Looking for Baryon Acoustic Oscillations of Galaxy Clusters

LAURO MOSCARDINI
DIP. FISICA E ASTRONOMIA, UNIBO
LAURO.MOSCARDINI@UNIBO.IT

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

In collaboration with
A. Veropalumbo, F. Marulli, M. Moresco & A. Cimatti

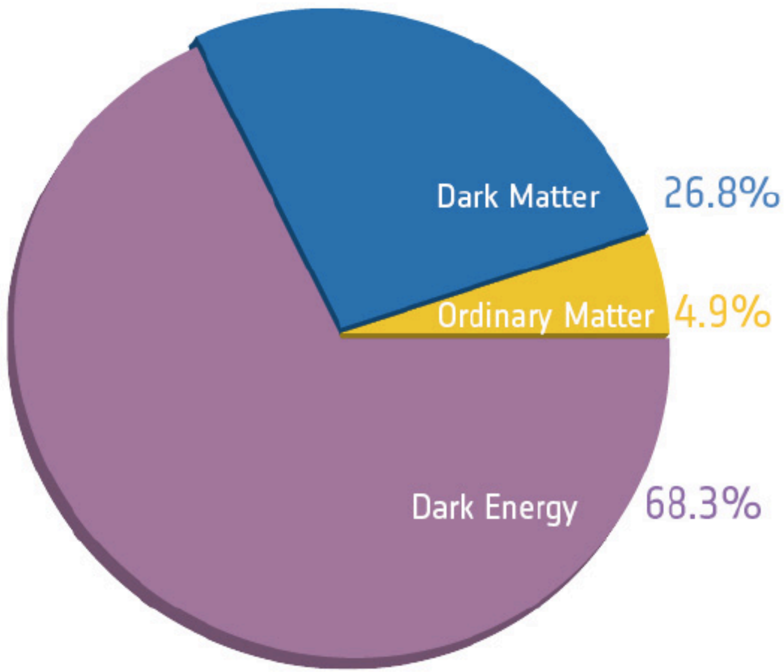
see Veropalumbo et al. 2014, MNRAS, 442, 3275 and
Veropalumbo et al., 2016, MNRAS, 458, 1909

Hot spots in the XMM sky, Mykonos, 15th-18th June 2016

The era of high-precision Cosmology

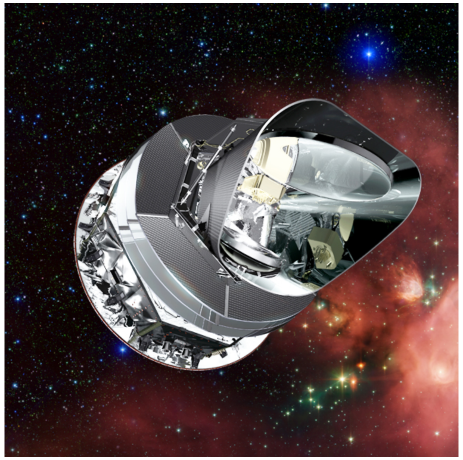
Different cosmological probes are converging towards the so-call concordance model: **the flat ΛCDM model**

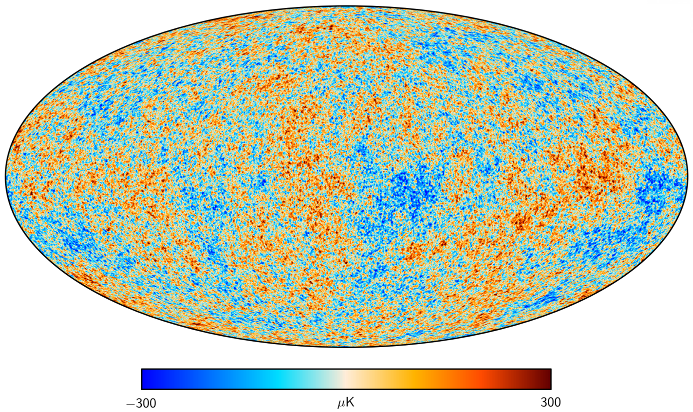
- a **flat** Universe: $\Omega_k=1-\Omega_M-\Omega_\Lambda=0$
- a **small baryonic** component: $\Omega_b \approx 5\%$
- a **dominant dark energy** component in the form of a **cosmological constant Λ**

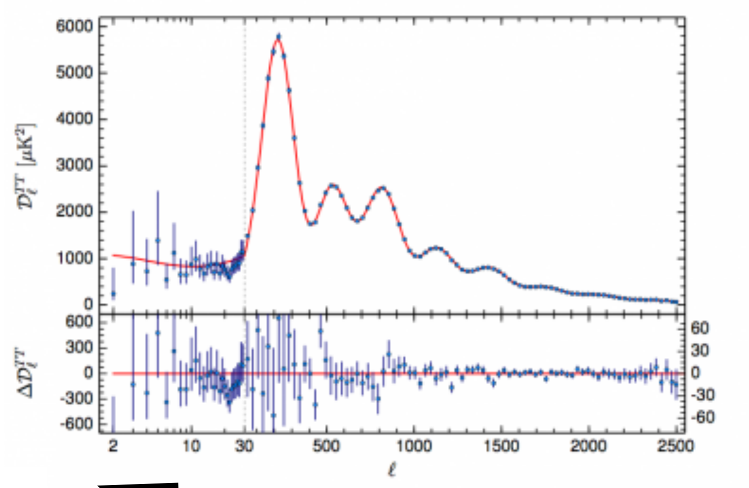


Planck Collaboration

The era of high-precision Cosmology







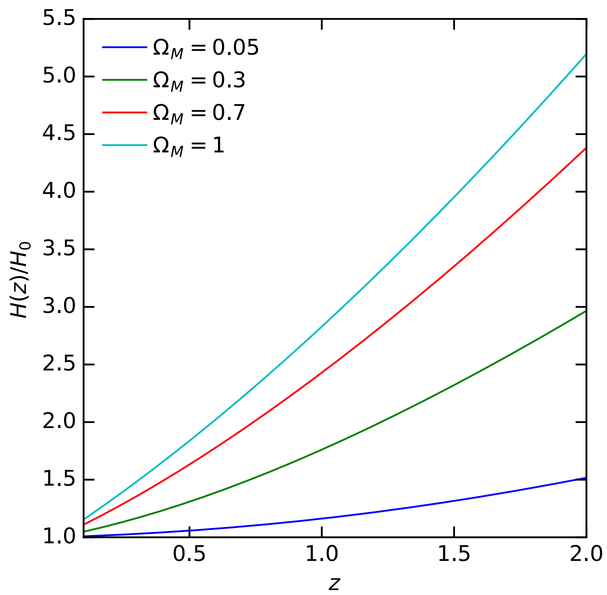
The **concordance cosmological model** received a strong support from the recent analysis of Cosmic Microwave Background data by Planck.

Constraining the cosmological parameters

We measure the main cosmological parameters through their effects on the **expansion of the Universe:** from the Friedmann equations we can derive how the **Hubble parameter H(z)** varies with redshift:

$$H(z) = H_0\left[\Omega_M(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)} + \Omega_k(1+z)^2\right]^{1/2} \equiv H_0 E(z)$$

An example for flat cosmologies



Constraining the cosmological parameters

Different approaches are now available:

- **standard candles**
  - measurements of **d_L** (an integral of $H(z)^{-1}$): SNIa, GRB, …
- **standard rulers**
  - measurements of **d_A** (an integral of $H(z)^{-1}$): BAOs
- **standard shapes**
  - deformations from perfect circles: Alcock-Paczynski test
- **standard clocks**
  - measurement of the age of the Universe **$t(z)$** (integral of $H(z)^{-1}$): cosmic chronometers, like massive and passive galaxies
- **growth of fluctuations**
  - in GR it depends on an integral of a (different) function of $H(z)$. Crucial for testing **modified gravity**: CMB, clustering of cosmic structures, weak lensing, **cluster counts and clustering,** redshift-space distortions, etc.

Standard cosmic rulers

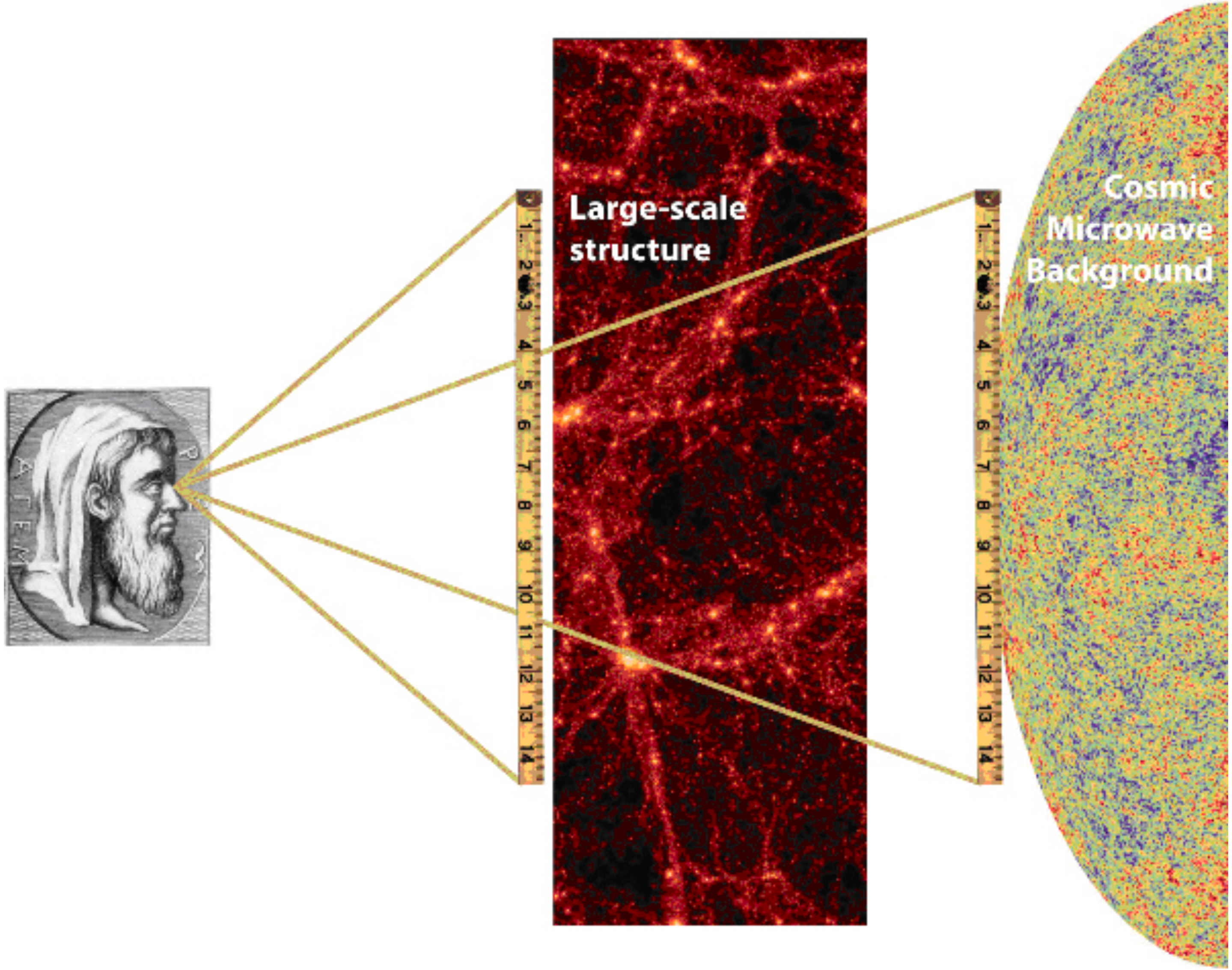
The idea is based on the assumption that there is an object whose **physical length** is known as a function of redshift.
By measuring the **angle** (Δθ) subtended by this ruler (Δχ) as a function of redshift we map out the **angular diameter distance d_A:**

$$\Delta\theta = \frac{\Delta\chi}{d_A(z)} \qquad\qquad d_A(z) = \frac{d_L(z)}{(1+z)^2} \propto \int_0^z \frac{dz'}{H(z')}$$

By measuring the redshift interval (Δz) associated with this distance we can derive the **Hubble parameter H(z):**

$$c\Delta z = H(z)\Delta\chi$$

Standard cosmic rulers



What are the properties of an ideal standard cosmic ruler?

We must be able

- **to calibrate it** accurately over most of the age of the universe
- **to measure it** over much of the volume of the universe
- **to measure it** in a very precise way

➔ there are not cosmic objects having these properties, because of their non-linear (complex) evolution

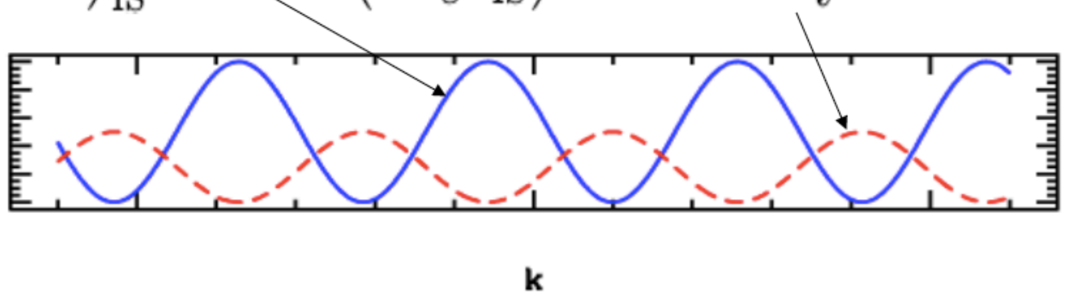
➔ look for something coming from **well-known physical processes** happened in the **early universe** and observable in the distribution of cosmic objects on very large scale (because easier to be modeled)

➔ the baryon acoustic oscillations of the Cosmic Microwave Background

Sound waves in the early Universe

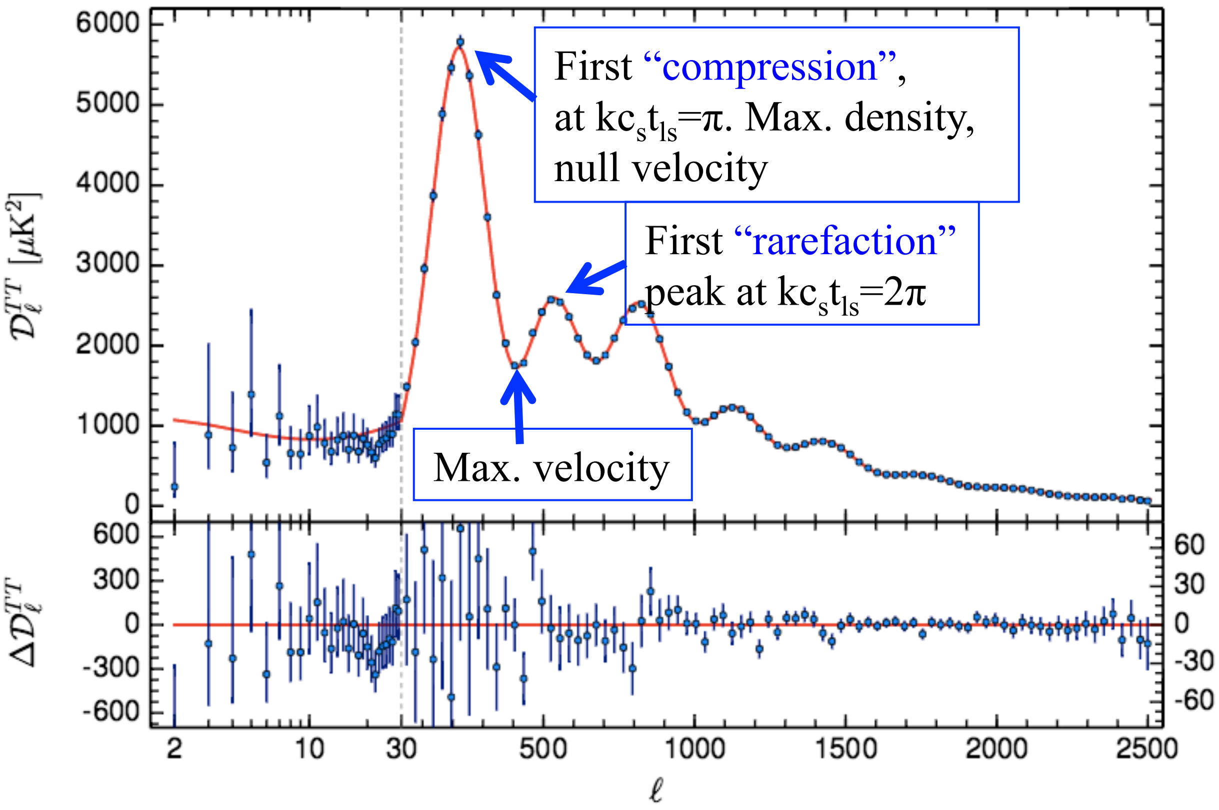
- At early times the universe was hot, dense and ionized. Photons and matter were tightly coupled by Thomson scattering (fluid approximation).
- Initial fluctuations in density and gravitational potential drive acoustic waves in the baryon-photon fluid with sound speed c_s: **compressions and rarefactions.**
- These show up as temperature fluctuations in the CMB.
- There is also a component due to the velocity of the fluid: **the Doppler effect**.
- A sudden **“recombination”** decouples the radiation and matter, giving us a snapshot of the fluid at “last scattering”.

$$(\Delta T)^2_{\rm ls} \sim \cos^2(k c_s t_{\rm ls}) + \text{velocity terms}$$



- These fluctuations are then projected on the sky with $\lambda \sim r_{ls}\theta$ or $l \sim k r_{ls}$.

