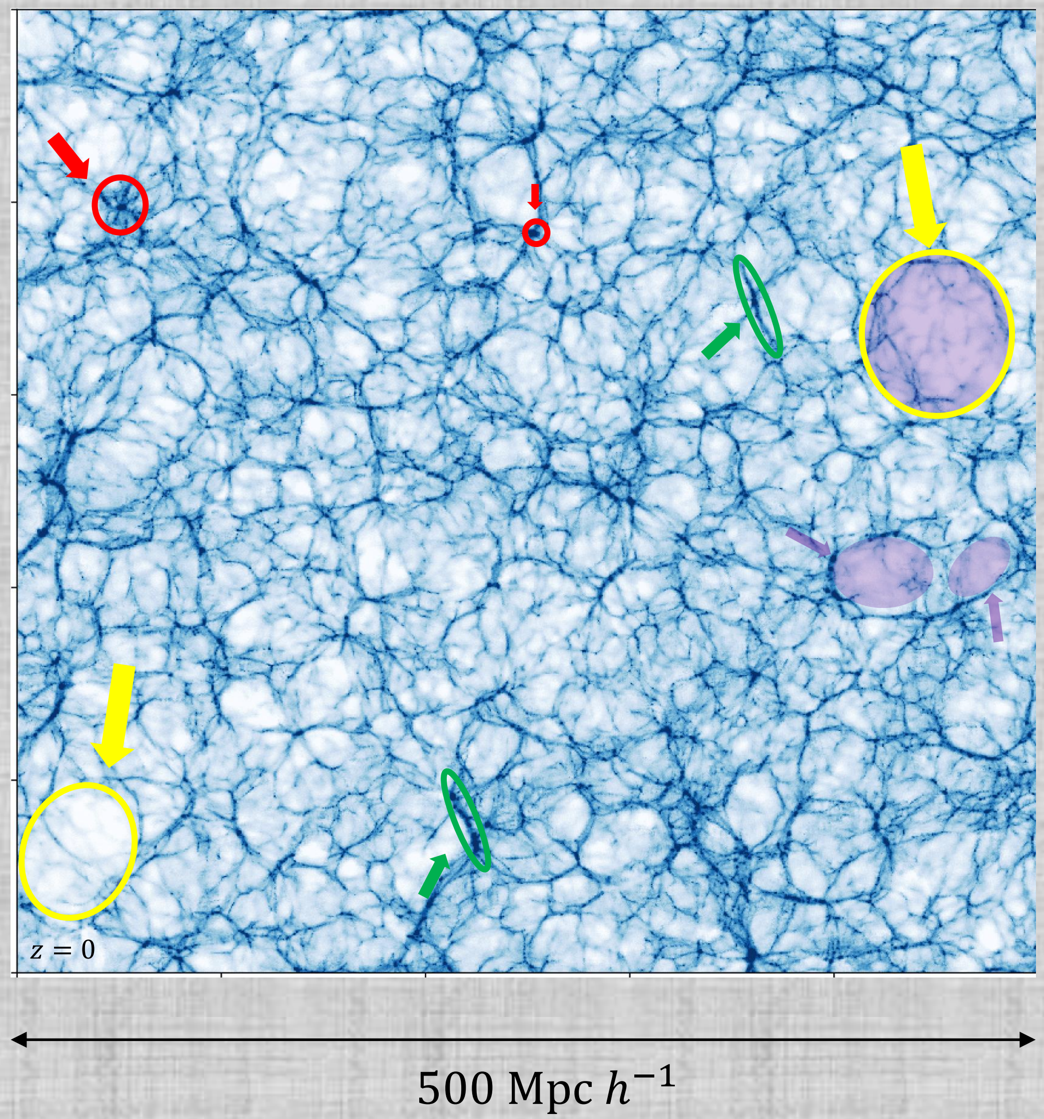
A new probe of the large-scale structure of the Universe

Joaquín Armijo, Carlton Baugh, Peder Norberg, Nelson Padilla

How to test gravity at large-scale?

Elephant simulations (Li et al. 2012)

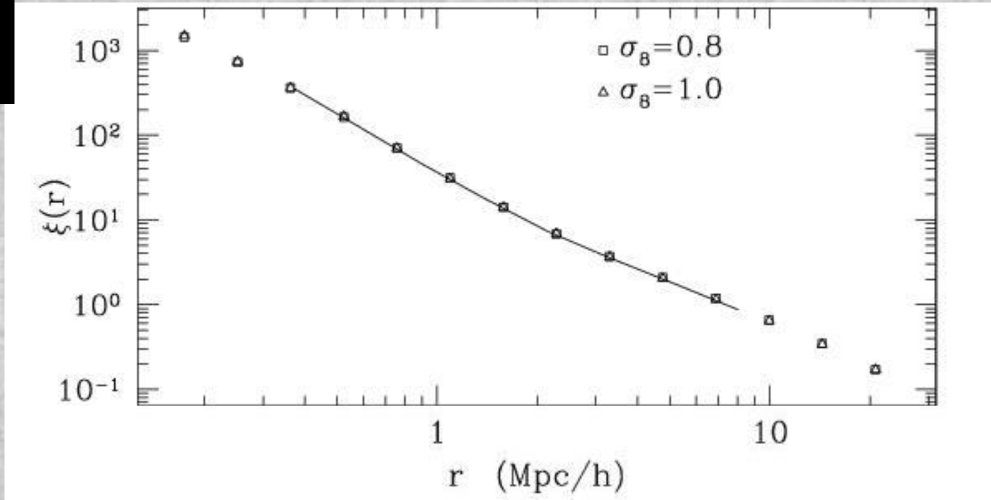


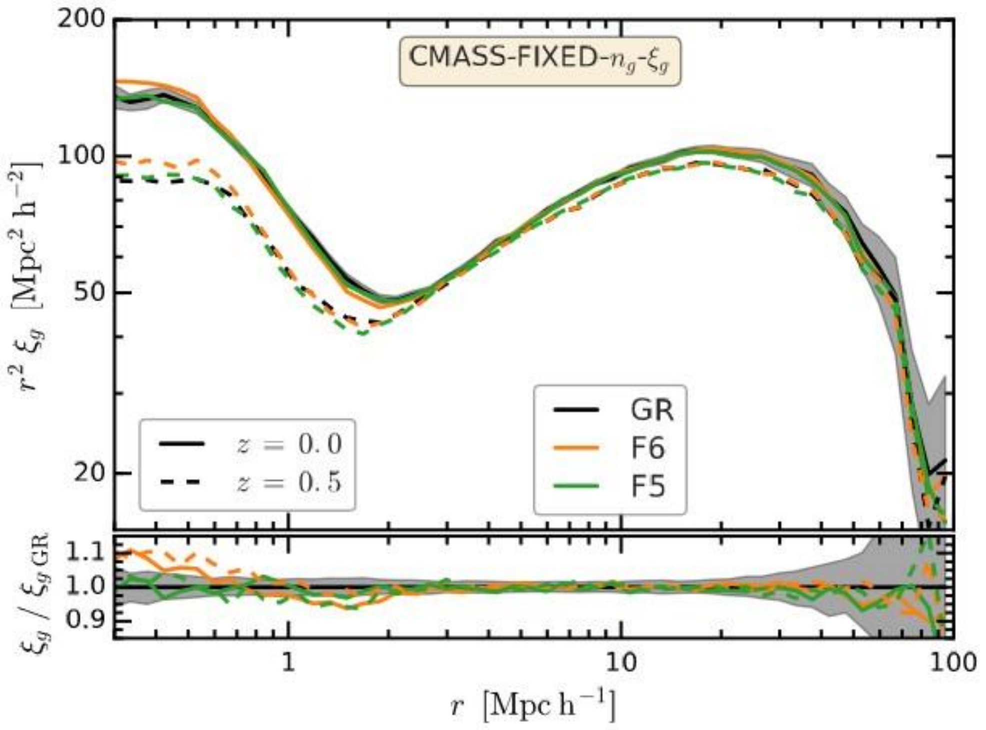
- The distribution of matter at late times forms a filamentary structure known as the cosmic web.
- At low-redshift, galaxies group in a large-scale network of nodes, filaments, walls and voids.
- The large-scale structures are mainly shaped by gravity and the late cosmic acceleration, creating different environments where galaxies live.

The galaxy two-point correlation function

- Currently, galaxy redshift surveys offer accurate measurements of the distribution of galaxies at large-scales.
- Mock galaxy catalogues should reproduce both the number density $n(z)$ and the projected 2-point clustering.
- The match between these metrics between the observation and the simulations permits the study of gravity on large-scale structures with detail.
- The tuning of HOD parameters can be used to generate galaxy catalogues that include such observational constraints (Cautun et al. 2017, Paillas et al. 2018).

