On the Fate of our Universe

Cumrun Vafa
Harvard University

Lemaitre Conference 2024
June, 2024

Based on:

De Sitter Space and the Swampland
Georges Obied, Hirosi Ooguri, Lev Spodyneiko, C.V.
[1806.08362][hep-th]

Trans-Planckian Censorship and the Swampland
Alek Bedroya, C.V.
[1909.1106][hep-th]

Moduli-dependent Species Scale
Damian van de Heisteeg, C.V., Max Wiesner, David Wu
[2212.06841][hep-th]

Bounds on Species Scale and the Distance Conjecture
Damian van de Heisteeg, C.V., Max Wiesner,
[2303.13580][hep-th]

Bounds on Field Range for Slowly Varying Positive Potentials &
Species Scale in Diverse Dimensions
Damian van de Heisteeg, C.V., Max Wiesner, David Wu
[2305.07701] & [2310.07213][hep-th]

Dark Energy

The small non-vanishing positive vacuum energy is one of the biggest mysteries in our Universe,

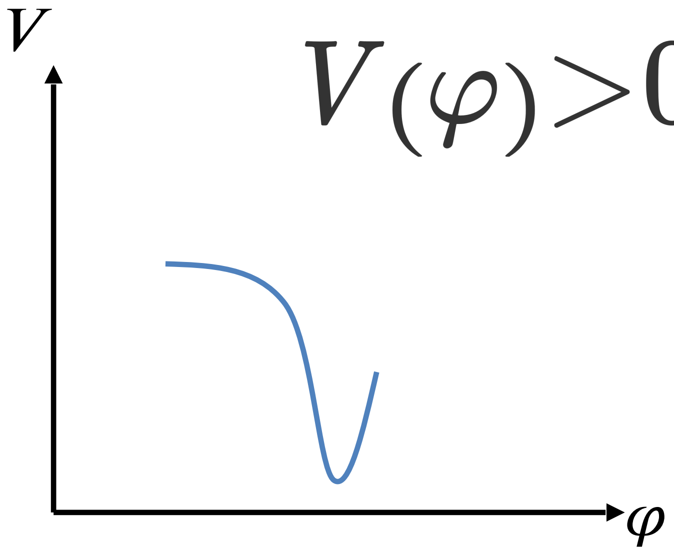
$$\Lambda \sim 10^{-122} M_{pl}^4$$

It is natural to ask how we can realize this?

In a quantum theory of gravity, there are no free parameters (a generalization of `no global symmetries'), so it is natural to assume vev of a field can vary it.

A potential with a local small positive minimum

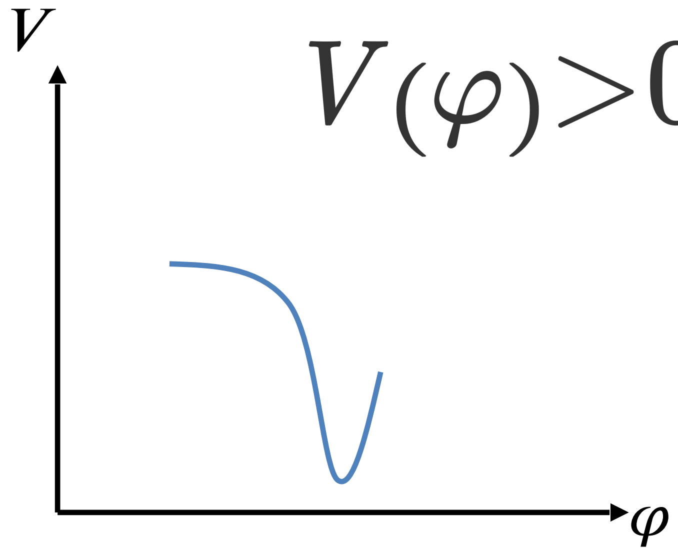
$$V(\varphi) > 0$$



Assumption of a local minimum/extremum is natural based on the observational bounds which give

$$|V'| \lesssim 10^{-122} M_{Pl}^3$$

A potential with a local small positive minimum



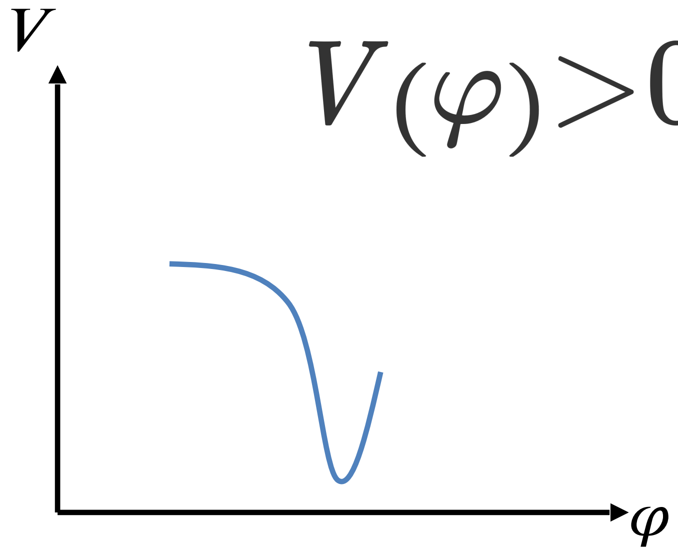
$$V(\varphi) > 0$$

Assumption of a local minimum/extremum is natural based on the observational bounds:

$$|V'| \lesssim 10^{-122} M_{Pl}^3 \sim c \frac{\Lambda}{M_{pl}}$$

A potential with a local small positive minimum

$$V(\varphi) > 0$$



Assumption of a local minimum/extremum is natural based on the observational bounds:

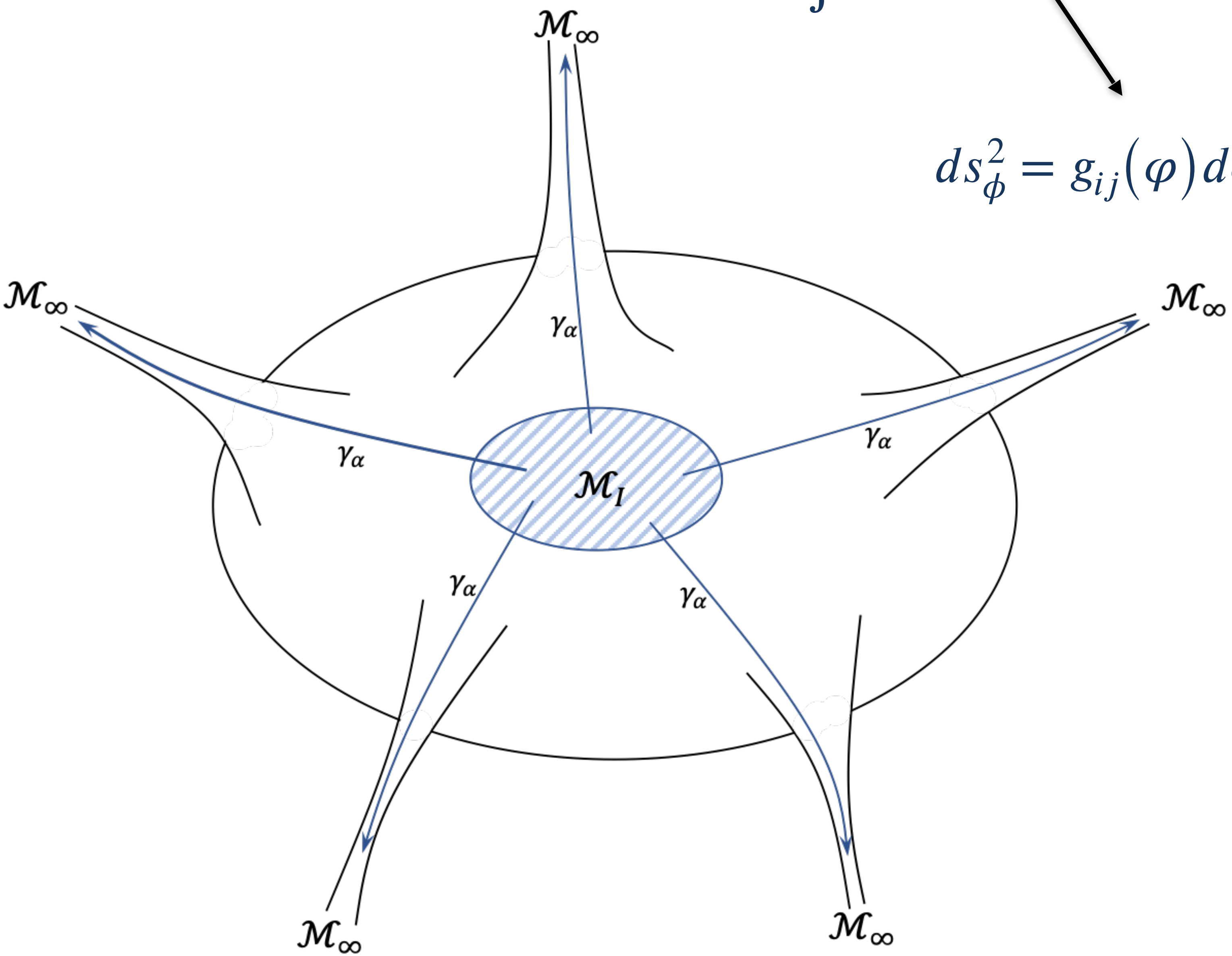
$$|V'| \lesssim 10^{-122} M_{Pl}^3 \sim c\frac{\Lambda}{M_{pl}} \sim c\frac{V}{M_{pl}}$$

