The large scale matter distribution of the Universe

Ruth Durrer
Université de Genève
Départment de Physique Théorique and Center for Astroparticle Physics

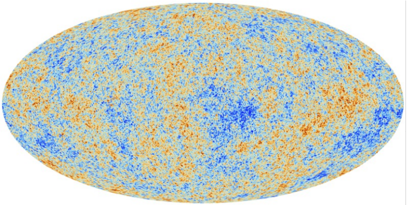
Work in collaboration with:
Camille Bonvin, Enea Di Dio, Francesco Montanari and Julien Lesgourgues
arXiv: 1105.5280, 1206.3545, 1307.1459, 1308.6186

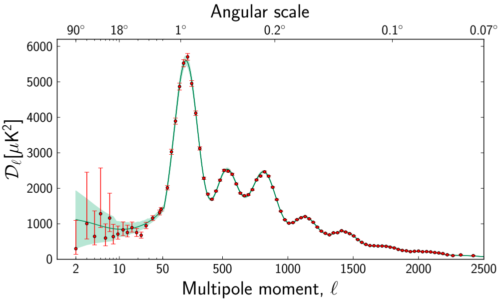
Oslo, September 11, 2013

Outline

The CMB

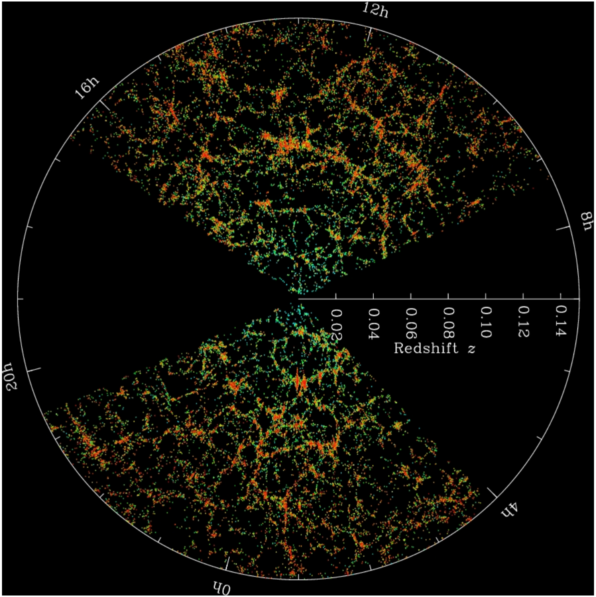
CMB sky as seen by Planck





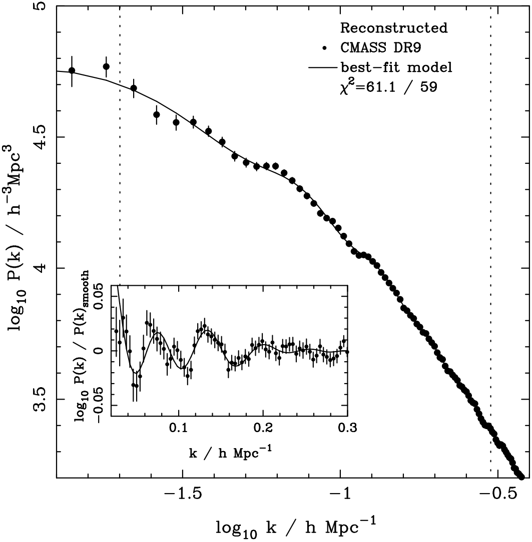
The Planck Collaboration:
Planck results 2013 XV

Introduction



M. Blanton and the Sloan Digital Sky Survey Team.

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

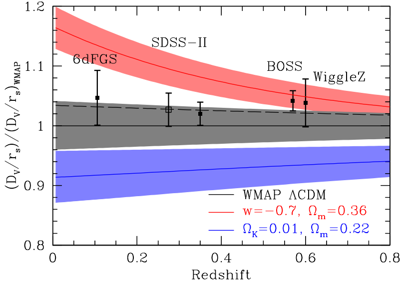


from Anderson et al. '12

SDSS-III (BOSS)
power spectrum.

