NEUTRINO COSMOLOGY

The role that neutrinos have played in the evolution of the Universe is one of the most fascinating research areas that has stemmed from the interplays between cosmology, astrophysics and particle physics. In this self-contained book, the authors bring together all aspects of the role of neutrinos in cosmology, spanning from leptogenesis to primordial nucleosynthesis, and from their role in CMB and structure formation to the problem of their direct detection.

The book starts by guiding the reader through aspects of fundamental neutrino physics, the standard cosmological model and statistical mechanics in the expanding Universe, before discussing the history of neutrinos in chronological order from the very early stages until today. This timely book will interest graduate students and researchers in astrophysics, cosmology and particle physics, who work with either a theoretical or experimental focus.

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9781107013957

First published 2013

Printed and bound in the United Kingdom by the MPG Books Group

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data
Lesgourgues, Julien.
Neutrino cosmology / Julien Lesgourgues, École Polytechnique Federale de Lausanne (EPFL), Switzerland, CERN, Switzerland, CNRS – Universite de Savoie, France, Gianpiero Mangano, Istituto Nazionale di Fisica Nucleare (INFN), Italy, Gennaro Miele, University of Naples "Frederico II", Italy, Sergio Pastor, CSIC – Universitat de Valencia, Spain.
pages cm
Includes bibliographical references and index.
ISBN 978-1-107-01395-7 (hardback)
1. Neutrinos. 2. Neutrino astrophysics. 3. Cosmology. I. Mangano, Gianpiero. II. Miele, Gennaro. III. Pastor, Sergio. IV. Title.
QC793.5.N42L47 2013
539.7′215 – dc23 2012042364

ISBN 978-1-107-01395-7 Hardback

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Preface

To Arianna, Carmen, Isabelle, and María José

When neutrinos first came on the scene in 1930, their father, Wolfgang Pauli, confessed to his colleague, the astronomer Walter Baade, that to save energy conservation in β-decays (quoted in Hoyle, 1967),

I have done a terrible thing today, something which no theoretical physicist should ever do. I have suggested something that can never be verified experimentally.

This was perhaps the only time Pauli was mistaken. Less than 30 years later, neutrinos were discovered by Reines and Cowan.

Since then, we have learned so many things about neutrinos that Pauli himself would be very surprised. More than this, understanding neutrino properties has always brought new insights into the whole field of fundamental interactions, and new theoretical paradigms.

Today we know quite accurately how to describe their feeble interactions with matter, from the very first attempts of Fermi to the succesful Standard Model of electroweak interactions. Many pieces of information have been collected in laboratory experiments, the traditional setting of particle physics. The study of neutrino interactions has been pursued at accelerators and reactors and, more recently, by sending neutrino beams produced at accelerators to underground laboratories. Accelerator experiments have also confirmed that there are only three generations of light neutrinos which are weakly interacting.

The main breakthrough in neutrino physics over the last few decades came from a different environment: astrophysics. The solar neutrino problem – an observed deficit of neutrino flux from the sun – along with the atmospheric neutrino anomaly, has led to the discovery that neutrinos are massive particles. We do not understand their mass spectrum yet, nor why they are such light particles. On the experimental side, remarkable improvements are expected in the next few years, both in measuring the neutrino mass scale using tritium β-decay, and in understanding the real *nature* of neutrinos as Dirac or Majorana particles. At the same time, intense theoretical activity is going on, addressing the neutrino mass problem, which is seen as a possible clue to unveiling the behaviour of fundamental interactions at high energy scales.

The most spectacular property of neutrinos is deeply rooted in quantum mechanics. As first suggested by Bruno Pontecorvo, neutrinos exhibit oscillations among different flavours during their time evolution, leading to an incredibly rich phenomenology. The parameters characterizing this oscillatory behaviour are currently quite well known, because of the interplay of a variety of different experimental techniques and neutrino sources of both terrestrial and astrophysical origin. Just at the time of writing this book, the last missing piece of the puzzle, one of the neutrino mixing angles, was measured with good precision. No doubt neutrino oscillation physics will represent a leading research line in the coming years.

Since the early works on the synthesis of light nuclei in the Big Bang model in the late forties, it was clear that neutrinos are not simply passive spectators during the expansion of the universe. Through their weak interactions with other particles, as well as their *gravity*, they influence a wide variety of phenomena which took place in the early stages of the life of the universe, till very recent epochs. This means that using observations of astrophysical quantities, related to specific phases of the expansion history, we have a further way to constrain neutrino properties at different energy, time and length scales, which in some cases are not accessible to laboratory experiments. Just to give a few examples, some constraints on the number of light weakly interacting neutrinos and on their mass scale were obtained using observations of primordial ^{4}He and of the total energy density of the universe well before laboratory experiments could provide comparable information.

This vast arena in which to test neutrino properties is usually referred to as *neutrino cosmology*, and that is what this book is about. By its very nature, it is a multidisciplinary reasearch field, where the different expertises and backgrounds of theoretical and experimental particle physicists, astrophysicists and cosmologists find a meeting point and a common language. It is a branch of an even broader scientific activity, commonly called *astroparticle physics*, aimed at understanding fundamental interactions by exploiting observations of very large objects, such as astrophysical sources, or the universe as a whole.

