WHAT CAN WE LEARN FROM STRINGY BLACK HOLES?*

NICK HUGGETT

In their article on singularities and black holes in the Stanford Encyclopedia of Philosophy, Peter Bokulich and Erik Curiel raise a series of important philosophical questions regarding black holes, including the following:

> "Black holes appear to be crucial for our understanding of the relationship between matter and spacetime. ... when matter forms a black hole, it is transformed into a purely gravitational entity. When a black hole evaporates, spacetime curvature is transformed into ordinary matter. Thus black holes offer an important arena for investigating the ontology of spacetime and ordinary objects." [1]

This paper aims to address these issues in the context of string theoretic models of black holes, with the aim of illuminating the ontological unification of gravity and matter, and the interpretation of cosmological models, within string theory. §1 will describe the central concepts of the theory: the fungibility of matter and geometry, and the reduction of gravity and supergravity. The 'standard' interpretation presented draws on that implicit in the thinking of many (but not all) string theorists, though made more explicit and systematic than usual. §2 will explain how to construct a stringy black hole, and some of its features, including evaporation. §3 will critically examine the assumptions behind such modeling, and their bearing on Curiel and Bokulich's ontological questions.

1. Strings and Superstrings

1.1. **Spacetime in string theory: fungibility of geometry and matter.** [7] explained the derivation of the Einstein Field Equations – the 'emergence' of general relativity – in string theory. Since this story is central to the points of this paper we must review it, but with emphasis on the conceptual picture, and without the technical details found in that paper (or the sources from which it is drawn, e.g. [13]).

The starting point for classical string theory is the Nambu-Goto action, which tells us to extremize the worldsheet spacetime area of a string in a d-dimensional Minkowski background (figure 1). So doing leads to a relativistic wave equation, with either Neumann (momentum conserving) or Dirichelet (position conserving) boundary conditions at the end points.

Date: December 10, 2018.

*This work was supported by a grant from the John Templeton Foundation. The views expressed do not necessarily represent those of the Foundation. Thanks to John Dougherty, Niels Linneman, and Christian Wüthrich for discussion and feedback, and especially to Keizo Matsubara: this paper is my contribution to a collaboration with him.

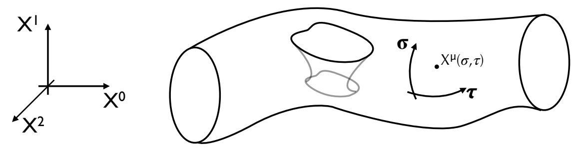


FIGURE 1. A closed string in spacetime. The trajectory is described by an embedding function from worldsheet coordinates to spacetime coordinates: $(\sigma, \tau) \to X^\mu$.

However, the Nambu-Goto formulation is infelicitous for quantization, so one shifts to the classically equivalent Polyakov action, given below in (1). So doing introduces an 'auxiliary' Lorentzian metric $h_{\alpha\beta}$ on the string worldsheet, *distinct* from the metric 'induced' on the world sheet by the Minkowski metric of background spacetime. (The subscripts range over the two coordinates σ and τ on the worldsheet.) Indeed, minimizing the Polyakov action requires only that the auxiliary metric agree with the causal structure of the background spacetime, and so the theory has 'Weyl symmetry' with respect to $h_{\alpha\beta}$: $h_{\alpha\beta} \to e^{\Omega(\sigma,\tau)} h_{\alpha\beta}$ for any smooth real function $\Omega(\sigma, \tau)$. Thus there is no physical significance to the auxiliary metric beyond the causal structure it ascribes to the string, which in turn must agree with that of the background spacetime in a classical solution. This symmetry will have profound implications later.

On canonical quantization the classical wave solutions become quanta *on* the string, in the way familiar from quantum field theory (QFT), and when grouped into states of equal energy form representations of $SO(1, d-1)$, just like relativistic particles in d-dimensional spacetime. Hence particles are reinterpreted as strings in the appropriate representation, with rest mass associated with the vibrational energy of the string – at length scales at which the string is indistinguishable from a point. By this mechanism string theory promises to unify the different fundamental particles: they are nothing but different modes of a single underlying object, the string, and hence fungible if the state of the string changes. In particular, the spectrum of the closed bosonic string contains the massless spin-2 representation that characterizes the graviton, the quantum of the metric field; these modes/particles are therefore in particular fungible with those of other fields. That said, several points should be made.

