Instituto de Física Teórica UAM-CSIC

Universidad Autónoma de Madrid

Cosmological Chameleons, String Theory & the Swampland

based on 2406.07614 [hep-th]
with Miguel Montero and Gonzalo F. Casas

Ignacio Ruiz ,

StringPheno 2024 , June 25th, 2024. Padova

1. Introduction: Desperately Seeking de Sitter

Why do we care about de Sitter?

Experimental measurements seem to indicate our Universe is accelerating, featuring a positive vacuum energy. [Supernova Search Team,'99]

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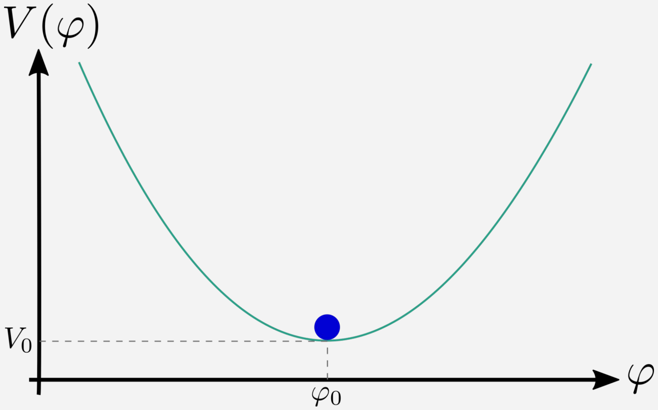
Several top-down constructions have been proposed in String Theory for a **positive minimum** $V(\vec{\varphi}_0) > 0$, but complete control remains elusive.

c.f. Andreas, Liam and Fernando Q.'s talks!



[de Alwis, Andriot, Balasubramanian, Bena, Bento, Berglund, Blåbäck, Blumenhagen, Cicoli, Chakraborty, Conlon, Flauger, Gao, Gligovic, Gorbenko, Graña, Gupta, Hebecker, Joyce, Junghans, Kachru, Kaddachi, Kallosh, Kovenski, Linde, Lüst, Maharana, McAllister, Obied, Ooguri, Polchinski, Parameswaran, Quevedo, Randall, Ruehle Sethi, Shiu, Silverstein, Spodyneiko, Toulikas, Tribedi, Vafa, Valandro, Wiesner, Xu, Zavala,...]

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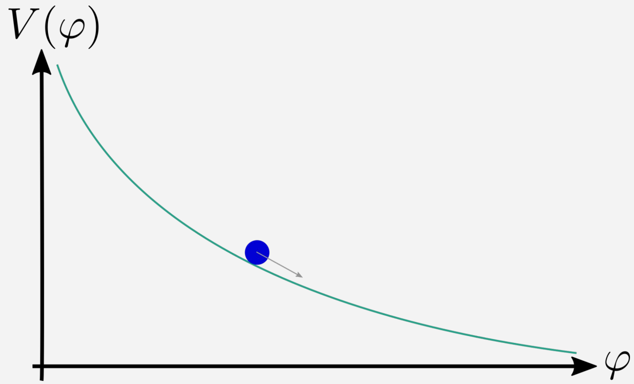
Other option is a *flat enough* runaway potential $V(\vec{\varphi}) = V_0 e^{-\vec{\lambda}\cdot\vec{\varphi}}$ (*i.e.* **quintessence**) with $|\vec{\lambda}| < \frac{2}{\sqrt{d-2}}$.

c.f. Susha and Francisco's talks!

c.f. Flavio's parallel!



[Andriot, Bedroya, Calderón-Infante, Cremonini, Cribiori, Erkinger, Gonzalo, Hebecker, Hertzberg, Kachru, Maldacena, Nuñez, Obied, Ooguri, Rajaguru, van Riet, **I.R.**, Schreyer, Seo, Shiu, Spodyneiko, Tang, Taylor, Tegmark, Tonioni, Tran, Vafa, Valenzuela, Venken, Wrase ...]

Technical difficulties in realizing this in String Theory remain!

