On the assumptions leading to the information loss problem

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Based on on arXiv:2107.05662 with Luca Buoninfante and Shinji Mukohyama.

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Introduction

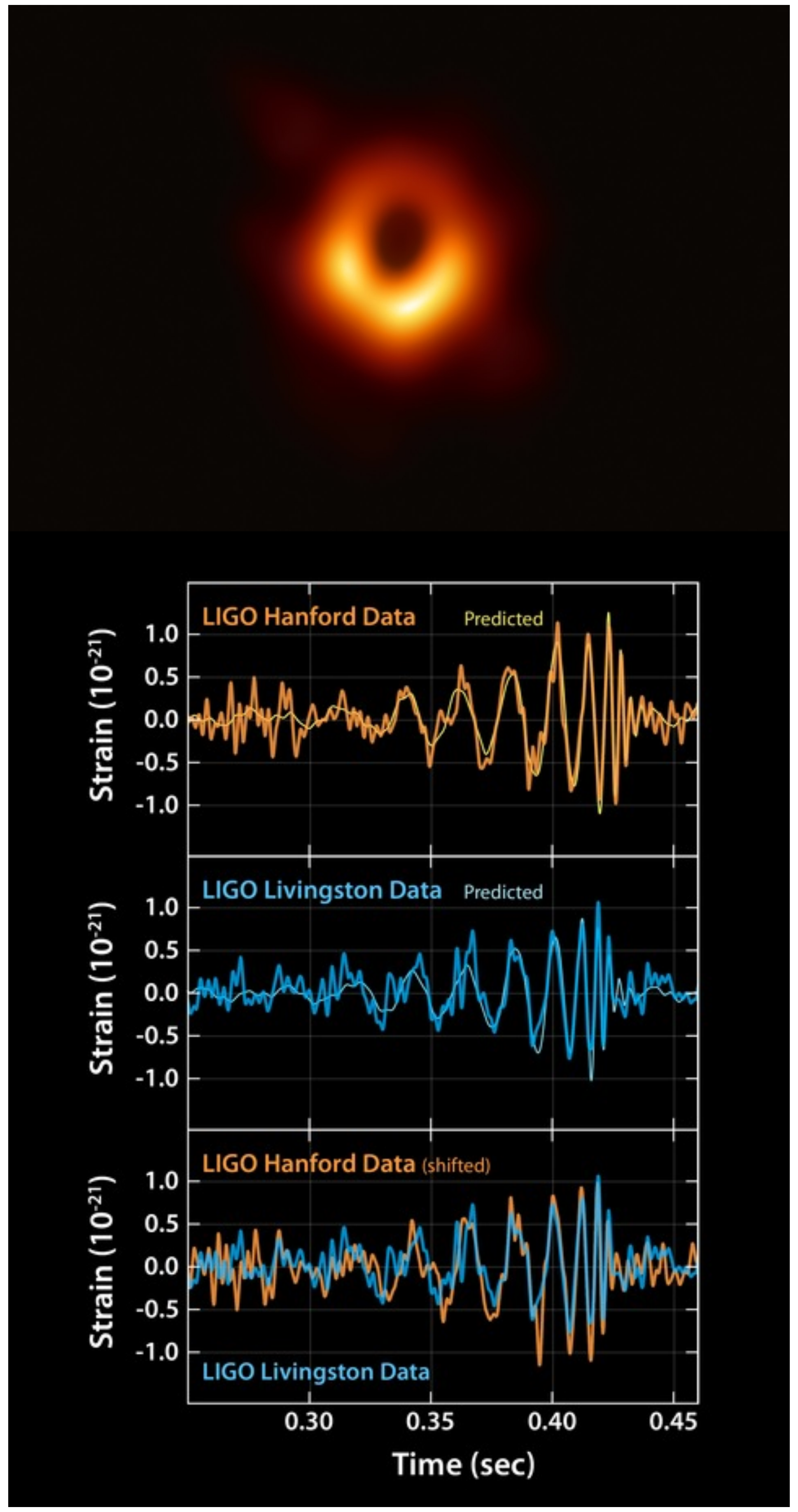
Observations of black holes exteriors constitute one of the most successful confirmation of general relativity predictions.

