What do we really know about dark energy?

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In this paper, we discuss what we truly know about dark energy. I shall argue that, to date, our single indication for the existence of dark energy comes from distance measurements and their relation to redshift. Supernovae, cosmic microwave background anisotropies and observations of baryon acoustic oscillations simply tell us that the observed distance to a given redshift $z$ is larger than the one expected from a Friedmann–Lemaître universe with matter only and the locally measured Hubble parameter.

Keywords: dark matter; dark energy; cosmological observations

1. Introduction

Nearly 13 years ago, measurements of the luminosity of type Ia supernovae (SN1a) as a function of their redshift [1,2] led to the interpretation that the expansion of our Universe is presently accelerated, and therefore the energy density of the Universe is presently dominated by a component with strongly negative pressure, $P < -\rho/3$, such as during inflation. This was an entirely unexpected result, but it has been confirmed with many more observations from SN1a data [3], from observations of cosmic microwave background (CMB) anisotropies and polarization [4], from weak lensing [5], from baryon acoustic oscillations (BAOs) [6], from galaxy surveys [7] and from cluster data [8]. All these data are consistent with the so-called concordance model, a Friedmann–Lemaître (FL) universe with a nearly scale invariant spectrum of Gaussian initial fluctuations as predicted by inflation.

In the concordance model, the energy content of the Universe is dominated by a cosmological constant, $\Lambda \simeq 1.7 \times 10^{-66}$ (eV)$^2$, such that $\Omega_\Lambda = \Lambda / (3H_0^2) \simeq 0.73$. Here, $H_0$ denotes the Hubble constant, which we parametrize as $H_0 = 100 \, \text{h} \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1} = 2.1332 \times 10^{-33} \, \text{eV}$. The second component of the concordance model is pressure-less matter with $\Omega_m = \rho_m/\rho_c = \rho_m / (3H_0^2/8\pi G) \simeq 0.13/\text{h}^2$. Here $G$ is Newton’s constant. About 83 per cent of this matter is ‘dark matter’, i.e. an unknown non-baryonic component (termed ‘CDM’ for cold dark matter), and only about 17 per cent is in the form of baryons (mainly hydrogen and helium), $\Omega_b h^2 \simeq 0.022$. The energy densities of photons and neutrinos are subdominant, $\Omega_\gamma h^2 = 2.48 \times 10^{-5}$, $0.002 < \Omega_\gamma h^2 < 0.01$, and curvature is compatible with zero.

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This situation is disturbing for two main reasons:

— The two most abundant components of the Universe have only been inferred by their gravitational interaction on cosmological scales. Dark matter: on the scale of galaxies, clusters and the Hubble scale. Dark energy: only on the Hubble scale.

— Including particle physics in the picture, we realize that the cosmological constant is in no way distinguishable from vacuum energy. The latter not only has the form \( T^\text{vac}_{\mu \nu} = \rho^\text{vac} g_{\mu \nu} \), but also it couples only to gravity. Hence there is no experiment that can ever distinguish between a cosmological constant \( \Lambda \) and a vacuum energy density\(^1 \) \( \rho^\text{vac} = \Lambda / (8 \pi G) \). My conclusion is that we, therefore, should not distinguish between the two. We then find that cosmology determines the present vacuum energy density to be \( \rho^\text{vac} \simeq (2.7 \times 10^{-3} \text{ eV})^4 h^2 \). On the other hand, ‘natural values’ for the vacuum energy are the supersymmetry breaking scale, which must be larger than about 1 TeV or, if there is no supersymmetry at this scale, the string scale and the Planck scale. The resulting estimates for \( \rho^\text{vac} \) are by 60, or, respectively, 120, orders of magnitude too large. Probably the worst estimate ever in physics! Of course, we can introduce a counter-term to compensate for the ‘bare vacuum energy’ in order to obtain the true, observed value. But, unlike the electric charge, vacuum energy density is not protected in quantum theory. Corrections to it run like \( E^4_{\text{max}} \), where \( E_{\text{max}} \) is the cut-off of the theory. Hence, the tiny value of \( \rho^\text{vac} \) has to be readjusted at each order in perturbation theory by a corresponding, much larger, counter-term. A truly unsatisfactory situation. Even if we are ready to accept this and say that this is a UV problem with quantum field theory, which should not be mixed up with the IR problem of the cosmological constant, in principle, we also have to introduce a time-dependent IR cut-off to the vacuum energy we expect to run like \( H(t)^4 \), where \( H(t) \) is the Hubble parameter at time \( t \). Such a contribution, which at present has to be of the order of \( 3 H_0^4 / (8 \pi G) \), was much larger in the past and is clearly in contradiction to cosmological observations. See Bianchi & Rovelli [9] for the opposite point of view on the dark energy problem.

