Swampland Conjectures in the High Energy Phase of QG

Ralph Blumenhagen

Max-Planck-Institut für Physik, München

(RB, Kneißl, Makridou, arXiv:2011.13956)
(Alvarez-Garcia, RB, Kneißl, Makridou,Schlechter, arXiv:2107.nnnnn)

The swampland program

The swampland program

Guided by general quantum gravity arguments and experience from string theory.

Problem: String theory as we understand it is a background dependent formulation of quantum gravity and can therefore be studied case by case $\rightarrow$ lamppost problem

By now we have a couple of swampland conjectures: Swampland distance- , dS swampland- , AdS distance conjecture with evidence mostly from perturbative string vacua. (Ooguri,Vafa), (Obied,Ooguri,Spodyneiko,Vafa),(Gautason,Van Hemelrick,Van Riet),(Lüst,Palti,Vafa),...

- Do they also hold in non-perturbative regimes?
- Or other extreme situations, like the high energy phase?

Review a couple of swampland conjectures.

dS swampland conjectures

dS swampland conjectures

The dS swampland conjecture:

$$|\nabla V| > c \cdot V$$

(Obied,Ooguri,Spodyneiko,Vafa, 1806.08362). This follows from the TCC in the asymptotic field limit (Bedroya,Vafa, 1909.11063).

The no eternal inflation principle imposes the weaker bound (Rudelius, 1905.05198)

$$\frac{|V'|}{V} > c \cdot V^{\frac{n-2}{4}} .$$

Applying the TCC to a sequence dS bubble decays leads to an effective potential marginally satisfying this bound (Bedroya,Montero,Vafa,Valenzuela, 2008.07555).

Quantum breaking

Quantum breaking

Quantum break time approach

(Dvali,Gomez, 1312.4795+1412.8077), (Dvali,Gomez,Zell, 1701.08776)

Viewing dS as a coherent state of gravitons over Minkowski space, the decoherence of this state, i.e. quantum scattering of gravitons from the coherent state, leads to the quantum break time

$$t_Q \sim \frac{t_{\rm cl}}{\alpha} \sim \frac{1}{H}\left(\frac{M_{\rm pl}}{H}\right)^{n-2}$$

No quantum breaking proposal: The theory must censor it by providing a classical mechanism that leads to a faster decay of de Sitter. (Dvali,Gomez, 1806.10877), (Dvali,Gomez,Zell, 1810.11002)
For a slowly rolling field this implies

$$\frac{|V'|}{V} > c \cdot V^{\frac{n-2}{4}}\,, \qquad \text{no eternal inflation.}$$

QB from Coarse Graining

QB from Coarse Graining

Can one get the dS swampland bound, as well?

(Bhg,Kneißl,Makridou, 2011.13956).

View quantum breaking of dS as a result of $\langle T^{\text{ren}}_{\mu\nu}\rangle \not\sim g_{\mu\nu}$.

(Markkanen, 1703.06898)

- Quantizing a scalar field according to the quasi-classical approach, one can define the Bunch-Davies vacuum in the usual FLRW coordinates and finds $\langle T^{\text{ren}}_{\mu\nu}\rangle \sim g_{\mu\nu}$.
- An observer in the center of the static patch sees a constant matter contribution with $\langle T^{\text{ren}}_{\mu\nu}\rangle \not\sim g_{\mu\nu}$ scaling like $\rho_m \sim H^n$. (thermal Hawking radiation from the horizon)
- The backreaction of this in the Friedmann equations leads to $\dot{H} \neq 0$ so that strinkingly $t_Q \sim \frac{1}{H}\left(\frac{M_{\text{pl}}}{H}\right)^{n-2}$

QB from Coarse Graining

QB from Coarse Graining

Acknowledge fruitful discussions on this issue with the authors of (Aalsma,Cole,Morvan,Shiu,van der Schaar, 2105.12737)

