MAX-PLANCK-INSTITUT
FÜR PHYSIK

de Sitter Quantum Breaking, Swampland Conjectures and Thermal Strings

Based on 2011.13956 with Ralph Blumenhagen and Christian Kneissl

Seminar Series on String Phenomenology

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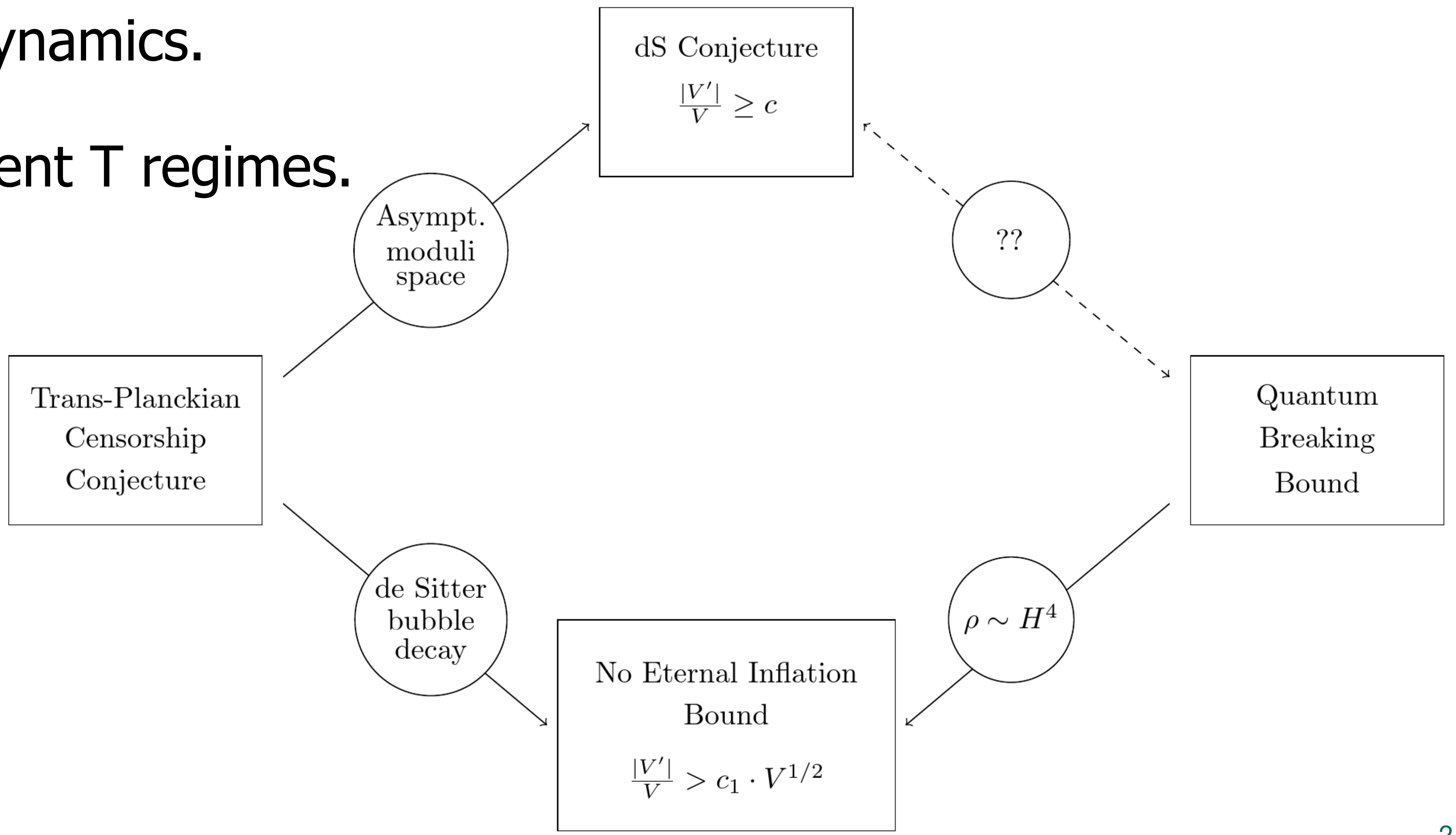
Outline

- (Swampland) bounds on potentials.
- dS quantum breaking.
- Coarse graining and thermal matter.
- String Thermodynamics.
- Bounds in different T regimes.



