Chapter x

The Hawking Effect

> Oh, where have you been, my blue-eyed son?
> Oh, where have you been, my darling young one?
> I've stumbled on the side of twelve misty mountains
> I've walked and I've crawled on six crooked highways
> I've stepped in the middle of seven sad forests
> I've been out in front of a dozen dead oceans
> I've been ten thousand miles in the mouth of a graveyard
> And it's a hard, and it's a hard, it's a hard, and it's a hard
> And it's a hard rain's a-gonna fall
>
> – Bob Dylan
> "A Hard Rain's A-Gonna Fall"

BOOTCAMP READERS (NOT THE SAME NOTES AS BEFORE)

1. this is a rough draft, better than previous drafts but not in anything like an even provisionally final form; the argumentative structure is, again, not as clean and well formed as I want; there are infelicities, inelegant repetitions and redundancy; some sections, marked '**[*** PRE-PUBESCENT ***]**', are given only as an outline of the claims and arguments, sometimes a detailed and thorough outline, and, when so, even though not fully grown, they are, I think, nonetheless both legible and intelligible; some of the sections spell out the problem but do not discuss possible resolutions or the possible consequences if no resolution can be found, which I mark with '**[*** INFANTILE ***]**'; some of the sections are outlined not even so skimpily, but exist only as inchoate lists of works and problems to discuss, which I mark with '**[*** ZYGOTIC ***]**', and you should feel *very* free to ignore those; finally, some are marked

‘**[*** IGNORE ***]**’, as they contain information relevant to myself alone—as always, *caveat lector*

2. there are a few exegetical passages, not part of the body of the chapter, but rather notes to myself or to the reader indicating where there are questions or problems I need to think more about, where I am dissatisfied with what is there, where I indicate further things I need or want to discuss, where I am reminding myself to do something, *etc.*; they are syntactically marked by being surrounded by asterisks enclosed in braces, *e.g.*, ‘[*** foo ***]’; the ones beginning ‘**BOOTCAMP READER**’ I want you to read; the others you may read or not as you will; some of them I think you should, some are unnecessary for following the career of the argument, and a few will be unintelligible to you; as always, *lector ad libitum*

Contents

With Regard to the Habilitation; Secondary Literature Notes Already Incorporated

[*** IGNORE ***]

1. Wall (2018)
2. for Habil: reduce discussion only to S-matrix, past-boundary, tunneling and stress-energy tensor operator approaches, mention others only *en passant*

x.1 Hawking's Original Derivation

Hawking (1974, 1975) shocked the physics world (or, at least, that very small part of it in the early 1970s that thought at all about black holes and QFT-CST). The idea that gravitational fields could perpetrate particle production in quantum fields had been around since Schrödinger (1939), and had been developed piece-meal at the hands of a few, isolated researchers in the intervening years. (See the appendix §x.25.2 below for a brief history of the idea before Hawking 1974.) The idea that a black hole could effect a perfectly thermalized—effectively black-body—radiation field, however, so that a physical temperature could be attributed to the black hole, was beyond the pale. Vehement opposition to the idea arose before the ink was dry on its initial proposal in print. (See, for example, Davies and Taylor 1974.) It was only gradually over the next two years after several alternative derivations were produced more acceptable to conventional quantum field theory, *e.g.*, those of Wald (1975) and Hartle and Hawking (1976), that acceptance of Hawking's result became wide-spread. Davies, for example, who had rejected the idea immediately on its publication (Davies and Taylor 1974), changed his mind so quickly and completely as to produce his own derivation of what is now known as the Unruh effect (ch. IX) the following year (Davies 1975), inspired by and based on Hawking (1975). He also gives there an interesting early discussion of the possible physical interpretation of Hawking's results.[1]

Before diving into the problems and opportunities the Hawking effect can afford, it will be instructive to set the stage by recapitulating an outline of Hawking's (1975) original derivation, focusing on the conceptual rather than the technical details.[2]

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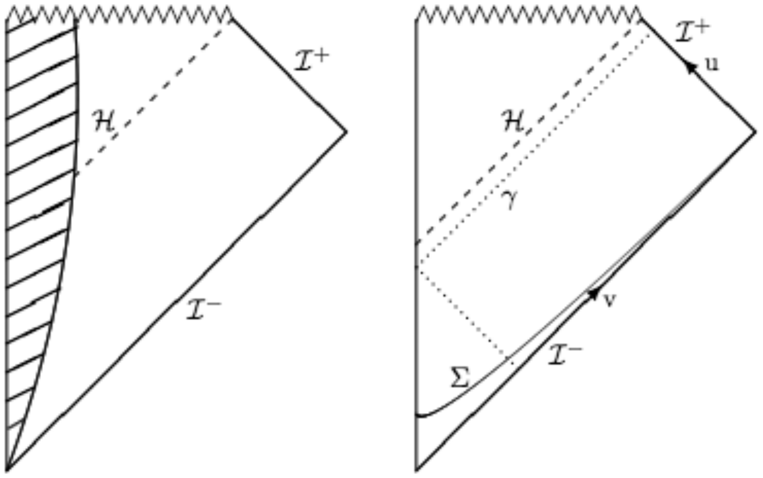
[1] For more on the early reception of Hawking's arguments and claims, even pre-publication, along with personal reminiscences, see Page (2005, starting on p. 3).

[2] See Traschen (2000) for a detailed and rigorous recapitulation of the original derivation.

Figure x.1.1



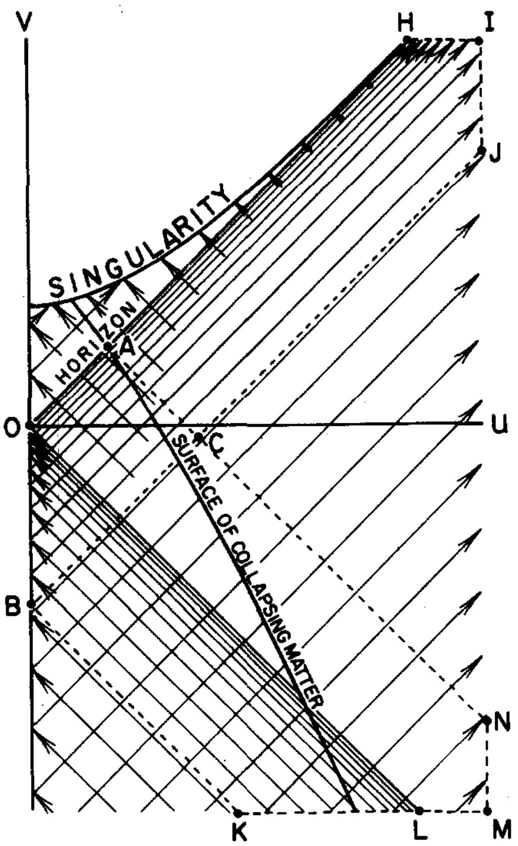
(a) (b)

Fig. 1. The setup for Hawking's calculation. (a) Carter–Penrose diagram for a star collapsing to form a black hole. (b) Coordinates, ray-tracing, and mode functions.

diagram (b): scattering, off the horizon, of ingoing radial modes from $\mathscr{I}^-$ to outgoing radial modes on $\mathscr{I}^+$

[*** this figure is shamelessly cribbed from Carlip (2014); I need to make my own ***]

Figure x.1.2



scattering, off the horizon, of ingoing radial modes from $\mathscr{I}^-$ to outgoing radial modes on $\mathscr{I}^+$ (note that this is a Kruskal diagram, not a Penrose diagram, *i.e.*, it does not show the conformal completion of the spacetime)

[*** this figure is shamelessly cribbed from DeWitt (1975); I need to make my own ***]

Consider a star collapsing to form a black hole (figure x.1.1, lefthand diagram, and figure x.1.2), in the presence of a massless quantum scalar field ψ not contributing to the curvature of the spacetime metric ("test matter"). Spacetime is essentially flat for a spatially distant observer in the distant past (on $\mathscr{I}^-$), so it makes physical sense to take the state of ψ to be the Minkowski vacuum there—the observer, in inertial motion, sees no excited modes. We want to calculate the state of ψ on $\mathscr{I}^+$ at late enough retarded time u so that an observer will see the collapse settle down to a (nearly) stationary state. Because of the near-stationarity, and because we are assuming that ψ is test matter, and so the classical spacetime geometry is essentially flat at $\mathscr{I}^+$, we can define a vacuum state there as well. The goal is to construct that state by calculating the Bogoliubov coefficients that define the transformation from one state to the other on a Cauchy surface near $\mathscr{I}^-$, in this case Σ (in the righthand diagram of figure x.1.1). We do this by fixing a null geodesic γ and propagating the orthonormal modes of ψ forward from $\mathscr{I}^-$ along γ to Σ, propagating the orthonormal modes of ψ backward from $\mathscr{I}^+$ along γ to Σ, and taking their inner products there.[3] (Since each point in the diagram really represents a 2-sphere, one can think of γ as a sphere of radiation shrinking as it propagates in from $\mathscr{I}^-$, culminating in a point near the horizon—$r = 0$ in the righthand diagram of figure x.1.1, point A in figure x.1.2—through which the sphere inverts and then grows again as it propagates outward to $\mathscr{I}^+$.)

By choosing u on $\mathscr{I}^+$ and v on $\mathscr{I}^-$ to be null affine coordinates, the metric asymptotically takes the form $\mathrm{d}s^2 = \mathrm{d}u\mathrm{d}v + f(r)(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2)$, where r is a "radial" coordinate, θ, ϕ are "angular" coordinates, and $f(r)$ is a function controlling the size of topological 2-spheres that respect the spherical symmetry of the spacetime. The form of the Klein-Gordon equation then simplifies considerably there, and one can explicitly represent the asymptotic orthonormal modes of the field's spectral decomposition induced by the natural time flow associated with the observer's state of motion:

$$\begin{aligned} h_{\omega\ell m} &\approx \frac{1}{r}\mathrm{Y}_{\omega\ell m}(\theta,\phi)\,e^{-i\omega v} \qquad \text{near } \mathscr{I}^- \\ h'_{\omega\ell m} &\approx \frac{1}{r}\mathrm{Y}_{\omega\ell m}(\theta,\phi)\,e^{-i\omega u} \qquad \text{near } \mathscr{I}^+ \end{aligned} \tag{x.1.1}$$

where $\mathrm{Y}_{\omega\ell m}(\theta,\phi)$ are the standard spherical harmonics.

Now, in general, to evolve the modes $h'_{\omega\ell m}$ from a point u on $\mathscr{I}^+$ along γ back to a point $p(u)$ on $\mathscr{I}^-$ (where p is the map induced by γ from $\mathscr{I}^+$ to $\mathscr{I}^-$) requires solving the Klein-Gordon equation with appropriate boundary conditions on $\mathscr{I}^+$. We shall assume, however, that the geometrical-optics approximation (which is in this case essentially the eikonal approximation) is appropriate for the physically relevant frequencies, so that we can take the modes to be massless scalar particles propagating along null geodesics. The $h'_{\omega\ell m}$, then, map to modes on Σ of the form

$$\frac{1}{r}\mathrm{Y}_{\omega\ell m}(\theta,\phi)\,e^{-i\omega p^{-1}(v)}$$

The calculation of the function $p(u)$, which depends solely on the spacetime geometry, then does most of the work. By tracking the position of γ relative to the event horizon $\mathcal{H}$ as u smoothly varies, one works out that

$$p(u) \approx A - Be^{-\kappa u}$$

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[3] See the exposition of standard QFT-CST in §v.7 for details.

where κ is the surface gravity of the black hole and A and B are constants. The exponential dependence on u reflects the blue-shifting of the modes as they pass near the event horizon. Thus, in terminology common today, $p(u)$ measures the "(exponential, affine) peeling" of neighboring null geodesics as they leave $\mathscr{I}^-$, pass close to the event horizon, and then continue on to $\mathscr{I}^+$.

The rest of the calculation is straightforward. The inner product of the modes on Σ used to calculate the Bogoliubov coefficients shows that the vacuum state at $\mathscr{I}^+$ will have a non-trivial population of particles as defined by the vacuum state at $\mathscr{I}^-$, as characterized by the expectation value of the number operator on the appropriate Fock space; and the peeling of neighboring null geodesics as they propagate from $\mathscr{I}^-$ to $\mathscr{I}^+$, moreover, as represented by $p(u)$ and governed by κ, yields the exponential behavior of the population characteristic of a Planckian thermal distribution with temperature proportional to κ.[4]

The heart of the argument consists in the following two points. First, this and all derivations remotely similar to it turn, in one way or another, on the idea that QFT-CST allows for different observers, in different states of motion and different spatiotemporal locations, to "see" different vacua; the trick, then, is to calculate the unknown one in the future from the known one in the past (or contrarily). Second, even though ϕ is test matter, in the sense that it does not contribute to the stress-energy content of the classical spacetime geometry, it nonetheless is not independent of that geometry: the metric induced by the collapsing star and resultant black hole defines the affine structure that "guides" the evolution of ϕ, just as it would determine the geodetic motion of a free classical test particle. One can see this most clearly by noting that the field equations are written using the derivative operator associated with the spacetime metric.

It is worth pausing for a moment to clarify a subtle point, that the literature is too often cavalier about. Talk of "the state of the quantum field that an observer sees" must be taken as shorthand for a more adequate physical description. On the standard understanding of a quantum field on a curved spacetime, whether one treats the field as test matter or couples it to the classical spacetime geometry by way of the SCEFE, the field is always and ever in one state and one state only. What an observer's (or a more general system's) "experience" of the field and its state may be—what modes in some spectral decomposition she sees as excited, *e.g.*—depends on two factors, *viz.*, the observer's state of motion and her physical constitution. When we say that an observer "sees no excited modes" or "sees excited modes with the characteristic spectrum of thermalized radiation", we are in general implicitly assuming that the observer is constituted in such a way that she is sensitive to the modes that arise from the "natural" decomposition of the state induced by the time flow associated with her state of motion. If the observer were excruciatingly clever (and rich), she could build a device that, while following an orbit of (say) the static Killing field, would rather record the modes that an inertial observer would "naturally" see.

Before turning to all the problems and opportunities that this remarkable argument has engendered, it will be illuminating to note several of its features—the necessities, the choices and the conclusions of the argument, some implicitly assumed, some explicitly stated—as one can already see many of those larger problems and opportunities in its microcosm.

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[4] I'm ignoring here, and will for the rest of the book, discussion of greybody factors (Page 1976a; Völkel et al. 2019), except where explicitly noted and invoked (*e.g.*, in §x.17 below). There is a lot of interesting physics there, but little of it holds interest for the kind of foundational issues I treat.

necessities

1. cosmic censorship: $\mathscr{I}^+$ is complete (implicit)
2. the domain of outer communication is topologically simple (Friedman et al. 1993; Jacobson and Venkataramani 1995; Galloway and Woolgar 1997)[5] and causally simple—one can assume global hyperbolicity, or at last strong asymptotic predictabality (Wald 1984, p. 299)—and there are no "holes" (Geroch 1977; Manchak 2009, 2014a, 2014b, 2016; Minguzzi 2012), all such that null geodesics determine a 1-1, onto map p from $\mathscr{I}^+$ to the connected region of $\mathscr{I}^-$ consisting of all points u such that no ingoing null geodesics from the point enter the event horizon (all of these are implicit)
3. the state of the quantum field is sufficiently "nice" everywhere that all the manipulations and calculations are guaranteed to make sense, *e.g.*, it is globally Hadamard (implicit)

choices

1. spacetime (GR): the shape and character of the spacetime is specified with a mixture of an abstract characterization and an exact solution, *viz.*, spherically collapsing matter that forms an event horizon and then asymptotically settles down to Schwarzschild
2. matter (QFT):
    a. S-matrix formulation
    b. scalar field
    c. eikonal approximation
    d. no global state assumed, rather induced boundary conditions on how the global state looks asymptotically in localized regions
    e. adiabaticity condition
    f. insensitivity to trans-Planckian phenomena (implicit)
3. combination of the two (GR and QFT):
    a. the framework is QFT-CST, *i.e.*, no coupling of quantum field's stress-energy to spacetime curvature by way of the SCEFE, although he does discuss, in a heuristic manner later in the paper, the effects of back-reaction
    b. the analysis focuses on the behavior of the field in localized, asymptotic regions near or at null infinity, as opposed, *e.g.*, to its behavior globally or near the horizon
    c. various, mostly implicit assumptions about asymptotic behavior and structure (asymptotic symmetries, "almost-conserved" quantities, energy fluxes that don't contribute to curvature, . . .)

conclusions

1. Planckian spectrum of excited modes at $\mathscr{I}^+$

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[5] The known proofs of such topological simplicity—known as topological censorship—all require the null energy condition, which it is known that Hawking radiation may (and often will) violate. Indeed, many of the fundamental theorems used in BHT in general and the Hawking effect in particular rely on energy conditions that Hawking radiation is known to violate. I will discuss this and related issues in §x.15 below and in a different context in §xii.8.

2. expressed using only $\langle N \rangle$, the expectation value of the number operator over the Fock space of constructed modes
3. in particular, neither a global nor a local state of the quantum field is constructed, nor any other observables

interpretation

1. thermalized radiation is generated by the interaction of a black hole and a scalar quantum field, with a temperature proportional to the black hole's surface gravity
2. we are warranted in thinking of the radiation as being related to the black hole itself in the same (or, at least, a relevantly similar) way as ordinary blackbody radiation is related to the ordinary hot matter that generates it
3. thus, when quantum effects are taken into account, black holes can and should be attributed a physical temperature, and thence a physical entropy
4. thus, such black holes are truly thermodynamical systems

I shall examine almost every one of these in the following.

Finally, a remark on terminology: by 'Hawking radiation', 'the Hawking effect' and other such locutions, I shall always mean the phenomenon purportedly associated with black holes as characterized by GR (or a spacetime theory relevantly similar) or associated with geometrical structures in relativistic spacetimes relevantly similar to the classical characterization of a black hole, such as a dynamical trapping horizon (Hayward et al. 2009) or a more general causal horizon (Jacobson and Parentani 2003)—*viz.*, a phenomenon arising in some way from the combined effects of gravitation and quantum field theory in an astrophysical or cosmological context.

In particular, unless explicitly stated otherwise, I shall never use those terms to refer to phenomena in analogue gravity systems, such as: the original dumb hole models (acoustics in fluids) of Unruh (1981) (and see, *e.g.*, de Oliveira et al. 2021 for more recent theoretical models and Weinfurtner et al. 2011 for experimental instantiation); electromagnetic radiation in solid-state dielectrics (Reznik 2000); electromagnetic radiation in waveguides (Schützhold and Unruh 2005); ultra-short laser filaments in a transparent Kerr medium (Belgiorno et al. 2010); acoustics of rotating ion rings (Horstmann et al. 2011); acoustics of a Bose-Einstein condensate (Steinhauer 2014; Muñoz de Nova et al. 2019); laser pulses in fiber optics (Bermudez and Leonhardt 2016); current in nonlinear LC circuits (Katayama et al. 2020); and Schrödinger evolution of fermions on a photonic chip (Wang et al. 2020). This list is not meant to be exhaustive, rather only to give a sense of the broad and varied applications of the idea. See Almeida and Jacquet (2022) for a recent review with particular regard to the relation of analogue gravity systems to the Hawking effect, and Barceló et al. (2011c) and Faccio et al. (2013) for somewhat dated but illuminating, synoptic reviews (and references therein).

x.2 The Spoiled for Choice Problem (Hawking Radiation)

One of the most fascinating aspects of Hawking radiation, from a foundational point of view, is the multiplicity and multifariousness of the derivations known for it. They all differ radically among themselves with regard to the mathematical rigor of the framework they adopt and the mathematical character of the structures they assume, and almost all are valid in different regimes than the others, using different types of physical systems and different approximations and idealizations, basing their arguments on different physical principles, with varying degrees of physical perspecuity and intuitiveness. In consequence, these different derivations seem to suggest different physical interpretations of Hawking radiation itself, both for its origin and for its character (Brout et al. 1995). It is thus not even clear, at a foundational level, what the physical content of the prediction of Hawking radiation is. Indeed, some of the derivations make assumptions that seem to contradict some of the assumptions of other derivations—but if A implies B and not-A implies B, then B must be a tautology.[6]

Since this is an unappealing attitude to take towards Hawking radiation, some other way must be found to reconcile the contrary derivations.

The Spoiled for Choice Problem (Hawking Radiation)

> How do all the different derivations of Hawking radiation relate to each other with regard to physical content and interpretation, in light of the different regimes, the different assumptions, and the different forms of the result associated with all the proofs?

I will treat here in some detail exemplary derivations characteristic of different formulations of and approaches to QFT-CST and SCG, spelling out the particular ingredients and conclusions of each, and discussing their respective virtues and demerits.

Before I address particular derivations in their idiosyncratic detail, I shall first sketch the basic form and variety of the ingredients any derivation requires, so as to facilitate drawing them out for the individual types of derivations I consider, and then comparing them in the final subsection of this section (§x.2.16).

