New constraints on the linear growth rate using cosmic voids in the SDSS DR12 datasets

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We present a new analysis of the inferred growth rate of cosmic structure measured around voids, using the LOWZ and the CMASS samples in the twelfth data release (DR12) of SDSS. Using a simple multipole analysis we recover a value consistent with ΛCDM for the inferred linear growth rate normalized by the linear bias: the β parameter. This is true in both the mock catalogues and the data, where we find β = 0.33 ± 0.06 for the LOWZ sample and β = 0.36 ± 0.05 for the CMASS sample. This work demonstrates that we can expect redshift-space distortions around voids to provide unbiased and accurate constraints on the growth rate, complementary to galaxy clustering, using simple linear modelling.

I. INTRODUCTION

The growth rate of cosmic structure f tells us how fast density fluctuations ∆ grow with respect to the scale factor of the Universe a:

\[
f \equiv \frac{d \ln \Delta}{d \ln a}
\]

(1)

Its measurement as a function of time and scale is a key cosmological probe, very sensitive to the nature of gravity (e.g. [28, 52]). To infer the growth rate, we can measure redshift-space distortions (RSD) in the galaxy clustering signal. These distortions are due to the peculiar motions of galaxies, which on large scales have a coherent motion sourced by the gravitational potential of cosmic structures. This gravitational potential is itself proportional to the growth rate, in the linear regime. For standard General Relativity (GR) and isotropic cosmologies, the linear growth rate does not depend on the comoving spatial scale and can be approximated by \( f \sim \Omega_m(z)^\gamma \) where \( \Omega_m \) is the matter density parameter at redshift \( z \), and \( \gamma \) is a constant. For a ΛCDM Universe \( \gamma \sim 0.55 \) independently of the environment. Constraints on the linear growth rate made with galaxy-galaxy correlation function measurements in redshift-space are well known, e.g. [9, 10, 18, 23, 40, 43]. These measurements have shown a general consistency with the ΛCDM cosmological model, up to a 2.5% precision, albeit in some cases showing tension with the predictions of the latest Cosmic Microwave Background measurements [37].

On the other hand, it was only recently that the growth rate has been inferred using the RSD pattern around cosmic voids. There are at least two reasons to perform this consistency test of the linear growth rate. First, certain models of modified gravity, such as f(R) [29], rely on the the chameleon screening mechanism which suppresses the 5th force in high density regions, while in under-dense regions the total gravitational force is enhanced (due to the presence of the 5th force), resulting in specific imprints on void abundance and density profiles around underdense regions (e.g. [1, 8, 9, 11, 15, 45]). These theories would naturally lead to an environmentally-dependent growth rate. In fact, in the non-linear regime, the linear growth rate is also sensitive to the underlying density, as shown in [5]. For very large under-dense regions, the effective cosmological parameters are expected to be different to the globally-averaged parameters, but the quantification of this critical scale can also serve as an interesting test for departures from Einstein gravity. Second, the formation and evolution of cosmic voids is non-linear and reduced compared to the dynamics of dark matter halos or the evolution of overdense regions with \( \Delta(r) \gg 1 \). This is why we can expect that quasi-linear or linear models can describe the RSD around voids relatively well, although recent works have shown the limitation of this assumption [2, 5, 12, 33].

The analyses that first constraints the growth rate around voids from galaxy surveys are [21], where the authors used the CMASS sample of the Sloan Digital Sky Survey (SDSS). [4], where we used the low redshift 6-degree Field Galaxy Survey (6dFGS) [27], and [24], where the authors used the high redshift VIPERS survey datasets. While these analyses have shown an overall consistency with the ΛCDM expectation of the linear growth rate, the GSM does assume a knowledge of the real space density profiles around voids, which may induce a bias in the analysis. In [20] the authors took

\[ \text{(1)} \]

although one can marginalized over the void profiles fitted parameters as it was done in [21].
advantage of the approximated linear behavior of cosmic void evolution to perform a multipole analysis of the RSD around voids using both the CMASS and the LOWZ galaxy samples of SDSS DR12. Such a multipole analysis allows to derive the growth rate purely from the data measurement, assuming a linear relationship between the monopole and the quadrupole (see also the recent work of [19] for a complementary approach). With this assumption they have derived a linear growth rate consistent with $\Lambda$CDM in the CMASS sample, but at a $\sim 2-3\sigma$ deviation from it in the LOWZ sample.