Our cosmic ruler: the CMB BAOs!

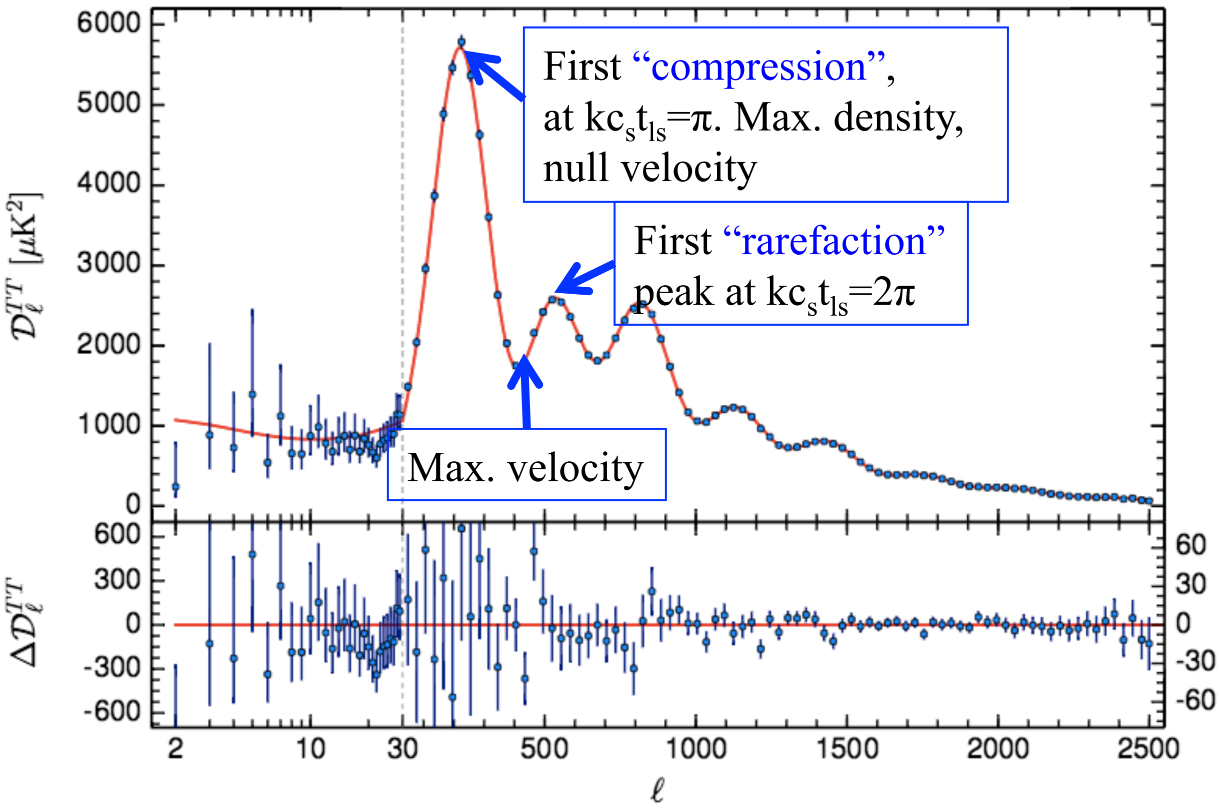


- It can be **calibrated** accurately over most of the age of the universe.
- It can be **measured** over much of the volume of the universe in a very precise way.
- It is due to **well-known physical processes** happened in the **early universe** and observable in the distribution of cosmic objects on very large scale (because easier to be modeled)

Acoustic scale is set by the **sound horizon at last scattering $r_s(z_{ls})$:**
Planck measured it accurately!

$$r_s(z_{ls}) = \int_{z_{ls}}^{\infty} \frac{c_s(z)}{H(z)} dz = 147.34 \pm 0.65 Mpc$$

Our cosmic ruler: the CMB BAOs!



Acoustic scale is set by the **sound horizon at last scattering $r_s(z_{ls})$:**
Planck measured it accurately!

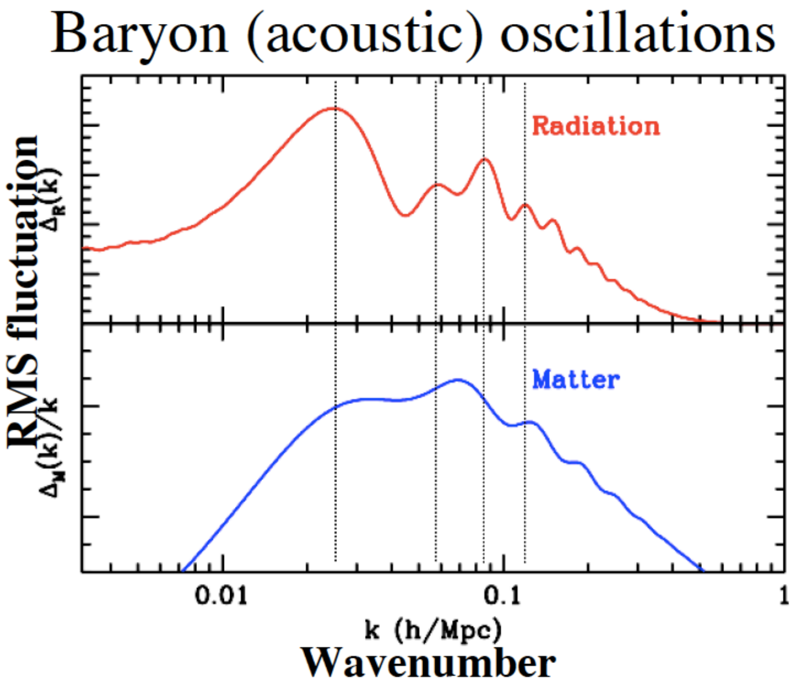
$$r_s(z_{ls}) = \int_{z_{ls}}^{\infty} \frac{c_s(z)}{H(z)} dz = 147.34 \pm 0.65 Mpc$$

The baryon oscillations in the large-scale structure of the universe

Baryons contribute to the total gravitational potential:

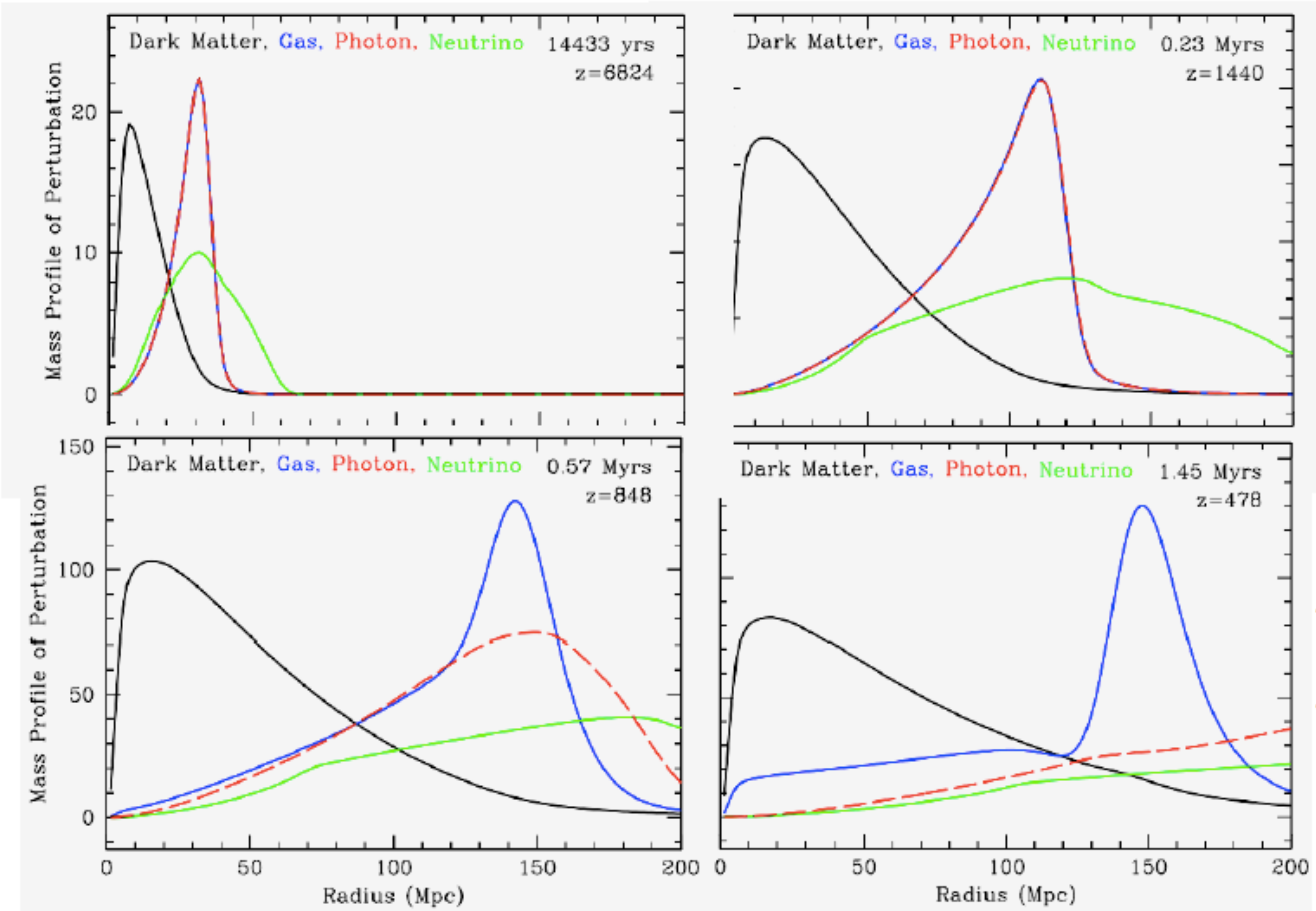
➔ we expect to **have oscillations** in the matter power spectrum P(k) with the same scale (the sound horizon at t_{ls});

➔ but, since the baryon are only ~15% of the total matter density, they will be **much smaller.**



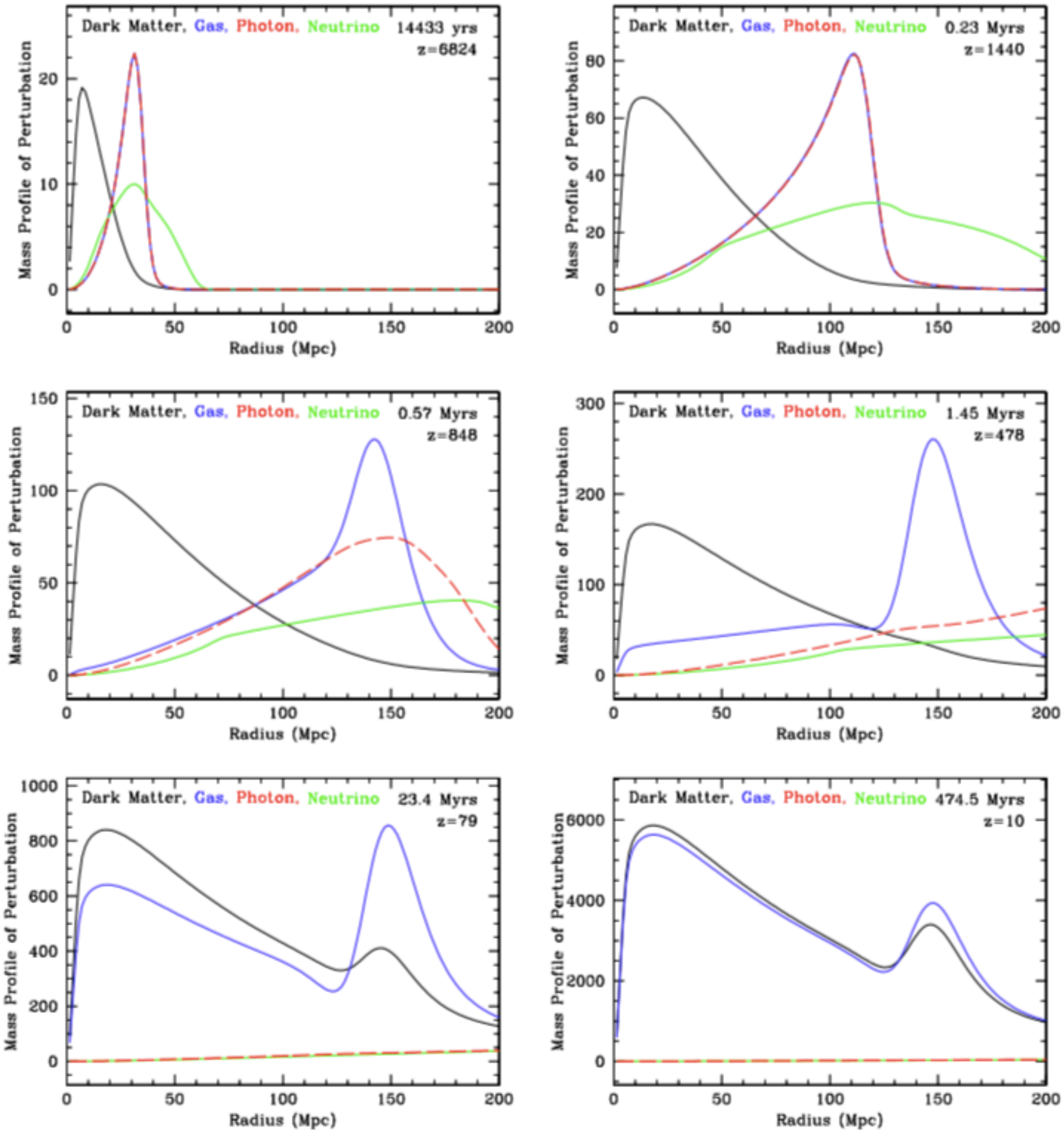
Key cosmological probe for the **Euclid mission** and for many ground-based future projects

Shape of *P(k)* in pictures



Eisenstein, Seo & White (2007)

