Looking for axions with lasers

Giacomo Marocco
with Konstantin Beyer, Gianluca Gregori

Supervisors: Subir Sarkar & John Wheater

17/10/2019

Strong CP problem

- $\mathcal{L}_{SM} \supset \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} + q^c M_q q, \quad \tilde{G}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} G_{\rho\sigma}$
- Anomaly: Under chiral rotations

$$q \to e^{i\alpha} q, \quad q^c \to e^{i\alpha} q \tag{1}$$

  the massless Lagrangian is not invariant, but transforms as

$$\theta \to \theta - 2\alpha. \tag{2}$$

- Invariant quantity $\bar{\theta} = \theta + \arg\det M_q \lesssim 10^{-10}$ from lack of CP-violation in neutron EDM $d_n \lesssim 3 \times 10^{-26}\,\mathrm{e\,cm}$.

Why?

QCD axion and ALPs

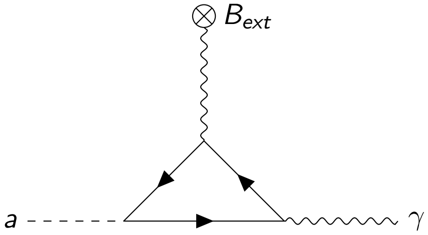
- To solve strong CP, introduce a new $U(1)_{\mathrm{PQ}}$ symmetry. Spontaneously broken at some high scale f_a, where the pseudo-Goldstone a is the QCD axion.
  - This symmetry is also anomalous, so couples to $G\tilde{G}$.
  - $\langle a \rangle = -f_a\bar{\theta} \implies$ No CP-violation!
- String theory compactification leads to (pseudo)scalars with compact field spaces. These are axion-like particles (ALPs).
  - ALPs do not necessarily couple to $G\tilde{G}$, so the ALP parameter space is less prescribed by theory.

Axion-photon coupling

- QCD axions and pions share the same quantum numbers: ought to be a loop-induced coupling to two photons for any field coupling to $G\tilde{G}$:

$$\begin{aligned}\mathcal{L}_{a\gamma\gamma} &= \frac{g_{a\gamma\gamma}}{4} aF\tilde{F} \\ &= -g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}\end{aligned} \tag{3}$$

- In the presence of an external magnetic field, this is an effective mass-mixing matrix between axions and photons (cf neutrinos).



Astrophysical constraints

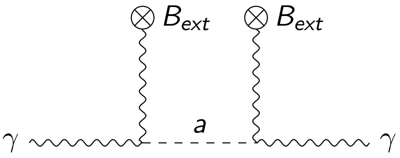
1. Stellar cooling
   - Axions with masses below $T_{\text{core}} \simeq 10\,\text{keV}$ can be produced in stars.
   - Weakly coupled particles allow efficient energy transport out of the star, leading to cooling and faster fusion (Primakoff process).
   - Lifetimes of horizontal branch stars $\implies g_{a\gamma\gamma} \lesssim 10^{-10}\,\text{GeV}^{-1}$.
   - Indirect: requires precise models of stellar cooling.
2. Solar axions
   - Helioscopes pointed at the Sun, e.g. CAST, can directly detect axions produced by conversion to photons in a magnetic field.

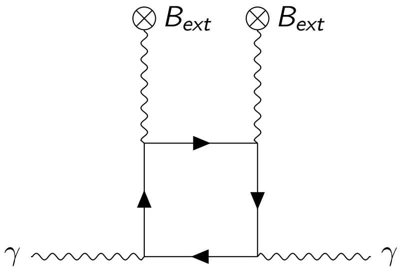
- Plasma and thermal effects also change effective couplings probed.

Laboratory constraints I

What model-independent constraints are there? Weak couplings and low masses suggest high intensity or rare processes are optimal.

1. Birefringence and dichroism
   - The effective photon mass in B-fields induces rotation of polarized lasers.
   - QED contribution comes from box diagram and is heavily suppressed. Even so, this sets an practical limit on axion couplings that can be probed: $\Delta n_{\mathrm{QED}} = 4 \times 10^{-24}\,\mathrm{T}^{-2}$.





Laboratory constraints II

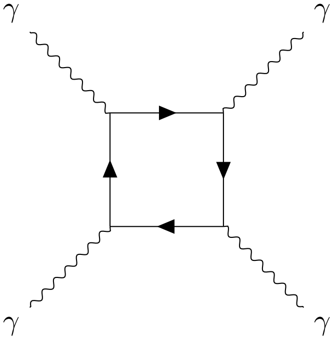
2. Light shining through walls (LSW)
   - Photons in a laser convert into axions in external B-field. These pass through an intervening wall, after which a photon can be reconverted with another B-field.

$$P_{a\to\gamma\gamma} = 4g_{a\gamma\gamma}^2 \frac{B^2}{q^2\beta_a} \sin\left(\frac{qL}{2}\right)^2, \tag{4}$$

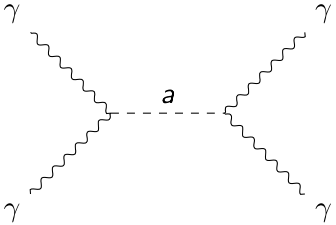
   for momentum transfer q, magnet length L.
   - Relativistic axions $\implies \sin\left(\frac{qL}{2}\right)^2 \simeq (\frac{qL}{2})^2$, so coherence across whole B-field region.

- How can we probe higher mass regions with optical photon frequencies $\omega \simeq 1\,\text{eV}$, where axion is no longer relativistic?

Light-by-light scattering



(a) QED light-by-light scattering with electrons running in the loop. $\sigma_{\text{QED}} \sim \frac{\alpha^4 \omega^6}{m_e^8}, \quad \omega \ll m_e$.

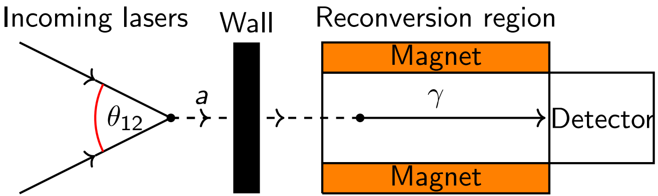


(b) Axion-mediated light-by-light scattering. $\sigma_a \sim g_{a\gamma\gamma}^4 \omega^2, \quad \omega \gg m_a$.

- For $\sigma_a \gtrsim \sigma_{\text{QED}}$, $g_{a\gamma\gamma} \gtrsim 10^{-5}\,\text{GeV}^{-1}$ - excluded by LSW.
- Resonance? If axion is on-shell, it will likely live too long to be produced by stimulated decay within the beam.

Using resonant scattering

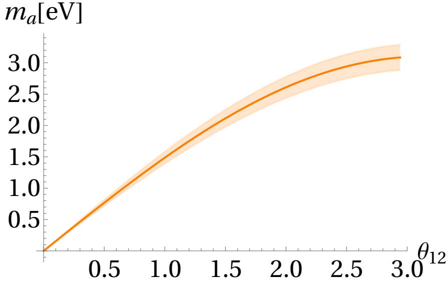
- To detect a real axion, we must reconvert it at a macroscopic distance from production region.

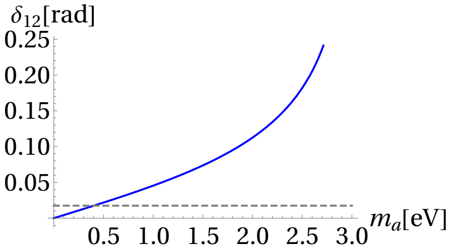


- No QED background. Scales as N_γ^2 (cf linear LSW scaling). But effect is $\mathcal{O}(g^4_{a\gamma\gamma})$ (like LSW, unlike birefringence).
- Coherence: laser substructures? Phase plates can create intensity patterns within beam, enhancing scattering - analagous to Bragg scattering.

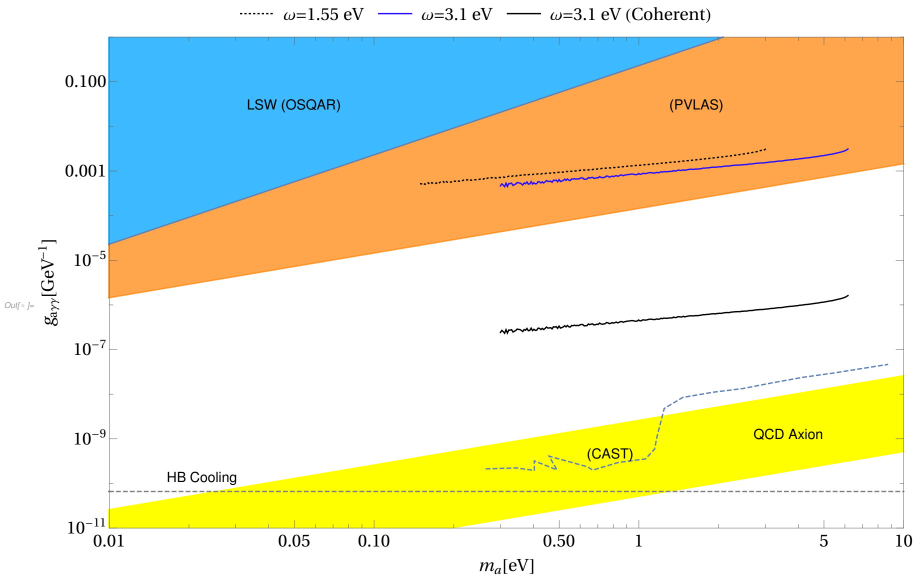
Scanning the mass range

- Difficulty in axion experiments is varying parameters to explore entire mass region.
- The laser collision angle θ_{12} can be adjusted to probe different centre-of-mass energies. Order of magnitude in m_a in ~ 30 shots - here we are limited by δ_{12}, the step-size in collision angle.





Possible experimental reach



Conclusions

- Important to explore available regions of axion parameter space in as model-independent a way as possible.
- Resonant $\gamma\,\gamma$ scattering allows for stringent bounds to be placed at $\sim 1\,\mathrm{eV}$ masses.
- Laser subtructures - more investigation needed. Possible applications to QED light-by-light scattering?

