

What do galaxy surveys really measure

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Galaxy surveys

Galaxy surveys measure the **number** of galaxies per unit of solid angle, in redshift bins → measurement of the **matter density** fluctuation.

Two difficulties:

- ◆ The luminous matter does not necessarily trace directly dark matter → **bias**.
- ◆ The number density is measured in redshift bins → **redshift space distortion**. Kaiser 1978, Hamilton 1997

$$\Delta(\mathbf{n}, z) = b \cdot \delta(\mathbf{n}, z) + \frac{1}{\mathcal{H}} \partial_r (\mathbf{v} \cdot \mathbf{n})$$

There are many corrections to this relation.

Corrections

- ◆ The **volume** of observation is **distorted** with respect to the physical volume at the source position.
- ◆ We observe the galaxy density as a function of **redshift**, rather than as a function of conformal time.

These effects modify the relation between

$$\Delta(\mathbf{n}, z) \text{ and } \delta(\mathbf{n}, z) = \frac{\delta\rho(\mathbf{n}, z)}{\bar{\rho}(\bar{z})}$$

These corrections will be relevant for future galaxy surveys that will observe galaxies at **high redshift** and over very **large areas** of the sky, like BOSS, DES, Euclid.

Outline

- ◆ Calculation of $\Delta(\mathbf{n}, z)$ at **first order** in perturbation theory.
 - New contributions.
- ◆ Calculation of the **angular power spectrum** $C_\ell(z)$ of $\Delta(\mathbf{n}, z)$
 - The effect of the corrections on C_ℓ becomes **important** for some configurations in the sky.
 - The corrections are **useful** to test cosmological models.

Derivation

Observers measure $N(\mathbf{n}, z)$ and average it to obtain $\langle N \rangle(z)$

$$\rightarrow \Delta(\mathbf{n}, z) = \frac{N(\mathbf{n}, z) - \langle N \rangle(z)}{\langle N \rangle(z)}$$

We want to relate this to $\delta(\mathbf{n}, z) = \frac{\delta\rho(\mathbf{n}, z)}{\bar{\rho}(\bar{z})}$

- ◆ **Volume** perturbations enter in $\rho(\mathbf{n}, z) = \frac{N(\mathbf{n}, z)}{V(\mathbf{n}, z)}$
- ◆ The background **redshift** \bar{z} differs from the measured one z

$$\boxed{\Delta(\mathbf{n}, z) = \delta(\mathbf{n}, z) - 3\frac{\delta z}{1 + \bar{z}} + \frac{\delta V(\mathbf{n}, z)}{V(z)}}$$

Result

Bonvin and Durrer, 2011

density

redshift space distortion

$$\Delta(\mathbf{n}, z_S) = D + \frac{1}{\mathcal{H}} \partial_r (\mathbf{V} \cdot \mathbf{n})$$

$$- \int_0^{r_S} d\lambda \frac{r_S - r}{rr_S} \Delta_\Omega(\Phi + \Psi) \rightarrow \text{lensing}$$

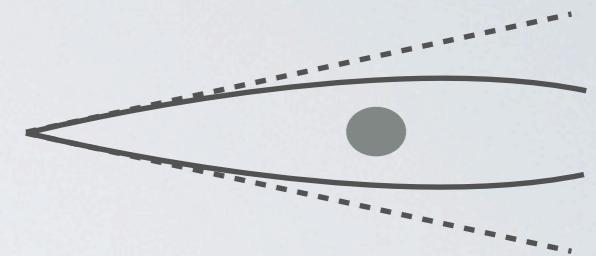
$$+ \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r_S \mathcal{H}} \right) \mathbf{V} \cdot \mathbf{n} \rightarrow \text{Doppler}$$

$$+ \Psi - 2\Phi + \frac{2}{r_S} \int_0^{r_S} d\lambda (\Phi + \Psi)$$

$$+ \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r_S \mathcal{H}} \right) \left(\Psi + \int_0^{r_S} d\lambda (\dot{\Phi} + \dot{\Psi}) \right)$$

$$- \frac{2a}{\Omega_m} \left(\frac{\mathcal{H}}{\mathcal{H}_0} \right)^2 \left(\Psi + \frac{\dot{\Phi}}{\mathcal{H}} \right)$$

