Large-Scale Distribution of Total Mass versus Luminous Matter from Baryon Acoustic Oscillations: First Search in the Sloan Digital Sky Survey III Baryon Oscillation Spectroscopic Survey Data Release 10

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Baryon acoustic oscillations in the early Universe are predicted to leave an as yet undetected signature on the relative clustering of total mass versus luminous matter. A detection of this effect would provide an important confirmation of the standard cosmological paradigm and constrain alternatives to dark matter as well as nonstandard fluctuations such as compensated isocurvature perturbations (CIPs). We conduct the first observational search for this effect, by comparing the number-weighted and luminosity-weighted correlation functions, using the SDSS-III BOSS Data Release 10 CMASS sample. When including CIPs in our model, we formally obtain evidence at 3.2σ of the relative clustering signature and a limit that matches the existing upper limits on the amplitude of CIPs. However, various tests suggest that these results are not yet robust, perhaps due to systematic biases in the data. The method developed in this Letter used with more accurate future data such as that from DESI, is likely to confirm or disprove our preliminary evidence.

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Introduction.—In the hot and dense early Universe, the interplay between the plasma pressure and the radiation pressure resulted in "sound waves": baryonic shells propagating around each initial overdensity of matter. At the time of recombination, approximately 370 000 years after the big bang, these baryonic sound waves froze, leaving an oscillatory signature in the distribution of baryons. After recombination, in the absence of significant radiation pressure, the distributions of baryons and cold dark matter (CDM) grew increasingly similar due to their mutual gravitational attraction. This resulted in a bump in the two point correlation function of the positions of galaxies, a signature known as "baryon acoustic oscillations" (BAOs). This feature has served, since its detection in the 2dF Galaxy Redshift Survey and the Sloan Digital Sky Survey (SDSS) [1–3], as a precious cosmological tool to probe the expansion of the Universe.

Another important aspect of BAOs, which has not yet been detected, is a related imprint on the clustering of light relative to mass. Indeed, while gravity helped the baryons catch up with the CDM distribution after recombination, this asymptotic process remains incomplete and the resulting scale dependence of the ratio of baryonic to total matter contrasts, $\delta_b/\delta_{\rm tot}$, should still be observable at present. Detecting this scale dependence would offer a new angle to compare the large scale distribution of light versus mass, an effort that dates back to the 1980s [4,5].

Specifically, the detection of the scale dependence of $\delta_b/\delta_{\rm tot}$ imprinted by BAOs is important for three reasons: The detection of the effect would provide a direct measurement of a difference in the large-scale clustering of mass and light and, thus, a novel confirmation of the standard cosmological paradigm (especially if the precise theoretically predicted form of the scale dependence is verified). It would present a strong challenge to alternative theories of gravity, specifically nondark matter models such as MOND [6] and its extensions [7] or modified gravity [8]. Direct evidence for the existence of dark matter includes the data from the bullet cluster [9]. The measurement of the scale dependence of $\delta_b/\delta_{\rm tot}$ from BAOs, would provide evidence comparable to the bullet cluster, with the significant advantage that this effect happens on linear scales and, thus, may be easier to interpret [10]. The amplitude of the effect would probe a novel aspect of galaxy formation, specifically calibrating the dependence of the average mass-to-light ratio of galaxies on the baryon mass fraction of their large-scale environment. Finally, we show, in this Letter, that such a detection would also constrain the

amplitude of compensated isocurvature perturbations (CIPs).

The measurement of the scale dependence of $\delta_b/\delta_{\rm tot}$ requires one to compare observable tracers of $\delta_{\rm tot}$ and δ_b. In this Letter, we follow and extend [11] the proposal of Barkana and Loeb [12] (BL11); i.e., we use the number density $\delta_{\rm n}$ of galaxies as a tracer of the total matter density fluctuation $\delta_{\rm tot}$ and the absolute luminosity density of galaxies δ_L as a tracer of the baryonic density fluctuation δ_b. The idea is as follows: The number density fluctuations δ_n are driven by the underlying total matter density fluctuation $\delta_{\rm tot}$, with a bias (i.e., ratio) $b_{n,t}$, which should be approximately constant on large scales. On the other hand, an area with a higher baryonic mass fraction $\delta_b/\delta_{\rm tot}$ than average is expected to produce more stars per unit total mass, hence, more luminous matter, and to result in galaxies with a lower mass-to-light ratio. As a result, the luminosity-weighted density fluctuation, δ_L, traces a combination of $\delta_{\rm tot}$ and δ_b. Therefore, the scale dependence of $\delta_b/\delta_{\rm tot}$ induced by BAOs should translate into a scale dependence of δ_L/δ_n.

