Scenarios of Early Universe Cosmology

Philosophical and Physical Challenges

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Outline

Plan

Current Paradigm for Early Universe Cosmology

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

It solves some conceptual problems of the previous paradigm, Standard Big Bang Cosmology:

- Solves horizon problem
- Solves flatness problem
- Solves size/entropy problem

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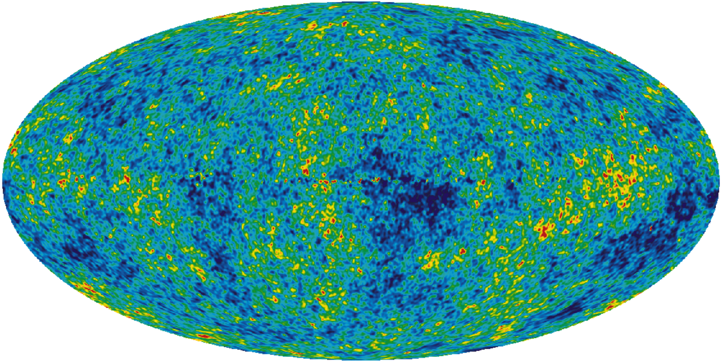
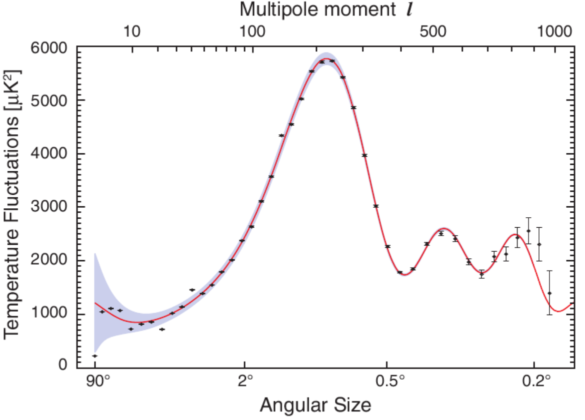


Credit: NASA/WMAP Science Team



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Challenges for the Current Paradigm

- In spite of the phenomenological successes, the inflationary scenario suffers from several conceptual problems.
- These problems lead to philosophical and physical challenges.
- In light of these challenges it is important to search for alternative early universe scenarios which can address some of the problems of inflationary cosmology.
- Alternative A: Emergent Universe Scenario [as realized e.g. in String Gas Cosmology]
- Alternative B: Matter Bounce.
- These new paradigms can be tested in cosmological observations.

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The successful match of inflationary cosmology with the angular power spectrum of CMB anisotropies is NOT a success unique to inflationary cosmology.

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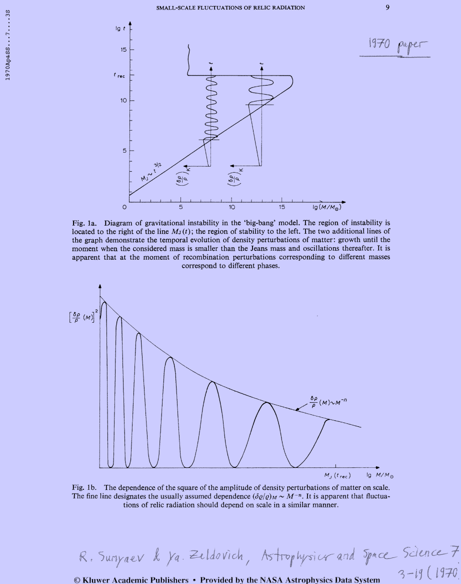
Historical Footnote



1970ApSS...7....3S

1970 paper

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.

Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

R. Sunyaev & Ya. Zeldovich, Astrophysics and Space Science 7 3-19 (1970)

Review of Inflationary Cosmology

Context:

- General Relativity
- Scalar Field Matter

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

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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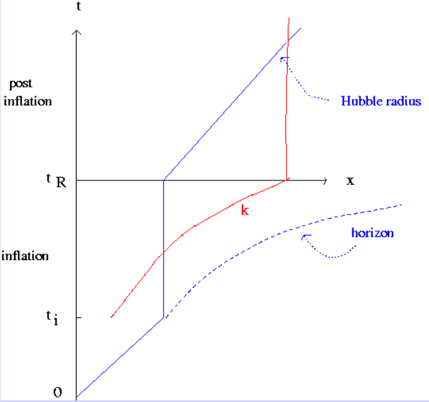
Space-time sketch of inflationary cosmology



Note:

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

Hubble Radius vs. Horizon

- Hubble radius $l_H(t) \equiv H^{-1}(t)$: local concept. Matter and gravitational fields oscillate on sub-Hubble scales, but are frozen out on super-Hubble scales. A microscopic structure formation mechanism can only work on sub-Hubble scales.
- Horizon: non-local concept. Zone of causal influence. Forward light cone starting at the initial time.

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Successes of Inflation

- 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

Conceptual Problems of Inflationary Cosmology

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

Singularity Problem

- 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 $\rho > 0, \quad \rho + 3p \geq 0$
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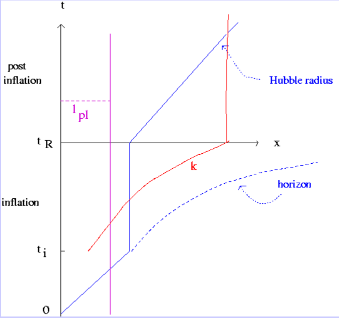
Trans-Planckian Problem for Fluctuations



- **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.

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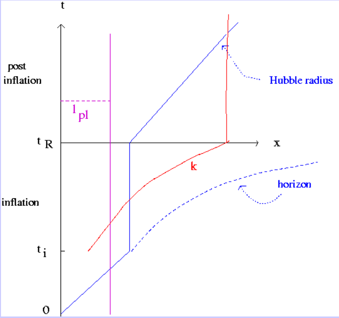

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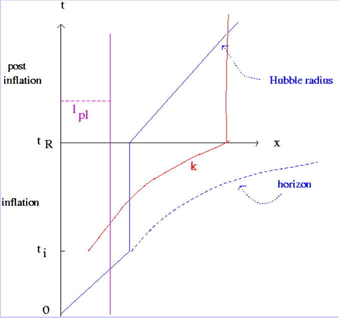

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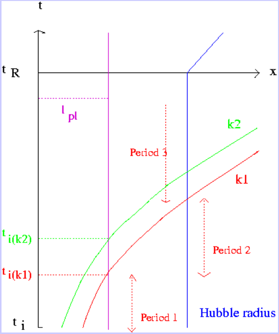
Recent Reference: A. Linde, V. Mukhanov and A. Vikman, arXiv:0912.0944

- It is not sufficient to show that the Hubble constant is smaller than the Planck scale.
- The frequencies involved in the analysis of the cosmological fluctuations are many orders of magnitude larger than the Planck mass. Thus, “the methods used in [1] are inapplicable for the description of the .. process of generation of perturbations in this scenario."

Trans-Planckian Window of Opportunity

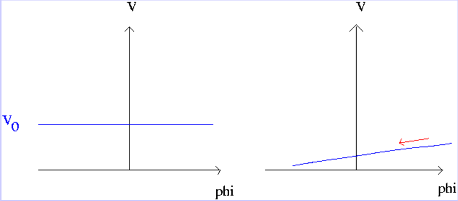


- If evolution in Period I is non-adiabatic, then scale-invariance of the power spectrum will be lost [J. Martin and RB, 2000]
- → Planck scale physics testable with cosmological observations!

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.

