Title: Holography in String Gas Cosmology

Date: Jul 16, 2009 04:00 PM

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Abstract: I will review the string gas scenario of structure formation, stressing the role which holography plays. I will also discuss another way of obtaining a scale-invariant spectrum of cosmological perturbations (with specific signatures in the bispectrum) which may be realizable in scenarios based on the AdS/CFT correspondence which can resolve the cosmological singularity.

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Holography in String Gas Cosmology

Robert Brandenberger McGill University & CERN

July 16, 2009

Outline

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- Introduction
- String Gas Cosmology
 - Principles
 - Features of String Gas Cosmology
 - Moduli stabilization in SGC
- 3 Holography in String Thermodynamics
 - Formalism
 - Application to a String Gas
 - Specific Heat
- String Gas Cosmology and Structure Formation
 - Review of the Theory of Cosmological Perturbations
 - Fluctuations in String Gas Cosmology vs. Inflation
 - Analysis
- Discussion
- 6 Conclusions

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Goal

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Goal: Alternative to inflation based on holographic thermodynamics.

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Goal: Alternative to inflation based on holographic thermodynamics.

$$C_V(R) \sim R^2$$
 (1)

Realization: String gas cosmology on a compact space (Nayeri, R.B. & Vafa, *Phys. Rev. Lett.* 2006).

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- Inflation has been phenomenologically successful:

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Credit: NASA/WMAP Science Team

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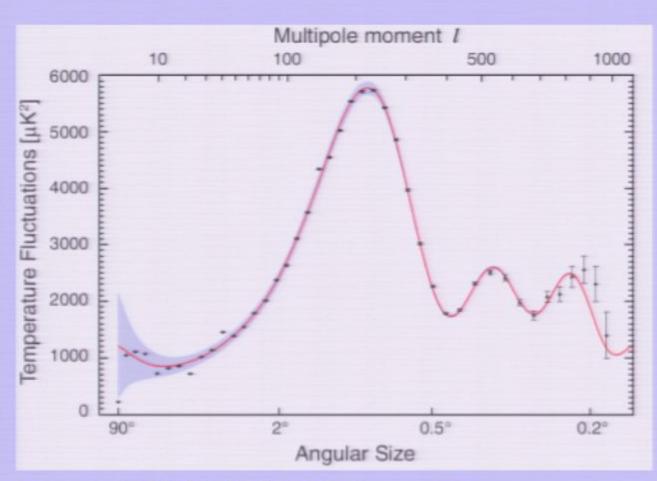
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- Inflation has been phenomenologically successful:
- However, inflation faces conceptual problems:

Conceptual Problems of Inflationary Cosmology

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- Nature of the scalar field φ (the "inflaton")
- Conditions to obtain inflation (initial conditions, slow-roll conditions, graceful exit and reheating)
- Amplitude problem
- Trans-Planckian problem
- Singularity problem
- Cosmological constant problem
- Applicability of General Relativity

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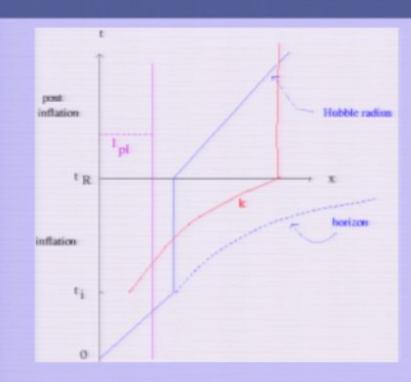
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- Success of inflation: At early times scales are inside the Hubble radius → causal generation mechanism is possible.
 - **Problem:** If time period of inflation is more than $70H^{-1}$, then $\lambda_p(t) < I_{pl}$ at the beginning of inflation
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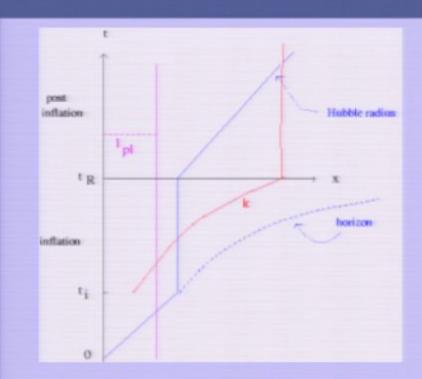
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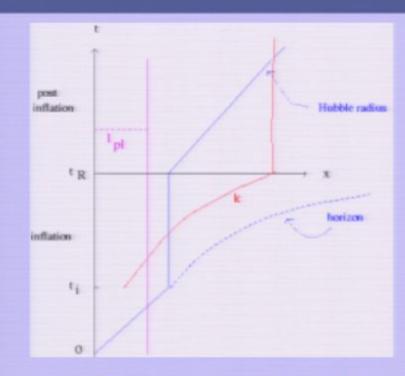
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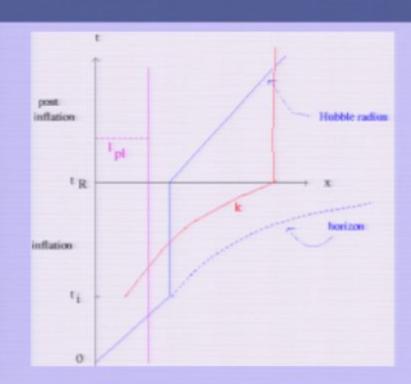
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- Success of inflation: At early times scales are inside the Hubble radius → causal generation mechanism is possible.
- **Problem:** If time period of inflation is more than $70H^{-1}$, then $\lambda_p(t) < I_{pl}$ at the beginning of inflation
- new physics MUST enter into the calculation of the fluctuations.