Heterotic String Compactifications and Model Building

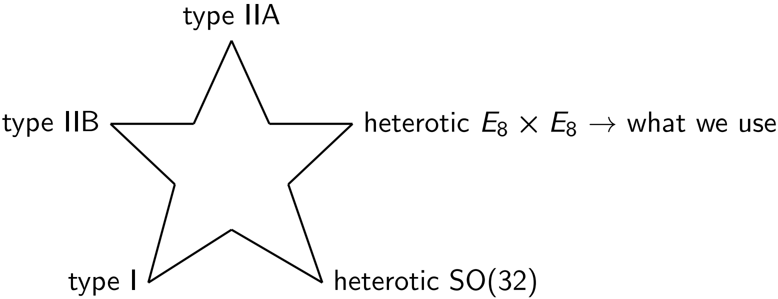
Pandora Dominiak

University of Oxford
with Andre Lukas and Rehan Deen

Compactification and String Theory

Compactification aims to reconcile our 4 observable dimensions with the 10 dimensions of string theory. We "**compactify**" the 10d spacetime $M_4 \times X_6$ such that M_4 is 4d Minkowski space and X_6 is a 6d, compact, curved manifold.

Fermions in the Standard Model are **chiral** $\rightarrow$ we must start with a chiral string theory which has potential **anomalies**.
The only anomaly-free chiral superstring theories are



Heterotic String Theory

We work with heterotic $E_8 \times E_8$! Why?

- $SU(3) \times SU(2) \times U(1) \subset E_8$,
- allows us to construct realistic particle physics models,
- low energy 10d effective field theory includes Yang-Mills interactions,
- heterotic ST has an associated vector bundle whose geometry determines many phenomenological features of the effective field theory obtained after compactification.

The 6d space that we compactify on is a Calabi-Yau manifold. Why?

- Spinors on X_6 determine spinors on M_4.
- To ensure chirality of fermions we must preserve $\mathcal{N} = 1$ SUSY at 4d.
- Covariantly constant spinors $\nabla_{X_6}\xi(x^m) = 0$ correspond to local unbroken supersymmetry.
- A generic 6d manifold has holonomy group $Spin(6) \simeq SU(4)$ - this gives no covariantly constant spinors.
- Covariantly constant spinors with the right supercharge count are guaranteed when they transform trivially under $SU(3)$ - manifolds with $SU(3)$ holonomy are Calabi-Yau manifolds!

Heterotic String Compactifications

When we compactify a heterotic string theory some of the gauge fields must exist in the compactified dimensions and are given in the form of a vector bundle V.

- The gauge connection must satisfy hermitian Yang-Mills equations to preserve $\mathcal{N} = 1$ supersymmetry
  - $F_{ij} = F_{\bar{i}\bar{j}} = 0 \implies V$ holomorphic,
  - $g^{i\bar{j}} F_{\bar{j}i} = 0 \implies V$ stable
- The structure of the bundle determines the breaking of E_8:
  - $E_8 \to SU(3) \times E_6$
  - $E_8 \to SU(4) \times SO(10)$
  - $E_8 \to SU(5) \times SU(5)$

Grand Unified Theories

Grand Unified Theories (GUT) propose that the SM gauge groups are unified into one single gauge group with the matter fields combined into multiplets.

- Allows us to incorporate the seesaw mechanism.
- Offers an explanation for charge quantization.

Why do we work with $SO(10)$?

- All quarks and leptons fit into the **16** spinor representation of $SO(10)$.
- This **16** contains an extra singlet - a right-handed neutrino
- After breaking $SO(10)$ to the SM gauge group there exists an additional $U(1)$ factor that could be responsible for preserving $B - L$

Wilson Lines

The GUT group (in our case $SO(10)$) must be broken to something resembling $SU(3) \times SU(2) \times U(1)$. To do this we introduce Wilson lines:

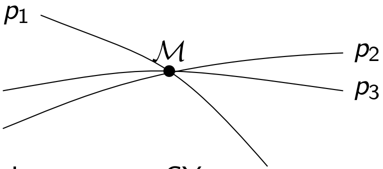
- divide the manifold by a freely acting discrete symmetry Γ
- e.g. $\Gamma = \mathbb{Z}_3 \times \mathbb{Z}_3$ breaks $SO(10)$ to $SU(3) \times SU(2) \times U(1)^2$

In summary, in order to have a complete heterotic string model we must have a Calabi-Yau manifold and an $SU(4)$ structure vector bundle with discrete symmetries that will reduce the GUT symmetry to the SM symmetry.

Complete Intersection Calabi-Yau manifolds

What are Complete Intersection Calabi-Yau manifolds? (CICY)

- Classification of Calabi-Yau's is an open problem - possibly and infinite number
- Complete Intersection Calabi Yau manifolds (CICY) are realised as the complete intersection of polynomials in a product of projective spaces $\mathbb{P}^{n_1} \times ... \times \mathbb{P}^{n_m}$.



Why do we use them?

- One of the simplest way to explicitly construct CYs.
- There is a finite number of CICYs.
- Easily identifiable discrete symmetries.

Monads

Theorem: Every bundle on $\mathbb{P}^n$ can be expressed as a monad

What are monads?

- Short exact sequences between vector bundles

$$0 \to V \to B \xrightarrow{f} C \to 0 \tag{1}$$

- Exact therefore $V = \ker(f) \to$ a way of constructing vector bundles.

Why monad construction of V?

- Vector bundles B and C can be constructed out of sums of line bundles.
- Line bundles on projective spaces are simply characterised by integers: $L = \mathcal{O}(\mathbf{k})$, where $\mathbf{k} = (k^1, ..., k^m)$
- Leads to a simpler construction of V.

Topological Invariants

Many physical characteristics of our 4d theory are affected by the topological invariants of the 6d compactified space

Physical constraint	Mathematical constraint
Calabi-Yau manifold	$c_1(V) = 0$
Anomaly cancellation	$c_2(TX) - c_2(V) \geq 0$
Three generations	$\text{ind}(V)$ divisible by 3
Stability	$h^0(X, V) = h^3(X, V) = 0$

For instance: the number of massless fields in 4d is counted by the number of solutions to the zero mode equations on X_6. The solutions are harmonic forms which are counted by the cohomology dimensions.

A recipe for model building

1. Pick a CICY with appropriate discrete symmetries: we pick the bi-cubic

$$X = \left[\begin{array}{c|c} \mathbb{P}^2 & 3 \\ \mathbb{P}^2 & 3 \end{array} \right] \tag{2}$$

2. Generate sets of integers which represent the line bundles B and C
3. Test these integers against the mathematical conditions listed above
4. Result: obtain Standard Model candidates!

Our current aim is to classify all possible monad bundles on the bi-cubic as a case study. The future outlook involves generalising our results to other CICYs.

Preliminary results

We're working on scanning the bi-cubic manifold for monads that satisfy our conditions. All of these monads guarantee the vanishing of $c_1(V)$, have an index that will give us 3 generations, and satisfy the anomaly cancellation condition.

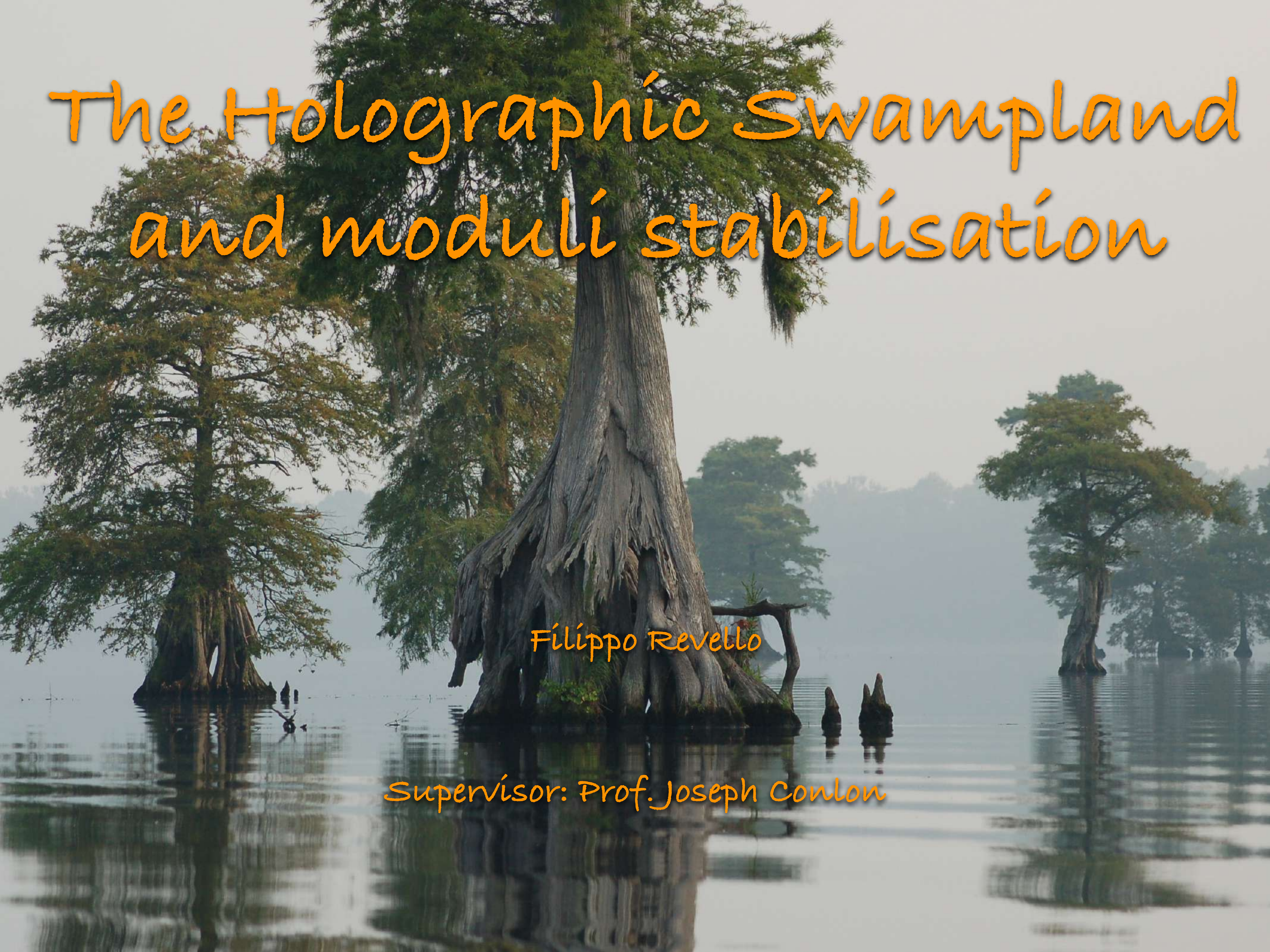
- $\mathrm{rk}(B) = 5, \mathrm{rk}(C) = 1$: no monads have been found
- $\mathrm{rk}(B) = 6, \mathrm{rk}(C) = 2$: only one monad bundle exists

$$0 \to V \to \mathcal{O}(1,0)^{\oplus 3} \oplus \mathcal{O}(0,1)^{\oplus 3} \to \mathcal{O}(1,1) \oplus \mathcal{O}(2,2) \to 0$$

- $\mathrm{rk}(B) = 7, \mathrm{rk}(C) = 3$: so far 27557 monads have been found, e.g.

$$0 \to V \to \mathcal{O}(5,1) \oplus \mathcal{O}(5,2) \oplus \mathcal{O}(7,8) \oplus \mathcal{O}(1,1) \oplus \mathcal{O}(0,1)^{\oplus 3} \to$$
$$\to \mathcal{O}(2,8) \oplus \mathcal{O}(8,2) \oplus \mathcal{O}(8,5) \to 0$$

We are working on finding additional constraints that could reduce the number of bundles we find.