In this work we perform an independent analysis from [20] using a different void finder and a different treatment of the errors which enter into the likelihood analysis. Using the 500 mocks from the publicly available mock galaxy catalogues produced with the Quick Particle Mesh (QPM) method [44], we test the validity of the multipole decomposition and use them to compute the covariance matrix that enters into the likelihood. We will show that in our case, we observe no deviation from $\Lambda$CDM when we disregard the multipole measurements at small scales ($< 10 \, h^{-1}\text{Mpc}$).

This paper is organized as follows: in section II we describe the data and the mocks we use to perform our analysis, in section III we explain how we obtain our void catalogues, in section IV we introduce the model we use to derive the linear growth rate, in sections V, VI we test our approach using the QPM mock catalogues and in the CMASS and LOWZ dataset. In section VII we present our conclusion.

II. DATA & MOCK CATALOGUES

We use the publicly available data of SDSS-III [8] Data Release 12 (DR12) which contains two datasets of galaxy catalogues from the Baryon Oscillation Spectroscopic Survey (BOSS) 2; the LOWZ and the CMASS samples. Both map the southern and the northern hemispheres. The LOWZ north/south sample contains $\sim 248/114 \times 10^3$ galaxies in redshift range $0.15 < z < 0.43$ and a median $\bar{z} = 0.32$ while the CMASS north/south sample contains $\sim 569/208 \times 10^3$ galaxies in redshift range $0.43 < z < 0.70$ with $\bar{z} = 0.54$.

To identify the voids in the galaxy samples and to compute the multipoles, we use the two random catalogues generated by the BOSS collaboration (for each sample e.g. LOWZ north/south and CMASS north/south), featuring the redshift distribution. Each of these catalogues are referred to as RAN and RAN2. These random catalogues are also publicly available and contain about 50 times more points than the observed galaxies.

2 http://www.sdss3.org/science/ boss_publications.php

To identify the cosmic voids in both the galaxy dataset and the QPM mocks, we use the void finder developed by [11], that was used in the 6dF Galaxy Survey analysis [11] to infer the growth rate. This void finder uses a sample of RAN2 to identify candidate voids with an effective radius $r_v$ that satisfies the following density constraints: $\delta(r_0) < -0.9$; $\delta(r_0 + dr) < -0.8$; $\delta(r_0 + 2dr) < -0.3$ ; $\delta(r_v) > 0.15$; $\delta(r_v + dr) > \delta(r_v)$; $\delta(r_v + dr) < 0.4$. where the binning is given in steps of $dr = 3 \, h^{-1}\text{Mpc}$, $r_0 = 1.5 \, h^{-1}\text{Mpc}$ and $\delta(r)$ is approximated by counting the number of galaxies around each random position we select from RAN2, divided by the number of randoms we compute from the RAN catalogues. The first 3 conditions ensure that the centre of the voids is underdense while the conditions around $r = r_v$ ensure that the selected voids have a ridge. We then perform two loops over these void candidates that satisfy the density conditions: the first loop to smooth the individual void profiles by requiring

![Figure 1: Number density of voids (blue histogram) and galaxies (red squares) in the LOWZ/CMASS samples, as a function of redshift. Both overlap with one another as expected from the void finder.](http://www.sdss3.org/science/boss_publications.php)
that \( \delta(r + 3dr < R < r_v/2) < -0.3 \). The second to remove overlapping voids, keeping the largest.

We use between 5 to 8 times the number of candidate positions as tracers, which is a good compromise between numerical computing power and having a convergence in the number of identified voids. Indeed, given that we remove overlapping voids, increasing the number of candidates can increase the number of identified voids up to a limited number. Keeping the same criteria for the data samples and the mocks, we end up with a selection of voids distributed in redshift as displayed in Fig. 1.