Swampland Bounds

- Swampland programme: not all EFTs have UV completion to QG.

[recent reviews: 1903.06239, 2102.01111]

- dS conjecture: $$\frac{|V'|}{V} \geq c, \quad c \sim \mathcal{O}(1) \quad \text{constant}\,.$$

  [1806.08362]

- Trans-Planckian censorship conjecture (TCC): [1909.11063]

  "Sub-Planckian quantum fluctuations should remain quantum."

- Asymptotic limits of field space: $$\frac{|V'|}{V} \geq \frac{2}{\sqrt{(n-1)(n-2)}}\,.$$

No eternal inflation principle [1905.05198]

- Conditions for (no) eternal inflation by solving Fokker-Planck equation.
- For linear potential in 4d: $M_{\rm pl}\dfrac{|V'|}{V} > \dfrac{\sqrt{2}}{2\pi}\left(\dfrac{V}{M_{\rm pl}}\right)^{1/2}.$
- In general: $\dfrac{|V'|}{V} > c \cdot V^{\frac{n-2}{4}}.$
- Relation to TCC: [2008.07555]

  Series of unstable dS (through bubble nucleation) $\leftrightarrow$ scalar EFT.

  TCC restricts potential, marginally excludes eternal inflation.

dS quantum breaking [1412.8077, 1701.08776]

- Corpuscular description of gravity.
- dS: coherent state of gravitons over Minkowski.
- Decoherence: initial description of state no longer valid after the quantum break time.
- For t_{cl} cl. timescale of system, α q. interaction strength: $t_Q \sim \dfrac{t_{cl}}{\alpha}$.
- Apply to dS: $t_{cl} \sim H^{-1}, \;\; \alpha \sim \left(\dfrac{M_{\rm pl}}{H}\right)^{n-2}$, $\;\; t_Q \sim \dfrac{M_{\rm pl}^{n-2}}{H^{n-1}}$.
- Quantum breaking due to backreaction of quantum state onto geometry.

Censoring quantum breaking [1806.10877,1810.11002]

- Claim: Quantum breaking should not occur. → Censorship of quantum breaking
- Classical effect forces faster decay of de Sitter: $t_d < t_Q$.
- For slow-rolling potential: $t_d \sim \dfrac{1}{\epsilon H}$.
- Can extract bound for potential:
- $\dfrac{|V'|}{V} > c \cdot V^{\frac{n-2}{4}}$. no eternal inflation type bound
- Can we get the stronger dS conjecture bound?
- r.h.s V-independent : $n = 2$, $t_Q \sim \dfrac{1}{H}$.
- Need coherent state of strings? We take a different approach.

[See also: 2007.00786, 2009.04504]

Coarse graining approach [1609.01738, 1610.06637, 1703.06898]

- Idea: Study dS decoherence by tracing over states beyond the horizon.
- Write BD vacuum as entangled state in static patch.

$$ds^2 = -(1 - H^2 r^2) d\tau^2 + \frac{dr^2}{1 - H^2 r^2} + r^2 d\Omega^2_{n-2}\,.$$

- Compute energy-momentum tensor with reduced density matrix.

$$\langle T_{\mu\nu} \rangle = Tr(\tilde{\rho} T_{\mu\nu})\,.$$

- New thermal matter component arises with $p_m = \frac{\rho_m}{3}$.
- H becomes time-dependent → dS decays.
- Interpret dS decay time as quantum break time.

Our setup [Generalization of 1703.06898]

- Action: $S_m = -\int d^n x \sqrt{-g}\left(\frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi + \frac{m^2}{2}\Phi^2 + \frac{\xi_n}{2} R\Phi^2\right)$. arbitrary m, n, $\xi_n = 0$
- Ansatz for solution in static coordinates: $\Phi = N_{L,\omega} f_{L,\omega}(r) Y_{L,l_1,\ldots,l_{n-3}}(\theta) e^{-i\omega\tau}$.
- Solutions continuous across horizon: $\Phi^A_{L,\lambda,\omega} + \gamma(\Phi^B_{L,\lambda,\omega})^*$, $\gamma(\Phi^A_{L,\lambda,\omega})^* + \Phi^B_{L,\lambda,\omega}$.
- BD vacuum: $|0_{L\lambda\omega}\rangle_{BD} = \sqrt{1-\gamma^2}\sum_{n_{L\lambda\omega}} |n_{L\lambda\omega}, A\rangle \otimes |n_{L\lambda\omega}, B\rangle$

