Dealing with Dark Energy

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Discoveries in the last few years have revolutionized our knowledge of the universe and our ideas of its ultimate fate. Measurements of the expansion of the universe show that it is not slowing down under normal gravity but accelerating due to an unknown, gravitationally repulsive “dark energy”. This may be a clue to new properties of quantum physics or of gravity beyond Einstein. I present an overview of the puzzles of dark energy and the means for unraveling them through cosmological probes, on both a generally accessible and a technical level. I also highlight the strong benefits of meshing supernova distance and weak lensing methods. Next generation experiments such as the Supernova/Acceleration Probe (SNAP) satellite would measure the supernova distance-redshift relation to high accuracy and map the evolution of structure and dark matter through gravitational lensing. These observations will explore the frontiers of physics and aim to uncover what makes up the still unknown 95% of our universe.

1 Introduction

Discovery of the acceleration of the expansion of the universe has prompted great excitement in physics, and energized speculation about the dark energy responsible. Such physics acts contrary to the ordinarily attractive nature of gravity. It is unknown whether the answer to this extraordinary puzzle lies within modifications of gravitation or new elements of high energy physics such as a quantum vacuum.

New, high precision experiments are being developed to reveal the nature of dark energy. In this next generation, the use of simple, well understood physical probes will be crucial to reduce the systematic uncertainties in the observations due to astrophysical effects. Complementary probes will also be essential to increase the rigor of the results: to provide crosschecks, synergy leading to tighter constraints, and improved accuracy. Ideally these comple-
mentary methods would also be capable of separating a gravitational origin of dark energy from a high energy physics origin.

In §2 we discuss the basic issues regarding our current understanding of and future characterization of dark energy. §3 investigates the requirements for substantial progress with the next generation of experiments, emphasizing systematics control and complementarity. In the conclusion, we summarize the possible techniques for probing the nature of dark energy and indicate the fundamental need for complementary measurements to explore the physics frontiers. Note that §2 is written at a level to make the discussion accessible to the general physicist; experts may wish to concentrate on §3 which examines more technical issues on how to reveal the physics.

2 Dark Energy – New Paradigm/New Paradox

Cosmology and fundamental physics have grown ever closer over the past few decades, with dark energy now firmly linking them together. Astrophysical observations, including Type Ia supernovae distance-redshift relations, cosmic microwave background measurements, and large scale structure properties, give clues to the expansion history of the universe: the growth in distance scales over time, $a(t)$. Within the cosmological dynamics this translates into the energy densities and physical properties of the components of the universe. These can be described in terms of present day energy densities relative to the critical density, e.g. the matter density $\Omega_m$ and the dark energy density $\Omega_w$, and the equations of state, or pressure to energy density ratios, $w(a)$. Finally, we hope to relate these to fundamental physics, such as the potential of a high energy scalar field, $V(\phi)$.

The paradigm is to link the observational data with the underlying physics, the astrophysical with the fundamental. The new aspect is that this appears to be much more direct and of vastly greater import than before – that the current (and ultimate future) state of the expansion of the universe is intimately tied to fundamental, new physics. Acceleration of the universe is giving us tangible clues to new gravitation, new quantum physics, or even the union of the two. Illustratively we can write

$$V(\phi(a(t))),$$  

(1)

to denote the interdependence of the astrophysics measuring the expansion history, the cosmology depending on the microphysical properties of the components, and the field theory describing the fundamental physics.

The flow can, and should, go both ways. Theories of high energy physics and extended gravitation can be predictive; the implications of a specific model can be calculated and compared to the data. As well, high precision measurements of subtle variations in the expansion behavior can guide researchers toward classes of theories. A happy medium exists in a model in-
dependent parametrization of the physics, such as the key quantity of the equation of state function of the dark energy, \( w(a) \).

We then proceed forward in our exploration of the universe in a manner analogous to uncovering, say, global warming of the Earth. The subtle slowing and growth of scales with time – precisely \( a(t) \) – map out the cosmic environment history like the lesser and greater growth of tree rings map out the Earth’s climate history. Whether it was a cold year, a wet year – the width of the tree ring growth – tells us the climate environment just as the growth of distances between cosmological markers tells us the expansion history. The search, for decades, in astronomy was to find suitable markers covering a substantial part of the universe’s 14 billion year history.

