Black Hole Information Loss
What's the problem?

SH and Lee Smolin, Phys. Rev. D81:064009 (2010) [arXiv:0901.3156]

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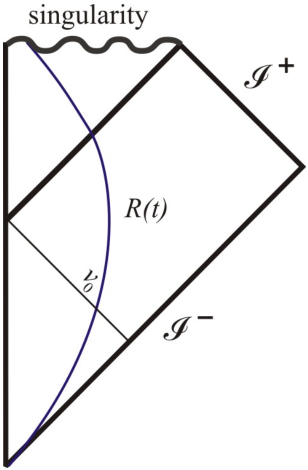
Why does Black Hole information matter?

- The black hole information loss problem resides at the intersection of classical general relativity and quantum field theory, touching on quantum gravity – a badly understood regime.
- Black holes have taught us a many things about the relation between particle physics, thermodynamics and general relativity – there's more to learn.
- Any believable theory of quantum gravity must be able to unambiguously solve this problem (for real black holes!)

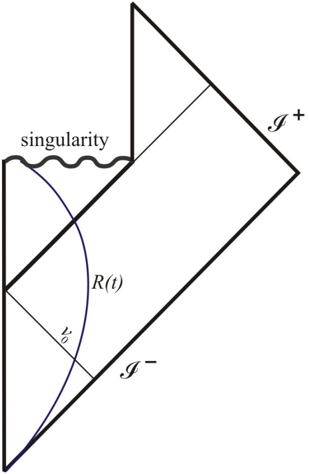
$\longrightarrow$ In the following: nonrotating uncharged black holes, in asymptotic Minkowski space, non-static.

Black Hole Collapse



No problem here

The Evaporating Black Hole - Hawking's Version



The final state is the same irrespective of the details of the initial state! Thus, the evolution is not reversible and in particular not unitary.

Problem: Conflict with quantum mechanics.

Features: Horizon and singularity.

How to deal with quantum gravity regions?

- Problem: we do not know whether in a qg region a metric, curvature or even spacetime and causality are meaningful concepts.
- Procedure: Identify problematic region and classify possible causal structures around it.
- Necessary: Asymptotically flat spacetime, so region with strong qg effects is compact.

Asymptotically Flat Quantum Spacetime: Definition

A quantum spacetime $\mathcal{QST}$ is partly semi-classical if

a) There is a procedure to define a manifold $\mathcal{R}$, a metric operator $\hat{g}_{ab}$ and a state $|\Psi\rangle$, such that $(\mathcal{R}, \langle\Psi|\hat{g}_{ab}|\Psi\rangle)$ defines a possibly extendible Lorentzian spacetime (which we call for short $(\mathcal{R}, \langle g_{ab}\rangle)$).

b) The semi-classical Einstein equations for $\langle g_{ab}\rangle$ are satisfied on $\mathcal{R}$, up to small quantum corrections.

The point is: $(\mathcal{R}, \langle g_{ab}\rangle)$ may not be complete, ie there may be regions of $\mathcal{QST}$ that do not have a classical or semi-classical description. If the quantum theory of gravity still allows us to define a manifold $\mathcal{M}$ such that $\mathcal{R} \subset \mathcal{M}$, then the $\mathcal{X} = \mathcal{M} - \mathcal{R}$ constitutes the *quantum region* of the quantum spacetime, while $\mathcal{R}$ constitutes its *semi-classical region* and $(\mathcal{R}, \langle g_{ab}\rangle)$ is its *classical approximation*.

- The classical approximation of a quantum spacetime is *semi-classically complete* if it contains all the regions of spacetimes that can be defined by the procedure that defines $(\mathcal{R}, \langle g_{ab}\rangle)$.
- A partly semi-classical quantum spacetime $\mathcal{QST}$ is *asymptotically flat* if its classical approximation $(\mathcal{R}, \langle g_{ab}\rangle)$ is asymptotically flat.