Dark matter cannot be any particle of the standard model as all stable standard model particles except the neutrino and the graviton either emit photons or would have left their imprint on nucleosynthesis (baryons). Neutrinos, on the other hand, have too small masses and too large free-streaming scales to account for the dark matter seen, e.g. in dwarf galaxies [10], and for other aspects of clustering on small scales (e.g. Ly-\( \alpha \) [11]). This is even more true for the graviton, which is massless. But we know from particle physics that there have to be modifications to the standard model at energies not much larger than 1 TeV. Most of the popular proposals of such modifications, e.g. supersymmetry, do predict massive stable particles with weak interaction cross sections and the correct abundance so that they could play the role of dark matter. Hence, there is no shortage

\(^1\) Differences of vacuum energies are of course very easily measurable, e.g. via the Casimir force or the Lamb shift in atomic spectra.
of very reasonable candidates which we have not been able to detect so far. Furthermore, if the simplest supersymmetric models are realized, and the dark matter particle is the neutralino, there is justified hope of detecting it soon, either at the Large Hadron Collider at CERN [12] or via direct dark matter detection experiments [13,14].

Dark energy, however, is very disturbing. On the one hand, the fact that such an unexpected result has been found by observations shows that present cosmology is truly data driven and not dominated by ideas that can be made to fit sparse observations. Present cosmological data are too good to be brought into agreement with vague ideas. On the other hand, a small cosmological constant is so unexpected and difficult to bring into agreement with our ideas about fundamental physics that people have started to look into other possibilities.

One idea is that the cosmological constant should be replaced by some other form of ‘dark energy’, perhaps an ordinary or a tachyonic scalar field [15]. Another possibility is to modify the left-hand side of Einstein’s equation, i.e. to modify gravity (for a review, see Durrer & Maartens [16,17]). Models in which the Einstein–Hilbert action is modified by \( R \to f(R) \) have been investigated [18]. Another possibility is the theories with extra dimensions (for reviews/introductions, see [19–21]), which, when reduced to four dimensions, contain terms that deviate from Einstein gravity; the simplest and best-studied example is the Dvali–Gabadadze–Porrati model [22,23].

All these models are quite speculative and one has to test in each case that they do not contain dangerous ‘ghosts’ or other instabilities, which are expected from generic higher derivative terms [24,25]. Furthermore, even if one of these models is realized in nature, the question of why we do not measure a cosmological constant gravitationally remains. However, there may be more satisfactory ways to address this question such as de-gravitation [26] or emerging gravity [27,28].

Another, more conservative, possibility is to take into account the fact that the true Universe is inhomogeneous, at least on small scales. The question then is whether the clumpiness could mimic the presence of a cosmological constant [29–31]. Another, more extreme, attempt is to assume that the background Universe is not homogeneous, but only isotropic, a Lemaître–Tolman–Bondi (LTB) model [32]. Interestingly, these questions are still open. I shall come back to this point later.

In the present paper, I do not want to discuss or judge these possibilities, but I want to investigate what present data really have measured. As always, when our interpretation of the data leads us to a very unexpected, unnatural ‘corner’ in the space of physical theories, it may be useful to take a step back and reflect on what the measurements really tell us and how much of what we conclude is actually an interpretation of the data that might be doubted.

In the next section, I shall go over the main physical observations one by one and address this question. In §3, we discuss what this means for dark energy and in §4 I conclude.