The efforts finally came to fruition in 1998 when two groups [1, 2] independently announced evidence for mapping the expansion history using Type Ia supernovae (SN Ia) as markers. These exploding stars are highly suitable for such work because they can be as bright as their entire host galaxy, and so are able to be observed at great distances and hence lookback times into the past. Crucially, they can be calibrated to about 7% in distance [3, 4] and so provide precise measurements. Furthermore, the supernova light comes from simple, clean nuclear physics and has a direct translation to the expansion history \( a(t) \): with the luminosity calibrated, the flux measures the distance through the cosmological inverse square law, and hence the lookback time \( t \), and the redshift \( z = a^{-1} - 1 \) measures the scale factor.

However, rather than deriving the details of the matter properties of the universe through the deceleration of the expansion under gravitational attraction, both groups found an acceleration. Some force was acting in a way contrary to attractive gravity. This was clearly an astonishing discovery and led to the new paradox: when is gravity not attractive?

In general relativity the gravitating mass depends on the energy-momentum tensor, not just the rest mass. For a perfect fluid, both the energy density \( \rho \) and the pressure \( p \) enter – as a specific combination \( \rho + 3p \). So a component with a sufficiently negative pressure can provide an effective negative gravitating mass, and hence turn gravity into a repulsive force.

More quantitatively, consider the acceleration arising from Newton’s law of gravitation,

\[
\ddot{R} = -\frac{GM}{R^2} = -(4\pi/3) G \rho R,
\]

where we take a test particle a distance \( R \) from the center of a homogeneous mass \( M \). For positive mass densities, the force is always attractive. But in Einstein gravity, the Friedmann equation of acceleration is

\[
\ddot{a} = -(4\pi/3) G (\rho + 3p) a.
\]

So as stated above, negative pressure can accelerate the expansion.

Since both the energy density and pressure appear in the equation, it is convenient to define their ratio, \( w = p/\rho \), known as the equation of state ratio. Acceleration then occurs for \( p < -(1/3)\rho \) or \( w < -1/3 \).
What is the physical meaning of a negative pressure? It is not as unusual as it might appear. Consider the first law of thermodynamics:

\[ dU = -p \, dV, \]  

(4)

where \( dU \) is the change in internal energy of a system upon expansion of the volume by \( dV \). Expansion then decreases the energy (for positive \( p \)), as (adiabatically) opening an oven door cools down the air inside, or breathing out through pursed lips gives a stream of cooler air than your internal temperature (contrast the feeling on your hand in front of your mouth when breathing with lips pursed vs. with mouth open).

Systems with negative pressure would have an overall positive sign for \( dU \), increasing energy upon expansion. Everyday examples include springs, \( dU = +k x \, dx \), and rubber bands, \( dU = +T \, dl \), where \( dx, \, dl \) are displacements, \( k \) the spring constant, and \( T \) the tension. So what we need for the acceleration of the expansion of the universe is a sort of springiness of spacetime.

Quantum physics, as developed in the 1920's, predicts that the very structure of the vacuum should have properties like a simple harmonic oscillator: a spring. So the universe filled with a quantum vacuum energy will have a springiness, or tension, and measurements of the acceleration could be interpreted as direct observations of a vacuum energy with negative pressure.

To quickly review: gravity says that the acceleration of the expansion depends on energy density and pressure, \( \rho + 3p \), thermodynamics says that pressure can negative, and quantum physics says that vacuum energy has such negative pressure. Cosmological “tree ring” markers can map the expansion history, measure the acceleration, and detect the vacuum energy. And they did.

The 1998 results have been strongly confirmed by further, more precise supernova observations, and by corroborating measurements of the cosmic microwave background (CMB) temperature anisotropies and of large scale structure (LSS) properties. SN Ia most directly probe the acceleration as such, saying that there is a nonzero vacuum energy and it is abundant enough to govern the expansion dynamics. CMB in combination with some large scale structure data (such as the Hubble constant, which gives the present expansion rate, or measurements of the matter density) indicates our cosmology is consistent with a spatially flat universe (total energy density equals the critical density) and one with a nonzero vacuum energy. Any two of the three data sets combine to imply that the vacuum energy, or more generically “dark energy”, must account for \( \sim 70 - 75\% \) of the energy density of the universe.

