Is gravity the weakest force?

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Abstract

It has recently been suggested that ‘gravity is the weakest force’ in any theory with a suitable UV completion within quantum gravity. One formulation of this statement is the scalar weak gravity conjecture (WGC), which states that gravity is weaker than the force originating from scalar fields. We study the scalar WGC in de Sitter (dS) space, and discuss its low-energy consequences in light of the experimental searches for fifth forces and violations of the equivalence principle. We point out that some versions of the scalar WGC forbid the existence of very light scalar particles, such as the quintessence and axion-like particles. The absence of the quintessence field means that these versions of the scalar WGC are in phenomenological tension with the recently-proposed dS swampland conjecture and its refinements. Some other versions of the scalar WGC escape these constraints, and could have interesting phenomenological consequences.

Keywords: quantum gravity, swampland conjectures, scalar weak gravity conjecture

(Some figures may appear in colour only in the online journal)

1. Introduction

Gravity has been studied extensively in physics for centuries. Yet despite its long history of research, gravity is still one of the most enigmatic phenomena of nature. The unification of gravity with all other forces of nature, which we hope to achieve in the putative theory of quantum gravity, has been a notoriously difficult subject, and gravity seems to be intrinsically different from anything else.

One of the rather peculiar features of gravity is that it is extremely weak. We learn this in kindergarten when we find that the electromagnetic force of a small magnet wins over the gravity of the whole Earth. Recently this simple observation, that ‘gravity is the weakest force’,
has been promoted to a principle in the context of the swampland program [1, 2], a program to work out the low-energy consequences of the existence of UV completions with gravity.

The most famous formulation of the weakness of the gravity is the weak gravity conjecture (WGC) [3], which states the following: in a theory with a consistent UV completion in theories of quantum gravity, there should exist a particle with mass $m$ and $U(1)$ integer gauge charge $q$ satisfying the inequality:

$$
\sqrt{2} q e \geq \frac{m}{\sqrt{2}}.
$$

where $M_{\text{Pl}} \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck mass and $e$ is the gauge coupling constant for the $U(1)$ gauge symmetry. While this is still a conjecture, there have been good arguments supporting this conjecture from the decay of non-extremal black holes [3], and there has recently been many more supporting arguments (see e.g. references [4–13]).

The inequality (1) means that the force mediated by the gauge boson (spin 1 particle) is stronger by that by the graviton (spin 2 particle), namely $F_{\text{gauge}} \geq F_{\text{gravity}}$ with

$$
F_{\text{gauge}} = \frac{(qe)^2}{4\pi r^2}, \quad F_{\text{gravity}} = \frac{m^2}{8\pi M_{\text{Pl}}^2 r^2}.
$$

This raises a natural question: what happens if we have a spin 0 particle, namely a scalar? Is gravity still the weakest force, and if so, how should we articulate this condition?

There has recently been several attempts toward answering this question, by formulating a set of ‘scalar versions’ of the WGC [14–18]. However, the contrast with the case of the original WGC (which we call the gauge WGC (GWGC), to be distinguished from the scalar WGC (SWGC)), SWGCs have much less evidence in general, and it is often not clear exactly which versions of the conjecture should be adopted.

For this reason we work out low-energy consequences of several versions of the WGC, and discuss observational constraints on them. Such bottom-up constraints on swampland conjectures have been extremely useful in sharpening our understanding of quantum gravity (see reference [19] for recent summary), and this paper is not an exception—we will draw interesting conclusions, including some phenomenological tension with the de Sitter (dS) swampland conjectures.

2. Scalar weak gravity conjecture

Let us begin by stating one version of the SWGC [14] (we will later comment on variations of the conjecture). Suppose a charged particle has a mass of $m$. This particle is arbitrary and not necessarily an elementary particle as long as it is a GWGC state, namely if it satisfies the inequality (1).

