Swampland and Cosmology

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Based on three joint papers

de Sitter Space and the Swampland

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On the Cosmological Implications of the String Swampland

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Distance and de Sitter Conjectures on the Swampland

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Among Swampland conditions, the distance conjecture characterizes the geometry of scalar fields and the de Sitter conjecture constrains allowed potentials on it. We point out a connection between the distance conjecture and a refined version of the de Sitter conjecture in any parametrically controlled regime of string theory by using Bousso's covariant entropy bound. The refined version turns out to evade all counter-examples at scalar potential maxima that have been raised. We comment on the relation of our result to the Dine-Seiberg problem.

The plan for this talk is:

-Some general aspects of String Landscape and Swampland

-Why do we believe in the existence of dS space?

-No quasi-dS swampland condition:

Lower bound $|\nabla V| \geq cV$ for c>0

-Further evidence based on swampland distance conjecture and dS entropy at weak couplings

-Cosmological Implication of two swampland criteria for past, present and future:

$$|\nabla V| \geq cV, \qquad |\Delta\varphi| < \Delta$$

String Landscape and Swampland

In string theory we construct vacua by going from higher dimensions (say 10,11,12) to lower dimensions by compactification: D—>d through a manifold M.

M ——————→ d-dimensional physics

Huge # of possible M’s—> huge string landscape
Invert the map: Just start from any consistent looking effective theory in d dimensions and let string theorists worry about finding the M!

However we have learned this is not a correct picture:

Almost no consistent looking effective theory can be coupled to gravity consistently and belong to the String Swampland! The ones that can couple to gravity consistently are rare!

Eff. Theories

What Distinguishes Landsacpe?

Based on string constructions we can try to identify criteria distinguishing Landscape from Swampland.

For example

Gravity is the weakest force (WGC);

U(1) gauge theory—> charged states

$$m \leq q$$

(For Non-SUSY case m<q).

Let us first restrict to supersymmetric case:

We have learned quite a bit about supersymmetric compactifications of string theory.

The allowed solutions for non-compact space are of two types:

Minkowski—With 0 cosmological constant.

AdS—With negative cosmological constant.

Many absolutely stable. No SUSY dS solutions.

SUSY theories typically have moduli given by scalar fields with:

$$V(\varphi^i) = 0$$

What is the geometry of the field space?
Can the scalars take arbitrary range?

Yes, but if you go too far in distance, you get a tower of light states:

$$m \sim exp(-\alpha \Delta\varphi)$$

In other words, for an effective theory to be valid the range of field space is effectively bounded.

Non Supersymmetric case?

No known perturbatively stable solution is known.

WGC with m<q, suggests that for AdS case all the non-supersymmetric situations are unstabale:

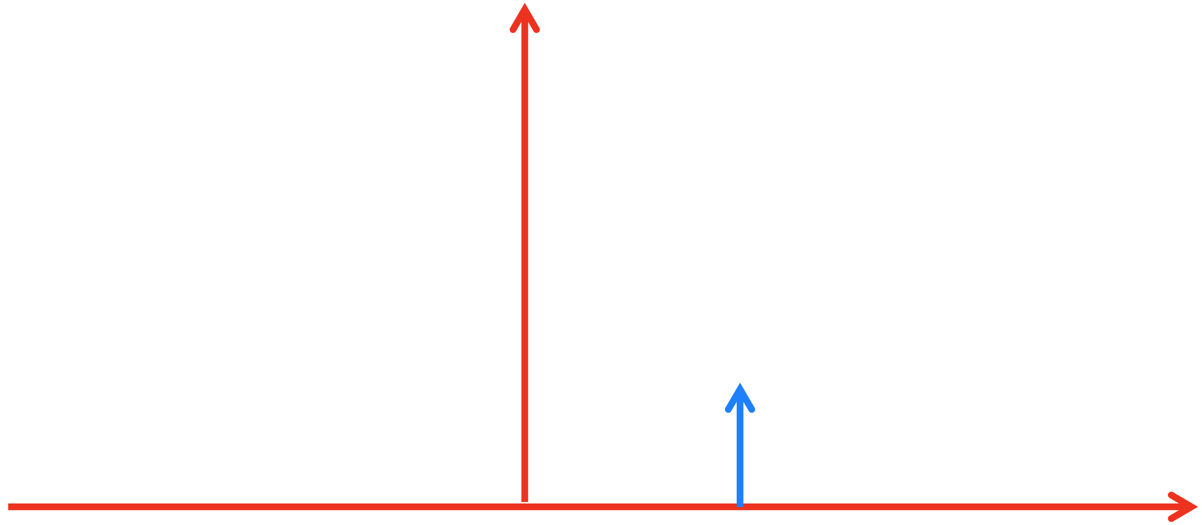
Electric replusion wins

How about non-susy dS?

