PhD Open Days

Testing GR with dynamical Black Hole formation

(work in collaboration with **V. Cardoso, D. Hilditch, J. Natario, U. Sperhake**, based on **ArXiv: 2209.12589**)

Advanced Studies Diploma in Physics

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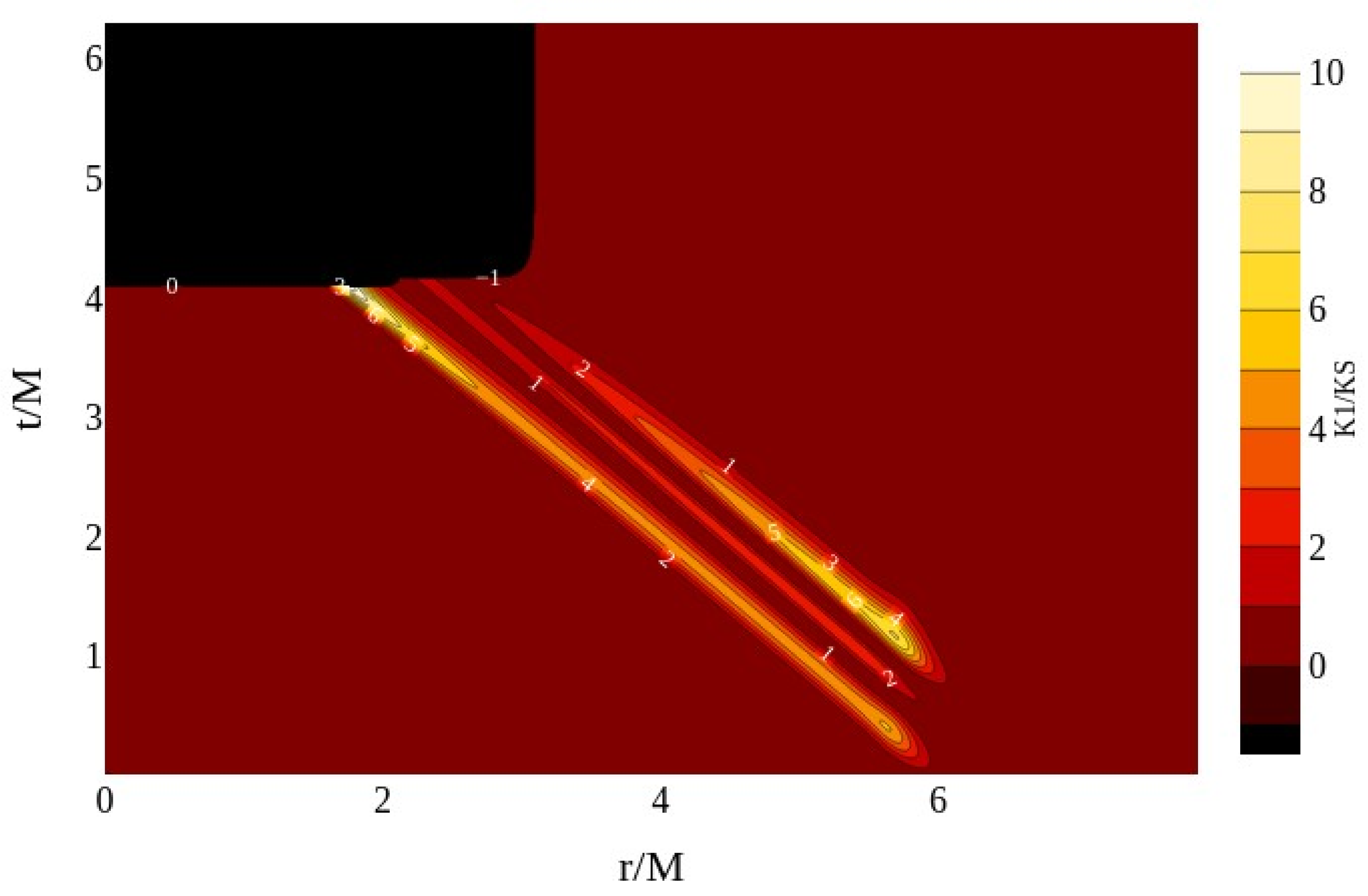
In search for new physics in BH spacetimes

