The Swampland, duality, and de Sitter entropy

Eran Palti
Max-Planck-Institut für Physik, Munich

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Vistas over the Swampland
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Many string theory settings satisfy a relation of the form

$$|\underline{\nabla} V| > c\, V \qquad\qquad c \sim \mathcal{O}(1)$$

See talks by Vafa, …

It was suggested that this may be a Swampland criterion: the dS conjecture

[Obied, Ooguri, Spodyneiko, Vafa ‘18]

Could there be general physics underlying this behaviour?

A different proposal is the Swampland Distance Conjecture

For supersymmetric settings (at least 8 supercharges) this can be stated most sharply: approaching any infinite distances locus in moduli space there is an infinite tower of states which becomes exponentially light

$$m_{tower} \sim e^{-a\,\phi} \quad \text{for} \quad \phi \to \infty$$

[Ooguri, Vafa '06]

For at least 8 supercharges, it is one of the most supported of the Swampland conjectures

[Cecotti '15; Grimm, EP, Valenzuela '18; Lee, Lerche, Weigand '18; Grimm, Li, EP '18 (To Appear)]

See talks by Valenzuela, Weigand

It can be tied to a Scalar version of the Weak Gravity Conjecture

[EP '17; Grimm, EP, Valenzuela '18]

The distance conjecture has a stronger version. The Refined SDC:

- The exponential behaviour appears at $\phi \sim M_p$
- The exponent $a \sim \mathcal{O}(1)$
- The conjecture holds for fields with a potential $V(\phi)$

[Baume, EP ’16; Klaewer, EP ‘16]

(Implicit to some degree in [Ooguri, Vafa ‘06])

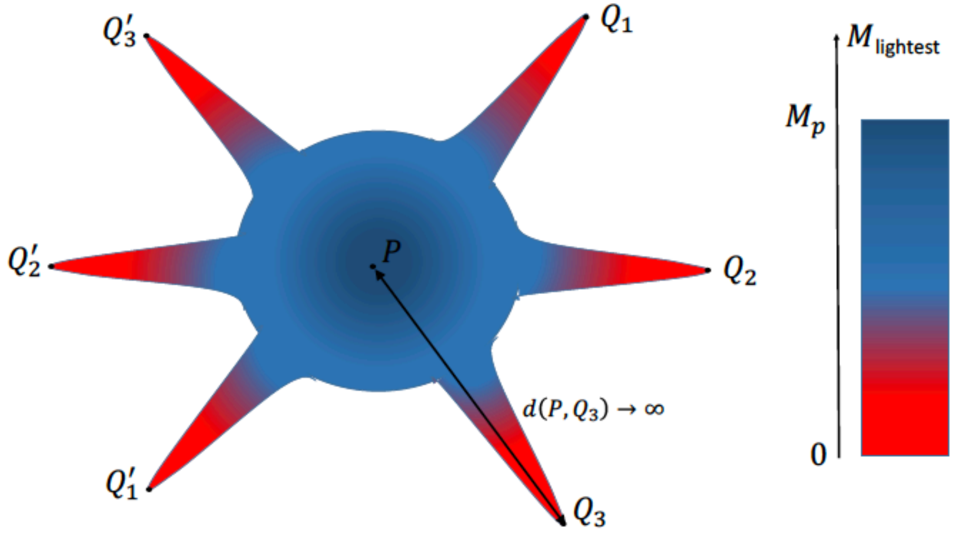
Has passed some non-trivial tests, <u>but still many open questions</u>

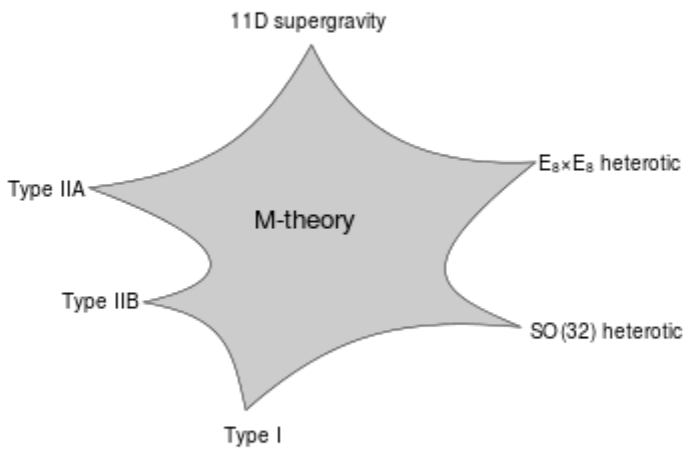
[Baume, EP ’16; Klaewer, EP ’16; Valenzuela ‘16; EP ’17; Blumenhagen, Valenzuela, Wolf ‘17; Hebecker, Henkenjohann, Witkowski ‘17; Cicoli, Ciupke, Mayrhofer, Shukla ‘18; Blumenhagen, Klaewer, Schlechter, Wolf ‘18]

