# What Galaxy Surveys Really Measure.

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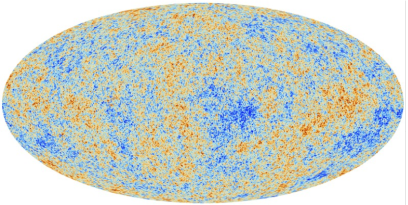
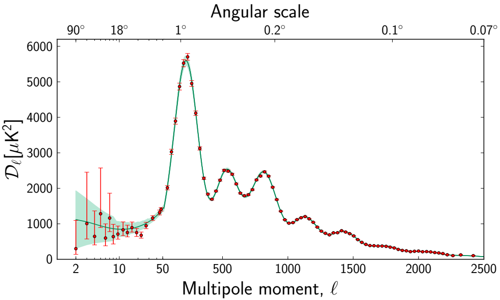
# Outline

## The CMB

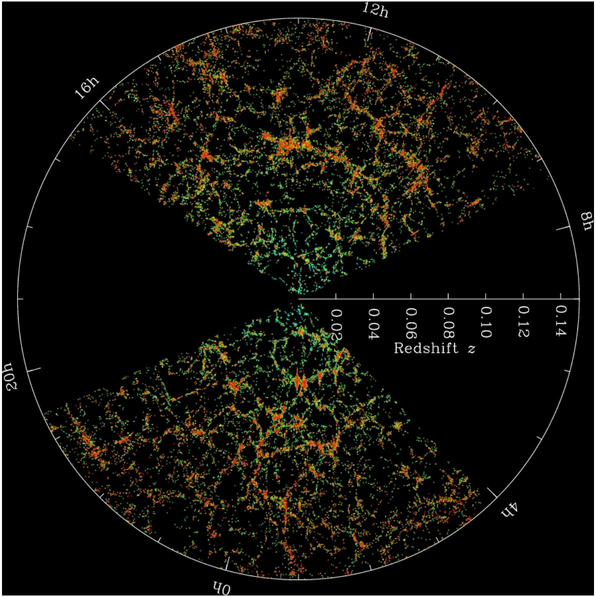
CMB sky as seen by Planck



The Planck Collaboration: Planck results 2013 XV

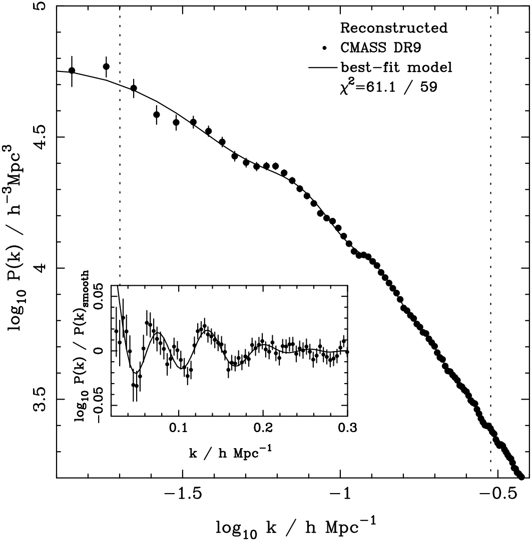


# Introduction




M. Blanton and the Sloan Digital Sky Survey Team.

# Galaxy power spectrum from the Sloan Digital Sky Survey (BOSS)

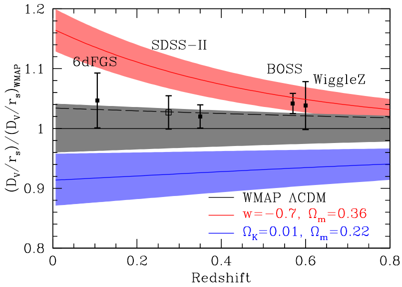



from Anderson et al. '12

SDSS-III (BOSS) power spectrum.

Galaxy surveys $\simeq$ matter density fluctuations, biasing and redshift space distortions.

