

Uncovering gravity's secrets with a fluid of atoms

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In 1972, physicist Bill Unruh gave a lecture on black holes that started with a tale about, well, fish. Imagine a pair of blind fish in a river approaching a waterfall, he said. The one farther downstream plunges over the precipice. As it plummets, it screams to warn the fish upstream. But the waterfall is too strong—the fish is falling downward faster than the speed of sound can carry away its screams. The second fish doesn't hear the warnings of the fate it, too, will soon meet.

Unruh argued that the fish's screams are trapped by the river's flow in much the same way that light is trapped by the gravity near a black hole (1). He suggested that this analogy could help physicists study the theory of black holes. Yet even he was doubtful that a lab-made "analogue black hole" would ever yield useful insights into the actual phenomena out in space.

But now, 50 years after Unruh's riverine musings, analogue experiments are being used to study the interplay between gravity and quantum fields such as light. Thanks to a quantum fluid of atoms called a Bose-Einstein Condensate (BEC), scientists are simulating everything from black hole physics to the origin of the universe in the lab. "We finally have something where we can get our hands dirty and... test our theories," says Silke Weinfurter, a physicist at the University of Nottingham in England.

Fishy Analogy

Our modern understanding of the universe consists of two disparate theories: general relativity and quantum field theory. General relativity says that space-time

Experiments using Bose-Einstein Condensates could help physicists better understand cosmological phenomena, including what happened to our universe in the first moments after the Big Bang. This recently released James Webb Space Telescope image shows the galaxy cluster SMACS 0723 as it appeared some 4.6 billion years ago. Image credit: NASA, ESA, CSA, and STScI.

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Published August 11, 2022.

is a deformable fabric that can be stretched and squeezed. Any massive object will warp the fabric, much like a bowling ball placed on a taut rubber sheet. Position a marble on this deformed sheet and it will roll down toward the bowling ball, emulating something like gravity's pull. The geometry or curvature of space-time is actually gravity. Quantum field theory describes everything else embedded in this space-time, all of which are excitations of different fields. Light, for example, is an excitation of the electromagnetic field.

In regions where the curvature of space-time, and hence the gravity, becomes extreme—near a black hole, for instance—the intersection of general relativity and quantum field theory causes weird things to happen to these fields. One classic case in point: Hawking radiation. Just outside of the region of a black hole where light can no longer escape, when a particle and its anti-particle spontaneously pop into existence, sometimes one falls into the black hole and its partner escapes and radiates outward.

This radiation is impossible to observe in a real black hole out in space. So, following Unruh's idea, physicists began looking for Hawking radiation around a system that was much more accessible—an *artificial* black hole.

In 2016, Jeff Steinhauer, a physicist at the Technion Israel Institute of Technology in Haifa, finally succeeded, using a BEC as an analogue of space-time (2). A BEC is a quantum state of matter where atoms in a cloud all condense to their lowest-energy state (see [Core Concept: How Bose-Einstein condensates keep revealing weird physics](#)). At this cold, low-energy state, the atoms collectively behave as a single quantum object. In the lab, physicists use lasers to create a "potential energy landscape" to confine the BEC. Often, this landscape looks something like a sinkhole, with the BEC at the bottom. The more intense the laser light, the deeper the hole. But by changing the focus and intensity of the lasers, one can arbitrarily change the shape of the landscape. The atoms then move and flow like a river winding through uneven terrain, always finding the lowest point. And pressure waves or sound waves can travel through this new quantum fluid.

Steinhauer engineered the landscape confining the quantum fluid to have a sudden drop, causing the BEC to plummet like a waterfall over a cliff. Right at the precipice, Steinhauer observed pairs of quantum packets of sound called phonons spontaneously pop into existence (a phonon and its partner anti-phonon)—this was the Hawking effect. Were a phonon to cross the precipice, it would, much like the fish's screams, be disconnected from the outside world.

Many saw Steinhauer's experiment as validation of Unruh's decades-old idea. It reinvigorated efforts to simulate other effects predicted by combining general relativity and quantum field theory. That includes the work of Markus Oberthaler, a physicist at Heidelberg University in Germany. Oberthaler has made an analogue gravity machine of his own, also with a BEC (3). By incorporating the ability to easily change the shape of the landscape the atoms feel, Oberthaler says he can configure arbitrary space-time geometries—not just the curvature of space near a black hole. In essence, he can create hypothetical worlds with bizarre, Escher-esque geometries or worlds that evolve in time. This allows Oberthaler to experiment

not just with analogues of black holes but potentially analogues of aspects of our universe as well.