Predictions.—BL11 provide a model for the tracers δ_n and δ_L of the quantities of interest δ_b and $\delta_{\rm tot}$

$$\delta_n = (b_{n,t} + Cb_{L,t} + Cb_{L,\Delta}[r(k) - r_{\rm lss}])\delta_{\rm tot}, \quad (1)$$

$$\delta_L = (b_{n,t} + (1+D)b_{L,t} + (1+D)b_{L,\Delta}[r(k) - r_{\rm lss}])\delta_{\rm tot}. \quad (2)$$

Within this model, bias factors $b_{n,t}$ and $b_{L,t}$ reflect the dependency of the number density and mean luminosity fluctuations on the underlying matter density fluctuation [13]. The mean luminosity fluctuations are also affected separately by the baryon fluctuations because the luminosity depends on the gas fraction in haloes, which itself depends—through the nonlinear process of halo collapse—on the baryon fraction of the surroundings. The parameter $b_{L,\Delta}$ quantifies the effect we search for: It is an effective bias factor that measures the overall dependence of galaxy luminosity on the underlying difference Δ between the baryon and total density fluctuations; C and D quantify effects emerging in surveys where the observed sample is flux limited (which introduces additional dependences on galaxy luminosity); and $r(k)$ is the fractional baryon deviation $r(k) = \delta_b/\delta_{\rm tot} - 1$, which can be predicted from the initial power spectra, and which approaches a constant (i.e., scale-independent though redshift-dependent) value $r_{\rm lss}$ on scales below the BAOs. Equations (1) and (2) refer to amplitudes at a given wave number k of Fourier-decomposed fluctuation fields.

Compensated isocurvature perturbations.—The measurement of the relation between dark matter and baryons is related to the search for CIPs [14]. Measurements of primordial density perturbations are consistent with adiabatic initial conditions, for which the ratios of neutrino, photon, baryon and CDM energy densities are initially spatially constant. Indeed, the simplest inflationary models predict adiabatic fluctuations [15,16]. However, more complex inflationary scenarios [17–19] predict fluctuations in the relative number densities of different species, known as isocurvature perturbations. Cosmic microwave background (CMB) temperature anisotropies limit a matter versus radiation isocurvature mode to a few percent of the adiabatic modes [20]. CIPs, however, are, specifically, perturbations in the baryon density δ_b that are compensated for by corresponding fluctuations in the CDM $\delta_{\rm CDM}$ (so that the total density is unchanged).

Such fluctuations are hard to detect, since gravity (and its effect on everything from galaxy numbers to CMB fluctuations) only depends on the total density. The uniformity of the baryon fraction of galaxy clusters [21] gives an upper limit on CIPs corresponding to $\Delta_{\rm cl} < 7.7\%$, where $\Delta_{\rm cl}$ is the rms fluctuation in the baryon to the CDM density ratio on galaxy cluster scales. Nonlinear effects on the CMB give a similar current limit, $\Delta_{\rm cl} < 11\%$ [14]. These constraints may be improved with future cosmological 21-cm absorption observations [22]. In this Letter, we added possible CIPs to the BL11 model under the standard assumption of a scale-invariant power spectrum for this field.

Model in terms of correlation function.—The observable quantities in galaxy surveys are not the fluctuations δ_n and δ_L but rather the two point statistics of such tracers, namely, the power spectrum or the two-point correlation function (2PCF). We reformulate the observational proposal of BL11 in terms of the 2PCF, defined as

$$\xi(\mathbf{x},\mathbf{y}) \equiv \frac{1}{2\pi^2}\int k^2 P(k) j_0(ks) dk, \quad (3)$$

where $s = |\mathbf{x} - \mathbf{y}|$ and $P(k)$ is the matter power spectrum defined by $\langle \delta(\mathbf{k})\delta(\mathbf{k}')\rangle \equiv P(k)\delta^D(\mathbf{k} - \mathbf{k}')$. Following the notation of BL11, we find that the observable 2PCFs ξ_n (of the galaxy number density) and ξ_L (of the galaxy luminosity density) can be expressed with three theoretically predicted functions, $\xi_{\rm tot}$, $\xi_{\rm add}$, and $\xi_{\rm CIP}$, the set of five BL11 parameters from Eqs. (1) and (2) and the parameter $B_{\rm CIP}$ (which determines the amplitude of CIPs). Defining total effective bias parameters $B_{n,t} = b_{n,t} + Cb_{L,t}$, $B_{n,\Delta} = Cb_{L,\Delta}$, $B_{L,t} = b_{n,t} + (1+D)b_{L,t}$, and $B_{L,\Delta} = (1+D)b_{L,\Delta}$, our model equations are