The observed Universe is well approximated by a $\Lambda$CDM model,
$\Omega_\Lambda \simeq 0.72$, $\Omega_m = \Omega_{cdm} + \Omega_b \simeq 0.28$, $\Omega_b \simeq 0.04$.

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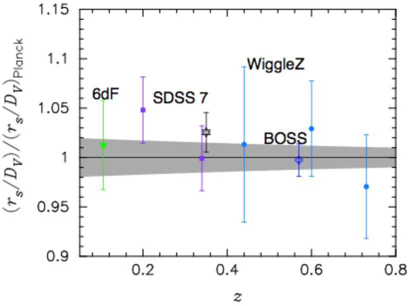


from Planck Collaboration, XVI

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- But of course much more for future surveys like DESspec, bigBOSS and Euclid.
- Whenever we convert a measured redshift or angle into a length scale, we make an assumption about the underlying cosmology.

$$D(z) = \int_0^z \frac{dz'}{H(z')}$$

# What are very large scale galaxy catalogs really measuring?

Following C. Bonvin & RD [arXiv:1105.5080]; F. Montanari & RD [arXiv:1206.3545]
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$$\Delta(\mathbf{n}, z) = \frac{N(\mathbf{n}, z) - \bar{N}(z)}{\bar{N}(z)}.$$

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$$\Delta(\mathbf{n}, z) = \frac{N(\mathbf{n}, z) - \bar{N}(z)}{\bar{N}(z)}.$$

$$\xi(\theta, z, z') = \langle \Delta(\mathbf{n}, z)\Delta(\mathbf{n}', z') \rangle \,, \qquad \mathbf{n} \cdot \mathbf{n}' = \cos\theta \,.$$

This quantity is directly measurable $\Rightarrow$ gauge invariant.

# What are very large scale galaxy catalogs really measuring?

Density fluctuation per redshift bin $dz$ and per solid angle $d\Omega$ as $\delta_z(\mathbf{n}, z)$.

$$\delta_z(\mathbf{n}, z) = \frac{\rho(\mathbf{n}, z) - \bar{\rho}(z)}{\bar{\rho}(z)} = \frac{\frac{N(\mathbf{n},z)}{V(\mathbf{n},z)} - \frac{\bar{N}(z)}{V(z)}}{\frac{\bar{N}(z)}{V(z)}}$$

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This together with the volume fluctuations, results in the directly observed number fluctuations

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Both these terms are in principle measurable and therefore gauge invariant. We want to express them in terms of standard gauge invariant perturbation variables.

# Matter fluctuations per redshift bin

We consider a photon emitted from a galaxy ($S$), moving in direction **n** into our telescope. The observer ($O$) receives the photon redshifted by a factor

$$1 + z = \frac{(n \cdot u)_S}{(n \cdot u)_O} \ .$$

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To first order in perturbation theory one finds (in longitudinal gauge)

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

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With this, the density fluctuation in redshift space becomes

$$\delta_z(\mathbf{n}, z) = D_g(\mathbf{n}, z) + 3(\mathbf{V} \cdot \mathbf{n})(\mathbf{n}, z) + 3(\Psi + \Phi)(\mathbf{n}, z) + 3\int_0^{\chi_S} (\dot{\Psi} + \dot{\Phi})(\mathbf{n}, z(\chi)) d\chi$$

This quantity is gauge invariant and therefore, in principle, measurable. But when we count numbers of galaxies per solid angle and per redshift bin, we also have to consider volume perturbations.

