String Gas Cosmology: Progress and Challenges

Robert Brandenberger
McGill University

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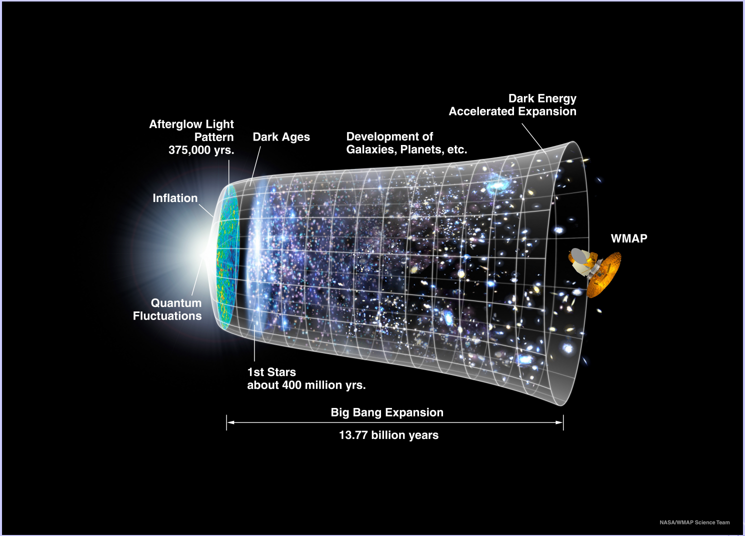
Outline

Plan


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

Goals of Early Universe Cosmology

- Understand the origin and very early evolution of the universe.
- Test theory of the very early universe against cosmological observations.
- Make predictions for future observations.

Current Paradigm for Early Universe Cosmology

The Inflationary Universe Scenario is the current paradigm of early universe cosmology.

Successes:

- Solves horizon problem
- Solves flatness problem
- Solves size/entropy problem
- Provides a causal mechanism of generating primordial cosmological perturbations (Chibisov & Mukhanov, 1981).

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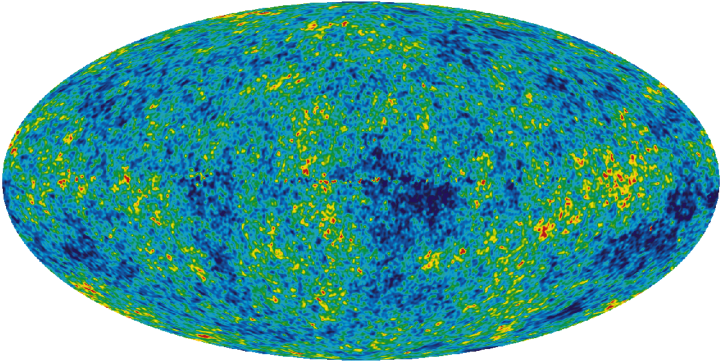
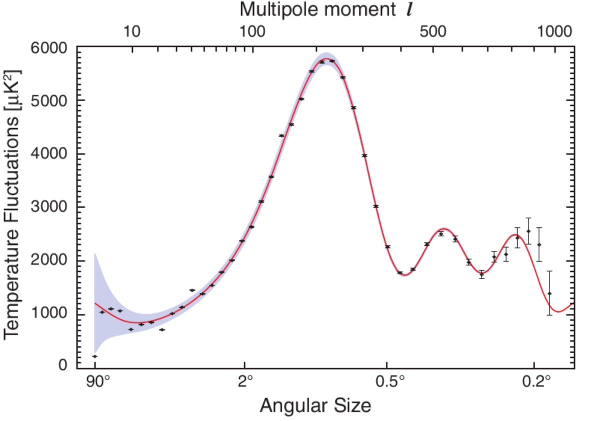


Credit: NASA/WMAP Science Team



Credit: NASA/WMAP Science Team

Deficiencies of the Inflationary Paradigm

- Does not eliminate cosmological singularity.
- $\rightarrow$ not a theory of the very early universe.
- Uses low energy field theory framework in a realm where this theory breaks down.
- Trans-Planckian problem for cosmological fluctuations.
- $\rightarrow$ analysis of cosmological fluctuations is based on incomplete physics.
- Not robust against our ignorance of what solves the cosmological constant problem.

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This Talk

- String Gas Cosmology Toy model of the very early universe based on fundamental principles and symmetries of superstring theory (R.B. and C. Vafa, 1989).
- String Gas Cosmology yields a structure formation mechanism alternative to inflation (A. Nayeri, R.B. and C. Vafa, 2005).
- Problems of superstring cosmology such as the moduli stabilization problem have new solutions (S. Patil and R.B., 2004, R.B. et al 2012).
- But: significant challenges before we will have a theory of superstring cosmology.

