De Sitter Quantum Breaking, Swampland Conjectures and the Hagedorn Transition

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Relevant Publications

- De Sitter quantum breaking, swampland conjectures and thermal strings [Blumenhagen, CK, Makridou '20]
- Swampland Conjectures for an Almost Topological Gravity Theory [Alvarez-Garcia, Blumenhagen, CK, Makridou, Schlechter '21]

The Swampland

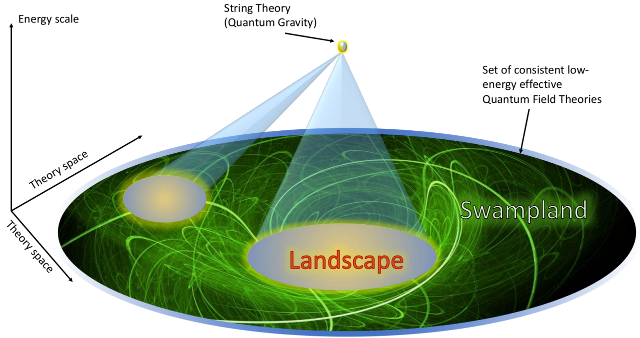

Figure: Illustration of the Swampland [Palti '19]

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De Sitter Swampland Conjecture

dS Swampland Conjecture [Obied, Ooguri, Spodyneiko, Vafa '18]

A potential $V(\phi)$ for any scalar field in a low energy effective field theory of any consistent quantum gravity theory has to obey the following bound:

$$M_{\rm pl}\,|V'| \geq c \cdot V \qquad (1)$$

- c assumed to be an $\mathcal{O}(1)$ constant in Planck units
- **Forbids** stable or meta-stable de Sitter vacua
- Based on multiple No-Go-theorems on de Sitter vacua from string tree-level constructions

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No Eternal Inflation Principle

No Eternal Inflation Principle [Rudelius '19]

The condition, under which inflation is not eternal, is for a linear scalar potential the following in 4 dimensions:

$$M_{\mathrm{pl}} \frac{|V'|}{V} > c' \cdot \frac{V^{\frac{1}{2}}}{M_{\mathrm{pl}}^2} \tag{2}$$

- Remarkably similar to the bound of the de Sitter conjecture, but less restrictive for $V(\phi) < 1$
- Several more scenarios like a quadratic hillltop-potential or non-perturbative decay possible $\rightarrow$ leading to different bounds

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Trans-Planckian Censorship Conjecture I

Trans-Planckian Censorship Conjecture [Bedroya, Vafa '19]

Sub-Planckian fluctuations should remain quantum in a consistent theory of quantum gravity:

$$\frac{a_f}{a_i} \cdot \mathrm{l}_{\mathrm{pl}} < \frac{1}{H_f} \quad \text{or} \quad \int_{t_i}^{t_f} H dt < \ln\left(\frac{M_{\mathrm{pl}}}{H_f}\right) \tag{3}$$

- Immediately introduces an upper bound on the lifetime T:

$$T \leq \frac{1}{H_f} \ln\left(\frac{1}{H_f}\right) \tag{4}$$

- Translates into bound on scalar potential $V(\phi)$, which leads to the **dS Conjecture** in the limit ϕ_i and $\phi_f \to \infty$:

$$\left(\frac{-V'}{V}\right)_{\infty} > \frac{2}{\sqrt{(d-2)(d-1)}} \tag{5}$$

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Trans-Planckian Censorship Conjecture II

- Connection to the "No Eternal Inflation"-bound via cascading bubble decay mimicking a scalar potential
- Requiring the TCC to hold for the subsequent bubble nucleations $\rightarrow$ leading to a restricted parameter space for V [Bedroya, Montero, Vafa, Valenzuela '20]
- Eternally inflating scenarios are precisely excluded, the linear "No Eternal Inflation"-bound is satisfied

$$M_{\mathrm{pl}} \frac{|V'|}{V} > c' \cdot \frac{V^{\frac{1}{2}}}{M_{\mathrm{pl}}^2} \tag{6}$$