The Holographic Swampland and moduli stabilisation

Filippo Revello

Supervisor: Prof. Joseph Conlon

Introduction

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk:

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk:

Swampland constraints

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk:

Swampland constraints

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk: AdS/CFT

Swampland constraints

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk: AdS/CFT

Swampland constraints $\longleftrightarrow$ CFT inconsistencies

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk: AdS/CFT

Swampland constraints

CFT inconsistencies
or
reformulation

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk: AdS/CFT

Swampland constraints ? CFT inconsistencies
or
reformulation

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk: AdS/CFT

Swampland constraints ? CFT inconsistencies
or
reformulation

Why?

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk: AdS/CFT

Swampland constraints ? CFT inconsistencies
or
reformulation

Why?

- Independent check for complicated constructions

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk: AdS/CFT

Swampland constraints ? CFT inconsistencies
or
reformulation

Why?

- Independent check for complicated constructions
- AdS/CFT universal - any theory of QG, not just ST

Introduction

Swampland program: criteria to distinguish low energy lagrangians admitting a UV completion in ST (QG)

Topic of this talk: AdS/CFT

Swampland constraints ? CFT inconsistencies or reformulation

Why?

- Independent check for complicated constructions
- AdS/CFT universal - any theory of QG, not just ST
- Bootstrap more successful in mapping space of allowed theories

The Large Volume Scenario

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

The Large Volume Scenario

Concrete setting: Low energy dynamics of **moduli** in ST

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

shape & size
of extra dim

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

↓

shape & size
of extra dim

LVS: simple holographic picture

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

shape & size
of extra dim

LVS: simple holographic picture

Stabilized at exponentially large volume $\langle \mathcal{V} \rangle \sim e^{a_s \langle \tau_s \rangle}$

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

shape & size of extra dim

LVS: simple holographic picture

Stabilized at exponentially large volume $\langle \mathcal{V} \rangle \sim e^{a_s \langle \tau_s \rangle}$

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

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

shape & size of extra dim

LVS: simple holographic picture

Stabilized at exponentially large volume $\langle \mathcal{V} \rangle \sim e^{a_s \langle \tau_s \rangle}$

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

canonically normalised volume modulus

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

shape & size
of extra dim

LVS: simple holographic picture

Stabilized at exponentially large volume $\langle \mathcal{V} \rangle \sim e^{a_s \langle \tau_s \rangle}$

$$\boxed{V = V_0 e^{-\lambda \Phi / M_P} \left(- \left(\frac{\Phi}{M_P} \right)^{3/2} + A \right) \qquad \Phi = \sqrt{\frac{2}{3}} \ln \mathcal{V}}$$

canonically normalised
volume modulus

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

$\downarrow$

shape & size
of extra dim

LVS: simple holographic picture

Stabilized at exponentially large volume $\langle \mathcal{V} \rangle \sim e^{a_s \langle \tau_s \rangle}$

$$\boxed{V = V_0 e^{-\lambda\Phi/M_P} \left(- \left(\frac{\Phi}{M_P} \right)^{3/2} + A \right) \qquad \Phi = \sqrt{\frac{2}{3}} \ln \mathcal{V}}$$

canonically normalised
volume modulus

AdS vacuum:

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

shape & size of extra dim

LVS: simple holographic picture

Stabilized at exponentially large volume $\langle \mathcal{V} \rangle \sim e^{a_s \langle \tau_s \rangle}$

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

canonically normalised volume modulus

AdS vacuum:

$$V_{\min} = -3 M_P^2 R_{AdS}^{-2} \qquad m_\Phi = \sqrt{\frac{3}{2}} \frac{\lambda}{R_{AdS}}$$

The Large Volume Scenario

Concrete setting: Low energy dynamics of moduli in ST

shape & size of extra dim

LVS: simple holographic picture

Stabilized at exponentially large volume $\langle \mathcal{V} \rangle \sim e^{a_s \langle \tau_s \rangle}$

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

canonically normalised volume modulus

AdS vacuum:

$$V_{\min} = -3 M_P^2 R_{AdS}^{-2} \qquad m_\Phi = \sqrt{\frac{3}{2}} \frac{\lambda}{R_{AdS}}$$

[Balasubramanian,Berglund,Conlon,Quevedo '05]

[Conlon,Quevedo,Suruliz '05]

Holographic reformulation

Holographic reformulation

4d moduli EFT in AdS

Holographic reformulation

4d moduli EFT in AdS

Putative 3d CFT dual

Holographic reformulation

4d moduli EFT in AdS

Putative 3d CFT dual

Holographic reformulation

AdS/CFT

4d moduli EFT in AdS

Putative 3d CFT dual

Holographic reformulation

AdS/CFT

4d moduli EFT in AdS

Putative 3d CFT dual

Crucial property of LVS:

$$m_\phi << m_{3/2} \text{ as } \mathcal{V} \to \infty$$

Holographic reformulation

AdS/CFT

4d moduli EFT in AdS

Crucial property of LVS:

$$m_\phi << m_{3/2} \text{ as } \mathcal{V} \to \infty$$

Putative 3d CFT dual

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

Holographic reformulation

AdS/CFT

4d moduli EFT in AdS

Crucial property of LVS:

$$m_\phi << m_{3/2} \text{ as } \mathcal{V} \to \infty$$

$+$

Putative 3d CFT dual

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

Holographic reformulation

AdS/CFT

4d moduli EFT in AdS

Crucial property of LVS:

$m_\phi << m_{3/2}$ as $\mathcal{V} \to \infty$

$+$

Putative 3d CFT dual

$$m^2 R^2_{AdS} = \Delta(\Delta - 3)$$

Small number of low lying operators:

Holographic reformulation

AdS/CFT

4d moduli EFT in AdS

Crucial property of LVS:

$$m_\phi << m_{3/2} \text{ as } \mathcal{V} \to \infty$$

+

Putative 3d CFT dual

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

Small number of low lying operators:

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

Holographic reformulation

AdS/CFT

4d moduli EFT in AdS

Crucial property of LVS:

$m_\phi << m_{3/2}$ as $\mathcal{V} \to \infty$

$+$

Putative 3d CFT dual

$m^2 R^2_{AdS} = \Delta(\Delta - 3)$

Small number of low lying operators:

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

[Conlon,Quevedo '18]

LVS Effective Lagrangian

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term

$$\mathcal{L} \supset \frac{3}{4} e^{-\sqrt{\frac{8}{3}}\frac{\Phi}{M_P}} \partial_\mu a \partial^\mu a$$

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term

$$\mathcal{L} \supset \frac{3}{4}e^{+\sqrt{\frac{8}{3}}\frac{\Phi}{M_P}}\partial_\mu a\partial^\mu a$$

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term

$$\mathcal{L} \supset \frac{3}{4} e^{+\sqrt{\frac{8}{3}}\frac{\Phi}{M_P}} \partial_\mu a \partial^\mu a$$

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term

$$\mathcal{L} \supset \frac{3}{4} e^{+\sqrt{\frac{8}{3}}\frac{\Phi}{M_P}} \partial_\mu a \partial^\mu a$$

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term →

$$\mathcal{L} \supset \frac{3}{4} e^{+\sqrt{\frac{8}{3}}\frac{\Phi}{M_P}} \partial_\mu a \partial^\mu a$$

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term → Divergent f_a as $\mathcal{V}\to\infty$

$$\mathcal{L}\supset\frac{3}{4}e^{+\sqrt{\frac{8}{3}}\frac{\Phi}{M_P}}\partial_\mu a\partial^\mu a$$

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term → Divergent f_a as $\mathcal{V} \to \infty$

$$\mathcal{L} \supset \frac{3}{4} e^{+\sqrt{\frac{8}{3}}\frac{\Phi}{M_P}} \partial_\mu a \partial^\mu a$$

LVS Effective Lagrangian

All interactions fixed in term of R_{AdS} only-
uniquely determined theory in large $\mathcal{V}$ limit

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

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

Some modifications certainly in the Swampland

Sign flip in axion kinetic term → Divergent f_a as $\mathcal{V}\to\infty$

$$\mathcal{L} \supset \frac{3}{4}e^{+\sqrt{\frac{8}{3}}\frac{\Phi}{M_P}}\partial_\mu a\partial^\mu a$$

What happens to the CFT?