These are profound and exquisite experimental results. Dark energy dominates the energy of the universe, governing the expansion, accelerating it like inflation did in the first fraction of a second of cosmic history, and determining the fate of the universe. But what is it? We do not even know whether it belongs to the right hand side or left hand side of the Einstein equations, i.e. whether it is a new, physical component, arising from a high energy physics scalar field, say, or a change in the gravitational framework, an extension to
general relativity due to extra dimensions, for example. Is it new quantum physics, new gravitational physics, or a sign of unification of the two?

A first attempt at a solution might be the cosmological constant, which is equally at home on the right and left hand sides. But it has two outstanding problems: the fine tuning and coincidence puzzles (for more details see, e.g., [5]). Thinking about the cosmological constant Λ as arising from the vacuum expectation value of a quantum zeropoint energy “sea”, one can calculate that the sea level should drown the matter energy density (the “land”) by a factor 10^{120} or so. Furthermore, the cosmological constant and matter energy densities evolve differently under expansion: a mere factor of 4 in expansion scale smaller (back in time) and dark energy would be undetectable, while a factor 4 larger and matter would be quite rare – we would not see a universe filled with clusters of galaxies. Dark energy cosmology is only possible today, where today means within a factor of 4 in expansion while the universe has expanded by a factor of about 10^{54} to date!

To attempt to overcome these difficulties, physicists consider dynamical models of dark energy. But guidance through the vast space of possible theories is required from observations precise enough to map the acceleration and discern subtle variations. The leading role in this endeavour is being played by SN Ia (other methods for the future are discussed in §3).

As mentioned at the beginning of this section, SN Ia have a high degree of robustness in their properties, enabling them to be calibrated to better than 10% accuracy. In a cartoon version of why nuclear physics provides a standard explosion, consider the scenario of a white dwarf star and a massive companion. The white dwarf accretes matter from the companion until it gets “full” enough, with full being related to the Chandrasekhar mass beyond which the electron degeneracy pressure can no longer support the white dwarf. Since degenerate stars have simple structures to begin with, and the explosions occur under near identical conditions, the class of SN Ia is remarkably homogeneous. The real situation is not quite so simple, but end to end computations show that a high degree of “stellar amnesia” – independence of initial conditions – occurs [6].

Moreover, each SN Ia does not merely provide a single data point, a single luminosity. They contain a rich array of information about their physical conditions in measurements of their lightcurve (flux vs. time evolution), energy spectrum, and images showing their galactic environment. Such a data set for each SN can provide robust control of systematic uncertainties [7].

Currently, of order 200 SN Ia have been analyzed, though few with the complete data characteristics just discussed at high quality. In combination with CMB and large scale structure data, they impose constraints on an a priori constant equation of state of w_{const} = −1.05^{+0.15}_{−0.20} ± 0.09 [8] or w_{const} = −1.08^{+0.18}_{−0.20}±? [9]. These appear roughly consistent with the cosmological constant value w = −1.

Ongoing projects to characterize many more SN include Essence (~ 200 at 0.15 < z < 0.75 [10]), Nearby Supernova Factory (~ 300 at 0.03 < z < 0.08
Canada-France-Hawaii Telescope Supernova Legacy Survey (∼ 700 at 0.3 < z < 0.9 [12]), Supernova Cosmology Project (∼ 25 at z > 0.8 [13]), and Carnegie Supernova Project (optical and near infrared, and spectroscopic, follow up [14]). Additional ground based surveys are proposed. The Supernova Cosmology Project and PANS groups are studying supernovae at high redshifts, z > 1, from space with the Hubble Space Telescope and may characterize ∼ 20 – 25 such SN.

While these improvements should allow constraints on $w_{\text{const}}$ without depending on combination with CMB and LSS data, they will not have the accuracy, precision, and reach to impose substantial limits on the dynamics at the heart of the physics responsible for the acceleration. Indeed, while one can use $w_{\text{const}}$ to test for consistency with the cosmological constant, it is dangerous to interpret it more broadly, extrapolating to any conclusion that the dark energy is the cosmological constant. See [15] for examples of how assuming that $w = w_{\text{const}}$ can deceive us about the true fundamental physics.

