Cosmology III : The Universe as a high energy physics laboratory

Ruth Durrer

Department of Theoretical Physics
Geneva University
Switzerland

UNIVERSITÉ
DE GENÈVE

CERN Summer school July 27, 2017

Contents

Introduction

So far we have studied how measuring cosmological distances and redshifts and the small fluctuations of the CMB can lead to new insights of fundamental physics: the existence of dark energy and dark matter.

Introduction

So far we have studied how measuring cosmological distances and redshifts and the small fluctuations of the CMB can lead to new insights of fundamental physics: the existence of dark energy and dark matter.
What is dark energy?

- What is dark energy? (70%)
- What is dark matter? (25%)

Introduction

So far we have studied how measuring cosmological distances and redshifts and the small fluctuations of the CMB can lead to new insights of fundamental physics: the existence of dark energy and dark matter.
What is dark energy?

- What is dark energy? (70%)
- What is dark matter? (25%)

Today we discuss other observations, studies where cosmology can provide information about fundamental physics:

- Nucleosynthesis

Introduction

So far we have studied how measuring cosmological distances and redshifts and the small fluctuations of the CMB can lead to new insights of fundamental physics: the existence of dark energy and dark matter.
What is dark energy?

- What is dark energy? (70%)
- What is dark matter? (25%)

Today we discuss other observations, studies where cosmology can provide information about fundamental physics:

- Nucleosynthesis
- Neutrinos

Introduction

So far we have studied how measuring cosmological distances and redshifts and the small fluctuations of the CMB can lead to new insights of fundamental physics: the existence of dark energy and dark matter.
What is dark energy?

- What is dark energy? (70%)
- What is dark matter? (25%)

Today we discuss other observations, studies where cosmology can provide information about fundamental physics:

- Nucleosynthesis
- Neutrinos
- Phase transitions at high temperature

Introduction

So far we have studied how measuring cosmological distances and redshifts and the small fluctuations of the CMB can lead to new insights of fundamental physics: the existence of dark energy and dark matter.
What is dark energy?

- What is dark energy? (70%)
- What is dark matter? (25%)

Today we discuss other observations, studies where cosmology can provide information about fundamental physics:

- Nucleosynthesis
- Neutrinos
- Phase transitions at high temperature
- Baryogenesis

Introduction

So far we have studied how measuring cosmological distances and redshifts and the small fluctuations of the CMB can lead to new insights of fundamental physics: the existence of dark energy and dark matter.
What is dark energy?

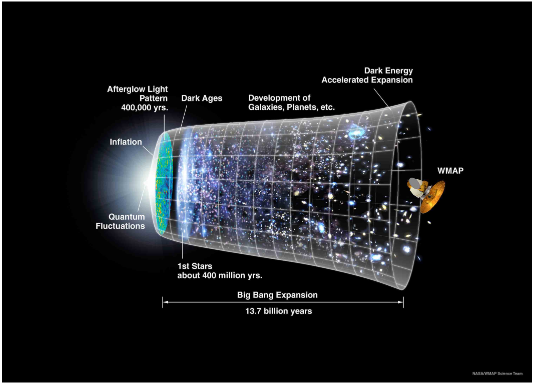
- What is dark energy? (70%)
- What is dark matter? (25%)

Today we discuss other observations, studies where cosmology can provide information about fundamental physics:

- Nucleosynthesis
- Neutrinos
- Phase transitions at high temperature
- Baryogenesis
- Inflation

The thermal history of the Universe

In the past the Universe was not only much denser than today but also much hotter.



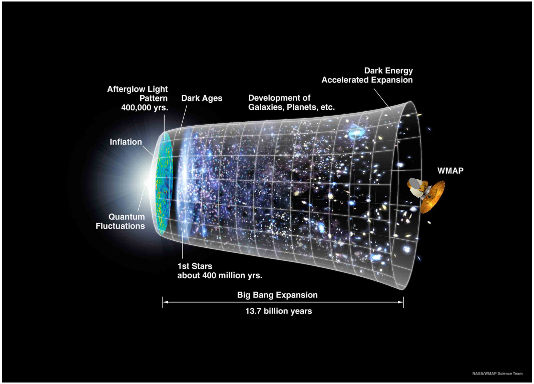
Age of the Universe: $t_0 \simeq 13.7$ milliards d'années

Important events in the early Universe

- Recombination

The thermal history of the Universe

In the past the Universe was not only much denser than today but also much hotter.



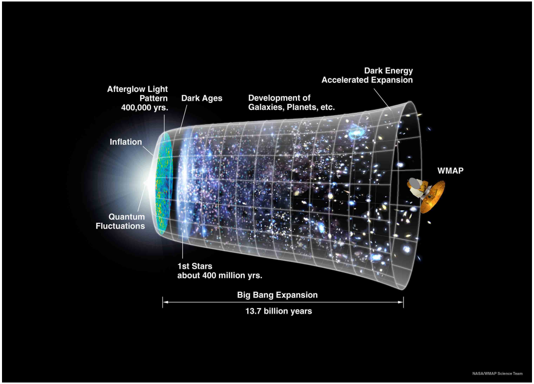
Age of the Universe: $t_0 \simeq 13.7$ milliards d'années

Important events in the early Universe

- Recombination
- Nucleosyhthesis (formation of Helium, Deuterium...)

The thermal history of the Universe

In the past the Universe was not only much denser than today but also much hotter.



