Towards the 'observable' matter power spectrum

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

Cosmology – KASI April 18, 2017

Collaboration

This is work in progress with

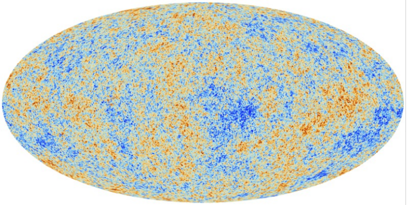
- Vittorio Tansella
- Camille Bonvin
- Basundhara Ghosh
- Elena Sellentin

Outline

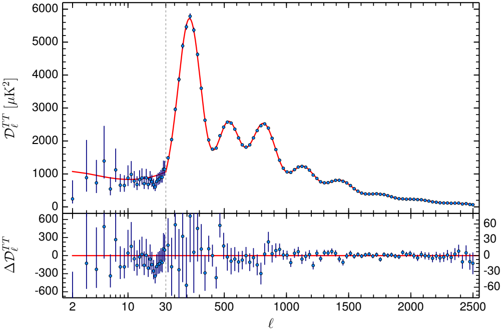
1. Introduction
2. What are very large scale galaxy catalogs really measuring?
3. $C_\ell(z, z')$ vs $P(k, \mu, \bar{z})$
4. Conclusion

Introduction

The CMB

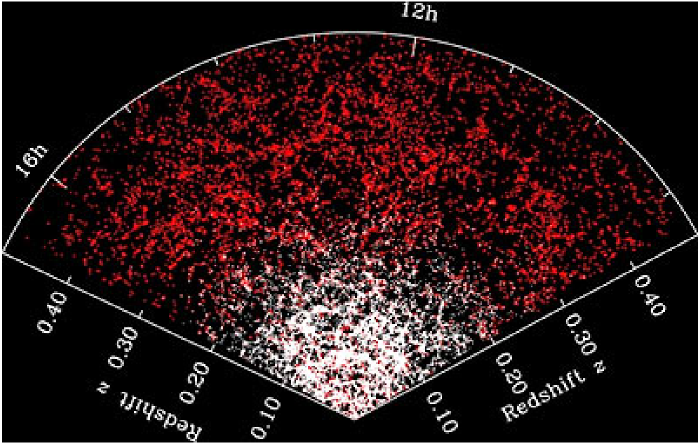


CMB sky as seen by Planck



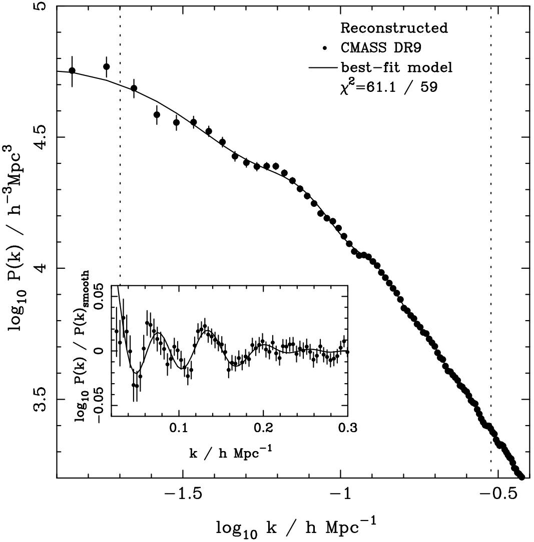
$D_\ell = \ell(\ell+1)C_\ell/(2\pi)$

The Planck Collaboration:
Planck results 2015 XIII



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.

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.
- The measured redshift is perturbed by peculiar velocities and by the gravitational potential.

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.
- The measured redshift is perturbed by peculiar velocities and by the gravitational potential.
- Not only the number of galaxies but also the volume is distorted.

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.
- The measured redshift is perturbed by peculiar velocities and by the gravitational potential.
- Not only the number of galaxies but also the volume is distorted.
- The angles we are looking into are not the ones into which the photons from a given galaxy arriving at our position have been emitted.

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.
- The measured redshift is perturbed by peculiar velocities and by the gravitational potential.
- Not only the number of galaxies but also the volume is distorted.
- The angles we are looking into are not the ones into which the photons from a given galaxy arriving at our position have been emitted.
- 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).

