Conceptual Insights into Black Paradoxes

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Based on:

The devil in the (implicit) details: On the amps paradox and its resolution (with E. Cinti). IJTP

Peeking Inside the Black Hole Interior (with E. Cinti). manuscript

Unveiling Paradoxes: Driving Progress in Physics. Sophia

I Paradossi dei Buchi Neri (with E. Cinti). Carocci

Un'Euristica del Paradosso. Cittanuova

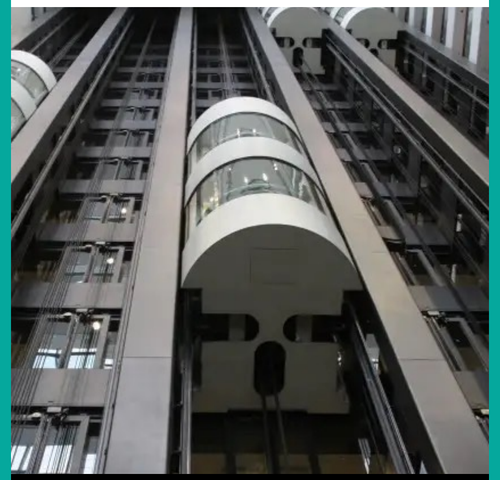
Intro & Motivations

Paradoxes played a major role in the **genesis**, **development** and **understanding** of our best scientific theories

THE TRAIN PARADOX

SPECIAL RELATIVITY

THE ELEVATOR PARADOX



GENERAL RELATIVITY

THE EPR PARADOX

QUANTUM MECHANICS

Intro & Motivations

These paradoxes share **common features**:

1. Arise from the clash of principles of between two leading scientific theories
2. These paradoxes involve inherent contradictions.
3. Generated through thought experiments, not empirical testing.

Train Paradox: classical mechanics (Galileo transformation) + electromagnetism (constancy of c)

Elevator paradox
classical mechanics (inertia) + gravitation (gravity as a force)

EPR
quantum mechanics (entanglement) + special relativity (light speed limit)

Intro & Motivations

Black Hole and their Paradoxes ***could*** play the same role for the genesis, development, and understanding of Quantum Gravity! Indeed they share the same features…

- They arise at the **intersection** of two leading scientific theories (i.e. Quantum Field Theory and General Relativity)
- They are paradoxes of **contradiction** (i.e. they arise from contradictory statements)
- They are generated by **thought experiments** (without a direct experimental reasoning)

Intro & Motivations

In the absence (almost) of experiments, paradoxes can serve as key insights into Quantum Gravity.

From a methodological perspective (e.g. Lakatos), paradoxes do not substitute experiment (for sure) but can help distinguish between progressive and regressive research programs.

Plan of Today

1. Start by defining a conceptual tool useful to analyze these paradoxes (Causal Structures)
2. Recast the AMPS Paradox (aka firewall paradox) using this conceptual tool
3. Draw some conclusions on the various resolutions of AMPS (without going into much details) + what this is helpful for

Causal Structures

What we want + Disclaimers

We would like to have a conceptual tool that is capable of telling us weather or not two objects of our theories are or are not robustly correlated.

By robustly correlated we mean that there is a robust counterfactual connection between them, i.e. a relation of the tipe: *If A had not happened, then C would not have happened.*

Causal Structure

A correlation between the increase in the price of bread in England and the rising water levels in Venice can be observed. However, this does not imply a robust counterfactual connection between these two phenomena. If the price of bread did not increase, we have no reason to expect a corresponding decrease in Venice's water levels.

Causal Structure

Disclaimer: When I speak of **Causality** in this talk I do not mean more than **robust counterfactual connection**.

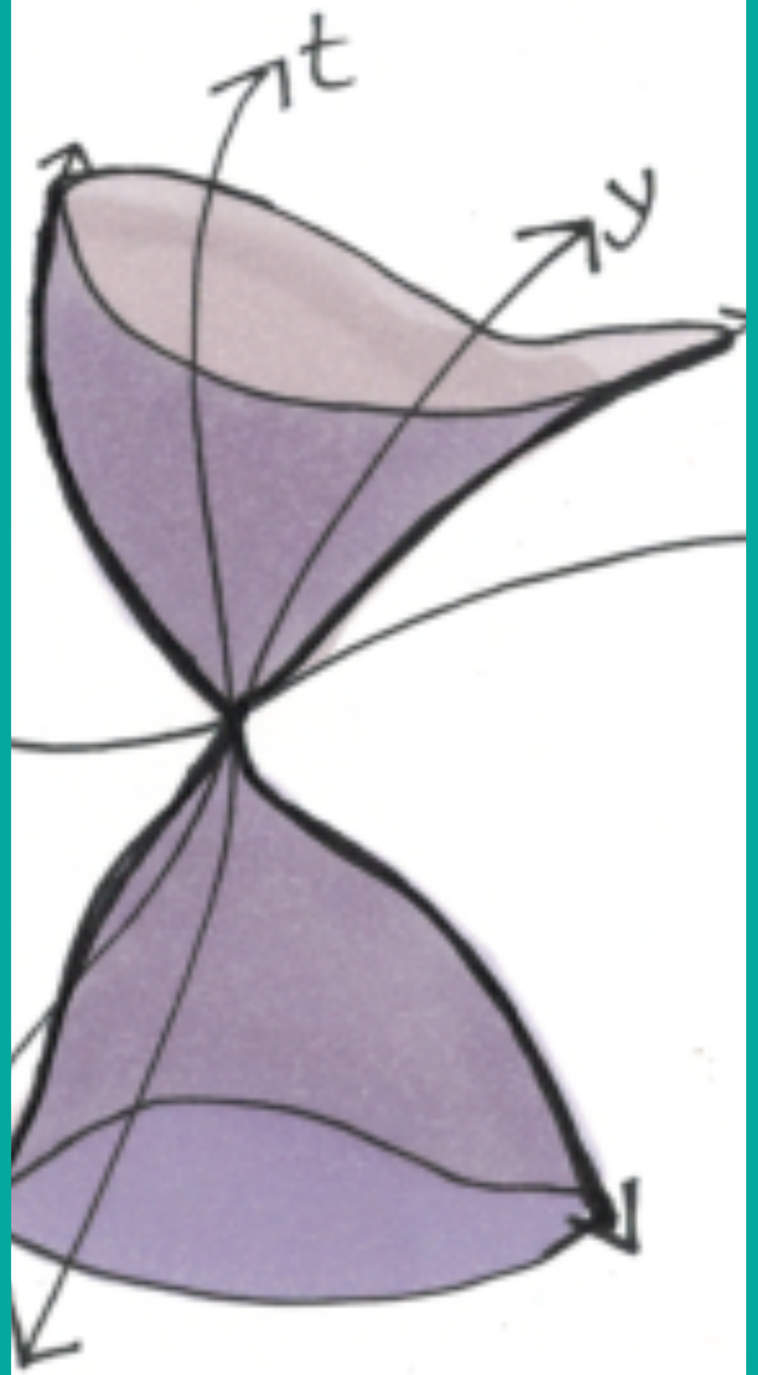
In the philosophy literature there is an account of causality based on counterfactuals (Lewis): Event A causes Event B if, and only if, in the absence of A, B would not have occurred.

