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, like BOSS, DES, Euclid.

Outline

- Computation of $\Delta(\mathbf{n}, z)$ at first order in perturbation theory.
  - → New contributions
- Computation 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 $\langle N\rangle(z)$

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

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

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

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

Result

Durrer, CB in preparation

See also: Yoo et al. 2009 & 2010
Challinor & Lewis in preparation

density — redshift space distortion

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

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

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

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

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

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

$\rightarrow$ gravitational potential

Angular power spectrum

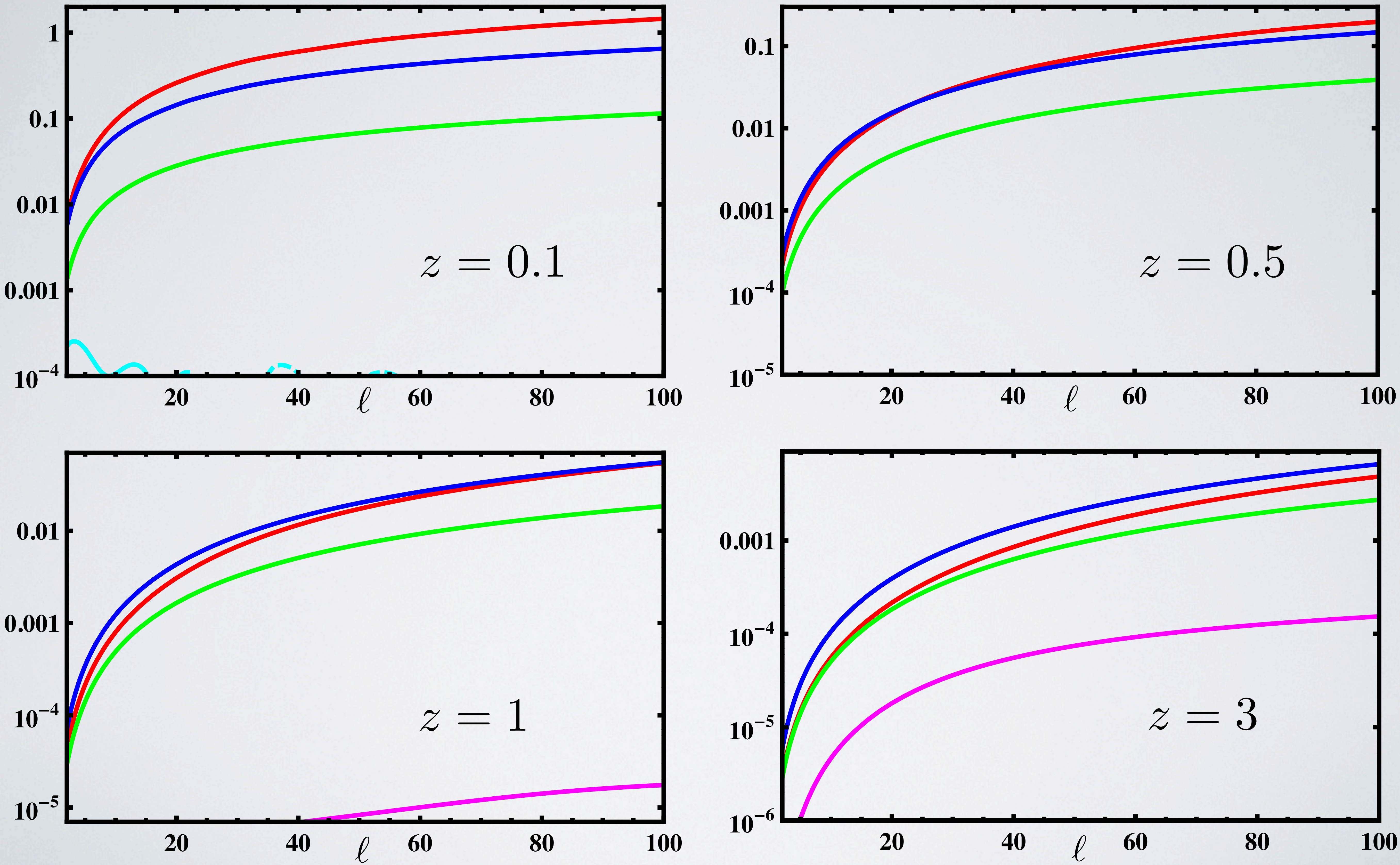
$$\Delta(\mathbf{n}, z) = \sum_{\ell m} a_{\ell m}(z) Y_{\ell m}(\mathbf{n})$$

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

- 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 ΛCDM Universe with CAMB.