White & Padmanabhan 2008





Cautun et al. 2017

The marked correlation function

$$\mathcal{M}(r) \equiv \frac{1}{n(r)\bar{m}^2} \sum_{ij} m_i m_j = \frac{1+W}{1+\xi}$$

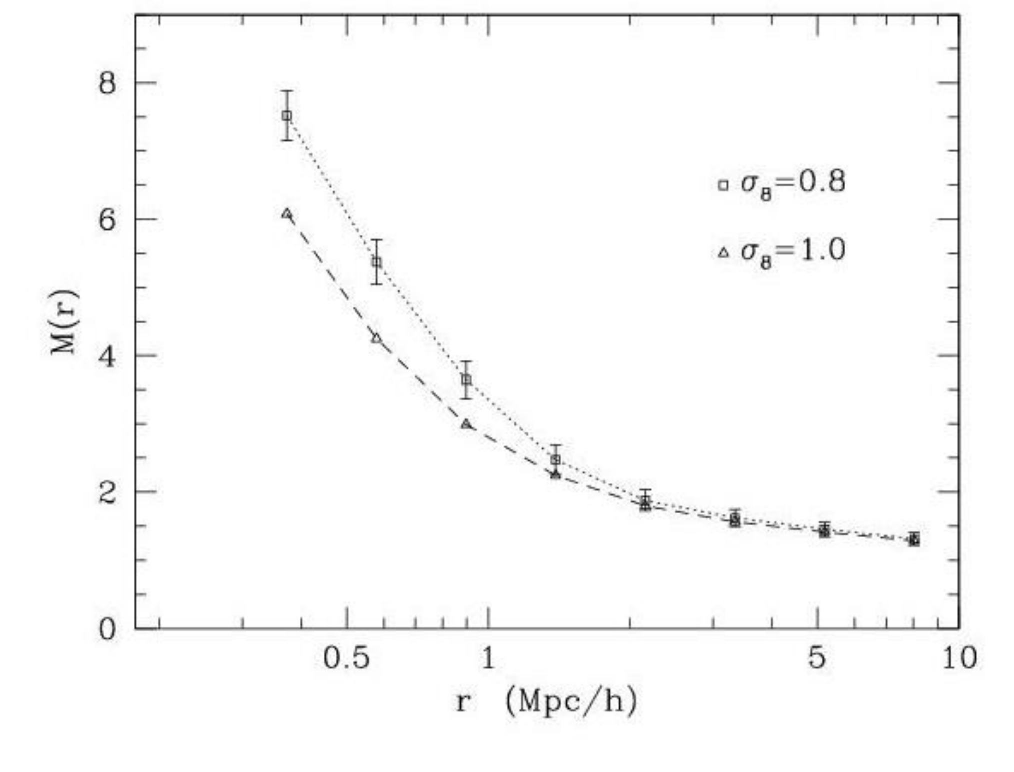
- When the two-point correlation function does not exhaust all the information of the data, marked statistic is a viable option.

- “Marks" can be used in two-point statistics to upweight models given a density environmental property.

- The mark choice to upweight MG models can be and the local density of galaxies the mass of the dark matter halos (Armijo et al. 2018).

- The marked correlation function has been used to distinguish between standard GR and MG (Hernandez-Aguayo et al. 2018).

Mark defined by local density



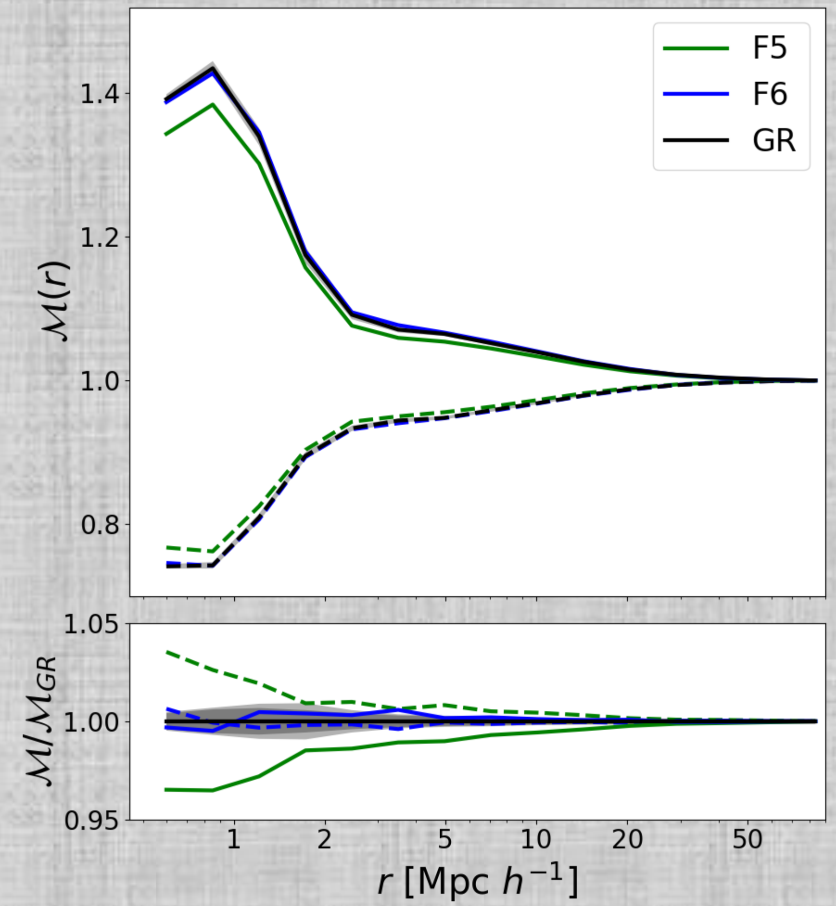
White & Padmanabhan 2008

The marked correlation function

$$\mathcal{M}(r) \equiv \frac{1}{n(r)\bar{m}^2} \sum_{ij} m_i m_j = \frac{1+W}{1+\xi}$$

- When the two-point correlation function does not exhaust all the information of the data, marked statistic is a viable option.
- "Marks" can be used in two-point statistics to upweight models given a density environmental property.
- The mark choice to upweight MG models can be and the local density of galaxies the mass of the dark matter halos (Armijo et al. 2018).
- The marked correlation function has been used to distinguish between standard GR and MG (Hernandez-Aguayo et al. 2018).

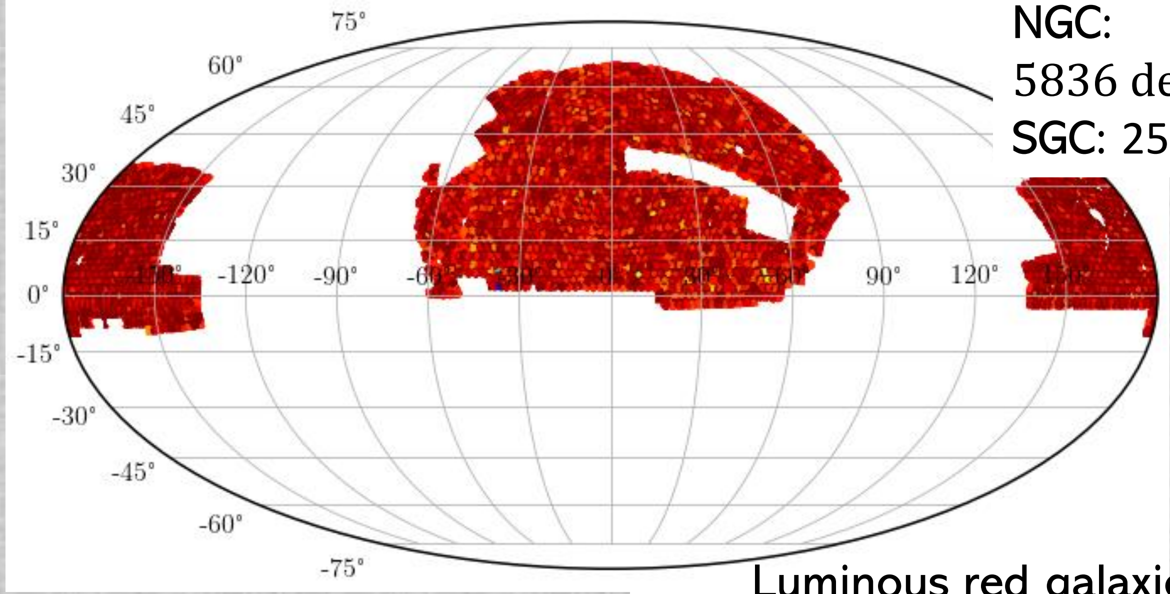
Mark defined by halo mass:



Armijo et al. 2018

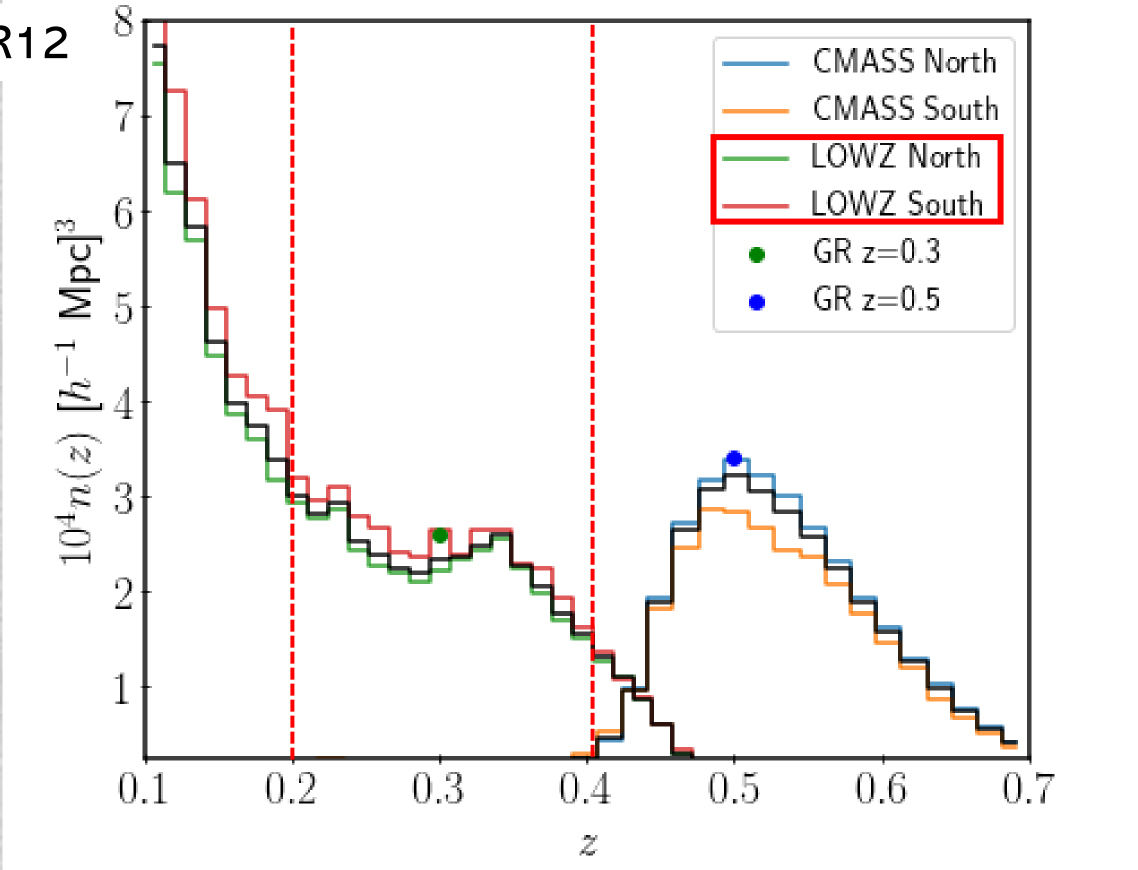
Galaxy & cluster samples

SDSS-III BOSS LOWZ

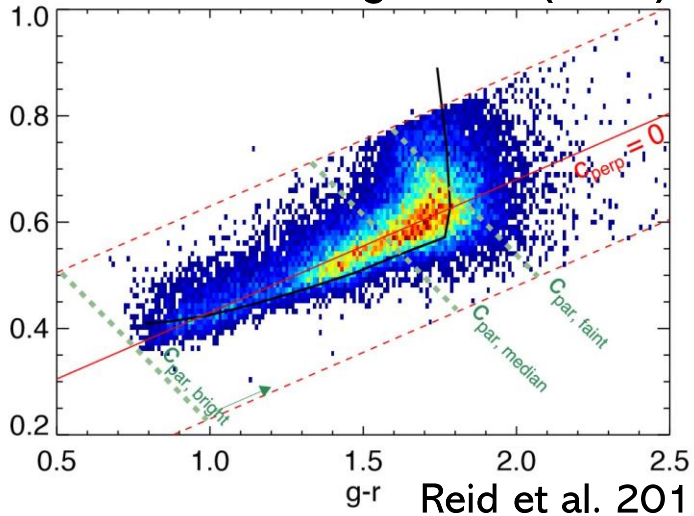


Survey footprint DR12

NGC:
5836 $\deg^2$
SGC: 2501 $\deg^2$



Luminous red galaxies (LRGs)



Reid et al. 2015

$r_{\rm cmod} < 13.5 + c_{\parallel}/0.3$

$|c_{\perp}| < 0.2$

$16 < r_{\rm cmod} < 19.6$

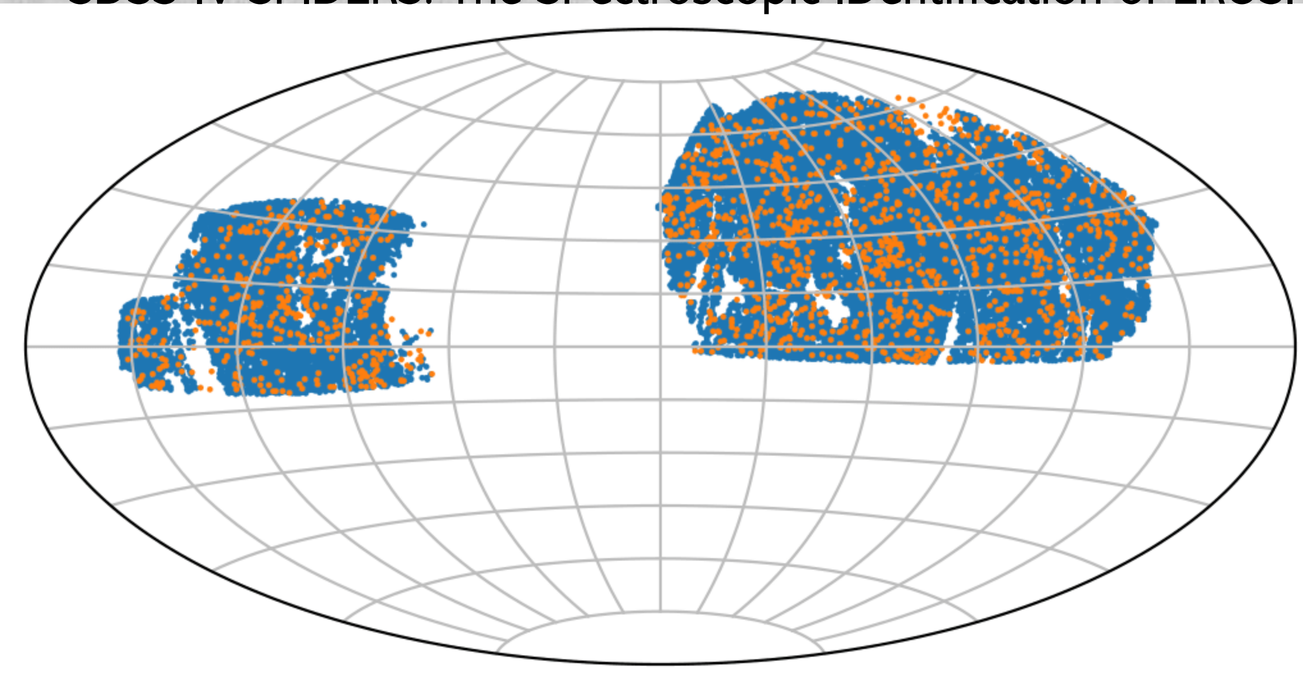
$r_{\rm psf} - r_{\rm cmod} > 0.3$

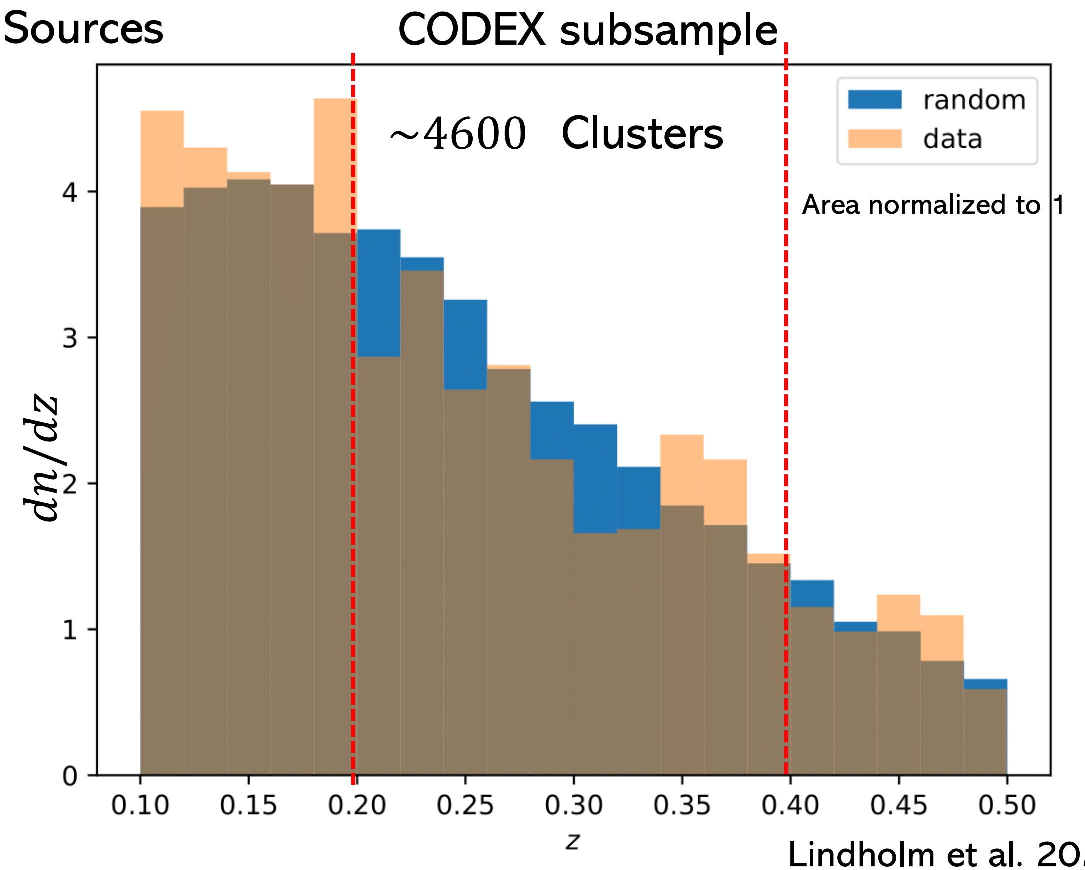
LOWZ $n_g \sim 3 \times 10^{-4}\ {\rm Mpc}^{-3} h^3$

