Testing Dark Energy Models with Large Scale Structure Observations

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Outline

Introduction

Within the assumption of homogeneity and isotropy, the background spacetime metric is determined by one single function of time, the scale factor $a(t)$.

$$ds^2 = -dt^2 + a^2(t)\gamma_{ij}dx^i dx^j \qquad z + 1 = a_0/a(t)$$

$$\left(\frac{\dot a}{a}\right)^2 + \frac{K}{a^2} = H^2 + \frac{K}{a^2} = \frac{8\pi G}{3}\left(\rho + \frac{\Lambda}{8\pi G}\right)$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\left(\rho + 3P - \frac{\Lambda}{4\pi G}\right)$$

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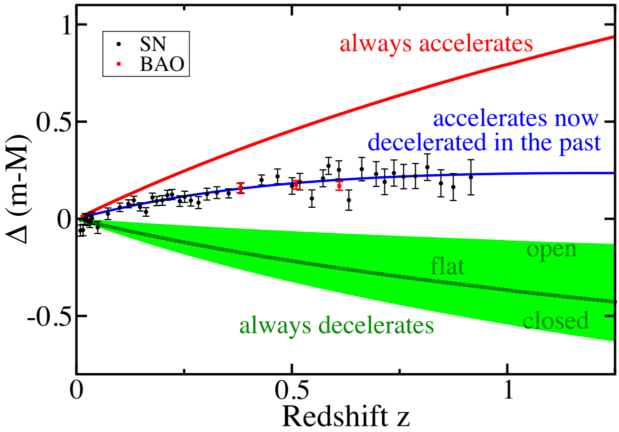
$$F(z) = \frac{L}{4\pi d_L(z)^2}$$

$$d_L(z) = (1+z)\chi_K\left(\int_0^z \frac{dz'}{H(z')}\right), \qquad \chi_K(\lambda) = \frac{\sin(\sqrt{K}\lambda)}{\sqrt{K}}$$



$m - M \propto \log d_L$

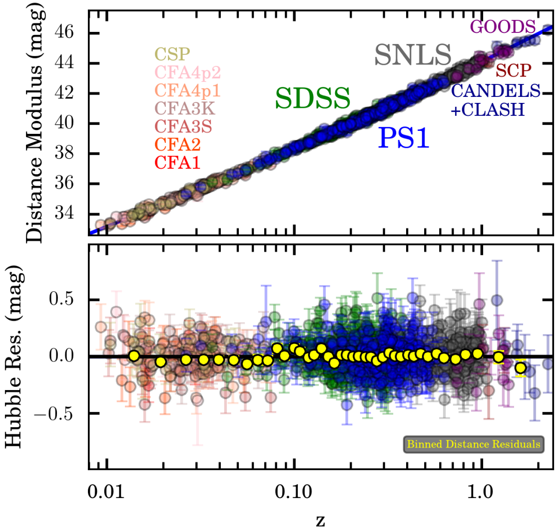
$\Delta(m - M) \propto \log(d_L/d_L^{\rm Milne})$

$\Omega_\Lambda \simeq 0.7$

$\Omega_m \simeq 0.3$

$\Omega_X = \rho_X/\rho_c$

Compilation by Huterer & Shafer ’17.
Binned from 870 SNe Ia (black) and 3 BAO points (from BOSS DR12, red).



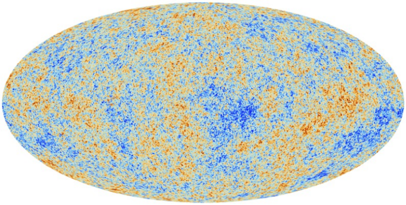
Pantheon Compilation 1048 SNe Ia (Scolnic et al. 2018).

Introduction

- The expansion rate of the Universe is compatible with a cosmological constant – ΛCDM.
- This model has two basic theoretical problems: 'fine tuning' and 'coincidence' : $\rho_\Lambda \simeq (2.5 \times 10^{-2}\mathrm{eV})^4$ and $z_\Lambda \simeq 0.3$.
- Other models, e.g. scalar field dark energy (quintessence, k-essence, modified gravity etc.) may lead to indistinguishable background evolution.
- At the last scattering redshift DE was most probably irrelevant. Therefore it enters CMB anisotropies mainly via the background evolution, i.e. the distance to the last scattering surface (see Vonlanthen et al. [arXiv:1003.0810]).
- In this talk I shall show how with the help of matter clustering observations, we can test different dark energy models beyond their expansion law.