See also: Yoo et al.
2009 & 2010
Challinor and Lewis
2011



→ gravitational potential

Angular power spectrum

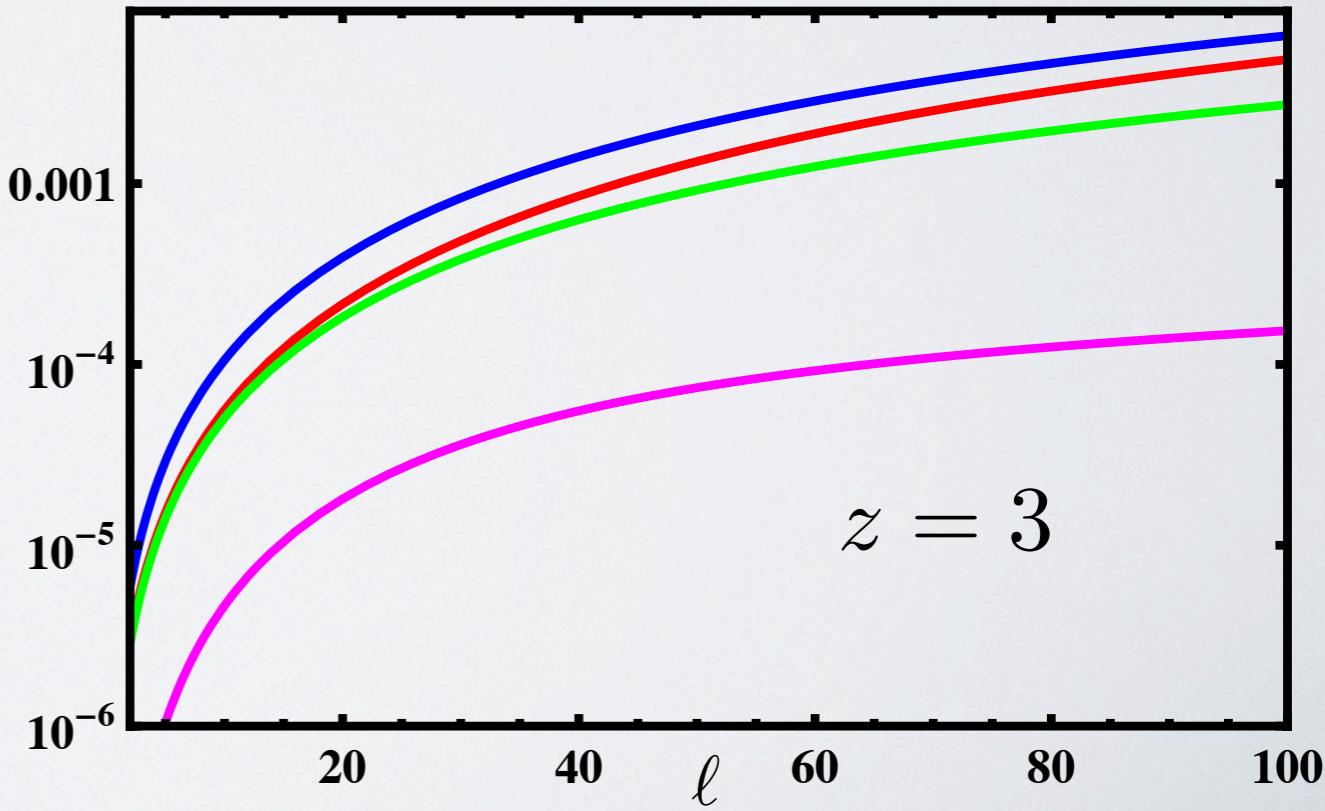
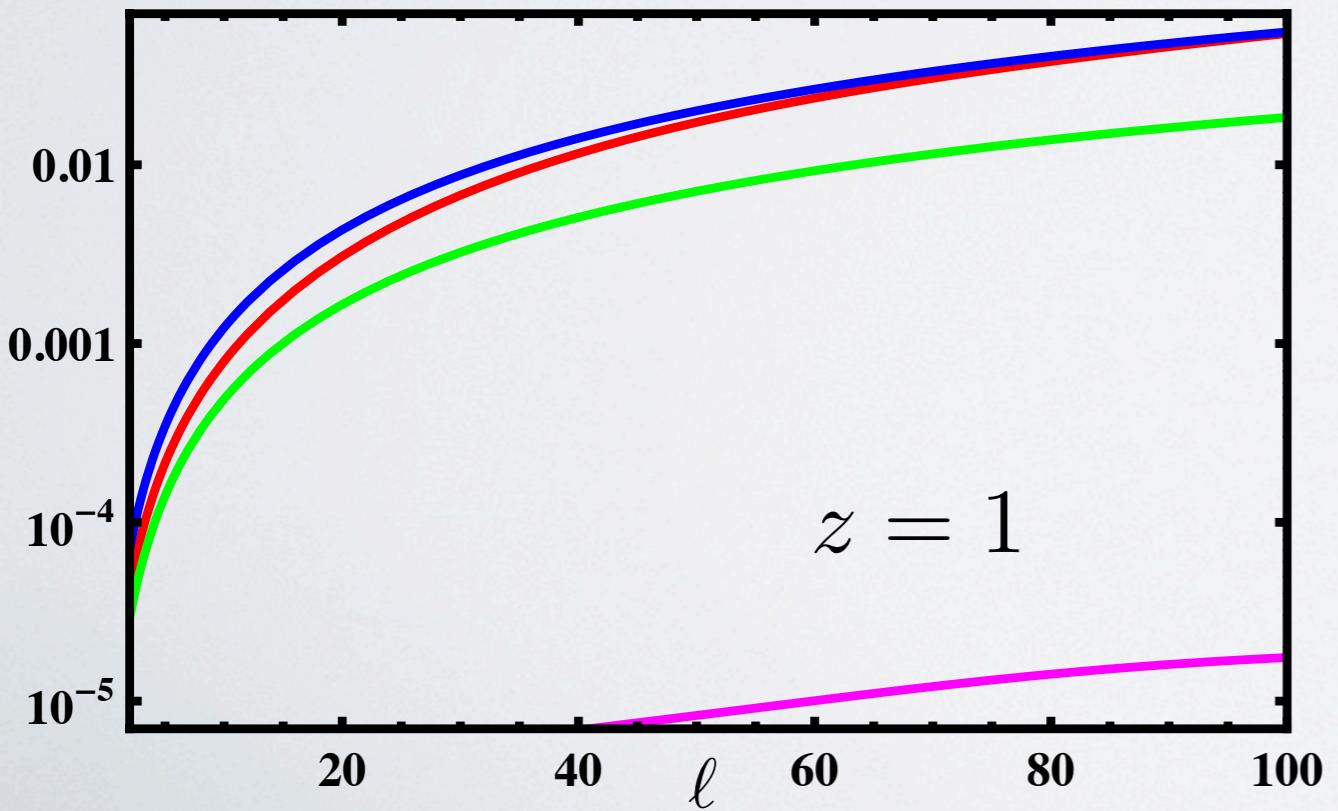
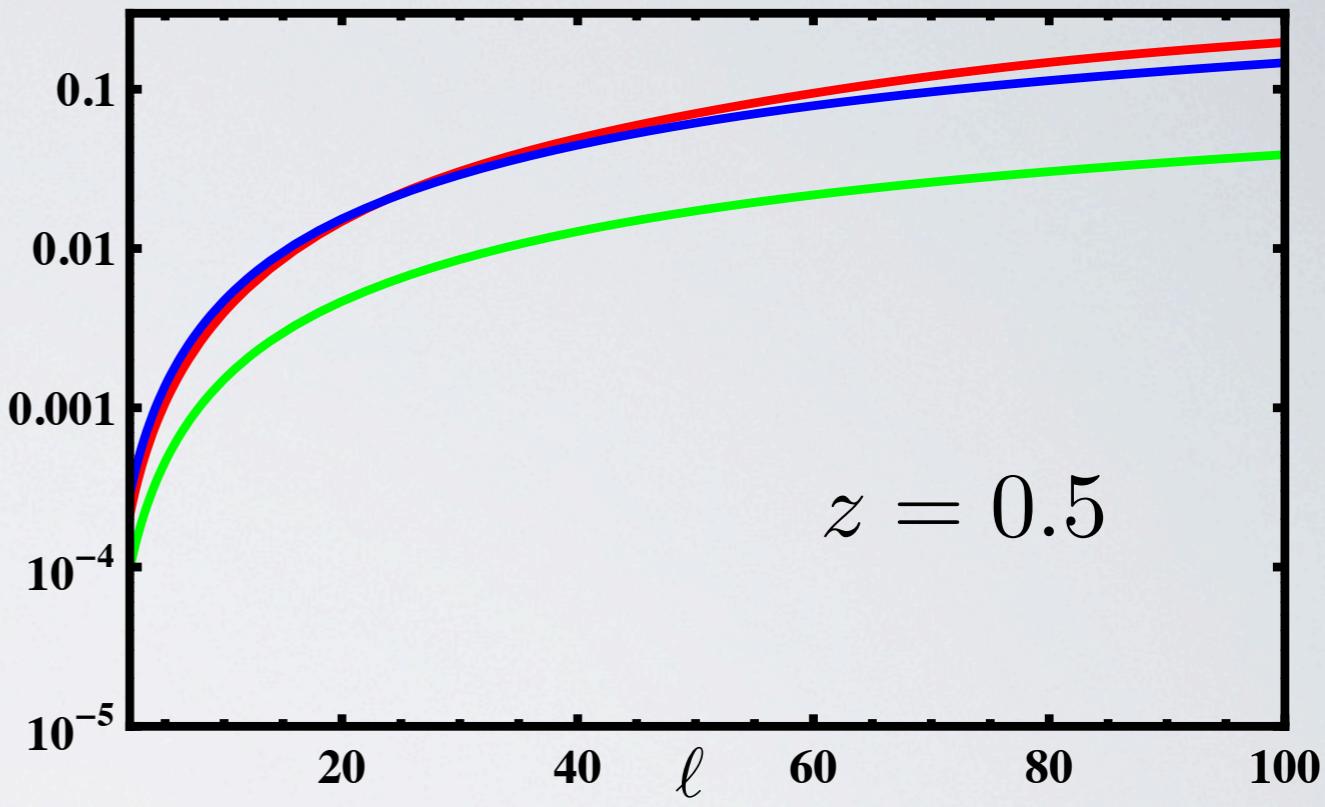
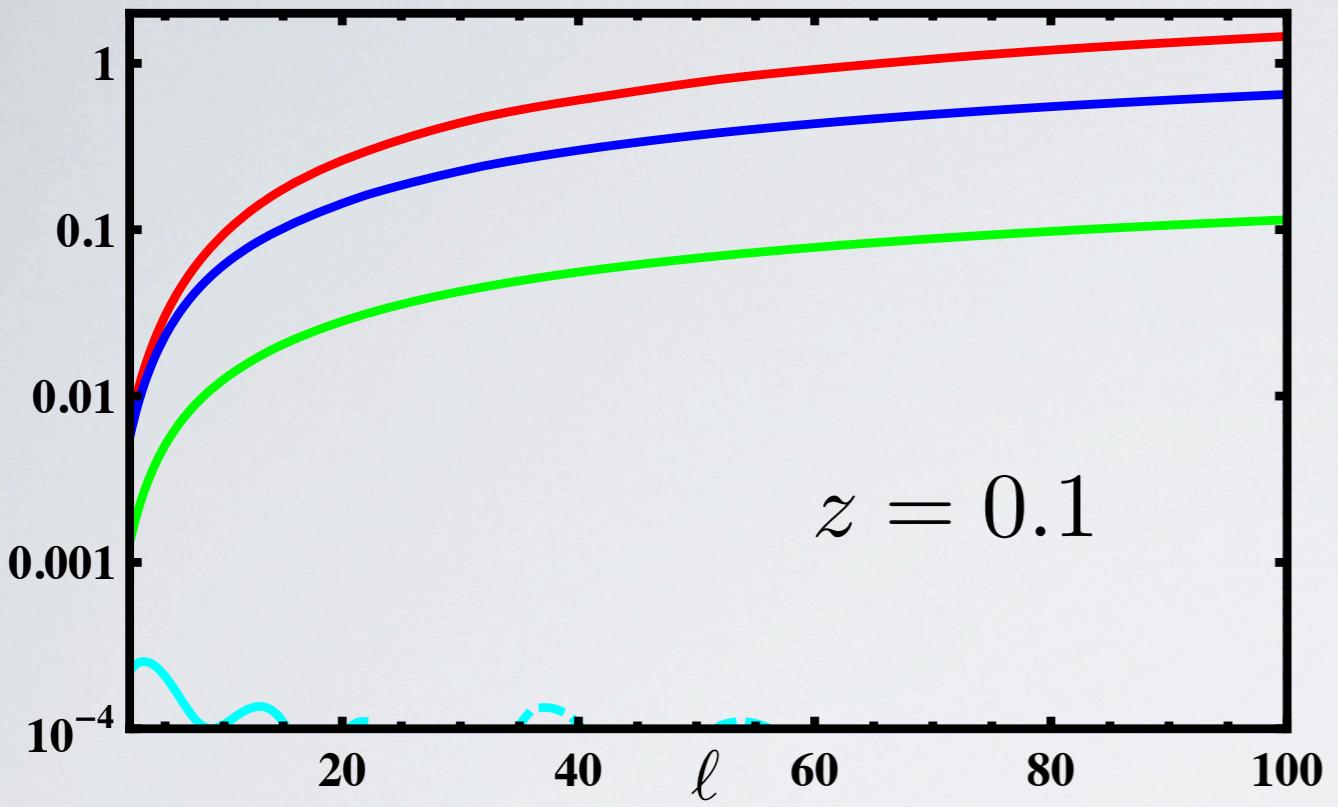
$$\Delta(\mathbf{n}, z) = \sum_{\ell m} a_{\ell m}(z) Y_{\ell m}(\mathbf{n})$$

$$\langle \Delta(\mathbf{n}, z) \Delta(\mathbf{n}', z') \rangle = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_{\ell}(z, z') P_{\ell}(\mathbf{n} \cdot \mathbf{n}')$$

- ◆ We use **Einstein's** equations to relate the density and velocity to the gravitational potential.
- ◆ We choose **gaussian** initial conditions, with a **flat** power spectrum.
- ◆ We compute the **transfer** function in a Λ CDM Universe with CAMB.