First, we are yet to identify *quanta* of the corresponding quantum fields as strings, since creation and annihilation of quanta would then require creation and annihilation of strings, about which nothing has yet been said. Modes on a string can be created and annihilated, but that does not change the number of strings, just the kind of particle that a string represents. Second, while massless spin-2 fields lead almost inevitably to general relativity (at least classically, e.g., [11, §18.1]) one does need further grounds to identify this mode as the quantum of a gravitational field in the fullest sense; we need to see that it relates dynamically to other fields in the appropriate way. Third, the bosonic string is completely incapable of reproducing the mass spectrum of the standard model; again, more structure must added. All three points will be developed later.

Progressing further requires shifting to a path integral approach, in which each path contributes an amplitude equal to the exponential of its action. Wick rotating the worldsheet coordinates $\tau \to i\tau$ to give the auxiliary metric $h_{\alpha\beta}$ a Euclidean signature, the Polyakov path integral is given by ([13, §3.2]):

$$\int_{paths} DXDh\ \exp\Big\{\frac{-1}{4\pi\alpha'}\int_M \mathrm{d}\sigma\mathrm{d}\tau\ h^{1/2}h^{\alpha\beta}g_{\mu\nu}\partial_\alpha X^\mu\partial_\beta X^\nu\Big\}, \tag{1}$$

where the 'Regge slope' α' is the characteristic string length squared, M is a specified worldsheet, and (for now) $g_{\mu\nu} = \eta_{\mu\nu}$, the background Minkowski metric. The path integral is taken over all embeddings X^μ and all auxiliary metrics $h_{\alpha\beta}$.

The path integral is also over all topologically distinct worldsheets: for the closed string, tori of all possible genera, with N open holes representing in/out strings at temporal infinity. The topological holes in the tori are produced by strings splitting/joining: for instance, figure 1 is a simple torus with $N = 2$, representing a single incoming string splitting into two strings, which then recombine into a single outgoing string. The tori therefore represent a perturbative sum of Feynman diagrams, in analogy with those for QFT (indeed under the identification of quanta with string modes, QFT diagrams are understood as approximations to stringy diagrams).

Therefore they assume the existence of a theory in which strings can be created and annihilated, or at least a theory in which Fock-like string states are a reasonable approximation (in some sector). (In)famously, this theory – 'M-theory' – is not known, and so string theory as we are discussing it is inherently perturbative.[1] However, once one accepts this perturbative understanding – and without it there is no string theory – then the identification of strings with the quanta of QFT is complete: any field state (in the Fock representation, a superposition of different numbers of quanta) is fundamentally a state of many strings (a superposition of different numbers of strings, each in the mode corresponding to the quantum of the field). Thus all fields are unified, composed of strings, differing only in their modes, and fungible if the many strings change mode.

We now have all the conceptual ingredients needed to understand the origin of GR in string theory. (i) First note that that string scattering could take place in a non-vacuum state, namely in a background of strings: some fixed number of strings, or some finite superposition of different numbers of strings, or in a 'coherent state' of strings. Fock space coherent states can be defined in various ways (see [3, §8.2-3]), but for our purposes, two conceptions are salient: first, such states are maximally classical, simultaneously minimizing the uncertainty in the canonical variables; second, they involve a superposition of every number of field quantum (and so are not finite superpositions).[2]

So, what if string scattering occurs in a background coherent state of strings (a superposition of every number of strings) all in the same mode? Well, since quanta are identified

[1]A bosonic string field theory, with a 3-point interaction exists (e.g., [17]), but is no longer viewed as a promising candidate for M-theory.

