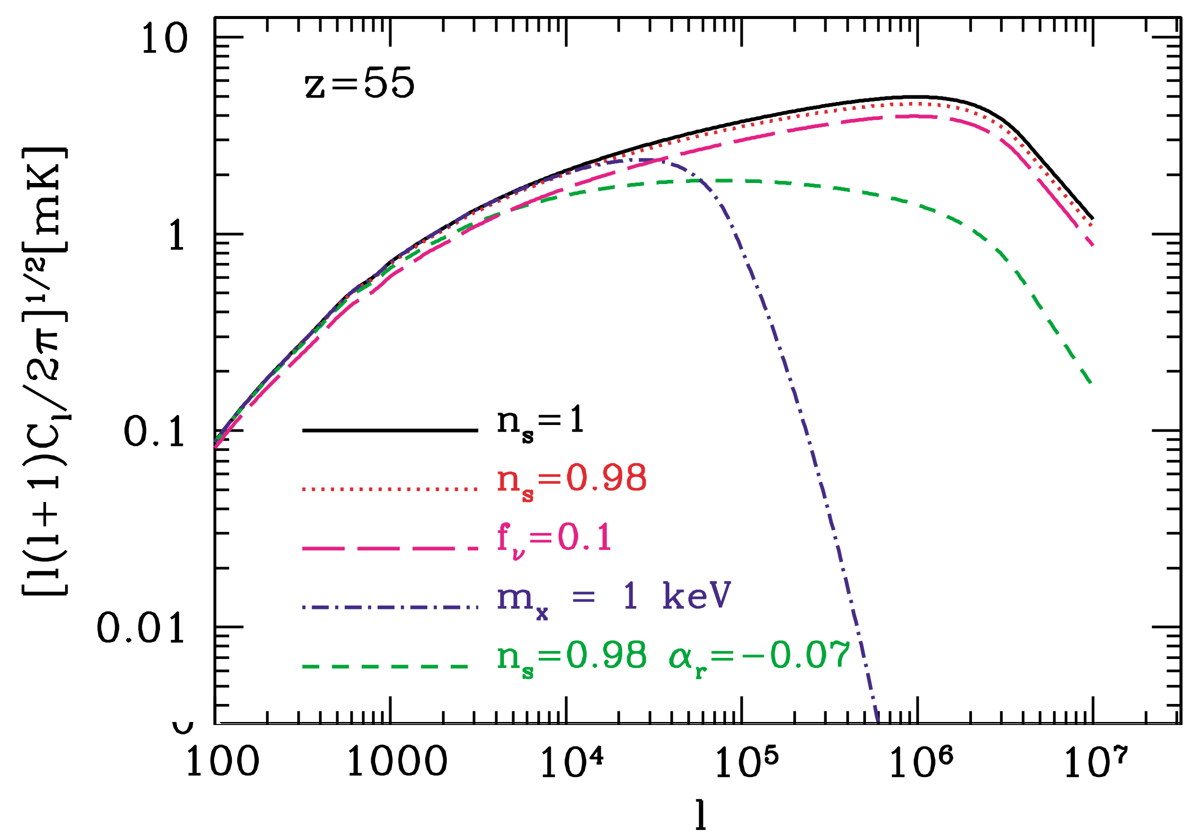
Characteristic 21cm fluctuations on large scales at z = 30 *(preliminary)*



Conclusions



- Relative velocity leads to O(1) suppression on Jeans scale and enhancement on BAO scale.



- Brings back small-scale physics to large angular scales!

Thank you, and keep posted!