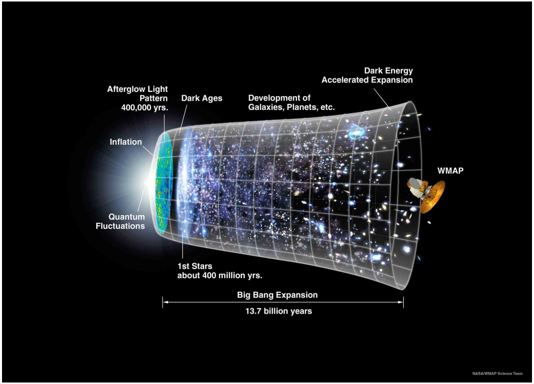
Age of the Universe: $t_0 \simeq 13.7$ milliards d'années

Important events in the early Universe

- Recombination
- Nucleosyhthesis (formation of Helium, Deuterium...)
- Neutrino decoupling

The thermal history of the Universe

In the past the Universe was not only much denser than today but also much hotter.



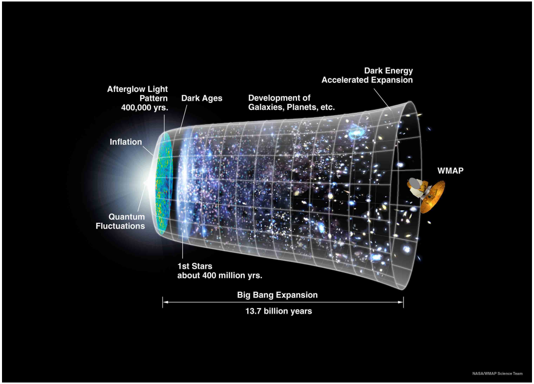
Age of the Universe: $t_0 \simeq 13.7$ milliards d'années

Important events in the early Universe

- Recombination
- Nucleosyhthesis (formation of Helium, Deuterium...)
- Neutrino decoupling
- Phase Transitions?

The thermal history of the Universe

In the past the Universe was not only much denser than today but also much hotter.



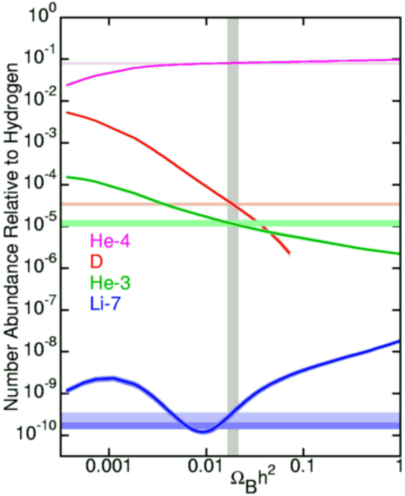
Age of the Universe: $t_0 \simeq 13.7$ milliards d'années

Important events in the early Universe

- Recombination
- Nucleosyhthesis (formation of Helium, Deuterium...)
- Neutrino decoupling
- Phase Transitions?
- Inflation ?

Nucleosynthesis

At $T_{\rm nuc} \simeq 0.08$MeV $\simeq 10^9$K, $z_{\rm nuc} \simeq 4 \times 10^8$, Deuterium $(p + n)$ becomes stable. At this moment virtually all the neutrons present in the Universe are 'burned' into He^4. Only traces of Deuterium, Helium^3 and Lithium^7 remain. Their abundance depends strongly on the baryon density.



Neutrino decoupling

- At $T_{\rm dec} \simeq 1.4\text{MeV} \simeq 1.6 \times 10^{10}\text{K}$, $z_{\rm dec} \simeq 6 \times 10^9$, weak interactions are no longer sufficiently frequent to keep the neutrinos in thermal equilibrium with the rest of the matter (baryons, electrons, photons, dark matter) neutrinos decouple.

Neutrino decoupling

- At $T_{\rm dec} \simeq 1.4\text{MeV} \simeq 1.6 \times 10^{10}\text{K}$, $z_{\rm dec} \simeq 6 \times 10^{9}$, weak interactions are no longer sufficiently frequent to keep the neutrinos in thermal equilibrium with the rest of the matter (baryons, electrons, photons, dark matter) neutrinos decouple.
- Subsequently they interact only gravitationally. They are neither generated nor destroyed but simply loose energy due to the expansion of the Universe (redshift).

Neutrino decoupling

- At $T_{\rm dec} \simeq 1.4\text{MeV} \simeq 1.6 \times 10^{10}\text{K}$, $z_{\rm dec} \simeq 6 \times 10^9$, weak interactions are no longer sufficiently frequent to keep the neutrinos in thermal equilibrium with the rest of the matter (baryons, electrons, photons, dark matter) neutrinos decouple.
- Subsequently they interact only gravitationally. They are neither generated nor destroyed but simply loose energy due to the expansion of the Universe (redshift).
- Later, at $T \simeq 0.5\text{MeV}$, electrons and positrons decay into photons and heat up the photons but not the decoupled neutrinos.

Neutrino decoupling

- At $T_{\rm dec} \simeq 1.4$MeV $\simeq 1.6 \times 10^{10}$K, $z_{\rm dec} \simeq 6 \times 10^9$, weak interactions are no longer sufficiently frequent to keep the neutrinos in thermal equilibrium with the rest of the matter (baryons, electrons, photons, dark matter) neutrinos decouple.
- Subsequently they interact only gravitationally. They are neither generated nor destroyed but simply loose energy due to the expansion of the Universe (redshift).
- Later, at $T \simeq 0.5$MeV, electrons and positrons decay into photons and heat up the photons but not the decoupled neutrinos.
- A neutrino background at a 'temperature' $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_0 \simeq 1.9$K should exist in the Universe.

