Testing General Relativity with Cosmological Observations

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Outline

Introduction

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- Light deflection
- Perihel advance of mercury & many other binary systems
- Shapiro time delay
- $\cdots$
- Gravitational waves

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$$R_{\mu\nu} = 0 \, .$$

Can we also test these equations with matter,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = G_{\mu\nu} = 8\pi G T_{\mu\nu} \qquad ?$$

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Cosmology is a non-vacuum solution of Einstein's equation:

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

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

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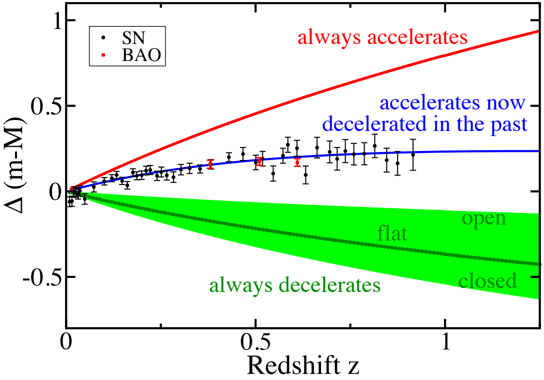
Have we 'tested' these equations in cosmology? What have we truly measured:

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

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



$m - M \propto \log d_L$

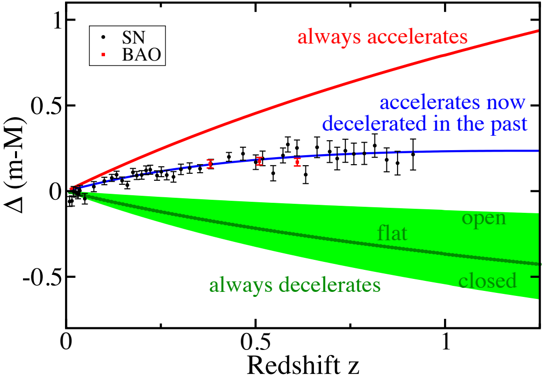
$\Delta(m - M \propto \log(d_L/d_L^{\text{Milne}})$

$\Omega_\Lambda \simeq 0.7$

$\Omega_m \simeq 0.3$

$\Omega_X = \rho_X/\rho_c$

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



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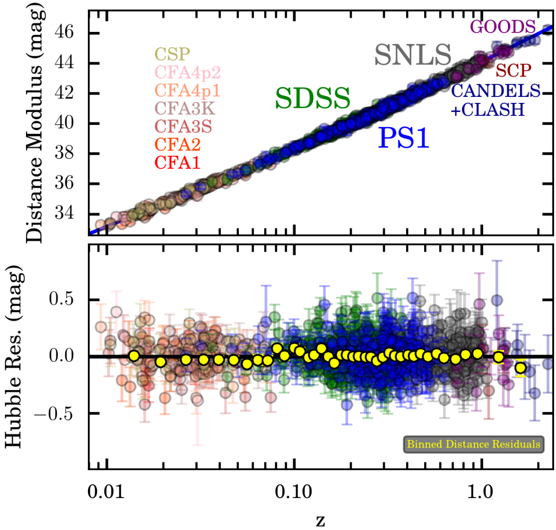
NO !
We have 'postulated' the existence of dark matter and dark energy to fit this data.



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

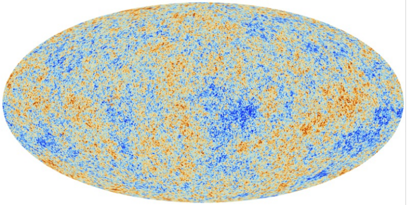
Introduction

In this talk I shall show that with the help of clustering observations, i.e. using the fact that the Universe is not perfectly homogeneous and isotropic, we can actually test Einstein's equations to some extent. . ..

We shall do this using the statistics of the galaxy distribution, more precisely we work with the 2-point correlation function $\xi(p, q)$ which determines the probability above (or below) the mean of having a galaxy in spacetime position q if there is one in position p.