$$c \sim O(1)$$

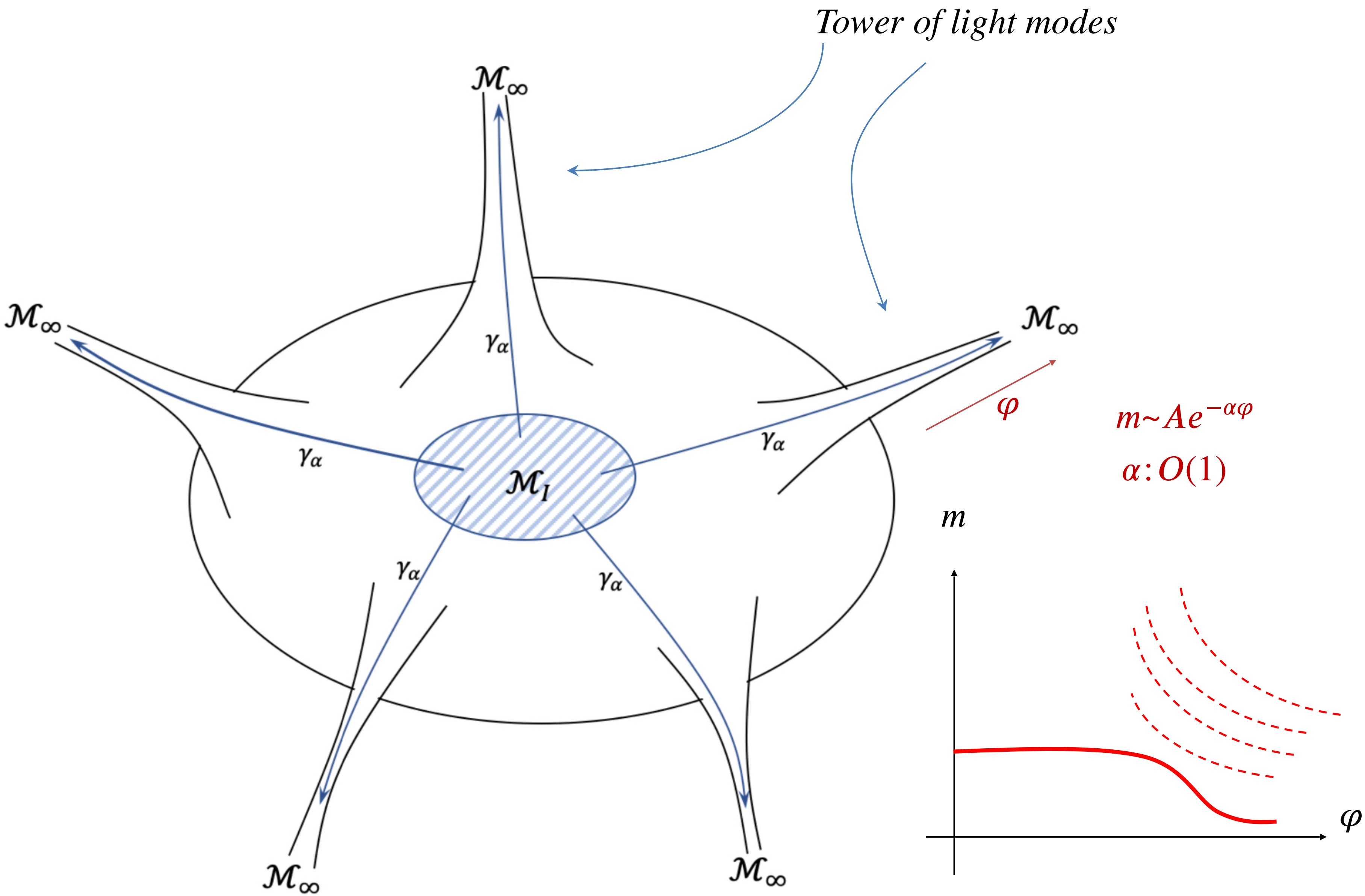
$\varphi - Space$

$$\int g_{ij}(\varphi)\, \nabla \varphi^i \nabla \varphi^j d^4x$$

$$ds_\phi^2 = g_{ij}(\varphi)\, d\varphi^i d\varphi^j$$



Distance Conjecture is a manifestation of String dualities [Ooguri, V.; 2006]