To correctly learn the new physics, we have to look for the generically expected time variation $w(z)$ – indeed essentially all models for dark energy other than the cosmological constant predict $w' = dw/da = 0$. Achieving robust measurements, with tight control of systematics over a long baseline of the expansion history of the universe, is a major challenge. In the next section we discuss how to address it.

3 Dark Energy – New Generation/New Physics

Data constraints in the plane of dimensionless matter density $\Omega_m$ vs. constant equation of state $w_{\text{const}}$ that suggest a concordance cosmological model solution of, say, $\Omega_m = 0.3$ and cosmological constant $\Omega_\Lambda = 0.7$ could also be fit at the ∼ 1% level in distance, out to redshift $z = 2$, by a very different cosmology: one containing $\Omega_m = 0.27$ with 0.73 of the critical density in a component with $w(a) = -0.8 - 0.6(1 - a)$, exhibiting physics rather unlike the cosmological constant. This extreme example shows the necessity for probing the dynamics.

To have confidence in our results uncovering the new physics we need to design the next generation of experiments properly. They should possess three crucial properties:

- Longer lever arm – i.e. data covering to higher redshift, more cosmic history;
- Better statistics – many more measurements, more precisely;
- High accuracy – robust control of systematic uncertainties.

As we will discuss later, complementary methods of probing the dark energy are also critical. Together, these give the science requirements for a successful experiment.
Consider the SN Ia method. To see the most distant supernovae, space observations are required because the SN light is redshifted into the near infrared part of the spectrum, but the Earth’s atmosphere is basically opaque there. Furthermore, correction of extinction – dimming due to dust – requires a broad wavelength coverage, also pushing observations into the near infrared. Currently the only applicable space telescope is the Hubble Space Telescope (HST). HST has indeed found a few supernovae of order 10 billion years back in the cosmic expansion history (a factor 2.7 in scale factor, or \(z = 1.7\)). But these are exceedingly faint, about the same flux as the limit of the Hubble Deep Fields (which required commitment of a substantial part of the HST observing schedule). Yet a Hubble Deep Field has scanned (just sufficient to detect, not to characterize, SN) only \(4 \times 10^{-8}\) of the sky. In proportion, this is like meeting about 10 people and trying to understand the complexity of the entire US population.

A new, dedicated dark energy experiment is required. To address the science needs above, its catchphrase has to be “wide, deep, and colorful”. This will 1) ensure sufficient numbers of SN for statistical and systematic analysis, 2) map a large fraction of cosmic history to pick up the subtle variations between dark energy theories, and 3) allow multiwavelength and spectral characterization of the sources to tightly control systematic uncertainties.

The Supernova/Acceleration Probe (SNAP: \cite{16}) is a possible realization of this experiment, specifically designed to meet these criteria. The experiment will employ a two meter space telescope to obtain optical and near infrared, high accuracy observations, including spectra, of more than 2000 SN from \(z = 0.1 – 1.7\) (over 70% of the age of the universe). The sky coverage will be 4 orders of magnitude greater than a Hubble Deep Field, and a wider survey aimed at using weak gravitational lensing (see later) as a partnering, complementary probe will cover 6 orders of magnitude more sky than a Hubble Deep Field, and almost as deep.

Systematics control will be a major challenge in this, as in any experiment utilizing any method. Supernovae, however, have a long history of use that has generated identification of the systematics and techniques for controlling them. We give an illustration of one approach here, but see \cite{17,18,19} for specifics.

With sufficient, highly characterized supernovae, one can imagine sorting them into subsets based on their slight residual heterogeneity after calibration. Subsets might be defined based on host galaxy morphology, spectral feature strength and velocity, early time behavior, etc. – obviously requiring a comprehensive set of measurements, far beyond what a typical supernova in the current data has. Then one analyzes each subset, of supernovae occurring over the full redshift range, and derives the cosmological model. By comparison of the results from subset to subset – “like vs. like” – one can gain strong confidence that the results are free from significant systematics. Conversely, by analyzing supernovae at the same redshift between subsets, one can further develop systematics controls. While theories of the supernova progenitor
and explosion mechanism can guide the establishment of subset criteria, such understanding is not required – only comprehensive measurements are – for robustness of the cosmological results.