Holographic CFT's

Holographic CFT's

Conformal block expansion

Holographic CFT's

Conformal block expansion

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

Holographic CFT's

Conformal block expansion

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}}C_{22\mathcal{O}}\frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}}C_{22\mathcal{O}}\frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}|x_{34}|^{2\Delta_2}}$$

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}}C_{22\mathcal{O}}\,\frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$

Dimension Δ_1, Δ_2

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}}C_{22\mathcal{O}}\frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$ Dimension Δ_1, Δ_2

OPE:

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}}C_{22\mathcal{O}}\frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$ Dimension Δ_1, Δ_2

OPE: $\mathcal{O}_1 \times \mathcal{O}_2 \supset \mathbb{1},\ \mathcal{O}_1,\ \mathcal{O}_2,\ \left[\mathcal{O}_1\mathcal{O}_2\right]_{n,l}$

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$ Dimension Δ_1, Δ_2

OPE: $\mathcal{O}_1 \times \mathcal{O}_2 \supset \mathbb{1},\ \mathcal{O}_1,\ \mathcal{O}_2,\ [\mathcal{O}_1\mathcal{O}_2]_{n,l}$

Double trace operators: $[\mathcal{O}_1\mathcal{O}_2]_{n,l} \sim \mathcal{O}_1 \Box^n \partial_{\mu_1}\partial_{\mu_2}\ldots\partial_{\mu_l}\mathcal{O}_2$

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$ Dimension Δ_1, Δ_2

OPE: $\mathcal{O}_1 \times \mathcal{O}_2 \supset \mathbb{1},\ \mathcal{O}_1,\ \mathcal{O}_2,\ [\mathcal{O}_1\mathcal{O}_2]_{n,l}$

Double trace operators: $[\mathcal{O}_1\mathcal{O}_2]_{n,l} \sim \mathcal{O}_1 \Box^n \partial_{\mu_1}\partial_{\mu_2}\ldots\partial_{\mu_l}\mathcal{O}_2$

$$\Delta = \Delta_1 + \Delta_2 + 2n + \ell$$

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$ Dimension Δ_1, Δ_2

OPE: $\mathcal{O}_1 \times \mathcal{O}_2 \supset \mathbb{1},\ \mathcal{O}_1,\ \mathcal{O}_2,\ [\mathcal{O}_1\mathcal{O}_2]_{n,l}$

Double trace operators: $[\mathcal{O}_1\mathcal{O}_2]_{n,l} \sim \mathcal{O}_1 \Box^n \partial_{\mu_1}\partial_{\mu_2}\ldots\partial_{\mu_l}\mathcal{O}_2$

$$\Delta = \Delta_1 + \Delta_2 + 2n + \ell + \gamma(n,l)$$

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$ Dimension Δ_1, Δ_2

OPE: $\mathcal{O}_1 \times \mathcal{O}_2 \supset \mathbb{1},\ \mathcal{O}_1,\ \mathcal{O}_2,\ [\mathcal{O}_1\mathcal{O}_2]_{n,l}$

Double trace operators: $[\mathcal{O}_1\mathcal{O}_2]_{n,l} \sim \mathcal{O}_1 \Box^n \partial_{\mu_1}\partial_{\mu_2}\ldots\partial_{\mu_l}\mathcal{O}_2$

$$\Delta = \Delta_1 + \Delta_2 + 2n + \ell + \gamma(n,l) \longrightarrow$$

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$ Dimension Δ_1, Δ_2

OPE: $\mathcal{O}_1 \times \mathcal{O}_2 \supset \mathbb{1},\ \mathcal{O}_1,\ \mathcal{O}_2,\ [\mathcal{O}_1\mathcal{O}_2]_{n,l}$

Double trace operators: $[\mathcal{O}_1\mathcal{O}_2]_{n,l} \sim \mathcal{O}_1 \Box^n \partial_{\mu_1}\partial_{\mu_2}\ldots\partial_{\mu_l}\mathcal{O}_2$

$\Delta = \Delta_1 + \Delta_2 + 2n + \ell + \gamma(n,l) \longrightarrow$ anomalous dimension

Holographic CFT's

Conformal block expansion

conformal blocks

$$\langle \mathcal{O}_1(x_1)\,\mathcal{O}_1(x_2)\,\mathcal{O}_2(x_3)\,\mathcal{O}_2(x_4)\rangle = \sum_{\mathcal{O}} C_{11\mathcal{O}} C_{22\mathcal{O}} \frac{G_{\Delta,\ell}(u,v)}{|x_{12}|^{2\Delta_1}\,|x_{34}|^{2\Delta_2}}$$

OPE coefficients

Single trace primaries $\mathcal{O}_1, \mathcal{O}_2$ Dimension Δ_1, Δ_2

OPE: $\mathcal{O}_1 \times \mathcal{O}_2 \supset \mathbb{1},\ \mathcal{O}_1,\ \mathcal{O}_2,\ [\mathcal{O}_1\mathcal{O}_2]_{n,l}$

Double trace operators: $[\mathcal{O}_1\mathcal{O}_2]_{n,l} \sim \mathcal{O}_1 \Box^n \partial_{\mu_1}\partial_{\mu_2}\ldots\partial_{\mu_l}\mathcal{O}_2$

$\Delta = \Delta_1 + \Delta_2 + 2n + \ell + \gamma(n,l)$ ⟶ anomalous dimension

CFT positivity bounds

CFT positivity bounds

Twist $\tau = \Delta - \ell$

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1}$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1} \longrightarrow$$

[Komargodski, Zhiboedov ’12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov ’16]

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1} \longrightarrow$$

$\gamma(0,\ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

[Komargodski, Zhiboedov ’12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov ’16]

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1} \longrightarrow$$

$\gamma(0,\ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1} \longrightarrow$$

$\gamma(0,\ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

Causality arguments
in the CFT:

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1} \longrightarrow$$

$\gamma(0,\ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

Causality arguments in the CFT:

$$\gamma(0,2) \leq 0$$

[Hartman, Jain, Kundu '16]

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1} \longrightarrow$$

$\gamma(0, \ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

Causality arguments in the CFT:

$$\gamma(0, 2) \leq 0$$

[Hartman, Jain, Kundu '16]

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1}$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

$\gamma(0,\ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

Causality arguments in the CFT:

$$\gamma(0,2) \leq 0$$

[Hartman, Jain, Kundu '16]

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1}$$

→ $\gamma(0, \ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

Causality arguments in the CFT:

$$\gamma(0, 2) \leq 0$$

[Hartman, Jain, Kundu '16]

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \le \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1}$$

$\gamma(0,\ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

Causality arguments in the CFT:

$$\gamma(0,2) \leq 0$$

[Hartman, Jain, Kundu '16]

$$\mathcal{L} = \frac{g}{\Lambda^4}(\nabla\varphi)^4 \qquad g > 0$$

on AdS

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1} \longrightarrow$$

$\gamma(0,\ell)$ for identical operators

convex & negative for $\ell \geq \ell_c$

$$\ell_c \geq 2$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

Causality arguments in the CFT:

$$\gamma(0,2) \leq 0$$

[Hartman, Jain, Kundu '16]

$$\longrightarrow \quad \mathcal{L} = \frac{g}{\Lambda^4}(\nabla\varphi)^4 \qquad g > 0$$

on AdS

Generalization of flat space S-matrix bounds

[Adams,Arkani-Hamed,Dubovsky, Nicolis,Rattazzi '06]

Can we apply them?

Can we apply them?

<u>Contact diagrams:</u>

Can we apply them?

Contact diagrams:

Finite support in the spin

Can we apply them?

Contact diagrams:

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

Can we apply them?

Contact diagrams:

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

Can we apply them?

Contact diagrams:

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

Can we apply them?

<u>Contact diagrams:</u>

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin '12]

Can we apply them?

<u>Contact diagrams:</u>

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin '12]

Can we apply them?

Contact diagrams:

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin '12]

VS

Can we apply them?

Contact diagrams:

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin '12]

VS

Exchange diagrams:

Can we apply them?

<u>Contact diagrams:</u>

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin '12]

VS

<u>Exchange diagrams:</u>

Arbitrary large spin

Can we apply them?

<u>Contact diagrams:</u>

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin '12]

VS

<u>Exchange diagrams:</u>

Arbitrary large spin

BUT

Can we apply them?

Contact diagrams:

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin '12]

VS

Exchange diagrams:

Arbitrary large spin

BUT

Manifestly negative

$$\gamma(0,\ell) \propto -\lambda^2$$

Can we apply them?

<u>Contact diagrams:</u>

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully '05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin '12]

VS

<u>Exchange diagrams:</u>

Arbitrary large spin

BUT

Manifestly negative

$$\gamma(0,\ell) \propto -\lambda^2$$

Can we apply them?

Contact diagrams:

Finite support in the spin

$$\ell \leq \frac{\#\partial}{2}$$

[Heemskerk,Penedones, Polchinski,Sully ’05]

also because

$$\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$$

[Fitzpatrick,Katz,Poland, Simmons-Duffin ’12]

VS

Exchange diagrams:

Arbitrary large spin

BUT

Manifestly negative

$$\gamma(0,\ell) \propto -\lambda^2$$

Not quite...