Putting the density and volume fluctuations together one obtains the galaxy number density fluctuations

$$\begin{aligned}\Delta(\mathbf{n}, z) \quad &= \quad D_g + \Phi + \Psi + \frac{1}{\mathcal{H}}\left[\dot{\Phi} + \partial_\chi(\mathbf{V}\cdot\mathbf{n})\right] \\ &+ \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{\chi(z)\mathcal{H}}\right)\left(\Psi + \mathbf{V}\cdot\mathbf{n} + \int_0^{\chi(z)} d\chi(\dot{\Phi} + \dot{\Psi})\right) \\ &+ \frac{1}{\chi(z)}\int_0^{\chi(z)} d\chi\left[2 - \frac{\chi(z)-\chi}{\chi}\Delta_\Omega\right](\Phi + \Psi).\end{aligned}$$

( C. Bonvin & RD '11)

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& + \frac{1}{\chi_S}\int_0^{\chi(z)} d\chi \left[2(\Phi + \Psi) - \boxed{\frac{\chi(z)-\chi}{\chi}\Delta_\Omega(\Phi + \Psi)}\right].
\end{aligned}
$$

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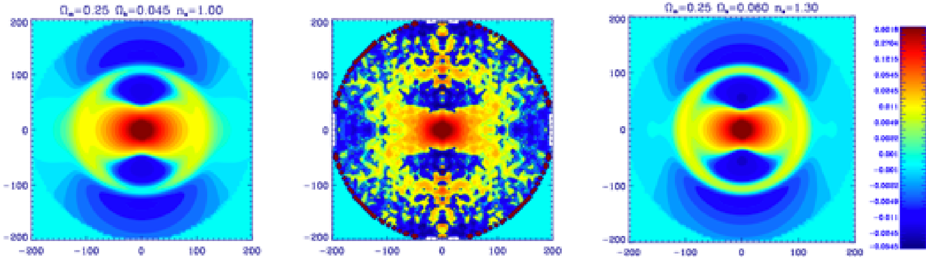
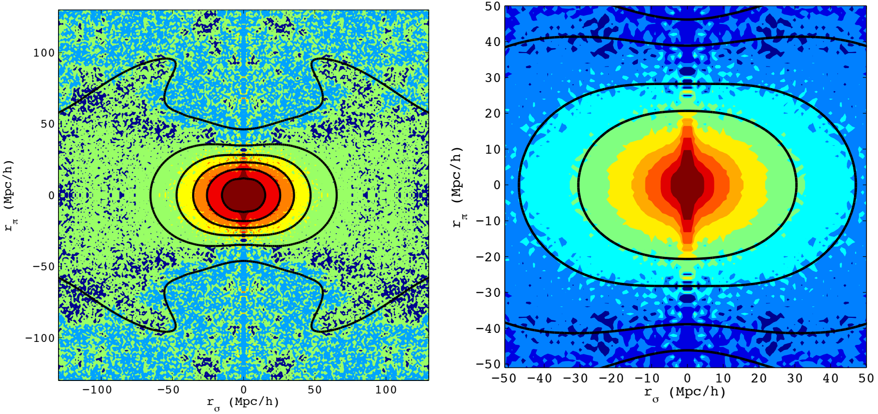


(From Gaztanaga et al. 2008)
The correlation function is not isotropic ⇒ redshift space distortions.

# Anisotropic clustering as seen in the BOSS survey

(from Reid et al. '12)



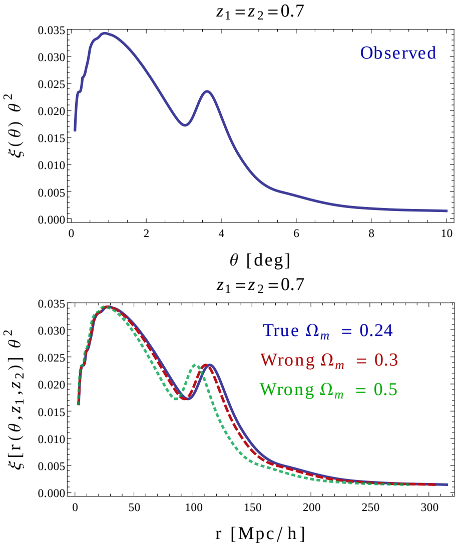
# The angular power spectrum of galaxy density fluctuations