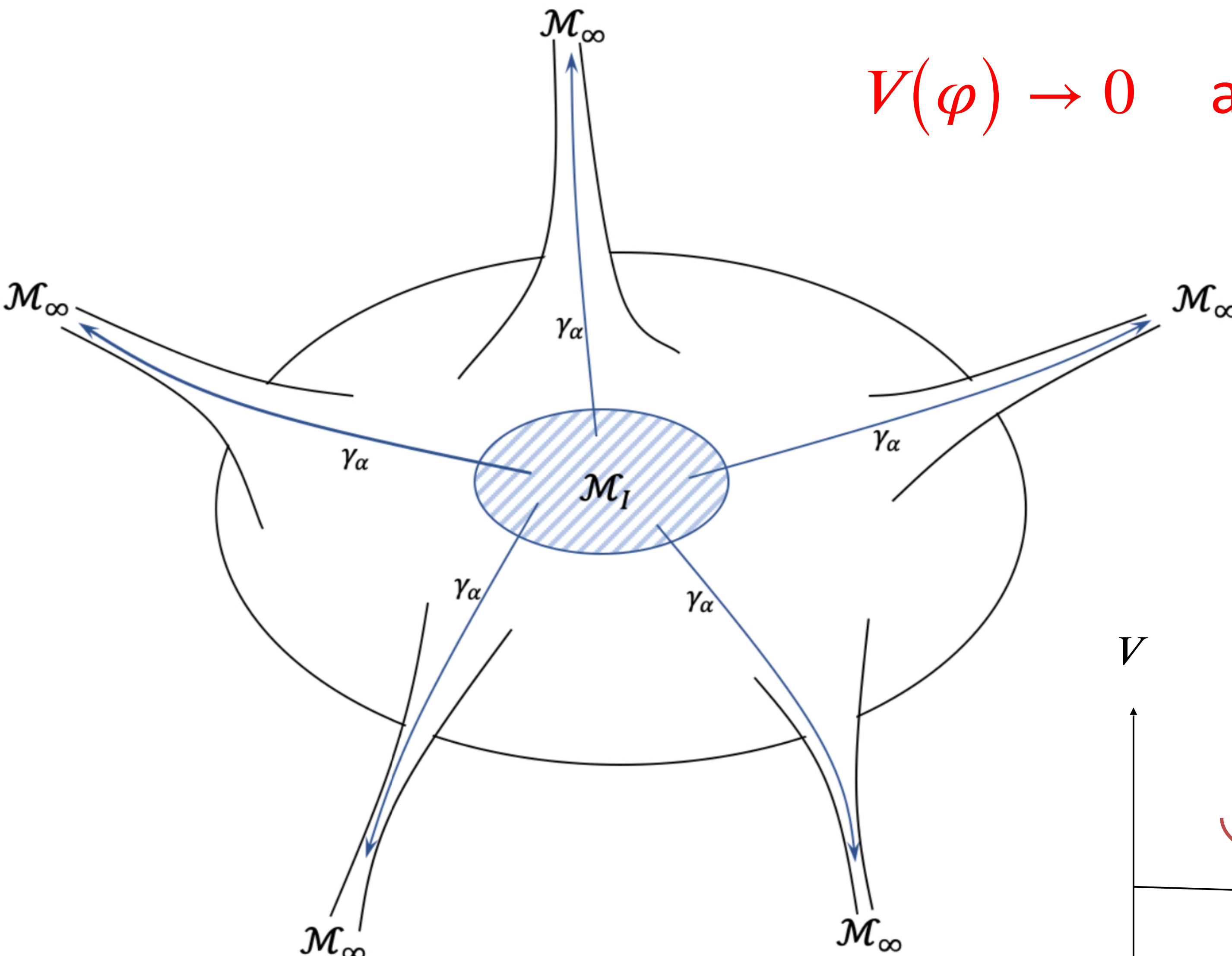


In string theory we can be more precise. In Planck units, where $M_{pl} = 1$ using the asymptotic emergence conjecture [LLW]

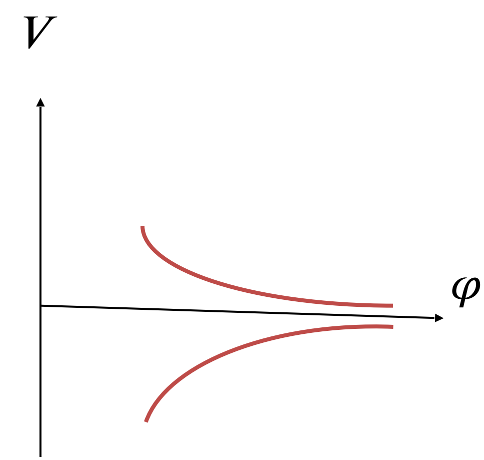
$$m \sim exp(-\alpha\phi) \qquad \frac{1}{\sqrt{d-2}} \leq \alpha \leq \sqrt{\frac{d-1}{d-2}}$$

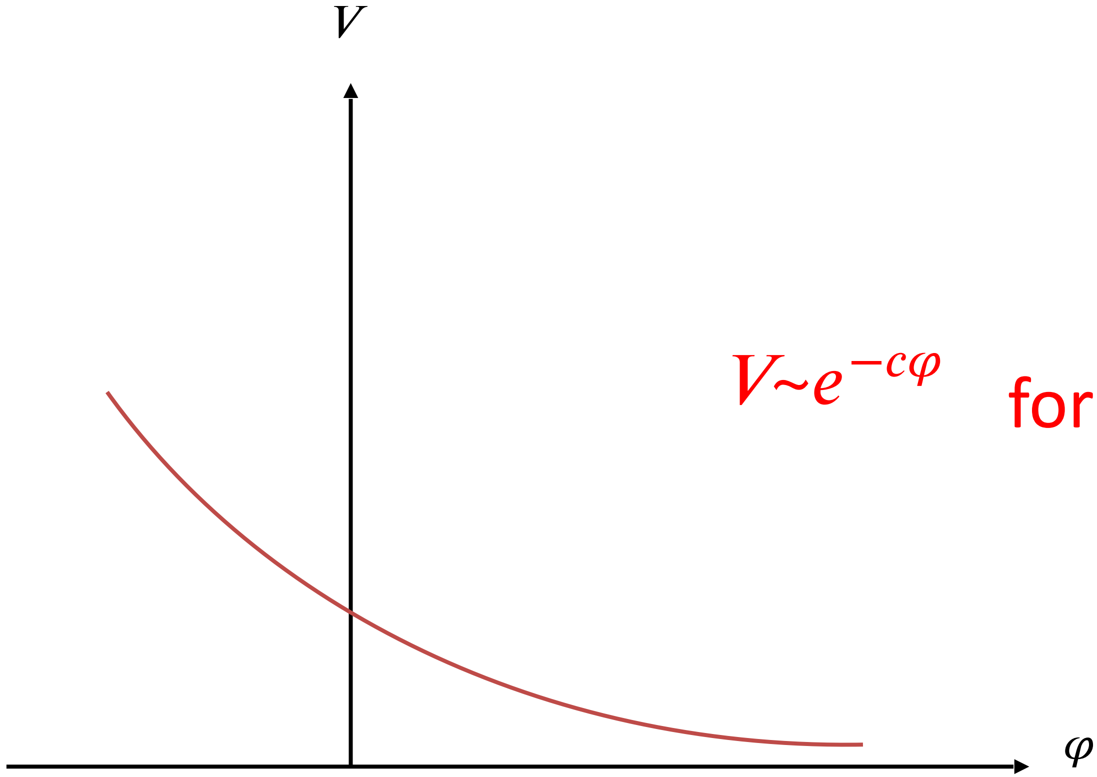
Where the lower bound is when the tower is a string tower and the upper bound is for one dimension opening up. In d=4 this gives the bound

