Contribution Prospectives 2020

Neutrino physics and direct dark matter search programme at APC

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Neutrinos and dark matter are the most abundant particles in the Universe and the most elusive, due to their feeble coupling to ordinary matter. The non-zero mass of neutrinos have been unambiguously demonstrated by neutrino flavor oscillation experiments. Nevertheless, neutrinos are assumed to be massless in the Standard Model as no right-handed neutrinos have ever been observed. Furthermore, some relevant parameters of the three-flavour neutrino framework are still missing. Among them, the size of a possible non-zero CP violation phase and the mass ordering are going to be measured in the forthcoming years.

Concurrently, the existence of dark matter, one of the greatest unsolved mysteries in cosmology at the present time, is supported by a wide range of astronomical evidence from the observation of gravitational effects not arising from matter constituted by Standard Model particles. Both neutrinos and dark matter particles are then the natural key to unlock the door toward the physics beyond the Standard Model.

The APC laboratory is at the forefront of this challenge, with a well-established 2020-2030 programme that will lead to the measurements of neutrino mass ordering with **ORCA** and CP-violation with **DUNE**, and to the direct search of Weakly Interacting Mass Particles (WIMPs), the favorite dark matter candidate, down to the so-called “neutrino floor” with **DarkSide**. Beyond the mentioned primary goals, each experiment has a rich scientific program with several synergies, as discussed in the following paragraphs.

ORCA

ORCA (*Oscillation Research with Cosmics in the Abyss*) is the low-energy branch of KM3NeT [KN2016], the next-generation deep-sea neutrino Cherenkov detector, currently under construction in the Mediterranean off the coast of Toulon (France). ORCA is dedicated primarily to fundamental neutrino physics studies, with the main objective of measuring the neutrino mass ordering. The detector will comprise 115 vertical strings with a horizontal spacing of ~20 m, each of them supporting 18 Digital Optical Modules (DOMs), for a total instrumented volume of about 6 Mtons of seawater. With this dense configuration, ORCA will focus on the study of atmospheric neutrino oscillations in the energy range ~1–100 GeV.

A measurement of the neutrino mass ordering with ~2.5 to 5σ statistical significance (depending on the actual ordering) is expected after three years of data taking. ORCA will also provide improved measurements of the atmospheric neutrino oscillation parameters Δm^2_{23}, θ_{23} and will probe the unitarity of 3-neutrino mixing by measuring the normalisation of the tau neutrino flux. Non-standard neutrino interactions, as well as astrophysical neutrino sources, dark matter, and other physics phenomena will also be studied. A first installation phase has started in 2015 and comprises 6 ORCA strings to be deployed by 2019. Four strings are already installed and taking data; the completion of the full ORCA array is planned for 2024. ORCA will provide early measurements of the oscillation parameters and observation of tau neutrino appearance already during the construction phase.

Recently, the P2O proposal has started to explore the possibility to direct a neutrino beam from the Protvino (Russia) accelerator facility towards ORCA [KN2019]. With a baseline of 2595 km, this experiment would allow for the determination of the neutrino mass ordering with a high level

of certainty after only a few years running. Further sensitivity to the CP violation phase could also be achieved by upgrading ORCA to a 10-times denser detector (SuperORCA).
The APC group has been at the forefront of establishing the physics case for ORCA, and is coordinating since 2016 the ANR project DAEMONS (*Demonstrating the Ability of Establishing the Mass Ordering of Neutrinos in the Sea*) in collaboration with CPPM (Marseille) and IPHC (Strasbourg). The group is involved in a wide spectrum of activities ranging from the characterization and calibration of the detector, to the development of simulation and reconstruction tools for the ORCA sensitivity to neutrino mass ordering, to the exploration of the potential of ORCA for low-energy neutrino astrophysics (MeV neutrinos from supernovae and GeV neutrinos from astrophysical hadronic accelerators). The group is also in charge of the design and construction of the first Calibration Unit, to be deployed on the ORCA site in 2020; and one engineer of the team serves since 2019 as KM3NeT Technical Project Manager.
The KM3NeT detector also offers new opportunities for Earth and Sea sciences, thanks to its unique location and capacity to continuously monitor the abyssal environment. The atmospheric neutrinos detected by ORCA can be used for studies of Earth composition by using the neutrino oscillation tomography method. To exploit and further develop these synergies, the APC group has initiated new collaborations with experts geophysicists and marine scientists from IPGP, a partner institute within the LabEx UnivEarthS (see GT12).