  $\gamma = e^{2\pi k/H}$

  A: inside horizon

  B: outside of horizon
- $\hat{\rho} = \prod_{L\lambda\omega}(1 - e^{-\frac{2\pi\omega}{H}}) \sum_{n_{L\lambda\omega}} e^{-\frac{2\pi\omega}{H} n_{L\lambda\omega}} |n_{L\lambda\omega}, A\rangle\langle n_{L\lambda\omega}, A|$. $\to$ thermal state of $T = \frac{H}{2\pi}$.
- For $m \gg H$, $m \ll H$, at leading order in $O(Hr)$:

$$\rho_m = \int \frac{d^{n-1}k}{(2\pi)^{n-1}} \omega \frac{1}{e^{2\pi\omega/H} - 1}, \quad p_m = \int \frac{d^{n-1}k}{(2\pi)^{n-1}} \frac{1}{n-1} \frac{\omega^2 - m^2}{\omega} \Theta_{\rm reg}\left(\frac{\omega}{H}\right).$$

flat space contributions

Physical consequences of coarse graining

- Integrated expressions: $\rho_m \sim \kappa_n H^n, \quad p_m = \dfrac{1}{n-1}\rho_m\,.$
- $\xi \neq \xi_{\text{conf}}$: H-dep. corrections but scaling set by flat space contributions.
- ρ, p time-independent - energy inflow at horizon.
- For observer at center of static patch:
  thermal energy density and pressure with $p = w\rho, \quad w > -1\,.$
- Backreaction - extra term in Friedmann equations, H time-dep. :
- $\dot{H}M_{\text{pl}}^{n-2} = -\dfrac{\rho_m + p_m}{n-2} \implies H(t) = \dfrac{H_0}{\left(1 + \frac{\kappa_n(1+w_m)(n-1)}{n-2}\frac{H_0^{n-1}}{M_{\text{pl}}^{n-2}}t\right)^{1/(n-1)}}\,.$
- Finally can estimate: $t_Q \sim \dfrac{n-2}{n}\dfrac{M_{\text{pl}}^{n-2}}{H_0^{n-1}}\,.$ same as in Dvali et al. → gives no eternal inflation type bound

Generalization to strings

- Would need to trace over states in stringy Hilbert space.

- Assume this gives once again E-M tensor for thermal ST in flat space.

Free energy for string gas in n dimensions.

$=$

$(n+1)$-dim. vacuum energy for ST compactified on Euclidean time circle.

- Free energy of string at T in n flat dimensions (string frame):

$$\mathscr{F}(T) = -\frac{T}{2}\left(\frac{M_s}{2\pi}\right)^{n-1}\int_F \frac{d^2\tau}{\tau_2^2}\frac{1}{\tau_2^{n/2-1}} Z_{\rm str}(\tau,\bar{\tau},T)\,.$$

with $Z_{\rm str}$ over string modes and Matsubara modes.

String thermodynamics [e.g.: hep-th/0505233]

- Winding Scherk-Schwarz orbifold (WSS):
  - Compactification on $S^1/(-1)^F S_w$ with $R = 1/(2\pi T)$, S_w winding shift.

- WSS + modular invariance → Thermal partition function:

$$Z(T) = Z_B \mathscr{E}_0(T) - Z_F \mathscr{E}_{1/2}(T) + Z_t^{(1)} \mathscr{O}_0(T) + Z_t^{(2)} \mathscr{O}_{1/2}(T)\,.$$

- Example: $Z_{IIB}(T) = \frac{1}{|\eta|^{16}}\Big((\chi_v\bar{\chi}_v + \chi_s\bar{\chi}_s)\mathscr{E}_0 - (\chi_v\bar{\chi}_s + \chi_s\bar{\chi}_v)\mathscr{E}_{1/2} + $
  $+(\chi_o\bar{\chi}_o + \chi_c\bar{\chi}_c)\mathscr{O}_0 - (\chi_o\bar{\chi}_c + \chi_o\bar{\chi}_c)\mathscr{O}_{1/2}\Big)$

- Tachyonic mode for $T > \frac{1}{\sqrt{2}}\frac{M_s}{2\pi}$. Hagedorn temperature T_H

- T_H thermal tachyons → indicate phase transition - new d.o.f. needed!

