Program of the Astroparticle Physics course
A.A. 2019/2020
(Prof. P. Belli)
(6 CFU)

Brief **historical overview** of fundamental interactions between particles, quantum mechanics, waves and particles, relativity, relativistic quantum field theories, fundamental fields, conservation laws, symmetries and Outline of the Standard Model of elementary particles. Historical references.

Interactions of charged particles with the matter; radiation-matter interactions; cross sections; range; mean free path; cross section p-p. Nuclei fragmentation.

Formation of nuclei in the Universe; theoretical explanation of the cosmic rays abundances. **Primordial nucleosynthesis**. Short history of the early Universe. The n/p ratio. The first 200 s (three minutes). Light elements abundances and ^{7}Li problem. The formation of nuclei heavier than A=7. Nucleosynthesis in the stars. Thermonuclear fusion processes. Evolution of a star. Fusion cross sections; S-factor; Gamow factor and peak. The fusion reactions in the Sun. Subsequent stages of a star. The triple alpha process. The s-, r-, and p- processes. The last stages of a star. Degenerate stars. The Chandrasekhar mass. White dwarfs. Supernovae (SN) and their classification. Neutron stars. Pulsars. Black holes.

Phenomenology of **Cosmic Rays**. Historical point of view. The role of the cosmic rays in the birth of physics of the elementary particles. The energy spectrum of primary cosmic rays; composition; knee and ankle in the spectrum; the spectral power laws; galactic and extragalactic origin. Secondary cosmic rays.

Methods of measurements of cosmic rays. The isotropy. Galactic magnetic field. Effect of Sun shield. Low energy CR. Solar modulation; solar wind; heliopause. Earth magnetic field; trajectory in geomagnetic field; trapped particles; Van Allen radiation belts; East-West effect;

Propagation of cosmic rays. Diffusion-loss equation. The leaky box model. Confinement of cosmic rays in the Galaxy. Abundances in CR and in the solar system; production of Li, Be, B in CR. Dependence of the B/C ratio with energy. Cosmic ray spectrum at the sources. The cosmic ray clock.

Production and acceleration mechanisms of cosmic rays. The Fermi mechanisms (1st and 2nd order). Electromotive acceleration and magnetic mirrors. SN and SN remnants as sources of cosmic rays below the knee. Maximum energy of CR from SN. Other more energetic CR sources; pulsars, AGN, Hillas plot. Radio-galaxies, neutron stars, magnetars, accretion disks, gamma ray bursts (GRB), top-down models.

Experiments for direct detection of cosmic rays. Particles identification. Experiments on balloon; some examples. Experiments in the space; some examples.

Experiments for detection of cosmic rays by extensive air shower (EAS). UHECR. Features of the shower; longitudinal and lateral distributions. Shower detectors at ground. Detection of fluorescence and Cerenkov light of the shower. **Cerenkov Telescopes**. Experiments of UHECR; some examples.

Chemical composition of CR in the region of EAS. **Propagation of UHECR**; possible extragalactic origin; **anisotropy of UHECR**. **GZK cut-off**.

Electrons and positrons in the cosmic rays. Diffusion halo model and processes of various interactions in the interstellar medium; synchrotron radiation; bremsstrahlung; inverse Compton diffusion. Energy spectra and their ratio. Nearby potential sources of electrons and positrons. Experimental measurements; some examples.

Gamma astronomy. Experimental situation. Sources of gamma's. Observation of diffuse gamma ray from galactic plane. Emission models of astrophysical gammas; the hadronic model; the leptonic model. Study of known gamma sources at different wavelength. GRB. Gamma astronomy with Cerenkov telescopes.

Neutrino Physics and neutrino astronomy. Astrophysical and terrestrial, natural and home-made sources of neutrinos. Overview of neutrino history. Neutrino interactions; neutrino oscillations in vacuum and in matter (MSW effect). Majorana neutrinos. **Solar neutrinos.** Production of neutrinos in the Sun. Detection schemes. Experiments and interpretation. Confirmation of oscillation parameters from long-baseline reactor antineutrinos. **Atmospheric neutrinos**. Detection methods and experimental results. Confirmation of oscillation parameters from long-baseline accelerator experiments. Disappearance of ν_μ; appearance of ν_τ. PMNS mixing neutrino matrix. Measurement of θ_{13} and CP violation phase. Sterile neutrinos. **Geoneutrinos** and their detection. **Supernovae neutrinos**. SN1987A and detection of SN neutrinos. Perspectives and estimates. First detection of **high energy (extragalactic) neutrinos**. Anisotropy and power law. **Relic cosmological neutrinos** and estimates on neutrino masses. Measurements of neutrino masses from the end-point of β decay. Neutrino masses and Majorana neutrino in 2β decay experiments; Schechter-Valle theorem; expectations. 2β decay experiments, a classification and description of the experimental method. Some examples of techniques, experiments and results.

The **Dark Universe**. Astrophysical evidences of Dark Matter (DM). Rotational curves of spiral galaxies; cluster of galaxies; the bullet cluster. The standard Big Bang model. Overview of **Cosmology**. The Friedmann equations. The geometry of the Universe. The basis of the Big Bang model. The cosmic microwave background (CMB); the anisotropy of CMB; information on the geometry of the Universe; the Ω budget. The expansion of the Universe (Hubble law); Sn type IA as standard candles; the expansion is accelerating; dark energy. Gravitational probes. Nucleosynthesis. The abundance of light elements. The Baryonic acoustic oscillations (BAO). Concordance ΛCDM model. Hot, Warm and Cold non-baryonic dark matter. Hot DM and neutrinos. Dark Matter candidates. Decoupling of DM particles in the early Universe. Relic cold DM. Axions and axion searches. Strategies for DM detection. Indirect detection. Overview of experimental techniques. The direct detection. Processes of direct detection. The cases of elastic and inelastic interactions on nuclei. Halo models, parameters. Expected signals. Uncertainties in the evaluation. Arguments related to the experimental procedures. Low-background techniques. The model independent signature. Classification of the different experimental efforts. Status, experimental signals and perspectives.

Gravitational waves. Overview of the GW and detection techniques. Phenomenology and recent results from interferometry. Follow up of NS-NS coalescence.

Multi-messenger astronomy. High-energy neutrinos and gamma-rays from AGN. Cosmic ray, gamma-ray and neutrino background interdependences. Examples of recent cosmic multi-messenger advances.

Recommended readings.

- M. Spurio, *Particles and Astrophysics, a multi-messenger approach*. Springer. DOI 10.1007/978-3-319-08051-2
- D. Perkins, *Particle Astrophysics*. Oxford Master series in Particle Physics.
- J. Rich, *Fundamentals of Cosmology*. Springer. DOI 10.1007/978-3-642-02800-7
- J.L. Basdevant, J. Rich, M. Spiro, *Fundamentals in Nuclear Physics*. Springer. ISBN 0-387-01672-4
- M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update.
- C. Grupen, *Astroparticle Physics*. Springer.
- S. Bilenky, *Introduction to the Physics of Massive and Mixed Neutrinos.* Springer DOI 10.1007/978-3-319-74802-3
- P. Blasi, *Acceleration of galactic cosmic rays*. Riv. Nuovo Cim. 42 (2019) 549.
- U. Sarkar, *Particle and Astroparticle Physics*. Taylor and Francis. ISBN-13: 978-1-58488-931-1
- K. Zuber, *Neutrino Physics*. CRC press. ISBN: 978-1-138-71889-0
- P.K.F. Grieder, *Cosmic Rays at Earth*. Elsevier.
- bibliography mentioned during lectures
- other references will be given upon request