What is wanted is the demonstration that radiation of a particular sort is present under some set of conditions, appropriately circumstantiated.[7] In order to get there, one must first fix the circumstantiation. That will then allow one to ascertain what assumptions are necessary, to decide what choices one will make given the possibilities left open, and what form the conclusion will take, which all finally will allow one to attempt to give an interpretation of the result, to interrogate and exhibit its physical significance. In Hawking's original derivation, as we saw (§x.1): the circumstantation was quantum field theory formulated in the S-matrix framework, posed on the spacetime of a collapsing star; a necessary assumption about spacetime was cosmic censorship, and

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[6] The situation is, of course, more complex than this, from both logical and conceptual points of view. I shall discuss this in more detail in §x.23 below.

[7]

I want a hero: an uncommon want,
  When every year and month sends forth a new one,
Till, after cloying the gazettes with cant,
  The age discovers he is not the true one;
Of such as these I should not care to vaunt,
  I'll therefore take our ancient friend [Hawking radiation]–
We all have seen him, in the pantomime,
Sent to the devil somewhat ere his time.
– Lord Byron
"Don Juan" (Canto the First)

about the state of the matter field that it was Hadamard (or something appropriately similar); a choice was the use of a scalar field; a conclusion was the value of the expectation value of the number operator for the relevant modes of the scalar field in a particular region of spacetime; and part of the interpreted physical significance was that those modes constitute thermalized radiation the physical temperature of which is an appropriate proxy for a physical temperature we can or must attribute to the black hole itself.

I state here the most important necessities, choices and conclusions for the circumstantiations of the types of derivations I examine. Some items may be necessities in only some circumstantiations, not others; some choices may be possible only in some but not others; and so on. The list is not meant to be exhaustive, merely suggestive and exemplary. I divide the necessities and choices into those pertaining to GR more or less on its own, those to QFT and those to a combination of the two, although the line will not always be able to be strictly drawn. I leave the possibilities for interpretation and analysis of physical significance for the discussion of the individual derivations. I will recapitulate them in the subsection below (§x.2.16) where I compare the derivations.

necessities

spacetime (GR)

1. some form of cosmic censorship: complete future null infinity; non-singular event horizon; . . .
2. topological assumptions (*e.g.*, topological censorship)
3. causality conditions (*e.g.*, chronology)
4. other niceness conditions (*e.g.*, “hole-freeness”)
5. stability assumptions (“small perturbations do not destroy any essential global or local property of the spacetime”)
6. assumptions about asymptotic behavior and structure (*e.g.*, asymptotic symmetries)

matter (QFT)

1. constructibility of stress-energy tensor operator
2. niceness of state (*e.g.*, “Hadamard”)
3. adiabaticity conditions
4. insensitivity to trans-Planckian phenomena
5. various forms of locality and causality
6. asymptotic freedom
7. cluster decomposition

joint (GR and QFT)

1. assumptions about asymptotic behavior and structure (“almost-conserved” quantities, energy fluxes that don’t contribute to curvature)

choices

spacetime (GR)

1. shape and character of spacetime:
    a. exact solution: Schwarzschild, Kerr, Reissner-Nordström, Kerr-Newman, dS, AdS, dS-Schwarzschild, AdS-Schwarzschild, . . .
    b. abstract characterization:
        i. type of horizon: event, isolated, trapping, cosmological, general causal, . . .
        ii. eternal, past horizon, stationary, quasi-static, dynamic
        iii. topology: form of domain of outer communication (if a black hole); . . .
        iv. symmetries
        v. other asymptotic structure, *e.g.*, some form of flatness or predictability
2. local or global region
3. near-horizon, other interior or asymptotic region

matter (QFT)

1. QFT formulation (S-matrix, algebraic, canonical based on a Lagrangian, holographic, low-energy quantum gravity, . . .)
2. flavor of QFT (scalar, vector, bosonic, fermionic, . . .)
3. eikonal or other approximation
4. choice of local or global eigenbasis, or generic conditions imposed on local or global decomposition of state
5. choice of local or global state, or generic conditions imposed on local or global state
6. boundary conditions on state

combined (GR and QFT)

1. QFT-CST or backreaction
2. stationary, quasi-static or dynamic evolution
3. entropy conditions (*e.g.*, satisfaction of the GSL)

conclusions radiation in some form or other:

1. in some regime (energetic, spatiotemporal, . . .)
2. in some region (local, global; near-horizon, other part of the interior, asymptotic)
3. characterized by some set of quantities, properties or behaviors (expectation values, distribution of occupied modes, a local or a global state of a particular sort, energy flux with characteristic spectrum, form of the stress-energy tensor operator, behavior of detectors, . . .)

Taking all possible, reasonable, consistent combinations of these, there are, at a conservative estimate,

2,069,547,534

possible derivations (with a tip of the hat to I. J. Good[8]).

The number of those possibilities that have been actualized runs to, I estimate, no more than a couple of hundred, in a family of papers whose cardinality is several thousand. (A search on iNSPIRE-HEP for papers with 'Hawking radiation', 'Hawking effect', 'particle creation black hole', *etc.*, in the title alone yields more than three thousand hits.) I have not looked at, much less mastered, all of them (but not for lack of trying!). I therefore will by no means consider every type or form of derivation extant in the literature. They are legion. I will restrict attention to the most popular and influential ones. My criterion for this: there are at least three examples of the type due to different authors. I shall try at least to give references to some of the more interesting niche ones in passing when discussing related derivations.

I will discuss minimal sets of conditions for the existence of something like Hawking radiation, such as those constructed in Visser (2003) and Barceló et al. (2011b), in §§x.23 and x.25 below.

[*** **IGNORE**

1. references in Carlip (2014), and discussion in §9 of the spoiled for choice problem
2. references in Wall (2018) and Visser (2003)
3. look through zotero
4. intriguing discussion in (Gibbons 1977)
5. various points in Kiefer (1999)

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x.2.1 *S*-Matrix Approaches

The essentials of this approach are already contained in the original derivation of Hawking (1974, 1975), which I discussed in §x.1 above.[9] It was simplified and extended to treat Kerr in DeWitt (1975) based on earlier work by Unruh (1974), and Kerr-Newman in Damour and Ruffini (1976). Both DeWitt (1975) and Damour and Ruffini (1976) follow Hawking (1975) in having as their conclusion the expectation values of the number operator.

Wald (1975) derived for the first time the full full probability distribution of the excited modes, not just the expectation values of the number operator. [*** discuss differences in necessities and choices for Wald (1975), simplification by Parker (1975) and Parker (1977) ***]

A great virtue of all these derivations is that they require at bottom very little: a vacuum near the horizon as seen by a freely falling observer, vacuum fluctuations that start in the ground state, and subsequent adiabatic evolution. Indeed, it all really boils down to the fundamental feature of QFT-CST that the vacuum is not unique but depends rather on spatiotemporal location and state of motion: in essence, Hawking showed that the Minkowski vacuum of a past inertial observer before the star's collapse differs from the vacuum of a future observer, inertial or static, looking back at the resulting collapse and formation of the black hole.

One of the most pressing problem of those early derivations is that, as Fredenhagen and Haag (1990, p. 274) observed, the eikonal modes of the radiation pass through regions in which the effective index of refraction changes extremely quickly due to steep curvature gradients, possibly leading

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[8] Good (1971)

[9] This is sometimes called 'the ξ-approach' in early literature (Iyer and Kumar 1979).

to strong dispersion and so calling into question the validity of the geometrical-optics approximation. Based on the earlier work of Fulling et al. (1978), Fulling et al. (1981), Haag et al. (1984), and Fredenhagen and Haag (1987) on the rigorous definition of quantum field theories on curved spacetime based on the behavior of the short-distance scaling limit of local states (*i.e.*, that the states be "Hadamard"), Fredenhagen and Haag (1990) avoid the problem entirely, and provide perhaps the first mathematically rigorous derivation of Hawking radiation in this circumstantiation for collapsing matter, with the conclusion again giving the expectation values of the number operator. [*** describe their method, its new necessities and choices, and how the new characterization of the QFT framework—states based on nice scaling behavior in tangent planes—changes the interpretation of the result ***].

Another serious problem of the early derivations in the spirit of Hawking's original is that their circumstantiation is based on the definitions of Fock space, vacuum state and particle number from standard QFT, but it is exactly one of the lessons of QFT-CST that states in curved spacetime behave very differently from those in flat spacetime, *e.g.*, non-uniqueness of the vacuum, one of the essential ingredients of such derivations. Partly in order to address such concerns, Unruh (1976) constructed a derivation with a circumstantiation modified to include an eternal black hole with both past and future horizon, and more importantly for these purposes which had as its conclusion the firing patterns of a particle detector treated in a simple model as a quantum system with a discrete number of energy eigenstates starting in the ground state and algebraically coupled to the ambient quantum field.[10] I discuss this approach in detail in §x.2.2 just below.

Yet another problems with derivations of this kind is that, as shown by Susskind (1994), they generically violate cluster decomposition (Wichmann and Crichton 1963), often taken as a fundamental axiom of QFT (Weinberg 1999). Strominger (1996) attempted to defuse the problem by modifying Hawking's original derivation so as to produce a unitary S-matrix. This still violated cluster decomposition on the whole, although he was able to define superselection sectors each of which individually satisfied it. [*** discuss how later treatments tried to avoid this, without attempting to impose/require/derive unitarity ***].

[*** now discuss later developments and improvements, with their different necessities, choices and conclusions

1. Birrell and Davies (1982, §8.1)

2. Traschen (2000)

3. Giddings (no date)

***]

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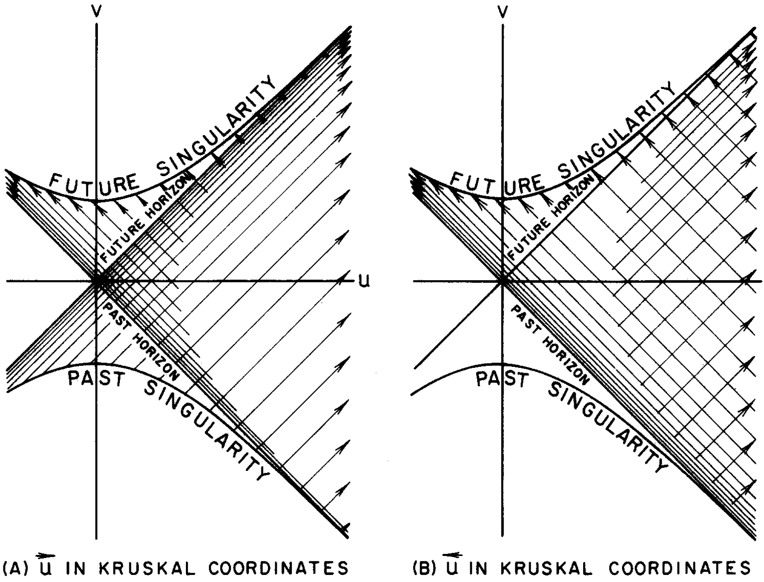
[10] In a related vein, Yu and Zhou (2008) showed that a 2-level atom outside an eternal Schwarzschild black hole with past and future horizon or outside a Schwarzschild black hole formed from collapse behaves as though immersed in a thermal bath of excitations of the quantum field, at the (appropriately red-shifted) Hawking temperature.

x.2.2 Past-Boundary Approaches

[* PRE-PUBESCENT ***]**

In order to effect some technical and conceptual simplifications, Unruh (1976) modified the original derivation of Hawking by using an eternal black hole with past horizon in the circumstantation, and imposing boundary conditions on the past horizon and on $\mathscr{I}^-$.[11] The lefthand side diagram of figure x.2.3 shows the behavior of the ingoing radial modes (scattering, off the future horizon, of ingoing radial modes from $\mathscr{I}^-$ and the past horizon to $\mathscr{I}^+$).

Figure x.2.3



scattering, off the future horizon, of ingoing radial modes from $\mathscr{I}^-$ and the past horizon to $\mathscr{I}^+$ (note that this is a Kruskal diagram, not a Penrose diagram, *i.e.*, it does not show the conformal completion of the spacetime)
[*** this figure is shamelessly cribbed from DeWitt (1975); I need to make my own ***]

The difference with Hawking's original derivation, and those like it, arises from the difference in the vacuum state seen by observers at $\mathscr{I}^-$: rather than seeing a Minkowski vacuum, they see particle production due to the boundary condition imposed on the past horizon. Indeed, the choice of boundary condition on the past horizon is a somewhat delicate matter. One has complete freedom to choose as one likes, and many "natural" choices give nothing like the Hawking effect (Boulware 1975). In order to derive the Planckian spectrum at $\mathscr{I}^+$, Unruh (1976) had to impose as boundary condition that normal modes entered the domain of outer communication from the past horizon with a complex exponential spectrum as a function of the affine parameter on the past horizon—which comes parlously close to gerrymandering the desired result ("exponential in, exponential out"). [*** discuss ***]

Unruh also introduced the idea of formulating the conclusion based on the behavior of particle

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[11] This is sometime called 'the ζ-approach' in early literature (Iyer and Kumar 1979).

detectors rather than expectation values of number operators or distributions of excited modes. [*** discuss ***]

[*** discuss

1. Iyer and Kumar (1979)
2. Birrell and Davies (1982, §8.3)

***]

x.2.3 Tunneling Approaches

The physical picture underlying the tunneling approach is clearly sketched by Hawking and Israel (1979, pp. 18–19):

> The Uncertainty Principle implies that 'empty' space is filled with pairs of 'virtual' particles and antiparticles which appear to gather at some point of spacetime, move apart and then come together again and annihilate each other. They are called virtual because unlike 'real' particles they cannot be observed directly with a particle detector but their indirect effects have been measured in a number of experiments such as the Lamb shift and the Casimir effect. If a black hole is present, one member of a pair may fall into the hole leaving the other without a partner with whom to annihilate. The forsaken particle or antiparticle may follow its mate into the black hole but it may also escape to infinity where it will appear to be a particle or antiparticle emitted by the black hole. Equivalently, one can think of the member of the pair that fell into the black hole (say, the particle) as an antiparticle travelling backwards in time and coming out of the hole. When it reached the point at which the particle-antiparticle pair first appeared, it would be scattered by the gravitational field into an antiparticle travelling forwards in time and going out to infinity. Thus one can think of the emitted radiation as having come from inside the black hole and having quantum mechanically tunnelled through the potential barrier around the hole created by the gravitational field, a barrier that could not be surmounted classically.

This idea was already gestured at by Hawking (1975), although in the picture he sketched there, he considers pair-production just outside the horizon with one positive- and one negative-energy particle; the negative-energy particle, which is classically forbidden from crossing the horizon, then quantum-mechanically tunnels through to the interior of the black hole. He was at pains to emphasize that his discussion of it was strictly heuristic and motivational, not based on anything like real calculations. Davies et al. (1976) provided further heuristic support for the idea based on the calculation of the expectation value of the stress-energy tensor operator in two-dimensions.

Damour and Ruffini (1976), based on the earlier work of Deruelle and Ruffini (1974, 1975), Damour and Ruffini (1975), and Nakamura and Sato (1976), were perhaps the first to try to support the heuristic picture with something like a detailed calculation, in this case for Kerr-Newman. Their derivation, however, otherwise closely followed Hawking's original S-matrix one, and suffers the same ambiguities and defects, now exacerbated by the fact that, in order to model the classically forbidden tunneling of the negative-energy particle through the horizon to the interior, they have to analytically extend the wave function to have support at "complexified" spacetime points, reached by analytical continuation from regular spacetime points. I will discuss this maneuver in §x.2.16 below.

Parentani and Brout (1992), inspired by the past-boundary analysis of Unruh (1976), gave a more perspicuous mathematical treatment, locating the tunneling as primarily occurring near the surface of the collapsing matter as it crosses the horizon. The physical and conceptual interpretation, however, is still problematic. In trying to sketch a physical picture corresponding to their calculations, Parentani and Brout (p. 182) describe the situation as follows: during the collapse, the state of the quantum field in the interior of the matter is essentially vacuum with Minkowskian fluctuations; as the boundary of the matter sweeps inward, the "confrontation" of those initially Minkowskian fluctuations with the sudden change in geometry from Minkowski to Schwarzschild provokes the creation of a particle-anti-particle pair; one manages to escape out through the horizon in finite Killing time, while the other races towards its inevitable demise at the central singularity. I do not find this description helpful. [*** give a more constructive, less snarky way of saying what I find puzzling here ***]

Parikh and Wilczek (2000) [*** crib diagram ***] proposed the most popular schema for tunneling approaches, the one most often relied on in contemporary work that invokes such ideas.[12] Their basic idea was that, rather than thinking of an interior particle as tunneling out through the horizon, one should rather think of the horizon as "sweeping inward past the particle"; although Parentani and Brout (1992) had adumbrated, albeit obscurely, such a picture, Parikh and Wilczek made it the foundation for their analysis. They begin by considering the emission of particle in an s-wave state just inside the horizon. Using a WKB approximation (a simplified eikonal approximation), it is then a straightforward calculation to show that the tunneling rate is given by $e^{\Delta S_{\mathrm{BH}}}$, where ΔS_{BH} is the change in the Bekenstein entropy (black hole area) induced by the decrease in mass due to the effective absorption of the negative-energy component of the $s-wave$.

Briefly, the argument, skipping detailed calculations, is as follows. When a virtual particle-antiparticle pair is created just inside the horizon, by general quantum mechanical considerations, there is a non-zero probability of the positive energy element of the pair tunneling outside the horizon and escaping to $\mathscr{I}^+$. By "energy conservation", therefore, the black hole absorbs a bit of negative energy, requiring its area (proportional to the square of its irreducible mass) to shrink. The tunneling is to be envisaged as the correlated process of the particle's motion towards the exterior and the horizon's motion toward the interior.[13] It follows, from the First Law of black hole mechanics and a condition they interpret as "energy conservation" when the back-reaction of the particle is accounted for, that

$$\Delta A_{\mathrm{BH}} = -8\pi\omega(M - \omega/2)$$

where ω is the s-wave frequency of the tunneling particle.

They argue for the use of $\omega(M - \omega/2)$ rather than ωM based on the earlier work of Kraus and Wilczek (1995), which attempts to include the effect the self-gravitation of Hawking radiation has

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[12] See also Parikh (2004) and Akhmedova et al. (2008).

[13] They also claim that their picture works equally well if one consider pair-creation outside the horizon, with the negative energy particle tunneling inside the horizon by "going backwards in time." Since I have no idea what that means, I ignore it here.

on both the black hole geometry and the motion of Hawking quanta. Ignoring momentarily the ω^2, the quantity reduces to

$$\Delta A_{\mathrm{BH}} = \Delta S_{\mathrm{BH}} = -8\pi\omega M = -\hbar\omega/T_{\mathrm{H}}$$

viz., a Boltzmann factor for the rate of emission for a particle with energy ω in thermalized radiation at the Hawking temperature. They claim that the ω^2 correction to the spectrum can be understood as following from the necessary rise in the black hole temperature as the area shrinks, consistent with their imposition of "energy conservation". Thus, the vacuum state near the horizon is not the standard Unruh vacuum. The time-asymmetry—outgoing positive-energy radiation rather than ingoing—follows, in solving for the imaginary part of the action of the outgoing s-wave particle, from their choice to order the integrand of and evaluate the contour integral so as to ensure that positive energy solutions decay forward in time.

One may take it as a virtue or a demerit of their derivation that the radiation is not exactly thermal. They claim it as a virtue, in so far as their more "realistic" treatment, includig back-reaction, ought to have corrections to the standard result of perfect thermality. I discuss this further in §x.5 below. They claim a further virtue of their approach to be its seeming reliance on purely local physics, without even the need to invoke a collapse phase. This, however, will raise problems for their interpretation of "energy conservation", in particular with regard to the issue of balancing local energy fluxes with changes in global quantities such as the ADM mass. I discuss this in §x.16.

Angheben et al. (2005) extended the treatment beyond the restriction to the WKB eikonal approximation, assuming only that the action satisfies a Hamilton-Jacobi equation. [*** explain why this in fact is much nicer, in so far as it is a much less demanding circumstantiation, with weaker necessities and a wider range of both spacetime and QFT choices ***]. This approach has now been used to derive the Hawking effect for a wide variety of types of black holes, including all the standard stationary solutions and several different kinds of dynamical scenarios (Vanzo et al. 2011).

The fundamental problem is that there is no cogent, coherent picture of an underlying physical mechanism. How to—or can we—represent and think of *quantum* tunneling as a phenomenon *in spacetime*? That is, as one represented unambiguously on the basis of spatiotemporal concepts. Akhmedov et al. (2008, 2454) elegantly sum up a few specific manifestations of this general, fundamental problem, shared by all tunneling approaches, which, to the best of my knowledge have still not yet been adequately addressed:

> However, the interpretation of the imaginary contribution to the particle's action as an indication of tunneling is subtle. First, if the pair is created behind the horizon neither of the particles can tunnel through the horizon, because the tunneling process in quantum mechanics is described via the solution to a Cauchy problem and has to be causal, while passing through the horizon is acausal. In quantum mechanics the vacuum remains unchanged, which is the reason why we can safely convert a time evolution problem into an eigenvalue problem. Second, if the pair is created outside a horizon the time for one of the particles to cross the horizon is infinite for the stationary distant observer. However, this same observer should see the radiation from the black

hole in finite time after the collapse. Finally, the description of black hole radiation as pair creation in a strong gravitational field via the production of virtual superluminal particles does not have an explicit calculation.