$$\frac{\ell(\ell + 1)C_\ell(z)}{2\pi}$$

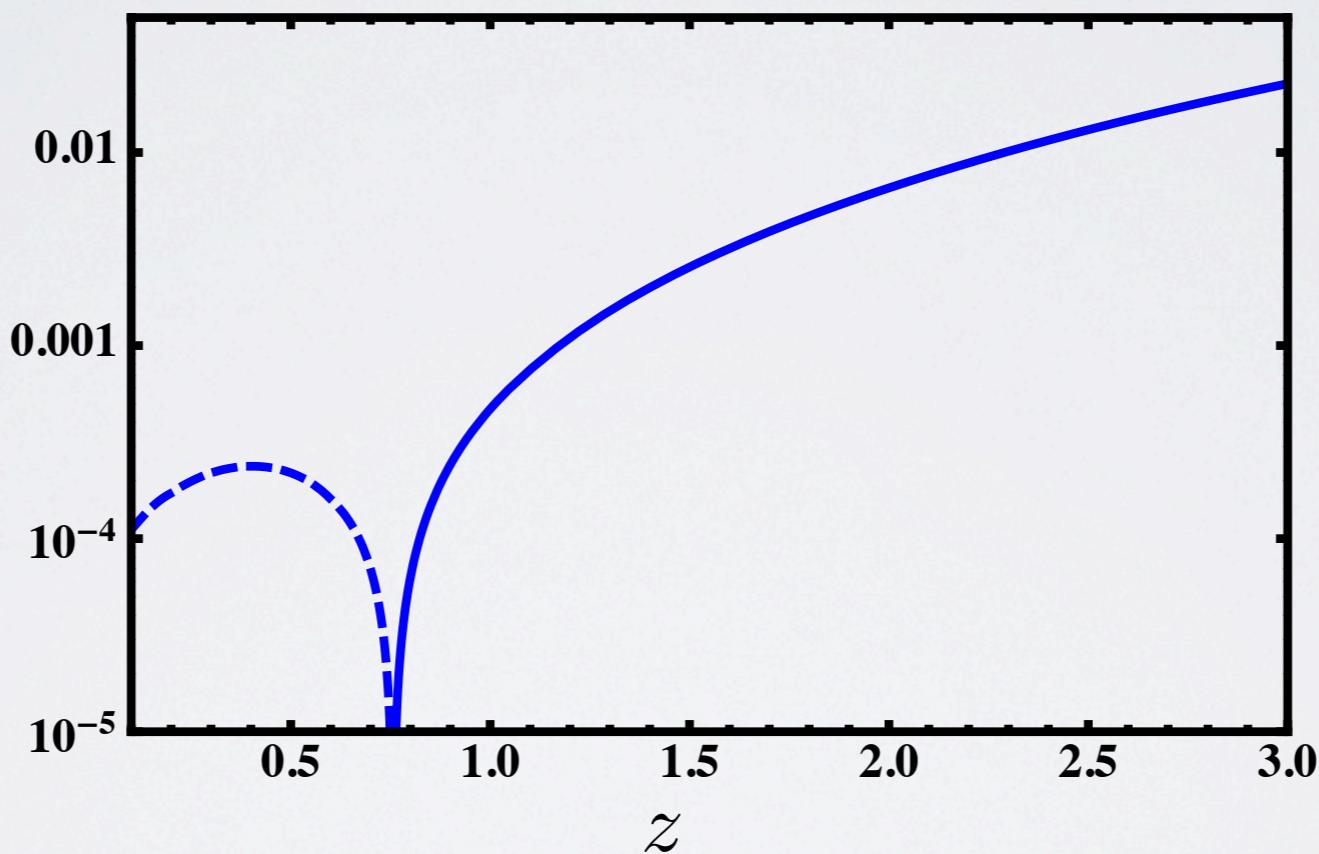
◆ density ◆ corr. dens-z ◆ Doppler
◆ z-distortion ◆ lensing ◆ potential



Relative contributions