Dark energy – the failure of attractive gravitation – is such a profound mystery, possibly such a clue to fundamental physics, that we should strive to probe it in as many useful, stringent ways as possible. While SN provide the most direct probe of cosmic acceleration, CMB and LSS measurements make contributions as well.

The CMB, except on very large scales, is basically a snapshot of the universe at 380,000 years old – only 0.003% its present age (when the reader was 0.003% of their present age, they were composed of merely two cells – independent of how old the reader is now!). So it is not surprising that the CMB, while fantastically precise and well understood, is not a strong probe of detailed dark energy properties, a more recent phenomenon. On large scales it can provide some rough clues, particularly in combination with full sky LSS surveys, but this is fundamentally limited by cosmic variance (there are few independent samples of large volumes, or, the sky only contains $4\pi$ steradians).

Nevertheless, it has excellent complementarity upon addition to SN data, as it breaks degeneracies between cosmological parameters \cite{20}. Together, SN+CMB (exemplified by the SNAP SN and Planck CMB \cite{21} experiments) can detect time variation of the dark energy equation of state, $w'$, at the 99% confidence level (this assumes a specific model, SUGRA \cite{22}, with $w' = 0.3$; see \cite{23} for further details and comparisons).

Large scale structure data can provide constraints on dark energy, both through breaking parameter degeneracies and through indirect measurement of the acceleration. In its most basic use, it enters not through data as such, but through a prior on, say, the matter density $\Omega_m$. Of course this must trace back to data in some way, and often the dependence of the observations is not purely on the matter density, but also involves assumptions about the dark energy, e.g. that it is a cosmological constant. Such assumptions can sometimes be hidden quite deeply, but must be sought out for a robust cosmological analysis.

One improvement on the “prior” approach, more closely related to the data, is to employ constraints on the logarithmic growth factor, $f = d \ln \delta / d \ln a$, at some redshift, where $\delta$ is the fractional overdensity of a matter density perturbation. This is directly related to the peculiar velocity field of large scale structure. Such a prior was used for the cosmological constraint analysis I set up for \cite{8}. An unpublished study by me shows that this prior is roughly equivalent to an $\Omega_m$ prior. That is, $\pm 0.03$ in $\Omega_m$ (11% uncertainty) has about the same effect as $\pm 0.035$ in $f$ (6% uncertainty). Note that due to its slight curvature in the $\Omega_m$-$w$ plane, its complementarity with SN is somewhat less than an $\Omega_m$ prior (though more realistic). Its tighter connection with data is a plus, however some doubt has been cast \cite{24} on the intermediate step of
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removing the galaxy bias parameter from velocity surveys (see, for example, [25]).

Direct use of large scale structure measurements is obviously the preferred method. The most promising technique appears to be weak gravitational lensing. Since gravity bends light, we can detect mass (including that contributed by dark matter) in structures such as galaxies and clusters of galaxies through the gravitationally distorted images of distant sources – lensing. While this happens on rare instances very visibly through the production of multiple images or grossly distorted arcs (strong lensing), it occurs copiously as more subtle, percent level shearing of image shapes (weak lensing). This signal must be pulled out statistically from vast surveys of millions of resolved galaxies.

By studying the growth of massive structure over cosmic history, one can infer properties of the dark energy. While mass aggregates in an expanding universe, with gravitational attraction causing overdense regions to become more and more so, this growth shuts down in an accelerating universe. As an analogy, consider a person trying to join a group of friends standing at the bottom of a uprunning escalator. Due to the “stretching” of space between the groups, the attraction is overcome and clustering does not increase.

Weak lensing was first measured in 2000 and is rapidly developing as a cosmological probe, though it has not yet achieved the precision and accuracy to provide constraints on dark energy. Next generation experiments compiling hundreds of millions of galaxy shears over a wide area of sky with precise redshift measurements, for a three dimensional catalog, will be needed. Plans for such surveys include PanStarrs [26] and LSST [27] from the ground and SNAP from space. Ground observing can cover large areas quickly and partners well with space measurements. Space provides access to 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, and 3) reduction of systematics such as atmospheric distortion of the shapes [28].