Trans-Planckian Window of Opportunity

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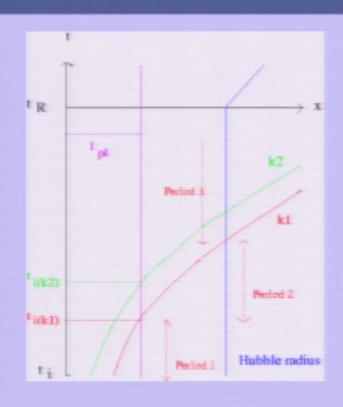
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- If evolution in Period I is non-adiabatic, then scale-invariance of the power spectrum will be lost [J. Martin and RB, 2000]
- Planck scale physics testable with cosmological observations!

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Singularity Problem

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- Standard cosmology: Penrose-Hawking theorems → initial singularity → incompleteness of the theory.
- Inflationary cosmology: In scalar field-driven inflationary models the initial singularity persists [Borde and Vilenkin] → incompleteness of the theory.

Penrose-Hawking theorems:

- Ass: i) Einstein action, 2) weak energy conditions
 ρ > 0, ρ + 3p ≥ 0
- space-time is geodesically incomplete.

Applicability of GR

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- In all approaches to quantum gravity, the Einstein action is only the leading term in a low curvature expansion.
- Correction terms may become dominant at much lower energies than the Planck scale.
- Correction terms will dominate the dynamics at high curvatures.
- The energy scale of inflation models is typically $\eta \sim 10^{16} \text{GeV}.$
- $\rightarrow \eta$ too close to m_{pl} to trust predictions made using GR.

Zones of Ignorance

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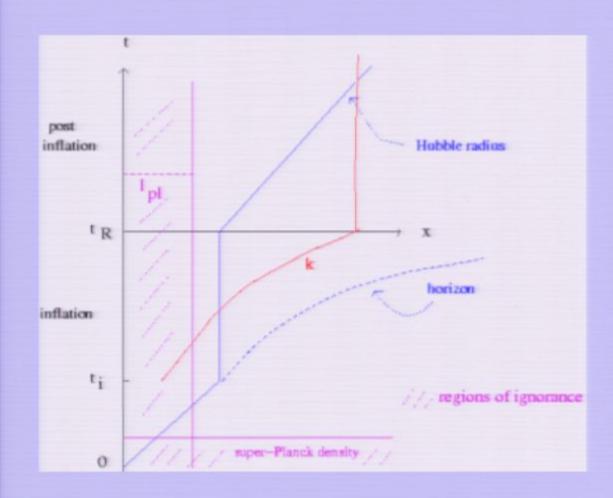
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- We need a new paradigm of early universe cosmology based on new fundamental physics. Can such a paradigm be based on holographic principles?

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- Holographic scaling of correlation functions emerges from String Gas Cosmology (SGC) [R.B. and C. Vafa, 1989]
- New structure formation scenario emerges from SGC [A. Nayeri, R.B. and C. Vafa, 2006].
- String Gas Cosmology makes testable predictions for cosmological observations
- Blue tilt in the spectrum of gravitational waves [R.B., A. Nayeri, S. Patil and C. Vafa, 2007]

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Idea: make use of the new symmetries and new degrees of freedom which string theory provides to construct a new theory of the very early universe.

Assumption: Matter is a gas of fundamental strings Assumption: Space is compact, e.g. a torus. Key points:

- New degrees of freedom: string oscillatory modes
- Leads to a maximal temperature for a gas of strings,
 the Hagedorn temperature
- New degrees of freedom: string winding modes
- Leads to a new symmetry: physics at large R is equivalent to physics at small R

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T-Duality

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T-Duality

- Momentum modes: $E_n = n/R$
- Winding modes: $E_m = mR$
- Duality: $R \rightarrow 1/R \ (n,m) \rightarrow (m,n)$
- Mass spectrum of string states unchanged
- Symmetry of vertex operators
- Symmetry at non-perturbative level → existence of D-branes

Adiabatic Considerations

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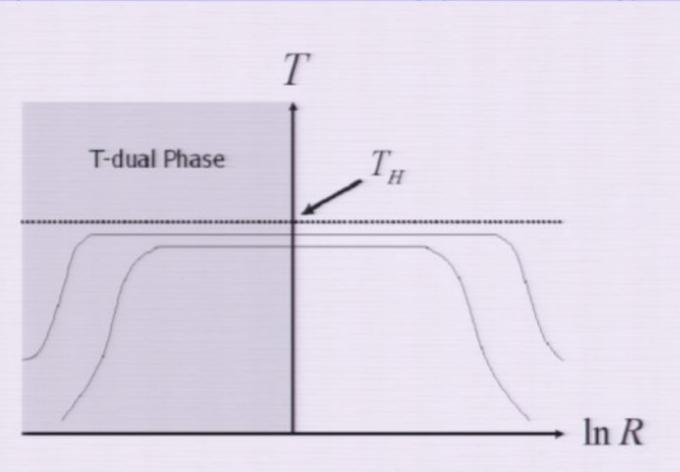
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Temperature-size relation in string gas cosmology



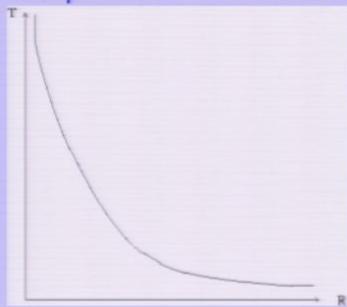
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Temperature-size relation in standard cosmology



