Alternatives to Inflation

Robert Brandenberger
McGill University

IAP, December 2014

Outline

Plan

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).

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).

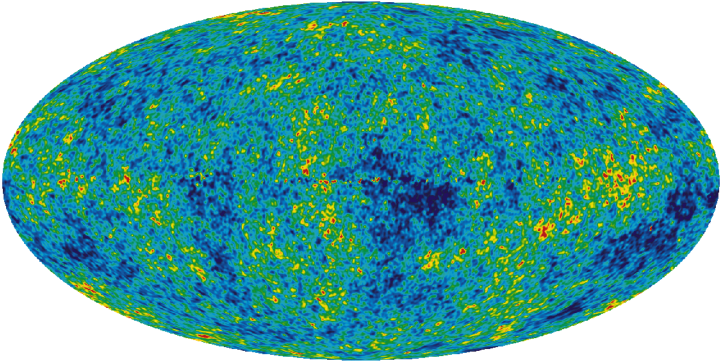
Current Paradigm for Early Universe Cosmology

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

Successes:

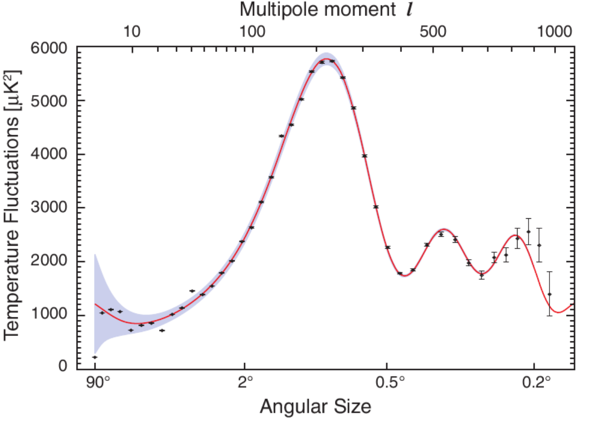
- Solves horizon problem
- Solves flatness problem
- Solves size/entropy problem
- Provides a causal mechanism of generating primordial cosmological perturbations (Chibisov & Mukhanov, 1981).

Map of the Cosmic Microwave Background (CMB)



Credit: NASA/WMAP Science Team

Angular Power Spectrum of CMB Anisotropies



Credit: NASA/WMAP Science Team

Early Work

1970 p.

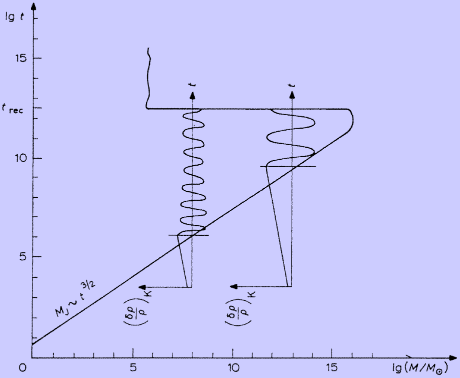


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until 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.

Key Realization

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 Realization

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 Realization

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.

Early Work

Alternatives

R. Brandenberger

Introduction

Perturbations

Scenarios

String Gas Cosmology

S-Brane Bounce

Inflation?

Conclusions

1970 paper

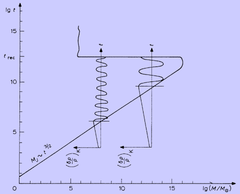


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until 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.

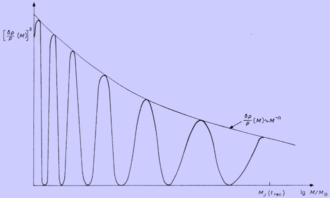


Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

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

Key Realization

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} (standing waves).
- $\rightarrow$ "correct" power spectrum of galaxies.
- $\rightarrow$ acoustic oscillations in CMB angular power spectrum.
- $\rightarrow$ baryon acoustic oscillations in matter power spectrum.
- Inflation is the first scenario based on causal physics which yields such a spectrum.
- But it is not the only one.

Key Realization

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} (standing waves).
- $\rightarrow$ "correct" power spectrum of galaxies.
- $\rightarrow$ acoustic oscillations in CMB angular power spectrum.
- $\rightarrow$ baryon acoustic oscillations in matter power spectrum.
- Inflation is the first scenario based on causal physics which yields such a spectrum.
- But it is not the only one.

Hubble Radius vs. Horizon

- Horizon: Forward light cone of a point on the initial Cauchy surface.
- Horizon: region of causal contact.
- Hubble radius: $l_H(t) = H^{-1}(t)$ inverse expansion rate.
- Hubble radius: local concept, relevant for dynamics of cosmological fluctuations.
- In Standard Big Bang Cosmology: Hubble radius = horizon.
- In any theory which can provide a mechanism for the origin of structure: Hubble radius $\neq$ horizon.

Hubble Radius vs. Horizon

- Horizon: Forward light cone of a point on the initial Cauchy surface.
- Horizon: region of causal contact.
- Hubble radius: $l_H(t) = H^{-1}(t)$ inverse expansion rate.
- Hubble radius: local concept, relevant for dynamics of cosmological fluctuations.
- In Standard Big Bang Cosmology: Hubble radius = horizon.
- In any theory which can provide a mechanism for the origin of structure: Hubble radius $\neq$ horizon.

