THE HOLOGRAPHIC SWAMPLAND

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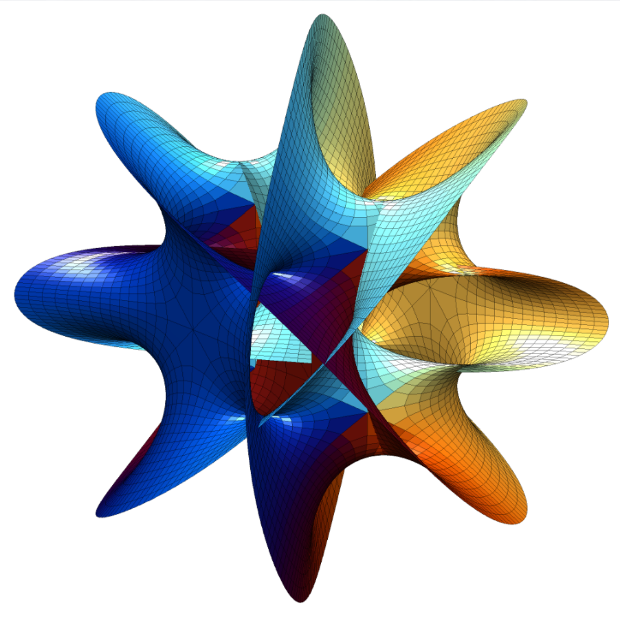
(based on JC, Quevedo 1811.06276,
JC, Revello 2006.01021
JC, Ning, Revello in progress)

MODULI: WHAT?

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{SM} + \mathcal{L}_{BSM}$$

- What is in $\mathcal{L}_{BSM}$?
- Simple concept: *massive scalar* Φ with *gravitationally suppressed couplings* to ordinary matter such as $\frac{\Phi}{M_P} F_{\mu\nu} F^{\mu\nu}$
- Such **moduli** are well motivated from e.g. string theory and extra-dimensional theories

MODULI: WHY?



- String theory is a theory of ***dynamical*** extra dimensions
- In 4d theory, geometry of extra dimensions (size and shape) parametrised by *moduli* - such as Kahler and complex structure moduli.
- Unstabilised, these lead to fifth forces, varying couplings or (fatal) decompactification.
- Essential to develop *moduli potentials* that fix this geometry
- Stabilisation also provides a minimum in which to compute couplings

MODULI: WHY?

- In an expanding universe

$$\rho_{matter} \sim \frac{1}{a^3} \qquad \rho_{radiation} \sim \frac{1}{a^4}$$

- As matter dominates over radiation, reheating is dominated by the *last* fields to decay *not* the first

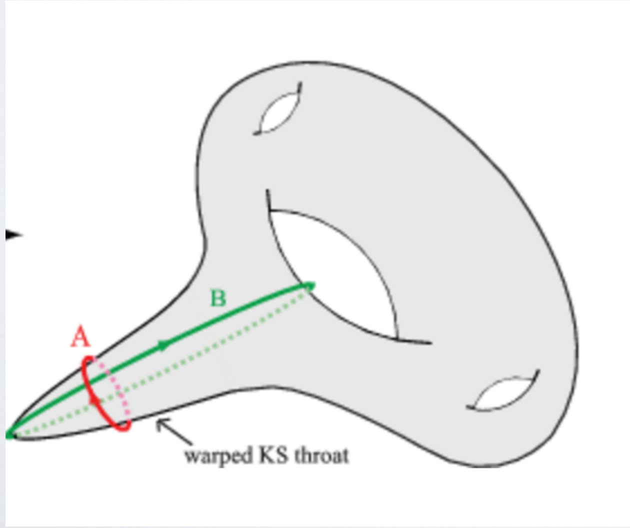
- The weaker the coupling, the longer the lifetime….