Suppose that the mass $m$ depends on a set of exactly massless scalar fields $\varphi^i$. This means that the GWGC states have trilinear couplings with the massless fields $\varphi^i$. To see this, suppose that the GWGC state is a complex scalar $\phi$. We then have a field-dependent mass term

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1. This is the so-called electric version of the WGC. We will not discuss the magnetic version of the WGC in this paper.
2. One should notice, however, there are several different versions of the WGC in the literature. For example, in one version the inequality (1) is satisfied by a black hole, rather than a particle.
3. In formulating SWGC there is a question of what counts as a ‘particle’, e.g. whether or not we allow a composite particle or an unstable particle with some lifetime, and depending on the choice we can formulate different version of the SWGC. For the purposes of our paper it is enough to consider a relatively strong version that the conjecture holds for the stable elementary particle inside the given low-energy effective field theory.
$m^2(\phi)|\phi|^2$, and when expanded around a VEV (vacuum expectation value) $\varphi_0$ of the field $\varphi$, we obtain a trilinear coupling

$$L \supset -\partial_\mu m^2(\varphi_0)(\delta\varphi)|\phi|^2.$$  \hfill (3)

The fermion case is similar.

Let us denote the metric for the kinetic term of $\varphi_i$ to be $g_{ij}$ (which can depend on $\varphi$ themselves); $L_{\text{kin}} = -g_{ij}\partial_i\varphi^i\partial_j\varphi^j$. Then the SWGC states that we have an inequality

$$|\partial_\mu m|^2 \equiv \sum_{i,j} g^{ij}(\partial_\mu m)(\partial_\mu m) \geq \frac{m^2}{M_{Pl}^2}.$$ \hfill (4)

The physical content of this inequality is that the total force mediated by the massless fields $\delta\varphi$ is stronger than that by gravity, when we consider the $2 \rightarrow 2$ scattering of the GWGC states. Namely, we have $F_{\text{scalar}} \geq F_{\text{gravity}}$ with

$$F_{\text{scalar}} = \frac{|\partial_\mu m|^2}{4\pi r^2}, \quad F_{\text{gravity}} = \frac{m^2}{8\pi M_{Pl}^2 r^2}.$$ \hfill (5)

Note that the trilinear coupling (3) generates the scalar force $F_{\text{scalar}}$.  

### 3. Scalar weak gravity conjecture in dS space

In this paper, we wish to apply the SWGC to our Universe, namely to a dS space with positive values of the cosmological constant and the Hubble constant $H$. While swampland conjectures are often formulated as theoretical constraints on possible low-energy physics and does not refer to the history of the Universe, our considerations in this paper are more physical, and our intention is to honestly formulate the statement that ‘gravity is the weakest force’ in our Universe.

In this context, we claim that we should allow the fields $\varphi_i$ to be not exactly massless, as long as they are nearly massless. More quantitatively, we allow the mass comparable to the $m_{\varphi_i}$ are of order of the Hubble constant, $H$: $m_{\varphi_i} \lesssim H$, and on the left-hand side of (4) we sum over all such fields.

There are several motivations for allowing such nearly-massless fields in the sum. First, when we consider $2 \rightarrow 2$ scattering of such particles inside the Universe the nearly-massless fields $\varphi_i$ are practically massless, since their Compton wavelength is comparable or larger than the current horizon scale $\sim H^{-1}$, where the scattering takes place. Second, in the Universe with the positive cosmological constant and one then expects the field $\varphi$ will generically obtain a mass of $O(H)$ from curvature couplings.

Unlike the supersymmetric case, it is generally hard to keep a scalar particle massless in the dS space. Even when the fields $\varphi_i$ are massless classically, we expect that the one-loop effect from the trilinear coupling (3) will generate a mass for $\varphi_i$, unless there is some symmetry reasons. Note that we cannot forbid such a mass term by imposing an exact global symmetry,\footnote{The scalar force (5) can be derived from the matrix element of the $T$-channel diagram of $\phi\phi^i \rightarrow \phi\phi^i$ mediated by the massless scalar $\delta\varphi$ in the non-relativistic limit. A convenient way to derive this is to compare it with the amplitude of the $\phi\phi^i \rightarrow \phi\phi^i$ amplitude mediated by a photon in scalar QED, which provides Coulomb force $F_{\text{Coulomb}} = q^2/(4\pi r)$. In the non-relativistic limit, the amplitude of the scalar QED is given by $(2m)^2q^2/k^2$, where $k$ is the momentum transfer of the virtual photon, while the interaction (3) leads to the amplitude $\delta m^2/k^2$. By comparing the two and replacing $(2m)^2q^2$ by $\delta m^2$, we can see that the interaction (3) leads to the scalar force $F_{\text{scalar}}$.}


