General Relativity and Gravitation (2025) 57:78
https://doi.org/10.1007/s10714-025-03391-4

PERSPECTIVE

Black hole evaporation – 50 years

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Received: 19 November 2024 / Accepted: 27 February 2025

Abstract

Personal reflections (this is not a scholarly history but my own memories and work on this topic). I apologize beforehand to everyone whose work I do not mention. Note that there is lots of such work, much brilliant. [This document is a transcription of the slides used at the conference, and as a result is rather rough as a document.]

Keywords Black-holes · History · Toy models

Contents

Early days

1967 – I began my work on my PhD at Princeton. After my Generals I asked John Wheeler if I could work with him. This was a heyday for his group, about nine graduate

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Published online: 09 May 2025

students [Robert Wald, Bei-Lok Hu, Claudio Teitelboim (now Bunster), Jacob Bekenstein, Steve Fulling (Wightman's student), Demetrios Christodoulou (Ruffini), Nial O'Murachadha (York), Cliff Rhoades, Brendan Godfry], one postdoc (Remo Ruffini), two assistant professors (Karel Kuchar, Jimmy York) and a sabbatical visitor (Charlie Misner).

The key topic of almost all of their research was quantum mechanics and gravity.

Key people whose research really influenced me:

Steve Fulling – gave informal lectures on quantum field theory (he had translated Bogoliubov's text from Russian to English in 1968), worked on quantum field theory in curved spacetime (strongly influenced by Leonard Parker's work on quantum fields in cosmological spacetimes [1]) and worked on quantization of quantum fields in Minkowski spacetime and in "Rindler" spacetime (he named the latter) [2].

Demetrios Christodoulou – showed that there was for Schwarzschild and Kerr, a quantity called the "irreducible mass", which had to increase if positive energy flowed through the horizon [3, 4]. At the same time, and independently, Hawking showed that the surface area of a sequence of cross-sections of the horizon of a black hole had to increase if the energy-momentum flux through the horizon was positive [5]. Both acted like entropy (i.e. increased with time).

Meanwhile Wheeler had given Bekenstein the problem of what happened to the second law of thermodynamics if entropy disappeared down the black hole.

Bekenstein chose Hawking's more general formulation as a better analogy of entropy. This led him, and then Jim Bardeen, Brandon Carter, and Hawking to formulate the "Thermodynamics of black holes" [6]. It was silly because there was no temperature. Black holes absorb. They do not emit anything. Bob Geroch threw another spanner in the works. Bekenstein had postulated a heat engine with black holes. Fill a box with high entropy radiation, lower it slowly on a rope toward the black hole horizon extracting its energy through the tension on the rope. However, by lowering to the horizon one could extract all of its energy, thus violating the 2nd law [7].

Disaster! Bekenstein's solution [8] was: You cannot lower the box all the way to the horizon. There is another new law of physics which says that the entropy to energy ratio of the contents of the box is limited by the radial dimension of the box (he cited many many examples of quantum fields in boxes for which this is true). Hawking decided to get involved in the game of the behaviour of quantum fields (scalar fields) in the vicinity of a Schwarzschild black hole formed by collapse [9, 10]. I recall in early 1973 visiting a conference at Cambridge in the UK (my girlfriend, had been left behind when I moved from Birkbeck college where I was Roger Penrose's postdoc, to a Miller Fellowship at Berkeley, so I found every excuse I could to go to the UK) and overhearing Don Page talking to Hawking about some calculation about quantum fields near black holes that Hawking was doing.

In the meantime I was getting interested in Fulling's thesis, in which he asked, but did not answer, the question as to whether or not field quantization was the same in Minkowski and Rindler spacetimes. I showed (to myself) that they were different, by using the horizon in Rindler spacetime as an initial value surface for the quantum fields, that one quantization corresponded using the affine parameter along the horizon to define "positive frequency" for field quantization, which gave the usual Minkowski quantization. while using the acceleration Killing parameter gave Rindler quantization.

