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Seeing the Nature of the Accelerating Physics: It's a SNAP

Overview White Paper to the Dark Energy Task Force

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1. Summary

For true insight into the nature of dark energy, measurements of the precision and accuracy of the Supernova/Acceleration Probe (SNAP) are required. Precursor or scaled-down experiments are unavoidably limited, even for distinguishing the cosmological constant. They can pave the way for, but should not delay, SNAP by developing calibration, refinement, and systematics control (and they will also provide important, exciting astrophysics).

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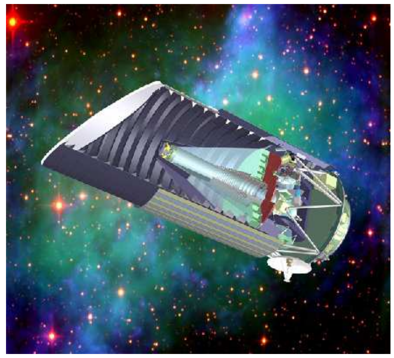

1. To understand dark energy requires accurate knowledge of the physical dynamics w, w'.

2. To see accurately the dynamics requires mapping of the expansion history, or geometric distance measurements, covering the full range $z = 0 - 1.7$.

3. To achieve robust results requires stringent systematics controls within a cosmological technique and crosschecking between techniques. Complementarity also provides enhanced constraints. It is particularly essential to conjoin a distance probe and a mass growth probe (e.g. supernovae and weak lensing) to reveal the physical origin of dark energy.

4. To attain the first three points requires the third generation of experiments, i.e. the Joint Dark Energy Mission (JDEM), e.g. SNAP. Experiments without w', the redshift range, mature, identified, and controlled systematics limits, and complementarity do not provide a substantial understanding of dark energy, despite statistical gains. Precursor experiments add value in developing systematics control and cosmological techniques directly in line with the third generation.

2. The Role of Precursors, The Role of JDEM

We need to meet the extraordinary challenge of the new physics behind cosmic acceleration by designing revelatory, robust experiments. Revelatory means detailed investigation of the dynamics of the dark energy, characterizing its equation of state value and variation, e.g. the "tilt" $1+w$ and "running" $w' = \dot{w}/H$. Robust means that we must have confidence that the data tell us the true answer, not one biased or degraded due to systematic uncertainties.

What we can do with JDEM is put together the most stringent, deep- and wide-seeing experiment possible in the next generation. A space mission requires strong justification and must provide a substantial step beyond previous experiments or what can be achieved from the ground: this has driven the SNAP design. For further details, see the SNAP supernovae and weak lensing white papers to the Dark Energy Task Force.

2.1. Dynamics

Precursors can give us a *glimpse* of dark energy in the form of $w_{\rm constant}$, but do not allow *study* of dark energy. Indeed, of the two major classes of quintessence models, the half that are "thawing" models (Caldwell & Linder 2005), will appear *nearly identical* to a cosmological constant when viewed in terms of w a priori constant, despite its dynamics (see Fig. 1). For example, an experiment aiming at a precision of 0.05 in $w_{\rm constant}$ would think it has found $w = -1 \pm 0.05$, concealing a thawing model with $w_0 = -0.8$. Such a biased result mistakes the physics for half the models in the phase space. Thus w' is essential, even for the question of whether dark energy is the cosmological constant or not.

As a true next generation experiment, SNAP will give strong constraints on w and w' and guide us in the quest for the nature of the new physics. Precursor experiments cannot match this fundamental requirement, being basically blind to the dynamics w' on scales finer than the Hubble time (Linder & Miquel 2004). Indeed a basic physics distinction in scalar field physics requires the precision on the dynamics to be of order the deviation of the equation of state from the cosmological constant value, $\sigma(w') \sim 2(1+w) \lesssim 0.1$ (Caldwell & Linder 2005).

The role of precursor experiments then is not fundamentally one of revelation, but of robustness. This does not stop them from doing exciting astrophysical science, but for dark energy their main role should be to move full speed ahead toward enabling JDEM. They should be valuable contributions to the development and refinement of experimental techniques, control of systematics, and astrophysical calibration. These are essential roles.

