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What's so special about black hole simulations?

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Abstract

This paper defends an epistemology for terrestrial black hole simulations based on Hesse's theory of material analogy in science. We outline the main verdicts and recommendations of this approach, arguing that they not only fit the experimental practice but are also more credible than those supported by competing proposals. Our analysis questions the role of so-called 'universality results' in establishing an evidential function for current experiments, while also escaping the conclusion that we learn nothing about black holes from simulating them.

Keywords Hawking radiation · Analogy · Black hole thermodynamics · Simulation · Universality

1 Introduction

Black hole simulations have recently gained attention among philosophers of physics (Crowther et al., 2019; Dardashti et al., 2017; Field, 2025; Hangleiter et al., 2022; Sterrett, 2017; Thébault, 2019). The experimental practice traces back to Hawking's (1975) striking demonstration that semi-classical assumptions, viz., approximations of quantum behavior in a relativistic framework, entail black hole radiation. Specifically, modeling black holes by the Schwarzschild solution to Einstein's equations, whose metric is:

$$ds^2 = -(1 - \frac{2M}{R})dt^2 + (1 - \frac{2M}{R})^{-1}dr^2 + r^2(d\theta^2 + sin^2\theta d\phi^2) \quad (1)$$

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and taking a Hermitian scalar field operator ϕ obeying the covariant wave equation $\phi_{ab}g^{ab} = 0$ in curved spacetime with metric g, a thermal emission of photons near the event horizon can be derived, strikingly proportional to the black hole's surface gravity κ. This result allows for a redescription of a black hole in terms of κ and horizon area A that is analogous to the relation of temperature with entropy in thermodynamics (Bekenstein, 1972). As suggestive as Hawking's result may be for the physics of black holes, a *trans-Planckian problem* remains. If, using Hawking's model, we trace the stories of emitted photons back to their distant past, they appear to come out of ultra-high energy regimes, with wavelengths below the Planck scale. Relativistic assumptions are expected to break down at those regimes, casting doubt on the credibility of Hawking's model. At the same time, the means for directly testing Hawking's prediction are currently missing.

To overcome the impasse, Unruh (1981) imagined building a surrogate black hole, where quantized linear sound fluctuations ('phonons') play the role of massless scalar fields (photons) and the acceleration of a homogeneous fluid the role of a fixed but curved spacetime. A crucial observation is that, at ordinary energy regimes, phonons obey mathematically the same equations as massless scalar fields in Hawking's model:

$$ds^2 = -c^2dt^2 + \left(dr \pm c\frac{{r_0}^2}{r^2}dt\right) + r^2\left(d\theta^2 + sin^2\theta\ d\phi^2\right), \tag{2}$$

which leads, after a change of coordinates, to the equation:

$$ds^2 = -c^2(1 - \frac{{r_0}^4}{r^4})d\tau^2 + (1 - \frac{{r_0}^4}{r^4})^{-1} dr^2 + r^2(d\theta^2 + sin^2\theta\ d\phi^2) \tag{3}$$

The explanation is that an accelerated fluid imposes a metric whose features are entirely determined by the velocity of sound and that of the fluid. When the latter quantities match, we have an acoustic horizon. Under an appropriate choice of radial velocity for the fluid, (3) is analogous to the Schwarzschild metric (1). Unruh called the resulting system a 'dumb hole', to signal that phonons are trapped by the converging fluid in much the same way that photons are by gravity in a black hole. He further noted that one can re-write Hawking's derivations to predict that sonic radiation occurs near a dumb hole's horizon, with a temperature proportional to the rate of change of fluid velocity at that horizon:

$$T = \frac{1}{2\pi}\frac{dv}{dr}|_{v=c} \tag{4}$$

There are now many proposed realizations of Unruh's 'dumb hole' (Barcelo, 2019), with many tests suggesting that the prediction of a Hawking-like radiation holds true. Tests on surface water waves gave an early indication of a thermal effect near a dumb hole horizon (Rousseaux et al., 2008; Weinfurtner et al., 2011). Other approaches push the analogy further, for example by attempting to measure sonic radiation in a homogeneous medium (Lahav et al., 2010) as in Unruh's original design, or in systems in which quantum fluctuations are directly accessible (Steinhauer, 2016). From an epistemological perspective, however, there remains an open question as to whether these tests could tell us anything about Hawking radiation. The ability of black hole simulations to reveal surprising properties of the systems being tested is beyond dispute. With regards to the question whether simulations can help us assess black hole radiation, instead, significant divergence exists. In the philosophical literature, this divergence is represented in rather stark ways by two opposite viewpoints. On one hand, Dardashti et al. (2017) have argued that inferences from black hole simulations are supported by a special class of *universality results*, allegedly probing their capacity to significantly confirm Hawking's prediction. On the other hand, Crowther et al. (2019) have defended a skeptical outlook, claiming that, in the absence of access to black holes, the simulations are uninformative. Further contributions in the current philosophy of physics literature fall within one of these two camps (Dardashti et al., 2019; Field, 2025; Hangleiter et al., 2022; Thébault, 2019).

In this paper, we propose a third approach to the epistemology of black hole simulations – one that we believe is closer to Unruh's original motivation for analogue experiments. We argue that the right way of looking at the experimental practice is neither Dardashti et al.'s universality-based justification nor Crowther et al.'s skepticism. In our *analogy-based* account, black hole simulations play a non-negligible role in the assessment of Hawking's prediction mainly based upon the recognition of the important similarities brought out by Unruh's (1981) work. In particular, Unruh's interest in dumb holes rested on the observation that, just as semi-classical equations break down at ultra-high energies, so also by approximating (3) to the hydrodynamic limit we obtain the same high energies for emitted phonons. In the latter case, however, the atomic theory of matter prevents energy regimes with frequencies much lower than interatomic spacing. The dispersion relation, i.e., the relation between frequency and wavenumber, is accordingly different in an atomic fluid than in a continuum. Observing analogue radiation is thus interesting insofar as we may expect a similar high-energy cutoff in the gravitational case. Starting from this and drawing upon Hesse's (1963) theory of *material analogy,* we claim that the evidential status of black hole simulations should be reconstructed not in terms of the discovery of a universal behavior but rather in terms of the identification of a significant *material analogue* for the assessment of the trans-Planckian problem. What we mean is that the role of black hole simulations in the assessment of Hawking's prediction turns on a set of physical similarities between black and dumb holes that are accessible to working experts and whose recognition does not presuppose the empirical adequacy of Hawking's semi-classical model. In defense of our alternative, we argue that it better reflects the current experimental practice and that it offers more reliable methodological guidance for physicists than other accounts in the current philosophical literature.

The following sections will spell out our case for the analogy-based approach in detail. Specifically, Sect. 1.1 starts out by critically reviewing the recent philosophical literature on black hole simulations. Section 2 defends our approach by reference to Hesse's theory of material analogy in science. Section 4 highlights the main advantages of our proposal compared to the alternatives. Section 4 concludes with a summary of the arguments.