Expanding the Analogy

Such "analogue cosmology" experiments could help physicists understand what happened to our universe in the first moments after the Big Bang. According to the standard model of cosmology, when our universe was a mere 10^{-36} seconds old, it underwent a process called inflation and grew by a factor of 10^{26} in just 10^{-33} seconds. The process stretched the "quantum fluctuations"—minuscule quantum mechanical variations in the universe's energy density—across the immense volume of space-time. These fluctuations in energy density would one day become fluctuations in the density of matter, and the denser regions would eventually coalesce to form stars and galaxies. Because direct observations of inflation are impossible, physicists began wondering about simulating aspects of it in the lab.

Weinfurter, for instance, is interested in how the initial minuscule quantum fluctuations grew into our current large-scale structure of the universe. But that's a huge problem to tackle. So, she's starting slow. "Before we start running, let's just start walking," she says. Other, potentially simpler effects of inflation are more readily accessible to analogue experiments. In fact, some of these effects have already been observed. Gretchen Campbell of the University of Maryland in College Park rapidly expanded her BEC to watch how pressure or sound waves are stretched and energy dissipated throughout the cloud of atoms (4). The inflation of space-time should have had a similar effect on the quantum fields in our early universe (5).

And like Hawking radiation near a black hole, particles should be spontaneously produced as the universe inflates. This "cosmological pair production" was first seen in an analogue system in 2019, when researchers rapidly changed the forces confining a pair of ions (6). More recently, Oberthaler has observed the effect by abruptly altering the interactions between atoms in his BEC to simulate inflation (3).

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A Wrinkle In Space-Time

Despite the striking similarities between the physics describing quantum fields in curved space-time and those describing acoustic waves in quantum fluids, the analogy only goes so far. "I don't think that a Bose-Einstein Condensate can explain what our reality is," says Stefano Liberati, a physicist at the International School for Advanced Studies in Trieste, Italy.

That's because if you zoom in on the fluid meant to represent the smooth, deformable fabric of space-time, you'll see that the fluid is, in fact, not so smooth. It's made up of discrete chunks: the atoms of the BEC. So analogue gravity experiments can only faithfully simulate effects that are large relative to their microscopic structure.

But in an ironic twist, it is precisely this breakdown of the analogy that could inspire the next breakthrough in the theory of gravity. Some physicists suspect that space-time, or gravity, is also pixelated at very short lengths of about 10^{-35} meters, called the Planck scale—necessitating a new, as-yet-undiscovered theory of “quantum gravity” to describe gravity at such scales.

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So, although analogue systems unquestionably miss the important details of quantum gravity at short length scales, they may nonetheless serve as models of how a system's macroscopic behavior emerges from its microscopic constituents.

For example, Liberati thinks that just as a BEC's large-scale properties emerge from a collection of individual atoms, smooth space-time, or gravity, might also be emergent from discrete units of space-time (whatever they might be). Although this analogy isn't literal (i.e., a single atom in the BEC doesn't correspond to a single “chunk” of space-time), he still thinks that BECs could be a good testing ground for some theories of emergent gravity (7).

Gravity Emerges

One such emergent theory that Liberati and Weinfurter are interested in simulating describes how gravity, space-time, and our universe may have come from “false vacuum decay” (8, 9).

The theory relies on the fact that everything tends toward its lowest energy state—the true vacuum state. A ball, for example, rolls down a hill to decrease its potential energy. But if the hill has a valley near the top, the ball could get stuck there, despite the fact that it's not at the lowest point. This is a “false vacuum” state—as far as the

ball is concerned, it has minimized its energy. But give the ball a bit of energy to roll out of the valley, and it will quickly find the true vacuum at the bottom.

As the false vacuum decay cosmological theory goes, before the universe as we know it existed, there was a field in a false vacuum state like the valley near the top of a hill. When quantum fluctuations gave it just enough energy to jolt it over the hump and find the true vacuum (or, at least a “truer” false vacuum, with a lower energy than the one that preceded it), our universe bubbled up and began inflating.

While mathematically modeling an analogous vacuum decay process in BECs in 2008, Liberati and his colleagues discovered that the model required a term that behaves exactly like dark energy—the mysterious substance thought to be causing the accelerating expansion of our universe (10).

Now, 14 years later, analogue experiments are at the cusp of being able to simulate this vacuum decay process and test Liberati's predictions about dark energy emerging from vacuum decay. Weinfurter, with her collaborators Hiranya Peiris at University College London, UK, and Zoran Hadzibabic at University of Cambridge, UK, have made progress to this end. They have figured out a way to simulate this false vacuum state by making a BEC with two different types of atoms; all indications are that the two-component BEC will enable the more ambitious vacuum decay experiments.

The hope is that these analogue experiments will help reveal the nature of gravity and space-time itself. Already, researchers have suggested the tantalizing possibility of understanding mysterious, distant phenomena, such as black holes and the very beginnings of the universe, within the confines of an ordinary lab. Says Liberati, “It's helping [us think] in a different out-of-the-box way.”

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