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.
- The measured redshift is perturbed by peculiar velocities and by the gravitational potential.
- Not only the number of galaxies but also the volume is distorted.
- The angles we are looking into are not the ones into which the photons from a given galaxy arriving at our position have been emitted.
- 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).
- But of course much more for future surveys like DES, DESI, Euclid, LSST, SKA and WFIRST.

In a Friedmann Universe the (comoving) radial distance is

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

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

Cosmological distances

In a Friedmann Universe the (comoving) radial distance is

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

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

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

Cosmological distances

In a Friedmann Universe the (comoving) radial distance is

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

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

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

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

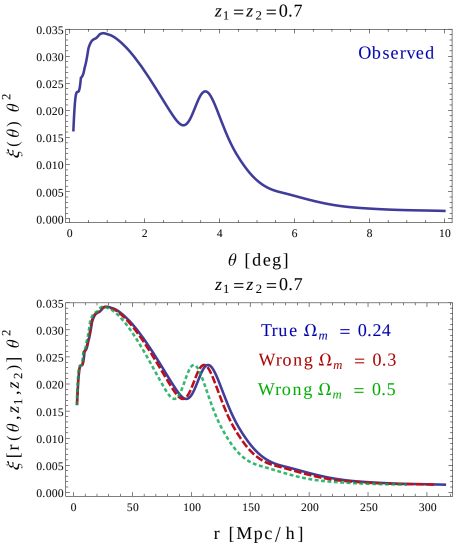
What are very large scale galaxy catalogs really measuring?

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

$$r(z_1, z_2, \theta) \stackrel{(K=0)}{=} \sqrt{\chi_1^2 + \chi_2^2 - 2\chi_1\chi_2 \cos\theta}.$$

$$\chi_i = \chi(z_i) = \int_0^{z_i} \frac{dz}{H(z)}$$

(Figure by F. Montanari)



What are very large scale galaxy catalogs really measuring?

We now consider fluctuations in the matter distribution and in the geometry first to linear order. (See J. Yoo et al. 2009; J. Yoo 2010, C. Bonvin & RD [arXiv:1105.5080]; Challinor & Lewis, [arXiv:1105:5092])

What are very large scale galaxy catalogs really measuring?

We now consider fluctuations in the matter distribution and in the geometry first to linear order. (See J. Yoo et al. 2009; J. Yoo 2010, C. Bonvin & RD [arXiv:1105.5080]; Challinor & Lewis, [arXiv:1105:5092])

For each galaxy in a catalog we measure

$$(\theta, \phi, z) = (\mathbf{n}, z) \quad + \text{info about mass, spectral type...}$$

What are very large scale galaxy catalogs really measuring?

We now consider fluctuations in the matter distribution and in the geometry first to linear order. (See J. Yoo et al. 2009; J. Yoo 2010, C. Bonvin & RD [arXiv:1105.5080]; Challinor & Lewis, [arXiv:1105:5092])

For each galaxy in a catalog we measure

$$(\theta, \phi, z) = (\mathbf{n}, z) \quad + \text{info about mass, spectral type...}$$

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

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

What are very large scale galaxy catalogs really measuring?

We now consider fluctuations in the matter distribution and in the geometry first to linear order. (See J. Yoo et al. 2009; J. Yoo 2010, C. Bonvin & RD [arXiv:1105.5080]; Challinor & Lewis, [arXiv:1105:5092])

For each galaxy in a catalog we measure

$$(\theta, \phi, z) = (\mathbf{n}, z) \quad + \text{info about mass, spectral type...}$$

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

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

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

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

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 to 1st order

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

(C. Bonvin & RD '11)