Notation. We use \( t \) as conformal time such that \( ds^2 = a^2(t)(-dt^2 + \gamma_{ij} dx^i dx^j) \). The scale factor is normalized to 1 today, \( a_0 = a(t_0) = 1 \), but spatial curvature \( K \) is arbitrary. \( \Omega_X = \rho_X(t_0)/\rho_c(t_0) = 8\pi G \rho_X(t_0)/(3H_0)^2 \) is the (present) density parameter of the component \( X \).
2. What do we really measure?

(a) Supernovae Ia

Let us start with the first data that gave a strong indication of an accelerating Universe, the SN1a observations. SN1a observations measure the light curve and the spectrum of supernovae. The latter not only is used to determine the redshift, but also is indicative of the type of the supernova, while the light curve can be translated into a luminosity distance, $D_L(z)$, to the supernova. For this, correlations between the light curve maximum and its width are used to reduce the scatter and derive the intrinsic luminosity. SN1a are the so-called modified standard candles [3]. By this correction, the intrinsic scatter of SN1a luminosities of about 1.5 mag can be reduced to 0.2 mag [33]. It is very likely that, in the near future, this error can be reduced by at least a factor of 2 (B. Nicols 2011, personal communication). Astronomical magnitudes are related to the luminosity distance by

$$m(z_1) - m(z_2) = 5 \log_{10} \left( \frac{D_L(z_1)}{D_L(z_2)} \right). \quad (2.1)$$

Hence, an error in the magnitude translates to an error in the luminosity distance via

$$\frac{\delta D_L(z)}{D_L(z)} = \frac{\log(10)}{5} \delta m(z) = 0.46 \delta m(z). \quad (2.2)$$

Or, an error of 0.2 in the magnitude corresponds to an error of nearly 10 per cent in the luminosity distance. This is the optical precision we can reach at this time, not including systematic errors such as evolution.

If we now assume that the geometry of the Universe is FL, we can relate the luminosity to the energy content of the Universe via the standard formula

$$D_L(z) = (1 + z) \chi_K \left( \int_0^z \frac{dz'}{H(z')} \right), \quad \text{where} \quad \chi_K(r) = \frac{1}{\sqrt{K}} \sin(r\sqrt{|K|}), \quad (2.3)$$

and

$$H(z) = H_0 \sqrt{\Omega_m (1 + z)^3 + \Omega_K (1 + z)^2 + \Omega_r (1 + z)^4 + \Omega_{DE}(z)}. \quad (2.4)$$

Here $K$ is the spatial curvature and $\chi_K(r) \to r$ for $K \to 0$. For negative values of $K$, the square roots become imaginary and $\sin(r\sqrt{|K|})/\sqrt{|K|}$. $\Omega_K = -K/H_0^2$ and $\Omega_m, \Omega_r$ are the matter and the radiation density parameter, respectively. $\Omega_{DE}(z) = \rho_{DE}(z)/\rho_c(z=0)$ is the contribution from dark energy. For a cosmological constant, $\Omega_{DE}(z) = \Lambda/(3H_0^2)$ is constant.

In figure 1, we show the relative difference in the luminosity distance of a CDM universe with the density parameters $(\Omega_A, \Omega_m, \Omega_K) = (0, 1, 0)$ between a concordance Universe with $(\Omega_A, \Omega_m, \Omega_K) = (0.7, 0.3, 0)$ and between an open Universe with $(\Omega_A, \Omega_m, \Omega_K) = (0, 0, 1)$. The first difference is already larger than 10 per cent for redshifts $z > 0.2$ and should therefore easily be visible in present supernova data. The second never gets larger than 0.1, but observations of many supernovae should still easily distinguish a $\Lambda$-dominated universe from a negative curvature-dominated one. This is what SN1a observers claim they can do. Most of the data come from redshifts below and up to $z \simeq 1$. In this regime, observers,
therefore, detect a luminosity distance that is significantly larger than the one of a flat matter-dominated or a curvature-dominated universe with the same Hubble constant.