[2]Note that 'coherence' in this sense comes from optics, and is *not* the opposite of 'decoherence' in the usual sense of that term.

with strings, such a background corresponds to a coherent state of a QFT; and this in turn corresponds to a classical state of that field. So not too surprisingly, the strings scatter exactly as if they were in the presence of a classical field – that found in the classical limit of the quantum field corresponding to the common string mode. In short, one can study the dynamics of strings in coherent state backgrounds by simply inserting the appropriate classical field into the Polyakov action in the path integral. These are called 'background' fields, but for the reasons just given they are taken to represent particular multi-string states, *not anything extrinsic to the theory.*

In particular, a background coherent state of stringy gravitons (i.e., a coherent superposition of strings, each in a massless spin-2 mode) introduces a factor in the path integral (1) of exactly the same form as the (exponentiated) Polyakov action, but with spacetime tensor $\gamma_{\mu\nu}$. Thus the path integral has the same form, but with $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$ instead of $g_{\mu\nu} = \eta_{\mu\nu}$. But that is *exactly* as if we had taken $g_{\mu\nu}$ to be curved rather than flat in the first place – the effect of the coherent stringy graviton background is *exactly* as if the strings propagate in a curved spacetime background. In other words, *stringy gravitons contribute to spacetime geometry*, just as they ought to. [4, §3.4.1] is the earliest presentation of this point of which we are aware.

(ii) Second, a path integral like (1) with a general curved metric is known as a 'non-linear sigma model'; broadly, it describes a field X^μ living on a 2-dimensional spacetime (the string worldsheet) with *variable* interaction $g_{\mu\nu}(X^\mu)$. The crucial result for our purposes is that this quantum theory will only retain the Weyl invariance of the classical action – as it must do in order to avoid a pathological 'anomaly' – if the background metric $g_{\mu\nu}$ and any other background fields satisfy the Einstein field equation (to lowest order in α'). For (1), in which there is only a background metric field, the result is the free field equation $R = 0$; in general, with additional background fields, the *full* non-linear equation is entailed.

It's worth stressing this point. The split $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$ is reminiscent of the split made in linearizing gravity ([11, §18.1]), but no assumption that $\gamma_{\mu\nu}$ is small is made here, and it is certainly not the case that the condition of Weyl invariance just leads to the linear equation for $\gamma_{\mu\nu}$. (The result does depend on an expansion in powers of α', which must be small: but $\alpha' \ll 1$ means that the radius of curvature is large compared to the string length, something close to the Planck length.) The result gives full general relativity (GR), not just linearized gravity.

Another possible misconception occurs if one applies a naive reading of $g_{\mu\nu}$ as describing the geometry of a literal classical spacetime. Formally that is correct, but we saw that physically it describes a background of strings in a coherent state, *not* a classical spacetime. So Weyl invariance imposes a condition, not on classical spacetime, but on possible coherent states of strings: when in graviton modes they must have a GR spacetime as a classical limit, completing the identification of massless spin-2 modes as quanta of the gravitational field.

One may point out that the curved metric nevertheless contains a *part* not corresponding to a stringy contribution: $g_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu}$, and only the second term denotes a coherent state. For the purposes of this paper, we can just accept this point: in what follows we are discussing cosmological models built from strings in a flat background of given topology. (Especially, this picture admits a 'background dependence' of the theory that many resist on first-principle grounds, but background independence is not a concern of this paper.) However, the picture can be resisted for perturbative string theory: for instance, consideration of dualities suggests that there is no fact of the matter about the background (or 'target space') metric and topology (e.g., [19, 10, 6]). Moreover, the split of $g_{\mu\nu}$ into background and stringy parts is not unique, and so arguably there is no physical significance to the choice of a flat background metric ([12]).

To summarize: avoiding a Weyl anomaly requires that background fields, including the metric, satisfy the Einstein field equations to lowest order in perturbation theory. Physically however, the background does not comprise classical fields in a classical spacetime: rather strings in appropriate modes form coherent states of effective QFTs, which in turn form effective classical fields. So the underlying ontology of the background fields, including the metric, is a multi-string state. And since the quanta of different fields, including the metric, are nothing but different string modes, they are fungible, so that gravity is on the same footing with any other force.

1.2. **Supergravity: stringy fermions, gauge fields, and p-branes.** The string theoretic model of a black hole that we will discuss requires more than the bosonic theory discussed so far, as it involves 'supersymmetric' strings. Since the world contains fermions one must extend string theory: as bosons arise from spatial modes, fermions arise from vibrations in 'anti-commuting directions'. A full discussion is well beyond the scope of this paper so we will only sketch points necessary for our stringy black hole. The most important point is that the recovery of GR from string theory just described applies *mutatis mutandis* to superstring theory.