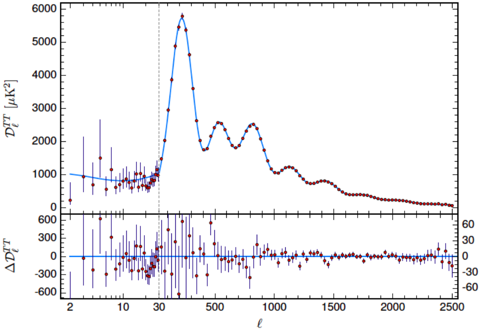
The CMB

CMB sky as seen by Planck



$D_\ell = \ell(\ell+1)C_\ell/(2\pi)$

The Planck Collaboration:
Planck results 2018
[1807.06209]



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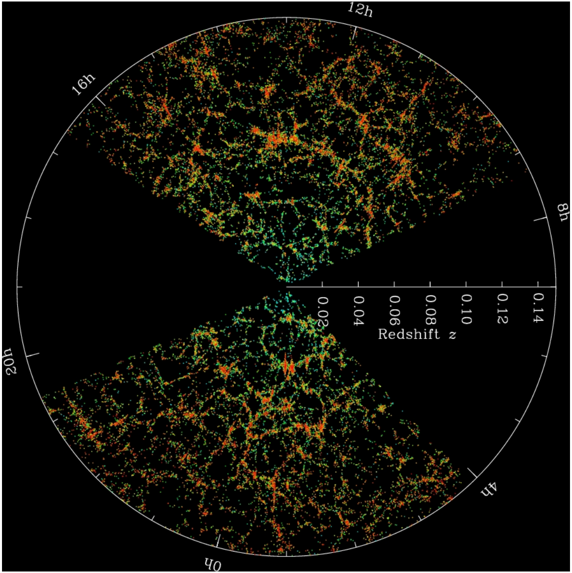
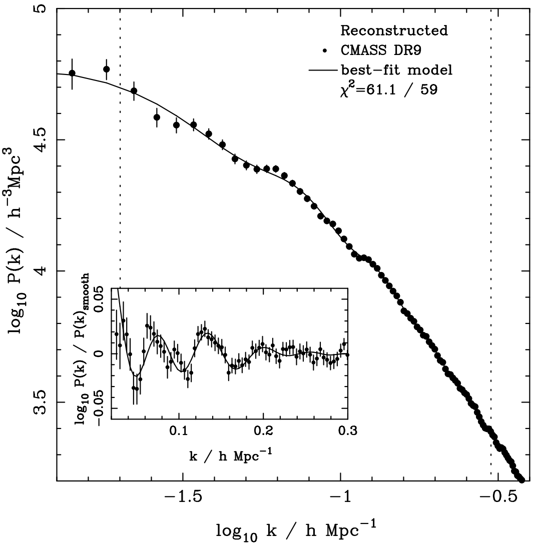


M. Blanton and the Sloan Digital Sky Survey Team.

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 which goes out to $z \simeq 0.2$ (main catalog) or even $z \simeq 0.7$ (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, WFIRST and SKA.

Cosmological distances

In a Friedmann Universe the (comoving) radial distance is

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

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

$$\begin{aligned} d_A(z) &= \frac{1}{(1+z)}\chi_K(r(z)) && \text{the angular diameter distance} \\ d_L(z) &= (1+z)\chi_K(r(z)) && \text{the luminosity distance.} \end{aligned}$$

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.

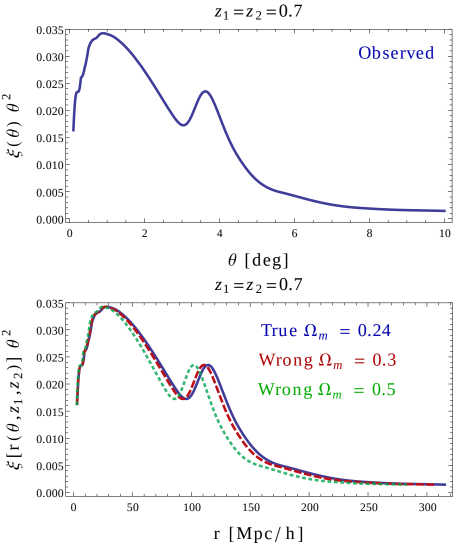
Very large scale galaxy surveys

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.