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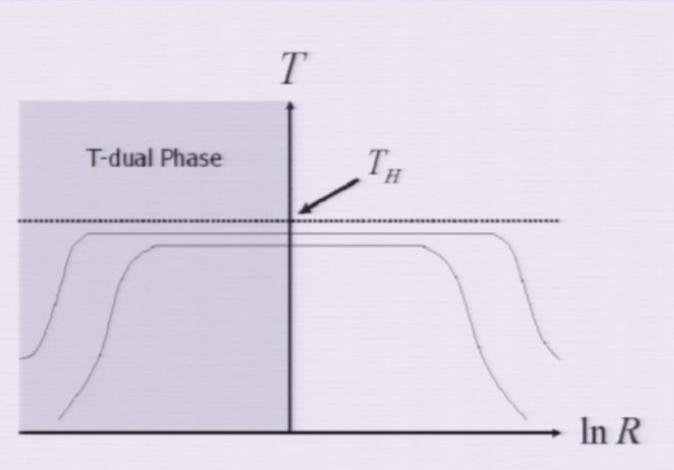
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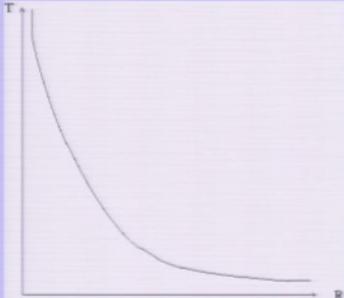
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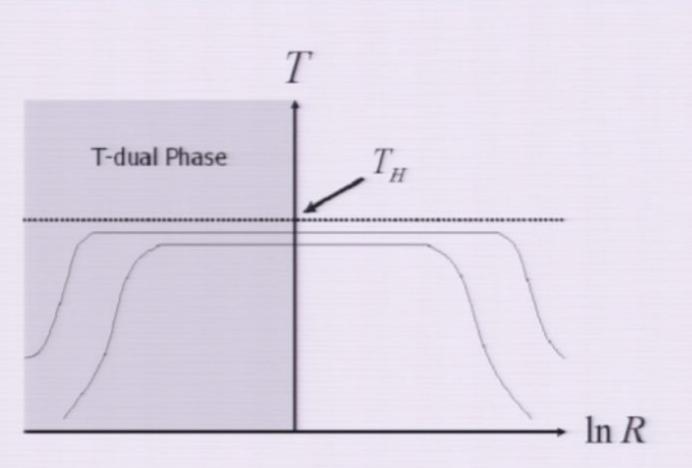
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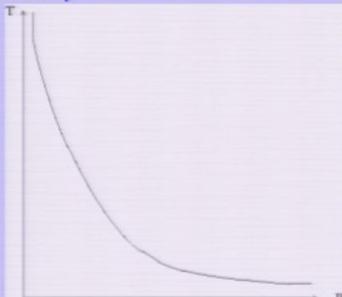
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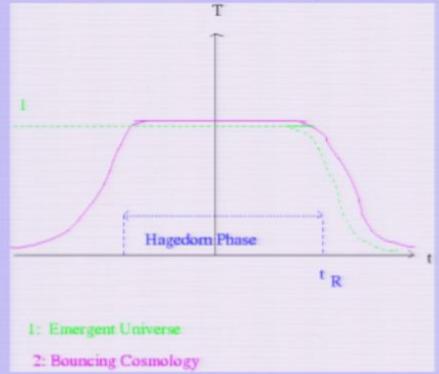
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Assume some action gives us R(t)



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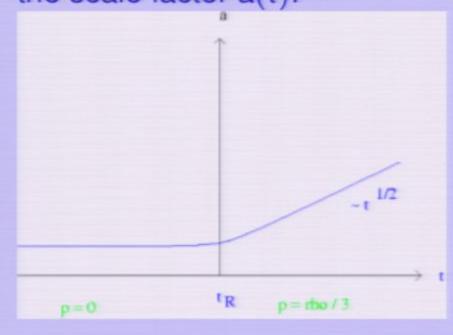
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We will thus consider the following background dynamics for the scale factor a(t):



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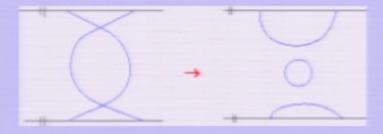
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- Begin with all 9 spatial dimensions small, initial temperature close to T_H → winding modes about all spatial sections are excited.
- Expansion of any one spatial dimension requires the annihilation of the winding modes in that dimension.



- Decay only possible in three large spatial dimensions.
- dynamical explanation of why there are exactly three large spatial dimensions.

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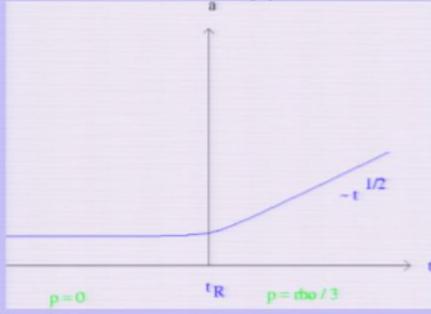
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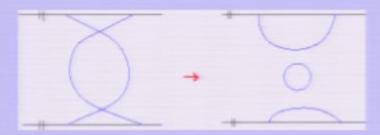
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Vote: this argument assumes constant dilaton (F. Danos A. Page 41/127

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Size Moduli [S. Watson, 2004; S. Patil and R.B., 2004, 2005]

