Cosmology from cluster clustering

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The XXL survey

The clustering of X-ray selected galaxy clusters at z~0.3

Marulli, Veropalumbo and the XXL Team

A&A in press

Sesto Pusteria

Paving the way for next generation of cosmological surveys: new results and new methods in galaxy clustering

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Goals of the work

- We investigate the spatial properties of a homogeneous sample of X-ray selected galaxy clusters from the XXL survey, the largest programme carried out by the XMM-Newton satellite.

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- The measurements are compared to Λ-cold dark matter predictions, and used in combination with self-calibrated mass scaling relations to constrain the effective bias of the sample, b_{eff}, and the matter density contrast, Ω_M.

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- On the other hand, it is much harder to exploit the clustering properties of galaxy clusters, due to the challenging task of collecting large homogeneous cluster samples, especially when the selection is done in the X-ray band.
- Despite the paucity, relative to galaxies, of cluster catalogues and the difficulty to build up complete and pure samples covering wide ranges of masses and redshifts, there are numerous advantages in exploiting clusters as cosmic tracers.

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- Furthermore, the non-linear damping in baryon acoustic oscillations of cluster clustering is small, thus improving the significance of peak detection (Veropalumbo et al. 2014, 2016).

XXL cluster catalogues

The XXL survey, the largest programme carried out by the XMM-Newton satellite to date, has been specifically designed to provide a large, well-characterised sample of X-ray detected clusters suitable for cosmological studies (Pierre et al. 2016). The XXL number counts are consistent with WMPA9 and below the Planck 2015 predictions (Pacaud et al. 2016).

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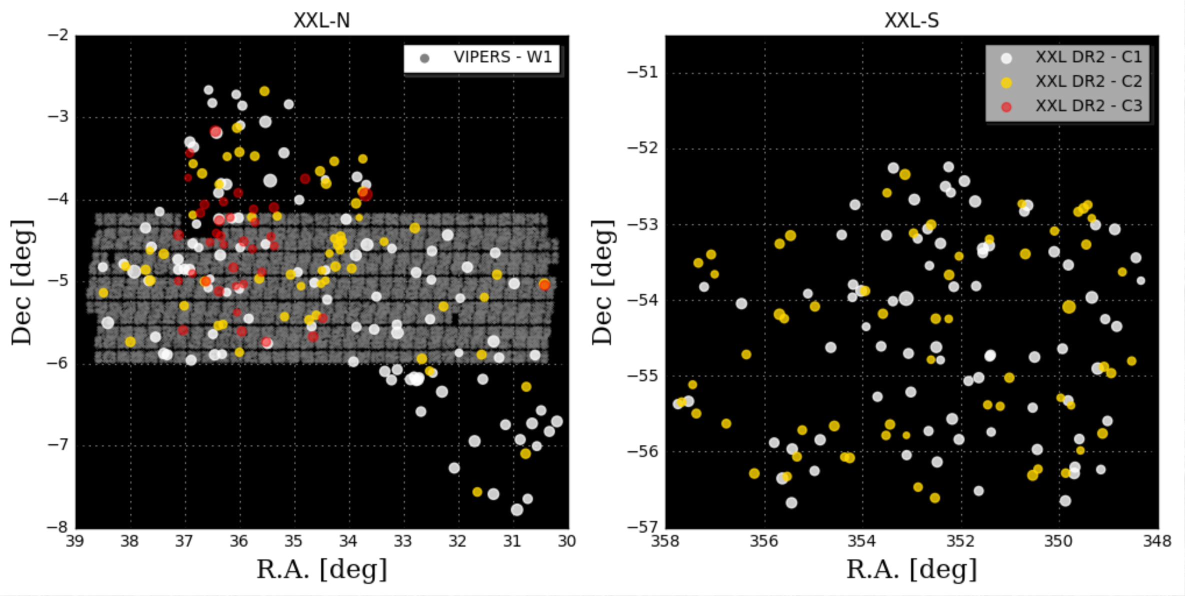
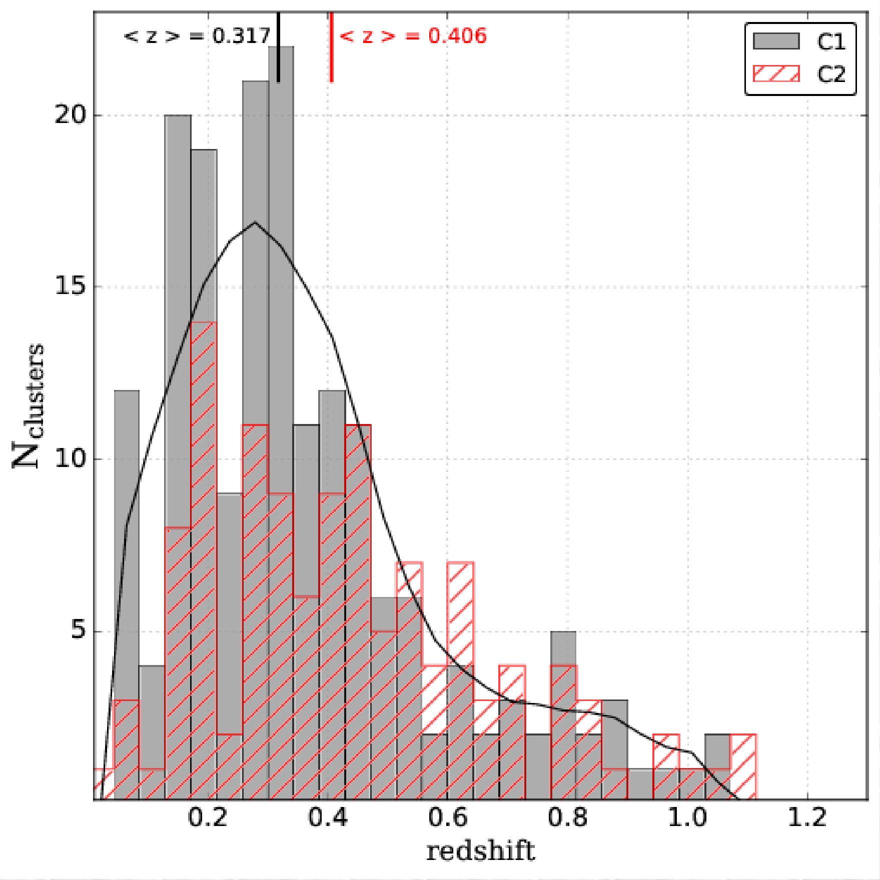
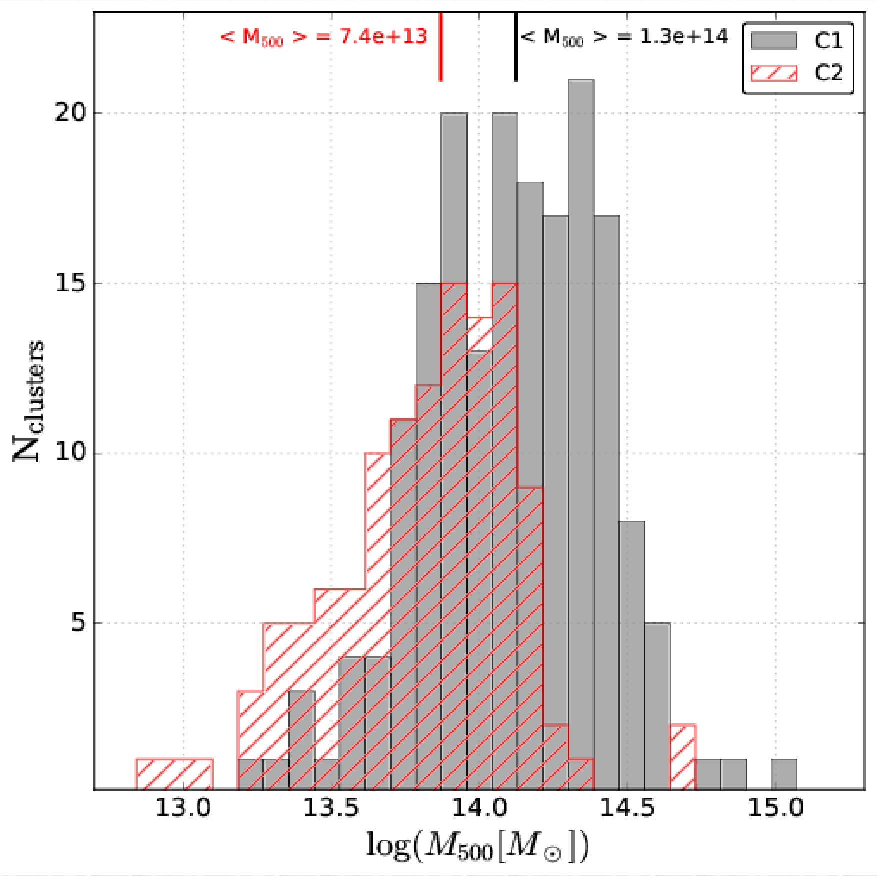