A wide field telescope in space has access to a wide variety of cosmological probes, depending on survey strategy. These include Type Ia supernovae, weak gravitational lensing, baryon acoustic oscillations, strong gravitational lensing, Type II supernovae, and cluster properties and abundances. Precursor experiments have an opportunity to realize, understand, and refine these varied techniques. During this development, the areas of advantage and disadvantage of each probe will become clearer, and systematic uncertainties must be identified and strategies designed to control them, before they can be considered seriously as useful tools. However, only SN Ia and weak lensing are developed to the point of currently being on the playing field of cosmological usefulness, and only SN Ia are mature.

Concurrently, the unprecedented depth and precision of SNAP must be leveraged by a firm foundation of calibration – understanding of photometric zeropoints, creation of standard star networks, crosswavelength calibration, PSF and atmospheric corrections, photometric redshift fitting, understanding heterogeneity of probe objects, etc. As one example, extremely well calibrated low redshift supernovae studies (see, e.g., the spectrophotometric approach of the Nearby Supernova Factory (Wood-Vasey et al. 2004)) have always been treated as an essential component of cosmology fitting for the SN Ia distance method. These precursor aspects are all true science and will further provide a lasting legacy for astrophysics.

2.2. Redshift Range

Redshift depth, completeness, and homogeneity of the sample are all key issues for both the leverage and robustness of the data. For distance measurements, the sensitivity curve of determining either w or w' poses a steep obstacle at redshifts $z < 1.5$ (see Fig. 2; Linder & Huterer (2003)), so data sampling the entire region from low redshift to $z > 1.5$ (with unified calibration) is necessary. Supernovae give a direct, geometric probe of the expansion history of the universe, an essential tool for understanding dark energy and a landmark of cosmology in its own right. Cobbling together disparate experiments will not provide the accuracy needed; indeed offsets of as little as 0.02 mag between redshift sets can lead to biases of order 0.7σ (Linder & Miquel 2004). These requirements, however, are beyond the reach of precursor experiments, and even handfuls of measurements at $z > 1$ cannot avoid systematic bias from gravitational lensing magnification and other observational difficulties. A unified supernova distance experiment covering the full range $z = 0.1 - 1.7$ is essential for understanding dark energy (see Fig. 3).

For weak gravitational lensing, depth is also a key advantage, strongly increasing the cosmological leverage, more so than sky area. The effective number density of galaxies entering the shear measurements scales as

$$n_{\rm eff}(z) \sim n_g C_l(z)/C_l(z_{\rm fid}) \approx n_g[1 + 2.5(z_m - 1)]/[1 + 2.5(z_{\rm fid} - 1)],$$

with C_l is the shear power, z_m is the median source redshift, and $z_{\rm fid}$ is the median source redshift for a comparison survey (Vale & Linder 2004). This implies that a survey with $n_g = 100/\mathrm{arcmin}^2$ and $z_m = 1.2$ has not 3.3, but 10 times the effective number density as a survey with $n_g = 30/\mathrm{arcmin}^2$ and $z_m = 0.8$. Such depth can therefore compensate for a *factor 100 in sky area*, in the shape noise dominated regime. SNAP will not have any competition in that regime from ground based weak lensing surveys before the Large Survey Telescope (LST).

2.3. Complementarity

Combining a purely geometric measure of distance, such as supernovae, with a probe that includes a sensitivity to mass growth, such as weak lensing opens important new avenues for understanding the physical origin of dark energy. While the growth information in weak lensing (or any other such probe) is admixed with distances in a complicated fashion, in synergy with supernova measurements it offers the opportunity for distinguishing a high energy physics component from an extension to the theory of gravity as an explanation for the acceleration of the universe (see Fig. 4; Linder (2005a)), i.e. testing whether Einstein gravity breaks down. Neither probe alone accomplish this.

The essential development, refinement, and calibration of cosmological techniques, and voluminous increase in our astrophysical knowledge, produced by precursor experiments are real science, and furthermore provide crucial foundations to the next generation of JDEM and LST.

3. "Ensure Rapid Progress"

The key role of precursor experiments is laid out in the agency charge to the Dark Energy Task Force: "ensure rapid progress... towards understanding the nature of dark energy". As shown above, that understanding will not come before SNAP. Precursor experiments should aim to provide rapid progress in realizing the far more comprehensive next generation.