2 Existing accounts

Using a surrogate to investigate the properties of an inaccessible system is a common practice in science (Bartha, 2009). In the case of black hole simulations, a large variety of terrestrial surrogates have been devised. In Weinfurtner et al.'s (2011) experiment with surface water waves, for instance, the proposed realization is entirely fluid-dynamic. The speed of water flowing in a shallow trough system impedes water waves from traveling upstream. The test consists in verifying that some surface waves still convert into deep water waves. Other experimental approaches, instead, seek to observe a sonic radiation effect in highly stable homogeneous media (Steinhauer, 2016). Sometimes, this is achieved indirectly, by simulating an analogue of a white hole and inferring radiation from the behavior of in-going modes and the symmetry of physical laws (Euvé et al., 2016); in other tests, a dumb hole system more similar to what Unruh had imagined is attempted. Due to their stability at low temperatures, Bose–Einstein condensates are thought to offer some of the best conditions for isolating a sonic radiation effect separate from other flow turbulence effects (Garay et al., 2000). Experimental noise can also be reduced by other means, such as more complex geometries or via optical analogues (Rosenberg, 2020). The number of proposed realizations of dumb holes keeps growing (Barcelo, 2019).

How should these and other attempts at simulating black holes be interpreted? From an epistemological viewpoint, the variety of experimental approaches represents a first turning point, since it is not obvious how it should be understood. On the one hand, existing approaches can be viewed as different approximations to the original experimental design outlined by Unruh (1981): from purely classical systems that replicate the geometric structure of a horizon (e.g., Rousseaux et al., 2008; Weinfurtner et al., 2011), to quantum systems that attempt to detect signals directly comparable to Hawking radiation in black holes (e.g., Steinhauer, 2016). On the other hand, it is also possible to interpret the variety of simulations as aiming to uncover some highly general fact about the physics of horizons, which occurs independently of any specific physical realization. In this case, the variety of purported analogue realizations is not merely a *pragmatic* feature dictated by difficulties in obtaining an unambiguous thermal signal, but has an *evidential* component to it, being itself a source of relevant information. Additionally, a related question of epistemological interest concerns the relation between terrestrial simulations and their intended targets – black holes. A traditional view in philosophy distinguishes two senses of analogy in science, possessing distinct epistemological profiles: *formal* and *material* (Hesse, 1963:32). The former refers to cases where there is a one-to-one correspondence between the properties and relations of two domains or systems, but where the latter are otherwise unrelated: for instance, when one finds out that notions in quantum mechanics can be applied to financial transactions (Arioli & Valente, 2021). This evidentially thin sense of analogy contrasts with the material one, in which inductive inferences about the target system can be justified by means of non-formal similarities. For instance, extrapolations from mice to humans are typically underwritten by similarities in biological features, so that defeasible inferences can often be drawn from, e.g., a given drug's effects on mice to its similar effects on humans.

Recent contributions by Dardashti et al., 2017 and Crowther et al., 2019, respectively, have mostly assumed that black hole simulations fall under the category of formally analogous systems, while disagreeing about other aspects of the reconstruction. In defending that black hole simulations can confirm Hawking radiation, Dardashti et al. (2017) have pointed to the variety of experimental realizations and the availability of 'universality theorems' for Hawking radiation as central features. Universality theorems are analytic results establishing that Hawking radiation follows invariably (no matter the microphysical details) from assuming a set of physical conditions of a general (multiply realizable) kind. In Unruh & Schützhold's (2005) theorem, these conditions are: (a) there exists a freely falling frame for observers near the event horizon; (b) the particles flowing out of the horizon are born in their 'ground state' with respect to freely falling observers; (c) the evolution of outgoing particles is adiabatic.[1] The position that Dardashti et al. (2017) reach, based on the above reconstruction, is that the practice of black hole simulation highlights a new form of scientific inference altogether. In their view, observations in diverse terrestrial simulations, when paired with a universality result to the effect that a thermal effect is insensitive to type of physical realization, form evidence that "Hawking radiation…is independent of the details of the underlying microphysics" (2019:4) and is accordingly robust to trans-Planckian energy regimes. The main novelty of the inferential practice lies in the fact that, while taking off from a mere syntactic isomorphism between Hawking's model for black holes and physical models for dumb holes (i.e., from merely formal analogies), black hole simulations are nonetheless capable of providing relatively strong evidence for the prediction of Hawking radiation.[2] In a related article, Dardashti et al. (2019) provide a Bayesian analysis in support of this conclusion.

The strong contentions by Dardashti et al. have generated resistance among philosophers of a skeptical bent (Crowther et al., 2019; Field, 2025). For our purposes, it will suffice to note that the criticisms are correct insofar as Dardashti et al.'s arguments do not vindicate the most high-sounding claims in their contribution. A key claim of theirs is that "we can plausibly take the work of Unruh and Schützhold to be an argument for *both* the robustness and the universality of the Hawking effect" (2019:4). In fact, the insensitivity to type of physical realization established by current universality results is not evidence for the robustness of Hawking radiation to trans-Planckian regimes. A universality theorem such as Unruh & Schützhold's (2005) *would be* evidence for Hawking radiation *if* we had independent evidence

[1] Other results mentioned by Dardashti et al. (2017) include Barcelo et al.'s (2009) and Coutant et al.'s (2012).

[2] Dardashti et al. (2019) additionally stress that black hole simulations involve "learning about the world by manipulating it" (2019:2) and "new evidence" (3). However, many ordinary analogical inferences in science involve manipulation and collection of new evidence: e.g., learning about humans from manipulating mice.

that conditions (a)-(c) hold for black holes. But, as Unruh & Schützhold (2005) themselves note, counterexamples to (a)-(c) "do not appear to be unphysical" (11). Absent further reason to think there is an intimate connection between dumb and black holes, the variety of analogue realizations to which Dardashti et al. appeal can hardly be much evidence for Hawking radiation, except in a weak enumerative sense. The epistemic situation is different from (among other things) working with *model organisms*, in which generalizations about a whole class of organisms are based on evidence from representative instances (Ankeny & Leonelli, 2021). In the latter case, a key driver of the extrapolation is the assumption of common ancestry. Conversely, on Dardashti et al.'s reconstruction, diverse realizations appear to be evidence for Hawking radiation only insofar as they are instances of the same *postulated* class of physical phenomena. But if the reconstruction is merely enumerative, their evidential weight is negligible: enumerative induction is known to be especially weak when there is antecedent knowledge of differences between observed and predicted instances, as in this case.[3]

Crowther et al. (2019) have used the flaws of Dardashti et al.'s arguments to establish a stronger claim, viz., that we cannot learn anything about black holes from current simulations. But while we agree with their criticism of Dardashti et al.'s position, Crowther et al.'s argument for the more general conclusion that black hole simulations are uninformative in cosmology raises several concerns. They contend that seemingly evidential pathways to Hawking's prediction "beg the question" (2019:3705), since any argument for Hawking radiation from analogue simulations "crucially rests on the assumption that quantum field theory (QFT) is applicable to [the target]" (3705). However, we find that Crowther et al. have yet to articulate a credible explanation for why this makes black hole simulations uninformative. On one hand, one may interpret their circularity objection as the argument that, since QFT is not well-confirmed, and since Hawking's derivations require QFT, terrestrial simulations cannot be evidence for Hawking radiation. This argument proves too much (cf. Lange, 2019; Evans & Thébault, 2020). When in *Sidereus Nuncius* Galilei argued that the Moon features mountains and valleys, based on the similarities between the "wavy lines" (1610:53) on its surface and the shadows that mountains cast on valleys, the hypothesis that light behaves on the Moon in straight lines just as it does on Earth was not well-confirmed, and yet was required to derive the prediction of lunar mountains. Applying Crowther et al.'s reasoning, we must rule out (implausibly) any confirmation of Galilei's hypothesis from the similarities of lunar wavy lines with terrestrial shadows. On the other hand, Crowther et al. may be read as claiming that the lack of experimental access to a target prevents confirmation of a prediction about the target from observations in a surrogate. As they write: "in those cases of material models and simulations where the target system is experimentally accessible, the fact that they can yield confirmation is reflective of the ability of the

[3] It also follows that there would be no basis for asserting, as the authors do, that "the strength or quality of the inferences via analogue simulation is much greater than that of those via analogical reasoning" (2017:68). Cf. Thebault (2019:312) for an even stronger claim about the simulations: "It is thus plausible to think of analogue experiments as prospective means for providing confirmatory support that is *substantial* [sic], rather than merely incremental".

models and simulations to be tested" (3724). However, the criterion of confirmability suggested by the passages is questionable. For instance, observed properties of stars (e.g., Cepheids's temperature) are routinely used to predict unobserved properties of more distant stars, despite our inability to access them (Lange, 2004). Hence, the criterion of empirical accessibility sets too high of a standard with regards to which predictions are capable of being confirmed.