See talk by Hebecker

The underlying motivation for the distance conjecture is duality

At large distance there is a dual description in terms of the light states





Couplings in String Theory are scalar fields $(g_s, t, u, g_I, f_I, \ldots)$

Weak Coupling $g \to 0$ Large distance $\phi \to \infty$

Examples in string theory: Type IIB on Calabi-Yau

- The conifold: [Strominger '95]

CY Moduli space — D3 brane wrapping 3-cycle

- Gopakumar-Vafa invariants (mirror): [Gopakumar, Vafa '98]

Geometric invariants — 1-loop integral of D2-D0 states

- Moduli space at infinite distance: [Grimm, EP, Valenzuela '18]

See talk by Valenzuela

$$g_{\phi\phi}(\partial\phi)^2$$
$$Im\, N_{IJ}\, F^{I,\mu\nu} F^{J}_{\mu\nu}$$

— Infinite tower of D3 branes

[See also Harlow '15; Heidenreich, Reece, Rudelius '17+'18]

We interpret the Swampland Distance Conjecture as:

Any weakly coupled region in string theory should have a dual description in terms of the tower of light states

Propose that can apply this to the potential $V(\phi)$

Some motivation: In $N = 2$ a potential can only be induced by gauging

$$Dz^i = \left(\partial z^i + k_I^i(z) A^I\right), \qquad V \sim k(z)$$

If the gauge fields are emergent then so must be the potential

How can we make a general connection between the tower and $V(\phi)$?

de Sitter space has a finite horizon for an observer, of radius R

It is natural to associate to this an entropy [Gibbons, Hawking '77; Banks '00]

$$S_{dS} = Log\, dim\, \mathcal{H} = R^2$$

We will consider de Sitter vacua or slow-rolling quasi-de Sitter

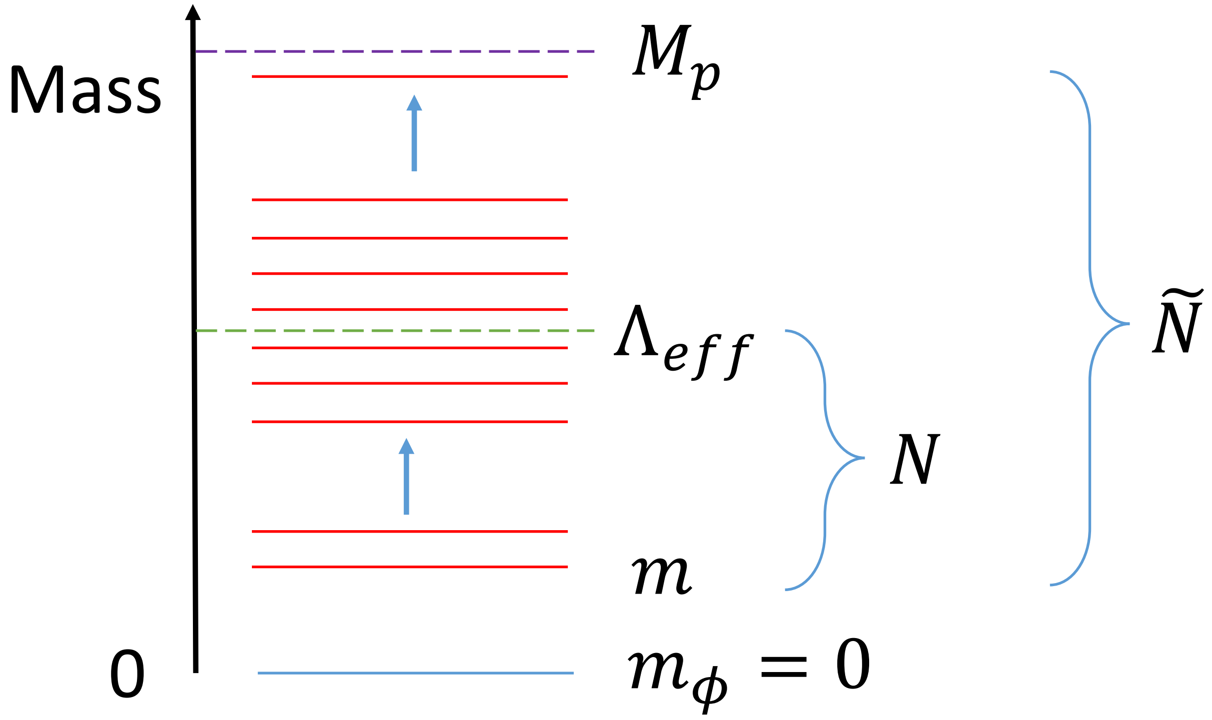
$$\partial_\phi V \sim \alpha\, V \qquad\qquad \alpha \ll 1$$

And identify

$$S_{dS}(\phi) \sim H^{-2} \sim \frac{1}{V(\phi)}$$

Note: we can not say too much away from these regimes. But if $\alpha \sim \mathcal{O}(1)$ then anyway the dS conjecture is satisfied.