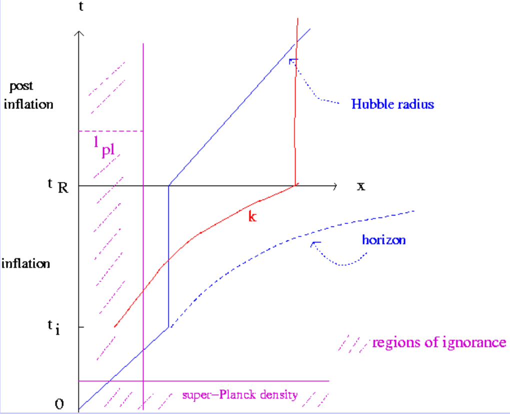
Cosmological Constant Problem



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

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

Zones of Ignorance



Message

- Current realizations of inflation have serious conceptual problems.
- These problems are both of physical (e.g cosmological constant problem, trans-Planckian problem for fluctuations) and philosophical (e.g. singularity problem - origin of time) nature.
- This motivates the search for alternatives.
- In these alternatives the philosophical issues appear in a different light.
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- How does the classicalization occur?

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What about the string inflationary multiverse?

Relies on two key assumptions

- 1. Landscape of string vacua.
- 2. Stochastic inflation: a way to populate these vacua.

However, keep in mind that:

- Non-perturbative string theory does not exist. Hence, we cannot talk about a string vacuum.
- In the context of large field inflation, the stochastic equation is missing terms which dominate.

Thus, the “string inflationary multiverse" is neither part of string theory nor a part of inflationary cosmology.

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Key conditions:

- Squeezing → r.m.s. quantum expectation values obey classical equations, [A. Guth and S-Y. Pi, Phys.Rev. D32 (1985) 1899-1920]
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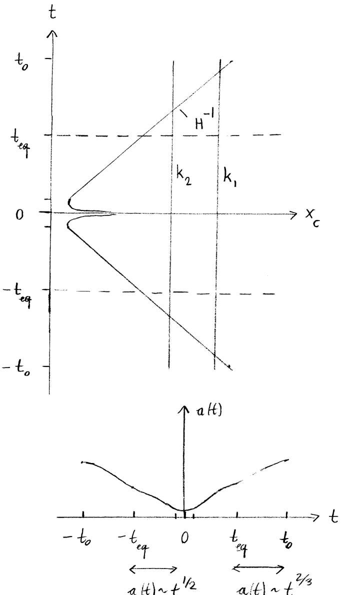
Alternative Scenarios

- Nonsingular cosmologies with a matter-dominated phase of contraction
- Emergent universe scenario [e.g. string gas cosmology]
- Pre-Big-Bang scenario [Gasperini and Veneziano]
- Ekpyrotic universe scenario [Khoury, Ovrut, Steinhardt and Turok]
- Conformal cosmology [Rubakov et al.]
- Varying speed of light (VSL) scenario [Moffatt, Albrecht and Magueijo]
- ....

Matter Bounce Scenario

F. Finelli and R.B., *Phys. Rev. D65, 103522 (2002)*, D. Wands, *Phys. Rev. D60 (1999)*



Features of Matter Bounce Scenario

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Emergent Universe Scenario

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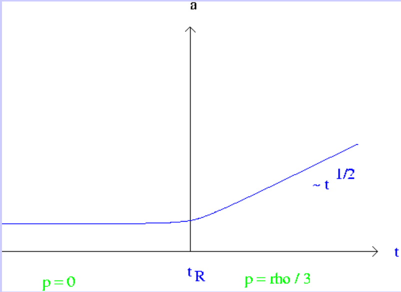
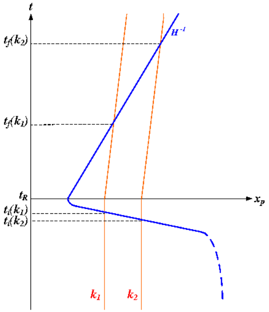


Space-time sketch



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Example: 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