- Generalization to string theory guided by assumption that there will be a thermal flat space matter contribution, too. (Bhg,Kneißl,Makridou, 2011.13956),
- New issue: Hagedorn transition at $T_H \sim M_s$, leading to a new phase of string theory (Atick,Witten, NPB 310 (1988) 291)
- It might be a sub-critical string theory or a lattice theory or a topological gravity theory (see e.g. (Agrawal,Gukov,Obied,Vafa, 2009.10077) and **talk by Gukov**)

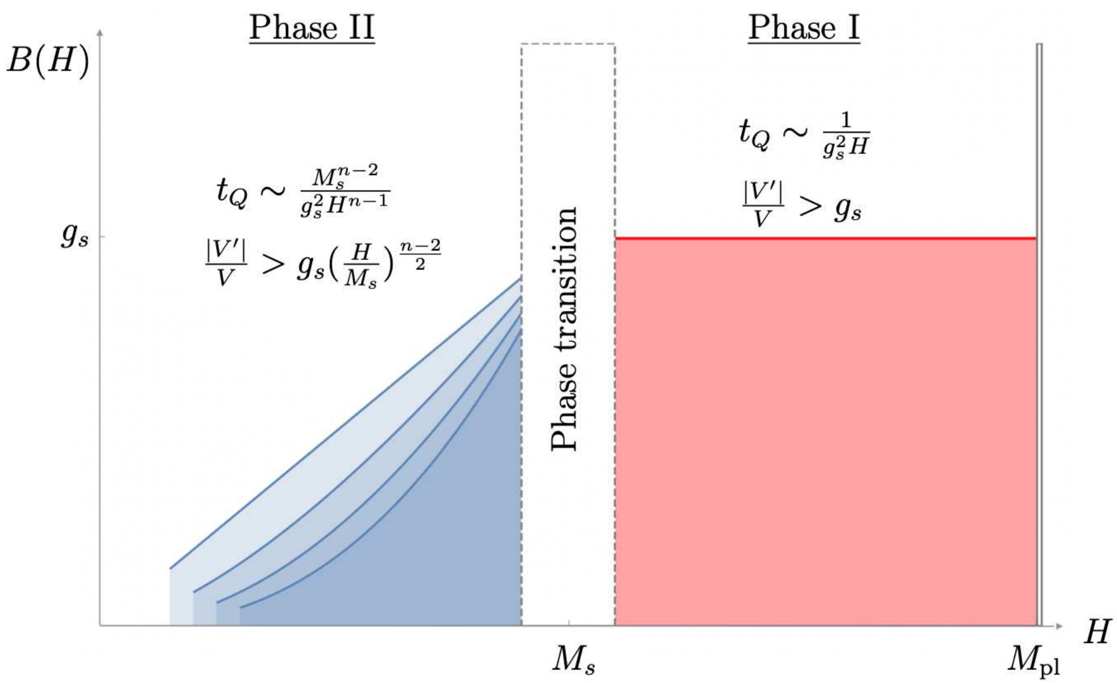
Hagedorn transition

Hagedorn transition

Atick-Witten argue that the extrapolation of the one-loop free energy to the $T > T_H$ regime gives a reasonable result:

$$\mathcal{F}(T) \sim T^2 \, .$$

Using this we found



B(H): lower bound on $|V'|/V$

High Energy Phase

High Energy Phase

Can one do the computation directly in the high T phase?

(Alvarez-Garcia,Bhg,Kneißl,Makridou,Schlechter, in progress)

- Due to the occurence of a tachyon, for critical string the high energy phase is largely unknown
- For non-critical ones in 2D, tachyons disappear and the theory can even be solved exactly by a matrix model
- Non-critical M-theory provides the underlying framework for 2D non-critical type 0 string theories.
- Defined as a non-relativistic Fermi liquid in 3D. For details see the series of papers by (Horava,Keeler, 0508024,0512325,0704.2230)

Partition function

Partition function

- It has a bosonic higher-spin Lie algebra, called $\mathcal{W}_0$ containing the conformal algebra $SO(3,2) \subset \mathcal{W}_0$.
- One gets an exact expression for the free-energy $(R = 1/(2\pi T))$

$$\frac{\partial^3 \Gamma}{\partial \mu^3} = -\frac{1}{2\pi} \mathrm{Im} \int_0^\infty d\tau e^{i\mu\tau} \frac{\tau/2}{\sinh^2(\tau/2)} \frac{\tau/(2R)}{\sinh\big(\tau/(2R)\big)}.$$

- For high T one finds $\Gamma \sim T^3$
- Remarkable the integrated partition function is very closely related to the topological A model on the resolved conifold.