We repeat the same procedure using 500 QPM mocks for LOWZ North/South and CMASS North/South. Finally, we introduce a cut in the minimum size of the voids for the RSD analysis \( r_v^{\text{min}} = 25 \, h^{-1}\text{Mpc} \). The motivation for this cut is that (i) small voids identified with galaxy tracers do not necessarily correspond to underdensities in the matter density field. They also show a stronger deviation from linear evolution, and the galaxy bias around small voids can be amplified compared to the large-scale average bias \([33, 39, 52]\). (ii) we found that the overall void size distribution matches the mean value of the QPM mocks distribution when \( r > r_v^{\text{min}} \). Although we are not interested in testing for void abundance in this work, having a mismatch in the void size distribution could introduce an offset between the mean void density profiles measured in the data and in the mocks, which could possibly introduce a bias in the derivation of our cosmological parameters. After applying this threshold, we found a total of 5986 voids identified in the LOWZ sample and 6373 in the CMASS sample. The normalized number of voids as a function of radius is displayed in Fig. 2. The blue/red histograms correspond to the LOWZ/CMASS samples while the blue/red dashed curves correspond to 5 randomly selected samples from LOWZ/CMASS, respectively. The mean void radius in the LOWZ/CMASS samples are, respectively, \( r_v = 38.5 \) and \( 38 \, h^{-1}\text{Mpc} \).

IV. METHODOLOGY

A. Multipole decomposition

The peculiar velocities of galaxies, \( v \), that are due to the local gravitational potential result, on small scales, in random motions of galaxies within virialized halos. In principle this effect is not present within voids, which are generally empty of galaxies in their centre. On large scales however, the coherent bulk flow pointing outwards from centres of voids is responsible for an overall coherent distortion known as the ‘Kaiser effect’ \([28]\). It is this coherent outflow that carries information of the linear growth rate. Indeed, the galaxy peculiar velocities sourced by the underlying mass distribution of a void can be expressed in the linear regime as \([12, 20, 22, 36]\):

\[
\mathbf{v}(r) = \frac{-1}{3} \frac{f(z)H(z)}{1 + z} \mathbf{r} \Delta(r)
\]

where \( f(z) \) is the linear growth rate, \( H(z) \) is the Hubble rate, \( \mathbf{r} \equiv \mathbf{x} - \mathbf{X} \) is the separation between the comoving coordinate of the void centre \( \mathbf{X} \), and a galaxy at position \( \mathbf{x} \). We also assume that on average the void density profiles are spherical and can be described by the density contrast \( \Delta(r) \) where \( \mathbf{r} \equiv |\mathbf{r}| \). To relate the averaged galaxy density contrast, \( \xi(r) \), to the matter density contrast, we generally assume a linear bias \( b \) such that \( \xi(r) = b \Delta(r) \) and

\[
\xi(r) \equiv \frac{3}{r^3} \int_0^r \xi(y)y^2dy
\]

where \( \xi(r) \) is equivalent to the galaxy density contrast at a scale \( r \) (i.e. the galaxy-void cross-correlation function).

The peculiar velocity of a galaxy gives a contribution to the redshift space separation between the galaxy and the void centre, and in the limit where \( |\mathbf{r}| \ll \mathbf{X} \),

\[
s = \mathbf{r} + \frac{(1 + z)\hat{\mathbf{X}} \cdot \mathbf{v} - \hat{\mathbf{X}}}{H(z)}
\]

where \( \hat{\mathbf{X}} \) is the unitary vector along the line of sight to our void centre.
Performing a Jacobian transformation between the coordinate s and r, at linear order, the redshift-space 2D correlation function can be described by (12, 20, 23, 28):

\[ \xi^s(r, \mu) = \xi_0(r) + \frac{3\mu^2 - 1}{2} \xi_2(r) \]  \hspace{1cm} (5)

where \( \mu = \cos(\theta) = \hat{X} \cdot \hat{r} \) is the cosine of the angle between the line-of-sight direction and the separation vector while \( \xi_0, \xi_2 \) are the monopole and the quadrupole respectively, computed using the Legendre polynomials \( P_l(\mu) \) via

\[ \xi_l(r) = \int_0^1 \xi^s(r, \mu)(1 + 2l)P_l(\mu)d\mu. \]  \hspace{1cm} (6)

In the linear regime (28),

\[ \xi_0(r) = \left( 1 + \frac{\beta}{3} \right) \xi(r) \]
\[ \xi_2(r) = \frac{2\beta}{3} \left( \xi(r) - \xi_0(r) \right), \]

where \( \beta = f/b \) and \( \xi(r) \) is the real-space galaxy-void correlation function. These expressions lead to a simple relationship between monopole and quadrupole:

\[ \xi_0(r) - \xi_0(r) - \xi_2(r) \frac{3 + \beta}{2\beta} = 0 \]  \hspace{1cm} (7)

This is the key equation that [20] have used to probe \( \beta \) solely by measuring the monopole and the quadrupole. We will also use this equation in what follows, but we will introduce a cut at the scale \( r_{\text{cut}} \) below which this approximation is no longer valid.

