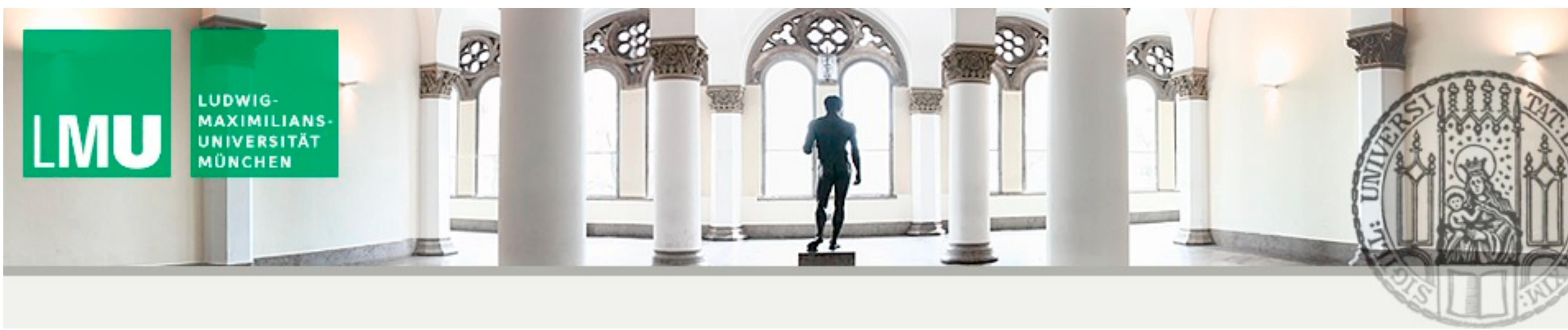
Higher Spin Theories, AdS Distances and the Swampland

DIETER LÜST (LMU, MPI)



String Phenomenology 2019, CERN, 28th. June 2019

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Joint work with D. Kläwer & E. Palti, arXiv:1811.07908
and with E. Palti, C. Vafa, arXiv:1906.05225

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[Review by E. Palti (2019)]

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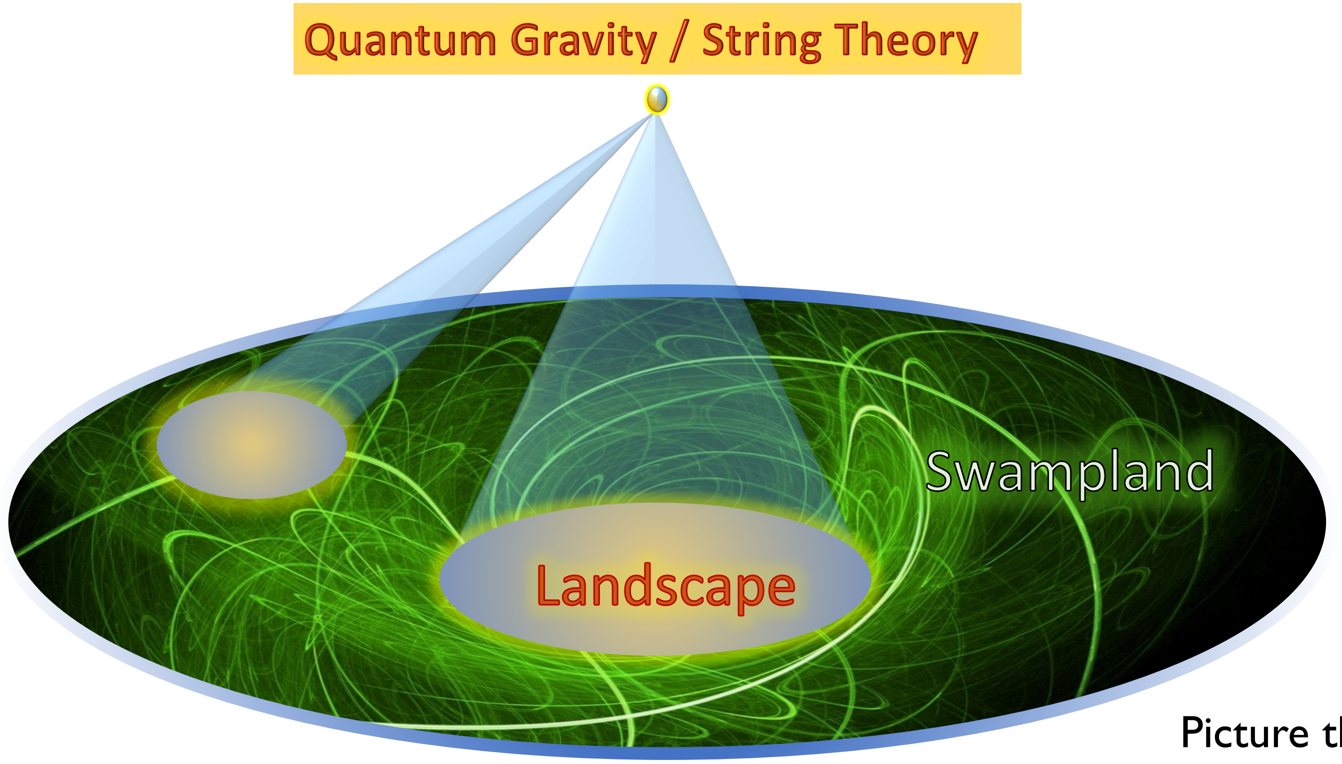