We do not have a consistent theory to describe black holes interiors.

Cosmic censorship conjectures $\Longrightarrow$ no problem for outside observers.

At the semiclassical level black holes evaporates.

This eventually leads to the information loss paradox.



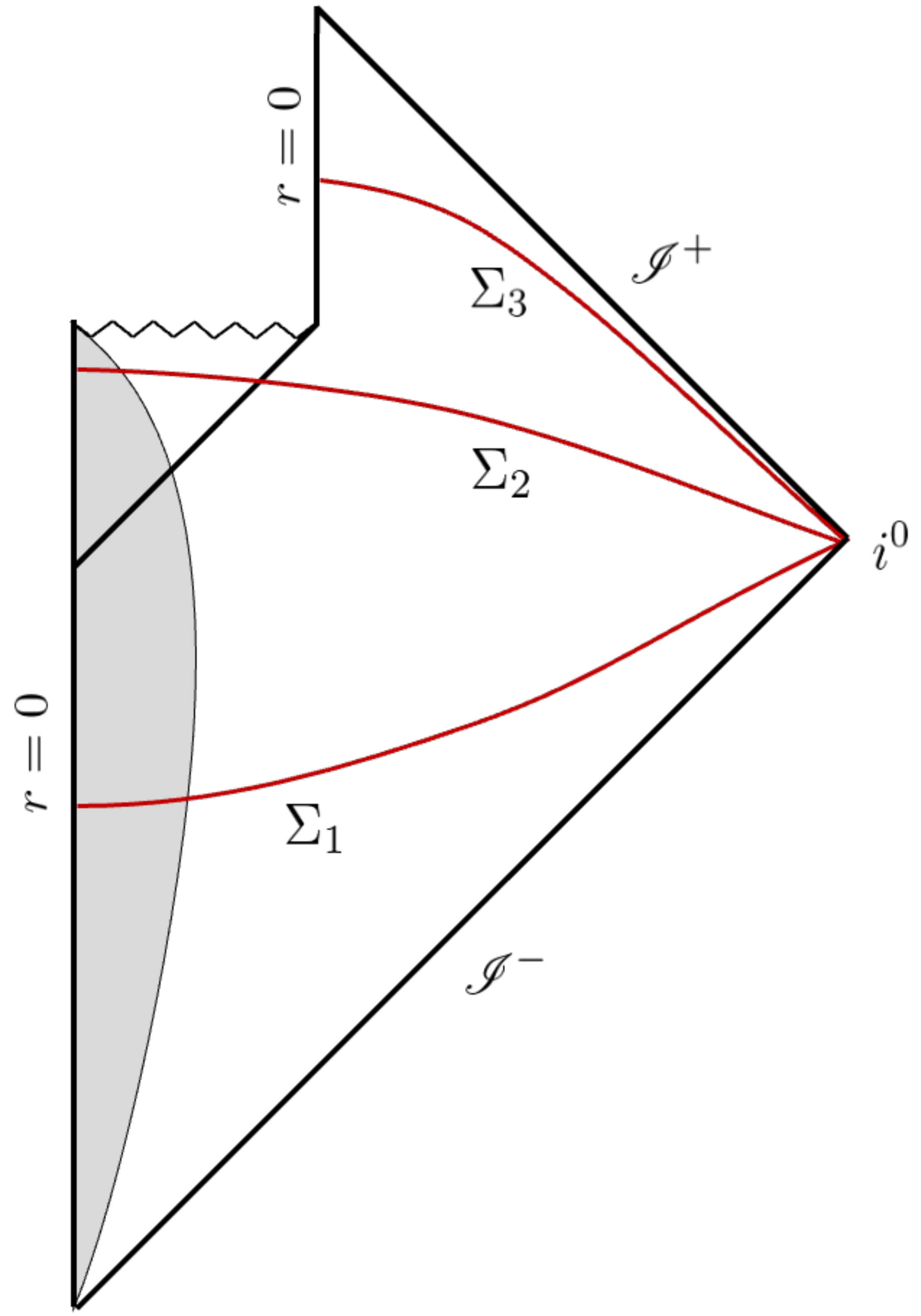
Formulation of the problem

Case A. Unitary Problem

A1. Quantum states evolve in a unitary way. Pure states evolve into pure states;