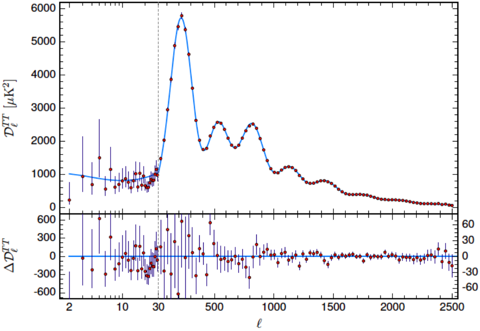
The CMB

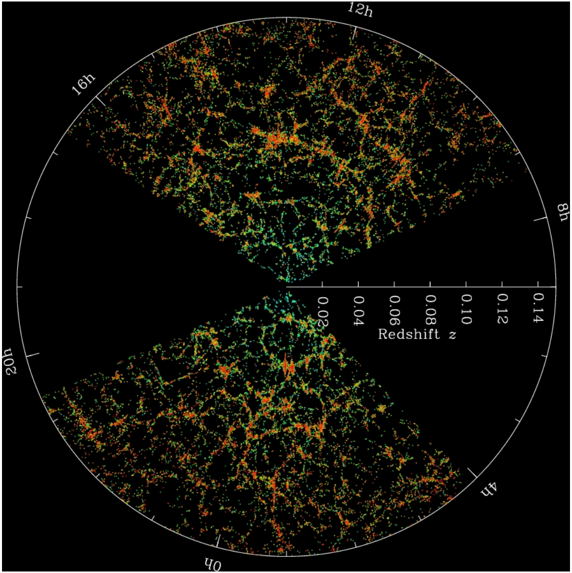
CMB sky as seen by Planck



$T(\mathbf{n}) = \sum a_{\ell m} Y_{\ell m}(\mathbf{n})$
$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$
$D_\ell = \ell(\ell+1) C_\ell / (2\pi)$

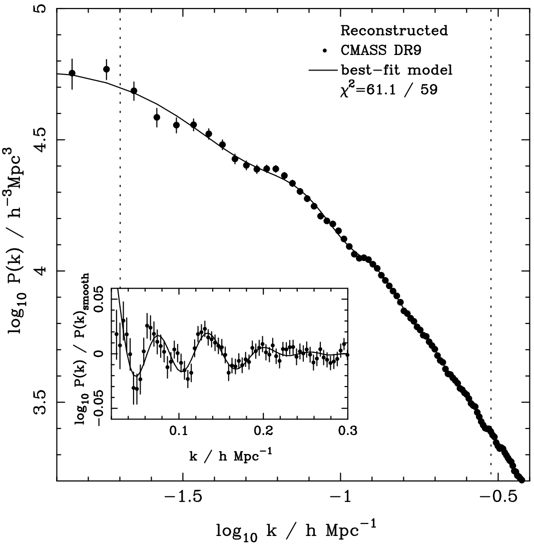
The Planck Collaboration:
Planck results 2018





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.

But...

- We have to take fully into account that all observations are made on our past lightcone which is itself perturbed.
  We see density fluctuations which are further away from us, further in the past.
  We cannot observe 3 spatial dimensions but 2 spatial and 1 lightlike, more precisely we measure 2 angles and a redshift.

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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 BOSS which goes out to $z \simeq 0.7$ (BOSS) or DES which goes to $z \simeq 0.8$.

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- But of course much more for future surveys like DESI, Euclid, LSST, SKA and WFIRST.

Cosmological distances

In a Friedmann Universe the (comoving) radial distance is

$$r(z) = \int_0^z \frac{dz'}{H(z')} = \frac{1}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_K(1+z')^2 + \Omega_\Lambda + \cdots}} .$$

In cosmology we infer distances by measuring redshifts and calculating them, via this relation. The result depends on the cosmological model.

