Comments on the Transplanckian Censorship Conjecture

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Abstract

We consider some aspects of the Transplanckian Censorship Conjecture (TCC), which states that for theories of quantum gravity there is a limit on the lifetime of dS or quintessence states not too different than the current Hubble horizon. If one accepts the de Sitter Swampland conjecture, then the former are ruled out. We consider some aspects of tunneling to an isolated ground state in the presence of time-varying fields, in quantum mechanics and quantum field theory in the absence of gravitation, and note that lifetimes are typically enormous; in fact, there is often a finite probability for the system to remain eternally in its original state. With gravity in a universe with superluminal expansion, while the field evolution may be slowed, Planck scale fluctuations would seem likely to grow to superhorizon size long before the universe decays. We argue that the TCC, if it is correct, requires that superluminal expansion occur only for a brief period in the history of the universe, and will be followed by a $p = \rho$ phase.
1 Introduction: The de Sitter Swampland Conjecture and Quintessence

It has proven challenging to construct de Sitter solutions of string theory, and this has motivated the de Sitter Swampland Conjecture\cite{1}. While the two present authors argued in \cite{2} that this is a question which is intrinsically inaccessible to current controlled approaches to string theory, in this paper we will generally assume that the conjecture is correct, and review and further explore some of its consequences. As discussed in \cite{1}, one of the most immediate is that the observed dark energy must be a form of quintessence. Quintessence requires equation of state parameter \( w < -1/3 \). Observations require \( w \) close to \(-1\). Whether such configurations arise in string theory – with sensible scales of energy, mass scales for the Higgs, and so on – is an interesting (and extremely challenging) question, which we will not explore here. We will confine ourselves to a narrower question. Assuming that one has a landscape in string theory with quintessence like configurations as well as negative cosmological constant stationary points, then these states are unstable to decay to AdS spaces (more precisely to states of negative cosmological constant). Ref. \cite{3} insisted on a criterion for sensible states\footnote{In the context of inflation, possible limits on the number of e-folds have been discussed by others, e.g. \cite{4,5}. On the other hand, the authors of \cite{6} present arguments that such transplanckian fluctuations might be consistent with successes of inflation}. They noted that in these quintessence states, one has superluminal expansion. If the state lives long enough, Planck scale fluctuations will redshift until they become larger than the horizon. The authors of \cite{3} argued that this is not sensible, and that there should be a limit on the lifetime, \( \Gamma \), of such states:

\[ \Gamma < H \log(H). \tag{1.1} \]

While not committing ourselves to a view on this basic question of principle, we will ask: is this plausible? What are the lifetimes of such quintessence states likely to be? This will require that we consider some aspects of tunneling, from a state which is evolving in time towards zero energy, to a lower energy state. We will first consider this in quantum mechanics, and then in quantum field theory without gravity, and finally in a generally relativistic theory. In the first two cases, we will see that the lifetimes can be quite long. In fact, typically, there is a finite probability that the system never makes a transition to the lower state at all. These systems are not amenable to conventional WKB/Euclidean path integral approaches, but it is not difficult to make rough estimates of the tunneling rates working with Minkowski signature.

Including general relativity, and more generally in a would-be quantum theory of gravity, we are on less certain ground. In string theory, in the absence of supersymmetry, one might expect that states with potentials which fall to zero for large values of scalar (“pseudomoduli”) fields are typical. Such potentials would go to zero at least exponentially rapidly in various regions of field space. We will generally model the tunneling
problem by considering potentials which, in one direction, labeled by a field $\phi$, are pure exponentials, $V(\phi) = Ae^{-\lambda\phi}$. There is another direction, $\chi$, such that at some point, there is a local minimum with negative c.c. for both $\lambda$ and $\chi$. As we will review, in the first regime, unless the coefficient in the exponential satisfies a certain bound, the potential quickly becomes negligible and one has a universe with $p = \rho$, i.e. $w = 1$. The TCC does not constrain these systems. For sufficiently small $\lambda$, the system may exhibit quintessence. We will focus our considerations on such states. We will argue that tunneling is highly suppressed, as in the non-gravitational case.

