Update on String Gas Cosmology

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Physics Department, McGill University

Workshop on Post-Inflationary String Cosmology,
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Outline

Plan

What is String Gas Cosmology?

String Gas Cosmology is a paradigm for early universe cosmology based on fundamental principles of superstring theory.

Principles: New degrees of freedom and symmetries which distinguish string theories from point particle theories.

String Gas Cosmology is in development.

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- **Moduli Stabilization in String Gas Cosmology**: S. Watson and RB, JCAP **0311**:008 (2003); S. Patil and RB, JCAP **0601**:005 (2006); RB, Y. K. Cheung and S. Watson, JHEP **0605**:025 (2006).
- **Structure Formation in String Gas Cosmology**: A. Nayeri, RB and C. Vafa, Phys. Rev. Lett. **97**, 021302 (2006); RB, A. Nayeri, S. Patil and C. Vafa, Phys. Rev. Lett. **98**, 231302 (2007).
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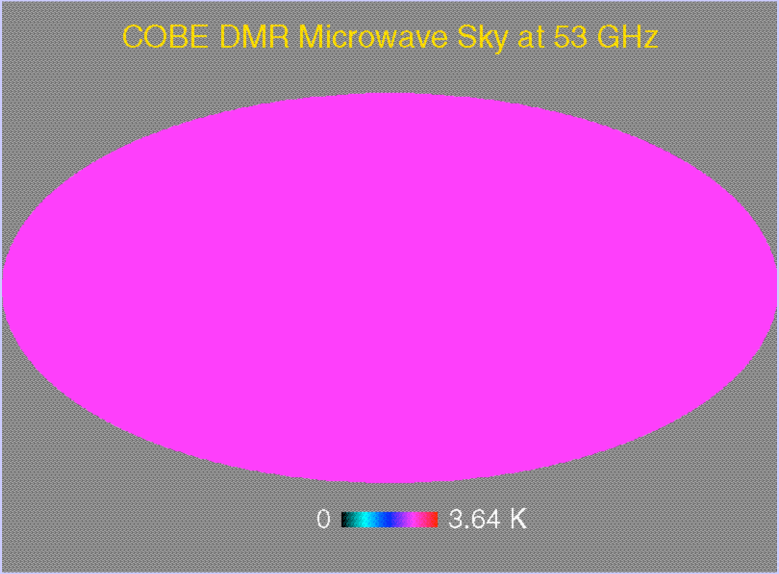
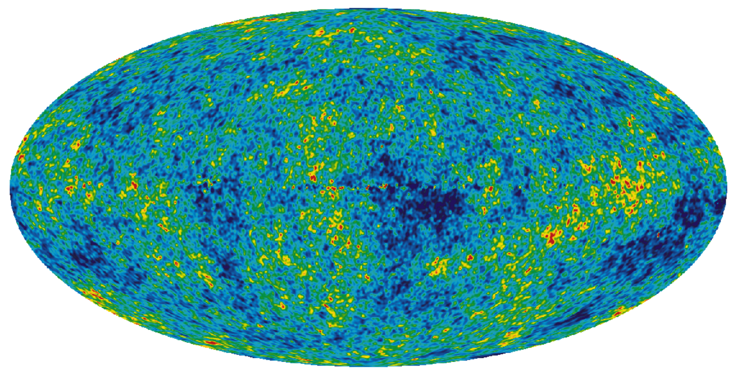
Data: Isotropic CMB Background