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Depending on the observational situation we measure directly $r(z)$ or

$$d_A(z) = \frac{1}{(1+z)}\chi_K(r(z)) \quad \text{the angular diameter distance}$$

$$d_L(z) = (1+z)\chi_K(r(z)) \quad \text{the luminosity distance.}$$

At small redshift all distances are $d(z) = z/H_0 + \mathcal{O}(z^2)$, for $z \ll 1$. At larger redshifts, the distance depends strongly on $\Omega_K,\ \Omega_\Lambda, \cdots$.

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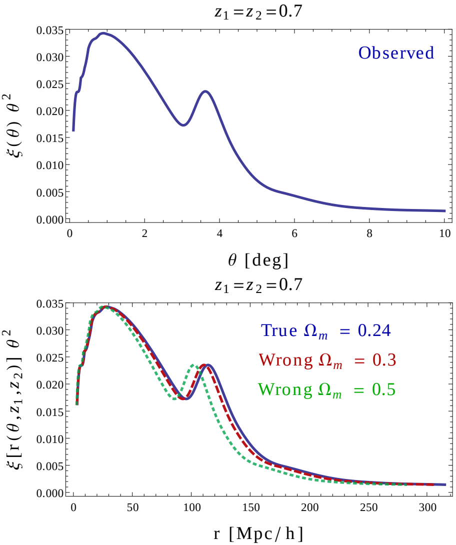
- Whenever we convert a measured redshift and angle into a length scale, we make assumptions about the underlying cosmology.

If we convert the measured correlation function $\xi(\theta, z_1, z_2)$ to a power spectrum, we have to introduce a cosmology, to convert angles and redshifts into length scales.

$$r(z_1, z_2, \theta) \overset{(K=0)}{=} \sqrt{r_1^2 + r_2^2 - 2r_1 r_2 \cos\theta}.$$

$$r_i = r(z_i) = \int_0^{z_i} \frac{dz}{H(z)}$$

(Figure by F. Montanari)



Large scale galaxy surveys

We now consider fluctuations in the matter distribution and in the geometry first to linear order. (See Yoo et al. 2009; Yoo 2010; Bonvin & RD 2011; Challinor & Lewis, 2011)

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We can count the galaxies inside a redshift bin and a small solid angle, $N(\mathbf{n}, z)$ and measure the fluctuation of this count:

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

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

This quantity is directly measurable.

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 from scalar perturbations to 1st order as function of the observed redshift z and direction $\mathbf{n}$

$$\begin{aligned}\Delta(\mathbf{n},z) &= D_g + (1+5s)\Phi + \Psi + \frac{1}{\mathcal{H}}\left[\dot\Phi + \partial_r(\mathbf{V}\cdot\mathbf{n})\right] \\ &+ \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2-5s}{r(z)\mathcal{H}} + 5s\right)\left(\Psi + \mathbf{V}\cdot\mathbf{n} + \int_0^{r(z)} dr(\dot\Phi + \dot\Psi)\right) \\ &\quad -\frac{2-5s}{2r(z)}\int_0^{r(z)} dr\left[\frac{r(z)-r}{r}\Delta_\Omega(\Phi+\Psi) - 2(\Phi+\Psi)\right].\end{aligned}$$

(Bonvin & RD '11, Challinor & Lewis '11)

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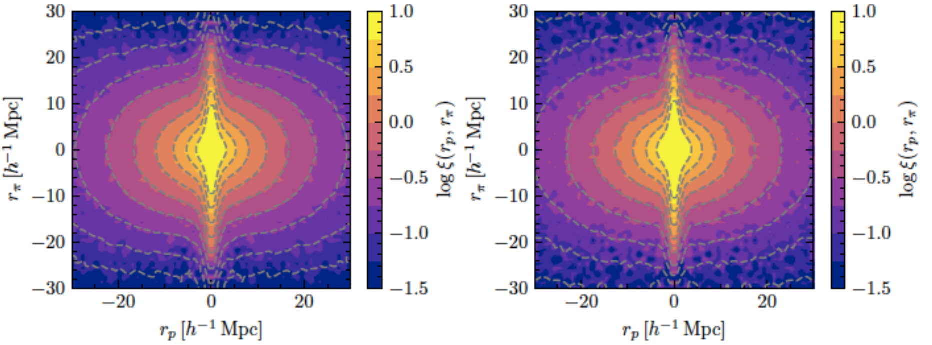
(C. Bonvin & RD '11, Challinor & Lewis '11)

