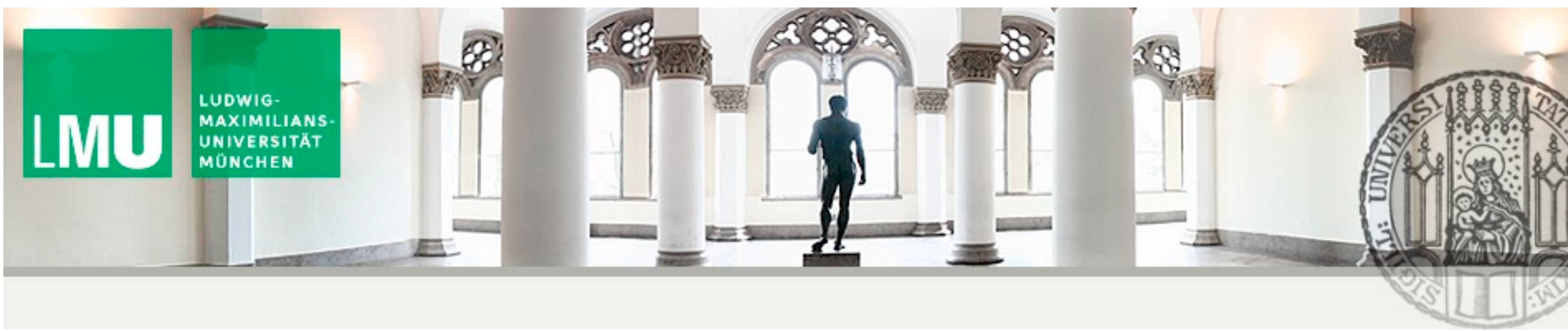
The Gravitino and the Swampland

DIETER LÜST (LMU, MPP)



SUSY 2022, Ioannina, 28th. June 2022

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Joint work with Niccolo Cribiori and Marco Scalisi,
arXiv:2104.08288, JHEP 06 (2021) 071

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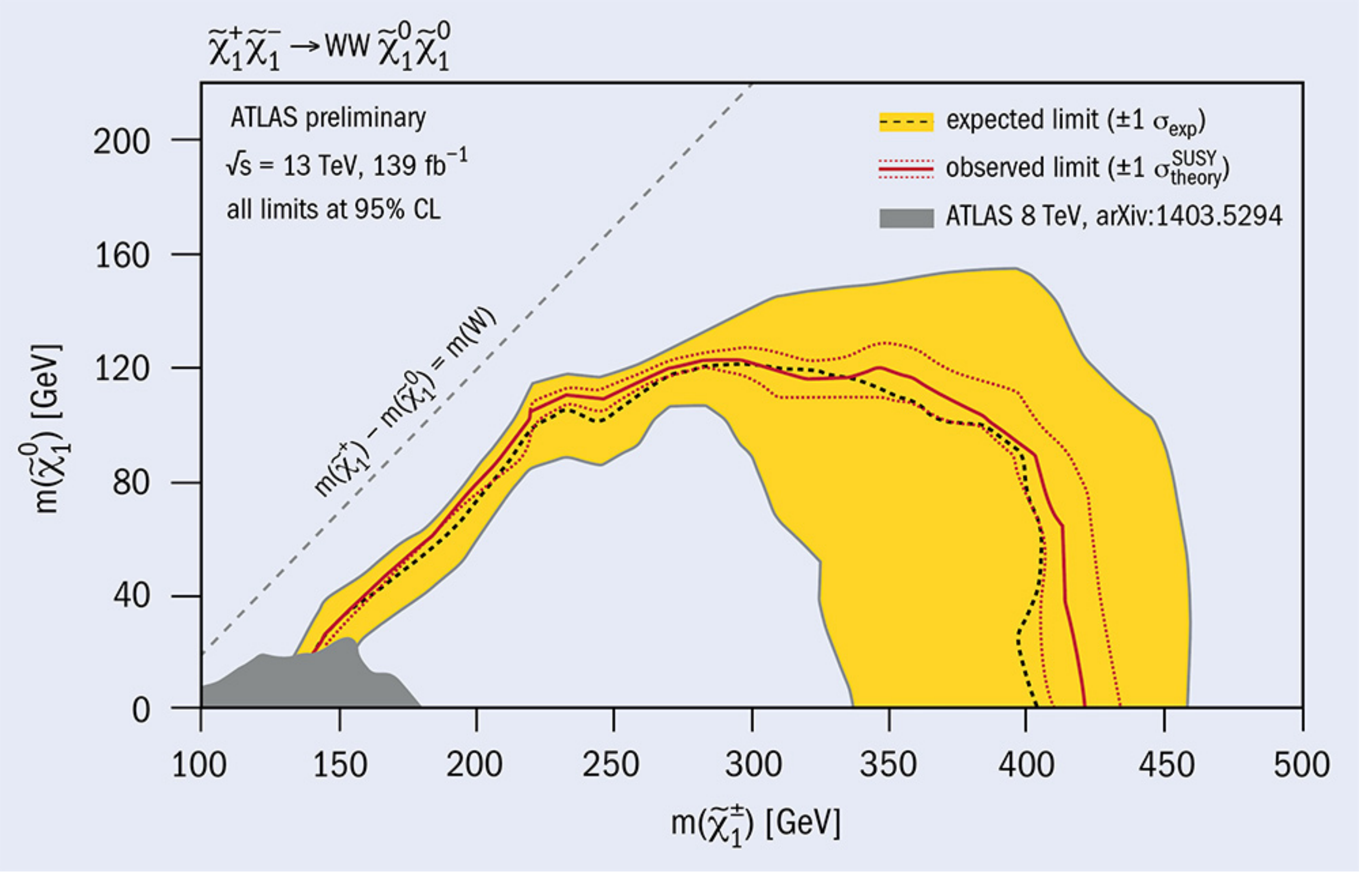
I) Introduction

Apparently low energy supersymmetry is not favoured by experiments:

$$M(\text{Susy partner}) > \mathcal{O}(TeV)$$



Is there any fundamental reason against low energy supersymmetry ??