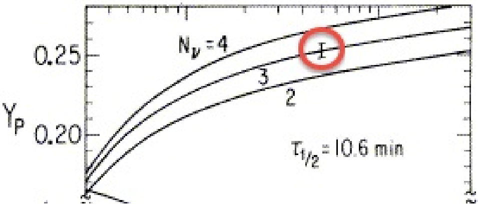
Neutrino decoupling

- At $T_{\rm dec} \simeq 1.4{\rm MeV} \simeq 1.6 \times 10^{10}{\rm K}$, $z_{\rm dec} \simeq 6 \times 10^{9}$, weak interactions are no longer sufficiently frequent to keep the neutrinos in thermal equilibrium with the rest of the matter (baryons, electrons, photons, dark matter) neutrinos decouple.
- Subsequently they interact only gravitationally. They are neither generated nor destroyed but simply loose energy due to the expansion of the Universe (redshift).
- Later, at $T \simeq 0.5{\rm MeV}$, electrons and positrons decay into photons and heat up the photons but not the decoupled neutrinos.
- A neutrino background at a 'temperature' $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_0 \simeq 1.9{\rm K}$ should exist in the Universe.
- But even if these neutrinos have a density of about 300 particles per cm^3 they have not been detected directly so far due to their extremely weak interaction.

Abundance of relativistic particles

Neutrinos are however 'observed' indirectly by their gravitational effects:

- They contribute to the expansion of the Universe (Friedmann eqn) which is relevant for the abundance of Helium-4. $\Rightarrow$ N_ν (number of relativistic neutrino species at $T \simeq 0.1$MeV).

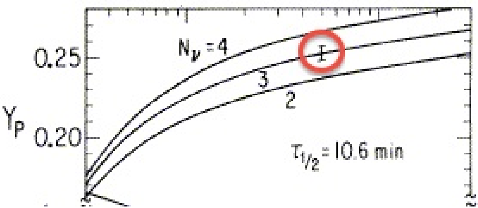


(Sarkar et al. '06)

Abundance of relativistic particles

Neutrinos are however 'observed' indirectly by their gravitational effects:

- They contribute to the expansion of the Universe (Friedmann eqn) which is relevant for the abundance of Helium-4. ⇒ N_ν (number of relativistic neutrino species at $T \simeq 0.1$MeV).



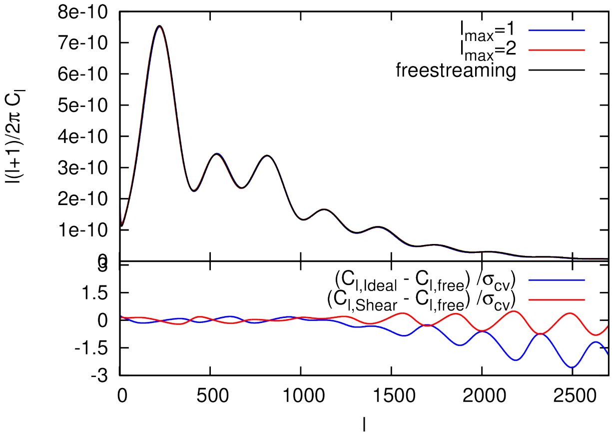
(Sarkar et al. '06)

$$\Rightarrow \quad \boxed{N_\nu \simeq 3 \pm 1}$$

- This limit applies to any species of relativistic particles with thermal abundance at $T \simeq 0.1$MeV.

Neutrinos in the CMB

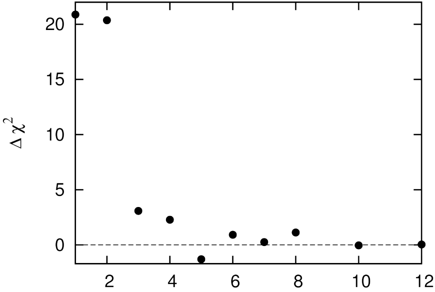
Neutrinos also contribute to the anisotropies of the CMB where one can even mesure the consequence of the fact that neutrinos are not a perfect fluid but collisionless particles.



(Sellentin & Durrer, 2015)

Neutrinos in the CMB

The CMB cannot be fit with neutrino's which are either a perfect fluid or a fluid with anisotropic stress.



(Sellentin & Durrer, 2015)

The probability that the fluid model is described by this data is

$$\exp(-\Delta\chi^2/2) \simeq 3.7 \times 10^{-5}$$

times smaller than the probability that the data is described by free streaming neutrinos.

Neutrino mass

Oscillation experiments request (see course by Pilar Hernandez):
$\sum_{\nu_i} m_{\nu_i} > 0.057\text{eV}$. Oscillation experiments measure mass differences; cosmological observations are mainly sensitive to the sum neutrino masses.
Massive neutrinos contribute to the dark matter density,

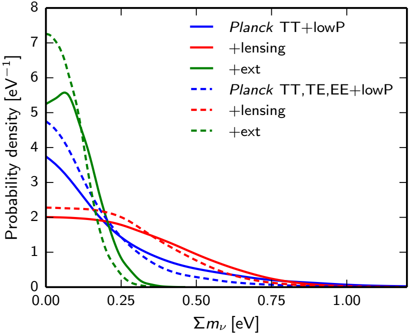
$$\Omega_{m\nu} h^2 = \frac{\sum_{\nu_i} m_{\nu_i}}{94\mathrm{eV}.}$$

As they are very light, the cannot form small scale structure: Observations of small scale structure limit neutrinos masses.

