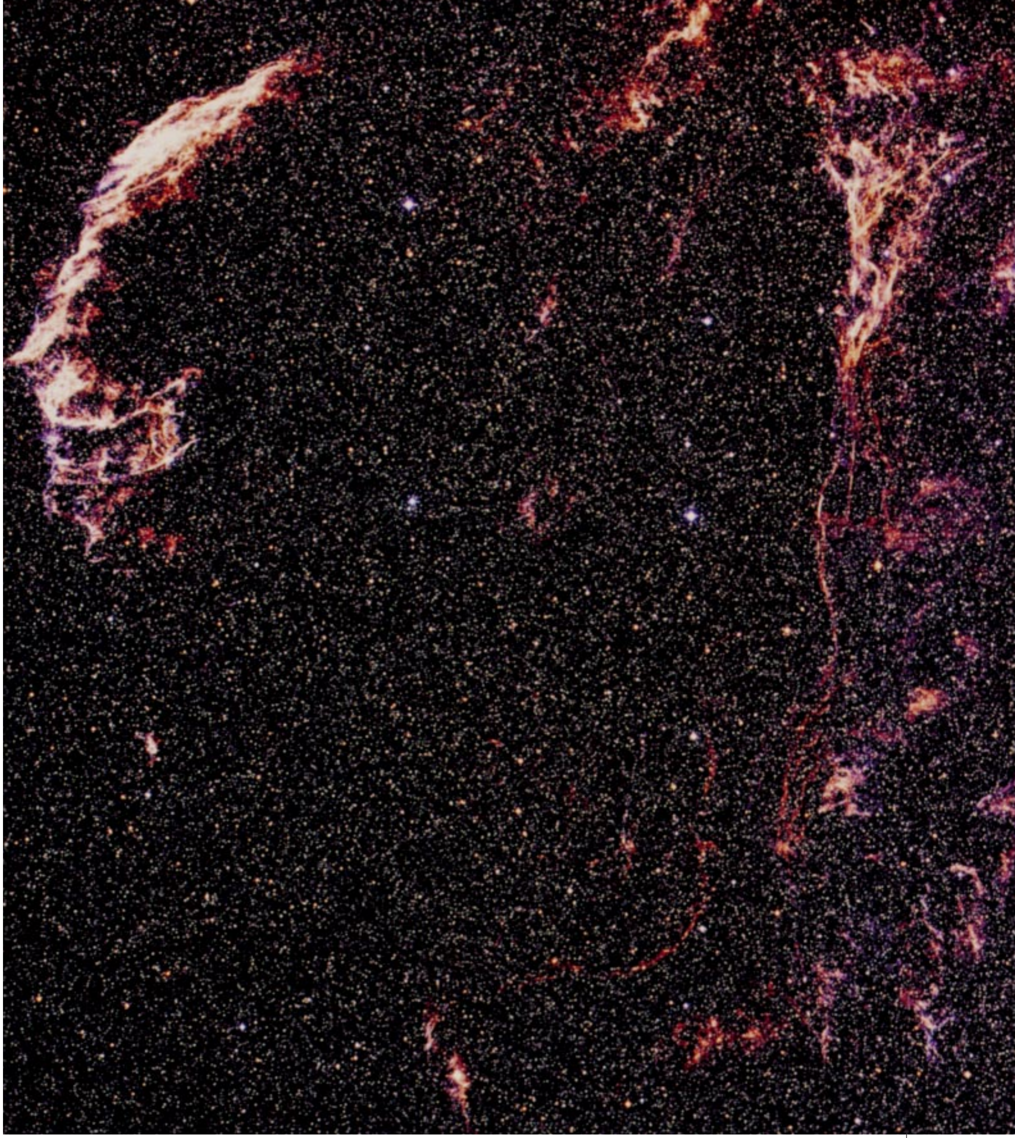
Tabletop astrophysics

Can a bowlful of cold atoms help physicists simulate some of the most extreme conditions in the Universe? Philip Ball goes on the trail of the laboratory-scale black hole.



