Peculiar Velocity Anomaly from Forces Beyond Gravity?

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We address recently reported anomalously large bulk flows on scales of 100h^{-1}Mpc and beyond. These coherent motions of galaxies challenge the standard ΛCDM concordance model as well as a large class of competitive models of dark energy and modified gravity. If confirmed, they may support alternative models that include extra forces enhancing the growth of perturbations on large scales. In such scenarios, current observational constraints on structure formation favor an onset of the extra forces in recent times, as predicted, e.g., in growing neutrino models. For the illustration of the main effects, we employ intuitive phenomenological parameterizations.

Recent observations of large-scale galaxy motions constitute one of the main challenges for the cosmological standard model [1]. In a Gaussian window of diameter 100h^{-1}Mpc, Watkins et al. [2] find a coherent bulk motion of 407 ± 81 km/s in conflict with the expectation of ≈ 200 km/s at the 2σ level. Other independent results confirm the presence of unexpectedly large bulk motions [3, 4]. Kashlinsky et al. [3] investigate scales of ≈ 300h^{-1}Mpc, where the expectation is even lower, obtaining the drastic result of 600-1000 km/s. Despite the large uncertainties still present today, such values have the potential of forming a highly significant anomaly for the ΛCDM model in the future.

Yet, the standard ΛCDM model has passed a series of stringent tests mainly from measurements of the cosmic microwave background (CMB), from galaxy, Lyman-α, weak lensing, and supernova Ia surveys [5, 6, 7, 8, 9]. It assumes a spatially flat universe essentially made up from dark energy in the form of a cosmological constant Λ, cold dark matter (CDM), baryons and radiation. According to the standard picture, matter perturbations from a nearly scale-invariant primordial spectrum grew solely due to Einstein gravity. Since the peculiar velocity field is intimately connected to the growth of structure, a modified growth history will typically affect the expected peculiar velocities. This can occur, e.g., in models of modified gravity [10, 11, 12], brane-world models [13, 14, 15] and models including extra couplings in the dark sector [16, 17, 18, 20, 21, 22, 23].

This letter aims at illustrating that a modified growth history could achieve the large peculiar velocities suggested by the observations, while at the same time remaining consistent with further observational constraints. Some authors have already proposed explanations of the anomaly, namely superhorizon sized non-Gaussian, non-inflationary inhomogeneities [24], cosmological-scale extra dimensions [13], and moving dark energy [25]. Instead of adopting any particular model, we parameterize modifications to the standard model phenomenologically. Thereby, we point out the basic features an explanation of the peculiar velocity anomaly should have. We will also in few words discuss the idea of altering the primordial spectrum rather than the dynamics. It is our hope that this letter motivates future investigations based on concrete cosmological models.

Before we introduce and study our phenomenological parameterizations in view of current observational constraints, we collect the relevant ingredients from perturbation theory. Inhomogeneities in the metric induce deviations from the uniform Hubble flow. They are accounted for by the peculiar velocity field \( v(x) \). The bulk flow \( u \) is the average peculiar velocity in some volume defined by a window function \( W \),

\[
u(x) = \int d^3y \, v(y) \, W(x - y).
\]

Every cosmological model predicts the mean square \( \langle u^2 \rangle \) for a window of given size and shape, which can be compared with observation. Throughout, we stick to statistical homogeneity and isotropy, which for the Fourier transformed velocity field \( v_k \) implies

\[
\langle v_k^* v_{k'} \rangle = (2\pi)^3 P_v(k) \delta^3(k - k'),
\]

where we have introduced the peculiar velocity power spectrum \( P_v(k) \). It enables us to write

\[
\langle u^2 \rangle = \frac{1}{2\pi^2} \int_0^\infty dk \, k^2 P_v(k) |\tilde{W}(k)|^2
\]

for a Fourier transformed spherically symmetric window \( \tilde{W}(k) \). In linear perturbation theory, \( P_v(k) \) can be obtained from numerical codes like CAMB [26] or CMBEASY [27]. We use the gauge-invariant velocity perturbation.