Hence, if the error estimates of SN1a observers can be trusted, these data indicate either that the geometry of the Universe is not Friedmann or that the luminosity distance is dominated at low redshift by an accelerating component, which behaves similarly to a cosmological constant.

(b) Baryon acoustic oscillations

Another way to measure distances is to compare angles subtended by objects of a given size when placing them at different redshifts. For any metric theory, this angular diameter distance is simply related to the luminosity distance by

\[ D_A = \frac{D_L}{(1 + z)^2}. \]

BAOs are the relics in the matter power spectrum of the oscillations in the baryon–photon plasma prior to decoupling. Once hydrogen recombines and the photons decouple from the electrons, the baryon perturbations evolve like the pressure-less dark matter. Matching this evolution to the oscillations prior to decoupling, one obtains for the positions of the peaks and troughs in the baryon spectrum

\[ k_{\text{through}} = \left( n + \frac{1}{2} \right) \frac{\pi}{s} \quad \text{and} \quad k_{\text{peak}} = \left( n + \frac{3}{2} \right) \frac{\pi}{s}, \quad (2.5) \]

where \( s \) is the co-moving sound horizon at decoupling,

\[ s = \int_0^{k_{\text{dec}}} c_s \, dt. \quad (2.6) \]

More precise values are obtained by numerical codes such as CAMBcode [34] and by analytical fits [35,36]. The angular diameter distance measures a scale...
What do we know about dark energy?

subtended at a right angle to the line of sight. If we can measure the difference in redshift \( \Delta z \) between the ‘point’ and the ‘tail’ of an object aligned with the line of sight, the corresponding co-moving distance is given by

\[
\Delta t(z) = \frac{\Delta z}{H} = \frac{\Delta z}{1 + z} D_H(z) \quad \text{and} \quad D_H = \frac{z + 1}{H(z)}.
\]

With the present data on large-scale structure, we have just measured the three-dimensional power spectrum in different redshift bins. We cannot yet distinguish between transverse and longitudinal directions. This measures a (co-moving) geometrical mean of \( D_V(z) = (D_H(z) D_A(z))^2 \). Results for this scale at redshifts \( z = 0.275 \) and the ratio \( D_V(z_2)/D_V(z_1) \) for \( z_2 = 0.3 \) and \( z_1 = 0.2 \) have been published [6].

The observational results from the luminous red galaxy sample of the Sloan Digital Sky Survey (SDSS) catalogue [6] are in good agreement with the cosmological concordance model \( \Lambda \)CDM cosmology with \( \Omega_A \simeq 0.7, \Omega_m \simeq 0.3 \) and no appreciable curvature. Of course, this experiment measures, in principle, the same quantity as SN1a observations since for all metric theories of gravity \( D_A = D_L/(1 + z)^2 \), but BAO observations have very different systematics and the fact that they agree well with SN1a is highly non-trivial. There are, however, objections to the significance of the BAO measurements (e.g. [37,38]).

Again, these data support a measurement of distance which is significantly larger than the distance to the same redshift with the same Hubble parameter in a \( \Omega_m = 1 \) universe.

(c) Cosmic microwave background

Our most precise cosmological measurements are the CMB observations that have determined the CMB anisotropies and polarization to high precision [4]. These measurements will be improved substantially by the Planck satellite presently collecting data (http://www.esa.int/esaSC/120398_index_0_m.html). The CMB data are doubly precious since they are not only very accurate but also relatively simple to calculate in a perturbed FL universe, which allows for very precise parameter estimation. For an overview of the physics of the CMB, see [39]. The positions of the acoustic peaks, the relics of the baryon–photon oscillations in the CMB power spectrum, allow for a very precise determination of the angular diameter distance to the last scattering surface. If this distance is changed, keeping all other cosmological parameters fixed, the CMB power spectrum changes in a very simple way, as shown in figure 2.