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.

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.

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.

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.

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.

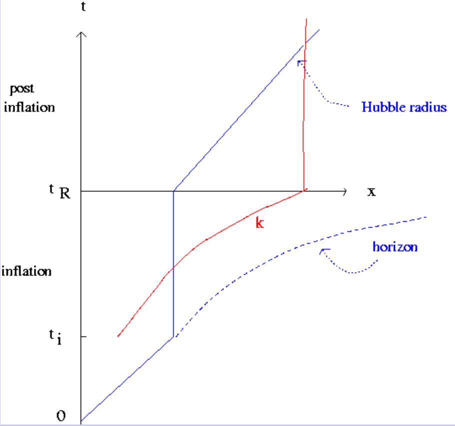
Criteria for a Successful Early Universe Scenario

- 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.

Criteria for a Successful Early Universe Scenario

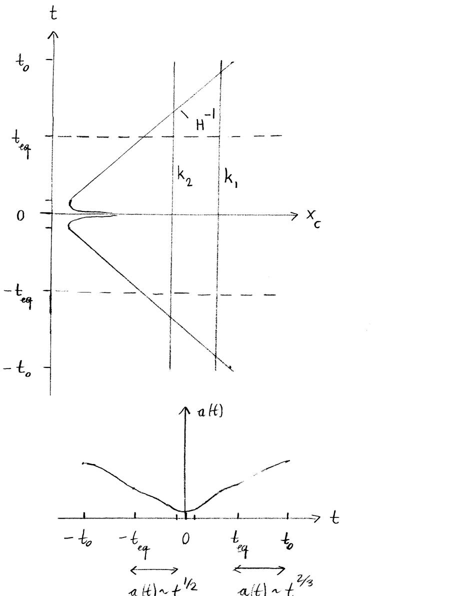
- Horizon $\gg$ Hubble radius in order for the scenario to solve the "horizon problem" of Standard Big Bang Cosmology.
- Scales of cosmological interest today originate inside the Hubble radius at early times in order for a causal generation mechanism of fluctuations to be possible.
- Squeezing of fluctuations 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.

Inflation as a Realization of Conditions 1 - 3



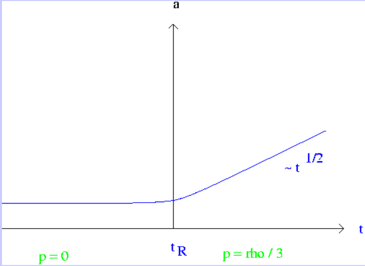
Bouncing Cosmology as a Realization of Conditions 1 - 3

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



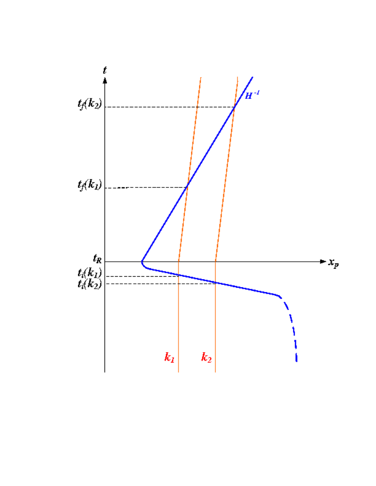
Emergent Universe

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



Emergent Universe as a Realization of Conditions 1 - 3

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



Main Points of This Talk

- There are alternatives to inflation for producing a spectrum of inhomogeneities compatible with current observations.
- Challenge: How to observationally distinguish between these scenarios.
- Non-Gaussianities.
- Amplitude and tilt of the gravitational wave spectrum.

Main Points of This Talk

- There are alternatives to inflation for producing a spectrum of inhomogeneities compatible with current observations.
- Challenge: How to observationally distinguish between these scenarios.
- Non-Gaussianities.
- Amplitude and tilt of the gravitational wave spectrum.

Main Points of This Talk

- There are alternatives to inflation for producing a spectrum of inhomogeneities compatible with current observations.
- Challenge: How to observationally distinguish between these scenarios.
- Non-Gaussianities.
- Amplitude and tilt of the gravitational wave spectrum.

Plan

Quantum Theory of Cosmological Fluctuations

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

Step 1: Metric including linear scalar fluctuations

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

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:

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

Quantum Theory of Cosmological Fluctuations

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

Step 1: Metric including linear scalar 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:

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

Comoving curvature fluctuation: $\zeta = z^{-1} v$.

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:

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

Comoving curvature fluctuation: $\zeta = z^{-1} v$.

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:

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

Comoving curvature fluctuation: $\zeta = z^{-1} v$.

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:

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

Comoving curvature fluctuation: $\zeta = z^{-1} v$.

Quantum Theory of 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:

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

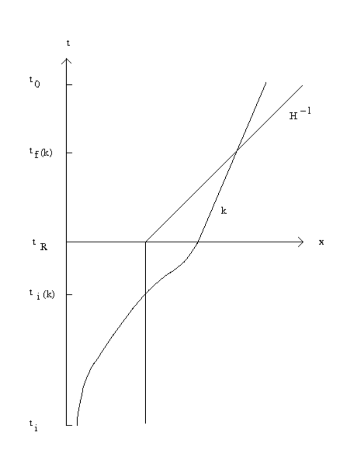
Squeezing on super-Hubble scales, oscillations on sub-Hubble scales.

