Cosmology

A short introduction

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What is cosmology all about?

*Kosmologìa* = study of the world

description of the origin, evolution and eventual fate of the Universe by physical laws
Cosmological Questions:

- What is the Universe made of?
- How does it’s structure look like?
- What is it’s origin?
- Can we reconstruct the history of the Universe?
- Where is the journey taking us?
Contents

- Dimensions of our Universe
- Dynamics of the Universe
- A Journey through Time
- Mysteries of the Universe
Dimensions of our Universe
The Cosmological Principle

“On large scales the Universe is homogeneous and isotropic”

We don’t find ourselves in a special place.

- isotropic, but not homogeneous
- homogeneous, but not isotropic
- homogeneous and isotropic
The Earth: $\approx 13000$ km in diameter
The Solar System:
\[ \approx 10 \text{ billion km in diameter} \]
Our Milky Way:

\[1.4 \times 10^{18} \text{ km} = 150,000 \text{ light years in diameter}\]
Andromeda Galaxy:
2.5 million light years distance
Local Group:
8 million light years in diameter
Virgo Supercluster: $\approx 130$ million light years in diameter
Size of Hubble eXtreme Deep Field on the Sky

Digitized Sky Survey (ground-based image) for comparison
Hubble Extreme Deep Field
Dynamics of the Universe
The Universe is bigger than we thought!

Edwin Hubble (1924) 
Mt. Palomar telescope

Observation of "nebulas" 
Proof of the existence of galaxies outside the Milky Way
Measuring of the Redshift

Spectroscopy in the lab

Emission lines

Wavelength [Å]

B2 1128+31 z=0.178
PKS 1217+02 z=0.240
4C 73.18 z=0.302
B2 1208+32A z=0.389
Cosmological Redshift vs. Doppler Effect

The cosmological redshift is comparable with a redshift caused by a relative movement of source and observer.
Cosmological Redshift

Space itself expands and “stretches” the wavelength of the photons.
Cosmological Redshift
Distance Ladder
Type Ia Supernova

Chandrasekhar limit: 

$M \approx 1.4 M_{\text{sun}}$
Standard Candles and Brightness
Example of a Supernova from 1994

Supernovae can temporarily release as much energy as a whole galaxy!
The Universe is expanding

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

redshift is proportional to the distance of the galaxies (galaxy escape)

Hubble's law: \( v = H_0 \cdot d \)

\( H_0 = 530 \text{ km/s} / \text{Mpc} \)
The present value of the Hubble "constant"

Today: $H = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$
The further we look back into the past, the smaller was the Universe.

Conclusion about the Big Bang
A Journey through Time
Unification of the Forces

age $10^{-36}$ s: strong and electroweak force get separated
HISTORY OF THE UNIVERSE

destruction battle

Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion

High-energy cosmic rays
Inflation
LHC proto

Big Bang

t = 10^−35
E = 10^16 GeV

Possible dark matter relics

t = 10^−10 s
E = 10^2 GeV

t = 10^−3 s
E = 10^2 GeV

t = 10^−3 s
E = 10^5 GeV

t = Time (seconds, years)
E = Energy (GeV)

Key:
- quark
- gluon
- electron
- muon
- tau
- neutrino
- ion
- atom
- photon
- star
- galaxy
- black hole

Particle Data Group, LBNL © 2014
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Nuclear Fusion

fusion in particle collisions

fusion needs high temperatures and high particle densities
Primordial Nucleosynthesis

Comparison of theory (curves) and observation (horizontal lines)

abundances of light elements:

74 % hydrogen
25 % helium
1 % rest
Recombination

- below $T = 3000$ K ($t = 380000$ a) neutral atoms can form
- afterwards photons don’t scatter any more on free electrons

The Universe becomes transparent!
The Cosmic Microwave Background (CMB)

During recombination the photons are in thermic equilibrium with the electrons and atomic nuclei.

Their energy spectrum is the one of a black body ("Planck spectrum")
1964 Penzias und Wilson discovered a noise, which they couldn’t explain.
Satellites for the investigation of the CMB

- COBE
  Cosmic Background Explorer
  1989-1993
  Nobel Prize 2006
  (Smoot & Mather)

- WMAP
  Wilkinson Microwave Anisotropy Probe
  2001-2010

- Planck
  2009-2013
Next problem for the Big Bang theory

The second analysis revealed no sign of any variation at a level of 1 part in 10,000! Where are the galaxies coming from, if not from density fluctuations?
The Echo of the Big Bang
The Echo of the Big Bang

The CMB is extremely isotropic with a temperature of $T_{\text{CMB}} = 2,725$ K. The temperature differences are in the range of microkelvin!

Planck

$-300 \mu K$ $+300 \mu K$
The spectrum of the CMB
Galaxy Distribution

In the past the Universe was much more homogeneous than today:

Each single point is a galaxy!
Geometry of the universe

1°

closed

flat

open

\beta > \alpha

\alpha

\gamma < \alpha
From the map to the spectrum...

- theory is not able to predict the exact position of individual hot or cool spots
- instead: prediction of statistical properties of the temperature map (for example mean value, variance, correlations,...)
The Angular Power Spectrum of the CMB

![Angular Power Spectrum of the CMB](image)

typical size of the hot and cool spots
Theoretical Predictions of the CMB Spectrum

- The theoretical CMB spectrum is depending on values of certain cosmological parameters.
- Comparison with the measured spectrum allows to distinguish between the models and to determine the values of the unknown parameters.
The Standard Cosmological Model

The simplest model, with which the data can be explained (Ockham’s Razor!)

About 95% of the Universe is still unknown...

dark energy?!?! (vacuum energy)
dark matter?!
“normal” matter
Mysteries of the Universe

What is dark matter?
Rotation Curves of Galaxies
Galaxy Cluster CL0024+17
Massive objects curve space-time and therefore distort the light of the objects behind.
Gravitational Lenses

Thereby light arcs of the objects behind are visible.

galaxy cluster Abell 2218
Structure building in the early universe
Future fates of the dark-energy universe

Big Bang

Current universe

Big Crunch

Indefinite expansion

Big Rip
Cosmology of the 21st century

- **Dark Matter**
  What is it made of, what are its properties?
  Or another model (e.g. MOND)?

- **Dark Energy**
  What kind of energy is it? How does it influence the expansion of the Universe?

- **Inflation**
  Can we find experimental confirmation? If yes, what caused it?

- **Matter-Antimatter Asymmetry**
  Where is the tiny surplus of matter coming from, from which everything around us is made of?

- **The Moment of the Big Bang**
  Will we find a unified theory, which describes the beginning of the Universe?

- **The Fate of the Universe...**
Students' conceptions about Cosmology

There are more stars in the Universe than there are grains of sand on earth — and it seems to be equally with students' conceptions.

About this project
Cosmology deals with the origin, development and possible fates of our universe. The insights we have obtained so far have formed the modern scientific worldview. Transferring this to students through science teaching is a frequent request in science literacy discussion.

However, it is not yet clear in science education if students' conceptions about cosmology vary by nationality, and therefore, if it is possible to apply the same teaching modules to students from different countries, who may have diverse social and cultural backgrounds and different curricula.

Information about participation in this project
About the target group:
Our target group are high school students in the age range of about 15-20 years. They shouldn't have had any instruction in cosmology yet. We would like to include students who have currently physics lessons as well as students who do not. Therefore, you are welcome to ask also your colleagues from your own or other schools to take part.

About the questionnaire:
It consists of 20 questions about cosmology and 10 questions about the
Students’ conceptions about cosmology – The questionnaire

[Image of the questionnaire]
Many thanks for your attention!
Are there any questions?