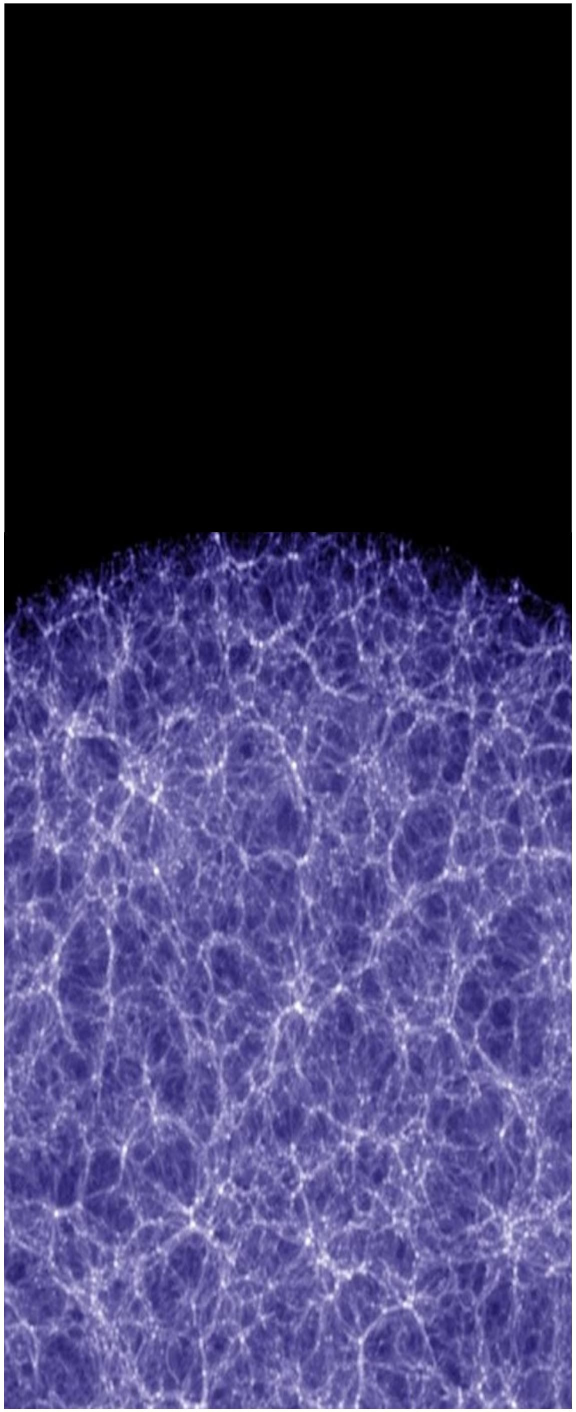
Defining the Issues: Baryon Acoustic Oscillations



Raul Angulo
MPA

15 September 2009

About the BAO technique

"This is the method least affected by systematic uncertainties [compared to Galaxy Cluster Counting, Supernovae and Weak Gravitational Lensing], and for which we have the most reliable forecasts of resources required to accomplish a survey of chosen accuracy."

Dark Energy Task Force

Outline

Current measurements

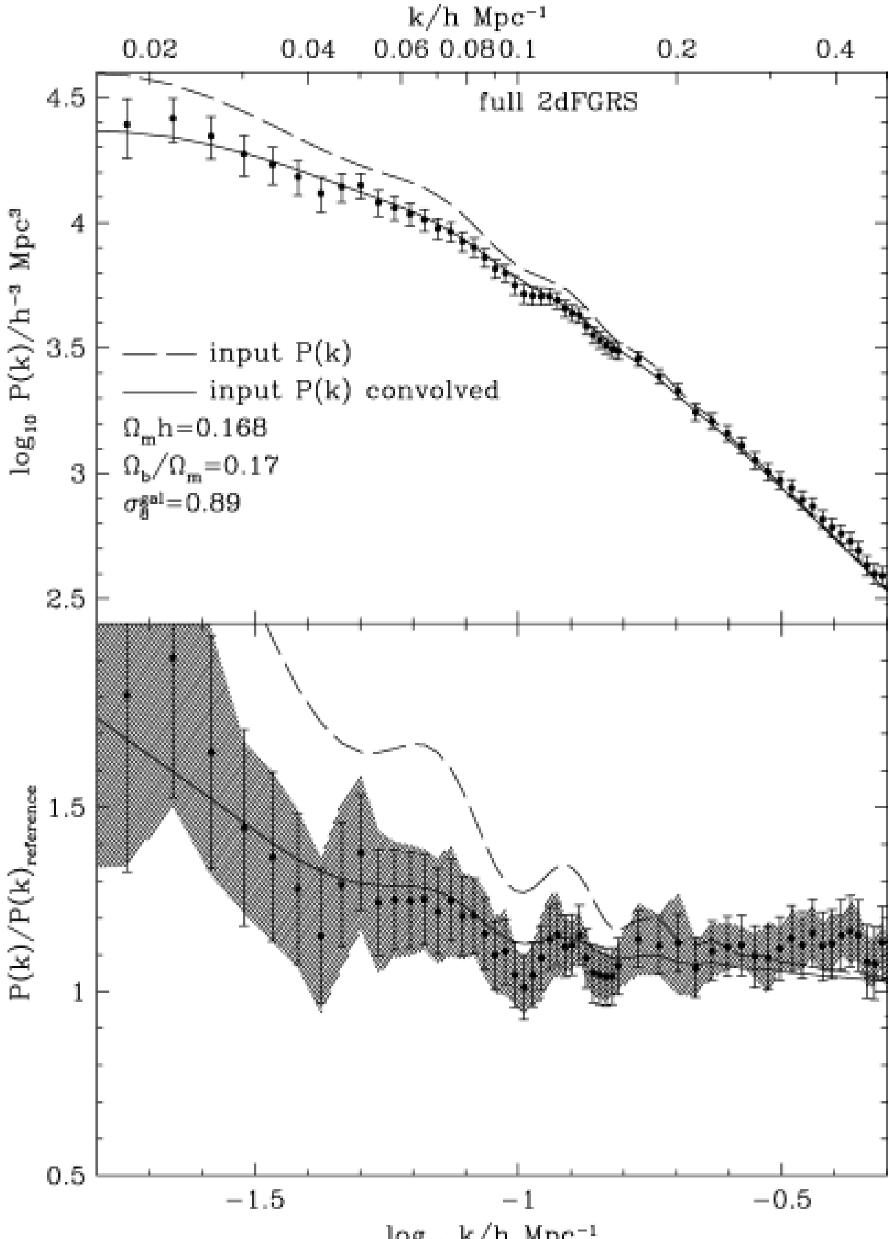
Modelling the density field in the Universe