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

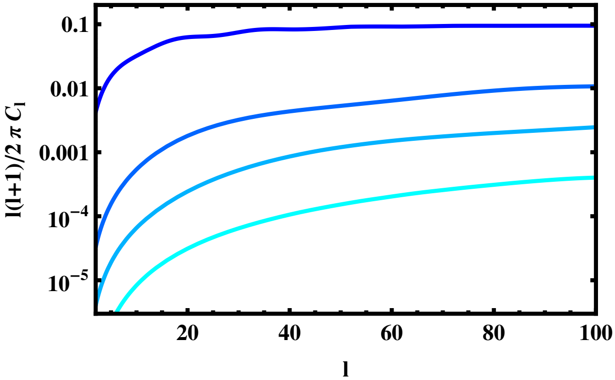
$$\Delta(\mathbf{n},z) = \boxed{bD} + (5s-2)\Phi + \Psi - 3\mathcal{H}V + \frac{1}{\mathcal{H}}\left[\dot\Phi + \boxed{\mathbf{n}\cdot\nabla(\mathbf{V}\cdot\mathbf{n})}\right]$$
$$+\left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2-5s}{\chi(z)\mathcal{H}} + 5s - f_{\rm evo}\right)\left(\Psi + \boxed{\mathbf{V}\cdot\mathbf{n}} + \int_0^{\chi(z)} d\chi(\dot\Phi + \dot\Psi)\right)$$
$$+\frac{5s-2}{2\chi(z)}\int_0^{\chi(z)} d\chi\left[2(\Phi+\Psi) - \boxed{\frac{\chi(z)-\chi}{\chi}\Delta_\Omega(\Phi+\Psi)}\right].$$

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

$C_\ell(z,z')$ are the angular-redshift power spectra of galaxy catalogs.

$C_\ell(z,z)$

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



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

- The $C_\ell(z, z')$'s contain all the linear clustering information.

Cosmology with the $C_\ell(z, z')$ and $\xi(\theta, z, z')$

- The $C_\ell(z, z')$'s contain all the linear clustering information.
- The radial & transversal BAO's in $\xi(\theta, z, z')$ provide an Alcock-Pacziniski test (Montanari & RD (2012); Lepori et al. (2016))

Cosmology with the $C_\ell(z, z')$ and $\xi(\theta, z, z')$

- The $C_\ell(z, z')$'s contain all the linear clustering information.
- The radial & transversal BAO's in $\xi(\theta, z, z')$ provide an Alcock-Pacziniski test (Montanari & RD (2012); Lepori et al. (2016))
- The off-diagonal $C_\ell(z, z')$, $z \neq z'$ can be used to measure the lensing potential (Montanari & RD (2015)).

- The $C_\ell(z, z')$'s contain all the linear clustering information.
- The radial & transversal BAO's in $\xi(\theta, z, z')$ provide an Alcock-Pacziniski test (Montanari & RD (2012); Lepori et al. (2016))
- The off-diagonal $C_\ell(z, z')$, $z \neq z'$ can be used to measure the lensing potential (Montanari & RD (2015)).
- Lensing is very relevant in $C_\ell(z, z')$, neglecting it leads to an overestimation of the neutrino mass (Cardona, RD, Kunz & Montanari (2016))

- The $C_\ell(z, z')$'s contain all the linear clustering information.
- The radial & transversal BAO's in $\xi(\theta, z, z')$ provide an Alcock-Pacziniski test (Montanari & RD (2012); Lepori et al. (2016))
- The off-diagonal $C_\ell(z, z')$, $z \neq z'$ can be used to measure the lensing potential (Montanari & RD (2015)).
- Lensing is very relevant in $C_\ell(z, z')$, neglecting it leads to an overestimation of the neutrino mass (Cardona, RD, Kunz & Montanari (2016))
- Relativistic effects can be measured on large scales or with multi-tracer methods, (Bonvin et al.; Alonso & Ferreira; Di Dio et al. $\cdots$)

$C_\ell(z, z')$ vs $P(k, \mu, \bar{z})$

Why are we not happy with this?
$C_\ell(z, z')$ is in principal observable and contains the full 2-point information about the galaxy distribution.

$C_\ell(z, z')$ vs $P(k, \mu, \bar{z})$

Why are we not happy with this?
$C_\ell(z, z')$ is in principal observable and contains the full 2-point information about the galaxy distribution.

- To fully profit from the redshift accuracy of a spectroscopic survey we would have to compute $C_\ell(z, z')$ for about $10^4 \times 10^4$ redshifts. At present speeds this means $\frac{1}{2}10^8 \times 2\text{min} = 6 \times 10^9\text{sec} \simeq$ 200 years. Of course we can parallelize, but for parameter estimation we need to run this about 10^5 times...