Higher spin CS theory

Higher spin CS theory

In the conformal $\alpha' \to \infty$ limit, the ground state should be $AdS_2 \times S^1$ plus a massless fermion

The off-shell action was proposed to be the higher spin Chern-Simons theory

$$S_{\rm HCS} = \frac{1}{4}\int_M \mathrm{Tr}\left(\mathcal{A}\wedge d\mathcal{A} + \frac{2}{3}\mathcal{A}\wedge\mathcal{A}\wedge\mathcal{A}\right)$$

with the one-form $\mathcal{A}$ taking values in $\mathcal{W}_0$.

Matter fields can be coupled to this topological theory at the level of the equations of motion

$$d|\Phi\rangle + \mathcal{A}\star|\Phi\rangle = 0\,,$$

Does this theory satisfy the swampland conjectures?

Conformal Gravity

Conformal Gravity

Restrict to the gravity sector plus a conformal scalar

$$S_{\text{eff}} = S_{\text{CS}} - \int d^3x \sqrt{-g} \Big(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{\xi_3}{2} R\, \phi^2 + \frac{\kappa}{6} \phi^6 \Big)$$

Equation of motion for metric

$$\begin{aligned} & C_{\mu\nu} - \frac{\phi^2}{8} \Big(R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \Big) + \frac{\kappa}{6} \phi^6 g_{\mu\nu} \\ & - \Big(\partial_\mu \phi \partial_\nu \phi - \frac{1}{2} g_{\mu\nu} (\partial \phi)^2 \Big) - \frac{1}{4} \Big(\phi \Box \phi + (\partial \phi)^2 \Big) g_{\mu\nu} \\ & + \frac{1}{4} \Big(\phi \nabla_\mu \nabla_\nu \phi + \partial_\mu \phi \partial_\nu \phi \Big) = 0\,. \end{aligned}$$

and for the scalar

$$\Box \phi - \frac{1}{8} R \phi - \kappa \phi^5 = 0\,.$$

Conformal gravity

Conformal gravity

The Einstein-Hilbert term reappears

- A non-vanishing VEV ϕ_0 induces a Planck scale

$$\widetilde{M}_{\rm pl} = -\frac{\phi_0^2}{8}\,.$$

- There exist AdS_3 and dS_3 solutions, if

$$\phi_0^4 = \frac{3}{4|\kappa|\ell^2}\,.$$

  with $\kappa > 0$ for AdS_3 and $\kappa < 0$ for dS_3.

- Check swampland conjectures!

