Title: Black hole evaporation and unitarity: a semi-classical resolution?

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Abstract:
I explore the possibility that semi-classical back-reaction, due to the partners of the Hawking radiation quanta accumulating over the time for the black hole to lose about one half of its mass (the Page time), might cause the trapped surfaces to disappear, permitting unitary evolution without any cloning of quantum information.


James Bardeen

Black hole evaporation and unitarity: a semi-classical approach

James M. Bardeen
University of Washington

Perimeter Institute July 10, 2013

Outline

- Review of the basics – Hawking radiation, Bekenstein-Hawking entropy, information loss?
- The conflict between quantum field theory (unitarity, locality, etc.) and general relativity (local flatness, near vacuum at the horizon as seen by freely falling observers. The AMPS argument..
- The semi-classical properties and interpretation of $< T_{\mu\nu} >$ in the Schwarzschild background outside the horizon.
- The trace anomaly as a guide to the semi-classical back-reaction inside the horizon.
- A semi-classical scenario for preserving unitarity without firewalls: might trapped surfaces and the apparent horizon disappear at or before the Page time?

Black Hole Mechanics

Consider stationary states of classical black holes in GR:

Characterized by the black hole mass M, angular momentum J, horizon area A, surface gravity κ, and angular velocity Ω.a

The formal analogy with thermodynamics (Bardeen, Hawking, Carter 1973):

Zeroth Law -- κ is uniform over the black hole horizon

(temperature T is uniform in thermodynamic equilibrium)

First Law – In a transition between nearby stationary states,

$$dM = \frac{\kappa}{8\pi} dA + \Omega dJ \quad (dE = TdS - pdV).$$

Second Law -- Penrose area theorem

$$dA \geq 0 \quad (dS \geq 0).$$

Originally thought only an analogy, since classically black holes can't radiate and therefore don't have a temperature.

Note: in this talk I adopt GR units, $G = c = 1$, so $\hbar = m_p^2$.

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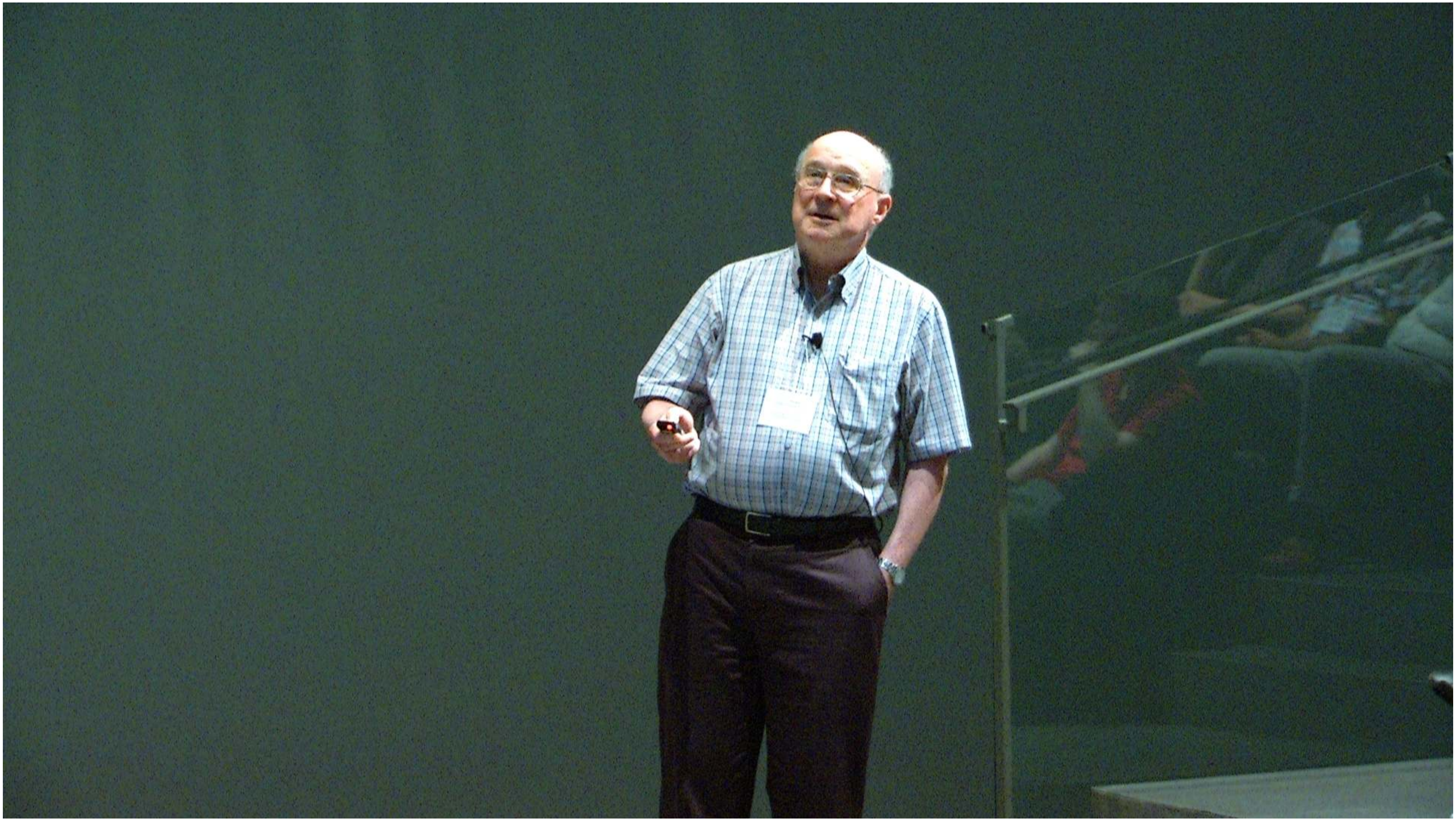