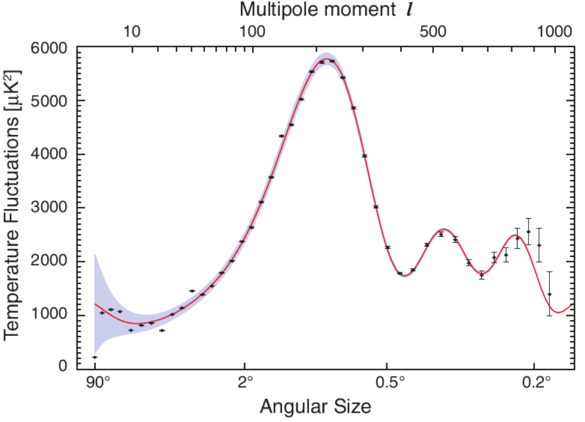


Data: Map of the Cosmic Microwave Background (CMB)



Credit: NASA/WMAP Science Team

Data: Angular Power Spectrum of CMB Anisotropies



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Early Work

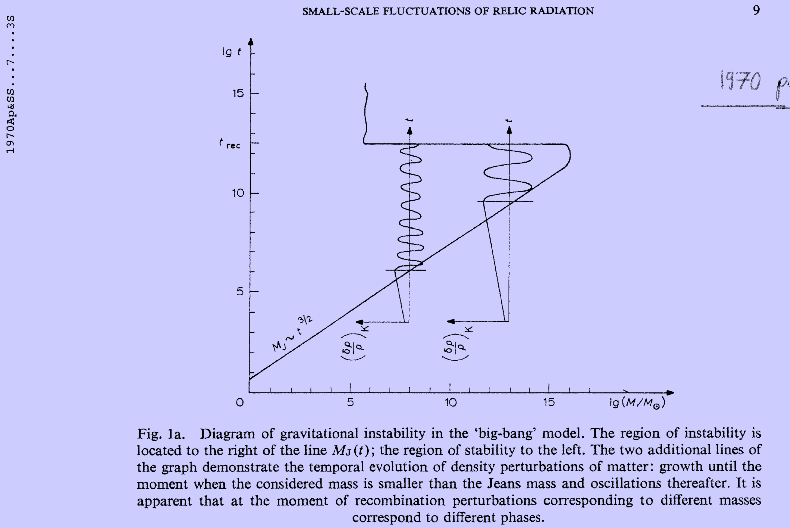

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Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.

Predictions from 1970

R. Sunyaev and Y. Zel'dovich, Astrophys. and Space Science **7**, 3 (1970); P. Peebles and J. Yu, Ap. J. **162**, 815 (1970).

- Given a scale-invariant power spectrum of adiabatic fluctuations on "super-horizon" scales before t_{eq}, i.e. standing waves.
- $\rightarrow$ "correct" power spectrum of galaxies.
- $\rightarrow$ acoustic oscillations in CMB angular power spectrum.
- $\rightarrow$ baryon acoustic oscillations in matter power spectrum.

Key Challenge

How does one obtain such a spectrum?

- Inflationary Cosmology is the first scenario based on causal physics which yields such a spectrum.
- String Gas Cosmology provides an alternative scenario.

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Criteria for a Successful Early Universe Scenario

- Horizon $\gg$ Hubble radius in order for the scenario to solve the “horizon problem” of Standard Big Bang Cosmology.
- Scales of cosmological interest today originate inside the Hubble radius at early times in order for a causal generation mechanism of fluctuations to be possible.
- Squeezing of fluctuations on super-Hubble scales in order to obtain the acoustic oscillations in the CMB angular power spectrum.
- Mechanism for producing a scale-invariant spectrum of curvature fluctuations on super-Hubble scales.

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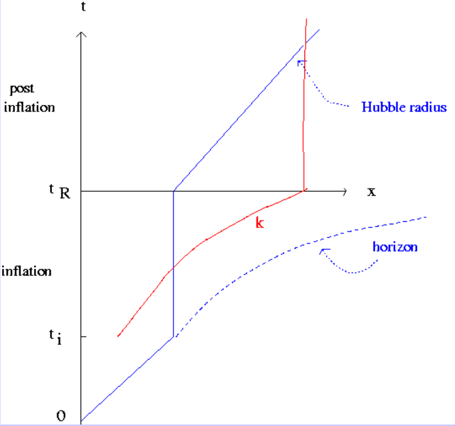
Inflation as a Solution

