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Probing dark energy with future surveys

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Abstract. I review the observational prospects to constrain the equation of state parameter of dark energy and I discuss the potential of future imaging and redshift surveys. Bayesian model selection is used to address the question of the level of accuracy on the equation of state parameter that is required before explanations alternative to a cosmological constant become very implausible. I discuss results in the prediction space of dark energy models. If no significant departure from $w = -1$ is detected, a precision on w of order 1% will translate into strong evidence against fluid–like dark energy, while decisive evidence will require a precision of order 10^{-3}.

1. Introduction

One of the most fundamental problems of contemporary physics is to elucidate the nature of the "Dark Sector" of the Universe. A wealth of cosmological observations seem presently to point to a concordance cosmological model where "normal" (i.e. baryonic) matter accounts for a mere 4% of the matter–energy contents of the cosmos. The remaining 96% makes up the so–called "Dark Sector", with about 19% of cold dark matter (CDM) and 77% of "dark energy". The details of this cosmic budget vary somewhat depending on the data sets used and the assumptions one makes, but the errors on the different components are below 10% (for details, see e.g. Efstathiou et al. 2002; Percival et al. 2002; Seljak at al. 2005; Sanchez et al. 2006; Spergel et al. 2006).

Guidance as to the nature of dark energy requires stronger observational proof of its properties today and in the past. A first important step is to discriminate between an evolving dark energy (whose energy density changes with cosmic time) and a cosmological constant of the form proposed by Einstein in the 1910s. A handle on this question is offered by the equation of state parameter, w, that measures the ratio of pressure to energy density of dark energy. Current data are consistent with $w = -1$ out to a redshift of about 1, with an uncertainty of order $5 - 10\%$, by using all of the available data sets (see e.g. Seljak et al. 2006). However, one must be very careful when assessing the combined constraining power of different data sets whenever each one of them does not provide strong constraints when taken alone. Combination of mutually inconsistent data can potentially lead to unwarranted conclusions on the dark energy parameters.

We first briefly review the observational prospects for constraining the dark energy equation of state parameter, referring the reader to Trotta & Bower (2006) for a more detailed discussion. In Section 3 we present and discuss some results on the required accuracy on w from the perspective of Bayesian model selection and conclude in Section 4.

2. What will we learn in the next decade?

The observable impact of dark energy can be broadly divided in two classes: modification of the redshift–distance relation and effects on the growth of structures. Accordingly, we can divide the different methods one can use to constrain dark energy following the effect through which they are mainly sensitive to dark energy: *probes of the redshift–distance relation* (supernovae as standard candles, acoustic oscillations as standard rulers) and *probes of the growth of structures* (galaxy clustering, number counts, weak lensing, Integrated Sachs–Wolfe effect). For a more detailed review of the advantages and weaknesses of each technique, see Trotta & Bower (2006).

While none of those methods possess by itself all of the *desiderata* that we would ideally want in trying to constrain dark energy, combination of (at least) two techniques offers many advantages. It allows for cross–calibration of observables and facilitates cross–checks of systematics, since the physical underpinnings of each observable are different, and so is the nature of the possible systematic errors.

In view of this, a very promising combination is given by weak lensing and baryonic acoustic oscillations, which together offer the advantages of potentially high accuracy (weak lensing) and robustness to systematics (acoustic oscillations). They independently probe the growth of structures (lensing) and the angular diameter distance relation (acoustic oscillations, once calibrated against the high–redshift ruler given by the cosmic microwave background). Weak lensing studies will need high–quality imaging surveys covering many thousands of square degrees, while spectrographic redshift surveys encompassing millions of galaxies will be necessary to exploit fully the potential of acoustic oscillations. Let us now review the observational perspectives in those fields over the next decade.