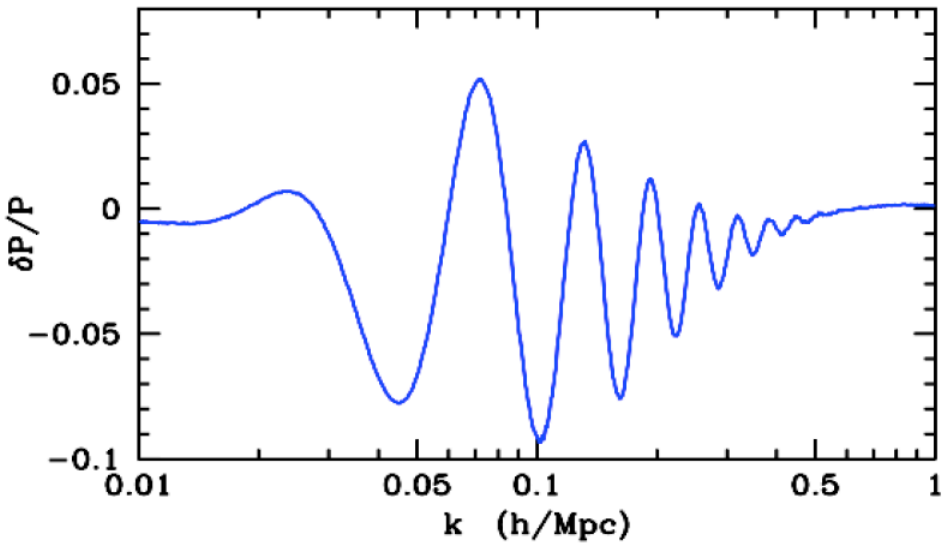
The shape of P(k) in pictures

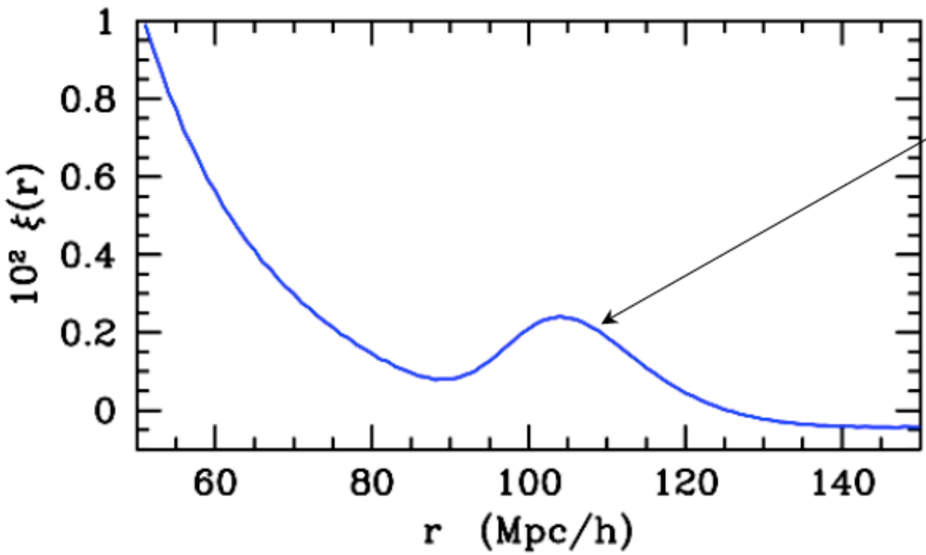


Eisenstein et al. 2007

The BAO signatures
in the clustering signals

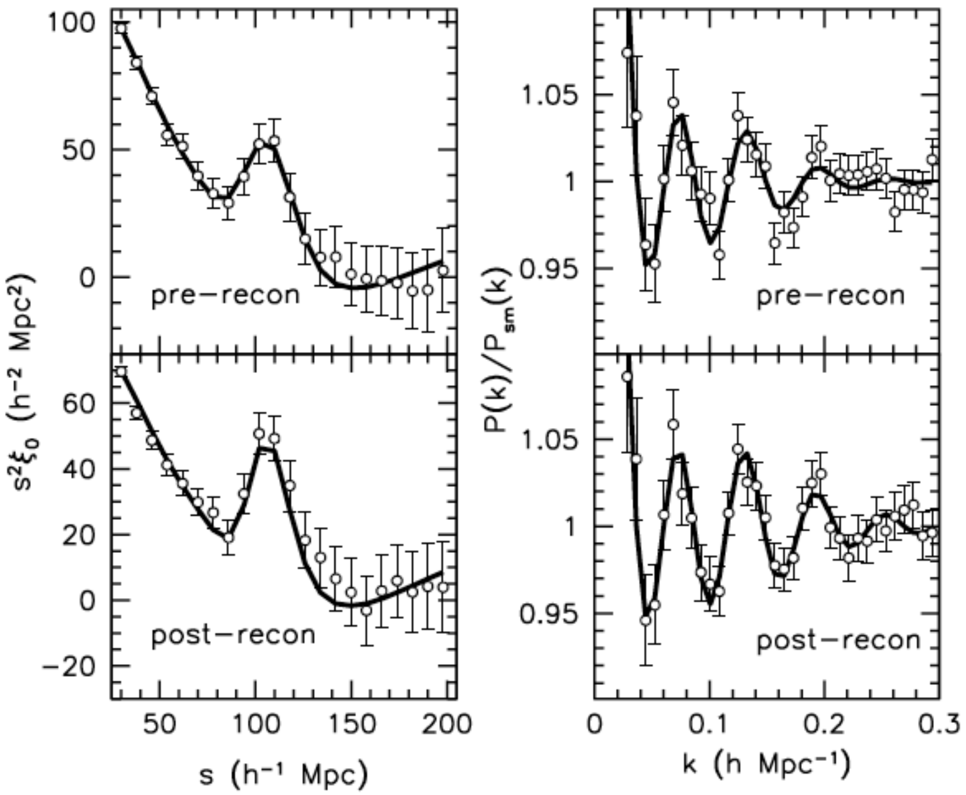
A damped, almost harmonic sequence of small **"wiggles"** (<10%) in the **matter power spectrum**





An **acoustic feature** (ξ≈0.02) at ~100 Mpc/h with width ~10 Mpc/h in the **two-point correlation function**

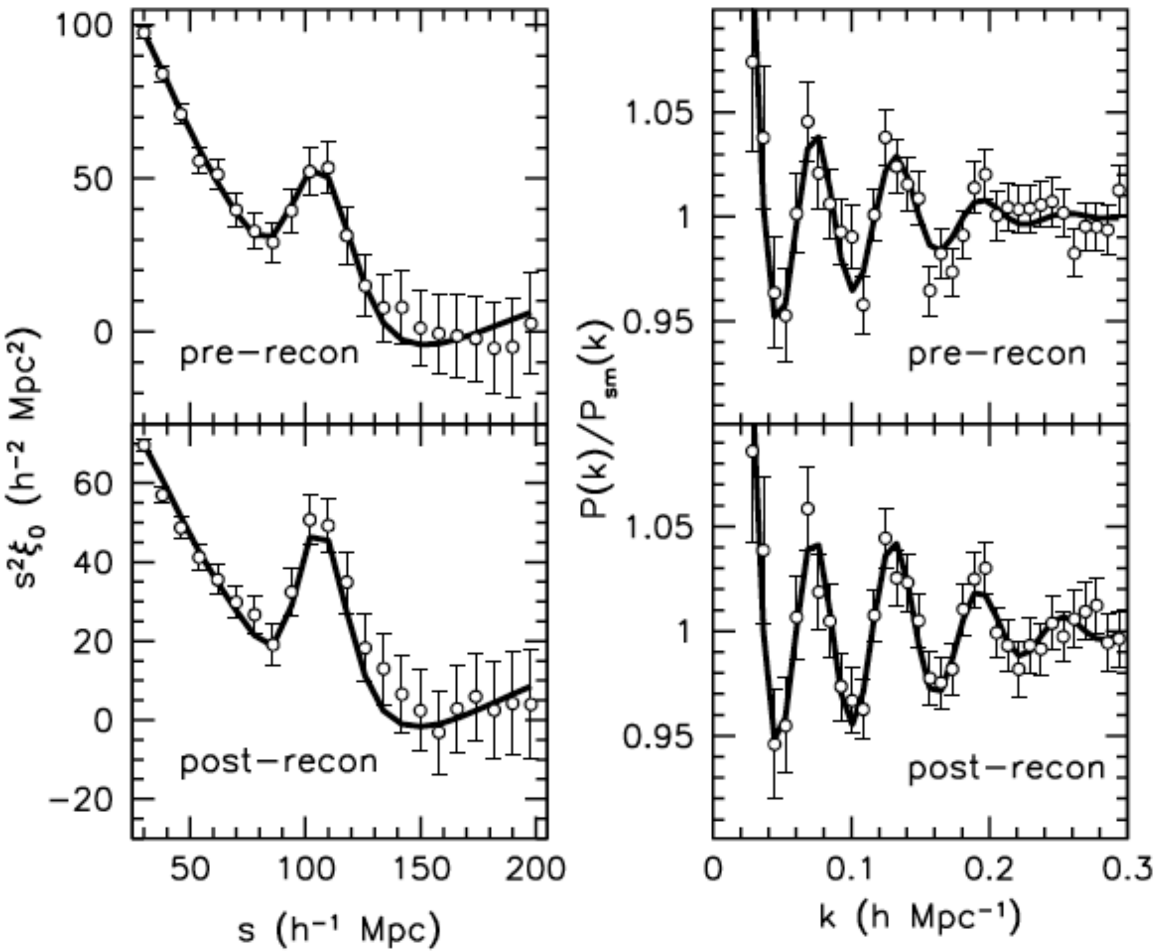
An example of application: BAOs in the SDSS BOSS DR11



SDSS BOSS DR11 results, Anderson et al. 2014

Shape and position of the BAO peak is influenced by non linear growth of structures: **reconstruction** of the density field improves the distance constraint.

The BAO signatures in the clustering signals: an example in the SDSS BOSS



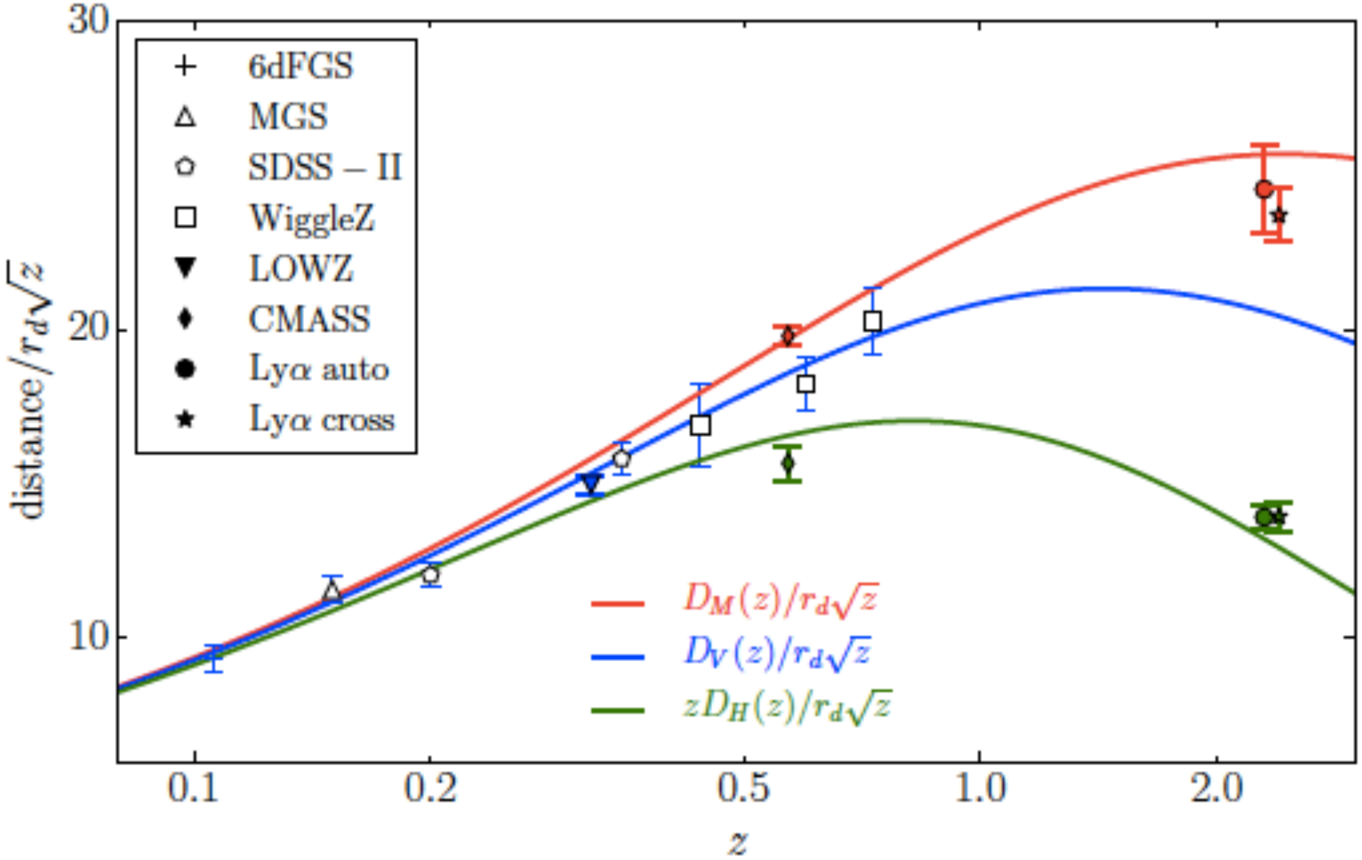
SDSS BOSS DR11 results, Anderson et al. 2014

An **acoustic feature** (ξ≈0.02) at ~100 Mpc/h with width ~10 Mpc/h in the **two-point correlation function.**

A damped, almost harmonic sequence of small **"wiggles"** (<10%) in the **matter power spectrum.**

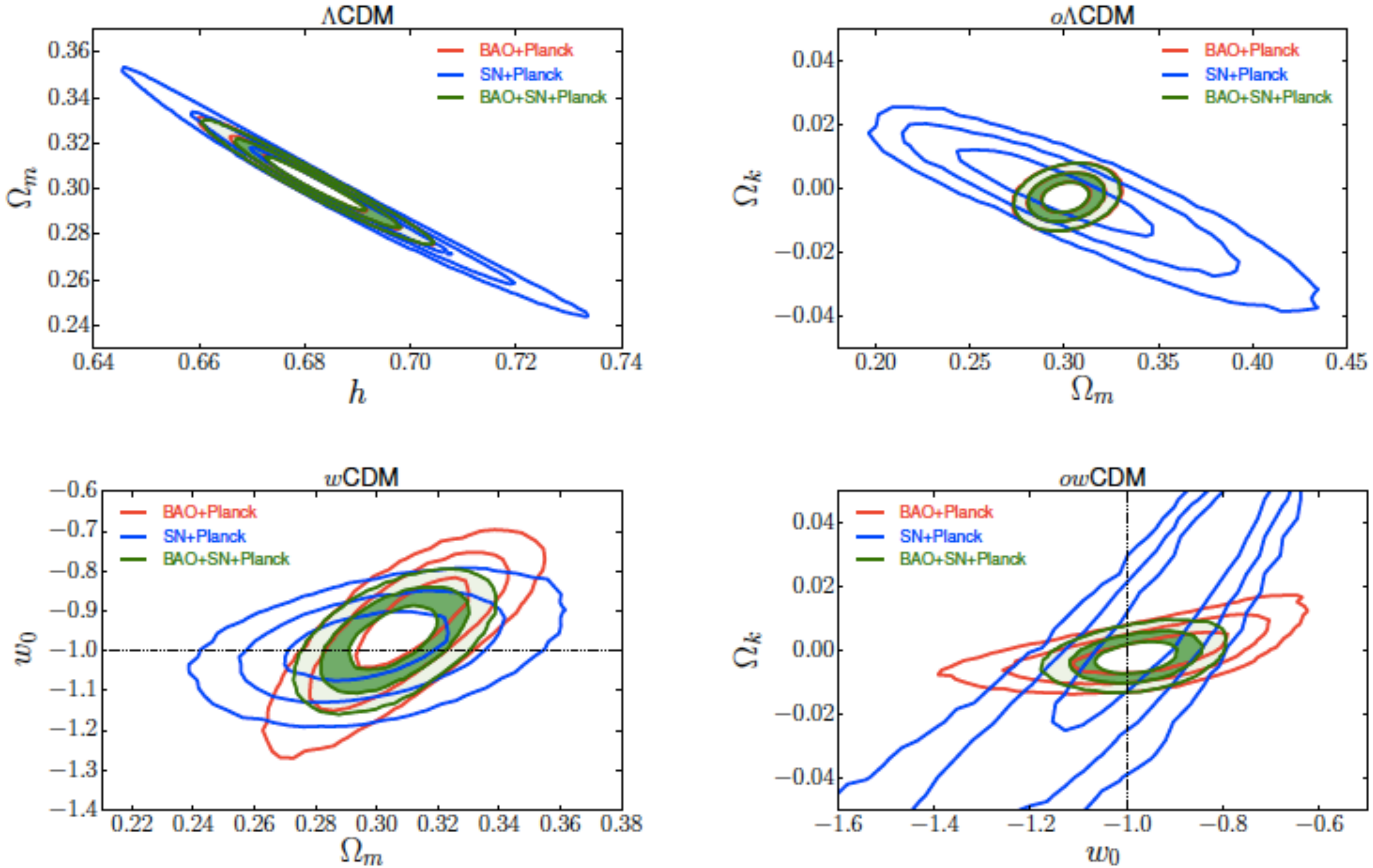
Shape and position of the BAO peak is influenced by non linear growth of structures: **reconstruction of the density** field improves the distance constraint.