$$\frac{1}{\sqrt{2}} \leq \alpha \leq \sqrt{\frac{3}{2}}$$



$V(\varphi) \to 0$ as $\varphi \to \infty$



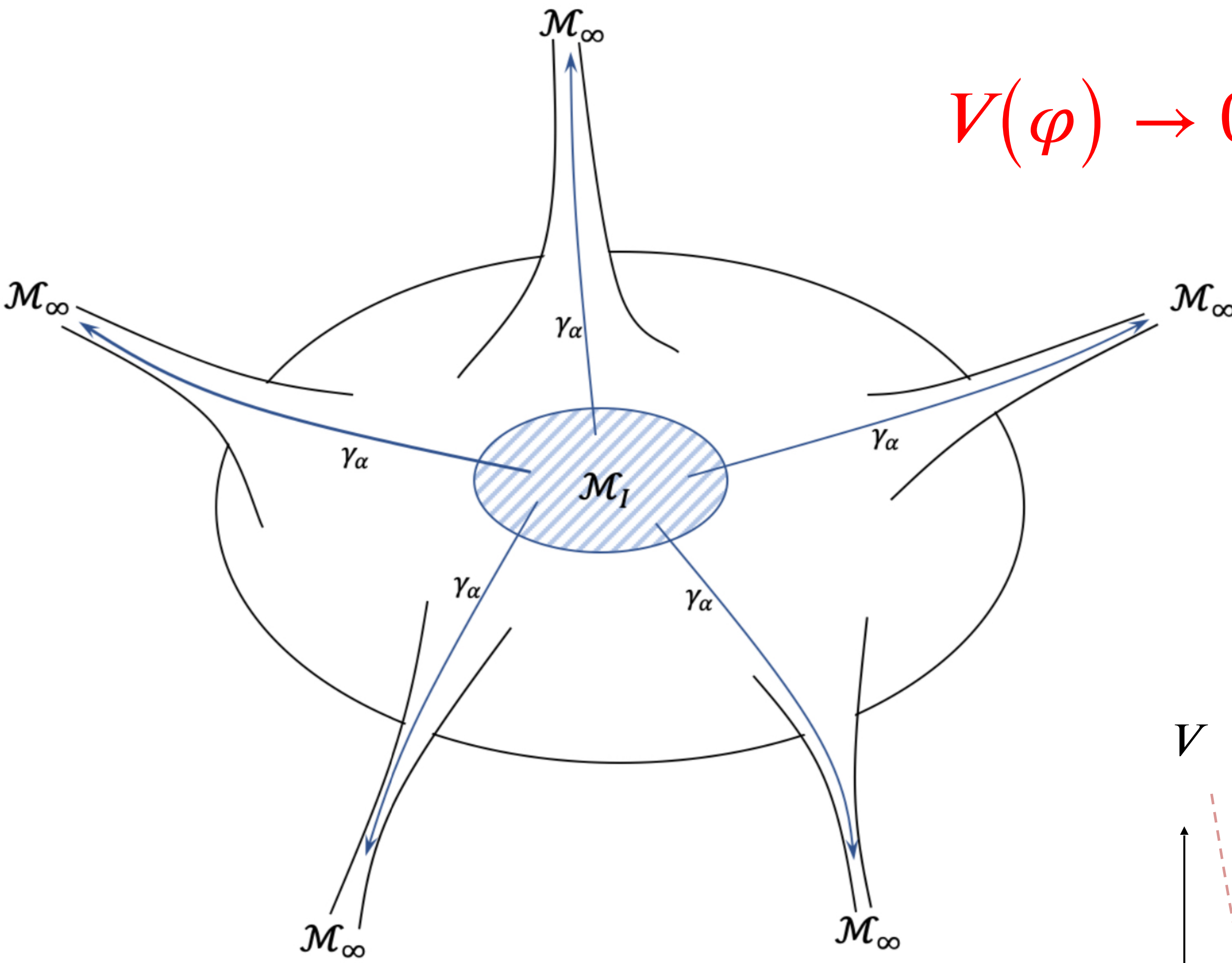


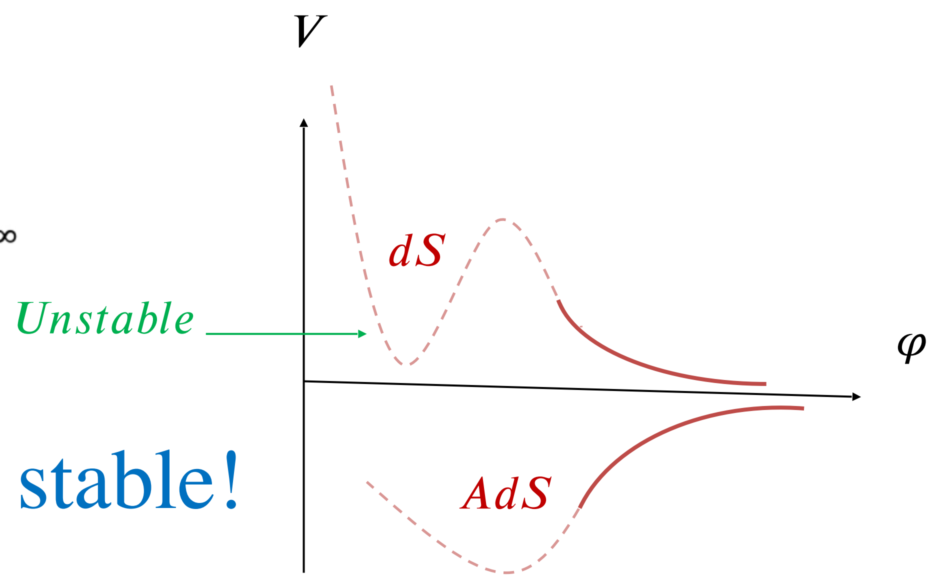
$V \sim e^{-c\varphi}$ for $\varphi \gg 1$

General String compactification analysis suggests:

$$\left|\frac{V'}{V}\right|_{\infty} \geq \sqrt{2}$$

$$V(\varphi) \to 0 \quad \text{as} \quad \varphi \to \infty$$





No model of dark energy is stable!

To gain more insights to the nature of allowed potentials in string theory it turns out to be important to study the notion of the quantum gravity cutoff scale

$$\Lambda_{QG}$$

This can in principle depend on the scalar field vev