since global symmetry is not allowed in theories of quantum gravity (unless it is emergent in the IR) \cite{20–22}.

When applied to the present-day Universe, the masses of the $\varphi_i$ are extremely small:

$$m_{\varphi_i} \lesssim H_0 \sim O(10^{-33}) \text{ eV}. \quad (6)$$

As this discussion makes clear, we impose weakness of gravity in at the IR, namely the horizon scale. While there could be other fields with masses much larger than the nearly-massless fields $\varphi_i$, they create only short-range forces at the horizon scale and hence do not affect our argument, as in the case of the GWGC (1).

4. Constraints on very light scalars

In the standard model (SM) of particle physics, there are no nearly-massless scalar fields whose masses satisfy (6). Such particles, however, often arise in extensions of the SM.

One scenario for a nearly-massless scalar is an ultralight axion-like particle (ALP)\(^6\). Another example is the quintessence field \cite{24–26}, a dynamical scalar field for the dark energy. Such a scalar field should be nearly massless and satisfy (6), to avoid rapid change of the size of the dark energy. More generally, string theory has many moduli, and some of these fields could have flat directions which are only broken by non-perturbative effects. Of course, these possibilities are not mutually exclusive, since part of the moduli could generate an ALP, which could play the role of the quintessence, for example.

Let us consider a minimal extension of the SM with very light scalar particles satisfying (6), which we collectively denote by $\varphi$. The SWGC inequality (4) now represents the presence of the fifth force, which acts stronger than gravity in any charged states, e.g., the electron and the proton\(^7\). Such a scenario is highly constrained in observational constraints on fifth force searches (see e.g., references [27–30]). First, one generically expects that the coupling of the field $\varphi$ (as in equation (3)) to other GWGC states are non-universal. This causes the violation of the weak equivalence principle, which has been checked to be very high accuracy (of order $10^{-13}$). The constraint is ameliorated when we somehow manage to couple the light field $\varphi$ universally to the matters as the gravity. It is still the case, however, that $\varphi$ modifies the gravitational potential, leading to sizable deviations of the gravitational potential in the parametrized post-Newtonian expansion. This observational constraint reads

$$|\partial_{\varphi} m|^2 < O(10^{-5}) \left(\frac{m}{M_{\text{Pl}}}\right)^2. \quad (7)$$

This is in immediate tension with the SWGC (4)\(^8\)

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\(^5\)One of the motivations for the SWGC comes from black holes in four-dimensional $\mathcal{N} = 2$ supersymmetry \cite{14}, where such massless scalar fields are present. It is difficult in general, however, to ensure the presence of such massless scalar fields in non-supersymmetric theory.

\(^6\)SWGC dictates that there should necessarily be a coupling of the form (3), which is in tension with the shift-symmetry of an axion. While it has often been argued that string theory motivates the presence of multiplet ALPs across all energy scales \cite{23}, axions require an approximate global symmetry of very high quality, which is often broken explicitly by various non-perturbative quantum gravity effects. This problem is especially severe for ultralight axions, as is the case discussed in this paper.

\(^7\)In general quintessence models there is no need for the coupling (3) to the SM particles. We have, however, assumed here the SWGC, which requires the existence of the coupling (3), just as in the discussions of ALPs.
The intuitive reason for our findings is clear—SWGC states that the fifth force originating from the scalar force should be stronger than gravity, which is already excluded from fifth-force searches.

Let us add that if $\varphi$ has a potential and the VEV of $\varphi$ has a time dependence, the masses of particles are time-dependent, and such time-variations are also strongly constrained by cosmological observations.