General Relativity (GR) is the classical theory of gravity with a rich history of predictions and debates of more than 100 years (since 1915). It is able to describe the most extreme objects in our Universe, such as **black boles (BHs)**. Black holes play the role of a cosmic laboratory, used to test our understanding of GR. According to the **singularity theorems** (Penrose 1965,1969) , classical GR must fail in BH interiors. **Quantum mechanics** in BH spacetimes also leads to puzzling consequences, such as the **information paradox** (Unruh 2017, Giddings 2017) . It is tempting to conjecture that a theory of quantum gravity will resolve these issues, but the scale and nature of quantum gravity corrections to BH spacetimes is unknown. One can quantify the importance of quantum corrections in the semi-classical regime by means of the magnitude of **higher order curvature invariants** , that can potentially become important due to the evolution of the classical Einstein equations. If one takes into account quantum corrections, these curvature invariants arise naturally in **effective field theory**. Thus, in principle, the dynamics could induce the dominance of these terms at the level of the action. Using numerical relativity as a tool, we are asking **´´Can dynamical, astrophysical processes probe the quantum-gravity regime?´´**

Horizon penetrating coordinates: BH excision

GR equations are written in covariant tensorial form and have a lot of **freedom** in the choice of coordinates. The relevant physics of each solution does not depend on the coordinates. However, depending on the problem, the choice of coordinates facilitates the study of specific aspects of it. Formulating GR as an **initial value problem**, one can reduce the tensorial equations into a system of **well-posed** partial differential equations that, depending on the choice of coordinates, can have some nice properties in order to study it numerically. In the case of collapse, **horizon penetrating coordinates** are very useful because it is very easy to probe the formation of an **apparent horizon (AH)** and then one can **dynamically excise** the BH region and solve for the domain of **outer communications** even after the formation of an AH.

In our case we evolve the Einstein field equations with a massless minimally coupled scalar field in Kerr-Schild like coordinates, using a free evolution scheme, a Runge-Kutta with method of lines, second order finite differencing and Kreiss-Oliger dissipation.



Here, we plot contours of the **Kretschmann** curvature invariant throughout the numerical domain in space and time, in units of the relevant value $K_S = \frac{3}{4M^4}$ of a Schwarschild spacetime with mass equal to the **newly formed** black hole mass of our evolution.

Classical vs Effective (semi-classical) action

The classical action of GR is:

$$S = \frac{c^4}{16\pi G}\int \sqrt{-g}(R-2\Lambda) + S_{\text{matter}}$$

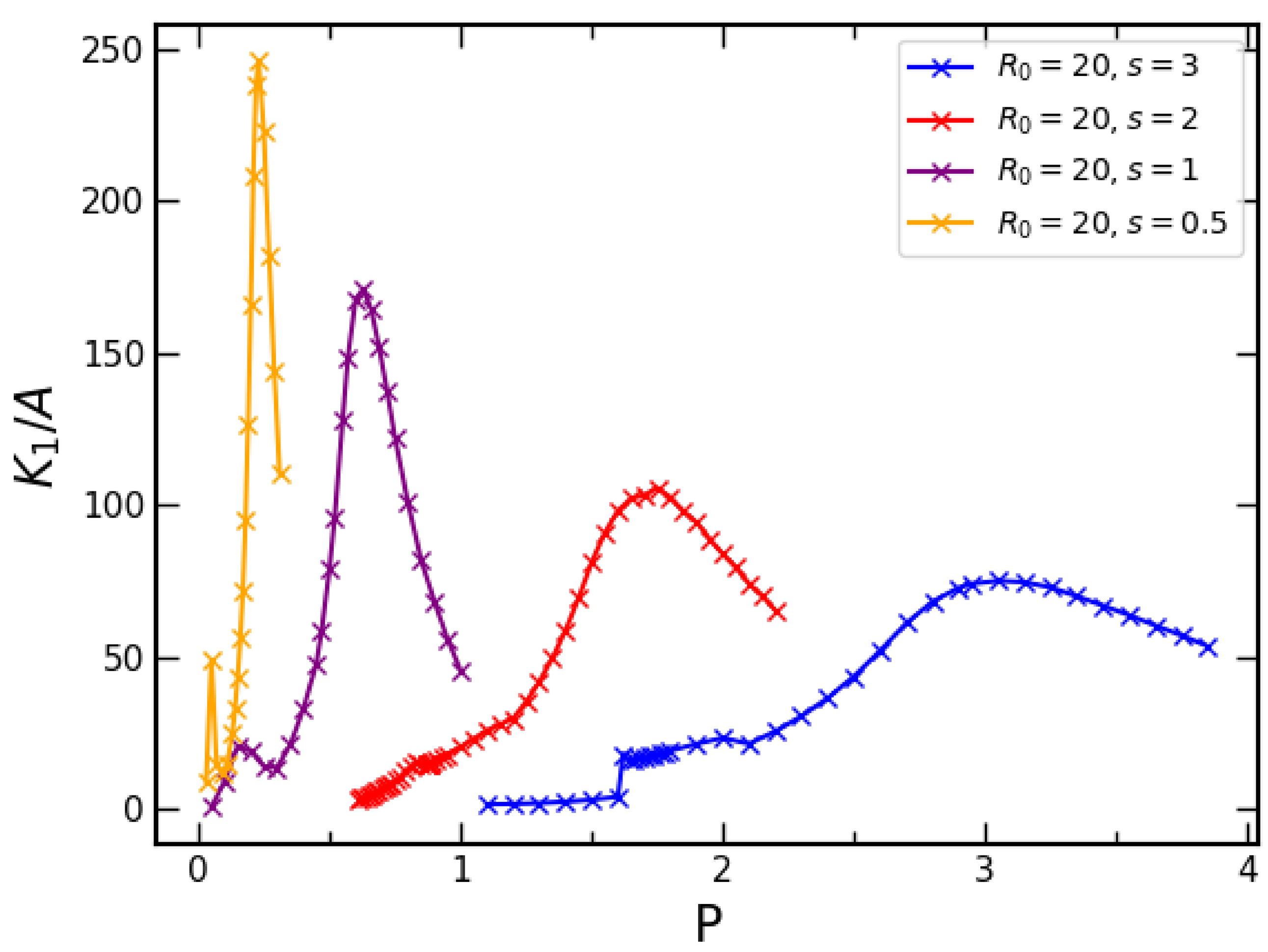
,where in our case, the matter sector is **a massless minimally coupled scalar field.**

If one considers **quantum corrections** to the scalar field stress energy tensor one point function, working at semi-classical level, the renormalized **1-loop effective action** can be realized as a **series of curvature invariants**:

$$S_{\text{eff}} = \int d^4x\sqrt{-g}\left(-\Lambda_{\text{eff}} + \frac{R}{16\pi G_{\text{eff}}} + M_{\text{P}}{}^2\left(a_1R^2 + a_2R_{\alpha\beta}R^{\alpha\beta} + a_3R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}\right) + \dots\right) + S_{\text{matter}}$$

where Λ_{eff} , G_{eff} are the effective cosmological and Newton's constant, respectively, and M_{P} is the Planck mass (Birrel&Davies 1984, Parker 2008, Burgess 2004). In the implementation, we use **geometrized units** $c = G = 1$ and a_i are constants that are not relevant for this discussion, but are calculated exactly in a semi-classical framework. The **Kretschmann** curvature invariant appears naturally in the effective action from the quantum corrections. We study dynamical solutions to the **classical equations of motion** to examine the behaviour of this curvature invariant, in an attempt to probe the importance of including these terms in the action. In an **equilibrium scenario** the magnitude of this term is suppressed outside the horizon in static BH spacetimes, by a factor of $(M_{\text{P}}/M)^2 \sim 10^{-76}$ or smaller, but can potentially grow in dynamical spacetimes. We are interested in **how much larger** than their **stationary values** curvature invariants can become during a generic dynamical evolution (and in particular whether they can become **Planckian**).

Results



In this figure, we explore some range of the **phase space** of initial data and we show the **global** maximum of each evolution for **different initial data**, in units $A = \max\left(K_{\text{initial}}, K_S\right)$

Conclusions

Our results show that in four-dimensional spacetimes describing dynamical BH spacetimes, curvature never grows too large during the dynamics. In other words, without carefully tuning the initial data, it seems very difficult to dynamically enter in a regime that would not be described by the classical equations of motion. Classical remains classical.

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