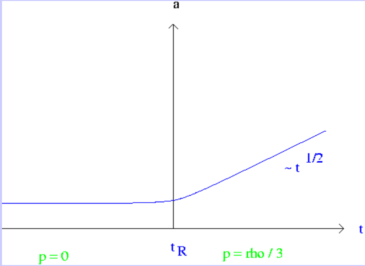


Addressing the Criteria

- Exponential increase in horizon relative to Hubbe radius.
- Fluctuations originate on sub-Hubble scales.
- Long period of super-Hubble evolution.
- Time translation symmetry → scale-invariant spectrum (Press, 1980).

Emergent Universe

R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*



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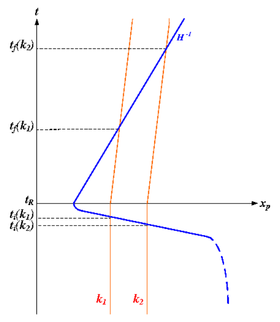
A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett. 97:021302 (2006)*



Addressing the Criteria

- Horizon given by the duration of the quasi-static phase, Hubble radius decreases suddenly at the phase transition → horizon $\gg$ Hubble radius at the beginning of the Standard Big Bang phase.
- Fluctuations originate on sub-Hubble scales.
- Long period of super-Hubble evolution.
- Curvature fluctuations starting from thermal matter inhomogeneities acquire a scale-invariant spectrum if the thermodynamics obeys holographic scaling.

Plan

Principles of String Gas Cosmology

R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

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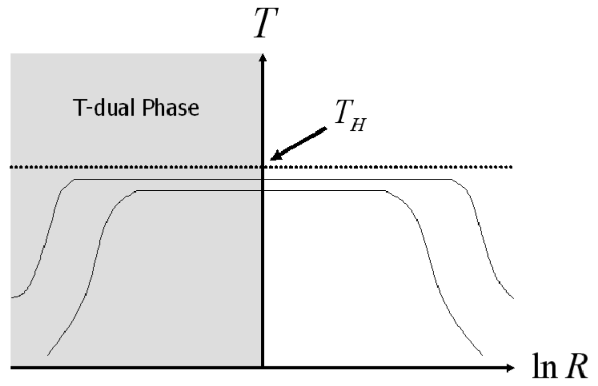
- Momentum modes: $E_n = n/R$
- Winding modes: $E_m = mR$
- Duality: $R \to 1/R \quad (n, m) \to (m, n)$.
- Mass spectrum of string states unchanged
- Symmetry of vertex operators
- Symmetry at non-perturbative level → existence of D-branes

Adiabatic Considerations

R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

Temperature-size relation in string gas cosmology



Physical Radius

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- $R > 1$: measure distance in terms of momentum mode rulers.
- $R < 1$: measure distance in terms of winding mode rulers.
- $R_p = R \quad R \gg 1$
- $R_p = \frac{1}{R} \quad R \ll 1$

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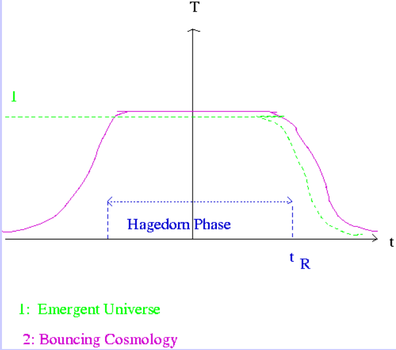
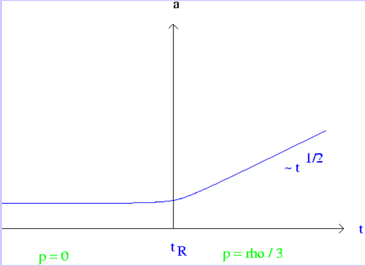
Dynamics

Assume some action gives us $R(t)$

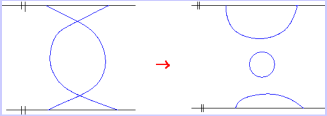


Background for string gas cosmology



Dimensionality of Space in SGC

- Begin with all 9 spatial dimensions small, initial temperature close to T_H $\rightarrow$ 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.
- $\rightarrow$ dynamical explanation of why there are exactly three large spatial dimensions.

