Black holes and their horizons in semiclassical and modified theories of gravity

by

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Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree at any university.

Sebastian Murk

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Abstract

Black holes are arguably the most celebrated prediction of general relativity (GR). Due to spectacular advances in observational astronomy, strong evidence for the existence of dark massive compact objects (so-called astrophysical black holes) has accumulated over the last few decades, thus gradually shifting our perception of black holes from purely mathematical curiosities to real physical entities.

For distant observers black holes correspond to trapped spacetime domains bounded by apparent horizons. In this thesis, we present properties of the near-horizon geometry emphasizing the consequences of two common implicit assumptions of semiclassical physics. The first is a consequence of the cosmic censorship conjecture, namely that curvature scalars are finite at apparent horizons. The second is that horizons form in finite asymptotic time (i.e. according to distant observers), a property implicitly assumed in conventional descriptions of black hole formation and evaporation. Taking these as the only requirements within the semiclassical framework, we find that in spherical symmetry only two classes of dynamic solutions are admissible, both describing evaporating black holes and expanding white holes. We derive their properties and present the implications.

The formation of black holes follows a unique scenario involving both types of solutions. The solutions are real-valued only if the null energy condition is violated in the vicinity of the outer horizon and satisfied in the vicinity of the inner apparent/anti-trapping horizon. Apparent and anti-trapping horizons are timelike surfaces of intermediately singular behavior, which is demonstrated in negative energy density firewalls. Close to the horizon, the energy-momentum tensor is uniquely identified up to a function of time and two pairs of signs. Using this result, we show that black hole evaporation and models of thin shell collapse do not have an independent physical meaning, but rather simply illustrate their underlying assumptions. The two principal generalisations of surface gravity to dynamic black hole spacetimes are discordant and do not match the semiclassical results. Neither of them can describe the emission of nearly-thermal radiation. If semiclassical gravity is valid, this implies that it is impossible to simultaneously realise all of the necessary elements (event horizon, evaporation, thermal character of the radiation) that would be required for a self-consistent formulation of the information loss paradox. Moreover, comparisons of the required energy and timescales with established semiclassical results suggest that the observed astrophysical black holes are horizonless ultra-compact objects, and the presence of a horizon would be indicative of new physics.

Modified theories of gravity must satisfy several constraints to be compatible with the dynamic black hole solutions of semiclassical gravity. We find that fourth-order gravity theories (generic modifications of the semiclassical Einstein equations including up to fourth-order derivatives of the metric) identically satisfy all of the necessary constraints and naturally accommodate both classes of semiclassical black hole solutions. Consequently, the semiclassical solutions can

be regarded as zeroth-order terms in perturbative solutions of these models, and the observation of an apparent horizon by itself may not suffice to distinguish between the predictions of the semiclassical theory and those of higher-derivative gravity theories with up to fourth-order derivatives of the metric.

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List of publications

Publications included in this thesis (listed in the order of their appearance):

1. R. B. Mann, S. Murk, D. R. Terno
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2. V. Baccetti, R. B. Mann, S. Murk, D. R. Terno
   Energy-momentum tensor and metric near the Schwarzschild sphere
   Valentina Baccetti, Robert B. Mann, Sebastian Murk, Daniel R. Terno
   E-print submitted to arXiv on 11 November 2018 [arXiv ID: arXiv:1811.04495]
   Published 11 June 2019 in Physical Review D (American Physical Society)
   Journal reference: Phys. Rev. D **99**, 124014 (2019) [DOI: 10.1103/PhysRevD.99.124014]

3. V. Baccetti, S. Murk, D. R. Terno
   Black hole evaporation and semiclassical thin shell collapse
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   Journal reference: Phys. Rev. D **100**, 064054 (2019) [DOI: 10.1103/PhysRevD.100.064054]

4. S. Murk, D. R. Terno
   Universal properties of the near-horizon geometry
   E-print submitted to arXiv on 8 October 2020 [arXiv ID: 2010.03784]
   Published 30 March 2021 in Physical Review D (American Physical Society)
   Journal reference: Phys. Rev. D **103**, 064082 (2021) [DOI: 10.1103/PhysRevD.103.064082]

5. R. B. Mann, S. Murk, D. R. Terno
   Surface gravity and the information loss problem
   E-print submitted to arXiv on 28 September 2021 [arXiv ID: 2109.13939]
   Published 16 June 2022 in Physical Review D (American Physical Society)
   Journal reference: Phys. Rev. D **105**, 124032 (2022) [DOI: 10.1103/PhysRevD.105.124032]