The survey covers two extragalactic sky regions of ~50 deg^2 in total, down to a point-source sensitivity of $\sim 6 \cdot 10^{-15}$ erg s^{-1} cm^{-2} , in the [0.5-2] keV band.

There are 341 XXL clusters in total in the XXL DR2 catalogue:
183 clusters of type C1, in $0.04 < z < 1.99$, $<z> = 0.366$
119 clusters of type C2, in $0.03 < z < 1.08$, $<z> = 0.435$
39 clusters of type C3, in $0.05 < z < 1.22$, $<z> = 0.446$

Redshift and mass distributions





The redshift and mass distribution of XXL C1 (grey histogram) and C2 (red histogram) clusters at z < 1.5. A follow-up programme has been tailored to obtain spectroscopic redshifts (e.g. VIPERS, GAMA, VVDS and dedicated XXL follow-up campaigns)

→ Masses will be used to compute the cluster effective bias.

XXL 3D cluster clustering

1st step to measure the XXL cluster clustering:
R.A., Dec, redshift → X, Y, Z assuming WMAP9 cosmology

The real comoving distance is:

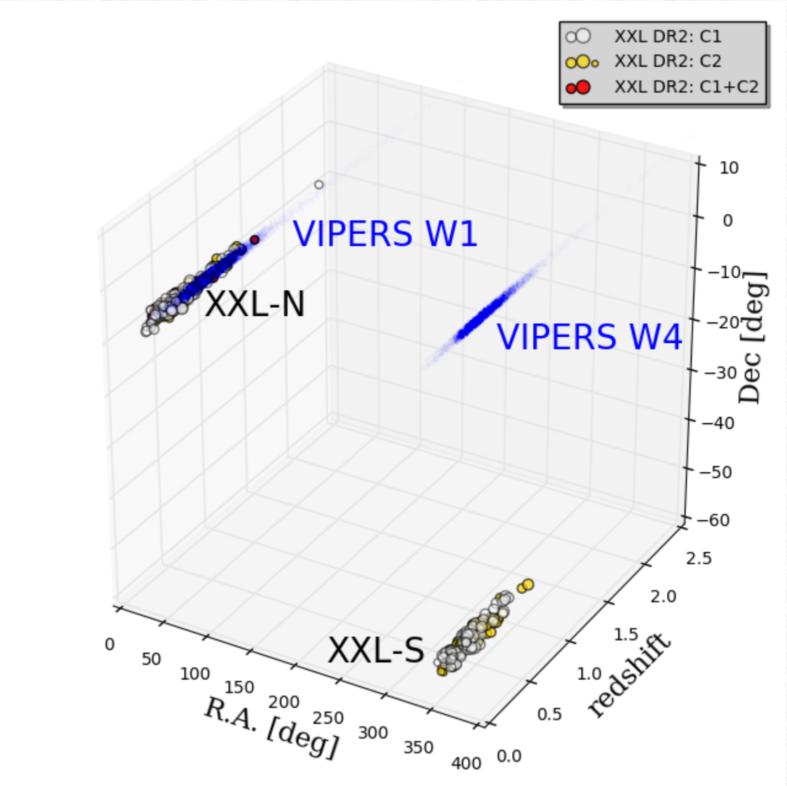
$$d_c = c \int_0^z \frac{dz'}{H(z')}$$

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

The observed redsfhit is:

$$z_{obs} = z + \frac{v_{\|}}{c}(1+z)$$

z_c : cosmological redshift due to the Hubble flow
$v_{||}$: component of the galaxy peculiar velocity parallel to the line-of-sight



XXL 3D cluster clustering

2nd step to measure the XXL cluster clustering:
compute a clustering estimator

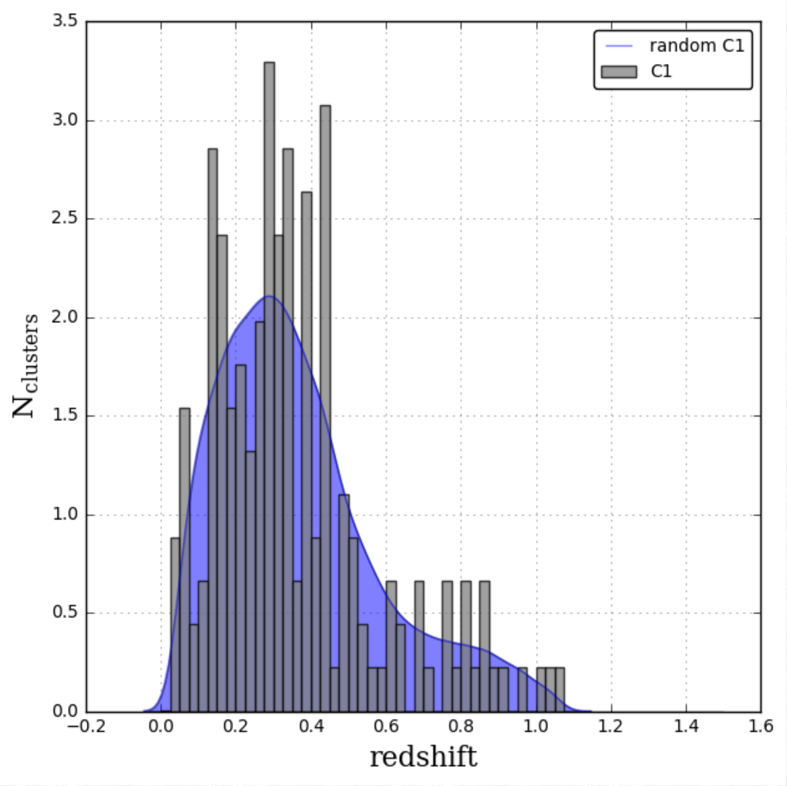
$$dP_{12} = n^2 dV_1 dV_2 \left[1 + \xi_{12}(r)\right]$$

where dP_{12} is the probability of finding a pair with one object in the volume dV_1 and the other in the volume dV_2, separated by a comoving distance r.

Landy & Szalay (1993) estimator:

$$\hat{\xi}(s) = \frac{N_{RR}}{N_{CC}} \frac{CC(s)}{RR(s)} - 2 \frac{N_{RR}}{N_{CR}} \frac{CR(s)}{RR(s)} + 1$$

CC(r), RC(r) and RR(r) are the fractions of cluster–cluster, cluster–random and random–random pairs, with spatial separation r, in the range [r-dr/2, r+dr/2].



