The latest frontier in analogue gravity: new roles for analogue experiments

Grace Field*

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Abstract

So far, the philosophy literature has treated analogue experiments as if they have a single goal: to confirm hypotheses about their target systems. But we should not be surprised if analogue experiments are able to do much more than that — even if they fail in their original goal, as several philosophers and physicists have suggested that they inevitably will (Crowther et al. 2019, Wolchover 2016).

I argue that recent analogue black hole experiments can, and already have, done much more than confirm the existence of astrophysical Hawking radiation. They are being used to detect instances of a generalized concept of Hawking radiation and to explore their source systems. Both of these new endeavours have already taught us a great deal about the robustness (i.e. multiple realizability, universality, generality) of Hawking radiation and other predicted black hole phenomena.

These developments in analogue gravity reveal new roles for analogue experiments in general. They show that analogue experiments, even if unable to confirm the existence of the phenomenon that they were originally designed to detect, often are able to confirm the existence of a more generalized version of that phenomenon. And they show that such analogue experiments can be used as exploratory tools — both for open-ended exploration, and to investigate the generality of some phenomenon or phenomena of interest. The second kind of exploration can be understood as a method of interrogating natural kind boundaries.

Contents

*University of Cambridge, Department of History and Philosophy of Science: *gef30@cam.ac.uk*.

1 Introduction

So far, the philosophy literature has treated analogue experiments as if they have a single goal: to confirm hypotheses about their target systems. But we should not be surprised if analogue experiments are able to do much more than that — even if they fail in their original goal, as several philosophers and physicists have suggested that they inevitably will (Crowther et al. 2019, Wolchover 2016).

I argue that recent analogue black hole experiments can, and already have, done much more than confirm the existence of astrophysical Hawking radiation. They are being used to detect instances of a *generalized* concept of Hawking radiation and to *explore* their source systems. Both of these new endeavours have already taught us a great deal about the robustness (i.e. multiple realizability, universality, generality) of Hawking radiation and other predicted black hole phenomena. I use 'robustness' as an umbrella term to capture various notions of generality, including multiple realizability and universality: I label an experiment an investigation of 'robustness' whenever it is an investigation of the different possible physical scenarios that can give rise to a phenomenon.

These developments in analogue gravity reveal new roles for analogue experiments in general. They show that analogue experiments, even if unable to confirm the existence of the phenomenon that they were originally designed to detect, often are able to confirm the existence of a more generalized version of that phenomenon. And they show that such analogue experiments can be used as exploratory tools — both for open-ended exploration, and to investigate the generality of some phenomenon or phenomena of interest. The second kind of exploration can be understood as a method of interrogating natural kind boundaries.

In Section 2, I summarize the theoretical basis for analogue black hole experiments, placing emphasis on the assumptions required for the link between the source (fluid) system and target (astrophysical) system to be theoretically well-founded. In Section 3, I analyse the formative decades of the analogue gravity research program, from 1981–2017. Following Jacquet, Weinfurtner, et al. (2020), I break this period into two eras: the theory era, from 1981-2008 (Section 3.1), and the experiment era, from 2008-2017 (Section 3.2). Section 3.3 articulates the goals that seem to characterize both of these eras.

Section 4 moves on to assess the latest developments in analogue gravity research, from 2017 to the present — and looking to the future. 2017 seems to mark a departure from the goals that had characterized the research program in its first few decades: the program is now interested not only in providing confirmation for the existence of astrophysical phenomena like Hawking radiation, but in detecting instantiations of *generalized gravity phenomena* (Section 4.2.1), and in exploring the behaviour of the analogue systems (Section 4.2.2) both to discover novel features and effects, and to learn about the robustness of predicted effects. Section 4.2.3 places these goals in context, asking whether they are really as new as they might first appear. Section 4.2.4 ties Sections 4.2.1, 4.2.2, and 4.2.3 together.

Section 5 assesses the import of these developments, identifying two new roles for analogue experiments in general: detection of general and/or recently generalized phenomena (Section 5.1), and exploration in two senses (Sections 5.2.1 and 5.2.2).

Sections 6.1.1 and 6.1.2 explain the impact of these new roles on analogue gravity research: they can lead, and already have led, to reinterpretation of old experiments (Section 6.1.1) and redirection of research programmes (Section 6.1.2).

Neither of the new roles, on the face of things, seems to have much at all to do with the target system. Section 6 looks at what this means for the *analogy* in analogue experiments. Is the link between the source and target systems made irrelevant by the new roles I have articulated? I suggest, no: although neither claims to immediately tell us anything about the target system, they both contribute to building up a bank of connections between input variables and output phenomena. Those connections can point theorists in interesting and fruitful directions, and they can tell us about what the target system *might* look like, *if* it turned out to have certain features.

2 The experiments and their theoretical basis

Analogue black hole experiments exploit an isomorphism between the mathematics that describes the propagation of quantum fields in a black hole spacetime and the mathematics that describes the propagation of sound waves (or some other quantized disturbance) in a fluid flow.

Of course, such an isomorphism between quantum field theory on curved spacetime and fluid dynamics does not hold in general: the fluid, and the excitations travelling through it, must satisfy several strict assumptions for the theoretical link between analogue black holes and astrophysical black holes to be well-founded.

In the simplest case — for a Schwarzschild (i.e. stationary, nonrotating) black hole — the derivation of the isomorphism proceeds as follows (Unruh 1981, 1351-1352).[1] Begin with the two fundamental equations of motion in fluid mechanics:

$$\textit{The continuity equation} \quad 0 = \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}), \tag{1}$$

$$\textit{Newton's second law} \quad F = m\mathbf{a} = \rho \left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} \right), \tag{2}$$

where $\rho(\mathbf{x}, t)$ is the density of the fluid and $\mathbf{v}(\mathbf{x}, t)$ is its velocity at every point.

Equation (1) is an expression of the conservation of mass, and relies on the assumption that the fluid is flux-free — that the total amount of fluid flowing out of the region we are describing is exactly equal to the total amount of fluid flowing into that region. Once ρ and $\mathbf{v}$ are defined, equation (2) is just Newton's second law.

The next step is to assume that the only forces at play are pressure and gravity. Then equation (2) becomes Euler's equation:

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} \right) = -\nabla p - \rho \nabla \Phi, \tag{3}$$

which is equivalent to

$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{\nabla p}{\rho} - \nabla(\frac{1}{2}\mathbf{v}\cdot\mathbf{v} + \Phi) + \mathbf{v}\times(\nabla \times \mathbf{v}), \tag{4}$$

where $p(\mathbf{x}, t)$ is the fluid pressure and $\mathit{\Phi}(\mathbf{x})$ is the gravitational potential.[2] By making this assumption, we are asserting that the fluid has negligible viscosity and that the evolution of the fluid is therefore adiabatic — otherwise another term would need to be included in equation (3) to account for dissipative effects.

Under the additional assumption that the fluid is irrotational (i.e. $\nabla \times \mathbf{v} = 0$), $\mathbf{v}$ can be rewritten as the gradient of some scalar potential ϕ, such that $\mathbf{v} = -\nabla \phi$.[3]

Equation (4) then becomes

$$\nabla \left(-\frac{\partial \phi}{\partial t} \right) = -\frac{\nabla p}{\rho} - \nabla \left(\frac{1}{2}(\nabla \phi)\cdot(\nabla \phi) + \Phi \right). \tag{5}$$

To deal with the problematic $-\frac{\nabla p}{\rho}$ term, we introduce the barotropic assumption: we assume that the density is a function of pressure only, such that $\rho(\mathbf{x}, t) = \rho(p)$. Then the function

$$h(p) = \int_0^p \frac{dp'}{\rho(p')} \tag{6}$$

can be defined (Barceló et al. 2011, 13), which clearly satisfies

$$\nabla h = \frac{\nabla p}{\rho}. \tag{7}$$

Equation (5) then simplifies to

1. Unruh's presentation is brief, omitting some intermediate steps. See e.g. Barceló et al. (2011, 12-15) or Visser (1998a, 1769-1774). Roberts (2021) breaks down the assumptions required in the derivation especially clearly. For more background on the fluid mechanics, see Landau and Lifshitz (1959).

2. The equivalence between (3) and (4) is based on the identity $\frac{1}{2}\nabla(\mathbf{v} \cdot \mathbf{v}) = \mathbf{v} \times (\nabla \times \mathbf{v}) + \mathbf{v} \cdot \nabla \mathbf{v}$.

3. This is an instance of the Helmholtz decomposition theorem; technically it also requires $\mathbf{v}$ to vanish at infinity.

$$-\frac{\partial \phi}{\partial t} + \frac{1}{2}(\nabla\phi)\cdot(\nabla\phi) + h + \Phi = 0. \tag{8}$$

Equations (8) and (1) together govern the behaviour of a fluid satisfying the assumptions detailed above. The next step is to introduce excitations — the sound waves — by linearizing (1) and (8) around some (ρ_0, p_0, ϕ_0) (Visser 1998a, 1770-1771):

$$\rho = \rho_0 + \epsilon\rho_1 + \mathcal{O}\left(\epsilon^2\right) \tag{9}$$
$$p = p_0 + \epsilon p_1 + \mathcal{O}\left(\epsilon^2\right) \tag{10}$$
$$\phi = \phi_0 + \epsilon\phi_1 + \mathcal{O}\left(\epsilon^2\right), \tag{11}$$

where $|\epsilon\rho_1|$, $|\epsilon p_1|$ and $|\epsilon\phi_1|$ are assumed to be small compared to $|\rho_1|$, $|p_1|$ and $|\phi_1|$, respectively.

