What was before the Big Bang?

Cosmology of the Very Early Universe

Robert Brandenberger
McGill University

February 21, 2013

Outline

Plan

Goals of Early Universe Cosmology

1. Understand origin and early evolution of the universe.
   - What is the “Big Bang"?
   - Was there a “Big Bang"?
   - What was before the “Big Bang"?
2. Explain observed large-scale structure.

Goals of Early Universe Cosmology

1. Understand origin and early evolution of the universe.
   - What is the “Big Bang"?
   - Was there a “Big Bang"?
   - What was before the “Big Bang"?

2. Explain observed large-scale structure.

Goals of Early Universe Cosmology

1. Understand origin and early evolution of the universe.
   - What is the “Big Bang"?
   - Was there a “Big Bang"?
   - What was before the “Big Bang"?
2. Explain observed large-scale structure.

Goals of Early Universe Cosmology

1. Understand origin and early evolution of the universe.
   - What is the “Big Bang"?
   - Was there a “Big Bang"?
   - What was before the “Big Bang"?

2. Explain observed large-scale structure.

Goals of Early Universe Cosmology

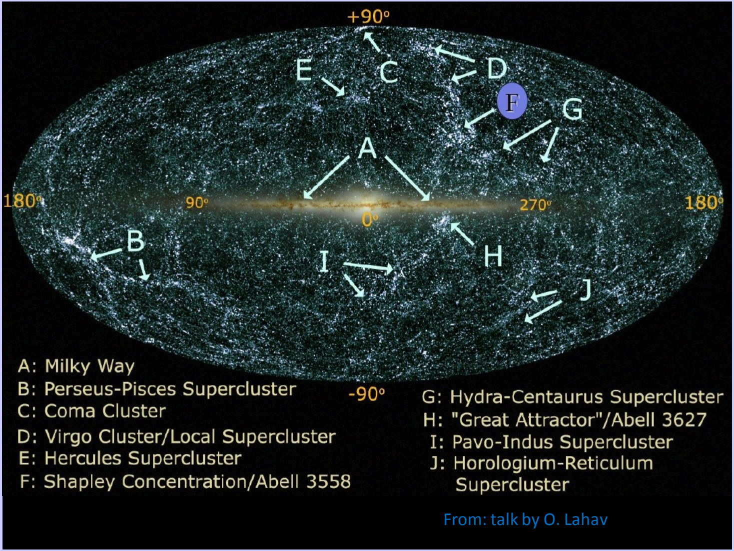
1. Understand origin and early evolution of the universe.
   - What is the “Big Bang"?
   - Was there a “Big Bang"?
   - What was before the “Big Bang"?

