Cosmological constants and the Swampland

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Lüst, EP, Vafa (1906.05225)

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Navigating the Swampland 2019, Madrid

We know for sure that string theory supports:

- Minkwoski vacua $(\Lambda = 0)$
- Minkwoski vacua $\times Y$
- AdS vacua $(\Lambda < 0) \times Y$ (No separation of scales $|\Lambda|^{\frac{1}{2}} \sim R_{AdS}^{-1} \sim R_Y^{-1}$)

So "Data" permits candidate Swampland conjectures:

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

[Obied, Ooguri, Spodyneiko, Vafa '18; Garg, Krishnan '18; Ooguri, EP, Shiu, Vafa '18]

- (A)dS Distance Conjecture: $m \sim |\Lambda|^{\alpha}$ [Lüst, EP, Vafa '19]
- Strong AdS Distance Conjecture: $m \sim |\Lambda|^{\frac{1}{2}}$ [Lüst, EP, Vafa '19]

- RdS: $\left|\underline{\nabla} V\right| \geq \frac{c}{M_p} V$ **or** $\min(\nabla_i \nabla_j V) \leq -\frac{c'}{M_p^2} V$
- ADC: $m \sim |\Lambda|^{\alpha}$
- SADC: $m \sim |\Lambda|^{\frac{1}{2}}$

Many other proposals that are not completely sure about, for example:

- KKLT Scenario (Susy AdS – IIB w/ non-perturbative) ✘ ADC
- KKLT Scenario (dS – IIB KKLT AdS + anti-D3) ✘ RdS + ADC

[Kachru, Kallosh, Linde Trivedi '03]

- LVS Scenario (Non-Susy AdS – IIB KKLT+α') ✓ (Non-susy SADC)

[Balasubramanian, Berglund, Conlon, Quevedo '05]

- DGKT Scenario (Susy AdS –IIA on CY) ✘ SADC

[DeWolfe, Giryavets, Kachru, Taylor '05]

Should we expect the cosmological constant to be a Swampland variable?

$N = 2$ supersymmetry relates potentials to gauge couplings

Example: IIB on Calabi-Yau $\quad C_4 = A_I \alpha^I \quad\quad S = \int d^4\mathrm{x} \left[-\frac{1}{8} Z_{IJ} F_2^I \wedge \star F_2^J \right]$

Fluxes are charges $F_3 = q_I \alpha^I \quad\quad V = \frac{1}{8} Z^{IJ} q_I q_J$

V is the magnitude of the gauge self-force between charged particles

Can also be phrased in terms of four-forms

$$C_6 = c_I^{(3)} \alpha^I \quad\quad S = \int d^4\mathrm{x} \left[-\frac{1}{8} Z_{IJ} F_4^I \wedge \star F_4^J + \frac{1}{4} F_4^I q_I \right]$$

[…,Dvali ‘05; Kaloper, Sorobo ‘08; Bandos, Bielleman, Carta, Dudas, Escobar, Farakos, Harraez, Ibanez, Lanza, Marchesano, Martucci, Montero, Staessens, Sorokin, Tenreiro, Uranga, Valenzuela, Zoccarato ’15-19]

Recall origin of scalar fields in distance conjecture are higher tensors

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

Take $M = S_d \times Y_{\mathrm{k}}$ $\quad g_{mn} \rightarrow e^{2\tau} g_{mn}$ $\quad \mathcal{L}_{kin} = -k^2 \left[\frac{d-1}{d-2} - \frac{k-1}{k} \right] (\partial \tau)^2$

Distance of Weyl rescalings goes as τ, so expect for A(dS)

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

$$\Lambda = -\frac{1}{2}(d-1)(d-2)e^{-2\tau} \qquad m \sim e^{-\lambda\tau} \sim |\Lambda|^{\alpha}$$

Interesting proposals relating distance to Ricci flow in metric space

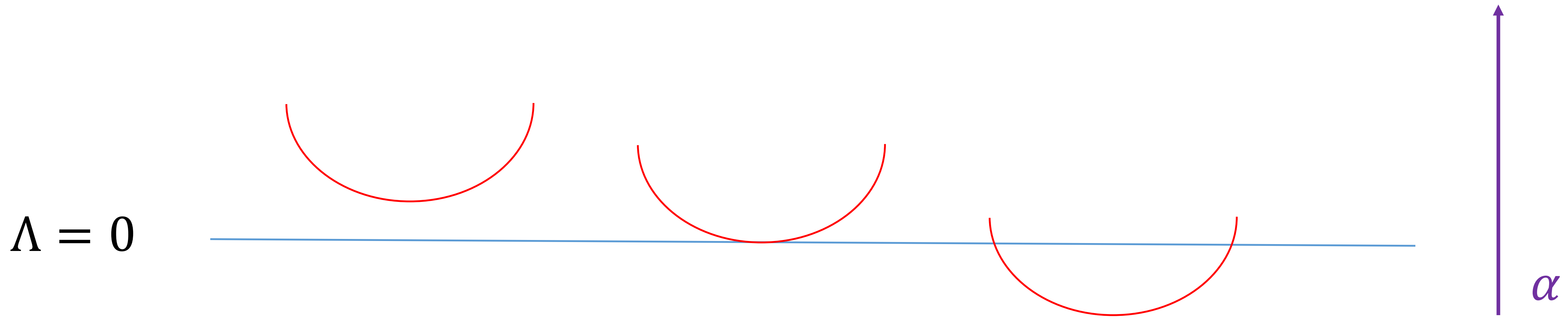
[A. Kehagias, D. Lüst, S. Lüst, To appear]

and to RG flows [C. Gomez '19]

