

**Final report programme**  
**"Mathematics and Physics of the Holographic Principle"**  
**16 September - 11 October 2013**

*Organisers: Antonio García-García (Cambridge), Hong Liu (MIT) and Jan Zaanen (Leiden).*

This four week programme has brought together more than one hundred fifty researchers with a broad spectrum of expertises and a common interest in holography. Overall it has been strikingly successful in shaping and moving forward this emerging research field.

Holographic duality (also called gauge/gravity duality or the AdS/CFT correspondence) relates a string theory — i.e. a quantum theory of gravity — to a strongly interacting quantum field theory without gravity. Information about the strongly coupled field theory is obtained by solving the equations of classical Einstein gravity with appropriate matter content. The versatility and generality of the holographic principle prompted many applications outside the realm of string theory, first in the context of the quark-gluon plasma physics and more recently in condensed matter and statistical physics. Although it is still heavily dominated by string theorists it is rapidly becoming a forefront research field located at the confluence of previously seemingly distant fields including superconductivity and other exotic phases of strongly coupled quantum matter in and out of equilibrium, numerical relativity and the theory of partial differential equations.

The programme has attracted experts in these diverse fields in order to reach a critical mass of knowledge and skills that help establish holographic duality as a powerful mainstream tool to tackle problems for which the traditional methods within each discipline have proved inadequate to address. We have put a special emphasis in stimulating cross-fertilization between experts in far from equilibrium dynamics, and quantum information, and classical gravity and numerical relativity communities. We have also aimed to find a common ground to turn predictions of the holographic principle into quantitative descriptions of realistic strongly interacting systems in condensed matter and related disciplines.

The launching event, the workshop "Holography: From Gravity to Quantum Matter", was a possibly unprecedented meeting point of not only the most reputed AdS/CFT practitioners, for instance Steve Gubser and Gary Horowitz, but also leading researchers in condensed matter theory, such as Subir Sachdev, and numerical relativity such as Frans Pretorius. The inclusion of outsiders from experimental condensed matter (Gaby Aeppli), cold atom (Gasenzer), quantum information (Verstraete) further stimulated innovation and pushed the boundaries of the field. Indeed, during the programme such cross-field fertilization has already provided new insights and in some cases tantalizing preliminary progress. Although many international gatherings dealing with this theme have been organized recently, it was a consensus among the participants that this Newton Institute programme outpaced them all with regard to the breakthrough atmosphere.

We highlight a few of the most relevant contributions:

The talks by Horowitz and Vegh, among others, reported substantial progress made in tailoring holographic strange metals to become more realistic by including the background ionic lattice, encountered by the electrons when they move through the solid. Such a lattice influences strongly the transport properties of strange metals and the first results are very promising. Initially it was felt that the holographic strange metals were merely useful metaphors to learn to think differently regarding the laboratory versions. However these new results reported in the programme are getting so close to reality that it is no

longer far fetched to think that a quantitative holographic description of strange metals is on the way.

Paul Chesler reported for the first time on his recent breakthrough, published in Science, about a holographic description of full developed superfluid turbulence, including Kolmogorov 5/3 law. Remarkably the calculation in the gravity dual is more stable and requires much less computer resources. It was found that remarkably the fractal turbulence of the boundary fluid imprints in the form of a black hole event horizon turning it into a fractal manifold!

One of the main research themes during the programme was the far from equilibrium evolution of strongly interacting systems. This is a hot topic in condensed matter as it has become possible to measure experimentally the time evolution after a quench and, in some cases, its eventual relaxation to equilibrium. Holography is especially relevant in this problem as there are no other methods to extract quantitative results in the far from equilibrium regime. We highlight the talk by Bizon, a leading expert in numerical relativity, who found that, in general, a perturbation in an AdS background leads to the formation of a black hole. In the field theory dual this implies that a quantum quench always leads to full thermalization for sufficiently long times. The discussion about whether there are exceptions to this result for some initial conditions led to some of the liveliest exchanges, involving from condensed matter theorists to experts in partial differential equations, of the programme.

Also with substantial impact potential was the research presented by Roberto Emparan on the application of the holographic duality to high dimensional field theories by a systematic expansion in the inverse of the spatial dimensionality. In condensed matter it is well known that this approximation is usually a fair description of the 3+1 dimension case but with the advantage that analytical results are available. It seems that the general relativity and string theory communities were not aware of these condensed matter results.

Veronika Hubeny, from Durham University, presentation about a novel prescription to compute entanglement entropy was very well received. It has implications for future holographic applications to quantum information.

Contributions by Peter Littlewood, former head of the Cavendish Laboratory, on polaritons and excitons, Warnick on stability conditions of partial differential equations in AdS spaces, and Verstraete on quantum information offered intriguing research lines with the potential to open new research themes for holographic dualities.

According to informal discussions, and the written questionnaires received from participants, the programme helped establish multiple collaborations, specially in the topics mentioned above, and open new research lines for many of the participants.

We also want to highlight the firm commitment of the programme with the training of PhD students and the promotion of the local UK community. About thirty PhD students, most of them based in UK, have received financial help to participate in the programme. It has been a unique opportunity for them to interact with research leaders and experience the excitement of an emerging field of research. Most of UK senior researchers interested in holography have not only participated in the programme but also were given the opportunity to give a talk on his most recent research results. The programme has been an important stimulus to raise the profile of this field in UK and help establish long term collaborations with scientists abroad.