Picture thanks to Eran Palti

Can gravity be in the swampland?

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New swampland conjectures:

Higher-spin (spin-2) theories and the swampland?

Massive gravity and the swampland?

Pure AdS vacua and the swampland?

Can higher spin states tell us something about de Sitter space?

- Weak gravity conjecture

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[B. Heidenreich, M. Reece, T. Rudelius (2015/17);
D. Klaewer, E. Palti (2016);
M. Montero, G. Shiu, P. Soler (2016);
S. Andriolo, D. Junghans, T. Noumi, G. Shiu (2018)
T. Grimm, E. Palti, I. Valenzuela (2018)];

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Electric version: $$m_q \leq g_{U(1)} |q| M_p$$

Magnetic version: $$\Lambda = g_{U(1)} M_p$$

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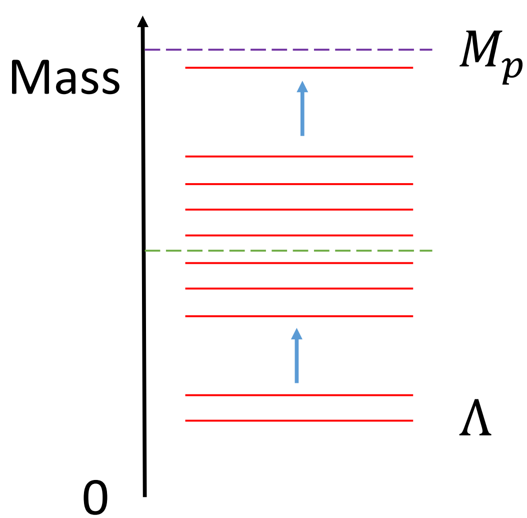

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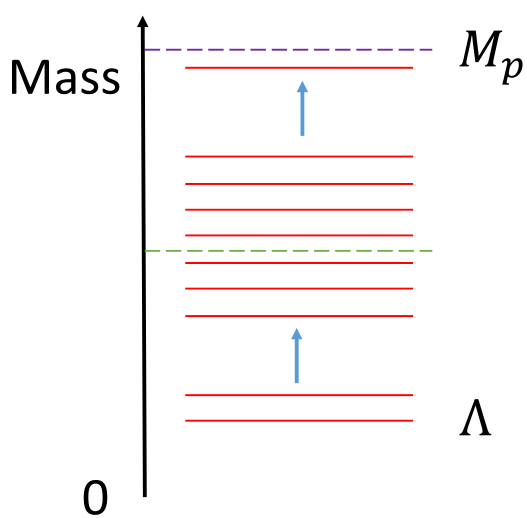

Infinite tower of states above $E \geq \Lambda$

Suggests that $g_{\mathrm{U(1)}} \to 0$ is at infinite distance.

Outline:

II) Spin-two swampland conjecture

III) AdS - Distance Conjecture

IV) de Sitter swampland and higher spins states

V) Summary

II) Spin-two swampland conjecture

Consider an EFT containing Einstein gravity plus a massive spin-two field (plus other matter fields):

- Massless spin-two graviton $g_{\mu\nu}$
- Massive spin-two field $w_{\mu\nu}$ with mass m.

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Is this theory also consistent at the quantum level?