Out with a bang: the explosion of a supernova, the remnants of which are seen here, could be modelled in the lab using very cold atoms.

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A new chapter has been added to the physics cook book. The recipes may be simple — take a gas of atoms, cool and stir — but the dishes that should result could hardly be more surprising: miniature black holes, white dwarfs and supernovae.

Key to this culinary magic is a strange state of matter that only exists in laboratories, known as a Bose–Einstein condensate (BEC). In 1995, when this state was first seen in a gas of cold atoms[1] — over 70 years after BECs were predicted to exist[2] — it caused a storm in the world of fundamental physics. But outside this arena, observers could be forgiven for asking what these strange condensates could be used for.

In recent months, an answer may have been found. Physicists have shown that BECs can mimic some of the properties of collapsing and exploding stars. So in much the same way that ripples on water can be used to study the properties of light waves, BECs might offer a way to bring extreme astrophysics into the lab.

All together now

BECs get their name from physicists Satyendra Nath Bose and Albert Einstein. In 1924, Einstein built on work by Bose to predict the existence of the condensates[2]. They have their roots in quantum mechanics, the physical theory of the microscopic world. In quantum theory each particle exists in a particular 'quantum state', which defines, for example, the particle's energy.

But when it comes to sharing quantum states, some particles are more friendly than others. All particles are divided into two types: fermions and bosons. Fermions are distinctly antisocial: they refuse to gather together in the same quantum state. Bosons, on the other hand, are remarkably gregarious, and it is this sociable nature that ultimately gives rise to a BEC.

These models may be the best chance of recreating dying stars in the lab.

Normally, thermal energy gives bosons a range of different energies and distributes them among different quantum states. Einstein showed that at low enough temperatures, there is no limit to the number of bosons that can exist in the same state. In other words, if you cool a group of bosons down sufficiently, they will all crowd into the lowest energy state. Quantum mechanics says that particles in the same state behave as a single particle, so the cooled crowd of bosons acts like a single collective particle — a BEC, sometimes described as a 'superatom'.

A little over a decade later, Einstein's predictions were invoked to explain the unusual behaviour of cold helium atoms. In 1938, Soviet physicist Pyotr Kapitza found that liquid helium lost all its viscosity when cooled to 2 kelvin — if you set it moving in a flask it would swirl around for ever[3]. Such liquids were later christened 'superfluids'. Just months later, German physicist Fritz London showed that Kapitza's discovery could be explained by assuming that the helium atoms — which are bosons — had condensed into the same quantum state[4]. Unknowingly, Kapitza had created a BEC.

But BEC research did not really take off until 1995, when Carl Wieman and his colleagues at the University of Colorado at Boulder managed to create a BEC from gaseous atoms. They used new laser-cooling technology to coax a low-pressure gas of rubidium atoms to close to absolute zero and into a BEC[1]. The rubidium atoms remain as a gas throughout the transition to a BEC, making the process easier to study than in liquid helium. Wieman's experiment was soon duplicated in laboratories around the world as fundamental physicists rushed to explore this unusual form of matter.

BECs do not exist outside the laboratory — even interstellar space is too warm for them. So are they nothing more than interesting oddities? At the beginning of last year, Ulf Leonhardt at the University of St Andrews in Scotland and Paul Piwnicki of the Royal Institute of Technology in Stockholm, Sweden, argued otherwise. They pointed out that a BEC could, under the right conditions, start to behave like a black hole[5].

Black holes are the remnants of old and massive stars. As a star ages, the pressure generated by the nuclear reactions at its centre diminishes, and it eventually collapses inwards under its own gravity. The collapse can result in spectacular explosions known as supernovae, which leave behind a dense core of matter. If the original star was five or six times larger than the Sun, this remaining matter becomes concentrated at a single point. This point, and the area around it, is called a black hole.