$$\Lambda_{QG}(\phi)$$

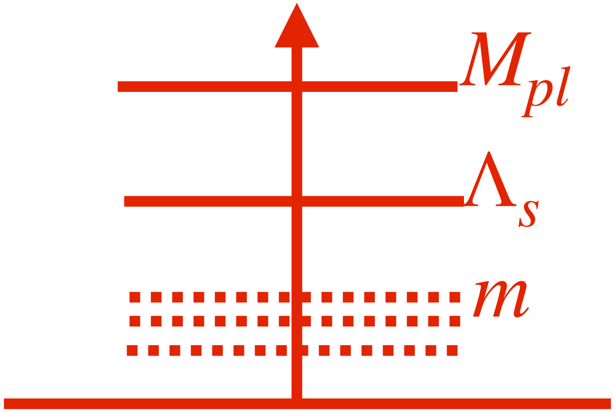
The reason this is not always M_{pl} and it varies is that as we vary the fields the masses of species move around and the effective cutoff can change this is why this is sometimes also called the species scale $\Lambda_s(\phi)$.

What this means is that we expect

$$S = \int d^d x \sqrt{-g} \left[\frac{M_{\rm pl}^{d-2}}{2} \left(R + \sum_n \frac{\mathcal{O}_n(R)}{\Lambda_s^{n-2}(\phi)} + \ldots \right) + \frac{1}{2}(\partial\phi)^2 + \ldots \right]$$

With coefficients of $O(1)$. Of course not all higher derivative terms will have coefficients of $O(1)$, but that should be the generic case.

