INTRODUCTION

A new golden age: testing general relativity with cosmology

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Gravity drives the evolution of the Universe and is at the heart of its complexity. Einstein’s field equations can be used to work out the detailed dynamics of space and time and to calculate the emergence of large-scale structure in the distribution of galaxies and radiation. Over the past few years, it has become clear that cosmological observations can be used not only to constrain different world models within the context of Einstein gravity but also to constrain the theory of gravity itself. In this article, we look at different aspects of this new field in which cosmology is used to test theories of gravity with a wide range of observations.

Keywords: gravitation; general relativity; cosmic expansion; cosmic growth; galaxy surveys

For almost a hundred years, Einstein’s theory of gravity has remained unchanged and at the heart of astrophysics. It can be used to explain the detailed dynamics of the Solar System, the energetics of supermassive black holes in the centre of galaxies and quasars and it seems to accurately describe the dynamics of the Universe. The fundamental ideas behind general relativity and the resulting Einstein field equations are often held up as the epitome of physical law: simple to state yet complex enough to explain a wealth of phenomena over a staggering range of scales. It is almost impossible to imagine doing any better.

It is in cosmology that general relativity has really opened up new vistas on fundamental physics. By studying the overall dynamics of the Universe, such as its expansion rate and its thermal history, as well as how large-scale structure in matter and radiation forms, it has been possible to explain the formation of the nuclei of light elements, the formation of atoms during recombination and it has been possible to get a handle on any manner of exotic particles which are left over from the hot primeval fireball. It is now routine to read about new ways of constraining not only the physics of the early Universe but also the current state of the Universe using, for example, measurements of the cosmic microwave background (CMB), of the large-scale structure of galaxies, of the relativistic lensing of distant light through inhomogeneous space–time or

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the luminosity distance of high redshift supernova (SN). With this tremendous synergy between theory and observations, we are beginning to characterize the large-scale structure of space–time, a goal first put forward in Kristian & Sachs [1]. Indeed, such is the success of the standard cosmological model which arises from general relativity that the current era has hubristically been dubbed the era of ‘Precision Cosmology’.

Quite possibly the most striking prediction to arise from the application of general relativity to cosmology is that we seem to live in a dark Universe. That is, over 95 per cent of the total energy density of the Universe is in the form of something that does not interact (or interacts very weakly) with light. The current consensus is that just under 25 per cent of the Universe is in a pressureless form of matter that clumps, known as Cold Dark Matter and the remaining 70 per cent is in a form of energy with negative pressure, known as Dark Energy. Such a model, known as the Concordance Model or Standard Model of Cosmology, is remarkably effective in fitting a host of cosmological data. It has done so remarkably well for over a decade, even as the quality and quantity of cosmological observations improve [2].

There has been a concerted effort to find a theory of dark energy—for a comprehensive study of dark energy models see [3]—with hundreds of candidate theories that in one way or another are argued as emerging from different fundamental principles. These many different theories of dark energy can, in principle, lead to different detailed predictions for the observable Universe. It is believed that with bigger and better instruments to make cosmological observations it should be possible to distinguish between the different possibilities. Measuring the properties of dark energy has become the holy grail of modern cosmology.

The situation with regards to general relativity and cosmology, which we are living in now, echoes that experienced by the field of gravitational physics in the 1960s and early 1970s. At the time, general relativity was experiencing what has been dubbed the golden age. Einstein’s theory had passed a number of tests in the laboratory and the Solar System. Black holes, for decades considered to be a bizarre and possibly unphysical prediction of general relativity, were shown to have astronomical relevance, as the engines behind newly discovered radio galaxies and quasars and more generally as the inevitable endpoint of gravitational collapse. The discovery of the relic radiation established the Big Bang cosmology as the preferred model that could correctly describe the origin and evolution of the Universe. With the discovery of neutron stars and millisecond pulsars, general relativity went on from strength to strength. A range of high-precision measurements have, over the years, tested the equivalence principle within the Solar System, the independence of a range of fundamental constants, such as the fine-structure constant, the universality of free-fall test bodies, and relative acceleration of the Earth and the Moon in the Sun’s gravitational field, via Lunar Laser ranging experiments. The success of general relativity has continued until today: the strong-field regime has been extensively, and exquisitely tested, with pulsar timing—we refer to Will [4] for a review—and most recently, Gravity Probe B has been used to accurately measure the consistency with general relativity when measuring the geodetic and frame-dragging drift rates [5].