This number density is close to optimal for large-scale cosmological studies (e.g., Kaiser 1986)

Galaxy & cluster samples

SDSS-IV SPIDERS: The SPectroscopic IDentification of EROSITA Sources





Lindholm et al. 2020

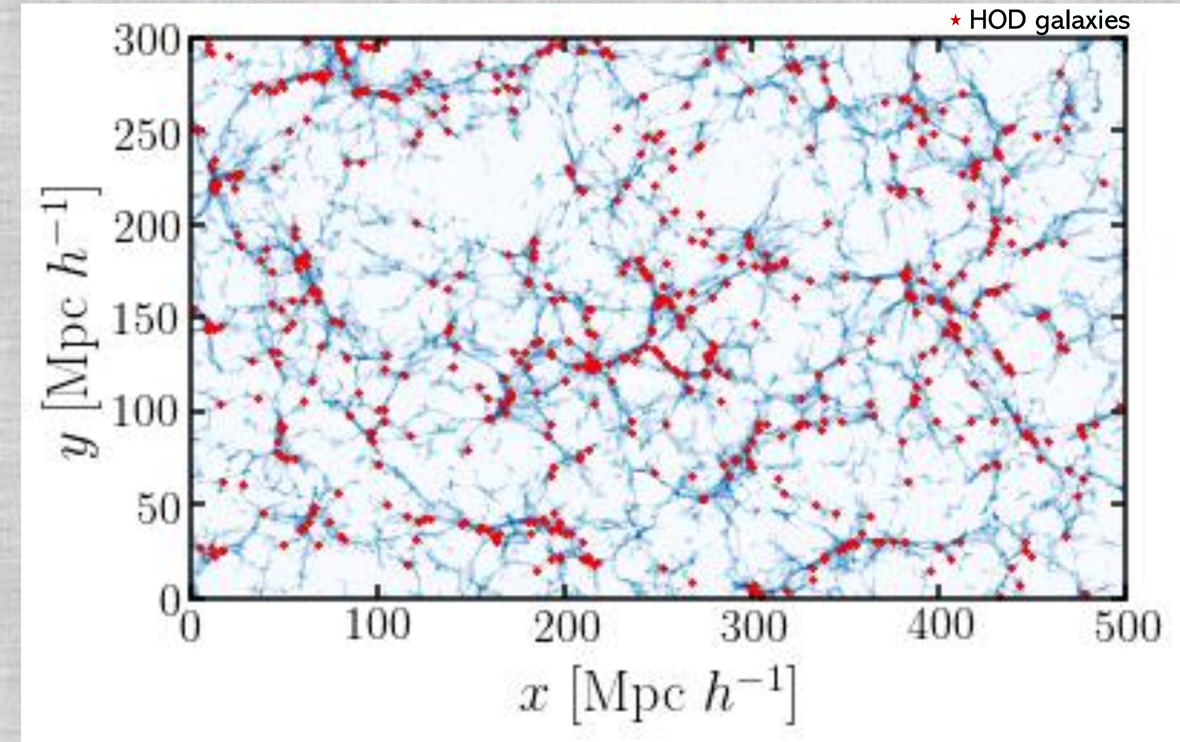
	CODEX
Number of clusters in SDSS DR8 footprint	10 415
Sky distribution	Full SDSS area
Average candidate density (deg^{-2})	0.8
Maximal redshift	~ 0.6
Red-sequence finder	redMaPPer v.5.2
Optical search	Around each X-ray source
Optical/X-ray association	Richness cut vs. chance identification

Clerc et al. 2016

- The final CODEX sample is obtained by using original X-ray catalogue and the red-sequence finder redMaPPer. The optical/X-ray association provides confident measurements for the redshift z and mass M_{200c} of each cluster.

HOD mock catalogues

Elephant simulations (Li et al. 2012)



- HOD parameters are tuned to obtain the same number density $n_g = 2.9 \times 10^{-4}\, h^3 \mathrm{Mpc}^{-3}$ and w_p than the LOWZ sample.

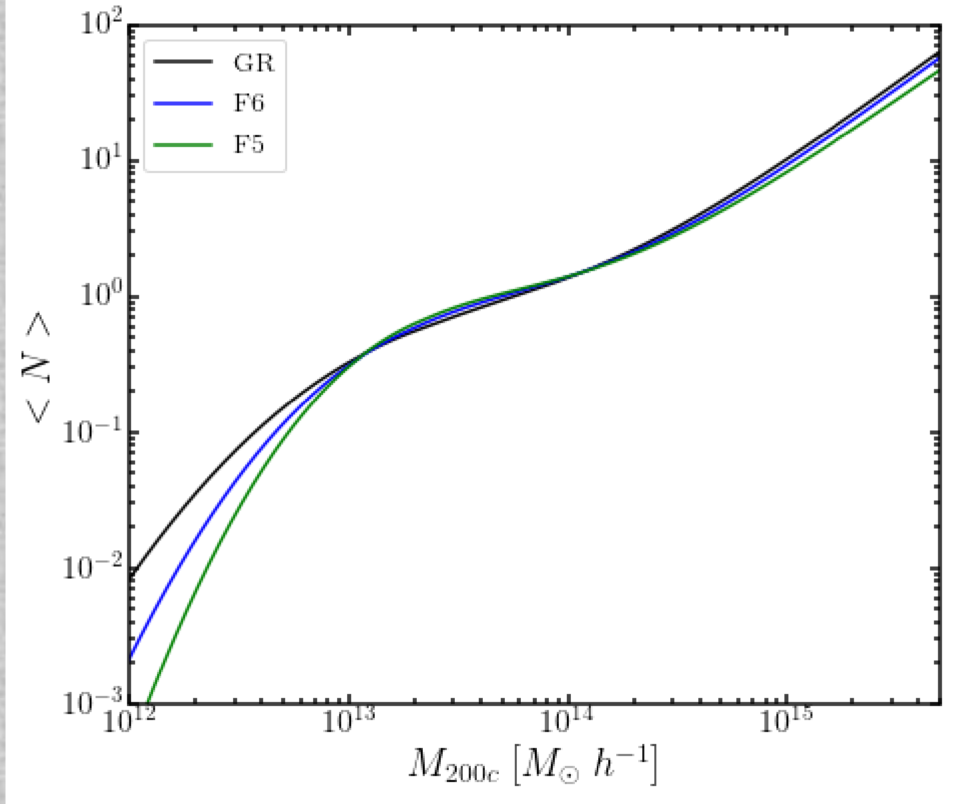
- The best parameters are obtained using MCMC fitting.

Halo occupation distribution

$$\langle N_{cen} \rangle = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M_{min} - M}{\sigma_{\log M_{min}}}\right)\right]$$

$$\langle N_{sat} \rangle = \langle N_{cen} \rangle \left(\frac{M - M_0}{M_1}\right)^{\alpha}$$

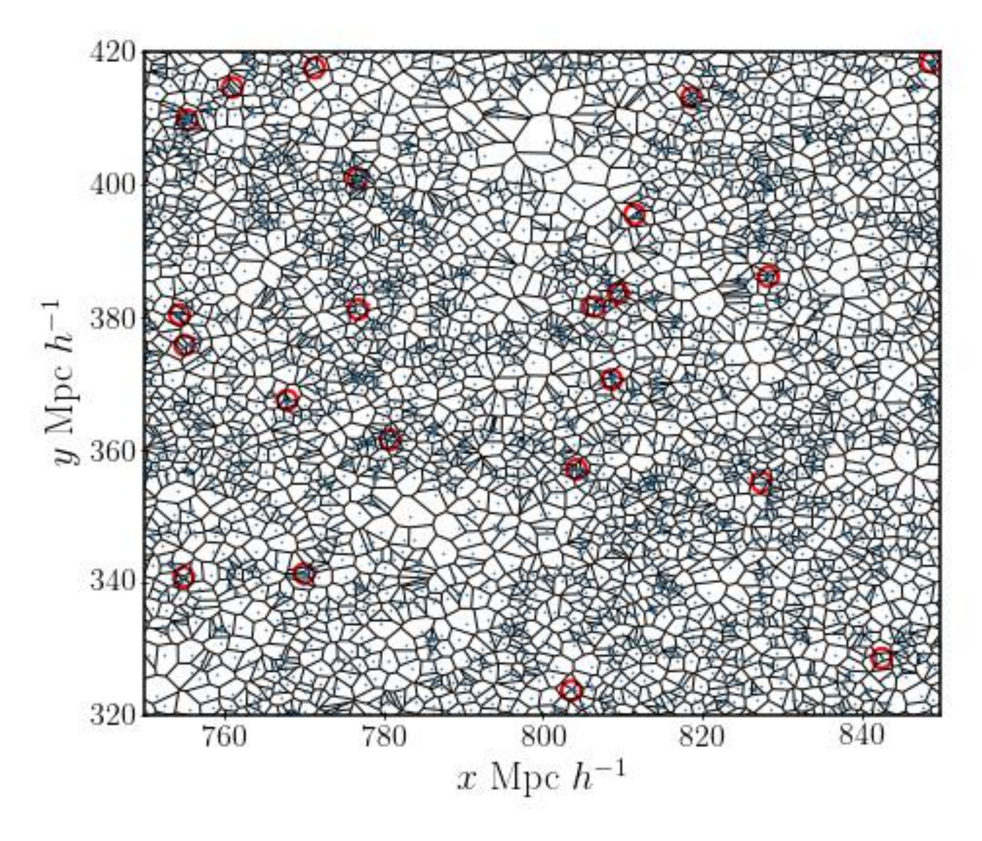
$$\langle N \rangle = \langle N_{cen} \rangle + \langle N_{sat} \rangle$$



New probes for large-scale structure

What we propose?