The combination of weak lensing and CMB data yields dark energy constraints roughly comparable to SN bounds. But the true synergy comes from bringing weak lensing and SN together. In this case complementarity is achieved on several levels. An experiment that incorporates both techniques is truly comprehensive in that no external priors are required: no outside determination of the matter density or CMB acoustic peak location 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 $\sim 6\%$ [29]). 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 baseline mission, including an estimate of systematics, and in the relatively insensitive scenario of a true cosmological constant:}
see Fig. 1. Such an experiment can give a truly exciting view into the nature of new fundamental physics.

![Graph showing constraints on dark energy models from supernovae and weak lensing surveys.](image)

**Fig. 1.** 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 show constraints on 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.
Other cosmological probes, not yet mature, may contribute to the next generation. These include angular distance-redshift tests through baryon acoustic oscillations in the matter power spectrum, growth of mass tests through cluster abundances identified by the Sunyaev-Zel’dovich effect or weak lensing, say, and possibly tests using some aspects of strong lensing or distances to another class of supernovae, Type IIs.

We must be cautious however about, first, identification, and then control of systematic uncertainties that might plague methods without a proven track record. The entanglement of astrophysical details with cosmology is another area needing great care. One can roughly regard probes as falling into three categories of shedding light on dark energy:

- Geometric methods – a standard: like a lightbulb, where you don’t need to know how the filament works, you can test it – e.g. supernovae Ia, weak lensing (crosscorrelation cosmography method), baryon oscillations, supernovae II
- Geometry+Mass methods – must understand aspects of the nonlinear mass distribution: like a flashlight, where you need to know about the lens and battery – e.g. weak lensing (shear), strong lensing
- Geometry+Mass+Gas methods – must understand aspects of hydrodynamics: like a candle, where you need to know about the wax, flame, wind – e.g. Sunyaev-Zel’dovich effect, cluster counts

4 Conclusion

The acceleration of the cosmic expansion poses a fundamental, and possibly revolutionary, challenge to physics. To probe the nature of the dark energy responsible for this behavior contrary to attractive gravity we need specially designed next generation experiments, as well as some clever theoretical ideas. We don’t know whether the new physics lies within the structure of the quantum vacuum, extensions to general relativity, or a unification of high energy physics and gravitation in the form of extra dimensions or string theory.

Uncovering the dynamics of dark energy should guide us in development of new fundamental physics. To achieve this understanding requires robust, well understood cosmological probes, with greatest leverage coming from techniques working in complementarity. Our picture of the universe is one where only 5% is familiar energy components within the standard model of particle physics, 25% lies in possibly theorized dark matter, and 70% in wholly unknown dark energy. The universe is mysteriously unsimple.

When you have a mystery ailment, you want a doctor with not just a stethoscope as a tool to give a diagnosis; you want blood tests, EKG, MRI to give confidence in the results. Our universe is out of sorts, and we should seek similar complementarity to achieve fundamental understanding.

Complementary probes give 1) croschecks, to test the results, 2) synergy, improved constraints from breaking degeneracies to reveal more of the physics,
Fig. 2. The expansion history and the mass fluctuation growth history can probe different elements of the physics responsible for the acceleration of the universe. Individually they offer leverage in constraining parameters of dark energy or gravitational models, and in complementarity they can distinguish between the different physical origins. An extra dimensional braneworld model (solid, black curve) and a quintessence model with $w_0 = -0.78$, $w_a = 0.32$ (dashed, red) appear indistinguishable, but when one takes into account the effects of altered gravity on the growth history (long dashed, blue curve) this allows distinction of these models. The expansion history in turn could rule out the quintessence model degenerate with the long dashed curve. In all cases, the cosmological constant curves (dotted magenta, with outliers indicating the effect of varying $\Omega_m$ by ±0.02) are distinct.
3) robustness, through reduced influence of systematics from one approach. Currently, in maturity and application, Type Ia supernovae and weak lensing give the greatest hope of understanding dark energy. Moreover, an experiment combining the two possesses the virtues of comprehensiveness, independence from external priors, and the ability to test the framework. By mapping both the expansion history and growth history, such an experiment can distinguish between a high energy physics origin for the acceleration (e.g. a scalar field) and new gravitational physics (see, e.g., Fig. 2). A space mission surveying the universe wide, deep, and colorful will naturally encompass further probes as well, and provide a bonanza for astrophysics, cosmology, and fundamental physics.

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