- Atick-Witten [Nucl.Phys.B 310 (1988) 291-334]: $\mathscr{F}(T) \sim \Lambda_{0B}^{(1)} T^2$.

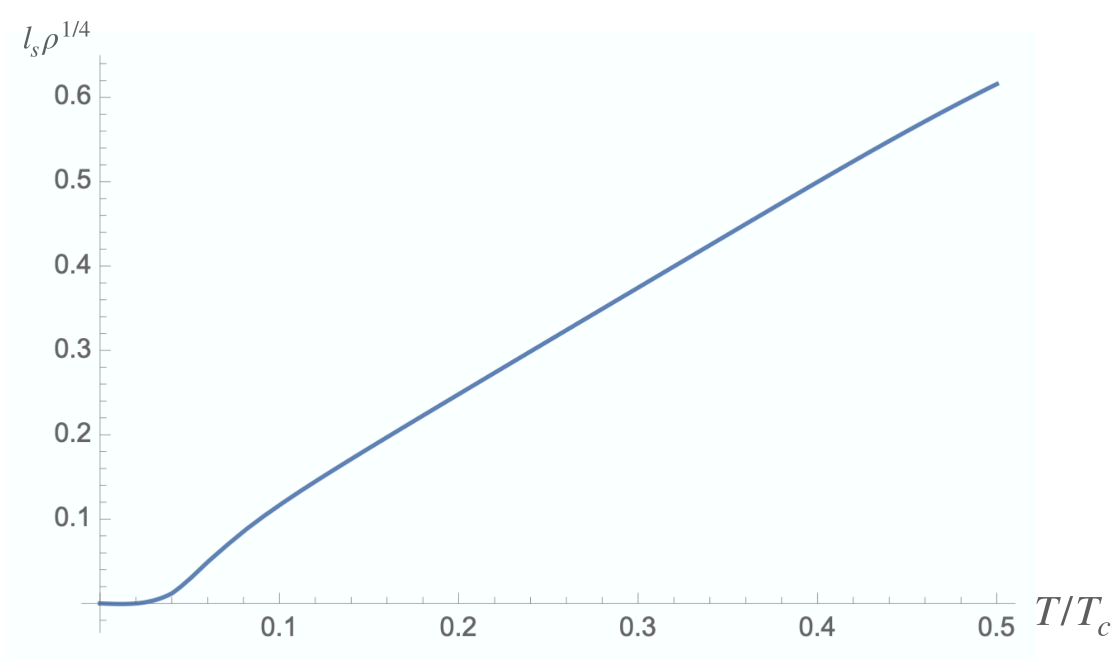
  → $\mathscr{F} \sim T^2$ generic feature after T_H!

$\rho(T)$ scaling at different T-regimes

Thermal partition function: $\mathscr{F}(T) = -\frac{T}{2}\left(\frac{M_s}{2\pi}\right)^{n-1}\int_F \frac{d^2\tau}{\tau_2^2}\frac{1}{\tau_2^{n/2-1}} Z_{\text{str}}(\tau,\bar{\tau},T)\,.$