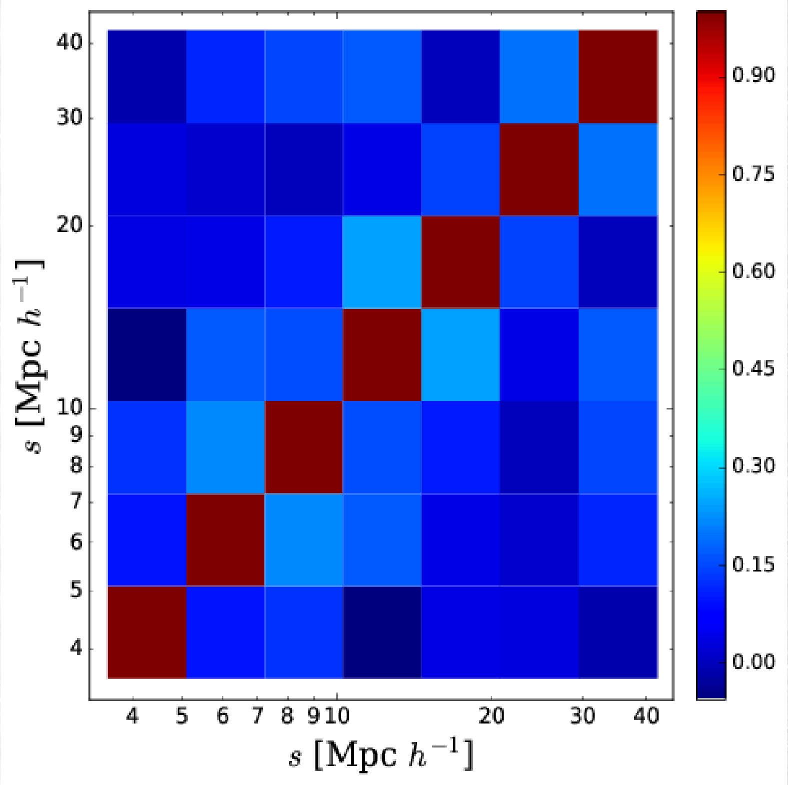
Random catalogue 100 times larger than the real one; R.A.-Dec distribution (shuffling) + z distribution (Gaussian smoothing the real one)

XXL 3D cluster clustering

3rd step to measure the XXL cluster clustering:
estimate the errors

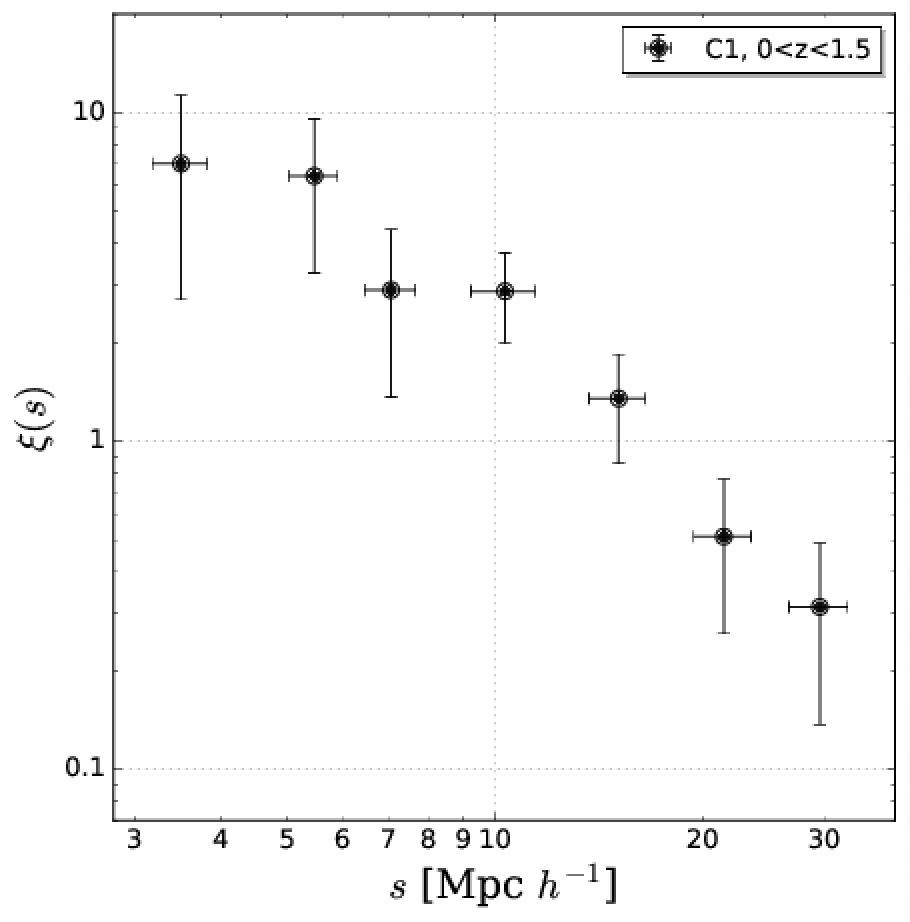
Bootstrap: We assess the XXL 2PCF covariance matrix with the Bootstrap method, using 1000 realisations obtained by resampling galaxy clusters from the original catalogue, with replacement.

$$C_{i,j} = \mathcal{F} \sum_{k=1}^{N_R} (\xi_i^k - \bar{\xi}_i)(\xi_j^k - \bar{\xi}_j)$$



The Bootstrap correlation matrix of C1 XXL clusters at z < 1.5.