Consequences for Tensor to Scalar Ratio r

Assuming adiabatic fluctuations:

- If EoS of matter is time independent, then $z \propto a$ and $u \propto v$.
- In this case $r \sim 1$.
- During a phase transition EoS changes and u evolves differently than v (z evolves differently than a).
- $\rightarrow$ Suppression of r.
- Example 1: Inflationary slow roll suppression (equiv.: change in EoS during reheating).
- Example 2: nonsingular bounce phase in a bouncing cosmology.

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

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

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

Tensor to Scalar Ratio in Inflation

- Canonical variables v and u for scalar and tensor fluctuations obey the same equation and the same initial conditions.
- $\zeta = z^{-1} v$ and $h = a^{-1} u$.
- Hence, the tensor to scalar ratio of the power spectrum is suppressed by the slow-roll factor $(z/a)^2$.

Tensor to Scalar Ratio in Inflation

- Canonical variables v and u for scalar and tensor fluctuations obey the same equation and the same initial conditions.
- $\zeta = z^{-1} v$ and $h = a^{-1} u$.
- Hence, the tensor to scalar ratio of the power spectrum is suppressed by the slow-roll factor $(z/a)^2$.

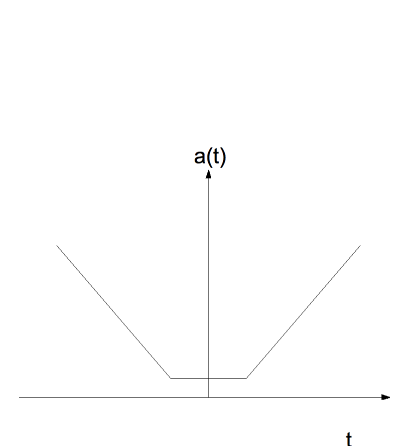
Tensor to Scalar Ratio in Inflation

- Canonical variables v and u for scalar and tensor fluctuations obey the same equation and the same initial conditions.
- $\zeta = z^{-1} v$ and $h = a^{-1} u$.
- Hence, the tensor to scalar ratio of the power spectrum is suppressed by the slow-roll factor $(z/a)^2$.

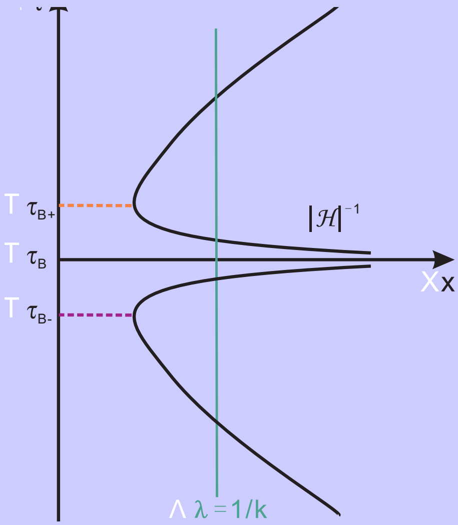
Matter Bounce Cosmology

D. Wands, Phys. Rev. D **60**, 023507 (1999): F. Finelli and R.B. Phys. Rev. D **65**, 103522 (2002).

Idea: Non-singular bouncing cosmology with a matter-dominated phase of contraction, can be realized in the context of Horava-Lifshitz gravity [R.B., arXiv:0904.2835].



Structure Formation in a Bouncing Cosmology



Origin of Scale-Invariance in Matter Bounce

- Vacuum spectrum of ζ ($\zeta \sim v$):

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

- To produce a scale-invariant spectrum a mechanism to boost long wavelength modes relative to short wavelength modes is needed.
- In a contracting phase ζ grows on super-Hubble scales.
- Dominant mode in the contracting phase in a matter universe:

$$v_k(\eta) \sim \eta^{-1} \text{ where } a(\eta) \sim \eta^2$$

- Hubble radius crossing condition:

$$k^{-1} a(\eta_H(k)) = t(\eta_H(k)) \rightarrow \eta_H(k) \sim k^{-1}$$

- Thus the power spectrum becomes

$$\begin{aligned} P_\zeta(k,\eta) &\sim k^3 z(\eta)^{-2} |v_k(\eta_H(k))|^2 \left(\frac{v_k(\eta)}{v_k(\eta_H(k))}\right)^2 \\ &\sim k^3 k^{-1} \left(\frac{\eta_H(k))}{\eta}\right)^2 z(\eta)^{-2} \sim \text{const} \end{aligned}$$

- Thus, a scale-invariant spectrum of curvature fluctuations results.
- The fluctuations can be followed through the bouncing phase, modeled as $a(\eta) = 1 + c\eta^2$.
- Use Hwang-Vishniac (Deruelle-Mukhanov) matching conditions at the two surfaces (between contracting matter and bounce phase, and between bounce phase and expanding matter phase) to complete the evolution of ζ.