To summarize, we agree with critics of Dardashti et al. that current universality results do not support enthusiastic assessments about black hole simulations. At the same time, we also believe that the shortcomings of the universality-based justification are not indicative of a general incapacity of black hole simulations to fulfill an evidential role in cosmology. In the next section, we start explaining our alternative viewpoint.

3 Material analogy

Here is a brief statement of our position. We interpret the experimental practice of black hole simulations as aiming to address a specific problem situation, viz., the trans-Planckian problem, via a specific strategy, viz., engineering a *material analogue* of a black hole (Hesse, 1963). This is a system that, while differing in many ways from the target, presents sufficient similarities and no critical differences to help extrapolate useful information about it, albeit in a merely limited and defeasible way. One of the main sources of information concerns the extent to which infinitary assumptions in the model for analogue black holes pose trouble for the occurrence of a radiation effect in the simulation. Physical considerations to be discussed below contribute to supposing that, if analogue radiation is observed, trans-Planckian regimes may not pose as large of an obstacle for Hawking radiation as initially thought. Compared to a universality-based justification, then, on our approach the variety of realizations of analogue radiation does not have evidential value *per se*: more than just adding instances to the generalization that a thermal effect is insensitive to type of physical realization, a simulation is valuable insofar as it usefully analogizes the trans-Planckian problem. Its main job is to exploit a series of known or expected features of black hole behavior that emerge to expert judgment – all of which are independent of the question of a semi-classical model's empirical adequacy – to help reduce the initial gap between one's confidence in the semi-classical model and that in Hawking's bold prediction.[4] This gap is generated by the trans-Planckian problem.

The inspiration for our account comes from Hesse (1963). In seminal work, Hesse has defended the epistemological distinctiveness of a class of analogies that she calls 'material' and that play a "predictive" (42) role in science, in supporting yet untested

[4] In the previous terminology, we give a mostly *pragmatic* interpretation of the existing variety of experimental approaches to black hole simulations, while acknowledging only a derivative evidential role (see Sect. 4).

hypotheses. To clarify this notion and explain its privileged status, Hesse has put forward the following requirements for *material analogy* between source and target:

(1) *Materiality*: The known similarities must be "material" or "pre-theoretic" (Hesse, 1963:32) – in a distinctive sense to be discussed below;
(2) *Relevance*: The known similarities must be causally (or explanatorily) relevant to the occurrence of the predicted similarities (Hesse, 1963:67)[5];
(3) *No-Critical-Difference*: There must be no known or expected differences which directly undermine the analogy's tenability (Hesse, 1963:70).

The applicability of material analogy to black hole simulations has encountered skepticism from authors in the current debate (Dardashti et al., 2019:2). In what follows, we aim to overturn this verdict, by showing that the conditions for material analogy are satisfied.

Two elements of the following reconstruction should be made explicit. Regarding the *problem situation*, we assume that a non-zero credence to the semi-classical model's being adequate for black holes (up to some degree of approximation) is permitted, but that the trans-Planckian problem mandates a strictly lower credence to Hawking's prediction, due to our ignorance of micro-physical details of radiation. It is only relative to this problem situation and accompanying expectations about what is plausible to assume in the situation that it makes sense to ask whether black hole simulations can be evidence for Hawking radiation. The *object of analysis* will then be a prototypical case of testing a classical out-going sonic radiation effect in the vicinity of an artificial horizon, where the test medium can be safely assumed to be homogeneous and with a dispersion relation that diverges from that described by classical dynamics at high energies. In what follows, we will take no stance as to whether any simulation has yet realized the prototypical one closely enough. Furthermore, the type of experiments that we target below are specifically those of the 'classical' stimulated variety, as in Unruh's original experimental design. While there have been attempts at observing spontaneous 'quantum' versions of the radiation effect (Steinhauer, 2016), we do not consider them here. One reason is simply dialectical: if we can show that classical simulations can function as evidential tools in cosmology, the verdict would be *a fortiori* plausible for simulations of the quantum variety.

The argument that, relative to the problem situation, the prototypical simulation satisfies the conditions of material analogy can be summed up as follows. First, we have the empirical premise that simulations resemble black holes in relevant kinematic aspects: horizon stability and the mode of propagation of scalar waves in general relativity are relevantly similar to, respectively, artificially generated horizons and the way sound propagates in a fluid (Barcelo et al., 2009; Leonhardt & Philbin, 2008). Secondly, we have the further premise that, while source and target are likely dissimilar in many dynamical respects, this is not yet a defeater for the analogy, since the relevant microphysical aspects should not be read off directly

[5] Hesse (1963:77) requires *causal connections* "in a scientifically acceptable sense". See also Nappo (2021).

from general relativity, but from a (quantum) theory of gravity. In this regard, critical differences between the behavior of horizons at extremes are not known. Importantly, neither of the above premises strictly depends on the adequacy of Hawking's semi-classical model for black holes and can therefore be used legitimately in induction. The following sub-sections flesh out this case in more detail.

3.1 Materiality

Dardashti et al. (2019) write that "analogue simulation… does not involve a material analogy in the sense of Hesse since there is not a *physical property* common between target and source" (2). Their argument assumes that 'material analogy' requires that the *same* properties of the source are instantiated in the target. However, this is a highly conservative reading of Hesse's condition. Among other things, Hesse's book-length treatment includes a discussion of "analogue machines" (1963:92) in science, where the source is not readily available but "built in order to simulate the [target]" (92). As Hesse writes, analogue machines are "useful and necessary as predictive models precisely in those cases where the material substance of parts of the analogue is not essential…, but where the mutual relations of the parts are essential" (92). She adds that inferences from analogue machines may still count as material ("do not… provide counterexamples to the conditions suggested", 92) despite the absence of physical properties common to source and target. On a more liberal (and textually plausible) reading, Hesse's condition requires solely that there be similarities among properties of source and target that could be recognized *before* and *independently* of the analogical inference, in virtue of the language and assumptions that a scientific community shares (Hesse, 1963:15). 'Material similarity' in this sense can obtain among properties that are not of the same physical type – including, but not limited to, cases of inferences from analogue machines. Moreover, and most crucially for our argument, a respect of similarity is to be classified as 'material' on Hesse's view *relative* to a scientific community and based on the language and assumptions that, *at a given time*, that community shares: "it is in contrast with these novelties, which may be called *theoretical statements*," Hesse writes, "that certain at present agreed kinds of description may be called [material]" (1963:15). Far from being set in stone, what counts as a 'material' similarity evolves with the growth of science.[6]

Understood in this way, various similarities between black and dumb holes can be classified as material. As a premise, we may recall that the description of a black hole as a region of space where gravity is so strong as to entrap light requires no more than classical physics.[7] With general relativity, confidence in the existence of black holes has surged, to the point that it is now taken for granted.[8] For the working physicist,

[6] See also Hesse's (1963) discussion on the uses of material analogy in quantum physics: "it need not trouble us that what stands in the place of the observation language here is…the language of classical physics… for we have already agreed that *what counts as an observation language is pragmatically relative*" (48, our emphasis).

