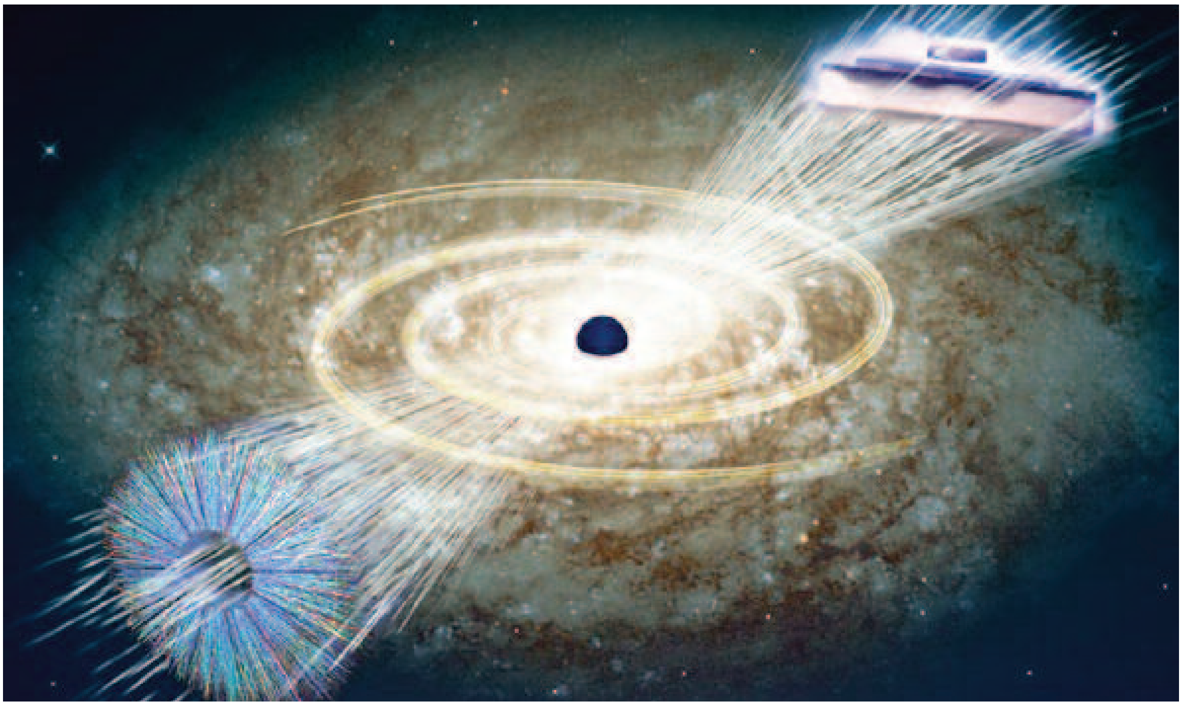
Holographic Duality: How Black Holes Illuminate Intractable Problems

Holographic duality (or the AdS/CFT correspondence), originally proposed by Maldacena in 1998, is arguably the most important theoretical development in physics in the past decade. Originally discovered in string theory, it has since been rolled out over much of modern fundamental physics with the goal of shedding light on strongly interacting many-body systems. It has yielded new insights in a wide variety of subjects, from general relativity to hydrodynamics. A high profile example was the description of transport properties of the quark-gluon plasma, one of the main motivations of the experimental program in the Large Hadron Collider and previously in the Relativistic Heavy Ion Collider. Results from the holographic principle, though semi-quantitative (the holographic dual of quantum chromodynamics is not yet known), are particularly valuable because this problem cannot be tackled by any other technique.

The 2013 *Mathematics and Physics of the Holographic Principle* (HOL) programme at the Isaac Newton Institute was conceived to exploit recent developments in this exciting field. It attracted an unusually diverse group, including general relativity experts, high energy and nuclear physicists, condensed matter and cold atom



physicists, quantum information specialists and leading string theorists. Many people from these different communities found, for the first time, that they shared common ground.

Holographic duality amounts to a mathematically precise, but indirect, relation between a gravitating universe ruled by Einstein's theory of general relativity (the "bulk") and a non-gravitational world in which the behaviour of matter in its most general sense is described by a theory of quantum fields (the "boundary"). This works somewhat like the holograms found in theme parks: the boundary is like a photographic plate with interference fringes (field theory), that produces a three dimensional figure (gravitational bulk) when laser light shines through it (the "duality").