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

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

(Figure by F. Montanari)



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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 $\mathbf{n}$.

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

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

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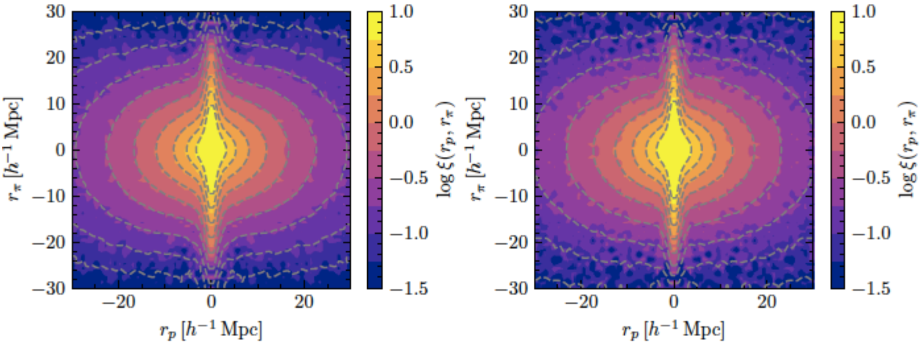
(C. Bonvin & RD '11, Challinor & Lewis '11)

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,

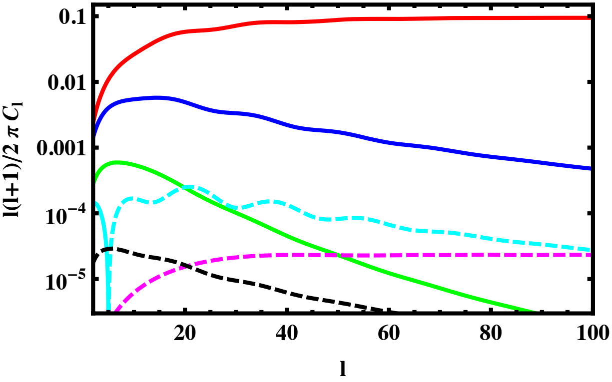
$$\Delta(\mathbf{n}, z) = \sum_{\ell m} a_{\ell m}(z) Y_{\ell m}(\mathbf{n}), \qquad C_\ell(z, z') = \langle a_{\ell m}(z) a^*_{\ell m}(z') \rangle.$$

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

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

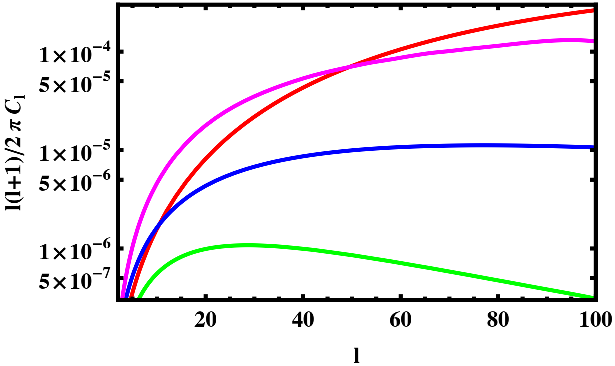
The transversal power spectrum

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



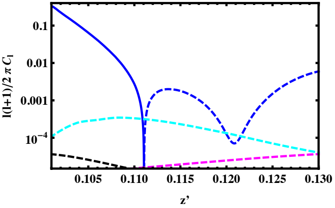
C_ℓ^{DD} (red), C_ℓ^{zz} (green), $2C_\ell^{Dz}$ (blue), $C_\ell^{Doppler}$ (cyan), $C_\ell^{lensing}$ (magenta) C_ℓ^{grav} (black).