[7] John Mitchell and Pierre Simon Laplace independently hypothesized black holes from Newtonian physics.

[8] Penrose shared the Nobel prize in physics for "the discovery that black hole formation is a robust prediction of general relativity" (https://www.nobelprize.org/prizes/physics/2020/penrose/facts/), in work dating to the 1960s.

the macro-level resemblances with sound being entrapped in a converging fluid are immediate. Unruh (2008) recounts using the analogy of a fish screaming inside a waterfall in a seminar in 1972 as an intuitive illustration of photons falling into a black hole. Although assenting to the relevant macro-level resemblances requires an acquaintance with basic notions in relativity, they are practically uncontroversial given the knowledge and assumptions of the current physics community. Their recognition in no way depends on the acceptance of Hawking's semi-classical model as adequate for black holes. As Visser et al. (2002) note: "ideas along these lines have… been quietly in circulation almost since the inception of general relativity" (2). Consequently, the requirement that the similarities can be recognized *before* and *independently* of the analogical inference is satisfied.

By recalling the full extent of accepted physical knowledge about black holes, further candidates for material similarities emerge (cf. Table 1). The most important ones are in broadly kinematic respects (Leonhardt & Philbin, 2008). On one hand, the equivalence between the propagation of sound and light (in terms of scalar waves) was already noted by Moncrief (1980), which led to the assumption of fixing velocity in developing the theory for both quantities. On the other hand, a long-lived horizon in the analogue system, by which the emission of radiation can be induced, is a kinematic phenomenon. Its stability allows for the fundamental characteristics of the horizon to emerge (in the same way as light-crossing time does for black holes). Additionally, high frequencies are expected to obtain on a micro-physical scale for both scalar fields and sound waves, leading to analogous high energy

Table 1 Stylized representation of similarities between black holes and dumb holes. By the *materiality condition*, only known material similarities can figure in an analogical argument with predictive use

Respect	Dumb holes (*source*)	Black holes (*target*)	Type	Status
Geometry	Fluid flow induces curved causal structure of horizon	Space–time geometry induces curved causal structure of horizon	Material	Known
Horizon stability	Acoustic horizon as a stable surface beyond which no sound can escape	Event horizon as a stable surface beyond which no light can (seemingly) escape	Material	Known
Propagation type	Phonon propagation is (approximately) 'wave-like'	Photon propagation is (approximately) 'wave-like'	Material	Known
Propagation speed	There is an upper bound speed to phonon propagation	There is an upper bound speed to photon propagation	Material	Known
High energies	Propagation can be affected by high-energy micro-scale	Propagation can be affected by high-energy micro-scale	Material	Known
Dynamics	On Unruh's model, phonons obey analogous Eq. (3)	On a semi-classical model, photons obey Eq. (1)	Formal	Known
Radiation prediction	Sonic radiation predicted by Unruh's derivation	Radiation predicted by Hawking's derivation	Formal	Known
Mode conversion at the horizon	In-going phonons convert to outgoing near the acoustic horizon	In-going photons become outgoing near the event horizon	Material	Unknown

problems. Again, it would be wrong to assume that, since physical theory is required to express these aspects of resemblance, they cannot be 'material' in Hesse's sense.[9] The terms adopted in expressing them do not in any sense represent a 'novelty' for the scientifically accepted language. The corresponding facts are widely agreed upon as part of our knowledge relative to the problem situation. Most importantly, the details of Hawking's semi-classical model are not needed to recognize the similarities as such. This marks an important difference with similarities that depend on the acceptance of Hawking's model and that, consequently, cannot be used in induction.

Of course, the above considerations should not deter us from also acknowledging differences between black holes and their terrestrial analogues (so-called 'negative analogies') – as well as many other aspects about which we do not know if the analogy holds ('neutral analogies'). Among other things, there is an obvious difference between the process whereby the spacetime geometry is generated: artificial black holes are created by moving media, but in general relativity the same role is played by the mass as stated by the Einstein field equations. Moreover, our ignorance concerning the regularization of waves at extremes shows that the analogy can be affected by dynamical or scaling aspects that are theoretically not well-described. The fact that the respects of similarity that we can count on for inference are limited to broadly kinematic ones motivates our cautious assessment about the evidential status of black hole simulations: while the experiments can be helpful in assessing Hawking's prediction, significant confirmation of Hawking radiation is only achievable by other means, such as direct observation. However, we will argue that critical differences are not known and that, therefore, there is potential for a limited evidential use of black hole simulations.[10] Before that, let's clarify why the material similarities satisfy Hesse's requirement of relevance.

3.2 Relevance

Can the material similarities in broadly kinematic respects alone make a difference to the standing of Hawking's prediction of black hole radiation? In what follows, two arguments will be reviewed for a positive answer. The first turns on the fact that Hawking-style derivations of thermal radiation effects do not require a specific mechanism by which outgoing radiation is emitted. In principle, several mechanisms for wave regularization at extremes are consistent with the derivation that Hawking devised. The second argument is that it can be shown analytically that quantum noise in linear amplifiers is thermal (classical) noise (Unruh, 2011). Importantly, neither argument for the applicability of the requirement of relevance *assumes* that a semi-classical model is "empirically adequate" (Crowther et al., 2019: 3704) for black

[9] Cf. also Hesse (1963:15) for the observation that, strictly speaking, there are no purely 'theory-free' statements. For historical discussions of Hesse in line with the above interpretation, see Franco (2025) and Nappo (2025).

[10] In Evans et al.'s (2024) terms, being tokens of the same kinematic type may be considered another variety of '*empirical type*' uniformity, in contrast with 'universality type' appealed to by Dardashti et al. (2017). Our account shows that there are other ways of exploiting empirical-type uniformity for induction besides Evans et al.'s way.

holes. The arguments considered below rest solely on the assumption that one places strictly higher confidence in the empirical adequacy of the semi-classical model than in Hawking's prediction of black hole radiation.[11]