However, Counterfactual Correlation does not imply strong causality (e.g., billiard balls colliding or a signal traveling from A to B). Indeed, Entanglement shows a robust counterfactual connection but not a direct causal mechanism. I use the word causal structure for convenience, not a claim about the nature of causality.

Causal Structure

Causal Structure (our definition)

given a theory *T*, we say that the causal structure of the theory *T* is given by a set of spacetime regions/objects (with their physical state) and a relation *R* which determines if two objects/regions of spacetime can or cannot be causally related.



Causal Structure

SPACETIME CAUSAL STRUCTURE

Theory T: General Relativity

Relation: R_{LC} (*being connected by a causal curve)*

Objects: Spacetime Points

The relation R_{LC} is istantiated between two points p and q in spacetime if and only if there is a causal curve, either timelike or lightlike, that connects them.

Causal Structure

ENTANGLEMENT CAUSAL STRUCTURE

Theory T: Quantum Field Theory

Relation: R_{ME} (*being 'maximally' entangled)*

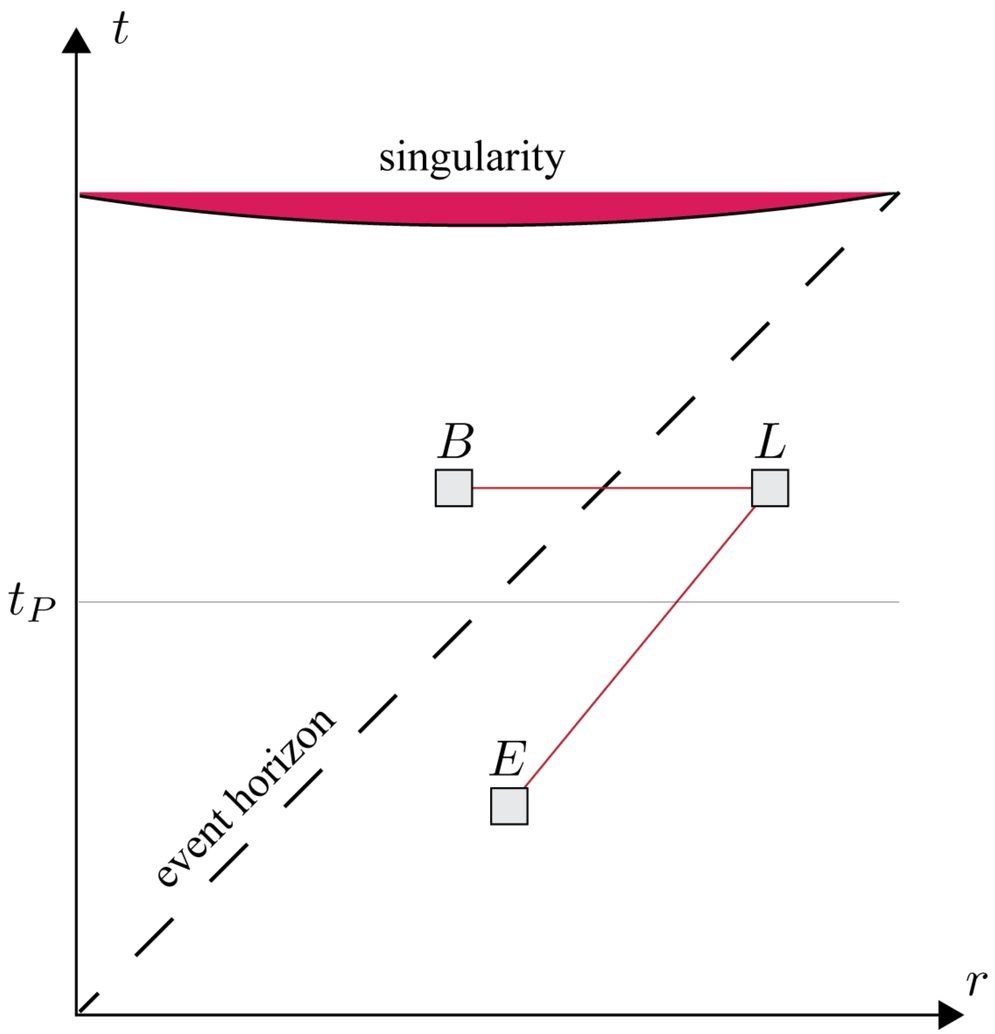
Objects: Quantum System

This relation R_{ME} holds between two quantum systems, A and B, if and only if A and B are in an entangled state. Note: I am not suggesting a true causal relationship here, but rather a robust counterfactual connection.

The Firewall **Paradox**

Now, without delving into the specifics of the derivation of the Firewall paradox (a detailed analysis of the assumptions can be found in the referenced papers), my goal here is simply to **outline the key statements** that lead to the contradiction causing the paradox and reinterpret it using our conceptual framework.

The Firewall Paradox



Consider an evaporating Black Hole (after the so-called Page time), and define

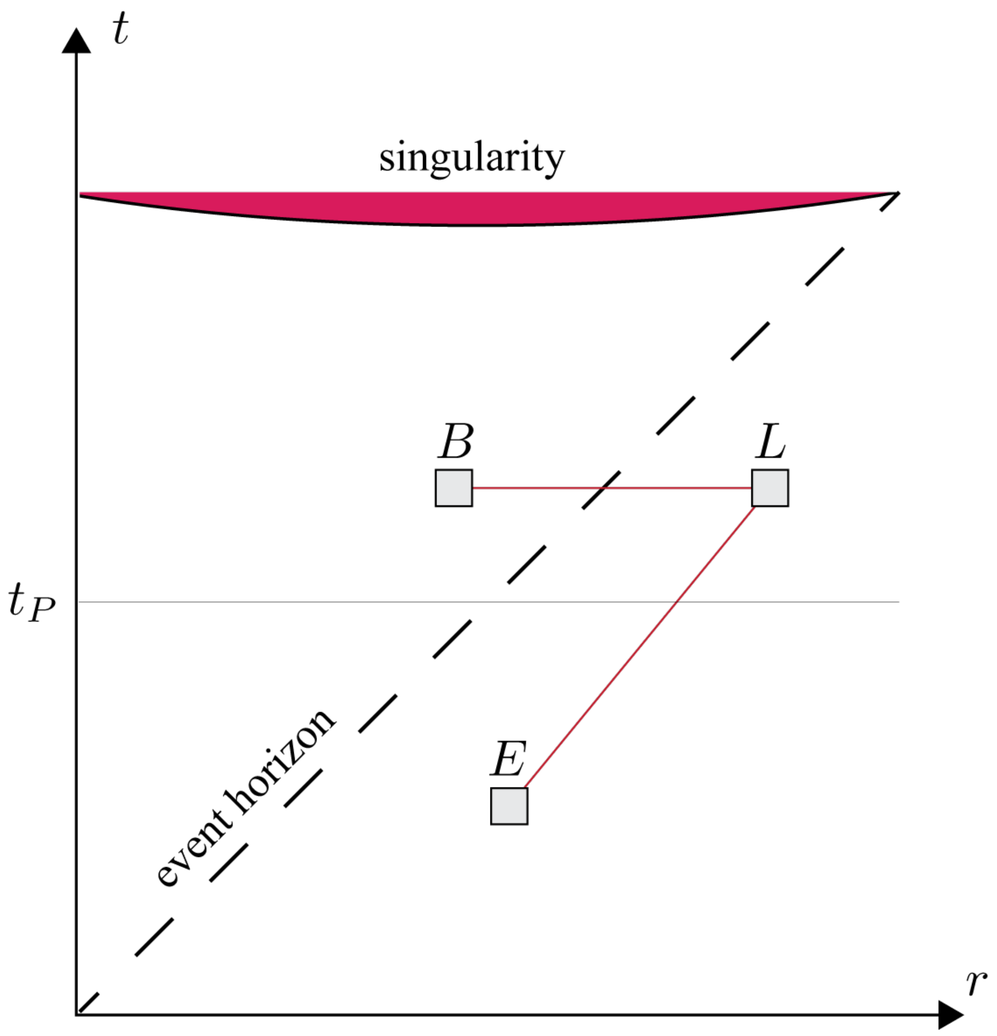
B: Interior mode

L: Late Radiation mode

E: Early Radiation mode

Then the Firewall Paradox emerges from the contradiction of the following statements:

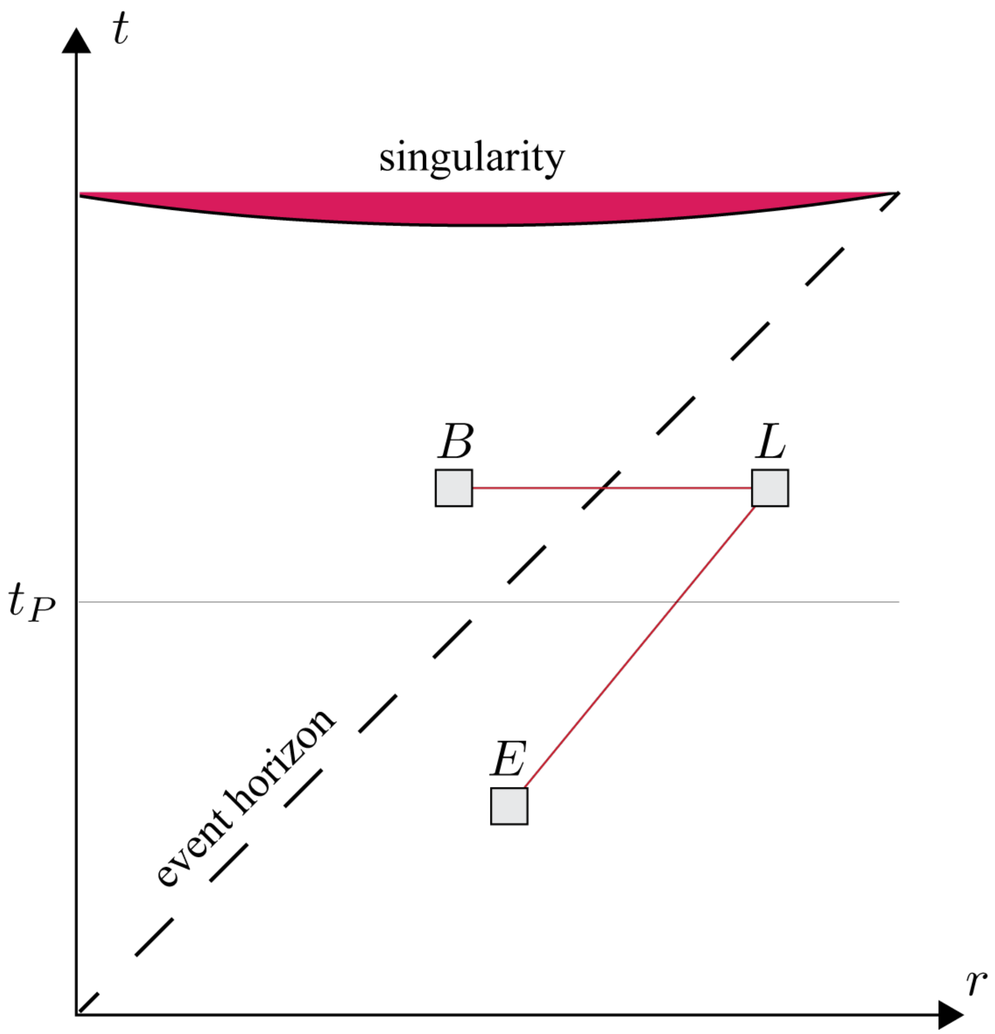
The Firewall Paradox



1. L and E are maximally entangled to preserve unitarity after the Page time (Page bound). [Postulate 1+3 of BHC]
2. L and B are maximally entangled to preserve smoothness across the horizon. [Postulate 2+4 of BHC]
3. A quantum system can be maximally entangled with only one other quantum system at a given time.

AMPS paradox: 1, 2 and 3 are mutually inconsistent.

The Firewall Paradox

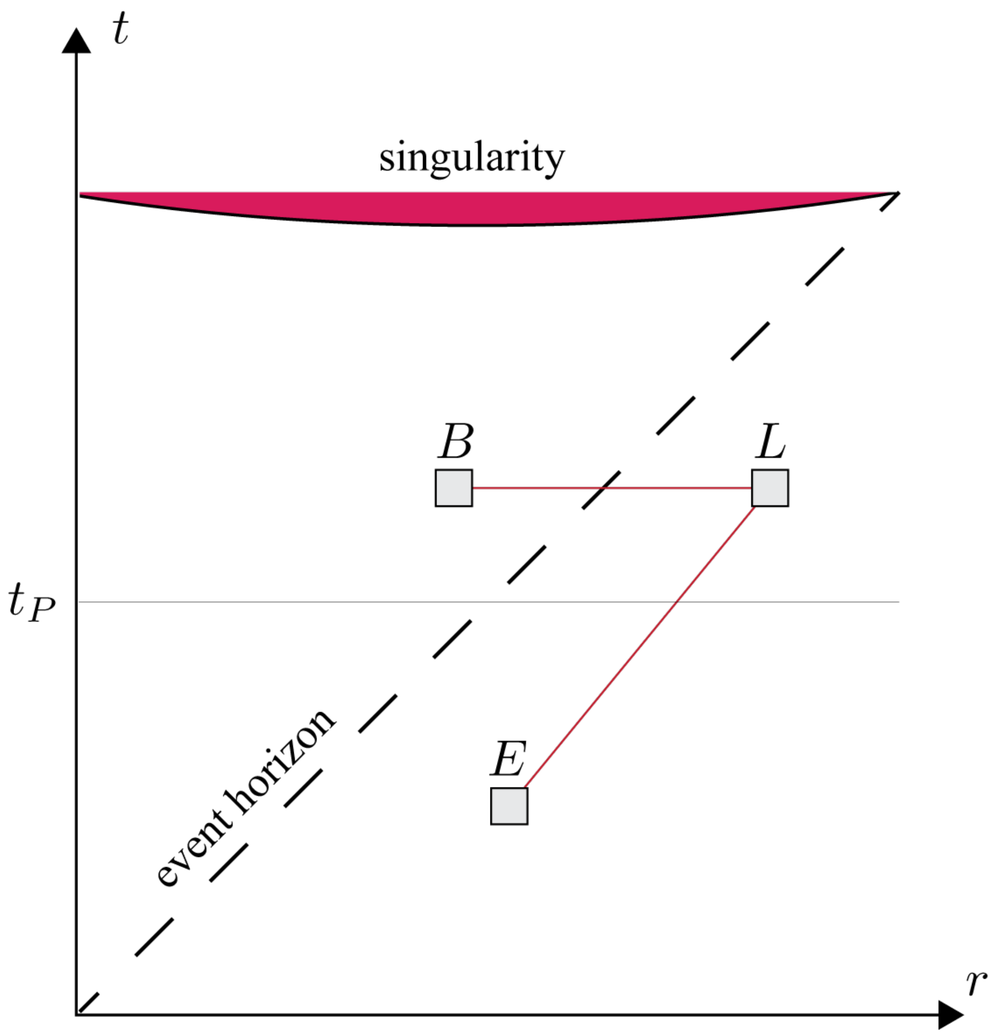


Note that, to derive their paradox AMPS have to **implicitly assume** that B and E are distinct systems. This is justified by their being space-like related.