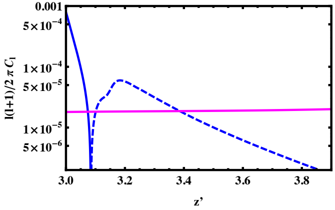
Contributions to the transverse power spectrum at redshift $z = 3$, $\Delta z = 0.3$ (from Bonvin & RD '11)

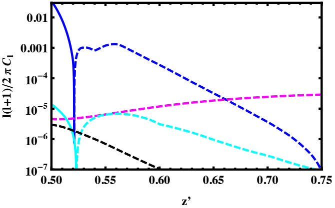


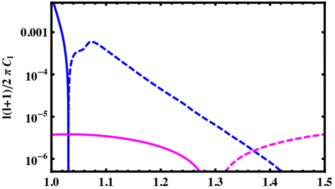
C_ℓ^{DD} (red), C_ℓ^{zz} (green), $2C_\ell^{Dz}$ (blue), $C_\ell^{lensing}$ (magenta).

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: $z = 3$

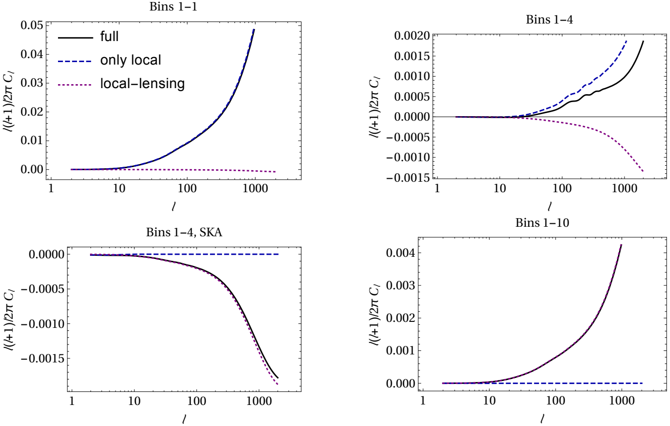
Standard terms (blue), $C_\ell^{lensing}$ (magenta),
$C_\ell^{Doppler}$ (cyan), C_ℓ^{grav} (black),
(from Bonvin & RD '11)

Measuring the lensing potential with Euclid

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

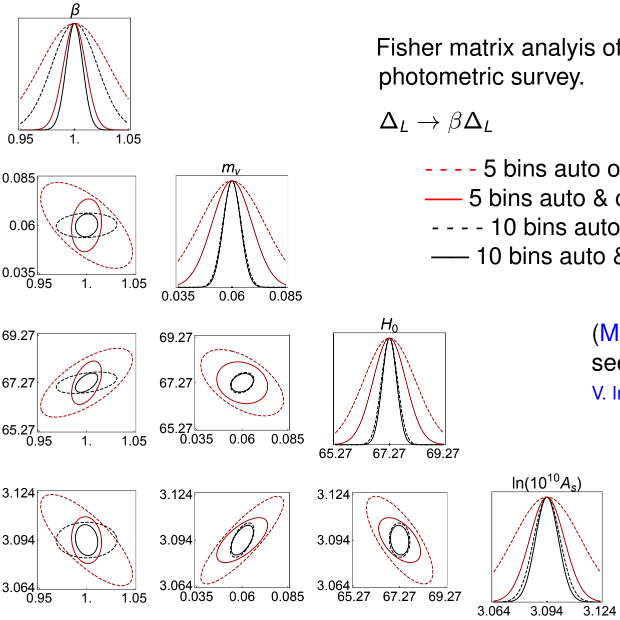
$$\langle \Delta(\mathbf{n}, z)\Delta(\mathbf{n}', z')\rangle \simeq \langle \Delta^L(\mathbf{n}, z)\delta(\mathbf{n}', z')\rangle \quad z > z'$$

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



(Montanari & RD) [1506.01369]