A summary of the BAO results



Aubourg et al. 2014

Cosmological constraints from BAOs

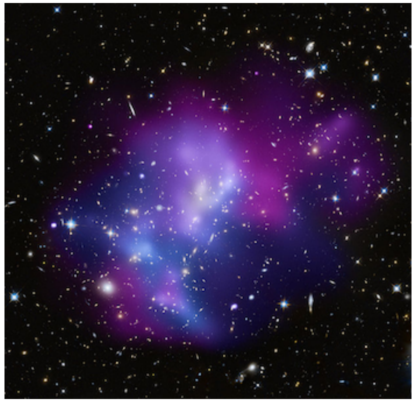
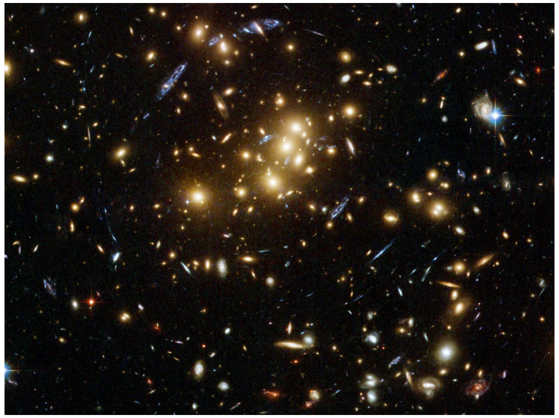


Aubourg et al. 2014

Cosmology with Galaxy Clusters

Galaxy clusters are an extremely powerful cosmological probe:

- **Mass function** ➔ cosmological parameters, dark energy models (Ω_Λ,w_0,w_a), neutrino mass, modified gravity, …
- **Baryon fraction** ➔ Ω_b
- **Matter density profiles** ➔ constraints on modified gravity and dark matter properties
- **Mass-concentration relation** ➔ cosmological constraints
- **X-ray-SZ-lensing observations** ➔ constraints using $D_A(z)$
- **Clustering properties** ➔ growth of structures, cosmological parameters, tests of GR, …

Why using Galaxy Clusters for BAO studies?

Galaxy Clusters represent the highest peaks in the matter density field

PROs

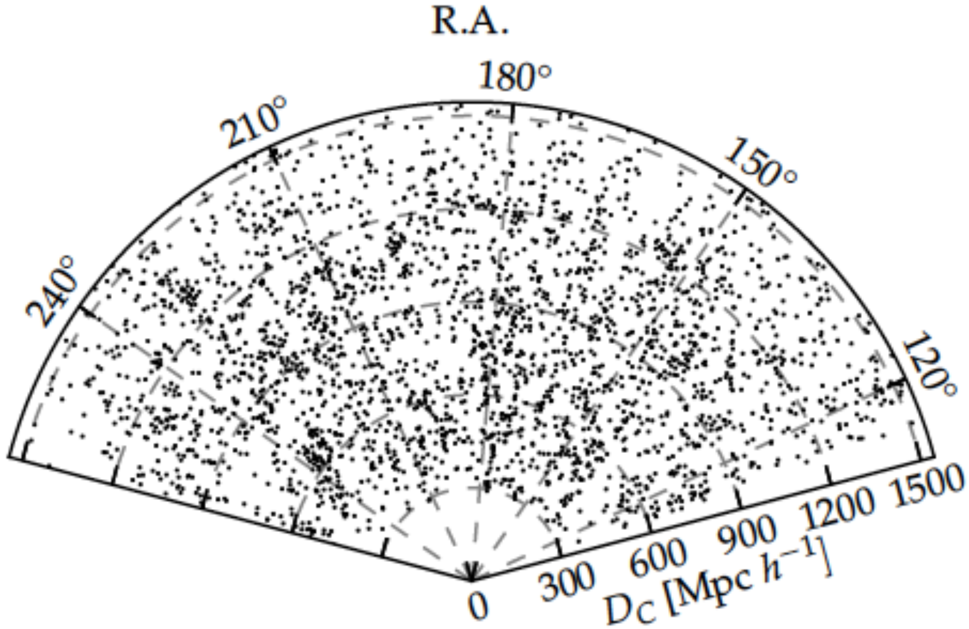
- They are more clustered than galaxies:
  → **Higher clustering signal**
- They are less affected by non-linear dynamics:
  → **No Fingers of God**

CONs

- They are sparser than other tracers:
  → **Larger error bars in the correlation function**

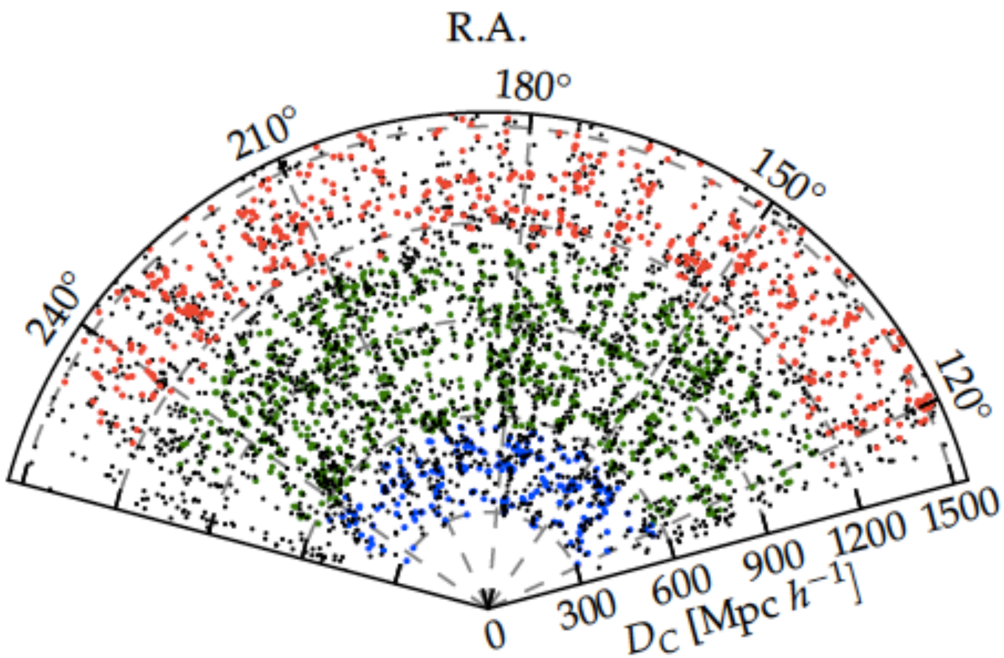
The catalogues of galaxy clusters

- Sample of **~130000** galaxy clusters (Wen, Han, Liu 2012) identified applying FoF on the photometric sample of SDSS DR8
- Area of **15000 deg^2**, covering $0.1 < z < 0.6$
- **Cluster center ➔ BCG angular coordinates + mean members photometric redshift**
- $M_{cl} \geq 6\ 10^{13}\ M_{\odot}$ (from weak lensing scaling relation)

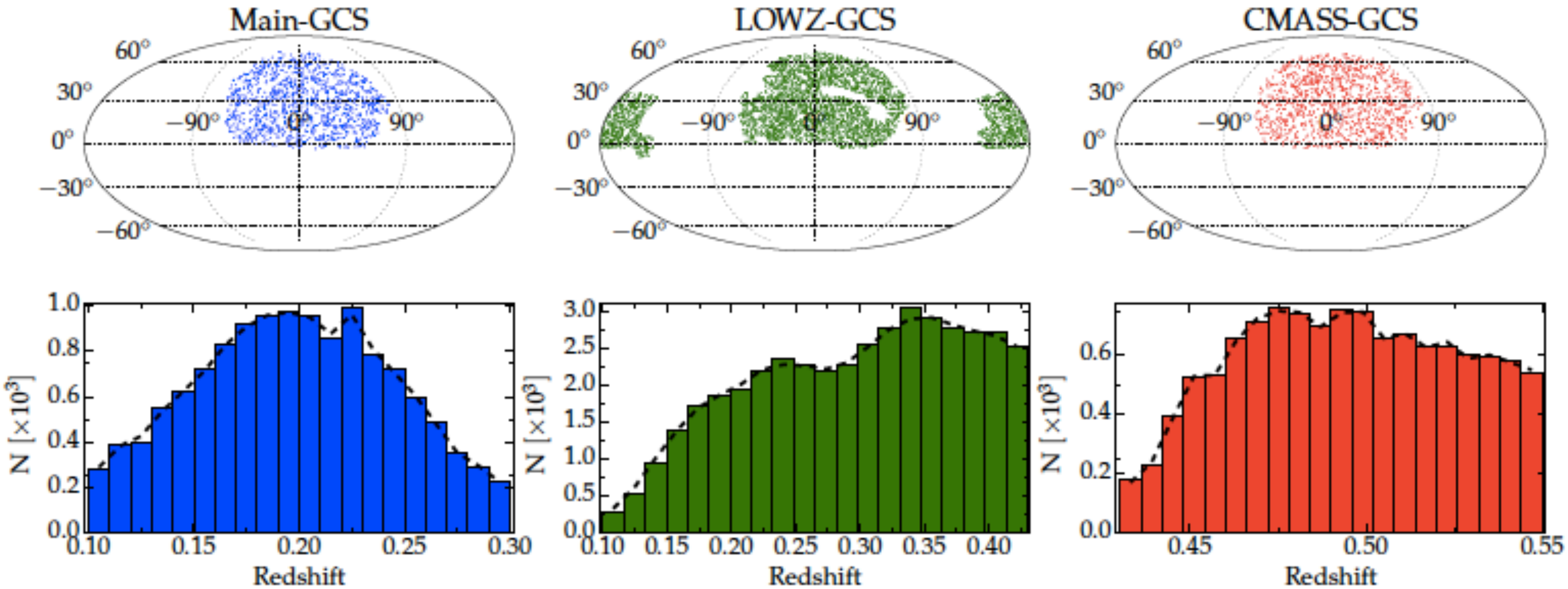


The catalogues of galaxy clusters

- Sample of ~130000 galaxy clusters (Wen, Han, Liu 2012) identified applying FoF on the photometric sample of SDSS DR8
- Area of **15000 deg^2**, covering $0.1 < z < 0.6$
- **Cluster center ➔ BCG angular coordinates + mean members photometric redshift**
- $M_{cl} \geq 6 \; 10^{13} \, M_\odot$ (from weak lensing scaling relation)
- **Spectroscopic redshift from SDSS DR12, assigned to a cluster if observed for the BCG**



The galaxy cluster samples



Summary of cluster samples fundamental quantities.

Sample Name	Number	Redshift Range	Median Redshift	bias
Main-GCS	12910	$0.1 \leq z \leq 0.3$	0.20	2.00 ± 0.05
LOWZ-GCS	42115	$0.1 \leq z \leq 0.43$	0.30	2.42 ± 0.02
CMASS-GCS	11816	$0.43 \leq z \leq 0.55$	0.50	3.05 ± 0.07

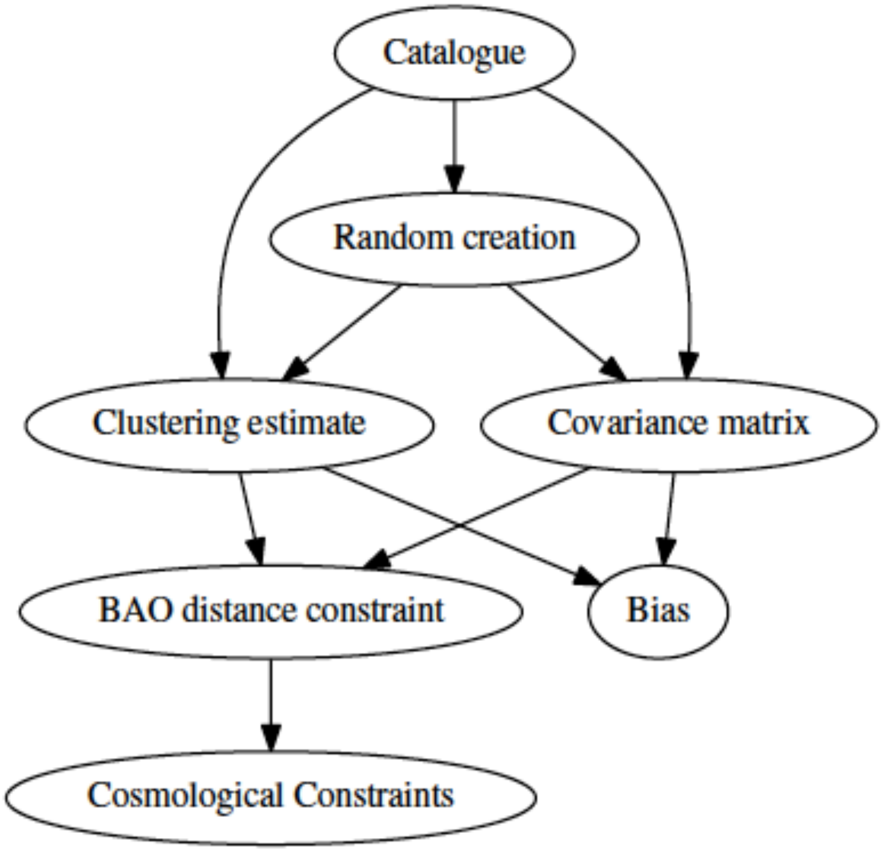
Measuring the two-point correlation function

We use the Landy & Szalay (1993) **estimator:**

$$\hat{\xi}(r) = 1 + \frac{N_{RR}}{N_{DD}} \frac{DD(r)}{RR(r)} - 2\frac{N_{RR}}{N_{DR}} \frac{DR(r)}{RR(r)}$$

The **covariance matrix** has been estimated using mock data or internal subsampling techniques (jackknife and/or bootstrap).

CosmoBolognaLib



There is an app for that...

