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Special Issue
Warm Inflation

Edited by
Prof. Dr. Rudnei O. Ramos and Prof. Dr. Kamali Vahid

MDPI

https://doi.org/10.3390/universe9040168

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Looking inside the Swampland from Warm Inflation: Dissipative Effects in De Sitter Expansion

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Abstract: This paper reviews the theoretical and phenomenological implications of the swampland conjectures from the perspective of inflationary cosmology, focusing on warm inflation. We demonstrate how the swampland conjectures appear to favor the strong dissipative regime, giving warm inflation a competitive edge over standard inflation. Additionally, we ponder the possible deeper implications of dissipation for constructing successful inflation models from string theory.

Keywords: warm inflation; swampland conjectures; effective field theories in curved spacetimes

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Citation: Berera, A.; Calderón-Figueroa, J. Looking inside the Swampland from Warm Inflation: Dissipative Effects in De Sitter Expansion. *Universe* **2023**, *9*, 168. https://doi.org/10.3390/universe9040168

Academic Editor: Kazuharu Bamba

Received: 1 March 2023
Revised: 27 March 2023
Accepted: 28 March 2023
Published: 30 March 2023

1. Introduction

The study of inflation as an effective field theory (EFT) is essential in order to evaluate its theoretical soundness and the robustness of its phenomenological predictions. That is a challenging task, given the technical complications of dealing with quantum fields in curved spacetimes, as well as additional complexities inherent to de Sitter spacetimes [1–3]. One can tackle these problems from either a top-down approach or a bottom-up approach [4–6] (see [7–10] for a new perspective). With the former method, one would begin with a UV-complete theory of gravity and investigate the implications it has on infrared (IR) degrees of freedom and the respective EFTs that describe their dynamic.

Arguably, the *swampland program* [11] serves as the prime example of such approaches (see [12–14] for reviews). This program seeks to distinguish the low-energy EFTs that are consistent with string theory, and thus belong to the *landscape*, from those that are not and are consequently relegated to the *swampland*. In order to make this program truly effective, it is essential to define the limits exclusively in terms of the parameters and properties of the EFT rather than relying on the specifics of the quantum theory of gravity [12]. Despite this difficulty, a number of conjectures have arisen regarding the 'location' of these boundaries, some of which have been tested through string theory constructions or black hole physics. While there is still much uncertainty, these tests have provided valuable insight into the connection between different conjectures, hinting at underlying quantum gravity principles.

In this way, the swampland conjectures have been widely used as criteria to test the consistency of Beyond the Standard Model theories with quantum gravity. As such, one of the most thrilling applications of the swampland program is inflationary cosmology [15], providing model builders with an invaluable set of guidelines to assess a model, in addition to experimental data. Notice that if these conjectures prove to be true, this is nothing but a manifestation of the mixing of UV and IR degrees of freedom through quantum gravity, thereby highlighting the importance of having an appropriate EFT description of inflation that (perhaps) we are yet to uncover.

As mentioned before, a number of swampland conjectures have been proposed over the years, and most of these can be related in some form [13]. The three main cornerstones of the swampland program are the no-global symmetries conjecture (NGC) [16], the weak gravity conjecture (WGC) [17], and the swampland distance conjecture (SDC) [18]. Broadly, the NGC proposes that global symmetries cannot exist in quantum gravity; otherwise there would be violations of entropy bounds for black holes, among other problems. The WGC (in its magnetic version) postulates that in any theory coupled to gravity with a $U(1)$ symmetry and associated coupling g, the cutoff scale Λ of the EFT must be bounded as $\Lambda \lesssim g M_{\rm Pl}$, where $M_{\rm Pl}$ is the reduced Planck mass. Finally, the SDC states that the moduli space of a theory is non-compact, meaning that two points can be infinitely separated, a limit that also corresponds to weak couplings. Consequently, a global symmetry could, in principle, be restored unless quantum gravity effects intervene, leading to a breakdown of the EFT description. The cutoff of quantum gravity then depends on the field variations $\Delta\phi$ (which define the distance in moduli space). As a result, only finite variations $\Delta\phi$ are allowed, and these depend on the cutoff Λ of the EFT.

The conjectures listed above form the basis of ongoing research in the field. However, we shall focus on those that are more pertinent to inflation model building. We will demonstrate how each of these constraints is typically in conflict with cold inflation (CI) [19–22], and how warm inflation (WI) [23,24] can naturally circumvent these issues [25–28]. We will pay closer attention to the trans-Planckian censorship conjecture (TCC), which apparently treats—and burdens—WI and CI on equal footing [29,30]. Nevertheless, we will also show evidence that seems to point at least towards a lighter version of TCC. Finally, we will speculate about the potential (deep) role of dissipation in shielding WI or similar theories from the swampland conjectures.

2. Swampland Burdens on Inflation

2.1. The Challenges of de Sitter States in an Inflationary Universe

Historically, the swampland program started with the so-called de Sitter conjecture [18,31], which remains one of the most contentious conjectures. Indeed, the appeal of inflation, and especially the discovery of a positive cosmological constant, demand that the string theory landscape be populated by theories with de Sitter vacua; otherwise, string theory would be unable to provide an adequate description of nature. However, it became apparent early on that anti-de Sitter vacua were far more ubiquitous in string theory, while dS solutions were notoriously difficult to obtain, giving rise to the longstanding conjecture that they may be completely unattainable. Constructions such as KKLT [32] and subsequent generalizations [33,34] looked to put these worries to rest, although they have faced criticisms related to the validity of the approximations and their status as proper solutions of string theory. On the other hand, it has been argued that slow-roll inflation is out of the reach of the dS conjecture, which is only limited to dark energy, where it favors quintessence models over a cosmological constant [35]. While the existence of dS vacua in string theory remains an open question, we will take the dS conjecture at face value and explore the viability of warm inflation in this context.

