Black holes, information loss and the measurement problem

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Introduction

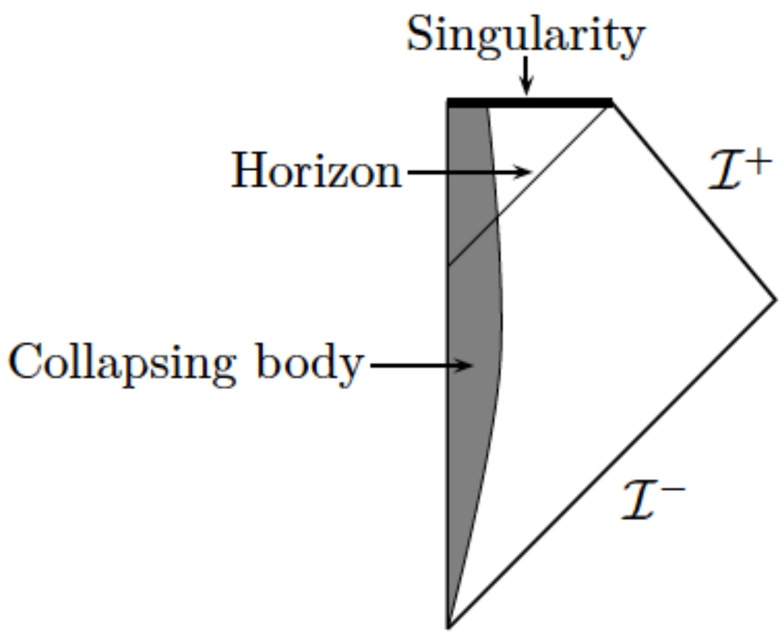
- The information loss paradox is often presented as an unavoidable consequence of well-established physics.
- However, in order for a genuine paradox to arise, non-trivial assumptions are required.
- **Objectives of the talk**:
  - Be explicit about these additional assumptions:
    - Nature of Hawking's radiation
    - Quantum aspects of spacetime
    - Foundations of quantum theory
  - Sketch a map of alternatives to tackle the issue.
  - Display a connection with the measurement problem.

Plan

1. **Black holes and information:**
   - **Classical setting:** BHs hide information.
   - **QFT on fixed curved background:** BHs radiate.
   - **Back-reaction and 1st QG input:** BHs evaporate.
   - **2nd QG input:** BH do not involve singularities.
2. **The information loss paradox**
3. **Alternatives:**
   - **Outgoing radiation encodes information**
   - **Unitarity is broken**
   - **Etc.**
4. **Information loss and the measurement problem**

Classical setting: BHs hide information.

- If mass of a cluster is big enough, a BH will form.
- It will eventually settle into one of the few stationary BH solutions.
- This seems to suggest that information will be lost in the process.
- However, this information loss only corresponds to that of outside observers.
- Therefore, no information loss.



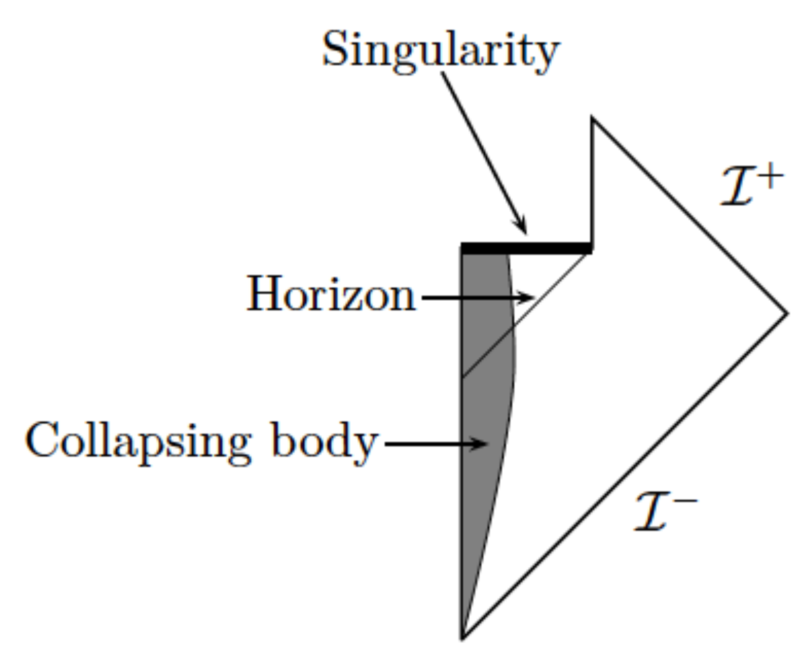
QFT on fixed curved background: BHs radiate.

- Hawking's analysis:
  - Formation of BH modifies quantum state of field.
  - At late times, flux of particles towards infinity.
  - Flux characterized by surface gravity.

