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Observing Dark Energy with SNAP

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Abstract. The nature of dark energy is of such fundamental importance – yet such a mystery – that a dedicated dark energy experiment should be as comprehensive and powerfully incisive as possible. The Supernova/Acceleration Probe robustly controls for a wide variety of systematic uncertainties, employing the Type Ia supernova distance method, with high signal to noise light curves and spectra over the full redshift range from $z = 0.1-1.7$, and the weak gravitational lensing method with an accurate and stable point spread function.

1. Introduction

Exploring the nature of the physics responsible for the current acceleration of the expansion of the universe is a major scientific goal for the next decade. The implications range over high energy physics, the theory of gravitation, and the fate of the universe. Current data, most notably Type Ia supernova distances, accompanied by cosmic microwave background (CMB) and large scale structure measurements, suggest a dark energy component comprising nearly three quarters of the total energy density, with negative pressure roughly equal to its energy density (i.e. pressure to energy density ratio $w \approx -1$).

But the physics possibilities behind this are manifold. Einstein's cosmological constant would have w identically -1 at all redshifts z, while models exist with $w(z)$ greater than or less than -1 and generically time varying. Moreover, many models possess an averaged value of w not too different from -1 over a limited redshift range, so even a 5% measurement of $\langle w \rangle$ or an assumed $w_{\rm constant}$ is unlikely to provide us with an important and unambiguous clue to fundamental physics.

To progress, we need a new, specially designed experiment that seeks to account for and control all reasonably possible sources of uncertainty in the astrophysics, while probing the cosmology through multiple, well understood methods. Ten years from now, we want to be in the position of having, if not the solution, then clear clues to solve the mystery of dark energy, but not to fail to obtain guidance after all that effort through lack of foresight and completeness. The requirements of depth and sufficiency drive the design of the Supernova/Acceleration Probe (SNAP; Aldering et al. 2004), a space based 2-meter telescope with optical and near infrared imaging and spectroscopy.

2. Beyond the Present

Ongoing ground based supernova surveys, necessarily limited to $z < 1$, will improve our knowledge of $w_{\rm constant}$, and of supernovae themselves – both extremely useful – but do not give us directly the equation of state ratio of the dark energy. From $w_{\rm constant}$ we cannot extract the present value w_0 or a measure of its variation w' in an unbiased manner, and merely admitting our ignorance of whether there exists a variation w' blows up the uncertainties in w_0 (Perlmutter & Schmidt 2003).

Space based surveys permit more accurate supernova photometry and the ability to extend to higher redshifts (e.g. Knop et al. 2003; Riess et al. 2004), but the time is not available to follow up and characterize substantial numbers of supernovae (even with a dedicated program on the Hubble Space Telescope, due to its narrow field). So these advances, while solid steps of progress, are insufficient to obtain significant constraints on the dynamics of the dark energy through w'. This lack of a dense, superbly characterized sample over the entire key redshift range of $z = 0 - 1.7$ obscures and disables discrimination of the physics.

Figure 1 illustrates this, showing the effect of a random irreducible systematic uncertainty of $0.1z$ per bin of redshift width 0.1. This could arise from a combination of extinction and K-corrections, gravitational lensing magnification, calibration errors, etc. Only an experiment obtaining scores of supernovae per bin over the full range, with exquisite systematics control, could achieve the sensitivity and power of the innermost, light yellow contour representing SNAP constraints at 68% confidence level.

Specifically, the requirements on the data sample are:

- Full redshift range $z = 0 - 1.7$ with dense sampling, to break parameter degeneracies and bound systematics.
- $\sim$2000 supernovae with optical/near infrared imaging and spectra to 1) divide into subsets for like-to-like comparison ("anti-evolution"), 2) obtain high signal to noise to bound systematics and prevent Malmquist bias, and 3) many $z > 1$ supernovae to prevent gravitational lensing bias.
- Space telescope ($\sim$2 meter aperture) for 1) infrared observations (essential for high z) and high accuracy color (dust extinction) corrections, and 2) precise and stable weak gravitational lensing shear measurements.
- Crosschecking and complementary methods for robust characterization of the nature of dark energy. Weak lensing adds great value in deep, medium wide, and panoramic surveys. *No need for Ω_M prior!*

3. SNAP Surveys

SNAP plans its observing strategy to maximize the science from both the supernova and weak lensing methods. In the reference mission, the deep survey covers 15 square degrees repeatedly in 9 wavelength bands for 120 visits, discovering and following supernovae down to AB magnitude 30.3 in each filter and