The de Sitter conjecture states that a scalar potential of an EFT weakly coupled to gravity must satisfy [31]

$$|\nabla V| \geq \frac{c}{M_{\rm Pl}} V\,, \tag{1}$$

where the derivatives are with respect to the scalar fields, and c is an $\mathcal{O}(1)$ constant. This was later refined in order to keep the Higgs potential outside of the swampland. For that, the potential could also satisfy

$$\min(\nabla_i \nabla_j V) \leq -\frac{c'}{M_{\rm Pl}^2} V\,, \tag{2}$$

where c' is another $\mathcal{O}(1)$ constant [36]. With these conditions, the dS conjecture disallows flat potentials that resemble a positive cosmological constant, effectively ruling out dS minima, though not other critical points.

In consequence, potentials with a rather pronounced slope are favored by this conjecture, as opposed to the roughly flat potentials required to achieve slow-roll (cold) inflation. For example, consistency with the dS conjecture (Equation (1)) imposes

$$\epsilon_V = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \geq \frac{c^2}{2}\,. \tag{3}$$

The slow-roll condition $\epsilon_V \ll 1$ would be in tension with the dS conjecture if we insists on $c \sim \mathcal{O}(1)$. To see this, notice that our current bounds on the tensor-to-scalar ratio, together with the consistency relation $r = 16\epsilon_V$, bound this parameter to $c < 0.067$ [12]. Similarly, one can check from Equation (2) that for single–field inflation, the slow-roll condition $|\eta_V| = M_{\rm Pl}^2|V''/V| \ll 1$ is in clear opposition to the requirement that $|\eta_V| \geq c'$.

This simple analysis already demonstrates the potential advantages of warm inflation from a swampland perspective. Indeed, slow-roll warm inflation requires, among other relations,

$$\epsilon_H = -\frac{\dot{H}}{H^2} \approx \frac{\epsilon_V}{1+Q} \ll 1\,, \quad \delta = -\frac{\ddot{\phi}}{\dot{\phi}H} \ll 1\,, \quad \theta = -\frac{\dot{Q}}{H(1+Q)} \ll 1 \tag{4}$$

where $Q = \Upsilon/(3H)$ quantifies the relative strength of the dissipative dynamics (parameterized by the dissipation term Υ in the inflaton evolution equation) compared to the expansion of the universe [37]. [1] In addition to the possibility of having larger values of ϵ_V, as favored by Equation (3), the conditions above also imply that

$$|\epsilon + \delta + \theta| \simeq \frac{M_{\rm Pl}^2}{1+Q}\left|\frac{V''}{V}\right| \ll 1\,, \tag{5}$$

which highlights that the constraint on the second derivative of the potential is also Q–suppressed. Consequently, even if potentials are steep, the universe can still be inflated provided that dissipation is strong enough. It is thus apparent that, from a model-building perspective, having a strong dissipative dynamic is one of the best ways to embrace the dS conjecture and benefit from inflation [26,28,38,39]. Such models would necessarily differ from a perfect dS universe, thereby allowing them to elude the tightest constraints of such spacetimes, such as those emanating from entropy bounds [40]. Moreover, it has been demonstrated that even if the dS conjecture is a result of these bounds, warm inflation is still in accordance with it, despite the presence of an additional entropy in the thermal bath [41]. Additionally, this picture is in line with the expected behavior of dS spaces coupled to interacting quantum fields, which break the de Sitter isometry group, resulting in the production of matter and radiation [3,42,43].

2.2. Bounds on the Amplitude of the Inflaton Excursions

Another challenge to the inflationary picture emerges when one considers the SDC together with the Lyth bound [44]. As discussed before, one of the consequences of the former is that the cutoff of the EFT and the field variations are coupled, with Λ exponentially suppressed for large values of $\Delta\phi$. This relation can be expressed as follows:

$$\Lambda := Ae^{-\alpha\Delta\phi/M_{\rm Pl}}M_{\rm Pl}\,, \tag{6}$$

where A and α are $\mathcal{O}(1)$ parameters. Then, $\Delta\phi$ must be small enough in order for Λ to remain relatively high, keeping the EFT description valid. For this, we ask

$$\Lambda > E_{\rm Inf} \simeq V^{1/4} \simeq 7.6 \times 10^{-3}\left(\frac{r}{0.1}\right)^{1/4} M_{\rm Pl}\,. \tag{7}$$

On the other hand, the field variation can be written in terms of r, as follows:

$$\frac{\Delta\phi}{M_{\rm Pl}} = \int_{N_{\rm end}}^{N_{\rm cmb}} dN\sqrt{\frac{r}{8}} \simeq \frac{\Delta N}{60} \times \left(\frac{r}{0.002}\right)^{1/2}, \tag{8}$$

where ΔN is the minimum number of $e-$folds required to solve the standard cosmological problems. Thus, accounting for the entire duration of inflation, we have

$$\frac{\Delta\phi}{M_{\rm Pl}} \geq \frac{\Delta N}{60} \times \left(\frac{r}{0.002}\right)^{1/2}. \tag{9}$$

Therefore, while large values of r would lower the EFT cutoff, it is not necessarily an issue due to the current upper bound of $r < 0.036$ [45]. Ultimately, the parameter A in Equation (6)—which corresponds to the mass scale of the tower of states—is the one that truly stands to limit inflationary models [12]. Nevertheless, the parameter α should not be disregarded, as even for Starobinsky models [46], one of the most favored by data [47], small variations in α could determine whether or not eternal inflation is accessible.