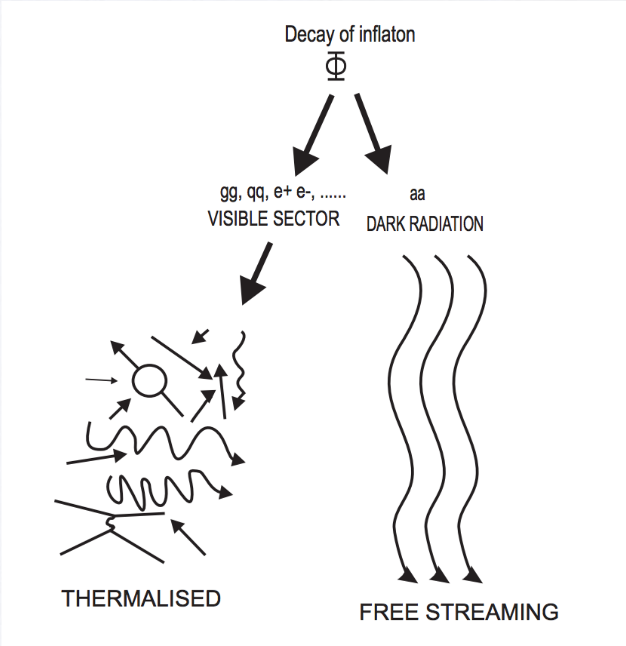
$$\tau_\Phi \sim \frac{8\pi M_P^2}{g^2 m_\Phi^3} \sim \left(\frac{10\mathrm{TeV}}{m_\Phi}\right)^3 10^{-3} s \qquad \tau \sim \frac{8\pi}{g^2 m}$$

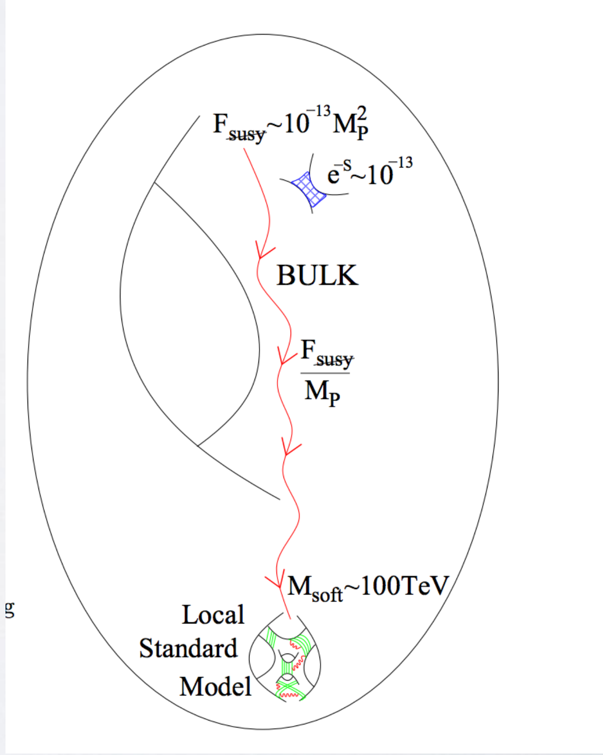
- Moduli potentials are everyone's business

MODULI STABILISATION

- Much work on developing moduli potentials (LVS, KKLT) and studying their dynamics with regards to
  Supersymmetry breaking
  Cosmology - late time de Sitter
  Cosmology - inflation
  Particle physics







LARGE VOLUME SCENARIO

Balasubramanian, Berglund, JC, Quevedo

- Perturbative corrections to K and non-perturbative corrections to W

$$W = \int G_3 \wedge \Omega + \sum_i A_i e^{-2\pi a_i T_i}$$

$$K = -2\ln\left(\mathcal{V} + \xi'\right) + \ln\left(\int \Omega \wedge \bar{\Omega}\right) - \ln(S + \bar{S})$$

- Resulting scalar potential has minimum at *exponentially large* values of the volume

$$V = \frac{A\sqrt{\tau_s}\, e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{B\tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{C}{\mathcal{V}^3}$$