Summarizing, we have concluded that the SWGC as formulated above is in phenomenological tension with the existence of a very light scalar. The case of multiple such scalars is similar.

5. Phenomenological tension with dS swampland conjecture

The results we have presented above has an interesting consequence: the SWGC is in phenomenological tension with another swampland conjecture, the dS swampland conjecture [35].

Let us quickly summarize the dS conjecture. After the initial proposal [35], some bottom-up constraints of the conjecture have been pointed out in references [36–40], leading to several proposals for refinements [38, 41–46]. In particular, references [43, 44] proposed that a scalar potential $V$ for a low-energy effective field theory should satisfy the inequality

$$M_{\text{Pl}} |\nabla V| > cV$$

or

$$M_{\text{Pl}}^2 \min(|\nabla\nabla V|) \leq -c'V.$$  \hspace{1cm} (8)

Here $c$ and $c'$ are $O(1)$ positive constants (a version with $c' = 0$ was proposed in reference [38]).

Irrespective of the details of the refinements, all of these conjectures imply that the (meta)stable dS space ($\nabla V = 0, V > 0$) are excluded (see also references [47–55] for related discussion). This gives a rather strong motivation for quintessence models as an explanation of the dark energy. This, as we have seen, contradicts the SWGC.

This in itself does not prove the inconsistency between SWGC and the (refined) dS conjectures, since one can try to explain dark energy by modifying the gravity instead of incorporating extra quintessence fields. However, many modifications of the gravity, such as scalar–tensor theories, have light scalar fields and tend to have issues similar to the quintessence. While experimental constraints can be evaded in certain low-energy models, it is a non-trivial question to see if such specific modifications of gravity can really be embedded into theories of quantum gravity, such as string theory.

We therefore conclude that the version of the SWGC discussed above is in phenomenological tension with the (refined) dS conjectures, in the sense that a quintessence field, which is the most viable phenomenological consequence of the dS conjectures, contradicts the present SWGC. This is a non-trivial result. Indeed, both conjectures are partly motivated by the same conjecture, namely the distance swampland conjecture [2, 58], at least in asymptotic regions of the parameter space. Moreover it was suggested in reference [44] that there are close analogies between the two conjectures, when the scalar potential is given by the mass itself. More broadly, consistency checks between different conjectures have been one of the primary guidelines in

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8 It would be interesting to see if we can evade these constraints by using some screening mechanisms [31, 32]. Of course, it is a separate question if such scenarios can be reproduced from theories of quantum gravity (see e.g. [33] for such an attempt). Note that some of the screening scenarios are accompanied by superluminal propagations, which are obstructions for UV completion [34].

9 The existence of the scalar field might not be a strict requirement, see e.g. [56, 57] for recent discussion.
the swampland program. It is fair to say that neither conjectures have solid evidence, and are open for possible modifications and refinements. Since we already mentioned on refinements on the dS conjectures, let us next discuss variations of the SWGC.

6. Variations of the scalar weak gravity conjecture

Let us discuss variations of the SWGC—when stating the inequality (6) there are many choices. Some variations, which impose stronger condition than above, clearly does not affect the argument above. For example, we can impose the inequality for arbitrary states, as opposed to only for GWGC particles. We can also replace the inequality ($\geq$) by a strict inequality ($>$) or an approximate inequality ($\gtrsim$), without affecting our argument.

One plausible modification of the SWGC is to consider the following: instead of imposing the inequality (4) for any state (or any GWGC state), we can require that there exists at least one particle (the SWGC particle) satisfying the SWGC condition (4). This extends the ‘weak version’ of the SWGC in reference [14] to the dS space, and represents most directly the spirit that the gravity is the weaker than the other forces$^{10}$

Note we still assume that there exists at least one particle satisfying the GWGC condition (1), but this particle can in general be different from the particle satisfying the SWGC. We can impose a stronger constraint that both inequalities are satisfied by the same particle.