To introduce the first argument, let us recall some key passages in Hawking's (1975) derivation of black hole radiation. From the scalar field operator ϕ, Hawking derived the expression for in-going particles using annihilation (a_i) and creation ($a^{\dagger}{}_i$) operators:

$$\phi = \sum_i \left(f_i a_i + \underset{-}{f_i} a^{\dagger}{}_i \right),$$

where $\{f_i\}$ is a family of complex solutions of the wave equation $f_{ab}g^{ab} = 0$. Similarly, one can derive the expression for out-going waves and waves crossing the horizon as:

$$\phi = \sum_i \left(p_i b_i + \underline{p}_i b^{\dagger}{}_i + q_i c_i + \underline{q}_i c^{\dagger}{}_i \right),$$

where $\{p_i\}$ and $\{q_i\}$ are sets of complex solutions standing for two respective wave equations. By equating the two expressions, one derives that annihilation operators for outgoing modes can be rewritten in terms of the operators for in-going modes, as follows:

$$b_i = \sum_i \left(\underset{-ij}{\alpha} a_i + \underset{-ij}{\beta} a^{\dagger}{}_i \right),$$

which leads to writing the expectation value of the operator $b^{\dagger}{}_i b_i$ for outgoing states as:

$$< 0_- | b^{\dagger}{}_i b_i | 0_- > \sum_i |\beta_{ij}|^2.$$

Using the Fourier transform, Hawking (1975) proposed to side-step the complexity of computing the coefficients β_{ij} via deriving an asymptotic form, which allows for arbitrarily high frequencies. He could then immediately estimate the number of particles emitted from the horizon, which is given by $(exp(\pi\omega/\kappa) - 1)^{-1}$ times the number of particles absorbed by the black hole. Although Hawking's passage raises interpretational hurdles for theoretical physicists, particularly regarding the problem of the origin and localization of radiation, it emerges as a crucial aspect in making black hole simulations relevant. The key observation is that the model entails a thermal effect without specifying a mechanism and partly by assumptions that we

[11] We recall that the assumptions of QFT in Hawking's model are relatively well-confirmed for flat spacetime; for curved spacetime, although the tests are less precise and conclusive, the theory remains a serious competitor.

can expect to be unphysical, such as trans-Planckian energy regimes. The prediction of radiation follows if we assume that Hawking's approximation is innocuous. A similar situation arises in the case of the simulation. Here, we know that the fluid is sufficiently well approximated by the equations of continuum fluid dynamics, despite our knowledge that at the atomic scale, when very high frequencies are in place, those equations lose meaning. Indeed, a theory of an entirely different type governs the dynamics of fluid flow below the atomic scale. Observing sonic radiation from the simulation would therefore show, at a minimum, that the approximation used in Unruh's derivation does not affect the prediction of sonic radiation. More than that, however, it would indicate that a previously unconceived relation between thermal radiation and the regularization of waves at the horizon may take place. It is in reference to this possibility that the material respects of similarity can be mobilized in support of Hawking's prediction. If such a relation occurs in the fluid system, it is a serious possibility (due to the broadly kinematic similarities noted above) that it may obtain in black holes – in which case Hawking's infinitary approximations may well be similarly innocuous.

Adding to the strength of this reasoning is a consideration not discussed by either Crowther et al. or Dardashti et al. Through analytic means, Unruh (2011) has shown that in a linear amplifier (such as a device that transforms an input signal into an output with different amplitude) quantum noise is thermal noise. Consider a simple model for amplifier, in which input and output are single modes denoted by x, p and Y, P:

$$Y = Ax \quad \text{and} \quad P = Ap,$$

and where A is the amplification function (which is time-dependent). To allow for non-trivial amplification, we add a second input channel (adding a degree of freedom). We fix:

$$Y = Ax + Bq \quad \text{and} \quad P = Ap + Er,$$

where r is the conjugate momentum to q. By demanding the standard commutation relation $[Y, P] = i\hbar$ for such a system, one obtains the following relations:

$$E = -B \quad \text{and} \quad A^2 - B^2 = 1,$$

or equivalently:

$$A = cos\left(\mu\right) \quad \text{and} \quad B = sinh\, sinh\left(\mu\right).$$

Interestingly, one can rewrite the above in terms of creation and annihilation operators, inducing an instance of the Bogoliubov transformations (Unruh, 2011). In light of this, and after computations involving density matrices and the temperature of input channels, one can prove that the output thermal noise T_{Out} due to vacuum fluctuations is:

$$T_{Out} = -\frac{\omega_{Out}}{2\ln\left(\tanh\left(\mu\right)\right)},$$

where ω_{Out} is the output frequency. This is significant because amplification $tanh(\mu)$ and frequency ω_{Out} are determined by the classical behavior of the amplifier. The argument generalizes to black holes insofar as, on Hawking's model, they are special cases of linear amplifiers. Indeed, starting from a semi-classical model, one can define a *norm* function (not necessarily positive) induced by the inner product between solutions $q_i{}', \pi_i{}'$ and q_i, π_i:

$$\left(q^{'}, q\right) = \frac{i}{2}\sum\nolimits_i \left(\pi_i^{'q_i} - q_i^{'\pi_i}\right).$$

If one then picks the solutions that have positive norm (thereby determining the associated set of complex conjugate solutions) and combines them with standard annihilation and creation operators, one obtains quantum operators Q_i and Π_i obeying standard commutation $[Q_i, \Pi_j] = i\delta_{ij}$. Hence, given the Hamiltonian's classical solutions, any quantum solution can be expressed as a linear combination of the classical ones.

In summary, we have argued that the material similarities are relevant insofar as broadly kinematic facts may figure prominently in an explanation of radiation in the analogue system. Assuming that we can detect such radiation in a simulation, then, the fact that the micro-physical substrate of black hole and sonic radiation is unknown while many facts about mode propagation have analogues for both sound and light lead to suppose that a similar horizon-induced radiation may also occur in the regularization of high-frequency modes at a black hole's event horizons. Therefore, when brought to bear on the problem situation of trans-Planckian regimes, the material similarities between dumb and black holes may rationally affect our confidence in Hawking's prediction.

3.3 No-critical-difference

The argument so far has been that, if experiments can demonstrate that the truncation of continuum fluid equations at the atomic scale does not affect sonic radiation, from the material similarities between black and dumb holes we may rationally place some additional confidence in the hypothesis that the truncation of the wave equations in black holes (at whatever energy cutoff it occurs) will fail to affect Hawking's prediction. However, the concern that, in advancing this argument, we are ignoring additional factors about black holes still appears to be haunting our assessment. Admittedly, physicists may have a variety of reasons for rejecting Hawking radiation, particularly when it conflicts with other theoretical commitments (such as specific cosmological theories). These debates form a complex backdrop to current discussions on black hole thermodynamics. In what follows, we are not going to offer an exhaustive list of possible reasons for skepticism. Still, one source of difficulty deserves to be addressed. It is that, while it may be admitted that light entrapped in the black hole may behave similarly to what is observed with sound in accelerating fluids, Hawking radiation is a quantum effect that must survive complications at a level of description of gravity that we ignore.[12] In particular, we ignore the mechanism whereby waves are regularized away from ultra-high energy regimes. This consideration may well strike as a 'critical difference', precluding responsible inferences via simulation.

Even though an attempt may be made to circumvent the difficulty by testing allegedly quantum varieties of thermal radiation (Steinhauer, 2017), here we will point to the availability of a response of a weaker but more general kind – one that does not rest on contested interpretations of current experimental results. It is enclosed in Unruh's (2014) claim that, even though "something could make the gravitational system behave differently from any analogue system…it is hard to imagine what that something could be" (544). To elaborate, we know that the mechanism of regularization of extreme waves at the horizon in analogue systems is the strongly dispersive regime that characterizes those systems. Conversely, the physics describing the dynamics of waves when approaching the black hole horizon, and specifically the mechanism for regularizing the extremes of waves at horizons, is unknown. Although the spacetime geometry due to the gravitational field is well defined in terms of Schwarzschild coordinates, waves are trapped oscillating with decreasing wavelengths and develop a logarithmic phase singularity that induces an exponentially long escape time for the rays close to the horizon. Hence, there is an open question about whether and how an analogue of the dispersion mechanism regularizes the extremes of waves at the horizon for black holes.