In very general terms, supersymmetric (SUSY) string theory is developed as for the bosonic string. First introduce an action that adds fermionic degrees of freedom $\psi^\mu(\sigma,\tau,)$ (a Majorana spinor) to the bosonic ones $X^\mu(\sigma,\tau,)$:

$$\int_{paths} DXDh\ \exp\big\{\frac{-1}{4\pi\alpha'}\int_M \mathrm{d}\sigma\mathrm{d}\tau\ h^{1/2}h^{\alpha\beta}g_{\mu\nu}(\partial_\alpha X^\mu\partial_\beta X^\nu - i\psi^{\dagger\mu}\rho_\alpha\partial_\beta\psi^\nu)\big\}, \tag{2}$$

where ρ^α are worldsheet Dirac matrices. ([4, §4.1]) discusses this action, and shows that it possesses classical supersymmetry. Because they are antisymmetric, there are new endpoint boundary conditions for the fermionic degrees of freedom – not Neumann and Dirichlet, but Ramond or Neveu-Schwarz – and correspondingly new modes. When one canonically quantizes as before, one's choice of boundary conditions produces a particular spectrum of bosons and fermions. Because of the underlying SUSY these are paired (in addition to [4, §4.2], [20, chapters 14-6] contains an approachable introduction to this topic): each mode is fungible with its 'superpartner', under a symmetry of the theory.

Proceeding exactly as before, the bosonic modes correspond to field quanta, but now of gauge fields. Coherent states of strings in the same mode thus have effective descriptions as classical gauge potentials, $A_\mu, A_{\mu\nu}, A_{\lambda\mu\nu}$, and so on. And of course to avoid the Weyl anomaly, with the metric these mutually satisfy the appropriate Einstein field equations, and hence because of their supersymmetry form models of classical 'supergravity'.

The question arises of the sources of these fields. $(n-1)$-dimensional bodies can couple 'electrically' to an n-form gauge field. (E.g., a point body couples as $A_\mu \frac{\mathrm{d}x^\mu(\tau)}{\mathrm{d}\tau}$ – the dimension of the body determines whether it has enough indices to 'eat' those on the field.) Similarly, $d-n-3$ dimensional objects with couple 'magnetically' (since they have 'eat' the indices on the Hodge dual). So the presence of gauge fields speaks for the presence of multidimensional objects, known as 'p-branes'. A discussion of their nature in the conceptual framework laid out here will have to wait for another occasion (they are typically thought of in terms of some stable 'solitonic' multi-string state). For now note that they also ground Dirichlet boundary conditions in string theory: if the end of a string is constrained to move within a p-brane, then it is fixed with respect to the remaining $d-1-p$ spatial dimensions. A p-brane to which open strings can attach is thus known as a Dp-brane.

Pulling this together, one of the choices of boundary condition leads to 'type IIB' superstring theory, which contains a a 2-form gauge field $B_{\mu\nu}$. So, for example in 10 spacetime dimensions, D1-branes couple electrically and D-5 branes magnetically to $B_{\mu\nu}$, and so may be present in a supergravity limit of type IIB superstring theory. In our model, a construction of these branes forms the interior of the black hole.

2. A Stringy Black Hole

In this section we sketch a realization of these ideas, a stringy black hole. In the final section this will help us address some of the ontological questions raised about the relation between geometry and matter by black holes, according to string theory. Our model is physically unrealistic (at least for our universe), but it is simple yet exhibits the principles behind more realistic examples (hence it is popular in pedagogical presentations, e.g. [2] and [20, chapter 22]). The origin of this type of construction is [15]; the specific approach discussed was proposed in [5].

We work in type IIB theory with its D1- and D5-branes, and suppose a background spacetime topology of $R^5 \times S^1 \times T^4$ with coordinates $(x_0, \dots x_4, x_5, x_6, \dots x_9)$, respectively. We are interested in the black hole appearing in the 5-dimensional spacetime described by $(x_0, \dots x_4)$ with topology R^5, and stipulate that the remaining compact dimensions are 'small'. However, the circumference C of the circular S^1 x_5 dimension is much larger than that of the toroidal T^4 $(x_6, \dots x_9)$ dimensions. The effect of this stipulation is that the minimum wavelength on the torus is much shorter than on the circle, so that the energy cost of excitations on the torus is much greater, and effectively any momentum in the compactified dimensions will be on the circle. Then the internal momentum of the black hole will be a scalar quantity $P = hN/C$, where N is the wavenumber on S^1.