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Main Messages

- Superstring theory give a completely different picture of the evolution of the very early universe than particle theory.
- String Gas Cosmology yields new theory of structure formation.
- - consistent with current observations
- - yielding predictions for future observations different from inflation
- Corollary: alternatives to inflationary cosmology exist.

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Review of Inflationary Cosmology

Context:

- General Relativity
- Scalar Field Matter

$$\text{Metric}: \; ds^2 \, = \, dt^2 - a(t)^2 d\mathbf{x}^2 \tag{1}$$

Inflation:

- phase with $a(t) \sim e^{tH}$
- requires matter with $p \sim -\rho$
- requires a slowly rolling scalar field φ
- - in order to have a potential energy term
- - in order that the potential energy term dominates sufficiently long

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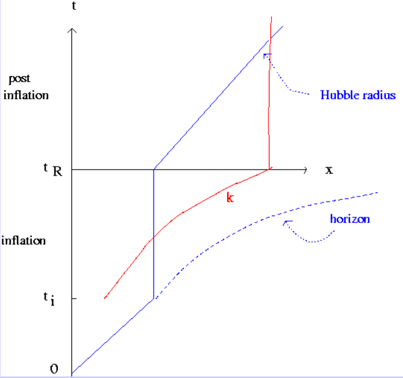
Review of Inflationary Cosmology II

Space-time sketch of inflationary cosmology:



Note:

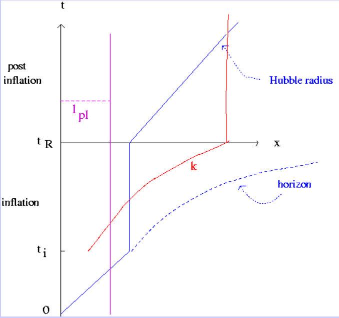
- $H = \frac{\dot{a}}{a}$
- curve labelled by k: wavelength of a fluctuation

- inflation renders the universe large, homogeneous and spatially flat
- classical matter redshifts → matter vacuum remains
- quantum vacuum fluctuations: seeds for the observed structure [Chibisov & Mukhanov, 1981]
- sub-Hubble → locally causal

Singularity Problem

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

Trans-Planckian Problem



- **Success of inflation**: At early times scales are inside the Hubble radius $\rightarrow$ 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
- $\rightarrow$ new physics MUST enter into the calculation of the fluctuations.

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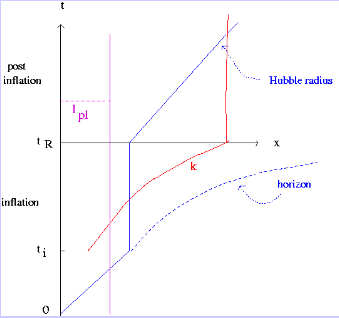

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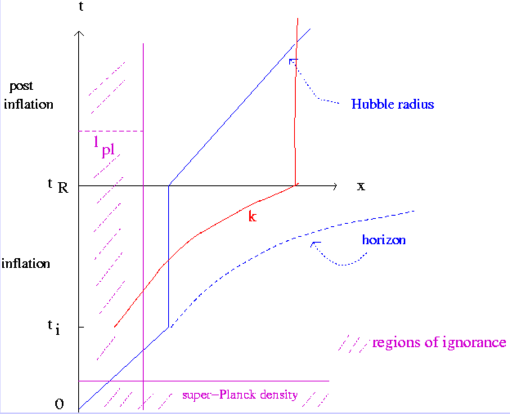
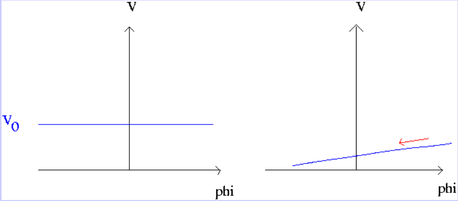
Applicability of GR

- 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 $\eta \sim 10^{16}$GeV.
- $\rightarrow \eta$ too close to m_{pl} to trust predictions made using GR.

Zones of Ignorance



Cosmological Constant Problem



- Quantum vacuum energy does not gravitate.
- Why should the almost constant $V(\varphi)$ gravitate?