- Thus the power spectrum becomes

$$P_\zeta(k,\eta) \sim k^3 z(\eta)^{-2} |v_k(\eta_H(k))|^2 \left(\frac{v_k(\eta)}{v_k(\eta_H(k))}\right)^2 \sim k^3 k^{-1} \left(\frac{\eta_H(k))}{\eta}\right)^2 z(\eta)^{-2} \sim \mathrm{const}$$

- Thus, a scale-invariant spectrum of curvature fluctuations results.
- The fluctuations can be followed through the bouncing phase, modeled as $a(\eta) = 1 + c\eta^2$.
- Use Hwang-Vishniac (Deruelle-Mukhanov) matching conditions at the two surfaces (between contracting matter and bounce phase, and between bounce phase and expanding matter phase) to complete the evolution of ζ.

Tilt and Running of the Spectrum

Y. Cai and E. Wilson-Ewing, arXiv:1412.2914

Consider the effects of dark energy:

- Net equation of state has $w < 0$ during phase of matter contraction.
- $\rightarrow$ red tilt (like for inflation).
- w increasing with time t
- $\rightarrow$ negative running (opposite to running in simple single field inflation).

Tilt and Running of the Spectrum

Y. Cai and E. Wilson-Ewing, arXiv:1412.2914

Consider the effects of dark energy:

- Net equation of state has $w < 0$ during phase of matter contraction.
- $\rightarrow$ red tilt (like for inflation).
- w increasing with time t
- $\rightarrow$ negative running (opposite to running in simple single field inflation).

Tilt and Running of the Spectrum

Y. Cai and E. Wilson-Ewing, arXiv:1412.2914

Consider the effects of dark energy:

- Net equation of state has $w < 0$ during phase of matter contraction.
- $\rightarrow$ red tilt (like for inflation).
- w increasing with time t
- $\rightarrow$ negative running (opposite to running in simple single field inflation).

Tensor to Scalar Ratio in the Matter Bounce

- ζ and h obey the same equation and the same initial conditions in the contracting phase.
- No slow-roll suppression because no slow-roll!
- Phase transition during the bounce phase $\rightarrow$ boost of ζ relative to h is possible [R.B., Y. Cai, J. Quintin, E. Sherkatghanad, in prep.], but not generic.
- Generically a large value of r is predicted.

Tensor to Scalar Ratio in the Matter Bounce

- ζ and h obey the same equation and the same initial conditions in the contracting phase.
- No slow-roll suppression because no slow-roll!
- Phase transition during the bounce phase $\rightarrow$ boost of ζ relative to h is possible [R.B., Y. Cai, J. Quintin, E. Sherkatghanad, in prep.], but not generic.
- Generically a large value of r is predicted.

Plan

Backgrounds

Background:

- Accelerated expansion.
- Contraction (followed by a bounce).
- Emergent (early quasi-static phase).

Fluctuations

Origin:

- Vacuum fluctuations.
- Thermal fluctuations.

Carrier:

- Adiabatic mode.
- An entropy mode.

Some Scenarios

- Inflation: almost exponential expansion, vacuum, adiabatic [Chibisov and Mukhanov, 1981]
- Warm Inflation: almost exponential expansion, thermal, adiabatic [Berera and Fang, 1995]
- Matter Bounce: matter-dominated contraction, vacuum, adiabatic [Wands, 1999, Finelli and RB, 2002].
- New Ekpyrotic: slow contraction, vacuum, entropy [Khoury et al., 2007]
- Pre-Big-Bang: dilaton gravity contraction, vacuum, entropy [Gasperini and Veneziano, 1992]
- String Gas Cosmology: emergent, string thermal, adiabatic [RB and C. Vafa, 1989; Nayeri et al, 2006].
- Conformal Universe: emergent, vacuum, “adiabatic” [Rubakov, 2009; Hinterbichler and Khoury, 2011].

Some Scenarios

- Inflation: almost exponential expansion, vacuum, adiabatic [Chibisov and Mukhanov, 1981]
- Warm Inflation: almost exponential expansion, thermal, adiabatic [Berera and Fang, 1995]
- Matter Bounce: matter-dominated contraction, vacuum, adiabatic [Wands, 1999, Finelli and RB, 2002].
- New Ekpyrotic: slow contraction, vacuum, entropy [Khoury et al., 2007]
- Pre-Big-Bang: dilaton gravity contraction, vacuum, entropy [Gasperini and Veneziano, 1992]
- String Gas Cosmology: emergent, string thermal, adiabatic [RB and C. Vafa, 1989; Nayeri et al, 2006].
- Conformal Universe: emergent, vacuum, “adiabatic” [Rubakov, 2009; Hinterbichler and Khoury, 2011].

Some Scenarios

- Inflation: almost exponential expansion, vacuum, adiabatic [Chibisov and Mukhanov, 1981]
- Warm Inflation: almost exponential expansion, thermal, adiabatic [Berera and Fang, 1995]
- Matter Bounce: matter-dominated contraction, vacuum, adiabatic [Wands, 1999, Finelli and RB, 2002].
- New Ekpyrotic: slow contraction, vacuum, entropy [Khoury et al., 2007]
- Pre-Big-Bang: dilaton gravity contraction, vacuum, entropy [Gasperini and Veneziano, 1992]
- String Gas Cosmology: emergent, string thermal, adiabatic [RB and C. Vafa, 1989; Nayeri et al, 2006].
- Conformal Universe: emergent, vacuum, “adiabatic” [Rubakov, 2009; Hinterbichler and Khoury, 2011].

