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The Peculiar Velocity Anomaly As a Hint for Recent Growth?

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We discuss possible cosmological implications of anomalously large coherent motions of galaxies on scales of $100h^{-1}$Mpc and beyond. We argue that the corresponding observations, if confirmed, do not only constitute an anomaly for the cosmological concordance model ΛCDM, but for a large class of competitive models of dark energy and modified gravity as well. We point out which basic features an explanation of the anomaly could have and discuss enhanced late-time growth of perturbations as a possible solution. The talk summarizes a recent work [1].

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1. Introduction

Perivolaropoulos [2] lists six puzzles (i. e. anomalies at the 2σ level and beyond) for ΛCDM cosmology. Most of these anomalies refer to non-linear scales where the well-established framework of linear perturbation theory cannot be applied and the model prediction must thus be inferred from methods like N-body simulations. As an anomaly on linear scales, Perivolaropoulos [2] mentions the recently reported peculiar velocity anomaly (on $\gtrsim 100h^{-1}$Mpc) [3, 4, 5]. These scales allow for a robust theoretical treatment within linear perturbation theory. Watkins et al. [3], investigating a Gaussian window of diameter $100h^{-1}$Mpc, report a coherent bulk motion of galaxies of (407 ± 81) km/s, which significantly exceeds the ΛCDM expectation of roughly ≈ 200 km/s. In the following, we shall concentrate on this observation when illustrating quantitative estimations. A drastic value of 600-1000 km/s is reported by Kashlinsky et al. [5] on even much larger scales (of $\approx 300h^{-1}$Mpc).[1] Although the evidence is still weak today, the observations illustrate that the peculiar velocity anomaly could become important in the future.

It might thus prove instructive to ask which modifications to the cosmological concordance model would resolve the peculiar velocity anomaly. As the peculiar velocity field originates from the growth of structure, it is a natural idea to investigate the effect of modified growth histories. These modifications, however, have to be chosen such that further observational constraints are still respected. The ΛCDM model in conjunction with a nearly scale-invariant primordial spectrum of perturbations is in good agreement with observations of the CMB and with current data from galaxy, weak lensing, Lyman-α, and supernova Ia surveys [7, 8, 9, 10, 11, 12]. In this talk, we illustrate that enhanced growth of perturbations in recent times could lead to the reported large peculiar velocities without losing agreement with the above-mentioned observational constraints. Specific proposed models have already been studied with regard to their potential of resolving the peculiar velocity anomaly [13, 14, 15]. In this talk, however, we shall focus on very general and basic arguments that we quantitatively illustrate with a rough parametrization.

2. Peculiar Velocities and Linear Perturbation Theory

We shall see in the following why the peculiar velocity anomaly does not only concern the concordance model but also the most popular competitive models. The *bulk flow* $\mathbf{u}$ is defined as the average of the peculiar velocity field $\mathbf{v}(\mathbf{x})$ in a window W. A cosmological model determines the statistics of the bulk flow, in particular the mean square $\langle u^2 \rangle$. Introducing the peculiar velocity power spectrum $P_v(k)$ (assuming statistical homogeneity and isotropy), we may write

$$\langle \mathbf{v}_\mathbf{k}^* \mathbf{v}_\mathbf{q} \rangle = (2\pi)^3 P_v(k) \delta^{(3)}(\mathbf{k} - \mathbf{q}) \tag{2.1}$$

and consequently for a spherically symmetric window,

$$\langle u^2 \rangle = \frac{1}{2\pi^2} \int_0^\infty \mathrm{d}k\, k^2 P_v(k) \, |\tilde{W}(k)|^2. \tag{2.2}$$

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[1] Due to an active discussion on whether this result is reliable or not, we do not use it for any quantitative analysis. If the reader wishes to form his own opinion, he may be interested in reading the companion paper [6] and the discussion on Wright's (`http://www.astro.ucla.edu/~wright/`) and Kashlinsky's (`http://www.kashlinsky.info`) homepages.

The continuity equation in the Newtonian limit links the peculiar velocity field to the growth of the density contrast $\delta(\mathbf{x})$ of matter perturbations,

$$\dot{\delta}_{\mathbf{k}} = -\mathrm{i}\mathbf{k}\cdot\mathbf{v}_{\mathbf{k}}, \tag{2.3}$$

where a dot is used for the derivative with respect to conformal time. In linear perturbation theory, this equation can be used to relate the peculiar velocity power spectrum $P_v(k)$ to the matter (density) power spectrum $P_\delta(k)$:

$$P_v(k) = \frac{f^2H^2}{k^2}P_\delta(k), \tag{2.4}$$

with the growth factor f and the physical Hubble parameter H. According to this equation, for a cosmological model to predict significantly larger bulk flows, it must produce considerably higher values of f or P_δ. We shall now give some general arguments why this is expected not to work for ΛCDM's main competitors. In models of uncoupled dark energy and modified gravity, f can be approximated by $f = \Omega_m^\gamma$ [16]. The range in which γ varies for different models is by far too narrow for predicting the observed bulk flows. For uncoupled dark energy models, γ shows only small dependence on the equation of state w. For modified gravity, the variation reaches only up to $\approx 20\%$ [17]. The power spectrum P_δ, on the other hand, is constrained on a large range of scales once a cosmological model is chosen and the primordial spectrum is assumed to be nearly scale-invariant. Taken together, these limitations cause the recently reported bulk flow observations to challenge a large class of cosmological models.

