Master 2 NPAC
Plan of the lectures on Neutrino and Dark Matter physics

Lecturers: Davide Franco, APC, CNRS
Asmaa Abada, LPT, Paris-Sud, Paris Saclay U.
Véronique Van Elewyck, APC, Université Paris 7

The lectures will tackle both experimental and theoretical aspects of modern neutrino physics, giving an overview of the most salient developments of the last decade. The proximity of the experimental techniques adopted in underground neutrino physics and direct dark matter detection offers the additional opportunity to discuss the latest developments in the field of dark matter.

The theoretical part covers the history of neutrino physics, which is strongly linked to the one of the Standard Model. The theory part spreads from Fermi Theory to Beyond Standard ones (BSM). The oscillation phenomena will be addressed with a discussion of the matter effect. The topics discussed in these lectures include general properties of neutrinos, their nature (Dirac or Majorana), their absolute mass scale, the violation of lepton number, and the potential of the lepton CP violating phases with their main signatures. An important part will be devoted to the origin of neutrino masses and their mixings, in link with BSM physics. In particular the different seesaw mechanisms will be addressed with their phenomenological consequences. A strong emphasis on the sterile neutrino hypothesis and all relevant implications and constraints (cosmological and phenomenological), depending on their mass regimes will close the theory part.

The experimental part will start with a historical discussion of the different processes and experiments that led to the discovery of neutrinos, and then to the study of their fundamental properties and interactions. An important part of the lectures is devoted to review neutrino oscillation results, with an emphasis on the variety of experimental approaches that have been used (solar and atmospheric neutrino detectors, reactor neutrinos and neutrino beams). The measurement of the neutrino masses is also addressed. Current challenges in neutrino physics will be discussed in the context of the next generation of neutrino experiments. Finally, the role of neutrinos in multi-messenger astronomy will be presented along with a presentation of the main astrophysical neutrino sources.

The dark matter part will first overview the evidences of the existence of dark matter through cosmological and astrophysical indirect observations. We briefly review the dark matter particle candidates, then focus on the Weakly Interacting Massive Particle (WIMP) and on the estimation of its flux. An important section will be dedicated to the experimental techniques, emphasizing the connections with background challenges already discussed in the experimental neutrino part. The next generation of experiments will be sufficiently sensitive to detect solar and atmospheric neutrino interactions via coherent scattering off nucleus, an irreducible background for WIPMs, but also a new window for observing neutrinos. We conclude with an outlook on the future of dark matter searches, on the envisaged techniques for discriminating neutrinos, and on the possibility to build giant observatories for both neutrinos and dark matter.

Lecture 1: The history of neutrinos – theoretical aspects (A. Abada)
Monday February 24th 9h – 12h, room "salle des conseils" (IJCLAB)
Building 210–code 26357-, Ex-Laboratoire de Physique Théorique, Orsay Campus)
- Pauli's hypothesis and Fermi Effective Theory
- Unexpected observations and interpretation
- Oscillation phenomena (in vacuum and in matter) (plane wave and wave packet derivation)
- Parameterization of the leptonic mixing matrix
- CP violation in the leptonic sector
- What is the absolute neutrino mass scale?|
- Theoretical aspects of beta and neutrino(-less) double beta decays
- Cosmological constraints on neutrinos

Lecture 2: Neutrino mass generation (A. Abada)
Tuesday February 25th 9h – 12h30, room "salle des conseils" (IJCLAB)
Building 210–code 26357-, Ex-Laboratoire de Physique Théorique, Orsay Campus)

- Neutrinos in the Standard Model (chiral and family structure of the weak interaction)
- Dirac and Majorana description of massive neutrinos
- Neutrino masses and Physics Beyond the Standard Model
- Different mechanisms of neutrino mass generation
- Neutrino mass generation at tree-level and basic seesaw mechanisms
- How to disentangle among the different possibilities
- Effective approach

Lecture 3: The history of neutrinos – experimental aspects (V. Van Elewyck)
Wednesday February 26th 9h – 13h, room 351A (APC, Condorcet Building)
- Early experiments and historical context
- The discovery of the (anti)neutrino
- Direct measurement of neutrino helicity
- Muon and tau neutrinos, number of families
- Neutrino scattering studies
- Solar neutrino experiments and solving the "solar neutrino problem"
- Discovery of oscillations in the atmospheric sector

