An Anti-Trans-Planckian Censorship Conjecture

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Outline

Trans-Planckian Problem

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Trans-Planckian ~~Problem~~

Censorship Conjecture

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Anti-Trans-Planckian ~~Problem~~

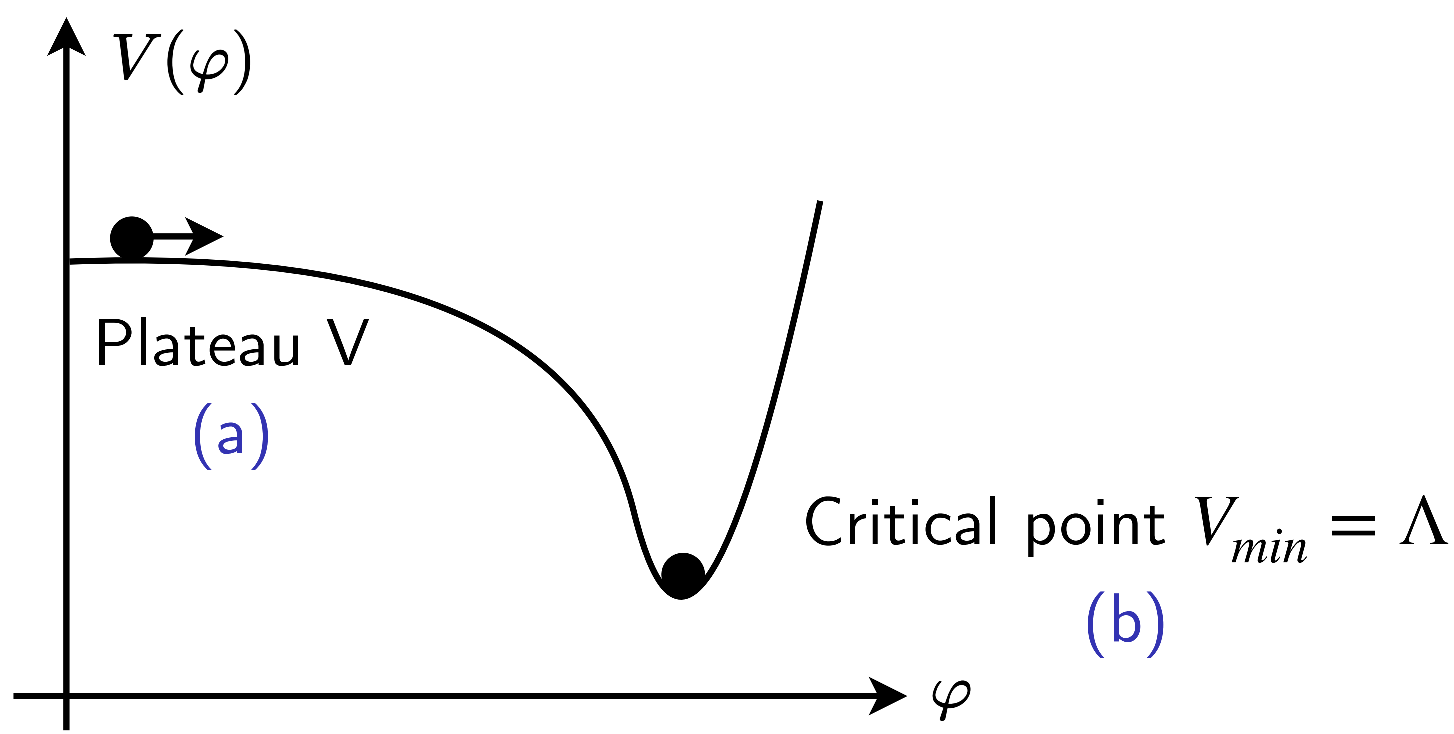
Censorship Conjecture

Standard cosmology

$$ds^2 = -dt^2 + a(t)^2 d\mathbf{x}^2 \quad \Rightarrow \quad \text{accelerated expansion } \ddot{a} > 0$$

(a) **Inflation**. **Single scalar** field rolling down $V > 0$, very flat $\frac{|V'|}{V} \ll 1$.

(b) **Today**. well-described by small, positive cosmological constant, $\Lambda \simeq +3 \cdot 10^{-122}$ [Planck Coll. '15].