Once formed, black holes have a voracious appetite. They use gravitational attraction to suck in anything that strays closer than a certain critical distance — called the event horizon. Even passing beams of light are devoured if they get too close. Some astrophysicists compare this effect to a whirlpool sucking in fish. The speed of the water is greater closer to the centre of the whirlpool. If a fish gets too near, and enters an area where the water speed is faster than the fish can move, it will be sucked inwards.

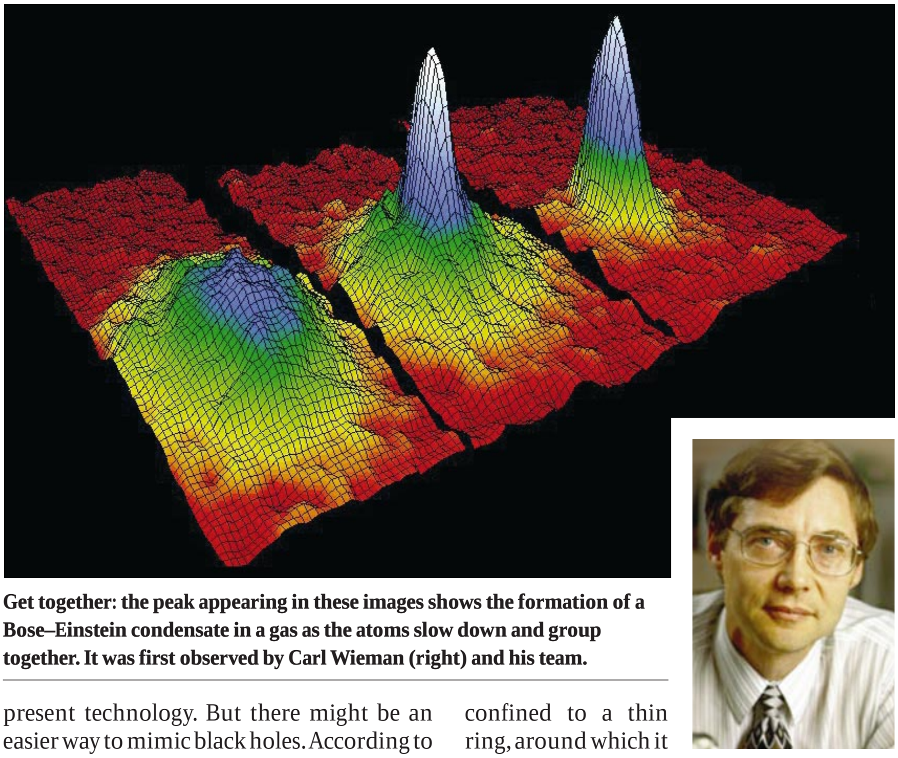
Spinning against the tide

In principle, black holes could be simulated by passing light close to a whirlpool of gas. If the centre of the whirlpool was moving faster than light, the light would be sucked inwards like the unfortunate fish. But creating a whirlpool that moves faster than the speed of light is a tall order. Unless, that is, light can be slowed down. And, over the past two years, physicists have managed to do just that using BECs.

In 1999, Lene Hau and her colleagues at the Rowland Institute for Science in Cambridge, Massachusetts, manipulated a cold vapour of sodium ions to form a BEC that slowed light to a trifling 17 metres per second[6]. Hau's group and, independently, Ronald Walsworth and his colleagues at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, have since brought light to a complete halt[7,8].

Leonhardt and Piwnicki suggested that if light was moving slowly enough, it could become trapped in a whirlpool within a BEC[5]. At a certain distance from the centre of the vortex, analogous to a black hole's event horizon, the light would circulate inexorably inwards. The swirling gas would become an optical black hole.