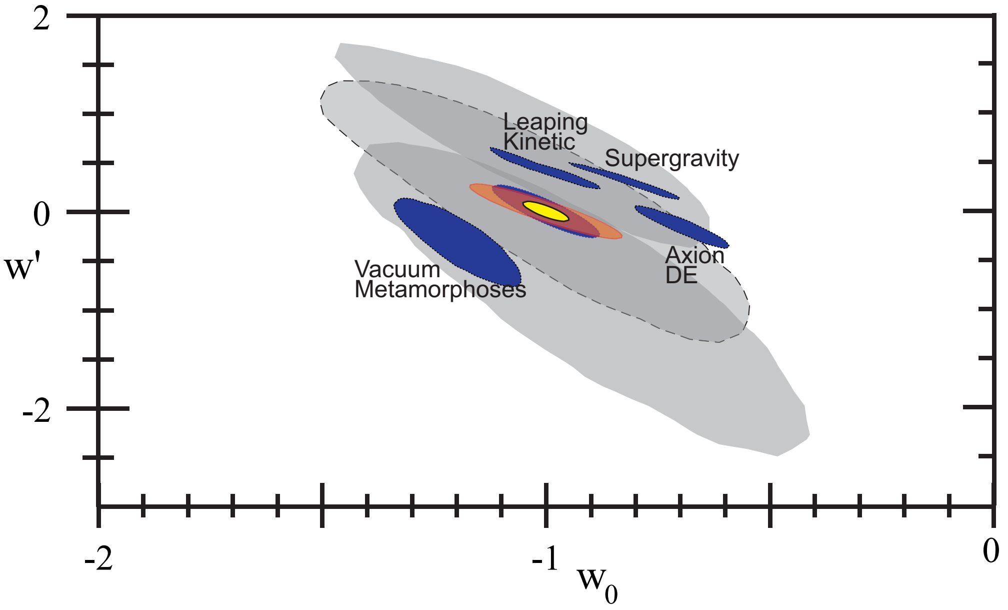

Figure 1. Current and imminent supernova surveys do not have the redshift range, statistics, and systematic control necessary to discriminate even roughly between different models of dynamical dark energy. The large central, dashed grey shaded region shows the current status, including HST supernovae, shifted to be centered on the cosmological constant model parameters ($\Omega_m = 0.3 \pm 0.04$ prior included). The flanking grey shaded regions show the effects of bias induced by the current level of systematics, completely obscuring various dark energy models. SNAP, as a new generation experiment, will be able to achieve the inner, light yellow contour.

measuring lensing shears for 10^7 galaxies with a number density of greater than 250 resolved galaxies per square arcminute. This will be superb for a wide area dark matter map. The wide survey scans 300-1000 square degrees once, down to AB 26.6 in each band, resolving 100 galaxies per square arcminute for a total of some 300 million galaxies. A panoramic survey is also under consideration of up to 10000 square degrees, AB=25, with 40-50 galaxies per arcmin^2 for a billion galaxies.

4. Observing Dark Energy

In order to determine accurately the cosmological parameters, the dark energy density Ω_{DE} and present equation of state w_0, and explore the crucial physics clue of the variation w', SNAP will achieve:

- Homogeneously calibrated supernova sample over the full redshift range $z = 0.1 - 1.7$;
- Tight systematics control;
- Unified, comprehensive mission without the need for external priors – SN Ia + Weak Lensing (+ Strong Lensing + SN II +...);

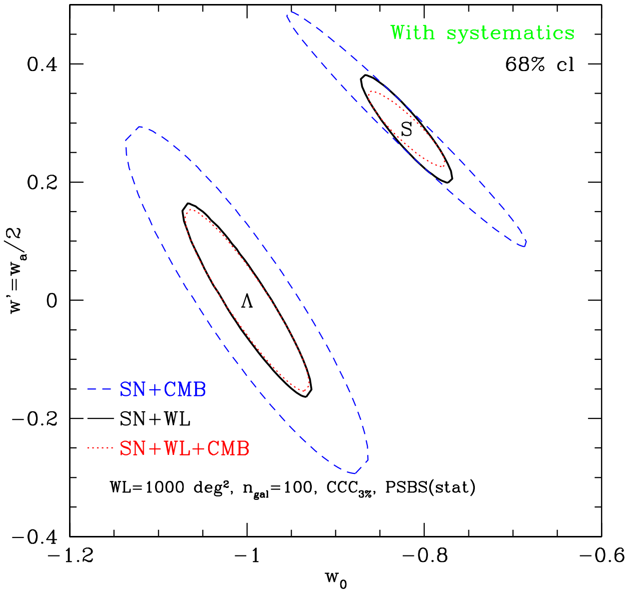

Figure 2. Weak gravitational lensing and supernovae distances work superbly together as cosmological probes. To realize the tightest bounds requires systematics control only possible from space – point spread function resolution, stability, and low noise. Here we include constraints for two dark energy models from 2000 supernovae and a 1000 square degree weak lensing survey (employing power spectrum and bispectrum data and cross-correlation cosmography), both with systematics. No external priors are needed.

- Precision *and* accuracy beyond proposed ground and non-dedicated space observations.

Moreover, SNAP will test the cosmological framework by directly mapping the expansion history $a(t)$ of cosmic scales over time, from the acceleration into the deceleration epoch, probing dark energy, higher dimensions, extensions to gravity, etc.

In addition, the science resources provided by the deep, wide, and panoramic fields will fuel a plethora of astronomical investigations into galaxy evolution, the high redshift universe, dark matter, stellar populations, rare, variable, and moving objects, etc. Furthermore SNAP will act in synergy with the next generation James Webb Space Telescope and carry out a Guest Survey program.

To observe dark energy and optimize the return on the investment of effort and funding by having the best chance for learning the essential dynamics to push the fundamental physics frontier, we need to have a comprehensive, robust experiment like SNAP.

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