Swampland Constraints on de Sitter and Quintessence

Difficulties in dS/Quintessence constructions and bottom-up arguments (observables, etc) motivate the **Swampland asymptotic dS conjecture**: [Obied, Ooguri, Spodyneiko, Vafa, '18]

$$\lambda = \frac{\|\nabla V(\vec{\varphi})\|}{V(\vec{\varphi})} \geq c_d = \mathcal{O}(1) \text{ in asymptotic regions of } \mathcal{M}$$

For $c_d^{\text{strong}} = \frac{2}{\sqrt{d-2}}$ **asymptotic** accelerated expansion is forbidden. [Rudelius, '21]

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On the other hand the **Transplanckian Censorship Conjecture** prevents too long- lived epochs of accelerated expansion:

$$t_{\text{accel.}} \leq \frac{1}{H_0} \log\left(\frac{M_{\text{Pl,d}}}{H_0}\right)$$

[Bedroya, Vafa, '19]

What about transient dS?

The current accelerated era has only lasted around $N \sim 0.5\, e$-folds!

$$t_{\text{accel.}} \approx 4 \cdot 10^9 \text{ years} \ll 4.5 \cdot 10^{12} \text{ years}$$

While we *possibly* live in an asymptotic region of $\mathcal{M}$, we *might not* be in the *asymptotically accelerated regime!*

What if we are currently experiencing a transient dS era?

[DESI collaboration, '24]

[Gomes, Hardy, Parameswaran,'23]; [Andriot, Tsimpis, Wrase, '23] [Andriot, Parameswaran, Tsimpis, Wrase, Zabala, '24], [Bhattacharya, Borghetto, Malhotra, Parameswaran, Tasinato, '24], [Alestas, Akrami, Delgado, Montero, Nesseris, **I.R.**,'24]; [Emparan, Garriga, Gutperle, Kallosh, Linde, Ohta, Roy, Russo, Strominger, Townsend, Wohlfarth ...]
Review: [Cicoli, Conlon, Mahrana, Parameswaran, Quevedo, '24]

c.f. Joaquim's parallel!

c.f. Yashar's parallel!

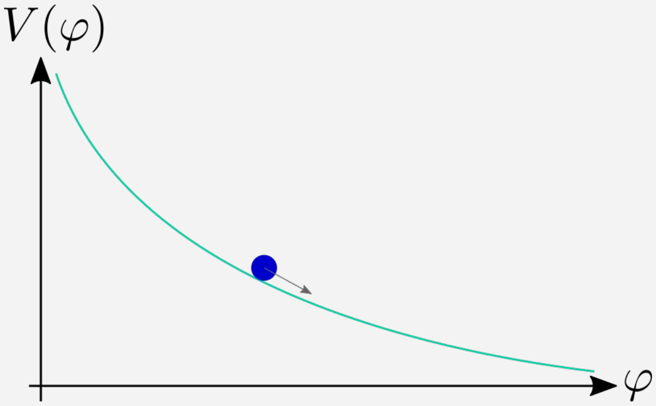
c.f. Lilia's parallel!

2. Cosmological Chameleons

Ingredient list for a transient dS

We consider d-dimensional EFT with canonically normalized moduli $\{\phi^i\}_{i=1}^K$ and massive states $\{\chi_I\}_I$:

$$S^{(d)} \supseteq \frac{1}{2}\int \mathrm{d}^d x\sqrt{-g}\left\{\kappa_d^{-2}\left[\mathcal{R}_g - \sum_{i=1}^{K}(\partial\phi^i)^2\right] - 2V(\vec{\phi}) - \sum_I m_I(\vec{\phi})^2\chi_I^2 - \sum_I(\partial\chi_I)^2\right\}$$



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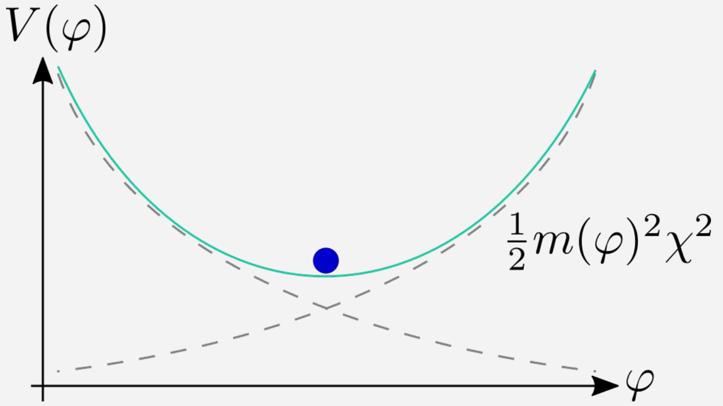
Non-vanishing densities result in effective potential:

$$V_{\text{eff}}(\vec{\phi}) = V(\vec{\phi}) + \frac{1}{2}\sum_I m_I(\vec{\phi})^2\chi_I^2 = V(\phi) - \frac{1}{d}\sum_I T_\nu^{(I)\nu}(\vec{\phi})$$



This can result in an effective **positive** minimum!