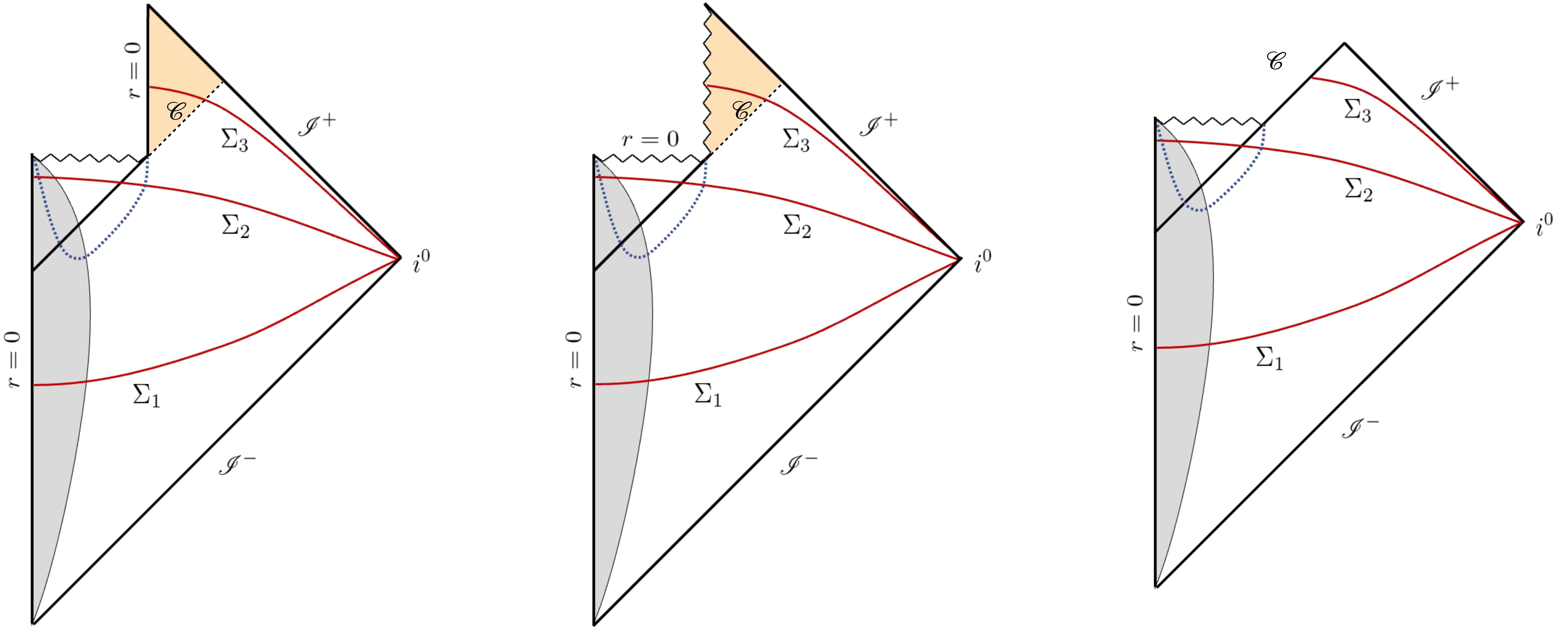
A2. Semiclassical general relativity is a valid low-energy effective field theory to describe black hole physics during the entire evaporation process;

A3. Black holes evaporate completely and end up leaving a regular spacetime.



