Title: Black hole evaporation without firewalls

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Abstract: There need not be any conflict between unitarity, locality, and regularity of the horizon in black hole evaporation. I discuss a scenario in which the initial collapse that forms the black hole results in a small non-singular core inside an inner event horizon. This core grows as the result of quantum back-reaction associated with the increasing entanglement entropy of Hawking radiation quanta and their partners trapped inside the core. By the Page time the inner and outer apparent horizons either merge into a degenerate horizon, shutting off the Hawking radiation and leaving a massive remnant, or they disappear completely, allowing the trapped quantum information to escape. The scenario is justified by appeals to the Bousso covariant entropy bound and the ER=EPR conjecture. The talk is largely based on arxiv.org/1406.4098.

Black hole evaporation without firewalls

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Outline

1. Review of the semi-classical results for $\langle T_{\mu\nu} \rangle_{\text{ren}}$ in the Unruh vacuum. Conformal anomalies and physical interpretation.

2. The information paradox. Unitarity versus locality. Critique of stretched horizons, fast scrambling, fuzzballs, etc. The need for new physics by the Page time.

3. The case for enhanced quantum back-reaction due to increasing entanglement across the horizon, based on the Bousso covariant entropy bound.

4. A model scenario, based on an ansatz for the metric in the black hole interior. Semi-classical extrapolation to the effective energy-momentum tensor in the exterior.

5. Possible endpoints: disappearance of trapped surfaces and dispersal or a large remnant with zero Hawking temperature?

6. Final thoughts on framing the discussion of black hole evolution.

Conventions and units

- Assume spherical symmetry, area of 2-sphere $= 4\pi r^2$, in an asymptotically flat spacetime.
- Units $G = c = 1$, $\hbar \equiv m_{\mathrm{p}}^2$ is left free.
- Consider only large black holes, mass $M \gg m_{\mathrm{p}}$.
- Black holes formed by gravitational collapse from a pure initial quantum state (Unruh vacuum).
- Bekenstein-Hawking entropy $S_{\mathrm{BH}} = \frac{1}{4}\frac{A_{\mathrm{H}}}{m_{\mathrm{p}}^2} = 4\pi\left(\frac{M}{m_{\mathrm{p}}}\right)^2 \sim 10^{77}$ for $M = M_{\odot}$.
- Hawking temperature $T_{\mathrm{H}} = \frac{\kappa m_{\mathrm{p}}^2}{2\pi}$, surface gravity $\kappa = \frac{1}{4M}$ for Schwarzschild.
- Stefan-Boltzmann constant $\sigma = \frac{\pi^2}{60 m_{\mathrm{p}}^6}$.

Semi-classical energy-momentum tensor

Analytic estimates and numerical results are known for massless scalar and e-m fields on a Schwarzschild background *outside* the horizon at $r = 2M$.

The four independent components allowed by spherical symmetry are:

energy density $E = -T_t^t$, energy flux $F = -(1-2M/r)^{-1} T_t^r$,

radial stress $P_r = T_r^r$, transverse stress $P_t = T_\theta^\theta = T_\varphi^\varphi$.

Non-trivial conservation equations $\nabla_\nu T_\mu^\nu = 0$, with no t-dependence:

$$\partial_r \left[r^2 (1-2M/r) F \right] = 0,$$

$$(E + P_r) \frac{M/r}{1-2M/r} + \frac{1}{r} \partial_r \left(r^2 P_r \right) - 2P_t = 0.$$

The trace due to the conformal anomaly arising from the renormalization of massless quantum fields:

$$T_\mu^\mu = \sum_s q_s \frac{m_p^2}{2880\pi^2} \left(C_{\alpha\beta\gamma\delta} C^{\alpha\beta\gamma\delta} + R_{\alpha\beta} R^{\alpha\beta} - \frac{1}{3} R^2 = 48 \frac{M^2}{r^6} \right),$$

$q_0 = 1$, $q_1 = -13$, $q_2 = 212$.

Unruh vacuum

No incoming radiation at past null infinity and regular on the future horizon. Effectively means a Minkowski vacuum state well before the black hole is formed by gravitational collapse.

For each field of spin s, there is a contribution to the energy flux

$$F_s = k_s \sigma T_{\mathrm{H}}^4 \frac{M^2}{r^2}(1-2M/r)^{-1},$$

with $k_0 = 14.26$, $k_1 = 6.49$, $k_2 = 0.749$ (Page).

