What is the best way to measure baryonic acoustic oscillations?

(arXiv:0804.0233)

Ariel Sánchez

Max-Planck-Intitut für Extraterrestriche Physik

Carlton Baugh, Raul Angulo (ICC)

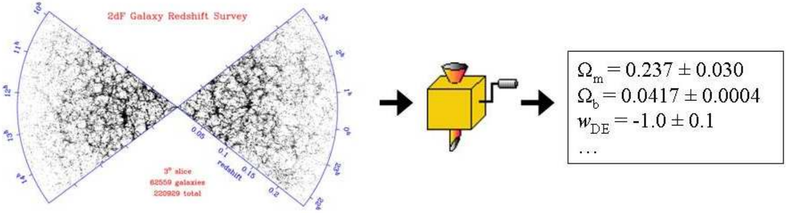
Contents

The nature of DE

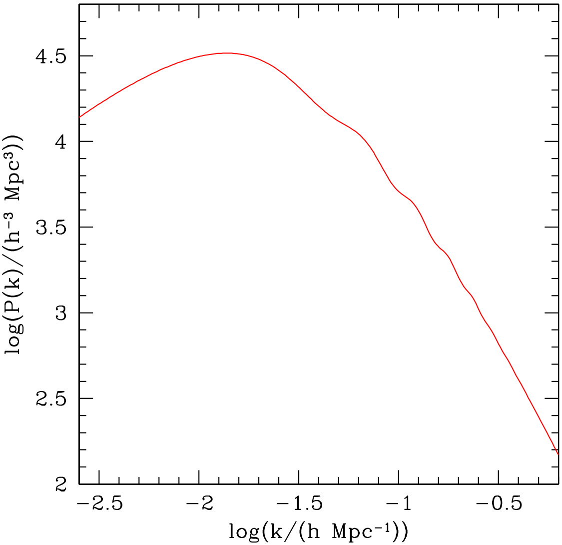
- What is the nature of Dark Energy?
- To distinguish between possible models: analyse

$$w_{\mathrm{DE}} = \rho_{\mathrm{DE}}/p_{\mathrm{DE}}$$

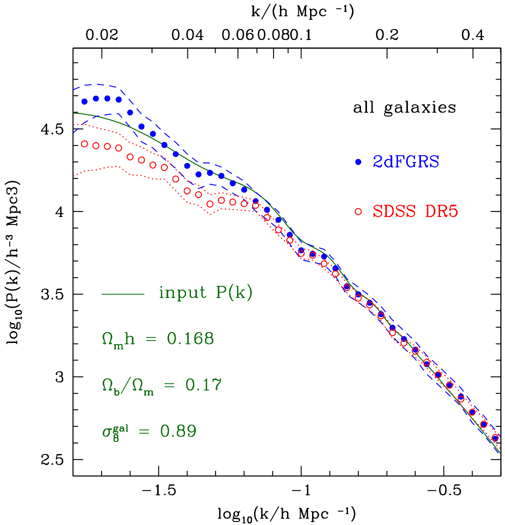
- Precision cosmology: need to control systematics in the analysis pipeline.



Baryonic acoustic oscillations

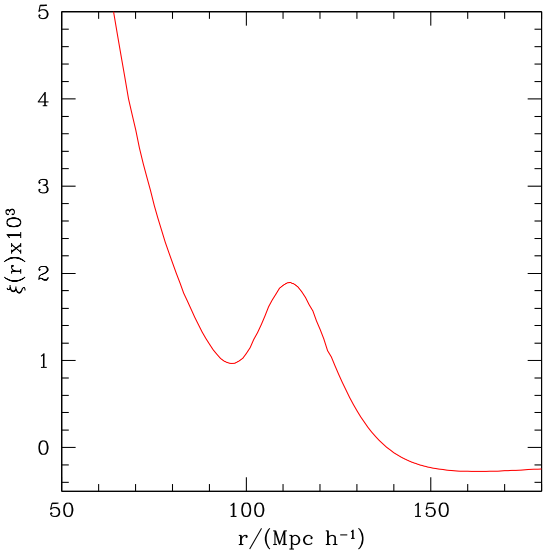


Baryonic acoustic oscillations



Sánchez and Cole (2008)

Baryonic acoustic oscillations



Baryonic acoustic oscillations

- Acoustic oscillations are related to the sound horizon at recombination s.
- Basic idea: use sound horizon scale imprinted in the clustering of galaxies as a standard ruler.
- This test is sensible to w_{DE} trough $D_{\mathrm{A}}(z)$ and $H(z)$.
- Key issue: how does the BAO signature evolves with time?