So far, no group has attempted to do the experiment Leonhardt and Piwnicki suggest. Ordinary BECs are difficult enough to create and maintain. The challenge of engineering one with a whirlpool in the middle is beyond present technology. But there might be an easier way to mimic black holes. According to a team led by Ignacio Cirac and Peter Zoller of the University of Innsbruck in Austria, sound, instead of light, could be used to model black holes in a BEC[9].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Get together: the peak appearing in these images shows the formation of a Bose–Einstein condensate in a gas as the atoms slow down and group together. It was first observed by Carl Wieman (right) and his team.

This 'sonic black hole' is similar to Leonhardt and Piwnicki's plan — a BEC is stirred to create a vortex that is moving faster than the speed of sound, trapping sound waves in the system. Because the BEC's bosons behave as a single particle, the swirling condensate does not contain any areas of turbulence that could obscure the effects physicists are looking for.

But stirring a BEC into a whirlpool is not easy. If the BEC is continually spiralling inwards, there must be some outlet that, like a plughole, removes atoms at the centre. This is hard to achieve, so Cirac and Zoller propose a different arrangement. The BEC is confined to a thin ring, around which it flows continuously. But one segment of the ring is thinner that the rest. The BEC is forced to speed up as it passes through the constriction into the thin part, accelerating it to supersonic speeds. The constriction is the sonic black hole's event horizon — sound passing this point cannot escape back out of the thinner area.

Zoller and his colleagues say that creating such a situation in a BEC is a delicate matter, but not impossible. "We believe that it may be carried out with present or near-future technology," says team member Luis Garay of the Institute of Mathematics and Fundamental Physics, an interdisciplinary research centre in Madrid run by Spain's national research council (CSIC).

BECs could also be used to study supernovae themselves, rather than the black holes

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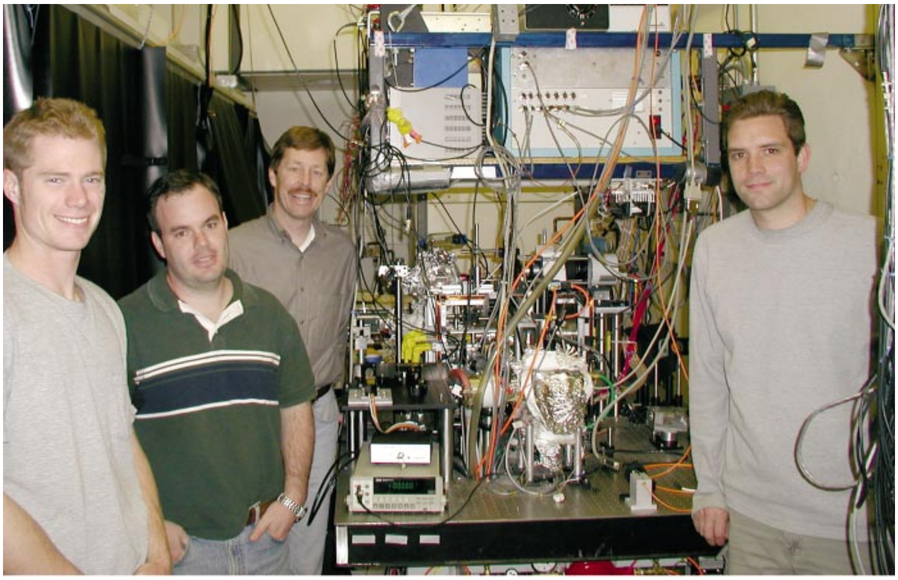
Into the abyss: a whirlpool in water provides a good analogy for the effect black holes have on matter.



Star-gazers: Randall Hulet (second right) and his team have mimicked white dwarfs in the lab.

that they sometimes leave behind. Shortly after Wieman's team produced the first gaseous BEC, Randall Hulet and his colleagues at Rice University in Houston observed a dramatic collapse in the BEC system they were working on[10]. Two sets of forces can act on the atoms in a BEC. Although they act as a single particle, the individual atoms in a BEC continue to move slowly, and this motion results in a weak pressure that keeps the atoms apart. Depending on the type of atoms used, there can also be weak quantum-mechanical attractive forces acting between the atoms in a BEC. Wieman's group had used atoms that did not experience this attractive force, but Hulet's lithium atoms did.

