The Case for Deep, Wide-Field Cosmology

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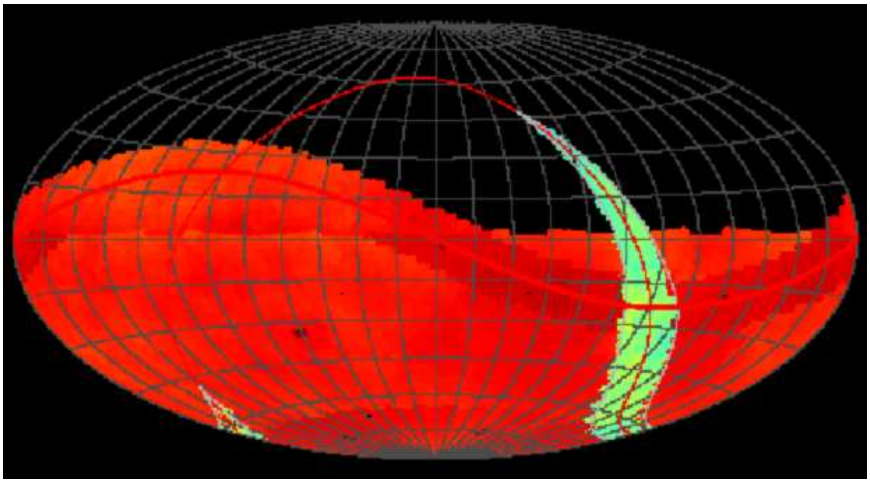

Overview

Much of the science case for the next generation of deep, wide-field optical/infrared surveys has been driven by the further study of dark energy. This is a laudable goal (and the subject of a companion white paper by Zhan et al.). However, one of the most important lessons of the current generation of surveys is that the interesting science questions at the end of the survey are quite different than they were when the surveys were being planned. The current surveys succeeded in this evolving terrain by being very general tools that could be applied to a number of very fundamental measurements. Likewise, the accessibility of the data enabled the broader cosmological and astronomical community to generate more science than the survey collaborations could alone. With that in mind, we should consider some of the basic physical and cosmological questions that surveys like LSST and JDEM-Wide will be able to address.

- **With the level of precision available in these surveys, what can they tell us about fundamental physics?** With the standard ΛCDM cosmology as determined by current surveys, we can use the precision available to next generation surveys to examine the foundations of particle physics and gravity. Is the current model of general relativity (GR) correct or are the effects that we have ascribed to the presence of dark energy actually a signal that GR is broken in some way? What can cosmology do to constrain extensions to the Standard Model of particle physics?

- **What can a deep, wide-field survey tell us about the basic assumptions behind the standard cosmology?** Now that the current generation of surveys have given us a stronger grasp on the basic cosmological model, we can begin to question its fundamental assumptions. Does the cosmological principle of isotropy and homogeneity hold true? Are the primordial perturbations that seeded structure formation Gaussian? Do we know enough about the intergalactic medium to trust measurements of background sources seen through foreground structure?

- **What are the technical challenges to making these future surveys productive for the larger cosmological and astronomical community?** Maximizing the science from these surveys will mean delving into the non-linear regime for many measurements and the data size and complexity will be considerably more daunting than current surveys. What improvements will need to be made to simulations to properly characterize these data sets? How will that analysis change when even the catalog data from these surveys is too large to transmit over the network?

Physics Beyond the Standard Model

Modifying General Relativity

There is a possibility that the observed cosmic acceleration results from a new theory of gravity at cosmological length scales. While a compelling underlying theory is still lacking in the community, we can consider constraints on General Relativity (GR). The model-independent *lingua franca* is the relationship between the Newtonian (ψ) and longitudinal

(ϕ) gravitational potentials. The potentials, as defined through the perturbed Robertson-Walker metric

$$ds^2 = a^2[-(1+2\psi)d\tau^2 + (1-2\phi)d\vec{x}^2], \quad (1)$$

are most familiar for their roles in Newton's equation, $\ddot{\vec{x}} = -\vec{\nabla}\psi$, and the Poisson equation, $\nabla^2\phi = 4\pi G a^2 \rho_m \delta_m$, under GR.