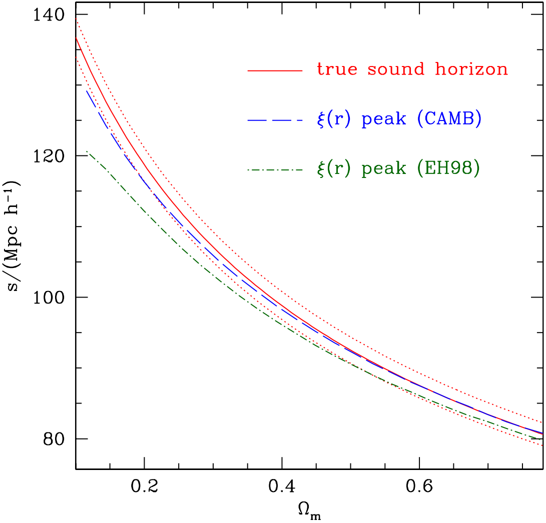
Baryonic acoustic oscillations

- According to linear theory the spatial patter does not change.
- Gravitational growth is a non-linear process, even at $r \sim 100\,\mathrm{Mpc}\,h^{-1}$.
- Percent level shifts can bias this test and affect its power to constraint w_{DE}.
- Numerical simulations show evidence of shifts (Smith et al. 2008, Crocce & Scoccimarro 2008).

Baryonic acoustic oscillations

- The peak shifts, but there is a bigger problem.
- The position of the peak in $\xi(r)$ does not correspond to the sound horizon.
- The BAO in $P(k)$ have neither a *fixed amplitude* nor a *fixed wavelength*.

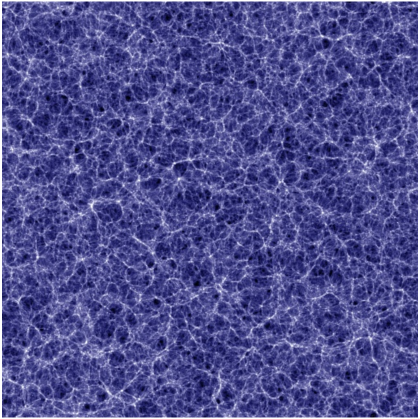
The peak in $\xi(r)$



The peak in $\xi(r)$

- Even according to linear theory this leads to biased constraints.
- We need to model the full shape of $\xi(r)$, including:
  - Non-linear evolution.
  - Redshift space distortions.
  - Scale dependent bias.

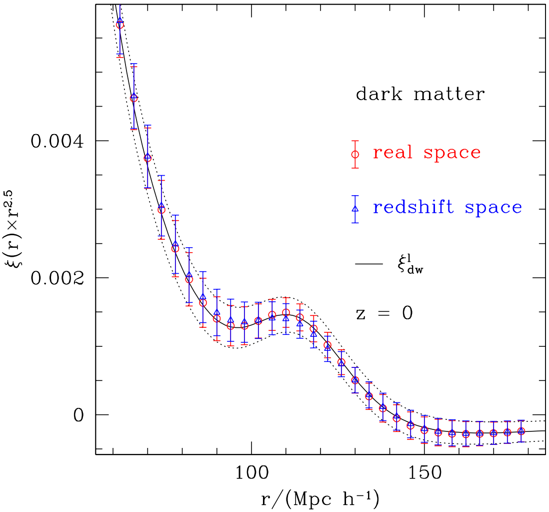
The L-BASICC II run



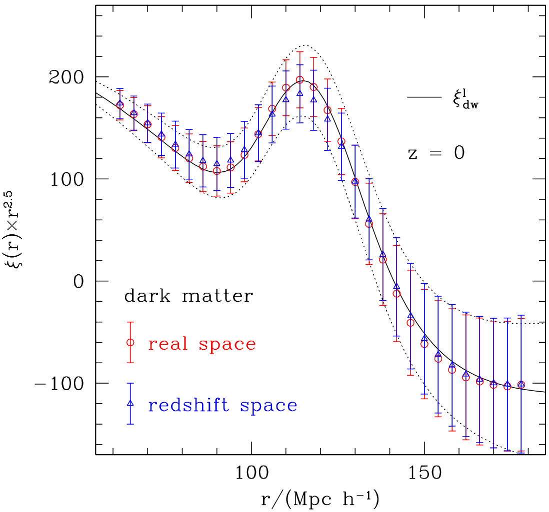
- 50 realizations
- $L_{Box} = 1340\,\mathrm{Mpc}\,h^{-1}$
- $N_p = 448^3$
- $m_p = 1.75 \times 10^{12}\,\mathrm{M}_\odot\,h^{-1}$
- Cosmological parameters from WMAP+2dF (Sánchez et al.2006)

$\Omega_m = 0.237,\ \sigma_8 = 0.77, n_s = 0.954$

The peak in $\xi(r)$



The peak in $\xi(r)$



The variance in $\xi(r)$

- The covariance matrix is given by

$$C_\xi(r,r') \equiv \left\langle (\xi(r)-\bar{\xi}(r))(\xi(r')-\bar{\xi}(r')) \right\rangle$$
$$= \int \frac{\mathrm{d}k\, k^2}{2\pi^2} j_0(kr) j_0(kr') \sigma_P^2(k)$$

  Where the variance in $P(k)$ is given by

$$\sigma_P(k) = \sqrt{\frac{2}{V}}\left(P(k) + \frac{1}{\bar{n}}\right)$$

- Direct application of this eq. overestimates the true covariance.