At the origin of the uncompactified space, $(x_1, \dots x_4) = (0,0,0,0)$, are located (a) Q_1 D1-branes wrapped around S^1, (b) Q_5 D5-branes wrapped around $S^1 \times T^4$, and (c) momentum P (in the x_0–x_5-plane, as just discussed); see figure 2. As we saw, the Dp-branes couple to the $B_{\mu\nu}$ gauge field of the theory (whose stringy nature we again emphasize), while P

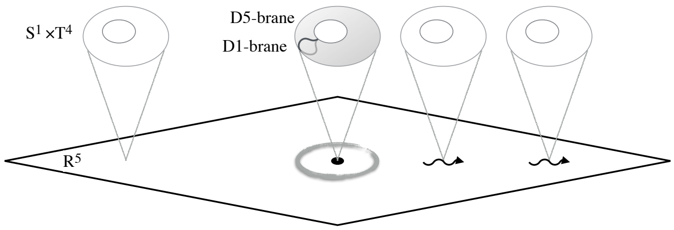


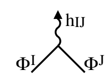
Figure 2. A stringy black hole: the background spacetime has a topology $R^5 \times S^1 \times T^4$ – time is not shown, and of space S^1, two dimensions of R^4 and one of T^4 are pictured. At a point of R^4 are located D1-branes around S^1 and D5-branes around $S^1 \times T^4$. If the string interaction is 'turned on', a spatial horizon forms around the branes in R^5, and gravitons are radiated.

is a source for the metric field $g_{\mu\nu}$ (likewise). Because the field equations hold for such background fields (to avoid the Weyl anomaly) the spacetime geometry can be computed, yielding a model of supergravity possessing a horizon in the four spatial dimensions of R^5, around the origin, as shown in figure 2.

The next step is to apply the technique of 'dimensional reduction' based on the work of Kaluza and Klein (see [8]); essential in string theory in order to determine the projection of the higher dimensional physics into the large dimensions that we directly observe. In short, gauge fields project into gauge fields, and so does the metric: from the point of view of the large dimensions, the geometry of the compact dimensions acts as if there was a new gauge field – the basis of the Kaluza-Klein scheme to 'geometrize' gauge fields. The upshot in our model is that the R^5 description of the solution is a Reissner-Nordström black hole with three point charges Q_1, Q_5, and P, and mass equal to its internal energy, located at the origin.

The point of constructing such models was to compare their Boltzmann entropy, calculated by counting the number of microstates of such an assembly of branes, with their Bekenstein-Hawking entropy, calculated for the dimensionally reduced supergravity black hole. The calculation is described in the references given, but the significance of the models is that these entropies agree, in some sense providing a 'novel' prediction of string theory. It should be noted however that the key element in this result is that the system is in a Bogomol'nyi-Prasad-Sommerfield (BPS) state of superstrings. These arise in SUSY because of the special symmetries ([2, §3.2] gives a simple illustration), but have the features that (a) they are energetically stable because of a selection rule, and (b) varying potential terms does not cause any splitting of energy levels. Because of (b) the number of microstates would be the same if the strings were non-interacting, a scenario in which the number of states is understood and computable: the Boltzmann entropy is the same when the interaction is 'turned on'. But because of (a) the black hole in the effective supergravity model is 'extremal', unable to Hawking radiate any further, though not completely evaporated away.[3]

However, as [18] explains, one can perturbatively model a near-extremal black hole, and verify that its Boltzmann and Bekenstein-Hawking entropies agree as well. Most significant for our discussion, there is a channel by which branes can radiate gravitons into R^5. That is, if Φ^I $(I = 7, 8, 9, 10)$ represents a quantum of D1-brane vibration in the T^4 directions, and h_{IJ} a graviton polarized in the T^4 dimensions propogating in R^5, then the following interaction exists:

(3) 

That is, the model has a mechanism for the black hole to radiate mass away; moreover, the energy cross-section of this radiation agrees with that computed semi-classically for Hawking radiation. Such an interaction thus provides a specific instance of how the fungibility of string modes, especially those of matter and geometry, play out in dynamical processes. We will discuss it in the following reflections on the lessons to be drawn from the interpretation and model laid out so far.