Optimal extraction of the BAO signal

Observational effects

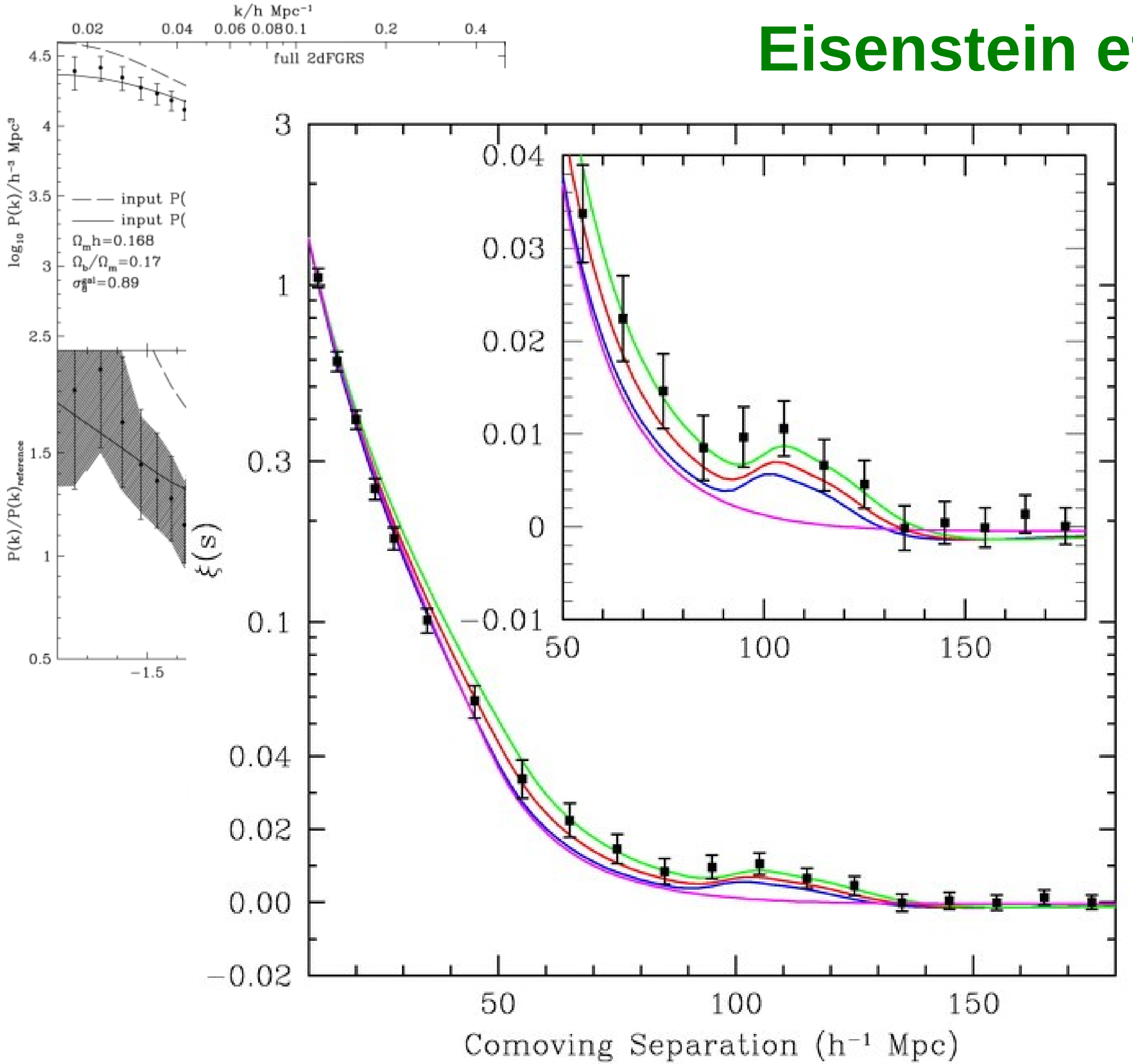
Summary & Conclusions

Current measurements



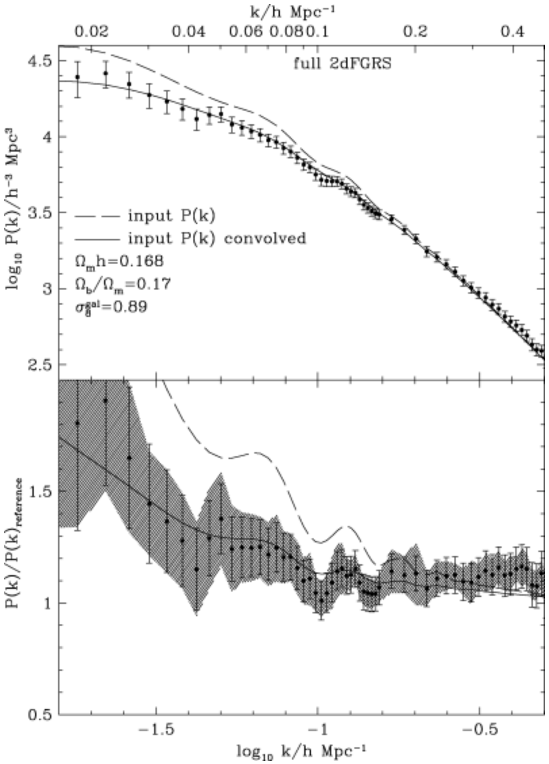
Cole et al 2005, 2dFGRS

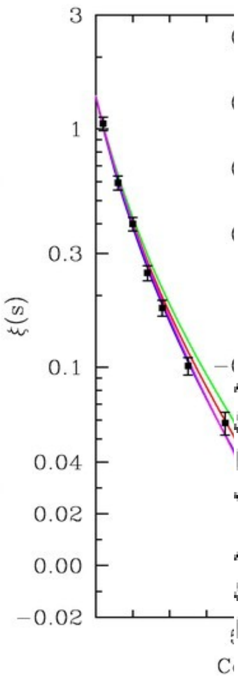
Current measurements

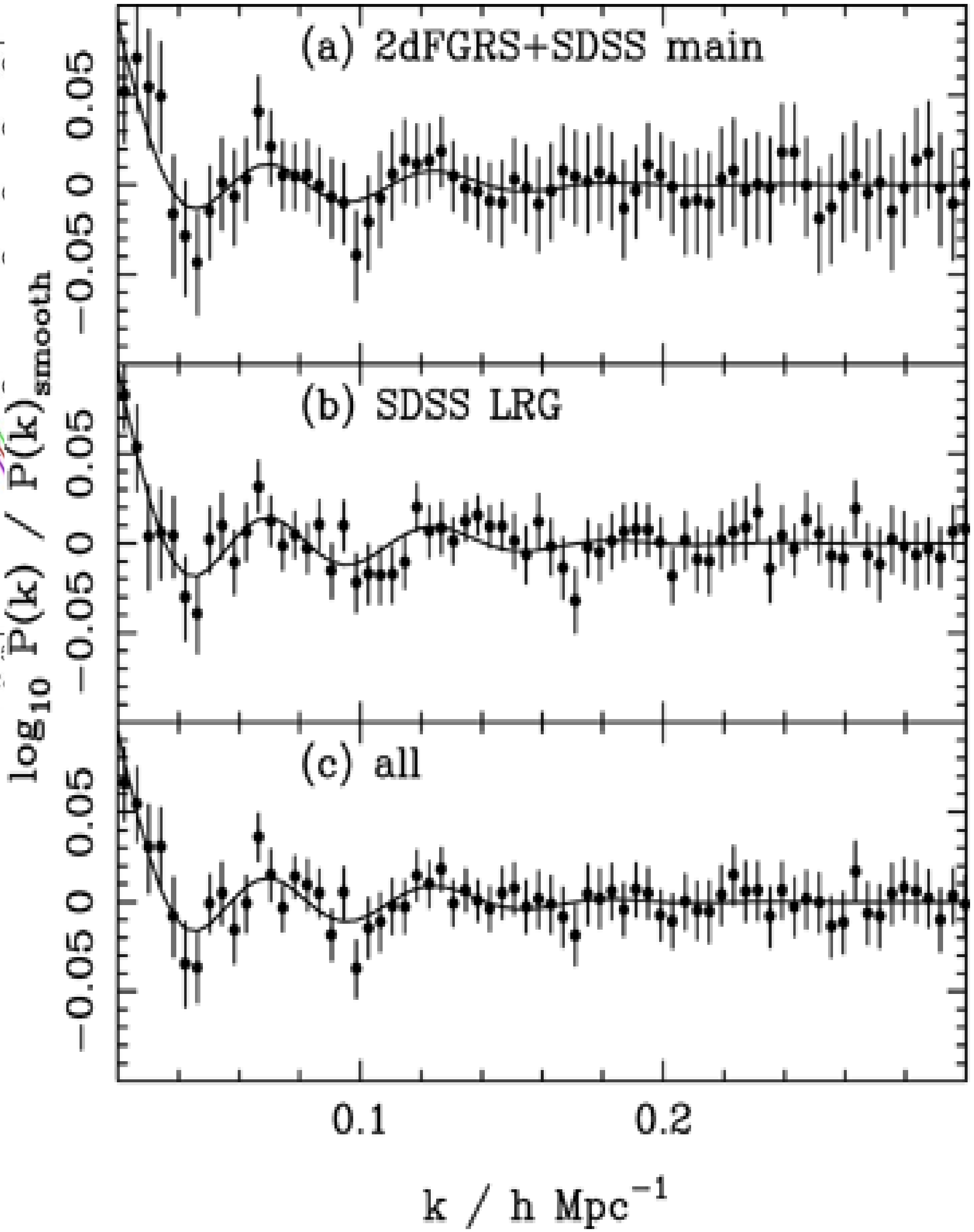


Eisenstein et al 2005, DR4 SDSS

Current measurements



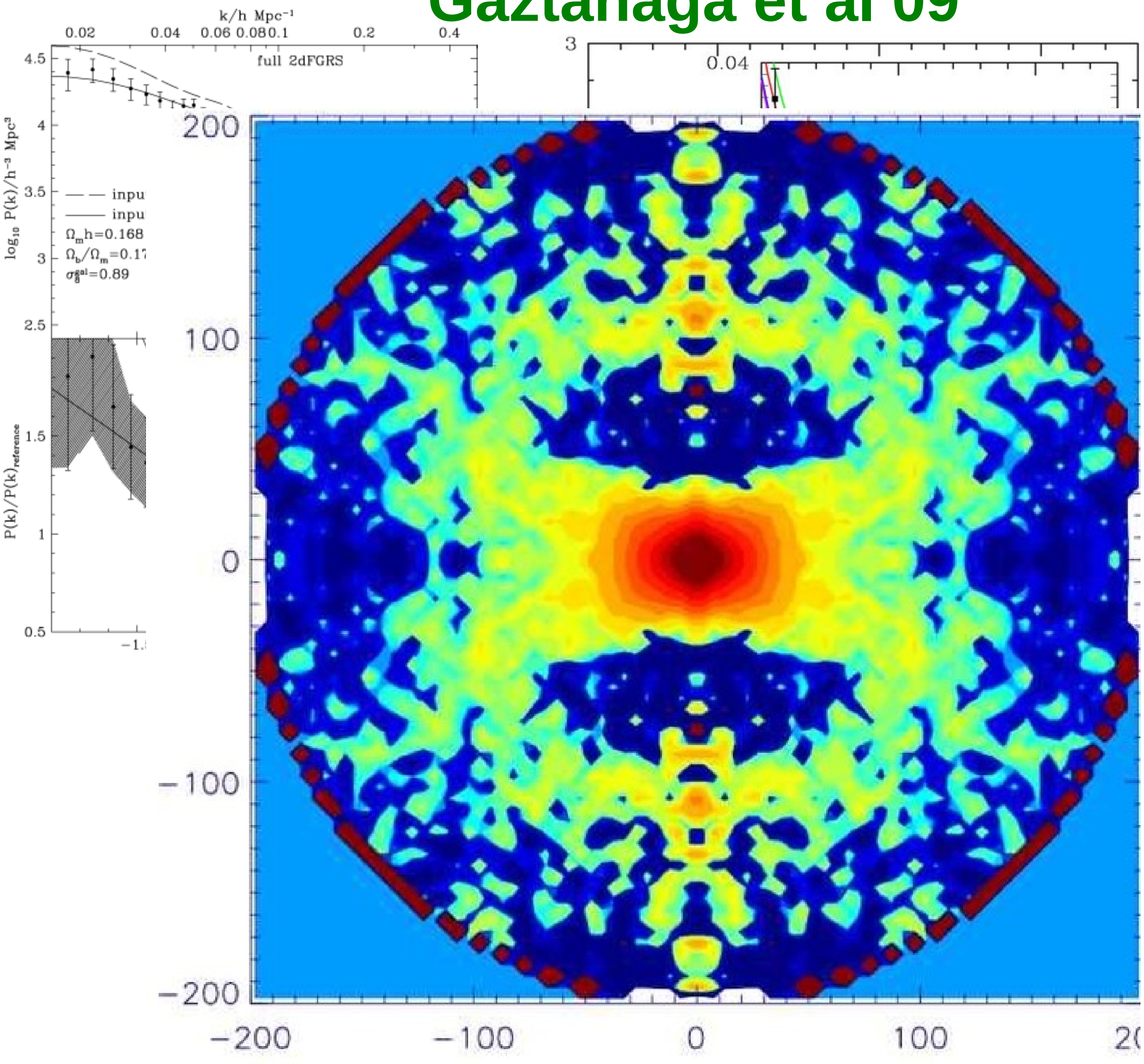


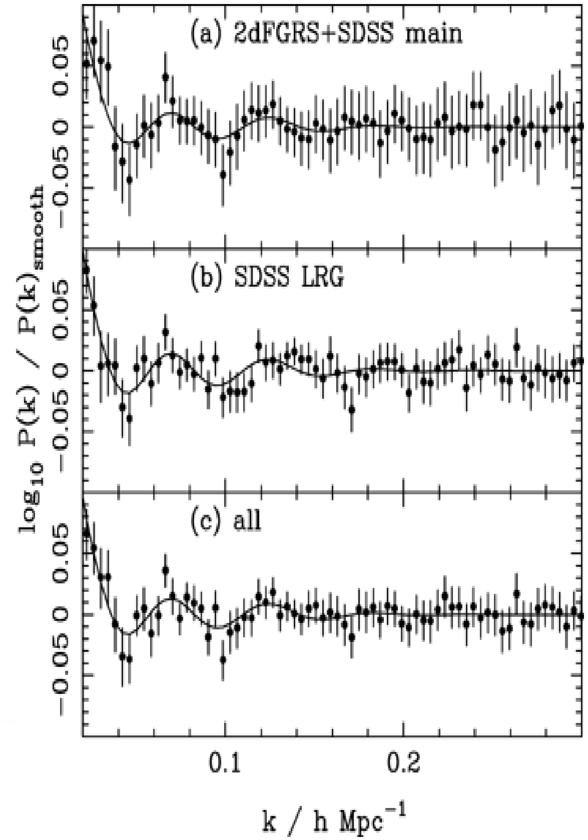


Percival et al 2007, SDSS+2dFGRS

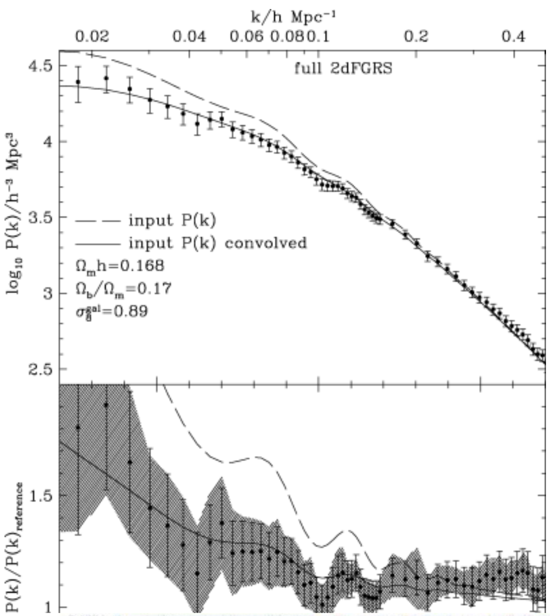
Current measurements

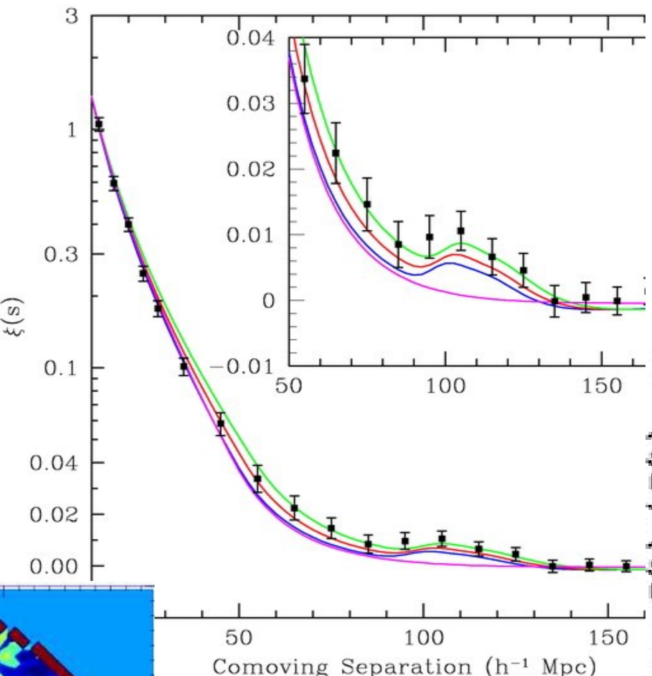
Gaztanaga et al 09

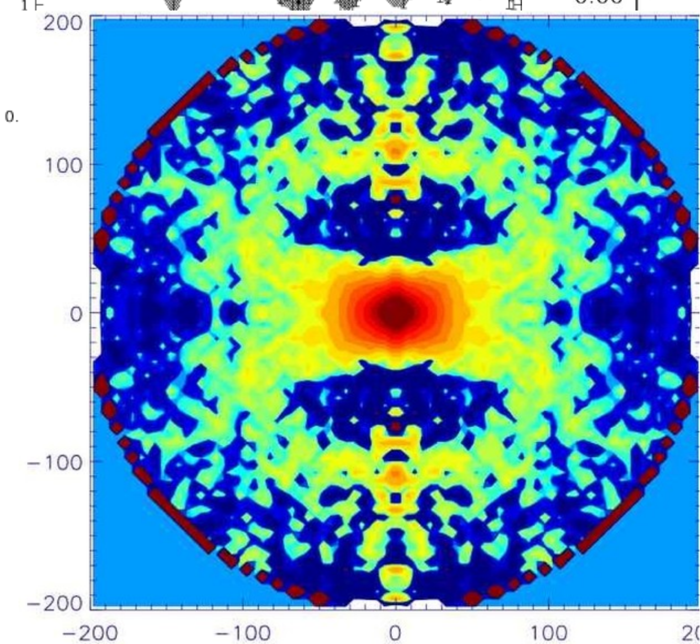