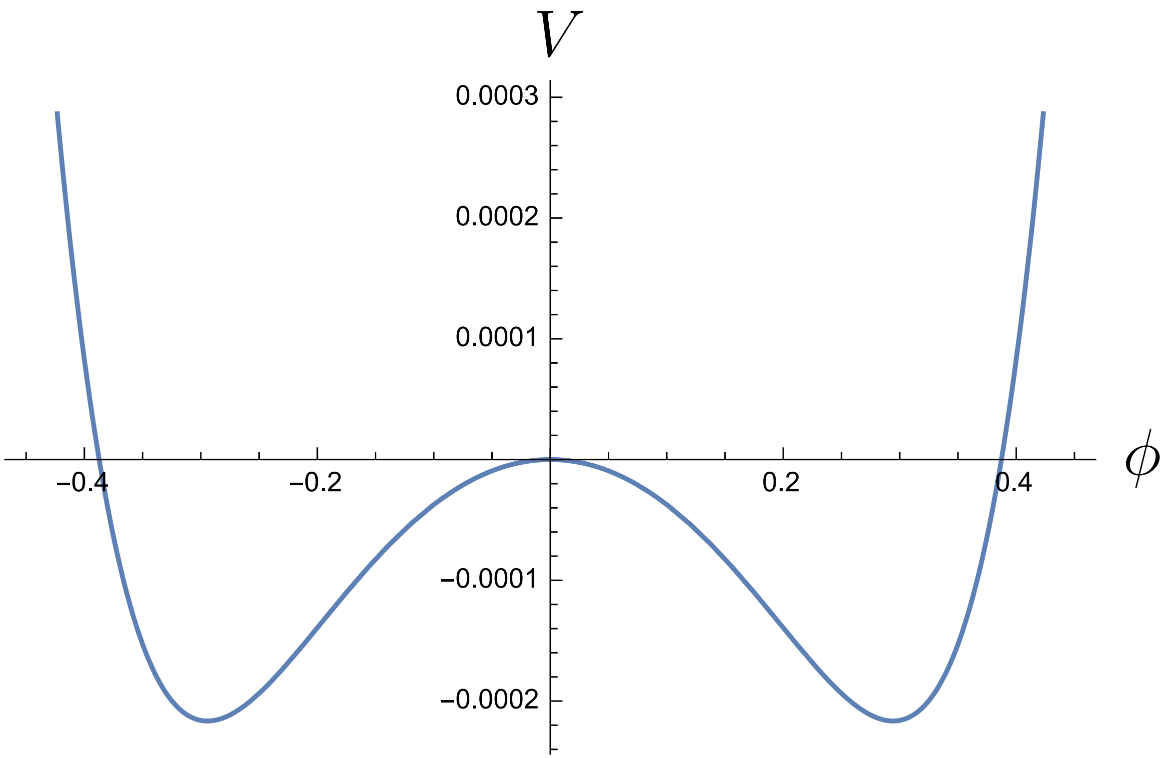
Conformal gravity

Conformal gravity

Defining an effective potential

$$V(\phi) = -\frac{3}{8\ell^2}\phi^2 + \frac{\kappa}{6}\phi^6 \,.$$

the AdS minimum is evident



Topologically massive gravity

Topologically massive gravity

This is nothing else than the well known theory of topologically massive gravity (TMG):

$$S_{\rm TMG} = \frac{\widehat{M}_{\rm pl}}{2}\int d^3x\Big[\sqrt{-g}\big(R-2\Lambda\big) + \frac{1}{2\mu}\epsilon^{\mu\nu\rho}\Big(\Gamma^{\alpha}_{\mu\beta}\partial_\nu\Gamma^{\beta}_{\rho\alpha} + \frac{2}{3}\Gamma^{\alpha}_{\mu\gamma}\Gamma^{\gamma}_{\nu\beta}\Gamma^{\beta}_{\rho\alpha}\Big)\Big]\,.$$

One finds a negative Planck scale $\widehat{M}_{\rm pl} = \widetilde{M}_{\rm pl}$ and

$$\mu = \frac{\phi_0^2}{8} = \frac{1}{16\ell}\sqrt{\frac{3}{|\kappa|}}\,, \qquad \Lambda = \mp\frac{1}{\ell^2}\,.$$

Around the Minkowski solution there is one massive propagating spin-2 degree of freedom of mass $m_{(2)} = \mu$.

(Deser,Jackiw,Templeton, Annals Phys. 185 (1982) 372)

AdS swampland conjectures

AdS swampland conjectures

AdS/moduli scale separation conjecture: $m_\phi \, \ell \leq c$ is satisfied as from $V(\phi)$ we find

$$m_\phi^2 = 3/\ell^2$$

AdS distance conjecture:

- The cosmological constant is

$$|\Lambda_{\mathrm{AdS}}| \sim \phi_0^4$$

  It vanishes for $\phi_0 = 0$ which is at finite distance in the moduli space.
- In contrast to the infinite distance case for the perturbative string.

AdS distance conjecture

AdS distance conjecture

There should be a tower of light states with scaling $m \sim |\Lambda|^{\alpha}$:

- From the (refined) swampland distance conjecture, one expects a tower of states

$$m = m_0 \, e^{-\Delta\phi/\sqrt{|\widetilde{M}_{\rm pl}|}} \sim \phi_0^2 \sim \frac{1}{\ell} \sim \Lambda_{\rm AdS}^{\frac{1}{2}}$$

  where we used $m_0 \sim \phi_0^2$.

