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The measured galaxy correlation function

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Outline

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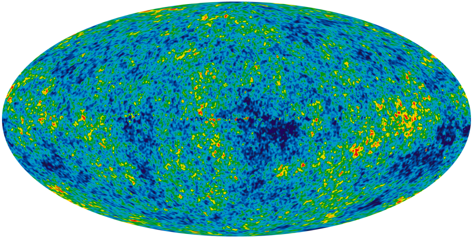
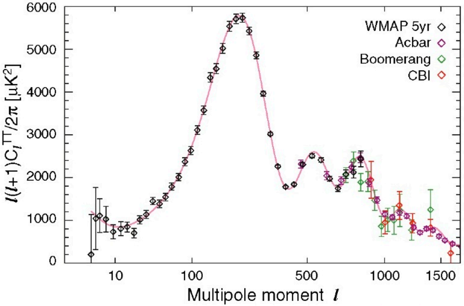
2. What are very large scale galaxy catalogs really measuring?
   - Matter fluctuations per redshift bin, volume perturbations
3. The angular power spectrum and the correlation function of galaxy density fluctuations
   - The transversal power spectrum
   - The radial power spectrum
4. Alcock-Paczyński test
5. Conclusions

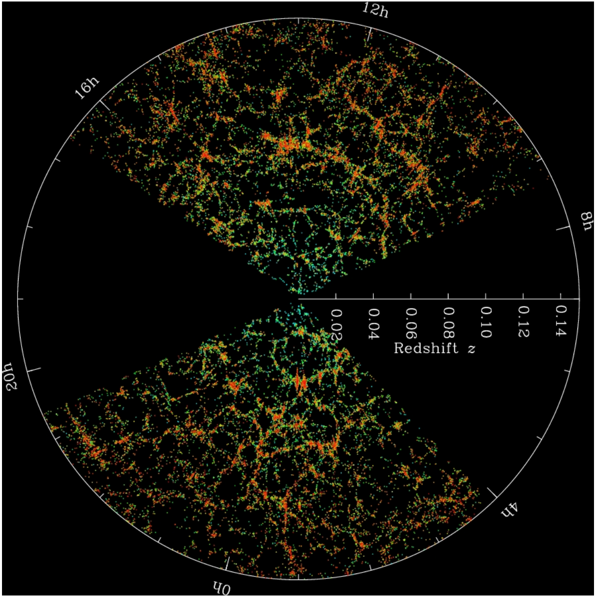
The CMB

WMAP 7 year CMB sky



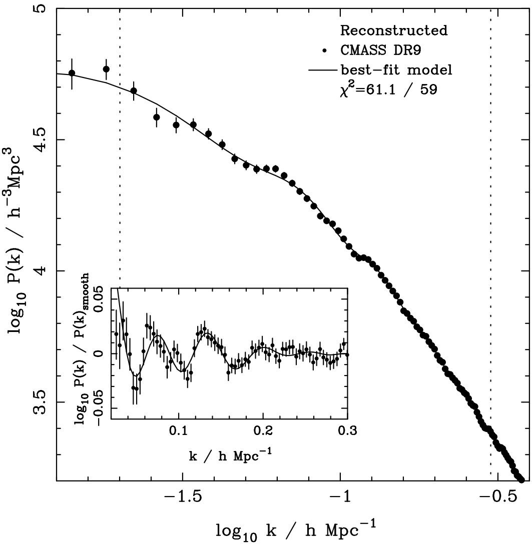


The WMAP Team



M. Blanton and the Sloan Digital Sky Survey Team.

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

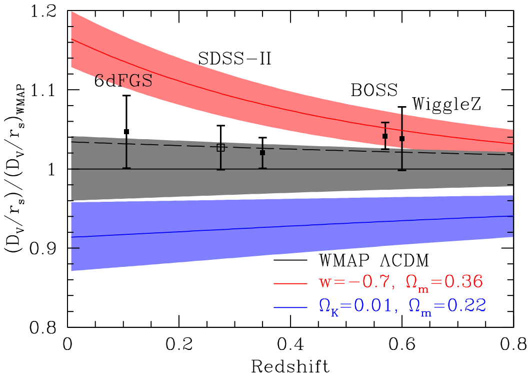


from Anderson et al. '12

SDSS-III (BOSS) power spectrum.

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

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



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

What are very large scale galaxy catalogs really measuring?