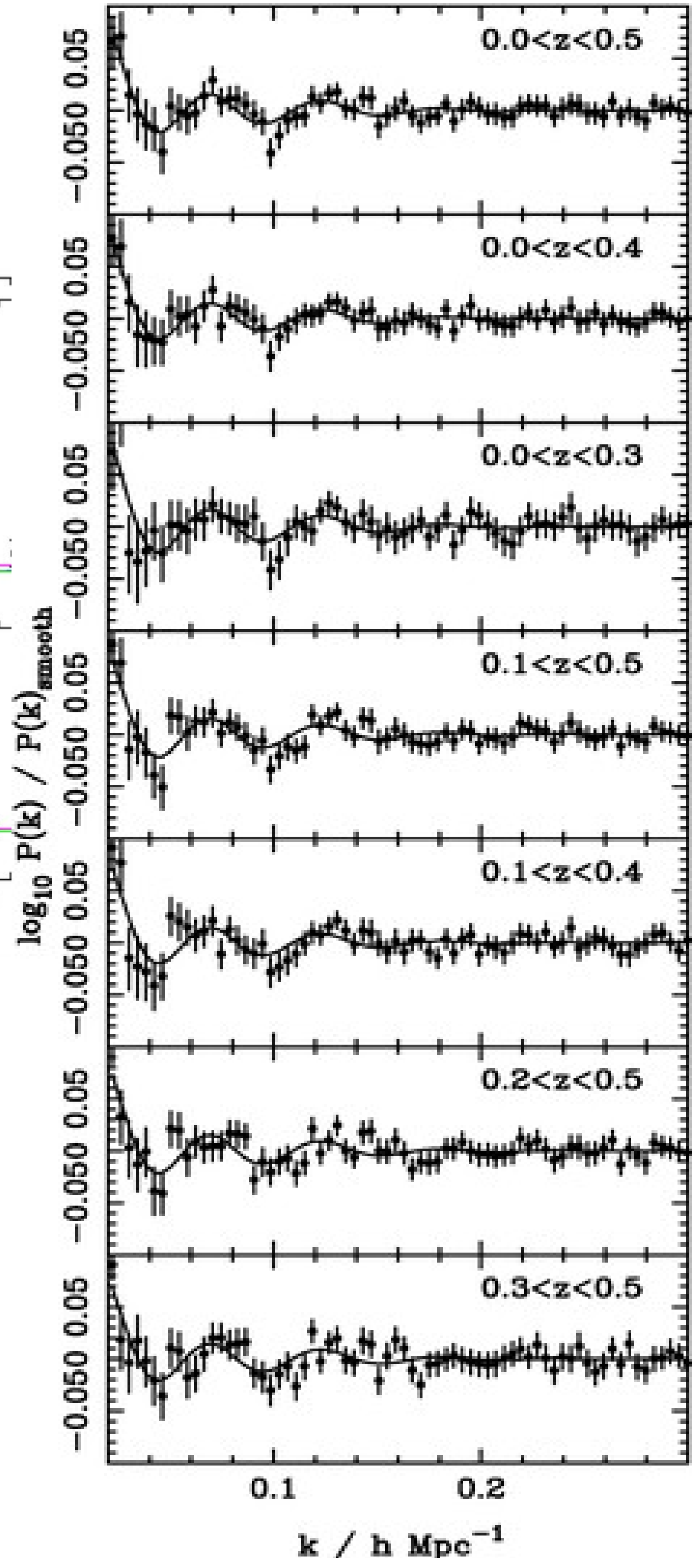


Current measurements

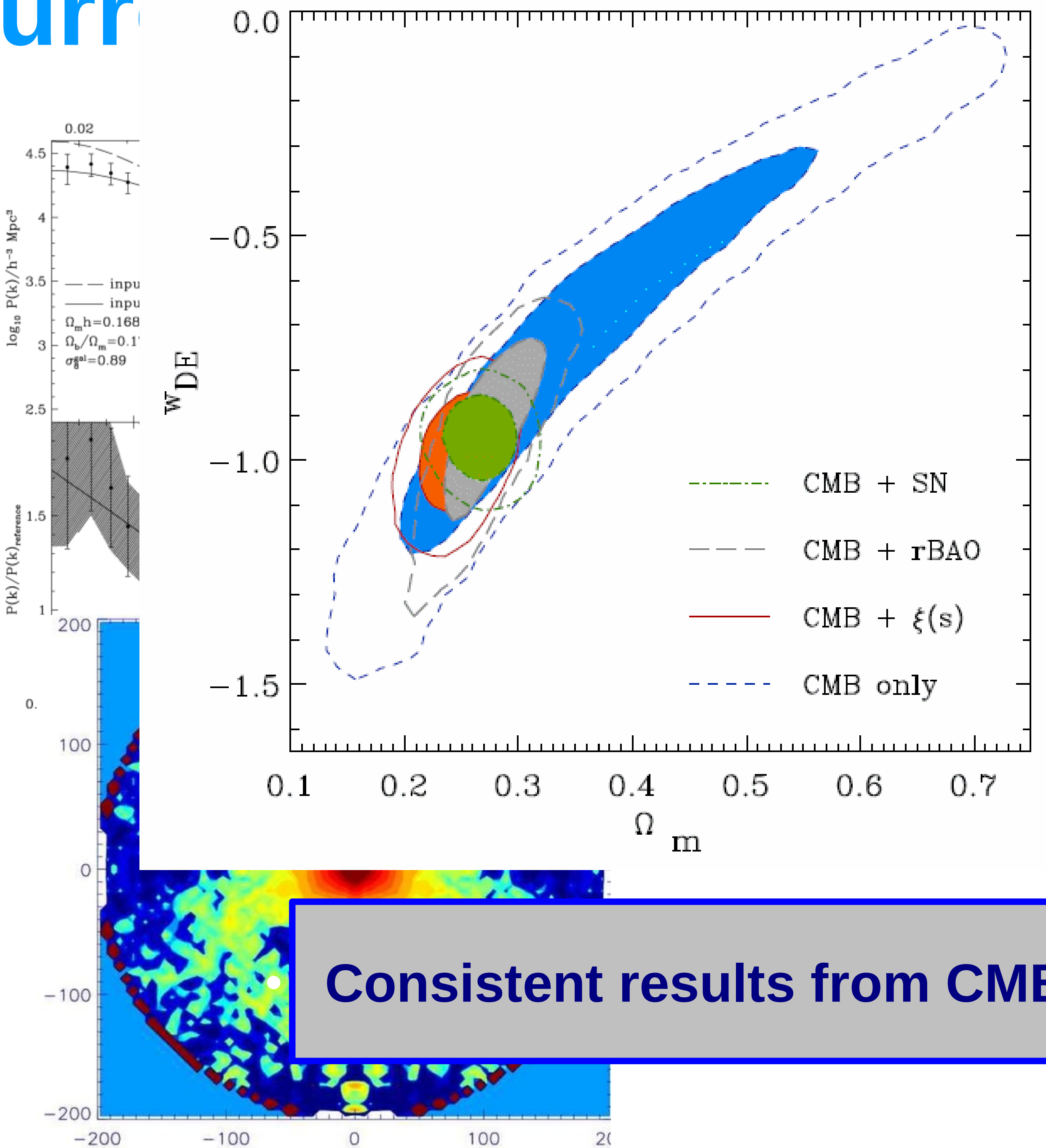




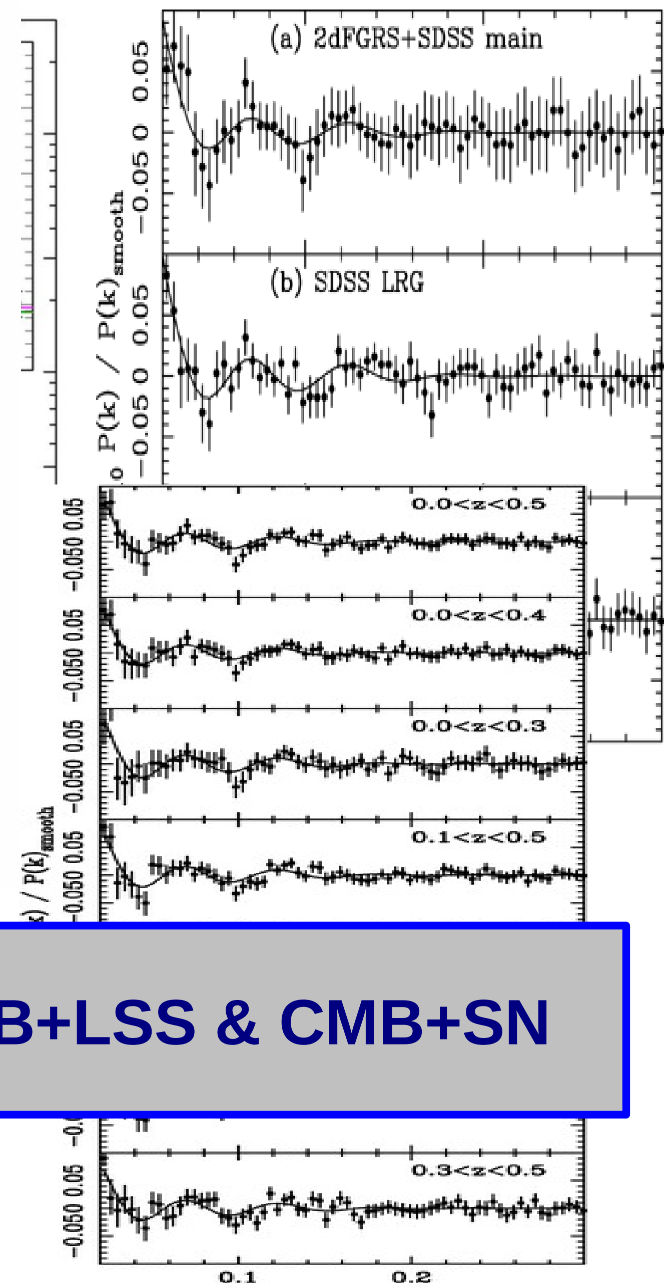




Current measurements

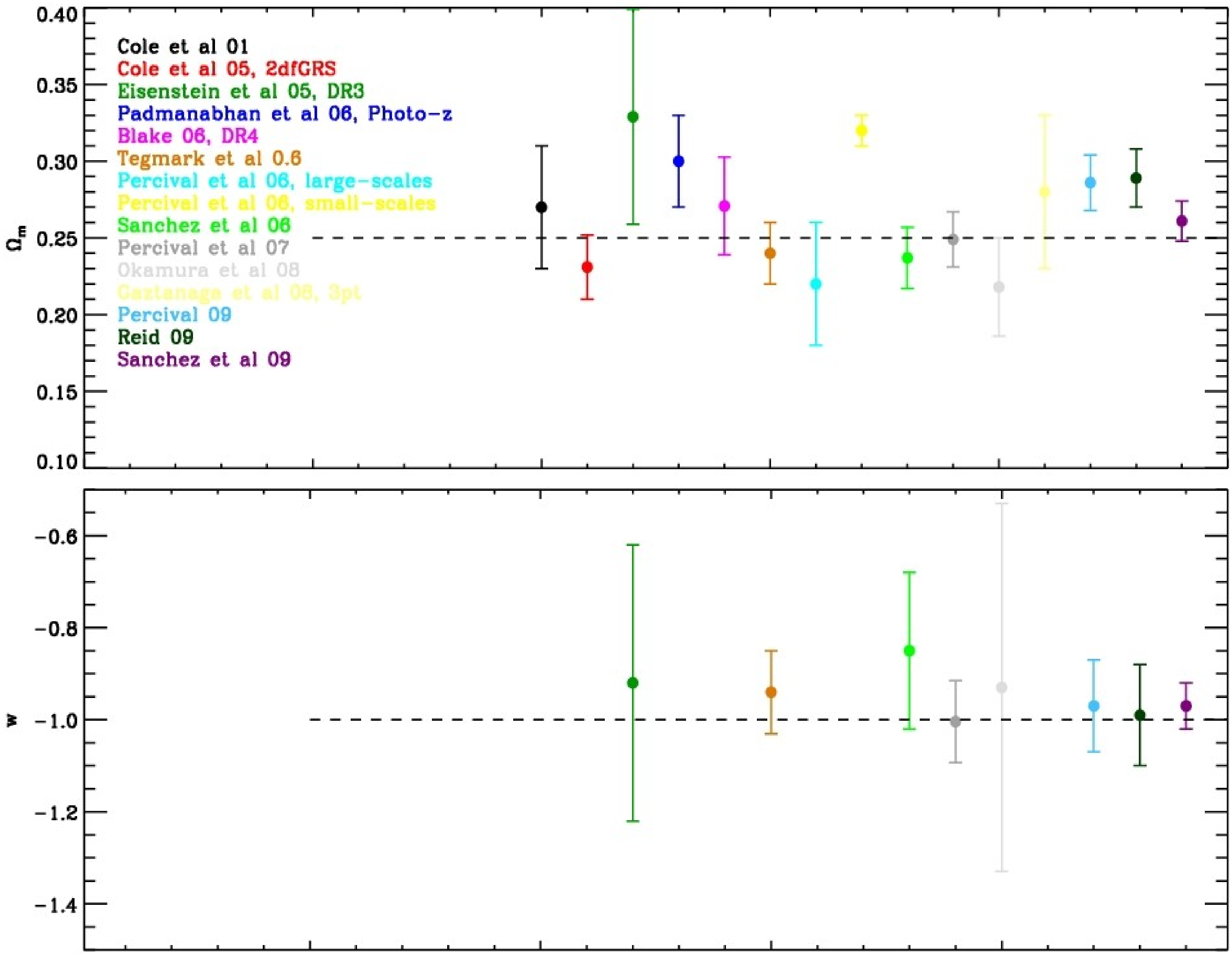


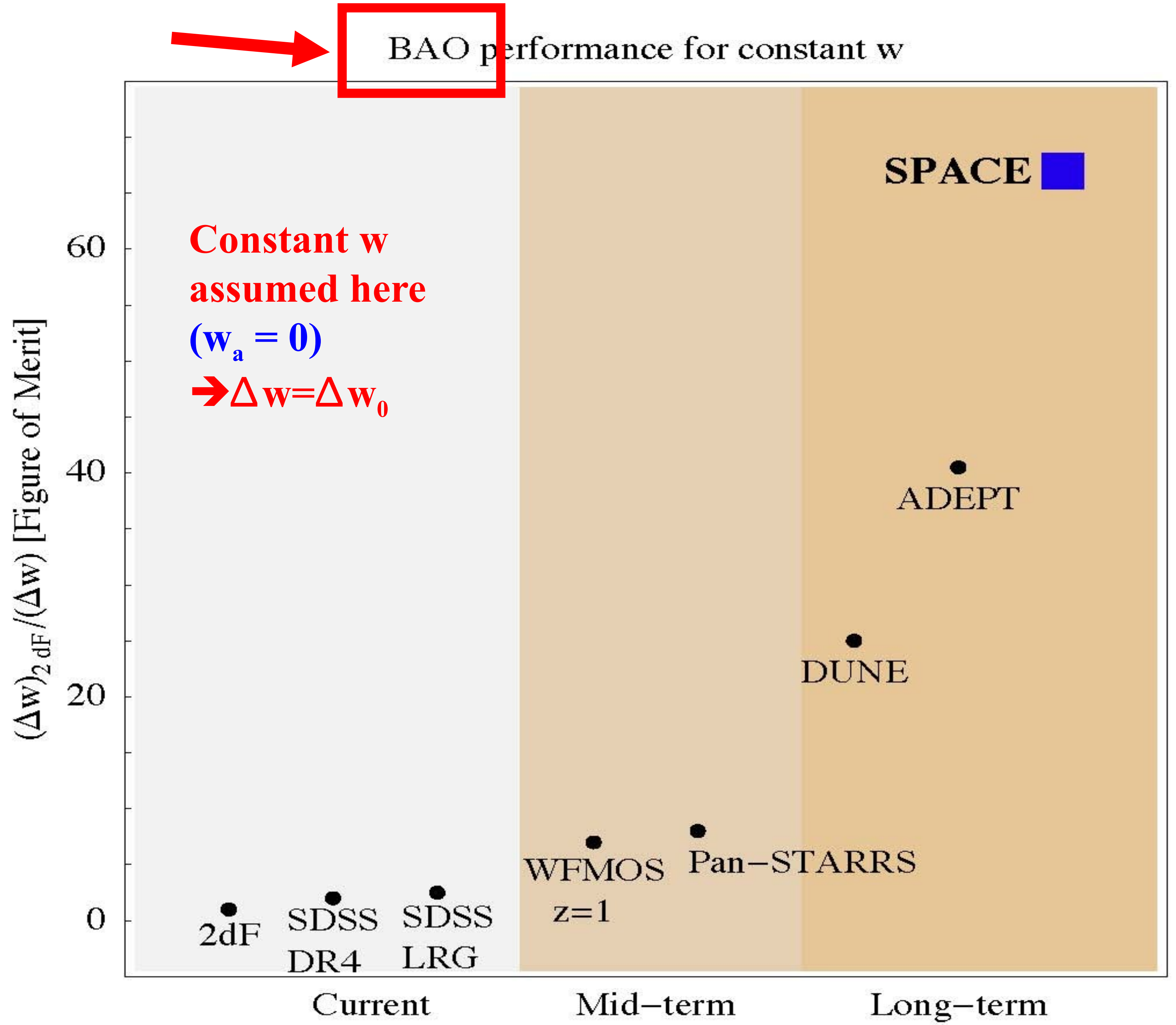
Sanchez et al 09



Consistent results from CMB+LSS & CMB+SN

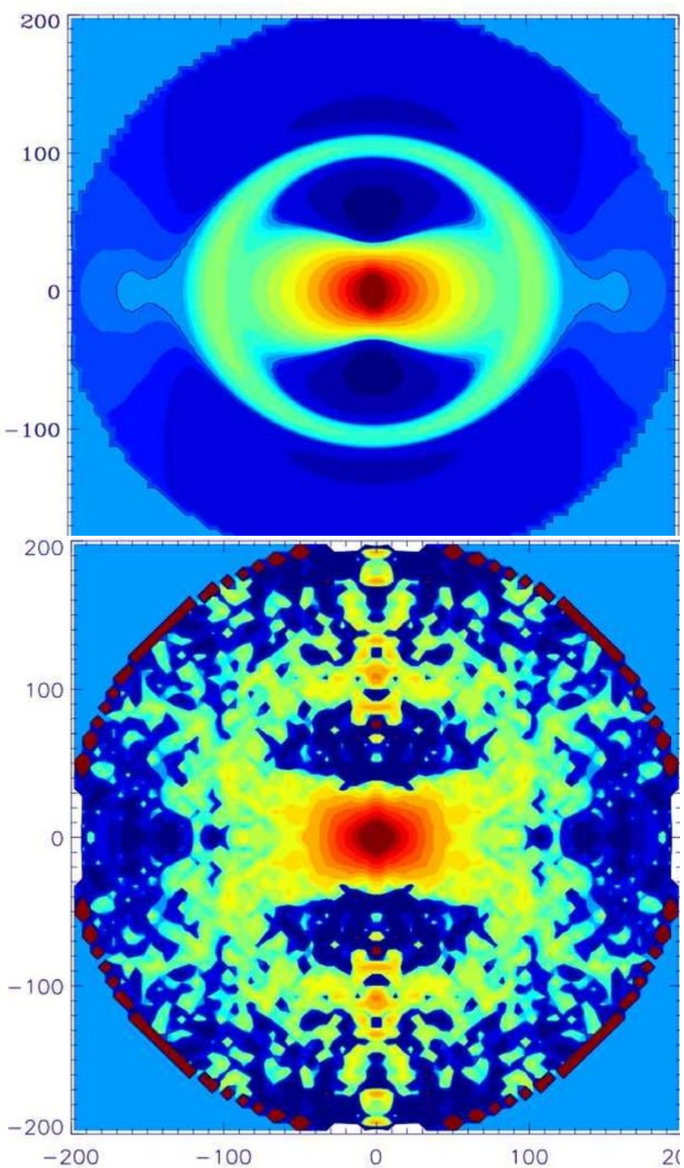
Current measurements





Accurate measurements demand accurate modelling!!

Do we understand the signal and errors in the measurements?



Gaztanaga et al 2009, SDSS DR7

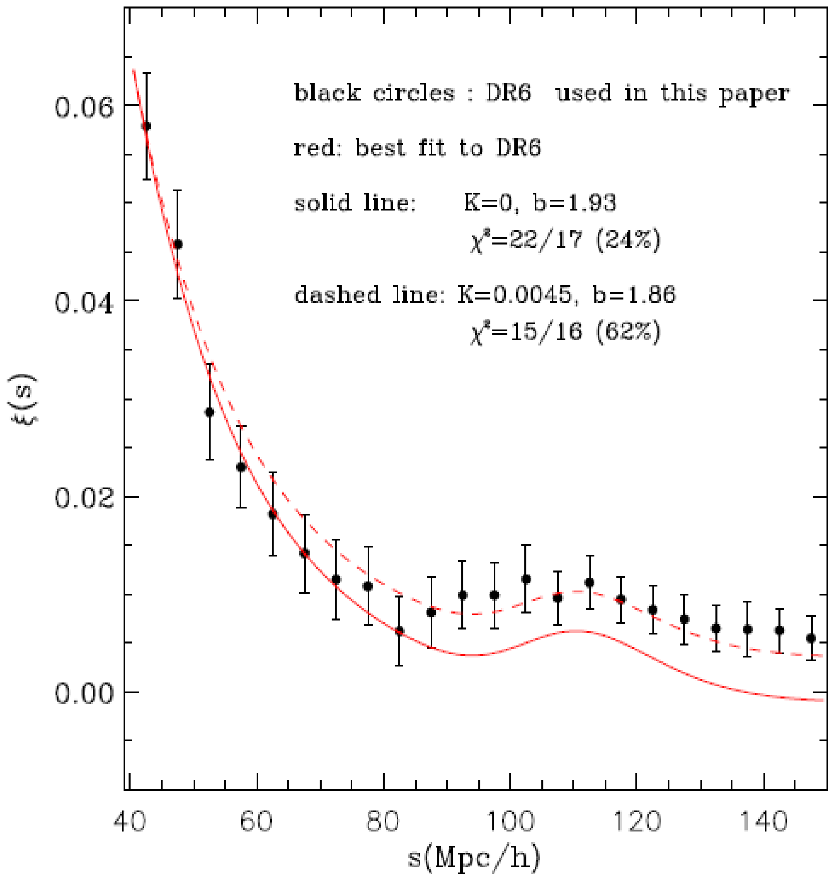
First detection and cosmological constraints from the radial BAO peak.
2% probability of being consistent with noise.