- Important to stress: back-reaction not considered.
  - Difficult to deal with.
  - Straightforward considerations lead to dramatic consequences…

Back-reaction and 1st QG input: BHs evaporate

- Hawking's result suggests a radical modification for fate of BHs.
- No back-reaction, but confidence on energy conservation:
  - Mass of BHs has to diminish.
  - Runaway picture, which suggest complete evaporation in finite time.
- Information loss? Not yet…



Back-reaction and 1st QG input: BHs evaporate

- QG might stop the evaporation, leading to a stable remnant.
    - Plank’s mass order.
    - Hard for it to encode all of the initial information.

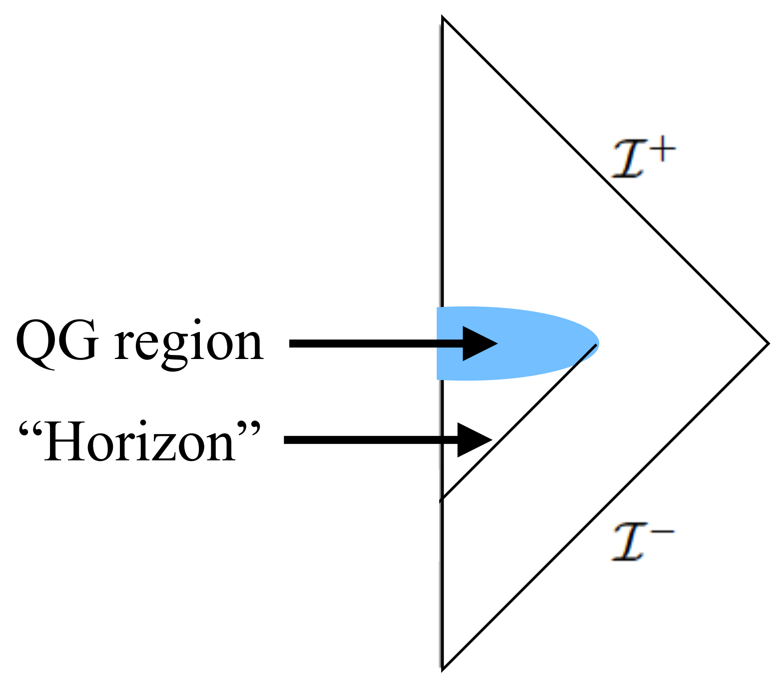
- QG effects could also open paths to other universes.
    - Ontological burden.
    - Possibility of universes emerging in ordinary processes (virtual BHs).
    - At any rate, we’re interested in effective description of our universe.

Back-reaction and 1st QG input: BHs evaporate

- Much more important: inevitable singularities.
  - Signal of breakdown of the theory.
  - Represent boundaries of spacetime.
  - Extra boundaries modify Information loss issue:
    - One has to make sure to compare information content on different Cauchy hypersurfaces.
    - E.g., one must compare initial Cauchy hypersurface with asymptotically null future *plus* the hypersurfaces surrounding the singularity.
- Still no information loss under these circumstances.

2nd QG input: BH do not involve singularities.

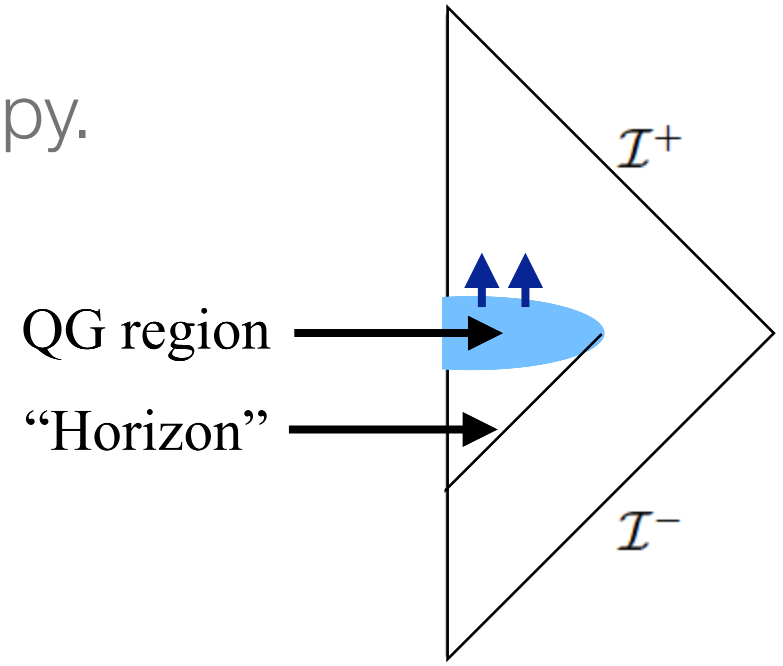
- Singularities signal breakdown of GR; indicate need to go further.
- QG is expected to cure singularities.