(see also numerical work by M. Sakellariadou)

Cosmological Scenario of SGC

- Begin in a quasi-static **Hagedorn phase**.
- Winding modes about three spatial dimensions decay into loops (i.e. radiation).
- → smooth transition to a post-Hagedorn radiation phase.

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Moduli Stabilization in SGC

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

- winding modes prevent expansion
- momentum modes prevent contraction
- $\rightarrow$ $V_{eff}(R)$ 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}
- $\rightarrow V_{eff}(R_{min}) = 0$
- $\rightarrow$ size moduli stabilized in Einstein gravity background

Shape Moduli [E. Cheung, S. Watson and R.B., 2005]

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

Dilaton stabilization in SGC

- The only remaining modulus is the dilaton.
- Make use of gaugino condensation to give the dilaton a potential with a unique minimum.
- $\rightarrow$ diltaton is stabilized.
- Dilaton stabilization is consistent with size stabilization [R. Danos, A. Frey and R.B., 2008].
- Gaugino condensation induces (high scale) supersymmetry breaking [S. Mishra, W. Xue, R.B. and U. Yajnik, 2012].

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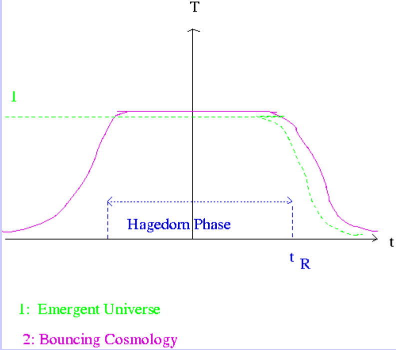

String Gas Bounce

Two possibilities:

- Thermal Bounce
- Emergent Scenario

In both cases, a **long Hagedorn phase** will allow thermalization of the string gas on large scales.

→ thermal initial conditions for fluctuations

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Plan

Quantum Theory of Linearized Fluctuations

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

Step 1: Metric including fluctuations

$$\begin{aligned} ds^2 &= a^2[(1+2\Phi)d\eta^2 - (1-2\Phi)d\mathbf{x}^2] \\ \varphi &= \varphi_0 + \delta\varphi \end{aligned}$$

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:

$$\begin{aligned} S^{(2)} &= \frac{1}{2}\int d^4x\big((v')^2 - v_{,i}v^{,i} + \frac{z''}{z}v^2\big) \\ v &= a\big(\delta\varphi + \frac{z}{a}\Phi\big) \\ z &= a\frac{\varphi_0'}{\mathcal{H}} \end{aligned}$$

Step 3: Resulting equation of motion (Fourier space)

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

Features:

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

Quantum vacuum initial conditions:

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

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Curvature Fluctuations

$$\zeta = z^{-1} v$$

Physical meaning: curvature perturbation in comoving gauge.

Gravitational Waves

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

- $h_{ij}(\mathbf{x}, t)$ transverse and traceless
- Two polarization states

$$h_{ij}(\mathbf{x}, t) = \sum_{a=1}^{2} h_a(\mathbf{x}, t)\epsilon_{ij}^a$$

- At linear level each polarization mode evolves independently.

Gravitational Waves II

Canonical variable for gravitational waves:

$$u(\mathbf{x}, t) \, = \, a(t) h(\mathbf{x}, t)$$

Equation of motion for gravitational waves:

$$u_k^{''} + (k^2 - \frac{a^{''}}{a}) u_k \, = \, 0 \, .$$

Squeezing on super-Hubble scales, oscillations on sub-Hubble scales.