The greatest leverage will come through increasing the robustness of the cosmological probes that have already proved themselves capable. Indeed, concrete, essential contributions have already been identified and are being implemented:

1. Detailed characterization of supernova heterogeneity through spectrophotometric study in a wide variety of environments. This is already in progress through, e.g., the Nearby Supernova Factory and Carnegie Supernova Project.

2. Testing of astrophysical systematic effects on supernova distances, e.g. theoretical studies of gravitational lensing magnification, observational studies of dust extinction properties, multicolor flux calibration. One example of projects in progress with HST is the "Decelerating and Dustfree" program, studying $z > 1$ supernovae in clusters of elliptical galaxies where extinction corrections should be minimal. The Canada-France-Hawaii Telescope Supernova Legacy Survey and CTIO Essence Project are underway to provide detailed multicolor light curves for over 800 Type Ia supernovae.

3. Weak lensing robustness in both larger observational data sets and improved algorithmic treatment of extracting the signal and separating telescope, atmosphere, and intrinsic systematics. The CFHT Legacy Survey is in progress to deliver some 140 square degrees of data to moderate depth and galaxy number density. Pan-Starrs is gearing up for a two order of magnitude increase over this area, within the next five years. On the analysis side, a widely international collaboration is testing data extraction through the Shear Testing Programs (STEP).

These requirements to "ensure rapid progress" in understanding dark energy are already underway. Dark energy is such a fundamental question that the community has not sat back and waited for this generation of experiments, but moved forward to make it happen. Nor should the revelatory and robust experiments of the succeeding generation, JDEM and LST, remain "in the dugout". They should be on deck, warming up, with the precursor lead-off experiments setting up the conditions for their home run on dark energy.

The two key components of this strategy not already underway are: 1) a comprehensive astrophysical flux calibration program, and 2) a comprehensive cosmological theory program so that interpretation of the incoming and forthcoming data will not be theory limited. Note that both components will have wide impact throughout astrophysics and cosmology while at the same time being the critical precursors to understanding dark energy.

Other hopes exist for methods of probing our universe; for example baryon acoustic oscillations appears promising. If baryon oscillation surveys achieve their potential they can help supernovae in distance determination; note, however, that baryon oscillations alone, even at high precision on distances, cannot match the cosmological parameter leverage of supernova distances, nor is baryon oscillations plus weak lensing the equal of supernovae plus weak lensing. This arises because baryon oscillations give distances relative to high redshift, where dark energy is negligible, rather than to low redshift where dark energy is dominant (Linder 2003, 2005b). But baryon oscillations will have a different, and possibly benign, set of systematics – issues of mode coupling, redshift space distortions, biasing, and simply obtaining sufficient high S/N observations need to be actively researched. With finite resources, decisions need to be made to ensure precursor projects should not delay revelatory, robust results for any longer than needed in direct support of that goal.

4. Overview of SNAP

The data characteristics for JDEM, as SNAP, that are driven by the science requirements for a revelatory and robust dark energy experiment 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) obtain 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 to supernovae, in deep and wide surveys. *No need for* Ω_M *prior!*

SNAP plans its observing strategy to maximize the science from both the supernova and weak lensing methods. In the basic mission, the deep survey covers 15 square degrees repeatedly in 9 wavelength bands for 120 visits, discovering and following supernovae to $z \approx 3$ and 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 basic wide survey scans 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. With an extended mission, the wide survey can be expanded over additional thousands of square degrees.

4.1. SNAP Probes

These surveys automatically provide data for other dark energy methods. For example SNAP will obtain a sample of some thousand clusters, measured in nine bands optically and through weak lensing, deeper in redshift and with a lower mass threshold than other proposed cluster surveys except for SPT. The wide survey maps baryon acoustic oscillations photometrically over 1000 square degrees (expandable) in the key redshift range $z \approx 1 - 2$, problematic from the ground. Such photometric surveys, while a factor 15 weaker than spectroscopic surveys for the same area, actually only require 4-5 times the area of a spectroscopic survey when used in complementarity with supernovae, to provide the same strength on the dark energy constraints.