Can it be coupled to quantum gravity, i.e does it belong to the swampland or not?

Action:

$$S_{g,w} = \int d^4x \sqrt{-g} \left[M_p^2 R(g) - \frac{1}{4} w^{\mu\nu} L_{\mu\nu}^{\rho\sigma} w_{\rho\sigma} - \frac{1}{8} m^2 \left(w_{\mu\nu} w^{\mu\nu} - w^2 \right) + \ldots \right]$$

$$L_{\mu\nu}^{\rho\sigma} w_{\rho\sigma} = -\frac{1}{2} \left[\Box w_{\mu\nu} - 2\partial_{(\mu} \partial_\alpha w_{\nu)}^\alpha + \partial_\mu \partial_\nu w - \eta_{\mu\nu} \left(\Box w - \partial_\alpha \partial_\beta w^{\alpha\beta} \right) \right]$$

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Five degrees of freedom of massive spin-two field:

[see e.g. G. Dvali, (2006)]

$$h = \pm 2 \qquad h = \pm 1 \qquad h = 0$$

$$\downarrow \qquad \downarrow \qquad \downarrow$$

$$w_{\mu\nu} = h_{\mu\nu} + 2\partial_{(\mu} \chi_{\nu)} + \Pi^L_{\mu\nu} \pi \ .$$

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Spin-one χ_μ : Massive $U(1)_\chi$ Stückelberg gauge field

[see also M. Reece, arXiv:1808.09966]

$$\mathcal{L}_{\rm FP} \supset -\frac{1}{8} m^2 F_{\mu\nu} F^{\mu\nu} \,, \qquad F_{\mu\nu} \equiv \partial_\mu \chi_\nu - \partial_\nu \chi_\mu$$

Now we want to apply WGC with respect to $U(1)_\chi$.

Free theory: there is no notion of normalised coupling.

$\Longrightarrow$ Need additional matter (or self coupling).

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$$\mathcal{L}_{\text{int}} = \frac{m^2}{M_w}\chi_\mu J^\mu \longrightarrow 0$$

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M_w arises also in non-linear completion of bi-metric theory:

$$S_{g,w} = \int d^4x \left[M_p^2\sqrt{-g}R\left(g\right) + M_w^2\sqrt{-w}R\left(w\right)\right] + \ldots$$

Spin-two mode $w_{\mu\nu}$ couples to tensor $T_w^{\mu\nu}$:

$$\mathcal{L}_{\rm int} = \frac{1}{M_w} w_{\mu\nu} T_w^{\mu\nu} = \frac{1}{M_w} \chi_\mu \partial_\nu T_w^{\mu\nu}$$

$$\Longrightarrow \quad \partial_\nu T_w^{\mu\nu} = m^2 J^\mu$$

[Compare with Bachas, Lavdas (2018), Bachas (2019)]

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From kinetic term: spin-two coupling

$$\boxed{g_\chi = \frac{m}{\sqrt{2} M_w}}$$

Then the (magnetic) weak gravity conjecture for $U(1)_\chi$ can be formulated as:

[D. Kläwer, D.L., E. Palti, arXiv:1811.07908]

Spin-two swampland conjecture:

$$\Lambda_w = g_\chi M_p = \frac{m M_p}{M_w}$$

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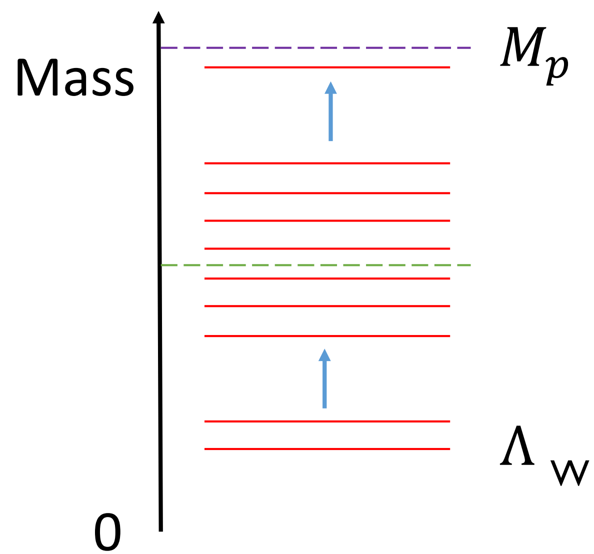
It predicts an infinite tower of higher spin states above Λ_w :



With $M_w \leq M_p \implies m \leq \Lambda_w \leq M_p$

Evidence for spin-two swampland conjecture:

A: KK compactification of 5D gravity

$U(1)_\chi$ coupling: $g_\chi = \frac{1}{(M_p R)^{\frac{3}{2}}}$ ($M_w = M_p$)

(Note that $U(1)_\chi$ is not the the same as massless $U(1)_{KK}$.)