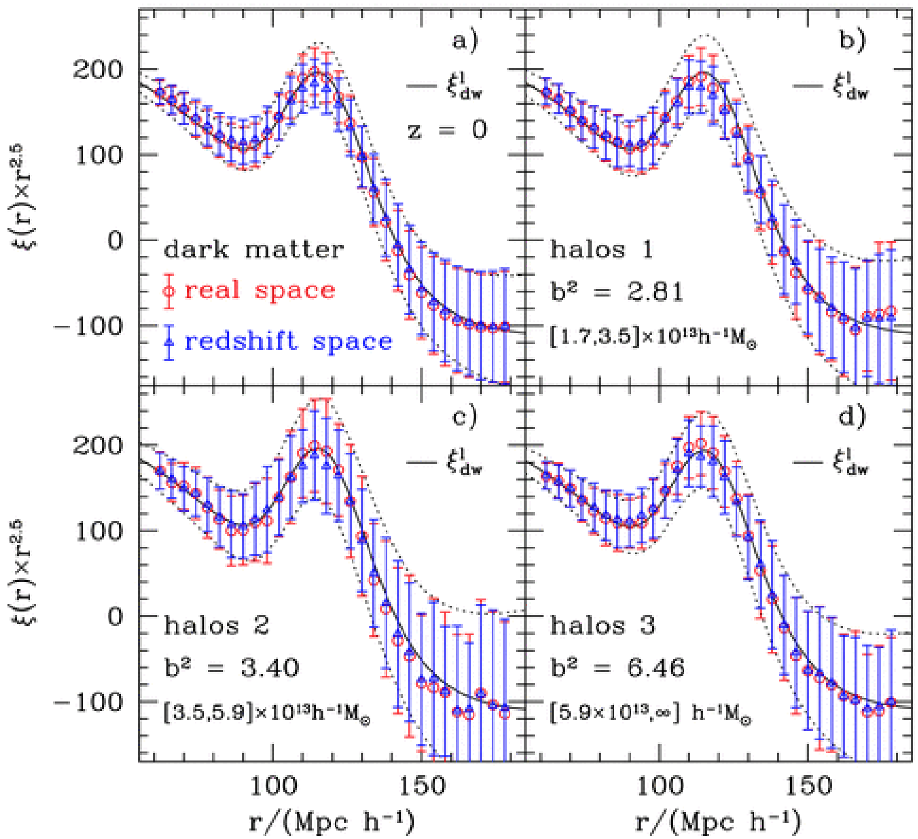
However, the signal is 10 larger than theoretical expectations!

So far there is no convincing explanation.

Do we understand what we are going to measure?

Sanchez et al 2009, LRG-SDSS DR6





The models agree remarkably well with simulations, however they do not reproduce the data!!

Challenges and goals for the future:

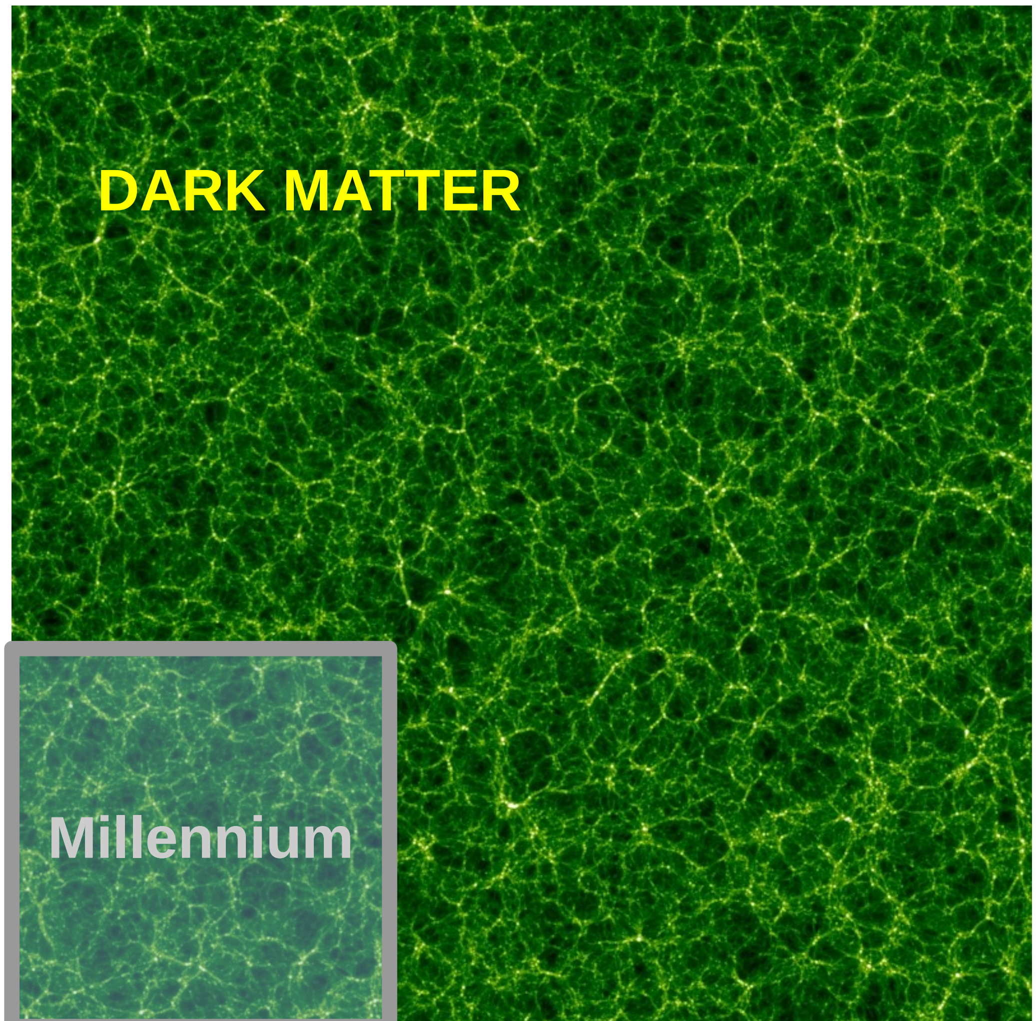
1. Understand and model the actual galaxy density field of the Universe
2. Establish the optimal methodology to extract the information encoded in the galaxy clustering
3. Understand the impact of observational errors and how to minimize them