Why are we not happy with this?
$C_\ell(z, z')$ is in principal observable and contains the full 2-point information about the galaxy distribution.

- To fully profit from the redshift accuracy of a spectroscopic survey we would have to compute $C_\ell(z, z')$ for about $10^4 \times 10^4$ redshifts. At present speeds this means $\frac{1}{2}10^8 \times 2\text{min} = 6 \times 10^9\text{sec} \simeq$ 200 years. Of course we can parallelize, but for parameter estimation we need to run this about 10^5 times...
- Worse is that a spectroscopic catalog with about 10^7 galaxies like Euclid would have only about 1000 galaxies per redshift bin $\Rightarrow$ large shot noise, under-sampling (1 gal. per 40 square degrees!).

Why are we not happy with this?
$C_\ell(z,z')$ is in principal observable and contains the full 2-point information about the galaxy distribution.

- To fully profit from the redshift accuracy of a spectroscopic survey we would have to compute $C_\ell(z,z')$ for about $10^4 \times 10^4$ redshifts. At present speeds this means $\frac{1}{2}10^8 \times 2\text{min} = 6 \times 10^9\text{sec} \simeq$ 200 years. Of course we can parallelize, but for parameter estimation we need to run this about 10^5 times...
- Worse is that a spectroscopic catalog with about 10^7 galaxies like Euclid would have only about 1000 galaxies per redshift bin $\Rightarrow$ large shot noise, under-sampling (1 gal. per 40 square degrees!).

I therefore suggest the following solution:

- Use the $C_\ell(z,z')$ spectra for photometric surveys and for binned spectroscopic surveys in bins of $\Delta z \sim 0.1$.

$C_\ell(z,z')$ vs $P(k,\mu,\bar{z})$

Why are we not happy with this?
$C_\ell(z,z')$ is in principal observable and contains the full 2-point information about the galaxy distribution.

- To fully profit from the redshift accuracy of a spectroscopic survey we would have to compute $C_\ell(z,z')$ for about $10^4 \times 10^4$ redshifts. At present speeds this means $\frac{1}{2}10^8 \times 2\text{min} = 6 \times 10^9\text{sec} \simeq$ 200 years. Of course we can parallelize, but for parameter estimation we need to run this about 10^5 times...
- Worse is that a spectroscopic catalog with about 10^7 galaxies like Euclid would have only about 1000 galaxies per redshift bin $\Rightarrow$ large shot noise, under-sampling (1 gal. per 40 square degrees!).

I therefore suggest the following solution:

- Use the $C_\ell(z,z')$ spectra for photometric surveys and for binned spectroscopic surveys in bins of $\Delta z \sim 0.1$.
- Inside each bin, $|z - z'| < \Delta z$ use the power spectrum $P(k,\mu,\bar{z})$.

$C_\ell(z, z')$ vs $P(k, \mu, \bar{z})$

Why are we not happy with this?
$C_\ell(z, z')$ is in principal observable and contains the full 2-point information about the galaxy distribution.

- To fully profit from the redshift accuracy of a spectroscopic survey we would have to compute $C_\ell(z, z')$ for about $10^4 \times 10^4$ redshifts. At present speeds this means $\frac{1}{2}10^8 \times 2\text{min} = 6 \times 10^9\text{sec} \simeq$ 200 years. Of course we can parallelize, but for parameter estimation we need to run this about 10^5 times...
- Worse is that a spectroscopic catalog with about 10^7 galaxies like Euclid would have only about 1000 galaxies per redshift bin $\Rightarrow$ large shot noise, under-sampling (1 gal. per 40 square degrees!).

I therefore suggest the following solution:

- Use the $C_\ell(z, z')$ spectra for photometric surveys and for binned spectroscopic surveys in bins of $\Delta z \sim 0.1$.
- Inside each bin, $|z - z'| < \Delta z$ use the power spectrum $P(k, \mu, \bar{z})$.
- With the information on the truly observed correlation function we can define the 'observed' $P(k, \mu, \bar{z})$.