The rest of this paper is organized as follows. In section 2, we review the de Sitter swampland conjecture and the Trans Planckian censorship conjecture. We note the conditions on exponential potentials to obtain $w < -1/3$. In section 3, we discuss what a landscape might look like which possesses quintessence states and AdS minima. We provide some model potentials on this landscape, which will guide our tunneling computations. In section 4, we consider tunneling in quantum mechanical models with small numbers of degrees of freedom, between states with one degree of freedom “rolling down a hill”, while in another direction, the potential exhibits a minimum. Then we treat the analogous problem in field theory, first in the absence of general relativity in section 5 and then coupling to general relativity in section 6. Finally we turn to conjectures about how such tunneling might look in a landscape. We are particularly concerned with how the requirement of slow variation of the potential, with resulting slow motion of the field, might allow different behaviors than in our quantum mechanics and field theory examples. We conclude in section 7 that the TCC is likely incompatible with the pictures which have been put forth for a landscape.

2 The de Sitter Swampland And Trans Planckian Censorship Conjectures

The vacuum states we can claim to understand in string theory generally possess a high degree of supersymmetry. States without supersymmetry, especially de Sitter space (or flat space) are hard to access by weak coupling methods. Indeed, as stressed in [2], typical non-supersymmetric states exhibit runaway to singular space-times and strong coupling, and one cannot claim to understand these in any systematic way. Such states might be candidates for quintessence. That said, the work of Bousso and Polchinski[8] and KKLT[9] suggests the possible existence of a landscape of states, with a discretuum of positive and negative cosmological constants. The existence of these states can hardly be viewed as rigorously established. Ooguri and Vafa[11] conjectured, based on the difficulty of finding dS stationary points of effective potentials of systems with branes and fluxes[10], that de Sitter vacua, stable or unstable, may not exist, and that the presently observed dark energy is a form of quintessence. In [2], it was demonstrated that there are

$^2$In terms of fields with canonical kinetic terms, potentials might well be expected to tend to zero far more rapidly.
fundamental obstacles to weak coupling searches, and argued that these don’t provide an argument, one way or the other, about the existence of metastable de Sitter space in string theory/quantum gravity. The work of that reference focused heavily on the fact that such would-be states are metastable, and in the past or future, the space-time becomes singular at the classical level.

In [3], Bedroya and Vafa set forth an additional conjecture. They argued that Planck scale fluctuations should not become classical. So for any would-be state, the lifetime, $T$, should satisfy

$$T < H_f^{-1} \log H_f,$$

(2.1)

where $H_f$ is the Hubble parameter at the moment of decay. This decay might represent a point in time where superluminal expansion ends. We will not focus on this possibility, though for $w$ close to $-1$, such a situation might well be tuned. It might also represent a moment of vacuum decay, in the sense of [14], which will be the focus of our current discussion.

If a landscape picture holds, any quintessence vacuum will be surrounded by classically stable, negative cosmological constant stationary points. As the quintessence field roles in its potential, it can decay to one of these stable minima, but we would expect that the decay amplitude would rapidly get smaller as the field $\phi$ rolls down its hill. This is a slightly unconventional tunneling problem, and we will consider it first in a quantum mechanics system with two degrees of freedom, and then in field theory without general relativity, before attacking the actual problem of interest. In both of these cases, we will find significant suppression of the decay amplitude. Turning to the gravitational case with quintessence, we lack an explicit, controlled string model. Still, it would seem that if such systems exist, lifetimes, for large values of teh quintessence field/small values of the energy density are likely to be very long, violating the conjecture. So there would seem to be a tension between the TCC and a landscape picture.

