Whitepaper: For a Comprehensive Space-Based Dark Energy Mission

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Abstract

A space-based mission would provide an unparalleled opportunity to explore dark energy, the biggest puzzle in physical science today. Independent analyses have shown that a comprehensive program combining results from supernovae, weak lensing, and baryon acoustic oscillations will be much more effective than any subset of them. Because the stakes are so high and our knowledge of the phenomenon is so limited it is essential that the three techniques provide independent and overlapping tests. A mission that enabled effective measurements of supernovae, weak lensing, and baryon acoustic oscillations would perforce yield a remarkable data set for the broader astrophysical and astronomical communities.

The discovery [1, 2] of the accelerating expansion of the universe places profound questions before the scientific community: is more than 70% of the energy content of the universe in the form of something that has negative pressure - dark energy - or does General Relativity fail on the large scale? Do we need Einstein's cosmological constant after all, despite the discomfort it causes particle theorists?

> In the absence of data, natural guesses for the vacuum energy density, or cosmological constant, might have been 10^{108} eV^4, from the quantum-gravity (Planck) scale, 10^{96} eV^4 from unified gauge symmetry breaking, or perhaps as small as 10^{44} eV^4 if low-energy supersymmetry enforces large cancellations. In reality it is no larger than 10^{-10} eV^4 ! In my opinion, this disparity is the biggest and most profound gap in our current understanding of the physical world.
>
> *Frank Wilczek* [3]

> The discovery of dark energy has greatly changed how we think about the laws of nature.
>
> *Ed Witten* [4]

Much of the initial data on Type Ia supernovae that revealed the dark energy phenomenon came from terrestrial observation, as did confirming data from further supernovae and baryon acoustic oscillations. However, space-based measurements were already important in the discovery papers themselves and the advantages of working from space for supernovae, weak lensing, and baryon acoustic oscillations are well known: low-noise observations in the NIR, superb PSF, absence of vibration and temperature variation, uninterrupted viewing, low sky backgrounds etc. The desirability of a space-based mission designed to investigate dark energy has been advocated by the Dark Energy Task Force [5] and the BEPAC study [6].

The fundamental nature of dark energy compels us to design experiments that will be as conclusive as possible. Indeed, the history of the discovery is instructive itself: had there been only a single experiment detecting the acceleration, its acceptance would likely have been quite slow. In the ensuing years we have become comfortable with a new paradigm, so comfortable that now any deviation from it would seem as remarkable as the very discovery of dark energy itself. Although analyses of new data will inevitably be done in the current paradigms that allow for a cosmological constant, dark energy, and even modest deviations from General Relativity, it is essential to confirm that the phenomena observed thus far continue to behave as expected beyond the ranges explored to date. While we anticipate concordance between the results obtained with supernovae, weak lensing, and baryon acoustic oscillations, **we need to see this concordance established by these distinct techniques in overlapping domains of the history of the universe**. With discordant results from two techniques, we would not know which to believe. Moreover, a variety of techniques is needed to test separately the expansion history of the universe and the history of the growth of structure in order to be sensitive to the possible failure of General Relativity. The DETF report [5] states “We recommend that the dark energy program have multiple techniques at every stage, at least one of which is a probe sensitive to the growth of cosmological structure...”

The study of dark energy is hampered by the absence of compelling models. There is but one, Einstein’s General Relativity supplemented with a phenomenally small (by the standards of the particle physics community) cosmological constant. There is a continuum of alternatives, none of which seems worthy of special attention. It is therefore customary to take the cosmological constant model as the standard and ask whether observations are consistent with it and how well some future experiments might distinguish between it and the alternatives. The Dark Energy Task Force proposed a particular way of quantifying this.

According to General Relativity, the scale-size of the universe, $a(t)$ obeys

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\rho + 3P) + \frac{\Lambda}{3} \tag{1}$$

The ratio $P/\rho = w(a)$ is the equation of state for the putative dark energy. While w is essentially zero for non-relativistic matter and $+1/3$ for relativistic matter, it must be less than $-1/3$ for dark energy so that the acceleration can be positive, or alternatively we must have a positive Λ, which acts as if w were -1. The Hubble parameter, $H(a) = \dot{a}/a$ reflects distribution of energy among non-relativistic, relativistic, and dark energy components today through

$$H(a)^2/H_0^2 = \Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_{DE} a^{-3(1+w)} \tag{2}$$

where we assumed for simplicity that w is constant. (The parameter Ω_m is the mass density today relative to the density $\rho_c = 3H_0^2/(8\pi G_N)$ and similarly for the radiation and dark energy terms Ω_r and Ω_{DE}. The curvature term is $\Omega_k = -kc^2/H_0^2$ and satisfies $\Omega_m + \Omega_r + \Omega_k + \Omega_{DE} = 1$.) In fact $w(a)$ has an unknown functional form. If dark energy is simply the cosmological constant, then $w = -1$ for all a. To assume that w is constant is unwarranted and the DETF chose as a simple prescription $w(a) = w_0 + w_a(1 - a)$. It then quantified knowledge of dark energy as the reciprocal of the area of an error ellipse in the $w_0 - w_a$ plane. A more detailed characterization has been proposed recently [7] but the simple DETF prescription suffices here. The Fisher matrix technique provides a convenient method for combining the results of existing and prospective experiments. The Fisher matrices for different experiments can simply be added together provided each allows for every parameter considered by any other experiment. In practice, anticipated results from CMB measurements are always included.