[*** discuss improvements, and bells and whistles:

1. Srinivasan et al. (1999) and Shankaranarayanan et al. (2002), as a definite improvement on Parentani and Brout (1992) in some ways, albeit facing problems introduced by the use of complex analysis at least as severe as those of Damour and Ruffini (1976)
2. Umetsu (2008): Ward identities and boundary conditions suffice, using simpler technical machinery (*e.g.*, no step functions)
3. Stotyn et al. (2009)
4. Moretti and Pinamonti (2012): gives more than heuristic evidence, heretofore lacking, for *local* nature of Hawking effect as a tunneling process
5. Di Criscienzo et al. (2007): circumstantiation choice of quasi-local black holes; Di Criscienzo et al. (2010) then resolves some ambiguities, *e.g.*, in definition of temperature; see also Hayward et al. (2009)
6. clean, perspicuous generalization to all Hayward's dynamical trapping horizons, showing continuity with the treatment of static cases: Giavoni and Schneider (2020)
7. Senovilla and Torres (2015b) and Dalui et al. (2021): circumstantiation choice of general horizons

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x.2.4 Algebraic Approaches

[*** ZYGOTIC ***]

are conclusions limited to local algebras, global state or particle detectors?
discuss:

1. static or stationary:
    a. Haag et al. (1984)
    b. Wald (1989)
    c. Kay and Wald (1991): if a somewhat strengthened Hadamard condition is imposed everywhere on the Kruskal extension then the only stationary quasifree states of the outside region are thermal states with Hawking temperature (summary due to Fredenhagen and Haag 1990)
    d. Wald (1994)
2. Hollands and Wald (2010)

3. Hollands and Wald (2013)
4. Hollands and Wald (2015)
5. Fewster and Verch (2015): more general considerations of stability of state at different scales, and "it is shown that the general framework excludes the possibility of there being a single preferred state in each spacetime, if the choice of states is local and covariant."
6. Gérard (2018)
7. Willem Janssen (2022): shows existence of well defined dynamics and algebras, but not generally states
8. Arageorgis (1995)
9. global states for Kerr: Superradiance and quantum states on black hole space-times, Visakan Balakumar, Rafael Bernar, Elizabeth Winstanley, arXiv:2303.13488 [hep-th]

x.2.5 Canonical and Cauchy Evolution Approaches

[* ZYGOTIC ***]**

usually based on Lagrangian; distinguish those that start from 3+1, explain conceptual difference ("$3 + 1 \neq 4$"); but also algebraically formulated null-characteristic Cauchy problem

1. Bachelot (1999): hard core rigorous mathematical derivation based on proof that solution to hyperbolic-mixed problem for Klein-Gordon field with positive mass, in spacetime stationary to past and collapsing to stationary black hole, is determined by a well behaved propagator; the conclusion is that a Schwarzschild observer, in the limit $t \to 0$, locally sees a thermal (KAM) state at the Hawking temperature
2. Jacobson (2005)
3. Schindler et al. (2021)
4. Giddings and Perkins (2022)
5. Janssen and Verch (2022)

x.2.6 Stress-Energy Tensor Operator Approaches

[* ZYGOTIC ***]**

1. Davies et al. (1976): expectation value of stress-energy tensor operator in 2-d, resolving regularization ambiguities
2. Davies (1976): expectation value of stress-energy tensor operator in 2-d, rigorously
3. J.M. Bardeen, Phys. Rev. Lett. 46 (1981) 382
4. R. Parentani, T. Piran, Phys. Rev. Lett. 73 (1994) 2805

5. S. Massar, Phys. Rev. D 52 (1995) 5861
6. Strominger (1995)
7. Robinson and Wilczek (2005):

   > We show that in order to avoid a breakdown of general covariance at the quantum level the total flux in each outgoing partial wave of a quantum field in a black hole background must be equal to that of a $(1 + 1)$-dimensional blackbody at the Hawking temperature.

8. Hollands and Wald (2005)
9. Banerjee and Kulkarni (2008)
10. see discussion of further literature in Kim et al. (2008)
11. Berezin (2014) (`berezin:2014:phenomenological-description-particle-creation-and-influence-on-spa`
12. Banerjee and Majhi (2020)
13. Carlip (2014, §5.5)

x.2.7 Periodic Green's Functions

[* ZYGOTIC ***]**

1. Bisognano and Wichmann (1976)
2. Gibbons and Perry (1976) and Gibbons and Perry (1978)

x.2.8 Near-Horizon Symmetries Approach

[* ZYGOTIC ***]**

1. Banerjee, R., S. Gangopadhyay, and S. Kulkarni (2010, Dec). Hawking radiation and near horizon universality of chiral Virasoro algebra. General Relativity and Gravitation 42(12), 2865–2871; Banerjee, R. and S. Kulkarni (2008, Jan). Hawking radiation and covariant anomalies. Phys. Rev. D 77, 024018
2. Birmingham, D., K. S. Gupta, and S. Sen (2001). Near horizon conformal structure of black holes. Phys. Lett. B505, 191–196
3. Iso, S., H. Umetsu, and F. Wilczek (2006a). Anomalies, Hawking radiations and regularity in rotating black holes. Phys. Rev. D74, 044017; Iso, S., H. Umetsu, and F. Wilczek (2006b). Hawking radiation from charged black holes via gauge and gravitational anomalies. Phys. Rev. Lett. 96, 151302
4. also one can get black hole entropy this way: Carlip, S. (2005). Horizon constraints and black-hole entropy. Classical and Quantum Gravity 22(7), 1303
5. Agullo et al. (2020)

x.2.9 Thermal Atmosphere Approaches

[* ZYGOTIC ***]**

The horizon is not in causal contact with future null infinity. If one takes the causal structure of the classical spacetime seriously, and one is not drawn to the tunneling approach, then this fact suggests that the radiation has to originate from some region outside of the horizon.

approaches explicitly excluding near-horizon sensitivity:

1. Giddings (2016)
2. Dey et al. (2017)
3. The semi-classical stress-energy tensor in a Schwarzschild background, the information paradox, and the fate of an evaporating black hole, James M. Bardeen, arXiv:1706.09204 [gr-qc]; Bardeen (2018): "the origin of the Hawking radiation is not pair creation or tunneling very close to the black hole horizon, but rather is a nonlocal process extending beyond $r = 3M$. Arguments are presented that the black hole information paradox cannot plausibly be addressed by processes occurring on or very close to the horizon of a large black hole whose geometry is close to Schwarzschild."
4. Hawking radiation as quantum mechanical reflection, Pritam Nanda, Chiranjeeb Singha, Pabitra Tripathy, Amit Ghosh, arXiv:2203.06588 [gr-qc]: "The derivation gives an exact local calculation of Hawking temperature that involves a region lying entirely outside the horizon. This is a crucial difference from the tunneling calculation, where it is necessary to involve a region inside the horizon."

x.2.10 Renormalization Group Approaches

[* ZYGOTIC ***]**

1. Hollands and Wald (2003)
2. Formation and evaporation of quantum black holes from the decoupling mechanism in quantum gravity, Johanna N. Borissova, Alessia Platania, arXiv:2210.01138 [gr-qc]

x.2.11 Low-Energy Quantum Gravity Approaches

[* ZYGOTIC ***]**

basically EFT for gravitons:

1. Massar and Parentani (2000): they claim (p. 335) universality as the virtue of their derivation, because the conclusion, that the probability of particle emission is proportional to the negative exponential of the change in horizon area (*à la* Parikh and Wilczek 2000), "follows directly from the universal form of outgoing trajectories in the near horizon geometry and the specification that the field configurations be in (Unruh) vacuum"—but that seems like

some serious gerrymandering, since the Unruh vacuum is, by definition, already a thermal state!

2. Thompson, R. and L. Ford (2008, 15 July). Enhanced black hole horizon fluctuations. Physical Review D 78(2), p. 024014, arXiv:0803.1980 [gr-qc], 10.1103/PhysRevD.78.024014
3. Quantum-Gravity Fluctuations and the Black-Hole Temperature, Shahar Hod, he European Physical Journal C (Letter) 75, 233 (2015), arXiv:1505.04718 [gr-qc], 10.1140/epjc/s10052-015-3465-y; see also Dynamical origin of black-hole radiance, James W. York, Jr., Phys. Rev. D 28(12, 15 December), 2929–2945, 10.1103/PhysRevD.28.2929
4. Burgess (2004)
5. Wallace (2019)

x.2.12 Path-Integral Approaches

[* ZYGOTIC ***]**

1. Hartle and Hawking (1976): roughly speaking, Wick-rotate, play off periodicity of imaginary time in Euclidean sector; restricted to static
2. Gibbons and Perry (1976), Gibbons and Perry (1978), Israel (1976), and Gibbons and Hawking (1977): still static, now plays off periodicity of Green's functions (§x.2.7)
3. Carlip (2014, §5.7)

x.2.13 Canonical and Loop Quantum Gravity Approaches

[* ZYGOTIC ***]**

1. early work by Rovelli, Smolin, Ashtekar, Lewandowski, . . .
2. Hawking radiation and black hole gravitational back reaction – A quantum geometrodynamical simplified model, João Marto, Universe 2021, 7(8), 297, arXiv:2108.06187 [gr-qc], 10.3390/universe7080297

x.2.14 String Theory Approaches

[* ZYGOTIC ***]**

1. D-brane Approach to Black Hole Quantum Mechanics, Curtis G. Callan, Juan M. Maldacena, Nucl.Phys.B472(3, 29 July):591–608, 1996, arXiv:9602043 [hep-th], 10.1016/0550-3213(96)00225-8
2. Hawking radiation in string theory, Sumit R. Das, Journal of Astrophysics and Astronomy volume 20, 131–148 (1999, 3, Dec), 10.1007/BF02702348; Sumit R. Das, String theory and Hawking radiation, Current Science, Vol. 77:1646–1658, No. 12, 25 December 1999

3. early work by Strominger and Vafa related to Strominger and Vafa (1996) (see discussion in "Conceptual Analysis of Black Hole Entropy in String Theory", Sebastian De Haro, Jeroen van Dongen, Manus Visser, and Jeremy Butterfield)
4. Lüst and Vleeshouwers (2019)

x.2.15 Holographic Approaches

[* ZYGOTIC ***]**

1. The Page curve of Hawking radiation from semiclassical geometry, Ahmed Almheiri, Raghu Mahajan, Juan Maldacena, Ying Zhao, Journal of High Energy Physics volume 2020, Article number: 149 (2020), arXiv:1908.10996 [hep-th], 10.1007/JHEP03(2020)149
2. Information Flow in Black Hole Evaporation, Hong Zhe Chen, Zachary Fisher, Juan Hernandez, Robert C. Myers, Shan-Ming Ruan, JHEP03(2020)152, arXiv:1911.03402 [hep-th], 10.1007/JHEP03(2020)152

x.2.16 Comparison of the Approaches

Recall that the necessities and choices of all the circumstantiations can be classified as those pertaining to the characters of the spacetime, of the matter field, and of their combination. I will not attempt to consider each in isolation from the others, for, as we have seen, they intermingle with and constrain each other so intimately and pervasively in the derivations as to make it difficult to disentangle them. Indeed, I think the following discussion will make clear that any attempt to examine one in detail or to any depth in isolation from the others does violence to the conceptual structure of the circumstantiations and the conclusions, and could lead to unhelpful and even misleading claims. I will along the way touch on the similarities and differences among the various possible conclusions (expectation values, distribution of occupied modes, . . .) and their interpretations, but I leave a detailed examination of that issue for §x.3 (The Problem of the Same Physics) below.

I start with the issue of choosing dynamic, stationary or eternal structures for the circumstantiation. In Hawking's original derivation, based on a dynamic spacetime structure, and all those relevantly similar, the calculation seems to suggest that the outgoing radiation is generated by scattering from points just before the event horizon forms. (For ease of reference, I will call this a 'collapse-point source' for a derivation.) Thus, this kind of derivation, based on S-matrix methods, *prima facie* seems inappropriate for stationary and eternal scenarios.

One may then well wonder how the past-boundary approaches (§x.2.2) of Unruh (1976), *et al.*, work, when they also choose S-matrix methods for their circumstantiation. There are two ways to think about it: first, the Hawking radiation has its source entirely in the modes generated by the past horizon; second, it has its source in the modes that come in from past infinity. In the latter case, of course, one can't include the modes that fall into the black hole itself, so the source must be the modes that nearly osculate the event horizon, perhaps wrap around it a few times in nearly bound orbits picking up red-shift—think of the $n = 0, 1, 2 \ldots$ rings in the Event Horizon Telescope (EHT) imaging (Broderick et al. 2022)—then escape out to $\mathscr{I}^+$. Thus the outgoing

Hawking modes will be produced along the entire extent of the horizon, which I will refer to as a 'horizon-extent source'.

In any event, it seems as though one must choose either one or the other picture, for allowing Hawking radiation to be produced both by the modes induced by appropriate boundary conditions on the past horizon *and* by the scattering of modes incoming from $\mathscr{I}^-$ risks double-counting: one will end up getting twice the expected—indeed, twice the *required*—energy flux for a blackbody at the relevant Hawking temperature. This issue of possible double-counting when considering how to reconcile seemingly disparate mechanisms will arise again in discussing The Problem of the Same Physics in more detail in §x.3 below.

Irrespective of whether the geometry is taken to be eternal, stationary or dynamic, any circumstantiation based on tunneling cannot, it seems, rely on the collapse-point source as the origin of the radiation. So long as the event horizon has not formed, no matter how close one gets to that boundary, there is nothing classically forbidden about a negative-energy particle journeying inwards nor a positive-energy one going out, and nothing in the causal structure to prevent a produced particle-antiparticle pair from being unable to recombine and annihilate each other. In consequence, the entire foundation of the tunneling calculations would fail, depending as they do on the complex amplitudes of the classically forbidden paths. Thus tunneling derivations seem forced to have a horizon-extent source.

When the circumstantiation of the derivation depends on fine deatils of the form of the quantum evolution, transition or transformation, *e.g.*, when a Schrödinger evolution or a Cauchy evolution (the last implying use of SCEFE) is used or even only implicitly relied upon, then a serious problem arises based on subtleties of the initial-value problem posed with initial data on $\mathscr{I}^-$, even for the S-matrix formulations. As Geroch (1978, p. 1300) says,

> There are a number of circumstances in general relativity in which it would be of interest to know whether or not a zero-mass field without sources in a well-behaved space-time is uniquely determined by its asymptotic behavior at past null infinity, *i.e.* by its incoming radiation. For example, quantum field theory in curved space-times is usually studied in an S operator framework. But this framework requires that in and out vacuum states can be identified, which requires in turn in and out creation and destruction operators, which requires that the classical fields in the space-time can be decomposed into their asymptotic positive and negative frequency parts, which requires, finally, that these classical fields can be characterized by their asymptotic behavior. Suppose, however, that one's space-time admits nonzero fields with zero incoming radiation. Then the resulting "classical particle creation," uncontrollable from null infinity, would, among other things, make ambiguous the S operator.

Geroch constructs just such an example, spacetime having a non-zero Maxwell field, with zero source, having no incoming radiation from past null infinity. I know of no work that shows that the conclusions of derivations relying, even if only implicitly, on such an initial-value formulation does not fall foul of such problems, although Wald (1979) and Ashtekar and Magnon-Ashtekar (1980) do discuss how to begin to address it for S-matrix approaches, and Tjoa and Gray (no date) for holographic approaches in asymptotically flat spacetimes. This issue needs to be addressed explicitly and definitively.

Several kinds of derivations that rely on particular applications of complex analysis raise quite general and, I think, deep problems of physical interpretation. Recall that Damour and Ruffini (1976), for example, have to introduce points with complex coordinates as a continuation of spacetime points part of the regular spacetime manifold, in order to conclude their derivation. [*** list other derivations and other physicists who do this, and who use complex coordinates more generally in ways that are not under epistemic control ***].

Although complex coordinates and complex vectors are used in many investigative contexts in classical GR, as in, *e.g.*, the introduction of spinors (Penrose and Rindler 1984), their introduction here must be viewed with suspicion. In those other contexts, such as with the use of spinors, the complex coordinates are strictly calculational devices aiding in the construction of structures with manifest physical significance, such as the null flags of Penrose and Rindler (1984), but they themselves have no pretense of supporting a physical interpretation associated with a physical phenomenon. Here, in derivations of the Hawking effect relevantaly similar to that of Damour and Ruffini (1976), they are essential to the attempt to spell and support the description of a purportedly physical process (in this case, quantum tunneling) in order to give the phenomenon of Hawking radiation a physical interpretation.

Their use in the case of spinors, and similar such cases, is benign, because we have epistemic control over such situations in a way we do not here. Whatever physical significance, if any, we may want to try to attribute to the complex coordinates, in the case of spinors will come from that of the null flags and the spinors themselves, which we know how to use in theoretical investigations with understood and successful empirical applications. More to the point, we understand the role that the complex coordinates play in those theoretical investigations, that leads to the physical significance we attribute to null flags and spinors, and thus we have epistemic control over their use. In trying to construct a picture of Hawking radiation such as tunneling, on which to base a derivation, we have none of that. Here, the complex coordinates are being used in the attempt to construct a spatiotemporal picture of a seemingly fundamentally non-spatiotemporal process, *viz.*, quantum tunneling, by stretching and distorting understood spatiotemporal concepts of such as a path in spacetime beyond its breaking point, in ways that seem to make no sense *as* physical concepts—beyond, that is to say, the regime of propriety of the concepts.

There are also technical problems with the introduction of complex coordinates that are almost never—ever?—acknowledged in this literature. When one introduces complex coordinates on a differential manifold, one must change the atlas of the manifold, which is to say: one changes the manifold itself, as a mathematical structure. *A fortiori*, one changes as well all the vector and tensor and principle bundles over the manifold—the vector, tensor, affine and frame fields—in non-trivial ways, such as their topology, and so, at a minimum, one changes the character and the possibilities of the global physics of the physical fields one is studying. Even worse, there is essentially never a unique or even merely privileged choice of complex structure for any given manifold one wants to complexify, even when one adds a spatiotemporal metric into the mix, so without at least a nod towards discussing these ideas, the physical possibilities in the spacetime one works with are left indeterminate. The introduction of complex coordinates is a delicate matter, but physicists too often show the manners of coarse brutes. (This issue does not arise with their use in the case of spinors, *e.g.*, because the choice of spin structure naturally singles out a canonical complex structure on the manifold; see, again, Penrose and Rindler 1984 for details.)

[* BOOTCAMP:** from hereon, the discussion is **INFANTILE**, and does still not contain mention of everything I plan to discuss, but is perhaps yet worth skimming *****]**

conclusions:

species spectrum remark somewhere that one expects the spectrum for macroscopic black holes to be dominated by neutrinos, with a sprinkling of photons, and a small pinch of gravitons and other exotica (Page 1976a, 1976b): do derivations respect this? are there derivations for neutrinos?

state :

1. when comparing derivations resulting in a global state to others that conclude only with characterizations of the state in different regions (*e.g.*, Hawking's original derivation), note that I'll discuss problems with the global state itself in §x.10
2. Colosi and Rovelli (2009)

particle detectors :

1. Colosi and Rovelli (2009)
2. Álvarez-Domínguez et al. (2023):

> We provide a reinterpretation of the quantum vacuum ambiguities that one encounters when studying particle creation phenomena due to an external and time-dependent agent. We propose a measurement-motivated understanding: Each way of measuring the number of created particles selects a particular vacuum. This point of view gives a clear and physical meaning to the time evolution of the number of particles produced by the agent as the counts in a specific detector, and at the same time relates commonly used quantization prescriptions to particular measurement setups.

local versus global

1. Parikh and Wilczek (2000): purely local analysis, but nothing to do with collapse, radiation arises right at the horizon

relation to GSL and entropy conditions:

1. Hawking (1976): gave a crude, heuristic argument that Hawking radiation is a consistency condition for the validity of the GSL; this may seem difficult to square with the demonstration of Visser (1998, 2003) that Hawking radiation is a purely kinematic effect, independent of black hole entropy, which is a dynamical phenomenon, but not necessarily: kinematical constraints are often necessary preconditions for a dynamical relation or dynamical effect (Curiel 2017a), so this may in fact be required

2. Parikh and Wilczek (2000) and Massar and Parentani (2000)

regime:

1. One of the necessary conditions for the validity of the semi-classical approximation is that the emission of a single quantum by the Black Hole not appreciably change the curvature. Let R be the Schwarzschild radius. Then the background Riemann tensor components are approximately $\frac{1}{R^2}$, and the radiation's stress-energy tensor is approximately $\hbar/R^4$ (from the normal energy density law for blackbody radiation $T^4/\hbar^3$, substituting in R for temperature as measured by the mass of the BH expressed by the radius). So the components of $G < T_{ab} >$ (G the gravitational constant) expressed in Planck length L_p, is approximately $(L_p/R)^2 R^{-2}$, which is much smaller than the curvature for $R \gg L_p$. This seems in tension with the tunneling approach as instigated by Parikh and Wilczek (2000).