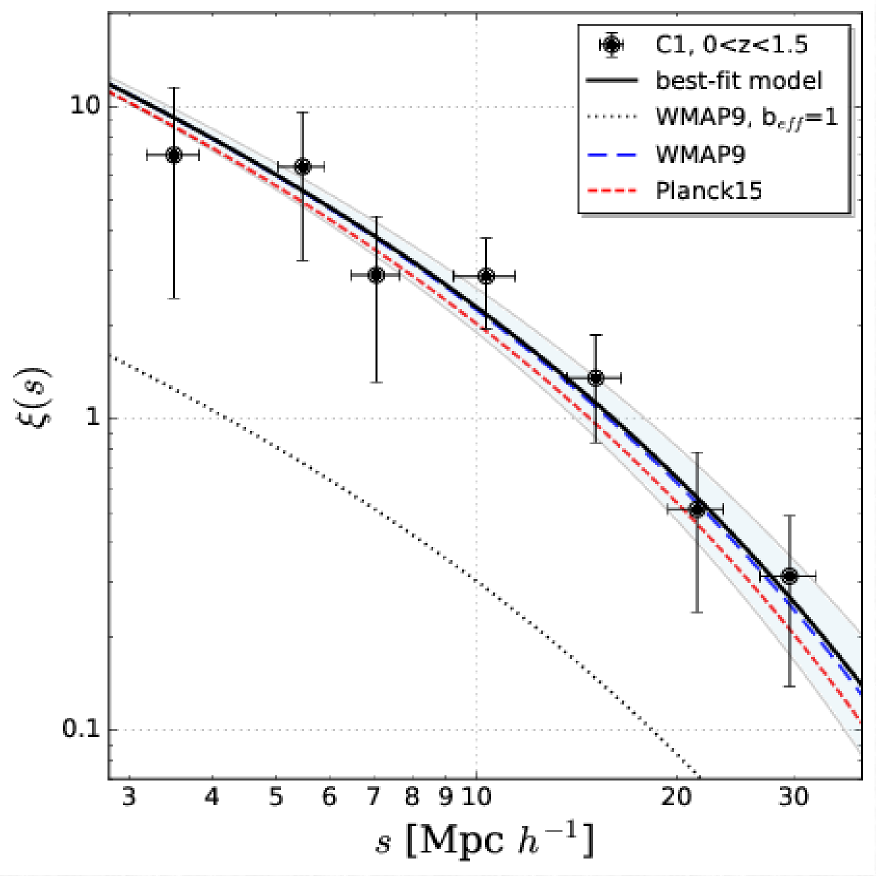
XXL 3D cluster clustering



The redshift-space 2PCF of the C1 XXL clusters. We define the comoving separation associated with each bin as the average cluster pair separation inside the bin. The vertical error bars are the diagonal values of the Bootstrap covariance matrix, while the horizontal error bars represent the standard deviation around the mean pair separation in each bin.

Modelling the XXL clustering

Measurements are consistent with theoretical predictions from CBM measurements



The Kaiser model is used to fit the redshift space two-point clustering

$$-2\ln\mathscr{L} = \sum_{i=1}^{N}\sum_{j=1}^{N}(\xi_i^d - \xi_i^m)C_{i,j}^{-1}(\xi_j^d - \xi_j^m)$$

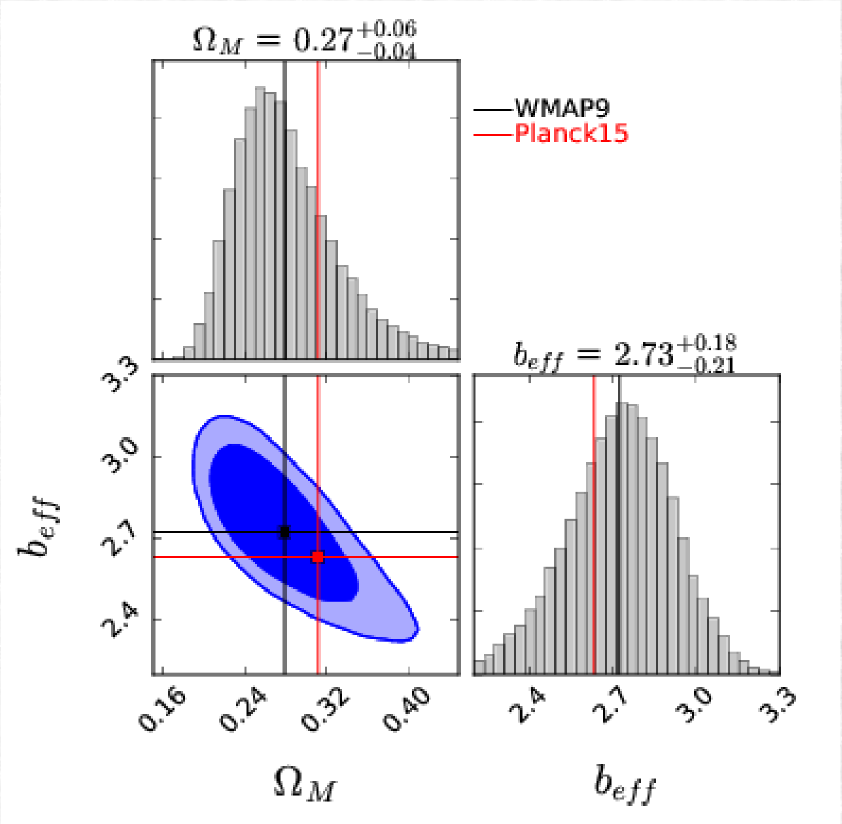
$$\xi^m(s) = \left[(b_{eff}\sigma_8)^2 + \frac{2}{3}f\sigma_8 \cdot b_{eff}\sigma_8 + \frac{1}{5}(f\sigma_8)^2\right]\frac{\xi_{\rm DM}(\alpha r)}{\sigma_8^2}$$