- There is no compactifcation and hence no tower of Kaluza-Klein modes involved here. Natural candidates are the infinitely many higher spin fields.

- Mass of the single spin-2 field

$$m_{(2)}^2 = \left(\mu + \frac{2}{\ell}\right)^2 - \frac{1}{\ell^2} = \frac{1}{\ell^2}(\mu\ell + 3)(\mu\ell + 1)$$

  with $\mu\ell = \sqrt{3/(256\kappa)}$. (Carlip,Deser,Waldron,Wise, 0803.3998)

AdS distance conjecture

AdS distance conjecture

- A natural conjecture for the mass of the higher spin fields would be

$$m_{(s)}^2 = \frac{(s-1)}{\ell^2}\Big((s-1)\mu\ell + (s+1)\Big)\Big(\mu\ell + 1\Big)\,,$$

which for $s \gg 1$ indeed gives the desired scaling

$$m_{(s)} \sim s\mu \sim s\phi_0^2 .$$

- There exist BTZ black-holes in TMG, which carry negative energy and therefore signal a non-perturbative instability of the AdS_3 background. Consistent with the proposed general instability of non-supersymmetric AdS-backgrounds. (Ooguri,Vafa, 1610.01533)

dS swampland conjecture

dS swampland conjecture

For dS the effective potential becomes

$$V(\phi) = \frac{3}{8}H^2\phi^2 - \frac{|\kappa|}{6}\phi^6$$

- dS maximum: refined dS swampland conjecture

$$M_{\rm pl}|V''| > c'\,V\,.$$

is satisfied with

$$V(\phi_0) = \frac{\kappa}{3}\phi_0^6$$
$$|M_{\rm pl}| \sim \phi_0^2$$
$$V''(\phi_0) = -4\kappa\phi_0^4 = -3H^2,$$

if $c' < 3/2$.

Quantum breaking

Quantum breaking

First observation:

- dS_3 is conformally flat $\Rightarrow$ solution to pure conformal gravity, which has no propagating modes $\Rightarrow$ dS is eternal
- Adding the conformal scalar field $\Rightarrow$ a massive propagating spin-2 mode $\Rightarrow$ quantum breaking can occur.
- Just by dimensional reasoning $t_Q \sim H^{-1}$.
- Naively differs from the quantum break time $t_Q \sim M_{\rm pl}/H^2$, but here $|M_{\rm pl}| \sim H$
- Censorship of quantum breaking is satisfied by tachyonic mode

All consistent with our claim that generally $t_Q \sim H^{-1}$ in high energy phase

Summary

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The results of our analysis for this toy model of the high energy phase of non-critical 3D M-theory suggest:

- It demonstrates that there is a good chance for the existence of non-standard effective gravity theories in the landscape of string theory.
- It gives credence to the proposal that the high energy phase of string theory does also satisfy the swampland conjectures, in particular the universal quantum break time $t_Q \sim H^{-1}$
- Using swampland conjectures as a guide to the high temperature phase: a purely topological theory without any propagating dof might be too simple

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Thank you!

Higushi bound

Higushi bound

Higushi bound for masses of higher spin modes in dS_d

$$m^2_{(s,t)} \geq H^2(s-t-1)(s+t+d-4)\,.$$

- In our case, the sign of the EH-term is reverved so that for $t=s$ mode

$$m^2_{(s,s)} \leq -H^2(2s-1)\,.$$

- Need to know the mass of the spin-2 mode for TMG:

$$m^2_{(2)} = -\left(\mu + \frac{2}{\ell}\right)^2 + \frac{1}{\ell^2}\,,$$

which correctly reproduces the mass of the tachyonic mode.

Higushi bound

Higushi bound

- This calls for the higher spin generalization

$$m_{(s)}^2 = -\left((s-1)\mu + \frac{s}{\ell}\right)^2 + \frac{1}{\ell^2} \le (-s^2+1)H^2 \,.$$

For $s \ge 2$ indeed satisfies the (sign reversed) Higuchi bound