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Hawking radiation (Hawking 1974)

Hawking showed from semi-classical quantum field theory (a quantum field on a classical background geometry) that if a quantum field is in its vacuum state before the black hole forms, after the black hole settles down there is a flux of radiation at future null infinity with a (somewhat modified) thermal spectrum at a temperature

$$T_{\mathrm{H}} = \hbar \frac{\kappa}{2\pi} \Rightarrow S_{\mathrm{BH}} = \frac{A}{4\hbar}$$

for all fields a black body would radiate at that temperature. Part of the thermal radiation at the event horizon is reflected by a potential barrier somewhat outside the horizon (at $r \sim 3M$).

The Bekenstein-Hawking entropy S_{BH} plays the role of a thermodynamic entropy. It is often interpreted as the number of microscopic quantum degrees of freedom associated with the macroscopic state of the black hole, or as an entanglement entropy based on tracing over the unobservable quanta inside the black hole that are entangled with the quantum degrees of freedom outside.

The energy flux approaching future null infinity has the form

$$F_{\infty} = \frac{k}{r^2}\frac{\hbar}{M^2} = \frac{k}{r^2}\left(\frac{m_p}{M}\right)^2 \Rightarrow \frac{dM}{du} = -L_H = -4\pi k\left(\frac{m_p}{M}\right)^2,$$