$\mathcal{N} = 1$ local supersymmetry:

Spin - 2 graviton $\underset{\text{Susy}}{\longleftrightarrow}$ Spin - 3/2 gravitino

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The scale of susy breaking is set by the gravitino:

$$\boxed{M^2_{SUSY} \simeq m_{3/2}\, M_P}$$

Exp: $m_{3/2} \geq \mathcal{O}(10^{-3}\mathrm{eV})$

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Is there any fundamental reason against a light gravitino ??

Can we get information about the scale of Susy breaking, i.e. about the mass of the gravitino from basic properties of quantum gravity ?

Swampland program:

[C.Vafa (2005);
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Which IR consistent quantum field theories cannot be embedded into a UV complete quantum gravity theory?

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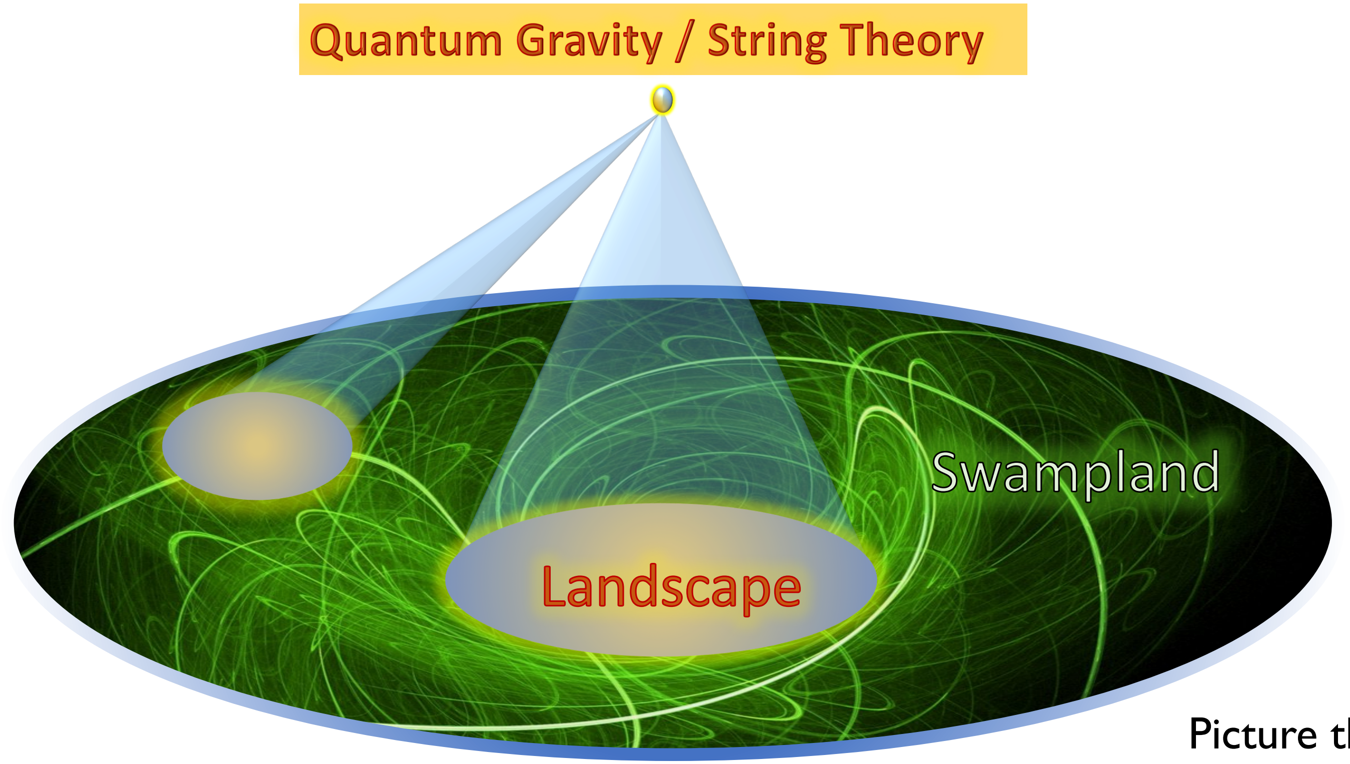

Picture thanks to Eran Palti

Outline:

II) Some swampland conjectures

III) AdS distance conjecture

IV) Gravitino mass conjecture

V) Phenomenological consequences

II) Global symmetries & distance conjectures

No global symmetry conjecture:

[T. Banks, L. Dixon(1988); T. Banks, N. Seiberg (2011)]

A theory with a finite number of states, coupled to gravity, cannot have exact global symmetries.

E.g. global baryon number cannot be exactly preserved in quantum gravity !!