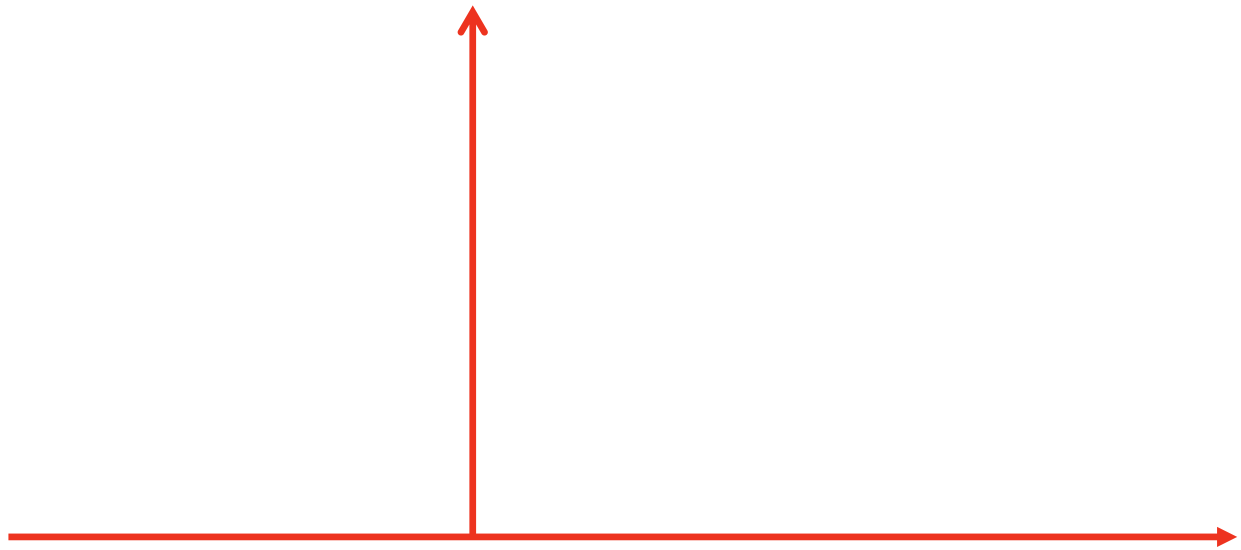
Why care about dS?

Because we live in one!

$$\Lambda > 0$$



Why not rolling scalar potentials (quintessence)?



The scalar would typically couple to some matter fields and its rolling would lead to observable effects.

But, e.g., from z=1 till now

$$\frac{\delta\alpha}{\alpha} < 10^{-6}$$

Also the coupling of the scalar field to matter would give rise to a new `fifth force' which would be detectable at astrophysical distance. The idea that the scalar field should couple to something is natural in string theory.
The fifth force would lead to apparent violations of equivalence principle.

The existence of fifth force is strongly bounded based on astrophysical observations, making this rather implausible.

Not a good argument:

The scalar field should couple strongly to SOME fields but not necessarily visible matter fields making their detection more difficult:

The scalar field could couple more strongly to DM.
The rolling scalar anticipates DM and can be part of it.

But there is another strange feature of quintessence models:

Not only
(in Planck units)

$$V \sim 10^{-122}$$

But also for the quintessence models not to be in contradiction with observational bounds on w we need

$$|\nabla V| \leq 10^{-122}$$

Sounds like double fine tuning unless we can naturally have $|\nabla V| \approx V$

Unlike AdS, constructing dS vacua (even meta-stable ones) in string theory seems very difficult.

Despite heroic efforts (see in particular KKLT, LVS) these attempts are at the level of proposed scenarios rather than rigorous constructions and there are a number of criticisms leveled against them.

To construct dS vacua one needs to do something exotic. For example:

Maldacena-Nunez no go theorem:

in the limit of supergravity (i.e. when not too much curvature in Planck units) no dS in M-theory!

So let us dare to ask: What if there are no metastable critical points of V with positive value?

If so, the next natural question is how close we can get gradient of V to zero? Could it be that there is a universal bound (at least for positive Hessian):

$$|\nabla V| > a > 0$$

This cannot be. For example in a supersymmetric theory with 0 cosmological constant, we can consider a massive field

$$V = \frac{1}{2} m^2 \varphi^2$$

and go arbitrarily close to 0.