3. Implications for the Nature of Spacetime and Matter

The primary goal of this paper is explicate the §1 'standard' interpretation of classical spacetime and matter according to string theory, and investigate it in the black hole model of §2: realizing the general account in the specific case will highlight some of the insights and issues of the interpretation. Within the scope of this paper, we will aim to highlight some salient points.

(1) First, the interpretation applies to the stringy black hole. Weyl symmetry leads to GR and classical supergravity, and with the brane construction on the matter side of the field equations, there is a horizon in the spacetime geometry. In turn, that geometry is an effective description of a multi-string coherent state (and not a fundamental, classical geometry).

Given a reductive account of spacetime structure, it is important to ask how the derived structure – the metric $g_{\mu\nu}$ – has empirical significance. When explained in §1 the empirical bite came through the role of $g_{\mu\nu}$ in determining scattering amplitudes: it appears in the path integral (1,2) and so different values lead to different cross-sections. Ultimately string scattering is observed as particle scattering, and so it is through observed particle cross-sections that the stringy metric has empirical content. The extension to cosmological models like the black holes demonstrates

[3] An earlier program due to Susskind, on which he reflects in [16], approached the same problem by adiabaticity; that slowly lowering the string interaction to zero would not change the state counting. This method is more general, allowing the Boltzmann entropy to be calculated for a range of realistic, non-extremal black holes, but is less reliable because it doesn't have the BPS guarantee that the density of states is constant.

further significance: astronomical observations of spacetime structure are taken to be low-resolution observations of fundamental stringy fields. These points show that one has to be cautious with the claim that string theory has no empirical consequences: it does predict the observation of GR including observable objects like black holes, and it does have predictions for QFT scattering (although a stringy realization of the standard model would be needed to derive specific predictions). String theory does have empirical consequences, and its concepts empirical significance. What it lacks (so far) are specific *novel* predications, testable using current technologies.

(2) But how cogent is the interpretation? The most questionable point concerns the existence (at least approximately) of suitable coherent states of strings: string theory as developed is inherently perturbative, and the possibility of such states is postulated in a unknown exact theory. That is no argument against the picture, and indeed once the basic framework of perturbative string theory is accepted, it is a small step to coherent states; but the point does emphasize how the interpretation is speculative (like string theory itself).

But supposing that coherent string states exist, and indeed that they have an effective description as coherent states of quanta, one must ask about the classical limit: as a general quaestion about QFT, do coherent states adequately explain the observed behaviors of classical fields? There is remarkably little discussion of this question in the literature ([14] is a significant exception), but one question in the present case is whether graviton coherent states remain coherent long enough to model cosmological scenarios? States will retain their coherence, and classical-like behaviour, only if their equations of motion are linear; so graviton coherent states will certainly lose their coherence, because of the non-linearity of the field equations. But on what time scales should we expect to see non-classical, quantum behaviour as a result? This is a general question about a canonically quantized metric, and addressed by [9] for a Schwarzschild black hole using the Wheeler-DeWitt framework: they find the dispersion time to be $10^{73} \times$ (mass in solar masses)^3 seconds, for a black hole with initial uncertainty of the order of Planck length. This is a comforting 56 orders of magnitude greater than the age of the universe (and of the order of the Hawking radiation time) for a solar mass black hole! In short (even if this is a substantial over-estimate), there is reason to suppose that the quantum state of spacetime will have an effective classical description for periods long enough for cosmology – as the interpretation does. (A similar set of questions can be asked about Dp-branes: what kind of field-theoretic object could they be from both the string and classical perspectives?)

(3) We can – finally – directly address the question raised by Bokulich and Curiel regarding the relation between matter and physical geometry. According to the standard interpretation the 'conversion' of classical matter to geometry, and the reconversion of geometry back to matter in the form of quantum radiation is ultimately a transition between different multi-string states. In the first case from

coherent states of strings in a matter mode to coherent states of strings in a graviton mode; in the latter, back from coherent states of stringy gravitons to stringy matter quanta.