$\sum m_\nu < 0.49\text{eV}$ (95%)
(Planck only)

$\sum m_\nu < 0.194\text{eV}$ (95%)
(Planck (2015) +BAO + SN1a+H_0)

$\sum m_\nu < 0.15\text{eV}$ (95%)
(SDSSIII/BOSS (Ly-α) +Planck (2013))



Neutrino number, sterile neutrinos

The number of relativistic degrees of freedom, $N_{\rm eff}$ which decouple before $e^{\pm}$ annihilation is defined by

$$\rho_{\rm rel} = \left[N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} + 1\right]\rho_\gamma$$

In the standard model $N_{\rm eff} = 3.046$. The Planck + BAO data requires

$$N_{\rm eff} = 3.04 \pm 0.33 \qquad (68\%)$$

Even with the Planck data alone, $\Delta N_{\rm eff} \geq 1$ is excluded at more than 4σ.

An additional sterile neutrino with $\Delta N_{\rm eff} \simeq 0.3$ and mass $0.5\ {\rm eV} \lesssim m_{\nu{\rm sterile}} \lesssim 5\ {\rm eV}$ can actually reduce the tension of Planck with lensing data (which has a lower σ_8).

A much heavier, ∼ keV, sterile neutrino could be warm dark matter.

Phase Transitions: confinement, electroweak transition

During the expansion and cooling of the Universe, its temperature has changed by many orders of magnitude.

- The QCD transition: at $T_c \simeq 100\text{MeV} \simeq 10^{12}\text{K}$, $z_c \simeq 4 \times 10^{11}$:
  quarks and gluons are confined into hadrons. Protons and neutrons are formed.

Phase Transitions: confinement, electroweak transition

During the expansion and cooling of the Universe, its temperature has changed by many orders of magnitude.

- The QCD transition: at $T_c \simeq 100\text{MeV} \simeq 10^{12}\text{K}$, $z_c \simeq 4 \times 10^{11}$:
  quarks and gluons are confined into hadrons. Protons and neutrons are formed.
- The electroweak transition: at $T_c \simeq 100\text{GeV} \simeq 10^{15}\text{K}$, $z_c \simeq 4 \times 10^{14}$:
  The $W^{\pm}$ and Z bosons become massive, only the photon remains massless $\Rightarrow$ weak interactions become weak.

Phase Transitions: confinement, electroweak transition

During the expansion and cooling of the Universe, its temperature has changed by many orders of magnitude.

- The QCD transition: at $T_c \simeq 100\text{MeV} \simeq 10^{12}\text{K}$, $z_c \simeq 4 \times 10^{11}$:
  quarks and gluons are confined into hadrons. Protons and neutrons are formed.
- The electroweak transition: at $T_c \simeq 100\text{GeV} \simeq 10^{15}\text{K}$, $z_c \simeq 4 \times 10^{14}$:
  The $\text{W}^{\pm}$ and Z bosons become massive, only the photon remains massless ⇒ weak interactions become weak.
- super-symmetry? ...

Phase Transitions: confinement, electroweak transition

During the expansion and cooling of the Universe, its temperature has changed by many orders of magnitude.

- The QCD transition: at $T_c \simeq 100\text{MeV} \simeq 10^{12}\text{K}$, $z_c \simeq 4 \times 10^{11}$: quarks and gluons are confined into hadrons. Protons and neutrons are formed.
- The electroweak transition: at $T_c \simeq 100\text{GeV} \simeq 10^{15}\text{K}$, $z_c \simeq 4 \times 10^{14}$: The $\text{W}^{\pm}$ and Z bosons become massive, only the photon remains massless $\Rightarrow$ weak interactions become weak.
- super-symmetry? ...

Possible observational consequences:

- Magnetic fields

Phase Transitions: confinement, electroweak transition

During the expansion and cooling of the Universe, its temperature has changed by many orders of magnitude.

- The QCD transition: at $T_c \simeq 100\text{MeV} \simeq 10^{12}\text{K}$, $z_c \simeq 4 \times 10^{11}$:
  quarks and gluons are confined into hadrons. Protons and neutrons are formed.
- The electroweak transition: at $T_c \simeq 100\text{GeV} \simeq 10^{15}\text{K}$, $z_c \simeq 4 \times 10^{14}$:
  The $\text{W}^{\pm}$ and Z bosons become massive, only the photon remains massless $\Rightarrow$ weak interactions become weak.
- super-symmetry? ...

Possible observational consequences:

- Magnetic fields
- Gravitational waves

Phase Transitions: confinement, electroweak transition

During the expansion and cooling of the Universe, its temperature has changed by many orders of magnitude.

- The QCD transition: at $T_c \simeq 100\text{MeV} \simeq 10^{12}\text{K}$, $z_c \simeq 4 \times 10^{11}$:
  quarks and gluons are confined into hadrons. Protons and neutrons are formed.
- The electroweak transition: at $T_c \simeq 100\text{GeV} \simeq 10^{15}\text{K}$, $z_c \simeq 4 \times 10^{14}$:
  The $W^{\pm}$ and Z bosons become massive, only the photon remains massless ⇒ weak interactions become weak.
- super-symmetry? ...