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Quantum Breaking

Quantum Breaking [Dvali, Gomez, Zell '17, '18]

De Sitter is described by a **quantum coherent state of gravitons**

With an upper life-time of $t_Q = \frac{t_{cl}}{\alpha} = \frac{N}{H} = \frac{M_{\rm pl}^2}{H^3}$

- Requires a classical mechanism to censor the quantum breaking phenomenon, for example a slow rolling scalar field with a decay time $t \sim 1/(\epsilon H) < t_Q$
- Introduces a bound on the associated potential:

$$M_{\rm pl}\frac{|V'|}{V} \gtrsim \sqrt{\alpha} = c \cdot \left(\frac{V}{M_{\rm pl}^4}\right)^{\frac{1}{2}} \quad (7)$$

- Remarkably, the same bound as the "No Eternal Inflation"-bound

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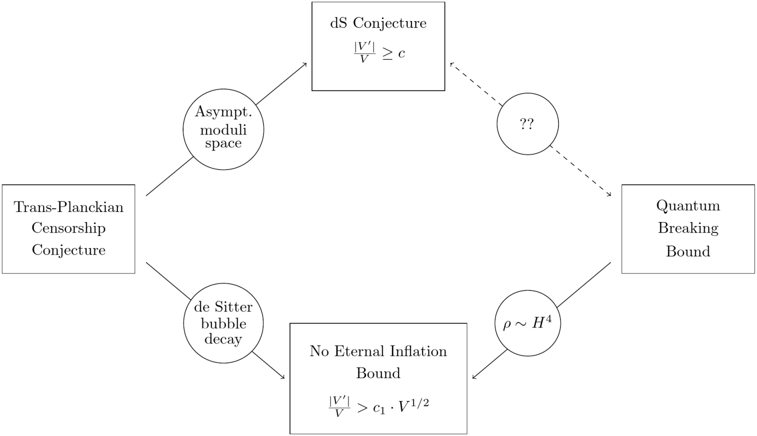
An Overview over the de Sitter bounds

- Is there an additional connection between Quantum Breaking and the de Sitter conjecture?



- Let's consider the simple example of a conformal scalar field in 2d de Sitter:

$$S = -\int d^2x\sqrt{-g}\left[\frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi + \frac{\xi}{2}R\Phi^2\right] \tag{8}$$

$$ds^2 = \frac{1}{H^2\eta^2}(-d\eta^2 + dx^2) \quad ds^2 = -(1 - H^2r^2)d\tau^2 + \frac{dr^2}{1 - H^2r^2} \tag{9}$$

And in light-cone coordinates:

$$ds^2 = -\frac{4}{H^2(U^2 + V^2)}dUdV \quad ds^2 = -\frac{1}{\cosh(\frac{H}{2}(v-u))}dudv \tag{10}$$

dS Quantum Breaking in the Static Patch II

- Now let's calculate the vacuum expectation value of the energy momentum tensor in the FLRW patch

$$\begin{aligned} \langle T_{UU}^{div,FLRW} \rangle_{BD} &= \langle T_{VV}^{div,FLRW} \rangle_{BD} = \frac{1}{4\pi} \int_0^\infty kdk \\ \langle T_{UV}^{div,FLRW} \rangle_{BD} &= 0 \end{aligned} \quad (11)$$

- Adiabatic regularization leads to the following renormalized results

$$\begin{aligned} \langle T_{UU}^{div,FLRW} \rangle_{BD} &= \langle T_{VV}^{div,FLRW} \rangle_{BD} = 0 \\ \langle T_{UV}^{div,FLRW} \rangle_{BD} &= -\frac{H^2}{24\pi} g_{UV} \end{aligned} \quad (12)$$

- The off-diagonal component stems from the conformal anomaly $\langle T_\mu^\mu \rangle = -\frac{c}{24\pi} R$ and $\langle T_{\mu\nu} \rangle \sim g_{\mu\nu}$

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dS Quantum Breaking in the Static Patch III