The variance in $\xi(r)$

- An estimate $\hat{\xi}_i$ corresponds to

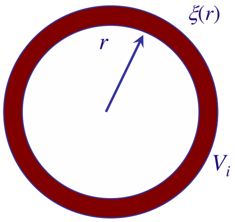
$$\hat{\xi}_i = \frac{1}{V_i}\int_{V_i} \xi(r)\,\mathrm{d}^3r,$$

- The covariance of this estimate is given by

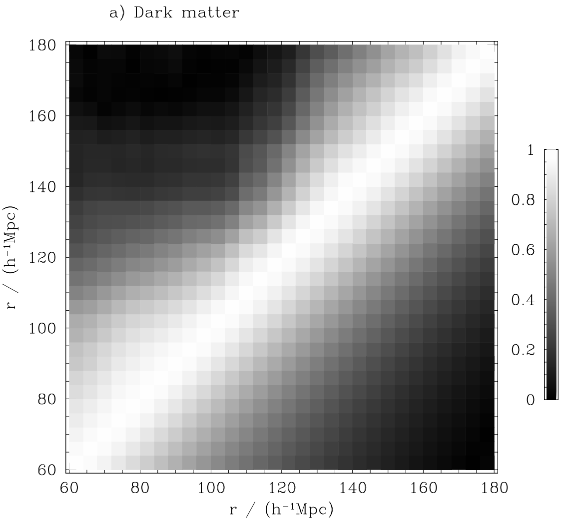
$$\begin{aligned} C_{\hat{\xi}}(i,j) &= \frac{1}{V_i\,V_j}\int \mathrm{d}^3r \int \mathrm{d}^3r' C_{\xi}(r,r') \\ &= \int \frac{\mathrm{d}k\,k^2}{2\pi^2}\bar{j}_0(k,i)\bar{j}_0(k,j)\sigma_P^2(k), \end{aligned}$$

where

$$\bar{j}_0(k,i) = \frac{1}{V_i}\int_{V_i} j_0(kr)\,\mathrm{d}^3r.$$

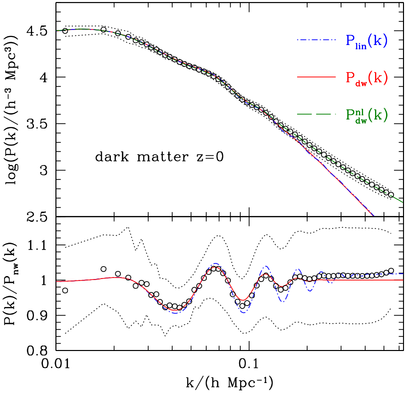


The full covariance matrix



Non-linear evolution

- NL evolution distorts the full shape of $P(k)$ (`halofit`).
- Erases the higher harmonic peaks (Crocce & Scoccimarro 2008).
- A model of the NL $P(k)$ must include both effects.
- What is the most important effect to model $\xi(r)$?.



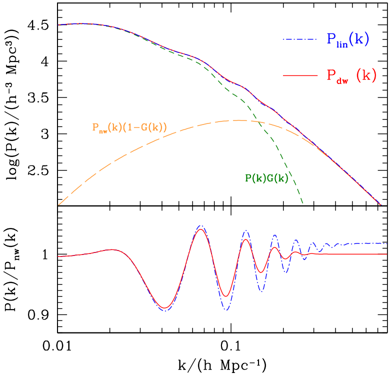
Non-linear evolution

- To model this compute a "dewiggled" power spectrum:

$$P_{\rm dw}(k) = P_{\rm l}(k)G(k) + P_{\rm nw}(k)(1 - G(k))$$

where

$$G(k) \equiv \exp\left[-(k/\sqrt{2}k_\star)^2\right]$$



Non-linear evolution

- This can be interpreted in terms of RPT (Crocce & Scoccimarro 2006).

$$P_{\rm nl}(k) = P_{\rm lin}(k)G(k) + P_{\rm mc}(k)$$

- The propagator behaves as a Gaussian *in the high-k limit*, with

$$k_\star = \left[\frac{1}{3\pi^2}\int {\rm d}k P_{\rm lin}(k)\right]^{-1/2}$$

- The term $P_{\rm mc}$ *does* show acoustic oscillations.