By allowing for dissipative dynamics, we can see that the above analysis for cold inflation must change, with Equation (8) now taking the form:

$$\frac{\Delta\phi}{M_{\rm Pl}} = \int_{N_{\rm end}}^{N_{\rm cmb}} dN \sqrt{\frac{r}{8}\left[1 + 2n_* + \frac{T}{H}\frac{2\pi\sqrt{3}Q}{\sqrt{3+4\pi Q}}\right]}, \tag{10}$$

where the expression inside the square brackets comes from the scalar power spectrum (without considering the growing mode present for temperature-dependent dissipative coefficients), and n_* represents the statistical distribution of modes at the horizon crossing (see, e.g., [37,48]). Once again, taking the limit of strong dissipation, we have

$$\frac{\Delta\phi}{M_{\rm Pl}} \gtrsim \frac{\Delta N}{60} \times \left(\frac{r^{(\rm WI)}}{0.002}\right)^{1/2}, \tag{11}$$

where we have made it explicit that in this case, one must consider the tensor-to-scalar ratio in warm inflation, which is necessarily smaller than its CI counterpart in Equation (9). Thus, WI can also fall into the category of small-field models, clearly alleviating the constraints emerging from Equations (6) and (7).

It is worth mentioning that the categorization of small and large-field models can be vital when discussing the initial conditions of inflation, particularly for plateau potentials. For instance, cold inflation necessitates large field excursions in order to be situated inside the attractor region [49]. This presents a challenge from a phenomenological standpoint, as seen from Equation (8), as it would then predict an overly large value of r. On the other hand, warm inflation requires smaller field excursions in order to comply with current bounds on r, although this would place it outside of the attractor region. Nevertheless, Ref. [50] has demonstrated that fluctuation–dissipation dynamics can be utilized to locate the field within a flat plateau about the origin, thus creating the necessary conditions for inflation.

Before going into the one conjecture warm inflation appears to be vulnerable to, it should be highlighted that the allure of WI from a swampland perspective is rooted in the strong dissipative regime ($Q \gg 1$). If dissipation is weak ($Q < 1$), the same constraints as for cold inflation apply, albeit with phenomenological differences still present. Conversely, if dissipation is not insignificant, but not sufficiently strong ($Q \sim 1$), then some of the appeal of WI may be restored, although one would still have to adjust the $\mathcal{O}(1)$ factors. Consequently, the consistency of warm inflation with the swampland conjectures is not generically guaranteed outside of the strong dissipative regime, but it is still arguably in a better position than cold inflation.

2.3. The Issue with Trans-Planckian Modes

Arguably, the most significant success of inflation is its ability to explain the origin of the macroscopic density perturbations as emerging from vacuum fluctuations during an earlier stage of the Universe. However, if inflation lasted long enough, certain present-day scales could be traced back to the trans-Planckian (TP) realm. If TP modes can reach visible wavelengths, inflation should be valid up to energy ranges beyond the Planck scale as an EFT [51–54]. Potential solutions such as setting a Planck-scale cutoff are not viable due to well-known issues such as the violation of diffeomorphism invariance or, for expanding backgrounds, the increase of the number of degrees of freedom with time, resulting in a complicated non-unitary evolution [55,56]. Against this background, the trans-Planckian censorship conjecture (TCC) has been proposed as a way to ensure that TP modes are not part of the EFT on curved spacetimes [29,30]. This conjecture states that the lifetime of metastable dS spaces must be such that TP modes cannot cross the horizon. For this, the lifetime of dS spaces must satisfy

$$t \leq \frac{1}{H} \ln \frac{M_{\rm Pl}}{H} \,. \tag{12}$$

Thus, EFTs that allow dS states whose lifetime violate this bound belong to the swampland. Notice that, string theory considerations aside, TCC stands out as one of the swampland conjectures with a particularly strong physical motivation. The notion of forbidding TP modes from crossing the horizon is to prevent them from becoming classical, thereby making them unobservable. That is why TCC applies ubiquitously to any inflation model.

Bounding the duration of inflation as prescribed by the TCC is highly taxing when constructing a model, especially concerning the energy scale of inflation. To better study this problem, let us focus on the WI case [28], although the analysis can be readily adapted for CI. First, the TP modes that have the longest time to cross the horizon are those that are trans-Planckian at the beginning of inflation, so that

$$\frac{\ell_{\rm Pl}}{a_i} < \frac{1}{a_f H_f} \qquad \Longrightarrow \qquad e^{N_e} := \frac{a_f}{a_i} < \frac{M_{\rm Pl}}{H_f} \tag{13}$$

where a_i (a_f) denotes the scale factor at the start (end) of inflation, H_f is the Hubble parameter at the end of inflation, and N_e is the number of e-folds of inflation. As can be seen, the relations above already set an upper bound on N_e.

On the other end, we consider the requirement that inflation should solve the horizon problem, for which it must persist for a sufficient number of e-folds. To guarantee that, one must impose that the present comoving horizon has to be contained within the comoving horizon at the beginning of inflation, i.e.,

$$\frac{1}{a_0 H_0} < \frac{1}{a_i H_i} \,. \tag{14}$$

Rearranging terms and conveniently introducing the scale factor at the end of inflation, the inequality above becomes

$$\frac{1}{H_0} < \frac{a_0}{a_f}\frac{a_f}{a_i}\frac{1}{H_i} \qquad \Longleftrightarrow \qquad \frac{1}{H_0} < \frac{T_f g_*^{1/3}(T_f)}{T_0 g_*^{1/3}(T_0)} e^{N_e}\frac{1}{H_i} \,, \tag{15}$$