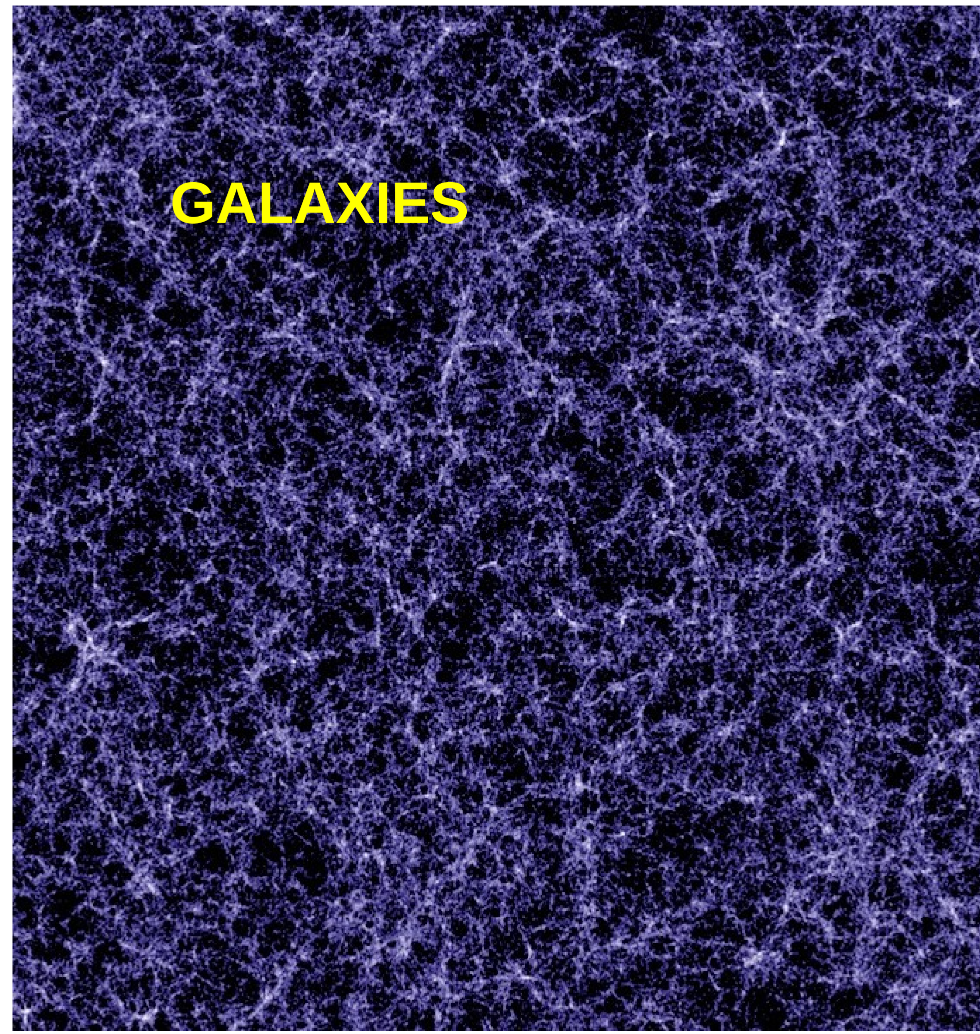
Modelling the density field of the Universe

Modelling I: The density field of the Universe

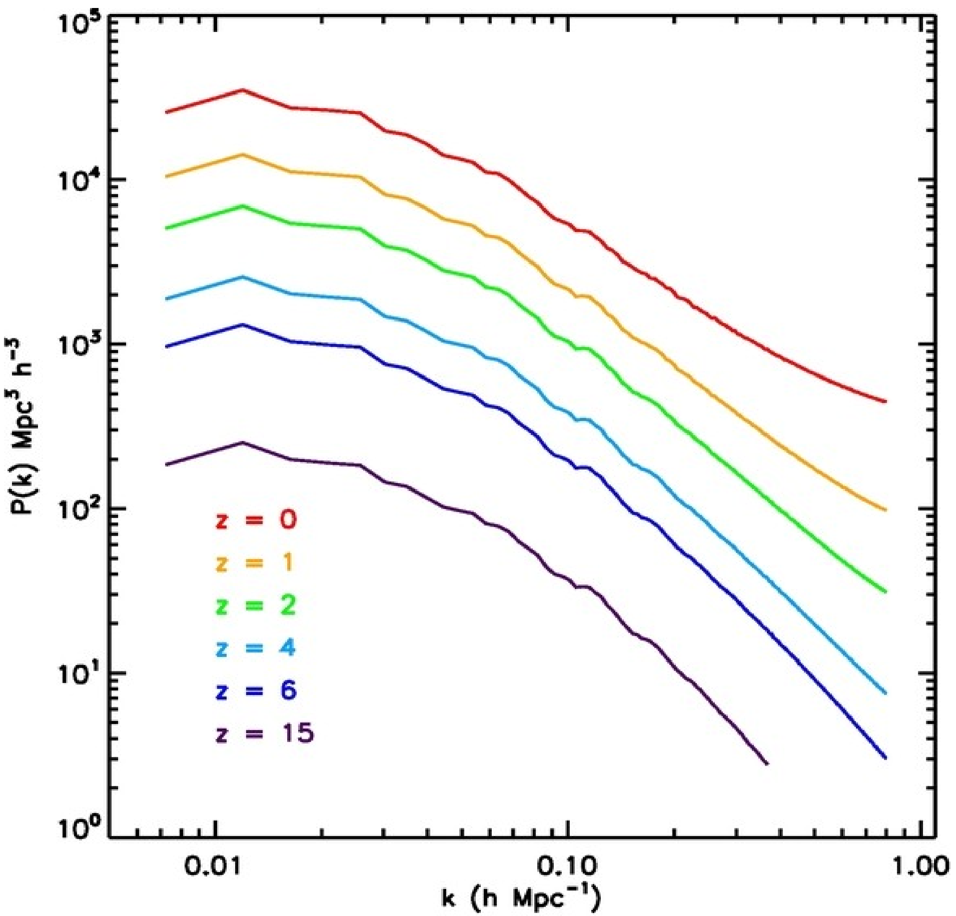
- Non-linearities
- Redshift-space distortions
- Dark Matter haloes
- Galaxy bias
- Evolution along the line of sight

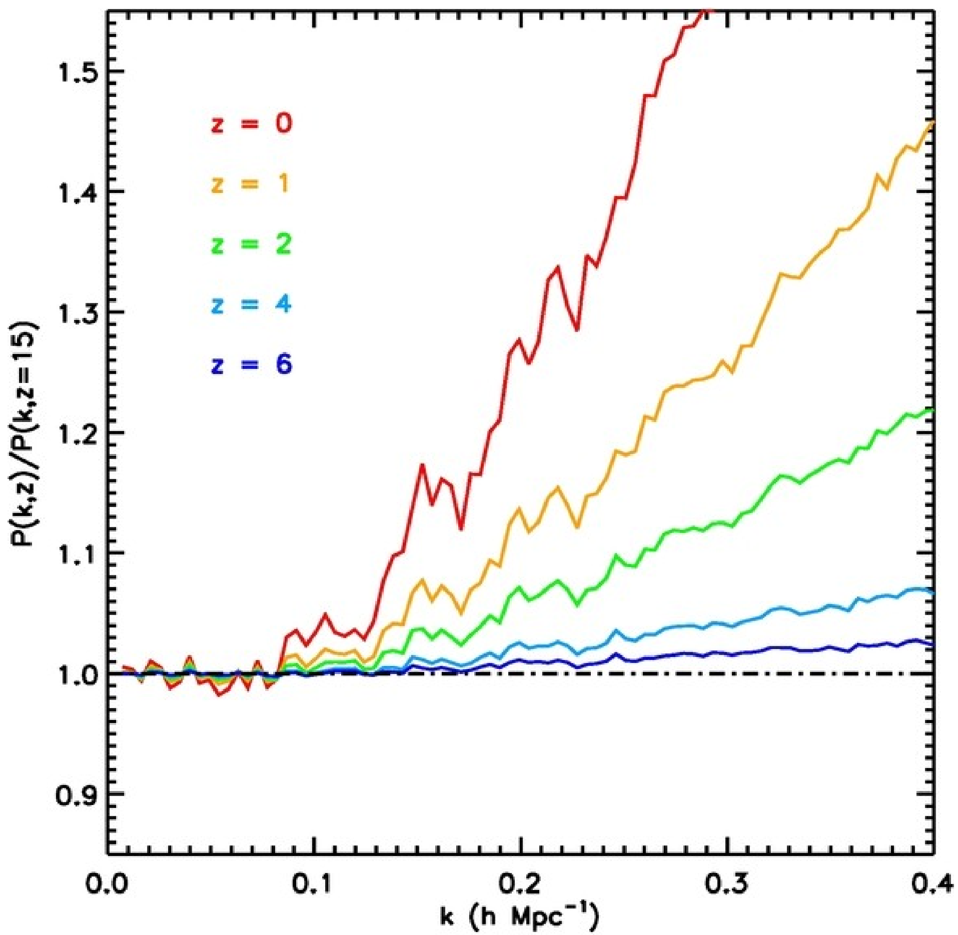
Modelling the density field of the Universe





Modelling the density field of the Universe: Dark Matter





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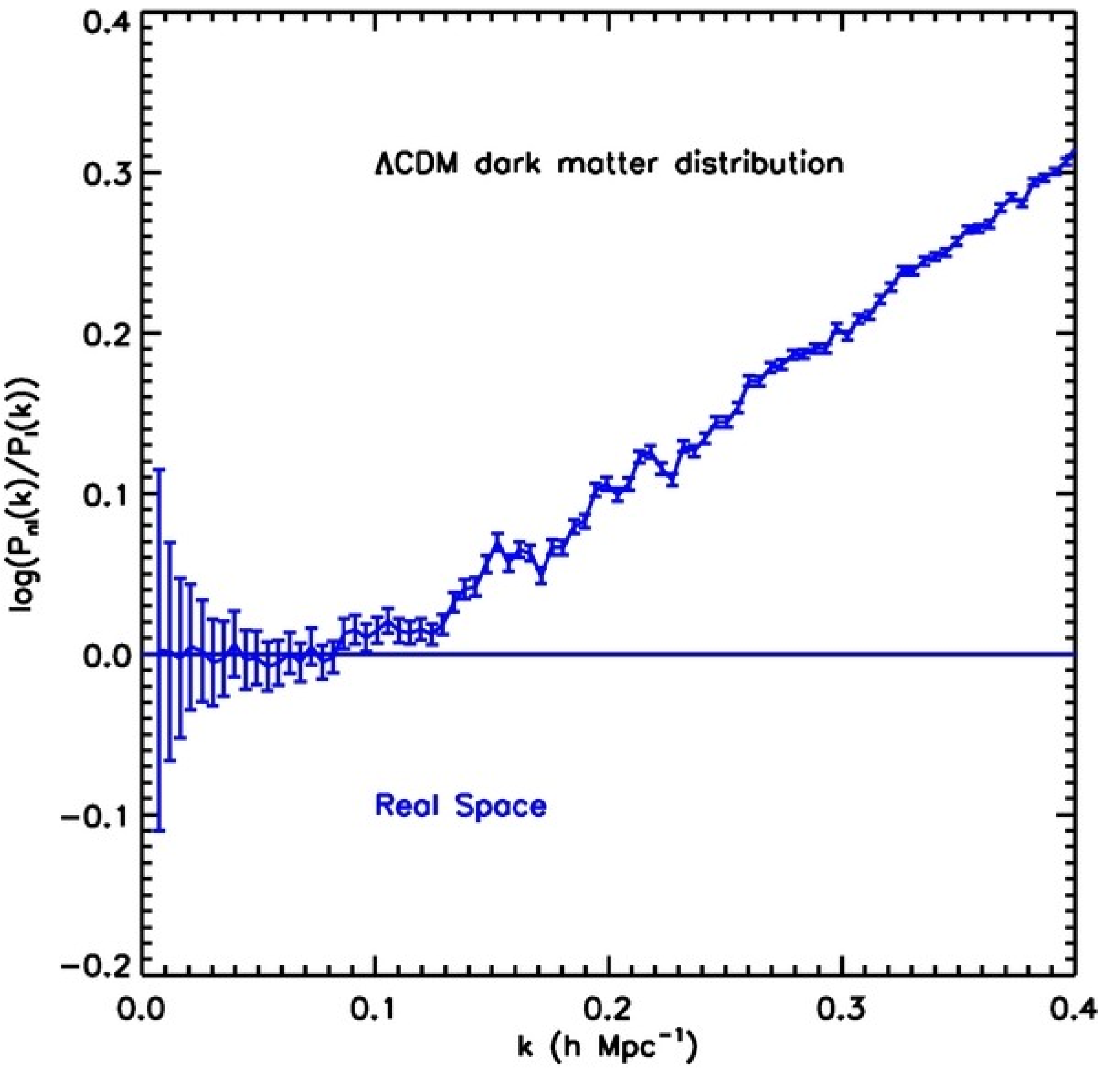
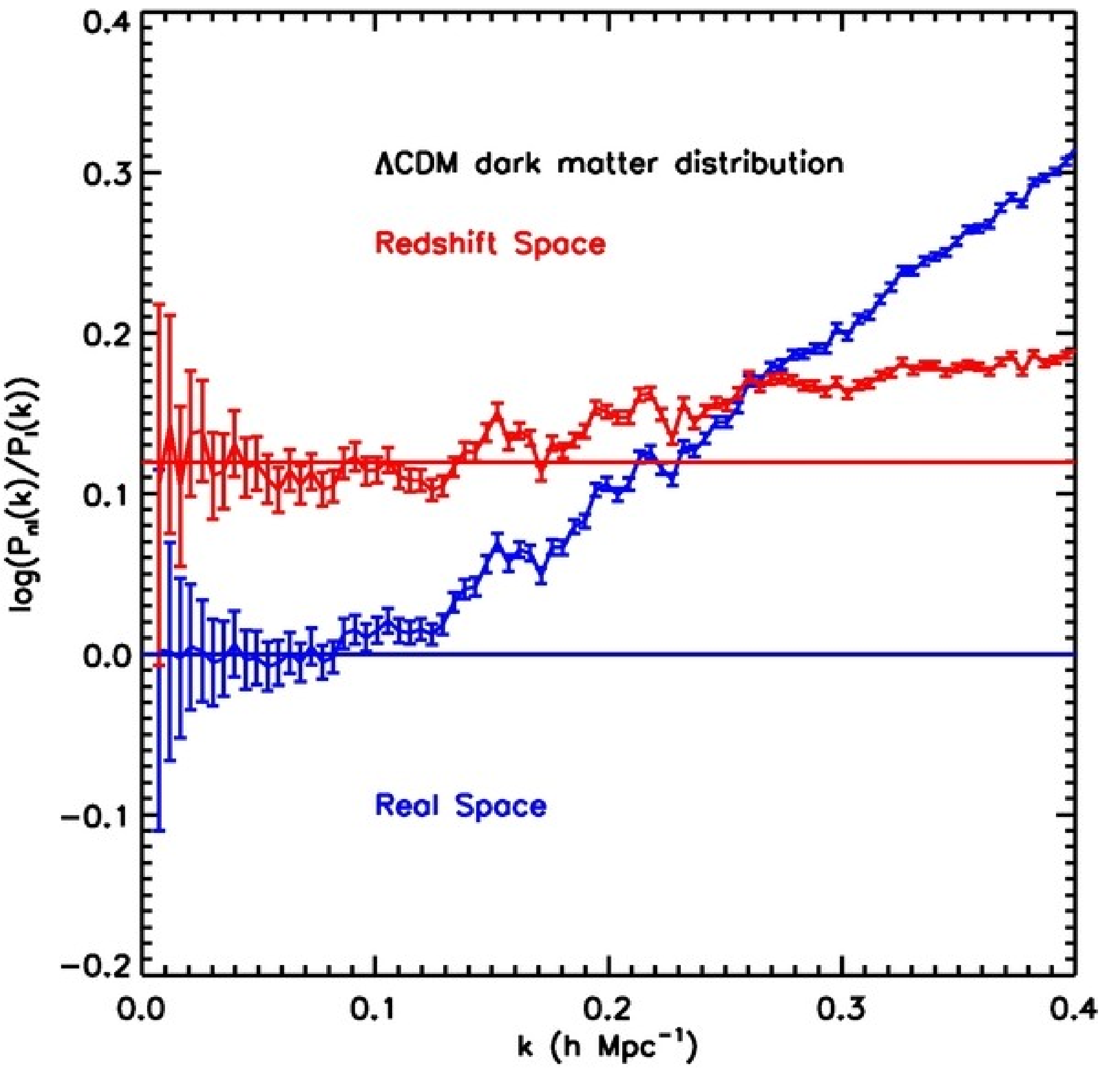