$$C_\ell^{\text{new}} / C_\ell^{\text{tot}}$$

$$\ell = 20$$

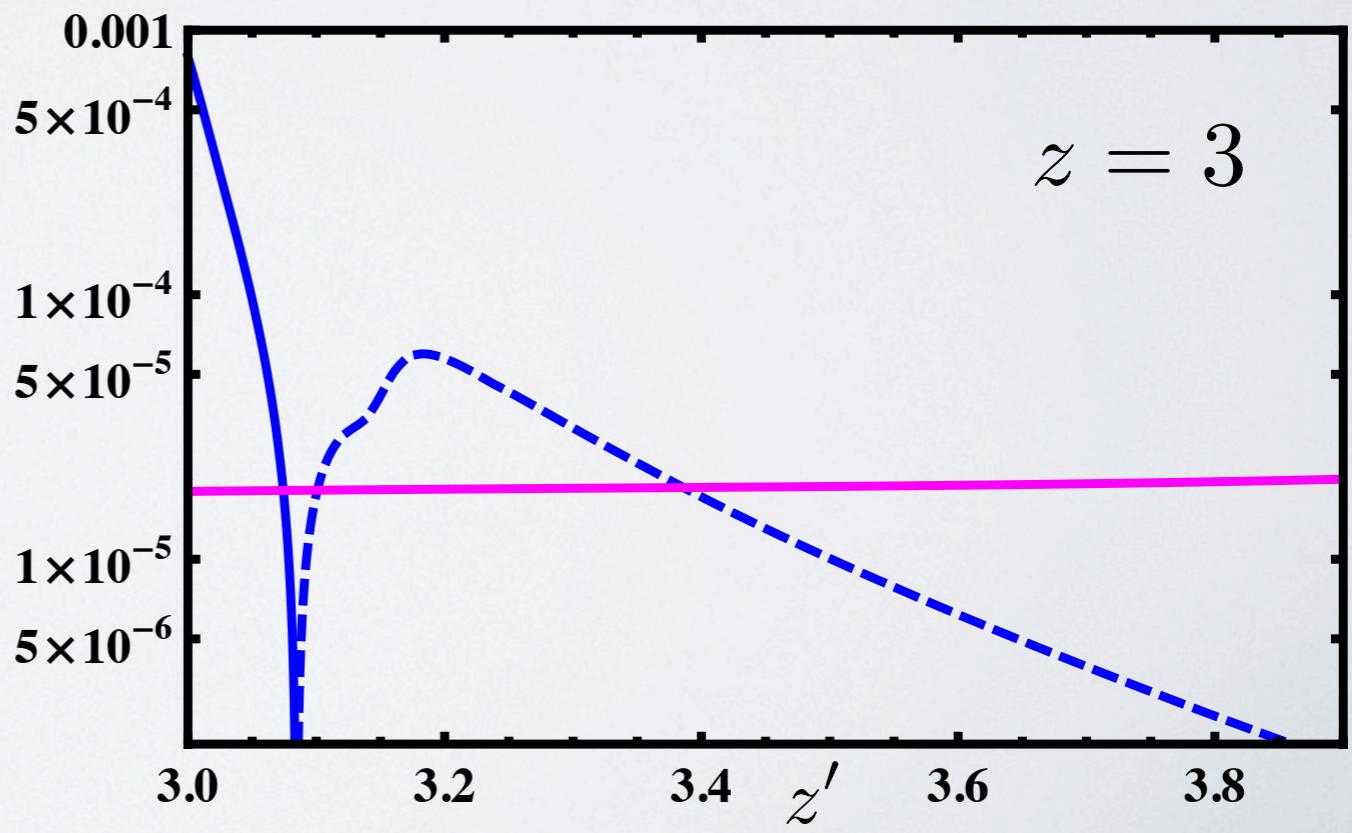
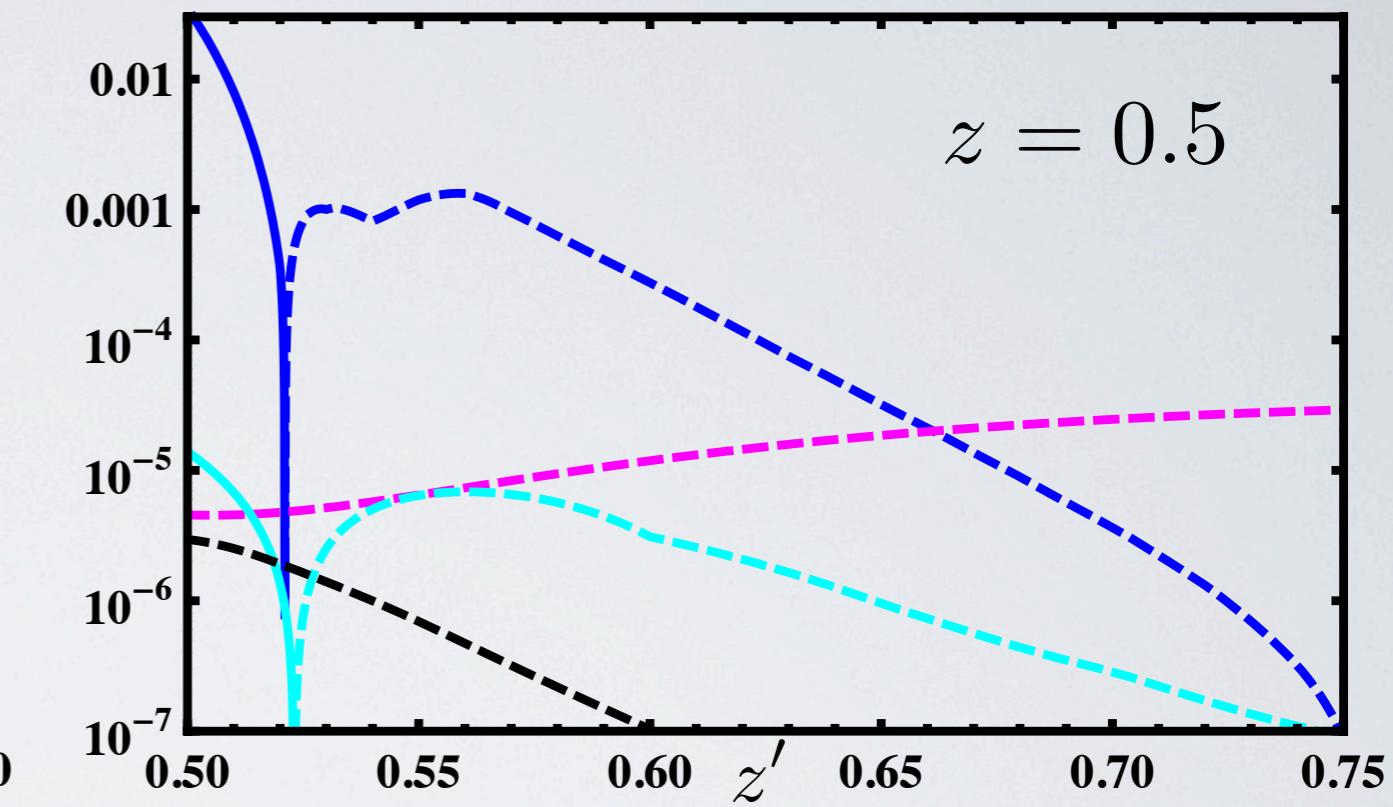
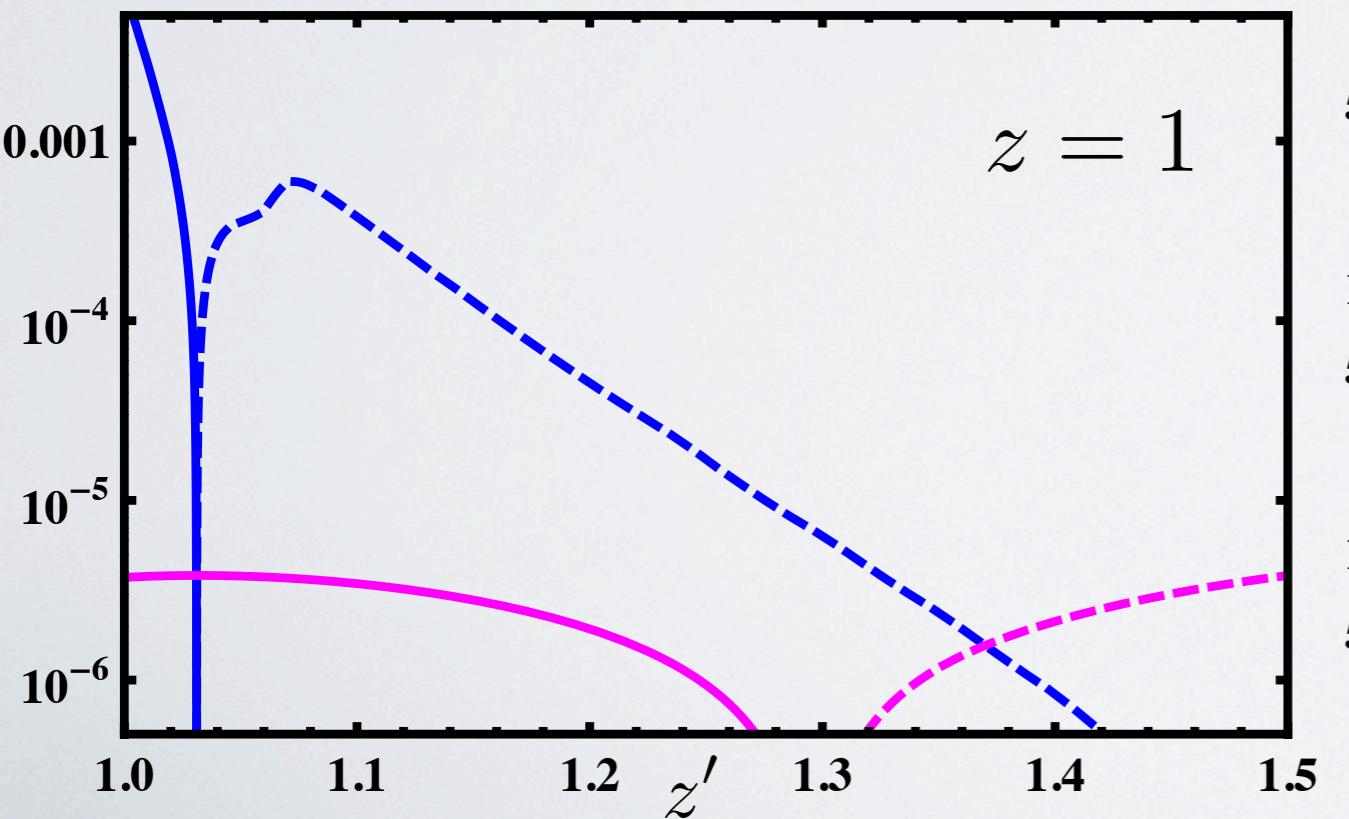
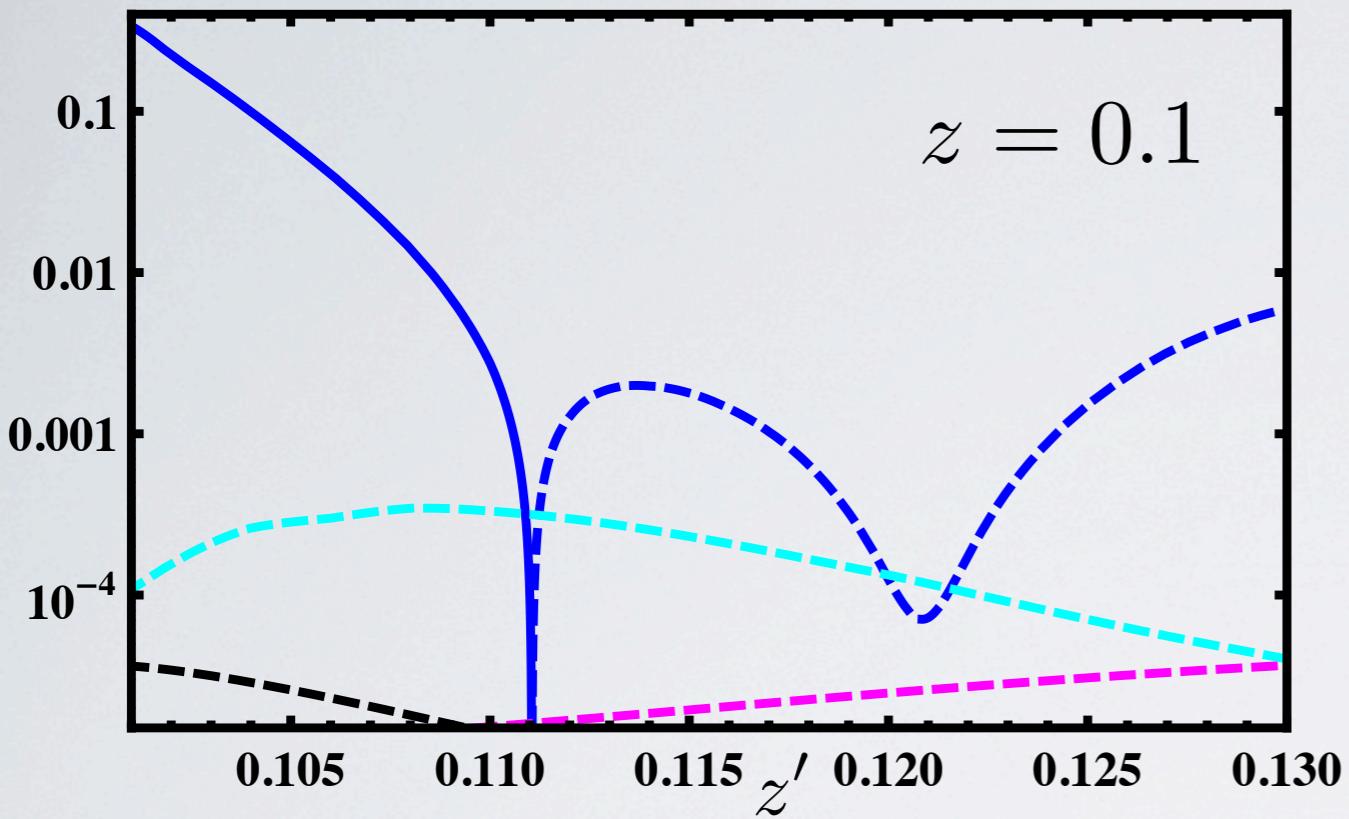