Some Scenarios

- Inflation: almost exponential expansion, vacuum, adiabatic [Chibisov and Mukhanov, 1981]
- Warm Inflation: almost exponential expansion, thermal, adiabatic [Berera and Fang, 1995]
- Matter Bounce: matter-dominated contraction, vacuum, adiabatic [Wands, 1999, Finelli and RB, 2002].
- New Ekpyrotic: slow contraction, vacuum, entropy [Khoury et al., 2007]
- Pre-Big-Bang: dilaton gravity contraction, vacuum, entropy [Gasperini and Veneziano, 1992]
- String Gas Cosmology: emergent, string thermal, adiabatic [RB and C. Vafa, 1989; Nayeri et al, 2006].
- Conformal Universe: emergent, vacuum, "adiabatic" [Rubakov, 2009; Hinterbichler and Khoury, 2011].

Some Scenarios

- Inflation: almost exponential expansion, vacuum, adiabatic [Chibisov and Mukhanov, 1981]
- Warm Inflation: almost exponential expansion, thermal, adiabatic [Berera and Fang, 1995]
- Matter Bounce: matter-dominated contraction, vacuum, adiabatic [Wands, 1999, Finelli and RB, 2002].
- New Ekpyrotic: slow contraction, vacuum, entropy [Khoury et al., 2007]
- Pre-Big-Bang: dilaton gravity contraction, vacuum, entropy [Gasperini and Veneziano, 1992]
- String Gas Cosmology: emergent, string thermal, adiabatic [RB and C. Vafa, 1989; Nayeri et al, 2006].
- Conformal Universe: emergent, vacuum, "adiabatic" [Rubakov, 2009; Hinterbichler and Khoury, 2011].

Some Scenarios

- Inflation: almost exponential expansion, vacuum, adiabatic [Chibisov and Mukhanov, 1981]
- Warm Inflation: almost exponential expansion, thermal, adiabatic [Berera and Fang, 1995]
- Matter Bounce: matter-dominated contraction, vacuum, adiabatic [Wands, 1999, Finelli and RB, 2002].
- New Ekpyrotic: slow contraction, vacuum, entropy [Khoury et al., 2007]
- Pre-Big-Bang: dilaton gravity contraction, vacuum, entropy [Gasperini and Veneziano, 1992]
- String Gas Cosmology: emergent, string thermal, adiabatic [RB and C. Vafa, 1989; Nayeri et al, 2006].
- Conformal Universe: emergent, vacuum, “adiabatic” [Rubakov, 2009; Hinterbichler and Khoury, 2011].

Some Scenarios

- Inflation: almost exponential expansion, vacuum, adiabatic [Chibisov and Mukhanov, 1981]
- Warm Inflation: almost exponential expansion, thermal, adiabatic [Berera and Fang, 1995]
- Matter Bounce: matter-dominated contraction, vacuum, adiabatic [Wands, 1999, Finelli and RB, 2002].
- New Ekpyrotic: slow contraction, vacuum, entropy [Khoury et al., 2007]
- Pre-Big-Bang: dilaton gravity contraction, vacuum, entropy [Gasperini and Veneziano, 1992]
- String Gas Cosmology: emergent, string thermal, adiabatic [RB and C. Vafa, 1989; Nayeri et al, 2006].
- Conformal Universe: emergent, vacuum, "adiabatic" [Rubakov, 2009; Hinterbichler and Khoury, 2011].

Challenge

- All of these scenarios produce a scale-invariant spectrum of cosmological perturbations.
- What observations allow us to distinguish between them?

Observational Diagnostics

- Matter bounce: bispectrum with $f_{nl} \sim 1$ and a distinctive shape.
- Matter bounce: gravitational wave spectrum with a large amplitude.
- Matter bounce: negative running of the power spectrum.
- String gas cosmology: gravitational wave spectrum with a blue tilt.
- New Ekpyrotic scenario, Pre-Big-Bang, conformal Universe: gravitational wave spectrum with a very small amplitude.

Observational Diagnostics

- Matter bounce: bispectrum with $f_{nl} \sim 1$ and a distinctive shape.
- Matter bounce: gravitational wave spectrum with a large amplitude.
- Matter bounce: negative running of the power spectrum.
- String gas cosmology: gravitational wave spectrum with a blue tilt.
- New Ekpyrotic scenario, Pre-Big-Bang, conformal Universe: gravitational wave spectrum with a very small amplitude.

Observational Diagnostics

- Matter bounce: bispectrum with $f_{nl} \sim 1$ and a distinctive shape.
- Matter bounce: gravitational wave spectrum with a large amplitude.
- Matter bounce: negative running of the power spectrum.
- String gas cosmology: gravitational wave spectrum with a blue tilt.
- New Ekpyrotic scenario, Pre-Big-Bang, conformal Universe: gravitational wave spectrum with a very small amplitude.

Observational Challenges for Inflationary Cosmology

- Amplitude and shape of the bispectrum.
- Amplitude and tilt of the spectrum of gravitational waves.
- Running of the spectrum of cosmological perturbations.