The above are then substituted into the continuity equation (1) and Euler's equation (8), yielding a pair of equations from each. The continuity equation, for example, becomes

$$0 = \frac{\partial \rho_0 + \epsilon\rho_1 + \mathcal{O}\left(\epsilon^2\right)}{\partial t} - \nabla\cdot\left(\left(\rho_0 + \epsilon\rho_1 + \mathcal{O}\left(\epsilon^2\right)\right)\nabla\left(\phi_0 + \epsilon\phi_1 + \mathcal{O}\left(\epsilon^2\right)\right)\right) \tag{12}$$
$$\Leftrightarrow 0 = \frac{\partial \rho_0}{\partial t} - \nabla\cdot(\rho_0\nabla\phi_0) + \epsilon\left[\frac{\partial\rho_1}{\partial t} - \nabla\cdot(\rho_1\nabla\phi_0 + \rho_0\nabla\phi_1)\right] + \mathcal{O}\left(\epsilon^2\right) \tag{13}$$

Thus, to first order, we are left with

$$0 = \frac{\partial\rho_0}{\partial t} - \nabla\cdot(\rho_0\nabla\phi_0) \tag{14}$$
$$0 = \frac{\partial\rho_1}{\partial t} - \nabla\cdot(\rho_1\nabla\phi_0 + \rho_0\nabla\phi_1). \tag{15}$$

By the same method, equation (8) yields

$$0 = -\frac{\partial\phi_0}{\partial t} + h_0 + \frac{1}{2}(\nabla\phi_0)^2 + \Phi \tag{16}$$
$$0 = -\frac{\partial\phi_1}{\partial t} + \frac{p_1}{\rho_0} + (\nabla\phi_0)\cdot(\nabla\phi_1). \tag{17}$$

Here we have used the barotropic assumption — in particular, the fact that h is a function of p only — to derive

$$h(p) = h|_{(\rho_0,p_0,\phi_0)} + (\epsilon p_1)\cdot\left.\frac{\partial h}{\partial p}\right|_{(\rho_0,p_0,\phi_0)} + \mathcal{O}\left(\epsilon^2\right) \tag{18}$$
$$\Rightarrow h(p) = h_0 + \epsilon\frac{p_1}{\rho_0} + \mathcal{O}\left(\epsilon^2\right). \tag{19}$$

This is the expression for h that is substituted into (8) to yield (16) and (17).

Once (17) is established, it can be rearranged to isolate for p_1:

$$p_1 = \rho_0\left(\partial_t\phi_1 - (\nabla\phi_0)\cdot(\nabla\phi_1)\right). \tag{20}$$

But, again based on the barotropic assumption,

$$\rho(p) = \rho|_{(\rho_0,p_0,\phi_0)} + (\epsilon p_1)\cdot\left.\frac{\partial\rho}{\partial p}\right|_{(\rho_0,p_0,\phi_0)} + \mathcal{O}\left(\epsilon^2\right) \tag{21}$$
$$\Rightarrow \rho_1 = \frac{\partial\rho}{\partial p}p_1. \tag{22}$$

So, using (20),

$$\rho_1 = \frac{\partial \rho}{\partial p}\rho_0 \left(\partial_t \phi_1 - (\nabla \phi_0) \cdot (\nabla \phi_1)\right). \tag{23}$$

This expression for ρ_1, when substituted into the first-order linearized continuity equation (equation (15)), yields the following wave equation:

$$-\frac{\partial}{\partial t}\left(\frac{\partial \rho}{\partial p}\rho_0 \left(\frac{\partial \phi_1}{\partial t} + \mathbf{v}_0 \cdot \nabla \phi_1\right)\right) + \nabla \cdot \left(\rho_0 \nabla \phi_1 - \frac{\partial \rho}{\partial p}\rho_0 \mathbf{v}_0 \left(\frac{\partial \phi_1}{\partial t} + \mathbf{v}_0 \cdot \nabla \phi_1\right)\right) = 0, \tag{24}$$

where $\mathbf{v}_0$ is defined by

$$\mathbf{v}_0 := -\nabla \phi_0. \tag{25}$$

Noting that the local speed of sound in a fluid is defined by $\frac{\partial \rho}{\partial p} = \frac{1}{c^2_{sound}}$, and taking $f^{\mu\nu}(\mathbf{x}, t)$ to be given by

$$f^{\mu\nu} := \frac{\rho_0}{c^2_{sound}} \begin{bmatrix} -1 & \vdots & -v_0^j \\ \cdots & \cdot & \cdots \\ -v_0^i & \vdots & (c^2_{sound}\delta^{ij} - v_0^i v_0^j) \end{bmatrix}, \tag{26}$$

where μ, ν run from 0 to 4 and i, j run from 1 to 3, equation (26) can be rewritten as

$$\partial_\mu \left(f^{\mu\nu} \partial_\nu \phi_1\right) = 0. \tag{27}$$

This is where the analogy with black hole physics begins to emerge. As is well known, the d'Alambertian equation of motion for the propagation of a minimally coupled massless scalar field in a (3+1)-dimensional Lorentzian geometry is defined by

$$\Box \phi := \frac{1}{\sqrt{-g}} \partial_\mu \left(\sqrt{-g} g^{\mu\nu} \partial_\nu \phi\right) = 0. \tag{28}$$

Thus, setting $f^{\mu\nu} = \sqrt{-g} g^{\mu\nu}$, we can view the sound waves in our fluid as a massless scalar field propagating in a (3+1)-dimensional Lorentzian geometry with metric[4]

$$g_{\mu\nu} = \begin{bmatrix} -\left(c^2_{sound} - (v_0)^2\right) & \vdots & -v_0^j \\ \cdots & \cdot & \cdots \\ -v_0^i & \vdots & \delta_{ij} \end{bmatrix}. \tag{29}$$

This should seem strikingly familiar, since Hawking radiation results from the propagation of a massless scalar field in a (3+1)-dimensional Lorentzian geometry governed by an isomorphic metric. Comparing $g_{\mu\nu}$ with the Schwarzschild metric $g_{\mu\nu}^{Schwarzschild}$ in Gullstrand-Painlevé coordinates (Dardashti et al. 2017, 63), the isomorphism should be clear:[5,6]

$$g_{\mu\nu}^{Schwarzschild} = \begin{bmatrix} -(c^2 - \frac{2GM}{r}) & \vdots & -\sqrt{\frac{2GM}{r}} r^j \\ \cdots & \cdot & \cdots \\ -\sqrt{\frac{2GM}{r}} r^i & \vdots & \delta_{ij} \end{bmatrix}. \tag{30}$$

4. $\mathbf{v}_0 := \left(v_0^1, v_0^2, v_0^3\right)$ and $v_0 := \sqrt{(\mathbf{v}_0 \cdot \mathbf{v}_0)}$.

5. $\mathbf{r} := \left(r^1, r^2, r^3\right)$ and $r := \sqrt{(\mathbf{r} \cdot \mathbf{r})}$.

6. Technically speaking, $g_{\mu\nu}$ is "conformal to the Painlevé-Gullstrand form of the Schwarzschild geometry but not identical to it", but "[s]ince surface gravity and Hawking temperature are conformal invariants this is sufficient for analysing basic features of the Hawking radiation process." But to even make them conformal to each other, the speed of sound c_{sound} must be assumed to be constant (Visser 1998a, 1777-1778). This is equivalent to assuming that the acoustic excitations follow a linear dispersion relation, i.e. $\omega = c_{sound} k$.

The mathematics used to derive the emission of Hawking radiation from a Schwarzschild black hole horizon can therefore be applied equally well to derive the emission of *analogue* Hawking radiation from an acoustic horizon. We are left not only with an intuitive analogy between the two systems — fluid and astrophysical — but with an isomorphism between the mathematical models by which we believe they can be adequately described.

This isomorphism is the basis for the reasoning behind analogue experimentation — both for black holes, and in general. Given two systems described by isomorphic mathematics, advocates of analogue experimentation suggest that we should be able to draw conclusions about one based on experimental data collected on the other.

But, as we have seen above, that isomorphism can in general only be established given several significant theoretical constraints on the analogue system. For analogue black hole experiments, seven assumptions are required:

1. **Fluid dynamical**: The evolution of the bulk fluid flow can be described by the evolution of two fields: the scalar field $\rho(\mathbf{x}, t)$ and the vector field $\mathbf{v}(\mathbf{x}, t)$.

2. **Flux-free**: The fluid is flux-free, so that the continuity equation — equation (1) — holds.

3. **Newtonian**: The fluid is Newtonian — in particular, it can be described by Newton's second law.

4. **Adiabatic**: The only forces present in the fluid are gravity and pressure. This means that the evolution of the fluid must be adiabatic — or equivalently, that its viscosity is zero. The presence of turbulence, an nonadiabatic effect related to the damping effect of viscosity (Landau and Lifshitz 1959, 62, 103), would undermine this assumption.

5. **Irrotational**: The fluid is irrotational, so that $\mathbf{v} = -\nabla\phi$ for some scalar field ϕ.

6. **Barotropic**: The density $\rho(\mathbf{x}, t)$ of the fluid depends only on pressure $p(\mathbf{x}, t)$, not on temperature or other variables.

7. **Linear (dispersion)**: In the region of interest, the speed of sound is approximately constant, such that the excitations in that region (in the frame co-moving with the fluid) can be adequately described by a linear dispersion relation $\omega = c_{sound}k$ for some constant c_{sound}.[7]

8. **Linear (perturbations)**: Excitations can be accurately described as linear perturbations of the bulk fluid motion — in other words, they must be small in amplitude and accurately modelled by equations (9)-(11).

Only under these strict theoretical conditions should we expect a fluid system to act as a reliable analogue of an astrophysical black hole. And that's *even if* we ignore the controversy about whether analogue experimentation should be taken as a reliable form of inference in the first place. Furthermore, any particular experiment will have to satisfy even more fine-tuned requirements to match the specific details of the theoretical scenario that it is designed to represent. Rotating black holes, for example, present even more complications.

So even if we believe that analogue experiments can work in principle, we should only expect them to work in practice under very strict conditions. And yet, we will see in the following Sections that for analogue black hole experiments — the analogue experiments to which most experimental effort has been dedicated so far — those conditions are very rarely, if ever, satisfied.

This, I will argue, should redefine our understanding of what analogue experiments are good for. That shift in perspective will be drawn out in Section 5, based on the analysis of analogue gravity experimental research and its history that I will present next (in Sections 3 and 4).

7. **Note**: this is an assumption I'm not entirely sure about. It's implied in various papers, but at the same time the exact dispersion relation for surface gravity waves (which is in general nonlinear, but approximately linear under certain conditions) appears in almost every water-tank paper, and no-one explicitly explains how that nonlinearity is dealt with.

3 Analogue gravity, 1981–2017

Following Jacquet, Weinfurtner, et al. (2020, 2), the history of analogue gravity can be broken into three eras: 1981–2008, 2008–2017, and 2017–present. This Section will examine the first two of those eras: 1981–2008, when analogue gravity was merely a theoretical enterprise (Section 3.1), and 2008–2017, when the first analogue gravity experiments became available. I label these periods the *theory era* and the *experimental era*, respectively. In Section 3.3, I summarize the goal that seems to dominate both periods: detection of analogue phenomena in the source system to confirm the existence of corresponding phenomena in the target astrophysical system.

3.1 The theory era: 1981–2008

Unruh published 'Experimental Black-Hole Evaporation?' in 1981, but the first experiments to implement his proposal arrived in 2008. In that almost thirty-year-long period, analogue gravity remained a primarily theoretical and speculative discipline.

Some of the work in this period was pedagogical. (Visser 1998a), for example, whose exposition we followed in Section 2, goes through the calculations in (Unruh 1981) — and the underlying assumptions that they require — in much more step-by-step detail than the original paper. He then shows how to define the ergosphere, trapped regions, the acoustic apparent horizon, and the acoustic event horizon for an acoustic analogue black hole.