I also showed the relation between them. I did not notice that the relationship was thermal.

I wrote Fulling a letter outlining this result, but did not publish it till 1976 [11], much to Fulling's disgust (and my future chagrin). In early 1974, I went to the conference at the Rutherford labs where Hawking first presented his results (he had sent out preprints in late 1973, and I got one just before Christmas via Abe Taub and Vince Moncrief, Taub's postdoc). Just before the conference, I had showed my paper on quantization in the Kerr metric to Sciama, and he told me I could have 10 min in the conference to present it. Instead I tried to present the Minkowski-Rindler results, but made a complete hash of the presentation.

Hawking

In early 1974, Hawking's result, that the quantization of a scalar field around a star which collapses to a black hole would produce a flux of radiation with temperature, was published [9, 10]

$$T = \frac{1}{8\pi M}\frac{\hbar c^3}{G k_B}. \tag{1}$$

Well not quite – because the black hole has an albedo to absorption and emission due to the angular momentum of the field and the curvature of the spacetime which filters out the low frequencies of the thermal spectrum, Hawking's result is valid for the (red-shift corrected) temperature of the black hole horizon, not of the emission temperature at infinity.

In 1976, I published my paper "Notes on black hole evaporation" [11] in which I tried to clarify what was happening in the emission process by the black hole, also using the same affine and Killing parameterizations I had used in showing that flat space-time had two quantizations. I argued that the affine quantization (which was the Minkowski quantization in flat spacetime) is roughly the state one would expect after the collapse of a start to a black hole. An accelerated observer (i.e. someone held at constant radius near a black hole, or at constant acceleration in flat spacetime) would see itself surrounded by a fluid of particles with a temperature proportional to the acceleration

$$T = \frac{a}{2\pi}\frac{\hbar}{c k_B}. \tag{2}$$

Near the black hole, the Hawking radiation looks just like this acceleration radiation. Further away (greater than about 1.5 times the radius of the black hole) the Hawking radiation looks like the radiation from a finite sized hot body with a low frequency non-zero albedo. This led to my favourite paper [12] (written with Wald), because of one of the references. I had always found Bekenstein's entropy-to-energy ratio argument problematic. However, the acceleration radiation gave an alternative argument for why black holes do not violate the second law. Near the black hole, as one lowers the box, it is surrounded by a thermal fluid, which exerts a buoyant force on the box, according to a pre-print written by a Greek by named Archimedes over 2200 years ago. Than buoyant force reduces the energy extracted in lowering and saves the second law, without the need for new physics.

One of the questions which bothered me from the beginning [13]: *"Where are the particles in black hole evaporation created?"*

What is a particle?

A quantum field theory is firstly a field. It exists everywhere at all times. A particle is something with a well defined location at any time, carrying a well defined energy and momentum. Traditional approach is to quantize the amplitude of the modes of the field (like the plane wave modes) as harmonic oscillators and call the resultant harmonic discrete energy levels – Particles

$$\phi(t,x) = \int d^3k \frac{a_k}{\sqrt{(2\pi)^3\,2\omega}} e^{-i\omega t} e^{ik\cdot x} + \text{H.C.} \tag{3}$$

But this is silly – This is totally delocalised definition and does not represent a localised particle.

My attitude was: *"A particle is what a particle detector detects."*

This is a localised definition since detectors (Geiger detector, cloud chamber, bubble bubble chamber, spark chamber,...) are localised. In particular one can look near a black hole to see what is happening there and perhaps see the particles being created.