DUNE

The Deep Underground Neutrino Experiment (DUNE) is a next generation neutrino oscillation experiment [Acc2016]. A high power wide-band beam operating in neutrino (anti-neutrino) mode will be produced at Fermilab, the flux and flavour composition will be characterised with the Near Detectors. At a baseline of 1,300 km, deep underground at the Sanford Underground Research Facility (SURF, South Dakota), four gigantic Far Detector modules will observe muon neutrino (antineutrino) disappearance and electron and tau neutrino (antineutrino) appearance with the goals of determining the Neutrino Mass Ordering at more than 5 sigmas, CP violation phase, oscillation parameters with high accuracy, and testing the 3 neutrino flavour paradigm.
The DUNE Far Detector modules will be liquid argon TPCs (LArTPC), each holding a fiducial mass of 10 ktons. With huge detectors deep underground, DUNE will also search for Nucleon Decay and the astrophysical observations of Galactic Supernovae.
The LArTPC technology provides excellent tracking and calorimetry which is ideal for massive neutrino detectors that require high signal efficiency and effective background discrimination. It allows to identify and precisely measure neutrino events over a wide range of energies, also providing high resolution reconstruction of kinematic properties. The full imaging of events in the DUNE detector will allow the study of neutrino interactions and other rare events with unprecedented detail.
The DUNE TPCs are conceived to make fine-grained (~3mm) 'images' of the ionisation tracks from the products of neutrino interactions in the liquid Argon. Two different technologies are proposed for the readout of the drifted ionization charge, which can be collected directly in the liquid (Single-Phase) or after extraction and multiplication in a layer of gaseous Argon (Dual-Phase). These two technologies are currently being trialled for the DUNE Far Detector at

the CERN neutrino platform. The protoDUNEs, one Single Phase and one Dual Phase, are a necessary R&D step towards the construction of the DUNE Far Detectors. With them all the engineering solutions and installation procedures will be tested. The prototypes are the largest liquid argon TPCs ever constructed, holding several hundreds of tonnes of liquid argon. With these large detectors, the long term performance and stability will be demonstrated. The Single Phase prototype has already taken data with a charged particle beam, which allows characterisation of the detector response over the energy range of interest for DUNE (~0.5 to 8 GeV). The Dual Phase prototype is currently undergoing commissioning and will be first tested with cosmic ray muons.

French groups are heavily involved with the development of the Dual Phase technology and the Dual Phase protoDUNE. The APC team has an important role in the development of the read out electronics of the liquid argon scintillation light (Light Read Out) which is vital for the localisation of the event within the detector by providing the time-stamp of the event. The system will also provide a trigger and complementary information for energy reconstruction and particle identification. As well as this technical development, the APC team has focused on the simulation of the response of the dual-phase detector and on the development of dedicated analysis algorithms, including machine learning techniques for particle and event classification. APC is also one of the few groups in the collaboration leading the first developments of the software for the Dual Phase detector in the global framework of DUNE.

The APC team intends to provide LRO cards for the final Dual Phase DUNE module which should be produced and installed at the detector during 2025. As well as a hardware contribution to DUNE, the APC team is also working on software, in particular simulation and reconstruction focussed towards the Dual-Phase module. The APC team is working on Dual-Phase dedicated reconstruction algorithms which will be tested on protoDUNE Dual-Phase which is currently undergoing commissioning. ProtoDUNE Dual-Phase will be first tested with cosmic rays muons and with a charged particle beam scheduled for 2021. The group aims to be heavily involved in the data analysis from this prototype and the analysis preparation towards the Dual Phase detector module including simulations, tuning of reconstruction and Particle ID algorithms, and sensitivity studies.

DarkSide

Dual-phase TPCs, based on a liquid xenon (LXe) or on argon (LAr) target, are currently the most sensitive detectors searching for WIMPs with masses above 1.8 GeV/c^2. The success of this technology is explained by its “intrinsic” scalability, radio-purity, background rejection, and very low energy threshold down to a few ionization electrons. LAr has the additional feature to discriminate electron recoil background with a large power (>10^8) by exploiting the scintillation pulse shape discrimination (PSD).

On the basis of this discrimination power and thanks to the use of argon extracted from deep underground (UAr), with a low content of cosmogenic contamination, the DarkSide Collaboration has built a multi-stage program aimed at searching for WIMP interactions in a background-free mode.

DarkSide-50, the current TPC operating with 50 kg active mass, has already reached two milestones: the most stringent exclusion limits on WIMPs in the [1.8, 4] GeV/c^2 mass range

[DS2018a], and the operation in complete background-free mode above 20 GeV/c^2 [DS2018b]. Building on this successful experience, the four world-leading argon dark matter projects (ArDM at LSC, DS-50 at LNGS, DEAP-3600 and MiniCLEAN at SNOLab) agreed on joining forces to carry out a unified program forming the Global Argon Dark Matter Collaboration (GADMC), counting ~350 scientists from ~80 institutes. The GADMC is engaged to build DarkSide-20k [DS2018c], at LNGS, which will operate from 2023 with 20 ton fiducial mass, and the ultimate detector Argo, at SNOLab, with 300 ton fiducial mass. This roadmap is perfectly in line with APPEC, which recommends "*a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.*"
DarkSide-20k TPC will be fully immersed in a LAr bath, housed by a 600 m^3 protoDUNE cryostat, and will be equipped with 300,000 low-background and high-efficiency silicon photomultipliers (SiPMs). Such innovative design is the key to unlocking the path to large LAr TPC detector masses, while maintaining an "instrumental background-free" experiment: less than 0.1 events (other than ν-induced nuclear recoils) are expected in the WIMP search region in 100 t yr exposure. A 1-ton prototype detector will be built at CERN in 2020 and deployed at LNGS in 2021 to test the new design.
APC, the pioneer institute of DarkSide in France, has provided fundamental contributions to the success of DarkSide-50, spanning over a wide range of experimental aspects from simulation development to data reconstruction and analysis, with leadership roles in the ARIS project, which has provided the most accurate measurement of the nuclear recoil quenching in LAr, and in the low-mass analysis.
In association with LPNHE and CPPM (active member of DarkSide-20k since January 2019), APC will focus its activity in the coming years on three main items: (1) calibration strategy, with the design of a guide tube that enables the circulation of neutron and gamma sources; (2) data reconstruction, with specific focuses on xy-reconstruction with neural network, and on optimum filter of SiPM waveforms; (3) low-mass physics analysis, to extend current limits on low-mass WIMPs and on alternative dark matter candidates, like axions and sterile neutrinos.