In the last two decades, we have witnessed a big boost along this research line, due to outstanding improvements in the number and quality of astrophysical observations. Large galaxy surveys, detailed maps of the cosmic microwave background, observations of primordial nuclear abundances and new ways to trace the expansion history of the universe are just a few examples of this experimental effort. Whereas only 20 years ago neutrino cosmology was in its infancy, and theoretical physicists were typically satisfied by order-of-magnitude calculations made on the back of the envelope, the situation has changed rapidly since then. Observations currently require a much more detailed analysis, and provide several new tests of theoretical models.

This book is a summary of the history of the universe from a neutrino perspective. The first two chapters introduce the three important theoretical tools that will be widely used in the following: the basics of neutrino interactions and properties in the framework of the Standard Model of particle physics, the homogeneous and isotropic cosmological model, and some concepts of kinetic theory. We have done our best to present a pedagogical and self-contained discussion of these topics, and we are not sure that we have succeeded in this respect. Indeed, the subject of this book is intrinsically multidisciplinary, and covering all topics in a detailed and self-consistent manner – while keeping the number of pages reasonable – was a major challenge. Readers who are not familiar with, say, quantum field theory, general relativity, gauge issues in cosmology or the theory of inflation will need further reading in more specialized books or reviews. In any case, we tried at least to introduce all the concepts that are necessary for understanding the remaining chapters. We hope that this part may also trigger the reader's interest in further studying the topics he or she might be unfamiliar with. To this end, we give a long list of possible references.

The remaining chapters are devoted to different aspects of the role of neutrinos in cosmology, in *chronological order*, as they intervene in the evolution of the universe, from the very early stages till today. Chapter 3 addresses the issue of baryogenesis, the dynamical production of the baryon asymmetry observed in our universe, and in particular a scenario deeply related to neutrino properties, called leptogenesis. Chapter 4 deals with the dynamics of neutrino oscillations in a cosmological setting, and also with primordial nucleosynthesis, one of the main pillars of the cosmological model, providing a lot of information about neutrino physics. Chapter 5 explains the properties of cosmic microwave background anisotropies, which contain a huge quantity of information about the whole history of the universe, and shows how they are impacted by neutrinos. Chapter 6 describes the dynamics of structure formation on very large scales – those of galaxies, clusters, etc. – which is crucially affected by the abundance, mass and properties of neutrinos. Finally, Chapter 7 presents a summary of the methods which have been proposed so far to detect the relic neutrino background in the laboratory, and a brief discussion of the anisotropies that such detectors would see if they could ever become operational. As we will see, this is a very challenging task, the ultimate dream of a *neutrino cosmologist*.

In this book we will adopt the signature $(-+++)$, except in Chapters 1 and 4, which are more particle physics oriented, where we adopt the more widely used $(+---)$. Unless otherwise mentioned, we use natural units.

If we look into some of the available Web archives for scientific papers related to both neutrinos and cosmology, the query will return a number of publications of the order of several thousands. This gives an idea of how intense the activity is in this research field. In the following pages, the reader will not find a complete analysis of all possible models and ideas proposed so far. Some alternatives to the mainstream scenarios – sometimes extremely interesting and intriguing – have not been considered in our discussion, and are cited in our (rather long) list of references. We apologize for all omissions. However, in writing this book, our guideline has been to try to present the main physical aspects of the phenomena neutrinos are involved in, rather than to go through all their possible variations. In a sense, what we have mainly considered is a *standard* neutrino cosmology, describing what is currently well established on solid theoretical and experimental bases. We hope this might be helpful for students and researchers who are interested in approaching this fascinating research field, starting from different cultural backgrounds. If this ambitious goal is achieved even partially, we will be happy with our contribution to a process that is well on the way, namely, the emergence of a homogeneous community of theoretical and experimental particle physicists, cosmologists and astrophysicists.

This book is the result of the authors' friendship over many years. However, it would not have been written were not for enlightening discussions and collaborations with many of our colleagues. Several topics that the reader hopefully will find interesting in the following pages are the outcome of their work and enthusiasm, and of their sharing with us their knowledge and experience.

We warmly thank Benjamin Audren, Steve Blanchet, Diego Blas, Alexei Boyarski, Marco Cirelli, Gaëlle Giesen, Martin Hirsch, Michal Malinský, Oleg Ruchayskiy, Pasquale Serpico, Mikhail Shaposhnikov and Mariam Tórtola for reading a draft version of this book.

We are also very much indebted to Alfredo Cocco, Alexander Dolgov, Salvatore Esposito, Giuliana Fiorillo, Jan Hamann, Steen Hannestad, Steen Hansen, Fabio Iocco, Alessandro Melchiorri, Marcello Messina, Marco Peloso, Serguey Petcov, Massimo Pietroni, Ofelia Pisanti, Georg Raffelt, Antonio Riotto, Thomas Tram, José W.F. Valle, Matteo Viel and Yvonne Wong.

Matteo Viel and his collaborators Martin G. Haehnelt and Volker Springel deserve special thanks for allowing us to use their beautiful N-body simulations on the cover of this book.

We are also pleased to acknowledge the Cambridge University Press staff for their help and continuous support.

Our families have given the strongest support in this adventure. This book was written by many hands: those of Aitana, Apolline, Arianna, Carmen, Constance, Davide, Diane, Héctor, Isabelle, María José and Matteo.