Title: Research Talk 4 - A universal pattern at infinite field distance

Speakers:

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A Universal Pattern at Infinite Field Distance

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In collaboration with Etheredge, Heidenreich, McNamara, Rudelius and Ruiz: 2306.16440 and ongoing
Castellano and Ruiz: 23xx.xxxx
Montero: 23xx.xxxx

Strings 2023, Perimeter, July 2023

Given an Effective Field Theory (EFT) coupled to Einstein gravity, what is the cut-off at which semiclassical gravity breaks down and how?

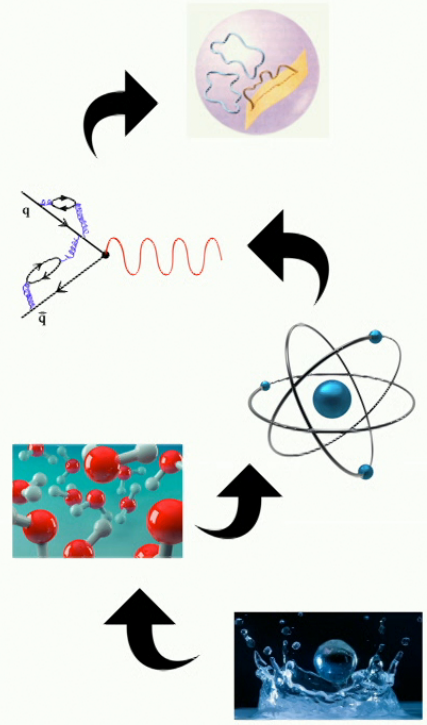
Energy

Is it M_p ?

Quantum Gravity

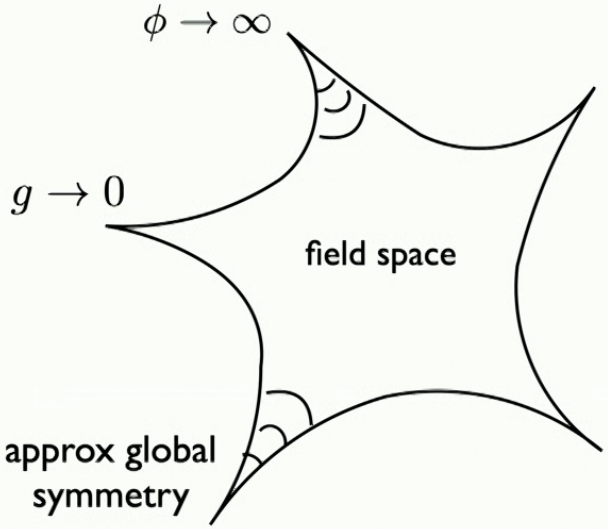
cut-off scale Λ

EFT coupled to classical gravity

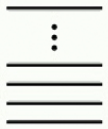


Given an Effective Field Theory (EFT) coupled to Einstein gravity, what is the cut-off at which semiclassical gravity breaks down and how?

String Theory data / Swampland considerations imply a cut-off $\Lambda < M_p$
(at the boundaries of the field space)



The cut-off goes to zero asymptotically:



infinite tower of states → $\Lambda \to 0$

Swampland/quantum gravity constraint:

Distance Conjecture [Ooguri-Vafa'06]

From EFT perspective, these are e.g. weak coupling limits for gauge theories, approximate global symmetry limits, … → $\Lambda \ll M_p$

Outline

1) Review of Distance Conjecture and drop-off of QG cut-off

2) Universal pattern underlying all known string theory examples

   → To sharpen the conjecture and provide a quantitative bound on the mass of the tower

3) Beyond moduli spaces: Implications for accelerated expansion and AdS scale separation

   → Non-perturbative test of DGKT AdS scale separated proposal

Distance Conjecture [Ooguri-Vafa'06]

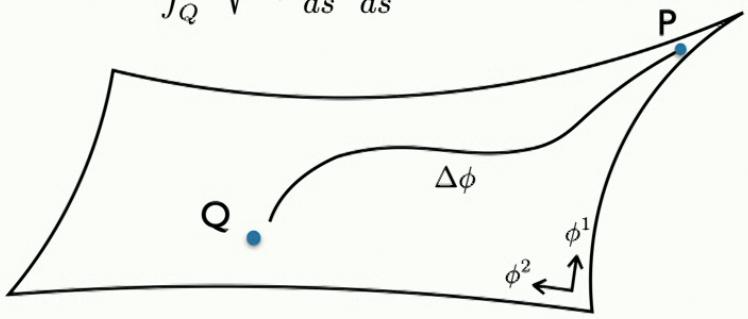
Given an EFT coupled to gravity, with a moduli space parametrized by the vacuum expectation value of some scalar fields:

There is an infinite tower of states becoming exponentially light at every infinite field distance limit of the moduli space

$$m(P) \sim m(Q) e^{-\alpha \Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

$\mathcal{L} = g_{ij}(\phi)\partial\phi^i\partial\phi^j$ → scalar manifold (moduli space)

$$\Delta\phi = \int_Q^P \sqrt{g_{ij}\frac{d\phi^i}{ds}\frac{d\phi^j}{ds}}\,ds \equiv \text{geodesic distance}$$



For example:

- Kaluza-Klein towers as $R \to \infty$
- winding modes as $R \to 0$
- string modes as $g_s \to 0$

Distance Conjecture

The tower signals a drastic breakdown of the effective theory at:

Quantum Gravity (QG) cut-off scale Λ

(above Λ no local field theory description coupled to semiclassical gravity is possible anymore)

Examples:

- The QG cut-off is the Planck scale of the higher dimensional theory in a decompactification limit

$$\Lambda = M_{\mathrm{pl,D}} \ll M_{\mathrm{pl,d}}$$

Distance Conjecture

The tower signals a drastic breakdown of the effective theory at:

Quantum Gravity (QG) cut-off scale Λ

(above Λ no local field theory description coupled to semiclassical gravity is possible anymore)

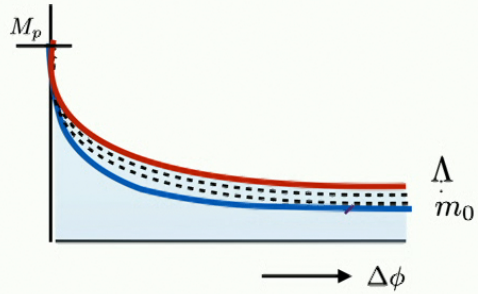
In general, it is also known as the species scale $\Lambda = \dfrac{M_p}{N^{1/d-2}}$ [Arkani-Hamed et al'05] [Dvali'07]

$N = \int^{\Lambda} \rho(m) dm$ (number of single-particle states weakly coupled to gravity)

In the presence of a tower of states $m \sim m_0 \exp(-\alpha \Delta\phi)$:

$$\Lambda \sim M_p \exp(-\lambda \Delta\phi)$$

$$\Delta\phi \lesssim \frac{1}{\lambda} \log\left(\frac{M_p}{\Lambda}\right)$$



Evidence

What general lessons can we extract from this?

❖ **Plethora of works testing the conjecture in string theory compactifications to flat space:**

(M-theory and Heterotic toroidal comp., F-theory and IIB on Calabi-Yau's, M-theory on G2, Type IIA orientifolds, non-SUSY heterotic…)

Álvarez-García, Andriot, Antoniadis, Basile, Baume, Bedroya, Angius, Benakli, Blasio, Blumenhagen, Brandenberger, Huertas, Buratti, Calderón-Infante, Castellano, Cecotti, Collazuol, Collins, Cota, Cremonini, Cribiori, Dalianis, Delgado, Dierigl, Etheredge, Farakos, Fierro Freitas, Gnecci, Gonzalo, Graña, Grimm, Hamada, Heidenreich, Herráez, Horer, Ibáñez, Jafferis, Kehagias, Lanza, Lee, Lerche, Li, Long, Lust, Marchesano, Mavromatos, McNamara, Melotti, Mininno, Montella, Montero, Morittu, Ooguri, Palti, Parra Petri, Bastian, Quirant, Rajaguru, Raman, Reece, Riet, Rudelius, Ruiz, Scalisi, Schlechter, Seo, Shiu, Stout, Tarazi, Tonioni, Tran, Tringas, Uranga, Van de Heisteeg, Vafa, Valenzuela, Weigand, Wiesner, Wrase, Wu, Xu, Yau...

Many interesting connections with mathematics (algebraic geometry, etc.)!