Testing GR with the lensing potential



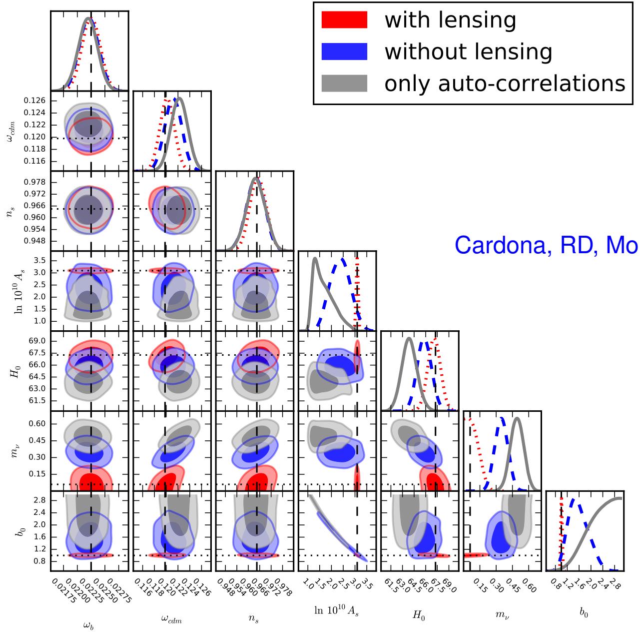
Fisher matrix analyis of an Euclid-like photometric survey.

$\Delta_L \to \beta\Delta_L$

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

(Montanari & RD 2015)
see also Alonso & Ferreira, 2015,
V. Iršič, E. Di Dio & M. Viel, 2016

Neglecting the lensing potential biases cosmological parameters

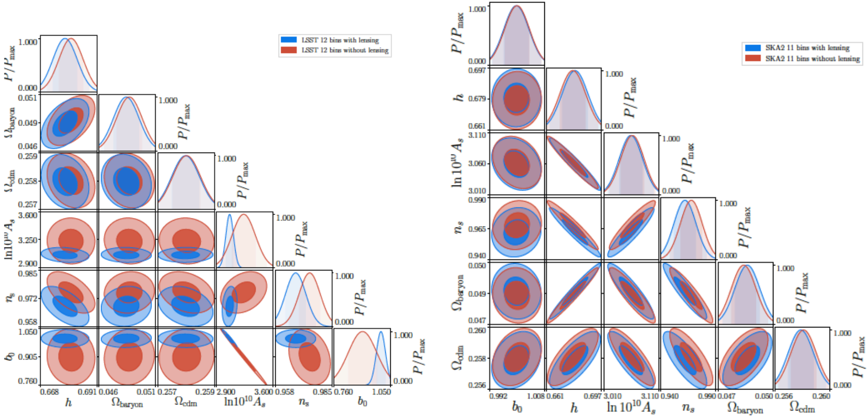


Cardona, RD, Montanari & Kunz, (2016)

Measuring the growth rate of perturbations

- The growth rate of perturbations is very sensitive to the theory of gravity.
- A cosmological constant is the only form of dark energy 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



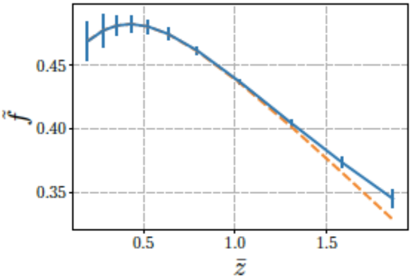
(Lepori, Jelic-Cizmek, Bonvin, RD 2020)

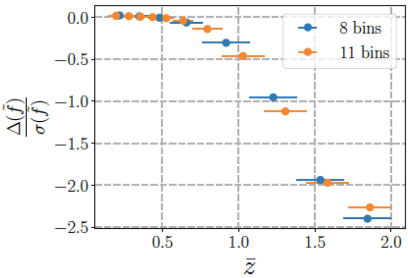
(Errorbars on std parameters from LSST will be similar to those from SKA2 h_0, n_s and $\Omega_{\rm cdm}$ will even be better determined with LSST than with SKA2 !)

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. $\Rightarrow$ Here we use the correlation function (coffe, https://github.com/JCGoran/coffe).
Including lensing, SKA2 will be able to determine it at the few % level (2 - 3% in a Fisher analysis).