At most percent-level corrections

$$\frac{\ell(\ell+1)C_\ell(z, z')}{2\pi}$$

$\ell = 20$

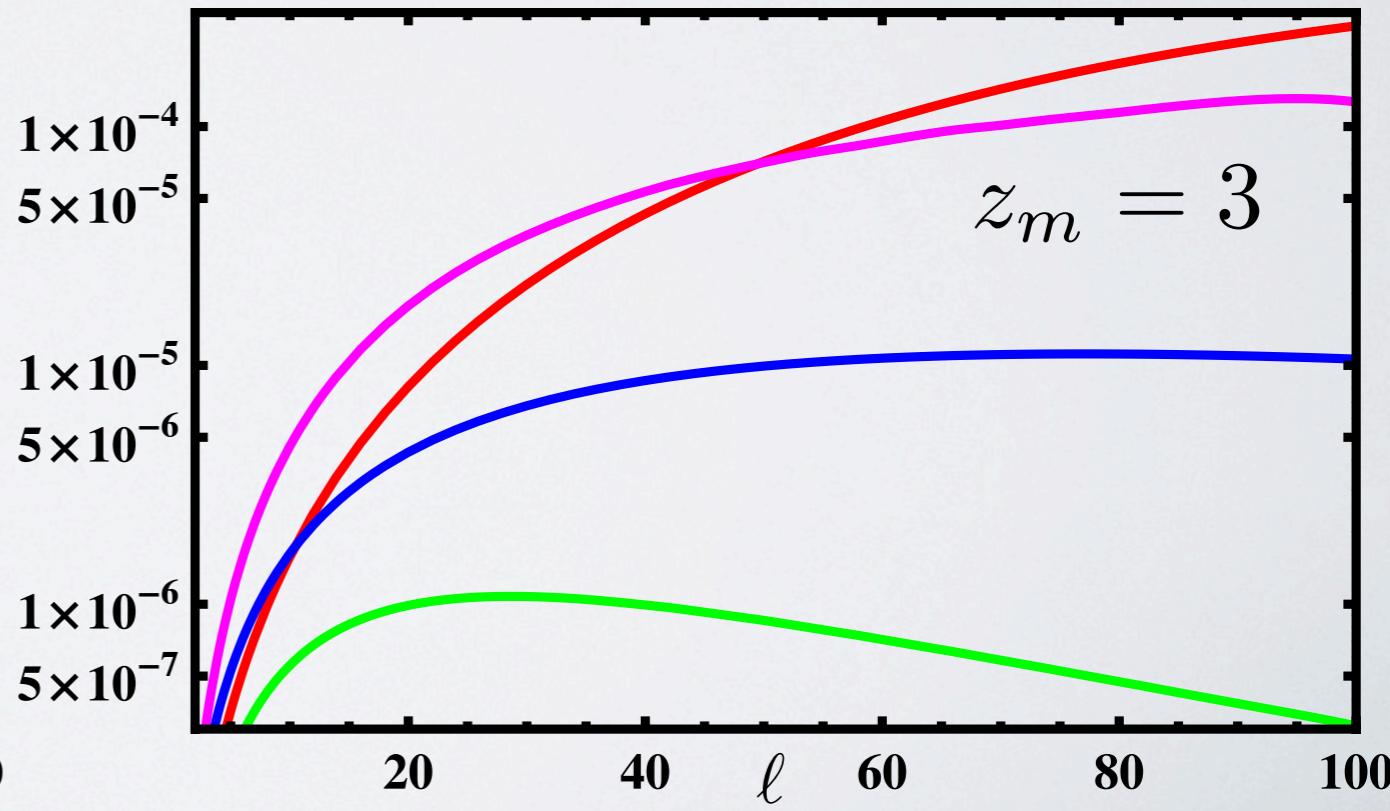
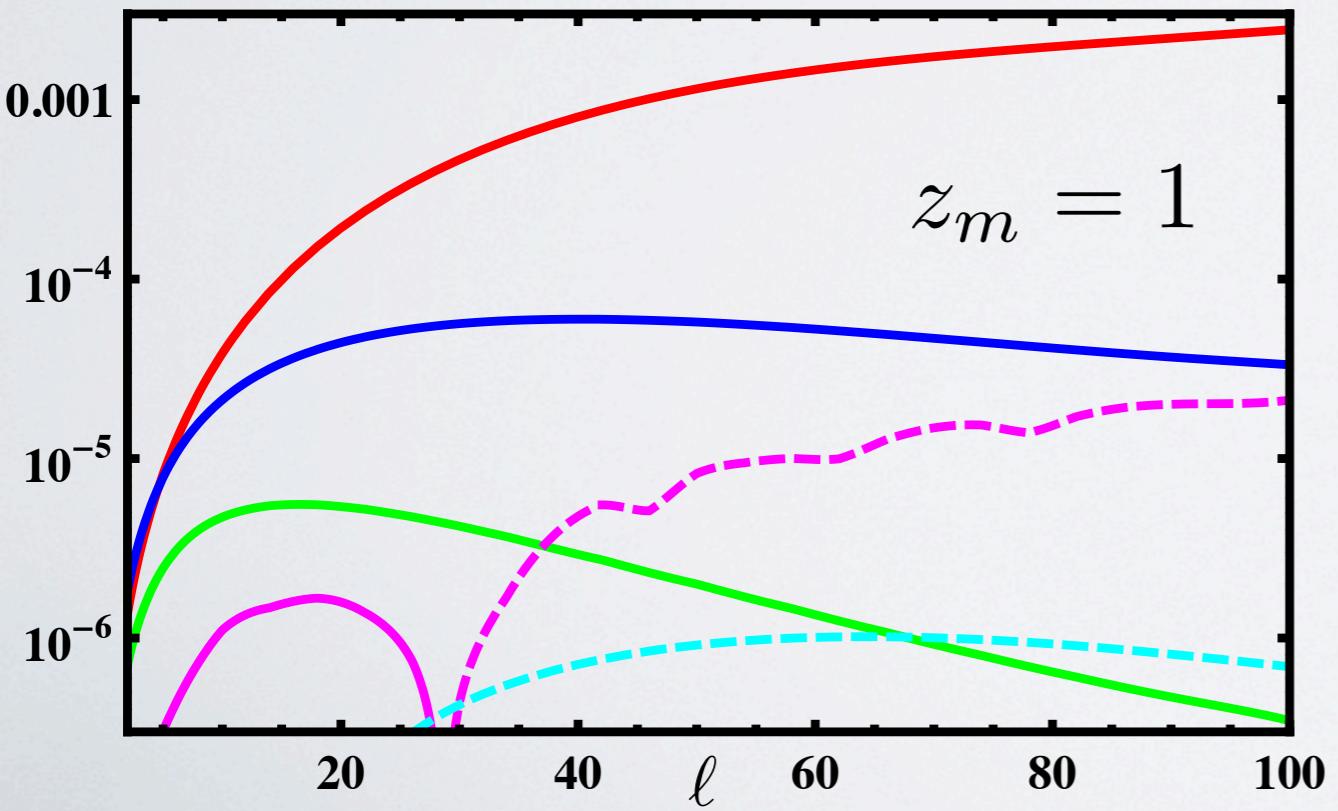
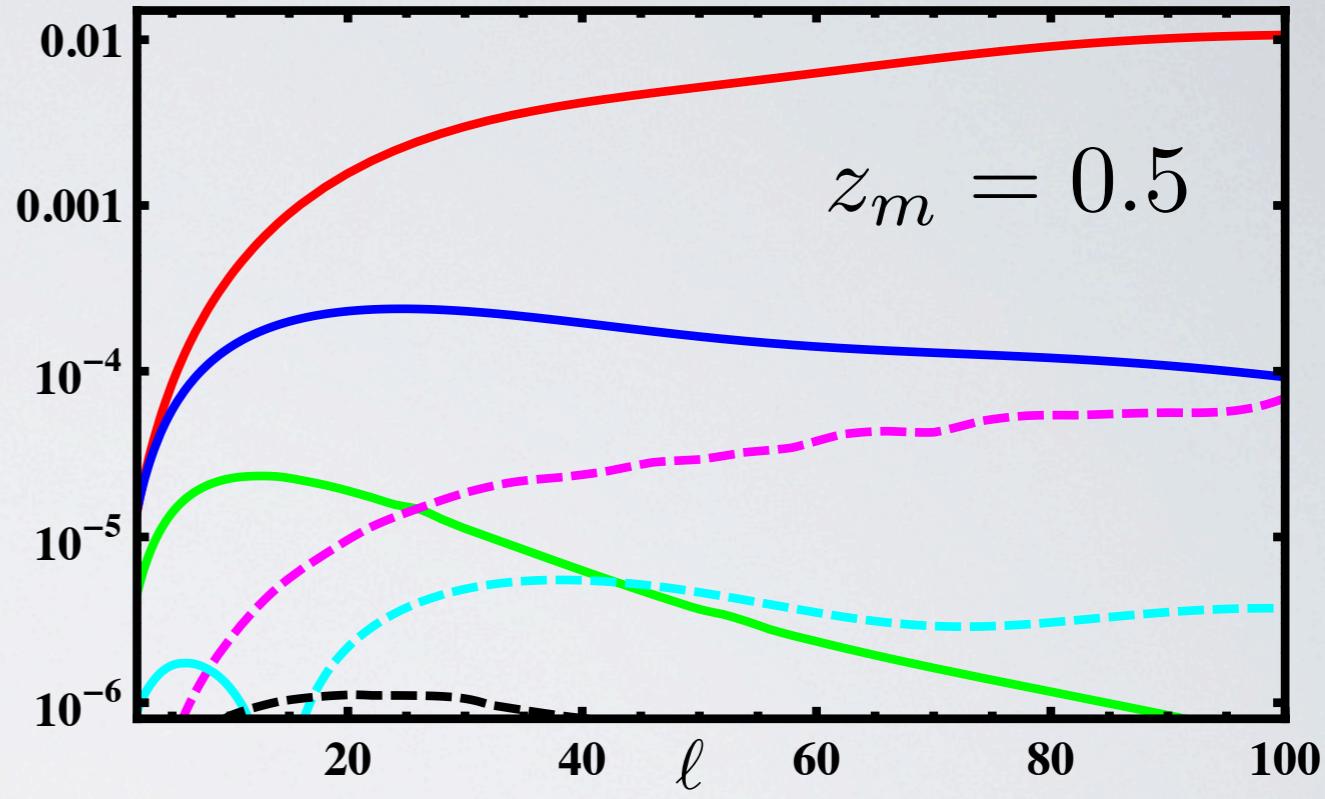
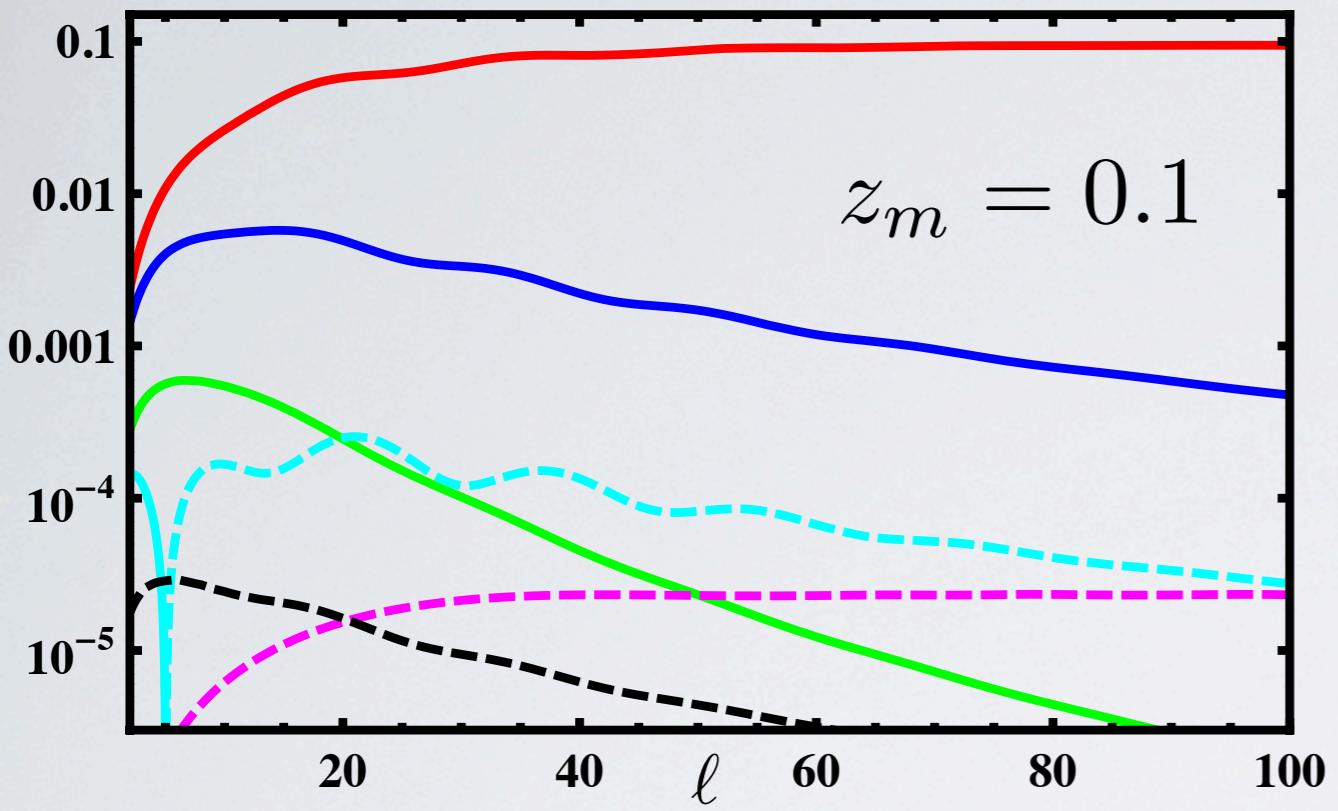
standard Doppler
lensing potential



