Light towers of states in String Theory

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Infinite towers of states are a fundamental and ubiquitous aspect of string theory

A tower may be characterised by a mass scale m: $m_n \sim n\, m$

A light tower of states is such that (in Einstein frame) $\frac{m}{M_p} \rightarrow 0$

When do light towers arise in string theory (quantum gravity?)

Proposals in terms of low-energy parameters:

- $\frac{m}{M_p} \sim g$

Weak Gravity Conjecture

[Arkani-Hamed, Motl, Nicolis, Vafa ’06]

[Heidenreich, Reece, Rudelius ’15+’16+’17; Klaewer, EP ’16; Montero, Shiu, Soler ’16; Grimm, EP, Valenzuela ’18; Lerche, Lee, Weigand ’18; Andriolo, Junghans, Noumi, Shiu ‘18]

- $\frac{m}{M_p} \sim e^{-\alpha\phi}$

Distance Conjecture

[Ooguri, Vafa ’06]

Evidence from type IIB string theory on CY manifolds: complex-structure (vector multiplet) moduli space

[Grimm, EP, Valenzuela ‘18]

BPS states: D3 branes wrapping 3-cycles

$$M_q = |Z_q| = \frac{q \cdot \Pi(t)}{\left|\Pi(t) \cdot \overline{\Pi(t)}\right|^{\frac{1}{2}}} \qquad K(t) = -\log \left|\Pi(t) \cdot \overline{\Pi(t)}\right|$$

N monodromy matrix about $t = +i\infty$ (Nilpotent Orbit Theorem):

$$\Pi(t, \xi) = e^{Nt} a_0(\xi) + \mathcal{O}(e^{2\pi i t})$$

[Schmid ’73]

Reproduces distance and weak gravity conjectures*

*(BPS stability can be shown for certain, but not all, infinite distances)

Generalised to multiple parameter infinite distances

[Grimm, Li, EP '18; Corvilain, Grimm, Valenzuela '18]

Results extended for various infinite distance loci

[Lee, Lerche, Weigand '18+'19; Corvillain, Grimm, Valenzuela '18; Joshi, Klemm '19; Blumenhagen, Klaewer, Schlechter '19; Marchesano, Wiesner '19; Font, Herraez, Ibanez '19; Grimm, Van De Heisteeg '19; Erkinger, Knapp '19; …]

D3 branes integrated out already in the moduli space (e.g. conifold)

[Strominger '95]

Suggests that asymptotic limits could be emergent from integrating out the tower of states ?

See also [Harlow '15; Heidenreich, Reece, Rudelius '18]

A massive spin-2 particle has 5 propagating degrees of freedom

$$w_{\mu\nu} = h_{\mu\nu} + \partial_{(\mu}\chi_{\nu)} + \Pi^L_{\mu\nu}\pi$$

helicity 2 helicity 1 helicity 0

The Fierz-Pauli mass term gives the kinetic term for the helicity-1 mode

$$m^2_{Spin-2}\left(w_{\mu\nu}w^{\mu\nu} - w^2\right) \sim m^2_{Spin-2}(\partial_{[\mu}\chi_{\nu]})^2$$

There is another mass scale which sets interactions strength $\frac{1}{M_w} w_{\mu\nu}T^{\mu\nu}$

The gauge coupling strength is $g_m \sim \frac{m_{Spin-2}}{M_w}$

[Klaewer, Lüst, EP ‘18]

Apply the Weak Gravity Conjecture to the helicity-1 mode $\frac{m}{M_p} \sim g_m$

Spin-2 Conjecture: $$\frac{m}{M_p} \sim \frac{m_{Spin-2}}{M_w}$$

[Klaewer, Lüst, EP '18]

Satisfied in all known String Theory settings (KK gravitons, String oscillators)

Strong Spin-2 Conjecture: $$\mathrm{m} \sim m_{graviton}$$

$$m_{graviton} < 10^{-22}\ eV$$

[Abbot et al. '16]

The spin-2 conjecture predicts $m_{graviton} = 0$ (or spectacularly light tower)

Could it be that there is an infinite tower of states whose mass is related to the magnitude of the cosmological constant (minimum of potential)?

$$|\Lambda| \to 0 \quad \Longrightarrow m \to 0 \quad ??$$

Any string theory potential sources vanish in the decompactification limit

$$\mathrm{Vol}\left(\mathrm{Y_p}\right) \to \infty \quad \Longrightarrow \begin{cases} |\Lambda| \to 0 \\ m \to 0 \end{cases}$$

General arguments?

[Lüst, EP, Vafa ‘19]

The Swampland Distance Conjecture states that given scalar fields (with no potential) with kinetic terms

$$\mathcal{L}_{kin} = -p_{ij}\partial\phi^i\partial\phi^j$$

One can associate a distance in field space to a path with parameter τ

$$\Delta = \int_{\tau_i}^{\tau_f} \left(p_{ij}\frac{\partial\phi^i}{\partial\tau}\frac{\partial\phi^j}{\partial\tau}\right)^{\frac{1}{2}} d\tau$$

The conjecture states that for $\Delta \gg 1$, there is an infinite tower of states with mass m which behaves as

$$m(\tau_f) \sim m(\tau_i)e^{-\alpha\Delta}, \qquad \alpha > 0, \alpha \sim \mathcal{O}(1)$$

[Ooguri, Vafa ’06]