Standard cosmology

- Both described by **4d theory**:

$$S = \int d^4x \sqrt{-g_4}\left(\frac{M_{pl}^2}{2}R_4 - \frac{1}{2}g_{ij}\partial_\mu\varphi^i\partial^\mu\varphi^j - V\right)$$

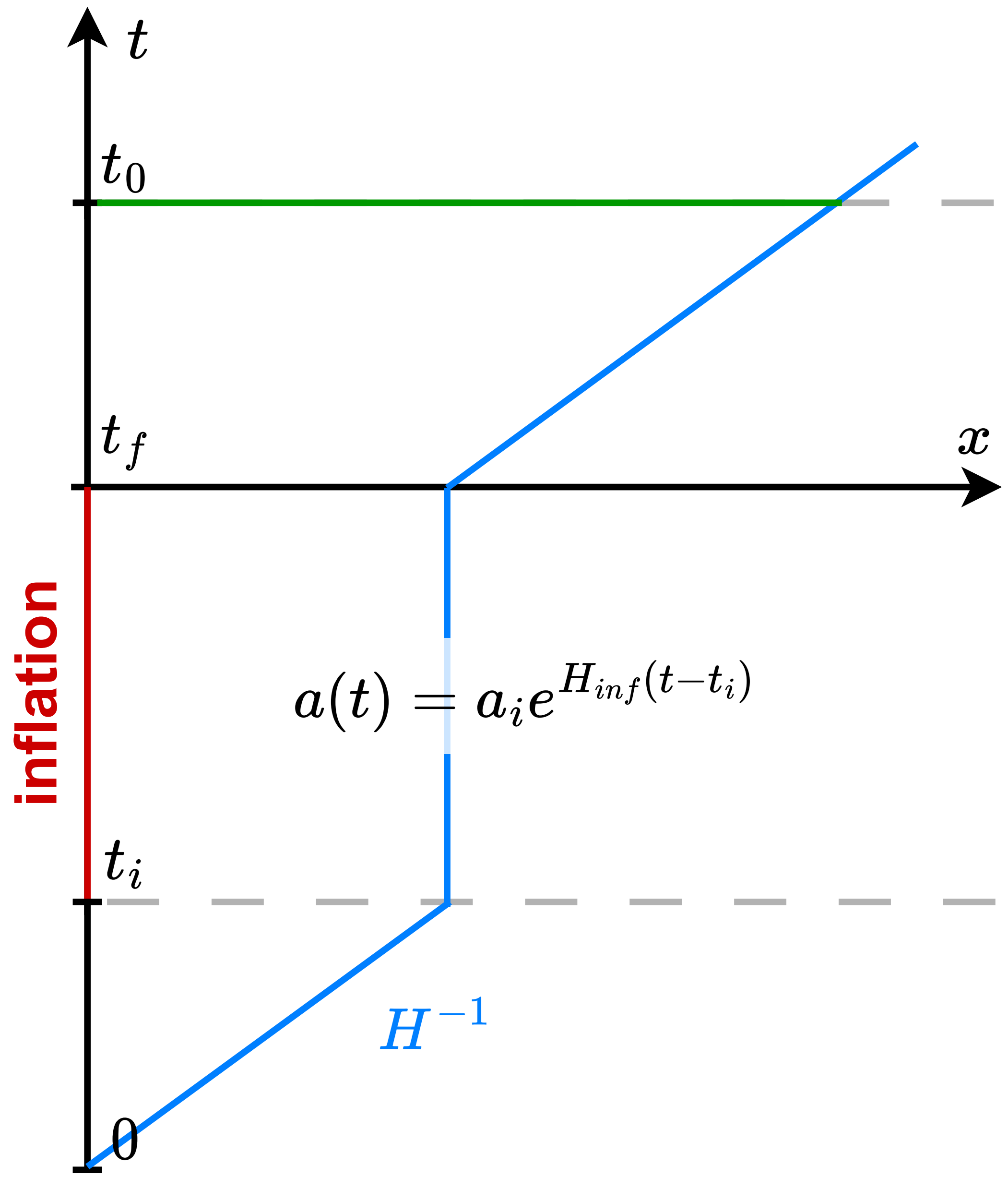
M_{pl} .. reduced Planck mass

φ^i .. minimally coupled scalar fields (most of the talk: $\varphi^i \to \varphi$)

- .. $+ V > 0 +$ **right shape of V** from string theory/quantum gravity?