As a result of its phenomenal success, a number of alternative theories were proposed to serve as ‘straw men’ against which relativity could be compared.
They involved a time, and spatially, varying Newton’s constant, higher-order corrections to the Einstein–Hilbert action, the introduction of preferred reference frames, fifth forces and extra metrics. From all of these theories, it was possible to extract predictions which could then be compared against Solar System data, allowing them to be ruled in and out. In parallel, and as a result of the large number of new theories being proposed, new techniques were developed for parametrizing deviations from Newtonian and Einstein gravity that could bridge the gap between theory and experiment. The most notable of which is the Parametrized Post-Newtonian approximation [6] and is still used today to quantify precision constraints of gravity.

Now, at the beginning of the twenty-first century, and with the unreasonable success of the Concordance Model, alternative models of gravity are being proposed again. The primary goal is to change the Einstein field equations in regions of low curvature or when the typical acceleration arising from the gravitational field falls below $10^{-10}$ km s$^{-1}$ [7], to explain the dark Universe as a gravitational phenomena. The range of possible models has greatly expanded when compared with almost 40 years ago. The bestiary of theories now ranges from scalar–tensor, Einstein–aether and bimetric theories, as well as Tensor-Vector-Scalar theory (TeVeS), $f(R)$, general higher-order theories, Horava–Lifshitz gravity to Galileons, Ghost Condensates and models of extra dimensions, including Kaluza-Klein, Randall-Sundrum, Dvali-Gabadadze-Porrati (DGP) and higher co-dimension braneworlds. The range of models is truly staggering [8].

Not only have there been attempts at modifying the Einstein field equations but also at reconsidering some of the other fundamental assumptions that go into building the Big Bang cosmology. Most notably there has been interest in analysing cosmological models which are not homogeneous. So, for example, over the past few years there has been extensive work analysing spherically symmetric universes that can model a cosmic void embedded in a Friedman–Robertson–Walker Universe, in understanding how large departures from homogeneity can affect large-scale observables or feed back (or ‘backreact’) on the large-scale evolution of the Universe. It has been argued, albeit not conclusively, that the evidence for the dark Universe, and specifically dark energy, is intimately tied with the assumption of large-scale homogeneity [9].

Crucially, all of the above proposals have varied, and potentially measurable, implications for observational cosmology. Some allow space–time-dependent variations in fundamental constants, others for perceptible variations between the dynamics of dark matter and baryonic matter, and in many cases differences, from those predicted by general relativity, in the motions of non-relativistic and relativistic particles. This last difference opens up the possibility for modifications to Einstein’s theory to be constrained by contrasting complementary measurements of the motion of photons, as constrained by gravitational lensing and the CMB, and measurement of the clustering and motions of galaxies and clusters of galaxies. The tremendous developments in observational cosmology are then the drivers in testing these different theories and it pays to have a sense of what they encompass and can achieve.

Cosmological probes of gravity can be divided into two types: probes of the expansion history of the Universe (so-called geometric probes), and probes of the dynamics of structure formation. The former include SN, baryonic acoustic oscillations (BAOs) and geometric properties of weak lensing (WL). These all

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probe the Hubble parameter as a function of epoch, $H(z)$, through angular or luminosity distances, which are sensitive to changes in the background cosmology. The dynamics of structure formation, or clustering, can be probed by WL, galaxy clustering (GC), redshift-space distortions (RSD), the abundance of galaxy clusters and the Integrated Sachs–Wolfe (ISW) effect.