The unity represents the predictions of linear theory.

Modelling the density field of the Universe: Dark Matter

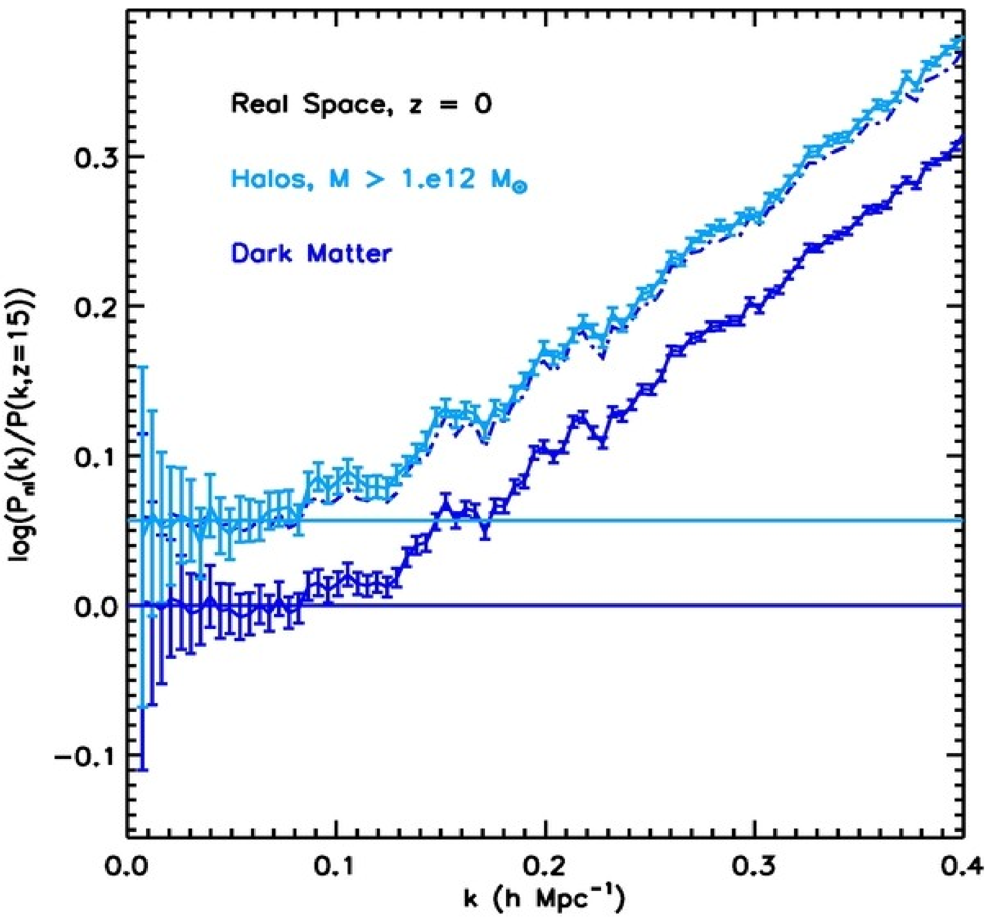


On large scales, the amplitude is increased due to the Kaiser effect.

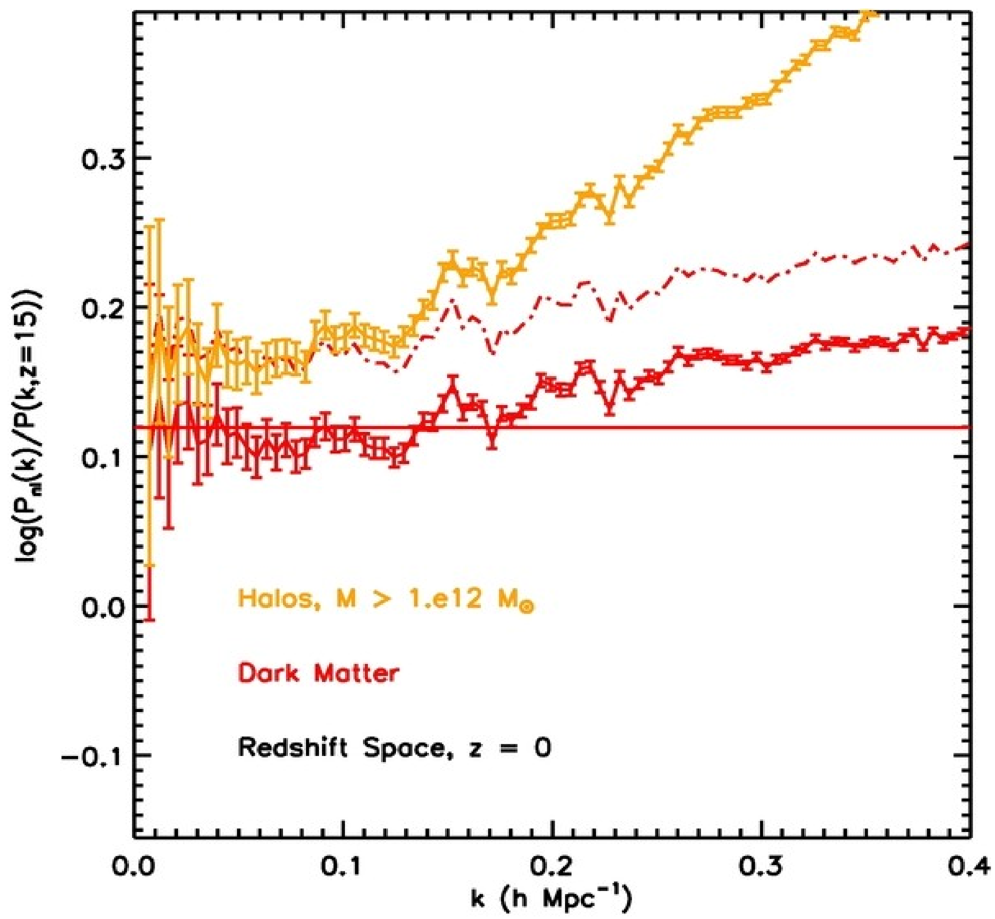
On small scales, the movements of DM within virialized structures damp the power spectrum.

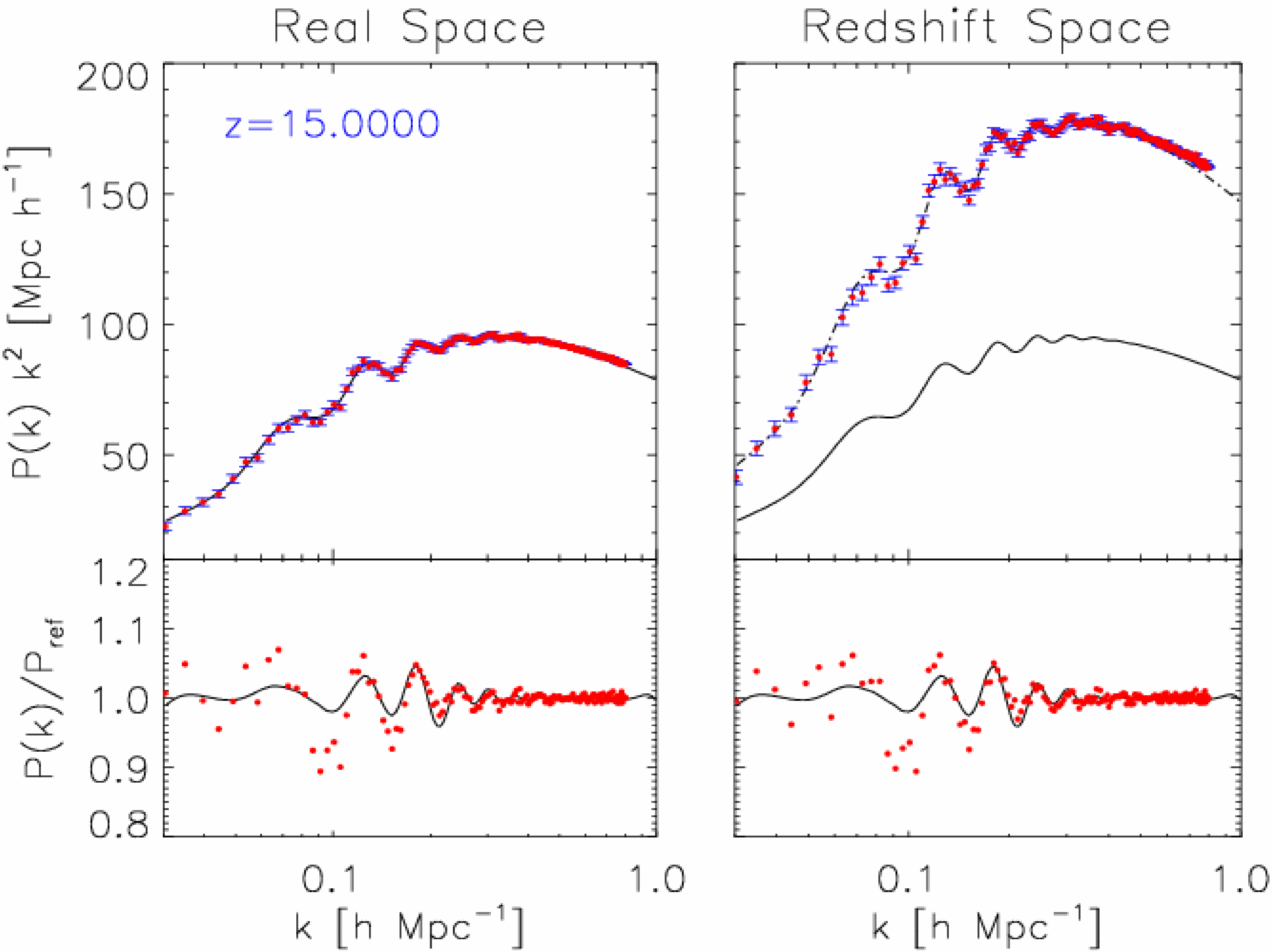
Modelling the density field of the Universe: Haloes

