PERSPECTIVE
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Analogue black-hole horizons

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Some gravitational phenomena are difficult or even impossible to observe in real spacetime. Laboratory analogues of black-hole horizons offer new perspectives on field theory effects that might help our understanding of gravitation.

In a seminal paper, William Unruh[1] found a precise formal equivalence between the behaviour of sound waves in a fluid cascade and that of light in a black-hole spacetime. Essentially, when the velocity of a fluid reaches the velocity of sound, waves cannot propagate upstream. This leads to the formation of a sonic horizon, analogous to the horizon that general relativity predicts for black holes. Since then, researchers have found many different ways to create analogues of black-hole horizons in the laboratory[2]. The study of these analogues has become an important source of insights into the physics of horizons.

Beyond the pure formal analogy, Unruh presented two important ideas. On the one hand, analogue systems developing a long-lived horizon should in principle exhibit Hawking radiation, because this phenomenon is kinematic and thus independent of any gravitational dynamics[3]. Here, I shall use the term long-lived in reference to a horizon that exists for longer than the other relevant timescales of a system. This gives time for the development of the more prominent characteristics of a horizon. In proper black holes, this timescale is essentially their associated light-crossing time.

On the other hand, Unruh had already pointed out almost immediately after Hawking proposed his evaporative effect[4] that Hawking's calculation suffered from the 'trans-Planckian problem'[5]. Shortly after the establishment of Hawking radiation, Hawking modes close to the horizon region possess huge frequency components beyond the Planck scale. However, these ultra-high energy scales are expected to be within the regime of quantum gravity, where a different and still unknown physics could be operating.

The existence of long-lived horizons might serve as a magnifying glass for this high-energy physics. However, assuming a more negative point of view, at the purely theoretical level and before any experimental confirmation or refutation, Hawking's effect appears too shaky to build upon, as it might not be a consequence only of the low-energy physics that we trust. Within this state of affairs, analogue black holes could be fantastic test benches to understand how high-energy physics might come into play in Hawking's effect. There are many other interesting phenomena that one can study from the analogue gravity perspective (see, for example, ref. [2]), but here we concentrate on the concrete and especially interesting case of analogue black holes and, more generally, analogue horizons.

Approaching the Planckian regime, we expect our spacetime description to become more blurry. Analogue systems provide clear examples of how a continuous and effectively low-energy relativistic spacetime diffuses when approaching the microscopic (atomic) high-energy description. In the presence of the first deviations, the description remains continuous, but with modifications to the effective relativistic dispersion relation[6,7]. These non-relativistic corrections in an analogue system can be complicated. At a first approximation, however, they can be described as superluminal or subluminal, depending on whether high-energy perturbations travel faster or slower than the relevant low-energy speed—the speed of sound, which plays the analogue role of the speed of light. From this perspective, one of the theoretical goals in the field is understanding to what extent Hawking radiation is independent of the high-energy characteristics of the dispersion relation.

On experimental verifications

Let me start by stressing that, in my opinion, the importance of Hawking's proposal of black-hole evaporation has already been validated by the number and relevance of the developments that it has inspired. Nevertheless, any theoretical prediction in physics has to be confronted with nature. Here we face an important problem: there are no clear prospects of probing Hawking's effect in gravitational black holes, certainly not in the near future. In fact, the problem can be separated into two distinct questions: are long-lived trapping horizons produced naturally in astrophysical scenarios? And if they are, do these horizons radiate and evaporate? For a discussion of the experimental status of the observation of black holes in nature, see ref. [8].

Let me assume, for the time being, a positive answer for the first of these two questions. Then, regarding the latter, observing the Hawking effect in analogue systems is something that would alleviate the lack of a strict observational verification. What I mean is that a systematic observation of Hawking radiation in analogue systems would strongly increase the odds for the reality of the Hawking effect in black holes. We need to show, without finetuning of the models, that setting up a horizon leads to spontaneous Hawking particle production. The importance of experimental developments is to show that simplifications, approximations and, most importantly, additional factors that are not directly apparent in initial theoretical analyses do not destroy the sought-for effect. And given that we are already dealing with an analogue effect, we should be especially demanding with the experimental verifications. From this perspective, although a lot of progress has been made, I would not answer Unruh's question "Has Hawking radiation been measured?"[9] in the affirmative just yet.

I will now describe the status of the main experimental lines under development in the context of analogue gravity. These experiments typically focus on observing the essentials of Hawking radiation: a specific form of the correlations between the different modes involved, which can be achieved in quantum as well as in classical systems; and the spontaneous nature of this radiation in quantum experiments, which is amenable to exploration only in the purely quantum regime.

