

Cosmology and the String Swampland

Cumrun Vafa
Harvard University

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de Sitter Space and the Swampland

Georges Obied,^a Hiroshi Ooguri,^{b,c} Lev Spodyneiko,^b Cumrun Vafa^a

^a Jefferson Physical Laboratory, Harvard University, Cambridge, MA 02138, USA

^b Walter Burke Institute for Theoretical Physics
California Institute of Technology, Pasadena, CA 91125, USA

^c Kavli Institute for the Physics and Mathematics of the Universe
University of Tokyo, Kashiwa, 277-8583, Japan

On the Cosmological Implications of the String Swampland

Prateek Agrawal,¹ Georges Obied,¹ Paul J. Steinhardt,^{2,3} and Cumrun Vafa¹

¹*Jefferson Physical Laboratory, Harvard University 17 Oxford Street, Cambridge, MA 02138, USA*

²*Department of Physics & Princeton Center for Theoretical Science,
Princeton University, Princeton, NJ 08544, USA*

³*Center for Cosmology and Particle Physics, Department of Physics,
New York University, New York, NY, 10003, USA*

The plan for this talk is:

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

-A new swampland condition:

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

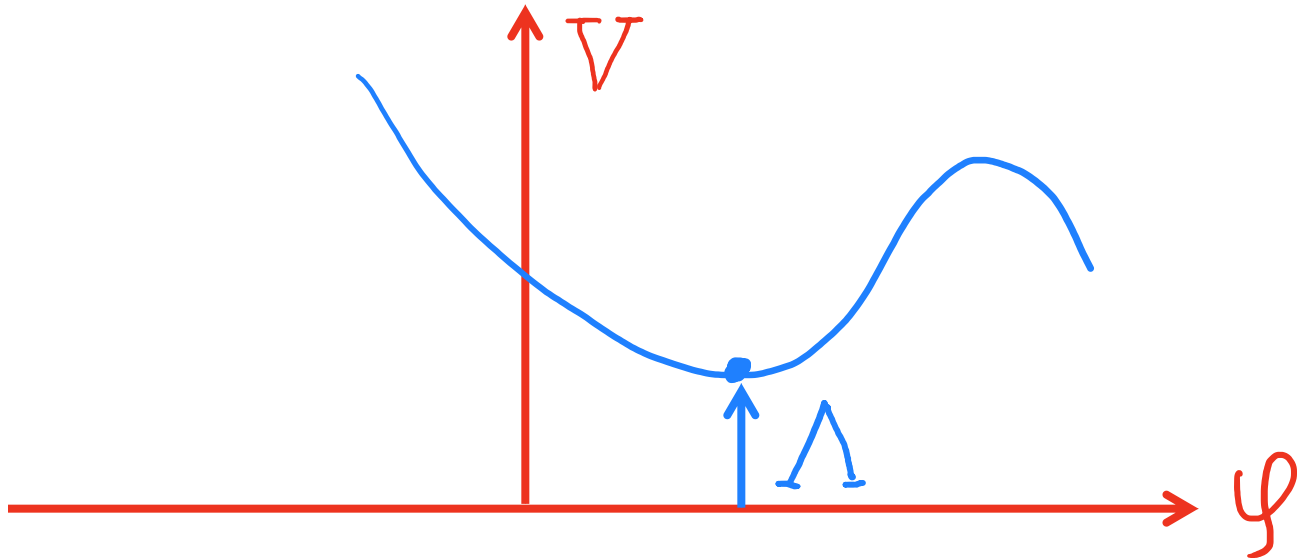
-Cosmological Implication of two swampland criteria for past, present and future:

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

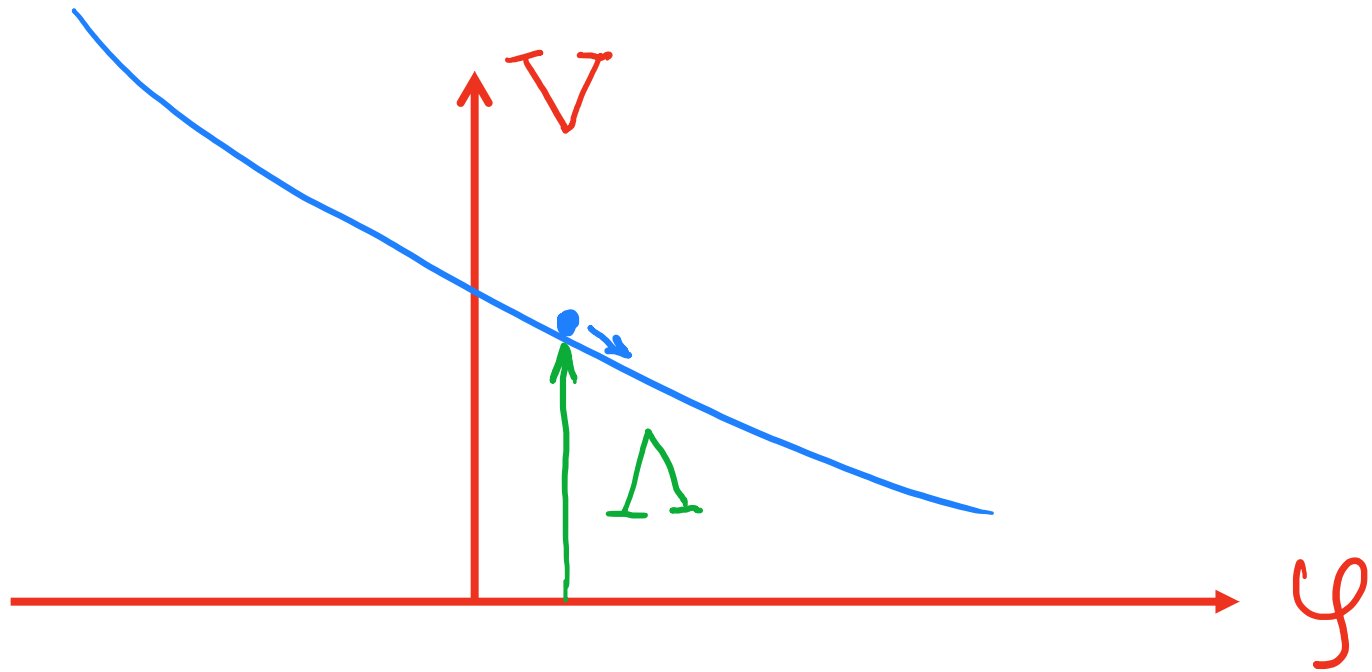
Why dS?

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

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

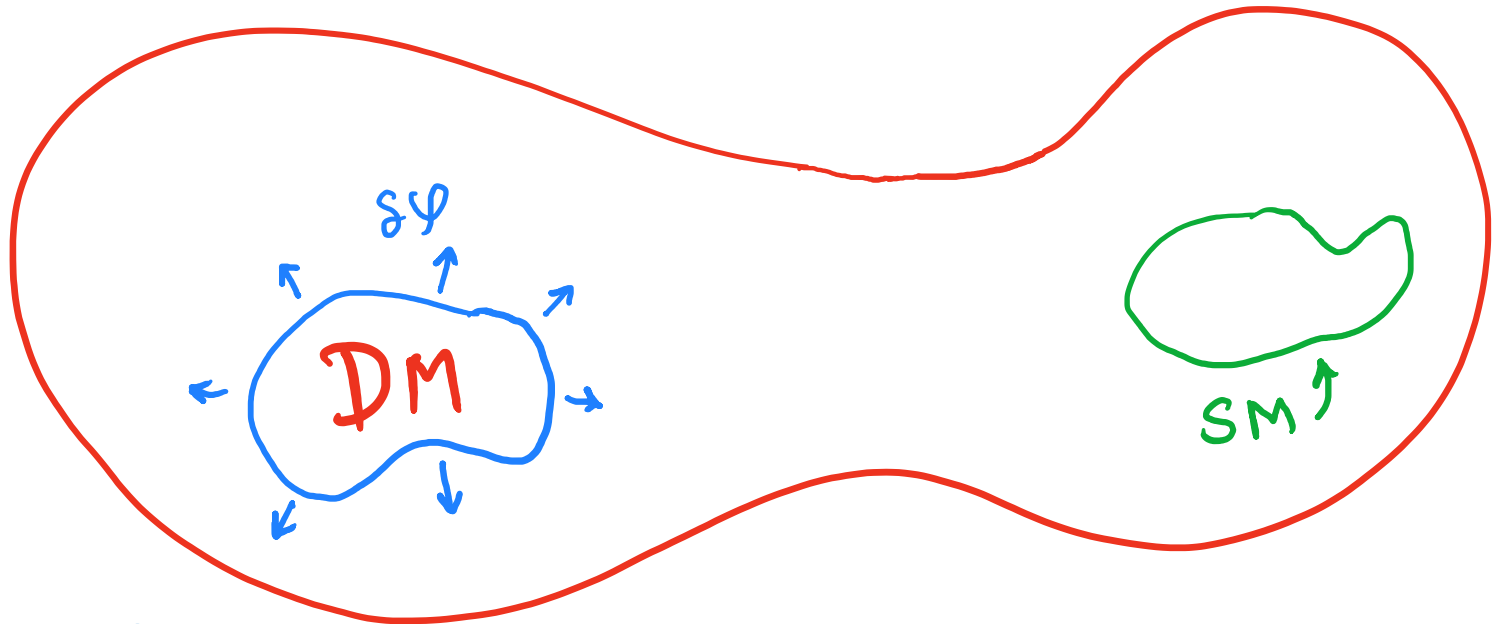
Also the coupling of the scalar field to matter would give rise to a new 'fifth force' which would be detectable at astrophysical distance. The idea that the scalar field should couple to something is natural in string theory.