➡ learning a lot about asymptotic geometry of string theory compactifications

❖ AdS_{d+1}/CFT_d All known infinite distance limits in the conformal manifold (for d>2) contain towers of higher spin operators decaying exponentially with the Zamolodchikov distance

➡ CFT Distance Conjecture [Perlmutter, Rastelli, Vafa, IV'21] [Baume, Calderon-Infante'21]

(part of the conjecture recently proven using CFT techniques in [Baume, Calderon-Infante'23])

Wish List

❖ Provide a bottom-up rationale beyond string theory examples

- AdS/CFT [Perlmutter,Rastelli,Vafa,IV'21] [Baume,Calderon-Infante'21-23]
- Quantum Gravity obstruction to restore global symmetries / factorization
- Emergence proposal [Grimm,Palti,IV'18] [Heidenreich et al'18] [Grimm,Palti,IV'18][Gendler,IV'20] [Cordova et al'22][Stout'21]
- Black hole entropy argument for weak coupling limits [Hamada et al'21] [Cribiori et al'22]

❖ Sharpen the conjecture to provide:

- The nature of the tower $m \sim m_0 \exp(-\alpha \Delta\phi) \qquad \alpha \sim \mathcal{O}(1)$
- The minimal possible value for the exponential mass decay rate α
- The quantum gravity theory that emerges at infinite distance above $\Lambda_{\rm QG}$

Does the tower signal extra dimensions? or a tensionless string?

Outline

1) Review of Distance Conjecture and drop-off of QG cut-off

2) Universal pattern underlying all known string theory examples

   → To sharpen the conjecture and provide a quantitative bound on the mass of the tower

3) Beyond moduli spaces: Implications for accelerated expansion and AdS scale separation

   → Non-perturbative test of DGKT AdS scale separated proposal

A Universal Pattern

We found a new universal pattern between the leading tower of states and the quantum gravity cut-off underlying all string theory examples

[Castellano,Ruiz,IV'ongoing]

At every point of the asymptotic regime:

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} \Lambda}{\Lambda} = \frac{1}{d-2}$$

(i.e. $G^{\phi^i \phi^j} \frac{\partial_{\phi^i} m}{m} \frac{\partial_{\phi^j} \Lambda}{\Lambda} = \frac{1}{d-2}$)

$G^{\phi^i \phi^j}$ → metric in field space

mass of the leading (lightest) tower of states

quantum gravity cut-off

$d =$ space-time dimension

In terms of the number of species: " lightest = less dense "

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} N}{N} = -1$$

$$N = \int^{\Lambda} \rho(m) dm \quad \text{with} \quad \Lambda \sim \frac{1}{N^{1/(d-2)}}$$

A Universal Pattern

The pattern implies a sharp lower bound for the exponential rate of the leading tower:

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} \Lambda}{\Lambda} = \frac{1}{d-2}$$

Since $m \leq \Lambda$ ➡ $m \sim m_0 \exp(-\alpha \Delta\phi)$

$$\alpha_{min} = \left| \frac{\vec{\nabla} m}{m} \right| \geq \frac{1}{\sqrt{d-2}}$$

It reproduces the proposed bound in [Etheredge,Heidenreich,Kaya,Qiu,Rudelius'22] which is consistent with the Emergent String proposal of [Lee,Lerche,Weigand'19]

Fixing the $\mathcal{O}(1)$ factors:

➡ Sharp upper bound on asymptotic field range: $\Delta\phi \leq \frac{1}{\alpha_{\min}} \log\left(\frac{M_p}{\Lambda}\right)$

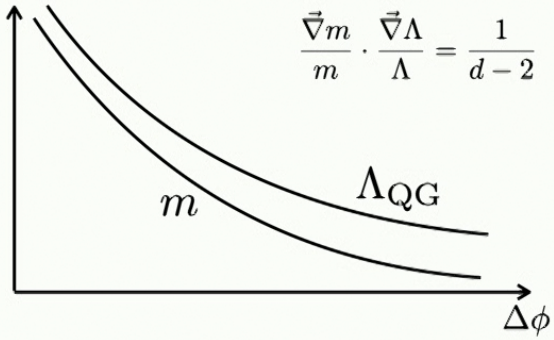
This should surprise you. Why?