One of the earliest entries in the holographic dictionary was a record of the realisation that black holes in the bulk correspond to heating up the boundary quantum matter. This is closely related to Hawking's famous discovery that black holes emit hot radiation. Similarly, electronically charging up the black hole in the bulk corresponds to adding a finite density of matter at the boundary. But the story does not stop there. One of the surprise results of holographic research is that the rich variety of behaviour exhibited by quantum matter is mirrored in a rich phase diagram of black holes.

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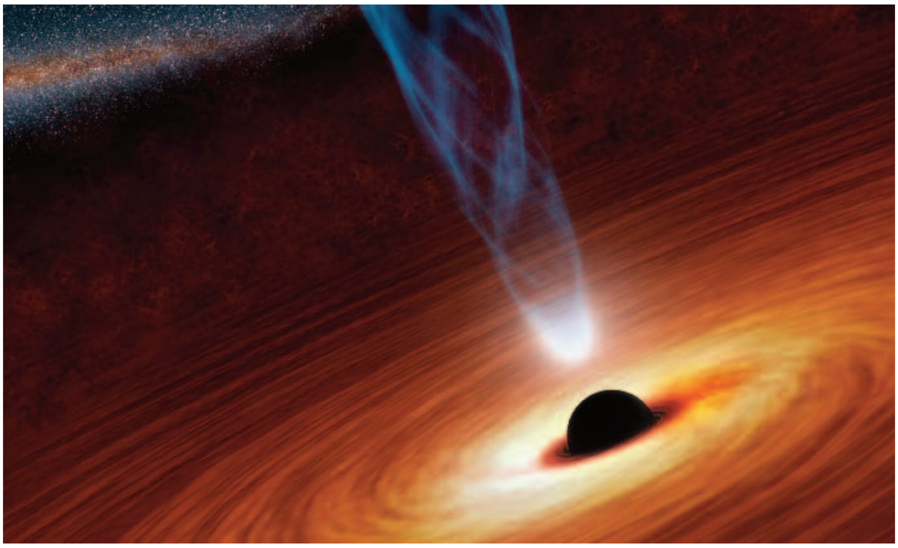

A good application from the subject of fluid dynamics was discussed at the opening HOL workshop when Paul Chesler (MIT) reported for the first time on his recent breakthrough, published in Science [1], with his colleagues Allan Adams and Hong Liu (also a participant on the HOL programme). Normal liquids, described by the 19th century hydrodynamic theories of Navier and Stokes, famously exhibit both tranquil and turbulent flows. Many aspects of turbulence are still poorly understood but it is widely accepted that typical patterns of vortices form and "cascade" to smaller and smaller scales without changing their average appearance. Such scale invariant patterns have the peculiar property of a fractal geometry: they "fill up" space more than the topological dimensions of space itself. By mapping the dynamics of a strongly interacting quantum liquid into the dynamics of classical gravity, Chesler, Adams and Liu were able numerically to construct turbulent flows in a holographic superfluid in two spatial dimensions. They showed that the superfluid kinetic energy spectrum obeys the Kolmogorov 5/3 Scaling Law and found that the fractal turbulence of the boundary fluid imprints in the form of a black hole event horizon turning it into a fractal manifold. The calculation in the gravity dual turned out to be more stable and required less computing resources.

Strange metals were another hot topic for the HOL programme and programme participants Gary Horowitz (University of California, Santa Barbara) and David Vegh (CERN) reported substantial progress in tailoring holographic models of strange metals to become more realistic by including the background ionic lattice encountered by the electrons when they move through the solid. New results reported in the programme are getting so close to reality that it appears that a quantitative holographic description of strange metals is within reach.

Holography is a powerful tool for classifying and describing a broad class of states of matter in the form of "black hole holograms". At the risk of mixing optical metaphors, holography provides a remarkable lens through which one can see more clearly many developments of modern physics.

Prepared with the assistance of David Tong (Cambridge) and Jan Zaanen (Leiden), organiser of the HOL programme.

References

[1] Chesler, P.M., Liu, H. and Adams, A. (2013) 'Holographic vortex liquids and superfluid turbulence', *Science.* Vol 341, no 6144, pp. 368-372.

For more information on the HOL programme see **www.newton.ac.uk/programmes/HOL/**

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