Redshift space distortions in the BOSS survey

(from Lange et al. '21)



$0.18 < z < 0.3$ $\qquad$ $0.3 < z < 0.42$

The angular power spectrum of galaxy density fluctuations

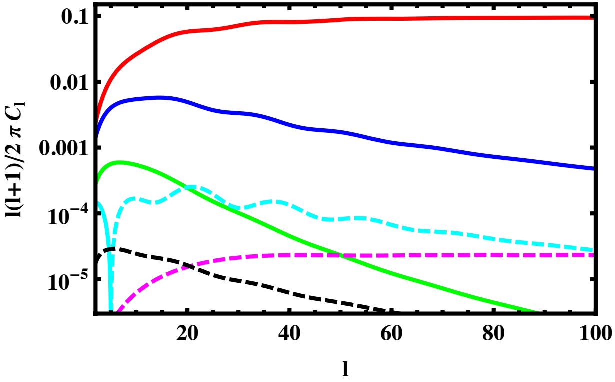
For fixed z, we can expand $\Delta(\mathbf{n}, z)$ in spherical harmonics,

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

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

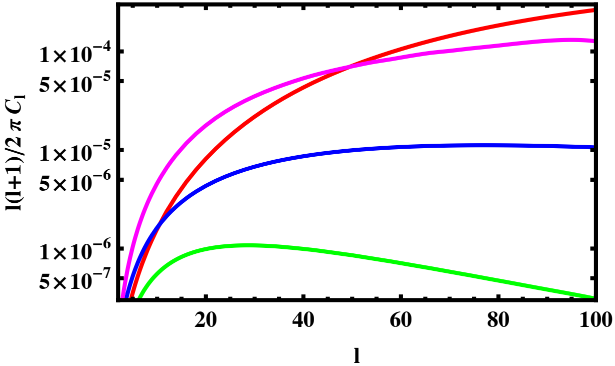
$$\cos\theta = \mathbf{n} \cdot \mathbf{n}'$$

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



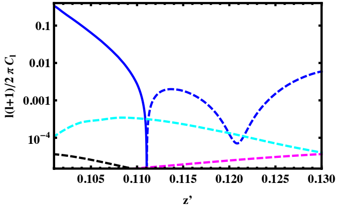
C_ℓ^{DD} (red), C_ℓ^{zz} (green), $2C_\ell^{Dz}$ (blue), $C_\ell^{Doppler}$ (cyan), $C_\ell^{lensing}$ (magenta) C_ℓ^{grav} (black).

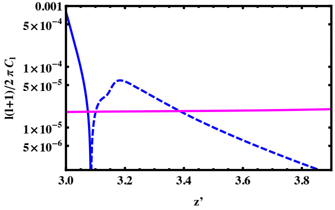
Contributions to the transverse power spectrum at redshift $z = 3$, $\Delta z = 0.3$ (from Bonvin & RD '11)

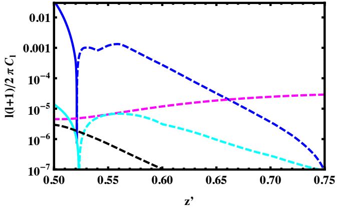


C_ℓ^{DD} (red), C_ℓ^{zz} (green), $2C_\ell^{Dz}$ (blue), $C_\ell^{lensing}$ (magenta).