Possible observational consequences:

- Magnetic fields
- Gravitational waves
- Primordial black holes

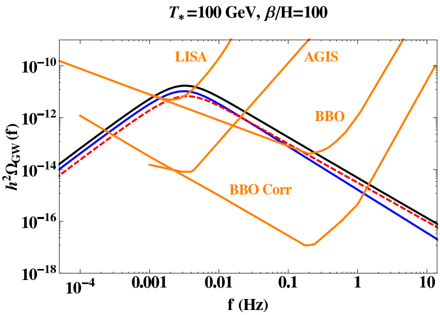
Phase Transitions: confinement, electroweak transition

During the expansion and cooling of the Universe, its temperature has changed by many orders of magnitude.

- The QCD transition: at $T_c \simeq 100\text{MeV} \simeq 10^{12}\text{K}$, $z_c \simeq 4 \times 10^{11}$: quarks and gluons are confined into hadrons. Protons and neutrons are formed.
- The electroweak transition: at $T_c \simeq 100\text{GeV} \simeq 10^{15}\text{K}$, $z_c \simeq 4 \times 10^{14}$: The $\text{W}^{\pm}$ and Z bosons become massive, only the photon remains massless ⇒ weak interactions become weak.
- super-symmetry? ...

Possible observational consequences:

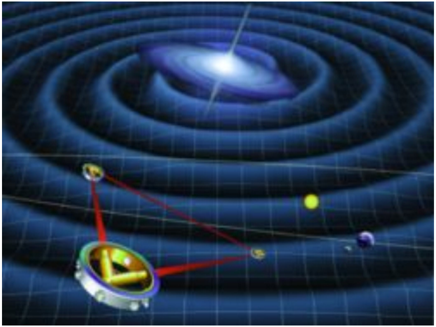
- Magnetic fields
- Gravitational waves
- Primordial black holes



$T_* = 100$ GeV, $\beta/H = 100$

(Caprini, Durrer & Servant, 2009)

The satellite LISA



The LISA satellite projet (artist's impression). Launch $>$2020.

The LISA pathfinder satellite (the real thing) successfully launched in December 2015.

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.
- The same is true for the Milky Way and the entire observable Universe.

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.
- The same is true for the Milky Way and the entire observable Universe.
- Is this baryon asymmetry an initial condition?

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.
- The same is true for the Milky Way and the entire observable Universe.
- Is this baryon asymmetry an initial condition?
- If not, how can we explain it?

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.
- The same is true for the Milky Way and the entire observable Universe.
- Is this baryon asymmetry an initial condition?
- If not, how can we explain it?

To generate a baryon asymmetry during the evolution of the Universe the three so called Sakharov criteria have to be satisfied:

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.
- The same is true for the Milky Way and the entire observable Universe.
- Is this baryon asymmetry an initial condition?
- If not, how can we explain it?

To generate a baryon asymmetry during the evolution of the Universe the three so called Sakharov criteria have to be satisfied:

- Violation of baryon number conservation (standard model ✓).

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.
- The same is true for the Milky Way and the entire observable Universe.
- Is this baryon asymmetry an initial condition?
- If not, how can we explain it?

To generate a baryon asymmetry during the evolution of the Universe the three so called Sakharov criteria have to be satisfied:

- Violation of baryon number conservation (standard model ✓).
- Violation of both, C (charge conjugation) and CP (P= parity) symmetry and therefore also T (time reversal) symmetry (standard model ✓).

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.
- The same is true for the Milky Way and the entire observable Universe.
- Is this baryon asymmetry an initial condition?
- If not, how can we explain it?

To generate a baryon asymmetry during the evolution of the Universe the three so called Sakharov criteria have to be satisfied:

- Violation of baryon number conservation (standard model $\checkmark$).
- Violation of both, C (charge conjugation) and CP (P= parity) symmetry and therefore also T (time reversal) symmetry (standard model $\checkmark$).
- The cosmic plasma must drop out thermal equilibrium (standard model $\lightning$).

Baryon asymmetry

- The solar system consists nearly exclusively of baryons ('normal' matter, protons and neutrons), it contains only very little anti-matter.
- The same is true for the Milky Way and the entire observable Universe.
- Is this baryon asymmetry an initial condition?
- If not, how can we explain it?

To generate a baryon asymmetry during the evolution of the Universe the three so called Sakharov criteria have to be satisfied:

- Violation of baryon number conservation (standard model ✓).
- Violation of both, C (charge conjugation) and CP (P= parity) symmetry and therefore also T (time reversal) symmetry (standard model ✓).
- The cosmic plasma must drop out thermal equilibrium (standard model ↯).

With small variations of the standard model particle physics can obtain a 1st order electroweak phase transition which would lead to out of equilibrium processes and allow the generation of a baryon asymmetry.

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?
- Why is the Universe so big and so flat?

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?
- Why is the Universe so big and so flat?
- Why is it so old ? ($t_0 \simeq 1.4 \times 10^{10}$years $\simeq 4.4 \times 10^{17}$sec, $t_P \simeq 5.4 \times 10^{-44}$sec)

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?
- Why is the Universe so big and so flat?
- Why is it so old ? ($t_0 \simeq 1.4 \times 10^{10}$years $\simeq 4.4 \times 10^{17}$sec, $t_P \simeq 5.4 \times 10^{-44}$sec)
- Why has it such a high entropy ? (entropy/baryon $\simeq 10^{10}$)

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?
- Why is the Universe so big and so flat?
- Why is it so old ? ($t_0 \simeq 1.4 \times 10^{10}$years $\simeq 4.4 \times 10^{17}$sec, $t_P \simeq 5.4 \times 10^{-44}$sec)
- Why has it such a high entropy ? (entropy/baryon $\simeq 10^{10}$)

An inflationary phase addresses these questions: During inflation, the energy density is dominated by the potential energy of a scalar field which is nearly constant.