The 'observed' $P(k, \mu, \bar{z})$

To go from the angular correlation function to the real space correlation function we need to assume a cosmology.

$$r(z_1, z_2, \theta) = \sqrt{\chi_1^2 + \chi_2^2 - 2\chi_1\chi_2 \cos\theta}\,.$$

For $z_1, z_2 \in [\bar{z} - \Delta z/2, \bar{z} - \Delta z/2]$,
we now set $r_\| = \chi_2 - \chi_1 \simeq \frac{z_2 - z_1}{\mathcal{H}(\bar{z})} = \mu r$ and $r_\perp = \sqrt{r^2 - r_\|^2} = r\sqrt{1-\mu^2}\,.$
Defining

$$\tilde{C}_\ell(\bar{z}, r_\|) \equiv C_\ell(\bar{z} - r_\| \mathcal{H}(\bar{z})/2, \bar{z} + r_\| \mathcal{H}(\bar{z})/2)$$

and using that

$$\cos\theta = \frac{r^2 - \chi_1^2 - \chi_2^2}{2\chi_1\chi_2} = c(r, r_\|, \bar{z})$$

we obtain

$$\xi(r_\|, r_\perp, \bar{z}) = \frac{1}{4\pi}\sum_\ell (2\ell+1)\tilde{C}_\ell(\bar{z}, r_\|)P_\ell(c(r, r_\|, \bar{z}))$$

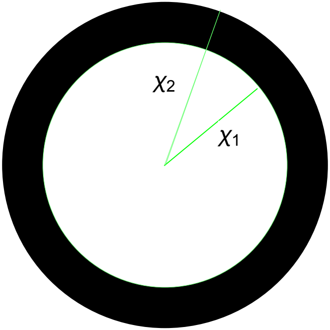
The power spectrum is then simply

$$P^{\rm obs}(k_\|, k_\perp, \bar{z}) \quad = \quad \int dr_\| d^2 r_\perp e^{i(k_\| r_\| + \mathbf{k}_\perp \cdot br_\perp)} \xi(r_\|, r_\perp, \bar{z})\,.$$

The 'observed' $P(k, \mu, \bar{z})$ (cont.)

$$P^{\rm obs}(k_\parallel, k_\perp, \bar{z}) = \sum_\ell \frac{2\ell+1}{2}\int_0^{2\chi(\bar{z})} dr r^2 \int_{-1}^{1} d\mu J_0\left(k_\perp r\sqrt{1-\mu^2}\right)\exp(ik_\parallel r\mu)\tilde{C}_\ell(\bar{z}, r\mu)P_\ell\left(c(r,\mu,\bar{z})\right) .$$

This gives the power spectrum from the density field in the shell with inner radius χ_1 and outer radius χ_2.



The meaning of the angle α with

$$\cos\alpha = \mu = (\chi_2 - \chi_1)/r$$

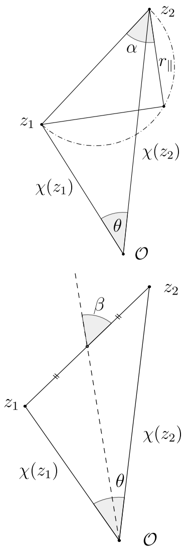
$$= \frac{2}{r}\sqrt{\bar{\chi}^2 - \frac{4\bar{\chi}^2 - r^2}{2(1+\cos\theta)}}$$

$$\cos\theta = \frac{4\bar{\chi}^2 + r^2\cos^2\alpha - 2r^2}{4\bar{\chi}^2 - r^2\cos^2\alpha}$$

$$\cos\beta = \frac{\chi_2^2 - \chi_1^2}{r\sqrt{\chi_2^2 + \chi_1^2 + 2\chi_1\chi_2\cos\theta}}$$

$$\cos\theta = \frac{1}{2\chi_1\chi_2}\left[\frac{(\chi_1^2 - \chi_2^2)^2}{r^2\cos^2\beta} - \chi_1^2 - \chi_2^2\right]$$

$$= 1 - \frac{8(1-\cos^2\beta)r^2\bar{\chi}^2}{16\bar{\chi}^4 - 8\bar{\chi}^2 r^2\cos^2\beta + r^4\cos^2\beta}$$

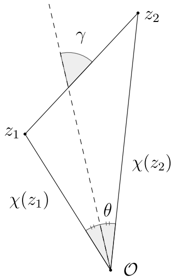


Angles (cont.)

