

# Vacuum polarization and regular gravitational collapse

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## Introduction

What we think of as empty space is never truly empty. The vacuum state of quantum fields is ever-present, and when spacetime curves this vacuum actually acquires an energy content of its own. As all forms of energy gravitate, this has to be taken into account in the Einstein field equations:

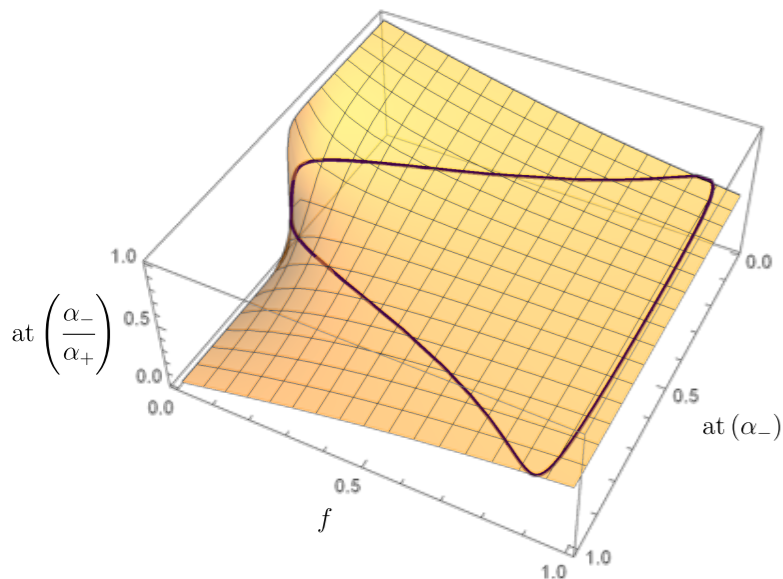
$$G_{\mu\nu} = 8\pi G (T_{\mu\nu}^{\text{class}} + \langle T_{\mu\nu} \rangle^{\text{ren}}).$$

The contribution of the quantum vacuum through the Renormalized Stress-Energy Tensor (RSET),  $\langle T_{\mu\nu} \rangle^{\text{ren}}$ , is suppressed by a Planck constant and is thus usually negligible. The exceptions to this rule are regions of extreme gravity: the early universe and **black holes**.

## Outer horizon effects

A compact spherical distribution of matter with a surface moving close to its gravitational radius (i.e. the radius corresponding to the outer horizon of a black hole with the same mass) at low enough velocities produces **large values of the RSET** in its vicinity. In particular, this occurs because such a configuration produces a quantum vacuum state close to the vacuum of a static black hole (the Boulware state), which contains a divergence.

Below we see the following plot: the bottom axis represents distance from the gravitational radius, the right axis - radial velocity toward or away from this radius, and the vertical axis - a magnitude the **slope of which is proportional to the RSET**. The curve represents an oscillating surface trajectory.



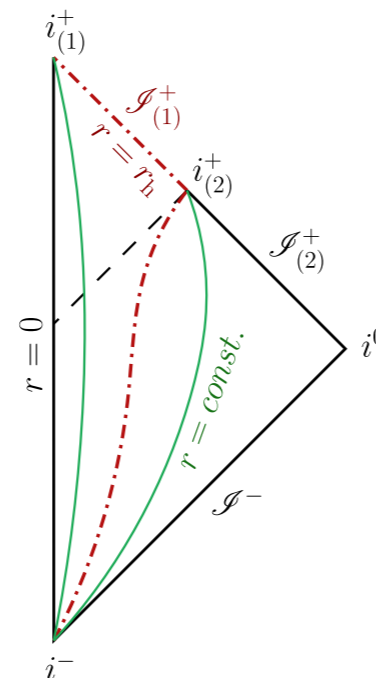
## Objectives

The goal of this thesis is to analyze the magnitude of quantum vacuum effects on spacetimes which represent different types of gravitational collapse which result in the formation of black-hole trapped regions. In particular, there are three types of dynamical regions we are interested in:

- **The formation of an outer trapped horizon:** under normal astrophysical conditions of fast-collapsing matter, quantum effects on the outer horizon are negligible on the short term. However, some dissipative processes may slow down matter enough for quantum effects to become large.
- **The formation of an inner trapped horizon:** the trapped region of a black hole has both an outer and inner bound. At the inner bound, known as the inner horizon, there is an instability both due to classical and quantum perturbative effects. The quantum effects are thought to dominate.
- **The formation of a curvature singularity:** such singularities are created often in otherwise perfectly reasonable solutions of classical General Relativity. However, quantum effects are thought to become dominant before this occurs, possibly leading to a completely different outcome. An example of this are time-symmetric bounce geometries, where the singularity is avoided by quantum effects which then permeate the entire trapped region and lead to a transition from a black hole to a white hole configuration.

## Causal structures

In exploring quantum vacuum effects near the outer horizon of a black hole, we discovered a peculiar type of geometry: one in which an **event horizon is present**, separating future null infinity in two, but **there are no trapped surfaces** anywhere along its evolution. There is only an asymptotic tendency (in time) to either form a single marginally trapped surface or to stretch space infinitely in the radial direction.

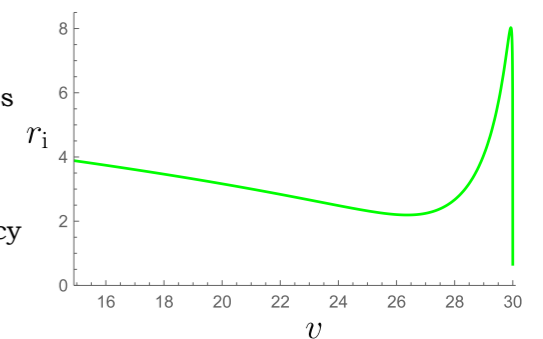


To the left we have a **conformal diagram** of one of the two types of such spacetimes: the one in which space is **stretched in the radial direction**. The event horizon is described by the first trapped light ray which does not asymptotically make it to an infinite separation from the origin, tending instead toward a finite radius. This event horizon separates future null infinity into two regions: one with infinite radius, exterior to the matter distribution, and one with finite radius, close to the surface of this distribution.

## Inner horizon effects

The inner horizon of a black hole trapped region, originally present in almost all black hole spacetimes, turns out to be a **highly unstable**. Under classical perturbations there is an **exponential mass inflation effect**, where an unbounded amount of gravitational potential energy is converted into mass which then backreacts and curves spacetime even more. Effects stemming from the quantum vacuum are even stronger, making the instability even less predictable due to the **violation of energy positivity**.

To the right we see a plot of the inner horizon position during **gravitational collapse with quantum corrections**. Classically, the trapped region of a black hole first forms at a finite radius away from the origin and then its inner bound moves inward. Under quantum vacuum corrections, however, this inner horizon quickly moves back out. The collapsing classical tendency only dominates at the end if the collapse is very fine-tuned, and then only after an initial bounce which can destroy the entire trapped region.



## References

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