Gauge/Scalar Swampland	Λ Swampland
$m \sim e^{-\alpha\phi}$	$m \sim \Lambda^{\alpha}$
$m_{min}^2 \leq g^2 q^2$	$\lvert \underline{\nabla} V \rvert^2 \geq c^2\, V^2 \quad \min(\nabla_i \nabla_j V) \leq -c^2\, V$ $m_{min}^2 \leq c^2\, \lvert\Lambda\rvert$
$m^2 \sim g^2$	$m^2 \sim \lvert\Lambda\rvert$
$g \to 0, \phi \to \infty \;\; \Rightarrow m \to 0$	$\Lambda_{dS} \to 0 \Rightarrow S_{dS} \to \infty$

Reasonable to think about cosmological constant analogously to the `traditional' Swampland conjectures

May expect string constructions to manifest such properties



Infinite distance? Entropy? …

Higuchi bound can develop further of some of these ideas

The Higuchi bound is a bound on the mass of spin 2 or higher fields in de Sitter space

$$m_{(l)}^2 \geq H^2(l-1)(l+d-4)$$

Comes form unitary representations of de Sitter group

It is part of a more general notion of partial masslessness [Deser, Waldron '01]

$$m_{(l,t)}^2 \geq H^2(l-t-1)(l+d+t-4)$$

At saturation, the t^{th}-helicity mode becomes pure gauge

Can gain some intuition from massive spin-2 field in flat space

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

helicity 2 helicity 1 helicity 0

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

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

Masslessness leads to pure gauge, naturally associated to a gauge coupling limit

$$g_m \sim \frac{m_{Spin-2}}{M_w} \qquad \frac{1}{M_w} w_{\mu\nu} T^{\mu\nu}$$

[Klaewer, Lüst, EP '18]

Partial masslessness conjecture:

Partial masslessness occurs in quantum gravity at infinite distance in field space, and is accompanied by an infinite tower of light states

[Lüst, EP '19]

Useful criteria for thinking about how approaching the Higuchi bound should behave

A first test of Higuchi bound in string theory

[Lüst, EP ‘19]

[Noumi, Takeuchi, Zhou ‘19]

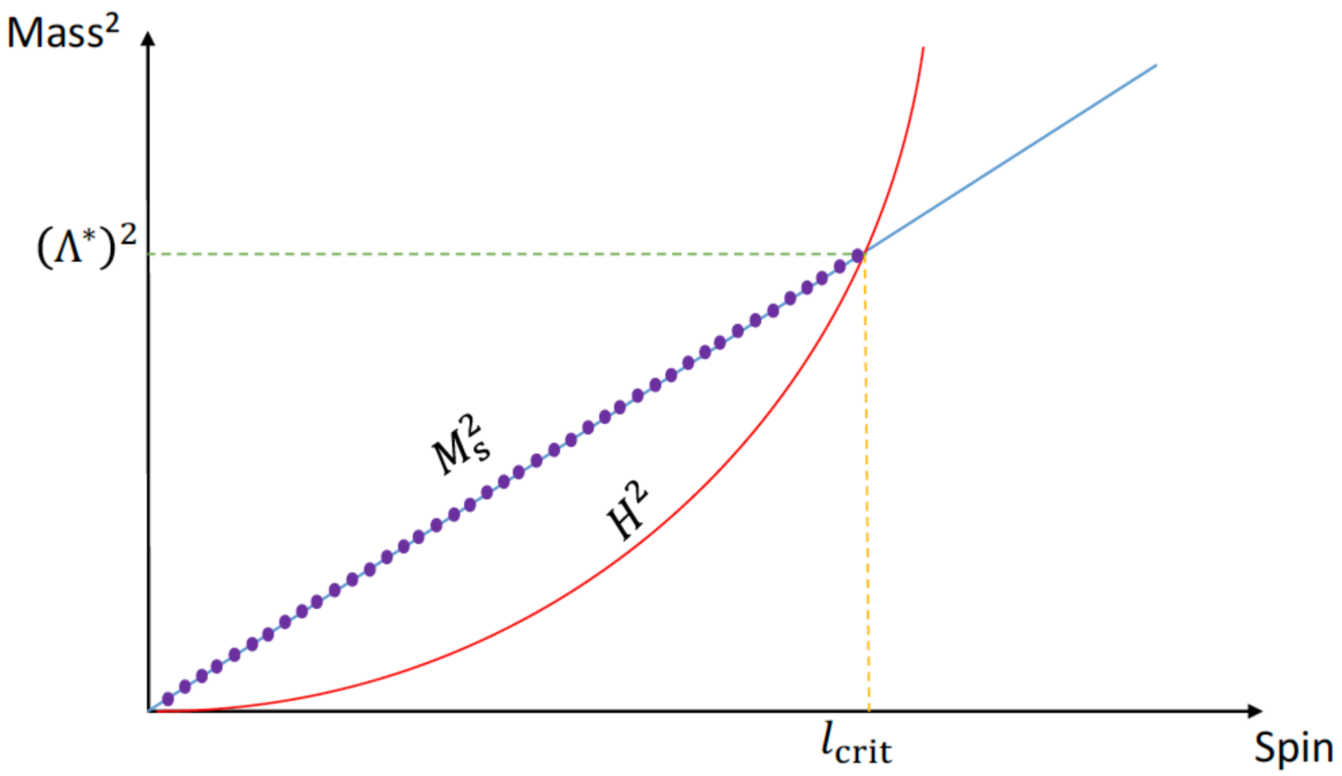
Higuchi bound scales quadratically with spin, but Regge trajectory is linear