Surface waves in water flows

Surface waves in shallow-water configurations exhibit a non-dispersive low-energy regime and a reasonably small (metres per

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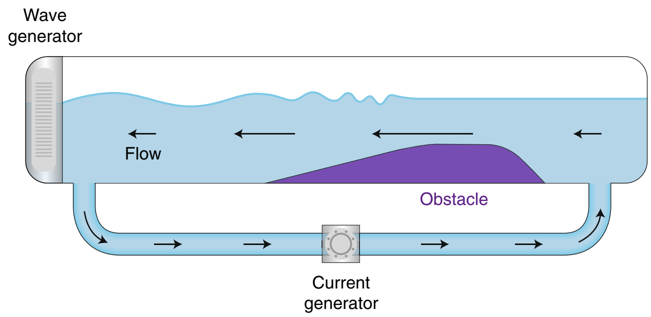

Fig. 1 | A horizon in a water flume. Sketch of the analogue gravity experiments in water flumes. A water flow is generated in the flume (from right to left in the figure), while surface waves are generated so that they travel upstream (left to right). At the bottom of the flume an obstacle modifies both the velocity of the flow and of the surface waves. The obstacle is set up in such a way as to act as a wave blockade, at least for some range of frequencies. In this way, the analogue of a white-hole horizon is produced.

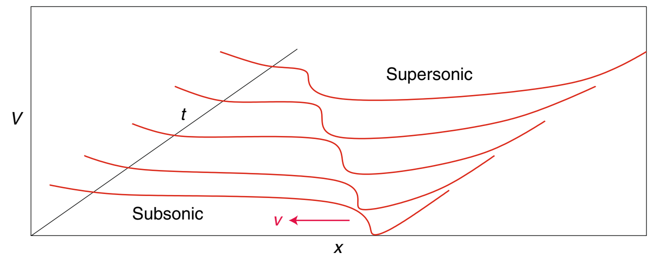

Fig. 2 | A horizon in a BEC flow. To create a black-hole horizon in a BEC, an effectively one-dimensional BEC was created in the experiments[23] by using an anisotropic harmonic potential. The x direction corresponds to the direction in which the potential V is the widest, in which a cigar-like BEC is established (the transverse directions are not shown in the graphic). This potential is then swept by a step-like jump, which creates a flow in the BEC in the form of a cascade. In this way, one creates a temporal subsonic-to-supersonic transition. The graphic represents the time evolution of the resulting overall potential.

second) and controllable propagation speed $c_s = \sqrt{gh}$ (where g is Newton's acceleration on Earth and h the depth of the fluid), so they are appropriate as analogue systems[10]. For long wavelengths, where surface tension effects can be neglected, these systems have a subluminal dispersion relation between the frequency ω and the wavenumber k of the form $(\omega - vk)^2 = gk\tanh(hk)$, where v is the speed of the fluid flow.

To generate a horizon, experimentalists set up a water flume with a subcritical (or subsonic) and steady flow. An obstacle is then placed at the bottom of the channel, leading to an increase of fluid velocity across the obstacle, while the speed of the surface waves simultaneously decreases (Fig. 1). This creates a blocking region such that waves travelling upstream will encounter a point that they cannot cross: an effective white horizon. With such a set-up, Rousseaux et al. reported the presence of negative mode conversion[11], a basic ingredient of the Hawking effect. However, the origin of this mode conversion is unclear[12]. Later, using an improved experimental set-up, Weinfurtner et al. reported the observation that the ratio of the Bogoliubov coefficients, $|\beta_f|^2/|\alpha_f|^2$, decays expontentially with the frequency[13]. They argued that this demonstrated the thermal properties of a stimulated (classical) version of the Hawking process.

The interpretation of this result is still under discussion, as the physical parameters used in both experiments were not such as to produce a region that was supercritical in the group velocity for all the relevant frequencies. The experiment[13] clearly shows the presence of negative mode conversion (that is, the scattered waves acquire negative norm components) due to changes in the flow velocity. However, part of this conversion appears to come from scattering between two different subcritical regimes; whether the exponential signature, which is an adjustment to a small frequency band of the scattering coefficients, should be taken as a horizon effect is still under debate (see, for instance, refs. [14–16]).

To better understand the system, and given the difficulty of setting up a water flow with large Froude numbers (v/c_s), Euvé et al.[17] decided to probe the scattering properties of subcritical flows by measuring the noise correlation functions. They identified strong correlations between the long-wavelength upstream incident mode and the two short-wavelength reflected modes (one with positive and one with negative energy), as well as between the latter two, all of which is reminiscent of the Hawking effect.