3 Quintessence in a Landscape

First, we recall some basic facts about quintessence. The equation of state $p = w\rho$ leads to evolution of the scale factor, according to:

$$a(t) = a(t_0)\left(\frac{t}{t_0}\right)^{\frac{2}{3(1+w)}}.$$  

(3.1)

For $w = 1$, a free massive field,

$$a(t) \propto t^{1/3}.$$  

More generally, this result holds when, in some era, one can neglect the potenital. $w \leq -1/3$ leads to quintessence; $a(t)$ grows faster than $t \sim \frac{1}{H}$.

We will focus on $w < -1/3$, considering a field $\phi$ with a canonical kinetic term and an exponential potential,

$$V(\phi) = \Lambda^4 e^{-\lambda \phi}$$  

(3.2)
in units with reduced Planck mass, $\tilde{M}_p = 1$. For $\lambda < \sqrt{6}$

$$w = -1 + \frac{\lambda^2}{3}$$ (3.3)

with $\lambda < \sqrt{2}$ necessary for quintessence\[12\]. One can quickly check this formula for small $\lambda$, noting that in this case the second derivative in the equation for $\phi$,

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi)$$ (3.4)

can be neglected. So $T_{00}$ and $T_{ij}$ can be computed simply for the exponential potential.

So now the interesting question is: suppose one has a string model with such a potential and that this accounts for the observed dark energy. In a landscape context, we expect that there are states nearby with negative cosmological constant. We can model this by considering two fields, $\phi$ and $\chi$, with potential such that $\chi = 0$, $\phi > 0$ corresponds to the quintessence state, and $\chi = \mu$, $\phi = 0$ corresponds to an AdS minimum. The TCC raises the question: what is the lifetime of the quintessence state?

We should note that, for the exponential potential, assuming $V$ is as small as the dark energy today, and that $\Lambda$ is not extremely small, $\phi$ is large, so it is likely that there are many light states. For the question of vacuum decay, this feature would seem likely to further suppress the decay rate. How this might effect the criteria for quintessence we won’t explore, but it might increase the tuning required to obtain the required brief period of superluminal expansion.

4 Tunneling from Quintessence-Like states in Quantum Mechanics

We first consider a quantum mechanical problem, with two degrees of freedom, $\chi$ and $\phi$, which exhibits tunneling from a time-dependent configuration of the coordinates. In particular, classically there is a lowest energy configuration for some value of $(\chi, \phi) = (\mu, 0)$ and a higher energy configuration, where $\chi = 0$ and $\phi$ is not uniquely fixed, but instead the potential falls to zero for large $\phi$ and $\chi = 0$:

$$V(\chi, \phi) = \lambda \phi^2 (\chi)^2 + \Gamma (\chi^2 - \mu^2)^2 + \delta \frac{(\chi - \mu)^2}{\phi^2 + \mu^2}$$ (4.1)

This has a global minimum at $\chi = \mu$, $\phi = 0$, $V = 0$. At $\chi = 0$, it has runaway behavior for $\phi$.

The false “minimum” has $\chi = 0$, $\phi$ rolling, with

$$V(\phi) = \delta \frac{\mu^2}{\phi^2 + \mu^2}$$ (4.2)

(Note we are assuming here that $\delta < \mu^4$; other parameters have been chosen for simplicity; small changes will not alter the behavior of the potential).
This model suggests focusing on a single degree of freedom, $x$, with:

$$V(x) = -V_0 \quad x < x_0 \quad V(x) = \frac{\delta}{x^2} \quad x >> x_0$$  \hspace{1cm} (4.3)

We are interested in tunneling from a configuration described by a wave packet centered at $x > x_0$, and evolving with time. If the wave packet is Gaussian, and sufficiently narrow, there will be a huge suppression of the wave function in the region $x < x_0$. The question is: what is the natural value for this width, and how does the width grow with time.

It is worth recalling some facts familiar from elementary quantum mechanics.