A physically appropriate decomposition of the energy-momentum tensor:

1) an outgoing null fluid, with $F^{\mathrm{out}} = P_r^{\mathrm{out}} = E^{\mathrm{out}}$,
2) an ingoing null fluid, with $F^{\mathrm{out}} = -P_r^{\mathrm{out}} = -E^{\mathrm{out}}$,
3) a traceless residual, with $P_r^{\mathrm{res}} = -P_t^{\mathrm{res}} = -E^{\mathrm{res}}$,
4) a piece associated with the trace, with $P_r^{\mathrm{ca}} = -\frac{1}{2}P_t^{\mathrm{ca}} = -E^{\mathrm{ca}} = \frac{1}{2}T_\mu^\mu$.

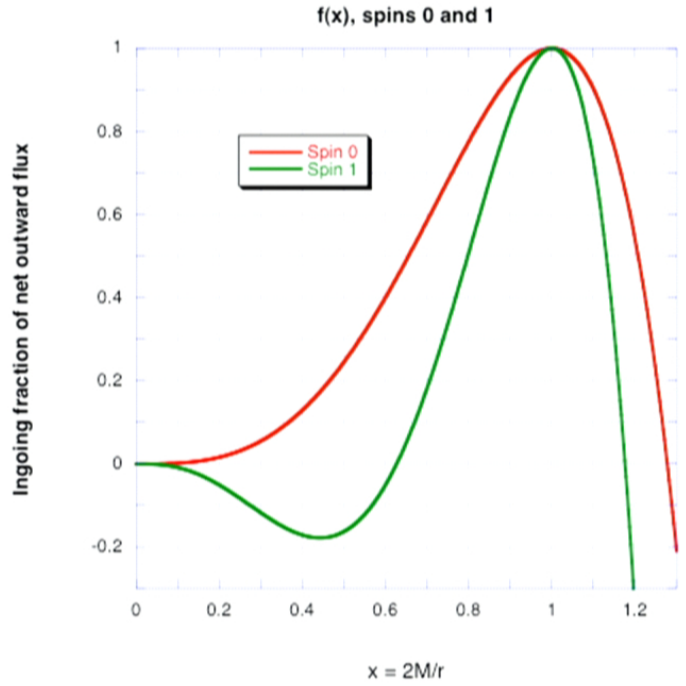
For each spin, let the fraction of the net energy flux that is *ingoing* be $f_s(x)$. Regularity at infinity and the horizon requires, with $x \equiv 2M/r$,

$$1 - f_s = (1-x)^2\left(1 + 2x + 3x^2 + 4h_s\right) = 1 + O\left(x^3\right),\ x \to 0,$$

with $h_s(x=1)$ finite and to be determined numerically from mode sums.

Results

A simple polynomial approximation to numerical results of Elster $(s=0)$ and Jensen, et al $(s=1)$ is $h_s = c_s$, $c_0 = 0.54$ and $c_1 = 3.8$.
There are no known results for $s = 2$; a guess is $c_2 = 25$.



Energy densities in a frame freely-falling from rest at infinity, evaluated on the horizon, in units of σT_{H}^4:

Spin	k_s	q_s	c_s	$E_{\mathrm{ff}}^{\mathrm{out}}$	$E_{\mathrm{ff}}^{\mathrm{in}}$	E^{res}	E^{ca}
0	14.26	1	0.54	116.4	-0.891	-60.15	32
1	6.49	-13	3.8	137.6	-0.406	-6.22	-416
2	0.742	212	25	79.7	-0.046	15.0	6784

Lessons from the semi-classical results

- The relative magnitudes of the ingoing and outgoing energy densities are highly sensitive to the choice of frame. In a frame freely-falling from just outside the horizon, rather than from infinity, the negative ingoing contribution can dominate.
- The quantum correlations associated with pair creation extend over macroscopic distances from the horizon. It is *not* correct to model the pair creation as occurring within a Planckian distance from the horizon.
- The part of the energy-momentum tensor associated with the conformal anomaly strongly dominates near the horizon and can be evaluated inside as well as outside the horizon.

Semi-classical back-reaction on the geometry

Solve the classical Einstein equations with the semi-classical T_μ^ν as a source, using advanced Eddington-Finkelstein coordinates (v,r).