CosmoBolognaLib
(Marulli, Moresco, Veropalumbo 2016,
[arXiv:1511.00012]):

CosmoBolognaLib

(Marulli, Moresco, Veropalumbo 2016, arXiv:1511.00012)

C++, Python libraries aimed at defining a common numerical environment for cosmological investigations of the large-scale structure of the Universe.

Fully documented and publicly available:

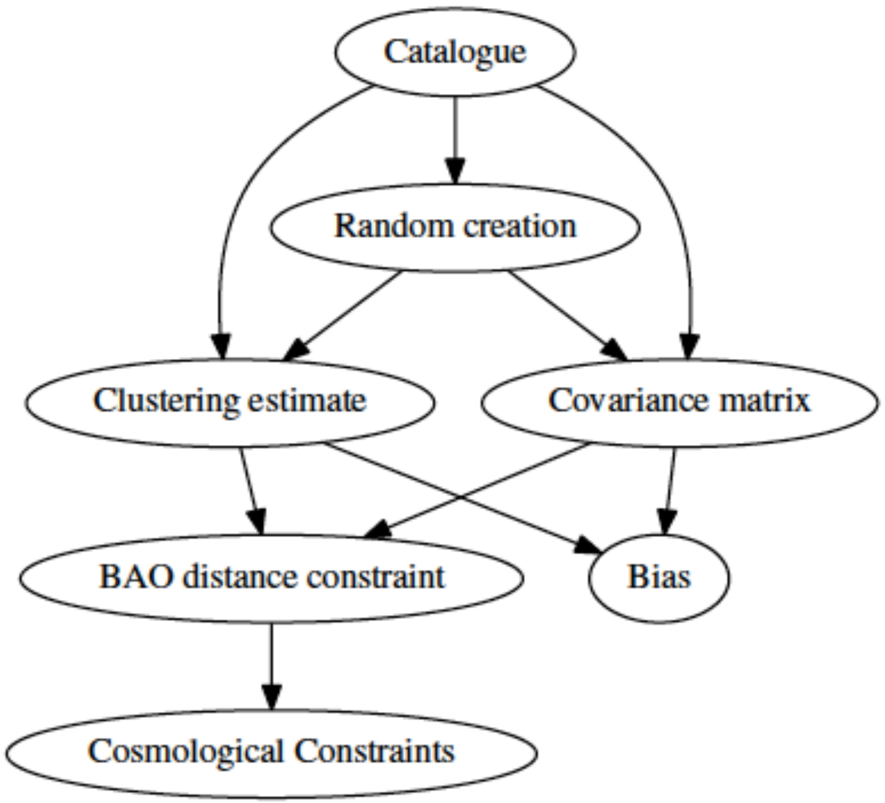
- **GitHub depository:**

https://github.com/federicomarulli/CosmoBolognaLib

- **Tar file and documentation:**

http://apps.difa.unibo.it/files/people/federico.marulli3/CosmoBolognaLib/

Measuring the two-point correlation function



CosmoBolognaLib

(Marulli, Moresco, Veropalumbo 2016, arXiv:1511.00012)

C++, Python libraries aimed at defining a common numerical environment for cosmological investigations of the large-scale structure of the Universe.

Fully documented and publicly available:

- **GitHub depository:**

https://github.com/federicomarulli/CosmoBolognaLib

Landy & Szalay (1993) **estimator:**

$$\hat{\xi}(r) = 1 + \frac{N_{RR}}{N_{DD}} \frac{DD(r)}{RR(r)} - 2 \frac{N_{RR}}{N_{DR}} \frac{DR(r)}{RR(r)}$$

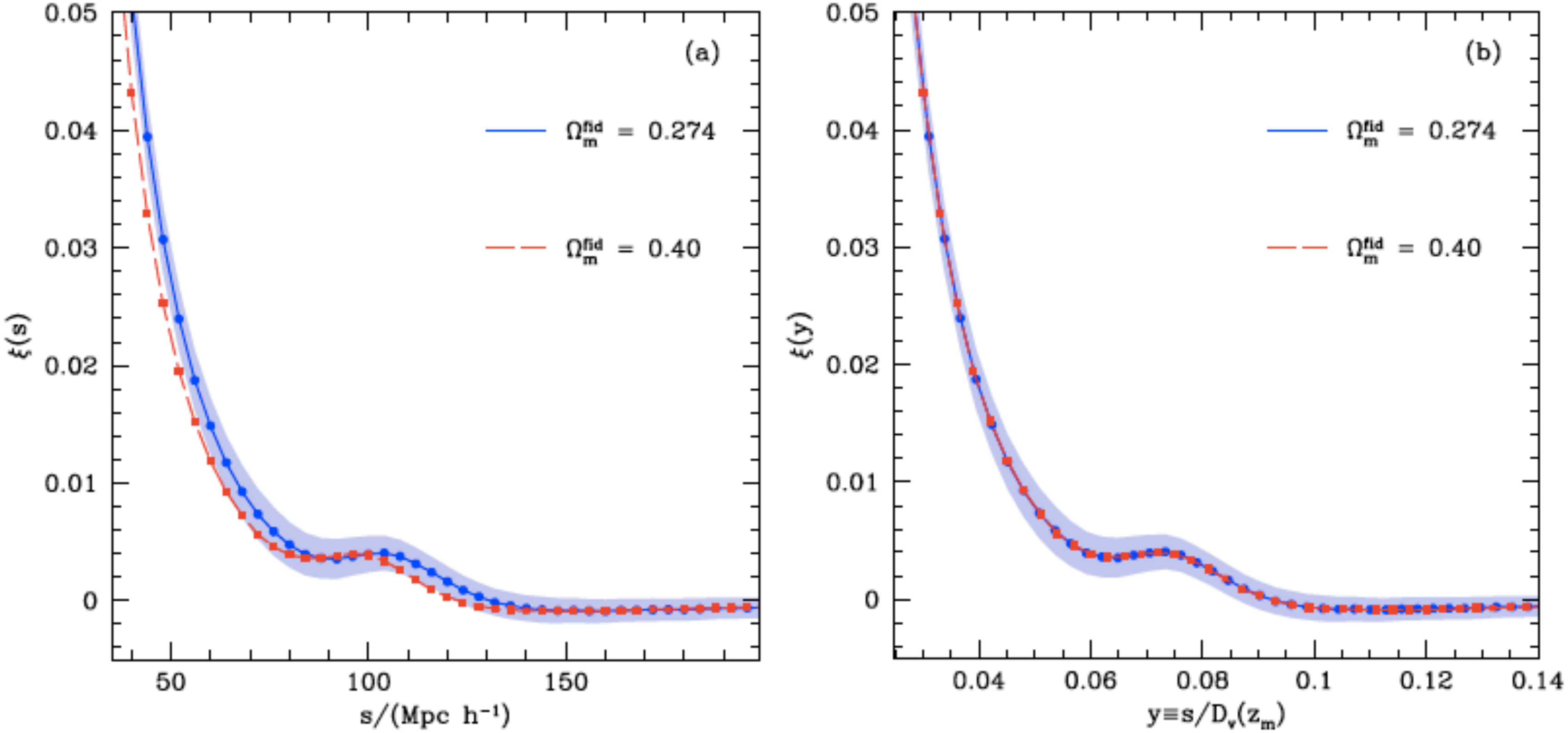
Measuring the two-point correlation function

Problem: two kinds of **distortions** affect the measurement:

- **Geometrical distortions:** consequence of assuming a **fiducial cosmology** to transform angular coordinates and redshift in physical cartesian coordinates:

$$dV = (1+z)^2 D_A^2(z) \frac{cz}{H(z)} d\Omega dz \equiv D_V^3 d\Omega dz$$

Correcting for the geometrical distortions



Sanchez et al. 2012

$$s \rightarrow y_s \equiv \frac{s}{D_V^{fid}(z)}$$

D_V is called isotropic volume distance

Measuring the two-point correlation function

Problem: two kinds of **distortions** affect the measurement:

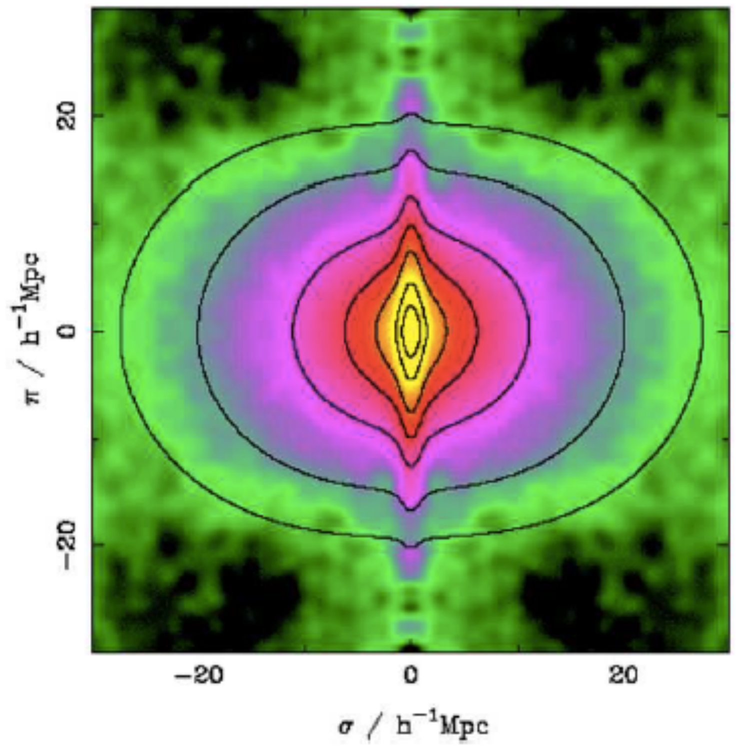
- **Geometrical distortions:** consequence of assuming a **fiducial cosmology** to transform angular coordinates and redshift in physical cartesian coordinates:

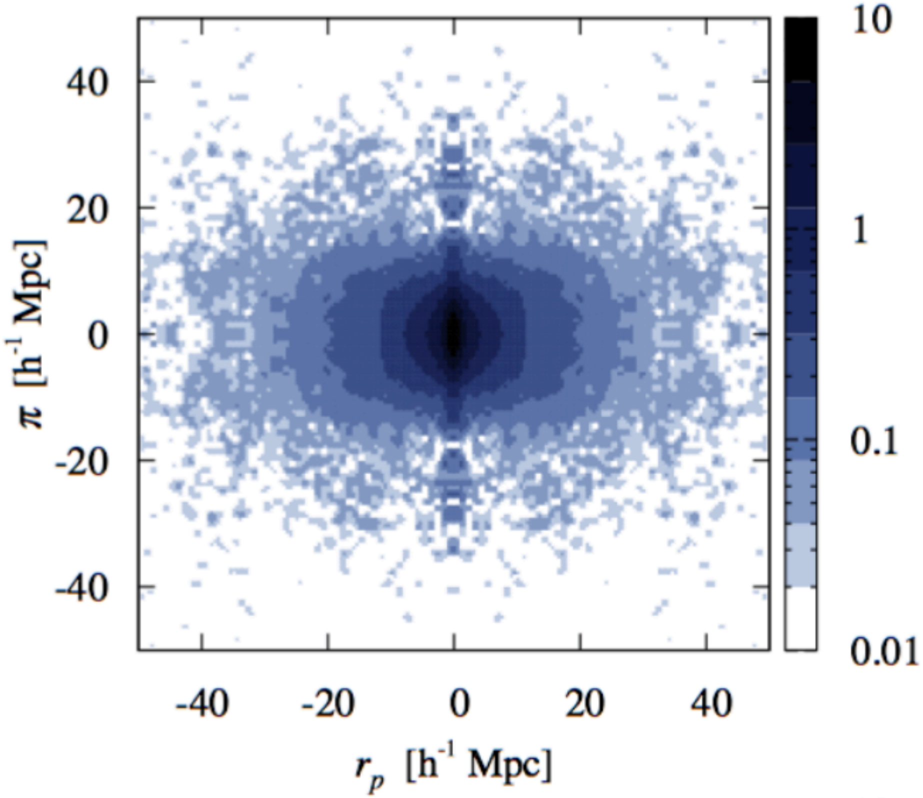
$$dV = (1+z)^2 D_A^2(z) \frac{cz}{H(z)} d\Omega dz \equiv D_V^3 d\Omega dz$$

- **Dynamical distortions:** the line-of-sight component of the **peculiar velocity** perturbs the cosmological redshift of the cosmic object:

$$z_{obs} = z_c + \frac{v_\parallel}{c}(1+z_c)$$

Dynamical distortions

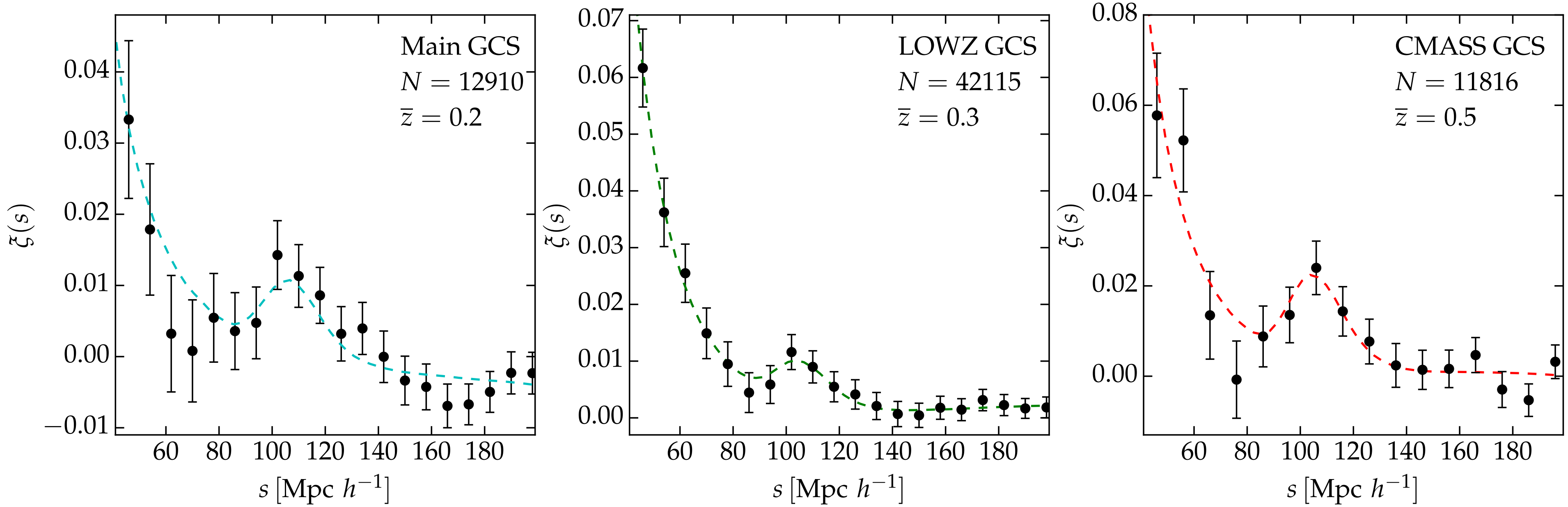




2dFGRS (Peacock et al. 2001); galaxies @ **z≤0.2**

VIPERS (de la Torre et al. 2013); galaxies @ **z~0.8**

The redshift-space two-point correlation function of galaxy clusters



bias=2.00±0.05 **bias=2.42±0.02** **bias=3.05±0.07**

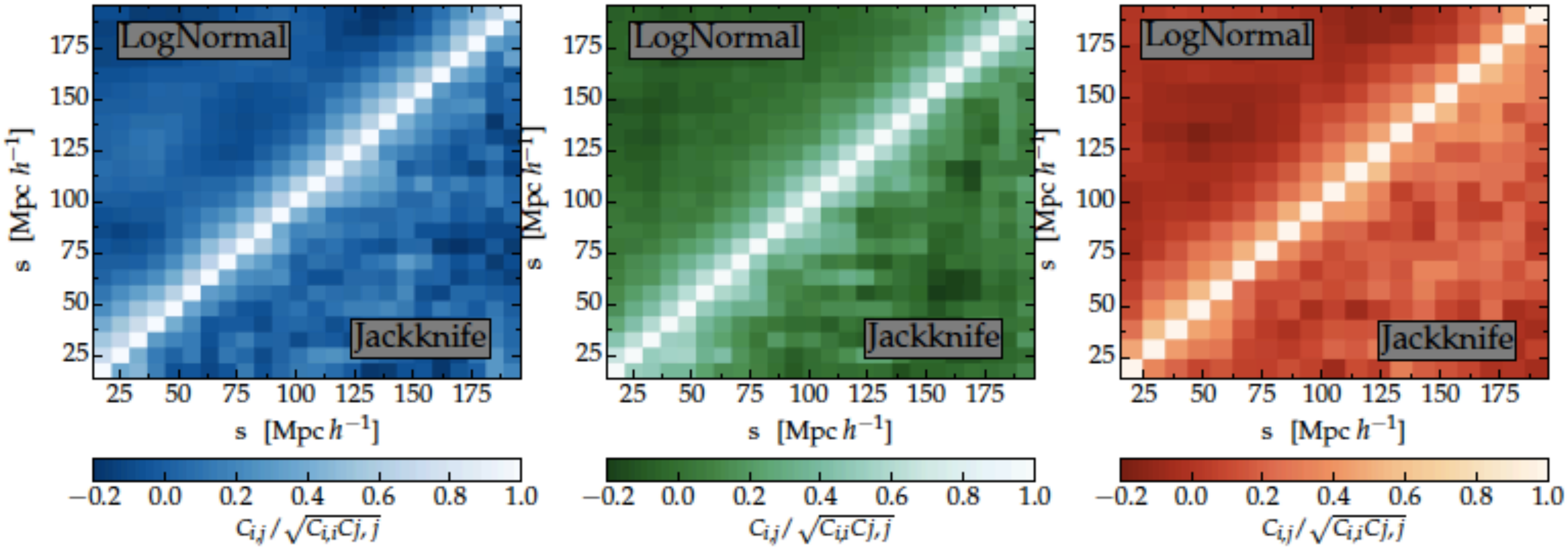
Error bars from lognormal mocks; shaded area represents 68% posterior uncertainties provided by the MCMC analysis