Mass of the tower:

$$m \sim m_0 \exp(-\alpha \Delta\phi)$$

Quantum Gravity cut-off:

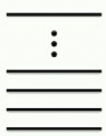
$$\Lambda_{\rm QG} \sim m^\gamma \sim M_p \exp(-\lambda \Delta\phi)$$



1) The structure/density of the towers of states fixes γ

We find that γ is related to the exponential decay rate α

Kaluza-Klein tower



$$m_k = k\, m_{\rm KK}$$

$$\Lambda = M_{p,d+n} \simeq m_{KK}^{1/(d+n-2)}$$

$$\alpha_{\rm KK} = \sqrt{\frac{d+n-2}{n(d-2)}}$$

String tower

This should surprise you. Why?

Mass of the tower:

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Quantum Gravity cut-off:

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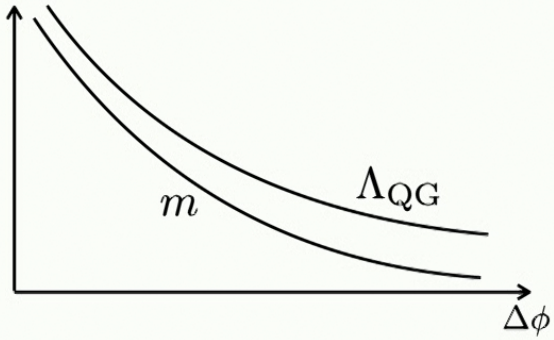
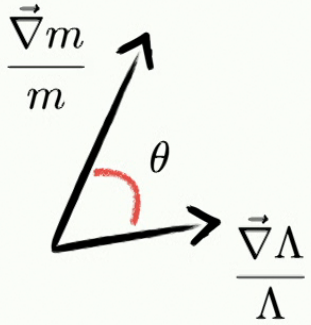


2) Λ is sensitive to all towers becoming light, and not only the leading one

Even though, the pattern is always satisfied!

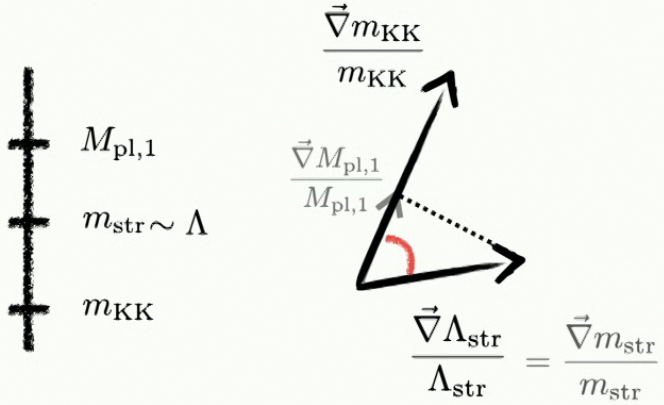
$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} \Lambda}{\Lambda} = \frac{1}{d-2}$$



How??

The angle between them is always such that the pattern gets satisfied

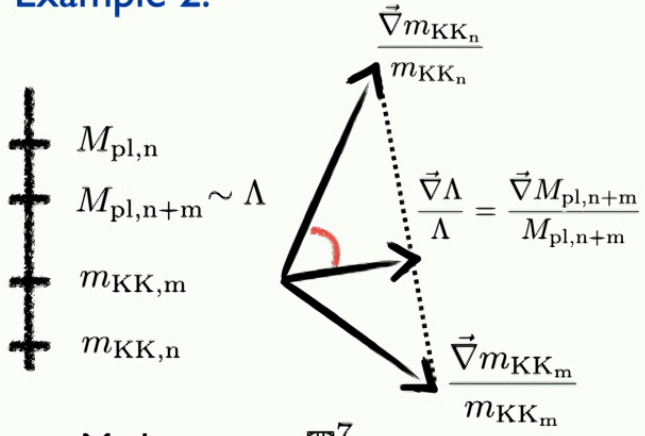
Example 1:



e.g. Type IIB on S^1 , $R\to\infty$, $g_s\to 0$

$$\frac{\vec\nabla m_{\rm KK}}{m_{\rm KK}}\cdot\frac{\vec\nabla\Lambda_{\rm str}}{\Lambda_{\rm str}}=\frac{1}{d-2}$$