$$\sigma_z = 0.1 \cdot z$$

$$\frac{\ell(\ell+1)C_\ell}{2\pi}$$

◆ density ◆ corr. dens-z ◆ Doppler
◆ z-distortion ◆ lensing ◆ potential

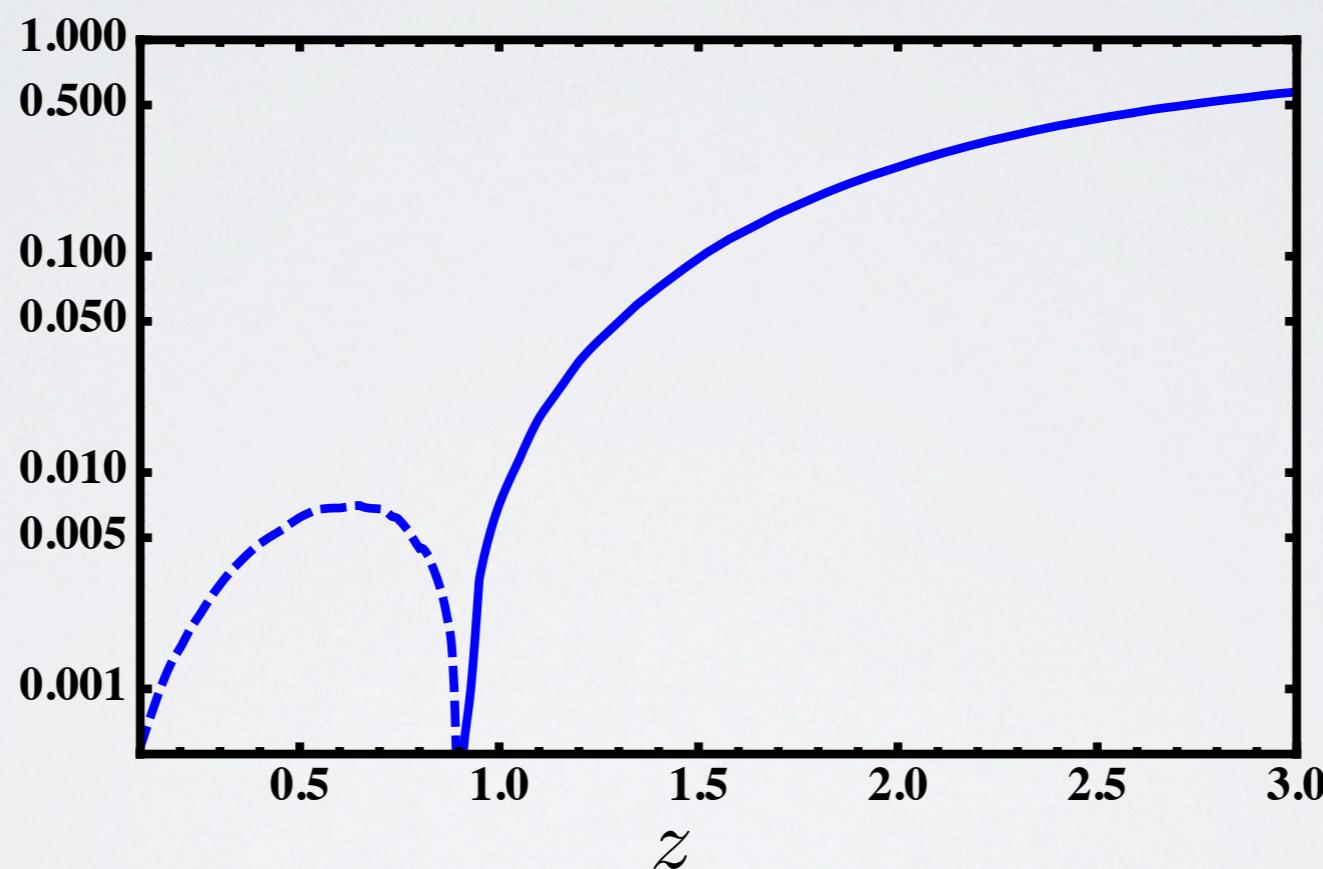


Relative contributions

$$C_\ell^{\text{new}} / C_\ell^{\text{tot}}$$

$$\ell = 20$$

$$\sigma_z = 0.1 \cdot z$$



More than 50 percent corrections

Conclusion

- ◆ We computed the number density of galaxy taking into account volume and redshift perturbations.
- ◆ We found **three** types of **corrections**: lensing, Doppler and gravitational potential.
- ◆ We computed the angular power spectrum.
 - At the **same redshift** and without window function the corrections remain **subdominant**.
 - For **different** redshifts or with a **window** function the **Doppler** term and **lensing** term become important. Since these corrections have different dependence on dark energy or modified gravity they provide new cosmological tests.

Derivation

$$\Delta(\mathbf{n}, z) = \delta(\mathbf{n}, z) - 3 \frac{\delta z}{1 + \bar{z}} + \frac{\delta V(\mathbf{n}, z)}{V(z)}$$

In longitudinal gauge

- ◆ $\delta = D - 3 \frac{\mathcal{H}}{k} (1 + w)V$ \$D\$ energy density in comoving gauge
- ◆ $\frac{\delta z}{1 + \bar{z}} = - \left[\Psi + \mathbf{n} \cdot \mathbf{V} + \int_0^{r_S} dr (\dot{\Phi} + \dot{\Psi}) \right]$
- ◆ $dV = \sqrt{-g} \epsilon_{abcd} u^a dx^b dx^c dx^d$