In these versions of the SWGC, if the mass $m$ of the SWGC particle satisfying the inequality (4) is extremely large (e.g. near the cutoff scale of theory), then it would likely be difficult to constrain the existence of such particles observationally. One possible exception is the case where such a particle is stable and a dark matter candidate.

In addition to the SWGC particle, we discussed very light scalar fields $\phi^i$. One should note that morally speaking the conjecture asks for the existence of a very light scalar. While we assumed the existence of such a particle in the discussion above in the formulation of the SWGC, the idea that gravity is the weakest force at least at the horizon scale seems to require such a particle—without such a light scalar particle the scalar force decays in the IR. While this light scalar does not need to couple directly to the SM particles, it will necessarily couple to them through gravitational interactions.

7. Scalar weak gravity conjecture in the past and the future

In the discussion above we have used the present-day value of the Hubble rate, and already derived strong constraints. It is, however, natural to extend the conjecture to the past and future of the Universe, and see what constraints we obtain.

The SWGC (4) states that the force mediated by scalar fields (with all the nearly massless scalar fields combined) is larger than the force of the gravity. The constraints from the SWGC is weaker when the value of the Hubble rate is large, e.g. during the inflationary epoch. This is because when the Hubble rate is larger more scalar fields are ‘nearly massless’ compared with the Hubble scale (for example, the Higgs field is nearly massless during inflationary states in this sense), and hence the total scalar force becomes larger. Since gravity is independent of the value of the Hubble rate, we find SWGC is weaker when the Hubble rate is larger, as claimed.

The situation is opposite when we lower the values of the Hubble rate. For example, if we consider quintessence-type scenario for dark energy, then the value of the Hubble rate will

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$^{10}$Yet another version of the conjecture is to claim the existence of a particle for which we have an inequality involving the three forces, $F_{\text{gauge}}, F_{\text{scalar}}$ and $F_{\text{gravity}}$ [14]. We emphasize that this is not what we discuss in this paper.
be smaller and smaller in the future, so that eventually all the scalar fields (unless they are completely massless) will have mass larger than the Hubble rate, leading to the violation of the SWGC. However, we have already shown above that the quintessence is in tension with SWGC already in the current Universe, and hence the question is not of relevance now.

There are still other scenarios where the values of the Hubble rate will be smaller in the future. For example, suppose that we are at a metastable dS vacuum, which after some time tunnels into a different dS vacuum with a much smaller value of the Hubble rate. This will lead to a violation of the SWGC.

There can be several interpretations of this. For example, one possibility is that such tunneling (and more generally such a landscape of vacua) might not be allowed in theories of quantum gravity. Another possibility is that we encounter some inconsistency of the semiclassical description of the Universe before this happens. In any case there are interesting questions concerning conceptual foundations of the SWGC, and it would be interesting to further study this in the future.

8. Strong scalar weak gravity conjecture

We have to this point formulated SWGC in the IR. One might however try to consider a ‘mixed UV/IR version’ of the SWGC. In this situation, many states, including massive states, begin to contribute to the forces, and \textit{a priori} we need to take into account all of them, and one might wonder if there is any hope for a simple statement, while keeping the statement applicable to any low-energy effective theory with UV completions.

Despite these potential obstacles, recently the authors of reference [18] boldly conjectured a version of the SWGC, which we call the strong SWGC (SSWGCG) (see also [59])

The SSWGCG states that the scalar potential \( V \), in a low-energy theory with UV completion with gravity, satisfies an inequality

\[
\chi \equiv 2(V''')^2 - V''' V'' \frac{(V'')^2}{M_{Pl}^2} \geq 0.
\]

If we write \( m^2 = V'' \), then this inequality can be written as

\[
2(\partial_\phi m^2)^2 - m^2(\partial_\phi^2 m^2) \geq (m^2)^2 \frac{1}{M_{Pl}^2},
\]

which looks similar to (4).