Example 2:



e.g. M-theory on $\mathbb{T}^7$

Leading tower: $m_{\rm KK_1}$

Subleading towers: $m_{\rm KK_i}$, $i=2,\dots 5$

$$\frac{\vec\nabla m_{\rm KK_1}}{m_{\rm KK_1}}\cdot\frac{\vec\nabla M_{\rm pl,9}}{M_{\rm pl,9}}=\frac{1}{d-2}$$

Evidence for the Pattern

We check it in string theory examples: See Ignacio Ruiz's poster

- 32 (and 16) supercharges: M-theory on (orientifold) toroidal compactifications
- 8 supercharges: Type II and M-theory Calabi-Yau compactifications
- 4d N=1 theories from heterotic, F-theory, Type II…

It is related to continuity of the exponential rate of the leading tower as we move in moduli space [Castellano,Ruiz,IV'ongoing]

Open question: can we find a bottom-up argument?

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} N}{N} = -1$$

constrains the variation (with the moduli) of the mass and the density of states

Maybe black hole/entropy bounds?

Taxonomy of infinite distance limits

Example: Consider a moduli space with a flat metric

Different asymptotic regimes are characterized by different leading towers of states, but the sum of all of the angles must be:

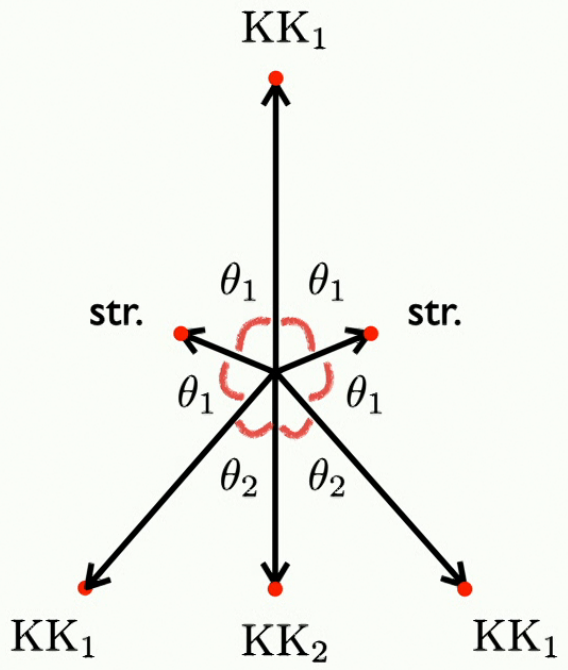
$$\sum \theta_i = 2\pi$$

For a 2-dim moduli space in 9d:

$$\cos\theta = \{\frac{1}{\sqrt{8}}, \frac{1}{8}\}$$

$\cos\theta_1$ $\quad$ $\cos\theta_2$

➡ Unique solution!



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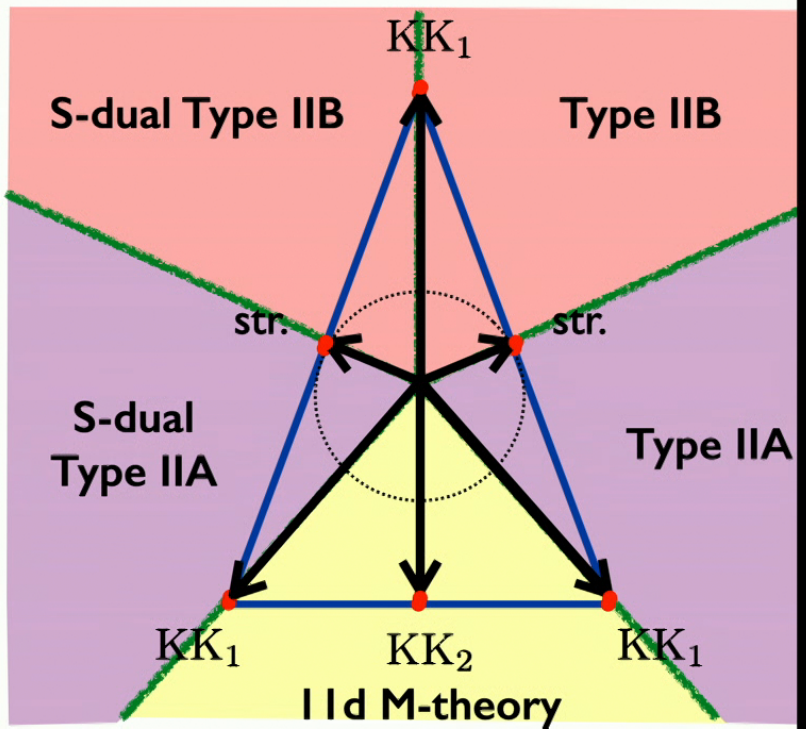
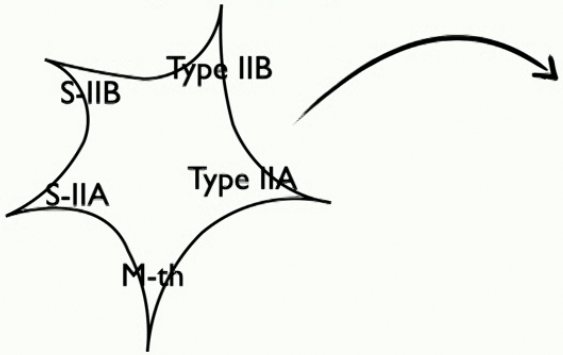
➡ Unique solution!

