Asymptotic Safety: Swampland or Wonderland?

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ABSTRACT: We investigate the consequences of combining swampland conjectures with the requirement of asymptotic safety. To this end, we explore the infrared regime of asymptotically safe gravity in the quadratic one-loop approximation, and we identify the hypersurface spanned by the endpoints of asymptotically safe renormalization group trajectories. These comprise the allowed values of higher-derivative couplings as well as standard logarithmic form factors. We determine the intersection of this hypersurface with the regions of parameter space allowed by the weak-gravity conjecture, the swampland de Sitter conjecture, and the trans-Planckian censorship conjecture. The latter two depend on some order-one constants, for generic values of which we show that the overlap region is a proper subspace of the asymptotically safe hypersurface. Moreover, the latter lies inside the region allowed by the weak gravity conjecture assuming electromagnetic duality. Our results suggest a non-trivial interplay between the consistency conditions stemming from ultraviolet completeness of the renormalization group flow, black hole physics, and cosmology.
1 Introduction

The 20th century has seen the development of two pillars of modern theoretical physics: quantum field theory (QFT) and general relativity (GR). The standard model of particle physics, which successfully describes the quantum properties of the strong and electroweak interactions, is based on the former framework. However, its naïve application to the latter yields a QFT of gravity prone to (perturbatively) non-renormalizable ultraviolet (UV) divergences [1–3].

Despite remarkable progress in a number of directions, the difficulties of formulating a complete theory of quantum gravity have led a considerable portion of the community to shift the focus on general, possibly model-independent lessons that could shed light on the nature of gravity at all scales. Many of these proposals, commonly dubbed “swampland conjectures” [4] in the context of string theory, rest on considerations on black-hole physics, which often can lie entirely in the semi-classical regime where one expects low-energy effective field theory (EFT) to be a reliable description.

On the other hand, some aspects of these conjectures arose from and are tied to string theory and, in particular, its spacetime-supersymmetric incarnations. These settings are much better understood, since quantum corrections are often under quantitative control [5–15] and can sometimes even be computed exactly [16, 17]. In certain settings, such as $\mathcal{N} = 2$ Calabi-Yau flux compactifications, one can even classify general families of models at
once [18–23]. In some string models with high-energy supersymmetry breaking, a variety of swampland proposals were verified [24, 25], although a construction of realistic and (meta-)stable vacua is still an open problem [26–57]. At any rate, it is paramount to understand the consequences of general consistency conditions outside of the specific contexts arising from (supersymmetric) string compactifications, although parametric control is most likely going to be problematic [32, 46, 48, 50, 58] due to unknown or uncalculable corrections. To wit, efforts to test swampland proposals have almost entirely focused on supersymmetric settings, and in particular on stringy constructions. In order to shed light on whether they only encode a “string lamppost principle” [59] or they hold in more generality, it is important to extend their exploration to a broader class of quantum gravity models. On the other hand, the more stringent and well-grounded swampland proposals, such as the “no global symmetries” [60–63] and weak gravity [64] conjectures, could help guide the search for asymptotic safety, which is currently faced with the daunting prospect of navigating ever-larger theory spaces [65, 66].

A concrete problem that can be phenomenologically relevant in the near future is constraining the possible values of the Wilson coefficients of a curvature expansion of the gravitational EFT. In particular, one can expect that generic detectable leading-order effects of quantum gravity be encoded in the coefficients of the quadratic curvature invariants, which we shall discuss in detail in the following, or in some specific non-local form factors [67, 68]. Some efforts in this direction have been made using the S-matrix bootstrap [69, 70], finding compelling agreement with the parameter space allowed by string theory. In the EFT framework, the problem has also been investigated via positivity bounds [71–80].

In this paper we approach this issue from a novel direction, studying the constraints coming from swampland conjectures together with the consistency conditions required by the existence of a UV fixed point of the gravitational renormalization group (RG) flow\(^1\). The latter scenario has been termed “asymptotic safety”, in analogy with asymptotic freedom as a particular case. This idea, originally due to Weinberg [82], would imply that the Wilson coefficients of the IR effective action stem from a UV-complete RG trajectory, which in turn would be determined by a finite number of relevant deformations from the fixed point. Recently, this area of research has witnessed considerable development of the theoretical framework to investigate RG flows beyond perturbation theory [83] and finding evidence for the existence of the Reuter fixed point in a variety of different approximation schemes [66, 84–113] (see also [114, 115] for critical assessments on the status of the field and its open questions). Possible implications of asymptotically safe gravity in astrophysics and cosmology (see [116, 117] for reviews) have been investigated using simplified models [118–140] and more elaborate computations [141], leading to the tentative conclusions that black-hole and cosmological singularities could be resolved by quantum effects, and that the nearly scale-invariant cosmological power spectrum could arise naturally from a nearly scale-invariant asymptotically safe regime.

\(^1\)See also [81] for related discussions on the weak gravity conjecture in the context of asymptotically safe gravity.
In this paper we shall propose a concrete method to extract the allowed region of IR parameters from the RG flow of asymptotically safe trajectories. In particular, we shall focus on the simpler case of the one-loop approximation in quadratic gravity \[87, 142, 143\] in order to test our construction and provide a proof of principle of our idea. We will show that the IR limit of asymptotically safe trajectories falls inside the region allowed by the weak gravity conjecture and electromagnetic duality, and display a non-trivial intersection with the one allowed by the de Sitter and trans-Planckian censorship bounds.

The contents of this paper are organized as follows. In sect. 2 we provide a brief overview of swampland conjectures, focusing on the weak gravity conjecture, the de Sitter conjecture and the trans-Planckian censorship conjecture, since they entail the most relevant bounds for our subsequent analysis. In sect. 3 we describe in detail the one-loop approximation to quadratic gravity that we employ as testing grounds, and our method of extracting the physical IR Wilson coefficients. The resulting effective action turns out to contain non-local form factors. In sect. 4 we collect our results: in sect. 4.1 we present the allowed region of parameter space that we found, which spans a plane in the three-dimensional space of dimensionless IR parameters, and in sect. 4.2 and sect. 4.3 we study the constraints stemming from the swampland conjectures discussed in sect. 2.1 and sect. 2.2 respectively. In sect. 4.4 we discuss and display the intersection of all regions. We conclude with a summary and some perspectives in sect. 5.

2 An overview of swampland conjectures

As we have anticipated in the introduction, swampland conjectures are proposals that ought to rule out EFTs of gravity that do not admit UV completions [4]. These conjectures are generally motivated in part by purely low-energy considerations, stemming from black-hole physics or inflation, but they also arise from detailed investigations of string-theoretic settings, where generally one has more control over corrections and patterns can be corroborated across families of EFTs. The latter approach has led some to describe a “lamppost” effect [59], whereby only settings that are somewhat under control can be investigated and thus it is unclear to which extent the resulting conclusions can be generalized. Furthermore, while at least minimal supersymmetry is generally unbroken in order to retain computational control, recent considerations [144, 145] point to a tension between low-energy supersymmetry breaking\(^2\) and the consistency of the EFT. As we have discussed in the preceding section, one of the motivations behind this work is indeed to go beyond the usual settings, seeking lessons for other approaches to quantum gravity.

Since its inception, the swampland program aims to describe the boundary between the landscape of consistent gravitational EFTs with a growing number of proposed criteria\(^3\), numerous relations among which \[152, 153\] point to a deeper underlying principle. In particular, connections between the distance conjecture \[154, 155\] and string dualities suggest that an organizing principle for these consistency criteria in the IR be related

\(^2\)Nevertheless, scenarios with high-energy supersymmetry breaking have been investigated in the context of the swampland \[24, 25, 146\]. See \[147-149\] for recent reviews.

\(^3\)See \[150, 151\] for reviews.
to a non-perturbative UV formulation of quantum gravity. Furthermore, as we shall see in the following, swampland considerations have provided intriguing clues toward a number of phenomenological puzzles [156].

In this paper we shall focus on some conjectures which can provide bounds for the Wilson coefficients of the gravitational EFT. In particular,

- The weak gravity conjecture (WGC) [64] relates the mass and charge of light states and black holes;
- The de Sitter conjecture (dSC) [157], along with its refined versions [155, 158, 159], constrains the behavior of scalar potentials and their derivatives, leading to an obstruction to the existence of de Sitter vacua that is $\mathcal{O}(1)$ in Planck units;
- The trans-Planckian censorship conjecture (TCC) [160, 161] constrains sub-Planckian cosmological perturbations to remain sub-Planckian across inflation, and leads to bounds on the lifetime of metastable de Sitter configurations as well as on the $\mathcal{O}(1)$ parameter that appears in the dSC, at least in asymptotic regions of field space.

In light of the latter consideration, for the purposes of this paper in the following we shall investigate the consequences of the TCC on Starobinsky-like inflationary potentials as a special case of the dSC. Indeed, we shall restrict ourselves to the asymptotic region of field space corresponding to small curvatures in Planck units, where the TCC could provide a dSC bound with a specific $\mathcal{O}(1)$, as we shall see below.

### 2.1 Weak gravity conjecture and black holes

Let us begin reviewing some features of the (electric) WGC, referring the reader to [150, 151] for more details. In its most basic form, it states that in a consistent EFT of gravity coupled to a $U(1)$ gauge field there exists a state whose mass $m$ is lower than its charge $q$ in Planck units. In four dimensions, the bound for charged particles reads

$$\frac{m}{M_{Pl}} \leq \mathcal{O}(1) q,$$

where the model-dependent $\mathcal{O}(1)$ constant is $\frac{1}{\sqrt{2}}$ in Einstein-Maxwell theory.

Among various motivations and evidence gathered in the literature, the WGC is grounded in black-hole physics from the requirement that charged, extremal black holes be able to decay, lest protected by a symmetry (such as supersymmetry, in the case of BPS-saturated states). The rationale behind this lies in avoiding remnants while keeping the black hole from violating the extremality bound, since a violation of either would presumably lead to consistency issues potentially within the EFT regime [64, 162, 163]. For charged black holes of mass $M$ and charge $Q$, this requirement translates into

$$\frac{M}{Q} \geq \left(\frac{M}{Q}\right)_{\text{extremal}},$$

(2.2)
where the latter is generally an $O(1)$ constant. However, higher-curvature corrections could potentially spoil this condition even for macroscopic black holes, provided they are sufficiently close to extremality. Writing the leading quartic corrections according to \[ \Delta \mathcal{L} = c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + c_3 R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}, \]

the resulting bounds for the corresponding Wilson coefficients $c_i$ comprise a family of inequalities for linear combinations of the $c_i$, parametrized by the extremality parameter of the black hole [64, 164–168]. The extremality bound in general now takes the form

\[ \frac{M}{Q} \geq \left( \frac{M}{Q} \right)_{\text{extremal}} \left( 1 - \frac{\Delta}{M^2} \right), \]

where the linear combination $\Delta$ of Wilson coefficients is to be non-negative in order for the WGC to hold, and is proportional to the coefficient $c_2 + 4c_3$ of the Weyl-squared term [164, 168].