1. Wave packet evolution for a free particle: consider a system described at $t = 0$ by a Gaussian wave packet with width $\Delta x$,

$$\psi(x, 0) = e^{i k_0 x} e^{-\frac{(x-x_{cl})^2}{(\Delta x)^2}}. \hspace{1cm} (4.4)$$

A standard approach to this problem is to Fourier transform, use the known behavior of plane waves, and Fourier transform back. In this case, one obtains:

$$\psi(x, t) = e^{i k_0 x - \frac{k_0^2}{2m} t - \frac{(x-x_{cl}(t))^2}{(\Delta x)^2 + \frac{1}{m}}} x_{cl}(t) = x_0 + \frac{k_0}{m} t \hspace{1cm} (4.5)$$

So the width of the wave packet grows with time according to:

$$(\Delta x(t))^4 = (\Delta x)^4 + \frac{t^2}{m^2} \hspace{1cm} (4.6)$$

This is what one expects from a simple-minded semiclassical argument. With the passage of time, the width of the packet grows as $(\Delta v)t = \frac{\Delta k}{m}t$, giving

$$(\Delta x(t))^2 = (\Delta x)^2 + \frac{(\Delta k)^2 t^2}{2m} \hspace{1cm} (4.7)$$

or

$$(\Delta x(t))^4 = (\Delta x)^4 + 2\frac{t^2}{m^2} + \mathcal{O}(t^4). \hspace{1cm} (4.8)$$

From equation (4.6) we have, at large times,

$$\Delta x(t) = \sqrt{\frac{t}{m}}, \hspace{1cm} (4.9)$$

independent of the initial width of the packet. The width grows much more slowly than the packet moves, i.e.

$$\frac{d\Delta x(t)}{dt} \ll v. \hspace{1cm} (4.10)$$
2. Wave packet evolution for a harmonic oscillator: here, the standard textbook result is that the center of the wave packet evolves classically, and the wave packet does not spread in time. We can see this directly in coordinate space. With
\[
\psi(x, t) = e^{-i\frac{\hbar^2}{2m} t} e^{-\frac{(x-x(t))^2}{(\Delta x)^2}} x(t) = A \cos(\omega t).
\] (4.11)
In the Schrodinger equation, we can compare the term \(-\frac{1}{2m} \frac{\partial^2 \psi}{\partial x^2}\) with the \(Kx^2\) term. This fixes \((\Delta x)^2 = \frac{1}{\omega^2}\). The wave packet does not spread.

3. Our problem is presumably somewhere in between, behaving nearly like a free particle, with the wave packet spreading, perhaps somewhat more slowly than that for a free particle, particularly in the region where the potential is growing.
\[
\mathcal{A} \propto e^{-\frac{\chi(t)^2}{\Delta x^2}}.
\] (4.12)
If this is the case, for large times, we have a huge suppression of the tunneling amplitude, Rather than a rate of decay per unit time, the rate falls exponentially to zero at large times; one has simply a finite probability to remain in the rolling condition forever.

5 Tunneling from Quintessence-Like states in Field Theory (Without Gravity)

For the analogous problem in field theory, we consider two fields, \(\chi, \phi\), with the potential of equation 4.1
\[
V(\chi, \phi) = \lambda \phi^2 (\chi)^2 + \Gamma (\chi^2 - \mu^2)^2 + \delta \frac{(\chi - \mu)^2}{\phi^2 + \mu^2}
\] (5.1)
Again, we have an isolated vacuum at \(\phi = 0, \chi = \mu\), and a quintessence-like configuration at \(\chi = 0\). For \(\phi > \mu\), the \(\chi\) potential gets steeper and steeper for larger \(\phi\). Since our interest is in estimating the decay from the region of large \(\phi\), it makes sense to model the system integrating out \(\chi\) and writing
\[
V_{model}(\phi) = -V_0 \phi < \mu; \quad V(\phi) = \frac{\delta}{\phi^2} \phi > \mu.
\] (5.2)
We want to investigate, again, the decay of the quintessence-like state to the isolated vacuum (we can smooth out \(V_{model}\) around \(\phi = \mu\), if desired).