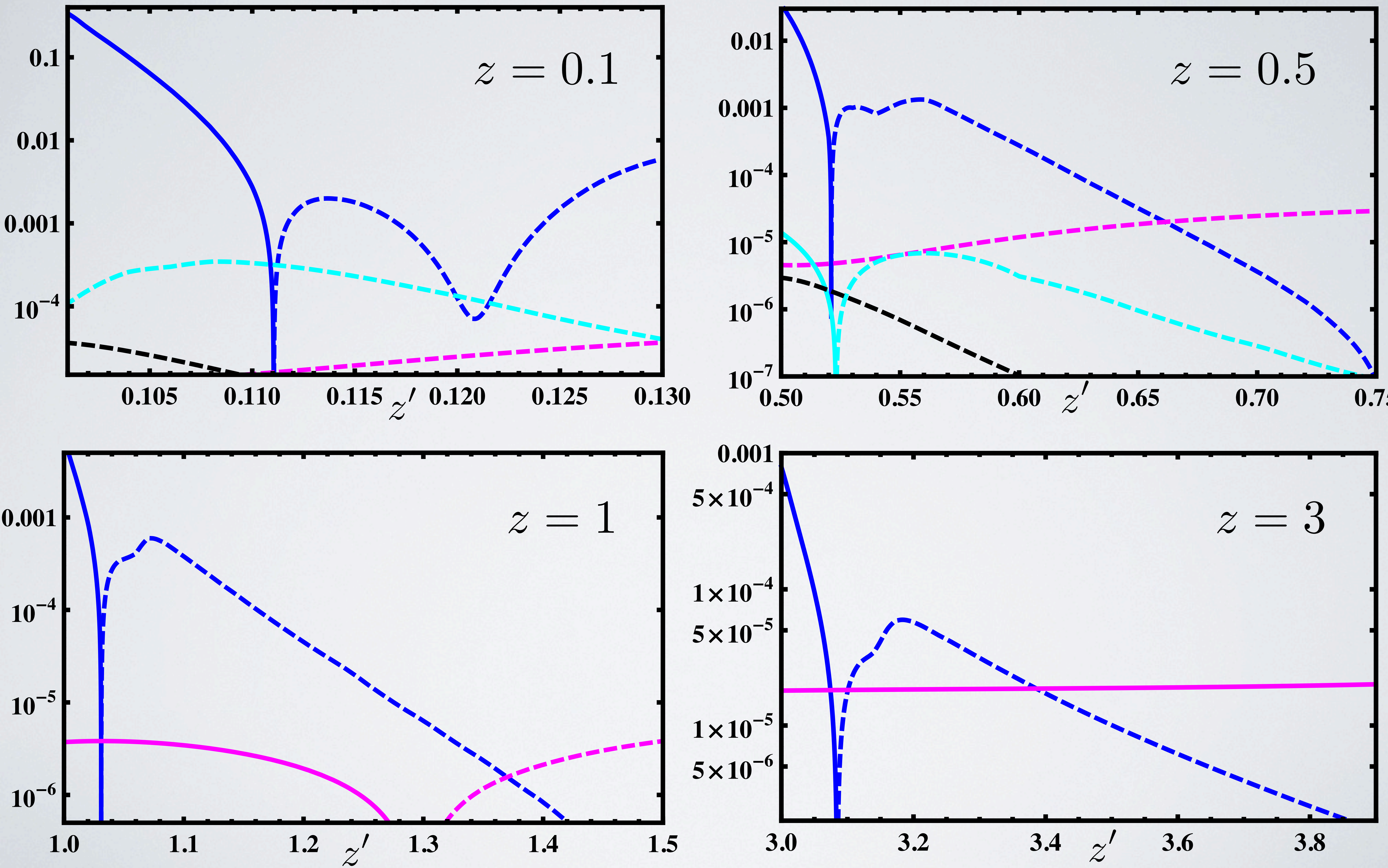
$$\frac{\ell(\ell+1)C_\ell(z)}{2\pi}$$

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



$$\frac{\ell(\ell+1)C_\ell(z,z')}{2\pi} \qquad \ell = 20$$

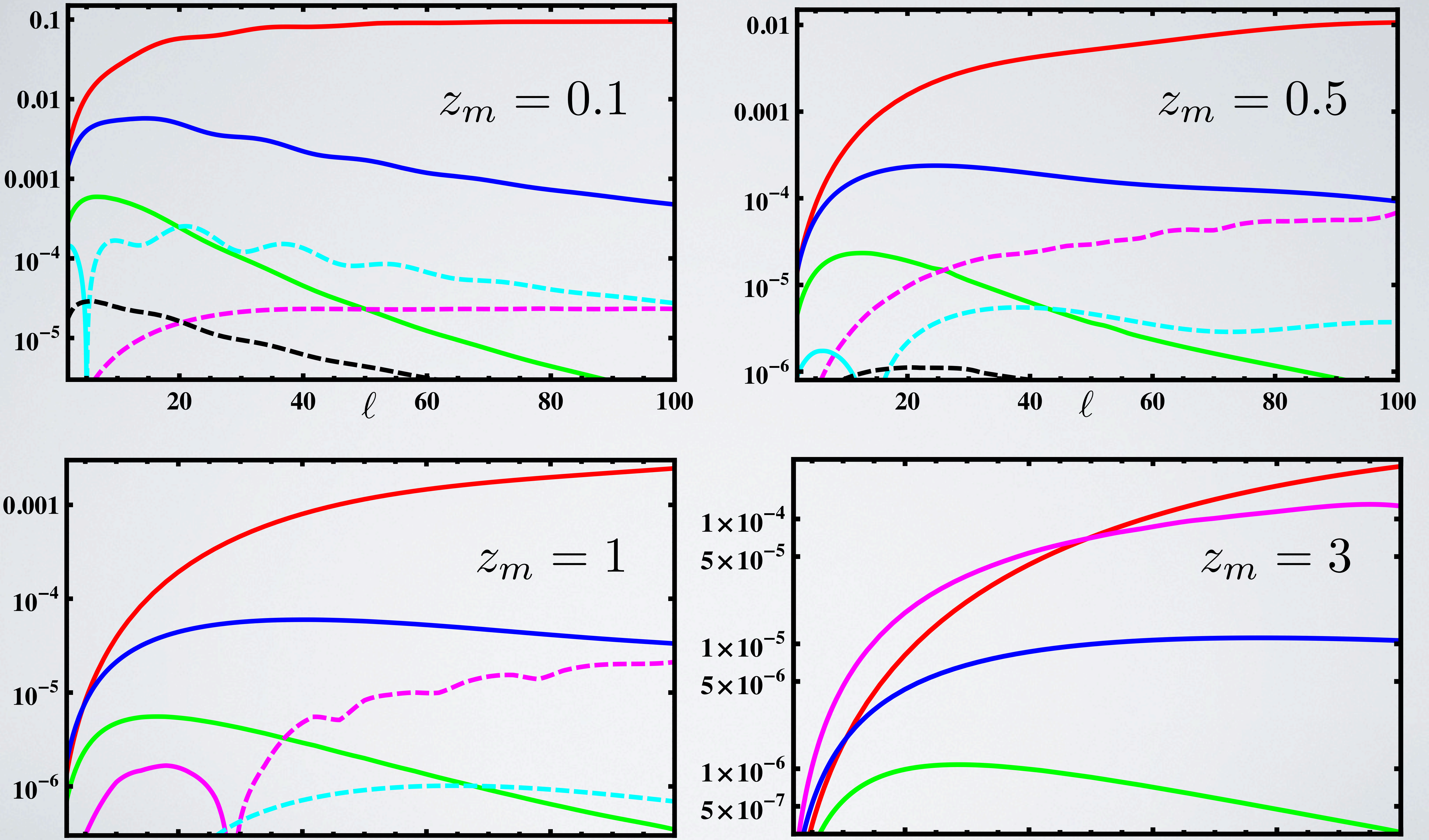
◆ standard ◆ Doppler
◆ lensing ◆ potential



$\sigma_z = 0.1 \cdot z$

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

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



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

- $$\frac{\delta z}{1+\bar{z}} = -\left[\Psi + \mathbf{n}\cdot\mathbf{V} + \int_0^{r_S} dr(\dot{\Phi}+\dot{\Psi})\right]$$

- $$dV = \sqrt{-g}\,\epsilon_{abcd}u^a \mathrm{d}x^b \mathrm{d}x^c \mathrm{d}x^d$$

