Title: New light on 21cm intensity fluctuations from the dark ages

Date: Jan 28, 2014 11:00 AM

URL: http://pirsa.org/14010097

Abstract: Fluctuations of the 21 cm brightness temperature before the formation of the first stars hold the promise of becoming a high-precision cosmological probe in the future. The growth of over densities is very well described by perturbation theory at that epoch and the signal can in principle be predicted to arbitrary accuracy for given cosmological parameters. Recently, Tseliakhovich and Hirata pointed out a previously neglected and important physical effect, due to the fact that baryons and cold dark matter (CDM) have supersonic relative velocities after recombination. This relative velocity suppresses the growth of matter fluctuations on scales kâˆ¼10âˆ’10^3 Mpc^âˆ’1. In addition, the amplitude of the small-scale power spectrum is modulated on the large scales over which the relative velocity varies, corresponding to kâˆ¼0.005âˆ’1 Mpc^âˆ’1. In this talk, I will describe the effect of the relative velocity on 21 cm brightness temperature fluctuations from redshifts zâ‰¥30. I will show that the 21 cm power spectrum is affected on most scales. On small scales, the signal is typically suppressed several tens of percent, except for extremely small scales (kâ‰³2000 Mpcâˆ’1) for which the fluctuations are boosted by resonant excitation of acoustic waves. On large scales, 21 cm fluctuations are enhanced due to the non-linear dependence of the brightness temperature on the underlying gas density and temperature. The enhancement of the 21 cm power spectrum is of a few percent at kâˆ¼0.1 Mpcâˆ’1 and up to tens of percent at kâ‰²0.005 Mpcâˆ’1, for standard Î›CDM cosmology. In principle this effect allows to probe the small-scale matter power spectrum not only through a measurement of small angular scales but also through its effect on large angular scales.

New light on 21cm intensity fluctuations from the dark ages:

effect of baryon-cdm relative velocities

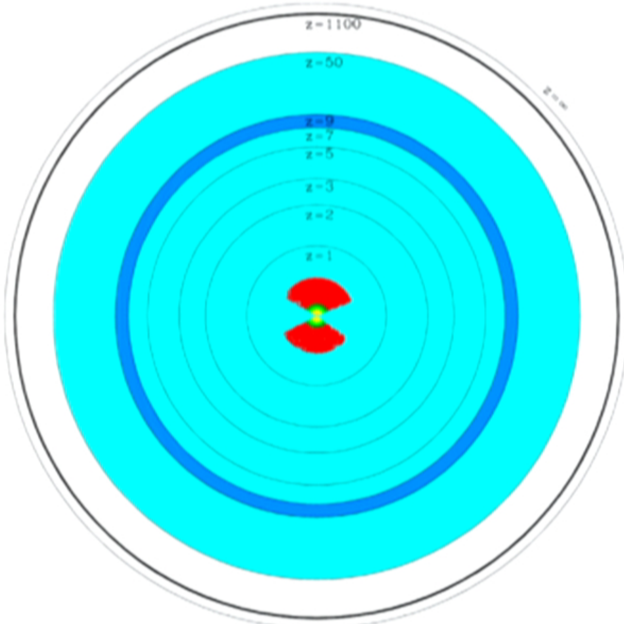
Yacine Ali-Haïmoud (IAS)

with Daan Meerburg & Sihan Yuan

arXiv:1312.4948

Perimeter Institute, january 28, 2014

New frontiers with 21cm cosmology



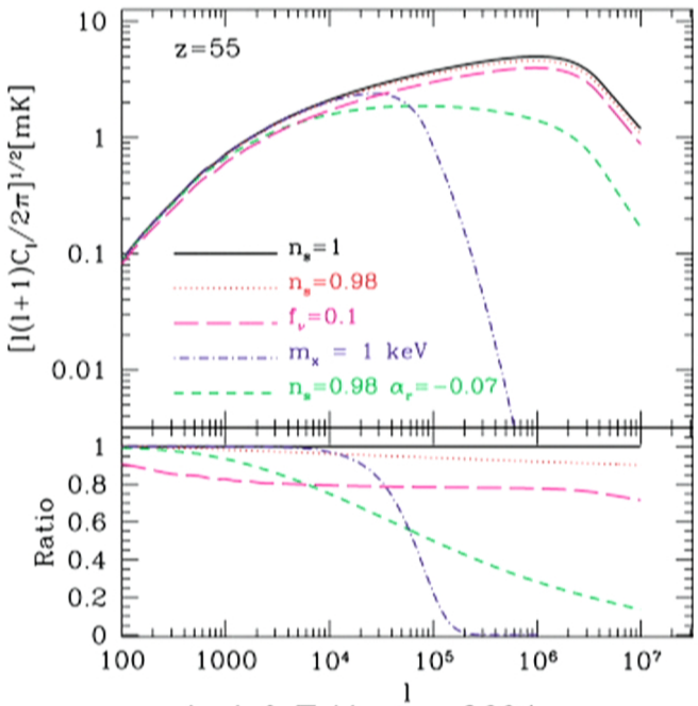
Tegmark & Zaldarriaga 2009

<u>The time frontier:</u>

CMB: thin shell around z=1100
Large-scale structure: $z \lesssim 1$
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



Loeb & Zaldarriaga 2004

The scale frontier:

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

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

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

- Tests of inflation: n_s, running
- Warm dark matter
- Massive neutrinos
- Non-gaussianity

A very challenging observation

- Earth ionosphere becomes opaque for $\nu \lesssim 10$ MHz ($z \gtrsim 140$)
- Foreground emission steeply raises at low frequencies

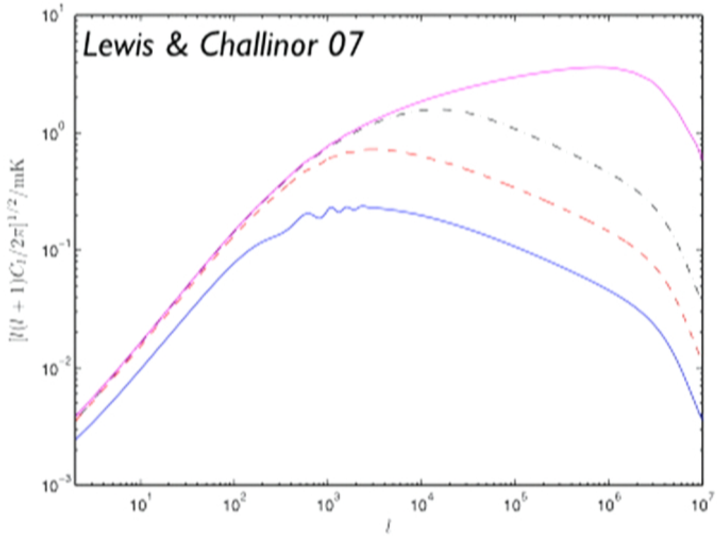


FIG. 8 (color online). The 21 cm power spectrum at $z = 50$ for $\Delta\nu = \{1, 0.1, 0.01, 0\}$ MHz (bottom to top). Large widths sup-

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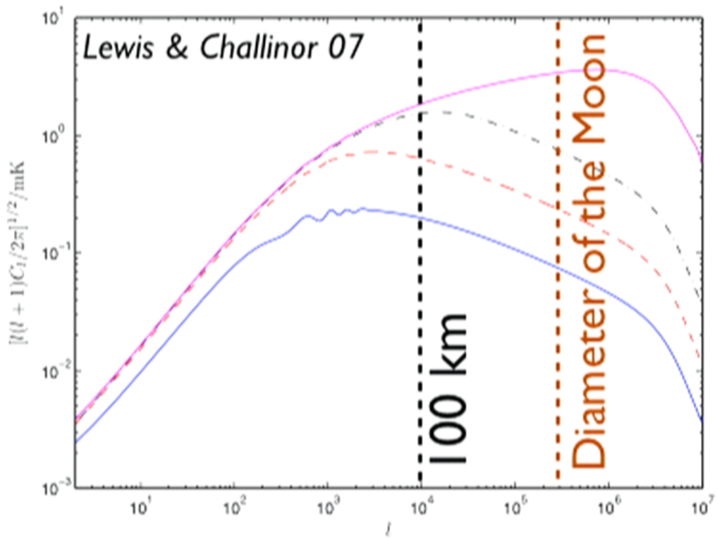

FIG. 8 (color online). The 21 cm power spectrum at $z = 50$ for $\Delta\nu = \{1, 0.1, 0.01, 0\}$ MHz (bottom to top). Large widths sup-

At z = 50, λ = 10 m.

Array size ≈ 1 km (ℓ /100)

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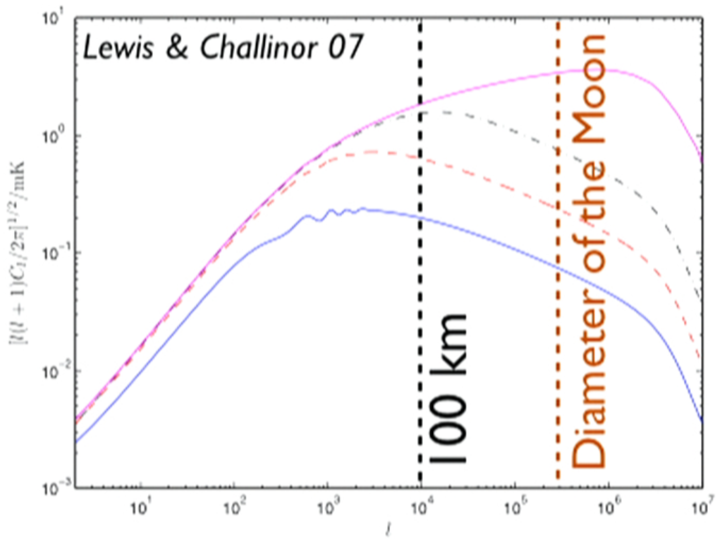


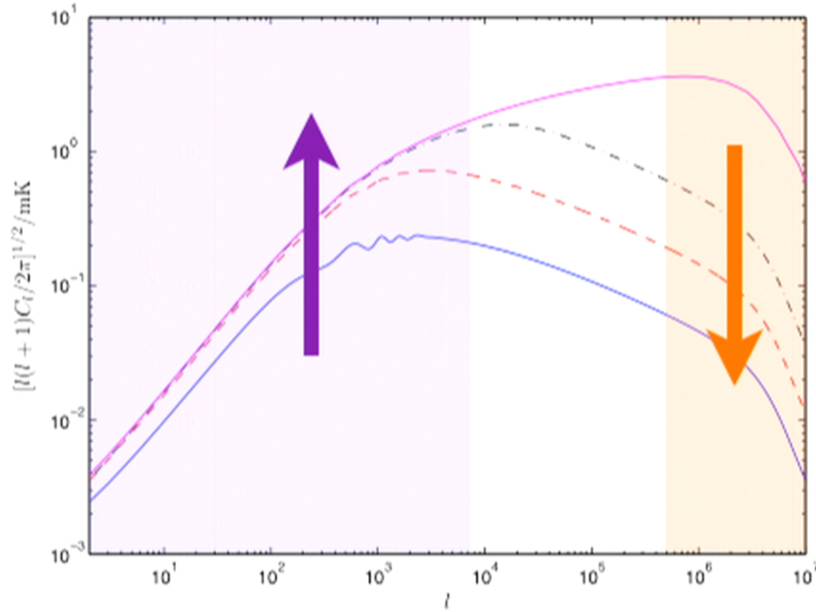
FIG. 8 (color online). The 21 cm power spectrum at $z = 50$ for $\Delta\nu = \{1, 0.1, 0.01, 0\}$ MHz (bottom to top). Large widths sup-

At z = 50, λ = 10 m.
Array size ≈ 1 km (ℓ/100)

Measuring anisotropies on angular scales $\ell \gtrsim 10^4$-10^5 (corresponding to k ≳ 1-10 Mpc^{-1}) is, in practice, undoable.