2. Explain observed large-scale structure.

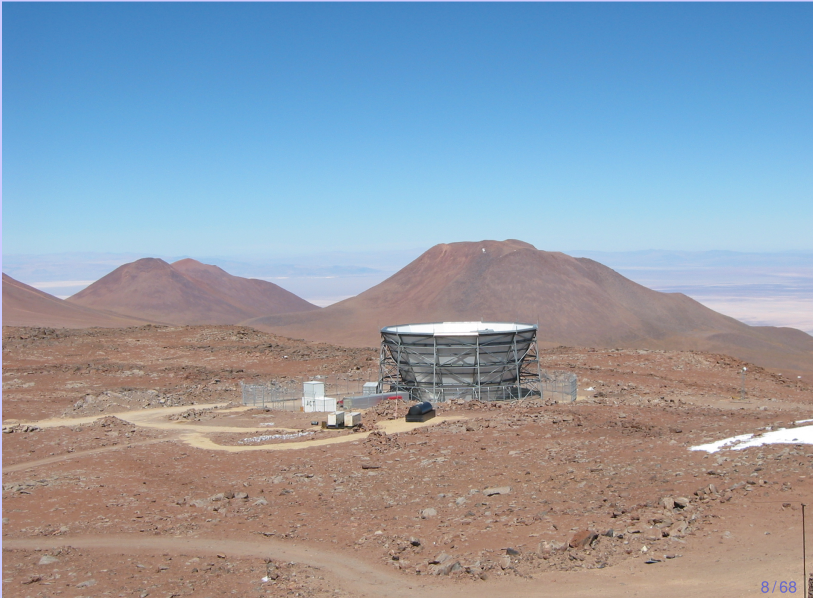
Optical Telescopes: Gemini Telescope

Galaxies: Building Blocks of the Cosmology

Large-Scale Structure

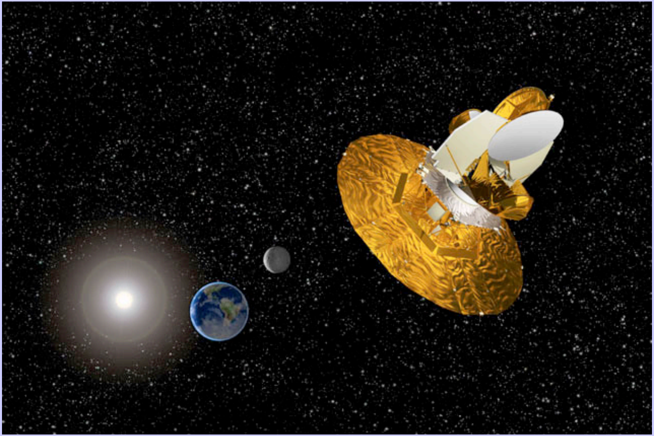


Microwave Telescopes on the Earth: ACT Telescope

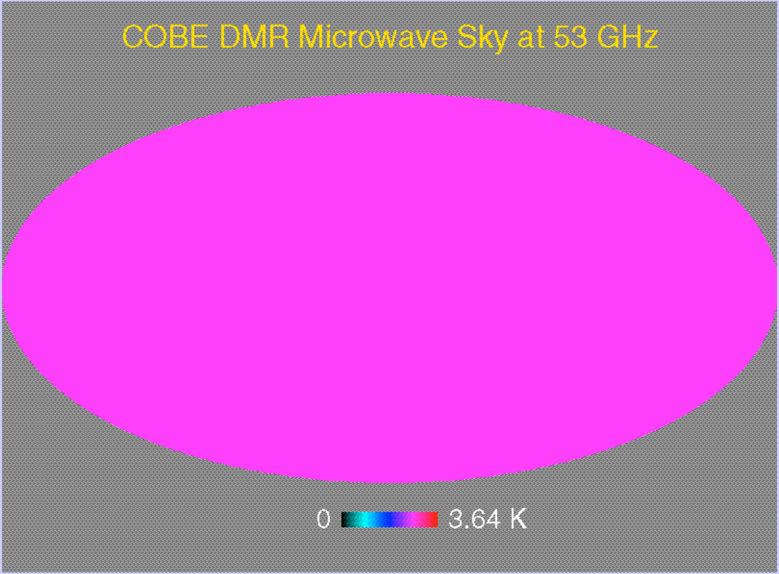


Microwave Telescopes on the Earth: SPT Telescope

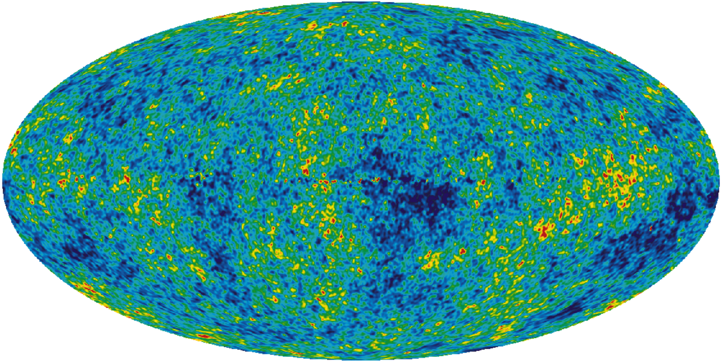
Microwave Telescopes in Space: WMAP Telescope



Isotropic CMB Background

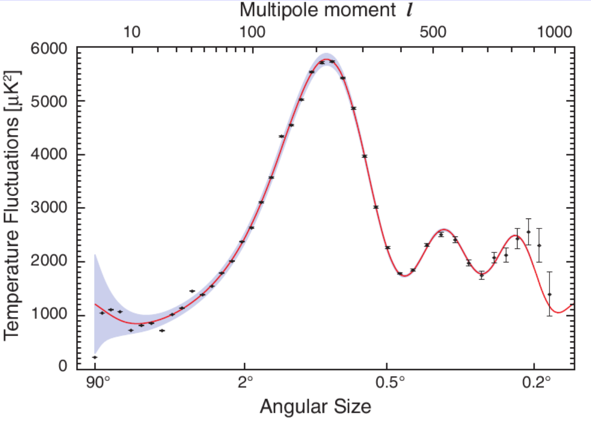


Anisotropies in the Cosmic Microwave Background (CMB)



Credit: NASA/WMAP Science Team

Quantification of the CMB data



Credit: NASA/WMAP Science Team

Goals of Early Universe Cosmology

1. Understand origin and early evolution of the universe.
   - What is the “Big Bang"?
   - Was there a “Big Bang"?
   - What was before the “Big Bang"?

2. Explain observed large-scale structure.
   - Patterns in the distribution of galaxies on large scales.
   - Anisotropies in CMB maps.

3. Make predictions for future observations.

Goals of Early Universe Cosmology

1. Understand origin and early evolution of the universe.
   - What is the “Big Bang"?
   - Was there a “Big Bang"?
   - What was before the “Big Bang"?
2. Explain observed large-scale structure.
   - Patterns in the distribution of galaxies on large scales.
   - Anisotropies in CMB maps.
3. Make predictions for future observations.

Plan

Framework

The Universe is:

- Space-time
- Matter which lives in space-time.

To describe the Universe:

- Space-time described by Einstein's theory of General Relativity.
- Matter as described by Physics.
- More specifically: matter described on large scale by classical physics, on small scales by quantum mechanics and on even smaller scales by superstring theory ?

Framework

The Universe is:

- Space-time
- Matter which lives in space-time.

To describe the Universe:

- Space-time described by Einstein's theory of General Relativity.
- Matter as described by Physics.
- More specifically: matter described on large scale by classical physics, on small scales by quantum mechanics and on even smaller scales by superstring theory ?

Framework

The Universe is:

- Space-time
- Matter which lives in space-time.

To describe the Universe:

- Space-time described by Einstein's theory of General Relativity.
- Matter as described by Physics.
- More specifically: matter described on large scale by classical physics, on small scales by quantum mechanics and on even smaller scales by superstring theory ?

Framework

The Universe is:

- Space-time
- Matter which lives in space-time.

To describe the Universe:

- Space-time described by Einstein's theory of General Relativity.
- Matter as described by Physics.
- More specifically: matter described on large scale by classical physics, on small scales by quantum mechanics and on even smaller scales by superstring theory ?

Framework

The Universe is:

- Space-time
- Matter which lives in space-time.

To describe the Universe:

- Space-time described by Einstein's theory of General Relativity.
- Matter as described by Physics.
- More specifically: matter described on large scale by classical physics, on small scales by quantum mechanics and on even smaller scales by superstring theory ?

Framework

The Universe is:

- Space-time
- Matter which lives in space-time.

To describe the Universe:

- Space-time described by Einstein's theory of General Relativity.
- Matter as described by Physics.
- More specifically: matter described on large scale by classical physics, on small scales by quantum mechanics and on even smaller scales by superstring theory ?

Framework

The Universe is:

- Space-time
- Matter which lives in space-time.

To describe the Universe:

- Space-time described by Einstein's theory of General Relativity.
- Matter as described by Physics.
- More specifically: matter described on large scale by classical physics, on small scales by quantum mechanics and on even smaller scales by superstring theory ?

Framework

The Universe is:

- Space-time
- Matter which lives in space-time.

To describe the Universe:

- Space-time described by Einstein's theory of General Relativity.
- Matter as described by Physics.
- More specifically: matter described on large scale by classical physics, on small scales by quantum mechanics and on even smaller scales by superstring theory ?