$$\xi_n = B_{n,t}^2\xi_{\rm tot} + 2B_{n,t}B_{n,\Delta}\xi_{\rm add} + B_{n,\Delta}^2 B_{\rm CIP}\hat{\xi}_{\rm CIP}, \quad (4)$$

$$\xi_L = B_{L,t}^2\xi_{\rm tot} + 2B_{L,t}B_{L,\Delta}\xi_{\rm add} + B_{L,\Delta}^2 B_{\rm CIP}\hat{\xi}_{\rm CIP}, \quad (5)$$

where (unlike the other ξ terms) we have separated $\xi_{\rm CIP}$ into its shape $\hat{\xi}_{\rm CIP}$ and its amplitude $B_{\rm CIP}$. In order to model the correlation functions, we begin with linear perturbation theory, for which $\xi_{\rm tot}(s)$ is given by Eq. (3),

$$\xi_{\rm add}(s) = \frac{1}{2\pi^2}\int k^2[r(k) - r_{\rm lss}]P(k)j_0(ks)dk,$$

$$\xi_{\rm CIP}(s) \equiv B_{\rm CIP}\hat{\xi}_{\rm CIP}(s) = \frac{B_{\rm CIP}}{2\pi^2}\int \frac{j_0(ks)}{k}dk.$$

Our full model with the addition of corrections for nonlinear clustering and for systematic effects is presented in the Supplemental Material [23].

Measurement.—In all this analysis, we use the latest public data release from the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS), DR10 [24] [25,26]. The BOSS collaboration has analyzed a larger set of data, denoted DR11 in [26], which will be publicly released with the final BOSS data set. For both DR10 and DR11, the BOSS collaboration has made public some "final products," namely, their measurement of ξ_n and the associated covariance matrix (but not ξ_L), and we checked that they are in good agreement with our measurement of ξ_n and give a reasonable fit to the ξ_n part of our model. Several practical problems inhibit our ability to accurately measure the 2PCF of the galaxy distribution. The discreet sampling by individual galaxies of the smooth density field leads to shot noise on small scales. Other difficulties arise from the irregular shape of galaxy surveys in angular sky coverage, due to dust extinction, bright stars, tracking of the telescope, etc. In this work, the two-point correlation functions ξ_n and ξ_L, are computed using the optimal Landy-Szalay estimator [27] which requires the creation of a catalog of random positions.

We calculate the two-point correlation function ξ_L of the absolute luminosity density fluctuations using the same estimator and algorithms as for ξ_n, but weighting each object with its absolute luminosity. The absolute luminosity is calculated using the i-band photometric data, from the CMASS DR10 catalogs. We use a jackknife resampling technique, as in Scranton *et al.* [28], to compute the full covariance matrix for the joint measurement of $\xi_n(r)$ and $\xi_L(r)$. This technique differs from the method adopted by the BOSS collaboration, where 600 mock catalogs were produced and used to estimate the covariance matrix for the fit [29,30]. Figure 1 shows our measurement of ξ_L and ξ_n and our best-fit model, as detailed in the next section.

Model fitting.—We adopt the model-fitting formalism of Hogg *et al.* [31] and assume that the only source for deviation of our data points from the model described by equations (4) and (5) is an offset in the ξ direction, drawn from a Gaussian distribution of zero mean and known covariances. We wish to get the set of parameters θ that maximizes the probability of our model $\mathcal{M}$ given the data $\mathcal{D}$, i.e., the posterior probability distribution $\Pr(\theta|\{\mathcal{D},\mathcal{M}\})$. We make a conservative choice of uniform (not "informative") priors for the parameters of our model: The prior on $B_{L,\Delta} \in [-10, 10]$ is intentionally taken to be broad, although BL11 forecasted it to be around 2.6.