Consequences for Tensor to Scalar Ratio r

R.B., arXiv:1104.3581

- If EoS of matter is time independent, then $z \propto a$ and $u \propto v$.
- Thus, generically models with dominant adiabatic fluctuations lead to a large value of r. A large value of r is not a smoking gun for inflation.
- During a phase transition EoS changes and u evolves differently than v
- $\rightarrow$ Suppression of r.
- This happens during the inflationary reheating transition.
- Simple inflation models typically predict very small value of r.

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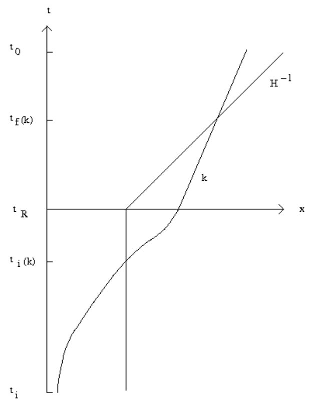
Structure formation in inflationary cosmology



N.B. Perturbations originate as quantum vacuum fluctuations.

Origin of Scale-Invariance in Inflation

- **Initial vacuum spectrum** of ζ ($\zeta \sim v$): (Chibisov and Mukhanov, 1981).

$$P_\zeta(k) \equiv k^3|\zeta(k)|^2 \sim k^2$$

- $v \sim z \sim a$ on super-Hubble scales
- At late times on super-Hubble scales

$$P_\zeta(k,t) \equiv P_\zeta(k,t_i(k))\left(\frac{a(t)}{a(t_i(k))}\right)^2 \sim k^2 a(t_i(k))^{-2}$$

- Hubble radius crossing: $ak^{-1} = H^{-1}$
- $\rightarrow P_\zeta(k,t) \sim \mathrm{const}$

Scale-Invariance of Gravitational Waves in Inflation

- **Initial vacuum spectrum** of u (Starobinsky, 1978):

$$P_h(k) \equiv k^3 |h(k)|^2 \sim k^2$$

- $u \sim a$ on super-Hubble scales
- At late times on super-Hubble scales

$$P_h(k,t) \equiv a^{-2}(t) P_u(k, t_i(k)) \Big(\frac{a(t)}{a(t_i(k))}\Big)^2 \simeq k^2 a(t_i(k))^{-2}$$

- Hubble radius crossing: $ak^{-1} = H^{-1}$
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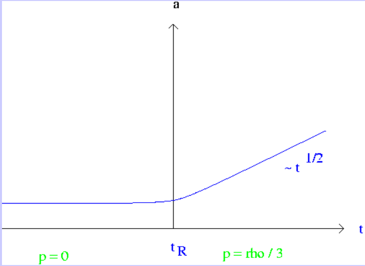
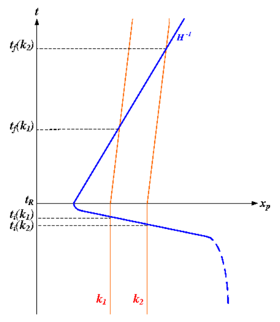


Structure formation in string gas cosmology

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



N.B. Perturbations originate as thermal string gas fluctuations.