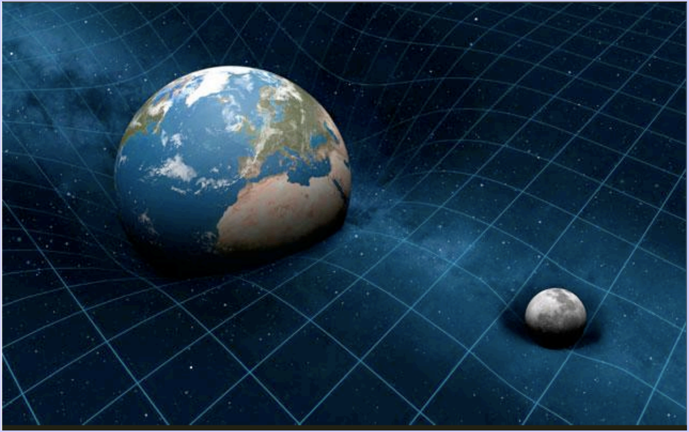
Space-Time as Described by General Relativity

- Space-time dynamical (no longer absolute like in Newtonian theory)
- Matter curves space-time.

Space-Time as Described by General Relativity

- Space-time dynamical (no longer absolute like in Newtonian theory)
- Matter curves space-time.

Mass curves Space-Time



Space-Time as Described by General Relativity

- Space-time dynamical (no longer absolute like in Newtonian theory)
- Matter curves space-time: Space-time is dynamical.
- Note: Newton's gravitational force is a consequence of the curvature of space.
- Einstein Equivalence Principle determines the motion of matter in curved space-time.
- Space with a homogeneous distribution of matter cannot be static - it must expand (or contract).

Space-Time as Described by General Relativity

- Space-time dynamical (no longer absolute like in Newtonian theory)
- Matter curves space-time: Space-time is dynamical.
- Note: Newton's gravitational force is a consequence of the curvature of space.
- Einstein Equivalence Principle determines the motion of matter in curved space-time.
- Space with a homogeneous distribution of matter cannot be static - it must expand (or contract).

Space-Time as Described by General Relativity

- Space-time dynamical (no longer absolute like in Newtonian theory)
- Matter curves space-time: Space-time is dynamical.
- Note: Newton's gravitational force is a consequence of the curvature of space.
- Einstein Equivalence Principle determines the motion of matter in curved space-time.
- Space with a homogeneous distribution of matter cannot be static - it must expand (or contract).

Space-Time as Described by General Relativity

- Space-time dynamical (no longer absolute like in Newtonian theory)
- Matter curves space-time: Space-time is dynamical.
- Note: Newton's gravitational force is a consequence of the curvature of space.
- Einstein Equivalence Principle determines the motion of matter in curved space-time.
- Space with a homogeneous distribution of matter cannot be static - it must expand (or contract).

The Expanding Universe

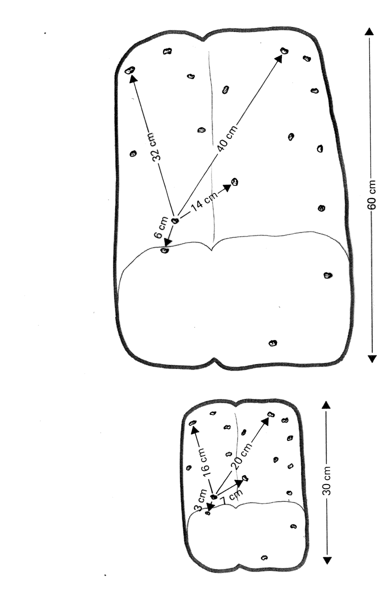
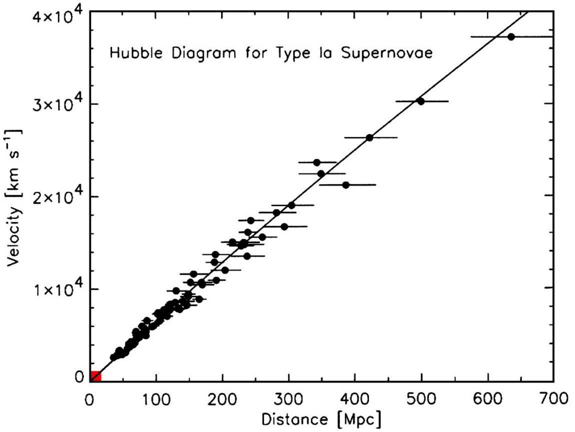


Figure 37.4 Expanding raisin bread.

Evidence for the Expansion of Space

The Hubble diagram for type Ia supernovae.



Kirshner R P PNAS 2004;101:8-13

Standard Big Bang Cosmology

Standard Big Bang Cosmology (SBB): the old paradigm of cosmology (ca. 1960).

The SBB is based on:

- Cosmological principle: universe homogeneous and isotropic on large scales.
- General Relativity governing dynamics of space-time.
- Classical matter as source in the Einstein equations.
- Classical matter: cold (pressure-less) matter (describing the galaxies) $+$ radiation(describing the CMB).

Standard Big Bang Cosmology

Standard Big Bang Cosmology (SBB): the old paradigm of cosmology (ca. 1960).

The SBB is based on:

- Cosmological principle: universe homogeneous and isotropic on large scales.
- General Relativity governing dynamics of space-time.
- Classical matter as source in the Einstein equations.
- Classical matter: cold (pressure-less) matter (describing the galaxies) + radiation(describing the CMB).

Standard Big Bang Cosmology

Standard Big Bang Cosmology (SBB): the old paradigm of cosmology (ca. 1960).

The SBB is based on:

- Cosmological principle: universe homogeneous and isotropic on large scales.
- General Relativity governing dynamics of space-time.
- Classical matter as source in the Einstein equations.
- Classical matter: cold (pressure-less) matter (describing the galaxies) + radiation(describing the CMB).

Standard Big Bang Cosmology

Standard Big Bang Cosmology (SBB): the old paradigm of cosmology (ca. 1960).

The SBB is based on:

- Cosmological principle: universe homogeneous and isotropic on large scales.
- General Relativity governing dynamics of space-time.
- Classical matter as source in the Einstein equations.
- Classical matter: cold (pressure-less) matter (describing the galaxies) + radiation(describing the CMB).

Standard Big Bang Cosmology

Standard Big Bang Cosmology (SBB): the old paradigm of cosmology (ca. 1960).

The SBB is based on:

- Cosmological principle: universe homogeneous and isotropic on large scales.
- General Relativity governing dynamics of space-time.
- Classical matter as source in the Einstein equations.
- Classical matter: cold (pressure-less) matter (describing the galaxies) $+$ radiation(describing the CMB).