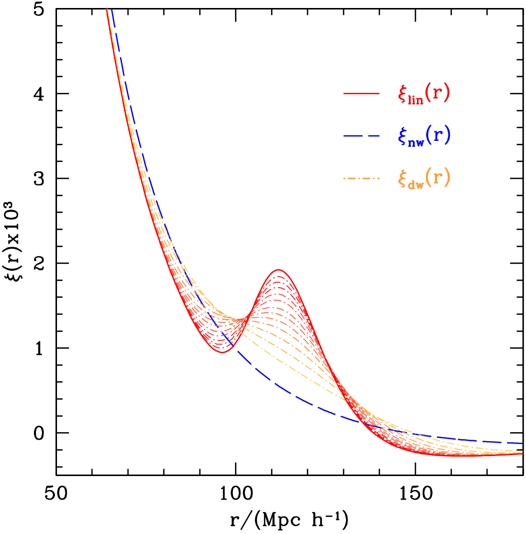
Non-linear evolution

- The correlation function will be given by

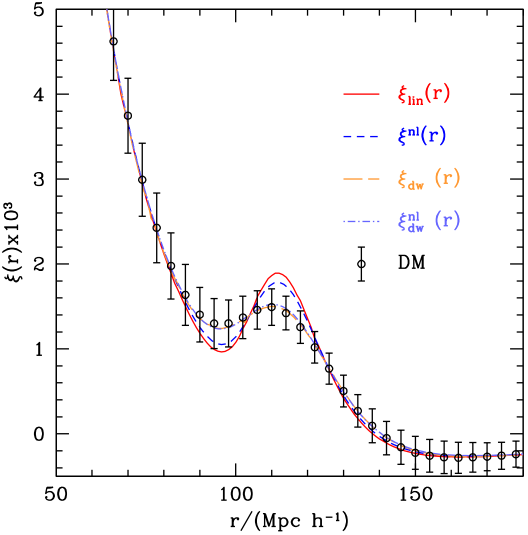
$$\xi_{\rm dw}(r) = \xi_{\rm lin}(r) \otimes \tilde{G}(r) + \xi_{\rm nw}(r) \otimes (1 - \tilde{G}(r))$$

- The BAO signal is contained in the first term.
- The convolution broadens and shifts the peak towards smaller scales.

Non-linear evolution



Non-linear evolution



Constraining w_{DE}

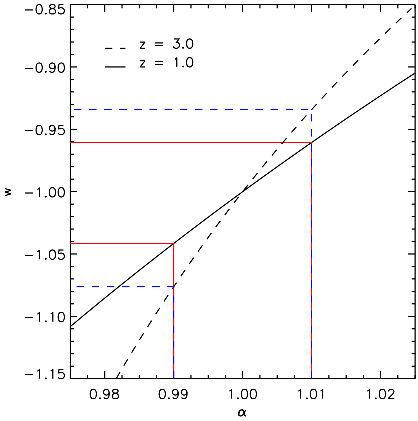
- We tested the efficiency of this model to constrain w_{DE}.
- A very simple case: we know everything except w_{DE}.
- A change in w_{DE} produces a rescaling of the wavenumber from k_{true} to k_{app}.

$$\alpha = \frac{k_{\mathrm{app}}}{k_{\mathrm{true}}}$$

- for the correlation function

$$r_{\mathrm{app}} = r_{\mathrm{true}}/\alpha$$

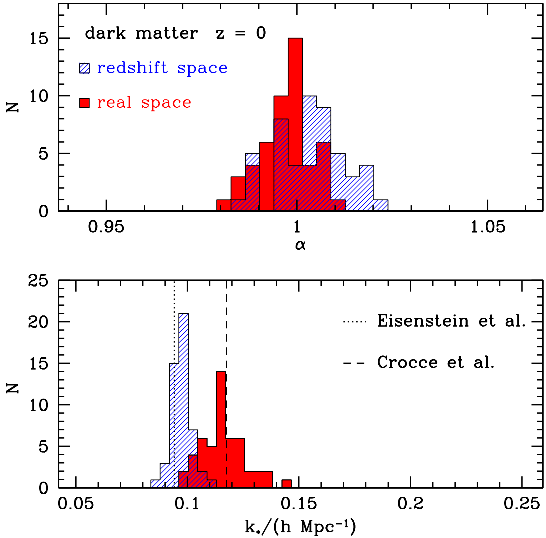
Constraining w_{DE}



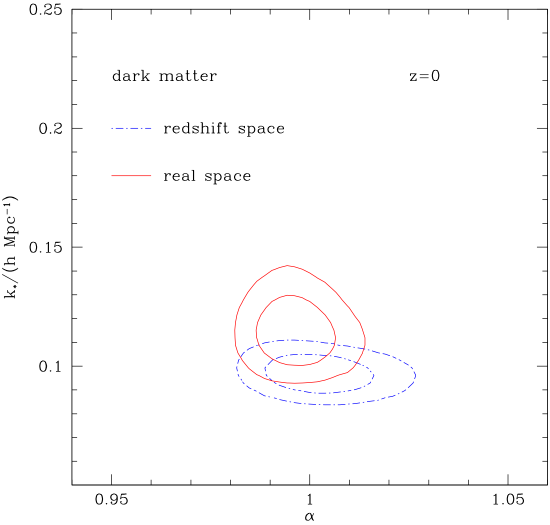
Angulo et al.(2008)

- Error in BAO scale translates to bigger error in w_{DE}.
- For fixed Ω_m require distance scale to 0.2% to get 1% in w_{DE}.
- Demands accurate knowledge of systematics