- winding modes prevent expansion
- momentum modes prevent contraction
- $\circ \to V_{eff}(R)$ has a minimum at a finite value of $R \to R_{-}$.
- in heterotic string theory there are enhanced symmetry states containing both momentum and winding which are massless at R_{min}
- $o \rightarrow V_{eff}(R_{min}) = 0$
- size moduli stabilized in Einstein gravity background

- enhanced symmetry states
- ullet o harmonic oscillator potential for heta
- shape moduli stabilized

Dimensionality of Space in SGC

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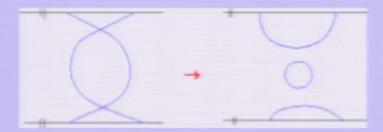
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Pirsa: 09070025

- Begin with all 9 spatial dimensions small, initial temperature close to T_H → winding modes about all spatial sections are excited.
- Expansion of any one spatial dimension requires the annihilation of the winding modes in that dimension.



- Decay only possible in three large spatial dimensions.
- dynamical explanation of why there are exactly three large spatial dimensions.

Note: this argument assumes constant dilaton [R. Danos, A. Frey and A. Mazumdar]

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Size Moduli [S. Watson, 2004; S. Patil and R.B., 2004, 2005]

- winding modes prevent expansion
- momentum modes prevent contraction
- $\circ \to V_{eff}(R)$ has a minimum at a finite value of
 - $R_+ \rightarrow R_{min}$
- in heterotic string theory there are enhanced symmetry states containing both momentum and winding which are massless at R_{min}
- $O \rightarrow V_{eff}(R_{min}) = 0$
- size moduli stabilized in Einstein gravity background

- enhanced symmetry states
- harmonic oscillator potential for θ
- shape moduli stabilized

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Dilaton stabilization in SGC

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The only remaining modulus is the dilaton

- Make use of gaugino condensation to give the dilaton a potential with a unique minimum
- diltaton is stabilized
- Dilaton stabilization is consistent with size stabilization
 [R. Danos, A. Frey and R.B., 2008]

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Partition Function

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Starting point: partition function of a string gas:

$$Z = \sum_{s} e^{-\beta\sqrt{-g_{00}}H(s)}. \tag{2}$$

The free energy follows:

$$F = -\frac{1}{\beta} ln Z. \tag{3}$$

The action follows from the free energy:

$$S = \int dt \sqrt{-g_{00}} F[g_{ij}, \beta]. \tag{4}$$

The action is used to determine the energy-momentum tensor.

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$$T^{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\delta S}{\delta g_{\mu\nu}}.$$
 (5)

$$\langle T^{\mu}{}_{\nu}\rangle = 2 \frac{g^{\mu\lambda}}{\sqrt{-g}} \frac{\delta \ln Z}{\delta g^{\nu\lambda}} \tag{6}$$

$$\langle T^{\mu}_{\nu} \rangle \langle T^{\sigma}_{\lambda} \rangle = 2 \frac{g^{\mu \alpha}}{\sqrt{-g}} \frac{\partial}{\partial g^{\alpha \nu}} \left(\frac{g^{\sigma \delta}}{\sqrt{-g}} \frac{\partial \ln Z}{\partial g^{\delta \lambda}} \right)$$

$$+ 2 \frac{g^{\sigma \alpha}}{\sqrt{-g}} \frac{\partial}{\partial g^{\alpha \lambda}} \left(\frac{G^{\mu \delta}}{\sqrt{-g}} \frac{\partial \ln Z}{\partial g^{\delta \nu}} \right) . \tag{7}$$

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The fluctuations of the energy-momentum tensor are

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Correlation Functions

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The scalar metric fluctuations are determined by the energy density correlation function

$$\langle \delta \rho^2 \rangle = \langle \rho^2 \rangle - \langle \rho \rangle^2 \tag{8}$$

$$= -\frac{1}{R^6} \frac{\partial}{\partial \beta} \left(F + \beta \frac{\partial F}{\partial \beta} \right) = \frac{T^2}{R^6} C_V. \tag{9}$$

The Specific heat capacity is given by

$$C_V = (\partial E/\partial T)|_V, \tag{10}$$

where

$$E \equiv F + \beta \left(\frac{\partial F}{\partial \beta}\right), \tag{11}$$

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Gravitational Waves

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The spectrum of gravitational waves is determined by the off-diagonal pressure fluctuations:

$$\langle \delta T^{i_j^2} \rangle = \langle T^{i_j^2} \rangle - \langle T^{i_j} \rangle^2, \qquad (12)$$

with $i \neq j$.

$$\langle \delta T^{i}{}_{j}^{2} \rangle = \frac{1}{\beta R^{3}} \frac{\partial}{\partial \ln R} \left(-\frac{1}{R^{3}} \frac{\partial F}{\partial \ln R} \right) = \frac{1}{\beta R^{2}} \frac{\partial p}{\partial R},$$
 (13)

The pressure is given by

$$p \equiv -\frac{1}{V} \left(\frac{\partial F}{\partial \ln R} \right) = T \left(\frac{\partial S}{\partial V} \right)_{E}. \tag{14}$$

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Starting point: the following expression for the entropy:

$$S(E,R) = \ln \Omega(E,R) \tag{15}$$

in terms of the density of states $\Omega(E, R)$.