The leading order contributions to $\Delta$ comprise not only the Wilson coefficients in the effective action of eq. (2.3), but also the Wilson coefficients that involve the $U(1)$ gauge field. It has been recently shown [169] that, assuming invariance under electromagnetic duality, higher-curvature corrections up to sextic order can be written in terms of purely gravitational terms, up to field redefinitions. Let us stress that our aim is to intersect swampland bounds with the constraints provided by asymptotic safety, and the technical obstacles to compute its consequences for quartic electromagnetic couplings in gravity, which would entail involved FRG computations along the lines of [66], compel us to focus on the duality-invariant scenario of [169], which at any rate appears intriguing on its own. Moreover, the electromagnetic couplings do not run under the RG flow at one loop because of tree-level duality [166, 168]. This has been used to argue that the low-energy behavior of the correction $\Delta$ to the extremality bound is dominated by the Weyl anomaly coefficients that drive the running of the $c_i$, and in particular of the Weyl-squared Wilson coefficient $c_2 + 4c_3$, as we shall see in the following. However, in the present case we would like to constrain the physical parameters built out of the Wilson coefficients and the Planck scale, in order to compare the resulting bounds with the constraints of asymptotic safety. We shall describe the procedure in detail in the following section.

2.2 de Sitter and trans-Planckian censorship

Let us now move on to discuss the dSC and the TCC. The former quantifies an obstruction to the existence of de Sitter vacua, in the form of a bound for the (field-space gradient of the) scalar potential $V(\phi)$. Indeed, since in this setting de Sitter vacua would arise as positive-energy critical points of $V$, a natural bound that would prevent these takes the form

\[ M_{Pl} |\nabla V| \geq cV \]

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4For Einstein-Maxwell theory, the extremality bound reads $\frac{M}{Q} \geq \sqrt{2} M_{Pl}$.

5Another instance of the interplay between duality and the WGC has been studied in [170].
for field ranges
\[ \Delta \phi \lesssim f M_{\text{Pl}}, \quad (2.6) \]
where \( c, f > 0 \) are (\emph{a priori} model-dependent) constants. Within the EFT framework, their natural values are \( \mathcal{O}(1) \), indicating that the obstruction is tied to the expected cutoff of the EFT. However, one is readily confronted with a tension between the bound in eq. (2.5) and slow-roll inflation \[158, 171\]^6, leading to refinements involving the Hessian matrix of the potential \[155, 158\]. In particular, whenever the bound of eq. (2.5) would be violated, the matrix
\[ M_{\text{Pl}}^2 \text{Hess}(V) + c' V \quad (2.7) \]
would be negative semidefinite, with \( c' > 0 \) another \( \mathcal{O}(1) \) constant. Further refinements were proposed in \[159\], but in our setting we shall find that the first bound of eq. (2.5) is sufficient, since it encompasses eq. (2.7) in the regions of parameter space that we are concerned with.

On the other hand, the TCC surmises that sub-Planckian quantum fluctuations in the early universe at initial time \( t_i \) never grow macroscopic at a final time \( t_f \). In particular, they ought to never cross the Hubble horizon and freeze. This requirement can be formulated, in terms of the scale factor \( a(t) \) and the corresponding Hubble parameter \( H \), by \[160, 161\]
\[ \frac{a(t_f)}{a(t_i)} \lesssim \frac{M_{\text{Pl}}}{H(t_f)}, \quad (2.8) \]
again up to an \( \mathcal{O}(1) \) constant. An intriguing consequence of eq. (2.8) is that de Sitter configurations are not prohibited, but they are metastable with a lifetime \( T \) bounded by
\[ T \lesssim \frac{1}{H} \log \frac{M_{\text{Pl}}}{H}, \quad (2.9) \]
of the order of a trillion years. This results points to a possible resolution of the coincidence problem in this setting.

The most relevant consequence of the TCC for the purposes of this paper is that, in the presence of a scalar potential, it leads to a bound of the form of eq. (2.5) with
\[ c = \frac{2}{\sqrt{(d-1)(d-2)}} \quad (2.10) \]
in \( d \) spacetime dimensions, at least in asymptotic regimes of field space. In the present setting, the scalar potential arises from the quadratic curvature terms, and the corresponding asymptotic regime for gravitational field fluctuations is that of small curvatures \[176\]. This regime is mapped to a neighbourhood of the origin in the inflaton description. For generic curvatures, one expects that both the purely gravitational description and the inflaton description be modified, including the geometry of field space. Nevertheless, since our current setup does not allow for precise quantitative bounds, we shall henceforth take eq. (2.10) simply as a reference point around which to study the more general bound of eq. (2.5). Let us also remark that this value appears in a number of related swampland

^6See also \[172–175\] for discussions on eternal inflation and the swampland.
bounds [152] and is well-behaved under dimensional reduction [173], and thus it may play a more prominent role in the story. At any rate, it would be interesting to explore the more direct implications of eq. (2.8) studying cosmological solutions or exploring the considerations of [161, 177] within our setup.

3 One-loop RG flow in quadratic gravity

Let us now discuss the concrete setting in which we shall compute the possible values of the Wilson coefficients of the effective gravitational action. In this work we focus on the quadratic truncation\footnote{Let us remark that here “quadratic” refers to the order in the curvatures. In terms of derivatives, the action in eq. (3.1) is quartic.}, in the one-loop approximation. In Euclidean signature, the Lagrangian pertaining to the full quadratic truncation reads

\begin{equation}
\mathcal{L} = \frac{2\Lambda - R}{16\pi G} + \frac{1}{2\lambda} C^2 - \frac{\omega}{3\lambda} R^2 + \frac{\theta}{\lambda} E,
\end{equation}

where $C^2 \equiv C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma}$ is the square of the Weyl tensor, $E$ is the Gauss-Bonnet density and and the Wilson coefficients

\begin{equation}
g_C \equiv \frac{1}{2\lambda}, \quad g_R \equiv -\frac{\omega}{3\lambda}
\end{equation}

can be related to the $c_i$ coefficients in eq. (2.3). Indeed, since

\begin{equation}
C^2 = R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} - 2 R_{\mu\nu} R^{\mu\nu} + \frac{R^2}{3},
\end{equation}

\begin{equation}
E = R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} - 4 R_{\mu\nu} R^{\mu\nu} + R^2,
\end{equation}

the $c_i$ are related to the couplings in eq. (3.1) according to

\begin{equation}
c_1 = \frac{1}{6\lambda} - \frac{\omega}{3\lambda} + \frac{\theta}{\lambda},
\end{equation}

\begin{equation}
c_2 = -\frac{1}{\lambda} + \frac{4\theta}{\lambda},
\end{equation}

\begin{equation}
c_3 = \frac{1}{2\lambda} + \frac{\theta}{\lambda}.
\end{equation}
While this setup holds in general spacetime dimensions $d$, we now restrict to $d = 4$. The one-loop beta functions of the couplings of eq. (3.1) read \cite{87, 142, 143}

\begin{align}
\beta_{\tilde{\Lambda}} &= -2\tilde{\Lambda} + \frac{1}{(4\pi)^2} \left[ \frac{1 + 20\omega^2}{256\pi G \omega^2} \lambda^2 + \frac{1 + 86\omega + 40\omega^2}{12\omega} \lambda \tilde{\Lambda} \right] \\
&\quad - \frac{1 + 10\omega^2}{64\pi^2 \omega} \lambda + \frac{2\tilde{G}}{\pi} - \frac{83 + 70\omega + 8\omega^2}{18\pi} \tilde{\Lambda}, \\
\beta_{\tilde{G}} &= 2\tilde{G} - \frac{1}{(4\pi)^2} \left[ \frac{3 + 26\omega - 40\omega^2}{12\omega} \lambda \tilde{G} - \frac{83 + 70\omega + 8\omega^2}{18\pi} \tilde{G}^2, \right. \\
\beta_{\lambda} &= -\frac{1}{(4\pi)^2} \frac{133}{10} \lambda^2, \\
\beta_{\omega} &= -\frac{1}{(4\pi)^2} \frac{25 + 1098\omega + 200\omega^2}{60} \lambda, \\
\beta_{\theta} &= \frac{1}{(4\pi)^2} \frac{7 (56 - 171\theta)}{90} \lambda,
\end{align}

(3.5)

where $\tilde{G}_k = G_k k^2$ and $\tilde{\Lambda}_k = \Lambda_k k^{-2}$ are the dimensionless Newton coupling and cosmological constant respectively, and we have suppressed the subscript $k$ in eq. (3.5) for the sake of clarity.

In our setting, the flow of the (classically) marginal couplings $\lambda$, $\omega$ and $\theta$ is decoupled from that of the Einstein-Hilbert couplings. Out of the UV fixed points

\begin{align}
\lambda_* &= 0, \quad \omega_* = \omega_\pm \equiv \frac{-549 \pm 7\sqrt{6049}}{200}, \quad \theta_* = \frac{56}{171},
\end{align}

(3.6)

UV completeness selects $\omega_* = \omega_+ \approx -0.023$ \cite{178}, which the solutions approach as the RG time\textsuperscript{8} $t \equiv \log \frac{k_0}{k} \rightarrow -\infty$, as is apparent from fig. 1. Let us remark that this fixed point is asymptotically safe, i.e. at least one coupling is not asymptotically free \cite{142, 143, 178, 179}. Indeed, the critical exponents of $G$ and $\Lambda$ are 2 and 4\textsuperscript{9}, while in the IR they become the canonical -2 and 2 respectively \cite{181}. The fact that all couplings are attracted to the fixed point in the UV \cite{178} is instead an artifact of the one-loop approximation. Indeed, more sophisticated FRG computations yield a fixed point with a three-dimensional critical surface \cite{89}.

The flow can be solved analytically in terms of the deformations $\delta \lambda$, $\delta \omega$ from the UV

\textsuperscript{8}Note that, since we are interested in the IR regime, our convention for the RG time is such that $t \rightarrow +\infty$ in the IR.

\textsuperscript{9}Although 2 and 4 are not the canonical mass dimensions of $G$ and $\Lambda$, they are the canonical dimension of the couplings $1/G$ and $\Lambda/G$ that multiply the operators $\sqrt{-g}$ and $\sqrt{-\tilde{g}} R$. This occurs because the transformation between these couplings is non-singular, as explained in \cite{180}. On the other hand, at the Gaussian fixed point the transformation between the couplings is singular, and the dimensions change accordingly.