There are, however, crucial differences between (4) and (9). First, as already stated the conjecture (10) is meant to be a ‘mixed UV/IR statement’ [18], while we have above been using the versions formulated in the IR. Second, (10) has a term involving the fourth derivative of the potential, which did not appear in (4). Third, the new proposal (9) does not refer to existence of nearly-massless or massless fields (\( \varphi_i \) in our previous notation), and refers only to the scalar field \( \phi \), which can be taken arbitrary.

In SSWGCG the self-interaction of the scalar field, without any help from other scalars, is claimed to win over gravity. We find a tower of massless states when the equality in (9) holds [18], and in [18] these states are proposed to play the role of the nearly-massless states (\( \varphi_i \) in the notation of this paper). In this situation, since we have a tower of very light scalar fields

\footnote{This should not be confused with some other versions of the SWGC discussed before, which are sometimes referred to as ‘strong’ versions of the SWGC.}
in the theory, we expect that our conclusions presented above from the fifth-force constraints seems to apply essentially the same manner to this new conjecture. However, such a tower often arises when the field range is of order the Planck scale, where the effective field theory breaks down according to the distance conjecture [2, 58]. For this reason SSWGC could possibly escape our observational constraints, despite the fact that the conjecture applies to any scalar.

One obvious question is if the SSWGC holds, at least in some corners of the landscape of quantum gravity. While we leave this question for future work, let us consider a simple setup where we have a classical compactification of the eleven-dimensional supergravity on $\mathbb{R}^{3,1} \times (7 - $ manifold). We assume that all the corrections, stringy and $\alpha'$, can be neglected.

The effective potential for the overall modulus $\rho$ of the compactification manifold is [35]

$$V_{\text{eff}} = V_{\text{Re}} - 6\sqrt{14}\rho M_{\text{Pl}} + V_{\text{Ge}} - 10\sqrt{14}\rho M_{\text{Pl}}, \quad (11)$$

where the two terms represent the contributions from the curvature and the four-form field strength ($V_G \geq 0$). This potential satisfies (9) irrespective of the sign of $V_R$.

Another question, which is natural for this paper, is if the SSWGC holds for the Higgs boson of the SM. The effective potential of the SM Higgs boson $h$ is approximately given by $V(h) = \lambda_{\text{eff}}(h)h^4/4$ for $h$ much greater than the electroweak scale. The SSWGC criteria (9) for the Higgs boson is approximated as,

$$\chi(h) \simeq \frac{3h^2}{8} \left[ 144(\lambda_{\text{eff}}(h) + \beta_{\text{eff}}(h))^2 + 23\beta_{\text{eff}}^2(h) \right], \quad (12)$$

where $\beta_{\text{eff}}(h) \equiv d\lambda_{\text{eff}}/d\log(h)$ and we neglect higher derivatives on $\beta_{\text{eff}}$, which are higher-loop suppressed. Unless both $\lambda$ and $\beta_{\text{eff}}$ are zero, the value of $\chi$ is positive and greater than $O(h^2/(16\pi^2)^2)$. Therefore, in the SM, the value of $\chi$ is greater than the Planck-suppressed combination $V''/M_{Pl}^2$. In figure 1, we show the $\chi/h^2 - V''/M_{Pl}^2$ as a function of $h$. The red band in the figure shows 2$\sigma$ uncertainty from the experimental and theory errors. To calculate the effective potential, we use the procedure of references [60, 61] and take the physical parameters as top quark mass $m_t = 173.0 \pm 0.4$ GeV and Higgs mass $m_h = 125.18 \pm 0.16$ GeV [62]. We add another error $\pm 0.5$ GeV to $m_t$ due to hadronic uncertainty. For the other parameters, we use same values as in reference [63].

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12 This question was previously discussed in [18], although their analysis is limited to the classical Higgs potential.
Note that we use the inequality (9) from v2 of reference [18]. In v1 of reference [18], the criteria is \( \chi/V'' \geq 1/M^2_{Pl} \), so that the direction of this inequality is opposite from that in version 2 when \( V'' < 0 \). The criteria in v1 is violated by the potential (11) for \( \rho > M_{Pl} \log(-25V_G/9V_R)/\sqrt{7}/8 \) with \( V_R < 0 \), and the Higgs potential \( V(h) \) for \( h \gg 10^{19} \) GeV.