2.1. Imaging surveys

Proposals for the next generation of imaging surveys driven by dark energy science typically feature a survey area covering 5,000 to 10,000 square degrees, a large field of view (2 square degrees or more) and four to five optical photometric bands. Those are the basic specifications for both the *Dark Energy Survey* (DES) and *darkCAM*, which would have optical cameras mounted on 4m class telescopes. DES is a US–led collaboration that will use a 520 megapixel CCD camera mounted on the Blanco telescope to image 300 million galaxies at a median redshift of $z \sim 0.7$ and to carry out weak lensing, baryonic oscillations, cluster counts and SNe observations over 5 years, starting in 2009. The European UK–led *darkCAM* proposal to image some 10^9 galaxies with weak lensing image quality was originally envisaged to share time on ESO's VISTA, but is now looking at a full–time site.

One of the most advanced projects is the *Pan-STARRS* survey (Panoramic Survey Telescope and Rapid Response System), a US Air Force funded project in Hawaii, primarily devoted to the identification of Earth-approaching objects, but with 30% of its time dedicated to supernovae, baryon oscillations and weak lensing surveys. The first of the planned four 1.8m telescopes is currently undergoing commissioning, and the full system could be online by about 2009, representing a major increase in power with respect to present–day surveys.

In purely statistical terms, the most precise constraints on the dark energy equation of state are likely to come from weak lensing. The details depend very much on which assumptions are made about the cosmology and on which other data sets are included. By exploiting all of the correlations that can be constructed from a weak lensing survey, weak lensing alone could achieve better than 5% accuracy on the effective equation of state, while in combination with CMB anisotropies measurements of Planck quality (an ESA satellite missione due for launch at the beginning of 2008) an accuracy of 1–2% might be within reach. This is of course only achievable if all of the systematic errors will be kept closely under control. This means an exquisite image quality, good seeing conditions (below 0.9 arcsec), excellent photometric redshift reconstruction and control of intrinsic and gravitational–intrinsic correlations. Arguably, the major hindrance in pushing weak lensing constraints below the 5% mark will indeed come from systematic error control.

The clusters and SNe method will be considerably less stringent, roughly a factor of 3 to 4 less precise than weak lensing, unless combined with strong CMB priors (i.e., Planck data), in which they case they will perform at about the 5% level. The performance of the cluster count technique relies however on self–calibration using clustering and weak lensing data, a difficult procedure compounded by the challenge of controlling systematic errors at this level of precision. The possibility of SNe evolution and missing pieces in our understanding of how a supernova explosion comes about are also likely to be limiting factors when trying to increase the accuracy on the equation of state below the 10–5% limit with this technique. Finally, measurements of acoustic oscillations from imaging surveys are not competitive with the other methods in terms of precision, reaching down to only about 20% accuracy because of the lack of resolving power in the radial direction (Blake & Bridle 2005, but see also Angulo et al. 2005).

2.2. Spectrographic surveys

There are a number of redshift surveys at various stages of planning, development or commissioning, that will have among their main science drivers measurements of the acoustic ruler at different redshifts.

Perhaps the most ambitious is the *Wide-Field Multi-Object Spectrograph (WFMOS)* (see Bassett et al. 2005), a proposal for a 1.5 deg^2 multi-object spectrograph which will be able to observe 4,000 to 5,000 objects simultaneously. The instrument is to be developed collaboratively by the Gemini and Subaru Observatories and will be deployed on the 8m Subaru telescope on Mauna Kea, Hawaii. Two baseline surveys are being proposed: a shallower and wider one, covering 2,000 square degrees at $z \sim 1$ which will target emission line blue galaxies; and a deeper one, over 300 square degrees at $z \sim 3$ targeting Lyman-Break Galaxies. The two WFMOS proposed baseline surveys will determine the angular diameter distance and the Hubble expansion rate at $z \sim 1$ and $z \sim 3$ with 1–2% accuracy. The corresponding constraints on the dark energy equation of state rely on the calibration of the acoustic scale. If combined with Planck forecasts and SDSS data, WFMOS observations should achieve an accuracy in the range of 5–10% in the effective equation of state.