6. P. K. Dahal, S. Murk, D. R. Terno
   Semiclassical black holes and horizon singularities
   E-print submitted to arXiv on 2 October 2021 [arXiv ID: 2110.00722]
   Invited contribution to the special topic collection "Celebrating Sir Roger Penrose's Nobel Prize" published in AVS Quantum Science (AIP Publishing)
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   Journal reference: AVS Quantum Sci. **4**, 015606 (2022) [DOI: 10.1116/5.0073598]

7. S. Murk, D. R. Terno
   Spherically symmetric black holes in metric gravity
   E-print submitted to arXiv on 21 December 2020 [arXiv ID: 2012.11209]
   Published 20 September 2021 in Physical Review D (American Physical Society)
   Journal reference: Phys. Rev. D **104**, 064048 (2021) [DOI: 10.1103/PhysRevD.104.064048]

8. S. Murk
   Physical black holes in fourth-order gravity
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   Published 22 February 2022 in Physical Review D (American Physical Society)
   Journal reference: Phys. Rev. D **105**, 044051 (2022) [DOI: 10.1103/PhysRevD.105.044051]

Publications not included in this thesis (sorted in chronological order):

1. S. Murk, D. R. Terno
   Physical black holes in semiclassical gravity
   E-print submitted to arXiv on 25 October 2021 [arXiv ID: 2110.12761]
   Accepted contribution to the proceedings of the 16th Marcel Grossmann meeting (5–10 July 2021) to be published by World Scientific [DOI: TBD]

2. S. Murk
   Constraining modified gravity theories with physical black holes
   E-print submitted to arXiv on 1 November 2021 [arXiv ID: 2111.00776]
   Accepted contribution to the proceedings of the 16th Marcel Grossmann meeting (5–10 July 2021) to be published by World Scientific [DOI: TBD]

Foreword

This thesis follows the "Thesis by publication" format as stipulated by Macquarie University. Rules and guidelines can be accessed here.

It comprises eight publications: one review [1] and seven journal articles [2–8]. Note that the chronological order of the publications differs from their sequence in this thesis (cf. "List of Publications" on pp. vii–viii). To reduce overlaps in content, the two conference papers [9, 10] are not included as part of the thesis.

The thesis is organised as follows: the first chapter provides a critical introduction to the subject area and elucidates the context surrounding the problems investigated/studied in the published works. The bulk part of the thesis is formed by the eight published works: the review [1] precedes the journal articles [2–8] and introduces the foundations upon which they are based. It also describes some of the mathematical formalisms and techniques (albeit not necessarily in the same level of detail). Each publication is preceded by a brief summary of the main result(s) (except for the review) and additional commentary, such as errata or differences in the conventions among publications, e.g. differences in notation or definitions of functions. British English is used throughout the thesis, although the published works follow U.S. English guidelines as per publisher requirements. Journal abbreviations follow the ISO4 standard.

The following abbreviations (and their plural forms) are frequently used throughout the thesis:

ABH	astrophysical black hole
EMT	energy-momentum tensor
GR	general relativity
MBH	mathematical black hole
MTG	modified theory/theories of gravity
NEC	null energy condition
PBH	physical black hole
QEI	quantum energy inequality
RBH	regular black hole
UCO	ultra-compact object

Introduction

Our physical understanding of the world currently rests on two fundamental frameworks: general relativity, which describes gravitational interactions, and quantum field theory, which describes all non-gravitational interactions (culminating in the so-called standard model of particle physics and its proposed generalisations/extensions). While both theories have been spectacularly successful in predicting physical phenomena within their respective domains of validity, foundational differences imply that they cannot be simultaneously correct. This is not only problematic from a logical viewpoint: it also means that we lack predictive power in the regime where both gravitational and quantum effects simultaneously play a role, including the physics of black holes, early universe cosmology, and the geometry of spacetime at the Planck scale. A new theory of quantum gravity is expected to reconcile quantum field theory with general relativity and resolve outstanding issues. However, despite more than a century of extensive efforts, quantitative predictions of quantum gravitational effects are so far only possible in effective field theory frameworks.