$\Rightarrow$ study scalar potentials

Inflationary scenario

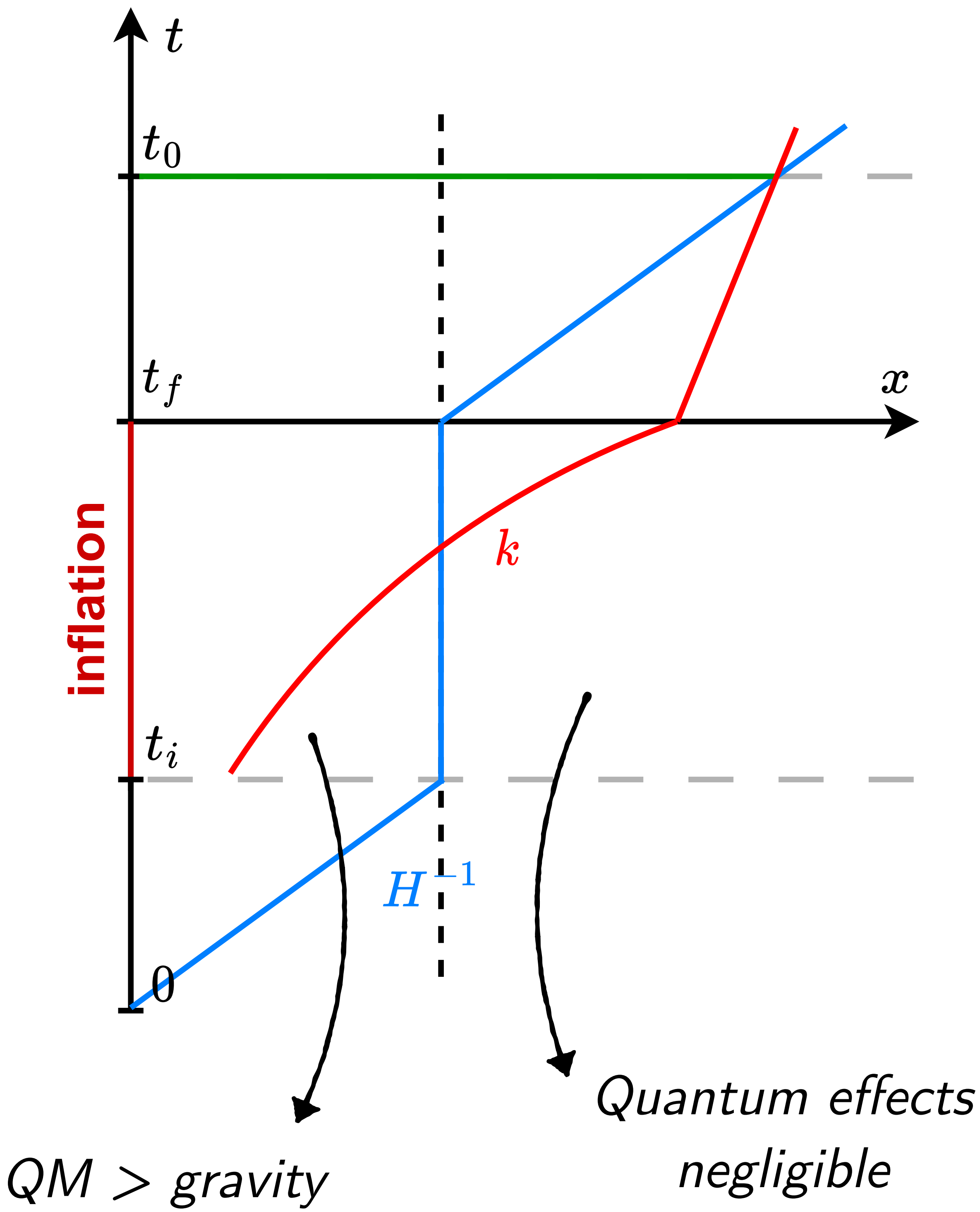


Current paradigm of early universe cosmology

$$a_f = e^N a_i$$

$H(t) \equiv \frac{\dot{a}}{a}$, $H^{-1}(t)$ .. Hubble radius

Inflationary scenario



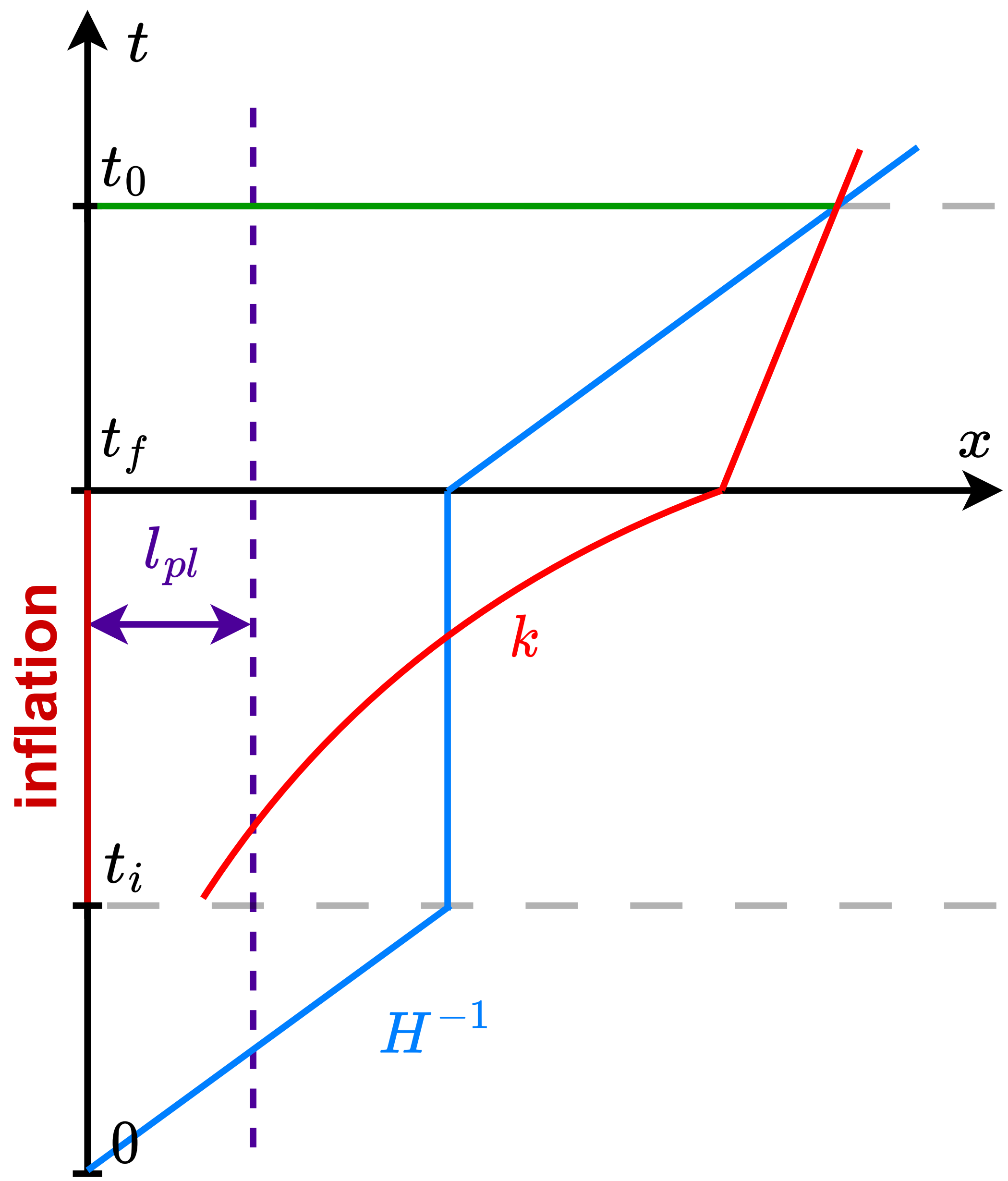
Current paradigm of early universe cosmology