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

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

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

T-Duality

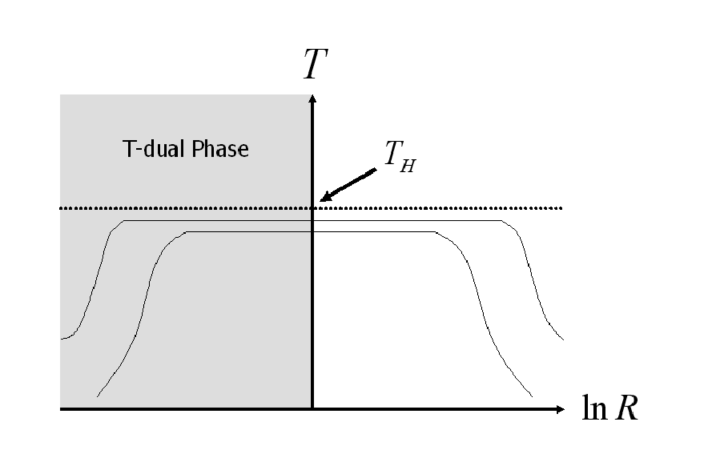
T-Duality

- 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 $\rightarrow$ existence of D-branes

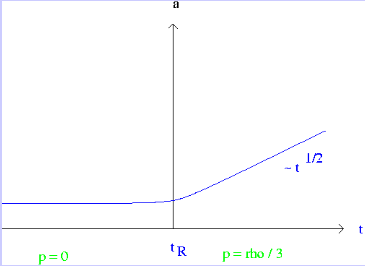
Adiabatic Considerations

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

Temperature-size relation in string gas cosmology

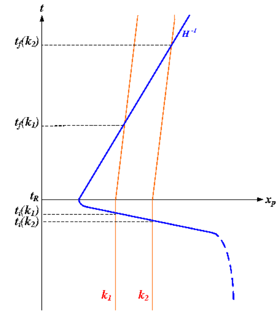


Background for string gas cosmology



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:

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

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 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

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

Key features:

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

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

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)

Spectrum of Gravitational Waves

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

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

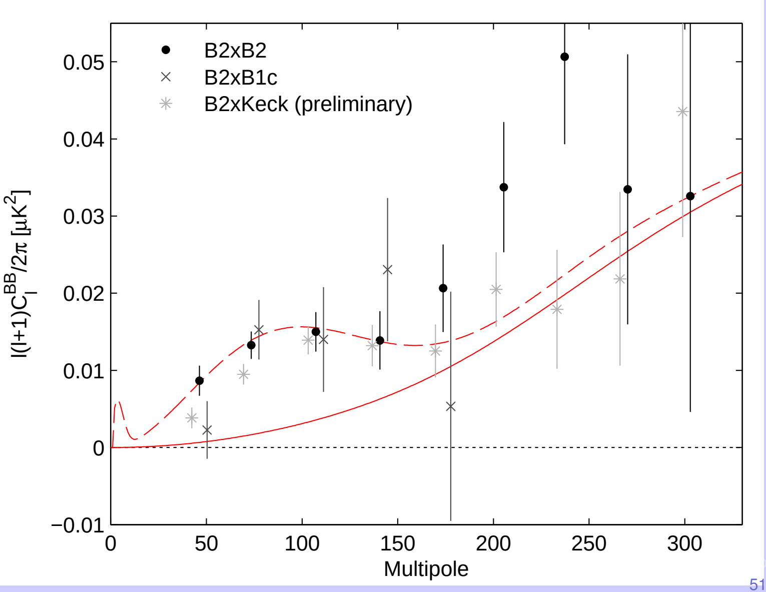
Key ingredient for string thermodynamics

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

Key features:

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

BICEP-2 Results



String Gas Consistency Relation

R.B., A. Nayeri and S. Patil, arXiv:1403.4927

$$r \simeq (1 - \hat{T})^2$$

$$n_t \simeq -(n_s - 1)(2\hat{T} - 1)$$

where $\hat{T} = T / T_H$.

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}
- 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 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.

Challenge for String Gas Cosmology

- Provide background dynamics of the Hagedorn phase.
- Einstein gravity and dilaton gravity do not apply (do not obey symmetries of string theory).
- Possible starting point: double field theory (Hull and Zwiebach, 2009).

Plan

Setup

C.Kounnas, H. Partouche and N. Toumbas, arXiv:1106.0946

- Type II superstring theory compactified on

$$\mathcal{M} = S^1(R_0) \times T^3 \times \mathcal{F}_6 \,,$$

- Euclidean time radius $R_0 = \beta/(2\pi)$.
- Gravitomagnetic fluxes threading the Euclidean time cycle and cycles of the internal space.
- Leads to T-duality about the Euclidean time cycle (thermal duality)

$$Z(\beta) = Z(\beta_c^2/\beta) \,.$$

- Large $T^3 \rightarrow$ effective field theory analysis under good control.
- Assumption: weak string coupling.

Setup

C.Kounnas, H. Partouche and N. Toumbas, arXiv:1106.0946

- Type II superstring theory compactified on

$$\mathcal{M} = S^1(R_0) \times T^3 \times \mathcal{F}_6 ,$$

- Euclidean time radius $R_0 = \beta/(2\pi)$.
- Gravitomagnetic fluxes threading the Euclidean time cycle and cycles of the internal space.
- Leads to T-duality about the Euclidean time cycle (thermal duality)

$$Z(\beta) = Z(\beta_c^2/\beta) .$$

- Large $T^3 \rightarrow$ effective field theory analysis under good control.
- Assumption: weak string coupling.