However, being **distinct** in QFT means that the operator algebras are mutually commuting.

In particular, **microcausality** connects spacelike separation with mutual commutativity in Quantum Field Theory.

The Firewall Paradox

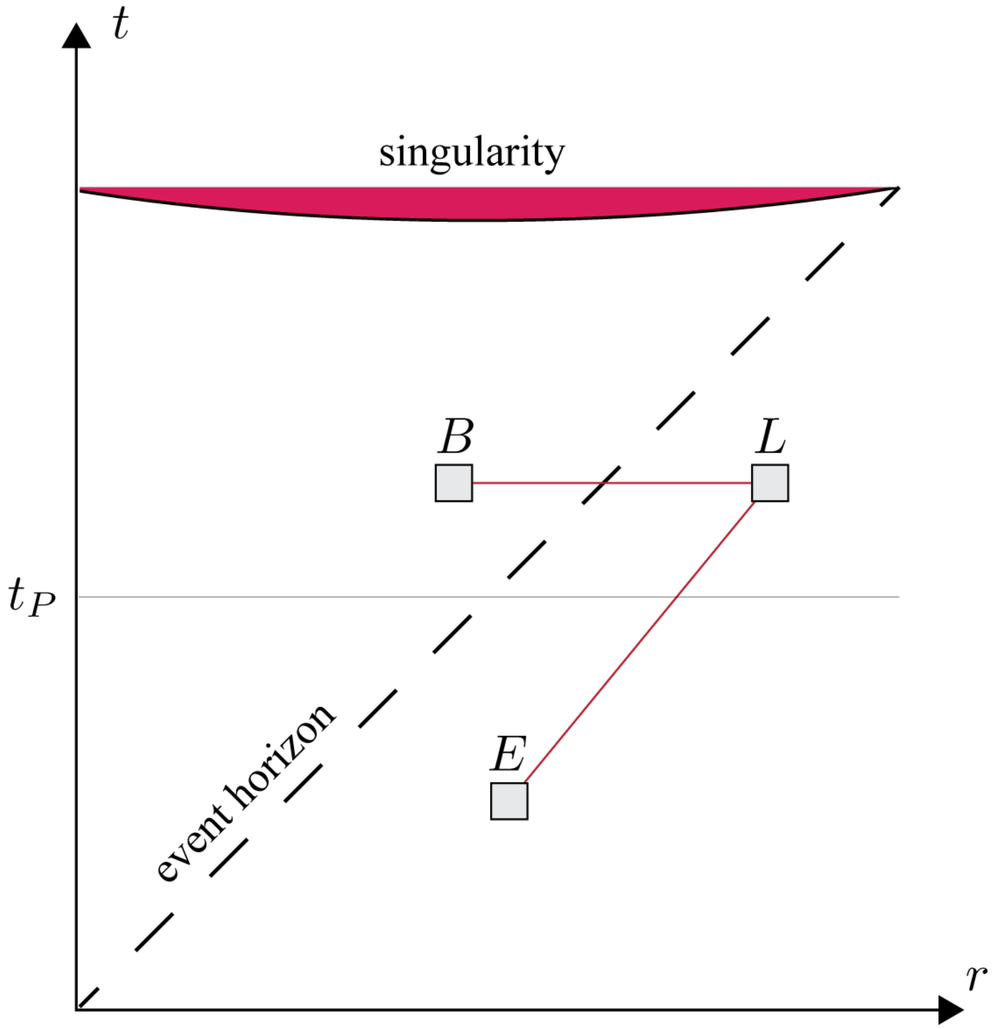


A working definition of what it means to be distinct in spacetime for a theory that aims to put together Quantum Field Theory with General Relativity would be the following:

Spacetime Distinctness (SD)

spacelike separated systems are distinct, i.e. mutually commuting.

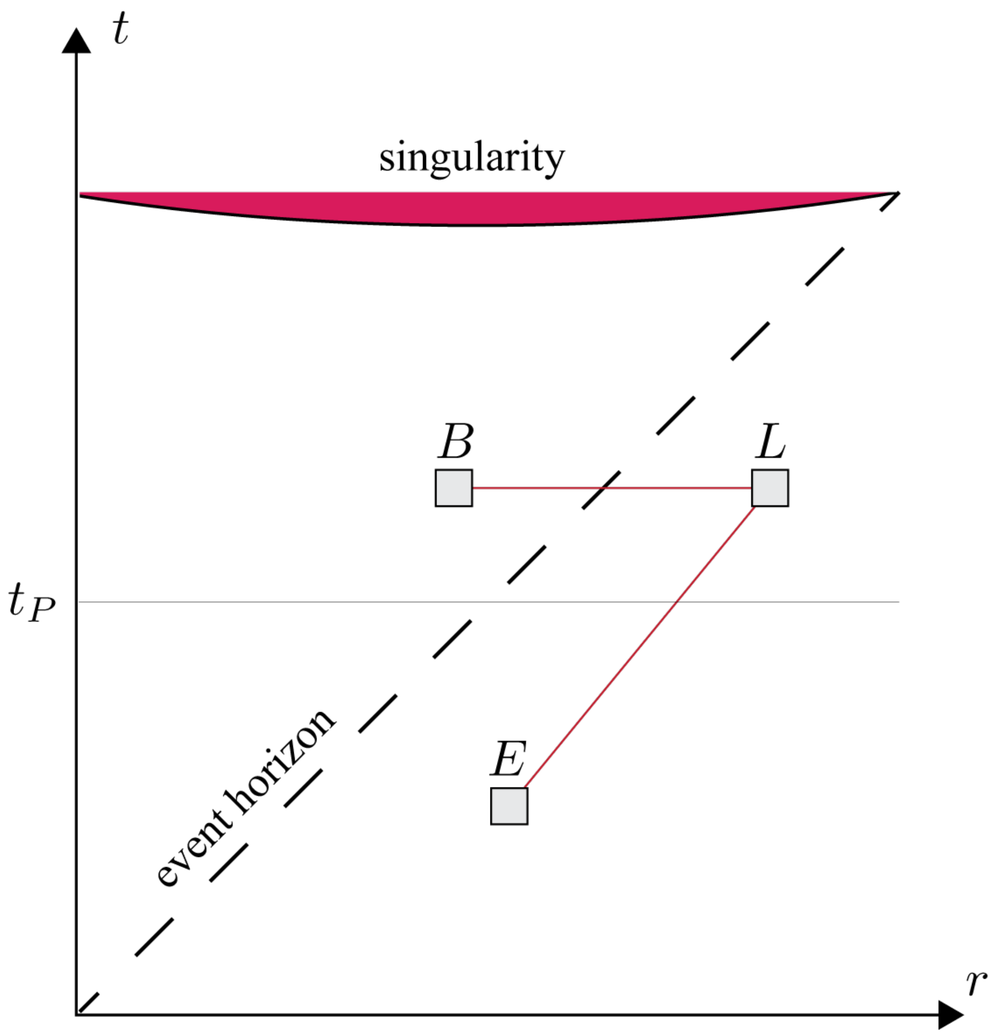
The Firewall Paradox



We can now recast the AMPS paradox with our conceptual framework + the definition of spacetime distinctness:

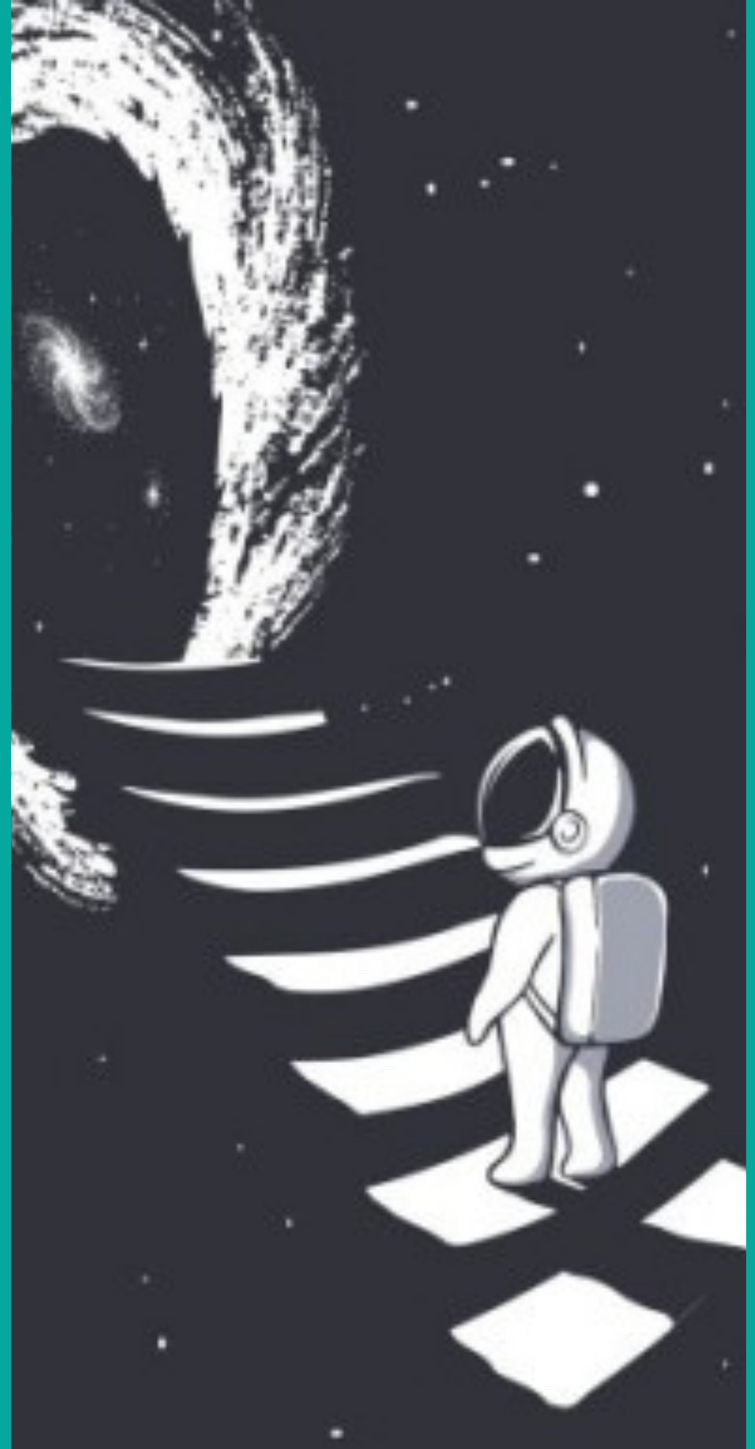
1. R_{ME}(L,B): L and B are maximally entangled
2. R_{ME}(L,E): L and E are maximally entangled
3. ~R_{LC}(B,E): B and E are spacelike related
4. B and E are distinct systems (by **SD**)

The Firewall Paradox



Accordingly, there are three possibile resolutions:

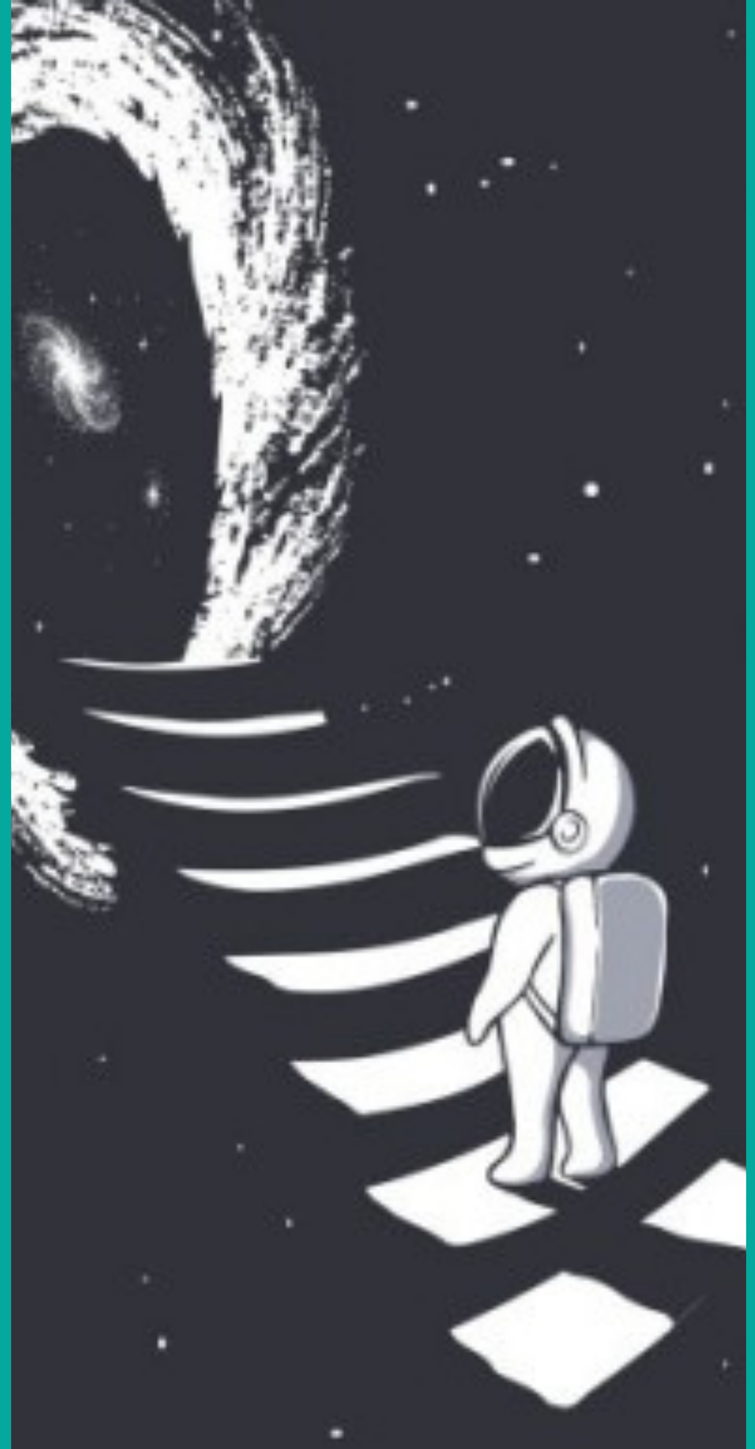
1. ~R_{ME}(L,B): drop entanglement between L and B –> Firewall at the Horizon
2. ~R_{ME}(L,E): drop entanglement between L and E –> Hawking non-unitarity
3. Drop **SD**, which entails that B and E are *not* distinct systems