The gravitational potentials are equal in the presence of non-relativistic stress-energy under GR, but alternate theories of gravity make no such guarantee and a *slip* between the two is expected such that $\phi \neq \psi$ in the presence of non-relativistic stress-energy. A possible parametrized-post-Friedmannian (PPF) description of this departure is the one discussed in [5] with

$$\psi = [1 + \varpi(z)]\phi, \quad \varpi(z) = \varpi_0(1+z)^{-3}. \quad (2)$$

The CMB probes primordial perturbations, while at late times ISW is a function of $\dot{\phi} + \dot{\psi}$ and weak lensing the sum $\phi + \psi$. Thus cosmological observations that combine CMB anisotropies with LSS data such as weak lensing can separate the ϕ and ψ and put constraints on the PPF framework.

In Figure 1, we show a summary of results comparing present-day constraints to those possible with *Planck* + LSST. In the latter case, it should be possible to determine ϖ_0 to within 10% at the 95% confidence level.

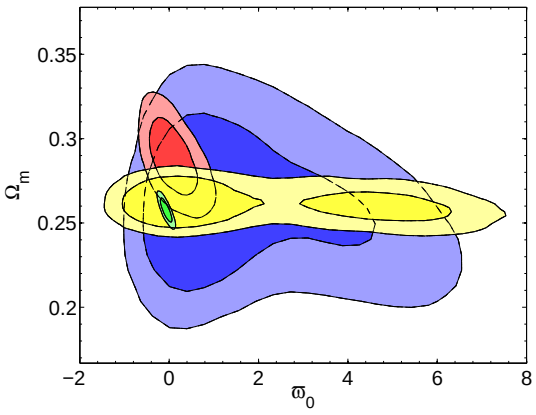

Figure 1: The projected 68% and 95% likelihood contours in the $\varpi_0 - \Omega_m$ parameter space are shown. The blue contours are based on current WMAP 5-year CMB data alone. The red contours add current weak lensing and ISW-galaxy correlation data. The yellow contours are based on mock *Planck* data. The green contours add mock weak lensing data of the type expected for a 20,000 deg^2 survey. The underlying model is assumed to be $\varpi_0 = 0$ with $\Omega_m = 0.26$.

Alternatively, one could examine departures from GR in a model-independent way using consistency relations[21]. As seen in Figure 2, there are four fundamental equations governing the relationships between the energy and momentum perturbations (δ_m & Θ_m, respectively) and the metric perturbations from Equation 1. From this basic set, we can form pairs of estimators, predicting the result of a measurement drawing from one side of the equation from another based on the opposite side. If these relations were found to be inconsistent, it would be a clear signal of a breakdown in GR. This sort of test is not prescriptive in the same way as the PPF treatment, but it is sensitive to any range of departures from standard GR.

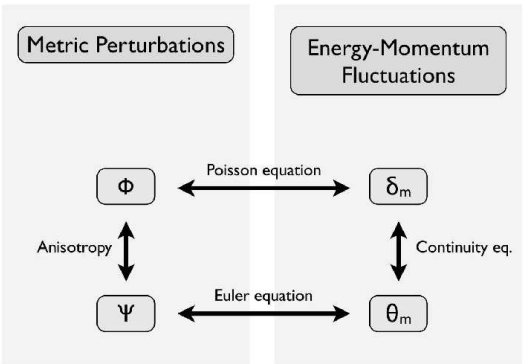

Figure 2: The web of interconnected GR consistency tests.

As an example, consider the Poisson equation given above. The left side of the equation is a function of the metric perturbation ϕ. Weak gravitational lensing is generated by the gradient of ϕ, making it a direct probe of those perturbations. For the right side of the equation, we need an estimator sensitive to δ_m. This can be found directly from the pair-wise velocity dispersion, which generally requires a redshift survey. In the absence of such a survey to the depth of LSST or JDEM-Wide, we can obtain a similar quantity by cross-correlating the induced lensing shear with the projected galaxy density. There are potential complications due to non-linearities, but at large scales the combination of these two measurements gives us an estimator for deviations from the Poisson equation that should be detectable at the few percent level with these future surveys[21]. This approach remains model independent and does not rely on any specific parametrization, so it would apply just as readily to any theory for modified gravity that altered the Poisson equation.

Massive Neutrinos

The primary tool for constraining massive neutrinos with a large scale structure survey is measurement of the 3D cosmic shear (cf. [9]); the mass of the neutrinos can be inferred based on the suppression of growth in the matter power spectrum inferred from the cosmic shear. There is a degeneracy between this effect and dark energy parameters[8], which can be characterized using a Fisher matrix approach with a prior based on the expected results from the *Planck* CMB experiment. The following constraints[11] are obtained allowing for non-zero curvature and for a dark energy component with equation of state parameterization given by w_0, w_a; all results on individual parameters are fully marginalized over all other cosmological parameters.