Case A. Unitary Problem

This formulation of the information loss paradox is not particularly worrisome



Case B. Entropy Problem

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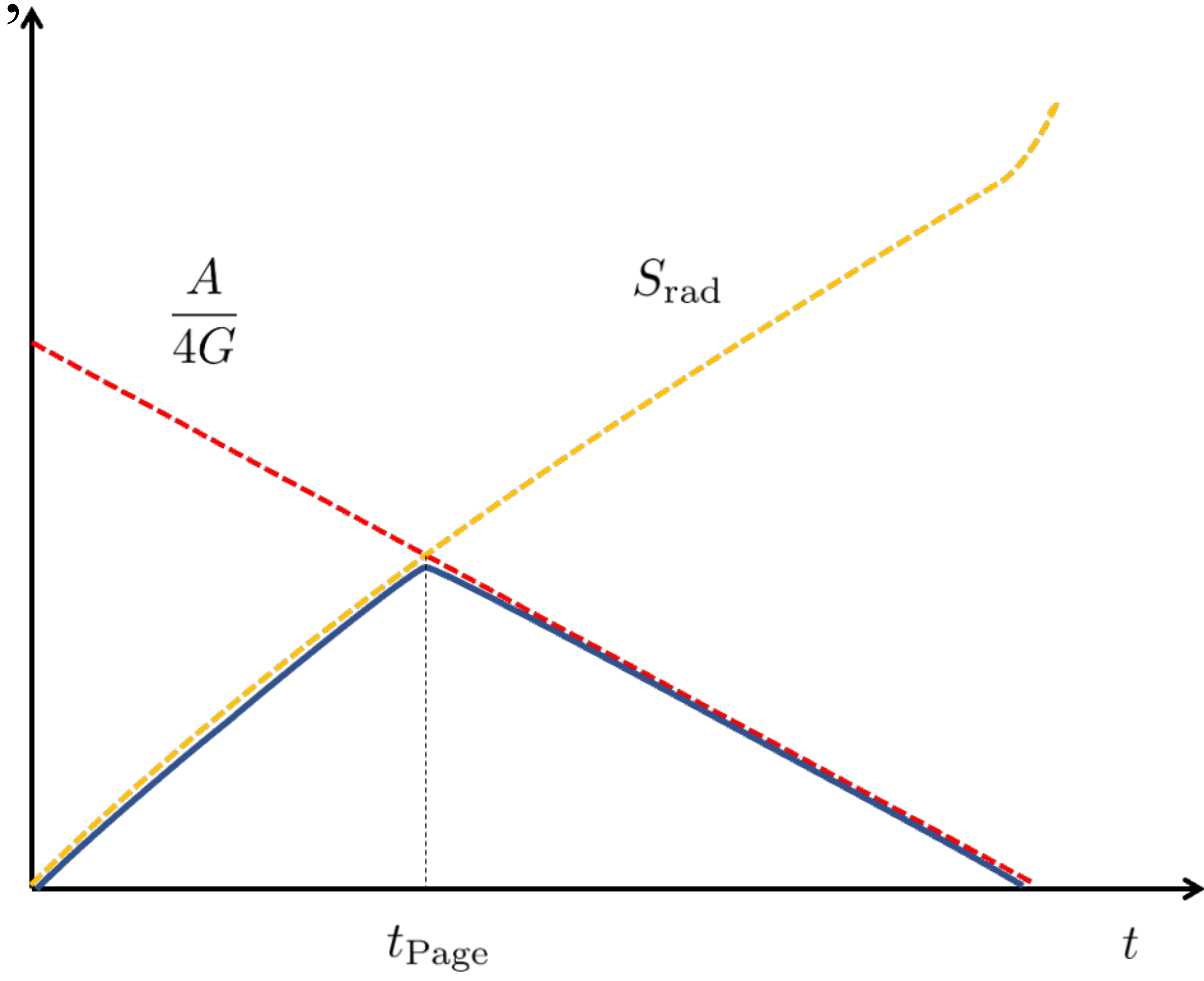
B1. Quantum states evolve in a unitary way. Pure states evolve into pure states;

B2. Semiclassical general relativity is a valid low-energy effective field theory to describe black hole physics far from the Planckian regime;