It is instructive to relate the peculiar velocity power spectrum \( P_v(k) \) to the matter density power spectrum \( P_\rho(k) \). This is achieved with the aid of the continuity equation. In conformal Newtonian gauge, it reads

\[
\dot{\delta}_k = -i k \cdot v_k + 3\dot{\phi}_k,
\]

where a dot denotes the derivative with respect to conformal time. We assume that the interactions of the matter fluctuations are dominated by gravity, with the metric perturbation \( \phi_k \) as in [28]. In the Newtonian limit, \( \dot{\phi}_k \) can be neglected. We define \( F_k = d \log \delta_k / d \log a \), such that Eq. (4) reads

\[
HF_k \dot{\delta}_k = -i k \cdot v_k,
\]
with the physical Hubble parameter $H$. In linear perturbation theory, correlations between $F_k$ and $\delta_k$ are neglected. Then, performing the averaging of Eq. (5) and introducing the averaged growth factor $f$, 

$$f(k) = \frac{1}{2} \frac{d \log P_k}{d \log a}.$$  

(6)

yields the simple relation 

$$P_{\gamma}(k) = \frac{f^2 H^2}{k^2} P_{\delta}(k).$$  

(7)

Equation (7) tells us that larger bulk flows demand higher values of $f$ or $P_{\delta}(k)$. This, however, poses a serious obstacle for most cosmological models that reproduce the standard expansion history. On the one hand, once a model is chosen, the density power spectrum $P_{\delta}(k)$ is constrained by various observations (like the CMB and galaxy surveys). Therefore, most cosmological models don’t allow for drastic deviations from the ΛCDM power spectrum. On the other hand, for a large class of dark energy and modified gravity models, $f$ can be parameterized by $f = \Omega_m^2$, with $\gamma$ constant in time [29]. Linder and Cahn [30] showed that for models of uncoupled dark energy, $\gamma$ only slightly depends on the equation of state $w$, and that even when considering models of modified gravity, $\gamma$ typically varies at most $\approx 20\%$, not enough to predict the observed bulk flows. Consequently, what at first was found as a challenge for the standard model ΛCDM, is in fact a problem for its most popular competitors as well.

This should come as no surprise since the direct influence of uncoupled dark energy, whether be dynamical or a cosmological constant, is restricted to the evolution of the background. Similar expansion histories thus imply similar growth histories. This correspondence is absent in models with extra couplings enhancing the growth of matter perturbations in recent times. For these models, the parameterization of $f$ mentioned above in general becomes invalid. Going back to Eq. (4) and using Eqs. (7) and (6), we obtain:

$$\langle u^2 \rangle = \frac{1}{8\pi^2 a^2} \int_0^\infty dk \frac{\dot{P}_\delta^2(k)}{P_\delta(k)} |\dot{W}(k)|^2.$$  

(8)

This formula shows what the continuity equation (1) already indicates: As $P_{\delta}$ and $\dot{P}_{\delta}$ are evaluated at the present time, the bulk flows are sensitive to the growth of matter perturbations today. Hence, it is possible to reach large bulk flow expectations if there is significant current growth. This can be mediated by extra forces as present in models of coupled dark energy [10, 17, 18, 19, 20, 21, 22, 23]. A rapid growth of perturbations would also contribute to the integrated Sachs-Wolfe effect (ISW), predicted too small for ΛCDM [31]. If the late-time growth has set in very recently, the impact on the present power spectrum $P_{\delta}$ may be moderate. There is thus a good chance to remain consistent with observational constraints on $P_{\delta}$.

In the following, we shall illustrate with the help of intuitive phenomenological parameterizations that amplified late-time growth actually can succeed in resolving the peculiar velocity anomaly. We build upon the standard WMAP-5 best-fit ΛCDM model [9], keeping the background evolution fixed, and introduce extra forces starting to act on the perturbations at some redshift $z_*$. We investigate two different scenarios. First, an attractive extra force may directly act upon matter perturbations. Second, cold dark matter may only indirectly be affected by some additional gravitational potential caused by an extra force between other constituents (e.g. dark energy and neutrinos, as in [17, 18, 19]). We will adjust the extra forces such that the observed bulk flows of [2] coincide with the theoretical expectation and check whether we are still consistent with observational constraints for the cold dark matter power spectrum from the SDSS DR7 [5], the ISW [31, 32], and the CMB angular power spectrum from WMAP-5 [33]. There are publicly available likelihood codes that can be implemented in COSMOMC [34].

The first scenario is modeled by amplifying the coupling between matter perturbations. In the perturbation equations, we modify the effective Newton constant $G_{\text{eff}}$:

$$G_{\text{eff}} = \begin{cases} G & \text{for } z > z_* \\ \alpha G & \text{for } z < z_* \end{cases}.$$  

(9)

Here, $G$ denotes the usual Newton constant and $\alpha \geq 1$ the amplification factor. This can be interpreted as adding an extra force of strength $\alpha - 1$ (compared to gravity) switched on at $z_*$. Since the bulk flow anomaly is found on large scales, it is sufficient to restrict the modifications to scales $k < k_*$, where $k_*$ is some large scale. Motivated by the bulk flow measurement by Watkins et al. [2] in a Gaussian window of radius $R = 50h^{-1}$Mpc, we chose $k_* = \pi/R$. Zhao et al. [35] provide a CAMB variant for modified gravity that makes the implementation of the modification (9) particularly simple.