Note that space-based weak lensing (for which SNAP would establish *three orders of magnitude* improvement in area) provides 1) a higher density of resolved images, useful for probing smaller scale structure where the growth effects are amplified by nonlinearities, 2) deeper lenses allowing mapping of the mass growth over more cosmic time, 3) accuracy allowing new kinds of weak lensing techniques such as cross-correlation cosmography, and 4) elimination of systematics such as atmospheric distortion of the galaxy shapes and thermal, wind, and gravity loading of the telescope.

4.2. SNAP Complementarity

True synergy comes from bringing weak lensing and supernovae together. In this case complementarity is achieved on several levels. An experiment incorporating both techniques is truly comprehensive in that no external priors are required: no outside determination of the matter density is necessary. Furthermore, the two methods conjoined provide a test of the spatial curvature of the universe to $\sim 1-2\%$ (for the SNAP experiment), independent of the CMB constraint on flatness (note that the Planck CMB measurements in isolation would only determine the curvature to $\sim 6\%$ (Eisenstein, Hu, & Tegmark 1999)). On dark energy properties, supernovae plus weak lensing methods conjoined determine the present equation of state ratio, w_0, to 5%, and its time variation, w', to 0.11 (for the SNAP experiment basic mission, including an estimate of systematics, and in the relatively insensitive scenario of a true cosmological constant; this improves to w_0 to 0.03 and w' to 0.06 in a fiducial SUGRA dark energy case). Finally, this synergy provides a real opportunity to test the physics framework, distinguishing between a new high energy physics component and an extension to Einstein gravity.

SNAP, as an implementation of JDEM, is an experiment that can give a truly exciting view, revelatory and robust, into the nature of new fundamental physics. No new technology or unproven methods are required. In terms of a realistic technology and mission timeline, SNAP can be launched by 2012. With the assistance of select, focused precursor experiments, the frontiers of science are within our reach.

Companion white papers give specifics on the SNAP supernova and weak lensing programs. For further, in-depth information see http://snap.lbl.gov and the comprehensive Aldering et al. article at http://arxiv.org/abs/astro-ph/0405232.

REFERENCES

R.R. Caldwell & E.V. Linder 2005, *The Limits of Quintessence*, submitted to Phys. Rev. Lett. [astro-ph/0505494]

D.J. Eisenstein, W. Hu, M. Tegmark 1999, *Cosmic Complementarity: Joint Parameter Estimation from Cosmic Microwave Background Experiments and Redshift Surveys*, Ap. J. 518, 2 [astro-ph/9807130]

E.V. Linder 2003, *Baryon Oscillations as a Cosmological Probe*, Phys. Rev. D 68, 083504 [astro-ph/0304001]

E.V. Linder 2005a, *Cosmic Growth History and Expansion History*, astro-ph/0507263

E.V. Linder 2005b, *The Ups and Downs of Baryon Oscillations*, astro-ph/0507308

E.V. Linder & D. Huterer 2003, *Importance of Supernovae at* $z > 1.5$ *to Probe Dark Energy*, Phys. Rev. D 67, 081303 [astro-ph/0208138]

E.V. Linder & R. Miquel 2004, *Is Dark Energy Dynamical? Prospects for an Answer*, Phys. Rev. D 70, 123516 [astro-ph/0409411]

C. Vale & E.V. Linder 2004, in *The Darkness of the Universe: Mapping Expansion and Growth*, http://supernova.lbl.gov/~evlinder/taiwan3.ppt

W.M. Wood-Vasey et al. 2004, *The Nearby Supernova Factory*, New Astron. Rev. 48, 637 [astro-ph/0401513]