For fixed $z$, we can expand $\Delta(\mathbf{n}, z)$ in spherical harmonics,

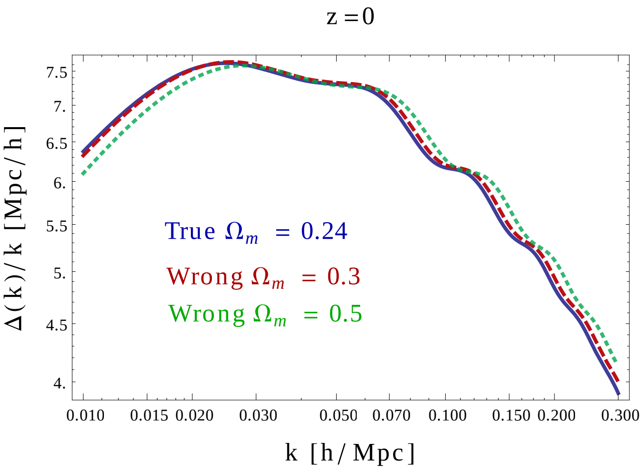
$$\Delta(\mathbf{n}, z) = \sum_{\ell m} a_{\ell m}(z) Y_{\ell m}(\mathbf{n}), \qquad C_\ell(z, z') = \langle a_{\ell m}(z) a^*_{\ell m}(z') \rangle .$$

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

If we convert the measured $\xi(\theta, z, z')$ to a power spectrum, we have to introduce a cosmology, to convert angles and redshifts into length scales. $r(z, z', \theta) = \sqrt{\chi^2(z) + \chi^2(z') - 2\chi(z)\chi(z')\cos\theta}$.




(Figure by F. Montanari)

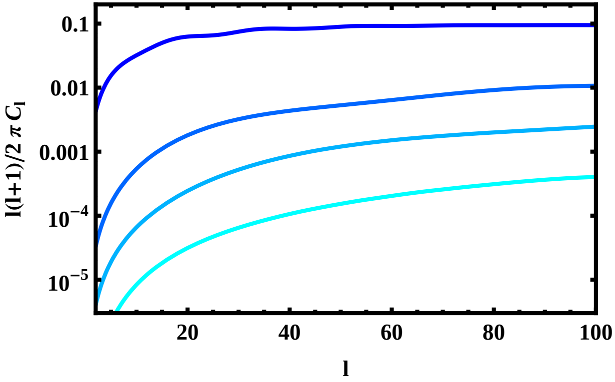



(Figure by F. Montanari)

$$\Delta(k)/k = k^2 P(k)$$

# The transversal power spectrum

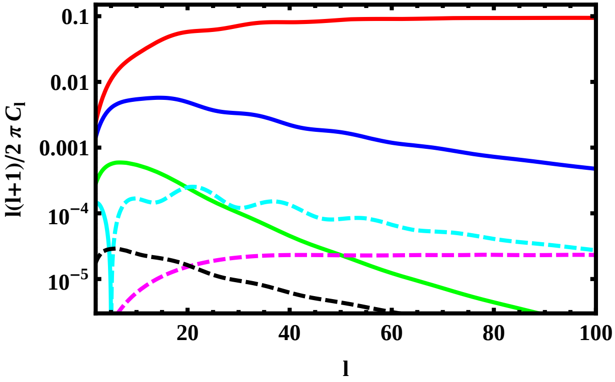
The transverse power spectrum, $z' = z$ (from Bonvin & RD '11)




From top to bottom $z = 0.1$, $z = 0.5$, $z = 1$ and $z = 3$.

