Growth rate of cosmological perturbations at $z \sim 0.1$ from a new observational test

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Spatial variations in the distribution of galaxy luminosities, estimated from redshifts as distance proxies, are correlated with the peculiar velocity field. Comparing these variations with the peculiar velocities inferred from galaxy redshift surveys is a powerful test of gravity and dark energy theories on cosmological scales. Using $\sim 2 \times 10^5$ galaxies from the SDSS Data Release 7, we perform this test in the framework of gravitational instability to estimate the normalized growth rate of density perturbations $f \sigma_8 = 0.37 \pm 0.13$ at $z \sim 0.1$, which is in agreement with the $\Lambda$CDM scenario. This unique measurement is complementary to those obtained with more traditional methods, including clustering analysis. The estimated accuracy at $z \sim 0.1$ is competitive with other methods when applied to similar datasets.

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Introduction.—Unraveling the origin of cosmic acceleration remains one of the biggest challenges in fundamental physics. Lacking a natural explanation within the standard paradigms of cosmology and particle physics, many theoretical models have been proposed, ranging from the inclusion of new scalar fields to genuine modifications of general relativity \cite{1,2}. Models that provide alternative explanations are mainly limited by the uncertainty of the Hubble expansion, and considered the same dataset as in Ref. \cite{27}. We have focused on the subsample of nearby galaxies $0^\circ < \lambda < 51^\circ$, and $0^\circ < \nu < 10^\circ$, and derived from the SDSS DR7 \cite{26}. To minimize incompleteness and systematics, we focused on the subsample safe and considered the same dataset as in Ref. \cite{27}. We then selected only galaxies in the range $0.06 < z < 0.12$ inside a rectangular patch specified in SDSS survey coordinates, $-33^\circ < \eta < 36^\circ$ and $-48^\circ < \lambda < 51.5^\circ$. The luminosity sample, which we used in the likelihood analysis below, is flux-limited in the $r$-band and
contains around $2 \times 10^5$ galaxies. To build peculiar velocity models, we also considered a second sample, tagged \textit{velocity}, which corresponds to the maximum volume-limited sample within $0.05 < z < 0.13$ trimmed to the range $0.06 < z < 0.12$ and typically includes $\sim 8 \times 10^4$ galaxies for spatially flat cosmologies with $\Omega \approx 0.3$. To compute absolute magnitudes, we assumed a linear evolution model $Q(z) = 1.6(z - 0.1)$ \cite{27} and $K$-corrections from the NYU-VAGC \cite{28}.

In addition, we used mock SDSS catalogs generated from the Millennium Simulation \cite{29,30} to assess the accuracy of the velocity models and the uncertainty on the $\beta$-estimates. These mocks were customized to match data characteristics such as number counts, luminosity distribution, and sky coverage.

\textbf{Method.}—A full account of the luminosity method can be found in Ref. \cite{24}. Here we provide a brief summary of its key ingredients. Given a galaxy survey with magnitudes, spectroscopic redshifts, and angular positions $\hat{r}_i$ on the sky, one traces the 3D galaxy distribution and reconstructs the linear peculiar velocity field as a function of $\beta$ \cite{31}. The correct value of $\beta$ is then estimated by maximizing the probability of observing the data,

$$P_{\text{tot}} = \prod_i P(M_i | z_i, v_i(\beta)) = \prod_i \left( \phi(M_i) / \int_{M_i^-}^{M_i^+} \phi(M) dM \right),$$

where $v_i(\beta)$ denotes the radial part of the peculiar velocity field evaluated at the position of galaxy $i$, and redshift errors are neglected \cite{24,22}. Here $\phi(M)$ is the galaxy luminosity function (LF) determined from the full dataset, and the limiting magnitudes $M^\pm$ depend on $v(\beta)$ through the cosmological redshift $z_c$. The goal of this approach is to find the $\beta$-value which minimizes the spread in the observed magnitudes.

Our study assumes a $\Lambda$CDM cosmology with fixed Hubble constant and density parameters taken from Ref. \cite{33}. Following the procedure of Ref. \cite{31}, the velocities were reconstructed in spherical harmonics up to a multipole $l_{\text{max}} = 150$ after smoothing the galaxy density field with a Gaussian kernel of $10h^{-1}$ Mpc radius. The monopole and dipole contributions cannot be reliably modeled for the dataset considered here. Excluding them from the velocity model ($l > 1$), we fixed the boundary conditions by setting the density contrast outside the observed volume to zero. Since the data covers a narrow $z$-range, we assumed no evolution of $\beta$ and $b$ in the analysis, and computed a set of model velocity fields varying $\beta$ between 0 and 1 in steps of $\Delta \beta = 0.05$. Dominated by large-scale structure, the cosmic velocity field is insensitive to small-scale features such as those related to galaxy bias. We checked that our models and results are robust to the precise choice of the smoothing scale.