or equivalently,

$$\frac{1}{H_0} < \frac{T_f}{T_0} e^{N_e} \frac{1}{H_i} \qquad \Longleftrightarrow \qquad \frac{H_i}{T_f}\frac{T_0}{H_0} < e^{N_e} \,, \tag{16}$$

where we have assumed that the ratio between the (cubic root) number of degrees of freedom g_* at the end of inflation and at present day is of order one. Thus, Equations (13) and (16) imply

$$\frac{T_0}{H_0} < \frac{T_f}{H_f}\frac{M_{\rm Pl}}{H_i} \,. \tag{17}$$

Finally, assuming slow-roll and a rapid thermalization, such that the radiation energy density scales with temperature as $\rho_r \propto T^4$, we have that [2]

$$\frac{T_f}{H_f} \simeq \left[\frac{9}{2}\frac{Q_f}{1+Q_f}\right]^{1/4}\frac{M_{\rm Pl}}{V_f^{1/4}}\,. \tag{18}$$

In the swampland context, the strong dissipative regime is the most interesting. In this regime, we obtain

$$V_i^{1/2}V_f^{1/4} < 5\times10^{-30}M_{\rm Pl}^3\,, \tag{19}$$

where we have used that $T_0/H_0 \approx 1.7\times10^{29}$. Furthermore, since $V_i > V_f$, we can find a bound for the energy scale at the end of inflation of

$$V_f^{1/4} < 1.7\times10^{-10}M_{\rm Pl} \sim 4\times10^8\ {\rm GeV}\,. \tag{20}$$

For comparison, the bound on the energy scale of cold inflation is $V^{1/4} \lesssim 3\times10^{-10}\,M_{\rm Pl}$ [30]. Then, TCC in the form here presented bounds r to be less than $\mathcal{O}(10^{-30})$, so any possibility of detection of tensor modes would be discarded.

Despite the severe bound on the energy scale of inflation, this is only an inconvenience from an experimental standpoint. In reality, it does not prevent inflation itself, as could be argued for the other swampland conjectures. [3] Thus, observational prospects aside, there are certainly models that can satisfy the constraints of TCC. For example, the strong dissipative regime of warm inflation can naturally lead to such a result [28,58,59]. In WI, the tensor-to-scalar ratio also serves the purpose of comparing the relative strength of quantum (tensor) and thermal (scalar) perturbations, and when the dissipation rate is high, the thermal perturbations will outweigh the quantum perturbations, resulting in a suppressed value of r. As such, several WI models satisfy the requirements of the TCC out of the box.

However, Is This Really an Issue?

Just as with the other swampland conjectures, TCC is not free of controversy. There are those who have argued that there is no such thing as a trans-Planckian problem in the first place. For instance, Ref. [60] suggests that at Planck scales, the Universe is essentially inhomogeneous and anisotropic, with fluctuations transforming some regions into black holes at such scales, which function effectively as a dynamical cutoff. This is only an example of how quantum gravity effects could take over in the Planckian regime. Along the same lines, one could argue that linear perturbation theory breaks down before classical modes can be blueshifted to the TP regime, thus necessitating quantum gravitational effects to take over from inflation. This line of thinking is reminiscent of what was expected to solve the horizon problem before inflation was introduced [61]. Going even further, Ref. [62] argues that it is not sensible to blueshift modes too far into the past, since their production is exponentially suppressed for wavelengths $\lambda \ll H^{-1}$. Thus, according to this argument, if we trace back a mode to the TP realm, we would be going beyond its birth time. In addition to all these arguments, Burgess et al. have asserted that even if the EFT includes TP modes and breaks down at earlier times, the late-time predictions of inflation are not affected provided that there is adiabatic behavior at those times [63].

TCC has also come under scrutiny for prohibiting TP modes from crossing the horizon on the basis that any quantum mode would decohere as it does so. However, this argument overlooks the fact that many interactions can cause decoherence even inside the cosmic horizon. For example, it was shown in Ref. [64] how the electroweak phase transition could have easily produced the classicalization of modes that were originally TP at earlier times.

Considering the arguments above, there is really no reason to strictly impose the bound shown in Equation (12). Instead, one could still limit the lifetime of dS spaces as follows:

$$N_e < \mathcal{O}(1) \ln \frac{M_{\rm Pl}}{H}\,, \qquad (21)$$

which is a condition that has been obtained from other swampland conjectures such as the SDC and the dS conjecture [64–68]. These modifications to TCC are not drastically different from the original formulation but are sufficient to support high-energy scales of inflation. Interestingly, it has been demonstrated that in order to regain the original TCC from other swampland conjectures, all quasi-dS spaces must be excluded. As a result, it is generally accepted that a limitation on the slope of the potential will imply a restriction on the duration of inflation, though not as firm as the one set by TCC. A strong support for a refined version of TCC comes from similar bounds obtained while investigating chaos and complementarity in dS spacetimes, which resulted in $N_e < 2\ln(M_{\rm Pl}/H)$ [69,70] (see also [71,72]). Bottom-up calculations have also arrived at similar conclusions, which suggest that the lifetime of dS spacetimes may indeed be finite, yet not short enough to impose any stringent phenomenological constraints [73].

3. Discussion

If some version of the dS conjecture (or its TCC reincarnation) is correct, then only short-lived dS vacua are allowed to have UV-completions. As we have pointed out multiple times in the draft, there appears to be plenty of arguments both in favour of and against such an assertion. However, in this section, let us assume that this conjecture is sacrosanct in quantum gravity and ponder the consequences invoked by such a hypothesis.