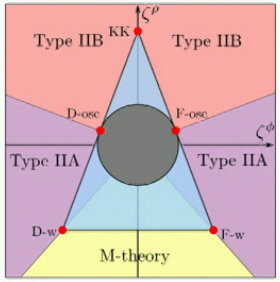
We recover the string theory result!



Taxonomy of infinite distance limits

We can characterize the different dualities of the moduli space in terms of a particular polytope (the convex hull of the towers)

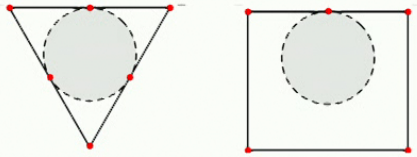




Can we classify all possibilities from bottom-up?

See Muldrow Etheredge's poster

In d=8:



[Etheredge,Heidenreich,McNamara, Rudelius,Ruiz,IV'ongoing]

[Etheredge,Heidenreich,McNamara,Rudelius,Ruiz,IV'23]

For lower SUSY setups: necessary to understand rules of jumping of states

(the convex hull can change as we move in moduli space)

Outline

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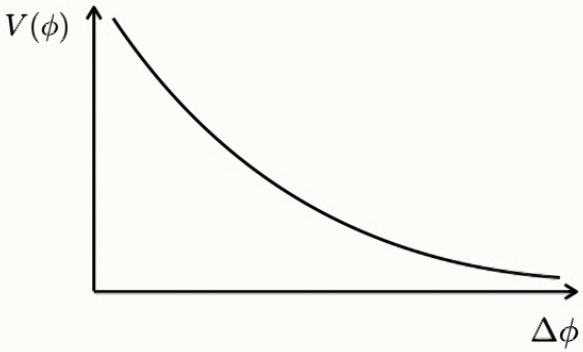
   → Non-perturbative test of DGKT AdS scale separated proposal

Beyond Moduli Spaces

What happens in the presence of a potential?

If the infinite distance limit is not obstructed, there are two typical scenarios:

Positive runaway

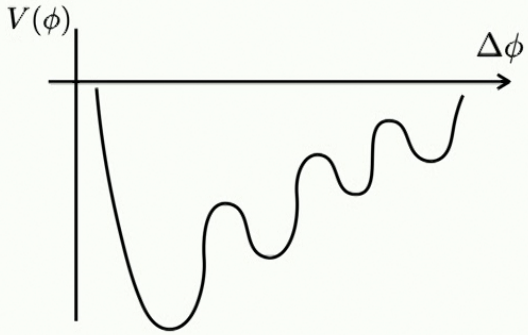


$$V_0 \sim m_{\text{tower}}^{\gamma}$$

[Ooguri et al'18]

Accelerated expansion?