Structure Formation in String Gas Cosmology

- 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

Ansatz for the metric including cosmological perturbations and gravitational waves:

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

Inserting into the perturbed Einstein equations yields

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

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

Power Spectrum of Cosmological Perturbations

Key ingredient: For thermal fluctuations:

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

Key ingredient: For string thermodynamics in a compact space

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

Power spectrum of cosmological fluctuations

$$\begin{aligned}
P_\Phi(k) &= 8G^2k^{-1} < |\delta\rho(k)|^2 > \\
&= 8G^2k^2 < (\delta M)^2 >_R \\
&= 8G^2k^{-4} < (\delta\rho)^2 >_R \\
&= 8G^2 \frac{T}{\ell_s^3} \frac{1}{1 - T/T_H}
\end{aligned}$$

Key features:

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

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&= 8G^2k^2 < (\delta M)^2 >_R \\
&= 8G^2k^{-4} < (\delta\rho)^2 >_R \\
&= 8G^2\frac{T}{\ell_s^3}\frac{1}{1 - T/T_H}
\end{aligned}$$

Key features:

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

Running of the Spectrum

R.B., G. Franzmann and Q. Liang, arXiv:1708.06793

Using a simple parametrization of the transition between the Hagedorn phase and the radiation phase we find:

$$\alpha_s \sim -(1 - n_s) .$$

This is same sign but parametrically larger in amplitude than the running in simple inflationary models:

$$\alpha_s \sim -(n_s - 1)^2$$

Spectrum of Gravitational Waves

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

$$\begin{aligned} P_h(k) &= 16\pi^2 G^2 k^{-1} < |T_{ij}(k)|^2 > \\ &= 16\pi^2 G^2 k^{-4} < |T_{ij}(R)|^2 > \\ &\sim 16\pi^2 G^2 \frac{T}{\ell_s^3}(1 - T/T_H) \end{aligned}$$

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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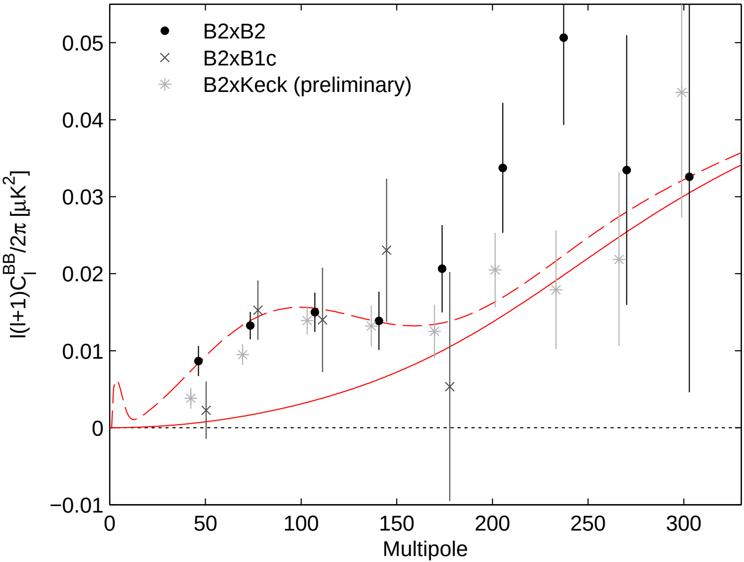
BICEP-2 Results



Requirements

- Emergent phase in thermal equilibrium
- $C_V(R) \sim R^2$ obtained from a thermal gas of strings provided there are winding modes which dominate.
- Cosmological fluctuations in the IR are described by Einstein gravity.

Plan

Doubled Space in SGC

R.B., R. Costa, G. Franzmann, S. Patil and A. Weltman, in prep.

Candidate for dynamics in the Hagedorn phase: Double Field Theory [C. Hull and B. Zwiebach, 2009]
Idea: For each dimension of the underlying topological space there are two position operators [R.B. and C. Vafa]:

- x: dual to the momentum modes
- $\tilde{x}$: dual to the winding modes

We measure **physical length** in terms of the **light** degrees of freedom.

$$\begin{aligned} l(R) &= R \quad \text{for} \quad R \gg 1\,, \\ l(R) &= \frac{1}{R} \quad \text{for} \quad R \ll 1\,. \end{aligned}$$

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Double Field Theory Approach

Idea Describe the low-energy degrees of freedom with an action in doubled space in which the T-duality symmetry is manifest.