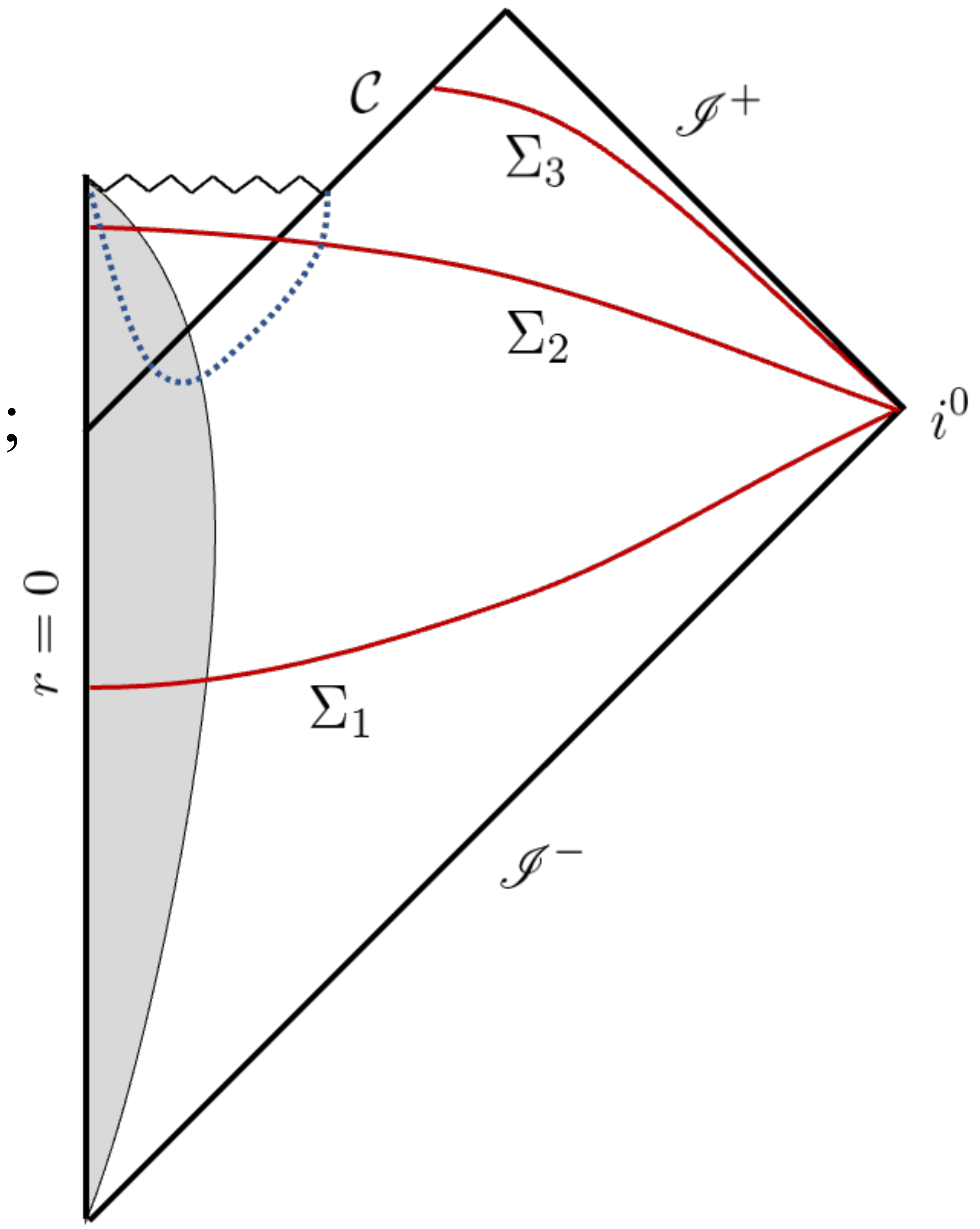
B3. As seen from the outside, a black hole behaves like a quantum system whose number of degrees of freedom is given by A/4G, with A being the apparent horizon area.



Case C. No Problem

C1. Quantum states evolve in a unitary way. Pure states evolve into pure states;

C2. Semiclassical general relativity is a valid low-energy effective field theory to describe black hole physics far from the Planckian regime;



Why the central dogma?

Bekenstein Hawking entropy

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- Black holes obey standard thermodynamic laws with the Bekenstein-Hawking entropy

$$S_{\mathrm{BH}} = \frac{A}{4G} \,.$$

  For a generic system

$$S_{\mathrm{th}} \geq S_{\mathrm{vN}} \,.$$

- This suggests that the apparent-horizon area $A = 16\pi G^2 M^2$ has an intrinsic statistical nature and the total number of internal states might be bounded by $e^{S_{BH}}$.