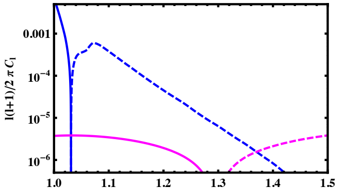
The radial power spectrum







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



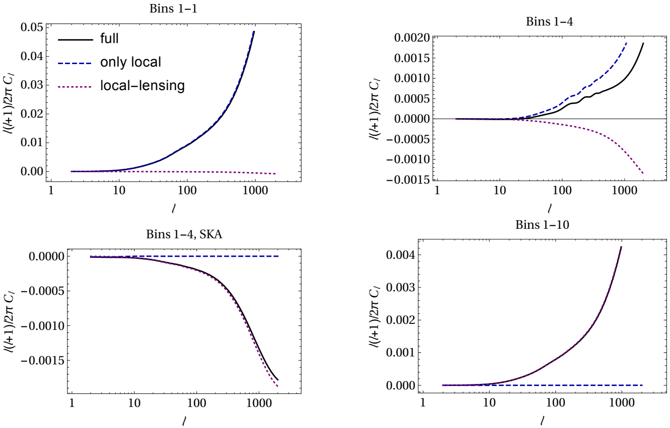
Standard terms (blue), $C_\ell^{lensing}$ (magenta), $C_\ell^{Doppler}$ (cyan), C_ℓ^{grav} (black), (from Bonvin & RD '11)

Measuring the lensing potential with Euclid

Well separated redshift bins measure mainly the lensing-density correlation:

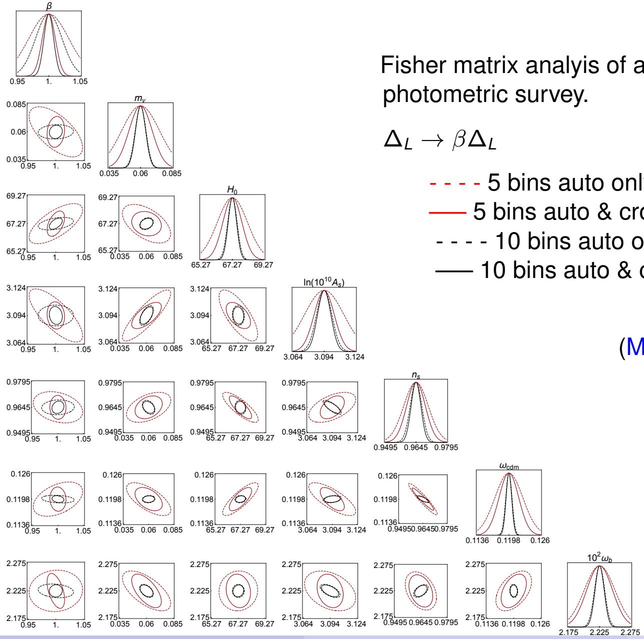
$$\langle \Delta(\mathbf{n}, z)\Delta(\mathbf{n}', z')\rangle \simeq \langle \Delta^L(\mathbf{n}, z)\delta(\mathbf{n}', z')\rangle \quad z > z'$$

$$\Delta^L(\mathbf{n}, z) = (2 - 5s(z))\kappa(\mathbf{n}, z)$$



(Montanari & RD 2015)

Testing modified gravity with the lensing potential



Fisher matrix analyis of an Euclid-like photometric survey.

$\Delta_L \to \beta\Delta_L$

- - - - 5 bins auto only
—— 5 bins auto & cross
- - - - 10 bins auto only
—— 10 bins auto & cross

(Montanari & RD 2015)

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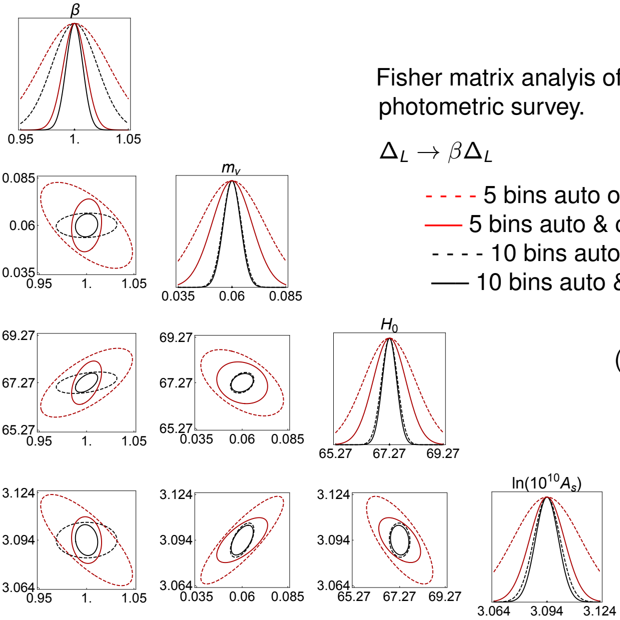