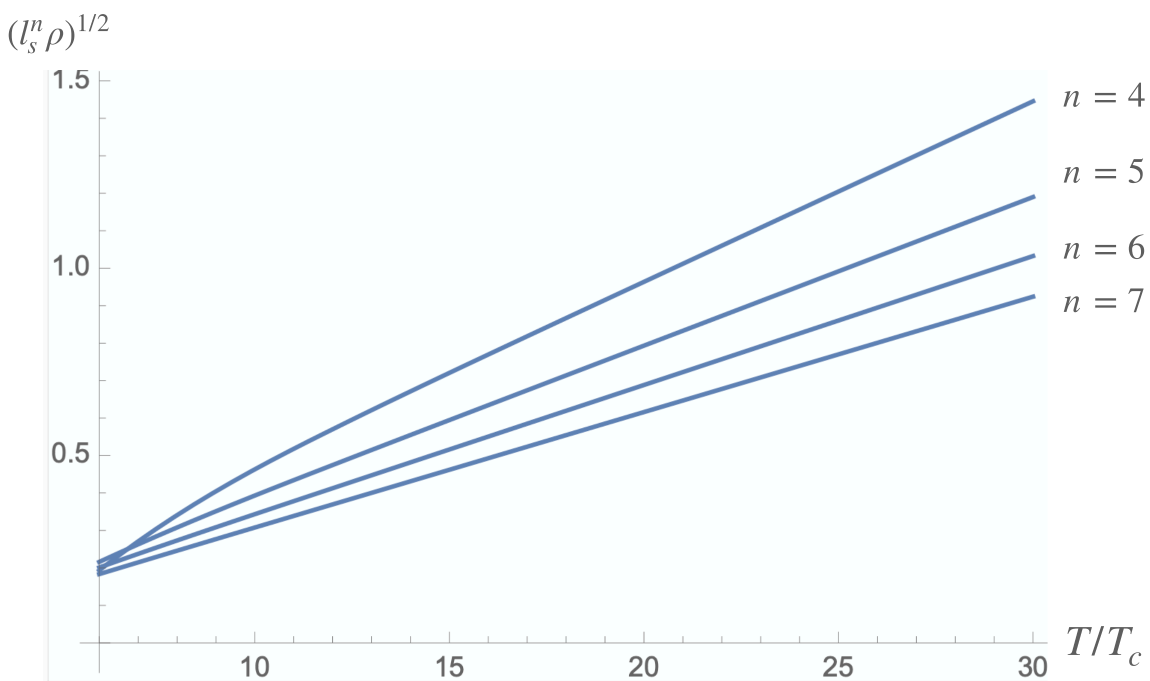
$T < T_H$ - Phase II

- Only light KK modes relevant.
- $\lim_{T\to 0}\mathscr{F} = \Lambda_0^{(1)}$.
- For $T^2 > \mathrm{Str}(M^2)$: $\rho \sim T^n$.
- Equation of state: $p = \frac{\rho}{n-1}$.