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fixed point, and yields the closed-form solution

\[
\begin{align*}
\lambda(t) &= \frac{\delta \lambda}{1 - \frac{133}{160 \pi^2} \delta \lambda t}, \\
\omega(t) &= \omega_+ - \omega_- \left( 1 + \frac{\Delta}{\delta \omega} \right) \left( 1 - \frac{133}{160 \pi^2} \delta \lambda t \right) \frac{7 \sqrt{6049}}{399}, \\
\theta(t) &= \frac{56}{171} + \frac{\delta \theta}{1 - \frac{133}{160 \pi^2} \delta \lambda t},
\end{align*}
\]  

(3.7)

where \(\Delta \equiv \omega_+ - \omega_-\). The vector field generating this flow is displayed in fig. 1 in the \((\omega, \lambda)\) subspace and in fig. 2 with various 3D plots. Let us observe that the UV completeness of the trajectory requires \(\delta \lambda > 0\), and that the IR flow ends at \(t = t_{\text{IR}} \equiv \frac{160 \pi^2}{133 \delta \lambda}\). However, since \(\delta \lambda \ll 1\) this RG time is parametrically large, and one can reliably extract the perturbative IR behavior for the Wilson coefficients. Furthermore, reaching a physical IR regime with \(\tilde{G} \to 0^+\) requires that \(\delta \tilde{G}, \delta \omega < 0\), in order that their flows remain between the UV and IR fixed-point values avoiding runaway. The flow of the relevant deformations from the fixed point is shown in Fig. 3.

Substituting the expressions of eq. (3.7) in eq. (3.5), one can then solve the remaining flow equations numerically varying the initial conditions, or, equivalently, the deformations \(\delta \omega, \delta \lambda, \delta \tilde{G}, \delta \Lambda\) from the UV fixed point. The RG flow then drives the running couplings to the weakly coupled IR, where the running couplings \(g_C\) and \(g_R\), defined in eq. (3.2), behave logarithmically (linearly in \(t\)) as \(t \to t_{\text{IR}}\). This result is consistent with perturbative computations, and the resulting asymptotic expressions read

\[
\begin{align*}
g_C(t) &\sim \frac{1}{2\delta \lambda} - \frac{133}{320 \pi^2} t, \\
g_R(t) &\sim -\frac{\omega_-}{3\delta \lambda} + \frac{133}{480 \pi^2} \omega_- t.
\end{align*}
\]  

(3.8)
Figure 2. Flow of the classically marginal couplings ($\omega, \lambda, \theta$) in one-loop quadratic gravity. The arrows point towards the IR, and different viewpoints are shown to better visualize the flow. The color coding of the arrows is identical to that of fig. 1.

In order to extract the physical IR parameters, we shall identify the (square of the) RG scale $k^2$ with the covariant Laplacian/d’Alembertian $\Box$. In order to eliminate the arbitrary reference scale $k_0$ that defines the initial condition for the RG flow, one can express every quantity in units of the IR Planck mass $^{10} M_{\text{Pl}}^2 = G$. To this end, since $e^{2t} \tilde{G}(t) \to \tilde{G}_0$ tends to a constant in the IR, one can evaluate the running Wilson coefficients of eq. (3.8) replacing $t \to -\frac{1}{2} \log \tilde{G}(t)$, so that

$$\log \frac{M_{\text{Pl}}}{k} = \log \frac{M_{\text{Pl}}}{k_0} + t$$

$$\sim -\frac{1}{2} \log \tilde{G}(t)$$

$$\sim -\frac{1}{2} \log \tilde{G}_0 + t.$$  

\(^{10}\)Notice that our convention for the Planck mass differs from the more widespread “reduced” Planck mass $\tilde{M}_{\text{Pl}}^{-2} = 8\pi G$. 

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Figure 3. Flow of the relevant deformations from the fixed point. The left panel depicts the flow in the \((\omega, \lambda)\) subspace. The right panel depicts the flow in the \((G, \Lambda)\) subspace where the classically marginal couplings have been set to the UV fixed point. The arrows indicate the flow from the UV to the IR.

Since \(\tilde{G}_0\) can be extracted from the numerical solution of eqs. (3.5), identifying

\[
\log \frac{k^2}{M_{\text{Pl}}^2} \rightarrow \log \frac{\Box}{M_{\text{Pl}}^2},
\]

according to the preceding considerations, one can reconstruct an effective action of the form

\[
\Gamma = \int d^4x \sqrt{g} \left( \frac{2\Lambda - R}{16\pi G} + g_C C^2 + g_R R^2 + b_C C \log \frac{\Box}{M_{\text{Pl}}^2} C + b_R R \log \frac{\Box}{M_{\text{Pl}}^2} R \right),
\]

where Weyl-tensor contraction is understood. The appearance of non-local form factors resonates with the considerations in [182–184]. While we shall neglect them in the following, the presence of form factors of this type seems largely consistent with preceding results [185–190] (see also [191] for a discussion of logarithmic form factors). Note that, despite their behavior at low energies, one expects a resummation of such non-local form factors to yield a result that is both well-defined and subleading in the IR compared to the local terms [183]\(^{11}\). Furthermore, they do not contribute to the scalar potential that we shall discuss in Section 4.3 in the context of the dSC. Notwithstanding the importance of form factors in establishing a non-local behavior of gravity, we would like to understand which values of the three dimensionless combinations

\[
G_A, \quad g_C, \quad g_R
\]

are allowed starting from any initial condition, \(i.e.,\) any perturbation of the asymptotically safe UV fixed point along UV-attractive directions. To this end, we have evaluated numerically these combinations in the IR, implementing the substitution of eq. (3.9). The

\(^{11}\)One exception could be a non-local form factor of the type \(\sim 1/\Box\), as discussed in [67, 68].
following plots highlighting the swampland constraints, the IR limits of asymptotically safe 
RG trajectories, as well as the final intersection between the allowed regions, will pertain 
to the \((G\Lambda, g_C, g_R)\) theory space.

To conclude this section, let us collect a few words of caution regarding the one-loop 
approximation. In general, in the context of gravity, one expects it to be only reliable in 
the IR, despite the appearance of a UV fixed point outside of the perturbative regime. 
The methods of the functional RG have been employed, both in earlier [89, 192] and 
recent [66] efforts, to obtain non-perturbative flow equations in the quadratic truncation, 
but applying our method to extract the allowed region of parameter space in the IR entails 
highly involved and unstable numerical analysis. In order to circumvent these obstacles, 
and address the problem in a more quantitative fashion, a natural first step would entail 
performing novel FRG computations. The simplest relevant setting would include the 
most general quadratic truncation coupling the electromagnetic field to gravity, which, 
while daunting, appears feasible via the methods that have been very recently introduced 
in [66] to study the purely gravitational sector. In light of these (and other related) issues, 
in this work we have focused on the one-loop approximation as a proof of principle, with 
the hope of uncovering some instructive general lessons from the results that we are now 
about to present.

Finally, let us stress that, although quadratic truncations of the gravitational action 
are typically associated with a loss of physical unitarity [193], the Stelle ghost could be a 
truncation artifact [194]. Integrating out quantum fluctuations could lead to well-behaved, 
unitary scattering amplitudes [183, 184], as explicit computations seem to suggest [195]. 
This issue was also discussed within the setting explored in this paper in [142, 143].

4 Results

Let us now describe in detail our results on the allowed values of physical IR parameters 
that we have obtained from the calculations outlined in the preceding section, along with 
the swampland constraints that we have discussed in sect. 2.

4.1 Infrared limit of asymptotically safe RG trajectories in one-loop quadratic 
gravity

In order to uncover the space of physical parameters appearing in the (local sector of the) 
effective action of eq. (3.11), we have sampled the space of allowed deformations 
\((\delta\omega, \delta\lambda, \delta\tilde{G}, \delta\tilde{\Lambda})\) from the UV fixed point, and extracted the resulting IR values of the 
parameters in eq. (3.12) evaluating the flow of \(\tilde{G}\) and \(\tilde{\Lambda}\) for a suitably large RG time 
t \approx 30, exploiting the rapid convergence of the combination in eq. (3.9). The resulting 
values for \(\tilde{G}\tilde{\Lambda} = G\Lambda\), or equivalently \(\Lambda/M^2_{\text{Pl}}\), span a wide range of values, of the order of 
\(10^5\) for the region of initial deformations that we have explored. Moreover, the closed-form 
flow that one obtains setting the classically marginal couplings to their fixed-point values 
spans the whole real axis [178]. We are thus led to conclude that the allowed (IR) values 
of \(G\Lambda\) are unrestricted. On the other hand, the values of \(g_C\) and \(g_R\) appear to lie on the
Figure 4. The line of equation $g_R = -0.74655 + 3.64447 g_C$ fitting the IR values obtained from the flow of eq. (3.5) sampling UV initial conditions. The covariance matrix evaluates to $O(10^{-8})$ with $10^6$ data points.

line

$$g_R \approx -0.74655 + 3.64447 g_C,$$

as depicted in fig. 4 and fig. 5. This result appears to be very robust upon increase of the sample size, and in particular for $10^6$ points the covariance matrix of the fit is of the order $O(10^{-8})$. Let us observe that, neglecting the intercept term, eq. (4.1) follows from eq. (3.8) as $t \to t_{IR}$, whereby $g_R \sim -2\omega_-/3g_C$. Since we instead evaluate the IR couplings at a fixed, albeit sufficiently large, RG time, it is tempting to speculate that the intercept term in eq. (4.1) is a correction arising from RG trajectories that approach the IR more slowly. Therefore, at least within the scope of our approximations, the presence of a UV fixed point appears to constrain the allowed physical coefficients in eq. (3.12) to a specific plane, and we shall now compare this result to the constraints arising from the swampland conjectures that we have discussed in sect. 2.