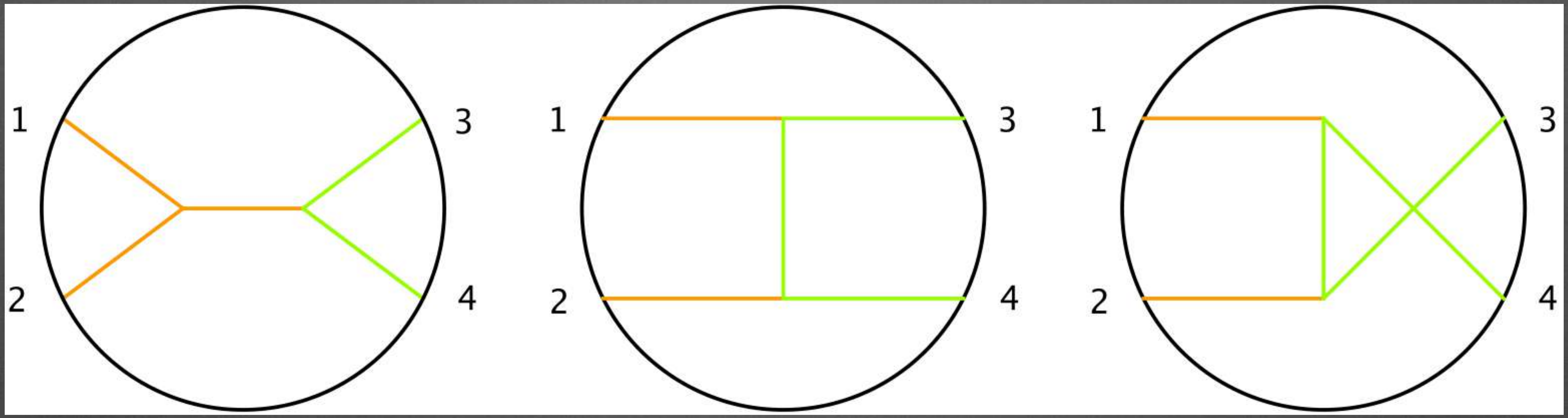
Mixed anomalous dimensions

Mixed anomalous dimensions

Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions

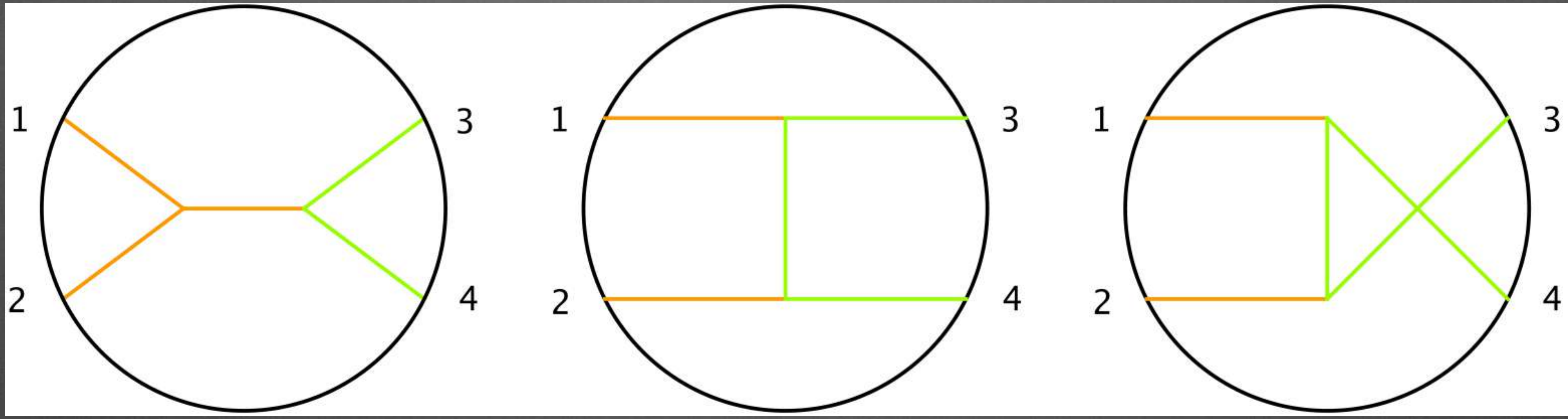
Mixed anomalous dimensions

Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions



Mixed anomalous dimensions

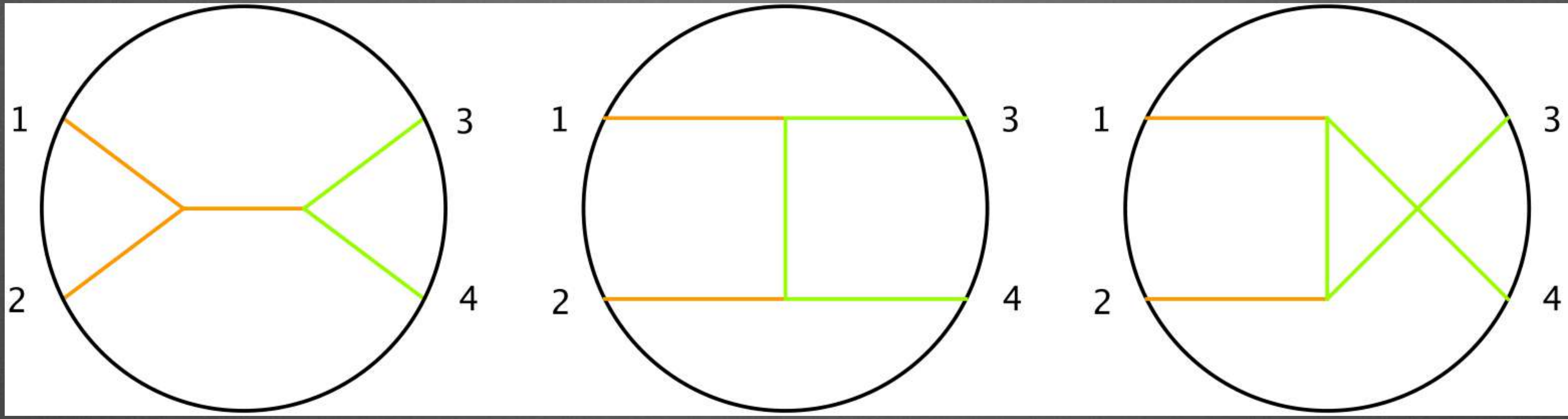
Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions



$$\gamma(0,\ell) \underset{\ell>>1}{\simeq} -\int_{-i\infty}^{+i\infty} \frac{ds}{2\pi i} M(s,0)\, \Gamma\left(\frac{s}{2}\right)^2 \frac{\Gamma(\Delta_1)\Gamma(\Delta_2)}{\ell^s}$$

Mixed anomalous dimensions

Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions

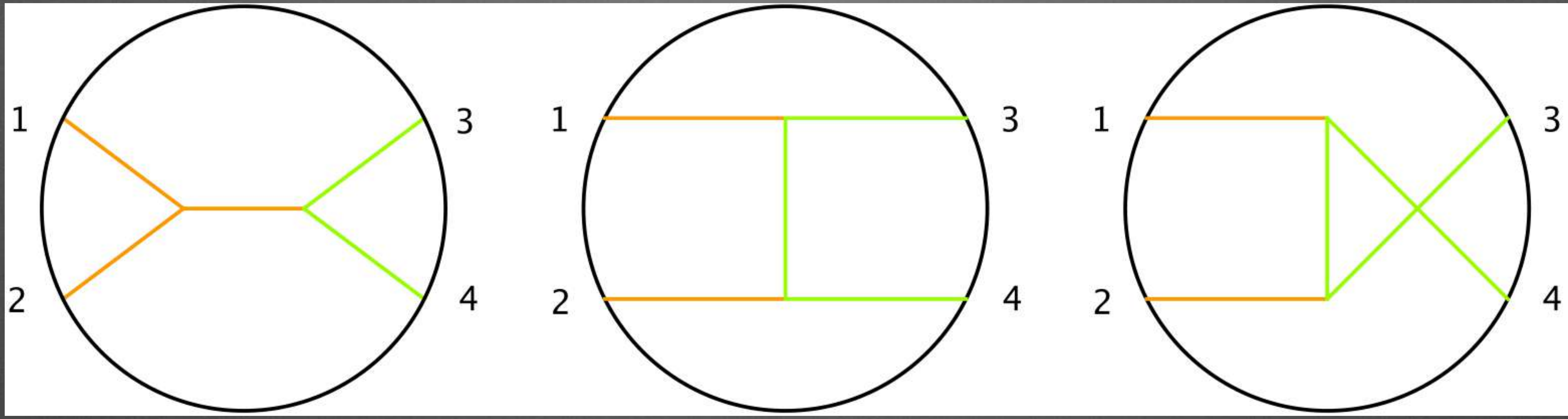


$$\gamma(0,\ell) \underset{\ell>>1}{\simeq} -\int_{-i\infty}^{+i\infty} \frac{ds}{2\pi i} M(s,0)\, \Gamma\left(\frac{s}{2}\right)^2 \frac{\Gamma(\Delta_1)\Gamma(\Delta_2)}{\ell^s}$$

[Costa,Goncalves,Penedones ’12]

Mixed anomalous dimensions

Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions

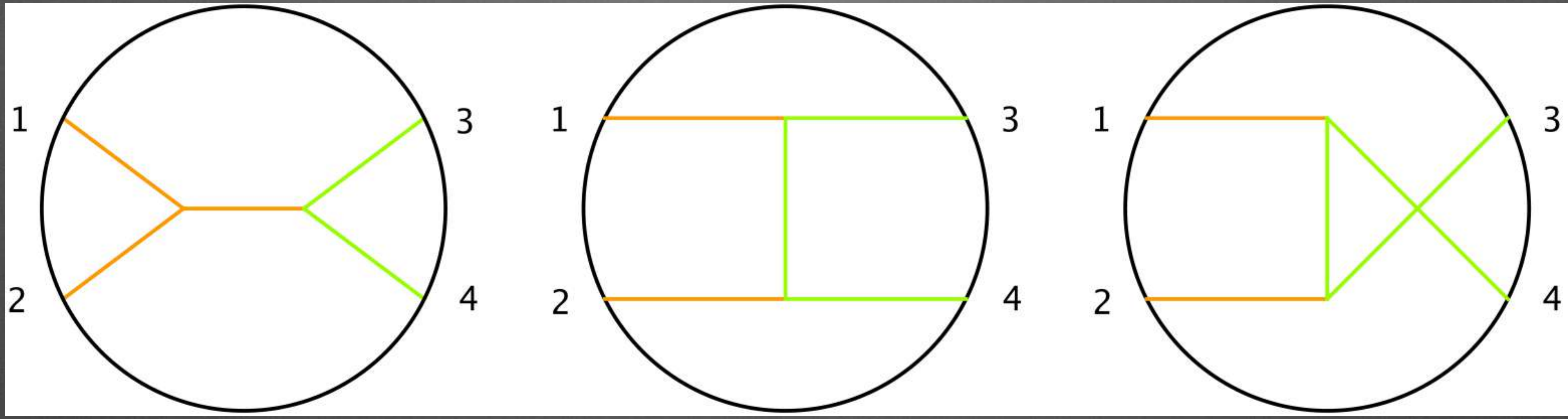


$$\gamma(0,\ell) \underset{\ell>>1}{\simeq} -\int_{-i\infty}^{+i\infty} \frac{ds}{2\pi i} M(s,0)\, \Gamma\left(\frac{s}{2}\right)^2 \frac{\Gamma(\Delta_1)\Gamma(\Delta_2)}{\ell^s}$$

[Costa,Goncalves,Penedones '12]