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

The observed Universe is well approximated by a 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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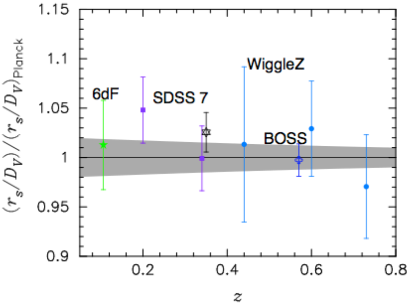

from Planck Collaboration, XVI ’13

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- For small galaxy catalogs, these effects are not very important, but when we go out to $z \sim 1$ or more, they become relevant. Already for SDSS which goes out to $z \simeq 0.2$ (main catalog) or even $z \simeq 0.6$ (BOSS).

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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]; Challinor & Lewis, [arXiv:1105:5092].
Relativistic corrections to galaxy surveys are also discussed in:
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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

$$\Delta(\mathbf{n}, z) = \delta_z(\mathbf{n}, z) + \frac{\delta V(\mathbf{n}, z)}{V(z)}$$

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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.

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

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

(C. Bonvin & RD '11)

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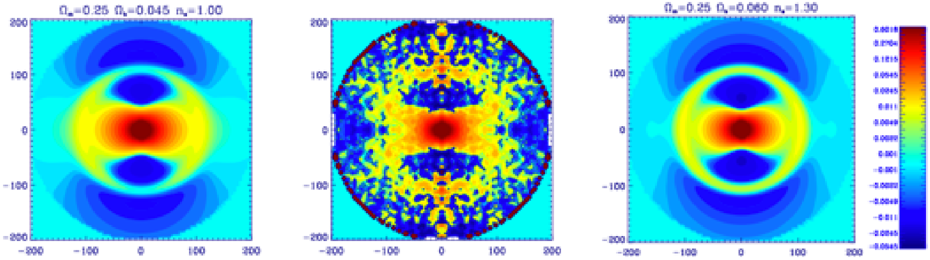
(C. Bonvin & RD '11)

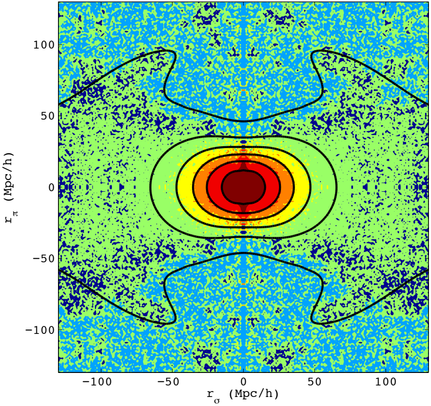


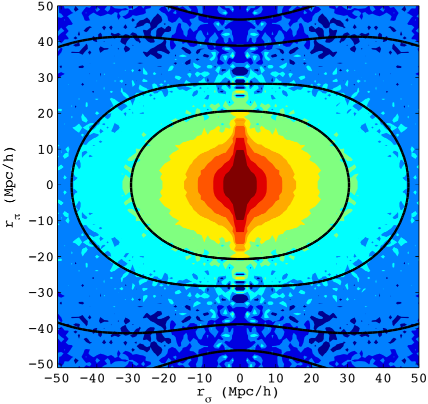
(From Gaztanaga et al. 2008)

The correlation function is not isotropic $\Rightarrow$ 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,

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

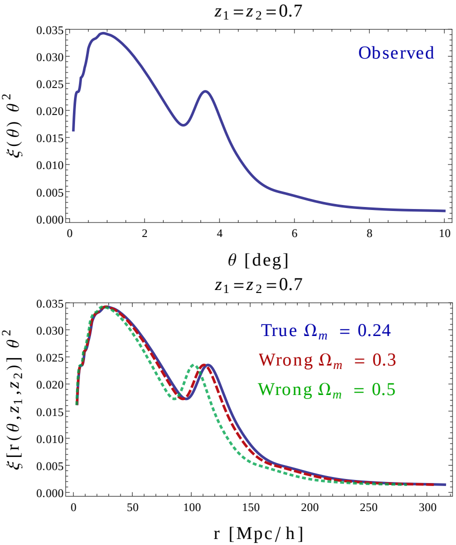
$$\xi(\theta, z, z') = \langle \Delta(\mathbf{n}, z) \Delta(\mathbf{n}', z') \rangle = \frac{1}{4\pi} \sum_\ell (2\ell + 1) C_\ell(z, z') P_\ell(\cos\theta)$$

What are very large scale galaxy catalogs really measuring?