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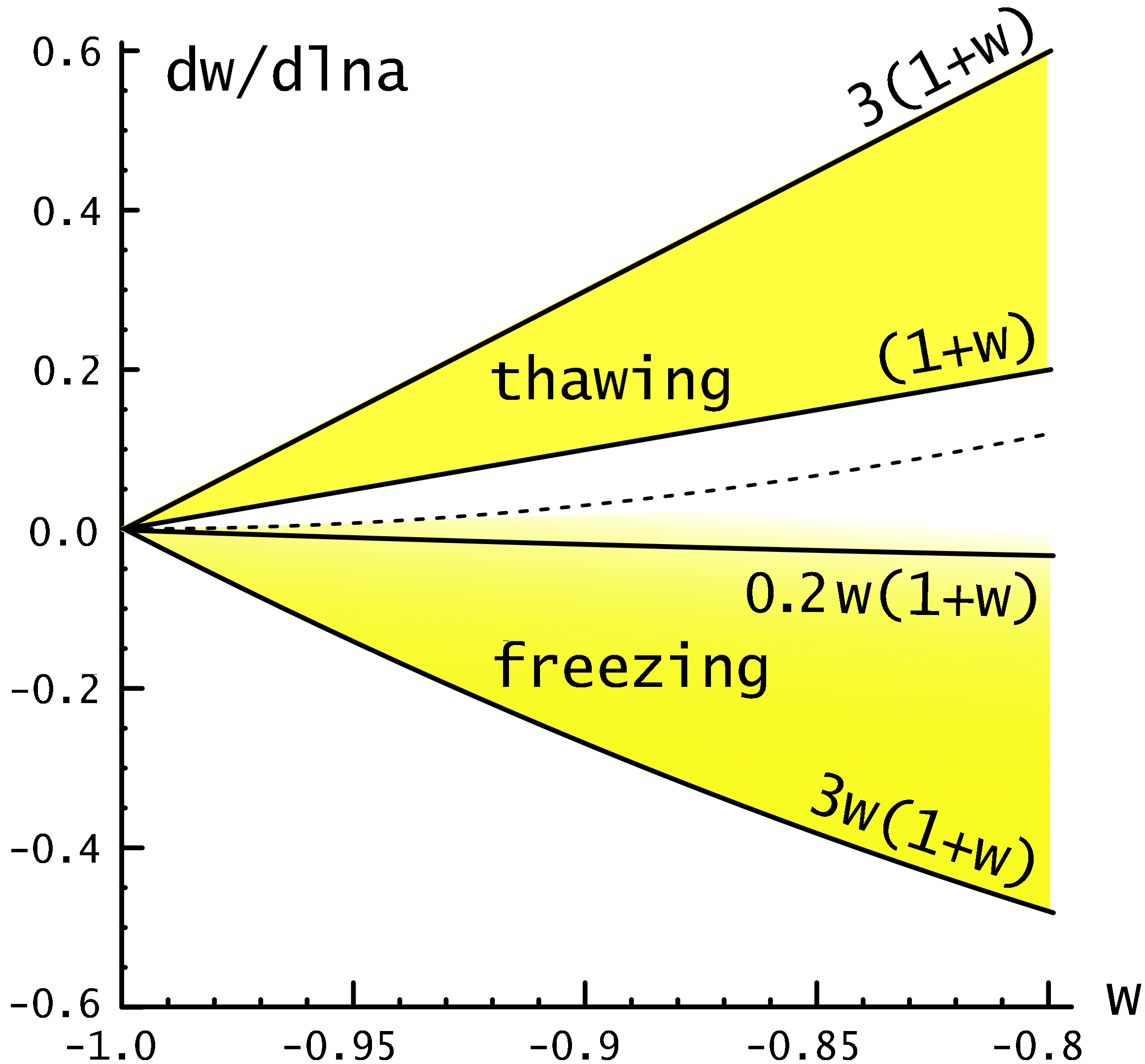

Fig. 1.— Scalar field models of dark energy can be separated into two distinct behaviors based on their dynamics, occupying narrow regions of the $w - w'$ phase space. “Freezing” models initially roll and then slow to a creep as they come to dominate the Universe. “Thawing” models initially are frozen and look like a cosmological constant, at $w = -1$, $w' = 0$, and then thaw and roll to $w' > 0$. Despite this dynamics, all models in the thawing region above would be mistaken for a cosmological constant ($w = -1$) by a ground based experiment with 5% precision on $w_{\rm constant}$. From Caldwell & Linder (2005).