Bekenstein bound - Holographic principle

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- The Bekenstein bound

$$S \leq 2\pi RE\,,$$

applied to the Schwarzschild geometry $R = 2GM$, $E = M$.

$$S \leq \frac{A}{4G}\,.$$

- Holographic principle. The number of degrees of freedom is proportional to the area.

Why not the central dogma?

Thought experiment

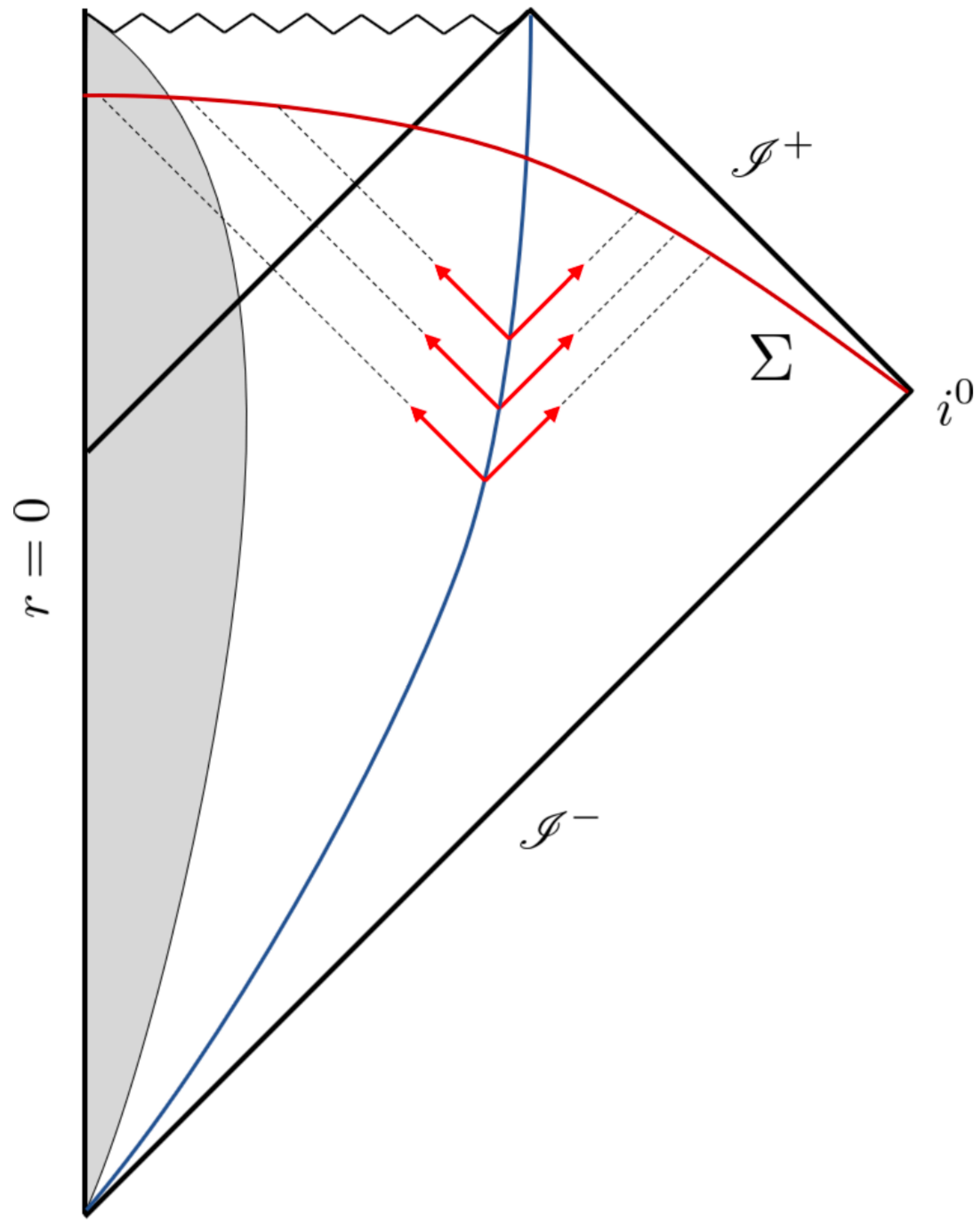
Let us assume that our assumption B2 holds