The angle \( \theta \) subtended by a given scale \( L \) simply changes to \( \theta' = \theta \cdot (D_A/D_A') \). Assuming that the signal comes entirely from the last scattering surface and is not influenced otherwise by the change in its distance from us (this neglects the integrated Sachs–Wolfe effect relevant for low harmonics \( \ell \)), we can assume that the correlation function of the CMB sky at distance \( D_A' \) at angle \( \theta' \) is equal to that of the CMB sky at distance \( D_A \) at angle \( \theta \), \( C'(\theta') = C(\theta) \). Translating this to the power spectrum, one obtains for \( \ell \gtrsim 20 \) (see [40])

\[
C_\ell = \left( \frac{D_A'}{D_A} \right)^2 C_\ell(D_A/D_A') \cdot \quad (2.8)
\]
Figure 2. The change in the angle subtended by the CMB acoustic peaks when changing only the distance to the last scattering surface.

In addition to this distance, which is very easily measured by CMB experiments, the matter and baryon density at the last scattering surface as well as the spectral index \( n \) and the fluctuation amplitude \( A \) are well determined by the CMB. Assuming that dark matter and baryons are neither destroyed nor generated between the time of the last scattering and today, this leads to the well-known value of their present density parameters.

Present CMB data can be fitted equally as well by the concordance \( \Lambda \)CDM model as by a flat matter-dominated model with nearly the same values for \( \Omega_m h^2 \), \( \Omega_b h^2 \) and \( n \) where the angular diameter distance is scaled to a value that is in good agreement with \( D_A \) from the concordance model, \( D_A(z_\ast) \simeq 12.9 \) Mpc. (Note that this is the distance as measured at decoupling; today its value is \((z_\ast + 1)D_A(z_\ast)\).) More details on these results can be found in Vonlanthen et al. [40].

We have discussed this here not because we think that the true model is actually the CDM model with \( \Omega_m = 1 \), but to clarify what aspect of dark energy the CMB data really measure: it is again a distance, the distance to the last scattering surface, i.e. to \( z_\ast \simeq 1090 \).

(d) Weak lensing

Weak-lensing measurements determine the weak distortion of galaxy shapes by gravitational lensing from the matter distribution in the foreground of the imaged galaxies. The advantage is that this signal is sensitive only to the total clustered mass in front of the galaxy. The disadvantage is that the signal is small, the ellipticity owing to lensing is only about 1 per cent of the typical intrinsic ellipticity of galaxies, and only statistical results can be obtained (for a review see [5]). So far, because of limitations on the knowledge of the redshift distribution of foreground galaxies and other statistical problems, weak lensing has mainly been used to determine the combination \( \sigma_s \sqrt{\Omega_m} \simeq 0.6 \), which leads to ‘bananas’ in the \( \sigma_s - \Omega_m \) plane. But future surveys like the Dark Energy Survey (DES) or Euclid (a satellite project of ESA) are expected to lead to significant improvements; see Joachimi & Bridle [41] for forecasts. Here, \( \sigma_s \) is the amplitude of matter fluctuations in spheres of radius \( 8h^{-1} \) Mpc. It is determined by the amplitude \( A \) of CMB anisotropies and the spectral index \( n \).

This measurement by itself may not be so interesting for dark energy, but in combination with CMB anisotropies it is consistent with the same amplitude, spectral index and, especially, matter density as the CMB and therefore can be
regarded as independent support of the CMB result. It is also interesting that this provides a measurement of $\Omega_m h^2$ at low redshift, $z < 1$, which is consistent with the CMB result at $z = z_* \simeq 1090$.

(e) Large-scale structure

One of the oldest cosmological measurements is determinations of the correlation function and the power spectrum of the galaxy distribution. At present, the biggest galaxy survey is the SDSS [7], which has mapped the galaxy distribution on the Northern Hemisphere out to redshift $z \simeq 0.2$ and the luminous red galaxies to $z \simeq 0.5$. This has led to a determination of the galaxy power spectrum down to $k \simeq 0.02 \, h \, \text{Mpc}^{-1}$ [42].