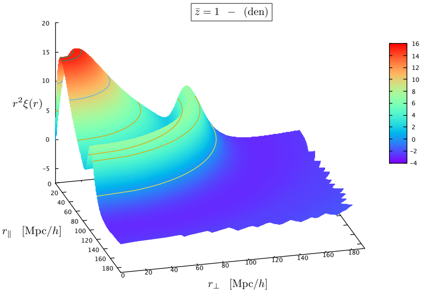
$$\cos\gamma = \frac{(1+\cos\theta)^{1/2}(\chi_2-\chi_1)}{\sqrt{2}r}$$

$$= \frac{\sqrt{r^2-2(1-\cos\theta)\bar{\chi}^2}}{r}$$

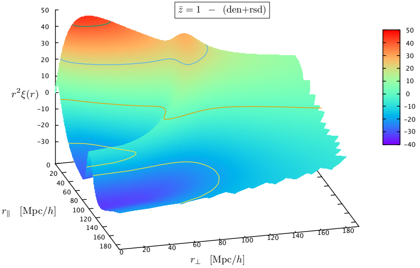
$$\cos\theta = 1 - \frac{r^2(1-\cos^2\gamma)}{2\bar{\chi}^2}\,.$$



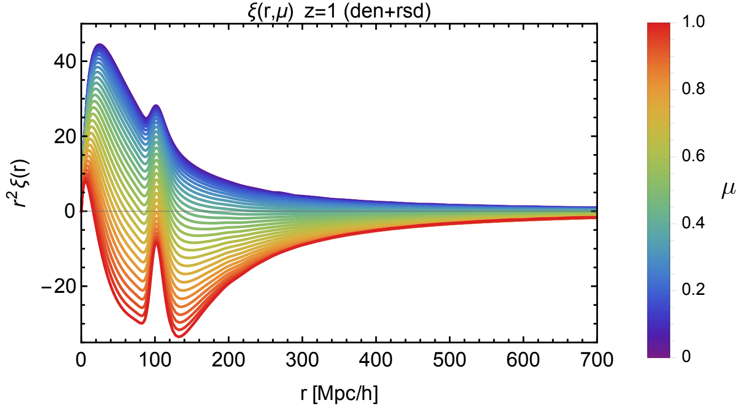
The correlation function



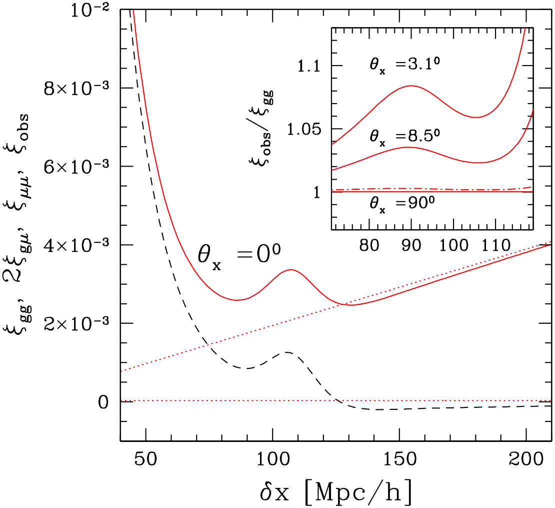
Density



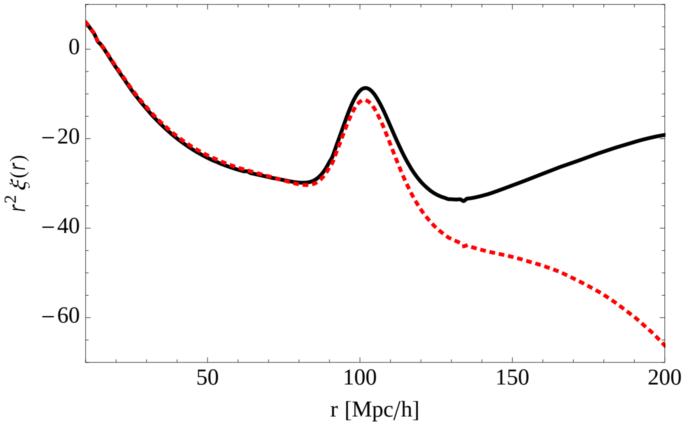
Density+RSD


$\xi(r,\mu)$ z=1 (den+rsd)
$r^2\xi(r)$
40
20
0
−20
0
100
200
300
400
500
600
700
r [Mpc/h]
1.0
0.8
0.6
0.4
0.2
0
μ