Following C. Bonvin & RD [arXiv:1105.5080]; F. Montanari & RD [arXiv:1206.3545]
see also Challinor & Lewis, [arXiv:1105:5092].
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$$\Delta(z, \mathbf{n}) = \frac{N(z, \mathbf{n}) - \bar{N}(z)}{\bar{N}(z)}.$$

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

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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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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)

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

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With this, the density fluctuation in redshift space becomes

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

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

The total galaxy density fluctuation per redshift bin, per sold angle

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

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

(C. Bonvin & RD '11)

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(C. Bonvin & RD '11)

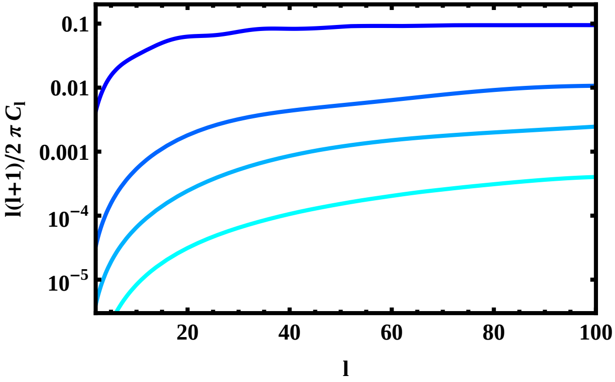
The angular power spectrum of galaxy density fluctuations

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

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

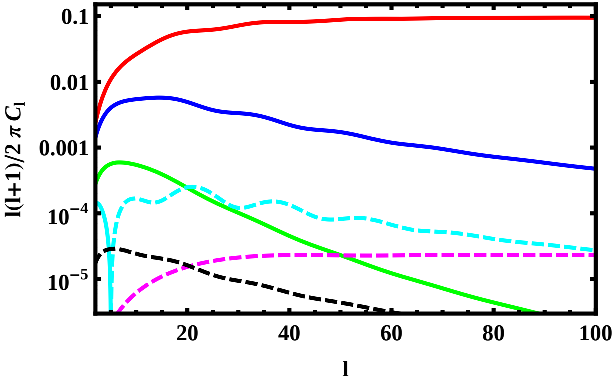
$$\xi(\theta, z, z') = \langle \Delta(\mathbf{n}, z) \Delta(\mathbf{n}', z') \rangle = \frac{1}{4\pi} \sum_\ell (2\ell + 1) C_\ell(z, z') P_\ell(\cos\theta)$$

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



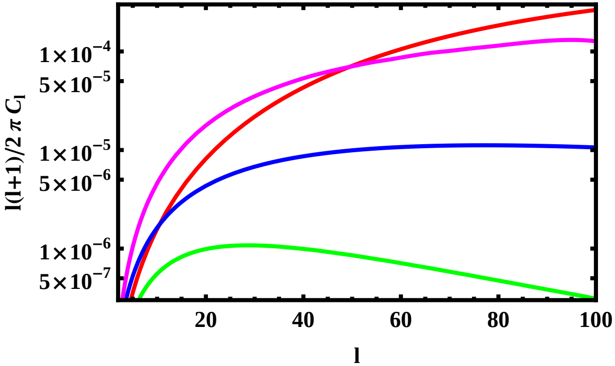
From top to bottom $z = 0.1$, $z = 0.5$, $z = 1$ and $z = 3$.

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



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

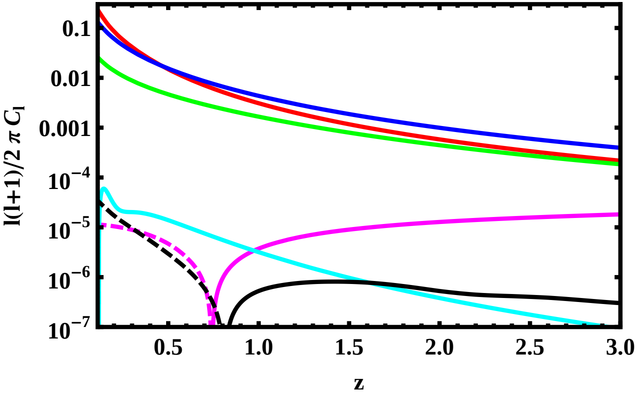
Contributions to the transverse power spectrum at redshift $z = 3$ (from Bonvin & RD '11)



C_ℓ^{DD} (red), C_ℓ^{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, $\ell = 20$ (from Bonvin & RD '11)



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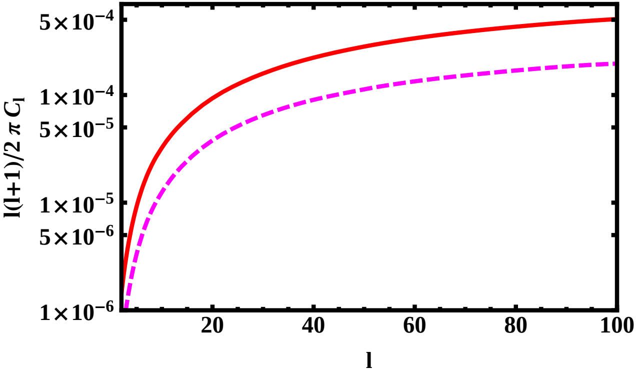
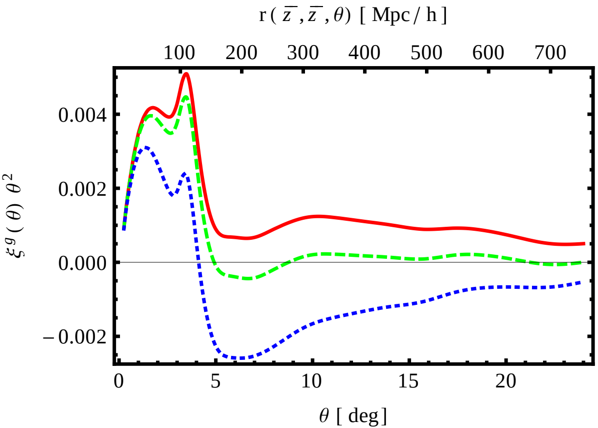