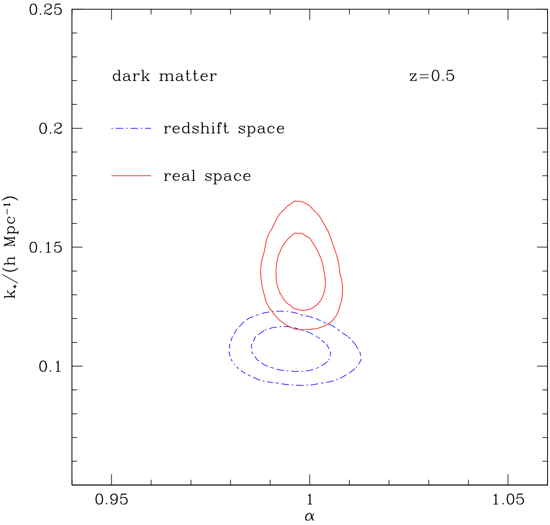
Constraining w_{DE}



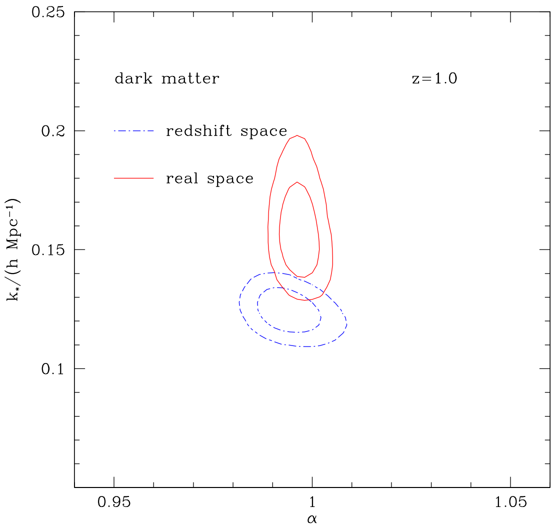
Constraining w_{DE}



Constraining w_{DE}



Constraining w_{DE}



Halo bias

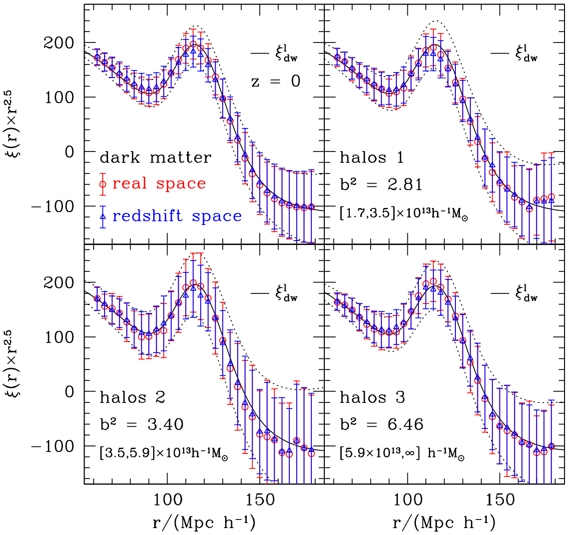
- Galaxies are hosted within dark matter haloes.
- Understanding halo bias is a first step towards galaxy bias.
- Clusters are good alternatives to galaxies in BAO analysis.
- We measured $\xi_{hh}(r)$ for three halo samples.

  - Sample 1: $1.7 \times 10^{13}\ \mathrm{M}_\odot\, h^{-1} < m < 3.5 \times 10^{13}\ \mathrm{M}_\odot\, h^{-1}$

  - Sample 2: $3.5 \times 10^{13}\ \mathrm{M}_\odot\, h^{-1} < m < 5.9 \times 10^{13}\ \mathrm{M}_\odot\, h^{-1}$

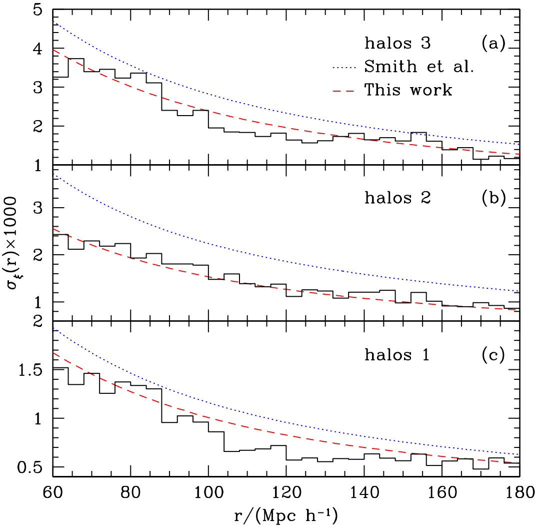
  - Sample 3: $5.9 \times 10^{13}\ \mathrm{M}_\odot\, h^{-1} < m$

Halo bias

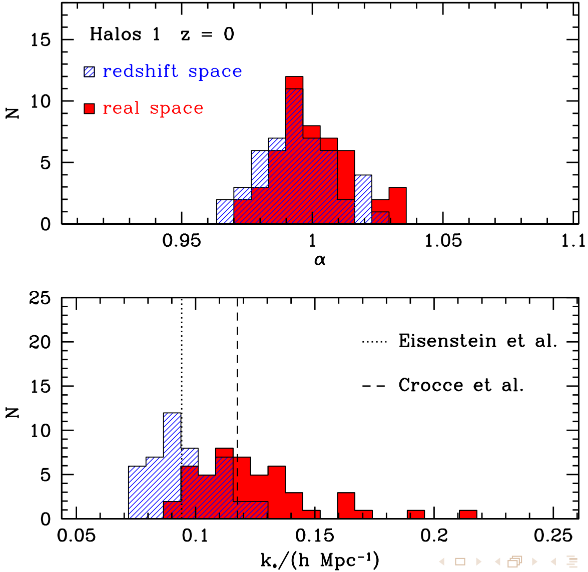


200
100
0
−100
ξ(r)×r^2.5
dark matter
real space
redshift space
z = 0
halos 1
b² = 2.81
[1.7,3.5]×10¹³h⁻¹M⊙
halos 2
b² = 3.40
[3.5,5.9]×10¹³h⁻¹M⊙
halos 3
b² = 6.46
[5.9×10¹³,∞] h⁻¹M⊙
100
150
r/(Mpc h⁻¹)