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?
- Why is the Universe so big and so flat?
- Why is it so old ? ($t_0 \simeq 1.4 \times 10^{10}$years $\simeq 4.4 \times 10^{17}$sec, $t_P \simeq 5.4 \times 10^{-44}$sec)
- Why has it such a high entropy ? (entropy/baryon $\simeq 10^{10}$)

An inflationary phase addresses these questions: During inflation, the energy density is dominated by the potential energy of a scalar field which is nearly constant.
The Friedmann equation then becomes

$$H^2 = \left(\frac{\dot R}{R}\right)^2 \simeq \frac{8\pi G}{3} V \simeq \text{constant}, \qquad \dot R = HR.$$

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?
- Why is the Universe so big and so flat?
- Why is it so old ? ($t_0 \simeq 1.4 \times 10^{10}$years $\simeq 4.4 \times 10^{17}$sec, $t_P \simeq 5.4 \times 10^{-44}$sec)
- Why has it such a high entropy ? (entropy/baryon $\simeq 10^{10}$)

An inflationary phase addresses these questions: During inflation, the energy density is dominated by the potential energy of a scalar field which is nearly constant.
The Friedmann equation then becomes

$$H^2 = \left(\frac{\dot R}{R}\right)^2 \simeq \frac{8\pi G}{3} V \simeq \text{constant}, \qquad \dot R = HR.$$

With solution $\qquad R(t) \simeq R_0 \exp(Ht).$

This rapid expansion renders the Universe large and flat.

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?
- Why is the Universe so big and so flat?
- Why is it so old ? ($t_0 \simeq 1.4 \times 10^{10}$years $\simeq 4.4 \times 10^{17}$sec, $t_P \simeq 5.4 \times 10^{-44}$sec)
- Why has it such a high entropy ? (entropy/baryon $\simeq 10^{10}$)

An inflationary phase addresses these questions: During inflation, the energy density is dominated by the potential energy of a scalar field which is nearly constant.
The Friedmann equation then becomes

$$H^2 = \left(\frac{\dot R}{R}\right)^2 \simeq \frac{8\pi G}{3} V \simeq \text{constant}, \qquad \dot R = HR.$$

$$\text{With solution} \qquad R(t) \simeq R_0 \exp(Ht).$$

This rapid expansion renders the Universe large and flat.
The inflationary phase ends when the potential decays and leads to the production of a lot of particles and hence a lot of entropy.

Inflation

Inflation addresses several fundamental problems of cosmology:

- Singularity ?
- Why is the Universe so big and so flat?
- Why is it so old ? ($t_0 \simeq 1.4 \times 10^{10}$years $\simeq 4.4 \times 10^{17}$sec, $t_P \simeq 5.4 \times 10^{-44}$sec)
- Why has it such a high entropy ? (entropy/baryon $\simeq 10^{10}$)

An inflationary phase addresses these questions: During inflation, the energy density is dominated by the potential energy of a scalar field which is nearly constant.
The Friedmann equation then becomes

$$H^2 = \left(\frac{\dot R}{R}\right)^2 \simeq \frac{8\pi G}{3} V \simeq \text{constant}, \qquad \dot R = HR.$$

$$\text{With solution} \qquad R(t) \simeq R_0 \exp(Ht).$$

This rapid expansion renders the Universe large and flat.
The inflationary phase ends when the potential decays and leads to the production of a lot of particles and hence a lot of entropy.

But an inflationary phase has also other consequences...

Fluctuations from inflation

In quantum field theory each particle species (electron, photon, neutrino, etc) corresponds to a field. This field fluctuates and particles are simply excitations of their field (like the sounds of a guitar which correspond to the excitations of its strings).

Fluctuations from inflation

In quantum field theory each particle species (electron, photon, neutrino, etc) corresponds to a field. This field fluctuates and particles are simply excitations of their field (like the sounds of a guitar which correspond to the excitations of its strings).

But a quantum field fluctuates a bit even in vacuum (i.e. in absence of particles).

Fluctuations from inflation

In quantum field theory each particle species (electron, photon, neutrino, etc) corresponds to a field. This field fluctuates and particles are simply excitations of their field (like the sounds of a guitar which correspond to the excitations of its strings).

But a quantum field fluctuates a bit even in vacuum (i.e. in absence of particles).

During an inflationary phase, these quantum fluctuations are excited (enhanced) by the rapid expansion of the Universe when they become larger than the Hubble scale during inflation.

Fluctuations from inflation

In quantum field theory each particle species (electron, photon, neutrino, etc) corresponds to a field. This field fluctuates and particles are simply excitations of their field (like the sounds of a guitar which correspond to the excitations of its strings).

But a quantum field fluctuates a bit even in vacuum (i.e. in absence of particles).

During an inflationary phase, these quantum fluctuations are excited (enhanced) by the rapid expansion of the Universe when they become larger than the Hubble scale during inflation.

After this 'Hubble crossing' they are no longer simple vacuum fluctuations but they have a non-vanishing energy density.

Fluctuations from inflation

In quantum field theory each particle species (electron, photon, neutrino, etc) corresponds to a field. This field fluctuates and particles are simply excitations of their field (like the sounds of a guitar which correspond to the excitations of its strings).

But a quantum field fluctuates a bit even in vacuum (i.e. in absence of particles).