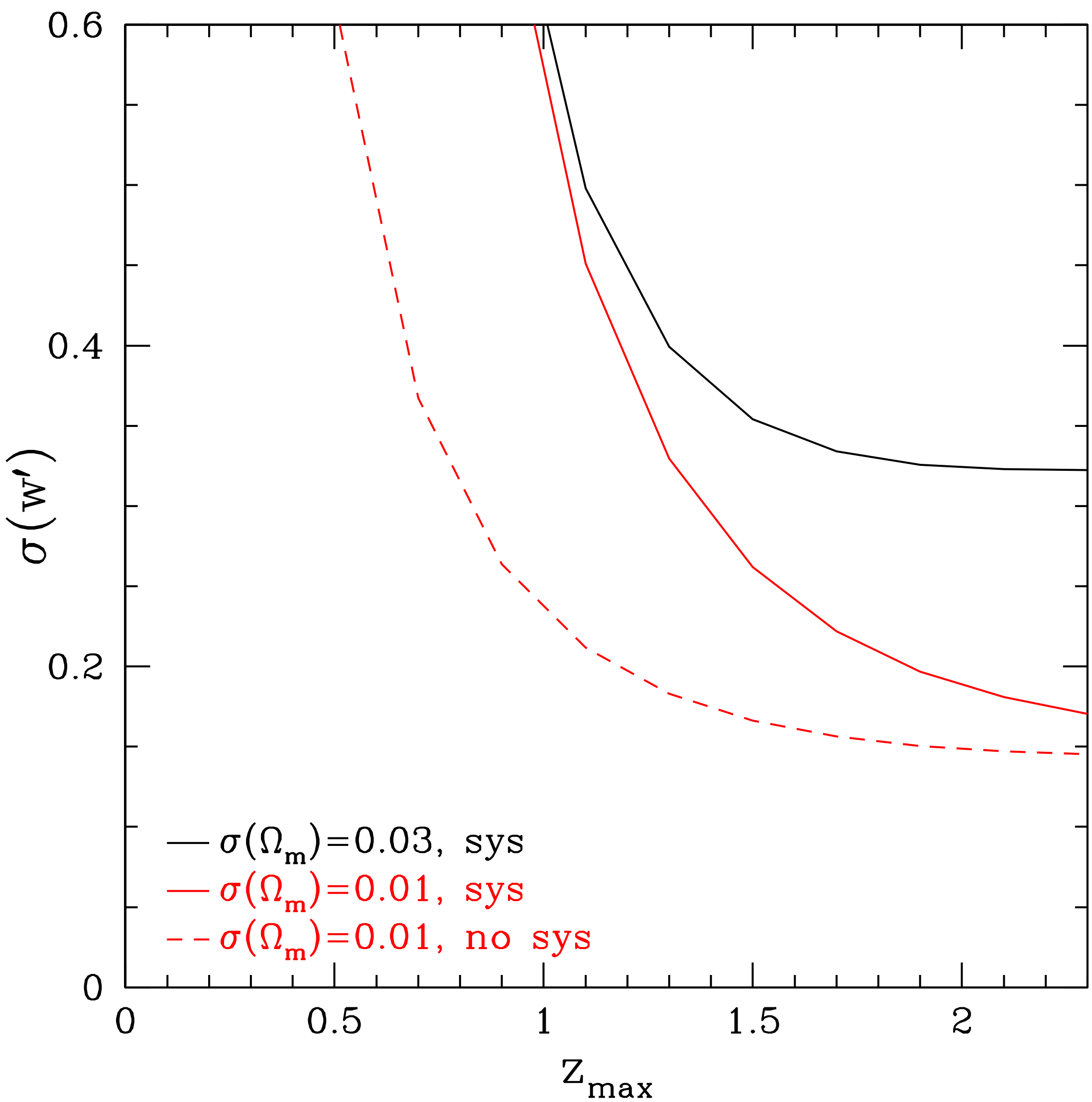

Fig. 2.— Uncertainty in determination of the time variation of the dark energy equation of state as a function of distance survey depth $z_{\rm max}$. Even in the idealized case of no systematic error the uncertainty rises steeply as $z_{\rm max}$ decreases. To detect the key discriminator of fundamental physics one requires a survey extending to $z_{\rm max} > 1.5$. From Linder & Huterer (2003).