Changing the topic slightly, Torres et al.[18] have created a different experimental set-up to probe superradiant scattering by an ergoregion (a region in which the flow acquire superluminal speeds but not on the radial direction). In superradiant scattering, a wave can gain some energy by scattering into a superluminally rotating configuration, at the expense of its rotational energy[19]. In a steady draining-bathtub configuration, water swirls around until reaching a drainage hole. Once steady flow is established, small surface waves are excited at one side of a rectangular tank and absorbed on the other side. The waves traverse the vortex configuration and produce a scattering pattern. By monitoring the behaviour of the waves, and applying a frequency filter and an azimuthal decomposition, the authors showed that the $m = 1,2$ co-rotating low-frequency modes experience amplification. This is interpreted as superradiant scattering and indicates that the superradiance condition $\omega - m\Omega(r) < 0$, with Ω the angular velocity, is satisfied in the central regions of the configuration.

Coming back to Hawking radiation, water flume experiments are unable to probe the quantum spontaneous aspects of Hawking radiation, as thermal effects are overwhelmingly dominant. To observe these quantum aspects, one needs a quantum analogue system such as a Bose–Einstein condensate (BEC)[20,21].

BECs

In a BEC, it is possible to achieve a Hawking temperature that is of the order of the background temperature of the system itself[22]. The typical dispersion relation for acoustic phonons in a BEC incorporates superluminal deviations when departing from its low-energy relativistic regime: $(\omega - vk)^2 = c_{\rm ph}(k^2 + k^4/k_0^2)$, with $c_{\rm ph}$ the low-frequency speed of sound.

In 2010, the group led by Jeff Steinhauer produced a sonic horizon in a BEC[23]. The system consisted of about 10^5 ^{87}Rb atoms condensed inside a harmonic trap. They generated a horizon by making the condensate fall down a step-like potential cascade (Fig. 2). In this way, the fluid condensate accelerates to a velocity higher than the speed of sound in a BEC (roughly millimetres per second). After that, they set up a roadmap towards the observation of the Hawking effect, analysing phonon propagation[24] and thermal distribution of phonons[25]. Steinhauer then managed to produce a black-hole laser configuration and show the existence of phononic excitations of the predicted characteristics[26]. A black-hole laser configuration is a combination of a black and a white horizon that, in theory and under superluminal dispersion relations, acts as a resonant amplifier[27]. The observation of spontaneous self-amplifying Hawking radiation in this experiment has been challenged in refs. [28,29]—where it was argued that what has been observed is a stimulated version of the process, understandable just in terms of the mean field Gross–Pitaevskii equation. Steinhauer has counter-argued in favour of his interpretation[30].

Finally, in 2016 Steinhauer reported the much sought-after observation of Hawking particles produced by a single black-hole horizon[31]. The observation is made through the determination of the correlation function[32], which exhibits correlations between outgoing and ingoing Hawking pairs[33]. In addition, the measured correlations are argued to correspond to genuine quantum correlations, namely from a non-separable quantum state (see ref. [34] for more details). This is taken to signal the presence of spontaneous Hawking emission. Michel et al. have analysed Steinhauer's experiments from a theoretical perspective, and the agreement is substantial[35]. We must mention that these results are still under discussion (see refs. [36,37] and the author response[38]). Again, the main source of controversy is the presence or not of a contribution coming from the spontaneous channel. In other words: what is the seed of the observed fluctuations?

Nonlinear optics

Dielectric systems with nonlinear properties opened up new ways to construct analogue systems. Philbin et al.[39] reported the formation of a horizon in an optical fibre. Subsequently, Belgiorno et al.[40] and Rubino et al.[41] reported an experiment in which a laser pulse propagating in a nonlinear optical fibre produces an alteration of its refractive index, so that in its comoving frame it produces a (nearly) stationary horizon. They have detected radiation coming precisely from the supersonic region and the appropriate frequency window. After excluding several potential origins for the radiation, they interpreted it as Hawking radiation. However, several characteristics of the experiment do not fit very well with those expected for a Hawking-like radiation[42–45]. For example, the configuration possesses phase velocity horizons, but not group velocity horizons. Further analyses suggest that the emission might be due to the steepness of the trailing edge of the pulse (the white horizon) in combination with the specific dispersive characteristics of fused silica[46], although other sources are still not discarded. Independently of their analogue-gravity interpretation, these experiments have shown the relevant presence of negative mode conversion[47].