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)



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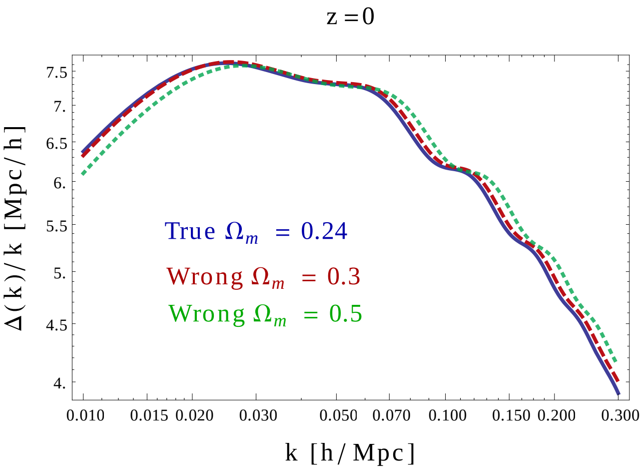
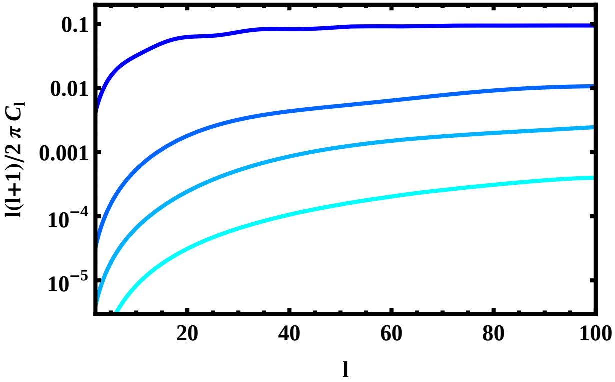


(Figure by F. Montanari)

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

The transversal power spectrum

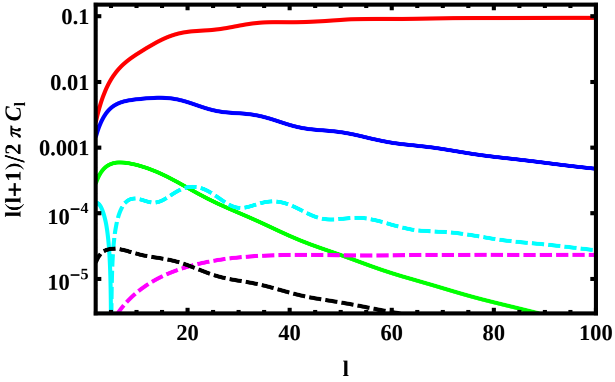
The transverse power spectrum, $z' = z$ (from Bonvin & RD '11)



$z = 0.1$, $z = 0.5$, $z = 1$ and $z = 3$.

