Université Joseph Fourier

Les Houches

Session LXXXVII

2007

String Theory and the Real World:

From Particle Physics to Astrophysics

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ÉCOLE D'ÉTÉ DE PHYSIQUE DES HOUCHES

SESSION LXXXVII, 2 JULY–27 JULY 2007

ÉCOLE THÉMATIQUE DU CNRS

STRING THEORY AND THE REAL WORLD: FROM PARTICLE PHYSICS TO ASTROPHYSICS

Edited by

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ELSEVIER

Amsterdam – Boston – Heidelberg – London – New York – Oxford
Paris – San Diego – San Francisco – Singapore – Sydney – Tokyo

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, The Netherlands
Linacre House, Jordan Hill, Oxford OX2 8DP, UK

First edition 2008

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-0805-4813-5
ISSN: 0924-8099

Printed and bound in The Netherlands

07 08 09 10 11 10 9 8 7 6 5 4 3 2 1

ÉCOLE DE PHYSIQUE DES HOUCHES

Service inter-universitaire commun
à l'Université Joseph Fourier de Grenoble
et à l'Institut National Polytechnique de Grenoble

Subventionné par le Ministère de l'Éducation Nationale,
de l'Enseignement Supérieur et de la Recherche,
le Centre National de la Recherche Scientifique,
le Commissariat à l'Énergie Atomique

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- Session XI: Gordon and Breach, Presses Universitaires
- Sessions XII–XXV: Gordon and Breach
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- Session LXXIX–LXXXV: Elsevier

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Foreword

The summer of 2007 is a propitious moment in the history of physics. While the Standard Model, developed in the early 70's and largely confirmed by the end of the decade, remains the cornerstone of our understanding of particle physics, many believe its days are numbered.

Experiments to begin in 2008 at CERN will probe energies almost an order of magnitude beyond what we can reach today. Not only can we expect to discover the Higgs boson of the original Standard Model, there are compelling theoretical reasons to believe that far more novel physics is there, connected with the large ratio between the energy scales of electroweak symmetry breaking, and those of more fundamental physics such as gravity. This connection gives us hope that new discoveries will bear directly on levels of structure associated with far higher energies than we can probe directly.

Many, many speculations have been made about this new physics. Two of the best known are supersymmetry and large extra dimensions, and there are many others. These ideas now exist in a plethora of variations, giving rise to a rich subject of "Beyond the Standard Model" physics. But the moment of truth is approaching, when many of these speculations will be cut down to size.

Fortunately, the lack in recent years of striking new discoveries from particle physics, has been more than made up for by a wealth of new data from observational cosmology. Deep sky surveys, maps of the cosmic microwave background, and other developments have led to what many consider to be a "Standard Model of cosmology," the Λ CDM inflationary model. Inflation (and its competitors) gives us another window on physics at higher energies, and it is reasonable to hope that given new discoveries at LHC, some sort of grand synthesis between our two main (avenues of investigation) of fundamental physics will emerge.

Many physicists feel that the best hope for such a synthesis lies within string theory, arguably the grandest speculation of all. For decades, the problem of reconciling quantum mechanics and general relativity was considered unsolvable, a rock on which even Einstein foundered. The solution of this problem by string theory, and the general failure of other approaches, has led to a widespread belief that string theory must contain essential clues about fundamental physics. We can even imagine that string theory is the complete theory from which all the rest of physics will someday be derived.

For a variety of reasons, it has been very difficult to propose decisive tests which would settle this claim. Most importantly, almost all specific predictions of string theory depend crucially on which particular solution we consider. Since string theory is ten dimensional, modelling four dimensional physics requires choosing a six dimensional compactification manifold, as well as specific background fields and other structures on that manifold, and the number of possibilities is vast. The development of M theory and duality in the 1990's, far from solving this problem, has only enlarged the set of possibilities, and increased our confidence that this analysis of the situation is valid.

An apparent death blow to the hope of a unique preferred solution has been dealt by the compelling evidence of recent years that our universe contains dark energy, well modeled by a non-zero positive cosmological constant. At present there is only one generally accepted theoretical explanation for this, namely the anthropic argument of Weinberg, as realized in string theory by Bousso and Polchinski. This explanation depends crucially on having a vast number of vacuum configurations, certainly more than 10^{60}. More precise estimates suggest that there are at least 10^{500} distinct solutions, and forming any picture of the range of their possible predictions to guide us in testing the theory is a formidable challenge.

Nevertheless we must try. Might it happen that the upcoming experiments at LHC will cut the grand speculation of string theory down to size as well? Or might we discover evidence for strings, or other predictions of the theory? Or could indirect arguments, combining the evidence from particle physics, cosmology and elsewhere, somehow point to a particular class of solutions, which would then make predictions we could test in future experiments?

Or might we be better off making contact between string theory and more accessible physics, such as that of QCD and nuclear physics? Of course, this was the original inspiration for string theory, and recently great strides have been made in this direction, in part fueled by theoretical developments such as string-inspired techniques for perturbative computation as well as the celebrated AdS/CFT correspondence, and in part by developments in heavy ion collider physics, which has revealed surprising new collective behaviors of matter with simple models in terms of the new theoretical ideas. While the relevance of this for fundamental physics remains unclear, the historical progress of string theory came from considering a wide variety of possible applications, and this will surely continue.