2. Issues for (near-)extremal black holes, important for many programs of QG, such as string theory [*** citations ***] which can handle only those cases: for any approach that relies on or implies cross-horizon correlations (tunneling, island scenarios), one way to think about fact that temperatures of Kerr and Reissner-Nordström black holes go to zero as they approach extremality is that, as the inner horizon approaches the event horizon, the room available for correlations between the inner and the outer modes shrinks, so the Hawking radiation emitted must decrease as well; this goes for tunneling also

see other discussions of comparison:

1. Helfer (2019) discusses the problem of reconciling the derivations for quantum field theory on curved spacetime versus tunneling approaches

2. Cosmic matter flux may turn Hawking radiation off, Javad T. Firouzjaee and George F. R. Ellis, General Relativity and Gravitation volume 47(2), Article number: 6 (2015), 10.1007/s10714-014-1848-2: at end of §2 (below equation 12), compares what they call the "eikonal approximation" method of Visser (2003) to the tunneling of Parikh and Wilczek (2000): "the tunneling method cannot apply for particle production whenever the MOTS surface is spacelike, because the whole concept of tunneling only makes sense for a timelike surface (where 'inside' and 'outside' are well defined concepts)"; this is a particular manifestation of the problem I mentioned at the end of §x.2.3, to wit, that it is difficult, at best, to make sense of the idea of quantum tunneling as a spatiotemporal process, in this case specifically for some classes of derivations that choose to work with dynamical trapping horizons. And one should add that tunneling also arguably makes sense for null surfaces.

3. the heuristic arguments of Hollands and Wald (2015), who claim that derivations based on eternal black holes suggest that black holes formed from collapse will emit thermal radiation, even though they do not strictly imply it.

x.3 The Problem of the Same Physics

Given the many unresolved dissonances the discussion in §x.2.16 has left us with, do the profound differences among all the different circumstantiations considered here demand different interpretations of all the phenomena physicists what to commonly denominate 'the Hawking effect'? That leads us to:

The Problem of the Same Physics What reason do we have to think that all the different circumstantiations point to or grab a hold of "the same physics in different spacetimes", or, indeed, in many cases, even the same physics in the same spacetime? Can one have a common interpretation of all the consequences, *i.e.*, show that they all have the the same physical significance?

One issue that immediately confronts us is that of "where the particles are created". DeWitt (1975) was perhaps the first to address this issue in a serious way in any detail. He remarks (pp. 130–131) that, for derivations like those of Hawking's original, there seem to be only two reasonable possibilities: either the radiation is generated at a steady rate near the horizon along its entire length (a horizon-extent source), or else the bulk of it is generated just prior to collapse, mostly inside the collapsing matter (a collapse-point source—region OACB in figure x.1.2). He says (p. 331):

> In the former case there is no problem; coupling between matter and radiation will not affect the steady-state temperature. In the latter case the following argument holds: Because the radiation is (a) thermal, and (b) inexhaustible (until the black hole itself decays, see below) any coupling between it and the matter can only serve to bring the matter to the same temperature that it has. The quanta that reach an observer at infinity will in this case mostly have been emitted by the matter (reradiation) but they will still carry the temperature T [*viz.*, the Hawking temperature]. That is, the observed temperature of the matter will stabilize at the value T instead of dropping exponentially to zero. Note that this implies an extremely high local temperature for the matter (infinite if the radiation energy were truly inexhaustible) near the point A of [figure x.1.2], in order to compensate for the red shift.

(Note that he also, *en passant*, introduces at the end the trans-Planckian problem, to be discussed in §x.6 below.) The point he makes about the second option, particle production almost wholly at or near the moment the event horizon forms, by the coupling of the ambient quantum field with the collapsing matter, is an important and subtle one. It first raises the question, what mechanism could there for bringing the collapsing matter to the Hawking temperature exactly at the moment the event horizon forms?

This question becomes even more poignant when one recalls that the matter itself has no way of knowing when or where the horizon does in fact form, as that is not a locally determinable matter, and that black holes in principle can be as large as one likes. The Milky Way is ~5×10^{12} solar masses. That mass has a Schwarzschild radius of ~4×10^{12} `km`, and a sphere of that radius has a volume of ~3×10^{38} `km`^{3}. The sun has a radius of ~7×10^5 `km`, and a volume of ~10^{12} `km`^{3}. It is easy to see that, if one began with 5×10^{12} stars the size and mass of the sun in a homogeneous, isotropic, spherical distribution whose initial radius was that of the Milky Way (10^{18} `km`), and began slowly moving them all isotropically and homogeneously inwards towards the center, they would all pass within their common Schwarzschild radius *long* before they came anywhere near to each other. The Hawking temperature of such a black hole is only $\sim 10^{-20}$ `K`, true, but how on earth is the ambient quantum field, whose excitations are to constitute the Hawking radiation, supposed to know that at the event horizon? And what is there at the event horizon for the quantum field to couple with? If the mechanism for producing Hawking radiation is to have a collapse-point source, it can do so only for certain types of collapsing systems, not for others.

Fredenhagen and Haag (1990, p. 275) attempt to refine DeWitt's analysis by taking back-reaction into account:

> To satisfy the (Bondi-Sachs) energy balance one has to take into account the change of the metric due to the energy of the quantum field. If, as done here, this back reaction is neglected then the infinite amount of energy radiated away in infinite time would have as its source a very small region prior in time to the crossing of the Schwarzschild radius by the surface of the star. If it is taken into account by letting the mass of the star and hence its Schwarzschild radius decrease in time then the radiation will originate from the surface of the black hole at all times after its formation. . .

At first glance, this seems like a compelling argument, driving one inexorably towards the conclusion that particle production must have a horizon-extent source. Otherwise, there could be no negative-energy flux into the black hole to cause it to shrink (evaporate). I think the conclusion is too quick, however, for two reasons.

First, too many derivations—indeed, the overwhelming majority—do not take back-reaction into account, and still arrive at what one wants to think of as the right conclusion. Those cannot simoply be dismissed. They must be accounted for. Second, as I discuss in §x.16 below, the issues of energy conservation and energy balance are delicate and subtle, involving the comparisons of often ill-defined local energy fluxes at the horizon, in the deep interior of the spacetime, both with asymptotic energy fluxes at $\mathscr{I}^+$ *and* with changes in a globally defined energetic quantity at spatial infinity ($\imath^0$), *viz.*, the ADM mass, which defines the black hole's own mass.

This dichotomy—horizon-extent source versus collapse-point source—seems to be at the root of many of the difficulties involved in trying to address the Problem of the Same Physics. Both mechanisms cannot be at work, as that would yield double-counting of the excited modes, and hence of the energy flux, as discussed in §x.2.16 with regard to the past-boundary approach. And yet approach has much to say in its favor, in many different circumstantiations.

[*** now discuss in more detail all the possible consequences, their inter-relations, similarities, differences and possible conflicts: expectation values, distribution of occupied modes, a local or a global state of a particular sort, energy flux with characteristic spectrum, form of the stress-energy tensor operator, behavior of detectors:

1. prefigure discussion of §x.2.9
2. Birrell and Davies (1982, ch. 8)
3. Gryb et al. (2019a):

> Various proposals have been made to provide a local physical mechanism for the production of Hawking radiation. The different proposals vary significantly in terms of where and how the thermal radiation is produced and are largely mutually inconsistent. The most significant possible mechanisms include: splitting of entangled modes as the horizon forms (Unruh 1977; Gibbons 1977); tidal forces pulling apart virtual particle-anti-particle pairs (Hawking and Israel 1979; Adler et al. 2001; Dey et al. 2017); entangled radiation quantum tunneling through the horizon (Parikh and Wilczek 2000); the effects of non-stationarity of the background metric field (Fredenhagen and Haag 1990; Jacobson 2005) and anomaly cancellation (Banerjee and Kulkarni 2008). The formal rigour of these proposals varies greatly, and none are entirely satisfactory from a physical perspective.

Later, they say:

> Notwithstanding this lack of unique physically plausible mechanism or region of origin associated with Hawking radiation, it is certainly significant that the formal expression for Hawking flux has proved 'remarkably robust' under the inclusion of various complicating factors (Leonhardt and Philbin 2008; Thompson and Ford 2008) and formal clarifications (Fredenhagen and Haag 1990).

4. Perhaps Fewster and Verch (2012) can suggest an answer; but their machinery seems easily applicable—perhaps only applicable—to derivations whose circumstantiations lend themselves to a formulation in an algebraic framework.

***]

x.4 The Decoupling Problem, Again

Recall the complaint discussed in §vii.11: according to almost every derivation, Hawking radiation *is not blackbody radiation.* At least, not in any normal sense. Blackbody radiation, such as the electromagnetic radiation emitted by a glowing lump of hot iron, is generated by the dynamics of the micro-degrees of freedom of the system itself—in the case of iron, the wiggling and jiggling of the iron's own atoms and free electrons that makes them radiate. That is not the mechanism by which Hawking radiation is produced. In the semi-classical picture, Hawking radiation is not generated by the dynamics of any micro-degrees of freedom of the black hole itself in any of the derivations, even when back-reaction is accounted for, but rather by the behavior of an external quantum field in the vicinity of the horizon.

The hope, presumably, is that a satisfactory theory of quantum gravity will be able to bring these two *prima facie* disparate phenomena—the micro-dynamics of the horizon on the one hand, and the dynamics of the external quantum field on the other—into explicit and harmonious relation with each other so as to demonstrate that the temperature of the thermalized quantum radiation is a sound proxy for the temperature of the black hole itself as determined by the dynamics of its very own micro-degrees of freedom. Since Hawking radiation is universally viewed as the strongest evidence in favor of attributing a temperature to black holes, and so attributing thermodynamical properties more generally to them, the lack of such an explicit connection ought to be troubling. It ought to become even more troubling when one considers the difficulties of defining black holes in all the different relevant contexts, and relating those different definitions in rigorous, clear, precise ways (§vi.9). How can the physicists across different fields hope to agree on an answer when they do not even agree on the question?

Hawking radiation is, *prima facie*, not like ordinary blackbody radiation. The radiation from a glowing lump of coal is generated entirely from internal degrees of freedom (the motion of its constituent molecules); it would exist whether there were an "ambient" or "external" electromagnetic field. Hawking radiation depends entirely on the existence of an external scalar field (external in the sense that it is a *test* field, not contributing to the structure or physical constitution of the black hole itself), and the radiation itself is radiative modes of that field as scattered off the black hole. Indeed, in standard derivations of Hawking radiation, back-reaction of the quantum field on the metric is ignored (*i.e.*, the field is treated as "test matter", its stress-energy not contributing to spacetime curvature), so excitations of micro-degrees of freedom of the black hole are *necessarily* excluded from playing a role in the generation of the Hawking radiation.

In order to argue that the characteristic thermal properties of Hawking radiation allow us to gain access to the relevant dynamical properties of the micro-degrees of freedom of the horizon, it has to be the case that the relevant properties of the quantum matter fields "mirror" in some appropriate sense those of the horizon. Thus, one has to make something like (at least) the following three assumptions:

1. the horizon is a perfect absorber (so it can "feel" all the dynamical behavior of the micro-dynamics of the matter fields)

2. the horizon is a perfect emitter, so it can manifest all that behavior in its own right, *i.e.*, so that it can in principle mirror the thermodynamical behavior of the matter fields whose behavior we want to infer from the behavior of those fields

3. that the micro-degrees of freedom of the horizon are "of the same kind", in the relevant sense, of those of the matter fields so that they can in detail manifest the same behavior

The first is a problematic assumption in this context. The strong presumption must be that the micro-degrees of freedom of the horizon, if they exist, are quantum in nature, and so will not reproduce in a semi-classical limit all the properties and behavior of a classical black hole. In particular, there is good evidence from several different programs of quantum gravity [*** cite ***] that we ought not to expect to recover the infinitely ecumenical permissivity of the classical horizon. The second two are related, but are problematic for slightly different reasons. One may question the second assumption on the grounds that the membrane paradigm, and related work, suggests that the horizon is fruitfully thought of as a viscöelastic membrane; as such, not all excitational frequencies (*e.g.*) are accessible to it, only the so-called quasi-normal modes of the black hole (Kiefer 2004). This restriction does not hold generically for quantum matter fields. This bears on the problems of the third assumption: no matter what kind of quantum entities metrical, affine, and causal structure turn out to be, and spatiotemporal curvature more generally, they will almost certainty be of radically different natures than those representing "ordinary" matter fields. One obvious sign of this: there is no stress-energy tensor for classical gravitational degrees of freedom Curiel 2019a, but there is no ordinary matter field *without* an associated stress-energy tensor, since it is exactly that property of matter that couples with spatiotemporal curvature. Since blackbody radiation is essentially an energetic phenomenon—energy is emitted with a characteristic power spectrum, characterized exactly by properties encoded in the stress-energy tensor—this should give one pause about the viability of the standard picture as an argument for attributing a temperature to the black hole itself. Real argument is needed to justify the assumption that such obvious differences between geometrical and spatiotemporal fields and matter fields don't break the analogy. [*** the same is true for identifying entanglement entropy with horizon entropy ***]

At the semi-classical level, moreover, Hawking radiation is a *kinematical* phenomenon or quantity, according to the compelling arguments of Visser (1998, 2003) and Barceló et al. (2011b). It would seem to follow, again, that in the semi-classical regime Hawking radiation *cannot* be standard blackbody radiation: as a kinematical phenomenon in this regime, whatever micro-degrees of freedom we may end up concluding the event horizon has in an underlying dynamical regime, they cannot couple to the degrees of freedom of the quantum field whose modes constitute the Hawking radiation. [*** perhaos this militates in favor of taking a Gibbsian approach to black hole thermodynamics? ***]

In sum:

1. one needs further assumptions to bring these two *prima facie* disparate phenomena—the (presumed) micro-dynamics of the horizon on the one hand, and those of the external quantum field on the other—into explicit and harmonious relation with each other
2. only then can one conclude that the temperature of the thermalized quantum radiation is a sound proxy for the temperature of the black hole itself as determined by the dynamics of (presumably) its very own micro-degrees of freedom
3. but it is exactly the lack of such bridging principles that, as we will see, calls into question the importance of the information-loss paradox (the SCG as EFT arguments, see the relevant .tex files, including slides for talks)
4. so perhaps the derivations of Hawking radiation themselves are already trying to tell us not to take any of this terribly seriously, with regard to fundamental issues anbout QG. . .

[* BOOTCAMP: the remainder is given as extended outline, and should, I think, be read ***]**

1. Manus Visser (23 Jul 2021) sent me his paper "Semi-classical thermodynamics of quantum extremal surfaces in Jackiw-Teitelboim gravity", Juan F. Pedraza, Andrew Svesko, Watse Sybesma, Manus R. Visser, arXiv:2107.10358 [hep-th], in which he claims to have given a partial answer to the puzzle around eq. 5 of arXiv v1 of the paper. I reply:

   > I must confess I am—at least initially, without yet having given the matter the serious and concentrated thought it deserves, having only read the first section of your paper somewhat quickly—somewhat skeptical of your proposed solution. (Please don't tell me you're turning into Dafermos, and all your papers from now on will be 100+ page technically dense monstrosities! :)) Semi-classical gravity (in the sense you employ in the paper) treats the spacetime geometry purely classically.

Nothing in your analysis modifies or changes that fact. The only "micro-dynamics" appearing in your argument is wholly segregated to the matter fields. [*** is this rectified in the new argument Manus now has, which he presented at the "Global Structure in SCG" conference in Munich, July 2022? ***]. In order for the T_H that appears in your eq. (1.5) to be interpreted as the temperature of the black hole in a way that shows that Hawking radiation is appropriately related to the micro-dynamics of the quantum degrees of freedom of the event horizon, however, you now need to argue that the *classical* Bekenstein entropy appropriately reflects those degrees of freedom, since the spacetime geometry is treated wholly classically. Invoking Hawking (1974,1975) as you do beneath eq. (1.3) won't do the job, since it also treats the spacetime geometry classically.

Gibbons-Hawking (1977), which you also invoke there, seems *prima facie* to have a better chance, since it explicitly takes account of quantum fluctuations of the metric, but I am skeptical of arguments of that kind, at least with regard to this kind of question. I can pinpoint my problem with their argument in particular, in section III of the paper, in which they argue that the path-integral gives the partition function, and that then, in turn, the logarithm of which, by "the normal thermodynamic argument" (p. 2755), can be set equal to minus the thermodynamic potential times the inverse temperature, and this leads directly, by application of Smarr's formula, to the equality of the entropy appearing in the thermodynamic potential with one quarter of the area. How are we to understand the claim that "the normal thermodynamic argument" applies unproblematically, indeed so perspicuously as to require no discussion of the interpretation of the terms and the propriety of their application in this way, nor indeed any elucidation of any kind, to the quantum state of a 3-metric on a spacelike slice? Is the relation of gravitational quantum statistical mechanics to gravitational thermodynamics so well understood that we should just happily nod and move on? I don't think so.

So it seems to me that you have pushed the problem back one step: how does the classical Bekenstein entropy know about the micro-dynamics of the quantum degrees of freedom of the event horizon? [Manus replied: "Strominger-Vafa!"]. Now, that may be a question you feel we are currently in a better position to give a satisfactory answer to than to my original question about Hawking radiation, and I may even agree with you if you do. But even if that is right, I think you will still have one further step you must take: you have to show that the way that the classical Bekenstein entropy gives us information about the micro-degrees of freedom of the event horizon in fact gives us the *right* information for us to be able to conclude that the behavior of those micro-degrees of freedom are appropriately related to the dynamics, and so the temperature, of Hawking radiation. [Manus replied: "Callan-Maldacena!"]. To have shown that T_H in (1.5) is a thermodynamical temperature, and that it is numerically equal to the temperature of the Hawking radiation, is not yet to have shown that it is the micro-degrees of freedom of the event horizon that generate the Hawking radiation in the appropriate sense.

Manus replied (email 3 August 2021—also see brief, interpolated replies I quote in my own email quoted just above)):

> Thanks for the extensive reply. This is very helpful, since it sharpens the problem itself for me. I think there are two puzzles, one for semiclassical gravity and one for quantum gravity, and we have only addressed the former puzzle in our paper. Probably in your lectures at the summer school you had the latter puzzle, for quantum gravity, in mind and I just misinterpreted what you said. But you might even disagree with me on this, because for you there might only be "one puzzle".
>
> The puzzle that worried me was that Hawking radiation is usually derived in a fixed classical background spacetime with quantum fields on top. On the other hand, the "laws" of black hole mechanics follow from the Einstein equation (in particular the "first law"), so this describes the "dynamics" of the event horizon. If the quantum fields are not coupled to the background spacetime, i.e. backreaction is not taken into account, then a priori these different computations have nothing to do with each other. So why can one identify the surface gravity in the first law with the temperature of Hawking radiation? Only if you take backreaction of quantum fields on the classical background into account, then you can add the quantum matter entropy to the first law, like we did in equation (1.5), and in fact, since the "temperatures" of the radiation and the event horizon are the same, the two terms combine into one term involving the variation of generalized entropy. I think this shows that the identification $T \propto \kappa$ is only valid in semiclassical gravity, and not in classical gravity (where there are no quantum fields). In QFT in curved spacetime the identification $T \propto \kappa$ is valid, but it is not related to the dynamics of the event horizon, you really need dynamical gravity for that, and I've tried to argue that you need semiclassical gravity to accomplish this. Moreover, I think it's need that the generalized entropy appears in the first law (1.5), since that also appears in the generalized second law, and it is this combination which seems to be invariant under RG flow.
>
> The puzzle you're worried about is whether the Hawking temperature describes black-body radiation associated to the microscopic quantum gravitational degrees of freedom of the black hole itself. I obviously haven't addressed that puzzle, since I only discussed semiclassical gravity. I know of one interesting reference, Callan-Maldacena https://arxiv.org/pdf/hep-th/9602043.pdf, where Hawking radiation is derived from a microscopic mechanics in string theory, namely as the emission of closed strings. Also see our section 4.2.1 on p. 40 in https://arxiv.org/pdf/1904.03232.pdf for a short description.

2. From the slides of a talk given by Manus Visser, 22 July 2022, at MCMP conference "Global Structure in SCG", he proposes a related problem:

> Puzzle in black hole thermodynamics
>
> There is a mismatch between the regimes of validity of Hawking radiation and the laws of black hole mechanics.

   a. The first law of BH mechanics follows from the dynamics of classical gravity.
   b. Hawking radiation is a property of quantum fields in a fixed classical black hole background.
   c. Puzzle: how does Hawking radiation know about the dynamics of the event horizon?