Event Horizons and Singularities

Extend notion of singularity and horizons to asymptotically flat spacetimes with intermediate regions of strong qg effects:

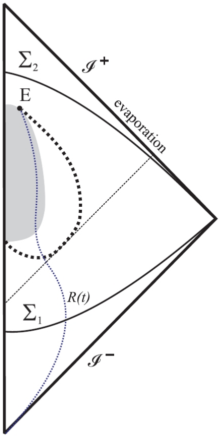
- A region of a quantum spacetime $\mathcal{QST}$ that is not in the causal past of I^+ of its classical approximation $(\mathcal{R}, \langle g_{ab} \rangle)$ is an *asymptotically future hidden region*.
- A quantum spacetime $\mathcal{QST}$ has a *future event horizon* if it contains an asymptotically future hidden region.
- A *complete spacelike surface* Σ of a quantum spacetime is a set of events of which no two are time- or lightlike to each other, and to which no events can be added without violating this condition.
- The quantum spacetime is *quantum non-singular* if for any two complete non-intersecting spacelike hypersurfaces Σ_1 and Σ_2, there is a reversible linear map $\mathcal{M}_{1,2} : \mathcal{H}_1 \to \mathcal{H}_2$, corresponding to dynamical evolution. Otherwise we say that the quantum spacetime is *quantum singular*.

Corrolary:

⟶ A quantum singular spacetime cannot have a unitary time evolution.

- This does not mean that a non-singular spacetime has no problem, but that we certainly have a problem as long as there's a singularity. Consequently, the minimal (conservative) solution attempt rests on removing the singularity.
- We don't know what's going on in the qg region, but we know how the embedding diagrams must look like.

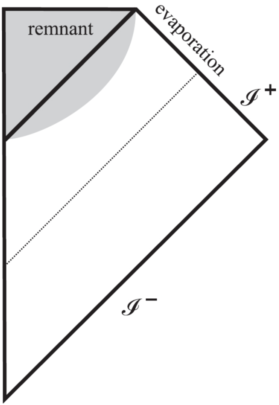
The Evaporating Black Hole - Possible Solution I



Quantum graviational effects prevent the formation of a singularity. There is no true event horizon, only a trapping horizon, which looks for a long time very similar to an event horizon. This corresponds to a quasi-stable remnant.

Features: No horizon, no singularity.

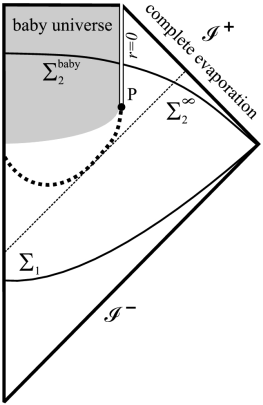
The Evaporating Black Hole - Possible Solution IIa



Quantum gravitational effects prevent the formation of a singularity. The quantum gravitational region never completely evaporates but stabilizes at small radius (but possibly large volume). This is a stable remnant scenario.

Features: Horizon, but no singularity.

The Evaporating Black Hole - Possible Solution IIb



Quantum gravitational effects prevent the formation of a singularity. The quantum gravitational region completely disconnects (zero surface area) from the rest of spacetime. This is a baby-universe scenario.

Features: Horizon, but no singularity.

Objections against (quasi-)stable remants?

- Arguments why a total evaporation implies a long-lived quasi-stable remant are very weakly founded: One paper assumes a small volume, the other one presupposes a horizon. If these arguments do not hold, there's no need for a remnant to begin with.
- Objections against (quasi-)stable remants are also weakly founded: They rely on the pair production problem which is based on an effective model. The more conservative conclusion to draw from this problem is that the effective model doesn't make sense.

Summary

- The most plausible solution to the black hole information loss problem is that quantum graviational effects remove the singularity.
- Then there's 3 possible options: complete evaporation, stable remnant, or a baby universe (or all of them, who knows?)
- There's no good reason why this solution should be outruled.
- These solutions (highly entropic objects with small or vanishing surface area but large volume, known as 'bags of gold' or 'monsters') are not in conflict with anything we know.
- They do not require Anti-deSitter space, long-range nonlocality, imposing boundary conditions on the singularity, complementarity or other 'radical' assumptions.