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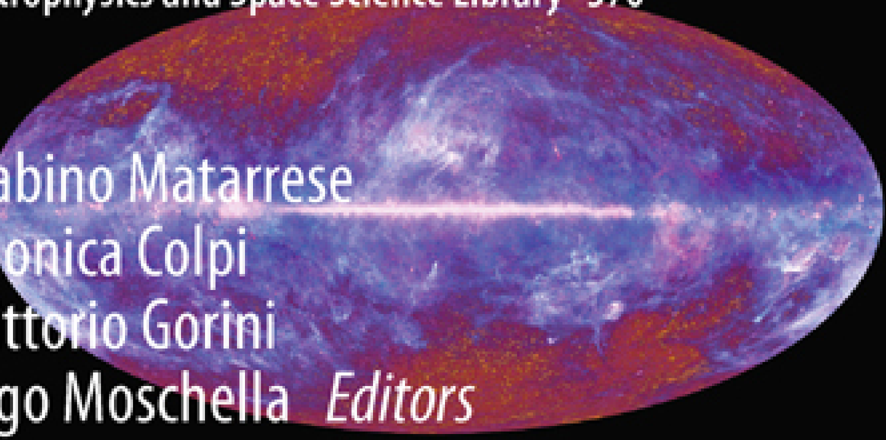

Sabino Matarrese
Monica Colpi
Vittorio Gorini
Ugo Moschella *Editors*

Dark Matter and Dark Energy

A Challenge for Modern Cosmology

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Editors

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Editors
Sabino Matarrese
Dipartimento di Fisica G. Galilei
Università degli Studi di Padova
Via Marzolo 8
35131 Padova
Italy

Monica Colpi
Dipartimento di Fisica G. Occhialini
Università de Milano Bicocca
Piazza della Scienza 3
20126 Milano
Italy

Vittorio Gorini
Dipartimento di Fisica e Matematica
Università dell'Insubria
Via Valleggio 11
22100 Como
Italy

Ugo Moschella
Dipartimento di Fisica e Matematica
Università dell'Insubria
Via Valleggio 11
22100 Como
Italy

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Introduction

Sabino Matarrese

The dark side of the Universe

This book aims at presenting a thorough and up-to-date introduction to the fundamental theoretical and observational aspects of the two dark components of the Universe: the dark matter and the dark energy.

During the last decades, many independent observations have provided growing evidence that the Universe is filled with two “dark” ingredients, a collisionless component, able to cluster on sub-horizon scales, called dark matter and an almost uniform component with negative pressure, called dark energy, whose physical nature is still largely unknown. The dark matter component yields almost one-quarter of the total cosmic energy today, while the dark energy is responsible for about 70%. The sum of their contribution to the present-day cosmic energy budget is just impressive: around 96% of the total. The visible material, to which physicists and astronomers paid all of their attention for millennia, appears now as a sort of minor “detail” in the cosmos. Indeed, even the majority of the overall ordinary, baryonic material is invisible to our telescopes: we have indications that at least half of it is concentrated in a network of thin interconnected large-scale filaments/sheet-like structures, the so-called Warm-Hot Inter-Galactic Medium, which we hope to detect with the next generation of X-ray satellites.

The discovery that almost three-quarters of the present cosmic energy density is to be ascribed to an almost uniform dark energy component able to produce, via its negative isotropic pressure, the accelerated expansion of the Universe, represents the most severe crisis of contemporary physics. At the same time, this discovery opens the door to new theoretical speculations and represents the new frontier for observational cosmology, in the joint effort to constrain the dynamical properties of

Sabino Matarrese
Dipartimento di Fisica “G. Galilei”, Università degli Studi di Padova and INFN, Sezione di Padova
via Marzolo 8, I-35131 Padova, Italy
e-mail: sabino.matarrese@pd.infn.it

the dark cosmic components and to unveil their physical nature. In this sense, the discovery of the "dark side" of the Universe, represents a formidable challenge for the cosmological research of the 21st Century.

The evidence that the vast majority of the Universe's energy is due to dark components appears as a sort of extreme consequence of the Copernican Principle: not only did we human beings have to accept that we do not live at the center of the Universe, but we are also gradually getting acquainted with the idea that the "ordinary" matter we are made of represents a negligible ingredient in the Universe's composition, playing a minor role in the global dynamics of the Universe.