Mixed anomalous dimensions

Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions

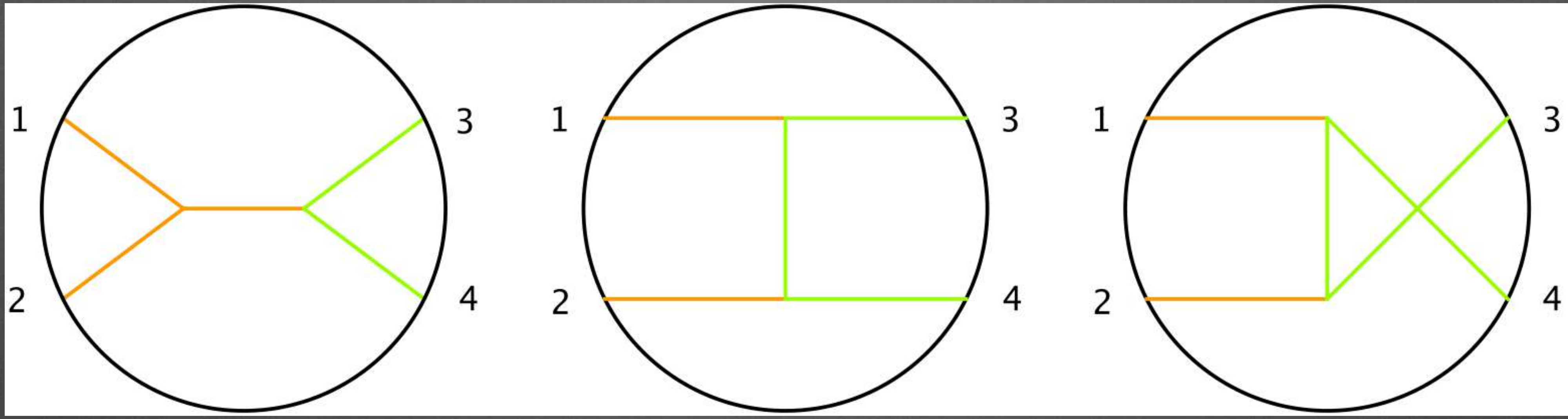


$$\gamma(0,\ell) \underset{\ell>>1}{\simeq} -\int_{-i\infty}^{+i\infty} \frac{ds}{2\pi i} M(s,0)\, \Gamma\left(\frac{s}{2}\right)^2 \frac{\Gamma(\Delta_1)\Gamma(\Delta_2)}{\ell^s}$$

[Costa,Goncalves,Penedones '12]

Mixed anomalous dimensions

Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions



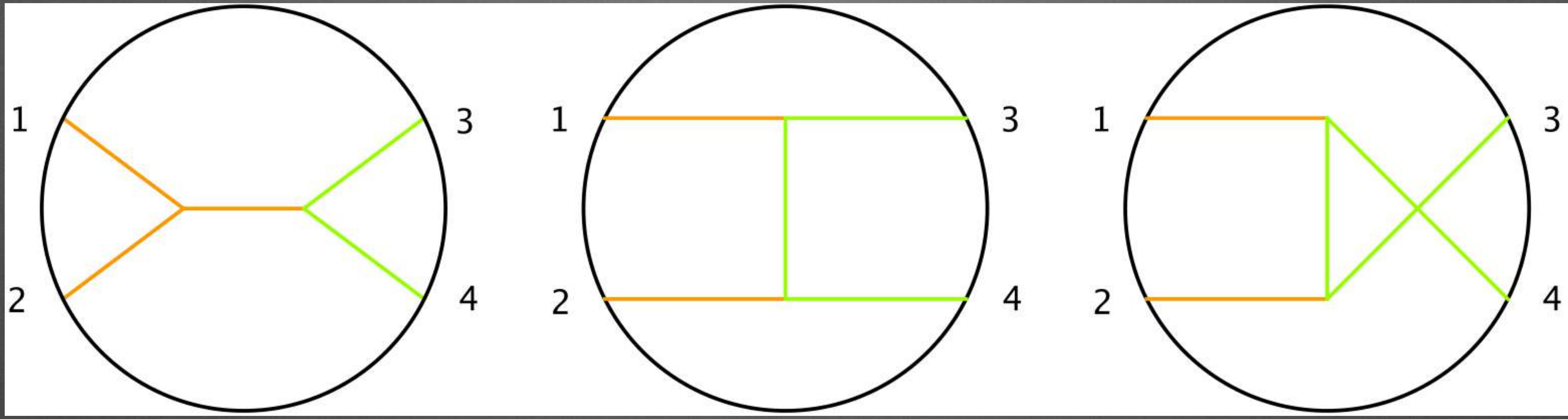
$$\gamma(0,\ell) \underset{\ell>>1}{\simeq} -\int_{-i\infty}^{+i\infty} \frac{ds}{2\pi i} M(s,0)\, \Gamma\left(\frac{s}{2}\right)^2 \frac{\Gamma(\Delta_1)\Gamma(\Delta_2)}{\ell^s}$$

[Costa,Goncalves,Penedones '12]

Lowest lying pole in s-channel dominates the integral

Mixed anomalous dimensions

Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions



$$\gamma(0,\ell) \underset{\ell>>1}{\simeq} -\int_{-i\infty}^{+i\infty} \frac{ds}{2\pi i} M(s,0)\, \Gamma\left(\frac{s}{2}\right)^2 \frac{\Gamma(\Delta_1)\Gamma(\Delta_2)}{\ell^s}$$

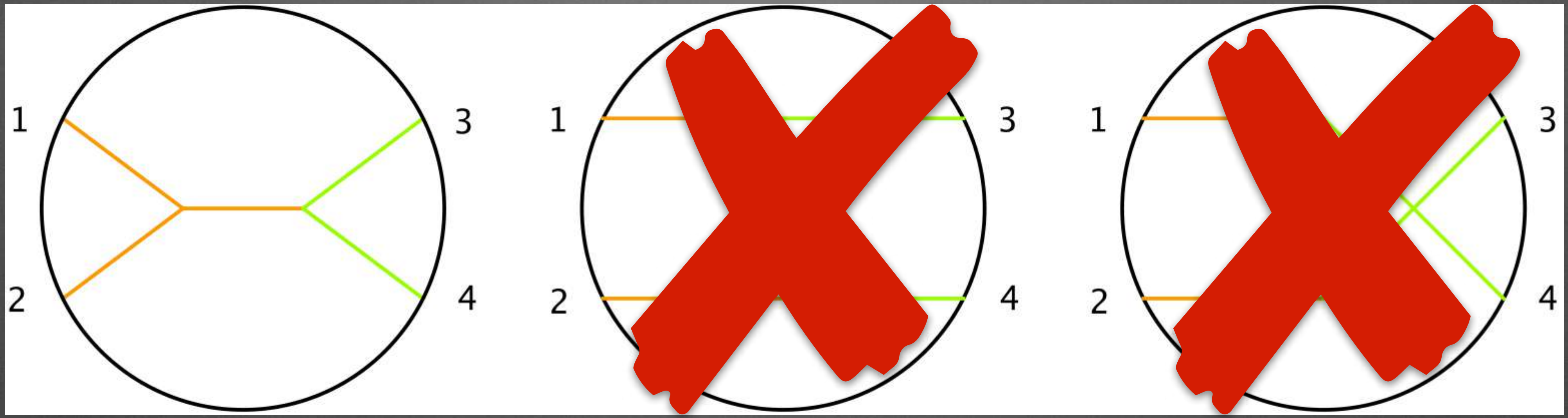
[Costa,Goncalves,Penedones '12]

Lowest lying pole in s-channel dominates the integral

$$M(s,t) \simeq \sum_{m=0}^{\infty} \frac{\mathcal{Q}_{\ell,m}(t)}{s-\Delta+\ell-2m} + P_{\ell-1}(t) + s \leftrightarrow t + s \leftrightarrow u$$

Mixed anomalous dimensions

Claim: $\gamma^{\varphi a}(0,\ell)$ correlates with swampland conditions



$$\gamma(0,\ell) \underset{\ell>>1}{\simeq} -\int_{-i\infty}^{+i\infty} \frac{ds}{2\pi i} M(s,0)\,\Gamma\left(\frac{s}{2}\right)^2 \frac{\Gamma(\Delta_1)\Gamma(\Delta_2)}{\ell^s}$$

[Costa,Goncalves,Penedones '12]

Lowest lying pole in s-channel dominates the integral

$$M(s,t) \simeq \sum_{m=0}^{\infty} \frac{\mathcal{Q}_{\ell,m}(t)}{s-\Delta+\ell-2m} + P_{\ell-1}(t) + s \leftrightarrow t + s \leftrightarrow u$$

Consequences for LVS

Consequences for LVS

$$\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}$$

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}}\frac{1}{M_P^2 R_{AdS}^2}}$$

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}}\frac{1}{M_P^2 R_{AdS}^2}}$$

Consequences for LVS

$$\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}$$

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}}$$

decouples higher order contributions at large volume

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

Consequences for LVS

$$\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

Sign flip in $g\mu$

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

Sign flip in $g\mu$ $\longleftrightarrow$

Consequences for LVS

$$\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

Sign flip in $g\mu$ $\longleftrightarrow$ $f_a \sim M_P \mathcal{V}^{\frac{2}{3}}$

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

Sign flip in $g\mu$ $\longleftrightarrow$ $f_a \sim M_P \mathcal{V}^{\frac{2}{3}}$

$\lambda \leq \sqrt{6} \quad (\Delta_\varphi \leq 6)$

Consequences for LVS

$$\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}}\frac{1}{M_P^2 R_{AdS}^2}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

Sign flip in $g\mu$ $\longleftrightarrow$ $f_a \sim M_P \mathcal{V}^{\frac{2}{3}}$

$\lambda \leq \sqrt{6} \quad (\Delta_\varphi \leq 6)$ $\longleftrightarrow$

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

Sign flip in $g\mu$ $\longleftrightarrow$ $f_a \sim M_P \mathcal{V}^{\frac{2}{3}}$

$\lambda \leq \sqrt{6} \quad (\Delta_\varphi \leq 6)$ $\longleftrightarrow$ $V \gtrsim M_S^4$

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

$$\left.\begin{array}{lcl} \text{Sign flip in } g\mu & \longleftrightarrow & f_a \sim M_P \mathcal{V}^{\frac{2}{3}} \\ \lambda \leq \sqrt{6} \quad (\Delta_\varphi \leq 6) & \longleftrightarrow & V \gtrsim M_S^4 \end{array}\right\}$$

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}} \frac{1}{M_P^2 R_{AdS}^2}}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

$$\left.\begin{array}{lcl} \text{Sign flip in } g\mu & \longleftrightarrow & f_a \sim M_P \mathcal{V}^{\frac{2}{3}} \\ \lambda \leq \sqrt{6} \quad (\Delta_\varphi \leq 6) & \longleftrightarrow & V \gtrsim M_S^4 \end{array}\right\}$$