SD Violation

GENERALIZED CAUSAL STRUCTURE

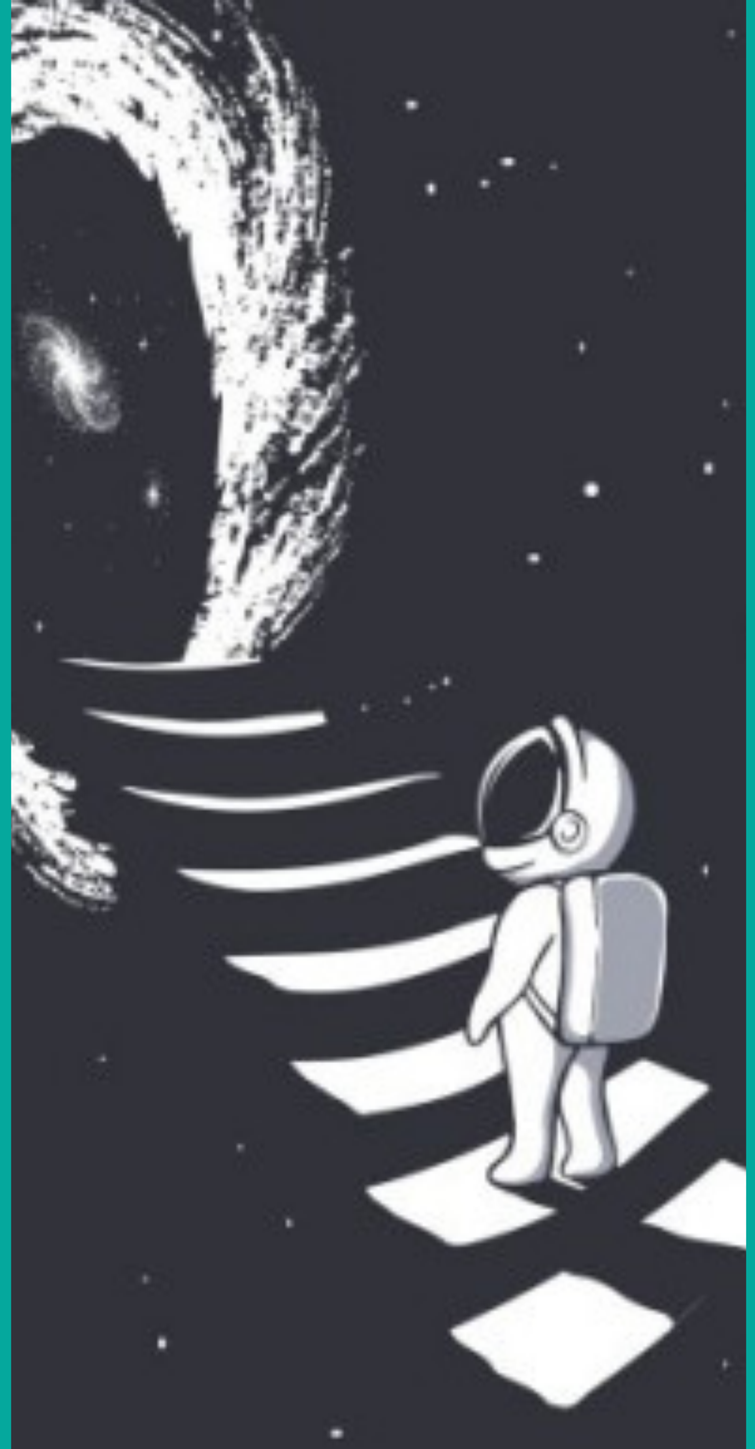
Drop **SD** relays to ER=EPR resolutions of the firewall paradox. This is done thanks to the wormhole connecting the two systems (wormhole between the two horizons in the eternal black hole or islands in the one-sided black hole) . This new connection is neither R_{LC} nor R_{ME}. Should be a new connection that we can call the generalized causal structure R_{WH}, leading to the violation of **(SD)**.



SD Violation

GENERALIZED CAUSAL STRUCTURE

The AMPS paradox arises from merely superposing R_{LC} and R_{ME}. In non-gravitational theories, this is not an issue (as shown by Jarret). However, ER=EPR resolution of AMPS point to the fact that this causal structure is inadequate for a theory of quantum gravity. Instead, we could adopt the generalized causal structure R_{WH}, where the paradox does not arise.