The results presented in this thesis focus on improving our understanding of black holes and their horizons in the frameworks of semiclassical [1–6] and modified [1, 4, 7, 8] theories of gravity. Despite the lack of a fully developed theory of quantum gravity, these two theoretical frameworks allow us to incorporate quantum effects into the gravitational dynamics of black holes, which is of crucial importance for a complete description of their evolution and includes processes such as their formation and evaporation. In fact, the prediction that black holes evaporate through the emission of Hawking (i.e. completely thermal) radiation [11, 12] is widely regarded as one of the most impressive achievements of semiclassical gravity. The works comprised in this thesis investigate the consequences that inevitably follow from the formation of a trapped region in finite time of a distant observer, including but not limited to the characterisation of admissible self-consistent solutions to the semiclassical (and modified) Einstein equations, determination of their properties and corresponding near-horizon geometries, identification of observable properties, and matching of their parameters with the semiclassical results. It is important to note that for conventional descriptions of black hole evaporation (e.g. as illustrated in Fig. 5 of Ref. [12]) and models of regular black holes [13] (e.g. Fig. 5 of Ref. [14]), the requirement of finite-time formation according to the clock of a distant observer is not an assumption, but an immediate consequence that follows directly from the formation and disappearance of the trapped region. However, in contemporary literature this fact is often either ignored or overlooked.

The development of various modified theories of gravity (MTG), i.e. extensions and/or generalisations of general relativity (GR), is motivated by the prospect of resolving some of the perceived shortcoming of GR (such as the presence of non-spacelike singularities) combined with the possibility to describe additional gravitational degrees of freedom through the inclusion of higher-order curvature corrections [15, 16]. In addition, theoretical considerations indicate that GR represents the low-energy regime of some effective theory of quantum gravity [17, 18]. Compact objects with strong gravitational fields maximally highlight differences in the predictions of GR and alternative theories of gravity [19]. Using a conceptually novel approach, Refs. [7, 8] establish how the existence of semiclassical black holes and the requirement of their observability constrain the possible contributions of metric MTG to the (modified) Einstein equations.

REVIEW

Black holes and their horizons in semiclassical and modified theories of gravity

Errata and conventions

In spherical symmetry, only two classes of solutions to the semiclassical Einstein equations describe dynamic PBHs. With respect to the scaling behavior $\lim_{r\to r_g} \tau \sim f^k$ of the effective EMT components close to the horizon, they correspond to the values $k = 0$ and $k = 1$. In the review [1], series expansions of the metric function C are written such that the lowest-order coefficient in x is negative, i.e.

$$C = r_g + c_{12}\sqrt{x} + \sum_{j\geqslant 1}^{\infty} c_j x^j\,, \quad c_{12} < 0\,, \tag{1}$$

for $k = 0$ solutions [cf. Eq. (34)], and

$$C = r + c_{32}x^{3/2} + \sum_{j\geqslant 2}^{\infty} c_j x^j\,, \quad c_{32} < 0\,, \tag{2}$$

for the unique $k = 1$ solution [cf. Eq. (55)]. All other publications [2–8] included in this thesis use the convention

$$C = r_g - c_{12}\sqrt{x} + \sum_{j\geqslant 1}^{\infty} c_j x^j\,, \quad c_{12} > 0\,, \tag{3}$$

$$C = r - c_{32}x^{3/2} + \sum_{j\geqslant 2}^{\infty} c_j x^j\,, \quad c_{32} > 0\,, \tag{4}$$

for $k = 0$ and $k = 1$, respectively.

In the articles corresponding to Refs. [2–4], the expanding white hole solution corresponding to the second row of Tab. 2 in the review [1] was misidentified as an accreting PBH solution. This conceptual error has been rectified in Refs. [5, 6].

Lastly, the published version contains two typos: Eq. (107) is printed as

$$\xi = \frac{r_g'^2}{2r_g''} = \frac{1}{4} r_g. \tag{5}$$

The correct form is

$$\xi = \frac{r_g'^2}{2|r_g''|} = \frac{1}{4} r_g. \tag{6}$$

In the second term of Eq. (C.5), r_g appears as $\sqrt{r_g}$, but the correct power is $r_g^{3/2}$, i.e. the published equation reads

$$C = r_g - 4\sqrt{\pi r_g}\Upsilon\sqrt{x} + \left(\frac{1}{3} + \frac{4\sqrt{\pi}e_{12}r_g^{3/2}}{3\Upsilon}\right)x + O(x^{3/2}), \tag{7}$$

but the correct form is

$$C = r_g - 4\sqrt{\pi}r_g^{3/2}\Upsilon\sqrt{x} + \left(\frac{1}{3} + \frac{4\sqrt{\pi}e_{12}r_g^{3/2}}{3\Upsilon}\right)x + O(x^{3/2}). \tag{8}$$

Both errors have been rectified in the latest arXiv version arXiv:2112.06515v5 that is included in this thesis.