4.2 Constraints on quadratic gravity from WGC

As we have discussed in sect. 2.1, the WGC entails positivity bounds for the Wilson coefficients of the higher-derivative corrections to Einstein gravity. Since these bounds involve charged particles and black holes, higher-derivative couplings of a $U(1)$ gauge field ought to be included, although the resulting RG flow is extremely involved technically and has not been computed hitherto. On the other hand, the considerations of [166, 168, 169], based on electromagnetic duality, show that one can still make use of our results to constrain higher-derivative corrections in a duality-invariant scenario using the WGC. To this end, expressing the higher-curvature in terms of the $c_i$ coefficients of eq. (2.3), the (family of) positivity bound(s) of [165] reads

$$(1 - \xi)^2 c_0 + 20\xi c_3 - 5\xi(1 - \xi)(2c_3) > 0$$

(4.2)

where $\xi \equiv \sqrt{1 - Q^2/M^2}$ is the extremality parameter of Reissner-Nordström black holes with mass $M$ and charge $Q$, $0 < \xi < 1/2$ for black holes with positive specific heat and

$$c_0 \equiv c_2 + 4c_3.$$

(4.3)
In terms of the couplings in eq. (3.1), the bound of eq. (4.2) takes the simpler form
\[
\frac{1}{\lambda} (10 \theta (\xi + 1) \xi + 6 \xi^2 + 3 \xi + 1) > 0,
\]
which holds for $\lambda > 0$ provided that $\xi > 0$ (which is always satisfied by the extremality parameter) and that $\theta > 0$. As we have discussed in sect. 3, the latter condition is fulfilled if $\delta \theta > 0$, since $\delta \lambda > 0$ in eq. (3.7). Hence, the (duality-invariant) WGC constrains $\lambda > 0$, which is included by the analysis of the preceding section and does not entail additional conditions. Let us observe that, although $\theta$ encodes the coupling of the Gauss-Bonnet invariant, it contributes to the entropy of a black hole [196–198] even in four dimensions, where it is topological. It does not contribute in the limit $\xi \ll 1$, since the resulting bound also describes the positivity of the extremality ratio [164, 168].

4.3 Constraints on quadratic gravity from dS and TC conjectures

Let us now discuss the constraints arising from the dSC and the TCC. As we have anticipated in sect. 2.2, we shall focus on the bounds that the dSC and the TCC entail for the scalar potential that arises from the higher-derivative corrections of eq. (3.11). In order to extract the potential proper, we shall concern ourselves with the local sector of
the theory, neglecting the form factors and the Weyl term, which vanishes on cosmological backgrounds.

Following the standard procedure to obtain inflaton potentials from $F(R)$ Lagrangians (see, e.g., [137, 199]), one begins from $R^2$ gravity with a cosmological constant,

$$F(R) = \frac{1}{16\pi G} \left( R - 2\Lambda + \frac{R^2}{6m^2} \right),$$

where the coupling $g_R$ is related to the inflaton mass according to

$$g_R = -\frac{M^2_{\text{Pl}}}{(8\pi) \cdot 12m^2}. \quad (4.6)$$

One then arrives at the inflaton potential

$$V(\phi) = \frac{M^2_{\text{Pl}}}{8\pi} e^{-2\sqrt{\frac{3}{2} \pi^2 \phi}} \left( \frac{3m^2}{4} \left( e^{\sqrt{\frac{3}{2} \pi^2 \phi}} - 1 \right)^2 + \Lambda \right). \quad (4.7)$$

In order to retain compatibility with the EFT, we shall consider field values in eq. (2.6) around $\phi \ll M_{\text{Pl}}$, since it corresponds to small curvatures. Indeed, the procedure to obtain inflationary potentials from quadratic gravity yields $\phi = \sqrt{\frac{3}{2}} M_{\text{Pl}} \log \left( 1 + O(M_{\text{Pl}}^2) \right)$ [137, 199]. One can then study dSC and TCC constraints of eqs. (2.5), (2.7) and (2.8) numerically varying the $O(1)$ constants $c$ and $f$, imposing that the bounds be satisfied for all $\phi$ in the range allowed by eq. (2.6). The resulting regions are highlighted in fig. 6 and in fig. 7, where each panel corresponds to a particular value of $f$ and consists of two plots which display the bounds in the $(m^2, \Lambda)$ (left panels) and $(g_R, G\Lambda)$ (right panels) planes. Due to the inverse relation in eq. (4.6) between $m^2/M_{\text{Pl}}^2$ and $g_R$, the linear bounds in the $(m^2, \Lambda)$ plane translate into hyperbolas in the $(g_R, G\Lambda)$ plane. Note that whether the dimensionless minimum $\phi_{\text{min}}/M_{\text{Pl}}$, which exists for $\Lambda/m^2 > -3/4$, falls inside the interval $(-f, +f)$ depends on the ratio $\Lambda/m^2$. In particular, the minimum falls outside the interval for $f < |\phi_{\text{min}}/M_{\text{Pl}}|$. Consequently, even if $V(\phi_{\text{min}})$ were to be positive for some $\Lambda$ and $m^2$, this would not necessarily violate the dSC/TCC bounds for fixed values of $f$ and $c$. Consequently, the bounds displayed in fig. 6 and in fig. 7 are non-trivially affected by eq. (2.6), and by the specific values of $f$ and $c$. For instance, it is worth noticing that smaller values of $f$ entail smaller field intervals where the dSC/TCC bounds are to be satisfied. Thus, the bounds are less stringent, and the allowed region bigger. Similarly, the bound is more restrictive for higher values of $c$. In particular, fig. 7 depicts the bounds derived from $c = \sqrt{2}/3$, the value pertaining to the TCC. While our analysis cannot probe the TCC in the large-excitation regime, where it differs substantially from the dSC, the additional considerations of [152, 173] point to a deeper role of this value of $c$ which could manifest itself, in the low-curvature regime at stake, in further investigations of swampland bounds and/or dimensional reduction.

### 4.4 Intersections of allowed regions: compatibility of asymptotic safety with dS, TC and WG conjectures

We are now ready to collect the results that we have discussed in the preceding sections, and to visualize the intersection between the different allowed regions. Within (an extrapolation...
Figure 6. dSC/TCC constraints for \( f = 0.1 \) (top panel), \( f = 0.5 \) (central panel) and \( f = 1 \) (bottom panel), and various values of \( c \). Due to the inverse relation in eq. (4.6) between the inflaton mass in Planck units \( m^2/M_{Pl}^2 \) and the coupling \( g_R \), the linear bounds in the \((m^2, \Lambda)\) plane translate into hyperbolas in the \((g_R, G\Lambda)\) plane.

of the) one-loop approximation, asymptotic safety of the RG flow constrains the physical IR parameters of eq. (3.12) to lie on the plane of eq. (4.1). On the other hand, while the (duality-invariant) WGC does not entail any additional constraint, the dSC/TCC
conditions for the inflaton potential place constraints on the cosmological constant and the inflaton mass. One can plot the intersections for any values of the $O(1)$ constants $c$ and $f$, and fig. 8, the main result of our work, refers to the representative choice $c = f = 1$.

Albeit difficult to visualize, there is in general a region of the asymptotically safe plane that appears compatible with the swampland constraints that we have investigated. One can straightforwardly verify that the same conclusion is reached for different values of $f$ and $c$. Our findings, based on the quadratic one-loop approximation, thus point at a non-trivial compatibility between the conditions for UV-completeness dictated by asymptotic safety and some of the most relevant swampland conjectures. Consequently, it also points at the possibility, partially supported by [200, 201], of a connection between the frameworks of asymptotic safety and string theory [81]. Within this picture, field-theoretical asymptotic safety would serve as a “pivot” for the RG flow from string theory to low-energy gravity, in the sense that below a certain scale the flow of string theory toward the IR closely approaches a field-theoretical trajectory controlled by a UV fixed point.

5 Conclusions

In this paper we have analyzed the intersection of consistency conditions for Wilson coefficients of gravitational EFTs, combining the constraints of asymptotic safety and swampland conjectures. In particular, in sect. 3 we have employed a systematic method to extract the hypersurface of allowed IR parameters stemming from UV-complete RG trajectories in gravitational theories by randomly sampling its relevant deformations, and we have applied this technique to the flow equations stemming from one-loop quadratic gravity [178]. Despite expecting that this approximation be reliable in the IR, the resulting RG flow exhibits a UV non-Gaussian fixed point, consistently with more refined functional RG computations [202–204]. However, the dimension of its critical surface is larger than what is suggested by the functional RG [66, 89, 192, 205]. As we have discussed in detail in sect. 4, our findings suggest that the requirement that the RG flow be asymptotically
Figure 8. Intersections between the regions allowed by asymptotic safety, the WGC and the dSC/TCC for the representative values $c = f = 1$. The WGC bound corresponds to the yellow region, while the dSC/TCC bound corresponds to the blue region. The green region depicts the space of IR parameters spanned by asymptotically safe trajectories, which lies within the region allowed by the WGC.

safe constrains the physical parameters to lie on a plane, which we have determined, within our one-loop framework, to a precision of order $O(10^{-8})$. The values of the cosmological constant in Planck units seems not to be restricted by these considerations, while the classically marginal couplings lie on a line.

In sect. 4.2 and sect. 4.3 we have investigated the constraints on the Wilson coefficients arising from the weak gravity conjecture (WGC), the de Sitter conjecture (dSC) and the trans-Planckian censorship conjecture (TCC). In particular, the WGC does not entail
additional bounds and is compatible with the UV-complete RG trajectories, while the dSC/TCC bounds are more restrictive. To wit, the Starobinsky-like scalar potential stemming from the (local sector of the) effective action involves the ratio of the cosmological constant to the (squared) inflaton mass, and therefore the corresponding bounds place constraints on the dimensionless ratios $\Lambda/M_{Pl}^2$ and $m/M_{Pl}$. These bounds depend on some dimensionless $\mathcal{O}(1)$ constants, which we have varied to some extent in our analysis, and generally trace out a region in the plane allowed by asymptotic safety. While we expect that the qualitative results be unaffected by improving the truncation scheme, at least to some extent, it would be interesting to investigate the quantitative deviations in this respect.

While in this work we have focused on the local sector of the effective action, our computation also yields the coefficients of non-local logarithmic form factors, akin to those arising from non-local heat kernel computations [206–211]. It would be interesting to explore their consequences and their role within asymptotically safe gravity [182–184] and their connection to massive matter fields [212].

All in all, our results suggest that swampland constraints can be compatible with restrictions coming from UV completeness of the RG flow, but in a non-trivial fashion: the allowed parameter space is restricted to a non-trivial intersection. In retrospect, one could have expected this result on the grounds that some swampland criteria purport to be necessary conditions for UV completeness that cannot be derived from purely field-theoretical considerations, and thus they could constrain further the parameter space compatible with asymptotic safety. On the other hand, the one-loop approximation that we have studied already features the appearance of non-local form factors. In general, non-locality at the level of the effective action is a feature of any standard (local) QFT, and thus it is in principle unrelated to possible fundamental non-localities in the bare (fixed-point) action. Precisely how the notion of (non-)locality is realized in quantum gravity is an open and intriguing question, partly related to the problem of observables [213–217]. However, a number of semi-classical considerations [162, 218–223] point to the breaking of the familiar concept of locality microscopically. Whether asymptotically safe gravity is realized by a bare action polynomial in derivatives (and thus “local” in some sense) is not established yet. Should fundamental non-locality turn out to emerge as a feature of asymptotic safety, this would strengthen its potential connections with the frameworks of non-local gravity [224–227] and string theory [228].