Close to the Hagedorn temperature (see Deo, Jain and Tan, 1992)

$$\Omega(E,R) \simeq \beta_H e^{\beta_H E + n_H V} [1 + \delta \Omega_{(1)}(E,R)], \qquad (16)$$

where

$$\delta\Omega_{(1)}(E,R) = -\frac{(\beta_H E)^5}{5!} e^{-(\beta_H - \beta_1)(E - \rho_H V)} \ll 1$$
 (17)

deep in the Hagedorn phase and

$$\beta_H - \beta_1 \sim \frac{l_s^3}{R^2}$$
 for $R \gg l_s$.

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$$\rightarrow S(E,R) \simeq \beta_H E + n_H V + \ln \left[1 + \delta \Omega_{(1)} \right], \qquad (19)$$

and

$$I_s^3 \delta\Omega_{(1)} \simeq -\frac{R^2}{T_H} \left(1 - \frac{T}{T_H} \right). \tag{20}$$

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The correlation functions of interest are:

$$C_V \approx \frac{R^2/l_s^3}{T(1-T/T_H)}, \qquad (21)$$

and

$$\langle \delta T^{i}{}_{j}^{2} \rangle \simeq \frac{T(1 - T/T_{H})}{l_{s}^{3} R^{4}} \ln^{2} \left[\frac{R^{2}}{l_{s}^{2}} (1 - T/T_{H}) \right].$$
 (22)

- holographic scaling of the correlation functions!
- The factor (1 T/T_H) arises in denominator vs.
 numerator because different derivatives are taker

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Theory of Cosmological Perturbations: Basics

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Cosmological fluctuations connect early universe theories with observations

- Fluctuations of matter → large-scale structure
- Fluctuations of metric → CMB anisotropies
- N.B.: Matter and metric fluctuations are coupled

Key facts:

- 1. Fluctuations are small today on large scales
- fluctuations were very small in the early universe
- can use linear perturbation theory
- 2. Sub-Hubble scales: matter fluctuations dominate
- Super-Hubble scales: metric fluctuations dominate

Theory of Cosmological Perturbations: Basics

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Quantum Theory of Linearized Fluctuations

V. Mukhanov, H. Feldman and R.B., Phys. Rep. 215:203 (1992)

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Step 1: Metric including fluctuations

$$ds^2 = a^2[(1+2\Phi)d\eta^2 - (1-2\Phi)d\mathbf{x}^2]$$
 (23)

$$\varphi = \varphi_0 + \delta \varphi \tag{24}$$

Note: Φ and $\delta \varphi$ related by Einstein constraint equations

Step 2: Expand the action for matter and gravity to second order about the cosmological background:

$$S^{(2)} = \frac{1}{2} \int d^4x ((v')^2 - v_i v'^i + \frac{z''}{z} v^2)$$
 (25)

$$v = a(\delta\varphi + \frac{\zeta}{2}\Phi) \tag{26}$$

$$z = a \frac{\varphi_0}{H}$$

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Quantum Theory of Linearized Fluctuations

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Step 3: Resulting equation of motion (Fourier space)

$$v_k'' + (k^2 - \frac{z''}{z})v_k = 0 (28)$$

Features:

- oscillations on sub-Hubble scales
- squeezing on super-Hubble scales $v_k \sim z$

Quantum vacuum initial conditions:

$$V_k(\eta_i) = (\sqrt{2k})^{-1}$$
 (29)

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Step 3: Resulting equation of motion (Fourier space)

$$v_k'' + (k^2 - \frac{z''}{z})v_k = 0 (28)$$

Features:

- oscillations on sub-Hubble scales
- squeezing on super-Hubble scales $v_k \sim z$

Quantum vacuum initial conditions:

$$V_k(\eta_i) = (\sqrt{2k})^{-1}$$
 (29)

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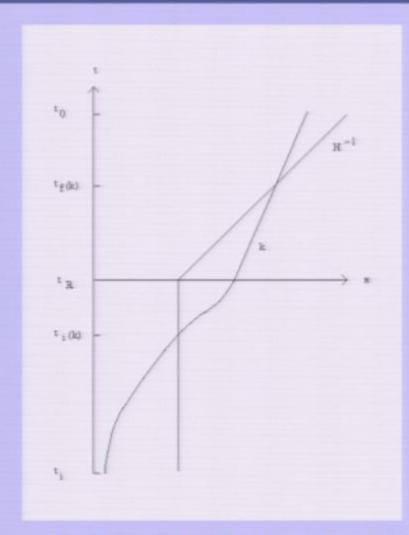
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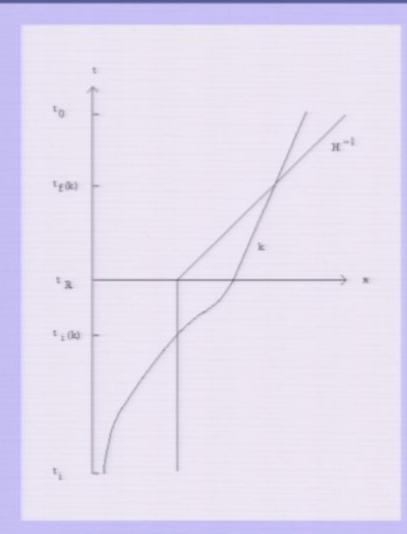
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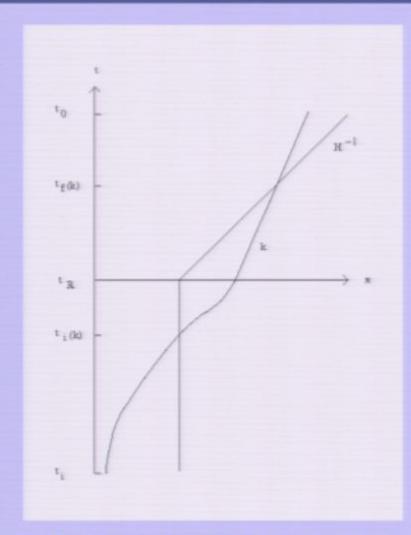
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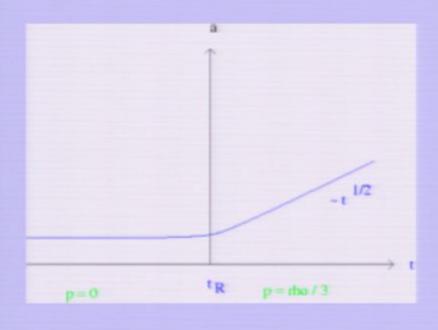
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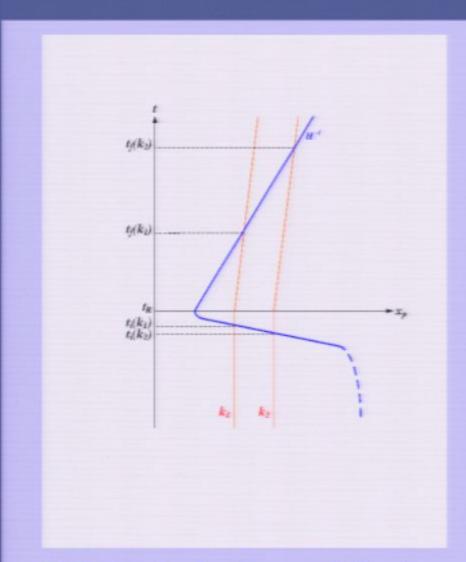
A. Nayeri, R.B. and C. Vafa, Phys. Rev. Lett. 97:021302 (2006)