On a shorter timescale, there are proposals to use the *AAOmega* wide–field spectrograph – an upgrade to the 2dF spectrograph for the Ango–Australian Telescope, which has now been successfully commissioned – to carry out large surveys (between 500 and 1,000 deg^2) in the redshift range $0.3 < z < 1$ to achieve 2% accuracy in the angular diameter distance and the expansion rate. A rather more revolutionary concept is being investigated for the *VIRUS* spectrograph, a proposal for the 9m Hobby-Eberly Telescope in Texas based on industrial replication of low–cost components.

In summary, the statistical accuracy from acoustic oscillations redshift surveys is less than what could be achieved with weak lensing. However, the acoustic oscillation method seems to be much more robust with respect to systematic errors, and it can probe a deeper redshift range than any other method.

2.3. On the pathway to the SKA

On a slightly longer timescale, proposals for next–to–next generation of instruments aim at taking dark energy investigations to an even more ambitious level. Among them, perhaps the most prominent are the *LSST* in the optical and the *SKA* in the radio.

The *LSST* (Large Synoptic Survey Telescope) is a project for a wide–field, 8.4m telescope and a 3 Gpixels

Model	(Δ_+, Δ_-)	$\ln B$ today ($\sigma = 0.1$)
Phantom	$(0, 10)$	4.4 (strongly disfavoured)
Fluid–like	$(2/3, 0)$	1.7 (slightly disfavoured)
Small departures	$(0.01, 0.01)$	0.0 (inconclusive)

Table 1. Strength of evidence disfavouring the three benchmark models against a cosmological constant model, using an indicative accuracy on $w = -1$ from present data, $\sigma \sim 0.1$.

Model	(Δ_+, Δ_-)	σ for evidence level	
		strong	decisive
Phantom	$(0, 10)$	0.4	$5 \cdot 10^{-2}$
Fluid–like	$(2/3, 0)$	$3 \cdot 10^{-2}$	$3 \cdot 10^{-3}$
Small departures	$(0.01, 0.01)$	$4 \cdot 10^{-4}$	$5 \cdot 10^{-5}$

Table 2. Required accuracy for future surveys in order to disfavour the three benchmark models against $w = -1$ with strong ($\ln B = 3$) or decisive ($\ln B = 5$) strength of evidence.

camera. The survey will cover the whole of the Southern hemisphere (or 20,000 deg^2) multiple times per month with 6 colours photometry. It will survey the largest volume ever proved and it will use a variety of techniques (weak lensing, acoustic oscillations, cluster abundance and a staggering 250,000 SNe per year) to constrain dark energy at the percent level. The current schedule expects construction to begin in 2009 and first light in 2013. Science will start in 2014.

The second half of the next decade will also see a great leap forward in radio astronomy, as the SKA (Square Kilometer Array) begins operations, first as a pathfinder (around 2015) and then as a full system with a total collecting area of a million square meters (around 2020). Thanks to its huge field of view, the SKA will be able to measure redshifts of a billion of galaxy over half of the sky in only a few months of operations, by detecting radio emissions from hydrogen gas (see eg Blake et al. 2004). The project is now beginning the design study phase, thanks to a recent funding decision by the European partners, including PPARC.

3. How far should we go in establishing $w = -1$?

If one could determine with high accuracy that $w = -1$ and constant in time, this would strongly support the case for a cosmological constant. This would imply that dark energy is a manifestation of a new constant of Nature, whose magnitude would however suffer from a strong fine tuning problem. Detecting an evolution with redshift of $w(z)$ would support a dynamical form of dark energy, perhaps in the form of a scalar field that could be linked to the inflationary phase of the early Universe. Either one of these results is likely to have a major impact on our knowledge of fundamental physics.