On the other hand, the distance conjecture says we get many light states



N is the number of fields below some scale Λ_{eff} which we will define

$$\widetilde{N} \sim Exp\,[a\,\phi] \qquad N \sim Exp\,[b\,\phi] \qquad a, b \sim \mathcal{O}(1)$$

The entropy associated to these light states is a function of N and R

$$S_{tower}(N, R)$$

The cutoff Λ_{eff} is then defined as the scale above which the states no longer contribute significantly to the entropy

Since $N, R \gg 1$, we expect $S_{tower}(N, R)$ to be dominated by a single term

$$S_{tower}(N, R) \sim N^p R^q$$

The duality proposal implies that this should account for the dS entropy

$$N^p R^q \sim R^2$$

We can then calculate

monotonic

$$V(\phi) \sim \frac{1}{R^2} \sim N^{\frac{2p}{q-2}} \qquad \frac{\partial V}{\partial \phi} = \frac{\partial V}{\partial N}\frac{\partial N}{\partial \phi} \sim b\left(\frac{2p}{q-2}\right)V$$

Which gives

$$\left|\frac{\partial V}{\partial \phi}\right| > c\,V \qquad \mathrm{c} \sim \frac{2bp}{2-q}$$

We therefore recover the de Sitter conjecture.

This is a generalisation of a Dine-Seiberg type argument to arbitrary couplings

[Dine, Seiberg ‘85]

<u>Note:</u> Even if the tower only accounts for a fraction of the total entropy, still there are no de Sitter vacua, but could have $c \ll 1$

Recall our assumptions:

- The SDC holds for potentials
- We are in a weakly-coupled regime where the tower is a dual description
- We are in a quasi-de Sitter setting (accelerating expansion with horizon)

$\Rrightarrow$ The de Sitter conjecture

We are not sure how to determine p, q, Λ_{eff}

The problem amounts to counting microstates in the dual theory

We will later parameterise this ignorance, but first let us try..

Recall, in de Sitter space have 3 types of states:

- QFT states localised within the bulk of de Sitter space
- Black holes
- States localised on the Horizon

One proposal for counting the microstates is to consider all localised QFT states within a box of order the de Sitter radius R

Consider a relativistic particle in a box of size R

We want to calculate the entropy associated to it by counting its momentum modes up to a maximum value k_{max}

$$S_1 \sim (k_{max}R)^3$$

The maximum energy associated to these modes is

$$E_1 \sim k_{max}(k_{max}R)^3$$

We count only localised QFT states, so not black holes, therefore $E_1 < R$

$$k_{max} < R^{-\frac{1}{2}} \qquad S_1 < R^{\frac{3}{2}}$$

[Page ’81; Banks ‘05]

Now we consider N species of such particles

We need these to be relativistic to contribute significantly to the entropy, so we have

$$\Lambda_{eff} \sim k_{max}$$

Can deduce the number of species needed by simple thermodynamics

To maximise entropy set temperature in each species equal ($k_{max} \rightarrow T$)