**B. Measurement of the galaxy-void correlation function**

To perform the multipole decomposition we start by measuring the void-tracer cross-correlation functions using the Landy-Szalay estimator:

\[ \xi_{v/g}(r, \mu) = \frac{N_{v/g}N_{v/g}}{R_{v/g}R_{v/g}} \left( \frac{D_{v/g}}{N_{v/g}} - \frac{D_{v/g}}{N_{v/g}} \right) + 1, \]  \hspace{1cm} (8)

where \( D_{v/g}, R_{v/g} \) is the number of data void-galaxy pairs, \( R_{v/g}, R_{v/g} \) the random void-galaxy pairs and \( D_{v/g}, R_{v/g} \) the number of galaxy/void data-random pairs, in bins at separation \( r \) and \( \mu \). The total number of galaxies, voids, galaxy-randoms and void-randoms are \( N_g, N_v, N_{rg} \) and \( N_{rv} \), respectively. In all cases we use a sample of the first random catalogues provided by the BOSS collaboration, having 10 times the number of galaxies/voids than our data samples.

We measure Eq. (8) in bins of \( d\mu = 0.045 \) and \( dr = 4 \, h^{-1}\text{Mpc} \).

**C. The likelihood analysis**

To infer the linear growth rate from the measurement of the monopole and quadrupole, we solve for the value of \( \beta \) which satisfies Eq. (7), performing a Gaussian likelihood

\[ L(\xi_0, \xi_2 | \beta) = \frac{1}{(2\pi)^{N/2}\sqrt{\det C}} \exp \left[ -\frac{1}{2} \sum_{i,j=l_{\text{min}}}^{N} \xi_i C^{-1}_{ij} \xi_j \right] \]  \hspace{1cm} (9)

where the sum is in radial bins \( r_i = [r_{\text{cut}}, r_{\text{max}}] \), \( \xi_i \equiv \xi_0(r_i) - \xi_0(r_i) - \xi_2(r_i) \frac{3 + \beta}{2\beta} \) is the left hand side of Eq. (7), and \( C \) is the covariance matrix \( C_{ij} = \langle \xi_i \xi_j \rangle \) which depends explicitly on \( \beta \). Hence the normalization of the likelihood needs to be taken into account. Unlike the analysis performed in [20], which uses a jackknife method to estimate the covariance matrix, in what follows we compute the covariance matrix using 500 QPM mocks.

In Fig. 3 we show the correlation matrix (covariance matrix of the residuals after normalization by its diagonal)
FIG. 4: Multipole measurements in the mocks (grey curves) and in the data (blue curves) we obtained from Eq. 6. The data multipoles are qualitatively in good agreement with the ones we obtain in the mocks.

which can be compared to Fig. 4 in [20]. The correlations between our bins follow the same qualitative trend as [20]: in the inner part of the voids, $r/r_v < 1$, the bins seem less correlated while for $r/r_v > 1$ we see some off diagonal correlations. We also note that in order to compute the galaxy-void correlation function we employ the Landy-Szalay (LS) estimator, while [20] use the approximation $\xi_l(r) \simeq \langle D_v D_g \rangle - \langle D_v R_g \rangle$.

V. ANALYSIS

We start by using Eq. 8 to measure the galaxy-void correlation function in the data and the mocks, and then we apply Eq. 6 to compute the monopole ($l=0$), quadrupole ($l=2$) and hexadecapole ($l=4$). The resulting multipoles are shown in Fig. 4 where the grey curves correspond to the mocks measurements (1000 in total for CMASS and LOWZ) and the blue curves to the data. First we observe that the multipoles computed from the data and the mocks are qualitatively in good agreement with one another. Second we observe that for $r/r_v \leq 0.3$, which corresponds to a radius below $r \sim 10 \ h^{-1}\text{Mpc}$, the slope of the monopole changes, and $\xi_0 \to -1$ while $|\xi_4| > 0$. These behaviours could indicate a breakdown of the linear assumptions and/or ill-defined regions due to the lack of particle counts at the core of the voids. In any case, these low scales can not be used within our current linear model hypothesis. Hence in what follows we define a cut-off scale $r_{\text{cut}}$ below which we disregard our measurements when performing the likelihood analysis.