Most papers in the literature have focused on what it means for physically accelerating solutions, describing both the very early and late universe expansions, if the dS conjecture is correct and how to circumvent it for cosmological models. Another important question, largely left unanswered, is the following—if indeed the dS phase "lives" for a short duration, what happens to it after that? In other words, what does the dS vacuum decay into? One traditional option is to consider the tunneling from the meta-stable minima to some Minkowski spacetime. Indeed, in string theory, it is well-known that on sufficiently long time-scales, the 4-d dS solution decompactifies to 10-d flat space [4]. Another idea in M-theory is to consider dS as a coherent (or Glauber–Sudarshan) state built over a supersymmetric Minkowski background. Once again, this is allowed only for a short duration of time, after which the system becomes strongly coupled, and one returns to the higher-dimensional flat space [77–80]. It might simply be that either dS is only allowed as an unstable maximum or, if realized as a meta-stable minimum, it must tunnel into a different, more stable minimum within the swampland-predicted timescale (which may or may not be the scrambling time). If indeed such a tunneling effect is to be responsible for ending a dS phase, one must come up with a physical reason behind it.

However, in the context of inflation, there is a much more elegant mechanism to deal with this. What if the energy of the inflaton dissipates continuously into another phase, such as has been long postulated for warm inflation? In other words, it might well be that the dS phase decays into a radiation era, and the coupling here is necessitated by considerations of UV physics. One way to think of this would be the standard interacting dark energy dark matter models, but now applied to inflation. Let us assume the inflaton to be one of the moduli from string theory. Then, as the inflaton rolls down its potential, it would reach asymptotic parts of moduli space and would lead to the descent of an infinite number of massless states (in the simplest case, these are the 'winding' or 'momentum' modes from string theory). It is very much possible that such winding modes annihilate each other, which would otherwise have stopped expansion, and a radiation-dominated era ensues. The argument regarding the winding modes is the standard one used in *string gas cosmology* [81] (see [82–84] for its more modern incarnations). However, in light of the more general swampland conjectures, it is easy to see how the winding modes may come into play through the rolling of one of the string moduli (the one corresponding to the inflaton), and this can henceforth lead to a radiation phase. The reasoning given here for decay of the dS phase into radiation could also apply to the reheating phase after cold inflation. Its simply down to timescales, where the decay in the warm inflation case would be more gradual versus for reheating after cold inflation, where it would be much faster. This question could only be understood if an actual dynamics for this proposed scenario was realized.

There is, perhaps, a complementary way to think of the above problem. If inflation was to last forever, we would end up in an empty universe, and thus, one posits a period of damped oscillations of the inflation field in order to account for the creation of the standard matter content in our universe. The role of IR modes during inflation can also raise some obstructions in a very long-lasting quasi-dS phase of expansion. Put differently, there have been some recent studies which show that away from the spurious limit of $k \to 0$, long wavelength modes can have a non-negligible effect through their backreaction on the background dynamics [85–88]. The role of IR modes in inflation has been a matter of some debate for some time (see, e.g., [89,90], and contrast with [2,91]). However, in warm inflation, one is not allowed to neglect the dissipative effects altogether, and this would lead to the energy density of inflation becoming sub-dominant to the thermal energy density of radiation at some point quite naturally. This implies that the quasi-dS evolution is naturally overpowered by the ambient radiation, and the IR modes need to play any crucial role in the process. These IR modes can be sensitive to the choice of the UV vacuum [92], and warm inflation, thus, is naturally free from such ambiguities.

It goes without saying that our discussion above is a rather heuristic one; nevertheless, it has its underpinnings in a very simple idea. If indeed dS vacua have to be short-lived, where does the energy of the dS phase leak into? We conjecture that it is natural to assume that this energy dissipates into a radiation phase. This was the original idea behind warm inflation and how it cured the reheating problem. However, the swampland seems to be suggesting that such a dissipation might not just be an elegant idea but rather a necessary one in order to have UV completion. If true, this would place warm inflation in a theoretically favored position, where it will automatically have an embedding in string theory.

Funding: A.B. is partially supported by STFC.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors thank Suddhasattwa Brahma for helpful discussions. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) licence to any author-accepted manuscript version arising from this submission.

Conflicts of Interest: The authors declare no conflict of interest.

Notes

1. Recall that in warm inflation, the damping term is $(3H + \Upsilon)\dot{\phi}$, where Υ is a dissipation term arising from the interaction between the inflaton and other fields.
2. We have used $g_* = 228.75$ in the expression for the radiation energy density corresponding to the MSSM. Other choices change the numerical values by a factor of $\mathcal{O}(1)$ at most.
3. It has also been argued that TCC also leads to a fine-tuning problem [57]. In particular, the models of cold inflation which survive the TCC are low-scale models, and these are typically the ones which require a high degree of fine-tuning to be started.
4. This is *not* a swampland statement—it merely states that, at the very least on Poincaré recurrence times, it is expected that the moduli destabilizes, and dS is not eternal. For reference, the swampland version of this statement for eternal inflation is given in [74–76]. Notice that the time-scales involved are nevertheless extremely large.