Bottom line of this work

Accounting for the relative velocity of baryons and CDM
(1) decreases the small-scale power spectrum
(2) enhances the large-scale power spectrum, with an **enhancement depending on small-scale power**



21cm line: basic facts

F = 1

F = 0

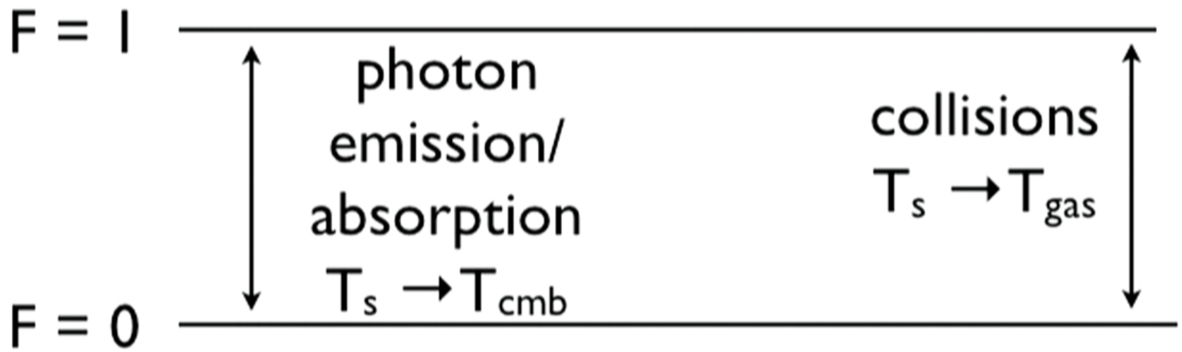
$E_{10} = 6\ \mu eV = 68\ mK$

$\nu_{10} = 1420\ MHz$

$\lambda_{10} = 21.1 cm$

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

Spin temperature



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

21cm brightness temperature

$h\nu \ll kT \qquad \tau \ll 1$

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

21cm optical depth

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

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

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

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

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

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

Bottom line

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

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

Fluctuations of T_b probe the underlying density power spectrum

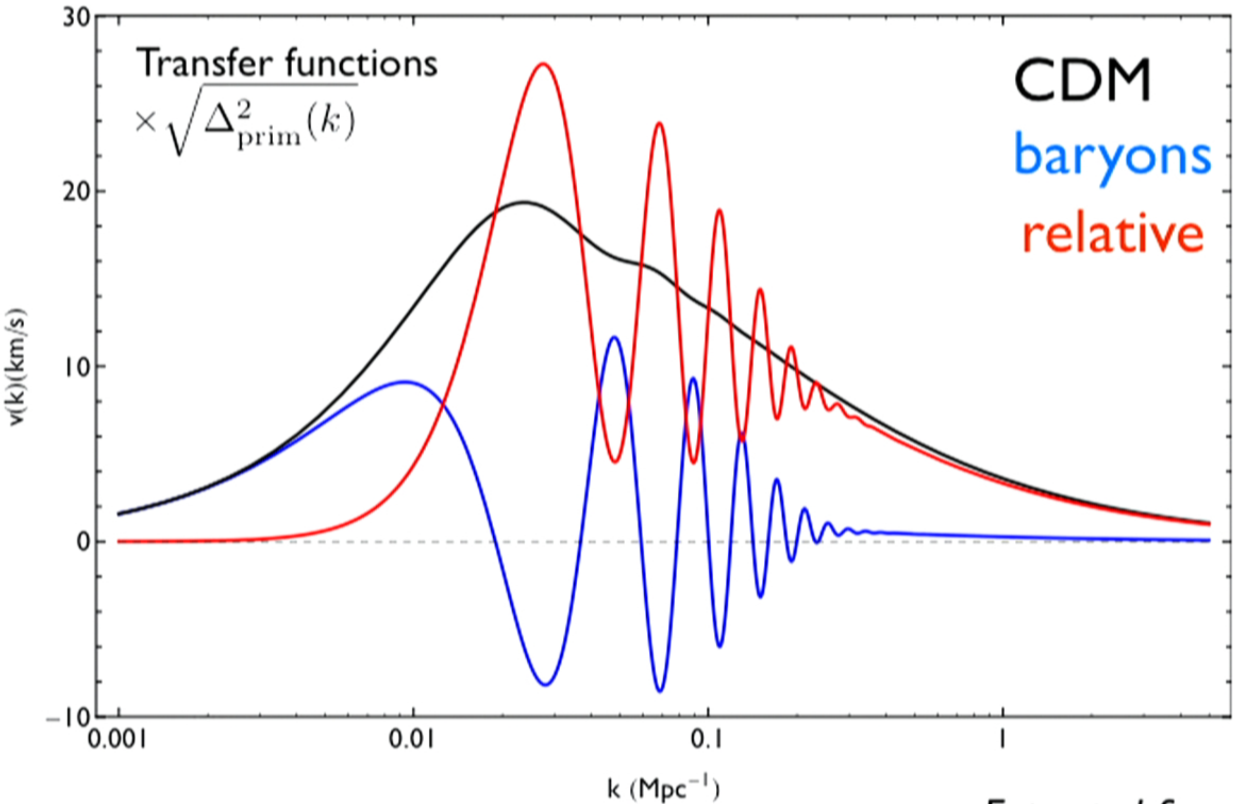
The relative velocity effect

(Tseliakhovich & Hirata 2010)

- Prior to recombination, baryons tightly coupled to photons ⇒ acoustic oscillations.
- Meanwhile, the CDM perturbations grow under their own gravity.
- After recombination, for $k < k_{Jeans}$, baryons and CDM perturbations grow together, BUT

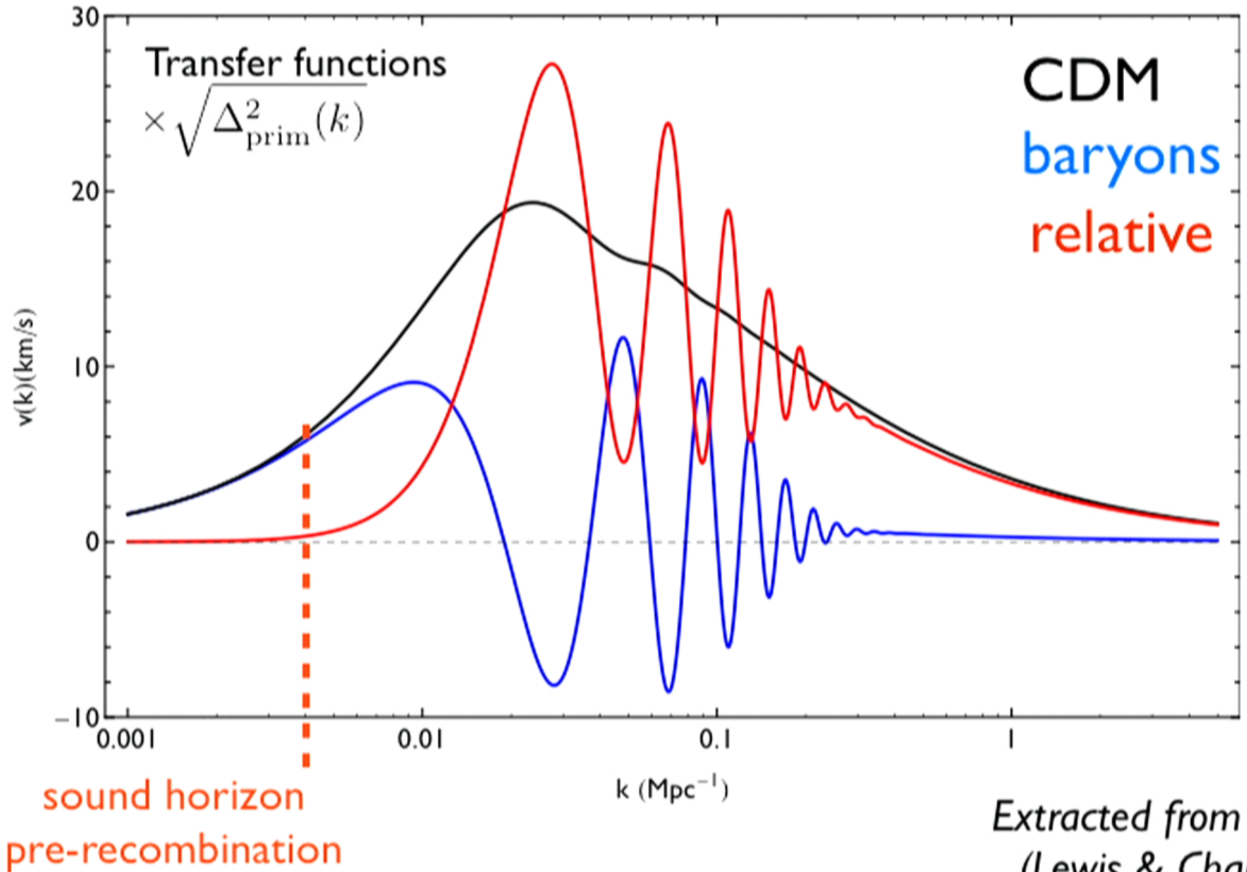
At $z = z_{rec} \approx 1000$, very different "initial conditions" for baryons and CDM.

Characteristic velocities at z = 1000



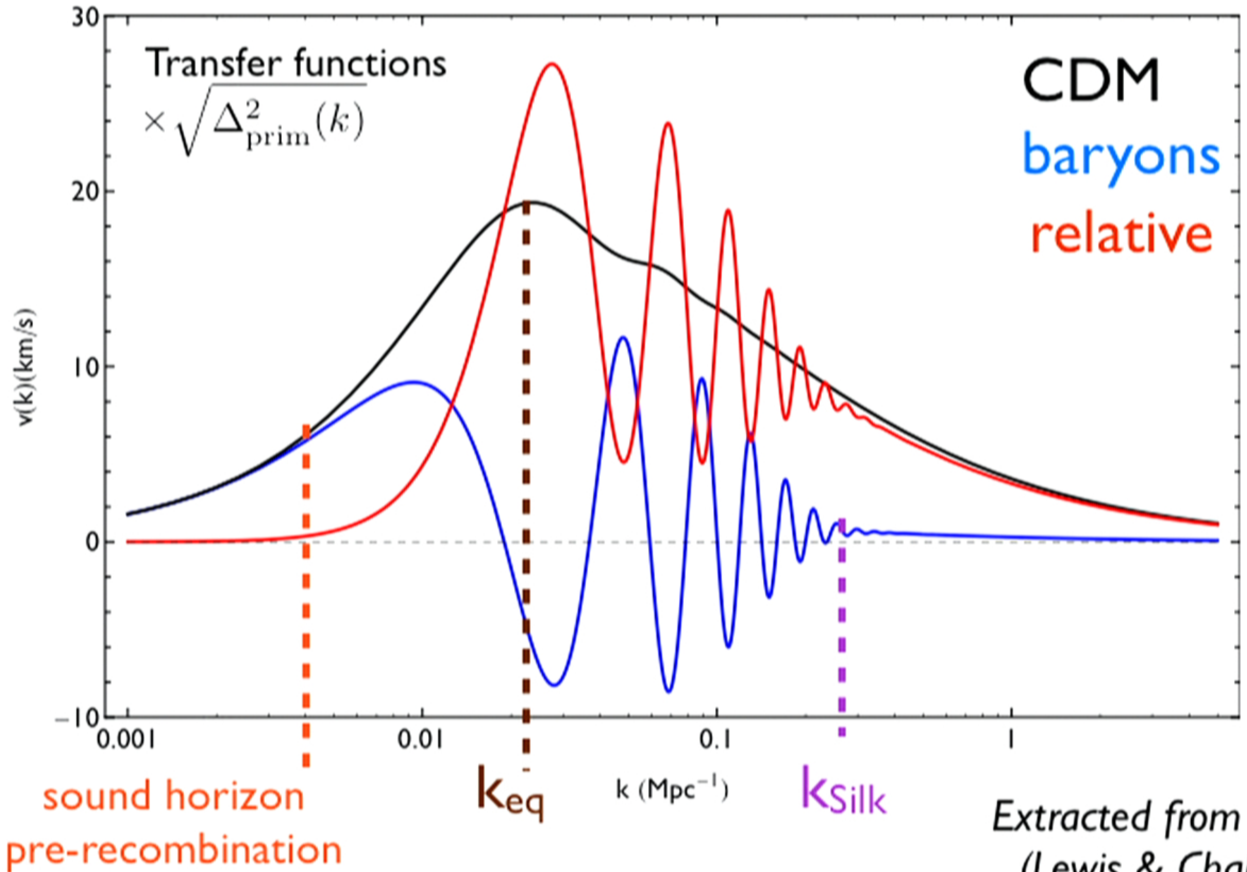
Extracted from CAMB (Lewis & Challinor)