Wald and I [14] wrote – *"What happens when an accelerated particle detector detects a particle?"* One answer would be that in the Minkowski vacuum, the detector never does click − the vacuum has no particles. False: whether or not it has particles depends on the state of motion of the detector. In $1 + 1$ dimensions, for example

$$\psi_{M\omega,k} = \frac{1}{\sqrt{(2\pi)2\omega}} e^{-i\omega t}; \qquad \omega > 0, \tag{4}$$

$$\psi_{R\nu,k} = \frac{1}{\sqrt{(2\pi)2\nu\sinh\nu\mathcal{M}}} \left[e^{\nu\mathcal{M}/2}\Theta(z)e^{-i\nu(\hat{\tau}-\rho_+)} + e^{-\nu\mathcal{M}/2}\Theta(\hat{\tau}+\rho)e^{i\nu(\hat{\tau}-\rho_-)}\right]; \quad \forall\nu. \tag{5}$$

Identical set of positive norm modes:

$e^{i\Omega t}$; Minkowski detector creation operator mode,
$e^{iN\tau}$; Rindler detector creation operator.

where τ is the proper time for the accelerated detector. If an accelerated detector detects a particle the probability of the emitted particle being in the acausal region of the detection is much higher than in the region containing the detector.

This has led people to say that this represents a tunnelling process (like the Schwinger EM particle creation). The evidence is against this.

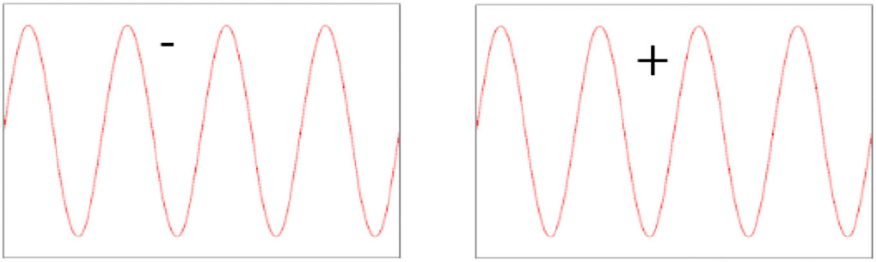

Fig. 1 Two impenetrable boxes with different vacua

Inside affects outside?

False: Consider two impenetrable boxes, length L, inside coordinates $x_\pm$ with fields inside the boxes (see Fig. 1). Assume that the walls are completely impermeable to the fields. One can have the usual plane wave modes to define two separate vacuum state, one in each box. A static detector will see nothing.

However one can put the field into another Gaussian pure state in which, using a Bogoliubov two mode set of squeezed states for each frequency in the two boxes, one gets a very different result [15]

$$\phi = a_n \frac{e^{-i\omega_n t} \sin n\pi x_\pm / L}{\sqrt{2\pi L 2\omega_{in}}} + \text{H.C.} \tag{6}$$

$$a_{n\pm}|0_M\rangle = ; \qquad \omega_n > 0. \tag{7}$$

This is a squeezed state Rindler analog. Now a detector at rest placed into either box will be thermally excited, exactly like how an accelerated detector at rest in Rindler coordinates would be:

$$b_{n+} = \cosh\theta_n a_{n+} + \sinh\theta_n a^\dagger_{n-}; \qquad \sinh\theta_n = \frac{e^{-\omega_n/4T}}{\sqrt{\sinh\omega_n/2T}} \tag{8}$$

$$b_{n\pm}|0_R\rangle = 0. \tag{9}$$

If the detector is placed into the usual vacuum, it will not be excited. If the detector is placed into squeezed vacuum, it can be excited while emitting a particle which is dominantly in the opposite box. For example, if the detector is in the + box and the detector frequency is much larger than the temperature T, then the probability is exponentially larger that the particle is in the "- box" than in the "+box". This is precisely the situation (except for boundaries) for an accelerated detector in the Minkowski vacuum.