Due to the nature of our approximations, this work constitutes only a first step toward determining whether the asymptotic safety scenario is compatible with the peculiar behavior and UV/IR mixing that gravity could exhibit already at the semi-classical level due to black holes (see [229] for a very recent discussion on their validity and limitations), or with general indications from string theory. In particular, a possible connection between asymptotically safe gravity and string theory has been conjectured in [81], and it is tempting to speculate that it could explain our findings. Computations combining the functional renormalization group techniques [83] with symmetries of string theory [230–235] have provided preliminary evidence in favour of this scenario [200, 201]. This possibility extends to the more general notion of “effective asymptotic safety” [236], and swampland bounds
could further constrain which RG flows controlled by the “effective” fixed point are closely approached by the RG flow arising from the proper UV completion in the IR.

Most prominently, the absence of continuous global symmetries\(^{12}\) is supported by a variety of arguments from black-hole physics, string theory and holography [60–63, 239–241], and it would be interesting to explore this foundational issue further in the direction that we have outlined in this paper.

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References

[1] G. ’t Hooft and M. J. G. Veltman, *One loop divergencies in the theory of gravitation*, Ann. Inst. H. Poincare Phys. Theor. A **20** (1974) 69.

[2] M. H. Goroff and A. Sagnotti, *The ultraviolet behavior of Einstein gravity*, Nuclear Physics B **266** (1986) 709.

[3] M. H. Goroff and A. Sagnotti, *Quantum gravity at two loops*, Physics Letters B **160** (1985) 81.

[4] C. Vafa, *The String landscape and the swampland*, hep-th/0509212.

[5] P. Berglund and P. Mayr, *Non-perturbative superpotentials in F-theory and string duality*, JHEP **01** (2013) 114 [hep-th/0504058].

[6] E. Gonzalo, L. E. Ibáñez and A. M. Uranga, *Modular symmetries and the swampland conjectures*, JHEP **05** (2019) 105 [1812.06520].

[7] F. Marchesano and M. Wiesner, *Instantons and infinite distances*, JHEP **08** (2019) 088 [1904.04848].

[8] R. Blumenhagen, M. Brinkmann and A. Makridou, *Quantum Log-Corrections to Swampland Conjectures*, JHEP **02** (2020) 064 [1910.10185].

[9] F. Baume, F. Marchesano and M. Wiesner, *Instanton Corrections and Emergent Strings*, JHEP **04** (2020) 174 [1912.02218].

[10] E. Palti, C. Vafa and T. Weigand, *Supersymmetric Protection and the Swampland*, JHEP **06** (2020) 168 [2003.10452].

\(^{12}\) The fate of global discrete symmetries has been investigated in the context of asymptotically safe gravity in [237, 238].
F. Marchesano, D. Prieto and M. Wiesner, \textit{F-theory flux vacua at large complex structure}, 2105.09326.

S.-J. Lee, W. Lerche and T. Weigand, \textit{Tensionless Strings and the Weak Gravity Conjecture}, \textit{JHEP} 10 (2018) 164 [1808.05958].

S.-J. Lee, W. Lerche and T. Weigand, \textit{A Stringy Test of the Scalar Weak Gravity Conjecture}, \textit{Nucl. Phys. B} 938 (2019) 321 [1810.05169].

S.-J. Lee, W. Lerche and T. Weigand, \textit{Modular Fluxes, Elliptic Genera, and Weak Gravity Conjectures in Four Dimensions}, \textit{JHEP} 08 (2019) 104 [1901.08065].

S.-J. Lee, W. Lerche and T. Weigand, \textit{Emergent Strings, Duality and Weak Coupling Limits for Two-Form Fields}, 1904.06344.

D. Klaewer, S.-J. Lee, T. Weigand and M. Wiesner, \textit{Quantum corrections in 4d $\mathcal{N} = 1$ infinite distance limits and the weak gravity conjecture}, \textit{JHEP} 03 (2021) 252 [2011.00024].

D. Klaewer, \textit{Modular Curves and the Refined Distance Conjecture}, 2108.00021.

T. W. Grimm, E. Palti and I. Valenzuela, \textit{Infinite Distances in Field Space and Massless Towers of States}, \textit{JHEP} 08 (2018) 143 [1802.08264].

T. W. Grimm and D. Van De Heisteeg, \textit{Infinite Distances and the Azion Weak Gravity Conjecture}, \textit{JHEP} 03 (2020) 020 [1905.00901].

T. W. Grimm, C. Li and I. Valenzuela, \textit{Asymptotic Flux Compactifications and the Swampland}, \textit{JHEP} 06 (2020) 009 [1910.09549].

N. Gendler and I. Valenzuela, \textit{Merging the weak gravity and distance conjectures using BPS extremal black holes}, \textit{JHEP} 01 (2021) 176 [2004.10768].

T. W. Grimm and C. Li, \textit{Universal axion backreaction in flux compactifications}, \textit{JHEP} 06 (2021) 067 [2012.08272].

B. Bastian, T. W. Grimm and D. van de Heisteeg, \textit{Modelling General Asymptotic Calabi-Yau Periods}, 2105.02232.

I. Basile and S. Lanza, \textit{de Sitter in non-supersymmetric string theories: no-go theorems and brane-worlds}, \textit{JHEP} 10 (2020) 108 [2007.13757].

I. Basile, \textit{Supersymmetry breaking, brane dynamics and Swampland conjectures}, 2106.04574.

S. Kachru, R. Kallosh, A. D. Linde and S. P. Trivedi, \textit{De Sitter vacua in string theory}, \textit{Phys. Rev. D} 68 (2003) 046005 [hep-th/0301240].

V. Balasubramanian, P. Berglund, J. P. Conlon and F. Quevedo, \textit{Systematics of moduli stabilisation in Calabi-Yau flux compactifications}, \textit{JHEP} 03 (2005) 007 [hep-th/0502058].

P. Koerber and L. Martucci, \textit{From ten to four and back again: How to generalize the geometry}, \textit{JHEP} 08 (2007) 059 [0707.1038].

U. H. Danielsson, S. S. Haque, G. Shiu and T. Van Riet, \textit{Towards Classical de Sitter Solutions in String Theory}, \textit{JHEP} 09 (2009) 114 [0907.2041].

J. Moritz, A. Retolaza and A. Westphal, \textit{Toward de Sitter space from ten dimensions}, \textit{Phys. Rev. D} 97 (2018) 046010 [1707.08678].

R. Kallosh and T. Wrase, \textit{dS Supergravity from 10d}, \textit{Fortsch. Phys.} 67 (2019) 1800071 [1808.09427].
[32] I. Bena, E. Dudas, M. Graña and S. Lüst, *Uplifting Runaways*, Fortsch. Phys. 67 (2019) 1800100 [1809.06861].

[33] F. Gautason, V. Van Hemelryck and T. Van Riet, *The Tension between 10D Supergravity and dS Uplifts*, Fortsch. Phys. 67 (2019) 1800091 [1810.08518].

[34] C. Córdova, G. B. De Luca and A. Tomasiello, *Classical de Sitter Solutions of 10-Dimensional Supergravity*, Phys. Rev. Lett. 122 (2019) 091601 [1812.04147].

[35] J. Blåbäck, U. Danielsson, G. Dibitetto and S. Giri, *Constructing stable de Sitter in M-theory from higher curvature corrections*, JHEP 09 (2019) 042 [1902.04053].

[36] Y. Hamada, A. Hebecker, G. Shiu and P. Soler, *Understanding KKLT from a 10d perspective*, JHEP 06 (2019) 019 [1902.01410].

[37] F. Gautason, V. Van Hemelryck, T. Van Riet and G. Venken, *A 10d view on the KKLT AdS vacuum and uplifting*, JHEP 06 (2020) 074 [1902.01415].

[38] N. Cribiori and D. Junghans, *No classical (anti-)de Sitter solutions with O8-planes*, Phys. Lett. B 793 (2019) 54 [1902.08209].

[39] D. Andriot, *Open problems on classical de Sitter solutions*, Fortsch. Phys. 67 (2019) 1900026 [1902.10093].

[40] P. Shukla, *T-dualizing de Sitter no-go scenarios*, Phys. Rev. D 102 (2020) 026014 [1909.08630].

[41] P. Shukla, *Rigid nongeometric orientifolds and the swampland*, Phys. Rev. D 103 (2021) 086010 [1909.10993].

[42] C. Córdova, G. G. B. De Luca and A. Tomasiello, *New de Sitter Solutions in Ten Dimensions and Orientifold Singularities*, 1911.04498.

[43] D. Andriot, P. Marconnet and T. Wrase, *New de Sitter solutions of 10d type IIB supergravity*, JHEP 08 (2020) 076 [2005.12930].

[44] D. Andriot, P. Marconnet and T. Wrase, *Intricacies of classical de Sitter string backgrounds*, 2006.01848.

[45] F. Farakos, A. Kehagias and N. Liatsos, *de Sitter decay through goldstino evaporation*, JHEP 02 (2021) 186 [2009.03335].

[46] X. Gao, A. Hebecker and D. Junghans, *Control issues of KKLT*, Fortsch. Phys. 68 (2020) 2000089 [2009.03914].

[47] I. Bena, G. B. De Luca, M. Graña and G. Lo Monaco, *Oh, wait, O8 de Sitter may be unstable!*, JHEP 03 (2021) 168 [2010.05936].

[48] I. Bena, J. Blåbäck, M. Graña and S. Lüst, *The Tadpole Problem*, 2010.10519.

[49] C. Crinò, F. Quevedo and R. Valandro, *On de Sitter String Vacua from Anti-D3-Branes in the Large Volume Scenario*, JHEP 03 (2021) 258 [2010.15903].

[50] M. Dine, J. A. P. Law-Smith, S. Sun, D. Wood and Y. Yu, *Obstacles to Constructing de Sitter Space in String Theory*, JHEP 02 (2021) 050 [2008.12399].

[51] V. Basiouris and G. K. Leontaris, *Note on de Sitter vacua from perturbative and non-perturbative dynamics in type IIB/F-theory compactifications*, Phys. Lett. B 810 (2020) 135809 [2007.15423].
[52] N. Cribiori, G. Dall’agata and F. Farakos, Weak gravity versus de Sitter, JHEP 04 (2021) 046 [2011.06597].

[53] A. Hebecker and S. Leonhardt, Winding Uplifts and the Challenges of Weak and Strong SUSY Breaking in AdS, JHEP 03 (2021) 284 [2012.00010].

[54] D. Andriot, Tachyonic de Sitter solutions of 10d type II supergravities, 2101.06251.