Characteristic velocities at z = 1000



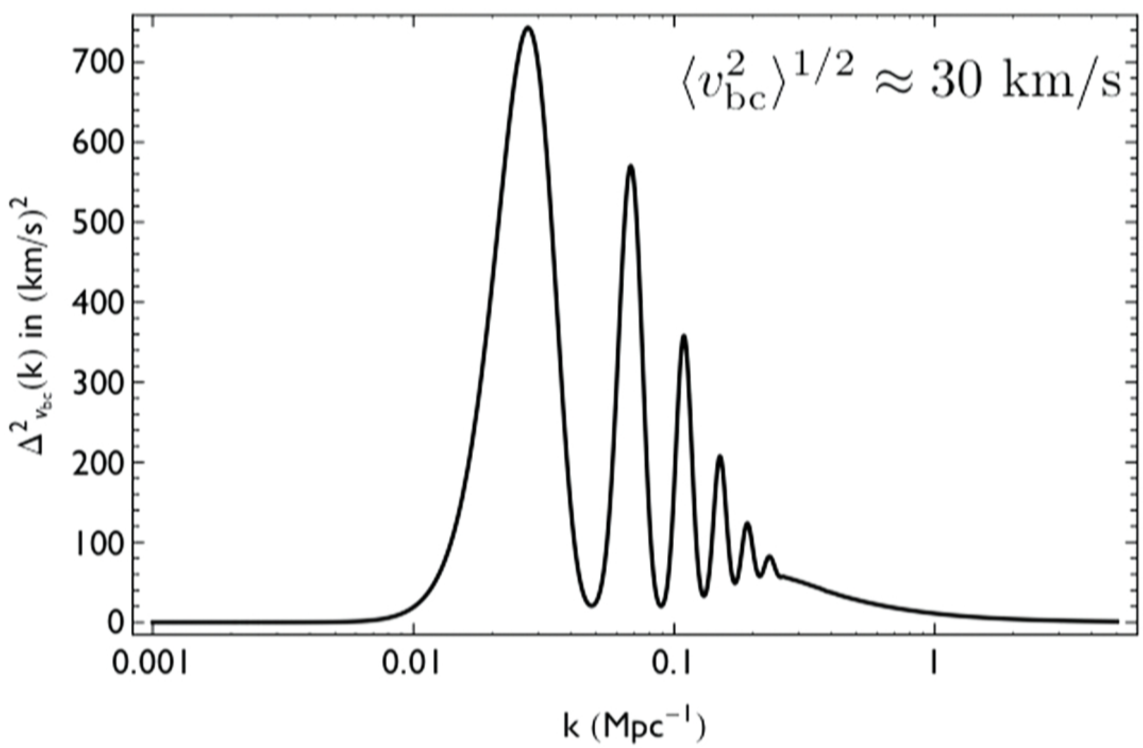
Extracted from CAMB (Lewis & Challinor)

Characteristic velocities at z = 1000

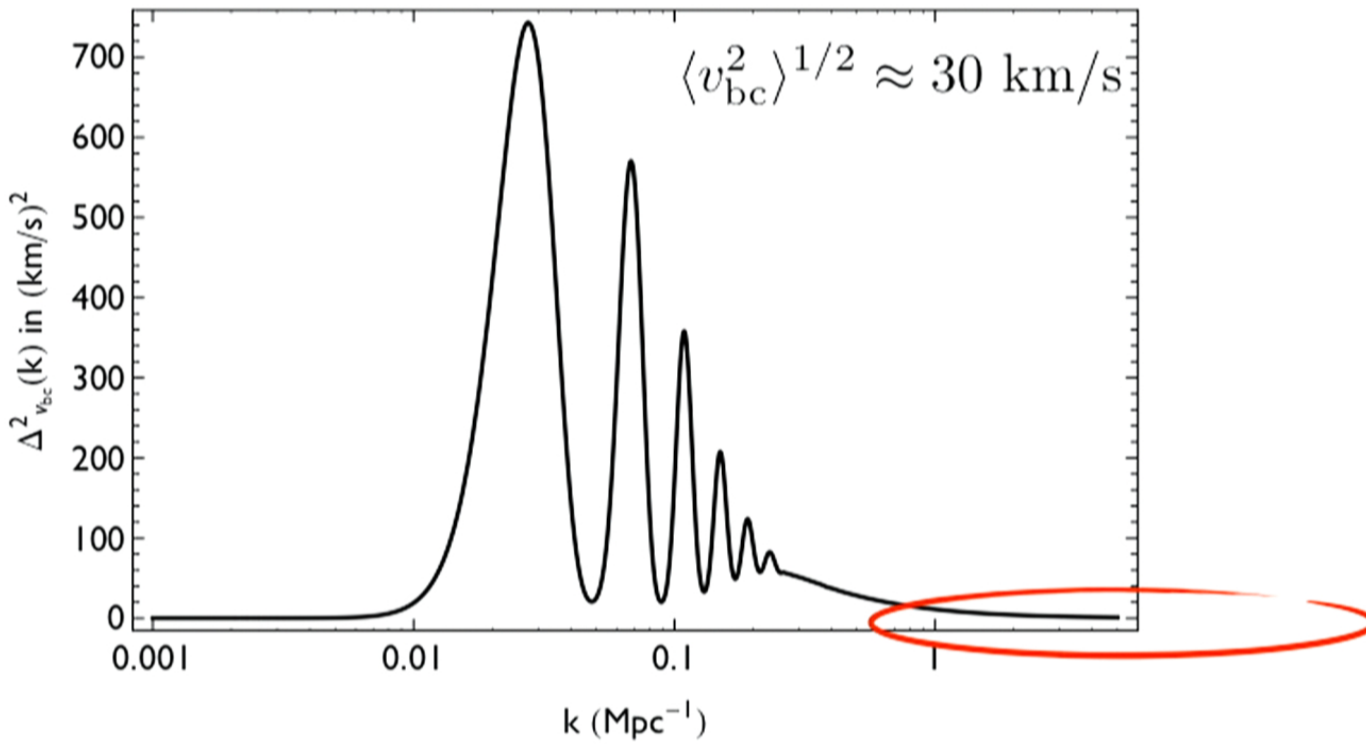


Extracted from CAMB
(Lewis & Challinor)

Relative velocity power spectrum

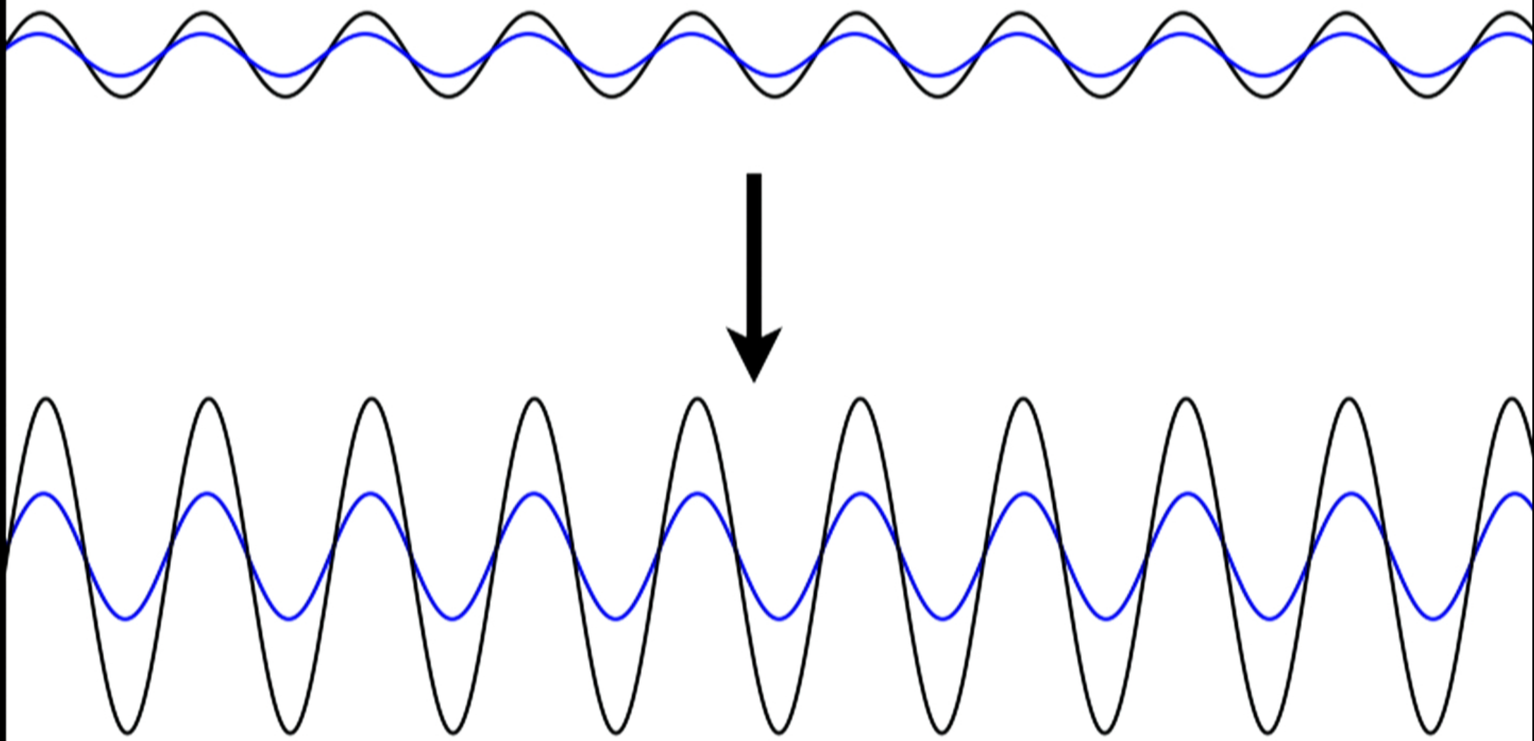


Relative velocity power spectrum

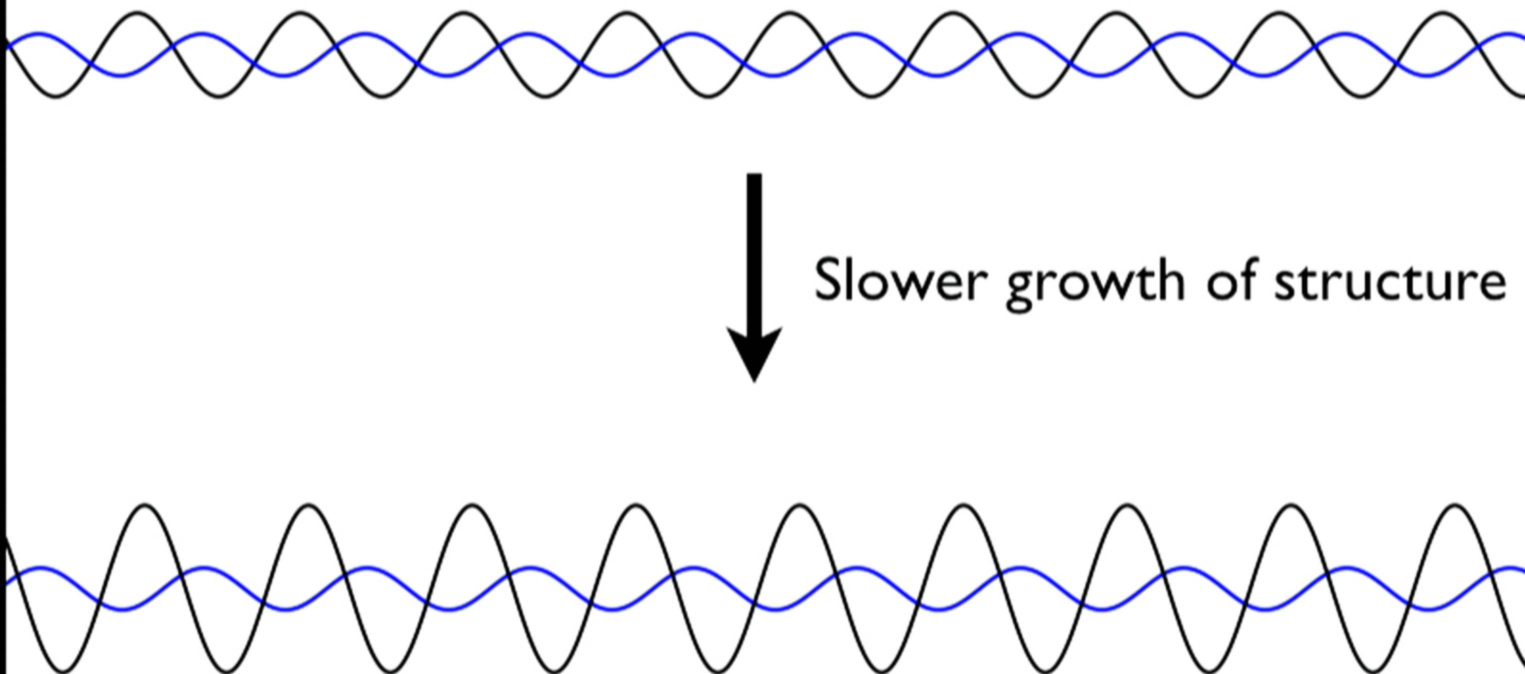


v_{bc} nearly uniform on a few Mpc scale: $k_{coh} \sim 0.3$ Mpc^{-1}

Without relative velocity



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



- Scale of suppression vs coherence scale:

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

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

- 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:

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

Method of computation

- Fluid equations in the local baryon rest frame

$$\dot{\delta}_c - ia^{-1}(\boldsymbol{v}_{\rm bc} \cdot \boldsymbol{k})\delta_c + \theta_c = 0,$$

$$\dot{\theta}_c - ia^{-1}(\boldsymbol{v}_{\rm bc} \cdot \boldsymbol{k})\theta_c + 2H\theta_c - k^2\phi = 0,$$

$$\dot{\delta}_b + \theta_b = 0,$$

$$\dot{\theta}_b + 2H\theta_b - \frac{k^2}{a^2}\phi - \frac{\bar{c}_s^2}{a^2}k^2\left(\delta_b + \delta_{T_{\rm gas}}\right) = 0,$$

$$\frac{k^2}{a^2}\phi = -\frac{3}{2}\frac{H_0^2}{a^3}\left(\Omega_b^0\delta_b + \Omega_c^0\delta_c\right),$$