SD Violation

GENERALIZED CAUSAL STRUCTURE

Theory

Quantum Gravity

Relation

R_{WH} (*being non-trivially connected)*

Objects

Quantum Systems

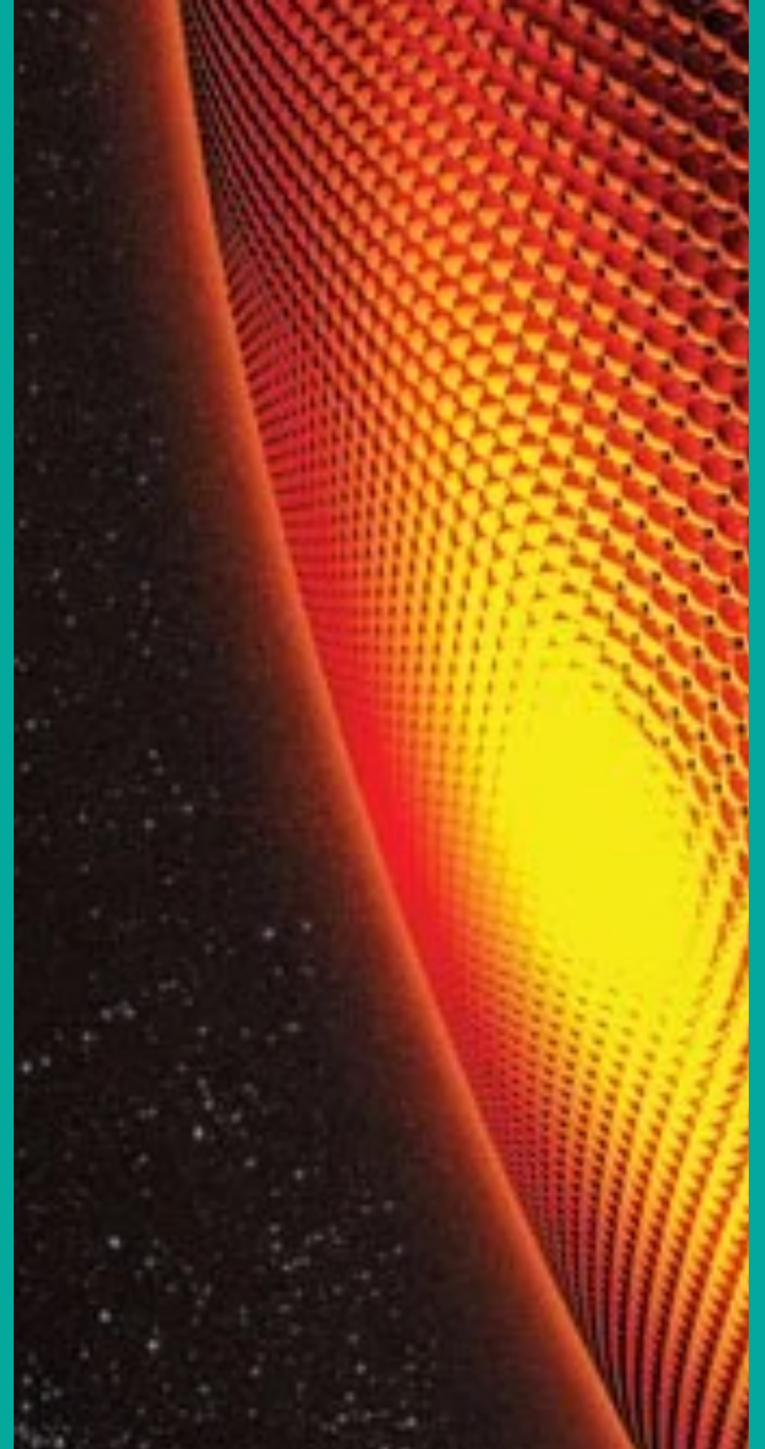
What We Did

✓ Analysis of the AMPS Paradox

Able to classify possible solutions in a well-defined framework and understand their consequences. Particularly, definition of Spacetime Distinctness and consequences of its violation. Presented Toady.

✓ Paradoxes of the Interior

Apply our framework to AMPSS paradox. Able to understand what **Physical Quantities** in perturbation theory mean. Recast the paradox as a failure of Semiclassical Exactness (i.e. the idea that one can define well-behaved physical quantities already at the semiclassical level)



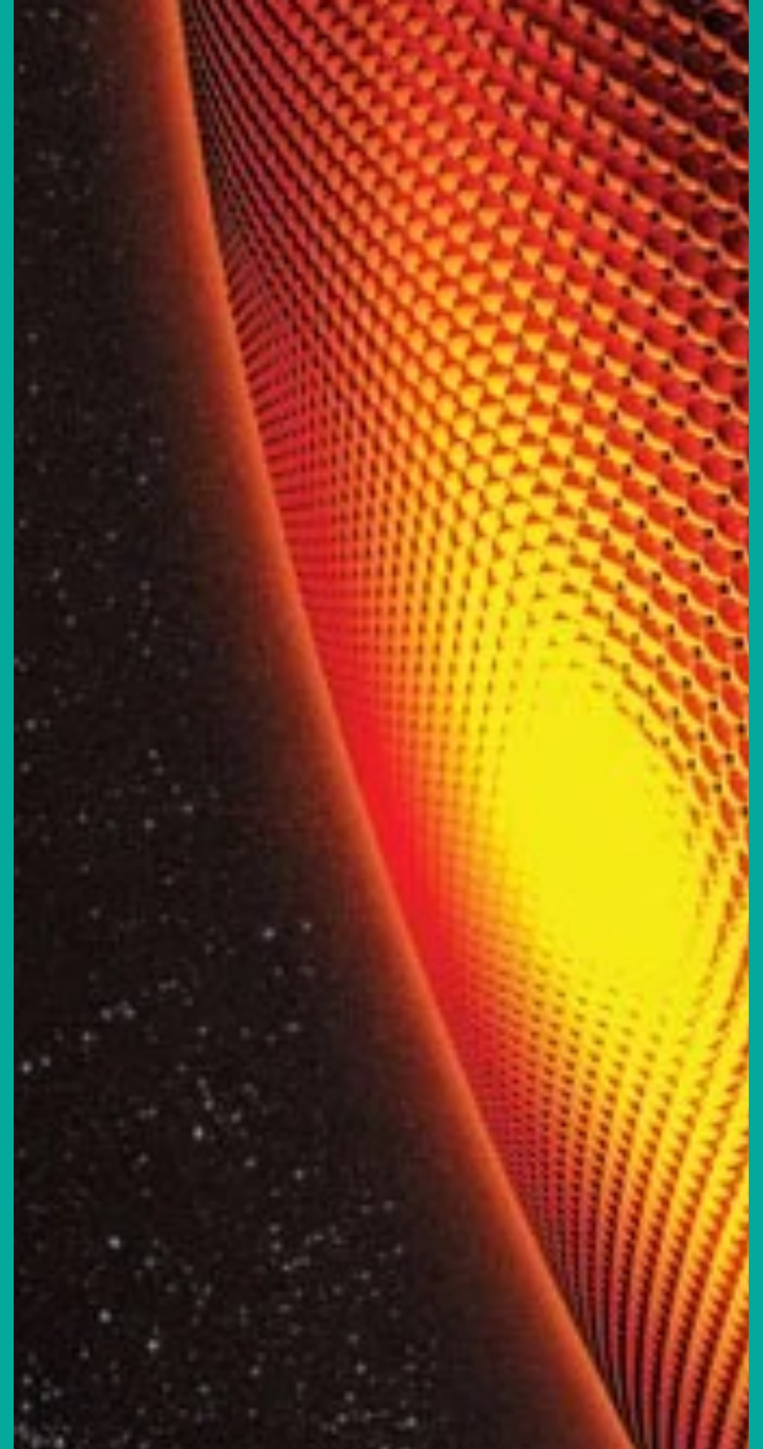
What We Did

✓ AMPS and AMPSS resolution

We are able to show that the strategy that solves AMPS (i.e. violation of spacetime distinctness) is the same as the one that solve AMPSS (i.e. violation of semiclassical exactness). In other other words violation of spacetime distinctness and of semiclassical exactness are in one-to-one correspondence.

✓ On The Membrane Paradigm

Evaluation of what Wallace called the Quantum Membrane Paradigm (i.e. the idea that the stretched horizon is promoted to a quantum membrane). By using our framework, we show that this idea is inconsistent with AMPS and AMPSS resolution based on the violation of Spacetime Distinctness.