[Khouri, Weltman, '03]

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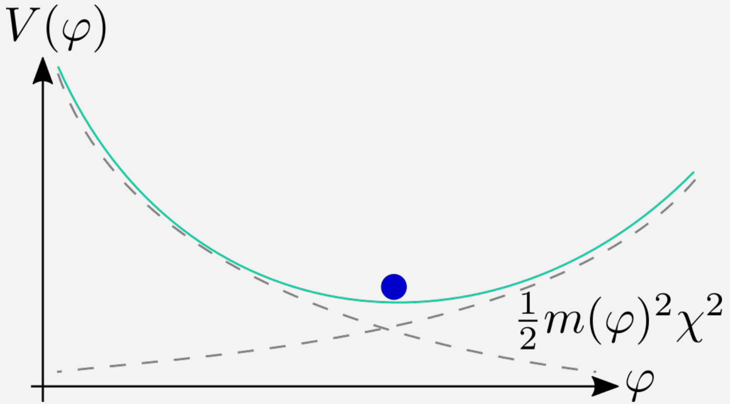

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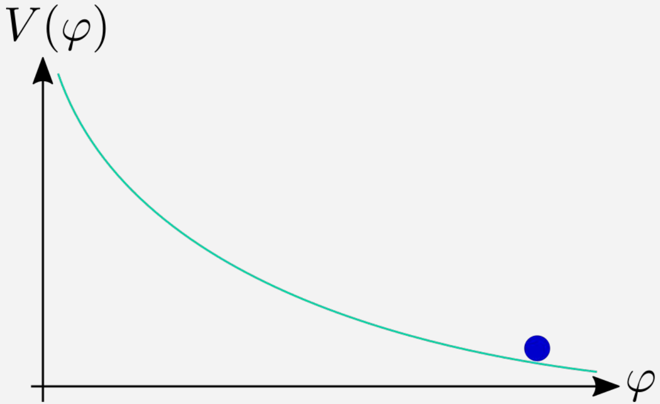

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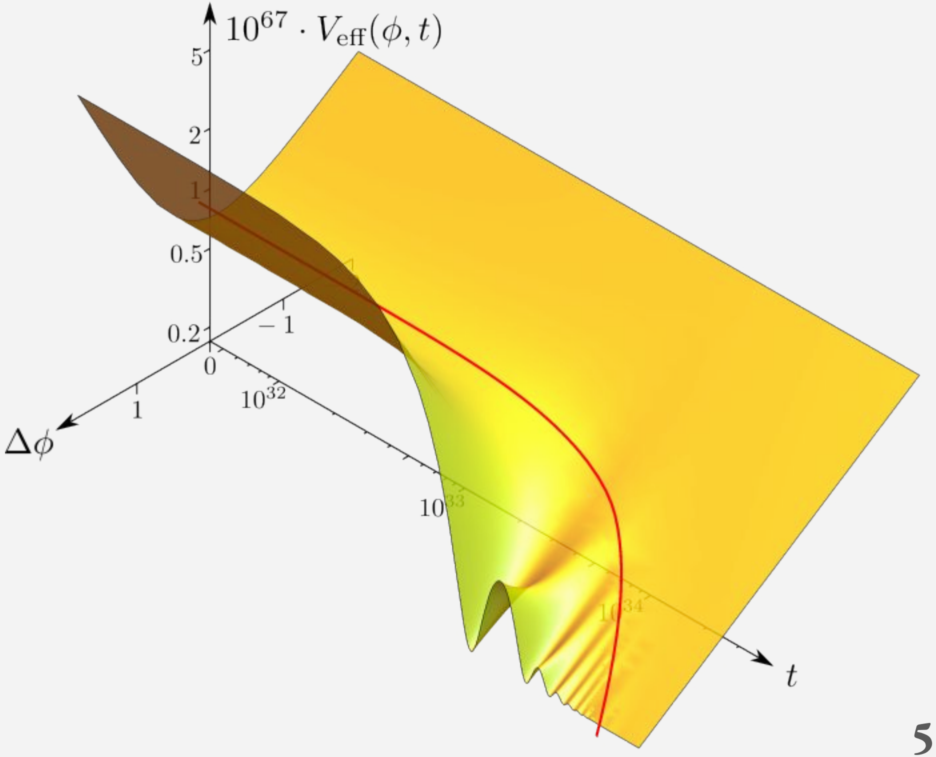
Case 1: Runaway potential + Heavy species