$$\frac{V_0}{\Lambda_{obs}} \sim 10^{120} \tag{2}$$

Plan

Principles

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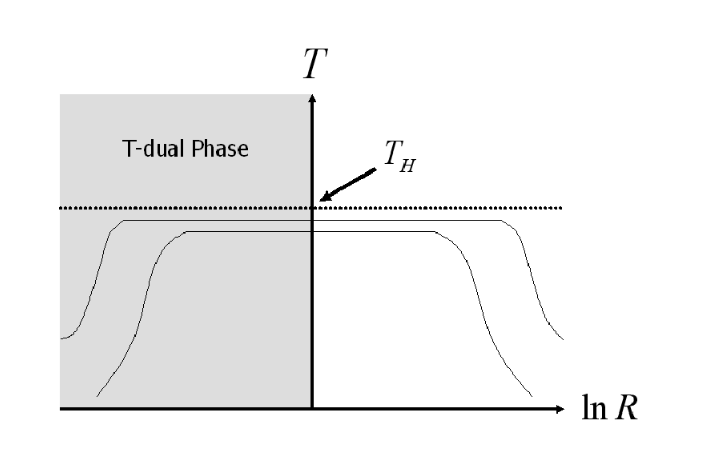
- Momentum modes: $E_n = n/R$
- Winding modes: $E_m = mR$
- Duality: $R \rightarrow 1/R \quad (n, m) \rightarrow (m, n)$
- Mass spectrum of string states unchanged
- Symmetry of vertex operators
- Symmetry at non-perturbative level $\rightarrow$ existence of D-branes

Adiabatic Considerations

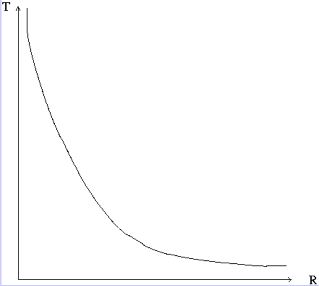
R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

Temperature-size relation in string gas cosmology



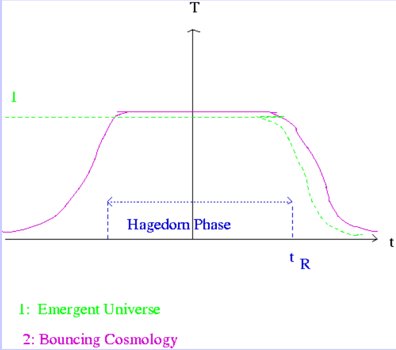
Singularity Problem in Standard and Inflationary Cosmology

Temperature-size relation in standard cosmology



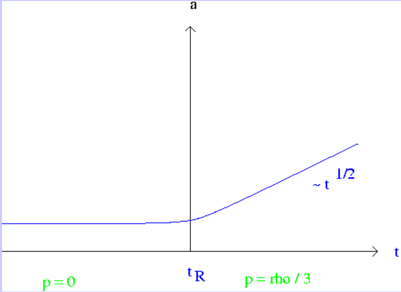
Dynamics

Assume some action gives us $R(t)$



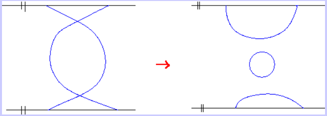
Dynamics II

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



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.

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

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String Cosmology

R. Brandenberger

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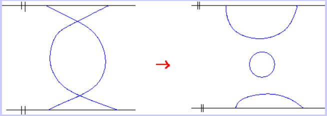

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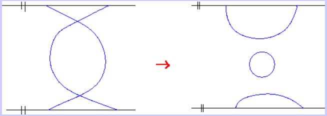

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Theory of Cosmological Perturbations: Basics

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:

- Fluctuations are small today on large scales
- → fluctuations were very small in the early universe
- → can use linear perturbation theory

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Quantum Theory of Linearized Fluctuations

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

Step 1: Metric including fluctuations

$$ds^2 = a^2[(1+2\Phi)d\eta^2 - (1-2\Phi)d\mathbf{x}^2] \quad (3)$$

$$\varphi = \varphi_0 + \delta\varphi \quad (4)$$

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:

$$S^{(2)} = \frac{1}{2}\int d^4x\left((v')^2 - v_{,i}v^{,i} + \frac{z''}{z}v^2\right) \quad (5)$$

$$v = a\left(\delta\varphi + \frac{z}{a}\Phi\right) \quad (6)$$

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Step 3: Resulting equation of motion (Fourier space)

$$v_k'' + (k^2 - \frac{z''}{z})v_k = 0 \quad (8)$$

Features:

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

Quantum vacuum initial conditions:

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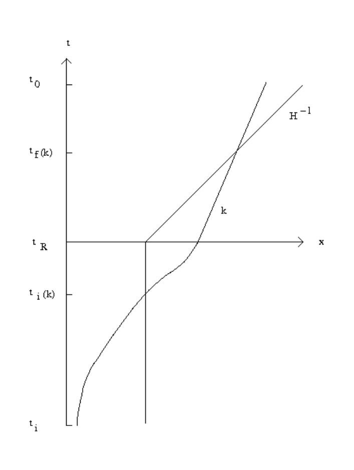
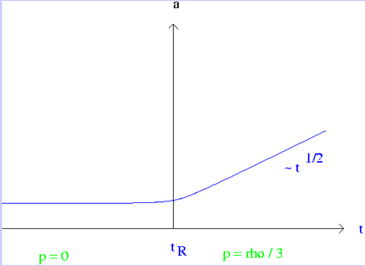
Structure formation in inflationary cosmology