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

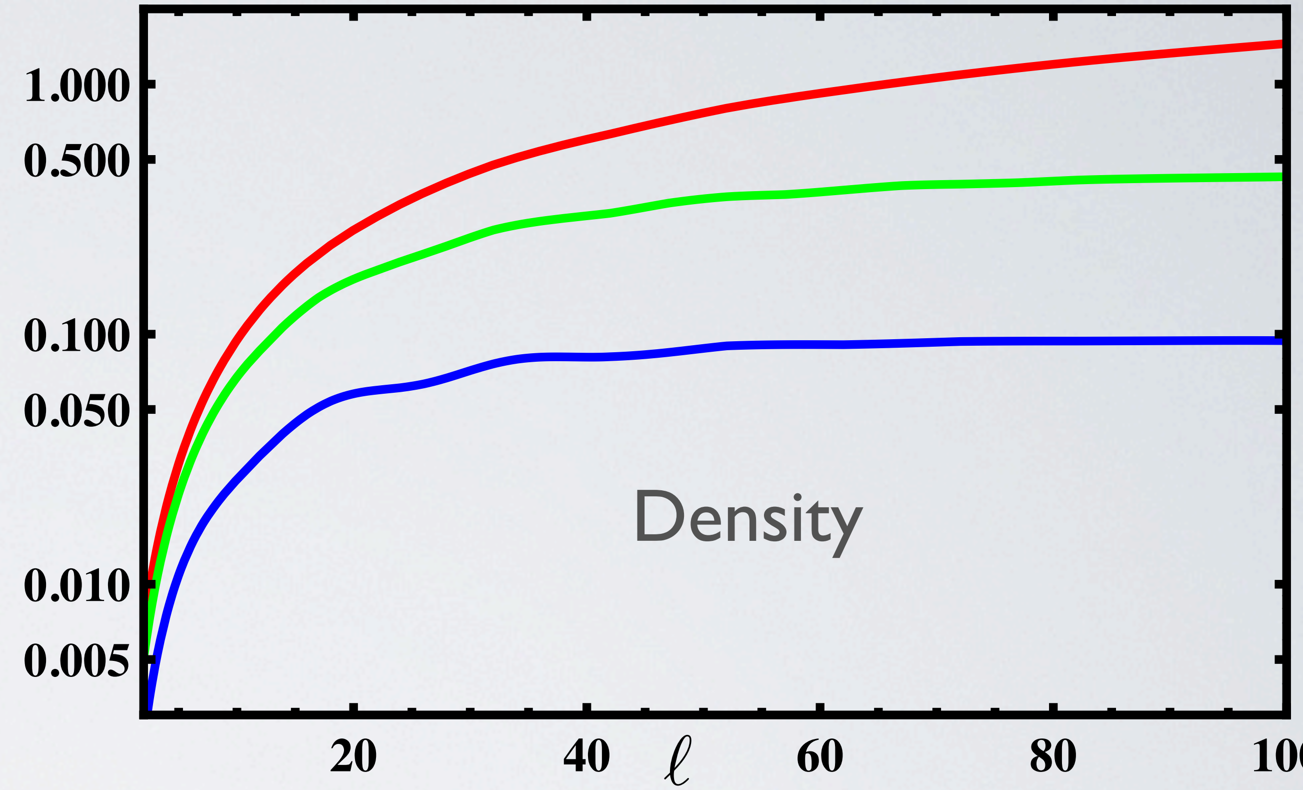
no window

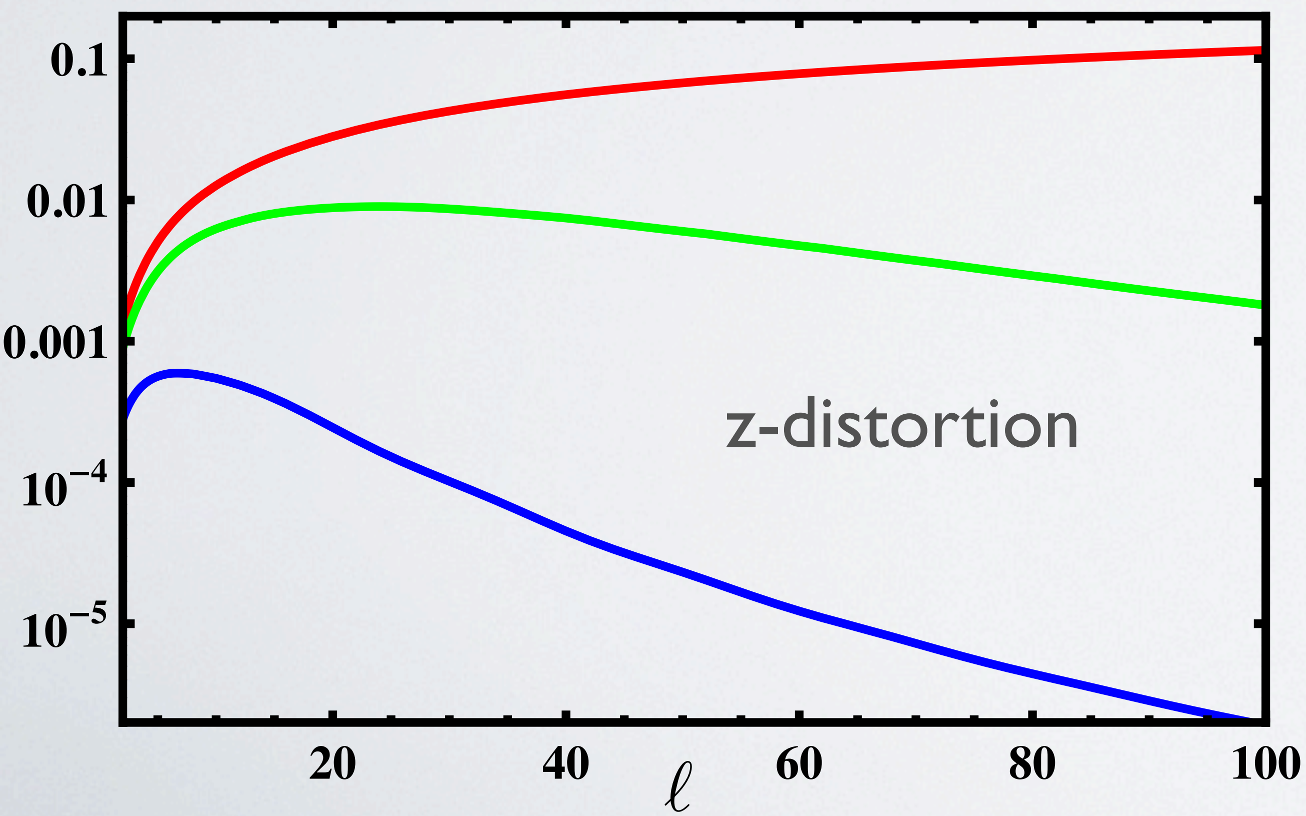