$\tilde{f}(z) = f(z)\sigma_8(z)$ (neglecting lensing / including lensing in the analysis)





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

E_g statistics

In GR photon propagation, which governs weak lensing is sensitive to the sum of the Bardeen potentials, $\Phi + \Psi$, which density fluctuations generate Φ. In standard GR $\Phi = \Psi$ such that thew following combination is independent of both, bias and scale:

$$E_g(k,z) \equiv \frac{H(z)(\Phi+\Psi)}{3H_0^2(1+z)V} = f(z) \simeq [\Omega_m(z)]^{0.55}\,.$$

(Zhang et al., 2007) This can be converted to (Pullen et al., 2015)

$$E_g(\ell,z) = \Gamma(z)\frac{C_\ell^{\kappa\delta}(z_*,z)}{\beta C_\ell^{\delta\delta}(z,z)}$$

It has, however been pointed out (Moradinezhad Dizgah & RD 2016), that when observing galaxies, we do not directly observe $C_\ell^{\kappa\delta}$ or $C_\ell^{\delta\delta}$ but rather

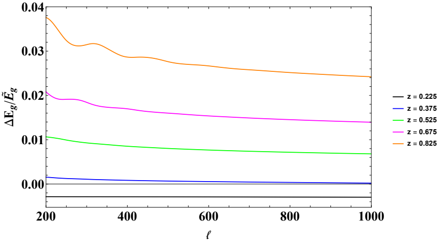
$$\begin{aligned}
C_\ell^{\kappa g}(z_1,z_2) &\simeq b(z_2)C_\ell^{\kappa\delta}(z_1,z_2) - (2-5s(z_2))C_\ell^{\kappa\kappa}(z_1,z_2) \\
C_\ell^{gg}(z_1,z_2) &\simeq b(z_1)b(z_2)C_\ell^{\delta\delta}(z_1,z_2) + (2-5s(z_1))(2-5s(z_2))C_\ell^{\kappa\kappa}(z_1,z_2) \\
&\quad -b(z_2)(2-5s(z_1))C_\ell^{\kappa\delta}(z_1,z_2) - b(z_1)(2-5s(z_2))C_\ell^{\kappa\delta}(z_2,z_1)
\end{aligned}$$

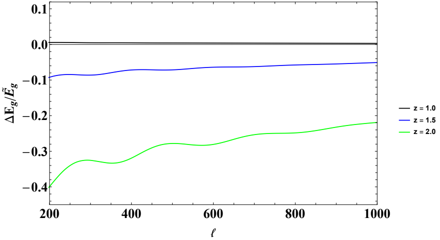
For low redshifts these corrections are not very relevant, but at high redshifts they are.

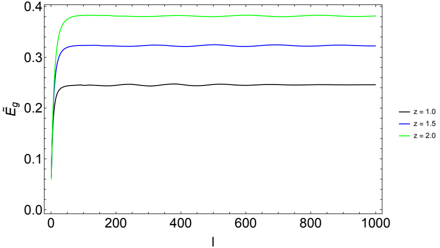
E_g statistics

Euclid like survey

DES-like survey







(From Ghosh & RD [1812.09546])

For intensity mapping $s \equiv 0.4$ and the correction terms vanish (Pourtsidou 2016).

Conclusions

- So far cosmological LSS data mainly determined $\xi(r)$, or equivalently $P(k)$ or $B(k_1, k_2, k_3)$. These are easier to measure (less noisy) but:
  • they require an fiducial input cosmology converting redshift and angles to length scales,
  $$r = \sqrt{r(z)^2 + r(z')^2 - 2r(z)r(z')\cos\theta}\ .$$
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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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- Especially $C_\ell^{\kappa g}(z,z')$ and $C_\ell^{gg}(z,z')$ if suitably corrected allow for quite model independent tests of GR via e.g. the E_g-statistics.
- The spectra $C_\ell(z,z')$, $b_{\ell_1,\ell_2,\ell_3}(z_1,z_2,z_3)$, $\cdots$ depend sensitively and in several different ways on the theory of gravity (growth factor, relation between Ψ and Φ), on the matter and baryon densities, and on the velocity. Their measurements provide a new route to estimate cosmological parameters and, especially, to test general relativity on cosmological scales.