The main problem here is that we compare this measured galaxy power spectrum with the calculated matter power spectrum. The latter can be calculated very accurately on large scales by relativistic cosmological perturbation theory and quite accurately on small scales by Newtonian $N$-body simulation. However, the relation between this matter distribution and the distribution of galaxies is still to some extent an unsolved debate that goes under the name of ‘biasing’. On small scales, it is clear that the galaxy formation process is highly nonlinear and may depend on other parameters than the matter density alone (e.g. the metallicity that would favour the formation of galaxies in the vicinity of already existing galaxies).

On large scales, most workers in the field assume that bias is linear and close to 1; however, simple investigations of a toy model-biasing scheme show that, contrary to the matter distribution, the galaxy distribution may very well acquire a white noise component, which would dominate on very large scales [43,44].

If we disregard these problems and assume that in the measured range, or at least where linear perturbation theory applies, bias is linear, we can also use the galaxy power spectrum to obtain $\sigma_8$, $n$ and $\Omega_m h^2$, with different systematics than from other probes. Interestingly, the power spectrum bends from $\propto k$ behaviour to $\propto k^{-3} \ln^2(kt_{eq})$ behaviour at the equality scale, $k_{eq} \simeq \pi / t_{eq} \propto \Omega_m h$ in units of $h/\text{Mpc}$. Since $t_{eq} \propto 1/(\Omega_m h^2)$ the position of this turnover (which is very badly constrained with present data), together with the amplitude which is proportional to $\Omega_m h^2$, would allow us to infer both the Hubble parameter and the matter density parameter, from the matter power spectrum.

Features in the galaxy power spectrum such as the BAOs or redshift space distortions might actually be less affected by biasing and therefore provide more promising cosmological probes. However, since they contain less information than the full power spectrum, measuring the latter will always have an advantage.

Finally, in future surveys which go out to very large scales, $z \simeq 2$, it will be very important to clearly relate the observed galaxy distribution to relativistic linear perturbation variables, i.e. to take into account relativistic effects in the matter power spectrum [45–47]. This actually represents not only an additional difficulty but even more a new opportunity.

(f) Cluster abundance and evolution

The earliest data favouring a low-density Universe probably come from the observation of cluster abundance and evolution [48]. Clusters are the largest
bound structures in the Universe and, as such, are very sensitive, the amplitude of density fluctuations on large scales $\propto \sigma_8 \Omega_m$. Actually, clusters usually form at fixed velocity dispersion. Therefore, the cluster density strongly constrains the velocity power spectrum, $P_V \propto \Omega_m^{1.2} \sigma_8^2$ (e.g. [39]). Comparing observations with numerical simulations gives [49]

$$\Omega_m^{0.6} \sigma_8 = 0.495 \pm 0.034 \pm 0.037.$$  

If we insert $\sigma_8 \simeq 0.8$, this is in rough agreement with $\Omega_m \simeq 0.3$, but certainly requires $\Omega_m < 1$.

3. What do we know about ‘dark energy’?

What do these observations really tell us about dark energy? I think it is clear, even though I did not enter into any details about observational problems, that each observation taken by itself is not conclusive. There are always many things that can go wrong for any one cosmological probe. We have assumed that systematics are reasonably well under control and we can trust our results. This is supported by the fact that many different probes with independent systematics give the same result: a value of $\Omega_m h^2 \sim 0.13$ and a distance to the redshift relation at $z \lesssim 1$ that is not in agreement with a flat matter-dominated universe, but with a $\Lambda$CDM universe.

However, we do not measure $\Lambda$ with any cosmological probe. We only infer it from distance measurements by assuming that the formula (2.4) can be applied, which only holds for homogeneous and isotropic FL models. On the other hand, we know that the true Universe is at least perturbed. Naively, one may argue that the gravitational potential is small, $\Psi \sim 10^{-5}$, and therefore corrections coming from clustering will be small. But even if $\Psi$ is small, we know that curvature perturbations that are second derivatives, $\partial_i \partial_j \Psi \sim 4\pi G \delta \rho \gtrsim 4\pi G \rho$, are not small. On galactic scales, they are many orders of magnitude larger than the background term, $|\partial_i \partial_j \Psi| \gg H^2$. Since such terms may well enter into the perturbed expansion law $H(z)$, it is not clear that they cannot affect the distance for redshifts where clustering has become relevant. This is the point of view of workers on the back reaction and clearly, before we have examined it in detail, we cannot exclude this possibility. Unfortunately, this is a relativistic effect of nonlinear clustering and our understanding of these effects is still rather poor.