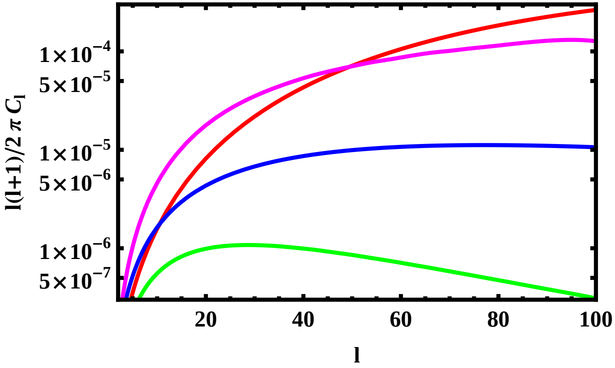
The transversal power spectrum

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



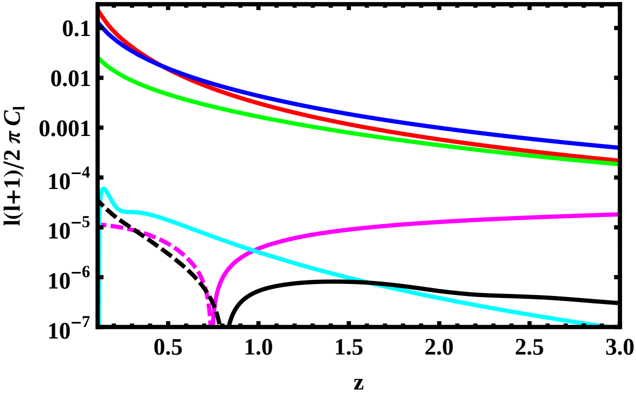
C_ℓ^{DD} (red), C_ℓ^{zz} (green), $2C_\ell^{Dz}$ (blue), $C_\ell^{Doppler}$ (cyan), $C_\ell^{lensing}$ (magenta) C_ℓ^{grav} (black).

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



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

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



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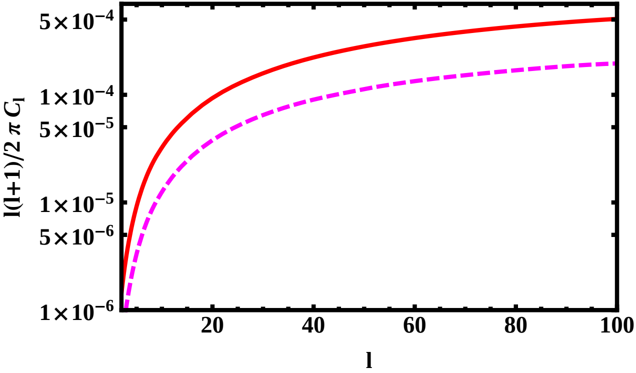
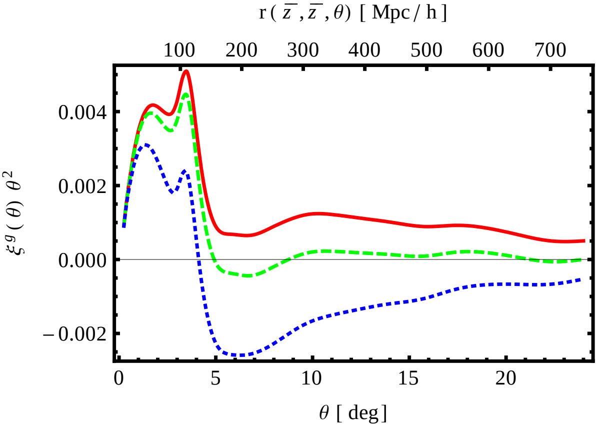


$0 < z < 2$

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

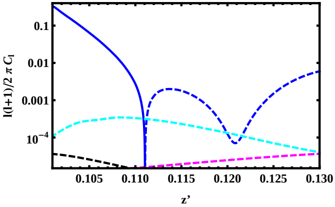
The transversal correlation function

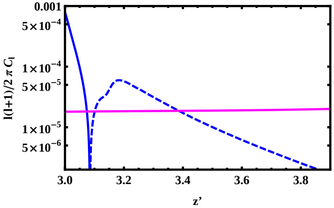


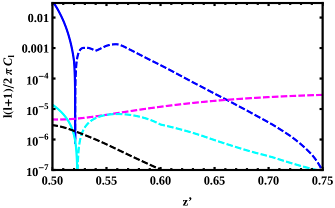
(from
Montanari & RD '12)

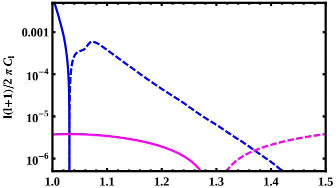
$\theta^2\xi(\theta, z, z)$

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!).



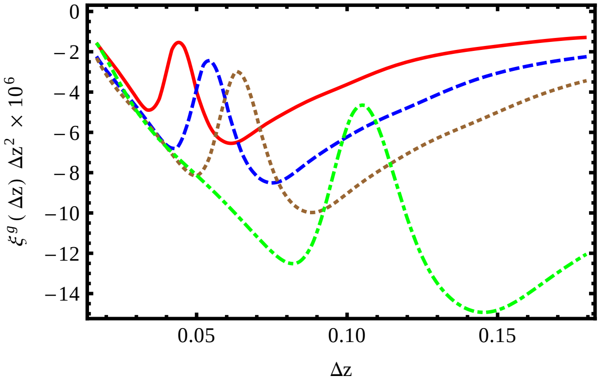






The radial power spectrum $C_\ell(z, z')$
for $\ell = 20$
Left, top to bottom: $z = 0.1,\ 0.5,\ 1,$
top right: $z = 3$