Other work took the analogy (or, more accurately, the isomorphism) further, and many papers assessed the experimental viability of Unruh's proposal. Each of the thirteen chapters of *Artificial Black Holes* (Novello et al. 2002) investigates a different theoretical aspect of the "two-way street" ((2002, v) between quantum field theory on curved spacetime and condensed matter physics. It reads more like a collected volume than a monograph: each chapter is written by a different set of experts, and the authors' backgrounds are diverse. Some chapters look at the theory of possible experimental protocols, others look at the theoretical issues that will have to be overcome by experimentalists, and the rest are purely forward-looking or spectulative theoretical papers — relevant to analogue gravity either because they are motivated by the newly revealed connections between QFT on curved spacetime and condensed matter physics, or because they highlight effects that might be observed in future analogue gravity experiments.[8]

As hinted by the diversity of topics in Novello et al. (2002), analogue gravity was not only about detecting Hawking radiation even in this early stage of the research programme. Indeed, Volovik (2003) is an entire monograph on the analogue *universe*, not the analogue black hole — it investigates, in even further detail than Chapter 4 of Novello et al. (2002), the connections between the superfluid quantum liquid^{3}He-A and the cosmological quantum vacuum.

However, analogue black holes and analogue Hawking radiation did dominate the early experimental research, as we will see in Section 3.2. Schützhold and Unruh (2002) were the first to suggest surface gravity waves in a flowing fluid as a possible analogue black hole system; that protocol would become the first experimental implementation of analogue gravity in 2008.

3.2 The experimental era: 2008–2017

Experimental analogue gravity developed gradually from 2008 onwards, and was initially focused on Hawking radiation — the first experiments merely displayed practically viable effective 1+1-dimensional

8. Chapter 1 is mostly pedagogic, but Section 1.4, for example, discusses several possible experimental protocols. Chapter 2 looks at Bose-Einstein Condensate analogues specifically, and Chapter 3 focuses on slow light analogues. Chapter 4 investigates the possibility of using a thin film of ^{3}He-A to model black hole formation, evaporation, and subsequent information loss to a disconnected 'baby' universe. Chapter 5 details the experimental challenges that might be encountered in trying to measure analogue Hawking radiation — specifically in superfluid ^{4}He and slow light analogue systems. Chapter 6 looks at how quantum liquids might be used to investigate open questions about the cosmological quantum vacuum. Chapter 7 proposes a new theory about the black hole event horizon: namely, that when an observer crosses a horizon, a quantum phase transition occurs. Chapter 8 brings in connections to quantum gravity, and Chapter 9 details a treatment that "provides the next order contribution after the semi-classical one, and takes into account the vacuum fluctuations of the energy-momentum tensor." Chapter 10 focuses on superfluids, and Chapter 11 looks at effective geometry in nonlinear field theory — both from the perspective of electrodynamics and gravity. Chapter 12 is titled "Non-inertial quantum mechanical fluctuations", and Chapter 13 is titled "Phonons and forces: Momentum *versus* pseudomomentum in moving fluids" (Novello et al. 2002).

black hole spacetime geometries, the next experiments observed the excitation spectrum associated with analogue Hawking radiation, and finally in 2016, both Euvé et al. (2016) and Steinhauer (2016) observed the correlations between positive and negative frequency modes that are a distinctive feature of Hawking radiation.

Philbin et al. (2008) began the experimental era, demonstrating the experimental viability of light propagation in optical fibre as a white hole analogue.[9] Soon after, Rousseaux et al. (2008) showed conversion of positive-frequency to negative-frequency modes at an effective white hole horizon — this time, using surface gravity waves as excitations in a water tank bulk fluid flow. [10] The next developments were in 2010, when bulk crystals (Belgiorno et al. 2010) and Bose-Einstein condensates (Lahav et al. 2010) were shown to be experimentally viable as effective *black* hole geometries.

In 2011, (Weinfurtner et al. 2011) made the next significant step: they observed the first *excitation spectrum* for the surface gravity waves scattering off an effective white hole horizon, using a setup similar to the one used in Rousseaux et al. (2008). The spectrum agreed with Hawking's predictions.

2012 to 2016 saw incremental progress (Jacquet, Weinfurtner, et al. 2020, 2). Negative frequency waves were observed (in addition to those observed in Weinfurtner et al. (2011)) at effective black hole horizons in various different materials (Rubino et al. 2012; McLenaghan and König 2014; Jacquet 2018). Light waves were seen tunneling across an optical horizon (Choudhary and König 2012), and polariton fluids emerged as a new experimental medium (Nguyen et al. 2015).

2016 was a pivotal year for analogue gravity research. Both (Euvé et al. 2016) and (Steinhauer 2016) observed not only excitation spectra, but the distinctive *correlations* between positive and negative modes that are thought to be an essential feature of the Hawking effect.[11] Euvé et al. (2016) revealed those correlations in a water-tank effective white hole analogue system. The experiment in Steinhauer (2016), conducted on an atomic Bose-Einstein condensate, was the first observation of positive and negative mode correlations in an analogue *black* hole system. Of his 2016 experiment, Steinhauer (2016, 964) writes, "[t]he measurement reported here verifies Hawking's calculation, which is viewed as a milestone in the quest for quantum gravity. The observation of Hawking radiation and its entanglement confirms important elements in the discussion of information loss in a real black hole."

Some experiments in this era did venture beyond Hawking radiation to investigate other analogue effects, but they were by far the exception. Wilson et al. (2011), for example, observed the dynamical Casimir effect — an effect hoped to confirm the presence of vacuum fluctuations in the cosmological quantum vacuum — in a superconducting circuit. Soon after, Jaskula et al. (2012) observed the sonic analogue of the same effect in a Bose-Einstein condensate analogue system. These experiments were the first analogues to model whole-universe effects, a direction of research suggested by theoretical work in the later chapters of Novello et al. (2002) that would not fully pick up steam until more recently.

To summarize, analogue gravity research in the 'experimental era' between 2008 and 2017 was dominated by experiments on 1+1-dimensional effective black and white hole spacetime geometries.[12] The first experiments aimed to show which effective geometries were practically viable, displaying various effects linked to Hawking radiation — including the conversion of positive to negative modes — but falling short of displaying analogue Hawking radiation in any full sense. That changed when Weinfurtner et al. observed an excitation spectrum consistent with the Hawking effect in 2011, and Euvé et al. and Steinhauer observed correlations between positive and negative modes in 2016.

9. Since a white hole is just the time reverse of a black hole, it is commonly understood that experimental results collected on analogue white holes, combined with appropriate mathematical analysis, can be interpreted as experimental results for analogue black holes.

10. This did not count as an outright observation of analogue Hawking radiation; instead, the mode conversion is a feature that we would expect to be associated with Hawking radiaiton. So the observation represented a step in the right direction. In the authors' own words, "We believe we have made the first direct observation of the conversion of incident waves with positive- into negative-frequency waves in a moving medium. In astrophysics, such a mode convsersion occurs at the event horizon of black holes. It represents the classical mechanism at the heart of Hawking radiation" Rousseaux et al. (2008, 11).

11. In fact, the full thermal excitation spectrum could not be extracted from Steinhauer (2016); that development followed in de Nova et al. (2019).

12. Of course, theoretical work continued in the background during this time.

3.3 The goals: 1981–2017

With few exceptions, the theoretical and experimental work in analogue gravity from 1981–2017 was dominated by one analogue system and one corresponding effect: the analogue black (or white) hole, and analogue Hawking radiation.

The experiments were designed to investigate the question: *do analogue black holes produce analogue Hawking radiation*? And that question was considered important to the extent that it could shed light on the question: *do astrophysical black holes produce astrophysical Hawking radiation*?

This is the interpretation of analogue gravity that has dominated the philosophy literature's perspective even in more recent years. Analogue black hole experiments, according to each of the philosophy papers so far published on the subject, aim to provide confirmation for the existence of astrophysical Hawking radiation (Dardashti et al. 2017, 2019; Crowther et al. 2019; Evans and Thébault 2020).

However, more recent experiments raise questions about whether that is now the only role for analogue gravity — and indeed, about whether it has ever been. These developments, which have dominated from 2017 onwards, will be addressed in the next Section.

4 The new frontier, 2017–future

According to Jacquet, Weinfurtner, et al. (2020, 2), the last few years have marked the start of a new era for analogue gravity. They write, "[o]ver the last few years, a new wave of experiments have appeared, facing different challenges and attempting to extend the analogy beyond the observation of the Hawking effect in the laboratory." They write that we have entered a 'new experimental age'.

Indeed, it does seem that 2017 marked a significant turning point for analogue gravity — a turning point that should be of interest not only to the physicists themselves, but to philosophers interested in the epistemological usefulness of analogue experiments.

To begin with, the research community seems to have become interested in new systems and new effects. It is no longer only, or mostly, interested in analogue black holes — we see further theoretical and experimental focus on other systems, including whole-universe analogues. And even for analogue black holes, the focus is no longer only on Hawking radiation — we see 2+1-dimensional effective rotating black hole geometries that attempt to model other effects, including superradiance.

But perhaps even more importantly, there seems to have been a fundamental shift in what the researchers are trying to accomplish. Many seem to be interested in their analogue systems — whether stationary black holes, rotating black holes, or whole universe models — not to provide confirmation for the existence of an astrophysical phenomenon like Hawking radiation, but to *detect more generalized phenomena* and/or to *explore the behaviour of the analogue systems.*

Section 4.1 will summarize the experimental developments from 2017 to the present, and Section 4.2 will show how new goals emerged alongside those developments: detection of generalized phenomena in Section 4.2.1 and exploration in 4.2.2.

4.1 New experiments

1+1-D developments

Since 2017, the 1+1-dimensional effective black hole platforms have been developed in various ways. The Steinhauer lab published further developments in 2019: they extracted the Hawking spectrum from a BEC analogue in de Nova et al. (2019), and they studied the radiation produced by an evolving effective black hole horizon in Kolobov et al. (2019).

Drori et al. (2019) reports observation of stimulated Hawking pairs in an optical analogue for the first time, using light pulses as excitations against a nonlinear fiber-optical background. Človečko et al. (2019) constructed the first effective white hole acoustic horizon in superfluid ^{3}He-B soon after.

Petty and König (2020), like Drori et al. (2019), use the optical platform. They use photonic crystal fibres to compare the Hawking process with the related process of resonant radiation.

Rousseaux and Kellay (2020) reflect on prior 1+1-dimensional water-wave experiments before introducing a new platform for analogue gravity: flowing films of soap. As a first step towards investigating that new medium, they show that it supports the creation of horizons.