Marked statistic using the projected correlation function.

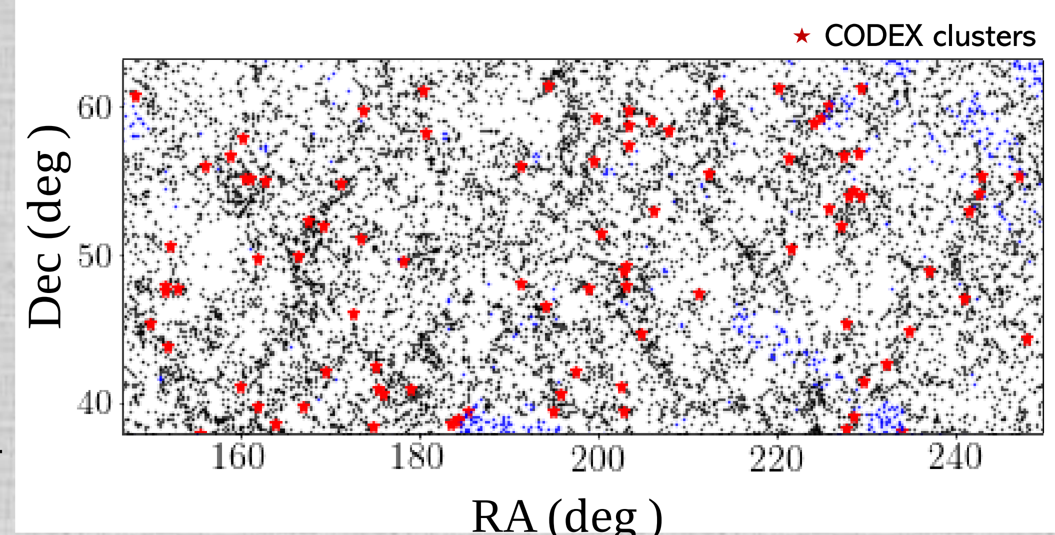


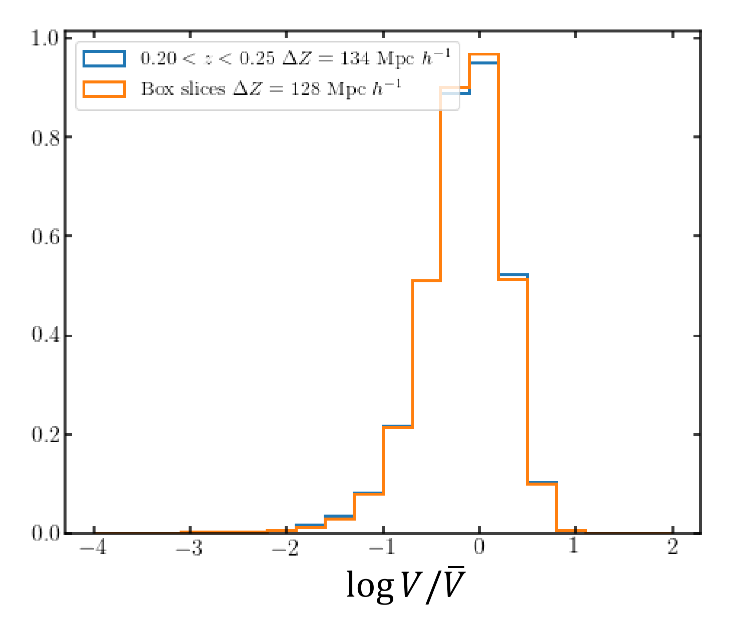
$$\mathcal{M}^p(r_p) = \frac{1 + W(r_p)}{1 + w_p(r_p)}$$

Best mark choices from Armijo et al. 2018:

- Voronoi tessellation density estimation on 2D.
- M_{200c} to mark high mass haloes (clusters).

$0.20 < z < 0.25$

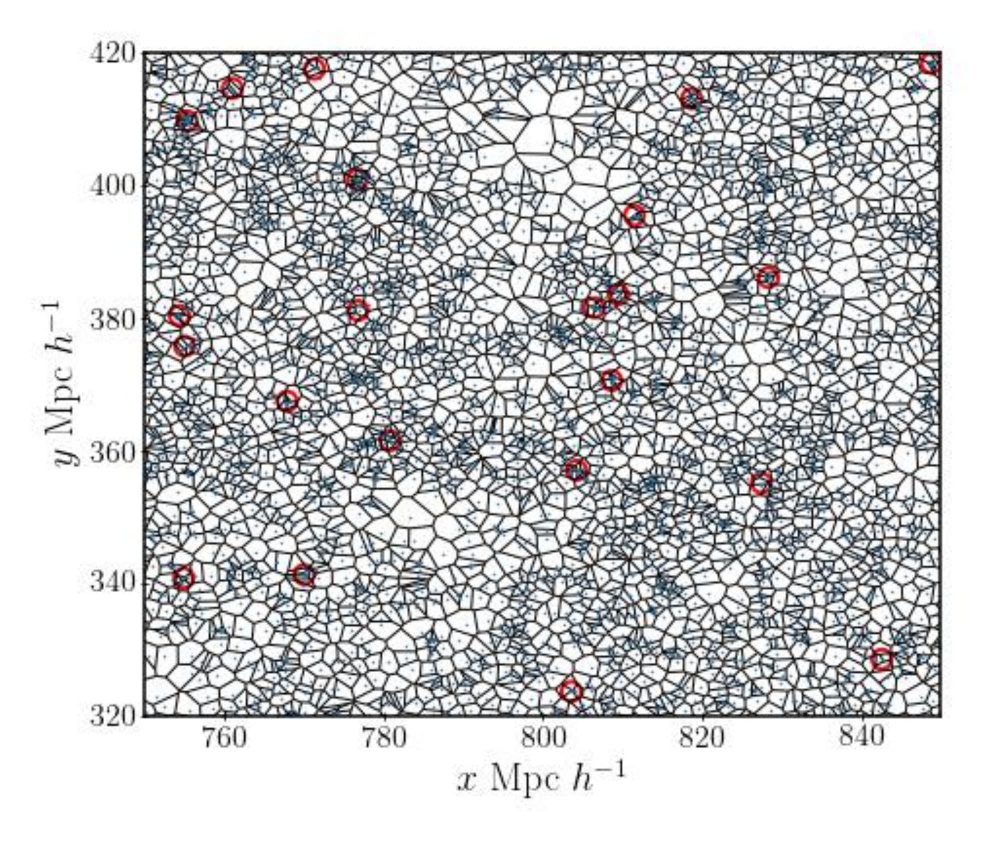




New probes for large-scale structure

What we propose?

Marked statistic using the projected correlation function.

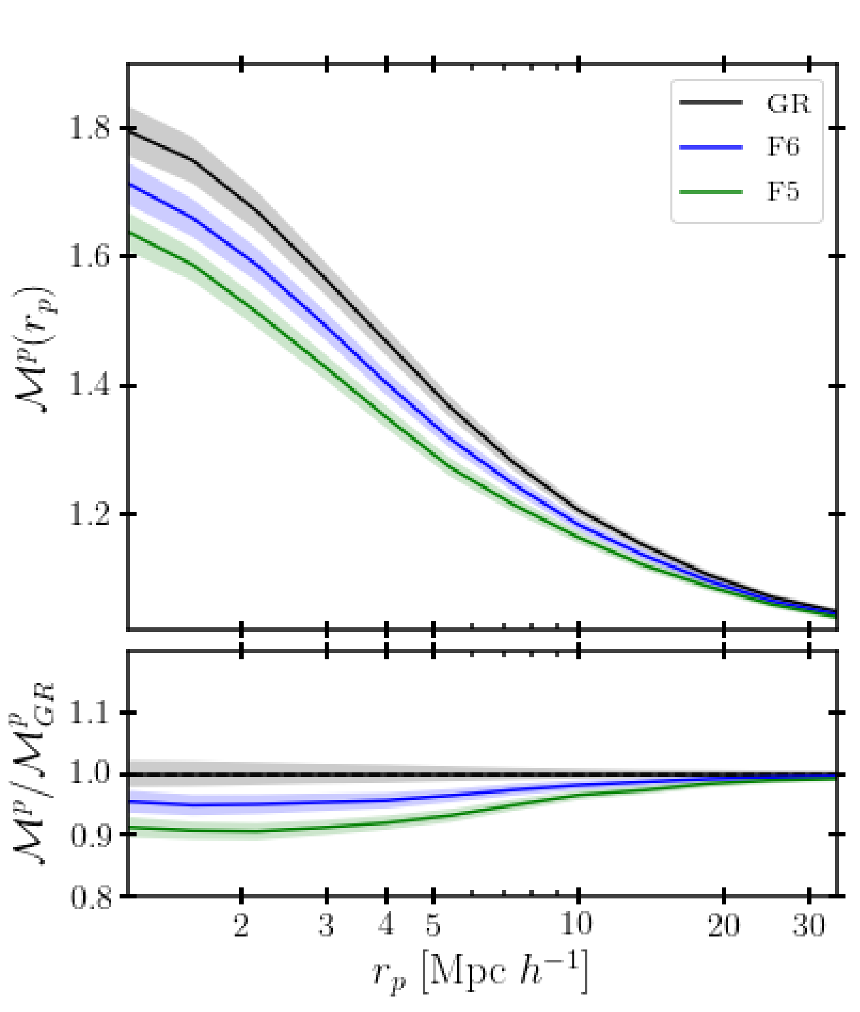


$$\mathcal{M}^p(r_p) = \frac{1 + W(r_p)}{1 + w_p(r_p)}$$

Best mark choices from Armijo et al. 2018:

- Voronoi tessellation density estimation on 2D.
- M_{200c} to mark high mass haloes (clusters).