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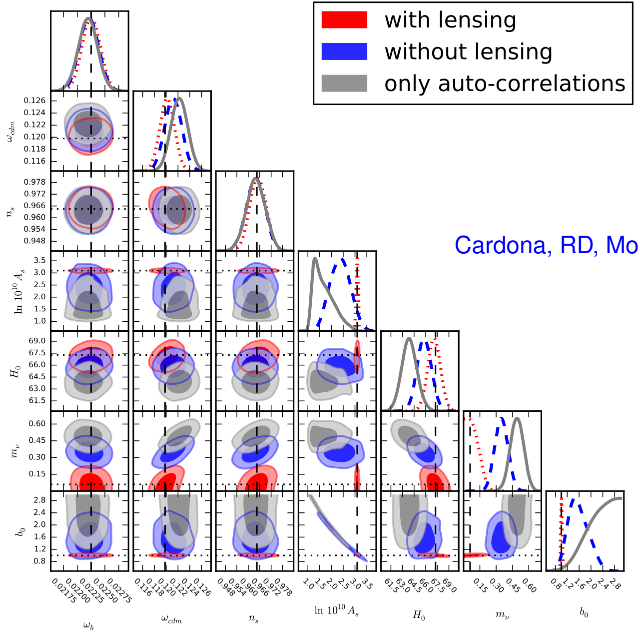
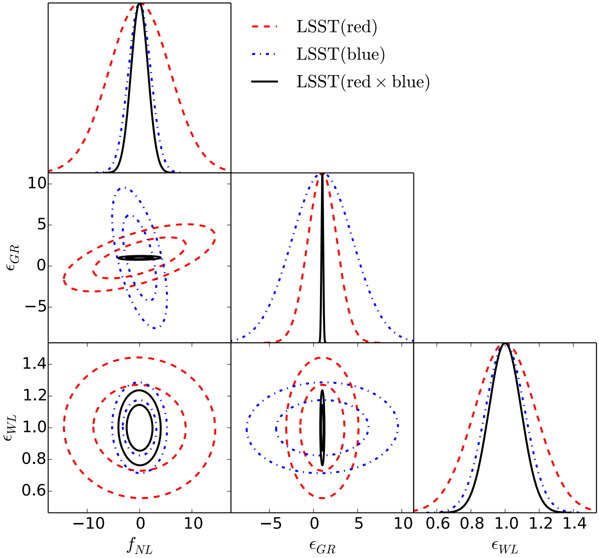
Neglecting the lensing potential biases cosmological parameters



Cardona, RD, Montanari & Kunz, (2016)

Measuring the relativistic terms via cross-correlations of the Vera Rubin Observatory LSST galaxy survey

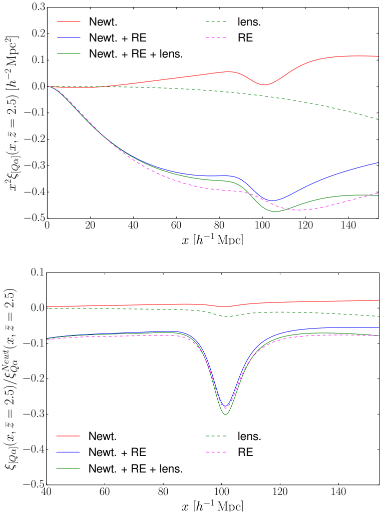
standard parameters fixed



Alonso & Ferreira (2015)

$$\sigma(\epsilon_{GR}) = 0.1$$
$$\sigma(\epsilon_{WL}) = 0.1$$
$$\sigma(f_{NL}) = 1.62$$

Measuring the relativistic terms with Quasar-Ly-α cross correlations



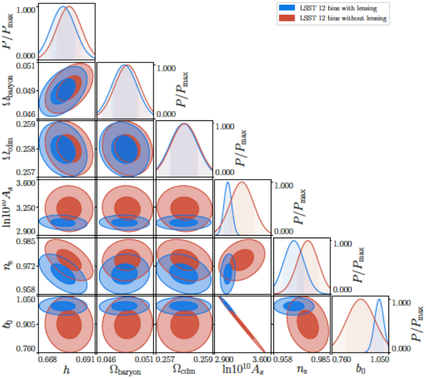
The antisymmetric part of the quasar–Ly-α cross correlation function. Contrary to the quasars, the Ly-α signal has no lensing term.
The relativistic term is dominated by the Doppler contribution.