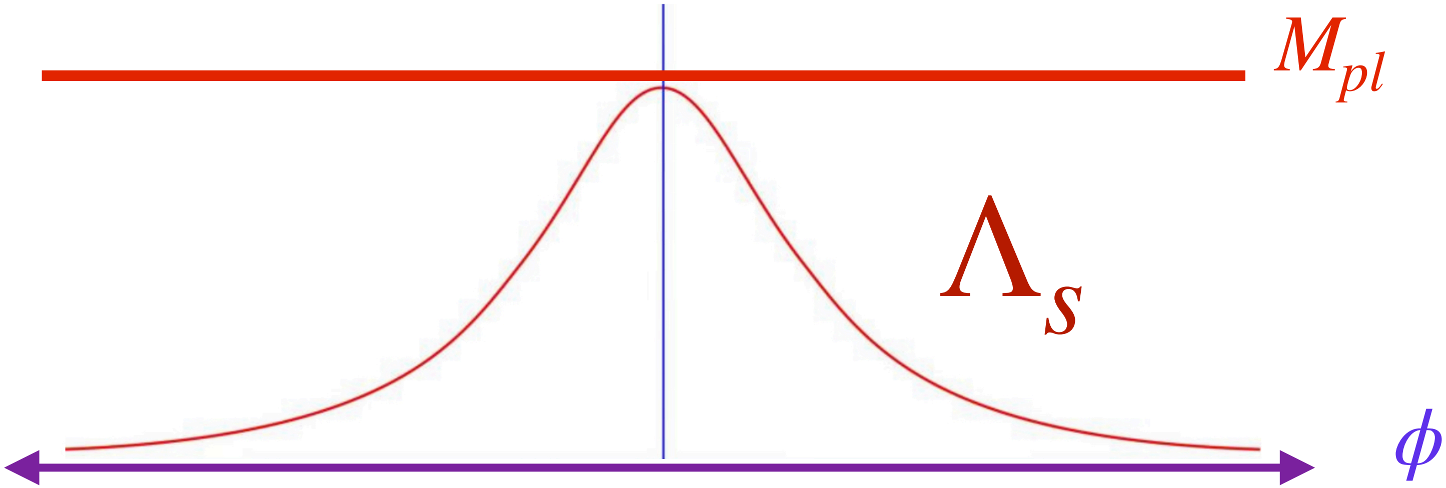
We are interested in the dependence of Λ_s on ϕ.



We expect $m \leq \Lambda_s(\phi) \leq M_{pl}$

Dependence of Λ_s on moduli

The general picture we expect to get:



Difficult to study this as a function of moduli. Asymptotically we know. How to find it inside? In a special class of theories this can be done.

Asymptotics of Λ_s

We expect for a tower of light states:

$$\Lambda_s \sim m^{\gamma} \sim \exp(-\beta\phi) \qquad \beta \sim O(1)$$

one finds

$$\beta = \frac{1}{\sqrt{d-2}} \quad strings; \qquad \beta = \sqrt{\frac{D-d}{(D-2)(d-2)}} \quad KK \quad (D \Rightarrow d);$$

Note in both cases

$$\beta \leq \frac{1}{\sqrt{d-2}} \Rightarrow |\Lambda_s'/\Lambda_s|^2 \lesssim \left(\frac{1}{d-2}\right) \qquad \phi \to \infty$$

Dependence of Λ_s on moduli

We consider $\mathcal{N} = 2$ supersymmetric theories in $d = 4$. These (with flux added to break SUSY) are the starting point of most phenomenological constructions.

Consider the vector multiples moduli ϕ. In this case there is a natural proposal for what $\Lambda_s(\phi)$ is:

$$\frac{1}{\Lambda_s^2} = F_1$$

Where F_1 is the effective term in the action:

$$\int d^4\theta d^4x \, F_1(\phi) \, . W^2 = \int d^4x \, F_1(\phi) \, . R^2 + \ldots$$

Expect this to be generically (but not always) a correct identification as far as vector multiplet moduli.

For CY compactification of Type II to 4d F_1 can be explicitly computed as it is related to genus one topological string partition function:

$$F_1 = \frac{1}{2}\int_{\mathcal{F}} \frac{d^2\tau}{\tau_2} \mathrm{Tr}\left[(-1)^F F_L F_R q^{H_0}\bar{q}^{\bar{H}_0}\right]$$

There are further motivations for why this is related to the species scale. Number of light degrees of freedom should be reflected in the spectrum of Laplacian and indeed we have

$$F_1 = \frac{1}{2}\sum_{p,q}(-1)^{p+q}\left(p-\frac{3}{2}\right)\left(q-\frac{3}{2}\right)\log(\det\Delta_{(p,q)})$$

We have checked that the asymptotic limits agree with that expected from the asymptotic behavior of the species scale.

Confirms the picture that Λ_s reaches maximum (`desert point’) somewhere in the middle of moduli (LG point for the quintic case) and vanishes exponentially asymptotically.
We have checked this for both KK boundaries where some dimensions open up and fundamental string boundaries

Question: Are there any features which hold generally?

The generic features:

1) $$\Lambda_s \leq \exp\left[-\frac{\phi}{\sqrt{d-2}}\right]\Big|_{\phi \gg 1}$$

2) In any region of field space of diameter $\Delta\phi$ we have a bound:

$$\Lambda_s \leq \Lambda_0 \exp\left(-\frac{\Delta\phi}{\sqrt{(d-2)(d-1)}}\right)$$