S-Brane at the Self-Dual Temperature

- At the critical temperature: thermal winding states become massless.
- enhanced gauge symmetry at $\beta = \beta_c$.
- Enhanced symmetry states enter the effective low energy action for the light degrees of freedom as an S-brane.
- S-brane: space-like topological defect: $\rho = 0$, $p < 0$.
- S-brane mediates violation of Null Energy Condition.
- S-brane allows for cosmological bounce.

S-Brane at the Self-Dual Temperature

- At the critical temperature: thermal winding states become massless.
- enhanced gauge symmetry at $\beta = \beta_c$.
- Enhanced symmetry states enter the effective low energy action for the light degrees of freedom as an S-brane.
- S-brane: space-like topological defect: $\rho = 0$, $p < 0$.
- S-brane mediates violation of Null Energy Condition.
- S-brane allows for cosmological bounce.

Effective Action

- Low energy effective action

$$S = \int d^4x \sqrt{-\tilde{g}} \left[e^{-2\phi} \left(\frac{\tilde{\mathcal{R}}}{2} + 2(\nabla\phi)^2 \right) + P \right] + S_B \,,$$

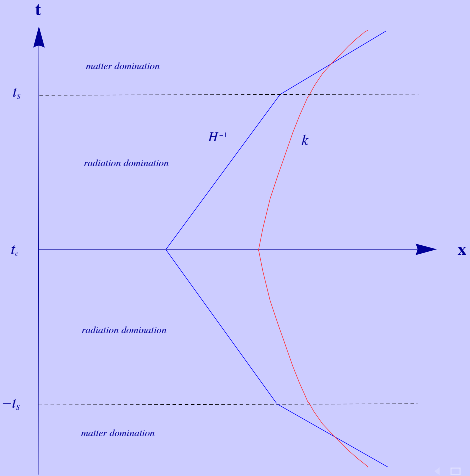
- Pressure:

$$P = \frac{e^{-|\sigma|}}{\beta_c} Z(|\sigma|) \,.$$

- S-brane action:

$$S_B = \kappa \int d^4x \sqrt{\tilde{h}} e^{-2\phi} \delta(\tau - \tau_B) \,,$$

Background Cosmology



Background Cosmology

R.B., C. Kounnas, H. Partouche, S. Patil and N. Toumbas, arXiv:1312.2524

Phases:

- Matter phase of contraction: supersymmetry broken
- Radiation phase of contraction: supersymmetry broken.
- Radiation/dilaton phase of contraction: supersymmetry restored.
- S-brane bounce
- Radiation/dilaton phase of expansion: supersymmetry unbroken.
- Radiation phase of expansion: supersymmetry broken.
- Current matter phase of expansion: supersymmetry broken.

Matching Conditions

W. Israel, Nuovo Cim. (1966), J-C. Hwang and E. Vishniac, Ap. J. (1991), N. Deruelle and V. Mukhanov, gr-qc/9503050, R. Durrer and F. Vernizzi, hep-ph/0203275

Matching two solutions of Einstein's equations across a brane. The following conditions must be satisfied:

- Induced metric continous
- extrinsic curvature jumps by a value corresponding to the amplitude of the S-brane source.

Matching Conditions

W. Israel, Nuovo Cim. (1966), J-C. Hwang and E. Vishniac, Ap. J. (1991), N. Deruelle and V. Mukhanov, gr-qc/9503050, R. Durrer and F. Vernizzi, hep-ph/0203275

Matching two solutions of Einstein's equations across a brane. The following conditions must be satisfied:

- Induced metric continous
- extrinsic curvature jumps by a value corresponding to the amplitude of the S-brane source.

Matching Conditions in S-Brane Bounce

R.B., C. Kounnas, H. Partouche, S. Patil and N. Toumbas, arXiv:1312.2524

Work in the string frame and in longitudinal gauge.

$$ds^2 = N(\tau, \mathbf{x})^2 d\tau^2 - A(\tau, \mathbf{x})^2 d\mathbf{x}^2$$

- Continuity of the metric.
- Continuity of the time derivative of the metric.
- Continuity of the dilaton Φ.
- Jump in Φ': $\Delta\Phi'/N = \kappa/2$

Combining the Results

R.B., C. Kounnas, H. Partouche, S. Patil and N. Toumbas, arXiv:1312.2524

- Growing mode of ζ at the end of the matter-dominated phase of contraction has a scale-invariant spectrum.
- Scale-invariant spectrum of both modes in the radiation-dilaton phase of contraction is induced.
- Spectrum preserved on large scales through the bounce.
- ζ constant on super-Hubble scales during the expanding phases.
- $\rightarrow$ scale-invariant spectrum of ζ at late times.

Challenge for Matter Bounce Cosmology

- BKL instability to the growth of anisotropies.
- Ad hoc solution: add Ekpyrotic scalar field which dominates after the phase of matter domination in the contracting phase (J. Erickson et al, hep-th/0312009).
- An Ekpyrotic scalar field with Galileon type kinetic term can yield a nonsingular bounce (Y. Cai, D. Easson and R.B., arXiv:1206.2382).
- The scale-invariant spectrum of cosmological perturbations is preserved (Y. F. Cai, E. McDonough, F. Duplessis and R. H. Brandenberger, JCAP **1310**, 024 (2013)).