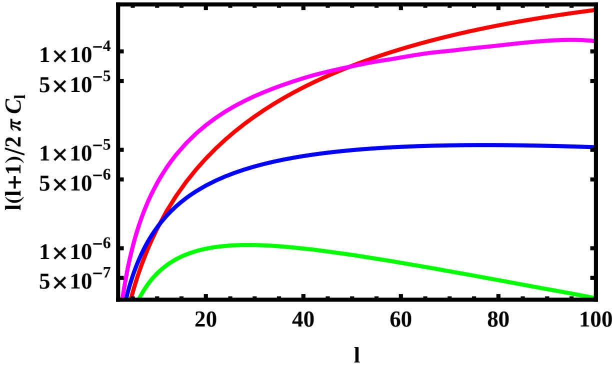
# The transversal power spectrum

Contributions to the transverse power spectrum at redshift $z = 0.1, \ \Delta z = 0.01$ (from Bonvin & RD '11)




$C_\ell^{DD}$ (red), $C_\ell^{zz}$ (green), $2C_\ell^{Dz}$ (blue), $C_\ell^{Doppler}$ (cyan, $C_\ell^{lensing}$ (magenta) $C_\ell^{grav}$ (black).

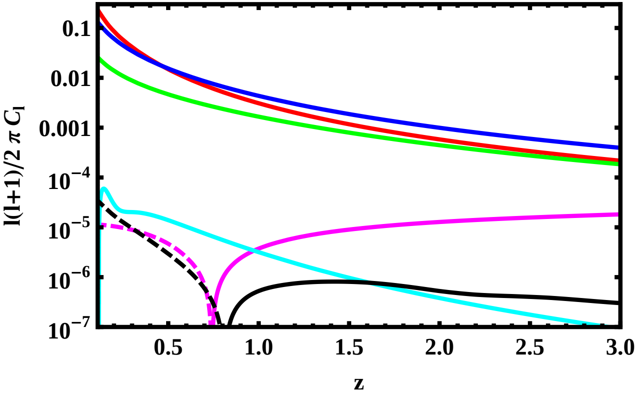
Contributions to the transverse power spectrum at redshift $z = 3$, $\Delta z = 0.3$ (from Bonvin & RD '11)




$C_\ell^{DD}$ (red), $C_\ell^{zz}$ (green), $2C_\ell^{Dz}$ (blue), $C_\ell^{lensing}$ (magenta).

# The transversal power spectrum

Contributions to the transversal power spectrum as function of the redshift, $\ell = 20$, $\Delta z = 0$ (from Bonvin & RD '11)

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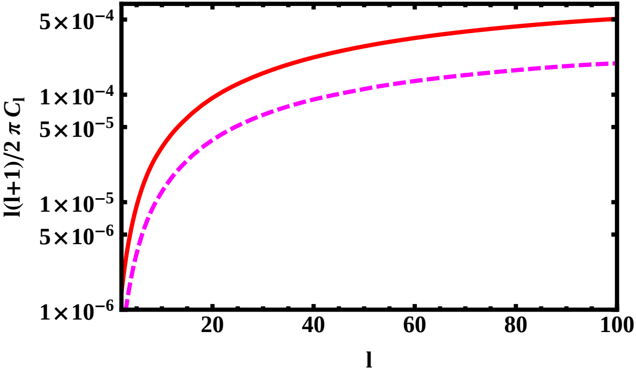
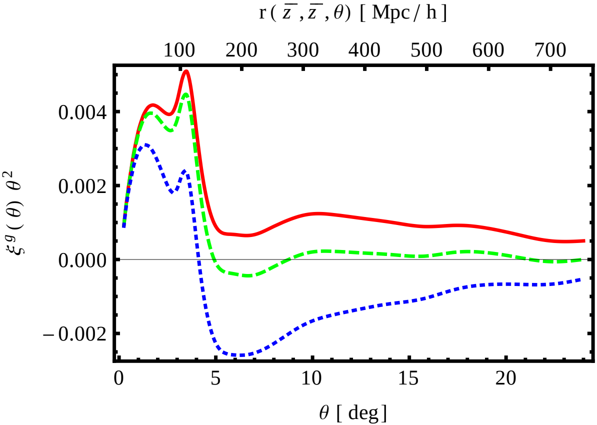



$0 < z < 2$

$C_\ell^{DD}$ (red), $C_\ell^{lensing}$ (magenta).