Cross-correlation Cluster-galaxy



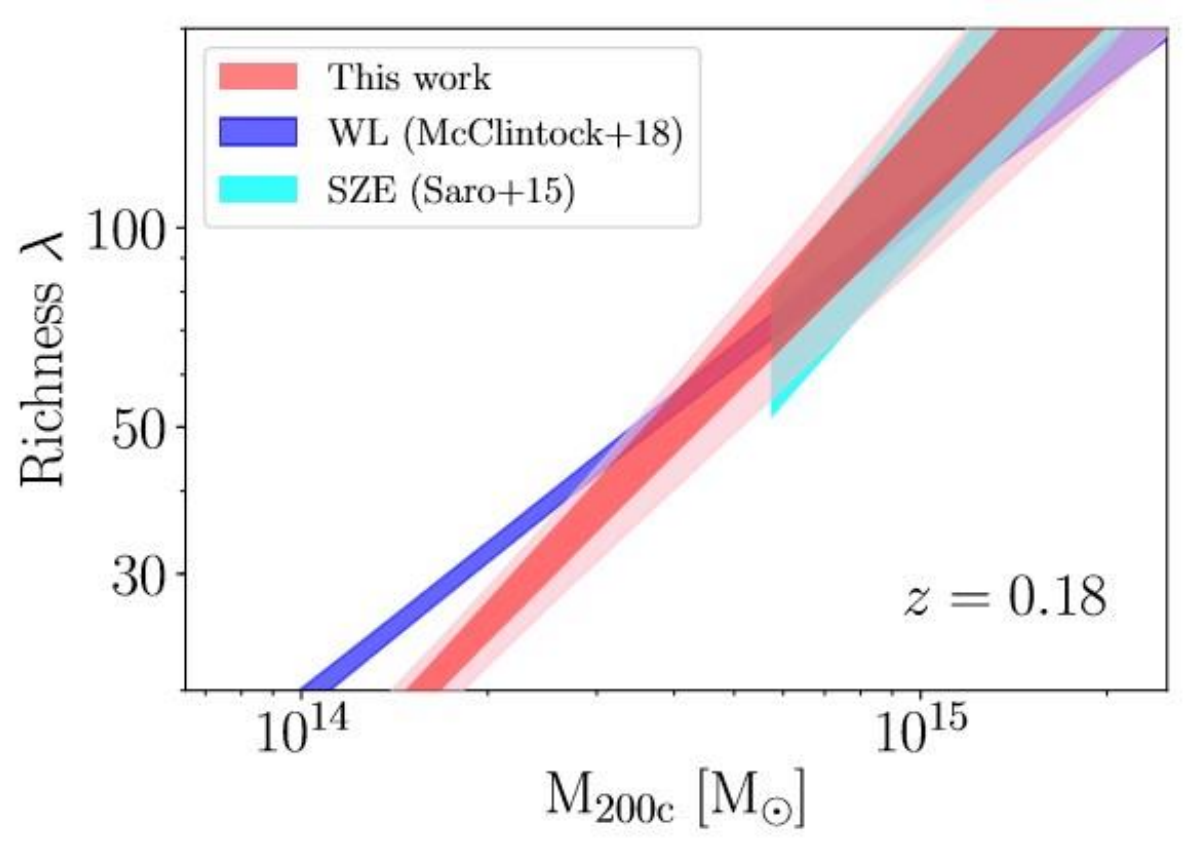
Summary and future work

- Use marked statistic to test gravity on large-scales and constrain the late accelerated expansion of the Universe.
- Large extragalactic surveys have the key information to perform such tests. The sample of luminous red galaxies from SDSS and the CODEX galaxy clusters that trace the distribution of matter in the Universe.
- Environmental properties like the local density and halo masses are good choices to mark galaxies and clusters. Test density dependent features like the screening mechanism in MG theories.
- HOD mock catalogues to model the effect of systematics errors in the sample to see how this affects the estimation of the marked correlation function.

Thank you for your attention!

Galaxy & cluster samples

- Optical Richness is estimated using the redMaPPer cluster-finder.
- The tracer members correspond to red sequence galaxies with full spectroscopic information from SDSS.
- Richness-Mass relation are calibrated using dynamical information (Jeans equation).
- This offers a catalogue with reliable measurements of halo mass to mark clusters.



$$\exp(\lambda) > 22\left(\frac{z}{0.15}\right)^{0.8} \quad \text{(Richness cut)}$$

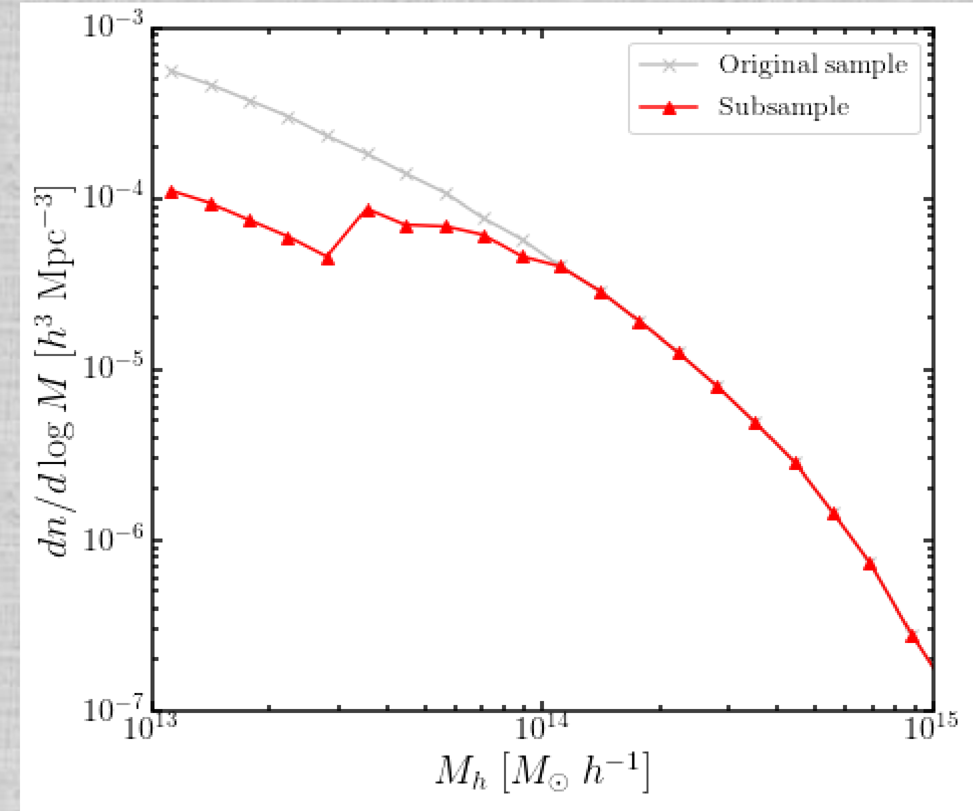
$$\lambda \equiv \ln(\text{SDSS Richness})$$

