Cosmology

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1.1 What is it about? – Subject of investigation and methods

- Cosmology differs from other areas of physics: The "physical system under investigation" is the "whole world", i.e. the (observable) Universe. There are no apriori limits to the scales to be investigated (time/length scales).
- Therefore: Cosmology is, in its experimental aspects, mainly *observational*. This differs from many other areas of physics, where the "physical system under investigation" can be prepared and manipulated in a lab, and consequently be observed and studied depending on the conditions by which it is manipulated.
- The observational characteristic of cosmology is shared with astronomy and astrophysics which are among the central pillars cosmology relies upon as an experimental science. Cosmology attempts to investigate all of the observable world around us at the largest time- and space scales.

- From around the 1960s onwards, cosmology developed from a theoretical (and in some sense, speculative) science more and more into a science that allows it to compare theoretical predictions with observations at a quantitative level, with ever increasing precision. The main features of theoretical models for cosmology developed beginning in the 1920s...1940s could be observationally verified from the 1960s onwards.

- The observations show compellingly that the observable Universe is not static but evolves significantly over large time scales, in line with the models for cosmology set out from the 1920s and later. That leads to the following basic questions of cosmology:

Basic questions of cosmology

- ⋆ What are the **dynamical laws** (if any) of the evolution of the (observable) Universe?
- ⋆ Is there an **initial** / **final state**?
- ⋆ Can the structure of the Universe as we observe it "today" be deduced from a dynamical law and an initial state? To which extent is the initial state "fixed" by the state of the Universe as observed "today" together with a dynamical law? (And similarly for a final state.)
- ⋆ Can the evolution of the Universe be described, in quantitative agreement with the observations, on the basis of the known, locally tested laws of physics (in particular, fundamental interactions), or is it necessary to consider additional physical laws (interactions)?

A **theory of cosmology** should answer those questions (in quantitative agreement with observations). Thereby, any theory of cosmology must take into account (and be compatible with) the following established **observational facts**:

- $\rightarrow$ Cosmological redshift: The recession velocity between galaxies and galaxy clusters increases with their distance.
- $\rightarrow$ Cosmic Microwave Background **(CMB)**: There is a (nearly perfectly isotropic) microwave radiation, coming in from all directions (not originating from localizable sources) with the spectrum of a black body at absolute temperature $\sim 2.7\,\mathrm{K}$.
- $\rightarrow$ Hydrogen and Helium are by far the most abundant elements in the observable Universe
- $\rightarrow$ The age of the Universe must be higher than 10^{10} years

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- $\rightarrow$ There are small fluctuations in the temperature distribution of the CMB
- $\rightarrow$ Rotation curves of galaxies indicate a non-luminous/transparent mass distribution in and around galaxies (“dark matter”)
- $\rightarrow$ The main two methods of distance determination of very remote galaxy clusters (luminosity / redshift) show a discrepancy which points at another non-luminous/transparent form of mass-energy distribution at large scales (“dark energy”)
- $\rightarrow$ The “local physics” in far away galaxies seems to follow the same laws as on Earth.

  Strictly speaking, this is more an hypothesis than an experimental fact, termed “Copernicanian principle”, but it is consistent with observations. In this sense, the effects related to “dark matter” and “dark energy” are non-local, i.e. not testable at lab scale.

1.2 Literature The present lecture series has originally not been designed as an online course, but out of necessity has been turned into one. Therefore, self-study — i.e. reading the textbook literature, is an important part of the course. There are some excellent textbooks on the subject, and here I list a few.

There are, traditionally, two main roads of approach to cosmology — one that starts from general relativity and emphasizes more the spacetime-geometric aspects of cosmology, and another that has elementary particle physics as its underlying backbone. In fact, cosmology, in particular, early cosmology, is the very place where general relativity and elementary particle physics come in close contact. In the course of the development of cosmology, there have been phases where either the general relativistic or the elementary particle physics perspective have been more dominant. The last 40 years may be seen as an era during which elementary particle physics has had a stronger influence on cosmology. However, that may change with the future development of gravitational wave astronomy.

The different perspectives mentioned are also noticable in the approaches taken in the various textbooks.

It should also be noticed that, due to the rapid development particularly on the observational side in cosmology, textbooks in this area tend to fall out of date fairly quickly. Yet, it seems that during the past 10 years or so, not many new cosmology textbooks have appeared on the market, or have offered substantially new material. That may, however, also be a sign that authors are less inclined to write textbooks nowadays and more up-to-date writings on cosmology appear online as open source material.

After these remarks, on the following pages I list some cosmology textbooks I find useful. The first four are my favorites and have provided inspiration and material for this lecture series — much (but not all) of what is in these notes is taken from those books. They start very much at the beginning but aim at an advanced level, so they go beyond what is covered in these lectures. They are written by theoretical physicists so that is the style to expect. I will provide some comments.