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- The universe is expanding now.
- In the past it was hotter and more dense.
- Thus, it was expanding faster in the past.
- At a finite time in the past the temperature was infinite . A finite box of space had zero size at that time.
- This is the Big Bang!

What is the Big Bang? What was before the Big Bang?

To be taken seriously a theory must have made successful observational predictions.

Standard Big Bang Cosmology (ctd.)

- Universe begins as a homogeneous and very hot fireball.
- Initially radiation dominates: hot plasma.
- Space expands and matter cools.
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
- Now the age of the universe is about 13 billion years.

Prediction: Existence and black body nature of the Cosmic Microwave Background.

Standard Big Bang Cosmology (ctd.)

- Universe begins as a homogeneous and very hot fireball.
- Initially radiation dominates: hot plasma.
- Space expands and matter cools.
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
- Now the age of the universe is about 13 billion years.

Prediction: Existence and black body nature of the Cosmic Microwave Background.

Standard Big Bang Cosmology (ctd.)

- Universe begins as a homogeneous and very hot fireball.
- Initially radiation dominates: hot plasma.
- Space expands and matter cools.
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
- Now the age of the universe is about 13 billion years.

Prediction: Existence and black body nature of the Cosmic Microwave Background.

Standard Big Bang Cosmology (ctd.)

- Universe begins as a homogeneous and very hot fireball.
- Initially radiation dominates: hot plasma.
- Space expands and matter cools.
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
- Now the age of the universe is about 13 billion years.

Prediction: Existence and black body nature of the Cosmic Microwave Background.

Standard Big Bang Cosmology (ctd.)

- Universe begins as a homogeneous and very hot fireball.
- Initially radiation dominates: hot plasma.
- Space expands and matter cools.
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
- Now the age of the universe is about 13 billion years.

Prediction: Existence and black body nature of the Cosmic Microwave Background.

Standard Big Bang Cosmology (ctd.)

- Universe begins as a homogeneous and very hot fireball.
- Initially radiation dominates: hot plasma.
- Space expands and matter cools.
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
- Now the age of the universe is about 13 billion years.

Prediction: Existence and black body nature of the Cosmic Microwave Background.

Standard Big Bang Cosmology (ctd.)

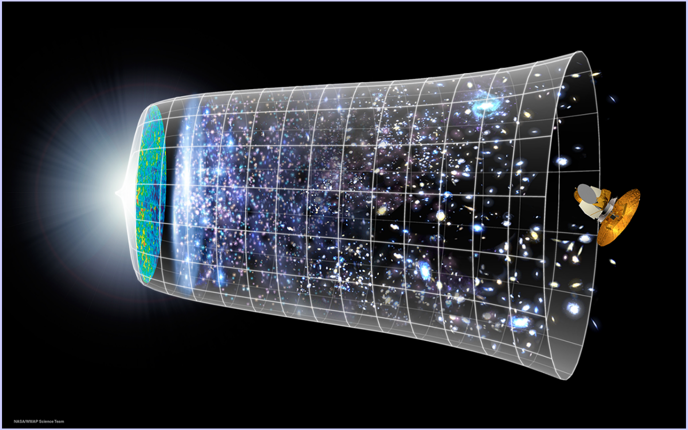
- Universe begins as a homogeneous and very hot fireball.
- Initially radiation dominates: hot plasma.
- Space expands and matter cools.
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
- Now the age of the universe is about 13 billion years.

Prediction: Existence and black body nature of the Cosmic Microwave Background.

Standard Big Bang Cosmology (ctd.)

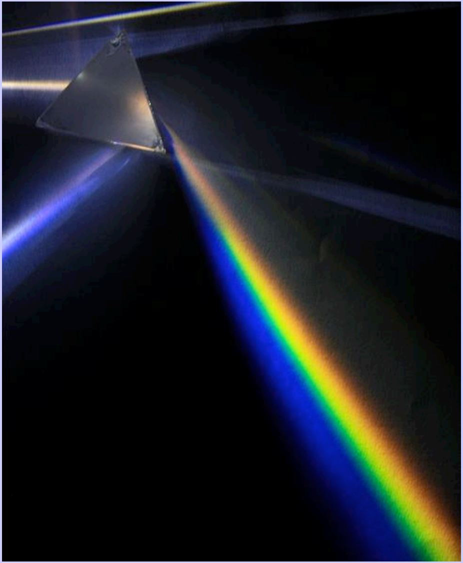
- Universe begins as a homogeneous and very hot fireball.
- Initially radiation dominates: hot plasma.
- Space expands and matter cools.
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
- Now the age of the universe is about 13 billion years.

Prediction: Existence and black body nature of the Cosmic Microwave Background.



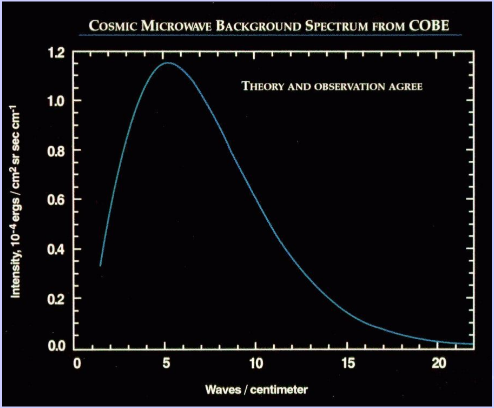
Credit: NASA/WMAP Science Team

Spectrometer



Successes of the SBB Model

Key success: Existence and black body nature of the CMB.



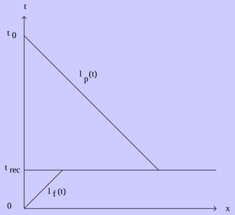
Unanswered Questions

- What is the Big Bang?
- What was before the Big Bang?

Conceptual Problems of the SBB Model

No explanation for the homogeneity, spatial flatness and large size and entropy of the universe.

Horizon problem of the SBB:



Conceptual Problems of the SBB Model II

No explanation of the observed inhomogeneities in the distribution of matter and anisotropies in the Cosmic Microwave Background possible!

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- $\rightarrow$ Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- $\rightarrow$ Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- $\rightarrow$ Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- $\rightarrow$ Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- → Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- $\rightarrow$ Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- $\rightarrow$ Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- $\rightarrow$ Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

What to do?