2+1-D developments

In addition to the developments in 1+1 effective dimensions, analogue rotating black holes (in 2+1-effective dimensions) have emerged. Torres et al. (2017) were the first to report results from such an experiment: in their 2+1-D water-wave vortex flow system, they observe superradiant scattering from an analogue rotating black hole despite the presence of dispersive effects.

Vocke et al. (2018) extend these investigations to light, constructing an analogue black hole in a two-dimensional photon superfluid. They write, "[w]hile most analog gravity experiments are performed in 1+1 dimensions (one spatial plus time) and thus can only mimic 1+1D spacetime, we present a (room-temperature) photon superfluid where the geometry of a rotating acoustic black hole can be realized in 2+1D dimensions by an optical vortex. By measuring the local flow velocity and speed of waves in the photon superfluid, we identify a 2D region surrounded by an ergosphere and a spatially separated horizon." (1099)

Solnyshkov et al. (2019) construct an acoustic Kerr black hole in a Bose-Einstein condensate and compare its features to the features we would expect to find in an astrophysical Kerr black hole.

Torres et al. (2020) takes the water-vortex system further, aiming not only to construct an analogue rotating black hole but to explore an aspect of its behaviour: its ringdown modes. They write, "Inspired by recent analogue gravity experiments, which demonstrate that certain black hole processes take place in gravitational and hydrodynamical systems alike, we conduct an experiment to search for quasinormal mode oscillations of the free surface of a hydrodynamical vortex flow. Our results demonstrate the occurence and hint at the ubiquity of quasinormal ringing in nonequilibrium analog black hole experiments." (1)

Finally, Torres (2020) reassesses the experimental results reported in Torres et al. (2017), focusing specifically on how that experiment deviated from the regime in which supperradiance had been predicted, but nevertheless showed the expected effect. He emphasizes the importance of including and studying the effects of such deviations in future experiments.

Whole-universe developments

Other experiments have gone beyond black holes to model the whole universe. These cosmological analogue experiments take the focus away from Hawking radiation and shed light on the potential of other theoretical proposals developed in the early years of what I have called the 'theoretical era' — for example, in Volovik (2003) and the later chapters of Novello et al. (2002). The two kinds of scenario — analogue black holes vs. analogue whole universe models — are realized by different means. In the words of Jacquet, Weinfurtner, et al. (2020, 3): "[e]ffective black hole horizons are set up by means of a spatially varying background, while cosmological scenarios are realized via a rapid temporal change in the background parameters."

The precursors to this new sub-field were Wilson et al. (2011) and Jaskula et al. (2012), mentioned already in Section 3.2. Ahead of their time, the first observed the dynamical Casimir effect in a superconducting circuit, and the second observed a sonic analogue of the dynamical Casimir effect in a BEC. The Casimir effect is important for our understanding of cosmology to the extent that its existence confirms the presence of quantum fluctuations in the cosmological vacuum. But, before Wilson et al. (2011), it had never been observed.

In their words, "[o]ne of the most surprising predictions of modern quantum theory is that the vacuum of space is not empty. In fact, quantum theory predicts that it teems with virtual particles flitting in and out of existence... From early on, it was discussed whether it might be possible to more directly observe the virtual particles that compose the quantum vacuum. Forty years ago, it was suggested that a mirror undergoing relativistic motion could convert virtual photons into directly observable real photons. The phenomenon, later termed the dynamical Casimir effect, has not been demonstrated previously. Here we observe the dynamical Casimir effect in a superconducting circuit consisting of a coplanar transmission line with a tunable electrical length." Wilson et al. (2011, 376)

The more recent whole-universe experiments go even further, investigating effects like cosmological redshift and pair creation. Eckel et al. (2018) shows sound waves exhibiting the analogue of cosmological redshift and Hubble friction in a rapidly expanding ring-shaped Bose-Einstein condensate. They write, "[c]osmological expansion is central to our understanding of the Universe. Here, we experimentally create a system where fields expand in a similar way as in the Universe: an expanding, ring-shaped atomic Bose-Einstein condensate (BEC)." (1)

Wittemer et al. (2019) produces phonon pairs in an ion chain as an analogue of cosmological pair creation. "At present", they write, "the rate of expansion of our Universe is too slow to create a measurable amount of particles. However, according to our standard model of cosmology, the process of cosmological particle creation played an important role in the early Universe... In this Letter, we report on the creation of pairs of particles, precisely phonons, by inflating quantum fluctuations of the motion of trapped ions. The phonon excitation is accompanied by the creation of spatial entanglement and can be described as a squeezing operation. We explain this process as an experimental analog to the cosmological particle creation." (1)

Braden et al. (2019) observes the evolution of an analogue vacuum state of the Universe in a BEC. They presented their results at the December 2019 Royal Society meeting titled *The next generation of analouge gravity experiments*.

Other developments

Not all of the recent experimental developments have been strictly in strictly 1+1-dimensional, 2+1-dimensional, or whole-universe systems. Jacquet, Boulier, et al. (2020), for example, report on an analogue plaform that can model black holes in both 1+1 and 2+1 dimensions. Polariton fluids in microcavities, they show, are an adaptable analogue gravity medium — capable of producing both stationary and rotating analogue black holes, and thereby opening the door to "future observation of the stimulated and spontaneous Penrose and Zeld'ovich effects as well as of regimes of instabilities in black hole systems." (11)

And, of course, the theory has continued to develop alongside the experiments — often pointing towards effects or regimes that could be empirically investigated in future. Blencowe and Wang (2020) assess the promise of superconducting circtcuits as an analogue platform to study both Hawking and Unruh radiation. Wittemer et al. (2020) reflects on the results in Wittemer et al. (2019), using machine-learning analysis to suggest possible improvements to the experimental protocol that revealed analogue cosmological pair creation in 2019. They write, "we build on previous results and detail extensions of our toolbox" (Wittemer et al. 2020, 2).

Analogue gravity has therefore developed substantially since 2017, in three key areas: 1+1-dimensional analogue black hole experiments, 2+1-dimensional analogue black hole experiments, and whole-universe experiments. The summary presented above is not exhaustive — several other developments, both experimental and theoretical, have been made — but it does, I hope, provide an accurate picture of the direction in which analogue gravity is headed.

In the next Section, I hope to provide an even clearer understanding of that direction by looking not only at *what* has been observed since 2017, but at *why* those observations have been made. I will argue that analogue gravity has changed direction not only in its content, but also in its goals. In Section 5, I will argue that this shift of focus reveals new roles for analogue experiments in general.

4.2 New goals

The recent work in analogue gravity has a new goal in a very simple sense: it is no longer only concerned about Hawking radiation. As we saw in Section 4.1, researchers are now also interested in effects like superradiance and cosmological pair creation. Relatedly, they are working to expand their experimental toolkit to be able to see 'new' effects, and to see 'old' effects (in particular, Hawking radiation) more easily.

Wittemer et al. (2020, 2,8), for example, write: "we build on previous results and detail extensions of our toolbox... The next step could be to consider more general time dependencies which opens the door for more analogies (e.g. the Sauter-Schwinger effect)." They are interested in 'extending their toolbox' to see new analogue effects.

Jacquet, Boulier, et al. (2020, 2) praise their polariton fluid analogue gravity platform because it can produce a variety of analogue effects easily and efficiently: "[t]his technique has the advantage of being widely adaptable to various cavity geometries without requiring the mechanical manufacturing of a new geometry for each gravity scenario to be investigated". And they are interested in seeing new effects, as well: later on, they write that the ergoregion and inner horizon in their rotating black hole geometry together "open the door to future observation of the stimulated and spontaneous Penrose and Zeld'ovich effects as well as of regimes of instabilities in black hole systems" Jacquet, Boulier, et al. (2020, 11).

On the promise of superconducting circuit analogue gravity systems, Blencowe and Wang (2020, 15) write: "we have described possible schemes for realizing analogues of the Hawking and (oscillatory) Unruh effects using superconducting microwave circuits with Josephson junction and FBAR elements. Superconducting circuits are, in principle, ideally suited for demonstrating such microwave photon production from vacuum processes, due to their low noise, controllability and existing advanced microwave fabrication and quantum-limited detector capabilities".

Furthermore, some authors are still pursuing what I will call the 'old goal': they are running their experiments and conducting their theoretical analysis primarily to confirm the existence of inaccessible astrophysical phenomena. Steinhauer's recent work can plausibly be interpreted along those lines (see e.g. de Nova et al. (2019)), as can some of the other publications that do still focus on Hawking radiation. Rosenberg (2020, 1), for example, writes very recently that "[a]nalogue systems are used to test theories of predicted phenomena that are hard to observe directly".

However, these developments in researchers' aims — interest in new analogue phenomena and continued interest in detecting analogue Hawking radiation for the purpose of confirming the existence of astrophysical Hawking radiation — are to be expected, and they are not my main interest here.

My main interest is in cases where researchers are interested in analogue phenomena — whether Hawking radiation or otherwise — for reasons *other* than direct confirmation of a corresponding effect in the target system. An abundance of such cases have presented themselves in the research literature. I split them into two categories: detecting generalized gravity phenomena (Section 4.2.1) and exploring the behaviour of analogue gravity systems (Section 4.2.2).

4.2.1 Detecting generalized gravity phenomena

The reasoning behind analogue gravity research, in its early days, was the following. There is some phenomenon in the target (astrophysical) system that we cannot access; we can produce an analogue of that phenomenon in the accessible source (analogue) system; that analogue phenomenon is not a genuine instance of the phenomenon of interest, but we can use mathematical similarities between the source and target to use its presence in the source as evidence for its presence in the target.

One of the changes in aims that have emerged in the past few years, especially since 2017, is a move away from this focus on extrapolation to the target system — which is, in any case, the highly controversial aspect of analogue experimentation — and towards detection of phenomena whose manifestations in the source system are considered genuine, and not only analogues of the 'real thing'. In this sense the phenomena of interest are becoming more general — or, in some cases, generalized.

Hawking radiation is a case in point. The phenomenon was originally predicted in an astrophysical context, but more and more authors in the analogue gravity literature are emphasizing that this was pure accident. Hawking radiation, they write, is in fact a much more general effect that could have been derived in any number of contexts. And — even if their ability to confirm the existence of astrophysical radiation is unclear — analogue systems are perfectly capable of detecting genuine instances of this more general notion of Hawking radiation, a kinematic effect which some authors dub the *Hawking process*. The phenomenon itself has been generalized, and that generalized phenomenon is what many experimentalists are trying to detect — not only because of what it might mean for astrophysical black holes, but for its own sake.