This also applies to a black hole spacetime, where the state after collapse is close (except at exponentially low final frequencies) to the Minkowski vacuum. If your detector clicks and thus detects a particle, the probability is much higher that the particle is inside the horizon if the detector is near the horizon (see Fig. 2)

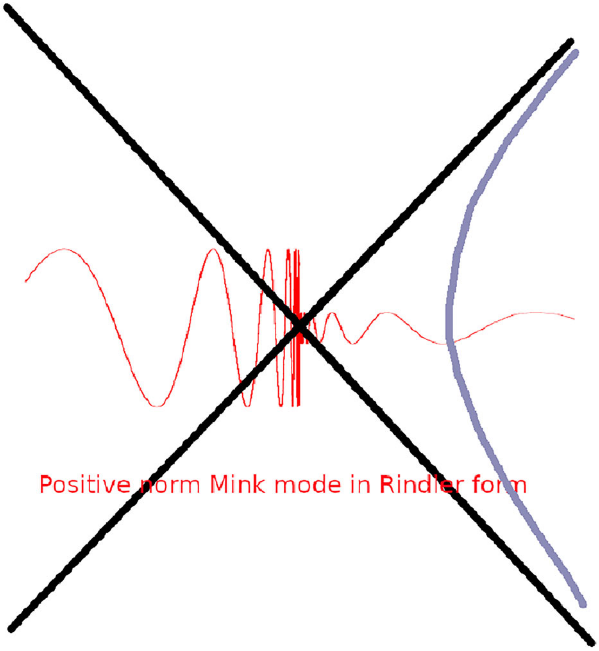

Fig. 2 Representation of a Minkowski mode on the Rindler wedge

Boundary condition on singularity?

To solve what is called the information paradox one needs to solve a problem: The information that went into the black hole must flow out of the black hole eventually (somehow). But it also flows into the singularity. This clones the inflowing information into to both outside the black hole and into the singularity. However one cannot clone a quantum state. Proposed solution: place boundary condition on the singularity.

However quantum mechanics is not classical mechanics. Future boundary conditions are not equivalent to past conditions. The predictions of quantum theory become very strange.

The simplest example is the following. Consider a two level system (e.g. a spin $1/2$ particle). At 9AM, the spin is measured in the x direction and found to be $+1/2$. At 11 it is measured in the y direction and found to be $+1/2$. At 10 a student snuck into the lab and measured it in a direction between x and y. What is the probability that she measured $+1/2$? Quantum mechanics answers this simply. It is a probability distribution such that if she measured it in the x direction, the probability must be unity. If she measured it in the y direction, the probability is also 1. Other angles give probabilities given by Fig. 3. Note that there is no state, or density matrix which gives this resultant distribution, and yet it is almost trivially calculated by quantum mechanics.

Yakir Aharonov and his collaborators have looked at the strange results that standard quantum mechanics gives for such initial and final state. As an example, let us take

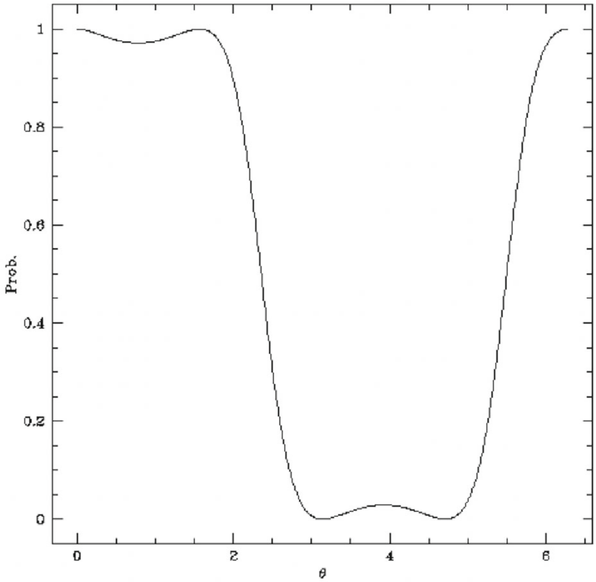

Fig. 3 Probability distribution of finding the spin in direction θ to be $1/2$ given initial and final knowledge of spin value in x and y directions