Family of AdS vacua



$$V_0 \sim m_{\text{tower}}^{\gamma}$$

[Luest,Palti,Vafa'19]

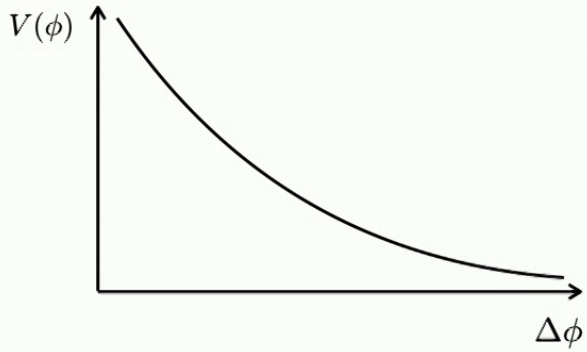
AdS scale separation?

(also important for Dark Dimension scenario, Cumrun's talk)

Beyond Moduli Spaces

What happens in the presence of a potential?

Positive runaway



$$V_0 \sim m_{\text{tower}}^{\gamma}$$

Accelerated expansion if

$$\left|\frac{\vec{\nabla} V_0}{V_0}\right| = \gamma \left|\frac{\vec{\nabla} m}{m}\right| \leq \frac{2}{\sqrt{d-2}}$$

Many recent string theory checks of $\left|\frac{\vec{\nabla} V_0}{V_0}\right|$

[Li,Grimm,IV'19][Valeixo et al'20] [Andriot et al'20-22] [Cicoli et al'21-22] [Calderon-Infante et al'22] [Shiu,Tonioni'23] [Cremonini et al'23]…

↪ we evade previous no-go's for accel. exp. but still, no explicit examples

Why is it so difficult to have small $\left|\frac{\vec{\nabla} V_0}{V_0}\right|$?

If the tower contains higher spin fields,

Higuchi bound implies $\gamma \geq 2$ [Montero,Vafa,IV'22] [Rudelius'22]

which combined with $\left|\frac{\vec{\nabla} m}{m}\right| \geq \frac{1}{\sqrt{d-2}}$

implies $\left|\frac{\vec{\nabla} V_0}{V_0}\right| \geq \frac{2}{\sqrt{d-2}}$ (no asymptotic accelerated expansion)

[Bedroya,Vafa'19] [Rudelius'22]

Beyond Moduli Spaces

What happens in the presence of a potential?

Known holographic SUSY examples have

$$\gamma = 2$$

(no scale separation between AdS length and internal dimensions)

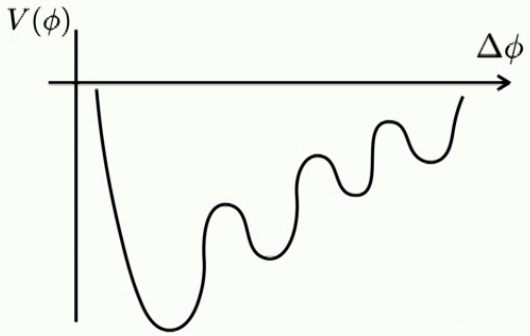
But DGKT-like proposals (with not known CFT dual) have $\gamma > 2$

No explicit 10d uplift

New results regarding consistency of the vacuum

[Montero, Valenzuela 'ongoing]

Family of AdS vacua



$$V_0 \sim m_{\text{tower}}^{\gamma}$$

AdS scale separation if

$$\gamma \geq 2$$

DGKT vacuum

[De Wolfe, Giddings, Kachru, Taylor '05]

4d N=1 AdS vacuum arising from compactifying massive Type IIA on a CY3 with O6-planes and fluxes for

$$F_0, F_4, H_3 \quad \Rightarrow \quad \text{AdS4xCY3}$$

There is one **unconstrained flux** that does not appear on the tadpole:

$$\int_{\omega_4} F_4 = N$$

By solving the 4d eoms, one finds a family of AdS vacua with

$$V_0 \sim N^{9/2}$$
$$m_{\rm KK}^{-2} \sim L_{\rm KK}^2 \sim N^{7/2} \quad \Rightarrow \quad \left(\frac{\ell_{AdS}}{L_{KK}}\right)^2 \sim N$$

So this solution is **scale-separated** in the large N limit.

DGKT vacuum

The consistency of the solution is not clear because we only solved **4d equations of motion** (zero mode of 10d eoms on CY3)

Lot of recent progress, everything seems fine so far, but no conclusive answer.