Although it may seem that there is no basis on which to ground an expectation of uniformity in wave regularization, some remarkable aspects of continuity must be noted. First, it is known that, as we move away from strongly dispersive regimes towards moderate ones, analogues of Hawking radiation still occur; only for very low dispersion regimes, numerical simulations and physical tests produce more ambiguous results, for reasons that are not theoretically well-understood (Leonhardt & Philbin, 2008). Secondly, it has been shown analytically that there are speculative mechanisms of regularization of extreme waves based on known physical patterns and alternatives to dispersion which still instantiate Hawking radiation (e.g., Brout et al., 1995). Consequently, the assumption that the actual mechanism of wave regularization at event horizon is not simple dispersion does not seem to prevent Hawking radiation from occurring. Overall, Hawking radiation appears to be remarkably robust to a variety of underlying dynamical assumptions, which provides further trust in its applicability to the case of black holes. Granted, the waves of interest for Hawking effects oscillate between two different physics (so to speak), one coming from the kinematics description providing the geometric framework, viz., general relativity, and the other that we expect from the dynamics of in the

[12] Among other things, Hawking's (1975) derivations assume that there is no back-reaction between the effective background geometry and the quantum field – something that we have reason to regard as a mere idealization.

microscopic high-energy description, viz., quantum mechanics. A quantum theory of gravity is one of the central open questions in the foundations of physics. However, the study of regularization of waves extreme at the horizon do not yet give signs of deep discontinuities as we approach lower dispersion regimes or alternative regularization mechanisms. Accordingly, our assessment is that, with regards to the sensitivity to high-energy regimes, no *critical* differences are yet known or expected between black and dumb holes. This completes our case for a reconstruction in terms of material analogy.

4 Discussion

The previous section has offered an account of black hole simulations as instances of material analogy. In our view, the philosophical literature so far has wrongly assumed that, because of the inaccessibility of black holes, an evidential role for the simulations could only be established via *universality* considerations, that is, by evidence that could somehow probe the insensitivity of thermal effects to physical realization. The debate between enthusiasts and skeptics has therefore mostly concerned what universality theorems combined with diverse experimental realizations tell us. We have proposed a different evidentiary route, which makes the evaluation of the experimental practice dependent on a set of physical similarities that are accessible to working experts and do not presuppose the empirical adequacy of Hawking's semi-classical model. On this account, an evidential role for black hole simulations can be established via an ordinary form of reasoning from analogy – not before getting clear on precisely which similarities can be mobilized as evidence. Albeit perhaps incompletely, our assessment has also elicited some of the physical arguments that support the cosmological relevance of observations about black hole simulations. Our proposal thus suggests that there is no single factor or result that translates observations from analogue simulations into information about black hole radiation. The justification for the holding of material analogy is highly context-dependent and turns crucially on expert judgment. The physical facts and expectations of uniformity that experts pick upon in assessing material analogy can be contested; but once they are admitted, there is no need to provide a deeper mechanism of evidence transfer. The evidential weight of the simulations depends on the analogy's strength, in a way that anyone capable of inductive judgment can understand.

A question that has so far been bracketed is whether we may then legitimately speak of *confirmation* of Hawking's prediction from black hole simulations. This is partly a linguistic and partly an empirical issue. Compared to other material analogies (such as extrapolations from mice to humans), black hole simulations involve few similarities and absence of a known common causal mechanism at work in the respective systems. This makes the amount of inductive support of which they are capable necessarily limited and defeasible. Nevertheless, on a Bayesian framework, confirmation occurs whenever the subjective probability assigned to a hypothesis H is greater conditional on some evidence E than on the background knowledge alone: formally, $P(H \mid E) > P(H)$. Several philosophers and physicists have questioned the applicability of such a liberal notion of confirmation to contemporary physics, arguing that we should refrain from using the term in situations of high uncertainty, reserving it to cases where converging evidence renders a hypothesis highly probable (e.g., Rovelli, 2019). Other methodologists, instead, consider Bayesian confirmation theory as an important tool for articulating fine-grained judgments of evidential support. Independently from the linguistic issue, an empirical question remains whether any current realization of analogue Hawking radiation (one yielding an unambiguous thermal signature separate from other turbulent flow effects) is a sufficiently close approximation of the prototypical configuration analyzed in the previous section.

Solely in order to match the probabilistic precision of Dardashti et al.'s account, while maintaining a neutral stance on these broader issues, let's show below that there can be paths to the Bayesian confirmation of Hawking's prediction via material analogy. Specifically, the aim is to show that detecting sonic radiation in a fluid system accelerated at supersonic speed (despite the breakdown of classical fluid equations at the micro-scale) can increase a rational agent's credence in the prediction of Hawking radiation vis-à-vis confidence in the empirical adequacy of a semi-classical model. For this reason, we set up a simple 'common-cause' Bayesian model using the following definitions:

T A radiation effect occurs in black holes.

E An occurrence of sonic radiation in a terrestrial simulation is observed.

B Within a range of variation that includes black and dumb holes, the radiation effect is robust to details at the level of the system's physical realization.

Based on the approach defended in Nappo (2022), we can show that the following conditions entail T's confirmation by E and are plausible precisely under the assumption that the terrestrial simulation stands in a relation of material analogy with black holes:

C1 $0 < P(T), P(E) < 1$.

C2 $0 < P(B) < 1$, where:

(a) $P(T \mid B) > P(T)$

(b) $P(T \mid E \,\&\, B) \geq P(T \mid B)$

(c) $P(T \mid E \,\&\, \neg B) \geq P(T \mid \neg B)$

C3 $P(E \mid B) > P(E \mid \neg B)$

The justification for the above conditions C1-C3 reflects the arguments of the previous section. To avoid burdening the methodological discussion, we leave this to a footnote.[13]

While the verdict of Bayesian confirmation is similar to Dardashti et al.'s (2019), we must stress the profound differences between the two models. Their reconstruction seeks evidence for Hawking radiation mainly from the diversity of experimental analogue realizations and analytic universality theorems for Hawking radiation. As discussed previously, absent a result that establishes an intimate connection between black holes and their terrestrial analogues, observations made in diverse experimental realizations constitute hardly more than enumerative evidence for Hawking radiation. Accordingly, on their Bayesian account every variation of analogue realization of a thermal effect must count something in favor of Hawking radiation, albeit in fact each realization does so in an extremely slight and increasingly imperceptible way (cf. Dardashti et al., 2019:6–7). On our account, instead, the evidential relevance of simulations for the assessment of Hawking's prediction turns mainly on exploiting a material analogue that was engineered to address a specific problem situation. The inferences demand an evaluation based on standard criteria for material analogy (Wylie, 1985). A primary evidential role is attributed to the verification of radiation in a simulation that approximates the prototypical one. Due to the relevance of the similarities, the evidential weight of this verification, though limited, is arguably larger than on a mere enumerative construal. The fact that diverse simulations realize analogue Hawking radiation only plays a more limited and derivative evidential role, mostly in the context of ruling out alternative explanations for thermal signals. Indeed, unless a simulation adds a new element of analogy or disanalogy relevant to the trans-Planckian problem (e.g., spontaneous rather than stimulated radiation), the evidential weight of diverse realizations quickly wears out. This is consistent with the idea that there is a limit as to what can be learned about black holes via multiple simulations.[14]

The difference between an analogical and a universality-based construal is not simply a matter of interpretation but of methodological guidance. A further look at the implications of the respective Bayesian models shows this clearly. For illustration, below we focus on Dardashti et al. and's (2019:11) claim that physicists ought to look