Dance the Bosenova

Hulet's group discovered that if the number of atoms in their BEC became too great, the combined attractive forces caused the BEC to collapse. In a later experiment[11], the researchers watched the BEC go into a kind of oscillatory motion, as the collapsing atoms rebounded outwards, only for the attractive forces to pull them together again.

Wieman and his colleagues have since developed sophisticated methods for switching the atoms in a BEC between attractive and non-attractive states, allowing them to monitor individual collapses and rebounds[12]. On close inspection, the collapsing BEC looks startlingly like a microscopic supernova.

The initial implosion is followed by an explosion in which the atoms are ejected as a hollow ball of atoms or in narrow jets, just as the collapsing star rebounds to form a characteristic expanding ball or streams of outflowing gas. In both a supernova and a 'Bosenova', as they are now known, a core of collapsed material is also left behind.

The big difference is in the amount of energy released. A supernova liberates 75 orders of magnitude more energy than the exploding condensate, which musters only enough energy to raise its temperature by 200 billionths of a kelvin. But the BEC's collapse appears to be forceful enough to expel some of the atoms from the experimental system completely. As yet, the reason for the explosion is not clear.

Under pressure

Another fate of a dying star might also be open to investigation using very cold atoms. Eventually, our Sun will collapse to form a dense, blue-white body called a white dwarf. Such stars are spared further compression because of a balancing act between the electrons they contain and gravity. Electrons are fermions and cannot be squeezed into the same quantum state. This refusal to get too close to other electrons results in an outward pressure, known as Fermi pressure, that balances the inward pull of gravity. Unless the gravitational pull is strong enough to force the electrons to fuse with protons to make neutrons, a white dwarf will not collapse any further.

Earlier this year, Hulet and colleagues observed Fermi pressure in a gas containing two isotopes of lithium cooled to about 250 nanokelvin[13]. One isotope, lithium-6, is a fermion; the other, lithium-7, is a boson. Hulet found that clouds of the two isotopes, which were mixed but could be imaged separately, were different sizes and shapes as the lithium-6 atoms are affected by Fermi pressure whereas the lithium-7 atoms are not. The shape of the lithium-6 cloud, argues Hulet, arises from the same mechanism that stabilizes white dwarfs against further collapse.

A community is forming with lots of interdisciplinary connections.

The potential analogies for BECs in the lab are intriguing, but will astrophysicists learn anything from studying these systems? Zoller thinks they can. One problem that they might help to shed light on, he says, is that of Hawking radiation. During the 1970s, Stephen Hawking of the University of Cambridge showed that black holes can become slightly warmer than the space surrounding them[14]. Black holes are no exception to the rule that heat flows from hot to cold, so they should, in theory, radiate energy — now known as Hawking radiation. This means that, given enough time, black holes should evaporate away altogether.

Hawking radiation poses a formidable challenge for physicists. It is too weak to be observed, but a theoretical description would have to combine quantum mechanics and gravity, and such a theory of quantum gravity does not yet exist. If an artificial black hole could be made, scientists could look for the presence of an analogue of Hawking radiation, providing useful evidence for the real thing.

Leonhardt points to other benefits, saying that the work on the astrophysical implications of BECs is bringing different scientific disciplines together. "A community is forming with lots of interdisciplinary connections between quantum optics, condensed-matter physics and astrophysics," he says.

If this community can make the analogies work, tabletop versions of astrophysical events could become reality. Whether or not these models will provide an insight into the real phenomena remains to be seen, but they may be the best chance researchers have of recreating the extreme conditions of dying stars in the lab. ■

Philip Ball is an consultant editor of *Nature*.

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