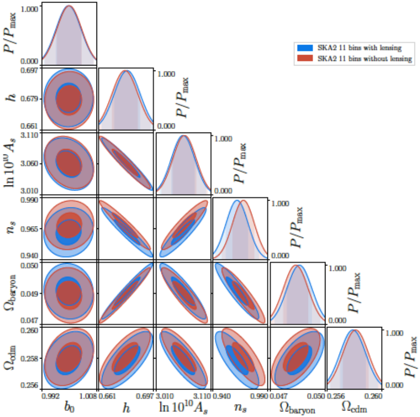
V. Iršič, E. Di Dio & M. Viel, 2016

Measuring the growth rate of perturbations

- The growth rate of perturbations is very sensitive to DE.
- A cosmological constant is the only form of DE which exhibits absolutely no clustering.
- Redshift space distortions are most sensitive to the growth rate. hence to measure it we need good redshift resolution $\rightarrow$ a spectroscopic survey.
- Even though 'lensing convergence' is not relevant for std cosmological parameter estimation with spectroscopic surveys, it does significantly affect the growth rate.

Standard parameter estimation from Vera Rubin Observatory (LSST) and SKA2 galaxy number counts





(Lepori, Jelic-Cizmek, Bonvin, RD 2020)

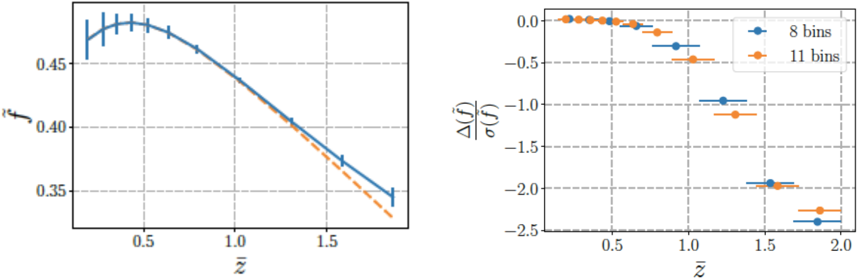
Errobars on std parameters from LSST will be similar to those from SKA2

h_0, n_s and $\Omega_{\rm cdm}$ will even be better determined with LSST than with SKA2 !

Growth rate estimation from SKA2 galaxy number counts

The growth rate is best estimated with RSD. However, in the k-power spectrum lensing is not easily included.
We used the correlation function to estimate the growth rate with the public code 'COFFE' (https://github.com/JCGoran/coffe, Tansella, Jelic-Cizmek, Bonvin, RD, 2018).
Including lensing, SKA2 will be able to determine it at the few % level (2 - 3% in a Fisher analysis).

$\tilde{f}(z) = f(z)\sigma_8(z)$ (no lensing / with lensing)



(Lepori, Jelic-Cizmek, Bonvin, RD 2020)

Conclusions

- So far cosmological LSS data mainly determined $\xi(r)$, or equivalently $P(k)$ or $B(k_1, k_2, k_3)$ etc. These are easier to measure (less noisy) but:
  • they depend on a fiducial input cosmology converting redshift and angles to length scales. This complicates especially the determination of error bars in parameter estimation.
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  • they depend on a fiducial input cosmology converting redshift and angles to length scales. This complicates especially the determination of error bars in parameter estimation.
  • It is not evident how to correctly include lensing.
- Future large & precise 3d galaxy catalogs like **Euclid**, **DESI**, **SKA**, **LSST** etc. will be able to determine directly the measured 3d correlation functions and spectra, $\xi(\theta, z, z')$ and $C_\ell(z, z')$ and $b_{\ell_1,\ell_2,\ell_2}(z_1, z_2, z_3)$ etc from the data.

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- 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) .

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- To correctly interpret our date a relativistic and accurate theoretical modelling is crucial.

Comparing DESI, LSST and SKA2

(The bias is marginalized over.)