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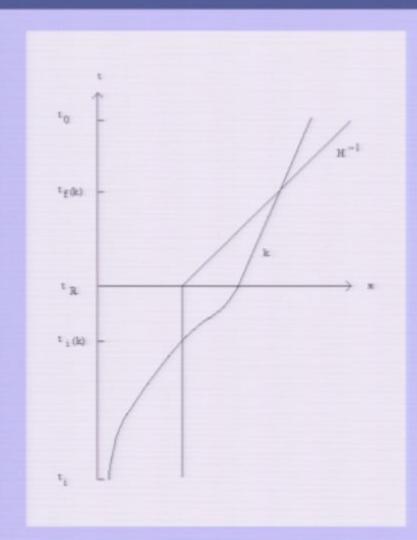
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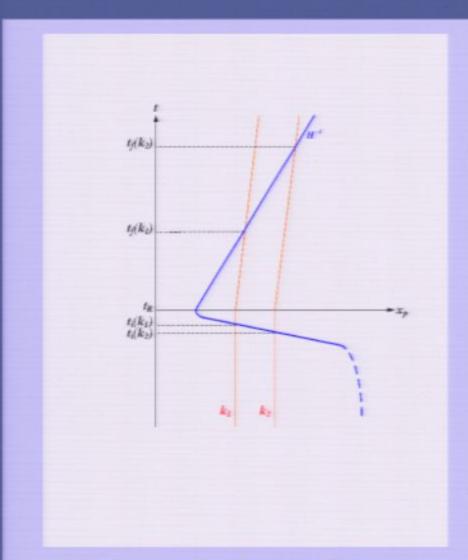
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- Calculate matter correlation functions in the Hagedorn phase (neglecting the metric fluctuations)
- For fixed k, convert the matter fluctuations to metric fluctuations at Hubble radius crossing $t = t_i(k)$
- Evolve the metric fluctuations for $t > t_i(k)$ using the usual theory of cosmological perturbations

Extracting the Metric Fluctuations

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Ansatz for the metric including cosmological perturbations and gravitational waves:

$$ds^{2} = a^{2}(\eta) \left((1 + 2\Phi) d\eta^{2} - [(1 - 2\Phi) \delta_{ij} + h_{ij}] dx^{i} dx^{j} \right). (30)$$

Inserting into the perturbed Einstein equations yields

$$\langle |\Phi(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^0_0(k) \delta T^0_0(k) \rangle, \qquad (31)$$

$$\langle |\mathbf{h}(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^i{}_j(k) \delta T^i{}_j(k) \rangle. \tag{32}$$

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Key ingredient: For thermal fluctuations:

$$\langle \delta \rho^2 \rangle = \frac{T^2}{R^6} C_V \,. \tag{33}$$

Key ingredient: For string thermodynamics in a compact space

$$C_V \approx 2 \frac{R^2/\ell_s^3}{T(1-T/T_H)}$$
 (34)