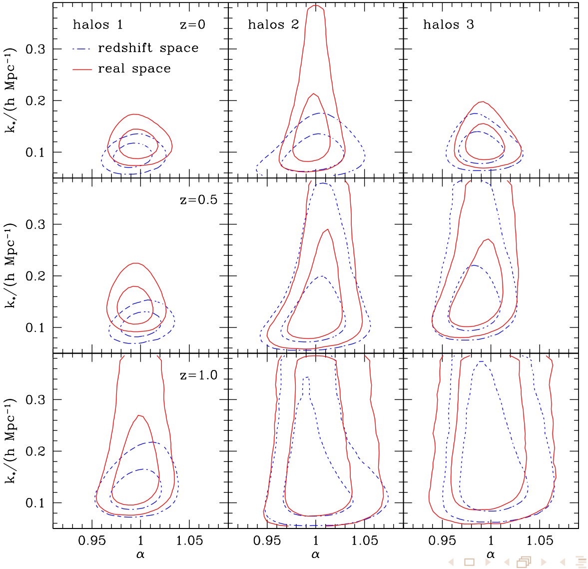
The variance in $\xi(r)$



Halo bias


Halos 1 z = 0
redshift space
real space
N
α
0.95
1
1.05
1.1
0
5
10
15
Eisenstein et al.
Crocce et al.
N
k*/(h Mpc⁻¹)
0.05
0.1
0.15
0.2
0.25
0
5
10
15
20
25

Halo bias

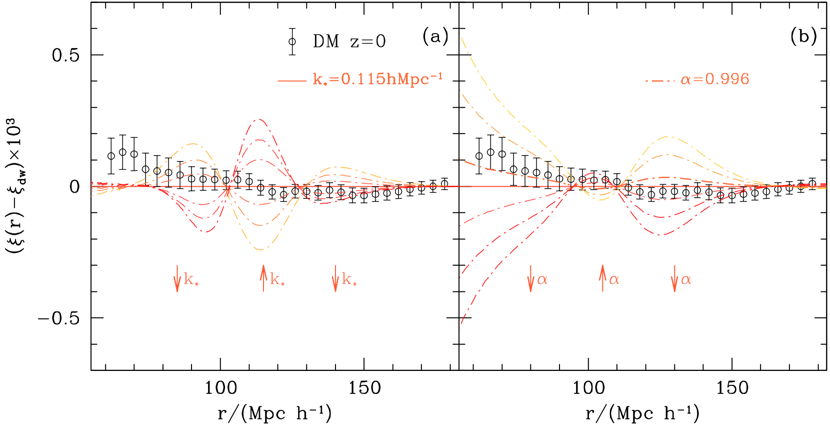


halos 1
z=0
redshift space
real space
halos 2
halos 3
z=0.5
z=1.0
$k_*/(h\ Mpc^{-1})$
0.1
0.2
0.3
0.95
1
1.05
α

Improving the model

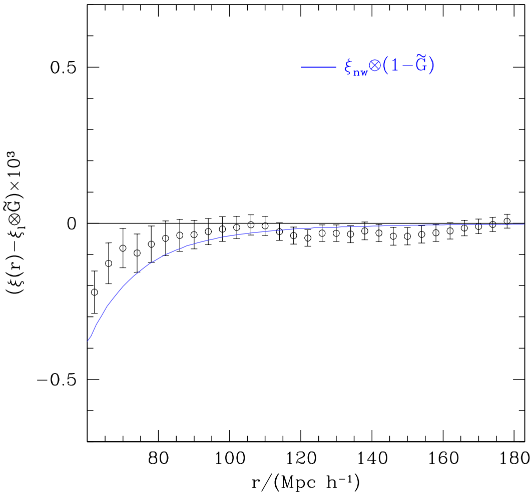
- The model is slightly biased towards $\alpha < 1$.
- Future surveys will have much smaller sample variances (e.g Euclid or ADEPT)
- This may lead to systematic errors in w_{DE}.
- How can we correct for this small bias?