References

1. Burgess, C.P.; Leblond, L.; Holman, R.; Shandera, S. Super-Hubble de Sitter Fluctuations and the Dynamical RG. *J. Cosmol. Astropart. Phys.* **2010**, *3*, 33. [CrossRef]
2. Giddings, S.B.; Sloth, M.S. Semiclassical relations and IR effects in de Sitter and slow-roll space-times. *J. Cosmol. Astropart. Phys.* **2011**, *1*, 023. [CrossRef]
3. Polyakov, A.M. Infrared instability of the de Sitter space. *arXiv* **2012**, arXiv:1209.4135
4. Cheung, C.; Creminelli, P.; Fitzpatrick, A.L.; Kaplan, J.; Senatore, L. The Effective Field Theory of Inflation. *JHEPJ. High Energy Phys.* **2008**, *3*, 14. [CrossRef]
5. Agarwal, N.; Holman, R.; Tolley, A.J.; Lin, J. Effective field theory and non-Gaussianity from general inflationary states. *J. High Energy Phys.* **2013**, *5*, 85. [CrossRef]
6. Green, D. EFT for de Sitter Space. *arXiv Preprint* **2022**, arXiv:2210.05820.
7. Burgess, C.P.; Holman, R.; Tasinato, G. Open EFTs, IR effects \& late-time resummations: systematic corrections in stochastic inflation. *J. High Energy Phys.* **2016**, *1*, 153. [CrossRef]
8. Shandera, S.; Agarwal, N.; Kamal, A. Open quantum cosmological system. *Phys. Rev. D* **2018**, *98*, 083535. [CrossRef]
9. Brahma, S.; Berera, A.; Calderón-Figueroa, J. Universal signature of quantum entanglement across cosmological distances. *Class. Quant. Grav.* **2022**, *39*, 245002. [CrossRef]
10. Colas, T.; Grain, J.; Vennin, V. Benchmarking the cosmological master equations. *Eur. Phys. J. C* **2022**, *82*, 1085. [CrossRef]
11. Vafa, C. The String landscape and the swampland. *arXiv* **2005**, arXiv:hep-th/0509212.
12. Palti, E. The Swampland: Introduction and Review. *Fortsch. Phys.* **2019**, *67*, 1900037. [CrossRef]
13. van Beest, M.; Calderón-Infante, J.; Mirfendereski, D.; Valenzuela, I. Lectures on the Swampland Program in String Compactifications. *Phys. Rept.* **2022**, *989*, 1–50. [CrossRef]
14. Casse, M.; Silk, J. Swampland Revisited. *Found. Phys.* **2022**, *52*, 86. [CrossRef]
15. Agrawal, P.; Obied, G.; Steinhardt, P.J.; Vafa, C. On the Cosmological Implications of the String Swampland. *Phys. Lett. B* **2018**, *784*, 271–276. [CrossRef]
16. Banks, T.; Seiberg, N. Symmetries and Strings in Field Theory and Gravity. *Phys. Rev. D* **2011**, *83*, 084019. [CrossRef]
17. Arkani-Hamed, N.; Motl, L.; Nicolis, A.; Vafa, C. The String landscape, black holes and gravity as the weakest force. *J. High Energy Phys.* **2007**, *6*, 60. [CrossRef]
18. Ooguri, H.; Vafa, C. On the Geometry of the String Landscape and the Swampland. *Nucl. Phys. B* **2007**, *766*, 21–33. [CrossRef]
19. Brout, R.; Englert, F.; Gunzig, E. The Causal Universe. *Gen. Rel. Grav.* **1979**, *10*, 1–6. [CrossRef]
20. Guth, A.H. The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems. *Phys. Rev. D* **1981**, *23*, 347–356. [CrossRef]
21. Linde, A.D. A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems. *Phys. Lett. B* **1982**, *108*, 389–393. [CrossRef]
22. Linde, A.D. Scalar Field Fluctuations in Expanding Universe and the New Inflationary Universe Scenario. *Phys. Lett. B* **1982**, *116*, 335–339. [CrossRef]
23. Berera, A.; Fang, L.Z. Thermally induced density perturbations in the inflation era. *Phys. Rev. Lett.* **1995**, *74*, 1912–1915. [CrossRef] [PubMed]
24. Berera, A. Warm inflation. *Phys. Rev. Lett.* **1995**, *75*, 3218–3221. [CrossRef] [PubMed]
25. Motaharfar, M.; Kamali, V.; Ramos, R.O. Warm inflation as a way out of the swampland. *Phys. Rev. D* **2019**, *99*, 063513. [CrossRef]
26. Das, S. Warm Inflation in the light of Swampland Criteria. *Phys. Rev. D* **2019**, *99*, 063514. [CrossRef]
27. Das, S. Distance, de Sitter and Trans-Planckian Censorship conjectures: The status quo of Warm Inflation. *Phys. Dark Univ.* **2020**, *27*, 100432. [CrossRef]
28. Berera, A.; Calderón, J.R. Trans-Planckian censorship and other swampland bothers addressed in warm inflation. *Phys. Rev. D* **2019**, *100*, 123530. [CrossRef]
29. Bedroya, A.; Vafa, C. Trans-Planckian Censorship and the Swampland. *J. High Energy Phys.* **2020**, *9*, 123. [CrossRef]
30. Bedroya, A.; Brandenberger, R.; Loverde, M.; Vafa, C. Trans-Planckian Censorship and Inflationary Cosmology. *Phys. Rev. D* **2020**, *101*, 103502. [CrossRef]
31. Obied, G.; Ooguri, H.; Spodyneiko, L.; Vafa, C. De Sitter Space and the Swampland. *arXiv* **2018**, arXiv:1806.08362.
32. Kachru, S.; Kallosh, R.; Linde, A.D.; Trivedi, S.P. De Sitter vacua in string theory. *Phys. Rev. D* **2003**, *68*, 046005. [CrossRef]
33. Kallosh, R.; Linde, A.D. Landscape, the scale of SUSY breaking, and inflation. *J. High Energy Phys.* **2004**, *12*, 4. [CrossRef]
34. Balasubramanian, V.; Berglund, P.; Conlon, J.P.; Quevedo, F. Systematics of moduli stabilisation in Calabi-Yau flux compactifications. *J. High Energy Phys.* **2005**, *3*, 7 . [CrossRef]
35. Akrami, Y.; Kallosh, R.; Linde, A.; Vardanyan, V. The Landscape, the Swampland and the Era of Precision Cosmology. *Fortsch. Phys.* **2019**, *67*, 1800075. [CrossRef]
36. Garg, S.K.; Krishnan, C. Bounds on Slow Roll and the de Sitter Swampland. *J. High Energy Phys.* **2019**, *11*, 75. [CrossRef]
37. Bastero-Gil, M.; Berera, A.; Calderón, J.R. Reexamination of the warm inflation curvature perturbations spectrum. *J. Cosmol. Astropart. Phys.* **2019**, *7*, 19. [CrossRef]
38. Das, S.; Goswami, G.; Krishnan, C. Swampland, axions, and minimal warm inflation. *Phys. Rev. D* **2020**, *101*, 103529.