Swampland

Consequences for LVS

$$\boxed{\gamma^{\varphi a}(0,\ell) \propto -\frac{g\mu(\Delta_\varphi - 6)}{\ell^{\Delta_\varphi}}\frac{1}{M_P^2 R_{AdS}^2}}$$

decouples higher order contributions at large volume

With the couplings in LVS $\gamma^{\varphi a}(0,\ell) < 0$, but the following modifications invert the sign :

$$\left.\begin{array}{lcl} \text{Sign flip in } g\mu & \longleftrightarrow & f_a \sim M_P \mathcal{V}^{\frac{2}{3}} \\ \lambda \leq \sqrt{6} \quad (\Delta_\varphi \leq 6) & \longleftrightarrow & V \gtrsim M_S^4 \end{array}\right\} \text{Swampland}$$

<u>Still neglecting pure gravity contribution:</u> $\gamma^{\varphi a}(0,\ell) \sim \ell^{-(d-2)}$

KKLT

KKLT

Well known example of dS vacuum - we consider it before uplifting

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$$\sigma_c a >> 1$$

$$\sigma >> 1$$

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a $\longrightarrow$

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a $\longrightarrow$ $\Delta_a > 3$

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a $\longrightarrow$ $\Delta_a > 3$

$$\mathcal{L} \supset \sigma^3, \sigma a^2, \sigma\partial_\mu a \partial^\mu a$$

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a $\longrightarrow$ $\Delta_a > 3$

$$\mathcal{L} \supset \sigma^3, \sigma a^2, \sigma\partial_\mu a \partial^\mu a$$

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a $\longrightarrow$ $\Delta_a > 3$

$\mathcal{L} \supset \sigma^3, \sigma a^2, \sigma\partial_\mu a\partial^\mu a$

$\Big\}$ qualitatively different

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a $\longrightarrow$ $\Delta_a > 3$

$\mathcal{L} \supset \sigma^3, \sigma a^2, \sigma\partial_\mu a \partial^\mu a$

$\Big\}$ qualitatively different

Negative anomalous dimensions in its regime of validity

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi ’03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a $\longrightarrow$ $\Delta_a > 3$

$\mathcal{L} \supset \sigma^3, \sigma a^2, \sigma\partial_\mu a \partial^\mu a$

qualitatively different

Negative anomalous dimensions in its regime of validity

KKLT

Well known example of dS vacuum - we consider it before uplifting

$$\mathcal{K} = -3\log(-i(T-\bar{T})) \qquad \mathcal{W} = W_0 + Ae^{-\alpha T}$$

[Kachru,Kallosh, Linde,Trivedi '03]

SUSY vacuum

$$\frac{W_0}{A} = -e^{-a\sigma_c}(1+\frac{2}{3}a\sigma_c)$$

$\sigma_c a >> 1$

$\sigma >> 1$

Potential for a $\longrightarrow$ $\Delta_a > 3$

$\mathcal{L} \supset \sigma^3, \sigma a^2, \sigma\partial_\mu a \partial^\mu a$

qualitatively different

Negative anomalous dimensions in its regime of validity

$$\gamma^{\sigma a}(0,\ell) \propto -\Big[a\sigma_c(a\sigma_c+2)(2a\sigma_c+3) + 2\Delta_\varphi(a\sigma_c) - 2\Delta_a^2(a\sigma_c) + 4\Delta_a(a\sigma_c) - 6\Big]$$

Concluding remarks

Concluding remarks

Hard to connect with CFT inconsistencies

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δs'…)

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'…)
- Gravity is often a problem

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'…)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'…)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δs'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Clear from both CFT and S-matrix bounds

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

<u>Clear from both CFT and S-matrix bounds</u>

However, interesting correlation with sign of $\gamma^{\text{mix}}(0,\ell)$

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Clear from both CFT and S-matrix bounds

However, interesting correlation with sign of $\gamma^{\text{mix}}(0,\ell)$

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Clear from both CFT and S-matrix bounds

However, interesting correlation with sign of $\gamma^{\text{mix}}(0, \ell)$

very similar to
unitarity constraints

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Clear from both CFT and S-matrix bounds

However, interesting correlation with sign of $\gamma^{\mathrm{mix}}(0,\ell)$

very similar to
unitarity constraints

Various applications:

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Clear from both CFT and S-matrix bounds

However, interesting correlation with sign of $\gamma^{\text{mix}}(0,\ell)$

very similar to
unitarity constraints

Various applications:

LVS, KKLT, Racetrack, Perturbative stabilisation

Concluding remarks

Hard to connect with CFT inconsistencies

- Technical obstructions (no CBs in 3D, non integer Δ s'...)
- Gravity is often a problem
- Known constraints on scalar contact interactions for $\#\partial \geq 4$

Clear from both CFT and S-matrix bounds

However, interesting correlation with sign of $\gamma^{\mathrm{mix}}(0,\ell)$

very similar to
unitarity constraints

Various applications:

LVS, KKLT, Racetrack, Perturbative stabilisation

Connection with other swampland conjectures? (e.g distance)

Thank you for your attention!

Back-up slides

Moduli stabilisation

Scalar fields parametrising shape and size of extra dimensions in ST

BSM Perspective: Planck Scale suppressed couplings

$$\frac{\varphi}{M_{PL}} F^{\mu\nu} F_{\mu\nu}$$

Potential "fifth forces"

Cosmological Moduli Problem
unless $m \gtrsim \mathcal{O}(10 - 100)\,\mathrm{TeV}$

Requires a potential - many constructions in literature

<u>These are the lagrangians we wish to constrain</u>

Specific realisation: LVS [Balasubramanian,Berglund,Conlon,Quevedo '05]
[Conlon,Quevedo,Suruliz '05]

The Large Volume Scenario

"Big" and "small" Kähler moduli T_b, T_s

$$\mathcal{V} = \frac{1}{\kappa}\left(\tau_b^{3/2} - \tau_s^{3/2}\right)$$

$$K = -2\ln\left(\frac{1}{\kappa}\left(\left(\frac{T_b+\bar{T}_b}{2}\right)^{3/2} - \left(\frac{T_s+\bar{T}_s}{2}\right)^{3/2}\right) + \frac{\xi}{g_s^{3/2}}\right)$$

$$W = W_0 + A_s e^{-a_s T_s}$$

α'^3 correction

Minimum for an exponentially large volume $\langle\mathcal{V}\rangle \sim e^{a_s\langle\tau_s\rangle}$

$$V_{eff} = \frac{1}{\mathcal{V}^3}\left(-A(\ln\mathcal{V})^{3/2} + \frac{B}{g_s^{3/2}}\right) \qquad \langle\tau_s\rangle \sim \frac{\zeta^{2/3}}{g_s}$$

CFT positivity bounds

Twist $\tau = \Delta - \ell$

Minimal twist operators dominate Lorentzian OPE

Deep Inelastic Scattering gedanken experiments:

$$\frac{\tau^*_{\ell_3} - \tau^*_{\ell_1}}{\ell_3 - \ell_1} \leq \frac{\tau^*_{\ell_2} - \tau^*_{\ell_1}}{\ell_2 - \ell_1}$$

$$C^{\mathcal{O}_{\tau^*}}_{\mathcal{O}\mathcal{O}}(\ell, m_1) C^{\mathcal{O}_{\tau^*}}_{\mathcal{O}\mathcal{O}}(\ell, m_2) \geq 0$$

$$\ell \geq \ell_c \geq 2$$

$$C^{\mathcal{O}_{\tau^*}}_{\mathcal{O}\mathcal{O}}(2, m) \geq 0$$

[Komargodski, Zhiboedov '12]

[Komargodski, Kulaxizi, Parnachev, Zhiboedov '16]

Causality arguments in the CFT:

$$\gamma(0,2) \leq 0$$

[Hartman, Jain, Kundu '16]