[13] C1 can be read as a minimal probabilistic rendition of the materiality condition. C2(a) is plausible if we take it that is a serious possibility that a semi-classical model may be a suitable approximation for the physics of black holes in the respects that are relevant to T's obtaining. C2(b) is a weak transitivity assumption, corresponding to the idea that the known similarities are relevant. C2(c) is acceptable on grounds that E is irrelevant to T if $\neg$ B is known (i.e., if we are certain that the micro-physics at ultra-high energies affects the radiation effect). Finally, corresponding to the no-critical difference condition, it is plausible that P (B | E) is ever slightly greater than P (B), which is equivalent to C3. It follows that Bayesian confirmation from an observation of sonic radiation occurs solely in virtue of material analogy and without assuming the empirical adequacy of Hawking's semi-classical model. A further Bayesian analysis can be used to show that, if an agent gives non-zero credence to Hawking's semi-classical model being empirically adequate (M) and a lower but still non-zero credence to T (a prediction that is entailed by that model but whose reliability is subject to a trans-Planckian problem), then upon observing E said agent would rationally 'drag' her credence in T closer to M's value (cf. Kotzen 2012 on 'dragging').

[14] Hence, it does not follow that "we can perform a large number of terrestrial analogue experiments and thereby achieve an ever increasing… confirmation" (Crowther et al., 2019:3722) for a cosmological effect. On our account, the evidential weight of the simulation is strictly limited to its bearing on the trans-Planckian regimes problem.

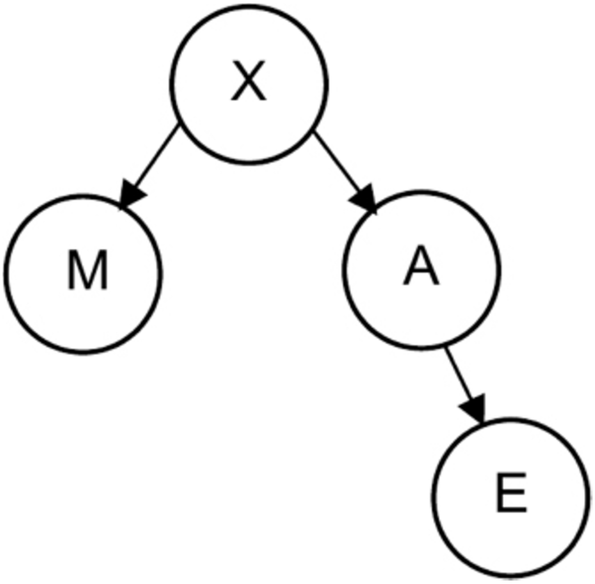

Fig. 1 Dardashti et al.'s (2019) Bayesian analysis of arguments from analogue simulations. The arrows between nodes express relations of probabilistic dependence: for instance, the arrow from X to A stands for P (X | A) > P (X). The absence of an arrow between two nodes expresses conditional independence: for instance, the absence of an arrow from A to M stands for P (M | A & X) = P (M | X)

for sonic radiation in media whose physics is not well-known rather than on media currently being used, whose physics is well- known. This recommendation derives from assuming that universality, rather than analogy, is key to the evidential status of the simulations. On their Bayesian model (Fig. 1), sonic radiation E confirms Hawking's model M by way of confirming A, that a model isomorphic to Hawking's is adequate for the dumb hole; in turn, A confirms the empirical adequacy of Hawking's model (M) when universality theorems vouch for the robustness of the radiation effect to ultra-high energy (X).[15] It follows that E confirms M to a greater extent when P (A) is low, that is, when one ignores the underlying physics of the medium. For us, Dardashti et al.'s recommendation does not constitute sound advice. Consider Mertens et al.'s (2022) realization of analogue Hawking radiation. The authors introduce a condensed matter analog in the form of a one-dimensional tight-binding model, which involves constructing an electronic band structure by approximating the Hamiltonian of the system. In this setting, it is possible to create an analog of a gravitational horizon by a quench of a homogeneous system into one with particular position-dependent hopping parameters (Morice et al., 2021). Evidently, no meaningful test of radiation could be achieved without prior knowledge of the properties of the system under investigation. Among other things, Mertens et al. argue that the number of particles measured by a

[15] Another issue with Dardashti et al.'s model is that it yields a result of confirmation for Hawking's semi-classical model, even though the issue is whether an *empirical prediction* of the model – Hawking radiation – is confirmed. We assume that this is an oversight in the representation rather than a necessary feature of their analysis.

static observer before and after formation of the horizon in a one-dimensional lattice model indicates a thermal effect. Making this claim requires important physical knowledge concerning the system under test. Our alternative Bayesian model offers a different advice. According to C1-C3, T is more confirmed by E the larger P (E | B) is than P (E | ¬ B). This can be interpreted by appealing to standard criteria for when an analogical inference is strengthened (Wylie, 1985). The first is by increasing the 'severity of the test': we learn more, the closer the conditions of the source are to those of the target. Thus, if a simulation come closer to replicating the alleged Hawking radiation, [P (E | B) – P (E | ¬ B)] will be larger, resulting in greater informativeness. Secondarily, one may strengthen the conclusion by expanding 'data points', i.e., by considering whether the same effect holds in a variety of conditions. By C1-C3, if 'F' terms an additional realization, it will confirm if and only if P (E & F | B) > P (E | B). Importantly, to claim that the variety of realizations can contribute to confirmation (and insofar as a new analogy or disanalogy is included) is not equivalent to placing an evidential premium on exotic media, since distinct analogue realizations can be obtained by experimenting on a variety of *familiar* media.[16]

In summary, this section has vindicated the claim that an analogy-based approach provides a genuine middle-ground between enthusiasts and skeptics, showing how black hole simulations can command limited yet non-negligible inductive support for Hawking radiation. Additionally, the above discussion has illustrated in what sense our approach is in a privileged position to offer sound methodological guidance to physicists. The advice that results from our reconstruction is more *plausible*, as it accords with common judgment; it is more *principled*, as it is grounded in a general account of analogical inference in science; and it is more *reliable,* as it is based on a documented record of applying material analogical reasoning in science, rather than on an *ad hoc* methodology.

5 Conclusion

This paper has outlined an epistemology for black hole simulations in physics based upon Hesse's general framework of material analogy in science. Our assessment is that black hole simulations are based on a limited set of similarities with black holes and may therefore only provide limited inductive support for the prediction of Hawking radiation. In the way of arguing for this claim, we have rejected proposals to ground the epistemology of black hole simulations on appeals to universality results (Dardashti et al., 2017). We have, at the same time, resisted arguments according to which terrestrial analogue simulations are entirely uninformative about black holes (Crowther et al., 2019). We believe that the current debate has wrongly assumed that the only way to ground an evidential role for black hole simulations is through universality considerations.

[16] We also reject the claim that, if we *could* isolate a sonic radiation effect in an exotic medium, that would provide more evidence. We do not think that observing the effect in exotic media would be any more surprising than observing it in familiar media. Indeed, the radiation effect is already very surprising in familiar physical media.

In further support of our account, we have argued that it offers recommendations to physicists aiming to assess current experiments and design new ones which are more credible than those supported by rival accounts. Applications of the analogy-based approach to the methodological appraisal of specific experiments will be the subject of future work.