   Along the same lines, the First Law is dynamical, but Hawking radiation is purely kinematical, so how can it know about even the classical dynamics of the horizon (especially given that Hawking radiation is often derived against *fixed* classical background)?

   he proposes a solution to the problem by moving to the "First and Second Laws of generalized entropy" (based on Microcanonical Action and the Entropy of Hawking Radiation Juan F. Pedraza, Andrew Svesko, Watse Sybesma, Manus R. Visser, arXiv:2111.06912 [hep-th]; and Semi-classical thermodynamics of quantum extremal surfaces in Jackiw-Teitelboim gravity Juan F. Pedraza, Andrew Svesko, Watse Sybesma & Manus R. Visser, Journal of High Energy Physics volume 2021, Article number: 134 (2021), 10.1007/JHEP12(2021)134)

   the proof is compelling in some ways, but it doesn't address the question of how and why the standard derivations of Hawking temperature work, given that they're on fixed backgrounds with classical geometry *not* coupled to the quantum fields

3. possibly *contra* my claim that this problem is not discussed in the literature, see Susskind et al. (1993):

   > If the considerations of this paper are correct then black holes catalyze a very different phenomenon than that envisioned by Hawking [16]. To begin with an incoming pure state of matter composed of low-energy particles falls into its own gravitational well. The matter is blue-shifted relative to stationary observers so that when it arrives at the stretched horizon it has planckian wavelengths. Thereupon it interacts with the "atoms" of the stretched horizon leading to an approximately thermal state. The subsequent evaporation yields approximately thermal radiation but with non-thermal long time correlations. These non-thermal effects depend not only on the incoming pure state but also on the precise nature of the Planck-scale "atoms" and their interaction with the blue-shifted matter. The evaporation products then climb out of the gravitational well and are red-shifted to low energy. The result is remarkable. The very low-energy Hawking radiation from a massive black hole has non-thermal correlations, which contain detailed information about Planck-scale physics [3,4]. The phenomenon is reminiscent of the imprinting of planckian fluctuations onto the microwave background radiation by inflation.

   Thanks to David Wallace (personal communication) for pointing this out to me. Nonetheless, this passage does not so much make the point I want to make as it rather implicitly assumes there is an unproblematic answer to the question I am raising, since no known calculation even mentions, much less uses the existence of, such "horizon atoms".

4. Also, email from Ted J. 02 Apr 2018:

> On what basis can you say that the quantum field in the vicinity of the horizon does not count as micro-degrees of freedom of the black hole? The black hole is a vacuum object, like a spacetime soliton. "Vacuum" in classical GR means "only spacetime, no matter". But quantum fields fill spacetime, and are always there even when there are no excitations, *i.e.* the vacuum with the quantum field includes the ground state of the field. The Hawking effect amounts to a vacuum instability, and to me it *is* generated by the dynamics of the micro degrees of freedom of this vacuum soliton.

On a related note, and a way to sharpen the problem: Hawking radiation can't define "thermal coupling" of black holes to other thermodynamical systems, because it's the wrong kind of energy. One needs gravitational energy. Ordinary blackbody radiation can serve as thermal-coupling mediator between glowing iron and something else, because the overwhelming amount of free energy in the ordinary black body—electromagnetic—is the same as that being radiated. That's not the case here: the overwhelming amount of energy in a black hole is gravitational, but that's not what's being radiated, but rather "quantum scalar field energy" (or whatever fields one takes to be present). Thus, Hawking radiation cannot be viewed as "ordinary quantum radiative cooling". See Wallace's paper on Information-Loss Paradox, gravity as effective field theory, ignoring quantum gravity effects—but David's response to my question, when I challenged him on this point, is unsatisfying, since it *relies* on a quantum gravity solution, but we don't know what the form of the modes/energies are at those scales (which is also why Ted's response, quoted above, is off the mark). David in effect implies that we can't be entirely confident in the effective field theory description after all—because what I want is an effective field theory/quantum field theory description of how *gravitational* energy of the black hole is converted into (say) quantum scalar field radiation so as to make Hawking radiation "ordinary quantum radiative cooling".

5. Fredenhagen and Haag (1990, p. 283)

> While it appears that the Bekenstein entropy and the Hawking temperature are completely model independent these quantities do not have a direct observational significance since they concern the "naked" black hole relative to the vector field of time translations which is distinguished as an asymptotic symmetry far away in the outside region. The radiation which is transmitted to the outside depends significantly on the quantum field theory model.

x.5 The Problem of Thermality

Many derivations of Hawking radiation conclude that it does not have a perfectly thermalized spectrum, only approximately so. Parikh and Wilczek (2000) is a paradigmatic case. In any event, the non-thermality is manifestly not of a type nor size to be relevant to a possible resolution of the Information-Loss Paradox, so I am more inclined to view it as a demerit.

If the radiation were non-thermal, it would be difficult to make the picture consistent with the idea that Hawking radiation is a purely kinematic effect (Visser 1998, 2003) at the semi-classical level, given heuristic arguments such as those of Hawking and Israel (1979, pp. 18–19) I quoted at the start of §x.2.3.

[* INFANTILE, but I think worth reading ***]**

1. Email from Sean G., 21. Aug 2018:

   > I've been thinking a lot about Hawking radiation lately and after reading a ton of literature of this I'm working on a really slick way of deriving the thermal spectrum assuming that only that the KG operator be self-adjoint on the future horizon (which it has to be in order to have a conserved probability current) and that there is no incoming radiation from spatial infinity [*** according to which observer? ***]. However, going through this process made me realise something pretty interesting.
   >
   > Do you know if anyone has every carefully thought about whether black holes can really radiate fast enough to maintain an approximately thermal spectrum for time-like observers at late times?
   >
   > The idea is that if the black hole starts to shrink – because of some as yet unknown back reaction process that no-one has been able to calculate – in a way that converses the ADM mass of the black hole/KG field system, then this will increase the size of the domain of the dependence of the late-time state on the near horizon state. But because there is an exponential red-shift between the affine time near the horizon and the Killing time far away, even a small change in the size of this domain of dependence could mean that you might have to wait a really long time to actually see a thermal spectrum again. But by then the black hole would have evaporated further still and so you have to wait even longer to observer thermality. So maybe an approximate thermal spectrum is just inconsistent with approximate conservation of ADM mass for late-time stationary observers.
   >
   > I started thinking about this because it occurred to me that if the change of the location of the horizon as determined by $< G_{\mu\nu} >$ is roughly the same size as the fluctuation of $G_{\mu\nu}$ in that region, then there is no way to justify the state of phi living in the self-adjoint domain of $\Box$: if ϕ is highly entangled or interacting with the geometric degrees of freedom on the horizon then you should only require that probability be conserved on the combined Hilbert space which includes both ϕ and the fluctuations of the horizon. This could cause the black hole to radiation much more slowly than it would if probability of ϕ was persevered. But would mean that the spectrum would not be thermal because a slow evaporation process could know about the early time state of ϕ or the details of the collapse.

   My reply:

   a. An operator does not need to be unitary (*i.e.*. derived from a self-adjoint operator) to conserve probability. There are weaker conditions on operators that will still guarantee this (though I forget what they are at the moment—maybe that they be normal?—Bryan Roberts will know).

b. One has to be careful about what one means by an observing "measuring a thermal spectrum". Do you mean "with one simultaneous measurement", *i.e.*, collecting a shitload of photons (or excited modes of whatever ambient field is there) all at once and seeing whether the power spectrum is thermal? If so, the black hole will need to be small enough that it's temperature is high enough that it radiates enough excited modes all at once for such a determination to be unambiguously made with a single measurement. If the black hole is big, and low temp, so not much radiation is coming off (say, a 10^6 solar-mass BH with temperature 10^{-13} Kelvin, giving off a single *very* low-energy quantum every 20 seconds—roughly speaking, a BH emits a single quantum at intervals on the order of the light-crossing time of the BH, and the peak energy of the quantum characteristic of that temperature will be 10^{-17} `eV`), then a distant observer would still be able to determine that the spectrum is thermal by making continual measurements for a few thousand years and collecting enough measurements of individual quanta to have a statistically significant collection to determine whether the spectrum of the entire ensemble so collected is thermal. If the black hole is big enough, and so the change in temperature is small enough over a long period of time (a few thousand years), then there should be no problem in detecting the thermality.

c. If the location of the horizon as determined by $< G_{\mu\nu} >$ is roughly the same size as the fluctuation of $G_{\mu\nu}$ in that region, then the semi-classical approximation (and so any calculation of Hawking rad) is not even valid. One of the necessary conditions for the validity of the semi-classical approximation is that the emission of a single quantum by the Black Hole not appreciably change the curvature. Let R be the Schwarzschild radius. Then the background Riemann tensor components are approximately $\frac{1}{R^2}$, and the radiation's stress-energy tensor is approximately $\hbar/R^4$ (from the normal energy density law for black-body radiation $T^4/\hbar^3$, substituting in R for temperature as measured by the mass of the BH expressed by the radius). So the components of $G < T_{ab} >$ (G the gravitational constant) expressed in Planck length L_p, is approximately $(L_p/R)^2 R^{-2}$, which is much smaller than the curvature for $R \gg L_p$. So I'm guessing that, for your example, your BH is on the order of a Planck length in radius. Another way to think about this: in order for the semi-classical EFE to be valid, the change in Hawking temperature due to the emission of a single quantum must be small compared to the background curvature.

Sean replies:

a. [*** in reply to my 2nd point: ***] My worry is whether the spectrum of Hawking modes actually has time to thermalise as the BH is evaporating. I guess the issue is whether the evaporation is happening faster than is required to assume that it is happening adiabatically. The problem I anticipate is basically this: the radius is decreasing at a rate that depends on the radius via a power law relationship. However, the error in the thermal spectrum scales exponentially with the retarded time of emission. Thus, even though the radius is dropping very slowly for a large BH, the retarded time required to see a thermal spectrum is growing exponentially. So if the temperature doesn't grow fast enough to match how the error is growing, then the relative error might be growing because of the evaporation process. Obviously large Black holes evaporate super slowly, but maybe not in logarithmic time. Anyway, this is very hand wavy at the moment, so maybe I'm just talking bullshit. I just wanted to ask your thoughts about this before spending too much time actually trying to work out the details.

b. [*** in reply to my 3rd point: ***] I completely agree with the point about the semi-classical approximation breaking down. However, I think there is one slight problem with your calculation: the energy you calculate for the Hawking radiation is the energy as seen by a Killing observer near infinity. However, for a free-falling observer near the horizon, this energy is exponentially red-shifted. If you have a look at Helfer's paper in sections 4.1.1 and 4.1.2 he estimates the energy of a Planck scale mode to be the energy of a time-like particle falling through the horizon 1 Planck time before crossing. This suggests to me that the relevant place for the semi-classical approximation to break down is right around a Planck length from the horizon (see also his analysis in 4.1.2). But any modifications on this scale should have really important modifications to the spectrum because these modes are the dominant contributions to the thermal spectrum at infinity. In other words, even modest energy Hawking modes originate from a region near the horizon that is highly non-semi-classical. In fact, this is why so little needs to be assumed about the bulk state of the Hawking modes before the collapse: because the Hawking spectrum is probing so deeply into the UV part of the 2-point functions that you are literally only seeing the conditions imposed by the regularity conditions on the 2-point functions: i.e., that the UV modes are essentially in a vacuum state. Since the vacuum is maximally entangled across the horizon, it's no surprise that when you trace over the in-going modes, you get a thermal spectrum. But it seems a bit nuts to me that the thermallity of the Hawking spectrums depends so strongly on the asymptotic form that is assumed for the 2-point functions. This story could change very dramatically if quantum gravity corrections are non-local. It's funny that even Polchinski points this out in his original paper on the nice slice argument. He actually spends a third of the paper trying to argue that string theory could actually screw up his own argument!! (I'm sure he changed his mind after that though.)

discuss:

1. Black Holes Do Evaporate Thermally, James M. Bardeen Phys. Rev. Lett. 46(1981, 6, 9 Feb), 382–385, 10.1103/PhysRevLett.46.382

2. on thermality of Hawking radiation: Journal of High Energy Physics, July 2015, 2015:9, "Thermality of the Hawking flux", Matt Visser, doi:10.1007/JHEP07(2015)009

3. A quantum-corrected approach to black hole radiation via a tunneling process, Milad Hajebrahimi, Kourosh Nozari, Progress of Theoretical and Experimental Physics, Volume 2020, Issue 4, April 2020, 043E03, https://doi.org/10.1093/ptep/ptaa032

4. Corrected Hawking Radiation of Dirac Particles from a General Static Riemann Black Hole, Ge-Rui Chen and Yong-Chang Huang, Advances in High Energy Physics, Volume 2013, Article ID 982146, 10.1155/2013/982146

x.6 The Trans-Planckian Problem

Many derivations of Hawking radiation share the following problem: it is a generic feature of all their results that Hawking radiation will contain modes of arbitrarily high frequency, *i.e.*, arbitrarily high energy, known as 'trans-Planckian modes'. [*** explain, using §x.1 as example ***]. Perhaps most troublingly, this problem seems to plague all the most "realistic" derivations, *viz.*, those whose circumstantiation includes dynamical collapse or other such dynamical processes (*e.g.*, a non-static trapping horizon).

When energies approach the Planck scale, one expects the semi-classical approximation to break down: effects associated with the presumed quantum nature of spatiotemporal geometry itself should dominate or at least become appreciably non-negligible, thus requiring a full theory of quantum gravity for a principled characterization of the phenomena associated with Hawking radiation, or at least an effective or otherwise approximative theory that accounts for quantum features of the spacetime geometry. In other words, what reason do we have to trust the semi-classical approximation here? This calls into question the existence of Hawking radiation itself.

Jacobson (2005, p. 79) has a nice way of putting the problem: the trans-Planckian problem amounts to "a breakdown in the usual separation of scales invoked in the application of effective field theory."

The Trans-Planckian Problem

> What should be done about the trans-Planckian modes? Do they call into question the propriety of the semi-classical framework used to derive the Hawking effect?

The standard response is to impose by hand cut-offs in the energetic scales permitted for the radiation modes treated in the calculations. One standard argument for this is that the low-energy regime, appropriately treated by the semi-classical approximation, is insensitive to the behavior of the high-energy modes. I will consider the most popular arguments in favor of this claim, including those of Polchinski (1995), Jacobson (2005), and Unruh and Schützhold (2005). Based on current and ongoing work(Curiel 2017b), I argue that all of them have conceptual problems, especially with regard to the justification of the assumptions they make. I will draw these out and discuss what would need to be done to provide satisfactory justifications for them.

Wallace (2018) relies on Polchinski (1995) to argue away the trans-Planckian problem. I think Polchinski's arguments, however, are seriously lacking. (I am not alone in that estimate: Harlow 2016, whom the Wallace cites immediately following the argument recapitulating Polchinski, notes at least one of my problems with the argument when discussing why he finds it unsatisfactory.) I will first name the problems, and then address them in more detail

1. assumes existence of preferred "nice" slicing
2. inappropriate use of adiabatic theorem
3. considers only spatial curvature
4. doesn't really address the *true* trans-Planckian problem anyway, since it doesn't address the exponential redshift between the horizon and late times; see Harlow (2016) against this.

In more detail, the problems are as follows.

1. Polchinski's arguments pertain only to spatial curvature, not to spacetime curvature, and as such cannot suffice to address all the phenomena associated with the redshift (which has components dependent on the "timelike parts" of the curvature).
2. Polchinski's arguments are dependent on a particular slicing of spacetime into hypersurfaces, and so one may worry that his results are not covariant; one might be able to argue that his results are not affected by the slicing dependence, *except* for the fact that, as already mentioned, the only curvatures Polchinski treats are spatial ones, as determined by the slicing, and in a generic relativistic spacetime one can always find a slicing that makes the spatial part of the curvature behave in almost any way one likes. Thus, a further argument must be given that the result does not depend on the specialness of the slicing. As Harlow (2016, p. 18) notes, however, the dependence in this case seems to inextricably show up in the energy of late-time states. Even if this issue were satisfactorily addressed, however, it would not address the problem that only spatial curvature is being treated.
3. Polchinski assumes that the trans-Planckian modes have their origin in near-singularity high curvature, but that is a complete *non sequitur* in several ways, most important among them being that the modes are generated at the horizon, which can be as low curvature as one likes, and is in any event in general nowhere "near" the singularity in any reasonable sense.
4. Polchinski appeals to the adiabatic theorem to justify his cut-off, but (as Harlow points out) the adiabatic theorem applies only to a global, conserved energy, not to center-of-mass energy of local excitations, as are relevant here.
5. Perhaps most damning, though, is that Polchinski's argument does not address what I think is the heart of the trans-Planckian problem: the exponential redshift between the horizon and *late times*.

[*** BOOTCAMP: INFANTILE, but I think worth skimming ***]

A sampling of more approaches to problem:

1. from email exchange with Sean G., starting 21. Aug 2018; I say:

   > If the location of the horizon as determined by $< G_{\mu\nu} >$ is roughly the same size as the fluctuation of $G_{\mu\nu}$ in that region, then the semi-classical approximation (and so any calculation of Hawking rad) is not even valid. One of the necessary

> conditions for the validity of the semi-classical approximation is that the emission of a single quantum by the Black Hole not appreciably change the curvature. Let R be the Schwarzschild radius. Then the background Riemann tensor components are approximately $\frac{1}{R^2}$, and the radiation's stress-energy tensor is approximately $\hbar/R^4$ (from the normal energy density law for blackbody radiation $T^4/\hbar^3$, substituting in R for temperature as measured by the mass of the BH expressed by the radius). So the components of $G < T_{ab} >$ (G the gravitational constant) expressed in Planck length L_p, is approximately $(L_p/R)^2 R^{-2}$, which is much smaller than the curvature for $R \gg L_p$. So I'm guessing that, for your example, your BH is on the order of a Planck length in radius. Another way to think about this: in order for the semi-classical EFE to be valid, the change in Hawking temperature due to the emission of a single quantum must be small compared to the background curvature.

Sean replies, referring to Helfer (2019):

> I completely agree with the point about the semi-classical approximation breaking down. However, I think there is one slight problem with your calculation: the energy you calculate for the Hawking radiation is the energy as seen by a Killing observer near infinity. However, for a free-falling observer near the horizon, this energy is exponentially red-shifted. If you have a look at Helfer's paper in sections 4.1.1 and 4.1.2 he estimates the energy of a Planck scale mode to be the energy of a time-like particle falling through the horizon 1 Planck time before crossing. This suggests to me that the relevant place for the semi-classical approximation to break down is right around a Planck length from the horizon (see also his analysis in 4.1.2). But any modifications on this scale should have really important modifications to the spectrum because these modes are the dominant contributions to the thermal spectrum at infinity. In other words, even modest energy Hawking modes originate from a region near the horizon that is highly non-semi-classical. In fact, this is why so little needs to be assumed about the bulk state of the Hawking modes before the collapse: because the Hawking spectrum is probing so deeply into the UV part of the 2-point functions that you are literally only seeing the conditions imposed by the regularity conditions on the 2-point functions: i.e., that the UV modes are essentially in a vacuum state. Since the vacuum is maximally entangled across the horizon, it's no surprise that when you trace over the in-going modes, you get a thermal spectrum. But it seems a bit nuts to me that the thermallity of the Hawking spectrums depends so strongly on the asymptotic form that is assumed for the 2-point functions. This story could change very dramatically if quantum gravity corrections are non-local. It's funny that even Polchinski points this out in his original paper on the nice slice argument. He actually spends a third of the paper trying to argue that string theory could actually screw up his own argument!! (I'm sure he changed his mind after that though.)

2. Gibbons (1977): One of first, if not first (Unruh or Wald earlier?) to notice that the derivation of Hawking radiation makes essential use of a curious breakdown in the separation between

micro- and macro- scales—dependence on trans-Planckian modes to generate IR modes far away.

3. analogy with Unruh effect by invocation of equivalence principle: Agullo, I., J. Navarro-Salas, G. J. Olmo, and L. Parker (2009). Insensitivity of Hawking radiation to an invariant Planck-scale cutoff. Phys. Rev. D80, 047503; Helfer, A. D. (2010). Comment on 'Insensitivity of Hawking Radiation to an invariant Planck-scale cutoff'. Phys. Rev. D81, 108501

4. horizon symmetries: Banerjee, R., S. Gangopadhyay, and S. Kulkarni (2010, Dec). Hawking radiation and near horizon universality of chiral Virasoro algebra. General Relativity and Gravitation 42(12), 2865–2871; Banerjee, R. and S. Kulkarni (2008, Jan). Hawking radiation and covariant anomalies. Phys. Rev. D 77, 024018; Birmingham, D., K. S. Gupta, and S. Sen (2001). Near horizon conformal structure of black holes. Phys. Lett. B505, 191–196; Iso, S., H. Umetsu, and F. Wilczek (2006a). Anomalies, Hawking radiations and regularity in rotating black holes. Phys. Rev. D74, 044017; Iso, S., H. Umetsu, and F. Wilczek (2006b). Hawking radiation from charged black holes via gauge and gravitational anomalies. Phys. Rev. Lett. 96, 151302; also one can get black hole entropy this way, Carlip, S. (2005). Horizon constraints and black-hole entropy. Classical and Quantum Gravity 22(7), 1303

5. modified dispersion relations: Himemoto, Y. and T. Tanaka (2000). 'Generalization of the model of Hawking radiation with modified high frequency dispersion relation'. Physical Review D 61(6), p. 064004; Barcelo, C., L. J. Garay, and G. Jannes (2009). Sensitivity of Hawking radiation to superlu- minal dispersion relations. Phys. Rev. D79, 024016.