Since current data are compatible with $w = -1$ at all redshifts < 1, it is interesting to ask what level of accuracy is required before our degree of belief in the cosmological constant is overwhelmingly larger than for an evolving dark energy. This of course assumes that future data will not detect any significant departure from $w = -1$. Bayesian model comparison is a quantitative tool to address this question that takes into account the predictivity of the more complicated model (in this case, a time varying dark energy) and the information content of the data, see Trotta (2007) and Kunz et al. (2006) for a discussion and general introduction. In this case, the relevant quantity is the Bayes factor B between a cosmological constant model ($w = -1$) and a varying dark energy model with an effective equation of state (averaged over redshift with the appropriate weighting factor for the observable, see Simpson & Bridle 2006) $w_{\rm eff} \neq -1$. The Bayes factor gives the amount by which our relative believe in the two models is modified by the data, with $\ln B > (< 0)$ indicating a preference for the cosmological constant (evolving dark energy) model. If we assume that the data are compatible with $w_{\rm eff} = -1$ with an uncertainty σ, then the Bayes factor in favour of a cosmological constant is given by

$$B = \sqrt{\frac{2}{\pi}} \frac{\Delta_+ + \Delta_-}{\sigma} \left[\mathrm{erfc}\left(-\frac{\Delta_+}{\sqrt{2}\sigma} \right) - \mathrm{erfc}\left(\frac{\Delta_-}{\sqrt{2}\sigma} \right) \right]^{-1}, \tag{1}$$

where for the evolving dark energy model we have adopted a flat prior in the region $-1 - \Delta_- \leq w_{\rm eff} \leq -1 + \Delta_+$ and we have made use of the Savage–Dickey density ratio formula (see Trotta 2007). The prior, of total width $\Delta = \Delta_+ + \Delta_-$, is best interpreted as a factor describing the predictivity of the dark energy model under consideration. For instance, in a model where dark energy is a fluid with a negative pressure but satisfying the strong energy condition we have that $\Delta_+ = 2/3, \Delta_- = 0$. On the other hand, phantom models will be described by $\Delta_+ = 0, \Delta_- > 0$, with the latter being possibly rather large (see e.g. Kujat et al. 2006 for an example). A model with a large Δ will be more generic and less predictive, and therefore is disfavoured by the Occam's razor of Bayesian model selection. We notice that the prior and its flatness over the range Δ do not necessarily need to be interpreted as reflecting a probability distribution of models in terms of frequency of outcomes (although the latter could easily be implemented if available) but rather our state of knowledge about the range of possibilities that can be realized by the model *a priori*. According to the Jeffreys' scale for the strength of evidence, we have a strong (decisive) preference for the cosmological constant model for $3.0 < \ln B < 5.0$ ($\ln B > 5.0$), corresponding to posterior odds of $20 : 1$ to $150 : 1$ (above $150 : 1$).

We plot in Fig. 1 contours of constant observational accuracy σ in the model predictivity space (Δ_-, Δ_+) for $\ln B = 3.0$ from Eq. (1), corresponding to strong evidence in favour of a cosmological constant. The figure can be interpreted as giving the space of extended models that can be significantly disfavoured with respect to $w = -1$ at a given accuracy. Present–day precision, roughly of order $\sigma \sim 10^{-1}$, gives odds stronger than $20 : 1$ against phantom models with $\Delta_- \lesssim 1$ as compared to a cosmological constant model. As we have seen, the next generation of dark energy surveys will reach $\sigma \sim 0.01$ and this will allow to strongly disfavour (or otherwise) fluid–like models, corresponding to the top left corner of the