One can instead consider a bound:

$$|\nabla V| > f(\varphi)$$

And a natural choice for f is:

$$f(\varphi) = cV(\varphi)$$

Where c>0 and order 1 in Planck units. In other words for a universal c

$$|\nabla V| \geq cV$$

Preliminary checks:

$|\nabla V| \geq cV$ is trivially satisfied with V<0. So this is compatible with susy and known critical points of V for AdS.

Also it is trivially satisfied for known supersymmetric examples with zero cosmological constant (say for type II string theory on Calabi-Yau threefolds).
For example the existence of moduli is compatible with it.

How about V>0? We can start from a supersymmetric case with 0 cosmological constant and deform.

If we deform it by going away from 0 cosmological constant, it is equivalent to giving vev to fields, and to leading order this is the same as changing V to

$$V = \frac{1}{2} m^2 \varphi^2$$

$$\frac{|\nabla V|}{V} = \frac{2}{|\varphi|}$$

This is consistent with the bound $\frac{|\nabla V|}{V} > 0(1)$

When one recalls that the effective field theory is expected to break down for large values of $|\varphi|$

One can consider M-theory in supergravity limit:

$$2\kappa_{11}^2 S = \int d^{11}x \sqrt{-g^{(11)}} \left(\mathcal{R} - \frac{1}{2}|G|^2 \right)$$

and consider compactifying to d dimensions on an arbitrary 7 manifolds with arbitrary flux. We get an effective potential $V(\varphi^i)$ which is a function of infinitely many scalars (which parameterize all possible internal metrics and fluxes on the 7-manifold). It is hard to believe but its true that for arbitrary metric and flux there is no critical point of V with V>0, as M-N no-go theorem shows (in supergravity approximation).

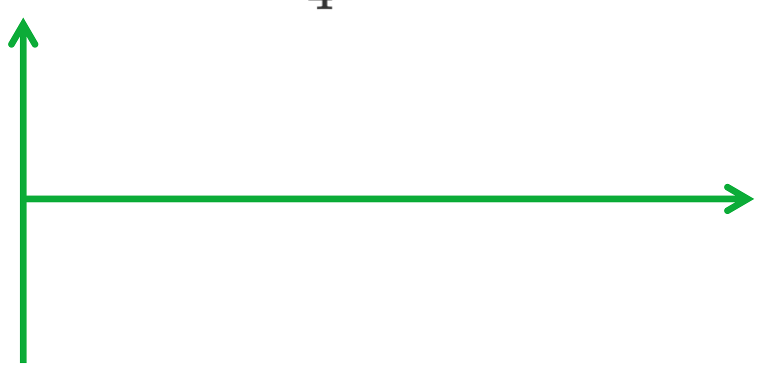
The M-N no-go theorem can be strengthened:

If we compactify M-theory to d dimensions, one can easily show, using volume rescaling, that in supergravity limit

$$\frac{|\nabla V|}{V} \geq \frac{6}{\sqrt{(d-2)(11-d)}}.$$

$$d = 4, \text{ this yields } 6/\sqrt{14} \sim 1.6$$

which is realized for $AdS_4 \times S^7$.



If we assume the Strong Energy Condition (SEC), or more precisely for compactifications respecting that,

$$\frac{|\nabla V|}{V} \geq \lambda_{SEC} \equiv 2\sqrt{\frac{D-2}{(D-d)(d-2)}}.$$

And for compactifications respecting Null Energy Condition (NEC) with zero or negative average scalar curvature

$$\frac{|\nabla V|}{V} \geq \lambda_{NEC} \equiv 2\sqrt{\frac{D-d}{(D-2)(d-2)}}$$

Where D=11,10 and d is the dimension we compactify to.
For example D=10, d=4:

$$\lambda_{NEC} = \sqrt{\frac{3}{2}} \simeq 1.2$$

Other examples:

Heterotic O(16)xO(16) strings. Non-susy, no tachyons in 10 d, and at weak coupling has positive cosmological constant:

$$\left|\frac{\nabla V}{V}\right| = \frac{5}{\sqrt{2}}$$

Also extending an argument of [Hertzberg,Kachru,Taylor,Tegmark] and [Wrase,Zagermann]:

q	No-Go (positive or zero $\langle \mathcal{R} \rangle$)	$c_\star^2$	No-Go (negative $\langle \mathcal{R} \rangle$)	$c_\star^2$
3	Yes w/o F_1 RR flux	6	Indeterminate	-
4	Yes w/o F_0 RR flux	98/19	Indeterminate	-
5	Yes	32/7	Yes w/o F_1 RR flux	2
6	Yes	54/13	Yes w/o F_0 RR flux	18/7
7	Yes	50/12	Yes	8/3
8	Yes	242/67	Yes	50/19
9	Yes	24/7	Yes	18/7

Constrains on $|\nabla V|/V$ in Type IIA/B compactifications to 4 dimensions with arbitrary RR and NS-NS flux (unless otherwise noted) and Oq-planes and Dq-branes with fixed q. The constant $c_\star$ in each entry is a lower bound on $|\nabla V|/V$.

So the upshot is that the conjecture is not unreasonable with c of order 1 in Planck units.

This makes quintessence more natural with |V'| of order V.

Heuristic link:

Distance Conjecture —> dS Conjecture

(at weak coupling)

Weak couplings—> correspond to points where some scalars field traverse super-Planckian distances.

We thus get towers of light states with energy

$$m \sim exp(-\alpha \Delta \varphi)$$

If there are N such towers then we expect $\frac{dN}{d\varphi} \geq 0$

Let us count how many `single particle' states we have with mass less than Planck mass (which we take to be 1 in Planck units)

$$N(\varphi)e^{\alpha\varphi}$$

We expect the light states to be dominated by such states for large phi, so we get that the total number of states in the single particle Hilbert space is dominated by the above term which leads to multiparticle state degeneracy

$$\# = e^{N(\varphi)e^{\alpha\varphi}}$$

If V is varying fast then the dS conjecture is true; if not, we can assume it is dS-like leading to entropy of dS:

S=1/V

Interpreting this as the dimension of the full Hilbert space (Banks, Witten,...) leads to

$$S = \frac{1}{V} = N(\varphi)e^{\alpha\varphi}$$

$$V = \frac{e^{-\alpha\varphi}}{N} \Rightarrow \ln V = -(\alpha\varphi + \ln N)$$

$$\frac{d\ln V}{d\varphi} \geq \alpha$$

This leads to the statement that at parametrically weak couplings we expect the conjecture is true and this is compatible with the no-go theorems we did find.

This analysis suggests that perhaps the dark sector is currently beginning to undergo a transition (as we will discuss next) where a tower of light states are emerging.

Cosmological Implications

We now turn to cosmological implications of two swampland criteria (for V'' not too negative):

$$|\nabla V| \geq cV \quad , \qquad |\Delta\varphi| < \Delta$$ [Ooguri,V]

with c, Δ being close to 1 in Planck units.

We divide the discussion to past, present and future.

Past

Early universe: Inflation has some tension with both criteria. The constant c is related to the slow roll parameter

$$\varepsilon = \frac{1}{2}c^2$$

The current observational bounds on the B-mode lead (for textbook inflation models) to $\varepsilon < 0.0044$ and $c < 0.09$. However the textbook models of inflation when combined with spectral tilt gets ruled out. Among the more favored inflationary models, the plateau models, one finds the bound $c < 0.02$.

Moreover, the number of e-fold being greater than 60 leads (for plateau models) to