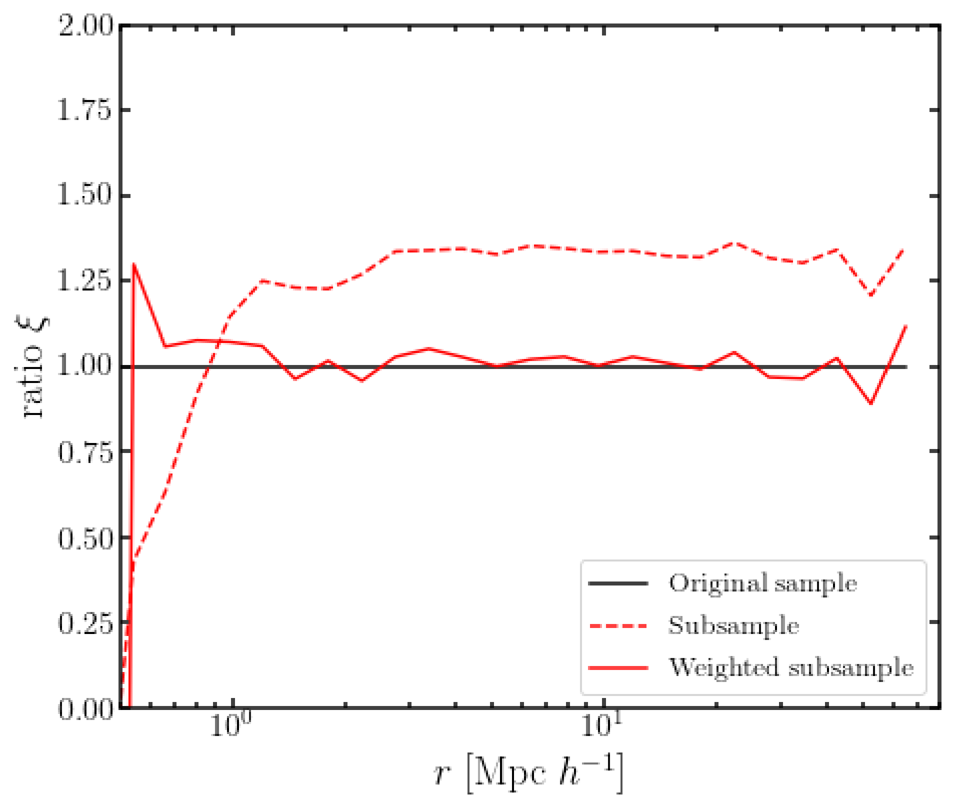
Rykoff et al. 2014

Richness-Mass relation (Capasso et al. 2019):

$$\lambda = A_\lambda \left(\frac{M_{200c}}{M_{\text{piv}}}\right)^{B_\lambda} \left(\frac{1+z}{1+z_{piv}}\right)^{\gamma_\lambda}$$

Halo weights



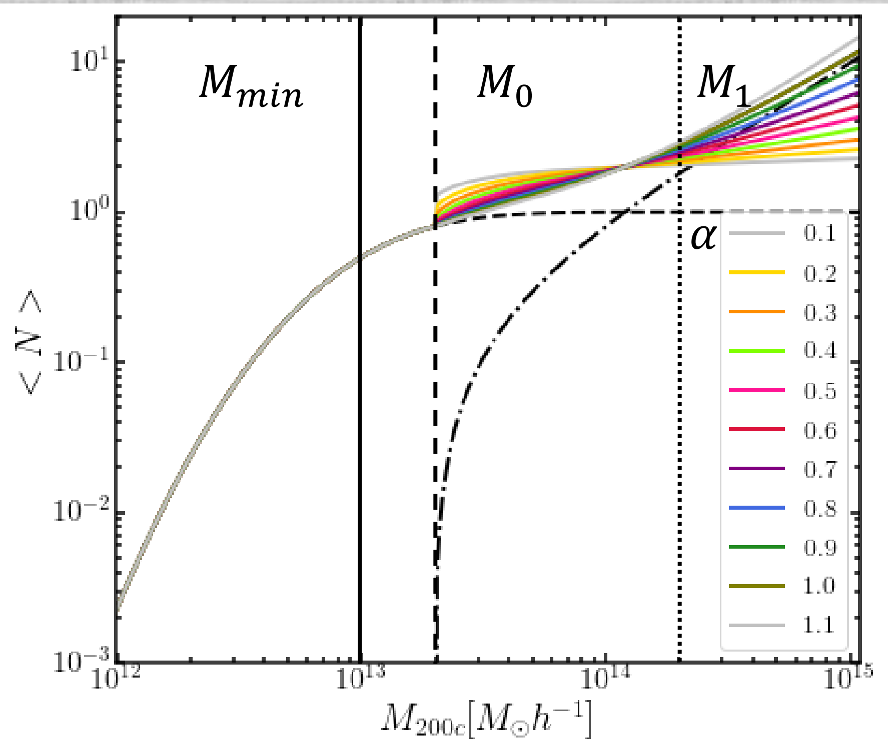


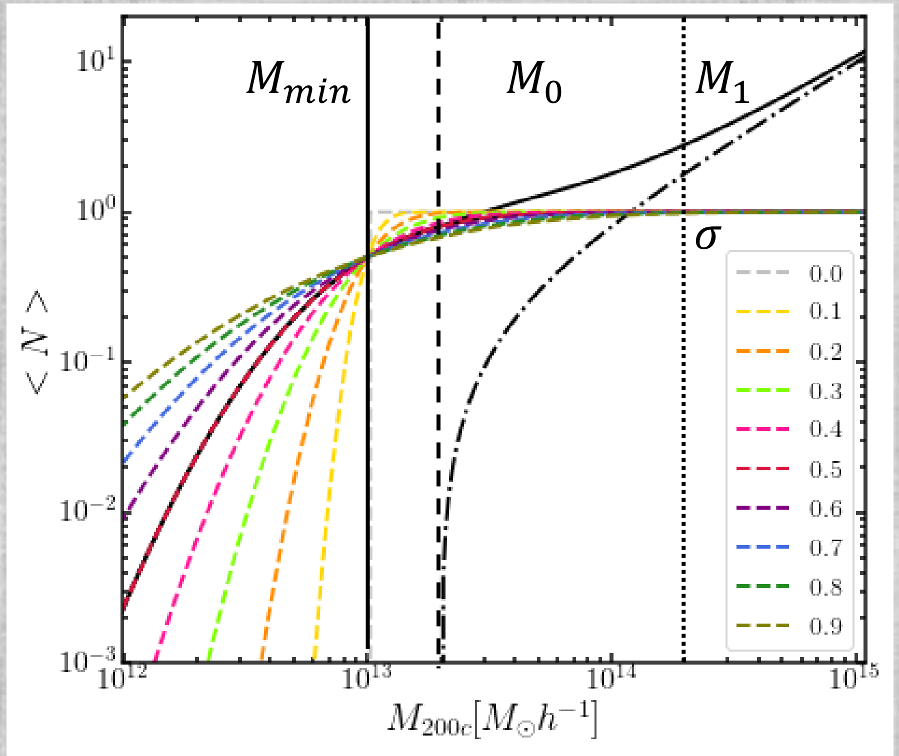
Halo occupation distribution

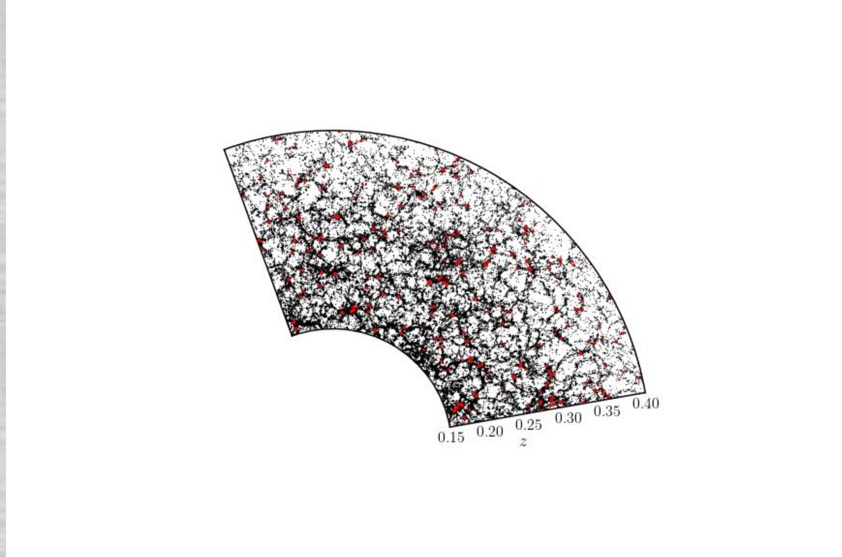
$$\langle N_{cen} \rangle = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M_{min} - M}{\sigma_{\log M_{min}}}\right)\right]$$