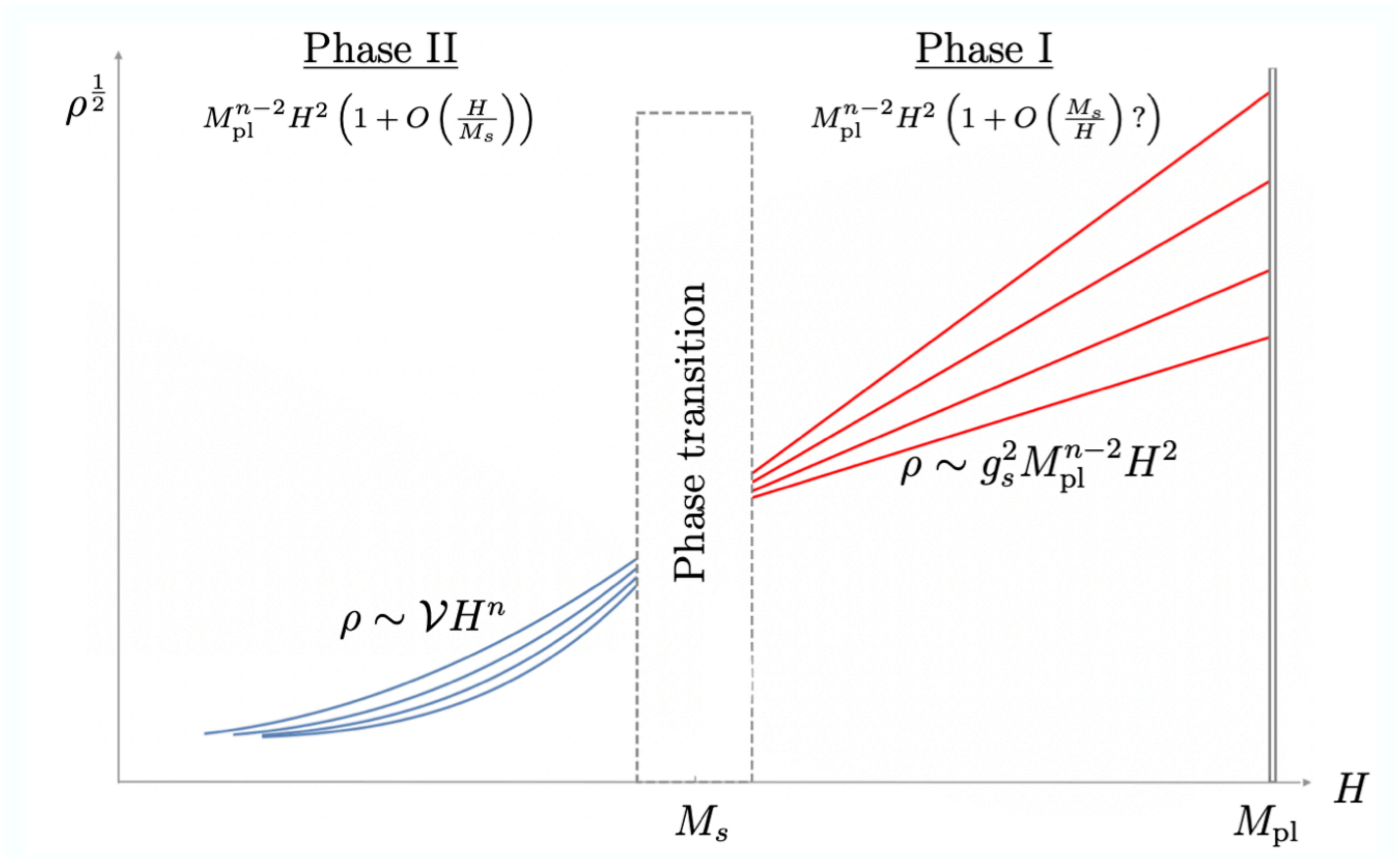
$T > T_H$ - Phase I

- Only light winding modes relevant.
- Universal scaling.
- For $T \gg T_H$: $\rho \sim M_s^{n-2}T^2$.
- Equation of state: $p = \rho$.



$\rho(T)$ scaling at different T-regimes

Thermal partition function: $\mathscr{F}(T) = -\frac{T}{2}\left(\frac{M_s}{2\pi}\right)^{n-1}\int_F \frac{d^2\tau}{\tau_2^2}\frac{1}{\tau_2^{n/2-1}} Z_{\rm str}(\tau,\bar\tau,T)\,.$



[Notation adapted from 2009.10077]