Assigning $v(\beta)$ to the subsample \textit{luminosity}, we removed galaxies near the sample edges (around 10\%) to avoid artifacts due to incorrect boundary conditions. To maximize the probability $P_{\text{tot}}$, we used a spline-based LF estimator with a separation $\Delta M = 0.5$ \cite{27,34}. The par-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{\textbf{Left.}—Histograms of $f\sigma_8$-estimates (and Gaussian fits) derived with the luminosity approach from 128 mock catalogs, considering only multipoles $l > 1$ (solid lines) and $l > 5$ (dashed lines) in the velocity reconstructions. The distributions peak near the true value, $(f\sigma_8)_{\text{true}} \approx 0.44$, and deviate from a symmetric Gaussian mainly because of the velocity field’s nonlinear $\beta$-dependence. \textbf{Right.}—Estimated $\Delta \chi^2$ (and quadratic approximations) as a function of $f\sigma_8$ for real SDSS galaxies and velocity models with $l > 1$ (filled circles) and $l > 5$ (open circles). The results assume the measured power spectrum amplitude of $L^*$-galaxies from Ref. \cite{23}.}
\end{figure}
tial sky coverage yields a statistical mixing between the velocity models and the LF parameters. This may result in biased constraints on \( \beta \) that can be easily avoided by appropriately fixing the LF model. To this end, we set the LF to its estimate for a vanishing velocity field, and evaluated \( f_{\sigma_8} \) for the different models of \( v(\beta) \). The maximum probability was then determined through interpolation.

**Results.**—The left panel of Fig. 1 shows the distribution of growth rates estimated from 128 mock catalogs for velocity models with \( l > 1 \). We express our results in terms of \( f\sigma_8 = \beta \sigma_{8,gal} \), where \( \sigma_{8,gal} \) is the measured amplitude of galaxy number counts in spheres of \( 8h^{-1}\text{Mpc} \) radius, related to the amplitude of mass fluctuations by \( \sigma_8 = \sigma_{8,gal}/b \). This combination eliminates \( b \) in the comparison to other measurements and cosmological predictions \(^{35}\). In addition to the case \( l > 1 \), we also considered models with \( l > 5 \) to test the robustness to low multipoles which are most susceptible to the choice of boundary conditions. In both cases, the distributions peak around the true value, \( (f\sigma_8)_{\text{true}} \approx 0.44 \), showing an average spread of about 40%. The results deviate from a symmetric Gaussian distribution mainly because of the velocity field’s nonlinear dependence on \( \beta \). Shifting the multipole cutoff from \( l > 1 \) to \( l > 5 \) removes information and slightly increases the observed spread as expected.

The analysis of the real data yielded \( \beta = 0.42 \pm 0.14 \) for \( l > 1 \), which, using the measured power spectrum amplitude of \( L^* \)-galaxies from Ref. \(^{24}\), translates into \( f\sigma_8 = 0.37 \pm 0.13 \) (see right panel of Fig. 1). Similarly, we estimated \( \beta = 0.63 \pm 0.28 \) and \( f\sigma_8 = 0.56 \pm 0.25 \) for the case \( l > 5 \). The quoted errors were derived from the quadratic approximation of the log-likelihood around its maximum. The corresponding relative errors of 35% and 45% are consistent with the mean errors found from the mocks. Both estimates agree well with the standard \( \Lambda \)CDM model which predicts a value of \( f\sigma_8 \approx 0.42 \) for our fiducial cosmological parameters. Performing a suite of basic tests \(^{22}\), we have verified that our results are insensitive to the adopted \( K \)-corrections and the modeling of luminosity evolution. Photometric uncertainties and a possible environmental dependence of the LF play a minor role since the method, comparing luminosities to peculiar velocities (dashed, empty square) \(^{10}\). The shaded areas denote the 68% and 95% confidence limits inferred from the Planck data (TT+lowP+lensing) \(^{36}\). The square data points correspond to \( z = 0.02 \) and are offset for clarity.

**Conclusions.**—Spatial modulations in the distribution of estimated galaxy luminosities trace the cosmic peculiar velocity field. As demonstrated by preliminary studies of very local samples \(^{24, 44}\), this can be combined with velocity reconstruction techniques to probe the linear growth factor with galaxy redshift surveys. The modulations in the luminosities of \( \sim 2 \times 10^5 \) SDSS galaxies from the NYU-VAGC yield a value of \( f\sigma_8 \) at \( z \sim 0.1 \) which is in agreement with the \( \Lambda \)CDM cosmological model as dictated by the Planck data \(^{36}\).

In Fig. 2 we present a compilation of recent measurements of the growth rate at low redshifts \((z < 0.3)\) which were obtained from RSDs \(^{11, 37–40}\), galaxy luminosities (filled square and circle) \(^{24}\), and direct estimates of peculiar velocities (dashed, empty square) \(^{10}\). The shaded areas denote the 68% and 95% confidence limits inferred from the Planck data (TT+lowP+lensing) \(^{36}\). The square data points correspond to \( z = 0.02 \) and are offset for clarity.
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