Challenge for Matter Bounce Cosmology

- BKL instability to the growth of anisotropies.
- Ad hoc solution: add Ekpyrotic scalar field which dominates after the phase of matter domination in the contracting phase (J. Erickson et al, hep-th/0312009).
- An Ekpyrotic scalar field with Galileon type kinetic term can yield a nonsingular bounce (Y. Cai, D. Easson and R.B., arXiv:1206.2382).
- The scale-invariant spectrum of cosmological perturbations is preserved (Y. F. Cai, E. McDonough, F. Duplessis and R. H. Brandenberger, JCAP **1310**, 024 (2013)).

Plan

Challenges for 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.

Challenges for 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.

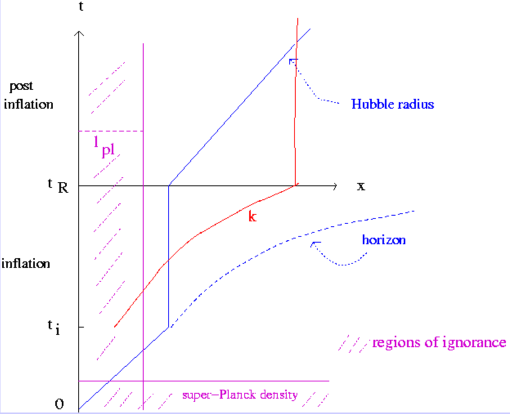
Challenges for the Inflationary Paradigm

- 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.

Challenges for 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.

Zones of Ignorance



Initial Conditions for Inflation

R.B. and J. Kung, Phys. Rev. D42, 1008 (1990); R.B., H. Feldman and J. Kung, Phys. Scripta T36, 64 (1991).

In the case of large field inflation the slow roll trajectory is an attractor in initial condition space, even in the presence of linear cosmological perturbations.

No-Go Theorems I

It has proven very difficult to embed inflation into a UV complete theory, e.g. superstring theory.

- No de Sitter ground states in supergravity (G. Gibbons, 1985; G. Gibbons, hep-th/0301117).
- Extended no-go theorem (J. Maldacena and C. Nunez, hep-th/0007018).
- Many explicit "constructions" of inflationary solutions (e.g. D. Baumann and L. McAllister, arXiv:0901.0265) in the context of Type IIB superstring theory.

No-Go Theorems I

It has proven very difficult to embed inflation into a UV complete theory, e.g. superstring theory.

- No de Sitter ground states in supergravity (G. Gibbons, 1985; G. Gibbons, hep-th/0301117).
- Extended no-go theorem (J. Maldacena and C. Nunez, hep-th/0007018).
- Many explicit “constructions" of inflationary solutions (e.g. D. Baumann and L. McAllister, arXiv:0901.0265) in the context of Type IIB superstring theory.

No-Go Theorems II

- No-go theorem on inflation in heterotic string theory (S. Green at al., arXiv:1110.0545).
- Constraints on inflation in Type IIA string theory (M. Herzberg et al, arXiv:0711.2512).
- Singularities in the Type IIB constructions (I. Bena et al, arXiv:1206.6369).
- No-go theorem on de Sitter in Type IIB (K. Dasgupta et al, arXiv:1402.5112).

Challenge for Inflationary Cosmology

- Find a consistent UV embedding of inflationary cosmology.
- Demonstrate the resolution of the conceptual problems of inflation.

Challenge for Inflationary Cosmology

- Find a consistent UV embedding of inflationary cosmology.
- Demonstrate the resolution of the conceptual problems of inflation.

Plan

Conclusions

- There are alternatives to cosmological inflation for explaining the current data on CMB and LSS.
- From the point of view of effective field theory inflation is at the present time the most complete scenario.
- But, inflation is not without its conceptual problems.
- Superstring theory may force us to look beyond the inflationary scenario.

Observations will tell: Focus on:

- non-Gaussianities
- amplitude and tilt of the spectrum of gravitational waves.
- running

Conclusions

- There are alternatives to cosmological inflation for explaining the current data on CMB and LSS.
- From the point of view of effective field theory inflation is at the present time the most complete scenario.
- But, inflation is not without its conceptual problems.
- Superstring theory may force us to look beyond the inflationary scenario.

Observations will tell: Focus on:

- non-Gaussianities
- amplitude and tilt of the spectrum of gravitational waves.
- running

Conclusions

- There are alternatives to cosmological inflation for explaining the current data on CMB and LSS.
- From the point of view of effective field theory inflation is at the present time the most complete scenario.
- But, inflation is not without its conceptual problems.
- Superstring theory may force us to look beyond the inflationary scenario.

Observations will tell: Focus on:

- non-Gaussianities
- amplitude and tilt of the spectrum of gravitational waves.
- running

Conclusions II

- String Gas Cosmology: Model of cosmology of the very early universe based on new degrees of freedom and new symmetries of superstring theory.
- Thermal string fluctuations lead to a scale-invariant spectrum of cosmological fluctuations with a blue tilt of the tensor modes.