As discussed before, some versions of the SWGC are in phenomenological tension with the existence of very light scalars. Since the Higgs or meson scalar field mediates forces much larger than the gravity, this tension may be relaxed in the SSWGC condition (9), if we suitably generalize the conjecture to multi-field cases. Of course, the fundamental question remains how to better motivate the SSWGC in itself.

In conclusion, SWGC is an attempt to articulate our intuition that gravity is the weakest force in Nature. Theoretically, however, it is not clear which version of the conjecture should hold. We have seen that observational constraints on fifth-force searches provide useful guidelines in formulating the SWGC. Our considerations highlights the fascinating link between theoretical studies of ‘high-scale’ quantum gravity and experimental studies of yet unknown ‘low-scale’ physics.

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References

[1] Vafa C 2005 arXiv:hep-th/0509212 [hep-th]
[2] Ooguri H and Vafa C 2007 Nucl. Phys. B 766 21
[3] Arkani-Hamed N, Motl L, Nicolis A and Vafa C 2007 J. High Energy Phys. JHEP06(2007)060
[4] Cheung C and Remmen G N 2014 J. High Energy Phys. JHEP12(2014)087
[5] Harlow D 2016 J. High Energy Phys. JHEP01(2016)122
[6] Shiu G, Soler P and Cottrell W 2016 arXiv:1611.06270 [hep-th]
[7] Hod S 2017 Int. J. Mod. Phys. D 26 1742004
[8] Fisher Z and Mogni C J 2017 arXiv:1706.08257 [hep-th]
[9] Crisford T, Horowitz G T and Santos J E 2018 Phys. Rev. D 97 066005
[10] Cheung C, Liu J and Remmen G N 2018 J. High Energy Phys. JHEP10(2018)004
[11] Hamada Y, Noumi T and Shiu G 2018 arXiv:1810.03637 [hep-th]
[12] Urbano A 2018 arXiv:1810.05621 [hep-th]
[13] Bellazzini B, Lewandowski M and Serra J 2019 arXiv:1902.03250 [hep-th]
[14] Palti E 2017 J. High Energy Phys. JHEP08(2017)034
[15] Lust D and Palti E 2018 J. High Energy Phys. JHEP02(2018)040
[16] Lee S-J, Lerche W and Weigand T 2018 J. High Energy Phys. JHEP10(2018)164
[17] Palti E 2019 arXiv:1903.06239 [hep-th]
[18] Gonzalo E and Ibáñez L E 2019 arXiv:1903.08878 [hep-th]
[19] Yamazaki M 2019 54th Rencontres de Moriond on Electroweak Interactions and Unified Theories (Moriond EW 2019) La Thuile, Italy 16–23 March 2019
[20] Misner C W and Wheeler J A 1957 Ann. Phys., NY 2 525
[21] Polchinski J 2002 Proc., Dirac Centennial Symp. Tallahassee, USA December 6–7
Polchinski J 2004 Int. J. Mod. Phys. A 19 S1 145
[22] Banks T and Seiberg N 2011 Phys. Rev. D 83 084019
[23] Arvanitaki A, Dimopoulos S, Dubovsky S, Kaloper N and March-Russell J 2010 Phys. Rev. D 81 123530
[24] Ratra B and Peebles P J E 1988 Phys. Rev. D 37 3406
[25] Wetterich C 1988 Nucl. Phys. B 302 668
[26] Zlatev I, Wang L and Steinhardt P J 1999 Phys. Rev. Lett. 82 896
[27] Fischbach E and Talmadge C L 1999 The Search for non-Newtonian Gravity (New York: Springer)
[28] Bertotti B, Iess L and Tortora P 2003 Nature 425 374