- The result of the static patch inside of the horizon can be obtained in two different ways:
- correct coordinate transformation $\rightarrow$ 2d conformal transformation
- reduced (thermal) density matrix $\langle \hat{T}_A \rangle = tr(\hat{\rho}\hat{T}_A)$

$$\begin{aligned} \langle T^{\mu}_{\nu} \rangle &= \langle T^{\mu}_{\nu} \rangle_M + \langle T^{\mu}_{\nu} \rangle_{CC} \\ &= \frac{H^2}{24\pi(1 - H^2 r^2)} diag(-1, 1) - \frac{H^2}{24\pi} g^{\mu}_{\nu} \end{aligned} \tag{13}$$

- In contrast to the FLRW result **dS isometries** are **broken**
- The matter-like component leads to a **quantum breaking effect**

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dS Quantum Breaking in the Static Patch IV

- The same matter-component is found in higher dimensions scaling like $\sim H^n$
- Two conceivable resolutions: **Disregarding** this component or requiring a larger **classical decay**, for instance a rolling field ϕ with slow-roll parameter ϵ and potential V
- This leads to the same decay time as for quantum breaking and also the same bound for the potential of the rolling field $V(\phi)$ as the "No Eternal Inflation"-bound and "Quantum Breaking"-bound:

$$M_{\mathrm{pl}} \frac{|V'|}{V} \gtrsim c \cdot \frac{V^{\frac{n-2}{4}}}{M_{\mathrm{pl}}^{\frac{n}{2}}} \tag{14}$$

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dS Quantum Breaking for Strings

- Connection to string theory: massive minimally coupled scalar $\rightarrow$ Much more complicated, but the **scaling** of the final expression for **energy density** and **pressure** is determined by the **flat space limit** $m \ll H$
- Proposal: Also in **string theory** there will be a **flat space contribution**, which can be evaluated from the thermal one-loop string partition function

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dS Quantum Breaking for Strings II

- Thermal one-loop partition function can be obtained by a **Winding Scherk-Schwarz Orbifold** with radius $R = 1/(2\pi T)$ and an additional thermal map [see e.g. Rohm '84, Alvarez, Osorio '87, Dienes, Lennek, Sharma '12]
- The scaling of low-energy field theoretic results are reproduced for low temperatures/large radius
- However, at the so called **Hagedorn temperature** $T_H \sim M_s$ a tachyonic mode appears in the spectrum indicating a **phase transition**
- Intriguingly, the high-temperature phase behaves like a 2d field theory in contrast to the perturbative string theory phase [Atick, Witten '88]

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dS Quantum Breaking for Strings III

- Unclear what theory correctly describes the high-temperature phase
- But: scaling of energy density and pressure is known $\rho \sim g_s^2 M_{\mathrm{pl}}^{d-2} H^2$
- The quantum break time is then simply given by $t_Q \sim \frac{1}{g_s^2 H}$ and leads to a bound alike the dS swampland conjecture

$$M_{\mathrm{pl}} \frac{|V'|}{V} \gtrsim c\, g_s \tag{15}$$

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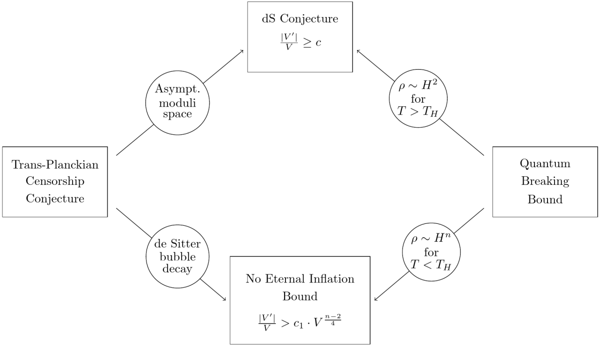
Final Overview & Recap



- Matter-like component of $\langle T_{\mu\nu} \rangle$ in the static patch leads to **Quantum Breaking**
- Generalization to string theory: "No Eternal Inflation"-Bound for low-temperature and de Sitter Conjecture in high-temperature phase

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Thank You!