While quantitative measures of future performance are an attractive way to evaluate proposals, great caution is appropriate. The JDEM Figure of Merit Science Working Group [7] stated

> It is important to stress that the FoMSWG feels that it would be ill advised to pursue a dark energy program on the sole basis of a figure of merit, or even several such numbers, or even the information generated following the FoMSWG procedure. Figures of merit, or the result of the FoMSWG procedure, are only as good as the data models used to generate them. Constructing a data model requires assumptions about many things, in particular systematic errors and performance of instruments.

These caveats are pertinent to comparisons of one proposal versus another. However, the general conclusions of the DETF are more robust. Particularly important is the conclusion [5]

> We find that no single observational technique is sufficiently powerful and well established that it is guaranteed to achieve by itself an order of magnitude increase in the DETF figure of merit. Combinations of the principal techniques have substantially more statistical power, much greater ability to discriminate among dark energy models, and more robustness to systematic errors than any single technique. The case for multiple techniques is supported as well by the critical need for confirmation of results from any single method.

These points are demonstrated by considering a potential JDEM mission with supernova, weak lensing, and BAO measurements. To make comparisons we consider using pairs of these together with prospective measurements from Planck. We then consider combining all three of them with Planck [8].

Table 1. The DETF figure of merit for various combinations of supernova, weak lensing, and BAO data. In each instance, the anticipated Planck result is used, together with anticipated results from a space-based dark energy mission. The addition of a new technique on top of two previous ones generally leads to a doubling of the figure of merit.

Input	FoM
Planck + SN + BAO	708
Planck + SN + WL	785
Planck + BAO + WL	621
Planck + SN + BAO + WL	1252

The general implication is simple: the addition of each new technique on top of two previous ones leads roughly to a doubling of the figure of merit. The DETF report further concluded "The SN technique is at present the most powerful and best proven technique for studying dark energy.", "BAO...is less affected by astrophysical uncertainties than other techniques." and "*If* the systematic errors are at or below the level asserted by the proponents, [weak lensing] is likely to be the most powerful individual Stage IV technique and also the most powerful component in a multi-technique program." Is the bird-in-the-hand supernova technique as good as the birds-in-the-bush weak lensing and baryon acoustic oscillations? The right answer is to go after all three birds.

While DETF did not quantify the test of General Relativity from growth of large-scale structure, this was done by the FoMSWG. A density perturbation δ grows as a result of gravity and the ratio $G = \delta/a$ is well approximated by

$$G(a) = G_0 \exp\left(\int_{0.1}^{a} d\ln a' \, [\Omega_m^{\gamma}(a) - 1]\right) \tag{3}$$

where $\Omega_m(a)$ is the fraction of the total energy density present as matter. For any dark matter model consistent with General Relativity, γ is very nearly 0.55, while in alternative models it can differ from this by 0.1 or more. Experiments that are expected to be complete by the time of JDEM launch ("Stage III") are predicted by the FoMSWG to give an uncertainty on γ of $\sigma_\gamma = 0.21$, which would not provide meaningful discrimination. The addition of JDEM would reduce this to $\sigma_\gamma = 0.019$, small enough to discriminate against many alternatives to GR.

In measuring supernovae, baryon acoustic oscillations, and weak lensing, JDEM will inevitably produce an extraordinary database of great value to the broader astronomical community. The coverage would likely include 10,000 square degrees or more for weak lensing and baryon acoustic oscillations, while 7.5 square degrees of supernova observation would be 2000 times larger than the Hubble Ultra-Deep-Field survey. The BEPAC report [6] states "The broader science potential of JDEM has been critical to the high urgency that the committee has assigned to JDEM..." and cited, for example

> A dataset that is over three orders of magnitude larger than that obtained from HST will allow a direct comparison with ground-based studies (present and future) of the nearby universe. A JDEM imaging survey ... would dominate the studies of how galaxies acquire their mass over time, reaching back through more than 90% of the age of the universe, from redshift zero to approximately 3.5.

A space-based dark energy mission will complement JWST by providing much greater sky coverage, with imaging in both visible and NIR wavelengths.

A space-based dark energy mission measuring simultaneously supernovae, weak lensing, and BAO can provide the definitive study of the phenomenon that has overturned our expectations for the large-scale behavior of the cosmos. We need to seize this opportunity to make sure that the mission is thorough and prudent. We need to make sure that the mission has the capability to test the measurements of one technique against another. To skimp on the mission design will endanger this one great opportunity and will reduce the value of the data to the broader astronomical community.

References

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[4] Quoted by Dennis Overbye, New York Times, June 3, 2008.

[5] A. Albrecht *et al.*, astro-ph/0609591.

[6] Committee on NASAs Beyond Einstein Program: An Architecture for Implementation. National Academies Press, 2007.

[7] A. Albrecht *et al.* astro-ph 0901.0721.

[8] The Fisher matrices for supernovae and weak lensing were supplied by Gary Bernstein. The Planck Fisher matrix is the one given by the Figure of Merit Science Working Group. For supernovae, it is assumed that there are data from $z = 0.1$ to $z = 1.6$, with an overall uncertainty of 0.01 magnitudes in each bin in z of width $\Delta z = 0.1$. The BAO Fisher matrix is from Daniel Eisenstein. There are 85 bins between $z = 0.67$ and $z = 2$ and uncertainties of roughly 1.4% in D and 2.5% in H in each bin. The weak lensing Fisher matrix assumes 10,000 square degrees and 30 galaxies per square arc minute.