B2. Semiclassical general relativity is a valid low-energy effective field theory to describe black hole physics far from the Planckian regime;

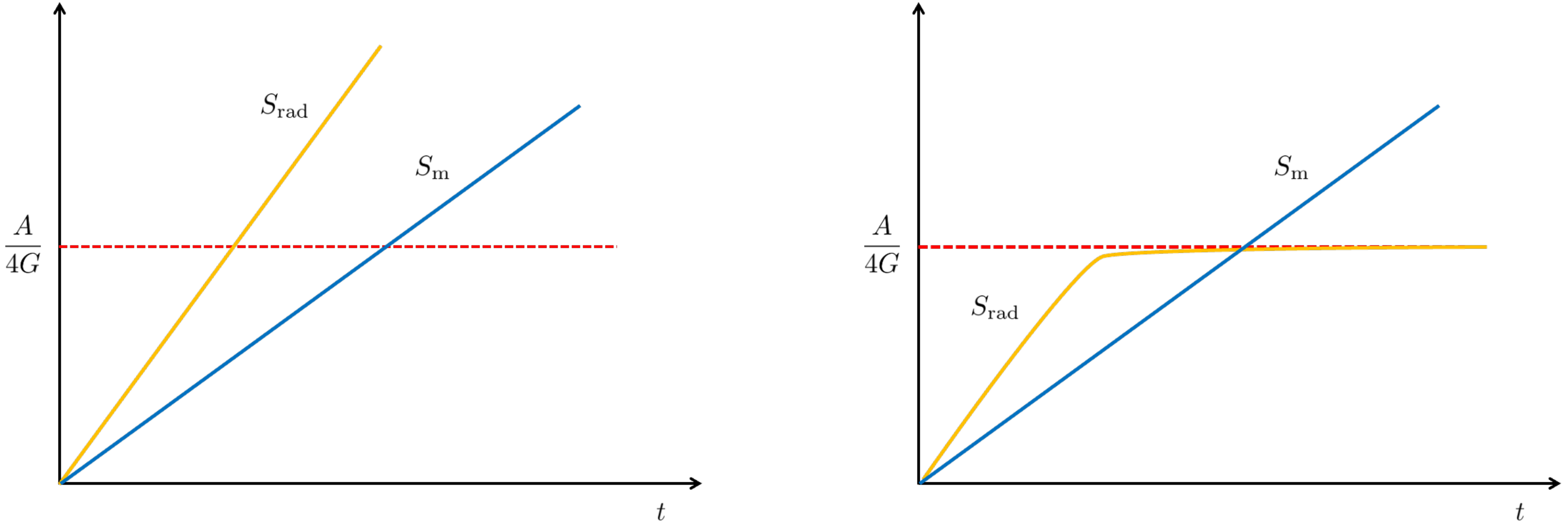
A far away observer prepares a pure state. Half of the state falls into the black hole, the other half reaches $\mathscr{I}^+$.

The ingoing energy flux is tuned to be equal to the outgoing Hawking flux.

The mass of the black hole is constant.



General relativity or the central dogma?



Independently on the behavior of S_{rad} the central dogma will be violated <u>if B2 holds</u>.

What went wrong?

Bekenstein—Hawking entropy

Consider a system made by two subsystems A and B

$$S_{\text{th}}(A \cup B) \geq S_{\text{vN}}(A \cup B)$$

If the two subsystems are not in causal contact, we can study their thermodynamics independently. However, we need to consider the full system for the von Neumann entropy if there is entanglement.

A

$$S_{\text{th}}(A) \ngeq S_{\text{vN}}(A \cup B)$$

In our thought example, the conclusion

$$S_{\text{vN}}\left(\text{gravity} \cup \text{matter}\right) \geq \frac{A}{4G}$$

Is not a paradox. It simply implies

$$\frac{A}{4G} = S_{\text{th}}\left(\text{gravity}\right) \neq S_{\text{th}}\left(\text{gravity} \cup \text{matter}\right)$$

B

This would also explain how the entropy goes from a volume law to an area law during the collapse

Microscopic interpretation of BH entropy

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There are several works looking for a microscopic interpretation of the BH entropy.