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

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

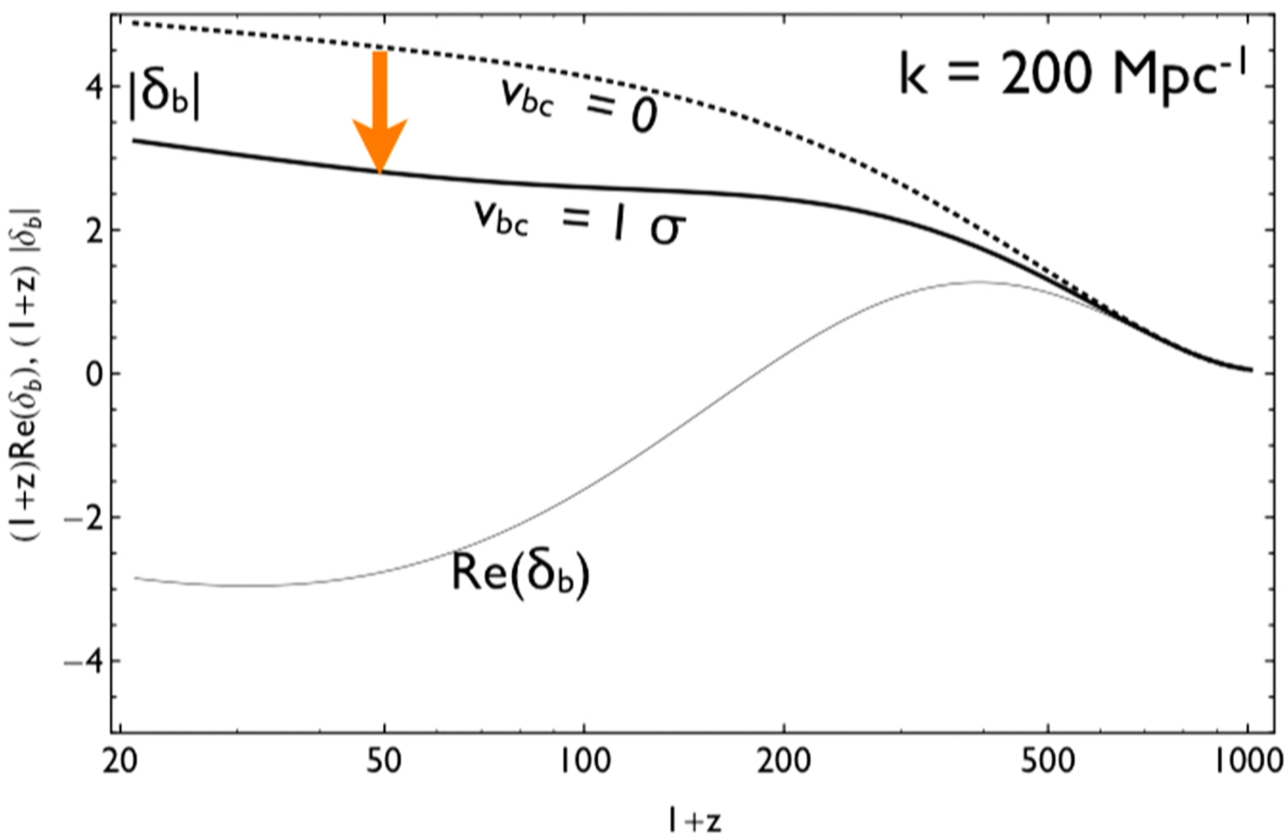
Peebles C-factor

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: 1- small scales



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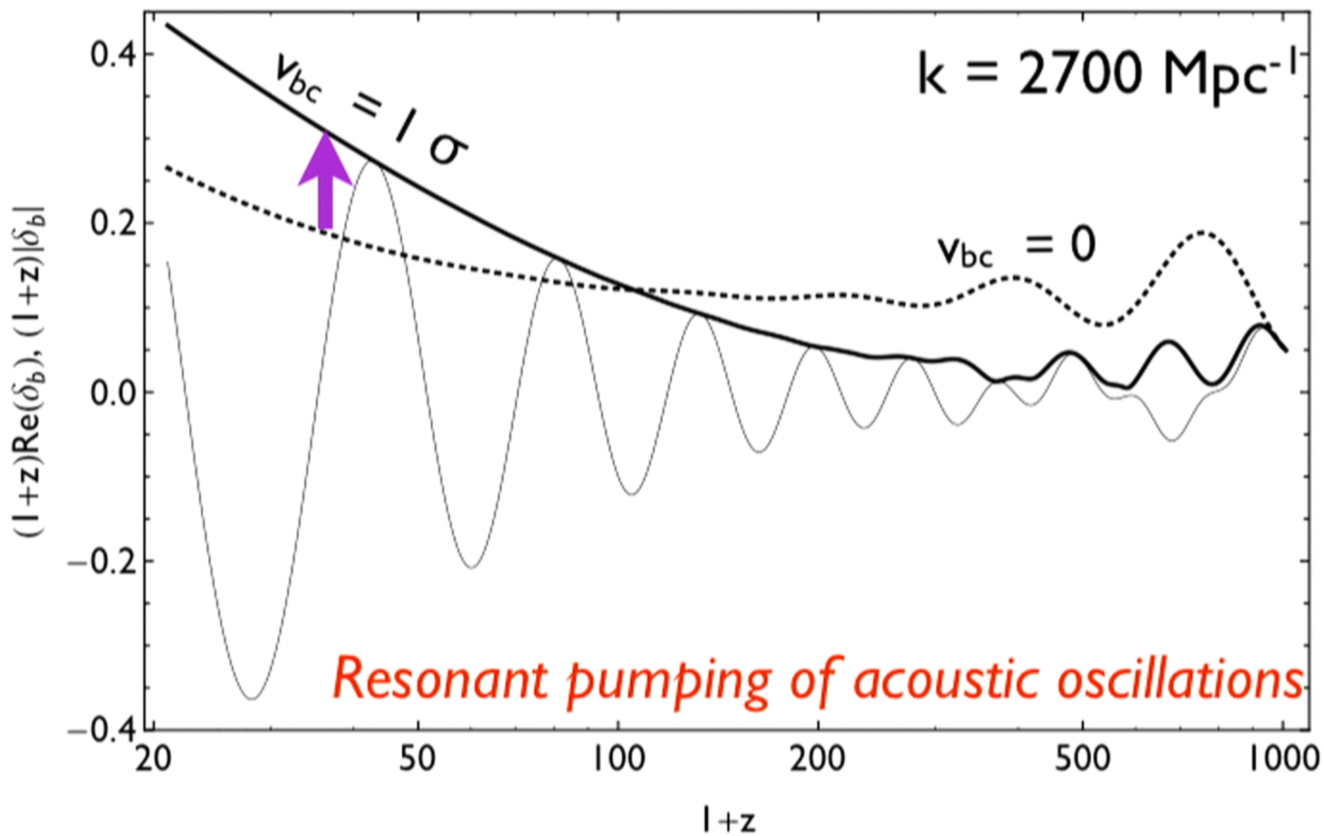
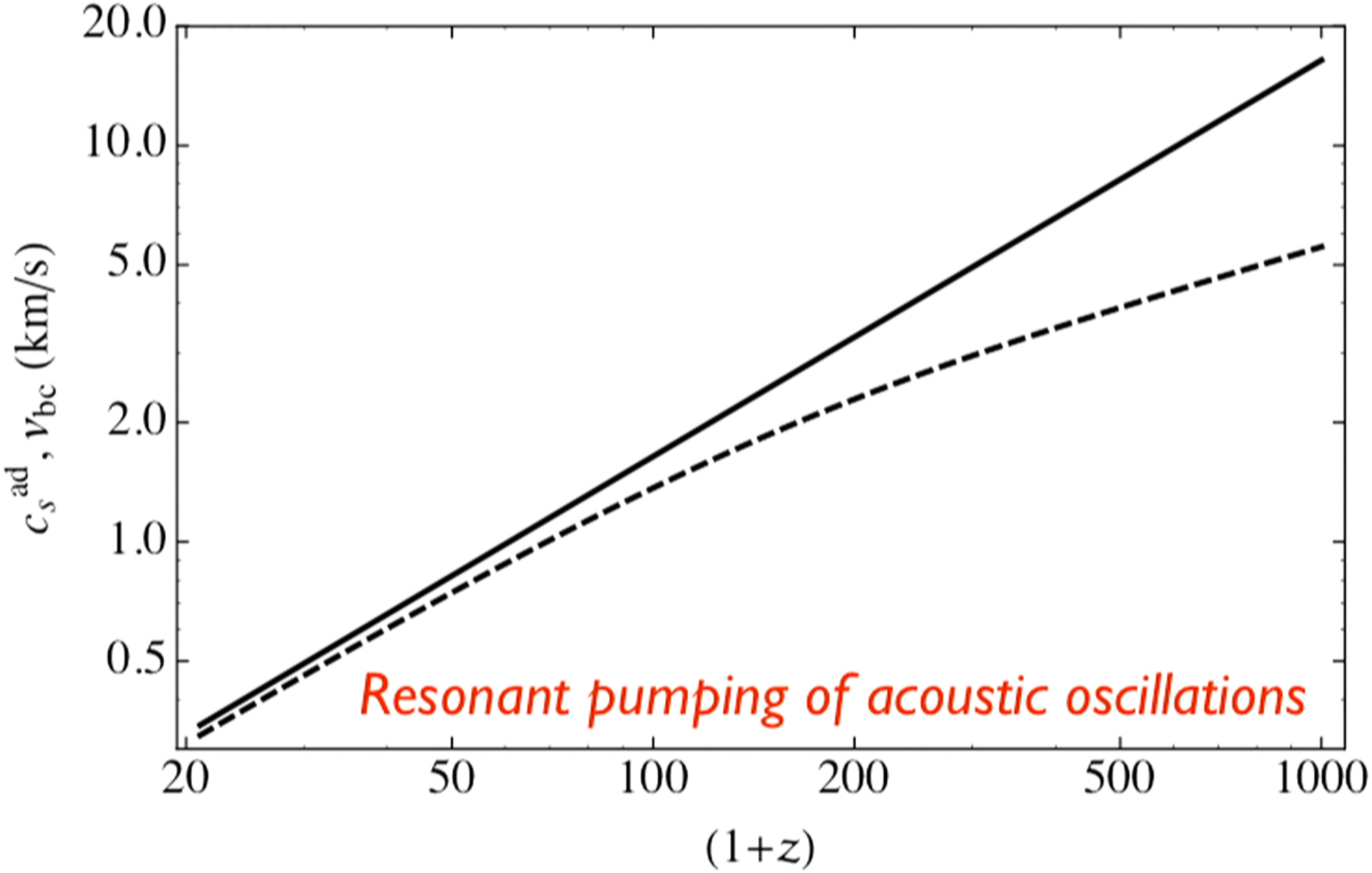
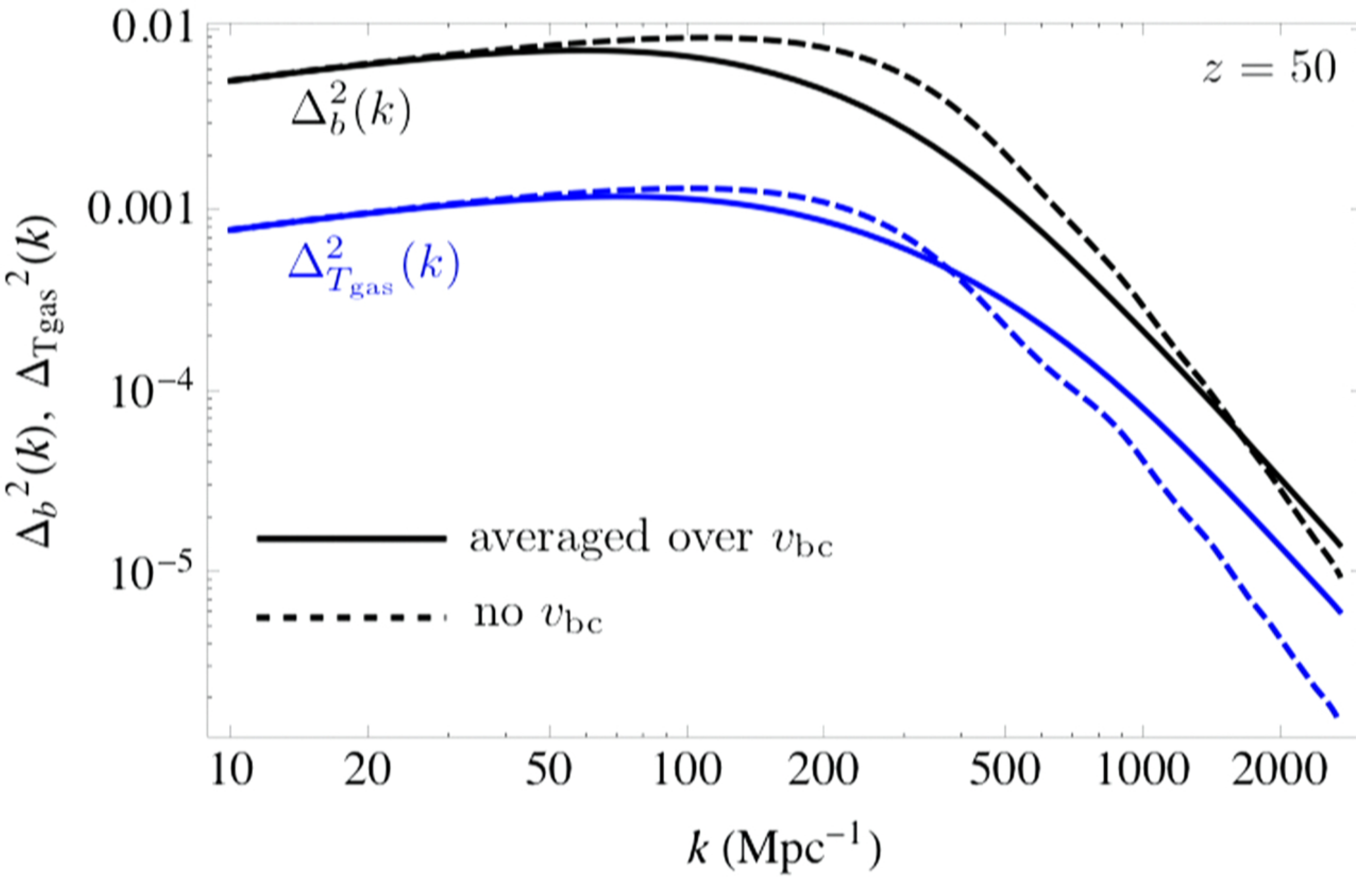