$0 < z < 2$

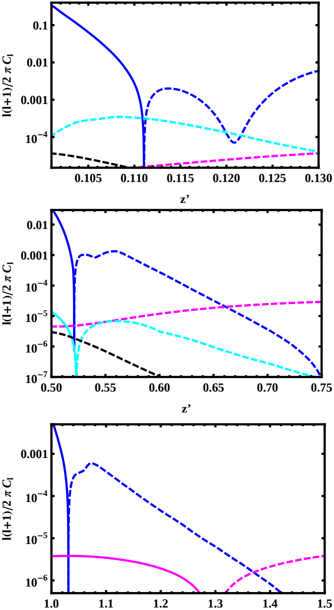
C_ℓ^{DD} (red), $C_\ell^{lensing}$ (magenta).

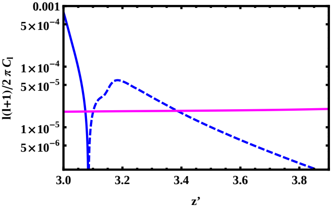


(from Montanari & RD '12)

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

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

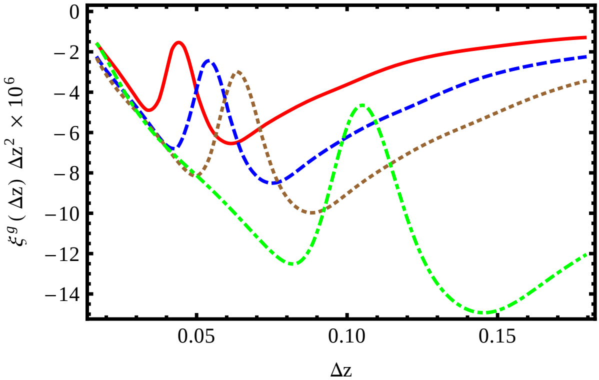




The radial power spectrum $C_\ell(z, z')$ for $\ell = 20$
Left, top to bottom: $z = 0.1,\ 0.5,\ 1$,
top right: $z = 3$

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

The radial correlation function



(from Montanari & RD '12)

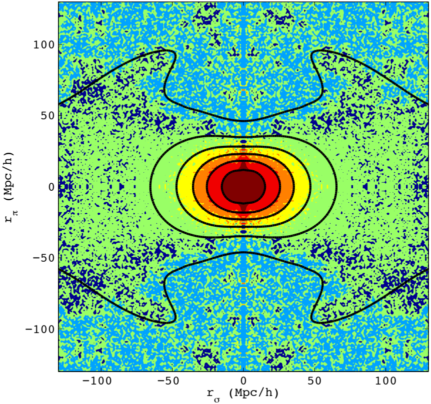
$z = 2$,
$z = 1$,
$z = 0.7$,
$z = 0.3$.

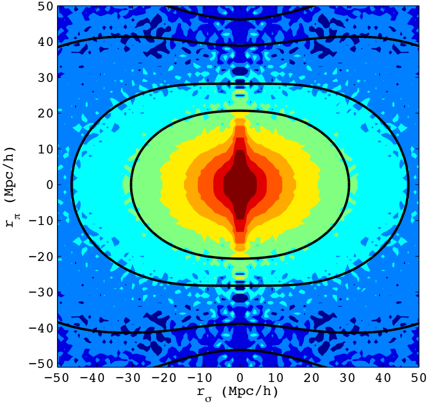
$$(\Delta z)^2 \xi(\theta, z - \Delta z/2, z + \Delta z/2)$$

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

Anisotropic clustering as seen in the BOSS survey

(from Reid et al. '12)

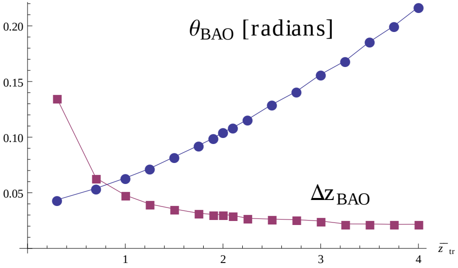




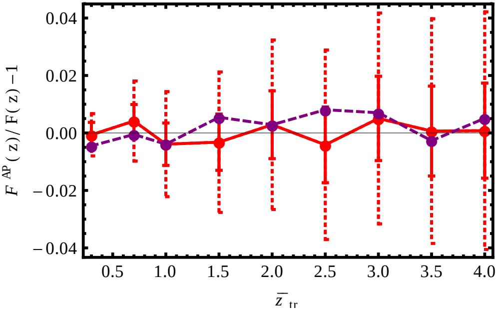
(Alcock & Paczyński '79)

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

(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,

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- An example is the Alcock-Paczyński test.