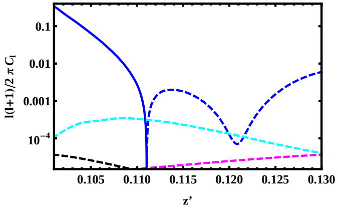


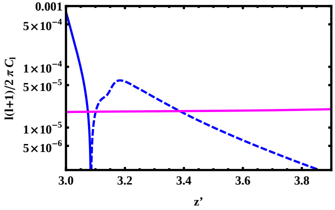

(from
Montanari & RD '12)

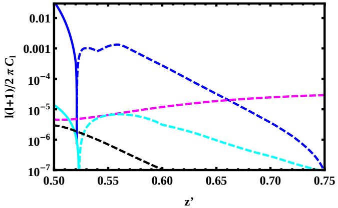
$\theta^2\xi(\theta, z, z)$

blue $C_\ell^{DD}$ (real space),
green flat space approximation for redshift space distortions,
red $C_\ell^{DD}$ , $C_\ell^{zz}$ and $2C_\ell^{Dz}$ (fully positive!).

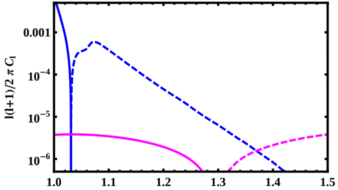
# The radial power spectrum



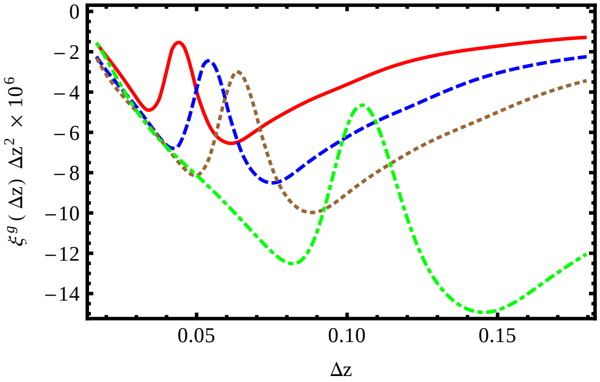




The radial power spectrum $C_\ell(z, z')$
for $\ell = 20$
Left, top to bottom: $z = 0.1,\ 0.5,\ 1,$
top right: $z = 3$




Standard terms (blue), $C_\ell^{lensing}$ (magenta), $C_\ell^{Doppler}$ (cyan), $C_\ell^{grav}$ (black),

# The radial correlation function



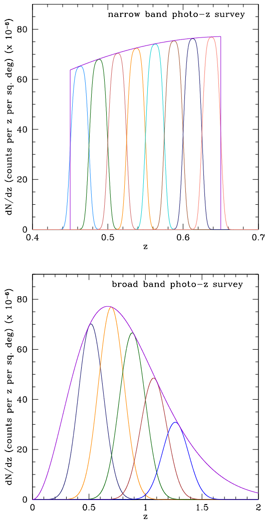

$(\Delta z)^2 \xi(\theta, z - \Delta z/2, z + \Delta z/2)$

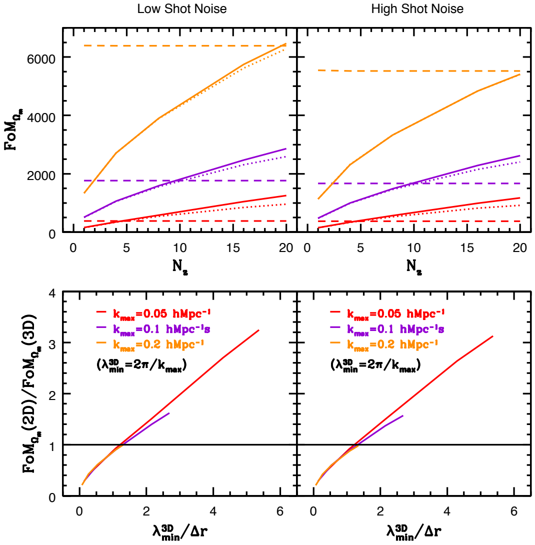
Purely negative for $\Delta z \gtrsim 0.01$.