39. Mohammadi, A.; Golanbari, T.; Sheikhahmadi, H.; Sayar, K.; Akhtari, L.; Rasheed, M.A.; Saaidi, K. Warm tachyon inflation and swampland criteria. *Chin. Phys. C* **2020**, *44*, 095101. [CrossRef]
40. Bousso, R. A Covariant entropy conjecture. *J. High Energy Phys.* **1999**, *7*, 4. [CrossRef]
41. Brandenberger, R.; Kamali, V.; Ramos, R.O. Strengthening the de Sitter swampland conjecture in warm inflation. *J. High Energy Phys.* **2020**, *8*, 127. [CrossRef]
42. Mottola, E. Thermodynamic Instability Of De Sitter Space. *Phys. Rev. D* **1986**, *33*, 1616–1621. [CrossRef] [PubMed]
43. Polyakov, A.M. Decay of Vacuum Energy. *Nucl. Phys. B* **2010**, *834*, 316–329. [CrossRef]
44. Lyth, D.H. What would we learn by detecting a gravitational wave signal in the cosmic microwave background anisotropy? *Phys. Rev. Lett.* **1997**, *78*, 1861–1863. [CrossRef]
45. Ade, P.A.R.; et al. BICEP/Keck Collaboration. Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season. *Phys. Rev. Lett.* **2021**, *127*, 151301. [CrossRef] [PubMed]
46. Starobinsky, A.A. A New Type of Isotropic Cosmological Models Without Singularity. *Phys. Lett. B* **1980**, *91*, 99–102. [CrossRef]
47. Chowdhury, D.; Martin, J.; Ringeval, C.; Vennin, V. Assessing the scientific status of inflation after Planck. *Phys. Rev. D* **2019**, *100*, 083537. [CrossRef]
48. Ramos, R.O.; da Silva, L.A. Power spectrum for inflation models with quantum and thermal noises. *J. Cosmol. Astropart. Phys.* **2013**, *3*, 32. [CrossRef]
49. Brandenberger, R. Initial conditions for inflation — A short review. *Int. J. Mod. Phys. D* **2016**, *26*, 1740002. [CrossRef]
50. Bastero-Gil, M.; Berera, A.; Brandenberger, R.; Moss, I.G.; Ramos, R.O.; Rosa, J.G. The role of fluctuation-dissipation dynamics in setting initial conditions for inflation. *J. Cosmol. Astropart. Phys.* **2018**, *1*, 2. [CrossRef]
51. Martin, J.; Brandenberger, R.H. The TransPlanckian problem of inflationary cosmology. *Phys. Rev. D* **2001**, *63*, 123501. [CrossRef]
52. Brandenberger, R.H.; Martin, J. The Robustness of inflation to changes in superPlanck scale physics. *Mod. Phys. Lett. A* **2001**, *16*, 999–1006. [CrossRef]
53. Brandenberger, R.; Zhang, X.m. The Trans-Planckian Problem for Inflationary Cosmology Revisited. *arXiv* **2009**, arXiv:0903.2065.
54. Brandenberger, R.H.; Martin, J. Trans-Planckian Issues for Inflationary Cosmology. *Class. Quant. Grav.* **2013**, *30*, 113001. [CrossRef]
55. Weiss, N. Constraints on Hamiltonian Lattice Formulations of Field Theories in an Expanding Universe. *Phys. Rev. D* **1985**, *32*, 3228. [CrossRef]
56. Jacobson, T. Trans Planckian redshifts and the substance of the space-time river. *Prog. Theor. Phys. Suppl.* **1999**, *136*, 1–17. [CrossRef]
57. Brahma, S.; Brandenberger, R.; Yeom, D.H. Swampland, Trans-Planckian Censorship and Fine-Tuning Problem for Inflation: Tunnelling Wavefunction to the Rescue. *J. Cosmol. Astropart. Phys.* **2020**, *10*, 37. [CrossRef]
58. Mohammadi, A.; Golanbari, T.; Nasri, S.; Saaidi, K. Brane inflation: Swampland criteria, TCC, and reheating predictions. *Astropart. Phys.* **2022**, *142*, 102734. [CrossRef]
59. Kamali, V.; Moshafi, H.; Ebrahimi, S. Minimal warm inflation and TCC. *arXiv* **2021**, arXiv:2111.11436.
60. Kaloper, N.; Scargill, J. Quantum Cosmic No-Hair Theorem and Inflation. *Phys. Rev. D* **2019**, *99*, 103514. [CrossRef]
61. Zee, A. The Horizon Problem and the Broken Symmetric Theory of Gravity. *Phys. Rev. Lett.* **1980**, *44*, 703. [CrossRef]
62. Dvali, G.; Kehagias, A.; Riotto, A. Inflation and Decoupling. *arXiv* **2020**, arXiv:2005.05146.
63. Burgess, C.P.; de Alwis, S.P.; Quevedo, F. Cosmological Trans-Planckian Conjectures are not Effective. *J. Cosmol. Astropart. Phys.* **2021**, *5*, 37 . [CrossRef]
64. Berera, A.; Brahma, S.; Calderón, J.R. Role of trans-Planckian modes in cosmology. *J. High Energy Phys.* **2020**, *8*, 71. [CrossRef]
65. Brahma, S. Trans-Planckian censorship conjecture from the swampland distance conjecture. *Phys. Rev. D* **2020**, *101*, 046013. [CrossRef]
66. Cai, R.G.; Wang, S.J. A refined trans-Planckian censorship conjecture. *Sci. China Phys. Mech. Astron.* **2021**, *64*, 210011. [CrossRef]
67. Seo, M.S. The entropic quasi-de Sitter instability time from the distance conjecture. *Phys. Lett. B* **2020**, *807*, 135580. [CrossRef]
68. Sun, S.; Zhang, Y.L. Notes on quantum corrections of swampland and trans-Planckian censorship conjectures. *Phys. Lett. B* **2021**, *816*, 136245. [CrossRef]
69. Aalsma, L.; Shiu, G. Chaos and complementarity in de Sitter space. *J. High Energy Phys.* **2020**, *5*, 152. [CrossRef]
70. Bedroya, A. de Sitter Complementarity, TCC, and the Swampland. *LHEP* **2021**, *2021*, 187. [CrossRef]
71. Dvali, G.; Gomez, C.; Zell, S. Quantum Break-Time of de Sitter. *J. Cosmol. Astropart. Phys.* **2017**, *6*, 28. [CrossRef]
72. Geng, H. Non-local entanglement and fast scrambling in de-Sitter holography. *Annals Phys.* **2021**, *426*, 168402. [CrossRef]
73. Brahma, S.; Alaryani, O.; Brandenberger, R. Entanglement entropy of cosmological perturbations. *Phys. Rev. D* **2020**, *102*, 043529. [CrossRef]
74. Brahma, S.; Shandera, S. Stochastic eternal inflation is in the swampland. *J. High Energy Phys.* **2019**, *11*, 16. [CrossRef]
75. Rudelius, T. Conditions for (No) Eternal Inflation. *J. Cosmol. Astropart. Phys.* **2019**, *8*, 9. [CrossRef]
76. Wang, Z.; Brandenberger, R.; Heisenberg, L. Eternal Inflation, Entropy Bounds and the Swampland. *Eur. Phys. J. C* **2020**, *80*, 864. [CrossRef]
77. Brahma, S.; Dasgupta, K.; Tatar, R. de Sitter Space as a Glauber-Sudarshan State. *J. High Energy Phys.* **2021**, *2*, 104. [CrossRef]
78. Bernardo, H.; Brahma, S.; Dasgupta, K.; Tatar, R. Crisis on Infinite Earths: Short-lived de Sitter Vacua in the String Theory Landscape. *J. High Energy Phys.* **2021**, *4*, 37. [CrossRef]