Recall origin of scalar fields in distance conjecture are higher tensors

$$\Delta = \int_{\tau_i}^{\tau_f} \left(p_{ij} \frac{\partial \phi^i}{\partial \tau} \frac{\partial \phi^j}{\partial \tau} \right)^{\frac{1}{2}} d\tau = \int_{\tau_i}^{\tau_f} \left(\frac{1}{V_M} \int_M \sqrt{g} g^{MN} g^{OP} \frac{\partial g_{MO}}{\partial \tau} \frac{\partial g_{NP}}{\partial \tau} \right)^{\frac{1}{2}} d\tau$$

For $S_d \times Y_p$, with S_d homogeneous, then in S_d Einstein frame

$$m(\tau_f) \sim m(\tau_i) e^{-\Delta}, \qquad \alpha > 0, \alpha \sim \mathcal{O}(1)$$

For Weyl rescaling:

$$g_{mn} \to e^{2\tau} g_{mn} \qquad \mathcal{L}_{kin} = -k^2 \left[\frac{d-1}{d-2} - \frac{k-1}{k} \right] (\partial \tau)^2$$

Distance goes as τ

Apply to external AdS metric

$$ds^2 = e^{2\tau}[-(\cosh\rho)^2 dt^2 + d\rho^2 + (\sinh\rho)^2 d\Omega_{d-2}^2\,]$$

$$\Lambda = -\frac{1}{2}(d-1)(d-2)e^{-2\tau}$$

Flat limit of AdS is at infinite distance

$$m \sim e^{-\lambda\tau} \sim |\Lambda|^{\alpha}$$

Caution: we are not sure how to implement the Einstein-frame condition for external metric…

(A)dS Distance Conjecture:

[Lüst, EP, Vafa '19]

AdS_d space in quantum gravity has infinite tower of states whose mass scale m, as $\Lambda \to 0$, behave as

$$m \sim |\Lambda|^{\alpha}$$

Strong AdS Distance Conjecture: for supersymmetric vacua

$$m \sim |\Lambda|^{\frac{1}{2}}$$

This implies no separation of scales between the AdS radius and the mass scale of the tower (usually KK modes)

Could be related to obstruction to unbounded spacetime-filling gauge group

[Vafa '06]

In Minkowski space the rank of the gauge group appears bounded

M-theory on $AdS_7 \times S^4/Z_k$ gives an $SU(k) \times SU(k)$ gauge group on AdS_7

This perspective suggests should have $AdS_d \times Y_p \rightarrow Mink_{d+p}$

- No known 10/11D counter examples (many, infinite, sets of examples)

- Arguments for no separation of scales ($\Longrightarrow \alpha = \frac{1}{2}$) in supergravity (require orientifolds, scalar gradients)

  [Gautason, Schillo, Van Riet ‘15]

- Strong version violated for IIA on CY with flux (not 10D solution)

  [DeWolfe, Giryavets, Kachru, Taylor ‘07]

- Both conjectures apparently violated by KKLT (may be implicitly satisfied)

  [Kallosh, Kachru, Linde, Trivedi ‘03]

- But satisfied by Large Volume Scenario (LVS)

  [DeWolfe, Giryavets, Kachru, Taylor ‘07]

CFT duals:

- $\alpha = \frac{1}{2}$ implies no parametric gap between dimension of finite and infinite number of operators.
- Proposal that strong version related to gauge symmetries rather than SUSY

[Alday, Perlmutter '19]

de Sitter vacua:

- AdS Distance conjecture suggests no effective theory can have family of vacua interpolating between AdS/Mink/dS
- If our universe is dS , then suggests tower of states at $10^{-120\,\alpha} M_p$

Summary

Discussed a number of Swampland conditions on light towers of states

- $\frac{m}{M_p} \sim g$ → Weak Gravity Conjecture [Arkani-Hamed, Motl, Nicolis, Vafa '06]
- $\frac{m}{M_p} \sim e^{-\alpha\phi}$ → Distance Conjecture [Ooguri, Vafa '06]

[Grimm, EP, Valenzuela '18]

- $\frac{m}{M_p} \sim \frac{m_{Spin-2}}{M_W}$ → Spin-2 Conjecture [Klaewer, Lüst, EP '18]
- $\frac{m}{M_p} \sim \left|\frac{\Lambda}{M_p^2}\right|^{\alpha}$ → (A)dS Distance Conjecture [Lüst, EP, Vafa '19]

Thank You

Some arguments suggest that in general AdS (not susy) $\alpha \geq \frac{1}{2}$

Refined de Sitter conjecture: $|\underline{\nabla} V| \geq \frac{c}{M_p} V$ **or** $\min(\nabla_i \nabla_j V) \leq -\frac{c'}{M_p^2} V$

[Obied, Ooguri, Spodyneiko, Vafa '18]
[Ooguri, Shiu, EP, Vafa '18]

Modify: $|\underline{\nabla} V|^2 \geq \frac{c^2}{M_p^2} V^2$

Bound on mass of lightest state $m \leq |\Lambda|^{\frac{1}{2}}$

[Gautason, Van Hemelryck, Van Riet '18]

Such bounds familiar from (scalar) WGC, which satisfied by towers of states

On the other hand, for dS expect $\alpha \leq \frac{1}{2}$

(must be so if tower contains spin-2 or higher - Higuchi bound: $m_{spin-2} \geq \Lambda^{\frac{1}{2}}$)