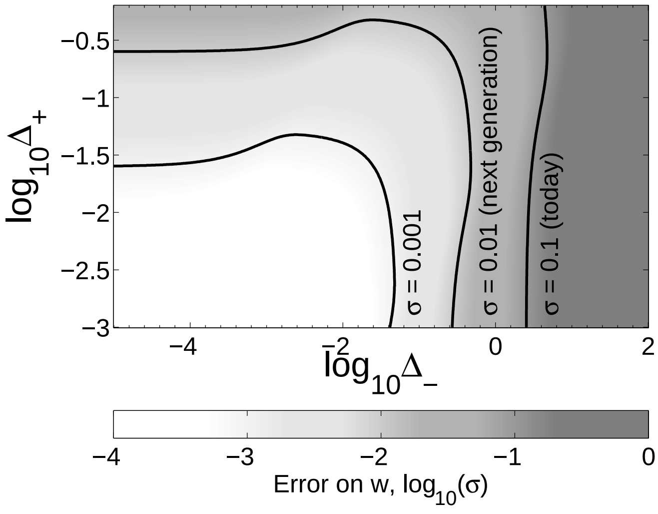

Fig. 1. Required accuracy on $w_{\rm eff} = -1$ to obtain strong evidence against a model where $-1 - \Delta_- \leq w_{\rm eff} \leq -1 + \Delta_+$ as compared to a cosmological constant model, $w = -1$. For a given σ, models to the right and above the contour are disfavoured with strong (i.e. $> 20 : 1$) odds. The benchmark models discussed in the text are located in the upper left corner (fluid–like dark energy, for $\log_{10} \Delta_- \to -\infty$), bottom right axis (phantom dark energy, for $\log_{10} \Delta_+ \to -\infty$) and at the coordinates $(-2, -2)$ (percent–level departures from $w = -1$).

figure. Another order of magnitude increase in precision is required to test with strong significance models which predict percent–level departures from $w = -1$. The results for the 3 benchmark models mentioned above (fluid–like, phantom or small departures from $w = -1$) are summarized in Table 1, where we list the outcome of present–day model comparison against $w = -1$. Only phantom models with large Δ_- are presently significantly disfavoured.

In Table 2 we show the required accuracy in terms of σ in order to achieve strong evidence against each of the models. We conclude that in the lack of significant departures from $w_{\rm eff} = -1$ future surveys will be able to accumulate decisive evidence against phantom models with large ($\Delta_- > 10$) negative effective equation of state. Disfavouring a fluid–like model where $-1 \leq w_{\rm eff} \leq -1/3$ will instead require better than percent accuracy on $w_{\rm eff}$ ($\sigma = 3 \cdot 10^{-3}$). If models can be constructed that naturally predict only percent–level departures from $w_{\rm eff}$ (that we termed "small departure models"), then Bayesian model selection will not be able to strongly disfavour them unless the error on $w_{\rm eff}$ could be decreased well below 10^{-4}.

We expect that a similar analysis could be easily carried out to compare the cosmological constant model against departures from Einstein gravity, thus giving some useful insight into the potential of future surveys in terms of Bayesian model selection (see also Mukherjee et al. 2005 for a similar approach).

4. Conclusions

We have argued that the most promising methods for dark energy investigation are weak lensing and acoustic oscillations, because of their statistical accuracy (weak lensing) and robustness to systematic errors (acoustic oscillations). Weak lensing has the potential of achieving 1% accuracy on $w_{\rm eff}$ but this precision requires an exquisite control of various systematic errors. Observations of baryonic oscillations with a spectroscopic survey have less statistical power than weak lensing (roughly a factor of 5), but are less prone to systematic errors due to the characteristics of the acoustic signature. The above goals could be reached within the next decade thanks to a vigorous observational campaign, involving collaborations such as DES, darkCAM, Pan–STARRS and WFMOS.

We have shown that Bayesian model selection can offer a guidance as to the level of precision required on $w = -1$ before explanations alternative to a cosmological constant appear extremely unlikely in terms of posterior odds of models. We have found that phantom models where one can have $w_{\rm eff} \ll -1$ are strongly disfavoured by present–day data. Gathering decisive evidence against a fluid–like model for dark energy will however require a precision of order 10^{-3} on $w_{\rm eff}$.

In conclusion, the observational study of dark energy is a crucial area of cosmological research. Thanks to a host of ambitious proposals and a strong support by several funding bodies, key advances are likely to be made within the next decade both from the observational and the theoretical points of view.

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