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 to DM.
So the rolling scalar anticipates DM!

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**) 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 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:

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

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).

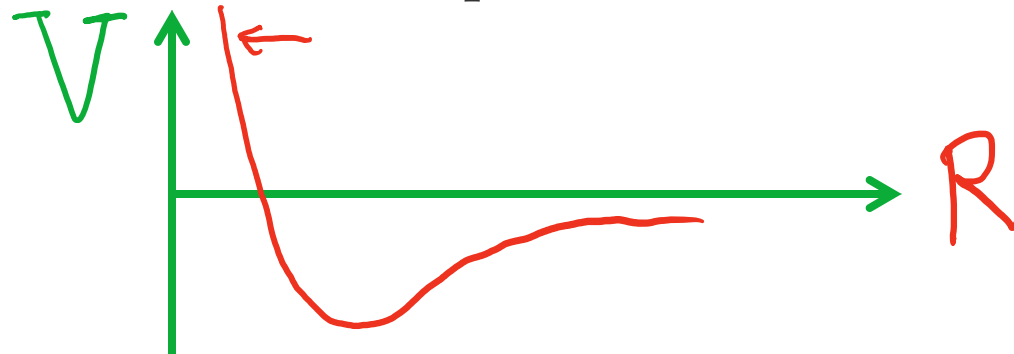
The M-N no-go theorem can be strengthened:

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

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

$d = 4$, 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

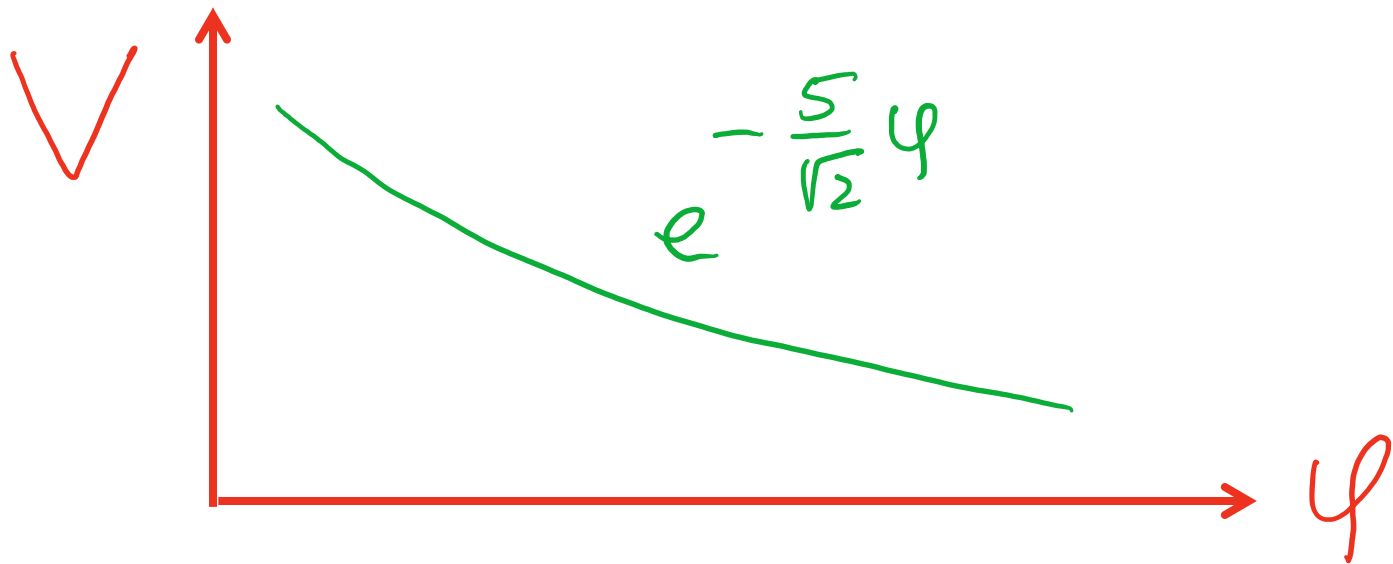
$$\frac{|\nabla V|}{V} \geq \lambda_{NEC} \equiv 2\sqrt{\frac{D-d}{(D-2)(d-2)}}$$