II) Global symmetries & distance conjectures

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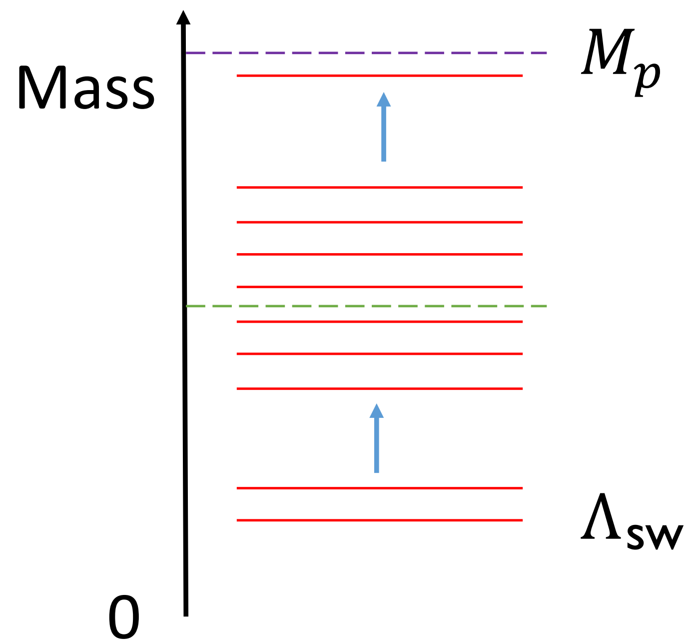
Now let us gauge the global symmetry, introducing an Abelian gauge coupling constant $g_{U(1)}$

Global limit $g_{U(1)} \to 0$ is apparently obstructed.

EFT typically breaks down above a swampland scale Λ_{sw}.

If swampland scale Λ_{sw} is lower than any characteristic energy scale of the EFT then the entire EFT belongs to the swampland.

Often there is an (infinite) tower of states above $E \geq \Lambda_{sw}$



Swampland distance conjecture:

At large distance Δ directions in the parameter space of string vacua there must be an infinite tower of states with mass scale m.

SDC:

$$\boxed{m = M_P e^{-\Delta}}$$

[H. Ooguri, C.Vafa (2006)]

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$$\Lambda_{sw} << M_P \text{ when } \Delta \to \infty$$

In general Δ determines the geodesic distance in the ϕ - parameter space of backgrounds in gravity: $\Delta = \Delta(\phi)$

$$\mathcal{L}_{eff} \simeq \frac{1}{2}(\partial\Phi)^2 + (V(\Phi)) \text{ with } \Phi = \Phi(\phi)$$

$$\boxed{\Longrightarrow \quad \Delta = \lambda\Phi}$$

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At the KK mass scale a new dimension is opening up.

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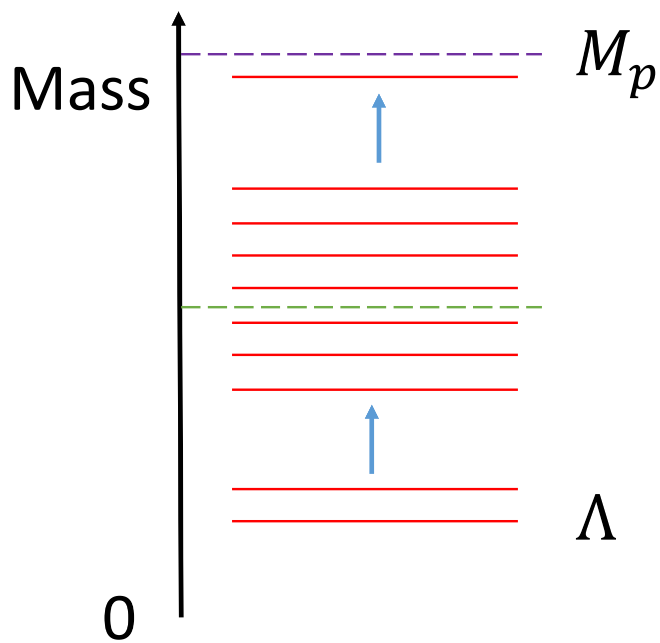
At the KK mass scale a new dimension is opening up.

For a compact circle of radius R, the relevant mass scale is

$$m = m_{KK} = 1/R\,, \quad \Delta_{KK}(R) = \log R$$



The relevant tower are the KK particles with masses

$$m_n = \frac{n}{R}$$

and also with U(1) gauge couplings

$$g_{U(1)} = \frac{1}{R}$$

Quantum gravity/string vacua are normally characterised by several parameters, like masses or other couplings,

$$g = g(\phi)\,, \quad m = m(\phi)$$

and we like to know, what is happening in certain (infinite distance) limits, e.g.

$$g \to 0 \qquad \text{or} \qquad m \to 0$$

and in particular, if these limits are obstructed in quantum gravity in the sense that they related to lowering the cut-off of the theory and are accompanied by a tower of light states.

III) AdS distance conjecture:

Consider AdS_d vacua in quantum gravity with varying negative cosmological constant Λ_{cc}.

AdS Distance conjecture (ADC):

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

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

$$\boxed{m \sim |\Lambda_{cc}|^{\alpha} \quad \text{with} \quad \alpha \geq \frac{1}{2}}$$

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AdS_d alone cannot exits alone as consistent background.