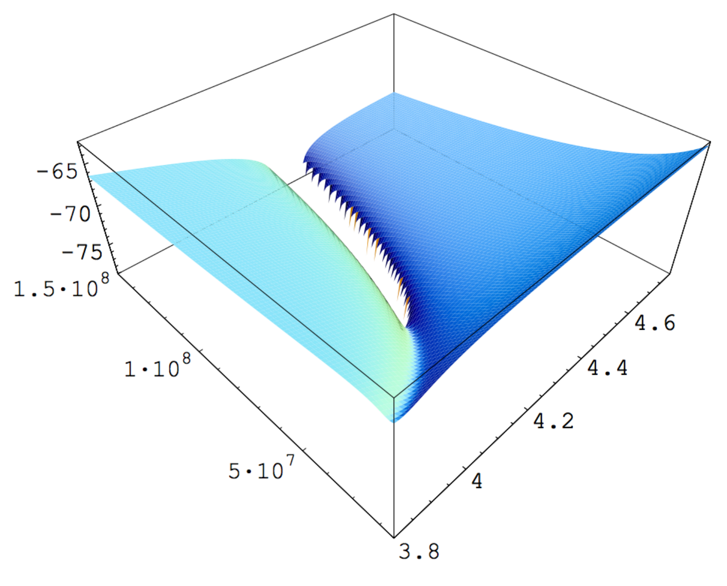


Figure 1: $\ln(V)$ for $P^4_{[1,1,1,6,9]}$ in the large volume limit, as a function of the divisors τ_4 and τ_5. The void channel corresponds to the region where V becomes negative and $\ln(V)$ undefined. As $V \to 0$ at infinite volume, this immediately

WHY LVS?

- In LVS, volume is exponentially large - can easily be

$$\mathcal{V} \sim 10^{50}(2\pi\sqrt{\alpha'})^6$$

- This *generates interesting hierarchies* and ensures *superb parametric decoupling* of heavy modes (KK modes, heavy moduli)

- Decoupling also has a clear geometric origin - large volume

$$\langle \mathcal{V} \rangle \sim e^{\xi/g_s}$$

- $\mathcal{V} \to \infty$ limit of LVS also leads to a unique effective theory

LARGE VOLUME SCENARIO

- LVS effective theory for volume modulus $\mathbf{\Phi}$ and axion a

$$\left(\lambda = \sqrt{27/2}\right)$$

$$V_{potential} = V_0 e^{-\lambda\Phi/M_P}\left(-\left(\frac{\Phi}{M_P}\right)^{3/2} + A\right)$$

$$\mathcal{L}_{kinetic} = \frac{1}{2}\partial_\mu\Phi\partial_\mu\Phi + \frac{3}{4}e^{-\sqrt{\frac{8}{3}}\Phi}\partial_\mu a\partial^\mu a$$

- Other terms are subleading in infinite volume limit by $\mathcal{O}\left(\frac{1}{\ln\mathcal{V}}\right)$

LARGE VOLUME SCENARIO

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- Solve for minimum and expand about it to determine masses and couplings

THE SWAMPLAND (Vafa et al)

- Which low-energy Lagrangians are forbidden by quantum gravity?
- Do de Sitter vacua exist in string theory?
- Can large (trans-Planckian) field inflation occur?

MODULI STABILISATION

- String theory

  ↓ EFT

- 10-dimensional supergravity with alpha' corrections

  ↓ EFT

- 4-dimensional supergravity of moduli and matter

  ↓ EFT

- Integrate out heavy modes to get potential for lightest moduli

  ↓ EFT

- Find vacuum as minimum of effective potential, construct de Sitter space in string theory…..

MODULI STABILISATION

- String theory
- 10-d ergravit ' corrections
- 4-di d matter
- Inte es to get potential for
  lighte

EFT

- Find vacuum as minimum of effective potential

MODULI STABILISATION

- String theory

EFT

- 10-dimensional supergravity with alpha' corrections

EFT

- 4-dimensional supergravity of moduli and matter

EFT

- Integrate out heavy modes to get potential for lightest moduli

EFT

- Find vacuum as minimum of effective potential

HOLOGRAPHY

- CFT dimensions of dual operators:

$$\Delta(\Delta - 3) = m_{\Phi}{}^{2} R_{AdS}^{2}$$

- In infinite volume limit can classify modes as

heavy $m_{\Phi}^{2} \gg R_{AdS}^{-2}, \Delta \to \infty \quad \text{as} \quad \mathcal{V} \to \infty$

light $m_{\Phi}^{2} \ll R_{AdS}^{-2}, \Delta \to 3 \quad \text{as} \quad \mathcal{V} \to \infty$

interesting $m_{\Phi}^{2} \sim R_{AdS}^{-2}, \Delta \to \mathcal{O}(1-10) \quad \text{as}\, \mathcal{V} \to \infty$