Mann, R. B., Murk, S., & Terno, D. R. (2022). Black holes and their horizons in semiclassical and modified theories of gravity. *International Journal of Modern Physics D*, 31(9), [2230015].
https://doi.org/10.1142/S0218271822300154

Journal Article

Energy-momentum tensor and metric near the Schwarzschild sphere

Brief summary

The formation of a trapped region in finite time of a distant observer is known to violate the NEC $T_{\mu\nu}\ell^\mu\ell^\nu \geqslant 0$ [20–22], where ℓ^μ denotes a null vector, $\ell^\mu\ell_\mu = 0$. In the article, this result is derived for spherically symmetric spacetimes without making any assumptions about their asymptotic structure. The "generic" solution identified here plays a principal role in the classification of semiclassical black holes. In fact, it is the main description for the dynamic evolution of PBHs. Since its main characteristic is that $k = 0$, where $\lim_{r\to r_g}\tau \sim f^k$ denotes the the scaling behavior of the effective EMT components τ close to the horizon, solutions of this class are referred to as $k = 0$ solutions in Refs. [1, 4–10].

In spherical symmetry, the formation of a regular apparent horizon $r_g(t)$ in finite time of a distant observer suffices to uniquely (up to a function of time $\Upsilon(t)$ and two pairs of signs $\varepsilon_\pm = \pm 1$) identify the EMT near the horizon. In the orthonormal frame, the limiting form of its (tr) block as $r \to r_g$ is given by

$$T_{\hat{a}\hat{b}} = \frac{\Upsilon^2}{f}\begin{pmatrix} -1 & \varepsilon_\pm \\ \varepsilon_\pm & -1 \end{pmatrix}, \tag{9}$$

which corresponds to the second expression in Eq. (40) of the article. A direct consequence of this result is that accreting Vaidya black hole solutions in advanced null (v, r) coordinates cannot describe PBHs as they satisfy the NEC (fourth row of Tab. I), and indeed, in this case the explicit construction of a transformation between (v, r) and (t, r) coordinates (provided in Appendix C of the article) results in complex-valued functions.

Errata and conventions

The expression for the trace of the EMT given in paragraph four of Sec. II. A. of the article is missing a minus sign. The correct expression is $T^\mu{}_\mu = -R/8\pi$, where R denotes the Ricci scalar. Rather than $\Upsilon(t)$, the article uses a function $\Xi(t) := -\Upsilon(t)^2$ [cf. Eq. (40) in the article vs. Eq. (9) above]. Also, the leading term of the metric function h is written as

$$h = -\ln\frac{\sqrt{x}}{\xi_0(t)} + O\left(\sqrt{x}\right), \tag{10}$$

whereas all other articles except Ref. [3] use a function $\xi(t)$ instead of $\xi_0(t)$ such that

$$h = -\frac{1}{2} \ln \frac{x}{\xi(t)} + \mathcal{O}\left(\sqrt{x}\right). \tag{11}$$

It has been assumed that there are no half-integer terms in the expansions of the effective EMT components τ, which is not true in general and affects higher-order terms.

Lastly, note that the solutions corresponding to the second and third row of Tab. I in the article describe an expanding and contracting white hole, respectively (cf. Tab. 2 on p. 25 of the review [1]). Consequently, the only viable (i.e. NEC-violating) black hole solution is an evaporating PBH (corresponding to the signature specified in the first row of Tab. I in the article).

Baccetti, V., Mann, R. B., Murk, S., & Terno, D. R. (2019). Energy-momentum tensor and metric near the Schwarzschild sphere. *Physical Review D: covering particles, fields, gravitation, and cosmology*, 99(12), [124014]. https://doi.org/10.1103/PhysRevD.99.124014

JOURNAL ARTICLE

Black hole evaporation and semiclassical thin shell collapse

Brief summary

Using the results of Ref. [2], the article investigates black hole evaporation in so-called thin shell collapse models (the simplest toy models of gravitational collapse; a concise overview is provided in Sections 3.9 and 3.11 of Ref. [23]), and explicitly derives higher-order terms in the EMT. The analysis demonstrates that black hole evaporation and thin shell models do not have an independent physical meaning, but rather, they simply illustrate their underlying assumptions: if the model uses a non-NEC-violating metric, i.e. a metric that is not compatible with the formation of a horizon in finite time of a distant observer, it will predict horizon avoidance. Similarly, if the model uses a metric that allows for violations of the NEC near the horizon, which is a mandatory requirement for finite-time horizon formation, it will predict horizon crossing.