Consider a single scalar ϕ running down an exponential potential and encountering a (stable) scalar state χ becoming heavy:

$$V_{\text{eff}}(\phi, t) = V_0 e^{-\lambda\phi} + \frac{1}{2} m_0^2 e^{2\mu\phi} \chi^2$$

Scalar is stabilized at effective minimum:

$$\phi(\chi) = \underbrace{\frac{1}{\lambda + 2\mu} \log\left(\frac{V_0}{m_0^2 \chi_0^2} \frac{\lambda}{\mu}\right)}_{\phi_0} - \log\left(\frac{\chi}{\chi_0}\right)^{\frac{2}{\lambda+2\mu}}$$



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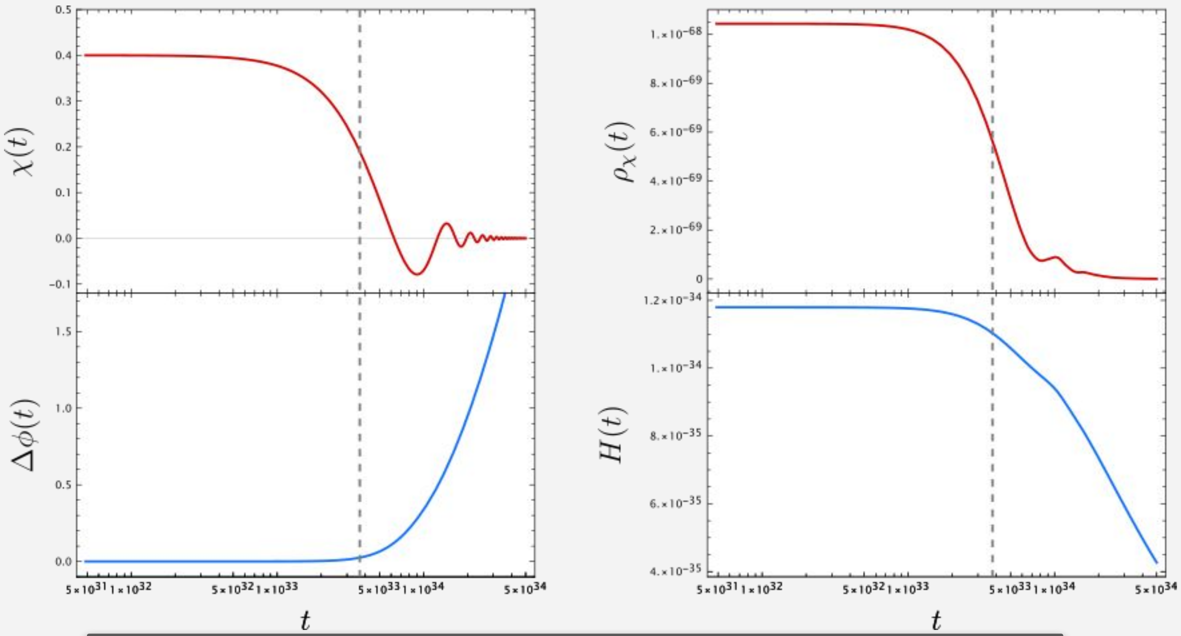