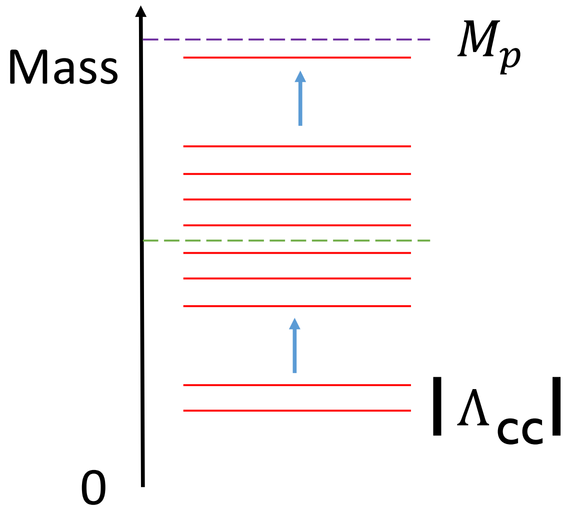
(Interesting implications for dual CFT description!)

[L. Alday, E- Perlmutter (2019), E. Perlmutter, L. Rastelli, C. Vafa, I. Valenzuela (2020)]

[S. Lüst, C. Vafa, M. Wiesner, K. Xu(2022)]

Strong AdS distance conjecture (SADC):

The bound $\alpha = 1/2$ is saturated for supersymmetric AdS vacua.



Infinite tower of states above Λ_{cc}

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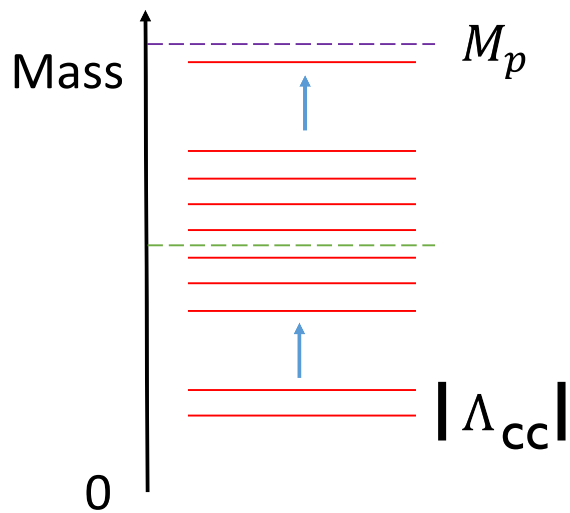

Infinite tower of states above Λ_{cc}

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

Consider (meta-stable) vacua with positive cosmological constant and assume that the ADC is still valid :

Then, in the standard cosmological scenario, the ADC leads to a very strong prediction, namely to a very light tower of states:

$$m \sim 10^{-120\alpha}$$ (in Planck units)

What could be this tower of states, and if it exists, can it escape observations?

The mass scale of the cosmological constant is related to single mesoscopic extra dimension and very light KK states:

[M. Montero, C.Vafa, I.Valenzuela, arXiv:2205.12293]

$$l \simeq \Lambda^{-1/4} \simeq 1\ \mu m\,, \qquad m_{KK} \sim \Lambda^{1/4} \simeq 2.3\ meV$$

Related species scale: $\Lambda_{QG} \simeq 10^{10}\ Gev$

This also leads to a tower of sterile neutrinos $m_{\nu_s} \sim 1\ eV$

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The mesoscopic extra dimension opens the possibility that all dark matter is given in terms of Primordial Black Holes:

[L. Anchordoqui, I. Antoniadis, D.L., arXiv:2206.07071]

$$10^{15}\ g \leq M_{BH} \leq 10^{21}\ g$$

Reason: longer BH life time due to mesoscopic dimension.

Gravitino mass conjecture (GMC):

[N. Cribiori, M. Scalisi, D.L. ; A. Castellano, A. Font. A. Harraez, L. Ibanez (2021)]

In the limit of small gravitino mass there exist an infinite tower of states with mass scale m, which behaves as:

$$\boxed{m \sim (m_{3/2})^n \quad \text{with} \quad n > 0}$$

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and the ADC and the GMC are equivalent to each other.

(Note that the case $m_{3/2} = 0$ is special and not continuously related to finite $m_{3/2}$.)

But in case of broken supersymmetry one has that

$$(m_{3/2})^2 > -\frac{\Lambda_{cc}}{3}$$

and the ADC and the GMC lead to different conclusions.

In particular the GMC allows for

$$|\Lambda_{cc}| \to 0 \quad \text{and} \quad m_{3/2} \ \text{finite}$$

and without a tower of light states.

Why the GMC can be true:

(i) The gravitino mass is related to extra dimensions

The GMC follows from the distance conjecture.

(ii) The gravitino mass is related to a U(1) gauge coupling

The GMC follows from the (magnetic) weak gravity conjecture.

(i) Extra dimensions

[See also I. Antoniadis, C. Bachas, D. Lewellen, T. Tomaras (1988)]

The $\mathcal{N} = 1$ effective action contains besides the graviton and the gravitino also a certain number of scalars ϕ (as well as their fermionic superpartners).

ϕ : Moduli parameters of the compactification

Their couplings in the effective action are determined by

Kähler potential: $K(\phi, \bar{\phi})$

Superpotential: $W(\phi)$

Kinetic terms of scalars:

$$\mathcal{L}_{eff} \simeq \frac{1}{2} K_{i\bar{j}} \partial\phi_i \partial\bar{\phi}_j + c.c$$

Supersymmetry breaking:

F-terms: $$F_i \equiv e^{G/2} G_i = e^{K/2} |W| \left(K_i + \frac{W_i}{W} \right) \neq 0$$

$$G(\phi, \bar{\phi}) = K(\phi, \bar{\phi}) + \log |W(\phi)|^2$$

Gravitino mass $$\boxed{(m_{3/2})^2 = e^{K(\phi, \bar{\phi})} |W(\phi)|^2 \equiv e^G}$$

Scalar potential (cosmological constant):

$$V \equiv \Lambda_{cc} = V_G + V_F$$

$$V_G = -3e^G = -3e^K |W|^2 = -3(m_{3/2})^2$$

$$V_F = e^G G^{i\bar{j}} G_i G_{\bar{j}} \geq 0 \,, \qquad \Longrightarrow \quad (m_{3/2})^2 \geq \frac{\Lambda_{cc}}{3}$$

Consider a (string) compactifcation from 10 to 4 space-time dimensions on a compact (Calabi-Yau) space with volume $\mathcal{V}$.