The correlation function with lensing



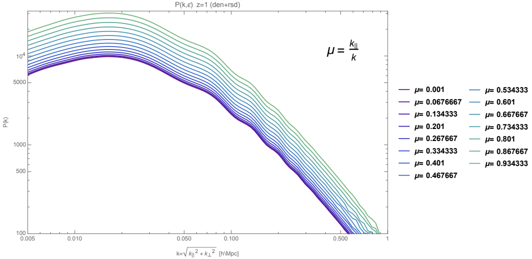
(from Hui et al. 0706.1071)

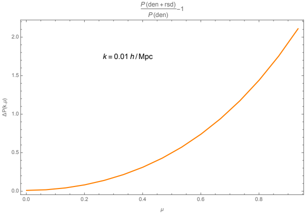


density +lensing

(Tansella et al., in preparation)

The standard power spectrum



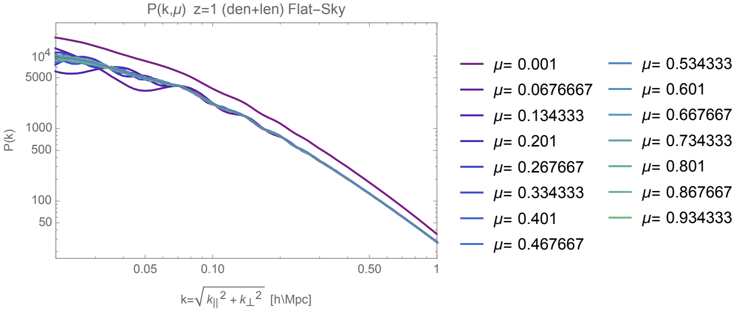


density+RSD (Tansella et al., in preparation)

The power spectrum with lensing in flat sky & Limber approximation

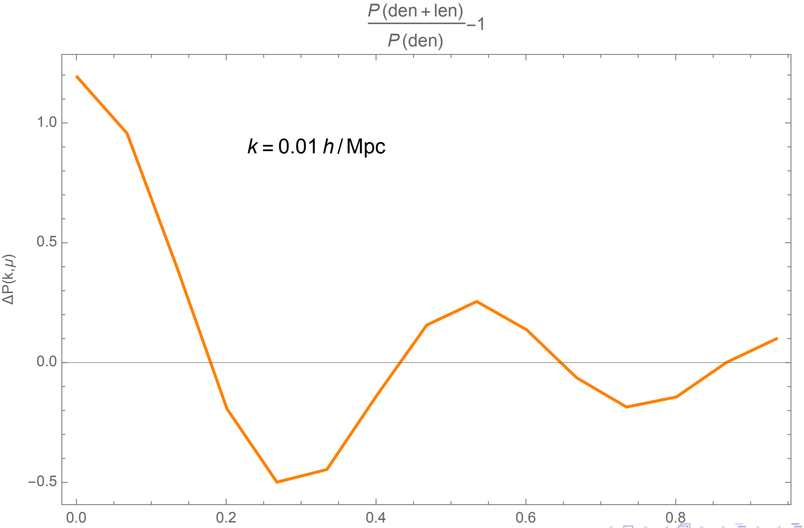
$$P(k_{\|}, k_{\perp}, \bar{z}) = 2\chi^2(\bar{z}) \int_0^{r_{\max}} dr_{\|}\, C_{\chi(\bar{z})k_{\perp}}(\bar{z}, r_{\|}) \cos(k_{\|} r_{\|}) \qquad r_{\max} = \frac{\Delta z}{\mathcal{H}(\bar{z})}$$

Out[397]=



The power spectrum with lensing in flat sky & Limber approximation

$$P(k_\parallel, k_\perp, \bar z) = 2\chi^2(\bar z)\int_0^{r_{\max}} dr_\parallel\, C_{\chi(\bar z)k_\perp}(\bar z, r_\parallel)\cos(k_\parallel r_\parallel) \qquad r_{\max} = \frac{\Delta z}{\mathcal{H}(\bar z)}$$



Conclusions

- The angular-redshift power spectra $C_\ell(z,z')$ are directly observable. The provide an alternative route to measure $\kappa = -1/2\Delta\psi$ which also gives $\gamma = -1/2\,\eth^2\psi$.