Covariance matrix

Crucial ingredient for clustering analysis: necessary for the Gaussian likelihood in the Monte Carlo Markov Chain technique.

Computed with 3 different approaches: two internal (jackknife and bootstrap, one external (lognormal mocks).

$$C_{i,j} = \frac{1}{N_{real.} - 1} \sum_{k=1}^{N_{real.}} \left(\xi_i^k - \hat{\xi}_i \right) \left(\xi_j^k - \hat{\xi}_j \right)$$



Modelling the two-point correlation function

The cluster redshift-space correlation function is assumed to follow the model proposed by Anderson et al. (2012):

$$\xi(s) = b^2 \xi_{DM}(\alpha s) + \frac{A_0}{r^2} + \frac{A_1}{r} + A_2$$

Modelling the two-point correlation function

The cluster redshift-space correlation function is assumed to follow the model proposed by Anderson et al. (2012):

$$\xi(s) = b^2 \xi_{DM}(\alpha s) + \frac{A_0}{r^2} + \frac{A_1}{r} + A_2$$

b ← bias parameter between clusters and DM (including the effect of redshift distortions)

α ← parameter entirely containing the distance information, then used to put constraints on the cosmological parameters

A_0,A_1,A_2 ← parameters of an additive polynomial used to marginalise over signals caused by **systematics** not fully accounted for

Modelling the two-point correlation function

The DM power spectrum is modeled using the **de-wiggled** template (Einsenstein et al. 2007)

$$P_{DM}(k) = \left[P_{lin}(k) - P_{nw}(k)\right]\exp\left(-k^2\Sigma_{NL}^2/2\right) + P_{nw}(k)$$

P_{lin} ← **linear** power spectrum (from CAMB)
P_{nw} ← power spectrum **without the BAO features** (Eisenstein & Hu 1998)
Σ_{NL} ← parametrizes the **non-linear broadening** of the BAO peak

The DM correlation function is simply the Fourier Transform of the DM power spectrum:

$$\xi_{DM}(r) = \frac{1}{2\pi^2}\int k^2 P_{DM}(k)\frac{\sin(kr)}{kr}dk$$

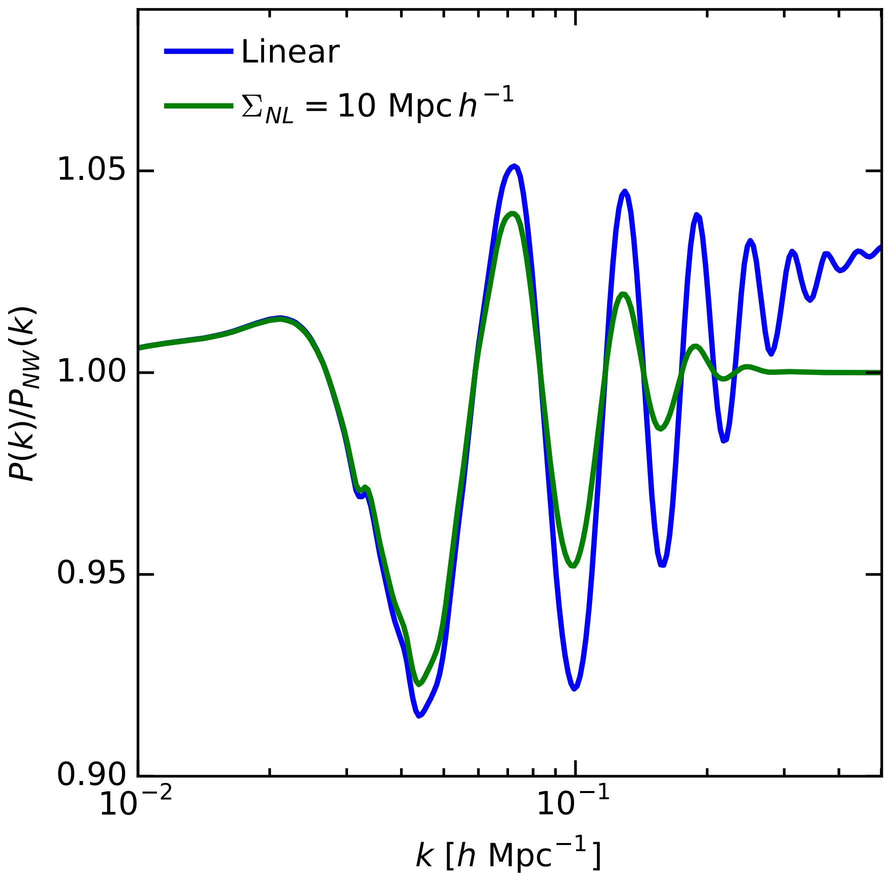
Modelling the two-point correlation function

The DM power spectrum is modeled using the **de-wiggled** template (Einsenstein et al. 2007)

$$P_{DM}(k) = \left[P_{lin}(k) - P_{nw}(k)\right]\exp\left(-k^2\Sigma_{NL}^2/2\right) + P_{nw}(k)$$

P_{lin} ← **linear** power spectrum (from CAMB)
P_{nw} ← power spectrum **without the BAO features** (Eisenstein & Hu 1998)
Σ_{NL} ← parametrizes the **non-linear broadening** of the BAO peak

Wiggled/De-wiggled Power Spectrum



BAO distance constraint

The distance constraint is entirely contained in α.

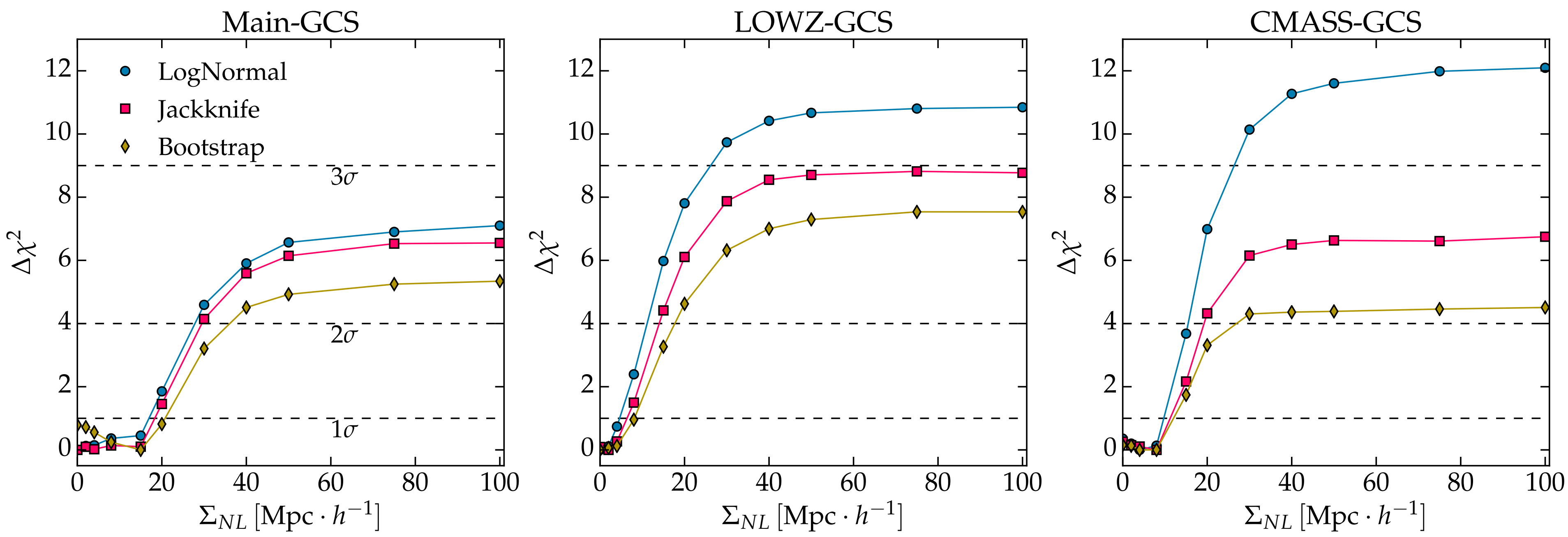
It is necessary to correct for the **geometric distortions** introduced by the assumption of a fiducial cosmology to compute the two-point correlation:

$$D_V(z) \equiv \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)} \right]^{1/3} = \alpha \frac{D_V^{fid}}{r_s^{fid}} \cdot r_s$$

Two possible methods:

- **Calibrated,** when one assumes that the true value of the sound horizon is known from CMB (i.e. Planck)
- **Uncalibrated,** when one prefer to use $D_v(z)/r_s$

Significance of the BAO detection



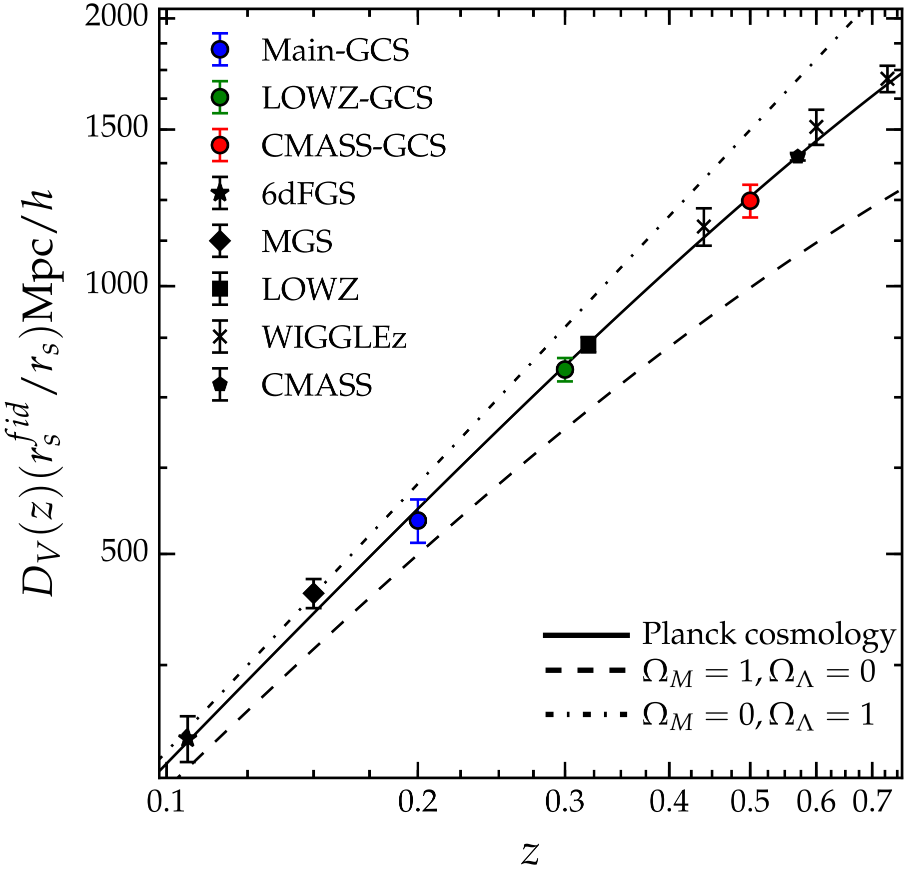
Estimated values of α and significance of the BAO detection for the galaxy clusters samples and the definitions of covariance matrix.