KK mass scale: $\boxed{m_{KK} = \left(\frac{1}{\mathcal{V}}\right)^{2/3}}$

$$K(\phi, \bar{\phi}) = -\alpha \log \mathcal{V}(\phi, \bar{\phi}) + K'$$

$$\langle W \rangle \sim \mathcal{V}^{\beta/2}$$

$\Longrightarrow \quad m_{3/2} \sim \left(\frac{1}{\mathcal{V}}\right)^{\frac{\alpha-\beta}{2}}$ Hence $\quad n = \frac{4}{3(\alpha - \beta)}$

Supersymmetric (KKLT) AdS vacua: [S. Kachru, R. Kallosh, A. Linde, S. Trivedi (2003)]

$$K = -3\log(T+\bar{T}) + \ldots = -2\log\mathcal{V} + \ldots$$

$$\langle W \rangle \sim T e^{-cT}$$

R. Blumenhagen, M. Brinkmann, A. Makridou (2019)

$$n = 1/3$$

+ log corrections

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Non-supersymmetric Minkowski vacua (Scherk-Schwarz):

[J. Scherk, J. Schwarz (1979); E. Cremmer, S. Ferrara, C. Kounnas, D. Nanopoulos (1983), R. Rohm (1984)]

$$K = -\log[(S+\bar{S})(T+\bar{T})(U+\bar{U})] + K'(\phi,\bar{\phi})$$

$$W = \text{const} \qquad n = 4/3$$

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Non-supersymmetric dS: anti-brane uplift

[G. Dvali, H. Tye (1999); S. Kachru, R. Kallosh, A. Linde, S. Trivedi (2003)]

$$V_{dS} = V_{AdS} + V_{up} \;, V_{up} = \frac{c}{\mathcal{V}^p} \qquad n = 1/3$$

(ii) U(1) gauge coupling

In case there is an underlying extended space-time supersymmetric, the gravitino is charged under an U(1) gauge symmetry.

E.g. $\mathcal{N} = 2$ supersymmetry:

Extended supergravity supermultiplet:

(Spin-2, spin-3/2, spin-1)

↑

Graviphoton U(1) gauge boson

Prepotential: $\boxed{m_{3/2} \simeq g_{3/2}}$

$g_{3/2} \to 0 \implies m_{3/2} \to 0$ Global symmetry !

V) Applications:

(i) Quantum gravity cutoff in an EFT with susy breaking.

N: number of light species in an EFT.

Gravity becomes strongly coupled at the species scale:

$$\Lambda_{QG} = \frac{M_P}{\sqrt{N}}$$

[G. Dvali (2007)]

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N: number of light species in an EFT.

Gravity becomes strongly coupled at the species scale:

$$\Lambda_{QG} = \frac{M_P}{\sqrt{N}}$$

[G. Dvali (2007)]

If species are built by the tower of states we get $N = \frac{\Lambda_{QG}}{m}$

For the gravitino mass conjecture we then get

$$\Lambda_{QG} \simeq M_P \left(\frac{m_{3/2}}{M_P}\right)^{\frac{n}{3}}$$

$$m_{3/2} < \Lambda_{QG} \quad \text{if} \quad n < 3 \qquad n \geq 3 \quad \Longrightarrow$$

No effective field theory of supersymmetry breaking.

(ii) Inflation and supersymmetry

The mass scale of inflation in the EFT is determined by the Hubble parameter H.

For consistency one needs $H < \Lambda_{QG}$

This translate into the following lower bound on the gravitino mass

$$m_{3/2} > M_P^{\frac{n-3}{n}} H^{\frac{3}{n}}$$

For $n = 3$ $m_{3/2} > H$ [see also R. Kallosh, A. Linde (2004)]

Susy breaking scale must be higher than the scale of inflation!

CMB and the scalar-to-tensor ratio r :