$$a_f = e^N a_i$$

Success: At early times, scales are inside the Hubble radius ⇒ causal generation mechanism.

Trans-Planckian problem

[Brandenberger, Martin '02]



Current paradigm of early universe cosmology

$$a_f = e^N a_i$$

Success: At early times, scales are inside the Hubble radius ⇒ causal generation mechanism.

$N > 70$: **Trans-Planckian Problem**

$$l(t_0) < H^{-1}(t_0) \;\hat{=}\; l(t_i) \ll l_{pl} = M_{pl}^{-1}$$

Inflation, analyzed using an EFT framework (semi-classical FT, coupled to Einstein gravity) ⇒ **breakdown**.

Trans-Planckian Censorship Conjecture

[Bedroya, Vafa '19]

Consistent QG model, no trans-Planckian modes exit the Hubble horizon.

$$e^N l_{pl} = \frac{a_f}{a_i} l_{pl} < H_f^{-1}$$

- Universe $\Lambda > 0 \leftrightarrow$ string theory gives well-controlled $\Lambda < 0$ vacua.

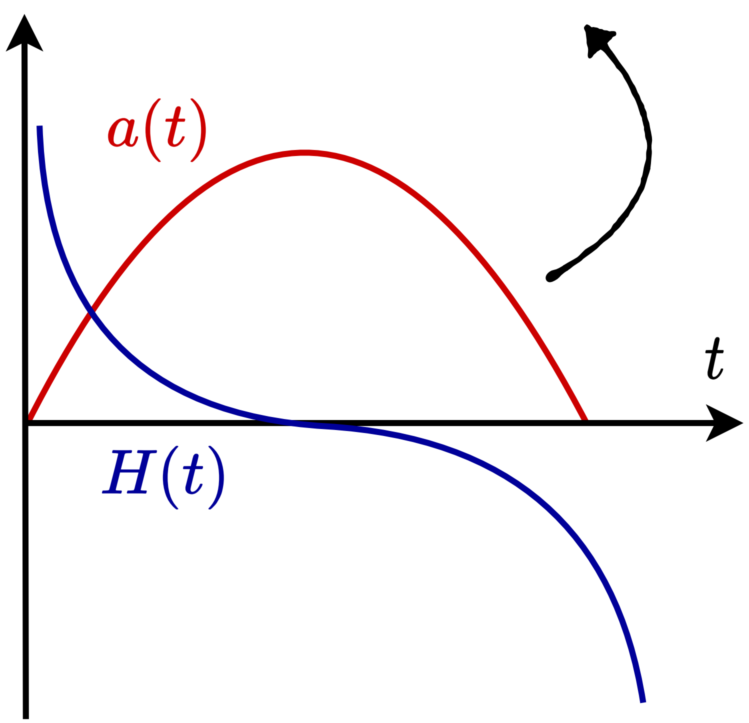
Negative scalar potentials

[Andriot, LH, Tringas '22]

- Characterize properties of $V < 0$ (**decelerating** universe), $\ni$ anti-de Sitter (AdS) vacua: $V' = 0$, $\Lambda = V_{min}/M_{pl}^2 < 0$.