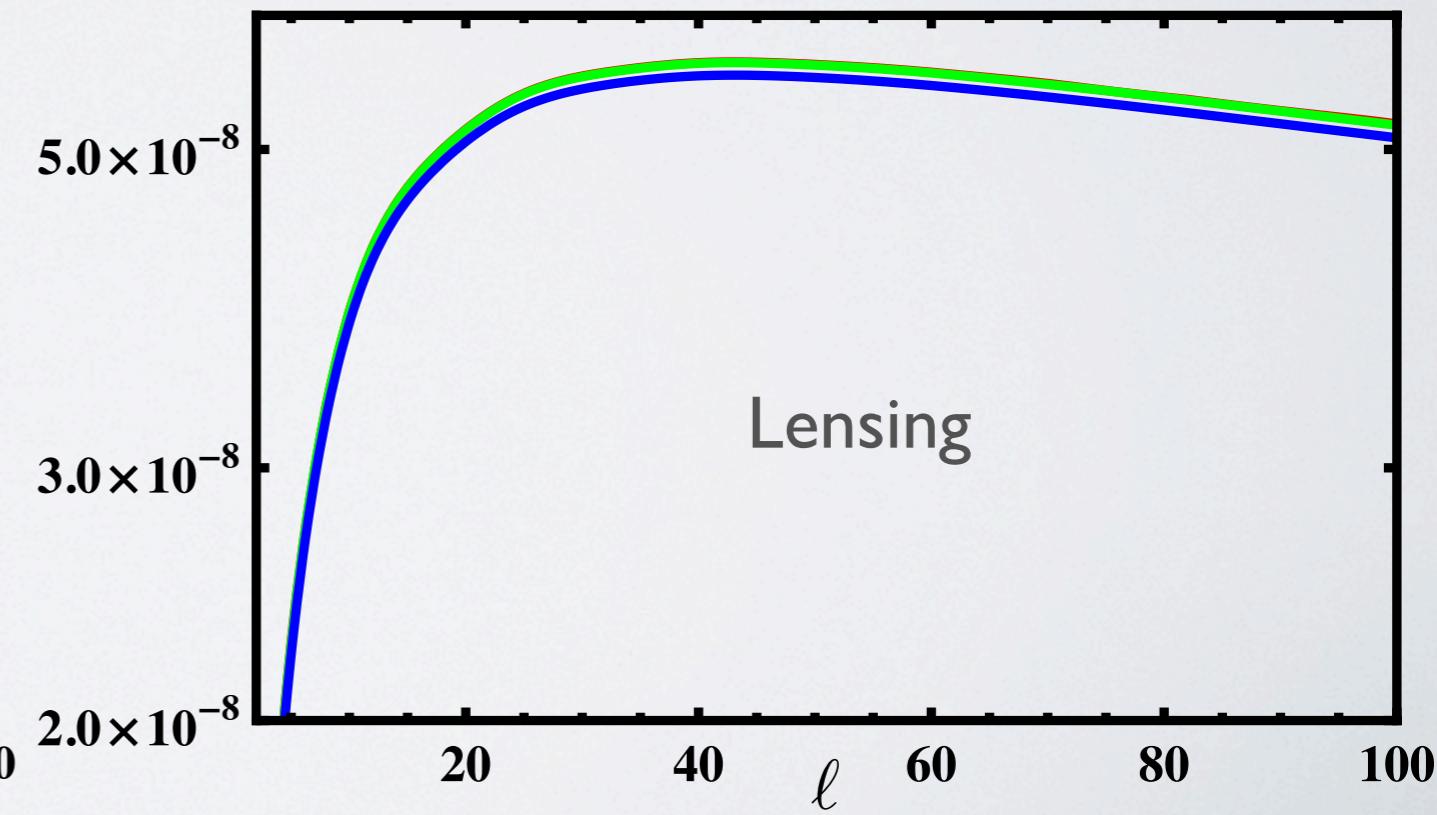
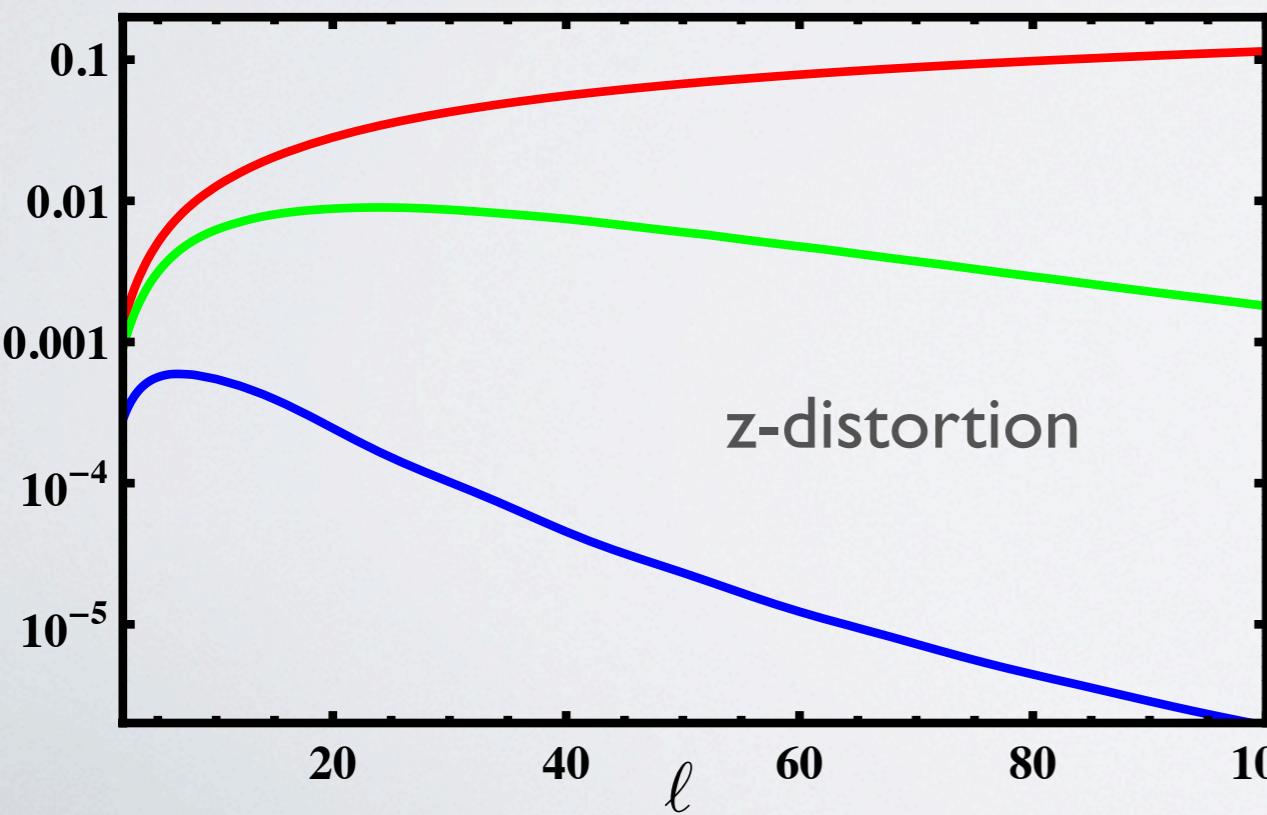
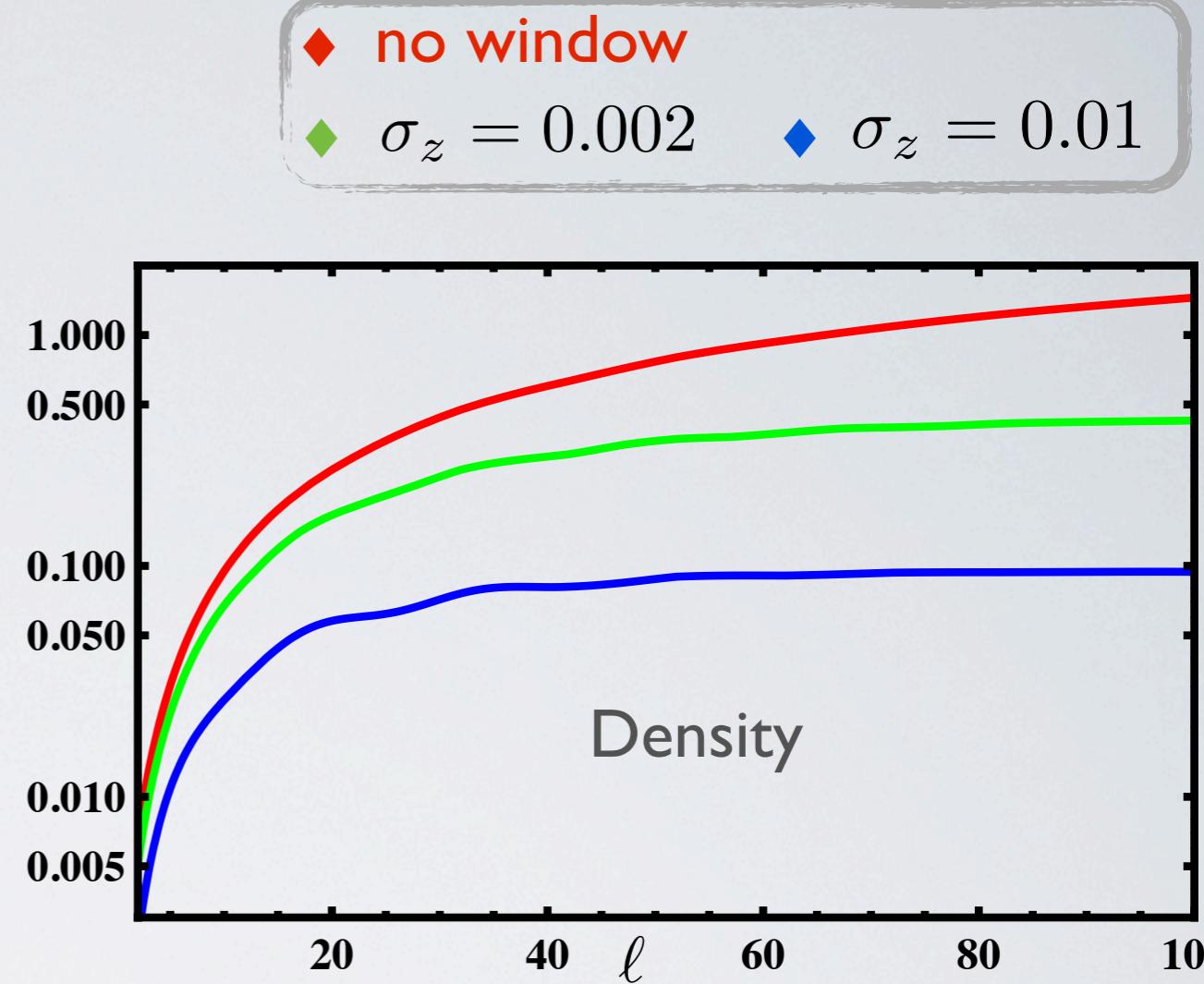
We relate the photon direction at the source to the photon direction at the observer by solving null geodesic equations.