α

Sample Name	LogNormal	Jackknife	Bootstrap
Main-GCS	$0.97 \pm 0.06\,(2.7\sigma)$	$0.97 \pm 0.08\,(2.6\sigma)$	$0.98 \pm 0.08\,(2.3\sigma)$
LOWZ-GCS	$0.99 \pm 0.03\,(3.3\sigma)$	$0.99 \pm 0.04\,(2.9\sigma)$	$0.99 \pm 0.05\,(2.7\sigma)$
CMASS-GCS	$0.99 \pm 0.03\,(3.5\sigma)$	$0.99 \pm 0.06\,(2.6\sigma)$	$0.99 \pm 0.08\,(2.1\sigma)$

Distance constraints

$$D_V(z) \equiv \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3} = \alpha \frac{D_V^{fid}}{r_s^{fid}} \cdot r_s$$



- Main-CGS

  $D_V(z=0.2)(r_s^{fid}/r_s) = 545 \pm 31\,\mathrm{Mpc}\,h^{-1}$

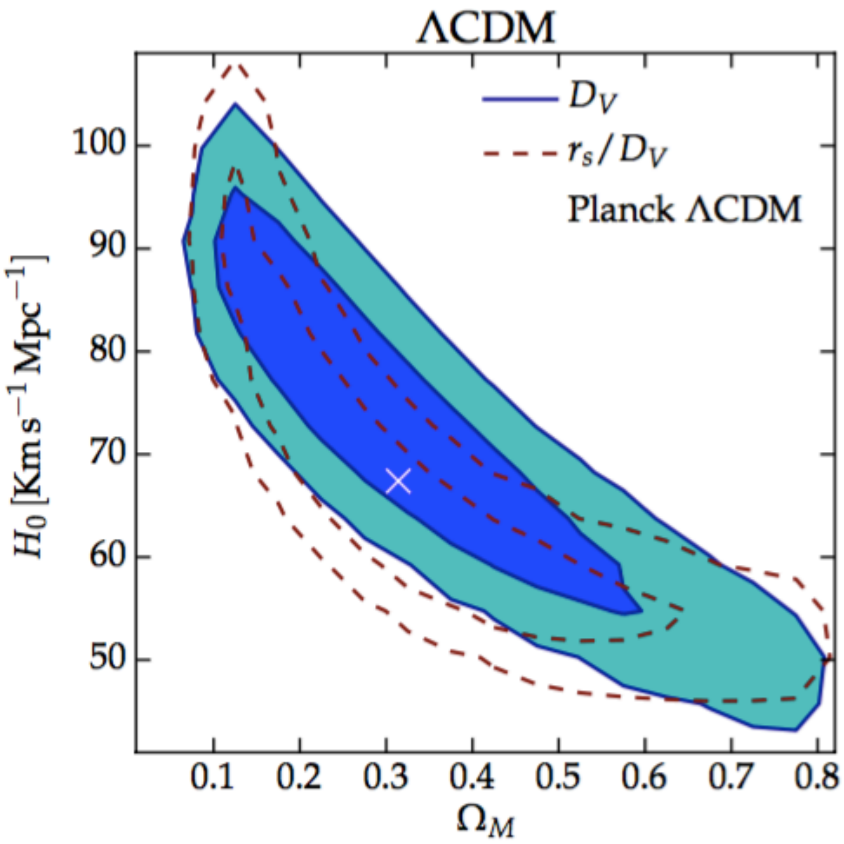
- LOWZ-CGS

  $D_V(z=0.3)(r_s^{fid}/r_s) = 806 \pm 24\,\mathrm{Mpc}\,h^{-1}$

- CMASS-CGS

  $D_V(z=0.5)(r_s^{fid}/r_s) = 1247 \pm 53\,\mathrm{Mpc}\,h^{-1}$

Cosmological constraints: ΛCDM model



Flat universe:

$\Omega_k = 1 - \Omega_M - \Omega_\Lambda = 0$

Dark energy with eq. of state parameter **w=-1**

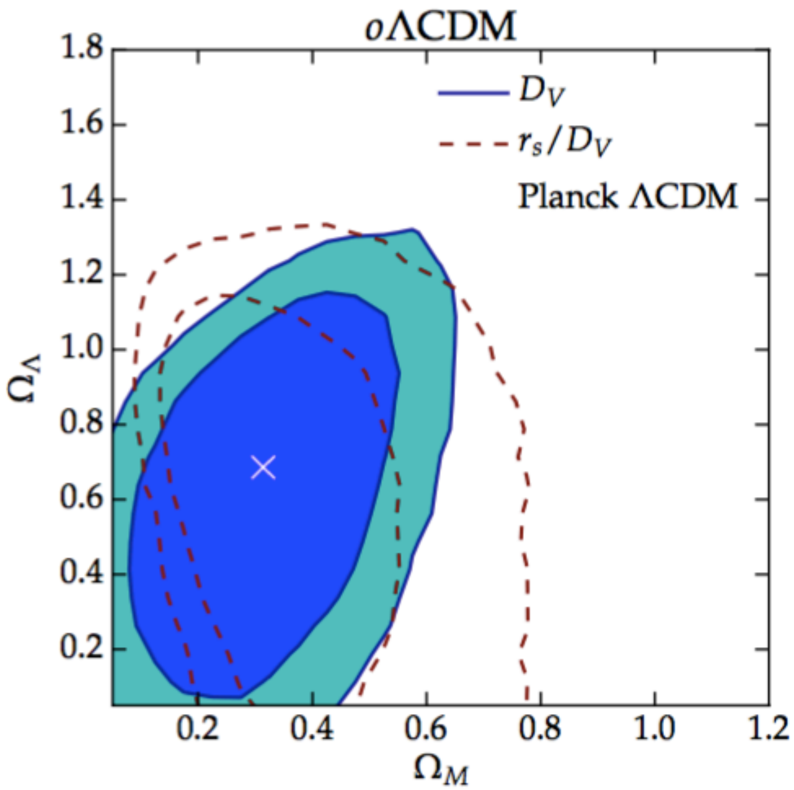
➔ **cosmological constant Λ**

$$H_0 = 64^{+17}_{-8} \frac{km}{s \cdot Mpc}$$

$$\Omega_M = 0.33^{+0.24}_{-0.16}$$

$$H^2(z) = H_0^2 \left[\Omega_M (1+z)^3 + \Omega_\Lambda \right]$$

Cosmological constraints: oΛCDM models



Non-flat universe:

$\Omega_k = 1 - \Omega_M - \Omega_\Lambda \neq 0$

Dark energy with eq. of state parameter **w=-1**

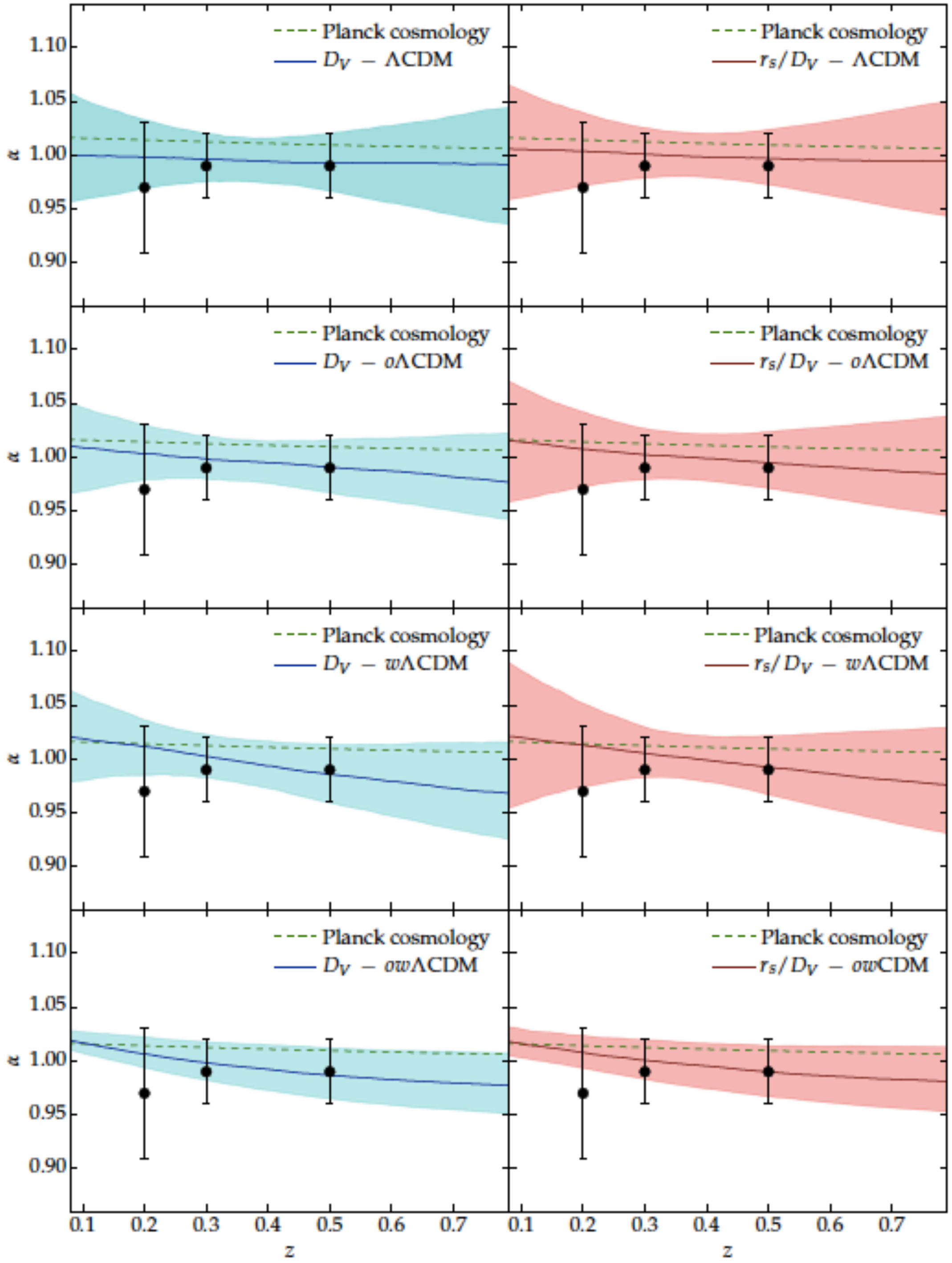
➔ **cosmological constant Λ**

$$H_0 = \mathrm{N}(67, 20)\frac{km}{s \cdot Mpc}$$

$$\Omega_k = -0.01^{+0.34}_{-0.33}$$

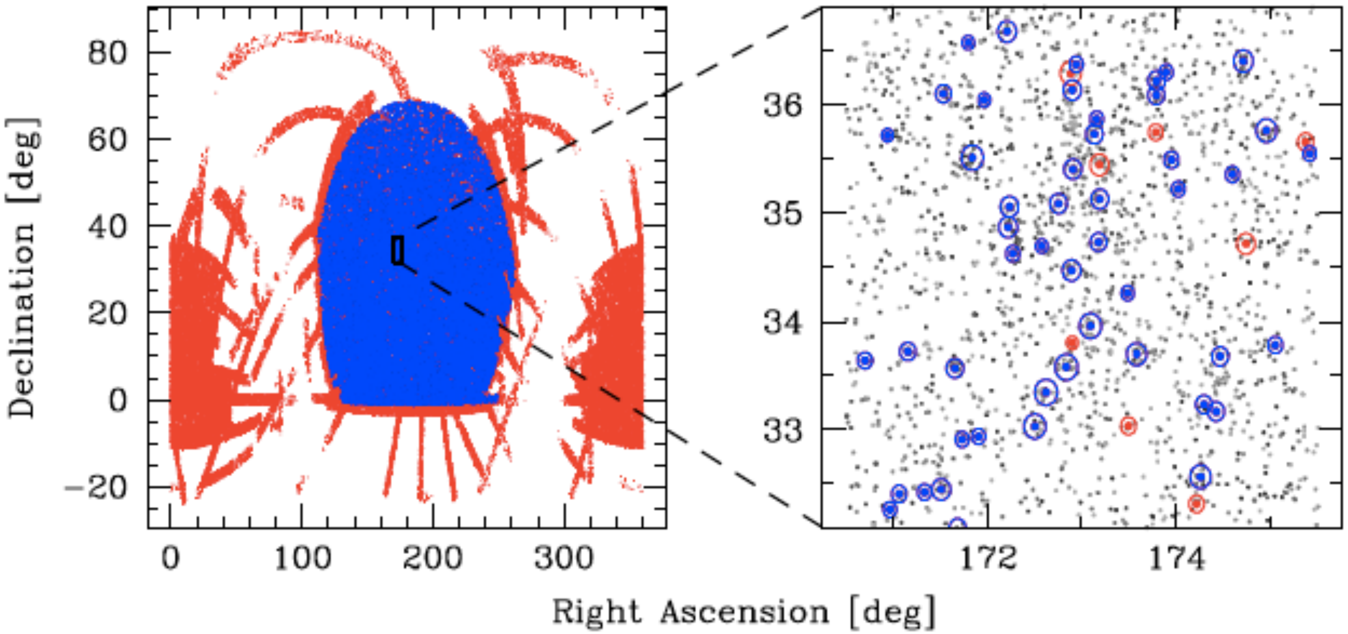
$$H^2(z) = H_0^2\left[\Omega_M(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2\right]$$

The Planck cosmology is **compatible** with the cluster BAO results

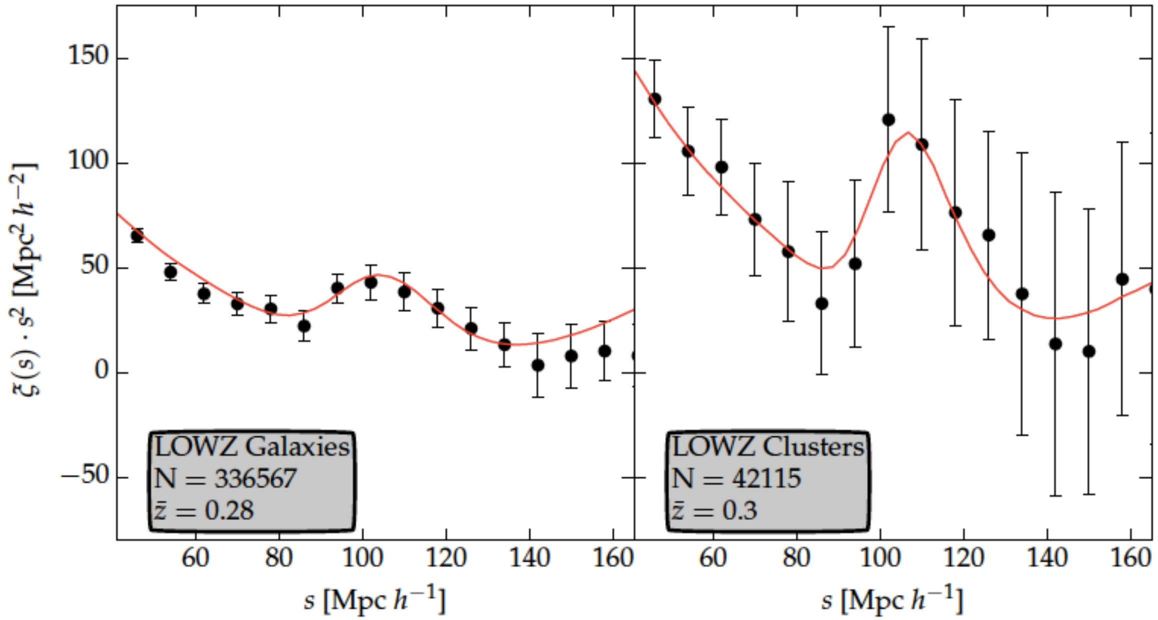


BAO: Galaxies vs. Clusters

BGCs at the centre of galaxy clusters are a (small) subsample of the whole BOSS galaxy catalogue.
What are the **differences** in their clustering properties and in the strength of the BAO signal?