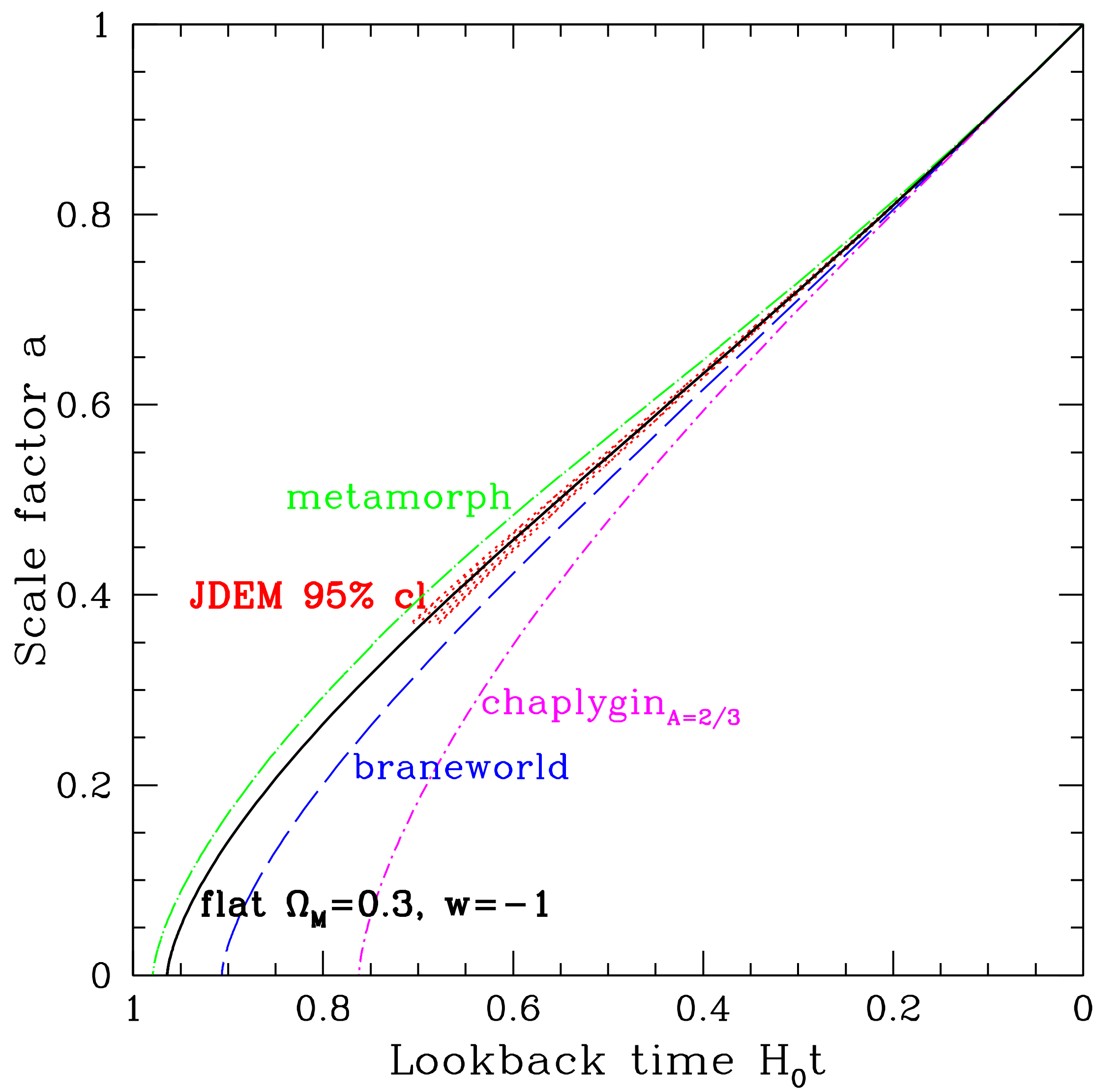

Fig. 3.— With percent level mapping of the cosmic expansion history by the direct supernova distance-redshift relation comes guidance to the nature of the dark energy, whether physics involving structure in the quantum vacuum (e.g. metamorph), extra-dimensional extensions to gravity (e.g. braneworld), interaction between dark energy and dark matter (e.g. chaplygin), or a fundamental cosmological constant Λ. Less accurate measurements will merely leave us confused. Knowledge of our history may then allow us to look to the future and explore the fate of the universe.