$$D_V \equiv \left[(1+z)^2 D_A^2 \frac{cz}{H}\right]^{1/2}$$

$$b_{eff}^2 = < b(\tilde{M}_i, z_i) b(\tilde{M}_j, z_j) >$$

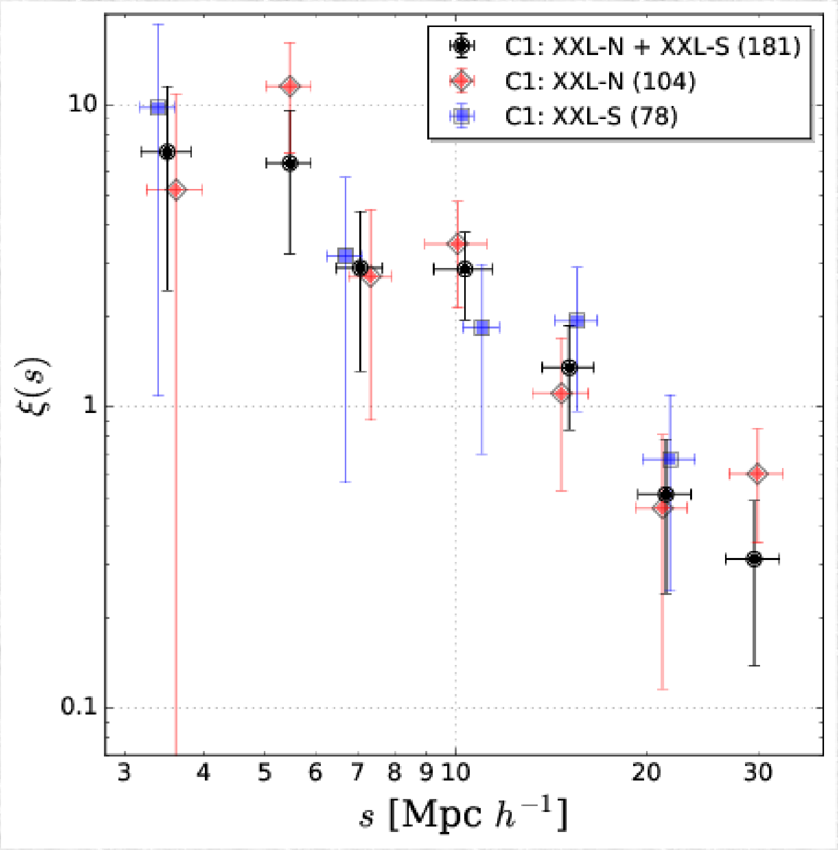
The redshift-space 2PCF of the C1 XXL clusters (black dots) compared to the best-fit model, that is the median of the MCMC posterior distribution (black solid line). The shaded area shows the 68% uncertainty on the posterior median. The derived best-fit model correlation length is s_0=16±2 Mpc/h. The red dashed and blue long-dashed lines show the WMAP9 and Planck15 predictions, respectively, computed as described in Section 4. Their correlation lengths are s_0=15.83 Mpc/h and s_0=14.81 Mpc/h, respectively. The black dotted line shows the WMAP9 prediction with b_{eff}=1, as a reference.

