DARK ENERGY

Observational and Theoretical Approaches

'Dark energy' is the name given to the unknown cause of the Universe's accelerating expansion, one of the most significant discoveries in recent cosmology. Understanding this enigmatic ingredient of the Universe and its gravitational effects is a very active, and growing, field of research.

In this volume, twelve world-leading authorities on the subject present the basic theoretical models that could explain dark energy, and the observational and experimental techniques employed to measure it. Covering the topic from its origin, through recent developments, to its future perspectives, this book provides a complete and comprehensive introduction to dark energy for a range of readers. It is ideal for physics graduate students who have just entered the field and for researchers seeking an authoritative reference on the topic.

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Edited by

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Pilar Ruiz-Lapuente
Frontmatter
More Information

Contents

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Preface

We commonly denote as dark energy the physics yet to be determined that causes the present acceleration of the universe. Dark energy is a very wide subject residing in unkowns of very different kinds, since the origin of the cosmic acceleration can be of very diverse nature. It can be linked to the presence of a new component of the universe in the form of a field with similarities to the field that causes inflation. It can be a departure of gravity from general relativity or it can be related to vacuum energy.

The importance of the subject, which involves the understanding of gravity and the present components of the universe, will make it a very active field of research in the next decades.

Many experiments are planned to try to identify the nature of dark energy. They involve the use of ground-based facilities or space missions designed specifically to study this phenomenon. There is a flurry of results coming every year, which put new constraints on what dark energy can be.

In the present volume, we have not tried to be exhaustive with such an open field, but we give diverse points of view, both theoretical and observational.

The theoretical perspectives try to present the various possibilities under discussion on what dark energy can be. The observational chapters present the field now and in the future with the advent of multiple experiments and new facilities.

In his chapter "Dark energy, gravitation and the Copernican principle", Jean-Philippe Uzan introduces the ingredients of our cosmological description of the universe and how we include dark energy. Proposals for dark energy are scrutinized. The models of dark energy are classified into: those in which acceleration is driven by the gravitational effect of new fields; models in which fields do not dominate the matter content but are coupled to photons and affect the observations; models in which a finite number of new fields are introduced and couple to the standard field models, such as in the case of scalar–tensor theories; and models in which drastic modifications of general relativity are required, such as the models introducing extra dimensions. The author discusses the constraints in modifying general relativity found in various regimes as well as the options to modify the Einstein–Hilbert action. He reconsiders our assumption of the place that we occupy in the universe. Usually in cosmology one works within what is called the Copernican principle, which merely states that we do not live in a special place (the center) in the universe. This principle is in general very minimal in its requirements when compared with the frequently used cosmological principle, which supposes that the universe is spatially isotropic and homogeneous. Within the Copernican principle, the cosmological principle is recovered if we assume that isotropy around the observer holds. Uzan asks which possibilities are open if we go beyond the Copernican principle; for instance, the possibility that we may be living close to the center of a large underdense region of the universe. Non-homogeneous models of the universe are considered. Many possibilities are open if one relaxes the Copernican principle. But their cosmological extensions are testable by the data and future surveys can further constrain them.

In their chapter, Ruth Durrer and Roy Maartens examine why most models proposed for dark energy are not good candidates. As candidates within general relativity, they consider quintessence models. They find that some aspects of quintessence models are not satisfactory: they require a strong fine tuning of the parameters of the Lagrangian to secure recent dominance of the field. More generally, the quintessence potential, like the inflaton potential, remains arbitrary until fundamental physics selects the potential. The authors look at other models involving scalar fields. Those with a non-standard kinetic term on the Lagrangian can be ruled out because they break causality.

Out of the frame of general relativity other possibilities can be considered, as argued by Durrer and Maartens, but present equal problems. One of those alternatives is $f(R)$ or scalar–tensor theories of gravity where the Lagrangian is described with an arbitrary function of the Ricci scalar. $f(R)$ models are the only acceptable low-energy generalization of the Einstein–Hilbert action of general relativity. In these theories gravity is mediated by an extra spin-0 degree of freedom. The requirement of late acceleration leads to a very light mass for the scalar. However, on solar system scales, the light scalar induces strong deviations from the weak field limit of general relativity in contradiction with the observations.

Another class of dark energy models that requires going beyond general relativity is the so-called braneworld dark energy models. Durrer and Maartens examine these candidates and pay attention to the Dvali, Gabadadze and Porrati (DGP) braneworld model, which modifies general relativity at low energies. This model produces “self-acceleration” of the late-time universe due to a weakening of gravity at low energies. Despite the good features of the DGP model to provide a simplified explanation for the acceleration, the predictions of the model are in tension with supernova observations and with WMAP5 data on large scales. From their overview, Durrer and Maartens conclude that none of the contenders for the ΛCDM model appears better than ΛCDM. However, the need to explore the realm of possibilities makes it worth testing models outside general relativity and other alternatives.