$\sigma_z = 0.002$ $\sigma_z = 0.01$

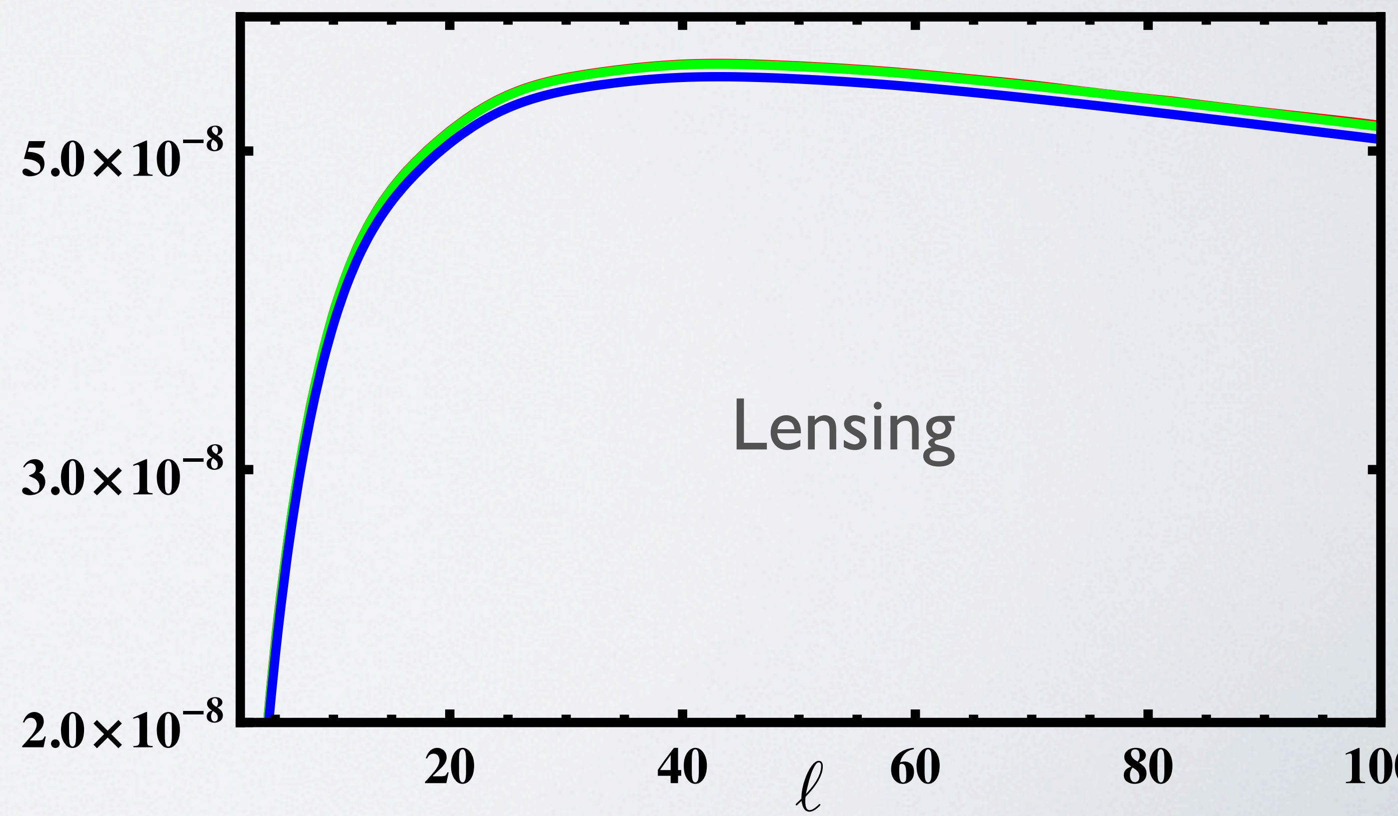
$$\int_0^\infty dz\, \Delta(\mathbf{n}, z) W(z)$$