During an inflationary phase, these quantum fluctuations are excited (enhanced) by the rapid expansion of the Universe when they become larger than the Hubble scale during inflation.

After this 'Hubble crossing' they are no longer simple vacuum fluctuations but they have a non-vanishing energy density.

This leads to real fluctuations in the energy density and, via Einstein's equations, in the geometry of the Universe.

Fluctuations from inflation

In quantum field theory each particle species (electron, photon, neutrino, etc) corresponds to a field. This field fluctuates and particles are simply excitations of their field (like the sounds of a guitar which correspond to the excitations of its strings).

But a quantum field fluctuates a bit even in vacuum (i.e. in absence of particles).

During an inflationary phase, these quantum fluctuations are excited (enhanced) by the rapid expansion of the Universe when they become larger than the Hubble scale during inflation.

After this 'Hubble crossing' they are no longer simple vacuum fluctuations but they have a non-vanishing energy density.

This leads to real fluctuations in the energy density and, via Einstein's equations, in the geometry of the Universe.

These fluctuations which can be computed in detail, are the initial fluctuations for the structures observed in the Universe, galaxies, clusters of galaxies, filaments, voids and the anisotropies in the CMB.

Fluctuations from inflation

In quantum field theory each particle species (electron, photon, neutrino, etc) corresponds to a field. This field fluctuates and particles are simply excitations of their field (like the sounds of a guitar which correspond to the excitations of its strings).

But a quantum field fluctuates a bit even in vacuum (i.e. in absence of particles).

During an inflationary phase, these quantum fluctuations are excited (enhanced) by the rapid expansion of the Universe when they become larger than the Hubble scale during inflation.

After this 'Hubble crossing' they are no longer simple vacuum fluctuations but they have a non-vanishing energy density.

This leads to real fluctuations in the energy density and, via Einstein's equations, in the geometry of the Universe.

These fluctuations which can be computed in detail, are the initial fluctuations for the structures observed in the Universe, galaxies, clusters of galaxies, filaments, voids and the anisotropies in the CMB.

The large scale structure of the Universe has been initiated by quantum fluctuations.

Fluctuations from inflation in the CMB

Simple models of inflation predict not only scalar fluctuations (fluctuations of the density) which lead to the formation of large scale structures, but also gravitational waves.

Fluctuations from inflation in the CMB

Simple models of inflation predict not only scalar fluctuations (fluctuations of the density) which lead to the formation of large scale structures, but also gravitational waves.

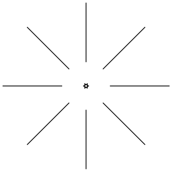
Like scalar fluctuations, gravitational waves generate anisotropies in the CMB. In addition, they generate a slight polarisation of the CMB photons.

Fluctuations from inflation in the CMB

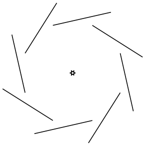
Simple models of inflation predict not only scalar fluctuations (fluctuations of the density) which lead to the formation of large scale structures, but also gravitational waves.

Like scalar fluctuations, gravitational waves generate anisotropies in the CMB. In addition, they generate a slight polarisation of the CMB photons.

Density perturbations (scalars) generate only one type of polarisation (E) while gravitational waves (tensor perturbations) generate also a second type (B).



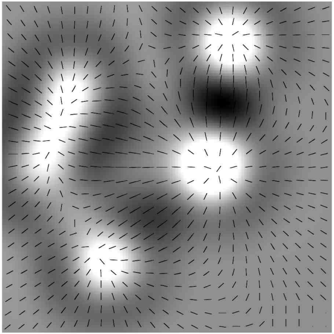
pure E-polarisation (scalars and grav. waves)



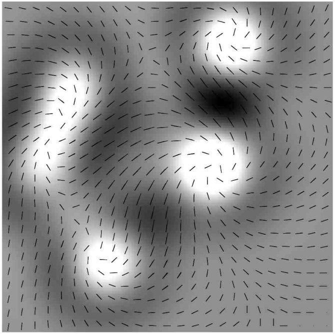
pure B-polarisation (only grav. waves)

Polarisation of the CMB

pure E-polarisation (scalars and grav. waves)

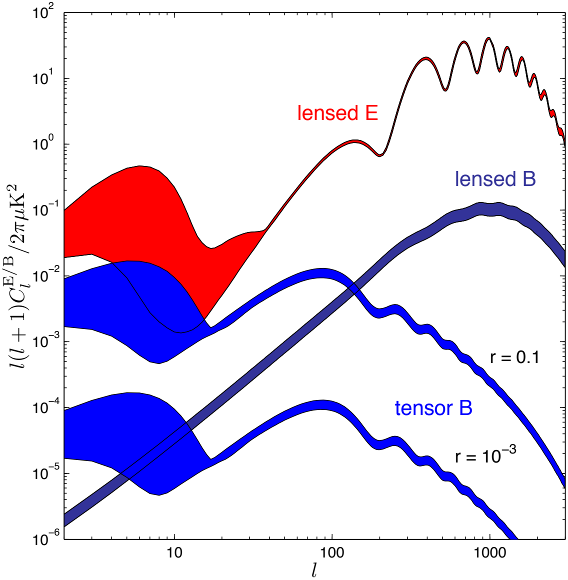


pure B-polarisation (only grav. waves)



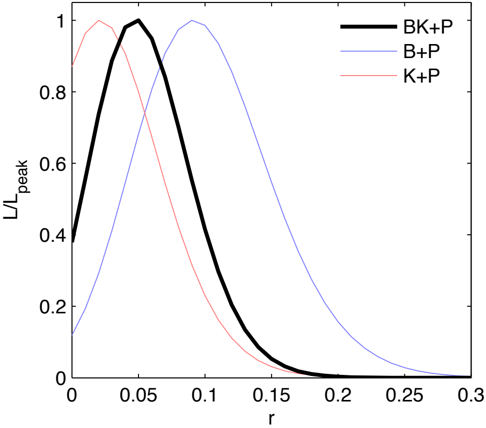
The discovery of B-polarisation is considered the 'holy grail' of inflation. It determines the energy scale of inflation.