a spin 12.5 particle and set the condition that the initial x and final y components are 12.5. At the intermediate time, measure the spin in the $(x + y)/\sqrt{2}$ direction. If one uses a measuring device which is inaccurate – for example, create a measuring apparatus whose pointer has a Hamiltonian of $H = PS_\theta\delta(t)$ where θ is the angle from the x axis. This detector has an intial state with a Gaussian initial distribution of width σ. After the measurement of the position of the "pointer", given some initial state of the spin, the pointer will have a probability distribution of a bunch of Gaussian functions of width σ centered at $12.5, 11.5, 10.5, \ldots - 12.5$ If one places the two time conditions on the measurements, ($S_x = 12.5$ before the measurement of S_{45} and $S_y = 12.5$ afterwards,) and the Gaussian of the measuring apparatus for S_{45} has a width much less than 1, the probability distribution is a bunch of narrow Gaussians each centered at one of the half integer values between -12.5 and 12.5, as seen in Fig. 4a. As σ becomes large, however, the peaks in the probability distribution become fewer, and move to higher values. At $\sigma = 1.5$ (Fig. 4b) - (i.e., such that the initial uncertainty of the pointer is 50% larger than the distance between the peaks in Fig. 4a – the peaks in the probability distribution become broad and center on values which have little relation to the eigenvalues of spin. By the time σ becomes 3 (Fig. 4c), there is only one single peak, of width about 8, and centered on a value of about 18 (close to $\sqrt{2} \cdot 12.5$). This is a value substantially larger than the maximum value of the spin in any direction (12.5). and substantially outside the range of the eigenvalues of the spin component.

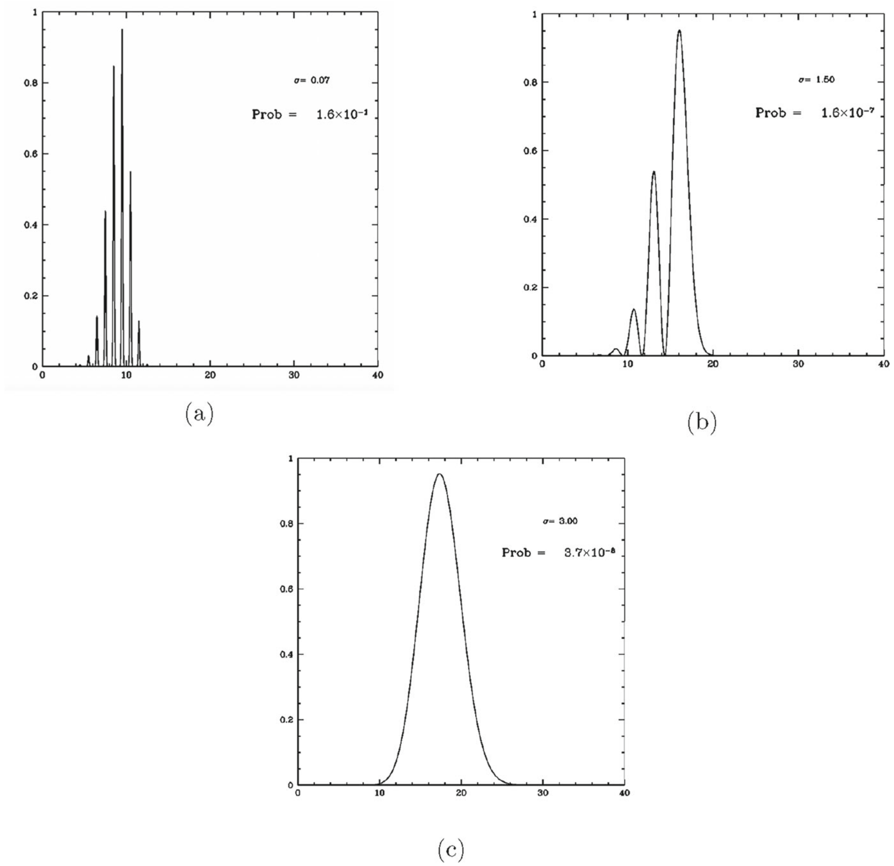

Fig. 4 Probability of measuring values of spin 12.5 particle if initial S_x and final S_y values were 12.5 and intermediate $S_{(x+y)/\sqrt{2}}$ measurements had uncertainty 0.02, 1.5, 3.0