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

$$z_m = 0.1$$







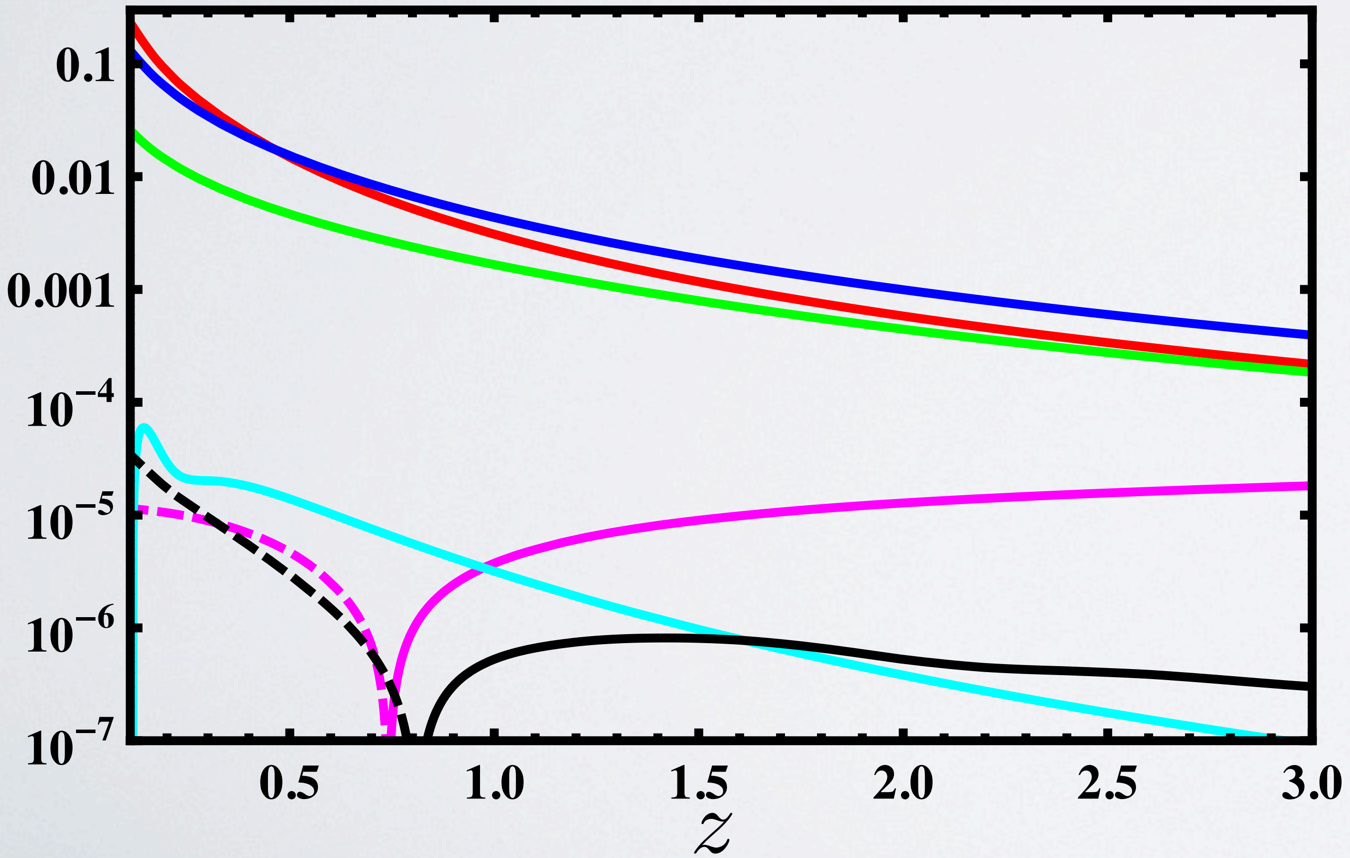
Redshift dependence

$\ell = 20$

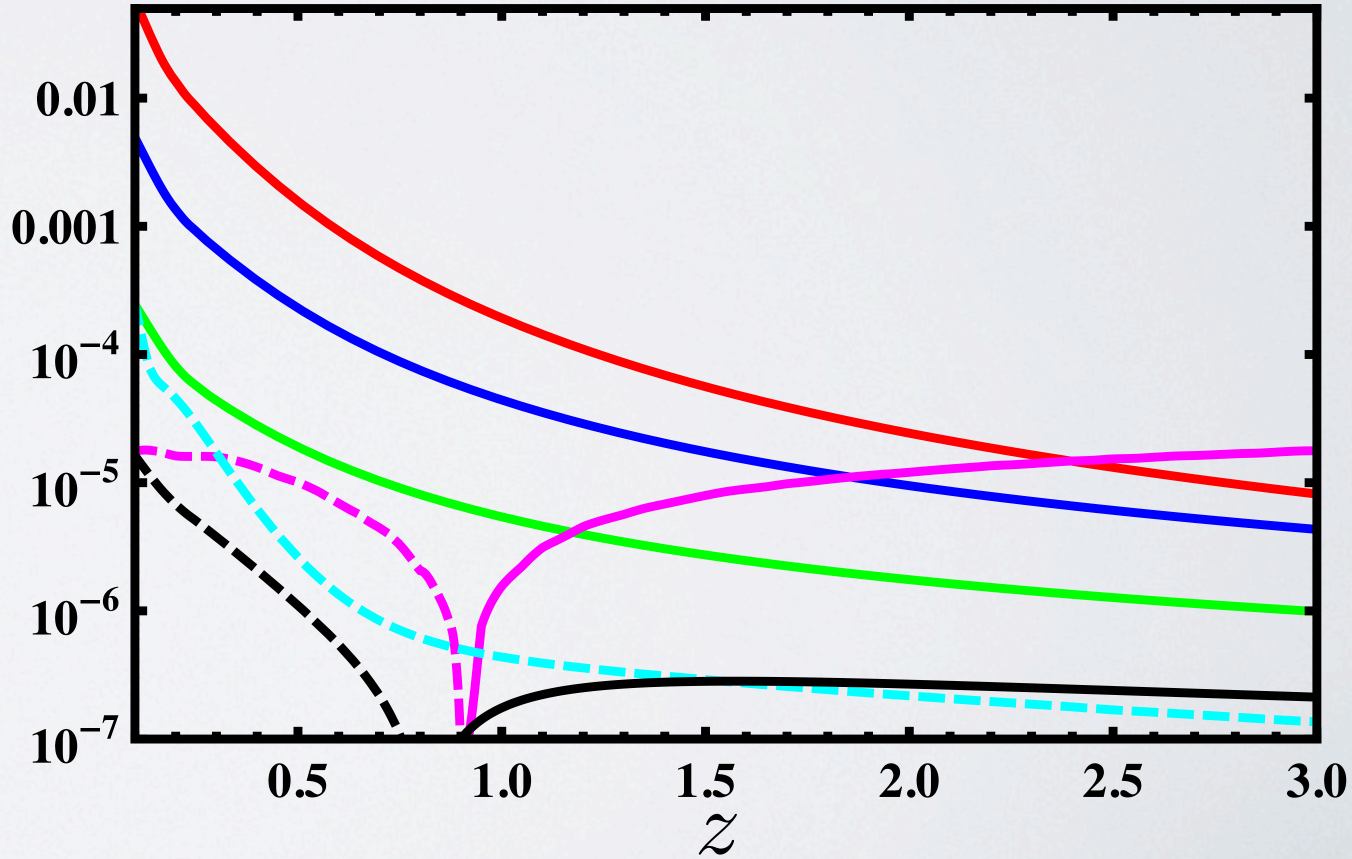