Outside the horizon $(x<1)$: $T_v^v = -E - F = -2E^{\text{out}} - E^{\text{res}} - E^{ca}$,

$$T_r^r = 2E^{\text{out}} - E^{\text{res}} - E^{\text{ca}},\ T_v^r = -(1-x)F = -\frac{1}{4}\sigma T_{\mathrm{H}}^4 x^2 \sum_s k_s,$$

$$T_r^v = (1-x)^{-1}(E + P_r + 2F) = 4(1-x)^{-1} E^{\text{out}}$$

$$= \sigma T_{\mathrm{H}}^4 x^2 \sum k_s \left(1 + 2x + 3x^2 + 4c_s x^3\right).$$

General spherically symmetric metric:

$$ds^2 = -Ae^{2\psi} dv^2 + 2e^{\psi} dv dr + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right),$$

$$g^{vv} = 0,\quad g^{vr} = e^{-\psi},\quad g^{rr} = A.$$

Einstein equations:

$$\frac{\partial m}{\partial v} = 4\pi r^2 T_v^r,\quad \frac{\partial m}{\partial r} = -4\pi r^2 T_v^v,\quad \frac{\partial \psi}{\partial r} = 4\pi r e^{\psi} T_r^v.$$

Outside horizon: $\partial m / \partial v$ is independent of r, exterior metric remains Schwarzschild to a very good approximation, with a slowly decreasing mass M.

Inside horizon: conformal anomaly gives an energy density $E^{\mathrm{ca}} \sim m_{\mathrm{p}}^2 M^2 / r^6$, modifies m substantially when $r < \left(m_{\mathrm{p}}^2 M\right)^{1/3}$.

Hawking radiation apparently continues as long as $M \gg m_{\mathrm{p}}$.

Hawking partners accumulate inside black hole, the entanglement entropy between the black hole interior and Hawking radiation quanta in the exterior grows. At the *Page time* this entanglement entropy equals the Bekenstein-Hawking entropy $S_{\mathrm{BH}} = 4\pi M^2 / m_{\mathrm{p}}^2$.

Information paradox: Hawking radiation is thermal, locality apparently forbids transfer of quantum information from the interior to the exterior. If the black hole evaporates completely, pure states evolve into mixed states, unitarity breaks down.

Ways out?

A Planck scale remnant? But if the remnant contains all the quantum information in the Hawking partners, its entropy vastly exceeds its Bekenstein-Hawking entropy.

Quantum information lost through subtle correlations in the Hawking radiation? Mathur argues small corrections to the Hawking radiation cannot remove the entanglement between the radiation and the black hole. And how does quantum information trapped deep inside the black hole get transferred to the Hawking radiation without violating locality?

Complementarity: To outside observer, quantum information never goes inside horizon, stored in "stretched horizon", thermalized in the "scrambling time" $\sim M \log\left(M / m_p\right)$, comes out in Hawking radiation. Cloning OK as long as it cannot be detected by any single observer.

Breakdown of spacetime into stringy "fuzzball" at horizon? But the event horizon location depends on the entire future evolution of the black hole. The apparent horizon is spacelike while matter is being added to black hole. What is it about either that triggers the fuzzball? Seems an implausible outcome for a *large* black hole.

Problems

Generic: Quantum information in the collapsing star cannot plausibly be "stripped" to propagate along the horizon, ends up deep inside the black hole where it cannot get even close to the horizon due to intervening trapped surfaces. The Hawking partners are created a macroscopic distance inside the horizon and trapped surfaces force them to smaller r. Outward radial null geodesics diverge away from the horizon both inside and outside, $\Rightarrow$ horizon is very stable (Bardeen 1981). There seems to be no way to transfer quantum information across horizon without violating causality.

"Scrambling" is just the decay of black hole hair due to radiation into and away from the black hole, not "thermalization". Storage of information close to horizon impossible without enormous energies in freely falling frame, no physical mechanisms for producing such energies.

The thermal "atmosphere" of the horizon seen by static observers is essentially just like that of a Rindler horizon in Minkowski spacetime. It is a property of the observers, not of the black hole, carries no quantum information, and has nothing to do with the von Neumann entropy of the black hole.

