

Physics of the Universe 2014-15

Course Outline

The lectures will cover both Particle Physics (PP, 12 lectures, first part) and Cosmology and Astroparticle Physics (CAP, 12 lectures, second part).

Overview

Particle Physics and Cosmology have provided humankind a deeper understanding of the structure of matter and of the properties of the Universe on the very largest observable scales. This has had a profound effect on our everyday life, and on our understanding of our place in the cosmos. This introductory course will try to provide the basics for this understanding and the remaining challenges.

The Particle Physics (PP) part of this course will provide the link between the first general introduction to PP, taught in 2nd year, and the 4th year option course Advanced PP.

In the first block of PP (~ 4 lectures) we will revise the material of the 2nd year course by first reviewing the general concepts and the four fundamental forces, or interactions, in Nature. Then we will focus on the Standard Model of particle physics, comprising quantum theories of three of the four fundamental interactions, its theoretical framework as well as on its general properties. The second block of PP (~ 4 lectures) will expand on the details of the interactions described by the Standard Model of particle physics, with a special emphasis on how these can be measured in experiments.

In the last PP block (~4 lectures) we will discuss the discovery of a Higgs boson at the Large Hadron Collider at CERN in 2012 and how this discovery completes the particle content of Standard Model. We will also study some of the shortcomings of the Standard Model, including its lack of explanation of the origin of dark matter, and the hierarchy problem.

In the Cosmology and Astroparticle Physics (CAP) part, we will focus on how our understanding of the Universe on the largest scales has evolved in the last 100 years. Starting from the basic principles of an expanding Universe, we will review the observational evidence for such an expansion. We will introduce some fundamental observable quantities and discuss how they related with the underlying quantities describing the cosmos (the so-called cosmological parameters).

We will then study one of the cornerstones of modern cosmology, the cosmic microwave background, and sketch how it can be used to learn about many properties of the Universe. The initial, inflationary period of expansion will be discussed, and observational evidence for inflation presented.

The two biggest mysteries of modern cosmology will be presented next: dark matter and dark energy. A review of the observational data will be presented, and possible models for the two dark components introduced.

In the last two lectures of CAP we will study the burgeoning astroparticle astronomy, where messengers from the Universe are particles of various kinds: dark matter, neutrinos and cosmic rays.

In Term 3 there will be one revision lecture including both parts.

Practicalities

Books

Particle Physics

- a) Williams, Nuclear and Particle Physics effectively covers the whole course.
- b) Das and Ferbel, Introduction to Nuclear and Particle Physics, a more recent book, is a possible, but less tested, alternative.
- c) For books individually on particle physics or nuclear physics, the following are approximately at (or slightly above) the right level
 - i) Martin and Shaw, Particle Physics,
 - d) There are several other good books slightly above the level of this course, for example, Perkins, Introduction to High Energy Physics, Krane, Introductory Nuclear Physics

Cosmology and Astroparticle Physics

- a) M.H. Jones and R.J.A. Lambourne (eds), *An introduction to galaxies and cosmology*, CUP & The Open University (2004). Chapters 5 and ff.
- b) A.R. Liddle, *An Introduction to Modern Cosmology*, Wiley (2003). Chapters 1-13
- c) B. Ryden, *An introduction to Cosmology*, Addison Wesley (2002). Chapters 2, 7, 8, 9, 10, 11,12
- d) P. Schneider, *Extragalactic Astronomy and Cosmology: An Introduction*, Springer (2006). Chapters 4, 8

More advanced, complementary material (non-examinable):

- e) S. Dodelson, *Modern Cosmology*, Academic Press (2003). Chapters 1, 2, 8
- f) J.A. Peacock, *Cosmological Physics*, CUP (1999). Chapters 3, 5, 11, 12, 13

Contact Details

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Office Hours

Dr. O. Buchmueller (Part 1, Particle Physics):

Office hours will be announced at the beginning of the Particle Physics part.

Dr R. Trotta (Part 2, Cosmology and Astroparticle Physics):

Office hours will be announced at the beginning of the CAP part.

Course Material

The course material of the PP part will consist of complementary notes and slides. The complementary note will appear on Blackboard a few days **before** the lectures. The slides will be provided on Blackboard **after** the lecture.

- Complementary notes and slides match in general content but can differ in details depending on the emphasis of the lecture.
- Complementary notes are an excellent preparation for the lecture and reading them before the lecture will allow you to better follow the lecture!
- Complementary notes can overlap in content with some of the handouts provided in the 2nd year PP course. This overlap is intentional and mainly occurs during the revision part of the PP lecture (part 1 – see above)

The course material of the CAP part will consist of lecture notes and slides matching what has been presented during the lectures. They will be posted on Blackboard immediately after the lectures.

Problem Sheets

There will be a set of problems handed out approximately every two weeks. These form an integral part of the course; there is not enough time in lectures to go through the details of all of the topics, so the problem sheets will fill in the gaps. It will be very hard to pass the exam without having done the problems. The problem sheets will have a range of questions, including examples of possible exam questions.

Course Outline

Part 1: Particle Physics (12 lectures)

- **Course Overview (1 Lecture):** Overview of lectures, office hours, books. Introduction to nuclear and particle physics. Units.
- **The Basics (~3 Lectures):** Fundamental forces and relativistic quantum mechanics. Decay rates, cross sections. Relativistic particles, energy and momentum conservation. Feynman diagrams.
- **The Forces in the SM (~4 Lectures):** Electrons, photons, Quarks, Gluons and Feynman diagrams. Self-interactions and two consequences; “confinement” and “asymptotic freedom”. Colourless hadrons as bound states of quarks; baryons, mesons, multiplets. C and P violation, CP violation. Massive W, Z force bosons and Feynman diagrams, left handed coupling, Electroweak Unification and the Higgs Mechanism.
- **Physics at Colliders (~4 Lectures):** The LHC and its experiments, how particle physics detectors function especially at colliders, Experimental verification of the predictions of the Standard Model. A special focus will be given to the discovery of a Higgs Boson at the LHC and how this fits into our current understanding of particle physics.

Part 2: Cosmology and Astroparticle Physics (12 lectures)

- **The Friedman-Robertson-Walker (FRW) model (1 lecture):** Expansion of the Universe, FRW metric, Hubble's law (observational). Newtonian dynamics. Cosmological parameters. Redshift. Look-back time. Recession velocities.
- **The Observable Universe (1 lecture):** Luminosity distance, angular diameter distance, growth factor, number counts.
- **The Early Universe (1 lecture):** Inflation (horizon problem; curvature problem; magnetic monopoles, gravitational waves). Baryogenesis. Big Bang Nucleosynthesis.
- **The Cosmic Microwave Background (2 lectures):** temperature and polarization anisotropies, angular scale in the power spectrum, determination of the curvature of the Universe, initial conditions. SZ effect.
- **Galaxy Distribution (1 lecture):** growth of structures, statistical properties (power spectrum), comparison with observations, Baryonic Acoustic Oscillations.
- **Dark Matter (2 lectures):** Observational evidence (weak/strong lensing; bullet cluster; BBN; flat rotation curves, virial theorem). Candidates: WIMPs miracle, cold dark matter vs hot/warm dark matter, non-WIMPs (axions, gravitinos).
- **Dark Energy (2 lectures):** Observational evidence (supernova type Ia, microwave background, Integrated Sachs-Wolfe effect), cosmological constant fine-tuning problem, anthropic solution, quintessence.
- **Astroparticle physics (2 lectures):** solar neutrinos, cosmic neutrino background, high-energy neutrinos, cosmic rays (origins, propagation, abundance), GZK cut-off for ultra-high energy cosmic rays.