The reason of this general result is that in models of uncoupled dark energy, the nature of dark energy essentially varies the expansion history and thereby only indirectly the growth of perturbations. Similar expansion histories typically lead to similar growth histories. A natural way of profoundly resolving this approximate degeneracy is to consider models of coupled dark energy [18, 19, 20, 21, 22, 23, 24]. In these models, extra forces may enhance the growth of matter perturbations, especially in recent times where dark energy starts to become important. This can lead to a significantly larger present value of the growth factor f. If the enhanced growth has started very recently, the change in the amplitude of perturbations quantified by P_δ may be moderate and thus still in agreement with observational constraints from galaxy surveys.

A completely different approach would be to keep the dynamics unchanged and to modify the primordial spectrum of perturbations instead. In order to reproduce the observed large bulk flows while remaining consistent with the constraints imposed by the CMB, a huge amplification of power would be needed on scales outside the horizon (a physical motivation might be pre-inflationary inhomogeneities [5]). Bearing in mind the lack of large-scale power in the CMB [25, 26, 27], however, a decrease of primordial power on very large scales is seemingly rather expected than a strong increase.

3. A Rough Parametrization

In order to illustrate the ability of scenarios including recent growth of perturbations to resolve the peculiar velocity anomaly, we employ a very rough parametrization without any ambition of providing a realistic cosmological model. We simply keep the ΛCDM background expansion fixed

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and amplify the Newtonian gravitational potential Φ by a factor of α in recent times $z < z_*$. This corresponds to writing the Poisson equation as

$$-k^2\Phi_{\mathbf{k}} = \alpha \times 4\pi G a^2 \bar{\rho}_m \delta_{\mathbf{k}}. \tag{3.1}$$

We restrict this modification to large scales $k > k_*$, where we choose k_* to be the typical scale of the bulk flow measurement [3], i. e. $k_* = \pi/R$ for $R = 50h^{-1}$Mpc.

We may imagine a physical scenario such as growing neutrino quintessence [20, 21] where the extra forces (in this case between dark energy and the neutrinos) lead to an additional gravitational potential on large scales. Equation (3.1) would then be a very rough imitation of such a behavior. For the numerical implementation and the comparison with observational constraints, we use MGCAMB [28] and COSMOMC [29].

Our results are then obtained as follows. For range of values for z_*, we numerically find values for α such that the expected bulk flow from Eq. (2.2) is in 1σ agreement with observation [3]. This gives the shaded region in Fig. 1(a). Obviously, the amplification α needs to be much larger than unity if we choose a very recent switch-on redshift z_*. As our parametrization only affects large scales $k > k_*$, we may ignore observational constraints on smaller scales (Lyman-α and weak lensing). The CMB likelihood from WMAP5 only marginally deviates from the ΛCDM value. A constraint that remains important is the observation of the matter power spectrum by the SDSS. The corresponding likelihoods are shown in Fig. 1(b). We observe that switch-on redshifts $z_* \gtrsim 1$ are excluded by the SDSS DR7, which means that the assumed extra forces should have become important only recently. If they are linked to dark energy, $z_* \approx 0.4$ is expected to be a characteristic time (there, we have equality of matter and dark energy in ΛCDM).

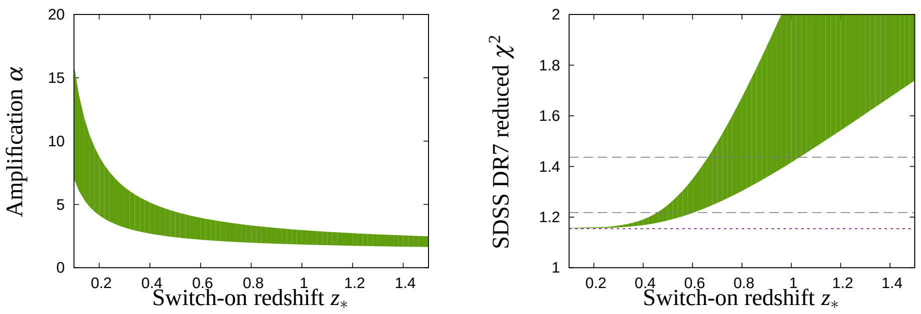

Figure 1: (a) Parameters consistent with the observed bulk flow. (b) The SDSS DR7 likelihoods for the corresponding parameters together with the 1 and 2σ borders (grey dashed) and the ΛCDM best-fit value (violet dotted).

Additionally to peculiar velocities, the ISW effect is a probe of the growth of perturbations, too. In fact, the ISW effect was observed with an amplitude about two times larger than expected in ΛCDM [30]. This result could be related to the anomalously large bulk flows [3]. Not surprisingly, the amplitude of the ISW effect and the likelihoods increase if we adopt our parametrization of recent growth (3.1) with the parameter values of Fig. 1(a). We thus reach better agreement with observation.

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4. Discussion

We have assumed that the peculiar velocity anomaly is not just a statistical coincidence or due to an unexpected feature of the primordial perturbation spectrum but in fact points to new physics. We have argued that, in this case, a scenario with enhanced growth of perturbations in recent times (e. g. mediated by an extra force) is a natural candidate. Even with a very rough parametrization of this recent growth, the reported large bulk flows can be reproduced while we remain in agreement with observational constraints (and even reach an improvement for the ISW effect). We expect this general result to also apply to realistic cosmological models including extra forces. Since our results suggest that these extra forces should have become important only recently ($z \lesssim 1$), one may speculate about a connection to the physics of dark energy.

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