Cosmological constraints on Ω_M

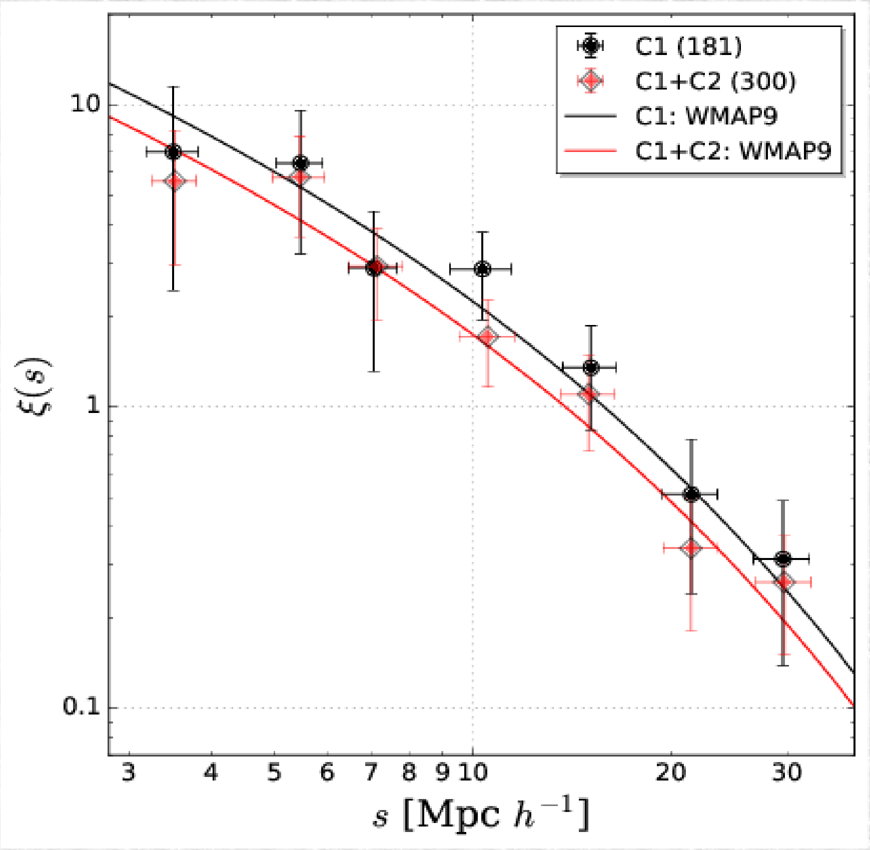


1-2σ confidence contours of Ω_M–b_{eff} provided by the MCMC; b_{eff} is a derived parameter, the ellipse width corresponds to the deviation of the σ_8 Gaussian prior. The histograms in the upper and right panels show the posterior distributions of Ω_M and b_{eff}, respectively. Black and red lines represent WMAP9 and Planck15 predictions, respectively.

Tests on systematics : sample selection



Comparison between the redshift-space 2PCF of XXL C1 in XXL-N (red diamonds), XXL-S (blue squares) and in the whole sample (black dots).

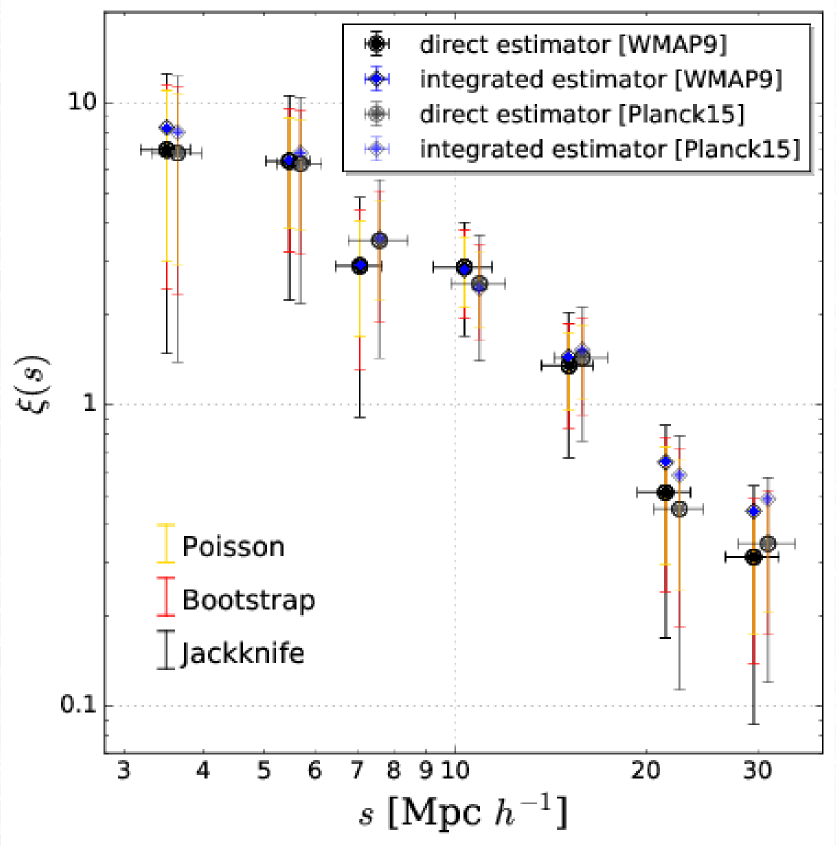


Comparison between the redshift-space 2PCF of XXL C1 (black dots) and C1+C2 clusters (red diamonds).

Tests on systematics : 2PCF estimator

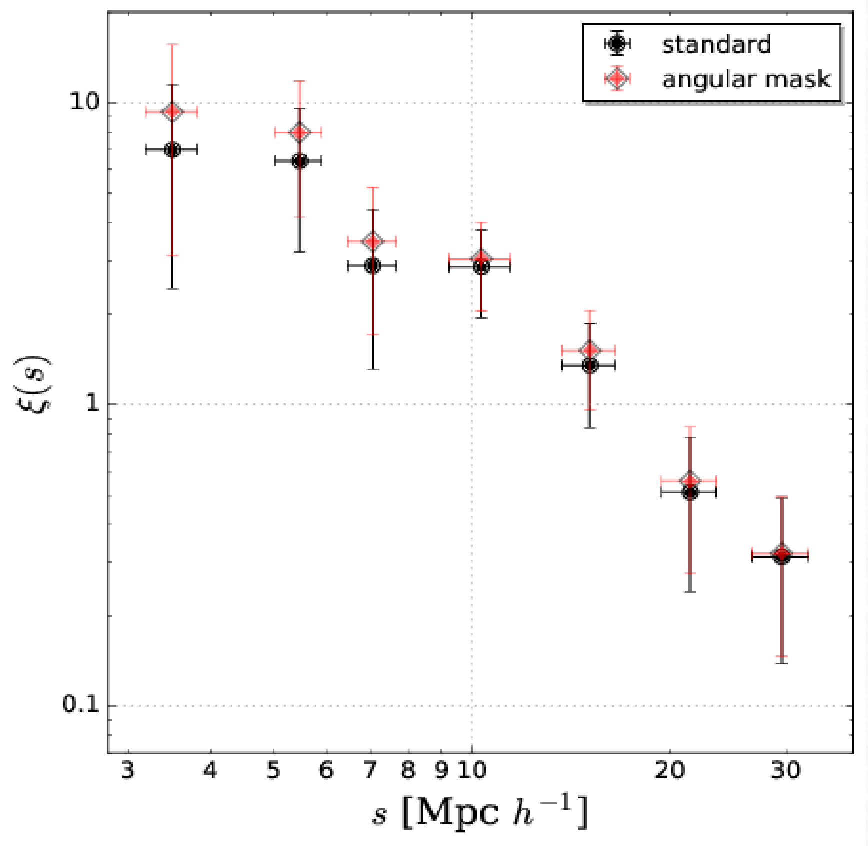
$$\xi_\ell(r) = \frac{2\ell+1}{2}\int_{-1}^{1} \mathrm{d}\mu\, L_\ell(\mu)\xi(r,\mu)$$