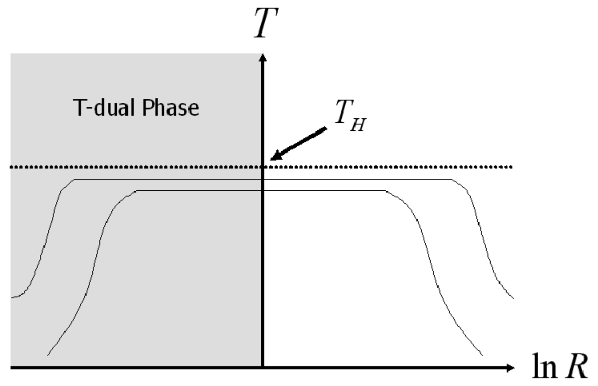
T-Duality

- 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 → existence of D-branes

Adiabatic Considerations

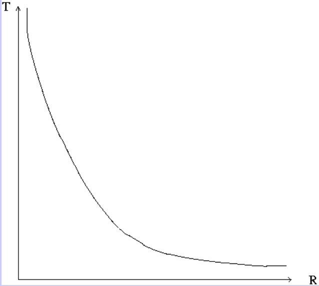
R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

Temperature-size relation in string gas cosmology



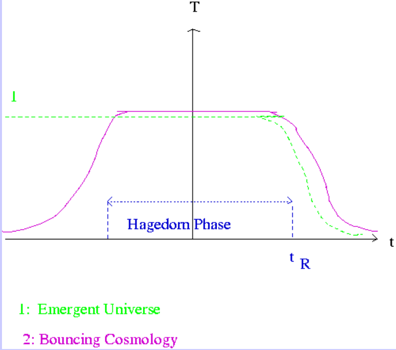
Singularity Problem in Standard and Inflationary Cosmology

Temperature-size relation in standard cosmology



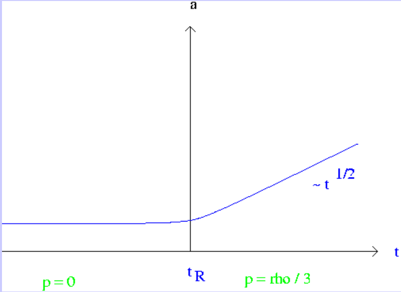
Dynamics

Assume some action gives us $R(t)$



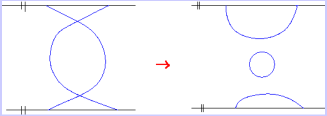
Dynamics II

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 → 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]

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
- → diltaton is stabilized
- Dilaton stabilization is consistent with size stabilization [R. Danos, A. Frey and R.B., 2008]

Plan

Overview

In order to obtain a bouncing cosmology it is necessary to:

- either modify the gravitational action
- or introduce a new form of matter which violates the NEC (null energy condition).
- or invoke quantum effects as in Loop Quantum Cosmology.

It is well motivated to consider models which go beyond the standard coupling of General Relativity to matter obeying the NEC - any approach to quantizing gravity yields terms in the effective action for the metric and matter fields which contain higher derivatives.

Ref: M. Novello and S. Perez Bergliaffa, Phys. Rep. **463**, 127 (2008).

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Bounce from String Gases

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

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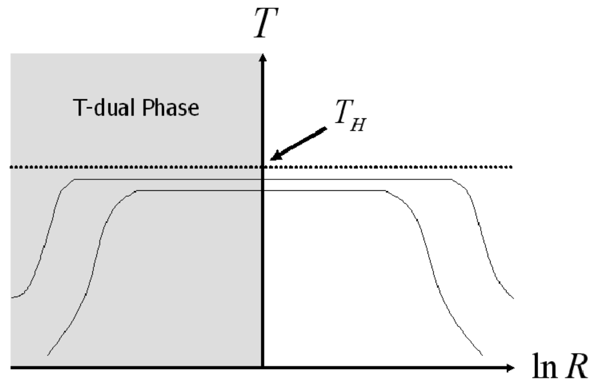
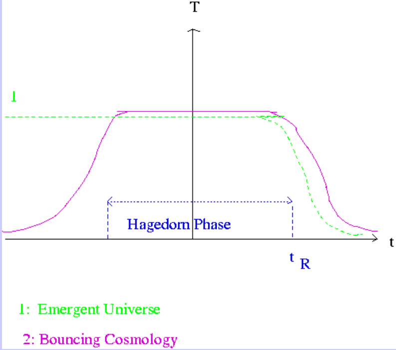


Bouncing Trajectory



Concrete Realization In the context of low energy effective action for Type IIB superstring theory coupled to string gas [R.B., C. Kounnas, H. Partouche and S. Patil, in prep.].