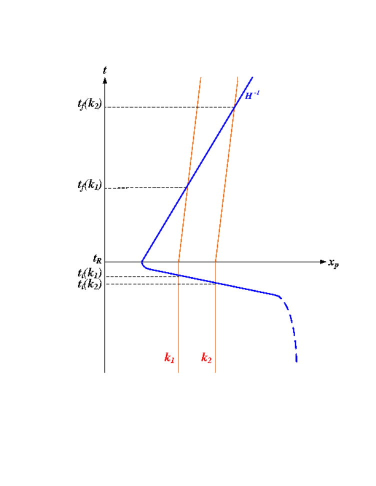
N.B. Perturbations originate as quantum vacuum fluctuations.

Background for string gas cosmology



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.

Method

- 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:

$$ds^2 = a^2(\eta)\big((1+2\Phi)d\eta^2 - [(1-2\Phi)\delta_{ij} + h_{ij}]dx^i dx^j\big)\,. \quad (10)$$

Inserting into the perturbed Einstein equations yields

$$\langle|\Phi(k)|^2\rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^0{}_0(k) \delta T^0{}_0(k)\rangle\,, \quad (11)$$

$$\langle|h(k)|^2\rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^i{}_j(k) \delta T^i{}_j(k)\rangle\,. \quad (12)$$

Power Spectrum of Cosmological Perturbations

Key ingredient: For thermal fluctuations:

$$\langle \delta\rho^2 \rangle = \frac{T^2}{R^6} C_V \, . \tag{13}$$

Key ingredient: For string thermodynamics in a compact space

$$C_V \approx 2 \frac{R^2/\ell_s^3}{T(1 - T/T_H)} \, . \tag{14}$$

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Power spectrum of cosmological fluctuations

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\begin{aligned}
P_\Phi(k) &= 8G^2k^{-1} < |\delta\rho(k)|^2 > && (15)\\
&= 8G^2k^2 < (\delta M)^2 >_R && (16)\\
&= 8G^2k^{-4} < (\delta\rho)^2 >_R && (17)\\
&= 8G^2 \frac{T}{\ell_s^3}\frac{1}{1 - T/T_H} && (18)
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Key features:

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

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

$$P_h(k) = 16\pi^2 G^2 k^{-1} < |T_{ij}(k)|^2 > \quad (19)$$
$$= 16\pi^2 G^2 k^{-4} < |T_{ij}(R)|^2 > \quad (20)$$
$$\sim 16\pi^2 G^2 \frac{T}{\ell_s^3}(1 - T/T_H) \quad (21)$$

Key ingredient for string thermodynamics

$$< |T_{ij}(R)|^2 > \sim \frac{T}{l_s^3 R^4}(1 - T/T_H) \quad (22)$$

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Requirements

- 1. static Hagedorn phase (including static dilaton) $\rightarrow$ new physics required.
- 2. $C_V(R) \sim R^2$ obtained from a thermal gas of strings provided there are winding modes which dominate.
- 3. 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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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

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 $R, \ \rightarrow \ R_{min}$
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Moduli Stabilization in SGC II

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

R. Danos, A. Frey and R.B., 2008

- 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
- Context Perturbative $E_8 x E_8$ superstring theory.
- Hidden sector gauge group becomes strongly coupled at a scale μ.
- At this scale gaugino condensation sets in.
- NB: Dilaton stabilization is consistent with size stabilization [R. Danos, A. Frey and R.B., 2008]

Supersymmetry Breaking in SGC

S. Mishra, W. Xue, R.B. and U. Yajnik, 2012

- Gaugino condensation scale μ.
- Gravitino mass $m_{3/2} \sim \frac{\mu^3}{M_4^2}$
- Supersymmetry breaking scale given by $M_s^2 \sim \frac{\mu^3}{M_4}$
- TeV scale gravitino mass implies high scale supersymmetry breaking.
- NB: consistent with moduli stabiliation.

Plan

Challenges for String Gas Cosmology

- Size and Entropy problems not solved.
- Dynamics of Hagedorn phase not known.
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Possible Approaches

- Double Field Theory as a way of obtaining dynamics of the Hagedorn phase?
- Emergent geometry as in matrix theory to replace the Hagedorn phase?
- Bottom line: we need a better understanding of non-perturbative string theory.

Plan

Conclusions

- String Gas Cosmology: Model of cosmology of the very early universe based on new degrees of freedom and new symmetries of superstring theory.
- String Theory leads to a very different picture for the very early universe than point particle theories.
- SGC $\rightarrow$ nonsingular cosmology
- SGC $\rightarrow$ natural explanation of the number of large spatial dimensions.

Conclusions II

- SGC $\rightarrow$ 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).
- String Theory testable through cosmological observations.

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