Hence, the behaviour of the quantum universe outside the horizon would be substantially different than its behaviour under quantum mechanics with initial conditions only.

Where are particles created?

The notion of particle depends on the state of motion of particle detector. Particles are carriers of energy. In 1974, Davies, Fulling and I [16] calculated the massless field energy-momentum tensor in $(1+1)$ dimensions. The conformal anomaly, the non-zero trace of the tensor being proportional to the curvature R, acts as a source for the flux of energy in 1+1 dimensions. In writing our paper, I pushed for interpretation of the curvature R as the source of energy flux. It was an argument which did not catch on with people working in the area. So let me try again to make the argument in a slightly different way.

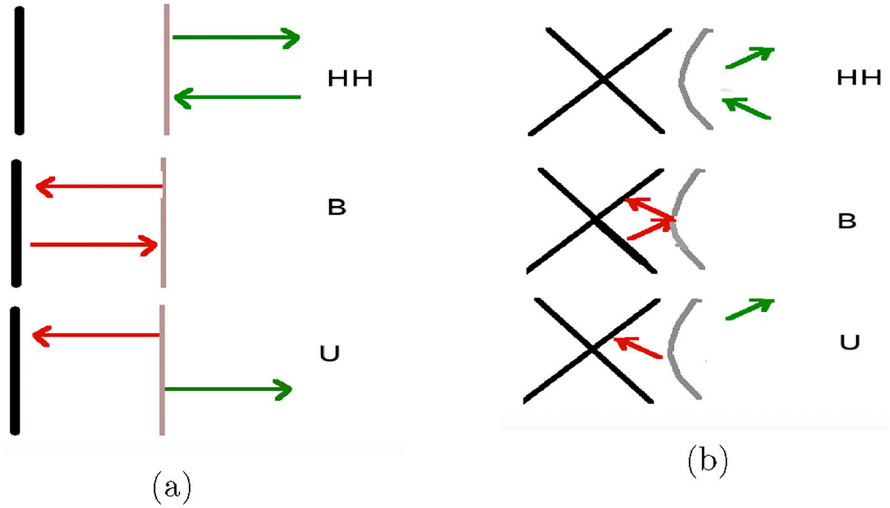

Fig. 5 Non-zero average energy fluxes. Thermal fluxes are depicted in green if positive and in red if negative. The left figure shows a spatial representation, while the right figure shows a null representation. There are different states. *Hartle–Hawking (HH):* No fluxes across horizons, near horizon like Minkowski vacuum. *Boulware (B):* No fluxes across infinity, near infinity like Minkowski vacuum. *Unruh (U):* No fluxes across past horizon or past infinity, like state from collapsing matter forming black hole

A model of black hole emission

The model [17] will be that of a two flat spacetimes sewn together along a timelike line which is an accelerated curve in one spacetime, and is a timelike geodesic as seen from the other spacetime. This junction lies along the coordinate $r = 1$, where there is a δ-function curvature (see Fig. 5):

$$ds^2 = \begin{cases} r^2 dt^2 - dr^2 & r < 1 \\ dt^2 - dr^2 & r > 1 \end{cases} \tag{10}$$

$$\begin{cases} \partial_t^2 \phi - r\partial\left(r\partial_r \phi\right) = 0 & r < 1 \\ \partial_t^2 \phi - \partial_r^2 \phi = 0 & r > 1 \end{cases} \tag{11}$$

In one section, we take (t, r) as Rindler coordinates, while in the other they are Minkowski coordinates. The Rindler coordinates have a horizon at $r = 0$, and are flat for $r > 1$. One can now choose a number of quantizations of the scalar field in these coordinates, corresponding to “vacuums” in eternal Schwarzschild – the Hartle–Hawking (HH) state, the Boulware state (B), and the Unruh (U) state. The energy fluxes in these states in this model take the form as in Fig. 5.