LVS MASS SPECTRUM

- In LVS we have
- **Heavy:** KK modes, complex structure moduli, all Kahler moduli except overall volume
- **Light:** Graviton, overall volume axion
- **Interesting:** overall volume modulus

LVS HOLOGRAPHY

Mode	Spin	Parity	Conformal dimension
$T_{\mu\nu}$	2	+	3
a	0	-	3
Φ	0	+	$8.038 = \frac{3}{2}\left(1+\sqrt{19}\right)$

Table 1. The low-lying single-trace operator dimensions for CFT duals of the Large Volume Scenario in the limit $\mathcal{V} \to \infty$.

In minimal LVS, AdS effective theory has small number of fields which correspond to specific predictions for dual conformal dimensions

No Landscape! (not true of KKLT)

LVS HOLOGRAPHY

- LVS is attractive as it offers a well-motivated Generalised Free Field Theory
- Large volume limit $\mathcal{V} \to \infty$ gives a unique theory
- Two scalars with fixed and radiatively stable anomalous dimensions
- All AdS interactions are also fixed and radiatively stable

LVS AND THE SWAMPLAND

- Now consider this small modification:

$$V_{potential} = V_0 e^{-\lambda\Phi/M_P}\left(-\left(\frac{\Phi}{M_P}\right)^{3/2} + A\right) \qquad \left(\lambda = \sqrt{27/2}\right)$$

$$\mathcal{L}_{kinetic} = \frac{1}{2}\partial_\mu\Phi\partial_\mu\Phi + \frac{3}{4}e^{+\sqrt{\frac{8}{3}}\Phi/M_P}\partial_\mu a\partial^\mu a$$

- This coupling is equivalent to axion decay constants that *diverge* in the decompactification limit - must be in the swampland!

$$f_a / M_P \to \infty \quad \text{as} \quad \mathcal{V} \to \infty$$

HOLOGRAPHIC SWAMPLAND

- n-point self interactions of volume modulus

$$\mathcal{L}_{n-pt} = (-1)^{n-1}\lambda^n (n-1)\left(-3\frac{M_P^2}{R_{AdS}^2}\right)\frac{1}{n!}\left(\frac{\delta\Phi}{M_P}\right)^n\left(1+\mathcal{O}\left(\frac{1}{\ln\mathcal{V}}\right)\right)$$

$$\left(\lambda = \sqrt{27/2}\right)$$

- Mixed interactions of volume modulus and axion

$$\mathcal{L}_{\Phi^n aa} = \left(-\sqrt{\frac{8}{3}}\right)^n \frac{1}{2n!}\left(\frac{\delta\Phi}{M_P}\right)^n \partial_\mu a \partial^\mu a$$

- The higher-point interaction define 3- and higher point-correlators within a dual CFT

HOLOGRAPHIC SWAMPLAND

- n-point self interactions of volume modulus

$$\mathcal{L}_{n-pt} = (-1)^{n-1}\lambda^n (n-1)\left(-3\frac{M_P^2}{R_{AdS}^2}\right)\frac{1}{n!}\left(\frac{\delta\Phi}{M_P}\right)^n\left(1+\mathcal{O}\left(\frac{1}{\ln\mathcal{V}}\right)\right)$$

- Now modify interactions of volume modulus and axion $\left(\lambda = \sqrt{27/2}\right)$

$$\mathcal{L}_{\Phi^n aa} = \left(+\sqrt{\frac{8}{3}}\right)^n \frac{1}{2n!}\left(\frac{\delta\Phi}{M_P}\right)^n \partial_\mu a \partial^\mu a$$

- This defines a perturbation to the Generalised Free Field CFT with axion decay constants that *diverge* in the decompactification limit - must be in the swampland!

$$f_a / M_P \to \infty \quad \text{as} \quad \mathcal{V} \to \infty$$

HOLOGRAPHIC SWAMPLAND

- The problem:

  1. Generalised Free Field + (some corrections)
     - **consistent theory**
  2. Generalised Free Field + (other corrections)
     - **swampland!**

Where does the difference lie? Can one correlate any properties of the CFT with this change from the consistent theory to the swampland theory?