Finally, we also show the measurement of the 2D galaxy-void correlation function in both LOWZ/CMASS samples in Fig. 5 that we have measured parallel ($\pi$) and perpendicular ($\sigma$) to the line of sight, using a binning of $4 \ h^{-1}\text{Mpc}$. This is just to illustrate the asymmetry due to the peculiar velocities of galaxies that have a coherent outflow due to the gravitational potential of the voids.
the void. This measurement could be used to extract the growth rate using a quasi-linear modelling (e.g. Gaussian Streaming Model), as it was done in \cite{4,21,24}. However it would require assumptions on the real space density profiles around the voids, which we know are sensitive to the underlying cosmology and to the void finder algorithm. Hence we do not explore further these 2D measurements.

VI. RESULTS

In what follows, we set $r_{\text{cut}} = 10 \ h^{-1}\text{Mpc}$ and we use our measurement in bins of $dr = 4 \ h^{-1}\text{Mpc}$ up to $r_{\text{max}} = 78 \ h^{-1}\text{Mpc}$. We have verified that the results we present in this section remain unchanged via the transformation $r_{\text{cut}} \rightarrow r_{\text{cut}} \pm dr$ or $r_{\text{max}} \rightarrow r_{\text{max}} \pm dr$. We also tested that the inferred value of $\beta$ is insensitive to the fiducial size of our voids $r_v$, nor to the hemisphere (splitting voids in large vs. small, separating north vs. south datasets). Thus for this analysis, we combined all the void sizes to obtain better statistical errors.

To obtain the best fit value for $\beta$, we use a large prior of $\beta = [-0.1, 1.2]$ in steps of $d\beta = 0.0024$. We have verified that our results remain unchanged by increasing the prior range.

A. Mocks

We start our analysis by inferring the value of $\beta$ on each individual mock catalogue, using the Likelihood computation given in Eq. \[9\] in order to evaluate the uncertainties on the $\beta$ measurement. In Fig. \[6\] we show the histogram of the best fit values we have found in the CMASS, LOWZ mocks as well as the mean values and the standard deviation: $\bar{\beta} = 0.36 \pm 0.06$ for the CMASS mocks and $\bar{\beta} = 0.21 \pm 0.05$ for the LOWZ mocks. It is not trivial to compare these values to the mock expectations. Indeed, given the fiducial cosmology of the QPM mocks \[44\] we can easily compute the expected value for the growth rate but the linear bias is not explicitly given at the mean redshift of the mocks. At $z = 0.5$ the linear bias is expected to be $b = 2.2$ for the QPM mocks \[8\]. In such case, we can extrapolate the value $\beta(z = 0.5) = 0.34$. This value can be compared to the CMASS mocks because in these mocks the redshift is $z \sim 0.54$. If we neglect the redshift dependence of the linear bias and keep $b = 2.2$ but use the growth rate at the redshift of the LOWZ mocks then we can expect a value of $\beta = 0.30$. Both theoretical values are within 2-$\sigma$ deviation from the mean of $\beta$ we obtain. Finally before performing the data analysis, we should make a few critical remarks:

- Galaxies around voids may be more biased compared to the average galaxies in the full simulation. In which case we can expect the fiducial value of $\beta$ to be lower than the one computed from $b = 2.2$. We note however that in \[4\] the value of the linear bias we have inferred in mocks using the galaxy-void and the galaxy-galaxy correlation functions were consistent with one another. This must depend on the fiducial void size and the characteristics of the void profiles (e.g amplitude at the void ridge).

- We note that if we would have inferred $\beta$ from the mocks mean measurement of the multipole, the systematic errors due to the linear assumptions would most likely dominate: in the LOWZ sample we have found the mean of the $\beta$ best fit values to be in agreement with the fiducial cosmology at 2-$\sigma$, but not 1-$\sigma$. This may be an issue for upcoming surveys such as TAIPAN which will probe a larger volume, with a higher density of galaxies and voids \[17\] at low redshift.

- We also point out the limitation of using QPM mocks \[44\] to test for the validity of the growth rate at low redshift. Indeed, unlike in full N-body simulations, efficient algorithms such as \[44\] have not yet fully investigated the validity of their approach to reproduce the statistical description of the undersense matter density field.