[55] G. B. De Luca, E. Silverstein and G. Torroba, Hyperbolic compactification of M-theory and de Sitter quantum gravity, 2104.13380.

[56] M. Cicoli, I. n. G. Etxebarria, F. Quevedo, A. Schachner, P. Shukla and R. Valandro, The Standard Model Quiver in de Sitter String Compactifications, 2106.11964.

[57] N. Cribiori, D. Junghans, V. Van Hemelryck, T. Van Riet and T. Wrase, Scale-separated AdS vacua of IIA orientifolds and M-theory, 2107.00019.

[58] M. Dine and N. Seiberg, Is the Superstring Weakly Coupled?, Phys. Lett. B 162 (1985) 299.

[59] M. Montero and C. Vafa, Cobordism Conjecture, Anomalies, and the String Lamppost Principle, JHEP 01 (2021) 063 [2008.11729].

[60] C. W. Misner and J. A. Wheeler, Classical physics as geometry: Gravitation, electromagnetism, unquantized charge, and mass as properties of curved empty space, Annals Phys. 2 (1957) 525.

[61] J. Polchinski, Monopoles, duality, and string theory, Int. J. Mod. Phys. A 19S1 (2004) 145 [hep-th/0304042].

[62] T. Banks and N. Seiberg, Symmetries and Strings in Field Theory and Gravity, Phys. Rev. D 83 (2011) 084019 [1011.5120].

[63] D. Harlow and H. Ooguri, Symmetries in quantum field theory and quantum gravity, Commun. Math. Phys. 383 (2021) 1669 [1810.05338].

[64] N. Arkani-Hamed, L. Motl, A. Nicolis and C. Vafa, The String landscape, black holes and gravity as the weakest force, JHEP 06 (2007) 060 [hep-th/0601001].

[65] D. Benedetti, K. Groh, P. F. Machado and F. Saueressig, The universal RG machine, Journal of High Energy Physics 6 (2011) 79 [1012.3081].

[66] B. Knorr, The derivative expansion in asymptotically safe quantum gravity: general setup and quartic order, 2104.11336.

[67] E. Belgacem, Y. Dirian, S. Foffa and M. Maggiore, Nonlocal gravity. Conceptual aspects and cosmological predictions, JCAP 03 (2018) 002 [1712.07066].

[68] B. Knorr and F. Saueressig, Towards reconstructing the quantum effective action of gravity, Phys. Rev. Lett. 121 (2018) 161304 [1804.03846].

[69] A. Guerrieri, J. Penedones and P. Vieira, Where is String Theory?, 2102.02847.

[70] S. Caron-Huot, D. Mazac, L. Rastelli and D. Simmons-Duffin, Sharp Boundaries for the Swampland, 2102.08951.

[71] C. de Rham, S. Melville, A. J. Tolley and S.-Y. Zhou, UV complete me: Positivity Bounds for Particles with Spin, JHEP 03 (2018) 011 [1706.02712].

[72] C. de Rham, S. Melville and A. J. Tolley, Improved Positivity Bounds and Massive Gravity, JHEP 04 (2018) 083 [1710.09611].
C. de Rham, S. Melville, A. J. Tolley and S.-Y. Zhou, *Positivity Bounds for Massive Spin-1 and Spin-2 Fields*, *JHEP* **03** (2019) 182 [1804.10624].

C. De Rham, L. Heisenberg and A. J. Tolley, *Spin-2 fields and the weak gravity conjecture*, *Phys. Rev. D* **100** (2019) 104033 [1812.01012].

L. Alberte, C. de Rham, A. Momeni, J. Rumbutis and A. J. Tolley, *EFT of Interacting Spin-2 Fields*, *JHEP* **01** (2020) 131 [1910.05285].

L. Alberte, C. de Rham, A. Momeni, J. Rumbutis and A. J. Tolley, *Positivity Constraints on Interacting Spin-2 Fields*, *JHEP* **03** (2020) 097 [1910.11799].

L. Alberte, C. de Rham, A. Momeni, J. Rumbutis and A. J. Tolley, *Positivity Constraints on Interacting Pseudo-Linear Spin-2 Fields*, *JHEP* **07** (2020) 121 [1912.10018].

L. Alberte, C. de Rham, S. Jaitly and A. J. Tolley, *QED positivity bounds*, *Phys. Rev. D* **103** (2021) 125020 [2012.05798].

L. Alberte, C. de Rham, S. Jaitly and A. J. Tolley, *Positivity Bounds and the Massless Spin-2 Pole*, *Phys. Rev. D* **102** (2020) 125023 [2007.12667].

C. de Rham, S. Melville and J. Noller, *Positivity Bounds on Dark Energy: When Matter Matters*, 2103.06855.

S. de Alwis, A. Eichhorn, A. Held, J. M. Pawlowski, M. Schiffer and F. Versteegen, *Asymptotic safety, string theory and the weak gravity conjecture*, *Phys. Lett. B* **798** (2019) 134991 [1907.07894].

S. Weinberg, *Critical Phenomena for Field Theorists, Erice Subnuclear Physics* (1976).

N. Dupuis, L. Canet, A. Eichhorn, W. Metzner, J. Pawlowski, M. Tissier et al., *The nonperturbative functional renormalization group and its applications*, 2006.04853.

W. Souma, *Non-Trivial Ultraviolet Fixed Point in Quantum Gravity*, *Progress of Theoretical Physics* **102** (1999) 181 [hep-th/9907027].

O. Lauscher and M. Reuter, *Flow equation of quantum Einstein gravity in a higher-derivative truncation*, *Phys. Rev. D* **66** (2002) 025026 [hep-th/0205062].

D. F. Litim, *Fixed Points of Quantum Gravity*, *Physical Review Letters* **92** (2004) 201301 [hep-th/0312114].

A. Codello and R. Percacci, *Fixed Points of Higher-Derivative Gravity*, *Physical Review Letters* **97** (2006) 221301 [hep-th/0607128].

P. F. Machado and F. Saueressig, *On the renormalization group flow of f(R)-gravity*, *Phys. Rev. D* **77** (2008) 124045 [arXiv:0712.0445].

D. Benedetti, P. F. Machado and F. Saueressig, *Asymptotic Safety in Higher-Derivative Gravity*, *Modern Physics Letters A* **24** (2009) 2233 [0901.2984].

J. A. Dietz and T. R. Morris, *Asymptotic safety in the f(R) approximation*, *Journal of High Energy Physics* **1** (2013) 108 [1211.0955].

P. Donà, A. Eichhorn and R. Percacci, *Matter matters in asymptotically safe quantum gravity*, *Phys. Rev. D* **89** (2014) 084035 [1311.2898].

A. Eichhorn, *On unimodular quantum gravity*, *Class. Quant. Grav.* **30** (2013) 115016 [1301.0879].
[93] P. Donà, A. Eichhorn and R. Percacci, Consistency of matter models with asymptotically safe quantum gravity, Canadian Journal of Physics 93 (2015) 988 [1410.4411].

[94] N. Christiansen, B. Knorr, J. M. Pawlowski and A. Rodigast, Global Flows in Quantum Gravity, Phys. Rev. D93 (2016) 044036 [1403.1232].

[95] K. Falls, D. Litim, K. Nikolakopoulos and C. Rahmede, Further evidence for asymptotic safety of quantum gravity, Phys. Rev. D 93 (2016) 104022.

[96] N. Christiansen, B. Knorr, J. Meibohm, J. M. Pawlowski and M. Reichert, Local Quantum Gravity, Phys. Rev. D92 (2015) 121501 [1506.07016].

[97] J. Meibohm, J. M. Pawlowski and M. Reichert, Asymptotic safety of gravity-matter systems, Phys. Rev. D 93 (2016) 104022.

[98] K. Y. Oda and M. Yamada, Non-minimal coupling in Higgs-Yukawa model with asymptotically safe gravity, Classical and Quantum Gravity 33 (2016) 125011 [1510.03734].

[99] P. Donà, A. Eichhorn, P. Labus and R. Percacci, Asymptotic safety in an interacting system of gravity and scalar matter, Phys. Rev. D 93 (2016) 044049 [1512.01589].

[100] J. Biemans, A. Platania and F. Saueressig, Quantum gravity on foliated spacetimes: Asymptotically safe and sound, Phys. Rev. D95 (2017) 086013 [1609.04813].

[101] A. Eichhorn, A. Held and J. M. Pawlowski, Quantum-gravity effects on a Higgs-Yukawa model, Phys. Rev. D 94 (2016) 104027 [1604.02041].

[102] J. A. Dietz, T. R. Morris and Z. H. Slade, Fixed point structure of the conformal factor field in quantum gravity, Phys. Rev. D 94 (2016) 124014 [1605.07636].

[103] K. Falls and N. Ohta, Renormalization group equation for f(R) gravity on hyperbolic spaces, Phys. Rev. D 94 (2016) 084005 [1607.08460].

[104] H. Gies, B. Knorr, S. Lippoldt and F. Saueressig, Gravitational Two-Loop Counterterm Is Asymptotically Safe, Physical Review Letters 116 (2016) 211302 [1601.01800].

[105] J. Biemans, A. Platania and F. Saueressig, Renormalization group fixed points of foliated gravity-matter systems, JHEP 05 (2017) 093 [1702.06539].

[106] N. Christiansen, D. F. Litim, J. M. Pawlowski and M. Reichert, Asymptotic safety of gravity with matter, Phys. Rev. D97 (2018) 106012 [1710.04669].

[107] Y. Hamada and M. Yamada, Asymptotic safety of higher derivative quantum gravity non-minimally coupled with a matter system, JHEP 08 (2017) 070 [1703.09033].

[108] A. Platania and F. Saueressig, Functional Renormalization Group Flows on Friedmann-Lemaître-Robertson-Walker backgrounds, Found. Phys. 48 (2018) 1291 [1710.01972].

[109] K. Falls, C. R. King, D. F. Litim, K. Nikolakopoulos and C. Rahmede, Asymptotic safety of quantum gravity beyond Ricci scalars, Phys. Rev. D97 (2018) 086006 [1801.00162].

[110] G. P. De Brito, N. Ohta, A. D. Pereira, A. A. Tomaz and M. Yamada, Asymptotic safety and field parametrization dependence in the f(R) truncation, 1805.09656.

[111] A. Eichhorn, S. Lippoldt and M. Schiffer, Zooming in on fermions and quantum gravity, Phys. Rev. D99 (2019) 086002 [1812.08782].