$T < T_H$ - Phase II

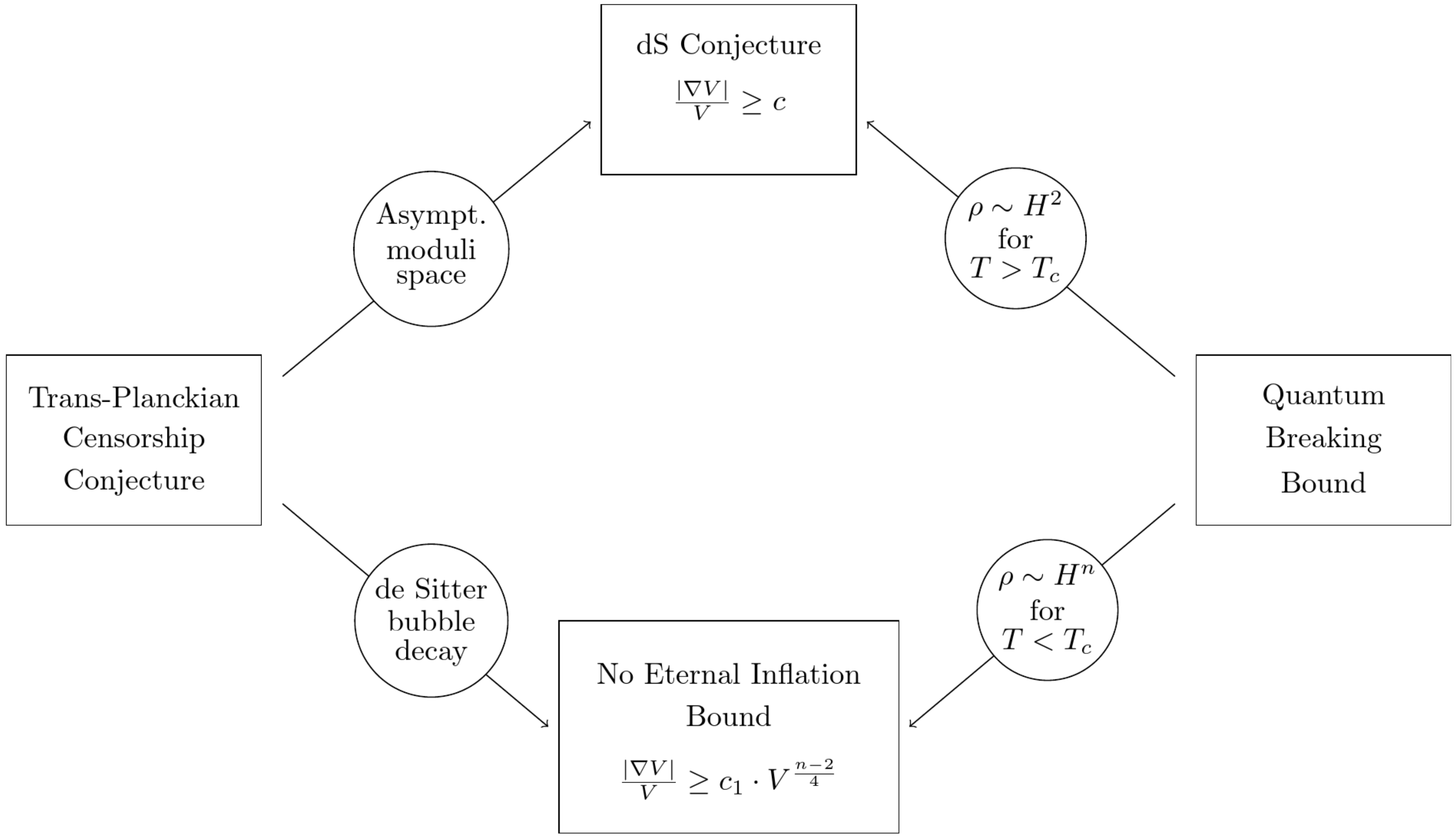
- Note: $M_s^{n-2} \sim \frac{g_s^2 M_{\rm pl}^{n-2}}{\mathscr{V}}$.
- Higher derivative corrections in Friedmann equations negligible.
- In Einstein frame, large volumes: $\rho \sim \mathscr{V} H^n$.
- Field-theoretic quantum break time modified: $t_Q \sim \frac{M_{\rm pl}^{n-2}}{\mathscr{V} H^{n-1}} \sim \frac{M_s^{n-2}}{g_s^2 H^{n-1}}$.
- Quantum breaking censorship: $\frac{|V'|}{V} \geq g_s \left(\frac{H}{M_s}\right)^{\frac{n-2}{2}}$.
- Comments: 1) Scales like $V^{(n-2)/4}$ (as no eternal inflation bound).
  2) Stronger bound due to factor of $\mathscr{V}$.
  3) M_s instead of $M_{\rm pl}$: compatible with species scale.

[0710.4344]

$T \gg T_H$ - Phase I

- $\dfrac{H}{M_s}$ now of $\mathcal{O}(1)$. - what about corrections?
- Assume at leading order Friedmann equations still hold.
- In Einstein frame: $\rho \sim \kappa_n \mathscr{V} H^2 \sim \kappa_n g_s^2 M_{\rm pl}^{n-2} H^2$.
- Different scaling so: $H(t) = \dfrac{H_0}{\left(1 + \frac{2\kappa_n g_s^2}{n-2} H_0 t\right)}$.
- Quantum break time modified: $t_Q \sim \dfrac{1}{g_s H_0}$.
- Quantum breaking censorship: $\dfrac{|V'|}{V} \geq g_s$.
- Comments: 1) Bound V-independent, but not pure number.
  2) Weaker bound since g_s appears - could it be an artefact?