With a little help from a friend , the particle physicist:

- At very high temperatures close to the Big Bang classical physics breaks down - and quantum mechanics and particle physics give the right description of matter.
- $\rightarrow$ Standard Big Bang theory breaks down.
- In the very early universe matter is a plasma of elementary particles.
- All described in terms of quantum fields.
- Quantum field (scalar fields) can lead to a different expansion rate of space namely inflationary expansion.

Plan

Time line of inflationary cosmology

- t_i: inflation begins
- t_R: inflation ends, reheating

Successes of Inflationary Cosmology

The Inflationary Universe Scenario is the current paradigm of early universe cosmology (1980).

Successes:

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

Successes of Inflationary Cosmology

The Inflationary Universe Scenario is the current paradigm of early universe cosmology (1980).

Successes:

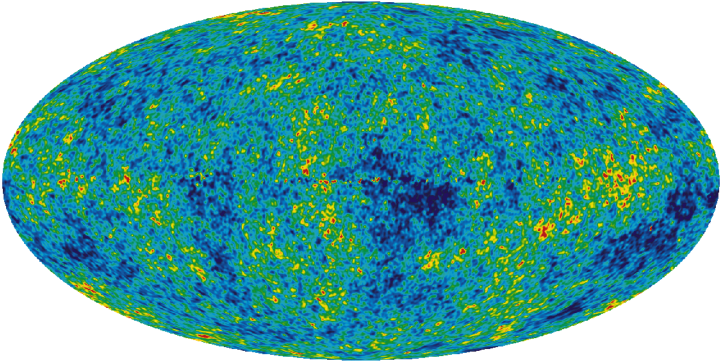
- Solves horizon problem
- Solves flatness problem
- Solves size/entropy problem
- Provides a causal mechanism of generating primordial cosmological perturbations (Chibisov & Mukhanov, 1981).

Successes of Inflationary Cosmology

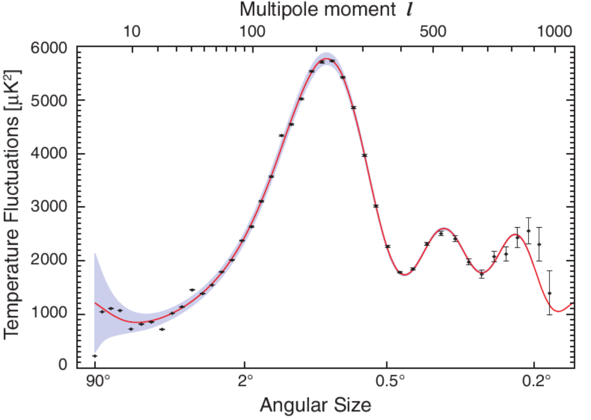
The Inflationary Universe Scenario is the current paradigm of early universe cosmology (1980).

Successes:

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



Credit: NASA/WMAP Science Team



Credit: NASA/WMAP Science Team

Review of Inflationary Cosmology

Context:

- General Relativity
- Scalar Field Matter

Inflation:

- phase with exponential expansion of space
- requires matter with negative pressure
- requires a slowly rolling scalar field φ

Review of Inflationary Cosmology

Context:

- General Relativity
- Scalar Field Matter

Inflation:

- phase with exponential expansion of space
- requires matter with negative pressure
- requires a slowly rolling scalar field φ

Review of Inflationary Cosmology

Context:

- General Relativity
- Scalar Field Matter

Inflation:

- phase with exponential expansion of space
- requires matter with negative pressure
- requires a slowly rolling scalar field φ

Review of Inflationary Cosmology

Context:

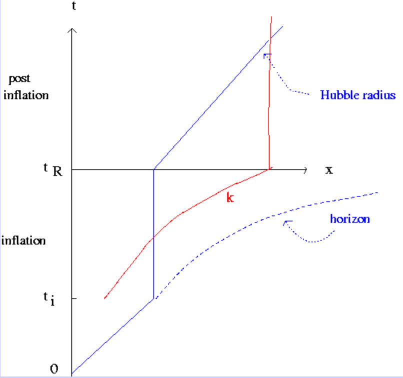
- General Relativity
- Scalar Field Matter

Inflation:

- phase with exponential expansion of space
- requires matter with negative pressure
- requires a slowly rolling scalar field φ

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

Successes of Inflation

- inflation renders the universe large, homogeneous and spatially flat
- classical matter redshifts $\rightarrow$ matter vacuum remains
- quantum vacuum fluctuations: seeds for the observed structure [Chibisov & Mukhanov, 1981]

Status of the Big Bang in Inflationary Cosmology

- The inflationary phase had a beginning.
- There was a Big Bang before the period of inflation.

Unanswered questions:

- What is the Big Bang?
- What was before the Big Bang?

Note: quantum field theory is not applicable very close to the singularity.

Status of the Big Bang in Inflationary Cosmology

- The inflationary phase had a beginning.
- There was a Big Bang before the period of inflation.

Unanswered questions:

- What is the Big Bang?
- What was before the Big Bang?

Note: quantum field theory is not applicable very close to the singularity.

Status of the Big Bang in Inflationary Cosmology

- The inflationary phase had a beginning.
- There was a Big Bang before the period of inflation.

Unanswered questions:

- What is the Big Bang?
- What was before the Big Bang?

Note: quantum field theory is not applicable very close to the singularity.

Challenges for the Current Paradigm

- In spite of the phenomenological successes, the inflationary scenario suffers from several conceptual problems.
- In light of these problems we need to look for input from new fundamental physics to construct a new theory which will overcome these problems.
- Question: Can Superstring theory lead to a new and improved paradigm?
- Question: Can this new paradigm be tested in cosmological observations?
- Question: Was there a Big Bang ?

Challenges for the Current Paradigm

- In spite of the phenomenological successes, the inflationary scenario suffers from several conceptual problems.
- In light of these problems we need to look for input from new fundamental physics to construct a new theory which will overcome these problems.
- Question: Can Superstring theory lead to a new and improved paradigm?
- Question: Can this new paradigm be tested in cosmological observations?
- Question: Was there a Big Bang ?

Challenges for the Current Paradigm

- In spite of the phenomenological successes, the inflationary scenario suffers from several conceptual problems.
- In light of these problems we need to look for input from new fundamental physics to construct a new theory which will overcome these problems.
- Question: Can Superstring theory lead to a new and improved paradigm?
- Question: Can this new paradigm be tested in cosmological observations?
- Question: Was there a Big Bang ?