A different approach in the field of nonlinear optics is based on quantum fluids of light[48,49]. It is possible to design a microcavity sandwiched between two mirrors and with an internal potential well so that the energy of the fundamental mode of the photon between the plates is resonant with the first excited state of the potential well. In this way an exciton-polariton degree of freedom is generated and satisfies a generalized Gross–Pitaevskii equation[50], behaving as a quantum fluid. This fluid can be manipulated like a BEC, opening the possibility of creating supersonic configurations. Recently, Nguyen et al.[51] have achieved in such a system a configuration containing a black-hole horizon, and have designed a strategy to look for spontaneous Hawking radiation (Fig. 3). On the other hand, Vocke et al.[52] have constructed a (2 + 1)-dimensional rotating configuration exhibiting a separated ergoregion and a horizon; this could serve to look for superradiance in the near future. Quantum fluids of light offer potential advantages with respect to atomic systems. For instance, they allow stationary configurations to be set up with a single black horizon and larger Hawking temperatures (a few kelvin).

Although many other experimental proposals exist, the ones described here are the more developed. In any case, the search for a clear and unambiguous spontaneous Hawking emission signal is still ongoing—but with good prospects.

What are we learning on the gravitational side?

The challenge of observing Hawking-like radiation in specific laboratory systems is helping to reach new levels of understanding of those specific systems. Beyond this important fact, by abstracting from the specifics of the different experimental systems, the gravitational community could start taking a few lessons back to the gravitational realm. On the one hand, it is becoming clear that, once a long-lived horizon is established, there is a high probability that it would radiate in a Hawking-like manner, regardless of the specific high-energy physics involved. Theoretical analyses of high-energy dispersion show two basic conditions for this robustness: the energy scale at which high-energy modifications set in should be much larger than the natural scale of Hawking radiation (that is, the surface gravity of the horizon), and, in the case of superluminal dispersion, the superluminal region should be sufficiently deep[53]. Although much less studied, analysis of dissipation at the high energies, necessary for the causal consistency of the models[54], also point to the robustness of Hawking radiation[55].

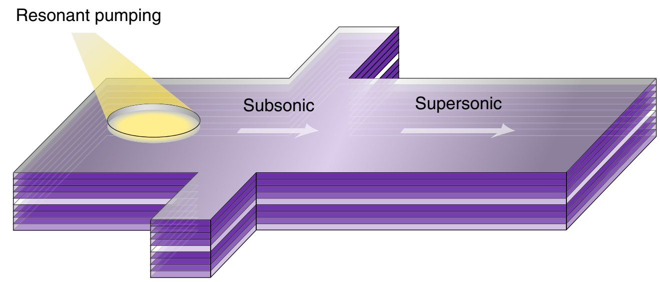

Fig. 3 | A horizon in an exciton-polariton device. The device consists of two Bragg mirrors enclosing a thin planar microcavity (the internal white colour). The pumping laser creates an exciton-polariton state in the cavity, which behaves as a flowing quantum fluid. The widening in the middle of the cavity then produces an increase in the velocity of the quantum fluid, which finally makes a transition from subsonic to supersonic, creating a horizon.

On the other hand, beyond the laboratory observation of analogue Hawking radiation itself—and in my opinion even more importantly—the understanding of the phenomenology associated with the presence of horizons in different analogue systems provides hints about phenomena that might also be present in the gravitational realm; phenomena that one can look for. For instance, the robustness analyses suggest that the details of the physics at high-energy can strongly affect the natural subsistence of a black hole horizon in the first place. Entirely regular configurations with long-lived horizons are difficult to achieve experimentally and are typically unstable. These instabilities under high-energy dispersion might also appear in the gravitational context. For instance, in the case of superluminal dispersion relations, the singular region inside a black hole would not be hidden from the outside[56]. Then, boundary conditions at the singularity can have a strong impact on the global behaviour of the system[57,58] and even make the very existence of horizons a transient phenomenon. This issue relates to earlier question as to whether long-lived trapping horizons are naturally produced in astrophysical scenarios, which my collaborators and I are exploring in a series of papers, such as ref. [59]. So, in a twisted way, although the presence of Hawking radiation—once a long-lived horizon is established—appears robust under high-energy specifics, the prior natural formation of a long-lived horizon appears not to be so.

Another interesting question that appears repeatedly in the field is the distinction between correlations of classical or quantum origin. Extrapolating again to real gravity, one could wonder whether classical dynamical phenomena might not appear in black-hole physics before any purely quantum regime is explored—in correspondence with stimulated Hawking emission. One could certainly expect any dynamical theory superseding general relativity (and, for instance, incorporating superluminal behaviour) to have a strong impact precisely on the question of the formation and disappearance of horizons. While this is a generic lesson one might take, it is not at all a theoretical proof that long-lived horizons cannot exist in any such theory. For example, Hořava and Einstein-aether gravity theories appear to have solutions with universal horizons[60], hiding definitively the nature of the singular region from outside.

In summary, the attempt to observe stimulated and spontaneous Hawking-like radiation in different laboratory settings is improving our understanding of those specific artificial systems. In the reverse direction, reflecting on the physics of analogue horizons is also serving as a source of new ideas for gravitational physics.

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