String theory [Strominger, Vafa 1996]

Loop quantum gravity [Rovelli 1996; Ashtekar, Baez, Corichi, Krasnov 1998]

Corpuscolar gravity [Dvali 2013-2015]

All these examples only consider gravitational degrees of freedom.

Violating the central dogma would simply mean that matter degrees of freedom should be taken into account as well.

Bekenstein bound

The Bekenstein bound can be formally proved only in the context of quantum field theory in flat spacetime [Casini 2008].

Bousso covariant entropy bound can be applied in curved spacetime and reduces to the Bekenstein bound for Schwarzschild black holes [Bousso 1999].

However, the proof of the Bousso bound requires the dominant energy conditions.

A quantum version of the Bousso bound can be applied, but it does not imply the central dogma.
[Bousso, Casini, Fisher, Maldacena 2014]

Holographic principle

It is usually advocated that the holographic principle is one of the main motivations of the central dogma.

However the contradiction between general relativity and the central dogma does not necessarily implies that general relativity is incompatible with the holographic priciple.

It is not clear how to either physically or mathematically define the exact location of the holographic surface.

Quantum gravity does not necessarily need to incorporate or predict holography.

A refined contradiction

The B2 assumption is sometime split in two pieces.

B2a. Black holes whose mass is larger than Planck mass emit thermal radiation according to semiclassical general relativity.

B2b. Infalling matter far from the Planckian regime obeys the laws of general relativity.

The entropy problem is formulated in terms of B2a.
The contradiction is between B2b and the central dogma.

Discussions

Link with other works

Complementarity and stretched horizon [Susskind, Thorlacius, Uglum 1993]

An outside observer can replace the black hole in terms of a hot membrane one Planck length above the horizon at the so-called stretched horizon.

The entropy coincides with the Bekenstein-Hawking entropy A/4G.

An infalling observer would not see any membrane in the proximity of the horizon, and would not experience any deviation from general relativity.

From the conclusion of our thought experiment, it follows that the entropy of the stretched horizon can be bounded by the area only if some new physics beyond general relativity is invoked at the horizon scale.

Firewall [Almheiri, Marolf, Polchinski, Sully 2013]

Black hole complementarity is not compatible with a smooth horizon.

However, the conclusion is reached assuming $B1 \cup B2a \cup B2b \cup B3$.

In this sense, our conclusion is compatible but more general.

Conclusions

The information loss paradox is usually stated as the incompatibility between the assumptions

B1. Quantum states evolve in a unitary way. Pure states evolve into pure states;

B2a. Black holes whose mass is larger than Planck mass emit thermal radiation according to semiclassical general relativity.

B2b. Infalling matter far from the Planckian regime obeys the laws of general relativity.

B3. As seen from the outside, a black hole behaves like a quantum system whose number of degrees of freedom is given by A/4G, with A being the apparent horizon area.

The information loss paradox has nothing to do with the loss of information!

Conclusions

The paradox might be formulated as the incompatibility between the assumptions

B1. Quantum states evolve in a unitary way. Pure states evolve into pure states;

B2a. Black holes whose mass is larger than Planck mass emit thermal radiation according to semiclassical general relativity.

B3. As seen from the outside, a black hole behaves like a quantum system whose number of degrees of freedom is given by A/4G, with A being the apparent horizon area.

But this assumptions are incompatible with the equivalence principle of general relativity.

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Conclusions

Is there an information loss paradox?

- The paradox is not due to an incompatibility between general relativity and quantum mechanics.
- It is due to a contradiction between general relativity and the central dogma.
- The usually stated information loss paradox has nothing to do with the loss of information!
- Information may or may not be lost due to the presence of an event horizon.

General relativity or central dogma?

Either, but not both!

Thank You

L. Buoninfante, FDF, S. Mukohyama, *On the assumptions leading to the information loss paradox.* arXiv 2107.05662

If you are interested in black hole physics check out the online conference **“Black Holes Inside and Out”** (Sep27-Oct1)
www.bhio2021.com