Challenges for the Current Paradigm

- In spite of the phenomenological successes, the inflationary scenario suffers from several conceptual problems.
- In light of these problems we need to look for input from new fundamental physics to construct a new theory which will overcome these problems.
- Question: Can Superstring theory lead to a new and improved paradigm?
- Question: Can this new paradigm be tested in cosmological observations?
- Question: Was there a Big Bang ?

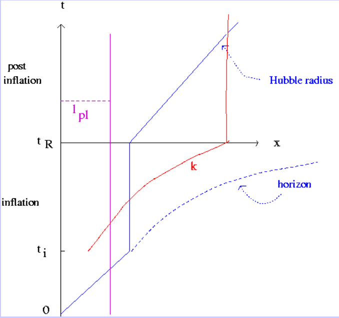
Challenges for the Current Paradigm

- In spite of the phenomenological successes, the inflationary scenario suffers from several conceptual problems.
- In light of these problems we need to look for input from new fundamental physics to construct a new theory which will overcome these problems.
- Question: Can Superstring theory lead to a new and improved paradigm?
- Question: Can this new paradigm be tested in cosmological observations?
- Question: Was there a Big Bang ?

Conceptual Problems of Inflationary Cosmology

- What is the scalar field?
- Why does it have the special conditions to obtain inflation?
- Trans-Planckian problem
- Singularity problem
- Applicability of General Relativity

Trans-Planckian Problem



- **Success of inflation**: At early times scales are inside the Hubble radius → causal generation mechanism is possible.
- **Problem:** If time period of inflation is slightly more than the minimal length it must have, then the wavelength is smaller than the Planck length at the beginning of inflation

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.

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.

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.

Applicability of GR

- Einstein's theory breaks down at extremely high densities.
- In models of inflation, the energy scale of at which inflation takes place is close to the limiting scale for the validity of Einstein's theory.
- We cannot trust the predictions made using GR.

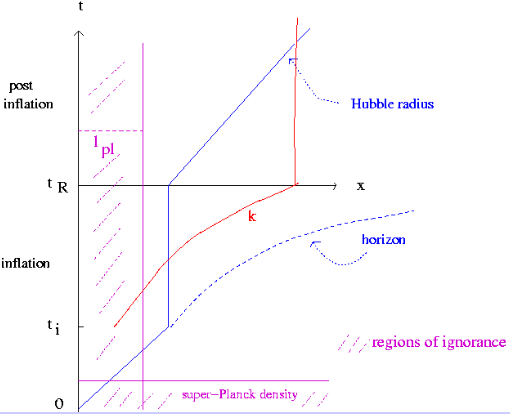
Applicability of GR

- Einstein's theory breaks down at extremely high densities.
- In models of inflation, the energy scale of at which inflation takes place is close to the limiting scale for the validity of Einstein's theory.
- We cannot trust the predictions made using GR.

Applicability of GR

- Einstein's theory breaks down at extremely high densities.
- In models of inflation, the energy scale of at which inflation takes place is close to the limiting scale for the validity of Einstein's theory.
- We cannot trust the predictions made using GR.

Zones of Ignorance



Message I

- The current cosmological paradigm has serious conceptual problems.
- We need a new paradigm of very early universe cosmology.
- With a little help from a friend - the string theorist!
- New cosmological model motivated by superstring theory: String Gas Cosmology (SGC) [R.B. and C. Vafa, 1989].
- New structure formation scenario emerges from SGC [A. Nayeri, R.B. and C. Vafa, 2006].

Message I

- The current cosmological paradigm has serious conceptual problems.
- We need a new paradigm of very early universe cosmology.
- With a little help from a friend - the string theorist!
- New cosmological model motivated by superstring theory: String Gas Cosmology (SGC) [R.B. and C. Vafa, 1989].
- New structure formation scenario emerges from SGC [A. Nayeri, R.B. and C. Vafa, 2006].

Message I

- The current cosmological paradigm has serious conceptual problems.
- We need a new paradigm of very early universe cosmology.
- With a little help from a friend - the string theorist!
- New cosmological model motivated by superstring theory: String Gas Cosmology (SGC) [R.B. and C. Vafa, 1989].
- New structure formation scenario emerges from SGC [A. Nayeri, R.B. and C. Vafa, 2006].

Message I

- The current cosmological paradigm has serious conceptual problems.
- We need a new paradigm of very early universe cosmology.
- With a little help from a friend - the string theorist!
- New cosmological model motivated by superstring theory: String Gas Cosmology (SGC) [R.B. and C. Vafa, 1989].
- New structure formation scenario emerges from SGC [A. Nayeri, R.B. and C. Vafa, 2006].

Message I

- The current cosmological paradigm has serious conceptual problems.
- We need a new paradigm of very early universe cosmology.
- With a little help from a friend - the string theorist!
- New cosmological model motivated by superstring theory: String Gas Cosmology (SGC) [R.B. and C. Vafa, 1989].
- New structure formation scenario emerges from SGC [A. Nayeri, R.B. and C. Vafa, 2006].

Message II

String Gas Cosmology makes testable predictions for cosmological observations

- Blue tilt in the spectrum of gravitational waves [R.B., A. Nayeri, S. Patil and C. Vafa, 2006]
- Line discontinuities in CMB anisotropy maps [N. Kaiser and A. Stebbins, 1984]
- Line discontinuities can be detected using the CANNY edge detection algorithm [S. Amsel, J. Berger and R.B., 2007, R. Danos and R.B., 2008, 2009]

Message II

String Gas Cosmology makes testable predictions for cosmological observations

- Blue tilt in the spectrum of gravitational waves [R.B., A. Nayeri, S. Patil and C. Vafa, 2006]
- Line discontinuities in CMB anisotropy maps [N. Kaiser and A. Stebbins, 1984]
- Line discontinuities can be detected using the CANNY edge detection algorithm [S. Amsel, J. Berger and R.B., 2007, R. Danos and R.B., 2008, 2009]

Message II

String Gas Cosmology makes testable predictions for cosmological observations

- Blue tilt in the spectrum of gravitational waves [R.B., A. Nayeri, S. Patil and C. Vafa, 2006]
- Line discontinuities in CMB anisotropy maps [N. Kaiser and A. Stebbins, 1984]
- Line discontinuities can be detected using the CANNY edge detection algorithm [S. Amsel, J. Berger and R.B., 2007, R. Danos and R.B., 2008, 2009]

Plan

What is String Theory?