My scenario

Quantum back-reaction must prevent the collapse forming the black hole from ending in a spacetime singularity at $r = 0$. Otherwise there is no hope of preserving unitarity. Instead there is a non-singular core bounded by an inner apparent horizon inside of which $2m/r < 1$, and spacetime is locally flat at $r = 0$.

A particular form for the metric of the black hole interior is suggested by the dominance of the conformal anomaly part of the semi-classical energy momentum tensor at the horizon. With $q^{\text{tot}} = \sum_s q_s = 199$, this gives

$$m = M - \frac{128\pi}{3} q^{\text{tot}} \sigma T_{\text{H}}^4 \frac{(2M)^6}{r^3} = M\left(1 - \frac{q^{\text{tot}}}{90\pi}\frac{m_{\text{p}}^2 M}{r^3}\right).$$

A simple non-singular extrapolation to $r = 0$ has the form

$m = \dfrac{Mr^3}{r^3 + 2a^2 M}$, with $a^2 = O\left(m_{\text{p}}^2\right)$. This or very similar expressions have been suggest as a model for a black hole interior by a number of authors, in some cases based on ideas about quantum gravity (Poisson and Israel 1988, Hayward 2005, Frolov 2014, Bonanno and Reuter 2006, Taves and Kunstatter 2014). The inner apparent horizon is at $r \cong a$ when $a \ll M$.

Bousso Covariant Entropy Bound

Start from a spacelike 2-surface B of area A, and construct a null hypersurface or "light sheet" orthogonal to B whose null geodesic generators *converge* going away from B. The light sheet ends when one of the generators encounters a caustic, at which point the area of the 2-surface of constant affine parameter is $A' < A$. The von Neumann entropy S_N of the particles crossing the light sheet cannot exceed the bound $\frac{1}{4}(A - A')/m_p^2$.

Take the 2-surface B to be a sphere at or just outside the inner apparent horizon at $r \cong a$, and the light sheet to be the ingoing radial null hypersurface. All of the quantum information accumulated by the black hole eventually ends up either inside or very close to the inner apparent horizon. Just after formation S_N measures the quantum information in the collapsing star, and is tiny compared with S_{BH}. However, by the Page time, by definition, $S_N = S_{BH}$, and the Bousso bound requires the area of the inner horizon to equal the area of the outer event horizon.

The Bousso bound in my application is a conjecture, since to date no proof of the Bousso bound applies in the presence of large quantum back-reaction.

Toy Model

Assume the metric in the *interior* of the black hole can be approximated by a metric of the Hayward form, with M and a both functions only of advanced time, so there is only an *ingoing* contribution to the energy flux and $\psi = 0$. The rate of decrease of M is given by the Hawking luminosity, $\frac{dM}{dv} = -4\pi M^2 \sigma T_H^4 \sum_s k_s \equiv -4\pi\alpha M^2 \sigma T_H^4$,

and Page has estimated that $dS_N / dv = (715M)^{-1}$. If the Bousso bound is saturated, so $\pi a^2 = m_p^2 S_N$, $\frac{da^2}{dv} = 2\pi\beta(2M)^3 \sigma T_H^4$, with $\beta = 21.5 \approx 3\alpha$.

The Einstein equations give for the coordinate components T_λ^μ

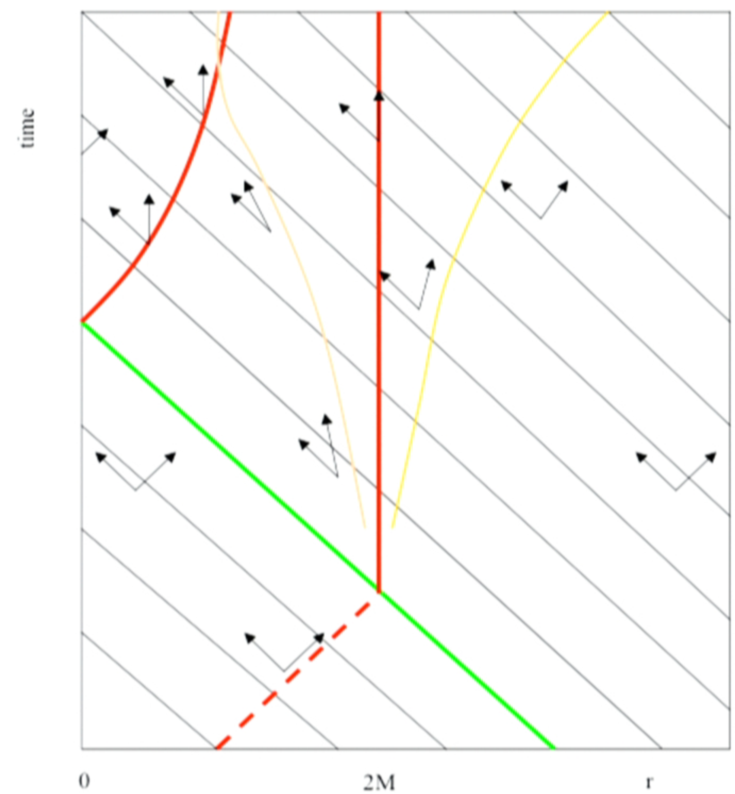
$$-T_v^v = \frac{1}{4\pi r^2}\frac{\partial m}{\partial v} = \frac{3}{2\pi}\frac{a^2 M^2}{\left[r^3 + 2a^2 M\right]^2},$$