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



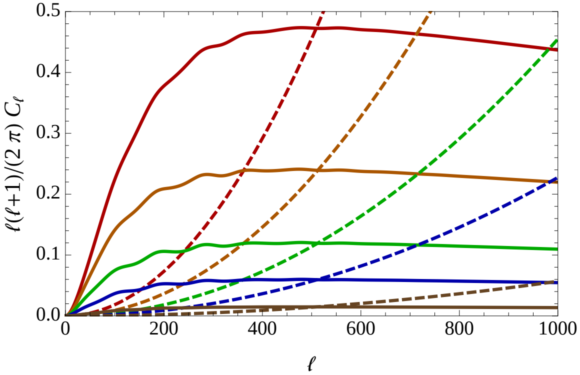
(from Montanari & RD '12)

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

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

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

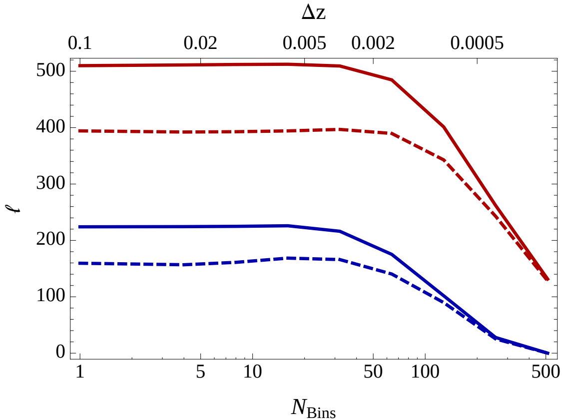
Real experiments (DESspec): Shot noise vs. signal



$\bar{z} = 0.55$
spectroscopic survey like DESspec for shot-noise contribution.

(From Di Dio, Montanari, Lesgourgues, RD, 1307.1459)

The angular power spectrum C_ℓ (solid lines) and the shot-noise contribution (dashed lines) for different top-hat window functions of half-widths: $\Delta z = 0.1$, $\Delta z = 0.025$, $\Delta z = 0.0125$, $\Delta z = 0.00625$, $\Delta z = 0.003125$.



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The multipole ℓ at which the shot-noise term starts to dominate. In red low shot noise, blue higher shot noise. Top-hat (solid lines) Gaussian window function (dashed lines).

For Euclid $\Delta z = 0.003$ corresponds to about 300 bins!

Fisher matrix, Figure of Merit

The Fisher matrix predicts the error in a parameter assuming Gaussian statistics for an experiment with a given covariance matrix for the signal.

For signals $s_i(\lambda_\alpha)$ with covariance matrix $\mathrm{Cov}_{ij} = \langle s_i s_j \rangle$ we have

$$F_{\alpha\beta} = \sum_{ij} \frac{\partial s_i}{\partial \lambda_\alpha} \frac{\partial s_j}{\partial \lambda_\beta} \mathrm{Cov}_{ij}^{-1}$$

In our case with signals $C_\ell(z_i, z_j) \equiv C_\ell^{ij}$ depending on cosmological parameters λ_α we obtain

$$F_{\alpha\beta} = \sum_{\ell} \frac{\partial C_\ell^{ij}}{\partial \lambda_\alpha} \frac{\partial C_\ell^{pq}}{\partial \lambda_\beta} \mathrm{Cov}_{\ell,(ij),(pq)}^{-1}$$