[29] Esposito-Farese G 2004 Phi In The Sky: The Quest for Cosmological Scalar Fields Proc., Workshop Porto, Portugal July 8–10
Esposito-Farese G 2004 AIP Conf. Proc. 736 3510.1063/1.1835173
[30] Will C M 2006 Living Rev. Rel. 9 3
[31] Vainshtein A I 1972 Phys. Lett. B 39 393
[32] Khoury J and Weltman A 2004 Phys. Rev. D 69 044026
[33] Hinterbichler K, Khoury J and Nastase H 2011 J. High Energy Phys. JHEP03(2011)061
Hinterbichler K, Khoury J and Nastase H 2011 J. High Energy Phys. JHEP06(2011)072 Erratum
[34] Adams A, Arkani-Hamed N, Dubovsky S, Nicolis A and Rattazzi R 2006 J. High Energy Phys. JHEP10(2006)014
[35] Obied G, Ooguri H, Spodyneiko L and Vafa C 2018 arXiv:1806.08362 [hep-th]
[36] Denef F, Hebecker A and Wrase T 2018 Phys. Rev. D 98 086004
[37] Conlon J P 2018 Int. J. Mod. Phys. A 33 1850178
[38] Murayama H, Yamazaki M and Yanagida T T 2018 J. High Energy Phys. JHEP12(2018)032
[39] Choi K, Chway D and Shin C S 2018 J. High Energy Phys. JHEP11(2018)142
[40] Hamaguchi K, Ibe M and Moroi T 2018 J. High Energy Phys. JHEP12(2018)023
[41] Dvali G and Gomez C 2019 Fortschr. Phys. 67 1800092
[42] Andriot D 2018 Phys. Lett. B 785 570
[43] Garg S K and Krishnan C 2018 arXiv:1807.05193 [hep-th]
[44] Obied G, Ooguri H, Spodyneiko L and Vafa C 2018 arXiv:1806.08362 [hep-th]
[45] Ooguri H, Palti E, Shiu G and Vafa C 2019 Phys. Lett. B 788 180
[46] Garg S K, Krishnan C and Zaid Zaz M 2019 J. High Energy Phys. JHEP03(2019)029
[47] Andriot D and Roupec C 2019 Fortschr. Phys. 67 1800105
[48] Dine M and Seiberg N 1985 Phys. Lett. B 162 299
[49] Maldecena J and Nuñez C 2001 Supergravity description of field theories on curved manifolds and a no go theorem Int. J. Mod. Phys. A 16 822
[50] Steinhardt P J and Wesley D 2009 Phys. Rev. D 79 104026
[51] McOrist J and Sethi S 2012 J. High Energy Phys. JHEP12(2012)122
[52] Sethi S 2018 J. High Energy Phys. JHEP10(2018)022
[53] Danielsson U H and Riet T V 2018 Int. J. Mod. Phys. D 27 1830007
[54] Heisenberg L, Bartelmann M, Brandenberger R and Refregier A 2018 Phys. Rev. D 98 123502
[55] Akrami Y, Kallosh R, Linde A and Vardanyan V 2019 Fortschr. Phys. 67 1800075
[56] Kachru S and Trivedi S P 2019 Fortschr. Phys. 67 1800086
[57] Heckman J J, Lawrie C, Lin L and Zoccarato G 2018 arXiv:1811.01959 [hep-th]
[58] Heckman J J, Lawrie C, Lin L, Sakstein J and Zoccarato G 2019 arXiv:1901.10489 [hep-th]
[59] Klaewer D and Palti E 2017 J. High Energy Phys. JHEP01(2017)088
[60] Brahma S and Hossain M W 2019 arXiv:1904.05810 [hep-th]
[61] Degrassi G, Di Vita S, Elias-Miro J, Espinosa J R, Giudice G F, Isidori G and Strumia A 2012 J. High Energy Phys. JHEP08(2012)098
[62] Buttazzo D, Degrassi G, Giardino P P, Giudice G F, Sala F, Salvio A and Strumia A 2013 J. High Energy Phys. JHEP12(2013)089
[63] Tanabashi M et al 2018 Particle data group Phys. Rev. D 98 030001
[64] Nagata N and Shirai S 2014 J. High Energy Phys. JHEP03(2014)049