- String theory is a quantum theory of all forces of nature including gravity.
- String theory unifies all forces of nature.
- Basic objects: elementary strings. Compared to elementary point particles.
- String theory is mathematically consistent only in 10 space-time dimensions.
- Thus, string theory predicts extra spatial dimensions.

Note: string theory is “in development".

What is String Theory?

- String theory is a quantum theory of all forces of nature including gravity.
- String theory unifies all forces of nature.
- Basic objects: elementary strings. Compared to elementary point particles.
- String theory is mathematically consistent only in 10 space-time dimensions.
- Thus, string theory predicts extra spatial dimensions.

Note: string theory is “in development".

What is String Theory?

- String theory is a quantum theory of all forces of nature including gravity.
- String theory unifies all forces of nature.
- Basic objects: elementary strings. Compared to elementary point particles.
- String theory is mathematically consistent only in 10 space-time dimensions.
- Thus, string theory predicts extra spatial dimensions.

Note: string theory is "in development".

What is String Theory?

- String theory is a quantum theory of all forces of nature including gravity.
- String theory unifies all forces of nature.
- Basic objects: elementary strings. Compared to elementary point particles.
- String theory is mathematically consistent only in 10 space-time dimensions.
- Thus, string theory predicts extra spatial dimensions.

Note: string theory is “in development".

What is String Theory?

- String theory is a quantum theory of all forces of nature including gravity.
- String theory unifies all forces of nature.
- Basic objects: elementary strings. Compared to elementary point particles.
- String theory is mathematically consistent only in 10 space-time dimensions.
- Thus, string theory predicts extra spatial dimensions.

Note: string theory is “in development".

What is String Theory?

- String theory is a quantum theory of all forces of nature including gravity.
- String theory unifies all forces of nature.
- Basic objects: elementary strings. Compared to elementary point particles.
- String theory is mathematically consistent only in 10 space-time dimensions.
- Thus, string theory predicts extra spatial dimensions.

Note: string theory is “in development".

What is String Theory?

- String theory is a quantum theory of all forces of nature including gravity.
- String theory unifies all forces of nature.
- Basic objects: elementary strings. Compared to elementary point particles.
- String theory is mathematically consistent only in 10 space-time dimensions.
- Thus, string theory predicts extra spatial dimensions.

Note: string theory is “in development".

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.

“Large" is Equivalent to “Small" in String Theory

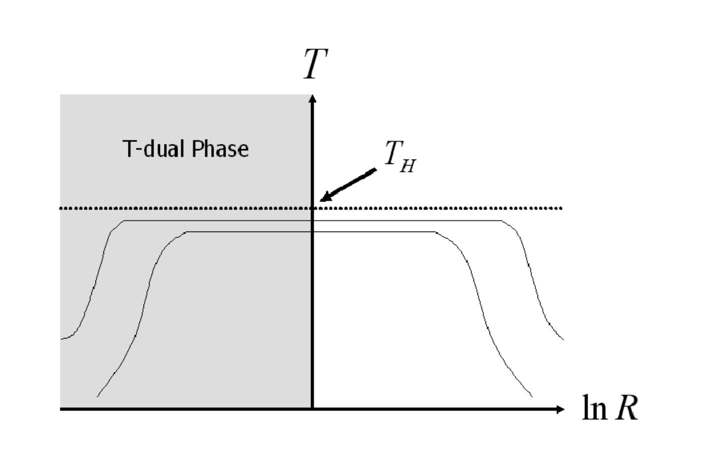
T-Duality

- 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

Temperature in String Cosmology

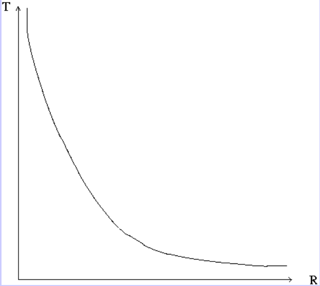
R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

Temperature of a box of strings in thermal equilibrium.



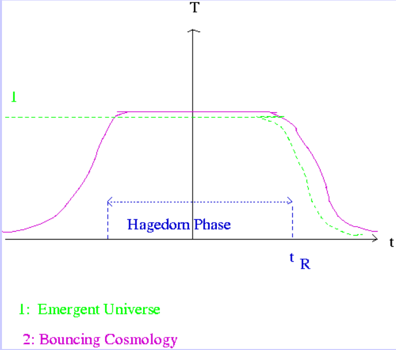
Temperature in Standard and Inflationary Cosmology

Temperature of a box of particles in thermal equilibrium.

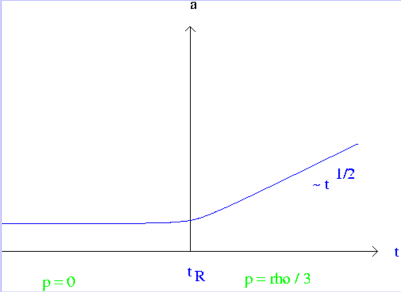


Dynamics

Assume some dynamical principle gives us $R(t)$

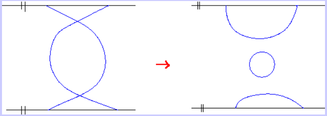


We will thus consider the following background dynamics for the scale factor $a(t)$:



Dimensionality of Space in SGC

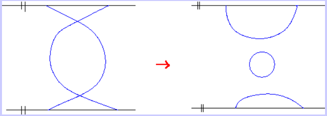
- Begin with all 9 spatial dimensions small, initial temperature close to T_H $\rightarrow$ winding modes about all spatial sections are excited.
- Expansion of any one spatial dimension requires the annihilation of the winding modes in that dimension.



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

Dimensionality of Space in SGC

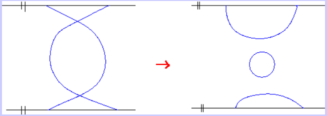
- Begin with all 9 spatial dimensions small, initial temperature close to T_H $\rightarrow$ winding modes about all spatial sections are excited.
- Expansion of any one spatial dimension requires the annihilation of the winding modes in that dimension.