Results: I- small scales



Results: I- small scales



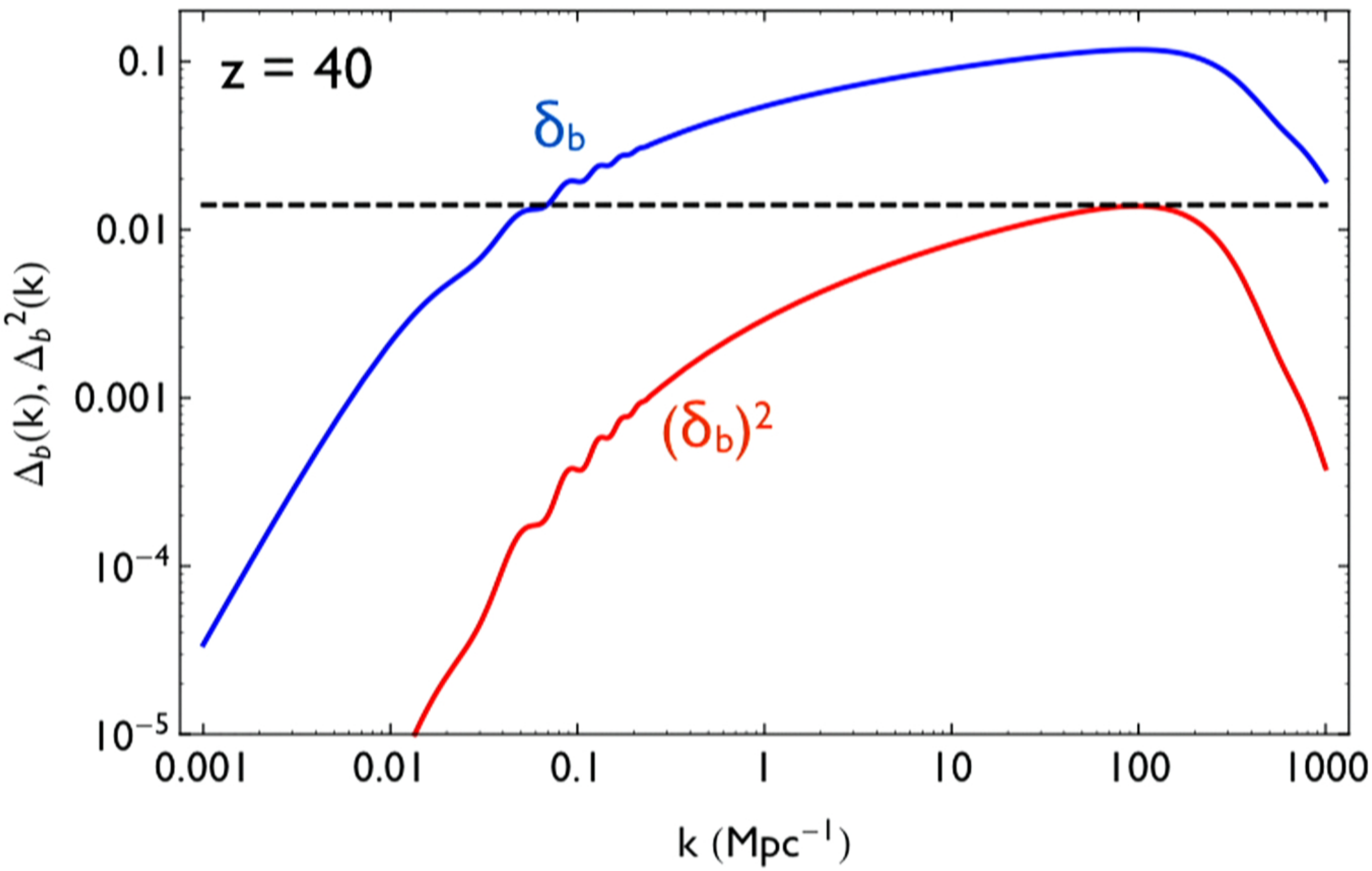
Effect on the large-scale signal

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

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

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

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


z = 40
δb
(δb)²
0.1
0.01
0.001
10⁻⁴
10⁻⁵
Δb(k), Δb²(k)
0.001
0.01
0.1
1
10
100
1000
k (Mpc⁻¹)

Effect on the large-scale signal

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

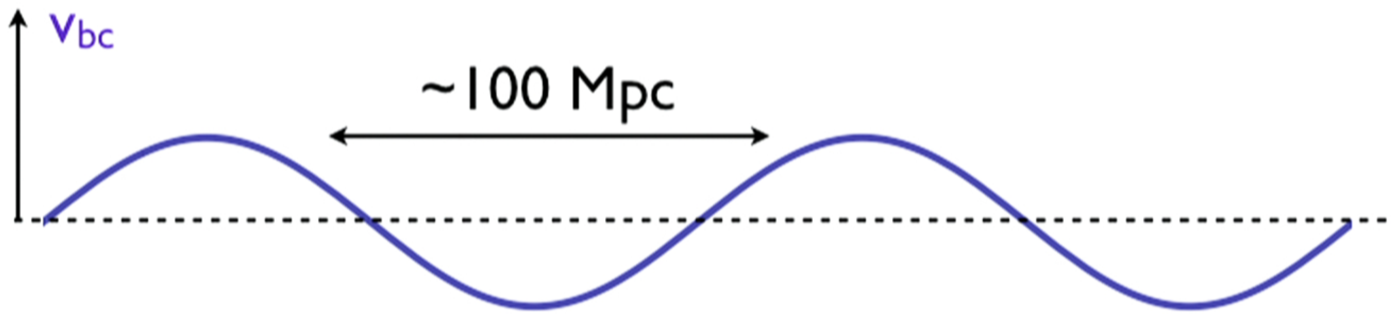
$\tau \propto \frac{n_{\rm H}}{T_s(H + \partial_{||} v_{||})}$ $\qquad T_s(n_{\rm H}, T_{\rm gas})$

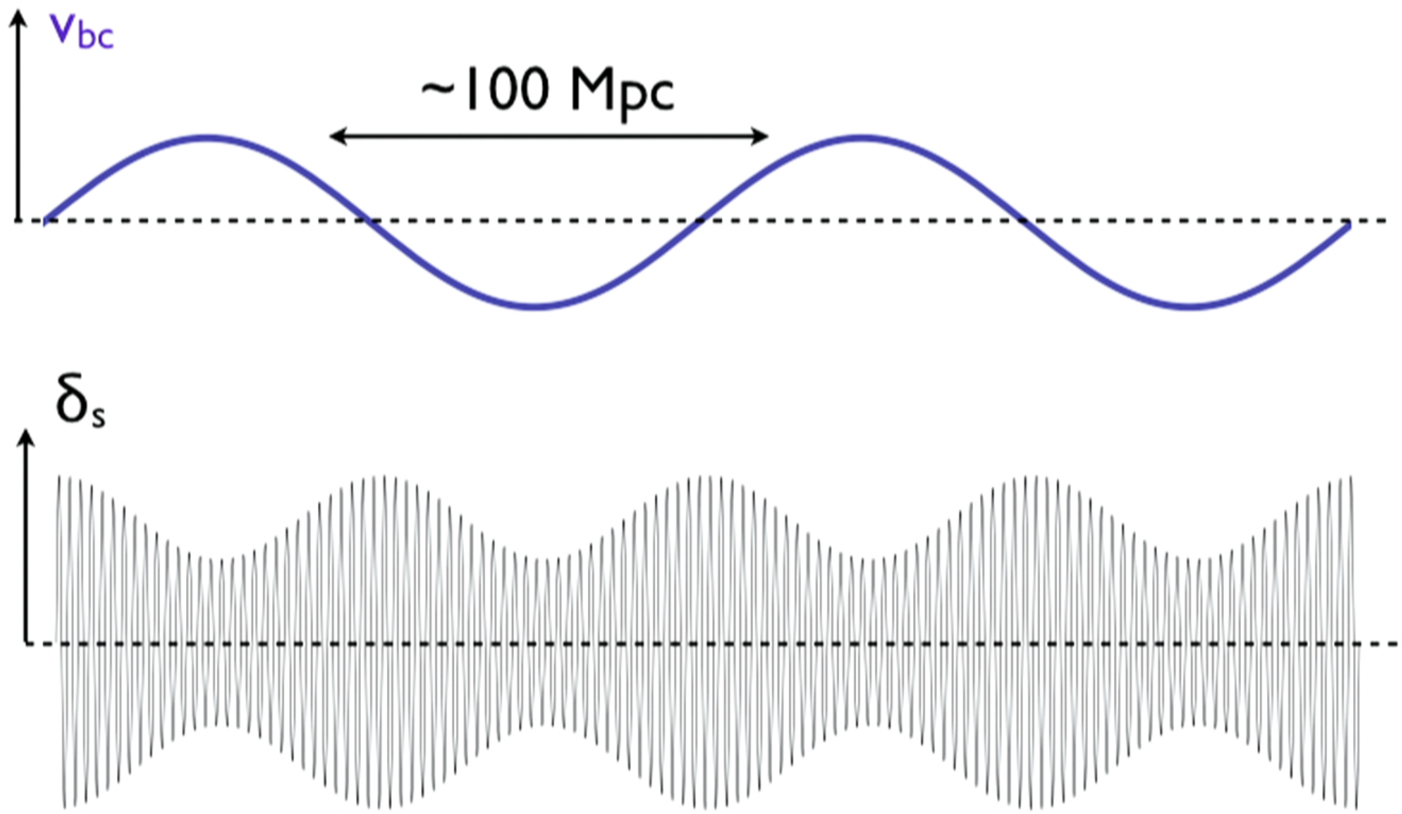
☞ **T_b is a fully non-linear function of the δ's**