Cosmological surveys designed to exploit these probes can also be divided into two types: either imaging the sky in several passbands to provide high-quality images for WL and galaxy photometric redshifts (GPR) for low-grade galaxy redshifts, or by making high-precision measurements of galaxy spectra for galaxy spectroscopic redshifts (GSR). Surveys such as the Canada–France–Hawaii-Telescope Legacy Survey (CFHTLS), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS-1 and -2), the Dark Energy Survey (DES), the VLT Survey Telescope Kilo-Degree Survey (VST-KIDS), the Large Synoptic Survey Telescope (LSST), Subaru Hyper-SuprimeCam (HSC), the High Altitude Lensing Observatory (HALO), Euclid and the Wide-Field Infrared Survey Telescope (WFIRST), all fall into the first camp. These surveys are designed to carry out three-dimensional (or tomographic) WL surveys to image the gravitational field over cosmic time, measure BAOs from the GC pattern, carry out studies of cluster abundances and, in combination with the CMB, measure the ISW effect. If the observations are sequenced for time-domain studies, by regularly repeating the same images of the sky, they can carry out SN studies.

The second type of survey are GSR surveys, which accurately measure galaxy or quasar redshifts. Past surveys of this type are the 2-degree Field Galaxy Redshift Survey (2dFGRS) and Sloan Digital Sky Survey (SDSS), and in the future include the Baryon Oscillation Spectroscopic Survey (BOSS), the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX), BigBOSS and Euclid. These produce galaxy redshift surveys which can be used for BAOs, RSD, cluster and clustering studies. The combination of galaxy imaging and redshift surveys opens up a direct route for comparing the motion of photons and galaxies to distinguish between different modified gravity theories.

Of particular importance for future constraints on modified gravity is the CMB. Although we may not expect there to be strong direct constraints on modified gravity from the CMB, since most modified gravity models seek to drive late-time acceleration (although in the case of, for example, TeVeS dark matter is exchanged for extra gravity fields which can effect the CMB), there is information from secondary effects such as WL of the CMB and the ISW effect which will imprint a distortion from lower-redshift structure. The CMB provides a distant point to fix the cosmological model at early times so that low-redshift probes have the leverage to probe for deviations. The NASA Wilkinson Microwave Anisotropy Probe (WMAP) satellite has dominated all-sky temperature and polarization measurements for the last decade, but the ESA satellite, Planck, will soon provide the highest resolution all-sky images. To remove the degeneracies between modified gravity parameters and unmodified cosmological parameters, it is usual in the planning of future probes to assume the Planck results will be available to combine with.