79. Bernardo, H.; Brahma, S.; Dasgupta, K.; Faruk, M.M.; Tatar, R. de Sitter Space as a Glauber-Sudarshan State: II. *Fortsch. Phys.* **2021**, *69*, 2100131. [CrossRef]
80. Brahma, S.; Dasgupta, K.; Faruk, M.M.; Kulinich, B.; Meruliya, V.; Pym, B.; Tatar, R. Resurgence of a de Sitter Glauber-Sudarshan State: Nodal Diagrams and Borel Resummation. *arXiv Preprint* **2022**, arXiv:2211.09181.
81. Brandenberger, R.H.; Vafa, C. Superstrings in the Early Universe. *Nucl. Phys. B* **1989**, *316*, 391–410. [CrossRef]
82. Brahma, S.; Brandenberger, R.; Laliberte, S. Emergent cosmology from matrix theory. *J. High Energy Phys.* **2022**, *3*, 67. [CrossRef]
83. Brahma, S.; Brandenberger, R.; Laliberte, S. Emergent metric space-time from matrix theory. *J. High Energy Phys.* **2022**, *9*, 31. [CrossRef]
84. Agrawal, P.; Gukov, S.; Obied, G.; Vafa, C. Topological Gravity as the Early Phase of Our Universe. *arXiv* **2020**, arXiv:2009.10077.
85. Brahma, S.; Berera, A.; Calderón-Figueroa, J. Quantum corrections to the primordial tensor spectrum: Open EFTs & Markovian decoupling of UV modes. *J. High Energy Phys.* **2022**, *8*, 225. [CrossRef]
86. Giddings, S.B.; Sloth, M.S. Cosmological observables, IR growth of fluctuations, and scale-dependent anisotropies. *Phys. Rev. D* **2011**, *84*, 063528. [CrossRef]
87. Matarrese, S.; Pilo, L.; Rollo, R. Resilience of long modes in cosmological observables. *J. Cosmol. Astropart. Phys.* **2021**, *1*, 62. [CrossRef]
88. Bartolo, N.; Carollo, G.B.; Matarrese, S.; Pilo, L.; Rollo, R. The physical content of long tensor modes in cosmology. *J. Cosmol. Astropart. Phys.* **2022**, *11*, 34. [CrossRef]
89. Urakawa, Y.; Tanaka, T. IR divergence does not affect the gauge-invariant curvature perturbation. *Phys. Rev. D* **2010**, *82*, 121301. [CrossRef]
90. Pimentel, G.L.; Senatore, L.; Zaldarriaga, M. On Loops in Inflation III: Time Independence of zeta in Single Clock Inflation. *J. High Energy Phys.* **2012**, *7*, 166. [CrossRef]
91. Woodard, R.P. Some Inconvenient Truths. *J. High Energy Phys.* **2016**, *5*, 152. [CrossRef]
92. Danielsson, U. The quantum swampland. *J. High Energy Phys.* **2019**, *4*, 95. [CrossRef]