(1) S. Weinberg, *Cosmology*. Oxford University Press, 2008

A very comprehensive textbook. In its initial chapters it also discusses what can be measured and how conclusively (we will touch upon that in the next section) to considerable extent, more than is usally covered in other cosmology textbooks. As Weinberg is really an expert on elementary particle physics, that aspect of cosmology is emphasized very much, with many detailed calculations. For everyone with a profound interest in cosmology, definitely worth reading. As mentioned, the material in the book is more than can be covered in the lectures.

(2) G.F.R. Ellis, R. Maartens, M.A.H. MacCallum, *Relativistic Cosmology*. Cambridge University Press, 2012

Again a comprehensive textbook, written from the spacetime-geometric perspective, with particular strenghts on that side. It is among the very few cosmology textbooks discussing also some non-standard cosmological spacetime models. Very rewarding to read.

(3) V. Mukhanov, *Physical Foundations of Cosmology*. Cambridge University Press, 2005

Also a comprehensive textbook, written from the elementary particle perspective, it aims at taking the readers very quickly at a high theoretical level. Some of the arguments are very lucid but not always easy to grasp for beginners. Recommended in particular for advanced topics where matters are brought to the point in a very efficient manner. A textbook for anyone who has ambitions in theoretical physics.

(4) S. Dodelson, *Modern Cosmology*. Academic Press, 2003

Once again a textbook which starts from basics and aspires to bring the readers up to a high level quickly. There are some very nice and crisp explanations of the fundamentals. One of the aims of the book is (apparently) to train future PhD students in the field of cosmology, so the book contains also some advanced material we won't get anywhere close to in these lectures. A new edition of the textbook, with co-author Fabian Schmidt, has been announced for publication in June 2020.

(5) E.W. Kolb, M.S. Turner *The Early Universe*. Westview Press, 1994
A very influential textbook for more than a decade, written very much from the elementary physics perspective, and strong on that topic, with extensive parts on baryogenesis and nucleosynthesis. Not the most modern textbook anymore but still highly appreciated by many.

(6) N. Vittorio, *Cosmology*. CRC Press, Taylor and Francis, 2018
One of the not so numerous new textbooks on cosmology. Comprehensive in its scope, it contains quite a bit of material on pattern formation in the Universe, apparently more than other textbooks.

The textbooks mentioned previously are comprehensive treatises on cosmology with more material than can be covered in the lectures. Here are two shorter, introductory texts that may serve as an overview — but perhaps not detailed enough for the lectures.

(7) A. Liddle, *Introduction to Modern Cosmology*. 3rd Edition, Wiley, 2015

A nice, very accessible introduction which is pleasant to read. The lastest edition comes with almost 200 pages, so it is not really a "short" introduction anymore, but still much less comprehensive than the books mentioned before that aim at a more advanced and more theoretically sophisticated level.

(8) C.G. Böhmer, *Introduction to General Relativity and Cosmology*. World Scientific, 2016

I have read some appraisals of this book, but I must admit that I haven't seen it myself so far. It appears here maily because of its positive reviews. I hope to have a look at it soon.

Finally, texts with some complementary background material

(9) P. Schneider, *Extragalactic Astronomy and Cosmology: An Introduction*. 2nd Edition, Springer-Verlag, 2014

As the title indicates, this book focuses more on the observational and astronomical underpinnings of cosmology. Particularly the beginning of the book discussing the main observational methods, establishing the "distance ladder", is highly recommended.

(10) S. Carroll, *Spacetime and Geometry*. Pearson, 2003 (New Edition available from Cambridge University Press, 2019)

A very well written and highly appreciated — by students and lecturers alike — contemporary textbook on general relativity, containing also a nice discussion of the standard cosmological spacetime models, and the arguments leading to inflationary cosmology. A very rewarding read, and one of the best textbooks on general relativity for self-study.

Background knowledge in elementary particle physics is important for the processes in early cosmology. Unfortunately, there is no elementary particle physics course on a regular basis at the UL. Here are some suggestions for filling the gap.

(11) F. Close, *Particle Physics: A Very Short Introduction*. Oxford University Press, 2004

Maybe a bit too elementary for MSc students, but short. About the minimal knowledge required.

(12) G. Kane, *Modern Elementary Particle Physics*. 2nd Ed., Cambridge University Press, 2017

With around 200 pages, this is still on the shorter side. Up to date and appealing, it contains also some material related to cosmology.

(13) C.G. Tully, *Elementary Particle Physics in a Nutshell*, Princeton University Press, 2011

Despite the modest title, the book is already at around 300 pages — but comprehensive books on elementary particle physics count easily more than 500 pages. More detailed than the previous entries.

There are several other good sources on cosmology, including online tutorials (lecture manuscripts), videos, computer animations etc. Some will be listed on the webpage, together with some more specialized literature on selected topics.