[146109] Advanced Topics in Theoretical Physics

	General information
Course	PHYSICS
Curriculum	Standard
Course type	Master
Academic year	2023/2024
Training activity type	Supplementary compulsory subjects
CFU	6 CFU
Didactic Activity Type	Lecture
Evaluation	Voto Finale
Teaching period	First semester
Holders	VAGNOZZI SUNNY ,
Teachers	RINALDI MASSIMILIANO ,
Length	48 hours (48 hours Lecture)
Subject area	FIS/02
Location	Polo di collina - Povo A - via Sommarive, 14

Goals

The course will cover the basics of cosmology, with the aim of providing the students with a vision of the evolution, contents, and future of the Universe, which is as modern and complete as possible. Over the past years, thanks to a series of increasingly precise observational data, cosmology has witnessed the birth of the so-called "standard ΛCDM model", which provides a rather complete description of a series of physical processes occurring right from the very first instants in the Universe. The course will provide the students the tools to understand the ΛCDM model, while at the same time pointing out its shortcomings, thus allowing the students to appreciate what are the current research frontiers in cosmology, particularly with regard to studies of the nature of the dark matter and dark energy which make up 95% of the energy of the Universe, as well as of the period of cosmic inflation. Particular attention will be devoted to the study of the evolution of cosmological perturbations (in Newtonian gauge) around the homogeneous and isotropic Universe, as these are an absolutely necessary tool to fully comprehend the observations which have brought to the birth of the ΛCDM model, such as measurements of the Cosmic Microwave Background and of the large-scale structure. Students who have completed the course will have a broad and coherent view of the history of the Universe, will be able to solve simple cosmological problems, will understand the observations which brought to the development of the ΛCDM model as well as the shortcomings of the latter, will possess the tools necessary to apply the acquired knowledge to real cosmological data, and those who wish to do so will be ready to explore in more detail the current research frontiers.

Required skills

From the point of view of physics knowledge, the student must be familiar with Special Relativity, particularly with regard to the manipulation of 4-vectors. Familiarity with General Relativity, and particularly with tensor calculus, are useful but not essential, as the first hours of the course will provide a review thereof. Familiarity with the tools of QFT (particularly the derivation of the equations of motion from a given Lagrangian, as well as the properties of scalar fields) is required especially for what concerns the part of the course covering cosmic inflation. From the mathematical point of view, familiarity with ordinary and partial differential equations up to second order is helpful. Finally, a good dose of physical intuition can be particularly helpful.

Subjects

0. Introduction to modern cosmology, preview of the contents of the rest of the course, particularly with regards to the expansion of the Universe, the concept of redshift, Hubble's law, cosmic inflation, dark matter and dark energy, the ΛCDM model and the observations which have brought to the development of the latter.

1. Brief review of General Relativity

2. The homogeneous, isotropic, and equilibrium Universe; the cosmological principle; Friedmann-Lemaitre-Robertson-Walker, Einstein and de Sitter models; energy conditions; first and second Friedmann equations, and solutions to the latter in the presence of fluid models with different equations of state; distances in an expanding Universe

3. Out of equilibrium processes in the Universe; introduction to the Boltzmann equations; applications to Big Bang Nucleosynthesis and thus to the production of light elements, to recombination and thus to the formation of Hydrogen atoms, and to freeze-out production of dark matter.

4. Boltzmann equations, with an example application to the harmonic oscillator; "collisionless" Boltzmann equations; collision term for Compton scattering; derivation of the Boltzmann equations for photons, dark matter, and visible matter ("baryons").

5. Perturbed Einstein equations; brief discussion of gauge transformations and the decomposition theorem.

6. Initial conditions for the evolution of perturbations; horizon and flatness problems;

7. Evolution of cosmological perturbations on large and small scales; matter power spectrum; extension to other tracers of the cosmic web (e.g. galaxies)

8. Anisotropies and their evolution; anisotropy spectrum of the Cosmic Microwave Background (CMB); cosmological parameter determination from the CMB.

9. ΛCDM model; observations which have brought to the development of the latter; shortcomings of the ΛCDM model.

10. Time allowing, other topics we can cover include: weak lensing; CMB polarization; statistical methods for the analysis of cosmological data; concrete models of dark matter and dark energy; big open problems in cosmology, among which the so-called "Hubble tension".

Teaching methods

The course lasts 48 hours (corresponding to 6 CFU), distributed in blocks of two hours twice a week. Lectures will be at the blackboard, with the help of slides where needed. Some of the mathematically more complex derivations will be deliberately left open (only quoting the final results), and it is recommended that the student complete the derivations which have been left open, in such a way as to gain more familiarity with the technical tools of the subject.

Verification of learning

The exam will be oral and will be concerned with the material covered in class. The questions will be quite general, so as to allow broad discussions, which will be evaluated both with regards to content and clarity of the presentation.

Books

Reference textbook:

S. Dodelson, “Modern Cosmology”, Academic Press (2003, second edition 2020 - both are equally fine)

Other texts/useful notes:

D. Baumann, Part III Mathematical Tripos Cosmology notes (available on various websites online, e.g. cmb.wintherscoming.no/pdfs/baumann.pdf)

O. F. Piattella, Lecture Notes in Cosmology, arxiv:1803.00070

Advanced textbooks:

D. Baumann, “Cosmology”, Cambridge University Press (2021)

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

Extra info

No additional information.