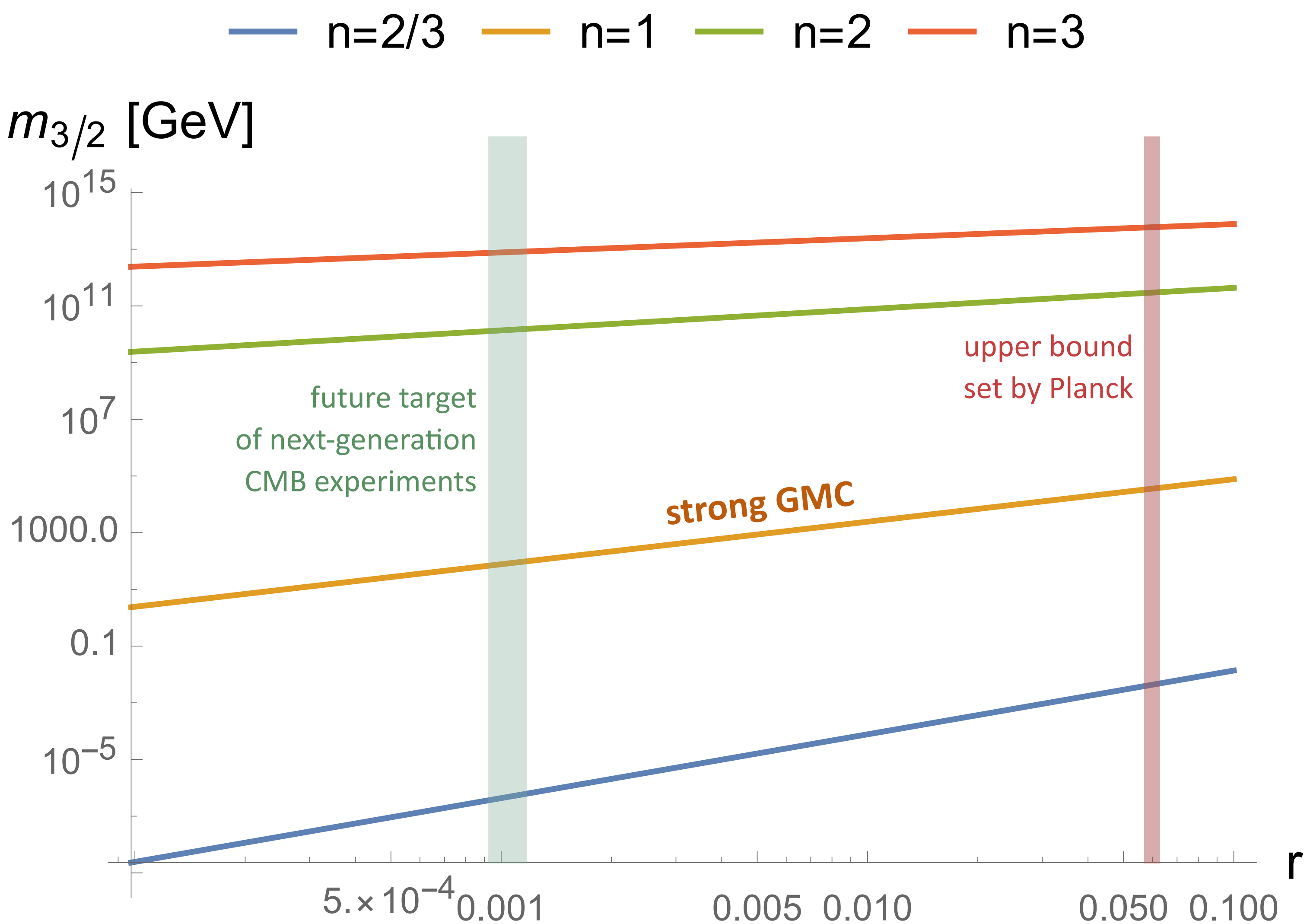
$$H = \sqrt{\frac{\pi^2 A_s\ r}{2}} M_P \simeq 10^{-4}\sqrt{r}\ M_P$$

So we get $$m_{3/2} > \left(10^{-12}\ r^{\frac{3}{2}}\right)^{\frac{1}{n}}\ M_P$$

Currently $$r_{exp} \lesssim 0.06$$

Next CMB experiments try to reach $r = \mathcal{O}(10^{-3})$

So one can reach $m_{3/2} \geq 10^2\,\mathrm{GeV} \qquad (n = 1)$



n=2/3
n=1
n=2
n=3
$m_{3/2}$ [GeV]
10^{15}
10^{11}
10^{7}
1000.0
0.1
10^{-5}
future target
of next-generation
CMB experiments
upper bound
set by Planck
strong GMC
r
$5.\times10^{-4}$
0.001
0.005
0.010
0.050
0.100

V) Outlook:

- There are various swampland conjectures, motivated from strings and black holes.

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  Many of them are related and hinting at a deeper common origin.

- Two specific swampland conjectures:

  ADC: Λ_{cc} is setting the cut-off of the theory.

  GMC: $m_{3/2}$ is setting the cut-off of the theory.