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References

Ankeny, R., & Leonelli, S. (2021). What's so special about model organisms? *Studies in History and Philosophy of Science Part A, 42*(2), 313–323.

Arioli, G., & Valente, G. (2021). What is really quantum in quantum econophysics? *Philosophy of Science, 88*(4), 665–685.

Barcelo, C. (2019). Analogue black-hole horizons. *Nature Physics, 15*, 210–213.

Barcelo, C., Garay, L., & James, G. (2009). Sensitivity of hawking radiation to superluminal dispersion relations. *Physical Review D, 79*, Article 024016.

Bartha, P. (2009). *By parallel reasoning*. Oxford University Press.

Bekenstein, J. (1972). Black holes and the second law. *Lettere Al Nuovo Cimento Series 2, 4*, 737–740.

Brout, R., Massar, S., Parentani, R., & Spindel, P. (1995). Hawking radiation without trans-Planckian frequencies. *Physical Review D, 52*, 4559–4568.
Coutant, A., Parentani, R., & Finazzi, S. (2012). Black hole radiation with short distance dispersion: An analytical S-matrix approach. *Physical Review D, 85*, Article 024021.
Crowther, K., Linnemann, N., & Wütrich, C. (2019). What we cannot learn from analogue experiments. *Synthese, 198*, 3701–3726.
Dardashti, R., Thébault, K., & Winsberg, E. (2017). Confirmation via analogue simulation: What dumb holes could tell us about gravity. *The British Journal for the Philosophy of Science, 68*(1), 55–89.
Dardashti, R., Hartmann, S., Thébault, K., & Winsberg, E. (2019). Hawking radiation and analogue experiments: A bayesian analysis. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 67*, 1–11.
Euvé, L.-P., Michel, F., Parentani, R., Philbin, T. G., & Rousseaux, G. (2016). Observation of noise correlated by the hawking effect in a water tank. *Physical Review Letters, 117*, Article 121301.
Evans, P., & Thébault, K. (2020). On the limits of experimental knowledge. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 378*(2177), Article 20190235.
Evans, P., Hangleiter, D., & Thebault, K. (2024). How to engineer a quantum wavefunction. *Philosophy of Science, 91*, 37–57.
Field, G. (2025). Putting theory in its place: The relationship between universality arguments and empirical constraints. *The British Journal for the Philosophy of Science, 76*(1), 95–122.
Franco, P. (2025). Mary Hesse's early work on scientific language and the open texture of models. In P. Gori (Ed.), *Mary B. Hesse (1924–2016): Metaphors, models, and the growth of scientific knowledge* (pp. 49–68). Springer.
Galilei, G. (1610). [2008] *The sidereal messenger*. In M. Finocchiaro (Ed.), *The essential galileo* (pp. 45–84). Hackett.
Garay, L., Anglin, J., Cirac, J., & Zoller, P. (2000). Sonic analogues of gravitational black holes in Bose-Einstein condensates. *Physical Review Letters, 85*, 4643.
Hangleiter, D., Carolan, J., & Thébault, K. (2022). *Analogue quantum simulations: A new instrument for scientific understanding*. Springer.
Hawking, S. (1975). Particle creation by black holes. *Communications in Mathematical Physics, 43*, 199–220.
Hesse, M. (1963). *Models and analogies in science*. University of Notre Dame Press.
Kotzen, M. (2012). Dragging and confirming. *Philosophical Review, 121*(1), 55–93.
Lahav, O., Itah, A., Blumkin, A., Gordon, C., Rinott, S., Zayat, A., & Steinhauer, J. (2010). Realization of a sonic black hole analog in a Bose-Einstein condensate. *Physical Review Letters, 105*, Article 240401.
Lange, M. (2004). Would 'Direct Realism' solve the classical problem of induction? *Nous, 38*(2), 197–232.
Lange, M. (2019). Idealism and Incommensurability. In T. Goldschmidt (Ed.), *Idealism: New essays in metaphysics* (pp. 259–274). Oxford University Press.
Leonhardt, U., & Philbin, T. (2008). The case for artificial black holes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366*, 2851–2857.
Mertens, L., Moghaddam, D., Chernyavsky, J., Morice, A. G., van den Brink, J., & van Wezel, J. (2022). Thermalization by a synthetic horizon. *Physical Review Research, 4*, 043084.
Morice, A. G., Moghaddam, D., van Chernyavsky, J., Wezel, J., & van den Brink, J. (2021). Synthetic gravitational horizons in lowdimensional quantum matter. *Physical Review Research, 3*, L022022.
Nappo, F. (2021). Close encounters with scientific analogies of the third kind. *European Journal for Philosophy of Science, 11*(82), 1–25.
Nappo, F. (2022). Confirmation by analogy. *Synthese, 200*(35), 1–25.
Nappo, F. (2025). Hesse on materiality and induction. In P. Gori (Ed.), *Mary B. Hesse (1924–2016): Metaphors, models, and the growth of scientific knowledge* (pp. 179–198). Springer.
Rosenberg, Y. (2020). Optical analogues of black-hole horizons. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 378*, Article 2177.
Rousseaux, G., Mathis, C., Maissa, P., Philbin, T., & Leonhardt, U. (2008). Observation of negative phase velocity waves in a water tank: A classical analogue of the Hawking effect? *New Journal of Physics, 10*, 053015.
Rovelli, C. (2019). The dangers of non-empirical confirmation. In R. Dardashti, R. Dawid, & K. Thébault (Eds.), *Why trust a theory?* (pp. 120–124). Cambridge University Press.
Steinhauer, J. (2016). Observation of quantum hawking radiation and its entanglement in an analogue black hole. *Nature Physics, 12*, 959–965.

Steinhauer, J. (2017). Response to version 2 of the note concerning the observation of quantum hawking radiation and its entanglement in an analogue black hole. Preprint retrieved from https://arxiv.org/abs/1609.09017 (available on).

Sterrett, S. (2017). Experimentation on analogue models. In L. Magnani & N. Nersessian (Eds.), *Springer handbook of model-based science* (pp. 857–877). Springer.

Thébault, K. (2019). What can we learn from analogue experiments?. In R. Dardashti, R. Dawid, & K. Thébault (Eds.), *Why trust a theory?* (pp. 184–201). Cambridge University Press.

Unruh, W. (1981). Experimental black hole evaporation? *Physical Review Letters, 46*, 1351–1353.

Unruh, W. (2008). Dumb holes: Analogues for black holes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366*, 2905–2913.

Unruh, W., & Schützhold, R. (2005). Universality of the hawking effect. *Physical Review D, 71*(2), Article 024028.

Unruh, H. (2014). Has Hawking radiation been measured? *Foundations of Physics, 44*(5), 532–545.

Unruh, W. (2011). Quantum noise in amplifiers and hawking/dumb-hole radiation as amplifier noise. In: V. Cardoso, L. Crispino, S. Liberati, E. Olieira, M. Visser (Eds.), *Analog spacetimes: The first 30 years* (pp. 1–13). EL editorial.

Visser, M., Barcelo, C., & Liberati, S. (2002). Analogue models of and for gravity. *General Relativity and Gravitation, 34*, 1719–1734.

Weinfurtner, S., Tedford, E. W., Penrice, M. C., Unruh, W., & Lawrence, G. (2011). Measurement of stimulated hawking emission in an analogue system. *Physical Review Letters, 106*(2), Article 021302.

Wylie, A. (1985). The reaction against analogy. *Advances in Archaeological Method and Theory, 8*, 63–111.