

THEORETICAL PHYSICS

A black hole full of answers

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A facet of string theory, the currently favoured route to a 'theory of everything', might help to explain some properties of exotic matter phases — such as those of the quantum liquids of high-temperature superconductors.

How are heat and charge transported within a high-temperature superconductor? And what happens when heavy nuclei are torn apart to make the soup of elementary particles known as a quark–gluon plasma? In a paper published on the *arXiv* preprint server, Hartnoll *et al.*¹ show convincingly that the easiest insight into the superconductor problem, just as into the quark–gluon plasma^{2,3}, is to be had by looking at a black hole. Not any old black hole, of course, but a black hole in a negatively curved space-time with an extra dimension.

What might sound like a theoretical physicist's idea of a bad joke could, in fact, be history in the making. The context is a highlight of string theory known as the 'anti-de-Sitter space/conformal field theory' correspondence⁴ — AdS–CFT for short — which demonstrates an intimate connection between Einstein's general theory of relativity and quantum physics. That it might also find use in such far-flung fields as superconductivity and the quark–gluon plasma is the stuff of physicists' dreams — the unifying power of physical laws as formulated in the language of mathematics.

Viewed as a whole, string theory amounts to a head-on attack on the incompatibility of general relativity and quantum theory, the two greatest accomplishments of twentieth-century physics. According to general relativity, space and time are dynamical entities, linked to matter and energy. By contrast, quantum physics tells us how matter and energy behave, but can only be formulated in a frozen space-time.

String theory is a collection of mathematical discoveries that might just offer a solution to this puzzle. But it has had a bad press of late. This is in part because its 40-year history is littered with claims that, if only we would stick to its true path of enlightenment, the answers to the big questions of physics would be just around the corner. Its failure to deliver on those promises and produce, so far, anything of con-

sequence to experiment has become rather an embarrassment.

The AdS–CFT correspondence is a case in point. It is a fascinating mathematical result, uncovered by the Argentinian physicist Juan Martín Maldacena in 1997, but had seemed unrelated to anything that happens in or outside the laboratory. The correspondence predicts a universe governed solely by gravity, being in this regard rather like ours, with stars, black holes and all the other familiar trappings. The difference is that it has an extra, fourth spatial dimension (plus the normal one time dimension) and a negative (anti-de-Sitter) overall curvature, so forming a universe closed in on itself.

As it turns out, this world corresponds precisely to a non-gravitating universe of just three spatial dimensions filled with something similar to the quantum fields that describe the elementary particles in the standard model of particle physics. Thus, general relativity and quantum-field theory seem to be embedded deep inside the same structure. But try as they might, string theorists have not been able to find an AdS–CFT-like theory that impinges directly on the world we live in. Until now, that is.

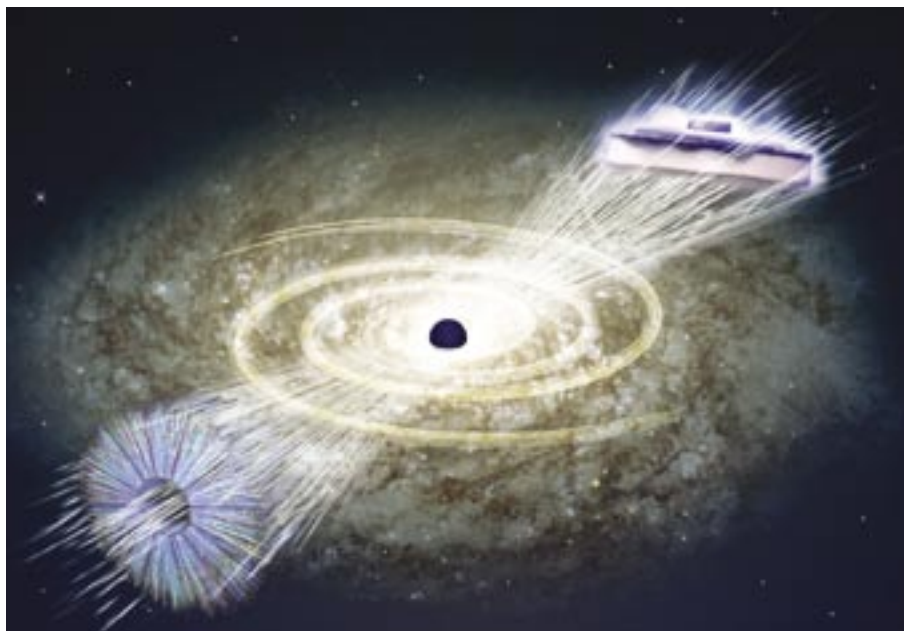
Hartnoll *et al.*¹ use the AdS–CFT correspondence to illuminate the real-life problem of how heat and charge currents flow in a 'quantum liquid' of electrons. These quantum liquids are found in the metallic state of copper-oxide (cuprate) superconductors above the transition temperature below which they become superconducting (which is generally around 100 kelvin). In terms of quantum mechanics, they are strange beasts. Somehow, the electrons manage to organize themselves in a quantum critical state, meaning that their collective quantum physics becomes scale-invariant — it looks the same, regardless of the time- and length-scales over which one observes the system⁵. High-temperature superconductivity below the