Synergies

The APC roadmap for neutrino physics and dark matter search will also rely on a number of synergies between the three main projects, covering both physics cases and technological challenges. On the physics side, ORCA and DUNE will measure the Neutrino Mass Ordering with two independent techniques: their combination will allow to strongly enhance the statistical significance. Such synergy will be extended to the CP-phase, in case the Protvino-to-ORCA beam project is carried out.
The three projects are fully complementary on Supernova neutrinos. Simultaneous DUNE/DarkSide detection of a galactic supernova would allow to inspect the neutrino mass hierarchy by comparing electronic neutrinos detected by DUNE via charged current, and the flavor insensitive detection by DarkSide via coherent scattering off nuclei. Concurrently, KM3NET/ORCA can collect a very large statistics sample of Supernova electron anti-neutrinos,

and potentially address the mass ordering by studying the neutrino light curve, in particular its rise time during the accretion phase.

Theoretically, serious effort will be required to fully understand neutrino flavor evolution in such environments and to perform solid predictions of the neutrino fluxes and spectra. The future time and energy measurement of neutrino signals from an (extra)galactic event, with complementary information from different observatories, will be crucial both for understanding the supernova dynamics and for neutrino properties. Such developments are also necessary to answer the longstanding issue of the sites for r-process nucleosynthesis, in relation with kilonovae. Theoretical neutrino astrophysics is and will be one of the axes developed at APC [Vol13].

In order to detect a supernova burst, all three experiments share the common challenge of defining a dedicated trigger strategy that would allow generating real-time alerts through the SNEWS network. The possibility to use the neutrino arrival time difference at three (or more) detectors to reconstruct the supernova position by triangulation is also under study.

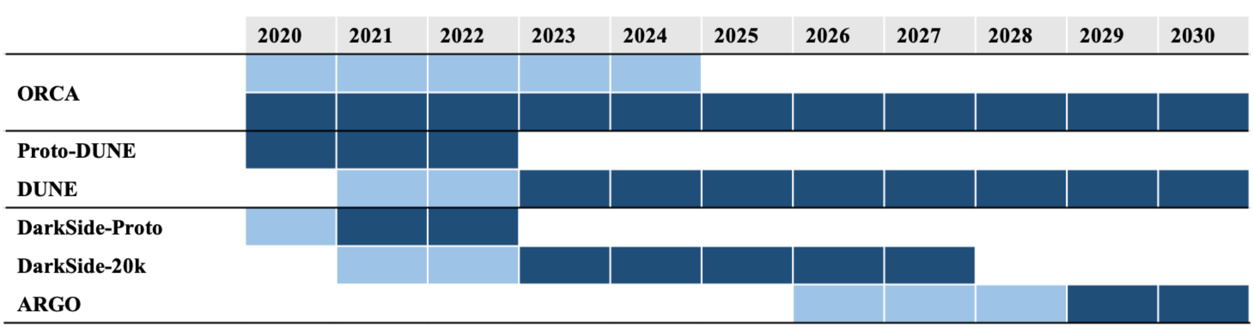
Furthermore, DarkSide and DUNE can provide a high-precision full neutrino spectroscopy of the Sun: DarkSide, thanks to the very low-background and high resolution, will have access to *pp*, *pep*, ^{7}Be and CNO components, exploiting elastic scattering off electrons and coherent scattering off nuclei [Fra2016]; DUNE, thanks to its gigantic target mass, will observe, via charged-current, low-flux and high-energy components from ^{8}B and *hep* [Cap2018].

From a technological point of view, the use of LAr TPCs, although optimized to the corresponding energy range, makes DUNE and DarkSide highly synergistic in facing common technological challenges, from cryogenics to photon detection and optical simulation.

In addition, APC is actively involved in a number of astrophysical experiments (LSST, Euclid, Simons Observatory, as well as the CMB Stage-4 proposal) which will measure the sum of neutrino masses with enough sensitivity to distinguish between hierarchies. In addition, CMB Stage-4 will have the sensitivity to test extensions of the Standard Model which predict predict low-mass relic particles, such as axion-like particles and sterile neutrinos, through measurements of the early thermal history of the Universe.

Timeline

The timeline of the three projects between 2020 and 2030 is shown in the following table (light blue: construction phase; dark blue: data taking)



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