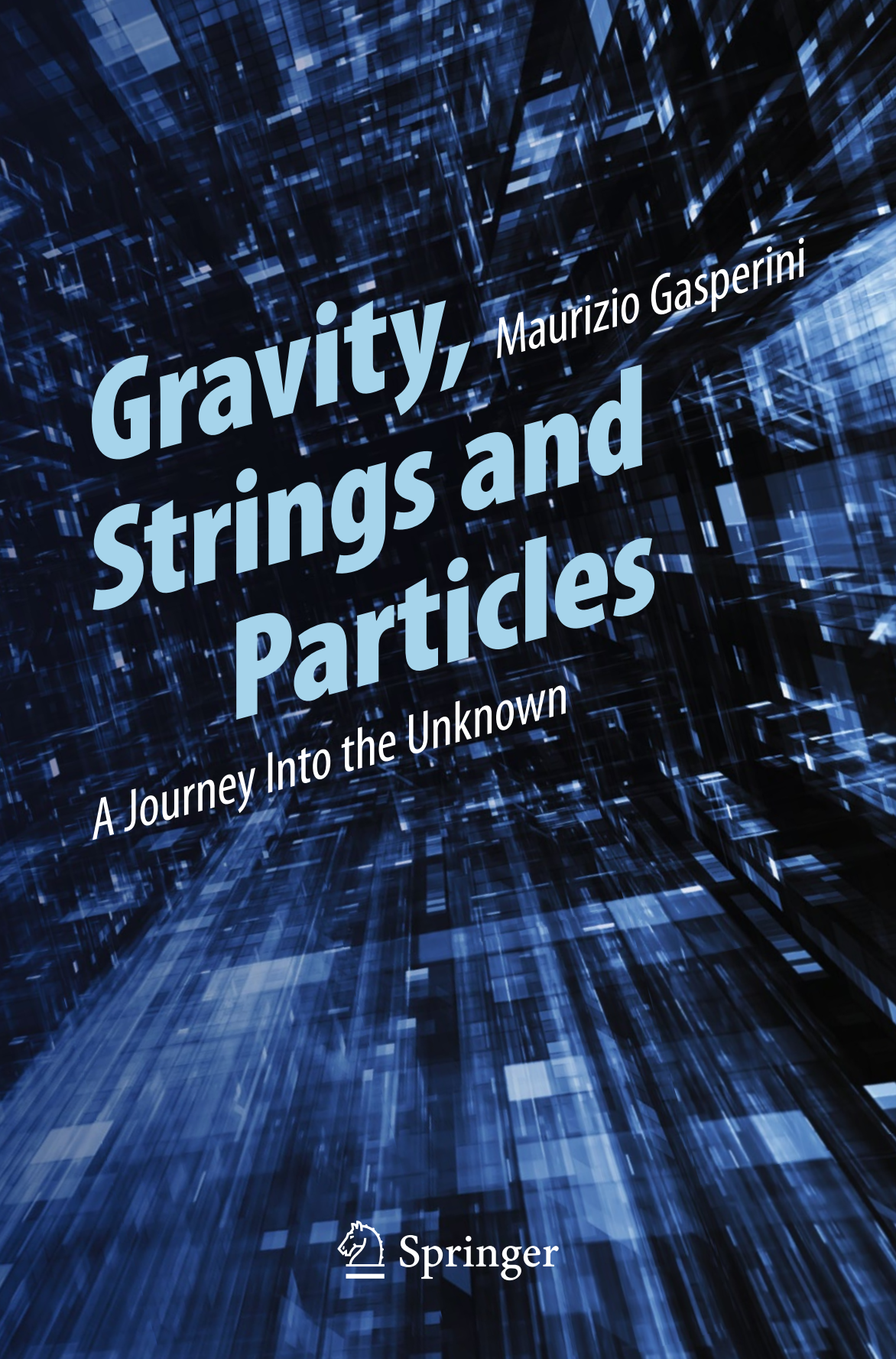




Gravity, Strings and Particles

Maurizio Gasperini

A Journey Into the Unknown



Springer

Gravity, Strings and Particles

Maurizio Gasperini

Gravity, Strings and Particles

A Journey Into the Unknown



Springer

Maurizio Gasperini
Dipartimento di Fisica
Università di Bari
Bari, Italy

ISBN 978-3-319-00598-0 ISBN 978-3-319-00599-7 (eBook)