This is also true of Dirac field. Is this also true of massive field in 1+1, or of fields in 3+1 in which the inner metric would be a cylindrical Rindler spacetime, and the outer would be flat Minkowski spacetime in polar coordinates?

My suspicion is yes. But there are many ways I could be wrong.

Planck-scale problem

Thermal radiation comes from exponentially super-Planckian scale vacuum fluctuations (1 s after solar mass black hole emission comes from amplification of 10^{10^5} Hz). I could argue (and I have) that adiabaticity explains why the super-Planckian origin of the radiation has no effect. Analog gravity calculations and experiments support this argument [18, 19]. But can we find a simple derivation of Hawking radiation which shows this? In black hole thermodynamics the only "reliable" calculation is that which associates a temperature with black holes. But most people worry about entropy, not temperature. There is no evidence that temperature has anything to do with Planck-scale physics, so why would entropy? It would be wonderful to get a derivation of the back-hole emission which did not rely on super Planckian modes.

Experimental black hole temperature

In 1980, I suggested that it might be possible to carry out experiments in the lab to see the analog of the quantum instability of black holes. Although slow, this has become a sizeable area of research. The history of these analogs runs something like the following:

1972: Oxford – Sonic analog of black holes to give physical feel for black holes.
1980: PRL "Experimental black hole evaporation?" [20]. I tried to call them "dumb holes" [21] – but that name failed to catch on. This field is now called "Analog Gravity" [22].
1990: Jacobson – Quantization of sound wave solutions of the inviscid fluid equations [23].
1995: Numerical solution shows that high-frequency dispersion does not alter the low-frequency results [24].
Late 1990: With Schützhold and others – many examples of possible experimental realizations [25].
2010: Weinfurtner et al., stimulated emission of Hawking radiation [18].
2015–2020: Quantized soundwaves in BEC – demonstration of the trans-horizon entanglement and temperature by Steinhauer [19, 26–28].
2020: Proposed measurement of acceleration temperature with bi-frequency laser microphone, Weinfurtner et al. [29].

String theory?

Of course, another of the developments in black hole evaporation has been the attempt to unify string theory with black holes. An example has been AdS/CFT, which has been used to advance the claim that black hole formation and evaporation is reversible (the black hole remembers its origins). This is often called the resolution to the "Information Paradox".

I am still far from convinced that there is any such paradox, or that a solution is needed or is provided by quantum gravity. It is of course possible that quantum gravity will solve the singularity problem, and that the eventual sate of the universe outside a black hole is unitarily related to the initial state of the universe before the black hole formed. For me, it is more probable that black hole entropy is a fundamental feature of quantum gravity. However, due to time constraints I cannot discuss this in any more depth.

What *is* clear is that black hole quantum mechanics is still a far from finished topic. 50 years after that initial discovery by Hawking, which we are celebrating here, there is still a massive amount that we do not know or understand about black hole quantum mechanics.

Acknowledgements I would like to thank the Natural Science and Engineering Research Council of Canada for their support of this research throughout the years. I would also thank the Hagler Institute and Marlan Scully and his group at the IQSE group at Texas A&M University for their support and insights into black hole evaporation and acceleration temperature which showed me that there was much more to the subject still to be understood. I would especially thank the organizers of the 2024 Black Hole-Inside and Out conference, not only for creating this exciting meeting but also for transcribing my talk into this paper. Any errors and omissions are of course my own.

Data availibility No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare no Conflict of interest.

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