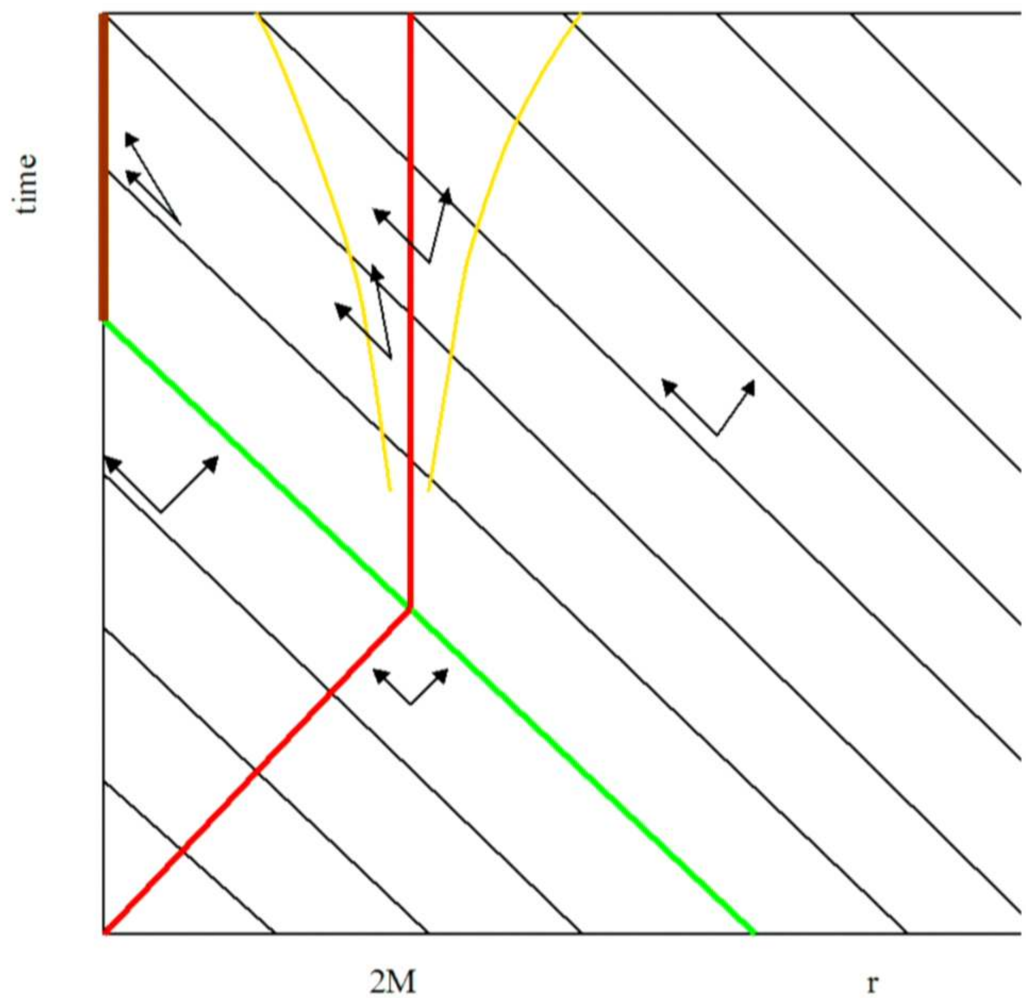
with k a numerical coefficient depending on the types of fields/particles able to radiate at the temperature T_{H}.

How is the Hawking radiation created?

For a black hole formed by gravitational collapse:

Modes of the initial Minkowski vacuum propagate in from past null infinity (where they are positive frequency in advanced time), through the center of the collapsing star (or shell), out along the event horizon, and then get pulled apart as they redshift to wavelengths comparable to the gravitational radius of the black hole. Part peels off inside the horizon, and the part outside that penetrates the potential barrier eventually reaches future null infinity. An observer near future null infinity measures a flux of quanta that are excitations of the out vacuum, the Hawking radiation.

In a basis treating the ingoing and outgoing modes of the Hawking radiation separately, the modes are extremely short wavelength, even sub-Planckian, as they compress close and closer to the horizon going backward in time, However, because the ingoing and outgoing modes are highly entangled, an observer freely falling inward across the horizon sees something very close to vacuum. The ingoing quanta have negative energy relative to infinity and decrease the energy of the black hole, to compensate the positive energy being carried off by the Hawking radiation quanta.


time
2M
r

Information loss?

Hawking's original position: The Hawking radiation is incoherent thermal radiation, described by a density matrix that has a von-Neumann entropy equal to the number of Hawking quanta. It carries no quantum information. If the black hole evaporates completely, all quantum information present initially is lost. Permanent Planck-scale remnant? Baby universe? Evolution of pure states into mixed states?