Improving the model



Improving the model

$$\xi_{\rm dw}(r) = \xi_{\rm lin}(r) \otimes \tilde{G}(r) + \xi_{\rm nw}(r) \otimes (1 - \tilde{G}(r))$$



Improving the model

- In the scales of the accoustic peak (Crocce & Scoccimarro 2008)

$$\xi_{\rm mc}(r) \propto \xi'_{\rm lin}\, \xi^{(1)}_{\rm lin}(r)$$

where

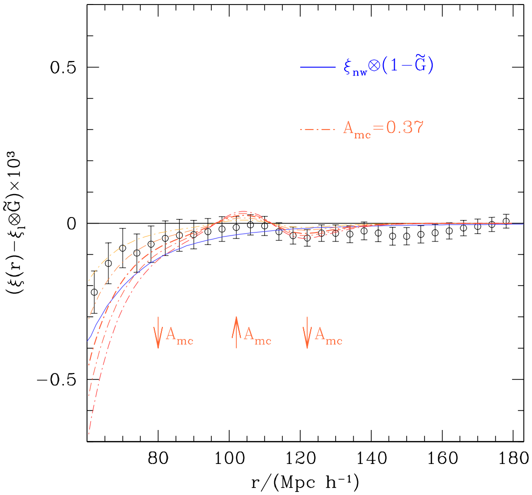
$$\xi^{(1)}_{\rm lin}(r) \equiv \hat{r} \cdot \nabla^{-1} \xi_{\rm lin}(r) = 4\pi \int P_{\rm lin}(k)\, j_1(kr) k\, {\rm d}k$$

- Based on this result they proposed an approximate model where

$$\xi_{\rm nl}(r) = \xi_{\rm lin}(r) \otimes \tilde{G}(r) + A_{\rm mc}\, \xi'_{\rm lin} \xi^{(1)}_{\rm lin}(r)$$

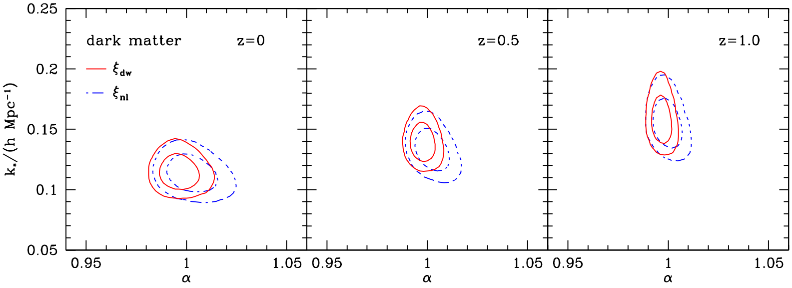
Improving the model

$$\xi_{\rm dw}(r) = \xi_{\rm lin}(r) \otimes \tilde{G}(r) + \xi_{\rm nw}(r) \otimes (1 - \tilde{G}(r))$$



Improving the model

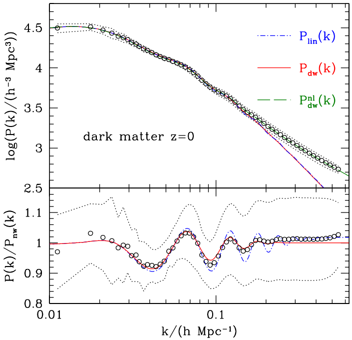
- The new model helps to alleviate the small bias towards $\alpha < 1$.
- RPT could help to improve the constraints even further.

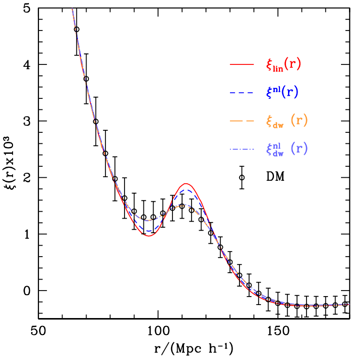


$P(k)$ vs $\xi(r)$

- $P(k)$ and $\xi(r)$ are affected in different ways by NL evolution, redshift space distortions and bias.

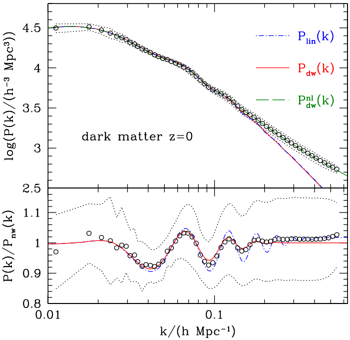
- Which one offers more advantages?

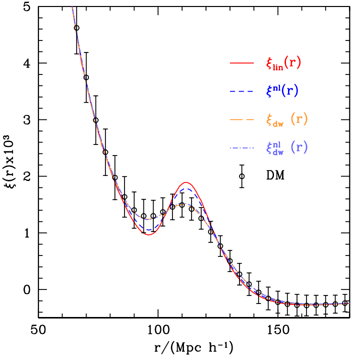




NL evolution

- The shape of $P(k)$ is strongly affected by NL evolution.
- $\xi(r)$: $k_\star$ accurately describes the damping of the oscillations.





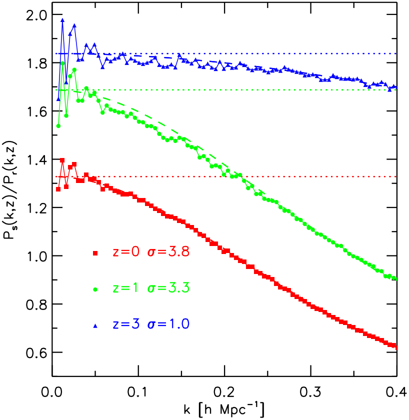
Redshift space distortions

- $P(k)$: Kaiser factor only applicable on large scales

$$S \equiv \left(1 + \frac{1}{5}\beta + \frac{2}{5}\beta^2\right)$$

- Distortions require extra parameter

$$\frac{P_s(k)}{P(k)} = S\left(1 + \sigma^2 k^2\right)$$



Angulo et al.(2008)