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 $O(16) \times O(16)$ 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 .

Cosmological Implications

We now turn to cosmological implications of two swampland criteria:

$$|\nabla V| \geq cV \quad , \quad |\Delta\varphi| < \Delta \quad [\text{Ooguri}, V]$$

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

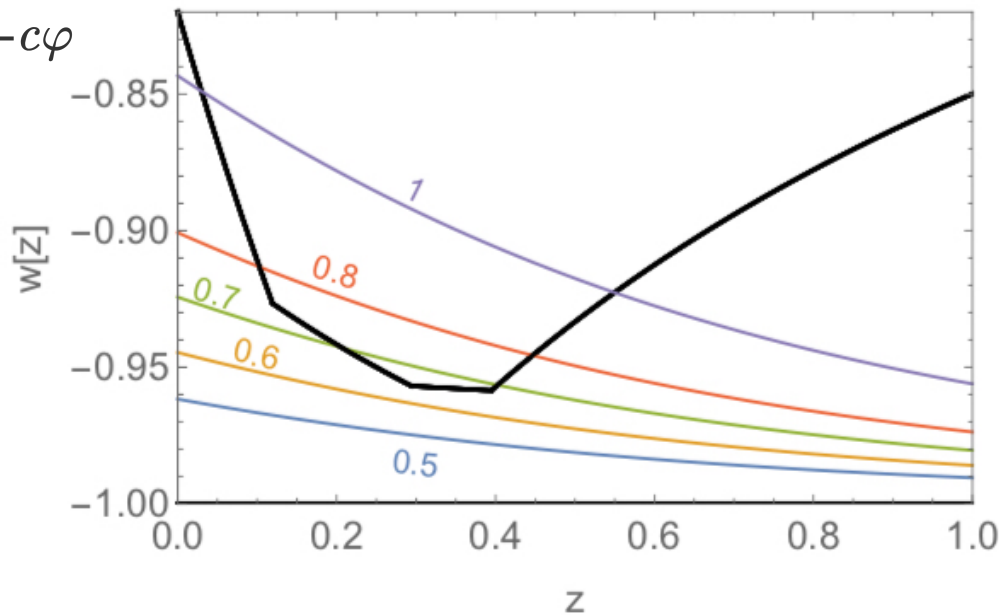
$$\Delta > 5$$

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 $c < 0.6$:

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



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

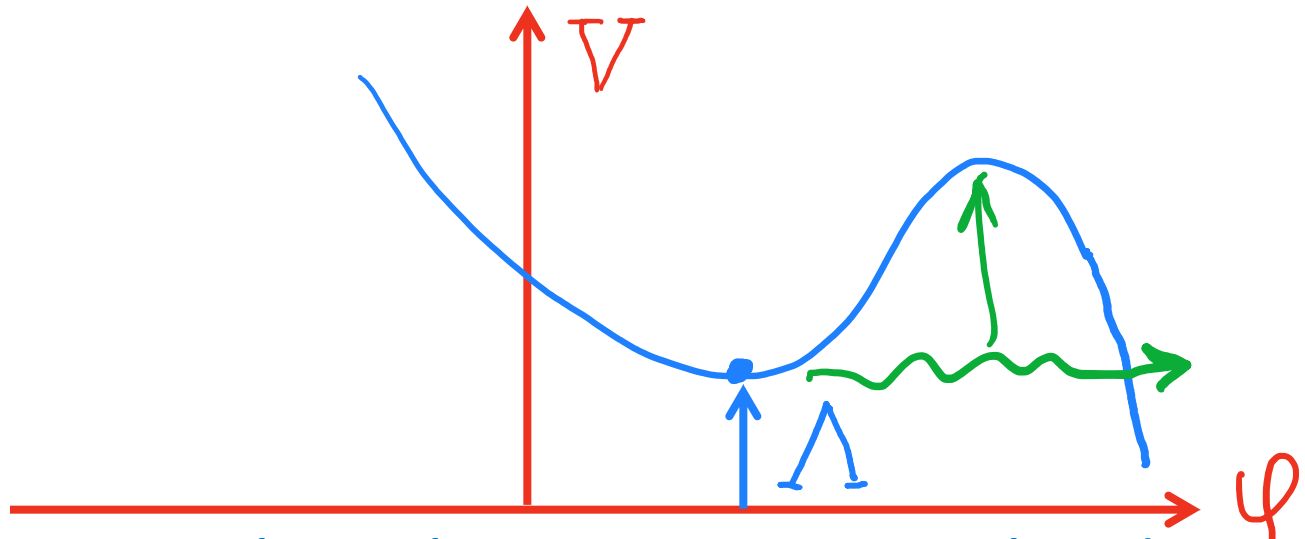
Also the initial condition for $z=1$ is not fine tuned due to tracking behaviour (except for the value of dark energy).