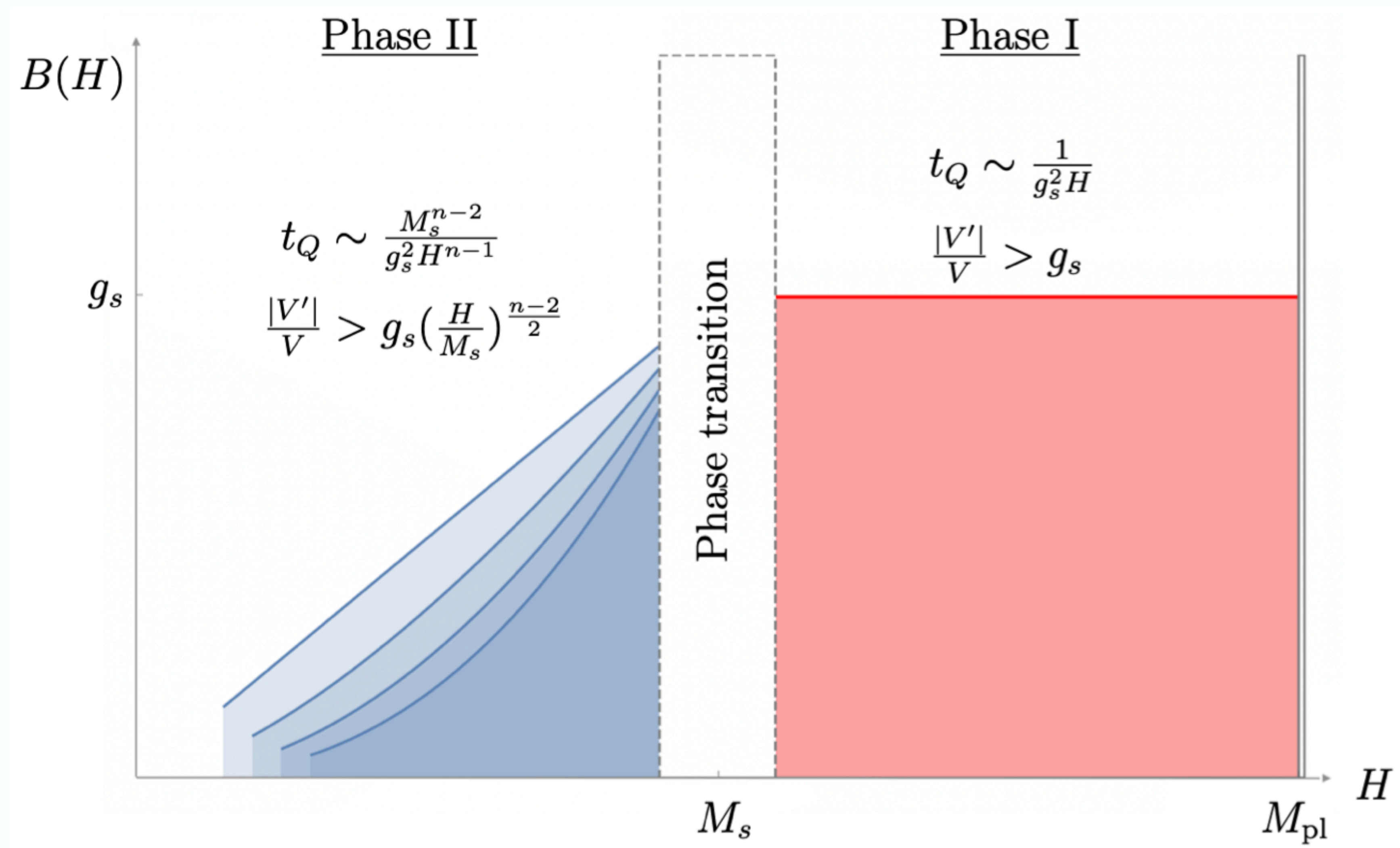
Outlook and future directions



- Better understanding of high-T regime needed.
- Possible explicit verification of T^2 behaviour.
- Concrete string examples where only TCC is verified would provide a lot of support for our picture.

Thanks a lot!

What bound is relevant for us? - Bonus slide



- Many concrete examples obey phase I bound. [0711.2512, 1806.08362]
- For $M_s \to 0$ phase II disappears.
- Such massless string can appear at infinite distance.

Emergent string conjecture [1910.01135]