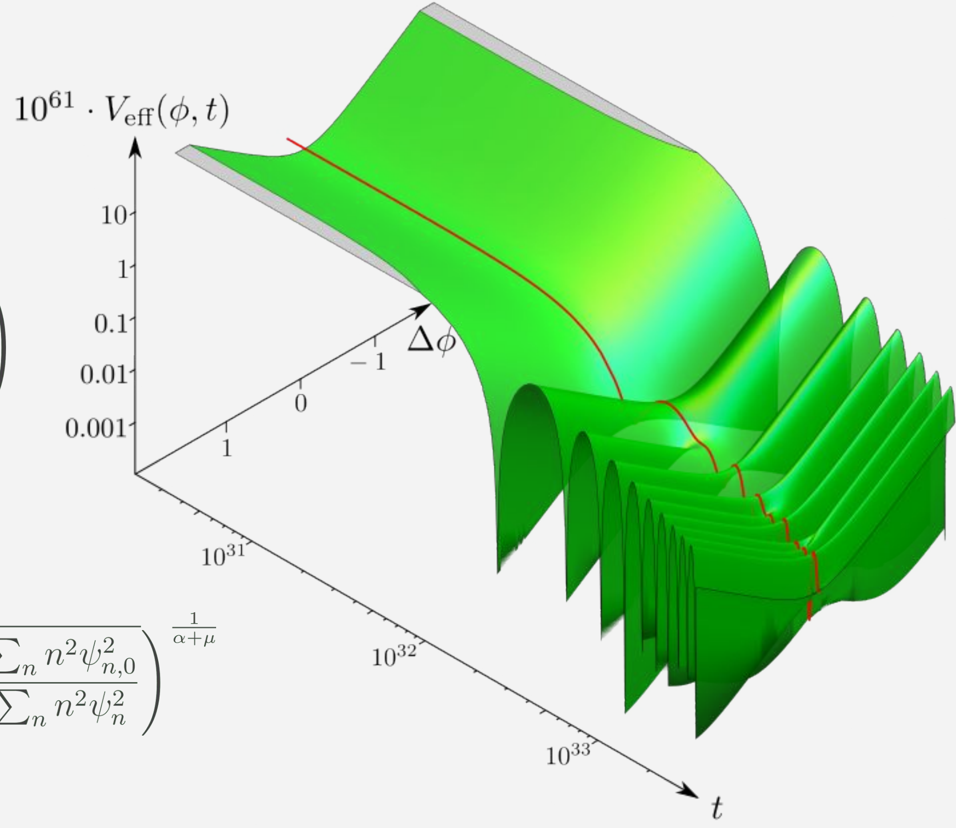
$$N \approx t_{\mathrm{dS}} H_0 = \sqrt{\frac{2(\lambda + 2\mu)}{\lambda(d-1)(d-2)}} \kappa_d |\chi_0| \leq \sqrt{\frac{2(1+\sqrt{d-1})}{(d-1)(d-2)}}$$

for $\mu \leq \sqrt{\frac{d-1}{d-2}}$, $\lambda > \frac{2}{\sqrt{d-2}}$ and $\kappa_d|\chi_0| \lesssim 1$.

Case 2: Light tower + Heavy species

Now the scalar ϕ controls the masses of a stable state χ becoming heavy, as well as a tower of light scalars $\{\psi_n\}_n$:

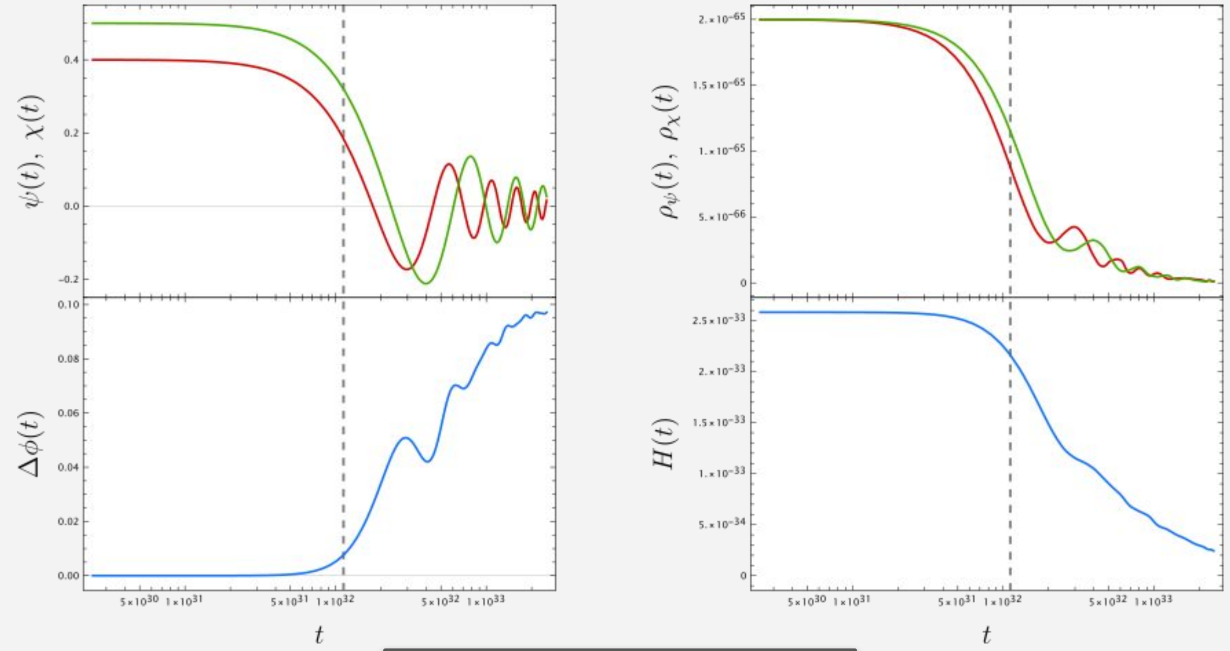
$$V_{\text{eff}}(\phi) = \frac{1}{2}\left(M_0^2 e^{-2\alpha\phi}\sum_n n^2\psi_n^2 + m_0^2 e^{2\mu\phi}\chi^2\right)$$



Scalar is stabilized at effective minimum:

$$\phi(\psi_n,\chi) = \underbrace{\frac{1}{\alpha+\mu}\log\left(\sqrt{\frac{\alpha}{\mu}}\frac{M_0}{m_0}\left|\frac{\sqrt{\sum_n n^2\psi_{n,0}^2}}{\chi_0}\right|\right)}_{\phi_0} - \log\left(\frac{\chi}{\chi_0}\sqrt{\frac{\sum_n n^2\psi_{n,0}^2}{\sum_n n^2\psi_n^2}}\right)^{\frac{1}{\alpha+\mu}}$$