6. Unruh and Schützhold (2005), particular manifest problems with characterization of parametrization of dispersion-relation modification by single function $F(k^2)$:
   a. how do we even know that quantities like k remain well defined in the trans-Planckian UV regime? This certainly won't be true in most quantum gravity programs.
   b. why think that $F(k^2)$ converges in a regime where k itself may not be well defined?
   c. we need not only that $F(k^2) \to 0$ as $k \to 0$ (so no modification in low-energy regime), but we also need it to do so quickly enough so that we don't see modifications in mid-level energy Hawking radiation
   d. why should we think that $F(k^2)$ grows no faster than k^2 (as must be the case, for it to have a well defined scaling limit in the required sense)?
   e. they *assume* there's an IR fixed point: completely begs the question. Compare true Wilsonian renormalization group arguments, which derive the existence of the fixed point.

7. approaches excluding near-horizon sensitivity: Parentani, R. (2010). From vacuum fluctuations across an event horizon to long distance correlations. Physical Review D 82(2), 025008; Giddings, S. B. (2016). Hawking radiation, the stefan-boltzmann law, and unitarization. Physics Letters B 754, 39–42; Dey, R., S. Liberati, and D. Pranzetti (2017). The black hole quantum atmosphere. Physics Letters B 774, 308–316

8. “On the Connections between Thermodynamics and General Relativity”, Jessica Santiago, https://arxiv.org/abs/1912.04470

9. survey of problems: Helfer (2003)

10. Thompson, R. and L. Ford (2008, 15 July). ‘Enhanced black hole horizon fluctuations’. Physical Review D 78(2), p. 024014, arXiv:0803.1980 [gr-qc], 10.1103/PhysRevD.78.024014

11. Linking the trans-Planckian and information loss problems in black hole physics, Stefano Liberati, Lorenzo Sindoni and Sebastiano Sonego, General Relativity and Gravitation volume 42(5), 1139–1152 (2010), 10.1007/s10714-009-0899-2

12. see papers by Jacobson on æther theories

x.7 The Problem of Interacting Field Theories

[*** ZYGOTIC ***]

Wald (1994, ch. 7, p. 162):

> Finally, we note that the derivation of Fredenhagen and Haag also brings to the fore one disturbing feature of the derivation of particle creation by black holes: The derivation of thermal behavior of the quantum field at asymptotically late times is seen to arise from the singularity structure of the two-point function at arbitrarily short distances. However, even ignoring possible new effects arising from the quantum nature of gravity itself at distance scales smaller than the Planck length, it is unreasonable to assume that the simple, linear field model considered in the derivation will provide an accurate model to a realistic field theory at ultra-short- distance scales. Thus, one might question whether the particle creation effect will occur for nonlinear (i.e., interacting) fields even if these fields can be treated as noninteracting on large distance scales (i.e., at "low energies"). In response to this issue, it should be noted that the derivation of the Unruh effect for linear fields discussed in section 5.1 similarly depends upon the ultra-short-distance singularity structure of the two-point function near the horizon. Nevertheless, the theorem of Bisognano and Wichmann 1976) shows that in Minkowski space- time, the Unruh effect continues to hold for nonlinear fields. Furthermore, the arguments given at the end of section 5.3 strongly suggest that the Unruh effect also continues to hold for nonlinear fields in static curved spacetimes. For this reason—and also because of the intimate relationship between black holes and thermodynamics discussed further in the next section—I see no reason to doubt that, even for interacting fields, a black hole will continue to emit in exactly the same manner as a perfect blackbody; see Jacobson 1993) for further recent discussion of this issue. Note that since nonlinear interactions will couple the (initially thermally populated) modes in $\mathfrak{H}_{\text{wh}}$ to the (initially unpopulated) modes in $\mathfrak{H}_{-\infty}$, the actual spectrum of particles seen by a distant observer should deviate from a thermal one in a manner that would depend upon the details of the nonlinear interactions. This same remark would apply, of course, to an ordinary blackbody which radiates into empty space.

1. Audretsch (1989)
2. Hollands and Wald (2005)

x.8 The Problem of the Stress-Energy Tensor Operator

[* ZYGOTIC ***]**

divergences in stress-energy tensor, at both inner and outer horizons, with particular regard to how to think about what "radiation" an observer will see (refer to §xii.3 and §xvi.13 for treatments of this and related issues with regard to other problems):

1. can be constructed completely in 2-dimensions, clearly shows relation to conformal anomaly:
    a. Birrell and Davies (1982, ch. 8)
2. Brout et al. (1995, §3.3)
3. Zeta function regularization of path integrals in curved spacetime, S. W. Hawking, Communications in Mathematical Physics volume 55, 133–148 (1977, June), 10.1007/BF01626516

x.9 The Problem of the Inner Horizon

[* ZYGOTIC ***]**

mass-inflation, divergences of stress-energy tensor operator, causes problems for approaches based on or implying cross-horizon correlations, or based on Cauchy evolution, or based on stress-energy tensor operator?

1. Pinamonti et al. (2019): states characteristic of Hawking radiation violate micro-locality in the interior of black holes? Any possible relation to the pervasive non-locality of the island calculations (§xvi.14)?
2. Quantum fluxes at the inner horizon of a spinning black hole, Noa Zilberman, Marc Casals, Amos Ori, Adrian C. Ottewill, Quantum Fluxes at the Inner Horizon of a Spinning Black Hole Noa Zilberman, Marc Casals, Amos Ori, and Adrian C. Ottewill Phys. Rev. Lett. 129(26, 23 Dec), 261102, arXiv:2203.08502 [gr-qc], 10.1103/PhysRevLett.129.261102:

    > This is the first time that irregularity of the Cauchy horizon under a semiclassical effect is conclusively shown for (four-dimensional) spinning black holes.

x.10 The Problem of the Global State

[* ZYGOTIC ***]**

The Problem of the Global State

> Hawking radiation seems to be a global phenomenon, requiring global constraints on the state of the quantum field. Is this consistent with various desiderata, such as being locally detectable?

1. existence but not uniqueness can be demonstrated for any spacetime with a bifurcate Killing horizon Kay and Wald (1991)
2. "State independence for tunneling processes through black hole horizons and Hawking radiation", Valter Moretti, Nicola Pinamonti: gives evidence for local nature of Hawking process
3. Kurpicz et al. (2021)

x.11 The Problem of the Coherent State

[*** INFANTILE ***]

The regime of propriety of SCG includes the condition that the state of the quantum field be appropriately coherent, in the sense that the variance of the stress-energy tensor operator be much smaller than its expectation value.[14]

Thermal states, however are *not* coherent in the appropriate sense, as can readily be seen by expanding them in the energy or the number eigenbasis. How, then, can we trust derivations of Hawking radiation whose conclusions are such states or the expectation values of operators?

1. Black hole state evolution and Hawking radiation, Doyeol Ahn, arXiv:1006.2198 [hep-th]
2. Quantifying the Unitary Generation of Coherence from Thermal Quantum Systems, Shimshon Kallush and Aviv Aroch and Ronnie Kosloff, Entropy 2019, 21(8), 810, 10.3390/e21080810
3. discuss Parikh et al. (2020)

x.12 The Equivalence Principle Problem

Some people claim that Hawking radiation violates the strong equivalence principle, by analogy with the Unruh effect *e.g.*: Helfer, A. D. (2010). Comment on 'Insensitivity of Hawking Radiation to an invariant Planck-scale cutoff'. Phys. Rev. D81, 108501; Singleton, D. and S. Wilburn (2011). Hawking radiation, Unruh radiation and the equivalence principle. Phys. Rev. Lett. 107, 081102; Gryb et al. (2019b) also discuss this briefly.

The Equivalence Principle Problem

> Does the Hawking effect violate the equivalence principle? If so, what would the consequences be?

Really, all those are terrible arguments for Hawking radiation is an effect intrinsically depending on the *curvature* of spacetime. The strong equivalence principle can govern only *local* physics that

---

[14] I discuss this issue in detail in §xii.16 below.

do *not* depend on curvature. No version of the equivalence principle should say that one can never tell the difference between the presence of curvature and acceleration in flat spacetime, as that is manifestly false even in classical general relativity. Eddington (1923, ch. i, §17, pp. 40–41, emphases his):

> The risk [in generalizing the laws of motion for a particle experiencing no force and the laws of the free propagation of light] is in passing from regions of the world where Galilean coordinates (x, y, z, t) are possible to intrinsically dissimilar regions where no such coordinates exist—from flat space-time to space-time which is not flat.
>
> The *Principle of Equivalence* asserts the legitimacy of this generalisation. [The Principle] is essentially an hypothesis to be tested by experiment as opportunity offers. Moreover it is to be regarded as a suggestion, rather than a dogma admitting of no exceptions. It is likely that some of the phenomena will be determined by comparatively simple equations in which the components of curvature of the world do not appear; such equations will be the same for a curved region as for a flat region. It is to these that the Principle of Equivalence applies. . . . But there are more complex phenomena governed by equations in which the curvatures of the world are involved; terms containing these curvatures will vanish in the equations summarising experiments made in a flat region, and would have to be reinstated in passing to the general equations. Clearly there must be some phenomena of this kind which discriminate between a flat world and a curved world; otherwise we could have no knowledge of world-curvature. For these the Principle of Equivalence breaks down.
>
> The Principle of Equivalence thus asserts that some of the chief differential equations of physics are the same for a curved region of the world as for an osculating flat region. There can be no infallible rule for generalising experimental laws; but the Principle of Equivalence offers a suggestion for trial, which may be expected to succeed sometimes, and fail sometimes.

Moreover, the equivalence principle manifestly cannot bear on any derivation whose circumstantiation depends on global features, properties or structures of the spacetime or of the quantum field.

Also, since Unruh radiation for rotating observers in Minkowski spacetime has a different spectrum than Hawking radiation for Kerr black holes, the whole thing falls apart anyway for astrophysical black holes anyway.

x.13 The Problem of Unruh versus Hawking

Unruh and Wald (1982) use acceleration (Unruh) radiation near the horizon to "save" the GSL from Geroch's infamous thought-experiment of lowering a radiation-filled box slowly from infinity to the event horizon. If Unruh is based on acceleration, not curvature, as the discussion of ix concluded, then why would not a non-inertial observer experience both Hawking and Unruh radiation as separate, additive effects?

The Problem of Unruh versus Hawking

> What is the conceptual and physical relationship between Unruh and Hawking radiation? Are they physically distinguishable? Are they closely enough related for the appropriate use of Unruh radiation in derivations of Hawking radiation?

Listing of *prima facie* differences between Unruh and Hawking:

1. one has non-zero energy flux at $\mathscr{I}^+$, other doesn't
2. correlatively, for one the temperature goes to zero as the acceleration of the Killing observer goes to zero, the other doesn't
3. most importantly, however, one is associated with curvature, the other with affine acceleration
4. one *big* difference between Hawking and Unruh:
    a. the minimal conditions for Unruh, according to the scheme of Barceló et al. (2011b) are even weaker, as the adiabaticity condition doesn't seem to be needed;
    b. think of the argument that Rainer told me about, that one will get Unruh thermality, asymptotically, of essentially any well behaved state in Minkowski spacetime, not just Minkowski vacuum
5. but one must also a count for the fact that the characteristic wavelengths of Unruh are larger than separation of Rindler observer to the Rindler horizon; does something similar happen for acceleration radiation in Schwarzschild?

[*** The following comes from conversations with Ramesh. ***]. In Schwarzschild spacetime, an observer in constant acceleration (along the static Killing orbits) somewhere in the interior of the spacetime will see Unruh radiation at the same local temperature as that of the Hawking flux (since in the interior, the local Hawking temperature goes as the redshift factor, which is just the acceleration of the static Killing field); Ramesh wants to say this shows that the two are in effect the same thing for the accelerating observer. But the Hawking radiation and the Unruh radiation are still distinct: if I'm a constantly accelerating observer, and I very slowly move from near the event horizon out "to infinity", everywhere following the static Killing orbits [*** spell out: this must happen in sequential step, since the static orbits are timelike and will never reach $\mathscr{I}^+$; so observer has to go along static orbit for a while, long enough to experience thermality of the radiation at that red-shift, then move radially outwards a bit, then repeat the process; then do same for inertial observer ***] then the Unruh radiation eventually vanishes (temperature goes to 0) because the Killing field stops accelerating far away, but the Hawking radiation settles down to its standard Hawking temperature; but that shows that the observer in constant acceleration *can't* see Unruh radiation at the same temperature as the local Hawking temperature in the interior of the black hole! So the guy in constant acceleration, I claim, will see radiation with separate contributions from the two kinds of flux. Very close to the event horizon, say, inside the photon sphere ($3M$), Hawking radiation looks isotropic, because the modes are bouncing off the momentum barrier at the photon sphere and mixing around, and only a tiny bit is leaking out; is the same true for Unruh radiation for a constantly accelerating observer? Is there an angular dependence for Unruh flux, picked out by the direction of acceleration? I don't think there is angular dependence for Unruh, because the effect depends only on the fact that energy it takes to accelerate drops the dude below the effective zero-point energy of the vacuum state, and the resulting "excitations" he sees depend only on the structure of the vacuum corrleation functions, which are isotropic (at least in Minkowski spacetime) Is there, however, angular dependence for Unruh in Schwarzschild spacetime, from the fact that there is a strong curvature gradient near the horizon? This seems to be ignored in standard treatments (*e.g.*, Unruh and Wald 1982); how to account for it in calculation? Far away from event horizon, it is easy to distinguish Hawking from Unruh, for both inertial and static observers. Very near horizon, the contributions from each become more or less identical for the static observer, but the inertial dude sees only Hawking [*** except near the horizon the inertial dude doesn't see Hawking, spacetime looks locally Minkowskian ***].

In Kerr spacetime, one can't even start to run similar arguments, because there is no such thing as "constant acceleration" in the sense relevant to Unruh radiation in Kerr; the guys in "stationary" orbits around the event horizon are the closest you can come, but their acceleration vector is rotating, so it's not clear what the "Unruh radiation" looks like. Think of an analogy: in Minkowski spacetime, insted of constant linear acceleration, I'm on a merry-go-round; the magnitude of acceleration is constant, but my acceleration vector is constantly changing direction; what is the "Unruh flux" I see? it has to pick up terms from the rotational motion, so it won't be exactly thermal; or will it be exactly thermal, just with non-trivial angular momentum? (What is ordinary blackbody radiation for a rotating body look like?). [*** discuss papers on "rotational Unruh effect", by Silke *et al.* ***]

[*** see:

1. Quantum power: a Lorentz invariant approach to Hawking radiation, Michael R. R. Good and Eric V. Linder, The European Physical Journal C volume 82(3), Article number: 204 (2022)
2. Quantum optics approach to radiation from atoms falling into a black hole, Marlan O. Scully and Stephen Fulling, David M. Lee, Don N. Page, Wolfgang P. Schleich and Anatoly A. Svidzinsky, 115 (32) 8131–8136, 10.1073/pnas.1807703115
3. Helfer (2019)

***]

x.14 The Problem of Causality (Hawking Radiation)

[* INFANTILE ***]**

For derivations whose circumstantiation includes correlations across null horizons (classical event horizon, null isolated surfaces, *etc.*):

The Problem of Causal Structure

> Does Hawking radiation, with its correlations across the event horizon, and possibly even tunneling through it, make a hash out of the classical null cone structure?

(See §xii.11, The Problem of Causal Structure (Cogency).) Hawking radiation "leaking/tunneling" through horizon: violates definition of event horizon? What is causal structure of evaporating black hole spacetime when back reaction is taken into account, or for tunneling derivations? For tunneling in particular, what is picture of mechanism? how to—or can we—represent and think of tunneling as a phenomenon *in spacetime*? That is what this problem turns on, how to try to understand that quintessentially quantum phenomenon using spatiotemporal concepts.

[*** see:

1. Causality Constraints on Gravitational Effective Field Theories, Claudia de Rham, Andrew J. Tolley, Jun Zhang, arXiv:2112.05054 [gr-qc]
2. Thermal nature of a generic null surface, Surojit Dalui, Bibhas Ranjan Majhi, T. Padmanabhan, arXiv:2110.12665 [gr-qc]
3. Akhmedov et al. (2008, 2454):

> However, the interpretation of the imaginary contribution to the particle's action as an indication of tunneling is subtle. First, if the pair is created behind the horizon neither of the particles can tunnel through the horizon, because the tunneling process in quantum mechanics is described via the solution to a Cauchy problem and has to be causal, while passing through the horizon is acausal. In quantum mechanics the vacuum remains unchanged, which is the reason why we can safely convert a time evolution problem into an eigenvalue problem. Second, if the pair is created outside a horizon the time for one of the particles to cross the horizon is infi- nite for the stationary distant observer. However, this same observer should see the radiation from the black hole in finite time after the collapse. Finally, the descrip- tion of black hole radiation as pair creation in a strong gravitational field via the production of virtual superluminal particles does not have an explicit calculation.

***]

x.15 The Problem of Energy-Condition Violations (Hawking Radiation)

[*** ZYGOTIC ***]

how much should violation of energy conditions make us worry about all the fundamental black hole theorems implicitly and explicitly relied on in derivations? List the theorems, and how they operate in the derivations.

1. "Gravitational vacuum polarization. I. Energy conditions in the Hartle-Hawking vacuum" Matt Visser, Phys. Rev. D 54, 5103, Vol. 54, Iss. 8, 15 October 1996, doi:10.1103/PhysRevD.54.5103; "Gravitational vacuum polarization II: Energy conditions in the Boulware vacuum", Matt Visser, arXiv:gr-qc/9604008, Phys.Rev.D 54(8, Oct):5116–5122,1996, doi:10.1103/PhysRevD.54.5116

2. A generalization of the Hawking black hole area theorem, Eleni-Alexandra Kontou, Veronica Sacchi, arXiv:2303.06788 [gr-qc]

x.16 The Problem of Local versus Global Energy

Perspicuous way to frame the problem in a way that makes clear how one could approach trying to solve it: can one show that an appropriate quasi-local mass of the black hole itself decreases due to a local influx of negative energy, and then show that the asymptotic limit of the quasi-local mass, which can be shown many cases to approach the ADM mass, in this case not only equals the ADM mass but decreases exacly in the way that the ADM mass does *à la* something like Ashtekar and Magnon-Ashtekar (1979)?

The Problem of Local versus Global Energy

> Need to show mot only that there is local negative energy flow into the black hole, that there is positive energy flux at $\mathscr{I}+$, and that the ADM mass decreases, but that in fact all of those terms, with appropriate coefficients (*e.g.*, red-shift factors for comparing interior and asymptotic energies) balance.

Parikh and Wilczek (2000) is a prime example: their interpretation of "energy conservation" requires local energy fluxes at the horizon to "immediately" balance with changes in global quantities such as ADM mass. But the ADM charge M (and J!) should hold as the definition for the final mass and angular momentum of the black hole even if not all the matter fell into it, as in the physical-process proof of the First Law for charged black holes (Gao and Wald 2001). Compare, however, Massar and Parentani (2000), which is similar in some important ways to the ideas underlying the tunneling approach of Parikh and Wilczek (2000), and based on the same earlier work (P. Kraus, F. Wilczek, Nucl. Phys. B 433 (1995) 403; P. Kraus, F. Wilczek, Nucl. Phys. B 437 (1995) 231; E. Keski-Vakkuri, P. Kraus, Nucl. Phys. B 491 (1997) 249) but they explicitly try to connect the emission of a quantum particle with the transition of a black hole state to a neighboring one with geometry having exactly compensatory less area, *à la* the First Law; but they end up explicitly admitting that in order to calculate the transition amplitudes of detectors, they must keep the ADM mass fixed!

Also discuss momentum: this will be even more complicated, because now we want to compare "local" momentum transfer between quantum field modes and black hole and try to figure out whether it is compensated for asymptotically in a global quantity, but there is now the supertranslation subgroup of BMS to deal with and all their attendant possible global quantities, not a single canonical global quantity like ADM mass.

Arguments such as that of Abdolrahimi et al. (2019) [*** discuss ***], moreover, do not directly address the issue of black hole shrinkage, since they show only the asymptotic decrease of total mass in the interior, not that the quasi-local mass of the black hole itself decreases due to a local influx of negative energy—it is still possible that the mass decrease is due to the build up of negative energy outside the black hole. The same holds as well for such arguments based on applications of the Noether Theorem to the variation of diffeomorphism-invariant Lagrangians, as the change in the associated charge is evaluated on a surface far from the event horizon.