Errata and conventions

In the published article, Eq. (23) is printed as

$$\Upsilon \approx \frac{\sqrt{\kappa}}{2\sqrt{2\pi} r_g^2}. \tag{12}$$

The correct expression is

$$\Upsilon \approx \frac{\sqrt{\kappa}}{2\sqrt{2\pi} r_g}. \tag{13}$$

This error has been corrected in the latest arXiv version arXiv:1812.07727v4. It is worth noting that some of the results in this article were derived using the expansion of effective EMT components provided by Eqs. (25)–(27) and accordingly matched metric functions $C(t,r)$ and $h(t,r)$. However, it was later demonstrated [24] that the only two self-consistent dynamic solutions correspond to those discussed in Ref. [4] and summarized in Tab. 1 of the review [1].

In addition, the derivations of Sec. III. A. are based on the assumption that the geometry near the horizon is well-approximated by a pure ingoing Vaidya metric, and Page's law [25] is valid in both (t,r) and (v,r) coordinates. However, the analysis presented in Ref. [5] demonstrates that these assumptions are mutually exclusive.

Lastly, it is worth pointing out that the conservation laws considered in Sec. III. D. do not yield any independent relations beyond the Einstein equations, but are useful in verifying the consistency of various series expansions.

Baccetti, V., Murk, S., & Terno, D. R. (2019). Black hole evaporation and semiclassical thin shell collapse. *Physical Review D: covering particles, fields, gravitation, and cosmology*, 100(6), [064054]. https://doi.org/10.1103/PhysRevD.100.064054

Journal Article

Universal properties of the near-horizon geometry

Brief summary
The article analyses properties of the near-horizon geometry of the two classes of dynamic spherically symmetric PBH solutions ($k \in \{0, 1\}$) and demonstrates that

1. the formation of PBHs follows a unique scenario that involves both types of solutions. For one of them ($k = 1$), only a single dynamic solution is self-consistent. It describes PBHs at the instant of their formation and is uniquely identified by its energy density $E := -T^t{}_t$ and pressure $P := T^r{}_r$ at the horizon, which take on their maximal possible values $E = -P = 1/(8\pi r_g^2)$.

2. generalisations of the peeling surface gravity to dynamic spacetimes diverge at the apparent horizon.

3. based on a comparison of the energy and timescale required for horizon formation with established semiclassical results, the observed ABHs are likely to be identified with horizonless UCOs, and the presence of a horizon would be indicative of new physics.

The continuous transition between the two classes of solutions is made possible by the fact that for $k = 1$ the NEC is marginally satisfied at r_g (as detailed in the review [1]).

Errata and conventions
The accreting PBH solution mentioned in the sentence leading up to Eq. (20) is actually an expanding white hole solution (as detailed in Ref. 6 and the review [1]). Eq. (24) is erroneously printed as

$$\mathfrak{f}'(R)R + 2\mathfrak{f}(R) + 3\Box\mathfrak{f}'(R) = 8\pi \mathrm{T}.$$

The correct expression is

$$\mathfrak{f}'(R)R - 2\mathfrak{f}(R) + 3\Box\mathfrak{f}'(R) = 8\pi \mathrm{T}.$$

The non-generalisability of the peeling surface gravity to dynamic black hole spacetimes is explored further in Ref. [5], and in fact it is shown that other definitions that are closely related in stationary spacetimes, e.g. Kodama surface gravity, are plagued by similar behaviours that are also incompatible with the predictions of semiclassical gravity.