Table 1 presents a summary of some of the major current, near-future and proposed cosmological surveys which will be capable of probing modified gravity models. We give the name (or acronym), location, type of probe it is optimized
Table 1. Some of the current, near-future and proposed cosmological surveys with capability of probing gravity. WL, weak lensing; GPR, galaxy photometric redshifts; GSR, galaxy spectroscopic redshifts; BAO, baryonic acoustic oscillations; SN, supernova; CMB, cosmic microwave background. Both GPR and GSR can be used for BAO studies, cluster surveys and the ISW effect.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Location</th>
<th>Probe</th>
<th>Area (square degree)</th>
<th>Depth (z)</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFHTLS</td>
<td>Hawaii</td>
<td>WL/GPR</td>
<td>170</td>
<td>0.7</td>
<td>2003–2011</td>
</tr>
<tr>
<td>Pan-STARRS-1</td>
<td>Hawaii</td>
<td>WL/GPR/SN</td>
<td>30000</td>
<td>0.5</td>
<td>2010–2014</td>
</tr>
<tr>
<td>Pan-STARRS-2</td>
<td>Hawaii</td>
<td>WL/GPR/SN</td>
<td>30000</td>
<td>0.7</td>
<td>2012–2016</td>
</tr>
<tr>
<td>VST-KIDS</td>
<td>Chile</td>
<td>WL/GPR</td>
<td>1500</td>
<td>0.6</td>
<td>2012–2017</td>
</tr>
<tr>
<td>DES</td>
<td>Chile</td>
<td>WL/GPR/SN</td>
<td>5000</td>
<td>0.7</td>
<td>2012–2017</td>
</tr>
<tr>
<td>LSST</td>
<td>Chile</td>
<td>WL/GPR</td>
<td>20000</td>
<td>0.9</td>
<td>2014–2024</td>
</tr>
<tr>
<td>SUBARU/HSC</td>
<td>Hawaii</td>
<td>WL/GPR</td>
<td>2000</td>
<td>0.6 &lt; z &lt; 1.2</td>
<td>2012–2017</td>
</tr>
<tr>
<td>WiggleZ</td>
<td>Australia</td>
<td>GSR/BAO</td>
<td>10000</td>
<td>0.2 &lt; z &lt; 1.0</td>
<td>2006–2011</td>
</tr>
<tr>
<td>BOSS</td>
<td>New Mexico</td>
<td>GSR/BAO</td>
<td>10000</td>
<td>0.5/2.5</td>
<td>2009–2014</td>
</tr>
<tr>
<td>HETDEX</td>
<td>Texas</td>
<td>GSR/BAO</td>
<td>420</td>
<td>1.9 &lt; z &lt; 3.5</td>
<td>2012–2015</td>
</tr>
<tr>
<td>BigBOSS</td>
<td>Arizona</td>
<td>GSR/BAO</td>
<td>14000</td>
<td>0.2 &lt; z &lt; 1.7</td>
<td>2017–2022</td>
</tr>
<tr>
<td>Planck</td>
<td>space/L2</td>
<td>CMB</td>
<td>30000</td>
<td>1100</td>
<td>2009–2011</td>
</tr>
<tr>
<td>HALO</td>
<td>balloon</td>
<td>WL</td>
<td>1000</td>
<td>0.9</td>
<td>2014–2015</td>
</tr>
<tr>
<td>Euclid</td>
<td>space/L2</td>
<td>WL/GPR/GSR</td>
<td>15000</td>
<td>0.9</td>
<td>2018–2023</td>
</tr>
<tr>
<td>WFIRST</td>
<td>space</td>
<td>WL/GPR</td>
<td>30000</td>
<td>1.0</td>
<td>2022–2027</td>
</tr>
</tbody>
</table>

*aPan-STARRS-1 (PS1) now has a clone, PS2, at the same site, due to start operations in 2012, with plans for another two telescopes, PS4, due for 2014.

*KIDS five passbands, ugriz, will be supplemented with Infrared bands (ZYJHK) from the VISTA (Visible and Infrared Survey Telescope for Astronomy) VIKING (VISTA Kilo-degree Infrared Galaxy) Survey.

Introduction. A new golden age

for, area of the sky surveyed, median depth in redshift (or range of redshift) and the currently proposed dates over which the survey will be carried out. In many cases, this is the least certain number. What is encouraging is the number of planned surveys which will be capable of probing gravity. Many of these overlap in type of probes that will allow many independent measurements of gravity. Most of the imaging surveys will carry out a number of different probes, WL, BAO, SN, GC, so that even within a given survey there will be internal consistency checks. There is also overlap between GSR surveys for BAOs and imaging/GPR surveys in the North. With planned balloon (HALO) and space-based missions (Euclid, WFIRST), there is further complementarity between ground and space measurements of WL and GSRs. The possibility of a large number of checks on these measurements is crucial for probes which hope to measure tiny (approx. 1%) deviations from the Standard Cosmological Model, since systematic effects will dominate over statistical uncertainties. It is also encouraging that there is a steady development of the surveys over the next decade, to progressively larger and more powerful surveys, so there is hope that both physical and instrumental systematics can be understood better. With such a wealth of data in prospect, these surveys will be used to probe gravity in ways unthought of today.

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It is clear that we have entered a new golden age for general relativity. The development of observational cosmology, and the promise of future observational programmes, allied with the explosion of activity in modifying Einstein’s theory of gravity have clearly brought general relativity to the fore. The purpose of this meeting, and the resulting Theo Murphy Meeting Issue, has been to bring together the various strands emerging in the field of modified gravity. We can look forward to more meetings such as this one over the coming years as we learn more about the role gravity plays in cosmology and how, in turn, cosmology can be used to constrain and ultimately understand the inner workings of gravity.

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References