B-polarisation in the CMB from tensors & lensing



Challinor & Lewis (2006)

Experimental limits



(Bicep-Keck-Planck, 2015)

Limits on the tensor to scalar ratio $r = A_T/A_S$ from observations.

The significance of detecting tensor fluctuations

- The amplitude of gravitational waves from inflation is proportional to the Hubble scale and hence energy density during inflation.

The significance of detecting tensor fluctuations

- The amplitude of gravitational waves from inflation is proportional to the Hubble scale and hence energy density during inflation.
- The amplitude of tensor fluctuations determines the energy scale of inflation:

$$r = A_T/A_S, \qquad A_S = 2.2 \times 10^{-9}, \qquad A_T = 4H_*^2/(\pi^2 M_P^2).$$

$$E_* = V_*^{1/4} = (r/0.1)^{1/4} 1.8 \times 10^{16}\mathrm{GeV}.$$

The significance of detecting tensor fluctuations

- The amplitude of gravitational waves from inflation is proportional to the Hubble scale and hence energy density during inflation.
- The amplitude of tensor fluctuations determines the energy scale of inflation:

$$r = A_T/A_S, \qquad A_S = 2.2 \times 10^{-9}, \qquad A_T = 4H_*^2/(\pi^2 M_P^2).$$

$$E_* = V_*^{1/4} = (r/0.1)^{1/4} 1.8 \times 10^{16}\text{GeV}.$$

- This is 12 orders of magnitude higher than the energy reached at LHC!

The significance of detecting tensor fluctuations

- The amplitude of gravitational waves from inflation is proportional to the Hubble scale and hence energy density during inflation.
- The amplitude of tensor fluctuations determines the energy scale of inflation:

$$r = A_T/A_S, \qquad A_S = 2.2 \times 10^{-9}, \qquad A_T = 4H_*^2/(\pi^2 M_P^2).$$

$$E_* = V_*^{1/4} = (r/0.1)^{1/4} 1.8 \times 10^{16}\mathrm{GeV}.$$

- This is 12 orders of magnitude higher than the energy reached at LHC!
- A primordial tensor signal in the CMB polarisation would be a signal from this energy scale.

The significance of detecting tensor fluctuations

- The amplitude of gravitational waves from inflation is proportional to the Hubble scale and hence energy density during inflation.
- The amplitude of tensor fluctuations determines the energy scale of inflation:

$$r = A_T/A_S, \qquad A_S = 2.2 \times 10^{-9}, \qquad A_T = 4H_*^2/(\pi^2 M_P^2).$$

$$E_* = V_*^{1/4} = (r/0.1)^{1/4} 1.8 \times 10^{16}\text{GeV}.$$

- This is 12 orders of magnitude higher than the energy reached at LHC!
- A primordial tensor signal in the CMB polarisation would be a signal from this energy scale.
- And we would see a quantum effect of the gravitational field,
  $\Rightarrow$ a 'glimpse' of quantum gravity.

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

- Limits for the neutrino masses and their number of families.

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

- Limits for the neutrino masses and their number of families.
- QCD and electroweak phase transitions.

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

- Limits for the neutrino masses and their number of families.
- QCD and electroweak phase transitions.
- Baryon asymmetry

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

- Limits for the neutrino masses and their number of families.
- QCD and electroweak phase transitions.
- Baryon asymmetry
- Inflation: what particle does the scalar field of inflation correspond to?

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

- Limits for the neutrino masses and their number of families.
- QCD and electroweak phase transitions.
- Baryon asymmetry
- Inflation: what particle does the scalar field of inflation correspond to?
- What is the energy scale of inflation and what can we learn about the physics at this scale?

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

- Limits for the neutrino masses and their number of families.
- QCD and electroweak phase transitions.
- Baryon asymmetry
- Inflation: what particle does the scalar field of inflation correspond to?
- What is the energy scale of inflation and what can we learn about the physics at this scale?
- Are there consequences of superstring theory for cosmology?

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

- Limits for the neutrino masses and their number of families.
- QCD and electroweak phase transitions.
- Baryon asymmetry
- Inflation: what particle does the scalar field of inflation correspond to?
- What is the energy scale of inflation and what can we learn about the physics at this scale?
- Are there consequences of superstring theory for cosmology?
- Can we observe effects of quantum gravity in the CMB?

Conclusions

Cosmological observations contain unique information about the physics at very high energies, beyond the standard model.

- Limits for the neutrino masses and their number of families.
- QCD and electroweak phase transitions.
- Baryon asymmetry
- Inflation: what particle does the scalar field of inflation correspond to?
- What is the energy scale of inflation and what can we learn about the physics at this scale?
- Are there consequences of superstring theory for cosmology?
- Can we observe effects of quantum gravity in the CMB?

Cosmology seems to be one of the most promising directions to give us access to the physics at very high energies, $E \gg 10\text{TeV}$.