Murk, S., & Terno, D. R. (2021). Universal properties of the near-horizon geometry.
Physical Review D: covering particles, fields, gravitation, and cosmology, 103(6), [064082].
https://doi.org/10.1103/PhysRevD.103.064082

Journal Article

Surface gravity and the information loss problem

Brief summary

The divergence of the generalised peeling surface gravity demonstrated in Ref. [4] indicates that Hawking-like radiation by PBHs may need to be re-evaluated. The following article shows that generalisations of peeling and Kodama surface gravity — the two principal generalisations of surface gravity that underpin different derivations of Hawking radiation on the background of evolving black hole spacetimes — do not agree with each other, and neither can describe the emission of nearly-thermal radiation. If semiclassical gravity is valid, an immediate consequence of this discrepancy is that it is impossible to simultaneously realise all of the necessary elements (event horizon, evaporation, thermal character of the radiation) that would be required for a self-consistent formulation of the information loss paradox. The argumentation presented in this analysis is complementary to a recent study [26] indicating that the standard form of the paradox can be formulated in a self-consistent way only if new physics begins to play a role before reaching the Planck scale.

Errata and conventions

Here, unlike in the preceding articles [2–4], solutions with an expanding Schwarzschild sphere ($r'_g > 0$) were correctly identified as expanding white holes (as opposed to accreting PBHs).

Mann, R. B., Murk, S., & Terno, D. R. (2022). Surface gravity and the information loss problem. *Physical Review D: covering particles, fields, gravitation, and cosmology*, 105(12), [124032].
https://doi.org/10.1103/PhysRevD.105.124032

Journal Article

Semiclassical black holes and horizon singularities

Brief summary

This article connects the early contributions of Sir Roger Penrose to the field of black hole physics to contemporary research topics, and in particular to our research program. It is demonstrated that both the outer apparent horizon of an evaporating PBH and the anti-trapping horizon of an expanding white hole are weakly singular hypersurfaces. Recall that neither accreting PBHs nor contracting white holes are viable solutions as both of them satisfy the NEC and thus cannot be formed in finite time of a distant observer (as the Einstein equations do not have real-valued solutions in this case). The role of firewalls is discussed in more detail.

Errata and conventions

Dahal, P. K., Murk, S., & Terno, D. R. (2022). Semiclassical black holes and horizon singularities. *AVS Quantum Science*, 4(1), [015606]. https://doi.org/10.1116/5.00735982

Journal Article

Spherically symmetric black holes in metric gravity

Brief summary

The article develops a perturbative effective-field-theory-inspired procedure to derive several constraints that arbitrary metric MTG must satisfy to be compatible with the two classes of dynamic semiclassical PBHs. The constraints manifest themselves in two ways: first, the series expansions of the MTG terms (i.e. terms that correspond to deviations from the Einstein equations) must follow a particular structure when expanded in terms of the coordinate distance $x := r - r_g$ from the apparent horizon. Second, several identities between their lowest-order coefficients must be satisfied. Note that if a particular MTG does not satisfy any the constraints, it may still possess solutions corresponding to PBHs, but their mathematical structure must then be fundamentally different from those of semiclassical gravity, which may or may not give rise to observationally distinguishable features.

Errata and conventions

The expression

$$\mathrm{T} := T^{\mu}{}_{\mu} = R/8\pi + O(\lambda) \tag{14}$$

printed in the paragraph following Eq. (2) is incorrect. The correct expression is

$$\mathrm{T} := T^{\mu}{}_{\mu} = -R/8\pi + O(\lambda). \tag{15}$$

Murk, S., & Terno, D. R. (2021). Spherically symmetric black holes in metric gravity.
Physical Review D: covering particles, fields, gravitation, and cosmology, 104(6), [064048].
https://doi.org/10.1103/PhysRevD.104.064048

Journal Article

Physical black holes in fourth-order gravity

Brief summary

The constraints derived in Ref. [7] are investigated in the context of $\mathfrak{f}(R)$ theories and generic MTG with up to fourth-order derivatives in the metric. All of the constraints are satisfied identically for both of the semiclassical solutions, i.e. without any additional requirements. This implies that the semiclassical PBH solutions can be regarded as zeroth-order terms in perturbative solutions of these models. Consequently, the observation of an apparent horizon by itself may not suffice to distinguish between the semiclassical theory and modifications including up to fourth-order derivatives in the metric. A detailed analysis of the response of the near-horizon geometry to perturbations is required to identify potentially observable differences in the predicitons of these models. The analysis in this article will be extended to test the recent reformulations of Gauß–Bonnet gravity in four dimensions with non-trivial gravitational dynamics [27, 28].

Errata and conventions

Murk, S. (2022). Physical black holes in fourth-order gravity.
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