Dyer & Roeder [50] have argued that the photons which end up in our telescope go preferentially through empty or at least under-dense space and therefore the distance formula should be corrected to the one of an open universe. But, as we have seen, this is not sufficient and actually Weinberg [51] has shown that the shear term which is present if matter is clustered in the case of simple ‘Schwarzschild clumps’ exactly corrects for the missing Ricci term and reproduces the FL universe formula. In a generic, clumpy space–time, the Sachs equation yields

$$\frac{d^2 D_A}{dv^2} = - \left( |\sigma|^2 + \frac{1}{2} R_{\mu\nu} k^\mu k^\nu \right) D_A.$$  

Phil. Trans. R. Soc. A (2011)
What do we know about dark energy?

Hence, the presence of shear always leads to deceleration, like matter density. But the measured quantity is not $D_A(v)$ but $D_A(z)$, so we have to study how the redshift is affected by clumping owing to the motion of observers,

$$\frac{dz}{dv} = u_{a;b}k^a_k^b.$$

If the expansion of matter (observers) is substantially reduced in a clumping universe, this can reduce the redshift at fixed $v$ and therefore lead to seemingly larger distance. Similar ideas have been put forward by Wiltshire [52–54] but of course we need to study this quantitatively.

Another possibility may be that the Universe is also statistically not homogeneous. From CMB observations, we infer that it is very isotropic and this leaves us with spherically symmetric LTB models. Clearly, this possibility, which violates the cosmological principle, is not very attractive. It is, therefore, important to investigate whether we can test it observationally, and the answer is fortunately affirmative: the relation between the speed of expansion, $H(z)$, and the distance $D_L(z)$ in an FL universe is given by equation (2.4). In an LTB model, this relation no longer holds. Therefore, independent measurements of both $H(z)$ and $D_L(z)$ (or $D_A(z)$) which test relation (2.4) can check whether distances are really given by the FL expressions. This at the same time also checks whether clustering modifies distances in an important way. At present, we do have relatively good distance measures out to $z \sim 0.5$, but no independent measurements of $H(z)$. These may be obtained in the future from large galaxy surveys such as DES or Euclid, which will allow us to measure separately the radial and the transverse matter power spectrum.

Other tests of whether ‘dark energy’ is truly a new component in the stress energy tensor or simply a misinterpretation of the observed distance can come from measurements of the growth factor of linear perturbations, which we can determine with future weak-lensing surveys like Euclid or via correlations of large-scale structure and the integrated Sachs–Wolfe effect. In a $\Lambda$-dominated universe, the linear growth of clustering is modified in a very specific way and we would not expect a simple misinterpretation of observed distances to also mimic this behaviour.

4. Conclusions

In this work, I have pointed out that all present claims about the existence of dark energy have not measured $\Omega_A$ or even less $\Omega_{DE}$ and $w$ directly, but just the distance redshift relation $D_L(z)$. They then have inferred the existence of dark energy by assuming the form (2.4) for this relation, which holds in an FL universe. Even though many of you (especially the observers, I guess) may regard this point as trivial, I believe that it is important to be aware of it before one is ready to postulate unobserved scalar fields with most unusual properties, or violations of general relativity on large scales.

I have not discussed the many possible pitfalls of the observations, which weaken any one observation, but my confidence relies on the fact that independent observations with different systematics find the same result. I hope they are not too strongly influenced by ‘sociology’, i.e. if your finding disagrees with the results.
of others it must be wrong and therefore you do not publish it; however, if it
agrees well it must be right and therefore you do not have to investigate every
possible systematics that would increase your error bars and make your result
less ‘competitive’.

The beauty of research in cosmology is that data come in fast and there
is justified hope that the question of whether relation (2.4) holds for the real
Universe will be answered in the not very far future.

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