Particle theorists: quantum mechanics and quantum field theory demand unitarity. If give up unitarity all sorts of weird bad things can happen. A pure state should evolve into a pure state. If the black hole evaporates completely after forming from a pure state, the Hawking radiation in toto must be in a pure state, the Hawking quanta must be perfectly entangled in pairs with each other. A remnant black hole cannot not contain more qbits than its BH entropy, cannot contain the potentially huge amount of quantum information present in the initial state. String theory, and particularly AdS-CFT duality, which maps bulk dynamics of quantum gravity to a manifestly unitary CFT on the AdS boundary, strongly imply unitarity for the bulk evolution. But how can the quantum information get out without violating causality (locality) or being cloned?

Hawking converted to unitarity in 2005.

Ideas on retrieving quantum information

1) Quantum information can be transferred from infalling particles to modes on a "stretched horizon", appeal to the "membrane paradigm" for describing dynamics of classical black hole horizons (Susskind, Thorlacius, Uglum, etc.). The information stored on the stretched horizon can leak out in the Hawking radiation. *Complementarity*: the cloning of the quantum information is OK as long as no single observer can detect the cloning. An observer always external to the black hole only sees the information coming out in the late Hawking radiation, an observer freely falling into the black hole only sees the information inside the black hole.

2) "Fuzzballs" – no black hole is formed. An incipient black hole is unstable to forming a complex of branes containing the quantum information on an inner boundary to the spacetime. Infalling matter, observers hit the fuzzball surface (Mazur). Similar to earlier proposals of "massive remnants" (Giddings).

3) Non-locality, to allow information transfer from inside the black hole to the Hawking radiation at late times (Giddings).

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No-go theorem of AMPS 1207.3123

Consider a black hole formed from a pure quantum state. The following properties of "black hole complementarity" are mutually inconsistent:

1) Unitarity: A distant observer sees a unitary S-matrix, which describes black hole evolution from infalling matter to outgoing Hawking-like radiation within standard quantum theory.

2) EFT: Outside the stretched horizon, the physics can be described by an effective field theory of Einstein gravity plus matter.

3) The dimension of the subspace of states describing a black hole of mass M is given by the Beckenstein-Hawking entropy as $\exp(S_{\rm BH})$.

4) No drama: A freely falling observer sees nothing out of the ordinary when crossing the horizon.

One argument is based on factorizing the overall Hilbert space at some time after the black hole has lost more than one-half of its mass into three separate subspaces: an "early" subspace A of Hawking quanta emitted previously; a newly created Hawking quantum B, and its partner C inside the horizon. 4) requires that B be entangled with C, to have local vacuum at the horizon, while the Hawking radiation ending up in a pure state requires entanglement of B with A. Double entanglement of B violates quantum mechanics. Further arguments are elaborated in AMPSS 1304.7483.

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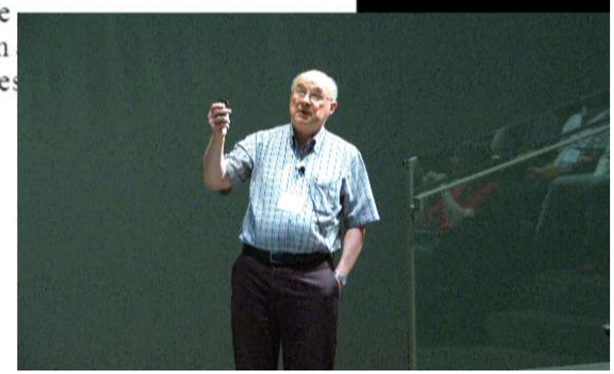

Practical considerations

Consider a spherically symmetric Schwarzschild black hole, initial mass $M_0 \sim 1 M_{\odot} \sim 10^{57}\,\mathrm{GeV}$, formed by the collapse of about 10^{57} particles (quanta) of energy $T_0 \sim 1\mathrm{GeV}$ in a pure quantum state.