Aguero-Santacruz and Bermudez (2020, 14), for example, explicitly argue that the term 'Hawking radiation' should be generalized. They write, "instead of collecting several related facts or 'stamps' and giving a different name to each one — astrophysical Hawking radiation, aquatic Hawking radiation, sonic Hawking radiation, optical Hawking radiation — we should generalize the concept of Hawking radiation. Yes, it was discovered originally in astrophysics, but it is realized in the same way in all analogue systems" (14).

Petty and König (2020, 1,2) write, "[w]hile Hawking radiation itself is strictly defined as spontaneous pair creation near the event horizon of an astrophysical black hole, it is one particular instance of a more general effect of emission into positive and negative norm partner modes which we could call the Hawking process... To date, the Hawking process has been studied in a huge variety of condensed matter systems".

Similarly, Rosenberg (2020, 7-8) emphasizes that "Hawking radiation is a universal geometric effect that emerges because of conversion of modes at a horizon, regardless of the microscopic physics that create the background space-time geometry. The same (generalized) derivation applies for both astrophysical black holes and analogue systems. This established universality proved insightful for both gravity and optics (arguably solving the trans-Planckian problem and discovering negative frequencies in optics are two examples)."

Rousseaux and Kellay (2020, 2) are perhaps most adamant about the existence of a generalized Hawking effect, of which analogues are able to detect genuine instances: "Let us dismiss from the start any misconceptions about Hawking radiation: this is not a pure quantum effect that can only occur in astrophysics! It turns out that Hawking's prediction was made historically in an astrophysical context with gravitational objects like black holes which act as amplifiers (like a Hi-fi system) of quantum noise (as discussed by Unruh), namely pairs of particles-antiparticles that would be separated by the tidal forces in the vicinity of an event horizon. Hence, the Hawking effect is primarily a wave mechanical effect, with many purely classical attributes that can be verified in a classical analogue gravity experiment. Its astrophysics exemplification has a classical counterpart in the mode mixing between positive and negative energy modes that will be detailed in the following as modes of opposite relative frequency in moving fluid media".

Hawking radiation is not the only example. Other phenomena have emerged which are general enough be directly detected in analogue gravity systems. Take superradiance, an effect predicted by Penrose in 1969 for rotating astrophysical black holes. Two years later, Zel'dovich generalized his idea, establishing a general prediction about the amplification of signals by rotating bodies (Cromb et al. 2020, 1069).

This generalized effect, known as Zel'dovich amplification, can be observed in analogue systems. And it has become a focus of recent research, as reported by Cromb et al. (2020). The abstract of their paper reads: "In 1971, Zel'dovich predicted that quantum fluctuations and classical waves reflected from a rotating absorbing cylinder will gain energy and be amplified. This concept, which is a key step towards the understanding that black holes may amplify quantum fluctuations, has not been verified experimentally owing to the challenging experimental requirement that the cylinder rotation rate must be larger than the incoming wave frequency. Here, we demonstrate experimentally that these conditions can be satisfied with acoustic waves. We show that low-frequency acoustic modes with orbital angular momentum are transmitted through an absorbing disk and amplified by up to 30% or more when the disk rotation rate satisfies the Zel'dovich condition. These experiments address an outstanding problem in fundamental physics and have implications for future research into the extraction of energy from rotating systems" (1069). A few months before, Gooding (2020) had published theoretical analysis of the same effect.

Another interesting example is the dynamical Casimir effect. It is especially interesting because it seems to have been detected in small-scale analogue gravity systems both in a generalized form (for which the detection counts as a genuine detection of the dynamical Casimir effect) and in a merely analogue form (for which the detection counts only as an observation of an *analogue* of the dynamical Casimir effect). This shows how more recent and more traditional goals can overlap even for a single effect.

In particular, Wilson et al. (2011) observe *the dynamical Casimir effect proper* in a superconducting circuit — they observe the conversion of virtual photons into observable real photons. Their experiment is only *analogue* in its scale: it observes the effect in a table-top superconducting circuit, not in the cosmological vacuum. Jaskula et al. (2012), on the other hand, do not observe the conversion of virtual photons into real ones. They observe the production of correlated *acoustic* pairs, thereby observing an acoustic *analogue* of the dynamical Casimir effect.[13]

So, overall, we are seeing a shift in focus towards phenomana that analogue systems can directly detect and claims that analogue gravity experiments can directly confirm. Philosophically speaking, this can often involve a change in the way that we delineate the type-token distinction for the phenomena of interest. For Hawking radiation, for example, *astrophysical Hawking radiation* used to be considered a different type of phenomenon than *sonic Hawking radiation*, and we therefore needed to rely on an extra bridge principle to claim to be able to learn about one from the other. But now there is a new type at play: *generalized Hawking radiation* or *the Hawking process*. Tokens of that new type can be detected directly in analogue

13. Another possible example of this new aim for analogue gravity — direct detection of generalized phenomena — may appear in Leonhardt (2020). In the words of Jacquet, Weinfurtner, et al. (2020, 4), Leonhardt "presents the Lifshitz theory of the cosmological constant that he has recently developed, and argues that future experiments of analogue gravity could test these predictions". Leonhardt might, plausibly, mean that his theory is general enough that it can be directly tested in systems that we would typically think of as 'analogue' gravity systems. But his goals might be more traditional — he might instead mean that his theory can be indirectly tested by observing its analogue in a small-scale source system and then using mathematical similarities with the target cosmological system to extrapolate that result. At present this line of research is not developed enough for its goals to be clear.

gravity systems.

There are some important points to note about this move towards direct detection of generalized phenomena. First, it is sometimes analogue investigations of the original kind (with the original goal of indirect detection supplemented with extrapolation to the target system) that can lead to generalization. Traditional analogue experiments can play a part in making us realize that a concept is much more general than we had originally thought. This seems to have played at least some part in the generalization of Hawking radiation: it was the theoretical discovery of analogue Hawking radiation, and its subsequent experimental detection, that pushed both theorists and experimentalists to think of Hawking radiation as a very general process that just happened to be originally predicted in an astrophysical context.

But, on the other hand, a distinction can still be made between generalized and ungeneralized phenomena. In particular, there can still be open questions about whether an ungeneralized phenomenon is just an instance of the corresponding generalized one, or whether it is a special case that we should have special concerns or questions about.

This seems, plausibly, to be the case for Hawking radiation. Even though analogue experiments are able to directly detect generalized Hawking radiation, thereby confirming the existence of this generalized effect, there are still open questions about whether *astrophysical black holes in particular* should be expected to exhibit Hawking radiation in any form. This is because quantum gravity might, plausibly, have features that undermine or 'cancel out' the Hawking effect — features that we should not expect to be present in the vast majority of other systems that do exhibit the generalized Hawking effect.[14]

Finally, this new goal — detection of generalized phenomena in analogue systems — makes the term 'analogue' for those systems somewhat redundant, meaningless, or even misleading. If an 'analogue gravity' system is detecting phenomena directly, it is not acting as an analogue in any meaningful sense — except, as in the case of the dynamical Casimir effect, with respect to scale. I acknowledge this redundancy, but to maintain consistency with the existing literature, I will continue to use the term 'analogue' to describe the small-scale, laboratory-compatible systems that we have come to call 'analogue gravity' systems. However, it is important to be clear that such systems are not always detecting *analogue* phenomena.

4.2.2 Exploring the behaviour of analogue gravity systems

Alongside its newfound interest in detection of generalized phenomena, recent analogue gravity research seems to have developed *exploratory* goals. Two kinds of exploration seem to be of particular interest: open-ended exploration of the analogue system (by which I mean any small-scale 'source' system that was originally conceived as an analogue of a much larger-scale gravitational system), and exploration of the robustness of analogue effects (by which I mean any effects detected in the small-scale 'source' or 'analogue' system, whether detected directly as generalized phenomena or otherwise). I will discuss each in turn, and then raise some connections and implications brought about by these newfound goals.

Open-ended exploration

Open-ended exploration of the analogue system can have many motivations — to discover new features and effects, to observe the time-evolution of a system, to investigate causal relationships, to find unexpected outcomes, to list just a few examples. In general it aims to go beyond our predictive capacities in a fairly undirected manner; to *look at the analogue system and see what we find.*

Several examples of this kind of exploration have emerged in recent analogue gravity research. Eckel et al. (2018), for example, show sound waves exhibiting cosmological redshift and Hubble friction in a rapidly expanding ring-shaped Bose-Einstein condensate. Their aims seem to be exploratory in exactly the sense I just outlined: they "experimentally create a system where fields expand in a similar way as in the Universe"(1), sit back, and watch what happens. They do not seem to be testing a hypothesis. Instead they are exploring the behaviour of the analogue system — in part to compare what they observe with what they expect to see in certain cosmological models, in part to assess the reliability and/or limitations of the analogy between the analogue system and the Universe, and in part to learn more about the analogue system for its own sake.

They write, summarizing their observations in the Introduction to the paper: "[c]osmological expansion is central to our understanding of the Universe. Here, we experimentally create a system where fields

14. This is where the Trans-Planckian problem comes in for astrophysical Hawking radiation.

expand in a similar way as in the Universe: an expanding, ring-shaped atomic Bose-Einstein condensate (BEC). Our laboratory test bed demonstrates three effects associated with the expanding Universe. First, we conclusively demonstrate a redshifting of phonons analogous to the redshifting of photons, which provided the first evidence for an expanding universe. Second, we observe hints of "Hubble friction" that damps the redshifted fields. Third, we observe a process in which energy is rapidly transferred from a homogenous radial mode into azimuthal modes by a nonlinear, turbulent cascade, reminiscent of that seen in some models of preheating at the end of cosmological inflation. Experiments such as these can thus emulate both linear and nonlinear field theoretic aspects of cosmology" (Eckel et al. 2018, 1).

Solnyshkov et al. (2019) seems exploratory in a similar sense. They set up an acoustic analogue rotating black hole and explore its features, with particular emphasis on the features that it shares with astrophysical Kerr black holes. They write, "[w]e implement an acoustic Kerr black hole with quantized angular momentum in a Bose-Einstein condensate. We show that the condensate's metric is equivalent to the Kerr's one, exhibiting a horizon and an ergosphere. We confirm that this metric is obeyed not only by weak density waves, but also by quantum vortices which behave as massive test particles. We use these topological defects to demonstrate a quantum Penrose effect, extracting the rotation energy of the black hole by quanta of angular momentum. The particle trajectories are well described by the timelike geodesics of the Kerr metric, confirming the potential of analogue quantum gravity" (1).