$$m_{(l)}^2 > l^2 H^2$$

$$m_{(l)}^2 \sim l M_s^2$$

Violated at: $$l_{crit} \sim \left(\frac{M_s}{H}\right)^2$$

$$M_{l_{crit}}^2 \sim M_s^2 \left(\frac{M_s}{H}\right)^2$$



For string consistency something must go wrong at

$$\Lambda^* < M_s \left(\frac{M_s}{H}\right)$$

Higher spin modes of string correspond to longer strings

$$L^2_{(l)} \sim \frac{l}{M_s^2}$$

The Higuchi bound is only violated by strings of order size of Hubble scale

$$L^2_{(l_{crit})} \sim \frac{l_{crit}}{M_s^2} \sim \frac{1}{H^2}$$

Good check that Higuchi is probing quantum gravity physics

Note that in either picture have a cutoff at

$$\Lambda^* < M_s \left(\frac{M_s}{H}\right)$$

This is a UV cutoff, relating to UV/IR mixing in string theory, what does it mean?

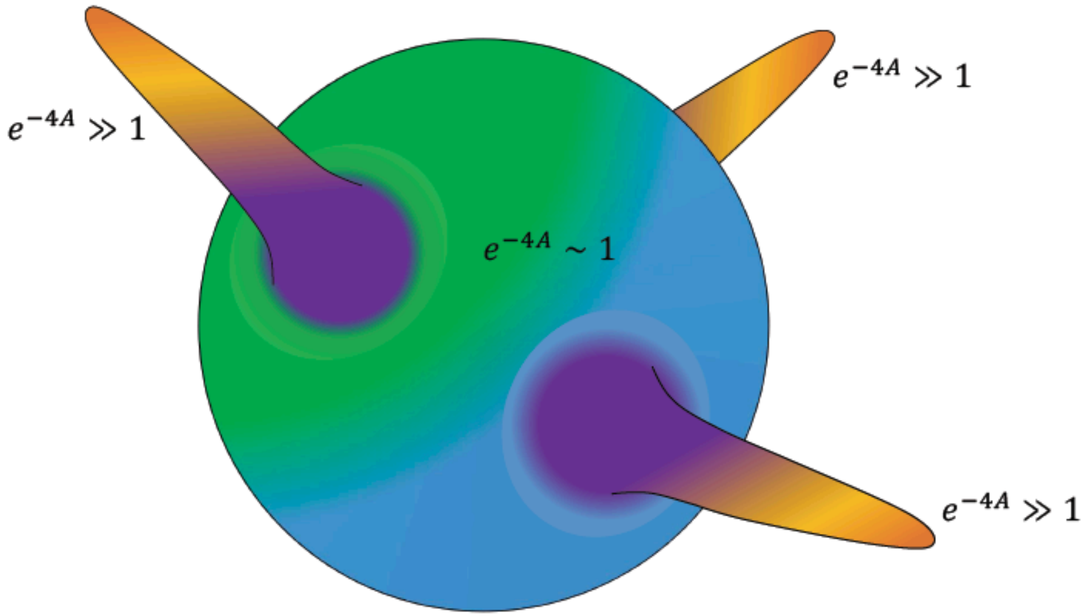
If we demanded $\Lambda^* > M_p$, then would require the constraint

$$M_s > \sqrt{H\, M_p}$$

Would place strong constraints on high scale inflation models

Higuchi / partial masslessness can be utilised to probe/test string constructions

For example, throats contain exponentially light higher spin fields…



Summary

- Proposed various conjectures which involve cosmological constants:

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

Partial masslessness at infinite distance

- Inspired by connections with more traditional Swampland constraints

- High spin fields are good testing ground for de Sitter vacua in string theory

Thank You