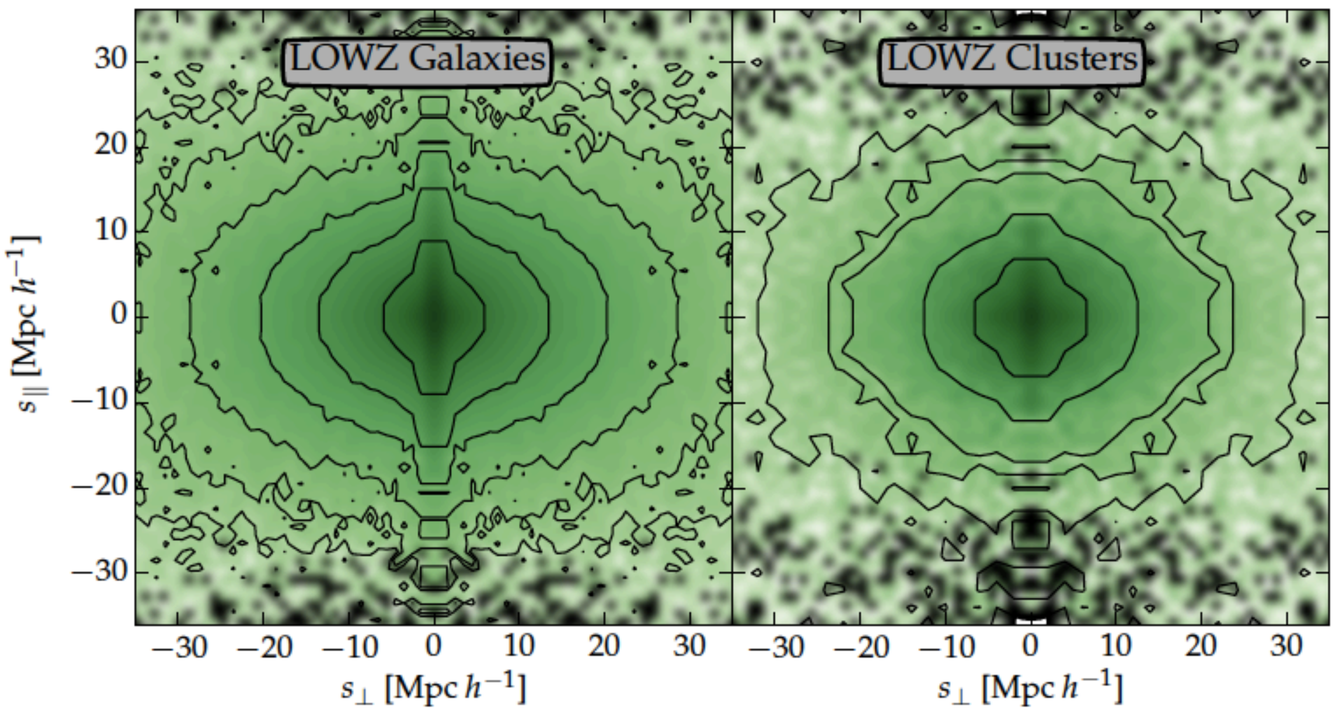
BAO: Galaxies vs. Clusters



- Clear difference in the **bias** ➔ galaxy cluster centre (BCGs) are not a random subsample of the whole galaxy population
- **BAO peak** very clear in the cluster correlation function despite of the largest measurement errors

$$\text{Galaxies:} \quad \rightarrow b \approx 1.5, \quad D_V = 814 \pm 23\,\mathrm{Mpc}\,h^{-1}$$
$$\text{Clusters:} \quad \rightarrow b \approx 2.4, \quad D_V = 805 \pm 26\,\mathrm{Mpc}\,h^{-1}$$

BAO: Galaxies vs. Clusters



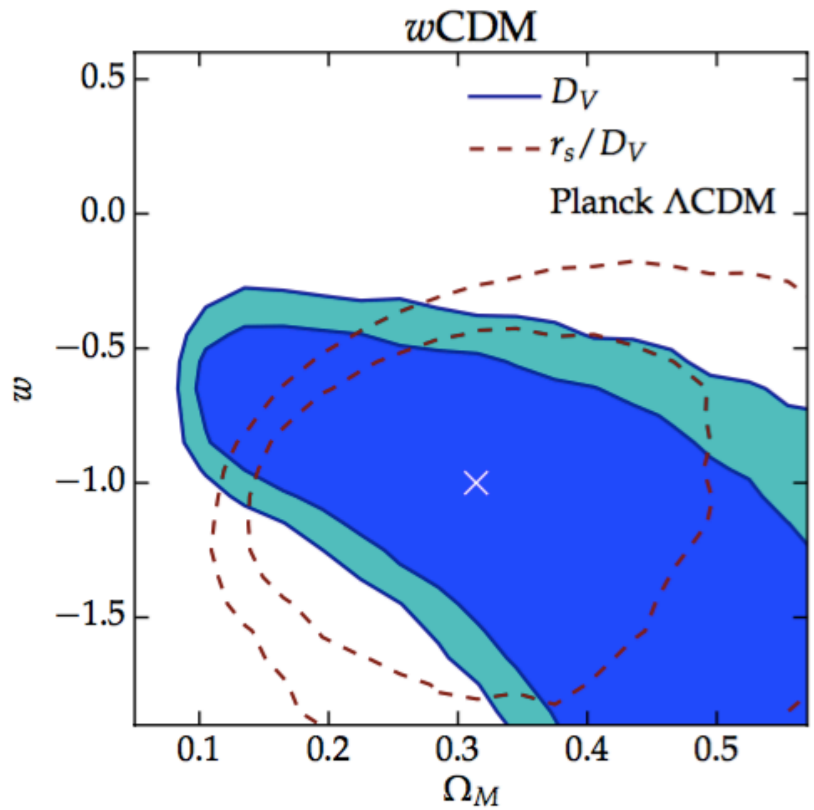
The **peculiar velocity term** in the observed redshift generates the Fingers of God. These distortions have influences on the BAO scale too.

$$z_{obs} = z_c + \frac{v_\parallel}{c}\left(1 + z_c\right)$$

Conclusions

- We computed the **two-point correlation function for galaxy clusters** at three different redshifts.
- **We showed that BAO distance constraints from galaxy cluster clustering are possible!**
- They have a **competitive precision** w.r.t. galaxy clustering BAO constraints.
- Cluster clustering shows **differences** in bias, FoG, NL w.r.t. galaxy clustering
- We derive **cosmological constraints** from distance redshift relation for a set of different cosmological scenarios.
- The results for cluster BAO can be used **in combination** with other cluster probes (like the mass function)

Cosmological constraints: wCDM models



Flat universe:

$\Omega_k = 1 - \Omega_M - \Omega_{DE} = 0$

Dark energy with generic

eq. of state parameter w

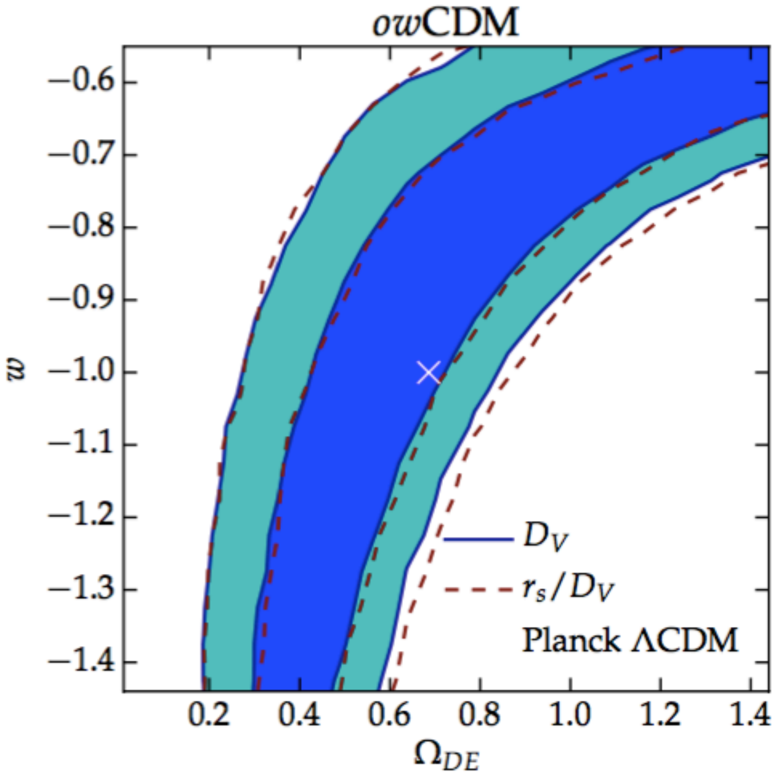
$$H_0 = N(67,20)\frac{km}{s\cdot Mpc}$$

$$\Omega_M = 0.38^{+0.21}_{-0.14}$$

$$w = -1.06^{+0.49}_{-0.52}$$

$$H^2(z) = H_0^2\left[\Omega_M(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}\right]$$

Cosmological constraints: owCDM models

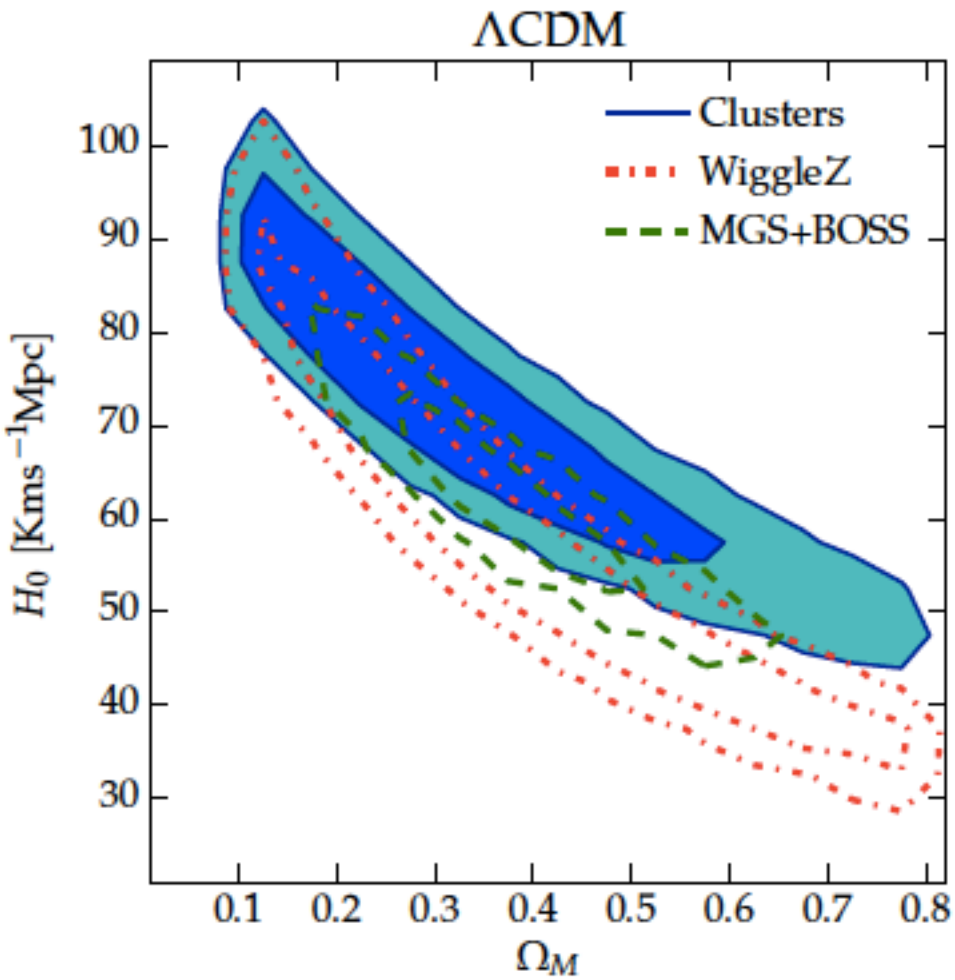


Non-flat universe:
$\Omega_k = 1 - \Omega_M - \Omega_{DE} \neq 0$
Dark energy with generic
eq. of state parameter w

$$H_0 = N(67, 2)\frac{km}{s \cdot Mpc}$$
$$\Omega_M = N(0.31, 0.02)$$
$$\Omega_{DE} = 0.68^{+0.44}_{-0.25}$$
$$w = -0.88^{+0.24}_{-0.37}$$

$$H^2(z) = H_0^2\left[\Omega_M(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)} + \Omega_k(1+z)^2\right]$$

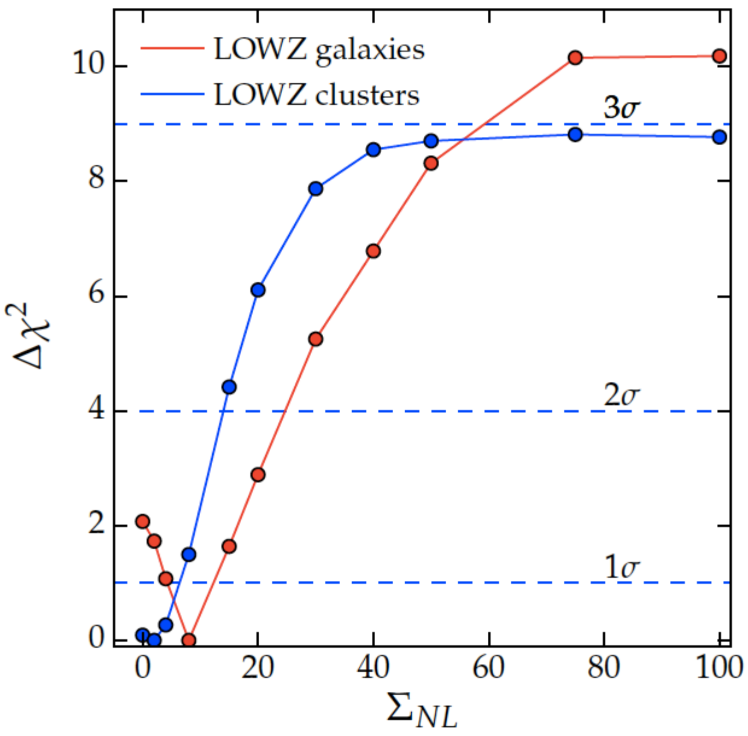
Comparing galaxy and cluster BAOs



Results are consistent!

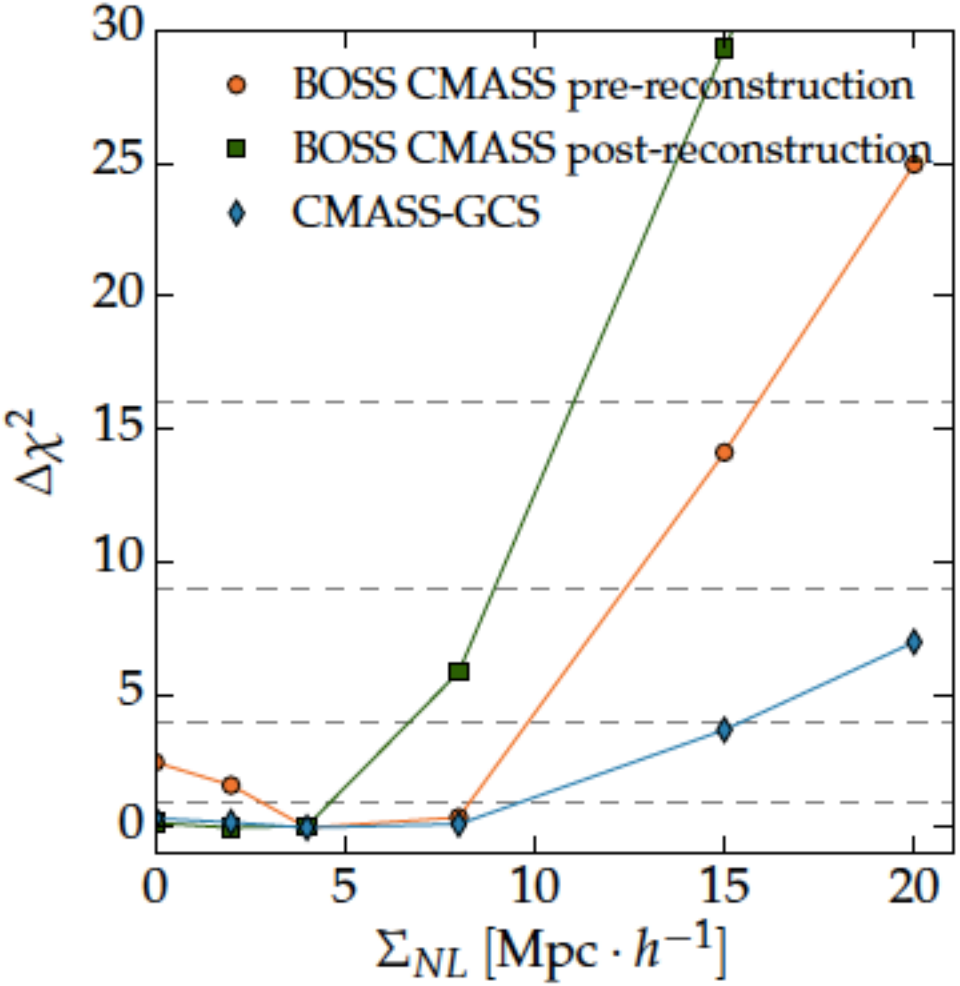
Constraints from clusters slightly better than the ones from WiggleZ, despite of the paucity of the samples, while broader w.r.t. BOSS results.

BAO: Galaxies vs. Clusters



Significance of the BAO detection is similar between the two samples.

BAO feature is sharper for galaxy clusters (Σ_{NL}=0 Mpc/h) w.r.t. galaxies (best fit Σ_{NL}=8 Mpc/h).



BOSS CMASS pre-reconstruction
BOSS CMASS post-reconstruction
CMASS-GCS
$\Delta\chi^2$
Σ_{NL} [Mpc $\cdot h^{-1}$]
0
5
10
15
20
25
30