Real Space



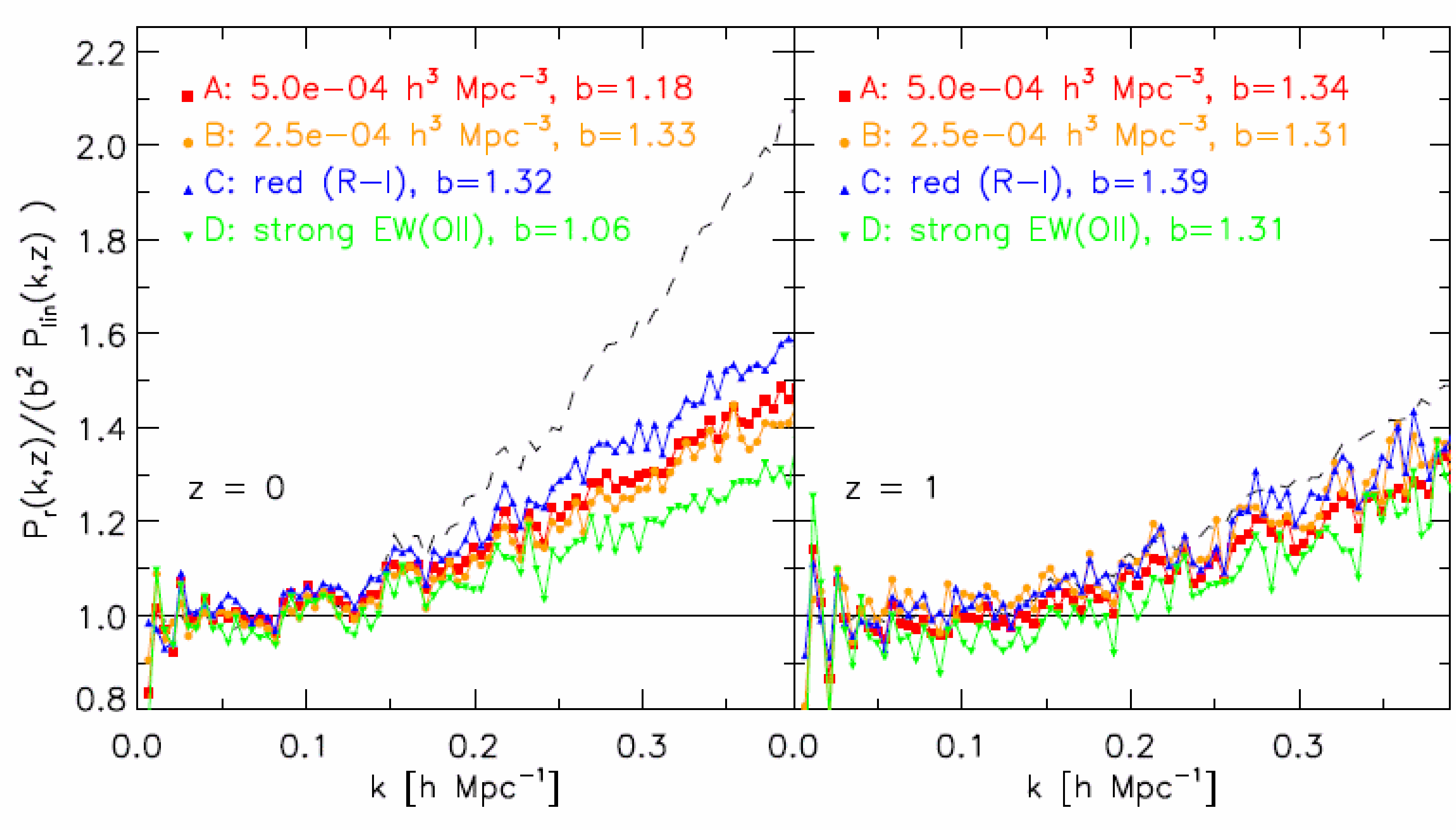
Redshift Space





Real Space
Redshift Space
z=15.0000
P(k) k^2 [Mpc h^-1]
P(k)/P_ref
k [h Mpc^-1]
k [h Mpc^-1]
200
150
100
50
1.2
1.1
1.0
0.9
0.8
0.1
1.0
0.1
1.0

Modelling the density field of the Universe: Galaxy bias



Modelling the density field of the Universe

Based on RPT (Crocce & Scoccimarro 07):

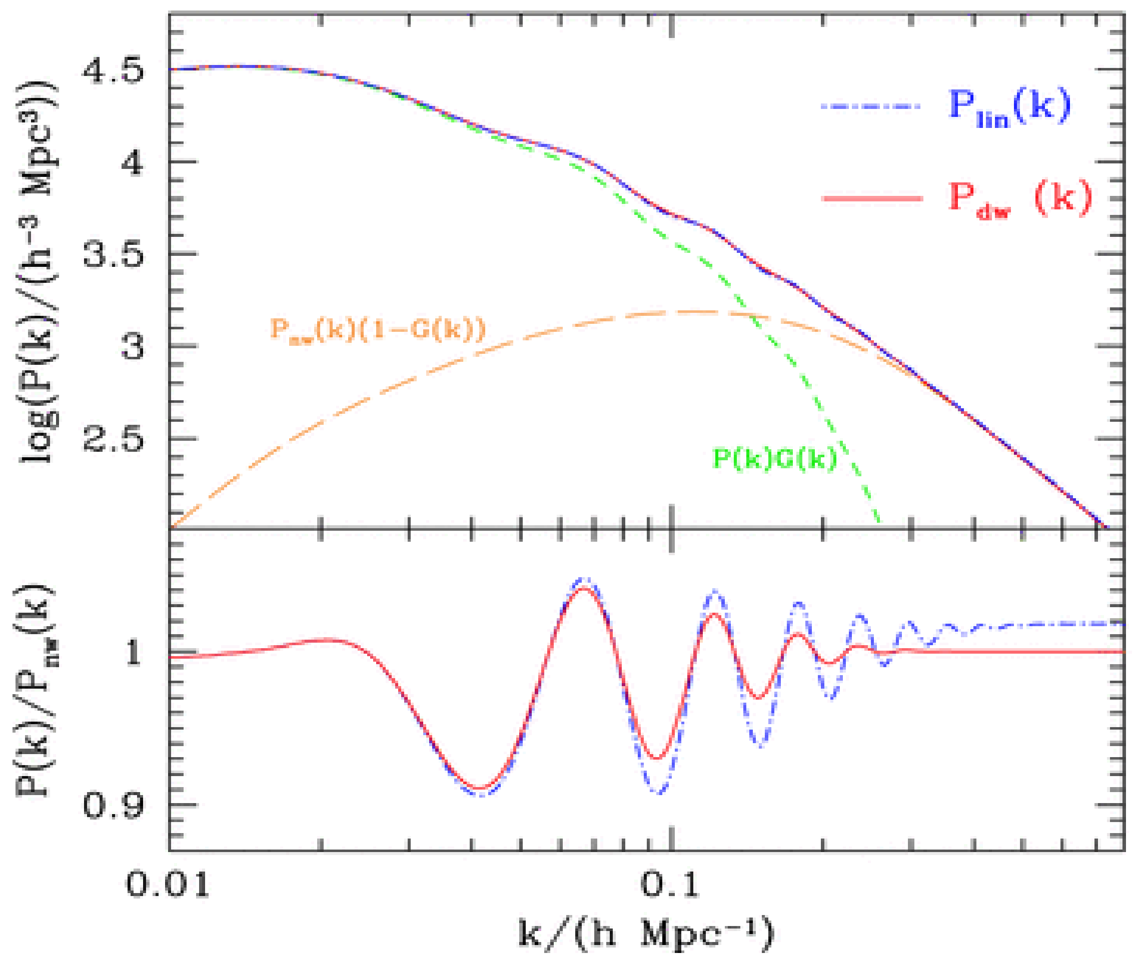
$P_{nl}(k) = P_{lt}(k)\, G(k) + P_{mc}(k)\, [1-G(k)]$,

$G(k) \sim \exp(-k^2/A)$.

These nonlinear effects cause:
I) degradation of the peak
ii) systematic error of ~0.5%

However, theoretical models can be built which show an impressive agreement with N-body simulations.

Are these models good enough for future surveys?



Modelling the density field of the Universe

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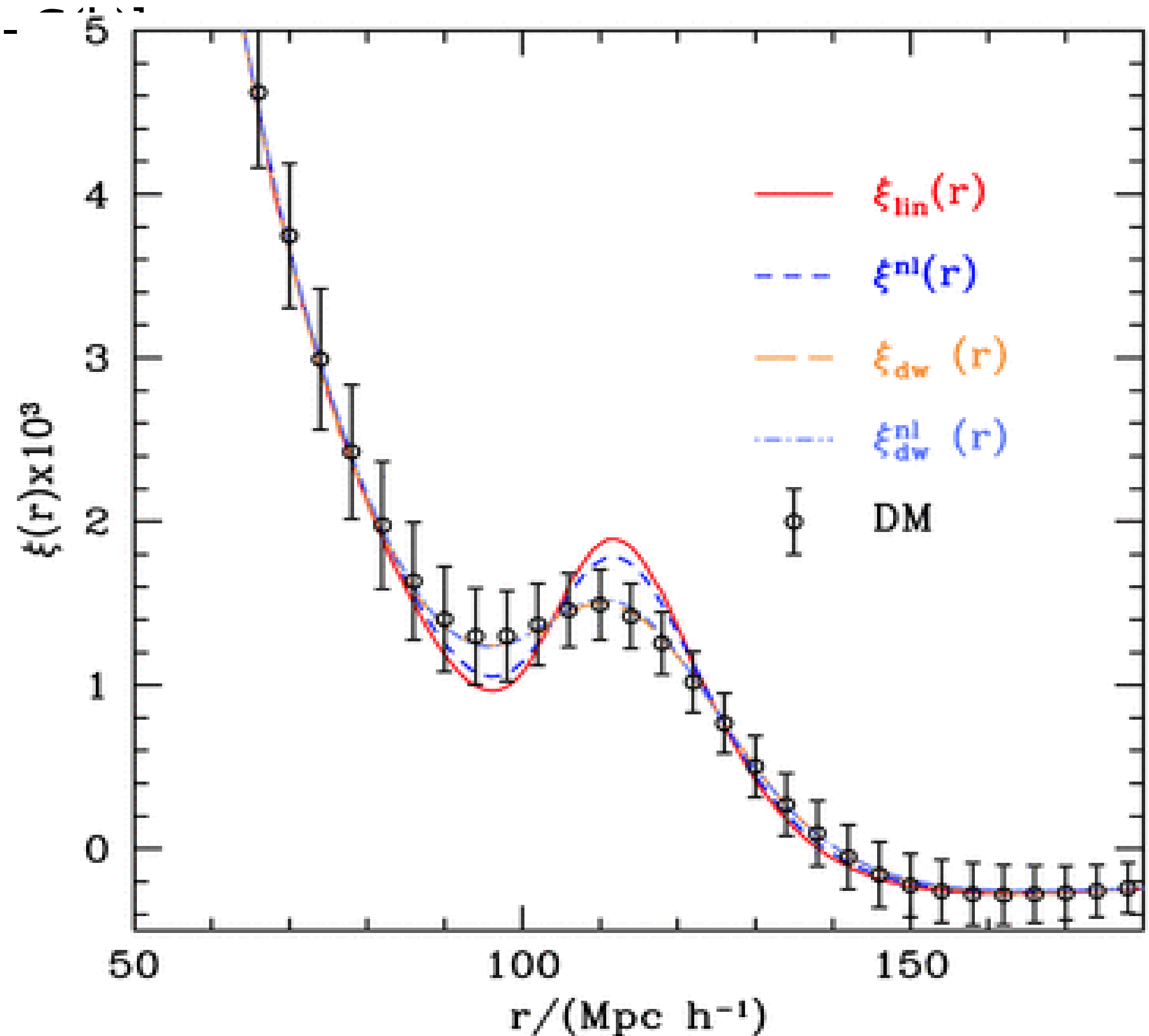
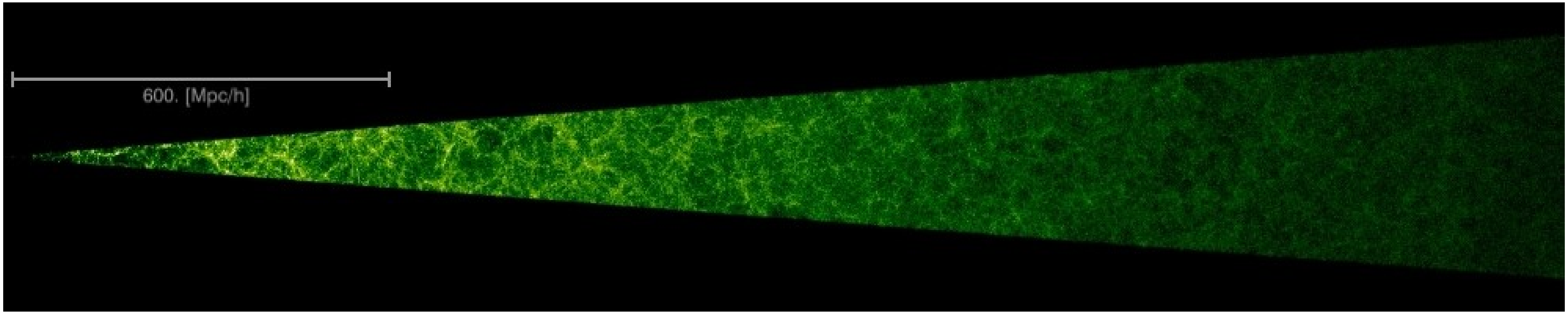
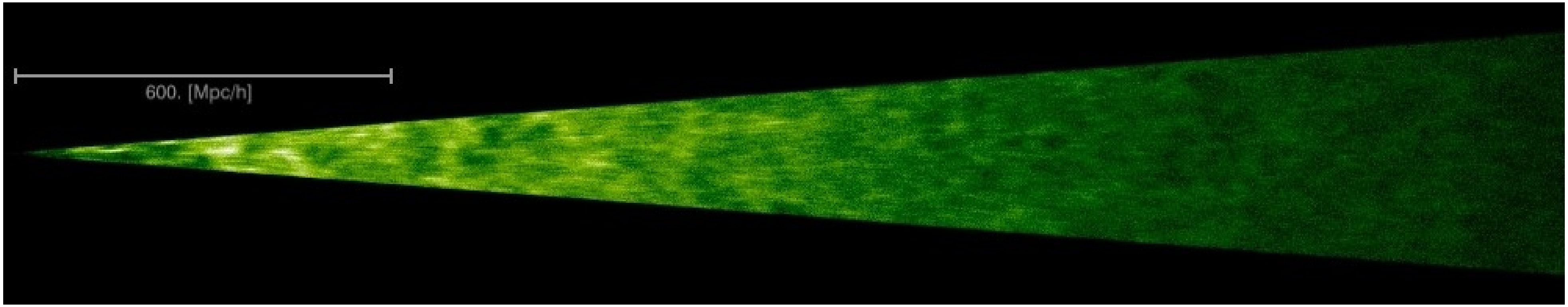