Once again, with only perturbative string theory in hand one does not have a full theory of how these transitions occur. However, the mechanism (3) provides a model for what may occur; namely excitations of the branes at the center of the black hole decay into stringy quanta in the exterior. True, the specific quanta are themselves gravitons, but presumably other channels to matter quanta are possible. Moreover the emitted gravitons are not in a coherent state, so do not contribute to the classical geometry; when gravity is unified with other forces in a QFT approach like string theory, not only do matter and geometry become fungible, there will be states that lie between them – graviton states that are not coherent.

Lastly, it is worth noting the implications of the model for the question of spacetime singularities, something also raised in [1]. Here one can make something of a virtue of ignorance. As we noted, the perturbative string account depends on the radius of curvature being large compared to the string scale, so the scheme will simply break down at finite curvature, and no singularity is implied. Of course, ignorance is also a vice, since the unknown full theory is needed to say what replaces the singularity (though techniques employing dualities may shed some light). At the level of the ideas developed here, one can only suppose that the quantum state in the region of the singularity will cease to be coherent, and no classical effective description will apply. Then according to string theory singularities are not objects, or edges, but are 'merely inadequate descriptions that will be dispensed with by a truly fundamental theory of quantum gravity' as Bokulich and Curiel ask.

References

[1] Erik Curiel and Peter Bokulich. Singularities and black holes. In Edward N. Zalta, editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, fall 2012 edition, 2012.
[2] Sumit R Das and Samir D Mathur. The quantum physics of black holes: Results from string theory. *Annual Review of Nuclear and Particle Science*, 50(1):153–206, 2000.
[3] Anthony Duncan. *The conceptual framework of quantum field theory*. Oxford University Press, 2012.
[4] MB Green, JH Schwarz, and E Witten. *Superstring Theory*, volume I. Cambridge University Press Cambridge, 1987.
[5] Gary T Horowitz, Juan M Maldacena, and Andrew Strominger. Nonextremal black hole microstates and u-duality. *Physics Letters B*, 383(2):151–159, 1996.
[6] Nick Huggett. Target space $\neq$ space. *Studies in history and philosophy of science part B: Studies in history and philosophy of modern physics*, 2015.

[7] Nick Huggett and Tiziana Vistarini. Deriving general relativity from string theory. *Philosophy of Science*, 82(5):1163–1174, 2015.
[8] K. Karaca. Kitcher's explanatory unification, kaluza-klein theories, and the normative aspect of higher dimensional unification in physics. *British Journal for the Philosophy of Science*, 63(2):287–312, 2012.
[9] Claus Kiefer and Jorma Louko. Hamiltonian evolution and quantization for extremal black holes. *arXiv preprint gr-qc/9809005*, 1998.
[10] Keizo Matsubara. Realism, underdetermination and string theory dualities. *Synthese*, 190(3):471–489, 2013.
[11] Thorne Misner and Kip S Thorne. *Wheeler, Gravitation*. Freeman, 1973.
[12] Luboš Motl. What is background independence and how important is it?, 2012.
[13] Joseph Gerard Polchinski. *String theory*. Cambridge university press, 1998.
[14] Joshua S Rosaler. *Inter-theory relations in physics: case studies from quantum mechanics and quantum field theory*. PhD thesis, University of Oxford, 2013.
[15] Andrew Strominger and Cumrun Vafa. Microscopic origin of the bekenstein-hawking entropy. *Physics Letters B*, 379(1-4):99–104, 1996.
[16] Leonard Susskind. The paradox of quantum black holes. *Nature Physics*, 2(10):665, 2006.
[17] Washington Taylor. String field theory. In Daniele Oriti, editor, *Approaches to Quantum Gravity: Toward a New Understanding of Space, Time and Matter*, pages 210–28. Cambridge University Press, 2009.
[18] Spenta R Wadia. A microscopic theory of black holes in string theory: Thermodynamics and hawking radiation. *CURRENT SCIENCE-BANGALORE-*, 81(12):1591–1597, 2001.
[19] Edward Witten. Reflections on the fate of spacetime. *Physics Today*, pages 24–30, April 1996.
[20] Barton Zwiebach. *A first course in string theory*. Cambridge university press, 2004.