$$S_N \sim N(TR)^3 \qquad E_N \sim NT(TR)^3$$

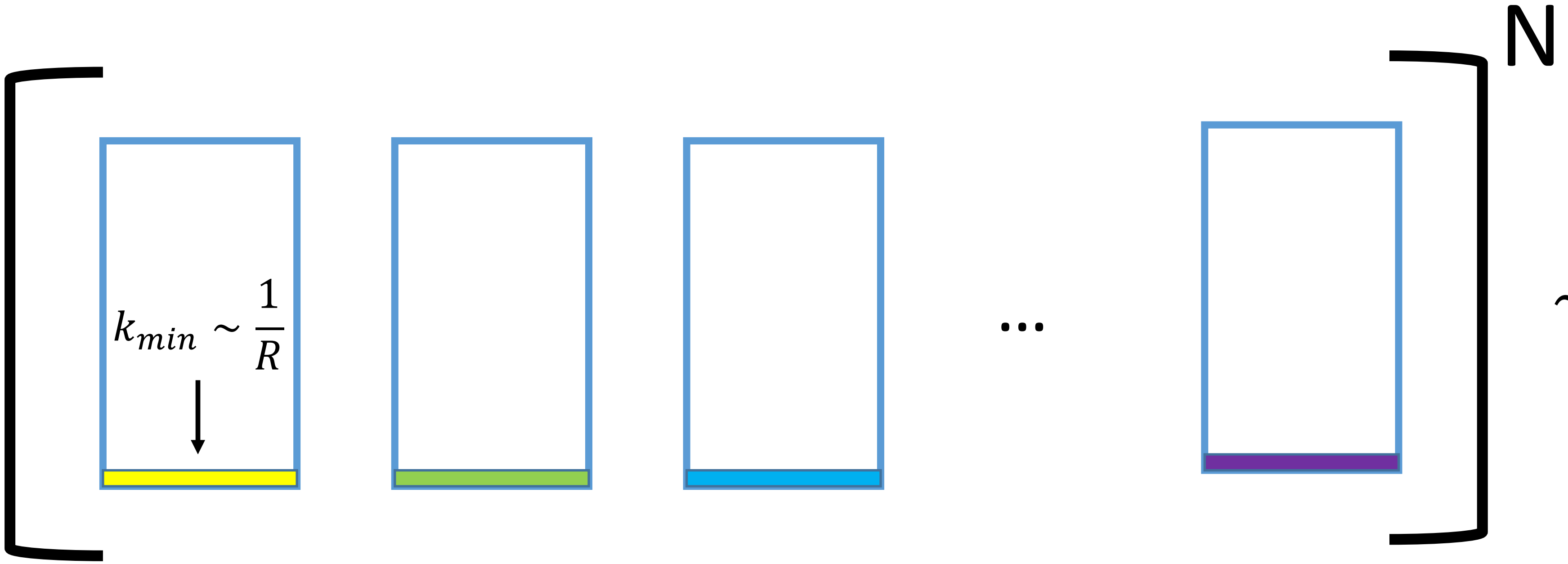
Not forming black holes implies

$$T \leq \frac{1}{N^{\frac{1}{4}}R^{\frac{1}{2}}} \qquad S_N \sim N^{\frac{1}{4}}R^{\frac{3}{2}}$$

We therefore find that we need

$$N \sim R^2 \qquad\qquad T \sim \frac{1}{R} \qquad\qquad S_1 \sim 1$$

The low temperature and entropy per species means at borderline of thermodynamics, but can explicitly check by counting microstates



$$\sim N \qquad\qquad NR^{-1} \leq R$$

While the de Sitter conjecture is not sensitive to the microstate counting scheme, the cosmology is

How would these bounds apply to our universe?

$$R \sim 10^{60} \qquad\qquad c \lesssim 0.6$$

[Agrawal, Obied, Steinhardt, Vafa '18]

We assume an equally-spaced tower of states $m_n \sim n\, m$

$$N \sim R^{\frac{2-q}{p}} \qquad \Lambda_{eff}^{(1)} \equiv 1 \qquad \Lambda_{eff}^{(2)} \equiv \frac{1}{\sqrt{N}} \sim R^{\frac{q-2}{2p}}$$

$$m^{(1)} \equiv \frac{\Lambda_{eff}^{(1)}}{N} \sim R^{\frac{q-2}{p}} \qquad m^{(2)} \equiv \frac{\Lambda_{eff}^{(2)}}{N} \sim R^{\frac{3(q-2)}{2p}}$$

- **QFT counting:** $q = \frac{3}{2}, p = \frac{1}{4}$

$\mathrm{N} \sim 10^{120}$ $\quad \Lambda_{eff} \sim \Lambda_{eff}^{(2)} \sim 10^{-60}$ $\quad m \sim 10^{-180}$

- **Scenario 1:** $q = \frac{3}{2}, p = 1$

$N \sim 10^{30}$ $\quad \Lambda_{eff}^{(2)} \sim 10^{-15} \sim TeV$

$m^{(1)} \sim 10^{-30} \sim m_\nu$

$m^{(2)} \sim 10^{-45} \sim 10^{-15} m_\nu$

- **Scenario 2:** $q = \frac{7}{4}, p = 1$

$N \sim 10^{15}$ $\quad \Lambda_{eff}^{(2)} \sim 10^{-7}$

$m^{(1)} \sim 10^{-15} \sim TeV$

$m^{(2)} \sim 10^{-22} \sim MeV$

- **Decoupling scenario**: $q = 2, p = p$

Summary

- Proposed that Weakly-coupled regions in string theory admit a dual description, including the potential, by the tower of light states of the Swampland Distance Conjecture

- In a quasi-de Sitter setting, the duality applied to the entropy leads to the Swampland de Sitter conjecture

- We have calculated an example approach to counting microstates

- For that approach, we find that our universe would not be in the weakly coupled regime. For other microstate counting recover varied cosmology.

Thank You