Surface gravity and the information loss problem

Based on

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The information loss paradox is widely regarded as one of the biggest open problems in theoretical physics. Several classical and quantum features must be present to enable its formulation. First, an event horizon is needed to justify the objective status of tracing out degrees of freedom inside the black hole. Second, evaporation must be completed (or nearly completed) in finite time according to a distant observer, and thus the formation of the black hole should also occur in finite time. In spherical symmetry these requirements constrain the possible metrics strongly enough to obtain a unique black hole formation scenario and match their parameters with the semiclassical results. However, the two principal generalizations of surface gravity, the quantity that determines the Hawking temperature, do not agree with each other on the dynamic background. Neither can correspond to the emission of nearly-thermal radiation. We infer from this that the information loss problem cannot be consistently posed in its standard form.

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Necessary elements for the formulation of the information loss problem

1. **Formation of a transient trapped region in finite time of distant observer**

   Such a region either completely disappears or turns into a stable remnant; in either case, this takes place in finite time as measured by a distant observer. This provides the scattering-like setting to describe the states (and their alleged information content) "before" and "after".

2. **Formation of an event horizon (and not just any other surface)**

   Its existence is necessary to provide an objective, observer-independent separation of the spacetime into accessible and inaccessible regions, and it is only with respect to this boundary that tracing out of the interior degrees of freedom is not just a technical limitation, but a fundamental physical restriction.

3. **Thermal (or nearly-thermal) character of the radiation**

   It is responsible for the eventual disappearance of the trapped region and for the high entropy of the reduced exterior density operator.

Generalizations of surface gravity to evolving black hole spacetimes

Surface gravity is unambiguously defined only in stationary spacetimes!

(several equivalent definitions)

General spherically symmetric metric:

$$ds^2 = -e^{2h(t,r)} f(t,r) dt^2 + f(t,r)^{-1} dr^2 + r^2 d\Omega$$

where $f(t,r) := 1 - C/r := \partial_\mu r \partial^\mu r$

In general dynamical spacetimes, there is no asymptotically timelike Killing vector.

⇨ Role of Hawking temperature captured either by

Peeling surface gravity or **Kodama surface gravity** $\frac{1}{2} K^\mu \left(\nabla_\mu K_\nu - \nabla_\nu K_\mu\right) := \kappa_{\mathrm{K}} K_\nu$

$$\kappa_{\text{peel}} = \frac{e^{h(t,r_g)} \left(1 - C'\left(t, r_g\right)\right)}{2 r_g}$$

(can also be defined using Painlevé-Gullstrand coordinates)

where Kodama vector field $K^\mu = \left(e^{-h_+}, 0, 0, 0\right)$

$$\Rightarrow \kappa_{\mathrm{K}} = \frac{1}{2} \left(\frac{C_+(v,r)}{r^2} - \frac{\partial_r C_+(v,r)}{r} \right)\Bigg|_{r=r_+} = \frac{(1-w_1)}{2 r_+}$$

Generalizations of surface gravity to evolving black hole spacetimes

In spherical symmetry, only two classes of dynamic solutions are compatible with finite-time horizon formation. In terms of the coordinate distance $x := r - r_g$ from the horizon, their metric functions are given by

$$\boxed{\begin{aligned} C &= r_g + x - c_{32}x^{3/2} + \sum_{j\geq 2}^{\infty} c_j x^j \\ h &= -\frac{3}{2}\ln\frac{x}{\xi} + \sum_{j\geq\frac{1}{2}}^{\infty} h_j x^j \end{aligned}}$$

describes formation of black hole

and

$$\boxed{\begin{aligned} C &= r_g - c_{12}\sqrt{x} + \sum_{j\geq 1}^{\infty} c_j x^j \\ h &= -\frac{1}{2}\ln\frac{x}{\xi} + \sum_{j\geq\frac{1}{2}}^{\infty} h_j x^j \end{aligned}}$$

describes black hole immediately after formation

Surface gravity results: $\kappa_{\mathrm{K}} = 0$

For both classes: $\kappa_{\mathrm{peel}} \to \infty$

Approaches static value $\kappa_{\mathrm{K}} = 1/(4M)$ only if metric is close to pure Vaidya metric, which leads to contradictions with semiclassical results.

$\Rightarrow$ Different notions of surface gravity that are equivalent in the stationary case are irreconcilable in the dynamical case, and neither version can describe the emission of thermal radiation!

One-sentence summary

1. Evaporation
2. Event horizon
3. Thermal character of the radiation

If semiclassical gravity is valid,

it is impossible to simultaneously realise all of the necessary elements

that are required for a self-consistent formulation of the information loss problem.