AdS radius $l^2 = \dfrac{(d-1)(d-2)}{-2\Lambda}$

contracting *phase*



- No meaningful characterization of typical length or horizon of the universe for AdS:

  (1) $H(t) \nsim \Lambda$

  (2) Divergent particle/event horizon.

ATCC, bottom-up

- Use potential, energy scale of EFT, as typical length scale.

(1) Modes with **typical energy scale** $E \sim \lambda^{-1}$ **of EFT**,
$1/(a(t_i)\lambda_0) \sim \sqrt{-V_i}/M_{pl}$.

$\downarrow$ *Contraction* $\Rightarrow$ *blueshift*

(2) Reach **super-Planckian energy**, $1/(a(t)\lambda_0) \sim M_{pl}$.

(3) Violate validity of EFT. Λ_{cutoff} of EFT of QG is expected to be lower than Planck scale.

Anti-Trans-Planckian Censorship Conjecture

Solutions with $V < 0$ in EFT of QG:

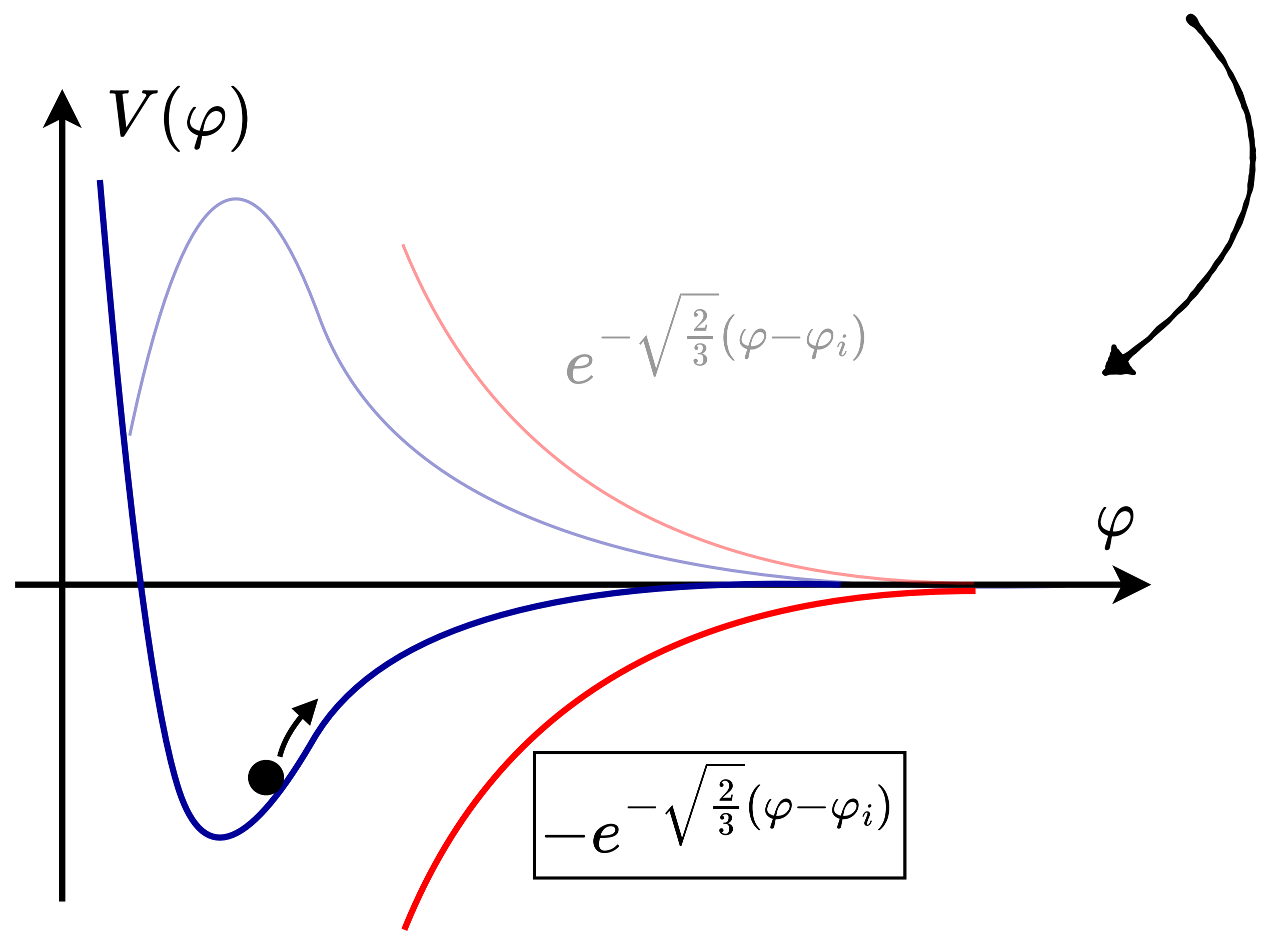
A mode having $\lambda(t_i) \sim$ typical length scale of the universe cannot reach $\lambda(t_f) \leq l_{pl}$ without violating validity of EFT.