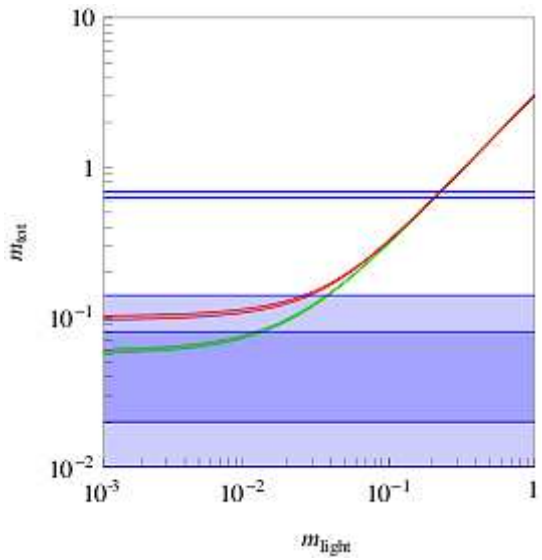

Figure 3: Forecasted constraints in the context of what is known today from neutrino oscillations experiments. The narrow green band represents the normal hierarchy and the red band the inverted one. The light blue regions represent the $1-\sigma$ constraints for the combination *Planck*+LSST for the two fiducial models (massive and near-massless neutrinos) discussed in the text. The darker band shows the forecasted $1-\sigma$ constraint obtained in the context of a power-law $P(k)$, ΛCDM + massive neutrinos model. (Figure courtesy of E. Fernandez-Martinez)

By combining 3D cosmic shear constraints with *Planck*'s, the massive neutrino (fiducial values $m_\nu = 0.66$eV ; $N_\nu = 3$) parameters could be measured with marginal errors of $\Delta m_\nu \sim 0.03$ eV and $\Delta N_\nu \sim 0.08$, a factor of 4 improvement over *Planck* alone. If neutrinos are massless or have a very small mass (fiducial model $m_\nu = 0$eV ; $N_\nu = 3$) the marginal errors on these parameters degrade ($\Delta m_\nu \sim 0.07$ eV and $\Delta N_\nu \sim 0.1$), but remain an equal improvment over *Planck* alone. This degradation in the marginal error occurs because the effect of massive neutrinos on the matter power spectrum and hence on 3D weak lensing is non-linear. These findings are in good agreement with an independent analysis[6] and should not degrade by more than a factor of $\sqrt{2}$ due

to systematic errors[10, 11]. Alternatively, the constraints could improve by as much as a factor of 2 if complementary data sets were used to break the degeneracies between m_ν and the running of the spectral index, w_a and w_0[12].

Figure 3 shows these constraints in the context of what is known currently from neutrino oscillations experiments. Particle physics experiments which will be completed by the time LSST will start producing results do not guarantee a determination of the neutrino mass m_{tot} if it is below 0.2 eV. Neutrino-less double beta decay experiments will be able to constrain neutrino masses only if the hierarchy is inverted and neutrinos are Majorana particles. On the other hand, oscillations experiments will determine the hierarchy only if the the composition of electron flavor in all the neutrino mass states is large. Cosmological observations are sensitive to the sum of neutrino masses, offering the possibility to distinguish between normal and inverted hierarchy. Thus, this data set combination could offer valuable constraints on neutrino properties, highly complementary to particle physics parameters like θ_{13}.

These constraints can also be considered in terms of Bayesian evidence[11]. As introduced in the companion "dark energy" white paper (see references therein), the Bayesian factor is a prediction of an experiment's ability to distinguish one model from another. The combination of *Planck*+LSST could provide strong evidence for massive neutrinos over models in which there are no massive neutrinos, and, if the neutrino mass is small $\delta m_\nu < 0.1$ eV, there will be substantial evidence for these models. One could also decisively distinguish between models in which there are no massive neutrinos and those in which $N_\nu < 3.00 - 0.40$ or $N_\nu > 3.00 + 0.40$ and $m_\nu > 0.25$ eV.

Testing Cosmological Assumptions

Universal Isotropy

While testing the homogeneity of the universe remains a very difficult task[14], a wide, deep survey like LSST or space-based mission with equivalent area would be in a prime position to check universal isotropy, specifically the isotropy of dark energy. There are two potential approaches: trying to measure the projected dark energy density quadrupole over the survey area or looking for variation in dark energy parameters in different patches of the sky. For the former, one could calculate the angular power spectrum of the luminosity fluctuations for the million SNe expected to be observed by LSST[3]. At large angles, this power spectrum would be sensitive to the projected inhomogenieties in the dark energy density. For an LSST-like survey, the quadrupole moment ($l = 2$) of this measurement would be able to detect fractional dark energy density fluctuations as small as 2×10^{-4}.