There is also a manifest tension, if not outright inconsistency in how the effective stress-energy tensor of the radiation (the expectation value of the stress-energy tensor operator of the quantum field) is treated locally and asymptotically, both in itself and in relation to the black hole's mass. Locally, in the "interior" of the spacetime, near the horizon, it is treated as a source for curvature; "at infinity", however, it is treated as test matter, not contributing to curvature (though still constrained by the metric in its dynamical evolution), as shown by the fact that null infinity is always taken to be asymptotically flat. Moreover, this strictly local, interior "interaction", or, perhaps better, joint evolution of stress-energy and curvature at the event horizon (where there is an effective negative energy flux into the black hole) is taken to *directly and immediately* modify a global, asymptotic quantity, *viz.*, the ADM mass. It is instructive to compare formulations and proofs of the First Law, where in some cases the perturbations of M and J are taken at spatial infinity, while that of A is at the horizon. See discussion at beginning of: "A note on the physical process first law of black hole mechanics", Antoine Rignon-Bret, arXiv:2303.06731 [gr-qc], p. 1, of the First Law proof for charged black holes by Gao and Wald (2001) (the proof by Wald 1994 for Kerr is all on the horizon):

> It might be a bit unexpected for a physical process first law to involve variations of asymptotic quantities rather than the mass or angular momentum of the matter fields crossing the black hole horizon. . . . As they work with the ADM masses and angular momentum, they cannot distinguish the mass and angular momentum of the black hole from the one of the matter outside.

[*** see also:

1. Conserved Energy Flux for the Spherically Symmetric System and the Backreaction Problem in the Black Hole Evaporation, Hideo Kodama, Progress of Theoretical Physics, Volume 63, Issue 4, April 1980, Pages 1217–1228, 10.1143/PTP.63.1217
2. Birrell and Davies (1982, ch. 8); in particular discussion of stress-energy tensor operator for Hawking radiation in §8.4
3. Brout et al. (1995, §3.4)

***]

x.17 The Evaporation Problem

The problems discuss in §x.16 already must give one pause in trusting the idea that black holes evaporate. I examine here further problems that need more satisfactory address in order to have confidence in the conclusion. In sum, one must cleanly separate the questions of whether, on the one hand, black holes appear to radiate, and whether, on the other, they shrink due to evaporation induced by the radiation.

The Evaporation Problem

> Are the "back-reaction" calculations trustworthy? Do black holes really evaporate?

Hawking (1975, p. 202) himself recognized the problem in his original paper, but expressed blithe faith that matters would work out:

> It should be emphasized that these pictures of the mechanism responsible for the thermal emission and area decrease are heuristic only and should not be taken too literally. It should not be thought unreasonable that a black hole, which is an excited state of the gravitational field, should decay quantum mechanically and that, because of quantum fluctuation of the metric, energy should be able to tunnel out of the potential well of a black hole.

To the contrary, I do not think the case for black-hole evaporation, and in particular, the claim that black holes shrink, based on back-reaction calculations, is so strong as Hawking and later commentators such as Wallace (2018, pp. 25*ff*) suggest. In particular, the argument that the negative energy of a quantum-field vacuum is exactly canceled by quanta in the thermal state of Hawking radiation is suspect. Similar calculations about energy density give an *enormously* erroneous value for the cosmological constant (off by $\sim 10^{120}$ order of magnitude), the *only* calculation based on quantum field theory on curved spacetime, note, that we can compare with observations—such errors make it *prima facie* difficult to trust such calculations.

Since, moreover, the vacuum energy diverges at the event horizon, it must be *enormous* in its vicinity; it is difficult, at best, to see how Hawking radiation could carry so much energy as required for cancellation. The back-reaction calculations all ignore grey-body factors. (The non-linearity of the full Einstein field equation makes it non-trivial to ignore this.) The approximations are justified only for "large" black holes, so the "shrinkage" may stop, or even reverse (leading to oscillation around that scale), for "small" (late-stage evaporation) black holes. As black holes become smaller, and the momentum barrier steeper and higher, more and more of the radiation will be reflected back into the black holes (the grey-body factor increases); does the greater flux of radiation due to the ever-increasing rapidity of the emission rate of quanta offset this effect?

Such arguments also assume that the stress-energy tensor is a simple sum of those of the vacuum and the Hawking radiation, with no interaction terms, surely false—the Hawking radiation consists of particles for the quantum field whose vacuum is at issue, leading to non-trivial back-reaction. (Again, the non-linearity of the full Einstein field equation makes it non-trivial to ignore this.) This issue pertains to derivations for interacting not free field theories, as discussed in §x.7. The problem becomes more severe when one tries to consider more "realistic" pictures of Hawking radiation, which will include contributions from all particles of the Standard Model (Page 1976a, 1976b, 1977), and in fact none from the Klein-Gordon scalar field used in the overwhelming majority of derivations.

Note that this is a serious issue that goes beyond the question of the mere validity of a certain kind of calculation. If the conclusion is correct, and the two energies cancel exactly, then the conditions of Hawking's Area Theorem are fulfilled, and so black holes should not be able to shrink at all!

[*** discuss:

1. Fate of gravitational collapse in semiclassical gravity, Carlos Barceló, Stefano Liberati, Sebastiano Sonego, and Matt Visser, Phys. Rev. D 77(2008, 4, 15 Feb), 044032, 10.1103/PhysRevD.77.044032
2. Schindler et al. (2020)

3. Models of evaporating black holes. I, William A. Hiscock Phys. Rev. D 23(1981, 12, 15 June), 2813–2822; Models of evaporating black holes. II. Effects of the outgoing created radiation, William A. Hiscock, Phys. Rev. D 23(1981, 12, 15 June), 2823–2827, 10.1103/PhysRevD.23.2823

4. Corrected Hawking Radiation of Dirac Particles from a General Static Riemann Black Hole, Ge-Rui Chen and Yong-Chang Huang, Advances in High Energy Physics, Volume 2013, Article ID 982146, 10.1155/2013/982146

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x.18 The Opportunity of Schematic Models of Black Hole Evaporation

Let's take stock of where were, to prepare to discuss the complex and difficult methodological and epistemological situation we find ourselves in—it turns out to be, from the point of view of a philosopher or a physicist interested in the structure of our knowledge in physics, extraordinarily rich and deserving of investigation.

We cannot (yet? ever?) solve the SCEFE so as to produce an exact model of an evaporating black hole. What to do, then, when one can't solve equations, *and*:

1. other mathematical difficulties prohibit even approximative methods and numerical simulation (as discussed in §xii.4);

2. and one does not in fact need detailed information about individual models or individual possible solutions (because, *e.g.*, one is interested only in the qualitative behavior of the kind of system at issue)?

The problem is especially acute here, in light of the—ever present, ever haunting—fact that we have no experimental access to the regimes in which one expects the behavior of interest to manifest itself.

Then one can try to prove or derive general results, *à la* the classic singularity theorems of GR. But what exactly is it that one is then doing?

Theorems either assume something of a suitably generic character (*e.g.*, an energy condition), and try to do derive or argue for something of a suitably generic character

1. non-existence claims (non-singular cosmological models)
2. rigidity/stability claims (topology—past-singular closed cosmological models satisfying the strong energy condition)
3. scarcity/genericity claims (measure—cosmological models with a Killing field)
4. non-constructive existence claims (classic singularity theorems)
5. non-constructive behavioral claims (formation of closed trapped surfaces under gravitational collapse)

schematic models or construct models based on general principles—what I will call *schematic models*:

1. fix general principles and generic conditions (the framework of SCG)
2. characterize general structures that embody the principles and conform to the conditions (a quantum field satisfying the semi-classical Einstein field equation on an asymptotically flat black hole spacetime)
3. derive a statement about generic features of the character and behavior of the general structures (Hawking effect: black holes evaporate)

what exactly is it that one is doing with a schematic model?

- these models often involve behavioral claims (in the sense of a general result)
- they are not individual solutions to equations of motion or field equations
- usually, no exact individual solutions are known that represent any thing like such systems, especially not in the generality postulated
- they do not otherwise represent individual systems in any straightforward sense
- sometimes, they are not grounded in exact, rigorous general results
- they are not approximations to or idealizations of solutions
- there are no clearly specifiable families of solutions they correspond to
- they rather represent general features that we expect certain (often loosely characterized, merely postulated) families of solutions to have
- almost always, one can (loosely) characterize such (postulated) families in several different, often mutually contradictory ways
- thus, they have an interpretive looseness and a flexibility of consequence to them not characteristic of exact or approximative solutions

x.19 The Problem of Brownian Kicks

[*** INFANTILE ***]

This is a problem about a possible inconsistency between Hawking radiation and the propriety of the use of the SCG framework not *stricto sensu*, but on the assumption that a classical black hole experiencing the Hawking effect can sensibly be ascribed underlying quantum observables.[15]

1. each emitted Hawking quantum gives the black hole a little momentum kick, like being hit by a molecule in Brownian motion

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[15] It was pointed out to me by Aron Wall in conversation, at conference "Energy Conditions in QFT", Leipzig, Sep 2022.

2. the accumulated variance in the momentum the black hole acquires won't go to zero, even with spherical symmetry, because the variance is not linear (just like total position change in Brownian motion)

3. so momentum uncertainty quickly grows, which should diffuse quantum fuzziness into the classical geometry when a non-trivial proportion of the mass has been radiated away, and yet one still wants to say that one is in SCG's regime of applicability; say 25% of the mass of an initially large black hole has now radiated away—momentum uncertainty of the same order of magnitude as the mass of the black hole itself will have been produced, so the variance in the stress-energy tensor operator wil lbe comparable to the value of its expectation value, which kind of state manifestly falls outside the regime of propriety of the SCEFE (§XII.16)

X.20 The Kay-Time Problem

[*** PRE-PUBESCENT ***]

This is another problem about a possible inconsistency between Hawking radiation and the propriety of the use of the SCG framework not *stricto sensu*, but oin this case on the assumption that a classical black hole experiencing the Hawking effect can sensibly be ascribed an underlying quantum state.[16]:

1. time scale over which black hole evaporates is enormous

2. in our models, there is no disturbance, no "measurement", no decoherence, nothing to stop the unitary evolution of the entire system, as it *very slowly* emits Hawking quanta

3. whatever narly stationary quantum state the black hole itself was in initially is presumably something like a Gaussian sharply peaked over the classical geometry, since we demand coherence of the quantum state in order for the system to fall within the regime of propriety of SCG (§XII.16)

4. but wave functions spread—it's just what they do when left alone, it's their bag, their groove;[17] but, more to the point, this wave function is *not* being left alone: the black hole is leaking energy

5. well before a significant percentage of the black hole's mass has evaporated, maybe 10-20%, the spread will have become so large that quantum fuzziness will begin to emerge from the classical black hole state; more precisely, the nontrivial support of the black hole's wave function will be larger than the classical Schwarzschild radius, *i.e.*, will extend beyond the classical event horizon

6. but at that point, SCG is no longer a valid framework, because the classical spacetime geometry is no longer well defined

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[16] Bernard Kay proposed this to me over beers, 21 Jul 2022, at MCMP conference "Global Structure in SCG".

[17] *Cf.* Malament's story about Ernest Nagel: Nagel, accompanies a student at the Columbia be-in in Morningside Park. **Nagel**: It is all very nice, but I do not understand. **Student**: That is ok, Professor Nagel. Just do your thing. **Nagel**: But understanding *is* my thing.

Spreading just is a wave-function's thing.

7. remember, this problem is about our idealized models, not real black holes in the universe
8. way to calculate: look at how wave-function of black hole is treated in Page (1993) and following analyses of Page curve; also see Quantum evolution of the Hawking state for black holes Steven B. Giddings and Julie Perkins, arXiv:2204.13126v2 [hep-th]

Possible ways to represent it more rigorously, possible resolution:

1. evaporating black hole reabsorbs some Hawking quanta, *viz.*, those that don't make it out of the momentum barrier
2. that will perhaps decohere it, but perhaps not if one thinks of that as a unitary process, since those quanta are (presumably) still "part of" the black hole's pure state
3. possibly relevant? any good for modeling it?: Geometry and thermodynamics of coherent quantum black holes, Roberto Casadio, arXiv:2103.00183 [gr-qc]
4. or, more flat-footedly: Ashtekar's (I think) quantization of Schwarzschild in canonical QG in the 80s
5. Quantum Signatures of Black Hole Mass Superpositions, Joshua Foo, Cemile Senem Arabaci, Magdalena Zych, and Robert B. Mann, Phys. Rev. Lett. 129(18), 181301, 28 October 2022, 10.1103/PhysRevLett.129.181301

X.21 The Opportunity of Non-Stationary Black Holes

[*** ZYGOTIC ***]

Figuring out non-equilibrium thermodynamics/statistical mechanics of black holes, could help us with many of these problems. One possible way to approach the issue: it should be possible to use the Raychaudhuri equation to prove that the dynamics of the area of a fairly general horizon can be expressed as an equation that has the form that one would expect from non-equilibrium thermodynamics. Then, assuming the Zeroth Law, the equilibrium version should just follow as special cases. Indeed, in the generic non-equilibrium case for ordinary thermodynamical systems, the friction matrix (which regulates entropy production) is interpreted as being a measure of the amplitude and relaxation time of the microscopic fluctuations. There should be a nice way to relate this (at least heuristically) to black hole ring-down at the moment of collapse, when the majority of Hawking radiation is being produced (in Hawking's original derivation, at least, and those relevantly similar). Indeed, it could also strengthen the case that BHT can be seen as having a classical basis (§VI.8).[18] See:

1. Irreversible Thermodynamics of Black Holes, P. Candelas, D.W. Sciama, Published in: Phys.Rev.Lett. 38 (1977, 23, 6 June) 1372–1375, 10.1103/PhysRevLett.38.1372

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[18] This idea was developed in conversation with Sean Gryb, largely from his instigation.

x.22 The Opportunity of Open Quantum Systems

[* ZYGOTIC ***]**

Treat the black hole in the Hawking effect as an open quantum system, with the quantum field evolving under something like Lindblad evolution from the start

1. The Open Systems View, Michael E. Cuffaro, Stephan Hartmann, arXiv:2112.11095 [physics.hist-ph]
2. Gravity, Horizons and Open EFTs, C.P. Burgess, Greg Kaplanek, arXiv:2212.09157 [hep-th]; and check out Section "Effective Quantum Gravity" in the book edited by C. Burgess and J. Donoghue of the *Handbook of Quantum Gravity* (Eds. C. Bambi, L. Modesto and I.L. Shapiro, Springer Singapore, expected in 2023)
3. Don N. Page, "Is Our Universe an Open System", in Proceedings Of The Third Marcel Grossmann Meeting on General Relativity, 30 August - 3 September. 1982, Shanghai, China, PART B, Edited by Hu Ning, Science Press, Beijing, 1983, North-Holland Publishing Company, Amsterdam New York Oxford, 1153–1155
4. A "black hole theorem," and its implications, Steven B. Giddings, Canonical Quantum Gravity accepted manuscript online, arXiv:2110.10690 [hep-th], 10.1088/1361-6382/acbe8b

x.23 The Problem of Epistemic Warrant (Hawking Radiation)

> The subtlety of Nature far exceeds the subtlety of sense and intellect: so that these fine meditations, and speculations, and reasonings of men are a sort of insanity, only there is no one at hand to remark it.
>
> Francis Bacon
> *Novum Organum*, Book I, Aphorism X

[*** move stuff about historical scientific and Wimsatt, *etc.*, to §x.25.1 ***]

[* BOOTCAMP: this section is a little chaotic, but more or less complete, at least for a first draft, some of it will end up being moved to §x.25.1 below. ***]**

The Hawking effect is without doubt one of the most central and important results in theoretical physics today, grounding and inspiring an enormous amount of work across a wide spectrum of theoretical and experimental fields. In light of the discussion of the problems attendant on it, this fact poses an urgent nexus of methodological and epistemological problems that neither physics nor philosophy has adequately attempted to address, much less dealt with in anything like a satisfactory way.

The Problem of Epistemic Warrant (Hawking Radiation)

> How did a theoretically predicted phenomenon, derived by combining seemingly incompatible theories in a novel way so as to extend their reach into regimes that we have no way of empirically accessing in the foreseeable future, with arguments constrained only by principles based on physical intuition not honed in those regimes, become one of the most important touchstones for testing novel ideas in theoretical physics? Can it play that role? What epistemic warrant do we or can we have for it in the end?

We have no experimental or observational evidence for any of it—why do we trust it? These questions become all the more poignant when one reflects on the circumstance, fascinating from a foundational point of view, that the multiplicity and multifariousness of the derivations known for it, their idiosyncratic problems and their comparative tensions, are staggering.

I began the chapter by describing how we seem to be spoiled for choice. I fear the issue may be more that we are spoiled, than that we have many equally desirable choices.

All those derivations differ radically among themselves with regard to the mathematical rigor of the framework they adopt and the mathematical character of the structures they assume, and almost all are valid in different regimes than the others, using different types of physical systems and different approximations and idealizations, basing their arguments on different physical principles, with varying degrees of physical perspecuity and intuitiveness. In consequence, these different derivations seem to suggest different physical interpretations of Hawking radiation itself, both for its origin and for its character, as discussed in §x.3 (The Problem of the Same Physics). It is thus not even clear, at a conceptual level, what the physical content of the prediction of Hawking radiation is.

I believe that we should, therefore, be more skeptical of the conclusions than the physics community tends to be today. Of course, I do not recommend that we reject them, rather only that we should be more cautious in attributing confirmational support and epistemic warrant to them in the face of a lack of empirical data directly relevant to the project of constraining, *inter alia*, the possibilities for physical interaction.

The problem, however, is even more severe than those remarks suggest. Consider the first defense of the credibility of Hawking radiation, which came, naturally, from Hawking (1975, p. 203) himself. He says,

> Perhaps the strongest reason for believing that black holes can create and emit particles at a steady rate is that the predicted rate is just that of the thermal emission of a body with the temperature $\kappa/2\pi$. There are independent, thermodynamic, grounds for regarding some multiple of the surface gravity as having a close relation to temperature.

He refers in particular to the analogies between the First and Second Laws of black hole mechanics and thermodynamics, and to Bekenstein's arguments for the Generalized Second Law. Thus the analogies between the hoped-for account of BHT on the one hand and phenomenological thermodynamics on the other served at the beginning as the most important evidential warrant for accepting these results. Since Hawking radiation is now used as the primary reason for believing that black holes are themselves thermodynamical systems (§vi.10), it would be viciously circular today to invoke BHT as grounds for believing in Hawking radiation. Another way must be found.

I will consider three strategies for arguing that we should give some non-trivial credence to the idea that something like the Hawking effect occurs or is at least possible in the actual world. Two have been discussed and championed in various forms by both physicists and philosophers: one based on the idea of consilience (even when not called by that name—see, *e.g.*, Wallace 2018, 2019; Carlip 2014; and one based on the idea that, appearances notwithstanding, there is in fact a common core to the many derivations and characterizations of Hawking radiation (Visser 1998, 2003; Barceló et al. 2011b). Based on what I will argue to be inadequacies in both those strategies, I shall propose a new one, based on the idea that there ought to be a common mechanism, a common conceptual picture, shared by all the derivations.

I will not talk about possible evidence in favor of the Hawking effect from analogue gravity experiments, as I think they cannot provide principled grounds for increasing our credence in the idea that something like the gravitational Hawking effect occurs, or possibly can occur, in the real world. The defense of the claim would take us too far afield, so I merely advert here to a few arguments in the literature in favor of the idea (Unruh and Schützhold 2005; Dardashti et al. 2017; Dardashti et al. 2019; Evans and Thébault 2020), and a few opposed (Curiel 2019b; Crowther et al. 2021)

Why then, do so many physicists and philosophers have confidence that Hawking radiation, or something very like, is a feature of the real world? And that, moreover, its theoretical prediction and characterization can be used as evidence for the correctness of further purely theoretical reasoning based on it? Carlip (2014, p. 2) is, I think, exemplary in giving voice to the most widely accepted reason:[19]

> [T]he Hawking temperature and the Bekenstein-Hawking entropy have been derived in so many independent ways, in different settings and with different assumptions, that it seems extraordinarily unlikely that they are not real.

Consilience!—that most puissant of all epistemic tools. Most physicists, when they consider the question of why one is warranted in having credence in Hawking radiation as a feature of the real world, invoke (albeit, almost always implicitly) this idea. [*** sketch the classic idea of consilience, from Newton and Whewell onward, for the non-philosophers; refer to §x.25.1 for more detailed analysis ***].

Whatever else may be the case, however, this cannot be traditional, standard consilience, in at least three ways:

1. the different derivations are all purely theoretical, not deriving from empirical support

2. This is not a case in which the same equations or relations or model, or values of quantities, are being derived for a given phenomenon based on different types of interactions among different types of physical systems, as in the classic case of Perrin's derivation of Avogadro's number (Perrin 1910).[20] This is rather a case in which different physical assumptions are

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[19] For philosophical *cognoscenti*: note the striking resemblance to the No-Miracles Argument for scientific realism (Putnam 1979).

[20] See Smith and Seth (2020) for an extraordinarily detailed and illuminating account of the kinds of evidence required for the different experiments in Perrin's work to count jointly as a case of consilience—exactly the kind of evidence we do *not* have for Hawking radiation.

made about the very same class of physical systems and interactions among them, and calculations and arguments run in very different mathematical and conceptual frameworks.