In this case, the authors seem especially focussed on exploring the similarities and differences between astrophysical Kerr black holes and the acoustic analogue Kerr black hole that they have built. Having established those similarities and differences, they might be able to use their analogue system for other purposes in future — including, for example, to test hypotheses about Kerr black holes using the analogue system. Exploration, in this sense, can be a precursor to more traditional hypothesis-directed analogue experiments.

Kolobov et al. (2019) look at Hawking radiation through an exploratory lens. They track the behaviour of the acoustic Hawking radiation emanating from an analogue BEC black hole horizon as that horizon evolves, in a study that Jacquet, Weinfurtner, et al. (2020, 3) explicitly label "exploration of the Hawking spectrum from an evolving effective black hole horizon". Kolobov et al. (2019, 1) write: "[s]pontaneous Hawking radiation in analogue black holes was suggested, developed theoretically, and observed. The observation was made at a particular time in the evoluion of the analogue black hole in a Bose-Einstein condensate. Here, we repeat the observation at various times and follow the time-evolution of Hawking radiation in an analogue black hole. We compare and contrast the evolution with the predictions for real black holes". So, again, we see a recent paper whose aims are: explore, compare, and contrast.

They conclude that "the analogue black hole exhibits four time periods with qualitatively different behaviors", noting both similarities and differences with the expected behaviour of astrophysical black holes. For example, they note that "the ramp-up and spontaneous periods are analogous to the expected evolution of a real black hole. However, after the spontaneous period, an inner horizon forms, which dramatically alters the further evolution... For a real black hole, lasing would rely on Lorentz violation, which might occur at an energy much higher than the Planck scale. The life of the analogue black hole ends with the shrinking of the region outside the horizon, rather than inside" Kolobov et al. (2019, 9-10).

Wittemer et al. (2019), like Eckel et al. (2018), explore whole-universe effects. Their aims seems even more well-defined: they are interested specifically in exploring causal connections and in exploring the outcomes related to different dynamics. In their words, "**our platform allows one to study the causal connections of squeezing, pair creation, and entanglement** and might permit one to cross-fertilize between concepts in cosmology and applications of quantum information processing" (Wittemer et al. 2019, 1, emphasis added); "[d]epending on the interpretation of the time coordinate (e.g., transformation from proper to conformal time), we may **simulate different dynamics of the related scale paremeter and investigate its consequences**" (5, emphasis added). So they are using their analogue system to *see what might happen* in processes like cosmological particle creation. They intend to interrogate causal relationships that they have not seen before and do not yet theoretically understand. And they intend to observe what *might* happen, *if* a system (cosmological or otherwise) were governed by various different underlying dynamics.

Torres et al. (2020) explore a 2+1-D analogue rotating black hole "to search for quasinormal mode oscillations of the free surface of a hydrodynamical vortex flow". Their results "demonstrate the occurence [of such oscillations] and hint at the ubiquity of quasinormal ringing in nonequilibrium analog[ue] black hole experiments" Torres et al. (2020, 1).

Exploration of robustness

Some researchers' exploratory goals seem less open-ended. Several recent papers have aimed specifically to push predicted effects to their limits — to go beyond the regime in which an effect is predicted, and see how far outside that regime they can go without destroying the effect. They are exploring the *robustness* of predicted phenomena.

Recall, from Section 2, that even the most straightforward analogue gravity system — a stationary eternal Schwarzschild black hole — should, in theory, only be able to mirror the behaviour of an astrophysical Schwarzschild black hole when several non-trivial conditions are satisfied. We labelled these conditions 1 through 8: 1. the **fluid dynamical** condition, 2. the **flux-free** condition, 3. the **Newtonian** condition, 4. the **adiabatic** condition, 5. the **irrotational** condition, 6. the **barotropic** condition, 7. the **linear (dispersion)** condition, and finally, 8. the **linear (perturbations)** condition. Several of these conditions — especially adiabaticity and linear dispersion – are incredibly difficult to satisfy in practice, which is one of the reasons why analogue gravity remained a theoretical discipline for so long.

But if we see analogue gravity effects even when these conditions are *not* satisfied, then those effects must be more robust than our theory expects them to be. Such observations have been made since the early years of the 'experimental era', but in recent years their importance has been recognized by theorists and experimentalists alike. Indeed, researchers have begun to make exploring the robustness of predicted phenomena a central *goal* of their research.

Torres et al. (2017), for example, observed superradiant scattering from an analogue rotating black hole despite the presence of vorticity and dispersive effects that take it outside the regime in which superradiant scattering should be expected. In a follow-up paper presented at the 2019 Royal Society conference titled *The next generation of analogue gravity experiments*, Torres explicitly argues that this unexpected robustness of the analogue superradiant effect — and not only the experiment's implications for our views on whether astrophysical superradiance exists — should be seen as one of the central findings of the experiment, and as a foundation for further research. He writes,

> "The Nottingham experiment was motivated by the analogy between surface waves on a flowing fluid and fields in curved space-time. However, it is known that this analogy holds only under specific conditions, which were not all satisfied in this experiment. In particular, it was clear that vorticity effects were significantly closer to the vortex core and that dispersive effects could not be neglected, implying that a direct analogy between the vortex flow of the Nottingham experiment and a rotating black hole was impossible. In this paper, we have somehow increased this gap by showing that the vortex flow was not a perfect absorber, unlike a black hole. **In our view, this gap makes the observation of superradiance in the Nottingham experiment even more interesting as it strengthened the robustness of the effect but also opened new questions to answer.**
> ...
> It is clear from this example that the deviations from the analogue regime (vorticity, dispersion, etc.) have spurred the development of our concepts to new regimes which deepened our understanding of various processes such as superradiance or vortex relaxation. These extra effects, inherently present in any experiment, compelled us to extend our ideas and are the sources of knew knowledge. **We therefore believe that performing analogue gravity experiments that include these extra features, instead of suppressing them, will stimulate new problems to solve and will result in advances not only in the field of analogue gravity, but also in condensed matter and gravitational physics**."

(Torres 2020, 11, emphasis added)

Jacquet, Weinfurtner, et al. (2020, 4, emphasis my own), in their analysis of the same paper, highlight the importance of the observed unexpected robustness. They write, "Torres calculates the spectrum of superradiance in dispersive media. His careful analysis of the system reveals that some waves are partially reflected by the drain that generates the vortex flow. This observation is in contrast to the behaviour of waves on Kerr black holes. And, yet, the interplay between vorticity and dispersion does not prevent superradiant amplification of incoming waves at the ergosurface. **Torres builds on this demonstration of the robustness of the effect to encourage researchers to push their platforms beyond the strict 'analogue regime' in search of new effects of waves in media**."

Researchers associated with at least two of the four main groups currently conducting experimental research in analogue gravity are interested in pursuing this kind of goal. Torres published the two papers discussed above as a PhD student in Silke Weinfurtner's Quantum Gravity Laboratory group at the University of Nottingham. Germain Rousseaux, who runs his own analogue gravity group at the Pprime Institute in Poitiers, France, is currently working on a paper whose sole goal is to explore the robustness of the analogue Hawking effect in the face of non-linear effects. It has also been clear in informal conversations with several experimentalists — including Germain Rousseaux and Sorbonne postdoc Maxime Jacquet — that the unexpected robustness of the Hawking effect within the analogue regime is considered exciting, both as an outcome of existing research and as a basis for further research.

We see examples of similar sentiment in Drori et al. (2019) and Rosenberg (2020). Drori et al. (2019) observe unexpected robustness in the production of stimulated Hawking pairs in an optical analogue, and explicitly describe that robustness as "remarkable": "[i]t is quite remarkable that both the violent pulse dynamics and the other effects of nonlinear fiber optics are not affecting the essential physics of the optical event horizon… In addition, this robustness and the demonstration of probe-controlled extreme frequency conversions — between positive and negative frequencies — seem to appear as important insights on their own" (4).

Rosenberg (2020) notes the unexpected robustness demonstrated in Drori et al. (2019), and suggests that this robustness should guide future research: "[t]he demonstrated robustness of the Hawking effect is calling for new experiments to lead the way" (Rosenberg 2020, 10).

Jacquet, Boulier, et al. (2020, 11) hint that they are interested in exploring regimes in which various effects are *not* robust — namely, "regimes of instabilities in black hole systems". This is an investigation of robustness in its own way: by learning more about the conditions under which black hole effects are unstable, we would be learning about the conditions under which they are stable.

Connections and implications

Overlapping goals

The exploratory goals described above need not be mutually exclusive. Open-ended exploration can reveal unexpected robustness of predicted phenomena, and investigations that intend to investigate the robustness of predicted phenomena can lead us towards other unexpected effects, which we can then explore further.

This interplay appears, for example, in Jacquet, Weinfurtner, et al. (2020, 4)'s analysis of Torres (2020). After highlighting the unexpected robustness revealed by Torres's experiment, they write that "Torres builds on this demonstration of the robustness of the effect to encourage researchers to push their platforms beyond the strict 'analogue regime' in search of new effects of waves in media". So observation of unexpected robustness has created a drive to explore the system further "in search of new effects".

Petty and König (2020) explore the similarities and differences between Hawking radiation and resonant radiation (a form of what I have called 'open-ended exploration') and also "investigate the limits of effects of this type, discovering a new regime of record efficiency" (1) (clearly an investigation of robustness).

Exploration as an avenue to technological advances and/or unexpected applications

Exploration, of both varieties, can lead to unexpected technnological advances and applications in other fields. The "regime of record efficiency" discovered by Petty and König (2020) can be used to construct a highly tunable laser source. In the authors' own words, "[w]e measure a 60% energy conversion efficiency from a pump to a visible femtosecond pulse by the process of resonant, and demonstrate its extraordinary tunability in wavelength and bandwidth. Beyond analogue gravity, these femtosecond visible pulses provide a desirable laser source useful across a variety of modern scientific fields... So in the quest to perform analogue gravity experiments we have inadvertently produced an important laser application" (1, 8).

Wittemer et al. (2020) realize that the experimental protocol developed in Wittemer et al. (2019), their recent exploratory paper, could be generalized for applications in quantum information processing. They write, “The next step could be to consider more general time dependencies which opens the door for more analogies (e.g. the Sauter-Schwinger effect). As another generalization, one could take into account more modes (not just the out-of-phase mode), which would facilitate the study of frequency-dependent spectra. Even though it is non-trivial to achieve full quantum control of a larger number of ions, many laboratories worldwide are pursuing this goal — mostly motivated by large-scale quantum information processing applications” Wittemer et al. (2020, 8).

So exploration of analogue gravity systems can be useful for reasons completely unrelated to gravity. By exploring the analogue systems, researchers are exploring avenues that might lead to unexpected applications in other contexts.