Conclusions

- The angular-redshift power spectra $C_\ell(z, z')$ are directly observable. The provide an alternative route to measure $\kappa = -1/2\Delta\psi$ which also gives $\gamma = -1/2\,\eth^2\psi$.
- At high redshift and especially for radial fluctuations lensing cannot be neglected in the correlation function/ power spectrum.

Conclusions

- The angular-redshift power spectra $C_\ell(z, z')$ are directly observable. The provide an alternative route to measure $\kappa = -1/2\Delta\psi$ which also gives $\gamma = -1/2\,\bar{\partial}^2\psi$.
- At high redshift and especially for radial fluctuations lensing cannot be neglected in the correlation function/ power spectrum.
- Neglecting lensing can e.g. 'fake' non-minimal neutrino masses.

Conclusions

- The angular-redshift power spectra $C_\ell(z, z')$ are directly observable. The provide an alternative route to measure $\kappa = -1/2\Delta\psi$ which also gives $\gamma = -1/2\,\eth^2\psi$.
- At high redshift and especially for radial fluctuations lensing cannot be neglected in the correlation function/ power spectrum.
- Neglecting lensing can e.g. 'fake' non-minimal neutrino masses.
- To determine the real space correlation function or the power spectrum a cosmological model has to be assumed to convert $(\theta, z, z') \to r(\theta, z, z')$.

Conclusions

- The angular-redshift power spectra $C_\ell(z, z')$ are directly observable. The provide an alternative route to measure $\kappa = -1/2\Delta\psi$ which also gives $\gamma = -1/2\,\eth^2\psi$.
- At high redshift and especially for radial fluctuations lensing cannot be neglected in the correlation function/ power spectrum.
- Neglecting lensing can e.g. 'fake' non-minimal neutrino masses.
- To determine the real space correlation function or the power spectrum a cosmological model has to be assumed to convert $(\theta, z, z') \rightarrow r(\theta, z, z')$.
- Within redshift bins the power spectrum $P(k, \mu, \bar{z})$ can be determined including all, lensing and relativistic effects.

Conclusions

- The angular-redshift power spectra $C_\ell(z, z')$ are directly observable. The provide an alternative route to measure $\kappa = -1/2\Delta\psi$ which also gives $\gamma = -1/2\,\eth^2\psi$.
- At high redshift and especially for radial fluctuations lensing cannot be neglected in the correlation function/ power spectrum.
- Neglecting lensing can e.g. 'fake' non-minimal neutrino masses.
- To determine the real space correlation function or the power spectrum a cosmological model has to be assumed to convert $(\theta, z, z') \to r(\theta, z, z')$.
- Within redshift bins the power spectrum $P(k, \mu, \bar{z})$ can be determined including all, lensing and relativistic effects.
- This is the measured power spectrum for a survey which measures the correlation function in a redshift bin.
- The correct masks / windows have to be applied to the density field.

Conclusions

- The angular-redshift power spectra $C_\ell(z, z')$ are directly observable. The provide an alternative route to measure $\kappa = -1/2\Delta\psi$ which also gives $\gamma = -1/2\,\eth^2\psi$.
- At high redshift and especially for radial fluctuations lensing cannot be neglected in the correlation function/ power spectrum.
- Neglecting lensing can e.g. 'fake' non-minimal neutrino masses.
- To determine the real space correlation function or the power spectrum a cosmological model has to be assumed to convert $(\theta, z, z') \to r(\theta, z, z')$.
- Within redshift bins the power spectrum $P(k, \mu, \bar{z})$ can be determined including all, lensing and relativistic effects.
- This is the measured power spectrum for a survey which measures the correlation function in a redshift bin.
- The correct masks / windows have to be applied to the density field.
- Again, for radial fluctuations and at significant redshifts, $z > 0.3$ or so, lensing cannot be neglected.

————-