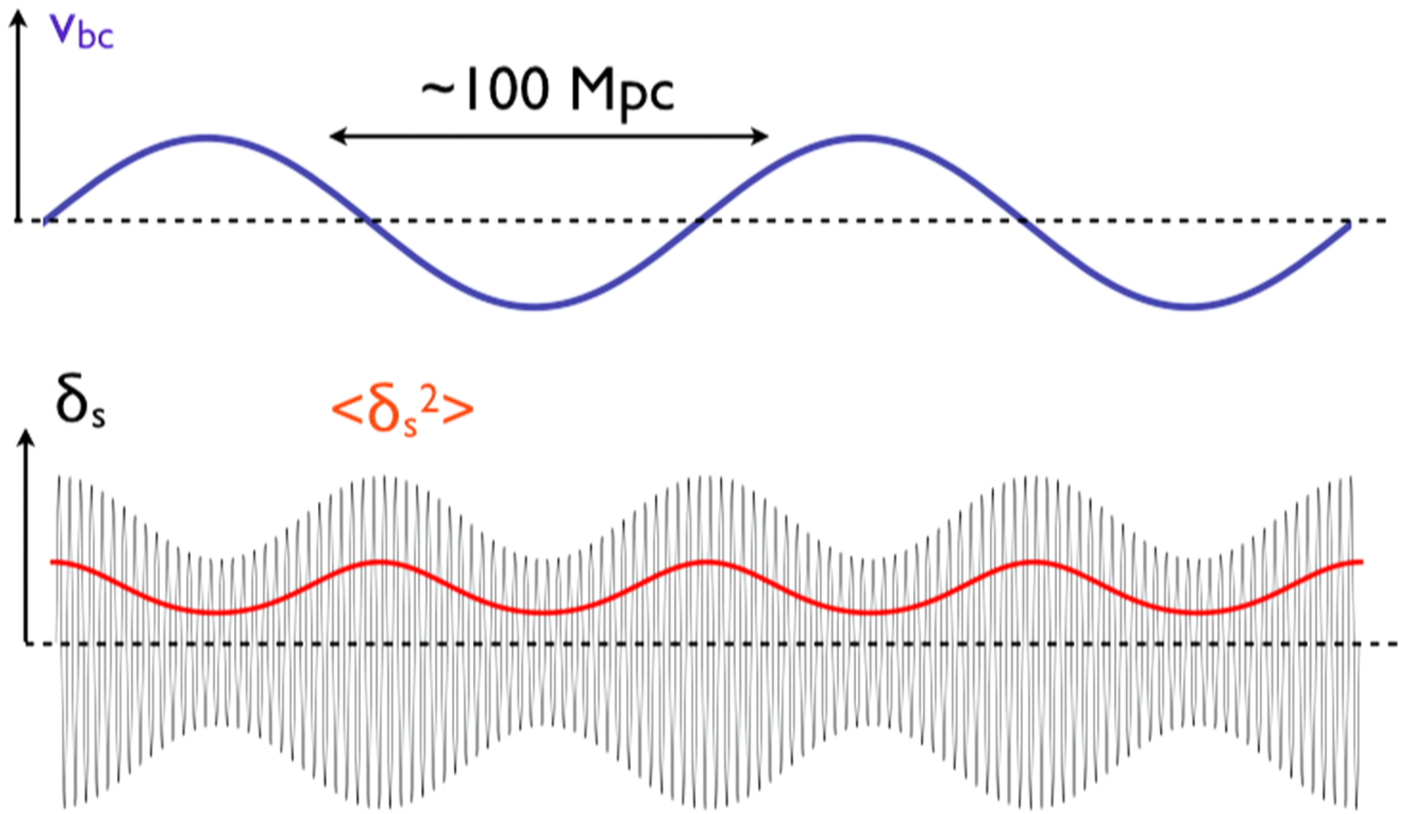
$$\delta T_b = T_1\ \delta + T_2\ \delta^2 + ...$$

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

$$(\delta T_b)_l = T_1 \delta_l + T_2 (\delta_s^2)_l + \ldots$$


v_bc
~100 Mpc


v_{bc}
~100 Mpc
δ_s



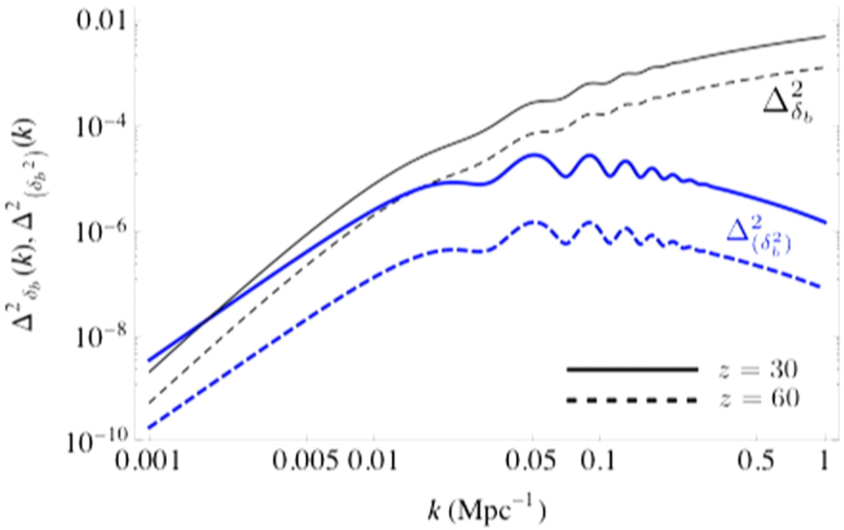
$$(\delta^2)_l = \langle \delta_s^2 \rangle_l \sim \delta_s^2$$

Power spectrum of (δ_b^2)

$$(\delta_s^2)_l = \langle \delta_s^2 \rangle_l = \Delta \int \frac{d^3k}{(2\pi)^3} P_\delta(k; v_{\rm bc})$$

Correlation function $\xi_{\delta^2}(x') \equiv \left\langle \langle \delta_s^2 \rangle_{v_{\rm bc}(x)} \langle \delta_s^2 \rangle_{v_{\rm bc}(x+x')} \right\rangle$

$$P_{\delta^2}(k) = \text{Fourier}(\xi_{\delta^2}(x))$$



- Expansion of δT_b to second order in fluctuations:

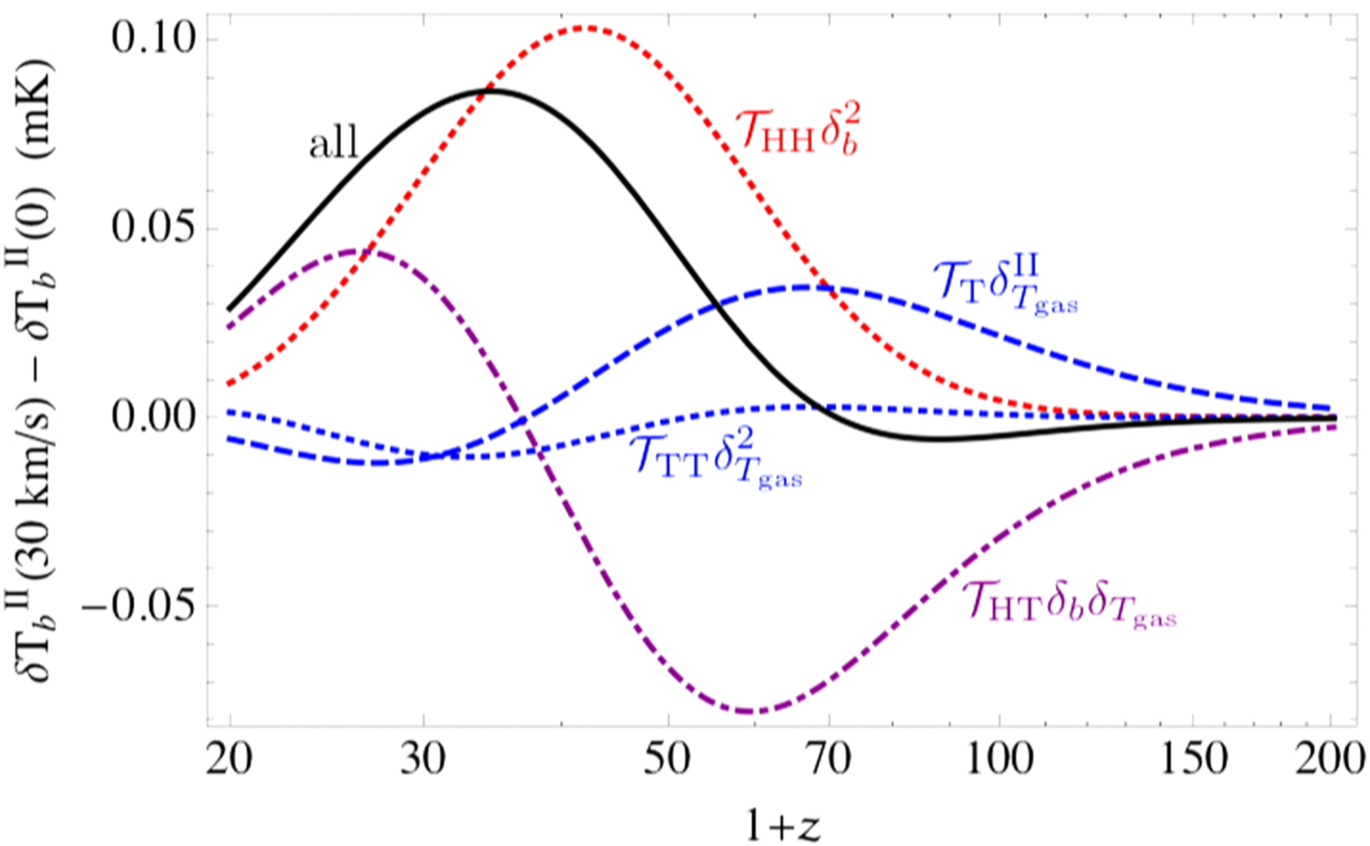
$$\delta T_b^{\rm obs} = \mathcal{T}_{\rm H}\ \delta_{\rm H} + \mathcal{T}_T\ \delta_{T_{\rm gas}} - \overline{T}_b\ \delta_v + \mathcal{T}_{\rm HH}\Delta(\delta_{\rm H}^2) + \mathcal{T}_{TT}\Delta(\delta_{T_{\rm gas}}^2) + \mathcal{T}_{{\rm H}T}\Delta(\delta_{\rm H}\delta_{T_{\rm gas}})$$

- Gas temperature fluctuations must also be expanded to second order:

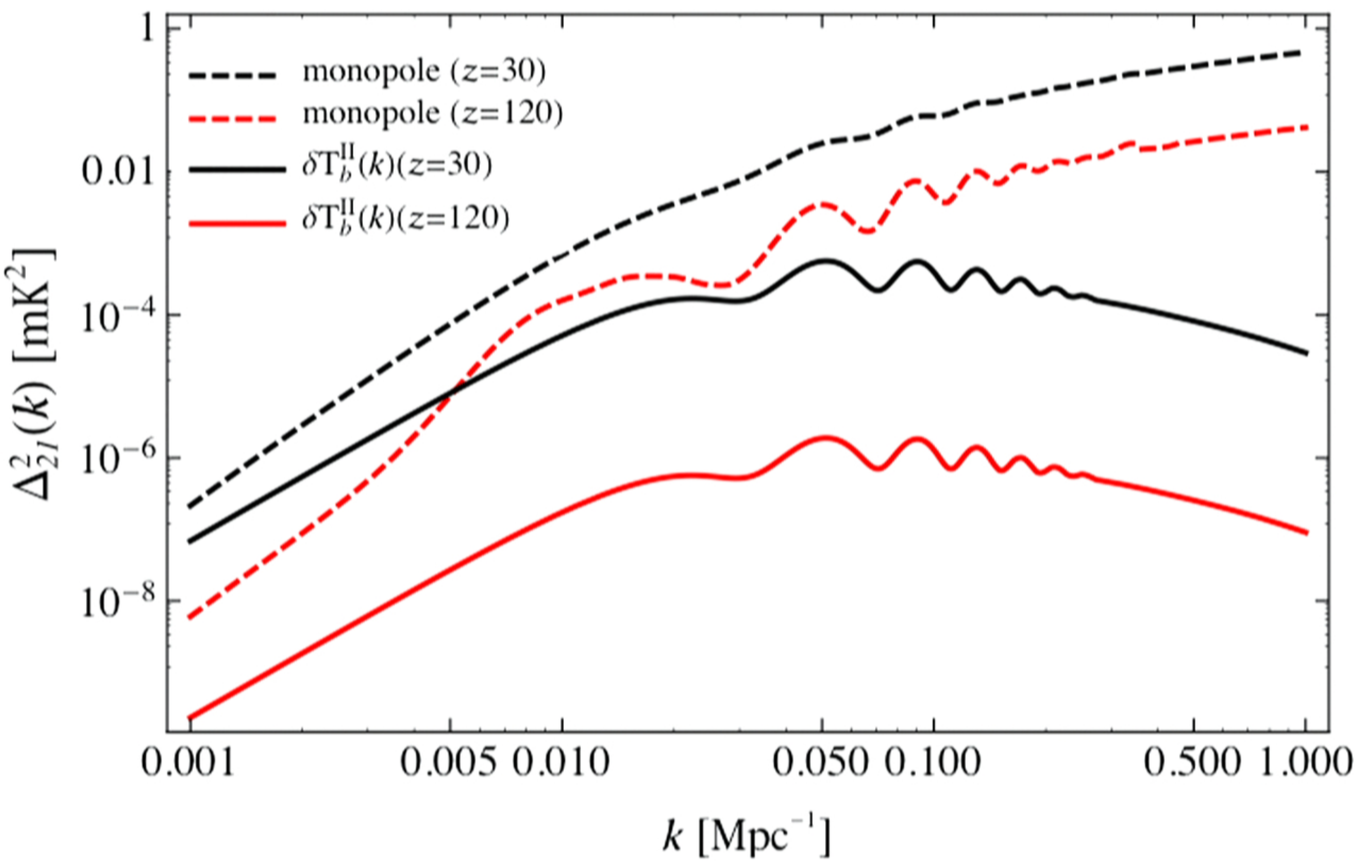
$$\delta_{T_{\rm gas}} = \delta_{T_{\rm gas}}^{\rm I} + \delta_{T_{\rm gas}}^{\rm II}$$