The creation of a two-way knowledge flow

Exploration of the analogue system can also facilitate a two-way knowledge flow between the system that would traditionally be labeled the ‘source’ and the system that would traditionally be labeled the ‘target’. This is made clear, for example, in the section of Barceló (2019) titled *What are we learning on the gravitational side?* He writes, “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 by taking a few lessons back to the gravitational realm**” Barceló (2019, 212, emphasis added). Or, in even more detail, see the following excerpt:

> "[B]eyond 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. Then, boundary conditions at the singularity can have a strong impact on the global behaviour of the system and even make the very existence of horizons a transient phenomenon. This issue relates to earlier question as to whether long-living 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.
>
> ...
>
> 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."
>
> Barceló (2019, 212-213)

Exploring the analogue system can teach us about what *might be there* in the corresponding gravitational system, in the same way that exploring the theoretical features of gravitational frameworks have taught us about what to expect in gravitational analogues.

The connection between generalization and exploration

The two new goals that I have discussed in this section — direct detection of generalized phenomena and exploration of the analogue system — are, or at least can be, connected. The connection is especially strong in one direction: from exploration to generalization. Exploration of the analogue system can reveal new phenomena, or reveal the generality of known phenomena. Those phenomena can then then be directly detected in the analogue system.

We can see the seeds of this kind of connection in Torres et al. (2020). They explore a vortex flow analogue black hole to search for quasinormal mode oscillations. And, upon observing such oscillations, they write that their results "hint at the **ubiquity** of quasinormal ringing in nonequilibrium analog[ue] black hole experiments" Torres et al. (2020, 1, emphasis added). It seems that they might be well on their way to generalizing their concept of quasinormal ringing — motivated, to begin with, by having explored the analogue manifestations of that phenomenon.

Leonhardt (2020) seems to be similar, except it reveals a connection between exploration and *direct testing of a theory*, not direct detection of a specific phenomenon. But the idea is much the same: exploration of the analogue system led to the development of a general theory — one that might have both cosmological and condensed-matter implications — which, in the future, should be testable in the analogue system. Speaking of the Lifshitz theory of the cosmological constant, which he himself developed, Leonhardt writes, "**[a]nalogues of gravity have played a decisive role in developing the theory and analogues may be important for testing crucial components of the theory in experiments**... While the physics of the Casimir effect of separate bodies is well understood, the Casimir force inside materials has remained a fairly underdeveloped subject. There is enormous scope for resesearch in both theory and experiment. If the Lifshitz theory of the cosmological constant does indeed agree with the astronomical facts in detail, either directly or after minor modifications, **it would not only shed light on a rather dark subject in cosmology, but also motivate a better understanding of the forces acting on the nanoscale in the everyday world**" (12, emphasis added).

Thus, the two new goals that seem to be guiding recent research in analogue gravity are not only interesting and valuable in isolation. They play into each other, and into the rest of our knowledge base, in interesting ways. I have shown here that the two goals — detection of generalized phenomena and exploration — can overlap. They can lead to unexpected technological advances and applications; they can contribute to the creation of a two-way knowledge flow between the analogue 'source' and the astrophysical target. And, finally, they can feed into each other: exploration in particular can lead the way to generalization of phenomena and future direct detection of those generalized phenomena analogue systems.

4.2.3 Are these goals really new?

The separation into eras that I have presented — 1981–2008 as the theoretical era, 2008–2017 as the experimental era with traditional goals, and 2017–future as a new era guided by new goals — is not strict. As we have already seen, some ideas that did not come to the fore of the literature until very recently were proposed and even investigated empirically early on, but by a minority of the community. The same holds for the new goals I have described. We can see hints of these goals developing early on.

Michel and Parentani (2014, 1), for example, probe the robustness of Hawking radiation by studying "how the spectrum deviates from thermality when reducing the maximal flow velocity, with a particular attention to subcritical flows". For such flows, they find that "the emission spectrum is strongly suppressed, and that its Planckian character is completely lost" (1). Robertson et al. (2016) examine the relationship between the thermality of the analogue Hawking spectrum and the frequency of incoming waves for a physical setup that matches the one used by surface gravity wave analogue black hole experiments. Again their work can be interpreted as an early exploration of the robustness of Hawking radiation.

It is also somewhat unclear when the goal of detecting generalized Hawking radiation truly developed. It has been particularly emphasized in explicit terms since 2017. But it is possible to find lots of talk before then, especially among theorists, about minimal conditions for establishing Hawking radiation and the idea that Hawking radiation is a kinematical not dynamical effect.[15] So the idea of using analogue experiments to directly detect a generalized version of Hawking radiation may well have become a goal of analogue gravity well before 2017, and indeed before any experiments at all were available.

Weinfurtner et al. (2011, 1) certainly hint that they are at least interested in the generality of Hawking radiation. They write: "[g]iven the close relationship between stimulated and spontaneous emission, our findings attest to the generality of the Hawking process". So even in 2011, in one of the first experimental realizations of analogue gravity, perhaps what they were trying to do was less like *indirectly detecting astrophysical Hawking radiation*, and more like *showing that the Hawking effect is a general one.*

On the whole it seems that many goals have been around in analogue gravity for a long time. But in the last few years, the balance of emphasis has shifted. It has shifted away from indirect detection of

15. See, for example, Novello et al. (2002, Section 1.5), Visser (1998b, 3436), and Visser (2003, 649-650).

astrophysical phenomena, a controversial goal, and towards exploration and direct detection of generalized phenomena, much less controversial goals.

And, what is certainly clear is that these less controversial goals — regardless of how long they have been around — have not yet been acknowledged or discussed by the philosophy community.

4.2.4 Summary

We have seen in this Section that the question of interest for analogue gravity used to be: do astrophysical systems produce some inaccessible phenomenon of interest, based on whether analogue systems exhibit the corresponding analogue phenomenon? Or, at least, that is how the philosophy literature has painted the early years of the research programme.

Other goals have emerged more recently, and seem to concern two other questions. First: do analogue systems produce some generalized phenomenon of interest (for which detection in the analogue system amounts to direct detection of that phenomenon, not just detection of an *analogue* of that phenomenon)?

Second: what do we see when we explore the behaviour of the analogue system? In particular, what happens to an analogue gravity system with particular features and parameters — for example, how does such a system evolve over time? And, relatedly but often independently, under what conditions do analogue gravity systems produce some predicted phenomenon of interest?

In the next Section I will argue that these new goals for analogue gravity can be generalized, revealing new roles for all analogue experiments.

5 New roles for analogue experiments

The previous Section reveals new roles for analogue gravity experiments. They can be used to directly detect instantiations of generalized concepts, and they can be used to explore — both open-endedly and to investigate limits on the conditions in which a phenomenon of interest will present itself.

None of these roles have anything to do with analogue gravity in particular, and they could easily be instantiated by analogue experiments in other contexts. The question then becomes: why are these new roles exciting? Why should we be interested in detecting instantiations of generalized concepts? Why should we be interested in observing unexpected robustness in analogue systems, and why should we be interested in exploring the behaviour of analogue phenomena?

I argue that we should be interested in detecting generalized phenomena in analogue systems for the same reason that we are interested in detecting any phenomena in standard (i.e. 'non-analogue') experiments: to confirm or disconfirm the effects' existence and investigate their properties (Section 5.1).

We should be interested in open-ended exploration because it can reveal new and unexpected results, which can teach us about other systems — including, perhaps, the analouge's 'target' system — in unexpected ways (Section 5.2.1).

And, finally, we should be interested in exploring the robustness of predicted phenomena for two reasons (Section 5.2.2). First, such exploration can confirm existing theoretical predictions about the robustness of those phenomena. And second, it can confirm the existence of robustness that has not yet been predicted, in two senses. It can confirm the existence of robustness that contradicts our existing theoretical predictions, or it can confirm the existence of robustness that — for one reason or another — we have not yet theorized about.

5.1 Direct detection of general/generalized phenomena

Using analogue experiments to provide confirmation for the existence of phenomena in the target system is controversial.[16] Why? Because it requires us to make a significant inductive leap, based on analogical reasoning, to infer that the source and target systems should exhibit similar behaviour with respect to the effect of interest.

But this is an issue only if the effect of interest is specific to the target system, such that whatever we see in the source system *is* merely similar — an 'analogue' — of that effect. If the effect is — or becomes

16. See, for example, Dardashti et al. (2017), Dardashti et al. (2019), Crowther et al. (2019), and Evans and Thébault (2020).

— more general, such that it can be directly detected in the source system, then our analogue experiment just becomes a standard experiment, and is useful for exactly the same reasons.

It can confirm the existence of the general effect of interest, and it can confirm various features and properties of that effect.

Furthermore, as we have seen in analogue gravity, analogue experiments of the traditional controversial kind can lead the way to generalization. Having pushed us to discover unexpected generality of phenomena, they can then play a role in testing and detecting those phenomena.

So, as far as detection with respect to general phenomena is concerned, the usefulness of analogue experimentation is twofold. It can be exactly what leads us to the realization that certain phenomena are more general than we might otherwise have thought. And it can play a direct role in the empirical investigation of general/generalized phenomena.

5.2 Exploration

5.2.1 Open-ended exploration

It is possible to explore the behaviour of an analogue system in a fairly undirected way — to see how it behaves under different conditions, or to see how it evolves over time, or for any number of other reasons. Indeed, we have seen that this kind of exploration is becoming a significant focus of modern analogue gravity resesarch.

But why is it useful to explore the analogue or 'source' system, not to test any hypothesis but just to see what we find? Some reasons have already been hinted at in the previous Section. We saw that this kind of open-ended exploration can act as an avenue to technological advances and unforseen applications in other fields. We saw, also, that this kind of exploration can pave the way for generalization of phenomena — which, in turn, can provide the benefits noted above in Section 5.1. Furthermore, we saw that open-ended exploration can support the creation of a two-way knowledge flow between the source and target systems, by which we can learn about one system from the other and vice versa.

This two-way knowledge flow might intially appear to suffer from exactly the same problem as traditional analogue experimentation. How, one might ask, can such a two-way knowledge flow work, if not by the traditional (and controversial) method of using detection in the source system to confirm hypotheses about the target system?

The answer is to look beyond immediate confirmation and think about the future development of the fields at hand. Every time we explore an analogue system, we see correlations between the presence of certain features and the presence of others. Sometimes we even see *causal* connections. And sometimes we see entirely new, previously unobserved and unpredicted phenomena.

So, by exploring an analogue system in an open-ended way, we are building up a bank of possible scenarios and their consequences. We are learning about which features, in general, are related to which others. And we are even learning about *how* those features might be related — via which theoretical pathways, or via which causal mechanisms. All of that information would be extremely useful if we were to discover, in the future, that the target system *did* have a set of features whose consequences we have observed in the analogue system. In this sense, we can use open-ended exploration of the analogue to investigate hypothetical scenarios for the target system — to learn about what the target system *might* be like, *if* certain conditions held true. All of this is possible even if we do not feel that we are currently in a position to gain confirmation for the existence of phenomena based on experimental tests conducted in the analogue system.