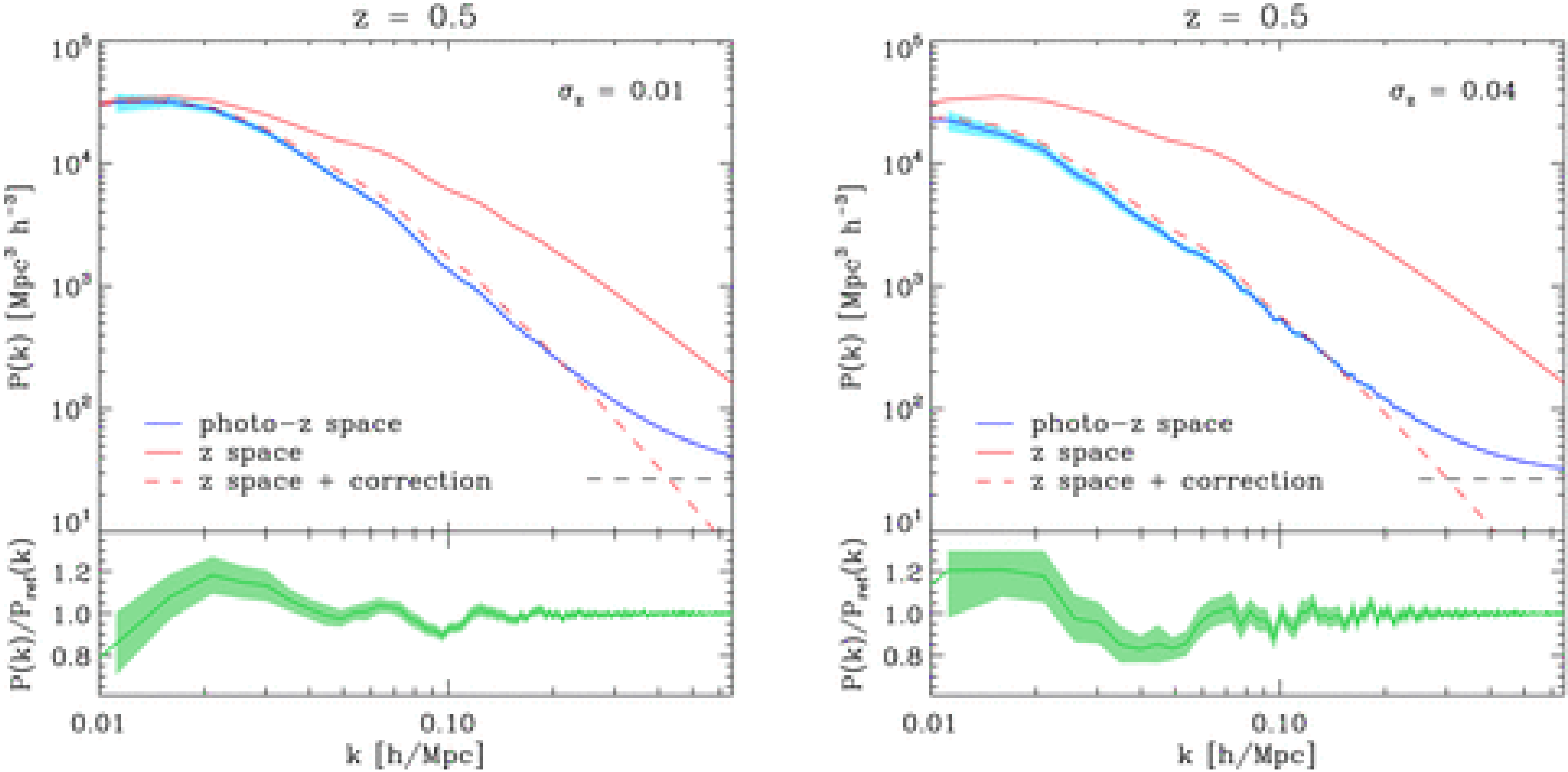
Modelling the density field of the Universe: Lightcone





Optimal extraction of the BAO signal

The effect of photo-z errors



Cai et al 09

Optimal extraction of the BAO signal

Optimal extraction of the BAO signal

- **Correlation function v/s power spectrum**
- **Can we use other characteristic scales?**
- **Reconstruction of the peak**
- 2d-clustering measurements
- Realistic covariance matrix
- Survey design

Optimal extraction of the BAO signal:

Correlation function v/s power spectrum:

The position of the peak is NOT enough!

In principle, they contain the same information and if one considers only the information in the BAO peak.

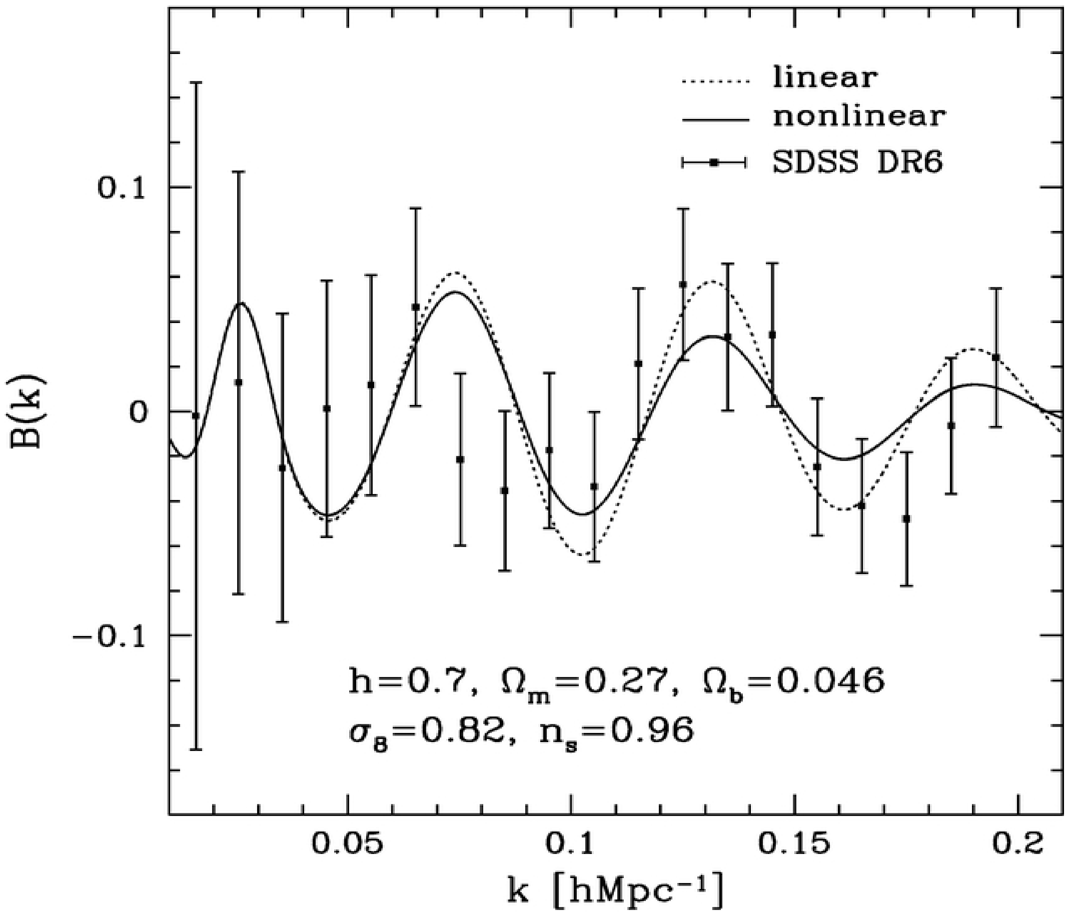
However, the scale dependent bias, nonlinear redshift space distortions are difficult to model in the power spectrum. Thus in practice, only modes with k<0.2 h/Mpc can be well modelled and used to place constraints.

Incorrect modelling could lead to biased estimates. For example the 2dF-SDSS tension (Cole & Sanchez 07).

Using the information on scales r = [50-100] can improve the constraints on w by 50% (Sanchez, Baugh & Angulo 08)

Optimal extraction of the BAO signal

Can we use other characteristic scales?



Nomura et al 09

Detection of a damping at a 3-sigma level.

In principle it is possible to extract cosmological information from G(z).

Dependence with bias? Degeneracy with other parameters?

Measuring the Turnover?

Optimal extraction of the BAO signal

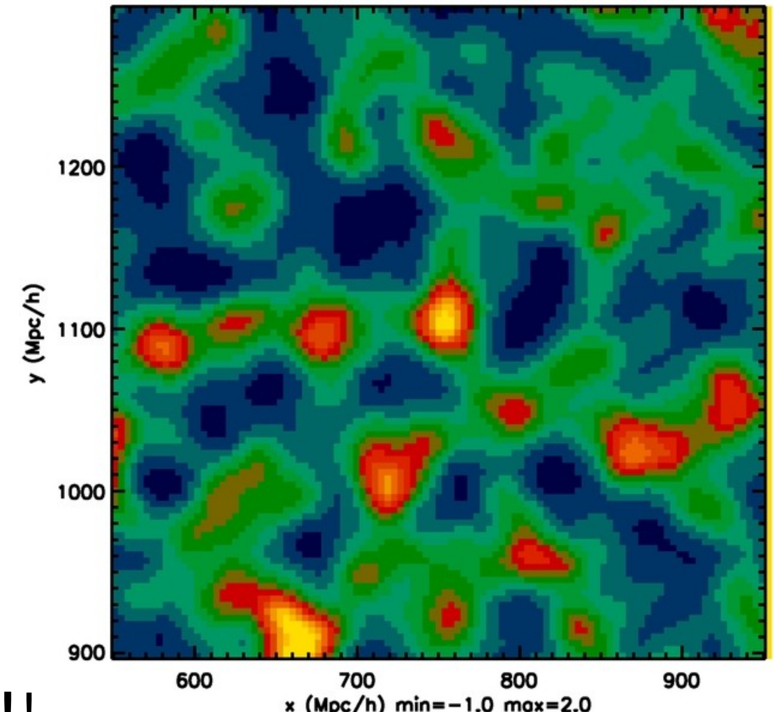
Reconstruction of the peak?

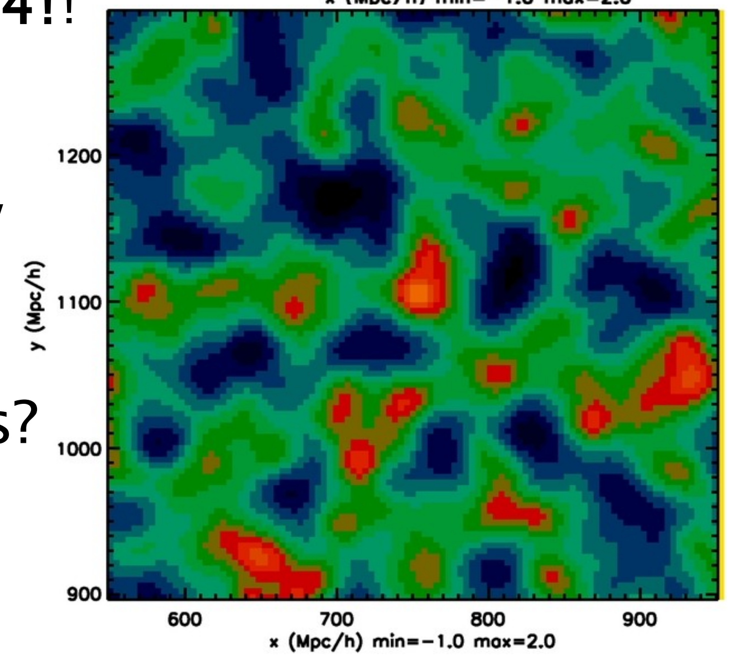
(Eisenstein 08, Padmanabhan 09, Yookyung 09)

Use a large-scale displacement field to move back galaxies, sharpening the peak.

It is claimed that this method could improve the accuracy by a factor of 2-4!!

1. Can be used with real data?
2. The impact of missing modes, window function, redshift space distortions, variation if the number density, etc?
3. Could they introduce systematic errors?
4. Need to assume a cosmology.





Observational effects

Is there an optimal survey design? e.g. WiggleZ

Errors in the photometric calibration, the integral constraint, etc. can cause systematic effetcs if are not taken into account.

1% error in (r-i) => 10% variations in the LRG number density (Eisenstein 2001)

Estimation of a realistic covariance matrix

Summary:

What we understand:

Nonlinearities

Redshift-space distortions (large-scales)

Dark Matter haloes

Correlation function v/s power spectrum

Summary

What we NOT fully understand:

The data

Galaxies (scale dependent bias and correlations)

Evolution along the line of sight

Other characteristic scales

3-pt statistics

Reconstruction of the peak

2d-clustering measurements

Realistic covariance matrix

Survey design

Photo-z errors

Conclusions

The BAO and the galaxy clustering are a very promising tool to explore the Universe. However, there is still a lot of work to do to make sure we really understand current and future measurements.

Example 1: The experimental rigour of Tycho Brahe allowed Kepler to find out that the orbits of the planets around the Sun are ellipses not circumferences.

Example 2: The detailed measurements of James Bradley led him to discover the Earth's nutation.

Personal view: We need to make efforts to model smaller scales.