The figure of merit is given by

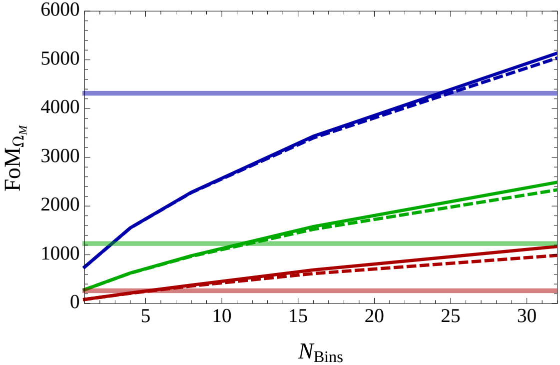
$$\mathrm{FoM} = \left[\det\left(F^{-1}\right)\right]^{-1/2} .$$

$$\mathrm{FoM}_{\mathrm{fixed}} = \left[\det\left((\hat{F})^{-1}\right)\right]^{-1/2} , \qquad \mathrm{FoM}_{\mathrm{marg.}} = \left[\det\left(\widehat{F^{-1}}\right)\right]^{-1/2} .$$

DES, Dark Energy Survey

DECam, an extremely sensitive 570-Megapixel digital camera, mounted on the Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory high in the Chilean Andes.
Start: August 31, 2013 (3×10^8 galaxies with photo-z)

Real experiments (DESspec): Figure of merit

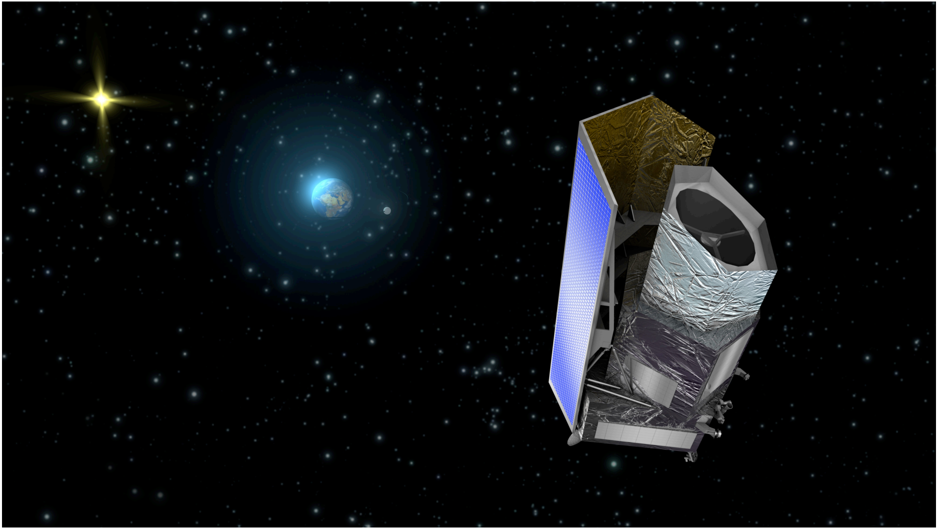


FoM for Ω_M as a function of bin number, for a spectroscopic survey like DESspec

(From Di Dio, Montanari, Lesgourgues, RD, 1307.1459)

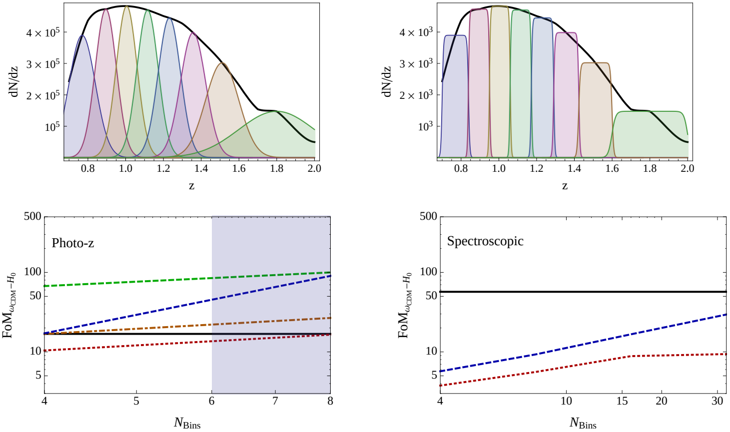
Cut-off wavenumbers (from top to bottom): $k_{max} = 0.2\ h\,\mathrm{Mpc}^{-1}$, $k_{max} = 0.1\ h\,\mathrm{Mpc}^{-1}$, $k_{max} = 0.05\ h\,\mathrm{Mpc}^{-1}$. FoM considering all the cross correlation spectra (solid lines) , only auto-correlation (dashed). Horizontal lines: 3D analysis based on $P(k, \bar{z}_i)$.