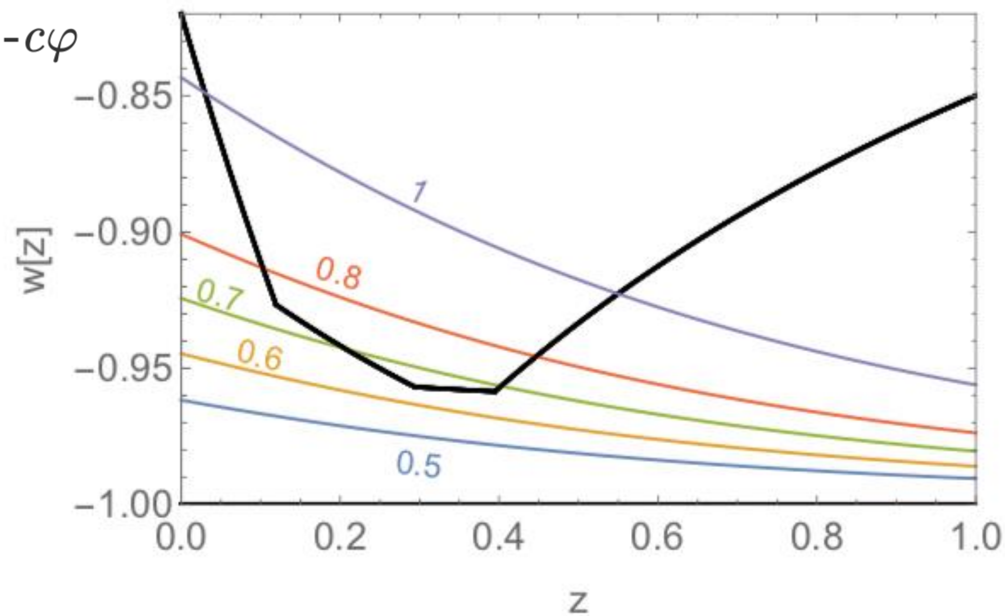
$$\Delta > 5$$

again in mild tension with swampland criteria (This tension has already been noted in the literature).

Present

Present epoch: The swampland criteria only allow quintessence models. Quite remarkably it can be shown that the current observational bounds are compatible with both criteria as long as c < 0.6 :

$$V = V_0 e^{-c\varphi}$$



$$w = \frac{p}{\rho}$$

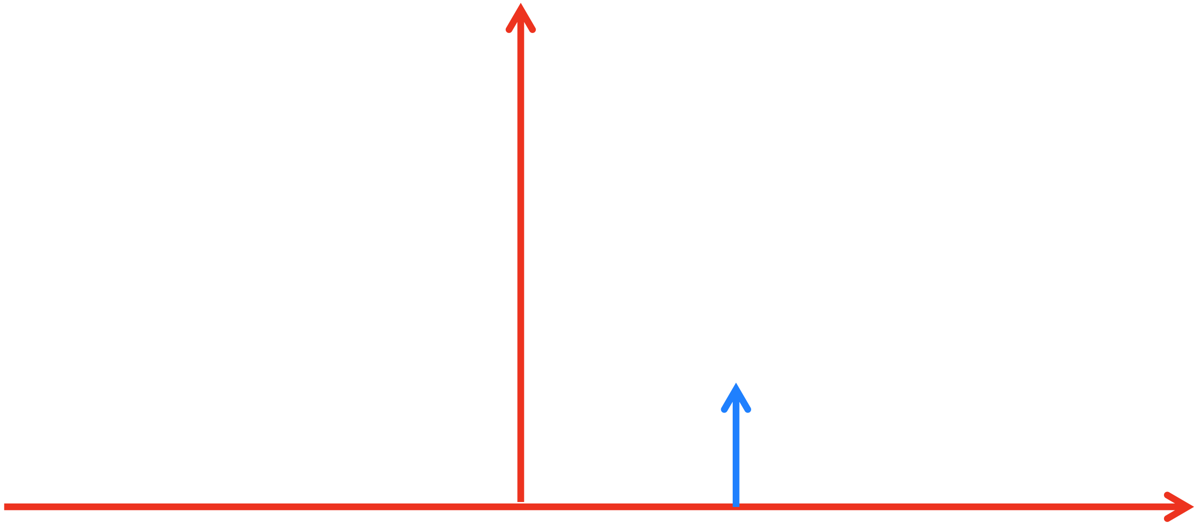
Also the initial condition for z=1 is not fine tuned due to tracking behaviour (except for the value of dark energy).

One finds that there is a universal bound on the value of (1+w) today. It predicts that it is bigger than

