Cosmology I

University of Trieste, master degree program in Physics

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Detailed program

Part 1: Black holes

1. **Introduction, Einstein equations:** introduction to the course. Einstein equations; conserved quantities in the motion of a free-falling particle. **Sources:** slides, Schutz: Chap. 7 and 8.

2. **Schwartzschild metric:** metric in spherical symmetry; solving Einstein's equations in spherical symmetry; Schwartzschild metric; Schwartzschild radius and Laplace argument; motion of a massive particle around a black hole. **Source:** Schutz, Chap. 10 and 11, Carroll, pag. 201-204.

3. **The event horizon:** time needed to cross the event horizon; future light cones; gravitational redshift. **Source:** Schutz, Chap. 11.

4. **Photon capture radius:** Motion of a massless particle around a black hole; photon capture radius; interpretation of M87* and SgrA* imaging. **Sources:** Schutz, Chap. 11, lecture notes.

Part 2: Friedmann-Robertson-Walker models

5. **Introduction to FLRW models:** the birth of cosmology; the cosmological principle; the cosmic distance ladder; the Hubble diagram with nearby and distant SNe; galaxies as tracers of the large-scale structure of the Universe; cosmological probes. **Sources:** Slides; Introduzione all'astrofisica, Chap. 5 and 6.

6. **Friedmann-Lemaitre-Robertson-Walker metric:** metric for a homogeneous and isotropic Universe; space part of the metric; flat, open and closed universes; length of a circle, area of spherical surface, volume. **Sources:** Schutz, Chap. 12, pag. 341-345; Vittorio, Chapter 1; Carroll, Chap. 8.

7. **The Hubble law:** cosmological redshift; proper distance; comoving distance; Hubble parameter; luminosity distance; diameter distance; Hubble law; superluminal motion; deceleration parameter. **Sources:** Schutz, Chap. 12, pag. 345-351; Vittorio, Chapter 2.

8. **Friedmann equations from Einstein equations:** from the metric to the Ricci tensor; 00 component: first Friedmann equation; space components: second Friedmann equation; continuity equation: third Friedmann equation. **Sources:** Vittorio, Chapter 1; Carroll, Chap. 8.

9. **Friedmann equations, Einstein-de Sitter model:** critical density and density parameters; solution of Friedmann equations for dust in a flat universe; Hubble parameter, deceleration parameter, density versus time, distances; age of the universe. **Source:** Vittorio, Chap. 2.

10. **Horizons:** particle horizon; speed of light sphere and Hubble horizon; past light cone in proper coordinates; conformal time, conformal diagrams and their interpretation. **Source:** Ellis & Rothman.

11. **Flat and non-flat models:** generic equation of state; solutions for a flat model; the radiation case; curved models; solutions for matter-dominated models; evolution of the density parameter. **Source:** Vittorio, Chaps. 1 and 2.

12. **Models with Λ:** Friedmann equations with a cosmological constant; flat models with Λ; Einstein's static universe; models with Λ and matter; age of the universe; observational evidence for acceleration; models in the $\Omega_m - \Omega_\Lambda$ plane. **Source:** Vittorio, Chaps. 1 and 2.

13. **Second test**.

Part 3: The early universe

14. **Introduction to the early Universe:** the Cosmic Microwave Background; evolution of temperature, recombination; the CMB dipole; temperature fluctuations; parameters of the ΛCDM model; matter-radiation equivalence; matter-dark energy equivalence; thermal history of the Universe; phase transitions; the horizon problem; big bang nucleosynthesis. **Sources:** slides; Introduzione all'astrofisica, Chap. 5; Vittorio, Chap. 3; Bonometto, Chap. V.

15. **Thermodynamics of the early Universe:** statistics of ultra-relativistic species; evolution of entropy and entropy density; entropy per baryon and η. **Source:** Bonometto, Chap. IV, appendices IV.A1 and IV.A2; Vittorio, Chap. 3.

16. **Planck time and phase transitions:** the Planck era; natural units; from the Planck era to the GUT breaking; phase transitions in the early Universe; entropy production during phase transitions. **Source:** Vittorio, Chap. 4; Bonometto, Chap. III.9, Chap. XI.

17. **Problems of the hot big bang:** the monopole problem; the horizon problem; the flatness problem; cosmological horizons; definition of inflation; kinematics of inflation. **Source:** Vittorio, Chap. 4.

18. **Inflation:** inflation with conformal diagrams; expansion History of the Universe with a de Sitter inflation; solution of the horizon problem; dilution, solution of the flatness problem; minimum number of e-folds. **Source:** Vittorio, Chap. 4.

19. **Quantum fields in an expanding Universe:** quantum fields in an FLRW universe; dynamics of a quantum scalar field; effective pressure and vacuum energy; cosmological constant as a vacuum energy. **Source:** Vittorio, Chap. 4.

20. **Thermal history of the early Universe:** baryogenesis; phase transitions and quark-hadron transition; the lepton era; neutrino decoupling and freezing of neutron to proton ratio; electron-positron annihilation and temperature of the neutrino background. **Source:** Bonometto, Chap. VI; Vittorio, Chap. 3.

21. **Big bang nucleosynthesis:** motivation for BBN; the deuterium bottleneck; Saha equation for the deuterium abundance in equilibrium; reactions chain; nucleosynthesis and comparison with observations; dependence of ^{4}He abundance on the number of neutrino families. **Source:** Bonometto, Chap. VI; Vittorio, Chap. 3.

22. **Recombination:** coupling of baryons and radiation; evolution of temperature for the coupled plasma; recombination; evolution of the CMB spectrum; evolution of matter temperature after recombination, with no ionization and in presence of residual ionization. **Source:** Vittorio, Chap. 3; Bonometto, Chapter VIII.4, VIII.5 and VIII.A1.

23. **Third test**.

24. **Precision cosmology:** a final discussion on hot topics in modern cosmology. **Sources:** slides.

Web site: `https://adlibitum.oats.inaf.it/monaco/cosmology1.html`

Textbooks:

- A FIRST COURSE IN GENERAL RELATIVITY, 2nd edition, Bernard F. Schutz, Cambridge University Press
- COSMOLOGY, Nicola Vittorio, CRC Press
- COSMOLOGIA & COSMOLOGIE, S. Bonometto, Zanichelli (in italian)
- SPACETIME AND GEOMETRY: AN INTRODUCTION TO GENERAL RELATIVITY, Sean M. Carroll, Pearsons
- INTRODUZIONE ALL'ASTROFISICA, P. Monaco, Aracne (in italian)

More material (available on the web page):

- Ellis, G.F.R. & Rothman, T., *Lost horizons*, 1993, American Journal of Physics, 61, 883
- Bean, R., *TASI 2009 - Lectures on cosmic acceleration*, 2010, arXiv:1003.4468