$$-T_v^r = \frac{1}{4\pi r^2}\frac{\partial m}{\partial v} = \sigma T_H^4 M^2 \frac{\alpha r^4 + \beta(2M)^3 r}{\left[r^3 + 2a^2 M\right]^2}, \quad T_r^v = 0, \quad T_r^r = T_v^v,$$

$$T_\theta^\theta = T_r^r + \frac{r}{2}\frac{\partial T_r^r}{\partial r}.$$

Note: as classical particles the Hawking partners really should have a positive energy density, which would require that they propagate "outward" rather than "inward", and thereby contribute to T_r^v.

Schematics. The diagonal lines are at constant advanced time v. The green line is the trajectory of the shell forming the black hole. The curved brown lines are trajectories of outgoing radial null geodesics.



Exterior energy-momentum tensor

As long as $a^2 \ll M^2$ the geometry in the vicinity of the outer apparent horizon is Schwarzschild to a good approximation, and the generation of Hawking radiation should still proceed according to the standard semi-classical treatment. However, the e-m tensor must be quite different from that assumed for the interior. At large r the Hawking radiation is moving along outgoing radial null trajectories and carries with it quantum information entangled across the horizon. Construct an exterior e-m tensor that, to first order in a^2 / M^2, has the right asymptotic properties and matches the interior e-m tensor without a surface layer at the apparent horizon.

First-order interior e-m tensor:

$$-T_v^v = -T_r^r = \frac{3}{2\pi}\frac{a^2 M^2}{r^6} = 5760\sigma T_{\rm H}^4 \left(\frac{\pi a^2}{m_{\rm p}^2}\right) x^6,$$

$$-T_v^r = \frac{1}{4}\sigma T_{\rm H}^4 \left(\alpha x^2 + \beta x^5\right), \quad T_r^v = 0, \quad T_\theta^\theta = -2T_r^r.$$

The diagonal components have the same form as the semi-classical conformal anomaly contribution. Note that $\pi a^2 / m_{\rm p}^2$ is the von Neumann entropy of the core, assuming the Bousso bound is saturated.

The end game

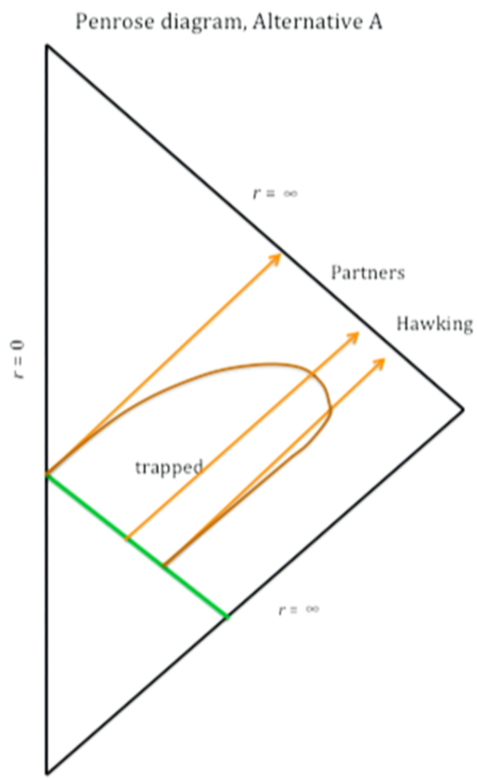
What happens when $a^2 / M^2 \sim 1$ approaching the Page time? This is beyond the scope of my quasi-classical estimates. Assuming the toy model interior metric, the apparent horizons approach each other at $r = 4M / 3$ when $a^2 = 16M^2 / 27$. As the apparent horizons merge, the surface gravity and therefore the Hawking temperature tend toward zero.