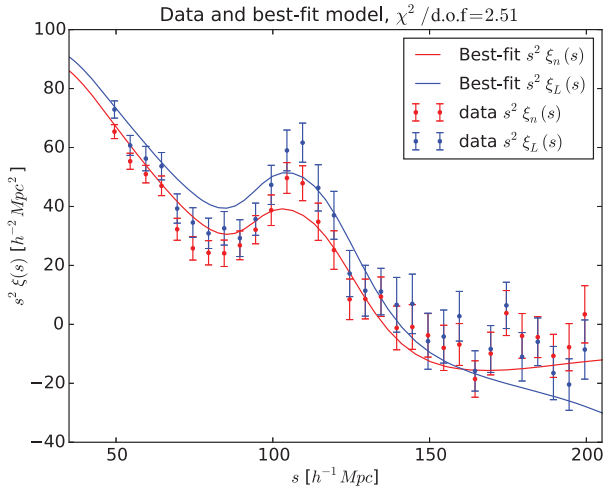

FIG. 1. Our measurement of $\xi_{\rm L}$ (blue) and $\xi_{\rm n}$ (red) [times s^2], using 31 radial bins, and our best-fit maximum likelihood model (allowing all parameters to be nonzero). The best fit corresponds to $\chi^2/{\rm d.o.f.} = 2.51$, where d.o.f. is the number of degrees of freedom in the fit. This high value of $\chi^2/{\rm d.o.f.}$ is partially due to the highly correlated errors among the various binned measurements and perhaps systematic errors (it drops to ∼1.5 when using 21 bins), which also make the fits difficult to judge visually.

The best current limits on $\Delta_{\rm cl}$ correspond [14] to an upper limit of $B_{\rm CIP} \approx 5 \times 10^{-3}$ from clusters or 1.1×10^{-2} independently from the CMB; we allowed a much broader range and applied the prior $B_{\rm CIP} \in [-0.3, 0.3]$. The other priors are given in the Supplemental Material [32].

In the case of a noninformative prior, the optimization of the likelihood function corresponds to the maximum of the posterior probability distribution, i.e., the maximum *a posteriori* value. To estimate the uncertainty in the maximum *a posteriori* value of each parameter, we obtain the distribution of parameters that is consistent with our data, and marginalize over it to get the distribution of each parameter. We did this using the Monte Carlo Markov chain algorithm MultiNest [33,34], to sample from the posterior probability distribution, and quote 1σ limits. We consider two cases, corresponding to the presence or absence of CIPs. In Figs. 1 and 2, we show the data and best fits for the correlation functions $r^2\xi_n$ and $r^2\xi_L$, and for a key quantity, their difference $r^2(\xi_L - \xi_n)$. We checked that all the following conclusions are not significantly altered when adding k corrections and evolutionary corrections and when simulating the effect of the photometric errors on the measurement of ξ_L.

Results.—When we allow CIPS, i.e., $B_{\rm CIP} \neq 0$, we obtain evidence at 3.2σ of $B_{L,\Delta} > 0.4$ (and evidence that $|B_{L,\Delta}| > 0.4$ at 3.7σ), which indicates the presence of the effect we search for, that of the baryon-CDM difference on galaxy luminosity. Moreover, the 1σ range of $1.1 < B_{L,\Delta} < 2.8$ is consistent with the prediction of BL11 of $B_{L,\Delta} \approx 2.6$ (our maximum likelihood value is 3.9) [35]. In addition, our best-fit value of $B_{\rm CIP}$ is 2.3×10^{-3}, with a 2σ upper limit of

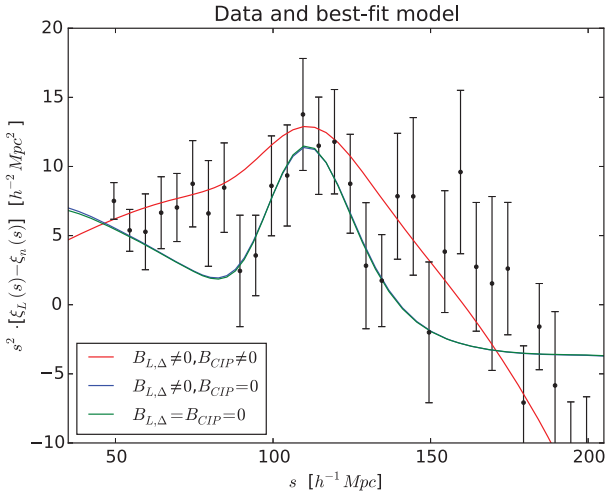

FIG. 2. Our measurement of the difference $\xi_L - \xi_n$ (times s^2), using 31 radial bins, and the same quantity in our best-fit model. The red line corresponds to our full model, the blue line corresponds to a model with $B_{CIP} = 0$, and the green line corresponds to a model with $B_{CIP} = B_{L,\Delta} = 0$.

$B_{CIP} = 6.4 \times 10^{-2}$, which is within an order of magnitude of the best existing limits noted previously. A full tabulation of our best-fit parameters, plus results with a smaller number of data bins, is given in the Supplemental Material [36].