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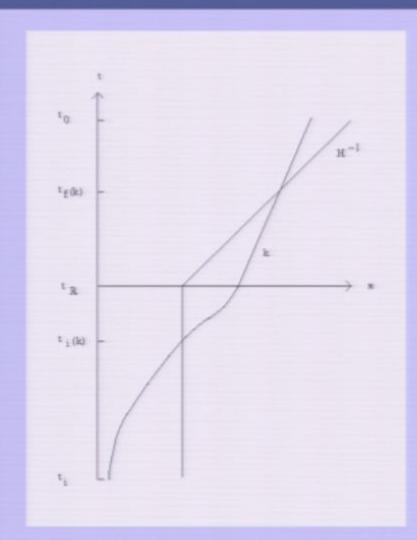
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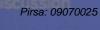
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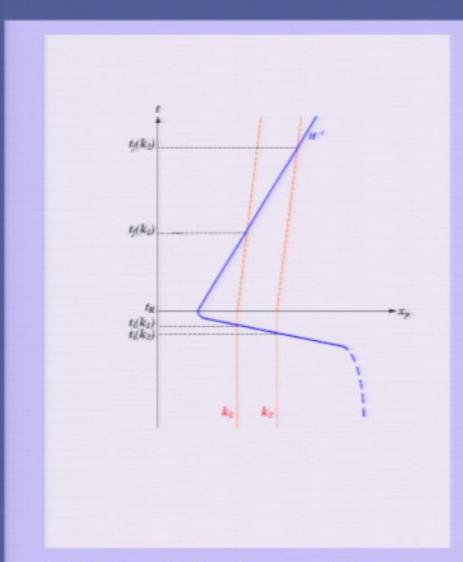
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Power spectrum of cosmological fluctuations

$$P_{\Phi}(k) = 8G^{2}k^{-1} < |\delta\rho(k)|^{2} >$$

$$= 8G^{2}k^{2} < (\delta M)^{2} >_{R}$$

$$= 8G^{2}k^{-4} < (\delta\rho)^{2} >_{R}$$

$$= 8G^{2}\frac{T}{\ell_{s}^{3}} \frac{1}{1 - T/T_{H}}$$
(35)
$$(36)$$

$$= 8G^{2}k^{-4} < (\delta\rho)^{2} >_{R}$$

$$= 8G^{2}\frac{T}{\ell_{s}^{3}} \frac{1}{1 - T/T_{H}}$$
(38)

- scale-invariant like for inflation
- slight red tilt like for inflation

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- Evolution for $t > t_i(k)$: $\Phi \simeq \text{const}$ since the equation of state parameter 1 + w stays the same order of magnitude unlike in inflationary cosmology.
- Squeezing of the fluctuation modes takes place on super-Hubble scales like in inflationary cosmology → acoustic oscillations in the CMB angular power spectrum
- In a dilaton gravity background the dilaton fluctuations dominate → different spectrum [R.B. et al, 2006;
 Kaloper, Kofman, Linde and Mukhanov, 2006]

Spectrum of Gravitational Waves

R.B., A. Nayeri, S. Patil and C. Vafa, Phys. Rev. Lett. (2007)

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$$P_h(k) = 16\pi^2 G^2 k^{-1} < |T_{ij}(k)|^2 >$$
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$$= 16\pi^2 G^2 k^{-4} < |T_{ij}(R)|^2 > \tag{40}$$

$$\sim 16\pi^2 G^2 \frac{T}{\ell_s^3} (1 - T/T_H)$$
 (41)

Key ingredient for string thermodynamics

$$<|T_{ij}(R)|^2> \sim \frac{T}{l_s^3 R^4} (1-T/T_H)$$
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- static Hagedorn phase (including static dilaton) → new physics required.
- holographic scaling C_V(R) ~ R² obtained from a thermal gas of strings provided there are winding modes which dominate.
- Cosmological fluctuations in the IR are described by Einstein gravity.

Note: Specific higher derivative toy model: T. Biswas, R.B., A. Mazumdar and W. Siegel, 2006

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- 1 Introduction
- String Gas Cosmology
 - Principles
 - Features of String Gas Cosmology
 - Moduli stabilization in SGC
- 3 Holography in String Thermodynamics
 - Formalism
 - Application to a String Gas
 - Specific Heat
- String Gas Cosmology and Structure Formation
 - Review of the Theory of Cosmological Perturbations
 - Fluctuations in String Gas Cosmology vs. Inflation
 - Analysis
- Discussion
- 6 Conclusions

Weak Points

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In its present form, the string gas cosmology structure formation scenario faces challenges:

- No consistent effective field theory description of the dynamics (for a toy model, see however R.B., A. Frey and S. Kanno, 2007).
- Keeping the metric flat during the Hagedorn phase is unrealistic.

Question: Is there an improved description of the Hagedorn phase?

Holographic Cosmology V

G. Veneziano, hep-th/0312182

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- Hagedorn phase: p = 0 gas of string holes with $r_s = H^{-1}$.
- string hole: black hole on the string correspondence curve $M=M_{\rm s}g_{\rm s}^{-2}$
- satisfies cosmological entropy bound: $\sigma = \sigma_{max} = HM_P^2$
- string holes decay into radiative string states
- \Rightarrow transition between p=0 and $p=1/3\rho$ state

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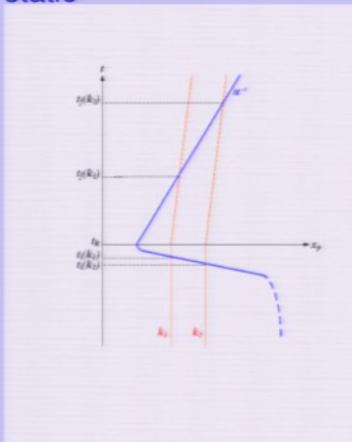
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Pirsa: 09070025

Assume Deep in the Hagedorn phase the universe is almost static



Also: holographic scaling $C_V(R) \sim R^2$.

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Matter Bounce

F. Finelli and R.B., Phys. Rev. D65 (2002); Y. Cai et al, arXiv:0810.4677

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- Message: In the context of a bouncing cosmology (possibly obtained by AdS/CFT approaches to singularity resolution) there is another way to obtain a scale-invariant spectrum of cosmological perturbations: a matter bounce.
- Matter bounce: bouncing cosmology with a matter-dominated phase of contraction when the relevant scales exit the Hubble radius.
- Statement: In a matter bounce setup, fluctuations which are in their vacuum state on sub-Hubble scales early in the contracting phase evolve into a scale-invariant spectrum of curvature fluctuations on super-Hubble scales at late times.