Euclid



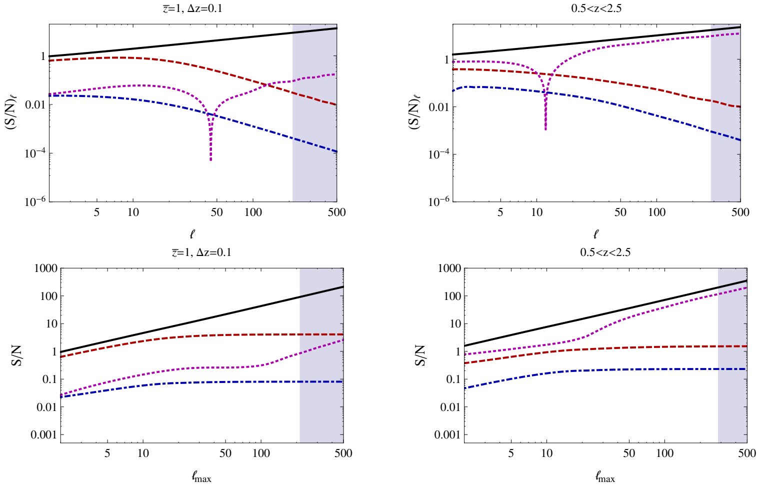
(10^7 galaxy redshifts, 10^9 galaxies with photo-z)

Real experiments (Euclid):



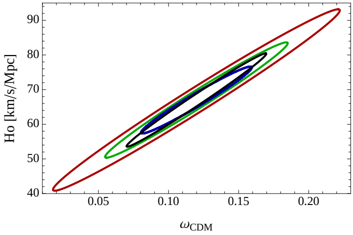
including cross-correlations, only auto-correlations
(From Di Dio, Montanari, Lesgourgues, RD, 1308.6186)

Real experiments (Euclid): Signal to Noise

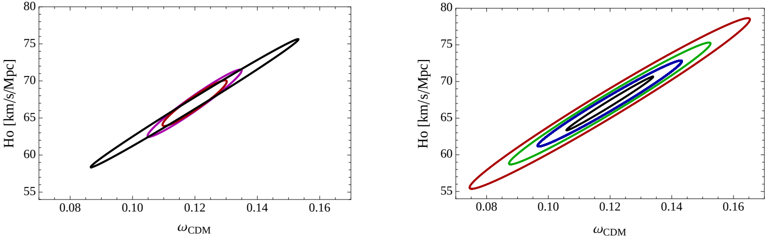


Signal to noise for different contributions:
density, redshidt-space distortions, lensing, potential
(From Di Dio, Montanari, Lesgourgues, RD, 1308.6186)

Real experiments (Euclid, DES): Parameter estimation



(DES)



(Euclid)

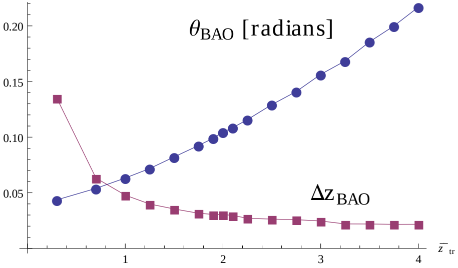
4 bins, 8 bins , 16 bins, 32 bins, 3D analysis black

(Alcock & Paczyński '79)

Consider a physical length L in the sky at redshift z.
Horizontally it is projected to the angle $\theta_L = \frac{L}{D_A(z)}$.

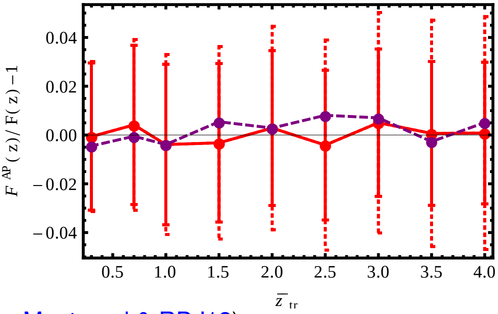
Radially its ends are at a slightly different redshifts, $\Delta z_L = L(1+z)H(z)$.

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



Alcock-Paczyński test

$F(z)^{AP} \equiv \Delta z_L/\theta_L$ 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)

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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.