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

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

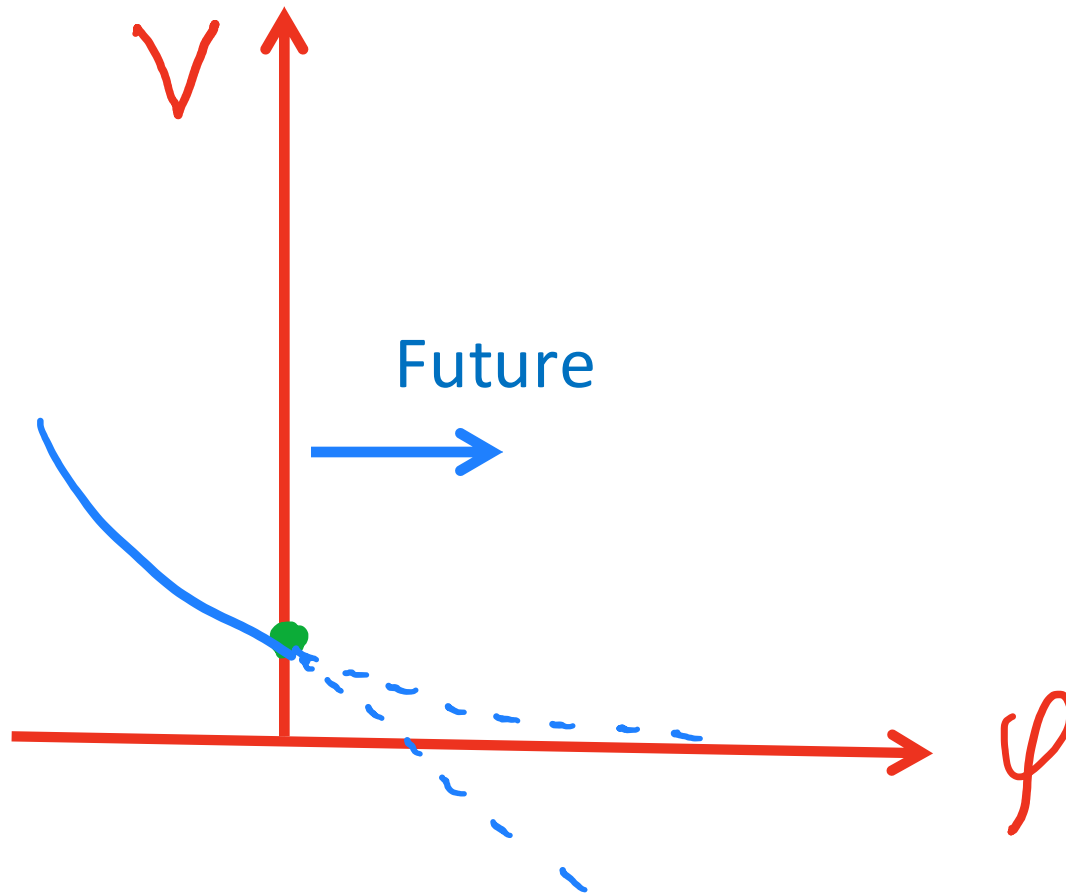
Future

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
 $\tau \sim H^{-1} \sim 1/\sqrt{\Lambda}$?

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



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

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

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

Swampland
criterion

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

bound
now

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

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

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.

Conclusion

It seems not unreasonable to believe 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 .

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. Either a tower of lights states emerge or cosmic acceleration stops.