What Will Do

➡️ SOON ER=EPR vs. Firewall

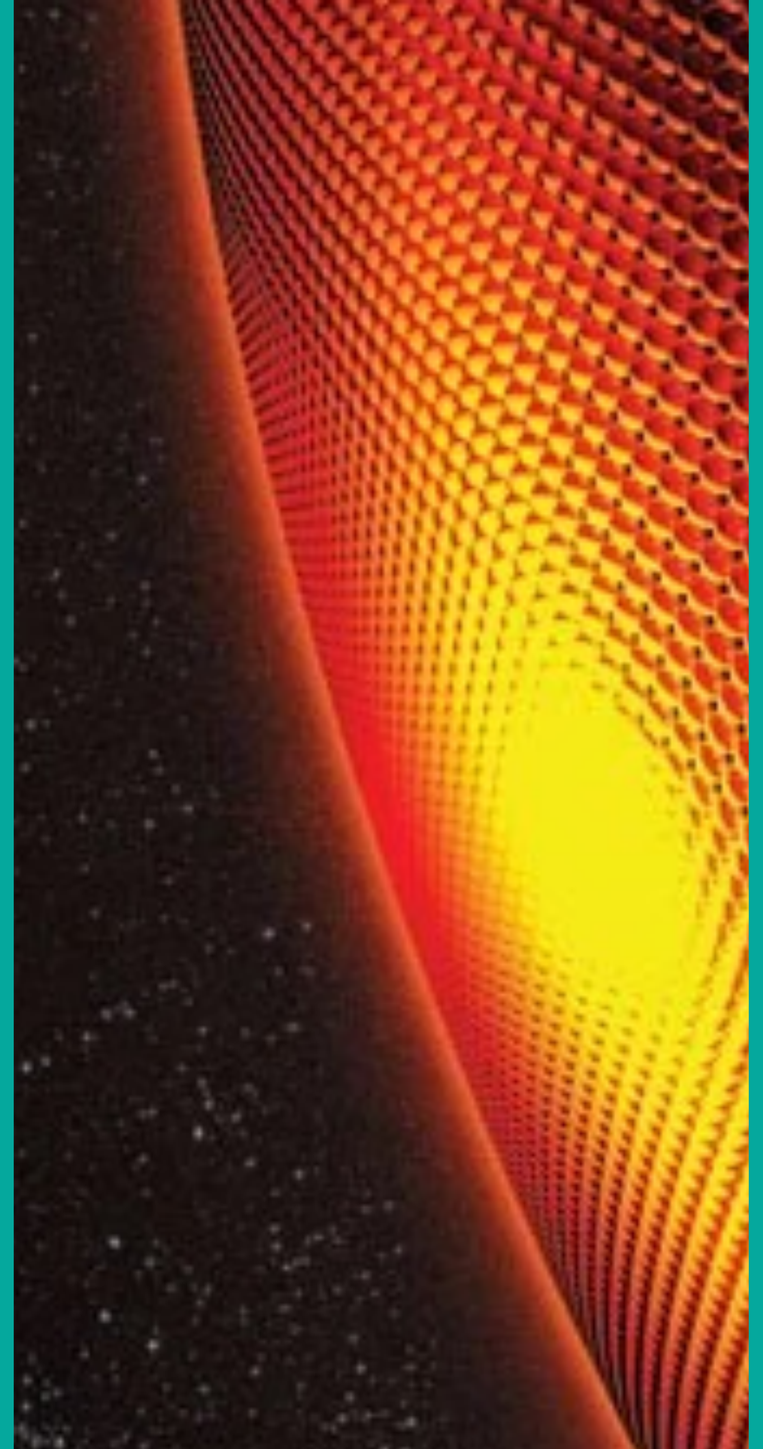
A detailed comparison between ER=EPR and Firewall approaches relying on tools from semiclassical gravity.

➡️ SOON Locality in Quantum gravity

Philosophical implications of the violation of Spacetime Distinctness for quantum black holes and locality in QG.

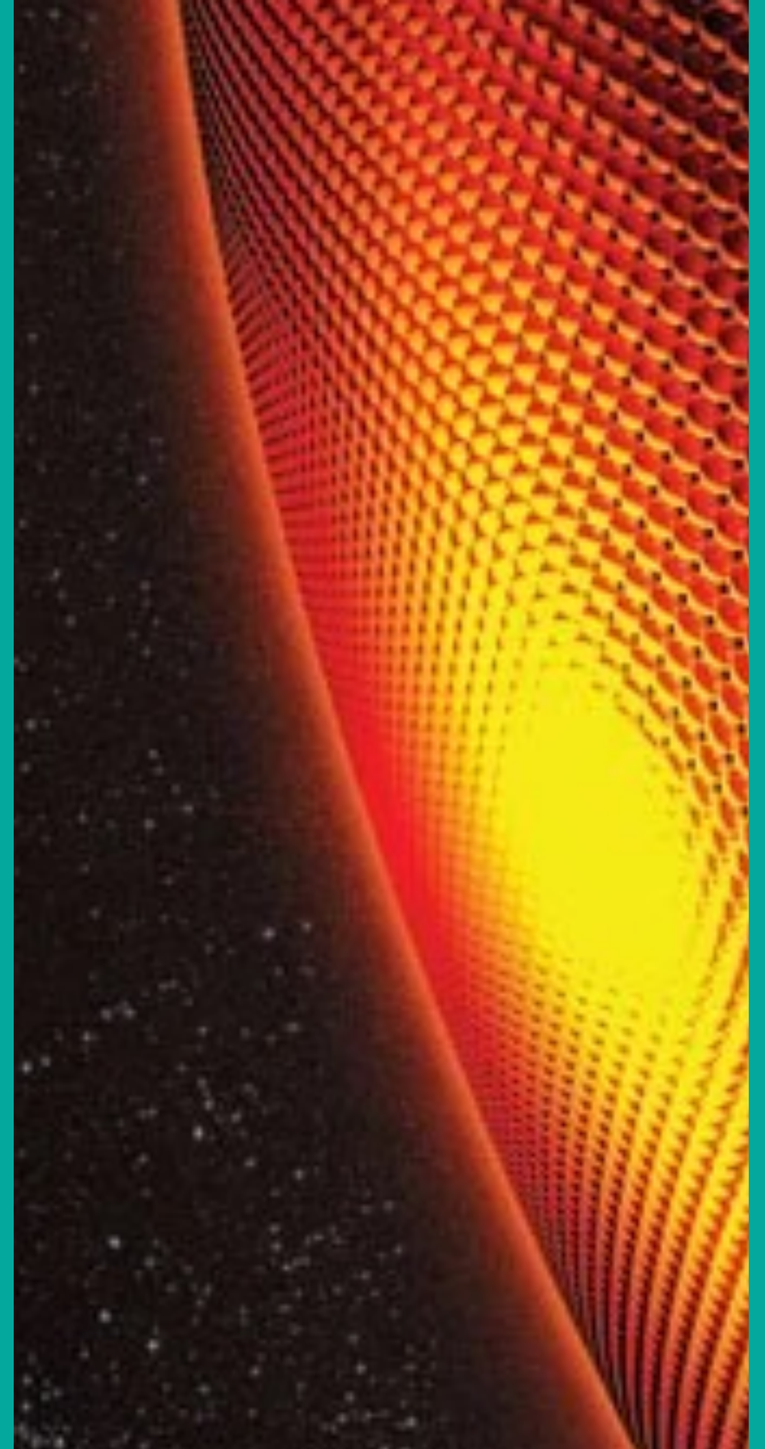
👷 ER=EPR and Factorization Problem

Explore the role of wormholes and non-commuting degrees of freedom in resolving the firewall problem, and investigate chaotic behavior in 4D theories through random matrix models.



Thank you!

And be careful not to fall into a black hole... you never know!



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