For varying values of $z_*$, we chose $\alpha$ such that the bulk flow prediction from Eq. (5) equals the measured bulk flow $u_{\text{obs}} = 407 \pm 81$ km/s. The results are shown in figure 1. A region of particular interest is around $z_* \approx 0.4$ where dark energy starts to dominate in ΛCDM. There, at the latest, the altered dynamics of coupled dark energy models are expected to become important. Figure 1 suggests that the observed bulk flows could be due to an extra force, turned on at $z_* = 0.4$ and two to four times stronger than gravity.

We next confront the parameters favored by the bulk flow measurement with further observational constraints. The constraints from Lyman-α and weak lensing needn’t be considered because we did not change small-scale dynamics. We find that the WMAP-5 likelihood varies only slightly compared with the ΛCDM model for the parameter range considered here. But as can be seen in figure 2(a), the SDSS DR7 imposes important constraints. All switch-off redshifts $z_* \geq 1$ are excluded beyond 2σ. These borders are sensitive to the choice of $k_*$ that defines the scales at which the extra force is acting. Going to smaller $k_*$ will
Let us now consider the second scenario, i.e., that matter is affected by an additional gravitational potential $\phi_{\text{extra}}$. Similar to the first scenario, we simply parameterize $\phi_{\text{extra}}$ by

$$\phi_{\text{extra}} = \begin{cases} 
0 & \text{for } z > z^* \\
\chi & \text{for } z < z^* 
\end{cases}, \quad (10)$$

where $\chi$ is a constant and $z^*$ a switch-on redshift. As before, the modification is restricted to large scales $k < k^*$. The strength of the additional potential is most clearly quantified by the ratio $\chi/\phi$, where $\phi$ is the gravitational potential in $\Lambda$CDM evaluated at very large scales. Figure 3 visualizes the parameter range for which the bulk flow measured by Watkins et al. [2] is reached. If the additional potential is switched on at $z^* = 0.4$ (equality of matter and dark energy), figure 3 indicates that $\chi/\phi$ should take values from approximately 1 to 3.

The constraints from the SDSS DR7 power spectrum and the ISW are very similar to the ones already found for the first scenario and visualized in figures 2(a) and 2(b). Again, $z^* \lesssim 1$ is strongly favored by the SDSS, and the ISW is in better agreement with observation than the $\Lambda$CDM prediction. The CMB, however, is notably affected. For the particular model with a sharp jump of $\phi_{\text{extra}}$, the predicted power spectra are excluded by the data at more than 2$\sigma$. This issue depends, however, in a crucial way on the particular time history and scale dependence of $\phi_{\text{extra}}$. One has to assess concrete models in order to see whether a scenario of this type can be consistent with WMAP-5 and nevertheless yield an enhanced bulk flow.
Finally, we briefly comment on the possibility of altering the primordial spectrum of perturbations in order to obtain the observed bulk flows without abandoning the standard dynamics. A significant shift of power on very large scales may in principle be motivated, e.g., by models of double inflation. Though an appealing idea at first sight, the CMB imposes stringent bounds. When the measured bulk flows are to be obtained without losing consistency with the CMB, extreme values have to be selected. Estimations suggest that one would have to go to scales far outside the horizon and to amplify the power spectrum by a large factor. Moreover, regarding the lack of large-scale power in the CMB maps $085$, $087$, $088$, it would seem more natural to assume less primordial power on the largest scales.

In this letter, we have tried to point out which sorts of modifications to the standard cosmological model could be required in order to solve the peculiar velocity anomaly. Enhanced growth of matter perturbations in recent times $z \lesssim 1$ is a natural possibility. We have illustrated this with a rough parameterization of an extra force $008$, which succeeds in explaining the measured peculiar velocities while respecting further constraints. Bearing in mind the simplicity of our parameterization, it is to be expected that more elaborate cosmological models leading to enhanced growth can equally resolve the anomaly. We have shown that ISW observations even support the idea of enhanced growth: the predicted amplitude, too small in $\Lambda$CDM, that ISW observations even support the idea of enhanced growth can equally resolve the anomaly. We have shown that scenarios of a fast-growing gravitational potential influence the CMB. It has to be studied carefully for every individual model whether the modifications are acceptable or not.

If the significance of the peculiar velocity anomaly increases with future observations, this would be a strong sign for physics beyond the $\Lambda$CDM concordance model. In our examples, modifications to $\Lambda$CDM can only become effective in the recent epoch. This might suggest that the new physics is connected with the transition to dark energy domination.

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[1] L. Perivolaropoulos (2008), 0811.4684.