Example changing the gravitational action

Hořava-Lifshitz bounce (R.B., 2009)

- Replace Einstein gravity by Hořava-Lifshitz gravity.
- Extra spatial derivative terms in the gravitational action act like matter which violates the NEC.

Example changing matter

Ghost condensate bounce (C. Lin, R.B. and L. Perreault Levasseur, 2010)

- Introduce new matter field which has negative (ghost) sign of the kinetic action.
- Kinetic operator condenses.
- Condensate has negative gravitational energy.
- Theory ghost-free about the condensate.

Plan

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:

- 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

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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

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

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:

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

where

$$v \sim a\zeta$$

where ζ is the curvature fluctuation in co-moving coordinates.

Step 3: Resulting equation of motion (Fourier space)

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

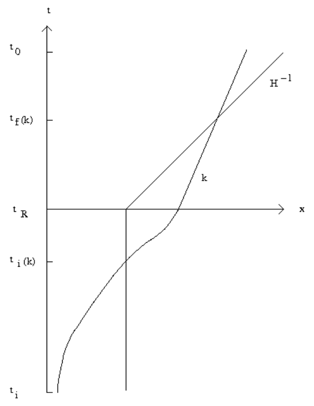
Features:

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

Quantum vacuum initial conditions:

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

Application to Inflationary Cosmology



N.B. Perturbations originate as quantum vacuum fluctuations.

Origin of Scale-Invariance

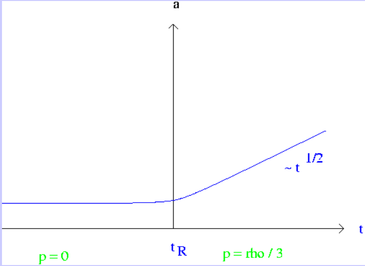
Heuristic analysis [W. Press, 1980]: time-translation symmetry of de Sitter phase → scale-invariance of spectrum.

Mathematical analysis [Mukhanov and Chibisov, 1982]:

$$\begin{aligned}\mathcal{P}_\zeta(k,t) &\propto \mathcal{P}_v(k,t)\\ &\sim k^3\left(\frac{a(t)}{a(t_H(k))}\right)^2 |v_k(t_H(k))|^2\\ &\sim k^3\eta_H(k)^2|v_k(t_H(k))|^2\\ &\sim k^0\end{aligned}$$

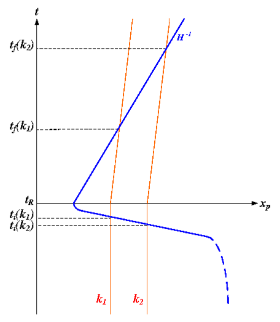
using $a(\eta) \sim \eta^{-1}$ in the de Sitter phase and $\eta_H(k) \sim k^{-1}$.

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:

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

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

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

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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}
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Key features:

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- slight red tilt like for inflation

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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

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

Key features:

- scale-invariant (like for inflation)
- slight blue tilt (unlike for inflation)

Requirements

- Static Hagedorn phase (including static dilaton) $\longrightarrow$ new physics required.
- $C_V(R) \sim R^2$ obtained from a thermal gas of strings provided there are winding modes which dominate.
- Cosmological fluctuations in the IR are described by Einstein gravity.

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

Is B-mode Polarization the Holy Grail of Inflation?

R.B., arXiv:1104.3581 [astro-ph.CO].