Case 2: Light tower + Heavy species

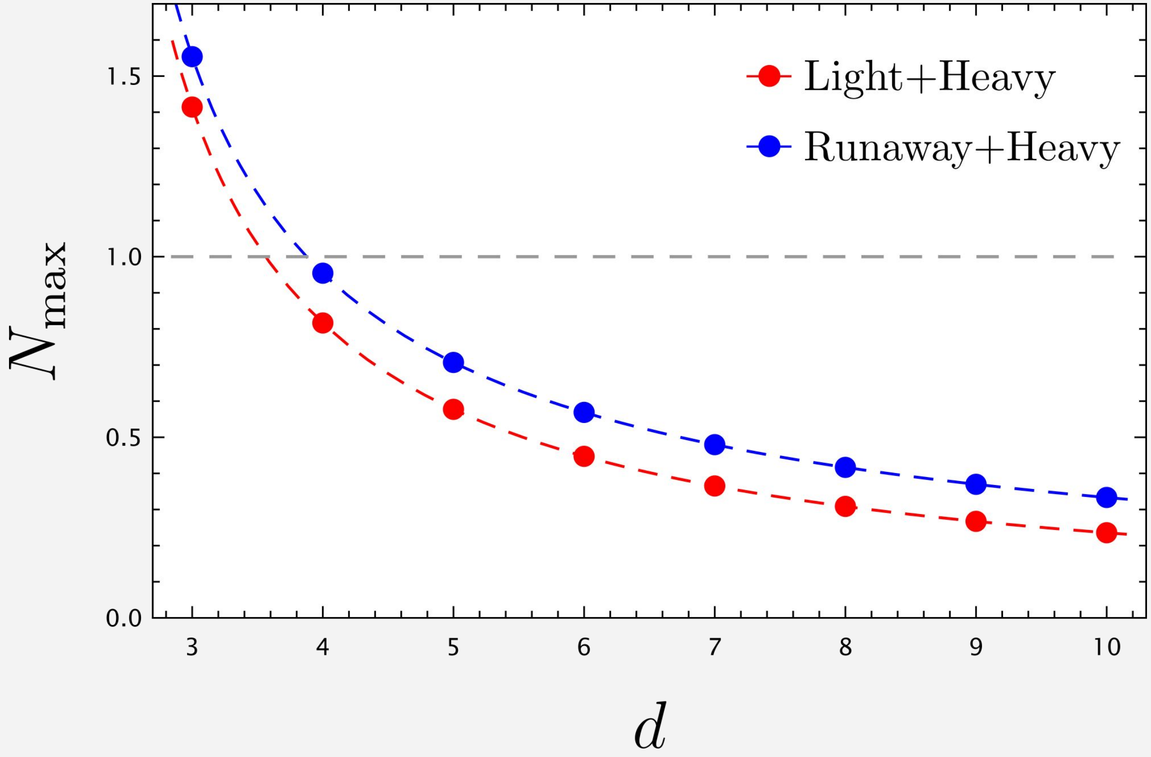


$$N \leq \frac{2}{\sqrt{(d-1)(d-2)}}$$

for $\frac{1}{\sqrt{d-2}} \leq \alpha,\, \mu \leq \sqrt{\frac{d-1}{d-2}}$ and $\kappa_d|\chi_0| \lesssim 1.$

Number of *e*-folds supported

The total number of *e*-folds that this transient dS phase last is always $\mathcal{O}(1)$:



3. String Embeddings (a.k.a. the tricky part)

Attempt 1: M-th on CY3 close to SCFT point

Consider M-theory on $\mathbb{M}^4 \times X_3 \times S^1$, with all moduli stabilized but radion ρ of S^1.

- Heavy states: M5-brane wrapping $\Sigma_4 \subset X_3$ cycle and S^1.
- Runaway potential: Casimir energy

$$V_{\text{eff}}(\rho, \chi) = V_0\, e^{-4\sqrt{\frac{2}{3}}\rho} + m_0^2 e^{\sqrt{\frac{2}{3}}\rho}\chi^2$$

This would result in $N \approx \frac{1}{2}\sqrt{\frac{5}{3}}\,\kappa_4|\chi_0| < 0.6455\,e$-folds.

★ How do we stabilize the rest of moduli close to the SCFT point?

★ Planckian values of the fields might make corrections important!

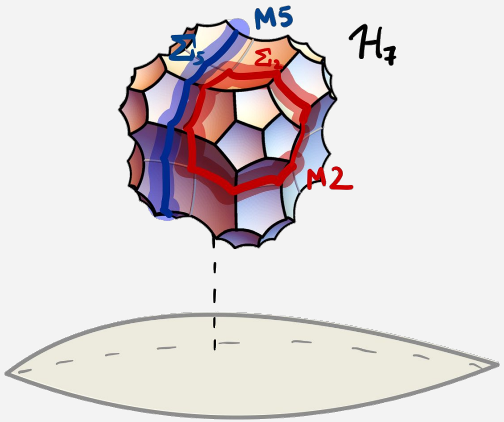
Attempt 2: M-th on hyperbolic manifold

Take M-theory compactified on **compact hyperbolic** 7-manifold $\mathcal{H}_7$ **with torsion**: All moduli are stabilized but volume ρ.

The effective potential comes from negative curvature and M2 and M5 branes wrapped on torsion 2- and 5-cycles:

$$V_{\text{eff}}(\rho, t) = M_{\text{Pl},4}^4 \frac{R_{g_7,0}}{\mathcal{V}_{\mathcal{H},0}^{2/7}} e^{-3\sqrt{\frac{2}{7}}\rho} + \frac{1}{2}\left[m_{\text{M2},0}^2 e^{-\sqrt{\frac{2}{7}}\rho}\psi(t)^2 + m_{\text{M5},0}^2 e^{\sqrt{\frac{2}{7}}\rho}\chi(t)^2\right]$$

At most $N = \sqrt{\frac{2}{3}} \approx 0.82$ e-folds are supported.