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

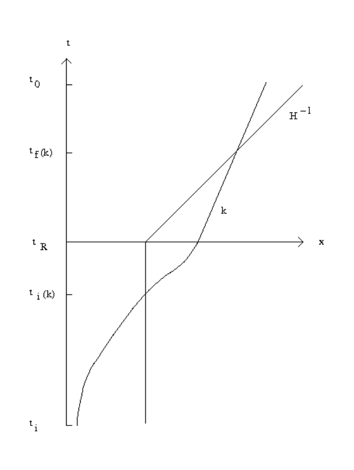
Dimensionality of Space in SGC

- 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.



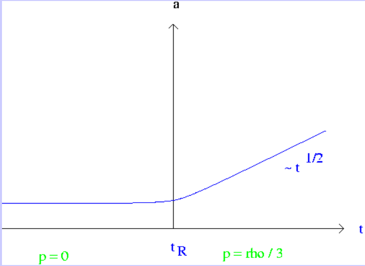
- Decay only possible in three large spatial dimensions.
- $\rightarrow$ dynamical explanation of why there are exactly three large spatial dimensions.

Structure formation in inflationary cosmology



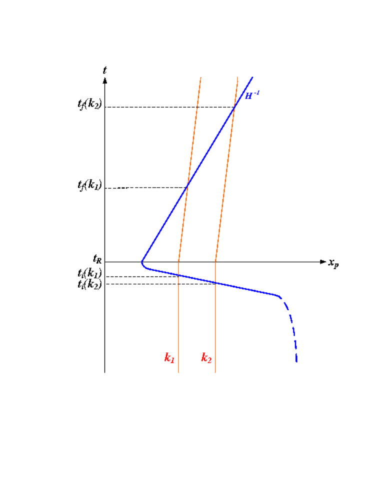
N.B. Perturbations originate as quantum vacuum fluctuations.

Background for string gas cosmology



Structure formation in string gas cosmology

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



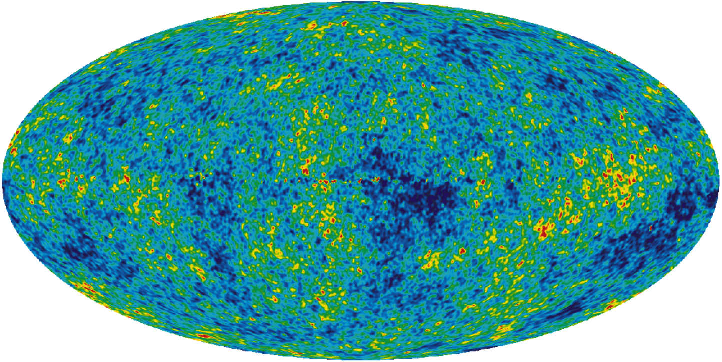
N.B. Perturbations originate as thermal string gas fluctuations.

Power spectrum of cosmological fluctuations

Key features:

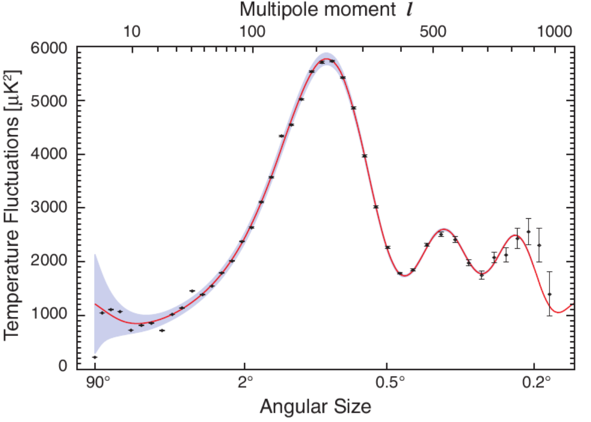
- scale-invariant like for inflation
- slight red tilt like for inflation

Anisotropies in the Cosmic Microwave Background (CMB)



Credit: NASA/WMAP Science Team

Quantification of the CMB data



Credit: NASA/WMAP Science Team

Spectrum of Gravitational Waves

Key features:

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

Status of the “Big Bang" in String Gas Cosmology

- The universe was very, very hot and dense 13 billion years ago.
- In this sense there was a hot “primordial" fireball.
- But: there was no Big Bang Singularity.
- There was no beginning of time.

Status of the “Big Bang" in String Gas Cosmology

- The universe was very, very hot and dense 13 billion years ago.
- In this sense there was a hot “primordial" fireball.
- But: there was no Big Bang Singularity.
- There was no beginning of time.

Status of the "Big Bang" in String Gas Cosmology

- The universe was very, very hot and dense 13 billion years ago.
- In this sense there was a hot "primordial" fireball.
- But: there was no Big Bang Singularity.
- There was no beginning of time.

Status of the “Big Bang" in String Gas Cosmology

- The universe was very, very hot and dense 13 billion years ago.
- In this sense there was a hot “primordial" fireball.
- But: there was no Big Bang Singularity.
- There was no beginning of time.

Plan

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems $\rightarrow$ motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems $\rightarrow$ motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems $\rightarrow$ motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems $\rightarrow$ motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems $\rightarrow$ motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems $\rightarrow$ motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems $\rightarrow$ motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems → motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Conclusions

- Cosmology is a vibrant field with lots of observational data.
- Paradigms of early universe cosmology have been developed.
- Paradigm 1: Standard Big Bang Model.
- Paradigm 2: Inflationary Universe scenario - current paradigm.
- In both Paradigms 1 and 2 there was a Big Bang singularity.
- Paradigm 2 has conceptual problems $\rightarrow$ motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

Status of the “Big Bang"

- We know that going back in time 13 billion years there was a very hot early phase, a primordial fireball.
- If this is what you mean by “Big Bang": then there WAS a “Big Bang".
- We do not know if there was a “Big Bang singularity", a beginning of time.
- Our current paradigms of early universe cosmology predict a beginning of time.
- But only if we extrapolate the models beyond where they can be used.
- Superstring theory may lead to a cosmology without a beginning of time.
- If this is true then there may not have been a “Big Bang" (singularity).