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Spin-two conjecture: $$\boxed{\Lambda_{\rm KK} = g_\chi M_p \equiv m_{\rm KK}}$$

Infinite tower of massive KK states: $m_n = \frac{n M_p}{(M_p R)^{\frac{3}{2}}}$

B: String realization of gravity plus massive spin-two:

Consider closed and open strings on D3-branes:

[S. Ferrara, A. Kehagias, D.L. arXiv:1810.08147]

$$M_p = M_s\sqrt{\mathcal{V}} \quad , \qquad g_\chi = \frac{g_s}{\sqrt{\mathcal{V}}}$$

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Spin-two conjecture: $$\boxed{\Lambda_s = g_\chi M_p \equiv g_s M_s}$$

Infinite tower of Regge states $m_n \simeq \sqrt{n} g_s M_s$

Massless limit: tension less string $M_s \rightarrow 0$

What about „massive gravity":

[D. Boulware, S. Deser (1972);
G. Dvali, G. Gabadadze, M. Porrati (2000);
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[G. Dvali (2006)]

Or one has to deal with an infinite tower of states !

Question:

Can we construct quantum gravity/string theories without a massless spin-two graviton field?

S-folds of Supergravity and of Superstrings:

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- Strongly coupled theories.
- Massless spin-two graviton is projected out - there are only massive higher spin fields with mass of order M_s
- Topological theories: topological twist by S - duality and diffeomorphisms
- Exist also for N=7 supersymmetry

Outline:

II) Spin-two swampland conjecture

III) AdS - Distance Conjecture

IV) de Sitter swampland and higher spins states

V) Conclusion and Outlook

III) AdS - distance conjecture:

[D.L. , E. Palti, C. Vafa (2019)]

[See talks by E. Palti and C. Vafa]

Consider AdS vacua in quantum gravity with varying negative cosmological constant Λ .

What is happening in the limit $\Lambda \rightarrow 0$?

III) AdS - distance conjecture:

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Consider AdS vacua in quantum gravity with varying negative cosmological constant Λ .

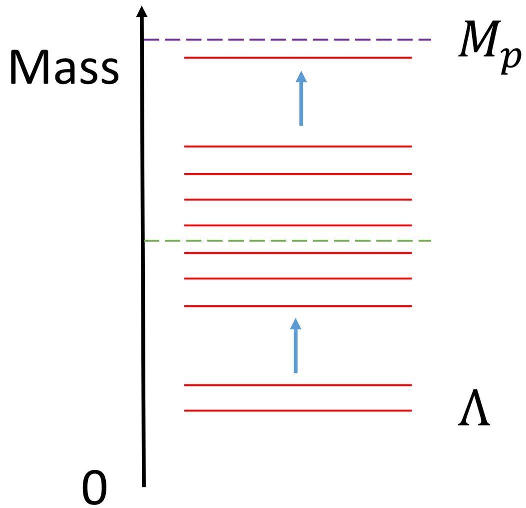
What is happening in the limit $\Lambda \rightarrow 0$?

AdS Distance conjecture (ADC):

There exist an infinite tower of states with mass scale m, which behaves as

$$m \sim |\Lambda|^{\alpha} \quad \text{with} \quad \alpha > 0$$

$\Lambda \to 0$ is at infinite distance !