$$\frac{a_f}{a_i} \geq \frac{\sqrt{-V_i}}{M_{pl}^2} \qquad \Leftrightarrow \qquad \int_{t_i}^{t} dt'\ H(t') = \ln\frac{a(t)}{a(t_i)} \geq \ln\frac{\sqrt{-V_i}}{M_{pl}^2}$$

Exponential bound on $V < 0$

Rest of the talk, assume field climbing up: $V' \geq 0$, $\dot{\varphi} \geq 0$ ($M_{pl} = 1$).

- Einstein equations (Friedmann) $\Rightarrow \int_{t_i}^{t} dt'\, H(t') \leq \frac{|\varphi - \varphi_i|}{\sqrt{(d-1)(d-2)}}$



"Integrated" ATCC

$$\int_{t_i}^{t} .. \geq \ln\sqrt{-V_i}$$

Bound on -V'/V

- Average of $-V'/V$ over $[\varphi_i, \varphi]$ in field space:

$$\left\langle \frac{V'}{-V} \right\rangle = \frac{1}{\Delta\varphi} \int_{\varphi_i}^{\varphi} d\tilde{\varphi}\, \frac{V'}{-V} = \frac{\ln(-V_i)}{\Delta\varphi} - \frac{\ln(-V)}{\Delta\varphi}$$

$$\xrightarrow[\varphi \to \infty]{\text{exp. bound}} \boxed{\left\langle \frac{V'}{-V} \right\rangle_{\varphi \to \pm\infty} \geq \frac{2}{\sqrt{(d-1)(d-2)}}}$$

- Asymptotic regimes, control of corrections and trust EFT (majority of models in string phenomenology).

Bound on -V'/V

$$\boxed{\left\langle \frac{V'}{-V} \right\rangle_{\varphi \to \pm\infty} \geq \frac{2}{\sqrt{(d-1)(d-2)}}}$$

- Well-tested in compactification examples: $V(\rho, \tau, \sigma)$, AdS no-go theorems (for dS: [Andriot, LH '22]), DGKT 4d.

- Counterexample? [Cremonini, Gonzalo, Rajaguru, Tang, Wrase '23]

Bound on V''/V and mass bound

- Compute $\int_{\varphi_i}^{\varphi} d\tilde{\varphi}\, \frac{V''}{V} \geq \frac{V'}{V}\Big|_{\varphi_i}^{\varphi} + \Delta\varphi \left\langle \frac{|V'|}{|V|} \right\rangle^2$

$$\left\langle \left| \frac{V'}{V} \right| \right\rangle_{\varphi\to\infty} \geq c_0$$

- **New** asymptotic bound: $$\left\langle \frac{V''}{V} \right\rangle_{\varphi\to\infty} \geq \frac{4}{(d-1)(d-2)}$$

$V'' = m^2$

AdS$_d$ with radius l: $-V_{min} = \frac{(d-1)(d-2)}{2l^2}$

- In any AdS$_{d\geq 4}$ solution, there is a scalar field whose mass obeys:

$$m^2 l^2 \lesssim -2$$

Examples from literature

BF bound: $\frac{-(d-1)^2}{4} < m^2 l^2 \lesssim -2$

$\Rightarrow$ Perturbatively unstable $\text{AdS}_{d\geq 4}$ ✓

Examples from literature

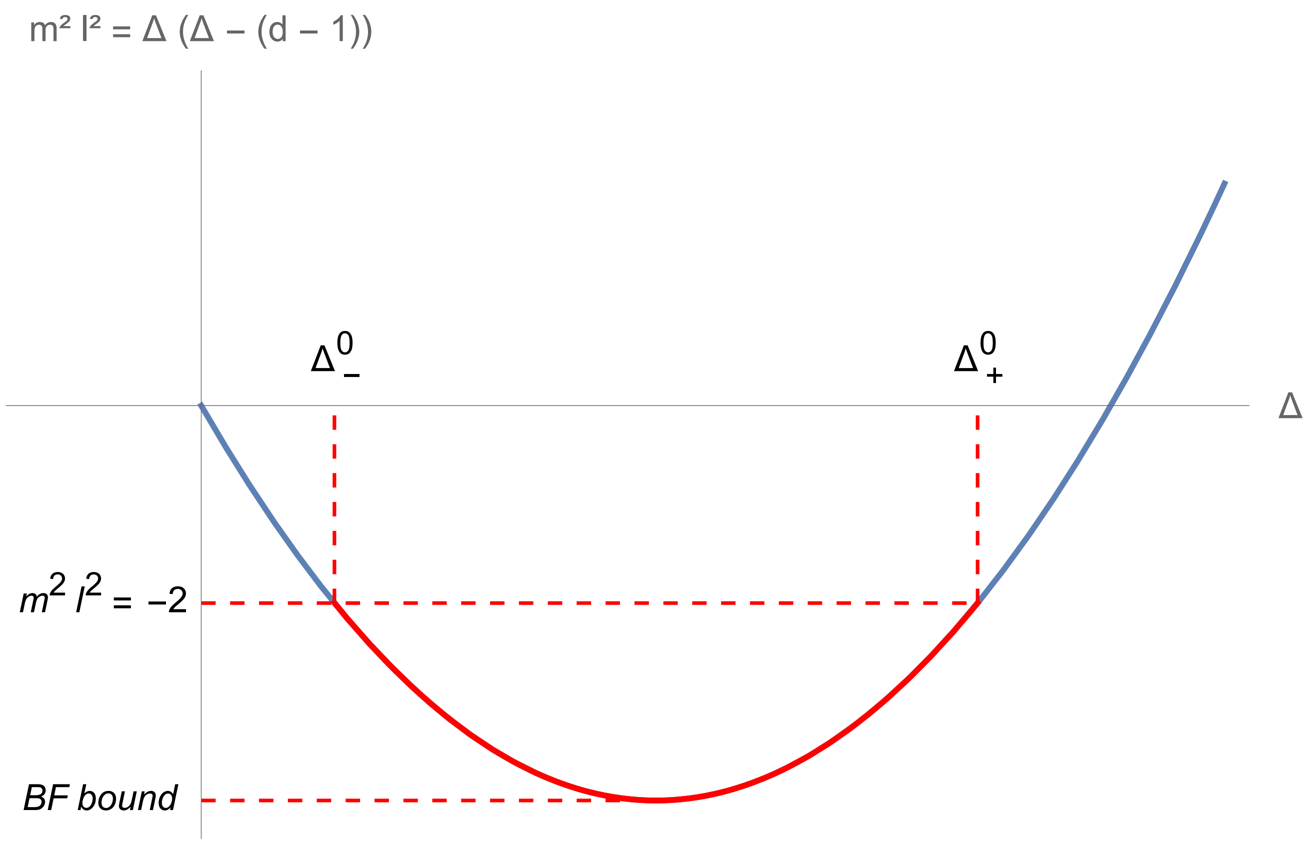
AdS$_d$	$\mathcal{N}$	Specification	Scalar lowest $m^2\, l^2$
$d=4$		AdS$_4$, M-th., with:	
	8	$SO(8)$	$-9/4$
	2	$SU(3)\times U(1)$	-2.222
	1	G_2	-2.242
	1	$U(1)\times U(1)$	-2.25
	1	$SO(3)$	-2.245
		AdS$_4\times$ S^6, IIA, with:	
	1	G_2	-2.24158
	2	$SU(3)\times U(1)$	$-20/9$
	3	$SO(3)\times SO(3)$	$-9/4$
	1	$SU(3)$	$-20/9$
	1	$U(1)$	-2.23969
	1	$\varnothing$	-2.24943
	1	$U(1)$	-2.24908
	1	DGKT, IIA	>0
	1	DGKT-like Branch A1-S1, IIA	-2
	1	KKLT, IIB	≥ 0
	1	LVS, IIB	≥ 0
		S-fold, IIB, with:	
	1	$U(1)^2$	-2
	2	$U(1)^2$	-2
	4	$SO(4)$	-2
$d=5$		AdS$_5\times$ S^5, IIB, with:	
	8	$SO(6)$	-4
	2	$SU(2)\times U(1)$	-4
$d=7$	1	AdS$_7\times$ S^3, IIA	-8

SUSY AdS solutions with QG uplift, together with number of preserved supersymmetries $\mathcal{N}$ and symmetry groups.

Holographic consequences

Standard relation to the conformal dimension Δ of operator in dual CFT:

$$\Delta(\Delta - (d-1)) = m^2 l^2 \qquad \Rightarrow \qquad \Delta^0_\pm = \frac{d-1}{2} \pm \frac{1}{2}\sqrt{(d-1)^2 - 8}$$



$$\Delta^0_- \leq \Delta \leq \Delta^0_+$$

$$d = 4 : 1 \leq \Delta \leq 2$$

CFT with integer conformal dimensions associated to the peculiarity of having scale separation, e.g. [Conlon, Ning, Revello '22].

Conclusion

- Trans-Planckian problem: $N > 70$ belongs to swampland $\Rightarrow$ TCC.
- Characterization of **negative** scalar potentials (ATCC).
- Well-tested **bounds** on $V, \ -V'/V$ in **asymptotics** (well-controlled field space regions).
- Mass bound in AdS $m^2 l^2 \lesssim -2$ $\Leftrightarrow$ holographic interpretation.

Thank you for your attention

Back-up

Scalar potentials from string theory

- Classical string compactifications to d dimensions, $3 \leq d \leq 10$, using 10d type II supergravity.