DOI 10.1007/978-3-319-00599-7

Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014937666

© Springer International Publishing Switzerland 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

*To my Mother
with my deepest gratitude*

Preface

This book grew out of conversations I had with a good friend of mine (Pier Paolo Casalbani, also known as “*Slim*”). During the summer vacations, while tanning on the beach in Cesenatico, he often asks me to tell him the latest news and the most peculiar ideas concerning my work as theoretical physicist.

In this book I will talk of physics addressing to readers who do not necessarily have a specific background in this field, but are nevertheless interested in discovering the novelty, the originality, and the possible weird implications of some amazing ideas used by modern physics of fundamental interactions. I will avoid introducing mathematical expressions as much as possible, trying to convey ideas rather than explaining formulas. Also, I will leave aside the cautious attitude typical of the academic style, following sometimes my excitement and my personal feelings concerning the topics under discussion.

We can say that this is a book of popular science, but of a rather unconventional type, as the emphasis is not only on what is known but also—and mainly—on what is still unknown. Indeed, many parts of the book are devoted to introduce and illustrate fundamental theoretical models and results which are potentially highly relevant to a deeper understanding of Nature, but still waiting to be directly confirmed (or disproved) by experimental observations. From this point of view the book may be of some interest also to professional physicists, working or not in the field of fundamental interactions.

I should explain, finally, the reason why the book is focused on the three topics mentioned in the title: gravity, strings, and particles. Why these three topics? What brings them together, selecting them among many other important issues of modern physical research?

It is known that there are many important links among them: for instance, as we shall see, the fact that a unified description of all elementary matter particles and all forces, including gravity, can be consistently achieved only within a model based on strings.

However, my choice is mainly motivated by the widespread belief that only a joint study of high-energy models of gravity, strings, and particles may help us to shed light on what seems to be (to me, at least) one of the biggest and most fascinating mysteries of modern science: besides time and three spatial dimensions, are there other dimensions in our Universe? If yes, how many are they?

Cesena, Italy
February 2013

Maurizio Gasperini

Notations

For a maximum simplification of the (very few) equations presented in this book I will always adopt the so-called natural system of units, where both the light velocity c and the Planck constant $\hbar$ are set equal to one.

With this choice of units mass and energy have the same physical dimensions, energy has dimensions of the inverse of a length, and energy density has dimensions of an inverse length to the fourth power.

We will often use, as a typical reference distance, the Planck length L_P defined (in the above units) by $L_P = \sqrt{G}$, where G is Newton's gravitational constant; we will also use, as a typical reference energy, the Planck mass M_P defined by $M_P = 1/L_P$.

We will usually express distances in centimeters (abbreviated as cm); energies in electron volts (abbreviated as eV), or billions of electron volts (abbreviated as GeV), or thousands of GeV (abbreviated as TeV). Sometimes we will use for the distances also the light year, roughly equivalent to 0.9×10^{18} cm. Finally, we will express temperatures in Kelvin degrees, remembering that one Kelvin degree (with the Boltzmann constant set equal to one) corresponds to 8.6×10^{-5} eV.

In the above units the Planck length is given by:

$$L_P \simeq 1.61 \times 10^{-33} \text{ cm},$$

the Planck mass is given by:

$$M_P \simeq 1.22 \times 10^{19} \text{ GeV},$$

and the Hubble radius L_H , which controls the size of the portion of space directly accessible to our observation, is presently given by:

$$L_H \simeq 1.28 \times 10^{28} \text{ cm}.$$

Other scales of energy and distance, possibly relevant to the topics of this book, will be introduced and discussed whenever necessary.