Infinite tower of states above Λ

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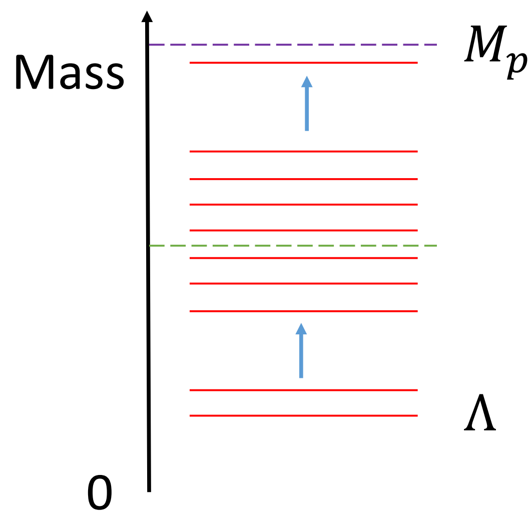

Infinite tower of states above Λ

Strong AdS distance conjecture (SADC):

The bound is satisfied for supersymmetric AdS vacua with $\alpha = 1/2$: $m \sim |\Lambda|^{1/2}$

The conjecture is satisfied for many know backgrounds of string and M - theory like $AdS_5 \times S^5$ via the tower of KK modes.

Refined de Sitter conjecture:

[G. Obied, H- Ooguri, L. Spodyneiko, C.Vafa (2018);
H. Ooguri, E. Palti. G. Shiu, E.Vafa (2018)]

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Instead of (1) consider (1'): $|\nabla V|^2 \geq c^2 V^2$

This condition is violated for AdS vacua.

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But we conjecture that there must be a full tower of states with $\alpha \geq 1/2$ for AdS vacua.

Generalized distance conjecture:

Apply the distance conjecture to the space-time metric.

Family of metrics with a distance on the space of metrics:

$$g_{MN} = g^{0}_{MN} + \delta g_{MN}$$

Associated distance:

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

If we apply this to the metric of $M = \mathrm{Mink}_4 \times \mathrm{CY}_6$

then this reduces to the known scalar distance conjecture of the CY moduli.

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Applied to Weyl rescalings:

$$\tilde{g}_{MN} = e^{2\tau} g_{MN}$$

$$\sqrt{|\tilde{g}|}\tilde{R} = e^{(d-2)\tau}\sqrt{|g|}\left[R + (d-2)(d-1)(\partial\tau)^2\right]$$

Associated distance:

$$\Delta = \sqrt{(d-2)(d-1)}(\tau_f - \tau_i)$$

Now consider AdS space with metric

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

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

Distance under Weyl rescaling:

$$\Delta = -\frac{1}{2}\int_{\Lambda_i}^{\Lambda_f}\sqrt{\left(d-2\right)\left(d-1\right)}d\log\Lambda$$

Now consider AdS space with metric

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

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

Distance under Weyl rescaling:

$$\Delta = -\frac{1}{2}\int_{\Lambda_i}^{\Lambda_f}\sqrt{\left(d-2\right)\left(d-1\right)}d\log\Lambda$$

This then immediately leads to the ADC:

$$m\left(\Lambda_f\right) = m\left(\Lambda_i\right)\left(\frac{\Lambda_f}{\Lambda_i}\right)^{\alpha} \quad \text{resp.} \quad m\left(\Lambda\right) = M_p\left(\frac{\Lambda}{M_p^2}\right)^{\alpha}$$

ADC in string theory:

- There is no separation of scales in AdS string vacua.

[M. Duff, B. Nilsson, C. Pope (1986);
M. Douglas, S. Kachru (2006);
F. Gautason, M. Schillo, T. Van Riet, M. Williams (2015);
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[CFT discussion: J. Conlon, F. Quevedo (2018)]

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- In the flat limit $\Lambda \rightarrow 0$ always a infinite tower of massless states is opening up - there always exists an extra space factor like

$$AdS_d \times M^{d'}$$

Pure AdS space cannot exist alone in quantum gravity.

The generalized distance conjecture should also hold for de Sitter vacua (if they exist):

There should exist a light tower of states like

$$m \sim 10^{-120\alpha} M_p$$

Outline:

II) Spin-two swampland conjecture

III) AdS - Distance Conjecture

IV) de Sitter swampland and higher spins states

V) Conclusion and Outlook

IV) dS swampland and higher spin states:

[D.L. , E. Palti, C. Vafa: unpublished]

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Generalization to states with higher spin k in d dimensions:

Higuchi bound:

$$M^2_{(k)} \geq H^2\,(k-1)\,(d+k-4)$$

Let us compare the Higuchi bound with the masses of the higher spin states on the Regge trajectory:

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At some critical spin the Higuchi bound will be violated:

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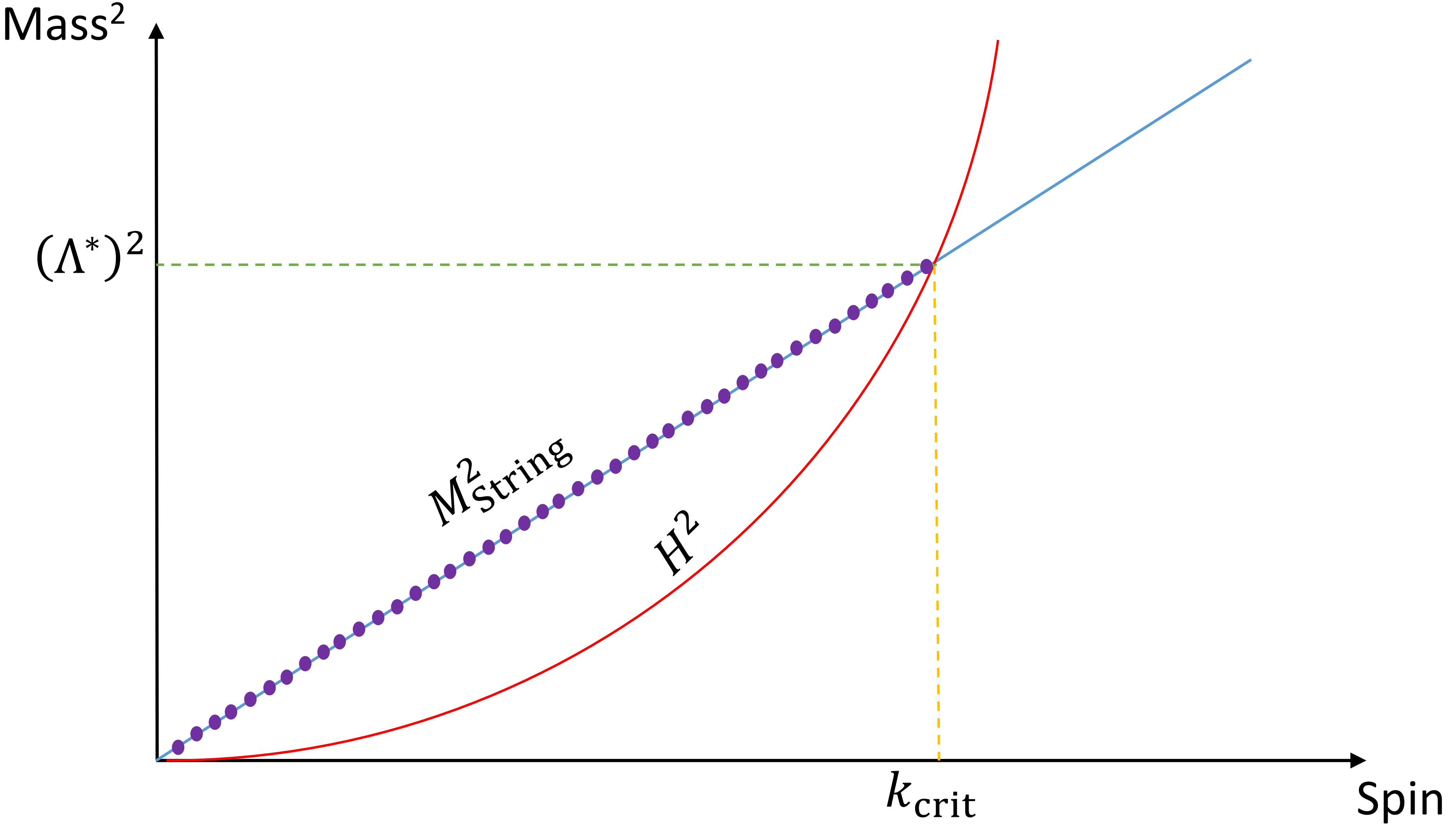
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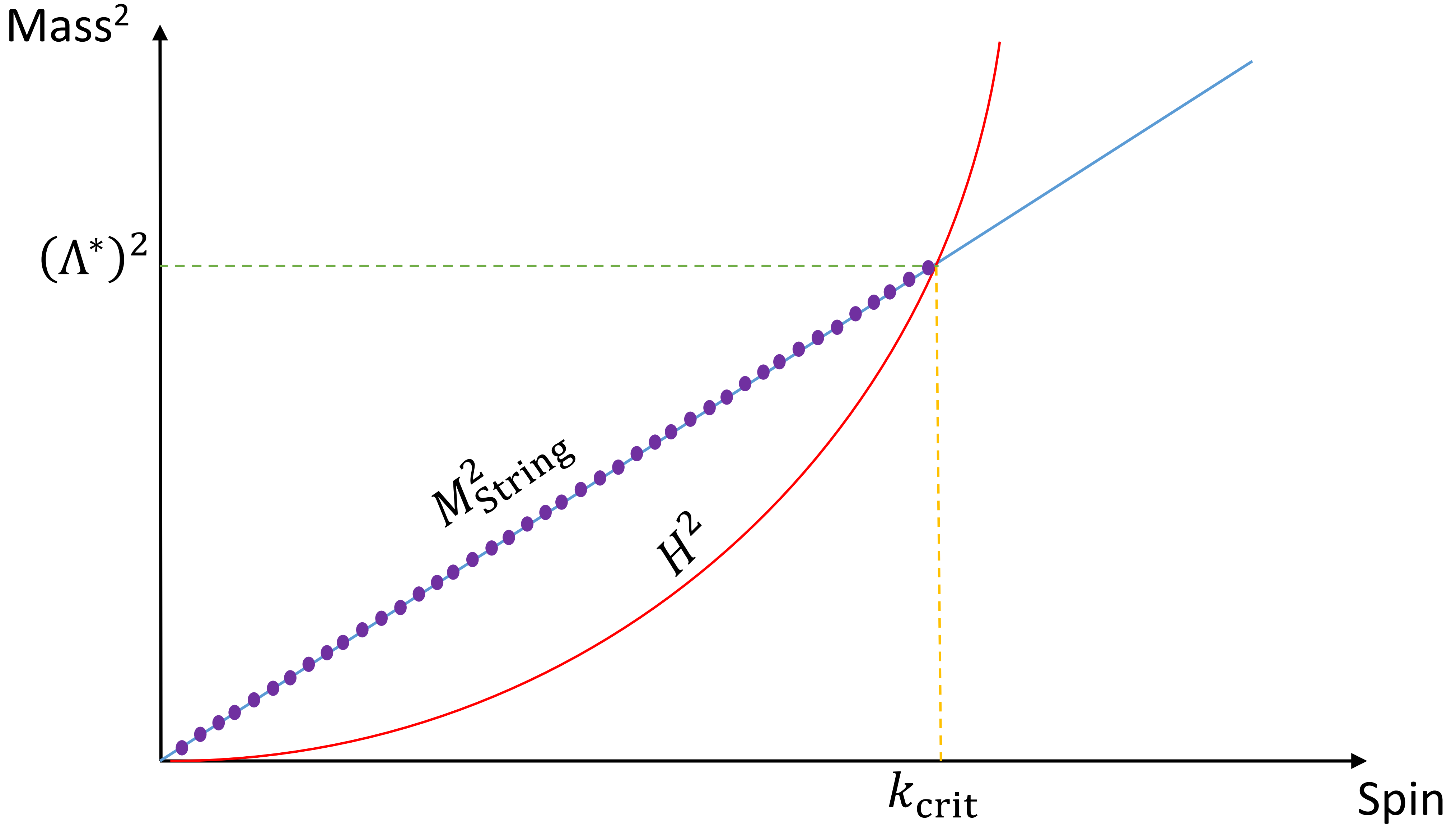
Therefore if we trust this argument, perturbative string theory would be inconsistent in de Sitter space for any finite value of H.

Note that the higher spin Regge states that violate the Higuchi bounds are precisely those, whose length exceeds the de Sitter horizon:

$$L_{(k)}^2 = M_{\rm string}^{-2} k \geq 1/H \quad \text{for} \quad k \geq k_{\rm crit}$$

I.e. they do not „fit“ into de Sitter space, and this may possibly ruin the consistency of string theory as theory for quantum gravity (problem with modular invariance).

Now let us relax the condition that all higher spin Regge states must satisfy the Higuchi bound, but only require this up to some scale Λ^* .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It also follows that consistency with the Higuchi bound implies a lower bound on the string coupling constant:

$$g_s > g_s^\star = \hat{R}^3 \sqrt{\frac{H}{M_p}} \qquad (d = 4)$$

This rules out (quasi) de Sitter solutions for weakly coupled strings !

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Can gravity be emergent?

Thank you !