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

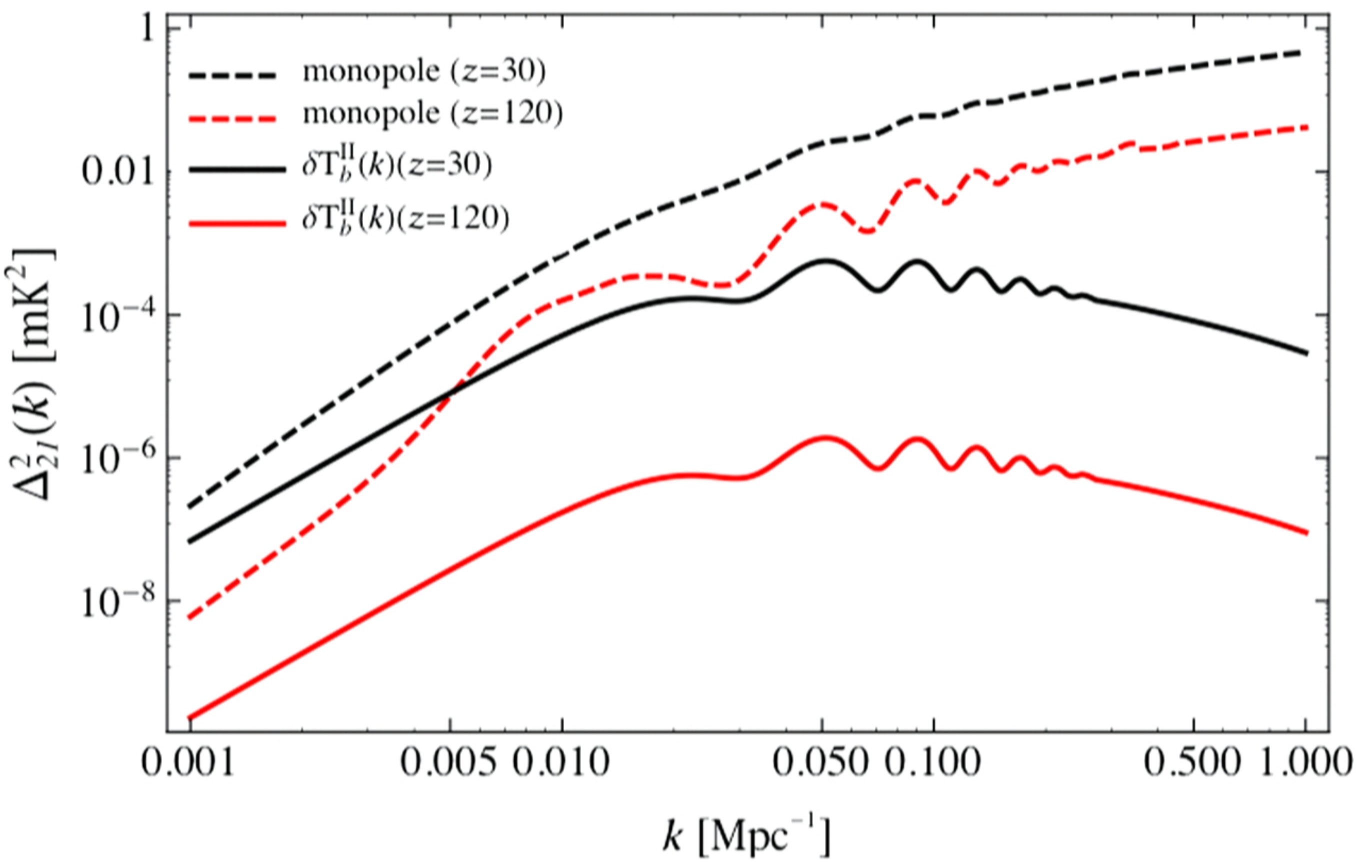
Contributions to quadratic piece of 21cm fluctuations