[112] A. Eichhorn and M. Schiffer, d = 4 as the critical dimensionality of asymptotically safe interactions, Phys. Lett. B793 (2019) 383 [1902.06479].
[113] G. P. De Brito, A. Eichhorn and A. D. Pereira, A link that matters: Towards phenomenological tests of unimodular asymptotic safety, JHEP 09 (2019) 100 [1907.11173].

[114] J. F. Donoghue, A Critique of the Asymptotic Safety Program, Front. in Phys. 8 (2020) 56 [1911.02967].

[115] A. Bonanno, A. Eichhorn, H. Gies, J. M. Pawlowski, R. Percacci, M. Reuter et al., Critical reflections on asymptotically safe gravity, Front. in Phys. 8 (2020) 269 [2004.06810].

[116] A. Bonanno and F. Saueressig, Asymptotically safe cosmology - A status report, Comptes Rendus Physique 18 (2017) 254 [1702.04137].

[117] A. Platania, From renormalization group flows to cosmology, Front. in Phys. 8 (2020) 188 [2003.13656].

[118] A. Bonanno and M. Reuter, Spacetime structure of an evaporating black hole in quantum gravity, Phys. Rev. D73 (2006) 083005 [hep-th/0602159].

[119] K. Falls and D. F. Litim, Black hole thermodynamics under the microscope, Phys. Rev. D89 (2014) 084002 [1212.1821].

[120] R. Torres and F. Fayos, On the quantum corrected gravitational collapse, Physics Letters B 747 (2015) 245 [1503.07407].

[121] B. Koch and P. Rioseco, Black Hole Solutions for Scale Dependent Couplings: The de Sitter and the Reissner-Nordström Case, Class. Quant. Grav. 33 (2016) 035002 [1501.00904].

[122] A. Bonanno and A. Platania, Asymptotically safe inflation from quadratic gravity, Phys. Lett. B750 (2015) 638 [1507.03375].

[123] A. Bonanno and A. Platania, Asymptotically Safe R+R2 gravity, PoS corfu2015 (2016) 159.

[124] G. Kofinas and V. Zarikas, Asymptotically Safe gravity and non-singular inflationary Big Bang with vacuum birth, Phys. Rev. D94 (2016) 103514 [1605.02241].

[125] K. Falls, D. F. Litim, K. Nikolakopoulos and C. Rahmede, On de Sitter solutions in asymptotically safe f(R) theories, Class. Quant. Grav. 35 (2018) 135006 [1607.04962].

[126] A. Bonanno, B. Koch and A. Platania, Cosmic Censorship in Quantum Einstein Gravity, Class. Quant. Grav. 34 (2017) 095012 [1610.05299].

[127] A. Bonanno, S. J. Gabriele Gionti and A. Platania, Bouncing and emergent cosmologies from Arnowitt-Deser-Misner RG flows, Class. Quant. Grav. 35 (2018) 065004 [1710.06317].

[128] A. Bonanno, B. Koch and A. Platania, Asymptotically Safe gravitational collapse: Kuroda-Papapetrou RG-improved model, PoS corfu2016 (2017) 058.

[129] A. Bonanno, B. Koch and A. Platania, Gravitational collapse in Quantum Einstein Gravity, 1710.10845.

[130] A. Bonanno, A. Platania and F. Saueressig, Cosmological bounds on the field content of asymptotically safe gravity-matter models, 1803.02355.

[131] L.-H. Liu, T. Prokopec and A. A. Starobinsky, Inflation in an effective gravitational model and asymptotic safety, Phys. Rev. D98 (2018) 043505 [1806.05407].

[132] A. Majhi, Singularity from star collapse, torsion and asymptotic safety of gravity, 1804.00960.
[133] F. K. Anagnostopoulos, S. Basilakos, G. Kofinas and V. Zarikas, Constraining the Asymptotically Safe Cosmology: cosmic acceleration without dark energy, *JCAP* **1902** (2019) 053 [1806.10580].

[134] A. Adeifeoba, A. Eichhorn and A. Platania, Towards conditions for black-hole singularity-resolution in asymptotically safe quantum gravity, *Class. Quant. Grav.* **35** (2018) 225007 [1808.03472].

[135] J. M. Pawlowski and D. Stock, Quantum-improved Schwarzschild-(A)dS and Kerr-(A)dS spacetimes, *Phys. Rev.* **D98** (2018) 106008 [1807.10512].

[136] G. Gubitosi, R. Ooijer, C. Ripken and F. Saueressig, Consistent early and late time cosmology from the RG flow of gravity, *JCAP* **1812** (2018) 004 [1806.10147].

[137] A. Platania, The inflationary mechanism in Asymptotically Safe Gravity, *Universe* **5** (2019) 189 [1908.03897].

[138] A. Platania, Dynamical renormalization of black-hole spacetimes, *Eur. Phys. J.* **C79** (2019) 470 [1903.10411].

[139] A. Bonanno, R. Casadio and A. Platania, Gravitational antiscreening in stellar interiors, *JCAP* **2001** (2020) 022 [1910.11393].

[140] A. Held, R. Gold and A. Eichhorn, Asymptotic safety casts its shadow, *JCAP* **1906** (2019) 029 [1904.07133].

[141] L. Bosma, B. Knorr and F. Saueressig, Resolving Spacetime Singularities within Asymptotic Safety, *Phys. Rev. Lett.* **123** (2019) 101301 [1904.04845].

[142] M. R. Niedermaier, Gravitational Fixed Points from Perturbation Theory, *Phys. Rev. Lett.* **103** (2009) 101303.

[143] M. Niedermaier, Gravitational fixed points and asymptotic safety from perturbation theory, *Nucl. Phys. B* **833** (2010) 226.

[144] N. Cribiori, D. Lust and M. Scalisi, The gravitino and the swampland, *JHEP* **06** (2021) 071 [2104.08288].

[145] A. Castellano, A. Font, A. Herraez and L. E. Ibáñez, A Gravitino Distance Conjecture, 2104.10181.

[146] Q. Bonnefoy, E. Dudas and S. Lüst, On the weak gravity conjecture in string theory with broken supersymmetry, *Nucl. Phys. B* **947** (2019) 114738 [1811.11199].

[147] J. Mourad and A. Sagnotti, An Update on Brane Supersymmetry Breaking, 1711.11494.

[148] I. Basile, Supersymmetry Breaking and Stability in String Vacua: brane dynamics, bubbles and the swampland, *Riv. Nuovo Cim.* **1** (2021) 98 [2107.02814].

[149] J. Mourad and A. Sagnotti, String (In)Stability Issues with Broken Supersymmetry, 7, 2021, 2107.04064.

[150] E. Palti, The Swampland: Introduction and Review, *Fortsch. Phys.* **67** (2019) 1900037 [1903.06239].

[151] M. van Beest, J. Calderón-Infante, D. Mirfendereski and I. Valenzuela, Lectures on the Swampland Program in String Compactifications, 2102.01111.

[152] D. Andriot, N. Cribiori and D. Erkinger, The web of swampland conjectures and the TCC bound, *JHEP* **07** (2020) 162 [2004.00030].
[153] S. Lanza, F. Marchesano, L. Martucci and I. Valenzuela, Swampland Conjectures for Strings and Membranes, JHEP 02 (2021) 006 [2006.15154].

[154] H. Ooguri and C. Vafa, On the Geometry of the String Landscape and the Swampland, Nucl. Phys. B 766 (2007) 21 [hep-th/0605264].

[155] H. Ooguri, E. Palti, G. Shiu and C. Vafa, Distance and de Sitter Conjectures on the Swampland, Phys. Lett. B 788 (2019) 180 [1810.05506].

[156] M. Graña and A. Herráez, The Swampland Conjectures: A bridge from Quantum Gravity to Particle Physics, 6, 2021, 2107.00087.

[157] G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, De Sitter Space and the Swampland, 1806.08362.

[158] S. K. Garg and C. Krishnan, Bounds on Slow Roll and the de Sitter Swampland, JHEP 11 (2019) 075 [1807.05193].

[159] D. Andriot and C. Roupec, Further refining the de Sitter swampland conjecture, Fortsch. Phys. 67 (2019) 1800105 [1811.08889].

[160] A. Bedroya and C. Vafa, Trans-Planckian Censorship and the Swampland, JHEP 09 (2020) 123 [1909.11063].

[161] R. Brandenberger, Trans-Planckian Censorship Conjecture and Early Universe Cosmology, 2102.09641.

[162] S. B. Giddings, Black holes and massive remnants, Phys. Rev. D46 (1992) 1347 [hep-th/9203059].

[163] L. Susskind, Trouble for remnants, hep-th/9501106.

[164] Y. Kats, L. Motl and M. Padi, Higher-order corrections to mass-charge relation of extremal black holes, JHEP 12 (2007) 068 [hep-th/0606100].

[165] C. Cheung, J. Liu and G. N. Remmen, Proof of the Weak Gravity Conjecture from Black Hole Entropy, JHEP 10 (2018) 004 [1801.08546].

[166] A. M. Charles, F. Larsen and D. R. Mayerson, Non-Renormalization For Non-Supersymmetric Black Holes, JHEP 08 (2017) 048 [1702.08458].

[167] Y. Hamada, T. Noumi and G. Shiu, Weak Gravity Conjecture from Unitarity and Causality, Phys. Rev. Lett. 123 (2019) 051601 [1810.03637].

[168] A. M. Charles, The Weak Gravity Conjecture, RG Flows, and Supersymmetry, 1906.07734.

[169] P. A. Cano and A. Murcia, Duality-invariant extensions of Einstein-Maxwell theory, 2104.07674.

[170] G. J. Loges, T. Noumi and G. Shiu, Duality and Supersymmetry Constraints on the Weak Gravity Conjecture, JHEP 11 (2020) 008 [2006.06696].

[171] W. H. Kinney, S. Vagnozzi and L. Visinelli, The zoo plot meets the swampland: mutual (in)consistency of single-field inflation, string conjectures, and cosmological data, Class. Quant. Grav. 36 (2019) 117001 [1808.06424].

[172] T. Rudelius, Conditions for (No) Eternal Inflation, JCAP 08 (2019) 009 [1905.05198].

[173] T. Rudelius, Dimensional Reduction and (Anti) de Sitter Bounds, 2101.11617.
[174] J. Chojnacki, J. Krajecka, J. H. Kwapisz, O. Slowik and A. Strag, Is asymptotically safe inflation eternal?, *JCAP* **04** (2021) 076 [2101.00886].

[175] C. Jonas, J.-L. Lehners and J. Quintin, Cosmological consequences of a principle of finite amplitudes, *Phys. Rev. D* **103** (2021) 103525 [2102.05550].

[176] D. Lüst, E. Palti and C. Vafa, *AdS and the Swampland*, *Phys. Lett. B* **797** (2019) 134867 [1906.05225].