The Compton wavelength of the particles is $\lambda_0 \sim \hbar / T_0 = m_p^{\,2} / T_0 = 10^{38}\,\mathrm{GeV} \ll M_0$, so how can the quantum information carried by the particles be transferred to a horizon which, as it is being formed, is not determined by any local physics?

If not, how can this information be transferred to either early or late Hawking radiation, as long as trapped surfaces exist?

The initial Hawking radiation is made up of quanta with wavelength $\lambda_{\mathrm{H}} \sim M_0$ and energy $T_{\mathrm{H}} \sim m_{\mathrm{p}}^{\,2} / \lambda_{\mathrm{H}} \sim 10^{-19}\,\mathrm{GeV}$. The Bekenstein-Hawking entropy is $S_{\mathrm{BH}} = 4\pi \left(\frac{M_0}{m_{\mathrm{p}}} \right)^2 \sim \left(\frac{10^{57}\,\mathrm{GeV}}{10^{19}\,\mathrm{GeV}} \right)^2 \sim 10^{76}$. This is roughly the maximum number of quanta which can fit into a black hole of the given mass-energy, since lower energy quanta would have wavelengths exceeding the black hole radius, and is the number of quanta radiated in a Page time.

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Ways out?

It is hard to fault the *logic* of the AMPS argument. But semi-classical arguments, which should be valid for a macroscopic black hole, strongly suggest that the Hawking modes inside and outside the black hole are strongly entangled. The outgoing Hawking modes have. a particle interpretation only well outside the horizon, for $r > 3M$ or so, beyond where the modes can be reflected back inside the horizon.

The first-order backreaction on the metric gives no indication of any instability of the horizon, as discussed in Bardeen, Phys. Rev. Lett. **46**, 382 (1981). One does need to assume that quantum gravity is UV safe, in that vacuum modes with initially sub-Planckian wavelengths evolve smoothly to macroscopic wavelengths as they are pulled apart by the divergence of the null geodesics near the horizon.

The arguments for the stationary behavior of the semi-classical energy-momentum tensor outside the horizon do not apply inside the horizon, where the spacetime is not at all quasi-stationary. Could the quantum backreaction inside the black hole become large on a time the order of the Page time, at which the number of Hawking modes inside and outside both approach $S_{\rm BH}$, perhaps large enough to destroy the horizon? If so, unitarity might be saved without a firewall, though perhaps with more modest "drama", by allowing the Hawking partners inside to escape.

Schwarzschild $< T_{\mu\nu} >$ at r > 2M

$< T_{\mu\nu} >$ outside the horizon must be conserved and should be, to first order in $\hbar$, time-independent. The conservation equations in Schwarzschild coordinates, as conditions on a static observer's energy density E , energy flux F , radial stress P_{rad}, and transverse stress $P_{\text{tr}} = P_\theta^\theta = P_\varphi^\varphi$, are then:

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

$$(E+P_{\text{rad}})\frac{M/r}{(1-2M/r)}+\frac{1}{r}\partial_r\left(r^2 P_{\text{rad}}\right)-2P_{\text{tr}}=0.$$

Given the Hawking luminosity $4\pi k\frac{m_p^2}{M^2}$, the energy flux F must be

$$F=k\frac{m_{\text{p}}^2}{M^2}\frac{1}{r^2}\frac{1}{1-2M/r}.$$

For a classically conformally invariant quantum field on a Schwarzschild background, the trace anomaly is

$$T=-E+P_{\text{rad}}+2P_{\text{tr}}=q\left(m_{\text{p}}/M\right)^2 x^4/r^2,\ x\equiv 2M/r.$$

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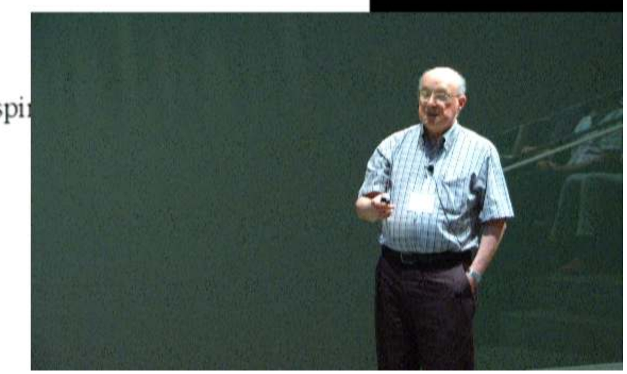