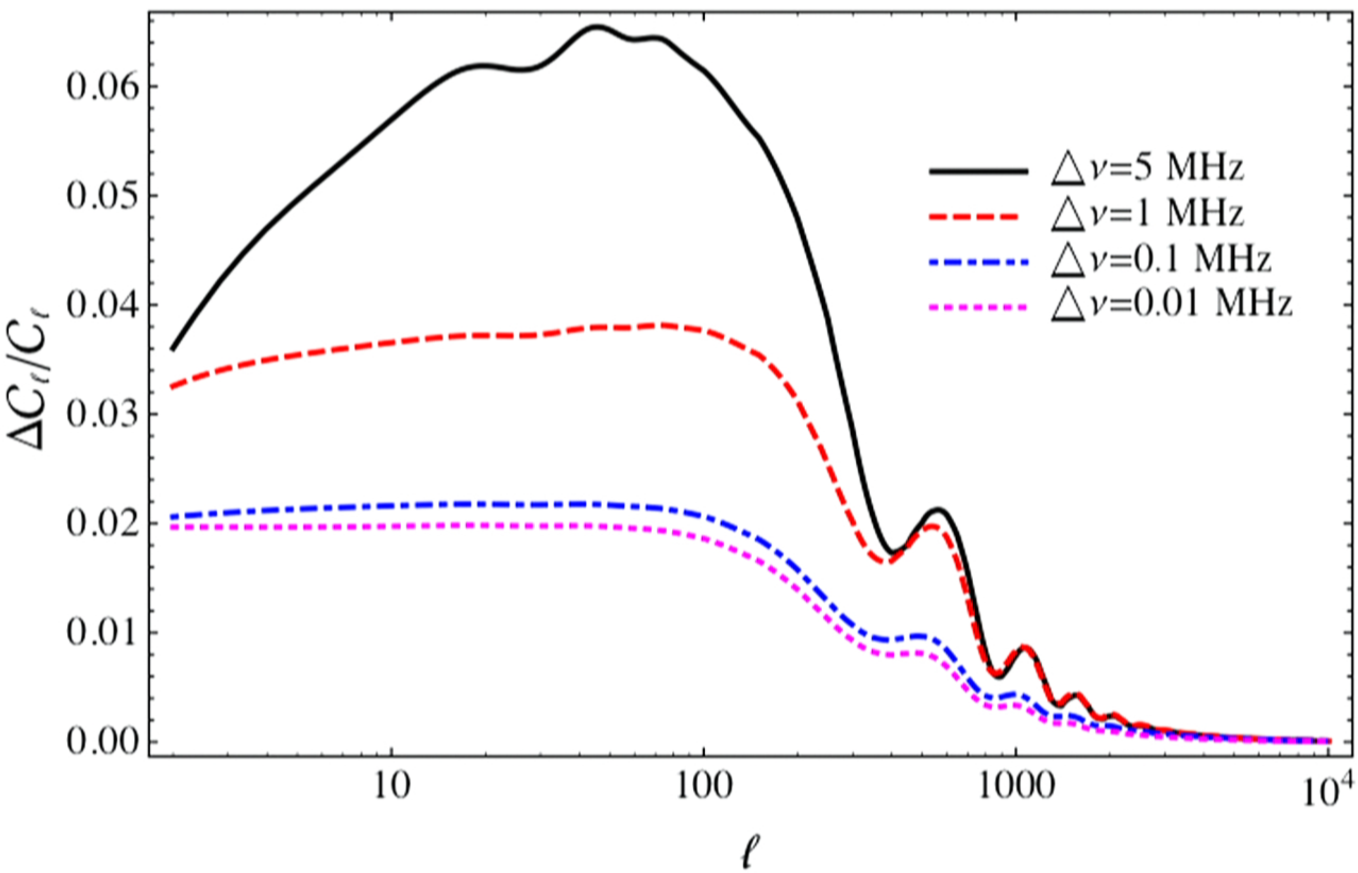
Results: II- Large scales

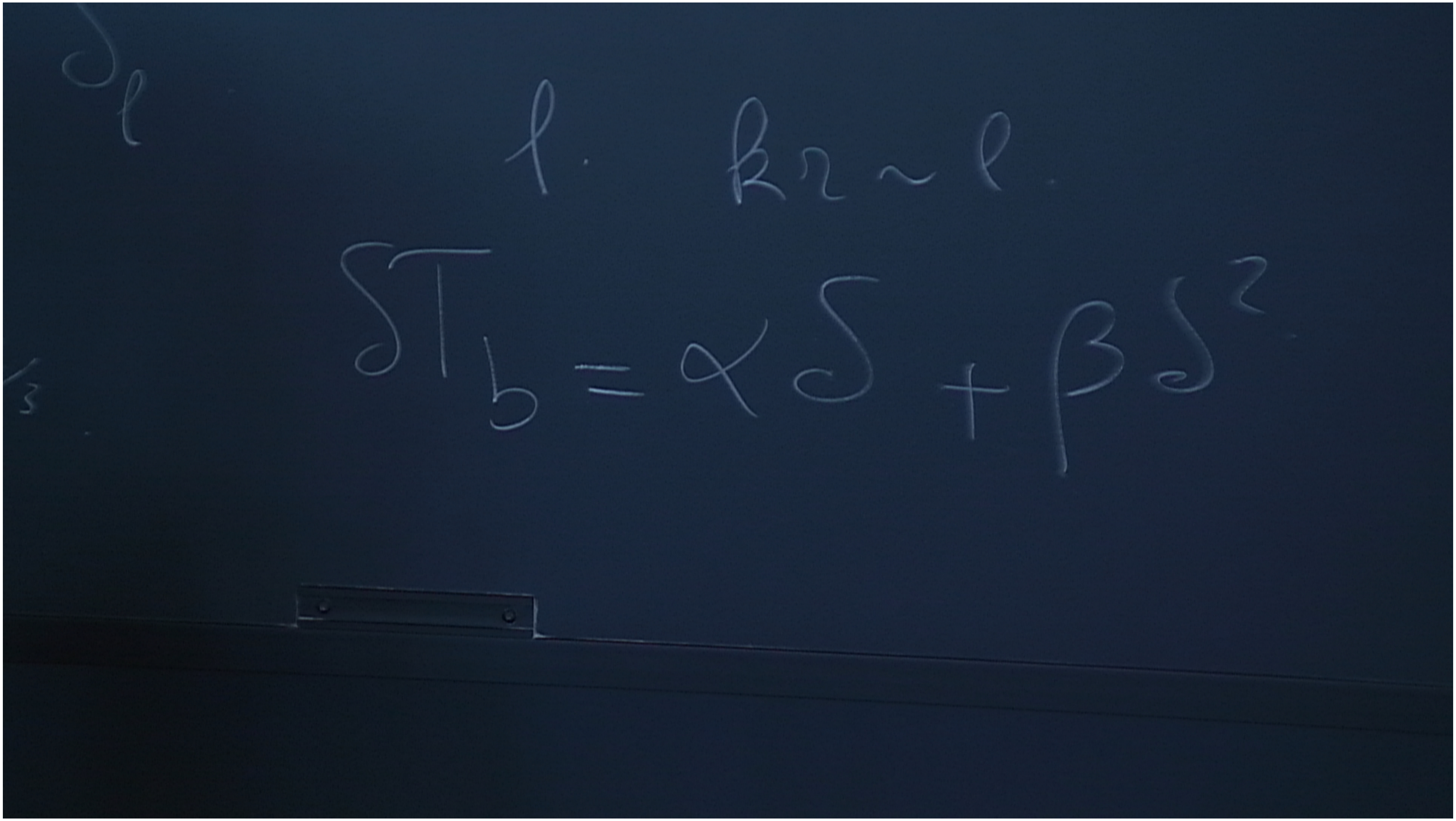


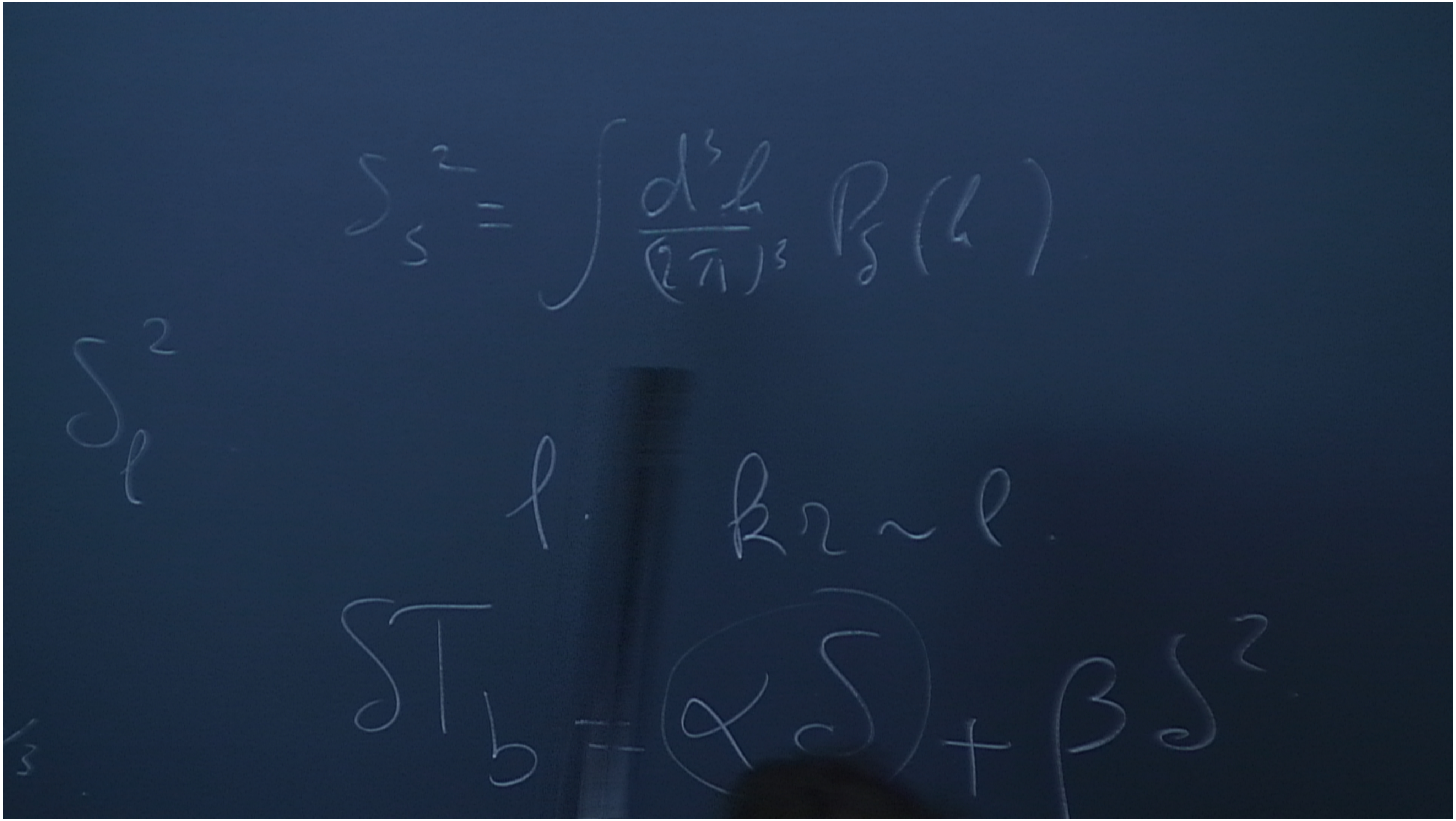
Results: II- Large scales



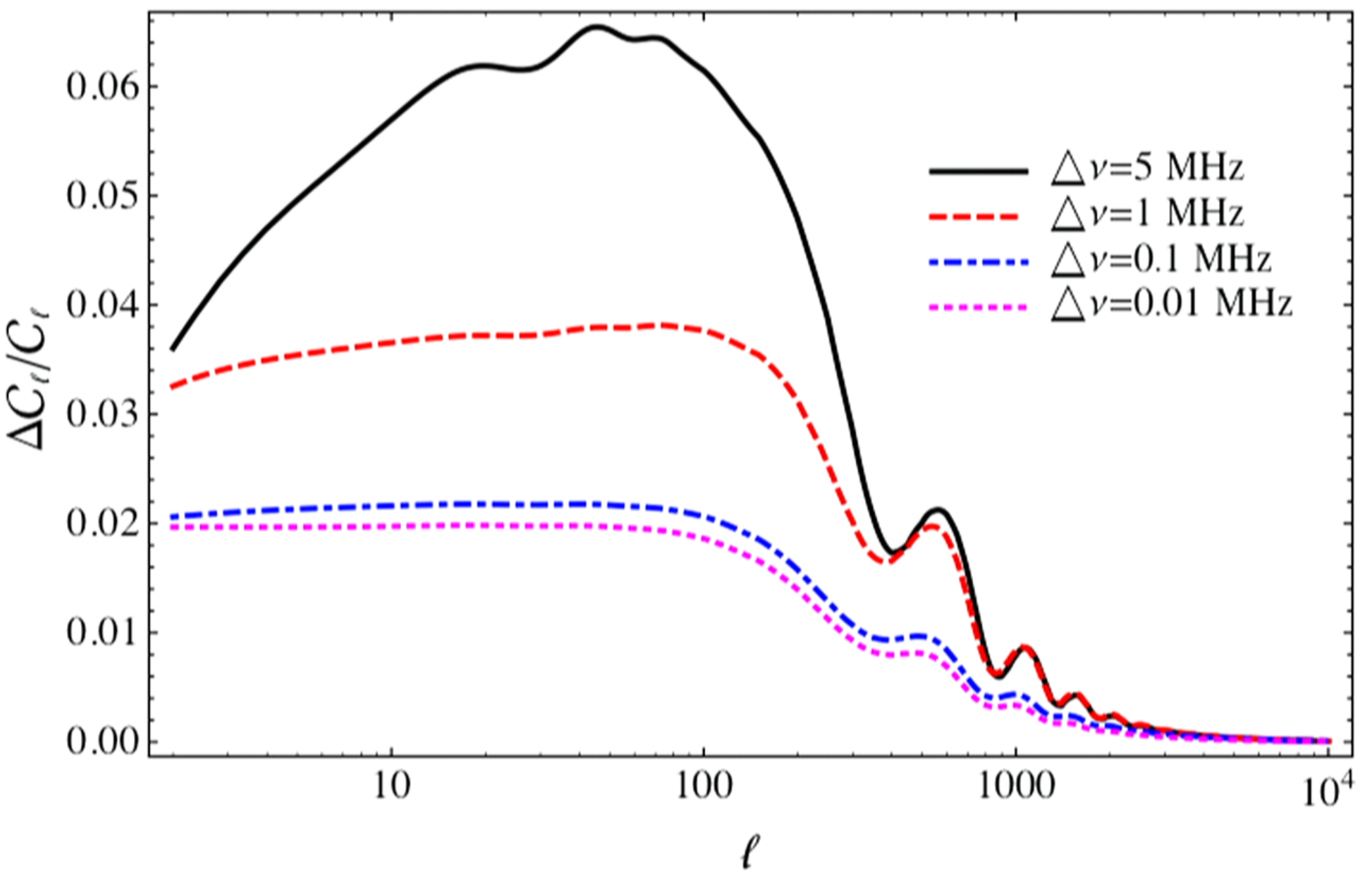
Results: II- Large scales



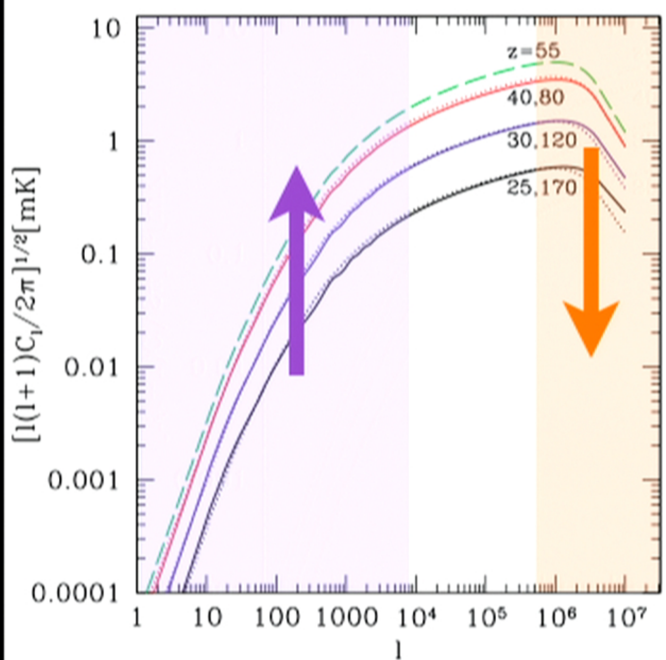

ℓ. $kr \sim \ell$.
$\delta T_b = \alpha \delta + \beta \delta^2$


$\delta_s^2 = \int \frac{d^3k}{(2\pi)^3} P_\delta(k)$
δ_ℓ^2
ℓ. $kr \sim \ell$.
$\delta T_b = \alpha\delta + \beta\delta^2$

Results: II- Large scales



Conclusions

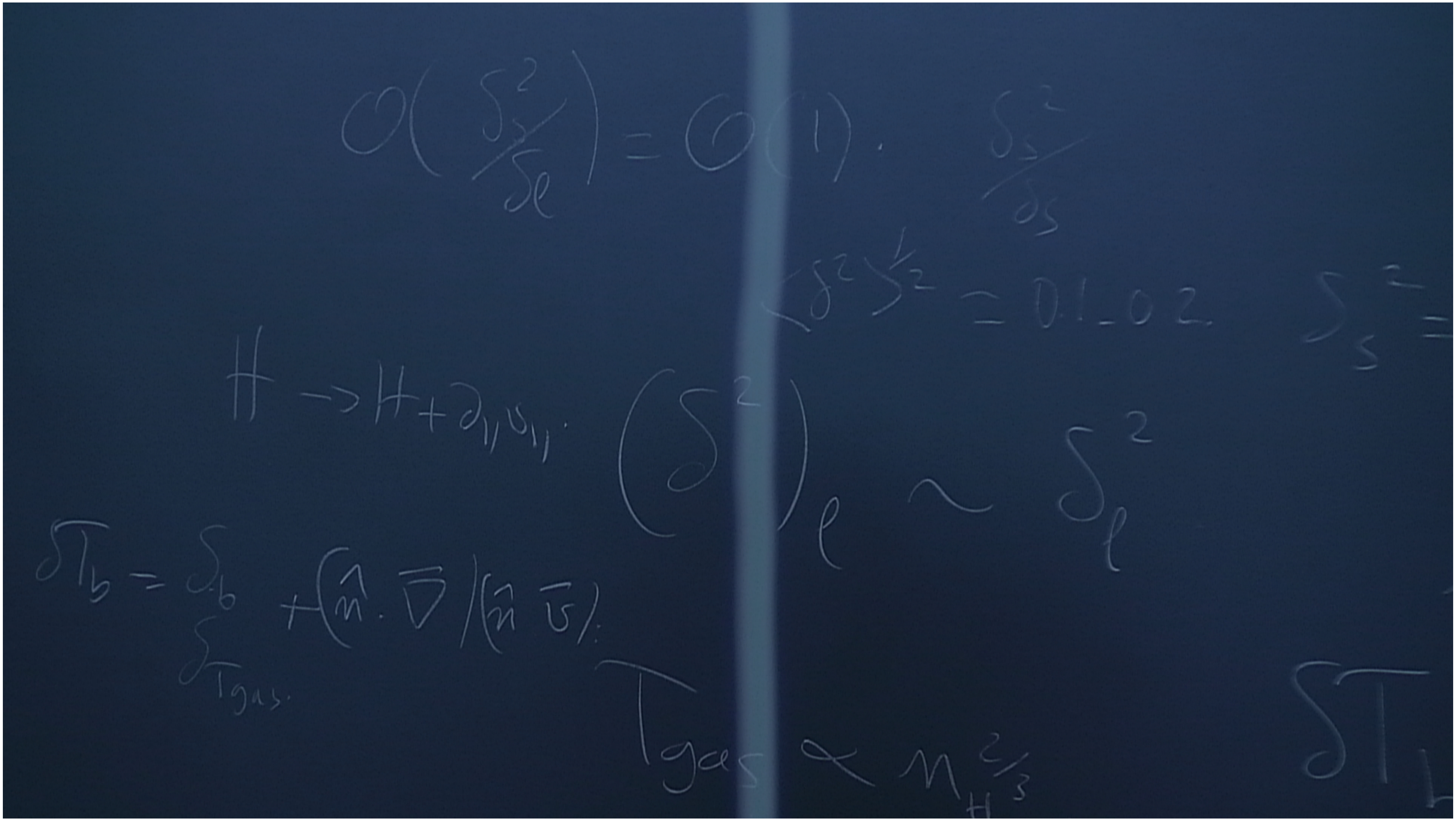


- Relative velocity leads to O(1) suppression on Jeans scale and enhancement on BAO scale.
- Brings back small-scale physics to large angular scales!

•Future work:

1- Quantify S/N for measurement of n_s, neutrino mass, WDM, etc...

2- Non-Gaussianities


O(δ_s²/δ_l) = O(1).
⟨δ²⟩^½ ≃ 0.1_0.2
H → H + ∂_∥ v_∥.
(δ²)_l ~ δ_l²
δT_b = δ_b + (n̂·∇̄)(n̂ v̄).
δ_Tgas.
T_gas ∝ n_H^(2/3)