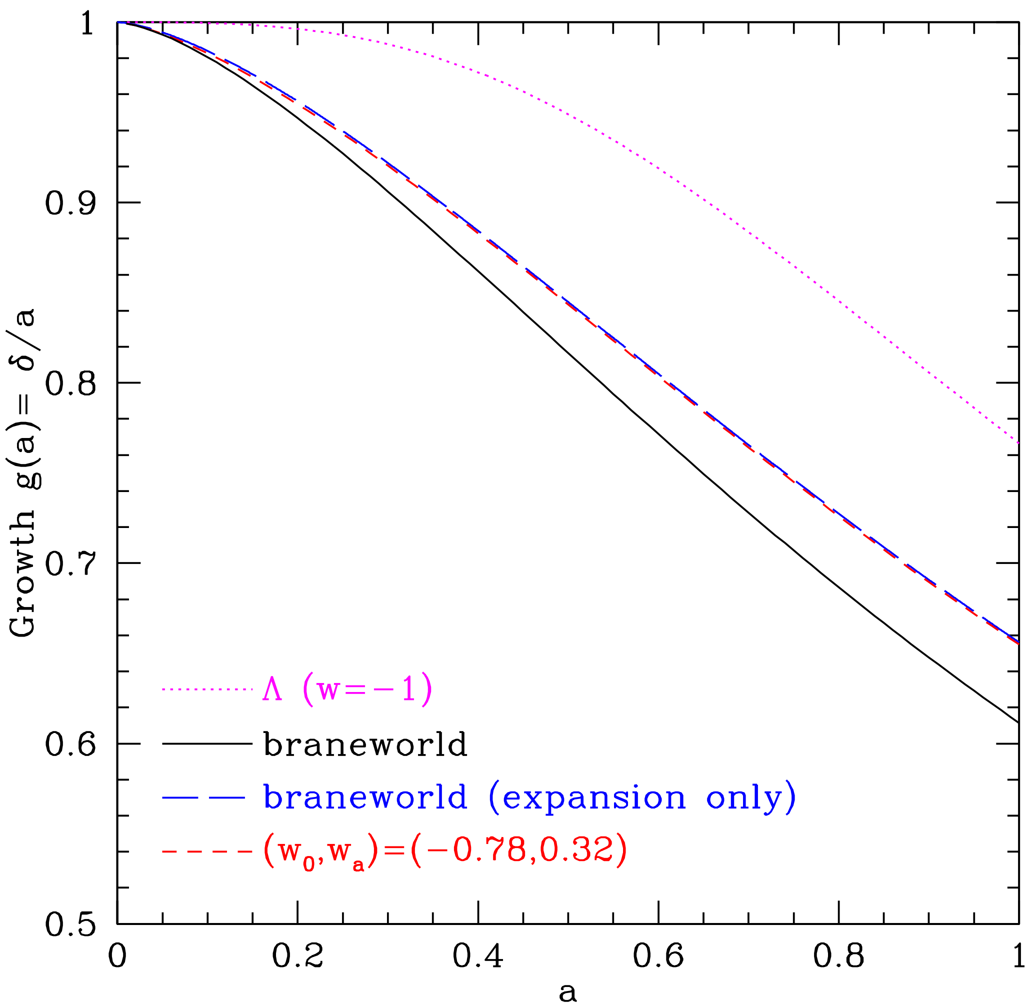

Fig. 4.— Growth history for linear perturbations in matter density is shown as a function of scale factor. This provides an important window on dark energy distinct from expansion history, since it also reacts to gravitational modifications. Extra-dimensional extension to gravity in the braneworld scenario modifies the growth so as to shift the long dashed, blue curve to the black, solid behavior, a deviation of 2-7% for $z = 0 - 2$. (The cosmological constant case, dotted magenta, is shown for comparison.) Without accounting for this modification, a scalar field model with the same expansion history (short dashed, red curve) could not be distinguished from the braneworld model. Conversely, a scalar field model agreeing with the growth history of the braneworld model would deviate in the expansion history. Therefore, accurate measurements of both expansion history and growth history, e.g. supernovae and weak lensing, are required to understand dark energy.