The chapter by David Polarski entitled “Some views on dark energy” reviews alternatives to dark energy and finds some of the problems mentioned by Durrer and Maartens. Polarski devotes significant attention to the scalar–tensor dark energy models. The author discusses limits placed on these models by the solar system experiments. He discusses the *f(R)* models that could in principle provide late acceleration of the universe without the need to invoke a cosmological constant. He points out that many *f(R)* models cannot produce a standard matter-dominated stage before the late-time accelerated expansion. However, there is still room for viable *f(R)* candidates. Polarski addresses the question of how to disentangle, from observations, dark energy candidates that are within general relativity from those that are outside. He outlines how the dynamics of the matter perturbation can give a clear test.

In his chapter entitled “Emergent gravity and dark energy” Thanu Padmanabhan gives a presentation of the cosmological constant problem, followed by a criticism of most current theoretical approaches to the dark energy problem. According to this author, the ultimate explanation for a non-zero cosmological constant should come from quantum gravity, but even in the absence of such a microscopic description of the structure of spacetime, new insights would be provided by an intermediate description, playing a role similar to that of thermodynamics, which, while being only phenomenological, depends on the existence of microscopic degrees of freedom and reveals them in a way that escapes the continuum mechanics description. The cosmological constant would be a low-energy relic of quantum gravitational physics. It introduces a fundamental length L_Λ, which would determine the lowest possible energy density due to quantum spacetime fluctuations. The relevant degrees of freedom, in calculating that, should scale as the surface area and not as the volume of the corresponding region of spacetime. Einstein’s equations can be obtained from an action principle that uses only the surface term of the Einstein–Hilbert action and the virtual displacements of horizons. The usual interpretation of the surface term as the entropy of horizons thus links spacetime dynamics and horizon thermodynamics. In such a framework, the bulk value of the cosmological constant decouples from the dynamical degrees of freedom and what is observable through gravitational effects should just be the fluctuations in the vacuum energy. The scale relevant to the structure of the gravitational vacuum should be the size L_Λ of the cosmological horizon. The size of the fluctuations in the energy density then gives the right magnitude for the cosmological constant: it is small because it is a quantum relic.

As observational accounts on the state of dark energy, we have several chapters devoted to dark energy from supernovae, which have been at the origin of the discovery of dark energy and are providing most of the data for determining the equation of state. There is, unavoidably, some overlap among them, but each chapter reflects different perspectives.

In his chapter, Robert P. Kirshner presents the history of how SNe Ia became such good cosmological distance indicators. He recalls the very first attempts to use them when the collected data were sparse and did not allow one to establish that the universe had a low Ω_m and moreover that there were indications that the cosmological constant was non-zero. As founder of the Harvard supernova team that has been the core of the High-Z Team, ESSENCE and now PARITEL, his recollections on the discovery of acceleration of the universe are most valuable. In this book, we have not had the opportunity to have a parallel presentation by Saul Perlmutter describing the successes and difficulties in getting the high-z supernova method to work, but his talk at the Gruber Prize ceremony in 2007 gives a summary of the long path towards the discovery of the acceleration of the universe. Recently, Gerson Goldhaber published his memoirs on the subject in the Dark Matter 2008 conference. He focused on year 1997 when many of us were attending the Santa Barbara Workshop on Supernovae. Being linked first to Harvard and afterwards to the Supernova Cosmology Project, I have a sense of how things developed. I agree that the year 1997 was crucial and at the Supernova Cosmology Project meeting in Berkeley that I attended, it seemed clear that Gerson's results were already pointing to the direction that ended in the discovery of non-zero Λ. The paper took a long time to get written but the seeds were sown early. I conclude that the teams led by both Robert P. Kirshner and colleagues and Saul Perlmutter and colleagues were necessary to the discovery.

The chapter by Pilar Ruiz-Lapuente gives an introduction to the method of supernovae to measure the expansion rate of the universe and the equation of state of dark energy. The basic relation that allows one to calibrate supernovae as distance indicators is presented. The author reviews how different samples of SNe Ia have allowed us to improve the determination of the index of the equation of state. The sources of error in the method are discussed. The progress in controlling those errors is shown by looking at their size at the time of discovery of the acceleration of the universe and their expected magnitude in planned missions to gather thousands of supernovae from space. Prospects for testing the isotropy of the universe with SNe Ia and how one will be able to assess FRW cosmologies are pointed out. The chapter mentions some dark energy models that have been tested with supernovae and the results that have been gathered. The complementarity of the supernova test with other probes is emphasized.