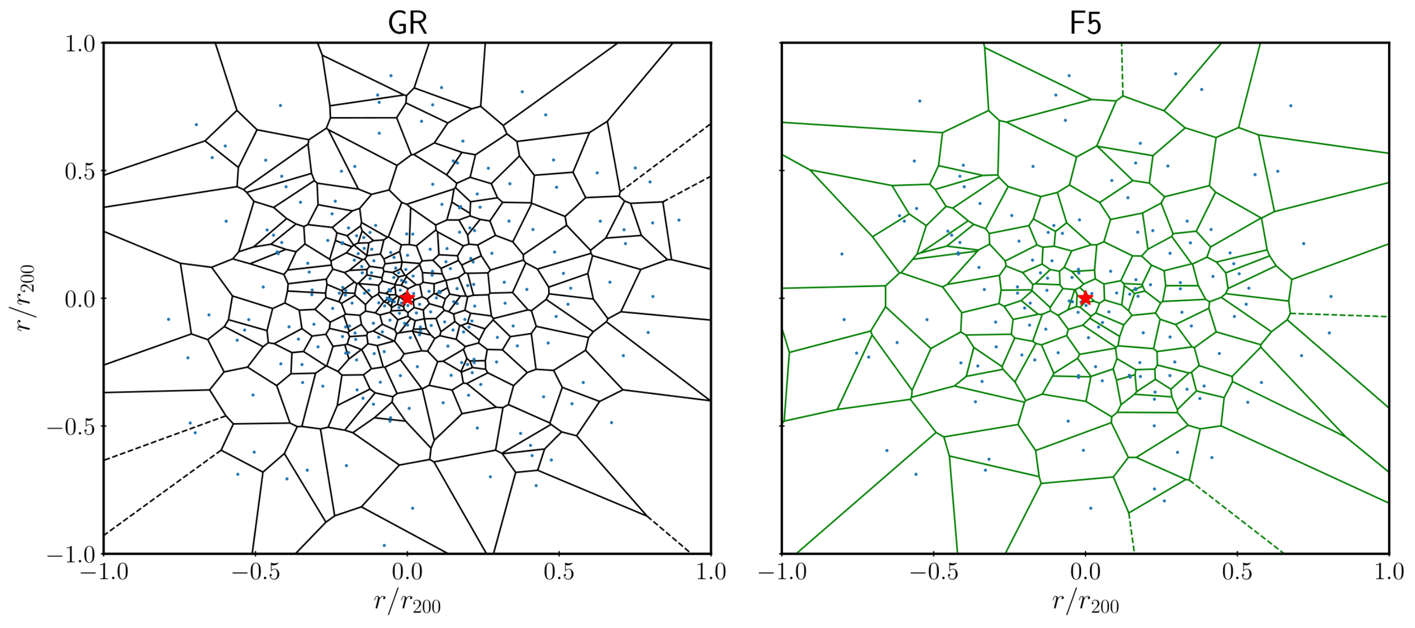
$$\langle N_{sat} \rangle = \langle N_{cen} \rangle \left(\frac{M - M_0}{M_1}\right)^{\alpha}$$

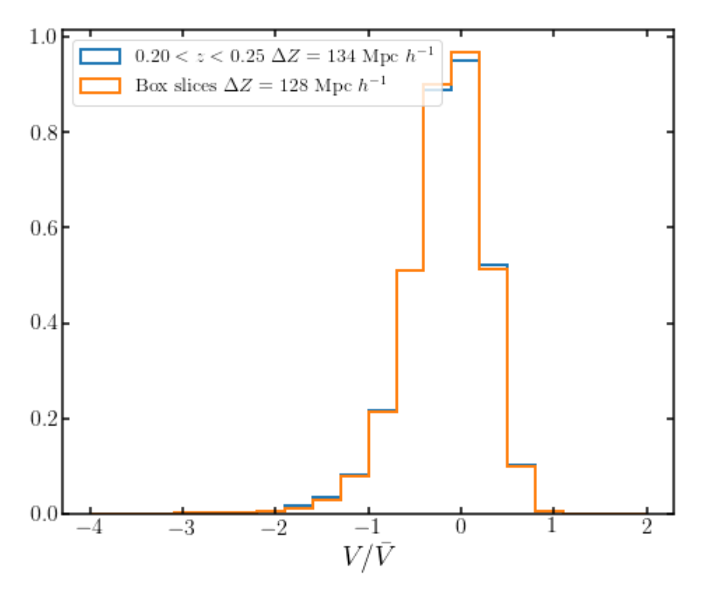
$$\langle N \rangle = \langle N_{cen} \rangle + \langle N_{sat} \rangle$$

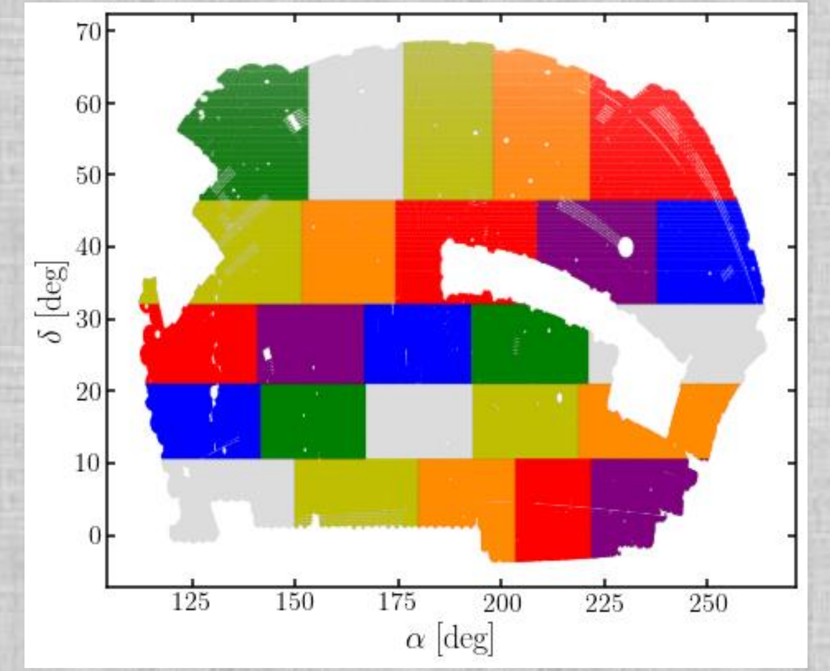


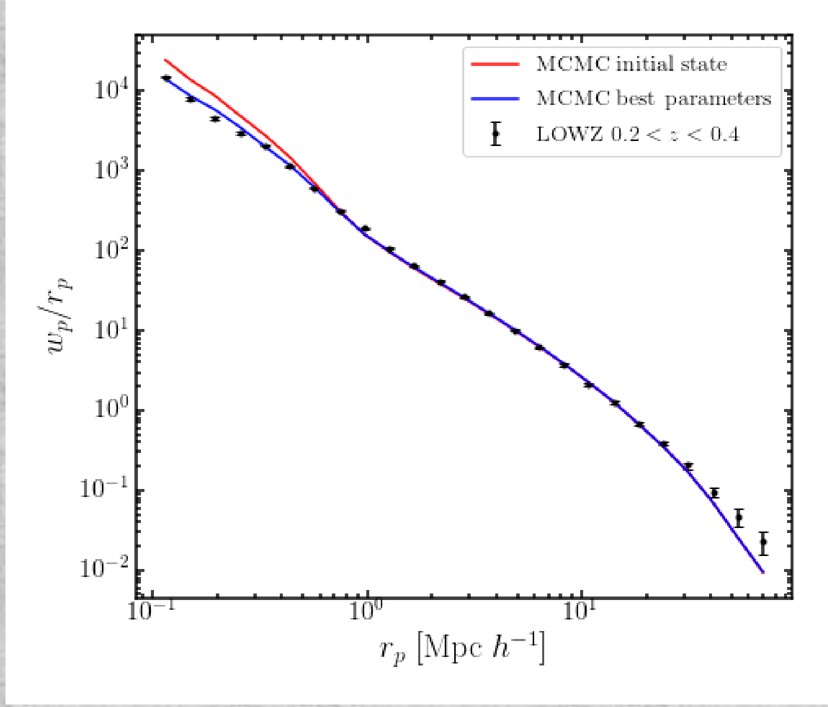


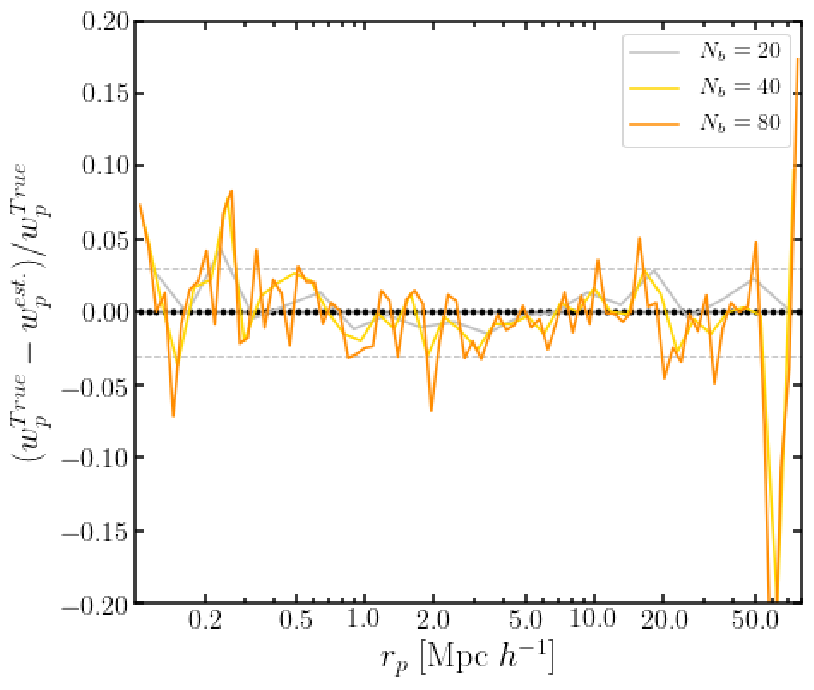

0.15 0.20 0.25 0.30 0.35 0.40
z


GR
F5
r/r200


0.20 < z < 0.25 ΔZ = 134 Mpc h^-1
Box slices ΔZ = 128 Mpc h^-1
V/V̄


δ [deg]
α [deg]
70
60
50
40
30
20
10
0
125
150
175
200
225
250


MCMC initial state
MCMC best parameters
LOWZ 0.2 < z < 0.4
w_p/r_p
r_p [Mpc h^{-1}]


$N_b = 20$
$N_b = 40$
$N_b = 80$
$(w_p^{True} - w_p^{est.})/w_p^{True}$
r_p [Mpc h^{-1}]