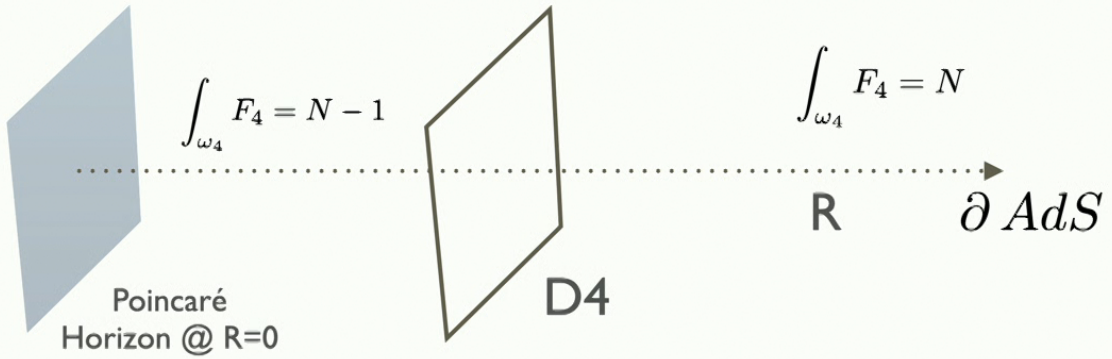
[Andriot, Apers, Casas, Castellano, Collins, Cribiori, Dall'Agata, De Luca, Emelin, Farakos, Graña, Herraez, Hoter, Ibañez, Junghans, Lust (x2), Marchesano, Marconnet, Montella, Morittu, Ning, Palti, Plauschinn, Prieto, Quirant, Revello, Shiu, Shukla, Tomasiello, Tonioni, Toulikas, Tringas, Tsimpis, Vafa, Van Hemelryck, Van Riet, Walcher, Wiesner, Wrasse, Xu, Yau, Zatti, …]

We will assume everything is OK, and study the fate of branes on DGKT vacuum, to perform a non-perturbative consistency check

[Montero, Valenzuela 'ongoing]

Test of DGKT vacuum

Consider a D4-brane wrarpping a holomorphic 2-cycle dual to the large N flux $\int_{\omega_4} F_4 = N$



In principle, it is **BPS**, so the position of the brane is a modulus

(see also [Aharony,Antebi,Berkooz '08])

Test of DGKT vacuum

However, at low energies the worldvolume theory is $3d\,\mathcal{N}=1$

This is so little SUSY that there are no protected quantities

The superpotential can receive corrections (unless there is a parity symmetry)

[Gaiotto-Komargodski-Wu '18]

In DGKT, the fluxes break the parity symmetries [Montero, Valenzuela 'ongoing]

By explicit computation, we show that a superpotential is generated

(SUSY is broken spontaneously on the brane)

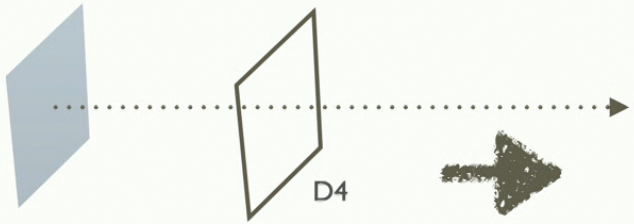
→ the position of D4 is not a modulus

(it feels an attractive force)

Test of DGKT vacuum

The result is in tension with the Weak Gravity Conjecture (WGC)

According to the WGC, a non-BPS brane should be repulsive



which would imply an instability of the DGKT vacuum

→ No SUSY AdS scale-separated vacuum

Ongoing work!

We are exploring the implications of this clash between DGKT vacuum and the WGC for membranes

[Montero, Valenzuela 'ongoing]

Stay tuned

Conclusions

❖ We are entering an era of precision in the Swampland program

Fix all "order one" factors $m \sim m_0 \exp(-\alpha \Delta\phi)$ $\Lambda \sim M_p \exp(-\lambda \Delta\phi)$

$V_0 \sim m^\gamma$

❖ We found a universal pattern between the leading tower of states and the quantum gravity cut-off underlying all string theory examples

- It provides a quantitative bound for the exponential rate of the tower

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} \Lambda}{\Lambda} = \frac{1}{d-2} \quad \Rightarrow \quad \alpha \geq \frac{1}{\sqrt{d-2}}$$

- It constraints the possible towers and how different limits fit together in the moduli space

- Implications for asymptotic accelerated expansion and AdS scale separation

Thank you!