In terms of the model potential, we can describe the initial bubble corresponding to decay of the system, if we treat \(\phi(t)\) as fixed, and take an even more drastic simplification of the potential:
\[
V_{simplified}(\phi) = -V_0 \phi < \mu; \quad V(\phi) = 0 \phi > \mu.
\] (5.3)
Now we might expect the critical bubble, on dimensional or simple scaling grounds, to have radius:

\[ R^2 = \frac{\phi(t)^2}{V_0}. \]  

(5.4)

Specifically, the kinetic energy term would be of order \( \phi(t)^2 R \), while the potential energy term would be of order \( R^3 V_0 \); the balance determines \( R \). Since the field, \( \phi \), is free mostly everywhere, we might expect it to have a Gaussian wave functional,

\[ \Psi(\phi) = e^{-\int d^3x \phi(x)(\nabla^2)\phi(x)} \]  

(5.5)

and correspondingly the amplitude to find such a bubble would behave as

\[ A \sim e^{-\phi^2 R^2} \sim e^{-\phi^4/V_0}. \]  

(5.6)

This is, of course, extremely suppressed at large \( \phi \).

We can obtain the estimate of equation \( 5.6 \) by a WKB analysis as in the thin wall case. If we think of a “standard bubble” with size of order \( R \) and variations of \( \phi \) on scales of order \( R \), the lagrangian for \( R \) is now:

\[ L = \phi_0^2 R \dot{R}^2 + V_0 r^2 - \phi_0^2 R. \]  

(5.7)

The critical point in the potential is then

\[ R^2 = V_0^{-1} \phi_0^2 \]  

(5.8)

so the WKB estimate yields

\[ B \sim \int dRR^{1/2} \sqrt{V_0 R^3} \sim \frac{\phi_0^4}{V_0} \]  

(5.9)

as above.

6 Including Gravity and Checking the TCC Criterion

Without gravity, for large \( \phi_0 \), we have seen that the amplitude for bounce production is enormously suppressed at large \( \phi \). Here we ask the extent to which gravity might qualitatively alter these results.

6.1 The Size of Gravitational Corrections

It is worth considering, first, the size of such corrections in the familiar case of thin wall tunneling\[\text{[11]}\], for small gravitational coupling, \( G_N \), and with energy splitting \( \epsilon \) and critical bubble radius \( R \). For the case of decay from flat space to de Sitter space, the energy of the bubble is of order \( \epsilon R^3 \), and the gravitational field is of order \( G_N \epsilon R^2 \). So
the corrections to the action for $R$ are of order $G_N \epsilon^2 R^5$, consistent with equation 3.19 of ref. [13]. These effects grow as $\epsilon$ becomes smaller, for fixed $G_N$, and can be quite dramatic, as stressed by Coleman and Deluccia. For the field theory systems described in the last section, this can also be true for very large $\phi(t)$, but there is a period where these corrections are under control and small. In this period the tunneling amplitude is extremely tiny.

It is in the presence of gravity that we can actually discuss quintessence, restricting the term to systems of time-dependent fields with $w < -1/3$. The model of the previous section does not satisfy this criterion. Instead, in considering the TCC and quintessence, we focus on models with exponential potentials yielding suitable $w$. For this and other systems which truly exhibit quintessence, precise statements require understanding of aspects of quantum gravity, but, if anything, tunneling rates are likely further suppressed.