The very fact that cosmologists had to change so radically their view on the Universe's matter content is also having a strong impact on the more general problem of cosmological model building. Indeed, many cosmologists recently started to question the strict validity of the standard model of the Universe based on the spatially homogeneous and isotropic Friedmann–Lemaître–Robertson–Walker (hereafter FLRW) solution of Einstein's field equations and considered more general/less symmetric background solutions as a viable possibility. The motivation for this new direction of investigation is twofold: observationally based and purely theoretical. From the observational point of view, some large angular scale "anomalies" detected in the Cosmic Microwave Background anisotropy pattern triggered the analysis of alternative background models, such as the homogeneous but anisotropic Bianchi solutions. On the theoretical side, the search for an alternative interpretation of the cosmic acceleration at late times, not requiring dark energy at a fundamental level, stimulated several groups to wonder whether our observable patch of the Universe could be better described by some inhomogeneous and anisotropic background metric. The underlying idea of such an approach is that by averaging over a large (e.g. Hubble radius-size) spatial volume such a non-FLRW metric and fitting it to a FLRW cosmology one unavoidably obtains extra "back-reaction" terms in the effective Friedmann equations (or, alternatively, in cosmological observables, such as the luminosity distance-redshift relation), that would possibly *mimic* a dark energy component. Whether such a back-reaction effect has the right equation of state (with negative pressure) and is large enough to explain the present-day accelerated phase of the cosmic expansion is a matter of controversy: much work has to be done yet before we can have have a realistic inhomogeneous and anisotropic alternative to the FLRW model able to recover the many successes of the standard cosmology and at the same time to explain the cosmic acceleration/dark energy puzzle.

Outline of the book

The book is organized in three, largely complementary, parts.

I Cosmology

The first part of the book starts with a chapter by Norbert Straumann, devoted to the introduction of some fundamental concepts in modern cosmology: cosmic inflation, a phase of accelerated expansion in the early Universe, which plays a fundamental role in providing a causal mechanism for the generation of cosmological perturbations, the seeds which gave rise to all cosmic structures, and to the anisotropies in temperature and polarization of the Cosmic Microwave Background (hereafter CMB) radiation. An introduction to the theory of linear gauge-invariant perturbations and of CMB anisotropies is also provided. This general introduction serves as a background to the analysis of the most important cosmological observables: the CMB and the large-scale structure distribution of matter, as revealed by the spatial clustering of galaxies, which are discussed in the chapter by Licia Verde. Another important cosmological observable, i.e. the gravitational lensing of light by the intervening matter distribution is introduced in the following chapter, written by Alan Heavens. These cosmological observables play a crucial role in constraining the amount and type of dark matter, but they also allow us to place formidable constraints on the physical properties of the dark energy component and of possible alternatives to the latter in the form of modifications of the theory of gravitation with respect to general relativity. This part of the book ends with a chapter, by Lauro Moscardini and Klaus Dolag, which presents an introduction to the techniques and the main results of numerical simulations of the matter distribution in the Universe, the so-called N-body simulations and their extension to include baryons, the hydrodynamical simulations.

II Dark Matter

The second part of this book deals with dark matter both from the astrophysical point of view and from the point of view of particle physics. There are indeed different perspectives under which the many phenomena associated to dark matter can be analyzed. The chapter written by Guido D'Amico, Marc Kamionkowski and Kris Sigurdson presents a review of the astrophysical and cosmological evidence for the existence of dark matter from the galactic to the largest cosmological scales. They also discuss the properties of Weakly Interacting Massive Particles (WIMPS) and of other dark matter candidates, like axions and sterile neutrinos. Antonio Masiero, in his chapter, analyzes the dark matter problem from the particle physics point of view, discussing some aspects of the Standard Model of particle physics and the motivations to go beyond it, and introduces the most likely particle dark matter candidates. The final chapter of this part, by Andrea Giuliani, reviews the status of the direct and indirect searches for the dark matter particles.

III Dark Energy

The third and final part of the book, written by Shinji Tsujikawa, present a very complete and up-to-date introduction to dark energy, both from the phenomenological and from the theoretical point of view. Starting from the observational bounds on dark energy coming from Type Ia Supernovae, CMB and Baryonic Acoustic Oscillations, the chapter reviews the various explanations proposed so far for the dominant component of the Universe today; these include a cosmological constant, several dynamical variants, such as quintessence, k-essence, coupled dark energy and unified models of dark matter and dark energy based on a scalar field component. Possible modifications of gravity, such as $f(R)$ theories are also discussed. The idea that the back-reaction of cosmic inhomogeneities could provide an alternative to dark energy at the fundamental level is also discussed.