Gaussian window function
 $W(z)$ centred at z_m of width σ_z

$$\int_0^\infty dz \Delta(\mathbf{n}, z) W(z)$$

$$\frac{\ell(\ell+1)C_\ell}{2\pi}$$

$$z_m = 0.1$$



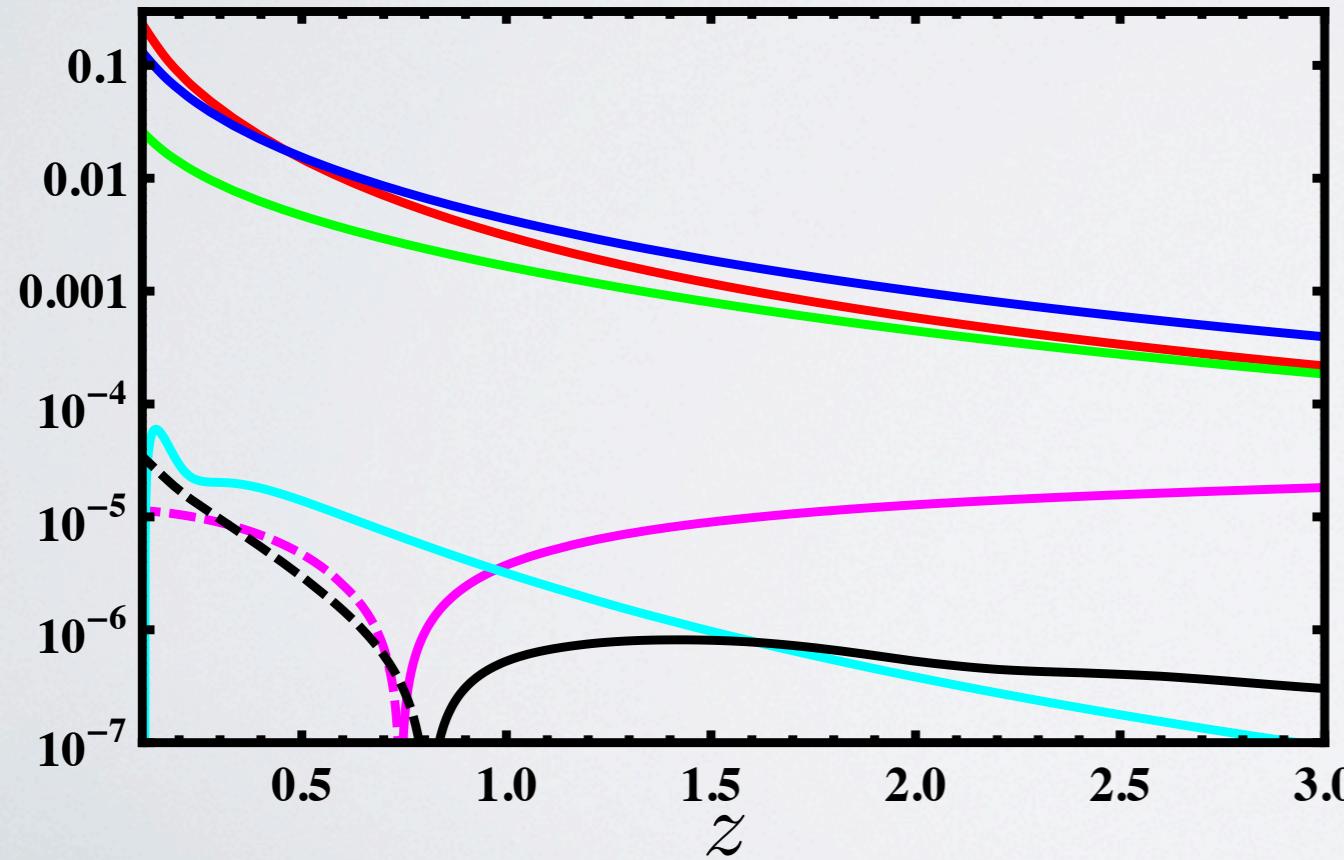
Redshift dependence

$\ell = 20$

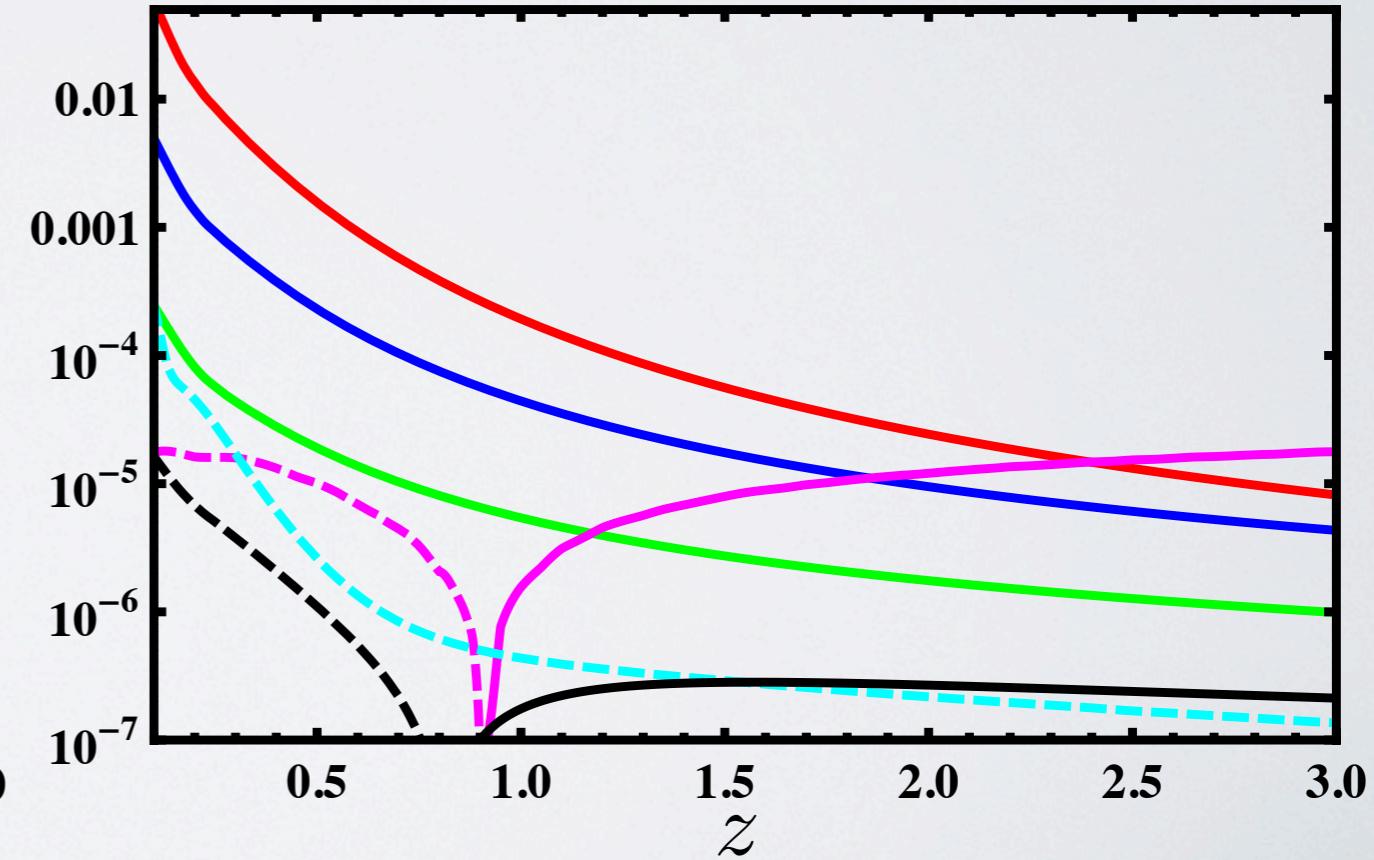
$$\frac{\ell(\ell+1)C_\ell}{2\pi}$$

- ◆ density
- ◆ z-distortion
- ◆ lensing
- ◆ corr. dens-z
- ◆ Doppler
- ◆ potential

No window function



10% window function

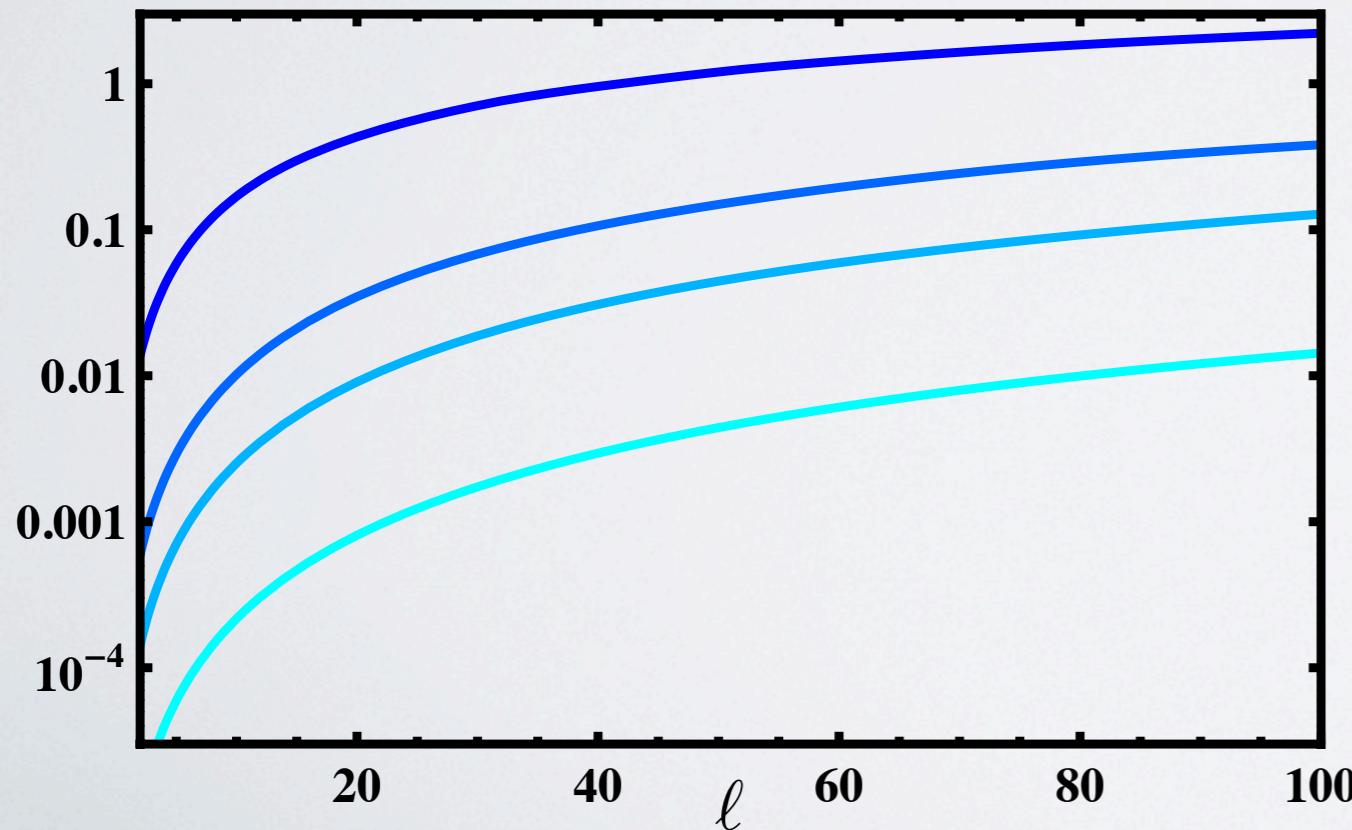


Total angular power spectrum

$$\frac{\ell(\ell+1)C_\ell(z)}{2\pi}$$

- ◆ $z = 0.1$
- ◆ $z = 0.5$
- ◆ $z = 1$
- ◆ $z = 3$

No window function



10% window function