$$\frac{\ell(\ell+1)C_\ell}{2\pi}$$

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

No window function



10% window function

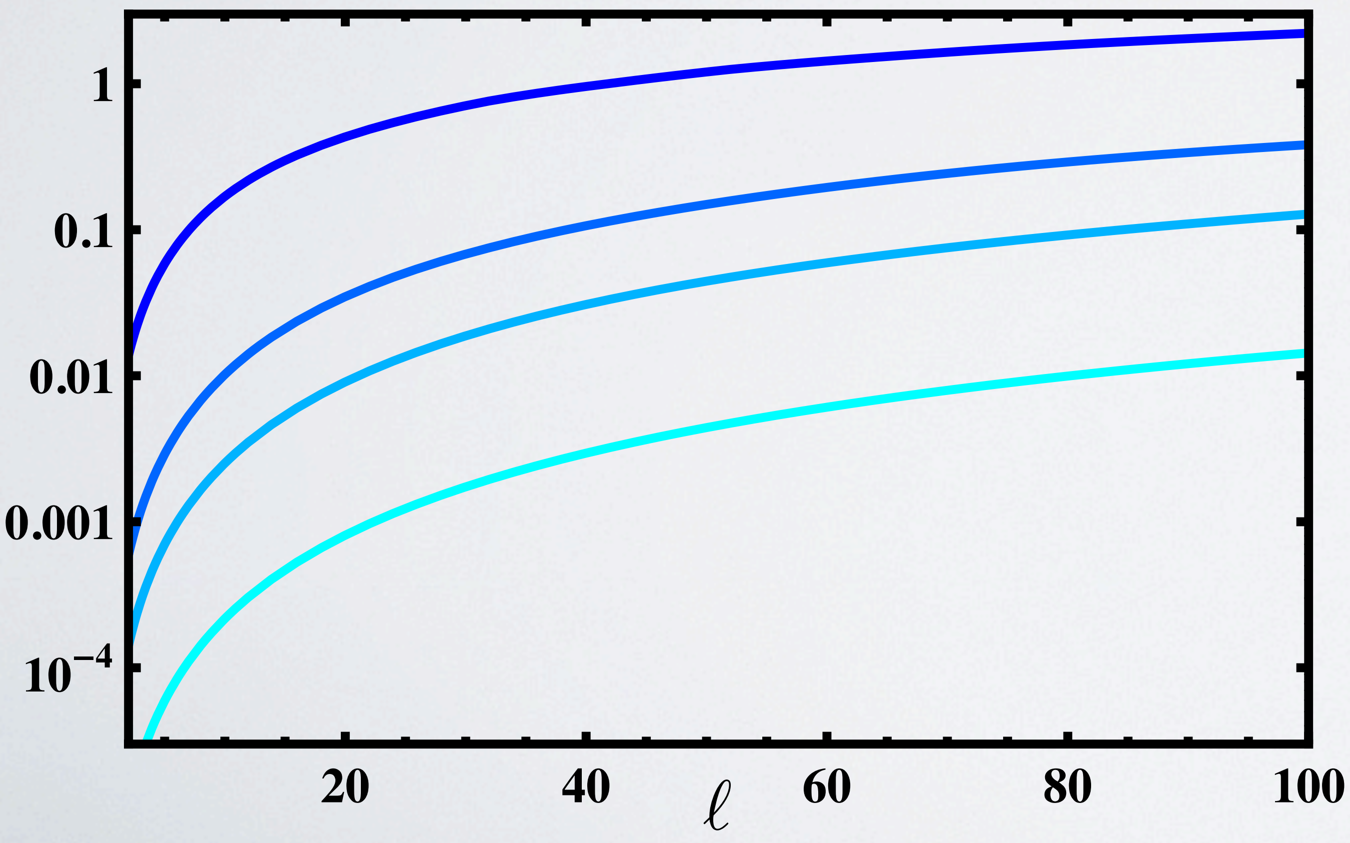


Total angular power spectrum

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

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

No window function



10% window function