Attempt 2: M-th on hyperbolic manifold

Possible problems:

- ★ A hierarchy is needed: $\mathrm{Vol}(\Sigma_2)^{1/2} \gg \mathrm{Vol}(\Sigma_5)^{1/5}$. **Interesting study on its own.**
- ★ Higher order terms might become important for Planckian values of massive states:
  - ○ Interaction between M2 and M5 particles are suppressed at large volume.
  - ○ **Supersymmetry is broken:** Not control on self-interactions between M2 and M5 as they intersect their world-volumes. **More study is needed!**

No full control is achieved! 

4. Bottom-up constraints from light towers of states.

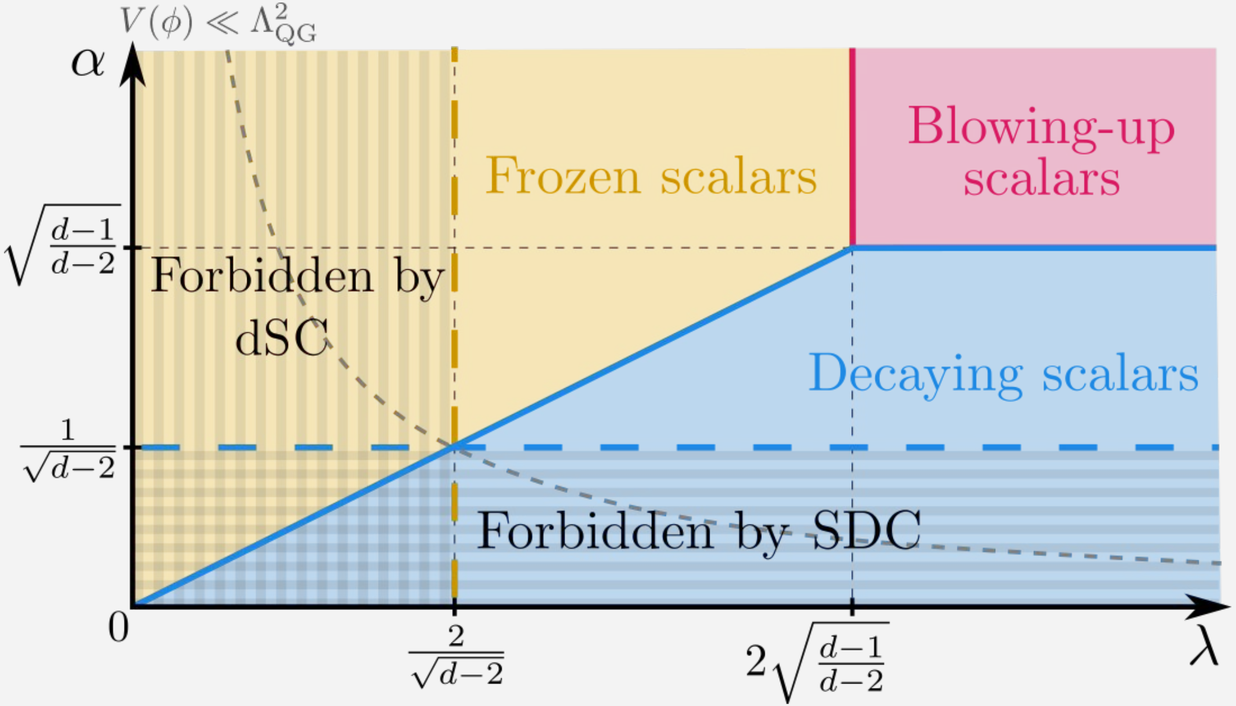
[2407.XXXXX] with Gonzalo F. Casas

Evolution of light towers with runaway potential

An analogous study can be done of the evolution of light towers in a FLRW background with a potential: **Bottom-up Swampland consistency constraints inferred!**

c.f. Joe's talk!

c.f. Fien's parallel!



Let's wrap up!

Conclusions and Outlook

- Transient dS phases can be consistent with both observational and Swampland principles.
- Cosmological chameleons offer $\mathcal{O}(1)$ *e*-folds of accelerated expansion with natural ingredients in asymptotic regions of $\mathcal{M}$.
- Stringy realizations can be complicated due to higher order corrections and need of "well-behaved" heavy states: **More research is needed!**
- Other possibilities: monodromic axions?
- Cosmological evolution of towers of states can provide interesting insights!

THINK OUTSIDE THE BOX!

Thanks for listening!