The chapter by Michael Wood-Vasey entitled "The future of supernova cosmology" gives an update on the diversity of questions that can be addressed with the new facilities opened to do large surveys of the sky, gathering hundreds of thousands of supernovae. Tests of the Copernican principle and precision tests on the equation of state of dark energy can be achieved by the Large Synoptic Survey Telescope and the Panoramic Survey Telescope and Rapid Response System, which will scan all the sky enabling a very large number of data to be collected.

In his chapter, "The space advantage for measuring dark energy with Type Ia supernovae", Alex Kim examines why a space mission is needed to be able to measure dark energy to the precision required to identify its nature. Space basically provides more potential for discovery. The author reviews the physics behind the supernova data points. He describes what goes into the so-called magnitude of a supernova. Ultimately, the advantages of going to space are presented. Rest-frame multichannel optical data of supernovae out to $z{\sim}1.8$ that extend redwards to 0.63 μm (and preferentially even further) can provide the required information on SNe Ia, foreground dust and ultimately dark energy models. The relative yields of surveys from the ground and surveys from space are evaluated. It is shown that for a ground-based survey to be competitive with a space-based one, the extent in angle covered and collecting areas must be 10^5 times larger than for a 2-m space telescope. It is seen how surveys such as those planned for the Large Synoptic Survey Telescope cannot be competitive at high z with a space mission based on a 2-m telescope.

Bassett and Hlozek review the method of baryon acoustic oscillations to measure dark energy and the ongoing projects that have begun to measure the Hubble parameter and the angular distances at various z with this method. Their chapter starts with a historical overview of methods that have used angular distances as cosmic distance indicators. Then it reviews the physics of baryon acoustic oscillations and their cosmological uses. As Bassett and Hlozek explain, before recombination and decoupling the universe consisted of a hot plasma of photons and baryons which were tightly coupled via Thompson scattering. The competing forces of radiation pressure and gravity set up oscillations in the photon fluid. The tightly coupled baryon–photon plasma underwent perturbations that propagated outwards as an acoustic wave. At recombination the cosmos becomes neutral and the pressure on the baryons is removed. The baryon wave stalls and quickly slows down while the photons propagate freely away forming what we now observe as the cosmic microwave background. The characteristic scale of the spherical shell formed when the baryon wave stalled is imprinted on the distribution of the baryons as an excess density transmitted through gravity to dark matter, which preferentially clumps on this shell. This leaves the imprint of the original baryon acoustic oscillation and expands as the universe does. Once the origin of the method has been reviewed, the authors take a close look at the observational challenges encountered by this approach. Bruce Bassett and Renée Hlozek discuss issues of non-linearity within the method. Various observational possibilities are discussed about where the measurement of the baryon acoustic oscillations could be made. Finally, forecasts for the use of this approach to measure dark energy are given.

As another observational approach to determine the nature of dark energy, Alan Heavens presents the method of weak lensing. Lensing, as noted by the author, is very appealing theoretically as the physics involved is simple and robust and a direct connection can be made between weak lensing observables and the statistical properties of the matter distribution. Those statistical properties depend on cosmological parameters in a known way, thus weak lensing can be employed as a cosmological tool. Heavens introduces the fundamental concepts in gravitational lensing such as shear and magnification. He points out that when distance information for the sources is available, it is possible to do a 3D reconstruction of the mass distribution. The procedure is to divide the survey into slices at different distances, and perform a study of the shear pattern on each slice.

Another very interesting test is the shear ratio test, an approach that has a simpler dependence on cosmological parameters and presents the advantage of probing cosmology with significant independence from the growth rate of fluctuations.

As models that could be explored by these gravitational lensing approaches, we have the contenders to ΛCDM such as braneworld models and other modified gravity approaches. In a section entitled "Testing gravity models", Heavens introduces Bayesian evidence as a useful way to select between alternatives for dark energy. The author shows the expected Bayesian evidence for models and experiments planned. Heavens finds that a weak lensing experiment could distinguish between general relativity and modified gravity before *Planck*. The expected evidence will depend on the number of galaxies surveyed.

The chapters above give an idea of the most active methods for determining the nature of dark energy. The major activity in the coming years will likely arise from the three selected methods above. Plenty of observational projects will bring results that hopefully will clarify the nature of dark energy.

I could not finish this preface without acknowledging Cambridge University Press and editor Vince Higgs for the support given to the project. I would also like to thank all the authors for providing their insights on this timely subject.

Pilar Ruiz-Lapuente