3. All leading to conclusions with varying physical interpretations not always straightforwardly consonant with each other.

4. One must face here the problem of reconciling this state of affairs with the standard account of consilience.[21]

    a. in historical sciences, consilience is sometimes characterized as convergence of results derived by independent methods or arguments: Elder (2020, ch. 3); Forber and Griffith (2011); Wylie (2011); Staley (2004)

    b. The Unity of Robustness: Why Agreement Across Model Reports is Just as Valuable as Agreement Among Experiments, Corey Dethier, Erkenntnis (2022), online, 10.1007/s10670-022-00649-0

    c. The multiple realizability of general relativity in quantum gravity, Rasmus Jaksland, Synthese (2021) 199 (Suppl 2, December):S441–S467 10.1007/s11229-019-02382-8, special issue "spacetime functionalism": argues for a similar kind of claim with respect to deriving EFE from from many profoundly different programs

    d. for similar reasons, one cannot view this as a kind of Wimsattian robustness (Wimsatt 1981)? well, perhaps in a way, but not in a way that lends credence to any of the methods of derivation, the theoretical framework and concepts underlying and behind them, only to the phenomenon itself. See also *Characterizing the Robustness of Science: After the Practice Turn in Philosophy of Science*, Editors: Léna Soler, Emiliano Trizio, Thomas Nickles, William Wimsatt, Boston Studies in the Philosophy and History of Science (BSPS, volume 292) Dordrecht:Springer, 10.1007/978-94-007-2759-5, the 2 essays: Robustness: Material, and Inferential, in the Natural and Human Sciences, William C. Wimsatt, ch 3, Pages 89–104, 10.1007/978-94-007-2759-5_3; and Multiple Derivability and the Reliability and Stabilization of Theories, Hubertus Nederbragt, ch 5, Pages 121–145, 10.1007/978-94-007-2759-5_5

5. but those approaches for the historical sciences will not suffice in physics, even in those fields, such as astrophysics and cosmology, which have much in common evidentiarily with the overtly historical sciences such as evolutionary biology and archaeology;

6. in physics, the methods and arguments *must* be based on streams of evidence derived from dynamically independent processes—where, presumably, to characterize "dynamical independence" will be non-trivial for multiple derivations of Hawking radiation, if possible at all

7. one might argue that this is the case for derivations in radically different frameworks, that suggest radically different mechanisms for the production and the nature of Hawking radiation itself, but until we have a better grip on the relationships between those different frameworks,

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[21] The GSL raises a similar problem (§xi.3), with, however, interesting differences that will require modification of some of the ideas and arguments I consider here.

until we have confidence that they reall are "treating the same kinds of systems in different enough ways" (where "different enough" will presumably need to be articulated and defended on a case by case, by the exact relationships involved), one cannot invoke this idea as a way to try to invoke consilience as a reason to have confidence in Hawking radiation

If arguments of the considered form, therefore, are to be capable of providing epistemic warrant for Hawking radiation, they must be new kind of consilience, or at least a new form of evidential argumentation having some similarities to traditional consilience. And that must be articulated and defended.

When I have made arguments like this in talks, I have gotten strong push-back from both physicists and philosophers, who seem almost to a person convinced that a situation like this *cannot* be problematic, indeed must rather be a virtue, in virtue of something like consilience.[22]

Wallace (2018, §4.2) lists 5 ways Hawking radiation can be derived, and asserts that this multiplicity of methods that all give essentially the same result should (in effect) count as a case of consilient induction, *i.e.*, they jointly provide stronger evidence than any on its own could, as they strongly suggest that Hawking radiation is a feature of quantum field theory on curved spacetime itself, and not an artifact of a particular way of modeling black holes. I think this is most likely correct in the end, but the argument cannot be as simple as Wallace intimates. Unlike standard cases of consilient induction, the methods of derivations fall into two camps, each having assumptions *prima facie* mutually inconsistent with those in the other camp. If this is correct, than Hawking radiation could in principle be either a tautology or a contradiction in the framework of semi-classical gravity, for either can be implied by inconsistent premises, but either case would manifestly not be what is wanted physically.

The apparent contradiction is as follows. In the first camp (*e.g.*, method 1), back-reaction is not considered, so the effective stress-energy tensor in the semi-classical Einstein field equation is zero; in the second (*e.g.*, method 3), it is not zero. The problem is that the "obvious" response—the first camp is just an approximation to the latter, so there is no real contradiction—cannot be asserted without further, substantive argument. The strong non-linearity of the Einstein field equation forbids such simple assertion. That the relevant approximation really is a good one must be shown by explicit calculation and physical argument. To assert it is good because it leads to the same (desired) result as the less-approximative case would be to beg the question.

1. see my referee report for the paper for discussion of these points
2. see Wallace's responses in item S3 in his reply to the report. I think David is off the mark in at least two ways:
   a. the "net stress-energy tensor" is probably not "very small" in the way required (and what about the conformal curvature, which is underdetermined by the stress-energy tensor?)

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[22] I know of only one case of someone's making a similar argument against the adequacy of the form of argument for the provision of epistemic warrant. It is a case I find baffling, however: after having vigorously defended the idea that epistemic warrant accrues to Hawking radiation from all the different derivations, Carlip (2014, §9) then turns around and argues that the claim that black hole entropy is one quarter its area may be something like a physical tautology, given that every developed program of quantum gravity has its own derivation of it, all radically different among themselves. I do not know why Carlip uses the same consideration in favor of epistemic warrant for Hawking radiation, and against it for Bekenstein entropy.

b. the perturbative methods used elsewhere in physics are almost all in the linear case; even in non-linear cases like fluid mechanics, we have direct experimental tests of the goodness of the perturbative expansions; here, with very few exceptions (Cosmic Microwave Background Radiation and cosmology, and LIGO which is linear anyway) we don't with general relativity

Finally, I think that in order for something like traditional consilience to work, one would need to have an understanding of the physical mechanism underlying Hawking radiation. As discussed in §x.3, however, it does not seem possible in our current current epistemic state to unambiguously fix a unique, canonical mechanism.

I conclude that the idea of something like the idea of consilience cannot in our current epistemic state suffice for conferring epistemic warrant on the Hawking effect. The fact that there are many arguments of many different kinds that yield Hawking radiation cannot by itself be used as evidence for the existence of Hawking radiation, nor even for the weaker claim of the robustness of the conclusion, because, as Visser (1998, 2003) has shown so trenchantly, one needs almost nothing—so very little—to get a Hawking effect (a Lorentz metric, a horizon, . . .)—that it begins to look something like a physical tautology. The many different kinds of derivations using so many different kinds of methods, therefore, really all just gild the lily in different ways, a lot of fancy bells and whistles on the same very basic wheel that's doing all the work. In light of that, it would be astonishing if all those derivations *didn't* derive Hawking radiation, and that for nothing having to do with anything like empirical entrenchment of the effect.

I therefore turn now to a second possible way to attempt to do so, based on the idea, just intimated, that all the different derivations and characterizations of Hawking radiation, although apparently disparate in ways that make it difficult to see what if anything they share in common, do in fact have a common core; and that common core, moreover, is captured by a set of minimally stringent physical conditions that all seem difficult to doubt, in so far as they individually seem to be supported by entrenched empirical knowledge we have, respectively, from GR and QFT.

To motivate the idea, consider the following logical situation. If both

$$A \wedge B \Rightarrow H$$

and

$$\neg A \wedge C \Rightarrow H$$

are true, then there are only 3 possibilities:

1. H is a tautology
2. B and C are both false
3. eactly one of $A \wedge B$ and $\neg A \wedge C$ is true

None, in this context, are appealing.

what is rather wanted is a way to try to construe 'A' and '$\neg A$' not as strict logical contradictories, but as something like:

- loose ways of expressing similar facts as they appear represented in different regimes

- or one as representing an approximation of the other
- or something like that

now, try to see whether one can garner support by looking at sets of minimal conditions:

1. Visser (2003)
2. Barceló et al. (2011a)
3. Barceló et al. (2011b): "We find that the irreducible core requirement is encoded in an approximately exponential "peeling" relationship between affine coordinates on past and future null infinity." – works for AdS? would be cool to figure it out
4. from email exchange with Sean G., starting 21. Aug 2018; I say:

   > If the location of the horizon as determined by $< G_{\mu\nu} >$ is roughly the same size as the fluctuation of $G_{\mu\nu}$ in that region, then the semi-classical approximation (and so any calculation of Hawking rad) is not even valid. One of the necessary conditions for the validity of the semi-classical approximation is that the emission of a single quantum by the Black Hole not appreciably change the curvature. Let R be the Schwarzschild radius. Then the background Riemann tensor components are approximately $\frac{1}{R^2}$, and the radiation's stress-energy tensor is approximately $\hbar/R^4$ (from the normal energy density law for blackbody radiation $T^4/\hbar^3$, substituting in R for temperature as measured by the mass of the BH expressed by the radius). So the components of $G < T_{ab} >$ (G the gravitational constant) expressed in Planck length L_p, is approximately $(L_p/R)^2 R^{-2}$, which is much smaller than the curvature for $R \gg L_p$. So I'm guessing that, for your example, your BH is on the order of a Planck length in radius. Another way to think about this: in order for the semi-classical EFE to be valid, the change in Hawking temperature due to the emission of a single quantum must be small compared to the background curvature.

   Sean replies:

   > I completely agree with the point about the semi-classical approximation breaking down. However, I think there is one slight problem with your calculation: the energy you calculate for the Hawking radiation is the energy as seen by a Killing observer near infinity. However, for a free-falling observer near the horizon, this energy is exponentially red-shifted. If you have a look at Helfer's paper in sections 4.1.1 and 4.1.2 he estimates the energy of a Planck scale mode to be the energy of a time-like particle falling through the horizon 1 Planck time before crossing. This suggests to me that the relevant place for the semi-classical approximation to break down is right around a Planck length from the horizon (see also his analysis in 4.1.2). But any modifications on this scale should have really important modifications to the spectrum because these modes are the dominant contributions to the thermal spectrum at infinity. In other words, even modest energy Hawking modes originate from a region near the horizon that is highly non-semi-classical. In

> fact, this is why so little needs to be assumed about the bulk state of the Hawking modes before the collapse: because the Hawking spectrum is probing so deeply into the UV part of the 2-point functions that you are literally only seeing the conditions imposed by the regularity conditions on the 2-point functions: i.e., that the UV modes are essentially in a vacuum state. Since the vacuum is maximally entangled across the horizon, it's no surprise that when you trace over the in-going modes, you get a thermal spectrum. But it seems a bit nuts to me that the thermallity of the Hawking spectrums depends so strongly on the asymptotic form that is assumed for the 2-point functions. This story could change very dramatically if quantum gravity corrections are non-local. It's funny that even Polchinski points this out in his original paper on the nice slice argument. He actually spends a third of the paper trying to argue that string theory could actually screw up his own argument!! (I'm sure he changed his mind after that though.)

Visser (2003) marked an important step forward in our understanding of these matters, by exhibiting a set of minimal conditions that permit the derivation of a Hawking effect, and emphasizing that the Hawking effect is, therefore, more a kinematical than dynamical phenomenon, as opposed to the other components of black hole thermodynamics, such as the First and Second Laws Wald (1993) and Gao and Wald (2001). This is most easily seen by the fact that the Einstein field equation is not required for the derivation of the Hawking effect, as Visser's conditions clearly show.

Barceló et al. (2011b) extended and deepened that understanding, by showing that significantly weaker and more minimal conditions suffice for a derivation of the effect. In fact, all that's needed is:

1. "exponential affine-peeling" between null affine coordinates on future and past null infinities ("something non-trivial in the interior for ingoing modes to scatter off in the right way")
2. and an adiabaticity condition: "the width of generic wave packets has to be much smaller than the frequencies at the peak of the Planck spectrum"

so not even a horizon! Any adiabatic process or structure that gets the peeling right is assured of the result, and that follows just from the geometry of the spacetime.

The upshot: the many different kinds of derivations that admit of making sense of and relying on those minimal conditions, using so many different kinds of methods, in fact only all just gild the lily in different ways, a lot of fancy bells and whistles on the same very basic wheel that's doing all the work. In light of that, it would be astonishing if all those derivations didn't derive Hawking radiation, and that for no reason having to do with anything like empirical entrenchment of the effect. Flat-footed derivations, moreover, rely essentially on the same machinery as Hawking's original one, albeit gussied up and made more precise in their manners. Fancier ones are all in frameworks that were developed specifically to recover BHT, so it would frankly be surprising if they didn't deliver the result.

But, how can we know that the *recherché* phenomena of QFT-CST, SCG and perturbative QG don't have confounders that spoil the affine-peeling or the other stuff needed? [*** discuss some possibilities along these lines mooted by Helfer (2003), where he argues some QG effects may screw things up for Hawking radiation in some regimes ***]. Or that make it so that the conceptual machinery required for formulating and applying the idea of "peeling" is not even available?

So, I suggest, we should rather try to understand what we do when we derive Hawking radiation as looking for an explicitly articulated *mechanism* or "physical picture" that explains the production of Hawking radiation based on the minimal prerequisites and witnessing the fact that they can be cogently formulated and appropriately applied. [*** Or, better: to try to capture a minimal, schematic mechanism shared by all, or almost, derivations, or perhaps a small set of such schematic mechanisms, each capturing a wide class of derivations, so that jointly they cover almost all possibilities, first, to see whether that or those can be argued to have more support or plausibility than the detailed derivations themselves, and second, if the latter is the case, to try to determine what the relations among the different schematic mechanisms may be, how they may or may not be consonant with each other ***]

Another possibility is that we should rather try to understand what we do when we derive Hawking radiation as:

- trying to capture a minimal, schematically articulated *mechanism* or "physical picture" shared by all, or almost all, derivations, or perhaps a small set of such schematic mechanisms
- based on the minimal prerequisites and witnessing the fact that they can be cogently formulated and appropriately applied
- each mechanism capturing a wide class of derivations jointly covering almost all possibilities
- first, to see whether that or those can be argued to have more support or plausibility than the detailed derivations themselves
- and second, if there is more than one, to try to determine what the relations among the different schematic mechanisms may be, how they may or may not be consonant with each other

[*** but can the vague idea of a "mechanism" or "physical picture" do any more work than a set of minimal conditions? what, if anything, is added epistemically? ***]

The discussion in §x.2.16, however, about the differences in the seeming physical significance of S-matrix and tunneling approaches, respectively, casts serious doubt on the viability of this strategy as well, even if one were able to articulate and defend it more cogently than I have here. The logical situation that presents us with is rather something like the following.

$$A \Rightarrow H_s$$

and

$$A \Rightarrow H_t$$

and

$$H_s \wedge H_t \Longleftrightarrow \perp$$

where H_s is a conclusion for the S-matrix approach and H_t for a tunneling one. Then A must itself be a contradiction. I discuss in §x.25.2 below how my proposals for understanding the role of mathematics in theoretical physics (Reveille, ch. III) may help us come to a satisfactory understanding of the epistemic situation.

x.24 Bringing It All Back Home

[* ZYGOTIC ***]**

What, then, can the Hawking effect, if a more or less accurate picture of what would happen around a black hole in the appropriate regime, under the right conditions, tell us about GR and QFT in particular and gravity, matter and their (joint) thermodynamical properties?

1. Wald (1999, p. A182):

    > [T]his result [*viz.*, thermal particle creation, the Hawking effect] relies only on the analysis of quantum fields in the region exterior to the black hole and it does not make use of any gravitational field equations.

2. Visser (1998, 2003)

x.25 Concluding Philosophical Postscript

x.25.1 Consilience

[* ZYGOTIC ***]**

1. Earman suggests reaching out to a historian of science to come up a good range of examples of consilience that may have more the flavor of the case of Hawking radiation. George Smith? Katherine Brading? Alex Blum? some historian/philosopher of biology?

2. give more in-depth philosophical discussion of consilence

x.25.2 Problems for Realists

The Problem of the Same Physics should trouble realists.

A possible reply: SCG is only an approximative framework, so we shouldn't take any putative metaphysical or ontological lessons from it seriously. A better, deeper theory will come along, to which SCG is an approximation, and that theory will tell us how to conceive of Hawking radiation in a way that support the drawing of metaphysical and ontological lessons.

That, however, is a pious hope, and a pious hope only. It is not grounds for dismissing what our best current physics—even if having itself only weak epistemic warrant—tells us, and that physics tells us that there are many ways to conceive of Hawking radiation such as to make a realist want to begin drawing ontological and metaphysical lessons, none privileged over the others *sub specie æternitatis*, or even privileged merely empirically.

In any event, there is no reason to expect that the better, deeper theory, if it does come along, will itself possess a canonical, privileged formulation that will support the drawing of univocal, unambiguous ontological and metaphysical lessons. No other physical theory thus far has ever had one, and there are many reasons to expect that no theory ever will, at least if we continue to practice physics we have done.

I suggest, therefore, that, in our current epistemic state, in so far as we want to take seriously the idea that there is something in the world corresponding to our idea of Hawking radiation and that all these radically different derivations are latching on to it in some way or other, we should not construe the mathematics of SCG as a picture of the world in the sense that a realist traditionally attempts to, as standing in a depictive or designative or verisimilar relation of representation to the world.

We should rather take a pragmatic attitude: the mathematics of our physical theories is not a picture of the world, but rather serves as only one subset among many conceptual tools we use to get a grip on the world, and different bits of the math, and often even the same bits in different contexts, are used in many different ways, some appearing to instantiate relations superficially similar to traditional representational ones, others not

Nonetheless, there are still interesting and important philosophical questions in the neighborhood that we can and should address. Rather than asking whether Hawking radiation is "REAL" or whether it "REALLY exists" and if so, "what it is REALLY like", we can rather ask in what ways Hawking radiation may be physical, what kinds or modes of physicality it may manifest, if there are phenomena in the world that appropriately correspond to some or all of our theoretical characterizations of it. [*** advert to, recapitulate discussion of Curiel (2018) ***].

Appendix: A Brief History of Particle-Production in Relativistic Spacetimes

[* INFANTILE ***]**

MOVE TO A NEW SECTION SUBSEQUENT TO §§v.10–v.11?

1. sketch brief history of particle creation (brief history of QFT-CST and SCG already given in §§v.10–v.11)
2. Schrödinger (1939): first prediction that particle/anti-particle pairs produced by gravitational effects in a relativistic spacetime (in partcular, in an expanding cosmological model); followed up by:
    a. DeWitt and DeWitt (1952)
    b. DeWitt (1953)
    c. Deser (1957)
    d. DeWitt (1957)
    e. Harrison (1967)
    f. Blum (2018)
3. the new methods in QFT-CST due to Parker 1968 Phys. Rev. Lett. 21 562, and Parker (1969, 1971), which Zel'dovič, Pitaevskiî, Misner, Starobinskiî, *et al.*, and finally Hawking relied on:

a. Zel'doviĉ (1971), Zel'dovich (1972), Zel'doviĉ and Pitaevskiî (1971), and Zel'dovich and Starobinskiĭ (1972)

b. Misner (1972)

c. Press and Teukolsky (1972)

d. Saul A. Teukolsky, Perturbations of a rotating black hole. 1. Fundamental equations for gravitational electromagnetic and neutrino field perturbations, Astrophys. J. 185 (1973) 635–648, 10.1086/152444

e. Starobinskiĭ (1973) and Starobinskiĭ and Churilov (no date)

f. Quantum effects in white holes, Ya. B. Zel'dovich, I. D. Novikov, ,and A. A. Starobinskiĭ, SOy. Phys.-JETP, Vol. 39, No.6, December 1974, originally in Zh. Eksp. Teor. Fiz. 66, 1897-1910 (June 1974)

g. Deruelle and Ruffini (1974) and follow-ups for Kerr-Newman geometry by T. Damour and R. Ruffini, Phys. Rev. Lett. 35, 463 (1975), in a Kerr geometry by N. Deruelle and R. Ruffini, Phys. Lett. 57B, 248 (1975), and in a Reissner-Nordstrom geometry by T. Nakamura and H. Sato, Phys. Lett. 61B, 371 (1976); a follow-up to this work specifically on the Hawking effect in Kerr-Newman, Damour and Ruffini (1976, footnote 3), makes reference to a work by Gibbons and Hawking in Dewitt-Morette (1974) on the extraction of Coulombic energy by superradiant scattering, but there is no record of a work by those authors in that book, but it seems to have been published as G.W. Gibbons, Vacuum Polarization and the Spontaneous Loss of Charge by Black Holes, Communications in Mathematical Physics volume 44, 245–264 (1975, 3, October), 10.1007/BF01609829

h. Unruh (1973) and Unruh (1974)

i. Ashtekar and Geroch (1974)

j. Fulling S A 1973 Phys. Rev. D 7 2850

k. Gibbons (1977): discussion of relation of super-radiance to stimulated emission in general, and with regard to the Hawking effect in particular

see the interesting discussion, along with personal reminiscences, in Page (2005, starting on p. 3)

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