Contents

1	Prologue: Inside the Energy Walls of Our “Cradle”	1
2	Gravity at Small Distances	5
2.1	New Fundamental Forces of Nature?	7
2.1.1	The Graviphoton and the Dilaton	9
2.1.2	“Chameleons” and “Fat” Gravitons	14
2.2	New Dimensions of Space?	18
2.3	The “Compact” Scenario	19
2.3.1	The Kaluza–Klein “Towers” and the Radion	21
2.3.2	A “Spontaneous” Compactification	23
2.4	The “Brane-World” Scenario	26
2.4.1	The Geometric Confinement of Gravity	28
3	Gravity at Large Distances	31
3.1	Extra Dimensions Strike Back	34
3.2	A New Form of “Dark” Energy?	35
3.2.1	The Cosmic “Quintessence”	38
3.3	The Fluctuations of the Vacuum Energy	43
4	Space, Time, and Space–Time	49
4.1	Maybe the Past Can Change?	50
4.1.1	Time and Memory	54
4.1.2	Time: An Intrinsic Property of All Bodies?	55
4.2	Maybe Space–Time Is Not Unique?	57
4.2.1	“Relative” Singularities	59
5	Strings and Fundamental Interactions	61
5.1	How to Quantize Extended Objects	62
5.2	Supersymmetry and Higher-Dimensional Spaces	67
5.3	The Five Superstrings	71
5.3.1	Type IIA and Type IIB Superstrings	71
5.3.2	Type I Superstring	72
5.3.3	The Two “Heterotic” Superstrings	74

5.4	Conformal Invariance and Equations of Motion.....	77
5.4.1	The Dilaton and the Topological Expansion	81
5.5	A New Symmetry: “Duality”.....	84
5.5.1	“Winding” Strings and Large Dimensions.....	89
6	The Very Early Past of Our Universe	95
6.1	String Cosmology	101
6.2	Brane Cosmology	104
6.2.1	The “Ekpyrotic” Scenario	107
6.2.2	Brane–Antibrane Inflation.....	109
6.3	Signals from Epochs Before the Big Bang?	110
6.3.1	The Cosmic Background of Relic Gravitons	112
7	Conclusion	119
	References	121
	Index	123

Chapter 1

Prologue: Inside the Energy Walls of Our “Cradle”

We often say that the physics of “small distances” is equivalent to the physics of “high energies.” This is indeed true, as a direct consequence of the celebrated Heisenberg’s principle (or uncertainty principle) stating that, in order to explore (and measure) smaller and smaller distances, we need probes with higher and higher momenta, namely with larger and larger kinetic energies. According to the uncertainty principle, in particular, the required energy E turns out to be inversely proportional to the considered distance d , so that E tends to infinity when the distance d goes to zero.

Even in the case of very large distances, however, we are unavoidably lead to the high-energy regime. This basically occurs for two reasons: one reason, of accidental type, is related to the expansion of our Universe; the other reason, of more fundamental nature, is related to the fact that all information and signals (of all types) are characterized by a finite speed of propagation.

According to this second (important) property of Nature, in fact, looking “far away in space” also means looking “back in time,” because the signals we receive from more and more distant sources have been emitted at increasingly remote epochs. If a galaxy is millions of light-years away from Earth, for instance, its light has been traveling for millions of years to get to us, and the information it can provide is referred to the epoch when the light left the galaxy—namely, to millions of years ago.¹

Because of the expansion of our Universe, on the other hand, looking back in time implies considering epochs in which matter and radiation were concentrated in increasingly smaller volumes of space, so that the temperature and the kinetic energy of their elementary components were higher and higher. Hence, the more remote is the signal which reaches us, the greater is the energy scale corresponding to the emission epoch.

¹The famous *Andromeda Galaxy*, whose picture is also used as a desktop background in recent versions of Mac computers, is one of the nearest galaxies, and is approximately 2.5 million light-years away from Earth (corresponding to a distance of about 2.4×10^{19} km).