HOLOGRAPHIC DUALITY IN CONDENSED MATTER PHYSICS

This pioneering treatise presents how the new mathematical techniques of holographic duality unify seemingly unrelated fields of physics. Morphing quantum field theory, general relativity and the renormalisation group into a single computational framework, this book is the first to bring together a wide range of research in this rapidly developing field. Set within the context of condensed matter physics and using boxes highlighting the specific techniques required, it examines the holographic description of thermal properties of matter, Fermi liquids and superconductors, and hitherto unknown forms of macroscopically entangled quantum matter in terms of general relativity, stars and black holes.

Showing that holographic duality can succeed where classic mathematical approaches fail, this text provides a thorough overview of this major breakthrough at the heart of modern physics. The inclusion of extensive introductory material using non-technical language and online Mathematica notebooks ensures the appeal to students and researchers alike.

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Preface

Not so long ago, two large and quite old fields in physics, string theory and condensed matter physics, were more or less at the opposite ends of the physics building. During the 40 or so years of its history, string theory has developed into a high art of "mathematical machine building", propelled forwards by the internal powers of mathematics as inspired by physics. Yet, it has suffered greatly for the shortcoming that its theoretical answers are always beyond the reach of experimental machinery. Modern condensed matter physics is in the opposite corner. It has been propelled forwards by continuously improving experiments, which have delivered one serendipitous discovery after another during the last few decades. However, its interpretational framework rests by and large on equations developed 40 years or so ago. There has been an increasing sense that it is these that fall short in trying to explain the strongly interacting quantum many-body systems as realised by electrons in high-T_c superconductors and other unconventional materials.

All this changed dramatically in 2007 when physicists started to feed condensed matter questions to the most powerful mathematical machine of string theory: the holographic duality in the title of the book, also known as the "anti-de Sitter/conformal field theory" (AdS/CFT) correspondence. This book introduces the explosion of answers that has followed since then.

The first (Jan) and last (Koenraad) of this book's authors are from such opposite corners. As soon as the seminal work of Herzog, Kovtun, Sachdev and Son in 2007 showed that these two subjects have dealings with each other, Jan and Koenraad recognised the potential and met up, almost literally half-way up the stairs. As has been characteristic for the development at large, it took us remarkably little effort to get on speaking terms, despite our superficially very different backgrounds. Shrouded by differences in language, string theory and condensed matter had already been on a collision course for a while, meeting each other on the common ground of quantum criticality/conformal field theory. In the years that

followed this dialogue only intensified and the upbeat tone of this book is a testimony of the great time we had together. The largest part of that time was shared with the two middle authors (Ya-Wen and Yan), who came to Leiden as postdocs in 2010, freshly graduated from the Chinese Academy of Science in Beijing. The seeds for this book were planted when Jan received the invitation to become the 2012 Solvay Professor in Brussels, with the request to organise an AdS/condensed-matter-theory lecture course. What you see before you grew from the notes of this course, joined together with lecture notes by Koenraad at the 2012 Cargèse and 2013 Crete schools.

This is an incredibly fast-moving field, and many pages had to be added to describe the developments that happened since the summer of 2012. In January 2014 we stopped playing catch up, and we decided to get it out as quickly as possible, given the high demand for such a text at this moment. The first nine months of 2014 turned into a writing frenzy for all of us, and the result is lying in front of you. We are well aware that in certain regards the book therefore has its limitations and that the text will already be obsolete as soon as it appears. Examples of significant developments that occurred since our cut-off are a holographically inspired theory of incoherent metals[1] and a holographic solution of the anomalous temperature scaling of the Hall angle as observed in high-T_c superconductors.[2] Nor do we claim this to be a comprehensive review that does justice to all of the papers which have been published on the subject. What we have done is to provide an introduction to serve a non-expert readership that wishes to be informed about the main developments. Our aim has been to catch the mainstream, those developments where one discerns a consensus in the expert community that these are the most significant accomplishments. As authors we found it quite obvious how to make this selection and we sincerely believe that our choices will be approved by the AdS/CMT experts. We felt that we just had the role of humble narrators working on the chronicles of a monumental physics odyssey. We wish to take you on board and we hope you will enjoy it as much as we do!

We are in the first instance indebted to numerous holographists who contributed to our understanding of the correspondence. We are particularly grateful to Andrea Amoretti, Steffen Klug, Richard Davison, Andrey Bagrov, Petter Sæterskog and Balázs Meszéna for their thorough proofreading of the manuscripts and their many helpful suggestions, and to Mihael Petač for his help on the figures. Both the Leiden and Madrid physics departments gave us all the room to concentrate on the writing of this book. We acknowledge financial support of various funding organisations, in particular the Solvay Foundation and the Dutch Foundation of Fundamental

[1] S. Hartnoll, *Nature Phys.* **11**, 54 (2015), arXiv:1405.3651.
[2] M. Blake, A. Donos, *Phys. Rev. Lett.* **114**, 021601 (2015), arXiv:1406.1659.

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