Space-Time Sketch

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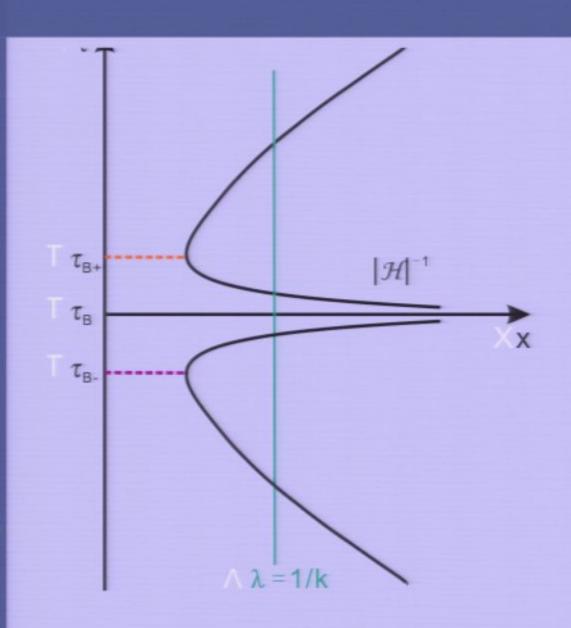
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- Vacuum spectrum: P_ζ(k) ~ k²
- need a boosting of IR modes relative to UV modes.
- In a contracting universe the dominant mode of ζ is growing on super-Hubble scales (whereas it is constant in an expanding phase).
- Long wavelengths are super-Hubble for a longer time
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- For a matter-dominated phase of contraction the boost is exactly right to convert a vacuum spectrum into a scale-invariant one.

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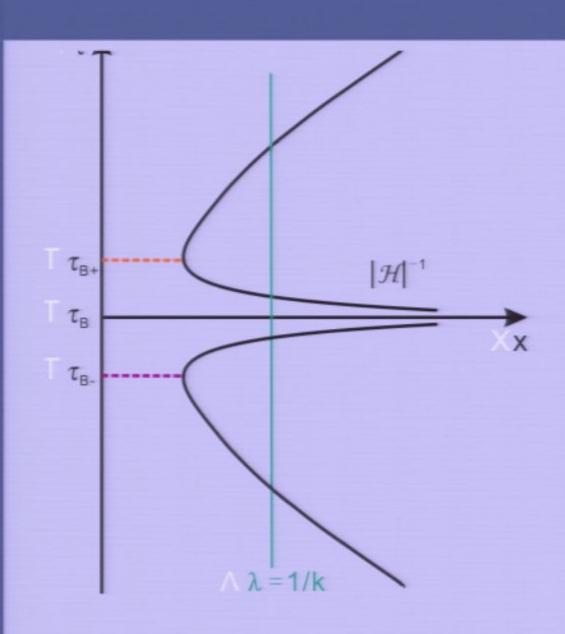
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- Vacuum spectrum: $P_{\zeta}(k) \sim k^2$
- need a boosting of IR modes relative to UV modes.
- In a contracting universe the dominant mode of \(\zeta \) is growing on super-Hubble scales (whereas it is constant in an expanding phase).
- Long wavelengths are super-Hubble for a longer time
 preferential growth of IR modes.
- For a matter-dominated phase of contraction the boost is exactly right to convert a vacuum spectrum into a scale-invariant one.

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- String Gas Cosmology: Model of cosmology of the very early universe based on new degrees of freedom and new symmetries of superstring theory.
- SGC → nonsingular cosmology
- SGC → natural explanation of the number of large spatial dimensions.
- Holographic scaling of SGC correlation functions → new scenario of structure formation
- Scale invariant spectrum of cosmological fluctuations (like in inflationary cosmology).
- Spectrum of gravitational waves has a small blue tilt (unlike in inflationary cosmology).
- But we need a better model of the Hagedorn phase

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Matter Bounce

F. Finelli and R.B., Phys. Rev. **D65** (2002); Y. Cai et al, arXiv:0810.4677

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- Message: In the context of a bouncing cosmology (possibly obtained by AdS/CFT approaches to singularity resolution) there is another way to obtain a scale-invariant spectrum of cosmological perturbations: a matter bounce.
- Matter bounce: bouncing cosmology with a matter-dominated phase of contraction when the relevant scales exit the Hubble radius.
- Statement: In a matter bounce setup, fluctuations which are in their vacuum state on sub-Hubble scales early in the contracting phase evolve into a scale-invariant spectrum of curvature fluctuations on super-Hubble scales at late times.

Holographic Cosmology V

G. Veneziano, hep-th/0312182

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- Hagedorn phase: p = 0 gas of string holes with $r_s = H^{-1}$.
- string hole: black hole on the string correspondence curve $M = M_s g_s^{-2}$
- satisfies cosmological entropy bound: $\sigma = \sigma_{max} \equiv HM_P^2$
- string holes decay into radiative string states
- \rightarrow transition between p = 0 and $p = 1/3\rho$ state

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- No consistent effective field theory description of the dynamics (for a toy model, see however R.B., A. Frey and S. Kanno, 2007).
- Keeping the metric flat during the Hagedorn phase is unrealistic.

Question: Is there an improved description of the Hagedorn phase?

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