A self-consistent analysis of black hole horizons

Valentina Baccetti[1], Robert B. Mann[2,3], Sebastian Murk[4], and Daniel R. Terno[4*]

[1]Department of Physics, RMIT University, Melbourne VIC, Australia
[2]Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada
[3]Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
[4]Department of Physics and Astronomy, Macquarie University, Sydney NSW 2109, Australia
[*] daniel.terno@mq.edu.au

Astrophysical black hole candidates are massive compact intrinsically dark objects. It is still not known how, when and if at all they develop the distinctive black hole properties, such as trapping of light, horizons or singularities.

Conceptual problems caused by quantum effects, including the information loss paradox, possible role of quantum gravity, and uncertainty regarding the end result of the gravitational collapse [1, 2]. motivate investigations of exotic compact objects that are the hypothetical products of collapse that does not lead to formation of an event horizon and/or singularity. Investigation of exotic models and their observable features requires understanding of the benchmark that is based on the minimal number of assumptions. Taking existence of a trapped region as the defining property of a black hole we assume its formation at finite time t of distance observer. In addition, we require regularity of the apparent horizon as expressed by finite values of the curvature scalars. A self-consistent approach within the framework of semiclassical gravity [3, 4] that is applied to a spherically-symmetric collapse allows to obtain the limiting form of the total energy-momentum tensor and metric in the vicinity of the apparent horizon [5] using these two assumptions. This is done by using the Schwarzschild (t, r) coordinates and building finite quantities from the divergent components it is found that the energy-momentum tensor takes a particular limiting form. The key parameters are the Schwarzschild radius r_g and its rate of change.

Real solutions of the Einstein equations that describe finite t formation of the trapped region require violation of the Null Energy Condition (NEC) regardless of the structure of infinity. In null retarded or advanced coordinate the geometry the metric has a particularly simple form with the ingoing Vaidya metric with decreasing mass corresponds to decrease of r_g, and the outgoing Vaidya metric with increasing mass to its growth. The NEC must be violated on both sides of the apparent horizon, but is satisfied in the vicinity of the inner apparent horizon [6].

The hypersurface $r = r_g(t)$ is timelike during both the expansion and contraction of the trapped region. Adapting a simple form of the quantum energy inequality we find that the estimated extent of the NEC-violating region may be incompatible with the standard analysis of black hole evaporation [5]. The requirement of the NEC violation for existence of the horizon is responsible for the horizon avoidance in the collapsing thin shell models [7] and constrains the possibility of having a firewall. Homogenous generalizations of the Oppenheimer-Snyder model cannot lead to finite t formation of the trapped regions.

If a trapped region forms at finite t, then the apparent horizon cannot grow, $r_g'(t) < 0$. Massive or massless test particles cannot fall into a black hole once it is formed. The values of energy density, pressure and flux on the boundaries of the trapped region indicate existence of discontinuities in physical properties of the matter [6].

1. References

[1] L. Barack, V. Cardoso, S. Nissanke, and T. P. Sotiriou (eds.), *Black holes, gravitational waves and fundamental physics: a roadmap*, arXiv:1806.05195 (2018).

[2] V. Cardoso and P. Pani, Nature Astr. **1**, 586 (2017).

[3] A. Paranjape and T. Padmanbhan, Phys. Rev. D **80**, 044011 (2009).

[4] V. Baccetti, R. B. Mann, and D. R. Terno, Class. Quant. Grav. **35**, 185005 (2018).

[5] V. Baccetti, R. B. Mann, S. Murk, and D. R. Terno, arXiv:1811.04835 (2018).

[6] D. R. Terno, arXiv: 1903.04744 (2019).

[7] V. Baccetti, S. Murk, and D. R. Terno, arXiv:1812.07727 (2018).