To determine whether we detect a scale-dependent bias of the luminosity correlation function requires answering the following question: Do the data support the inclusion of a nonzero extra parameter $B_{L,\Delta}$? Rather than a question of parameter estimation, this is a question of model comparison between two models $\mathcal{M}$, with or without $B_{L,\Delta}$. Within a Bayesian framework [37], the key quantity for comparing them is the evidence (or model-averaged likelihood), $E = \int \Pr(\theta|\mathcal{M}) \Pr(\mathcal{D}|\theta, \mathcal{M}) d\theta$. The ratio of the evidences, also called the Bayes factor, can be calculated using the multimodal nested sampling algorithm, MultiNest [33]. In the $B_{CIP} \neq 0$ case, the evidence ratio is $\ln(E_{B_{L,\Delta}\neq 0}/E_{B_{L,\Delta}=0}) = 6.08 \pm 0.23$, which we interpret as strong evidence for $B_{L,\Delta} \neq 0$ according to the slightly modified Jeffreys' scale [37–39].

However, we believe that the results are not yet robust enough for making strong claims. For one thing, if we model the data without allowing for CIPs (i.e., setting $B_{CIP} = 0$), the evidence for a detection of nonzero $B_{L,\Delta}$ goes away. Our 1σ range of $-1.0 < B_{L,\Delta} < 7.8$ in that case is consistent with the previous ($B_{CIP} \neq 0$) case and with the BL11 prediction, but also with a value of zero. This lack of evidence is reflected by the evidence ratio $\ln(E_{B_{L,\Delta}\neq 0}/E_{B_{L,\Delta}=0}) = 0 \pm 0.23$, corresponding to no evidence toward one model versus the other [40]. The high value of χ^2/d.o.f., partially due to the high correlated errors between the various binned measurements [41] points at the need to eliminate systematic errors or try more sophisticated models in future implementations of this method. The fact that the parameter values are affected by the choice of the number of radial bins is another sign of the lack of robustness of our result. More generally, disentangling the various effects is difficult, since the model of Eqs. (4) and (5) shows that any ability to set a limit on CIPs depends on a definitive detection of nonzero $B_{L,\Delta}$ (and/or $B_{n,\Delta}$). Conversely, the presence of a significant CIP term in the fit strongly affects the best-fit values of $B_{L,\Delta}$ and $B_{n,\Delta}$. Trying to measure two novel effects (one of them expected but with an uncertain amplitude, the other highly speculative) when they are entangled in this way is tricky. Another difficulty comes from the fact that $\hat{\xi}_{CIP}$ has a smooth shape (in contrast with BAO-scale features in ξ_{tot} and ξ_{add}), and such a slowly varying term may more easily be emulated by systematic effects; we note that standard BAO measurements (e.g., [30]) typically add several such "nuisance" terms, which are necessary to get good fits to the data, do not significantly affect the BAO peak or trough positions, but are not theoretically well understood. We also note that several of our best-fit parameters change strongly between the zero and nonzero B_{CIP}. Especially worrying is that, in our full model, a strongly negative $B_{sys,L}$ makes a large negative contribution that is nearly canceled out by large positive contributions from the other terms.

Conclusion.—We have compared the large-scale distribution of total mass and luminous matter, through measurement of the number-weighted and luminosity-weighted galaxy correlation functions ξ_n and ξ_L in the latest public data release from the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS). We have shown that such a measurement is potentially of great importance for verifying the standard cosmological model and for putting new limits on nonstandard possibilities. In particular, such a measurement can be used to detect the large-scale modulation from BAOs of the ratio of baryonic matter to total matter. Within the framework of the model of Barkana and Loeb [12], the effect of this modulation on galaxy surveys is characterized by a parameter, $B_{L,\Delta}$, which we have measured in the BOSS CMASS DR10 data. When including nonstandard (but currently weakly constrained) CIPs in our model, we obtain evidence at 3.2σ of the modulation effect with a value of $B_{L,\Delta}$ consistent with the theoretical prediction, and an upper limit on the CIP amplitude that is within an order of magnitude of the best existing limits. However, current data limit the robustness of this test and we believe our results only demonstrate that current data are on the threshold of detecting the BAO-induced modulation and setting strong limits on CIPs. Future observational efforts, such as the Dark Energy Spectroscopic Instrument (DESI) [42], will provide more accurate data. In particular, while we used $\sim 0.5M$ galaxies for this analysis, DESI will have $\sim 20M$ galaxies, which will reduce the statistical error on the correlation function measurement and increase the redshift coverage. The better quality

imaging will reduce the error on the luminosity measurement and subsequently on ξ_L. We expect new data sets, as well as more robust theoretical modeling, to improve the robustness of the evidence and, thus, to definitively verify or rule out the predicted effect.

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