- Without singularities, information loss issue resurfaces.

2nd QG input: BH do not involve singularities.

- One option (Peres & Unruh): information could be encoded in low-energy modes that go through the "singularity."
    - Like remnants case, hard to encode all information.
    - Vacuum-like state with unbounded entropy.



- Paradox? Not yet. We need fundamental theory that forbids information loss.

A paradox?

What is needed in order for a genuine paradox to arise?

1. Due to Hawking's radiation, BH evaporates completely or leaves small remnant.
2. Remnant, if present, cannot encode initial information.
3. Information is not transferred to a parallel universe.
4. QG cures the singularities.
5. Information is not encoded in low-energy modes that go through the "singularity."
6. Outgoing radiation does not encode the initial information.
7. Quantum evolution is always unitary.

- Arguments for 1, 2, 3, 4 and 5 are reasonable (if not conclusive).
- What about 6 and 7?

A paradox?

- In order to avoid a paradox, assuming 1-5 are true, at least one of 6 and 7 has to be negated. How to decide which?
- Hawking: initial pure state evolves into final one which, when tracing over inside region, reduces to mixed thermal state.
- Question: How to interpret such mixed state when

  i) The BH is gone, so there is no inside region to trace over.

  ii) There is no singularity (or additional boundary) for the information to "escape into."

- Two options:

  a) Mixed state arises only as a result of tracing; outgoing radiation encodes information — i.e,. negating 6.

  b) Information is in fact lost — i.e, negating 7.

Outgoing radiation encodes information

- AdS/CFT correspondence allows exploration of dual settings without BHs.
- Since breakdown of unitarity is not expected in such scenarios, there should be no room for breakdown of unitarity in situations involving BHs.
- Then, the outgoing radiation must encode the initial information.
- However, this leads to the formation of a firewall:
  - Divergence of energy-momentum tensor over the horizon.
  - Breakdown of equivalence principle.

Unitarity is broken

- Hawking's radiation was initially taken to imply information loss at the fundamental level (e.g., Hawking and Penrose).
- Banks et al. (1984) suggested that such ideas would lead to serious difficulties, but Unruh and Wald (1995) showed they could be evaded.
- We have explored the viability of breakdown of unitarity both qualitatively and quantitatively.
- In particular, we have used objective collapse models to successfully describe the required transition from an initial pure state into a mixed final one.
- **For more details, see next talk by Daniel Sudarsky!**

Information loss and the measurement problem

- Most discussions of BHs and information loss do not incorporate foundational issues of quantum theory.
- Ignoring such issues is not always acceptable.
- Standard quantum mechanics is essentially instrumentalist, i.e., written in terms of observers or measurements.
- Such instrumentalism becomes a problem if one intends to regard the theory as fundamental:
    - Useful not only to make predictions in suitable experimental settings.
    - Applicable also to measurement apparatuses, observers or non-standard contexts, such as BHs or the universe as a whole.
- This, so-called, **measurement problem** has been amply discussed.

Information loss and the measurement problem

- A particularly precise way to state the problem, due to T. Maudlin, is as a list of three statements that cannot be all true at the same time:

  A. The physical description given by the quantum state is complete.

  B. Quantum evolution is always unitary.

  C. Measurements always yield definite results.

- Maudlin's formulation is useful to motivate and classify solutions:

  ¬A: Hidden variable theories.

  ¬B: Objective collapse models.

  ¬C: Everettian scenarios.

Information loss and the measurement problem

- Note that assumptions 7 and B are, in fact, identical: Quantum evolution is always unitary.
- Therefore, the strategy one decides to adopt regarding information loss (i.e., negating 6 or 7) has implications with respect to solving the measurement problem (i.e., negating A, B or C):
    - Insisting on a purely unitary evolution not only demands a violation of the equivalence principle and a divergence of the energy-momentum tensor, but also a commitment either with many worlds or with an acknowledgment that standard quantum mechanics is incomplete.
    - If one decides to abandon unitarity, the same move automatically not only avoids a breakdown of the equivalence principle, but also guarantees success with respect to the measurement problem.
- **The upper hand of the second option seems evident to us.**
- **Allows for a unified description of diverse phenomena.**

Thank you!

Bibliography

- E. Okon and D. Sudarsky, “Benefits of Objective Collapse Models for Cosmology and Quantum Gravity,” Found Phys (2014) 44:114-143.
- E. Okon and D. Sudarsky, “The Black Hole Information Paradox and the Collapse of the Wave Function,” Found Phys (2015) 45:461-470.
- E. Okon and D. Sudarsky, “Black holes, information loss and the measurement problem,” forthcoming.