Redshift space distortions

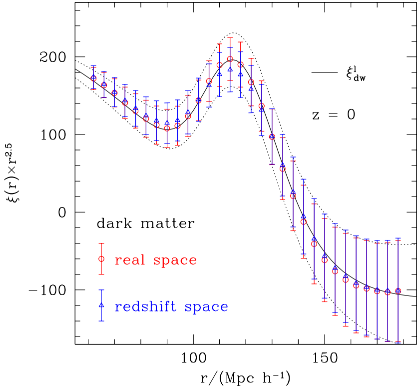
- $\xi(r)$: well described by Kaiser factor

$$S = \frac{\xi_s(r)}{\xi(r)} \equiv \left(1 + \frac{1}{5}\beta + \frac{2}{5}\beta^2\right)$$

- The effect of σ is masked in the value of $k_\star$

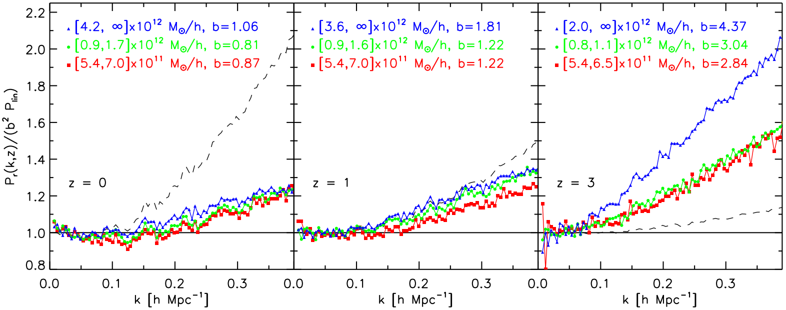
$$k_\star = 0.115 \pm 0.009$$

$$k_\star = 0.097 \pm 0.004$$



Halo bias

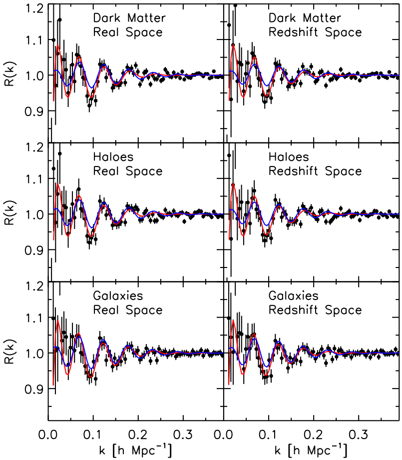
- $P(k)$: halo bias is scale dependent.
- $\xi(r)$: halo bias can be treated as constant.



Angulo et al.(2008)

Which one is better?

- $\xi(r)$ is less sensitive to these problems.
- Other methods propose to divide $P(k)$ by a smooth function.
- These approaches can not be easily generalized to $\xi(r)$.
- How do these approaches perform in our case?.



Angulo et al.(2008)

Which one is better?

- The shape of $\xi(r)$ provides extra information.
- This gives better constraint on the distance scale (and hence on w_{DE}).
- Large-scale shape of $\xi(r)$ useful to constraint other parameters.

- $z = 0$

$$p(k): \ \alpha = 1.006 \pm 0.008$$
$$\xi(r): \ \alpha = 1.003 \pm 0.008$$

- $z = 0.5$

$$p(k): \ \alpha = 1.003 \pm 0.007$$
$$\xi(r): \ \alpha = 1.002 \pm 0.005$$

- $z = 1.0$

$$p(k): \ \alpha = 1.000 \pm 0.006$$
$$\xi(r): \ \alpha = 1.000 \pm 0.003$$

Which one is better?

- The results from $P(k)$ show a bias towards $\alpha > 1$.
- Future surveys will cover much larger volumes.
- The results obtained from $\xi(r)$ are more consistent with $\alpha = 1$.

- $z = 0$

$$p(k): \quad \alpha = 1.006 \pm 0.008$$
$$\xi(r): \quad \alpha = 1.003 \pm 0.008$$

- $z = 0.5$

$$p(k): \quad \alpha = 1.003 \pm 0.007$$
$$\xi(r): \quad \alpha = 1.002 \pm 0.005$$

- $z = 1.0$

$$p(k): \quad \alpha = 1.000 \pm 0.006$$
$$\xi(r): \quad \alpha = 1.000 \pm 0.003$$

Conclusions

- Peak position is *not* equivalent to s, even in linear theory.
- It is necessary to model the full shape of $\xi(r)$.
- A simple model for $\xi(r)$: NL evolution, redshift-space distortions and halo bias.
- Systematics are simpler to deal with in $\xi(r)$ than in $P(k)$.
- Full shape of $\xi(r)$ provides tighter constraints on w_{DE} than $P(k)$.
- Both statistics will allow to reach the full potential of BAO as DE probes.

Pan-STARRS

"Data! Data! Data!, he cried impatiently. I can't make bricks without clay".

Sherlock Holmes,
The Adventure of the Copper Beeches (1892)

Thank you!

Pan-STARRS

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