$$S = \int dx d\tilde{x} e^{-2d} \mathcal{R},$$

$$\begin{aligned}\mathcal{R} &= \frac{1}{8}\mathcal{H}^{MN}\partial_M \mathcal{H}^{KL}\partial_N \mathcal{H}_{KL} - \frac{1}{2}\mathcal{H}^{MN}\partial_M \mathcal{H}^{KL}\partial_K \mathcal{H}_{NL} \\ &+ 4\mathcal{H}^{MN}\partial_M \partial_N d - \partial_M \partial_N \mathcal{H}^{MN} - 4\mathcal{H}^{MN}\partial_M d \partial_N d \\ &+ 4\partial_M \mathcal{H}^{MN}\partial_N d + \frac{1}{2}\eta^{MN}\eta^{KL}\partial_M \mathcal{E}^A{}_K \partial_N \mathcal{E}^B{}_L \mathcal{H}_{AB} .\end{aligned}$$

$$\begin{aligned}
\mathcal{H}_{MN} &= \begin{bmatrix} g^{ij} & -g^{ik} b_{kj} \\ b_{ik} g^{kj} & g_{ij} - b_{ik} g^{kl} b_{lj} \end{bmatrix} . \\
X^M &= (\tilde{x}_i, x^i), \\
\eta^{MN} &= \begin{bmatrix} 0 & \delta_i{}^j \\ \delta^i{}_j & 0 \end{bmatrix} .
\end{aligned}$$

Singularity Resolution in SGC

R.B., R. Costa, G. Franzmann, S. Patil and A. Weltman, in prep.

- Consider test particles in a DFT background.
- Derive geodesic equation of motion
- Consider a cosmological background with $b = 0$ and fixed dilaton.
- Find that the geodesics can be extended to infinite proper time in both time directions.
- → geodesic completeness in terms of physical time:

$$\begin{aligned} t_p(t) &= t \quad \text{for} \quad t \gg 1 \, , \\ t_p(t) &= \frac{1}{t} \quad \text{for} \quad t \ll 1 \, . \end{aligned}$$

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Plan

Conclusions

- String Gas Cosmology is a paradigm of early universe cosmology based on fundamental principles of superstring theory.
- In SGC our universe emerges from an early Hagedorn phase.
- Thermal string fluctuations in the Hagedorn phase yield an almost scale-invariant spectrum of cosmological fluctuations.
- **Characteristic signal**: blue tilt in the spectrum of gravitational waves.
- Cosmological evolution in **nonsingular**.

What about Effective Field Theory?

- Standard EFT is missing ALL of the features which differentiate string theory from point particle theories.
- → at the string scale expect EFT to be inapplicable.
- Since the string scale is comparable to the inflation scale expect EFT to be inapplicable for inflation.
- Swampland: **"The string landscape is surrounded by a vast landscape of consistent-looking semiclassical EFT which are actually inconsistent"** (C. Vafa, hep-th/0509212; see also H. Ooguri and C. Vafa, hep-th/0605264 & 1610.01533, N. Arkani-Hamed et al, hep-th/0601001).
- Some EFT string inflation models are **not** solutions of the higher dimensional field equations (K. Dasgupta et al, arXiv:1402.5112; S. Sethi, arXiv:1709.03554).

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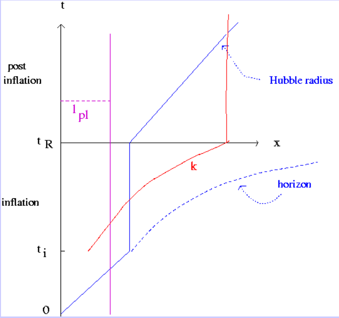
Trans-Planckian Problem



- **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 $\lambda_p(t) < l_{pl}$ at the beginning of inflation.
- → new physics MUST enter into the calculation of the fluctuations.

Applicability of GR

- 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