Alternative A: the apparent horizons merge and disappear, leaving all trapped quantum information free to escape. There would be a unitary S-matrix, consistent with naive expectations from AdS-CFT, but no expectation that the particle content would survive in anything like its original form.

Alternative B: the inner and outer horizons approach each other only asymptotically, producing a degenerate event horizon with zero Hawking temperature. The mass of the remnant would be about half of the original mass of the black hole. Its von Neumann entropy would be close to or equal to the Bekenstein-Hawking entropy; the black hole would retain all of its quantum information. There would be no unitary S-matrix, but would unitarity be violated? It depends. In the context of AdS/CFT there might be a way for the CFT to track the trapped quantum information, as argued by Papadodimas and Raju, but the existence of a Cauchy horizon in the interior destroys predictability of the quantum evolution of the interior.

Alternative C: as the inner and outer apparent horizons approach very close to each other, the Hawking partner quanta propagating close to the inner apparent horizon might be able to tunnel through the horizons and escape, thereby lowering both the mass and the von Neumann entropy of the black hole. The tunneling would require only a small violation of locality. If the near degeneracy of the horizons were maintained, the black hole could gradually shrink, emitting Hawking partner quanta entangled with earlier Hawking radiation quanta. There would no need for a singular firewall, since emission of new Hawking quanta would cease. This might continue until the black hole shrinks down to the Planck scale and disappears, with no quantum information being lost.

All of these options are quite speculative. Alternatives A and C would be entirely consistent with a unitary S-matrix and the unitarity of the CFT in AdS/CFT. Unfortunately proving or disproving any of these options would seem to require a rather complete theory of quantum gravity. Perhaps the ER=EPR conjecture of Maldacena and Susskind could be the basis of exploring the physical link between entanglement and geometry. Microscopic Einstein-Rosen bridges linking entangled Hawking radiation and Hawking partner quanta could polarize the vacuum and give an effective energy-momentum tensor for the macroscopic geometry.


Penrose diagram, Alternative A
r = ∞
Partners
Hawking
r = 0
trapped
r = ∞

Final thoughts

A careful analysis of old semi-classical results for the effective energy-momentum tensor for a large Schwarzschild black hole formed by gravitational collapse, i.e., for the Unruh vacuum, provides absolutely no support for the idea that quantum information can be stored in some kind of a "stretched" horizon.

Generation of the Hawking radiation involves macroscopic quantum correlations extending over $\Delta r = O(M)$ both outside and inside the horizon. It is not something that happens at the Planck scale near the horizon. It results from the stretching of modes of the Unruh vacuum, not a tunneling process.

A realistic black hole should not be viewed as being in a thermal state at the Hawking temperature. The von Neumann entropy of a black hole is tiny compared to S_{BH} at times after formation much less than the Page time (assuming the particles involved in formation have energies/masses much greater than the Hawking temperature). There is no "fast scrambling" distributing energy over $\exp(S_{\mathrm{BH}})$ quantum states. There may be $\exp(S_{\mathrm{BH}})$ *potential* quantum states inside the black hole, but the number actually excited is typically much smaller and grows only as Hawking partners accumulate.

A black hole is a classical concept, depending on the existence of a "quasi-classical" spacetime a region of which has certain properties (such as trapped surfaces). Quantum fields may live on the spacetime (including quantum gravitational fields) and modify the geometry. If these modifications are non-perturbative, many different quasi-classical histories may contribute to the overall quantum wavefunction. Quantum fluctuations about each classical history would be small due to the large number of quanta contributing to a large overall quantum back-reaction.

A fundamental theory of quantum gravity may include many quantum configurations that cannot be interpreted in terms of a quasi-classical spacetime. Also, some states may correspond to fully thermalized black holes, some to black holes with firewalls, and some to "fuzzballs". But I claim that such exotic states are not the result of quantum evolution from reasonable initial conditions for our universe, at least until the Page time.

Something like the scenario proposed in this talk would seem to be the least radical way of avoiding the black hole information paradox.