$$(1+w) > 0.15c^2$$

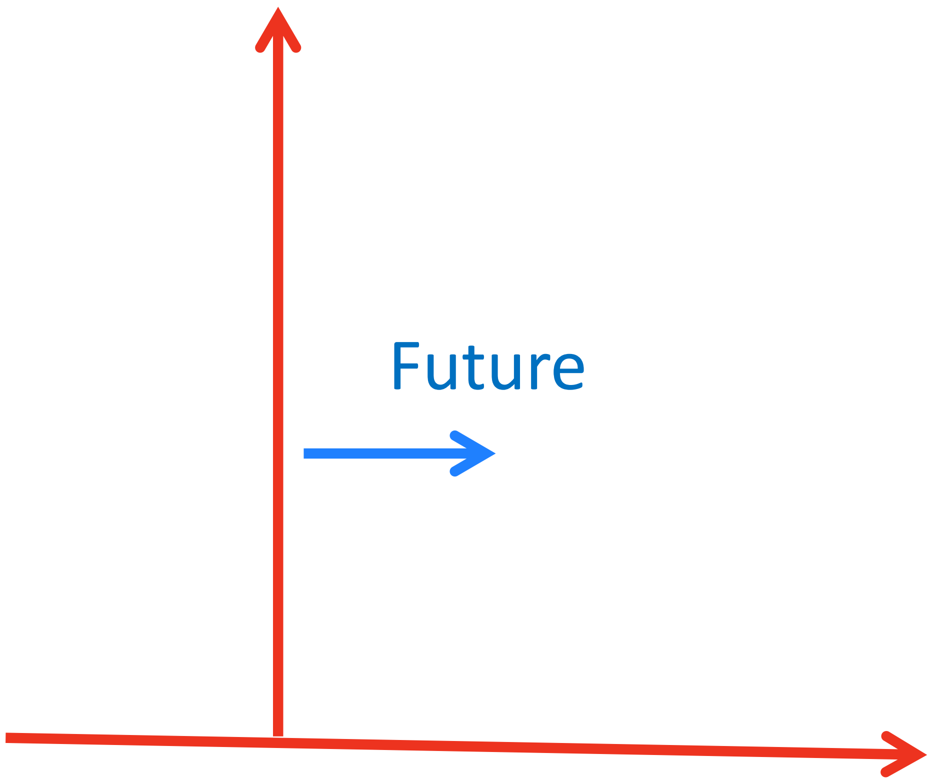
Future

If we lived in dS space, the lifetime of the universe, before there is a phase transition can be arbitrarily large and typically has nothing to do with the time scale set by the dark energy:



This leaves a puzzle: Why current age is related to

$$|\nabla V| \geq cV$$



Future

The two swampland criteria can be used to show that in a time of order of Hubble time, the universe will undergo a phase transition: Either we get a tower of light modes, or accelerating expansion will stop.

It can be shown that this will happen in N Hubble times

$$N < \left(\frac{3}{2\Omega_{\varphi}^{0}} \right)^{\frac{\Delta}{c}}$$

The basic idea is that the current kinetic term for the rolling field is away from 0 and that the rolling cannot exceed Δ without undergoing phase transition.

This uses the relation

$$x = \frac{d\varphi}{dt} H^{-1}$$

$$\Delta > \Delta\varphi = \int x \, dN > x_0 N$$

$$x_0 > \frac{2}{3} c \Omega_{\varphi}^{0}$$

$$\Delta > \frac{2}{3} c \Omega_{\varphi}^{0} N$$

$$N < \left(\frac{3}{2\Omega_{\varphi}^{0}} \right) \frac{\Delta}{c}$$

A New Perspective on the Cosmological Constant

Without loss of generality we can take (for V>0) and start with Planckian energy (i.e. 1). Then

$$V = e^{-\int \frac{d\varphi}{m(\varphi)}}$$

$$\Delta \ln V \approx -280$$

$$\int d\ln V = \int \frac{V'}{V} d\varphi \sim -\int \lambda d\varphi = -\bar{\lambda}\,\Delta\varphi \approx -280$$

$$\bar{\lambda} \sim \frac{280}{\Delta\varphi}$$

$$V \sim e^{-\frac{\varphi}{M}} \Rightarrow M \sim \frac{\Delta\varphi}{280} \sim 4\times 10^{-16}\left(\frac{\Delta\varphi}{Mp}\right) GeV$$

$$\Lambda \approx e^{-\frac{Mp}{M\varphi}} \Rightarrow M_{\varphi \sim} M_{GUT}$$

$$\Lambda \approx exp\left(-\frac{M_p}{M_{GUT}}\right)$$

Observational Consequences

1-More accurate measurements of $w(z)$:
Is $(1+w)$ significantly different from 0 as we predict?

2-Dark sector couplings have been changing over time as they presumably couple to the quintessence fields. Observational consequences (apparent violation of equivalence principle in the dark sector) may be detectable. This is specially so if the heuristic arguments based on dS entropy are correct, leading to tower of states with neutrino mass scales.

Conclusion

It seems not unreasonable to believe meta-stable dS is not realizable in a quantum theory of gravity. This motivates a new swampland criterion putting a bound on the slope of V in terms of V. (Even if dS is realizable, quintessence models are rather natural.)

This together with another swampland criterion (bound on range of fields) leads to

-Some tension with inflation

-Present epoch must be based on quintessence

-The universe is about to undergo a phase transition in O(1) Hubble time. Most likely a tower of lights states emerge in DS and this may have already started.