Furthermore, open-ended exploration of the analogue system can show researchers of the target system, especially theorists, where to look. If, for example, we see an unexpected and unpredicted effect in the analogue system, we can use that as motivation to set theorists to work on investigating whether the target system should exhibit an analogous effect. If we observe a previously mysterious causal mechanism in action, we can direct theorists towards investigating whether a similar causal mechanism might govern the behaviour of the target system. Those theoretical exploits could then lead us even further, revealing other new and interesting results about the target system.

This two-way knowledge flow is therefore a key benefit of open-ended exploration in the analogue system. It will come up again in Section 6.2.

Of course, alongside these benefits — technological advances, generalization of phenomena, and creation of a two-way knowledge flow — exploration of the analogue system is interesting for its own sake. There is no reason why knowledge about astrophysics should be considered intrinsically more valuable than knowledge about condensed matter physics, and the same should hold for the fields invoked by any analogue experiment. We should give the analogue system credit for being interesting and valuable in itself.

5.2.2 Exploration of robustness

Exploration in the other sense — exploration of the robustness of effects in the analogue system — can also support technological advances, generalization of phenomena, and the creation of a two-way knowledge flow between the source and target.

But it is especially useful in two other ways: it can confirm predicted robustness and reveal unexpected robustness, both outcomes that deepen our understanding of the analogue system. That deepened understanding can indirectly teach us about the target system, contributing to the two-way knowledge flow, by teaching us about how the phenomena of interest are related to changes various underlying parameters.

Confirming predicted robustness

By exploring the robustness of phenomena in the analogue system, we can confirm existing theoretical predictions. Suppose we already have a theoretical argument which predicts that the phenomenon of interest should be insensitive to changes in certain features — call them features $\{f_1, f_2, ..., f_n\}$.

Suppose, further, that we are able to manipulate those features in the analogue system. Then we can use empirical investigation of the analogue system to confirm or disconfirm our theoretical argument. By manipulating features $\{f_1, f_2, ..., f_n\}$ within the analogue system — in other words, by exploring robustness in the analogue system — we can test whether the phenomenon of interest is indeed insensitive to changes in those features. Exploration of analogue phenomena can therefore confirm existing theoretical predictions about robustness. That confirmation

Revealing unexpected robustness

Experiments that explore analogue phenomena should not only be expected to confirm predicted robustness: they can equally well reveal unpredicted robustness. They might empirically reveal robustness that contradicts our existing theoretical predictions, thereby disconfirming our theory about the relationship between different features of the analogue system. This disconfirmation, in turn, might be able to point us towards an analogous error in our theory about the relationship between features of the corresponding target regime.

Or they might empirically reveal universality that we have not yet theorized about — either because we happen not to have devoted time to that particular theoretical problem, or because we do not have the theoretical tools that we would need to solve it. In addition to teaching us about the behaviour of a new relationship between a phenomenon of interest and underlying parameters — knowledge which could eventually be transferred to the target system in the manner outlined in Section 5.2.1 — this kind of empirical confirmation can show us where to direct our theoretical energy. By revealing a new robustness phenomenon, which we do not yet understand, such experiments can point us towards areas that might be productive grounds for further theoretical research.

Analogue experiments can therefore do much more than provide confirmation for hypotheses about their target systems. They can directly detect general and/or recently generalized phenomena and they can explore — both in an open-ended way and to test the robustness of phenomena. These results can indirectly teach us about the target system, especially by showing how the target system *might* behave *if* it had certain features and by pointing theorists towards promising avenues for further research.

6 Outlook

These new roles for analogue experiments shift the focus away from confirming hypotheses about the target system. But what are the implications of that shift?

In Section 6.1 I will discuss the possible impact on research programmes, and in Section 6.2 I will explain why the *analogy* in analogue experimentation still has a role to play.

6.1 What happens to the research programme(s)?

6.1.1 Old experiments reinterpreted

Even once the goals of an analogue research project have shifted, old experiments remain valuable resources. Often their results can be reinterpreted to inform the new goals — for example, features that had previously been considered unimportant can become significant results.

Weinfurtner et al. (2011, 1), for example, observed analogue Hawking radiation in a water tank despite the presence of turbulent and non-linear effects. They write: "[t]he presence of thermal emission in our physical system, which exhibits turbulence, viscosity, and nonlinearities, would indicate the generic nature of the Hawking thermal process". This means, based on Section 2, that their experiment did not satisfy all of the conditions required to establish the analogy with astrophysical black holes. Condition 4., the adiabatic assumption, cannot be satisfied by any system that has a non-zero viscosity and/or exhibits turbulence. At the same time, conditions 7. and 8. — linearity of the dispersion relation and the perturbations — were likely undermined by the "non-linear effects".

Thus, although Weinfurtner et al. (2011) has been interpreted by many as a step towards empirical confirmation of astrophysical Hawking radiation (see e.g. Unruh (2014)), it could equally well be interpreted as empirical confirmation of generalized Hawking radiation, or empirical confirmation of the unexpected universality of analogue Hawking radiation.

When an analogue research programme adopts new goals, its old experiments can be reinterpreted in light of those goals.

6.1.2 Research programmes redirected

A shift in goals can redirect an entire research programme. Even if the results of old experiments are not rendered useless, as explained in Section 6.1.1 above, the community may well choose to adopt a different focus in their *new* experiments. Forward-looking experiments may be set up, for example, to look specifically at robustness of predicted phenomena. Or they may be set up to support open-ended exploration — in which case they will be designed to be as flexible as possible, allowing for a wide array of parameters to be adjusted easily and efficiently.

Analogue gravity does seem to have been redirected in light of the new goals that I have highlighted in this paper. We see this, for example, in the forward-looking sentiment in Torres (2020, 11). He writes, "We therefore believe that performing analogue gravity experiments that include these extra features, instead of suppressing them, will stimulate new problems to solve and will result in advances not only in the field of analogue gravity, but also in condensed matter and gravitational physics" — thereby encouraging the research community to perform new experiments that *focus* on exploring robustness.

We see it, also, in forthcoming work: Rousseaux, for example, is currently working on a paper whose sole goal is to investigate the robustness of analogue Hawking radiation with respect to nonlinear effects.[17]

When a research community adopts new goals, they adopt a new *domain of interest*. And, alongside reinterpreting old experiments that overlap peripherally with that domain, they will seek to construct new experiments that lie fully within it.

6.2 What happens to the analogy?

It would be sensible to ask, at this point: if analogue experimentation is no longer concerned primarily with using the analogue system to confirm features of the target system, then what role does the analogy play?

It is true that the analogy is put on the back burner. But I argue that it is not rendered useless or pointless.

First, it is important to note that traditional analogue experiments, which aim to confirm features of their target systems, have not completely died out (see, for example, the beginning of Section 4.2). And

17. Personal communication.

they need not; probably even should not. Their persistence does not in any way undermine the arguments I have presented in this paper. I have merely articulated some *other* roles that analogue experiments might play — roles that come along with the added benefit of evading the controversy that has plagued analogue experimentation in its traditional form.

Furthermore, even the new goals that I have articulated here can use the analogy to teach us about the target system, albeit indirectly and in a hypothetical way. This is where the two-way knowledge flow, introduced in Section 4.2.2 and discussed in more detail in Sections 5.2.1 and 5.2.2, comes in.

By investigating the analogue system we are learning about the relationships between different sets of features. We can learn, for example, that some phenomenon of interest seems to be insensitive to changes in certain features but highly sensitive to changes in others. This kind of knowledge can teach us about how the target system *might* behave *if* it had certain features, even if we are not yet confident about whether it does have those features.

As we learn more and more about the target system in question, we will learn more and more about its underlying structure. Eventually, we might learn that it does have the same type of structure as the analogue system in relevant ways — that they are the same 'type' of system — in which case we would be able to uncontroversially infer that they should behave in similar ways. This potential for future transfer of evidence highlights the value in exploring as many effects as possible within as many different analogue systems as possible. Every new investigation of an analogue system, even if it does not immediately tell us anything about the target system, tells us more about how the target system might behave. The more effects we explore in analogue systems with different underlying features, the more possible scenarios we will understand. We will come to know what to expect not only if the target system turns out to have an underlying structure defined by features $\{a_1, ..., a_n\}$, but also if it turns out to have a structure defined by features $\{b_1, ..., b_n\}$, or features $\{c_1, ..., c_n\}$ — or any other type of structure whose behaviour we have already investigated in an analogue system.

Even further, as already discussed in Sections 5.2.1 and 5.2.2, the effects that we observe in the source system can point theorists of the target system in new ant potentially fruitful directions.

So the new roles for analogue experiments that I have articulated in this paper — direct detection of general/generalized phenomena and exploration of the analogue system — do not render the analogy redundant. Instead they keep the analogy alive and well behind the scenes.

7 Conclusion

Within the philosophy literature, analogue experiments have so far been discussed as if they are useful if they are able to confirm hypotheses about their target systems, and useless if they are unable to provide that confirmation. In the face of significant doubt about the reliability of such evidence transfer, this has left the literature with a rather bleak outlook on the value of analogue experimentation.

I have argued here that our outlook should not be so bleak, because analogue experiments are able to do more than directly confirm hypotheses about their target systems. They can be used to directly detect general and/or recently generalized phenomena; they can be used to explore the analogue system in an open-ended way; and they can be used to explore the robustness of analogue phenomena.

Such investigations are clearly interesting and valuable in themselves. They teach us about the source system, which is arguably no less intrinsically interesting than the target system. But I have argued that at the same time, they are interesting and valuable — albeit indirectly — for our understanding of the target system. By building up a bank of possible scenarios and their corresponding behaviours, we are able to learn more about what the target system might look like, if it turned out to be structured in various different ways. And by revealing relationships between phenomena and underlying parameters that we do not yet understand, we are able to direct theoreticians towards promising theoretical problems.

Even analogue experiments that were built with the traditional goal in mind can be used for these other purposes. The results articulated in Weinfurtner et al. (2011), for example, can be taken to confirm the unexpected robustness of analogue Hawking radiation with respect to non-linear effects. That interpretation can be drawn even if Weinfurtner et al. (2011) originally conducted their experiment to confirm the existence of astrophysical Hawking radiation.

But even more importantly, it seems as if the new goals that I have articulated in this paper are quickly becoming the intended goals of analogue gravity research. The next generation of analogue gravity experiments will, it seems, be about much more than whether astrophysical Hawking radiation exists.

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