- Cosmic strings produce direct B-mode polarization [R. Danos, R.B. and G. Holder, 2010].
- → gravitational waves not the only source of primordial B-mode polarization.
- Cosmic string loop oscillations produce a scale-invariant spectrum of primordial gravitational waves with a contribution to $\delta T/T$ which is comparable to that induced by scalar fluctuations (see e.g. A. Albrecht, R.B. and N. Turok, 1986).
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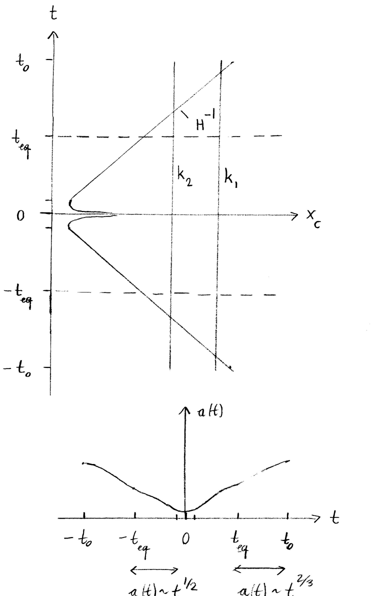
Application to the Matter Bounce Scenario

F. Finelli and R.B., *Phys. Rev. D65, 103522 (2002)*, D. Wands, *Phys. Rev. D60 (1999)*



Overview of the Matter Bounce

- Fluctuations originate as quantum vacuum perturbations on sub-Hubble scales in the contracting phase.
- Adiabatic fluctuation mode acquires a scale-invariant spectrum of curvature perturbations on super-Hubble scales.
- Horizon problem: absent.
- Anisotropy problem: weak point.
- Size and entropy problems: not present if we assume that the universe begins cold and large.

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Origin of Scale-Invariant Spectrum

- The initial vacuum spectrum is blue:

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

- The curvature fluctuations grow on super-Hubble scales in the contracting phase:

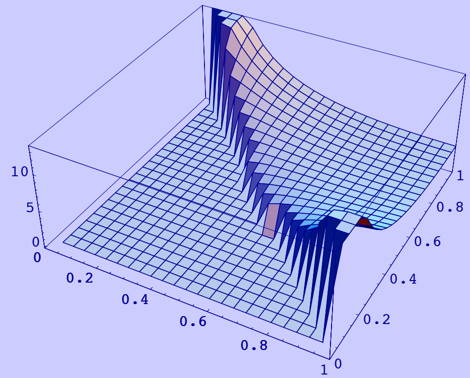
$$v_k(\eta) \, = \, c_1\eta^2 + c_2\eta^{-1} \, ,$$

- For modes which exit the Hubble radius in the matter phase the resulting spectrum is scale-invariant:

$$\begin{aligned} P_\zeta(k,\eta) \quad &\sim \quad k^3|v_k(\eta)|^2 a^{-2}(\eta) \\ &\sim \quad k^3|v_k(\eta_H(k))|^2 \Big(\frac{\eta_H(k)}{\eta}\Big)^2 \, \sim \, k^{3-1-2} \\ &\sim \quad \mathrm{const} \, , \end{aligned}$$

Bispectrum of the Matter Bounce Scenario

Y. Cai, W. Xue, R.B. and X. Zhang, *JCAP 0905:011 (2009)*



Challenges for the Matter Bounce Scenario

- Obtaining a matter bounce in a model free of ghosts and other unwanted degrees of freedom.
- Instability to anisotropic stress.
- Initial conditions for fluctuations?

Cyclic Cosmology - Never Cyclic

R.B. , Phys.Rev. D80 (2009) 023535

- Consider a 4-d cyclic background cosmology.
- Curvature fluctuations grow both in the contracting and in the expanding phase.
- Fluctuations break the cyclicity (related to Tolman's entropy problem).
- Index of the spectrum of cosmological perturbations changes by -2 from cycle to cycle.
- 4-d cyclic cosmology is not predictive.

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Conclusions

- Inflationary cosmology suffers from several conceptual problems.
- These problems motivate the investigation of alternatives.
- Alternative A: Emergent Universe scenario, realized in the context of String Gas Cosmology — Based on fundamental principles of superstring theory.
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Conclusions II

- These alternatives are consistent with current observations.
- In A: Thermal fluctuations of a gas of strings → scale-invariant spectrum of cosmological perturbations.
- In B: Vacuum fluctuations exiting Hubble radius in a matter-dominated phase of contraction lead to a scale-invariant spectrum of adiabatic perturbations.
- Both alternatives make testable predictions for future observations.
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