Overall, apart from these remarks, we find that the mean of $\beta$ from the best fit values of the mocks are within 2-$\sigma$ deviation of the expected fiducial cosmology, which validate our approach given the statistical errors we have.
FIG. 7: Posterior distribution for $\beta$ in the CMASS and LOWZ data. The long-dashed line corresponds to the expected $\Lambda$CDM cosmology with a linear bias $b = 1.85$ as it was inferred in [14] while the dotted line corresponds to the $\Lambda$CDM cosmology with $b = 2.2$ (i.e., the value of the linear bias in the QPM mocks at $z = 0.5$).

B. Data

Following the same procedure but for the data sample, we find a best fit $\beta = 0.33 \pm 0.06$ and $\beta = 0.36 \pm 0.05$ for the LOWZ and CMASS samples, respectively, with a reduced $\chi^2$/d.o.f. of 22.6/16 = 1.41 and 21.8/16 = 1.36. The posterior distribution is shown in Fig. 7. We note that our errors on $\beta$ are consistent with what we found using the standard deviation of the best fit values from the mocks and that the best fit values correspond to the mean value of the likelihood PDF.

Once again we can compare these results with the expected values of $\beta$ in the case of a $\Lambda$CDM cosmology (see sec. II for cosmological parameter values). With a linear bias $b = 1.85$ (as inferred in [14]), the theoretical values for LOWZ/CMASS are $\beta = 0.37, 0.41$ respectively. These are the same reference values that [20] have used to compare with their results. In Fig. 7 they correspond to the long dashed lines. Unlike what the authors in [20] have found, we obtain a 1-$\sigma$ agreement with respect to $\Lambda$CDM, both for the LOWZ and the CMASS samples. We also show in Fig. 4 the fiducial values of $\beta$ for $b = 2.2$ (motivated by the discussion in sec. VIA). The latter is also consistent at 1-$\sigma$ with our best fitting values.

VII. CONCLUSION

In this work we have probed the parameter $\beta = f/b$, using the public galaxy catalogues released by the BOSS collaboration and an RSD multipole analysis of the galaxy-void cross-correlation function. The model we used to infer the growth rate is derived from linear theory and was initially used in [20] to perform a similar analysis. However, in this work we find that our derived values for the growth rate are consistent with a $\Lambda$CDM cosmology within 1-$\sigma$. The main differences in this analysis compared to the one presented in [20] are:

- Our void catalogues are completely independent and based on different criteria (density criteria [1] vs. watershed transform [41]). While the peak of the void size distribution is relatively similar in both studies, we have better statistics on the number of voids in the LOWZ sample. As a result, our errors on $\beta$ are similar in both the LOWZ $\Delta \beta = 0.06$ and CMASS sample $\Delta \beta = 0.05$.

- Motivated by our analysis with the mocks, we introduce a cut in scale to disregard our measurement at the centre of the voids where $|\delta| \rightarrow -1$, which corresponds to the non-linear regime where Eq. 7 does not hold in principle, as we discuss in sec. V.

- The treatment of the covariance matrix is different: in this work we used the mocks to compute the covariance while in [20] they used a jackknife method.

Overall, this work has provided some interesting results:

- Using mock catalogues, we have shown that $\beta$ can be extracted using no theoretical modelling of the void-galaxy correlation function in real space. This is particularly interesting to avoid assuming a fiducial cosmology in order to predict the void density profiles, which could lead to potential bias of the growth rate value (the void density profiles carry the imprints of the cosmology e.g. [3, 7, 13, 31, 34]), or to avoid parametrizing the real space density profile and/or marginalising over the profile parameters, which would introduce potentially weaker constraints on the growth rate.

- The values of $\beta$ that we obtain in the LOWZ/CMASS datasets are consistent with the value probed in [14]. However in [14] the scale range used to derive $\beta$ is $[40 - 180] h^{-1}$Mpc, while we used the information contained within ranges $[10 - 78] h^{-1}$Mpc. This illustrates again the complementarity of using cosmic voids to perform cosmological analysis: we have access to additional information, and the systematic errors are different.
Finally we can emphasise on the fact that that the value of $\beta$ we obtained in this analysis is in good agreement with the $\Lambda$CDM linear prediction. It would be interesting to probe the information contained in smaller scales (e.g. below 10 $h^{-1}$Mpc) where the non-linearities can carry more information. For instance, in [5] we have shown how the growth rate of cosmic structure can vary considerably when the underlying matter density $|\Delta| \geq 1$. We hope to perform such analysis in future work.

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