Indeed, from the work of Coleman and DeLuccia [11], it is known in the thin wall case that inclusion of gravitation further suppresses tunneling, and that there is no semi-classical tunneling if the radius of the would-be anti-deSitter universe is smaller than the would-be bubble size in the absence of gravity. In the absence of gravity, we argued for the models of the previous section that the bubbles would be quite large, of order $\phi_0/\sqrt{V_0}$, while the tunneling amplitude is of order $e^{-\phi_0^2/V_0}$. Gravitational effects may not be within our control, but this estimate is likely to provide some guidance as to tunneling rate. For quintessence, in particular, the kinetic and potential terms in the action are of comparable importance, so we might expect that neglect of the potential term would yield an ($O(1)$ correction to the (large) exponential factor. We need to ask: How large is $\phi_0$?

### 6.2 How large is $\phi_0$?

The value of the field, $\phi_0$, at any given time, will control the tunneling amplitude. It is of interest to ask how large $\phi_0$ would be if the present universe is described by quintessence. Again, without good control of the quantum theory, this may be a hard question to answer. But the exponential potential is instructive, and strongly suggests that the tunneling amplitude is extremely suppressed if quintessence describes the observed dark energy. Note that in a landscape picture of quintessence, such states would have to be quite common, so the sort of estimates we are making here would be fairly typical.

So consider a field, $\phi$, with a nearly canonical kinetic terms and potential

$$V = \Lambda^4 e^{-\lambda \phi} \quad (6.1)$$

If $\Lambda = \text{TeV}$, say, then $\lambda \phi \sim \log(10^{50})$ to describe the current dark energy. We know that $\lambda$ can’t be too large for quintessence, probably not larger than $\frac{1}{\sqrt{3}}$, so $\phi$ has to be something like 200 in Planck units (note that if $\Lambda$ is larger than $\text{TeV}$ scales, as one might expect, $\phi_0$ is larger still). So $\phi_0^2/V_0$ which is the action of the critical bubble without gravity, is potentially huge. E.g. if $V_0 \sim M_p^4$, then the bubble is huge, as is the bounce
action. The would-be initial bubble itself is two orders of magnitude larger than the AdS radius, suggestive, following [11] that the tunneling amplitude may vanish altogether.

We cannot make completely reliable statement for the strongly coupled system we are considering, but we would be surprised if the gravitational result were wildly different from the result neglecting general relativity. Indeed, because of the large size of the critical bubble in the semiclassical treatment, as we have said, we think it likely that the tunneling amplitude simply vanishes for \( \phi_0 \) sufficiently large, and in particular for \( \phi_0 \) as large as required to account for the presently observed dark energy.

7 Conclusions: Plausibility of the Conjectures

Our results suggest a possible conflict between the TCC and conventional (albeit highly speculative) conjectures about the string landscape. If we abandon the de Sitter Swamp-land Conjecture, then the TCC either limits the extent in time of any superluminal expansion, or provides a significant constraint on possible metastable de Sitter states. While little is known about such would-be states (though there are plausible conjectures, for example [9], it would seem to rule out, for example, states with positive cosmological constant and even very approximate supersymmetry[14]. If we hold to the conjecture, so that the observed dark energy is a form of quintessence, than it is possible that the current rapid expansion might be relatively short lived, followed by a universe with \( p \approx \rho \). Alternatively, quintessence might persist, and these states are extremely long lived once the field has evolved to a region with very small cosmological constant. This follows if, as one might expect, there are some modest number of negative cosmological constant states accessible to the system. Validity of the TCC implies this quintessence state must be surrounded by some sort of dense set of AdS minima, or we have to be extremely lucky that it there is a well placed such state nearby.

There is another possible way out. If the parameter \( \Lambda \) in equation 6.1 is extremely small, one might avoid the necessity for large \( \phi \). This would imply a tuning condition comparable to the usual one for the cosmological constant. It is not clear to us whether this might have a straightforward anthropic explanation. We leave to the reader the question of how plausible this might seem.

It appears most likely that either the landscape picture does not hold, or that the TCC is not valid and the theory somehow escapes the puzzles associated with the growth of subplanckian fluctuations to horizon size.

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