$$\hat{\xi}_\ell(r) = \frac{2\ell+1}{2}\int_{-1}^{1} \mathrm{d}\mu\, L_\ell(\mu)\left(\frac{N_{RR}}{N_{CC}}\frac{CC(s,\mu)}{RR(s,\mu)} - 2\frac{N_{RR}}{N_{CR}}\frac{CR(s,\mu)}{RR(s,\mu)} + 1\right)$$



Comparison between the redshift-space 2PCF of XXL C1 clusters computed with the direct (dots) and integrated (diamonds) estimators, assuming either WMAP9 (solid coloured) or Planck15 (fuzzy coloured, slightly shifted for reasons of clarity). The error bars compare the Poisson, Bootstrap and Jackknife estimated errors.

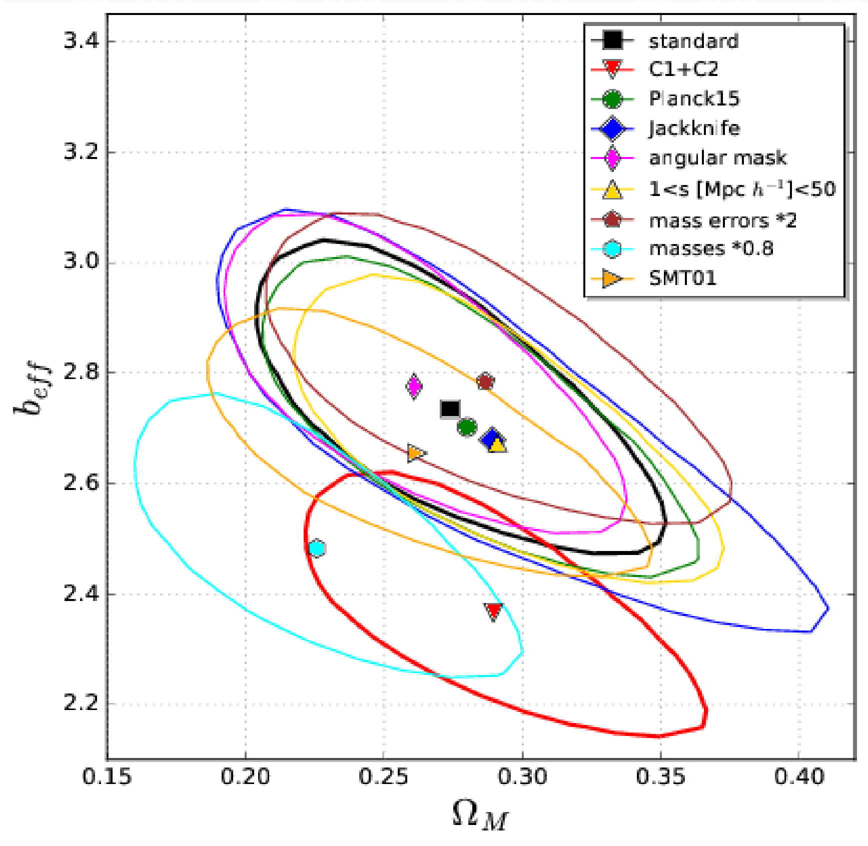
Tests on systematics : random catalogue



Comparison between the redshift-space 2PCF of XXL C1 clusters computed with the random catalogue constructed (black dots) and considering the angular mask (red diamonds).

Tests on systematics : modelling

1σ MCMC confidence contours of Ω_M–b_{eff} obtained with different assumptions: standard analysis - black; considering C1+C2 XXL clusters, instead of C1 only - red; assuming Planck15 as reference cosmology, instead of WMAP9 - green; with Jackknife covariance, instead of Bootstrap - blue; considering the angular mask to construct the random catalogue – magenta; considering the fitting scale range 1<r[Mpc/h]<50, instead of 10<r[Mpc/h]<40 - yellow; doubling the statistical mass errors - brown; reducing the masses by 20% - cyan; assuming the Sheth et al. (2001) bias model to compute the effective bias of the sample - orange.



Summary

- We measured the 2PCF in redshift space of a sample of 182 X-ray selected galaxy clusters at median redshift $\langle z \rangle = 0.317$ and median mass $\langle M_{500} \rangle = 1.3 \cdot 10^{14}$ Msun. This is the first time that the clustering of an X-ray selected cluster catalogue at such relatively high redshifts and low masses has been measured.

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- Though the current measurement uncertainties are not small enough to discriminate between WMAP9 and Planck15 cosmologies, this work demonstrates the feasibility of a cosmological exploitation of XXL cluster clustering, paving the way for a joint analysis in combination with cluster number counts.

Thank you!