  Perhaps there is parametric link of the form

$$m_{3/2}^2 \sim |\Lambda|^p$$

Strong constraints from inflation on $m_{3/2}$

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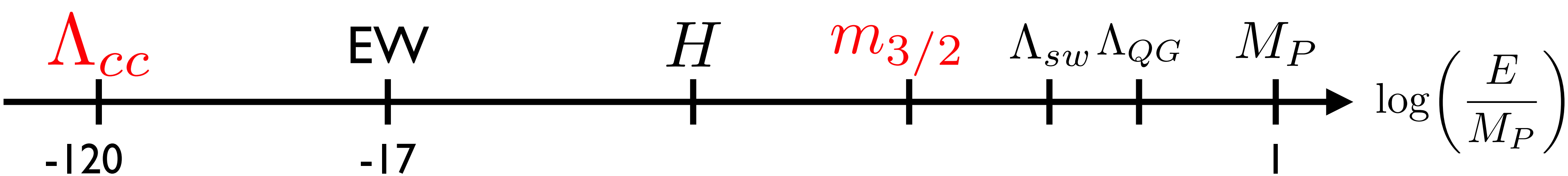
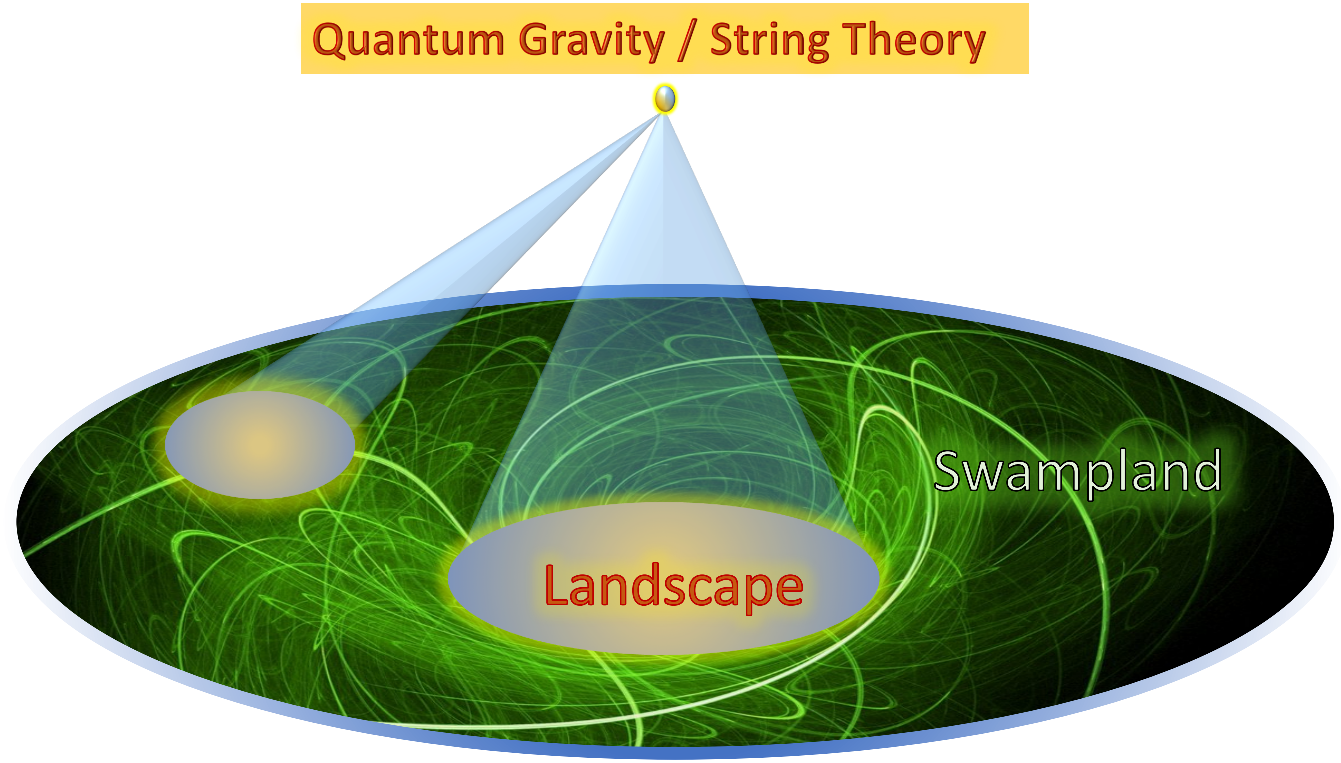
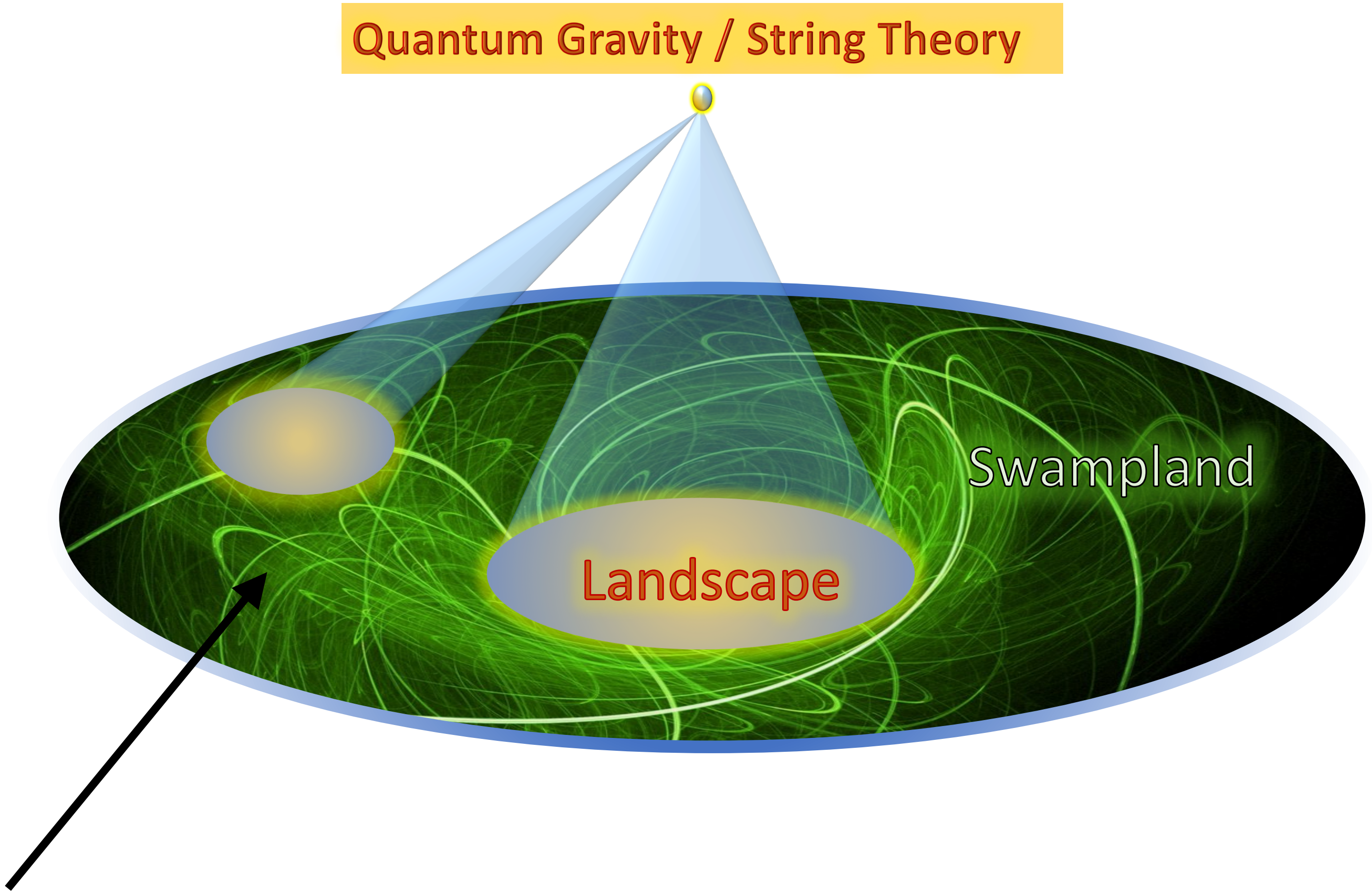