(from Montanari & RD '12)

$z = 2$,
$z = 1$,
$z = 0.7$,
$z = 0.3$.

# Cosmological parameters from the angle redshift correlation function



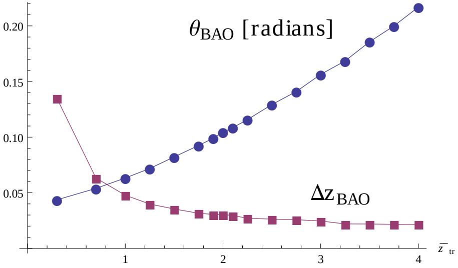




(From Asorey et al. 2012)

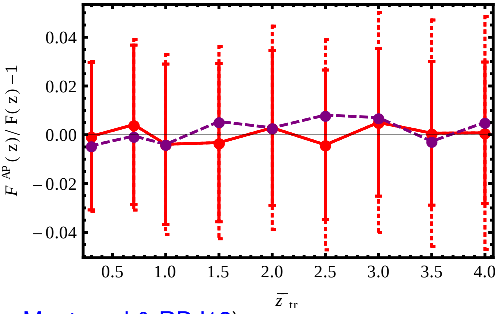
(Alcock & Paczyński ’79)

Consider a comoving scale $L$ in the sky.
Horizontally it is projected to the angle $\theta_L = \frac{L}{(1+z)D_A(z)}$.
Radially its ends are at a slightly different redshifts, $\Delta z_L = LH(z)$.

$$\frac{\Delta z_L}{\theta_L} = (1+z)D_A(z)H(z) = F(z) \equiv \int_0^z \frac{H(z)}{H(z')}dz'$$



$F(z)^{AP} \equiv \Delta z_L/\theta_L$ measured from the theoretical power spectrum (with Euclid-like redshift accuracies) $F(z) \equiv \int_0^z \frac{H(z)}{H(z')} dz'$.




solid errors:
angular resolution $0.02^o$
dashed errors:
angular resolution $0.05^o$
violet: linear $P(k)$

(from Montanari & RD '12)

## Conclusions

- So far cosmological LSS data mainly determined $\xi(r)$, or equivalently $P(k)$. These 1d functions are easier to measure (less noisy) but they require an input cosmology converting redshift and angles to length scales,

$$r = \sqrt{\chi(z)^2 + \chi(z')^2 - 2\chi(z)\chi(z')\cos\theta} \, .$$

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- The spectra depend sensitively and in several different ways on dark energy (growth factor, distance redshift relation), on the matter and baryon densities, bias, etc. Their measurements provide a new route to estimate cosmological parameters.

## Conclusions

- So far cosmological LSS data mainly determined $\xi(r)$, or equivalently $P(k)$. These 1d functions are easier to measure (less noisy) but they require an input cosmology converting redshift and angles to length scales,

$$r = \sqrt{\chi(z)^2 + \chi(z')^2 - 2\chi(z)\chi(z')\cos\theta}\,.$$

- But future large & precise 3d galaxy catalogs like **Euclid** will be able to determine directly the measured 3d correlation function $\xi(\theta, z, z')$ and $C_\ell(z, z')$ from the data.
- These 3d quantities will of course be more noisy, but they also contain more information.
- These spectra are not only sensitive to the matter distribution (density) but also to the velocity via (redshift space distortions) and to the perturbations of spacetime geometry (lensing) .
- The spectra depend sensitively and in several different ways on dark energy (growth factor, distance redshift relation), on the matter and baryon densities, bias, etc. Their measurements provide a new route to estimate cosmological parameters.
- An example is the Alcock-Paczyński test.