transition temperature is commonly believed to have to something to do with this enigmatic, normally conducting state in which quantum and thermal fluctuations merge.

Although they are in all other regards vastly different, the quantum fields that pop up in the AdS–CFT correspondence share the quantum-critical (or ‘conformal’, the C in CFT) property with this quantum-thermal brew. The scale invariance they share is a mighty principle; in fact, it is so powerful that the many differences between the two types of field don’t matter. It was thus shown in 2001 that at energies small compared with the temperature, the transport properties of a substance containing a conformal quantum field relate mathematically through the AdS–CFT correspondence to the geometry of a black hole in anti-de-Sitter space². This makes it possible to derive the equations describing transport in the quantum-thermal critical brew in a few easy lines, instead of the pages of algebra that one encounters in the direct evaluation of quantum field theory of the type that one encounters, for example, in superconductivity⁶.

Hartnoll *et al.*¹ push what one might term the ‘AdS-to-high- T_c correspondence’ to its logical conclusion. They study its application to a particular, rather recondite transport phenomenon known as the Nernst effect — the crosswise flow of heat and charge currents in the presence of a magnetic field⁷ — in the nearly quantum-critical matter of a two-dimensional cuprate system. In a theoretical *tour de force*, they use the physics of a black hole in a three-dimensional anti-de-Sitter space that carries both electrical and magnetic charge to guide them in the very complex derivation of the relevant transport equations directly from quantum field theory. They show that these theoretical results are seemingly consistent with a number of hitherto unexplained features of the Nernst effect in a high-temperature superconductor⁷.

So where does the quark–gluon plasma fit in? Here, the AdS–CFT correspondence comes to the aid of the experimentalists in a similar



The answer's out there. The easiest path to enlightenment on the mysterious phenomena of superconduction (levitating magnets; top) and the quark–gluon plasma (bottom; an event display from the Relativistic Heavy-Ion Collider RHIC at Brookhaven National Laboratory in New York) leads through a black hole, say Hartnoll and colleagues¹.

way³. The background is the observation that the quark–gluon fireballs created in the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island behave in a remarkably simple way, but one that current theories find difficult to explain — they are governed by normal hydrodynamics, but have extremely low viscosity. Quite simply, the AdS–CFT correspondence tells us that when the quantum physics is scale invariant, the viscosity of such a system can be that small. This result is far from obvious given our current understanding of quantum chromodynamics, the standard-model quantum-field theory of the strong nuclear force that governs interactions in the quark–gluon plasma.

So what does this mean for the greater ambition of using string theory to unite gravity and quantum physics? I take the discovery that

black holes are so useful for sorting out the behaviour of real-life quantum systems as a signal that string theory might somehow be on the right track. But only further work like that of Hartnoll *et al.*¹ will confirm that hunch. ■

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1. Hartnoll, S. A., Kovtun, P. K., Mueller, M. & Sachdev, S. Preprint at <<http://arxiv.org/abs/0706.3215>> (2007).
2. Policastro, G., Son, D. T. & Starinets, A. O. *Phys. Rev. Lett.* **87**, 081601 (2001).
3. Riordan, M. & Zajc, W. A. *Sci. Am.* **294** (5), 24–31 (2006).
4. Maldacena, J. *Sci. Am.* **293** (5), 33–39 (2005).
5. van der Marel, D. *et al. Nature* **425**, 271–274 (2003).
6. Herzog, C. P., Kovtun, P., Sachdev, S. & Son, D. T. *Phys. Rev. D* **75**, 085020 (2007).
7. Wang, Y., Li, L. & Ong, N. P. *Phys. Rev. B* **73**, 024510 (2006).