Quantum Gravity / String Theory
Swampland
Landscape



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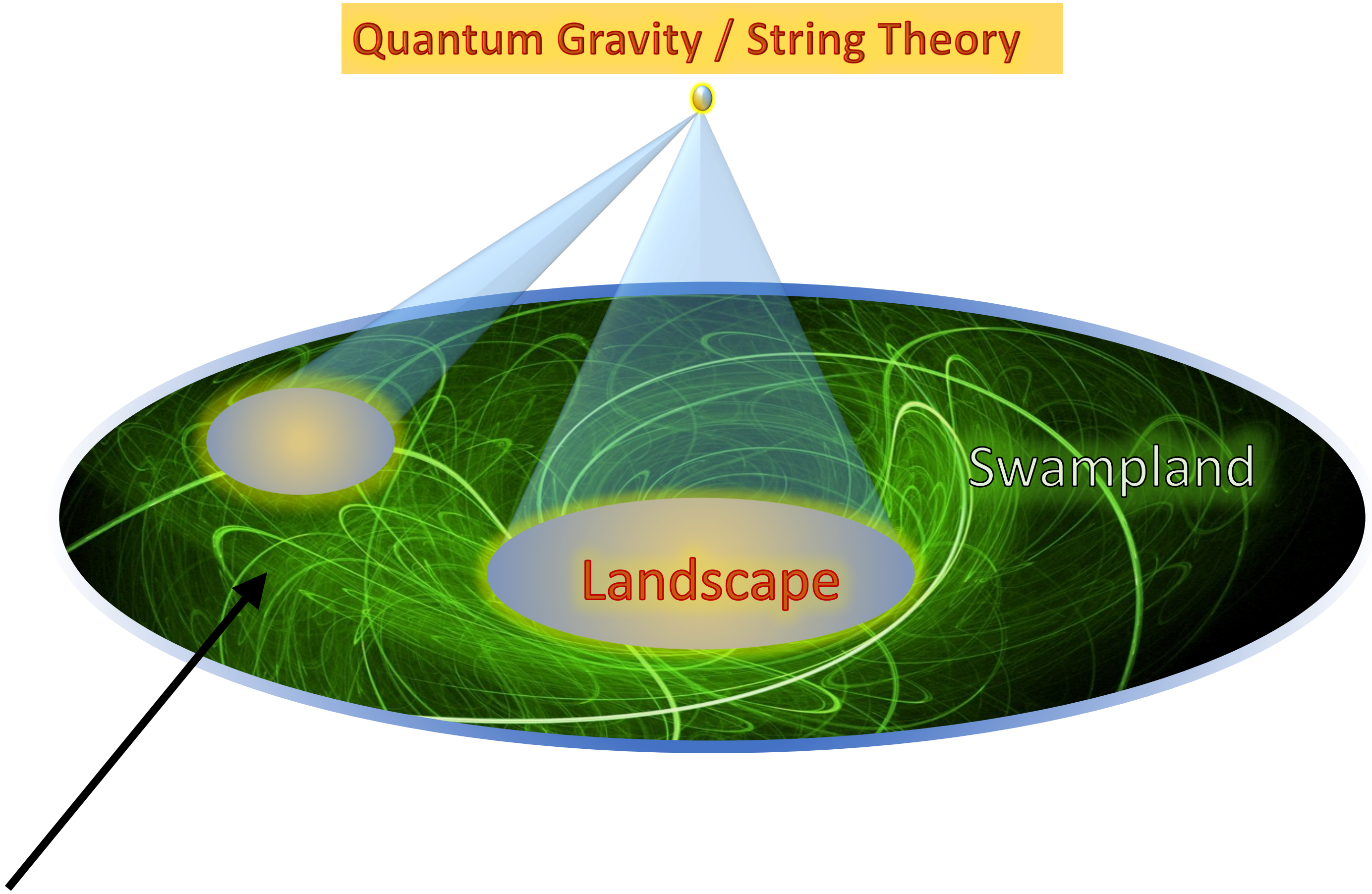

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Thank you !