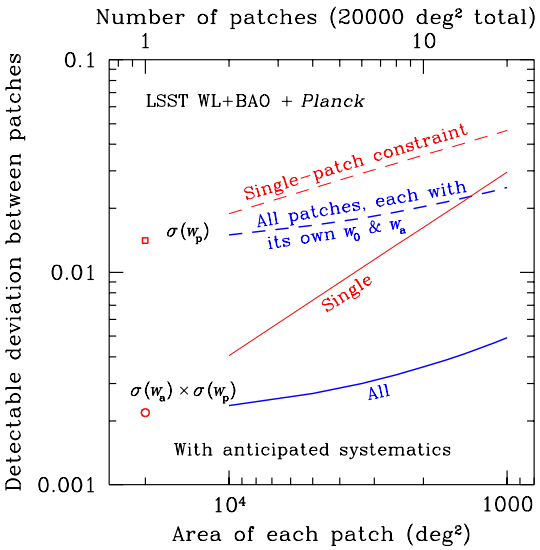

Figure 4: Detectable deviation between LSST measurements of dark energy parameter w_p and error product as a function of the number of patches.

Alternatively, one could take a divide-and-conquer approach: dividing the total survey area into a number of separate patches and measuring the scatter in dark energy parameters measured via weak-lensing (WL) and baryon acoustic oscilations (BAO) in each section. The expected results for such a test using LSST are shown in Figure 4, where w_a is the linearly evolving dark energy EOS and w_p is the EOS orthogonal to w_a. The constraints are marginalized over 9 other cosmological parameters including the curvature and over 140 parameters that model the linear galaxy clustering bias, photometric redshift bias, rms photometric redshift error and additive & multiplicative errors on the power spectrum[22]. Such a measurement should be able to constrain the product $\sigma(w_a) \times \sigma(w_p)$ to $< 0.04\%$ in < 10 patches over the sky.

Primordial Perturbations

One of the core predictions of inflationary cosmology is that the initial perturbations that seeded structure formation have a nearly Gaussian distribution. Measuring the deviation from this non-Gaussianity can provide us with strong clues as to the flavor of inflationary model that drove the expansion of the very early universe. In particular, curvaton or multi-field inflationary models can produce large values of f_{NL}, a parameter commonly used to describe the magnitude of the non-Gaussian contribution to the perturbations: $\Phi = \phi + f_{NL}(\phi^2 - \langle\phi^2\rangle)$.

Recently, it has been shown[4, 16] that primordial non-Gaussianity affects the clustering of dark matter halos, inducing a scale-dependent bias. This is in addition to the contribution to the standard halo bias arising even for Gaussian initial conditions. In this case, the non-Gaussian correction ($\Delta b^{f_{NL}}$) to the standard halo bias increases as $\sim 1/k^2$ at large scales and evolves over time as $\sim (1+z)$. This is detectable for a survey like LSST or JDEM-Wide through measurements of the galaxy power spectrum at large scales. This is a smooth feature on the power spectrum, so large photometric surveys are particularly well suited to study the effect. LSST should be able to detect even a value of $f_{NL} \lesssim 1$ at 1σ[1].

While this error could be in principle reduced further if cosmic variance could be reduced (cf. [19, 20]) this limit of $\Delta f_{NL} \lesssim 1$ is particularly interesting for two reasons. First, it is comparable if not better than the limit achievable from an ideal CMB experiment, making this approach highly complementary with the CMB approach. Second, many well-motivated inflationary models yield f_{NL} well above this threshold. Detecting f_{NL} at this level of precision will be a critical test for these models.

Universal Transparency

Recent work[17] has revealed that the amount of dust in the intergalactic medium is roughly twice that of previous estimates. While the dust content of the universe remains small by mass ($\Omega_{dust} \sim 10^{-5}$), the physical extent of the dust around galaxies was found to far exceed that of the visible light, stretching to scales beyond 100 h^{-1}kpc. Preliminary calculations[18] also indicate that the extinction is large enough to bias cosmological parameter estimates from the ~ 300 "Union" supernovae[15], moving the values for $\Omega_{\rm M}$, $\Omega_{\rm B}$ & w by $\sim 0.5\sigma$.