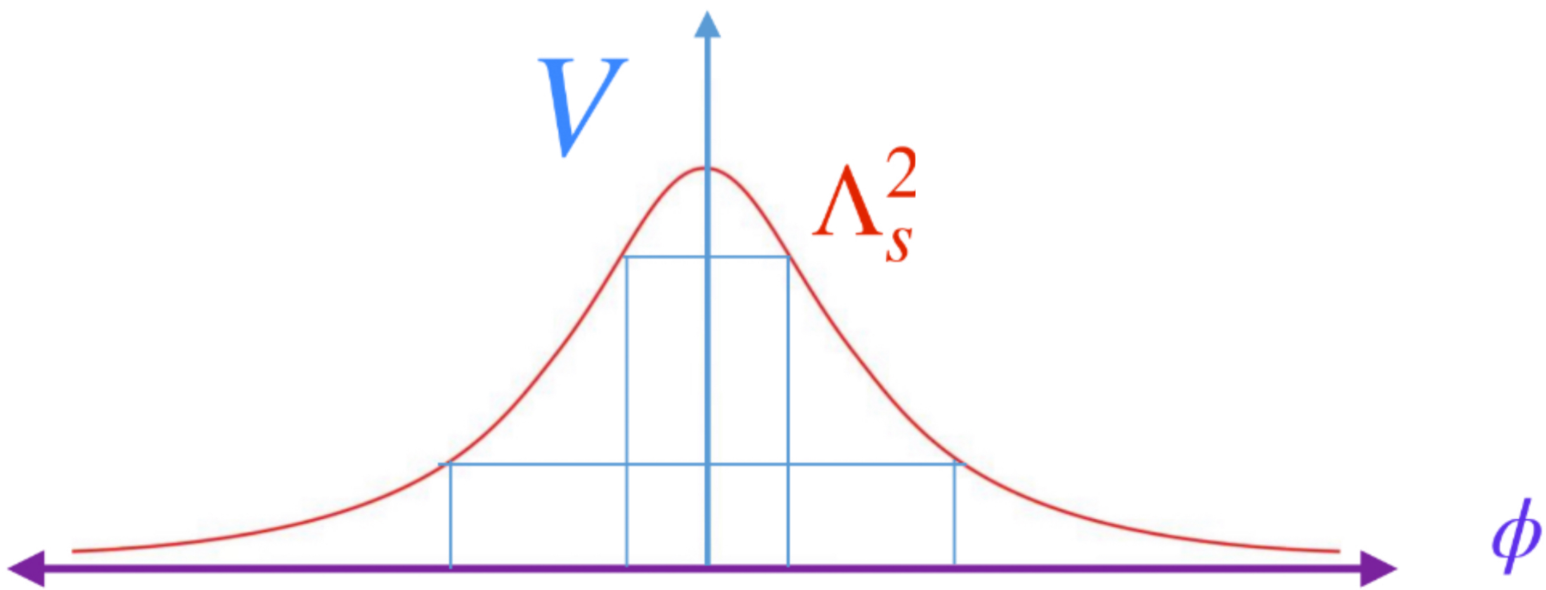
Relevance for potential: In any consistent EFT

$$V \leq \Lambda_{QG}^2 = \Lambda_s^2$$

This follows from the fact that the Hubble horizon

$$l_H \sim \frac{1}{\sqrt{V}} > l_{QG} \sim \frac{1}{\Lambda_{QG}}:$$

$$l_H > l_{QG} \Rightarrow V \lesssim \Lambda_s^2$$



V
Λ_s^2
ϕ

We learn

1) $$V \le \exp\left[-\frac{2\phi}{\sqrt{d-2}}\right]\Big|_{\phi\gg 1}$$

2) In any region of field space of diameter $\Delta\phi$ we have a bound:

$$V \le V_0 \exp\left(-\frac{2\Delta\phi}{\sqrt{(d-2)(d-1)}}\right)$$

This mean if we want to have a flat region of V, the largest it can be is bounded by the value of V:

$$\Delta\varphi < \sqrt{(d-2)(d-1)}\log(1/V_0)$$

These are some restrictions on V but is there a unifying explanation of these features from a simpler principle of quantum gravity?

Also there is one more feature of dark energy which is surprising: Why do we live at a cosmological epoch where the acceleration has just taken over? I.e. why

$$\tau_{now} = \frac{1}{\sqrt{\Lambda}} ?$$

Transplanckian Censorship Conjecture [BV]:

In an expanding universe, it should never be possible for subplanckian length scales to expand so much that they would exit the Hubble horizon:

$$ds^2 = -dt^2 + a(t)^2 dx^2$$

$$\frac{a(t_f)}{a(t_i)} \cdot l_{pl} < \frac{1}{H_f}$$

By studying expanding cosmologies driven by $V(\phi)$ one finds that this implies the two conditions (asymptotic behavior and bounds on flat range) we had found using string theory! TCC allows metastable potential, but they need to be short lived:

$$\tau_{lifetime} \leq \frac{1}{H} \log \frac{1}{H} \sim 2 \text{ trillion years}$$

As a bonus, this offers an explanation for the why now problem:

In any universe where a quasi-static dark energy is measured it also sets the lifetime in that universe. In particular a typical time in that universe is set by the dark energy!

The fact that dark energy has to decay at a time scale set by Hubble, may be tested soon, thanks to DESI and similar ongoing experiments!

Conclusion

We have seen that ideas from string theory and quantum gravity sets a strong bound on the nature of positive potentials. We expect positive dark energy to decay away. The lifetime for such an expectation is naturally the Hubble scale. This may also explain the why now problem.

The measurement of the dark energy may very well end up being the first signal for the `near future' demise of our universe and the beginning of another.