The lectures that four authors present in this volume investigate core topics related to the accelerated expansion of the Universe. Accelerated expansion occurred in the very early Universe – an exponential expansion in the inflationary period $10^{-36}$ s after the Big Bang. This well-established theoretical concept had first been proposed in 1980 by Alan Guth to account for the homogeneity and isotropy of the observable universe, and simultaneously by Alexei Starobinski, and has since then been developed by many authors in great theoretical detail.

An accelerated expansion of the late Universe at redshifts $z < 1$ has been discovered in 1998; the expansion is not slowing down under the influence of gravity, but is instead accelerating due to some uniformly distributed, gravitationally repulsive substance accounting for more than 70% of the mass–energy content of the Universe, which is now known as dark energy. Its most common interpretation today is given in terms of the so-called $\Lambda$CDM model with a cosmological constant $\Lambda$.

This pathbreaking result was obtained almost simultaneously by the Supernova Cosmology Project led by Saul Perlmutter of the Lawrence Berkeley National Laboratory and the University of California at Berkeley, and the High-z Supernova Search Team around Brian Schmidt of the Australian National University in Canberra, and Adam Riess, who is now at the Johns Hopkins University and the Space Telescope Science Institute, both in Baltimore, Maryland. It is presently not clear whether there is any relationship between inflation in the early Universe and the accelerated expansion in the late Universe. Dark energy is somewhat similar to cosmological inflation, but its energy scale of $10^{-12}$ GeV is about 27 orders of magnitude smaller than the typical energy scale of inflation. In its physical interpretation, the solution for the cosmological constant problem is the clue to further progress in both cosmology and particle physics – in particular, the correct explanation of the smallness of the cosmological constant, and the reason for the approximate equality of its energy density and the matter energy density at the present epoch.

The discovery of the accelerated expansion in the late Universe relied on data from type Ia supernovae. These are fairly reliable standard candles, and can hence be used in the cosmic luminosity-distance determination. The accelerated expansion in the redshift range $z < 1$ has subsequently been and will further be investigated in detail not only through refined data from type Ia supernovae, but also through observations of the temperature fluctuations in the cosmic microwave
background, in particular with the Planck satellite, of baryonic acoustic oscillations, the weak-lensing effect, and through galaxy cluster counts with the South Pole Telescope and other equipment. At larger redshifts, the acceleration becomes a deceleration, owing to the lessening impact of dark energy at earlier times – as has been confirmed by recent supernova data from the Hubble space telescope.

Selected aspects of the vast field of accelerated expansion of our Universe in different epochs are treated in the four selected lectures that are presented in this volume. The first chapter by David Langlois of the Université Paris 7 considers inflation and how it accounts for the primordial seeds of the cosmological perturbations which we can observe today with great precision. It also serves as an introduction to the principles of the Hot Big Bang Model and its limitations. Particular emphasis is placed on the amplification of the quantum vacuum fluctuations during the inflationary phase. The constraints on inflationary models are discussed, as well as more general models of inflation involving multiple fields, and non-Gaussianities of the primordial perturbations.

The second chapter written by Mark Sullivan of Oxford University introduces dark energy in a review of type Ia supernovae results in cosmology. The physics which leads to the near-uniform peak brightness of these supernovae, allowing astronomers to use them for precise luminosity-distance determinations, is explained. Modern SN Ia searches and distance estimation techniques have allowed to measure the average equation of state of dark energy to better than 5% statistical error, when combined with complementary probes of large-scale structure such as baryonic acoustic oscillations. Future prospects for determining dark energy with SN Ia in the next generation of planned experiments are given.

The third chapter by Shinji Tsujikawa of Tokyo University concerns modified gravity models of dark energy. Such theories presently appear to be the most serious competitors to conventional dark-energy models based on a cosmological constant, or its time-dependent counterparts arising from a scalar field, although the physical origin of the modifications of gravity are not always clear. A number of modified-gravity models that satisfy local gravity and cosmological constraints are presented. Signatures that may distinguish modified gravity models from $\Lambda$CDM cosmology are discussed. The braneworld models treated in this chapter as possible candidates for late-time cosmic acceleration are, however, ruled out from observational constraints.

Finally, the last lecture by Licia Verde from the Universitat de Barcelona about statistical methods in cosmology gives a summary of the currently available statistical methods that are indispensable for the analysis of cosmological data, and are thus necessary prerequisites for many of the results that have been presented in this volume and elsewhere in cosmological research.

The lectures have grown out of the annual Winter School of the Transregional Research Center TRR33 “The Dark Universe” of the joint Universities Heidelberg, Bonn, and LMU Munich. The center is funded by the Deutsche Forschungsgemeinschaft. The first Winter School was established in 2007 by the Research Center following the request and initiative of the young researchers, including postdoctoral, doctoral, and master students. The most active group of them acted as organizers and
set up the school in the Italian mountain resort, Tonale, at moderate cost but great scientific benefit for the center. The main idea was to present “theory for observers and observations for theorists,” to initiate discussions and joint projects between theorists, observers, and scientists working with simulation methods.

The school was a big success, and it is scheduled to continue every year during the funding period of TRR33. The four selected lectures in this book arose from the second school in 2008, which was mainly organized by the young researchers, M. Baldi, C. Byrnes, T. Koivisto, M. Maturi, C. Mignone, D. Mota, V. Pettorino, G. Robbers, M. Viola, and J.C. Waizmann, with the help of some more senior people in the background. The four authors of this Lecture Notes volume have expressed their gratitude to the organizers for setting up this very useful and enjoyable Research School and for their hospitality. We all hope that this endeavor will contribute further to the bright future of dark energy.

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