With the next generation of wide, deep surveys, we should be able to make significant strides in understanding the nature and distribution of this intergalactic dust. One obvious motivation to do so would be to prevent it from acting as a significant source of systematic error on supernova magnitudes used as standard candles. Beyond its role as a source of error,

however, detecting dust on these scales represents an intriguing glimpse into the history of star formation in and around galaxies. Current models for dust generation vary in their conclusions about how extended dust halos should be and how the halo is generated (in situ, as a result of dust outflows, galaxy interactions and so on). Likewise, the current measurements at SDSS wavelengths are unable to make any conclusions about the chemical composition of the dust or how the opacity of the universe has evolved, which would be a key indicator of whether the dust was generated by on-going processes or if it was a relic of the earliest days of star formation. By extending this measurement to higher redshifts and increasing the sensitivity, we should gain considerable insight into the star formation history of galaxies across a wide range of environments, types and luminosities as well as understanding more about the intergalactic medium.

Data Challenges

Next Generation Simulations

In order to extract signatures of new physics beyond the Standard Model as detailed in the previous sections, a next-generation simulation and modeling capability is essential. Currently, all observations are described within the ΛCDM model at 10% error. The signatures of new physics will be subtle and to extract them from upcoming observations, the corresponding theoretical predictions must be obtained at unprecedented accuracies. The state of the art in modeling and simulation must improve by at least an order of magnitude in order to match the precision of the observations. Improvements are necessary in three areas.

First, the dynamic range of the simulations has to increase – larger volumes and higher force and mass resolution are needed. The next-generation surveys will cover enormous volumes that the simulations must capture along with all the halos hosting galaxies within. To model a survey such as the LSST one would like to cover a $(3\mathrm{Gpc})^3$ volume. To match the mass resolution of the "Millennium" run with a particle mass of $\sim 10^9 M_\circ$ would require a trillion particle simulation. This will be possible on next-generation petaflop supercomputers, but will require major rewriting of current cosmology codes and a new paradigm for analyzing the large data volume (petabytes) that will be produced. First efforts in this direction are already underway[7].

Second, we have to include cosmological new physics in the simulations and extract its signatures on the large-scale distribution of galaxies. Precision is again key, as numerical errors can easily mimic effects at the several percent level. The simulations will be extremely important to help distinguish the detection of new and unexpected physics from systematic errors. They will also serve in their traditional role as a testbed for new ideas.

And finally, we have to improve the treatment of gas physics and feedback effects. Currently, such treatments are accurate at most at the 10 - 20 % level. Here the key issue is not so much accuracy as fidelity. There are still astrophysical effects that remain to be properly understood and incorporated in the simulations. Such effects will be extremely important if we start beginning to explore smaller and smaller scales; extracting cosmological information from the non-linear regime from galaxy clustering, for example. Because these effects may never be incorporated at a first-principles level, it is imperative to develop a phenomenological approach that appropriately combines simulations with observations. At the same time we have to improve semi-analytic modeling as an attractive alternative to a full simulation.

Data Size & Complexity

As mentioned in the overview, one of the keys to the success of the current generation of cosmological surveys was their use by members of the astronomical community outside of the survey collaborations themselves. This brought in astronomers with a wider range of interests and skills and began a process of deep data mining that will continue for the next several years. For surveys like LSST and JDEM-Wide, this degree of access will be complicated by the sheer volume of the data involved (tens of petabytes for LSST) and the increase in complexity for both surveys. Both of these factors will push astronomical data analysis away from the current model where data is downloaded and processed through custom software packages like IRAF or IDL. Instead, these surveys will need to adopt a "cloud computing model", creating a work environment at the survey data centers where astronomers can query and analyze the data remotely, downloading only the results of the job rather than the raw data.

Conclusions

Building the next generation of deep, wide-field surveys will profoundly increase our knowledge about the universe. They will yield not only a better insight into the nature of dark energy, but also allow us to examine physics on an incredible range of scales, from gigaparsec to sub-atomic. LSST and JDEM-Wide will test fundamental cosmological and physical models with unprecedented precision, probing the foundations of the theories that inform modern astrophysics. The technical challenges of turning these data sets into science are formidable, but surmountable, and the resulting insights into cosmology and fundamental physics will be well worth the effort. Further, the wide net cast over the skies by these surveys will serve as an invaluable resource for the broader astronomical community, driving advances in galaxy and stellar science as well as variability studies and solar system science.

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