Lecture 4: The sterile fermion (right-handed neutrino) hypothesis (A. Abada)
Thursday February 27h 9h – 12h30, room "salle des conseils" (IJCLAB)
Building 210–code 26357-, Ex-Laboratoire de Physique Théorique, Orsay Campus)
- The type I seesaw mechanism at different mass scales
- Consequences of the existence of right-handed neutrinos on the leptonic mixing matrix
- How to probe the existence of right-handed neutrinos
- Role of sterile fermions in cosmology

Lecture 5: Neutrino oscillation experiments (3h30, V. Van Elewyck)
Friday February 28th 9h – 13h, room 437A (APC, Condorcet Building)
- Reactor neutrinos and the quest for θ_{13}
- Neutrino beams and precision oscillation experiments
- Current challenges: neutrino mass hierarchy and leptonic CP violation
- Experimental "anomalies": a sterile neutrino ?
- Perspectives for future experiments

Lecture 6: The neutrino mass and nature; neutrino astronomy (V. Van Elewyck)
Monday March 2nd 9h – 12h, room 437A (APC, Condorcet Building)

- The neutrino mass: direct and indirect experimental searches (single beta decay, neutrinoless double beta decay, constraints from cosmology)
- Neutrinos and geophysics
- Neutrino astronomy: motivations and link with other cosmic messengers
- Supernovae neutrinos: observation of SN1987a and future perspectives
- High energy astrophysical neutrinos: sources, first detections and perspectives
- GZK neutrinos

Lecture 7: Evidences of dark matter and particle candidates (D. Franco)
Tuesday March 3rd, 9h-12h30, room 437A (APC, Condorcet Building)

- Indirect evidences of dark matter
- Candidate dark matter particles
- WIMP interaction rates

Lecture 8: Experimental techniques in dark matter searches (D. Franco)
Wednesday March 4th, 9h-12h30, room 351A (APC, Condorcet Building)

- Experimental detection techniques
- Background sources
- Techniques of background rejection

Lecture 9: Experimental techniques in dark matter searches (D. Franco)
Thursday March 5th, 9h-12h30, room 437A (APC, Condorcet Building)

- Sensitivities
- Additional dark matter signatures (directionality, annual modulations)
- Neutrino background
- Future detectors

References:

BOOKS

- R. N. Mohapatra and P. B. Pal, “Massive neutrinos in Physics and Astrophysics”, World Scientific (3d edition, 2004)
- C. Giunti and C. W. Kim, "Fundamentals of Neutrino Physics and Astrophysics", Oxford University Press (2007)
- K. Zuber, "Neutrino Physics", CRC Press (2d edition, 2012)
- A. Kouchner and S. Lavignac, « A la recherche des neutrinos », éd. Dunod, Coll. Quai des Sciences (in French)

REVIEWS

- A. Abada, *et al.*, "Low energy effects of neutrino masses", JHEP 0712 (2007) 061, https://arxiv.org/pdf/0707.4058.pdf
- C. Giganti, S. Lavignac and M. Zito, "Neutrino oscillations: the rise of the PMNS paradigm", Prog. Part. Nucl. Phys. 98 (2018) 1, https://arxiv.org/pdf/1710.00715.pdf
- Particle Data Group Reviews: http://pdg.lbl.gov/2018/reviews/contents_sports.html
    - → K. Nakamura & S. T. Petcov, "Review on Neutrino mass, mixing and oscillations"
    - → various authors, "Particle detectors for non-accelerator physics"
    - → Particle properties – Neutrinos (several reviews)
- M. C. Gonzalez-Garcia and M. Maltoni, "Phenomenology with massive neutrinos", http://arxiv.org/pdf/0704.1800.pdf
- T. Marrodan Undagoitia and L. Rauch, "Dark matter direct-detection experiments", J. Phys. G43 (2016) no.1, 013001, https://arxiv.org/abs/1509.08767

WEBSITES

- *Neutrino Unbound*, http://www.nu.to.infn.it/
- *History of the Neutrino*, https://neutrino-history.in2p3.fr/