$$\mathcal{L} = \frac{g}{\Lambda^4}(\nabla\varphi)^4 \quad g > 0$$

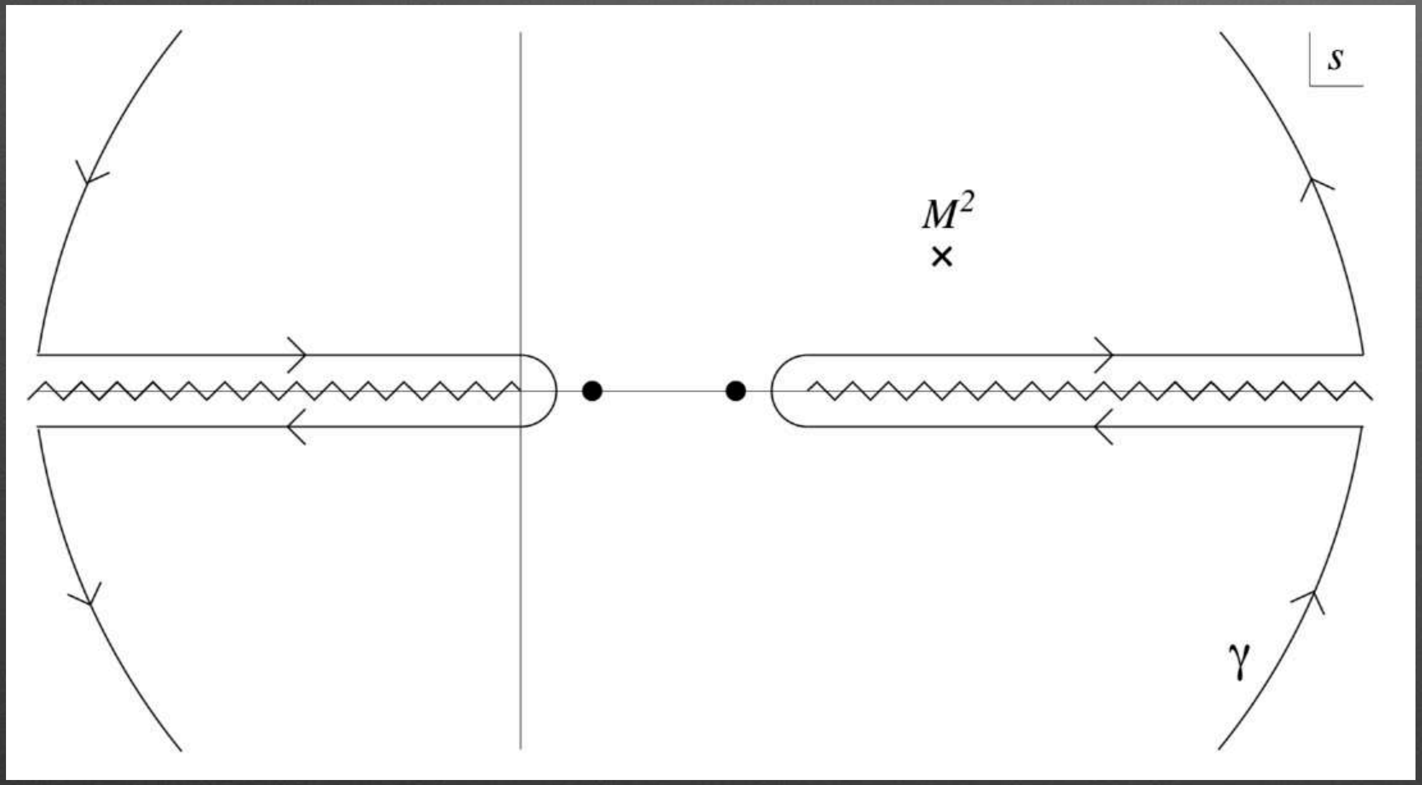
on AdS

S-Matrix positivity

unitarity + analiticity + weak coupling expansion

$$\mathcal{A}(s)_{tree} = g(c_2 s^2 + c_4 s^4 \ldots)$$

$g\, c_i > 0$



E.g.

$$\mathcal{L} = \frac{g}{\Lambda^4}(\partial\varphi)^4 \qquad g > 0$$

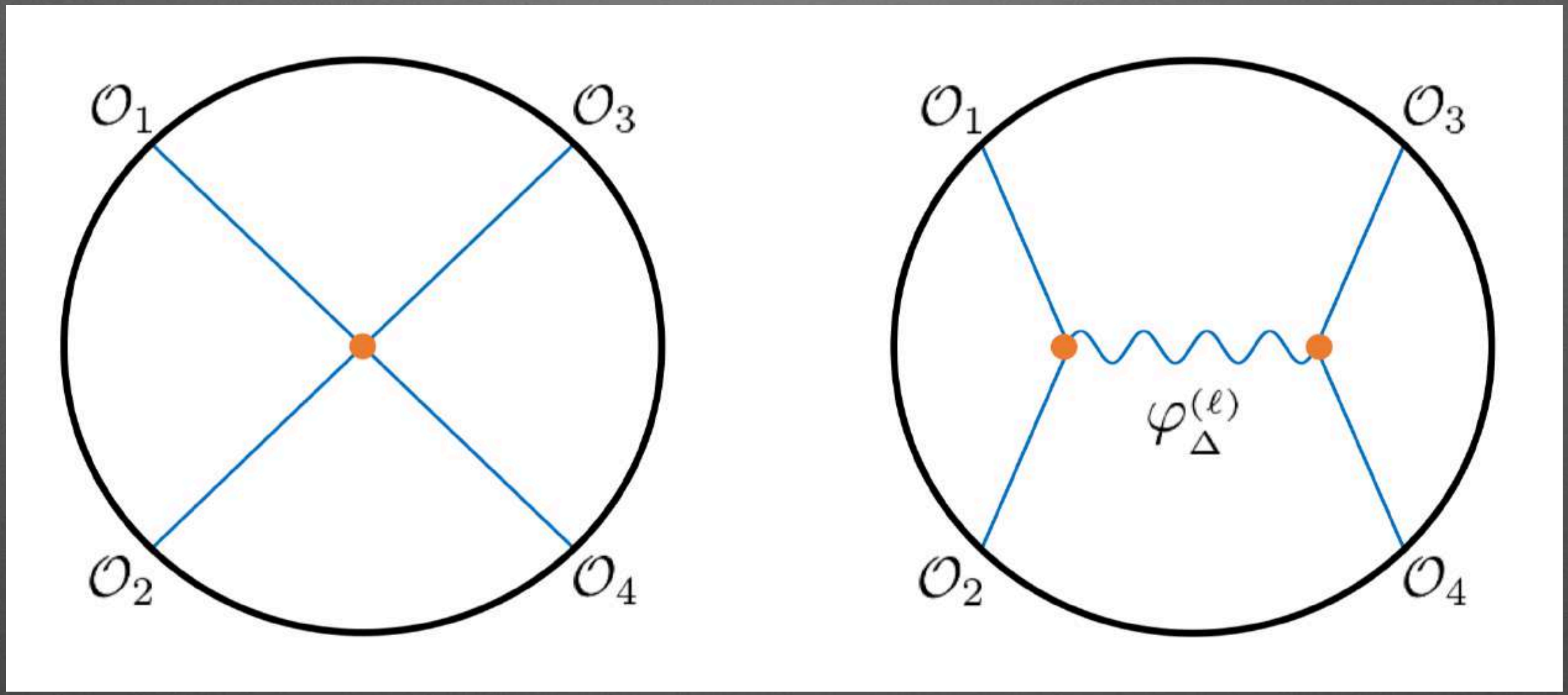
" QFT Swampland"

CAVEAT: $\mathcal{A}_{grav}(s,t) \supset \frac{1}{M_{PL}^2}\frac{s^2}{t} \longrightarrow \Lambda << M_{PL}$

[Adams,Arkani-Hamed,Dubovsky,Nicolis,Rattazzi '06]

How do we compute ?

Correlation functions → Witten Diagrams in AdS



Other techniques:

- Bootstrapping correlators (good for exchanges)
  [Zhou '18; Alday,Bissi,Perlmutter '17 + others]
- Eigenvalues of dilatation operator : $\gamma(n,\ell) = \langle n,\ell|\Delta H|n,\ell\rangle$
  [Fitzpatrick,Katz,Poland,Simmons-Duffin '12]
- Mellin amplitude formula for $\gamma(0,\ell)$
  [Costa,Goncalves,Penedones '12]

Mellin Amplitudes (1)

Convenient representation of correlators

$$A(x_i) \supset \langle \mathcal{O}_1(x_1)\ldots\ldots\mathcal{O}_n(x_4)\rangle_c = \prod_{1\le i<j\le n}\int_{-i\infty}^{+i\infty}\frac{\mathrm{d}\delta_{ij}}{2\pi i}M(\delta_{ij})\Gamma(\delta_{ij})\left(x_{ij}^2\right)^{-\delta_{ij}}$$

$$\boxed{e^{-s_i s_j P_{ij}} = \int_{c-i\infty}^{c+i\infty}\frac{d\gamma_{ij}}{2\pi i}\Gamma(\gamma_{ij})(s_i s_j P_{ij})^{-\gamma_{ij}}}$$

→ arises naturally due to Euler star formula

with $\delta_{ii} = -\Delta_i \quad \sum_i \delta_{ij} = 0$

→ n(n-3)/2 independent variables - analogue to n-particle scattering

Can introduce fictions moments s.t.

$$p_i \cdot p_j = \delta_{ij} \quad \sum_{i=1}^{n} p_i = 0 \qquad s_{ij} = -(p_i + p_j)^2 = \Delta_i + \Delta_j - 2\delta_{ij}$$

Mellin Amplitudes (2)

$$\mathcal{A}(u,v) = \int_{-i\infty}^{+i\infty} \frac{dtds}{(4\pi i)^2} M(s,t) u^{s/2} v^{-(s+t)/2} \Gamma\left(\frac{\Delta_1+\Delta_2-s}{2}\right)\Gamma\left(\frac{\Delta_3+\Delta_4-s}{2}\right)$$
$$\Gamma\left(\frac{\Delta_{34}-t}{2}\right)\Gamma\left(\frac{-\Delta_{12}-t}{2}\right)\Gamma\left(\frac{t+s}{2}\right)\Gamma\left(\frac{t+s+\Delta_{12}-\Delta_{34}}{2}\right)$$

Contact interactions:

$$M(s,t) = \frac{g\pi^{\frac{d}{2}}}{2}\Gamma\Big(\frac{\sum\Delta_i - d}{2}\Big)\prod_{i=1}^{n}\frac{1}{\Gamma(\Delta_i)}$$

scalar vertex

$$M(s,t) = \frac{g\pi^{\frac{d}{2}}}{2}\Gamma\Big(\frac{\sum\Delta_i - d}{2}\Big)\prod_{i=1}^{n}\frac{1}{\Gamma(\Delta_i+\beta_i)}\prod_{i<j}^{n}(-2\delta_{ij})^{\alpha_{ij}}$$

derivative vertex

Closest analogue to scattering amplitudes in AdS!

Perturbative stabilisation

$$V_{eff} = Ae^{-\lambda_1\varphi} - Be^{-\lambda_2\varphi} \qquad \varphi_{min} = \frac{1}{\lambda_1-\lambda_2}\log\left(\frac{A\lambda_1}{B\lambda_2}\right)$$

string loops $\sim \mathcal{V}^{-\frac{10}{3}}$

α'^3 correction $\sim \mathcal{V}^{-3}$

typical example

$$\Delta_\varphi = \frac{3}{2}\left(1 \pm \sqrt{1+\frac{4}{3}\lambda_1\lambda_2}\right) \qquad \Delta_a = 3$$

$$\gamma^{\varphi a}(0,\ell) \propto \quad -\mu\lambda_1\lambda_2(\lambda_1+\lambda_2)g(\Delta_\varphi - 6)\frac{1}{M_P^2 R_{AdS}^2}$$

$$\lambda_1\lambda_2 \geq 6?$$

Racetrack

$$\mathcal{K} = -3\log -i(T-\bar{T}) \qquad \mathcal{W} = Ae^{-aT} - Be^{-bT}$$

[Krasnikov '87, Taylor '90,
De Carlos, Casas, Munoz '93]

Potential for a $\longrightarrow$ $\Delta_a > 3$

$\mathcal{L} \supset \sigma^3, \sigma a^2, \sigma\partial_\mu a \partial^\mu a$

similar to KKLT

Negative anomalous dimensions for $\sigma_c \gtrsim \frac{1}{a}, \frac{1}{b}$

$\Delta_a < \Delta_\varphi < 2\Delta_a$ $\longrightarrow$ no need to decouple higher order contributions