This then, the contact between "String theory and the real world," was the theme of our school. Our general approach was "bottom-up", in that most of the lecturers tried to explain the known facts and prospects for discovery in some established area of particle or nuclear physics, or of astrophysics and cosmology, and then move towards the question of how string theory might make contact with these developments.

Let us begin with the lectures and seminars more closely related to particle and nuclear physics. The general topic of physics beyond the standard model was surveyed by John Ellis, who described both the capabilities of LHC and some of the more popular models for BSM physics. An in-depth description of LHC and its experiments was given by Fabiola Gianotti. Finally, Nigel Glover described the status of the perturbative QCD computations which will be necessary to interpret LHC data. This area has seen an influx of new ideas and techniques from string theory, and Glover's even-handed appraisal of the old and new techniques combined with his clear description of what was needed by experimentalists was of great value.

Several lecturers covered ideas for beyond the standard model (BSM) physics in detail. Perhaps the most popular class of BSM models postulate low energy supersymmetry. Supersymmetric phenomenology was covered in depth by Gian Giudice, while the question of how supersymmetry breaking arises from the dynamics of a theory was discussed by Ken Intriligator. Another popular class of models postulates observable consequences of the extra dimensions of string/M theory. This was capably surveyed by Ignatios Antoniadis.

Any contact between these more phenomenological ideas, and string/M theory, will necessarily involve detailed string model building. This is a large subject and rather than survey it all, we chose to provide in-depth lectures on a few of its better understood parts. Angel Uranga covered the subject of brane constructions of the Standard Model in type II superstring theory. Elias Kiritsis discussed similar issues using the very different techniques of CFT and Gepner models.

Frederik Denef described flux compactification and moduli stabilization, and how its study has led to the current picture of the string landscape. Michael Douglas raised various general questions about the landscape whose better understanding might lead to significant progress.

Finally, the study of gauge/gravity duality, particularly, the AdS/CFT correspondence, has led to important technical developments in nonperturbative gauge theory, which may have important applications to QCD. Igor Klebanov introduced and reviewed this general subject, surveying most of the developments of recent years and covering his work on models of confinement in detail. Juan Maldacena added to this with a lecture on recent developments in finding an integrable sector within $N = 4$ super Yang–Mills theory.

A particularly interesting recent development is the suggestion that the collective phenomena seen in heavy ion collisions at RHIC, and to be studied at LHC as well, can be modeled using AdS/CFT techniques. This area was described by Urs Wiedemann, starting with the original experimental discoveries, and explaining the arguments according to which these indicate novel collective phenomena, before going into the recent theoretical developments.

We now turn to lectures primarily focusing on astrophysics and cosmology. Juan Maldacena began his lectures with an introduction to inflationary cosmology, and a detailed explanation of how to compute the spectrum of fluctuations in the cosmic microwave background. He went on to explain nongaussianity, which led into a discussion of what a speculative "de Sitter/CFT" duality would look like. Finally he discussed how inflation might arise in string models.

Steve Shenker's lectures covered inflation at a more conceptual level. The primary goal was to explain the many confusing issues surrounding the notion of "eternal inflation," which is a central part of arguments for the string theory landscape. He concluded with a survey of proposals for the measure factor in cosmology.

Nima Arkani-Hamed described anthropic considerations at length. He then explained recent work on the limits of effective field theory in cosmology. Eliezer Rabinovici described the possible role of broken scale invariance in solving the cosmological constant problem. Jose Barbón discussed topology change in spacetime is related the Hagedorn regime in critical string theories using the string/black hole correspondence principle. Pierre Vanhove described the recent progresses in the analysis of the ultra-violet behaviour of maximally extended supergravities and reviewed the dualities arguments indicating that such quantum field theories of gravity could be perturbatively finite in four dimensions. Laurent Baulieu described new techniques for handling the off-shell properties of super-Yang–Mills theories.

Finally, Thibault Damour began with a detailed explanation of the membrane description of black hole horizons, which has found recent application in AdS/CFT computations of collective phenomena. He then surveyed the present status of experimental tests of general relativity. He concluded by explaining how primordial cosmic strings might be detected at gravitational wave observatories, perhaps leading to direct evidence for fundamental string theory.

Only time will tell which if any of these ideas will find experimental support. Perhaps, in a few years, many of the specific proposals we discussed at the school will seem irrelevant, or naive. If even one hits the mark squarely, we will have reason to celebrate. But whatever their fate, we suspect that the fundamental ideas behind them will retain their interest, and we hope these lectures will guide our students and readers to meet the coming challenges and contribute in their turn.

We would like to thank Giora Mikenberg as well as other members of the ATLAS collaboration for having allowed the students of this school to visit the ATLAS detector, which is an essential part of the experimental apparatus of the LHC campaign. We wish to address our warmest thanks to our main Sponsor, the European Science Foundation, which has agreed to fund a series of summer schools in theoretical physics linked to elementary particles, astroparticles and cosmology. We also thank the Bureau de la formation permanente du CNRS and the Les Houches summer school for their financial support. We are grateful to Brigitte Rousset and Isabelle Lelièvre for their invaluable help with the local organisation of the school.

Paris, 2008

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