- Canonical fields $\hat{\varphi}^i : g_{ij} \to \delta_{ij}$

$$2V(\hat{\rho}, \hat{\tau}, \hat{\sigma}) = \dots$$

Universal fields

ρ.. (10-d)-dimensional internal volume

τ.. d-dimensional dilaton

σ.. internal volume wrapped by sources

Scalar potentials from string theory

- Classical string compactifications to d dimensions, $3 \leq d \leq 10$, using 10d type II supergravity.
- Canonical fields $\hat{\varphi}^i : g_{ij} \to \delta_{ij}$

$$
\begin{aligned}
2V(\hat{\rho},\hat{\tau},\hat{\sigma}) = e^{\frac{-2}{\sqrt{d-2}}\hat{\tau}} \Bigg(& - e^{-\sqrt{\frac{4}{10-d}}\hat{\rho}} R_{10-d}(\hat{\sigma}) + \frac{1}{2} e^{-3\sqrt{\frac{4}{10-d}}\hat{\rho}} \sum_n e^{(-An-B(3-n))\sqrt{\frac{-4}{AB(B-A)}}\hat{\sigma}} |H^{(n)}|^2 \Bigg) \\
& + \frac{1}{2} e^{\frac{2-2d}{\sqrt{d-2}}\hat{\tau}} e^{(3-d)\sqrt{\frac{4}{10-d}}\hat{\rho}} \sum_n e^{(-An-B(7-n))\sqrt{\frac{-4}{AB(B-A)}}\hat{\sigma}} |H_7^{(n)}|^2 \\
& - e^{-\frac{d+2}{2\sqrt{d-2}}\hat{\tau}} e^{\frac{2p-8-d}{4}\sqrt{\frac{4}{10-d}}\hat{\rho}} e^{\frac{1}{2}B(p-9)\sqrt{\frac{-4}{AB(B-A)}}\hat{\sigma}} g_s \frac{T_{10}}{p+1} \\
& + \frac{1}{2} g_s^2 e^{\frac{-d}{\sqrt{d-2}}\hat{\tau}} \sum_{q=0}^{10-d} e^{\frac{10-d-2q}{2}\sqrt{\frac{4}{10-d}}\hat{\rho}} \sum_n e^{(-An-B(q-n))\sqrt{\frac{-4}{AB(B-A)}}\hat{\sigma}} |F_q^{(n)}|^2
\end{aligned}
$$

Scalar potentials from string theory

$$2V(\hat\rho,\hat\tau,\hat\sigma) = e^{\frac{-2}{\sqrt{d-2}}\hat\tau}\left(- e^{-\sqrt{\frac{4}{10-d}}\hat\rho} R_{10-d}(\hat\sigma) + \frac{1}{2} e^{-3\sqrt{\frac{4}{10-d}}\hat\rho} \sum_n e^{(-An-B(3-n))\sqrt{\frac{-4}{AB(B-A)}}\hat\sigma} |H^{(n)}|^2 \right)$$

$$+ \frac{1}{2} e^{\frac{2-2d}{\sqrt{d-2}}\hat\tau} e^{(3-d)\sqrt{\frac{4}{10-d}}\hat\rho} \sum_n e^{(-An-B(7-n))\sqrt{\frac{-4}{AB(B-A)}}\hat\sigma} |H_7^{(n)}|^2$$

$$- e^{-\frac{d+2}{2\sqrt{d-2}}\hat\tau} e^{\frac{2p-8-d}{4}\sqrt{\frac{4}{10-d}}\hat\rho} e^{\frac{1}{2}B(p-9)\sqrt{\frac{-4}{AB(B-A)}}\hat\sigma} g_s \frac{T_{10}}{p+1}$$

$$+ \frac{1}{2} g_s^2 e^{\frac{-d}{\sqrt{d-2}}\hat\tau} \sum_{q=0}^{10-d} e^{\frac{10-d-2q}{2}\sqrt{\frac{4}{10-d}}\hat\rho} \sum_n e^{(-An-B(q-n))\sqrt{\frac{-4}{AB(B-A)}}\hat\sigma} |F_q^{(n)}|^2$$

- $\hat\rho$, $\hat\tau \to \infty$, large volume and small string coupling. $\hat\sigma \to \pm\infty$.
- R_{10-d}, T_{10} (negative terms) verify the ATCC bound for $d \geq 4$.

Scalar potentials from string theory

$$\left\langle \frac{V'}{-V} \right\rangle_{\varphi\to\pm\infty} \geq \frac{2}{\sqrt{(d-1)(d-2)}}$$

$$\varphi \to \infty : V(\varphi) \sim e^{-c\varphi} \Rightarrow c \geq \frac{2}{\sqrt{(d-1)(d-2)}}$$

- No-go theorems for anti-de Sitter (in 4d)

$$aV + \sum_i b_i \partial_{\hat{\varphi}^i} V \geq 0 \quad \Rightarrow \quad c = \frac{a}{\sqrt{\sum_i b_i^2}}$$