[177] A. Bedroya, R. Brandenberger, M. Loverde and C. Vafa, Trans-Planckian Censorship and Inflationary Cosmology, *Phys. Rev. D* **101** (2020) 103502 [1909.11106].

[178] A. Codello, R. Percacci and C. Rahmede, Investigating the ultraviolet properties of gravity with a Wilsonian renormalization group equation, *Annals of Physics* **324** (2009) 414 [0805.2909].

[179] F. Saueressig, K. Groh, S. Rechenberger and O. Zanusso, Higher Derivative Gravity from the Universal Renormalization Group Machine, *ArXiv e-prints* (2011) [1111.1743].

[180] R. Percacci, *Asymptotic Safety*, 0709.3851.

[181] D. Litim and A. Satz, Limit cycles and quantum gravity, 1205.4218.

[182] B. Knorr, C. Ripken and F. Saueressig, Form Factors in Asymptotic Safety: conceptual ideas and computational toolbox, *Class. Quant. Grav.* **36** (2019) 234001 [1907.02903].

[183] T. Draper, B. Knorr, C. Ripken and F. Saueressig, Finite Quantum Gravity Amplitudes: No Strings Attached, *Phys. Rev. Lett.* **125** (2020) 181301 [2007.00733].

[184] T. Draper, B. Knorr, C. Ripken and F. Saueressig, Graviton-Mediated Scattering Amplitudes from the Quantum Effective Action, *JHEP* **11** (2020) 136 [2007.04396].

[185] R. J. Riegert, A Nonlocal Action for the Trace Anomaly, *Phys. Lett. B* **134** (1984) 56.

[186] S. Deser, Conformal anomalies: Recent progress, Helv. Phys. Acta **69** (1996) 570 [hep-th/9609138].

[187] J. Erdmenger and H. Osborn, Conserved currents and the energy momentum tensor in conformally invariant theories for general dimensions, *Nucl. Phys. B* **483** (1997) 431 [hep-th/9605009].

[188] J. Erdmenger, Conformally covariant differential operators: Properties and applications, *Class. Quant. Grav.* **14** (1997) 2061 [hep-th/9704108].

[189] S. Deser, Closed form effective conformal anomaly actions in D >= 4, *Phys. Lett. B* **479** (2000) 315 [hep-th/9911129].

[190] T. Bautista, A. Benevides and A. Dahholkar, Nonlocal Quantum Effective Actions in Weyl-Flat Spacetimes, *JHEP* **06** (2018) 055 [1711.00135].

[191] J. F. Donoghue and B. K. El-Menoufi, Covariant non-local action for massless QED and the curvature expansion, *JHEP* **10** (2015) 044 [1507.06321].

[192] D. Benedetti, P. F. Machado and F. Saueressig, Taming perturbative divergences in asymptotically safe gravity, *Nuclear Physics B* **824** (2010) 168 [0902.4630].

[193] K. S. Stelle, Classical Gravity with Higher Derivatives, *Gen. Rel. Grav.* **9** (1978) 353.

[194] A. Platania and C. Wetterich, Non-perturbative unitarity and fictitious ghosts in quantum gravity, *Phys. Lett. B* **811** (2020) 135911 [2009.06637].
A. Bonanno, T. Denz, J. M. Pawlowski and M. Reichert, *Reconstructing the graviton*, 2102.02217.

R. C. Myers and J. Z. Simon, *Black Hole Thermodynamics in Lovelock Gravity*, Phys. Rev. D 38 (1988) 2434.

R. C. Myers, *Black holes in higher curvature gravity*, pp. 121–136. 11, 1998. gr-qc/9811042. 10.1007/978-94-017-0934-78.

T. Clunan, S. F. Ross and D. J. Smith, *On Gauss-Bonnet black hole entropy*, Class. Quant. Grav. 21 (2004) 3447 [gr-qc/0402044].

J. Martin, C. Ringeval and V. Vennin, *Encyclopædia Inflationaris, Physics of the Dark Universe* 5 (2014) 75 [1303.3787].

I. Basile and A. Platania, *Cosmological α’-corrections from the functional renormalization group*, JHEP 21 (2020) 045 [2101.02226].

I. Basile and A. Platania, *String Tension between de Sitter vacua and Curvature Corrections*, 2103.06276.

R. Percacci, *An Introduction to Covariant Quantum Gravity and Asymptotic Safety*, vol. 3 of 100 Years of General Relativity. World Scientific, 2017, 10.1142/10369.

M. Reuter and F. Saueressig, *Quantum Gravity and the Functional Renormalization Group*. Cambridge University Press, 2019.

J. M. Pawlowski and M. Reichert, *Quantum gravity: a fluctuating point of view*, 2007.10353.

K. Falls, N. Ohta and R. Percacci, *Towards the determination of the dimension of the critical surface in asymptotically safe gravity*, Phys. Lett. B 810 (2020) 135773 [2004.04126].

A. O. Barvinsky and G. A. Vilkovisky, *Beyond the Schwinger-Dewitt Technique: Converting Loops Into Trees and In-In Currents*, Nucl. Phys. B 282 (1987) 163.

A. O. Barvinsky and G. A. Vilkovisky, *Covariant perturbation theory. 2: Second order in the curvature. General algorithms*, Nucl. Phys. B 333 (1990) 471.

A. O. Barvinsky and G. A. Vilkovisky, *Covariant perturbation theory. 3: Spectral representations of the third order form-factors*, Nucl. Phys. B 333 (1990) 512.

A. O. Barvinsky, Y. V. Gusev, V. V. Zhytnikov and G. A. Vilkovisky, *Covariant perturbation theory. 4. Third order in the curvature*, 0911.1168.

I. G. Avramidi, *The Nonlocal Structure of the One Loop Effective Action via Partial Summation of the Asymptotic Expansion*, Phys. Lett. B 236 (1990) 443.

A. Codello and O. Zanusso, *On the non-local heat kernel expansion*, J. Math. Phys. 54 (2013) 013513 [1203.2034].

N. Ohta and L. Rachwal, *Effective action from the functional renormalization group*, Eur. Phys. J. C 80 (2020) 877 [2002.10839].

W. Donnelly and S. B. Giddings, *Diffeomorphism-invariant observables and their nonlocal algebra*, Phys. Rev. D 93 (2016) 024030 [1507.07921].

K. Rejzner, *Effective quantum gravity observables and locally covariant QFT*, Int. J. Mod. Phys. 1 (2017) 13 [1603.06993].
[215] W. Donnelly and S. B. Giddings, Observables, gravitational dressing, and obstructions to locality and subsystems, Phys. Rev. D 94 (2016) 104038 [1607.01025].

[216] N. Klitgaard and R. Loll, Introducing Quantum Ricci Curvature, Phys. Rev. D 97 (2018) 046008 [1712.08847].

[217] T. Rudelius, Asymptotic Observables and the Swampland, 2106.09026.

[218] L. Susskind, L. Thorlacius and J. Uglum, The Stretched horizon and black hole complementarity, Phys. Rev. D 48 (1993) 3743 [hep-th/9306069].

[219] A. Almheiri, D. Marolf, J. Polchinski and J. Sully, Black Holes: Complementarity or Firewalls?, JHEP 02 (2013) 062 [1207.3123].

[220] S. B. Giddings, Nonviolent nonlocality, Phys. Rev. D 88 (2013) 064023 [1211.7070].

[221] G. Dvali, C. Gomez, R. S. Isermann, D. Lüst and S. Stieberger, Black hole formation and classicalization in ultra-Planckian 2 - N scattering, Nucl. Phys. B 893 (2015) 187 [1409.7405].

[222] L. Keltner and A. J. Tolley, UV properties of Galileons: Spectral Densities, 1502.05706.

[223] R. B. Mann, Black Holes: Thermodynamics, Information, and Firewalls, SpringerBriefs in Physics. Springer, 2015, 10.1007/978-3-319-14496-2.

[224] L. Modesto, Super-renormalizable Quantum Gravity, Phys. Rev. D 86 (2012) 044005 [1107.2403].

[225] L. Modesto and L. a. Rachwal, Nonlocal quantum gravity: A review, Int. J. Mod. Phys. D 26 (2017) 1730020.

[226] L. Buoninfante, G. Lambiase and A. Mazumdar, Ghost-free infinite derivative quantum field theory, Nucl. Phys. B 944 (2019) 114646 [1805.03559].

[227] L. Buoninfante, A. S. Koshelev, G. Lambiase and A. Mazumdar, Classical properties of non-local, ghost- and singularity-free gravity, JCAP 09 (2018) 034 [1802.00399].

[228] S. B. Giddings, Locality in quantum gravity and string theory, Phys. Rev. D 74 (2006) 106006 [hep-th/0604072].

[229] L. Buoninfante, F. Di Filippo and S. Mukohyama, On the assumptions leading to the information loss paradox, 2107.05662.

[230] G. Veneziano, Scale factor duality for classical and quantum strings, Phys. Lett. B 265 (1991) 287.

[231] K. Meissner and G. Veneziano, Symmetries of cosmological superstring vacua, Phys. Lett. B 267 (1991) 33.

[232] K. A. Meissner, Symmetries of higher order string gravity actions, Phys. Lett. B 392 (1997) 298 [hep-th/9610131].

[233] O. Hohm and B. Zwiebach, T-duality Constraints on Higher Derivatives Revisited, JHEP 04 (2016) 101 [1510.00005].

[234] O. Hohm and B. Zwiebach, Non-perturbative de Sitter vacua via α’ corrections, Int. J. Mod. Phys. D 28 (2019) 1943002 [1905.06583].

[235] O. Hohm and B. Zwiebach, Duality invariant cosmology to all orders in α’, Phys. Rev. D 100 (2019) 126011 [1905.06963].
[236] A. Held, *Effective asymptotic safety and its predictive power: Gauge-Yukawa theories*, Front. in Phys. 8 (2020) 341 [2003.13642].

[237] A. Eichhorn and M. Pauly, *Constraining power of asymptotic safety for scalar fields*, Phys. Rev. D 103 (2021) 026006 [2009.13543].

[238] P. Ali, A. Eichhorn, M. Pauly and M. M. Scherer, *Constraints on discrete global symmetries in quantum gravity*, JHEP 05 (2021) 036 [2012.07868].

[239] T. Banks and L. J. Dixon, *Constraints on String Vacua with Space-Time Supersymmetry*, Nucl. Phys. B 307 (1988) 93.

[240] R. Kallosh, A. D. Linde, D. A. Linde and L. Susskind, *Gravity and global symmetries*, Phys. Rev. D 52 (1995) 912 [hep-th/9502069].

[241] J. McNamara and C. Vafa, *Cobordism Classes and the Swampland*, 1909.10355.