Christensen and Fulling, Phys. Rev. D **15**, 2088 (1977):

The above, plus regularity on the event horizon for a freely falling observer, go a long way to determining the form of $<T_{\mu\nu}>$. In a more physically transparent decomposition:

$$E = E^{\text{out}} + E^{\text{in}} + E^{\text{vp}} + E^{\text{ta}}, \quad P_{\text{rad}} = E^{\text{out}} + E^{\text{in}} - E^{\text{vp}} - E^{\text{ta}},$$

$$F = E^{\text{out}} - E^{\text{in}} = k\left(\frac{m_{\text{p}}}{M}\right)^2 \frac{1}{r^2}\frac{1}{1-x}, \quad P_{\text{tr}} = E^{\text{vp}} + 2E^{\text{ta}}.$$

Define a function $f(x)$ such that

$$E^{\text{out}} = (1-f)F, \quad E^{\text{in}} = -fF.$$

At $x=1$ a static observer is moving outward at the speed of light. Regularity there requires $E^{\text{out}}(1) = 0 \Rightarrow f(1) = 1,\ f'(1) = 0$, so

$$f(x) = 4x^3 - 3x^4 - 4(1-x)^2 h(x).$$

Momentum conservation gives:

$$E^{\text{vp}} = k\left(\frac{m_{\text{p}}}{M}\right)^2 \frac{8}{r^2}\left[(1-x)h - x^2\int_0^x\left(3 + 3\frac{h}{x'^2} - 2\frac{h}{x'^3}\right)dx' + Dx^2\right],$$

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Massless scalar field:

Visser (gr-qc/9703001v1) obtained an analytic fit to earlier numerical results accurate to better than 1%. In my notation

$$h(x) = 0.540x^3, \quad D = 0.621,$$

giving $f(x) = 1.84x^3 + 1.32x^4 - 2.16x^5$.

With $k = \sum_s k_s$, $q = \sum_s q_s$,

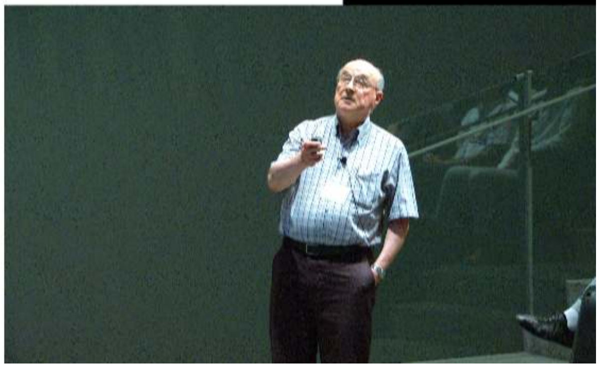
$$k_0 = \frac{14.26}{256 \times 960\pi^2} = 5.88 \times 10^{-6}, \quad q_0 = \frac{1}{960\pi^2}.$$

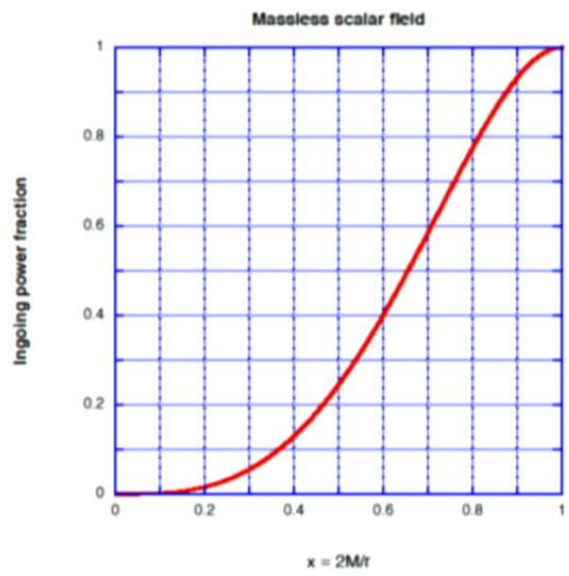
For higher spins:

$$k_1 = \frac{6.49}{256 \times 960\pi^2}, \quad q_1 = -\frac{13}{960\pi^2},$$

$$k_2 = \frac{0.742}{256 \times 960\pi^2}, \quad q_2 = +\frac{212}{960\pi^2}.$$

I expect $h(x)$ to be larger for higher spins, to allow for more reflection of the outgoing waves from the potential barrier, possibly resulting in $f(x) < 0$ for a range of x.




Massless scalar field
Ingoing power fraction
0
0.2
0.4
0.6
0.8
1
x = 2M/r

Backreaction when $r < 2M$

- No apparent reason why $< T_{\mu\nu} >$ should only depend on r.
- Extrapolating the exterior expressions gives $f \to -\infty$ as $r \to 0$. This is physically unreasonable.
- What can be extrapolated is the trace anomaly

$$T \propto m_p^2 \left(C_{\alpha\beta\gamma\delta} C^{\alpha\beta\gamma\delta} + R_{\alpha\beta} R^{\alpha\beta} - \frac{1}{3} R^2 \right).$$

- Backreaction is small only if $r^2 T \ll 1$.
- In the Schwarzschild background $r^2 T \sim 1$ when $r \sim \sqrt{m_p M} \gg m_p$.
- This suggests that semi-classical backreaction could possibly prevent the $r = 0$ Schwarzschild singularity, without invoking quantum gravity.
- Getting a bounce at the center of the star collapsing to form the black hole may require an appeal to quantum gravity.

A non-singular black hole model

Hayward (gr-qc/0506126):

The metric in advanced Eddington-Finkelstein coordinates is

$$ds^2 = -\left[1 - \frac{2M(v)r^2}{\left(r^3 + a^2M\right)}\right]dv^2 + 2dvdr + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right).$$

If $a \ll M$, this is Schwarzschild-like for $r \gg a$ and DeSitter-like for $r \ll a$. The metric is regular everywhere and geodesically complete.

Form the black hole by having M increase from 0 to $M \gg a$. Then assume mass loss at the Hawking rate, $\frac{dM}{dv} = -4\pi k \frac{m_p^2}{M^2}$ for $v > v_0$. Once $M < \frac{3}{4}\sqrt{\frac{3}{2}}a$, there are no horizons or trapped surfaces. If $a \gg m_p$, the horizons disappear well before the geometry is strongly affected by quantum gravity. For the right value of $a = O\left(m_p\right)$ the energy-momentum tensor derived from the Einstein equations matches the trace anomaly energy-momentum tensor at large r.

Final thoughts

- Can the backreaction gradually increase over the Page time to remove the trapped surfaces everywhere, as the number of ingoing Hawking quanta trapped inside the apparent horizon builds up close to S_{BH}? This doesn't seem out of the question if there is no singularity to absorb the trapped quanta. If so, and all the trapped quanta escape, including the high energy quanta that formed the black hole, unitarity is preserved without any need to entangle the outgoing Hawking quanta among themselves, and there is no reason to have a firewall along the apparent horizon. The entanglement of the outgoing and ingoing Hawking quanta is never disturbed.

- In this scenario, only a fraction of the initial mass of the black hole would come out in the form of soft Hawking quanta. Most if the energy would be released at the end, perhaps in a highly processed form. The black hole would be like a very long lived resonance in the scattering of the particles that formed the black hole.
- It is conceivable, but far from established, that the resolution of the quantum information paradox need not, for macroscopic black holes, involve quantum gravity in a major way.
- These issues have been debated vigorously for almost 40 years. The final resolution is not in sight.


RESERVED